

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

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- π^0 production

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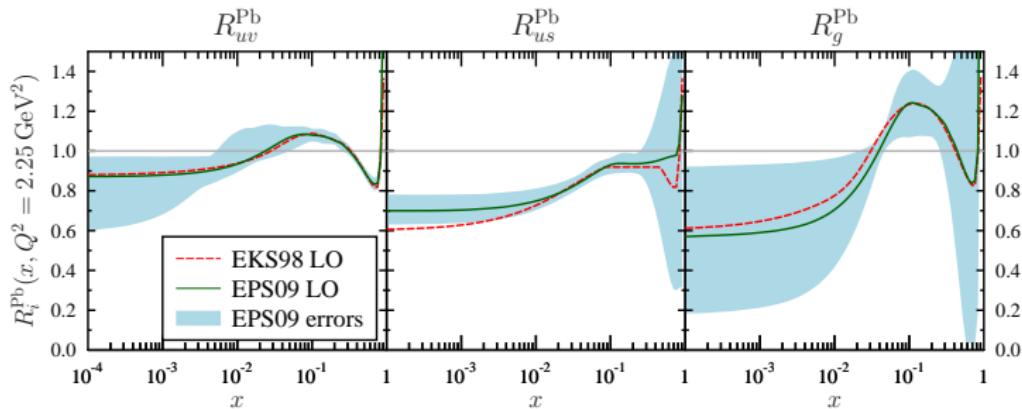
Nuclear Parton Distribution Functions (nPDFs)

- Decomposition of nPDFs

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

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

- $R_i^A(x, Q^2)$ determined from global fits; No spatial dependence
 - EKS98 (LO DGLAP evolution) [*Eur.Phys.J.*, C9:61-68, 1999]
 - EPS09 (LO and NLO + error sets) [*JHEP*, 04:065, 2009]



Nuclear Geometry

Production of k at impact parameter \mathbf{b}

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

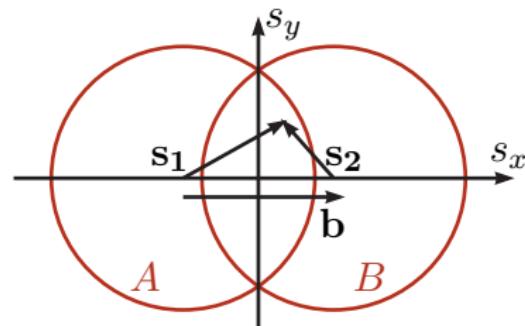
Nuclear overlap function

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

$$T_{AB}(\mathbf{b}) = \int d^2\mathbf{s} T_A(\mathbf{s}_1) T_B(\mathbf{s}_2),$$

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:

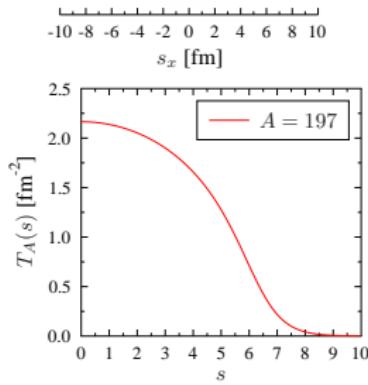
$$T_A(\mathbf{s}) = \int_{-\infty}^{\infty} dz \frac{n_0}{1 + \exp\left[\frac{\sqrt{s^2 + z^2} - R_A}{d}\right]}$$

$$d = 0.54 \text{ fm}$$

$$R_A = 1.12A^{1/3} - 0.86A^{-1/3} \text{ fm}$$

$$n_0 = \frac{3}{4} \frac{A}{\pi R_A^3} \frac{1}{(1 + (\frac{\pi d}{R_A})^2)}$$

$$A = \int d^2\mathbf{s} T_A(\mathbf{s})$$



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

$$R_i^A(x, Q^2) \equiv \frac{1}{A} \int d^2\mathbf{s} T_A(\mathbf{s}) r_i^A(x, Q^2, \mathbf{s}),$$

where $R_i^A(x, Q^2)$ from EKS98 or EPS09 (=data!)

- Assumption: spatial dependence related to $T_A(\mathbf{s})$

$$\begin{aligned} r_A(x, Q^2, \mathbf{s}) = & 1 + c_1(x, Q^2)[T_A(\mathbf{s})] + c_2(x, Q^2)[T_A(\mathbf{s})]^2 \\ & + c_3(x, Q^2)[T_A(\mathbf{s})]^3 + c_4(x, Q^2)[T_A(\mathbf{s})]^4 \end{aligned}$$

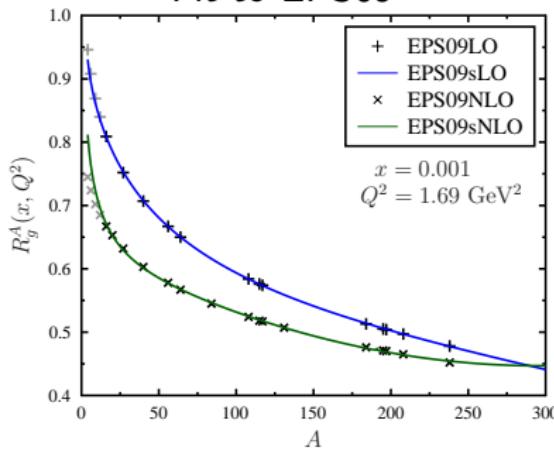
Important: No A dependence in the fit parameters $c_j(x, Q^2)$
(unlike some earlier analyses with only one fit parameter)

Fitting Procedure

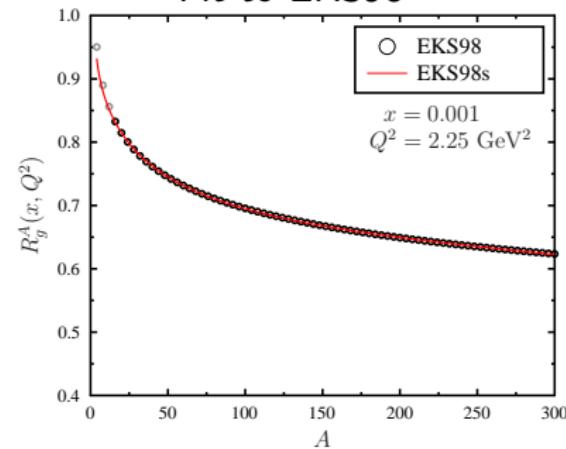
Parameters $c_j(x, Q^2)$ obtained by minimizing the χ^2

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

Fit to EPS09

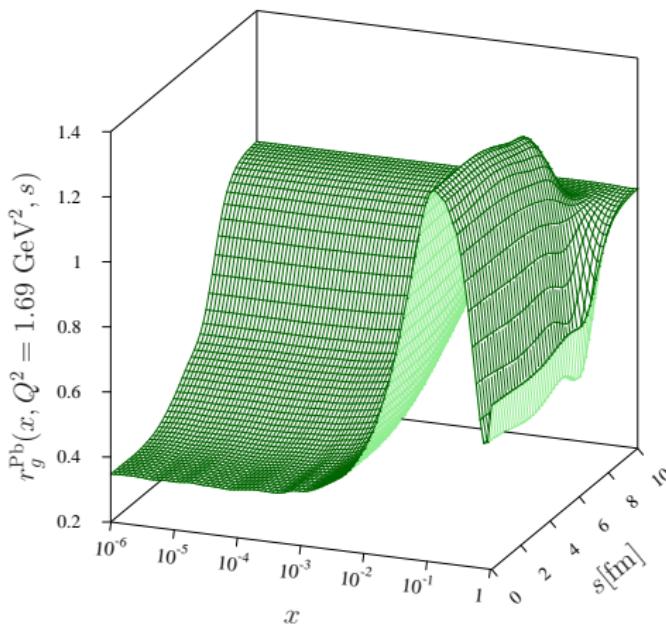


Fit to EKS98



Spatial Dependence of Nuclear Modifications

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



Observations

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

Observables

Nuclear Modification Factor

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

The Central-to-Peripheral Ratio

$$R_{CP}^k = \frac{\left\langle \frac{d^2 N_{AB}^k}{dp_T dy} \right\rangle \frac{1}{\langle N_{bin} \rangle}(C)}{\left\langle \frac{d^2 N_{AB}^k}{dp_T dy} \right\rangle \frac{1}{\langle N_{bin} \rangle}(P)} = \frac{\int_{b_1^c}^{b_2^c} d^2 \mathbf{b} \frac{d^2 N_{AB}^k(\mathbf{b})}{dp_T dy} / \int_{b_1^c}^{b_2^c} d^2 \mathbf{b} T_{AB}(\mathbf{b})}{\int_{b_1^p}^{b_2^p} d^2 \mathbf{b} \frac{d^2 N_{AB}^k(\mathbf{b})}{dp_T dy} / \int_{b_1^p}^{b_2^p} d^2 \mathbf{b} T_{AB}(\mathbf{b})}$$

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

Calculation of $dN_{AB}^k(\mathbf{b})$

Spatially averaged nPDFs

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

Spatially dependent nPDFs

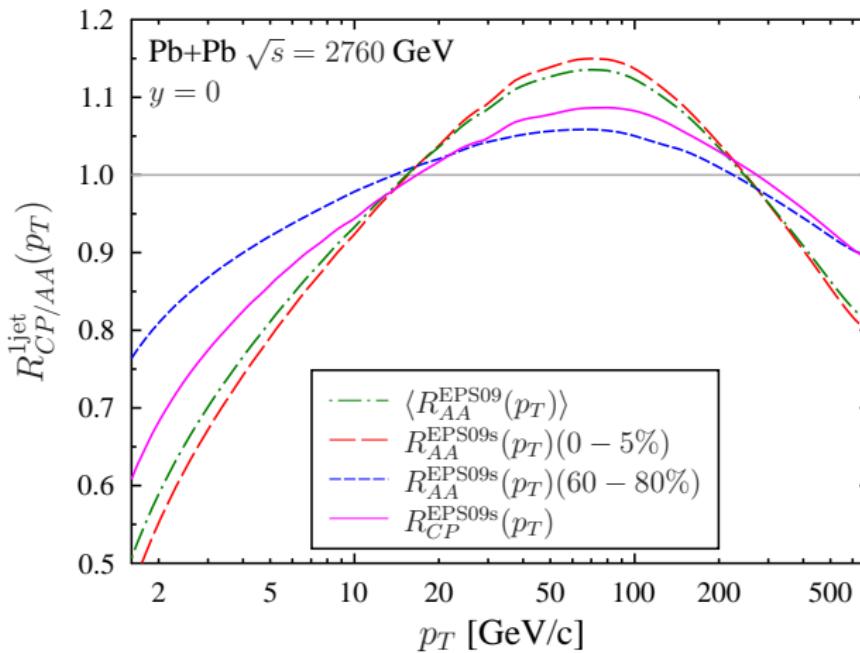
$$dN^{AB \rightarrow k+X}(\mathbf{b}) = \sum_{n,m} \int d^2\mathbf{s} [T_A(\mathbf{s} + \mathbf{b}/2)]^{n+1} [T_B(\mathbf{s} - \mathbf{b}/2)]^{m+1} \\ \sum_{i,j} c_i^n f_i^N \otimes c_j^m f_j^N \otimes d\hat{\sigma}^{ij \rightarrow k+X}$$

- We provide the coefficients $c_i^n(x, Q^2)$ in EKS98s and EPS09s codes¹

¹<https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/>

Pb+Pb collisions at LHC

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



Observations

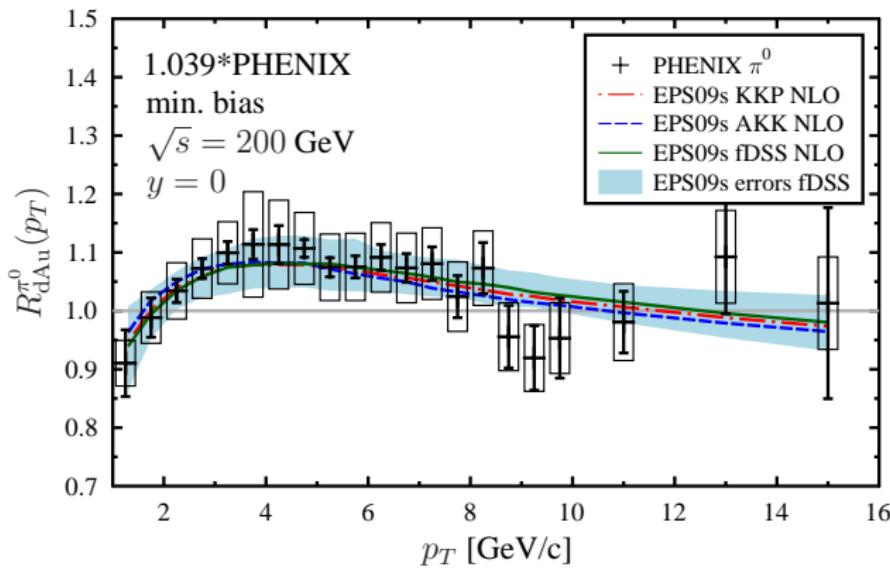
$R_{AA}(\text{central}) \approx \langle R_{AA} \rangle$

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

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

d+Au collisions at RHIC

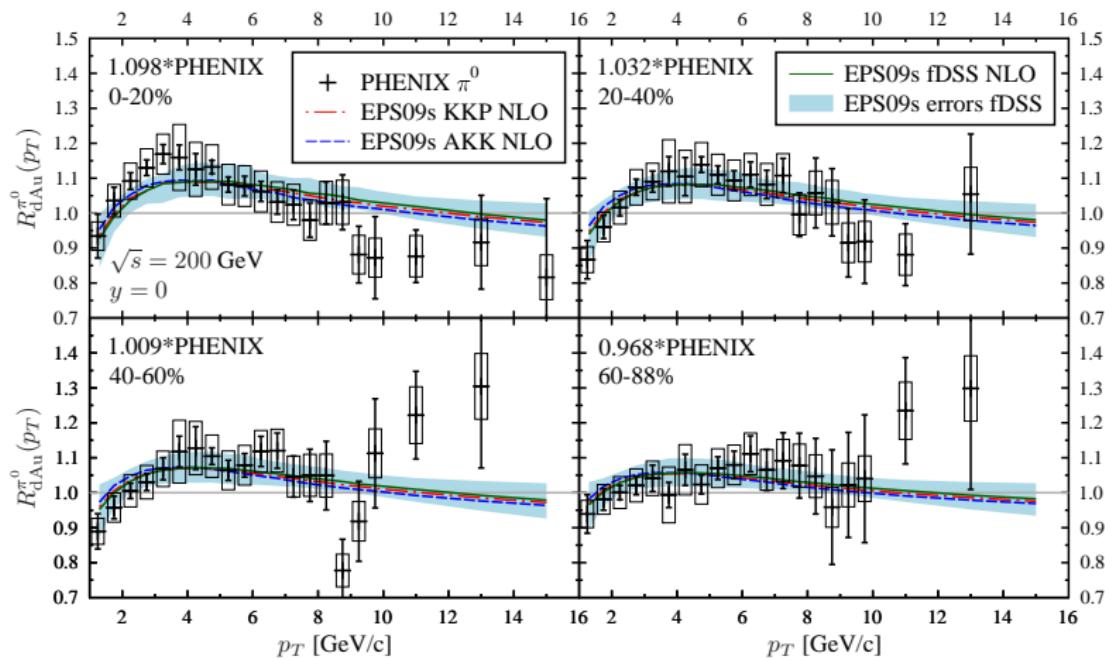
Min. bias $R_{d\text{Au}}$ for π^0 production at $y = 0$ in NLO
(calculated with INCNLO)



- Data used in EPS09 global fit

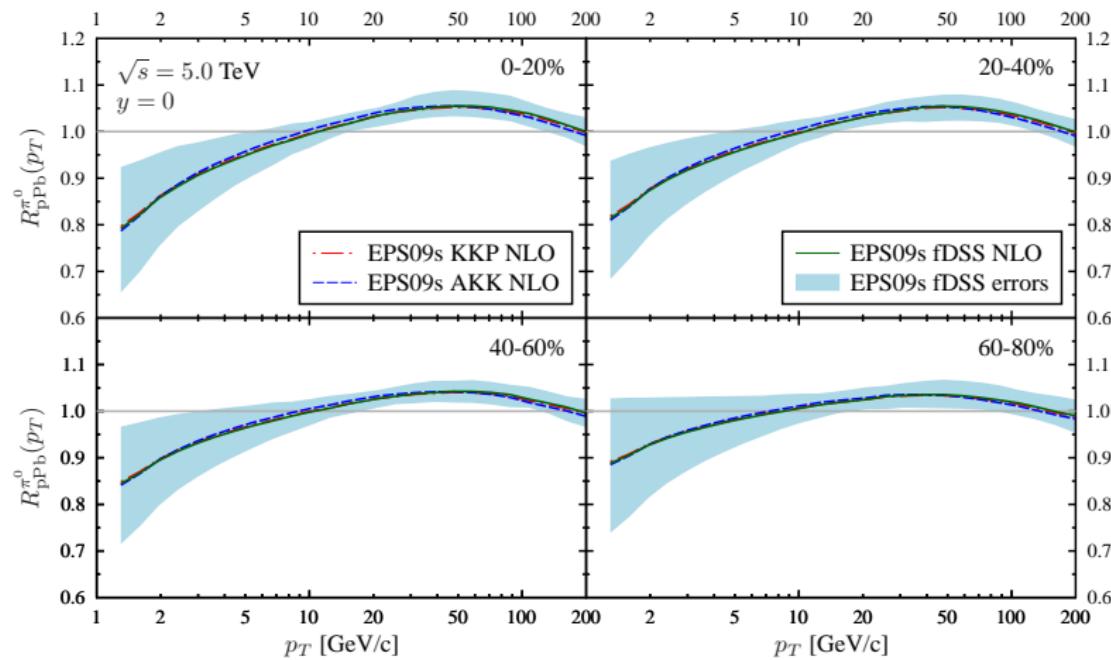
d+Au collisions at RHIC

$R_{d\text{Au}}$ 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)



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 $T_A(s)$
- Calculated $R_{AA}^{1\text{jet}}$, $R_{CP}^{1\text{jet}}$, $R_{dAu}^{\pi^0}$ and $R_{pPb}^{\pi^0}$

We will

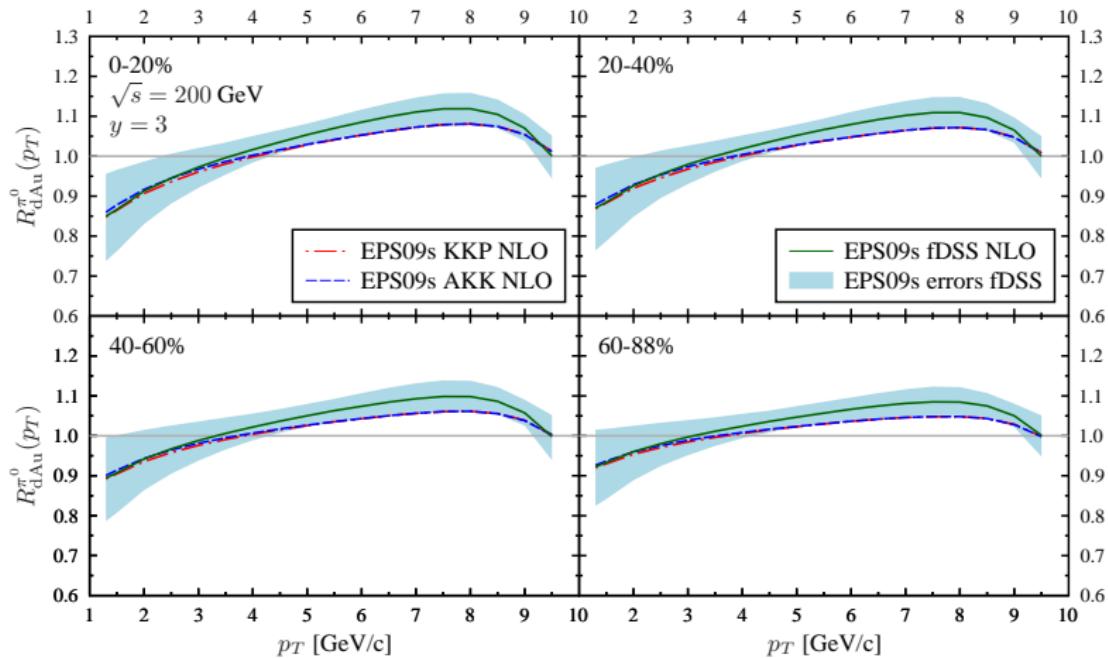
- Calculate R_{pPb} also for photon production
- Publish routines **EPS09s** and **EKS98s**² for $r_i^A(x, Q^2, s)$
 - ⇒ Nuclear modifications of any hard process in any centrality class can be computed consistently with global fits!

²<https://www.jyu.fi/fysiikka/en/research/highenergy/urhic/>

Backup

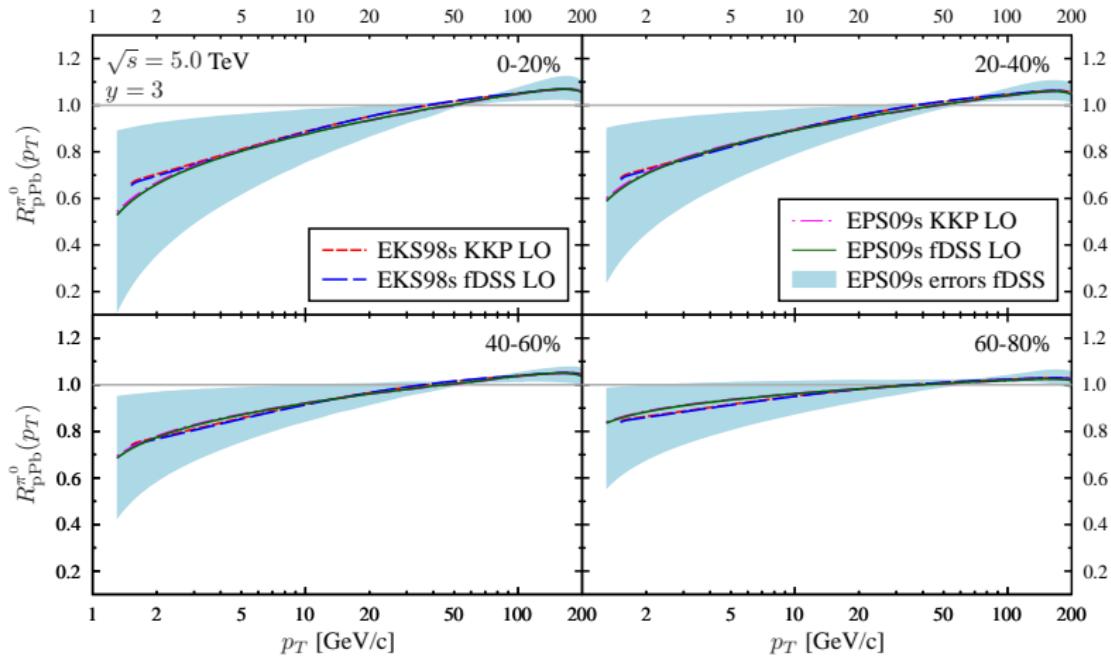
d+Au collisions at RHIC

$R_{d\text{Au}}$ for π^0 production at $y = 3$ in different centrality classes in NLO (calculated with INCNLO)



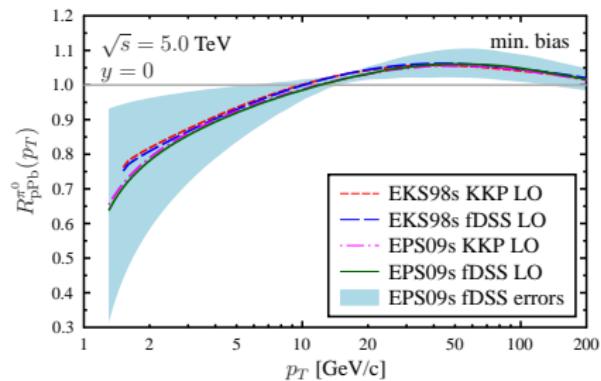
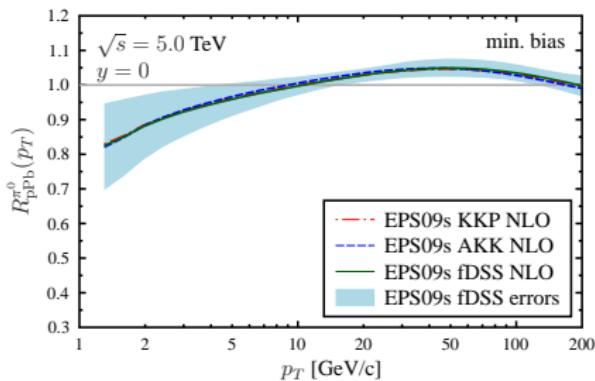
p+Pb collisions at LHC

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



p+Pb collisions at LHC

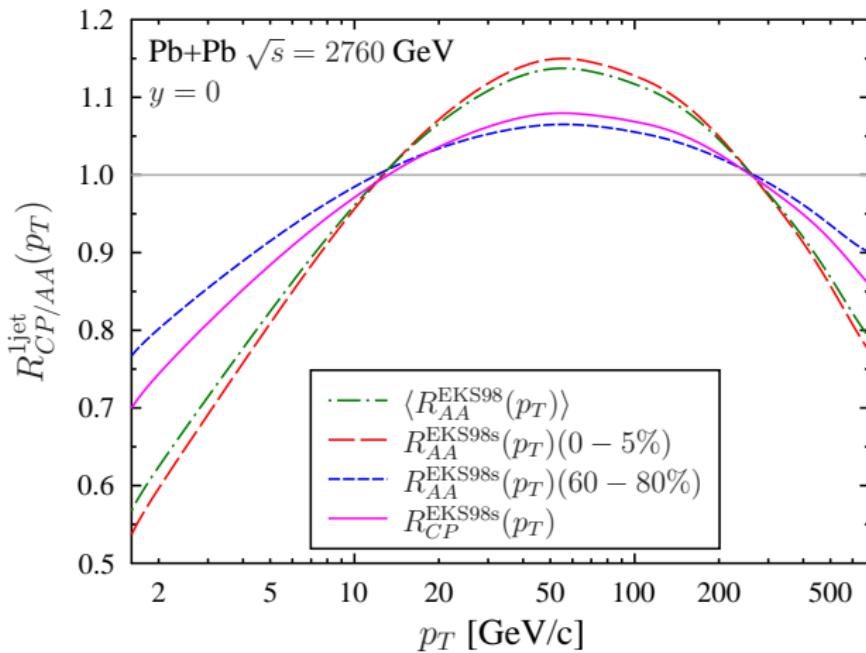
R_{pPb} for π^0 production in minimum bias collisions at $y = 0$



⇒ Some difference between LO and NLO results

Pb+Pb collisions at LHC

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



Observations

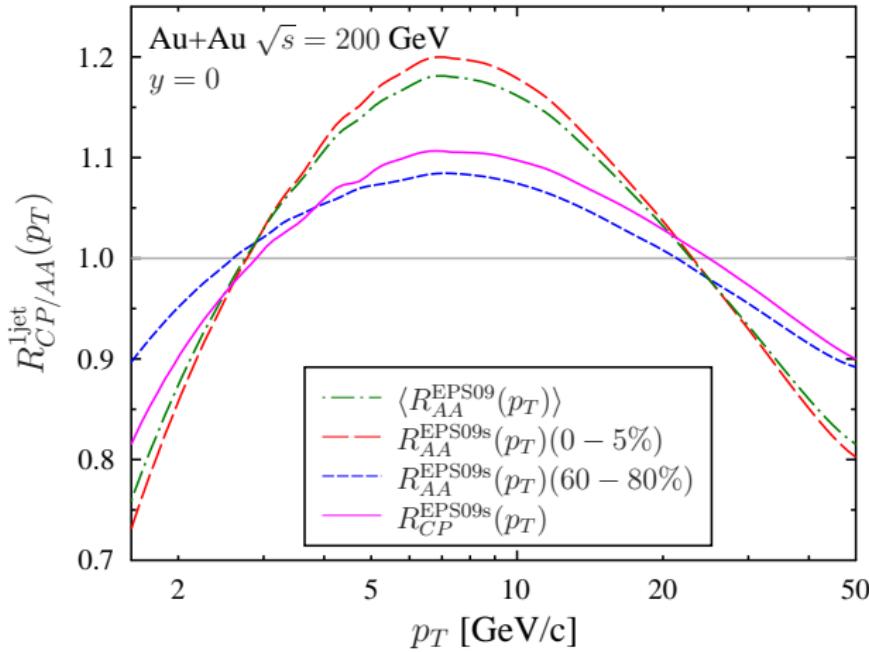
$R_{AA}(\text{central}) \approx \langle R_{AA} \rangle$

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

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

Au+Au collisions at RHIC

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



Observations

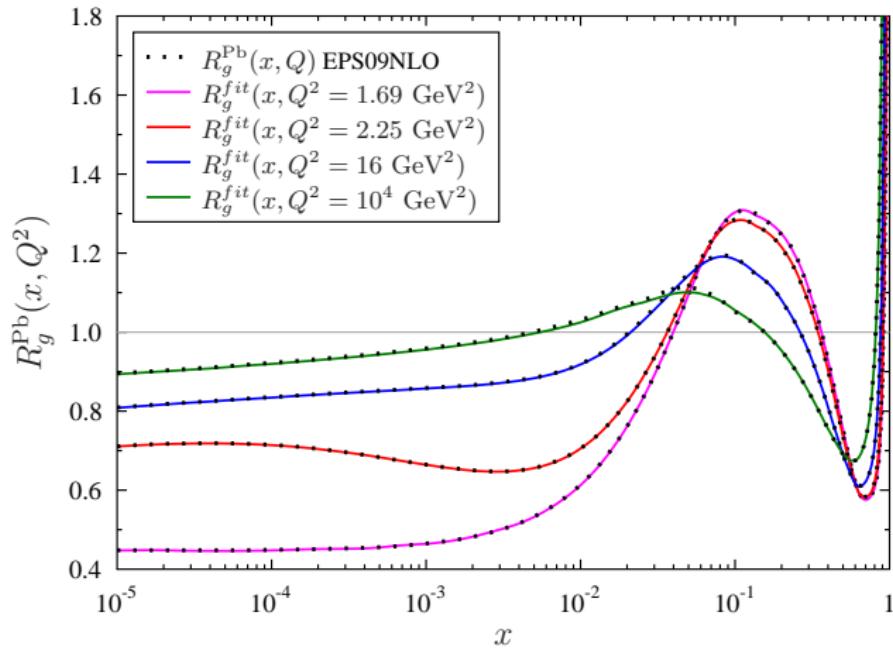
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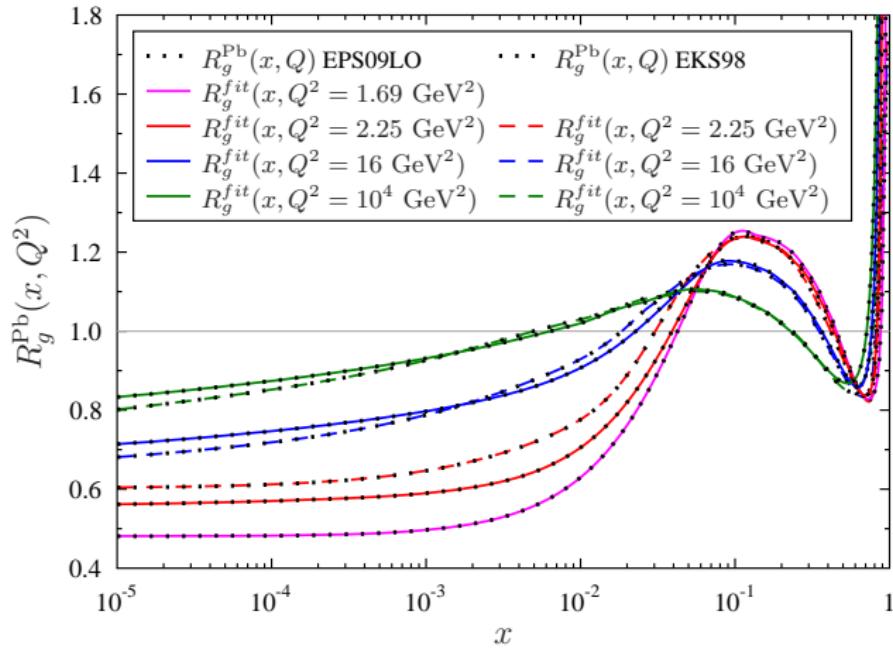
Fitted $R(x, Q^2)$ vs. old $R(x, Q^2)$

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



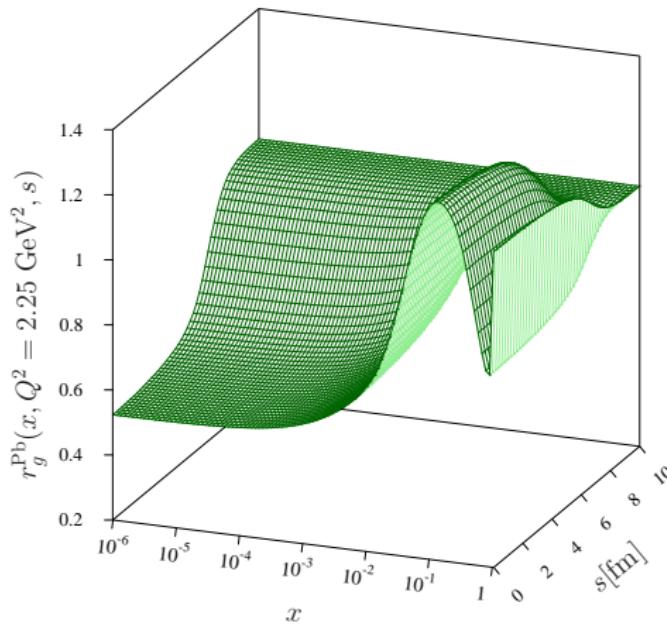
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Spatial Dependence of Nuclear Modifications

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



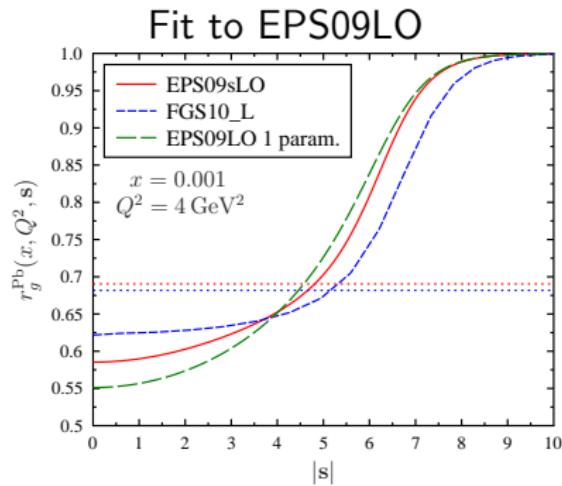
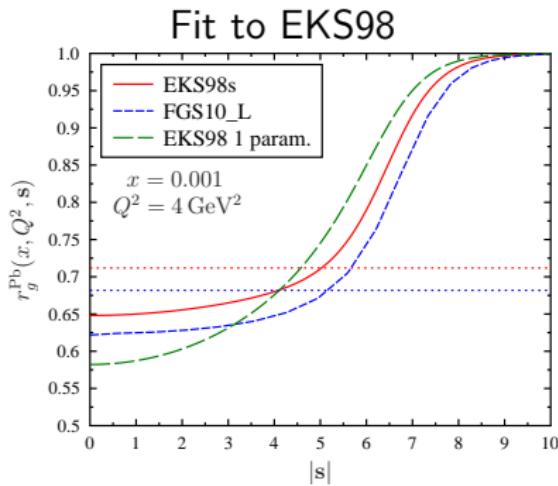
Observations

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

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]



A-dependent modification

Thickness function

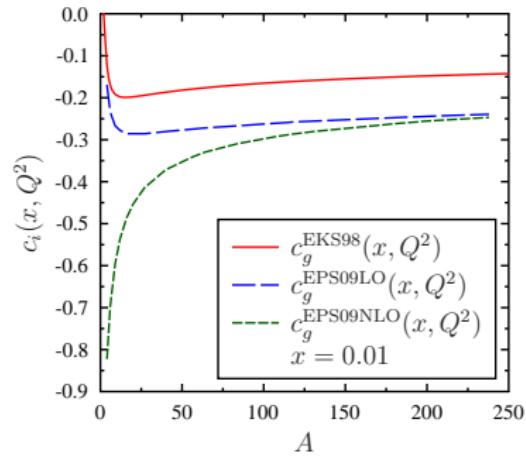
- If the Modification of the form

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

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

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

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



⇒ 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

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

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

Centrality Classes from $p_{inel}^{AB}(\mathbf{s})$

$$\sigma_{inel}^{AB}(b_1, b_2) \approx \int_{b_1}^{b_2} d^2\mathbf{b} \left[1 - e^{-T_{A(B)}(\mathbf{b})\sigma_{inel}^{NN}} \right].$$

