Centrality and rapidity dependence of inclusive pion and prompt photon production in p+Pb collisions at the LHC with EPS09s nPDFs

High-p_T workshop

Ilkka Helenius

University of Jyväskylä
Department of Physics

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Outline

1. Introduction
   - Nuclear Parton Distribution Functions
   - Geometry of a Heavy Ion Collision
2. Framework
   - Spatially dependent nPDFs
     - [I.H, K.J. Eskola, H. Honkanen, C.A. Salgado, *JHEP* 1207 (2012) 073]
   - Centrality classes with Optical Glauber model
3. Results
   - π^0 and charged hadron production in p+Pb
     - [I.H, K.J. Eskola, H. Honkanen, C.A. Salgado, *JHEP* 1207 (2012) 073]
   - Prompt γ production in Pb+Pb and p+Pb
     - [I.H, K.J. Eskola, H. Paukkunen, *JHEP* 1305 (2013) 030]
4. Summary

Nuclear Parton Distribution Functions (nPDFs)

Collinear Factorization in A+B collisions

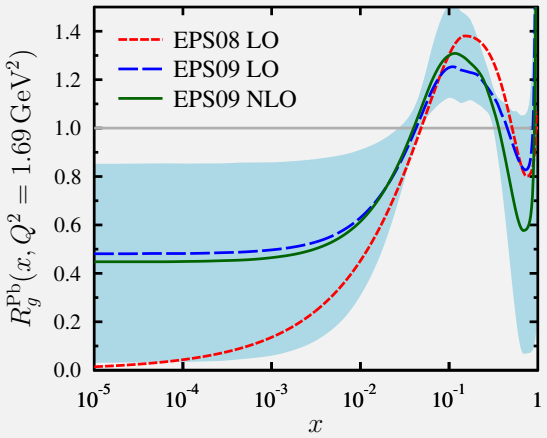
$$\mathrm{d}\sigma^{AB\to k+X} = \sum_{i,j,X'} f_i^A(x,Q^2) \otimes f_j^B(x,Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'} + \mathcal{O}(1/Q^2)$$

Nuclear Modification of the PDFs

- Bound nucleon PDFs $\neq$ free nucleon PDFs

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

- $R_i^A(x,Q^2)$ determined via global analyses
  - EKS98 (LO DGLAP evolution)
  - EPS08 (LO DGLAP evolution)
  - EPS09 (LO and NLO + error sets)

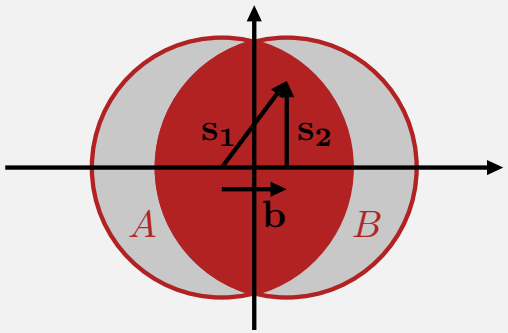


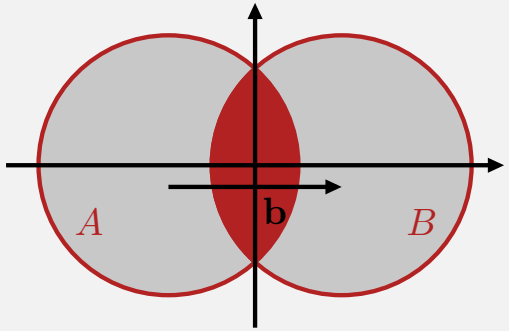
- All global fits have considered only minimum bias collisions

Geometry of a Heavy Ion Collision

Heavy nuclei collide with impact parameter b

- Small b: Central collisions
- Large b: Peripheral collisions





- Minimun bias collisions = average over all b
- Measurements often binned in centrality

Nuclear overlap function

$$T_{AB}(\mathbf{b}) = \int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s_1}) T_B(\mathbf{s_2})$$

$$\mathbf{s_1} = \mathbf{s} + \mathbf{b}/2 \quad \mathbf{s_2} = \mathbf{s} - \mathbf{b}/2$$

Nuclear thickness function

$$T_A(\mathbf{s}) = \int \mathrm{d}z\, \rho_A(\mathbf{s}, z)$$

Model Framework

Nuclear modifications with spatial dependence

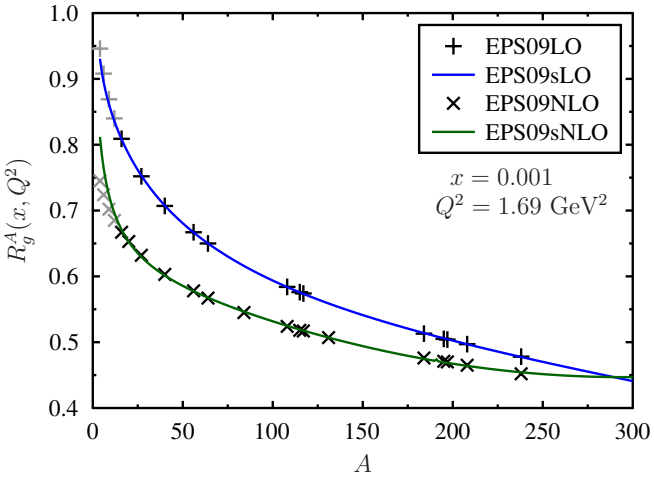
- We replace
$$R_i^A(x,Q^2) \to r_i^A(x,Q^2,\mathbf{s}),$$
where $\mathbf{s}$ is the transverse position of the nucleon
- Definition
$$R_i^A(x,Q^2) \equiv \frac{1}{A}\int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s})\, r_i^A(x,Q^2,\mathbf{s}),$$
where $R_i^A(x,Q^2)$ is taken from EKS98 or EPS09 global fits
- Assumption: spatial dependence related to $T_A(\mathbf{s})$ as follows:
$$r_i^A(x,Q^2,\mathbf{s}) = 1 + \sum_{j=1}^{n} c_j^i(x,Q^2)\,[T_A(\mathbf{s})]^j$$
- Important: No A-dependence in the fit parameters $c_j^i(x,Q^2)$

Fitting Procedure

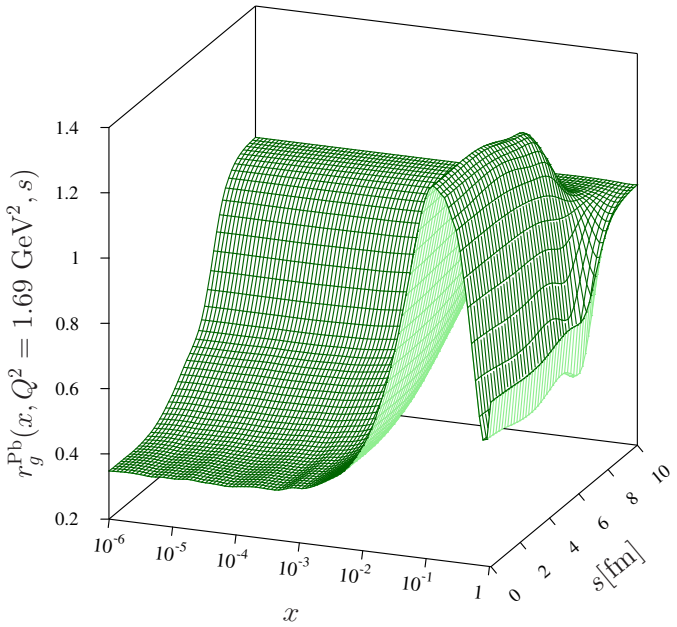
Parameters $c_j(x, Q^2)$ obtained by minimizing the χ^2

$$\chi_i^2(x, Q^2) = \sum_A \left[\frac{R_i^A(x, Q^2) - \frac{1}{A} \int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s}) r_i^A(x, Q^2, \mathbf{s})}{W_i^A(x, Q^2)} \right]^2$$

- A-dependence of $R_i^A(x, Q^2)$ well reproduced with $n = 4$:



- Fitting is done also for the EPS09 error sets (LO&NLO)



Outcome: Spatially dependent nPDF sets EPS09s and EKS98s

Centrality dependent R_{AB}

The yield depends on $\mathbf{b}$ also via nPDFs:

$$\mathrm{d}N^{AB\to k+X}(\mathbf{b}) = \int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s_1})\, T_B(\mathbf{s_2}) \sum_{i,j,X'} r_i^A(x, Q^2, \mathbf{s_1}) f_i^N(x, Q^2) \otimes r_j^B(x, Q^2, \mathbf{s_2}) f_j^N(x, Q^2) \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X'}$$

Nuclear Modification Factor

$$R_{AB}^k(b_1, b_2) = \frac{\left\langle \frac{\mathrm{d}^2 N_{AB}^k}{\mathrm{d}p_T \mathrm{d}y} \right\rangle_{b_1,b_2}}{\frac{\langle N_{bin}\rangle_{b_1,b_2}}{\sigma_{inel}^{NN}} \frac{\mathrm{d}^2\sigma_{pp}^k}{\mathrm{d}p_T \mathrm{d}y}} = \frac{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b} \frac{\mathrm{d}^2 N_{AB}^k(\mathbf{b})}{\mathrm{d}p_T \mathrm{d}y}}{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, T_{AB}(\mathbf{b}) \frac{\mathrm{d}^2\sigma_{pp}^k}{\mathrm{d}p_T \mathrm{d}y}}$$

- Centrality classes defined in terms of impact parameter intervals
- b_1 and b_2 from optical Glauber model

Centrality classes

Optical Glauber Model

- Probability for inelastic collision

$$p_{inel}^{AB}(\mathbf{b}) \approx 1 - \mathrm{e}^{-T_{AB}(\mathbf{b})\sigma_{inel}^{NN}}$$

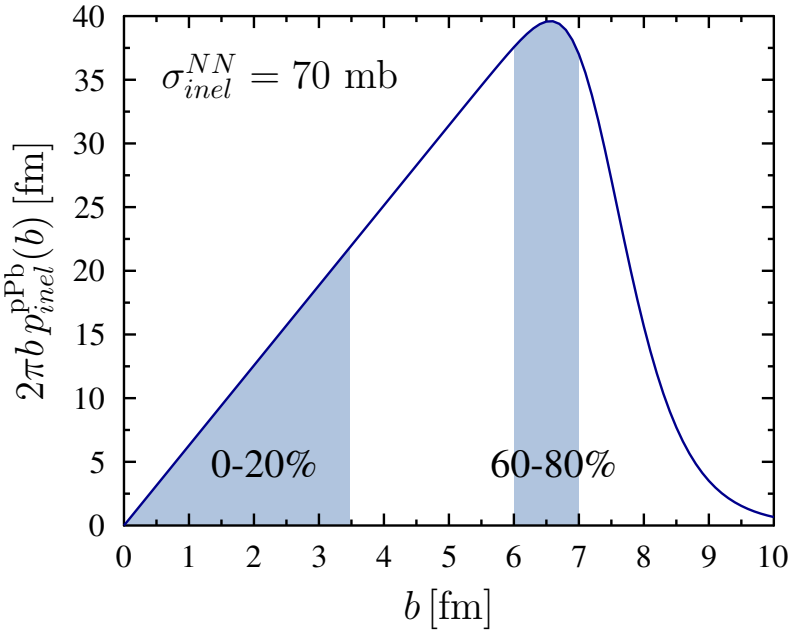
- Inelastic cross section for $[b_1, b_2]$

$$\sigma_{inel}^{AB}(b_1, b_2) = \int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, p_{inel}^{AB}(\mathbf{b})$$

- For p+A we assume a point-like proton $\Rightarrow T_{\mathrm{p}A}(\mathbf{b}) = T_A(\mathbf{b})$
- $T_A(\mathbf{s})$ from Woods-Saxon density:

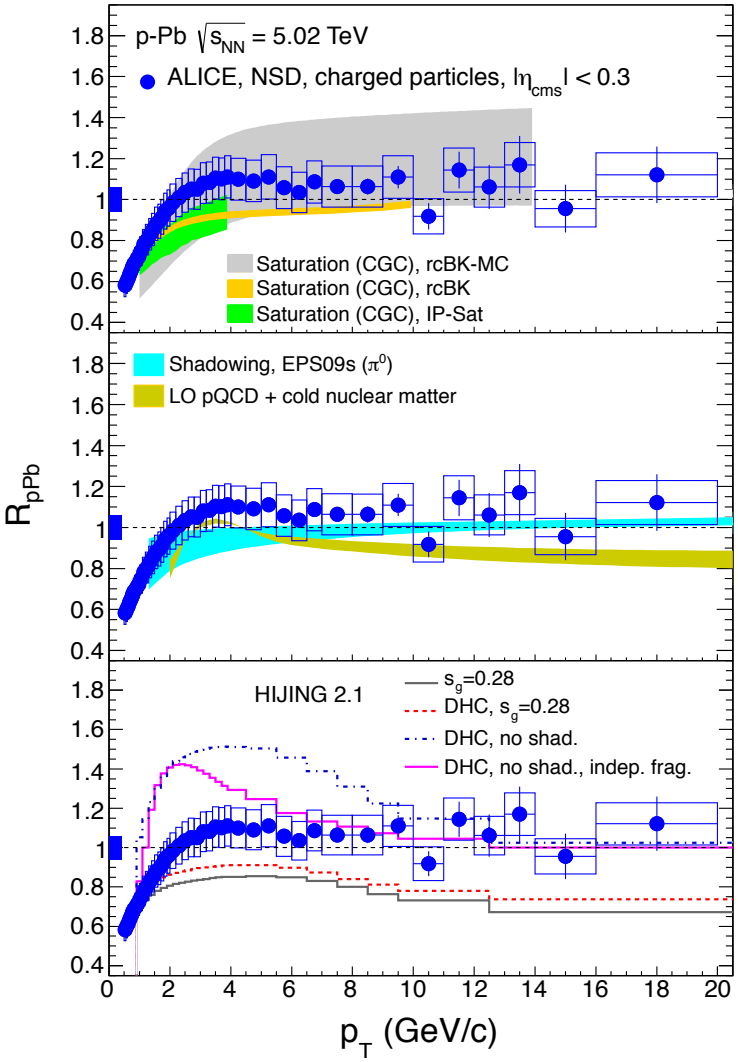
$$\rho_A(\mathbf{s}, z) = \frac{n_0}{1 + \exp[\frac{\sqrt{\mathbf{s}^2+z^2}-R_A}{d}]}$$

- Example: p+Pb at the LHC $\sqrt{s_{NN}} = 5.0$ TeV, $\sigma_{inel}^{NN} = 70$ mb



	b_1 [fm]	b_2 [fm]	$\langle N_{bin} \rangle$
0-20%	0.0	3.471	14.24
20-40%	3.471	4.908	11.41
40-60%	4.908	6.012	7.663
60-80%	6.012	6.986	3.680

p+Pb collisions at the LHC



Phys. Rev. Lett., 110: 082302, 2013

p+Pb pilot run in 2012

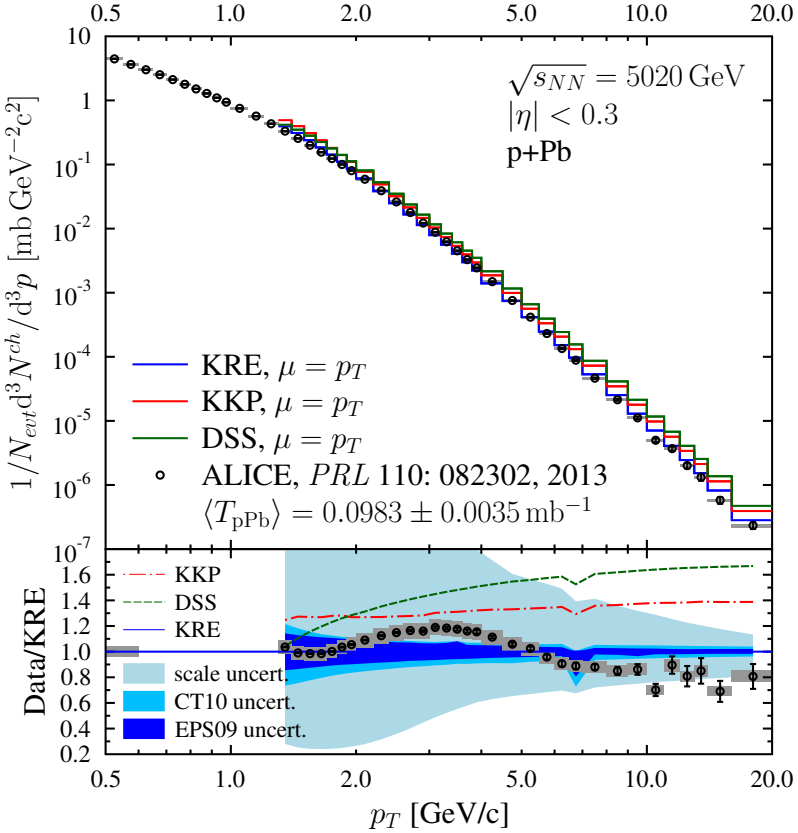
- ALICE measurement for charged particles
- Minimum bias result = averaged over all centralities

← Our π^0 prediction (*JHEP* 07 (2012) 073) consistent with the data

← HIJING with scale independent strong gluon shadowing not supported by the data

p+Pb collisions at the LHC

Charged particle yield in p+Pb:



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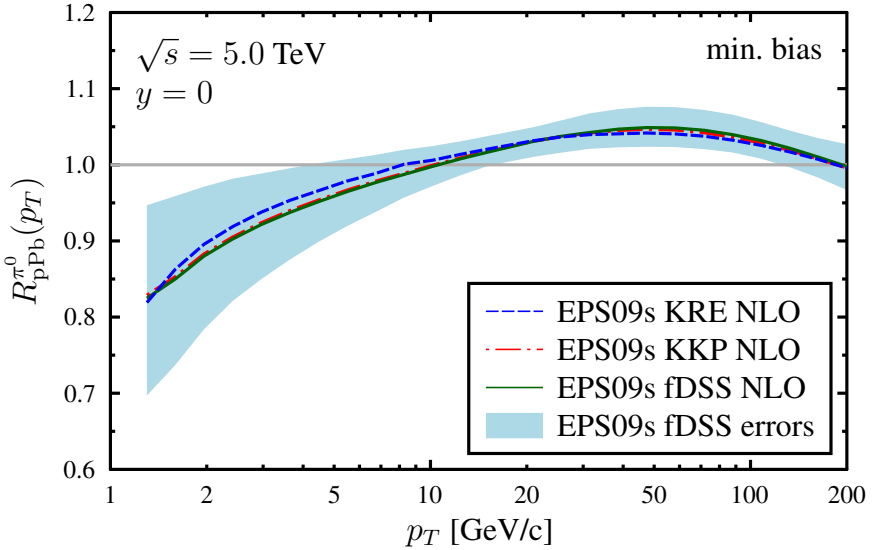
Work in progress

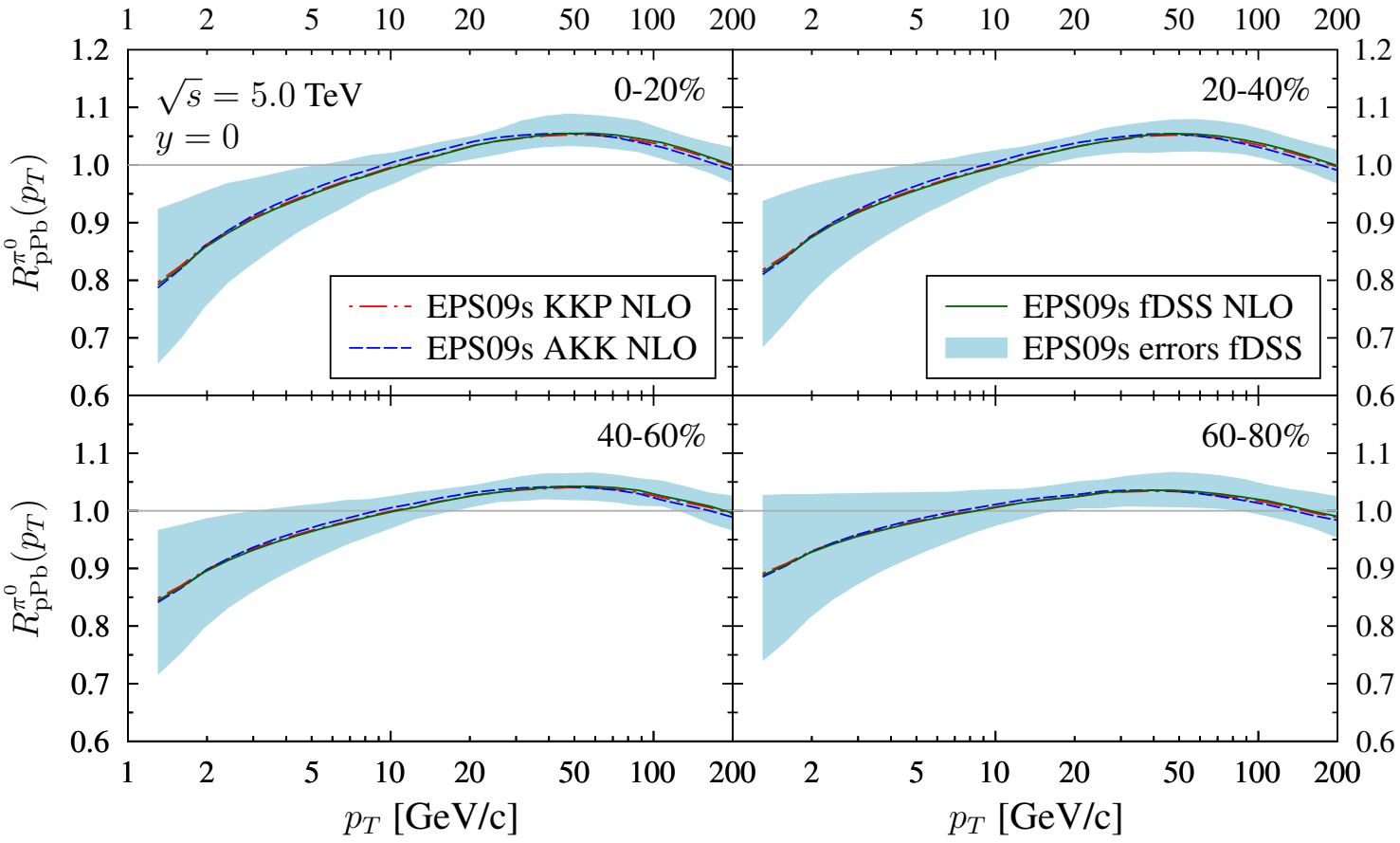
Nuclear modification factor:



- Data best described with Kretzer fragmentation functions
- Differences in dN cancel out in ratio $R_{\rm pPb}$
  $\Rightarrow R_{\rm pPb}$ not sensitive to FFs

π^0 production in p+Pb at $y = 0$

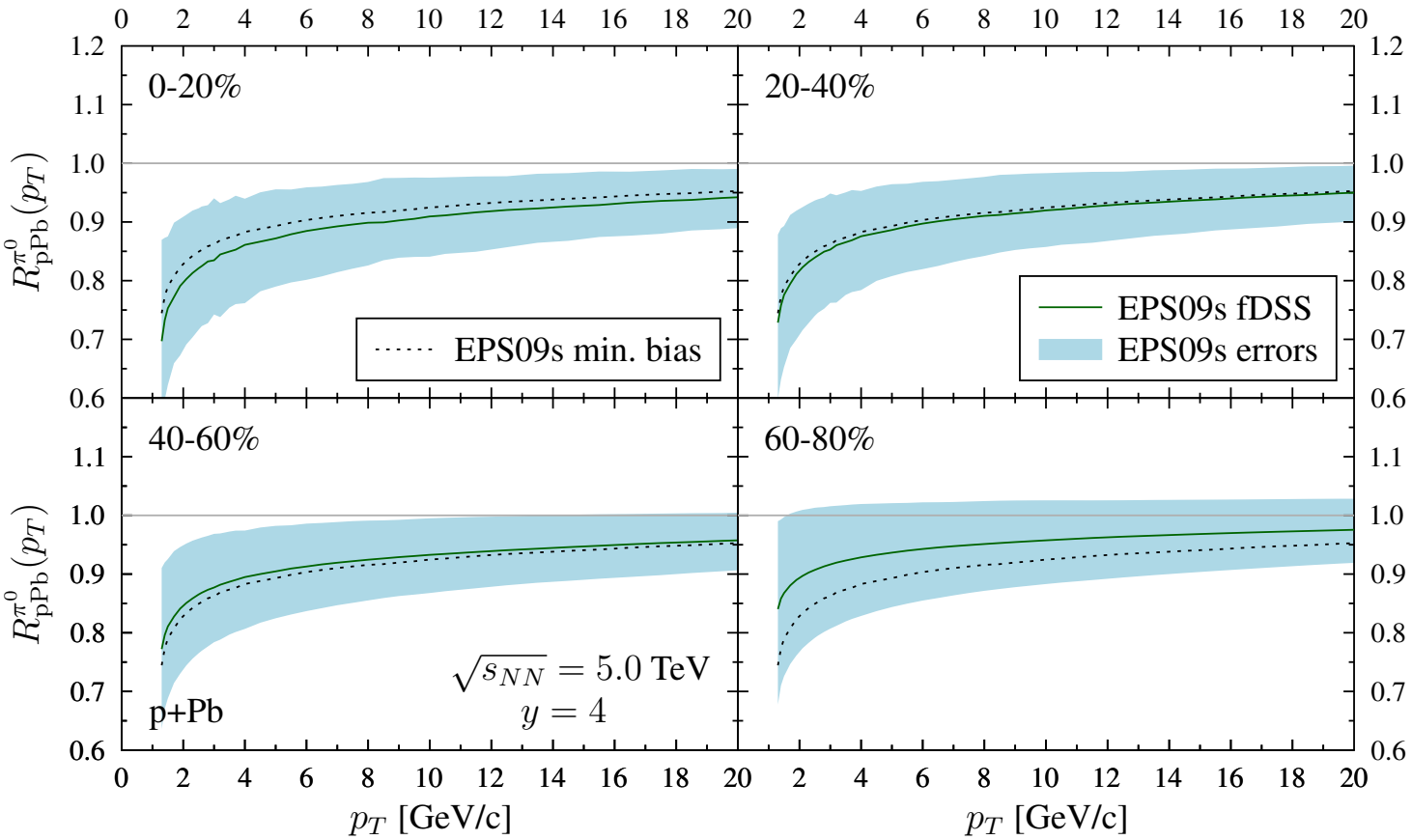
- R_{pPb} for inclusive π^0 at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [*JHEP* 1207 (2012) 073]



- Stronger nuclear effects in central collisions

π^0 production in p+Pb at $y = 4$

- R_{pPb} for inclusive π^0 at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 4$ in four centrality classes in NLO (with `INCNLO`) [*Work in progress*]

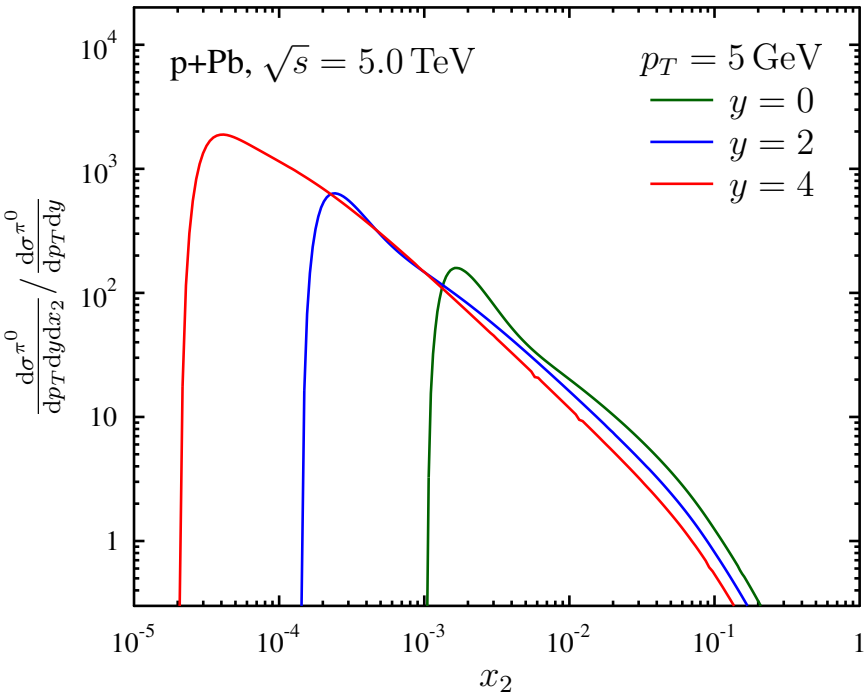


- More suppression at small p_T than at $y = 0$

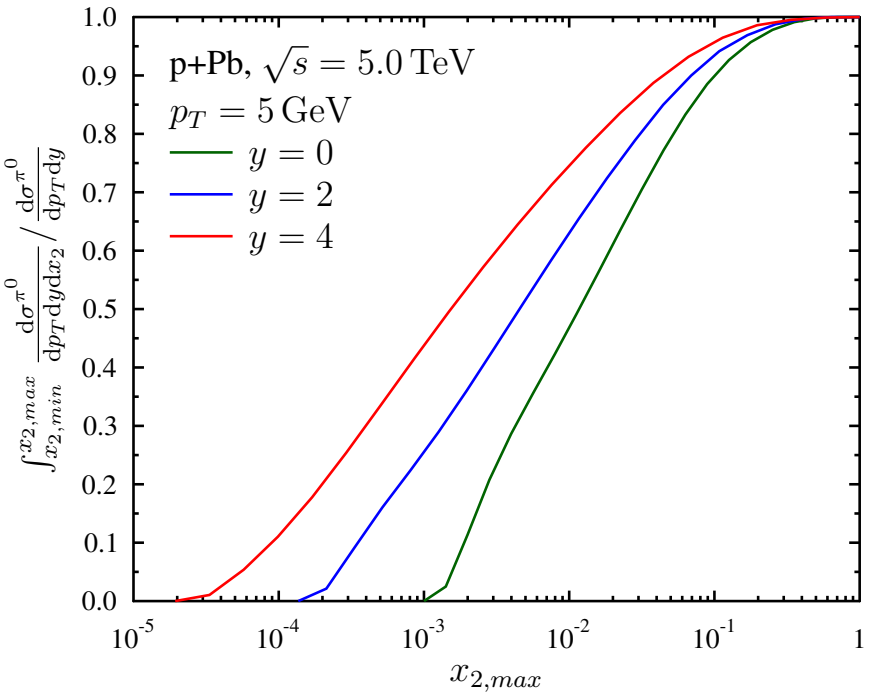
x_2 values for different rapidities

- Which x_2 values different rapidities probe?

Normalized $\mathrm{d}\sigma$ w.r.t. x_2



$\mathrm{d}\sigma$ accumulation w.r.t. x_2



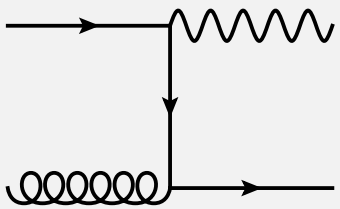
- Contribution to $\mathrm{d}\sigma$ from broad x_2 range also at forward rapidities

[*Work in progress*]

Prompt γ production

Direct photon production

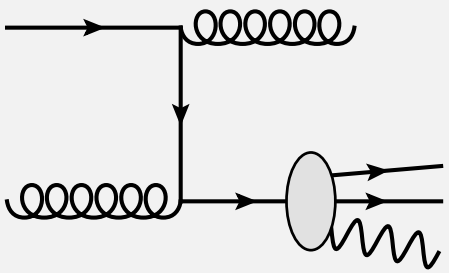
e.g. Compton scattering



- Calculable from perturbative QCD

Fragmentation photon production

parton fragments into photon, e.g.



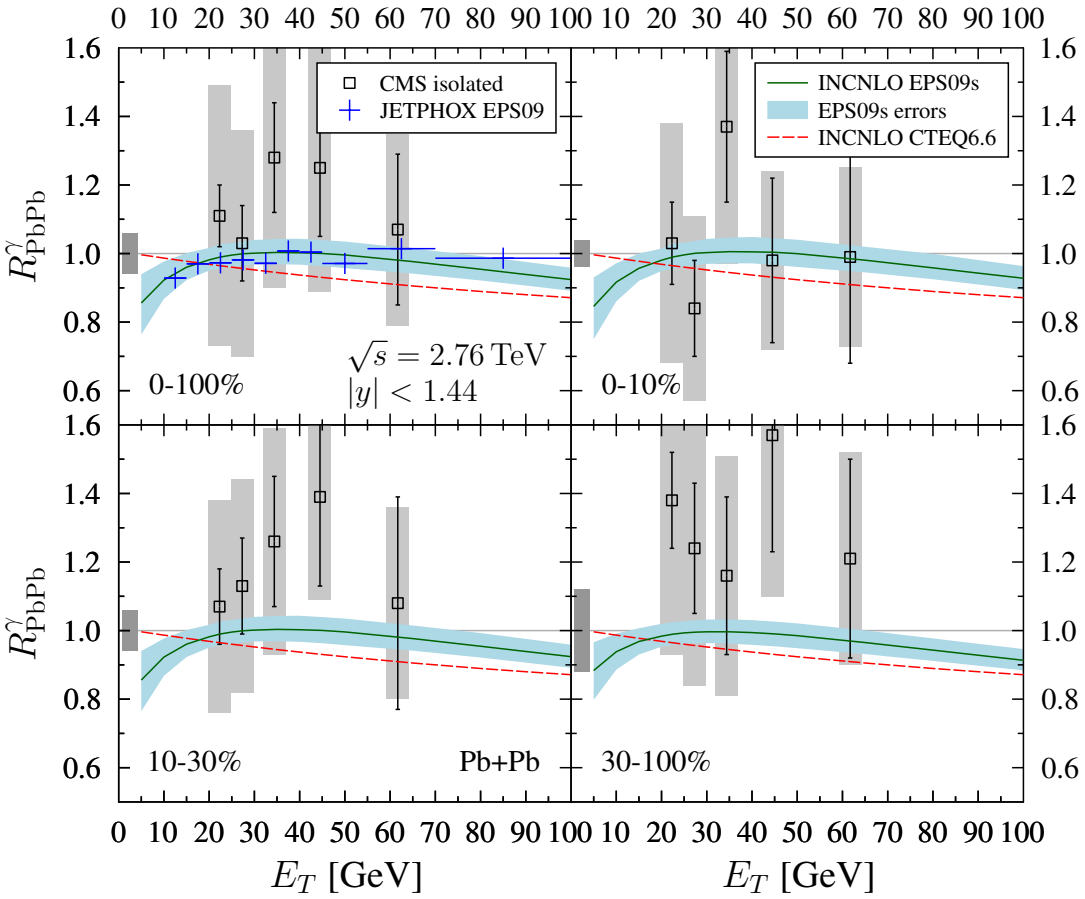
- Calculated by convoluting the parton spectra with non-perturbative fragmentation functions

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

Prompt γ production in Pb+Pb

R_{PbPb} for inclusive γ at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ and $|y| < 1.44$ in different centrality classes in NLO [*JHEP* 1305 (2013) 030]



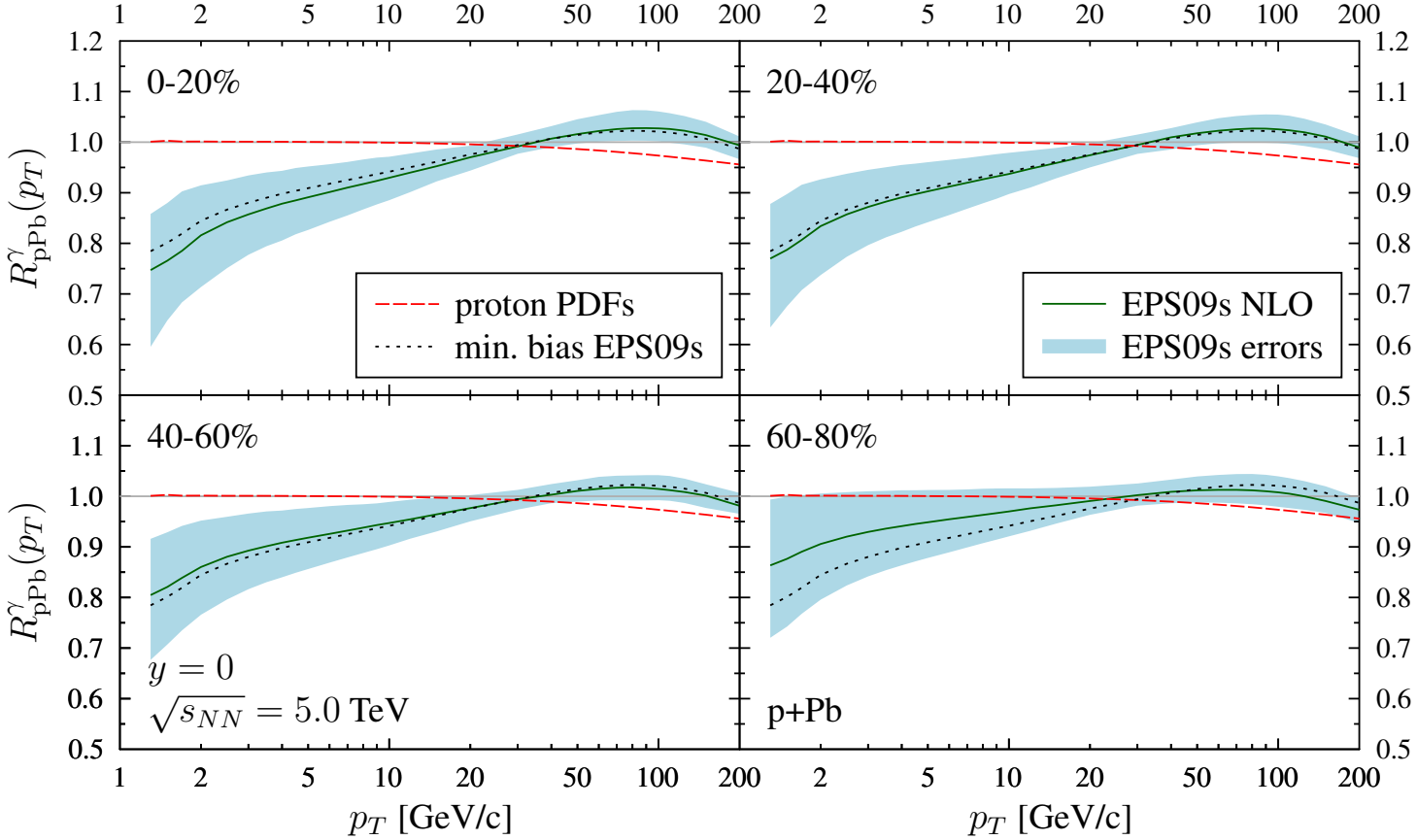
- CMS data for isolated and calculation for inclusive photons
- Isolated (JETPHOX) and inclusive (INCNLO) $R^{\gamma}_{\mathrm{PbPb}}$ compatible in min. bias

$\Rightarrow$ Comparison ok

- Note smaller nPDF uncertainties than in CMS paper [*Phys.Lett.* B710 (2012) 256-277]

Prompt γ production in p+Pb at $y = 0$

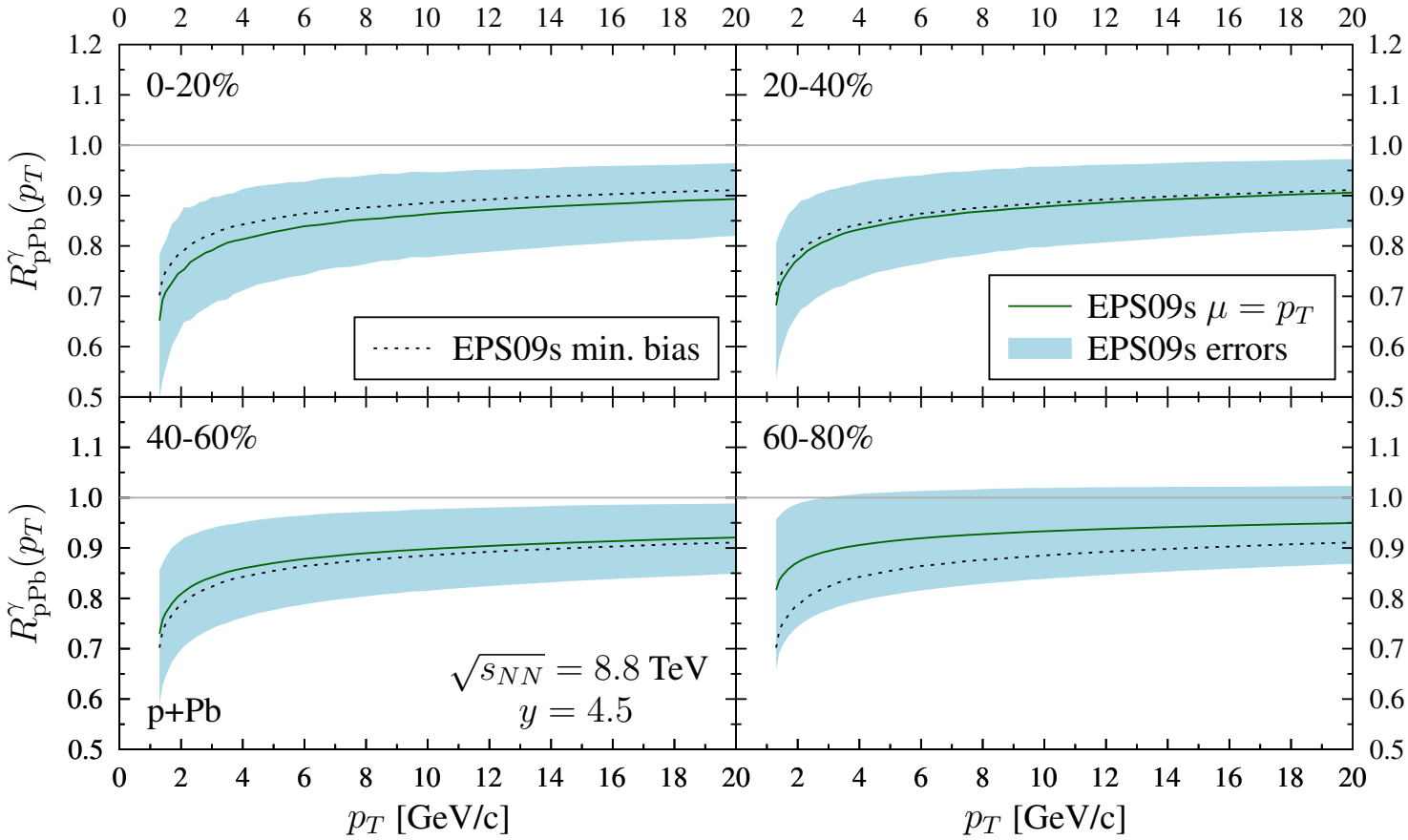
- R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [*JHEP* 1305 (2013) 030]



- More suppression than for π^0's at low p_T

Prompt γ production p+Pb at $y = 4.5$

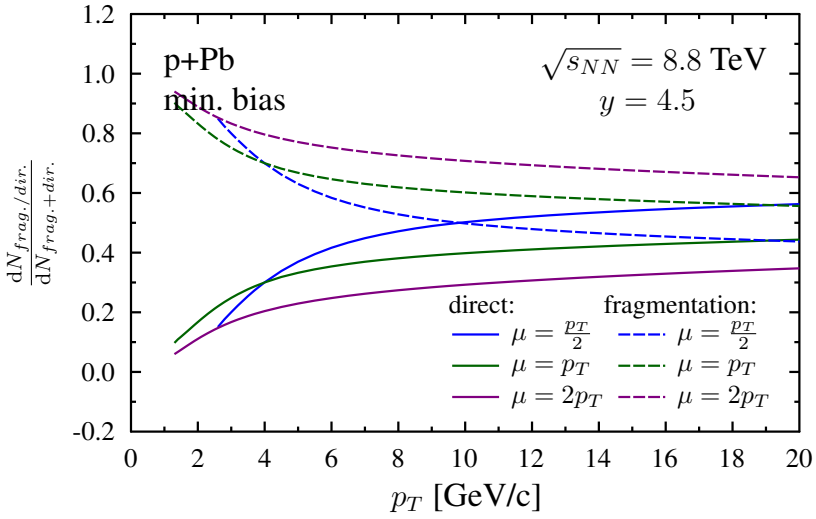
- R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in four centrality classes in NLO (with `INCNLO`) [*Work in progress*]



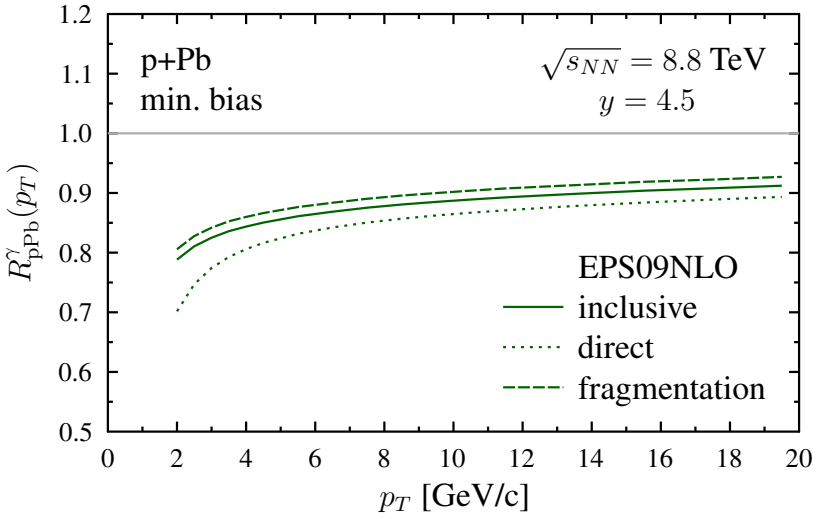
- Larger suppression than at $y = 0$

Direct vs. fragmentation photons

- The contribution from direct and fragmentation component



- The R_{pPb} for direct and fragmentation component



- In NLO the division scale dependent
- At low p_T the fragmentation photons dominate
- Isolation suppresses mostly fragmentation component
  $\Rightarrow$ Isolated $R^{\gamma}_{\mathrm{pPb}}$ between the inclusive and direct $R^{\gamma}_{\mathrm{pPb}}$

Summary and Conclusions

Summary

- Determined new spatially dependent nPDF sets EPS09s and EKS98s based on
  - A-dependence of the globally fitted nPDFs
  - Power series ansatz in $T_A(\mathbf{s})$
- Made EPS09s and EKS98s publicly available at our web page
- Calculated the R_{AB} for inclusive π^0 and prompt γ at mid- and now also at forward rapidities for various collisions and centralities

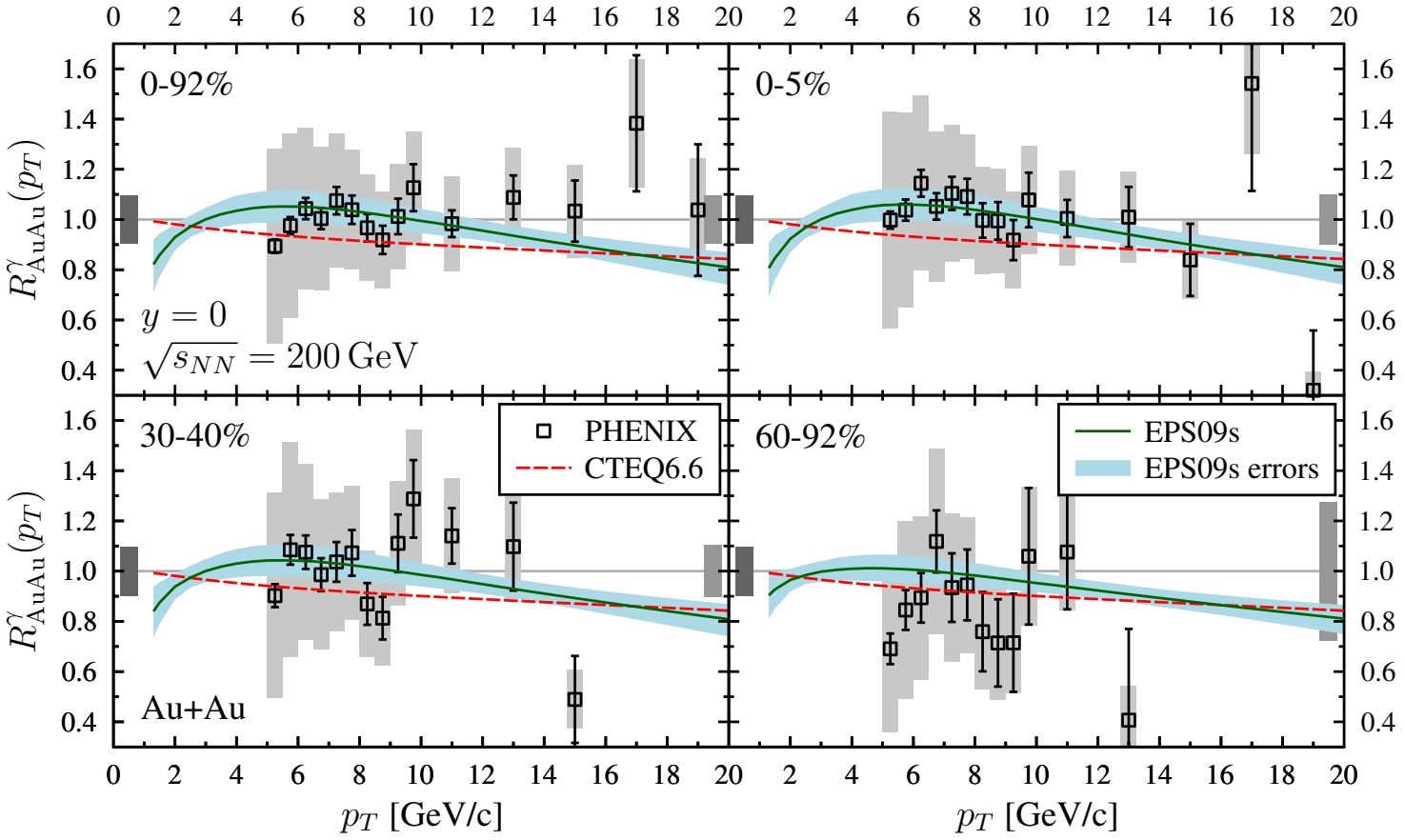
Conclusions & Outlook

- Predicted centrality dependence mild but prehaps measurable in p+Pb at LHC
- Contribution to $\mathrm{d}\sigma^{\pi^0}$ from broad x_2 range also at large y
- Which x_2 region isolated photons probe?

Backup

Prompt γ production in Au+Au at $y = 0$

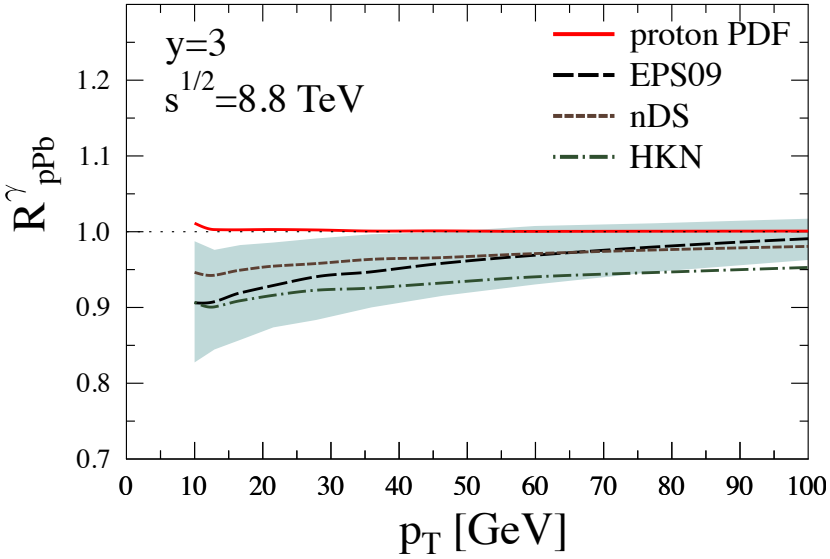
- R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [*JHEP* 1305 (2013) 030]



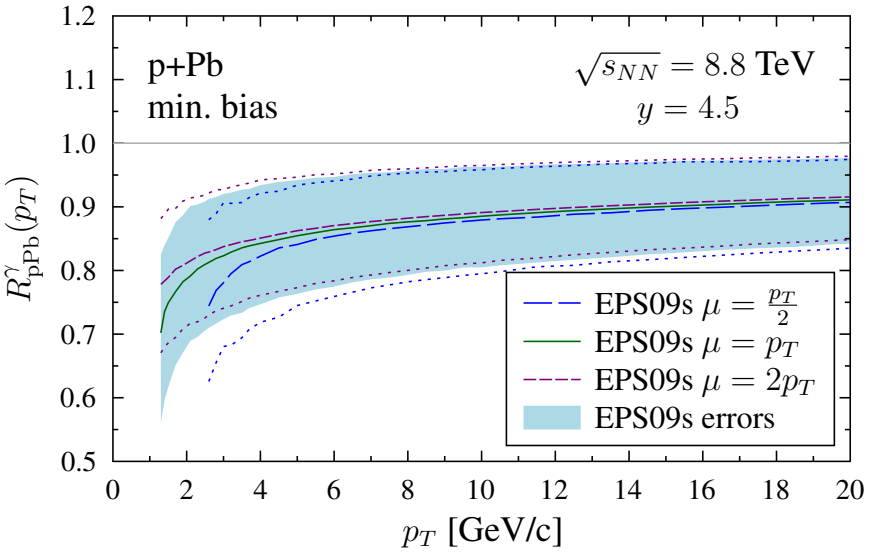
- At $p_T < 4\,\mathrm{GeV/c}$ contribution from thermal photons also

Prompt γ production at forward rapidities

- We have now resolved the numerical issues at small x in the `INCNLO` code (v1.4)
  $\Rightarrow$ We can go to lower p_T's also at the forward rapidities



F. Arleo *et al.*, *JHEP* 1104 (2011) 055



I.H., H.P. and K.J.E. *Work in progress*

Prompt γ production at forward rapidities

- We have also studied whether the planned forward calorimeter in ALICE could provide further constraints for the nPDFs:

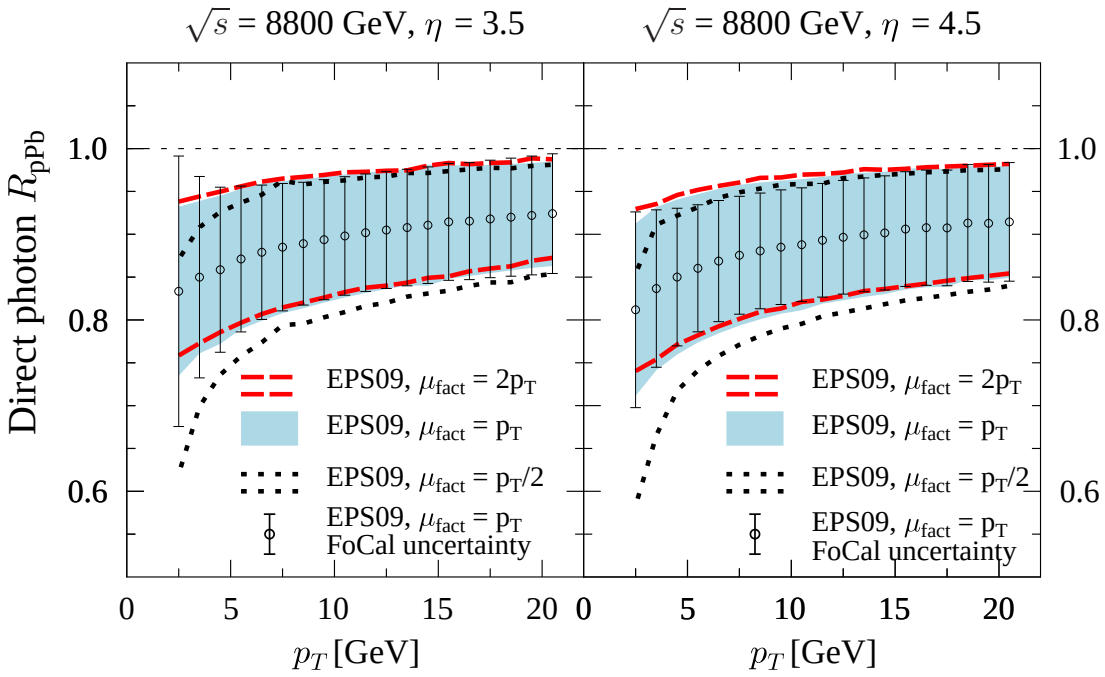
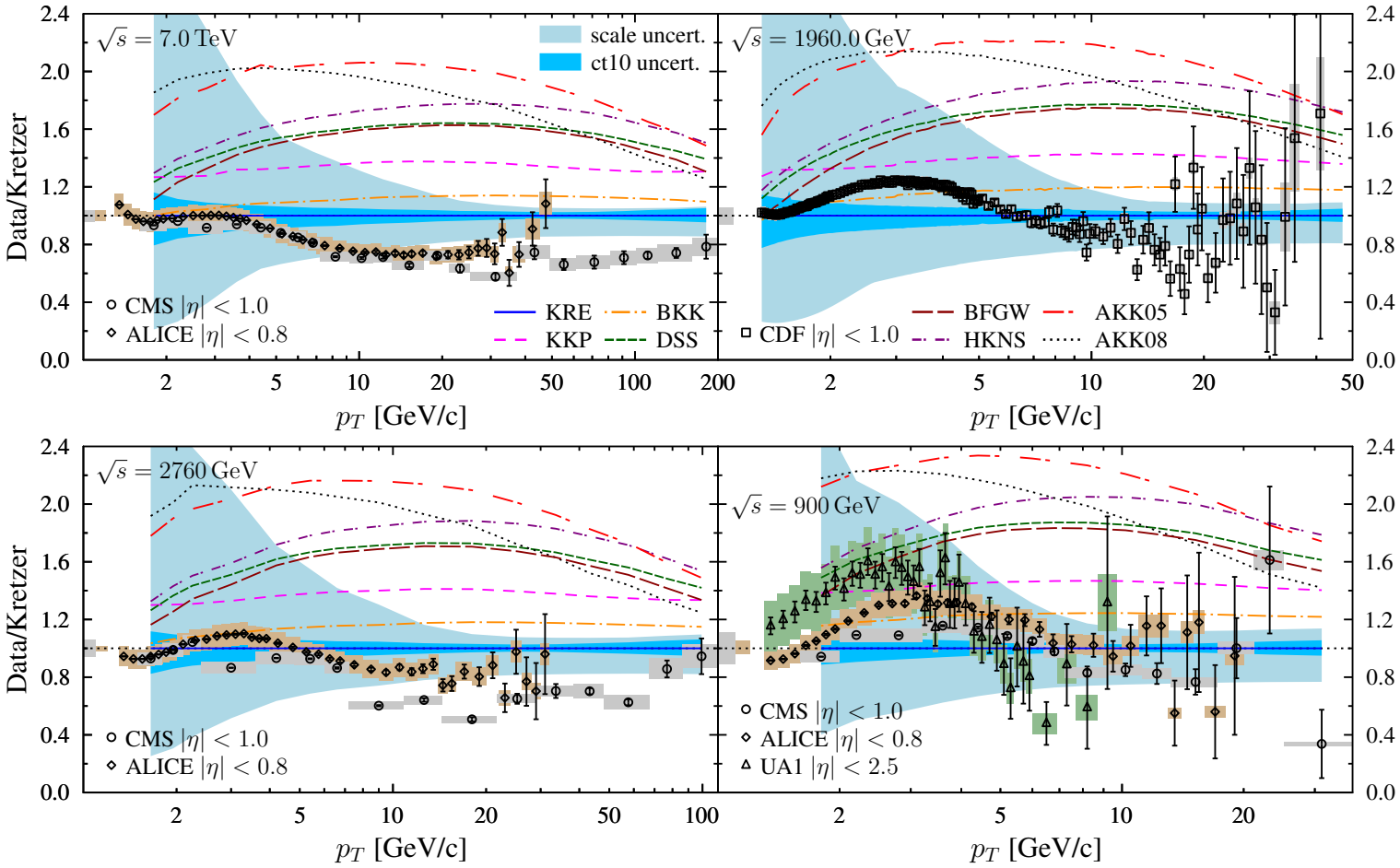


Figure from H. Paukkunen, relative error estimates from M. Leeuwen

- Estimated errors of the same order than in the EPS09 nPDFs

Charged hadron yield in p+p

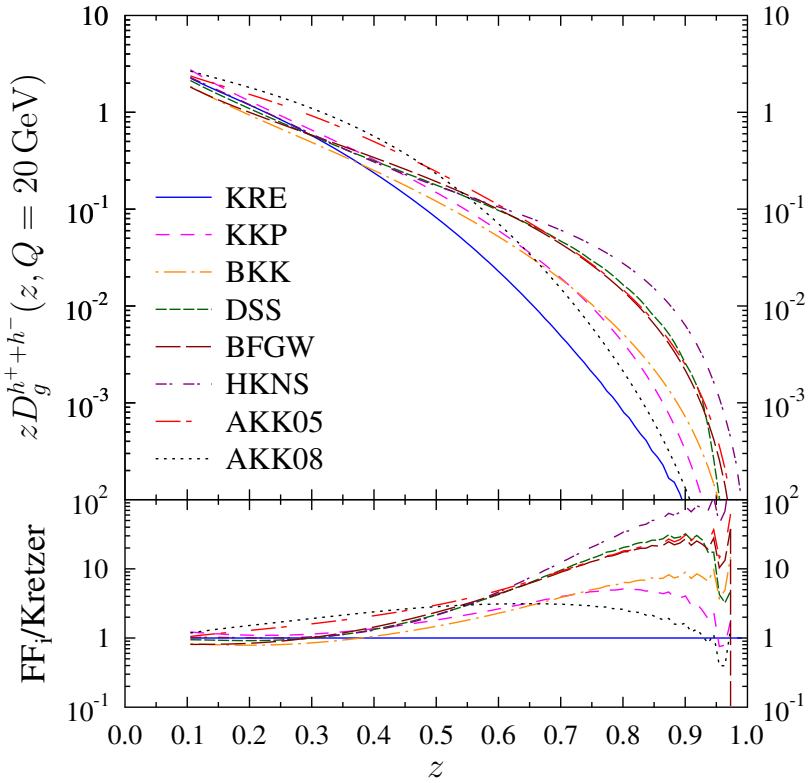
- Data/NLO ratios with different FFs for high $\sqrt{s}$ data



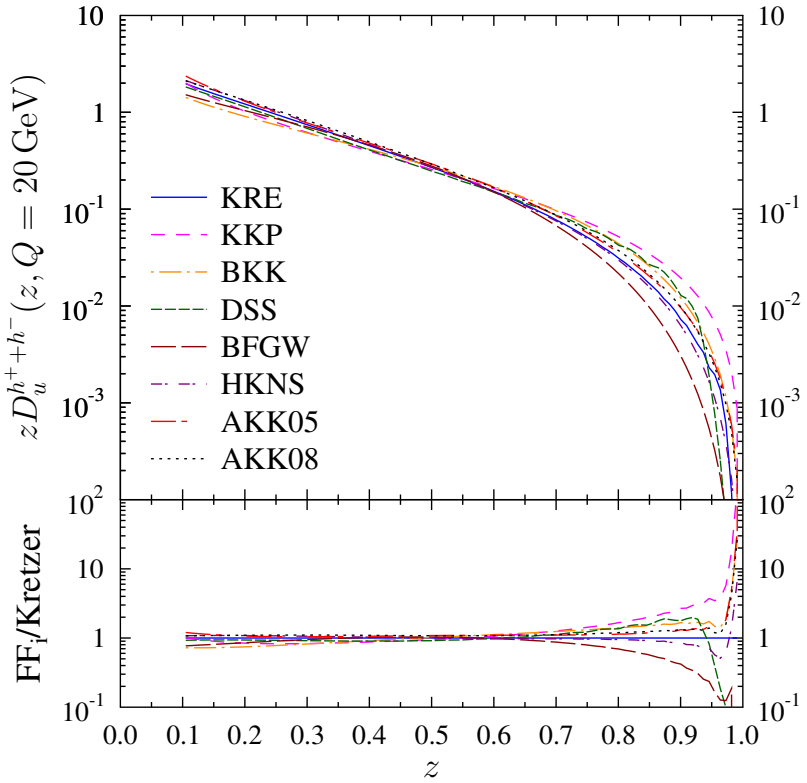
- Most recent FFs overpredict the high p_T and $\sqrt{s}$ data

Fragmentation Functions

Charged hadron FFs for gluons:



Charged hadron FFs for u-quarks:



- Quark FFs well constraint with $\mathrm{e}^+ + \mathrm{e}^-$ data
- Large diffenrences in gluon FFs