Global Analysis of Nuclear PDFs

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based on work in collaboration with

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Theory seminar, SMU Dallas

Outline

- Parton distribution functions (PDFs)
- From protons to nuclei
- Global analysis of nCTEQ nuclear PDFs
- The nuclear gluon distribution
- The gluon from hard processes at the LHC/RHIC
- Nuclear corrections in neutrino DIS

Parton distribution functions (PDFs)

Nuclear PDFs (NPDF)

- Information on hadronic structure
- Initial state for hard processes in collisions involving hadrons
  - Deep inelastic scattering (DIS): ℓA, νA
  - Drell-Yan (DY): $A + B \to \ell^+ + \ell^-$
  - Jets, Photons, Hadrons at large p_T; Heavy Quarks; ...
    in pA, AA, (γA, eA) collisions
- Provide nuclear corrections for global analyses of **proton PDFs** in a flexible way

Theoretical Basis: Factorization

- Factorization theorems
  - provide (field theoretical) definitions of universal PDFs
  - make the formalism predictive
  - make a statement about the error
- PDFs and predicitions for observables+uncertainities **refer to this standard pQCD framework**
- There might be breaking of QCD factorization, deviations from DGLAP evolution — in particular in a nuclear environment

  Still need solid understanding of standard framework to establish deviations!

In the nuclear case, consider factorization as a working assumption to be tested phenomenologically

Predictive Power

Universality: <u>same</u> PDFs/FFs enter different processes:

- DIS: $$F_2^A(x,Q^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,Q^2)$$
- DY: $$\sigma_{A+B\to\ell^+ + \ell^- + X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to\ell^+ + \ell^- + X}$$
- A+B -> H + X: $$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$
- Predictions for unexplored kinematic regions and for your favorite new physics process

From protons to nuclei

From protons to nuclei

Starting point: (CTEQ) global analysis framework for free nucleons

Make sure it can be applied to the case of PDFs for nuclear targets (A, Z)

- Variable: $0 < x_N < A$
- Evolution equations
- Sum rules
- Observables

Apart from the validity of factorization which is (possibly up to precision effects) a working assumption and to be verified phenomenologically

DIS ON NUCLEAR TARGETS

Consider deep inelastic lepton–nucleon collisions: $l(k) + A(p_A) \to l'(k') + X$

Introduce the usual DIS variables: $q \equiv k - k'$, $\quad Q^2 \equiv -q^2$, $\quad x_A \equiv \frac{Q^2}{2 p_A \cdot q}$

Hadronic tensor: $W^A_{\mu\nu} \propto \langle A(p_A)|\, J_\mu J^\dagger_\nu \,|A(p_A)\rangle = \sum_i a^{(i)}_{\mu\nu}\, \tilde{F}^A_i(x_A, Q^2)$,
where $a^{(i)}_{\mu\nu}$ are Lorentz-tensors composed out of the 4-vectors q and p_A and the metric $g_{\mu\nu}$

Express structure functions in the QCD improved parton model in terms of NPDFs

$$\tilde{\mathcal{F}}^A_k(x_A, Q^2) = \int_{x_A}^1 \frac{\mathrm{d}y_A}{y_A}\, \tilde{f}^A_i(y_A, Q^2) C_{k,i}(x_A/y_A) + \tilde{\mathcal{F}}^{A,\tau\geq 4}_k(x_A, Q^2)$$

NPDFs: Fourier transforms of matrix elements of twist-two operators composed out of the quark and gluon fields:

$$\tilde{f}^A_i(x_A, Q^2) \propto \langle A(p_A)|\, O_i \,|A(p_A)\rangle$$

Definitions of $\tilde{F}^A_i(x_A, Q^2)$, $\tilde{f}^A_i(x_A, Q^2)$, and the varibale $0 < x_A < 1$ carry over one-to-one from the well-known free nucleon case

Evolution equations and sum rules

DGLAP as usual:

$$\frac{d\tilde{f}_i^A(x_A, Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_{x_A}^1 \frac{dy_A}{y_A} P_{ij}(y_A)\, \tilde{f}_j^A(x_A/y_A, Q^2) \,,$$
$$= \frac{\alpha_s(Q^2)}{2\pi} \int_{x_A}^1 \frac{dy_A}{y_A} P_{ij}(x_A/y_A)\, \tilde{f}_j^A(y_A, Q^2) \,,$$

Sum rules:

$$\int_0^1 dx_A\, \tilde{u}_v^A(x_A, Q^2) = 2Z + N \,,$$
$$\int_0^1 dx_A\, \tilde{d}_v^A(x_A, Q^2) = Z + 2N \,,$$

and the momentum sum rule

$$\int_0^1 dx_A\, x_A \left[\tilde{\Sigma}^A(x_A, Q^2) + \tilde{g}^A(x_A, Q^2)\right] = 1 \,,$$

where $N = A - Z$ and $\tilde{\Sigma}^A(x_A) = \sum_i(\tilde{q}_i^A(x_A) + \tilde{\bar{q}}_i^A(x_A))$ is the quark singlet combination

RESCALED DEFINITIONS

Problem: average momentum fraction carried by a parton $\propto A^{-1}$
since there are 'A-times more partons' which have to share the momentum

- Different nuclei (A, Z) not directly comparable
- Functional form for x-shape would change drastically with A
- Need to rescale!

PDFs are number densities: $\tilde{f}_i^A(x_A)\,\mathrm{d}x_A$ is the number of partons carrying a momentum fraction in the interval $[x_A, x_A + \mathrm{d}x_A]$

Define rescaled NPDFs $f_i^A(x_N)$ with $0 < x_N := Ax_A < A$:

$$\boxed{f_i^A(x_N)\,\mathrm{d}x_N := \tilde{f}_i^A(x_A)\,\mathrm{d}x_A}$$

The variable x_N can be interpreted as parton momentum fraction w.r.t. the **average** nucleon momentum $\bar{p}_N := p_A/A$

Evolution:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N/A}^{1}\frac{\mathrm{d}y_A}{y_A}\,P(y_A)\,f_i^A(x_N/y_A,Q^2)\,,$$
$$= \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{A}\frac{\mathrm{d}y_N}{y_N}\,P(x_N/y_N)\,f_i^A(y_N,Q^2)\,.$$

Assume that $f_i^A(x_N) = 0$ for $x_N > 1$, then **original, symmetrical** form recovered:

$$\frac{\mathrm{d}f_i^A(x_N,Q^2)}{\mathrm{d}\ln Q^2} = \begin{cases} \frac{\alpha_s(Q^2)}{2\pi}\int_{x_N}^{1}\frac{\mathrm{d}y_N}{y_N}\,P(y_N)\,f_i^A(x_N/y_N,Q^2) & : 0 < x_N \leq 1 \\ 0 & : 1 < x_N < A, \end{cases}$$

Sum rules for the rescaled PDFs:

$$\int_0^A \mathrm{d}x_N\, u_v^A(x_N) = 2Z + N\,,$$
$$\int_0^A \mathrm{d}x_N\, d_v^A(x_N) = Z + 2N\,,$$

and

$$\int_0^A \mathrm{d}x_N\, x_N\left[\Sigma^A(x_N) + g^A(x_N)\right] = A\,,$$

RESCALED STRUCTURE FUNCTIONS

The rescaled structure functions can be defined as

$$x_N \mathcal{F}_i^A(x_N) := x_A \tilde{\mathcal{F}}_i^A(x_A) \ ,$$

with $\mathcal{F}_{1,2,3}(x) = \{F_1(x), F_2(x)/x, F_3(x)\}$.

More explicitly:

$$\begin{aligned} F_2^A(x_N) &:= \tilde{F}_2^A(x_A) \ , \\ x_N F_1^A(x_N) &:= x_A \tilde{F}_1^A(x_A) \ , \\ x_N F_3^A(x_N) &:= x_A \tilde{F}_3^A(x_A) \ . \end{aligned}$$

This leads to consistent results in the parton model using the rescaled PDFs.

PDFs of bound nucleons

Further decompose the NPDFs $f_i^A(x_N)$ in terms of effective parton densities for **bound** protons, $f_i^{p/A}(x_N)$, and neutrons, $f_i^{n/A}(x_N)$, inside a nucleus A:

$$f_i^A(x_N, Q^2) = Z\, f_i^{p/A}(x_N, Q^2) + N\, f_i^{n/A}(x_N, Q^2)$$

- The bound proton PDFs have the **same** evolution equations and sum rules as the free proton PDFs **provided** we neglect any contributions from the region $x_N > 1$
- Neglecting the region $x_N > 1$, is consistent with the DGLAP evolution
- The region $x_N > 1$ is expected to have a minor influence on the sum rules of less than one or two percent (see also [PRC73(2006)045206])
- Isospin symmetry: $u^{n/A}(x_N) = d^{p/A}(x_N)$, $d^{n/A}(x_N) = u^{p/A}(x_N)$

An observable $\mathcal{O}^A$ is then given by:

$$\mathcal{O}^A = Z\, \mathcal{O}^{p/A} + N\, \mathcal{O}^{n/A}$$

In conclusion: the free proton framework can be used to analyse nuclear data

Global analysis of nCTEQ nuclear PDF

Global Analysis: General Procedure

1.) Parameterize x-dependence of PDFs at input scale Q_0:

$$f(x,Q_0)=A_0 x^{A_1}(1-x)^{A_2} P(x;A_3,\ldots);\; f=u_v,d_v,g,\bar{u},\bar{d},s,\bar{s}$$

2.) Evolve from Q_0 --> Q by solving the DGLAP evolution equations

--> f(x,Q)

3.) Define suitable Chi^2 function and minimize w.r.t. fit parameters

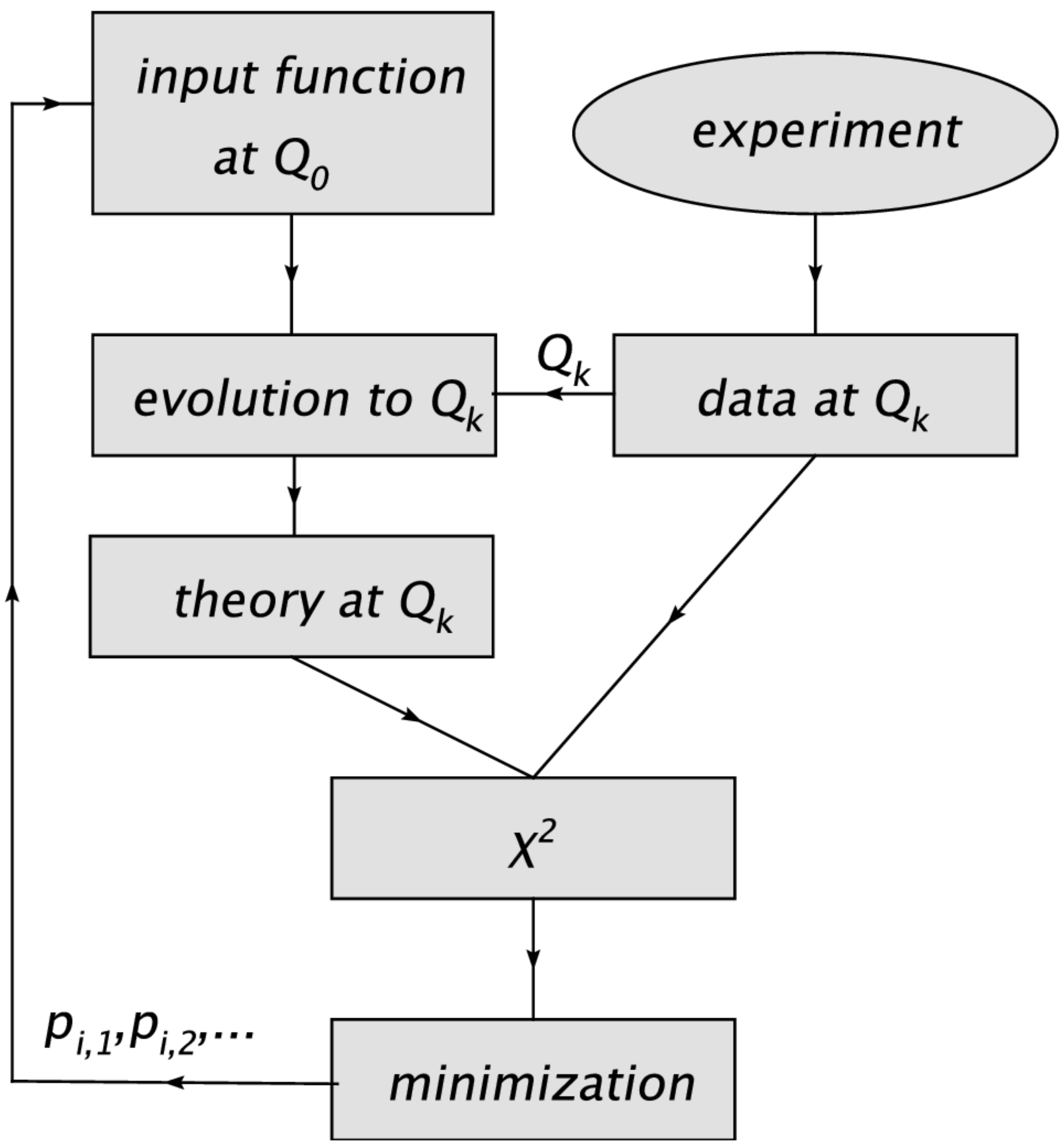
$$\chi^2_{global}[A_i]=\sum_n w_n \chi^2_n;\; \chi^2_n=\sum_I \left(\frac{D_{nI}-T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets

Flowchart



input function at Q_0
experiment
evolution to Q_k
Q_k
data at Q_k
theory at Q_k
χ^2
$p_{i,1}, p_{i,2}, \ldots$
minimization

NPDFs from ℓA DIS and DY data

Global analyses of NPDF by four groups:

- **HKN'07** [PRC76(2007)065207]
  LO, NLO, error PDFs, $\chi^2/dof = 1.2$
- **EPS'09** [JHEP0904(2009)065]
  LO, NLO, error PDFs, $\chi^2/dof = 0.8$
  Use also inclusive π^0 data at midrap. from $d + Au$ and $p + p$ coll. at RHIC $\rightarrow$ gluon
- **DS'04** [PRD69(2004)074028]
  first NLO analysis, 'semi-global', no error PDFs, $\chi^2/dof = 0.76$
- **nCTEQ** [PRD80(2009)094004]
  NLO, same data as HKN'07 (up to cuts), no error PDFs (so far), $\chi^2/dof = 0.95$, official release soon

Table from Hirai et al.,arXiv:0909.2329

	R	Nucleus	Experiment	EPS09	HKN07	DS04
DIS		D/p	NMC		O	
DIS	A/D	4He	SLAC E139	O	O	O
DIS	A/D	4He	NMC95	O (5)	O	O
DIS	A/D	Li	NMC95	O	O	
DIS	A/D	Be	SLAC E139	O	O	O
DIS	A/D	C	EMC–88, 90		O	
DIS	A/D	C	NMC 95	O	O	O
DIS	A/D	C	SLAC E139	O	O	O
DIS	A/D	C	FNAL–E665		O	
DIS	A/D	N	BCDMS 85		O	
DIS	A/D	N	HERMES 03		O	
DIS	A/D	Al	SLAC E49		O	
DIS	A/D	Al	SLAC E139	O	O	O
DIS	A/D	Ca	EMC 90		O	
DIS	A/D	Ca	NMC 95	O	O	O
DIS	A/D	Ca	SLAC E139	O	O	O
DIS	A/D	Ca	FNAL–E665		O	
DIS	A/D	Fe	SLAC E87		O	
DIS	A/D	Fe	SLAC E139	O (15)	O	O
DIS	A/D	Fe	SLAC E140		O	
DIS	A/D	Fe	BCDMS 87		O	
DIS	A/D	Cu	EMC 93	O	O	
DIS	A/D	Kr	HERMES 03		O	
DIS	A/D	Ag	SLAC E139	O	O	O
DIS	A/D	Sn	EMC 88		O	
DIS	A/D	Au	SLAC E139	O	O	O
DIS	A/D	Au	SLAC E140		O	
DIS	A/D	Pb	FNAL–E665		O	
DIS	A/C	Be	NMC 96	O	O	O
DIS	A/C	Al	NMC 96	O	O	O
DIS	A/C	Ca	NMC 95		O	
DIS	A/C	Ca	NMC 96	O	O	O
DIS	A/C	Fe	NMC 96	O	O	O
DIS	A/C	Sn	NMC 96	O (10)	O	O
DIS	A/C	Pb	NMC 96	O	O	O
DIS	A/Li	C	NMC 95	O	O	
DIS	A/Li	Ca	NMC 95	O	O	
DY	A/D	C	FNAL–E772	O	O	O
DY	A/D	Ca	FNAL–E772	O (15)	O	O
DY	A/D	Fe	FNAL–E772	O (15)	O	O
DY	A/D	W	FNAL–E772	O (10)	O	O
DY	A/Be	Fe	FNAL E866	O	O	
DY	A/Be	W	FNAL E866	O	O	
π pro	dA/pp	Au	RHIC–PHENIX	O (20)		

What are the differences?

Main differences:

- **Choice of data sets** (see previous table)
- **Parametrization of input distributions**
- **Assumptions on PDFs**
  - Data less constraining than in proton case $\to$ need to make more assumptions (otherwise flat directions in χ^2 function and fits don't converge)
  - Assumptions replace uncertainty! $\to$ error bands (of a single fit) underestimate true uncertainties

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Consequences?

- **Use different sets of NPDFs to scan over assumptions**
- Include more data sets $\to$ allows to relax assumptions
- New ideas to handle flat directions?
- Neural Network NPDFs?

Further differences:

- **Heavy flavor schemes**
  - **DS'04:** 3-Fixed Flavor Number Scheme (3-FFNS) $\rightarrow$ no charm PDF
  - **HKN'07**, **EPS'09**, **nCTEQ**: Variable Flavor Number Schemes (VFNS)

  $\rightarrow$ Beware of comparing 'apples with oranges'!

- **Parameters and other**
  - Input scale Q_0, $\alpha_s(M_Z)$, m_c, m_b
  - Evolution in n-space (DS) and x-space (HKN,EPS,nCTEQ)
  - Target Mass Corrections (TMC)
    see, e.g., [IS et al.,JPG35(2008)053101; Qiu, Accardi, JHEP0807(2008)090]

NUCLEAR PDFS

- Review of existing global analyses of nuclear PDF

1. Multiplicative nuclear correction factor

$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

free parton density

Hirai, Kumano, Nagai [PRC76(2007)065207] arXiv: 0709.0338

Eskola, Paukkunen, Salgado [JHEP0904(2009)065] arXiv: 0902.4154

→ **de Florian, Sassot, Stratmann, Zurita** arXiv: 1112.6324

2. Convolution relation

$$f_i^A(x_N, Q_0^2) = \int_{x_N}^{A} \frac{\mathrm{d}y}{y} W_i(y, A, Z) f_i(x_N/y, Q_0^2)$$

nucleon density in nucleus with y/A mom. fraction

de Florian, Sassot [PRD69(2004)074028] hep-ph/0311227

3. Native nuclear PDF

$$f_i^A(x_N, Q_0^2) = f_i(x_N, A, Q_0^2)$$

bound parton density

$$f_i(x_N, Q_0^2) = f_i(x_N, A = 1, Q_0^2)$$

free parton density

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

Karlsruhe Institute of Technology

DS'04

Connected to GRV'98 proton PDFs $f_i^p(x,Q)$:

- $Q_0^2 = 0.4\ \mathrm{GeV}^2$ (NLO), $Q_0^2 = 0.26\ \mathrm{GeV}^2$ (LO), m_c, m_b, α_s as in GRV'98
- 3-Fixed flavor scheme (no charm PDF)
- strange PDF dynamically generated, i.e., $s^p(x, Q_0^2) = 0$

Parametrization of input distributions:

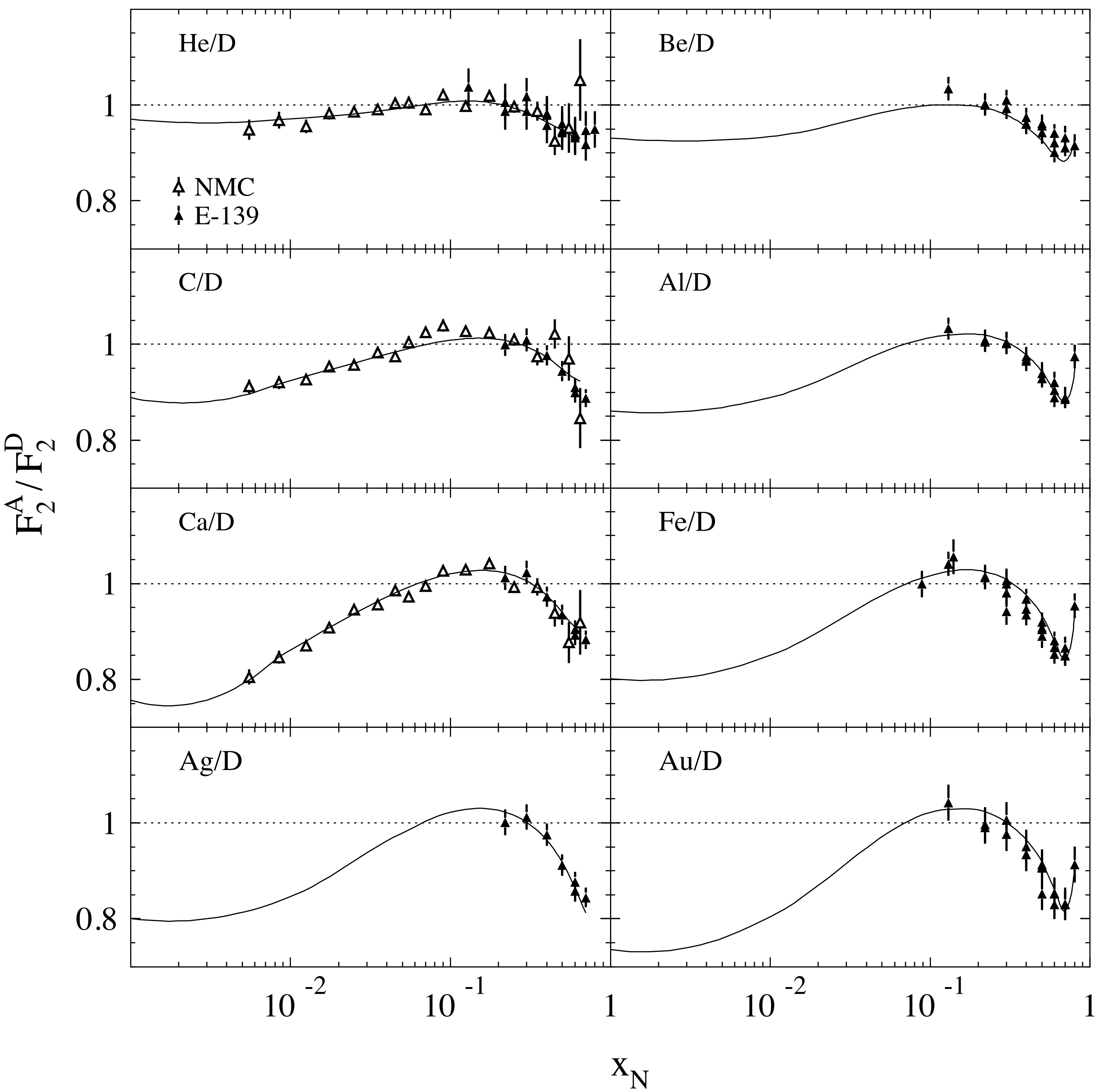
- PDFs for bound protons inside nucleus A: $f_i^{p/A}(x,Q)$
- Convolution relation: $f_i^{p/A}(x_N, Q_0^2) = \int_{x_N}^{A} \frac{dy}{y} W_i(y,A,Z) f_i^p(x_N/y, Q_0^2)$
- Weight functions W_v (valence), W_s (sea), W_g (gluon). For example:

$$\begin{aligned} W_v(y,A,Z) &= A[a_v\delta(1-\epsilon_v - y) + (1-a_v)\delta(1-\epsilon_{v'} - y)] \\ &\quad + n_v(y/A)^{\alpha_v}(1-y/A)^{\beta_v} + n_s(y/A)^{\alpha_s}(1-y/A)^{\beta_s} \end{aligned}$$

- Note:
  - Convolution simple product in Mellin moment space: very elegant
  - Ansatz valid for $0 < x_N < A$!
  - The x-space approaches (HKN,EPS, nCTEQ) are restricted to $0 < x_N < 1$
  - However, the DS'04 PDF grids apparently are restricted to $0 < x_N < 1$ (and the momentum sum rule integrates to unity in this range)

DS'04

Excellent fit to a restricted data set (420 points): $\chi^2/dof = 0.75$



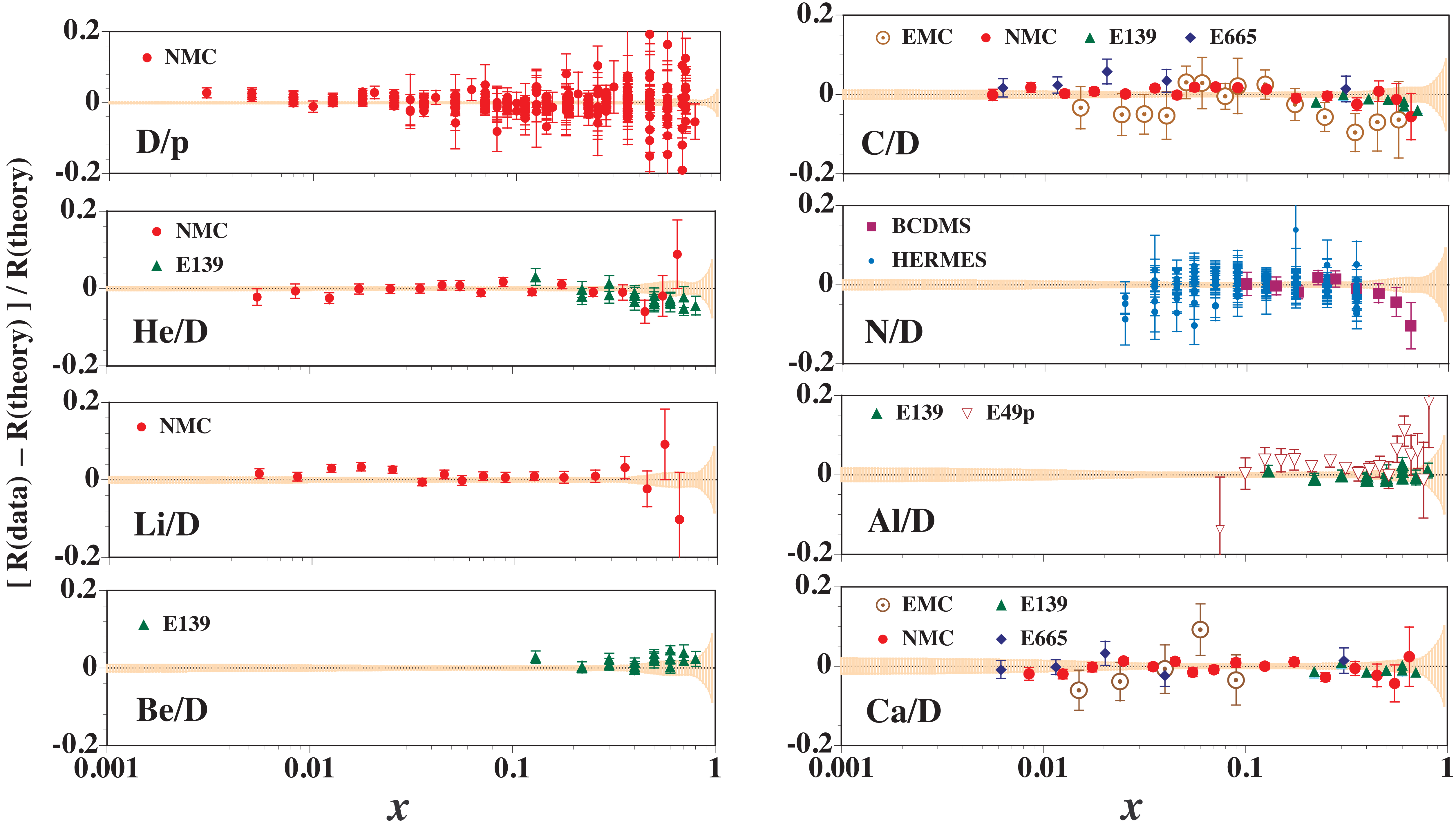
HKN'07

HIRAI,KUMANO,NAGAI,PRC76(2007)065207

- LO, NLO, error PDFs
- Related to MRST'98 proton PDF: $Q_0^2 = 1\ \mathrm{GeV}^2$
- Uses multiplicative ansatz: $\boxed{f_i^{p/A}(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i^p(x_N, Q_0^2)}$
- Weight factor: $R_i(x, A, Z) = 1 + (1 - \frac{1}{A^\alpha}) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$ $(i = u_v, d_v, \bar{q}, g)$
- neglects region $x_N > 1$
- includes all current DIS & DY data sets, in particular deuterium data
- uses Hessian method to produce error PDFs

HKN'07

- Reasonable fits: $\chi^2/dof = 1.2$



Monday, April 23, 12

- LO, NLO, error PDFs
- Related to CTEQ6.1M proton PDF: $Q_0 = 1.3\,\mathrm{GeV}$
- Uses multiplicative ansatz: $f_i^{p/A}(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i^p(x_N, Q_0^2)$
- Weight factor is a piecewise defined function:

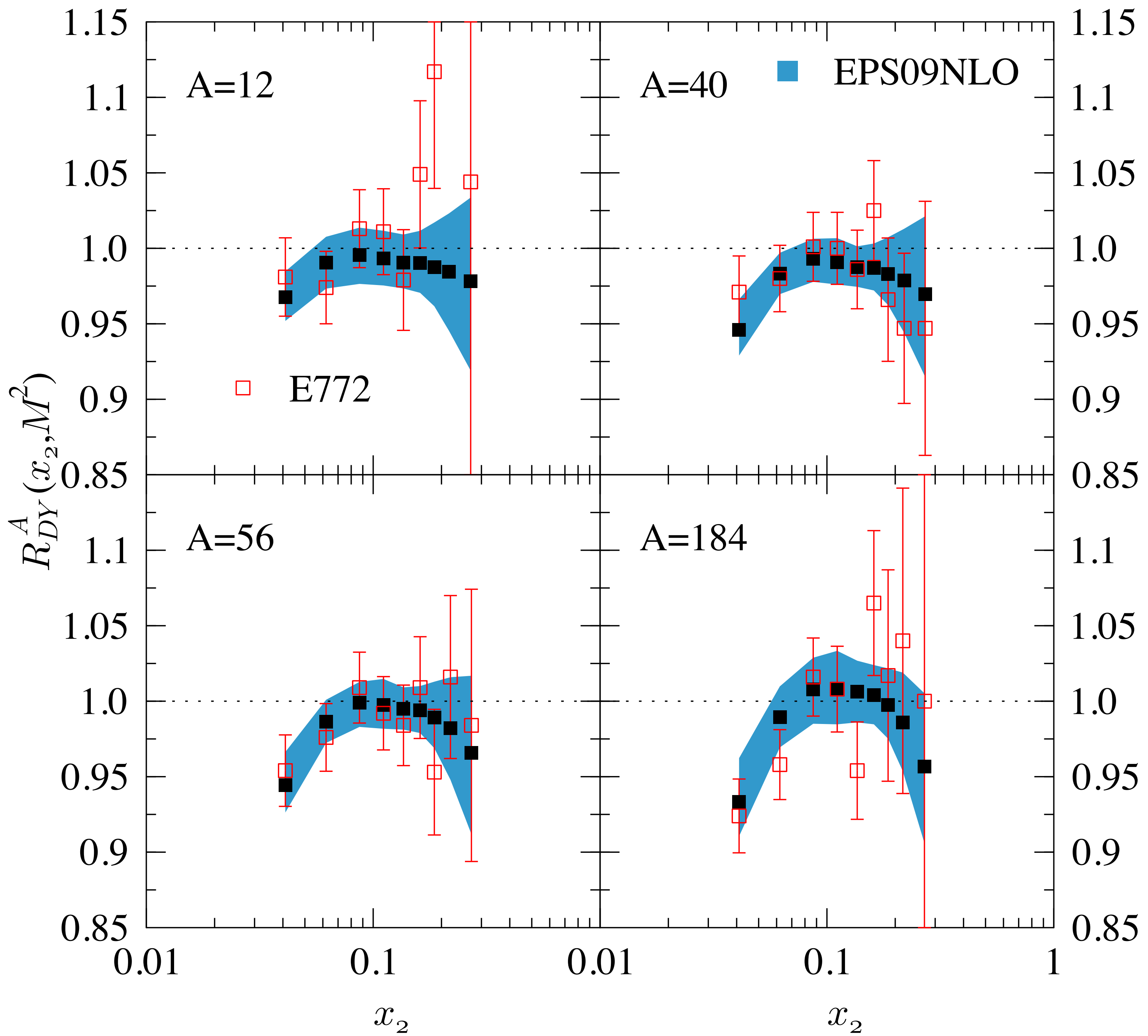
$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

  where the parameters $a_i, b_i, c_i, \beta, x_a, x_e$ are A-dependent

- neglects region $x_N > 1$
- includes π^0 RHIC data with a weight 20 to constrain gluon
- uses Hessian method to produce error PDFs

EPS'09

- Excellent fit: $\chi^2/dof = 0.8$
- Show here, as an example, comparison with DY data



Work in collaboration with:

- People from LPSC Grenoble: K. Kovarik, J. Y. Yu, T. Stavreva, IS
- CTEQ-members: F. Olness (SMU), J. Owens (FSU), J. Morfin (FNAL), C. Keppel (JLAB)

- The results shown in the following are from
  IS,Yu,Kovarik,Keppel,Morfin,Olness,Owens,PRD80(2009)094004

nCTEQ PDFs available at: http://projects.hepforge.org/ncteq

Nuclear CTEQ

Framework as in CTEQ6M proton fit:

- **Same functional form** for bound proton PDFs inside a nucleus A as for free proton PDFs (restrict x to $0 < x < 1$):

$$
\begin{aligned}
x\, f_k^{p/A}(x, Q_0) &= c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}, \quad k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}\,, \\
\bar{d}(x, Q_0)/\bar{u}(x, Q_0) &= c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}
\end{aligned}
$$

  (bound neutron PDFs $f_k^{n/A}$ by isospin symmetry)

- **A-dependent fit parameters:** (reduces to free proton paramters $c_{k,0}$ for $A = 1$)

$$
\boxed{c_k \to c_k(A) \equiv c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}}), \quad k = 1, \ldots, 5}
$$

- **PDFs for a nucleus** (A, Z)**:** $f_i^{(A,Z)}(x, Q) = \frac{Z}{A}\, f_i^{p/A}(x, Q) + \frac{A-Z}{A}\, f_i^{n/A}(x, Q)$

- **Input parameters:** $Q_0 = m_c = 1.3\ \mathrm{GeV}$, $m_b = 4.5\ \mathrm{GeV}$, $\alpha_s^{NLO,\overline{\mathrm{MS}}}(M_Z) = 0.118$

- **Heavy quark treatment:** ACOT scheme

- **Standard DIS-cuts:** $Q > 2\ \mathrm{GeV}$, $W > 3.5\ \mathrm{GeV}$

Experimental input

Use same data as HKN'07 (up to cuts)

- DIS F_2^A/F_2^D data sets: 862 points (before cuts)
- DIS $F_2^A/F_2^{A'}$ data sets: 297 points (before cuts)
- DY data sets $\sigma_{\rm DY}^{pA}/\sigma_{\rm DY}^{pA'}$: 92 points (before cuts)

Table from Hirai et al.,arXiv:0909.2329

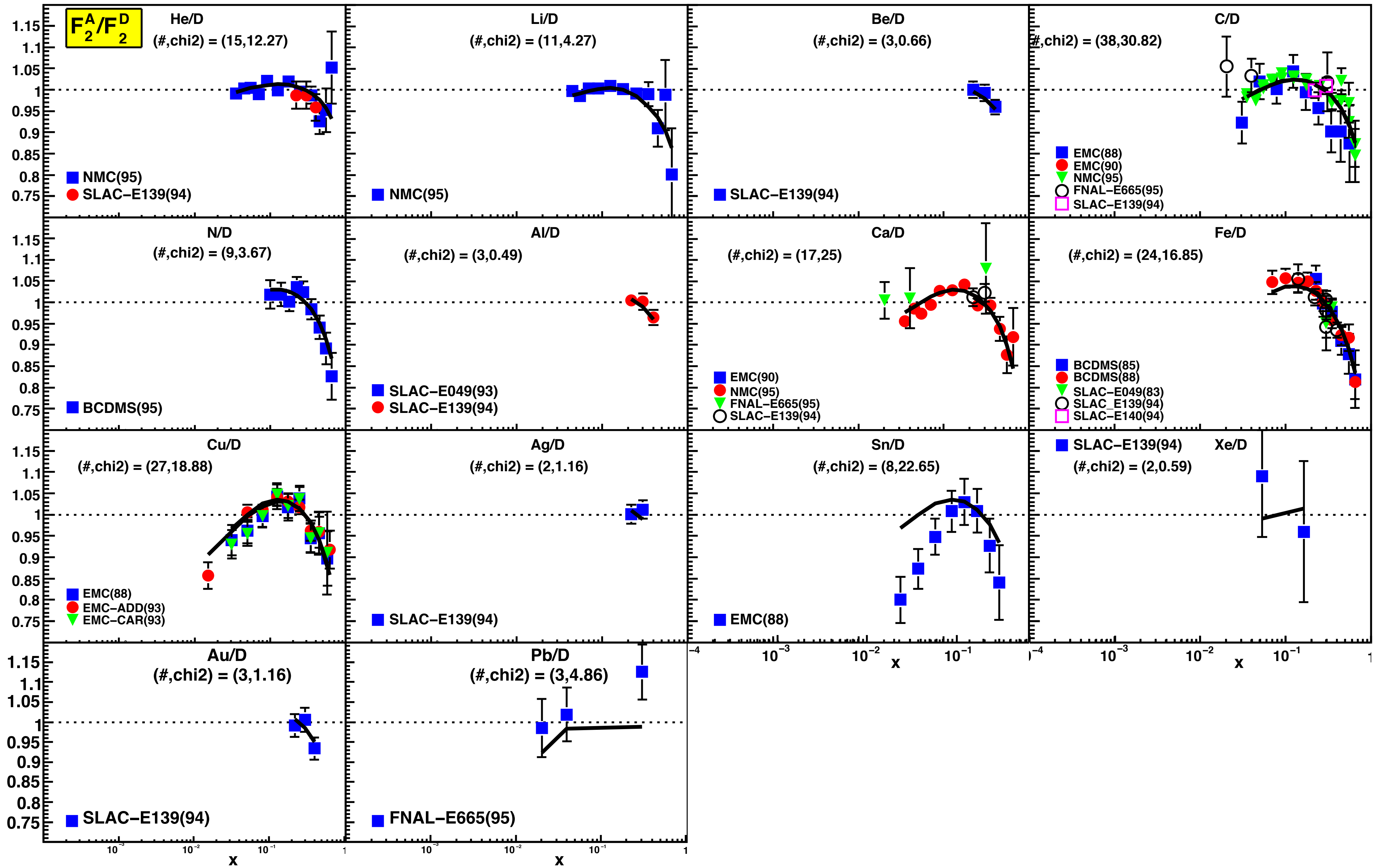
	R	Nucleus	Experiment	EPS09	HKN07	DS04
DIS		D/p	NMC		O	
	A/D	4He	SLAC E139	O	O	O
			NMC95	O (5)	O	O
		Li	NMC95	O	O	
		Be	SLAC E139	O	O	O
		C	EMC–88, 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL–E665		O	
		N	BCDMS 85		O	
			HERMES 03		O	
		Al	SLAC E49		O	
			SLAC E139	O	O	O
		Ca	EMC 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL–E665		O	
		Fe	SLAC E87		O	
			SLAC E139	O (15)	O	O
			SLAC E140		O	
			BCDMS 87		O	
		Cu	EMC 93	O	O	
		Kr	HERMES 03		O	
		Ag	SLAC E139	O	O	O
		Sn	EMC 88		O	
		Au	SLAC E139	O	O	O
			SLAC E140		O	
		Pb	FNAL–E665		O	
	A/C	Be	NMC 96	O	O	O
		Al	NMC 96	O	O	O
		Ca	NMC 95		O	
			NMC 96	O	O	O
		Fe	NMC 96	O	O	O
		Sn	NMC 96	O (10)	O	O
		Pb	NMC 96	O	O	O
	A/Li	C	NMC 95	O	O	
		Ca	NMC 95	O	O	
DY	A/D	C	FNAL–E772	O	O	O
		Ca		O (15)	O	O
		Fe		O (15)	O	O
		W		O (10)	O	O
	A/Be	Fe	FNAL E866	O	O	
		W		O	O	
π pro	dA/pp	Au	RHIC–PHENIX	O (20)		

RESULTS: DECUT3 FIT

- 708 (1233) data points after (before) cuts
- 32 free paramters; 675 d.o.f.
- Overall $\chi^2/\mathrm{d.o.f.} = 0.95$
- individually:
  - for F_2^A/F_2^D: $\chi^2/\mathrm{pt} = 0.92$
  - for $F_2^A/F_2^{A'}$: $\chi^2/\mathrm{pt} = 0.69$
  - for DY: $\chi^2/\mathrm{pt} = 1.08$

RESULTS: DECUT3 FIT

DIS DATA VS *x*



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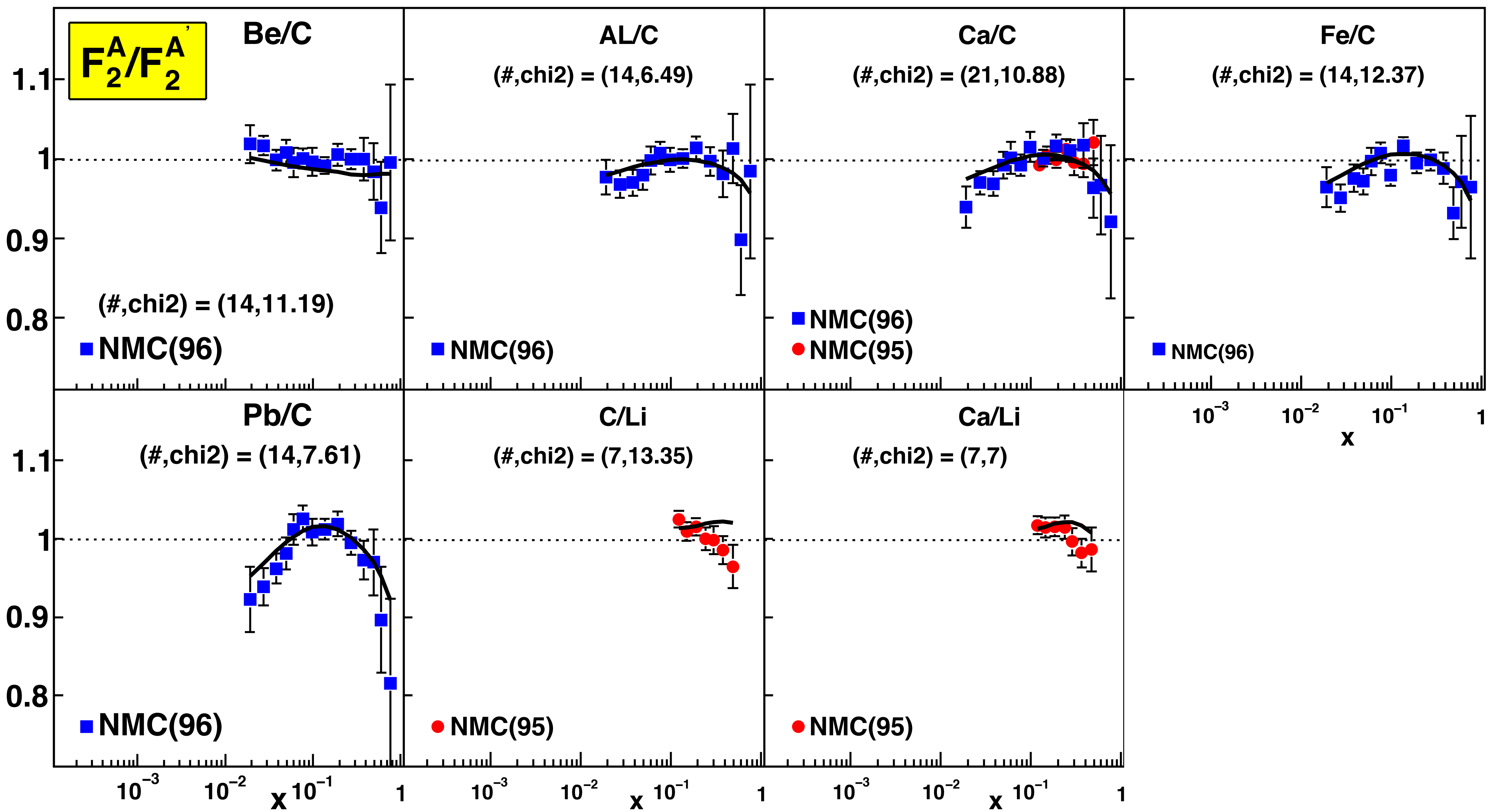
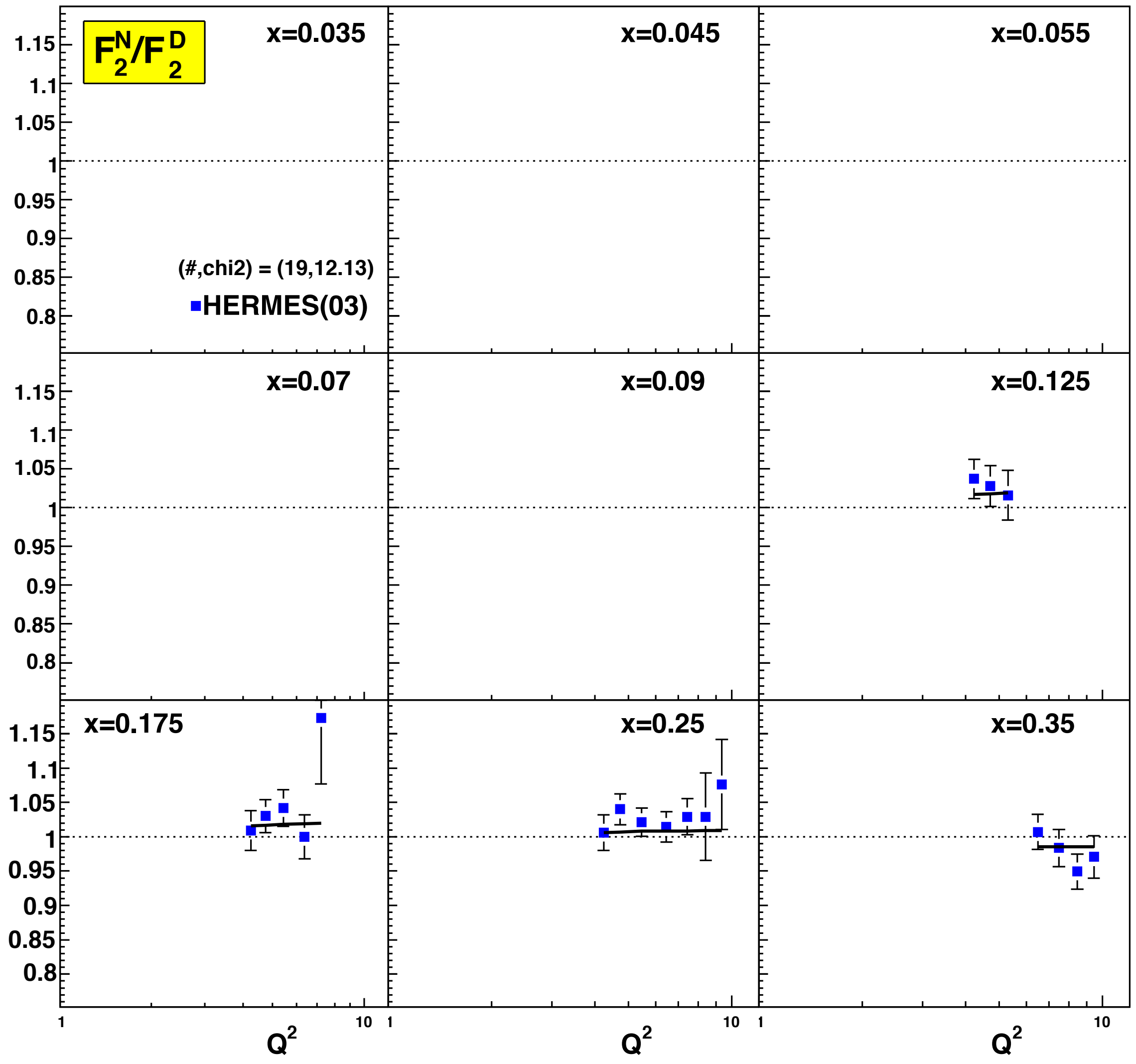
RESULTS: DECUT3 FIT

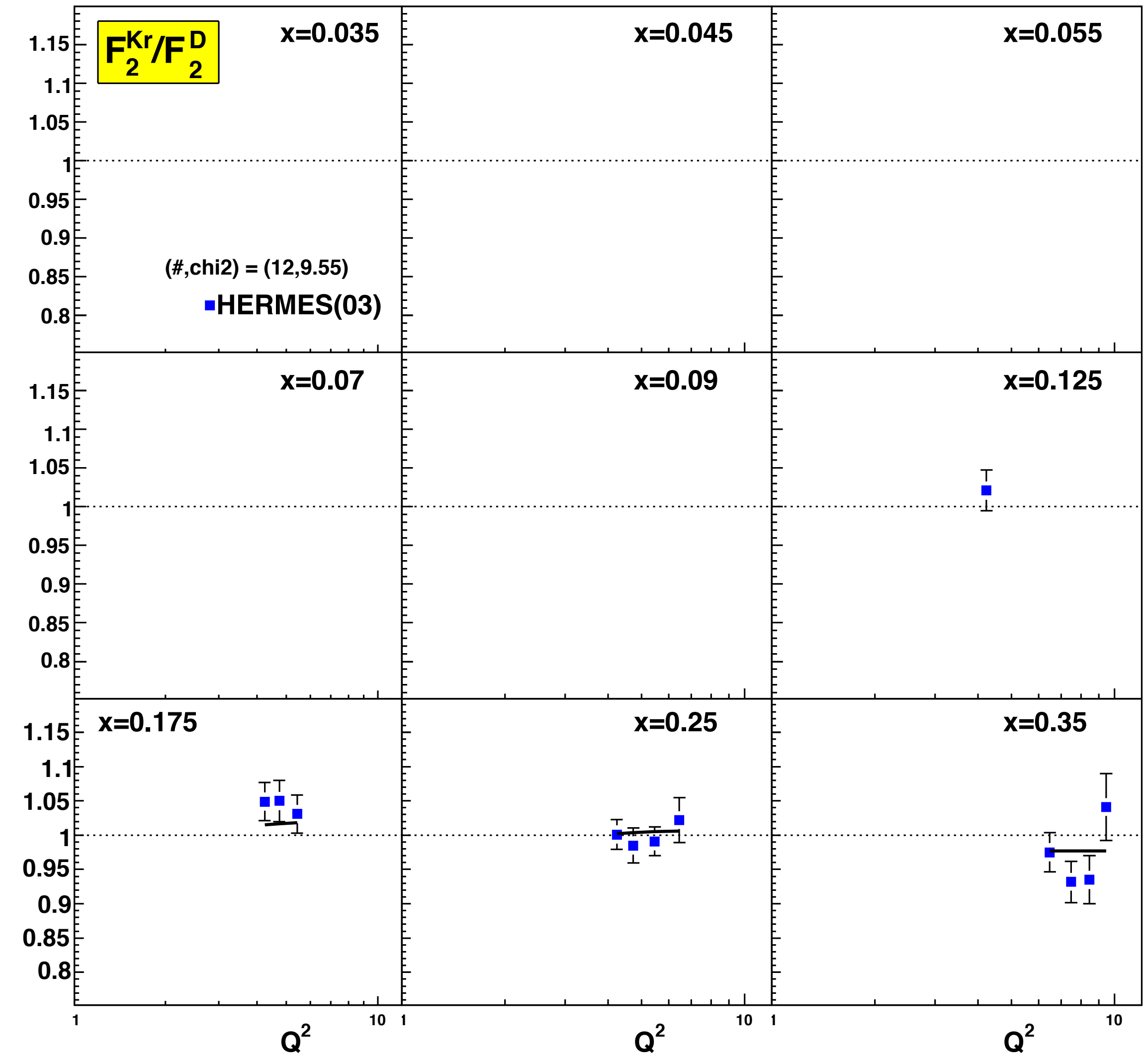
DIS DATA VS x



RESULTS: DECUT3 FIT

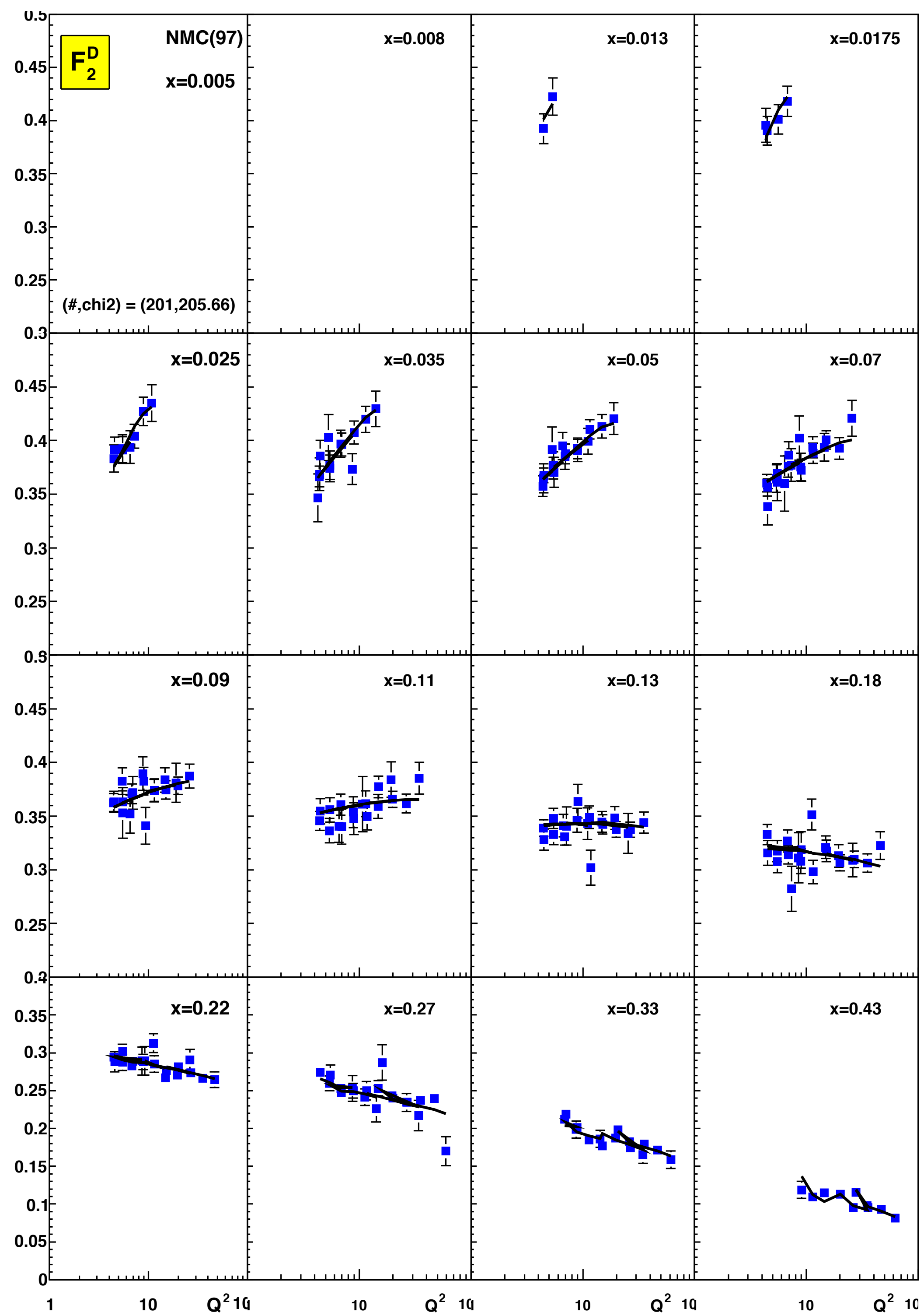
HERMES DATA VS Q^2

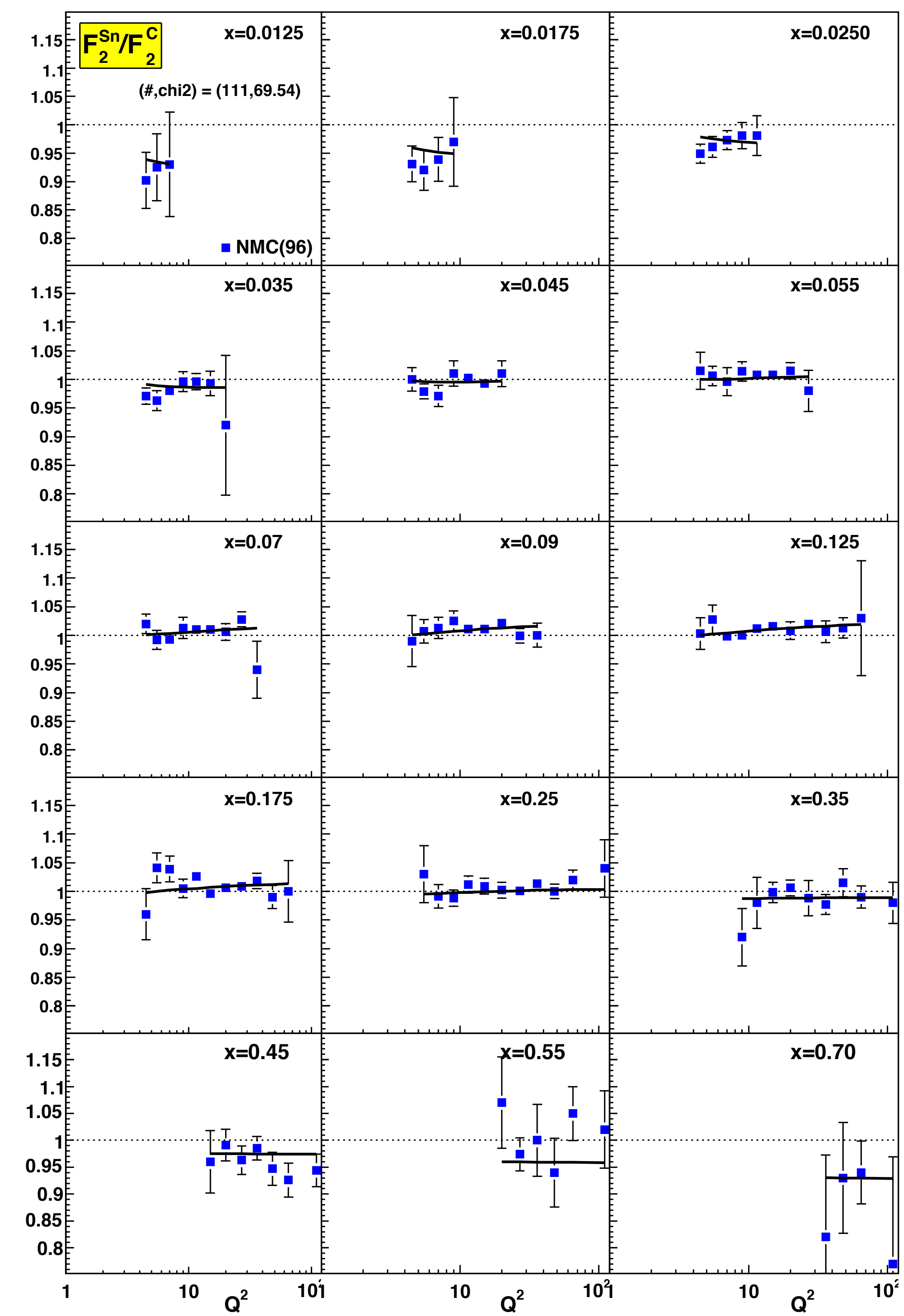




RESULTS: DECUT3 FIT

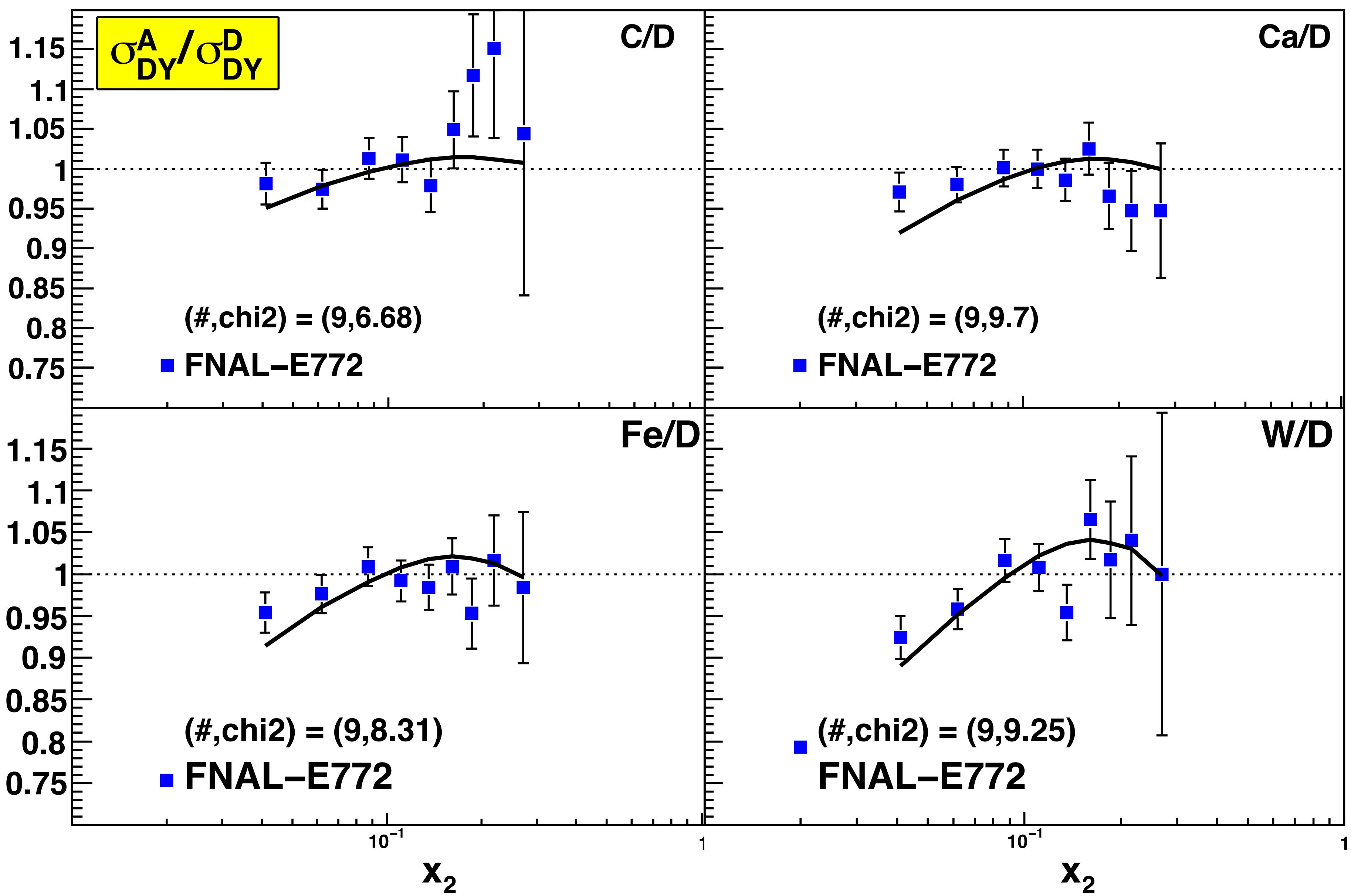
NMC DATA FOR D AND Sn/C VS Q^2





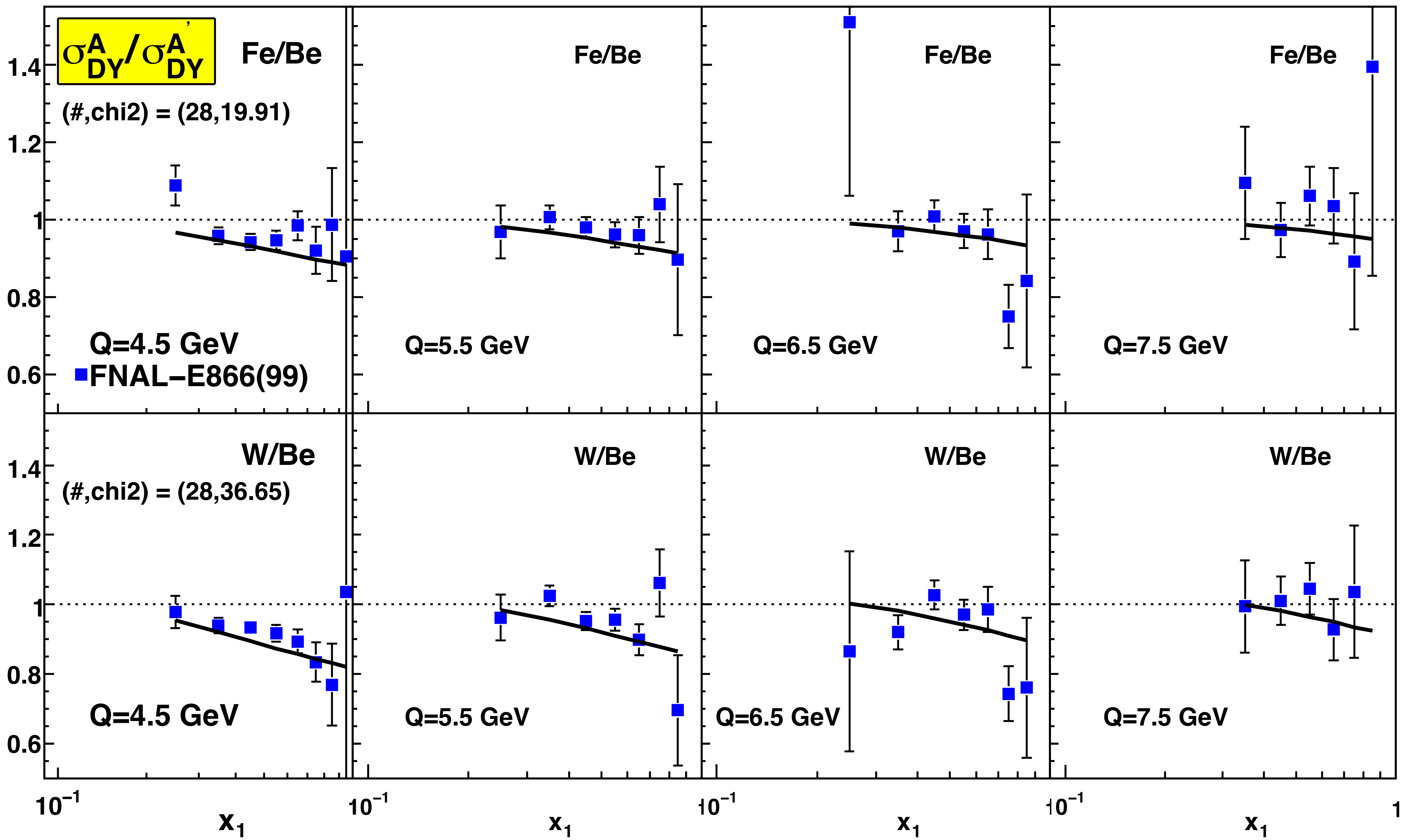
RESULTS: DECUT3 FIT

DRELL–YAN DATA



RESULTS: DECUT3 FIT

DRELL–YAN DATA



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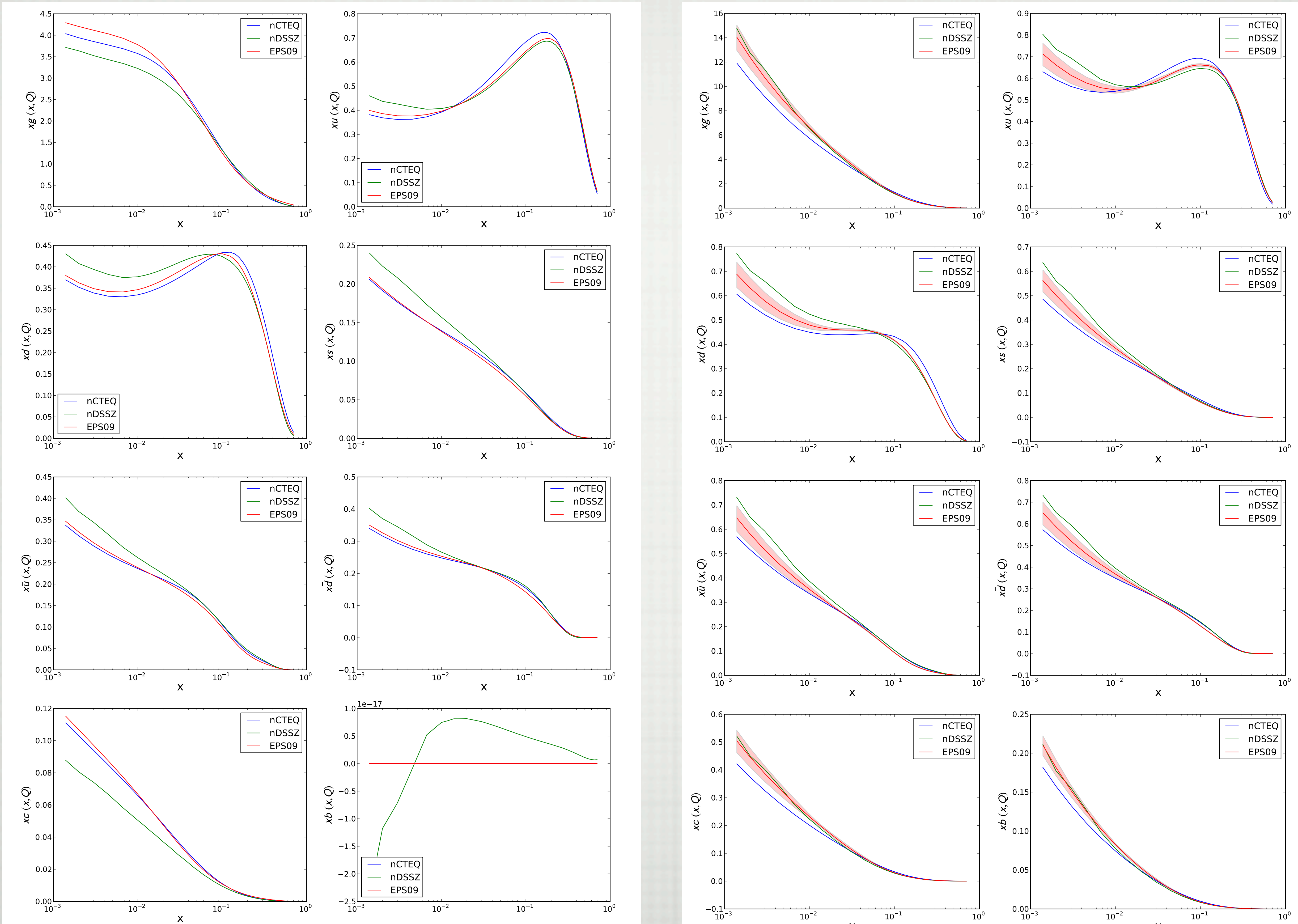
Talk by K. Kovarik at DIS12



Conclusion I

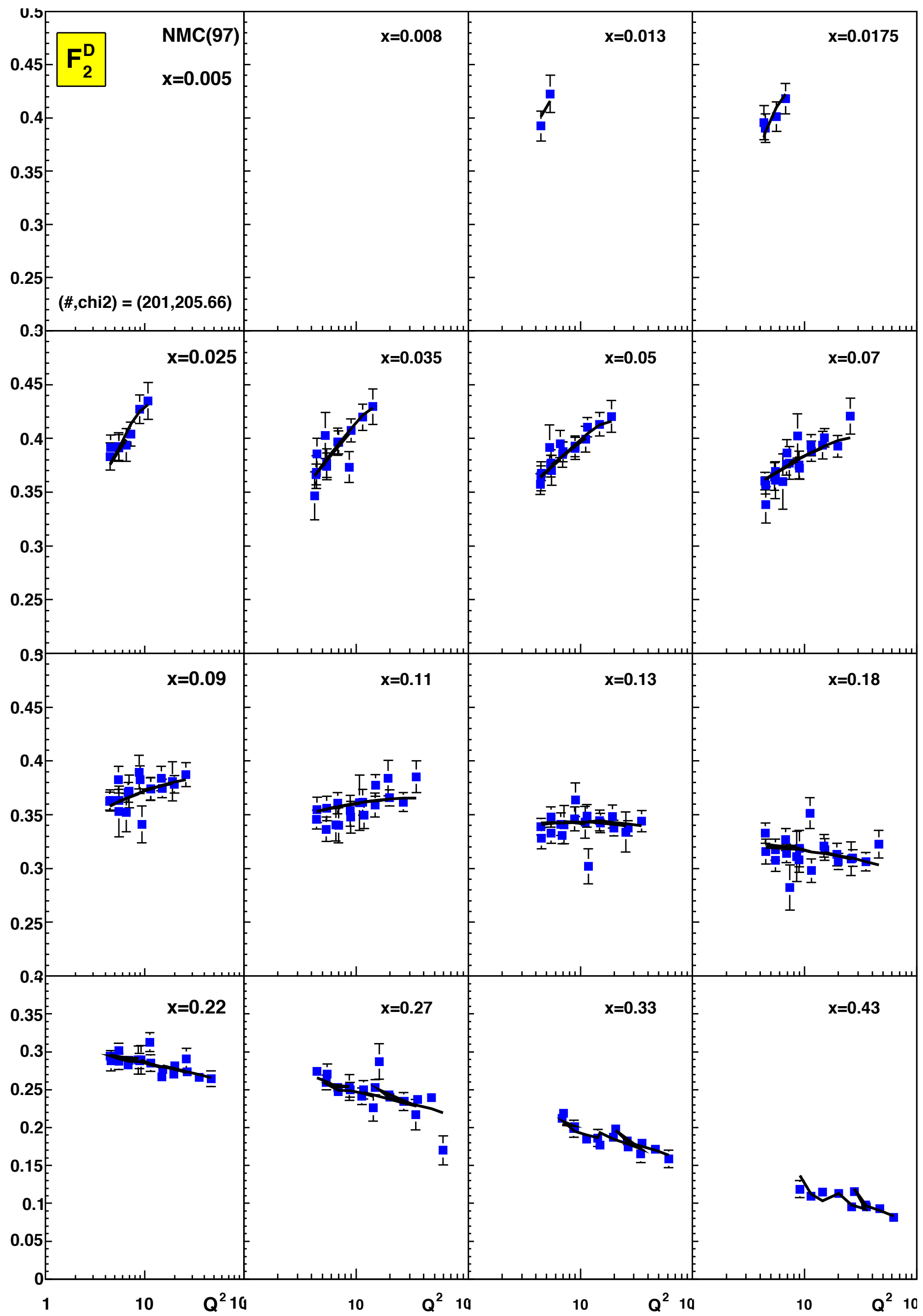
Excellent agreement between NLO pQCD and the lA DIS and DY data in the kinematical range $0.02 < x < 1,\ m_c{}^2 < Q^2 < 150\, GeV^2$ is found.

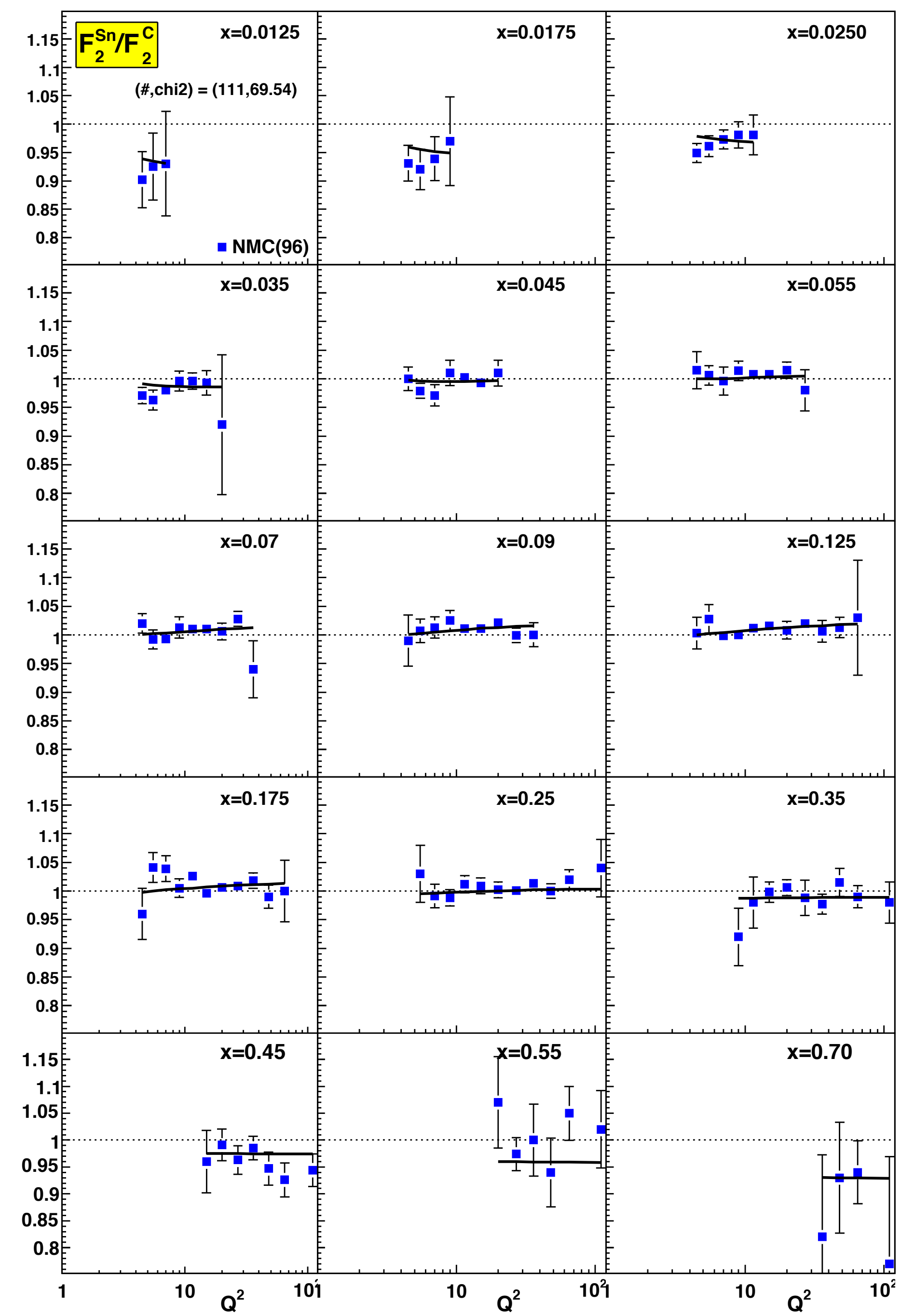
Factorization theorem in hard nuclear processes seems to work well.

nCTEQ PDFs available upon request

The nuclear gluon distribution

$g^A(x, Q^2)$ weakly constrained by Q^2-dependence of NMC data





- $x \sim 0.01 \ldots 0.4$, $Q^2 \sim 10 \ldots 100\ \mathrm{GeV}^2$

gluon nCTEQ decut3gx fits

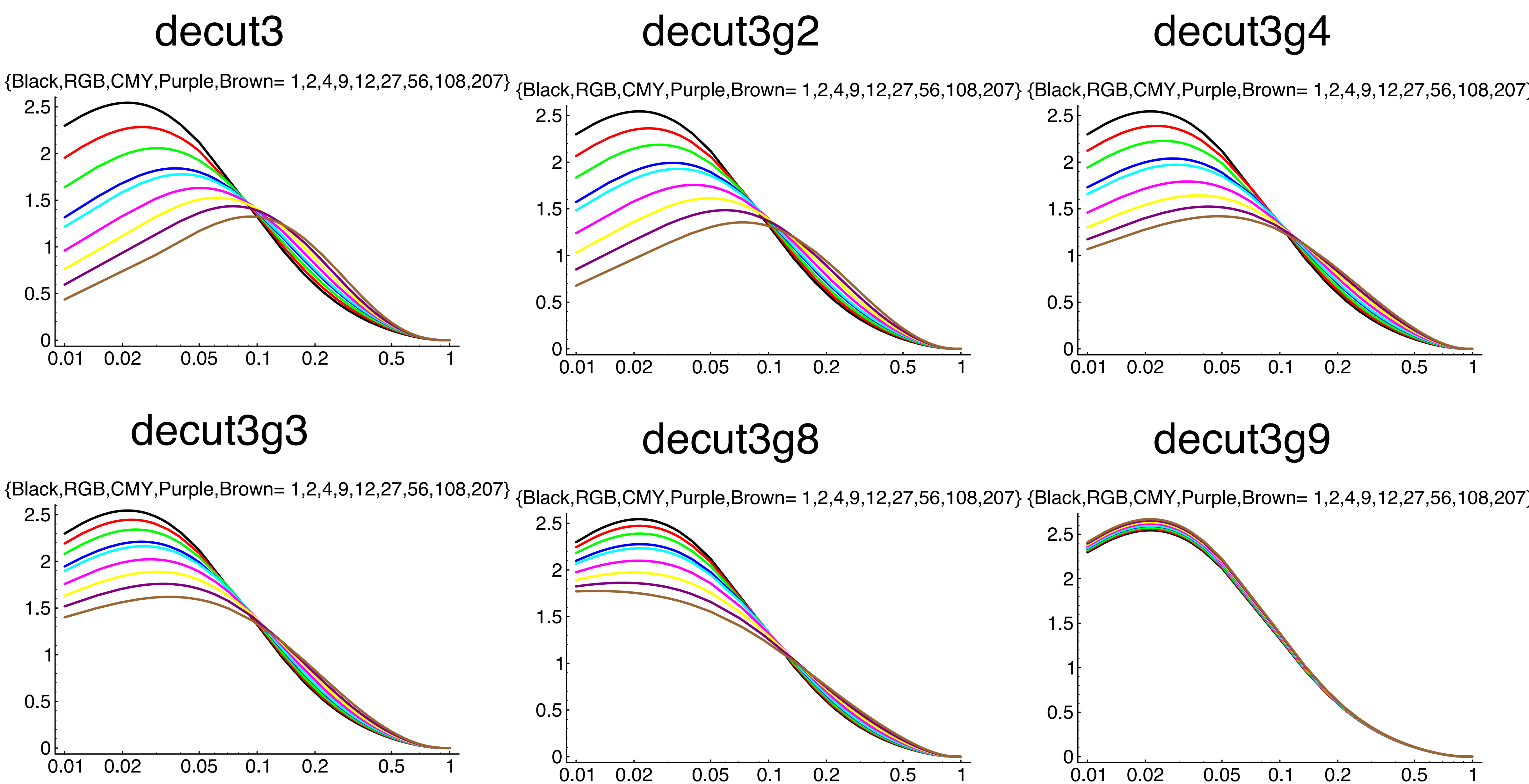
$$c_1 = c_{1,0} + c_{1,1}(1 - A^{-c_{1,2}})$$

Name	(initial) fit parameter	$c_{1,1}$	$c_{1,2}$
decut3	free	-0.29	-0.09
decut3g1	fixed	0.2	50.0
decut3g2	fixed	-0.1	-0.15
decut3g3	fixed	0.2	-0.15
decut3g4	free	0.2	-0.15
decut3g5	fixed	0.2	-0.25
decut3g7	fixed	0.2	-0.23
decut3g8	fixed	0.35	-0.15
decut3g9	fixed – free proton	0.0	—

- Vary c_1 influencing small-x behaviour of gluon nPDF
- Each fit equally acceptable with excellent $\chi 2$/dof~0.9

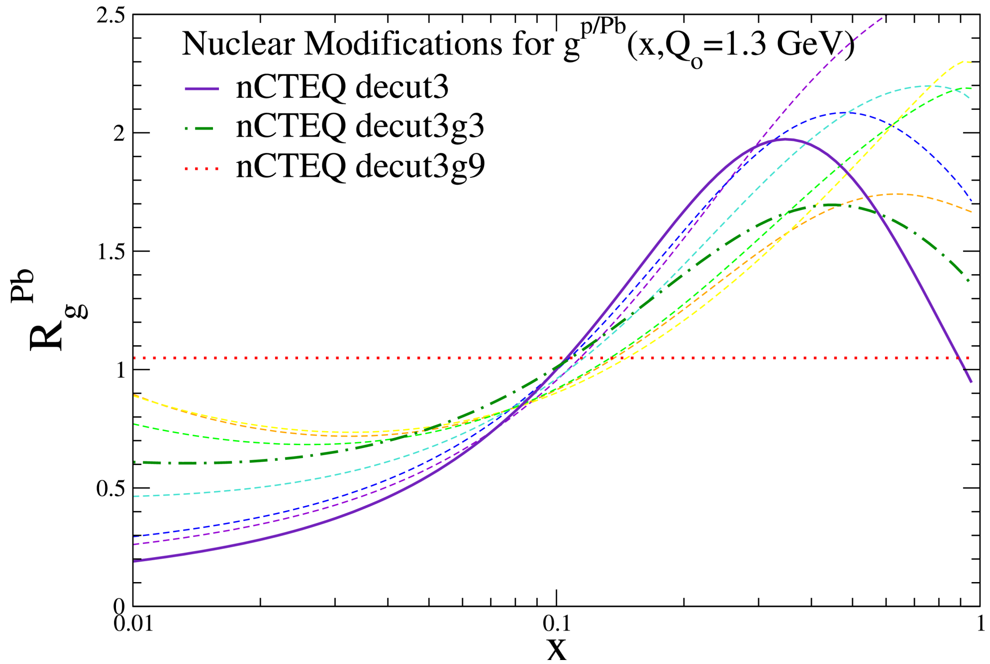
The nuclear gluon distribution

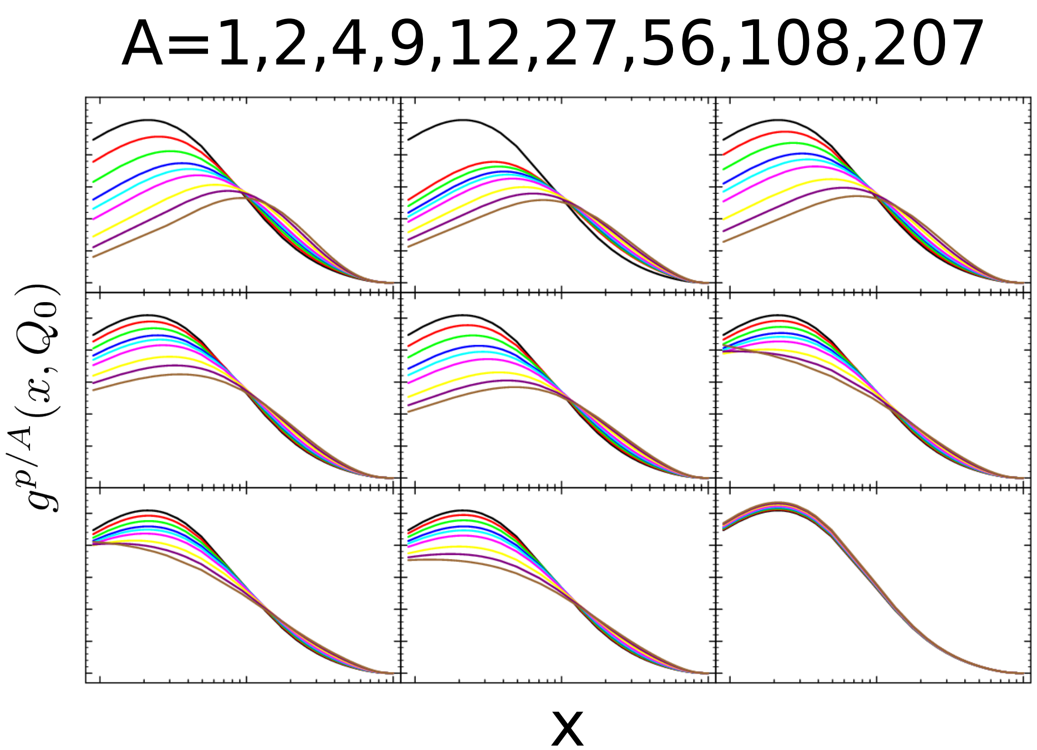
A series of equally good fits ($\chi^2/pt \simeq 0.9$) to ℓA+DY data with different gluons



Shown are the gluon distributions at the scale $Q_0 = 1.3\ \mathrm{GeV}$ for different A vs x

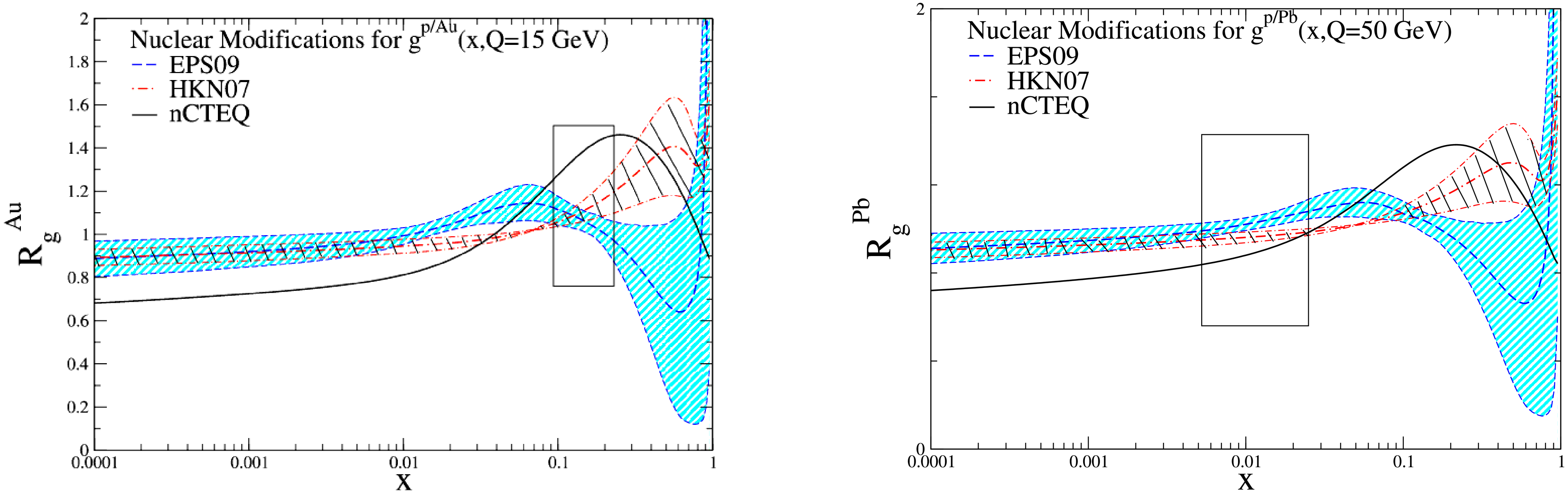
gluon nCTEQ decut3gx fits





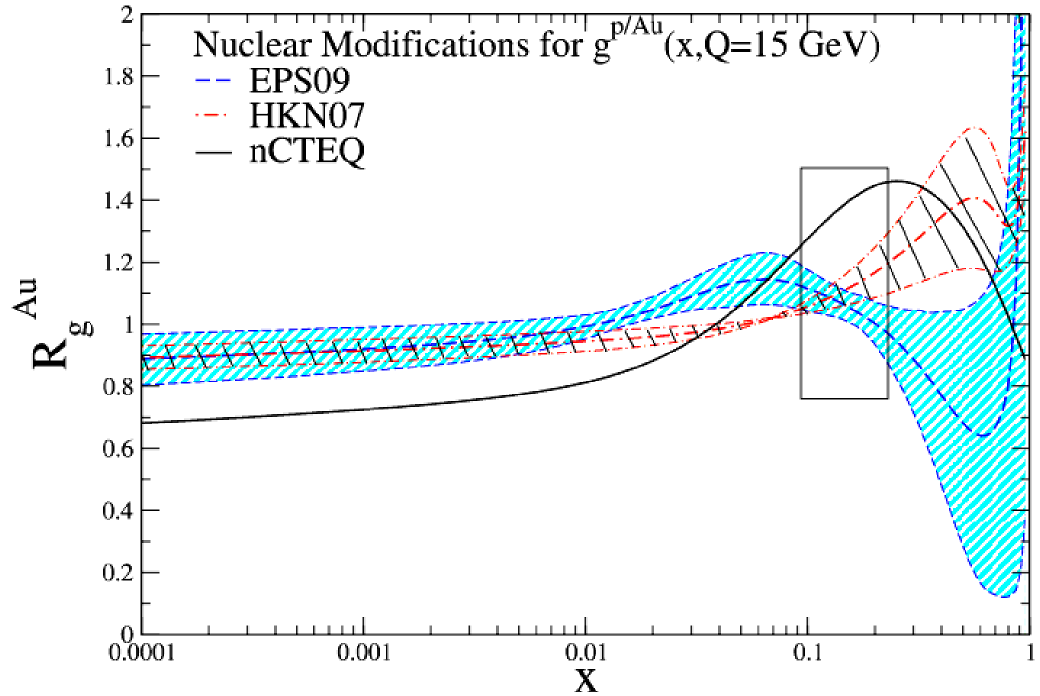
- This still underestimates the true uncertainty
- Some **curves lie outside the error bands** of EPS'09 and/or HKN'07!

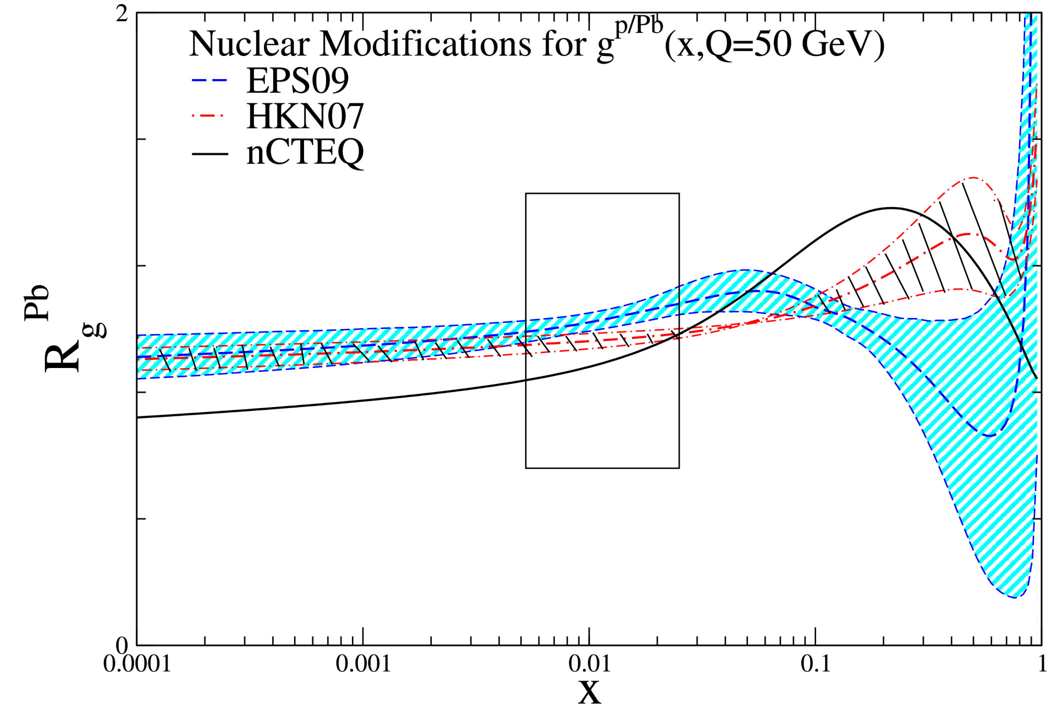
At higher scales



- At larger Q error still large
- nPDFs quite different – individual error bands underestimate uncertainty
- Need more experimental constraints!

At higher scales





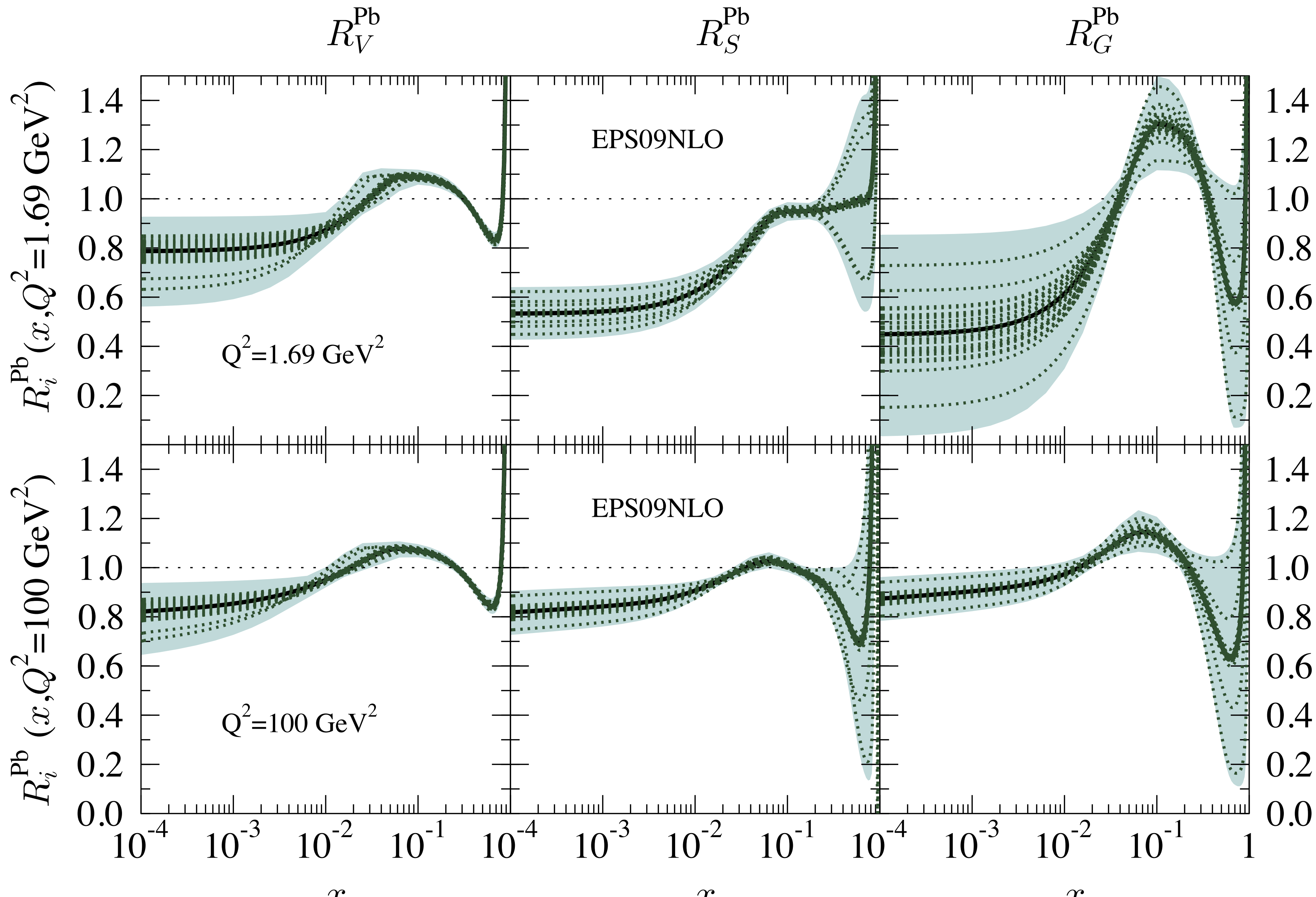
- At larger Q error still large
- nPDFs quite different – individual error bands underestimate uncertainty
- Need more experimental constraints!

Essential for ion-ion physics at LHC

GLUON UNCERTAINTY IN EPS'09

- EPS'09 also uses RHIC data for inclusive pion production to constrain the gluon
- This involves fragmentation functions $D_i^\pi(z,\mu^2)$ into pions
- Large uncertainties! Still some of the gluons of the decut3g series lie outside the error band of R_G^{Pb}

Central fits!



The gluon from hard processes at the LHC and RHIC

Need hard probes in pA to constrain nPDFs

Hard probes in pp, $p\bar{p}$ to constrain proton PDFs:

- Tevatron inclusive jet data $\rightarrow$ gluon
- Lepton pair production $\rightarrow$ sea quarks
- Vector boson production $\rightarrow$ sea quarks

(need high precision due to high scale Q ~ M_W)

The gluon from hard processes

- Inclusive jet production
- Inclusive hadron production
- Heavy quark production
- Heavy quarkonium production?
- Direct photon production
- Direct photon + jet
- **Direct photon + heavy quark jet**

Tevatron inclusive jet data used in proton case

Cacciari et al, Kniehl, Kramer, IS, Spiesberger

Arleo, d'Enterria

Stavreva et al

Photon + Q production

- Dominated by Compton subprocess:

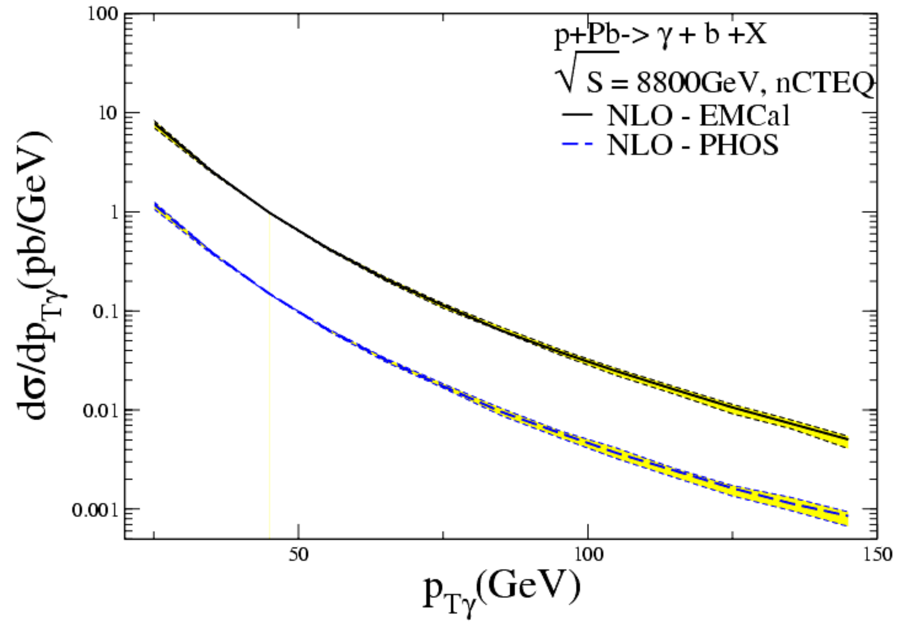
$$g + Q \to \gamma + Q$$

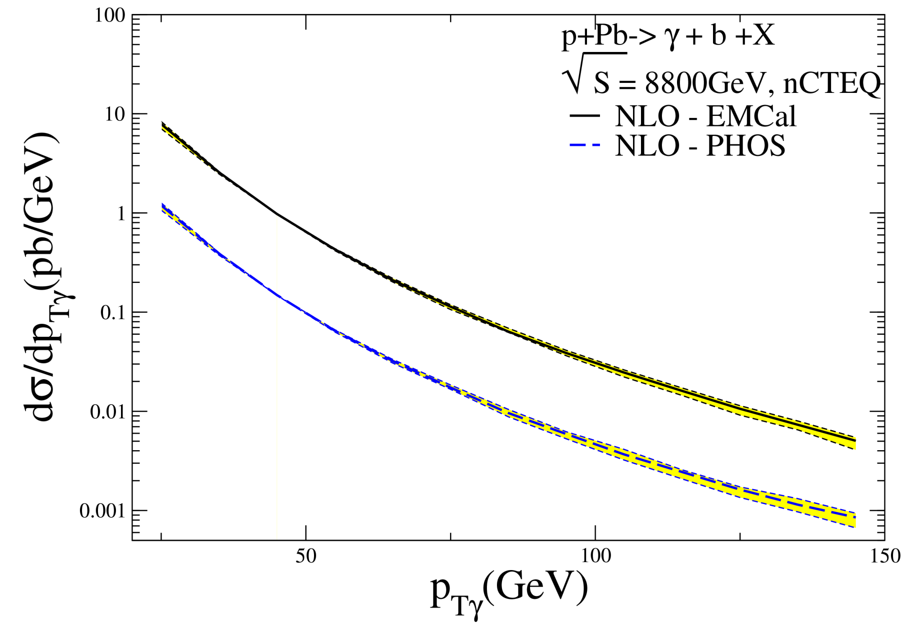
- Heavy quark PDF depends entirely on gluon PDF (disregarding possible intrinsic charm)

- Use nuclear correction ratio to determine gluon:

$$R_{pA}^{\gamma Q} = \frac{\sigma(pA \to \gamma Q X)}{A\sigma(pp \to \gamma Q X)}$$

Photon + Q at the LHC





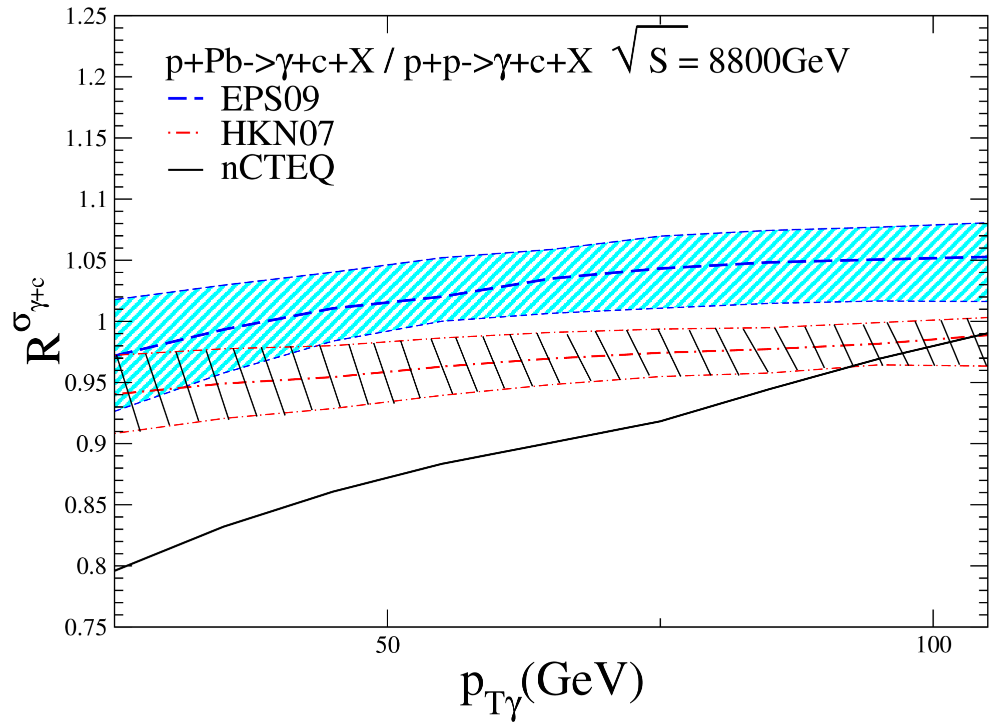
	σ^{tot}	N_{event}
$\gamma + c$ PHOS	131 pb	2700
$\gamma + b$ PHOS	20 pb	400
$\gamma + c$ EMCal	684 pb	14200
$\gamma + b$ EMCal	131 pb	2700

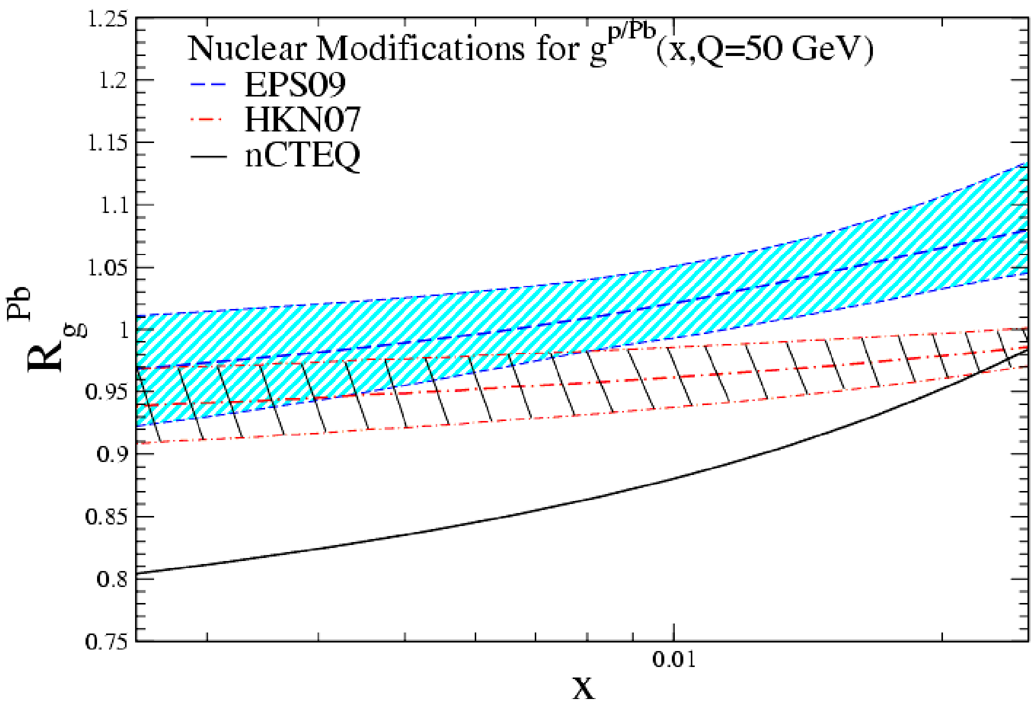
ALICE

- σ sufficiently large to measure γ+c and γ+b

Stavreva et al, JHEP2010

Constraining the gluon nPDF





- The nuclear ratio follows closely the gluon ratio
- Measurement with sufficiently small errors will allow to constrain the gluon distribution
- Similar at RHIC, but higher x probed

Conclusions II

- Nuclear gluon poorly known!
- Problem for heavy ion physics Disentangle:
  - initial state
  - cold nuclear matter effects
  - hot nuclear matter effects (QGP)
- Photon + Q useful to constrain gluon
- decut3gx series of nCTEQ fits available

Nuclear corrections in neutrino DIS

Why neutrino DIS?

- **Data interesting for global analyses of proton PDF and nuclear PDF (nPDF)**
  - **Flavor separation:**
    Neutrino structure functions depend on different combinations of PDFs

- **Dimuon production:**
  - Main source of information on the strange sea
  - Large uncertainty on $s(x,Q^2)$ has significant influence on the W and Z benchmark processes at LHC

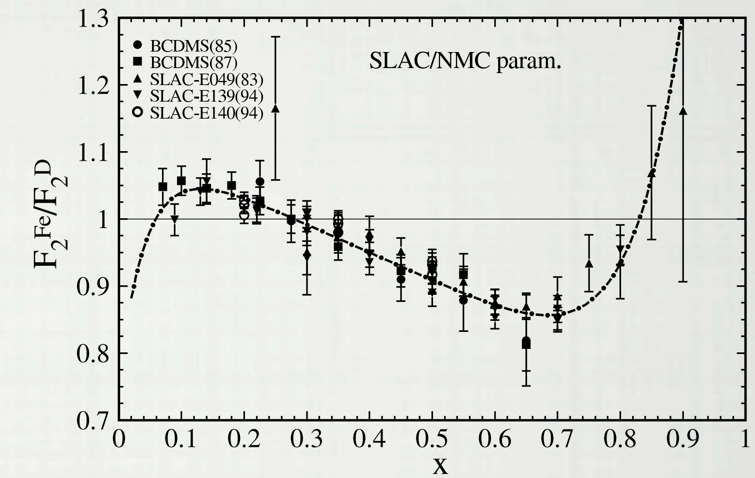
- **For proton PDF: need nuclear corrections!**

Why neutrino DIS?

- **LBL precision neutrino experiments:**
  Need good understanding of ν-A cross sections (A=Oxygen, Carbon)

- **EW precision measurements:**
  Paschos-Wolfenstein analysis: extraction of $\sin^2\theta_W$

NUCLEAR PDFS



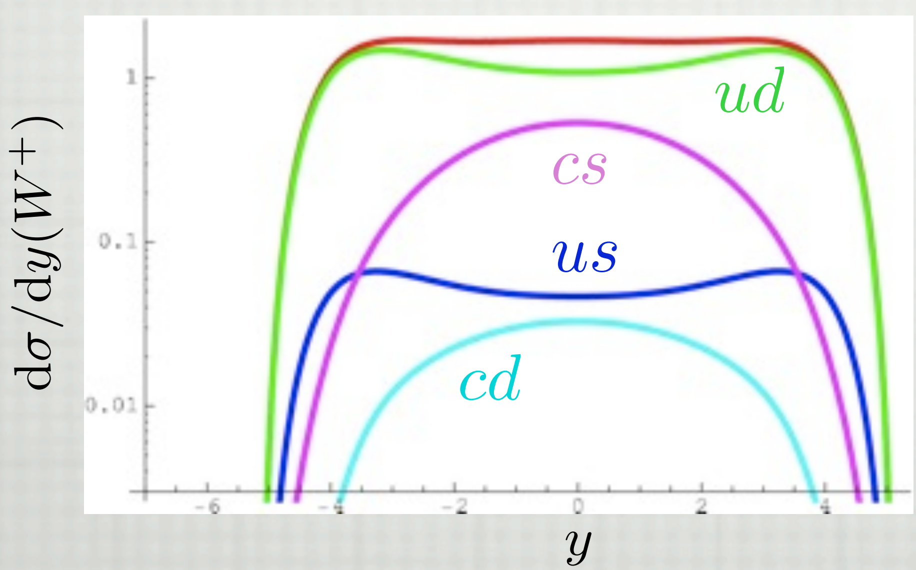
- What are nuclear parton density functions (nPDF) ?
  - parton densities for partons in bound proton & neutron

- Where are nuclear parton density functions useful ?

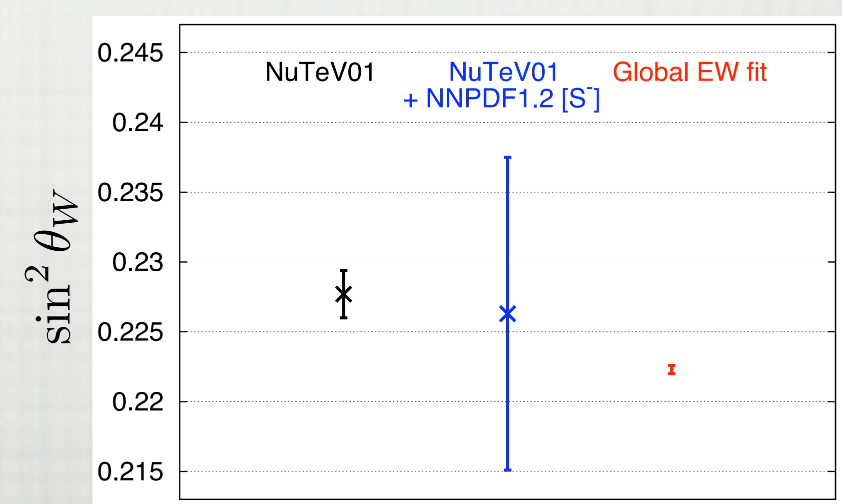
  1. Strange quark content of the proton

  (anti-)strange PDF from (anti-)neutrino DIS with heavy nuclei - nuclear effects important

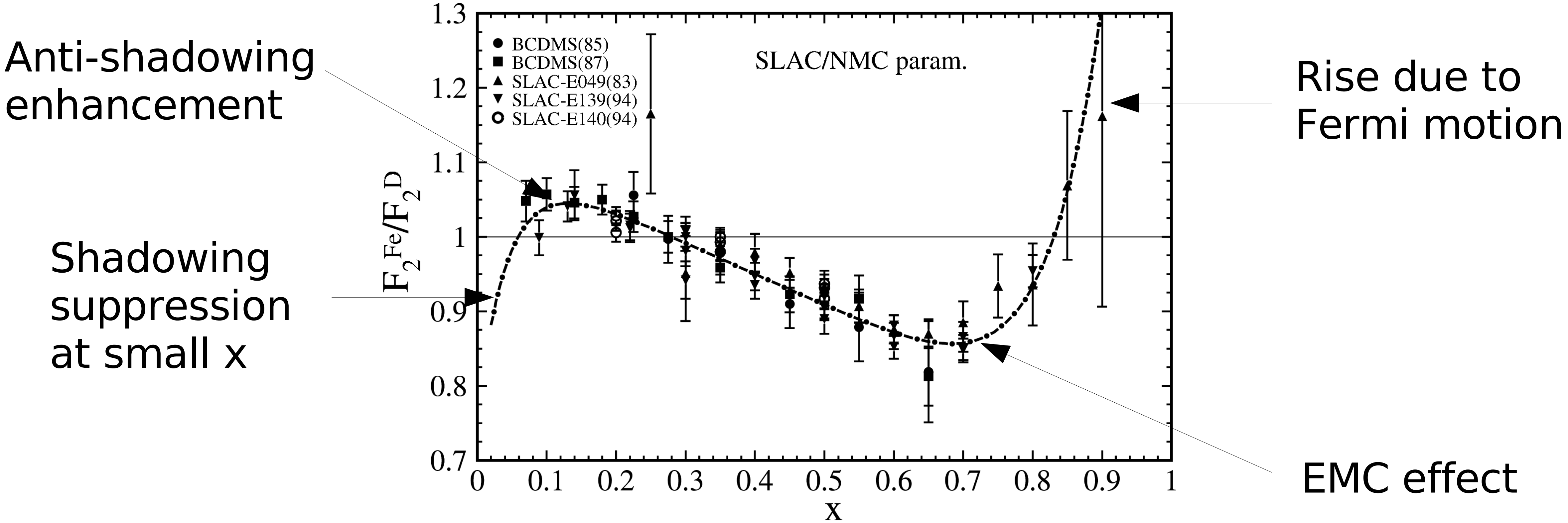
crucial for: W-boson production at the LHC (standard candle process)



crucial for: determining weak mixing angle from NuTeV experiment



Nuclear corrections: Historically



- Historically, nuclear corrections from charged-lepton DIS data are applied to neutrino DIS data
- Same correction for all scales Q^2
- Same correction for all observables (F_2, F_3, cross section, dimuon production)
- **Idea:** study nuclear corrections in the parton model (PM) using nuclear PDF

Nuclear correction factors in the PM

- Be O an **observable** calculable in the parton model

  Define **nuclear correction factor:**

$$R[\mathcal{O}] = \frac{O[\text{nuc.PDF}]}{O[\text{freePDF}]}$$

- Compare below: **R[F_2^{lA}]** (lA DIS) with **R[$F_2^{\nu A}$]** (υA DIS)

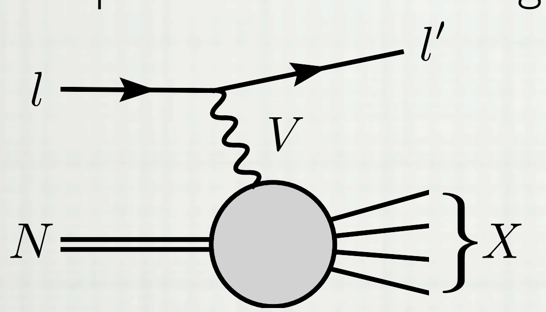
- Advantage:
  - very flexible (applicable to other observables: F_3, dσ, ...)
  - scale dependent

NEUTRINO DIS

- Experiments included in the analysis:

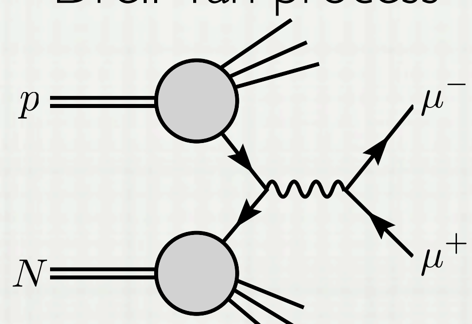
Charged lepton

Deep Inelastic Scattering



$$l + N \to l' + X$$

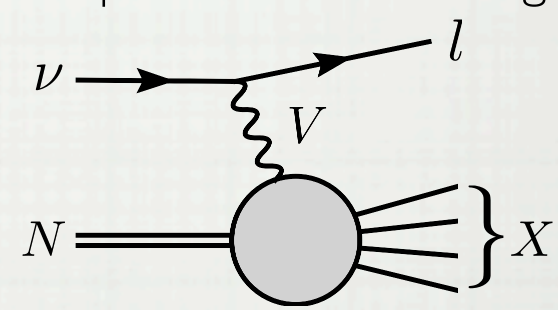
Drell-Yan process



$$p + N \to \mu^+ \mu^- + X$$

Neutrino

Deep Inelastic Scattering



$$\nu(\bar{\nu}) + N \to l + X$$

CERN BCDMS & EMC & NMC
$N = (\mathrm{D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W})$

FNAL E-665
$N = (\mathrm{D, C, Ca, Pb, Xe})$

DESY Hermes
$N = (\mathrm{D, He, N, Kr})$

SLAC E-139 & E-049
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

FNAL E-772 & E-886
$N = (\mathrm{D, C, Ca, Fe, W})$

1233 data points (708 after cuts)

CHORUS
$N = \mathrm{Pb}$

CCFR & NuTeV
$N = \mathrm{Fe}$

3832 data points (3134 after cuts)

Neutrino data

- Correlated errors
- Radiative correct.
- with and w/o iso-scalar corrections

ID	$\mathbf{d\sigma^{\nu A}/dxdy}$: Observable	Experiment	# data
33	Pb	CHORUS ν	607 (412)
34	Pb	CHORUS $\bar{\nu}$	607 (412)
35	Fe	NuTeV ν	1423 (1170)
36	Fe	NuTeV $\bar{\nu}$	1195 (966)
37	Fe	CCFR ν di-muon	44 (44)
38	Fe	NuTeV ν di-muon	44 (44)
39	Fe	CCFR $\bar{\nu}$ di-muon	44 (44)
40	Fe	NuTeV $\bar{\nu}$ di-muon	42 (42)
	Total:		4006 (3134)

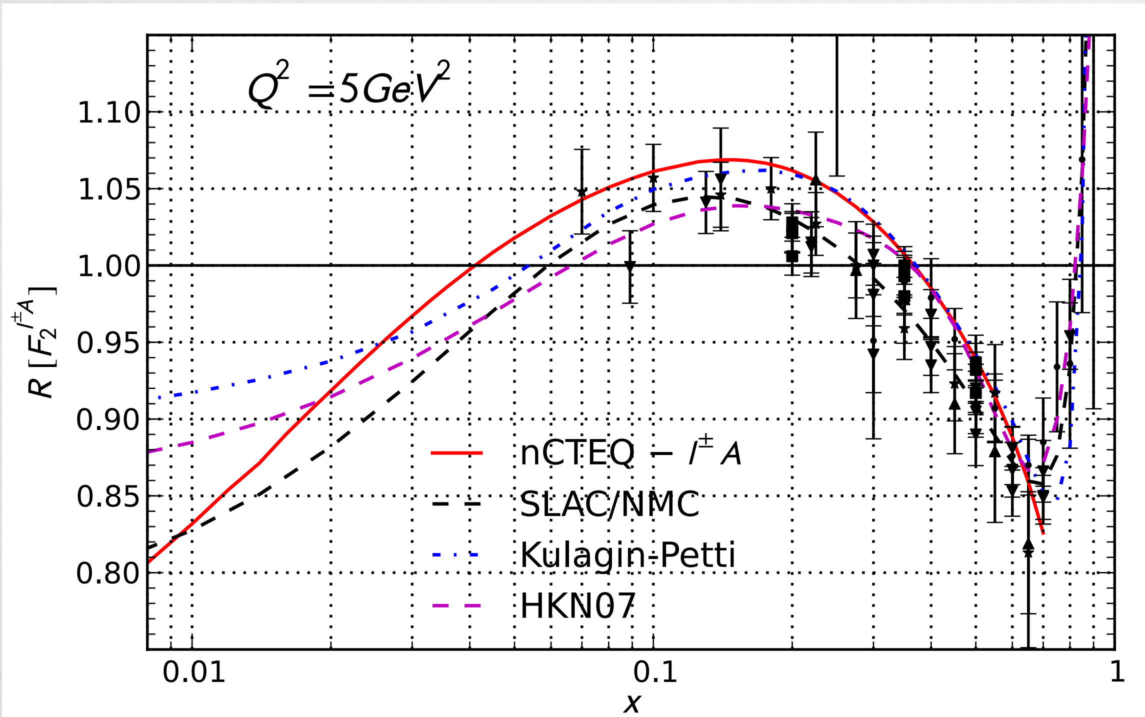
NEUTRINO DIS

- Comparison of charged lepton and neutrino fits

Fit to charged lepton data

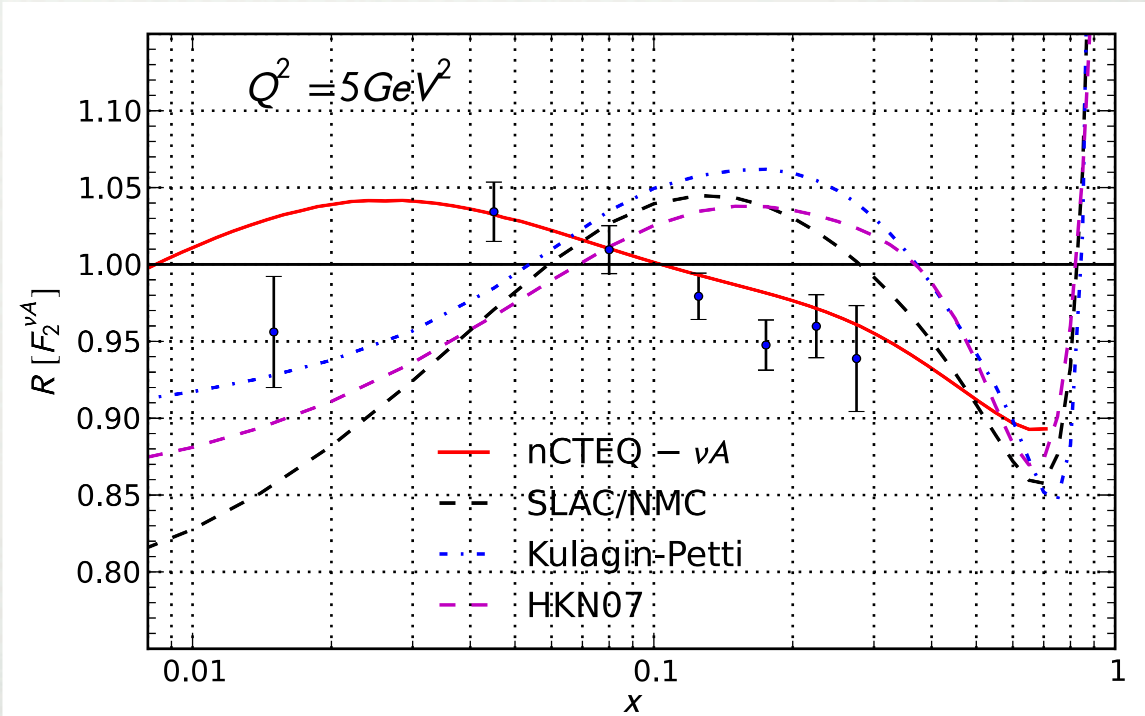
DIS & DY

$\chi^2/\mathrm{d.o.f} = 0.89$



Fit to only neutrino DIS

$\chi^2/\mathrm{d.o.f} = 1.33$



- can we explain the difference and fit all data together in a global fit ?

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Fits to lA, DY and νA data

- Many neutrino data points
- Use a weight parameter w to combine data sets
- w=0: only lA+DY data
- w=∞: only νA data

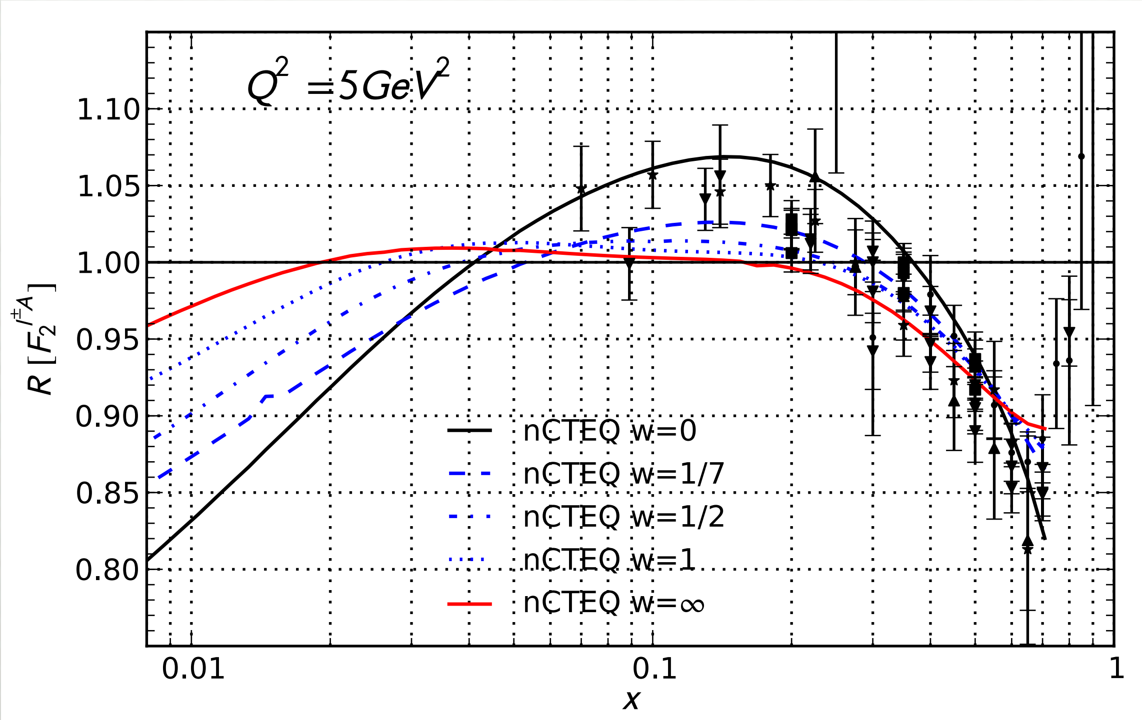
Weight	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	708	639 (0.90)	-	-	639 (0.90)
$w = 1/7$	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	-	-	3134	4192 (1.33)	4192 (1.33)

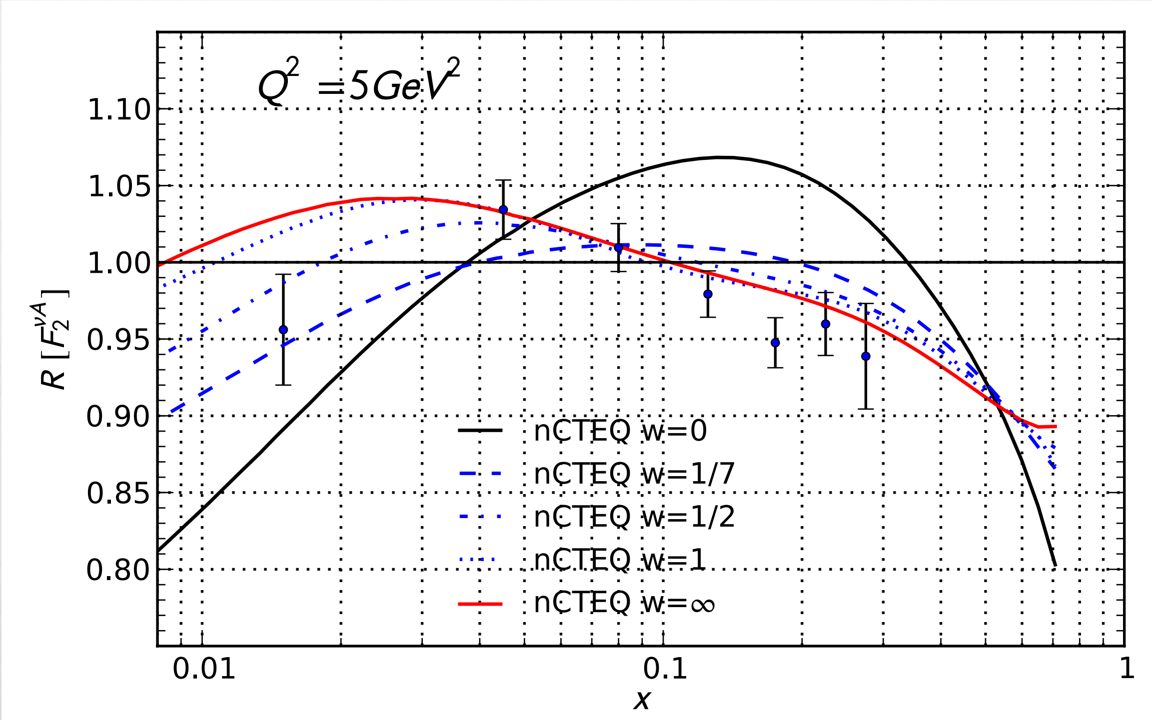
NEUTRINO DIS

- Analysis of fits with different weights of neutrino DIS (correlated errors)

w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	630 (0.89)	-	-	630 ± 58
1/7	708	645 (0.91)	3134	4681 (1.50)	5326 ± 203
1/2	708	680 (0.96)	3134	4375 (1.40)	5055 ± 192
1	708	736 (1.04)	3134	4246 (1.36)	4983 ± 190
∞	-	-	3134	4167 (1.33)	4167 ± 176

$$P(\chi^2, N) = \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$





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NEUTRINO DIS

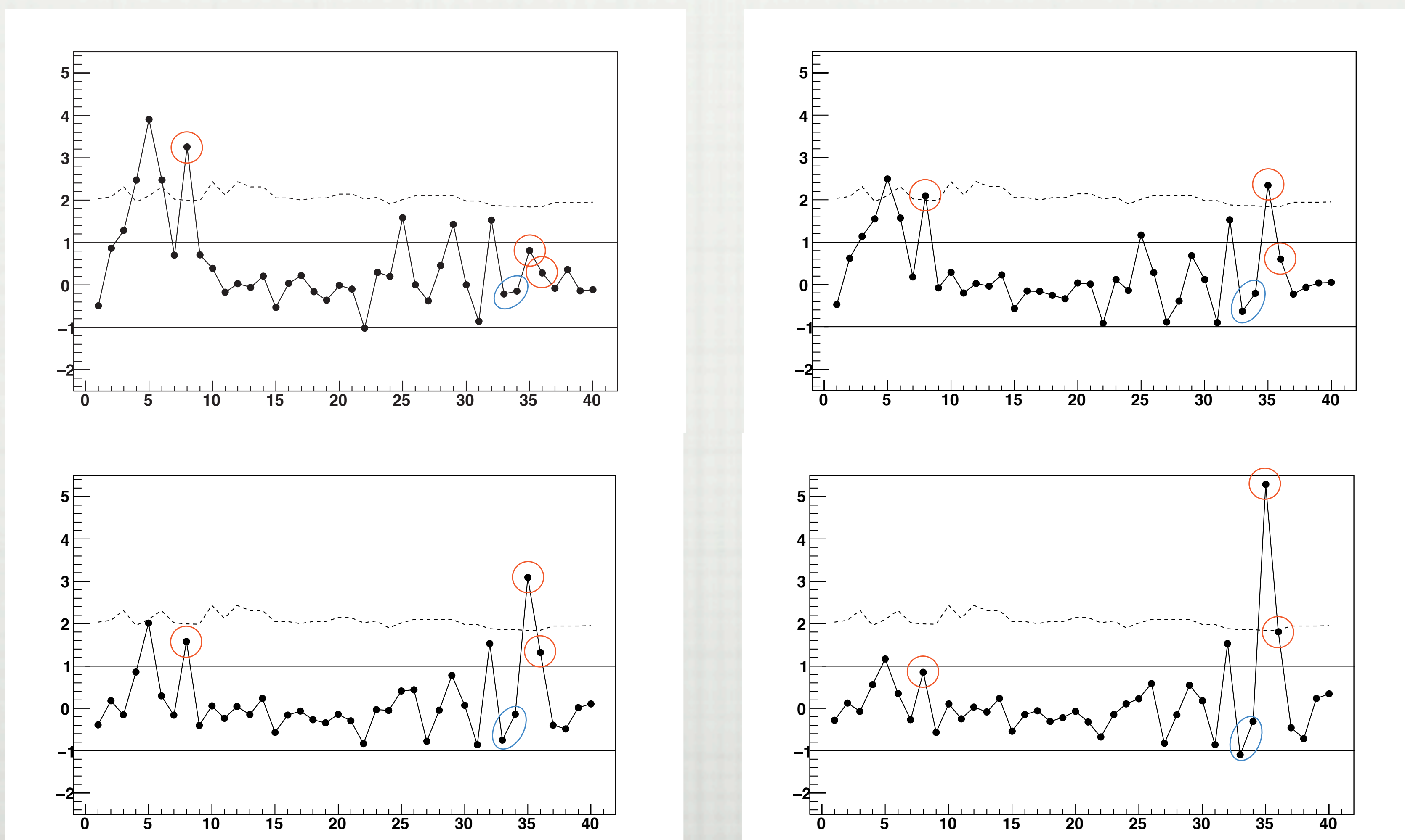
- Analysis of fits with different weights of neutrino DIS (corr. errors)
  - χ^2- distribution criterion $$P(\chi^2, N) = \frac{(\chi^2)^{N/2-1} e^{-\chi^2/2}}{2^{N/2}\Gamma(N/2)}$$

90% percentile (solid line at 1) $$\int_0^{\xi_{90}} P(\chi^2, N) d\chi^2 = 0.90$$

99% percentile (dotted line) $$\int_0^{\xi_{99}} P(\chi^2, N) d\chi^2 = 0.99$$

(w=1) (w=1/2)

(w=1/4) (w=1/7)



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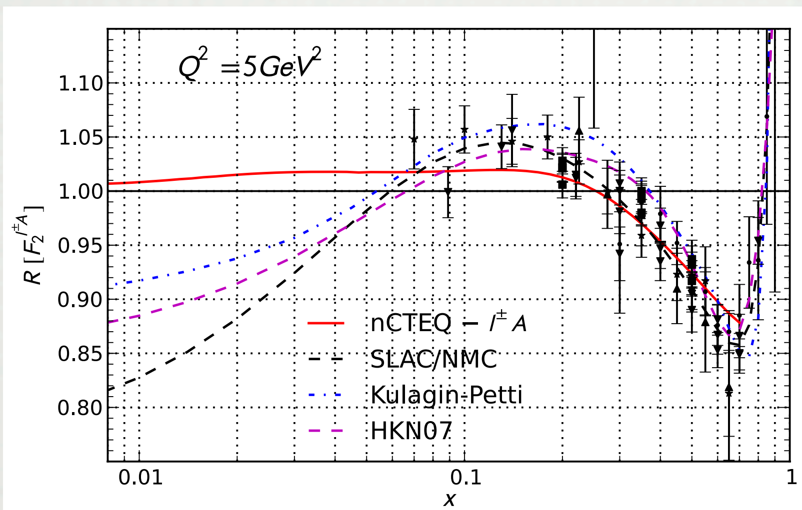
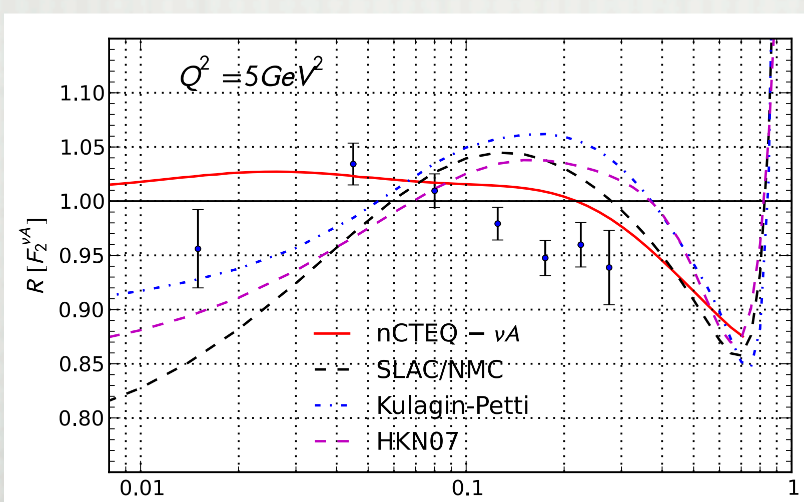
NEUTRINO DIS

- Analysis of fits with neutrino DIS (uncorrelated errors)

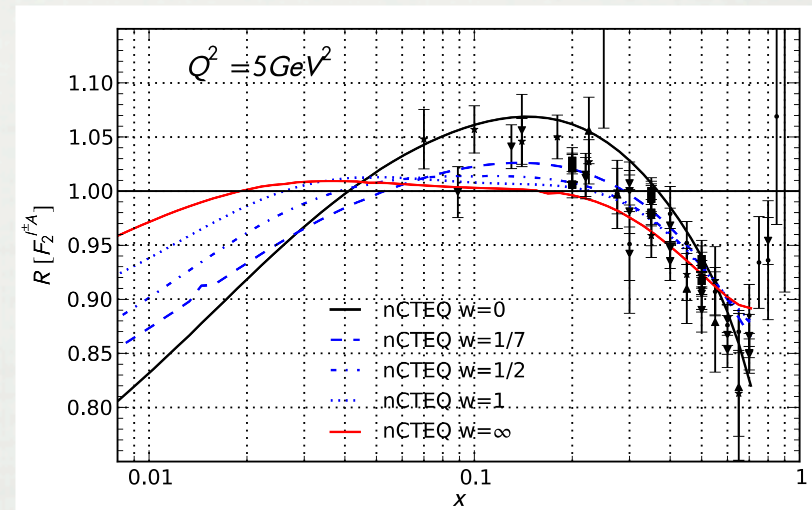
w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
1-corr	708	736 (1.04)	3134	4246 (1.36)	4983 (1.30)
1-uncorr	708	809 (1.14)	3110	3115 (1.00)	3924 (1.02)

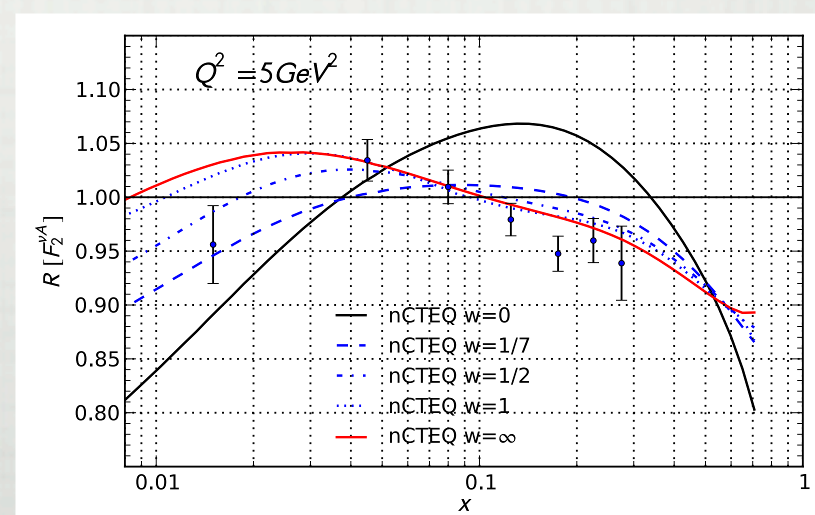
uncorrelated errors





correlated errors





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Conclusions III

- Incompatibility of neutrino DIS with charged lepton DIS?
  - Conclusions heavily rely on NuTeV data (most precise)
  - Incompatibility a "precision effect" - the result changes e.g. when using uncorrelated errors
  - Tension in NuTeV data, high Chi^2 in fit to NuTeV data alone
  - NOMAD data can help to decide
- If confirmed, important consequences for:
  - global analyses of proton and nuclear PDF; impact on strange PDF?
  - models explaining the nuclear effects
  - precision observables in the neutrino sector
- Possible explanations
  - Non-universal nuclear effects (breaking of factorization)
  - Twist-2 factorization valid but nuclear-enhanced higher-twist effects

Backup

PDF Uncertainties

<u>Sources:</u>

- Experimental Errors to be propagated to the PDFs
- Theoretical Uncertainties
- Details of the Global Fits
- Inconsistencies in the use of the PDFs/application of the theoretical framework

There are known Unknowns ...

Errors of experimental data

Methods: to propagate exp. errors to PDFs

- **Hesse Matrix**
  - Eigenvector PDFs
  - Quadratic approximation
  - Simple computation of correlations
- **Lagrange Multipliers**
  - No quadratic approximation
  - Time consuming
- **Monte Carlo Methods**
  - generate N data samples by varying data within errors
  - N fits to the N samples -> Estimate uncertainty

Hessian method:

Assume only one fit parameter a --> Expand $\chi^2(a)$ around Minimum a_0

$$\chi^2(a)=\chi^2(a_0)+\frac{1}{2}\chi^{2''}(a_0)(a-a_0)^2+...$$

Eigenvalue of Hessian 'matrix'

Determine Tolerance T <--> 1-sigma uncertainty: $T=\Delta\chi^2$

--> 1-σ uncertainty range for parameter a such that:

$$\chi^2(a)=\chi^2(a_0)+\Delta\chi^2 \Rightarrow \Delta a=T\sqrt{2/\chi^{2''}(a_0)}$$

--> best fit PDF: a_0 , two 'Eigenvector' PDFs: $a_0+\Delta a, a_0-\Delta a$

1-σ uncertainty for Observable X:

$$\Delta X=\frac{X(PDF[a_0+\Delta a])-X(PDF[a_0-\Delta a])}{2}\propto\Delta a\propto T$$

Generalization to n parameters: add in quadrature

Details of a global analysis

'Internal choices':

- **Choice/Weight of data sets** used
- **Assumptions on PDFs** (replace uncertainty!)
- Choice of Nuclear corrections to be applied to data taken with nuclear targets (D, Fe)
- Estimate/Choice of tolerance T corresponding to 1-sigma uncertainties
- Choice of the input scale
- Choice of the functional form of the PDFs at the input scale
- Scale evolution: x-space or n-space, spurious terms, soft-gluon resummation (evolution)

Details of a global analysis

'Public choices':

- Perturbative Order (LO, NLO, NNLO)
- Parameters: mc, mb, alphas(Mz)
- Factorization Scheme
- Heavy Flavour Scheme
- Central Factorization/Renormalization Scales
- Include?
  - Resummations (hard part)
  - Target Mass Corrections (TMC), Higher Twist
  - QED-effects

Remarks:

- 'Public choices' are choices also to be made by the user of the PDFs.

- For each public choice need in principle consistent set of PDFs

- Note: **Changes in the "details" may lead to results which lie outside previous error bands!**

- Certain items on the list become relevant due to the ever increasing demand for precision

Conclusion: Useful and necessary to have several different global analyses of PDFs.

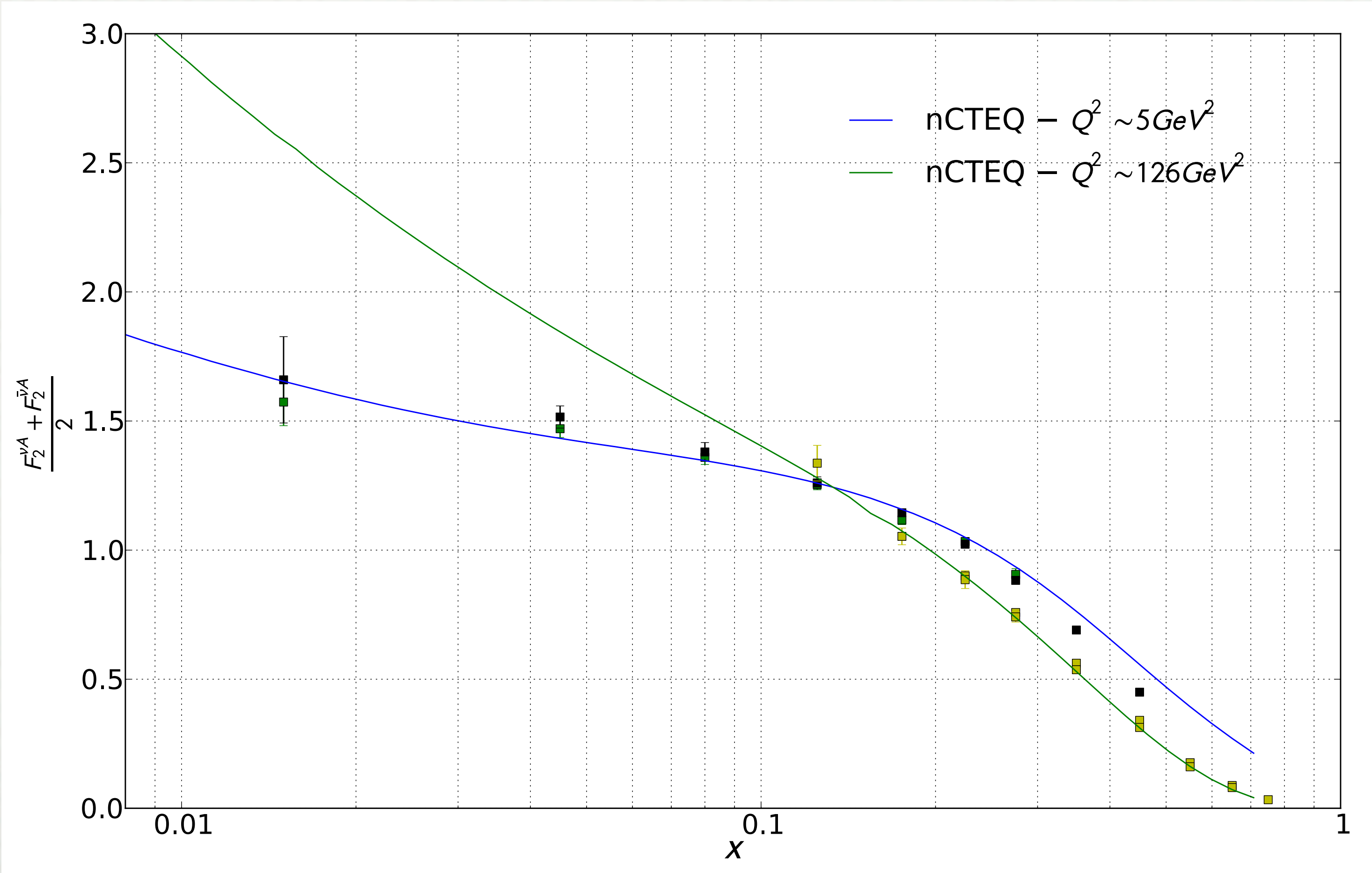
Inconsistencies

Examples:

- Use NLO PDFs with LO cross sections
- Use LO PDFs with NLO cross sections
- Use different schemes for PDFs and hard scattering cross sections
- Use different mc, mb, alphas than utilized in the global fit
- Use intrinsic k_T

NEUTRINO DIS

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - comparison against extracted NuTeV data at different Q^2
  - identical theory predictions for different nPDF



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NEUTRINO DIS

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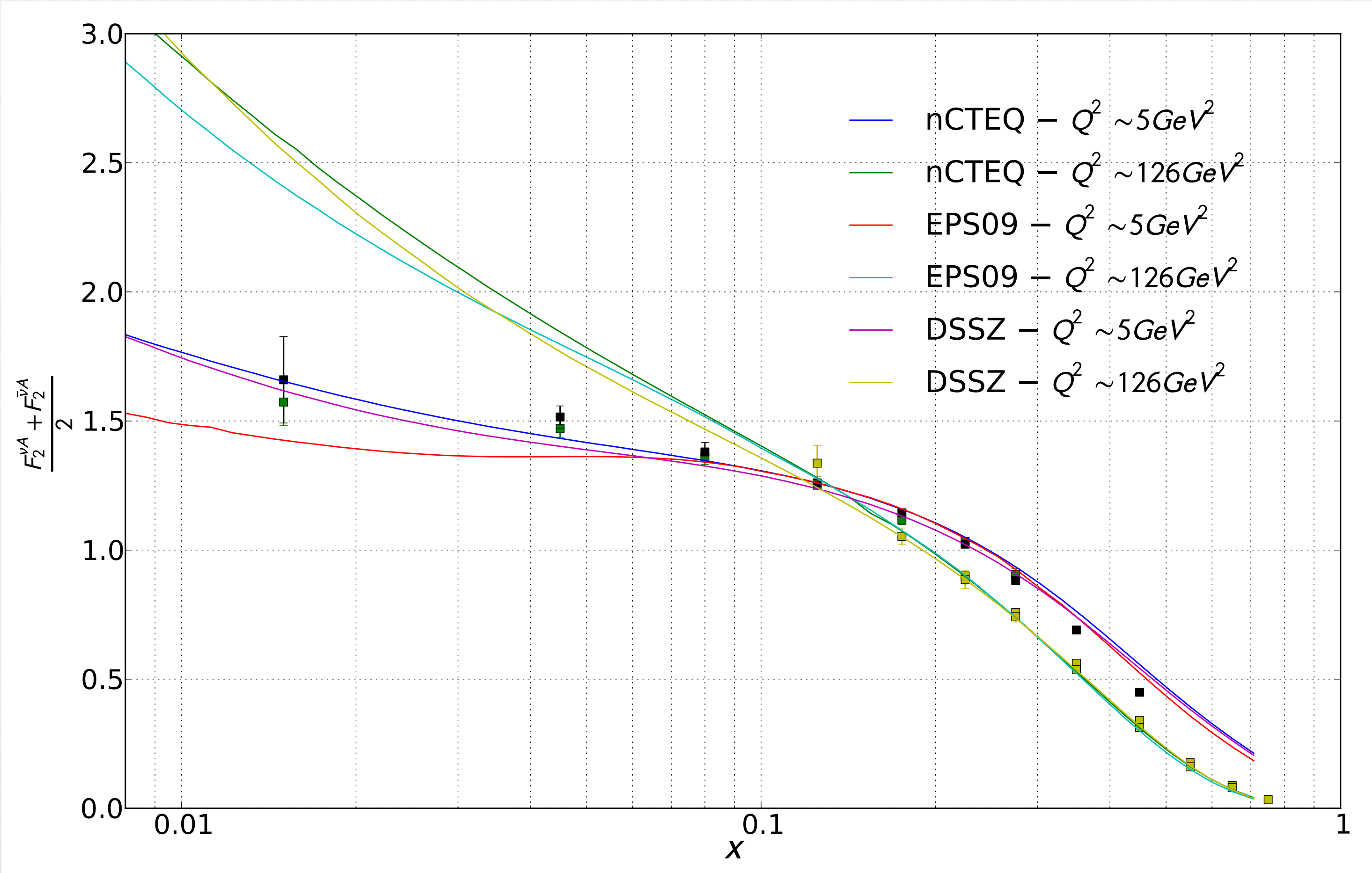
  - comparison against extracted NuTeV data at different Q^2
  - identical theory predictions for different nPDF (nCTEQ-neutrino, EPS09, DSSZ prelim.)



  - general problems to fit data at high x ~0.5
  - tension with charged lepton data at low x ~ 0.01

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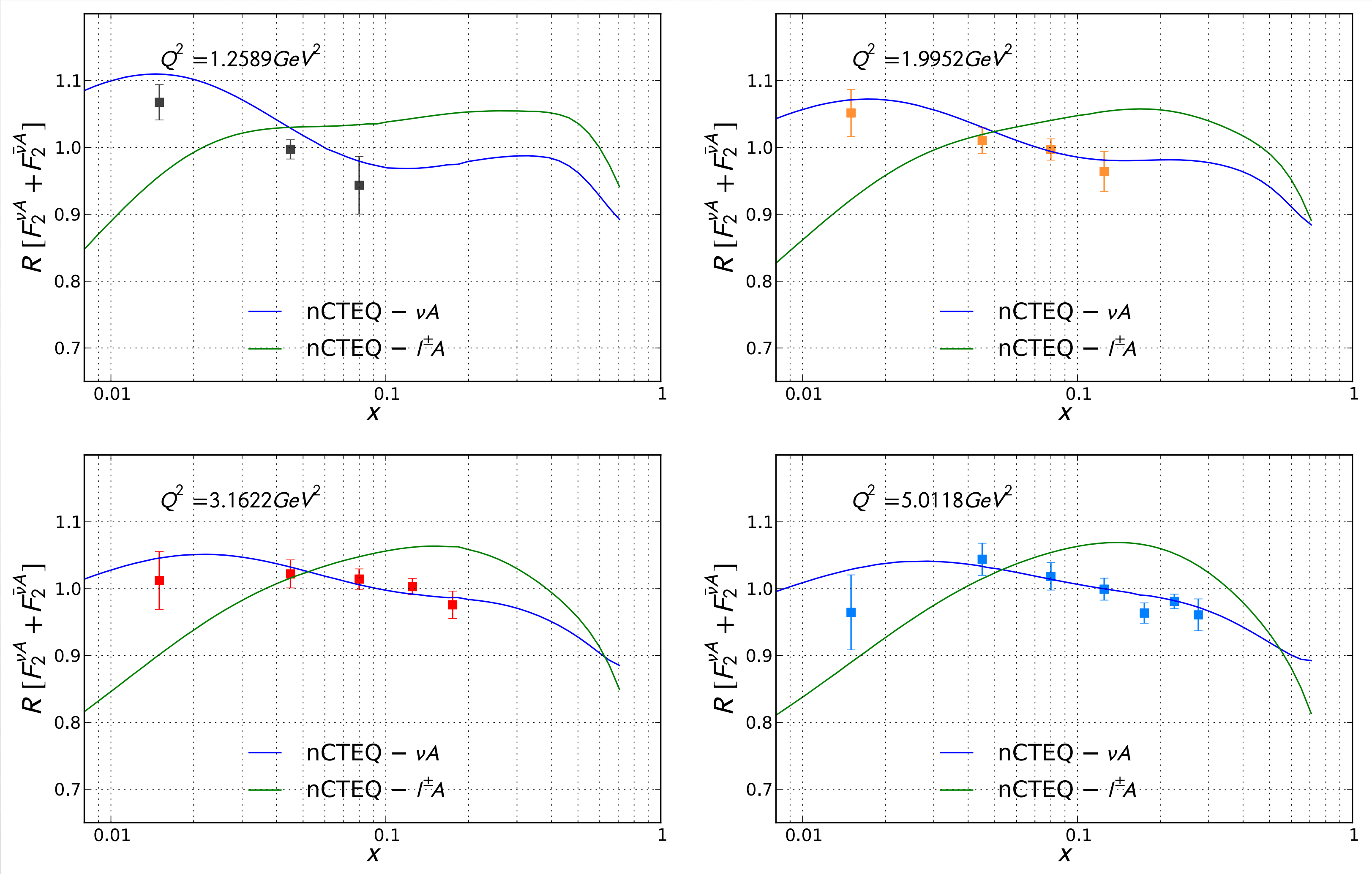
NEUTRINO DIS

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - comparison of nCTEQ - only neutrino fit against extracted NuTeV data at different Q^2
  - charge lepton fit undershoots low-x data & overshoots mid-x data
  - low-Q^2 and low-x data cause tension with the shadowing observed in charged lepton data



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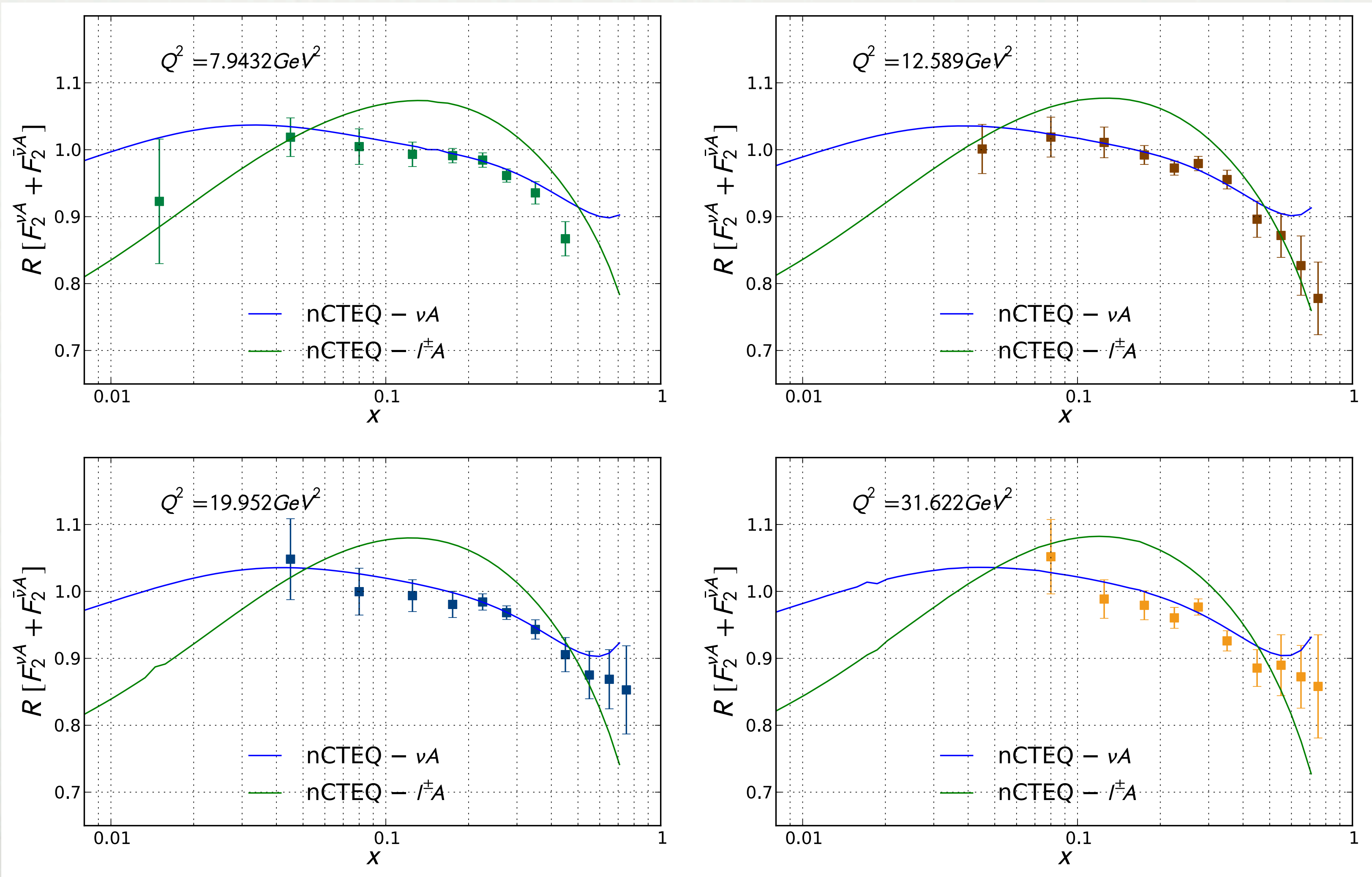

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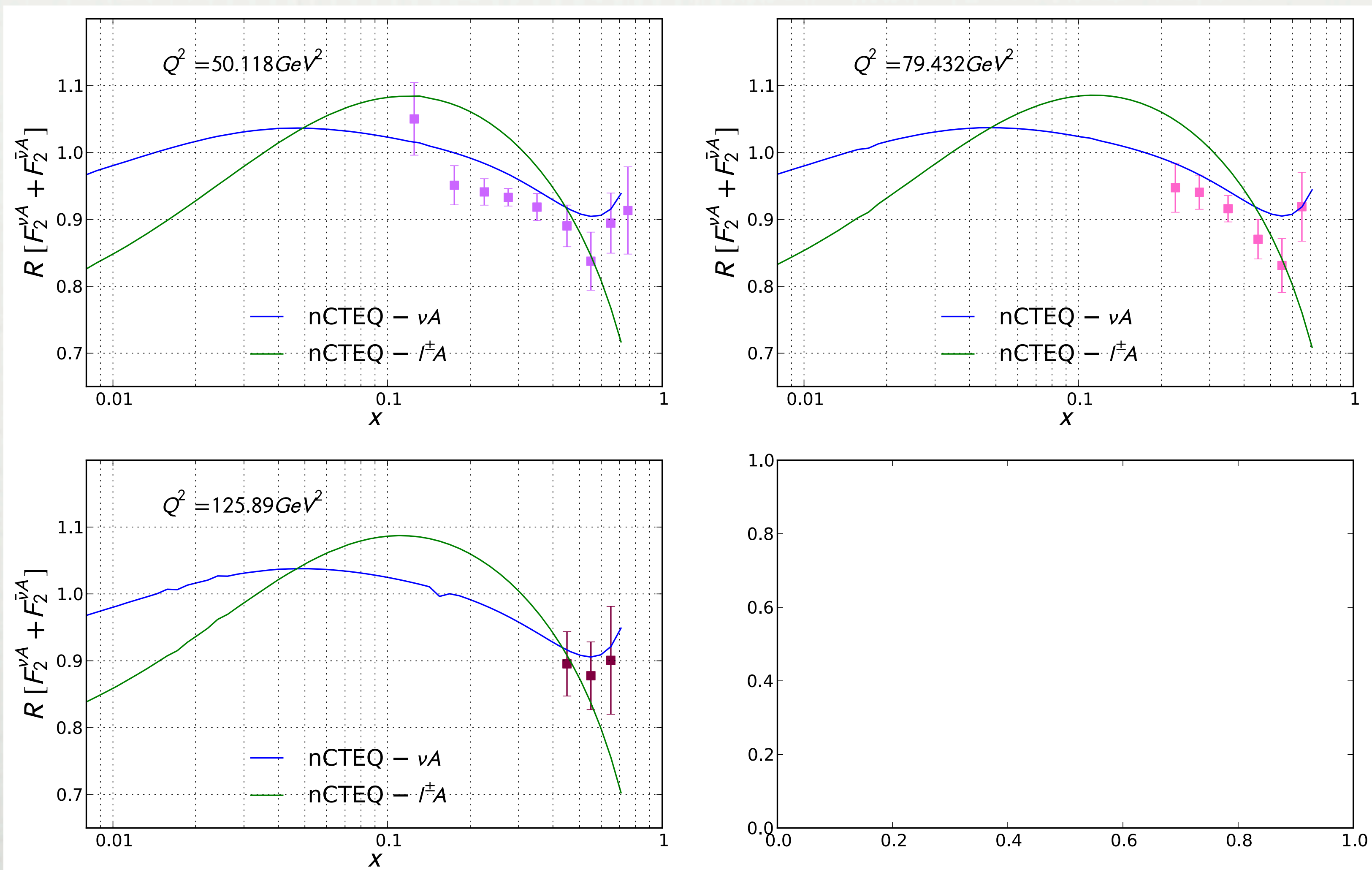

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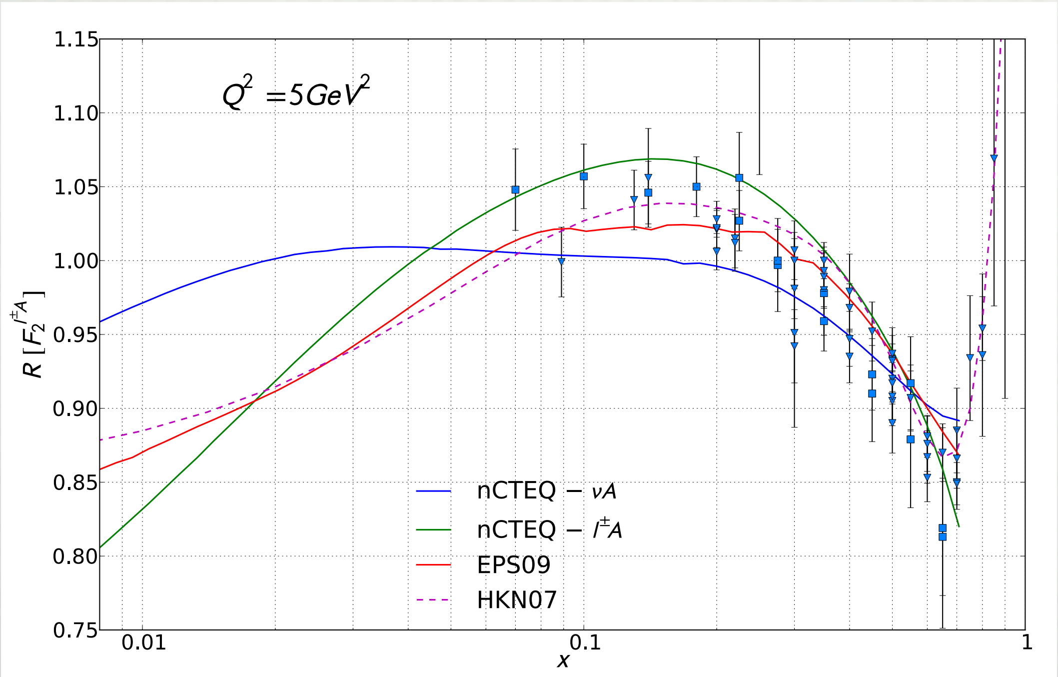
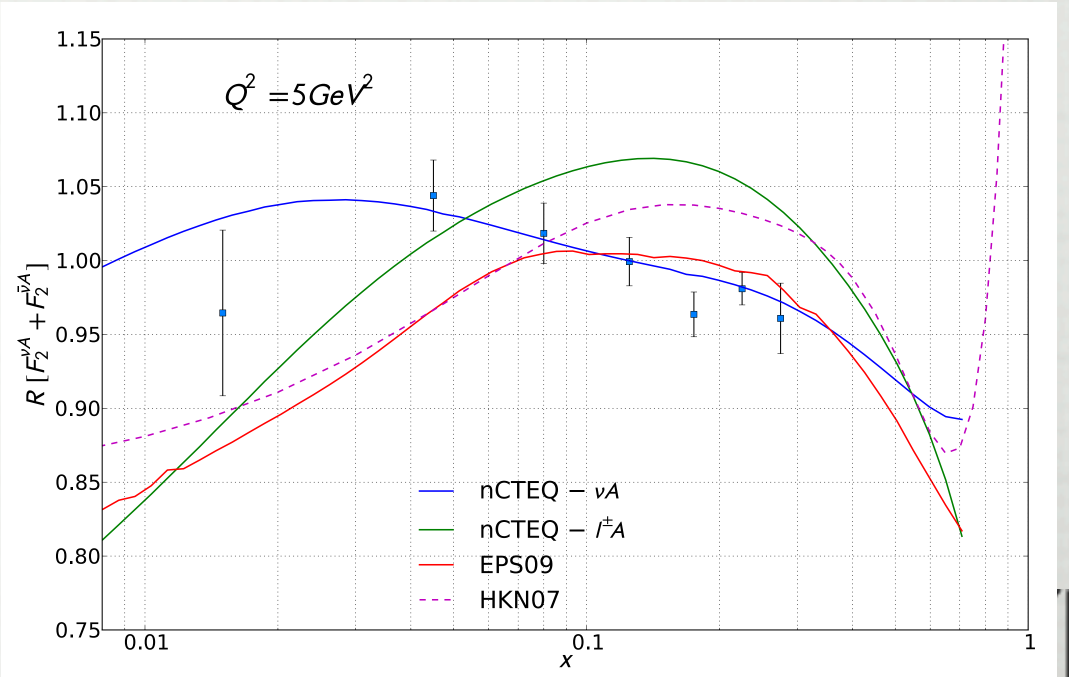
NEUTRINO DIS

- Properties of neutrino fits
  - CHORUS data are in good agreement with the charged lepton data

    combined: χ^2/pt=1.03
  - NuTeV data (with correlated errors) difficult to fit alone or with the charged lepton data

    alone: χ^2/pt=1.35 combined: χ^2/pt=1.33
  - Neutrino data dominate the combined fit without re-weighting - final result depends from the weight chosen





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CONCLUSIONS

- Incompatibility of neutrino DIS with charged lepton DIS (?)

  - conclusions heavily rely on only NuTeV data - most precise
  - incompatibility a "precision" effect - the result changes e.g. when using uncorrelated errors
  - tension in NuTeV data → high χ^2 of the fit to NuTeV alone → problem of NuTeV data ?
  - NOMAD data can help decide

- The impact of nuclear PDF from neutrino DIS on proton PDF

  - how does the incompatibility of neutrino DIS impact the uncertainty of strange quark PDF ?

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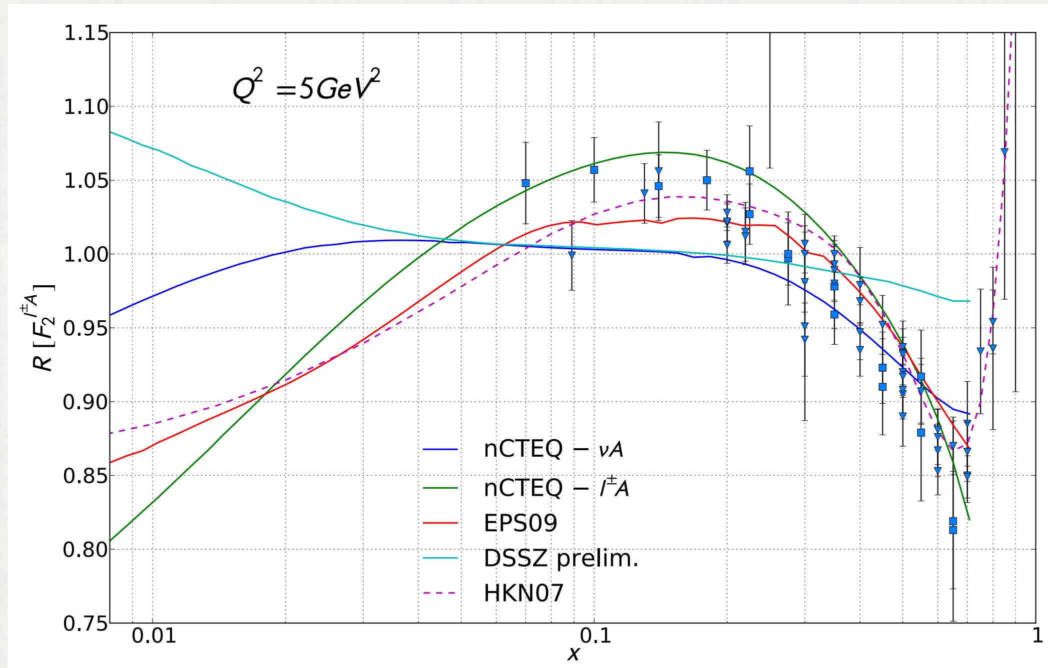
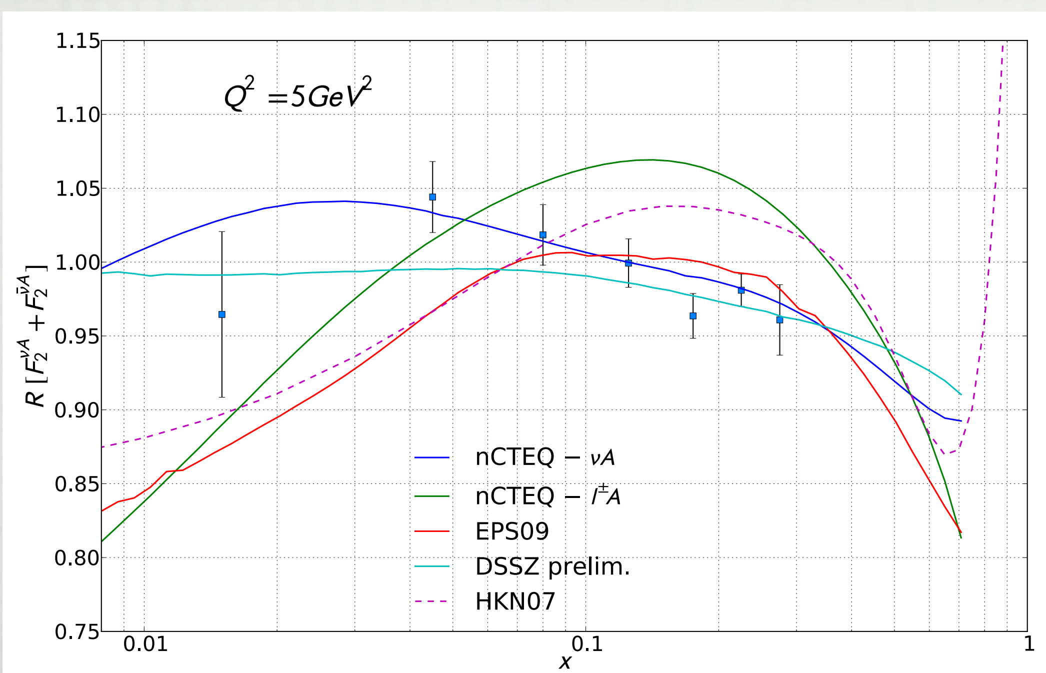
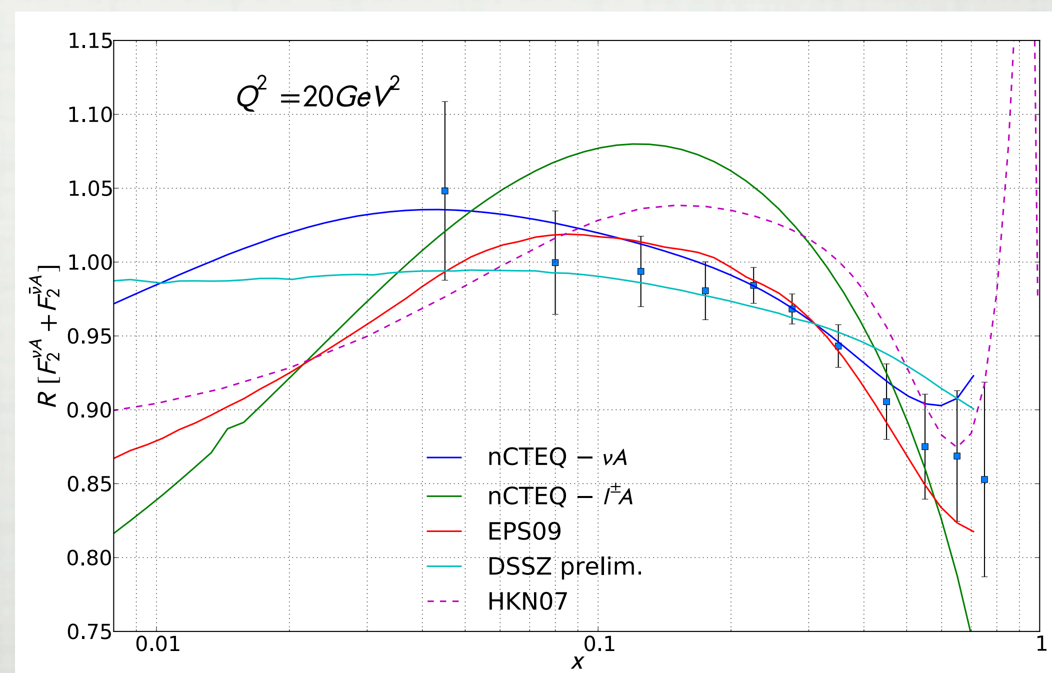
NEUTRINO DIS







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