Spatially dependent nPDFs and their applications in inclusive pion and prompt photon production

Hard Probes

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Outline

1. Introduction
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   - Spatially dependent nPDFs
2. π^0 production in p+Pb
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3. Prompt γ production in p+Pb
   - x_2 sensitivity
   - Centrality dependence
   - Isolated γ
4. Summary & Conclusions

Nuclear Parton Distribution Functions (nPDFs)

Collinear Factorization framework

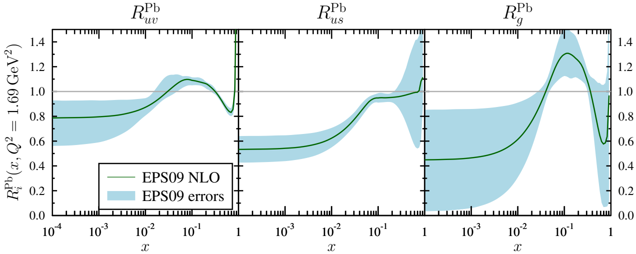
$$d\sigma^{AB\to k+X} = \sum_{i,j,X'} f_i^A(x,Q^2) \otimes f_j^B(x,Q^2) \otimes d\hat{\sigma}^{ij\to k+X'} + \mathcal{O}(1/Q^2)$$

- PDFs modified in nuclear collisions ⇒ Nuclear PDFs (nPDFs)

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

- Nuclear modifications $R_i^A(x,Q^2)$ from global analysis
- Here we use EPS09 NLO nPDFs

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



- More constraints for gluon nPDF from p+Pb collisions?

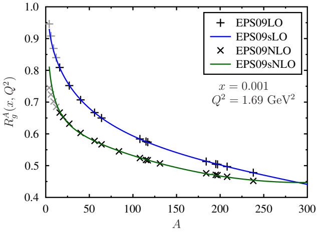
Spatially dependent nPDFs

We have also published spatially dependent nPDF sets, e.g. EPS09s
[I.H, Eskola, Honkanen, Salgado *JHEP* 07 (2012) 073]

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

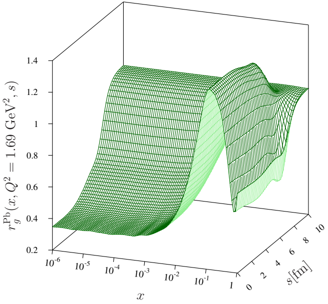
$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{4} c_j^i(x, Q^2) \left[T_A(\mathbf{s})\right]^j$$

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



3. Repeat the fitting for each parton flavor

4. Outcome: Spatially dependent nPDFs



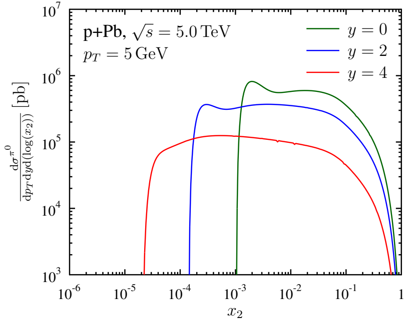
x_2 sensitivity in different rapidities

Hadron production

- Involves convolution with fragmentation functions (FFs):

$$d\sigma^{\pi^0}_{\rm pPb} = \sum_k d\sigma^k_{\rm pPb} \otimes D^{\pi^0}_k(z, Q^2_F),$$

$\Rightarrow$ Contribution to $d\sigma^{\pi^0}_{\rm pPb}$ from broad x_2 range in NLO



- Even at $y = 4$ $d\sigma^{\pi^0}_{\rm pPb}$ is not sensitive only to small x_2!

Nuclear modification factor

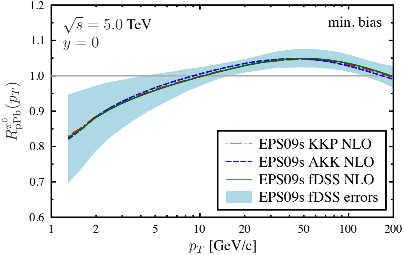
$R_{\rm pPb}$ quantifies the nuclear modification

$$R^{\pi^0}_{\rm pPb,MB}(p_T,y) = \frac{1}{A}\frac{{\rm d}^2\sigma^{\pi^0}_{\rm pPb,MB}}{{\rm d}p_T{\rm d}y}\Bigg/\frac{{\rm d}^2\sigma^{\pi^0}_{\rm pp}}{{\rm d}p_T{\rm d}y},$$

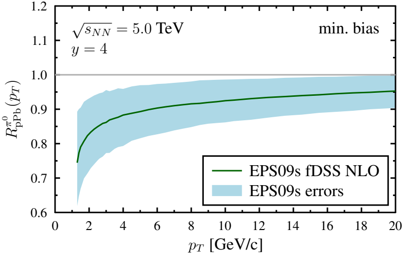
where MB = Average over all centralities

- $R_{\rm pPb}$ for inclusive π^0 at $\sqrt{s_{NN}} = 5.0\,{\rm TeV}$ in NLO (with `INCNLO`)

$y = 0$: [*JHEP* 07 (2012) 073]



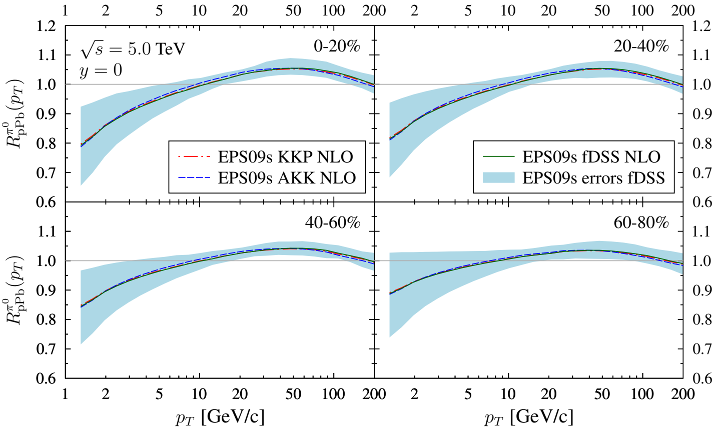
$y = 4$: [*work in progress*]



- At $y = 0$ Suppression due to shadowing at $p_T < 10\,{\rm GeV}$
- At $y = 4$ suppression also for higher p_T

Centrality dependence of π^0 production 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]



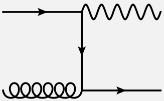
- Centrality classes determined using Optical Glauber model
- Stronger nuclear effects in central collisions

Prompt γ production in pQCD

- Prompt photons consists of two components:

Direct photon production

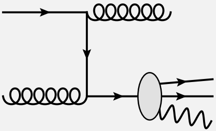
e.g. Compton scattering



- Calculated from pQCD
- Provides a direct probe to the gluon PDFs

Fragmentation photon production

parton fragments into photon, e.g.

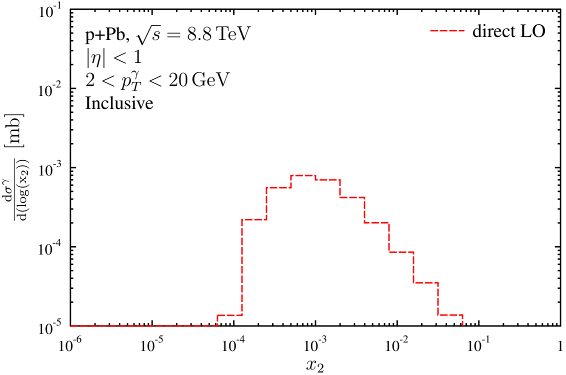


- Calculated by convoluting the hard parton spectra with FFs (BFG II)
  $\Rightarrow$ Smears the x_2 distribution

- Two components experimentally indistinguishable
- In NLO the division depends on scale choice
  $\Rightarrow$ Only the sum of these two is a meaningful observable

x_2 sensitivity for inclusive γ

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



- Direct LO component peaked around $x_2 = 7 \cdot 10^{-4} \approx \frac{2\langle p_T \rangle}{\sqrt{s_{NN}}} e^{-\eta}$

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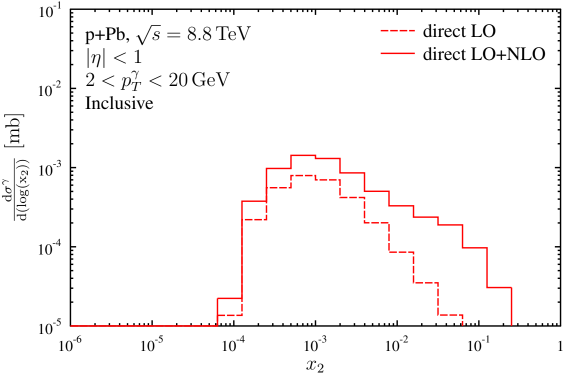

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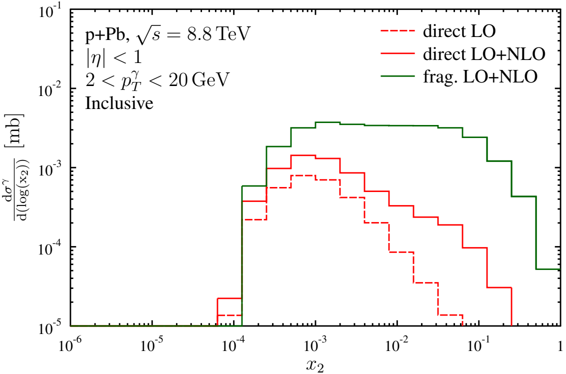

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- Fragmentation component dominant, sensitive to broad x_2 range

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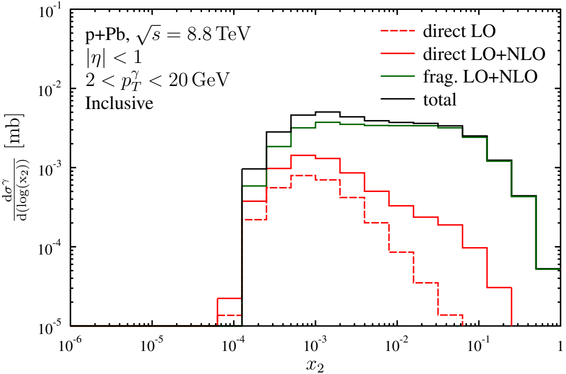

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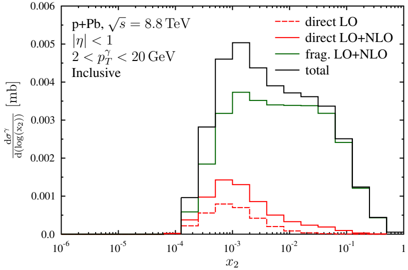
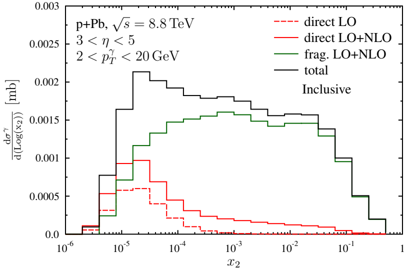
x_2 sensitivity at forward rapidities

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

Mid-rapidity:



Forward rapidity:

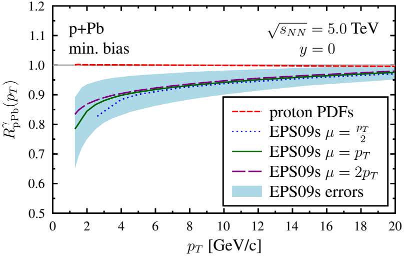


- In forward rapidities contribution from smaller x_2 values
- The fragmentation component dominant also at large η
  $\Rightarrow$ Not very sensitive to small x_2

- R_{pPb} for inclusive prompt γ (with INCNLO) for min. bias collisions ($y = \eta$ for γ)

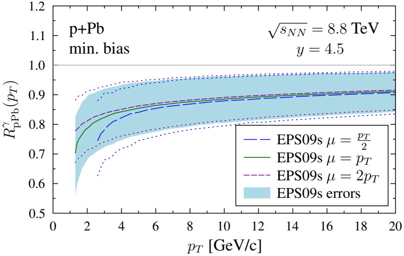
$\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$

[*JHEP* 1305 (2013) 030]



$\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$

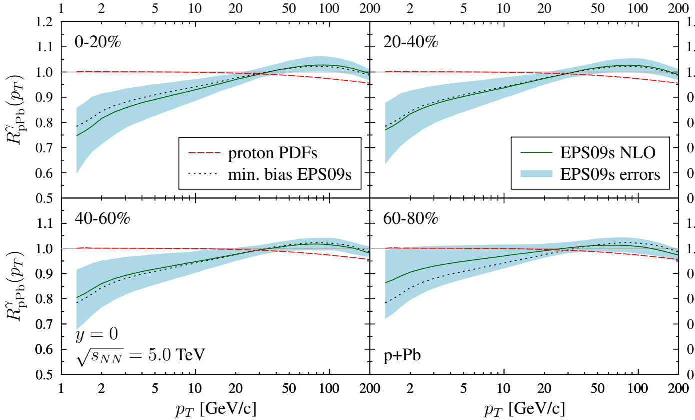
[*Work in progress*]



- Isospin effect negligible (red dashed line)
- Some scale dependence in $p_T < 5\,\mathrm{GeV}$
- At $y = 0$ suppression below $p_T \sim 20\,\mathrm{GeV}$ due to shadowing
- Larger suppression at $y = 4.5$

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

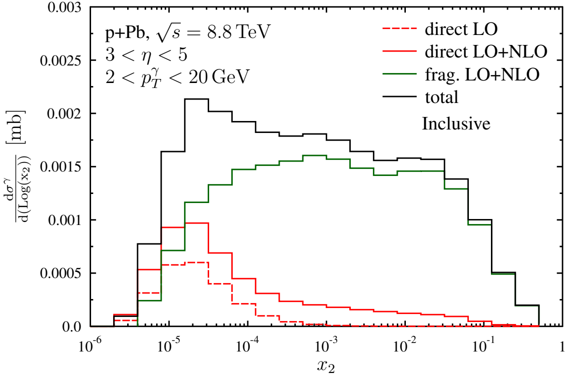
R_{pPb} for inclusive prompt γ at $\sqrt{s_{NN}} = 5.0\,\mathrm{TeV}$ and $y = 0$ in four centrality classes in NLO (with INCNLO) [*JHEP* 1305 (2013) 030]



- Slightly more suppression than for π^0
  $\Rightarrow$ Also the centrality dependence more visible

Isolated γ

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



- Fragmentation component dominant for inclusive γ

Isolated γ

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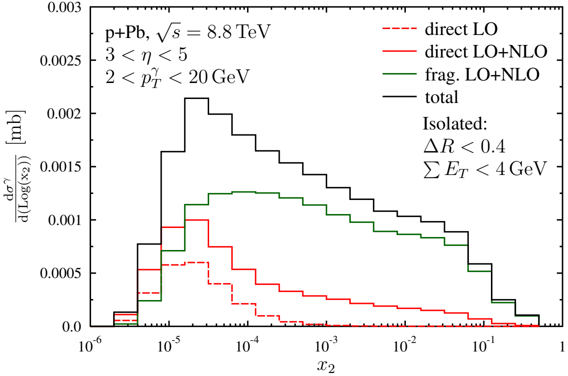

- Fragmentation component dominant for inclusive γ
- Isolation suppress the fragmentation component at large x_2

Isolated γ

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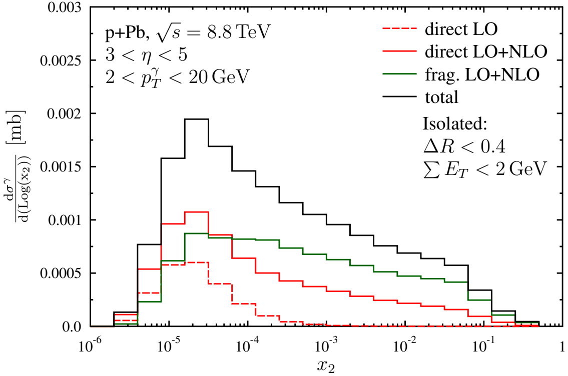


- Fragmentation component dominant for inclusive γ
- Isolation suppress the fragmentation component at large x_2
- Further suppression with tighter isolation cut
  $\Rightarrow$ Sensitive to small x_2!

Summary & Conclusions

Summary

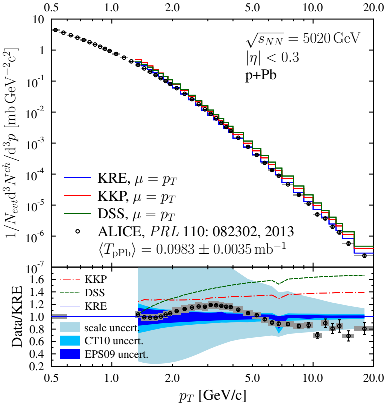
- p+Pb at the LHC collisions can be used
  - to constain the nPDF uncertainties at small x_2
  - to constrain the centrality dependece of the nPDFs
- We have calculated the R_{pPb} at mid- and forward rapidities for
  - inclusive π^0 production
  - prompt γ production
- Studied the x_2 distributions for different observables
- Studied the centrality dependence of R_{pPb} with EPS09s

Conclusions

- Convolution with FFs makes the x_2 distribution wide
- Isolated γ at large η most sensitive to small x physics!
- Centrality dependence more prominent with large nuclear modifications (e.g. at small x)

Backup

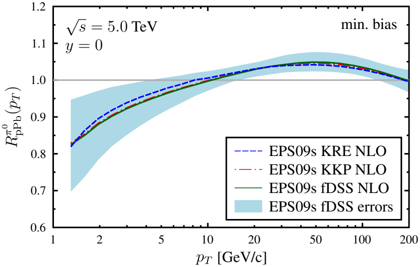
Charged particle yield in p+Pb:



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

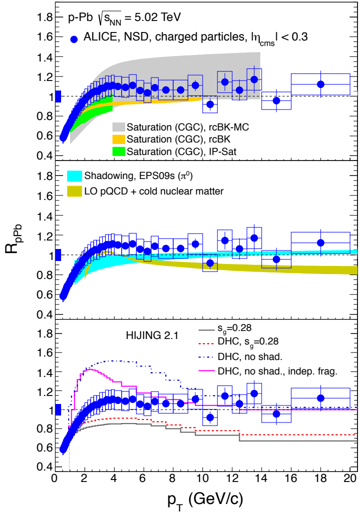
Work in progress

Nuclear modification factor:



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

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

Centrality dependent R_{AB}

Nuclear Modification Factor

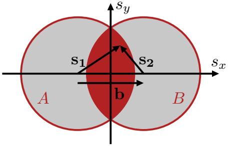
$$R^k_{AB}(b_1,b_2) = \frac{\left\langle \frac{\mathrm{d}^2 N^k_{AB}}{\mathrm{d}p_T\mathrm{d}y} \right\rangle_{b_1,b_2}}{\frac{\langle N_{bin}\rangle_{b_1,b_2}}{\sigma^{NN}_{inel}} \frac{\mathrm{d}^2\sigma^k_{pp}}{\mathrm{d}p_T\mathrm{d}y}} = \frac{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b} \frac{\mathrm{d}^2 N^k_{AB}(\mathbf{b})}{\mathrm{d}p_T\mathrm{d}y}}{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, T_{AB}(\mathbf{b}) \frac{\mathrm{d}^2\sigma^k_{pp}}{\mathrm{d}p_T\mathrm{d}y}}$$

The yield dependents on b also via nPDFs:

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

where

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



Centrality classes

Optical Glauber Model

- Probability for inelastic collision

$$p^{AB}_{inel}(\mathbf{b}) \approx 1 - \mathrm{e}^{-T_{AB}(\mathbf{b})\sigma^{NN}_{inel}}$$

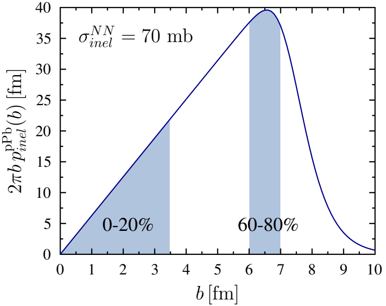
- Inelastic cross section for $[b_1, b_2]$

$$\sigma^{AB}_{inel}(b_1, b_2) = \int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, p^{AB}_{inel}(\mathbf{b})$$

- 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:

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

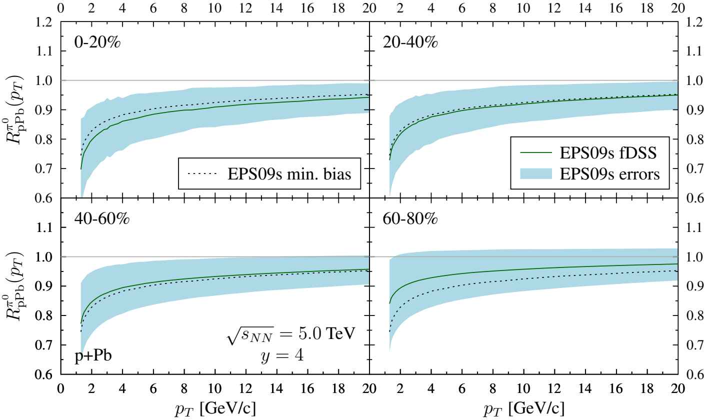
- Example: p+Pb at the LHC
$\sqrt{s_{NN}} = 5.0$ TeV, $\sigma^{NN}_{inel} = 70$ mb



	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

Centrality dependence of π^0 production 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*]



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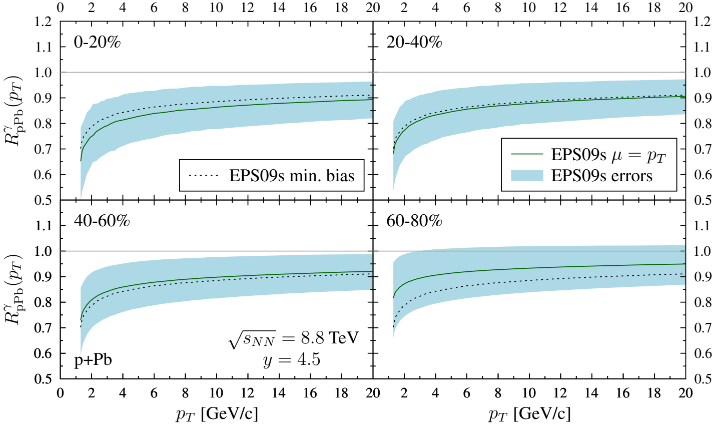
Centrality dependent R_{pPb} at $y = 4.5$

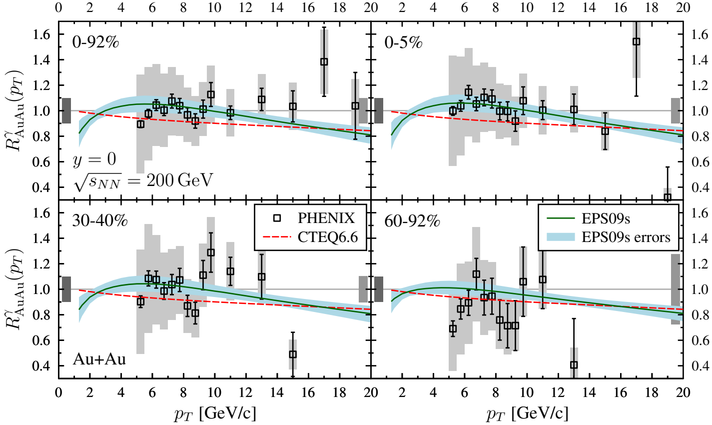
R_{pPb} for prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in four centrality classes in NLO (with `INCNLO`) *Work in progress*



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

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

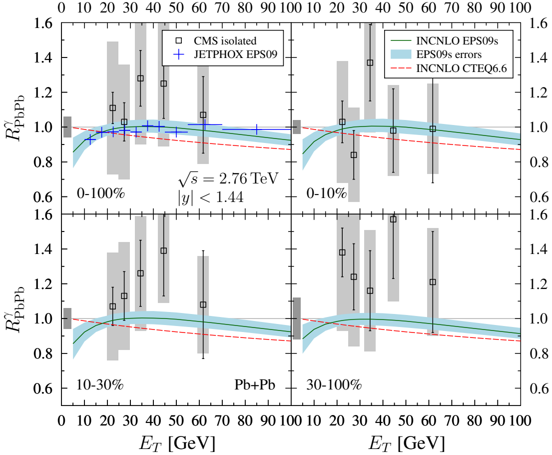
- R_{AuAu} for prompt γ at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ and $y = 0$ in four centrality classes in NLO (with `INCNLO`) [*JHEP* 1305 (2013) 030]



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

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]



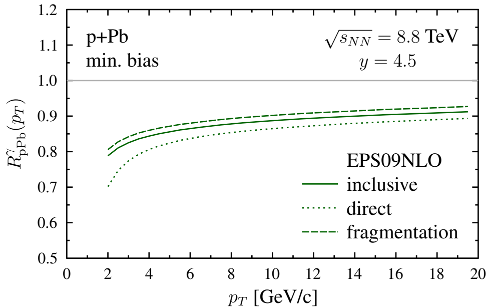
- CMS data for isolated and calculation for inclusive photons
- Isolated (JETPHOX) and inclusive (INCNLO) $R^{\gamma}_{\mathrm{PbPb}}$ compatible in min. bias

$\Rightarrow$ Comparison ok

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

Isolated R_{pPb}?

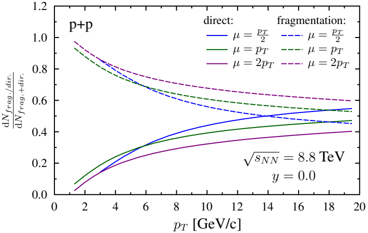
- R_{pPb} for inclusive prompt γ at $\sqrt{s_{NN}} = 8.8\,\mathrm{TeV}$ and $y = 4.5$ in NLO [I.H., K.J. Eskola, H. Paukkunen *work in progress*]

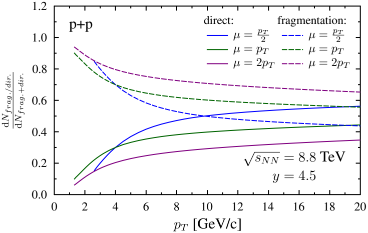


- Isolation increase the relative contribution from direct photons
  $\Rightarrow$ Isolated R_{pPb} closer to R_{pPb} with direct component only
- Work in progress...

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
- Calculated with BFGII FFs for photons and CT10 proton PDFs