Frascati Physics Series Vol. XXXVIII (2005), pp. 165–178
II Workshop Italiano sulla Fisica di ATLAS e CMS – Napoli, October 13 - 15, 2004

W AND Z PHYSICS AT THE LHC

M. Vos
INFN - Sezione di Pisa, Italy
P. Ferrari
CERN, Switzerland

Abstract

The two general-purpose experiments in the Large Hadron Collider at CERN, ATLAS and CMS, offer a wide range of "new" and "standard" physics. In this note the Standard Model physics potential - and more specifically that of W and Z bosons - is briefly outlined. An overview is given of feasibility studies for gauge boson precision measurements. Further, the use of W and Z final states to improve the existing experimental limits on triple gauge couplings is discussed. Finally, the importance of the Z and W samples during the commissioning phase - for calibration and alignment of the detector, but also as a reference physics sample for studies of the underlying event and the determination of parton density functions - is discussed.

1 Introduction

The LHC is primarily intended as a discovery machine exploring the energy frontier. In several articles in these proceedings the "new" physics reach of ATLAS and CMS is discussed. However, the characteristics of the collider offer very interesting possibilities for Standard Model physics as well. The production rate for gauge bosons is unprecedented: during the initial years of operation, with the "low" luminosity of $2 \times 10^{33} cm^{-2}s^{-1}$, 100 million W bosons decaying into an electron and a neutrino and 10 million Z to electron-positron events per year (10 fb^{-1}) are produced. In combination with the large center-of-mass energy the LHC opens up several windows for Standard Model physics. In the following, two fields are discussed: precision measurements of electroweak gauge boson properties and the study of triple gauge couplings.

Precision measurements of gauge boson properties provide an important constraint of the Standard Model. The Higgs boson mass can be predicted from the mass of the top quark and W boson via the following formula:

$$m_w = \sqrt{\frac{\pi \alpha_{EM}}{\sqrt{2} G_F}} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}} \tag{1}$$

where all constants (Fermi's constant G_F, the electro-weak fine-structure constant α_{EM} and the Weinberg weak mixing angle θ_W) are well-known. The top and Higgs mass are related through the radiative corrections Δr that have a quadratic dependence on the top mass, $\Delta r \propto m_t^2$, and a logarithmic dependence on the Higgs boson mass: $\Delta r \propto \log m_H$. The current precision of the top and W mass determination (by Tevatron [1]) for the former and by LEP [2]) and Tevatron [3]) for the latter) is such that the constraint from formula 1 is considered an indirect measurement of the Higgs mass within the Standard Model: $m_H = 114^{+69}_{-45}$ GeV. Alternatively, an upper limit, again valid within the Standard Model, can be derived: $m_H < 260$ GeV at 95 % confidence level.

The LHC will produce approximately 10 million top-quark pairs per year at low luminosity, about 4 orders of magnitude more than at the Tevatron. Therefore, in the first years of the LHC, an important improvement in the (statistical) precision of the measured top mass is expected. In order for the W and top mass measurement to contribute equally to the uncertainty of the Higgs mass prediction, the W mass error should be reduced to 10-15 MeV. In section 2 the expected statistical and systematic uncertainties for the W mass measurement at the LHC are reviewed.

The Standard Model is based on the principle of gauge invariance. The non-Abelian structure of the gauge group, leads to a specific prediction of the self-couplings of the electroweak gauge bosons $W^{\pm}$, Z and γ. The study of the triple (and quartic) couplings of gauge bosons therefore provides a powerful test of the Standard Model. The measurement of non-zero values for the neutral couplings or deviations from the Standard Model prediction for the charged couplings would be very compelling evidence for new physics. The LEP and Tevatron experiments have established that the anomalous triple gauge boson couplings, if they exist, are small. The expected sensitivity of the LHC experiments for the various types of anomalous triple gauge-boson couplings presented above, are related to the experimental limits form the LEP and Tevatron experiments in section 3.

The ATLAS and CMS collaborations are preparing large detectors with an unprecedented level of complexity. Consequently, the task of understanding and calibrating the detectors requires an unprecedented effort. Moreover, the statistical error on many measurements will be so small that a very precise control of systematic detector effect is required. In this task, the very precisely known properties of the Z boson (and to a lesser extent also the W) may well turn out to be anchors of crucial importance. In section 4, the use of Z and W events in the commissioning phase of the experiment - calibration of the energy scale, alignment, magnetic field map - is discussed.

The most important findings are summarized in section 5.

2 Precision measurements of W properties

In the introduction it was shown how precision measurements of the properties of the W boson provide an important cross-check of the Standard Model. In this section, the uncertainty on the W mass measurement is discussed in some detail. The statistical and systematic contributions to the error are analysed for the W mass measurement as performed at the Tevatron experiments. Given a set of assumptions, an expectation for the LHC is inferred. An alternative approach that could be applied at the LHC is discussed at the end of this section.

The W mass measurements by CDF and D0 are described in detail in the literature [3]. Here, only the basic procedure is explained. The best results at the Tevatron are obtained in the decay channels to electron (muon) and neutrino. The signal events are selected by requiring a relatively hard and central lepton ($p_T > 25$ GeV, $|\eta| < 2.4$) to be reconstructed. Further, a significant missing energy $E_T^{miss} > 30$ GeV is required. Events containing jets with transverse momentum $p_T > 30$ GeV or a large recoil (> 20 GeV) are rejected.

As the neutrino escapes detection, its transverse momentum can only be reconstructed by measuring the unbalanced transverse energy of the recoiling system, i.e. the missing transverse energy. The longitudinal component of the neutrino momentum is unknown. The transverse mass is defined as:

$$m_T^W = \sqrt{2p_T^l p_T^\nu (1 - \cos\Delta\phi)} \tag{2}$$

where p_T^l is the lepton transverse momentum, p_T^ν the neutrino transverse momentum (inferred from missing E_T) and $\Delta\phi$ the difference in azimuthal angle between the lepton and neutrino. A distribution of the transverse mass shows the typical Jacobian peak, abruptly falling at m_W, see figure 1. The W mass is determined from the transverse mass distribution by matching the experimental distribution with Monte Carlo templates generated for different W masses.

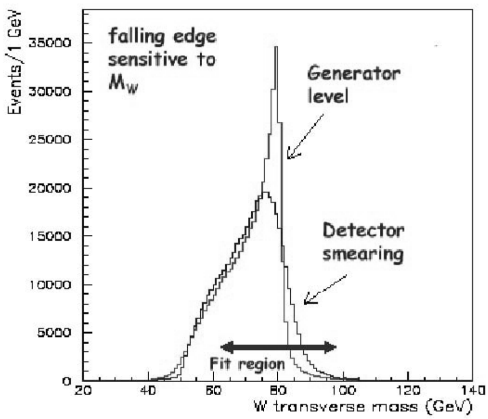

Figure 1: The distribution of the transverse W mass at generator level and with the effect of the detector smearing are shown.

Table 1: A comparison of a recent Tevatron (runIb 84 pb^{-1}) break-down of the error contributions to the W mass measurement to that expected for a single low-luminosity year at the LHC.The errors are expressed in MeV.

source	stat	En. scale	E/p	recoil	Γ_W	p_T W	bkg	rad. decay	PDF	tot
Teva-tron	65	75	25	33	10	45	5	20	15	113
LHC	2	15	5	5	7	5	5	10	10	25

A large number of systematic effects have been identified that have a significant contribution to the error. Several weaknesses in the generator description of the W production and decays are contributing to the systematic errors: the uncertainty on the width of the W, on the parton density functions, on backgrounds and radiative decays. For the Tevatron measurements, a large contribution comes from the W transverse momentum distribution: the theoretical model of (hard) gluon emission does not reach the required precision. A better constraint is obtained by using a semi-empirical distribution as input to the Monte Carlo:

$$p_W^T = [p_Z^T]_{data} \times [\frac{p_W^T}{p_Z^T}]_{theory} \quad (3)$$

While at Tevatron the statistics in the $Z \rightarrow l^+l^-$ calibration channel constitutes a limiting factor for this approach, statistics won't be a problem at LHC.

While at the Tevatron the rather poor statistics in the $Z \rightarrow l^+l^-$ calibration sample limits the effectiveness of this approach, at the LHC statistics will soon cease to be a problem. Therefore, ATLAS and CMS should be able to reduce considerably the systematic error contribution from the transverse momentum spectrum. Guideline numbers for this and other physics systematics, from a recent CDF study and the expectation for the LHC, are given in table 1.

A second source of systematic uncertainty is related to the description of the detector. The uncertainty in the response of the detector to the (partly) hadronic recoiling system leads to a significant systematic error at the Tevatron. Another source is the description of the E/p resolution of electrons (the energy measured in the calorimeter, divided by the momentum as measured in the tracker). The largest source of systematic uncertainty at the Tevatron comes from the uncertainty in the lepton energy scale. The techniques used to calibrate the energy scale and their expected performance during the initial phase of the experiment are discussed in more detail in section 4. Figure 2 shows the dependence of the systematic error on the W mass measurement on the the uncertainty in the lepton energy scale for the ATLAS detector after one year at the LHC.

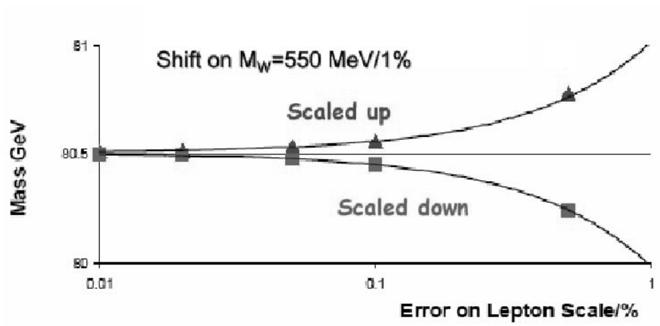

Figure 2: The dependence of the systematic error on the W mass measurement on the the uncertainty in the lepton energy scale for the ATLAS detector after one year at the LHC.

Table 1 shows how at LHC the favorable statistics for the signal and calibration samples leads to smaller errors. This is reflected not only in the smaller statistical errors, but also in the smaller contribution from the lepton energy scale that is dominated by the statistics in the Z sample. It should be noted, however, that the expectations for the LHC in table 1 are based on the assumption that the detector alignment and calibrations are very well known. This will most likely not be the case during the first year of the LHC. The W mass measurement is a strong incentive for pushing the knowledge of the detector calibrations to the limits. The total systematic error on the W mass per LHC experiment per year will be about 25 MeV, and about 15 MeV when combining ATLAS and CMS.

For an early W mass measurement it may well be worth looking for alternative approaches that depend less strongly on the calibration. A good example is the W/Z ratio method, that was studied by the D0 collaboration [4]. The basic idea is to use the measured lepton distribution in Z-boson decay, along with the calculated ratio of the W- over Z-boson distribution, to predict the equivalent leptonic distribution in the W-boson case. By comparing this prediction to the measured leptonic distribution, the W-boson mass and width can be extracted relative to those of the Z-boson, whose properties are well known from LEP measurements.

The advantages of this method are the smaller dependence on theoretical errors in the description of the recoil and the cancellation of common systematics in the ratio, mainly the detector response to the lepton and the recoil. In a proof-of-principle study by D0 [5], it was shown that the impact of correlated experimental errors is much reduced using this method. This gain should be balanced against the increase in the statistical error: the Z production rate is an order of magnitude smaller than that of the W. Indeed, in the D0 study the additional statistical error due to the limited statistics in the Z sample turned out to be larger than the gain in the systematical error.

The method might be more suitable to the LHC environment than the Tevatron. Recently, CMS has started to evaluate the potential of a similar approach. For an "early" measurement of the W mass, when detector and physics are likely not fully under control. The CMS approach differs from the D0 method in that the shape of the W transverse mass spectrum, rather than the lepton transverse momentum distribution, is obtained from Z events. The results of this feasibility study are very promising [6].

3 Triple gauge couplings

The structure of the Standard Model gauge group yields a prediction for the couplings between triplets of electroweak gauge bosons. The existence of small, but non-zero, anomalous triple gauge-boson couplings has not been ruled out experimentally. The study of Triple Gauge Couplings (TGC) is appealing since the present precision on TGC is of the order of 10% despite most of the electroweak parameters of the Standard Model are known to 0.1%. In the most general Lorentz-invariant parameterisation, the triple gauge-boson vertices are described by a large number of independent couplings. For the $WW\gamma$ and WWZ vertices, a total of fourteen independent couplings can be written. Assuming electro-magnetic gauge-invariance and C and P conservation, five couplings remain [7]. At the tree level in the Standard Model these couplings have well-defined values:

$$g_Z^1 = k_\gamma = k_Z = 1 \qquad \lambda_\gamma = \lambda_Z = 0 \tag{4}$$

The existence of neutral ZZZ, $\gamma\gamma\gamma$, $ZZ\gamma$ and $Z\gamma\gamma$ vertices in the Standard Model would violate the combined CPT symmetry. The $Z\gamma$ and ZZ anomalous couplings are parametrised by $h^V_{1,3}$, $h^V_{2,4}$ and $f^V_{4,5}$, respectively, with V=γ,Z. Since the anomalous contributions to those coupling grow with the center-of-mass energy of the hard scattering process $\hat{s}$, the sensitivity of LHC is greatly increased with respect to previous experiments.

The existence of anomalous couplings could lead to unitarity violation at relatively low energies [8]. Unitarity violation is avoided if the couplings are introduced as form factors rather than mere constants. Often a dipole form factor is chosen

$$A = \frac{A_0}{(1 + \hat{s}/\Lambda^2_{FF})^n} \tag{5}$$

where Λ_{FF} plays the role of a cut-off scale, related to the energy scale at which new physics becomes important in the weak boson sector. The exponent n should be chosen greater than that in the dependence of the coupling on $\hat{s}$ to avoid unitarity violation. The choice of the value of the cut-off scale Λ_{FF} and the exponent n affect the experimentally observed distributions in machines (like the LHC) that cover a large $\hat{s}$ range. Therefore, many analyses quote their results for different values of these two parameters.

The experimental signature of the anomalous triple gauge-boson couplings is an enhanced production cross-section of the di-boson final state with respect to the Standard Model expectation. Moreover, several differential distributions show marked differences between the Standard Model production and that due to anomalous couplings. Notably, anomalous couplings tend to yield events with larger transverse momenta for the final state bosons, see figure 3.

Limits on Anomalous TGCs can be extracted by simply comparing the expected and observed event rates. A preferable approach is to construct a likelihood that compares the experimental distribution in one or more dimensions to reference distributions. The reference distributions are generated for several values of the couplings using Monte Carlo techniques. This method has the advantage to be less dependent on the overall normalisation scale, while the analysis of the differences in the shape can give hints on the type of anomalous coupling originating them.

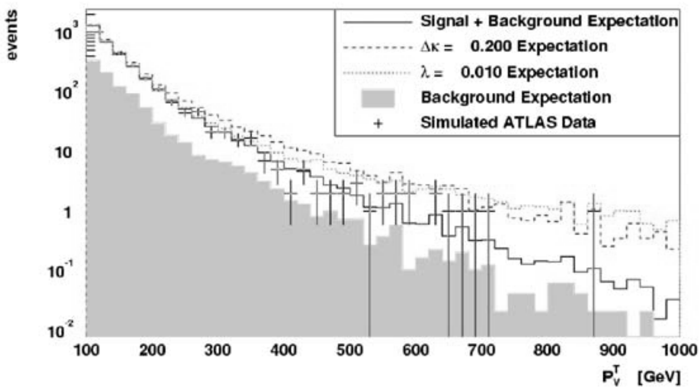

Figure 3: The distribution of the transverse momentum of the photon in $pp \to W\gamma$ events for a luminosity of 30 pb^{-1} from the ATLAS study [10]. The distributions predicted by Standard Model TGC as well as in the presence of anomalous couplings are shown. The contribution of the background is shown as a shaded histogram.

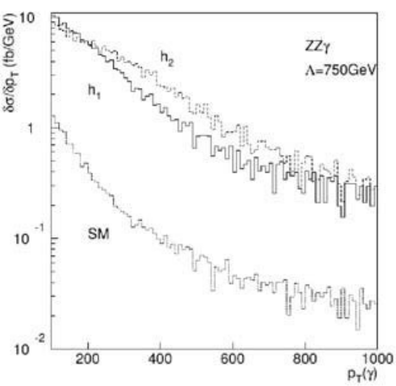

Figure 4: The distribution of $\mathrm{d}\sigma/\mathrm{d}p_T(\gamma)$ for the SM (h_i=0) and anomalous CP violating coupling limits (h_1=0.5,h_2=0.05) at Λ = 750 GeV for the $ZZ\gamma$ vertex as from the CMS study [19].

The $W\gamma$ final state, with the W decaying to an electron or muon and a neutrino, is selected requiring an isolated photon with a transverse momentum of at least 100 GeV, a lepton with at least 25 GeV in the tracker acceptance and a missing p_T of at least 25 GeV. In reference [9], an exhaustive list of background sources to this final state is studied and it is shown that, with some additional cuts, all of them can be reduced to be an order of magnitude lower than the signal when requiring $p_T^{\gamma} > 200$ GeV.

Both ATLAS and CMS have prepared sensitivity studies for this final state [10, 11, 12]. In all cases, the detector response is parameterised in so-called "fast simulation". ATLAS, assuming an integrated luminosity of $30fb^{-1}$ and using a constant form factor, expects the following constraints at 95 % confidence level:

$$-0.0035 < \lambda_\gamma < 0.0035 \qquad -0.075 < \Delta k_\gamma < 0.076 \tag{6}$$

where statistical and systematic uncertainties are considered. CMS uses a cut-off $\Lambda_{FF} = 2$ GeV and quote their results for an integrated luminosity of $10fb^{-1}$. The expected limits at 95 % confidence level:

$$-0.0019 < \lambda_\gamma < 0.0019 \qquad -0.17 < \Delta k_\gamma < 0.17 \tag{7}$$

These fast simulation studies indicate that the LHC can, even with the limited statistics of a few years' running, tighten the existing experimental limits on the anomalous coupling λ_γ and from LEP [13] and the Tevatron [14] by roughly an order of magnitude. The improved sensitivity is mostly due to the high center-of-mass energy reach of the LHC. The sensitivity to Δk_γ is of the same order of the existing limits.

The WWZ coupling is studied using the $WZ \to l^+l^-l\nu$ final state, where l is taken to be an electron or a muon. The signal sample is selected requiring three leptons with a transverse momentum of at least 25 GeV in the tracker acceptance and a missing transverse momentum of at least 25 GeV. From this channel, ATLAS [15] expects the following sensitivities on an integrated luminosity of $30fb^{-1}$:

$$-0.0086 < \Delta g_Z^1 < 0.011 \qquad -0.11 < \Delta k_Z < 0.12 \qquad -0.0072 < \lambda_Z < 0.00 \tag{8}$$

where the form factors are taken constant like in the $WW\gamma$ channel.

The neutral triple gauge-boson coupling show a very strong dependence on the center-of-mass energy of the hard scattering process. Therefore, one would expect these analyses to benefit most from the large beam energy at the LHC. The analyses by ATLAS [17, 18] and CMS [11, 19] concentrate on the $Z\gamma \rightarrow ll\gamma$ to constrain the $h^V_{1,3}$ and $h^V_{2,4}$, while the $f^V_{4,5}$ coupling is constrained by the $ZZ \rightarrow ll\nu\nu$ and $ZZ \rightarrow lll'l'$ final states. Figure 4 shows the distribution $\mathrm{d}\sigma/\mathrm{d}p_T(\gamma)$ for the SM (h_i=0) and anomalous CP violating coupling limits (h_1=0.5,h_2=0.05) at $\Lambda = 750$ GeV for the $ZZ\gamma$ vertex as from the CMS study.

For an integrated luminosity of $100 fb^{-1}$ and a cut-off energy in the form factor of 6 to 8 TeV, the sensitivity to the neutral couplings mentioned above is of the order of several 10^{-4}. Indeed, these studies indicate that three to five orders of magnitude can be gained with respect to the LEP2 sensitivity.

4 Commissioning of the experiments

The determination of the absolute energy scale for leptons and jets is one of the greatest challenges during the initial phase of the experiment. It requires the knowledge of a large number of detector parameters: the tracker alignment, the magnetic field map in the tracker volume, the tracker material distribution (for electrons), the calorimeter calibration and the muon energy loss in the calorimeters. In particular the first two items are correlated: precisely disentangling effects due to both causes may prove to be very challenging indeed.

Both ATLAS and CMS perform precision measurements during the construction and integration phase: the tracker detector module mounting precision is specified to be better than 500 microns, while the magnetic field map can be measured using an array of Hall probes. A sub-set of calorimeter modules is calibrated in test beams.

Alignment and calibration constants are expected to vary with time: thermal effects and out-gassing of the support structure lead to movements of the tracker, the gradual increase in bias voltage will lead to a change in Lorentz angle in the silicon detectors, radiation damage will change the light yield of calorimeter crystals and light guides, etc. During the operation of the experiment, the response of all detectors is extensively monitored. A laser alignment system is continuously monitoring the position of the tracker elements. Several systems based on diodes (electromagnetic calorimeter) and radioactive sources (hadronic calorimeters) are used to monitor the response of the calorimeters.

Controlling the construction dispersion and monitoring of the detector response are essential tools for the understanding the detector. It is clear, however, that these techniques do not provide the precision required by the physics analyses. The absolute energy scale has to be calibrated from data. As an example, the tracker alignment is considered.

The tracker alignment and magnetic field map are determined from tracks in the overlaps between modules. The statistics are not expected to limit the precision: one day's data should allow to obtain a statistical precision of the order of 1 micron [21]. The alignment from single tracks, however, does not fully determine the energy scale: deformed topologies are possible that satisfy the constraints. The calibration of the energy scale is obtained from a resonance with a well-known mass decaying to a lepton pair (the Z at 90 GeV and the J/Ψ and Υ at $\sim$ 5 GeV). The scale can be determined using either of them. Then the extrapolation to different masses is cross-checked using the second resonance. Recent Tevatron studies [22] favour the use of the lighter resonances for setting the energy scale. The reconstructed Z mass is within 1.5 standard deviations of the world average.

Similarly, the jet energy scale is calibrated using hadronically decaying W bosons.

5 Summary

The LHC is expected to offer considerable new opportunities for the physics of electro-weak gauge bosons.

A precise measurement of the W mass provides a test of the Standard Model and helps to tighten the constraint on the Higgs mass. The large statistics of W and Z bosons produced at the LHC, together with a thorough control of the detector and physics systematics, will allow an improvement of the accuracy on the W mass (with respect to the Z mass) to approximately 15 MeV.

The study of triple gauge-boson couplings at LHC is very promising. A range of di-boson final states can be studied at the LHC, yielding information on a large number of couplings. The large center-of-mass energy reach is expected to lead to a much larger reach for the cut-off scale Λ_{FF}. Especially for couplings that depend strongly on the center-of-mass energy, the sensitivity is significantly improved with respect to previous experiments, in some cases by many orders of magnitude.

In many measurements the control of the detector and physics systematics is of utmost importance. Even though the information from the construction phase is vital, the most precise calibration comes, in many cases, from a reference data sample. The large production rate and well-known properties make the Z mass constraint the most important handle for the calibration of the lepton energy scale.

The authors would like to thank the convenors of the session, Marcello Manelli and Giacomo Polesello, and O. Buchmuller, C. Buttar, M.Dobbs, S. Haywood, C. Marques and A. Schmidt for useful discussions.

References

1. CDF-NOTE-6955, D0-NOTE-4417, hep-ex/0404010.

2. M. Thomson for the LEP collaborations Eur.Phys.J.C33:S689-S693, 2004.

3. CDF Collaboration and D0 Collaboration (V.M. Abazov et al.). hep-ex/0311039.

4. W.T. Giele and S. Keller Phys.Rev.D57:4433-4440, 1998.

5. S. Rajagopalan for the $D0$ collaboration FERMILAB-CONF-96-236-EF.

6. A. Schmidt, Diploma thesis, University of Karlsruhe (2004), IEKP-KA/2004-2 .

7. U. Baur and D. Zeppenfeld, Nucl. Phys. B308: 127, 1988.

8. U. Baur and D. Zeppenfeld, Physics Letters B201: 383, 1988.

9. G. Azuelos et al. CERN-TH-2000-102, hep-ph/0003275.

10. ATL-PHYS-2002-022.

11. Th. Müller, D. Neuberger, W.H. Thümmel. CMS note 2000/017.

12. C.K. Mackay, P.R. Hobson CMS note 2001/056.

13. D. Abbaneo et al. CERN-EP-2000-016 (2000).

14. B. Abbott et al. (D0 collaboration) Phys. Rev. D 58:3102 (1998).

15. M. Dobbs and M Lefebvre ATL-PHYS-2002-023.

16. C.K. Mackay, ,P.R. Hobson CMS note 2001/052.

17. S. Hassani ATL-PHYS-2002-023.

18. S. Hassani ATL-PHYS-2002-022.

19. C.K. Mackay, P.R. Hobson CMS note 2002/028.

20. P.J. Bell ATL-PHYS-2004-015.

21. EPJdirect A1, 1-11 (2004).

22. W. Hays presented at ICHEP 2004, submitted to World Scientific.