Parton Showers since LEP

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Abstract: We briefly discuss the development of Monte Carlo event generators over the last fifteen years. During this period there has been a revolutionary transformation in the accuracy of these programs as matching to higher-multiplicity matrix elements and next-to-leading order calculations has become standard with the first next-to-next-to-leading order processes now available. Finally the prospects for future improvements are discussed.

Monte Carlo Simulations at LEP

Monte Carlo event generators came of age at LEP where for the first time a combination of better understanding of QCD and increased computing power provided simulated events which were in good quantitative agreement with the experimental results. These simulations used:

- a leading-order matrix element for $e^+e^- \to q\bar{q}$;
- a parton shower simulation for the evolution from the hard scale of the partonic collision to the infrared cut-off including the correct treatment of colour coherence;
- hadronization using either the non-perturbative string or cluster models.

The main programs used by the end of the LEP programme were PYTHIA 6[1] and HERWIG 6[2]. These simulations also included the matching of the hardest gluon emission for processes with a single colour line, for example $e^+e^- \to q\bar{q}$, Deep inelastic scattering and Drell-Yan, which effectively gave for $e^+e^- \to q\bar{q}$, apart from the trivial normalisation by a K-factor a next-to-leading order (NLO) simulation of the hard process.* The alternative dipole shower of ARIADNE (together with the string hadronization model) often provide the best agreement with the data [4].

From LEP to the LHC

Starting in the early 2000's there was a major programme to develop better Monte Carlo simulations in order to describe the data from the energy frontier hadron colliders, first the Tevatron and now the LHC. This started with the development of the first viable approach allowing multiple hard emissions to be described correctly at leading order together with a parton shower simulation of soft and colinear radiation (CKKW)[5]. This was first used to describe the production of four jet events in e^+e^- collisions where it gave quantitative improvements. However the main success of the approach was in hadron-hadron collisions where it allowed the accurate description of multiple jet production, for example in association with electroweak vector bosons, for the first time.

*In the case of $e^+e^- \to q\bar{q}$ the approach used by both HERWIG and PYTHIA is equivalent to more general POWHEG method [3] provided the total rate is normalised to the NLO value.

Together with the development of many variants of the original CKKW merging procedure Monte Carlo event generator development in the early 2000's focused on producing simulations that in addition to correctly treating hard emission (initially only the hardest emission) also had the correct NLO normalisation. All these approaches rely on rearranging the NLO cross section formula,

$$\mathrm{d}\sigma = B(\Phi_B)\mathrm{d}\Phi_B + (V(\Phi_B) + C(\Phi_B, \Phi_R)\mathrm{d}\Phi_R)\mathrm{d}\Phi_\mathrm{B} + (R(\Phi_B, \Phi_R) - C(\Phi_B, \Phi_R))\mathrm{d}\Phi_B\mathrm{d}\Phi_R, \quad (1)$$

where $B(\Phi_B)$ is the leading-order contribution, Φ_B the N-body phase-space variables of the leading-order Born process whereas Φ_R are the radiative variables describing the phase space for the emission of an extra parton. The real contribution, $R(\Phi_B, \Phi_R)$, is the matrix element including the radiation of an additional parton multiplied by the relevant parton flux factors, and is regulated by subtracting the counter terms $C(\Phi_B, \Phi_R)$ which contain the same singularities as $R(\Phi_B, \Phi_R)$.

The first successful approach MC@NLO [6] chose to use the shower approximation for soft and colinear emission as the subtraction term

$$\mathrm{d}\sigma = B(\Phi_B)\mathrm{d}\Phi_B + (V(\Phi_B) + C_\text{shower}(\Phi_B, \Phi_R)\mathrm{d}\Phi_R)\mathrm{d}\Phi_\mathrm{B} + (R(\Phi_B, \Phi_R) - C_\text{shower}(\Phi_B, \Phi_R))\mathrm{d}\Phi_B\mathrm{d}\Phi_R, \quad (2)$$

which allows a simulation to be constructed without double counting of radiation from the parton shower and hard real corrections. However, while correctly incorporating the resummation of the parton shower and the fixed NLO calculation this approach does lead to negative weighted events. Additionally as the subtraction term depends on the details of the specific parton-shower algorithm used it must be analytically recalculated for different approaches which can be complicated depending on the details of the parton-shower algorithm.

Later an alternative rearrangement POWHEG [3] was suggested

$$\mathrm{d}\sigma = \overline{B}(\Phi_B)\mathrm{d}\Phi_B \left[\Delta_R^{(\mathrm{NLO})}(0) + \Delta_R^{(\mathrm{NLO})}(p_\perp)\frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)}\mathrm{d}\Phi_R\right], \quad (3)$$

where

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int R(\Phi_B, \Phi_R)\mathrm{d}\Phi_R, \quad (4)$$

$$\Delta_R^{(\mathrm{NLO})}(p_\perp) = \exp\left[-\int \mathrm{d}\Phi_R \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)}\theta(k_\perp(\Phi_B, \Phi_R) - p_\perp)\right]. \quad (5)$$

While this looks more complicated it has the advantage that it is independent of the parton shower algorithm used to describe subsequent emissions and only generates positive weights. While a number of variants have been developed and different theoretical approaches suggested only these approaches, together with the more recent KrKNLO [7], have proved viable in practice.

Following the development of approaches for handing multiple emissions at leading order and one emission at NLO a number of approaches have now been developed to allow the merging of multiple emissions at NLO [8][9][10][11][12][13] together with the first processes at NNLO [14][15][16].

Together with the development of new approaches for the simulation of the hard processes with higher accuracy the last ten years has also seen the development of a number of new parton shower algorithms [17][18][19][20][21][22][23] primarily motivated by improving the matching to higher-order calculations.

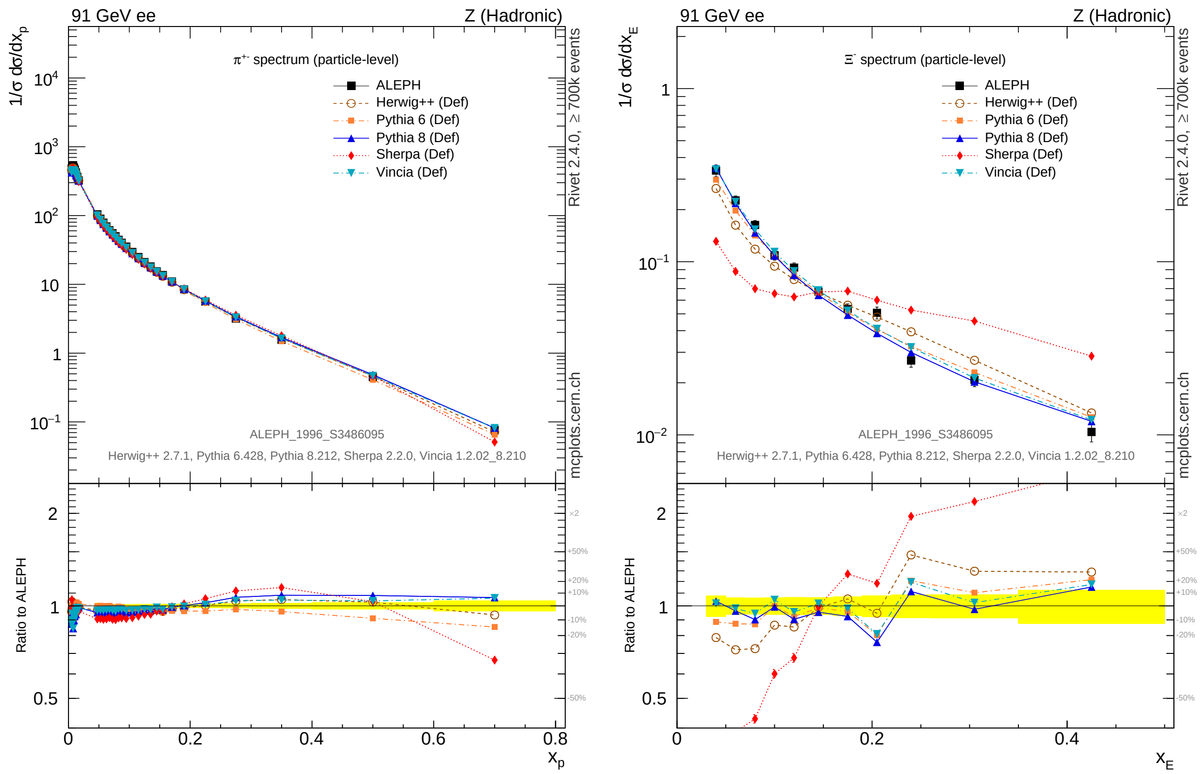

Figure 1: The π^+ and Ξ^- spectra measured by the ALEPH experiment at LEP I compared to the predictions from taken from modern event generators. Plot from MCplots[28].

In the early 2000's it also became clear that the programming paradigm in particle physics was changing from procedural programming in FORTRAN to object oriented programming in C++. This led to the development of new programs to replace the successful HERWIG [24] and PYTHIA [25] simulation programs and the new SHERPA [26] program developed from scratch in C++. This new generation of event generators are now the workhorses for simulation at the LHC, together with specialised programs for the calculation of hard processes in the various merging schemes.

It is clear that there has been a dramatic development in Monte Carlo simulations over the last fifteen years motivated by the need to describe the unprecedented energy scale and accuracy of the LHC results. For a recent review of the current status of Monte Carlo event generators see [27]. However, describing LEP data is still important and all new shower algorithms are still developed, tested and tuned using data from e^+e^- collisions. Many properties of the non-perturbative models, particularly relating to the production of specific hadrons are hard, if not impossible, to measure in the more complicated hadron–hadron environment, for example the Ξ^- spectrum shown in Fig. 1. Some aspects of hadronization, particularly the production of baryons and hadrons containing strange quarks, remain poorly understood.

LHC and the Future

The new generation of Modern Carlo event generators provide an impressive quantitative agreement with the LHC data, see for example [29] for the latest results on the production of a Z boson in association jets. While there has been dramatic progress in incorporating higher multiplicity matrix

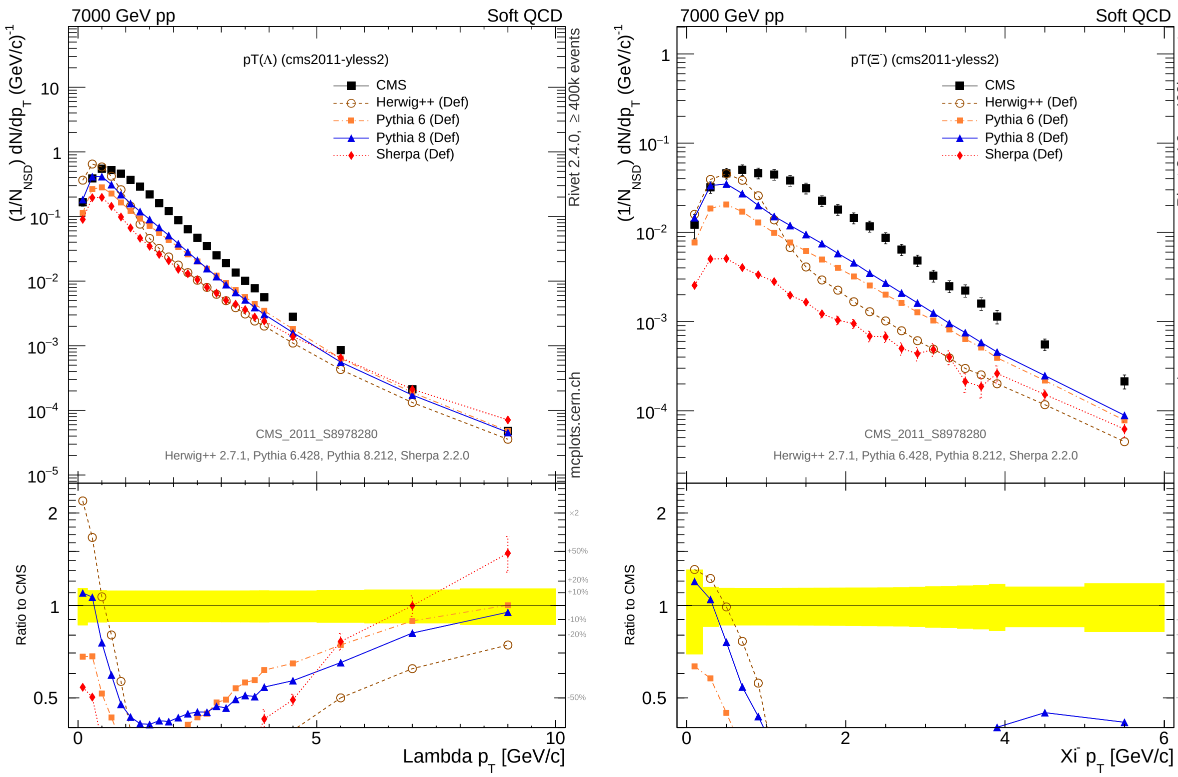

Figure 2: The Λ^0 and Ξ^- spectra measured by the CMS experiment at the LHC compared to the predictions from taken from modern event generators. Plot from MCplots[28].

elements and higher-order virtual corrections there has been little progress improving either the underlying accuracy of the parton shower resummation or the non-perturbative modeling of the hadronization process.

Recent work has started on improving the accuracy of the parton-shower algorithm which will be required as the accuracy of the matrix elements increases. This has looked at including subleading colour effects [30][31], and sub-leading colinear logarithms [32]. While this is the area where there is probably the greatest potential for improvement it remains to be seen if we can consistently improve the logarithmic accuracy particularly for all observables, or whether the accuracy can at least be improved for those classes of observables where higher-order analytic resummations are possible.

The standard assumption of universality was that we could develop the hadronization models using e^+e^- data and then apply them in hadron–hadron collisions. Simulating hadronic collisions has always needed additional non-perturbative modeling of the underlying event and non-perturbative colour reconnection. However in the complicated environment of the LHC clearly other things are going on, or colour reconnection is much more complicated, and we need better modeling of non-perturbative effects, e.g. for strange hadron spectra (see Fig. 2). While there are some new ideas, e.g. [33], this is an area where clearly more work is required in order to describe the LHC results.

Outlook

Given the massive progress in Monte Carlo event generation over the last 15 years it is impossible to say what the state-of-the-art in event simulation will be by the time of FCC-ee. Certainly there will continue to be significant developments over the course of the LHC high-luminosity programme to include higher order matrix elements, more accurate resummation and better non-perturbative modelling. While for the foreseeable this will be driven by the need to describe the results of the LHC given the much simple nature of leptonic collisions the results of LEP and earlier e^+e^- colliders will continue to be used when developing new approaches. Given the decades of work we are looking forward to in order to fully exploit the LHC and improved understanding of QCD and better simulations that surely must follow it is impossible to say at this stage what, if any, further understanding would be obtained from the FCC-ee.

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