Confronting current NLO charged-hadron fragmentation functions with LHC data

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in collaboration with

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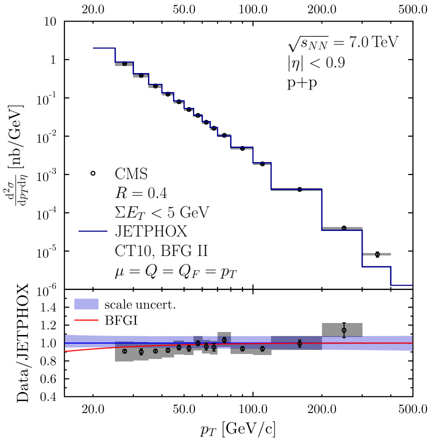
June 11

1. Introduction
    - Motivation
    - Collinear factorization
2. Fragmentation functions
    - Comparison between FF sets
    - z sensitivity
    - Sensitivity to gluon FFs
3. Comparison with the data
    - Unidentified charged hadrons
    - Identified charged hadrons
    - p+Pb collisions
4. Summary & Conclusions

Motivation

- Isolated photons at the LHC



[Data: Phys.Rev. D84:052011 (2011)]

- Very well described by NLO pQCD
- Same holds also for inclusive jets

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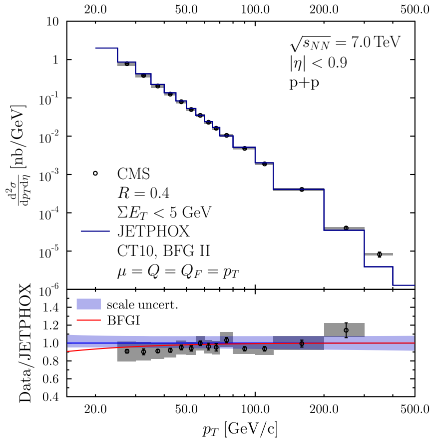
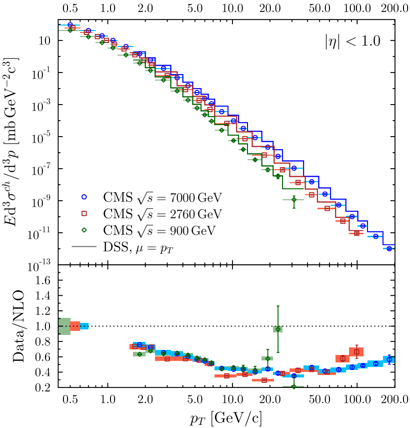


[Data: Phys.Rev. D84:052011 (2011)]

- Charged hadrons at LHC



[JHEP 1108 (2011) 086]

[Eur.Phys.J. C72 (2012)]

- Very well described by NLO pQCD
- Same holds also for inclusive jets

- NLO pQCD with recent FFs overshoots the data by factor of 2!

Goal: Quantify the observed inconsistency and try to identify the origin

Collinear factorization

Inclusive hadron production in p+p collisions

$$d\sigma^{p+p\to h+X} = \sum_{i,j,k,X'} f_i(x_1,Q^2) \otimes f_j(x_2,Q^2) \otimes d\hat{\sigma}^{ij\to k+X'} \otimes D_k^h(z,Q_F^2)$$

- $f_i(x,Q^2)$ are the parton distribution functions (PDFs)
- $d\hat{\sigma}^{ij\to k+X'}$ is the partonic piece calculated from pQCD
- $D_k^h(z,Q_F^2)$ is the parton-to-hadron fragmentation function (FF)

Global DGLAP analysis

1. Parametrize $D_i^h(z,Q^2)$ at the initial scale Q_0

$$D_i^h(z,Q_0^2) = N_i z^{a_i}(1-z^{b_i})F(z,c_i,\ldots)$$

2. Use DGLAP evolution equations to calculate $D_i^h(z,Q^2)$ at $Q > Q_0$

$$\frac{\partial D_i^h(z,Q^2)}{\partial \log Q^2} = \frac{\alpha_s}{2\pi}\sum_j P_{ij}\otimes D_j^h(z,Q^2)$$

3. Fit to wide range of data to obtain the parameters

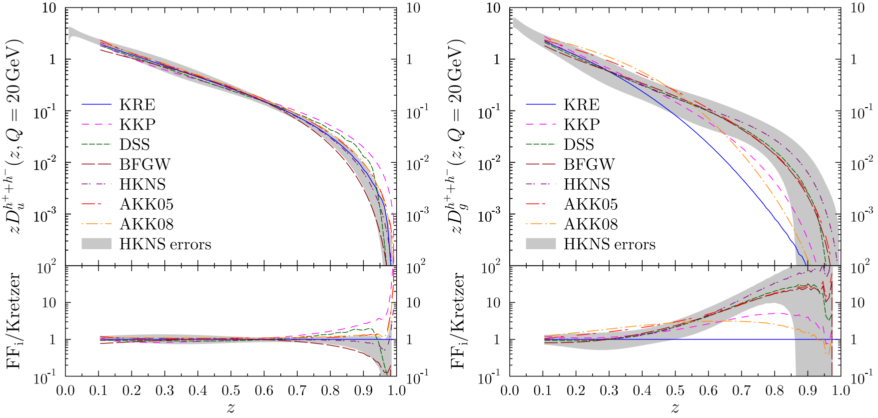
Comparison between FFs

- The PDFs and pQCD seem okay (photons, jets)
- How about fragmentation functions?
- Currently there are several analyses for the charged hadron FFs available:

FF set	Species	Fitted data	uncert.	$z_{\min}$	Q^2 [GeV^2]
Kretzer (kre)	$\pi^{\pm}$, $K^{\pm}$, h^{+}+h^{-}	$\mathrm{e^+e^-}$	no	0.01	0.8–10^6
kkp	π^{+}+π^{-}, K^{+}+K^{-}	$\mathrm{e^+e^-}$	no	0.1	1–10^4
	$p+\bar{p}$, h^{+}+h^{-}				
bfgw	$h^{\pm}$	$\mathrm{e^+e^-}$	yes	10^{-3}	2–$1.2\cdot 10^4$
akk05	$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$	$\mathrm{e^+e^-}$	no	0.1	2–$4\cdot 10^4$
hkns	$\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$	$\mathrm{e^+e^-}$	yes	0.01	1–10^8
akk08	$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$	$\mathrm{e^+e^-}$, p-p	no	0.05	2–$4\cdot 10^4$
dss	$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, $h^{\pm}$	$\mathrm{e^+e^-}$, p-p, e-p	yes	0.05	1–10^5

- Only AKK08 and DSS include data from p+p collisions (DSS include also SIDIS data)
- Only HKNS provides error estimates that quantify how the uncertainties in the fit propagate to observables

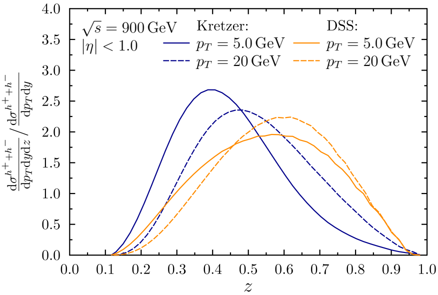
- Comparison of quark (left) and gluon (right) FFs as function of z

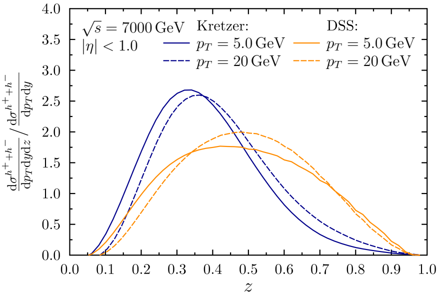


- Quark-to-hadron FFs well constrained by the $\mathrm{e^+e^-}$ data
- Large deviations in the gluon-to-hadron FFs, especially at $z > 0.5$

Inclusive hadron production: The z sensitivity

- The z distributions at different $\sqrt{s}$

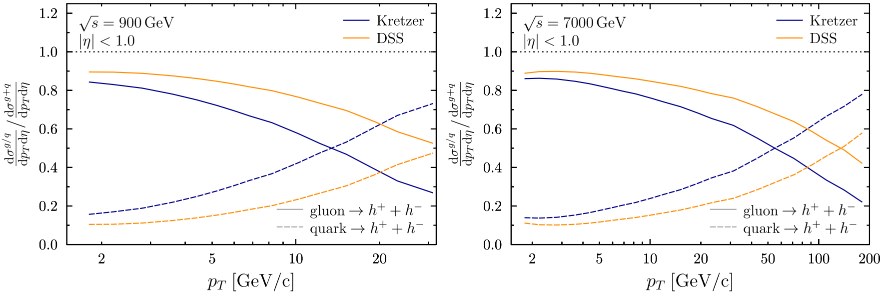




- Very small contribution from theoretically difficult $z < 0.1$
- The dominant z values depend on the chosen FF set
- Common features:
  - Larger $p_T \Rightarrow$ sensitivity to larger z
  - Larger $\sqrt{s} \Rightarrow$ sensitivity to smaller z

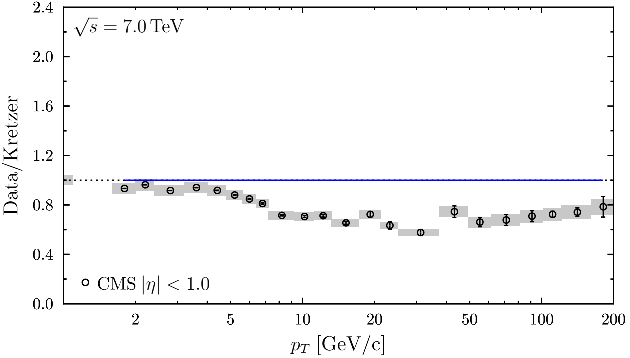
Sensitivity to quark and gluon FFs

- The relative contributions to cross sections from $D_g^{h^+ + h^-}(z, Q_F^2)$ (solid) and from $\sum_q D_q^{h^+ + h^-}(z, Q_F^2)$ (dashed)



- Gluons dominate up to the highest p_T
- Exact contributions depend on the FF set

Comparison between data and NLO calculation (using `INCNLO` with `CT10`)



- Discrepancy beyond experimental uncertainties

Charged hadron production at $\sqrt{s} = 7.0\,\mathrm{TeV}$

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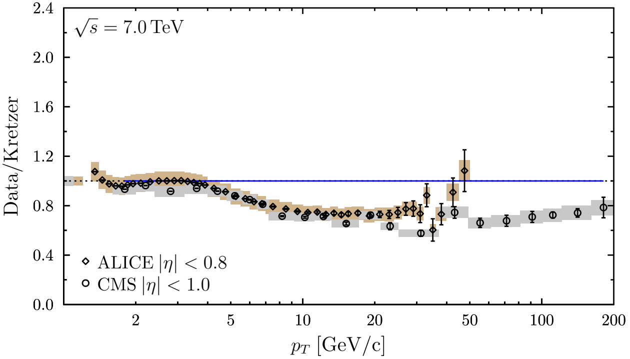

- Discrepancy beyond experimental uncertainties (CMS & ALICE agree)

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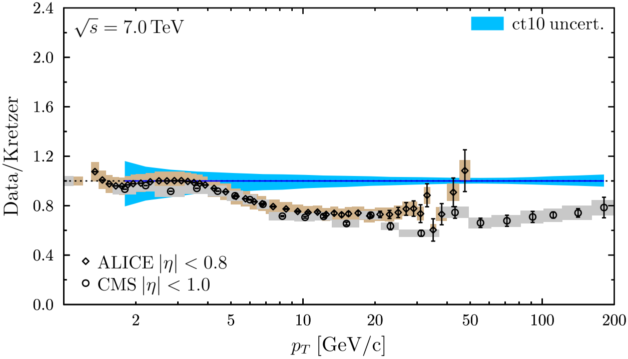

- Discrepancy beyond experimental uncertainties (CMS & ALICE agree)
- PDF uncertainties small

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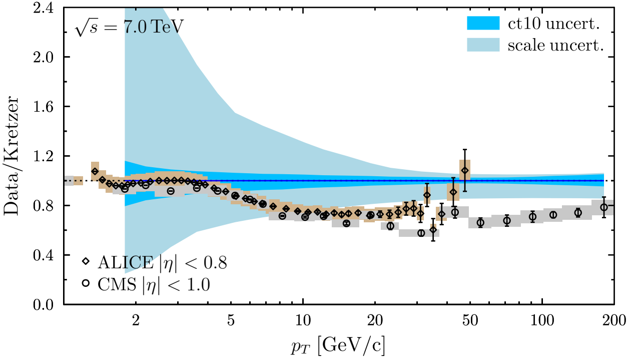

- Discrepancy beyond experimental uncertainties (CMS & ALICE agree)
- PDF uncertainties small, scale uncertainties large at $p_T \lesssim 10\,\mathrm{GeV}$

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

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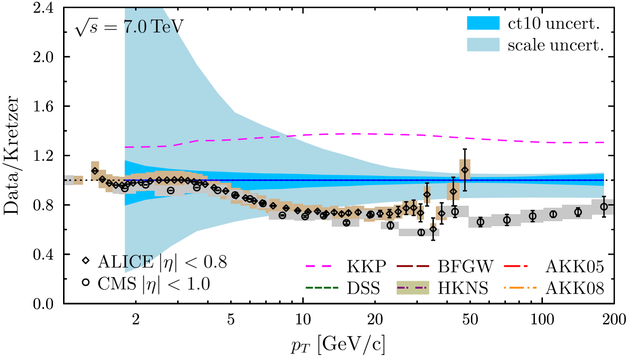

- Discrepancy beyond experimental uncertainties (CMS & ALICE agree)
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- Large deviations between different FF sets

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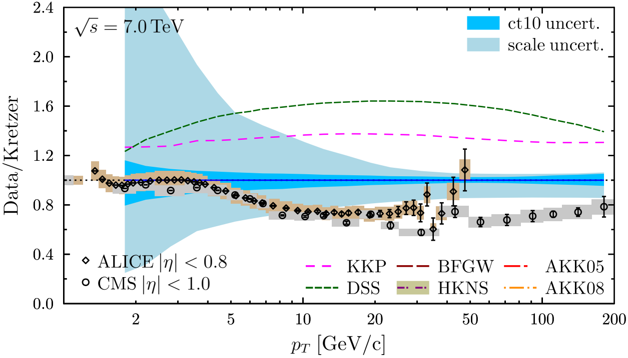

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  - Especially the FF fits with low $\sqrt{s}$ p+p data overshoot the data

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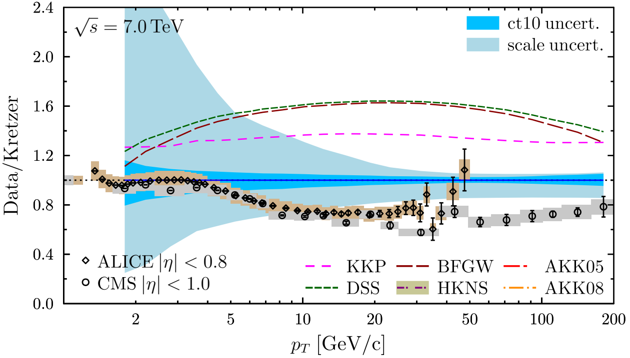

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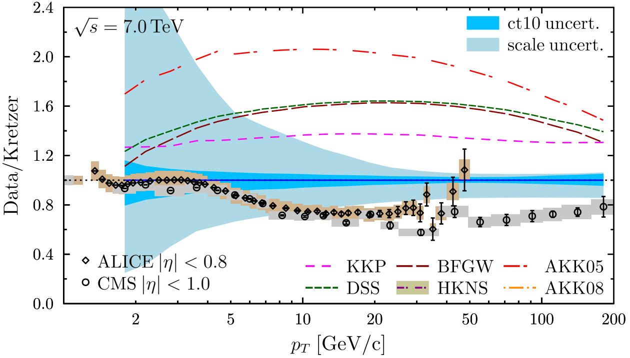

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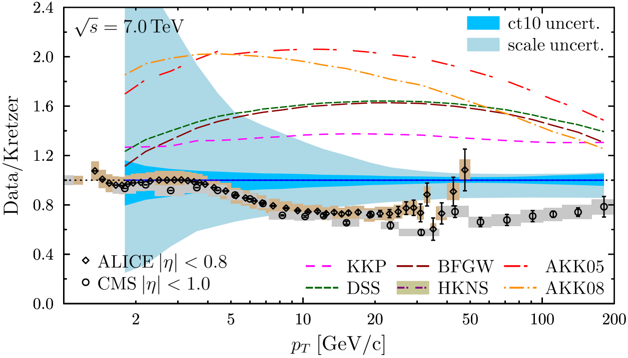

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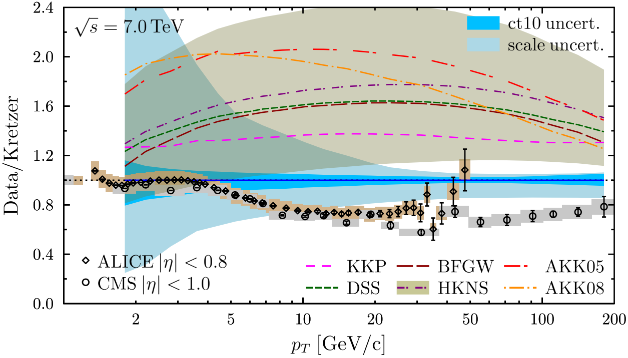
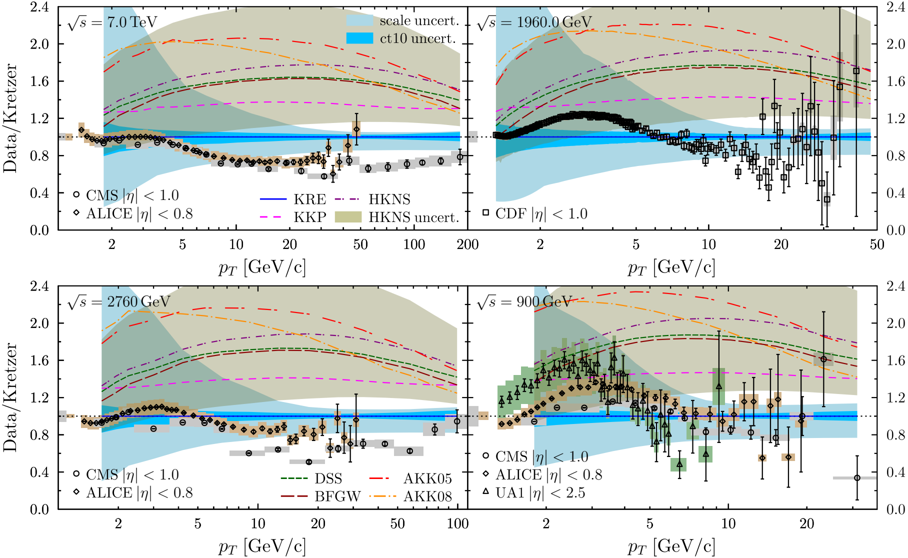


- Discrepancy beyond experimental uncertainties (CMS & ALICE agree)
- PDF uncertainties small, scale uncertainties large at $p_T \lesssim 10\,\mathrm{GeV}$
- Large deviations between different FF sets
  - Especially the FF fits with low $\sqrt{s}$ p+p data overshoot the data
- Even the large uncertainty band from `HKNS` not consistent with the data

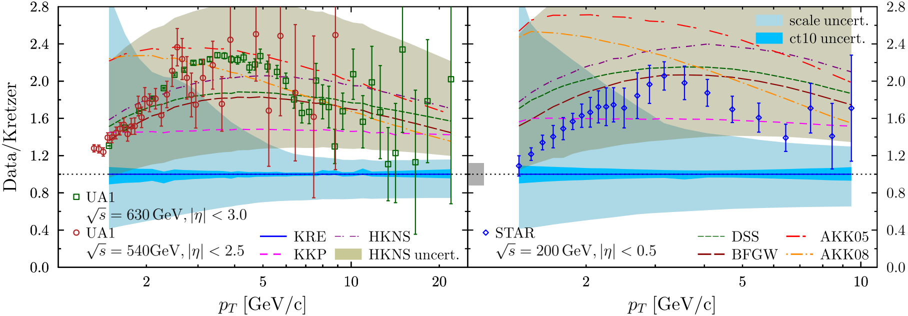
Charged hadron production at different $\sqrt{s}$



- Conclusions are the same for all $\sim$ TeV -energies at high p_T

Charged hadrons at lower $\sqrt{s}$

p+p data used in the present FF fits (DSS and AKK08):

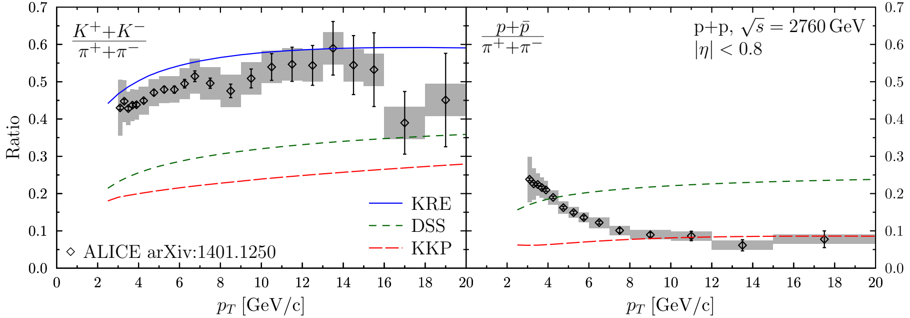


- Here Kretzer clearly below the data
- DSS gives a good describtion of the data
- Only few data points above $p_T > 10\,\mathrm{GeV/c}$ and those with large uncertainties
- Constraints from data mostly from the region $p_T < 5\,\mathrm{GeV/c}$ where the theoretical uncertainties (=scale variations) are very large

Identified charged hadrons

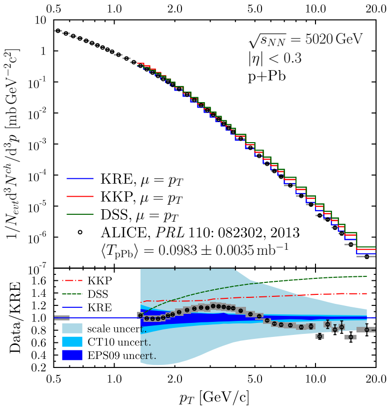
[To appear in my Thesis]

- Kaon-to-pion and proton-to-pion ratios at $\sqrt{s} = 2.76\,\mathrm{TeV}$



- Qualitative agreement in kaon-to-pion ratio (with `Kretzer` FFs even quantative)
- The measured proton-to-pion ratio not consistent with independent fragmentation at $p_T < 10\,\mathrm{GeV/c} \Rightarrow$ Non-perturbative effects?
- At $p_T > 10\,\mathrm{GeV/c}$ qualitative agreement with data

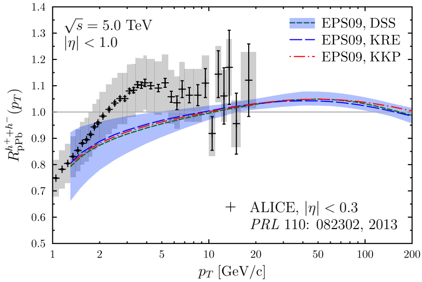
Charged particle yield in p+Pb:



- Similar behaviour as in p+p:
  - DSS overshoots the data
  - Kretzer consistent
  - Large scale uncertainty!

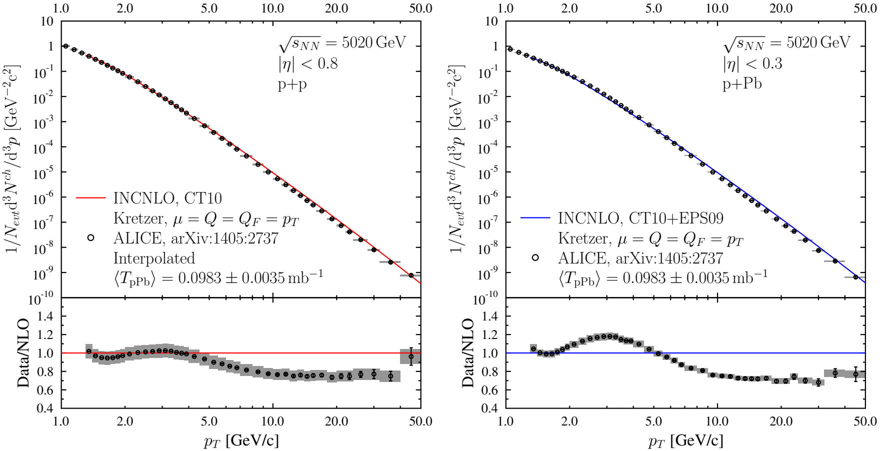
Nuclear modification factor:

$$R_{\rm pPb} = \frac{\mathrm{d}N_{\rm pPb}/\mathrm{d}p_T\mathrm{d}\eta}{\langle T_{\rm pPb}\rangle \mathrm{d}\sigma_{\rm pp}/\mathrm{d}p_T\mathrm{d}\eta}$$



- FF differences in $\mathrm{d}N$ cancel out in ratio $R_{\rm pPb}$
  $\Rightarrow$ $R_{\rm pPb}$ not sensitive to FFs

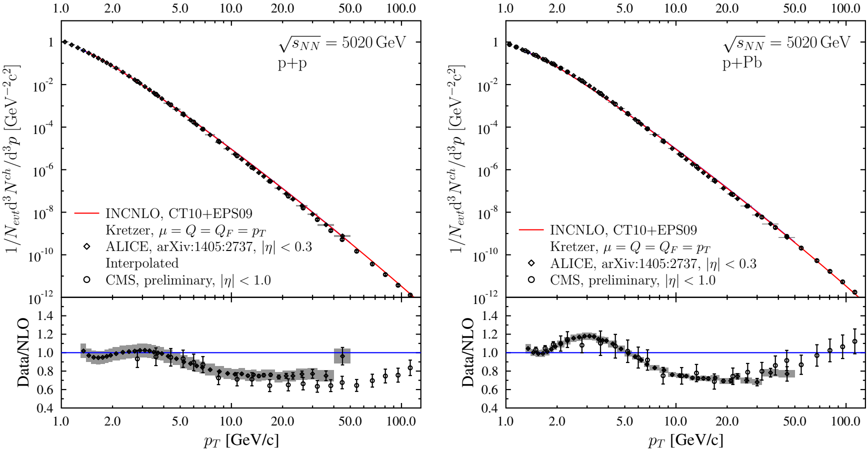
- New data for charged hadrons in p+Pb from ALICE



- At $p_T \gtrsim 10\,\mathrm{GeV/c}$ the data/NLO ratios are flat for both p+p and p+Pb
  $\Rightarrow$ The ALICE baseline seems to be in control up to $p_T = 40\,\mathrm{GeV/c}$

Charged hadrons in p+Pb

- New data for charged hadrons in p+Pb from CMS



- Disclaimer: CMS spectra read "by eye" (from H. Paukkkunen)!
- Rise in CMS data/NLO ratio at $p_T > 50\,\mathrm{GeV/c}$ in both p+p and p+Pb

Summary & Conclusions

Summary

- NLO pQCD calculations overshoot the charged hadron data in p+p collisions at the LHC energies
  - Especially the recent FFs with low-$\sqrt{s}$, low p_T p+p data included are clearly above the data
- Similar behaviour is observed in ALICE p+Pb data
  - However, the differences between different FFs cancel in ratios like R_{pPb}

Conclusions

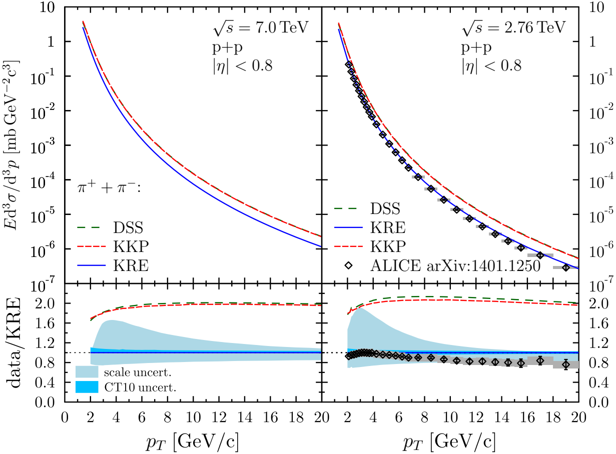
- This behavior is due to the too hard gluon-to-hadron FFs

  $\Rightarrow$ Calls for a complete re-analysis of the FFs using the high-$\sqrt{s}$ data at $p_T > 10\,\mathrm{GeV/c}$
- Supported also by ALICE data for $(\mathrm{p} + \bar{\mathrm{p}})/(\pi^+ + \pi^-)$

Backup

Charged pion cross section

Charged pions in p+p collisions



- Data consistent within the uncertainties when using `Kretzer` FFs
- With `DSS` and `KKP` calculation a factor two of above the ALICE data

Comparison with data

χ^2/N values for different FF sets with different scales

$$\chi^2 \equiv \sum_i \left(\frac{D_i - T_i}{\delta_i^{\rm tot}} \right)^2$$

Scales choices: $\mu \equiv (\mu_{\rm ren}/p_{\rm T}\,, \mu_{\rm fact}/p_{\rm T}\,, \mu_{\rm frag}/p_{\rm T}\,)$

μ		(1,1,1)			(1/2,1/2,1/2)			(2,2,2)	
$p_{\rm T}^{\rm min}$ [GeV/c]	1.3	5.0	10.0	1.3	5.0	10.0	1.3	5.0	10.0
N	368	169	103	368	169	103	368	169	103
kre	5.512	8.536	11.20	32.94	30.03	23.06	12.77	4.034	2.935
kkp	28.90	51.63	56.81	151.6	143.3	108.2	9.216	14.62	19.25
dss	63.36	112.3	114.2	248.5	319.5	245.6	16.68	33.50	40.96
hkns	85.80	149.5	151.1	303.9	396.8	312.6	24.28	48.59	57.49
akk05	169.9	236.7	218.4	594.6	619.0	428.9	51.39	84.58	89.88
akk08	150.1	177.7	154.4	566.6	486.5	300.3	40.82	59.13	60.70
bfgw	57.15	106.3	108.7	203.2	294.1	230.5	15.71	31.65	38.70

Same conclusions as "by eye":

- Best agreement with the Kretzer FFs with softest gluons
- Agreement is improved with $p_T^{\rm min} = 10\,{\rm GeV/c}$

Correlated systemic uncertainties separately:

$$\chi^2_{\rm corr} = \sum_{\rm k\in data\,sets} \chi^2_k, \qquad \chi^2_k = \sum_i \left(\frac{f_k D_i - T_i}{\delta_i^{\rm uncor}}\right)^2 + \left(\frac{1-f_k}{\delta_i^{\rm norm}}\right)^2$$

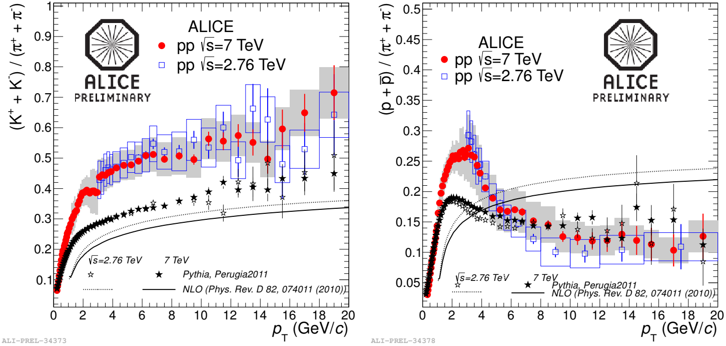
f_k determined from χ^2 minimization

μ	(1,1,1)			(1/2,1/2,1/2)			(2,2,2)		
$p_{\rm T}^{\rm min}$ [GeV/c]	1.3	5.0	10.0	1.3	5.0	10.0	1.3	5.0	10.0
N	368	169	103	368	169	103	368	169	103
kre	5.460	5.063	5.158	11.73	9.675	10.25	5.020	3.402	2.031
kkp	14.54	17.97	22.34	36.06	37.69	43.16	8.893	7.648	8.061
dss	31.74	35.11	44.75	113.4	82.19	98.73	13.86	14.00	16.59
hkns	41.30	45.73	58.50	130.9	101.1	123.9	17.58	18.67	22.72
akk05	44.89	66.01	86.08	208.4	159.0	175.9	21.00	27.13	35.42
akk08	29.72	49.73	63.47	160.3	137.1	130.9	15.79	19.42	25.51
bfgw	35.61	33.91	43.09	118.0	77.23	93.59	13.86	13.61	16.18

- χ^2/N values become somewhat lower but yield $|1-f_k|$ beyond experimental uncertainties $\delta_i^{\rm norm}$
- Conclusions the same as with the other method

Pion-to-proton ratio

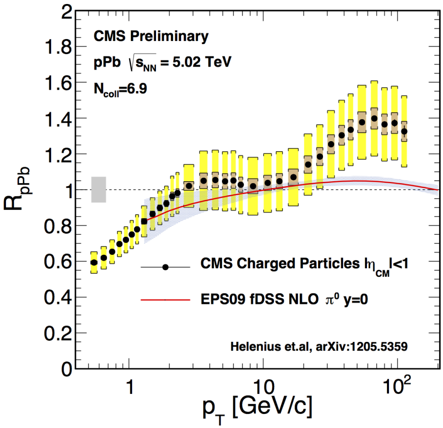
ALICE measurement for Kaon-to-pion and proton-to-pion ratios:

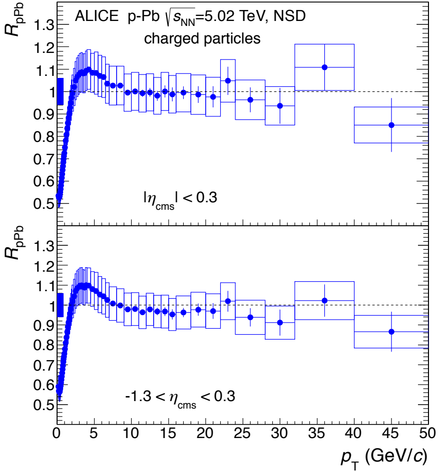


[arXiv:1304.0899 [hep-ex]]

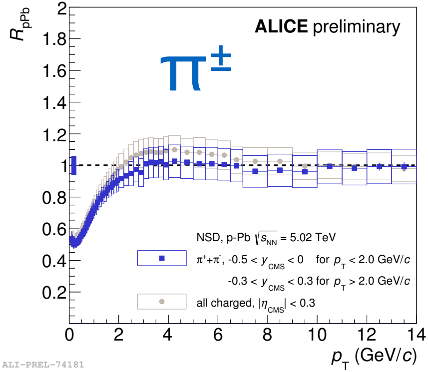
- $(\mathrm{p}+\bar{\mathrm{p}})/(\pi^+\pi^-)$ not consistent with independent fragmentation at $p_T \lesssim 8\,\mathrm{GeV/c}$
  $\Rightarrow$ Shouldn't be used for global fits

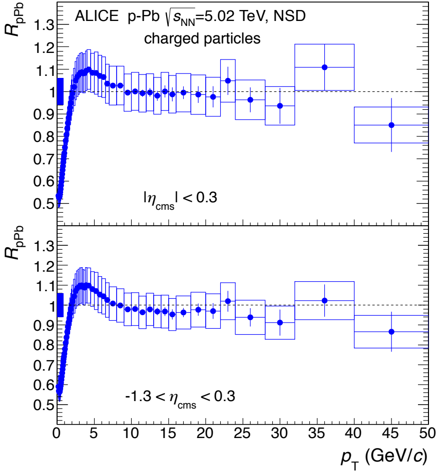
New results for charged hadrons in p+Pb



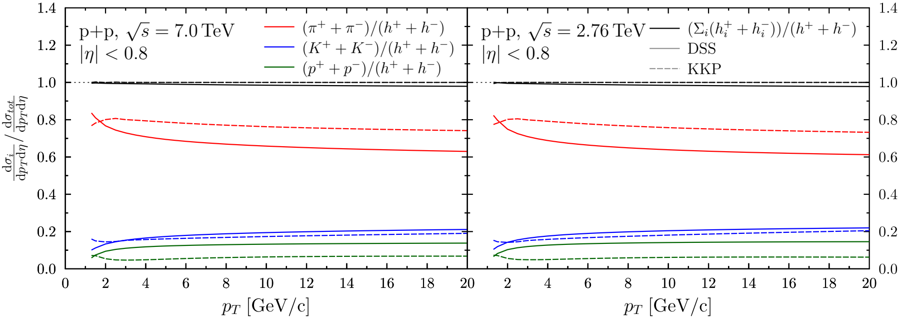


Charged pion R_{pPb}



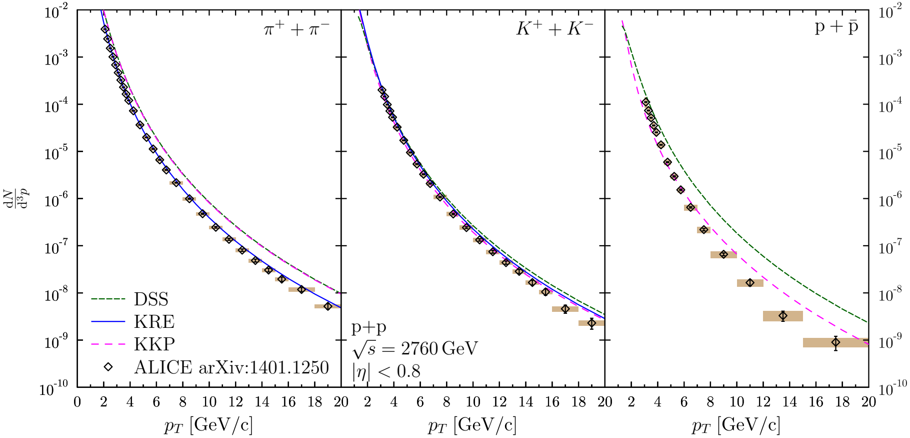


- Unidentified charged hadrons sum of pions, kaons and (anti)protons



- Roughly (according to the DSS and KKP analyses):
  - $10\,\%$ protons
  - $20\,\%$ kaons
  - $70\,\%$ pions
- In DSS analysis the fraction of residual hadrons $\lesssim 2\,\%$

Charged pions, kaons and (anti)protons in p+p collisions



- Pion described accurately with `Kretzer` FFs
- Kaons described well with all considered FFs
- Neither the shape nor the normalization consistent with the data