PROCEEDINGS OF SCIENCE

LHC data challenges the contemporary parton-to-hadron fragmentation functions

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We discuss the inclusive high-pT charged-particle production in proton-proton collisions at the LHC. The experimental data are compared to the NLO perturbative QCD calculations employing various sets of parton-to-hadron fragmentation functions. Most of the theoretical predictions are found to disastrously overpredict the measured cross sections, even if the scale variations and PDF errors are accounted for. The problem appears to arise from the presently too hard gluon-to-hadron fragmentation functions.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects,
28 April - 2 May 2014
Warsaw, Poland

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PoS(DIS2014)148

1. Motivation

The principal motivation for our study [1] was the observation that the next-to-leading order (NLO) perturbative QCD (pQCD) calculations for inclusive charged hadron production shown along with the published p+p data from CMS [2] and ALICE [3] appeared to clearly overshoot the measurements at large transverse momentum (p_T). This called for a systematic study to chart the different sources of theory uncertainties and thereby, hopefully, identify the cause of the apparent mismatch.

2. Framework

The inclusive high-p_T charged-particle (h_3) production in collision of two hadrons h_1 and h_2 can be computed as a convolution of the initial-state parton distribution functions $f_i(x,\mu^2_{\rm fact})$ (PDFs), final-state parton-to-hadron fragmentation functions $D_{k\to h_3}(z,\mu^2_{\rm frag})$ (FFs), and partonic coefficient functions $d\sigma^{i+j\to k+X}(\mu^2_{\rm ren},\mu^2_{\rm fact},\mu^2_{\rm frag})$ as

$$d\sigma(h_1+h_2\to h_3+X)=\sum_{ijk} f_i^{h_1}\otimes d\sigma^{i+j\to k+X}\otimes f_j^{h_2}\otimes D_{k\to h_3}, \tag{2.1}$$

where $\mu^2_{\rm ren}, \mu^2_{\rm fact}$, and $\mu^2_{\rm frag}$ denote the renormalization, factorization, and fragmentation scales, respectively. Figure 1 presents a schematic illustration of the process ingredients. In practice, we evaluate the cross sections to NLO in strong coupling $\alpha_s(\mu^2_{\rm ren})$ utilizing the public INCNLO code [4, 5]. For the PDFs we use CT10NLO [6] and its error sets. The FF uncertainty is estimated by performing the calculations with various parametrizations: Kretzer (KRE) [7], KKP [8], BFGW [9], HKNS [10], AKK05 [11] DSS [12, 13], and AKK08 [14]. From all these, only HKNS offers a possibility to estimate the propagation of FF uncertainties to further observables.

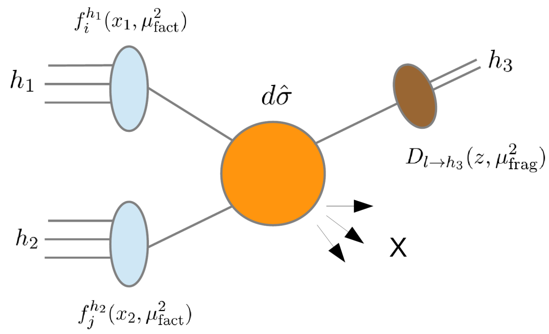

Figure 1: Ingredients of inclusive hadron production in hadronic collisions.

We illustrate the differences in these FFs by plotting, in Figure 2, the FFs for u-quarks and gluons. While the u-quark FFs are all rather tightly packed together, the spread among the different gluon FFs is huge. The main reason for the large differences is that the e^+e^- annihilation data which constitutes the bulk of the FFs constraints are predominantly sensitive to the quark fragmentation, leaving the gluons rather unconstrained. To improve the situation DSS and AKK08 included also hadroproduction data from RHIC, SPS and Tevatron, but predominantly at rather low values of p_T where the NLO pQCD calculations are in doubt (see later). Along with the LHC p+p runs at several center-of-mass energies it has now become possible to fit the FFs at higher p_T and also cross-check between different experiments. As illustrated in Figure 3, the gluon fragmentation dominates the cross sections up to the highest measurable values of p_T and the large spread of gluon FFs seen in Figure 2 should therefore make a difference at the LHC.

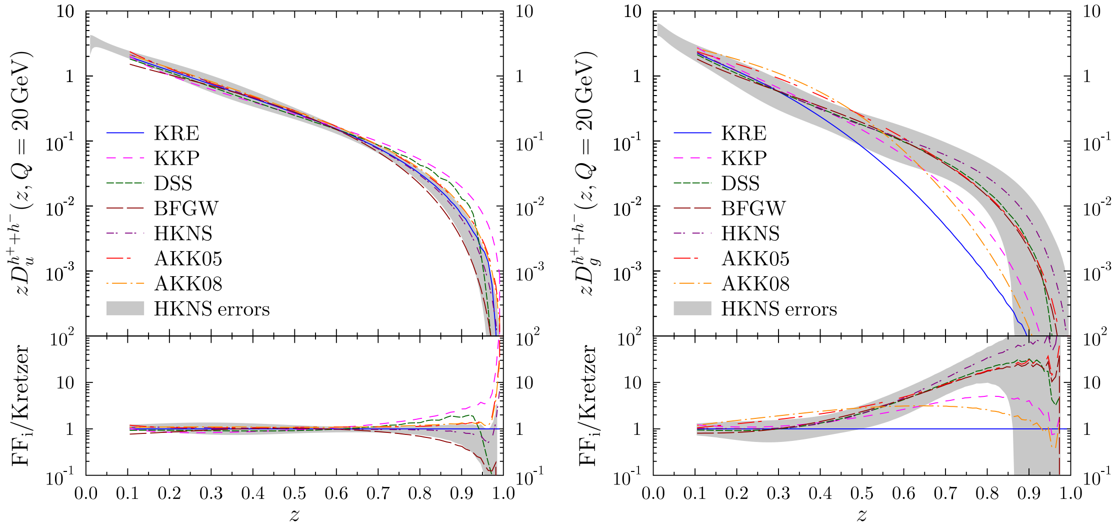

Figure 2: The absolute charged-hadron FFs for u-quarks (left) and gluons (right) at $\mu_{\text{frag}} = 20\,\text{GeV}$, and their ratios to Kretzer FFs. Figure from [1].

Our default choice for the involved QCD scales is $\mu_{\text{ren}} = \mu_{\text{fact}} = \mu_{\text{frag}} = p_T$, and we explore the sensitivity of the NLO calculation to this particular choice by varying the scales independently by a factor of two. However, we exclude the variations with

$$\frac{\mu_{\text{ren}}}{\mu_{\text{frag,fact}}} = 4 \text{ or } \frac{1}{4},$$

as this gives rise to artificially large logarithms $\log(\mu^2_{\text{ren}}/\mu^2_{\text{fact}})$ and $\log(\mu^2_{\text{ren}}/\mu^2_{\text{frag}})$, in terms involving partonic splitting functions P_{ij}. Schematically,

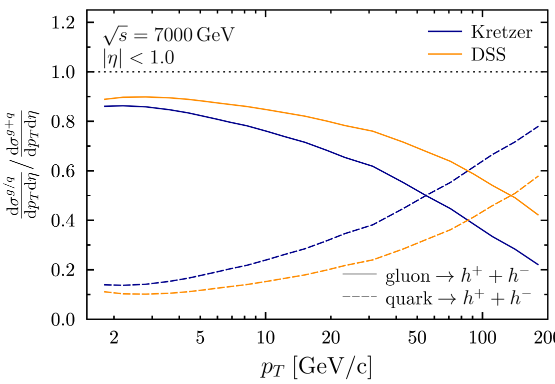

Figure 3: Relative importance of gluon (solid) and quark (dashed) fragmentation to the total charged-hadron yield with $\sqrt{s} = 7000\,\text{GeV}$ (right) at midrapidity. Calculation is shown for Kretzer (dark blue) and DSS (orange) FFs. Figure from [1].

$$\frac{\alpha_s(\mu^2_{\text{ren}})}{2\pi} \log\left(\frac{\hat{s}}{\mu^2_{\text{fact,frag}}}\right) P_{ij} \approx \frac{\alpha_s(\mu^2_{\text{fact,frag}})}{2\pi} \log\left(\frac{\hat{s}}{\mu^2_{\text{fact,frag}}}\right) P_{ij} + \frac{\alpha_s^2(\mu^2_{\text{ren}})}{2\pi}\frac{\beta_0}{4\pi} \log\left(\frac{\mu^2_{\text{fact,frag}}}{\mu^2_{\text{ren}}}\right) \log\left(\frac{\hat{s}}{\mu^2_{\text{fact,frag}}}\right) P_{ij}, \tag{2.2}$$

which follows from the QCD renormalization group equation (β_0 is the first term in the QCD β-function and $\hat{s}$ denotes the partonic center-of-mass energy). Whereas the first term tends to moderate effect of varying $\mu_{\text{fact,frag}}$, the second term can become large.

3. Results

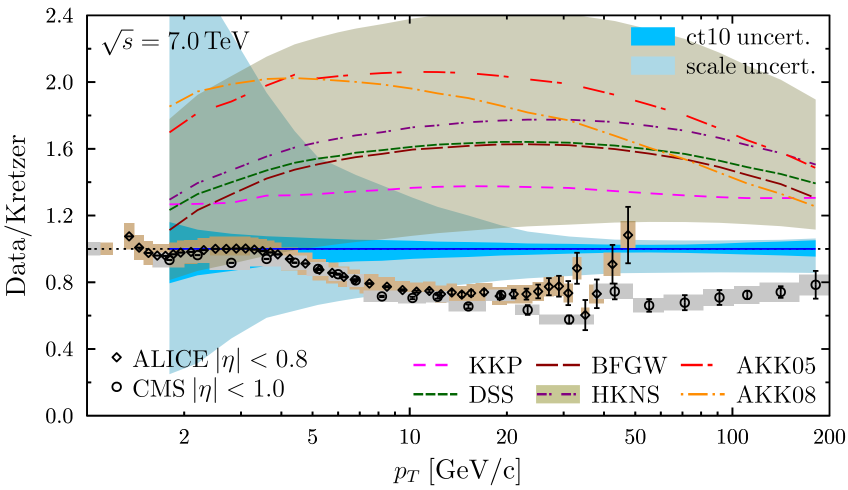

Figure 4: Comparison between the CMS and ALICE 7 TeV data and the calculations with various FFs. Figure adapted from [1].

Figure 4 shows a representative example of what we find when contrasting the NLO calculations against the measurements. The data as well as all the calculations with various FFs have been normalized by the results obtained with the Kretzer FFs. The main points we want to emphasize are:

- The CMS and ALICE data are in a fair agreement.
- The PDF-originating uncertainty (dark blue band) turns out rather small, around 5% at high p_T.
- The scale uncertainty (light blue band) is huge at small p_T, but levels off beyond $p_T \sim 10\,\mathrm{GeV}$.
- The calculation with Kretzer FFs gives the best description of the data, being around 20% above the data beyond $p_T \sim 10\,\mathrm{GeV}$. The data-to-theory ratio is remarkably flat despite the fact that the absolute cross section drops around eleven orders of magnitude.
- All other FFs overshoot the data even more. The error band of HKNS is large but not large enough to enclose the data.

Although we presented here only the 7 TeV LHC data as an example, the situation remains more or less the same when considering the other LHC energies and also with the data from the CDF collaboration [15] (see Ref. [1] for more details). It should be noted that related processes like inclusive jet [16, 17] or isolated photon production [18, 19] at the LHC are in agreement with the NLO calculations. This reinforces the idea that the mismatch between the LHC data and the NLO calculations is indeed due to the current gluon FFs which have either (almost) no data constraints or have been constrained at very low p_T where the scale uncertainty is enormous. The scale uncertainty is, however, not the only reason why the region below $p_T \sim 10\,\mathrm{GeV}$ should be discarded from charged-hadron FF fits: The qualitative difference between the $(K^+ + K^-)/(\pi^+ + \pi^-)$ and $(p^+ + p^-)/(\pi^+ + \pi^-)$ ratios measured by ALICE [20, 21] indicate that the baryon production at this low-p_T region cannot be considered being just independent parton-to-hadron fragmentation but different (collective?) physics seems to be involved. From $p_T \sim 10\,\mathrm{GeV}$ onwards such differences appear to disappear and the NLO calculations, like the ones presented here, should be adequate.

Despite the significant data-to-theory mismatch in the case of absolute cross sections it has been noticed [3] that the ratios of cross section between different $\sqrt{s}$ are, however, much better described by the NLO pQCD. This is demonstrated in Figure 5 presenting some ALICE data and calculations with two different FFs, Kretzer and DSS. Indeed, even DSS which grossly overshoots the absolute spectra (see Figure 4) is, more or less, consistent with the data. This follows from the fact that the cross-section ratios in Figure 5 are more sensitive to the shape of the gluon FFs and not that much to their absolute magnitude.

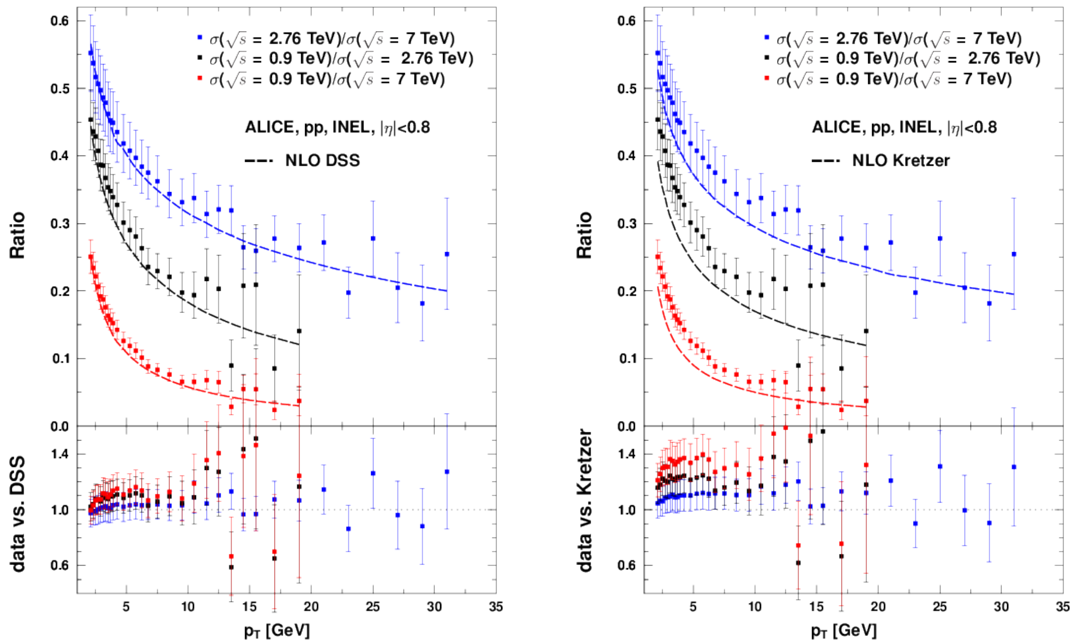

Figure 5: Ratios between the charged-hadron yields at different center-of-mass energies. The data points are from ALICE [3] (constructed by dividing the cross sections and adding the uncertainties in quadrature) and the calculations (dashed lines) are obtained using the DSS (left) and Kretzer (right) FFs.

4. Summary

In conclusion, we have found that none of the current sets of FFs can optimally describe the LHC (or Tevatron) data for inclusive charged hadron production at $p_T \gtrsim 10\,\mathrm{GeV}$. Below $p_T \sim 10\,\mathrm{GeV}$ the scale uncertainty is enormous prohibiting to make practically any conclusion and, in addition, in this low-p_T region there are evidence for excess baryons which do not seem to originate from independent parton-to-hadron fragmentation. For these reasons we conclude that only the region $p_T \gtrsim 10\,\mathrm{GeV}$ should be used in the forthcoming fits of charged-hadron FFs.

Acknowledgments

We acknowledge the financial support from the Magnus Ehrnrooth Foundation (I.H.) and from the Academy of Finland, Project No. 133005.

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