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

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based on an article written in collaboration with

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Motivation for the present study

The NLO calculations for the inclusive charged hadron production appeared to significantly overshoot the CMS and ALICE data. This called for a systematic study to chart the different sources of uncertainties and identify the cause of the mismatch.
The inclusive $h^+ + h^-$ production at the LHC

The factorization formula for inclusive hadron production

$$\frac{d\sigma(h_1 + h_2 \rightarrow h_3 + X)}{dp_T d\eta} = \sum_{ijl} \int dx_1 \int dx_2 \int \frac{dz}{z} f_{i}^{h_1}(x_1, \mu^2_{\text{fact}}) f_{j}^{h_2}(x_2, \mu^2_{\text{fact}})$$

$$D_{l \rightarrow h_3}(z, \mu^2_{\text{frag}}) \frac{d\hat{\sigma}(\hat{p}_1^l + \hat{p}_2^j \rightarrow \hat{p}_3^l, \mu^2_{\text{ren}}, \mu^2_{\text{fact}}, \mu^2_{\text{frag}})}{d\hat{p}_3^l d\eta}$$

- $f_{i}^{h_1}(x_1, \mu^2_{\text{fact}})$ = parton distributions (PDFs)
- $D_{l \rightarrow h_3}(z, \mu^2_{\text{frag}})$ = fragmentation functions (FFs)
- $d\hat{\sigma}$ = coefficient functions

The coefficient functions and the DGLAP evolution of the FFs known up to NLO in pQCD.

Numerical NLO calculations with improved INCNLO program with CT10NLO PDFs and various FFs.
Compare the contemporary FF sets

- We consider 7 different FF sets:

<table>
<thead>
<tr>
<th>FF set</th>
<th>Species</th>
<th>Fitted data</th>
<th>Error estimates</th>
<th>$z_{\text{min}}$</th>
<th>$Q^2$ (GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kretzer (KRE) [52]</td>
<td>$\pi^\pm, K^\pm, h^+ + h^-$, $e^+ e^-$</td>
<td>no</td>
<td>0.01</td>
<td>0.8–10$^6$</td>
<td></td>
</tr>
<tr>
<td>KKP [53]</td>
<td>$\pi^+ + \pi^-, K^+ + K^-$, $e^+ e^-$</td>
<td>no</td>
<td>0.1</td>
<td>1 –10$^4$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p + \bar{p}, h^+ + h^-$</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>BFGW [54]</td>
<td>$h^\pm$</td>
<td>yes</td>
<td>$10^{-3}$</td>
<td>2–1.2 · 10$^4$</td>
<td></td>
</tr>
<tr>
<td>AKK05 [56]</td>
<td>$\pi^\pm, K^\pm, p, \bar{p}$</td>
<td>$e^+ e^-$</td>
<td>no</td>
<td>2–4 · 10$^4$</td>
<td></td>
</tr>
<tr>
<td>HKNS [55]</td>
<td>$\pi^\pm, K^\pm, p + \bar{p}$</td>
<td>$e^+ e^-$</td>
<td>yes</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>AKK08 [59]</td>
<td>$\pi^\pm, K^\pm, p, \bar{p}$</td>
<td>$e^+ e^-, p$$p$</td>
<td>yes</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>DSS [57, 58]</td>
<td>$\pi^\pm, K^\pm, p, \bar{p}, h^\pm$</td>
<td>$e^+ e^-, p$$p, e$$p$</td>
<td>yes</td>
<td>$10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

- Only HKNS provides error sets (for $h^+ + h^-$)

- The hadrons in $e^+ e^-$ annihilation & DIS originate mainly from quark fragmentation

- Leave gluons weakly constrained

- DSS & AKK08 include also p+p data to better constrain the gluon FFs
Compare the contemporary FF sets

- As an example, up quark and gluon FFs

- The quark FFs in fair agreement

- The gluon FFs radically different above $z \approx 0.3$!
Choices for the hard scales $\mu_{\text{ren}}, \mu_{\text{fact}}, \mu_{\text{frag}}$

- Explore the scale dependence by calculating the cross sections with 16 combinations:

$$\left( \frac{\mu_{\text{fact}}}{p_T}, \frac{\mu_{\text{ren}}}{p_T}, \frac{\mu_{\text{frag}}}{p_T} \right) = \left( \frac{1}{2}, \frac{1}{2}, \frac{1}{2} \right), \left( \frac{1}{2}, \frac{1}{2}, 1 \right), \left( \frac{1}{2}, 1, \frac{1}{2} \right), \left( \frac{1}{2}, 1, 1 \right), \left( 1, \frac{1}{2}, \frac{1}{2} \right), \left( 1, \frac{1}{2}, 1 \right), \left( 1, 1, \frac{1}{2} \right), \left( 1, 1, 1 \right), \left( 1, 2, \frac{1}{2} \right), \left( 1, 2, 1 \right), \left( 2, 1, \frac{1}{2} \right), \left( 2, 1, 1 \right), \left( 2, 2, \frac{1}{2} \right), \left( 2, 2, 1 \right), \left( 2, 2, 2 \right).$$

- This a “conservative” estimate as we omit combinations with

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

to avoid large artificial logarithms of the form

$$\log(\mu_{\text{ren}}^2/\mu_{\text{fact}}^2), \log(\mu_{\text{ren}}^2/\mu_{\text{frag}}^2)$$

originating from contributions involving the splitting functions

$$\frac{\alpha_s(\mu_{\text{ren}}^2)}{2\pi} P_{qq} \log\left( \frac{\hat{p}_T^2}{\mu_{\text{fact}}^2} \right) \approx \left[ \frac{\alpha_s(\mu_{\text{fact}}^2)}{2\pi} + \frac{\alpha_s^2(\mu_{\text{ren}}^2) \beta_0}{2\pi} \log\left( \frac{\mu_{\text{fact}}^2}{\mu_{\text{ren}}^2} \right) \right] P_{qq} \log\left( \frac{\hat{p}_T^2}{\mu_{\text{fact}}^2} \right)$$
Typical $z$ distributions and gluonic share

- The $z$ distributions appear broad

- Contributions always from a wide $z$ interval

- Practically no contributions from the problematic $z < 0.1$ region (where e.g. the DGLAP evolution for FFs is not stable)

- Gluons dominate up to the highest $p_T$ values
CMS data vs. Kretzer FFs: NLO calculation overshoots data by 20% at large pT
The ratio remarkably flat
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ALICE data compatible with CMS
An example: LHC 7TeV data

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• Enormous scale uncertainty at small $p_T$ – moderate at large $p_T$

• The other FFs disastrously overshoot the data!
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Comparison to the “world” data

- The current FFs clearly overpredict the world data in the TeV energy realm!
- Kretzer FFs gives the best description at large pT - AKK05 the worst
  The LHC and Tevatron data prefer “soft” gluons FFs
- The scale uncertainty below pT = 10GeV is enormous – need the NNLO
- Larger the c.m. energy, more the predictions overshoot the data
Comparison to the “world” data

At the same time, there is a good agreement for the direct photons and inclusive jets

Reinforces that the problem lies in the gluon FFs and not in the pQCD formalism
Also the “chemistry” goes wrong

- proton-to-pion & kaon-to-pion ratios at the LHC

Notice the “bumb” at $p_T \sim 3\text{GeV}$ for the low-$p_T$ protons (even at 7TeV)

Enhanced non-perturbative contribution for baryons

To shelter from all non-perturbative effects requires $p_T > 10\text{GeV}$
Also the “chemistry” goes wrong

- Seen such a bump before?

- Effect presumably even more pronounced for low-energy measurements - used to constrain DSS and AKK08...
Energy ratios

- Ratios between different center-of-mass energies (at fixed $p_T$)

- More sensitive to the shape of the gluon FFs, not that much to the absolute magnitude.

- Robust against higher-order QCD corrections

- The non-perturbative “bump” near $p_T=3\text{GeV}$ partly cancels – somewhat misleading below $p_T\sim 10\text{GeV}$...
Summary

- None of the current sets of NLO FFs can optimally describe the LHC and Tevatron charged particle measurements.

- Below $p_T=10$ GeV the scale uncertainty is enormous and prohibits any strict conclusions.

- Below $p_T=10$ GeV there are also evidence for non-perurbative excess of baryons.

- For FF fits only the region $p_T > 10$ GeV (only modest scale uncertainty) appears “safe.”

- The 8TeV LHC data to provide definite answers?
Comparison to some low-energy data

At lower energy, STAR and UA1 data