Modeling the Impact Parameter Dependence of the nPDFs With EKS98 and EPS09 Global Fits

Heavy Ion Collisions in the LHC Era

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Outline

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    - Nuclear Geometry in Heavy Ion Collisions
2. Framework
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    - Fitting Procedure
    - Outcome
3. Applications
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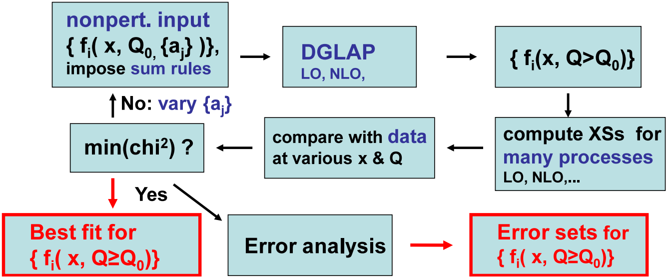
    - π^0 production
    - Inclusive γ production
4. Summary and Outlook

Determination of the nPDFs

Collinear factorization framework:

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

- f_i^A's determined via global analysis:



[from K.J. Eskola]

- So far globally analysed f_i^A's spatially independent

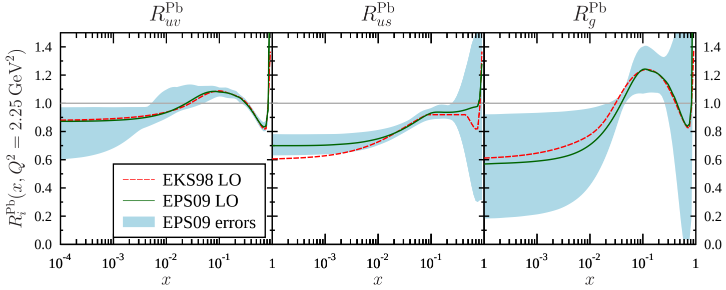
Nuclear Modification to PDFs

- nPDFs often decomposed as

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

where $f_i^N(x,Q^2)$ free nucleon PDF (e.g. CTEQ)

- We consider two globally fitted $R_i^A(x,Q^2)$'s:
  - EKS98 (LO DGLAP evolution) [*Eur.Phys.J.* C9 (1999) 61-68]
  - EPS09 (LO and NLO DGLAP evolution with uncertainties) [*JHEP* 04 (2009) 065]



Nuclear Geometry

Production of k at impact parameter $\mathbf{b}$

$$\mathrm{d}N^{AB\to k+X}(\mathbf{b}) = T_{AB}(\mathbf{b}) \sum_{i,j} f_i^A \otimes f_j^B \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X}$$

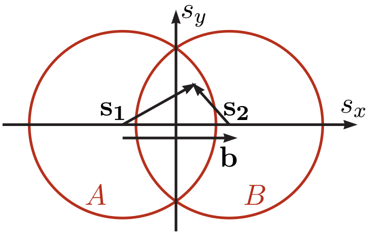
Nuclear overlap function

Amount of interacting matter at impact parameter $\mathbf{b}$.

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

where

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



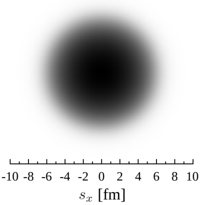
Nuclear Geometry

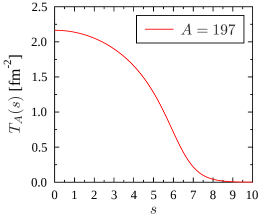
Amount of nuclear matter in beam direction

Nuclear thickness function

Woods-Saxon density profile:

$$
\begin{aligned}
T_A(\mathbf{s}) &= \int_{-\infty}^{\infty} \mathrm{d}z \frac{n_0}{1+\exp[\frac{\sqrt{\mathbf{s}^2+z^2}-R_A}{d}]} \\
d &= 0.54 \text{ fm} \\
R_A &= 1.12A^{1/3} - 0.86A^{-1/3} \text{ fm} \\
n_0 &= \frac{3}{4}\frac{A}{\pi R_A^3}\frac{1}{(1+(\frac{\pi d}{R_A})^2)} \\
A &= \int \mathrm{d}^2\mathbf{s}\, T_A(\mathbf{s})
\end{aligned}
$$





Model Framework

Nuclear modifications with spatial dependence

- We replace
$$R_i^A(x,Q^2) \rightarrow r_i^A(x,Q^2,\mathbf{s}),$$
where $\mathbf{s}$ = 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 $R_i^A(x,Q^2)$ from EKS98 or EPS09 (=data!)
- Assumption: spatial dependence related to $T_A(\mathbf{s})$
$$r_A(x,Q^2,\mathbf{s}) = 1 + c_1(x,Q^2)[T_A(\mathbf{s})] + c_2(x,Q^2)[T_A(\mathbf{s})]^2 + c_3(x,Q^2)[T_A(\mathbf{s})]^3 + c_4(x,Q^2)[T_A(\mathbf{s})]^4$$

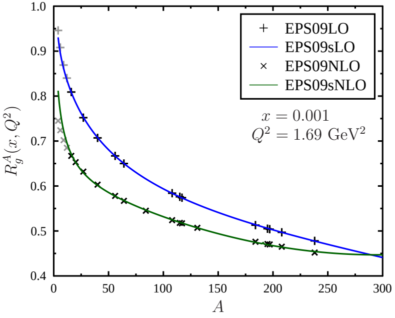
Important: No A dependence in the fit parameters $c_j(x,Q^2)$ (unlike some earlier analyses with only one fit parameter)

Fitting Procedure

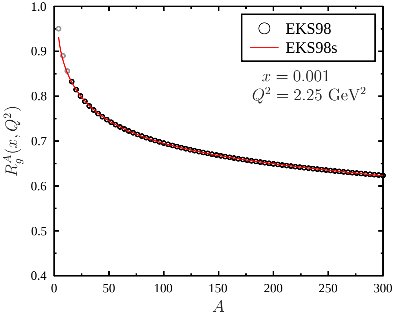
Parameters $c_j(x, Q^2)$ obtained by minimizing the χ^2

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

Fit to EPS09

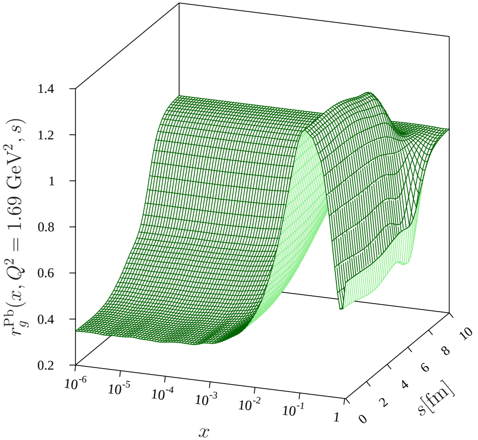


Fit to EKS98



Spatial Dependence of Nuclear Modifications

$$r_i^A(x,Q^2,\mathbf{s}) = 1 + \sum_{j=1}^{4} c_j^i(x,Q^2)[T_A(\mathbf{s})]^j \quad (A=208,\ \text{EPS09sNLO})$$



Observations

- The shape in x is similar to $R_i^A(x,Q^2)$
- small $\mathbf{s}$: $|1 - r_i^A(x,Q^2,\mathbf{s})| > |1 - R_i^A(x,Q^2)|$
- large $\mathbf{s}$: $r_i^A(x,Q^2,\mathbf{s}) \approx 1$

Observables

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 Central-to-Peripheral Ratio

$$R^k_{CP} = \frac{\left\langle \frac{\mathrm{d}^2 N^k_{AB}}{\mathrm{d}p_T \mathrm{d}y} \right\rangle \frac{1}{\langle N_{bin}\rangle}(C)}{\left\langle \frac{\mathrm{d}^2 N^k_{AB}}{\mathrm{d}p_T \mathrm{d}y} \right\rangle \frac{1}{\langle N_{bin}\rangle}(P)} = \frac{\int_{b_1^c}^{b_2^c} \mathrm{d}^2\mathbf{b}\, \frac{\mathrm{d}^2 N^k_{AB}(\mathbf{b})}{\mathrm{d}p_T\mathrm{d}y} \Big/ \int_{b_1^c}^{b_2^c} \mathrm{d}^2\mathbf{b}\, T_{AB}(\mathbf{b})}{\int_{b_1^p}^{b_2^p} \mathrm{d}^2\mathbf{b}\, \frac{\mathrm{d}^2 N^k_{AB}(\mathbf{b})}{\mathrm{d}p_T\mathrm{d}y} \Big/ \int_{b_1^p}^{b_2^p} \mathrm{d}^2\mathbf{b}\, T_{AB}(\mathbf{b})}$$

- Impact parameter values b_1 and b_2 for given centrality class from optical Glauber model

Optical Glauber model

Centrality classes

- Probability for inelastic collision

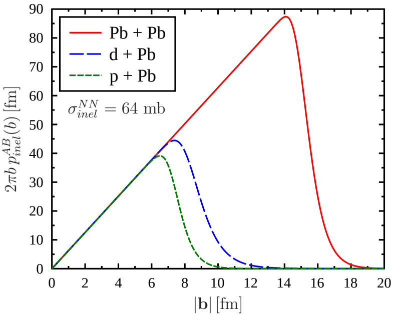
$$p^{AB}_{inel}(\mathbf{b}) \approx 1 - \mathrm{e}^{-T_{AB}(\mathbf{b})\sigma^{NN}_{inel}}$$

- Inelastic cross section

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

- Impact parameters from

$$(c_1 - c_2)\,\% = \frac{\sigma^{AB}_{inel}(b_1, b_2)}{\sigma^{AB}_{inel}(0, \infty)}$$



p+A collisions

- Replace $T_{AB}(\mathbf{b}) \rightarrow T_A(\mathbf{b})$

Calculation of $\mathrm{d}N^k_{AB}(\mathbf{b})$

Spatially averaged nPDFs

$$\mathrm{d}N^{AB\to k+X}(\mathbf{b}) = T_{AB}(\mathbf{b}) \sum_{i,j} R_i^A f_i^N \otimes R_j^B f_j^N \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X}$$

Spatially dependent nPDFs

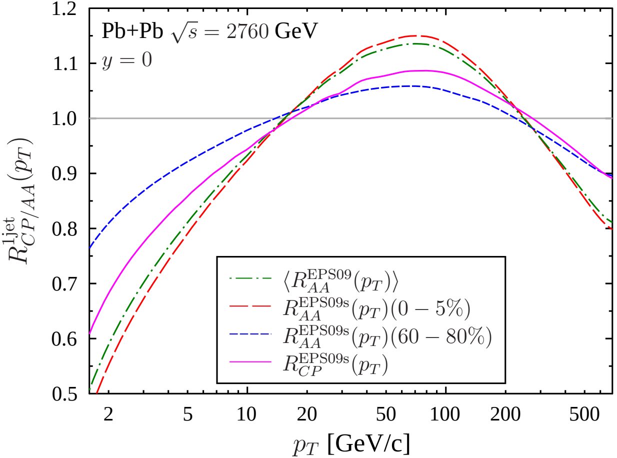
$$\mathrm{d}N^{AB\to k+X}(\mathbf{b}) = \sum_{n,m} \int \mathrm{d}^2\mathbf{s}\, [T_A(\mathbf{s}+\mathbf{b}/2)]^{n+1}\, [T_B(\mathbf{s}-\mathbf{b}/2)]^{m+1} \sum_{i,j} c_i^n\, f_i^N \otimes c_j^m\, f_j^N \otimes \mathrm{d}\hat{\sigma}^{ij\to k+X}$$

- We provide the coefficients $c_i^n(x, Q^2)$ in EKS98s and EPS09s codes[1]

[1] https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/nPDFs

Pb+Pb collisions at LHC

R_{AA} and R_{CP} for partonic-jet production in LO; Baseline for E-loss



Observations

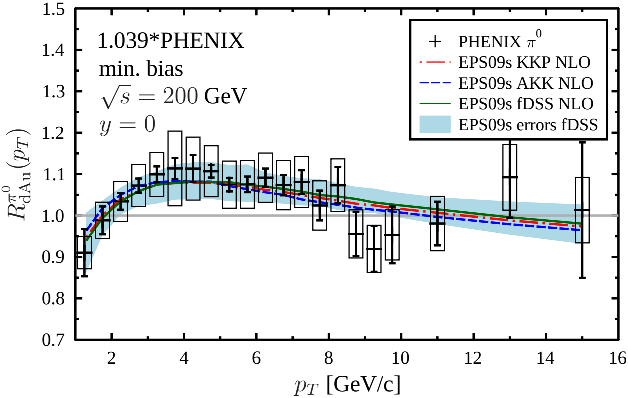
$R_{AA}(central) \approx \langle R_{AA} \rangle$

$R_{AA}(peripheral) \neq 1$

$R_{CP} \neq \langle R_{AA} \rangle$

d+Au collisions at RHIC

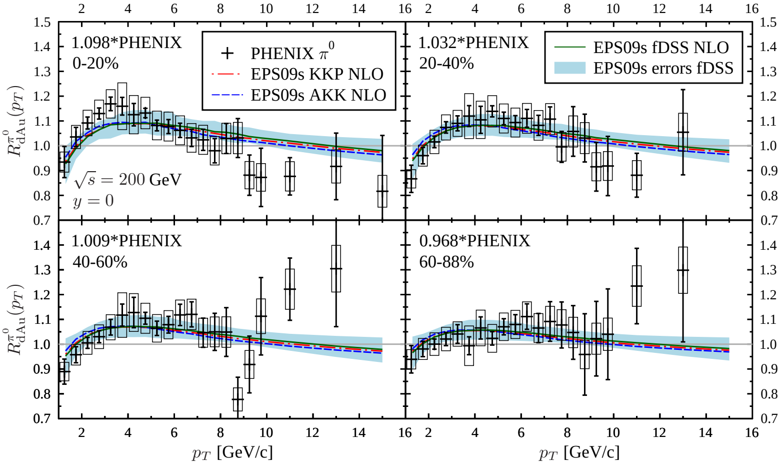
Min. bias R_{dAu} for π^0 production at $y = 0$ in NLO
(calculated with INCNLO)



- Data used in EPS09 global fit

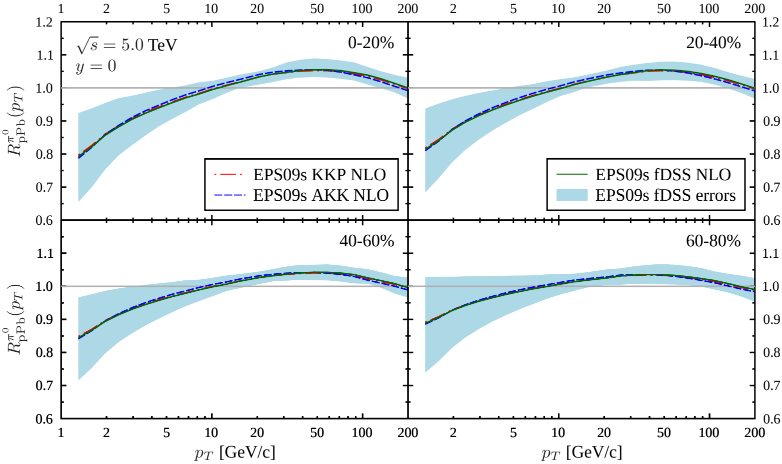
d+Au collisions at RHIC

R_{dAu} for π^0 production at $y = 0$ in different centrality classes in NLO (calculated with `INCNLO`)



p+Pb collisions at LHC

R_{pPb} for π^0 production at $y = 0$ in different centrality classes in NLO (calculated with `INCNLO`)



d+Au collisions at RHIC

Min. bias R_{dAu} for inclusive γ production at mid-rapidity

Inclusive photons

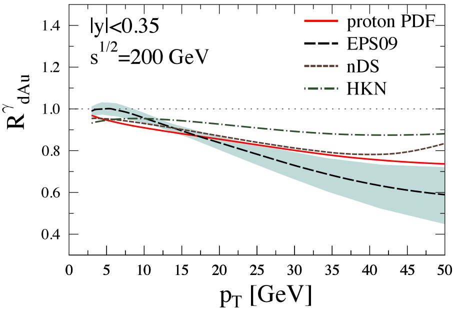
- direct
- fragmentation

Isospin effect

- Also neutrons in nuclei

⇒ Less charge to couple with

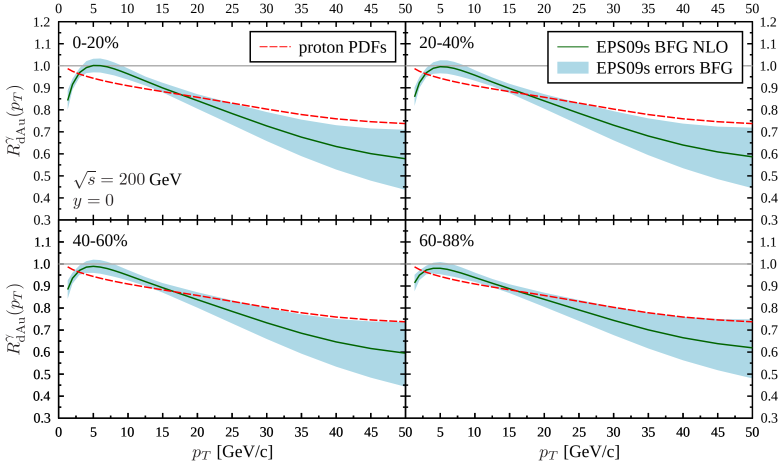
⇒ R_{dAu} not normalized to unity!



[Arleo *et al.* *JHEP* 1104 (2011) 055]

d+Au collisions at RHIC

R_{dAu} for inclusive γ production at $y=0$ in different centrality classes in NLO (preliminary, calculated with INCNLO)



Summary & Outlook

We have

- Determined the spatial dependence of nuclear modifications using
  - The A dependence of the EKS98/EPS09 (= data!)
  - The power series of the $T_A(\mathbf{s})$
- Published routines EPS09s and EKS98s for $r_i^A(x, Q^2, \mathbf{s})$

  $\Rightarrow$ Nuclear modifications of any hard process in any centrality class can now be computed consistently with global fits!
- Calculated $R_{AA}^{\rm 1jet}$, $R_{CP}^{\rm 1jet}$, $R_{\rm dAu}^{\pi^0}$, $R_{\rm pPb}^{\pi^0}$ and $R_{\rm dAu}^{\gamma}$ in different centrality classes

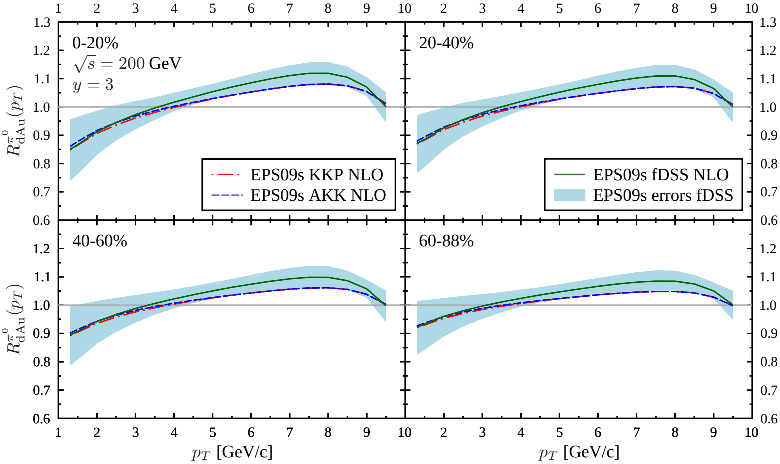
We will

- Calculate also $R_{\rm pPb}^{\gamma}$ in different centrality classes
- Consider also implementation to MC-calculations

Backup

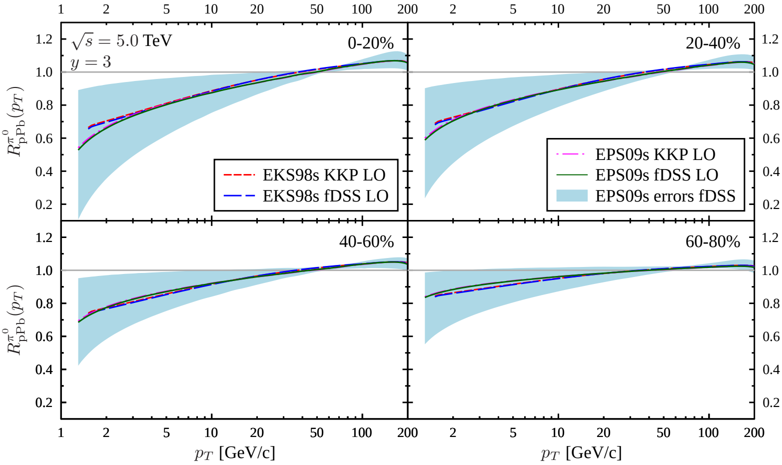
d+Au collisions at RHIC

R_{dAu} for π^0 production at $y = 3$ in different centrality classes in NLO (calculated with `INCNLO`)



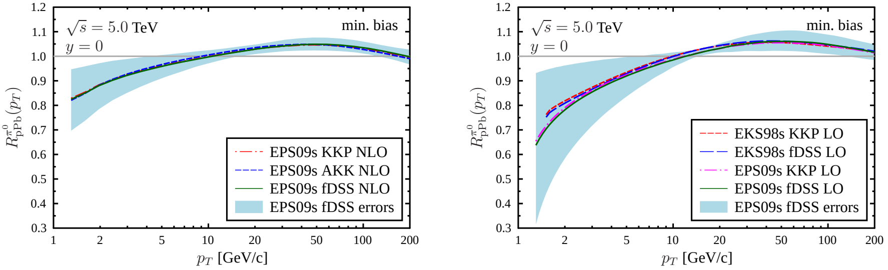
p+Pb collisions at LHC

R_{pPb} for π^0 production in different centrality classes at $y = 3$ in LO



p+Pb collisions at LHC

R_{pPb} for π^0 production in minimum bias collisions at $y = 0$



$\Rightarrow$ Some difference between LO and NLO results

$\langle N_{bin} \rangle$ for p+Pb and d+Au

p+Pb with $\sigma_{inel}^{NN} = 70$ mb ($\sqrt{s} = 5.0$ TeV)

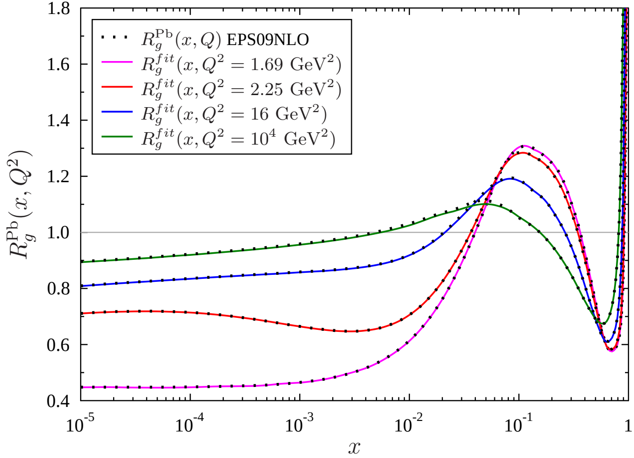
	b_1 [fm]	b_2 [fm]	$\langle N_{bin} \rangle$
$0-20\%$	0.0	3.471	14.24
$20-40\%$	3.471	4.908	11.41
$40-60\%$	4.908	6.012	7.663
$60-80\%$	6.012	6.986	3.680

d+Au with $\sigma_{inel}^{NN} = 42$ mb ($\sqrt{s} = 200.0$ GeV)

	b_1 [fm]	b_2 [fm]	$\langle N_{bin} \rangle$
$0-20\%$	0.0	3.798	15.57
$20-40\%$	3.798	5.371	10.95
$40-60\%$	5.371	6.583	6.013
$60-88\%$	6.583	8.336	2.353

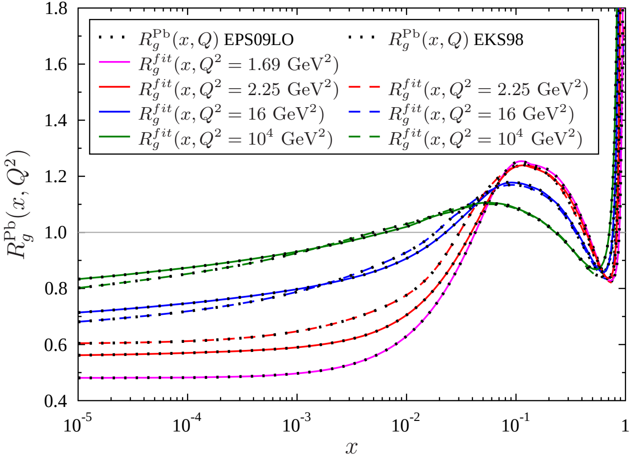
Fitted $R(x,Q^2)$ vs. old $R(x,Q^2)$

$$R^{fit}(x,Q^2) = \frac{1}{A}\int \mathrm{d}^2\mathbf{s}\, T_A(s)\left[1 + \sum_{i=1}^{4} c_i(x,Q^2)[T_A(s)]^i\right]$$



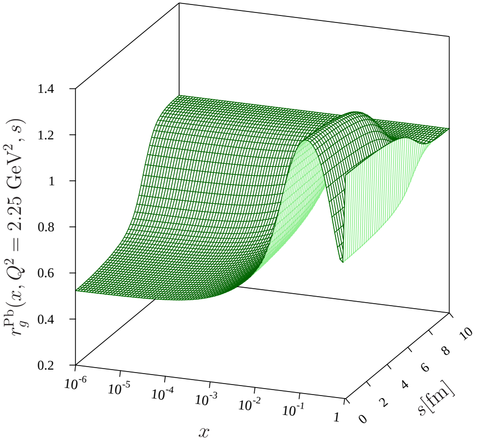
Fitted $R(x,Q^2)$ vs. old $R(x,Q^2)$

$$R^{fit}(x,Q^2) = \frac{1}{A}\int d^2\mathbf{s}\, T_A(s)\left[1 + \sum_{i=1}^{4} c_i(x,Q^2)[T_A(s)]^i\right]$$



Spatial Dependence of Nuclear Modifications

$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{4} c_j^i(x, Q^2)[T_A(\mathbf{s})]^j \quad (A = 208,\ \text{EKS98})$$



Observations

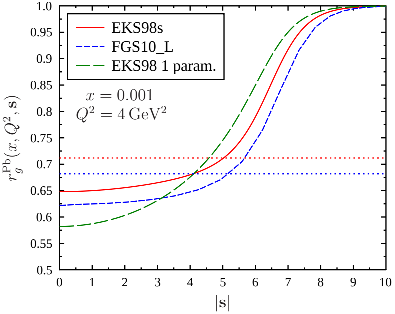
- The shape in x is similar to $R_i^A(x, Q^2)$
- small s: $|1 - r_i^A(x, Q^2, \mathbf{s})| > |1 - R_i^A(x, Q^2)|$
- large s: $r_i^A(x, Q^2, \mathbf{s}) \approx 1$

Comparision With Other Models

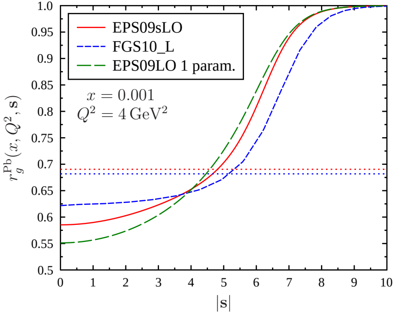
Nuclear modifications with spatial dependence

- 1-parameter fit (R. Vogt et al.) [*Phys.Rev.* C61 044904, 2000]
- FGS10 (Frankfurt, Guzey, Strikman) [*Phys.Rept.* 512 255-393,2012]

Fit to EKS98



Fit to EPS09LO



A-dependent modification

Thickness function

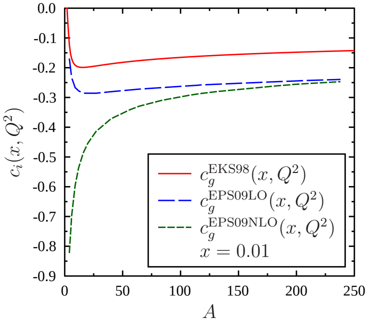
- If the Modification of the form

$$r_A(x, Q^2, s) = 1 + c(x, Q^2)[T_A(s)]$$

[*Phys.Rev.*, C61:044904, 2000]

- The parameter $c(x, Q^2)$ from the normalization condition

$$c(x, Q^2) = \frac{A(R_i^A(x, Q^2) - 1)}{\int d^2\mathbf{s}\, [T_A(\mathbf{s})]^2}$$



⇒ Strong A dependence of $c(x, Q^2)$!

The s dependence not entirely decomposed from $c(x, Q^2)$.

A+B Collisions

- The 1-jet distribution for a centrality class with $b \in [b_1, b_2]$ calculated from

$$\left\langle \frac{\mathrm{d}^2 N_{AB}^{\mathrm{1jet}}}{\mathrm{d}p_T \mathrm{d}y} \right\rangle_{b_1,b_2} = \frac{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b} \frac{\mathrm{d}^2 N_{AB}^{\mathrm{1jet}}(\mathbf{b})}{\mathrm{d}p_T \mathrm{d}y}}{\int_{b_1}^{b_2} \mathrm{d}^2\mathbf{b}\, p_{AB}^{inel}(\mathbf{b})}$$

- $p_{AB}^{inel}(\mathbf{b}) = 1 - e^{-T_{AB}(\mathbf{b})\sigma_{inel}^{NN}}$ (optical Glauber model)

Parameters from optical Glauber model

	$central = 0-5\%$			$peripheral = 60-80\%$		
	b_1 [fm]	b_2 [fm]	$\langle N_{bin} \rangle$	b_1 [fm]	b_2 [fm]	$\langle N_{bin} \rangle$
RHIC	0.0	3.355	1083	11.62	13.42	15.11
LHC	0.0	3.478	1772	12.05	13.91	19.08

- RHIC: $\sigma_{inel}^{NN} = 42$ mb
- LHC: $\sigma_{inel}^{NN} = 64$ mb