Nuclear PDF constraints from p+Pb collisions at the LHC

DIS2015

Ilkka Helenius

Lund University
Department of Astronomy
and Theoretical Physics

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Outline

- Introduction
  - Nuclear parton distribution functions
- New data from p+Pb at LHC
  - Hadron production
  - Dijet η distributions
  - $\mathrm{W}^{\pm}$ production
- Direct photon production
  - Production mechanisms
  - Sensitivity to small-x
  - Isolation cut
  - $R^{\gamma}_{\mathrm{pPb}}$ at forward rapidities
- Summary & Conclusions

Mostly based on

JHEP 1409 (2014) 138 [arXiv:1406.1689 [hep-ph]]
with Kari J. Eskola and Hannu Paukkunen from U. of Jyväskylä

Parton distribution functions

Collinear factorization

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

- $f_i(x,Q^2)$ are the parton distribution functions (PDFs) of proton
- $\mathrm{d}\hat{\sigma}^{ij\rightarrow k+X'}$ is the partonic cross section calculated from pQCD

Parton distribution functions

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Global DGLAP analysis

1. Parametrize $f_i(x,Q^2)$ at chosen initial scale Q_0

$$f_i(x,Q_0^2) = N_i x^{a_i}(1-x)^{b_i}F(x,c_i,\ldots)$$

2. Use DGLAP evolution equations to calculate $f_i(x,Q^2)$ at $Q>Q_0$

$$\frac{\partial f_i(x,Q^2)}{\partial \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\sum_j P_{ij}\otimes f_j(x,Q^2)$$

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

Nuclear PDFs

The PDFs are modified in nuclear collisions:

$$f_i^A(x,Q^2) = R_i^A(x,Q^2)f_i(x,Q^2)$$

- $R_i^A(x,Q^2)$ from global DGLAP-based analysis
- Goal: Test factorization and provide accurate pQCD baseline for A+A

Recent NLO analyses

- HKN07
- DSSZ
- nCTEQ
- EPS09

[JHEP 04 (2009) 065]

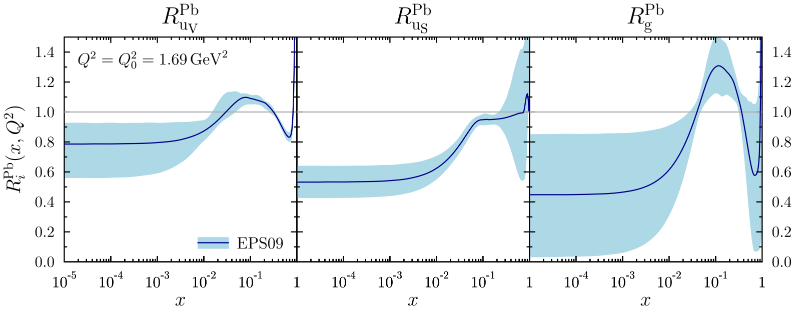
Data used in the fits

- Deep inelastic scattering (DIS)
- Drell-Yan dilepton production (DY)
- Pion production in d+Au collisions at RHIC

$\Rightarrow$ Kinematic reach limited to $x > 0.001$

$\Rightarrow$ Gluons not very well constrained

nPDF uncertainties (from EPS09NLO)



- Quarks well constrained, especially at $x > 0.01$
- Large uncertainty for small-x gluons!

More constraints from p+Pb collisions at the LHC?

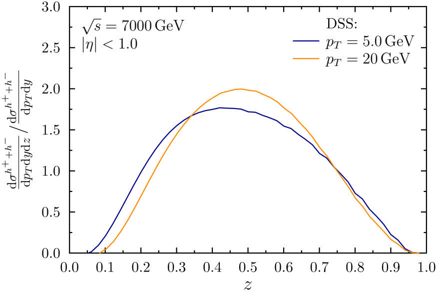
- Inclusive hadrons (ALICE, CMS, ATLAS)
- Dijet production (CMS)
- $W^{\pm}$ production (CMS)
- Direct photons

Inclusive hadron production

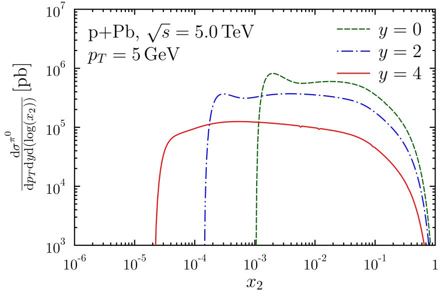
Convolution of parton spectra and fragmentation function (FF)

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

$\Rightarrow$ No direct connection between hadron p_T, η and parton x_2

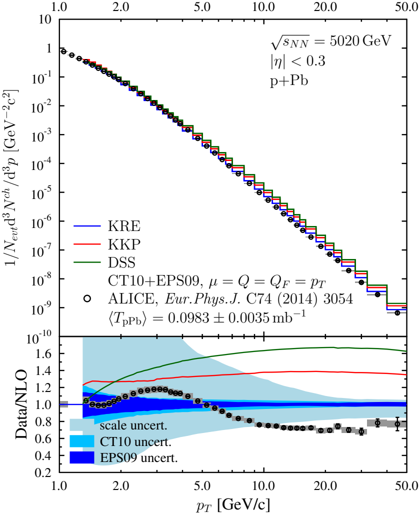


- Contribution from broad range of z $(= p/q)$



- Sizable contribution from $x_2 > 10^{-2}$ even at $\eta = 4$

Charged hadron spectra in p+Pb:

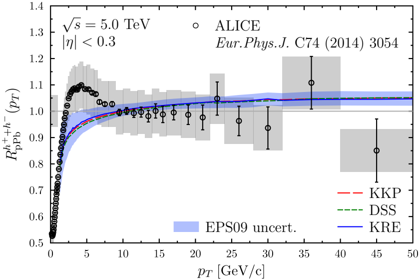


- NLO calculations overshoot the data at $p_T > 10\,\mathrm{GeV/c}$

p+p: [Nucl.Phys. B883 (2014) 615-628]

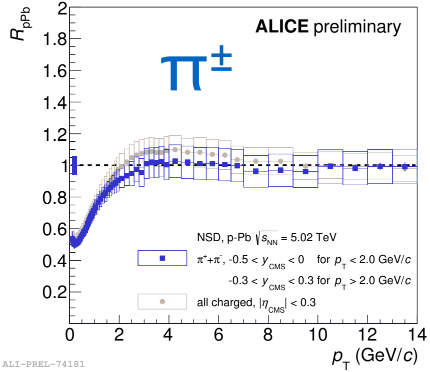
Nuclear modification ratio

$$R^h_{\mathrm{pPb}}(p_T, \eta) = \frac{1}{208} \frac{\mathrm{d}^2\sigma^h_{\mathrm{pPb}}}{\mathrm{d}p_T \mathrm{d}\eta} \Big/ \frac{\mathrm{d}^2\sigma^h_{\mathrm{pp}}}{\mathrm{d}p_T \mathrm{d}\eta}$$



- FF differences cancel in ratio $\Rightarrow R_{\mathrm{pPb}}$ not sensitive to FFs
- Enhacement in the data at $p_T \sim 3\,\mathrm{GeV/c}$

ALICE R_{pPb} for charged pions:



[Quark Matter 2014]

- No enhancement for mesons

$\Rightarrow$ Some non-perturbative effects in baryon production

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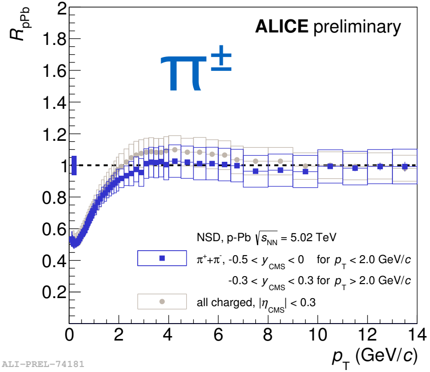

[Quark Matter 2014]

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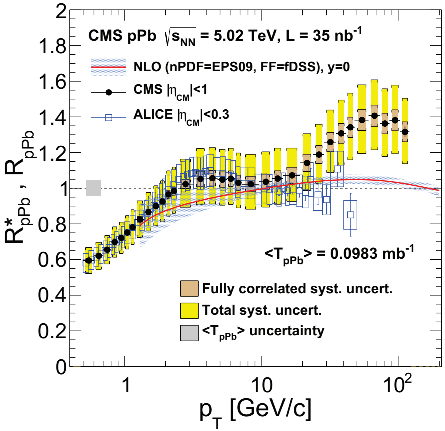
CMS result for charged hadron R_{pPb}



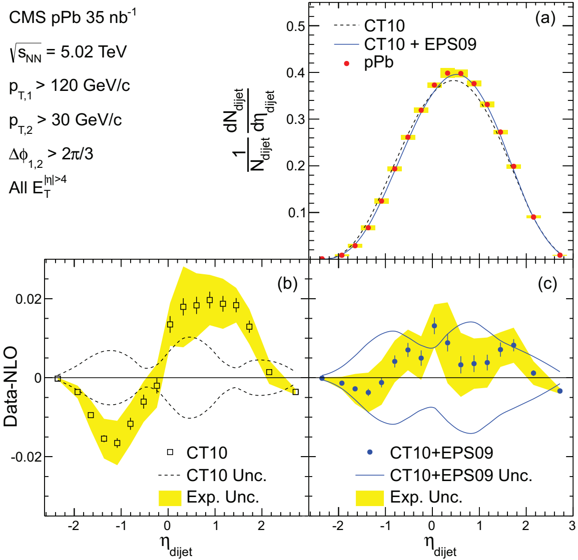
[arXiv:1502.05387]

- Enhacement at $p_T > 20\,\mathrm{GeV}/c$
- Different p+p baseline between ALICE and CMS?

Dijet pseudorapidity

$$\eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2}$$

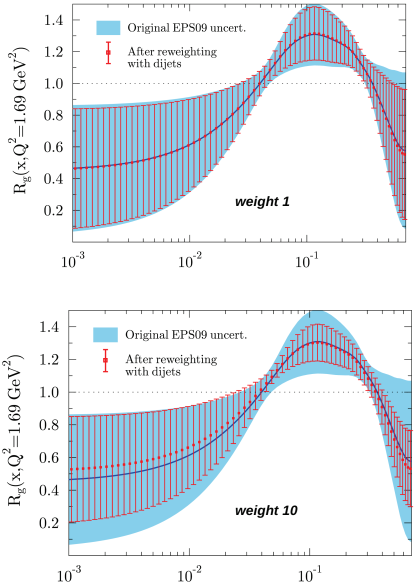
- at $\eta_{\text{dijet}} < 0$ data sensitive to antishadowing region
- at $\eta_{\text{dijet}} > 0$ data sensitive to EMC effect
- Good description with EPS09



[*Eur.Phys.J.* C74 (2014) 2951]
[*JHEP* 1310 (2013) 213]

Impact of dijet data

- The impact of new data to nPDF fit can be studied by Hessian reweighting method
- Dijet data would improve gluon nPDFs at $x > 0.05$ (if given enough weight)
- Supports gluon antishadowing and EMC suppression



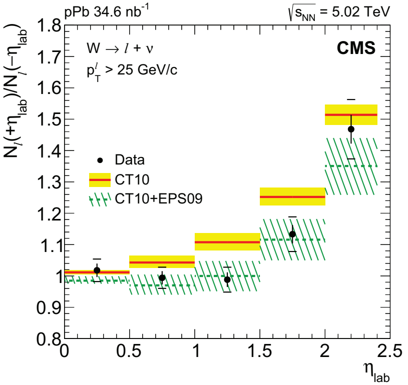
[*Nucl.Phys.* A931 (2014) 331-336]

$\mathrm{W}^{\pm}$ production

Forward-backward asymmetry

$$N(+\eta_{\mathrm{lab}})/N(-\eta_{\mathrm{lab}})$$

- Sum over W^{+} and W^{-}
- $\eta_{\mathrm{lab}} = \eta + 0.465$
  where η pseudorapidity in nucleon-nucleon CMS frame
- Dominating processes:
  $\mathrm{u}\bar{\mathrm{d}} \rightarrow \mathrm{W}^{+}$ and $\mathrm{d}\bar{\mathrm{u}} \rightarrow \mathrm{W}^{-}$
- Sensitive to
  - $\eta_{\mathrm{lab}} > 0$: $0.002 < x < 0.02$
  - $\eta_{\mathrm{lab}} < 0$: $0.02 < x < 0.2$
- Good agreement with EPS09



[arXiv:1503.05825]
[*JHEP* 03 (2011) 071]

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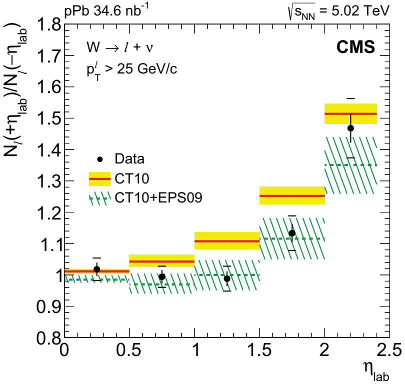


[arXiv:1503.05825]
[*JHEP* 03 (2011) 071]

The gluon nPDFs at small-x remain badly constrained!

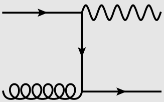
Direct γ production

Two components in direct photon cross section

$$\mathrm{d}\sigma_{\mathrm{pPb}}^{\gamma+X} = \mathrm{d}\sigma_{\mathrm{pPb}}^{\mathrm{prompt}\,\gamma+X} + \mathrm{d}\sigma_{\mathrm{pPb}}^{\mathrm{fragmentation}\,\gamma+X}$$

Prompt photon production

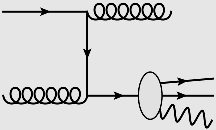
e.g. Compton scattering



- Calculated from pQCD
- Sensitive to gluon PDFs

Fragmentation photon production

parton fragments into photon, e.g.

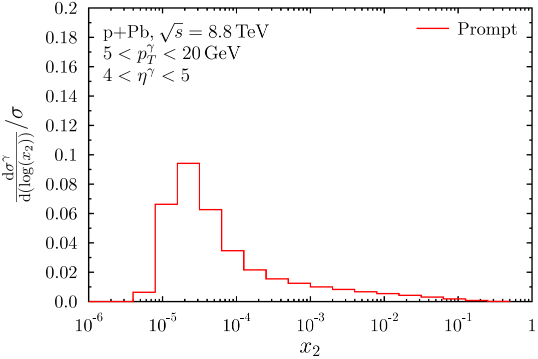


- Calculated by convoluting with parton-to-photon FFs

- At NLO the decomposition ambiguous (scale dependent)
- More sensitivity to small-x physics than hadrons?

Sensitivity to small-x

- The contribution from different x_2 values to NLO cross section Calculated with JETPHOX [JHEP 0205 (2002) 028] ($Q = p_T$)



- Prompt component very sensitive to small values of x_2

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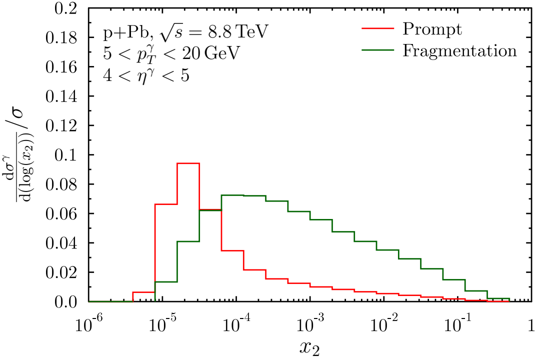

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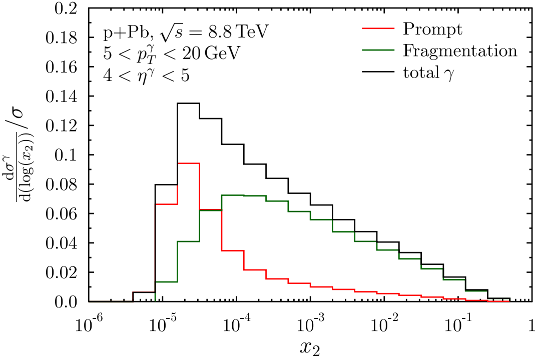

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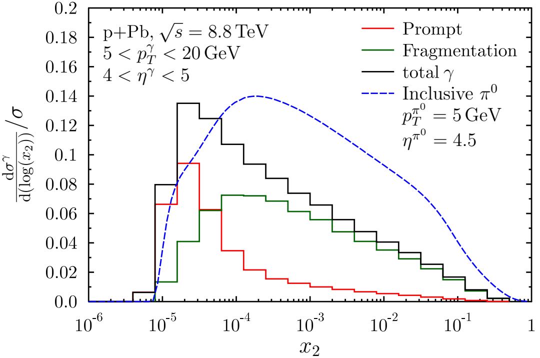
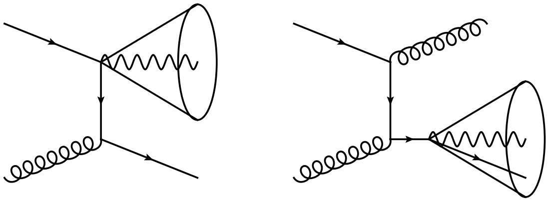


- Prompt component very sensitive to small values of x_2
- Fragmentation component have contribution also from larger x_2's
- Total cross section not sensitive only to small values of x_2
- The relative sensitity still larger than for hadrons

Isolated photons

Isolation cut

- Reject photons that have $\Sigma E_T > E_T^{max}$, where
$$\Sigma E_T = \sum_i E_T^i \theta(R - R_i), \text{ and } R_i = \sqrt{(\eta_\gamma - \eta_i)^2 + (\phi_\gamma - \phi_i)^2}$$
Sum runs over all hadrons i.



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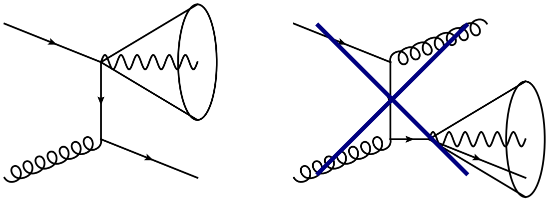
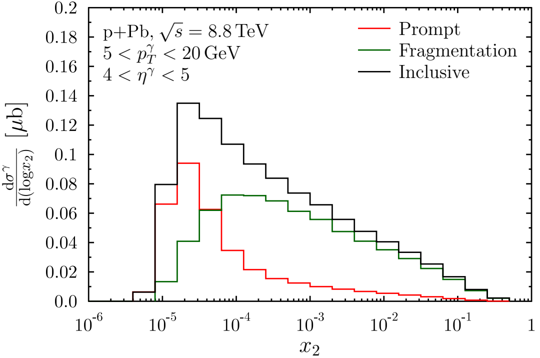


- Isolation cut suppresses the fragmentation component
- Increase the sensitivity to smaller values of x_2

Isolation and x_2 sensitivity

- The contribution from different x_2 values to NLO cross section



- Only the sum of two components physical observable

Isolation and x_2 sensitivity

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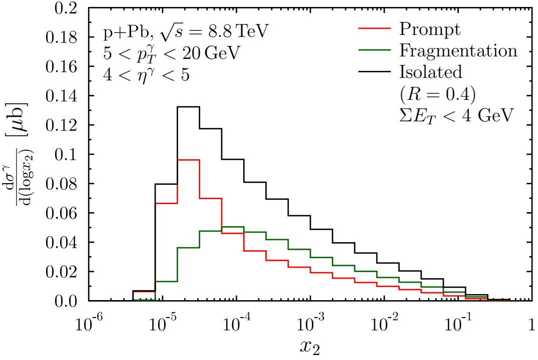

- Only the sum of two components physical observable
- Isolation cut with $\Sigma E_T < 4\,\mathrm{GeV}$ suppresses fragmentation component
  $\Rightarrow$ Decrease contribution from larger values of x_2

Isolation and x_2 sensitivity

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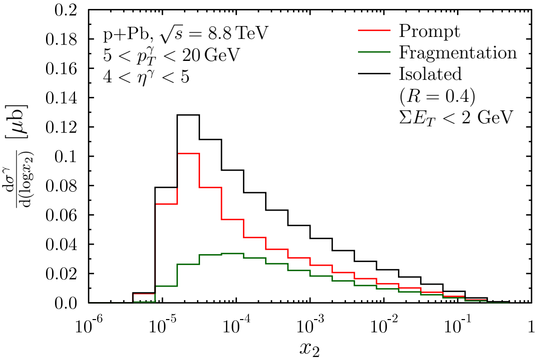
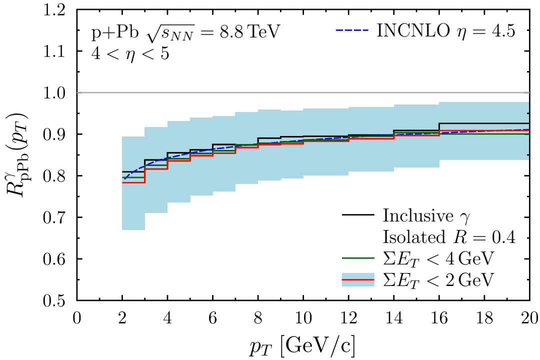


- Only the sum of two components physical observable
- Isolation cut with $\Sigma E_T < 4\,\mathrm{GeV}$ suppresses fragmentation component
  $\Rightarrow$ Decrease contribution from larger values of x_2
- Tighter isolation cut ($\Sigma E_T < 2\,\mathrm{GeV}$) further suppresses the fragmentation component but small effect to total distribution

Nuclear modification factor

- $R^{\gamma}_{\rm pPb}$ for inclusive and isolated direct photons using
  - CTEQ6.6M proton PDFs with EPS09 nuclear modifications
  - BFGII parton-to-photon FFs
  - Scale choice $\mu = Q = Q_F = p_T$



- Suppression in $R^{\gamma}_{\rm pPb}$ due to shadowing in the nPDFs
- Sligthly stronger suppression with isolation at small p_T
- Uncertainty due to nPDFs of the order 10%

Yield asymmetry Y^{asym}_{pPb}

Accuracy of R_{pPb} measurement

- If no p+p run at the given energy interpolation required
- If no luminosity measurent in p+Pb glauber modeling required
  $\Rightarrow$ Can cause uncertainties $\gtrsim 10\%$

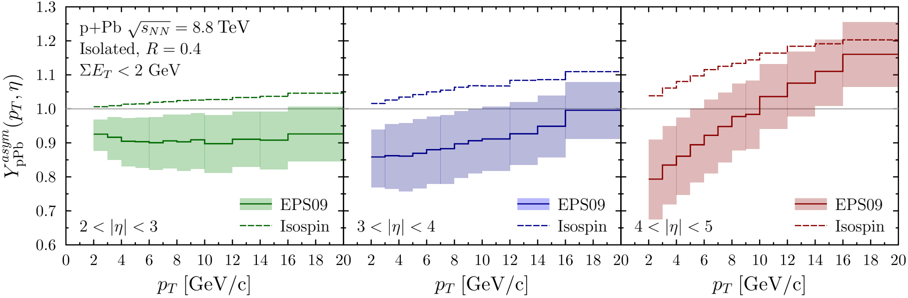
Yield asymmetry between forward and backward rapidities

$$Y^{asym}_{\mathrm{pPb}}(p_T,\eta) \equiv \left.\frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}}{\mathrm{d}p_T\mathrm{d}\eta}\right|_{\eta\in[\eta_1,\eta_2]} \Big/ \left.\frac{\mathrm{d}^2\sigma_{\mathrm{pPb}}}{\mathrm{d}p_T\mathrm{d}\eta}\right|_{\eta\in[-\eta_2,-\eta_1]}$$

- No need for the p+p baseline
- Many experimental uncertainties cancel in the ratio
- Nuclear modifications at backward rapidities well constrained by DIS and DY data

Prediction for $Y^{asym}_{\mathrm{pPb}}(p_T, \eta)$

- NLO prediction with `CTEQ6.6M+EPS09` PDFs and `BFGII` FFs



Yield asymmetry

- Smaller charge density in nuclei $\Rightarrow$ Isospin effect
- nPDFs uncertainties mainly from small-x
  $\Rightarrow$ Provides further constraints to nPDFs
- Serves also as a test of factorization

Summary & Conclusions

Summary

- New data from p+Pb collisions at the LHC
  - Inclusive hadron production (not an ideal observable)
  - Dijet data constraints gluon nPDFs at $x \gtrsim 0.01$
  - $\mathrm{W}^{\pm}$ data provides constraints for quarks at $x > 0.002$

$\Rightarrow$ Gluons remain weakly constrained at $x < 0.01$

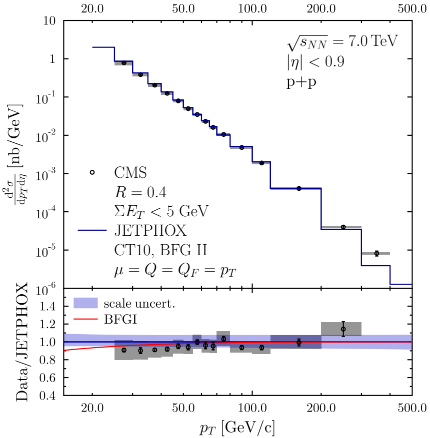
Conclusions

- Direct photons more sensitive to small-x than inclusive hadrons
- Isolation cut increases the sensitivity to smaller values of x
- If no accurate p+p baseline available, the yield asymmetry can be used

Backup

Data comparison

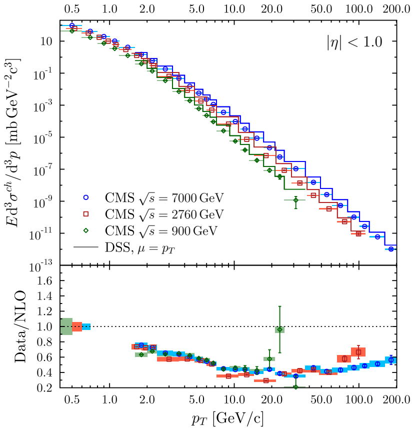
- Isolated photons at the LHC



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

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

- Charged hadrons at LHC

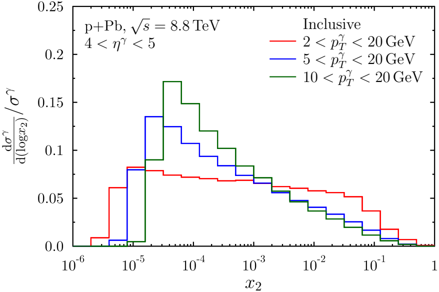


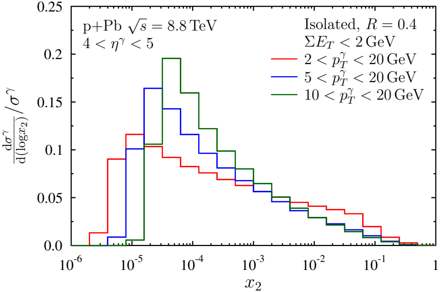
[JHEP 1108 (2011) 086]

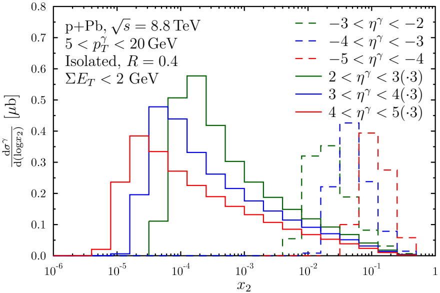
[Eur.Phys.J. C72 (2012)]

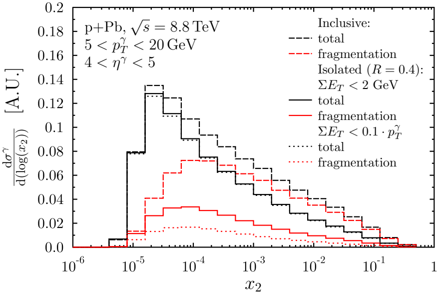
- NLO pQCD with recent FFs overshoots the data by factor of 2!

p_T systematics

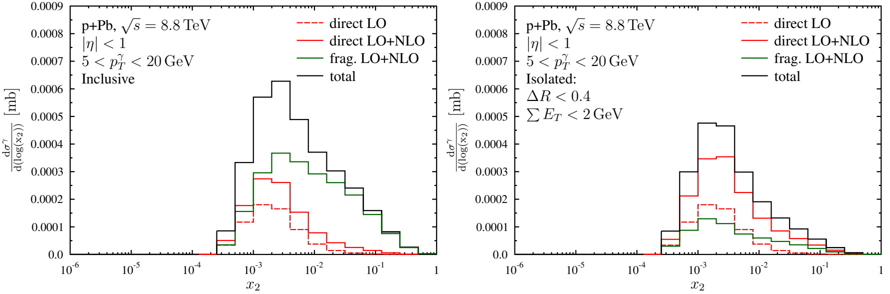








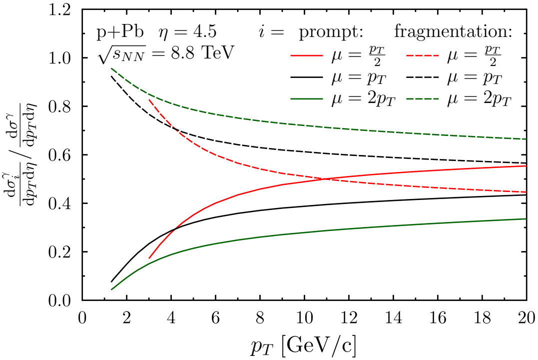
Isolated photons at midrapidity



- More sensitivity to small-x than hadrons
- Contribution also from quark initiated processes

Prompt vs. Fragmentation

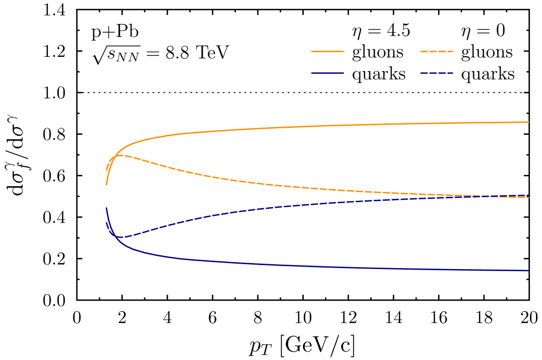
- The relative contributions to direct photon cross section with
  - three scale choices ($\mu = Q = Q_F$)
  - CTEQ6.6M PDFs [Phys. Rev. D78 (2008) 013004] with EPS09
  - BFGII FFs [Eur. Phys. J. C2 (1998) 529]



- In NLO the division depends on the scale choice
  $\Rightarrow$ Meaninful observable only when both processes are included!
- At small p_T the fragmentation component dominant

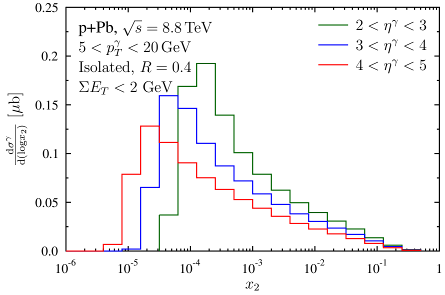
Sensitivity to gluon PDFs

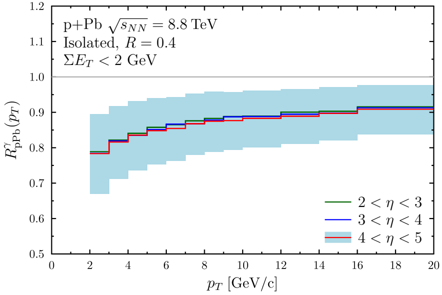
Relative contributions from quarks and gluons in the Pb-nucleus at mid- and forward rapidities



- At $\eta = 0$ similar contribution from gluons and quarks
- At $\eta = 4.5$ about 80% from gluons

Rapidity systematics of isolated photons

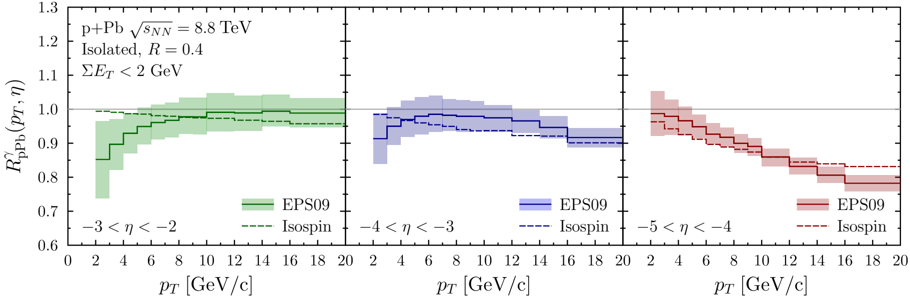




- Larger rapidities $\sim$ smaller x_2
- Weak x dependence in the EPS09 at $x < 0.01$
  $\Rightarrow R_{\mathrm{pPb}}$ independent of rapidity at $\eta > 2$ for isolated photons
- Uncertainties similar in each rapidity bin
- Accurate measurements required!
  - FoCal in ALICE?
  - LHCb capabilities?

Isolated photons at backward rapidities

- At $\eta < -2$ cross section mainly sensitive to quarks at $x_2 > 0.01$
  $\Rightarrow$ nPDFs well constrained by DIS and DY data:

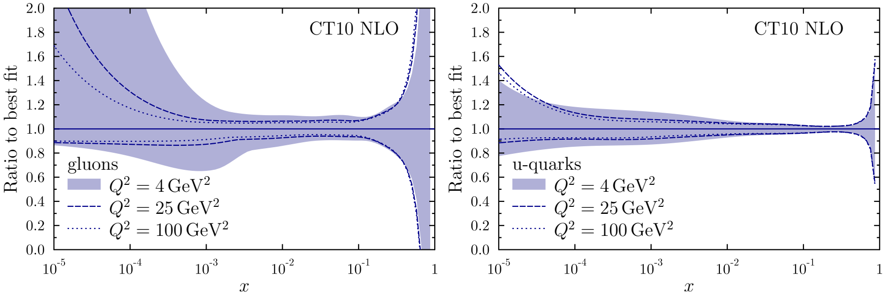


Isospin effect

- Nuclei consist of protons and neutrons
  $\Rightarrow$ Smaller charge density than in protons
- Photons couple to electric charge
  $\Rightarrow$ Suppression in the large x region where valence quarks dominate

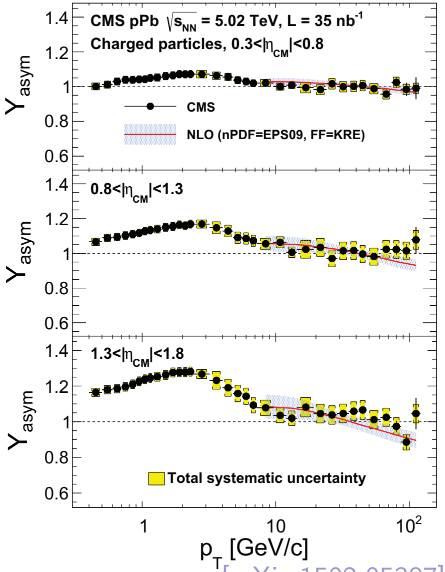
Uncertainties in proton PDFs

- Proton PDFs from `CT10` analysis [Phys.Rev. D82 (2010) 074024]



- Large uncertainties also for gluon PDFs in proton at $x < 10^{-4}$
  $\Rightarrow$ Further constraints would be welcome to here also

Charged hadron yield asymmetry

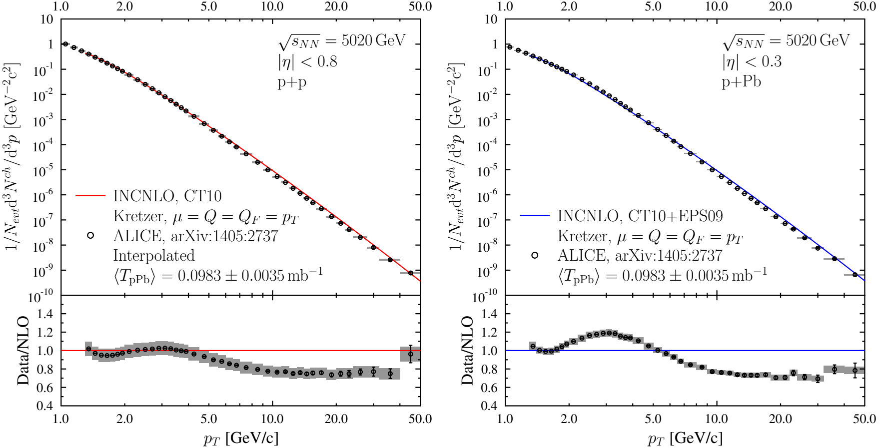


[arXiv:1502.05387]

- No unexpected effects at $p_T > 10\,\mathrm{GeV/c}$
- Enhacement in R_{pPb} independent of rapidity
- Baseline/normalization effect?

Charged hadrons in p+Pb

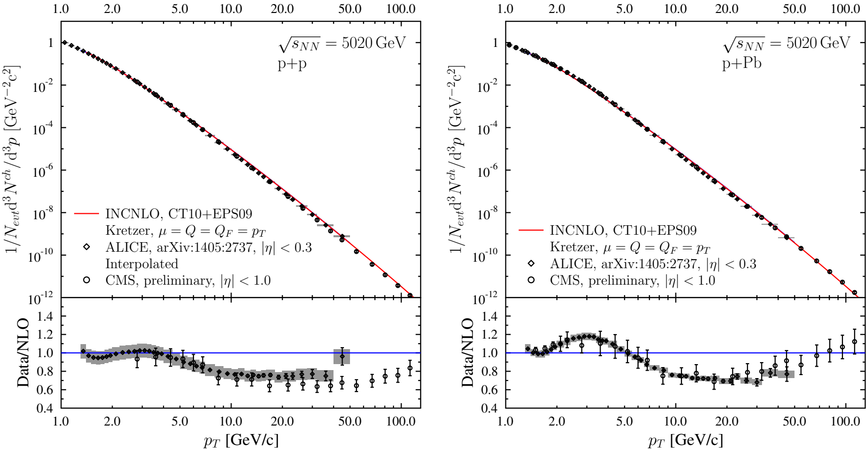
- New data for charged hadrons in p+Pb from ALICE



- 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 $p_T = 40\,\mathrm{GeV/c}$

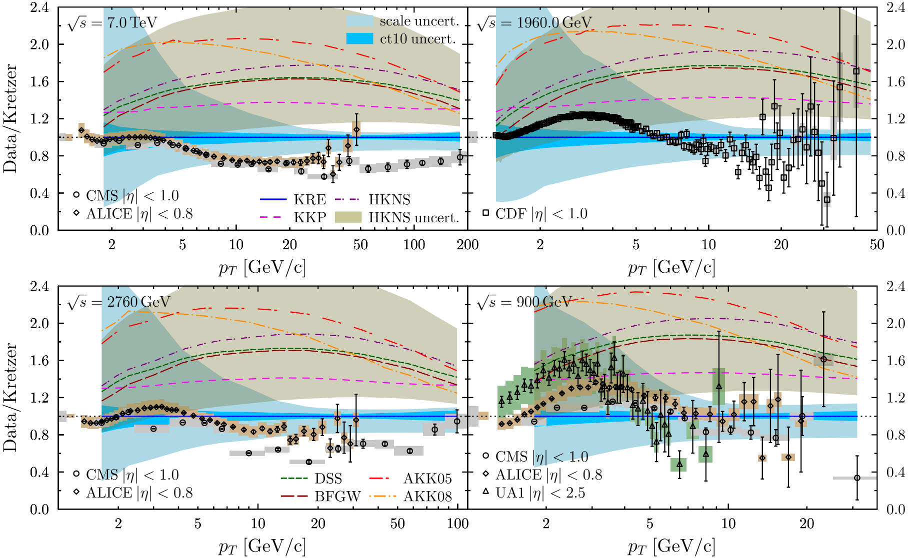
Charged hadrons in p+Pb

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



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

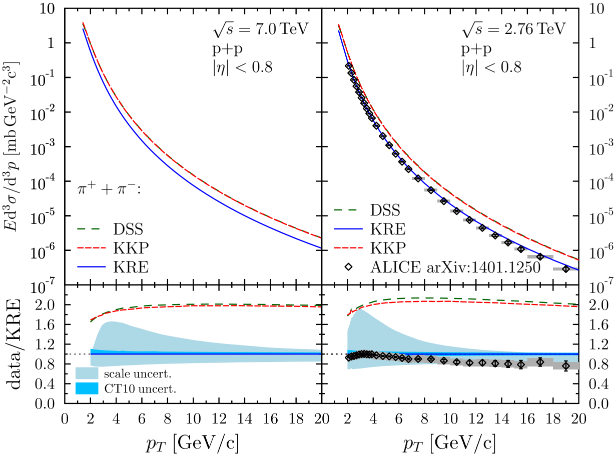
Charged hadron production in p+p at different $\sqrt{s}$



[Nucl.Phys. B883 (2014) 615-628]

Charged pion cross section

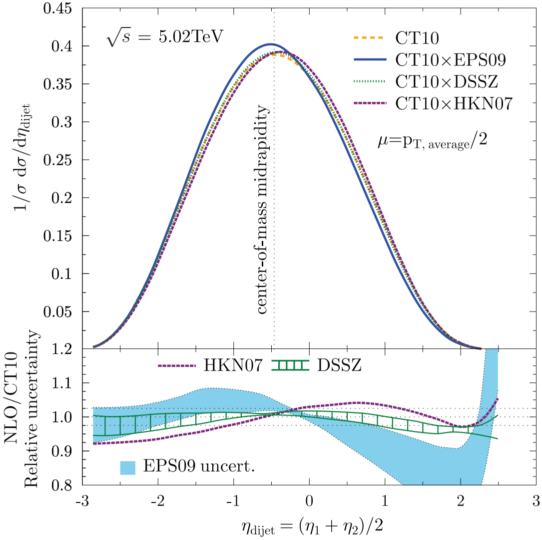
Charged pions in p+p collisions



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

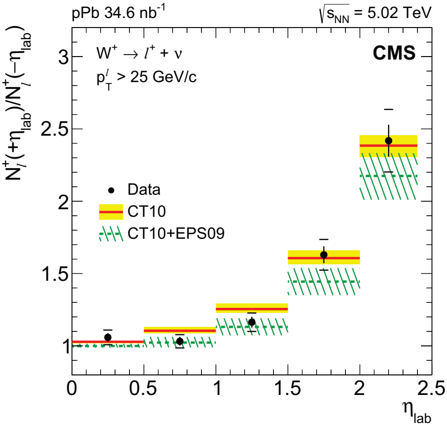
Dijets in p+Pb

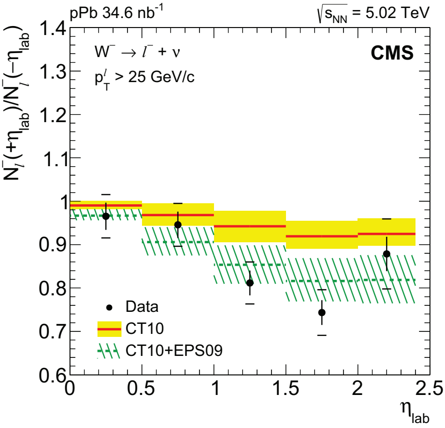
Comparison of different nPDF sets



[*JHEP* 1310 (2013) 213]

$W^{\pm}$ production





[arXiv:1503.05825]