HIGH-Q^2 PHYSICS AT THE LHC

F. KRAUSS
Institut für Theoretische Physik
TU Dresden
***D-01062** Dresden*
Germany
E-mail: krauss@theory.phy.tu-dresden.de

In this talk, several aspects of high-Q^2 physics at the LHC are reviewed, with special emphasis on QCD.

1. Introduction

The physics programme of the LHC at the highest energies is dominated by searches for new particles or other signals for new physics scenarios. Clearly, the primary goal is the discovery of the Higgs boson or – if not existent – an alternative explanation of electroweak symmetry breaking. In addition there is a plethora of physics scenarios motivated by the hierarchy problem intrinsic to the Standard Model. These include, most notably, supersymmetry in its minimal or non-minimal form, and extra space-time dimensions in various versions. However, most of the searches for these exiting new physics scenarios are hampered by severe backgrounds, most of which are largely influenced by QCD. This renders a detailed understanding of the in principle well-known theory of strong interactions a *sine qua non* of QCD phenomenology at all scales, including the highest ones. This prominent role of QCD is exemplified by the importance of the central for Higgs searches in the vector boson fusion channel and by the impact of multijet backgrounds in searches for supersymmetric partner particles. In fact, this is yet another instance for the finding that todays signals nearly always translate into tomorrows backgrounds.
Therefore, in this talk, I chose not to talk about the many potential signals for models of interesting physics at the LHC, but rather would like to stress that (nearly) nothing comes for free. In the world of LHC physics this means that, accepting that a signal is what remains after background subtraction,

a legitimate and important question is: How well do we understand bread-and-butter physics, *i.e.* QCD?

2. Knowledge of the initial state: PDFs

One of the basic ingredients for the understanding of physics at collider experiments is the precision with which measurements can be matched to the underlying theory. One of the basic inputs for this is the calculation of corresponding total or differential cross sections, where parton density functions (PDFs) are a basic input. Since they cannot determined from first principles, but only their scaling behaviour, they must be measured and fitted to the respective data. The quality of the results shows the viability of this approach and, ultimately, is a clear indication of the quality in the current understanding of QCD. However, so far, most of the standard PDFs [1]are mainly determined from deep-inelastic scattering data. Independent of the high precision of these data, unfortunately uncertainties, typically around 5%-10%, remain in the fits. But due to lack of data there also remain larger uncertainties in some regions of phase space, most notably in the gluon distribution in the high-Q^2 region [a]. With the LHC becoming operational and exploring new scales, the inclusion of LHC data into the PDF fits will thus become mandatory.

In such a combined fitting procedure, the calculation of parton-level cross sections at next-to leading order accuracy (or better) is a necessary ingredient. In principle the idea is to compare the calculated cross section for a given process $pp \to X$

$$\sigma_{pp\to X}(s) = \int \mathrm{d}x_1 \mathrm{d}x_2 f_i(x_1,\, Q_F^2) f_j(x_2,\, Q_F^2) \hat{\sigma}_{ij\to X}(\hat{s},\, \mu_R^2) \qquad (1)$$

with data. However, the calculation indicated above is very CPU-expensive and limits abilities for a fast fit and therefore for a thorough analysis. In order to circumvent this problem, there are approaches to disentangle the differential parton-level cross section from the PDFs in the equation above. The underlying idea common to these approaches is to replace integration by summation (*i.e.* MC integration) and to write

$$\sigma_{pp\to X}(s) = \sum_{x_1,\, x_2,\, Q^2} W_{\hat{\sigma}} \cdot W_{\mathrm{PDF}}\,, \qquad (2)$$

where $W_{\hat{\sigma}}$ is a weight emerging after binning the partonic cross section $\hat{\sigma}$, and W_{PDF} takes care of the product of PDFs, $f_i(x_1,\, Q_F^2) f_j(x_2,\, Q_F^2)$.

[a]In fact, this is a region where hadron colliders can have significant input.

Adding in suitable interpolation between the bins and a pre-tabulated array $W_{\hat{\sigma}}$, which has to be calculated only once and for all, allows a fast evaluation/fitting of the PDFs.
Currently, there are two projects, FastNLO [2] and NLO@Grid [3] centering around the issue of fitting PDFs at the LHC. In Fig. 1 the accuracy of the resulting grid interpolation for both projects are exhibited. Clearly, the accuracy is of the order of 1 per mille, sufficient for high-precision fits.

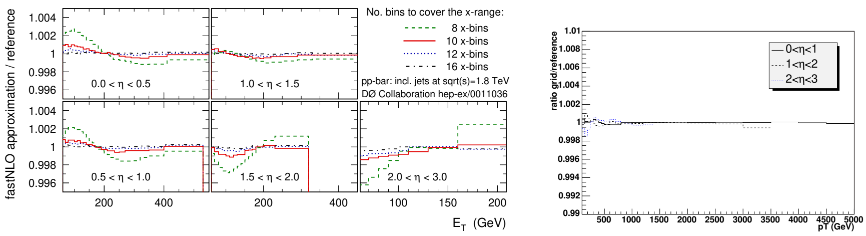

Figure 1. Accuracy of the grid interpolation of FastNLO (left) and NLO@Grid (right), both for the example of jet production. For FastNLO, jet production at the Tevatron has been considered, whereas the NLO@Grid plot exhibits the accuracy for jet production at the LHC.

3. Knowledge of QCD evolution: Jets

The next issue discussed here is the precision with which hadronic material in the final state, *vulgo* jets, can be mapped onto initial partons, the objects of QCD perturbation theory. This is especially important, since nearly all physics signals at the LHC are connected with the emergence of jets. This necessitates jet definitions with “good” properties, allowing for a match of jets with underlying partons. Currently there are two types of algorithms used by the experiments, namely cone-algorithms and k_T-algorithms.
In order to investigate the quality of the algorithms w.r.t. the accuracy with which the respective jets can be mapped onto the partons from which they emerge, D. Benedetti *et al.* (contribution to [4]) introduce quality markers, namely the angular distance α^i_{jp} (the $\Delta R(p^i, j^i)$ of i th parton p to its jet j) and the energy difference β^i_{jp} (β^i_{jp} is the distance from the energy calibration curve in terms of its error σ). In terms of these quality markers, jets are considered well-clustered, if $\alpha^i_{jp} \leq 0.3$ and if $\beta^i_{jp} \leq 2$. This has been applied to the case of $t\bar{t}$ and $t\bar{t}H$-production at the LHC, where the decays of the heavy particles yields 2 ($t\bar{t}$, fully leptonic), 4 ($t\bar{t}$, semi leptonic), 6

($t\bar{t}H$, semi leptonic), or 8 ($t\bar{t}H$, fully hadronic) quark jets. In Fig. 2 the fraction of correctly selected jet numbers and the fraction of well-clustered jets in dependence on the cone size R are depicted for the iterative cone. Results obtained with the midnight cone or the k_T-algorithm, respectively, exhibit a nearly identical behaviour. The results shown here indicate that more work is needed in order to connect events with high jet multiplicity at the LHC with the underlying theory.

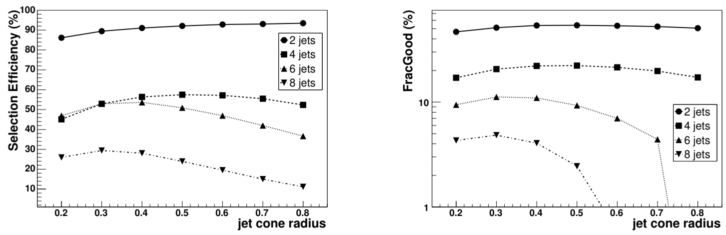

Figure 2. Ratio of well-selected 8left) and well-selected and well-clustered (right) events for the iterative cone algorithm in $t\bar{t}$ (2 and 4 jets) and $t\bar{t}H$ (6 and 8 jets) production at the LHC.

4. Knowledge of background topologies: Multijets

As noted in the introduction, multijet backgrounds are of great importance already at the Tevatron, but their understanding will become paramount at the LHC. By and large, however, it is quite unlikely that in the next few years there will be many predictions reaching up to, say, 6 jets at the NLO level and therefore other methods capable of describing such events will be indispensable. In the past years the construction of new Monte Carlo tools has started, [5,6], and some of them are already equipped with a new method of merging LO matrix elements with the parton shower in such a way that leading logarithms are systematically accounted for [7]
Recently [9], one of these new tools, SHERPA, has been compared with PYTHIA 6.2 [8] in its performance describing $p\bar{p} \to Z + X$ events at the Tevatron at detector level. In Fig. 3 the respective jet rates are shown, whereas in Fig. 4 the $p_\perp$ distribution of the third hardest jet is depicted. The results here indicate that modern Monte Carlo tools are well equipped to describe multi-jet cross sections and distributions at the Tevatron.

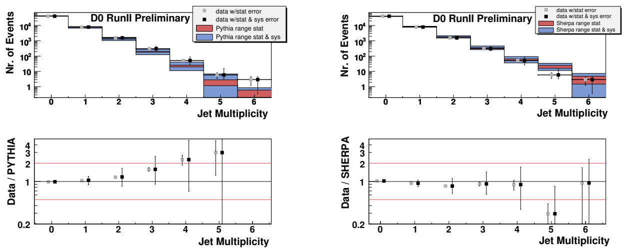

Figure 3. Jet rates in $p\bar{p} \to Z + X$ events at the Tevatron. To the left, results of PYTHIA are depicted, to the right the results of SHERPA are shown.

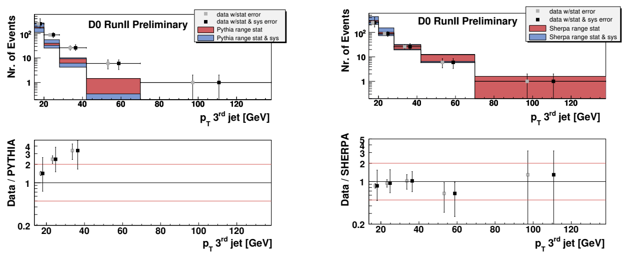

Figure 4. $p_\perp$-distribution of the 3rd jet in $p\bar{p} \to Z + X$ events at the Tevatron. To the left, results of PYTHIA are depicted, to the right the results of SHERPA are shown.

5. Knowledge of non-factorisable QCD: Underlying event

Finally, a phenomenon known as the underlying event, will briefly be discussed. After various analyses, especially at the Tevatron, there seems to be no doubt that this is an important phenomenon with the potential to severely harm various analyses at the LHC. The reason for this is that, because its description clearly is beyond standard factorisation and therefore beyond current understanding of perturbative QCD, there is no theoretically sound way to extrapolate findings already made to LHC energies.

Fitting the parameters of the respective phenomenological model to data is not trivial and in fact there is a lot of freedom, especially when the energy extrapolation of the model is concerned. This is best reflected in the findings of Fig. 5 where different tunes of the same models at Tevatron and their results at the LHC are shown (contribution by C. Buttar to [4]). Clearly, our knowledge of the underlying event, both on theoretical grounds and on our ability to extrapolate known results to higher energies is far from being perfect.

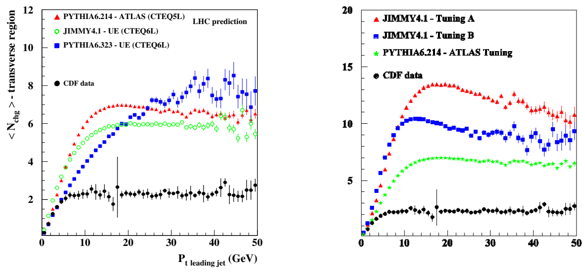

Figure 5. Results for the number of charged particles in the transverse region at the LHC as given by different tunes for current underlying event models.

6. Summary

To summarize:

- Most probably, the success of LHC probably depends on a detailed understanding of QCD;
- Especially in the first years of LHC running QCD issues will be central, rendering it a great time for QCD-lovers;
- Apparently, there is considerable leeway for an improved understanding of QCD - on all levels between theory and experiment
- There are still puzzles and problems to be resolved, reaching from technicalities (sufficient precision in PDFs, jets and their definitions, multijets, . . .) to basics (underlying event, interplay of soft & hard QCD . . .).

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