EPS09 – Global NLO analysis of nuclear PDFs and their uncertainties

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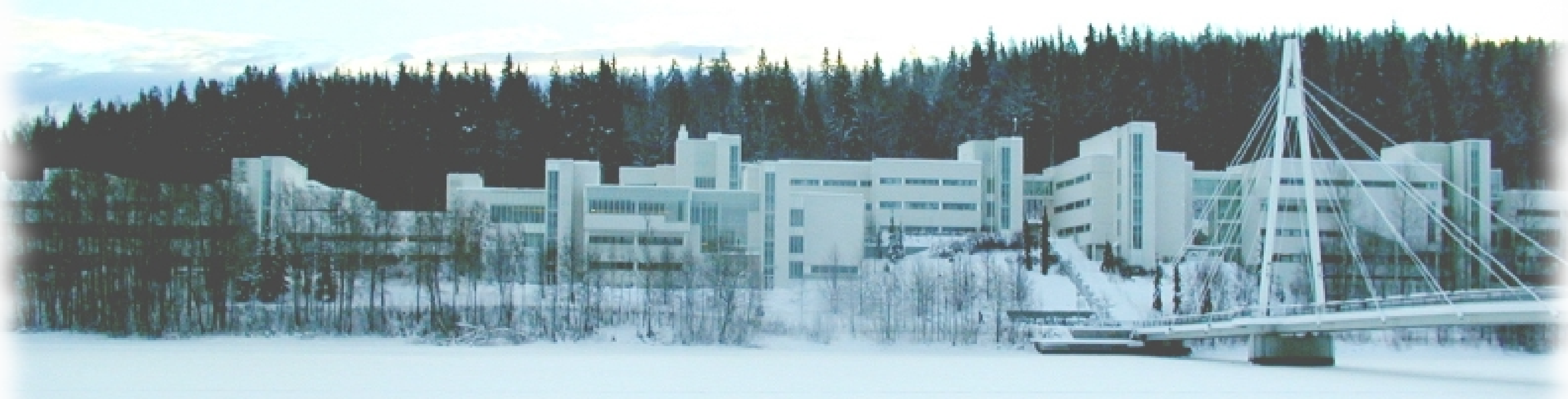
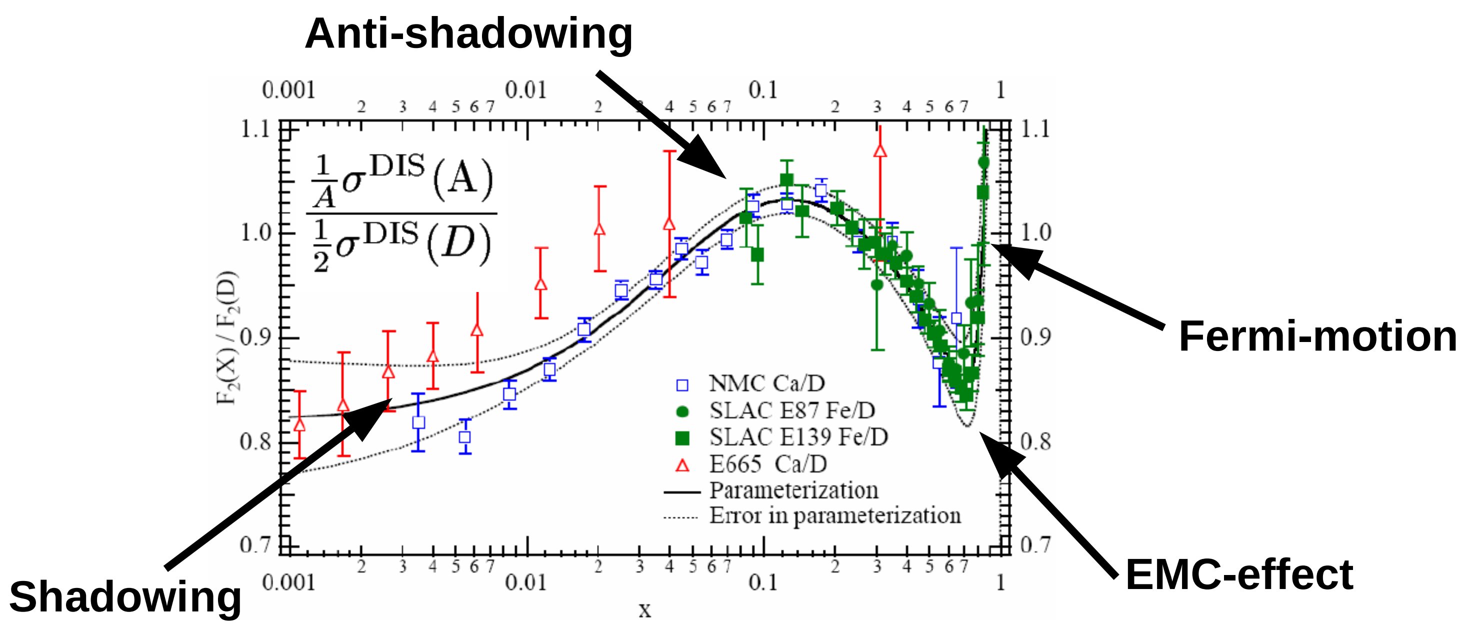


DIS'2009, Madrid, May 2009

Global nPDF analysis – Test of Factorization



- **In General: $\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}$ in hard scattering.**
- **Try to find <u>process independent</u> nuclear PDFs to account for these effects**

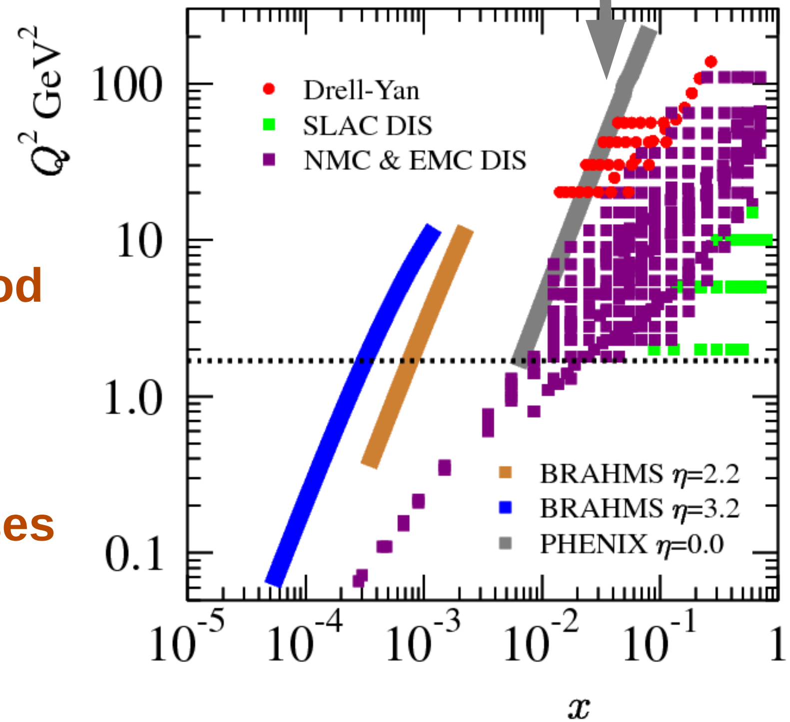
$$\sigma_{AB\to h+X} = \sum_{ij} \underbrace{f_i^A(x_1,Q^2) \otimes f_j^B(x_2,Q^2)}_{\text{Nuclear PDFs, obeying DGLAP equations}} \otimes \underbrace{\sigma^{i+j\to h+X}}_{\text{Standard pQCD cross-sections}}$$

Ingredients in EPS09:

- **Supplement the usual DIS & Drell-Yan data with inclusive π^0 midrapidity data from d+Au and p+p collisions at RHIC**

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

  - Kinematical cut: $p_T > 1.7$ GeV
  - Choice of fragmentation functions D(x,Q) is not critical - all modern sets give ~ equal description for π^0.



- **Uncertainty analysis with Hessian method**
  - 30 error sets for practical use ☆
  - Both NLO and LO analysis

- **In comparison to the free proton analyses**
  - Smaller amount and types of data
  - Kinematical plane more restricted
  - Need to parametrize the A-dependence from He to Pb

NLO Framework

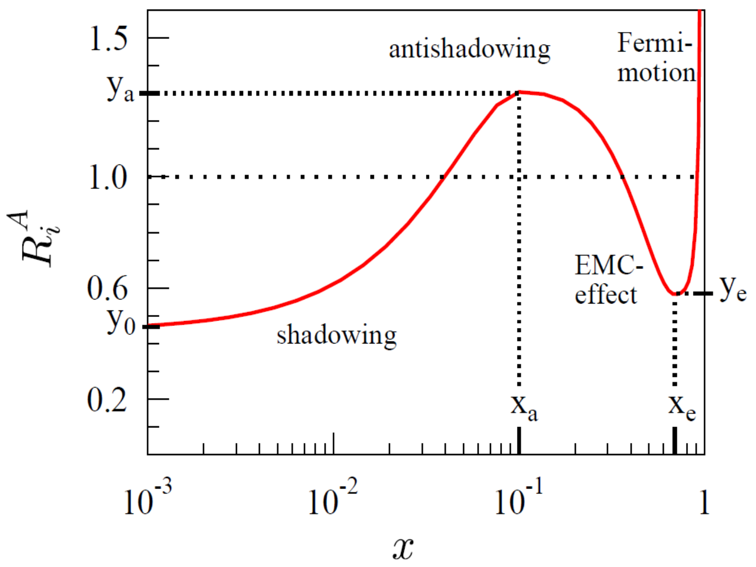
- We define the bound proton PDFs $f_i(x,Q)$ in a nucleus A as

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

- $\overline{\mathrm{MS}}$, 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



constrained by Baryon number & momentum conservation sum rules

- A-dependence goes to the fit parameters as

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

Best-fit definition: Generalized χ^2

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

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

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.

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

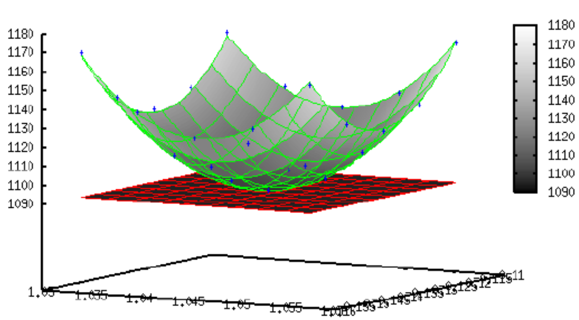
Uncertainty analysis

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

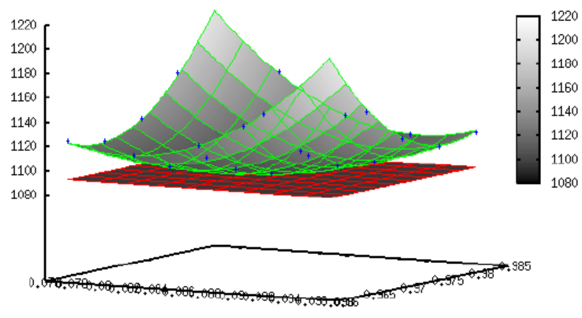
$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j$$

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

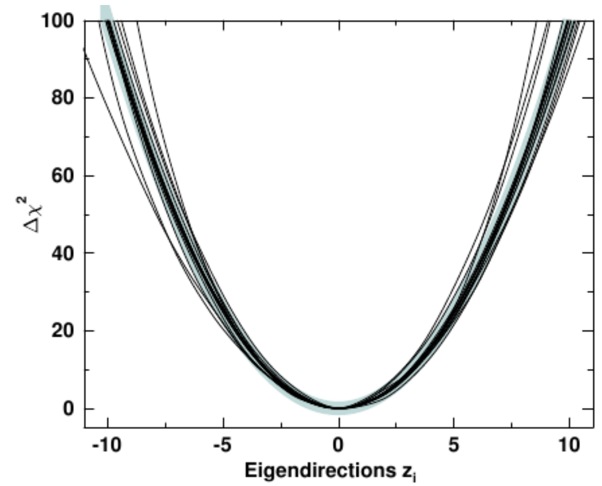
$$f(a_i, a_j) = \chi_0^2 + c_i(a_i - a_i^0)^2 + c_j(a_j - a_j^0)^2 + c_{ij}(a_i - a_i^0)(a_j - a_j^0)$$



(a) Uncorrelated



(b) Correlated

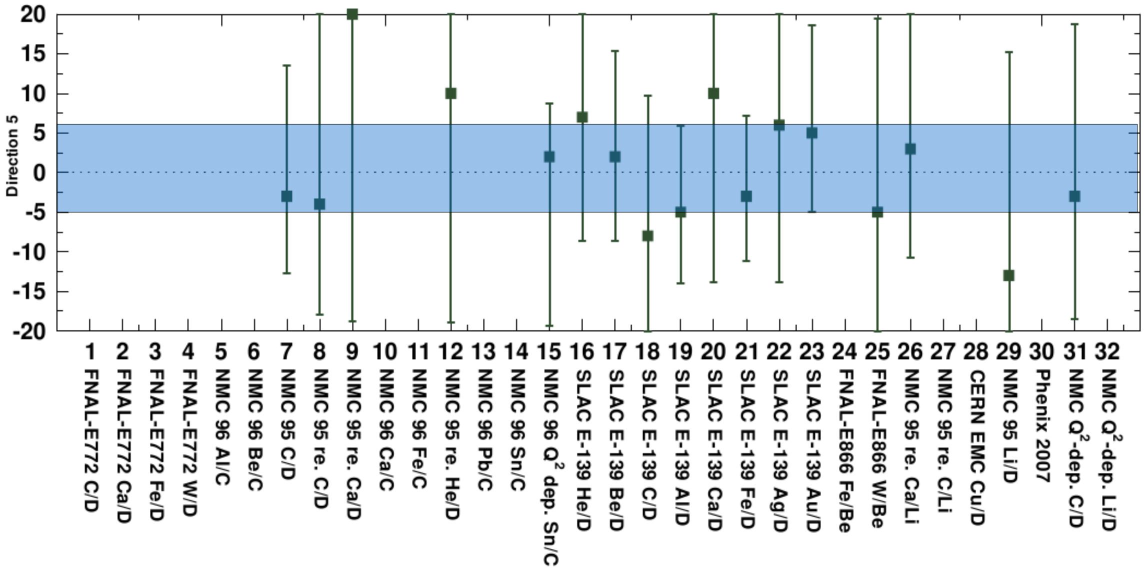


- The 15 eigendirections of the Hessian serve as an uncorrelated basis

$$\chi^2 \approx \chi_0^2 + \sum_{i} z_i^2$$

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.



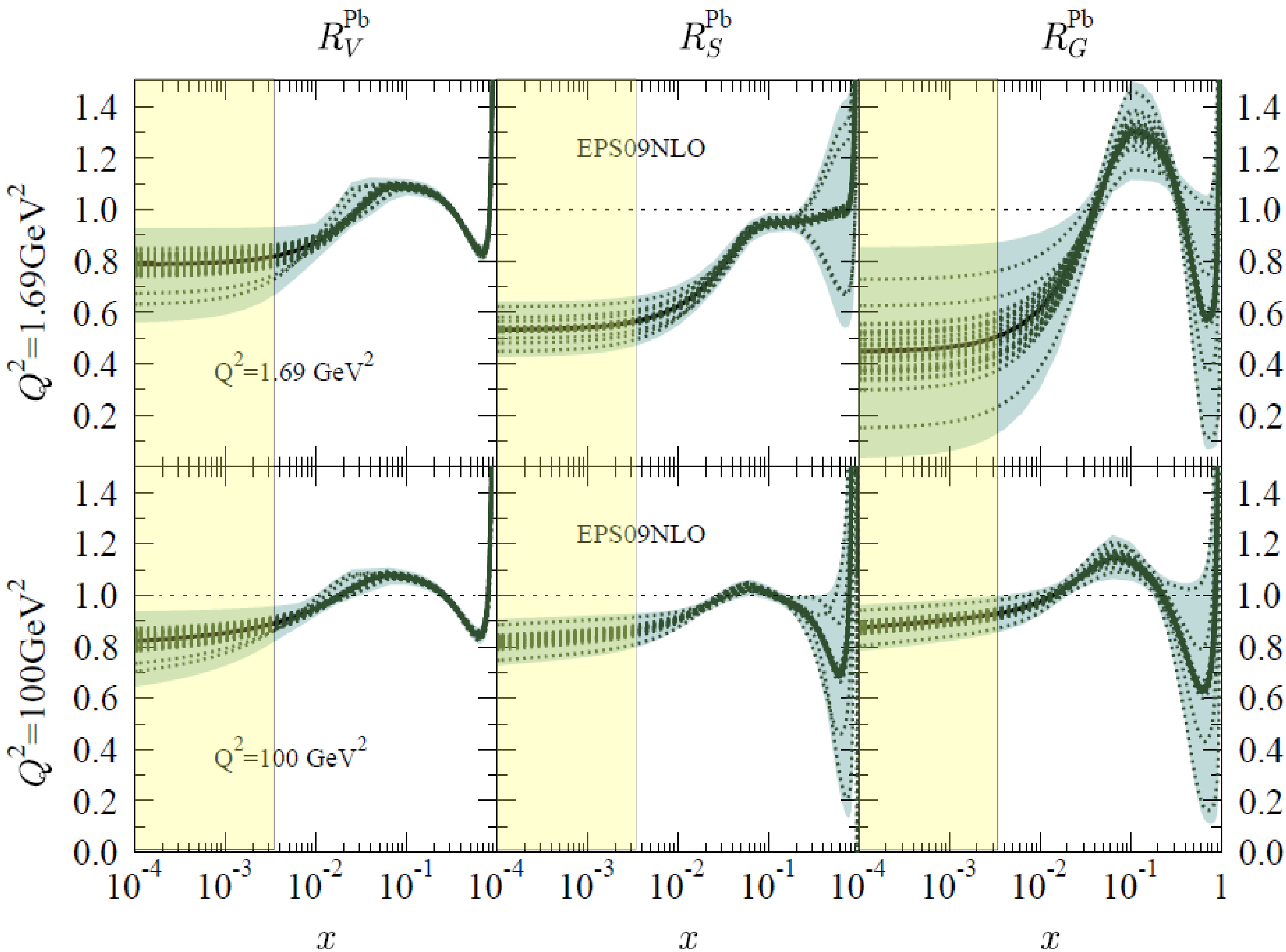
- We construct the nPDF error sets $S_k^{\pm}$ such that they all give $\Delta\chi^2 = 50$

- 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**

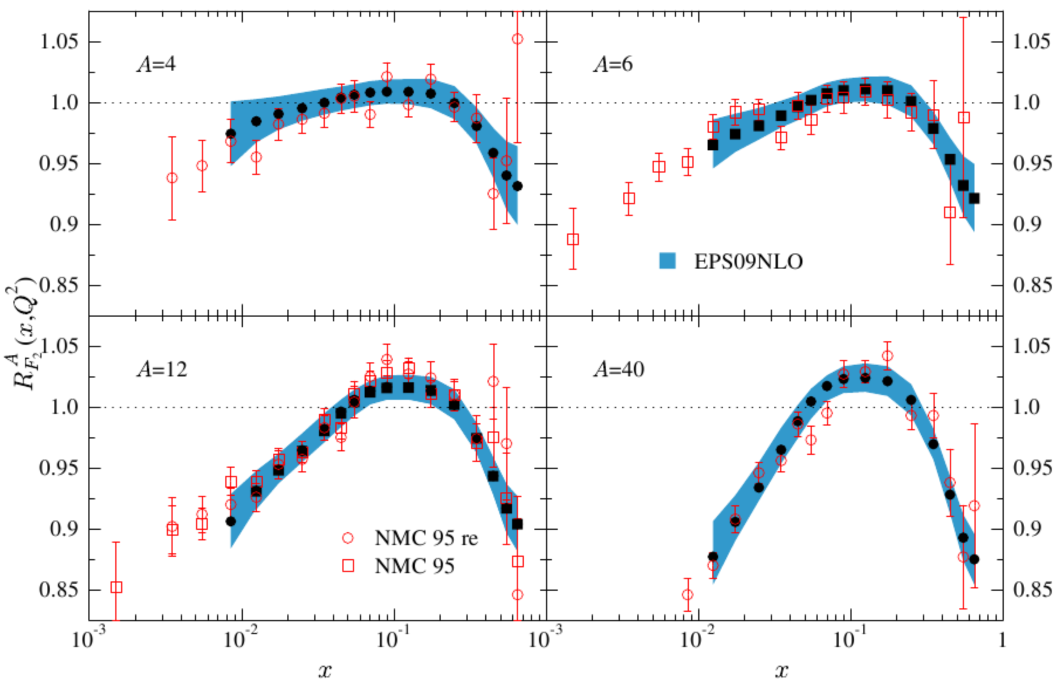


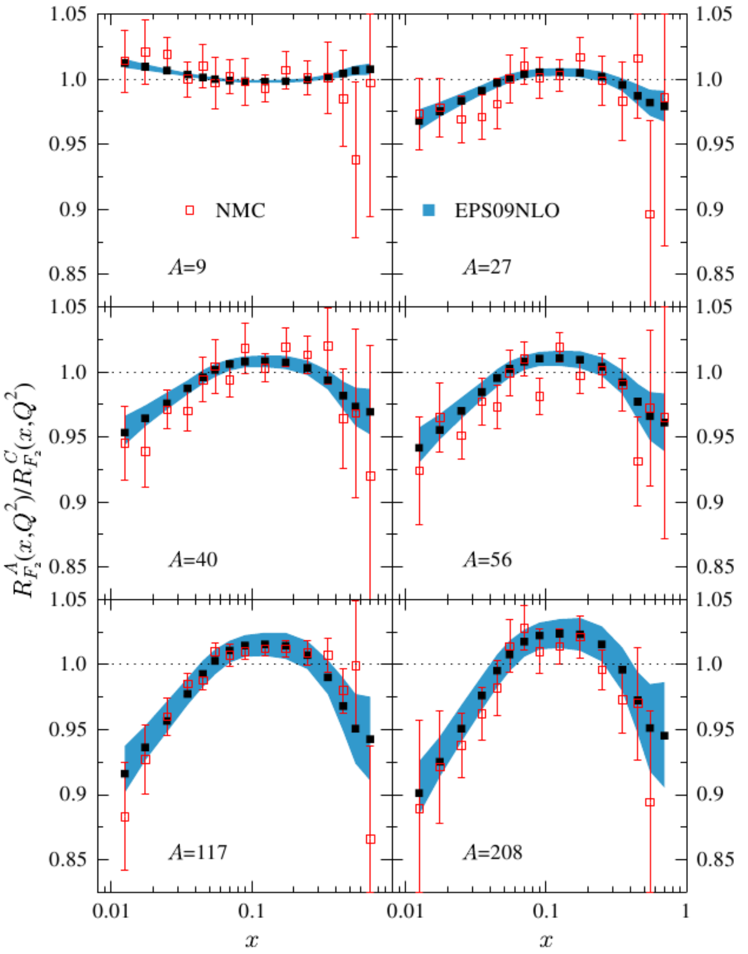
= **No data. Significant fit-function dependence**

Comparison with data: NLO DIS F_2

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

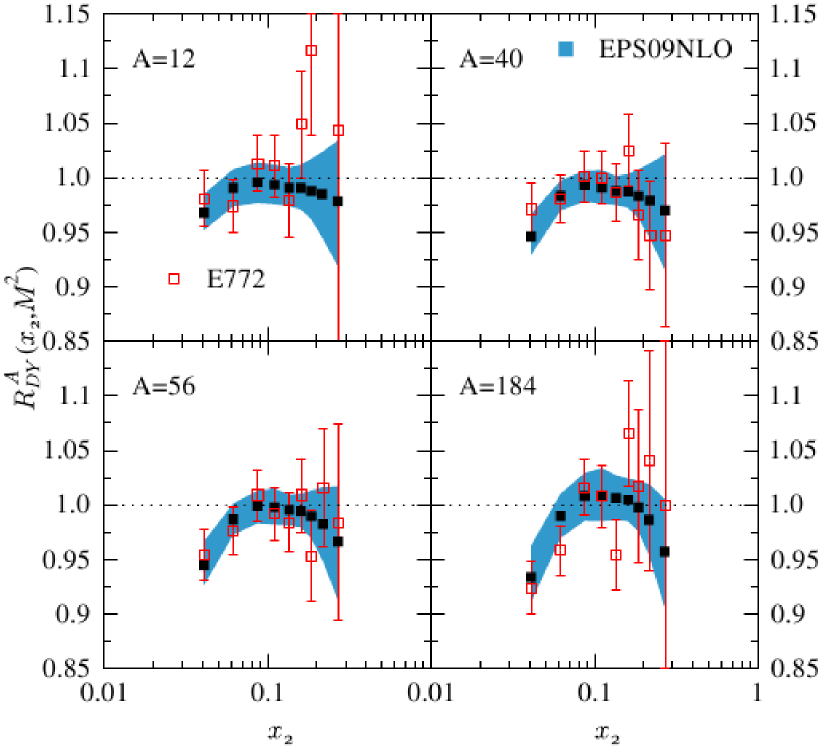
$$\frac{\frac{1}{A}d\sigma^{lA}/dQ^2dx}{\frac{1}{12}d\sigma^{l\mathrm{C}}/dQ^2dx} \stackrel{\mathrm{LO}}{=} \frac{R^A_{F_2}(x,Q^2)}{R^{\mathrm{C}}_{F_2}(x,Q^2)}$$



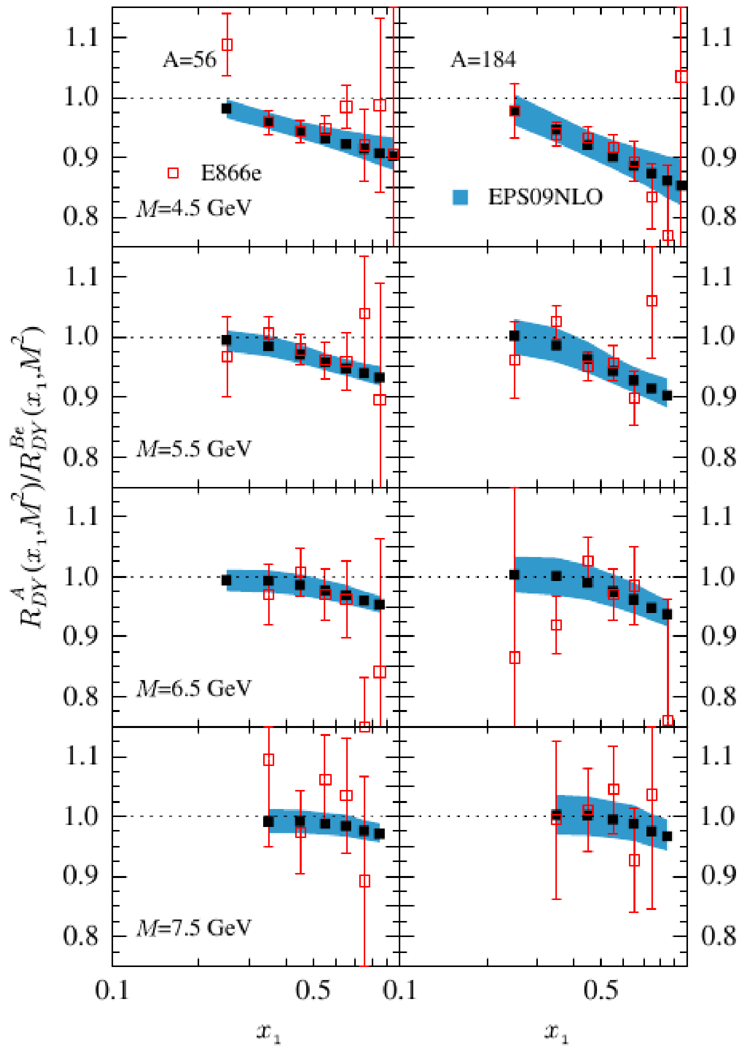


Comparison with data: NLO Drell-Yan

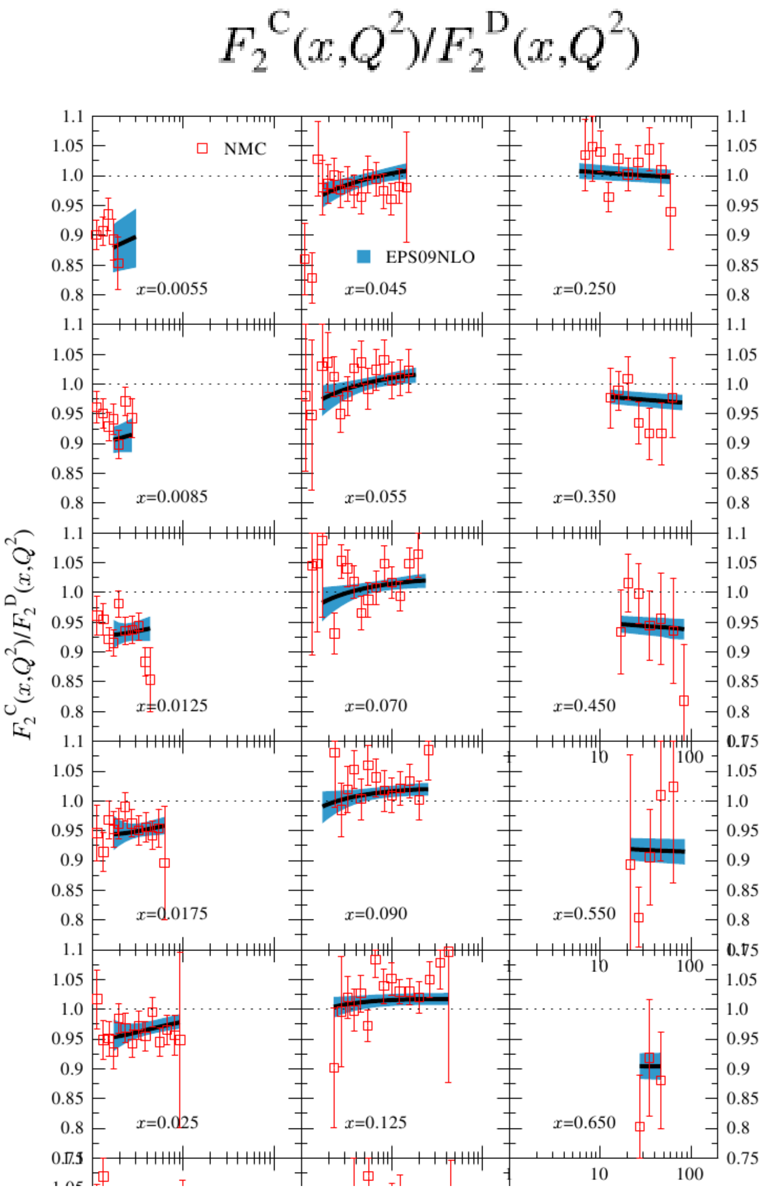
$$\frac{\frac{1}{A}d\sigma^{\mathrm{p}A}_{DY}/dx_2dQ^2}{\frac{1}{2}d\sigma^{\mathrm{pD}}_{DY}/dx_2dQ^2}$$

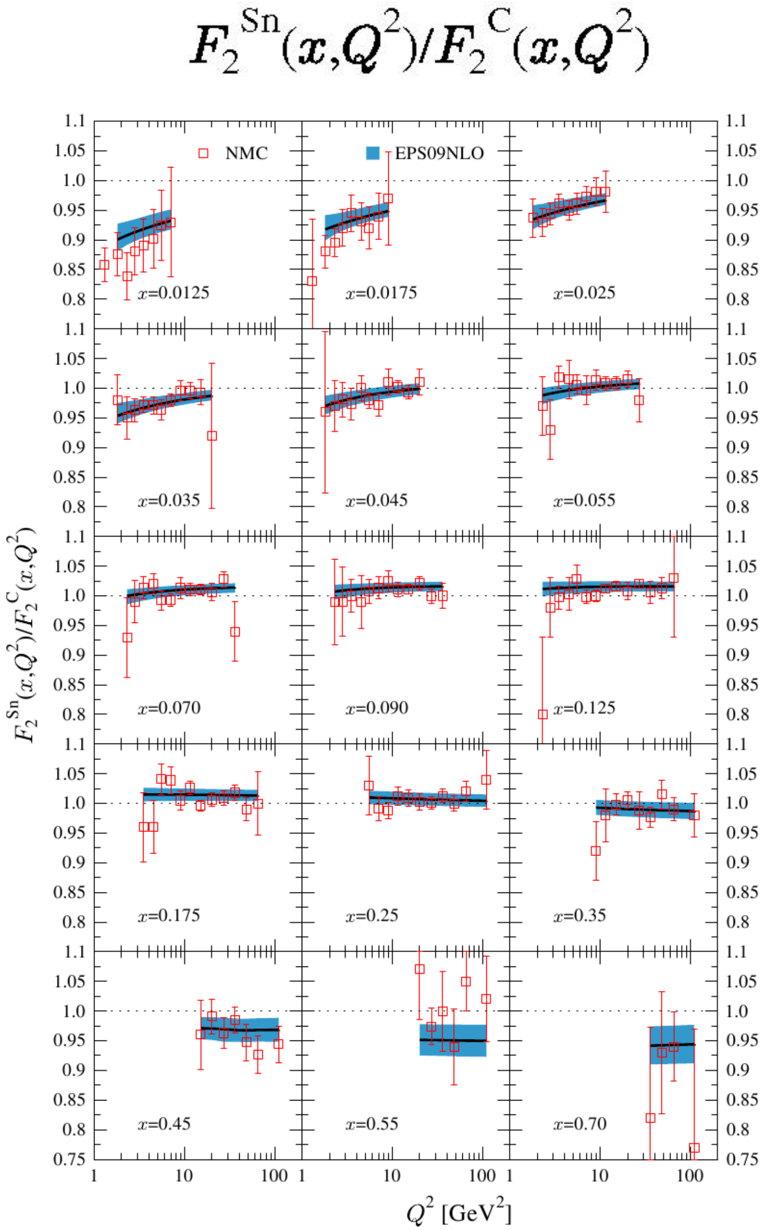


$$\frac{\frac{1}{A}d\sigma^{\mathrm{p}A}_{DY}/dx_1dQ^2}{\frac{1}{9}d\sigma^{\mathrm{pBe}}_{DY}/dx_1dQ^2}$$



Q^2-slopes in F_2: NLO DGLAP evolution

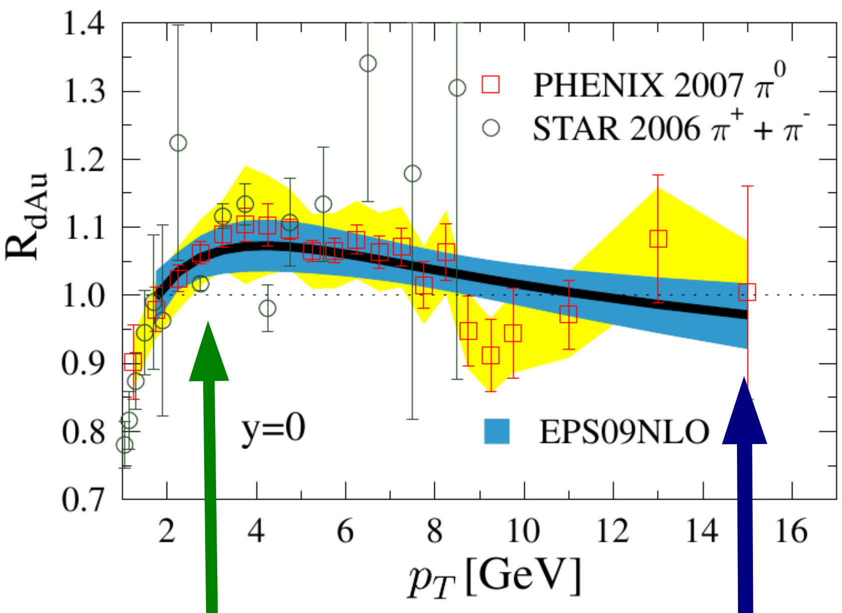


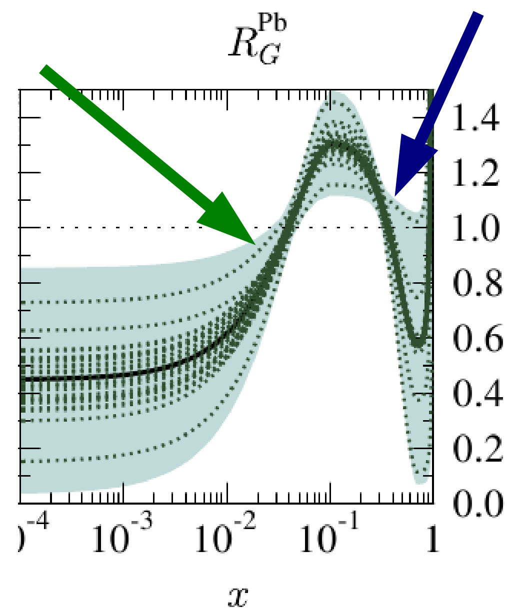


Gluon constraints from π^0-data

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

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

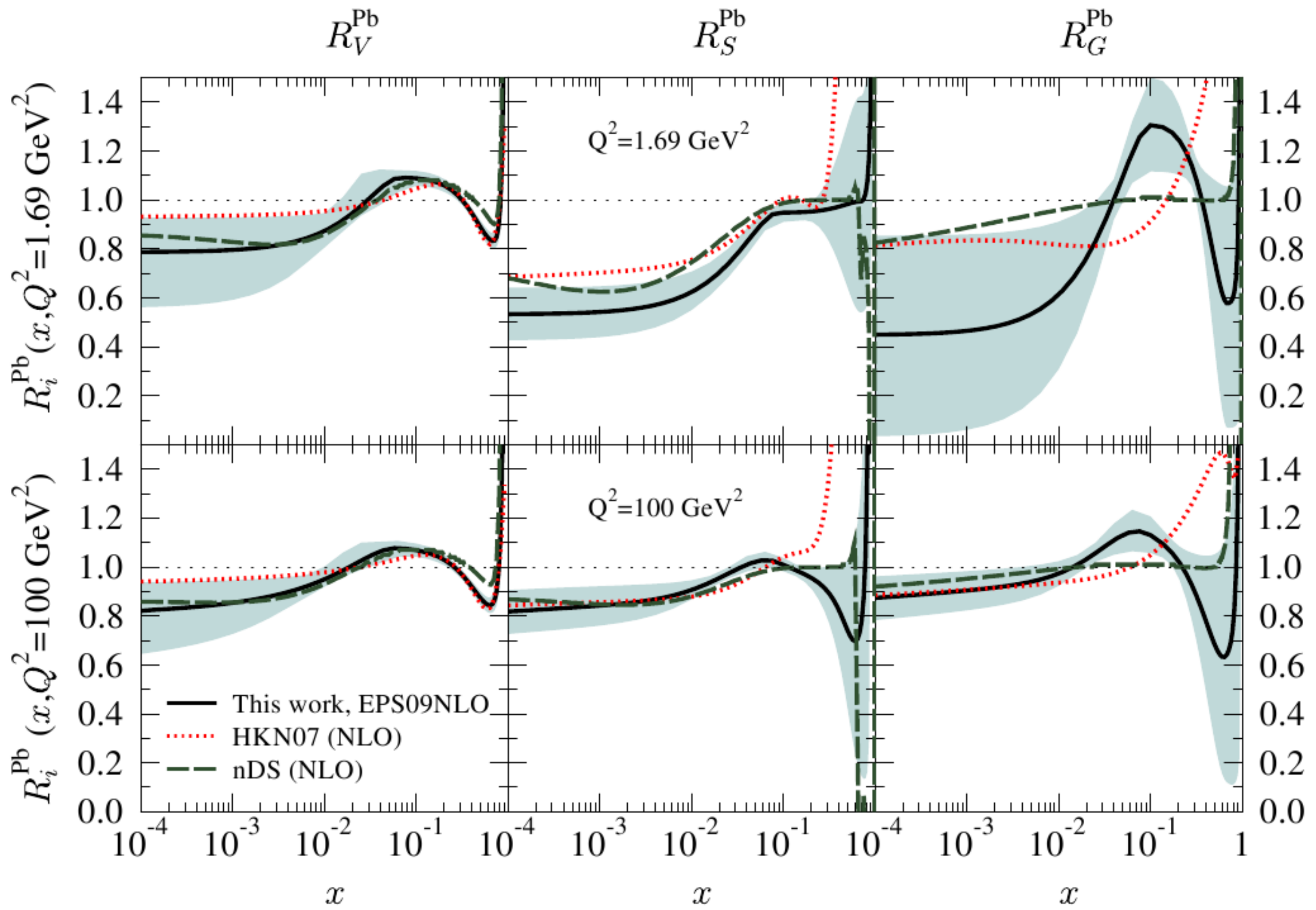




Suppression at low-pT comes from shadowing

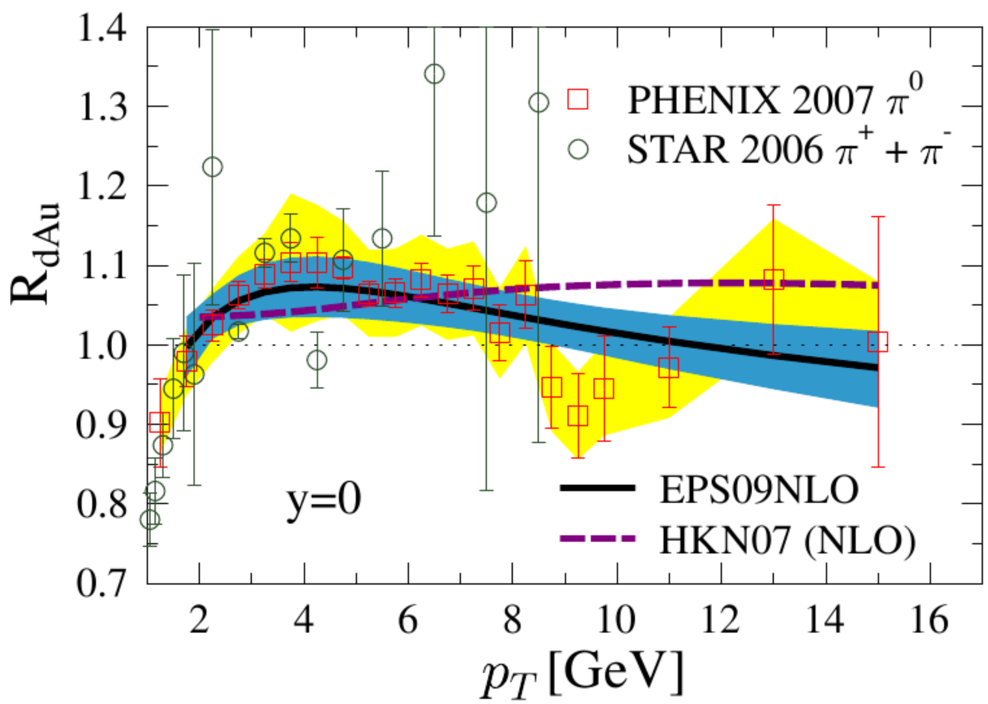
Downward trend is partly caused by gluon EMC-effect!

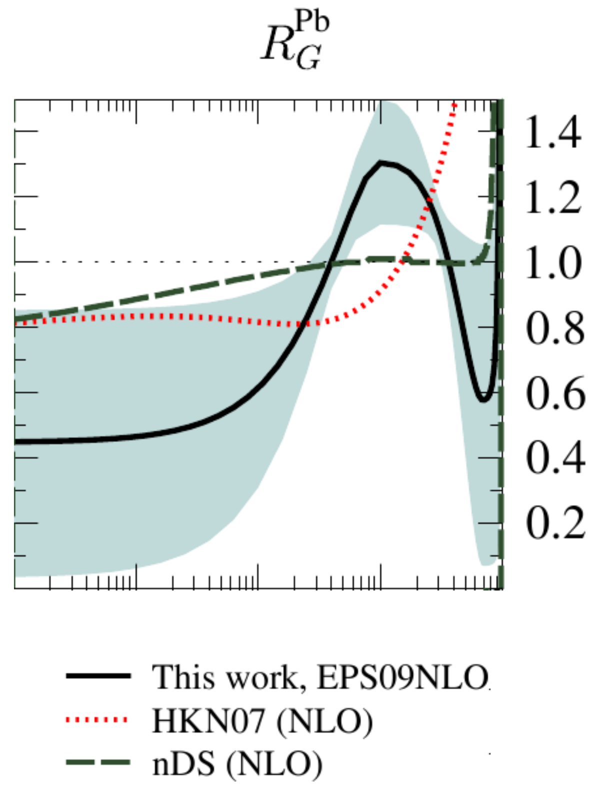
Comparison with earlier works: NLO



- **Note: Form of HKN07 fit-function was very restricted, and they did not include pion data**

Comparison with earlier works: NLO





- Pion pT-data with better statistics could potentially discriminate between different suggested gluon PDFs.

Summary & Outlook

- We find an excellent agreement between NLO pQCD and the hard-process nuclear data for DIS, DY, and π^0 production in the kinematical range $0.005 < x < 1$, $1.69\ GeV^2 < Q^2 < 150\ GeV^2$. This means that:

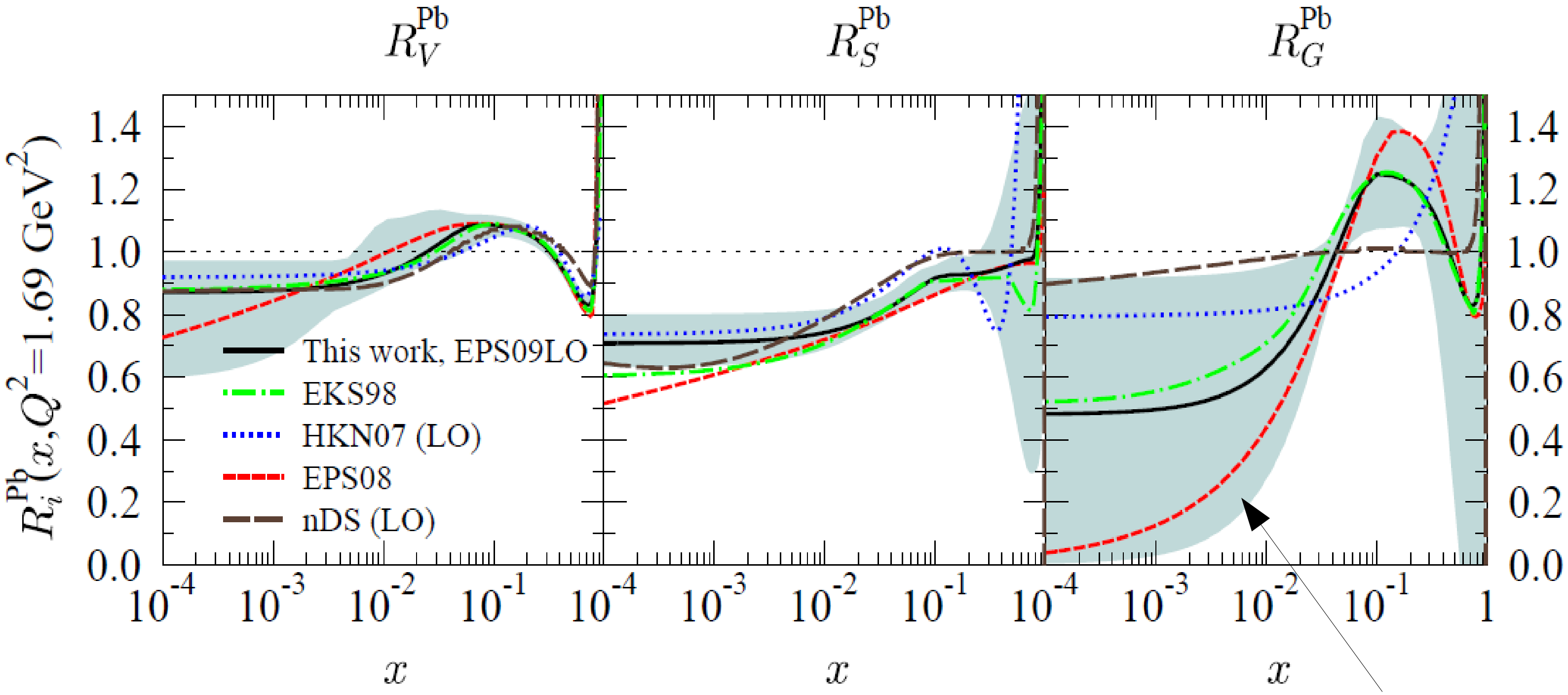
  Factorization theorem in hard nuclear processes seems works well.

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

- Future work with nuclear PDFs:
  - New π^0 & direct photon data should soon appear from RHIC
  - See whether the NuTeV & CHORUS neutrino data can be consistently included into same game.
  - Extend the analysis to general-mass framework

Some Backup slides

Comparison with earlier works: LO



EPS08 was a set with extreme shadowing

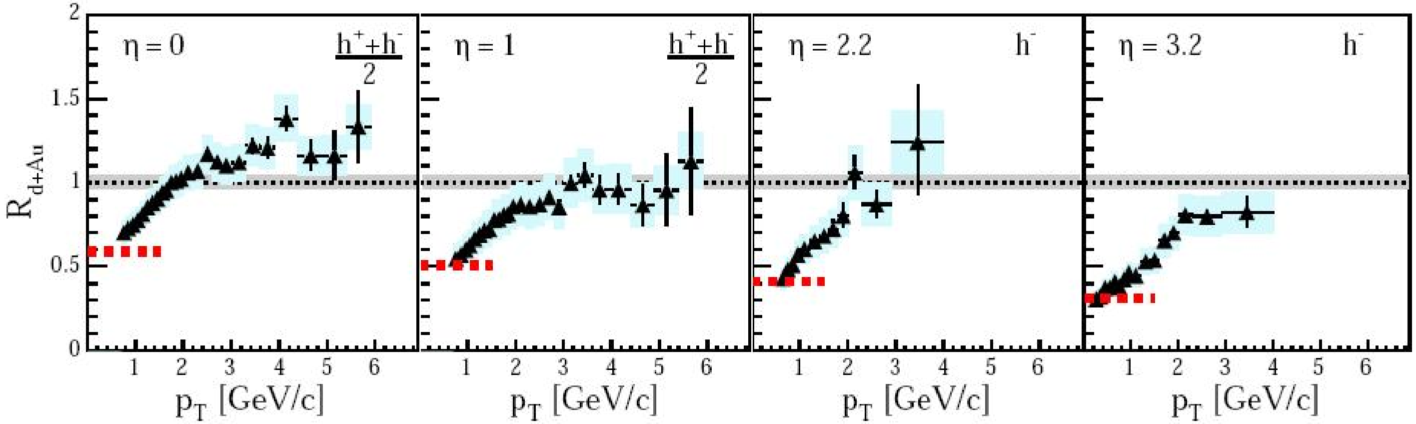
- **The leading order errorbands are larger than in NLO**

Suppression in BRAHMS R_{dAu}

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

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

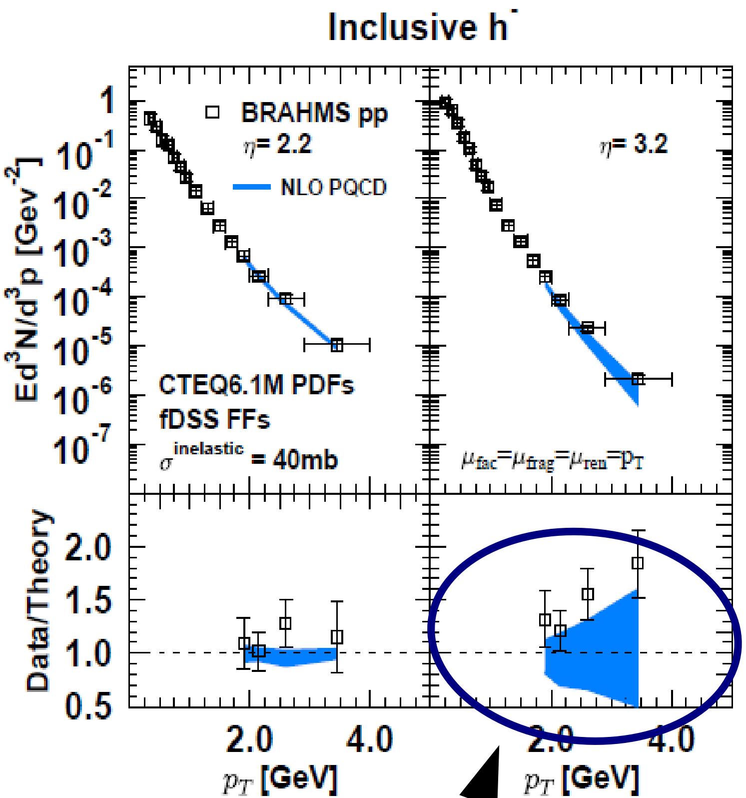
BRAHMS data:
PRL **93**, 242303 (2004)

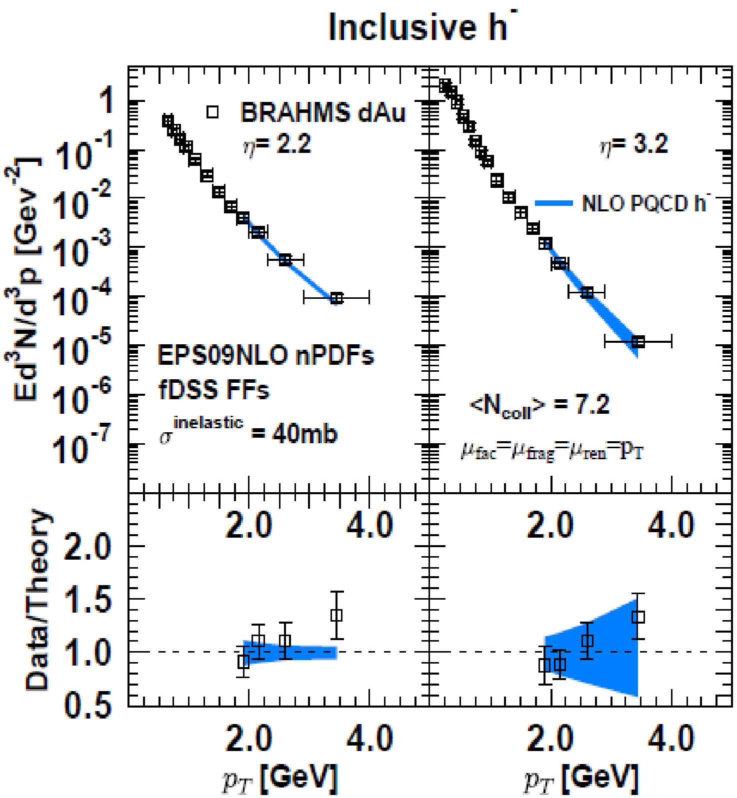


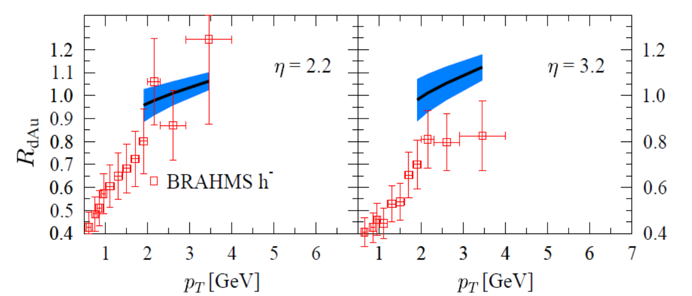
- **When interpreting these data, one should not look R_{dAu} alone but pay a serious attention the also to absolute spectra, especially to the p+p baseline.**

Suppression in BRAHMS R_{dAu} ?

- NLO pQCD predictions for the absolute spectra





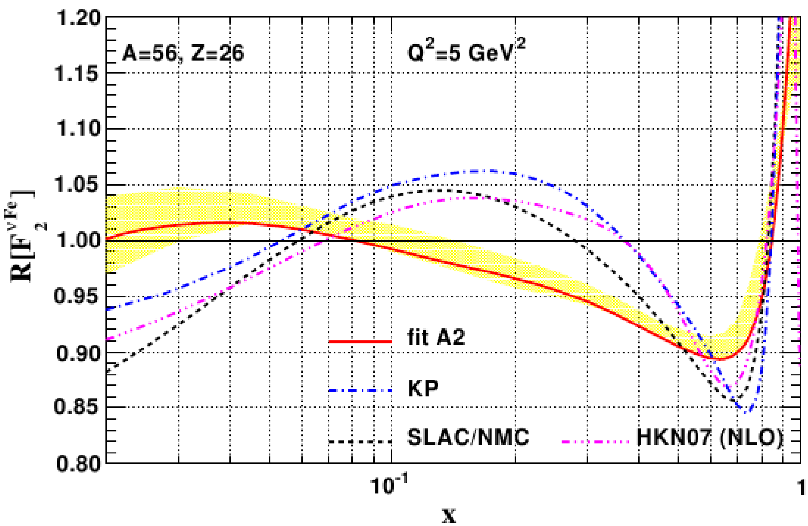


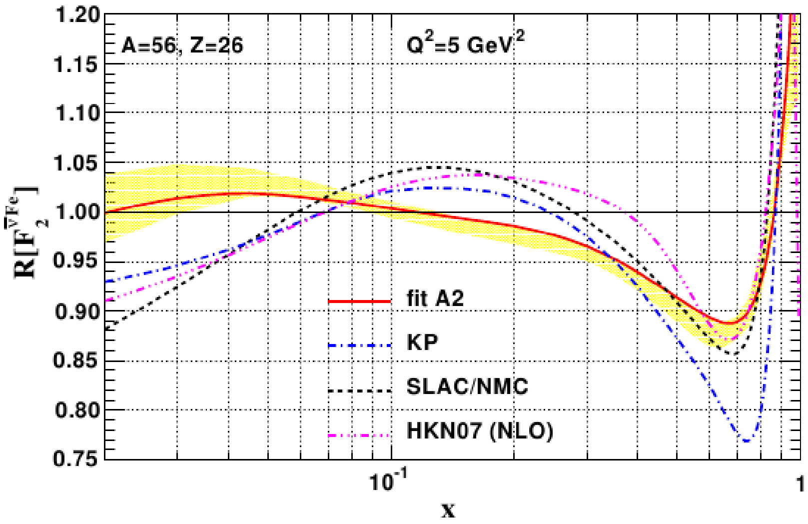
- Reliable use of BRAHMS R_{dAu} not possible – it's not included in the EPS09 sets.

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.