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

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based on an article written in collaboration with

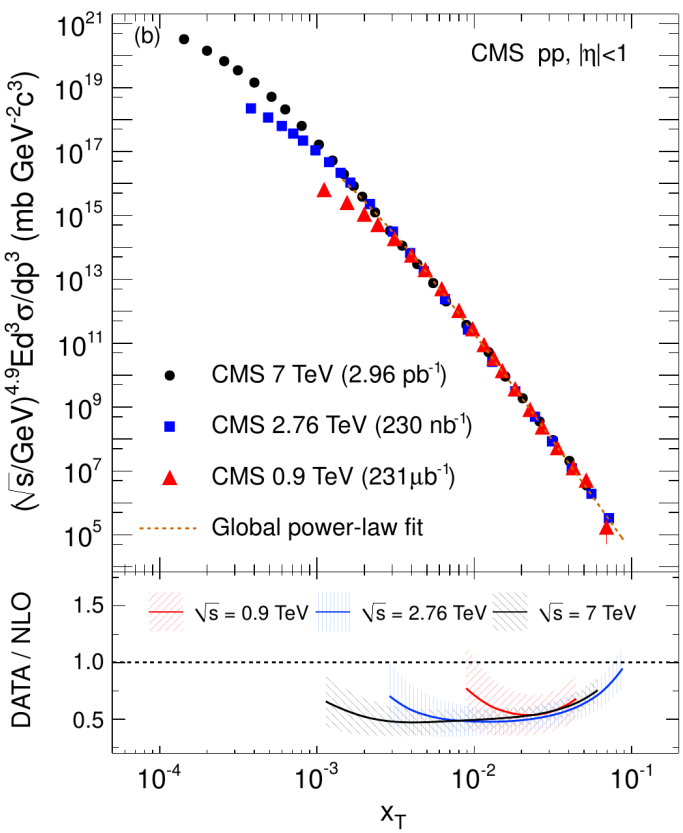
Ilkka Helenius, David d'Enterria, Kari J. Eskola

Reference: arXiv:1311.1415 [hep-ph]

Motivation for the present study

- The NLO calculations for the inclusive charged hadron prodution appeared to significantly overshoot the CMS and ALICE data

Eur. Phys. J. C 72 (2012) 1945



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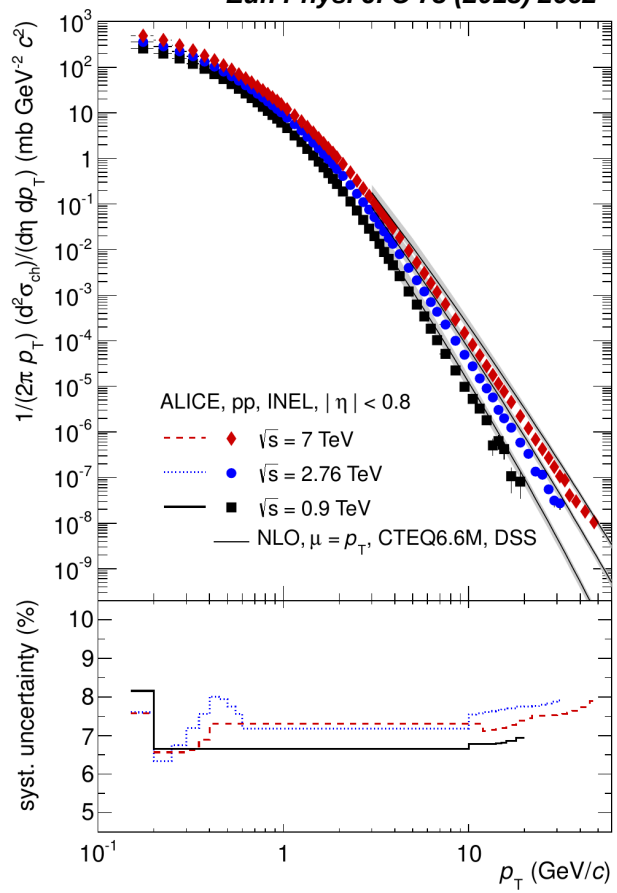


- Called for a systematic study to chart the different sources of uncertainties and identify the cause of the mismatch.

The inclusive h^++h^- production at the LHC

- The factorization formula for inclusive hadron production

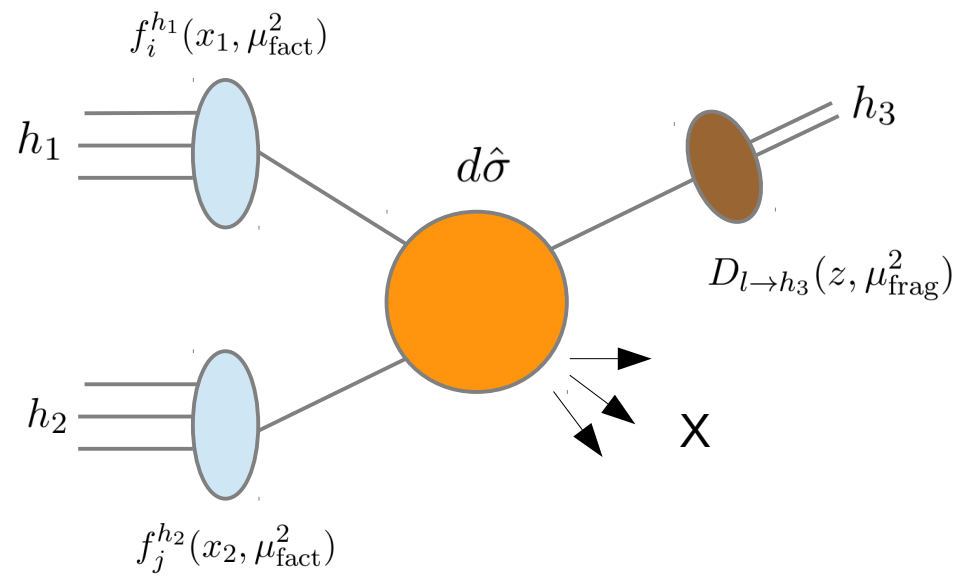
$$\frac{d\sigma(h_1+h_2\to h_3+X)}{dp_{\rm T}d\eta}=\sum_{ijl}\int dx_1\int dx_2\int\frac{dz}{z}f_i^{h_1}(x_1,\mu^2_{\rm fact})f_j^{h_2}(x_2,\mu^2_{\rm fact})$$

$$D_{l\to h_3}(z,\mu^2_{\rm frag})\,\frac{d\hat\sigma(\hat p_1^i+\hat p_2^j\to\hat p_3^l,\mu^2_{\rm ren},\mu^2_{\rm fact},\mu^2_{\rm frag})}{d\hat p_{3T}d\eta}\Bigg|_{\substack{\hat p_1=x_1p_1\\ \hat p_2=x_2p_2\\ \hat p_3=p_3/z}}.$$

$f_i^{h_1}(x_1,\mu^2_{\rm fact})$ = parton distributions (PDFs)

$D_{l\to h_3}(z,\mu^2_{\rm frag})$ = 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.

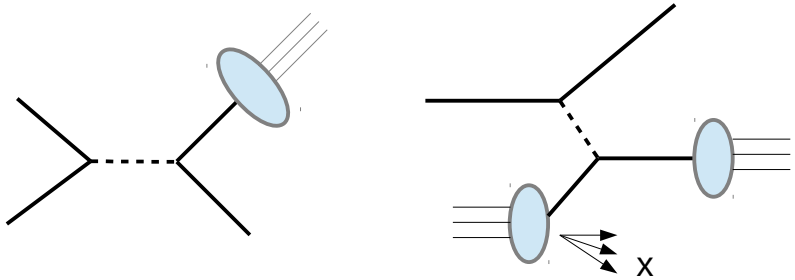
Compare the contemporary FF sets

- We consider 7 different FF sets:

FF set	Species	Fitted data	Error estimates	$z_{\min}$	Q^2 (GeV^2)
Kretzer (KRE) [52]	$\pi^\pm, K^\pm, h^+ + h^-$	e^+e^-	no	0.01	0.8–10^6
KKP [53]	$\pi^+ + \pi^-, K^+ + K^-$ $p + \bar{p}, h^+ + h^-$	e^+e^-	no	0.1	1 –10^4
BFGW [54]	$h^\pm$	e^+e^-	yes	10^{-3}	2–1.2 $\cdot 10^4$
AKK05 [56]	$\pi^\pm, K^\pm, p, \bar{p}$	e^+e^-	no	0.1	2–4 $\cdot 10^4$
HKNS [55]	$\pi^\pm, K^\pm, p + \bar{p}$	e^+e^-	yes	0.01	1–10^8
AKK08 [59]	$\pi^\pm, K^\pm, p, \bar{p}$	e^+e^-, p-p	no	0.05	2–4 $\cdot 10^4$
DSS [57], [58]	$\pi^\pm, K^\pm, p, \bar{p}, h^\pm$	e^+e^-, p-p, e-p	yes	0.05	1–10^5

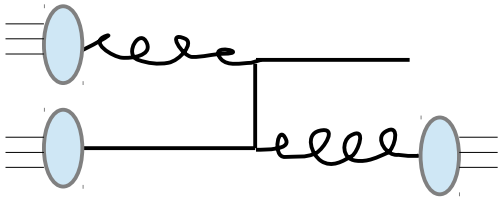
- Only HKNS provides error sets (for $h^+ + h^-$)

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



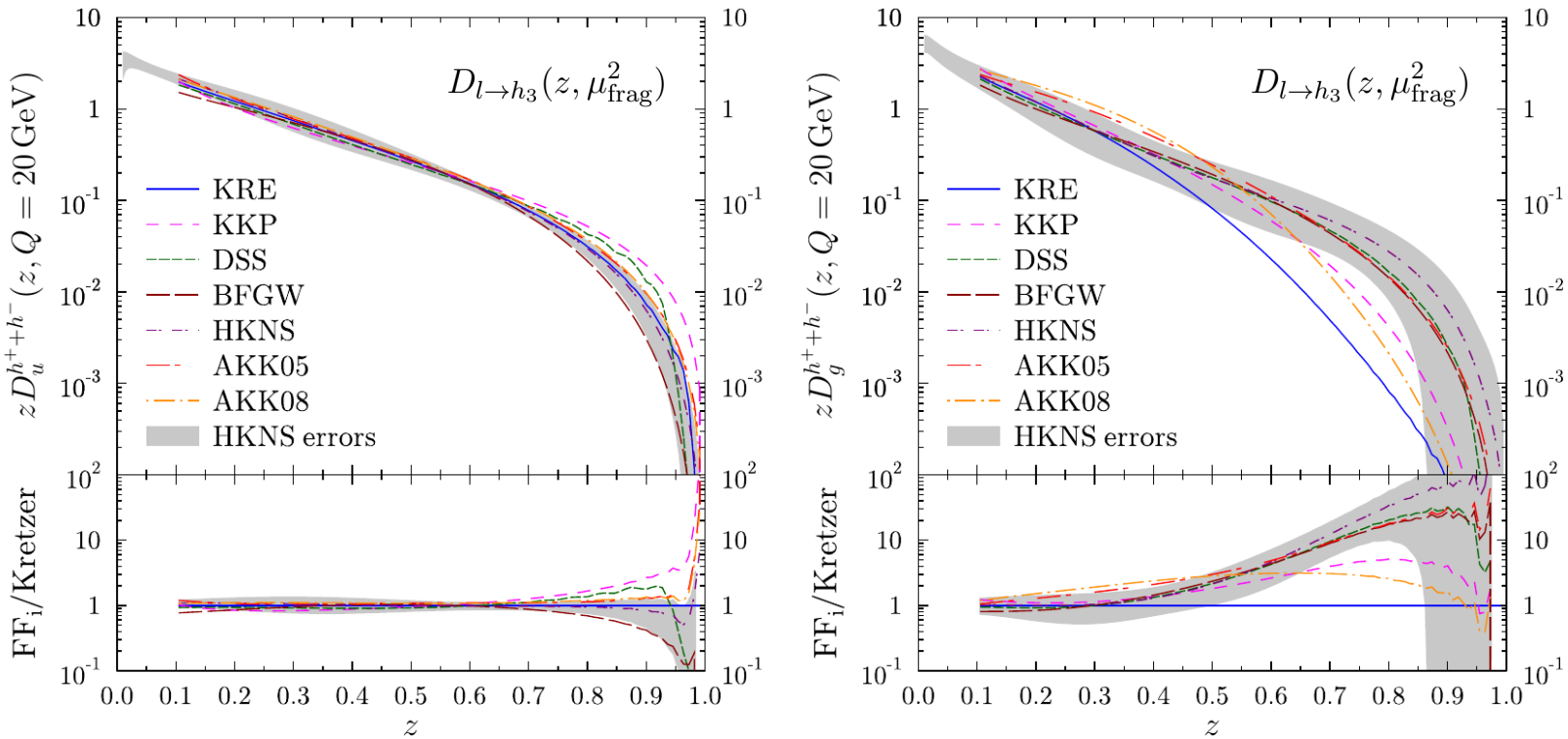
→ Leave gluons weakly constrained

- 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 ≈ 0.3!

Choices for the hard scales μ_{ren}, μ_{fact}, μ_{frag}

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

$$\left(\frac{\mu_{\rm fact}}{p_{\rm T}}, \frac{\mu_{\rm ren}}{p_{\rm T}}, \frac{\mu_{\rm frag}}{p_{\rm T}}\right) = \begin{array}{cccc} (\frac{1}{2},\frac{1}{2},\frac{1}{2}), & (\frac{1}{2},\frac{1}{2},1), & (\frac{1}{2},1,\frac{1}{2}), & (\frac{1}{2},1,1), \\ (\frac{1}{2},1,2), & (1,\frac{1}{2},\frac{1}{2}), & (1,\frac{1}{2},1), & (1,1,\frac{1}{2}), \\ (1,1,2), & (1,2,1), & (1,2,2), & (2,1,\frac{1}{2}), \\ (2,1,1), & (2,1,2), & (2,2,1), & (2,2,2). \end{array}$$

- This a "conservative" estimate as we omit combinations with

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

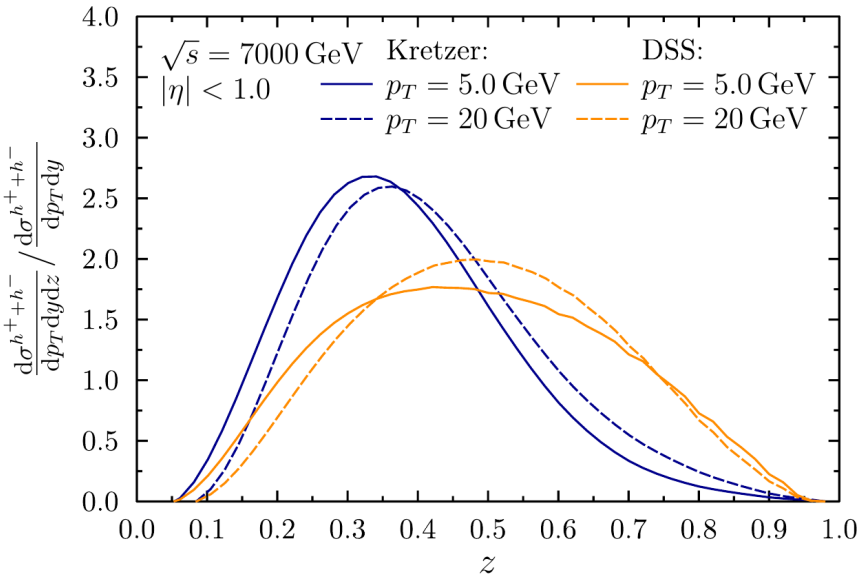
to avoid large artificial logarithms of the form

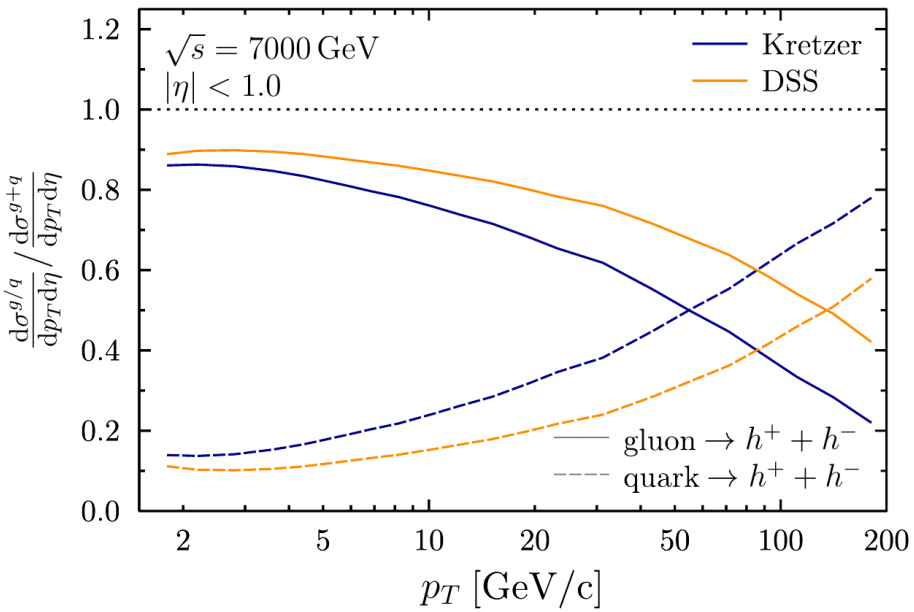
$$\log(\mu_{\rm ren}^2/\mu_{\rm fact}^2),\ \log(\mu_{\rm ren}^2/\mu_{\rm frag}^2)$$

originating from contributions involving the splitting functions

$$\frac{\alpha_s(\mu_{\rm ren}^2)}{2\pi} P_{qg} \log\left(\frac{\hat{p}_T^2}{\mu_{\rm fact}^2}\right) \approx \left[\frac{\alpha_s(\mu_{\rm fact}^2)}{2\pi} + \frac{\alpha_s^2(\mu_{\rm ren}^2)}{2\pi}\frac{\beta_0}{4\pi}\log\left(\frac{\mu_{\rm fact}^2}{\mu_{\rm ren}^2}\right)\right] P_{qg} \log\left(\frac{\hat{p}_T^2}{\mu_{\rm fact}^2}\right)$$

Typical z distributions and gluonic share





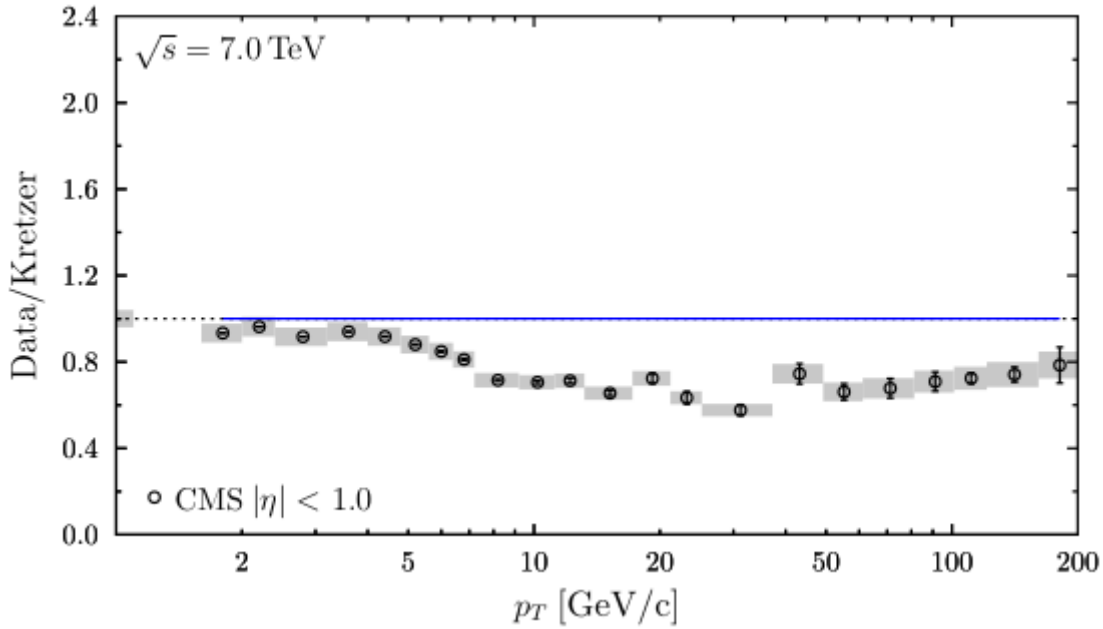
- The z distributions appear broad

  → 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 pT values

An example: LHC 7TeV data



- **CMS data vs. Kretzer FFs:** NLO calculation overshoots data by 20% at large pT
  The ratio remarkably flat

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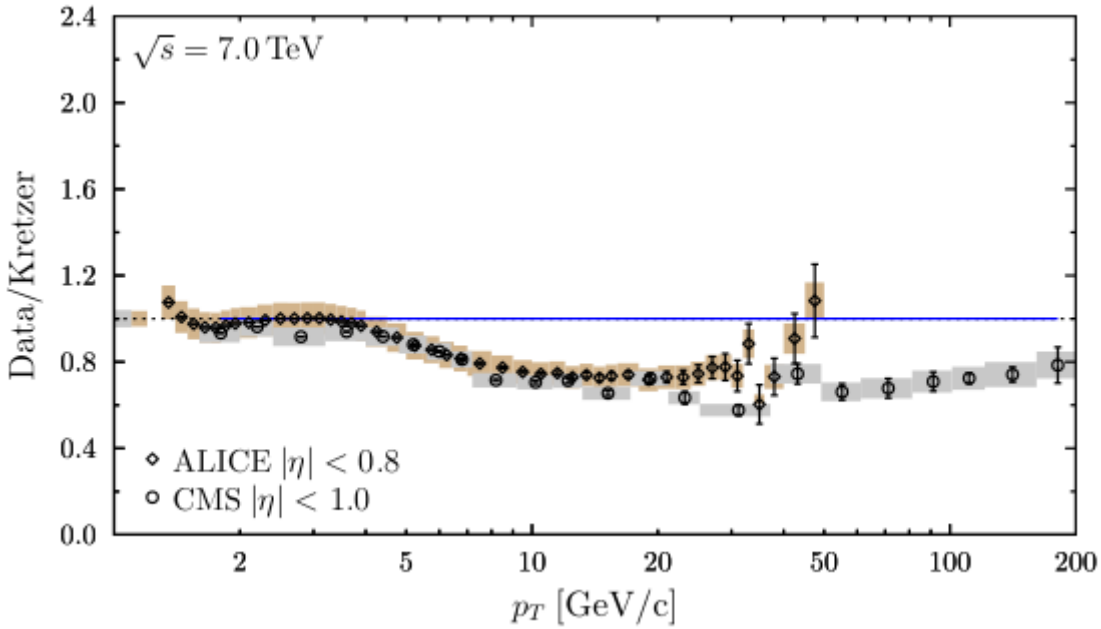

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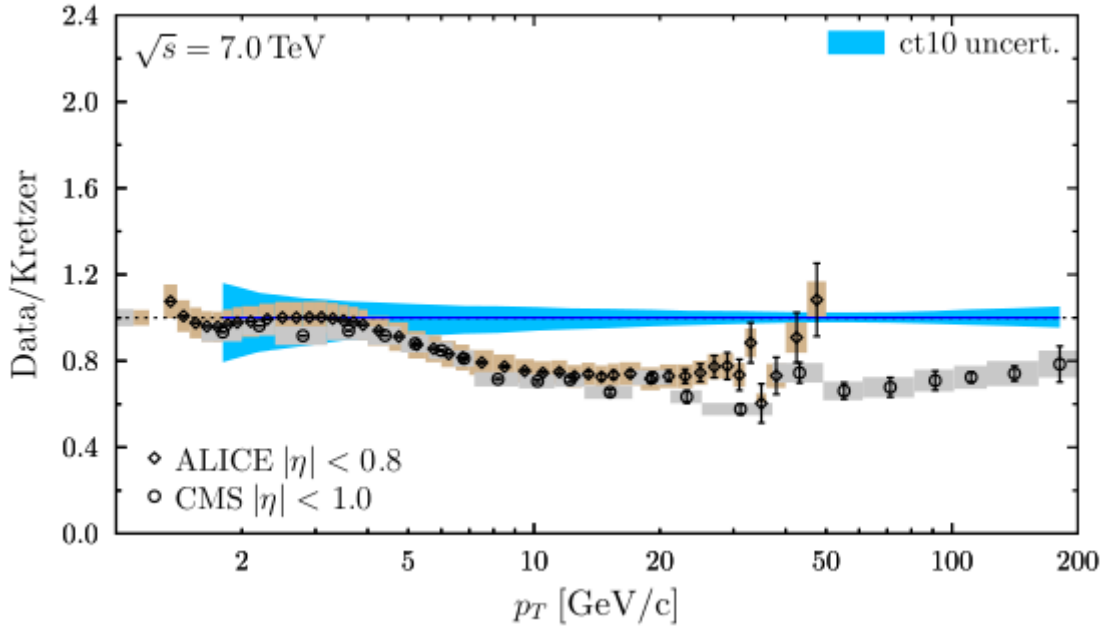

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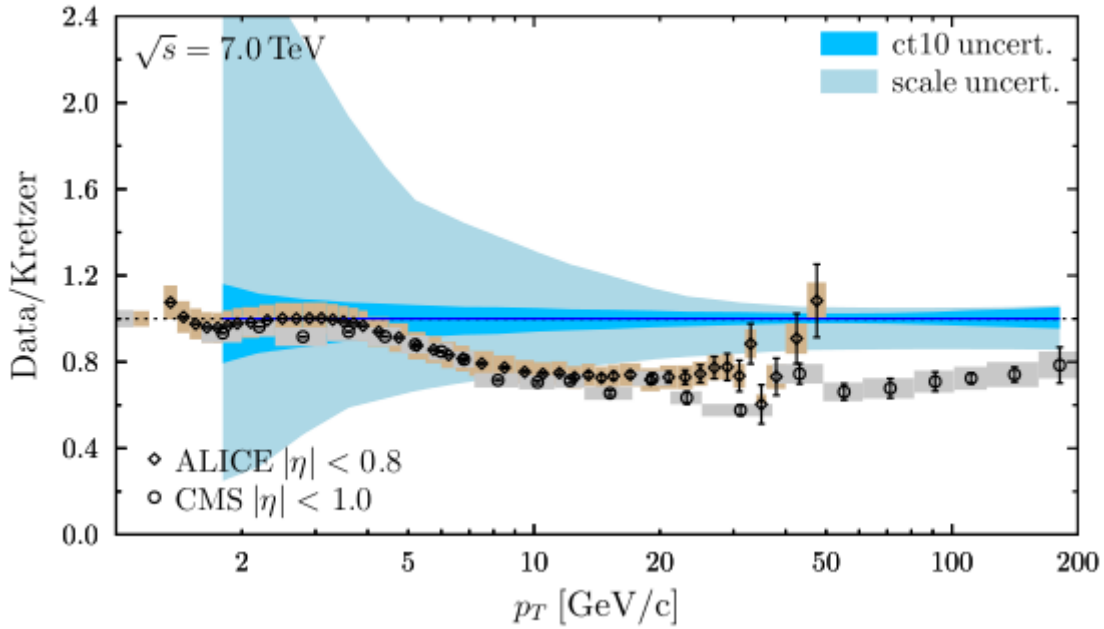

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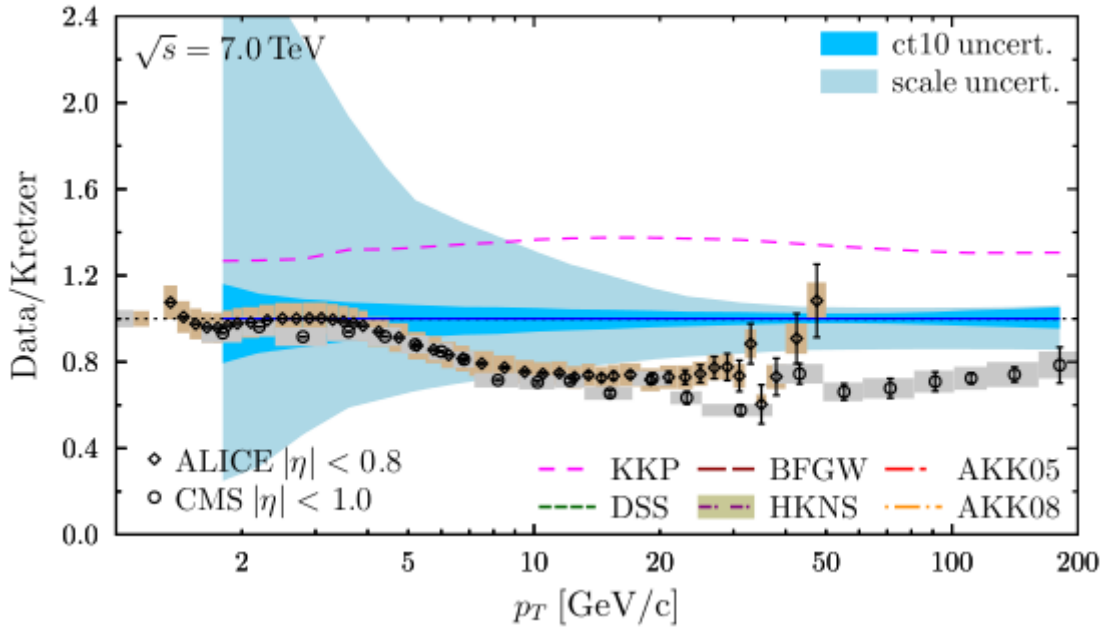

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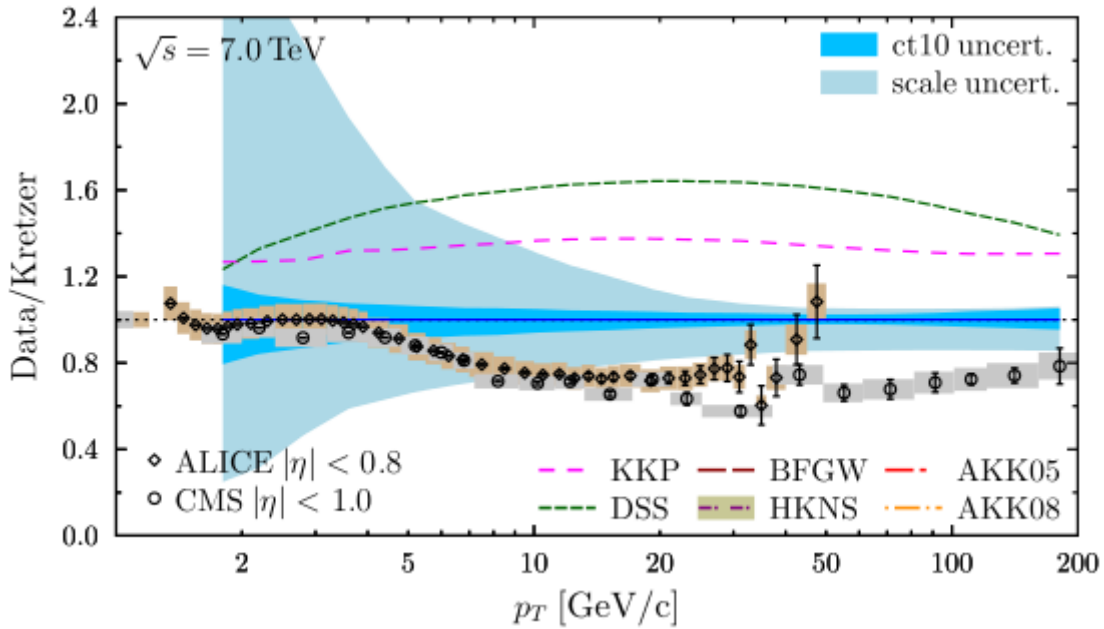

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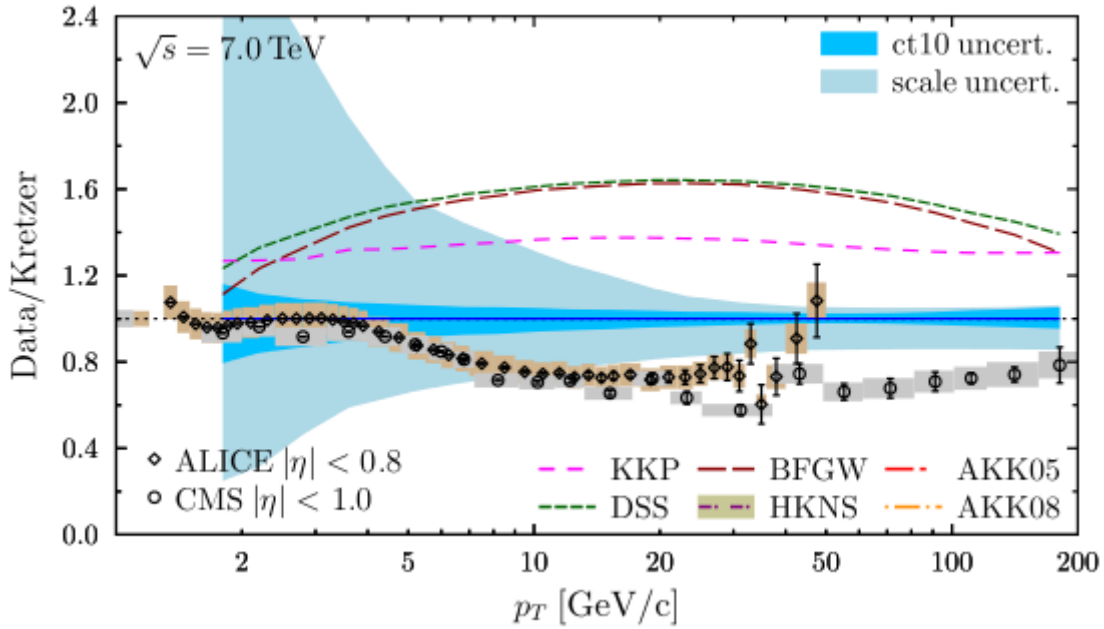

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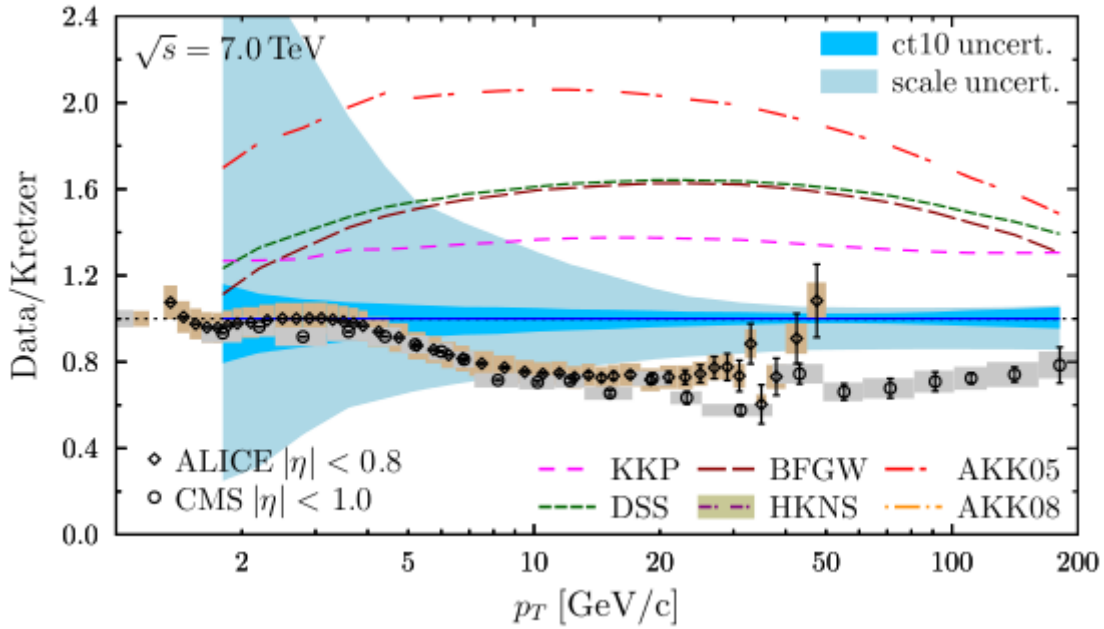

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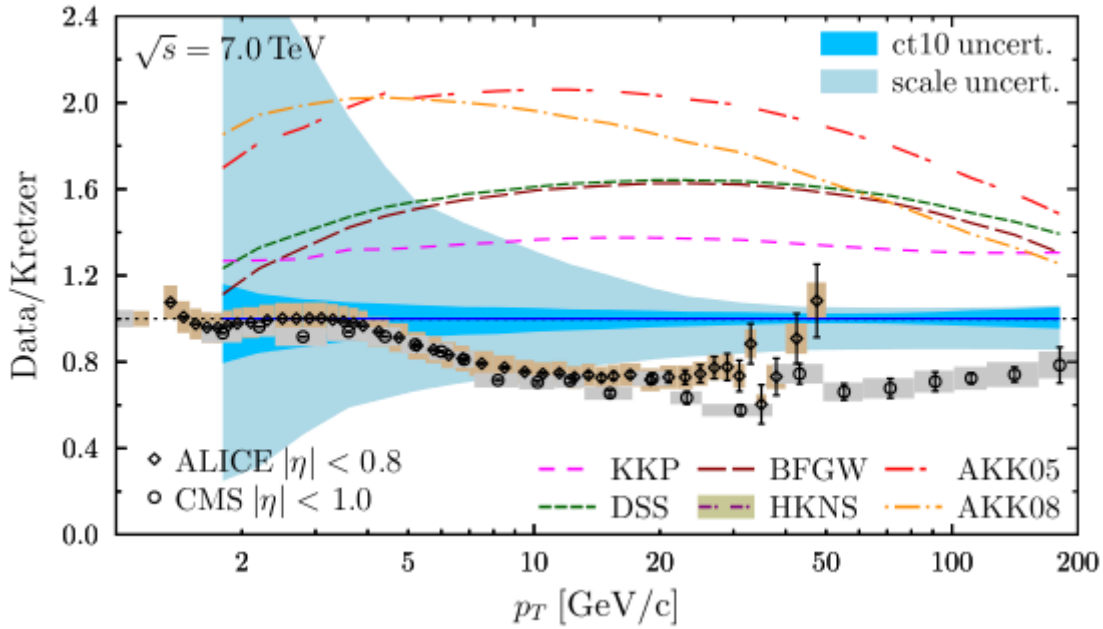

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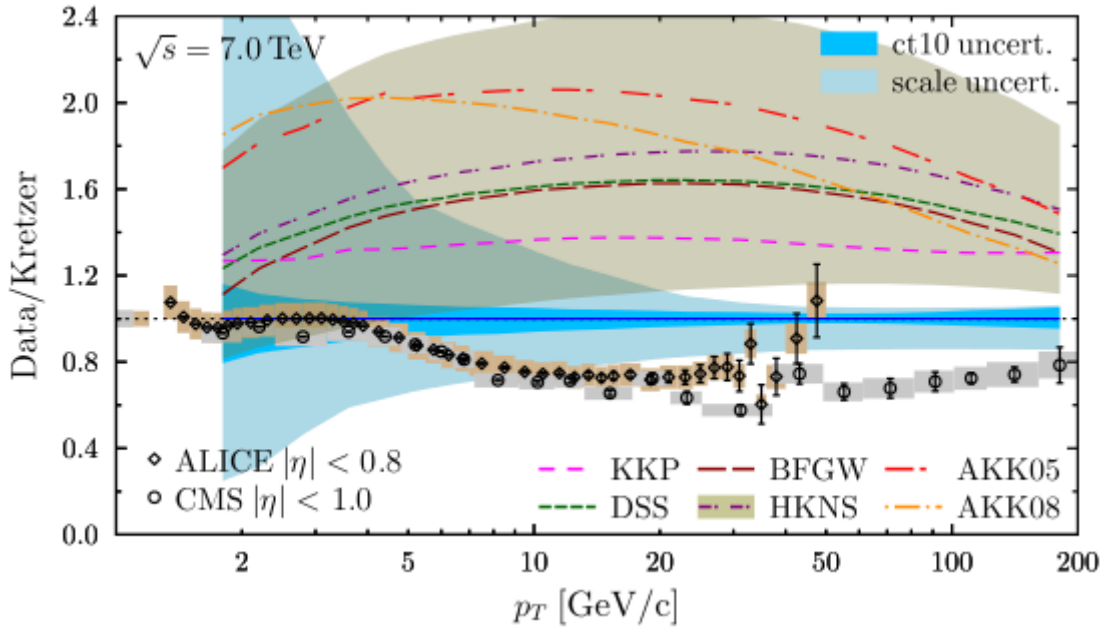

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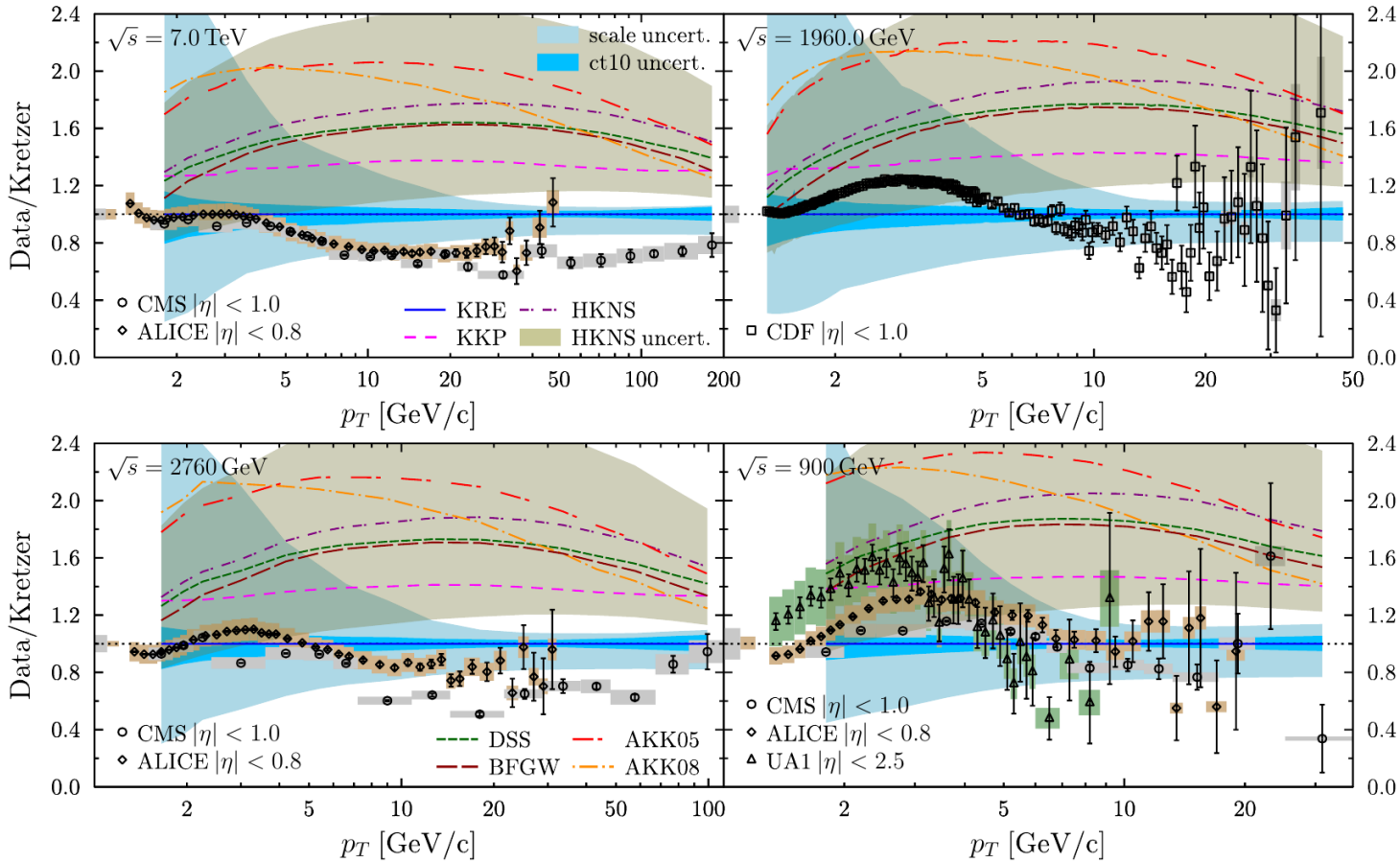
Comparison to the "world" data



- 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 belw 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

Figure from Phys.Rev. D84 (2011) 052011

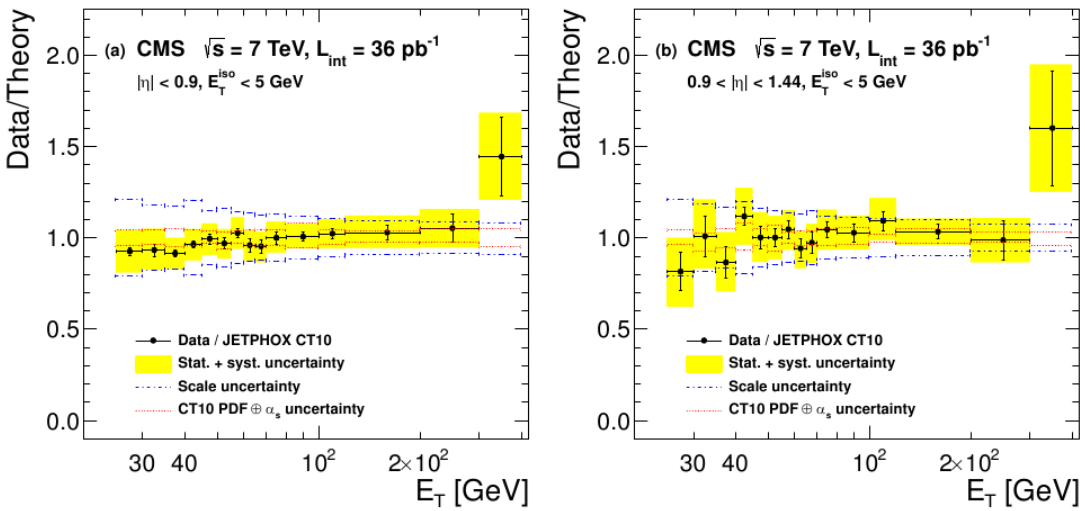
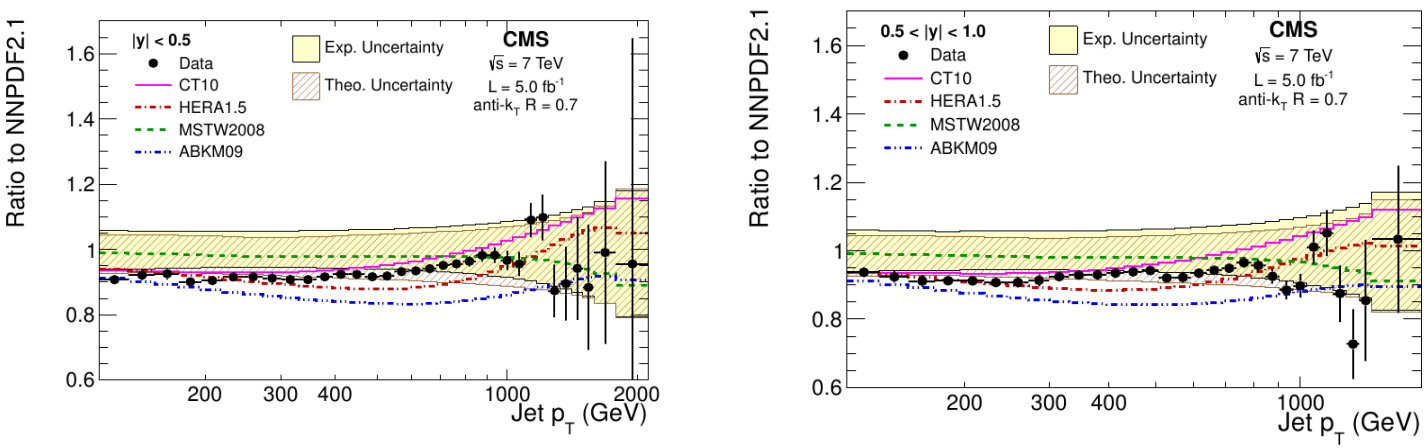


Figure from Phys.Rev. D87 (2013) 112002

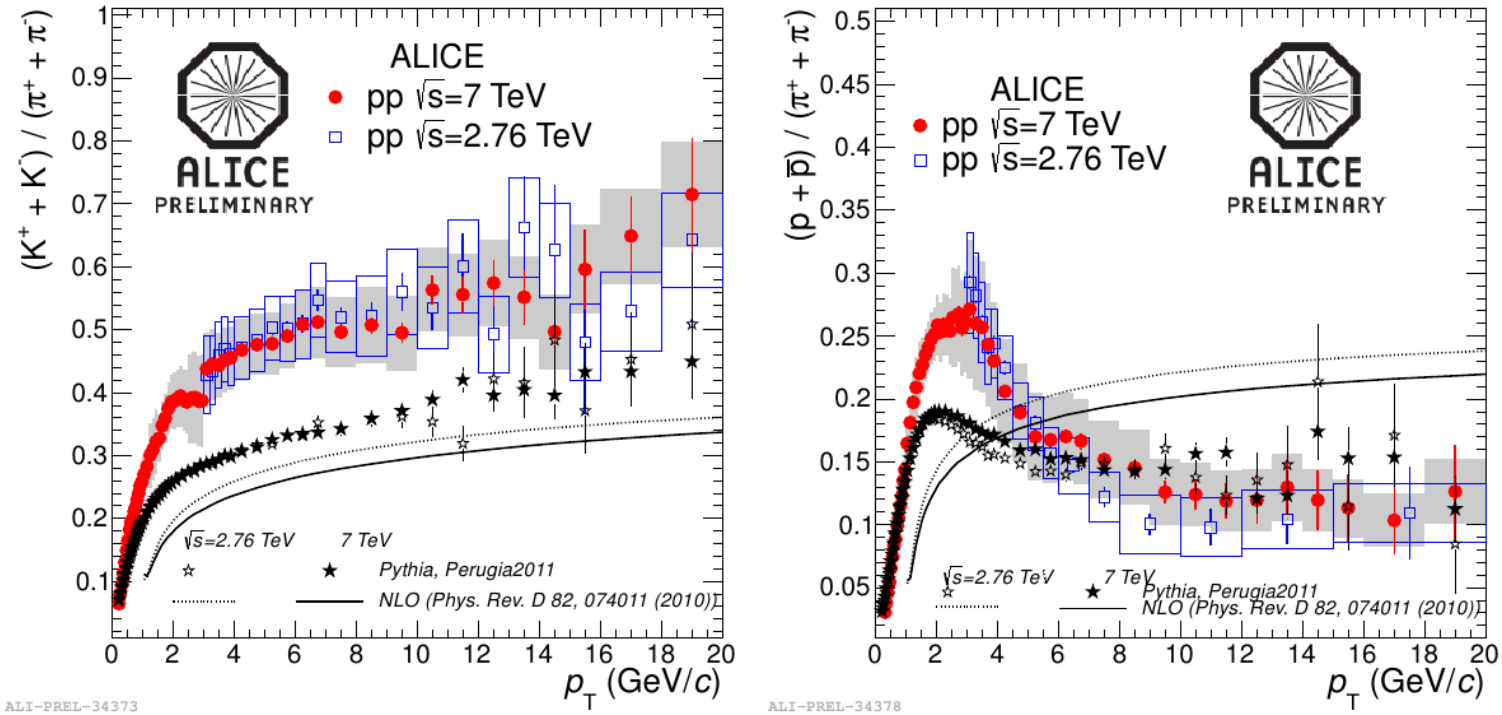


- Reinforces that the problem lies in the gluon FFs and not in the pQCD formalism

Also the "chemistry" goes wrong

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

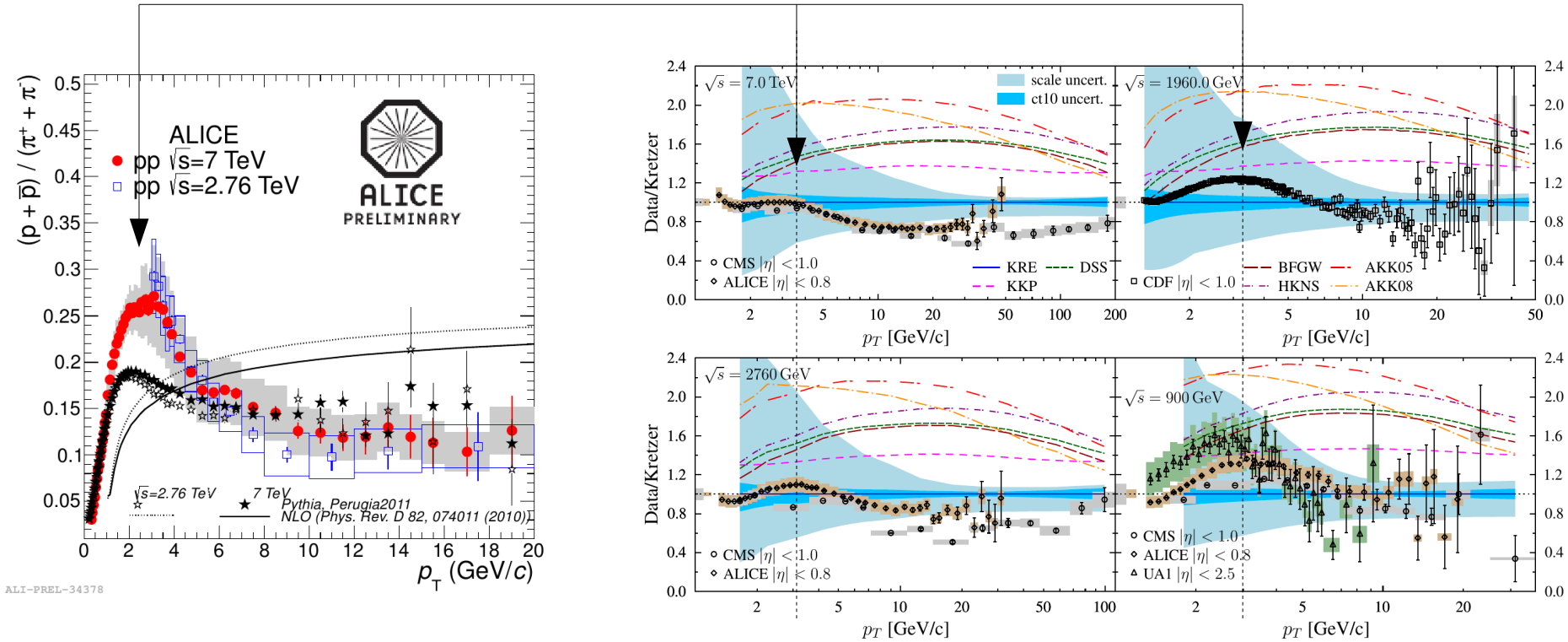
Figure from arXiv:1304.0899



- Notice the "bumb" at pT~3GeV for the low-pT protons (even at 7TeV)
- Enhanced non-perturbative contribution for baryons
- To shelter from all non-perturbative effects requires pT > 10GeV

Also the "chemistry" goes wrong

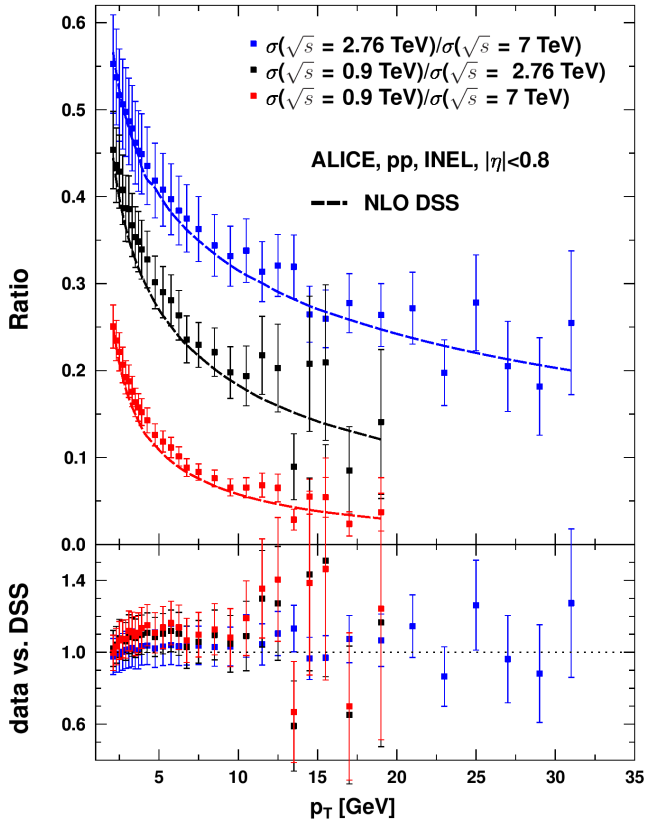
- Seen such a bumb before?

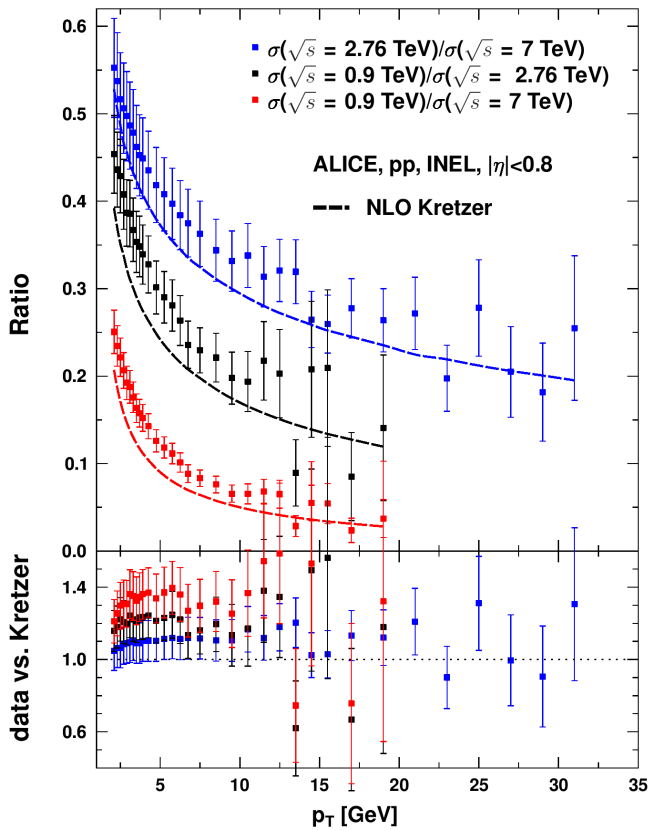


- Effect presumably even more pronounced for low-energy measurements - used to constrain DSS and AKK08...

Energy ratios

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



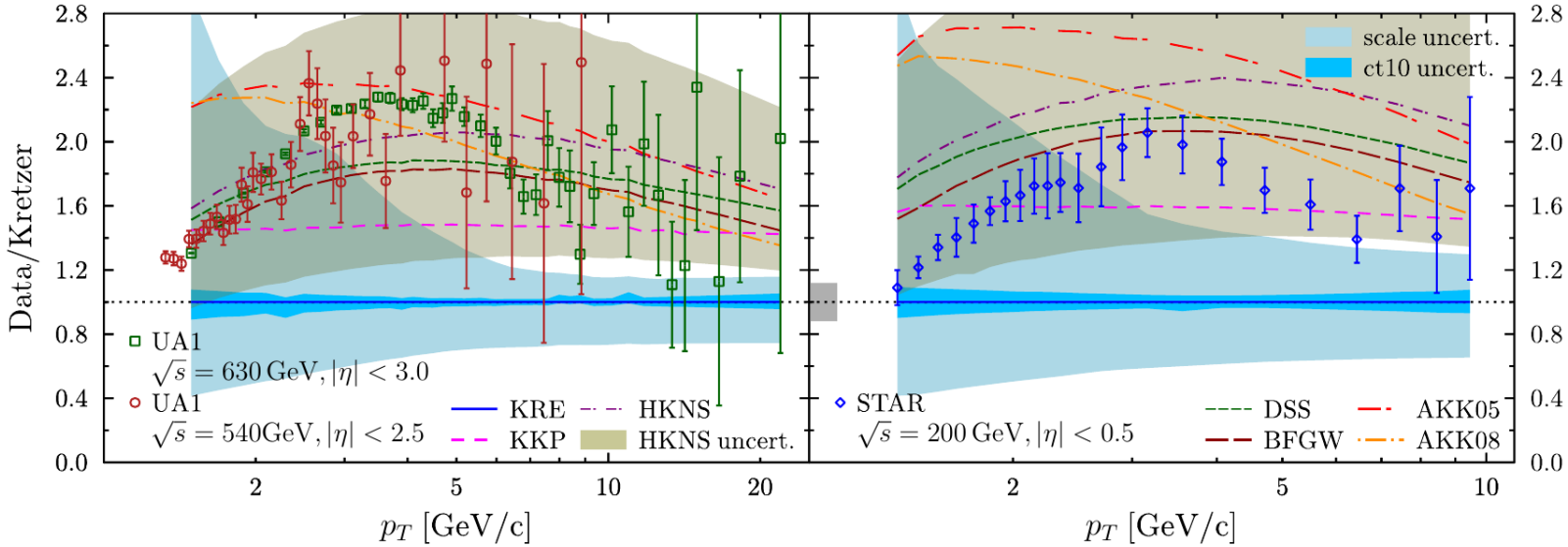


- The non-perturbative "bumb" near pT=3GeV partly cancels – somewhat misleading below pT~10GeV...
- More sensitive to the <u>shape</u> of the gluon FFs, not that much to the absolute magnitude.
- Robust against higher-order QCD corrections

Summary

- None of the current sets of NLO FFs can optimally describe the LHC and Tevatron charged particle measurements
- Below pT=10GeV the scale uncertainty is enormous and prohibits any strict conclusions.
- Below pT=10GeV there are also evidence for non-perurbative excess of baryons
- For FF fits only the region pT > 10GeV (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**