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Internal Note

The ALICE Event Generator Pool

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Abstract

A description and comparison of various commonly used event generators for very energetic hadron-hadron, hadron-nucleus and nucleus-nucleus collisions is presented together with a description of the ALICE universal output format and some simple examples of how to install and run the programs.
This report is intended to provide the necessary information for people who want to know the basic physics behind the various models, run the various generators and analyse the produced output.

Contents

1 Introduction

The ALICE event generator pool is a batch of programs, intended to study the physics of very energetic hadron-hadron, hadron-nucleus and nucleus-nucleus collisions upto LHC energies.

To enable analysis of the various models by means of the same user program, a universal output format has been defined and implemented in the generators discussed in this report. Due to this universal format, the produced output files of the various generators can be used as input to the ALICE detector simulation package [1] to serve detector design- and feasability studies.

The generator programs are maintained in CMZ [2] format and the code of each of the various packages is contained in a single source code file (e.g. hijing.cmz) which is available from the central ALICE offline program pool **/afs/cern.ch/alice/offline/pams** at CERN.

2 Program installation and execution

The complete library of a certain generator package (e.g. SHAKER) is created and installed by means of the automatic installation procedures provided by CMZ [2].
To create the SHAKER library, it is sufficient to enter the command

```
cmz -install shaker
```

By invoking this command, the CMZ machinery is activated and the installation macros provided in the **shaker.cmz** file make sure that compilation and library creation is performed.

Since various sequences of other packages (e.g. JETSET [3]) may be used within the code, the corresponding cmz file(s) have to be contained in the same directory as where the generator cmz file (e.g. shaker.cmz) is located. In case a certain generator package needs such additional sequences, this will be mentioned in the discussion of that generator hereafter.

Once the compilation and library creation steps have been completed, a library file (e.g. libshaker.a) is created which contains the compiled subroutines of the complete generator package. This library file may then be moved to a directory containing the libraries of the various other ALICE offline packages. At CERN all these libraries of the offline program pool can be found at **/afs/cern.ch/alice/offline/libs**.

To prevent problems with different compiler versions, it is NOT recommended to copy these binary libraries to your home institute. Make sure to always create the libraries from scratch at your home institute by following the procedures outlined above.

When the library of a certain package has been installed at some central location, various users can use that library to run their private generator jobs. The procedures on how to run the various packages will be explained hereafter.

3 The universal output format

As mentioned before, the output data format of the ALICE event generators is identical for all of them and as such a detailed description of the structure of the data written onto the output stream will be presented here.

- The format adopted is the exchange format of column wise ntuples [4] (CWN). This means that the data files can be transported by binary FTP and reading can be performed interactively by using PAW [5] directly or in batch using the HBOOK [4] facilities.
- The data structure is based on track information, which means that each record (i.e. a row in the ntuple scheme) contains all the information belonging to a certain track.

  This will keep the number of columns needed for all our data well within the HBOOK limit of 50000 and will enable a direct investigation of the detector simulation results [1] against the original input data for each individual particle.
- To indicate also the run and event structure, the first track record of an event contains some additional header data blocks, namely :

  [GENHDR]

  The contents of these data blocks will be explained hereafter.
- As described in the HBOOK and PAW manuals [4, 5], the so produced files are direct access files, which means that only the data requested will be read-in. In case of our large data samples this easily gives large gain factors in reading speed compared to conventional sequential files, whereas also a certain event can be addressed directly by the record number without 'skipping' the events in front.
- The CWN's contain the possibility of bit-wise packing of the data to be stored and this packing can be performed automatically and very efficiently [4]. This results in a considerable reduction of the data volume.

3.1 Description of the data blocks

Some words of the header data blocks are meant for identification purposes and as such they contain some pre-defined values. The contents of these data blocks will be described in detail here.

[GENHDR] : Event header data

Data stored : NIHEAD,IHEAD(NIHEAD),NRHEAD,RHEAD(NRHEAD)

In general, the contents will differ according to the event generator package used. However, the words NIHEAD, NRHEAD and IHEAD(1-6) will be universally defined for all event generators we will use for ALICE.

A complete header description for each generator will be presented hereafter in the discussion of the various packages. In addition, a complete format description is available in every generator cmz file, available in the ALICE offline program pool. Various generators are currently available and to serve as an example, the contents of the SHAKER event header is given below.

Layout of the SHAKER event header data

NIHEAD = Number of words stored in IHEAD()
NRHEAD = Number of words stored in RHEAD()

IHEAD(1) = Generator identifier (2=SHAKER)
IHEAD(2) = date
IHEAD(3) = time
IHEAD(4) = run number
IHEAD(5) = event number
IHEAD(6) = number produced particles
IHEAD(7) = dn/dy of charged particles
IHEAD(8) = not used
IHEAD(9) = not used
IHEAD(10) = not used
IHEAD(11) = not used
IHEAD(12) = not used

RHEAD(1) = lowerbound of rapidity window (YMIN)
RHEAD(2) = upperbound of rapidity window (YMAX)
RHEAD(3) = maximum Pt cutoff (GeV/c)
RHEAD(4) = η/π ratio
RHEAD(5) = p/π ratio
RHEAD(6) = $K^{\pm}/\pi^{\pm}$ ratio

[GENDAT] : Track data

Data stored : IDPART,THETA,PHI,P,E

IDPART = Particle identification code (GEANT3.21/GALICE convention [6])
THETA = Polar angle in degrees [0,180]
PHI = Azimuthal angle in degrees [0,360]
P = Momentum in GeV/c
E = Total energy in GeV

The definition of the contents of this track data block is absolutely identical for all the ALICE event generators.

Note : The generator identifier codes (i.e. IHEAD(1)) are defined as follows :

1 = Venus
2 = Shaker
3 = Hijing
4 = Luciae
5 = Dtujet
6 = Dpmjet
7 = SFM
8 = TPHIC (two photon generator)
9 = Fragment (generation of nuclear fragments)
10 = Phojet (two photon generator)

3.2 Example of a data file

To illustrate the structure of a data file containing several events, the following example shows a schematic layout of a data file with 3 events containing 6, 10 and 5 tracks respectively.

Track 1 ...	[GENHDR]	[GENDAT]
Track 2 ...		[GENDAT]
Track 3 ...		[GENDAT]
Track 4 ...		[GENDAT]
Track 5 ...		[GENDAT]
Track 6 ...		[GENDAT]
Track 1 ...	[GENHDR]	[GENDAT]
Track 2 ...		[GENDAT]
Track 3 ...		[GENDAT]
Track 4 ...		[GENDAT]
Track 5 ...		[GENDAT]
Track 6 ...		[GENDAT]
Track 7 ...		[GENDAT]
Track 8 ...		[GENDAT]
Track 9 ...		[GENDAT]
Track 10 ...		[GENDAT]
Track 1 ...	[GENHDR]	[GENDAT]
Track 2 ...		[GENDAT]
Track 3 ...		[GENDAT]
Track 4 ...		[GENDAT]
Track 5 ...		[GENDAT]

4 The phase space generator SHAKER

4.1 Description

The SHAKER program is a simple central rapidity phase space event generator developed for the simulation of LHC Heavy Ion events. All event information is managed according to the Lund conventions within the JETSET 7.3 program [3].

The main input parameter is the charged particle density at central rapidity, according to which the various types of particles are generated (π^0, η, π^+, p, K^+, K^0 and their anti-particles). The rapidity distributions are flat between fixed limits. The transverse momentum distributions are those measured at the Tevatron [7], with the exception of that of the η particle, for which the Tevatron π^0 distribution has been used applying m_T scaling [8]. Furthermore, for $P_t > 2$ GeV/c the spectra of $p, \bar{p}$ and kaons have been given the form of the corresponding pion spectra.

Particle ratios are fixed by isospin invariance (π^0/π^+, K^0/K^+), by the measured Tevatron values (K^+/π^+, p/π^+) [7], or by m_T-scaling of the measured asymptotic values (η/π^0).

In the generation of the central event sample discussed hereafter, a rapidity window $-1.5 \leq y \leq 1.5$ and a flat charged particle density of dN/dy=8000 was used.

4.2 Program execution

Since the SHAKER program makes use of some JETSET [3] sequences, the source code file **jetsethi.cmz** (an updated jetset version to cope with very large particle multiplicities) has to be available during the creation of the shaker library.

Once the SHAKER library has been installed at some central location, various users can use that library to run their private SHAKER event generation jobs.

The running conditions for the event generation are tailored by means of FFREAD [9] steering cards. The functionality of the various steering cards is explained by the comment lines in front of them as shown in the example given below.

An example job for a UNIX environment looks as follows :

```
#!/bin/sh
#
# SHAKER phase space event generation
#
# The output file
ln -s $HOME/test.cwn shaker.cwn
#
ln -s $ALICE/pams/shaker.cmz shaker.cmz
cat << *EOR >cradle.kumac
exec $HOME/cmzlogon
set f -lan
file shaker -r
```

```
cd shaker
cc shaker
rel shaker
exit
*EOR
#
cmz -b cradle.kumac
#
f77 *.o -L$ALICE/libs -lshaker -ljetsethi -L$CERN/libs -lgenlib -lkernlib -lpacklib
a.out << *EOR
C — Steering cards for SHAKER event generation —
LIST
C — Run number
SHRUN  2
C — Maximum number of events to be generated
SHNEV  50
C — Debug level
SHDEB  0
C — Print a line with event info every SHNPR events
SHNPR  10
C — I/O pars LUNOUT (0=none) and IOFINL (1=only final state part.)
SHOUT  20  1
C — dN/dY value
SHNDY  8000
C — Ymin and Ymax rapidity window (Ymin ≤ y ≤ Ymax)
SHYLM  -1.5   1.5
C — Minimum and maximum Pt in GeV/c
SHPTL   0.   10.
C — Particle generation parameters (1=on 0=off)
C —       pi0 eta pic p kc k0 weak-decays weighted-gen.
SHGEN   1    1    1   1   1   1        0                  0
C — Define (anti)particles to be regarded as stable (LUND codes)
C —       pi0(111) eta(221) lambda(3122)
SHSTB   111 221 3122
END
*EOR
```

The produced output file may be investigated directly using PAW [5], or can be analysed by means of a batch job using the HBOOK [4] facilities.
A detailed description of the event header data has already been provided in the previous section.

5 VENUS

5.1 General information

VENUS (Very Energetic NUclear Scattering) is a Monte-Carlo procedure to simulate hadronic interactions at ultrarelativistic energies (hadron-hadron, hadron-nucleus, nucleus-nucleus scattering), and also interactions involving leptons (e+e-annihilation, lepton-nucleon, lepton-nucleus scattering). VENUS is based on Gribov-Regge theory of multiple pomeron exchange and classical relativistic string dynamics. A detailed description can be found in [10]. Here we use the version VENUS 4.12. A FORTRAN text of the program can be obtained from the author via e-mail: werner@tick.mpi-hd.mpg.de. This code should not be distributed without notifying the author, indicating what the code is going to be used for. Depending on the type of reaction and the kind of observables analysed, the systematic uncertainties of the VENUS simulations vary strongly, and this should be clarified before using VENUS.

5.2 Important features

- Covariant treatment of secondary interactions. Each produced particle is allowed to reinteract with other produced particles or with spectators. Important for hadron-nucleus, nucleus-nucleus and lepton-nucleus scattering. No final state interaction, if the parameter 'radiac' is set zero.

- Participation of antiquarks (in addition to quarks) in the colour exchange mechanism to form strings.

- Possibility of diquark breakup, leading to multi-strings, like a forward quark linked via two (!) strings to two backward quarks (double-string). Such strings fragment differently than quark-diquark strings. In case of the double-string, the forward quark will fragment via two breaks into a leading baryon.

- Sophisticated fragmentation procedure. Since space-time evolution is an important issue concerning final state interactions, it is not enough to have a fragmentation model which works, it should have the right space-time description! Therefore the Field-Feynman model of earlier versions (<3.00) has been abandoned and replaced by a very powerful and appealing procedure suggested by Artru/Mennessier.

- Very large resonance table, including for example all nucleon resonances up to 2 GeV.

- For version ≥4.01, Gribovs cut-pomeron probabilities to determine the weights for multi-colour-exchange have been used.

5.3 File definitions

The subroutine 'afiles' contains all file definitions. The files are:

optns: input file (may be the terminal).
check: contains information and error messages.
histo: used for analysis (not described here).
data : collects all produced particles.

5.4 Some parameters

A list of parameters is very long. Most of them have been fitted to reproduce experimental data. Here we point out the parameters important to run VENUS.

- labsys: (D=1).
  =1: laboratory frame of the fixed target.
  $\neq$1: nucleon-nucleon center of mass frame.
- bminim: (D=0.0 fm) minimum impact parameter.
- bmaxim: (D=10000.0 fm) maximum impact parameter.
- seedi: (D=0.0) initial seed for random number generator.
- ndecay: (D=0) decay suppression. Specifies which resonances are not decayed.
  = 0000001 : all resonances.
  = 0000010 : K_S^0, K_L^0.
  = 0000100 : Λ and its anti-particle.
  = 0001000 : Σ^+, Σ^- and its anti-particles.
  = 0010000 : Ξ^-, Ξ^0 and its anti-particles.
  = 0100000 : Ω^- and its anti-particle.
  = 1000000 : π^0.
- ndecax: (D=0) decay suppression. specifies which resonances are not decayed.
  = 0000001 : J/Ψ.
  = 0000010 : K^0 and its anti-particle.
  = 0000100 : $\Delta^{++}, \Delta^+, \Delta^-, \Delta^0$ and its antiparticles.
  = 0001000 : ρ, ω, ϕ.
  = 0010000 : η.
  = 0100000 : η'.

5.5 Input to run VENUS

To simulate a nucleon-nucleon, nucleon-nucleus, nucleus-nucleus collision, the following input is required:

```
’had’
nevent ndisplay energy zproj aproj ztarg atarg i
’param1’ value1
’param2’ value2
...
’parami’ valuei
’stp’
```

where ’had’ and ’stp’ has to be taken litterally. The variables are:

nevent : number of events
ndisplay: a message occurs after ndisplay events being done
energy: colliding energy (GeV) per nucleon (in the case of NN c.m.s. it should be negative)
zproj: number of projectile protons
aproj: number of projectile nucleons
ztarg: number of target protons
atarg: number of target nucleons
i: number of parameters or options to be changed

If i>0 one has to provide i lines each containing

```
’param’ value
```

param is the name of the parameter or option, value is the new value. A list of parameters/options and there default values can be found in subroutine ’ainitl’.

- example 1:
  O + Pb at 200 A GeV, 5000 events, message after 100, default parameter values:
  ```
  ’had’
  5000 100 200.0 8 16 82 207 0
  ’stp’
  ```

- example 2:
  Pb + Pb at $\sqrt{s} = 6.0$ GeV, 1 central event, no message, suppress decays of Λ, Ω^- and its anti-paticles:

```
'had'
1 1000 -6000.0 82 207 82 207 4
'labsys' 0
'bminim' 0.0
'bmaxim' 3.0
'ndecay' 100100
'stp'
```

5.6 Output

The results are stored in the file 'ifdt', defined in subroutine 'afiles'. The storage is performed in subroutine 'astore', which is written in a very tranparent way to make changes by users very easy. In order to learn what kind of variables are stored in which way, the user is referred to subroutine 'astore' (subroutines are written in alphabetic order).

For use within the ALICE pool, the routine astore has been updated such that our universal output format is produced. The contents of the VENUS event header is the following.

Layout of the VENUS event header data

IHEAD(1) = Generator identifier (1=VENUS)
IHEAD(2) = date
IHEAD(3) = time
IHEAD(4) = run number
IHEAD(5) = event number
IHEAD(6) = number produced particles
IHEAD(7) = number of projectile participants
IHEAD(8) = number of target participants
IHEAD(9) = Z of the projectile
IHEAD(10) = Z of the target
IHEAD(11) = particle decay parameter 'ndecay'
IHEAD(12) = number of collisions

RHEAD(1) = number of effective collisions
RHEAD(2) = impact parameter in fm
RHEAD(3) = momentum per incoming nucleon (GeV/c)
RHEAD(4) = CMS energy per nucleon-nucleon collision (GeV)
RHEAD(5) = Baryon radius in fm
RHEAD(6) = Meson radius in fm

5.7 Particle numbering scheme

The VENUS internal particle numbering scheme is the same as for the ISAJET code. Quarks and leptons are numbered in order of mass:

$$\begin{array}{ll}
u = 1 & \nu_e = 11 \\
d = 2 & e^- = 12 \\
s = 3 & \nu_\mu = 13 \\
c = 4 & \mu^- = 14 \\
b = 5 & \nu_\tau = 15 \\
t = 6 & \tau^- = 16
\end{array}$$

with a negative sign for antiparticles. Arbitrary conventions are:

$$\begin{array}{ll}
g = 9 & \gamma = 10 \\
K_S^0 = 20 & K_L^0 = -20 \\
W^+ = 80 & Z^0 = 90
\end{array}$$

The code for a meson is an integer $+-jkl$, where $j \leq k$ are the quarks and l is the spin. The sign is for the j quark. Flavor singlet mesons are ordered by mass:

$$\begin{array}{ll}
\pi^0 = 110 & \eta = 220 \\
\eta' = 330 & \eta_c = 440
\end{array}$$

Similarly, the code for a baryon is a compound integer $+-ijkl$ formed from the three quarks i,j,k and a spin label $l = 0, 1$. The code for a diquark is $+-ij00$.
The full list of the particle codes is pointed out in the program.

5.8 Restrictions

The following dimensions are used (defined with parameter statemt):

max number of strings per event: mxstr=20000
max number of particles per event: mxptl=150000

To simulate Pb+Pb event at $\sqrt{s}$=6.0 TeV/n the parameter 'mxptl' should be increased upto 700000. The program is only valid for collisions with c.m. energy $\sqrt{s}$ above 12 GeV/n.

5.9 Typical running time

The running time largely depends on the energy and the type of collisions. For example on CSF/CERN (not including initialization):

$S + S$(central)	$\sqrt{s}$=6.0 TeV/n $\sim$ 1 event/10 min.
$Ag + Ag$(central)	$\sqrt{s}$=6.0 TeV/n $\sim$ 1 event/2 hours
$Pb + Pb$(central)	$\sqrt{s}$=6.0 TeV/n $\sim$ 1 event/10 hours

6 HIJING

6.1 General information

HIJING (Heavy Ion Jet INteraction Generator) combines a QCD inspired model for jet production [12] with the Lund model [13] for jet fragmentation. The formulation of HIJING was guided by the Lund FRITIOF [14] and Dual Parton model [15] for soft nucleus-nucleus reactions at intermediate energies ($\sqrt{s} \approx 20$ GeV/nucleon) and the successful implementation of perturbative QCD processes in the PYTHIA [11] model for hadronic collisions.

Binary approximation and Glauber geometry for multiple interaction are used to simulate pA and AA collisions. A parametrized parton distribution function inside a nucleus is used to take into account parton shadowing. Jet quenching is modeled by an assumed energy loss dE/dz of partons traversing the produced dense matter. A simplest color configuration is assumed for the multiple jet system and Lund jet fragmentation model is used for the hadronization. HIJING does not hold secondary interactions.

PYTHIA subroutines and Lund jet fragmentation scheme are used. Therefore, HIJING uses the same particle identification code as JETSET.72. Users can also use subroutines in JETSET.72 and change the values of parameters in JETSET.72 and PYTHIA therein. But there are some special parameters in HIJING which users have to specify or change. To save compiling time, JETSET.7.2 is not included in HIJING. To meet some specific needs of HIJING, JETSET.72 has been modified and renamed as HIPYSET. One should link HIJING with HIPYSET and the main program.

HIJING is available via anonymous ftp nsdssd.lbl.gov. The program package is in the directory /pub/xnwang after you login via anonymous ftp. The package contains:

hijing.f - HIJING program
hipyset.f - modified JETSET for use in HIJING
hijing.doc - short description of HIJING
hijing.tex - long LaTex file of HIJING description
readme.doc - description of changes in the latest version

Please report any problems with the program to the author Xin-Nian Wang xnwang@nsdssd.lbl.gov. The event samples used in the analysis described here were produced using the version HIJING 1.31.

6.2 Main subroutines

After supplying the desired parameters, the first subroutine a user has to call is HIJSET. Then subroutine HIJING can be called to simulate the specified events.

SUBROUTINE HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)
Purpose: to initialize HIJING for specified event type, collision frame and energy.

EFRM: colliding energy (GeV) per nucleon in the frame specified by FRAME.
FRAME: character variable to specify the frame of the collision.

'CMS': nucleon-nucleon center of mass frame, with projectile momentum in $+z$ direction and target momentum in $-z$ direction.
'LAB': laboratory frame of the fixed target with projectile momentum in $+z$ direction.

PROJ, TARG: character variables of projectile and target particles.

'P': proton.
'PBAR': anti-proton.
'N': neutron.
'NBAR': anti-neutron.
'PI+': π^+.
'PI−': π^-.
'A': nucleus.

IAP, IAT: mass number of the projectile and target nucleus. Set to 1 for hadrons. IZP, IZT: charge number of the projectile and target nucleus, for hadrons it is the charge number of that hadron (=1, 0, −1).

SUBROUTINE HIJING (FRAME, BMIN, BMAX)
Purpose: to generate a complete event as specified by subroutine HIJSET and the given parameters as will be described below. This is the main routine which can be called (many times) only after HIJSET has been called once.

FRAME: character variable to specify the frame of the collision as given in the HIJSET call.
BMIN, BMAX: low and up limits (fm) between which the impact parameter

squared b^2 is uniformly distributed for pA and AB collisions. For hadron-hadron collisions, both are set to zero and the events are automatically averaged over all impact parameters.

6.3 Common blocks for event information

There are mainly two common blocks which provide users with important information of the generated events. Common block HIMAIN1 contains global information of the events and common block HIMAIN2 of the produced particles.

COMMON/HIMAIN1/NATT, EATT, JATT, NT, NP, N0, N01, N10, N11
Purpose: to give the overall information of the generated event.

NATT: total number of produced stable and undecayed particles of the current event.
EATT: the total energy of the produced particles in c.m. frame of the collision to check energy conservation.
JATT: the total number of hard scatterings in the current event.
NP, NT: the number of participant projectile and target nucleons in the current event.
N0, N01, N10, N11: number of N-N, N-$N_{wounded}$, $N_{wounded}$-N, and $N_{wounded}$-$N_{wounded}$ collisions in the current event (N, $N_{wounded}$ stand for nucleon and wounded nucleon respectively).

COMMON /HIMAIN2/KATT(130000,4), PATT(130000,4)
Purpose: to give information of produced stable and undecayed particles. Parent particles which decayed are not included here.

KATT(I, 1): (I=1,$\cdots$,NATT) flavor codes (see appendix) of the produced particles.
KATT(I, 2): (I=1,$\cdots$,NATT) status codes to identify the sources from which the particles come.

=0: projectile nucleon (or hadron) which has not interacted at all.
=1: projectile nucleon (or hadron) which only suffers an elastic collision.
=2: from a diffractive projectile nucleon (or hadron) in a single diffractive interaction.
=3: from the fragmentation of a projectile string system (including gluon jets).
=10 target nucleon (or hadron) which has not interacted at all.
=11: target nucleon (or hadron) which only suffers an elastic collision.

=12: from a diffractive target nucleon (or hadron) in a single diffractive interaction.
=13: from the fragmentation of a target string system (including gluon jets).
=20: from scattered partons which form string systems themselves.
=40: from direct production in the hard processes (currently, only direct photons are included).

KATT(I,3): (I=1,$\cdots$,NATT) line number of the parent particle. For finally produced or directly produced (not from the decay of another particle) particles, it is set to 0 (The option to keep the information of all particles including the decayed ones is IHPR2(21)=1).
KATT(I,4): (I=1,$\cdots$,NATT) status number of the particle.

=1: finally or directly produced particles.
=11: particles which has already decayed.

PATT(I, 1-4): (I=1,$\cdots$,NATT) four-momentum (p_x, p_y, p_z, E) (GeV/c, GeV) of the produced particles.

6.4 Example program

The following is an example program for calling HIJING. One should include all the common blocks and the data values which are listed below in his own program.

```
      CHARACTER FRAME*8, PROJ*8, TARG*8
      DIMENSION DNDPT(50),DNDY(50)
      COMMON/HIPARNT/HIPR1(100), IHPR2(50), HINT1(100), IHNT2(50)
C....information of produced particles:
      COMMON/HIMAIN1/NATT, EATT, JATT, NT, NP, N0, N01, N10, N11
      COMMON/HIMAIN2/KATT(130000,4), PATT(130000,4)
C....information of produced partons:
      COMMON/HIJJET1/NPJ(300), KFPJ(300,500), PJPX(300,500),
     &   PJPY(300,500), PJPZ(300,500), PJPE(300,500), PJPM(300,500),
     &   NTJ(300), KFTJ(300,500), PJTX(300,500), PJTY(300,500),
     &   PJTZ(300,500), PJTE(300,500), PJTM(300,500)
      COMMON/HIJJET2/NSG, NJSG(900), IASG(900,3), K1SG(900,100),
     &   K2SG(900,100), PXSG(900,100), PYSG(900,100), PZSG(900,100),
     &   PESG(900,100), PMSG(900,100)
      COMMON/HISTRNG/NFP(300,15), PP(300,15), NFT(300,15), PT(300,15)
C....initialize HIJING for Au+Au collisions at c.m. energy of 200 GeV:
      EFRM=6000.0
      FRAME='CMS'
      PROJ='A'
      TARG='A'
```

```
               IAP=207
               IZP=82
               IAT=207
               IZT=82
               CALL HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)
C....generating 1 central events:
               N_EVENT=1
               BMIN=0.0
               BMAX=0.0
               DO 2000 J=1,N_EVENT
                    CALL HIJING (FRAME, BMIN, BMAX)
C....calculate rapidity and transverse momentum distributions of
C....produced charged particles:
                    DO 1000 I=1,NATT
C........      exclude beam nucleons as produced particles:
                         IF(KATT(I,2).EQ.0 .OR. KATT(I,2).EQ.10) GO TO 1000
C........      select charged particles only:
                         IF (LUCHGE(KATT(I,1)) .EQ. 0) GO TO 1000
                         PTR=SQRT(PATT(I,1)**2+PATT(I,2)**2)
                         IF (PTR .GT. 10.0) GO TO 100
                         IPT=PTR/0.2
                         DNDPT(IPT)=DNDPT(IPT)+1.0/FLOAT(N_EVENT)/0.2/2.0/PTR
100                      Y=0.5*LOG((PATT(I,4)+PATT(I,3))/(PATT(I,4)-PATT(I,3)))
                         IF(ABS(Y) .GT. 10.0) GO GO 1000
                         IY=ABS(Y)/0.2
                         DNDY(IY)=DNDY(IY)+1.0/FLOAT(N_EVENT)/0.2/2.0
1000                CONTINUE
2000           CONTINUE
C....print out the rapidity and transverse momentum distributions:
               WRITE(*,*) (0.2*(K-1),DNDPT(K),DNDY(K),K=1,50)
               STOP
               END
```

6.5 Restrictions on the complexity of the problem

The program is only valid for collisions with c.m. energy $\sqrt{s}$ above 4 GeV/n. For central $Pb + Pb$ collisions, some arrays have to be extended above $\sqrt{s} = 10$ TeV/n.

6.6 Output

The contents of the HIJING event header is the following.

Layout of the HIJING event header data

IHEAD(1) = Generator identifier (3=HIJING)
IHEAD(2) = date
IHEAD(3) = time
IHEAD(4) = run number
IHEAD(5) = event number
IHEAD(6) = number of produced stable and undecayed particles.
IHEAD(7) = 10000 (the number of projectile participants) + (the number of target participants)
IHEAD(8) = 1000 (the number of hard scatterings) + (the number of N-N collisions)
IHEAD(9) = Z of the projectile
IHEAD(10) = Z of the target
IHEAD(11) = not used
IHEAD(12) = 10000 (the number of N-$N_{wounded}$ collisions) + (the number of $N_{wounded}$-N collisions)

RHEAD(1) = the number of $N_{wounded}$-$N_{wounded}$ collisions.
RHEAD(2) = impact parameter in fm
RHEAD(3) = lab. system (1) or c.m.s. (0)
RHEAD(4) = beam energy (GeV/n) for lab., $\sqrt{s}$ (GeV) for CMS
RHEAD(5) = Min. impact parameter in fm
RHEAD(6) = Max. impact parameter in fm

6.7 Typical running time

The running time largely depends on the energy and the type of collisions. For example on SPARCstation ELC (not including initialization):

pp	$\sqrt{s}$=200 GeV	~ 700 events/min.
pp	$\sqrt{s}$=1.8 TeV	~ 250 events/min.
$Au + Au$(central)	$\sqrt{s}$=200 GeV/n	~ 1 event/min.
$Pb + Pb$(central)	$\sqrt{s}$=6.4 TeV/n	~ 1 event/10 min.

6.8 Unusual features of the program

The random number generator used in the program is a VAX/VMS system subroutine RAN(NSEED). When compiled on a SPARCstation, `-xl` flag should be used. This function is not portable. Therefore, one should supply a random number generator to replace this function whenever a problem is encountered.

7 The dual parton model generator DPMJET-II

7.1 The model

Soft multiparticle production characterizing hadronic interactions at supercollider or Cosmic Ray energies cannot be understood purely within theoretical approaches provided by perturbative QCD. The nonperturbative soft component of hadron production, which is responsible for all of hadron production at low energies is still acting at higher energies.

Using basic ideas of the dual topological unitarization scheme [16, 17] the Dual Parton Model (DPM) (a recent review is given in Ref.[18]) has been very successfully describing soft hadronic processes. Observations like rapidity plateaus and average transverse momenta rising with energy, KNO scaling violation, transverse momentum–multiplicity correlations and *minijets* pointed out, that soft and hard processes are closely related. These properties were understood within the two–component Dual Parton Model [19, 20, 21, 22, 23, 24, 25]. The hard component is introduced applying lowest order of perturbative hard constituent scattering [26].

The Dual Parton Model provides a framework not only for the study of hadron–hadron interactions, but also for the description of particle production in hadron–nucleus and nucleus–nucleus collisions at high energies. Within this model the high energy projectile undergoes a multiple scattering as formulated in Glaubers approach; particle production is again realized by the fragmentation of colorless parton–parton chains constructed from the quark content of the interacting hadrons.

For the details of the model we refer to the original publication [27].

7.2 Description of the DPMJET–II code

7.2.1 Program Summary

Title of the program:	DPMJET–II [27]
Program language:	FORTRAN-77
Number of program lines:	about 56,000 (in addition JETSET with about 10,500 lines and the evaporation module from FLUKA with 16,000 lines.)
Other programs called: (included in DPMJET–II in modified form)	DIAGEN [28] Sampling of configurations for nucleus-nucleus interactions within the Glauber formalism BAMJET [29, 30] Sampling the hadronization of strings.

DECAY [31]
  Sampling the decay of hadron resonances.
HADRIN [32]
  Sampling hadron-nucleon interactions below 5 GeV.
parts of DTUJET [25, 33]
  Sampling of minijets and multiple soft chains.
parts of FLUKA [34]
  Nuclear evaporation module.
JETSET–7.3 [35]
  Sampling the hadronization of strings
  according to the Lund model [35]
  (converted to double precision compilation)

7.2.2 Description of the program DPMJET–II [27]

The basic event generating unit of the code is the subroutine KKINC. Each call of this routine samples one inelastic hadron–nucleus or nucleus–nucleus interaction. Use and necessary initializations are described first in this section; a test program provided with the program package demonstrates the potential application. In the following subsection we discuss important model parameters and define their location in the code for potential user access. The basic structure of the supplied code is described in further subsections.

The event generator KKINC and its initialization

As already mentioned the code DPMJET–II uses several other programs. The initialization of the **BAMJET**[29, 30], **DECAY**[31] and **HADRIN**[32] codes requires *one single call* of the subroutines DPRIBL, DDATAR, DCHANT, DCHANH and DHADDE.

Calls to PRBLM2 and JDTU initialize the multi–Pomeron sampling and the sampling of minijets like in the DTUJET–93 [25, 33] code.

A call to LUNDIN initializes the JETSET-7.3 sampling of chain decay.

Further initializations and parameter definitions are provided in the routine DNINIT, via the named BLOCK DATA BLKDT1 and the subroutine DEFAUL(EPN,PPN).

Basic information for the application of the Glauber formalism according to the code **DIAGEN**[28] is generated by by the subroutine

SHMAKI (IP, IPZ, IT, ITZ, RPROJ, RTARG, PPN)

which requires the following input parameters defining the actual interaction:

IP, IPZ: nucleon number/atomic number of the projectile nucleus; set IP=IPZ=1 for incident hadrons;

IT, ITZ: nucleon number/atomic number of the target nucleus;

PN: projectile momentum in GeV/c (per nucleon)

Since the calculations performed by SHMAKI are time consuming, in particular for heavy target nuclei, and in general have to be repeated for each different reaction type and energy, resp., the test program provided offers an option to prepare a data file 'GLAUBTAR.DAT' containing the necessary information for hadron–nucleus and nucleus–nucleus interactions to be considered. This file may be generated in a separate run of the test program using the option 'GLAUBERI' and GLAUBERA, compare Section 2. The information from this file is read for a given projectile (projectile nucleus) (IP,IPZ) and target nucleus (IT, ITZ) by means of a subroutine call

CALL SHMAKF(IP,IPZ,IT,ITZ)

. For the use of different target materials and or different projectiles in one calculation SHMAKF has to be called subsequently with the corresponding parameters (IP,IPZ,IT,ITZ). The information read from the file 'GLAUBTAR.DAT' is numbered internally by the index KKMAT=1,2,... according to the sequence of SHMAKF calls; up to 50 materials may be stored in the standard version of the program. If a larger number of materials is to be used the corresponding dimension in the common /DTUMAT/ has to be increased. (If the required data are not found in the file 'GLAUBTAR.DAT' the execution is stopped.)
After these initializations each call of the subroutine

KKINC (EPN, IT, ITZ, IP, IPZ, IPROJ, KKMAT)

generates a single event. The input parameters not yet described have the following meaning:

IPROJ: projectile type for hadron–nucleus collisions;

KKMAT: controls the access of the event generator to the information on the Glauber formalism:
KKMAT=0 : Glauber data expected from SHMAKI calculation;
KKMAT>0 : Glauber data expected from the KKMAT'th call of the subroutine SHMAKF.

If DPMJET–II is used as event generator in a hadron cascade code, it is practical to write an interface routine. For the use of DPMJET–II in the Cosmic Ray cascade code HEMAS–DPM [36] there exists such an interface in the file dpmevt.f.

The following commands will cause the generator to sample one inelastic π^+Cu event at 200 GeV laboratory energy:

```
*** BAMJET and DECAY initialization
      CALL DPRIBL
      CALL DDATAR
      CALL DCHANT
*** HADRIN initialization
      CALL DHADDE
      CALL DCHANH
*** JETSET initialization
```

```
      CALL LUNDIN
*** initialization of the random number generator supplied with DPMJET--II
      CALL RNDMST(12,34,56,78)
*** initialization of DPMJET--II parameters (output: EPN=200 GeV)
      CALL DEFAUL(EPN,PPN)
*** initialization for the Glauber formalism by explicit calculation
*** for the actual reaction (projectile/target/energy = pi+/Cu/200 GeV)
      IP=1
      IPZ=1
      IT=64
      ITZ=29
      CALL SHMAKI(IP,IPZ,IT,ITZ,RPROJ,RTARG,PPN)
*** sampling of 1 event (pi+ has type IPROJ=13)
      IPROJ=13
      KKMAT=0
      CALL KKINC(EPN,IT,ITZ,IP,IPZ,IPROJ,KKMAT)}
      STOP
```

To use the information from the file 'GLAUBTAR.DAT' one has to call SHMAKF instead of SHMAKI and define KKMAT=1.

Information on the final state particles

During the generation of single events several entries are scored in the common block /HKKEVT/ characterizing subsequent stages of the sampling process: Information on initial state nucleons as well as on interacting partons and constructed parton chains, decaying resonances and final state particles is stored into this common block. It has the following structure, completely defined hereafter :

```
PARAMETER (NMXHKK=.....)
        COMMON /HKKEVT/ NHKK,NEVHKK,ISTHKK(NMXHKK),IDHKK(NMXHKK),
       &                JMOHKK(2,NMXHKK),JDAHKK(2,NMXHKK),
       &                PHKK(5,NMXHKK),VHKK(4,NMXHKK),WHKK(4,NMXHKK)
COMMON /EXTEVT/ IDRES(NMXHKK),IDXRES(NMXHKK),NOBAM(NMXHKK),
       &                IDBAM(NMXHKK),IDCH(NMXHKK),NPOINT(10)
```

The structure of this common block closely follows the suggestions of Ref. [37, 38]; conventions for the description of the event history are described in some detail hereafter.

7.3 The test program DPMJET–II

The test program demonstrates the application of the event generating routine KKINC and the extraction of information on the produced secondaries from the common block /HKKEVT/ (in the routine DISTR). Furthermore, it allows a simple redefinition of some important model parameters. It may also be used to prepare data files containing reaction specific information needed for the application of the Glauber formalism. In the case of event generation few standard histograms are constructed from sampled events.

All program activities are monitored by input options. Each input option is identified by a code word and either changes the default values of variables and/or demands some action.

7.3.1 Description of input options and default parameters

All input records of DPMJET–II have the following form:

```
CODEWD, (WHAT(I), I = 1,6), SDUM
FORMAT (A8, 2X, 6E 10.0, A8)
```

In the following we describe the meaning of the corresponding variables for some input options.

We give also the default values of the parameters .

- Code word = 'PROJPAR'

  This card defines the type of the projectile;
  if given it has to be included <u>before</u> the MOMENTUM/ENERGY option(s).

  SDUM: defines the projectile to be a hadron if given; for naming conventions see Table 1.
  If SDUM is given WHAT(1) and WHAT(2) need no specification; for projectile nuclei SDUM has no meaning.

  WHAT(1): mass number of projectile nucleus - IP

  WHAT(2): atomic number of projectile nucleus - IPZ

  default: incident proton (IP=1, IPZ=1).

Table 1

Some particle codes, SDUM is the parameter to be given on the PROJPAR input card. In the output of DPMJET, in COMMON HKKEVT, the particles are characterized with the PDG code.

SDUM	internal code	internal name	particle	PDG number	charge	q1	q2	q3
PROTON	1	P	p^+	2212	1	2	2	1
APROTON	2	AP	$\bar{p}^-$	-2212	-1	-2	-2	-1
	7	GAM	γ	22	0	0	0	0
NEUTRON	8	NEU	n^0	2112	0	2	1	1
ANEUTRON	9	ANEU	$\bar{n}0$	-2112	0	-2	-1	-1
KAONLONG	12	K0L	K_L^0	130	0	0	0	0
PION+	13	PI+	π^+	211	1	2	-1	0
PION-	14	PI-	π^-	-211	-1	1	-2	0
KAON+	15	K+	K^+	321	1	2	-3	0
KAON-	16	K-	K^-	-321	-1	3	-2	0
LAMBDA	17	LAM	Λ^0	3122	0	0	0	0
ALAMBDA	18	ALAM	$\bar{\Lambda}^0$	-3122	0	0	0	0
KAONSHRT	19	K0S	K_S^0	310	0	0	0	0
SIGMA-	20	SIGM-	Σ^-	3112	-1	1	1	3
SIGMA+	21	SIGM+	Σ^+	3222	1	2	2	3
SIGMAZER	22	SIGM0	Σ^0	3212	0	2	1	3
PIZERO	23	PI0	π^0	111	0	2	-2	0
KAONZERO	24	K0	K^0	311	0	1	-3	0
AKAONZER	25	AK0	$\bar{K}^0$	-311	0	3	-1	0
	97	TETA0	Ξ^0	3322	0	2	3	3
	98	TETA-	Ξ^-	3312	-1	1	3	3

SDUM	internal code	internal name	particle	PDG number	charge	q1	q2	q3
	99	ASIG-	$\bar{\Sigma}^-$	-3222	-1	-2	-2	-3
	100	ASIG0	$\bar{\Sigma}^0$	-3212	0	-2	-1	-3
	101	ASIG+	$\bar{\Sigma}^+$	-3112	1	-1	-1	-3
	102	ATETA0	$\bar{\Xi}^0$	-3322	0	-2	-3	3
	103	ATETA+	$\bar{\Xi}^+$	-3312	1	-1	-3	-3
	109	OMEGA-	Ω^-	3334	-1	3	3	3
	115	OMEGA+	$\bar{\Omega}^+$	-3334	1	-3	-3	3
	116	D0	D^0	421	0	4	-2	0
	117	D+	D^+	411	1	4	-1	0
	118	D-	D^-	-411	-1	1	-4	0
	119	AD0	$\bar{D}^0$	-421	0	2	-4	0
	120	DS+	D_s^+	431	1	4	-3	0
	121	DS-	D_s^-	-431	-1	3	-4	0
	129	CHI1C	χ_1^c	20443	0	4	-4	0
	130	JPSI	J/ψ	443	0	0	0	0
	137	LAMC+	Λ_c^+	4122	1	2	1	4
	138	XIC+	Ξ_c^+	4232	1	2	3	4
	139	XIC0	Ξ_c^0	4132	0	1	3	4
	140	SIGC++	Σ_c^{++}	4222	2	2	2	4
	141	SIGC+	Σ_c^+	4212	1	0	0	0
	142	SIGC0	Σ_c^0	4112	0	1	1	4
	150	AXIC-	$\bar{\Xi}_c^-$	-4232	1	-2	-3	-4
	151	AXIC0	$\bar{\Xi}_c^0$	-4132	0	-1	-3	-4
	152	ASIGC–	$\bar{\Sigma}_c^{--}$	-4222	-2	-2	-2	-4
	153	ASIGC-	$\bar{\Sigma}_c^-$	-4212	1	0	0	0
	154	ASIGC0	$\bar{\Sigma}_c^0$	-4112	0	-1	-1	-4

- Code word = 'TARPAR'

  This card defines the type of the target nucleus.

  WHAT(1): mass number of projectile nucleus - IT

  WHAT(2): atomic number of projectile nucleus - ITZ

  default: Nitrogen N target (IT=14, ITZ=7)

- Code word = 'ENERGY'

  This card defines the energy of the projectile in the target rest system. For incident nuclei the energy per nucleon is expected.
  NOTE: only one of the ENERGY and the MOMENTUM options is necessary, the last defined option is applied; both these options are to be given after the PROJPAR definition.

  WHAT(1): projectile energy in GeV

- Code word = 'MOMENTUM'

  This card defines the momentum of the projectile in the target rest system. For incident nuclei the momentum per nucleon is expected.
  NOTE: only one of the ENERGY and the MOMENTUM options is necessary, the last defined option is applied; both these options are to be given after the PROJPAR definition.

  WHAT(1): projectile momentum in GeV/c;

  Default: 100 000 GeV/c

- Code word = 'CENTRAL'

  This code word forces central nucleus-nucleus collisions, i.e. most nucleons of the projectile nucleus are forced to interact. The actual requirement depends on the atomic number of both the projectile and the target nuclei and is defined in the subroutine KKEVT (source file DPMNUC2, after CALL SHMAKO). Furthermore, the actual impact parameter is set near to zero for this case in subroutine MODB (source file DPMTCBSH).

  WHAT(1): central collisions forced for WHAT(1)= 1.0;
  default: 0.0, i.e. no forcing.

  Please note: The definition of central collisions is not unique, see the actual definitions in routine KKEVT (DPMNUC2.f). The same parameter with values different from 0. or 1. might als be used in order to define other special types of collisions, i.e. peripheral collisions.

- Code word = 'START'

This option starts the generation of events including the output of standard histograms.

WHAT(1): number of events to be sampled;   default: 100

WHAT(2): the Glauber initialization is forced to be calculated in SHMAKI,
i.e. no data read from file GLAUBTAR.DAT, if WHAT(2) = 1.0

- Code word = 'SINGDIFF'

This option controls the generation of single diffractive events.

WHAT(1): ISINGD;
ISINGD=1: Single diffraction included,
ISINGD=0: Single diffraction supressed,
default: 0

- Code word = 'SINGLECH'

WHAT(1): ISICHA;
ISINGD=1: include Regge (single chain) contributions,
ISINGD=0: single chains supressed,
ISINGD=2: Only single contribution,
default: 0

Please note: The single chain (Regge) contributions are only essential at low energies. they are at present only implemented for antibaryon and meson projectiles.

- Code word = 'EVAPORAT'

Evaporation is performed if the EVAPORAT card is present Default:No evaporation

- Code word = 'PARTICLE'

This card triggers a printout of all the particles defined in the BAMJET-DECAY chain fragmentation, including name conventions, quantum numbers and decay channels.

- Code word = 'STOP'

This option stops the execution of the program.

7.3.2 Sample Input

In the following several typical examples of input data are reproduced. In general we give all input cards, even if most of the parameters given agree with the default parameters.

Hadron-Nucleus collisions

```
TITLE
 DPMJET-II p-Air WITH  JETSET Fragm./ 1000 TeV LAB  w. Diffr.
PROJPAR   PROTON
TARPAR        14.0        7.
MOMENTUM  1000000.
NOFINALE    1.
OUTLEVEL   0.        0.       0.         -1.       0.        0.
STRUCFUN        215.        0.
SAMPT             4.
GLUSPLIT          1.        0.
SELHARD           0.        2.        0.        0.        3.        3.
SIGMAPOM          0.       10.      482.       30.      100.        2.
PSHOWER           1.
CENTRAL         0.
CMHISTO         0.
SEASU3        0.50
RECOMBIN        1.
SINGDIFF        1.       0.        1.
CRONINPT        1.      0.64
POPCORN       0.15
TAUFOR        105.0       0.
SEADISTR        1.0      1.1       1.1        5.0
XCUTS          2.00      2.0      0.30     0.901
PAULI           1.        0.
FERMI           1.        0.6
INTPT           1.
HADRONIZE  2.
START      100000.       1.
STOP
```

Central Nucleus-Nucleus collisions

```
TITLE
 DPMJET-II Pb-Pb central  WITH JETSET Fragm. LHC energy cms-hist
PROJPAR      208.0       82.
TARPAR       208.0       82.
MOMENTUM  20000000.
SEAQUARK    1.
NOFINALE    0.
OUTLEVEL   0.        0.       0.         -1.       0.        0.
STRUCFUN        215.        0.
SAMPT             4.
GLUSPLIT          1.        0.
SELHARD           0.         2.       0.        0.        3.        3.
SIGMAPOM          0.       10.      482.       30.      100.        2.
PSHOWER           1.
CENTRAL         1.
SEASU3        0.50
RECOMBIN        1.
SINGDIFF        0.       0.        0.
CRONINPT        1.      0.64
POPCORN       0.5
TAUFOR          5.0      25.
TAUFOR        105.0       0.
SEADISTR        1.0      1.1       1.1        5.0
XCUTS          2.00      2.0      0.30     1.201
PAULI           1.        0.
FERMI           1.        0.6
INTPT           1.
HADRONIZE  2.
START      50.       1.
STOP
```

7.4 Event history and the common block /HKKEVT/

7.4.1 Structure of the common block

During the generation of individual events several entries are scored in the common block /HKKEVT/ characterizing subsequent stages of the sampling process. Scored entries are, for instance, initial state nucleons, partons and parton chains, decaying resonances as well as final state particles. These entries are characterized by their type, 4-momenta and coordinates; additional pointers define 'parents' and 'daughters' of the actual entry (if any). The structure of this common block closely follows the suggestions of Ref. [37, 38]. Within the code there are extensive comments explaining the variables used in this common block. Below the common block is reproduced together with these comments.

```
      PARAMETER (NMXHKK=20000)
      COMMON /HKKEVT/ NHKK,NEVHKK,ISTHKK(NMXHKK),IDHKK(NMXHKK),
     &                JMOHKK(2,NMXHKK),JDAHKK(2,NMXHKK),
     &                PHKK(5,NMXHKK),VHKK(4,NMXHKK),WHKK(4,NMXHKK)
      COMMON /EXTEVT/ IDRES(NMXHKK),IDXRES(NMXHKK),NOBAM(NMXHKK),
     &                IDBAM(NMXHKK),IDCH(NMXHKK),NPOINT(10)
C
C  Based on the proposed standard COMMON block (Sjostrand Memo 17.3,89)
C
C NMXHKK: maximum numbers of entries (partons/particles) that can be
C    stored in the common block.
C
C NHKK: the actual number of entries stored in current event. These are
C    found in the first NHKK positions of the respective arrays below.
C    Index IHKK, 1 <= IHKK <= NHKK, is used below to denote a given
C    entry.
C
C ISTHKK(IHKK): status code for entry IHKK, with following meanings:
C    = 0 : null entry.
C    = 1 : an existing entry, which has not decayed or fragmented.
C        This is the main class of entries which represents the
C        "final state" given by the generator.
C    = 2 : an entry which has decayed or fragmented and therefore
C        is not appearing in the final state, but is retained for
C        event history information.
C    = 3 : a documentation line, defined separately from the event
C        history. (incoming reacting
C        particles, etc.)
C    = 4 - 10 : undefined, but reserved for future standards.
C    = 11 - 20 : at the disposal of each model builder for constructs
C        specific to his program, but equivalent to a null line in the
C        context of any other program. One example is the cone defining
C        vector of HERWIG, another cluster or event axes of the JETSET
C        analysis routines.
C    = 21 - : at the disposal of users, in particular for event tracking
C        in the detector.
C
C IDHKK(IHKK) : particle identity, according to the Particle Data Group
C    standard.
C
```

```
C JMOHKK(1,IHKK) : pointer to the position where the mother is stored.
C    The value is 0 for initial entries.
C
C JMOHKK(2,IHKK) : pointer to position of second mother. Normally only
C    one mother exist, in which case the value 0 is used. In cluster
C    fragmentation models, the two mothers would correspond to the q
C    and qbar which join to form a cluster. In string fragmentation,
C    the two mothers of a particle produced in the fragmentation would
C    be the two endpoints of the string (with the range in between
C    implied).
C
C JDAHKK(1,IHKK) : pointer to the position of the first daughter. If an
C    entry has not decayed, this is 0.
C
C JDAHKK(2,IHKK) : pointer to the position of the last daughter. If an
C    entry has not decayed, this is 0. It is assumed that the daughters
C    of a particle (or cluster or string) are stored sequentially, so
C    that the whole range JDAHKK(1,IHKK) - JDAHKK(2,IHKK) contains
C    daughters. Even in cases where only one daughter is defined (e.g.
C    K0 -> K0S) both values should be defined, to make for a uniform
C    approach in terms of loop constructions.
C
C PHKK(1,IHKK) : momentum in the x direction, in GeV/c.
C PHKK(2,IHKK) : momentum in the y direction, in GeV/c.
C PHKK(3,IHKK) : momentum in the z direction, in GeV/c.
C PHKK(4,IHKK) : energy, in GeV.
C PHKK(5,IHKK) : mass, in GeV/c**2. For spacelike partons, it is allowed
C    to use a negative mass, according to PHKK(5,IHKK) = -sqrt(-m**2).
C
C VHKK(1,IHKK) : production vertex x position, in mm.
C VHKK(2,IHKK) : production vertex y position, in mm.
C VHKK(3,IHKK) : production vertex z position, in mm.
C VHKK(4,IHKK) : production time, in mm/c (= 3.33*10**(-12) s).
C
C WHKK(4,NMXHKK) gives positions and times in projectile frame.
```

7.4.2 Conventions for the scoring of the event history in /HKKEVT/

In the following we briefly characterize the subsequent entries to /HKKEVT/ together with the most important conventions for their classification.

- projectile hadron/nucleons;
  for projectile nuclei Fermi momenta in the projectile rest frame and coordinates

within the nucleus are stored in the arrays PHKK and VHKK, resp., by the subroutine KKEVT;
interacting and non-interacting nucleons have the status ISTHKK=11 and 13, resp.;

- target nucleons;
  Fermi momenta in the target rest frame and coordinates within the nucleus are defined in PHKK and VHKK, resp. (KKEVT);
  interacting and non-interacting nucleons have the status ISTHKK=12 and 14, resp.;

- valence quarks / diquarks from the interacting projectile hadron/nucleon(s) defined in the subroutine XKSAMP (total number IXPV);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=21;

- sea quarks from interacting projectile hadrons defined in XKSAMP (total number IXPS);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=31;

- valence quarks / diquarks from interacting target nucleons defined in XKSAMP (number IXTV);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=22;

- sea quarks from interacting target nucleons defined in XKSAMP (number IXTS);
  PHKK(3,...)=PHKK(4,...) contains the actual momentum fraction, VHKK the position of the 'mother' hadron;
  defined status ISTHKK=32;

- characteristics of the individual parton-parton chains (before hadronization) from subroutines KKEVVV, KKEVSV, KKEVVS and KKEVSS; for each chain there are three entries:
  (1) two entries for the quark systems forming the chain;
  PHKK gives their 4-momenta; the status of the corresponding quark system is increased by 100 as compared to the previous entry from the subroutine XKSAMP (i.e. ISTHKK=121,122,131 or 132 ,resp.);
  (2) one entry for the complete chain;
  PHKK gives the total 4-momentum, the 'particle' type for chains is defined to be IDHKK=88888;
  the actual status ISTHKK points to the chain generating subroutine:

ISTHKK=3 for chains from KKEVVV (constructed from valence quark systems),
ISTHKK=4 for chains from subroutine KKEVSV (sea-valence chains),
ISTHKK=5 for chains from subroutine KKEVVS (valence-sea chains),
ISTHKK=6 for chains from subroutine KKEVSS (sea-sea chains);

- hadrons from the hadronization of chains, entries from subroutines HADRSS, HADRVS, HADRSV, HADRVV;
  assignment of values to all arrays of /HKKEVT/, status ISTHKK=1;
- hadrons from resonance decay in subroutine DECHKK
  (presently called after completion of the primary interaction of the projectile treated in KKEVT);
  the status of decaying hadrons is changed to ISTHKK=2, added decay products have ISTHKK=1;
- hadrons from intranuclear cascade interactions (monitored by FOZOKL):
  the status of interacting secondary is changed to ISTHKK=2; interacting target nucleons get ISTHKK=12, interacting projectile nucleons with ISTHKK=11; final state hadrons have the status ISTHKK=1.
  Particular cases:
  (i) If a given secondary interaction is found to be forbidden because of the Pauli principle the initial state particles are stored in /HKKEVT/ with their original properties, but the actual position; so they may participate in further intranuclear interactions.
  (ii) One (or two) nucleons from a secondary interaction cannot escape from the nuclear potential, but the particular collision is not forbidden by Pauli's principle (i.e. several nucleons knocked out of the nucleus already):
  Store the nucleon(s) with the actually generated momentum at the collision site, assigning the status ISTHKK=15 (16) for interactions in the target (projectile) nucleus. Those nucleons are available as target (projectile) nucleons in subsequent steps of the intranuclear cascade development.
  (iii) Negative particles with energies too low to escape from the potential are forced to be absorbed within the nucleus ; absorbed π^-, K^- and $\bar{p}$ are characterized by the status ISTHKK=19.
- Evaporation nucleons, nuclear fragments and residual target nuclei from the interface to the evaporation mudule.
  (i) The evaporation protons and neutrons and deexcitation Gammas are stored with ISTHKK(i)=-1.

(ii) The stable residual nuclei after the evaporation step are stored with ISTHKK(i)=1001, IDHKK(i)=8000. The mass number A and the charge Z are storerd as A=IDRES(i) and Z=IDXRES(i).

(iii) The nuclear fragments like α particles are stores with ISTHKK(i)=–1 and IDHKK(i)=80000. The mass number A and the charge Z are storerd as A=IDRES(i) and Z=IDXRES(i).

The information from this common block allows a rather detailed reconstruction of the actual event history, and is particularly useful for consistency tests and debugging.

7.5 Residual nuclei and nuclear fragments

The DPMJET–II model includes a detailled treatment of the nuclear fragmentation [39]. In the first step the model calculates excitation energies of the excited target and projectile prefragments. These excitation energies are used in a second step to treat nuclear evaporation inte p, n and light fragments, high energy fission, Fermi breakup and γ–deexcitation of the prefragments. The model has been extensively compared to data on grey and black prongsn and to distributions on stable residual nuclei and nuclear fragments from the fragmentation of the target nuclei in hadron–nucleus and nucleus–nucleus collisions [39].

In Fig. 1 we present as an example the nuclear mass distribution of residual nuclei and nuclear fragments obtained in minimum bias Pb–Pb collisions at LHC energies. The 4–momentum of all these residual nuclei and fragments as well as mass and charge is kmown to the model, so many other distributions could be generated. In the average collision the evaporation and fragmentation fragments the target as well as the projectile nucleus into 11.2 protons, 28.8 neutrons, 2.9 deexcitation photons and 6.9 nuclear fragments. It is believed, that this feature of the model could be of use for simulations of the performance of certain detector components like zero–degree calorimeters, it is already used for simulations of the cosmic ray cascade initialized by cosmic ray nuclei.

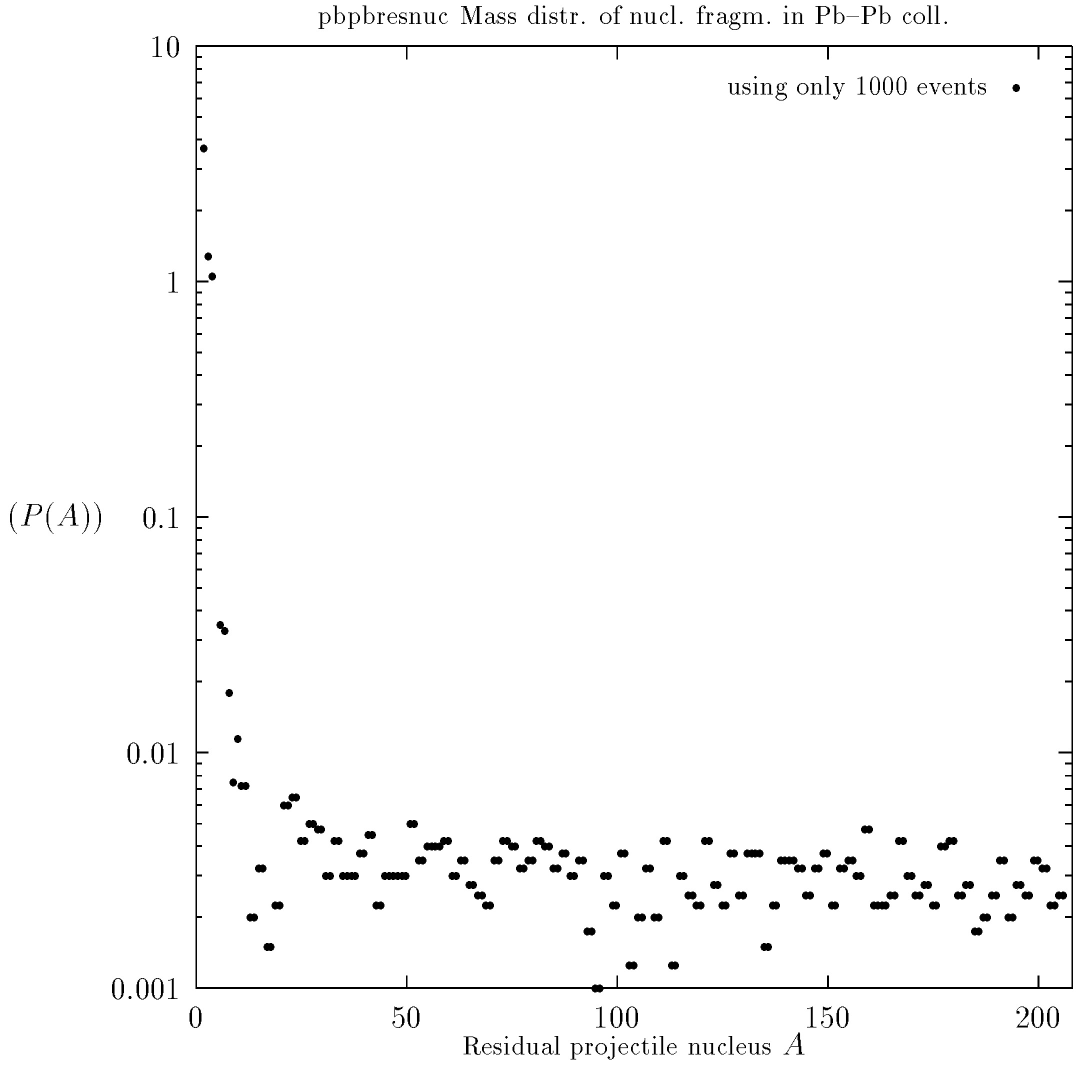

Figure 1: We plot the probability to find as a result of Pb–Pb collisions at LHC energies residual nuclei and nuclear fragments with mass number A from either the projectile or target Pb nucleus. The plot was generated using only 1000 minimum bias Pb–Pb events from the DPMJET–II event generator [27]. More events would be needed to reduce the statistical fluctuations

8 The proton–(anti)proton generator DTUJET–93

8.1 The model

DTUJET–93 is based on the two-component Dual Parton Model which includes the dual topological unitarization of soft and hard cross sections. The model treats both soft (low $p_\perp$) and hard (minijet, large $p_\perp$) processes in a unified and consistent way. The unified description is important at TeV-energies of hadron colliders, where the hard perturbative cross sections of QCD become large and comparable to the total cross sections.

New in the code DTUJET–93 [25, 33] is the use of modern parton structure functions for calculating the minijet component, new fits to total, elastic, inelastic, and single diffractive cross sections, a careful treatment of the low–mass and high–mass single diffractive component [24] .

Experimental observations at collider energies made it clear that the soft and hard components of hadronic multi-particle production are closely related. We refer to the discovery of correlations between the average transverse momentum of produced hadrons and the multiplicity density in the central rapidity range .

For more details about the model we refer to the papers [20, 21, 22, 23, 24, 25] .

8.2 Program Summary

Title of the program:	DTUJET–93 [25]
Program language:	FORTRAN-77
Number of program lines:	about 45,000 (including data files
Other programs called: (included in DPMJET–II in modified form)	BAMJET [29, 30] Sampling the hadronization of strings. DECAY [31] Sampling the decay of hadron resonances. JETSET–7.3 [35] Sampling the hadronization of strings according to the Lund model [35] (converted to double precision compilation)

Restrictions on the complexity of the problem : Above 40 TeV arrays have to be enlarged. No tests were done below $\sqrt{s} = 50$ GeV.

8.3 The Structure of DTUJET–93

The DTUJET source code consists of several FORTRAN files.

Most parts of the program, for instance the
sampling of multi-Pomeron events,
hadron structure functions,
hard perturbative constituent scattering cross sections,

the method of string fragmentation into hadrons,

and the method of selecting the exclusive parton events (x-values and flavors),

are programmed as distinct entities, which can in principle be exchanged by suitable other codes. For some of these tasks DTUJET–93 offers several options; for others this is foreseen and easy to implement.

8.4 The Main Program

The main program DTMAIN is provided to allow for a stand-alone running of the program. It is unnecessary for a user who wants to call the event generator from its own programs.

It contains the following lines

```
PROGRAM DTMAIN
CALL DTPREP(NEVNT)
DO 9 I=1,NEVNT
CALL DTCOLL
CALL DTHIST
GOTO 1
END
```

which are largely self explanatory.

To prepare the generator a call to `DTPREP` is necessary. It initializes variables in a way chosen by the user and allows for preparatory tasks. Its actions are controlled by input cards. Each input card is identified by a code word which specifies its function as described in the next section. Without specification default values are taken. The subroutine is left if the code word START is encountered. Please note, that the nature of these initializations makes it for many tasks impossible to create events, which need a different initialization during one run of the code. A good praxis is therefore, to have a separate run of the code for each problem to be solved.

A call to the subroutine `DTCOLL` generates one event. The event is stored in a `COMMON` block `/USER/` and `/PARTCL/` as described below.

To check the generated events, a call to the subroutine `DTHIST` provides short histogram output, which was prepared in `DTPREP` and `DTCOLL` without action of the user. It contains a call to a dummy routine `DTHSTO(I)`, which can be replaced by a histograming routine supplied by the user. It is called at the beginning with the argument $I = 1$ for initialization and preparatory work, with the argument $I = 2$ each time a new event has been generated to allow summations needed for the calculation of expectation values and with the argument $I = 3$ after all the desired events have been generated for normalizations and print outs.

8.5 Input Cards and Options

The subroutine DTPREP uses input cards. All input cards of DTUJET have the following form:

```
 CODEWD, (WHAT(I), I = 1,6), SDUM
 FORMAT ( A8, 2X, 6E 10.0, A8)
```

The initial code word, which is read in as `CODEWD`, determines the meaning of the remaining variables, as described in the following.

Code word: TITLE
Parameter used: none
This card must be followed by a card giving the title of the run, which will be reproduced in the output.

Code word: CMENERGY
Parameter used: `ECM = WHAT(1)`
This card defines the center of mass energy `ECM` of the collision in GeV.
The default is `ECM = 1800` GeV.

Code word: PROJPAR
Parameter used: `PROJTY = SDUM`
Defines the projectile particle type, defined to move into positive z-direction.
The possible values are: `PROTON, APROTON` The default is `PROTON`

Code word: TARPAR
Parameter used: `TARGTY = SDUM`
Defines the target particle type, defined to move into negative z-direction.
The possible values are: `PROTON` The default is `PROTON`

Code word: SINGDIFF
Parameters used: `ISINGD = WHAT(1), IDUBLD = WHAT(2), SDFRAC = WHAT(3)`

Calls or suppresses diffractive events.
`ISINGD`
= 0 :Single diffraction suppressed.
= 1 :Single diffraction included to a fraction given by third parameter.
`IDUBLD`
= 0 :Double diffraction included.
= 1 :Only double diffractive events.
`SDFRAC`
= 0 .. 1 :Fraction of single diffractive events to be included in inelastic events. The value 1 (0.05) means that all (5%) of the single diffractive events are included.

The defaults are `ISINGD = 0, IDUBLD = 0, SDFRAC = 0 .`

Code word: STRUCFUN

Parameter used: `ISTRUF = WHAT(1)`

Defines the structure functions used in the sampling of hard constituent scattering [40, 41].

`ISTRUF`

= 13 : Martin, Roberts, Stirling (1992): Set S0

= 14 : Martin, Roberts, Stirling (1992): Set D0

= 15 : Martin, Roberts, Stirling (1992): Set D_-

= 16 : CTEQ Collaboration (1993): Set 1M

= 17 : CTEQ Collaboration (1993): Set 1MS

= 18 : CTEQ Collaboration (1993): Set 1ML

= 19 : CTEQ Collaboration (1993): Set 1D

= 20 : CTEQ Collaboration (1993): Set 1L

= 213 .. 220 : as above with energy dependent $p_\perp$ threshold value

The default is 215 .

The fits include functions with conventional $1/x$ singularity of sea-quarks and gluon distributions (for instance the MRS[D0] functions) as well as functions with a $1/x^{1.5}$ singularity (for instance the MRS[D_-] functions) with and without shadowing.

The hard process contributes above a $p_\perp$ threshold. The threshold is set for less than three digits ISTRUF values to 3 GeV by default. This option was used in the earlier DTUJET–92 version of the program. An energy dependent cutoff can avoid a hard scattering cross section too large to be treated in our simple eikonal approximation. To use this new option the number 200 has to be added to the chosen ISTRUF value.

Code word: START

Parameters used: `NEVNT = WHAT(1), PTLAR = WHAT(5)`

Starts the sampling of hadronized events and the calculation of the standard histogram output.

`NEVNT` Number of events sampled.

`PTLAR` Cutoff parameter to sample only selected events.

= 0.0:DTUJET samples without constraint on sampled events.

> 2.2:DTUJET samples only events with at least one jet (minijet) with $p_\perp \geq$ `PTLAR`, rejecting all other events.

< -0.1:DTUJET samples only events without hard jets (minijets).

Defaults are not effective, as this card is necessary to run the program. The code word START should be used only once per run.

Code word: STOP

Parameter used: none

Stops the running of the code.

8.6 Particle codes in DTUJET-93

The codes for stable particles considered at the end are given in Table 1.

Table 1: List of the codes for stable particles used in BAMJET and DTUJET93.

$1 = p$	$14 = \pi^-$	$98 = \Xi^-$	$121 = D_s^-$
$2 = \bar{p}$	$15 = K^+$	$99 = \bar{\Sigma}^-$	$137 = \Lambda_c^+$
$3 = e^+$	$16 = K^-$	$100 = \bar{\Sigma}^0$	$149 = \bar{\Lambda}_c^+$
$4 = e^-$	$17 = \Lambda$	$101 = \bar{\Sigma}^+$	$138 = \Xi_c^+$
$5 = \nu$	$18 = \bar{\Lambda}$	$102 = \bar{\Xi}^0$	$139 = \Xi_c^0$
$6 = \bar{\nu}$	$19 = K_S^0$	$103 = \bar{\Xi}^+$	$150 = \bar{\Xi}_c^+$
$7 = \gamma$	$20 = \Sigma^-$	$109 = \Omega^-$	$151 = \bar{\Xi}_c^0$
$8 = n$	$21 = \Sigma^+$	$115 = \bar{\Omega}^-$	$140 = \Sigma_c^{++}$
$9 = \bar{n}$	$22 = \Sigma^0$	$116 = D^0$	$141 = \Sigma_c^+$
$10 = \mu^+$	$23 = \pi^0$	$117 = D^+$	$142 = \Sigma_c^0$
$11 = \mu^-$	$24 = K^0$	$118 = D^-$	$152 = \bar{\Sigma}_c^{++}$
$12 = K_L^0$	$25 = \bar{K}^0$	$119 = \bar{D}^0$	$153 = \bar{\Sigma}_c^+$
$13 = \pi^+$	$97 = \Xi^0$	$120 = D_s^+$	$154 = \bar{\Sigma}_c^0$

The conversion to the PDG codes is done for all the stable particles given above by the `INTEGER FUNCTION MPDGHA(NR)` included in the `dtu93lun.f` file.

8.7 Common Blocks of Interest for the User

It is possible to run the event generator within a user supplied program package. For this purpose the user needs to know how the event is stored in COMMON blocks.

The COMMON block /USER/

```
  CHARACTER*8 PROJTY,TARGTY
  CHARACTER*80 TITLE
  COMMON /USER/TITLE,PROJTY,TARGTY,CMENER,ISTRUF
&   ,ISINGD,IDUBLD,SDFRAC,PTLAR
```

contains the parameters, expected to be modified by input cards. The meaning of the possible values of these parameters were described above.

The COMMON block /PARTCL/

```
  PARAMETER (MXNUPA=2500)
```

```
  COMMON/PARTCL/
&  PARTPX(MXNUPA),PARTPY(MXNUPA),
&  PARTPZ(MXNUPA),PARTP0(MXNUPA),
&  NPARTY(MXNUPA),NPART
```

contains the final particles of the last generated event. The first NPART's positions in the arrays

```
PARTPX,PARTPY,PARTPZ,PARTP0,NPARTY
```

are transverse momenta, longitudinal momentum, energy and the type of the particles where

```
NPART
```

is number of particles in the event.

8.8 Exemplary Input and Command Files

In Fig. I we reproduce an input file which allows to run DTUJET–93. This file, where we include some possible input cards even when they do not change the default settings, will lead to the calculation of 5000 events at $\sqrt{s} = 1.8$ TeV generating standard histograms.

In Fig. IIa we list an exemplary command file used for compiling DTUJET–93 files under DEC–ULTRIX, the same is given in Fig. IIb and c for HP–UX and IBM AIX respectively. Please note, that the code, not written explicitly in DOUBLE PRECISION is transformed to DOUBLE PRECISION using the compiler option for the redefinition of the constants and D-commented ("debug"–) cards in the files.

```
TITLE
Antiproton-Proton with diffraction, STRUCFUN 215 and JETSET fragmentation.
CMENERGY      1800.
PROJPAR                                                               APROTON
TARPAR                                                                PROTON
SINGDIFF          1.        0.      1.00
START          5000.        0.        0.        0.        2.
STOP
```

Fig I: DTUJET–93 sample input file.

```
f77  -c -diag -fpe2 -o0 -K -d_lines -r8 -C -V <file name>.f
```

Fig IIa: Command file for compiling DTUJET–93 Fortran files under DEC–ULTRIX.

```
f77  -c -a +e  -K -D -R8  +T +R -C -V <file name>.f
```

Fig IIb: Command file for compiling DTUJET–93 Fortran files under HP–UX.

```
xlf  -C -c -qsource -qdpc -D <file name>.f
```

Fig IIc: Command file for compiling DTUJET–93 Fortran files under IBM-AIX.

9 The string fusion model generator SFM

9.1 General information

SFM (String Fusion Model) [42, 43, 44, 45] is a Monte Carlo event generator for soft hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at relativistic and ultra-relativistic energies. It contains two versions, namely, with string fusion and without string fusion, which predictions become distinguishable for heavy-ion collisions at energies $\sqrt{s} \geq 20$ GeV.

SFM is based on Gribov-Regge theory of multi-Pomeron exchange and parton picture of strong interactions [46]. The fragmentation procedure uses Artru-Mennessier algorithm [47] of string decay. The produced particles belong to the basic states of 35 and 56 multiplets of $SU(6)$. Like VENUS (see this Note), SFM is compatible with the ISAJET code and uses the ISAJET resonance decay code.

The DPM (see this Note) and SFM are similar models. Both of them assume the creation of the sea quark-antiquark and diquark-antidiquark pairs. The only principal difference is the string fusion mechanism incorporated into the SFM code. Compare to SFM, VENUS assumes the fusion of particles and resonances into large clusters which decay isotropically.

9.2 Description of the model

The simulation procedure consists of the following parts:
i) the definition of the initial states of the interacting objects;
ii) the simulation of longitudinal and transverse momenta of the interacting partons and the computing of the kinematical characteristics of the strings;
iii) string decay and multiparticle production, including the decay of resonances.
No rescatterings of partons are included in this version of SFM.

9.2.1 Input parameters of the code

The input file for running the code contains the information about the colliding objects. The example of the INPUT.DATA file is given below.

Layout of the SFM input data file

208. 82. 1120 = A1, Z1, IKINA
208. 82. 1120 = A2, Z2, IKINB
6300.0 = ECMI
10 = LIMC
0.545 0.545 = PAR2A, PAR2B
0.05 0.05 1.07 1.07 = D1, D2, R0A, R0B
2 = NFRAME
F 0.000 3.000 = IMPAR (Logical), B1, B2
F = STRFM (Logical)

Description:

A1/2 = Atomic mass of the projectile/target
Z1/2 = Atomic number of the projectile/target
IKINA/B = 1120 = ISAJET code of proton
IKINA/B = -1120 = ISAJET code of antiproton
ECMI = initial cms energy in (GeV/nucleon) units
LIMC = number of events to be generated

Nuclear density cut parameters (see below):
PAR2A/B = 0.545 for heavy nuclei (A $\geq$ 11)
D1/2 = 0.05
R0A/B = nucleon radius
NFRAME = 1 - simulation in a target rest frame
NFRAME = 2 - simulation in equal velocities frame

Flags:
IMPAR = .TRUE. for simulations at fixed impact parameter B1 = B2
= .FALSE. for simulations at impact parameters between B1 and B2
STRFM = .FALSE. - simulations without string fusion (eikonal)
STRFM = .TRUE. - simulations with string fusion

9.2.2 Definition of the initial states

Definition of the initial states includes the calculation of nuclear radii and relative positions of nuclear centers, maximal Fermi-momentum of nucleons, coordinates and Fermi-momenta of the nucleons inside the nuclei according to nuclear density distribution functions (Gaussian for light nuclei and Woods-Saxon for heavy nuclei) using PAR2A, PAR2B, ALPA,ALPB,R0A,R0B parameters.

To determine the initial states of the colliding nuclei we compute the nuclear radii, R, from the condition:

$$\frac{\rho(R)}{\rho(0)} = \alpha, \quad \text{where } \alpha = 0.05 \quad \text{(D1 or D2)} \tag{1}$$

The nucleon coordinates are chosen randomly according to the nuclear density distribution

$$\rho(r) = \begin{cases} \rho_0/(1+\exp(\frac{r-r_0}{a})) & \text{if } A > 11, \text{ with} \\ & r_0 = 1.19A^{1/3} + 1.61A^{-1/3} \\ \rho_0 \cdot \exp(-r^2/R_1^2) & \text{if } A \leq 11 \end{cases}$$

and the inter-nucleon distance have to be more than 0.8 fm. The density parameters are $b = 0.545$ fm (PAR2A or PAR2B) and $a = r_0 A^{1/3}$, where $r_0 = 1.07$ fm (R0A or R0B).

The nucleon momenta, $\vec{p}$, were generated uniformly in the range $0 \leq |\vec{p}| \leq p_F$. The most Fermi momentum in terms of the local nucleon density $\rho(r)$ is given by:

$$p_F = (3\pi^2)^{1/3} \cdot \hbar \cdot \rho^{1/3}(r), \tag{2}$$

where $\hbar = 0.197$ fm·GeV/c. Then the value of the nuclear impact parameter $\vec{b}$ is choosen randomly in the region $0 \leq b \leq R_1 + R_2$ with probability $w_b \sim d^2b$.

The SFM is based on the parton picture of hadronic and nuclear collisions. This scenario assumes the collision as a single interaction between two clouds of slowly moving partons. The partons in projectile and target particles are formed before the collision. The distribution of number of strongly interacting partons is directly connected to the value of the multi-Pomeron vertices in the Regge theory which is used in the DPM (see this Note) to define number of newly produced strings. In the eikonal approximation for the multi-Pomeron vertices the corresponding probability to have n strongly interacting partons in a hadron is given by the Poisson distribution

$$P(n) \ = \ \frac{\gamma^n}{n!} \cdot \exp\left(-\gamma\right) \tag{3}$$

with parameter, γ, which depends on the energy $\sqrt{s}$ and the parton-parton interaction cross-section, σ_p, as:

$$\gamma \ = \ \gamma_0 \, s^{\Delta}, \ \Delta = 0.09, \ \gamma_0 = g/\sigma_p^{0.5}, \ g = 1.8 \ \mathrm{GeV}^{-1}. \tag{4}$$

The positions of the slowly moving partons are distributed in the plane of the impact parameter. The probability density to find a value for the parton impact parameter b_p, with the respect of the center of the hadron is

$$F(b_p) = \ \frac{1}{\pi\lambda} \cdot \exp\left(-b_p^2/4\lambda\right) \tag{5}$$

where

$$\lambda \ = \ \alpha' \cdot (Y - y) \ \text{ and } \ \alpha' = 0.21 \ \mathrm{GeV}^{-2}. \tag{6}$$

Here Y and y are the hadron and parton rapidity, respectively. The partons from the different colliding hadrons interact with each other in impact parameter plane with parton-parton interaction cross-section, which is independent from their rapidity:

$$\sigma_p \ = \ 3.5 \ mb. \tag{7}$$

The numerical values of parameters were chosen to describe the nucleon-nucleon inelastic cross section.

Partons are assumed **to interact only once (no rescatterings)**. In the language of the Reggeon diagrams this consideration corresponds to the non-enhanced diagrams.

The nuclear parton wave function is a convolution of the parton distribution within the nucleon and the nucleon distribution of the nucleus.

9.2.3 Production and fusion of strings

Partons, discussed above, are $q_v - \bar{q_v}$ and $q_v q_v - q_v$ pairs or similar sea quark pairs from one hadron. In our consideration a parton-parton interaction leads to the creation of *two* strings with triplet and antitriplet colour charges at their ends, briefly called as triplet strings. Since both the projectile and target should remain colourless, the strings have to be formed in pairs with opposite colours at their ends. Strings stretch between a quark and antiquark, or between a quark and a diquark, originating from different hadrons, i.e. between colour triplet and antitriplet state.

Each parton in a nucleon carries a fraction $x = p_+/P_+$, where $p(P)$ is the parton(hadron) momentum according to the nucleon structure function, obtained within the Regge theory:

$$u(x_1, x_2, \ldots, x_n) = \delta(1 - \sum_{i=1}^{n} x_i) \prod_{i=1}^{n} x_i \qquad (8)$$

$$u_v(x) = u_s(x) = x^{-0.5} \text{ for valence or sea quarks and}$$
$$u_{vv} = x^{1.5} \text{ for diquark}$$

with a cutoff at small $x: \ x \geq x_{min} = m_t/P_+$.

For the transverse momentum distribution of valence or sea quarks the Gaussian distribution is used:

$$f(p_t^2)\, p_t\, dp_t \ \sim \ \exp(-\alpha p_t^2)\, p_t\, dp_t. \qquad (9)$$

The total transverse momentum of the quarks in a nucleon is compensated by the diquark momentum.

The kinematical characteristics of the strings are fully determined by the longitudinal and transverse momenta of the quarks at the ends of the strings. Only $u-$, $d-$ and $s-$ quarks are considered. The probability to find a strange sea quark pair inside the nucleon was suppressed by factor 0.29 as compared to a non-strange sea quark pair.

The SFM predicts the increase of the string density in 1.5 times for pp collisions and in 3 times for Pb+Pb collisions with increase of energy from 19.4 (SPS) to 6300 (LHC) AGeV, which corresponds to 4015 (15.4) strings with density 28.5 (2.2) fm^{-2} in Pb+Pb (pp) collisions at LHC. So high densities can lead to the overlapping and interaction of strings.

In SFM the strings can fuse if their transverse positions fall within the interaction area of order of the string proper transverse dimension, a. The energy-momentum of the fused string is taken as the sum of the energy-momenta of the daughter strings. During the fusion the colour sources (ends) at one side of two triplet strings (i.e. (anti)quarks and (anti)diquarks combine and form a quark complex with a colour charge, Q, obtained according to the standard $SU(3)$ composition laws. Only triplet- [**3**], sextet-[**6**] and octet- [**8**] representations are included. In particular two triplet strings fuse into a triplet and a sextet strings with the relative probabilities 1/3 and 2/3. A triplet and an antitriplet strings fuse into a singlet (meson or baryon) and in an octet with 1/9 and 8/9 probabilities. The flavours of the fused strings depend on the flavours of the daughter strings.

Due to the fusion the total number of strings in a given transverse area becomes limited that can lead to the substantial reduction of multiparticle production. However the concrete characteristics of particles production strongly depend on the string decay procedure.

9.2.4 String decay

During the decay the fused [**6**]$-$ or [**8**]$-$ strings with colour charges Q and $-Q$ at the ends are neutralized by a pair of parton complexes with opposite charges, $-Q$ and Q. Parton complex is a set of (anti)quarks in $SU(3)-$representation with arbitrary flavours and masses. The probability rate for the constant colour field of the two opposite colour charges, $Q-\bar{Q}$, and transverse mass M_t for the unit string lenght and after time Δt is taken in the spirit of Schwinger expression [48] for the probability to create e^+e^- pair by a constant electromagnetic field:

$$w \;\sim\; K^2_{[N]} \exp\left(-\pi M_t^2/K_{[N]}\right). \tag{10}$$

Here [**N**] denotes an $SU(3)$ representation of dimension N; K is the string tension and it has been assumed that new strings have the same transverse areas as the triplet one.The string tension K is proportional to the quadratic Casimir operator Q^2 for the corresponding representation:

$$Q^2_{[3]} = \frac{4}{3}, \quad Q^2_{[6]} = \frac{10}{3}, \quad Q^2_{[8]} = 3, \tag{11}$$

which gives you $K_{[\mathbf{8}]} \approx K_{[\mathbf{6}]} \approx 2.5 K_{[\mathbf{3}]}$. The string decay algorithm of X. Artru and G. Mennessier [47] and the following parameters of the simulation are used:

- the single $q\bar{q}$ string decays via $\bar{q}-q$ or $\bar{q}\bar{q}-qq$ production with probabilities $P_{qq}/P_q = 0.085$, $p_s/p_{d,u} = 0.29$.
- the probability of the decay depends exponentially on the area A swept by string, according to the invariant area decay law: $P = 1 - \exp\left(-b_{[3]}A\right)$, where $b_{[3]} = A_t \sum_f (w_f) = 0.4$ GeV^{-2}.
- the strange quark and diquark suppression parameters can be obtained by proper choice of the quark masses: $M_{u,d} = 0.23$ GeV, $M_s = 0.35$ GeV, $M_{q_1 q_2} = M_{q_1} + M_{q_1}$.
- the last decay of the string is determined by the mass of the rest of the string: $M_s = M_h + \Delta M$, where M_h is corresponding hadron mass and $\Delta M = 0.36$ GeV.
- [**6**]$-$ and [**8**]$-$ strings have the same transverse areas A_t as a triplet one and use the same invariant area decay law $b_{[8]} \approx b_{[6]} \approx 2b_{[3]}$
- The transverse momentum distribution each single - or multi-quark object produced in the decay of the string is taken in Gaussian form so that the total transverse momentum of the produced pair of such objects is equal to zero:

$$f(p_t^2)\, p_t\, dp_t \;\sim\; \exp(-\alpha_{[N]} p_t^2)\, p_t\, dp_t, \tag{12}$$

where

$$\alpha_{[N]} = \alpha_{[3]} \cdot \left(\frac{K_{[3]}}{K_{[N]}}\right)^{0.5}, \quad \alpha_{[8]} \approx \alpha_{[6]} \approx 1.5\alpha_{[3]}, \quad \alpha_{[3]} = 5\ \mathrm{GeV}^{-2}. \tag{13}$$

After the decay two new $Q\bar{Q}-$ strings are treated in the same manner and decay into more $Q\bar{Q}-$ strings, until we come to objects with masses comparable to hadron masses, which are identified with observable hadrons by combining the produced (anti)quarks into them with statistical weights and energies.

Including the fusion of two ordinary $q\bar{q}$-strings into a $[\bar{\mathbf{3}}]$- string with the formation of (anti)diquark at the end, will lead predominantly to its decay into (anti)baryons, and thus leads to an enhancement of the (anti)baryon content. The decay procedure leads to the enhancement of (anti)baryon production, especially the strange one, for the fused strings in contrast to two single triplet strings. This is the result of the increasing the string tension $K_{[\mathbf{N}]}$ as compared to $K_{[\mathbf{3}]}$. On the other hand the fused strings decay faster than triplet strings that leads to suppression of the hadron production.

9.3 Running the program

The SFM package contains:
QWCWN.f - head program adjusted to ALICE conventions
QN1.f - main SFM program
RWCN.f - initialization of the CWN-format and particle ID conversion table.
TABDEC.DATA - particle decay table. Must be provided before starting.

One has simply to compile 3 fortran files in the sequence they are mentioned, improve the INPUT.DATA file, if necessary, and submit the job for the batch process. The INPUT.DATA file should be used as input file, and arbitrary file, e.g. **f1**, may be used as a file to store the supplementary information about the simulations. Example:

```
bsub -q normal -i INPUT.DATA -o f1 SFMW
```

for the IBM RS6000 cluster.

9.3.1 Output

The universal ALICE output format is used (see this Note).

9.3.2 Typical running time

The running time depends on the energy and the type of the collision, as well as on the computer facilities. For instance, on IBM RS-6000 cluster (not including initialization):

pp	$\sqrt{s}$=200 GeV	$\sim$ 1200 events/min.
$Au + Au$(central)	$\sqrt{s}$=200 GeV/n	$\sim$ 5 events/min.
pp	$\sqrt{s}$=6.0 TeV/n	$\sim$ 300 events/min.
$S + S$(central)	$\sqrt{s}$=6.0 TeV/n	$\sim$ 10 events/1 min.
$Pb + Pb$(central)	$\sqrt{s}$=6.0 TeV/n	$\sim$ 1 event/70 sec. (no string fusion)
$Pb + Pb$(central)	$\sqrt{s}$=6.0 TeV/n	$\sim$ 1 events/50 sec. (with string fusion)

10 The heavy-ion two-photon event generator TPHIC

TPHIC is an event generator for two photon interactions induced by coherent heavy ion collisions. Two photon collisions provide a possibility to study various processes in the framework of the Standard Model as well as in the advanced models based on supersymmetry which cannot be explored at hadron and lepton colliders. The basis of the generator is the effective $\gamma\gamma$ luminosity function derived in the equivalent photon approximation. The generator allows to simulate processes of two photon interactions such as minimum bias events, resonance production, fermion, charged weak boson and supersymmetric chargino pair production. Further details can be found elsewere [49].

10.1 Effective $\gamma\gamma$ luminosity function

In the equivalent photon approximation [50, 51] the cross section of two photon processes can be expressed in a factorized form [50, 52, 53]:

$$\frac{d\sigma}{d\Omega}(AA \to AAX) = \int dW \frac{d\mathcal{L}_{\gamma\gamma}}{dW} \frac{d\sigma}{d\Omega}(\gamma\gamma \to X), \tag{14}$$

where the effective $\gamma\gamma$-luminosity function $\mathcal{L}_{\gamma\gamma}$ is determined in terms of the equivalent photon number $N(\omega, b)$ with energy ω and impact parameter b:

$$\begin{aligned} \frac{d\mathcal{L}_{\gamma\gamma}}{dW} &= \int_R^\infty b_1 db_1 \int_R^\infty b_2 db_2 \int_0^{2\pi} d\phi \\ & N(\frac{W}{2}e^{Y}, b_1) N(\frac{W}{2}e^{-Y}, b_2) \theta(b_1^2 + b_2^2 - 2b_1 b_2 \cos\phi - 4R^2). \end{aligned} \tag{15}$$

Here R is a cutoff of the impact parameter in order to avoid nuclear overlapping and, therefore, to get a clean signal. R is a nuclear radius defined as $R = 1.2A^{1/3}$ fm. The photon spectrum $N(\omega, b)$ is given by expression:

$$N(\omega, b) = \frac{Z^2\alpha}{\pi^2}\frac{\omega^2}{\gamma^2} K_1^2(\frac{\omega b}{\gamma}), \tag{16}$$

where γ stands for the c.m.s. Lorentz factor of a heavy ion, $\gamma = \sqrt{s_{AA}}/2M_A$; $K_1(x)$ is the modified Bessel function of the second kind. The energy of photons mainly limited by the nucleus radius: $\omega \leq \gamma/R$. This feature of a photon spectrum in heavy ion collisions makes a difference in comparison with that in e^+e^--collisions.

10.2 Physical processes in $\gamma\gamma$ collisions

The TPHIC generator simulates two photon interactions in high energy heavy ion collisions. The generator allows to calculate the effective $\gamma\gamma$ luminosity function $d^2\mathcal{L}_{\gamma\gamma}/dWdY$ on a grid according to the formula (15) and save it into a file for the next usage. Then it produces event configurations and calculates the cross sections for the following five processes:

No.	Process type
1	minimum bias events (based on the approach of ref. [54]);
2	$\gamma\gamma \to$ quarkonium, where quarkonium can be any charmonium or bottomonium $J^{PC} = 0^{-+}$, 0^{++}, 2^{++};
3	$\gamma\gamma \to f^+ f^-$ (basic formula of the cross section is given by [55]);
4	$\gamma\gamma \to W^+ W^-$ [56];
5	$\gamma\gamma \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ with subsequent chargino decay $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 l^+ \nu_l$, where $l^\pm$ is either electron or muon [55, 57].

Expressions for differential cross sections of processes 3–5 were obtained by means of the computer system of analytical matrix elements evaluation CompHEP [58]. The cross section of a chosen process is calculated by means of numerical integration with expressions (14), (15) and a cross section of the elementary two-photon process.

The generator uses well known event generators Pythia v.5.706 [59] for the process 1 to produce minimum bias events in $\gamma\gamma$ collisions (analogous approach can be found in ref. [60]), Isajet v.7.13 [61] for the process 5 to calculate masses and decay parameters in MSSM and Jetset v.7.4 [59] for all processes to perform fragmentation, decays etc. Therefore the generator should be linked with these packages. Be aware of linking the program with Pythia and Jetset with release date not earlier than August 25, 1994, otherwise Tphic will not work with the process 1 properly.

10.3 Structure of a user's program

A user program has to contain some user assignments to fix initial variables and change their defaults values (if needed), to call subroutine `GGINIT` to initialize the generator, a loop over certain number of events by calling `GGRUN` in each event to obtain the event configuration and to call `GGEXIT` at the end of the run to output a process cross section:

```
      PROGRAM SAMPLE
      ...
      User codes
      ...
      CALL GGINIT
      DO 100 IEVENT=1,NEVENT
        CALL GGRUN
        ...
        User codes
        ...
100     CONTINUE
      CALL GGEXIT
      ...
      User codes
      ...
      END
```

10.3.1 Initialization of the generator

At the initialization phase a user needs to define some variables from the following common blocks:

```
+KEEP,ggini.
      COMMON /ggini/ iproc,nevent,ilumf,lumfil,ebmn,eb,iz,ia,amas,
     &               amin,amax,ymin,ymax,nmas,ny,
     &               kf_onium,xmres,xgtres,xggres, xlumint, moddcy
      CHARACTER lumfil*80
```

where

`IPROC`	(D = 1) process number, see above
`NEVENT`	(D = 10000) number of events to be generated
`ILUMF`	(D = −1)flag to calculate Luminosity Function: 1 – read from a file, −1 – new calculation
`LUMFIL`	(D = 'gglum.dat') character variable with a file name with luminosity function
`EBMN`	beam energy per nucleon
`IZ`	beam ion atomic number
`IA`	beam ion atomic mass
`AMAS`	beam ion mass in GeV
`AMIN, AMAX`	range of 2-gamma mass
`YMIN, YMAX`	range of 2-gamma rapidity
`KF_ONIUM`	LUND code for quarkonium, the only parameter necessary for initialization, all other parameters are calculated in `GGINIT`
`XGGRES`	two photon width of the quarkonium in GeV
`NMAS, NY`	(D = 50,50) number of steps in luminosity function calculation in two photon mass and rapidity, max{`NMAS,NY`}= 10 000
`MODDCY`	a key to select chargino decay modes (for `IPROC` =5); =1 for decay into leptons (electrons and muons), =0 for all decay modes (not implemented yet).

A common block to the event output in the CWN format (see below):

```
+KEEP,ggcwn.
      COMMON /ggcwn/ icwn, cwnfil
      CHARACTER cwnfil*80
```

where

`ICWN`	(D = 0) a flag to produce the event output in the CWN format (if `ICWN`=1)
`CWNFIL`	(D = 'ggout.cwn') a file name with the CWN output

```
+KEEP,ggmssm.
      COMMON /ggmssm/ xm1,   xm2,    xmg,    xms,    xmtl,   xmtr,
     &                xmll,  xmlr,   xmnl,   xtanb,  xmha,   xmu,
     &                xmt,   xat,    xmbr,   xab,    u11,    v11
```

This common block is used for `IPROC`=5 only and contains parameters of MSSM breaking. Masses and decay branchings of chargino and neutralino are defined through `XM1`, `XM2`, `XMU`, `XTANB`. All parameters have some default values and may be changed by the user. Default (D) and recommended (R) values are following:

	(D)	(R)	
`XM2`	50.	$40 <$ `XM2` < 1000 GeV	M_2
`XM1`	30.	`XM1` = `XM2`/2	M_1
`XMU`	$-300.$	$-1 <$ `XMU` < 1 TeV	μ
`XTANB`	4.	$1 <$ `XTANB` < 50	$\tan\beta$
`XMS`	700.		squark mass
`XMTL`	600.		left soft breaking stop mass
`XMTR`	600.		right soft breaking stop mass
`XMLL`	400.		left slepton mass
`XMLR`	400.		right slepton mass
`XMNL`	400.		sneutrino mass
`XMHA`	300.		pseudo-scalar Higgs mass
`XMT`	174.		top quark mass
`XAT`	300.		stop squark trilinear term
`XMBR`	300.		right soft breaking sbottom mass
`XAB`	300.		sbottom squark trilinear term

```
+KEEP,ggxs.
      COMMON /ggxs/ xsmax, xscur, xsbra, xssum, ntry, xstot, xstote,
     &  ssbr(10)
```

Only the variable `XSBRA` from this common block may be defined during the initialization; during the run the cross section calculation will be multiplied by a factor `XSBRA`. Normally it is a squared branching ratio of studied decay modes. Other variables from this common block are calculated by the generator and may be used by a user to inquire cross section information of a process:

`XSTOT`	the total cross section of the current process in nbarn, can be used after any full event, the more events, the more precise it is.
`XSTOTE`	statistical error of `XSTOT`

10.3.2 Event output

Some items of the event configuration are made available to the user through the common block `GGEVNT`.

```
+KEEP,ggevnt.
      COMMON /ggevnt/ nrun,ievent,wsq,ygg,xmg1,xmg2, p2g(5),
     &                ptag1(4),ptag2(4), ngg, kgg(10),pgg(20,5)
```

`NRUN`	run number
`IEVENT`	current event number
`WSQ`	squared 2-photon mass
`YGG`	2-photon rapidity
`XMG1, XMG2`	virtual photons masses
`P2G(5)`	4-momentum + mass of a 2-photon system

The full information about event configuration (code of each particle, its status, where it originates from, its momentum) is stored in the JETSET common block `LUJETS`

```
+KEEP, LUJETS
      COMMON/LUJETS/N,K(4000,5),P(4000,5),V(4000,5)
      SAVE /LUJETS/
```

The description of this common block can be found in the PYTHIA/JETSET manual. Since JETSET does not know about supersymmetric particles, we have implemented two new entries in particle codes table:

KF	name	printed
41	$\tilde{\chi}_1^-$	`chi_1-`
42	$\tilde{\chi}_1^0$	`chi_10`

The generator has also the interface to transform event records into the Column Wise Ntuple format (CWN) which is considered to be the standard ALICE output format for various event generators. This interface is represented by 3 subroutines:

`CALL CWNINI (OUTFILE)`	opens output file `OUTFILE` (of CHARACTER type) for event data in CWN format;
`CALL CWNFNT`	event output routine in CWN format, called in each event after `GGRUN`;
`CALL CWNEND`	closes the output CWN properly

10.3.3 Cross section calculation

The Cross section of a process is calculated in each event and can be retrieved through the common block `GGXS` as described above. Besides after the run, calling of the subroutine `GGEXIT` prints out the process cross section and its statistical error.

10.4 Installation of Tphic

The Tphic package contains files `TPHIC.CAR`, `TPHIC.CRA` and `TPHIC_MAKE.COM`. The latter is a command file to create object library at VAX and Alpha/OpenVMS. This library contains two `BLOCK DATA` modules `GGDATA` and `GAUSSDATA`, some linkers do not take these modules during linking stage and therefore these modules should be included explicitly. Examples of Tphic usage can be produced by the command file `TPHIC_EXA.COM` with cradle files `TPEXA1.CRA` – `TPEXA4.CRA`.

Warning! In some versions of CERN library (at least, in version 94b for VAX/VMS and AXP/OpenVMS) `JETSET74` object library is compiled improperly and does not correspond to the actual version of Pythia. If it is so on your local computer it is necessary to recompile this library.

11 PHOJET a two-photon event generator

Program name: Phojet [62]
Version: Phojet 1.04 of 20 October 1995
Author: Ralph Engel
Institute of Theoretical Physics
University Leipzig
Augustusplatz 10, D-04109 Leipzig, Germany
Phone: + 49 – 341 - 97 32444
E-mail: eng@tph200.physik.uni-leipzig.de
Program size: 31000 lines
Program location: can be obtained by e-mail from the author

Phojet is a minimum bias event generator for hadronic pp, γp and $\gamma\gamma$ interactions. The interactions are described within the Dual Parton Model (DPM) [15] in terms of reggeon and pomeron exchanges. The realization of the DPM with a hard and a soft component in Phojet is similar to the event generator Dtujet-93 [63, 64]. Regge arguments are combined with perturbative QCD to get an almost complete description of the leading event characteristics. Special emphasis is taken on diffractive and soft interactions. Soft and hard interactions are unitarized together leading to the possibility to have multiple soft and hard scatterings in one event.

In the following, some comments on LEP 2 specific aspects are given. In the model [62], the dual nature of the photon is taken into account by considering the physical photon state as a superposition of a "bare photon" and virtual hadronic states having the same quantum numbers as the photon. Two generic hadronic states $|q\bar{q}\rangle$ and $|q\bar{q}^\star\rangle$ have been introduced to describe the hadronic piece of the photon. The low-mass state $|q\bar{q}\rangle$ corresponds to the superposition of the vector mesons ρ, ω and ϕ and a $\pi^+\pi^-$ background. The state $|q\bar{q}^\star\rangle$ is used as an approximation for hadronic states with higher masses. The physical photon reads

$$|\gamma\rangle = \sqrt{Z_3}\ |\gamma_{\rm bare}\rangle + \frac{e}{f_{q\bar{q}}}\ |q\bar{q}\rangle + \frac{e}{f_{q\bar{q}^\star}}\ |q\bar{q}^\star\rangle. \tag{17}$$

The interaction of the hadronic states via pomeron/reggeon exchange is subdivided into processes involving only *soft* processes and all the other processes with at least one large momentum transfer (*hard* processes) by applying a transverse momentum cutoff $p_\perp^{\rm cutoff}$ to the partons. On Born-graph level, for example, the photon-photon cross sections is built up by: **(i)** soft reggeon and pomeron exchange, **(ii)** hard resolved photon-photon interaction, **(iii)** single direct interactions, and **(iv)** double direct interactions. The soft pomeron cross sections is parametrized using Regge theory. The hard cross sections are calculated within the QCD Parton Model using lowest order matrix elements. For soft processes, photon-hadron duality is assumed. The energy-dependence of the reggeon and pomeron amplitudes is assumed to be the same for all hadronic processes. Therefore, data on hadron-hadron and photon-hadron cross sections can be used to determine the parameters necessary to describe soft photon-photon interactions.

The amplitudes corresponding to the one-pomeron exchange between the hadronic fluctuations are unitarized applying a two-channel eikonal formalism similar to [63]. The probabilities $e^2/f_{q\bar{q}}^2$ and $e^2/f_{q\bar{q}^\star}^2$ to find a photon in one of the generic hadronic states, the coupling constants to the reggeon and pomeron, and the effective reggeon and pomeron intercepts cannot be determined by basic principles. These quantities are treated as free parameters and determined by cross section fits [62]. Once the parameters are fitted, the model allows for predictions on photon-photon collisions without new parameters.

The probabilities for the different partonic final state configurations are calculated from the discontinuity of the scattering amplitude (optical theorem). Using the Abramovski-Gribov-Kancheli cutting rules [65] the cross section for graphs with k_c soft pomeron cuts, l_c hard pomeron cuts, m_c triple- or loop-pomeron cuts, and n_c double-pomeron are estimated. For pomeron cuts involving a hard scattering, the complete parton kinematics and flavors/colors are sampled according to the Parton Model using a method similar to [66], extended to direct processes. For pomeron cuts involving parton configurations without a large momentum transfer, the partonic interpretation of the Dual Parton Model is used: photons or mesons are split into a quark-antiquark pair whereas baryons are approximated by a quark-diquark pair. The longitudinal momentum fractions of the soft partons are given by Regge asymptotics [67]. One obtains for the valence quark (x) and diquark ($1-x$) distribution inside the proton $\rho(x) \sim (1-x)^{1.5}/\sqrt{x}$ and for the quark antiquark distribution inside the photon $\rho(x) \sim 1/\sqrt{x(1-x)}$. For multiple interaction events, the sea quark momenta are sampled from a $\rho(x) \sim 1/x$ distribution. The transverse momenta of the soft partons are sampled from an exponential distribution in order to get a smooth transition between the transverse momentum distributions of the soft constituents and the hard scattered partons.

In diffraction dissociation or double-pomeron scattering, the parton configurations are generated using the same ideas described above applied to pomeron- photon/pomeron scattering processes. According to the kinematics of the triple- or loop-pomeron graphs, the mass of the diffractively dissociating systems is sampled from a $1/M_D^{2\alpha_{I\!P}(0)}$ distribution. The momentum transfer in diffraction is obtained from an exponential distribution with mass-dependent slope (see Ref. [62]). For the parton distributions of the pomeron, the CKMT parametrization with a hard gluonic component [68] is used. The low-mass part of diffraction dissociation is approximated by the superposition of high-mass vector mesons. In order to take into account the transverse polarization of quasi-elastically produced vector mesons, diffractively scattered ρ, ω and ϕ are decayed anisotropically.

Finally, the fragmentation of the sampled partonic final states is done by forming color neutral strings between the partons according to the color flow. In the limit of many colors in QCD, this leads to the two-chain configuration characterizing a cut pomeron and a one-chain system for a cut reggeon. In hard interactions the color flow is taken from the matrix elements directly [69]. The leading contributions of the matrix elements give a two-chain structure which corresponds to a cut pomeron. The chains are fragmented using the Lund fragmentation code JETSET 7.3 [11].

The photon fluxes in heavy ion and proton collisions are available in PHOJET. In the model only photons with very low virtualities are considered at the moment. The extension to virtual (and longitudinally polarized) photons is in progress.

For example, the following input file [70] can be used to generate 1000 photon–photon events in Pb-Pb collisions at the LHC.

```
***********************************************************
*      input file      PHOJET
***********************************************************
PDF           45     2   0   0
PROCESS       1  1  1  1  1  1  1  1  1  1  1
E-TAG1        4.E-4   0.1     0.0  0.0    0.0   0.0
E-TAG2        4.E-4   0.1     0.0  0.0    0.0   0.0
ECMS-CUT      2.0    6000.0
WW-HION       3000.0   3000.0   207    92     1000
ENDINPUT
```

12 Fragmentation of nuclei

Most of the existing modern event generator models consider nucleus-nucleus interactions at high energies as the interaction of unbound nucleon pairs. The noninteracting parts of the nuclei are represented by a flow of single protons and neutrons flying off at angles of 0^o and 180^o relative to the collision axis. However, detailed investigation of detector responses in experimental setups require the knowledge of the characteristics of nuclear fragments. A simple simulation of the fragmentation of the colliding nuclei can be used for this aim.

In this section the scheme of such a simulation model is outlined based on the following :

- The estimate of the number of spectator nucleons in the interaction of the colliding nucei. In our case this estimate was based on the HIJING model. These spectator nucleons are considered as a 'residual' nucleus with mass and charge equal to the sum of the masses and charges of the nucleons.

- The fragmentation of the 'residual' nucleus, based on the fragmentation characteristics of projectile nuclei, as obtained from experimental data.

  The charge composition of the 'residual' nuclear fragments is generated according to the experimental distributions of fragment charges as observed from the EMU01 data [71] for interactions of Au nuclei with emulsion nuclei at 11 AGeV. Also the number of tritons, deutrons and protons among the single charged fragments were generated according to the emulsion data [72]. The shares of the t, d and protons for Si+(Ag,Br) interactions at 4.5 AGeVwere found to be 15%, 32% and 53%, respectively.

  The transverse momentum of the fragment was estimated on basis of a parabolic law [73].

  $$d\sigma/dP_{\perp} \approx exp(-P_{\perp}^2/2\sigma) \tag{18}$$

  where

  $$\sigma = (1/5)^{1/2}(F(A-F)/(A-1))^{1/2}P_F \tag{19}$$

  with A, F the atomic number of the projectile and fragment respectively and a Fermi momentum P_F of 221 MeV/c.

This model has been used for simulation studies of the WA98 Zero Degree Calorimeter [74], in which estimates of the deposited energy in the scintillator tiles and wavelength shifters were obtained in case Pb nuclei of 160 AGeV beam energy were incident on the detector.

The model, based on experimental observations, described above can be used in a wide energy range, provided the momentum of the projectile nucleus is above the fragmentation limit of 4 AGeV/c. An example for Pb+Pb interactions at 6000 AGeV cms energy is shown on fig. 2 and fig. 3.

The source code of the model together with the code for reading the events generated by the HIJING model and reformatting these events into our general ntuple format together with the generated nuclear fragments can be found in the ALICE offline program area in the file named HIJFRAG.CMZ.

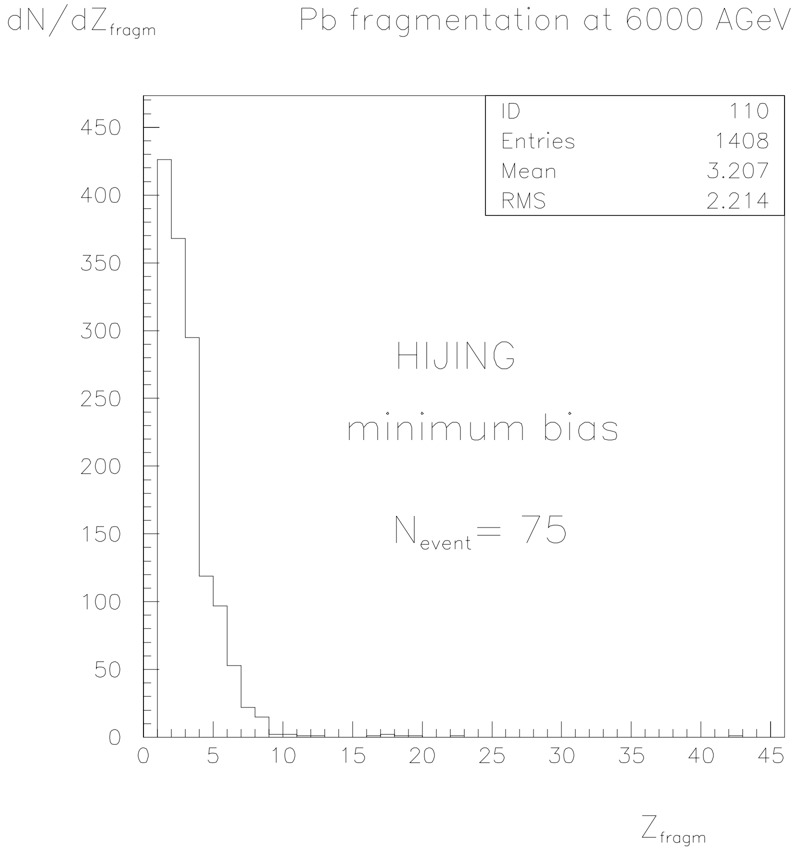

Figure 2: Charge distribution of nuclear fragments for Pb+Pb interactions at a cms energy of 6 ATeV.

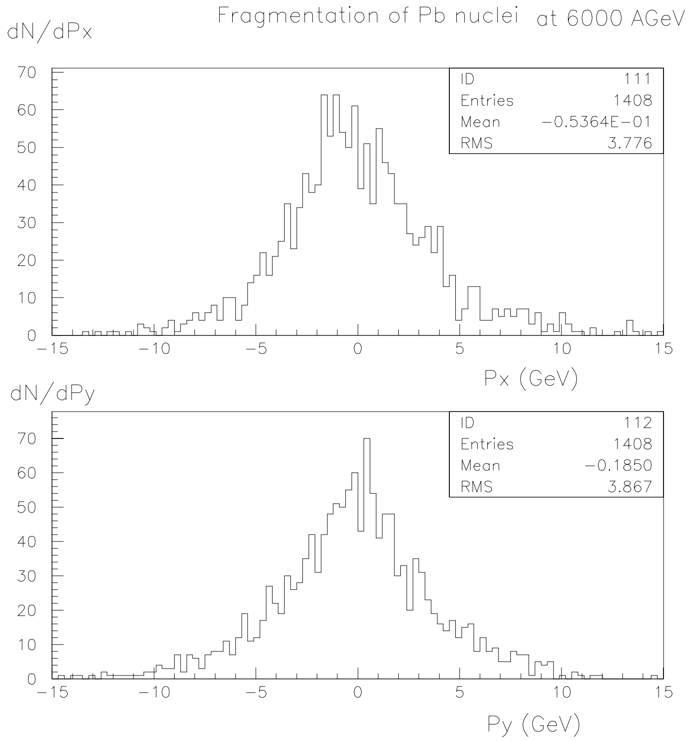

Figure 3: Px and Py distribution for nuclear fragments of Pb+Pb collisions at 6 ATeV cms energy.

13 Comparison of results

For Pb-Pb collisions at a LHC beam energy of 3 TeV per nucleon two data samples

- 5 % most central ($0 \leq b \leq 3$ fm), 50 events
- 30 % most peripheral ($11 \leq b \leq 14$ fm), 50 events

have been generated with the help of the SHAKER (only central events), VENUS, HIJING, DPMJET-II (30 central events), SFM (no-fusion) and SFM (fusion) codes. The corresponding CWN format output data can be founded in the areas

- **/afs/cern.ch/alice/offline/data/evtgen/shaker**
- **/afs/cern.ch/alice/offline/data/evtgen/venus**
- **/afs/cern.ch/alice/offline/data/evtgen/hijing**

- **/afs/cern.ch/alice/offline/data/evtgen/dpmjet**
- **/afs/cern.ch/alice/offline/data/evtgen/sfm**

In the generation the following particles (and their anti-particles) were declared as stable

$$\gamma, \nu, e^+, \mu^+, \pi^+, K_L, K_S, K^+, n, p, \Lambda, \Xi^-, \Omega^-$$

Recall that SHAKER does not generate $\nu, \mu, n, \Lambda, \Xi$ and Ω. Other codes include additionally

- Ξ^0 and its anti-particle for VENUS
- $\Sigma^+, \Sigma^-, \Xi^0, D^+, D^0, D_s^+$ and their anti-particles for DPMJET-II
- Σ^+, Ξ^0 and their anti-particles for SFM

In the following a comparison of the data samples of the different generators will be presented, firstly as a whole and then in the following areas of interest

- Barrel region $-1 \leq \eta \leq 1$
- Forward Multiplicity Detectors (FMD) region $1.5 \leq \eta \leq 4$
- Zero Degree Calorimeters (ZDC) region $\eta \geq 8.43$

13.1 General outlook

In fig. 4 the various multiplicity distributions for the central event samples are shown. The charged particle densities at mid-rapidity for VENUS, SHAKER, HIJING, DPMJET-II and SFM (without and with fusion) were found to be 7000, 6300, 5200, 3700, 3400 and 1400 respectively. Here it is seen that the SHAKER data with our current input parameters overestimates nearly all of the predicted particle multiplicities at mid-rapidity. The SFM generator is seen to yield relatively low particle densities around mid-rapidity, whereas the VENUS particle densities are found to be the highest ones. In the following subsections we will consider multiplicity distributions in detail.

The maximum number of charged particles within the acceptance of the barrel detectors (i.e. $-0.88 \leq \eta \leq 0.88$) is found to be about 12000.

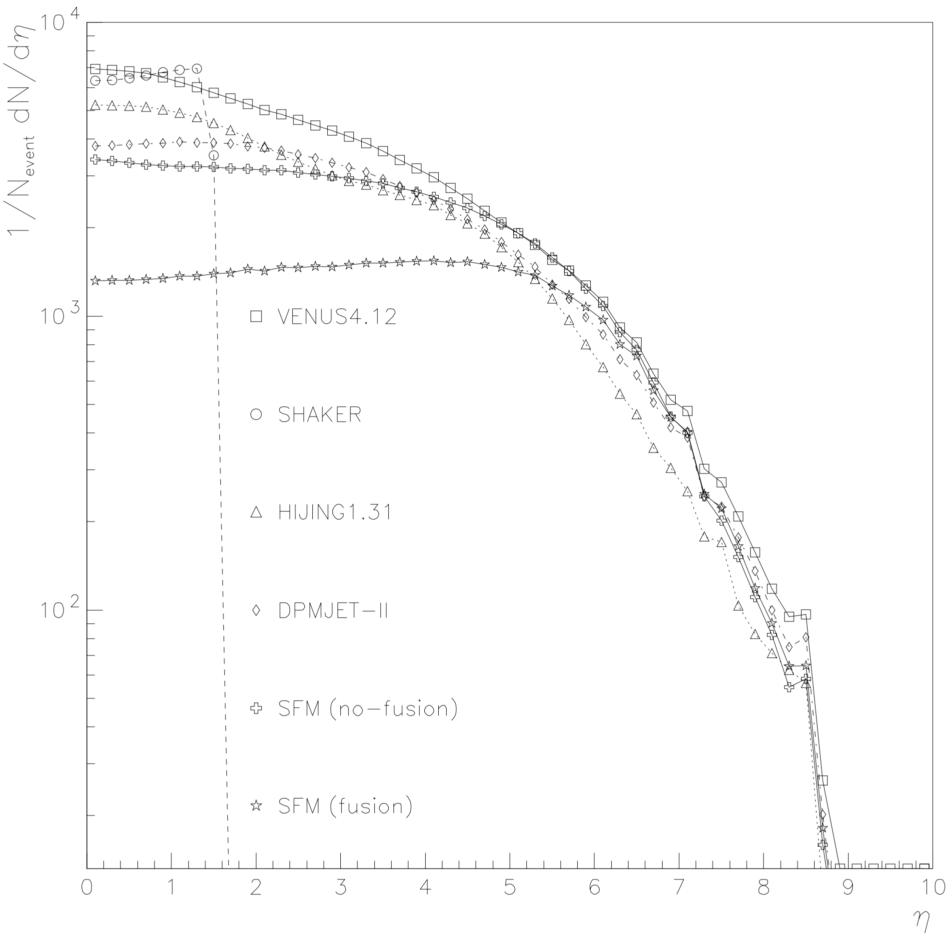

Figure 4: Pseudorapidity distribution of charged particles for central Pb-Pb events at a beam energy of 3 TeV per nucleon

The various transverse momentum distributions for the central event samples are presented in fig. 5.
The mean P_T values for SHAKER, VENUS, HIJING, DPMJET-II and SFM (with and without fusion) were found to be 535, 442, 432, 560, 403 and 352 MeV/c respectively. Here it is seen that for $P_T \leq 1$ GeV/c (i.e. the region around the mean P_T values) most theoretical models agree amongst eachother and that also the SHAKER data reproduces the theoretical predictions rather well. The inverse slopes of the spectra in the range $0.1 \leq P_T \leq 1$ GeV/c are 216, 217, 205, 237, 197 and 176 MeV/c for SHAKER, VENUS, HIJING, DPMJET-II and SFM (with and without fusion) respectively. For $P_T > 1$ GeV/c the various models start to differ substantially, where the SFM generator

is seen to produce a more soft spectrum than the other models.

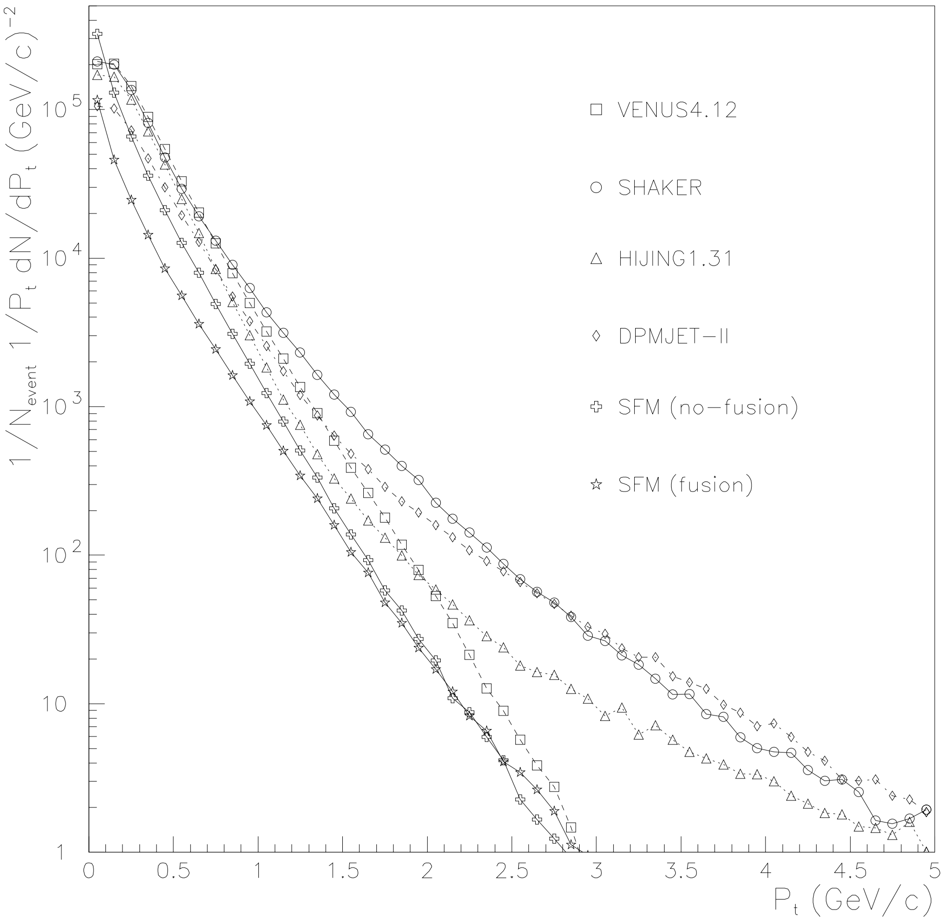

Figure 5: Charged particle transverse momentum distributions in the pseudo-rapidity interval $-1.5 \leq \eta \leq 1.5$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

To conclude the global comparison of the models, the net baryon rapidity distribution for the central Pb-Pb events is shown in fig. 6. All the models predict almost the same rapidity gap $-3 \leq y \leq 3$ free from net baryons. HIJING gives the smallest stopping of nuclei (this model does not include secondary interactions). The largest stopping is seen in the DPMJET-II model.

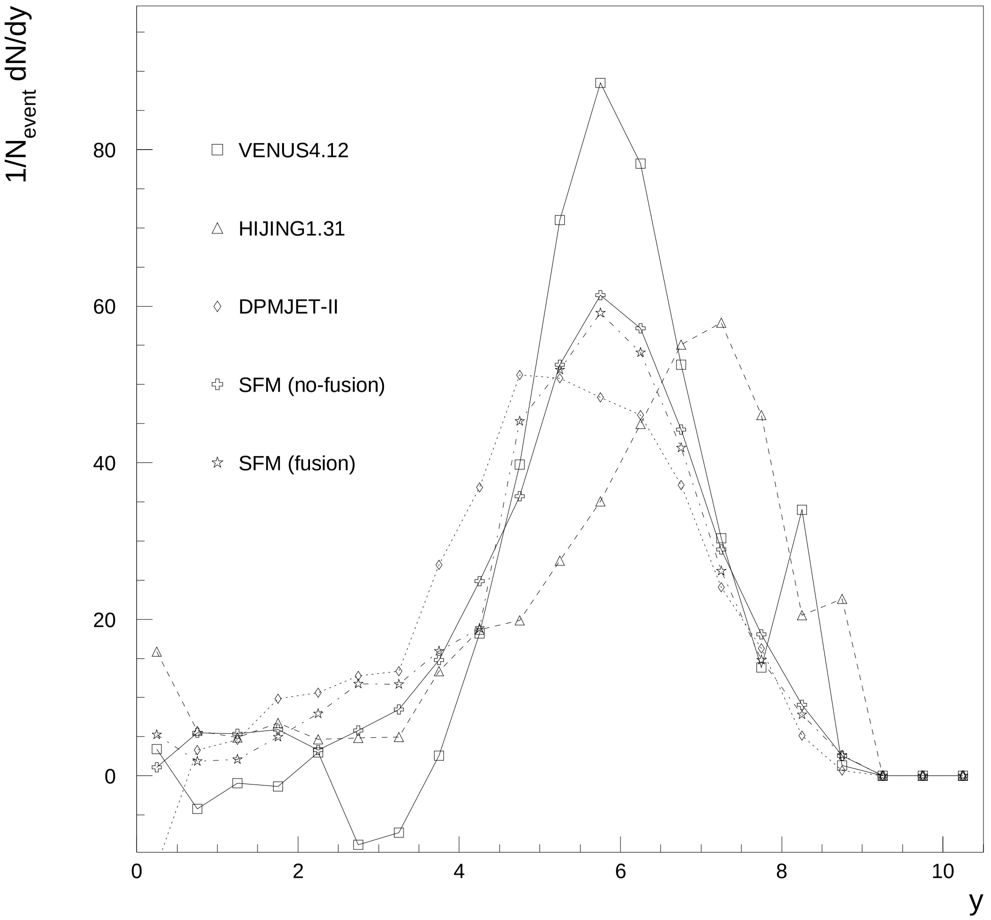

Figure 6: Rapidity distribution of net baryons $(p-\bar{p})+(n-\bar{n})$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

13.2 Barrel region $-1 \leq \eta \leq 1$

Average multiplicities of all our stable particle species generated by central Pb-Pb collisions in the Barrel region are presented in fig. 7. It is seen that the VENUS model gives the highest values for all particles except nucleons and muons. Other model multiplicities are up to 50% lower, of which SFM with string fusion is overall seen to be the lowest. The model discrepancies are the largest for two and three strange baryons and reach one and two orders of magnitude for Ξ and Ω respectively. The best agreement is observed for Λ, of about 100 particles per event.

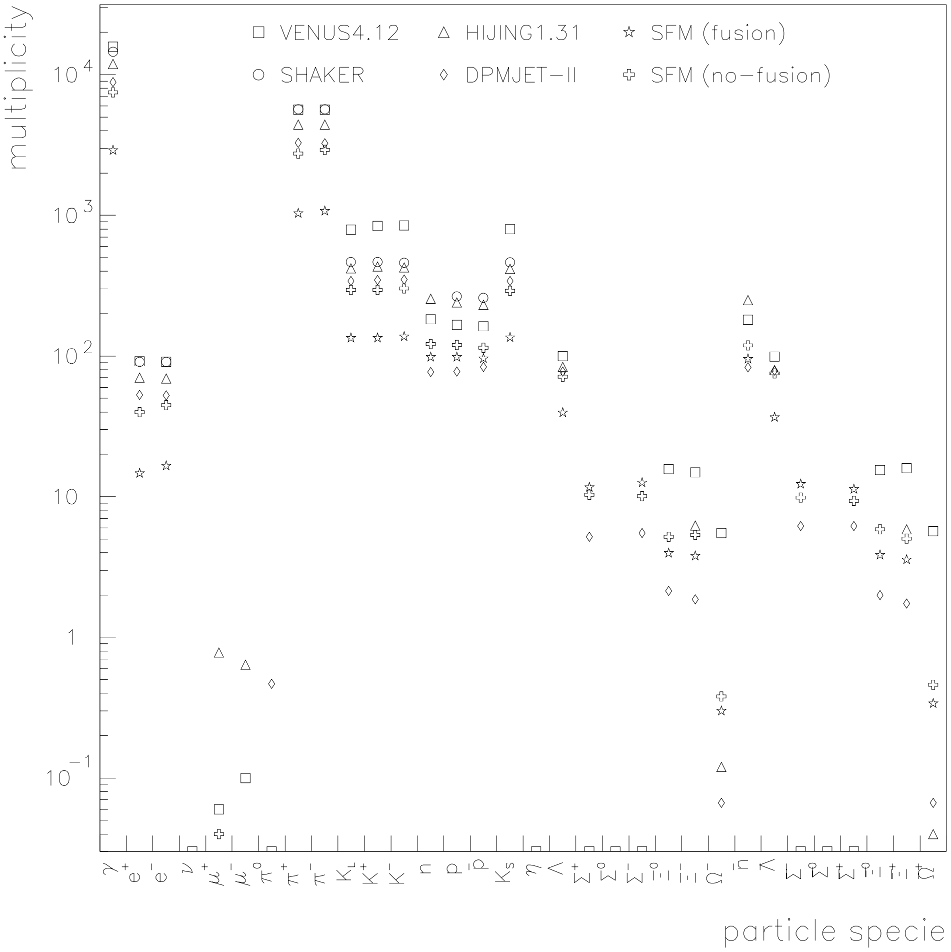

Figure 7: Multiplicities per event of particle species in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

Multiplicities of particles in the Barrel range for peripheral Pb-Pb events are shown in fig. 8. Almost the same situation as in the central case is observed, except that

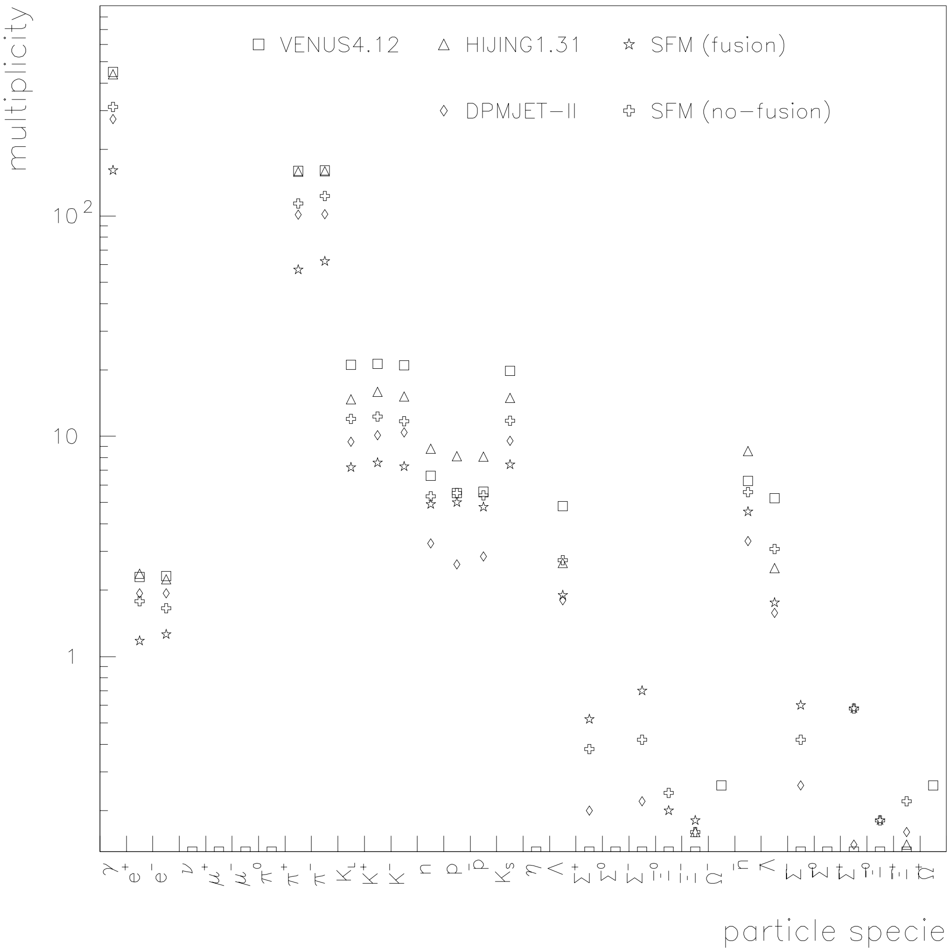

Figure 8: Multiplicities per event of particle species in the Barrel range $-1 \leq \eta \leq 1$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

all multiplicities are about 30 times smaller. It is interesting to point out that the average number of participants in the peripheral collisions (20 nucleons) is about 10 times smaller than in the central ones, compared to a factor of about 30 in the event multiplicities.

Furthermore, it is seen that in case of Λ the discrepancies are larger than in the central case, whereas for the other particles they are comparable.

Charged particle densities for the central Pb-Pb events in the Barrel range are shown in fig. 9. This influences directly the desired TOF granularity and occupation level, and as such the DAQ design by the number of readout channels and the produced amount of data. In addition this also affects the performance of the pattern recognition algorithms. It is seen that the pseudorapidity distribution is flat. The corresponding distribution for the peripheral collisions is also flat as is shown in fig. 10.

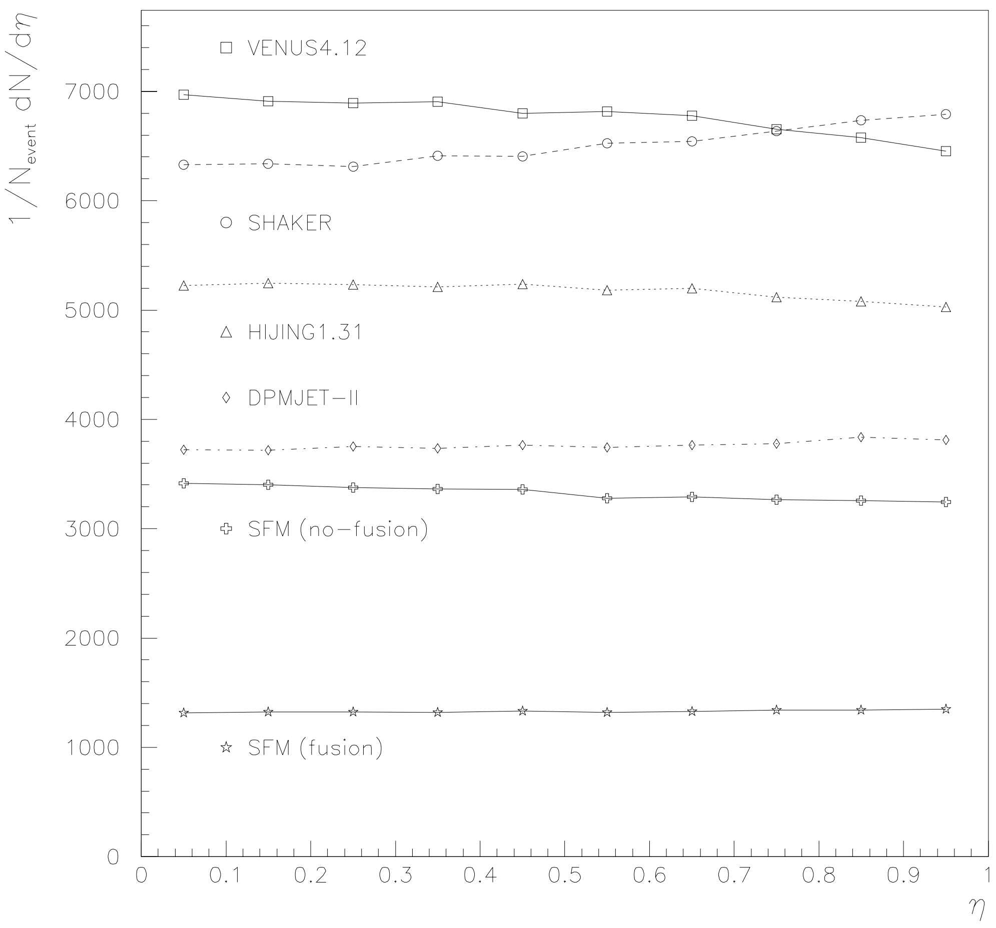

Figure 9: Pseudorapidity distribution of charged particles in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

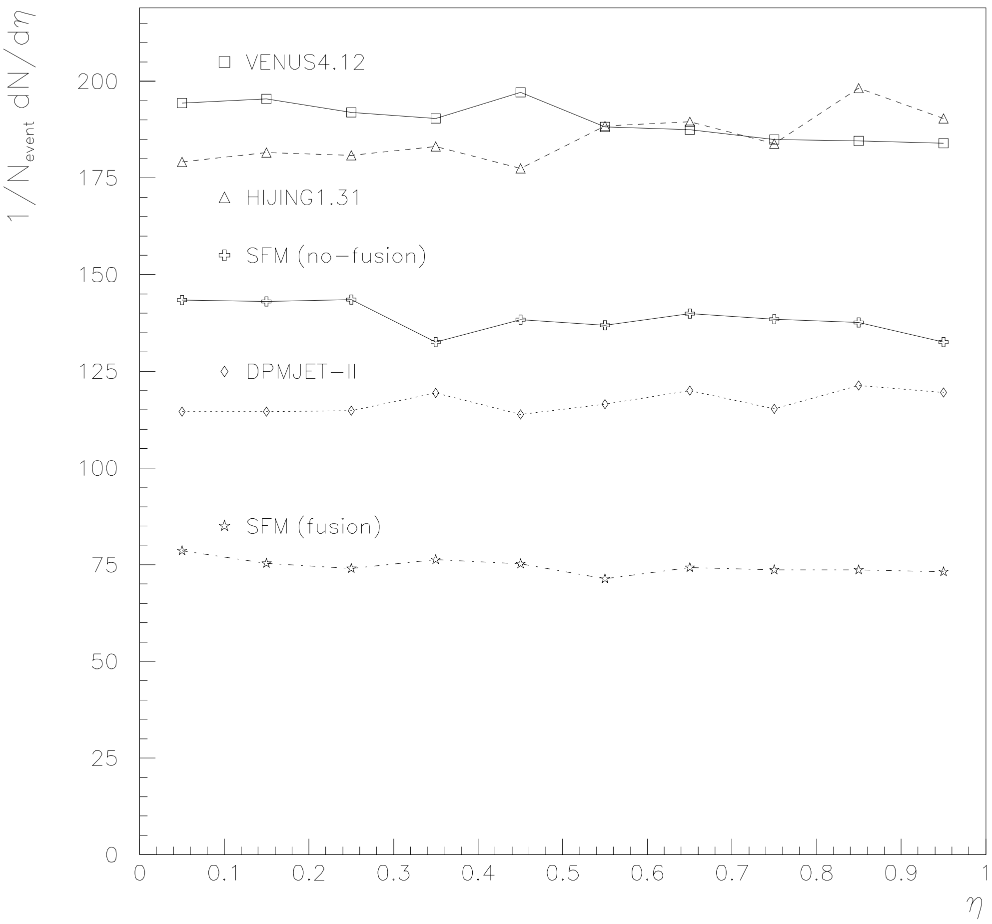

Figure 10: Pseudorapidity distribution of charged particles in the Barrel range $-1 \leq \eta \leq 1$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

In a similar way the photon multiplicities in the Barrel region have been obtained to enable a study of the particle density on the photon spectrometer (PHOS). The results are shown in figs. 11 and 12 for the central and peripheral sample respectively and it is seen that the photon distributions are very similar to the charged particle ones, since the main contribution to the photon yield comes from π^0 decays.

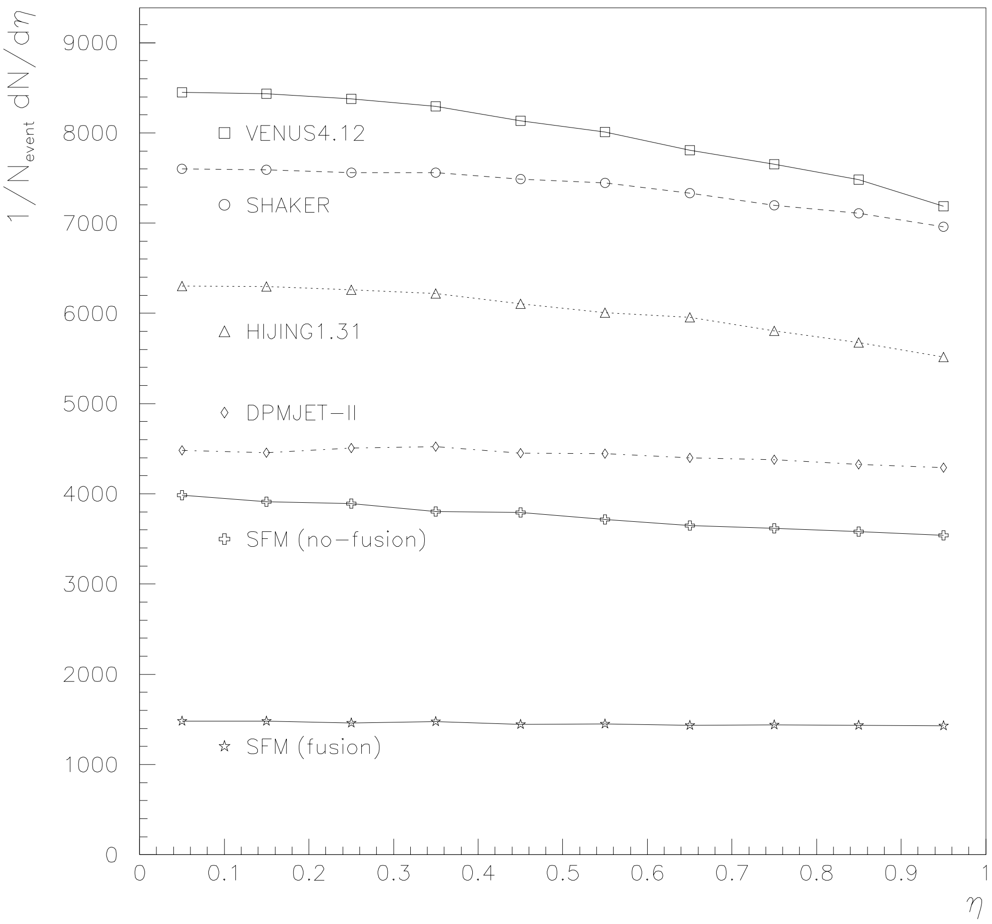

Figure 11: Pseudorapidity distribution of γ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

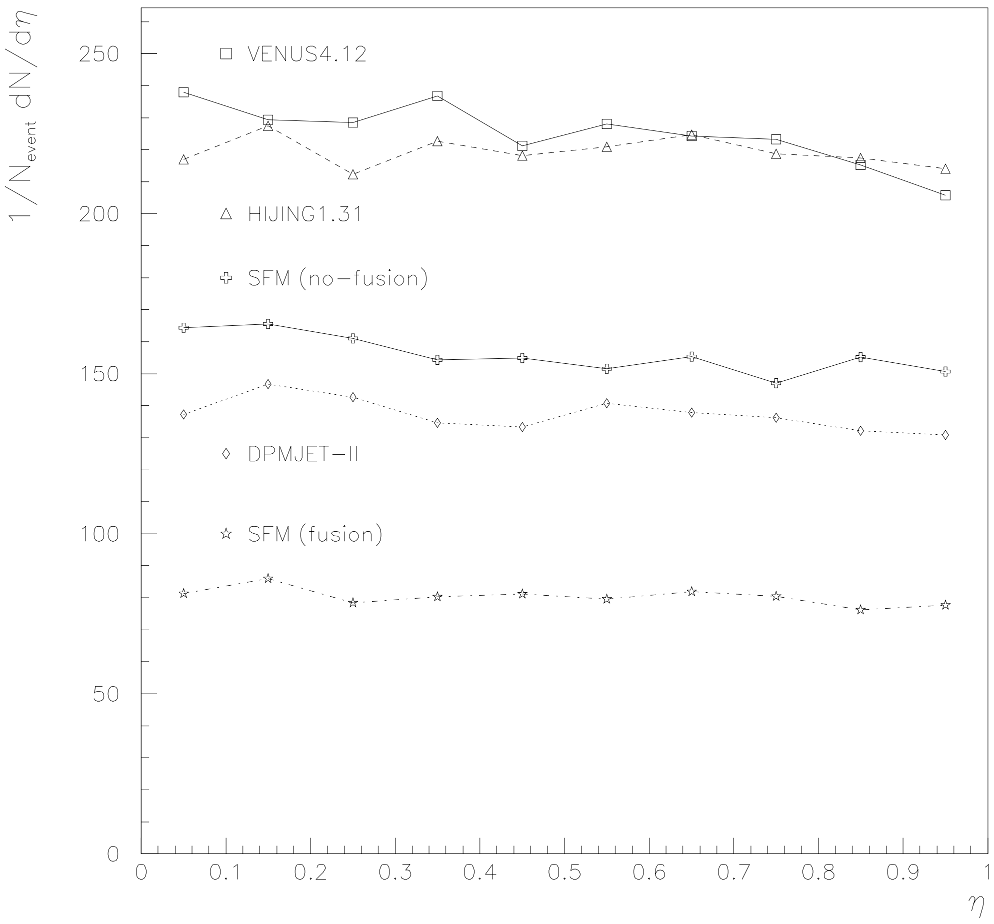

Figure 12: Pseudorapidity distribution of γ in the Barrel range $-1 \leq \eta \leq 1$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

Transverse momentum distributions in the Barrel range for all our stable particle species (except for Ξ, μ and Ω for which statistics is poor, see fig.7) produced in the central Pb-Pb events are presented in figs. 13 - 20. Since the multiplicities of particles and anti-particles are the same in the Barrel region, the sum of the spectra is shown.

The distribution of this observable influences the required accuracy on the produced space points of the various tracking detectors in order to obtain a certain precision in the momentum reconstruction at a given magnetic field strength.

In the range of $P_t \leq 1$ all the generators predict approximately the same slope of the charged particle spectrum (see fig. 14 for $\pi^{\pm}$, which give the main contribution).However, at higher transverse momentum there are considerable discrepancies.

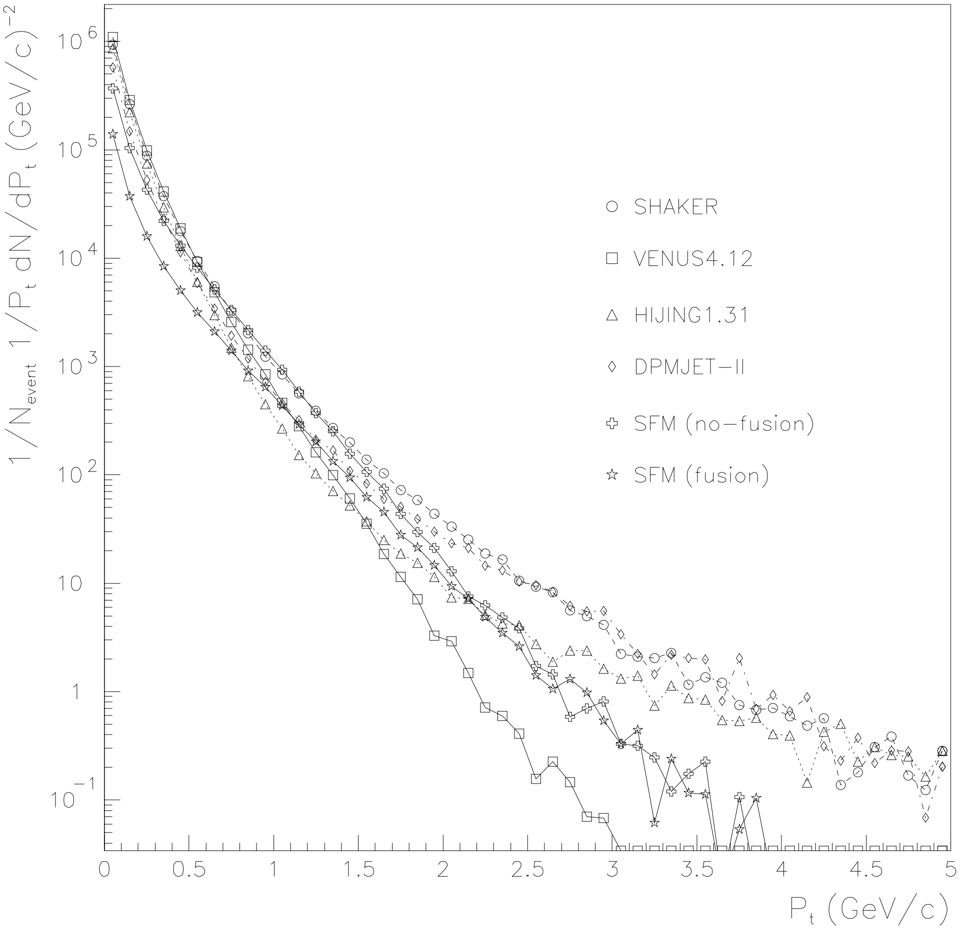

Figure 13: Transverse momentum distributions of γ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

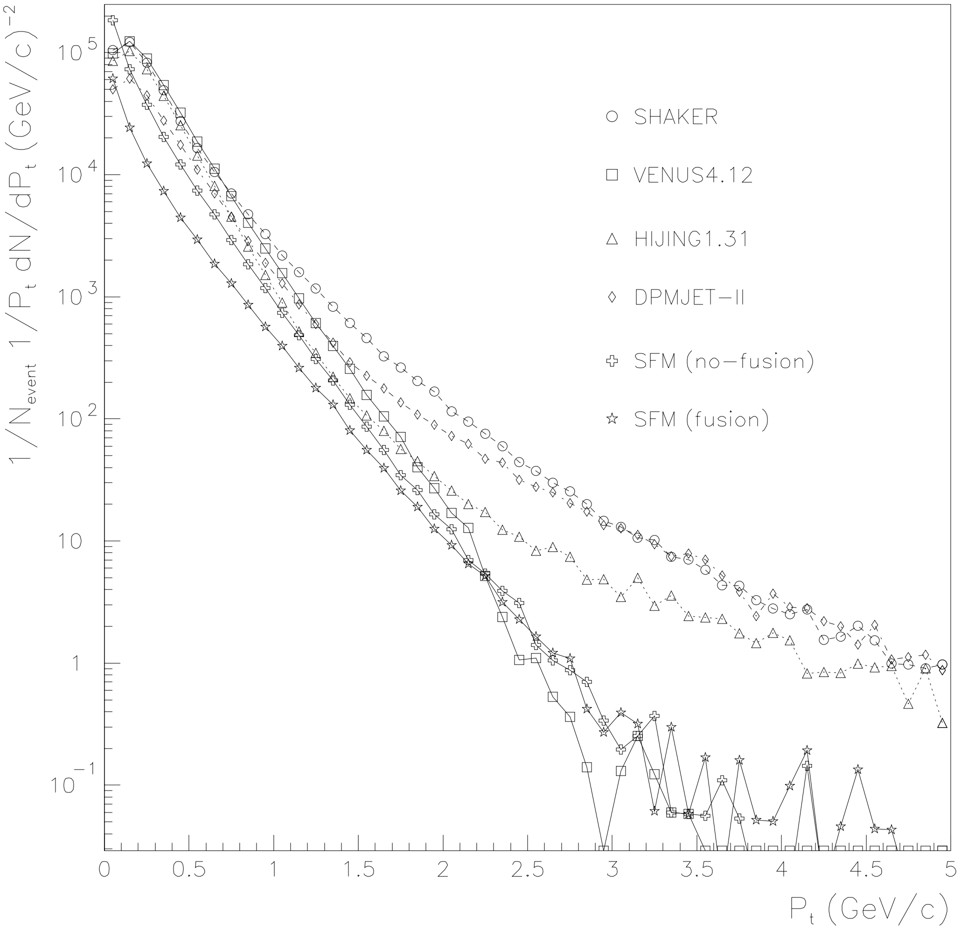

Figure 14: Transverse momentum distributions of $\pi^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

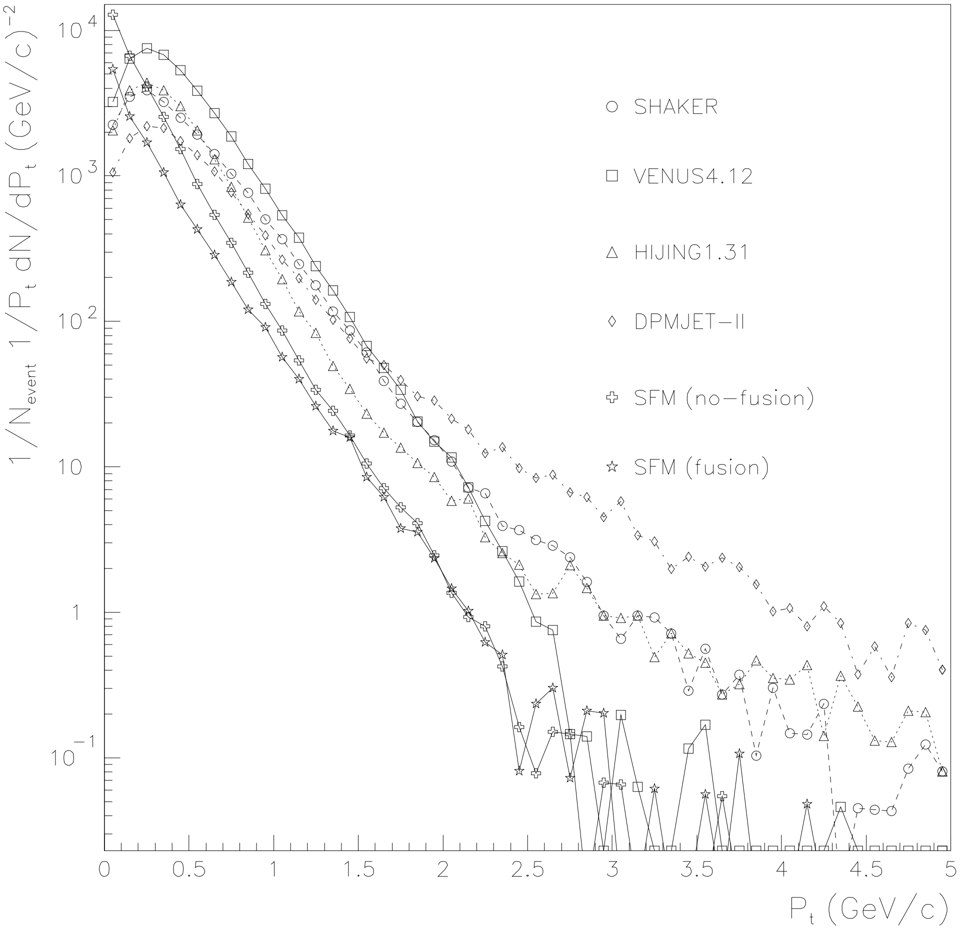

Figure 15: Transverse momentum distributions of $K^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

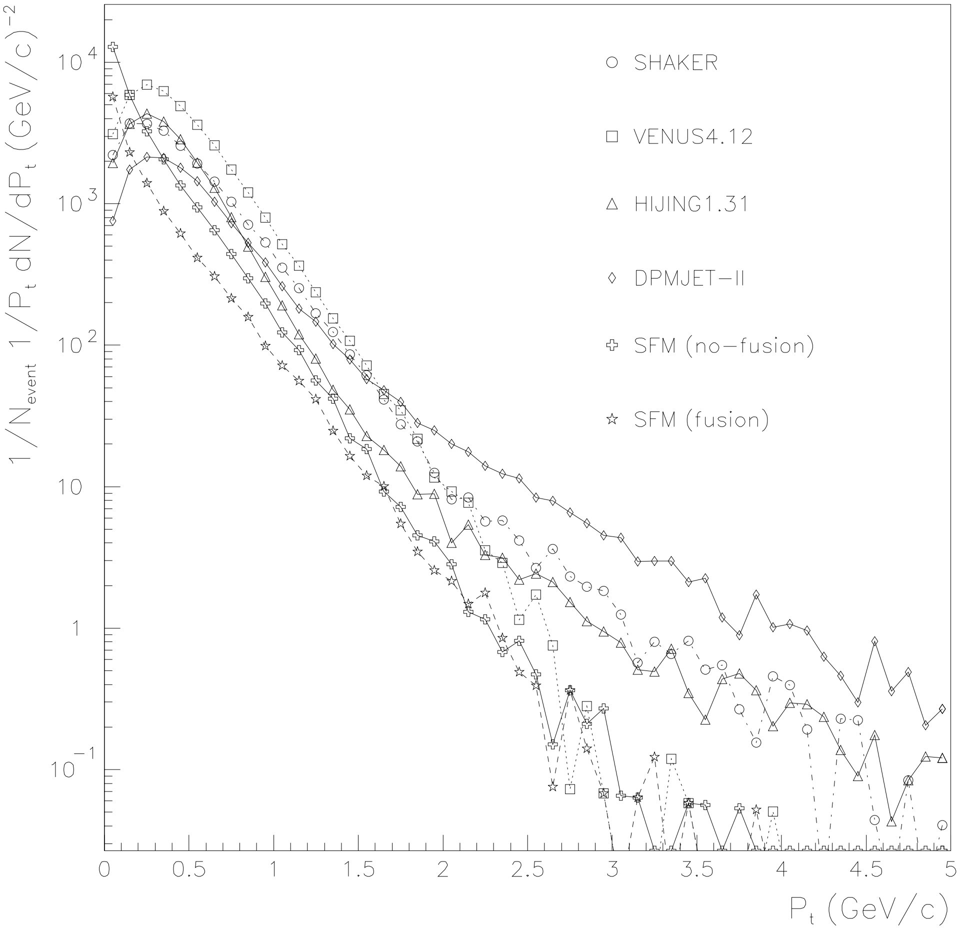

Figure 16: Transverse momentum distributions of K_L and K_S in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

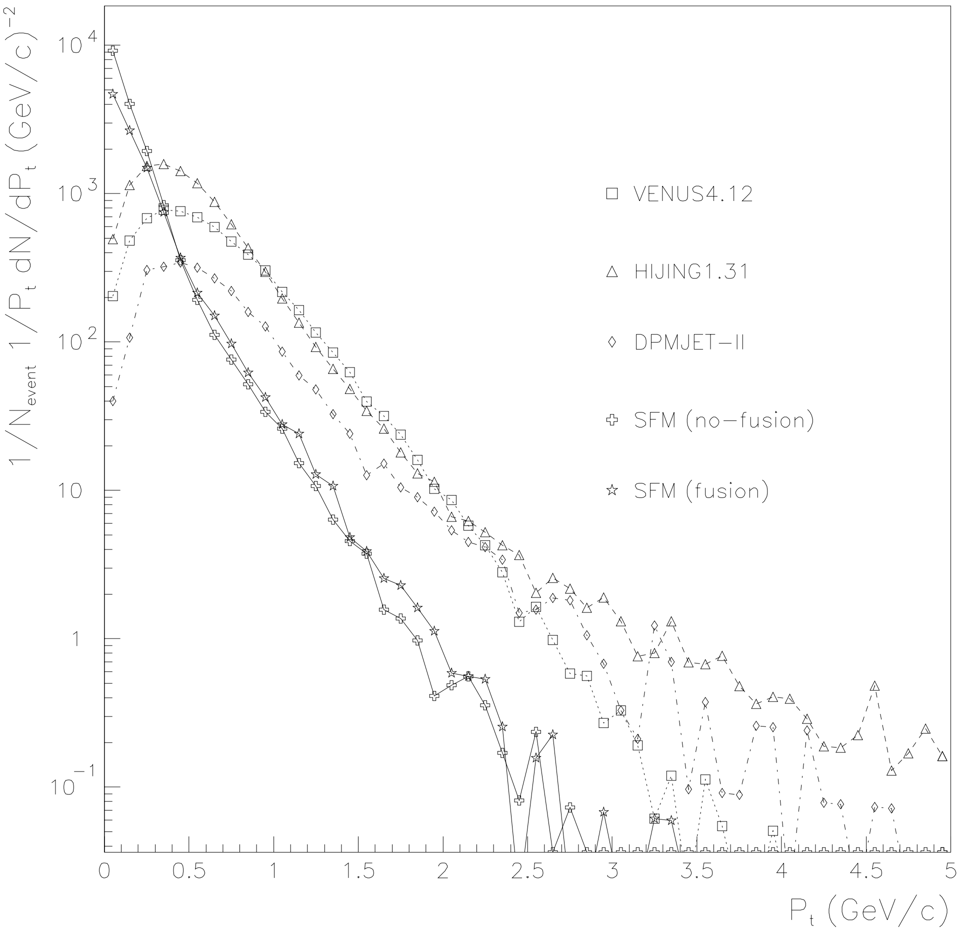

Figure 17: Transverse momentum distributions of $n, \bar{n}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

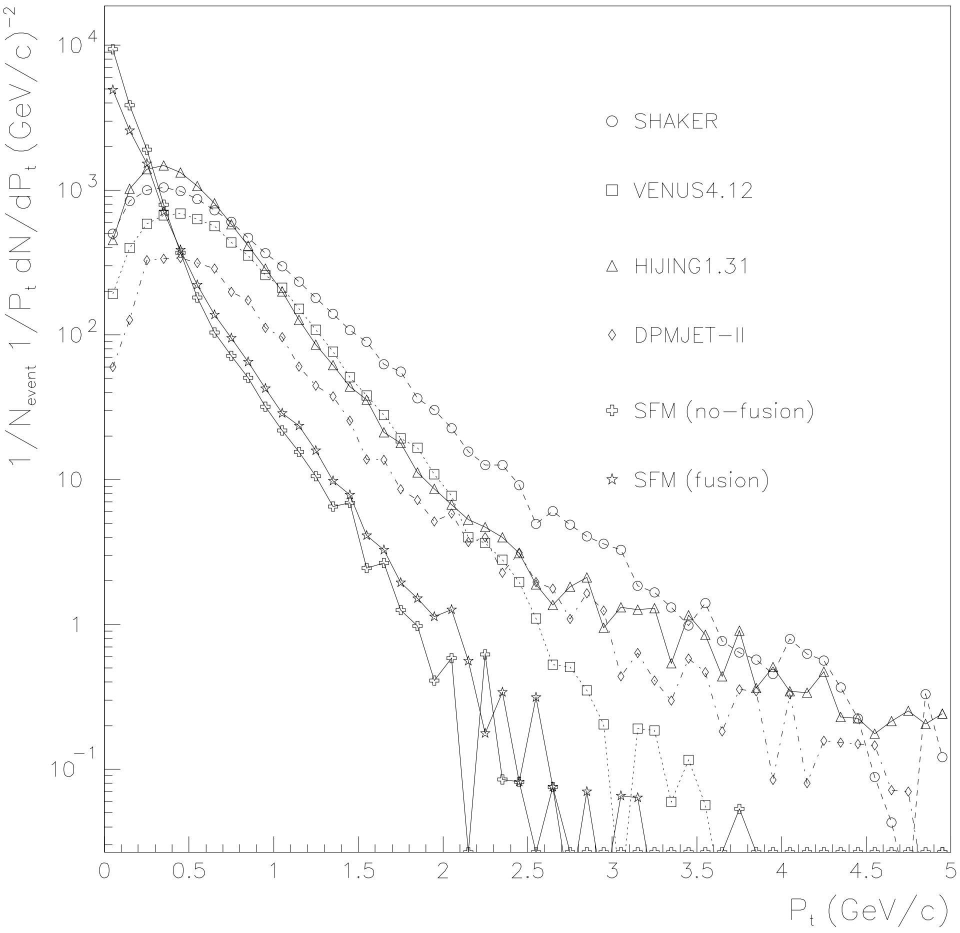

Figure 18: Transverse momentum distributions of $p, \bar{p}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

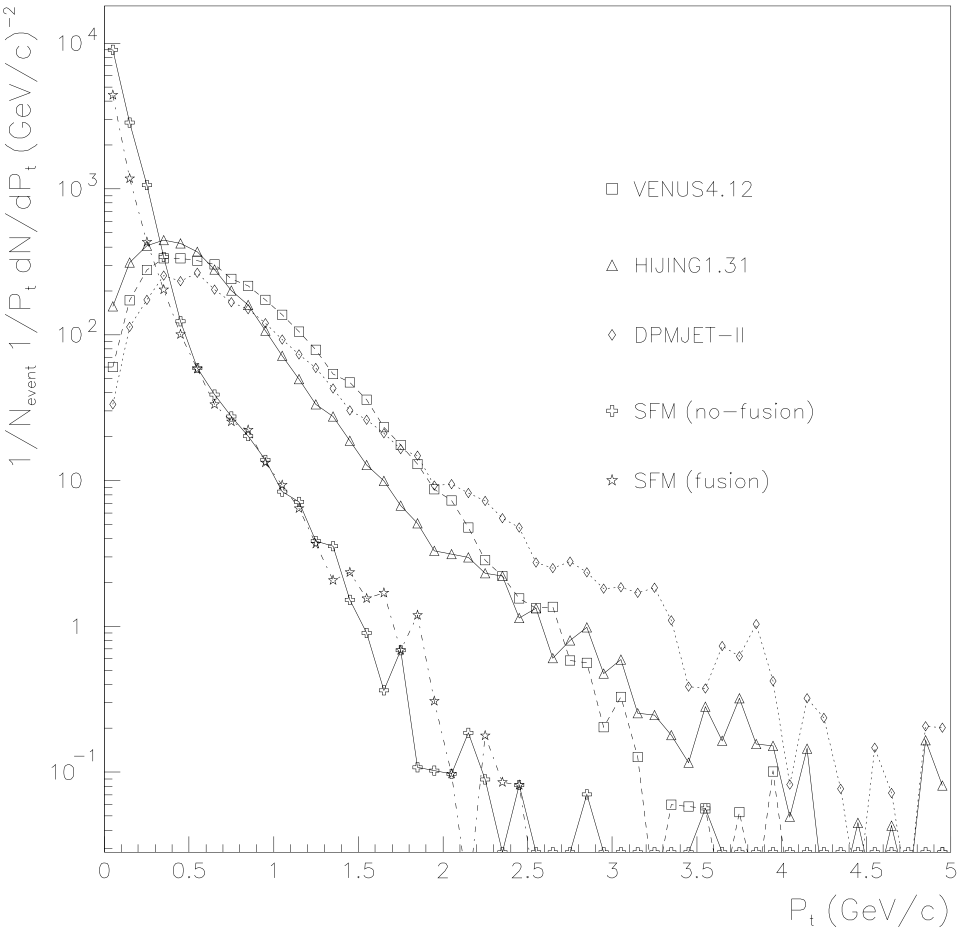

Figure 19: Transverse momentum distributions of $\Lambda, \bar{\Lambda}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

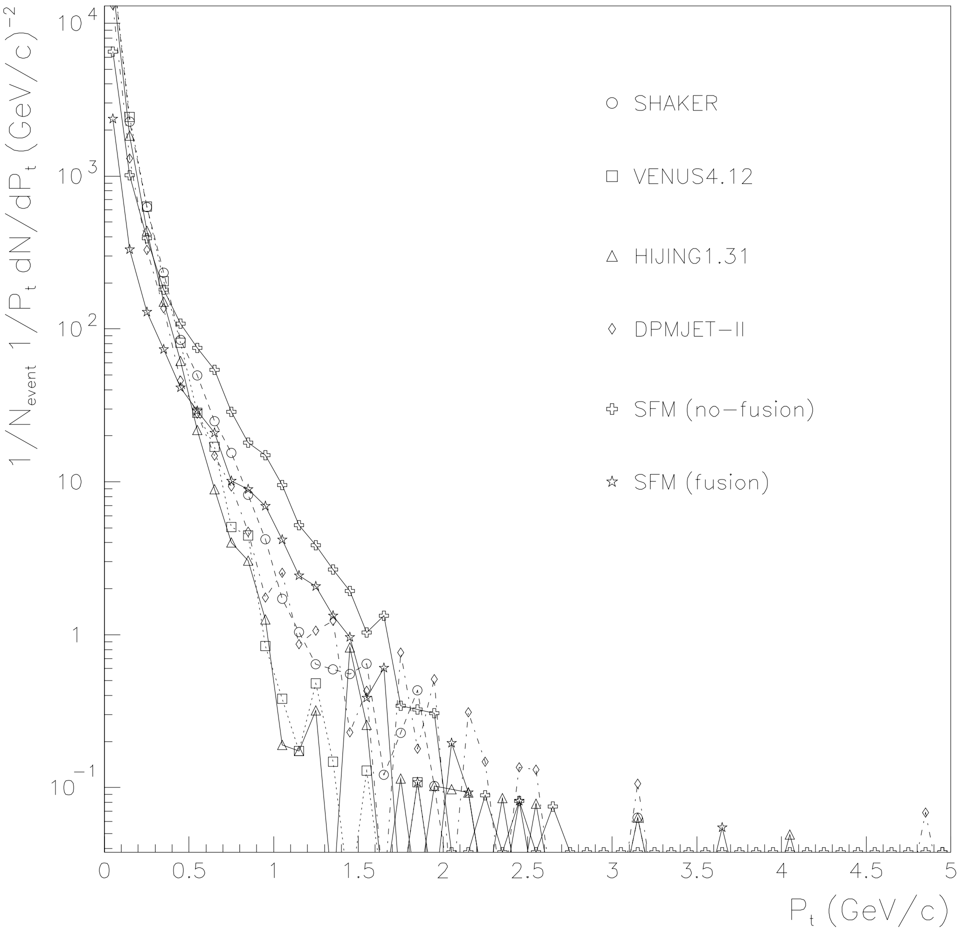

Figure 20: Transverse momentum distributions of $e^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

The HIJING and DPMJET-II models include directly the simulation of multiple minijets and as a consequence these models show long P_t tails which are more flat than the SHAKER one. Though VENUS and SFM take into account the effect of minijet production, the applied mechanism is probably not sufficient to describe the full effect.

In figs. 21 and 22 the transverse momentum distributions for γ and $\pi^{\pm}$ produced in the peripheral Pb-Pb events are shown. For the other particle species statistics are too poor.

The plots are similar to those for the central sample. However, the P_t tails for the HIJING and DPMJET-II codes are not clearly visible due to poor statistics.

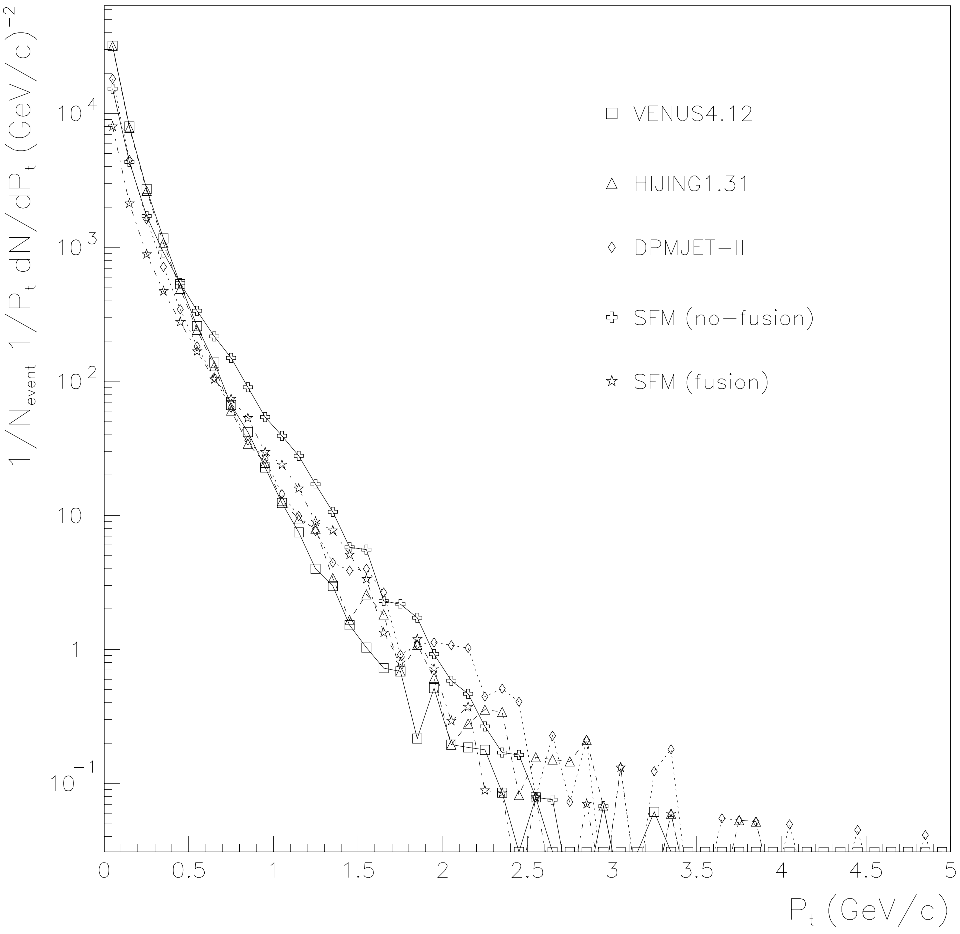

Figure 21: Transverse momentum distributions of γ in the Barrel range $-1 \leq \eta \leq 1$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

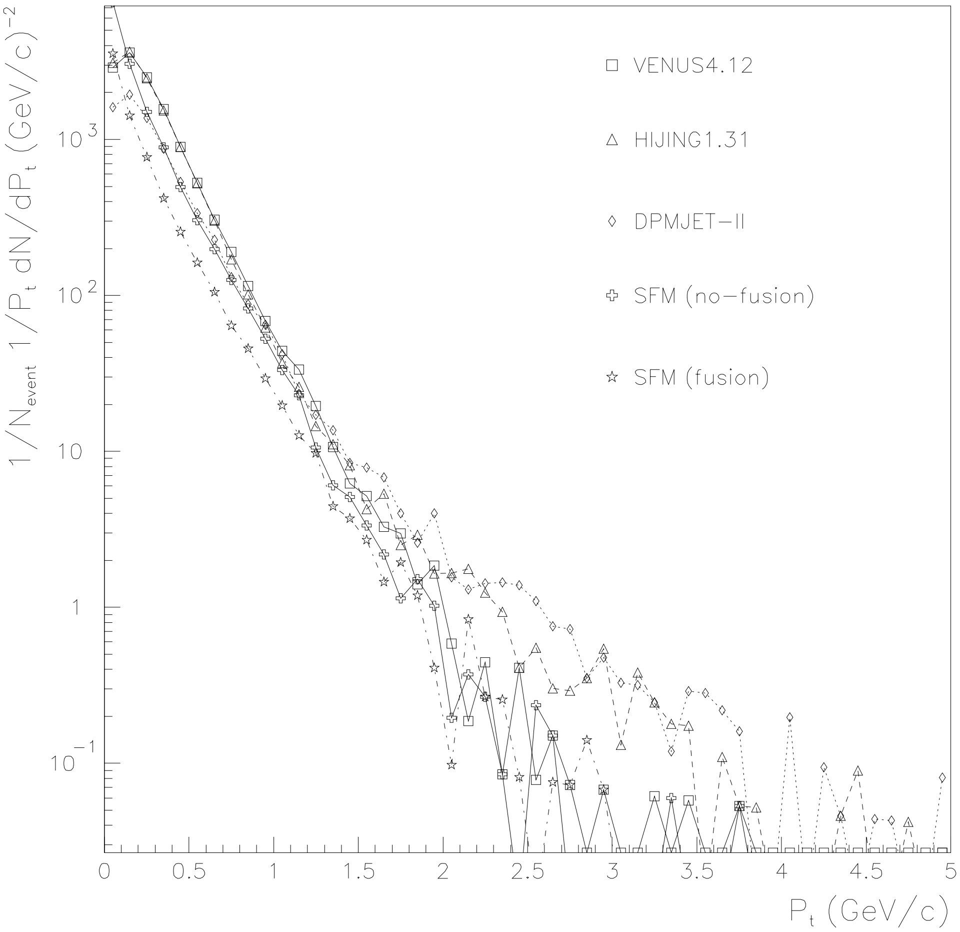

Figure 22: Transverse momentum distributions of $\pi^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

Transverse mass distributions for central Pb-Pb events are shown in figs. 23 - 28.

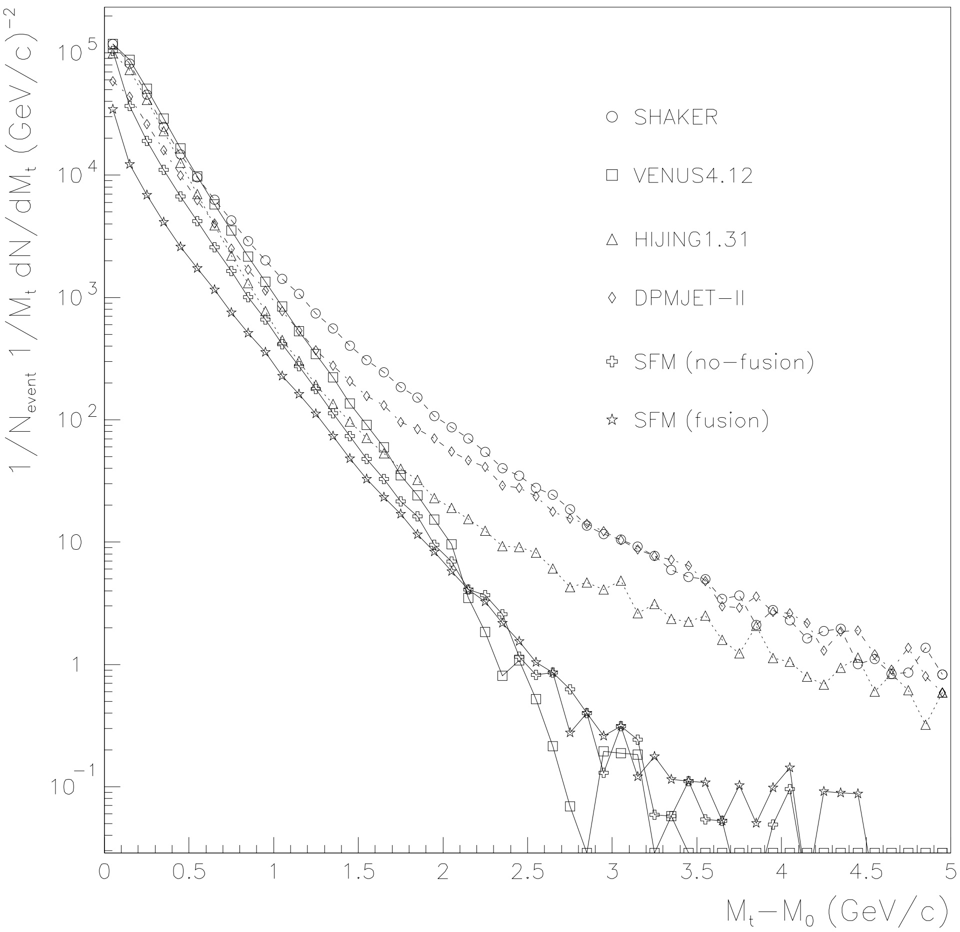

Figure 23: Transverse mass distributions of $\pi^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

The inverse slope T of particles defined by fitting the transverse mass distribution in the range $0.1 \leq M_t - M_0 \leq 1$ GeV according the formula

$$\frac{1}{M_t}\frac{dN}{dM_t} = Aexp(-\frac{M_t}{T})$$

is presented in table 1. Large discrepancies in the inverse slopes of the different models are observed. The largest slopes are produced by the SHAKER, VENUS and DPMJET-II codes. The SFM generator demonstrates the lowest ones. The results of HIJING have intermediate values.

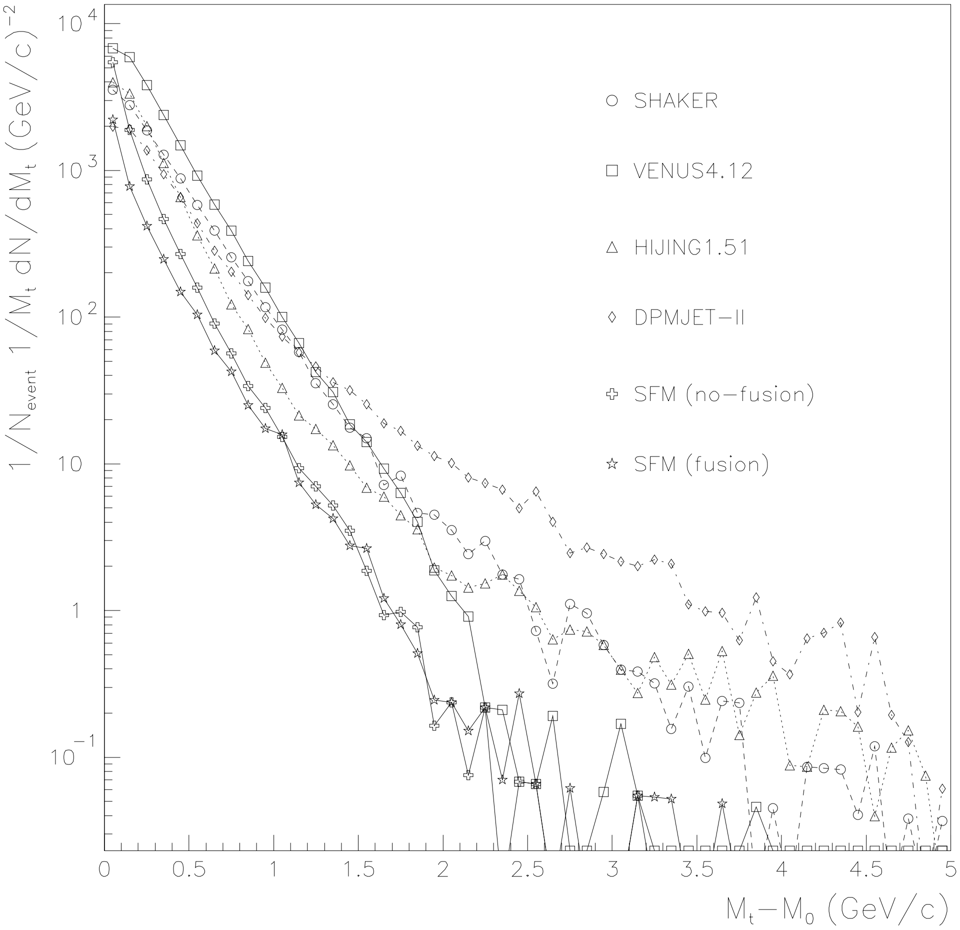

Figure 24: Transverse mass distributions of $K^{\pm}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

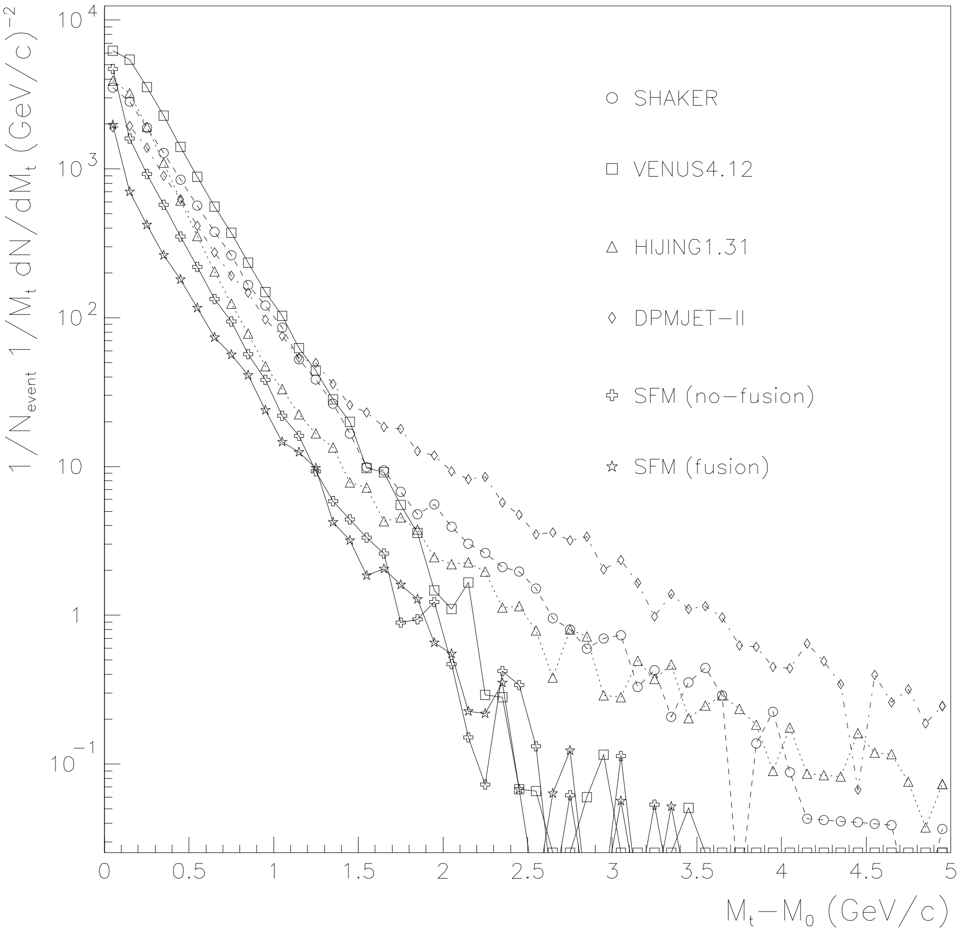

Figure 25: Transverse mass distributions of K_L, K_S in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

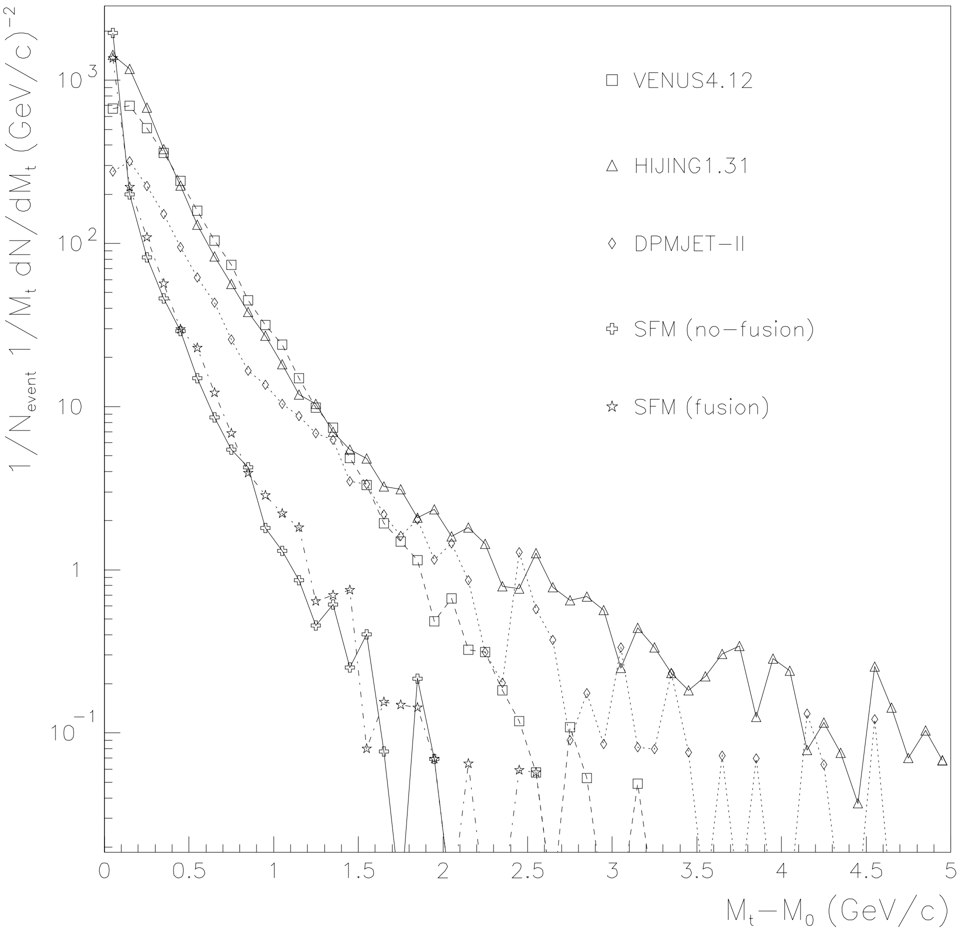

Figure 26: Transverse mass distributions of $n, \bar{n}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

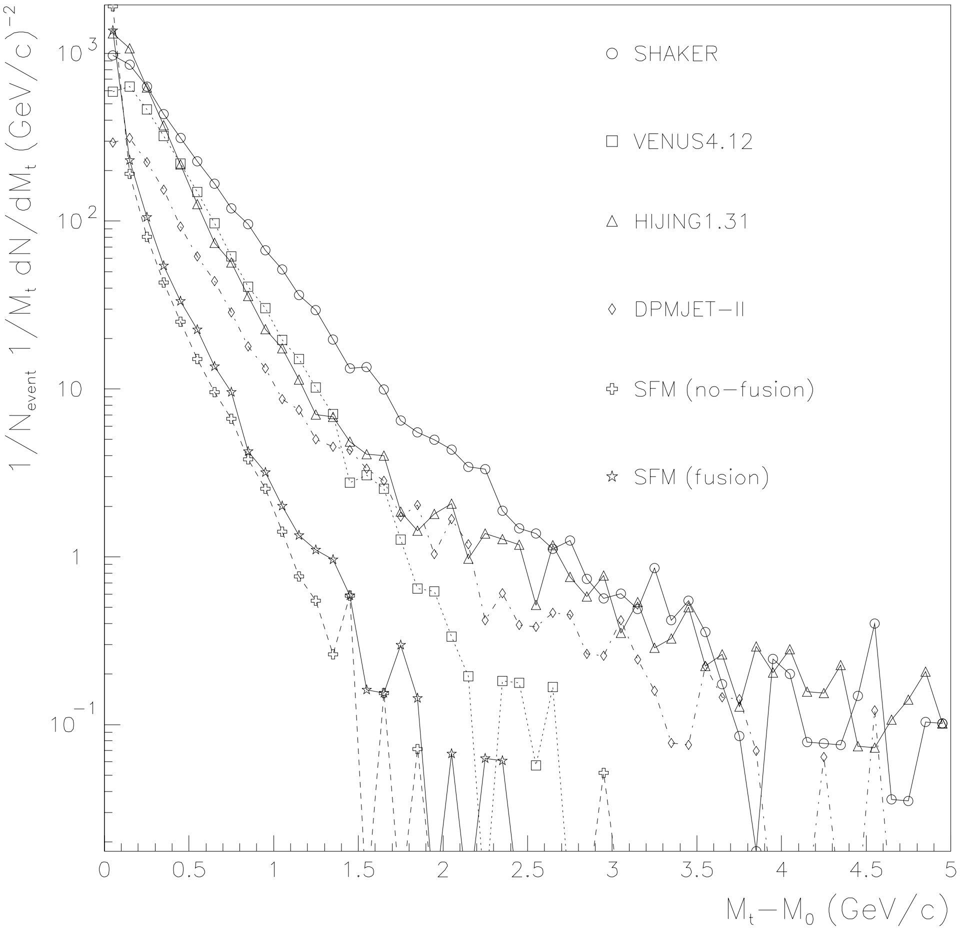

Figure 27: Transverse mass distributions of $p, \bar{p}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

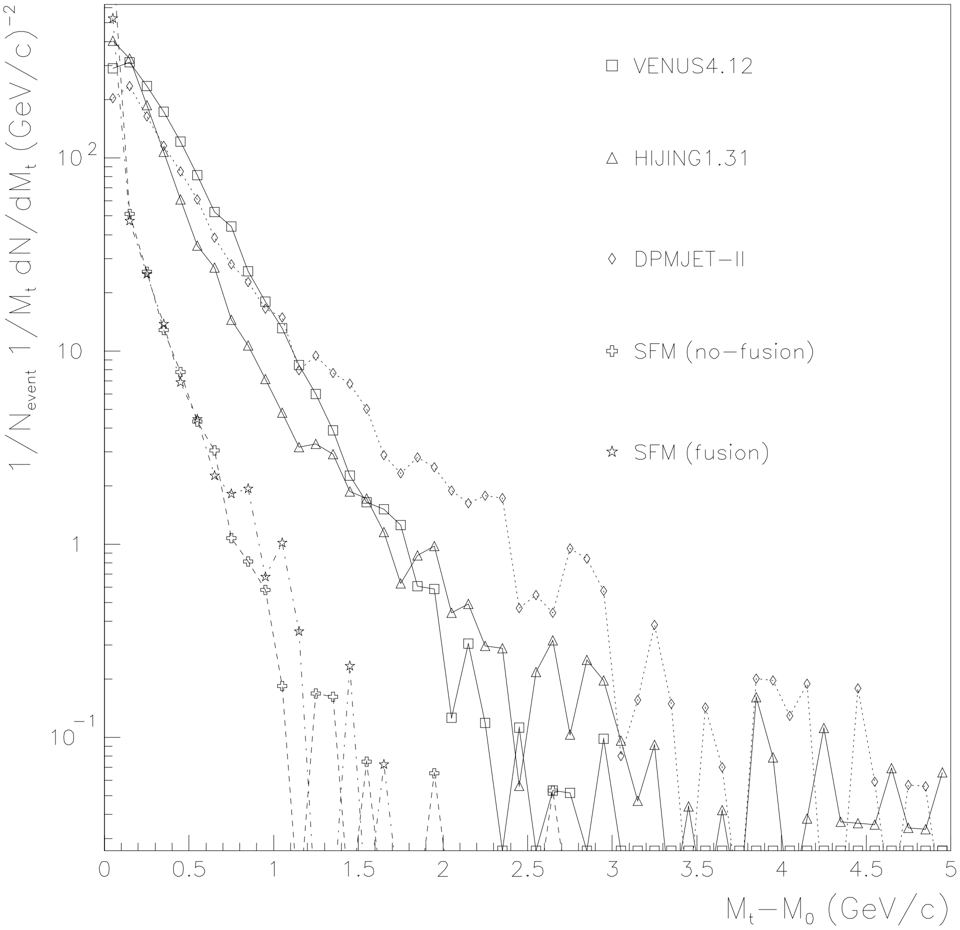

Figure 28: Transverse mass distributions of $\Lambda, \bar{\Lambda}$ in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

particle	SHAKER	VENUS	HIJING	DPMJET-II	SFM(nf)	SFM(f)
$\pi^\pm$	193±1	185±1	173±1	209±1	187±1	217±3
$K^\pm$	251±5	218±2	184±4	270±7	162±5	198±9
K_L, K_S	250±6	222±2	184±4	257±7	206±6	231±11
$n, \bar{n}$	-	267±11	191±7	236±15	157±63	166±16
$p, \bar{p}$	315±13	264±11	194±7	246±16	158±18	169±16
$\Lambda, \bar{\Lambda}$	-	288±18	190±13	289±23	160±29	168±32

Table 1: The inverse slope of particles produced in the Barrel range $-1 \leq \eta \leq 1$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

13.3 FMD region $1.5 \leq \eta \leq 4$

To estimate the trigger performance of the forward multiplicity detectors (FMD), the pseudorapidity distribution of charged particles in the FMD range have been obtained. The results are shown in figs. 29 and 30 for the central and peripheral Pb-Pb events respectively. Again VENUS produces the largest multiplicities. On average we observe about 4400/160 charged particles for the central/peripheral collisions.

13.4 ZDC region $\eta \geq 8.43$

In view of our feasability studies of the zero-degree calorimeter system (ZDC), particle multiplicities in the very forward region have been investigated. The results are shown in Figs. 31 and 32. In central collisions the number of produced nucleons becomes comparable to the pion yield and the amount of anti-nucleons is about one order of magnitude lower than for nucleons. For the peripheral VENUS and HIJING events one observes the very large number of nucleons, most of which are expected to be contained in spectator fragments which are not simulated in these models.

Pseudorapidity distributions of charged particles and photons produced in the central Pb-Pb events are presented in figs. 33 and 34. The observed jumps are due to poor statistics. Note that the figs. 33 and 34 do not include particles with exactly zero polar angle, for example spectator particles. The plots for the peripheral sample are not shown here because statistics is too poor.

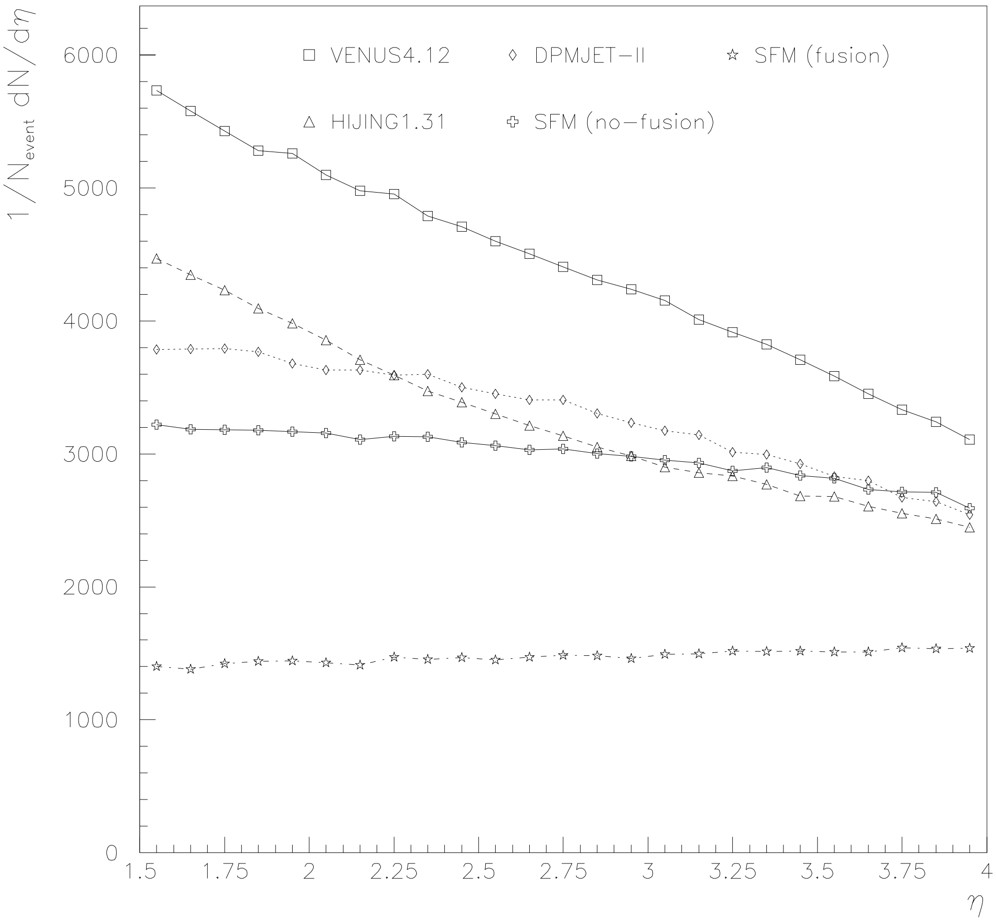

Figure 29: Pseudorapidity distribution of charged particles in the FMD range $1.5 \leq \eta \leq 4$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

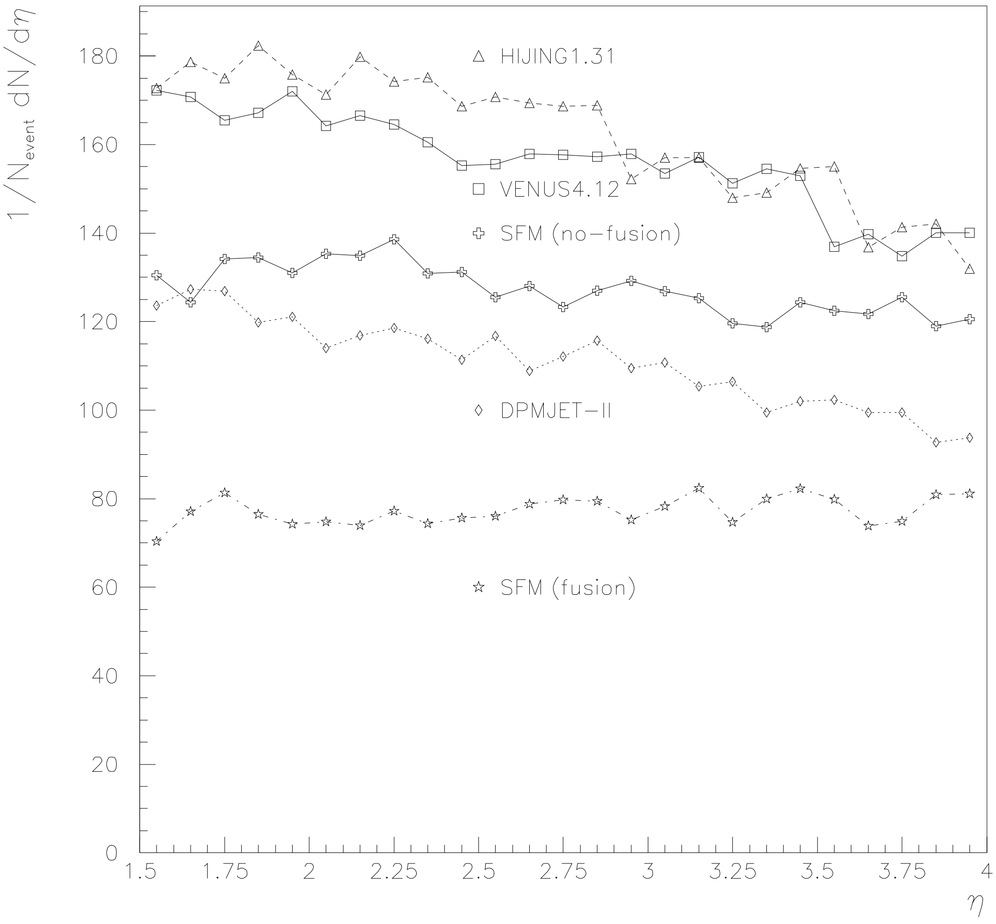

Figure 30: Pseudorapidity distribution of charged particles in the FMD range $1.5 \leq \eta \leq 4$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

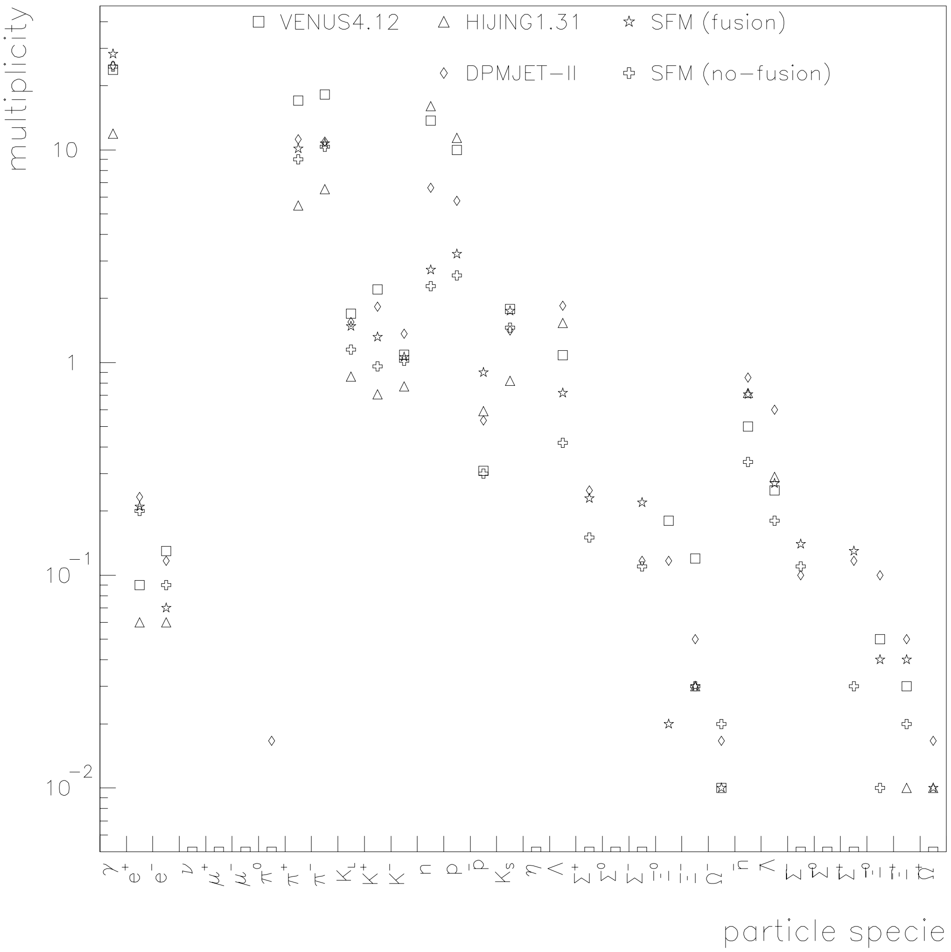

Figure 31: Multiplicities per event of particle species in the ZDC range $\eta \geq 8.43$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

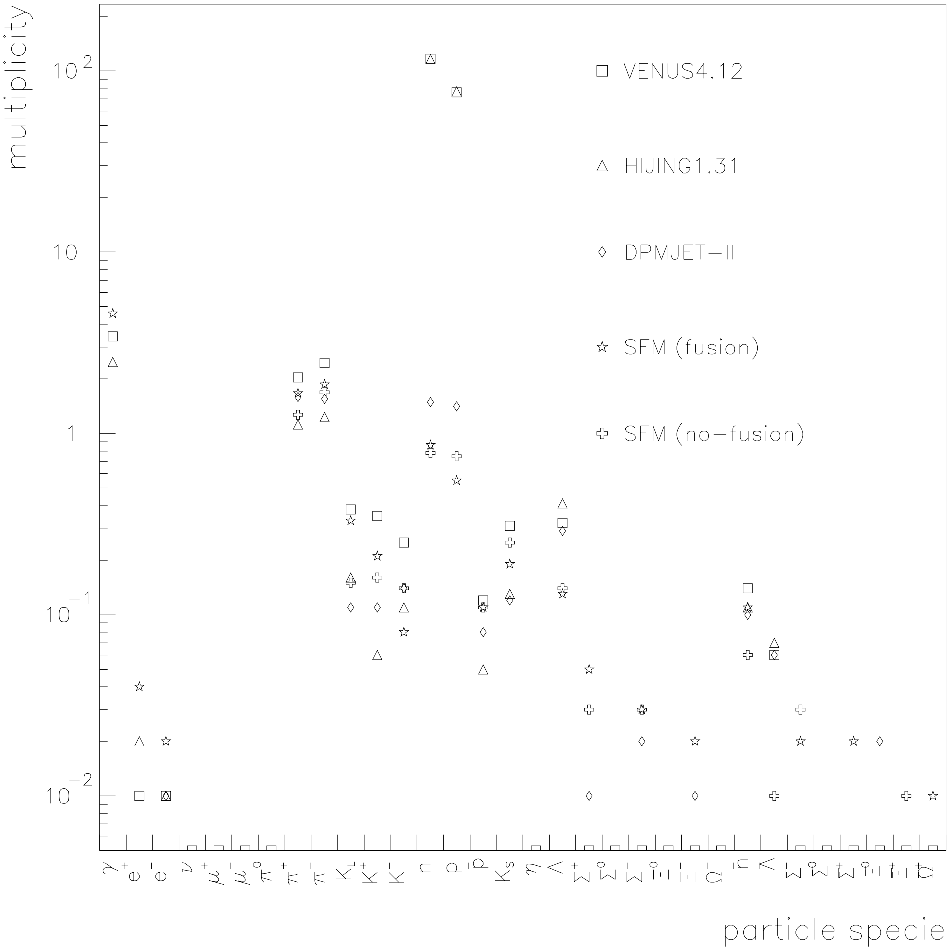

Figure 32: Multiplicities per event of particle species in the ZDC range $\eta \geq 8.43$ for peripheral Pb-Pb events at a beam energy of 3 TeV per nucleon

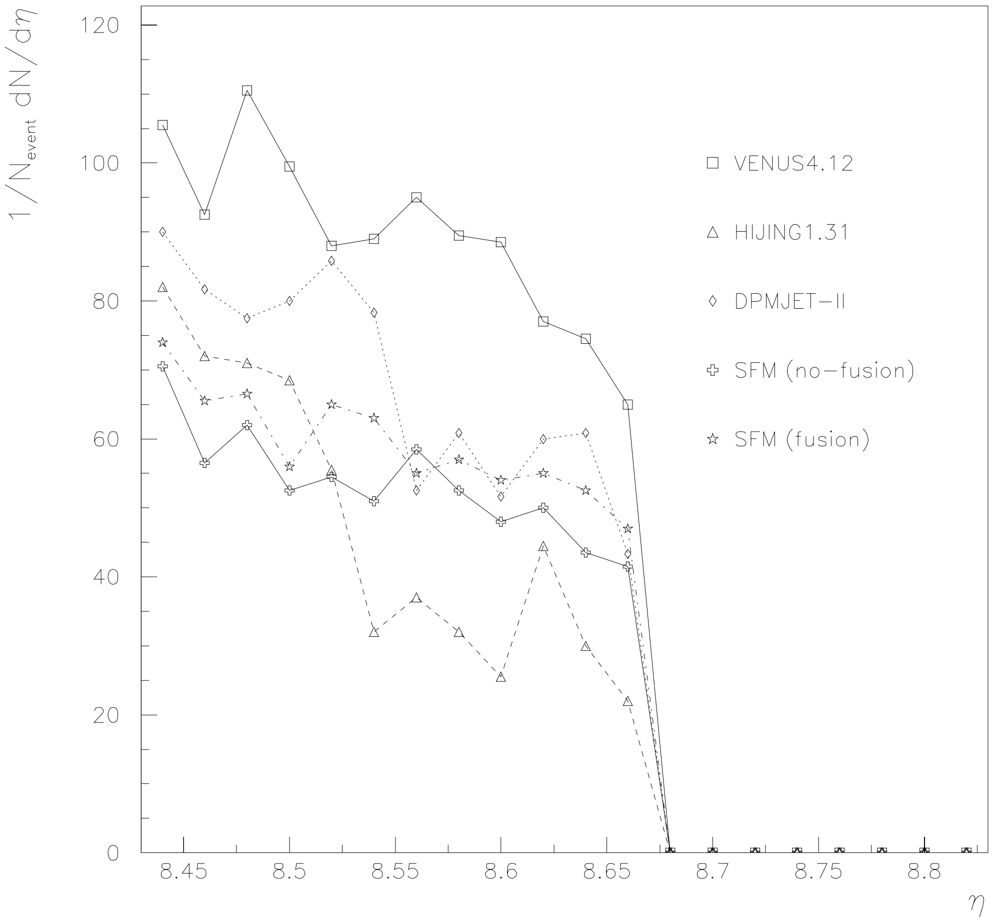

Figure 33: Pseudorapidity distribution of charged particles in the ZDC range $\eta \geq 8.43$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

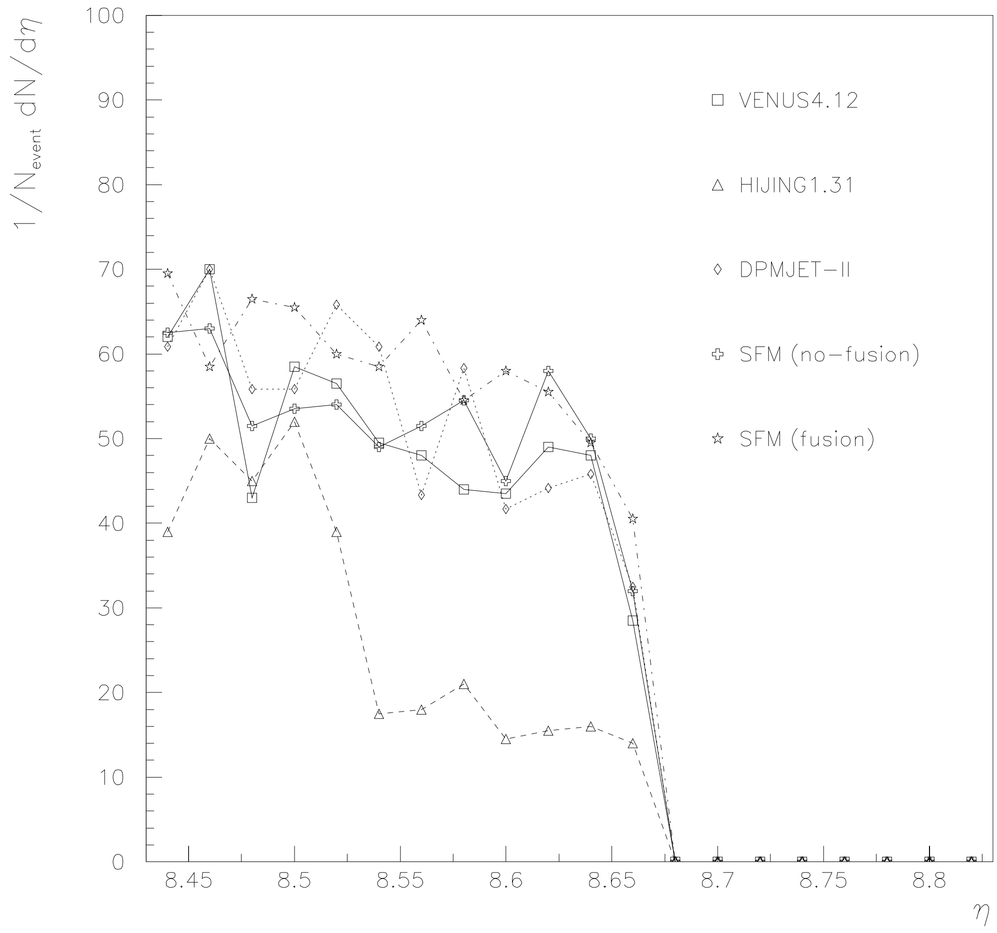

Figure 34: Pseudorapidity distribution of γ in the ZDC range $\eta \geq 8.43$ for central Pb-Pb events at a beam energy of 3 TeV per nucleon

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