Status of pQCD calculations from Jyväskylä

Workshop on Saturation Signals, Utrecht

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In collaboration with

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23.10.2013

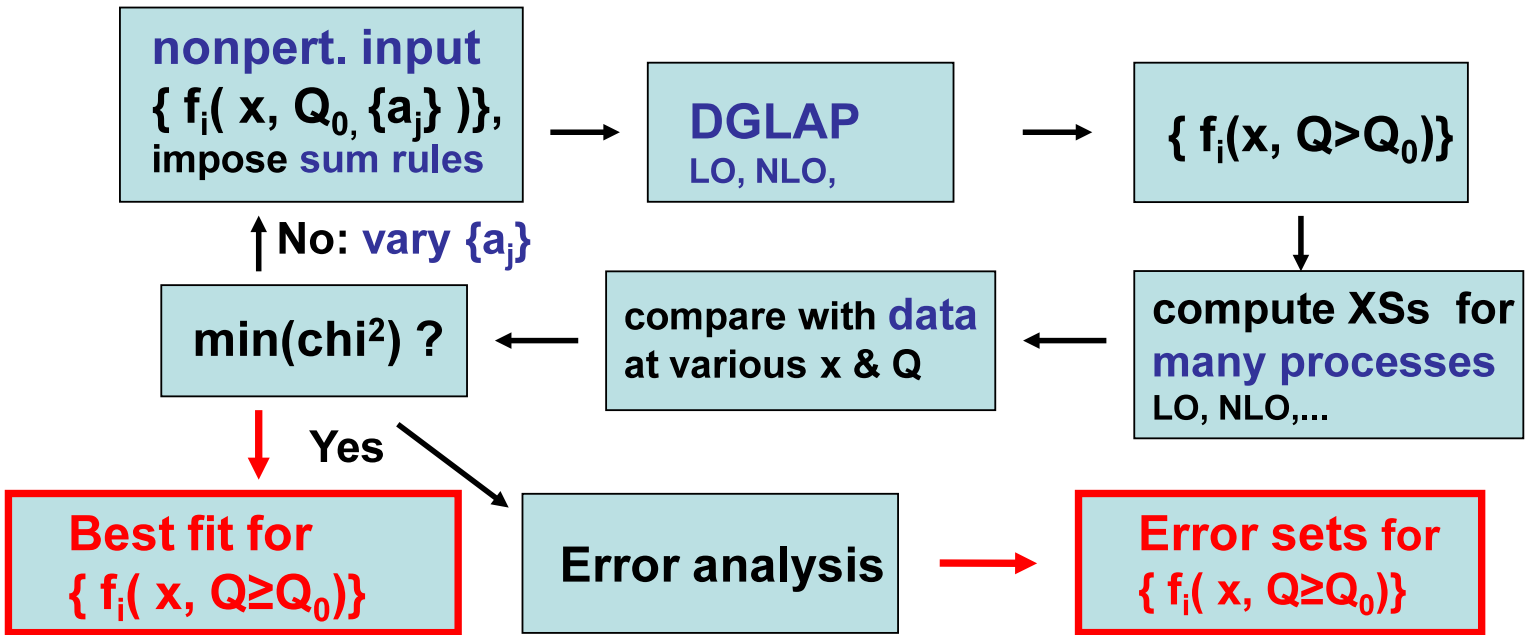
Outline

Parton Distribution Functions (PDFs)

Collinear Factorization framework

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

- $f_i(x,Q^2)$ determined through global analysis:



[from K.J. Eskola]

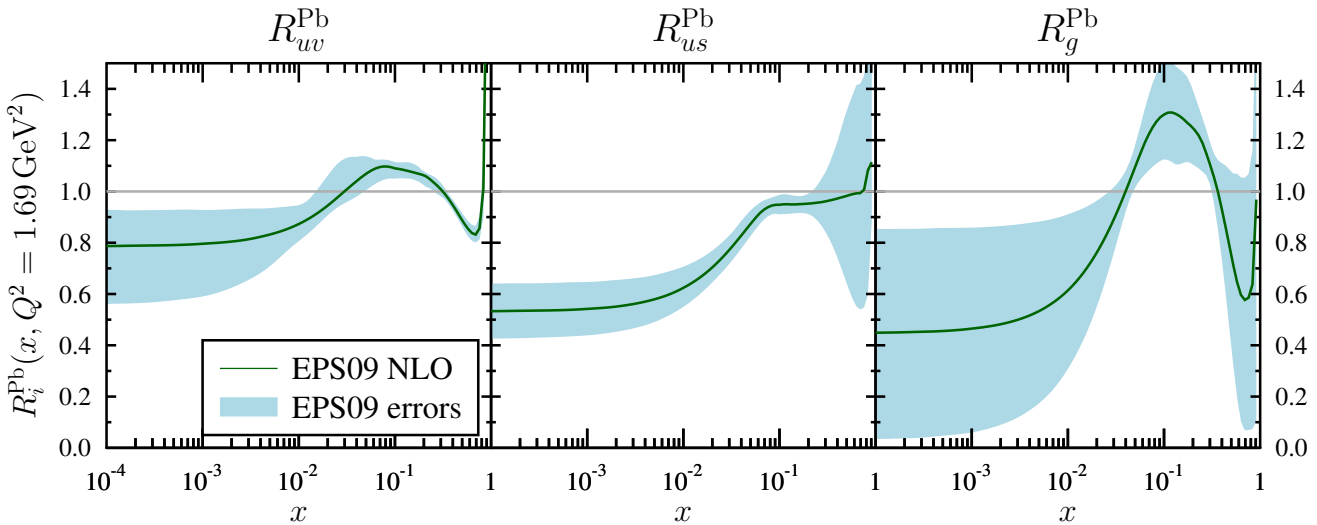
Nuclear PDFs

- PDFs modified in nuclear collisions $\Rightarrow$ Nuclear PDFs (nPDFs)

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

- Nuclear modifications $R_i^A(x, Q^2)$ also from global analysis
- Here we use EPS09 nPDFs with the error sets

  [Eskola, Paukkunen, Salgado *JHEP* 04 (2009) 065]



- Gluon modification poorly constrained in present fits
  - More constraints from prompt photon data?

Spatially dependent nPDFs

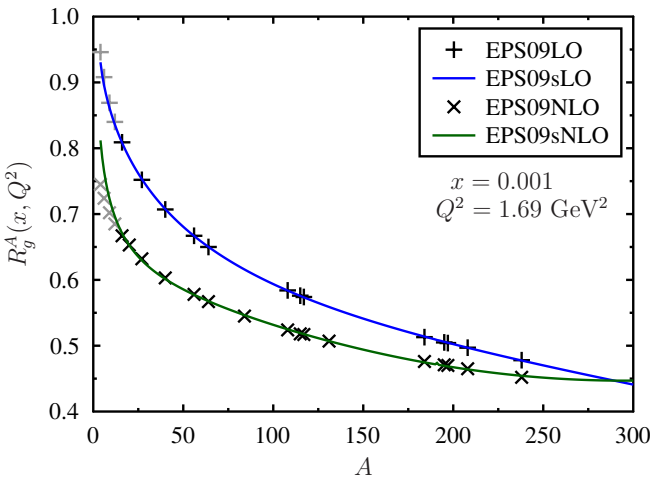
We have published also spatially dependent nPDF sets, e.g. EPS09s

[I.H, Eskola, Honkanen, Salgado *JHEP* 07 (2012) 073]

1. Assume a power series from for $r_i^A(x, Q^2, \mathbf{s})$:

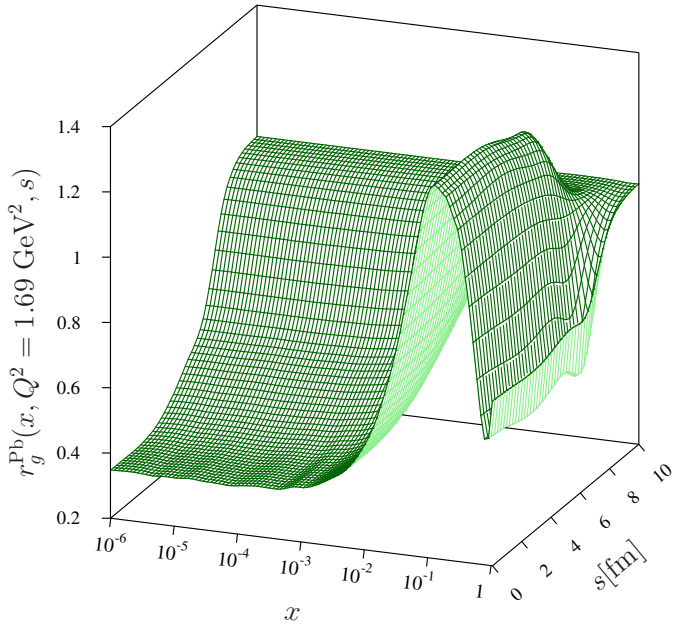
$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{n} c_j^i(x, Q^2) \, [T_A(\mathbf{s})]^j$$

2. Use A dependence of EPS09 to get values for $c_j^i(x, Q^2)$

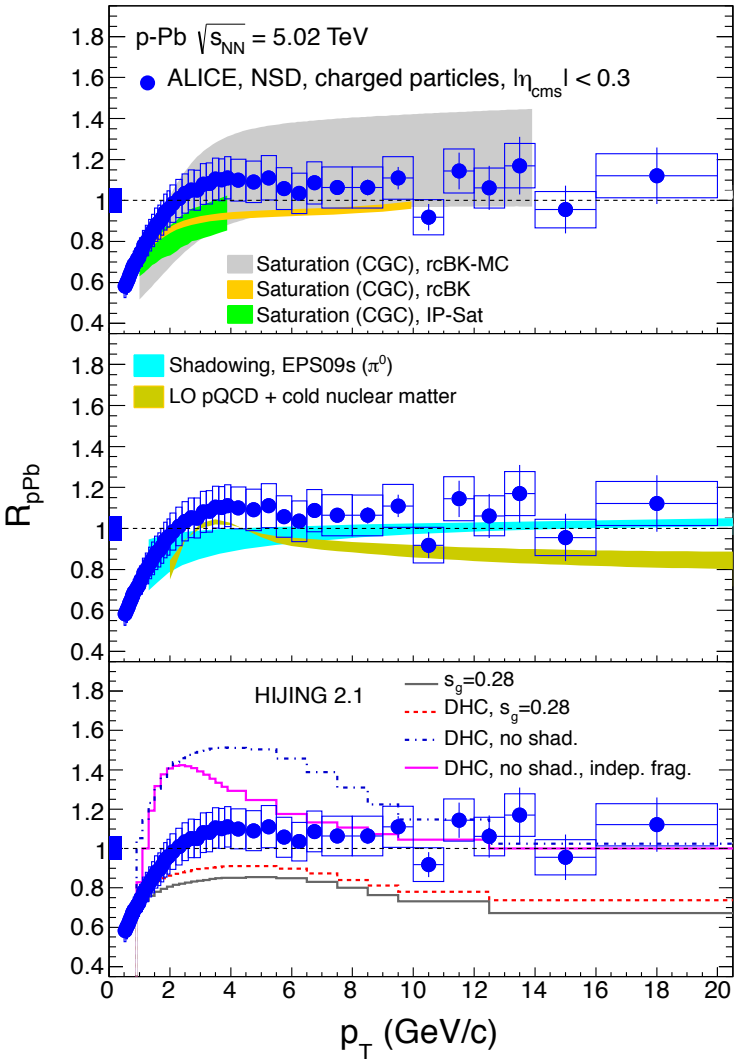


3. Repeat the fitting for each parton flavors

4. Outcome: Spatially dependent nPDFs



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

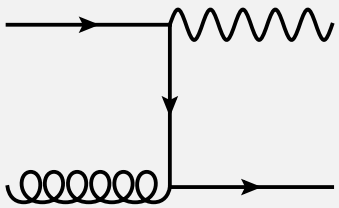
Our π^0 prediction (*JHEP* 07 (2012) 073) consistent with the data

Prompt photon production

- Prompt photons consists of two components:

Direct photon production

e.g. Compton scattering

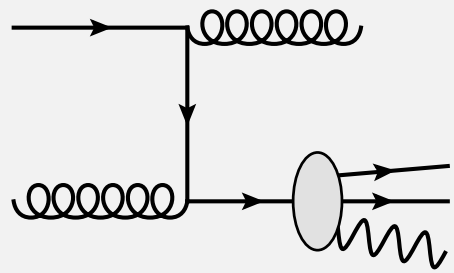


- Calculated from pQCD
- Provides a direct probe to the gluon PDFs
- Naive LO approximation:

$$x_2 \sim \frac{2p_T}{\sqrt{s}} \mathrm{e}^{-y}$$

Fragmentation photon production

parton fragments into photon, e.g.



- Calculated with non-perturbative fragmentation functions
- Carries a fraction of the parent partons momenta

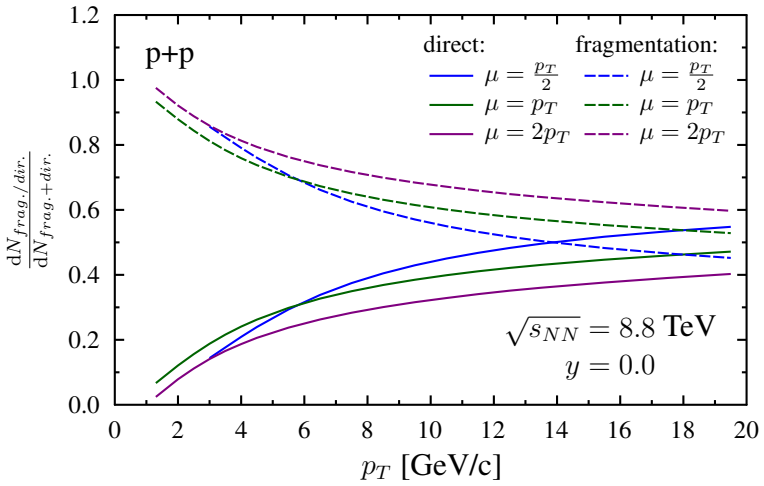
$$p_T^{\gamma} = z \cdot p_T^{p},$$

typically $\langle z \rangle \sim 0.5$

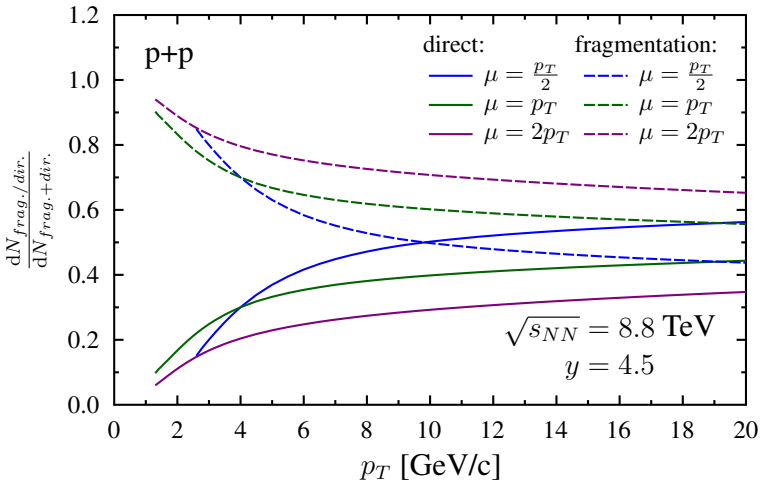
- Two components experimentally indistinguishable

Direct vs. fragmentation photons

- The relative contribution from direct and fragmentation
- At mid-rapidity



- At forward rapidity



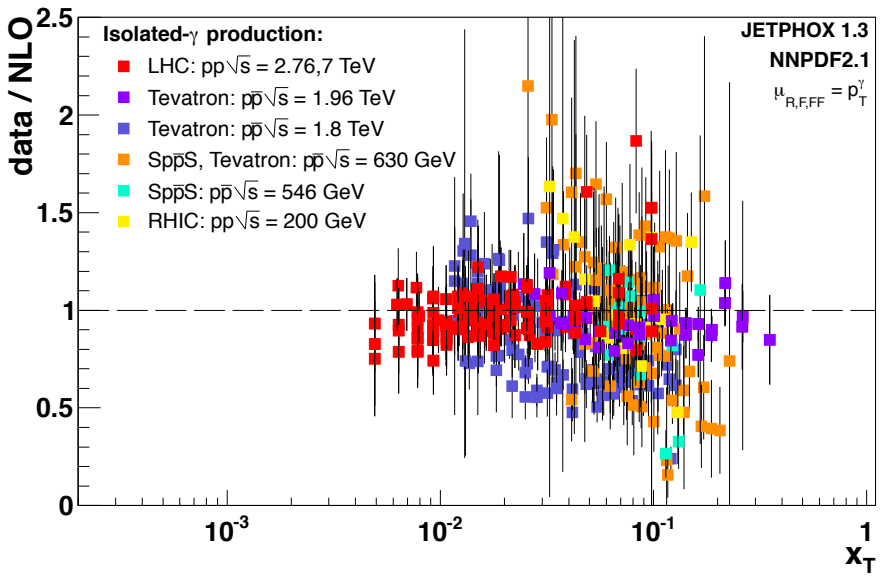
- In NLO the division scale dependent
- At low p_T the fragmentation photons dominate
- Similar behaviour in mid- and forward rapidities
- We use BFGII FFs for photons and CTEQ6.6 or CT10 proton PDFs

Isolated photons

- Isolation cut reduce the background from hadronic decays:
  - Reject photons which have $\sum E_T^{had} > E_T^{max}$ inside a cone

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- Isolation cut reduces also fragmentation photons
  $\Rightarrow$ Isolated photons more sensitive to smaller x values

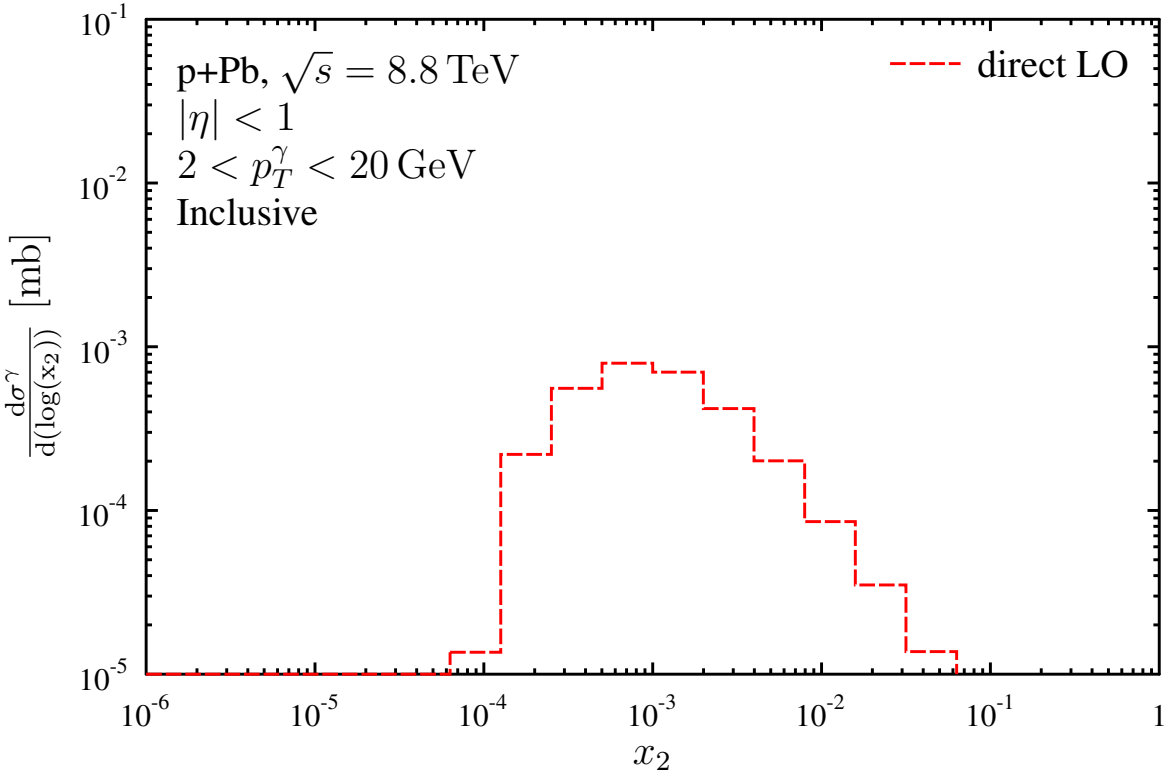


- Good agreement with NLO pQCD and data in wide range of $\sqrt{s}$

[d'Enterria, Rojo *Nucl.Phys.* B860 (2012) 311-338]

x_2 sensitivity at mid-rapidity

- The inclusive NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



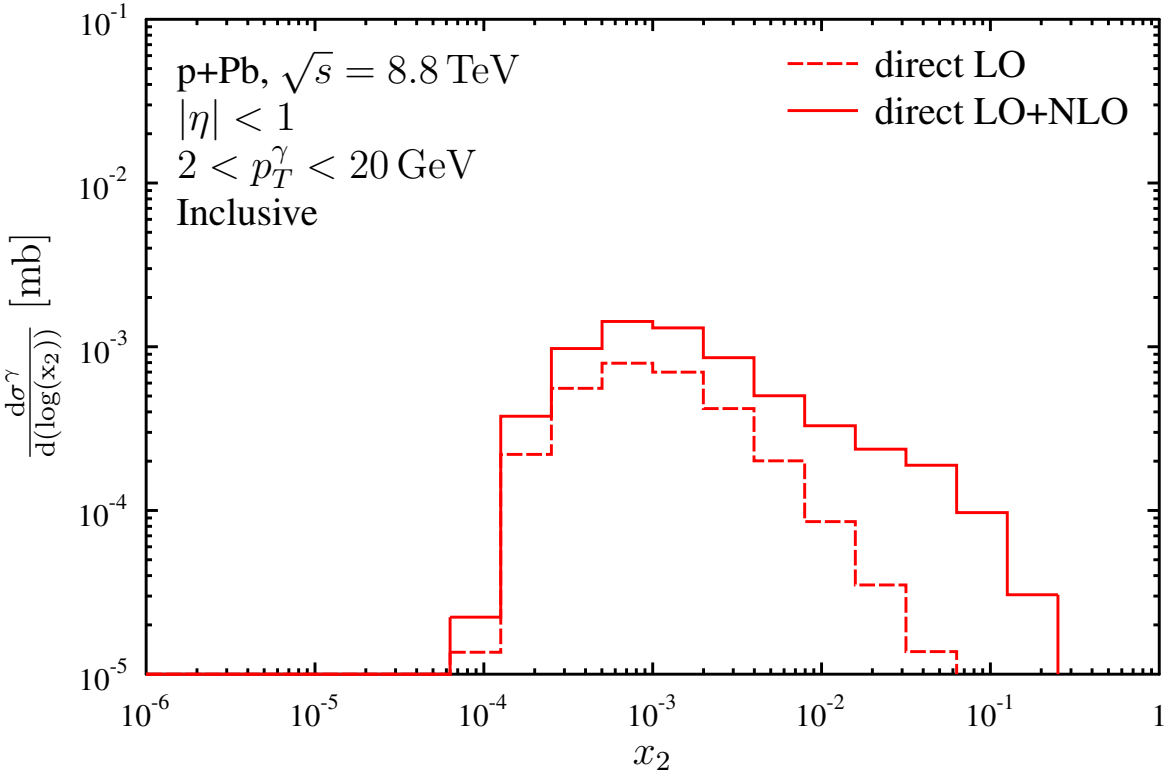
- The LO direct component follows the naive expectation

$$x_2 \sim \frac{2p_T}{\sqrt{s}} \mathrm{e}^{-y} \approx 7 \cdot 10^{-4}$$

- some spread due to a finite p_T and η interval

x_2 sensitivity at mid-rapidity

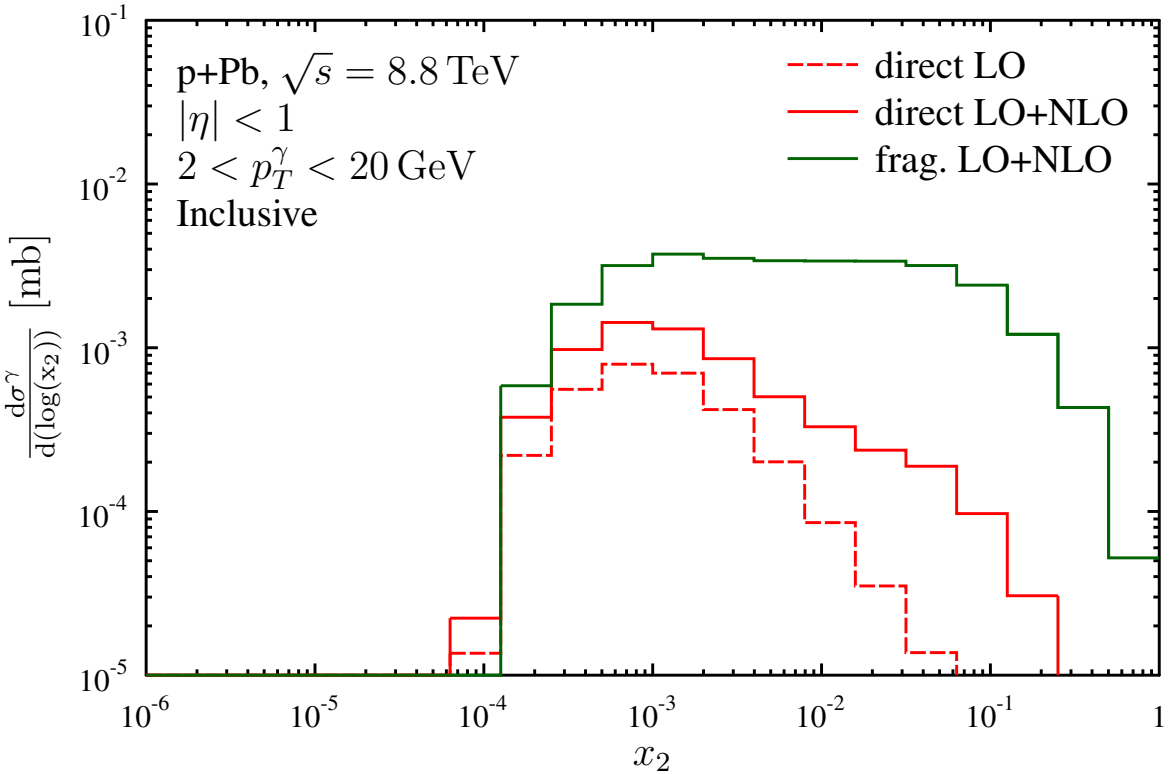
- The inclusive NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- NLO corrections introduce more channels (e.g. $2 \to 3$)
  $\Rightarrow$ Contribution also from higher x_2 values

x_2 sensitivity at mid-rapidity

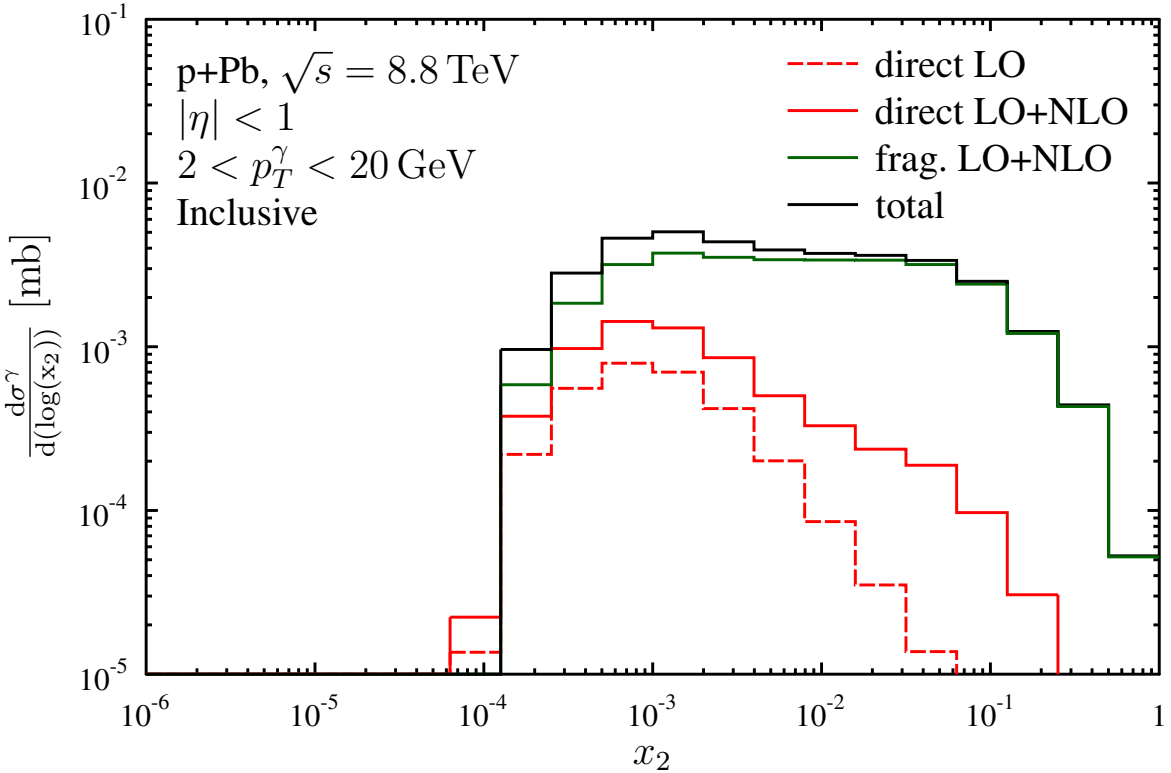
- The inclusive NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- The peak is shifted to higher x_2 due to the $z < 1$
- Large contribution from higher x_2 values from the fragmentation component

x_2 sensitivity at mid-rapidity

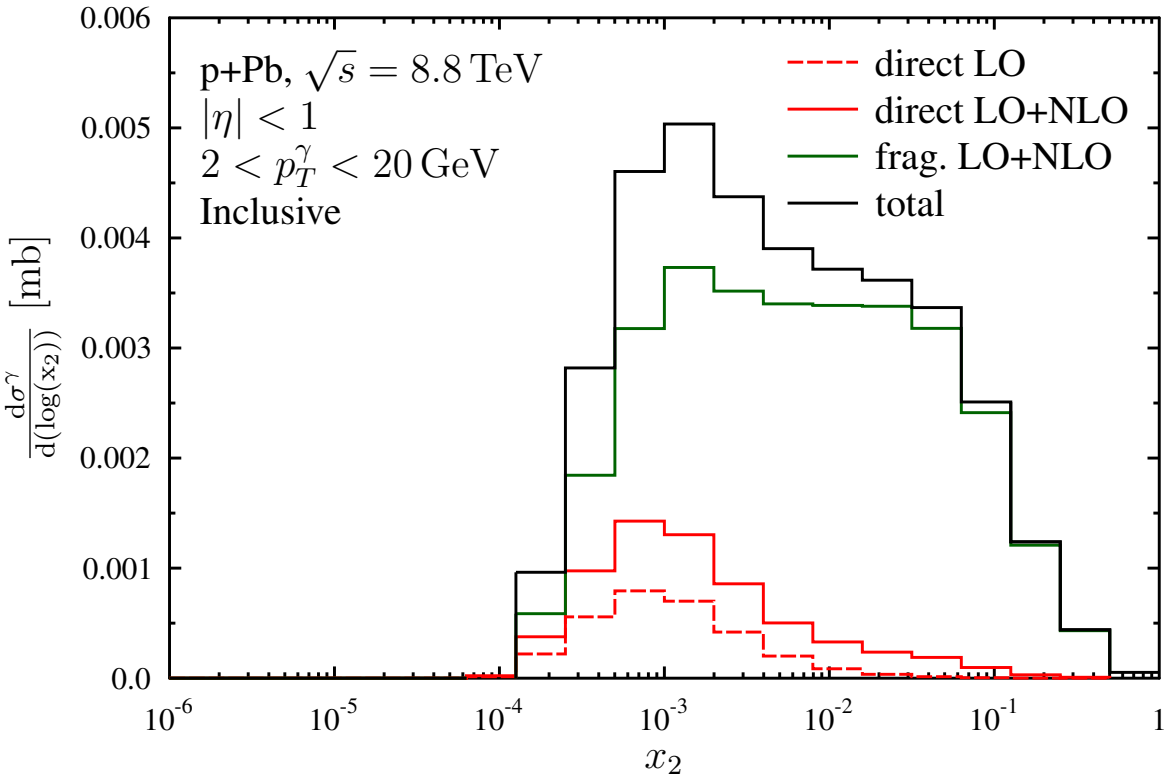
- The inclusive NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Fragmentation component dominant in this kinematical region
- Contribution to total inclusive NLO prompt photon cross section from a broad range of x_2
- How much does isolation suppress the fragmentation component?

x_2 distribution and isolation criteria

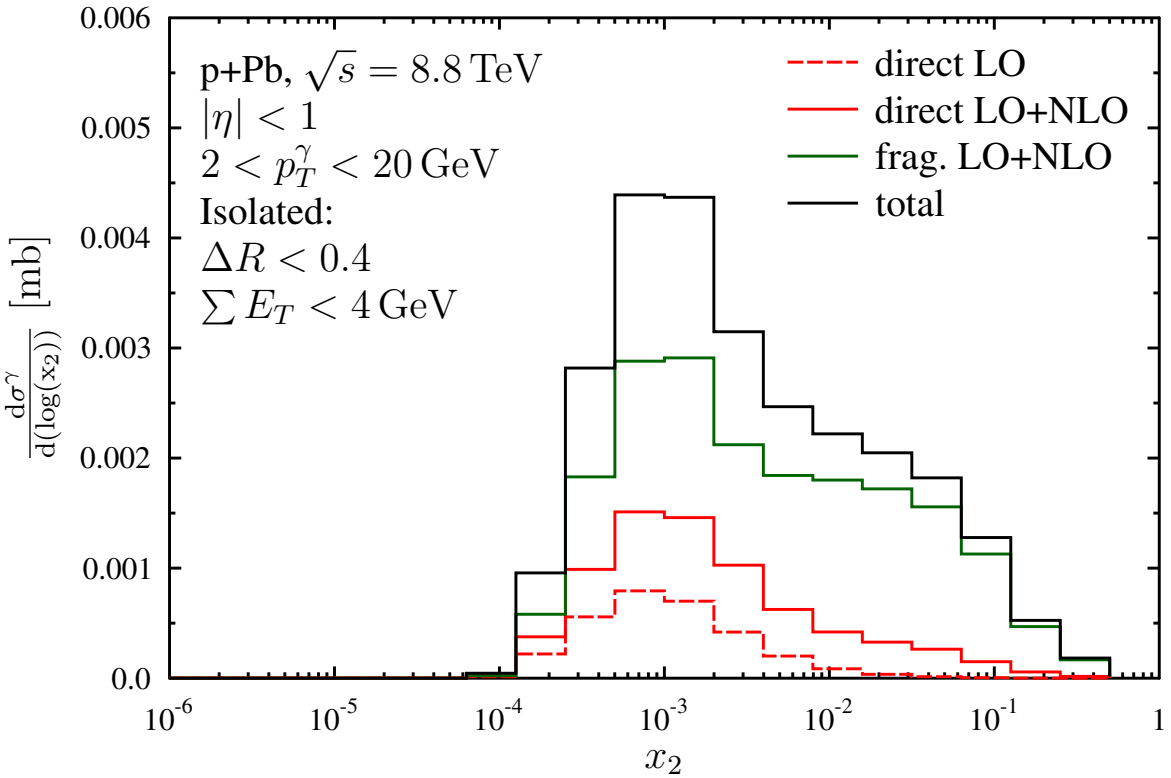
- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Same result as before but now with linear scale in $\mathrm{d}\sigma^\gamma$
- For inclusive photons $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.17$

x_2 distribution and isolation criteria

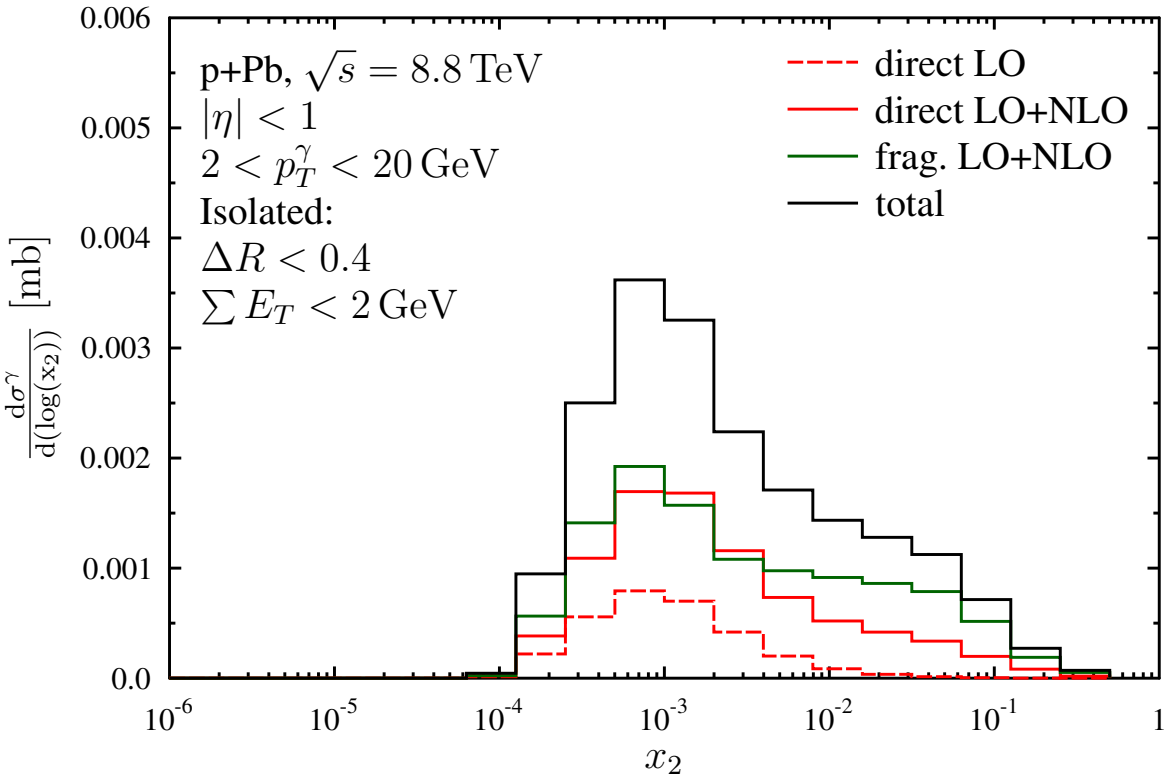
- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Isolation suppresses fragmentation component especially from larger x_2 values (small z)
- For $E_T^{max} = 4\,\mathrm{GeV}$ we have $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.28$

x_2 distribution and isolation criteria

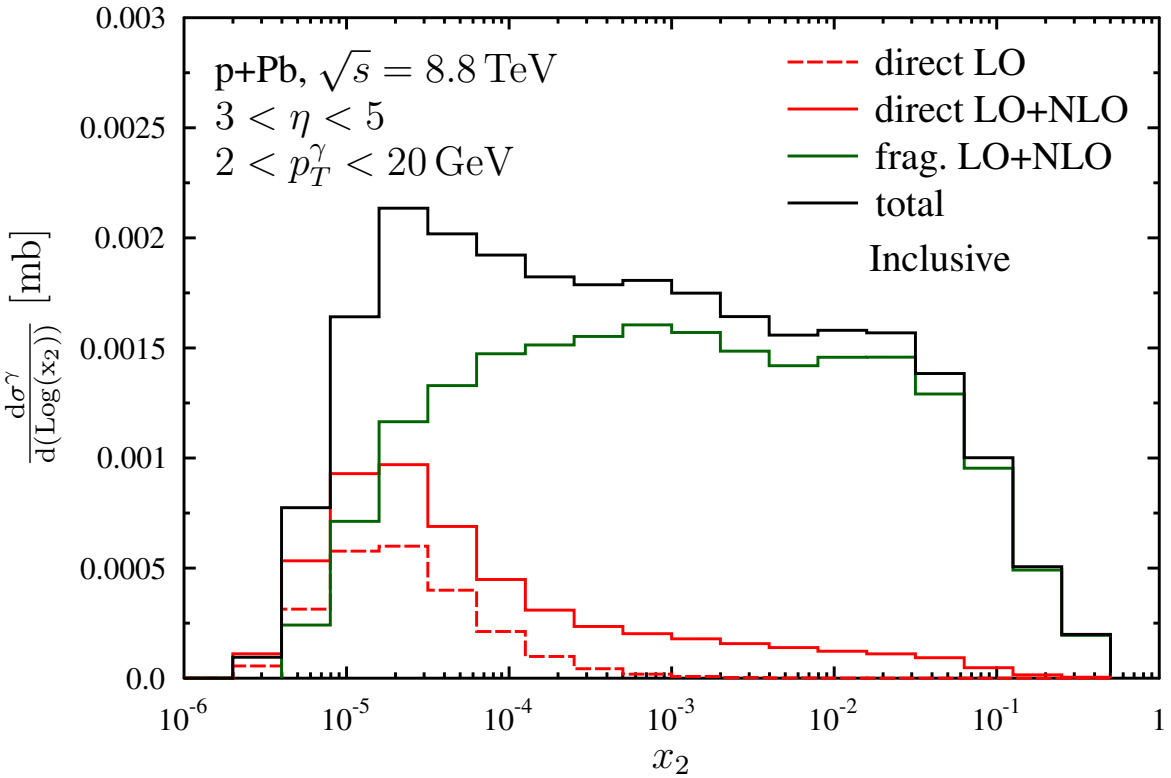
- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Further suppression with smaller E_T^{max}
- For $E_T^{max} = 2\,\mathrm{GeV}$ we have $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.43$
- Small increase of the direct NLO contribution with isolation

x_2 distribution in forward rapidities

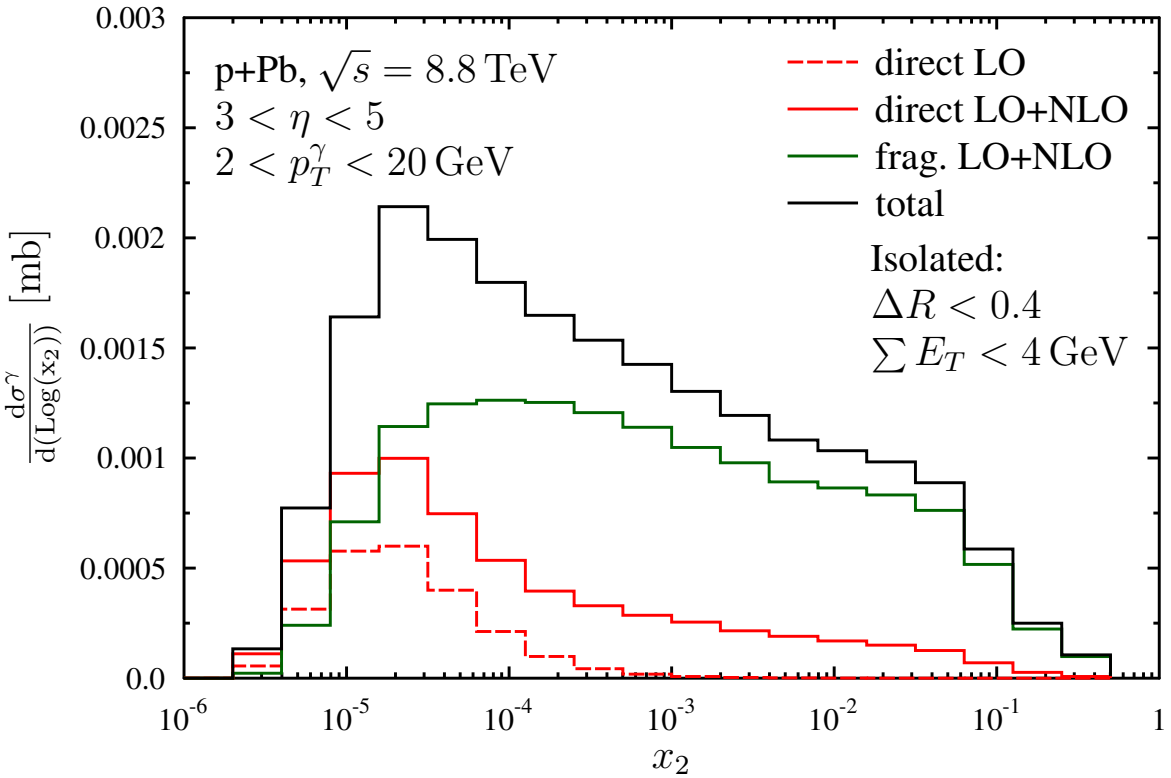
- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Forward rapidities probe smaller x_2 values
- Large contribution from larger x_2 values due to fragmentation
- For inclusive photons $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.21$

x_2 distribution in forward rapidities

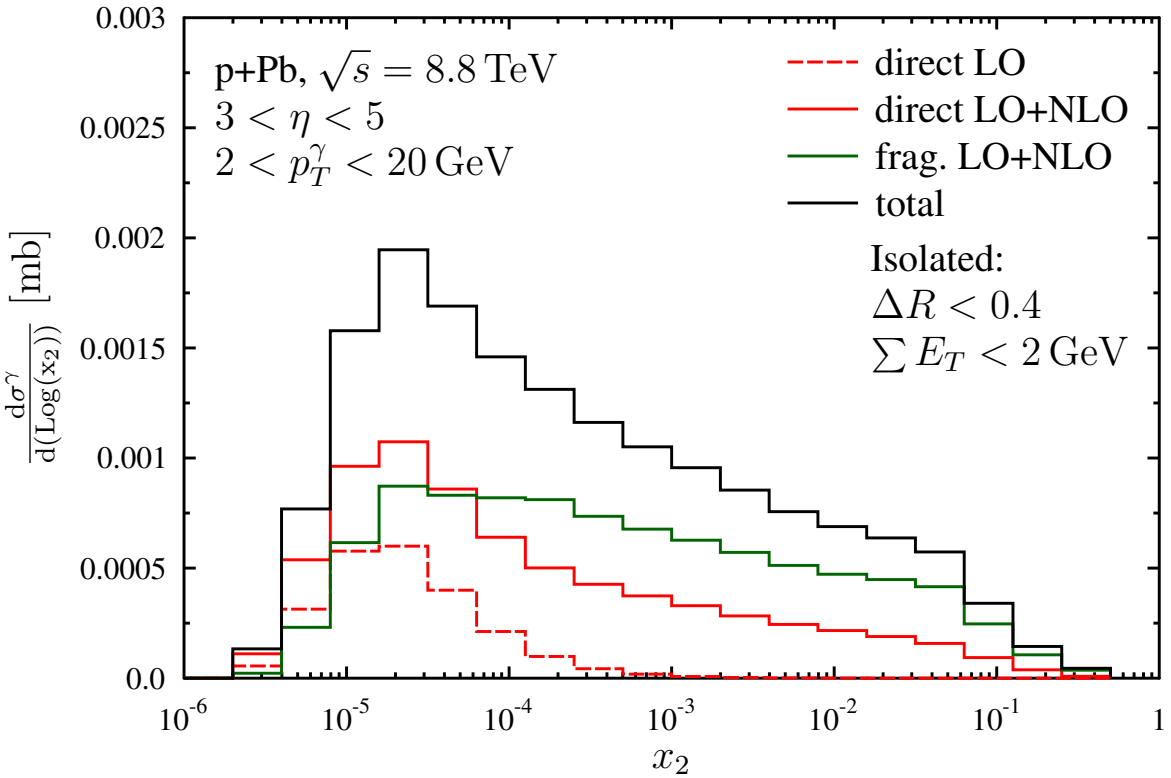
- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



- Isolation suppresses the fragmentation in large x_2 region
- For $E_T^{max} = 4\,\mathrm{GeV}$ we have $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.30$

x_2 distribution in forward rapidities

- The NLO cross section of prompt photons for p+Pb collisions, calculated using `JETPHOX 1.3.1_1` ($\mu = p_T$)



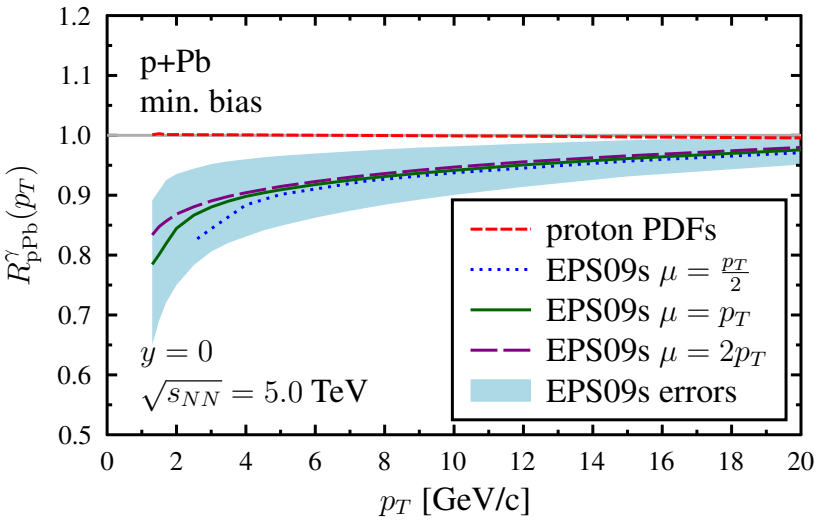
- Even with $E_T^{max} = 2\,\mathrm{GeV}$ some contribution also from larger x_2
- For $E_T^{max} = 2\,\mathrm{GeV}$ we have $\frac{\sigma^\gamma_{dir}}{\sigma^\gamma_{tot}} \approx 0.44$

R_{pPb} at mid-rapidity

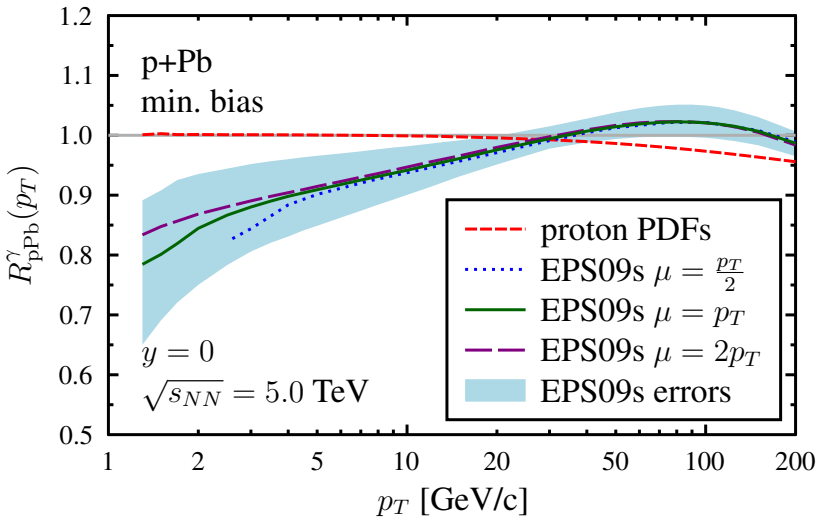
- R_{pPb} for inclusive prompt γ at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in NLO (with `INCNLO`)

  [I.H., K.J. Eskola, H. Paukkunen *JHEP* 1305 (2013) 030]

Linear scale in p_T



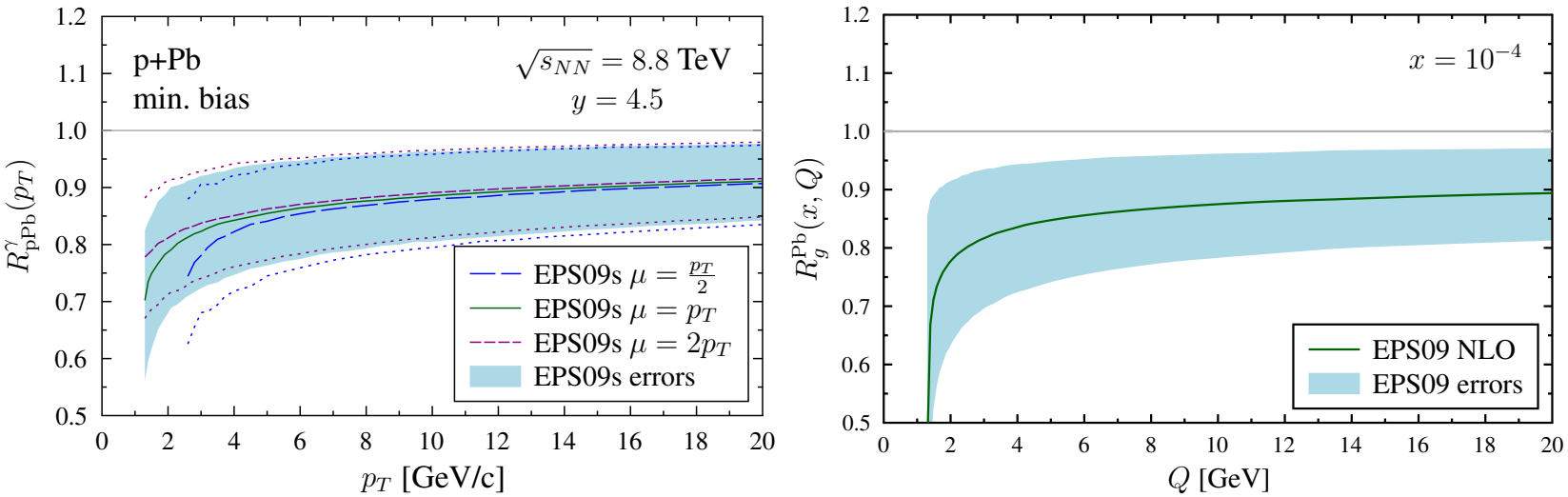
Logarithmic scale in p_T



- Suppression at $p_T < 20\,\mathrm{GeV}$ due to shadowing in the nPDFs
- Isospin effect negligible (red dashed line)
- Some scale dependence in $p_T < 5\,\mathrm{GeV}$

R_{pPb} at forward rapidities

- R_{pPb} for inclusive prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in NLO (with `INCNLO`) [I.H., K.J. Eskola, H. Paukkunen *work in progress*]



- More suppression than at $y = 0$ due to lower x_2 values
- Very rapid scale evolution in $R_g^{\mathrm{pPb}}(x, Q^2)$ from NLO DGLAP
  $\Rightarrow$ No factor 2 suppression even at the lowest p_T

R_{pPb} at forward rapidities

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

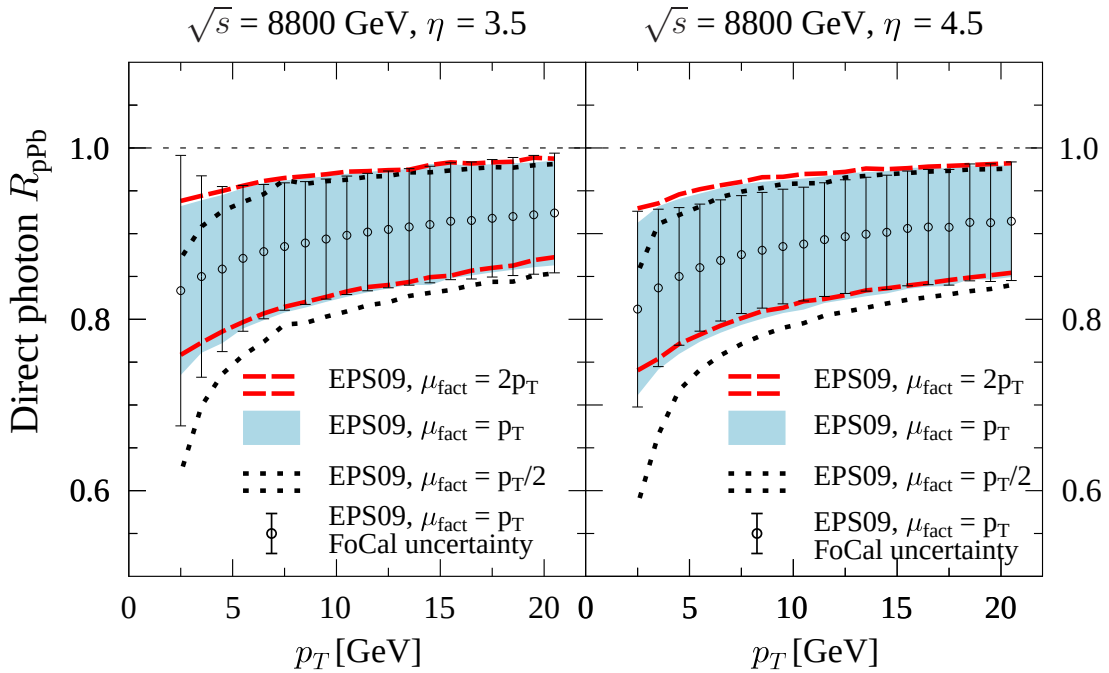
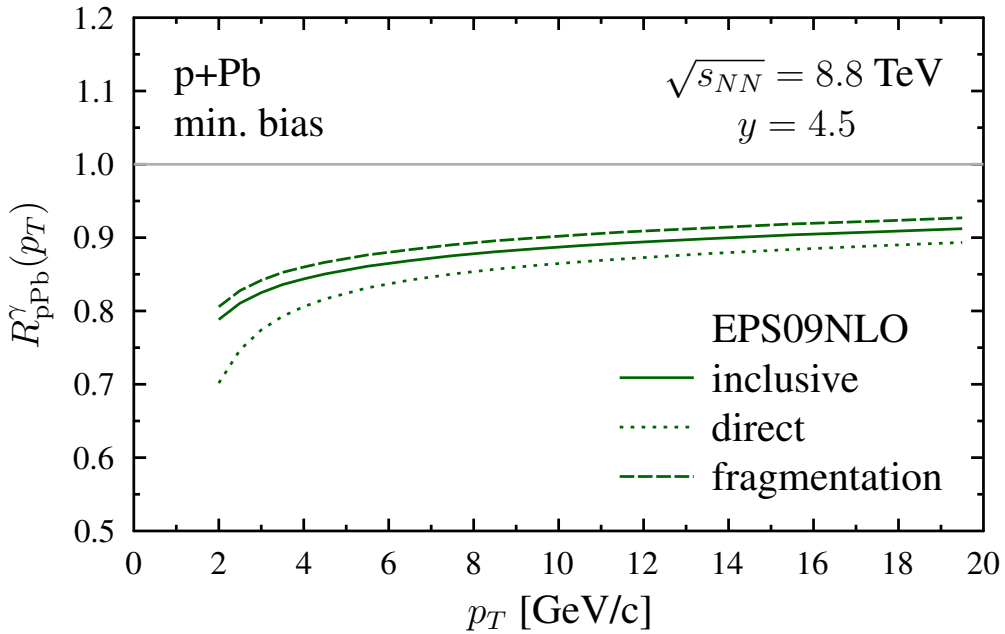


Figure from H. Paukkunen, relative error estimates from M. Leeuwen

- Estimated errors of the same order than in the EPS09 nPDFs
  $\Rightarrow$ Not clear how much the data could reduce the uncertainty

Isolated R_{pPb}?

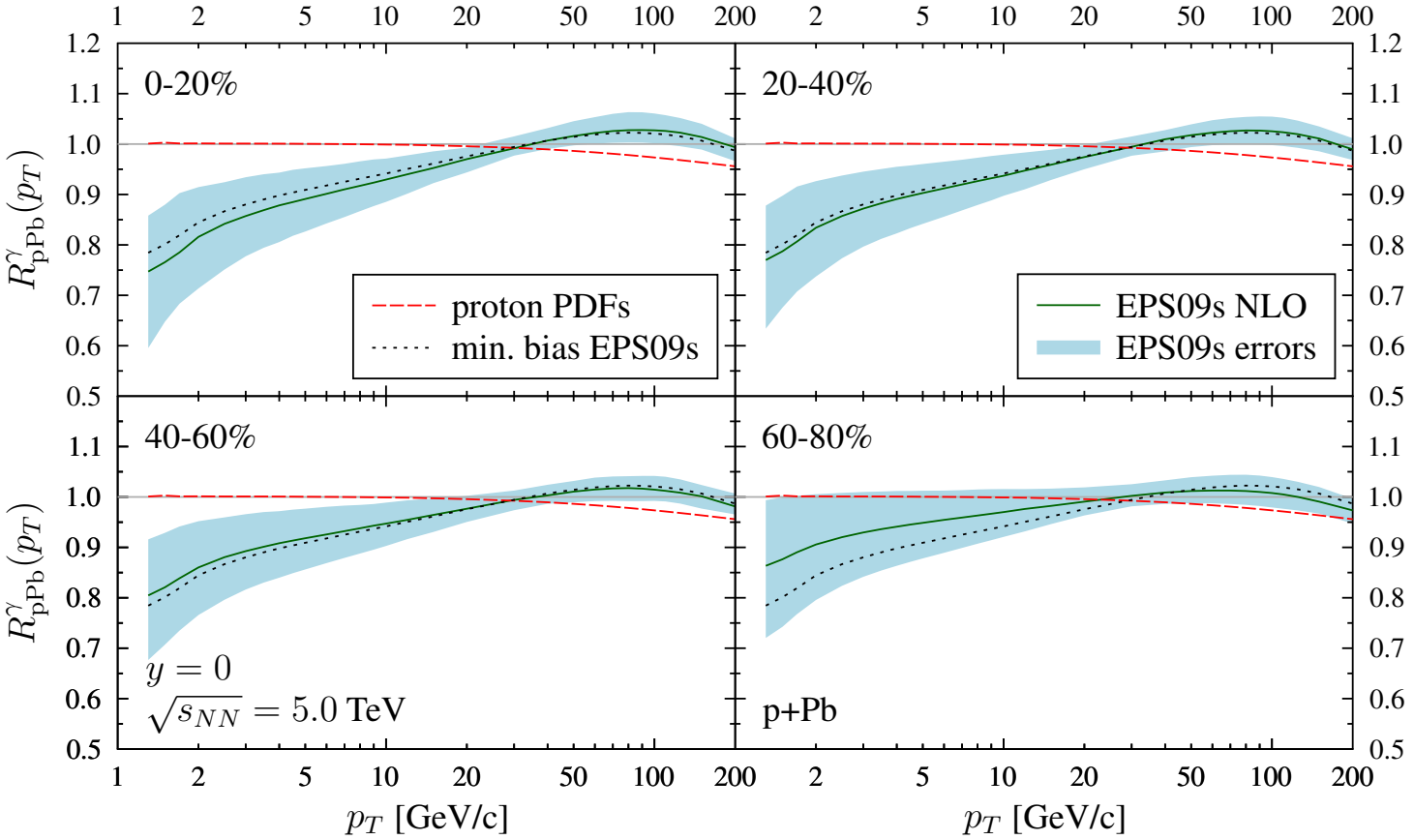
- R_{pPb} for inclusive prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in NLO [I.H., K.J. Eskola, H. Paukkunen *work in progress*]



- Isolation increase the relative contribution from direct photons $\Rightarrow$ Isolated R_{pPb} closer to R_{pPb} with direct component only
- Work in progress...

Centrality dependent R_{pPb} at $y = 0$

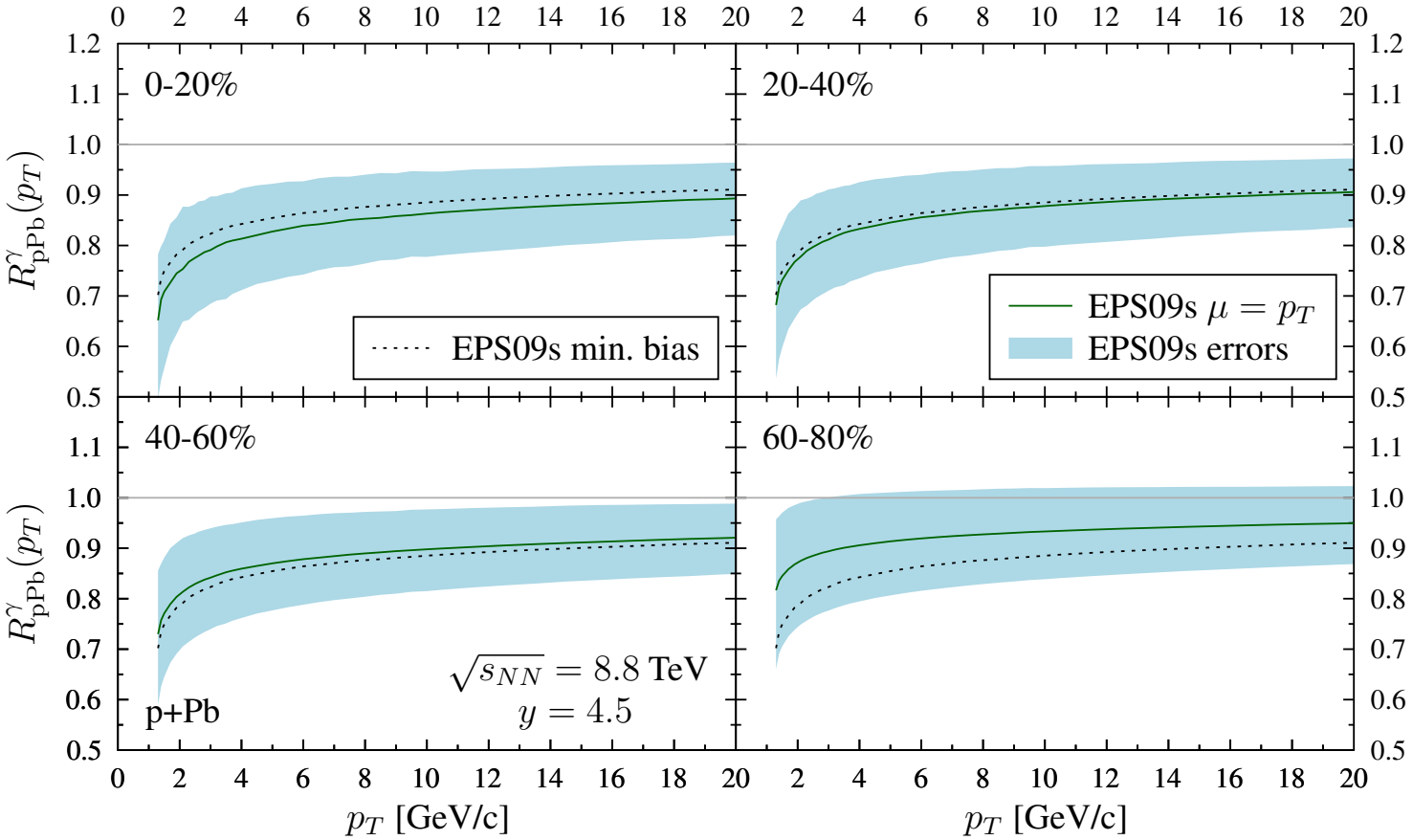
R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [I.H., K.J.E., H.P. *JHEP* 1305 (2013) 030]



- Nuclear effects stronger in central collisions than in peripheral collisions

Centrality dependent R_{pPb} at $y = 4.5$

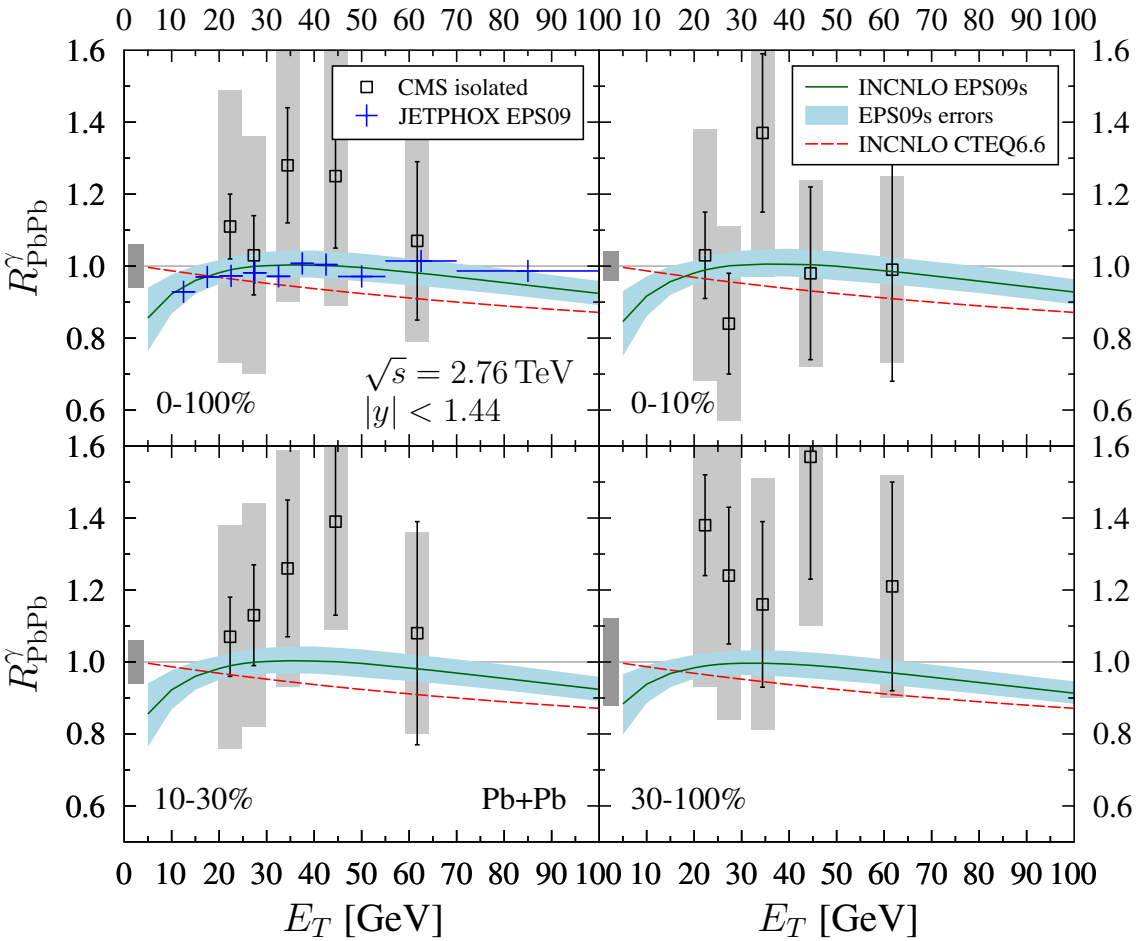
R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in four centrality classes in NLO (with `INCNLO`) *Work in progress*



- Larger suppression than at $y = 0$ for $p_T < 20\,\mathrm{GeV}$
  $\Rightarrow$ Centrality dependence more apparent

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]

Summary & Outlook

Summary

- The prompt photons have a large contribution from fragmentation component at low p_T
- Isolation cut suppresses the fragmentation contribution
  $\Rightarrow$ Isolated photons probe smaller x_2 values in p+Pb collisions
- We expect slightly more suppression for isolated photon R_{pPb} than for inclusive photons
- Centrality dependence more apparent at forward rapidities

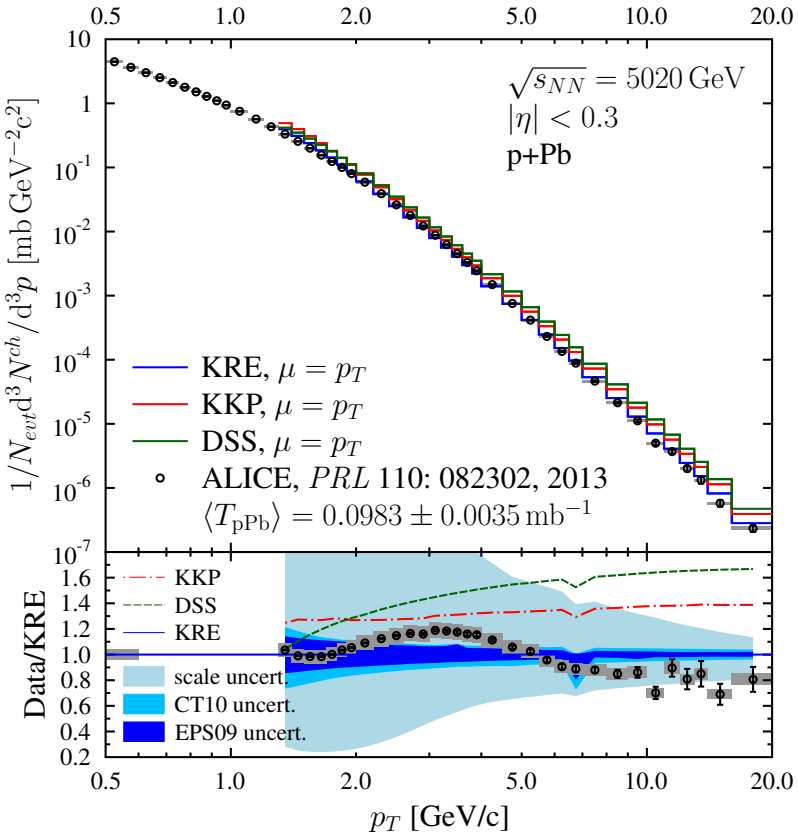
Outlook

- Calculate the R_{pPb} for isolated photons at mid- and forward rapidities
- Publish our results for particle production at forward rapidities (during this year?)
- New nPDF fit with the p+Pb data?

Backup

p+Pb collisions at the LHC

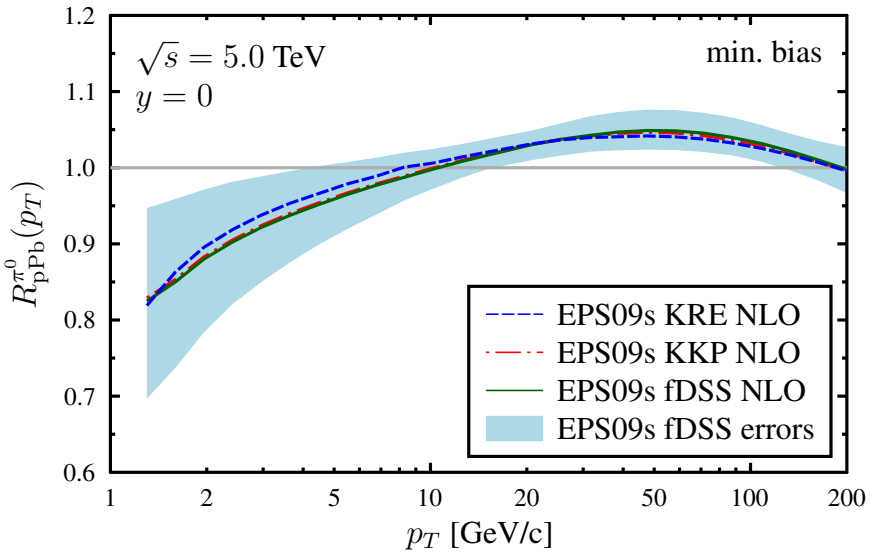
Charged particle yield in p+Pb:



I.H., H.Paukkunen., D. d'Enterria

Work in progress

Nuclear modification factor:



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

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 $[b_1, b_2]$

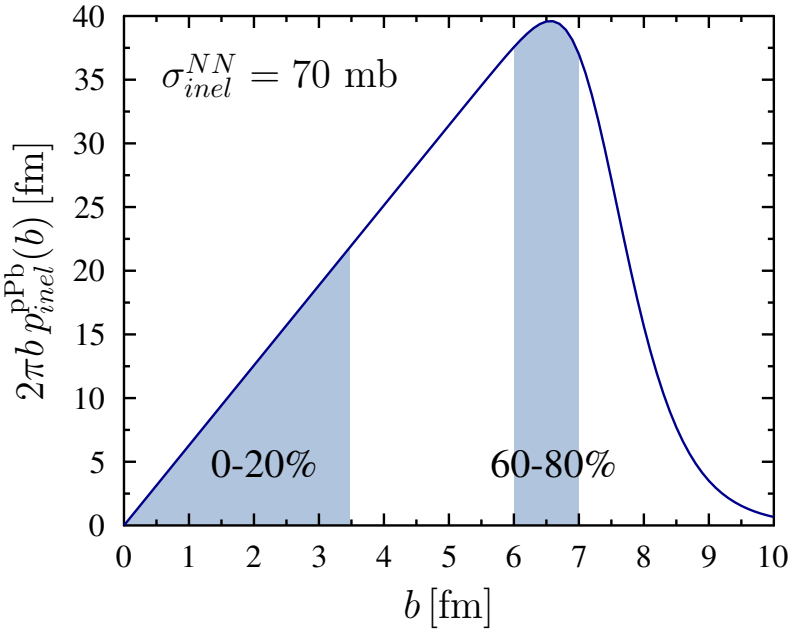
$$\sigma_{inel}^{AB}(b_1, b_2) = \int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, p_{inel}^{AB}(\mathbf{b})$$

- 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

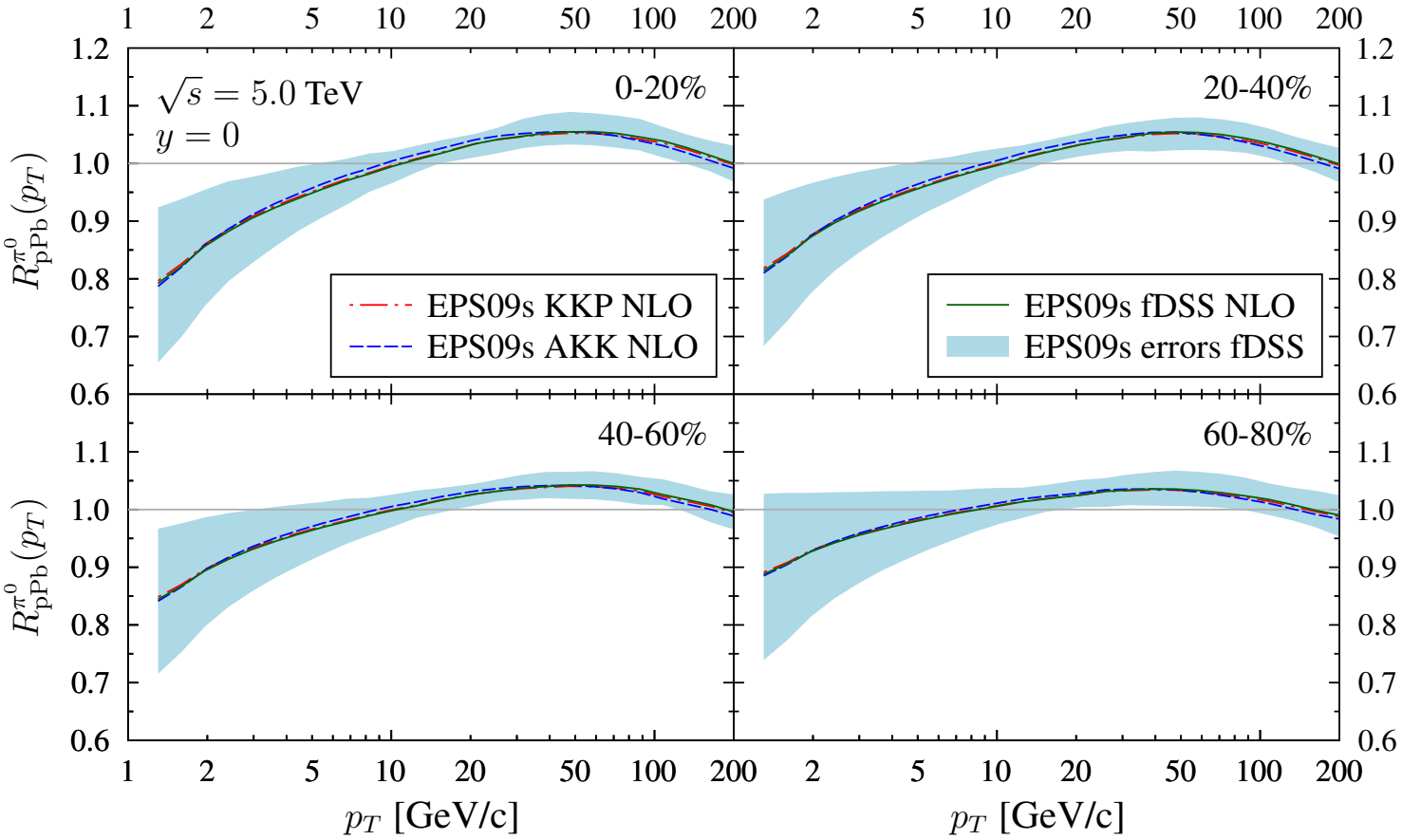
$\sqrt{s_{NN}} = 5.0$ TeV, $\sigma_{inel}^{NN} = 70$ mb



	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

π^0 production in p+Pb at $y = 0$

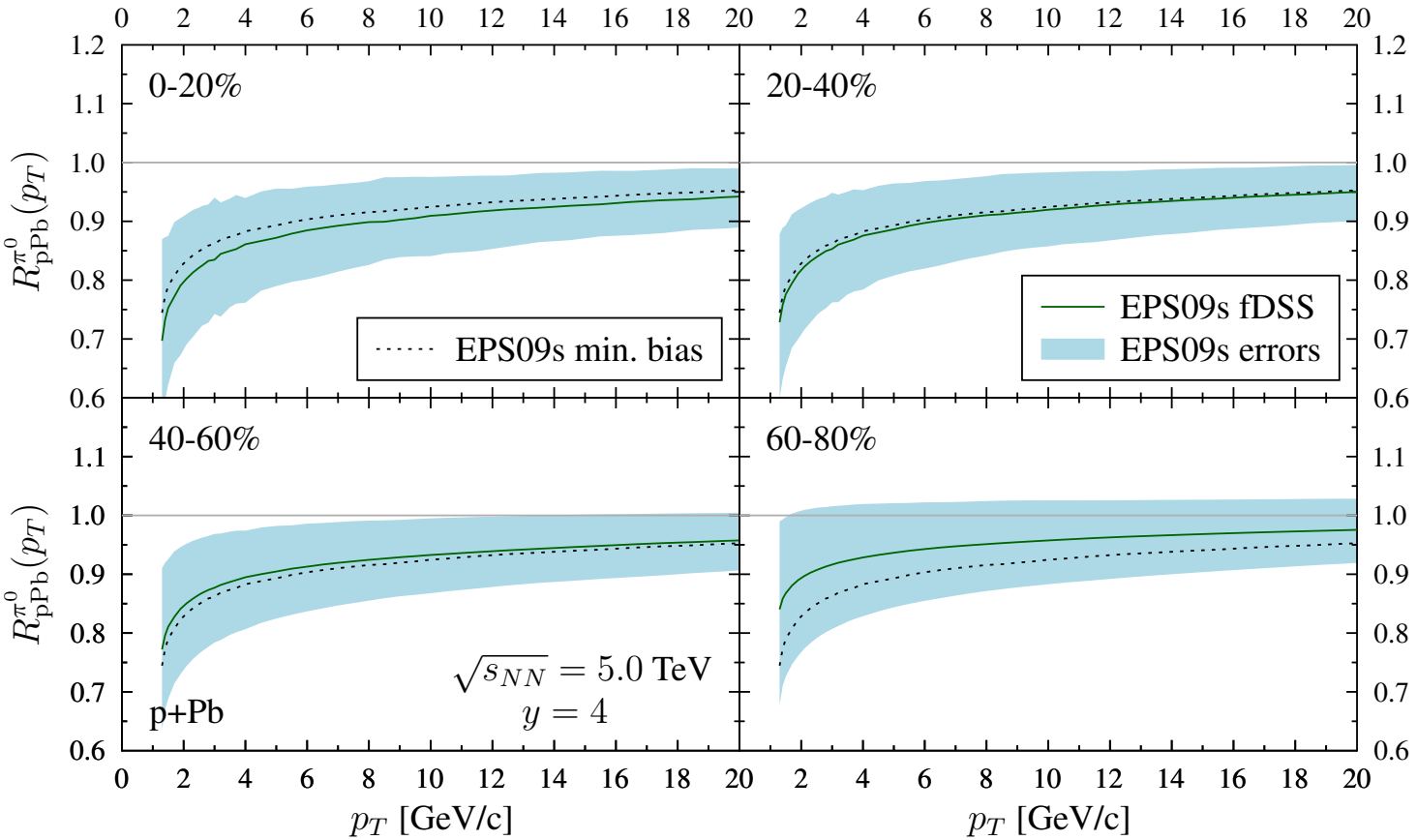
- R_{pPb} for inclusive π^0 at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [*JHEP* 1207 (2012) 073]



- 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*]

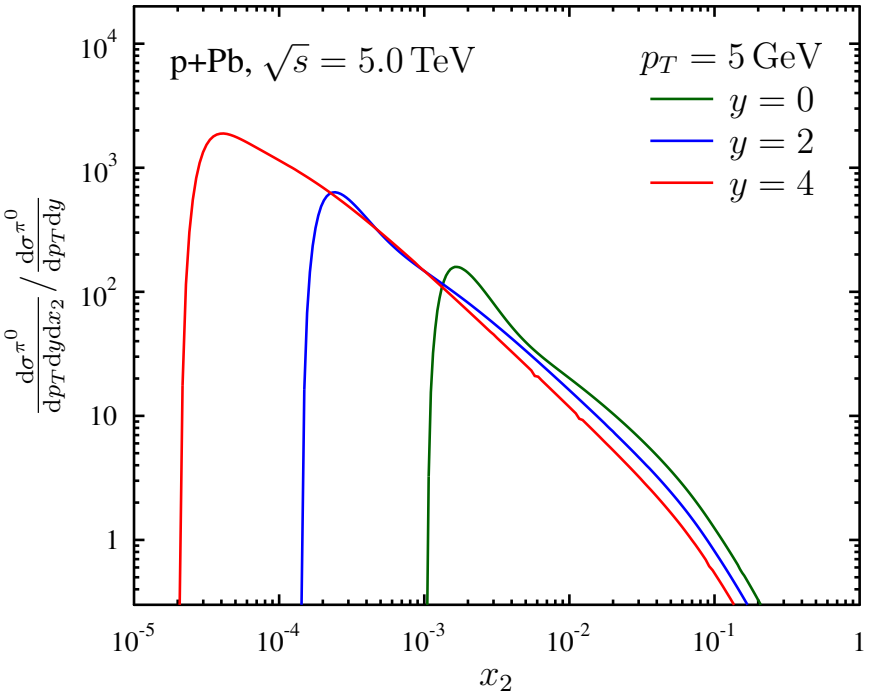


- More suppression at small p_T than at $y = 0$

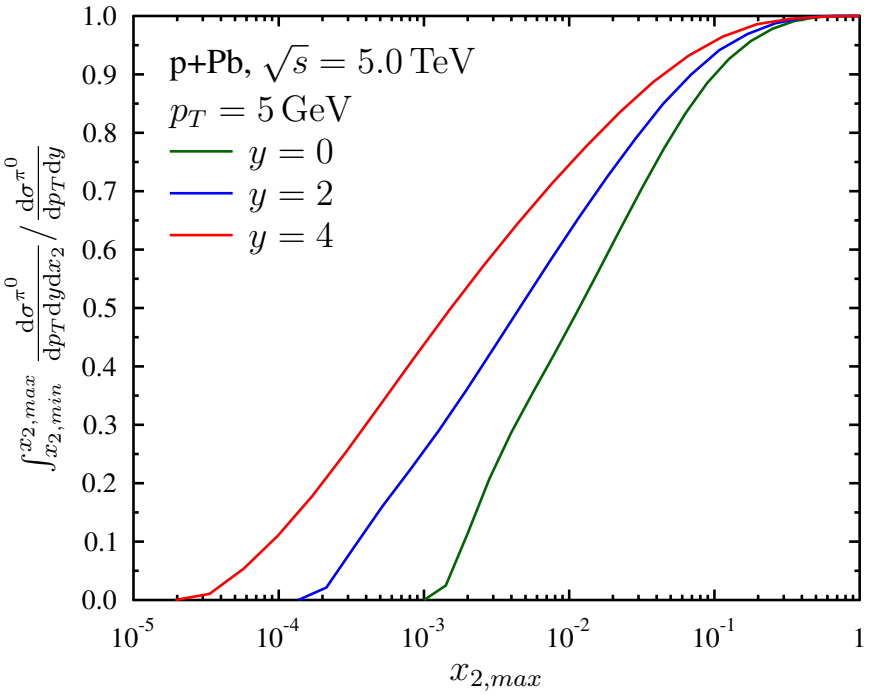
x_2 values for different rapidities

- 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

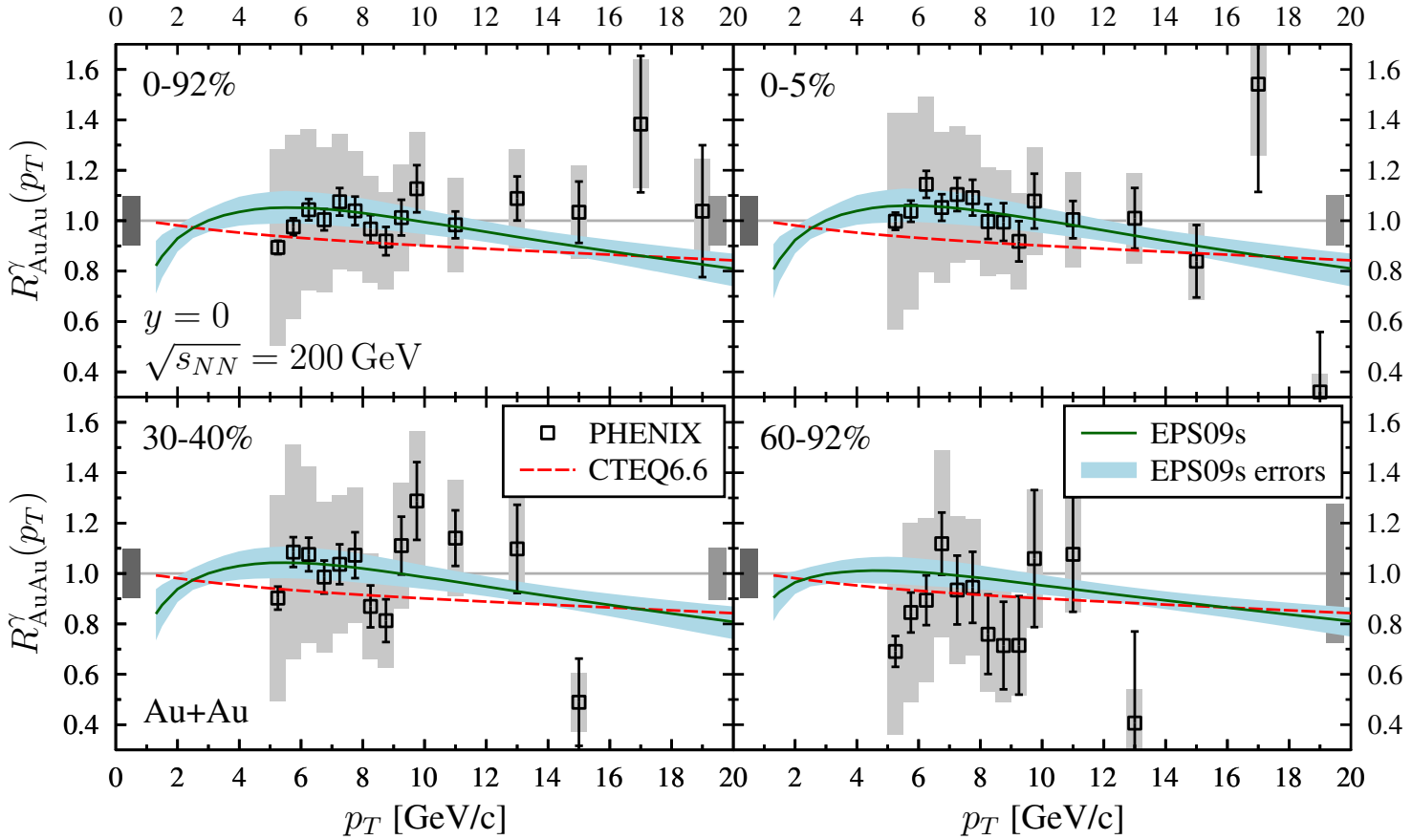


- Contribution to $\mathrm{d}\sigma$ from broad x_2 range also at forward rapidities

[Work in progress]

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

- R_{AuAu} 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