The present status of the EPS nuclear PDFs

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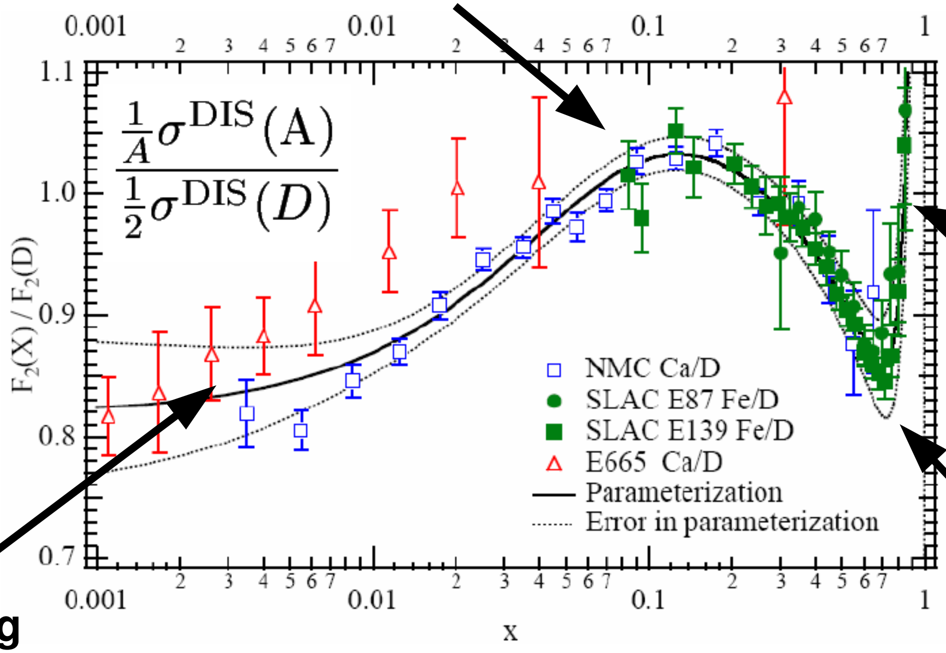
Global nPDF analysis – a test of *factorization*



Anti-shadowing

Fermi-motion

EMC-effect

Shadowing

- Generally, $\boxed{\sigma^{\text{bound nucleon}} \neq \sigma^{\text{free nucleon}}}$
- Search for <u>process independent</u> nPDFs to realize the differences

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\bar{q},g} \underbrace{f_i^A(\mu^2)}_{\text{Nuclear PDFs, obeying the standard DGLAP}} \otimes \underbrace{\hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)}_{\text{Usual pQCD partonic cross-sections}}$$

12 years of EPS-studies

- **1998: EKS98** (Eskola, Kolhinen, Ruuskanen, Salgado) **LO**

  The pioneering work – demonstrated that the factorization works for

  $e+A \rightarrow e + X$ *(DIS)*

  $p+A \rightarrow \mu^{+}+\mu^{-} + X$ *(Drell-Yan)*

  The "fit" was done by hand.

- **2007 : EKPS** (Eskola, Kolhinen, Paukkunen, Salgado) **LO**

  Reanalysis of EKS98 – automated minimization (MINUIT) and a first try to estimate the uncertainties.

- **2008 : EPS08** (Eskola, Paukkunen, Salgado) **LO**

  Motivated by small-pT suppression of BRAHMS pion data, the purpose was to study how strong gluon suppression at small-x would be possible.

- **2009 : EPS09** (Eskola, Paukkunen, Salgado) **LO & NLO**

  The analysis extended to NLO and an error analysis "a la CTEQ" was carried out.

Experimental constraints in EPS09

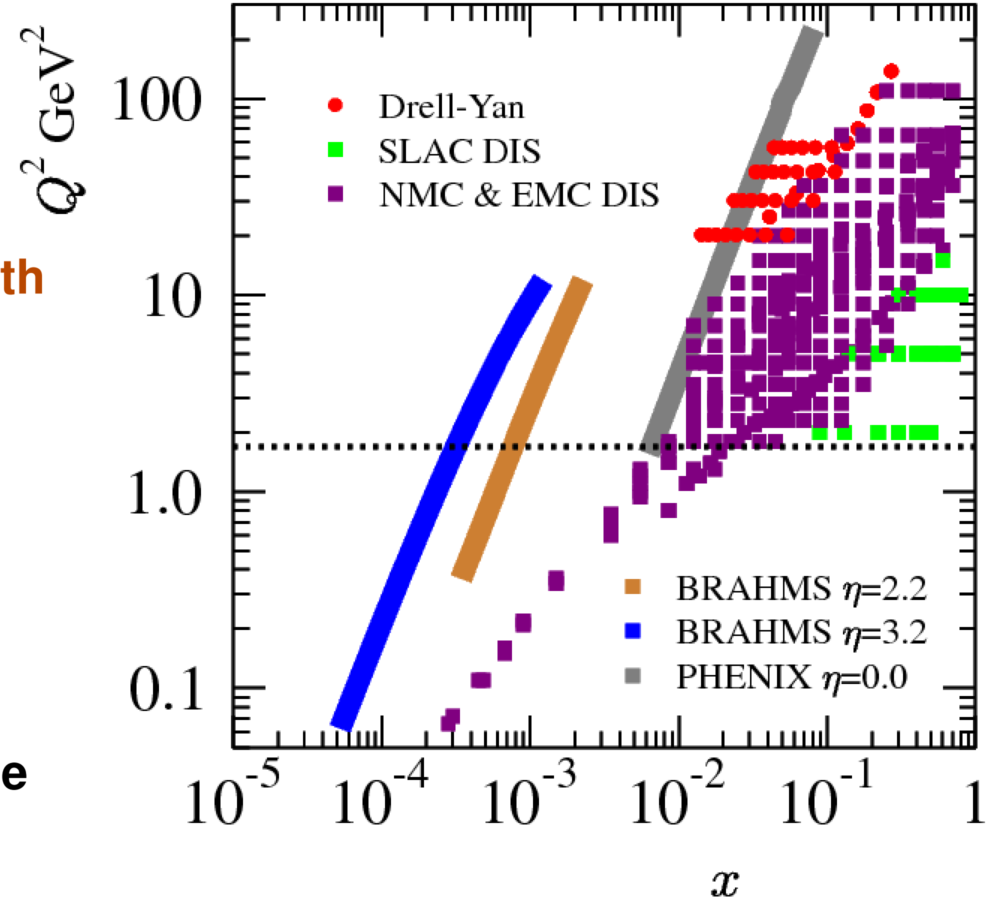
- Three types of data:

Deeply inelastic scattering: e + A → e + X
Drell-Yan dilepton production: p + A → μ^+ + μ^- + X
Inclusive pion production: d + Au → π + X

- The **mutual consistency** between the data sets is necessary. For example:

  - HERMES DIS data display a Q^2-dependence not in agreement with other data. Not used.

  - The forward rapidity pions from BRAHMS display tension with other data. Not used.



- The use of pion data depends of the fragmentation functions which might be different in d+Au than they are in p+p. *(Sassot et. al, Phys.Rev.D81:054001, 2010)*

The Framework of EPS09

- The bound proton PDFs $f_i(x,Q)$ in a nucleus A are defined as

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

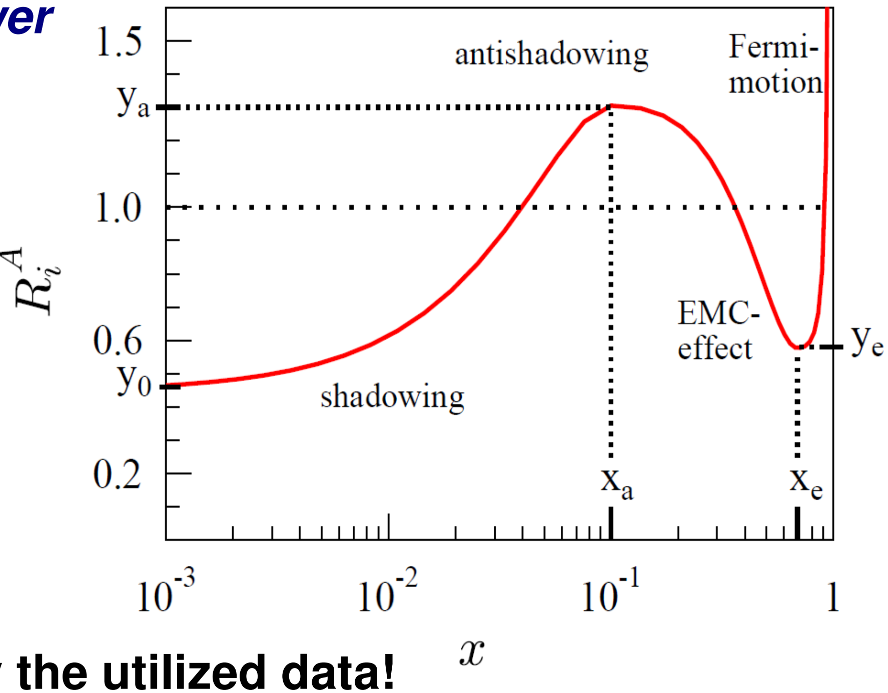
- $\overline{\text{MS}}$, Zero-mass variable flavour number scheme

Our studies utilizing the SACOT-prescription (with e.g. CTEQ6.6) for the heavy quarks do not display large deviations from the zero-mass results in the regions constrained by the data.

→ *One may safely use EPS09 also with newer sets of CTEQ6.6, CT10 , etc...*

- The nuclear modifications are parametrized at initial scale 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



- **The flavor-separation not well constrained by the utilized data!**

Best-fit definition: Generalized χ^2

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

$$\chi^2(\{a\}) \equiv \sum_N w_N \, \chi^2_N(\{a\})$$

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

D_i = Experimental values

T_i = Theory values

σ_i = Uncertainty

- With weight factors w_N have emphasized certain data sets with “important physics content” but small amount of data points.

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

- The re-weighting induces some subjectivity to the central fit as well as to the error analysis... → too optimistic errorbands?

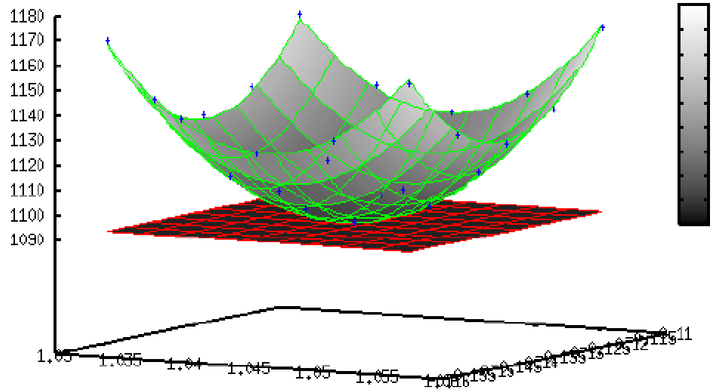
Uncertainty analysis: Hessian method

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

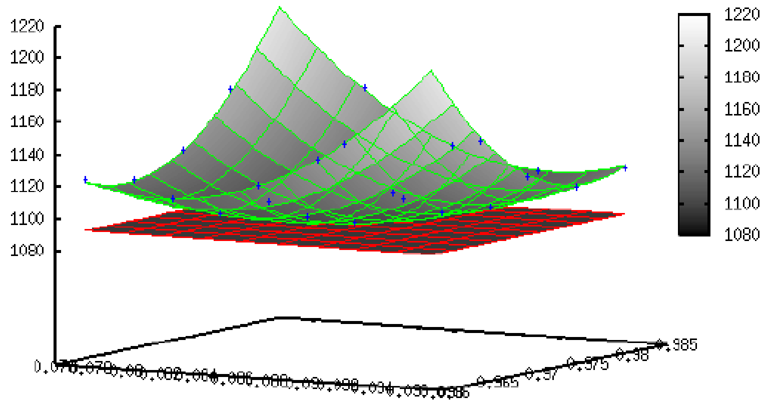
$$\chi^2 \approx \chi_0^2 + \sum_{ij} \delta a_i H_{ij} \delta a_j$$

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

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



(a) Uncorrelated



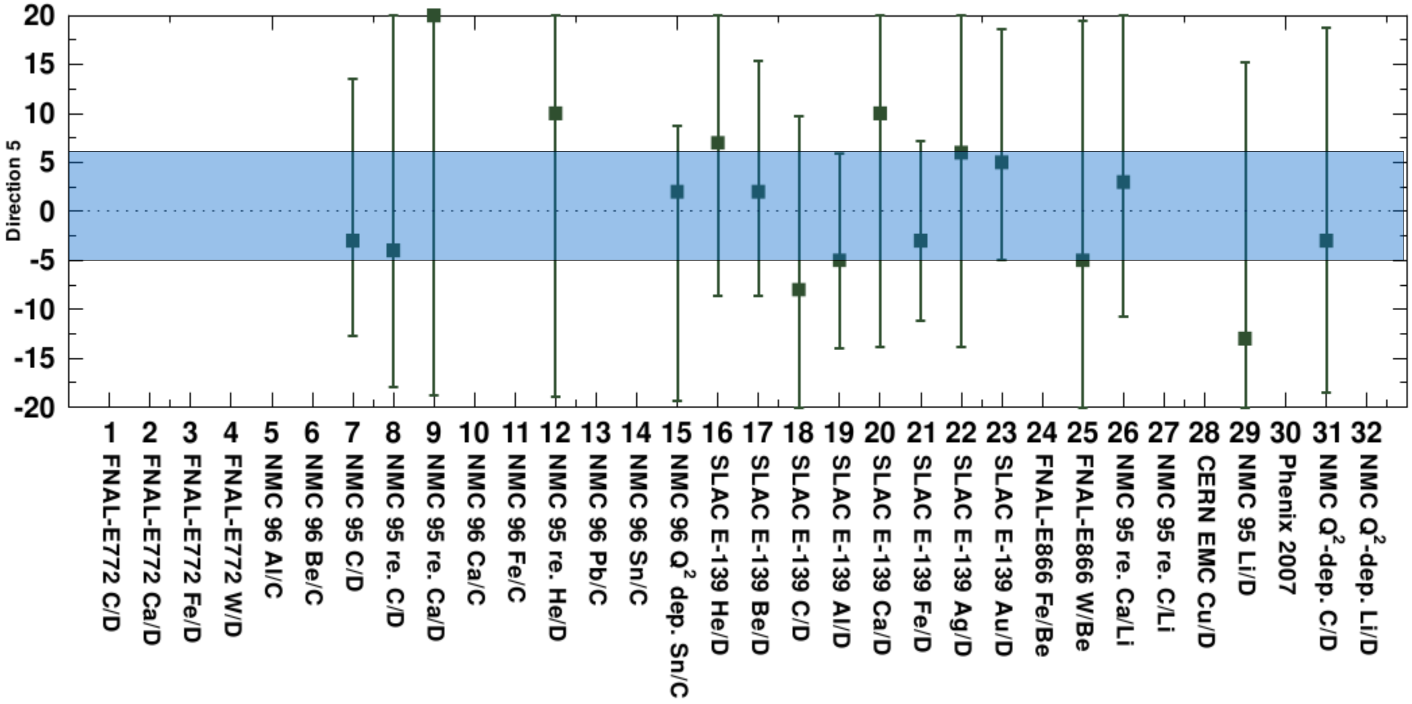
(b) Correlated

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

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

Hessian method: Choice of $\Delta\chi^2$

- Requiring the χ^2-contribution of each data set to stay roughly within its 90% confidence range, we end up with $\Delta\chi^2 = 50$ as a reasonable estimation for permitted variation around the central fit.



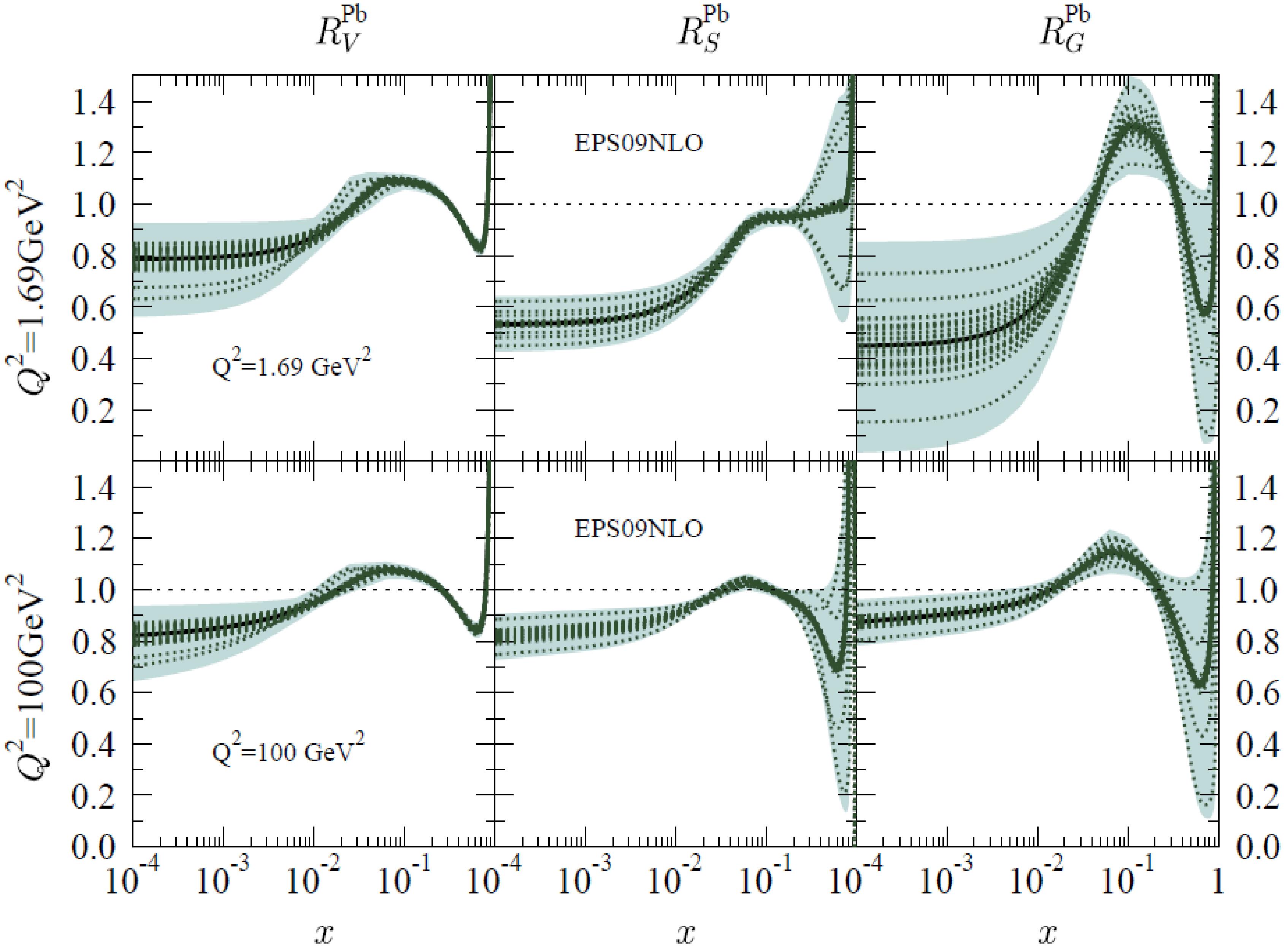
- Each uncertainty set $\{S\}_i$ set increases χ^2 by 50. The error to quantity X should be computed by

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

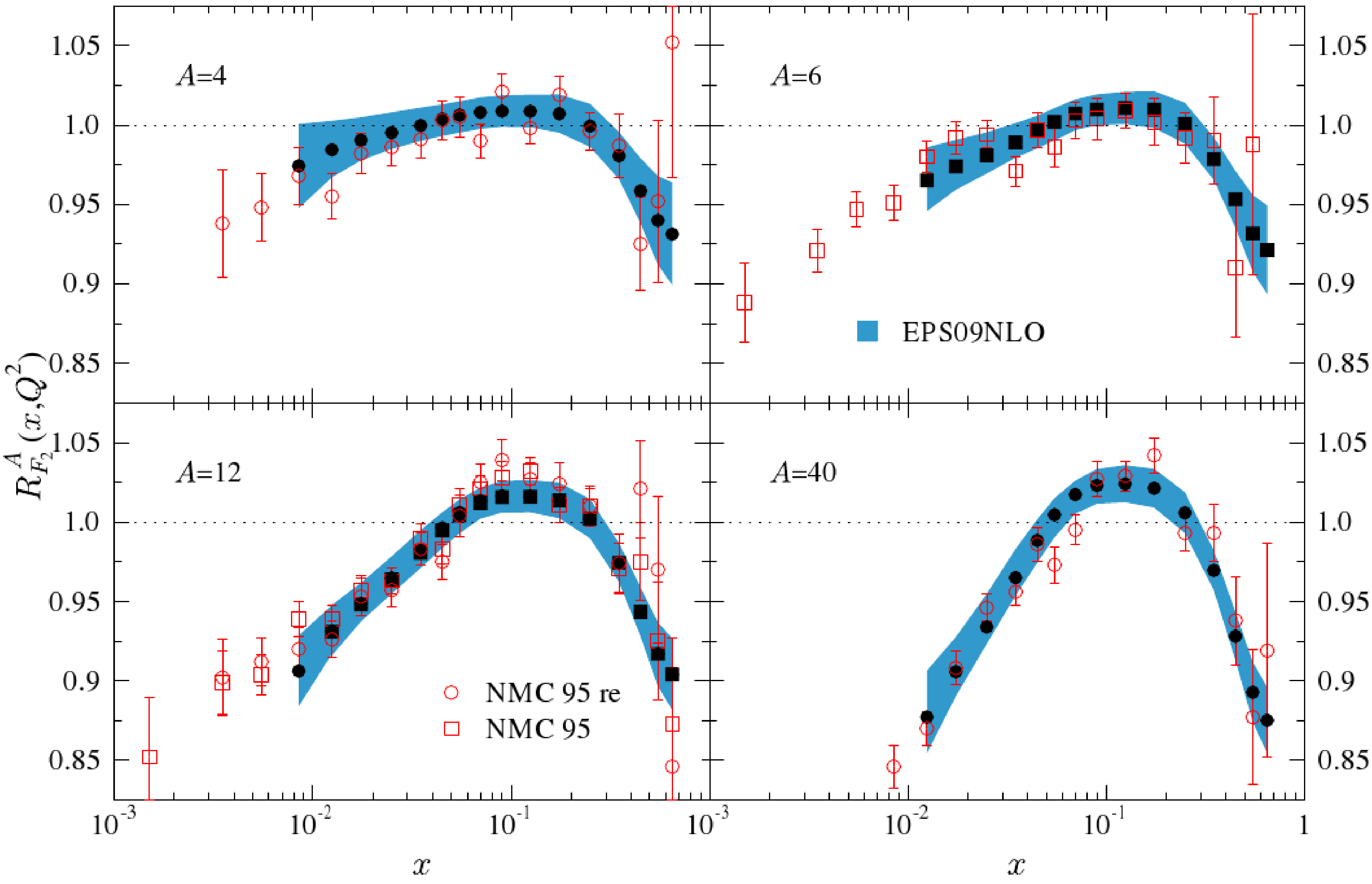
$$(\Delta X^-)^2 \approx \sum_k \left[\max\left\{X(S^0) - X(S_k^+), X(S^0) - X(S_k^-), 0\right\}\right]^2$$

How the EPS09 look like...

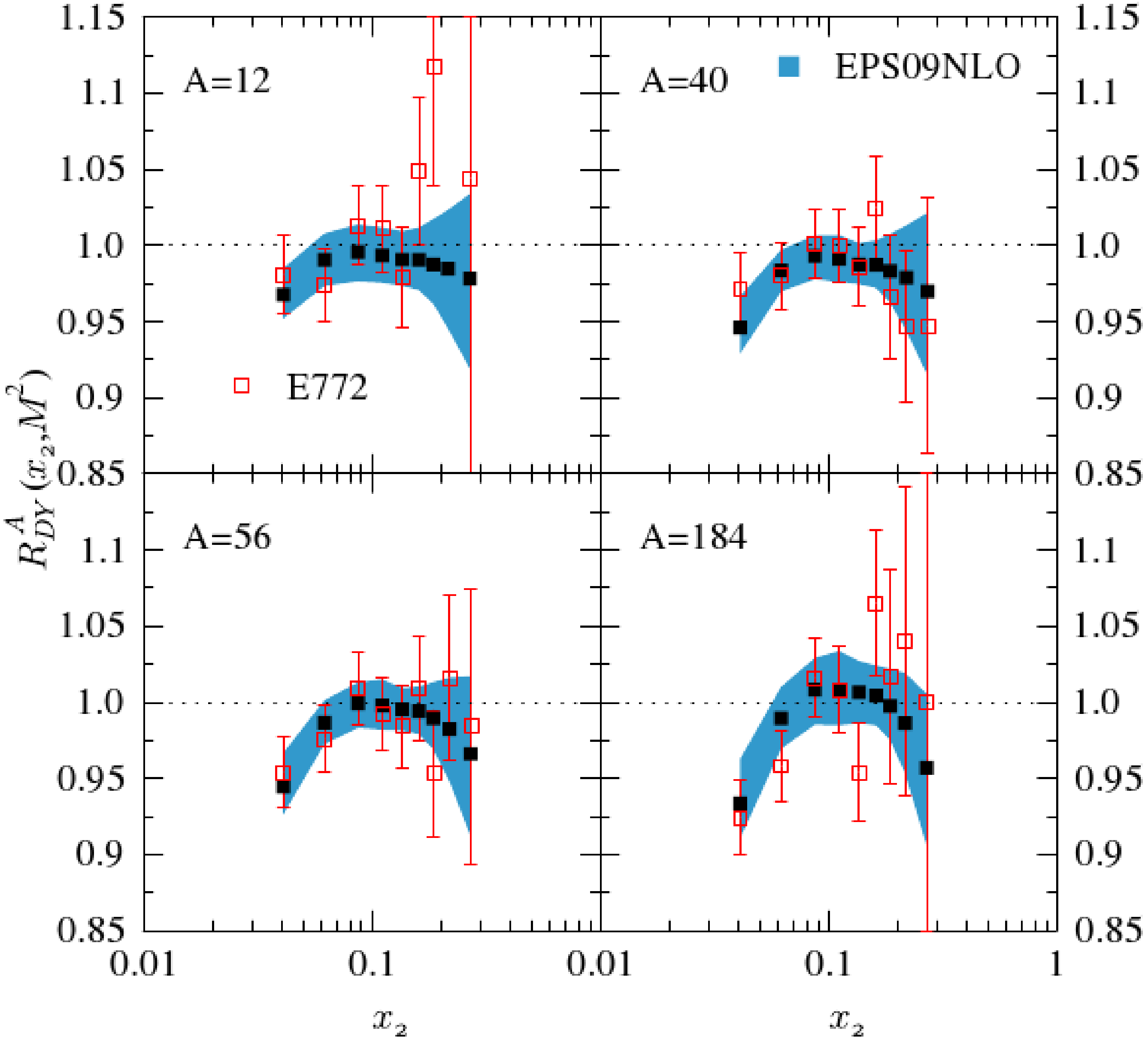
- **NLO nuclear modifications**



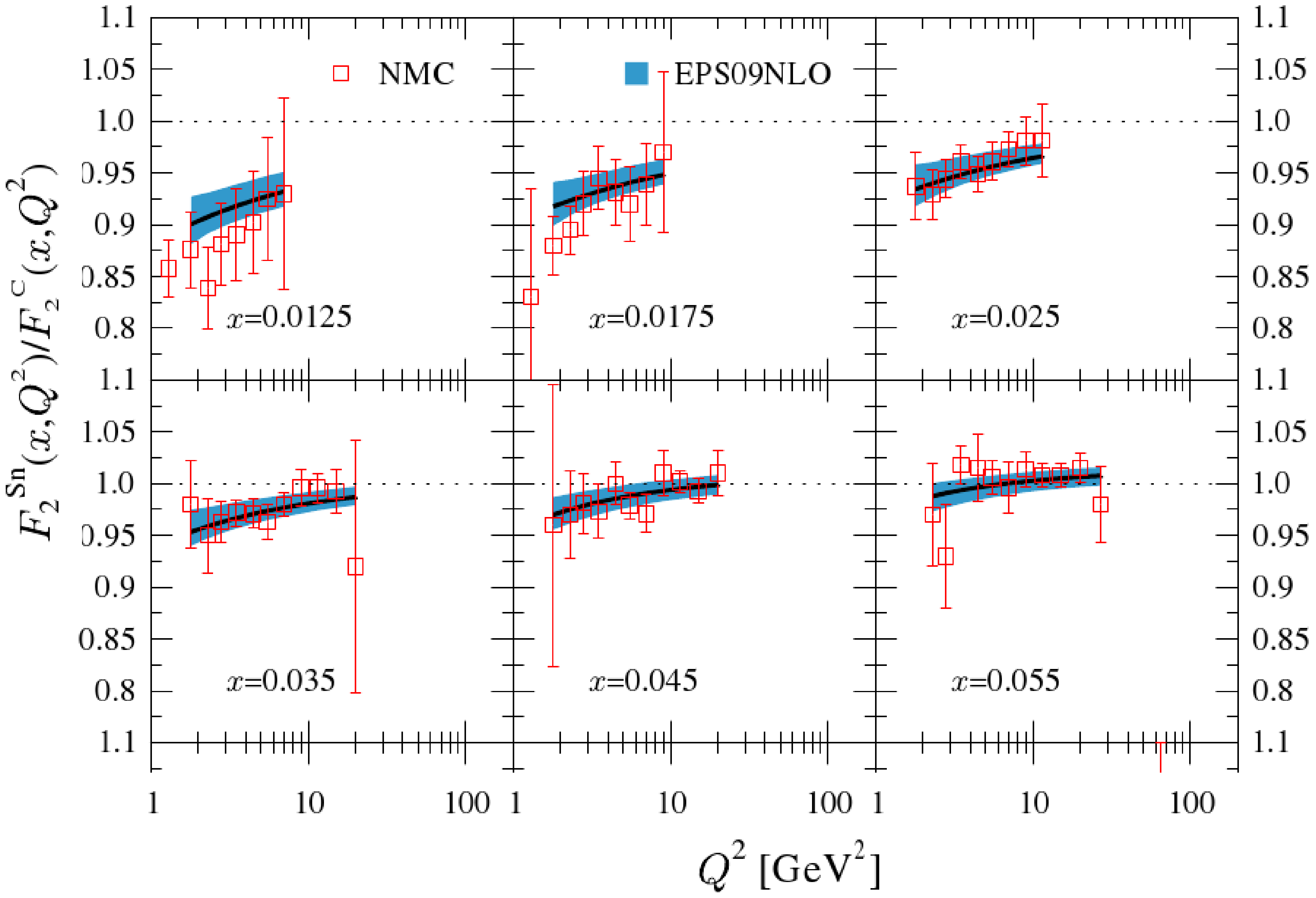
Comparison with data: NLO DIS F_2



Comparison with data: NLO Drell-Yan



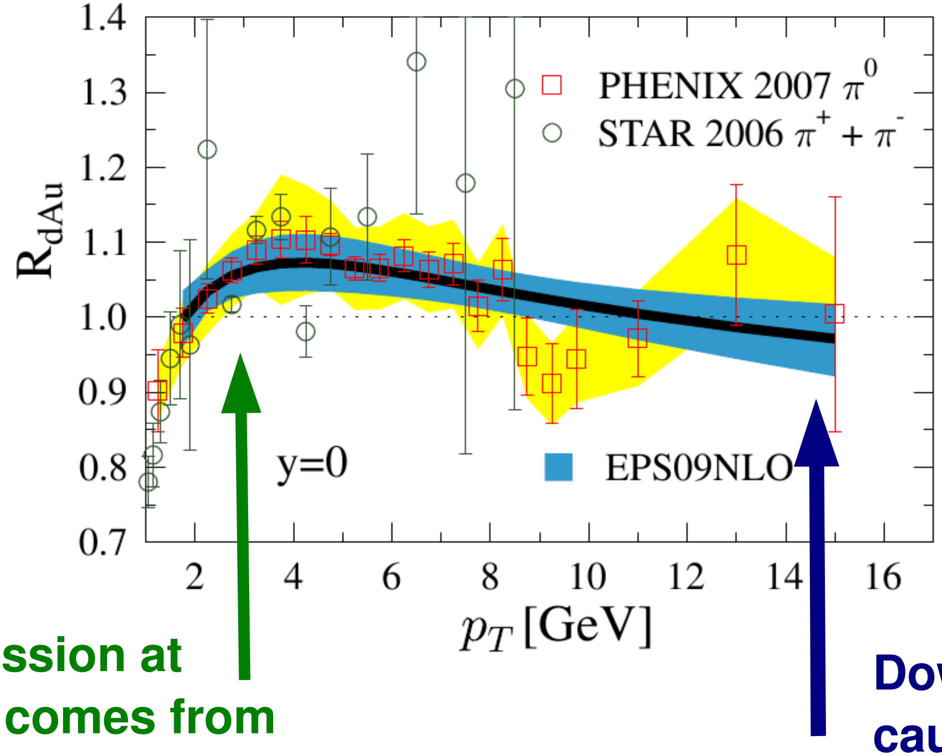
Q^2-slopes in F_2: NLO DGLAP evolution

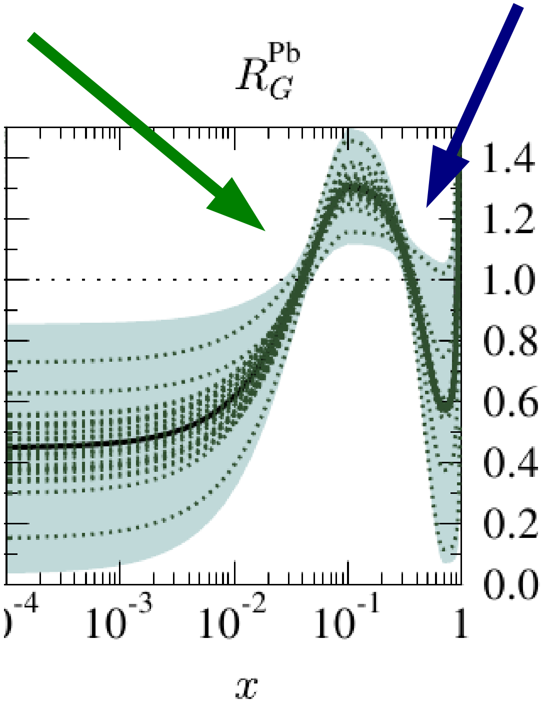


The Q^2-slopes from the DGLAP correctly reproduce the data → evidence for the factorization

Gluon constraints from π^0-data

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





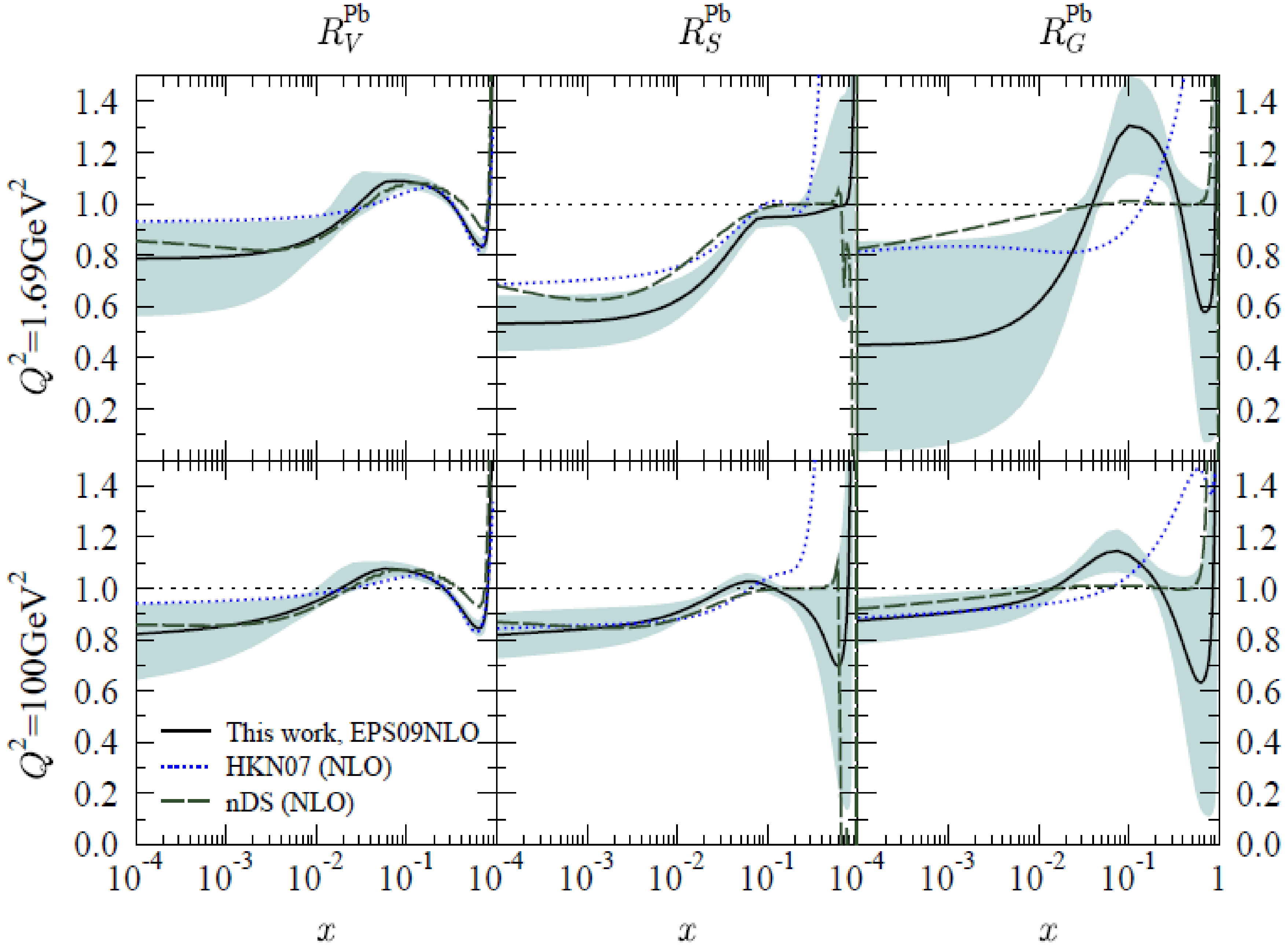
Suppression at low-pT comes from shadowing

Downward trend is partly caused by gluon EMC-effect!

- **Note: This data set was heavily weighted in the fit.**
  In the present way of quantifying the errors this additional weight artificially reduces the error bands!

  Including the new STAR-data (*arXiv:0912.3838*) could reduce the need for such extra weight.

Comparison other works: nDS & HKN07



About the recent EPS-activities

Analysis of Neutrino DIS Data

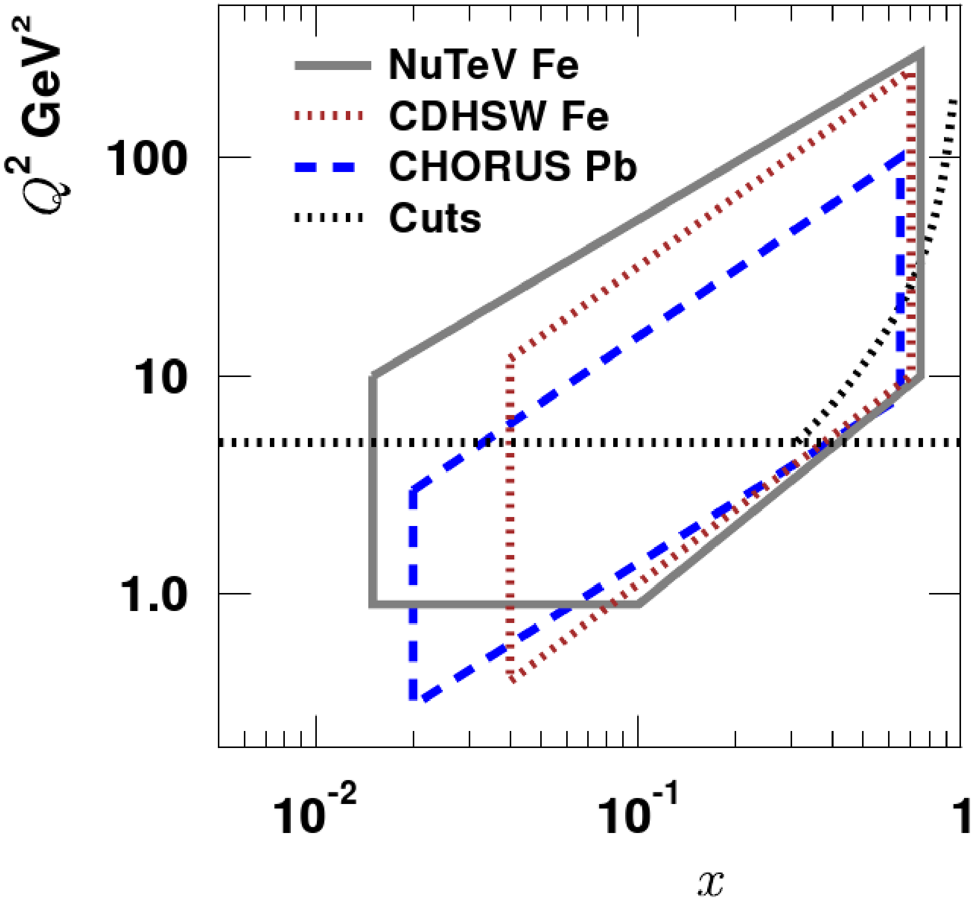
JHEP 1007:032,2010

See also my talk 183,
At 15:20, Track 4!

- **Consistency check:** **Can we reproduce the nuclear effects in neutrino DIS by the nPDFs extracted from other data?**

- **Three ν-A DIS data sets: NuTeV (Fe), CDHSW (Fe), CHORUS (Pb)**

  - **NuTeV : 2041 data points**
  - **CDHSW : 700 data points**
  - **CHORUS: 768 data points**



- **Our Calculation includes all relevant effects as:**
  - **- Target Mass Correction**
  - **- Electroweak Radiation**
  - **- Heavy Quark Effects (SACOT)**

JHEP 1007:032,2010

Analysis of Neutrino DIS Data

- **Generally, we obtain excellent values of χ^2 :**

RAD + TM	CTEQ6.6	CTEQ6.6 + EPS09
NuTeV	1.51	1.05
CHORUS	1.15	0.78
CDHSW	1.10	0.69

- **The x-shape of the nuclear modification becomes well-revealed by Q^2-averaged ratios:**

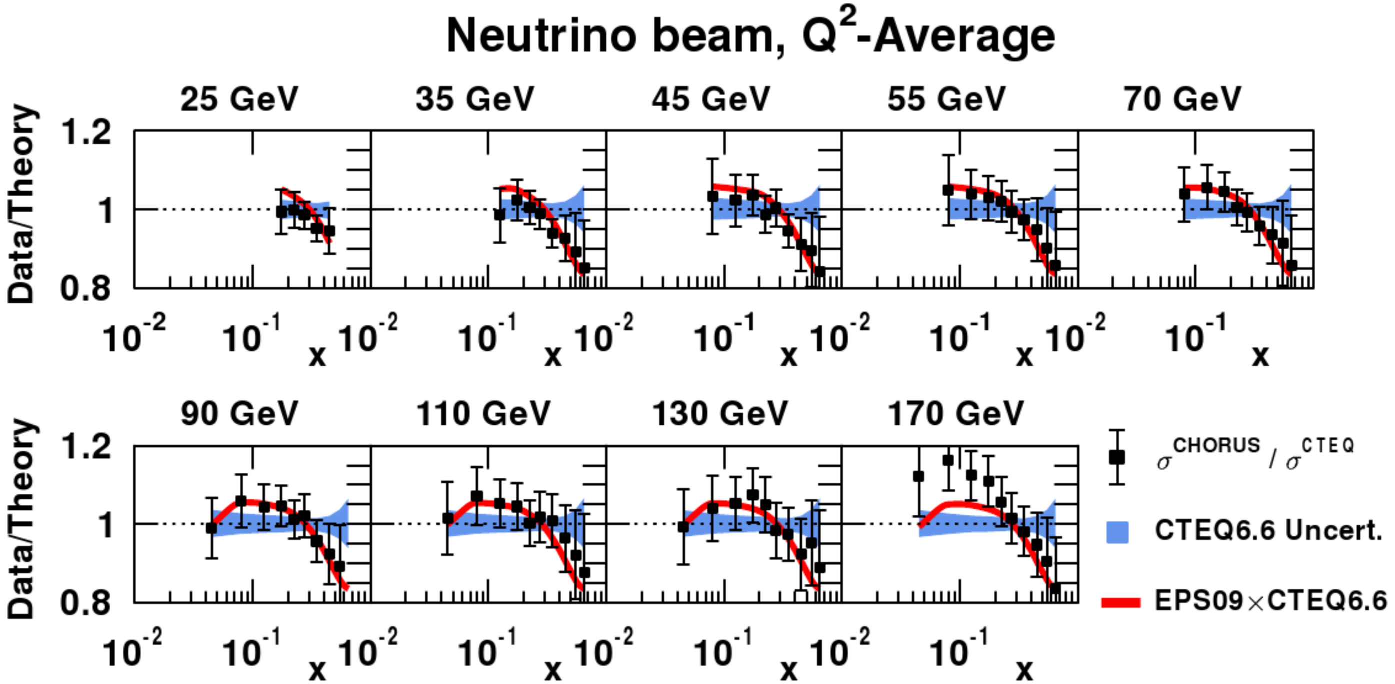
$$R^{\mathrm{CTEQ6.6}} \equiv \frac{\sigma^{\nu,\overline{\nu}}\,(\mathrm{Experimental})}{\sigma^{\nu,\overline{\nu}}\,(\mathrm{CTEQ6.6})}$$

$$R^{\mathrm{CTEQ6.6\times EPS09}} \equiv \frac{\sigma^{\nu,\overline{\nu}}\,(\mathrm{CTEQ6.6}\times \mathrm{EPS09})}{\sigma^{\nu,\overline{\nu}}\,(\mathrm{CTEQ6.6})}$$

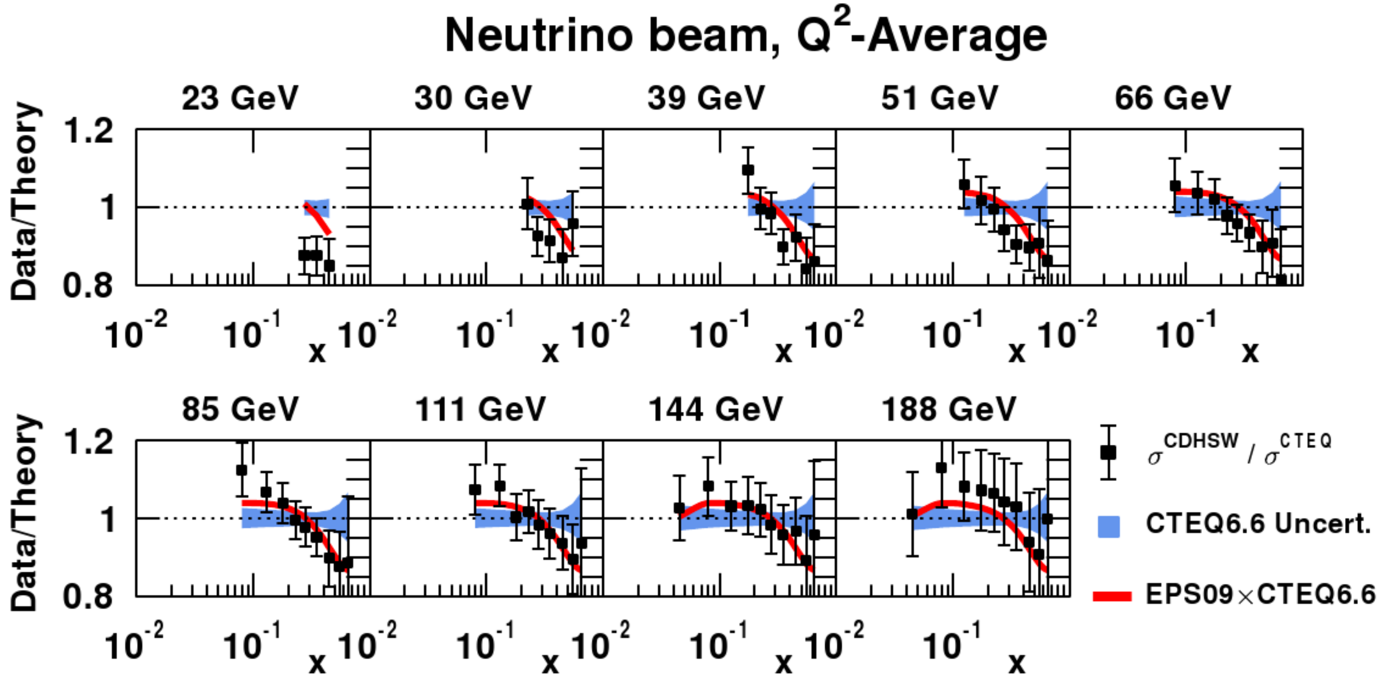
Analysis of Neutrino DIS Data

JHEP 1007:032,2010

CHORUS (Pb):



CDHSW (Pb):



NuTeV (Fe)

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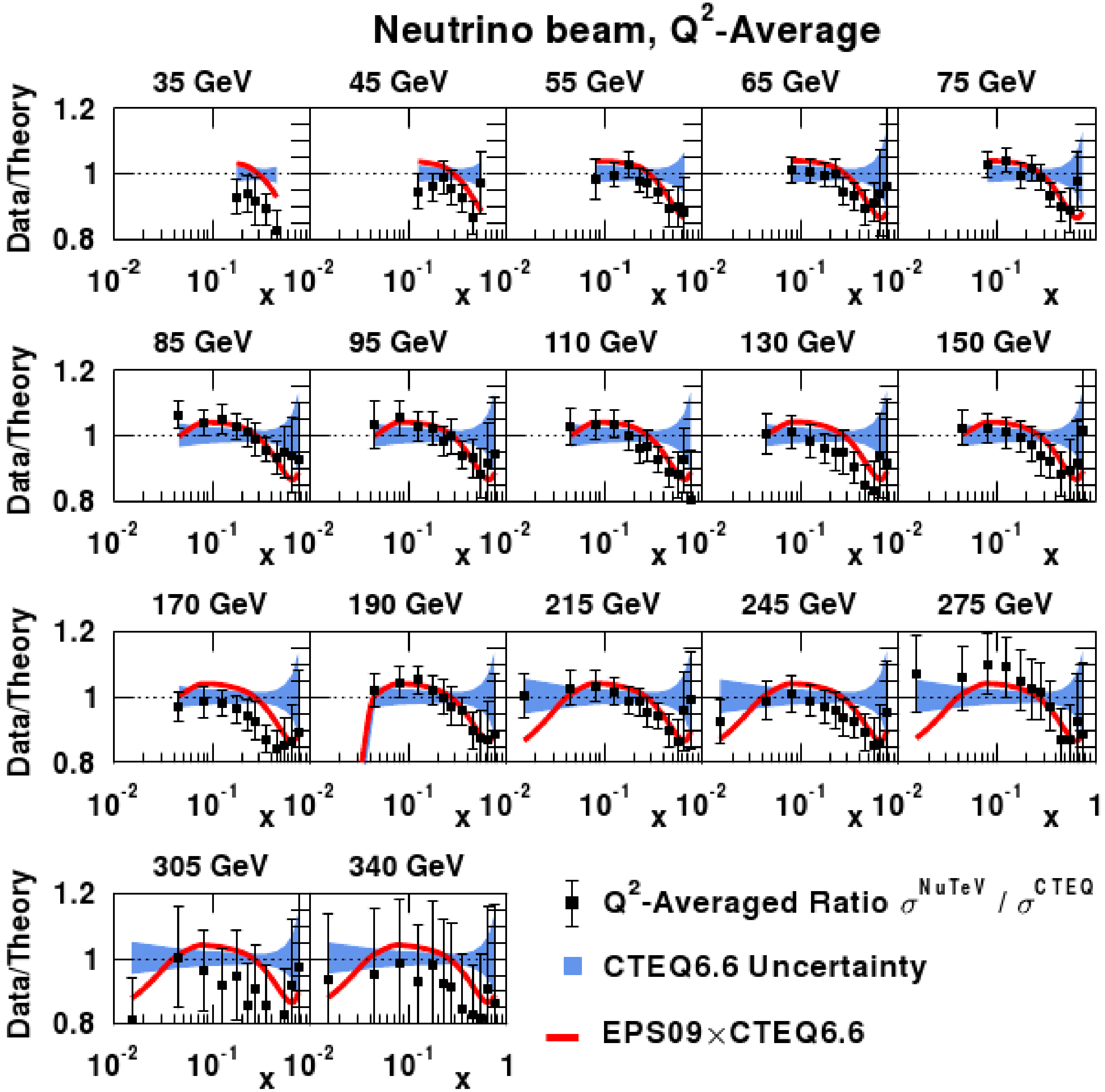

NuTeV (Fe)

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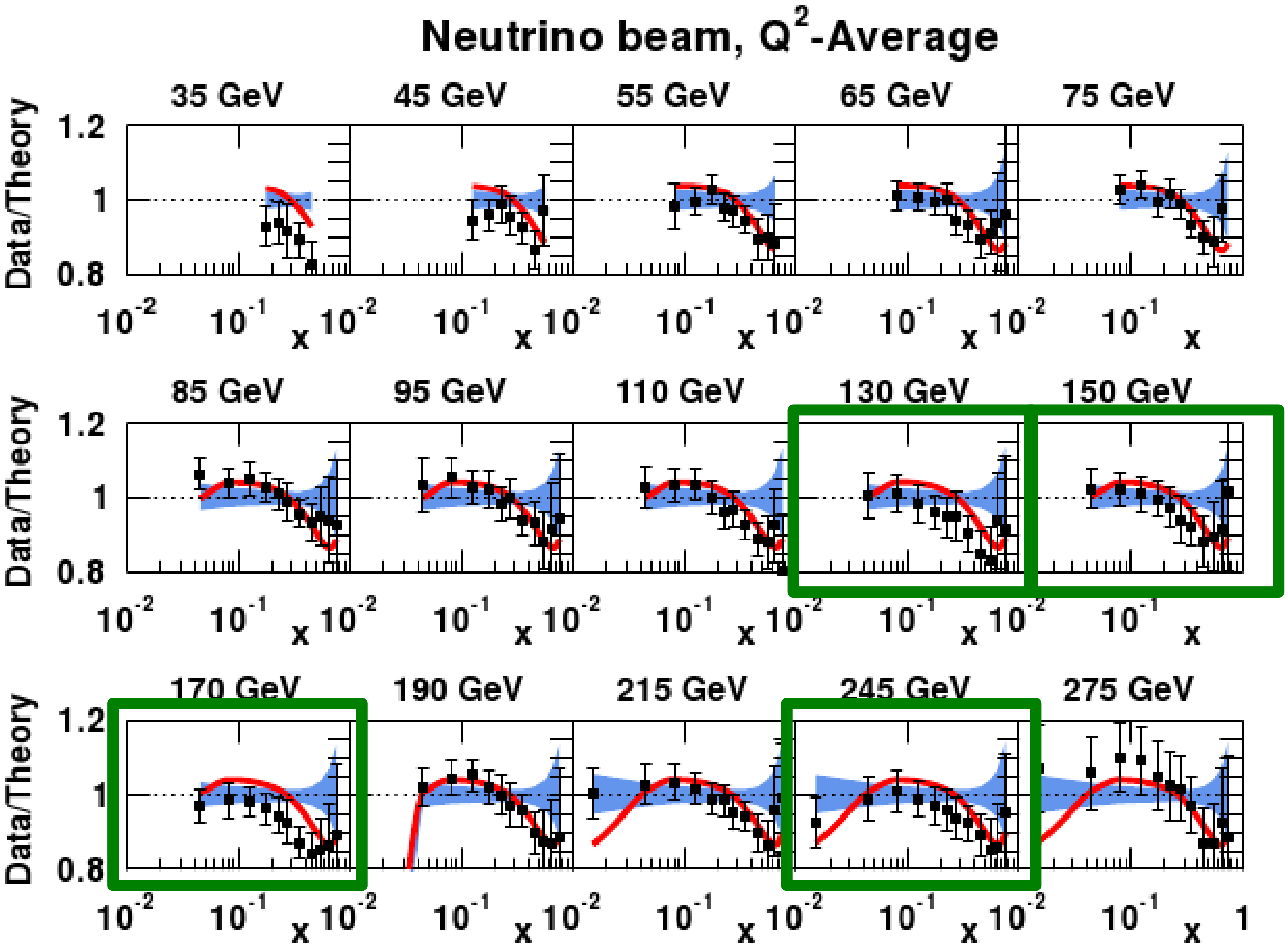
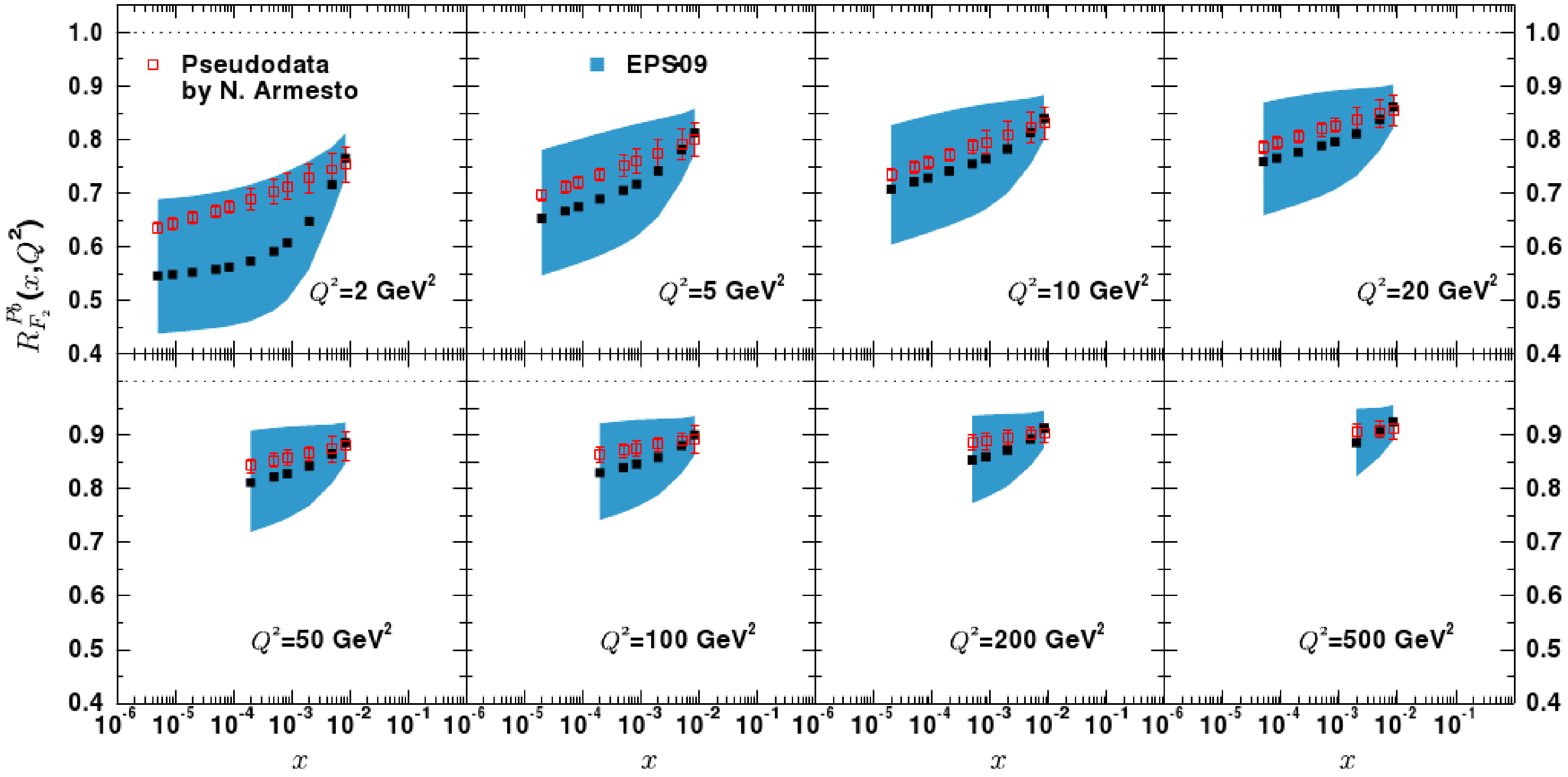


The NuTeV neutrino data in different E_ν bins display mutual tension!!

Expectations: Electron-Ion Collider LHeC

- EPS09-predictions for structure function ratio:

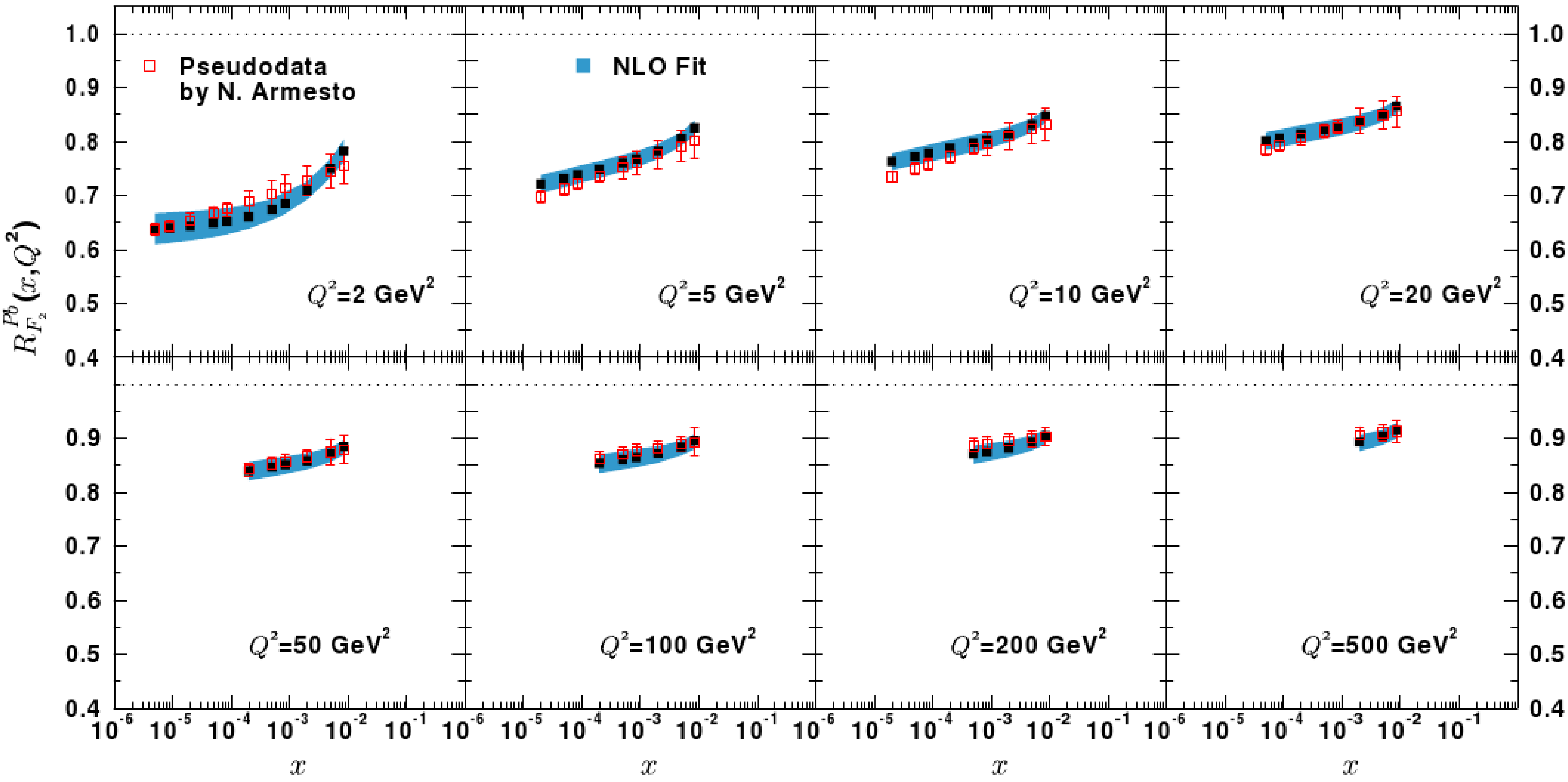
$$R_{F_2}^{\mathrm{Pb}}(x,Q^2) \equiv F_2^{\mathrm{Pb}}/F_2^{\mathrm{p}}$$



Expectations: Electron-Ion Collider LHeC

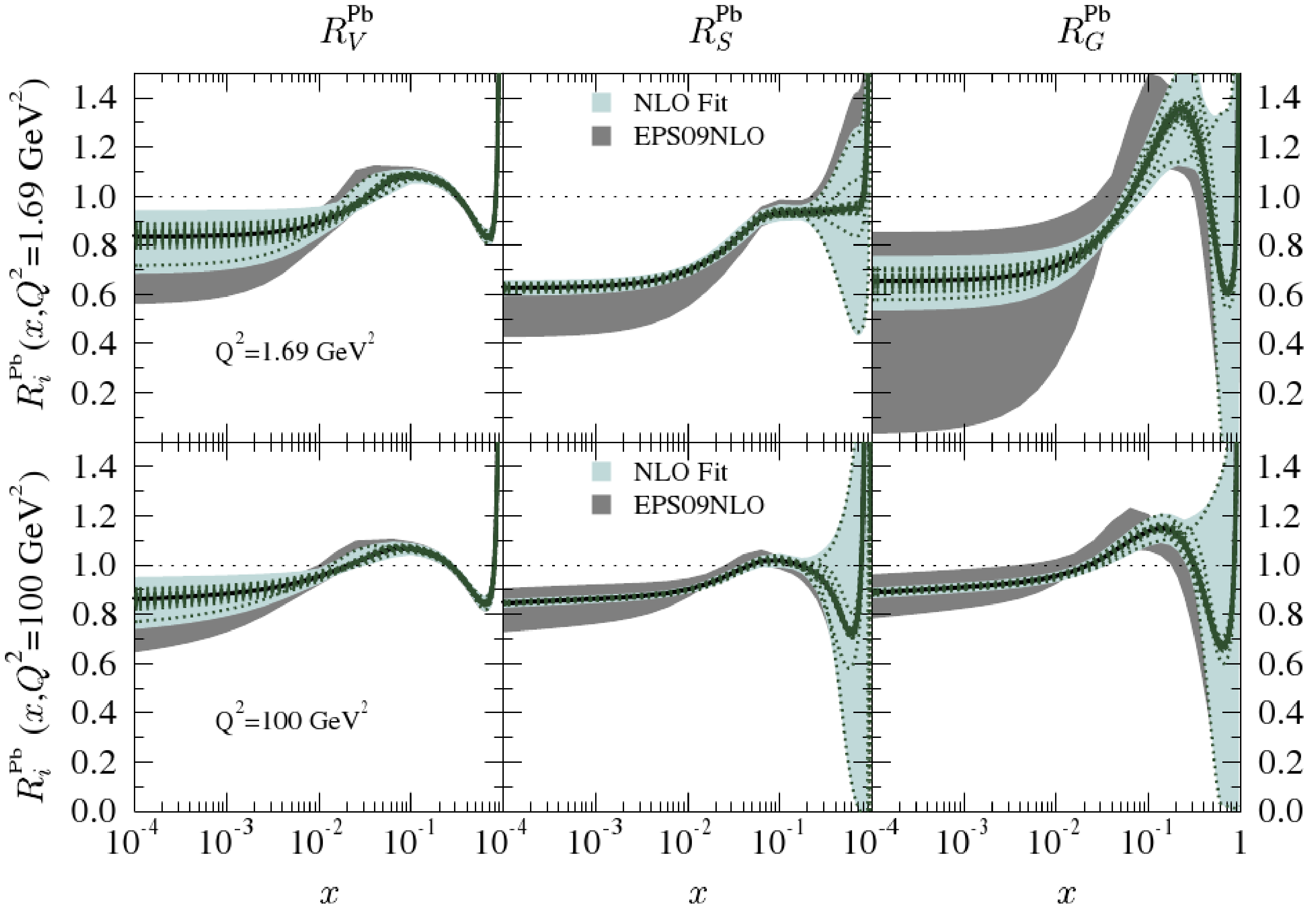
- After a fit to simulated pseudo data for:

$$R_{F_2}^{\rm Ca}(x,Q^2) \equiv F_2^{\rm Ca}/F_2^{\rm p} \quad \text{and} \quad R_{F_2}^{\rm Pb}(x,Q^2) \equiv F_2^{\rm Pb}/F_2^{\rm p}$$



Expectations: Electron-Ion Collider LHeC

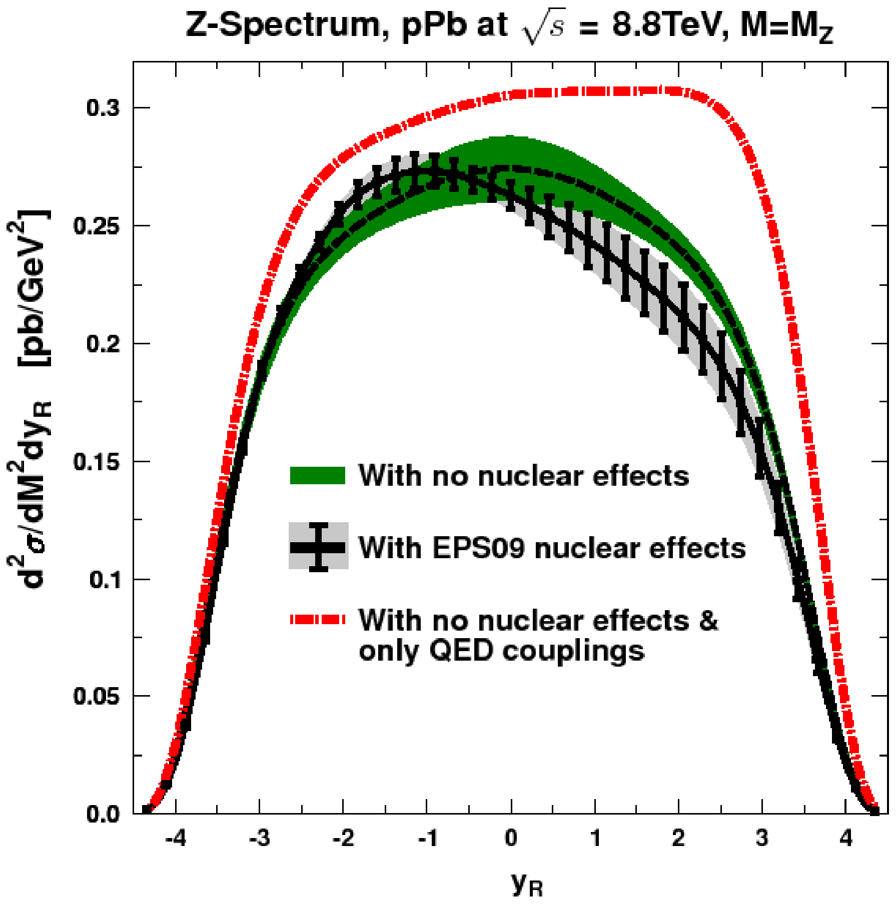
- This would greatly decrease the uncertainties for nuclear effects at small x:



- More sophisticated study is under way...

Heavy Boson Production at LHC

- Significant nuclear effects are predicted for p+Pb runs at LHC for heavy boson production.



In preparation...

- Combining the data in a suitable way, the uncertainties originating from the free proton PDFs can be suppressed... Promising probe for nPDFs.

Summary & Outlook

- NLO pQCD and the hard-process nuclear data for DIS, DY, and π^0 production agree well in the explored kinematical range

  $0.005 < x < 1$, 1.69 GeV^2 $< Q^2 <$ 150 Gev^2 .

- Further experiments (hopefully) will open the door to small-x
  1. p+Pb runs at LHC looks very promising...
  2. Electron-Ion collider: eRHIC or LheC would provide a very clean probe.

- What to do while waiting?
  - Some new data coming from RHIC, most importantly direct photons.
  - Make use of the neutrino data.
  - Explore the flavor decomposition of valence and sea quarks.
  - Combined “master” analysis of free & bound nucleon data
  - etc...