Sensitivity of direct photons to small-x gluon nPDFs in p+Pb collisions at the LHC

11th MCnet Meeting

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Outline

- Introduction
  - Nuclear parton distribution functions
- Hadron production
  - Sensitivity to small-x
- Direct photon production
  - Different components
  - Sensitivity to small-x
  - Isolation cut
- Summary & Conclusions

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

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

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

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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 parameters

Nuclear PDFs

The PDFs are modified in nuclear collisions:

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

- $R_i^A(x,Q^2)$ quantifies the nuclear modification, determined via global DGLAP analysis

Recent NLO analyses

- HKN07
- DSSZ
- nCTEQ
- EPS09

[JHEP 04 (2009) 065]

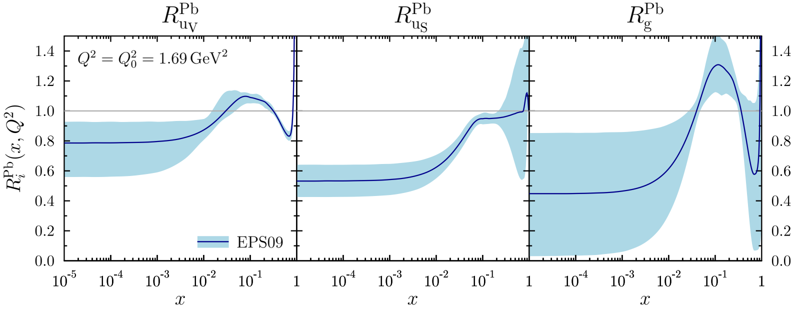
Data used in the fits

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

$\Rightarrow$ Data not very sensitive to gluons!

Uncertainties in nPDF fits

EPS09 uncertainties:



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

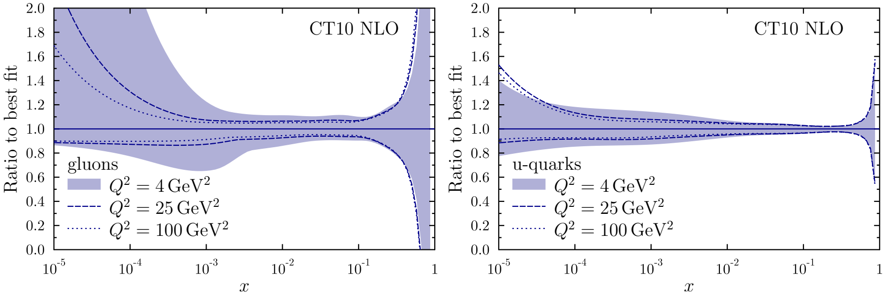
Probed values of x in hadronic collision

$$x \approx \frac{2p_T}{\sqrt{s_{NN}}}\mathrm{e}^{-\eta}$$ (using partonic LO $2 \to 2$ kinematics)

$\Rightarrow$ Forward rapidities in p+Pb collisions at the LHC

Uncertainties in proton PDFs

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



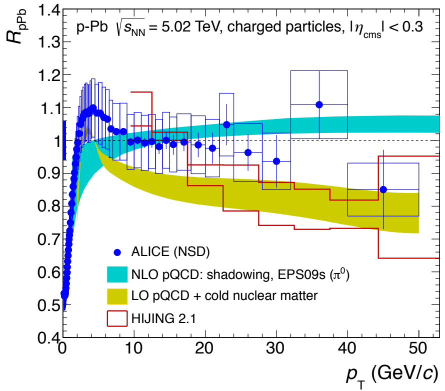
- Large uncertainties also for gluon PDFs in proton at $x < 10^{-4}$
  $\Rightarrow$ Further constraints would be welcome to here also

Inclusive hadron production

Nuclear modification ratio

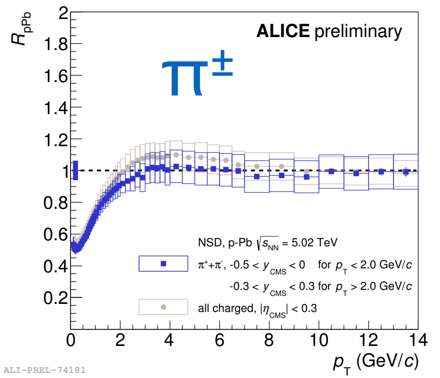
$$R^h_{\mathrm{pPb}}(p_T,\eta) = \frac{1}{208}\frac{\mathrm{d}^2\sigma^h_{\mathrm{pPb}}}{\mathrm{d}p_T\mathrm{d}\eta}\Big/\frac{\mathrm{d}^2\sigma^h_{\mathrm{pp}}}{\mathrm{d}p_T\mathrm{d}\eta}$$

- Inclusive charged hadrons



[Eur.Phys.J. C74 (2014) 3054]

- Inclusive charged pions



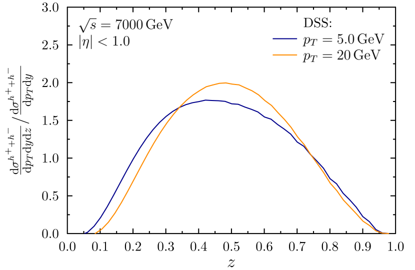
[Quark Matter 2014]

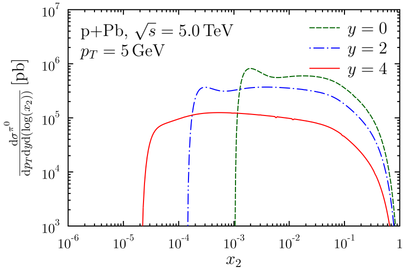
Inclusive hadron production

Collinear factorization

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

- Convolution with the fragmentation functions (FFs) $D_k^h(z, Q_F^2)$ smears the relation to partonic kinematics (calculations: `INCNLO`)





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

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

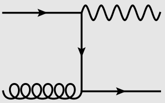
Direct γ production

Two components in direct photon cross section

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

Prompt photon production

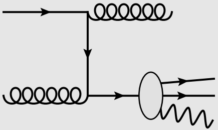
e.g. Compton scattering



- Calculated from pQCD
- Sensitive to gluon PDFs

Fragmentation photon production

parton fragments into photon, e.g.

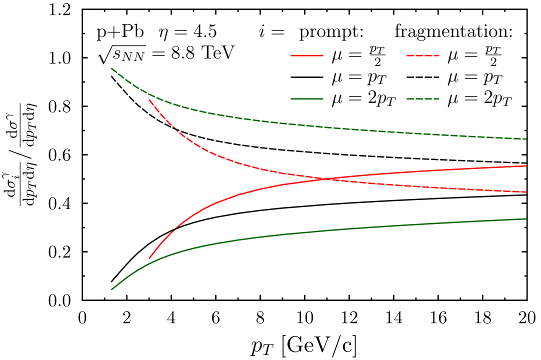


- Calculated by convoluting with parton-to-photon FFs

- Two components experimentally indistinguishable
- More sensitivity to small-x physics than hadrons?

Prompt vs. Fragmentation

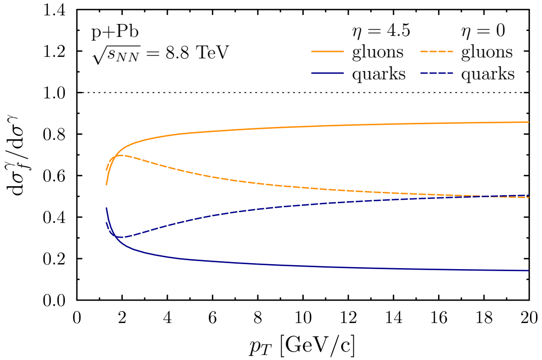
- The relative contributions to direct photon cross section with
  - three scale choices ($\mu = Q = Q_F$)
  - CTEQ6.6M PDFs [Phys. Rev. D78 (2008) 013004] with EPS09
  - BFGII FFs [Eur. Phys. J. C2 (1998) 529]



- 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

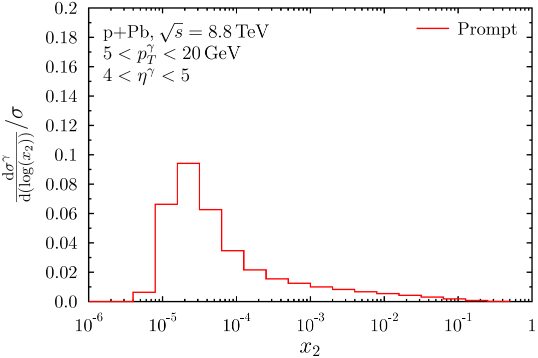
Relative contributions from quarks and gluons in the Pb-nucleus at mid- and forward rapidities



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

Sensitivity to small-x

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



- Prompt component very sensitive to small values of x_2

Sensitivity to small-x

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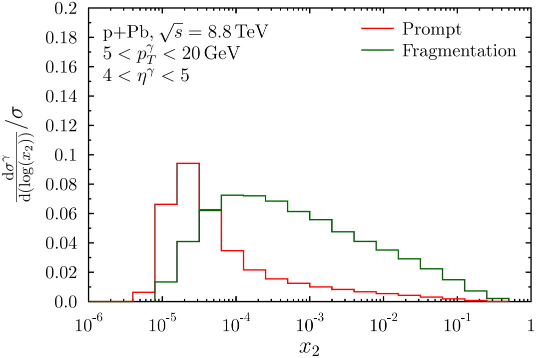

- Prompt component very sensitive to small values of x_2
- Fragmentation component have contribution also from larger x_2's

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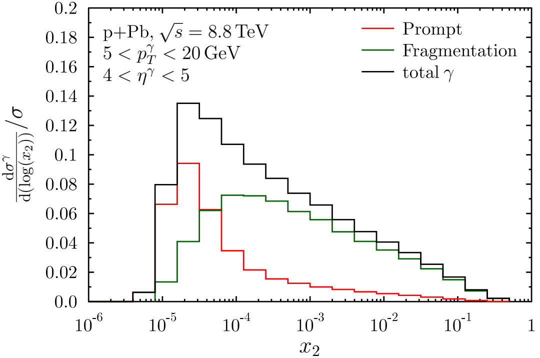

- Prompt component very sensitive to small values of x_2
- Fragmentation component have contribution also from larger x_2's
- Total cross section not sensitive only to small values of x_2

Sensitivity to small-x

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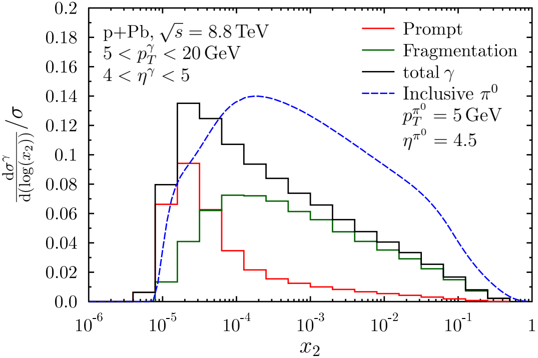


- Prompt component very sensitive to small values of x_2
- Fragmentation component have contribution also from larger x_2's
- Total cross section not sensitive only to small values of x_2
- The relative sensitity still larger than for hadrons

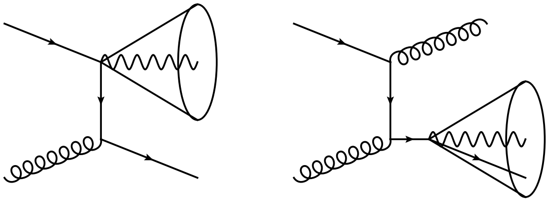
Isolation

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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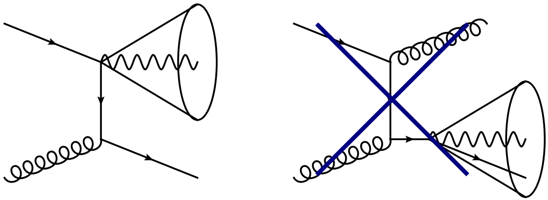
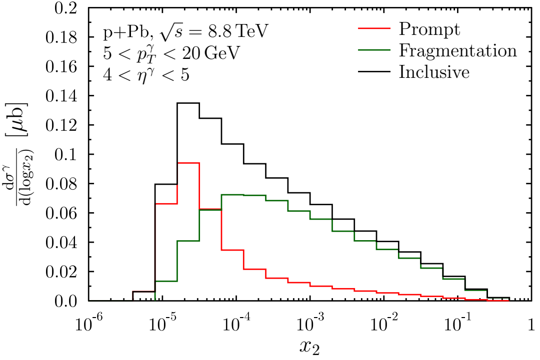


- Isolation cut suppresses the fragmentation component
- Increase the sensitivity to smaller values of x_2

Isolation and x_2 sensitivity

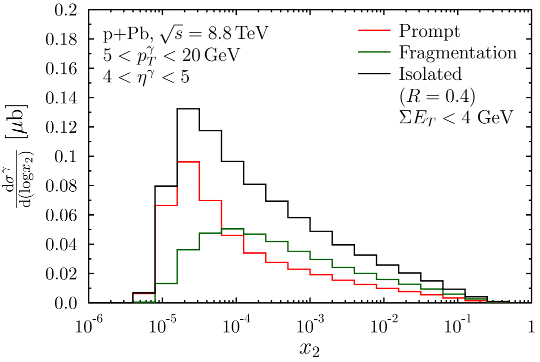
- The contribution from different x_2 values to NLO cross section



- Only the sum of two components relevant

Isolation and x_2 sensitivity

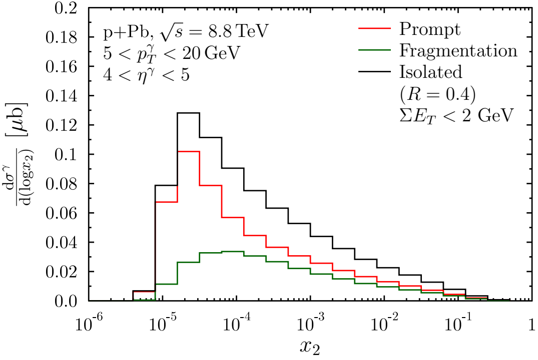
- The contribution from different x_2 values to NLO cross section



- Only the sum of two components relevant
- Isolation cut $\Sigma E_T < 2\,\mathrm{GeV}$ suppresses fragmentation component
  $\Rightarrow$ Decrease contribution from larger values of x_2

Isolation and x_2 sensitivity

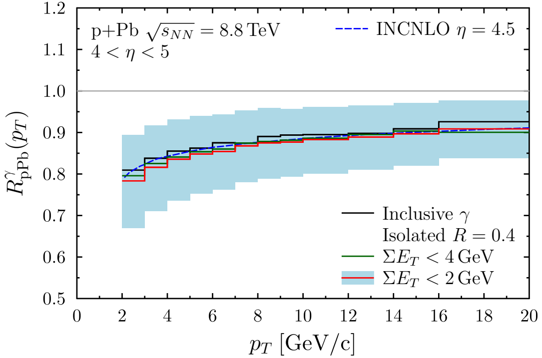
- The contribution from different x_2 values to NLO cross section



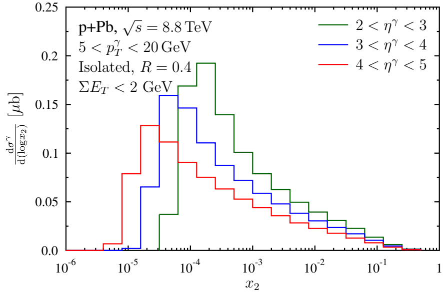
- Only the sum of two components relevant
- Isolation cut $\Sigma E_T < 2\,\mathrm{GeV}$ suppresses fragmentation component
  $\Rightarrow$ Decrease contribution from larger values of x_2
- Tighter isolation cut $\Sigma E_T < 2\,\mathrm{GeV}$ furhter suppresses the fragmentation component but small effect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

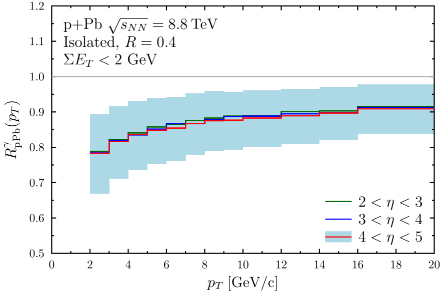
Nuclear modification factor

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





- 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
- Also uncertainties very similar in each rapidity bin ($\sim 10\%$)
- Accurate measurements required!
  - FoCal in ALICE?

Yield asymmetry Y_{pPb}^{asym}

Shortcomings of R_{pPb}

- 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 $\gtrsim 10\%$

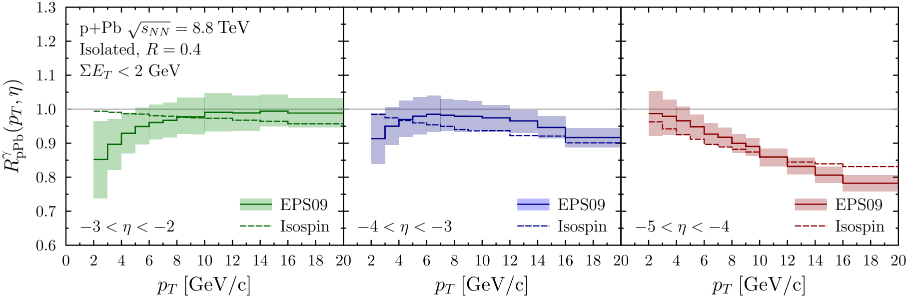
Yield asymmetry between forward and backward rapidities

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

+ No need for the p+p baseline
+ Many uncertainties cancel in the ratio
− Might require flipping the beams (p+Pb $\rightarrow$ Pb+p)
− Requires good control of the p+Pb cross section at $\eta < -2$

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:

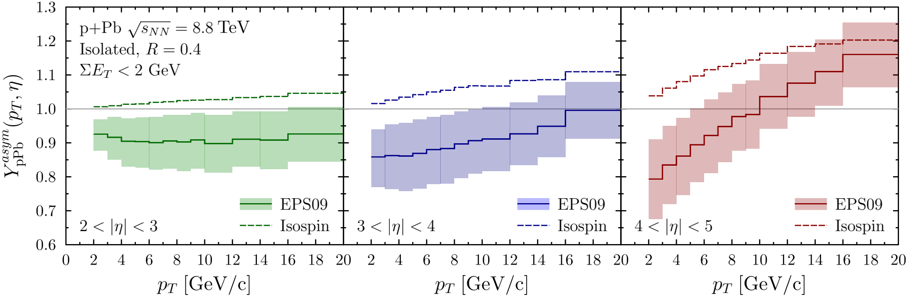


Isospin effect

- 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

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

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



Yield asymmetry

- nPDFs uncertainties mainly from small x
  $\Rightarrow$ Should provide important constraints to nPDFs
- Sizable isospin effect at $|\eta| \in [4, 5]$

Summary & Conclusions

Summary

- Gluon nPDFs unconstrained at small x
  - Also proton PDFs have large uncertainties at $x < 10^{-4}$
- p+Pb collisions at the LHC could provide more constraints

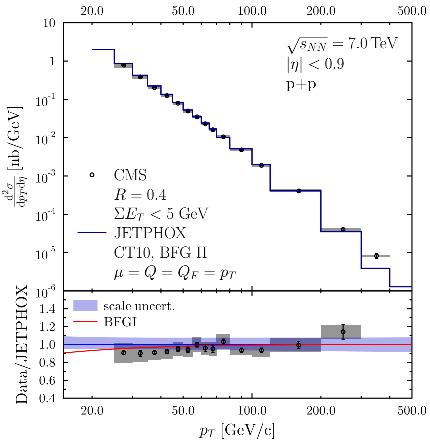
Conclusions

- Direct photons more sensitive to small-x physics than 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

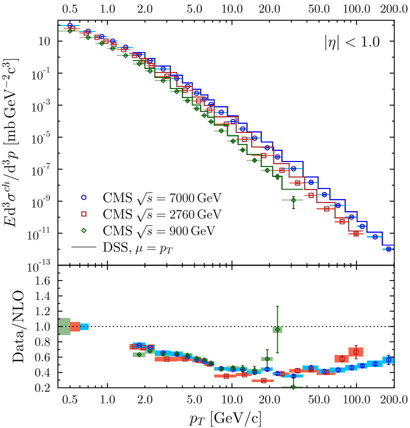
- Isolated photons at the LHC



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

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

- Charged hadrons at LHC

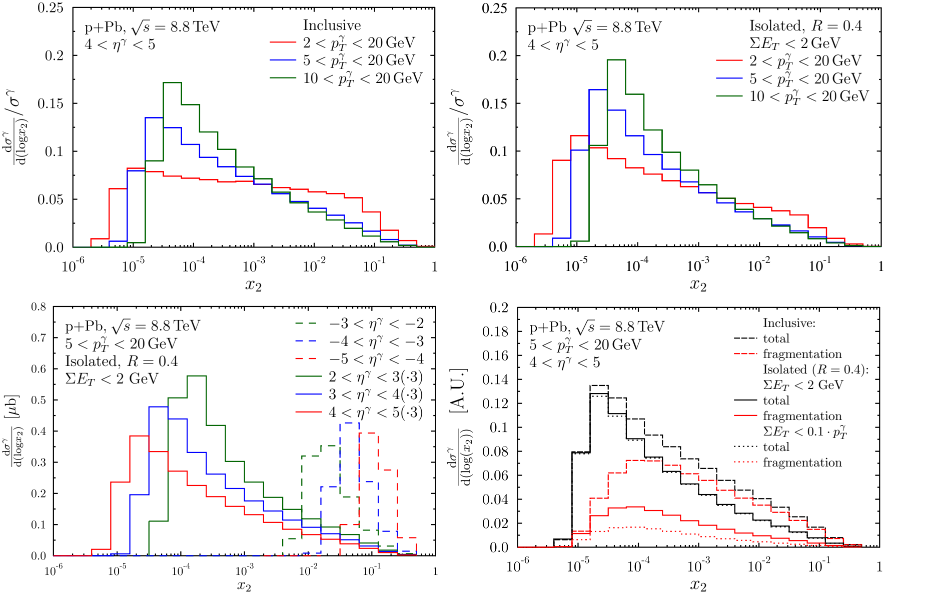


[JHEP 1108 (2011) 086]

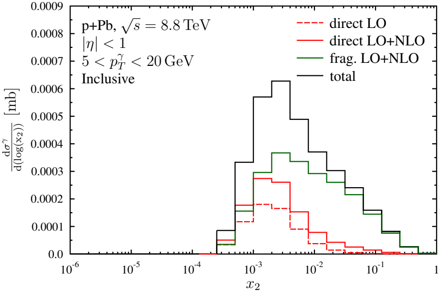
[Eur.Phys.J. C72 (2012)]

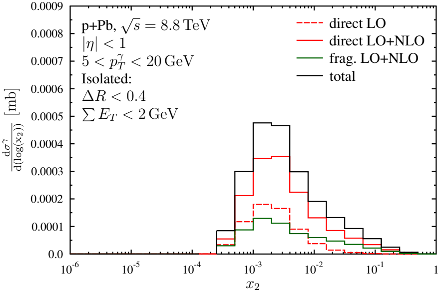
- NLO pQCD with recent FFs overshoots the data by factor of 2!

p_T systematics



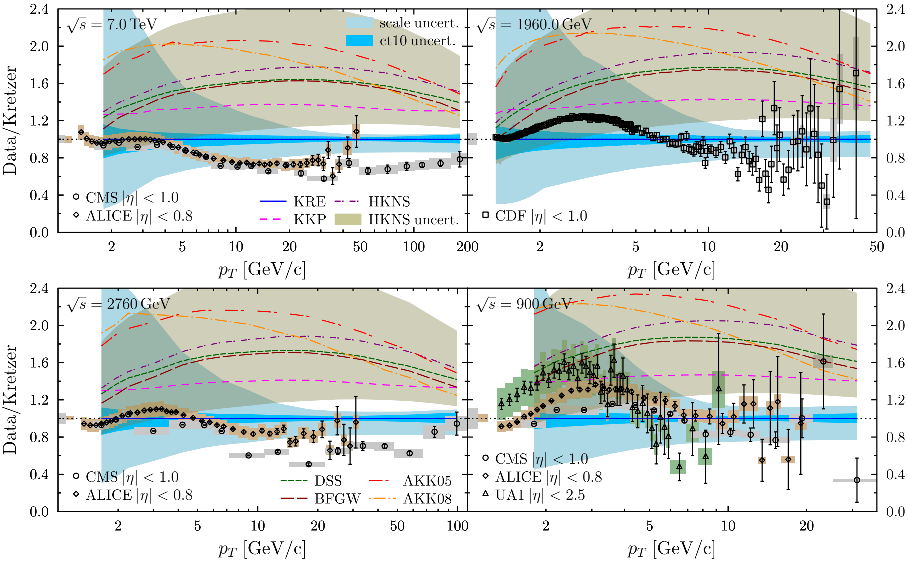
Isolated photons at midrapidity





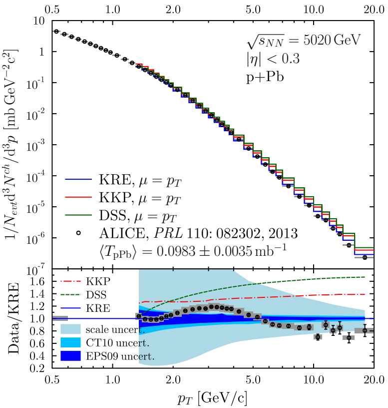
- More sensitivity to small-x than hadrons
- Contribution also from quark initiated processes

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

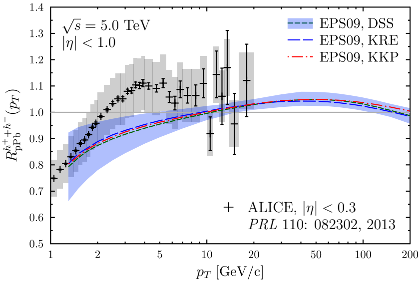


p+Pb collisions at the LHC

Charged particle yield in p+Pb:



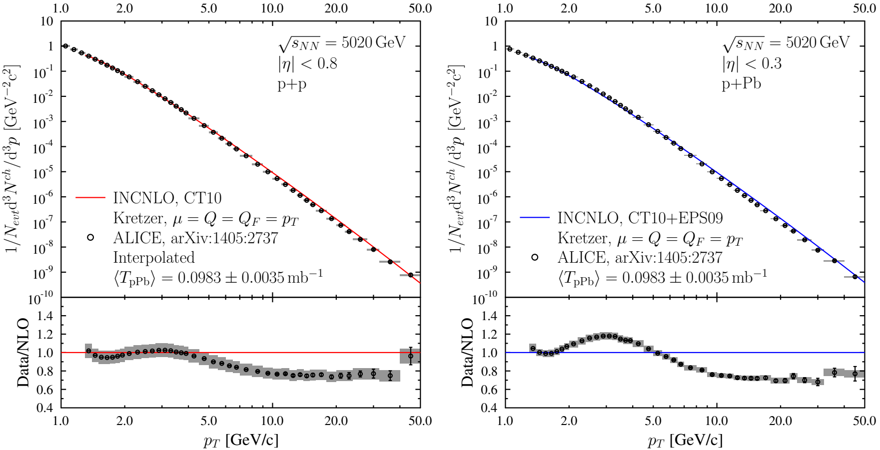
- Similar behaviour as in p+p



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

Charged hadrons in p+Pb

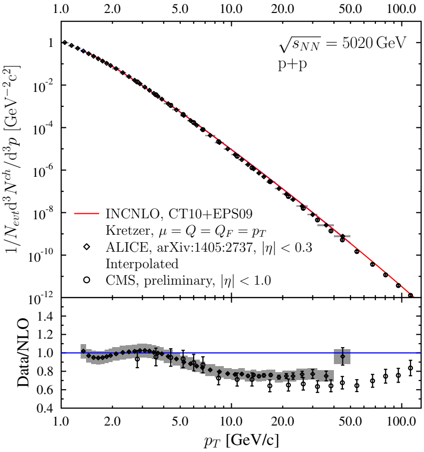
- New data for charged hadrons in p+Pb from ALICE

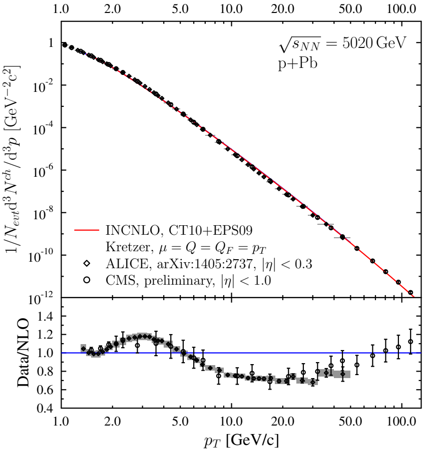


- At $p_T \gtrsim 10\,\mathrm{GeV/c}$ the data/NLO ratios are flat for both p+p and p+Pb
  $\Rightarrow$ The ALICE baseline seems to be in control up to $p_T = 40\,\mathrm{GeV/c}$

Charged hadrons in p+Pb

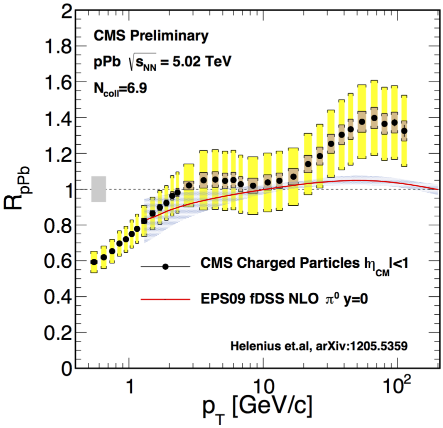
- New data for charged hadrons in p+Pb from CMS

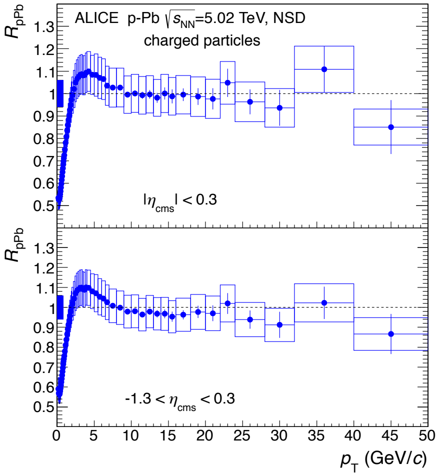




- Disclaimer: CMS spectra read "by eye" (from H. Paukkunen)!
- Rise in CMS data/NLO ratio at $p_T > 50\,\mathrm{GeV/c}$ in both p+p and p+Pb

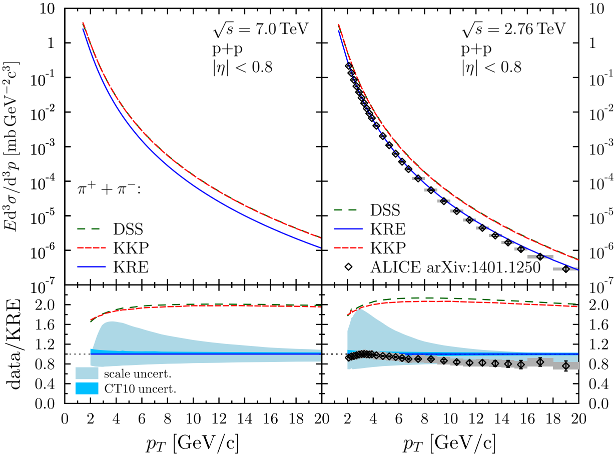
New results for charged hadrons in p+Pb





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