

Proton-nucleon collisions at LHC: a tool to constrain nuclear PDFs

Paloma Quiroga-Arias

CERN and Universidade de Santiago de Compostela

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In collaboration with

J. Guilherme Milhano (CENTRA-IST and CERN) and Urs A. Wiedemann
(CERN)

Outline

- nPDFs needed as benchmarks for characterization of hot QCD matter in HIC
- They may show novel signatures in non-linear QCD evolution
- Factorization of long range phenomena into process-independent PDFs: extends to nuclear case?

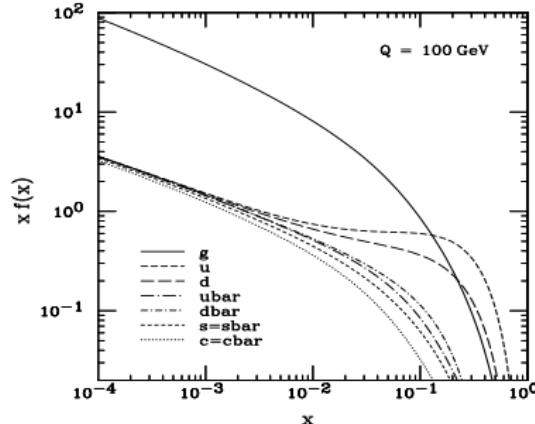
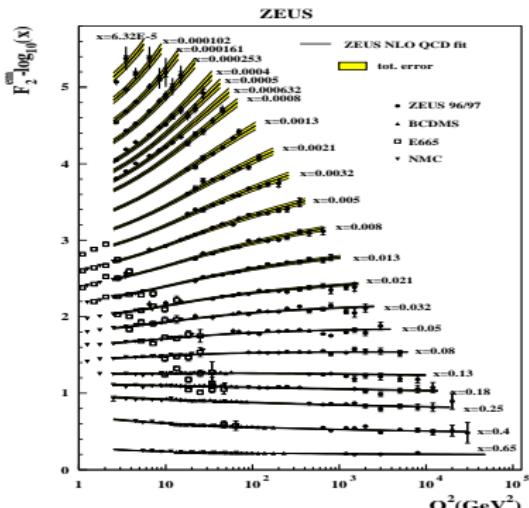
Reliability of nPDFs for benchmark calculations

- test numerical accuracy of their extraction
- phenomenological tests of the factorization assumption

Free nucleon PDFs

Sets of collinearly factorized universal PDFs: obtained in global pQCD analysis (MSTW, CTEQ, GRV, NNPDF)

- data: DIS (e-p), DY, W/Z and jet production



Logarithmically wide ranges in Q^2 and x

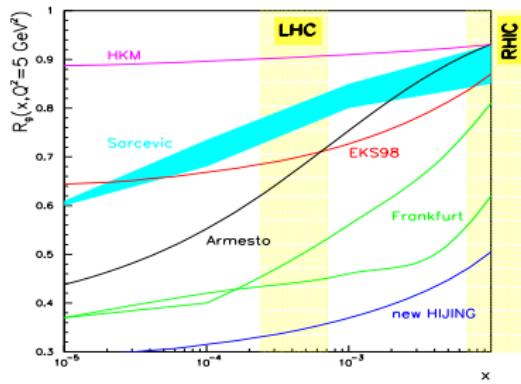
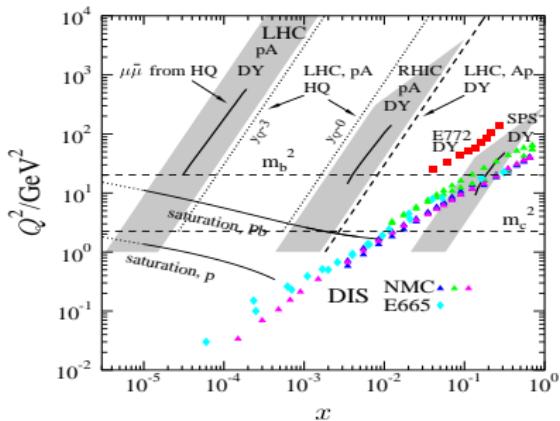
tight constraints on PDFs and precision testing of linear pQCD evolution

Nuclear PDFs situation

- Understanding much less mature. Importance of nPDFs $f_{i/A}(x, Q^2)$:
 - in HIC (quantitative control of hard processes)
 - can reveal non-linear features of QCD evolution
- Global QCD analysis of nPDFs (EKS98,nDS,HKM,HKN,EPS)

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- Understanding much less mature. Importance of nPDFs $f_{i/A}(x, Q^2)$:
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DIS in eA: very little data, small Q^2 range \Rightarrow almost no access to the **gluon**

How (n)PDFs are constrained

	DIS	DY	W,Z and jet production
PDF	•	•	•
nPDF	~	~	✗

- PDFs: **DIS** and **DY** + data from **W, Z and jet production**
- nPDFs: how can **hadronic collisions** be used to further constrain nPDFs?
 - AA: dominant nuclear effects are final state ✗ (Improved nPDFs needed to quantify "jet quenching")
 - What about pA ? Working assumption: dominant nuclear effects reside in nPDFs ✓
- at RHIC: W, Z and jet production not accessible, resort to **high p_T single inclusive hadron spectra (EPS09)**

Focus on π^0 spectrum in pA

$$E \frac{d\sigma^{pA \rightarrow \pi^0 + X}}{d^3 p} = K(\sqrt{s}) \sum_{ijk} A \int dx_2 f_{j/A}(x_2) \int dx_1 f_{i/p}(x_1) \int dz E \frac{d\hat{\sigma}^{ij \rightarrow k}}{d^3 p} D_{k \rightarrow \pi^0}(z)$$

RHIC data included in EPS09

- Entering the game:

- parton distribution functions: $x_{i(j)} f_{i/p(j/A)}(x_{1(2)}, Q^2)$
- partonic cross sections (LO): $d\hat{\sigma}^{ij \rightarrow kl}(\hat{s}, \hat{t}, \hat{u})$
- fragmentation functions: $D_{k \rightarrow h}(z, \mu_F^2)$
- $K(\sqrt{s})$ factor: accounts for higher-order effects

Entire nuclear dependence resides on nPDFs

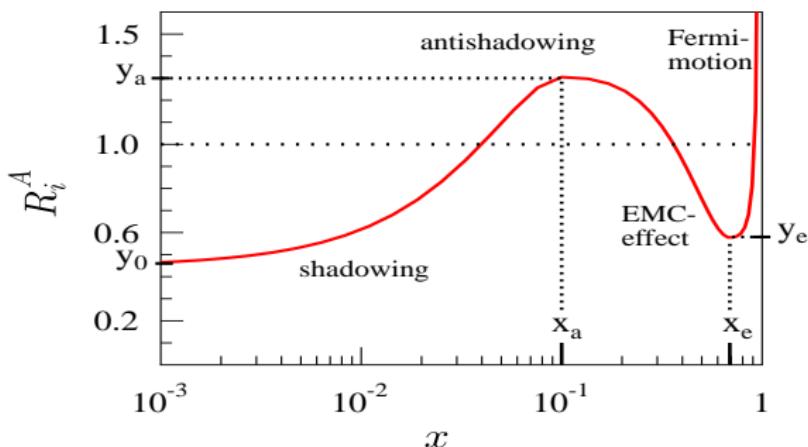
Factorization as a theorem

not proven for nuclear effects (*working assumption*)

Characterization of nPDFs

- nPDFs: deviation from linear superposition of PDFs at all scales

$$R_i^A \equiv \frac{xf_{i/A}}{xf_{i/p}}$$



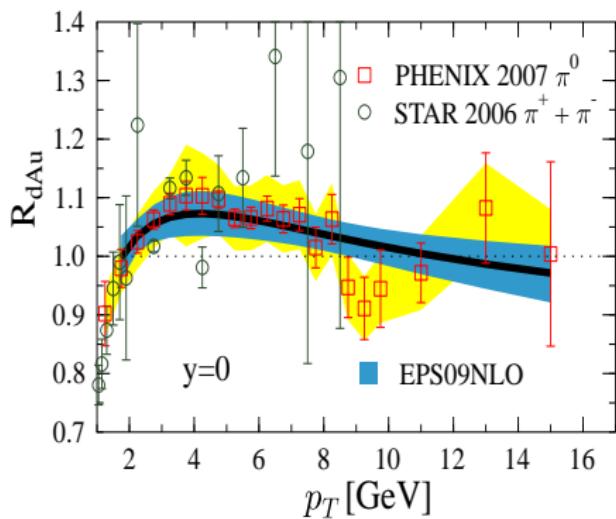
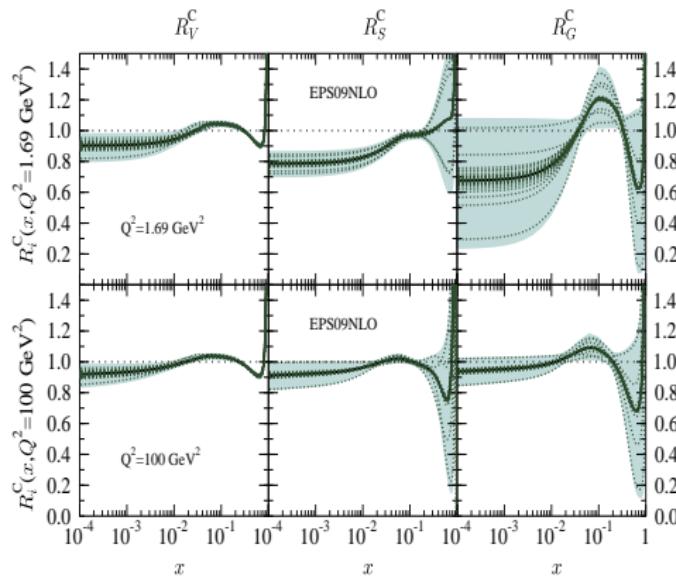
- Physics not fully understood at any scale. Testable at large Q^2
- To discuss:
 - **model assumptions** to extract R_i^A from data
 - use of **hadron collider** experiments to **improve R_i^A** and to **test the physics assumptions** underlying the extraction

EPS09: The nuclear modification factor $R_{pA}^{\pi^0}$

ESP09 assumption: all nuclear effects in $R_{pA}^{\pi^0}$ resides in nPDFs

$$R_i^A = \frac{xf_{i/A}}{xf_{i/p}}$$

Definition min.bias: $R_{pA}^h \equiv \frac{\frac{d^2\sigma_{pA}^h}{dq_T dy}}{A \frac{d^2\sigma_{pp}^h}{dq_T dy}}$



EPS09: nuclear PDFs uncertainties

- S^0 : EPS central set (best fit-lowest χ^2)
- $S_{k=1,\dots,15}^\pm$: displacing fit parameters ($\Delta\chi^2 = 50$) \rightarrow 30 sets
- Error propagation:

$$X(S^0) + \Delta X^+ - \Delta X^-$$

$$\Delta X^+ \approx \sqrt{\sum_k [\max(X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0)]^2}$$

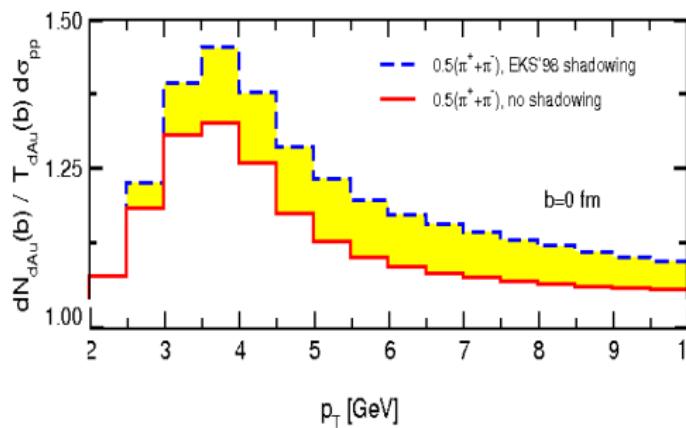
$$\Delta X^- \approx \sqrt{\sum_k [\max(X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0)]^2}$$

Is this the whole story?

- Factorization of cross-sections into nPDFs \otimes hard process not proven
- Models exist assuming initial state mult. scatt. (p_T broadening)

nPDF

mult.scatt.
I.Vitev



How to distinguish mult.scatt. and nPDF approach?

Results: pPb collisions @ the LHC

- We have chosen an observable: π^0 single inclusive spectra
- Assumption: factorization in pA holds
- Model: EPS09 nPDF parameterization (CTEQ6L, KKP)

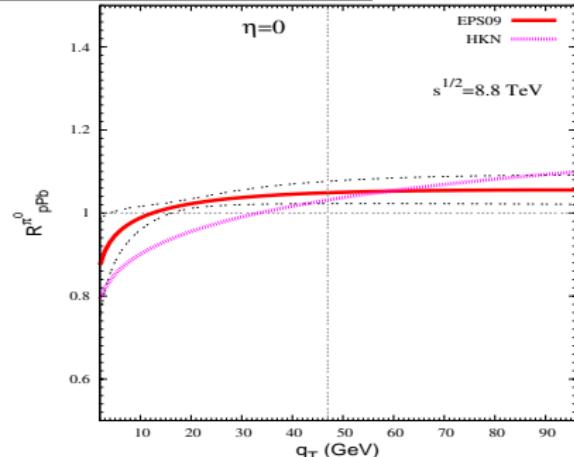
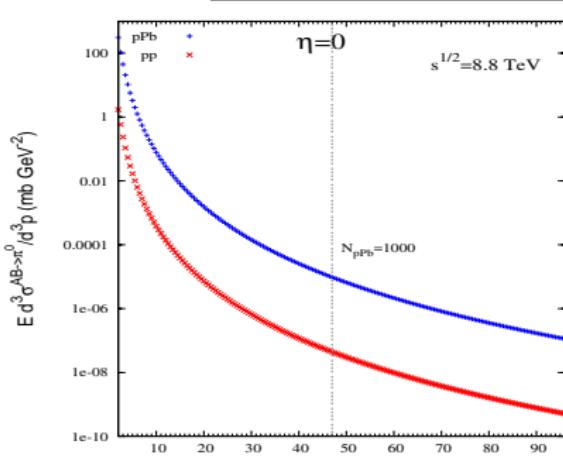
π^0 production in pPb @ LHC

Basic LHC parameters for pA running:

- The two beams same rigidity \Rightarrow beam momenta $p = 7 \text{ TeV} \frac{Z}{A}$
- Center of mass energy: $\sqrt{s} = 14 \text{ TeV} \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \Rightarrow \boxed{\sqrt{s}_{pPb} = 8.8 \text{ TeV}}$
- Shift between center-of-mass and lab systems: $y_{cent} = \frac{1}{2} \ln \frac{Z_1 A_2}{Z_2 A_1}$
- $\Delta y_{pPb} \sim 0.5$
- Nominal luminosity: $\boxed{L = 1.1 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}}$

π^0 in pA @ the LHC mid-rapidity

pPb LHC program : 1 year = 1 month $\simeq 2 \times 10^6$ s, $L = 1.1 \times 10^{29} \text{ cm}^{-2} \text{s}^{-1}$



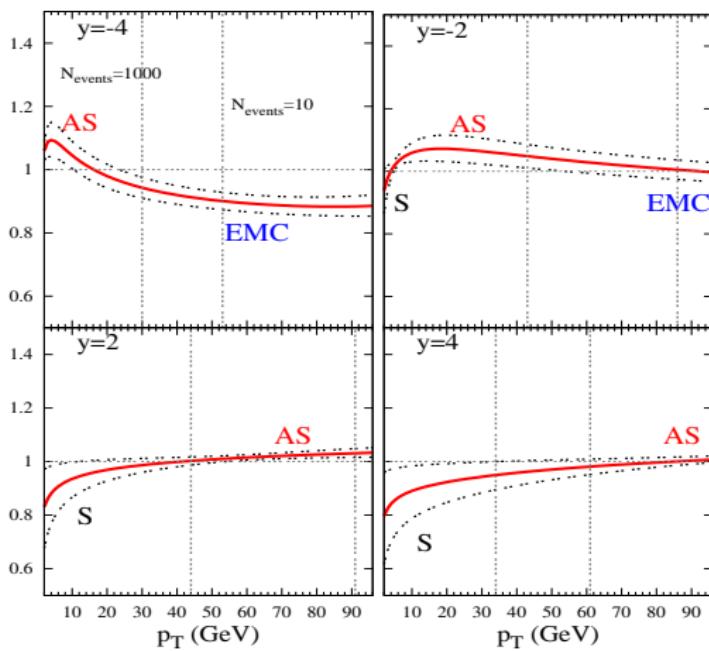
- Cut: accessible p_T for N_{events} in 1 year run at LHC
- No maximum around $p_T \sim 10 \text{ GeV} \Rightarrow$ Incompatible with multiple scattering of incoming partons

Repeating the RHIC experiments at 30 times \sqrt{s} in the TeV scale

we discriminate between two fundamentally different dynamical explanations

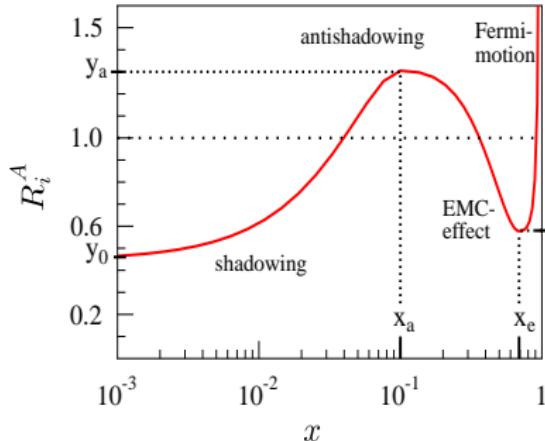
Exploiting the wide rapidity range at the LHC

$$R_{pPb}^{\pi^0}$$



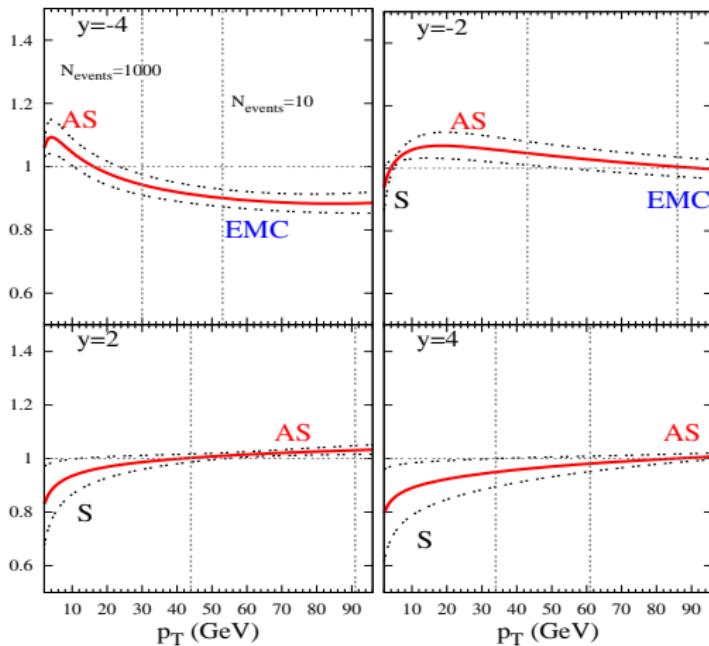
forw.y → back.y

$$x \sim \frac{p_T}{\sqrt{s}} e^{-y}$$



Exploiting the wide rapidity range at the LHC

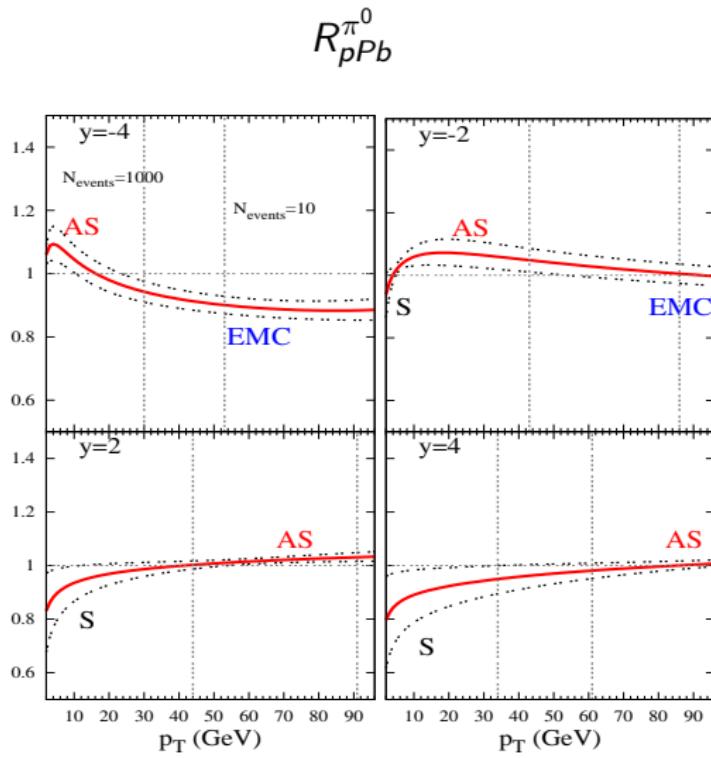
$$R_{pPb}^{\pi^0}$$



Rapidity dependence of R_{pA}^h traces directly characteristic x-dependence of nPDFs

Confirming y -dependence of R_{pA}^h
strong support to factorization assumption

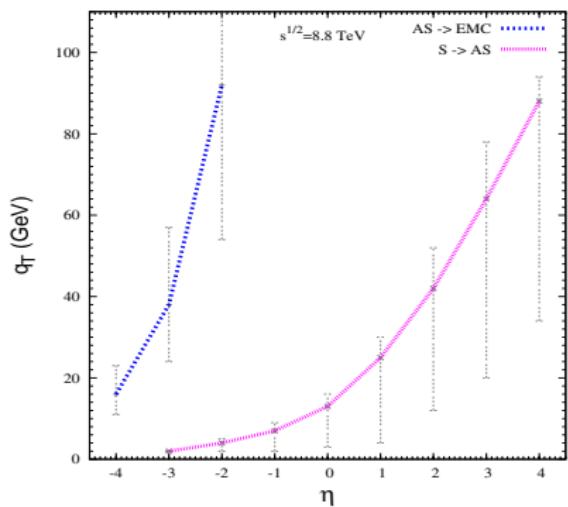
Exploiting the wide rapidity range at the LHC



Transition q_T vs η

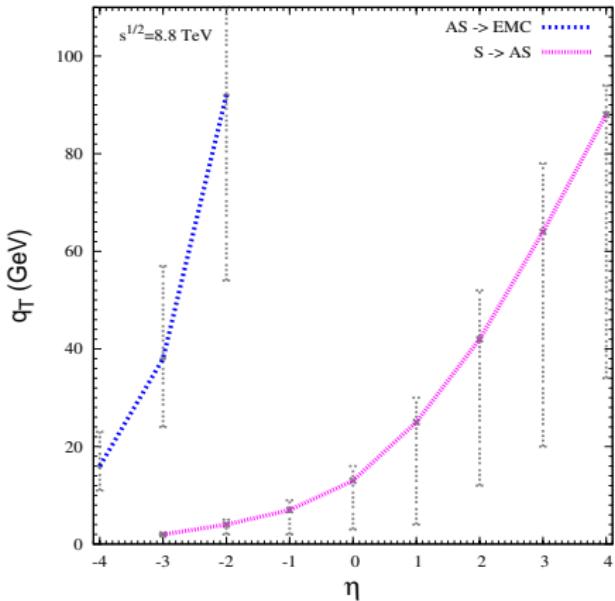
$$R_{pPb}^{\pi^0} > 1 \rightarrow R_{pPb}^{\pi^0} < 1$$

$$R_{pPb}^{\pi^0} < 1 \rightarrow R_{pPb}^{\pi^0} > 1$$



Extended kinematic range

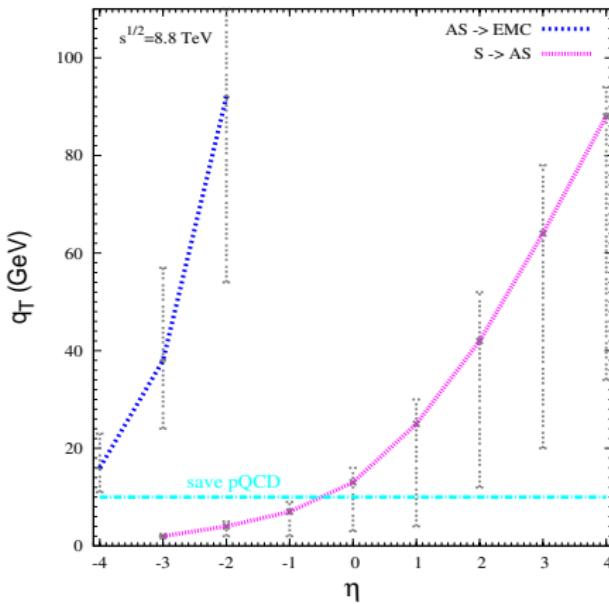
$$x \sim \frac{p_T}{\sqrt{s}} e^{-y}$$



high x_2 —→ low x_2

Extended kinematic range

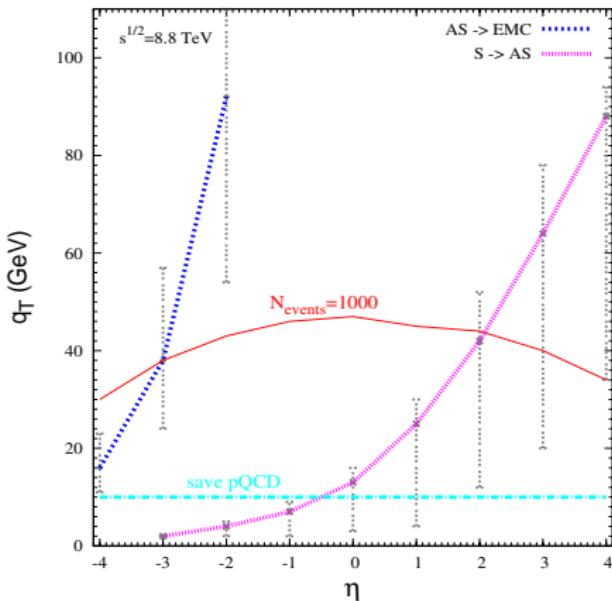
$$x \sim \frac{p_T}{\sqrt{s}} e^{-y}$$



$$x_2 \simeq 0.062 \quad \longrightarrow \quad x_2 \simeq 2.2 \times 10^{-5}$$

Extended kinematic range

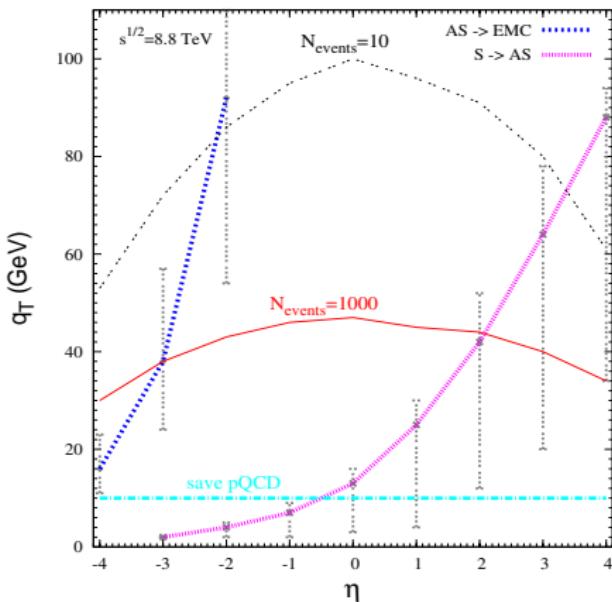
$$x \sim \frac{p_T}{\sqrt{s}} e^{-y}$$



$$x_2 \simeq 0.189 \quad \longrightarrow \quad x_2 \simeq 9 \times 10^{-5}$$

Extended kinematic range

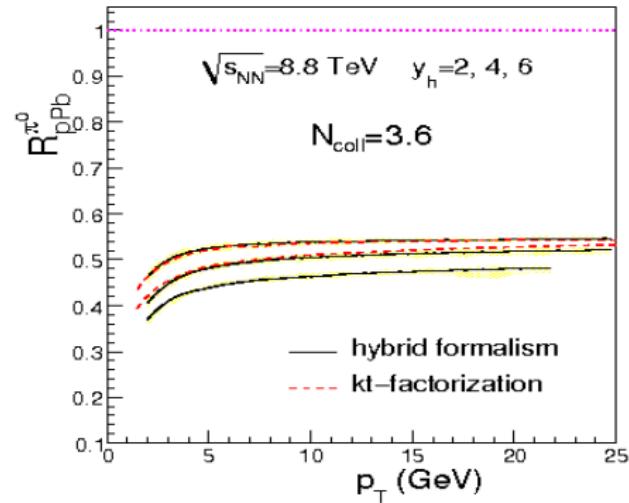
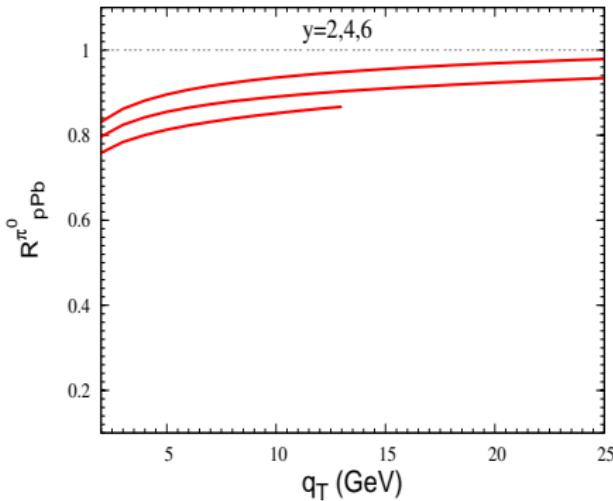
$$x \sim \frac{p_T}{\sqrt{s}} e^{-y}$$



$$x_2 \simeq 0.33 \quad \longrightarrow \quad x_2 \simeq 2 \times 10^{-4}$$

What about non-linear effects?

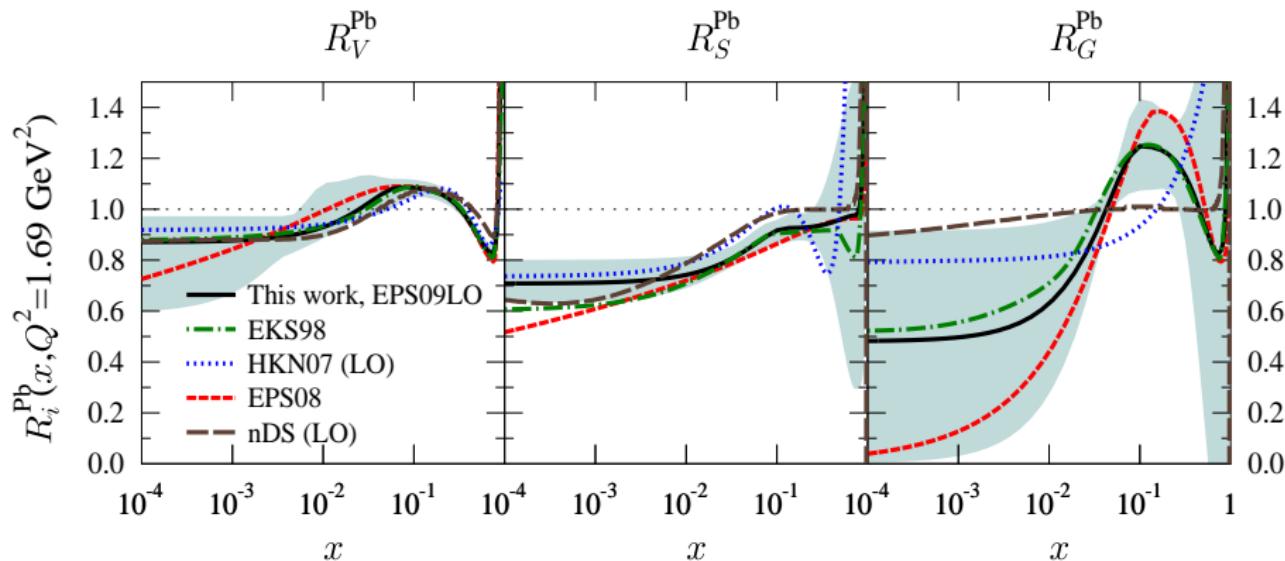
- Collinearly factorized approach:
mild suppression
- Non-linear small-x evolution:
suppression factors of order 2
Albacete and Marquet 09



Non-linear ev. like suppression inconsistent with all existing nPDFs

Can we use the LHC to constrain gluon distribution?

Nuclear modifications for Pb at the initial scale $R_{pPb}(x, Q_0^2)$ comparison to other LO analysis

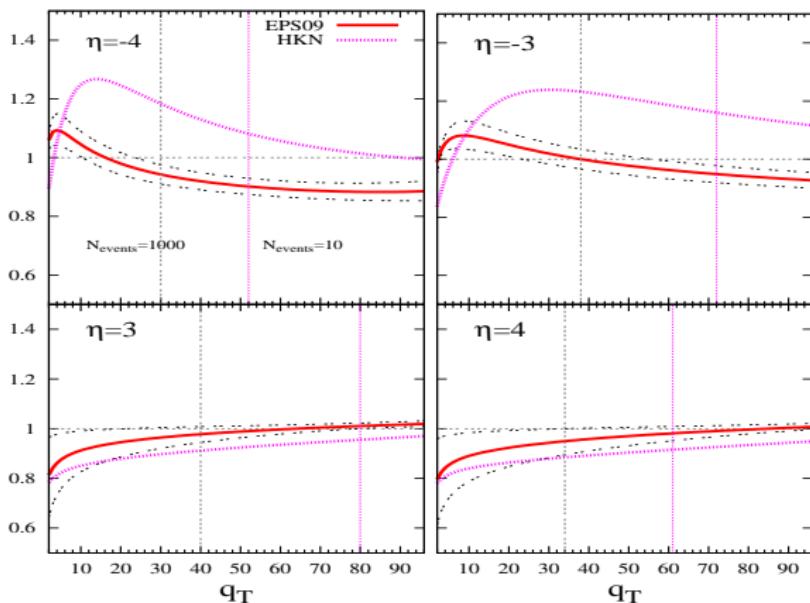


Eskola et al., 09

LHC data constrain nPDFs!!

LHC data can improve our knowledge of nuclear gluon distributions

Use of $xf_{g/Pb}^{HKN07}$



Indeed if factorization holds

data will allow to discriminate between different recent global nPDFs-fits

Conclusions

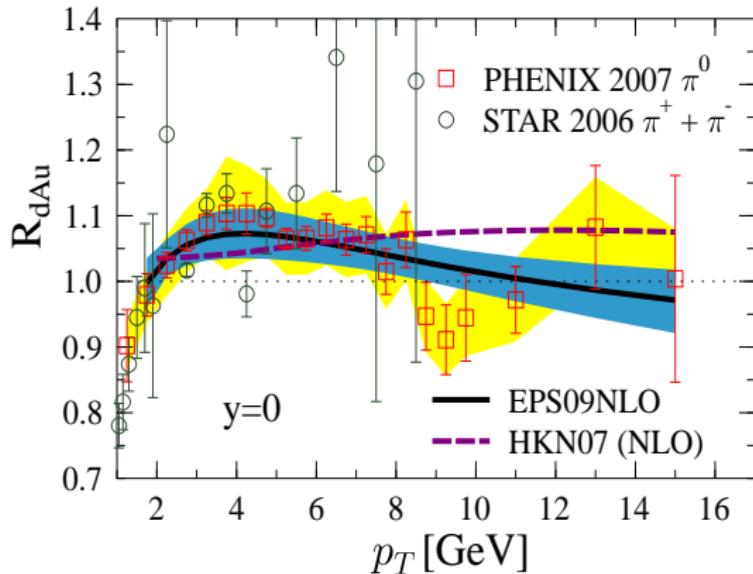
- With pA collisions at the LHC we will be able to say if factorization holds by scanning in rapidity (*i.e.* we *will be able to say if the working assumption global nPDF fits is correct*)
- Data in much wider x and Q^2 ranges \Rightarrow fits using the new data will further constrain nPDFs
- Data will allow to discriminate between different recent global nPDFs-fits

Importance of nPDFs for characterizing benchmark processes in HIC
pA run at LHC!!

BACKUP SLIDES

Description of RHIC data: EPS09 and HKN07

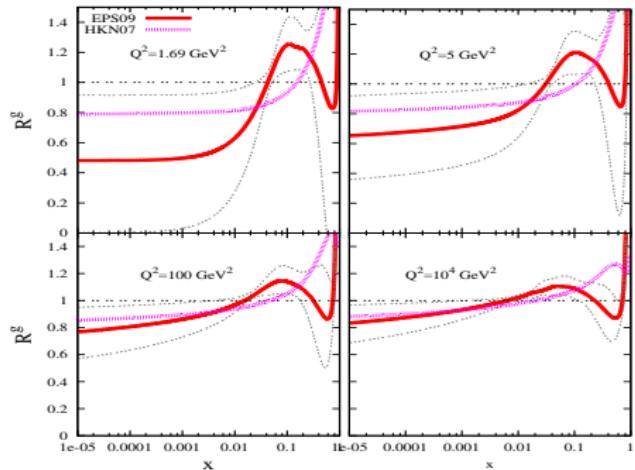
- PHENIX data from 2009 at mid-rapidity: NLO EPS09 and HKN07



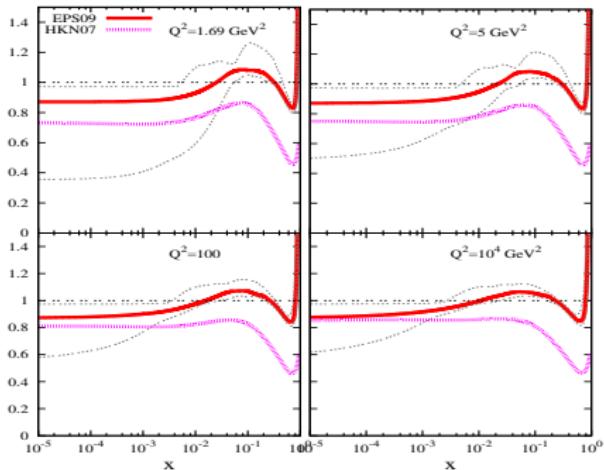
Eskola et al., 2009

The valence up quark nuclear modified PDFs in both parameterizations

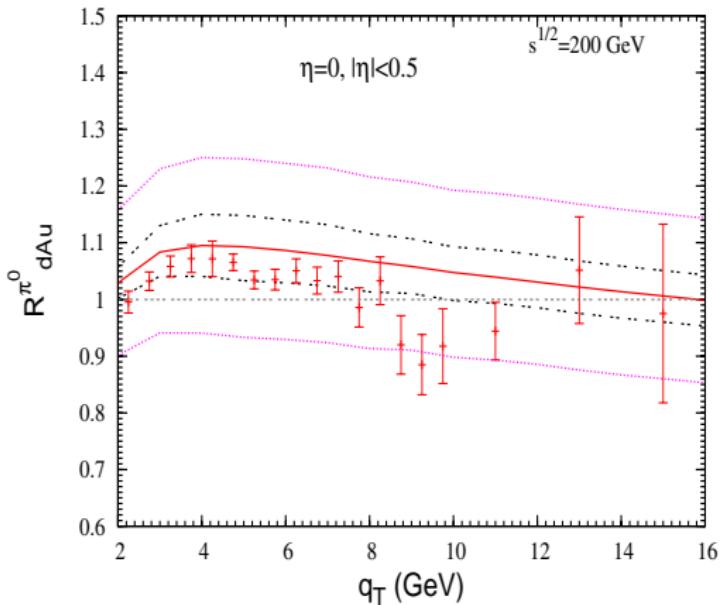
$$R_g^{Pb}$$



$$R_u^{Pb}$$



Description of RHIC data

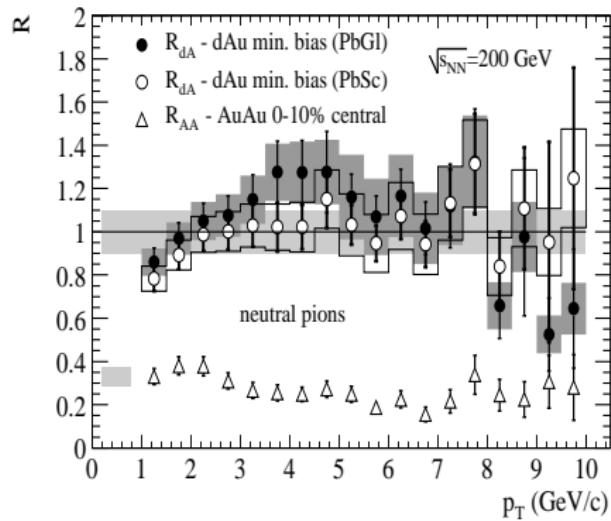


- **points:** RHIC data with stat.err.
- **line:** our LO calculation with S_{EPS09}^0
- **lines:** EPS09 uncertainty band to **line**
- **lines:** lines including RHIC data normalization uncertainty

Agreement of data and calculation: **support of collinear factorization**

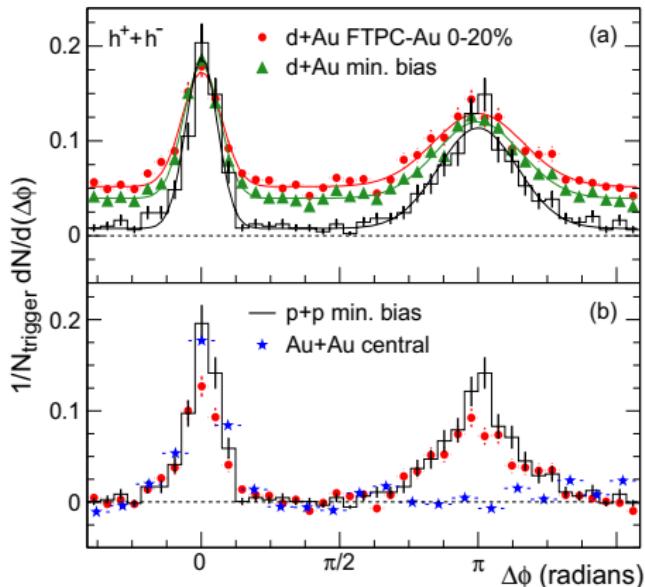
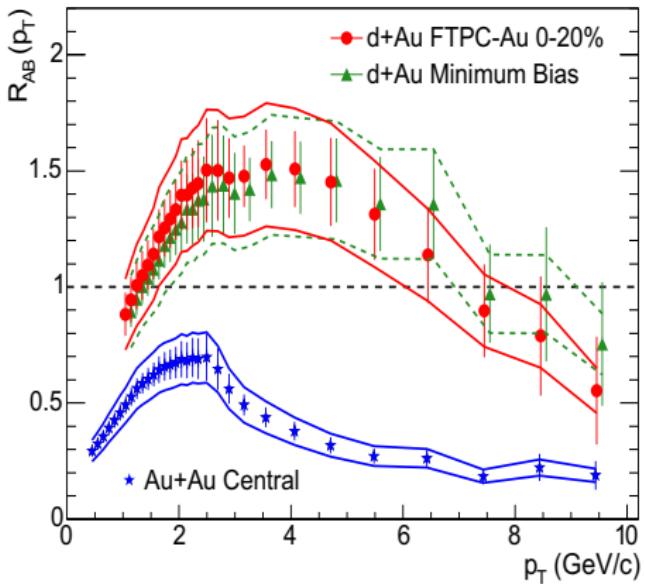
Measurements at RHIC: PHENIX

"Absence of Suppression in Particle Production at Large Transverse Momentum in $\sqrt{s} = 200$ GeV d+Au Collisions", **PHENIX collaboration 2003**



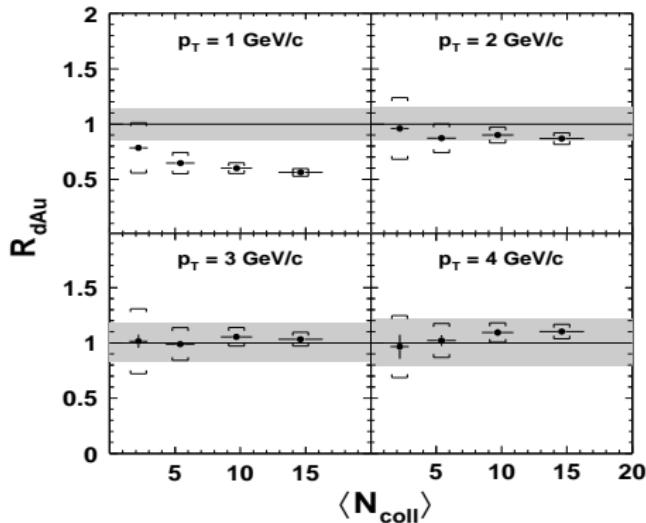
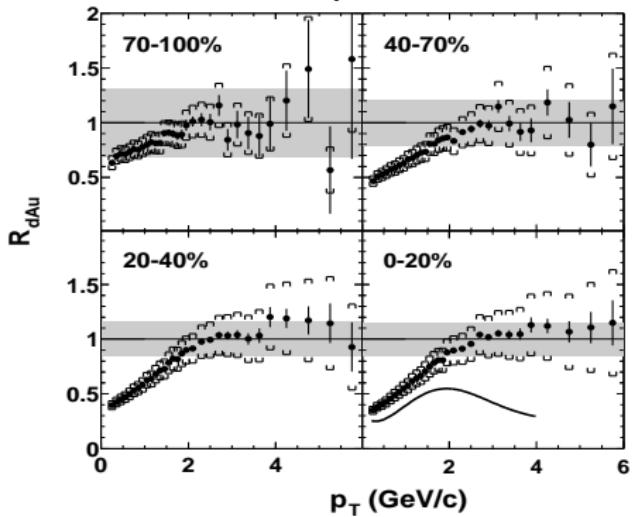
Measurements at RHIC: STAR

"Evidence from d+Au measurements for final-state suppression of high p_T hadrons in Au+Au collisions at RHIC ", **STAR collaboration, 2003**



Measurements at RHIC: PHOBOS

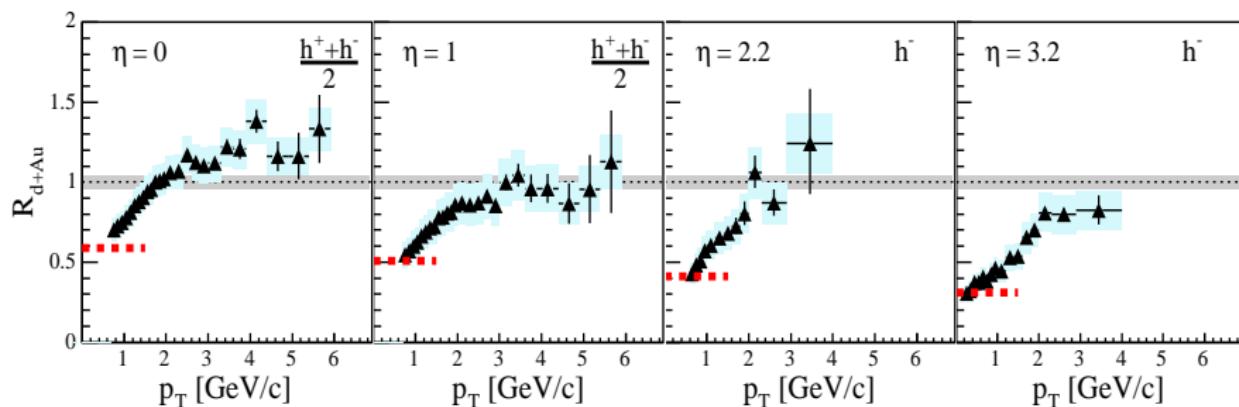
"Centrality dependence of charged hadron transverse momentum spectra in d+Au collisions at $\sqrt{s} = 200$ GeV " **PHOBOS collaboration, 2003**



- Data disfavor prediction from parton saturation model \Rightarrow observed high p_T suppression in AuAu cannot be accounted for by *initial state effects*

Measurements at RHIC: BRAHMS

"Evolution of the nuclear modification factors with rapidity and centrality in d+Au collisions at $\sqrt{s} = 200 \text{ GeV}$ ", **BRAHMS collaboration, 2004**



- Significant and systematic decrease of R_{dAu} with increasing rapidities

Free proton PDFs parameterizations

- Method to extract PDFs from experimental data well established:
 - initial nonperturbative distributions parameterized at Q_0^2
 - then evolved to higher scales according to the DGLAP equations
 - comparison with data in various regions of the (x, Q^2) -plane
 - best global fit: parameters of $f_i^P(x, Q_0^2)$ are fixed
 - DIS data are most important for these global DGLAP fits (HERA)
 - the sum rules for momentum, charge and baryon: further constraints
- Through global DGLAP fits sets of PDFs: MSTW, CTEQ, GRV, NNPDF

nPDFs also obey the DGLAP equations in the large- Q^2 limit

- can be determined by using a similar global DGLAP fit procedure
- additional variables (A, Z) and limited number of data points in the perturbative region: nuclear case is more complicated
- DIS (eA) data play dominant role; also DY processes in fixed target pA ; Single inclusive spectrum in pA .

EPS09 parametrization

- They are a fit to data
- They include new data from RHIC
- error treatment
- Isospin symmetry assumed to hold for bound nucleons:
 $f_u^{n/A} = f_d^{p/A} = f_{d/A}$ and $f_d^{d/n} = f_u^{p/A} = f_{u/A}$

$$f_{u/A}(x, Q^2) = \frac{Z}{A} f_{u/A}(x, Q^2) + \frac{A-Z}{A} f_{d/A}(x, Q^2)$$

$$f_{d/A}(x, Q^2) = \frac{Z}{A} f_{d/A}(x, Q^2) + \frac{A-Z}{A} f_{u/A}(x, Q^2)$$

EPS09 errors

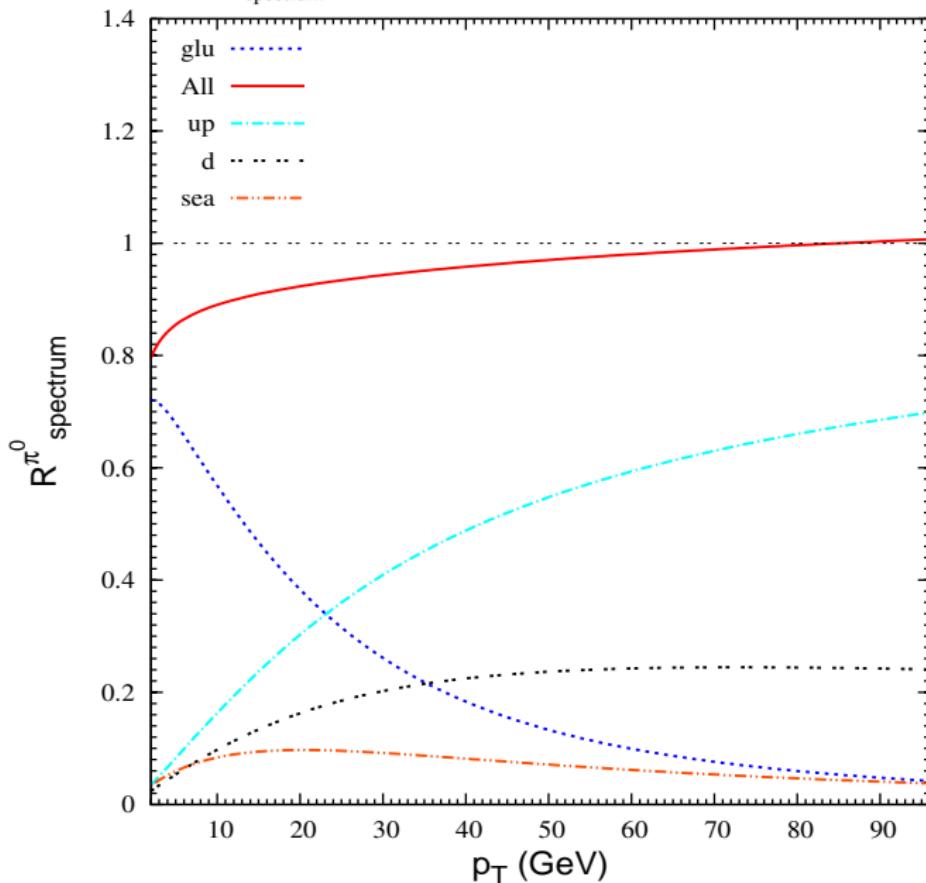
- S^0 : EPS central set (best fit-lowest χ^2)
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- Error propagation:

$$X(S^0) + \Delta X^+ - \Delta X^-$$

$$\Delta X^+ \approx \sqrt{\sum_k [\max(X(S_k^+) - X(S^0), X(S_k^-) - X(S^0), 0)]^2}$$

$$\Delta X^- \approx \sqrt{\sum_k [\max(X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0)]^2}$$

$$R_{\text{spectrum}}^{\pi^0} = d\sigma^{\text{pPb} \rightarrow \pi^0 + X} / \sigma^{\text{pp} \rightarrow \pi^0 + X}, \eta = 3, |\delta\eta| = 1, s^{1/2} = 8.8 \text{ TeV}$$



- Initial state partons Bjorken x:

$$x_1 = \frac{p_T}{\sqrt{s}} (e^{y_2} + e^{y_1}), \quad x_2 = \frac{p_T}{\sqrt{s}} (e^{-y_2} + e^{-y_1})$$

- Rapidity of the final state parton hadronizing: $y_f = y_1 \Rightarrow$ integrate over all the rest (y_2)

$$y_{2,min} = -\log \left(\frac{\sqrt{s}}{p_T} - e^{-y_f} \right), \quad y_{2,max} = \log \left(\frac{\sqrt{s}}{p_T} - e^{y_f} \right)$$

$$y(\eta, q_T; m) = \frac{1}{2} \ln \left(\frac{\sqrt{\frac{m_T^2}{q_T^2} + \sinh^2 \eta} + \sinh \eta}{\sqrt{\frac{m_T^2}{q_T^2} + \sinh^2 \eta} - \sinh \eta} \right)$$

Backup slides

$$\frac{d\sigma^{AB \rightarrow h+X}}{dq_T^2 dy} = K(\sqrt{s}) J(m_T, y) \sum_f \int \frac{dz}{z^2} \frac{d\sigma^{AB \rightarrow f+X}}{dp_T^2 dy_f} D_{f \rightarrow h}(z, \mu_F^2) \Big|_{p_T^2, y_f}$$

$$J(m_T, y) = \left(\frac{\partial y}{\partial \eta} \right) = \frac{1}{\sqrt{1 - \frac{m^2}{m_T^2 \cosh^2 y}}}$$

$$\begin{aligned} \frac{d\sigma^{AB \rightarrow f+X}}{dp_T^2 dy_f} &= \int dy_2 \sum_{ij} \frac{1}{1+\delta_{ij}} \frac{1}{1+\delta_{kl}} \cdot \left[x_1 f_{i/A}(x_1, Q^2) x_2 f_{j/B}(x_2, Q^2) \left(\frac{d\hat{\sigma}^{ij \rightarrow kl}(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}} \delta_{fk} + \frac{d\hat{\sigma}^{ij \rightarrow kl}(\hat{s}, \hat{u}, \hat{t})}{d\hat{t}} \delta_{fl} \right) \right. \\ &\quad \left. + x_1 f_{j/A}(x_1, Q^2) x_2 f_{i/B}(x_2, Q^2) \left(\frac{d\hat{\sigma}^{ij \rightarrow kl}(\hat{s}, \hat{u}, \hat{t})}{d\hat{t}} \delta_{fk} + \frac{d\hat{\sigma}^{ij \rightarrow kl}(\hat{s}, \hat{t}, \hat{u})}{d\hat{t}} \delta_{fl} \right) \right] \end{aligned}$$

Mandelstam variables for the partonic subprocess

$$\hat{s} = x_1 x_2 s = \frac{p_T^2}{s} (1 + 1 + 2 \cosh(y_1 - y_2)) s = 2 p_T^2 (1 + \cosh(y_1 - y_2))$$

$$\hat{t} = -\frac{\hat{s}}{2} \left(1 - \sqrt{1 - \frac{4 p_T^2}{\hat{s}}} \right) = -p_T^2 (1 + \cosh(y_1 - y_2)) \left(1 - \sqrt{1 - \frac{2}{1 + \cosh(y_1 - y_2)}} \right)$$

$$\hat{u} = -\frac{\hat{s}}{2} \left(1 + \sqrt{1 - \frac{4 p_T^2}{\hat{s}}} \right) = -p_T^2 (1 + \cosh(y_1 - y_2)) \left(1 + \sqrt{1 - \frac{2}{1 + \cosh(y_1 - y_2)}} \right)$$