EPS09 and the state of the art nuclear PDFs

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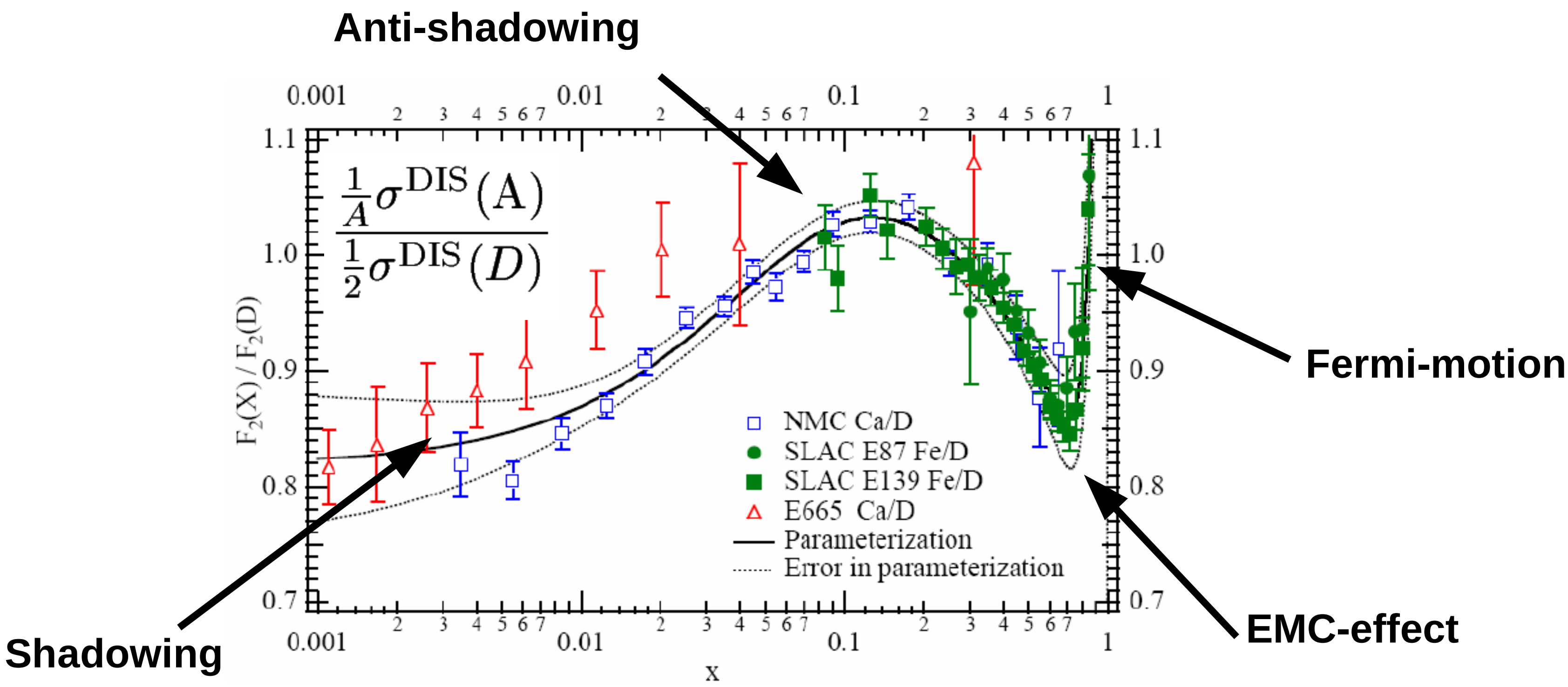
PDF4LHC, DESY, October 23, 2009

Existing Global NLO-analyses

- **2004 : nDS** by de Florian, Sassot — *No uncertainty analysis*
- **2007 : HKN07** by Hirai, Kumano, Nagai — *Uncertainty analysis*
- **2009 : EPS09** by Eskola, Paukkunen, Salgado — *Uncertainty analysis*



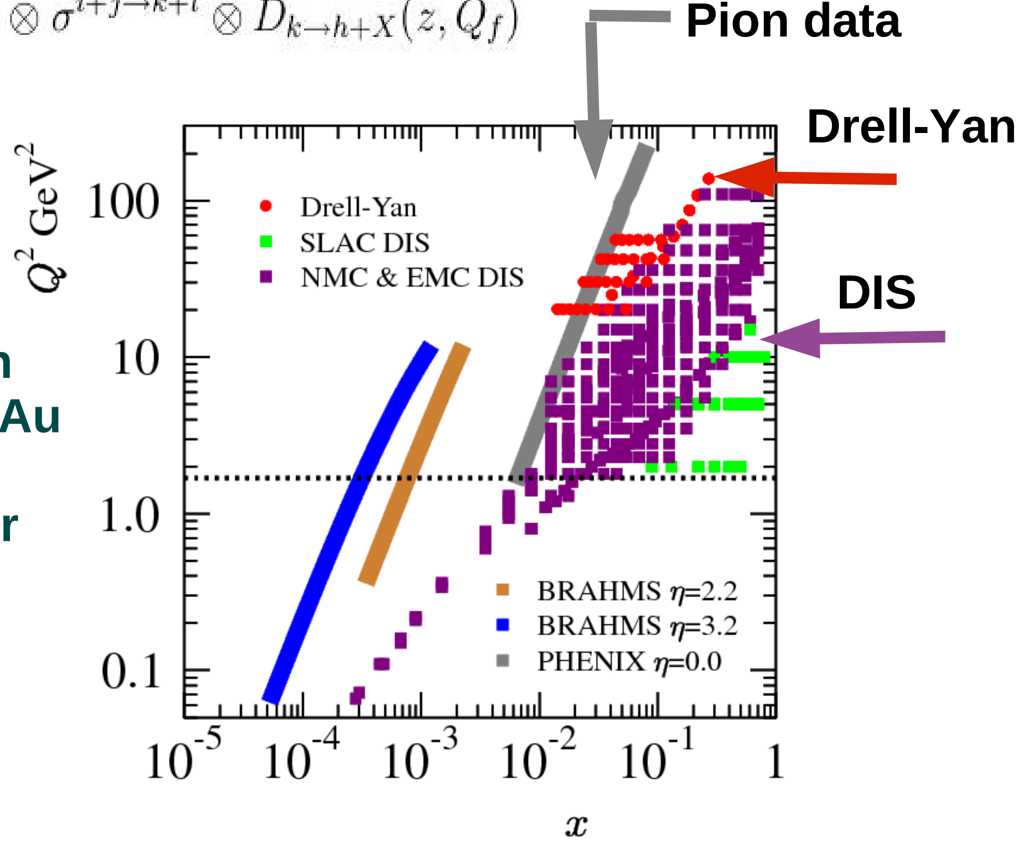
Ingredients in EPS09:

- **DIS & Drell-Yan data with π⁰-data from d+Au and p+p collisions at RHIC**

$$\sigma^{AB\to h+X} = \sum_{ijkl} f_i^A(x_1,Q) \otimes f_j^B(x_2,Q) \otimes \sigma^{i+j\to k+l} \otimes D_{k\to h+X}(z,Q_f)$$

- Addition of π⁰-data avoids the need of fixing some gluon parameters by hand.

- Assumes that the fragmentation functions D(x,Q) are same in d+Au as they are in p+p. (See *arXiv:0906.5521* for another point of view.)



- **Hessian uncertainty analysis**

- 30 error sets for practical use
- For both NLO and LO analysis

About the Framework

- We define the bound proton PDFs $f_i(x,Q)$ in a nucleus A as

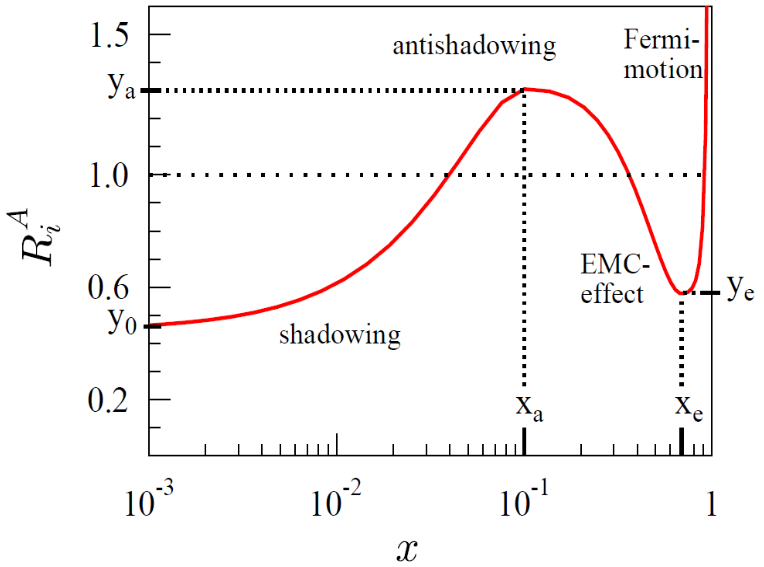
$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2) f_i^{\rm CTEQ6.1M}(x,Q^2)$$

- $\overline{\rm MS}$, Zero-mass variable flavour number scheme

- nPDFs are parametrized at Q_0=1.3 GeV by

$R_V^A(x,Q_0^2)$	for all valence quarks
$R_S^A(x,Q_0^2)$	for all sea quarks
$R_G^A(x,Q_0^2)$	for gluons

Flavor separation not possible with the data presently used.



- A-dependence goes to the fit parameters as

$$z_i^A = z_i^{A_{\rm ref}} \left(\frac{A}{A_{\rm ref}}\right)^{p_{z_i}}$$

Our definition of χ^2

- The best parameters are found by minimizing the generalized χ^2-function:

$$\chi^2 = \sum_N w_N \chi^2_N$$

$$\chi^2_N = \left(\frac{1-f_N}{\sigma_N^{\mathrm{norm}}}\right)^2 + \sum_{i\in N}\left[\frac{f_N D_i - T_i(\{z\})}{\sigma_i}\right]^2$$

D_i = Experimental values

T_i = Theory values

σ_i = Uncertainty

- With weight factors w_N we emphasize certain data sets with important physics content but small amount of data points.

  ↳ - Improves the convergence of the fit in the badly constrained regions.
  - Induces, however, also piece of subjectivity to the fit.

- Relative normalization uncertainties σ^{norm} are accounted for by normalization factors $f_N \in [1-\sigma^{\mathrm{norm}}, 1+\sigma^{\mathrm{norm}}]$.

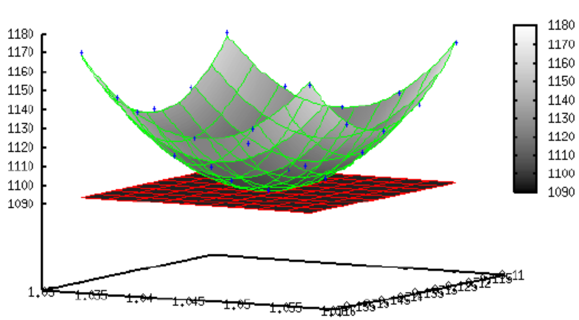
Uncertainty analysis

- We use the Hessian method for quantifying the nPDF errors with 15 fit parameters

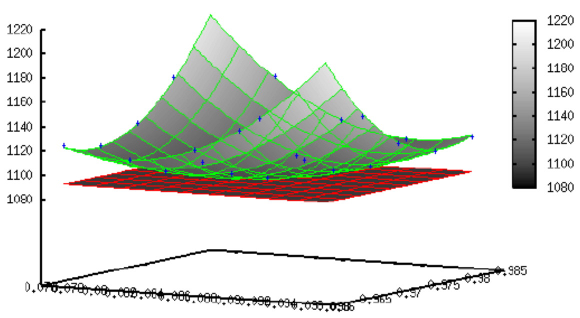
$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j$$

- We compute the Hessian matrix H by a fit a qudratic function to actual χ^2

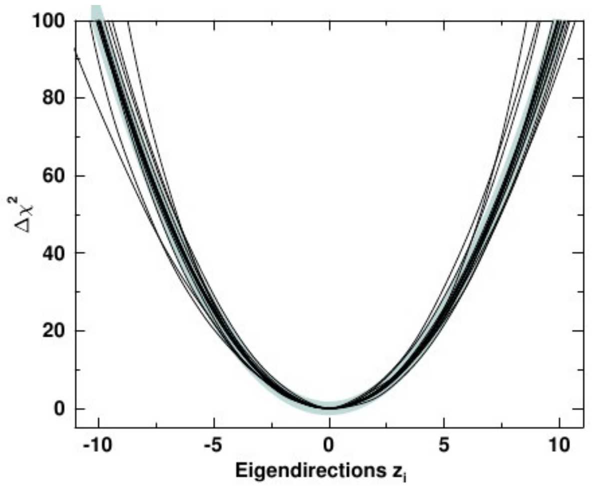
$$f(a_i, a_j) = \chi_0^2 + c_i(a_i - a_i^0)^2 + c_j(a_j - a_j^0)^2 + c_{ij}(a_i - a_i^0)(a_j - a_j^0)$$



(a) Uncorrelated



(b) Correlated

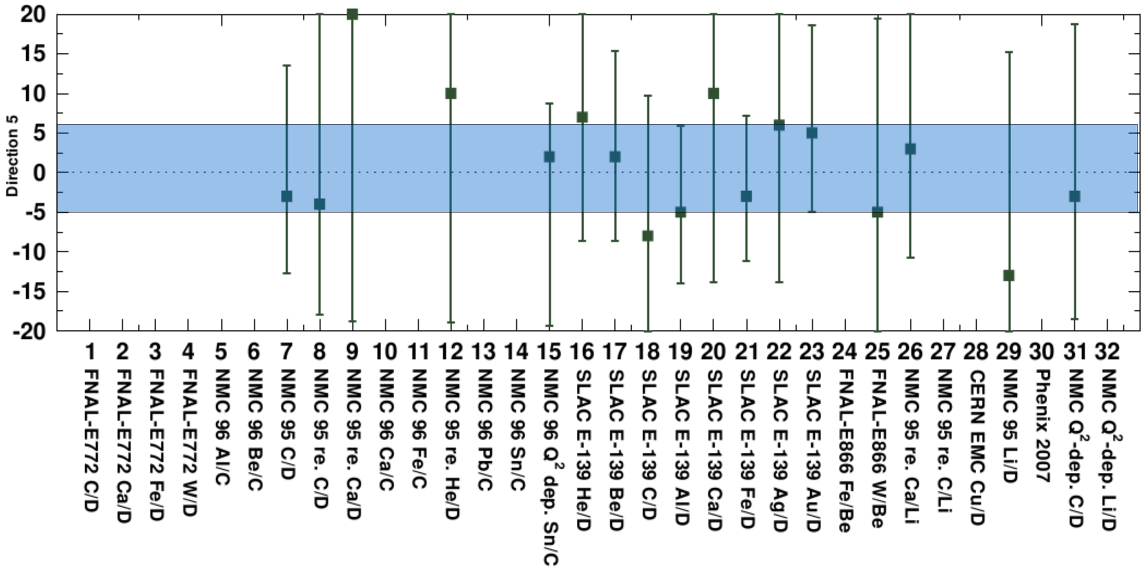


- The 15 eigendirections of the Hessian serve as an uncorrelated basis

$$\chi^2 \approx \chi_0^2 + \sum_i z_i^2$$

Uncertainty analysis

- We take **$\Delta\chi^2 = 50$** based on requiring the χ^2-contribution of each data set to remain within its 90% confidence range.



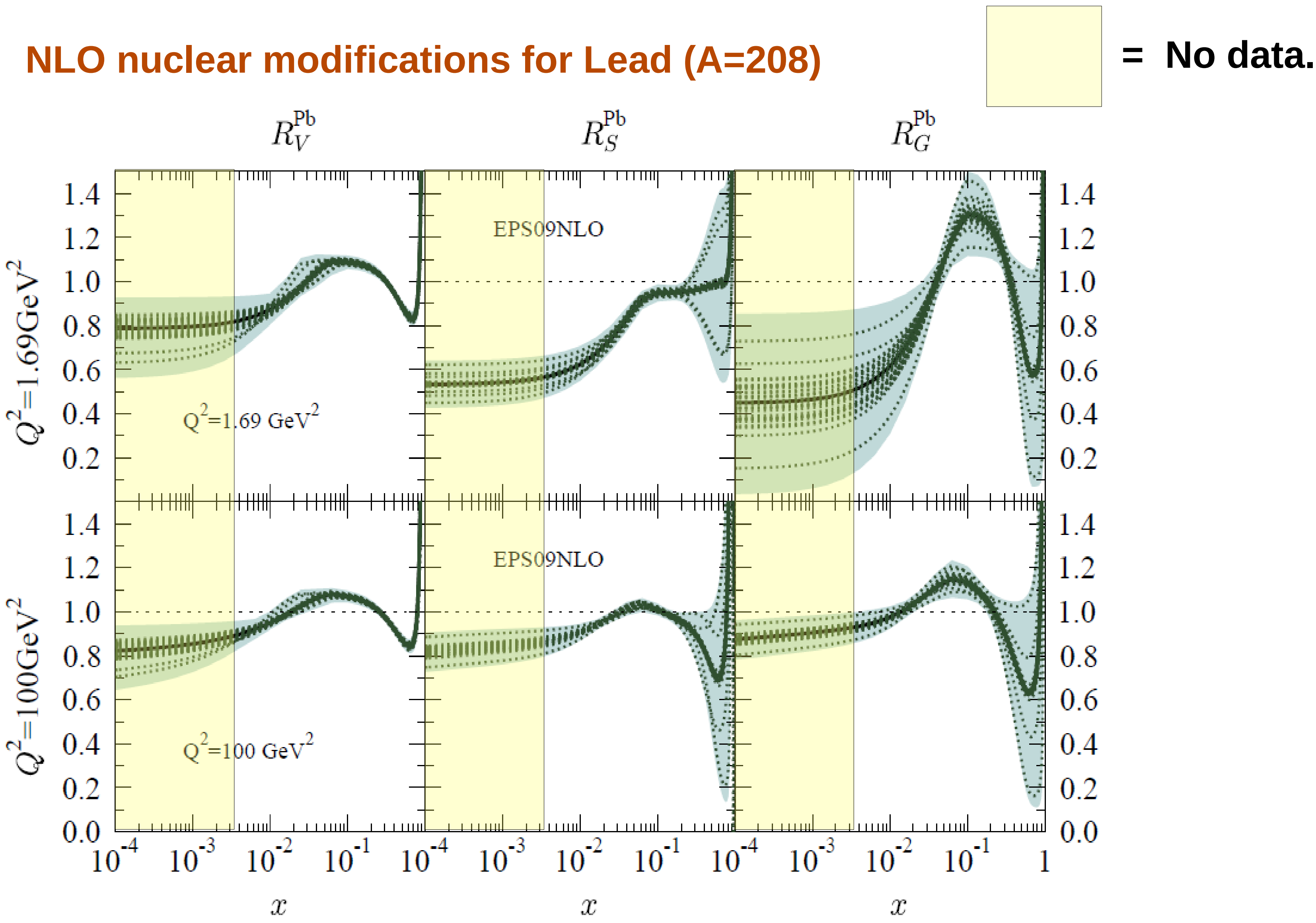
- We construct the nPDF error sets $S_k^{\pm}$ such that they all give **$\Delta\chi^2 = 50$**

- The uncertainty in any quantity X is then obtained e.g as

$$(\Delta X)^2 \approx \frac{1}{4}\sum_k \left(X(S_k^+) - X(S_k^-)\right)^2$$

Some Results

- NLO nuclear modifications for Lead (A=208)

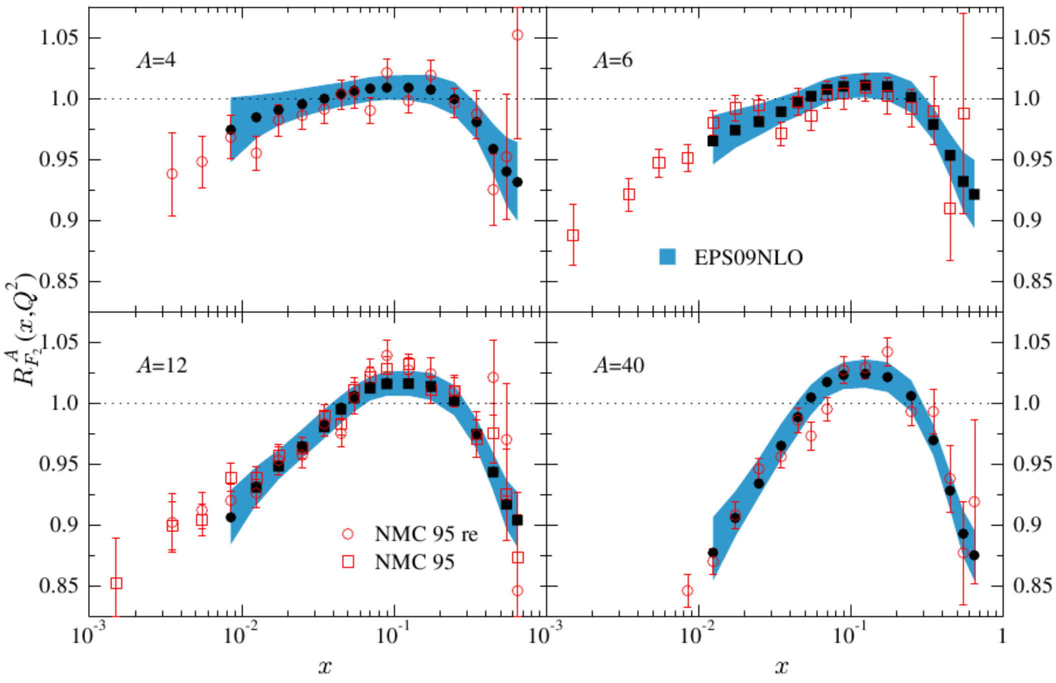


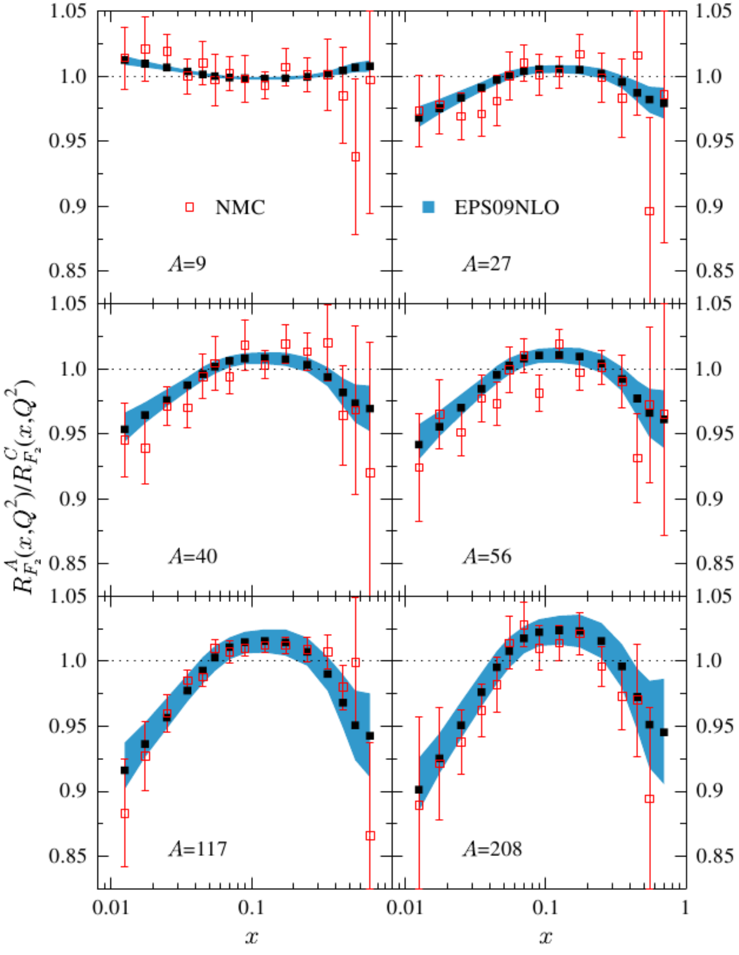
- LO result similar but with larger uncertainties

Comparison with data: DIS F_2

$$R^{\mathrm{A}}_{F_2}(x,Q^2) \equiv \frac{F_2^A(x,Q^2)}{F_2^d(x,Q^2)}$$

$$\frac{\frac{1}{A}d\sigma^{lA}/dQ^2dx}{\frac{1}{12}d\sigma^{lC}/dQ^2dx} \overset{\mathrm{LO}}{=} \frac{R^A_{F_2}(x,Q^2)}{R^C_{F_2}(x,Q^2)}$$

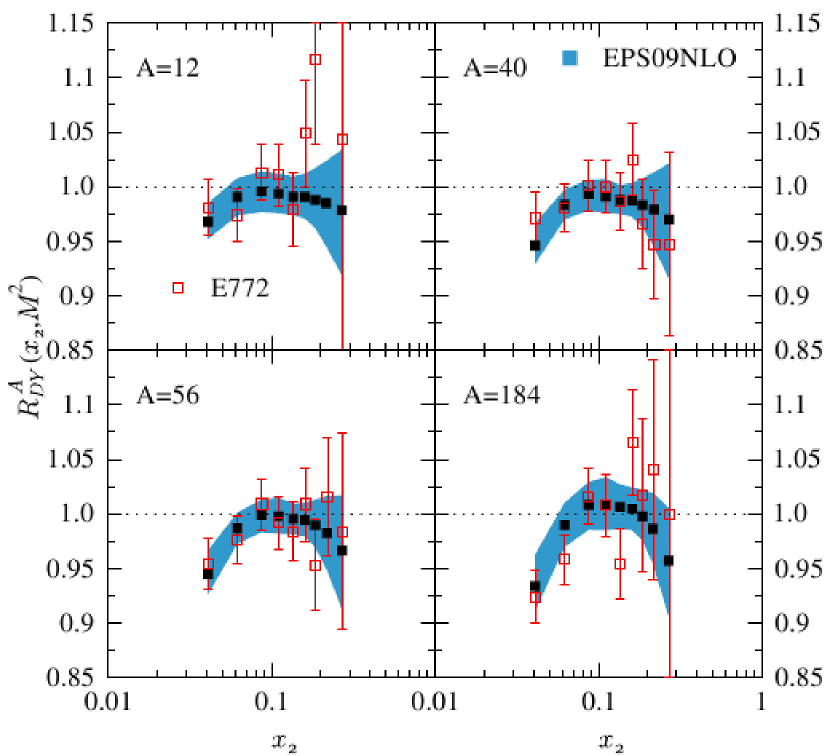


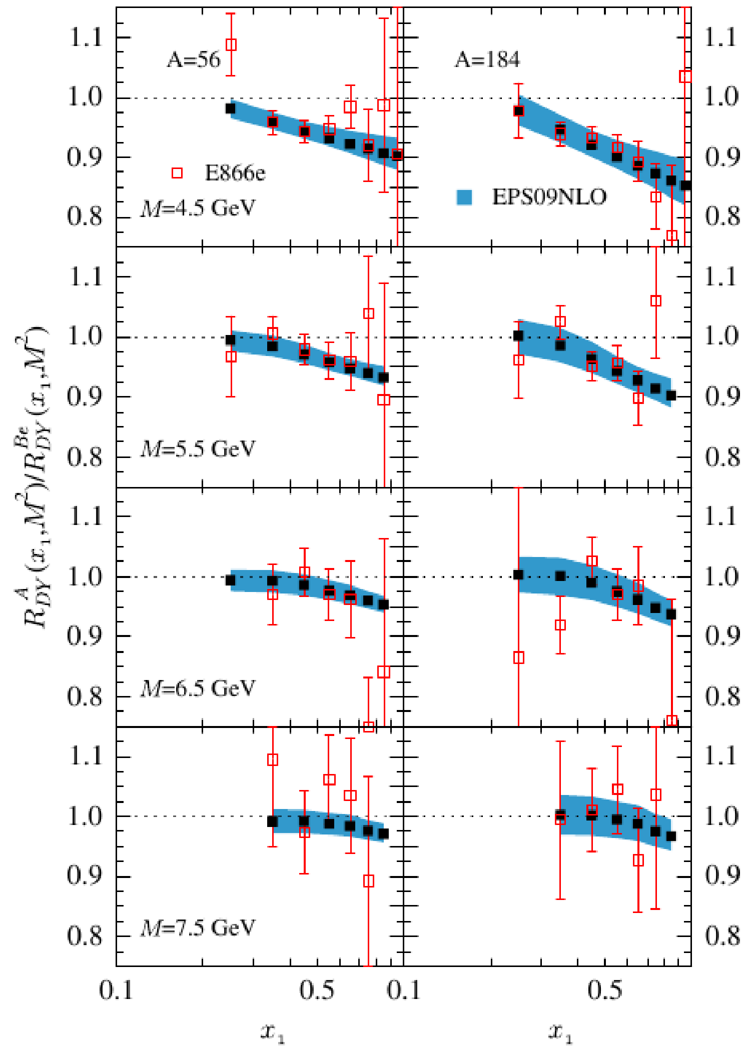


Comparison with data: Drell-Yan

$$\frac{\frac{1}{A}d\sigma^{\mathrm{p}A}_{DY}/dx_1dQ^2}{\frac{1}{9}d\sigma^{\mathrm{pBe}}_{DY}/dx_1dQ^2}$$

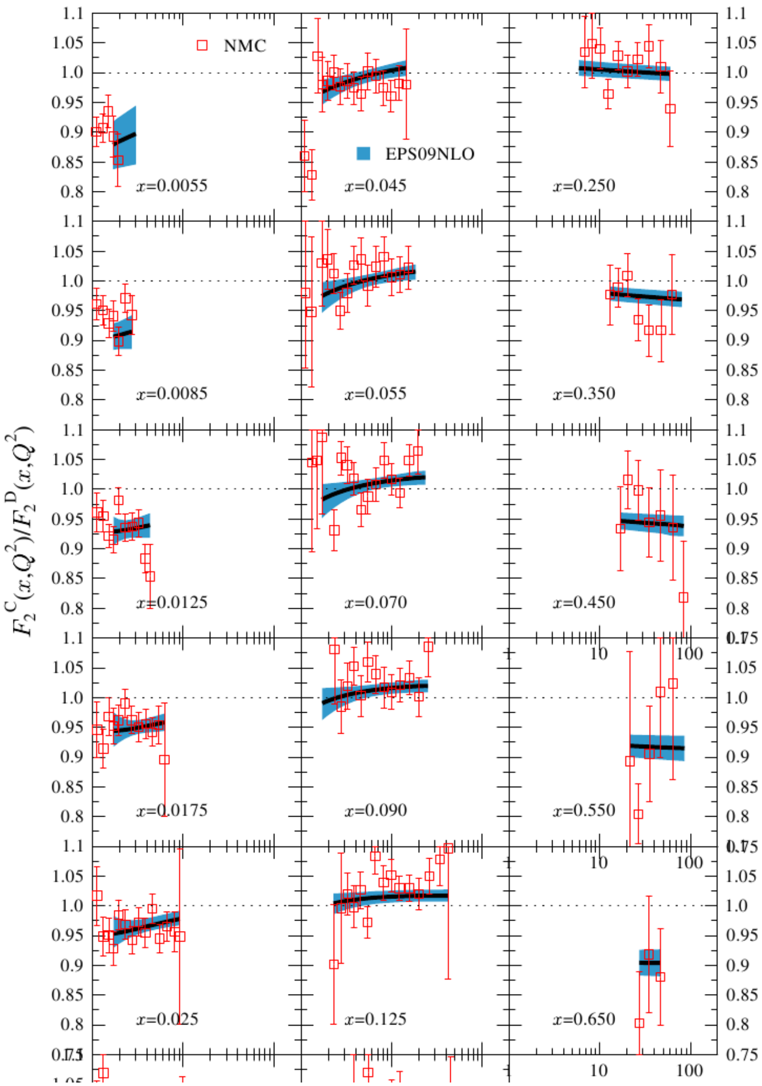
$$\frac{\frac{1}{A}d\sigma^{\mathrm{p}A}_{DY}/dx_2dQ^2}{\frac{1}{2}d\sigma^{\mathrm{pD}}_{DY}/dx_2dQ^2}$$



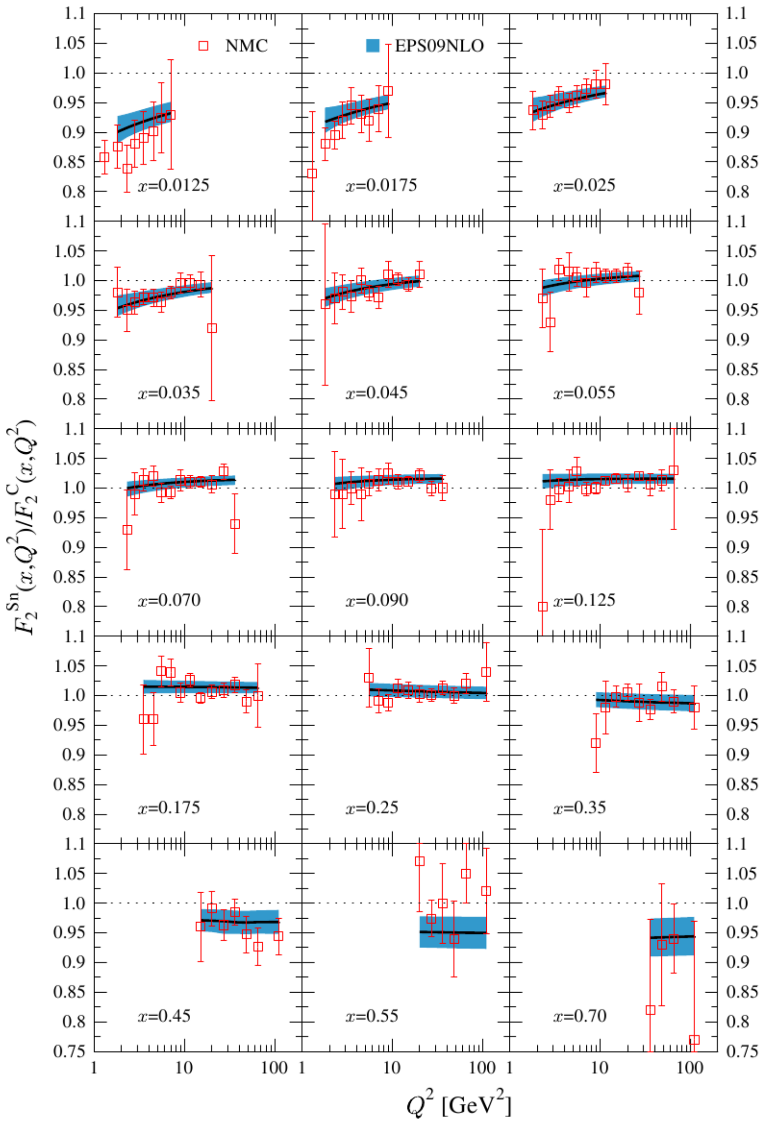


Q^2-slopes in F_2: DGLAP evolution

$F_2^{C}(x,Q^2)/F_2^{D}(x,Q^2)$



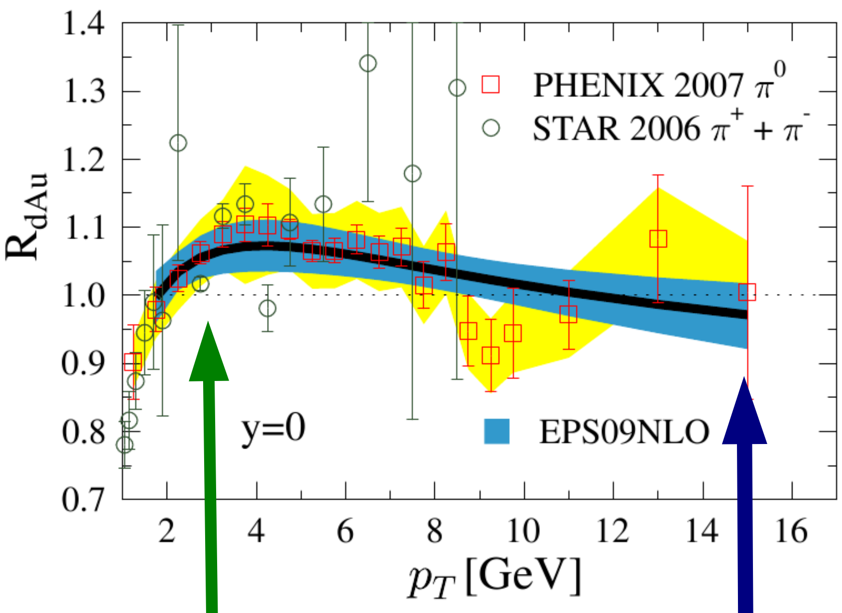
$F_2^{Sn}(x,Q^2)/F_2^{C}(x,Q^2)$

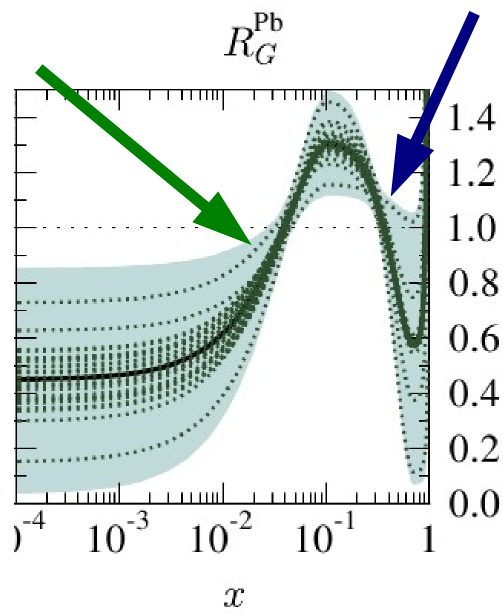


Gluon constraints from π^0-data

- **EMC-effect and shadowing in gluons**

$$R_{\mathrm{dAu}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2 N^{\mathrm{dAu}}/dp_T d\eta}{d^2 N^{\mathrm{pp}}/dp_T d\eta} \overset{\mathrm{min.bias}}{=} \frac{\frac{1}{2A} d^2\sigma^{\mathrm{dAu}}/dp_T d\eta}{d^2\sigma^{\mathrm{pp}}/dp_T d\eta}$$



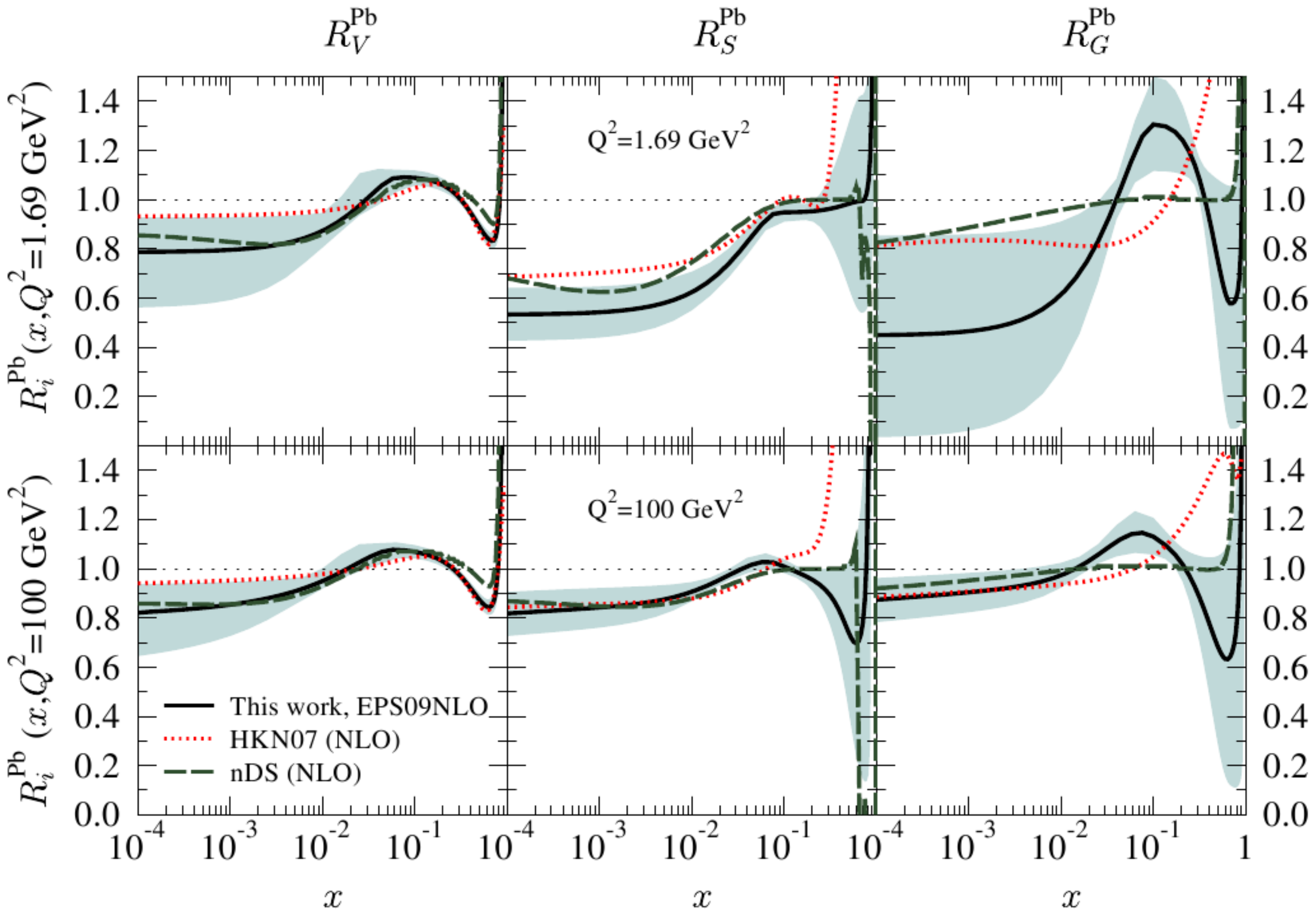


Suppression at low-pT comes from shadowing

Downward trend is partly caused by gluon EMC-effect!

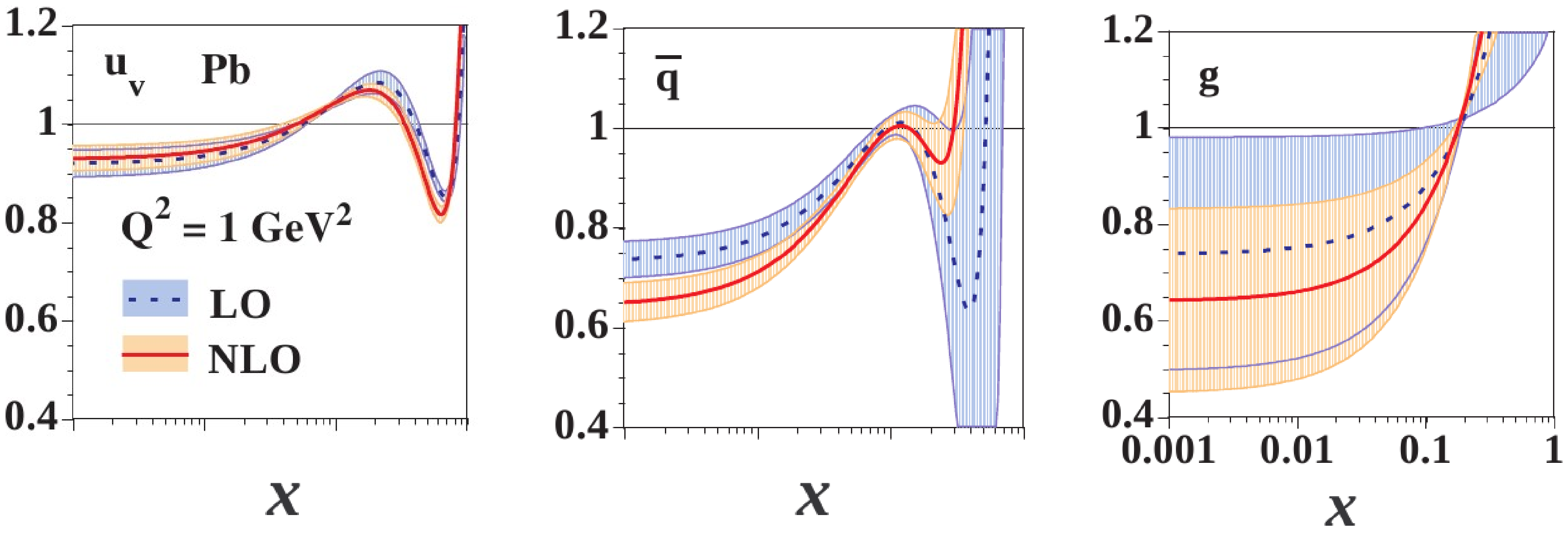
Comparison with other works:

- **Nuclear effects in Lead (A=208):**



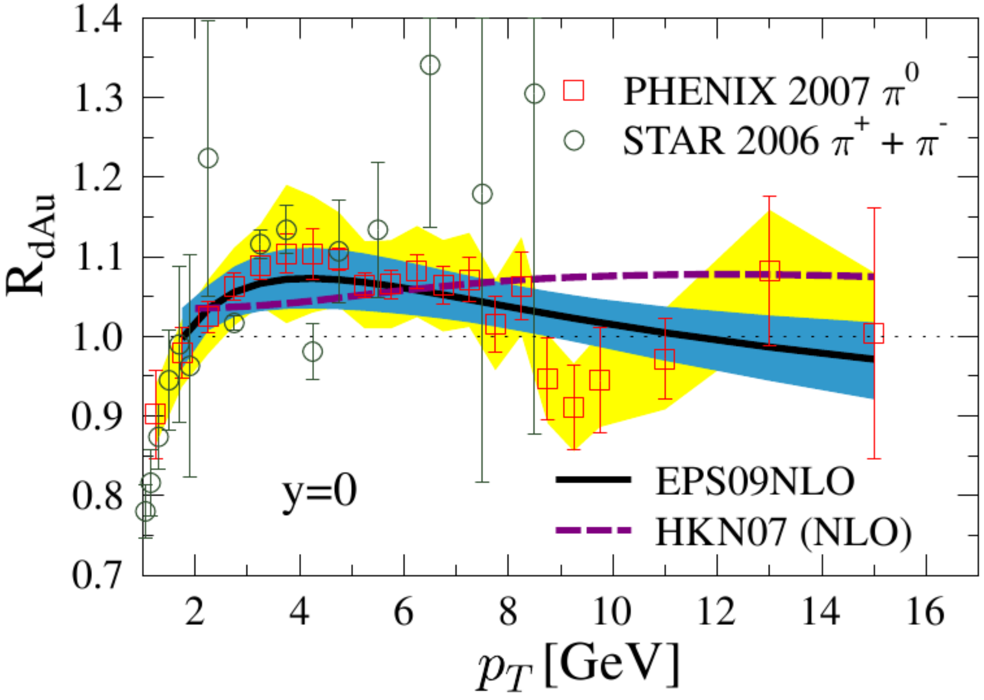
Error-analysis in HKN07

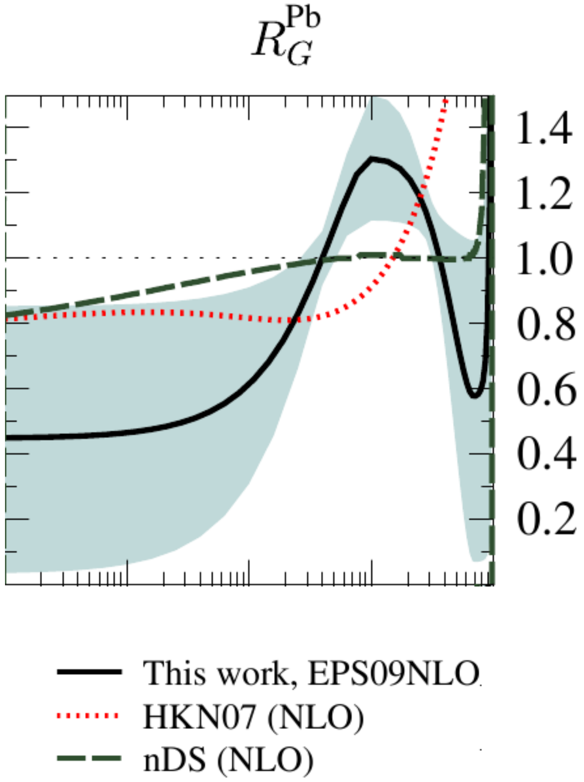
- Hessian-method with $\Delta\chi^2 = 13.7$



- Restricted form of HKN07 fit-function induces even a node to the gluon uncertainty!
- No uncertainty sets available for practical use.

Contrast between EPS09 and HKN07 in π^0-production





- **Inclusive pion data with better statistics could potentially discriminate between different suggested gluon PDFs.**

Summary & Outlook

- Factorization in hard processes involving nuclear targets seem to work well – for the data types considered and in the kinematical domain they cover.

- Further experiments might be needed to see the possible violations:
  - p-A runs also at LHC?
  - Electron-Ion collider: eRHIC, LHeC, ...

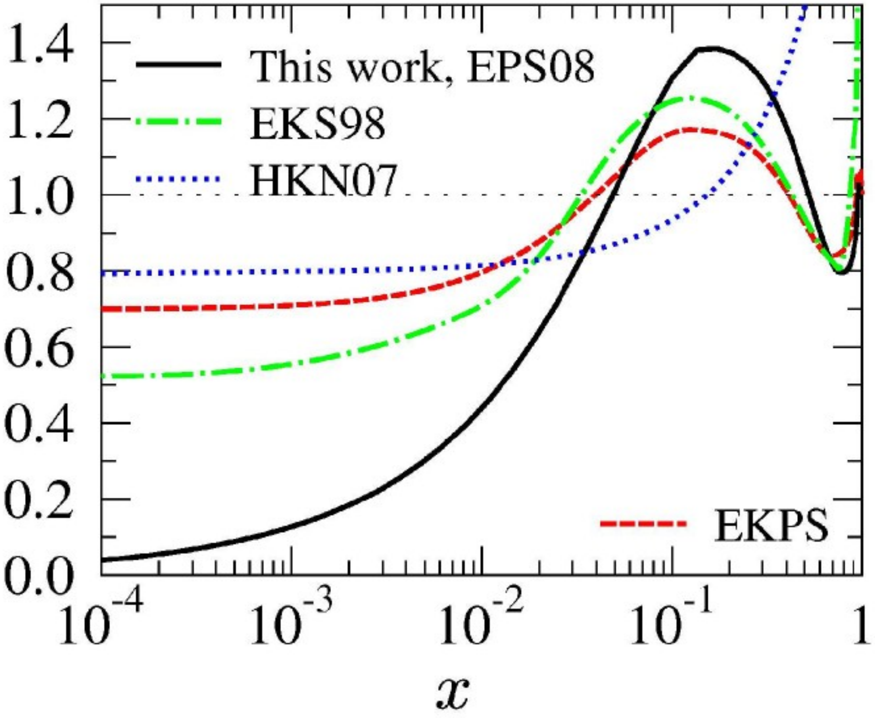
- Near-future tasks with the nuclear PDF:
  - Extend the analysis to general-mass framework (in progress)

    ↳ Look then also the neutrino data (NuTeV & CHORUS)
  - Include run 8 data from RHIC when available. Direct photons...

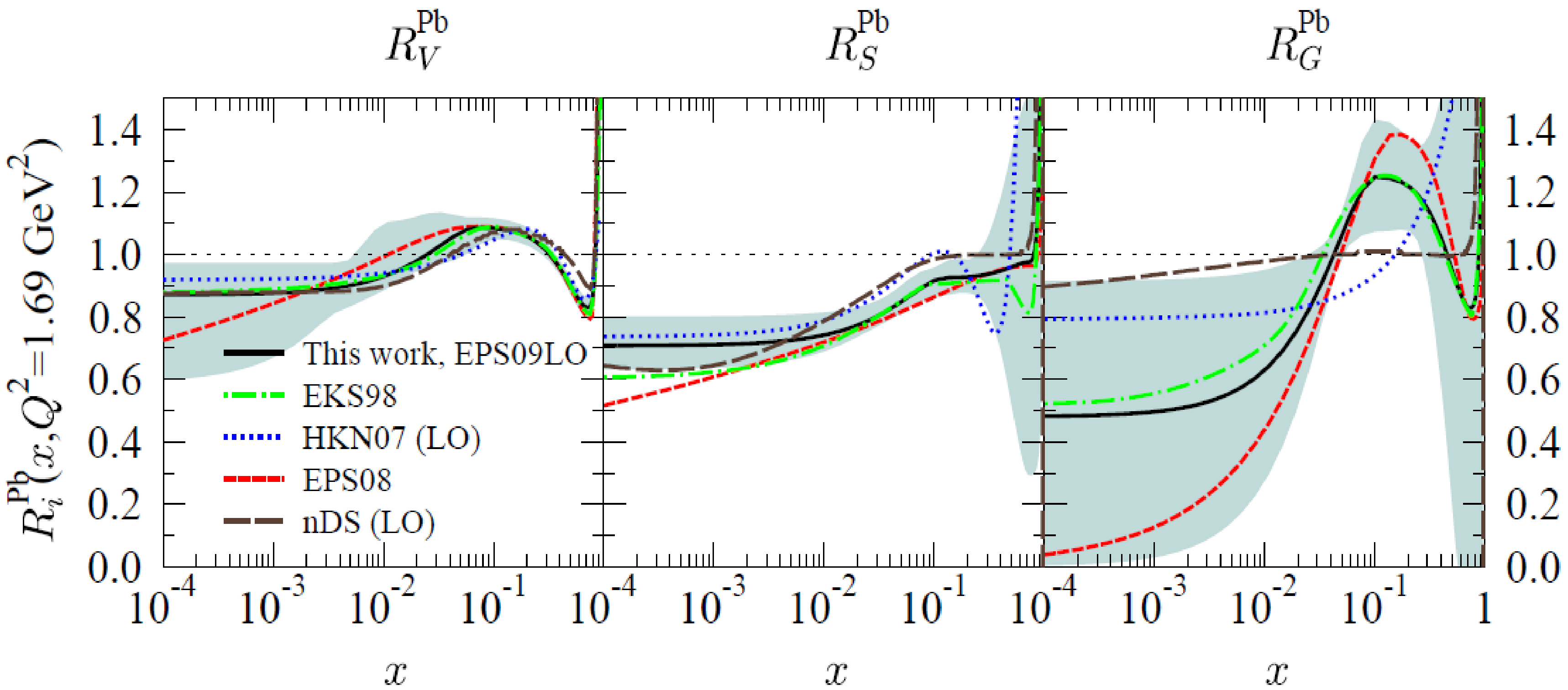
PDF4LHC, in February 2008...

- **By the leading-order analysis EPS08 we pointed out the large uncertainty in the nuclear modification for gluon PDFs.**

G(Pb) / G(p)



Comparison with earlier works: LO

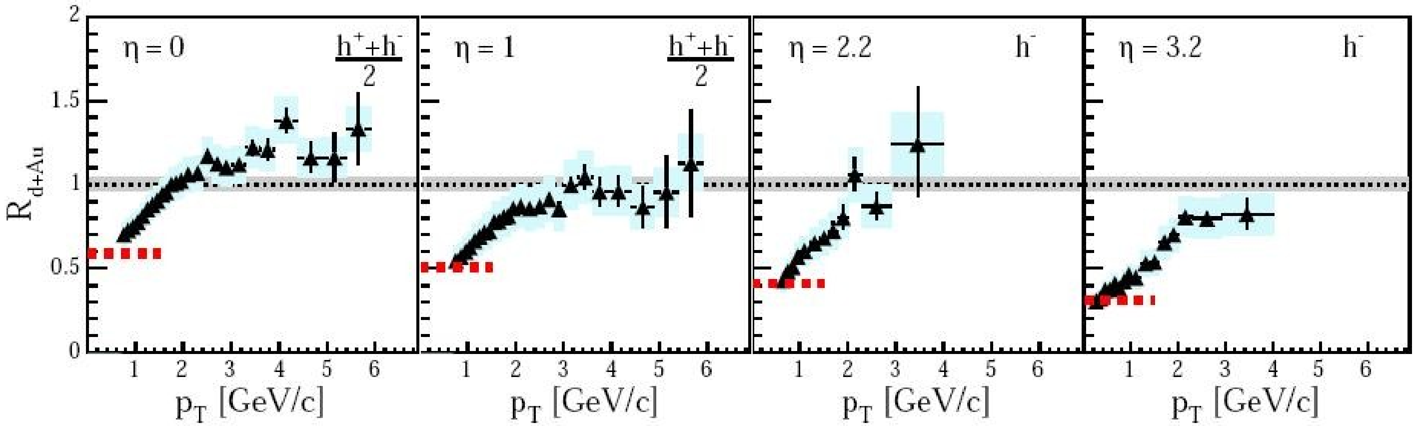


Suppression in BRAHMS R_{dAu}

- **Nuclear modification R_{dAu} for inclusive hadron production:**

$$R_{\rm dAu} = \frac{1}{\langle N_{\rm coll}\rangle}\frac{d^2N^{\rm dAu}/dp_T d\eta}{d^2N^{\rm pp}/dp_T d\eta} \overset{\rm min.bias}{=} \frac{\frac{1}{2A}d^2\sigma^{\rm dAu}/dp_T d\eta}{d^2\sigma^{\rm pp}/dp_T d\eta}$$

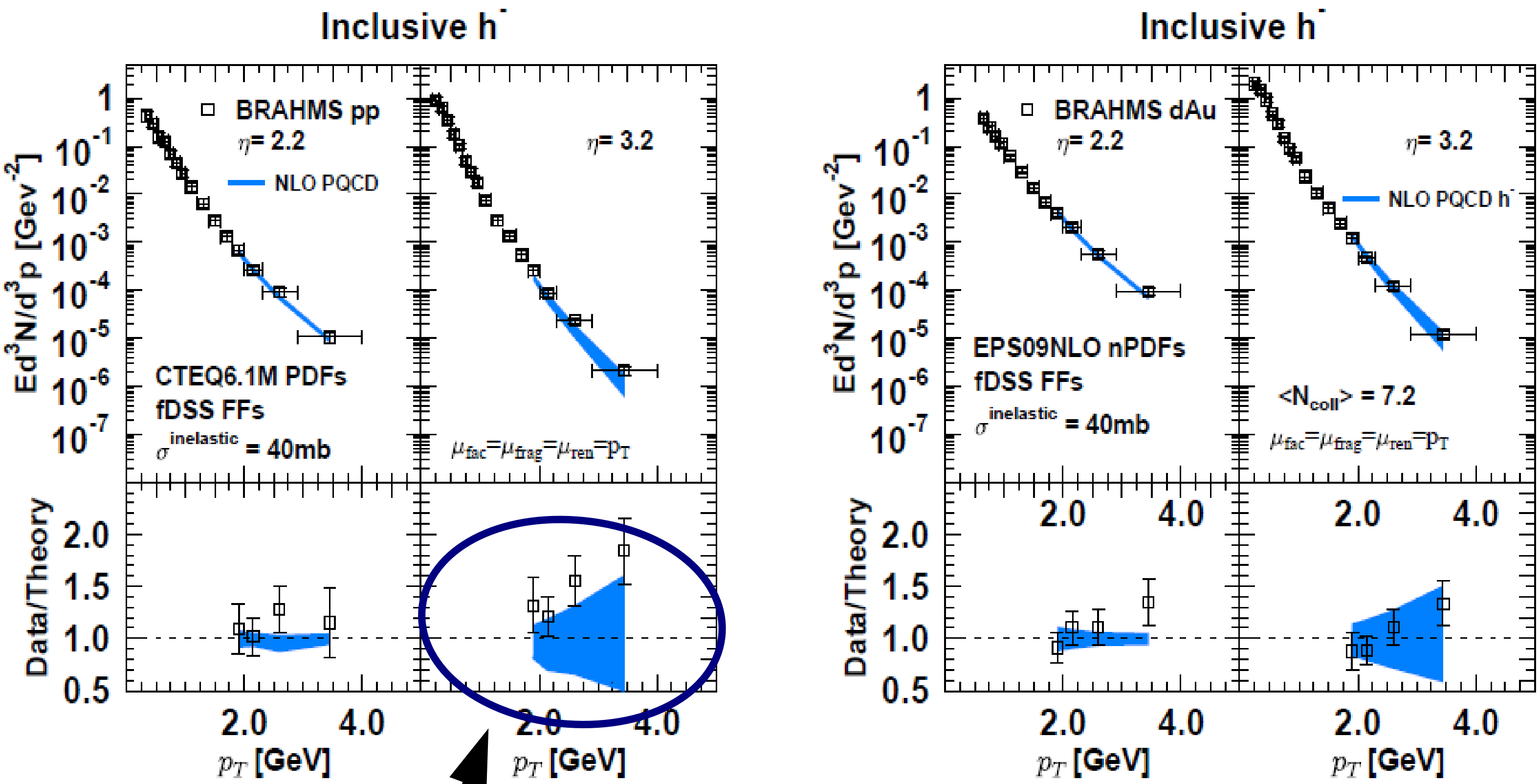
BRAHMS data:
PRL **93**, 242303 (2004)



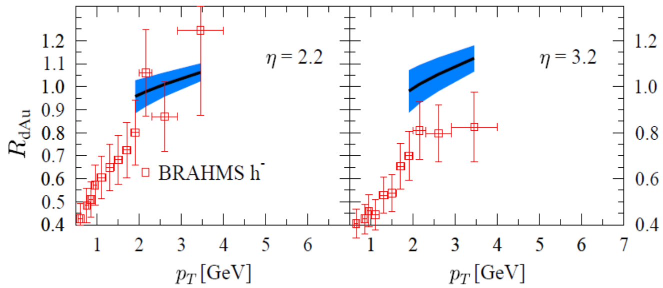
- **When interpreting these data, one should not look R_{dAu} alone but pay a serious attention the also to absolute spectra, especially to the p+p baseline.**

Suppression in BRAHMS R_{dAu} ?

- NLO pQCD predictions for the absolute spectra



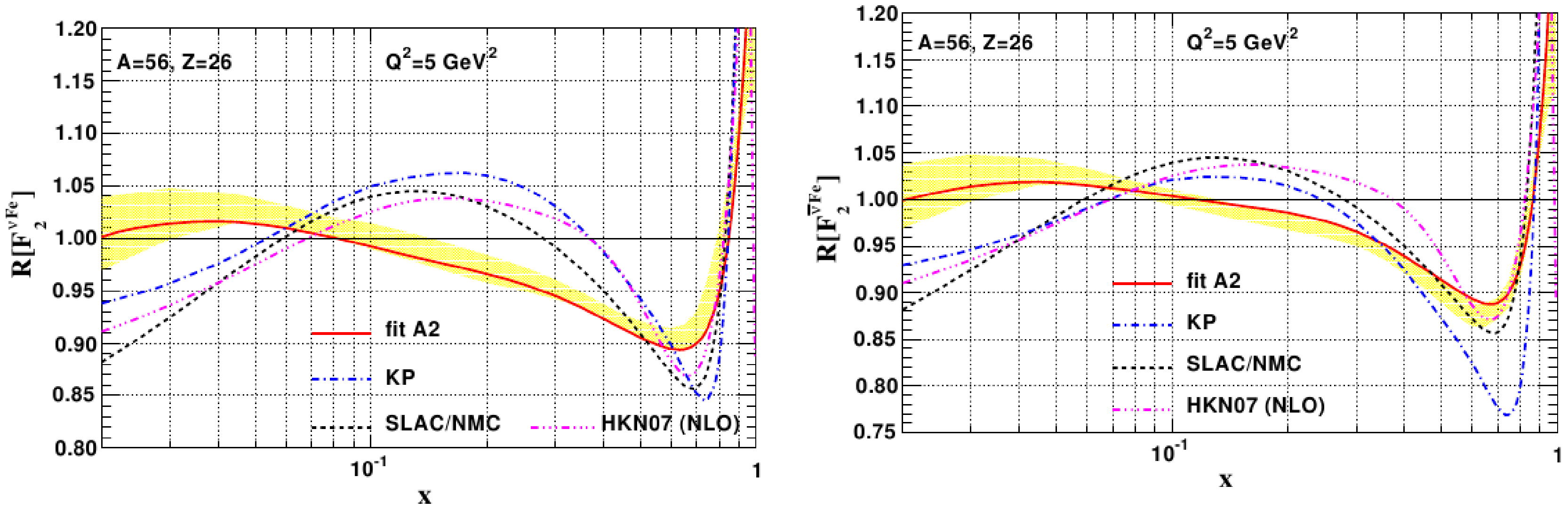
- Reliable use of BRAHMS R_{dAu} not possible – it's not included in the EPS09 sets.



Open issue: Nuclear effects in ν-Fe DIS

- **CTEQ collaboration's first results seem to indicate different nuclear effects in neutrino DIS**

I. Schienbein et.al Phys.ReV. D77:054013,2008



- **Only ν-Fe data was used – number of simplifications was thus needed**
- **A full global analysis should be performed to see whether there is a true discrepancy or not.**