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

High p_T Physics at LHC

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Outline

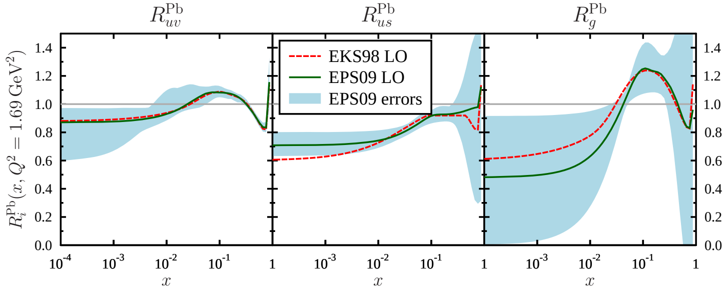
Nuclear Parton Distribution Functions (nPDFs)

- 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, NLO DGLAP evolution, with uncertainties) [*JHEP*, 04:065, 2009]



Hard Processes in Heavy Ion Collisions

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

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

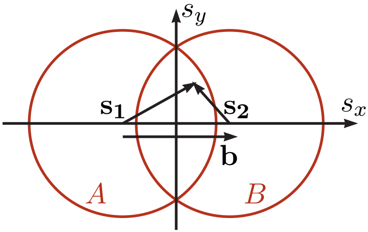
Nuclear overlap function

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 Thickness Function

Amount of nuclear matter in beam direction

Thickness function

Woods-Saxon density profile:

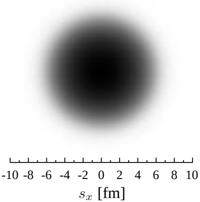
$$T_A(\mathbf{s}) = \int_{-\infty}^{\infty} \mathrm{d}z \frac{n_0}{1+\exp[\frac{\sqrt{\mathbf{s}^2+z^2}-R_A}{d}]}$$

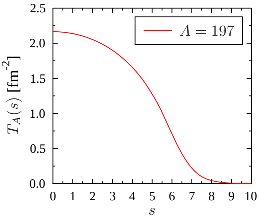
$$d = 0.54 \text{ fm}$$

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

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

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





Model Framework

Nuclear modifications with spatial dependence

- We replace

$$R_i^A(x_1, Q^2) \rightarrow r_i^A(x_1, Q^2, \mathbf{s}),$$

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

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

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

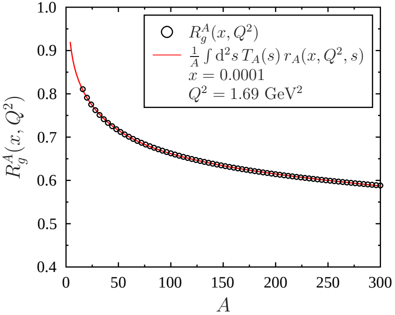
Important: no A dependence in the fit parameters $c_j(x, Q^2)$!

Fitting Procedure

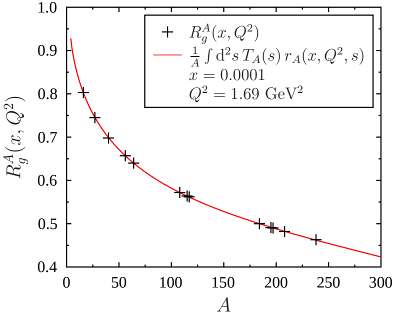
Parameters $c_j(x,Q^2)$ obtained by minimizing the χ^2

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

Fit to EKS98

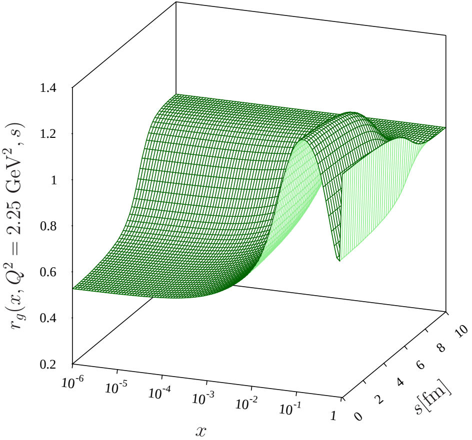


Fit to EPS09



Spatial Dependence of Nuclear Modifications

$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{4} c_j^i(x, Q^2)[T_A(\mathbf{s})]^j \quad (A = 197, \text{EKS98})$$

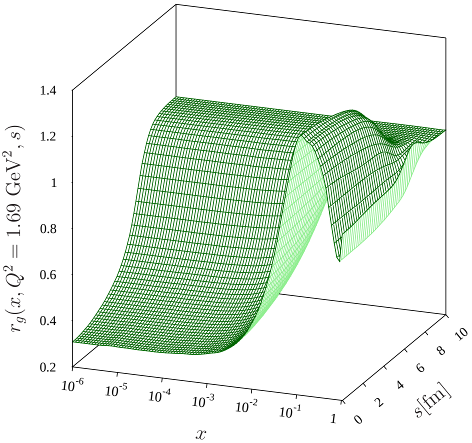


Observations

- 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: $r_i^A(x, Q^2, \mathbf{s}) \approx 1$

Spatial Dependence of Nuclear Modifications

$$r_i^A(x, Q^2, \mathbf{s}) = 1 + \sum_{j=1}^{4} c_j^i(x, Q^2)[T_A(\mathbf{s})]^j \quad (A = 208, \text{EPS09})$$



Observations

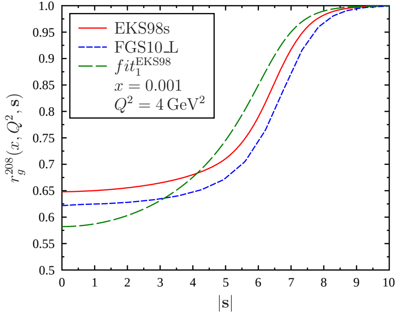
- Basic features similar as with EKS98
- Stronger $\mathbf{s}$ dependence than with EKS98

Comparision With Other Models

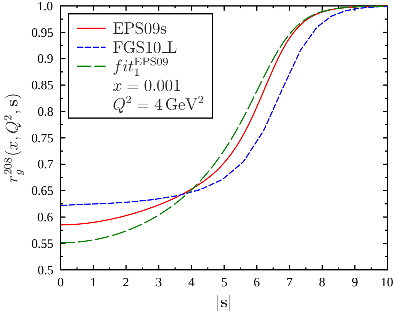
Nuclear modifications with spatial dependence

- 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 EPS09



Observables

Nuclear Modification Factor

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

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

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

Spatially averaged nPDFs

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

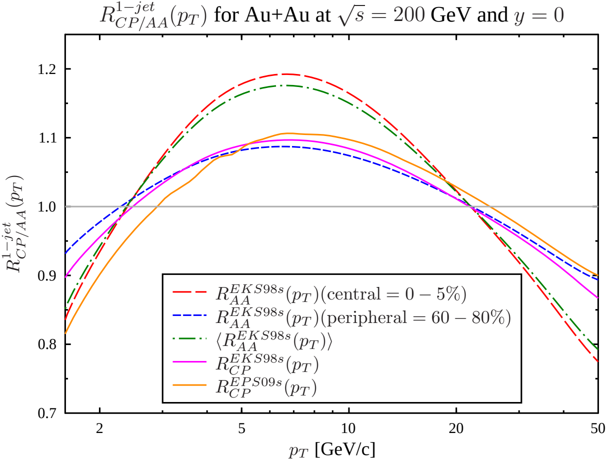
Spatially dependent nPDFs

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

- We provide tables for $c_i^n(x, Q^2)$ for EKS98 and EPS09 fits

Au+Au collisions at RHIC

R_{AuAu} and R_{CP} for LO-jet production; Baseline for E-loss



Observations

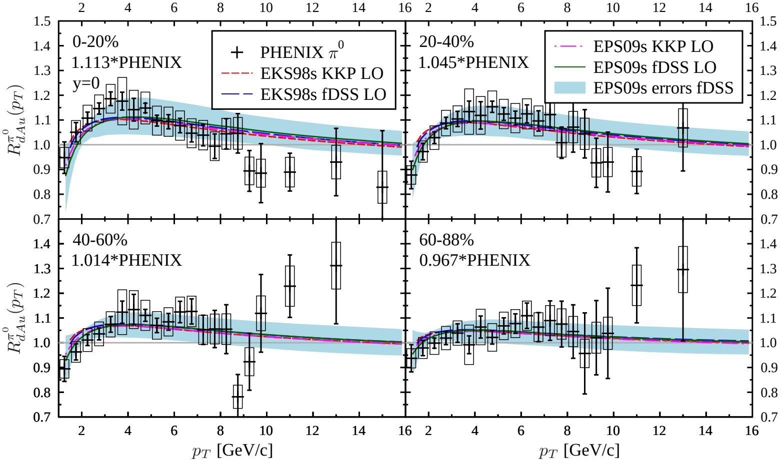
$R_{AA}(central) \approx \langle R_{AA} \rangle$

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

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

d+Au collisions at RHIC

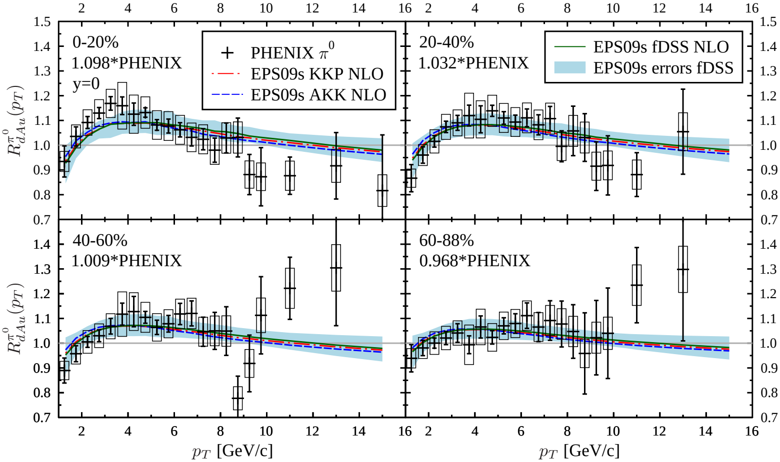
R_{dAu} for π^0 production in different centrality classes at $y = 0$ in LO



Agreement within the normalization uncertainties of the data

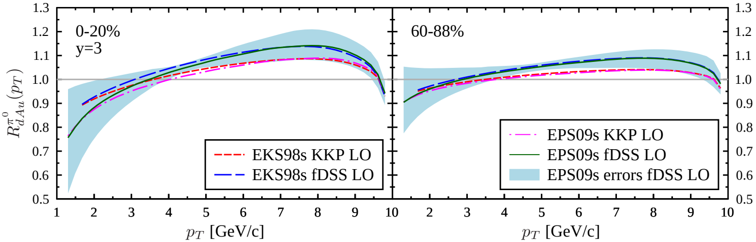
d+Au collisions at RHIC

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



d+Au collisions at RHIC

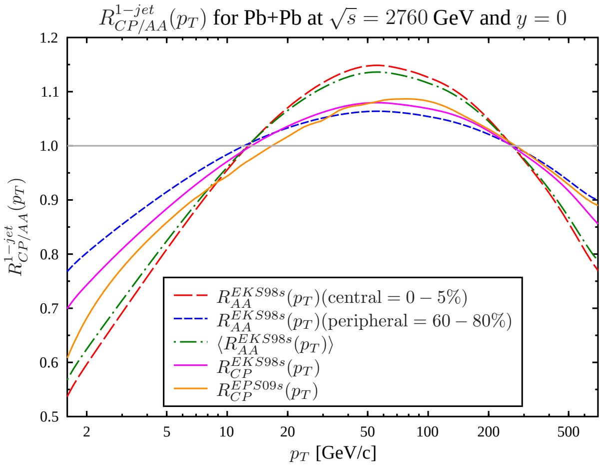
R_{dAu} for π^0 production for central and peripheral collisions at forward region ($y = 3$) in LO



- More shadowing at small p_T than for $y = 0$
- Sensitive also to FF set (large-z differences)

Pb+Pb collisions at LHC

R_{PbPb} and R_{CP} for LO-jet production; Baseline for E-loss



Observations

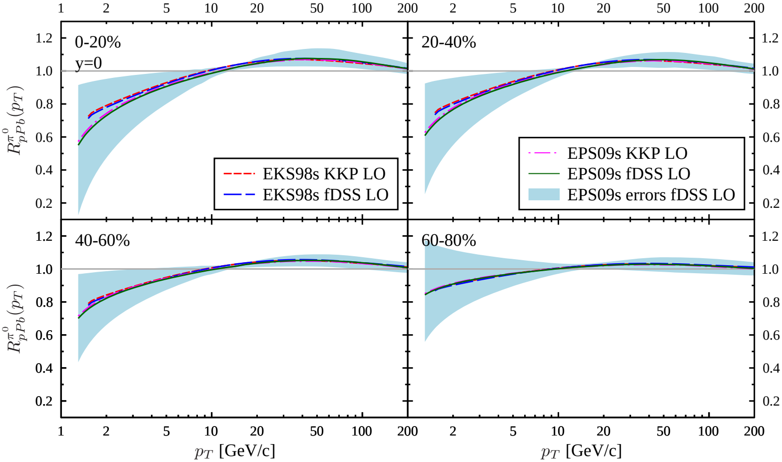
$R_{AA}(central) \approx \langle R_{AA}\rangle$

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

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

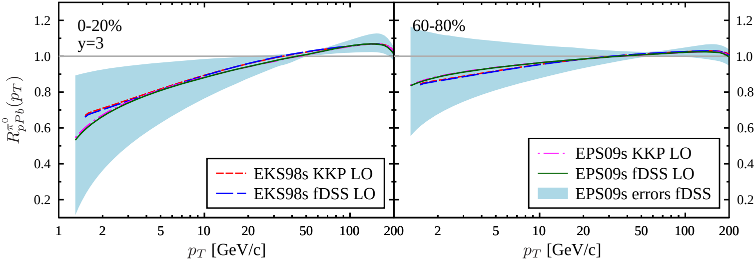
p+Pb collisions at LHC

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



p+Pb collisions at LHC

R_{pPb} for π^0 production for central and peripheral collisions at forward region ($y = 3$) in LO



- Similar amount of shadowing at small p_T as for $y = 0$
- p+Pb at LHC will provide important constraints for nuclear modifications

Summary & Outlook

We have

- Determined the spatial dependence of nuclear modifications based on
  - The A dependence of the EKS98/EPS09 (= data!)
  - The nuclear thickness function $T_A(\mathbf{s})$
- Written a code to calculate $r_i^A(x, Q^2, \mathbf{s})$
- Calculated R_{AA}^{1-jet}, R_{CP}^{1-jet} and $R_{dAu}^{\pi^0}$ in LO and NLO

We will

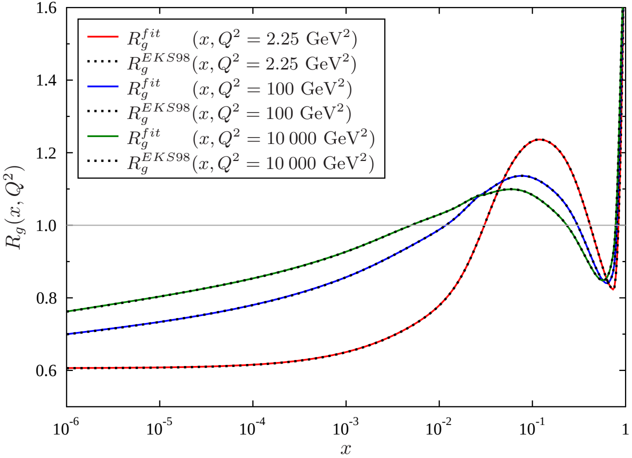
- Calculate predictions for p+Pb collisions at LHC in NLO
- Make the codes for $r_i^A(x, Q^2, \mathbf{s})$ calculation, named EKS98s and EPS09s, publicly available

  $\Rightarrow$ Nuclear modifications of any hard process in different centrality classes can now be computed consistently with EKS98/EPS09!

Backup

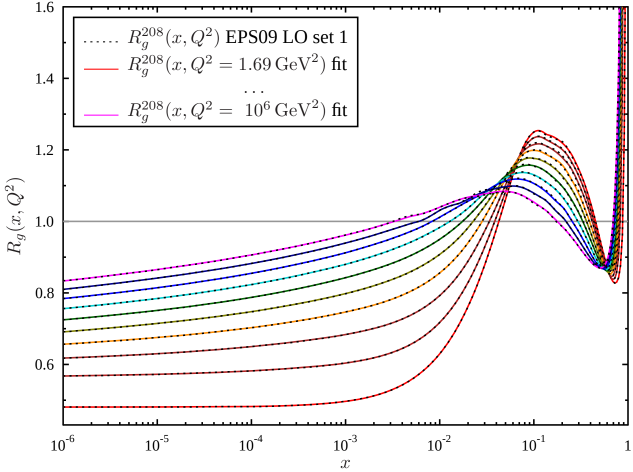
Fitted $R(x, Q^2)$ vs. old $R(x, Q^2)$

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



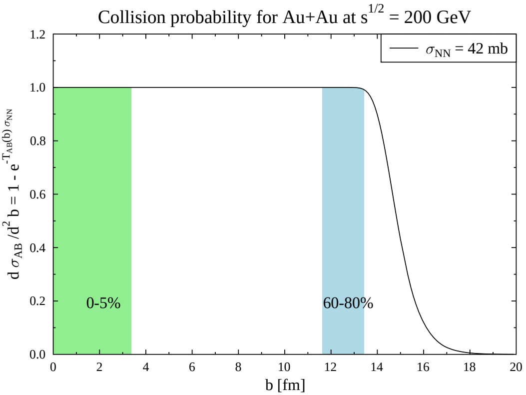
Fitted $R(x, Q^2)$ vs. old $R(x, Q^2)$

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



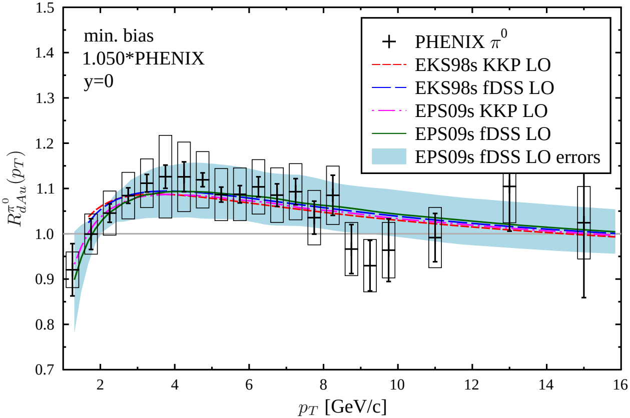
Centrality Classes for Au+Au at RHIC

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



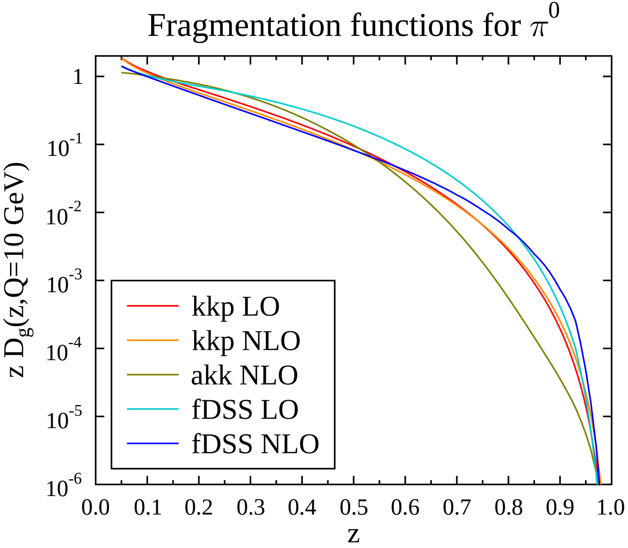
d+Au collisions at RHIC

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



Used in EPS09 global fit!

Fragmentation Functions



A+B Collisions

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

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

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

A-dependent modification

Thickness function

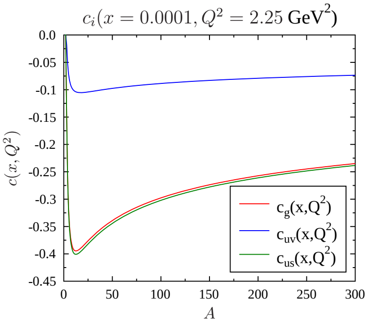
- If the Modification of the form

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

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

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

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



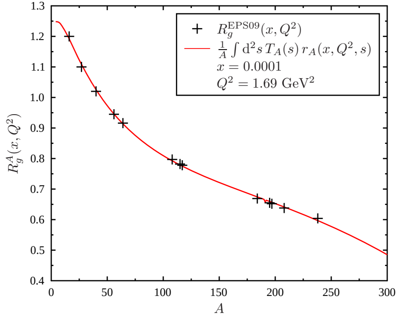
$$\frac{c_g^{208}(x,Q^2)}{c_g^{12}(x,Q^2)} = 0.65$$

⇒ Strong A dependence of $c(x, Q^2)$!

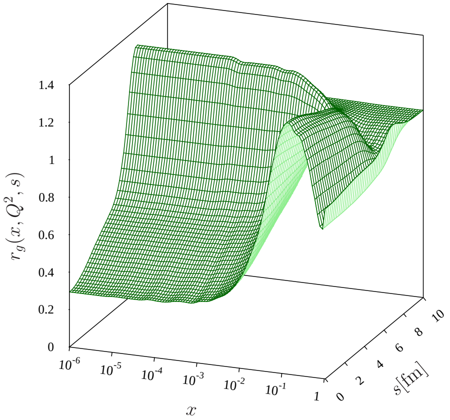
The s dependence not entirely decomposed from $c(x, Q^2)$.

Spatial Dependence of EPS09LO set 7

Fit to EPS09LO set 7



Spatial dependence of EPS09s set 7



p+Pb collisions at LHC

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