nCTEQ

parton distribution functions

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OUTLINE

1. Motivation & Review of available nPDFs
2. New results from nCTEQ analysis
3. Conclusions & Outlook

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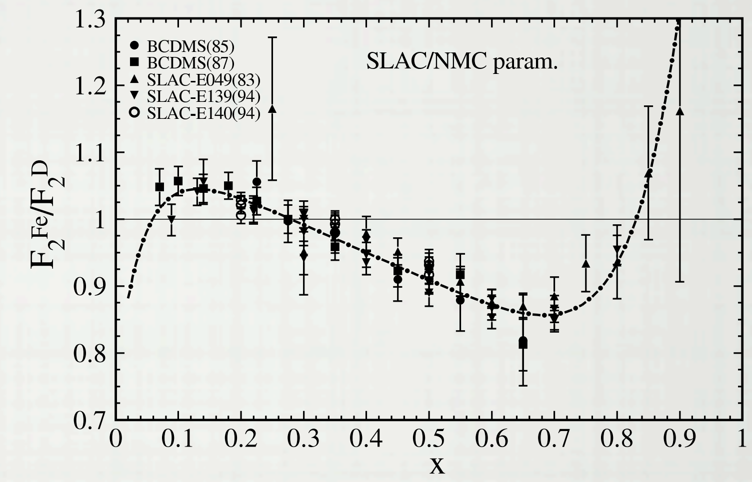
Motivation

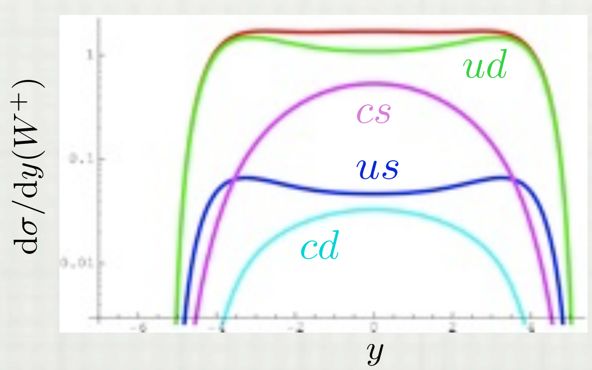
- What are nuclear parton density functions (nPDF) ?
  - parton densities for partons in bound proton & neutron



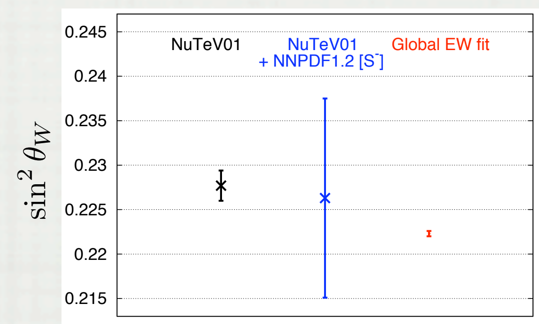
- Where are nuclear parton density functions useful ?

1. **Strange quark content of the proton**

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



W-boson production @ LHC



weak mixing angle from NuTeV experiment

2. **Heavy ion collisions @ RHIC, LHC**

   lead & gold heavy nuclei - nuclear effects in gluon PDF substantial

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nPDF REVIEW

- Review of existing global analyses of nuclear PDF

1. Multiplicative nuclear correction factor

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

bound parton density

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 [PRD85(2012)074028]arXiv: 1112.6324

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2. Native nuclear PDF

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

bound parton density

free parton density

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

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nPDF review

- Review of existing global analyses of nuclear PDF

HIRAI, KUMANO, NAGAI'07 [PRC76(2007)065207]
LO, NLO, ERROR PDFS

- uses multiplicative factor

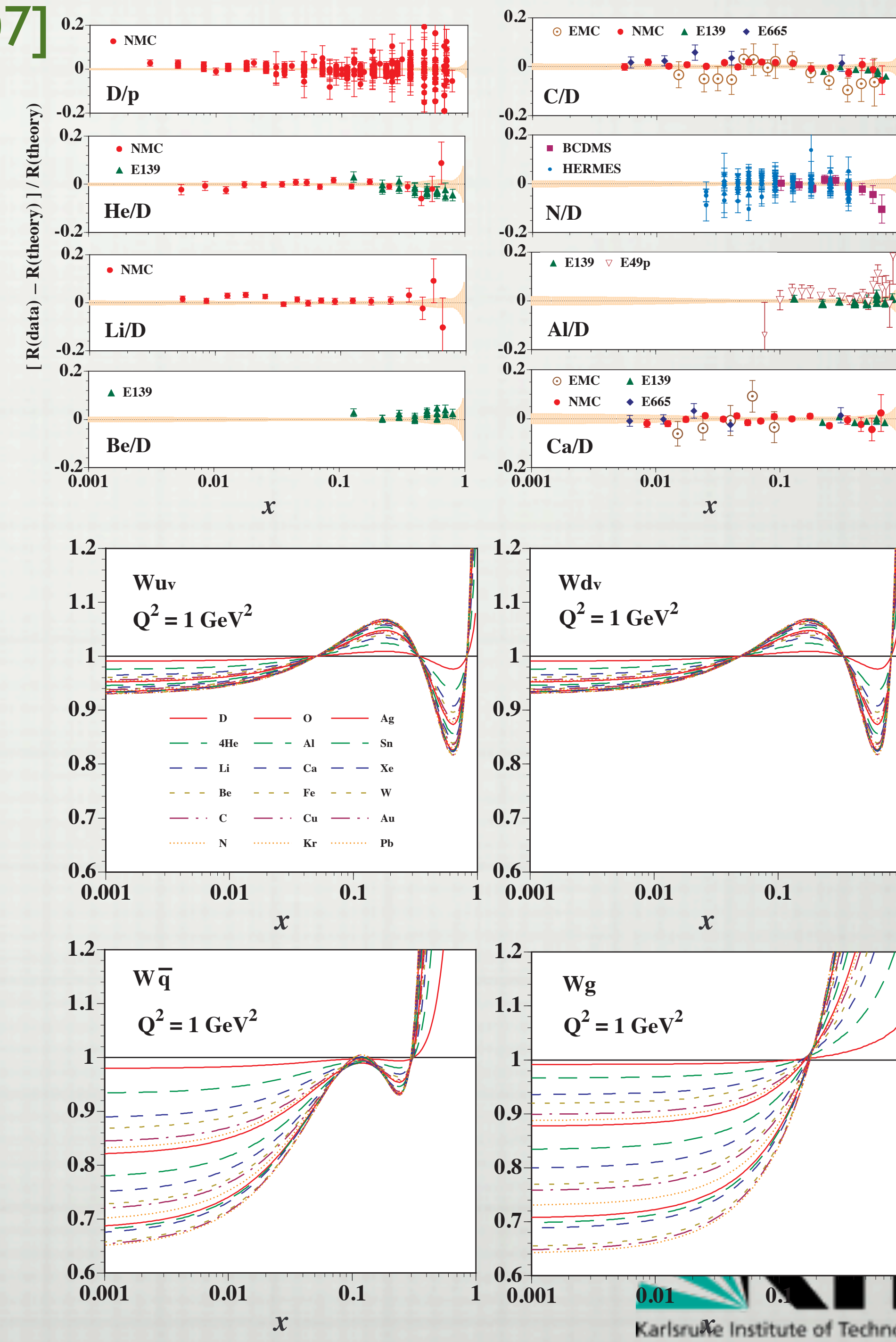
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in MRST 1998 and factor

$$R_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

- neglects region x>1
- includes all current DIS & DY data set (same as our analysis - discussed later)
- use Hessian method to produce error PDFs

χ^2/dof = 1.2



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nPDF review

- Review of existing global analyses of nuclear PDF

ESKOLA, PAUKKUNEN, SALGADO'09 [JHEP0904(2009)065]
LO, NLO, ERROR PDFS

χ^2/dof = 0.8

- uses multiplicative factor

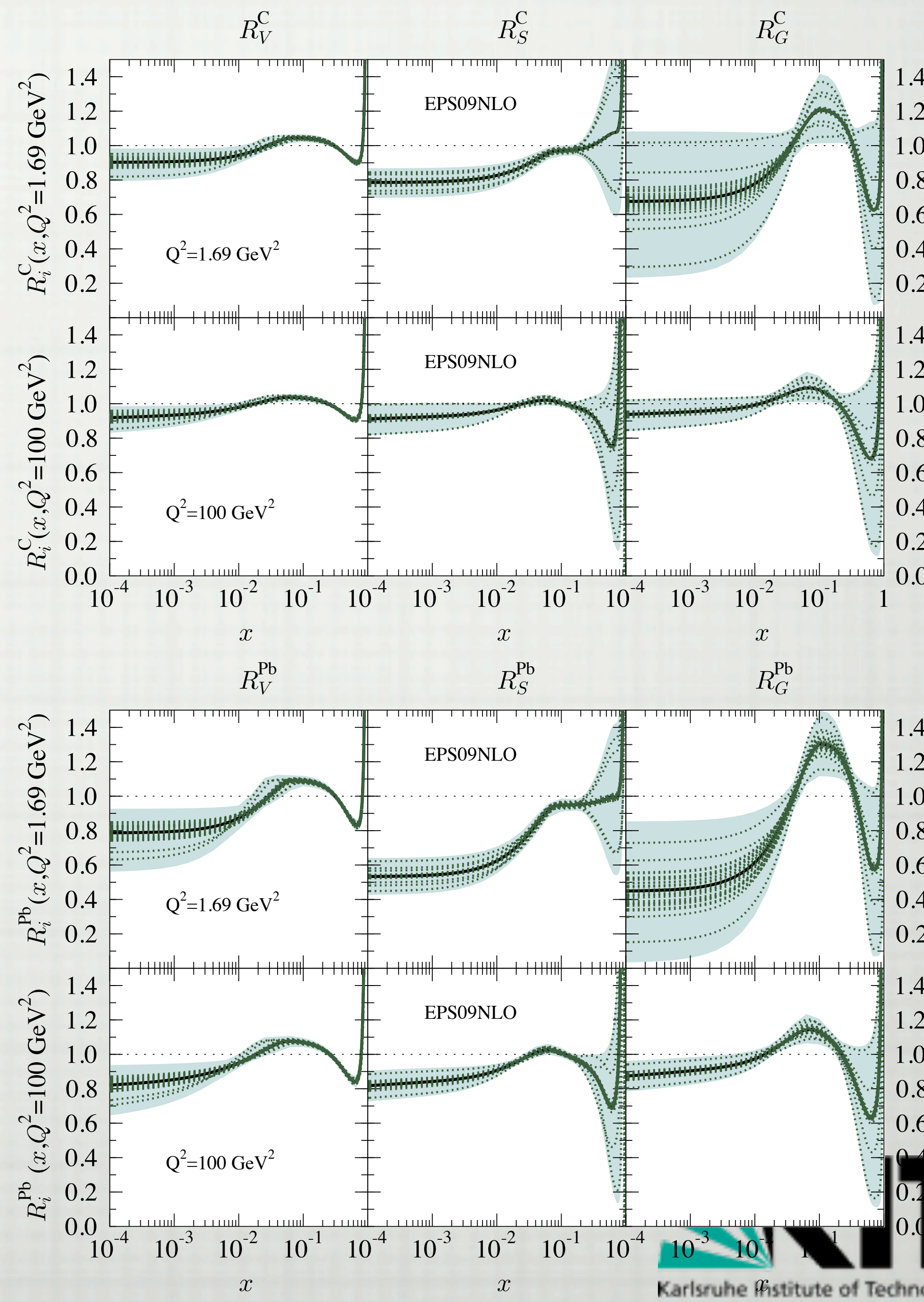
$$f_i^A(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i(x_N, Q_0^2)$$

where proton PDF in CTEQ6.1M and factor is a complicated piecewise defined function

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

with A-dependent parameters

- neglects region x>1
- includes all current DIS & DY data set & π^0 RHIC data to constrain gluon
- use Hessian method to produce error PDFs



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nPDF review

- Review of existing global analyses of nuclear PDF

DE FLORIAN, SASSOT, STRATMANN, ZURITA [PRD85(2012)074028]
LO, NLO, ERROR PDFS

- uses multiplicative factor

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

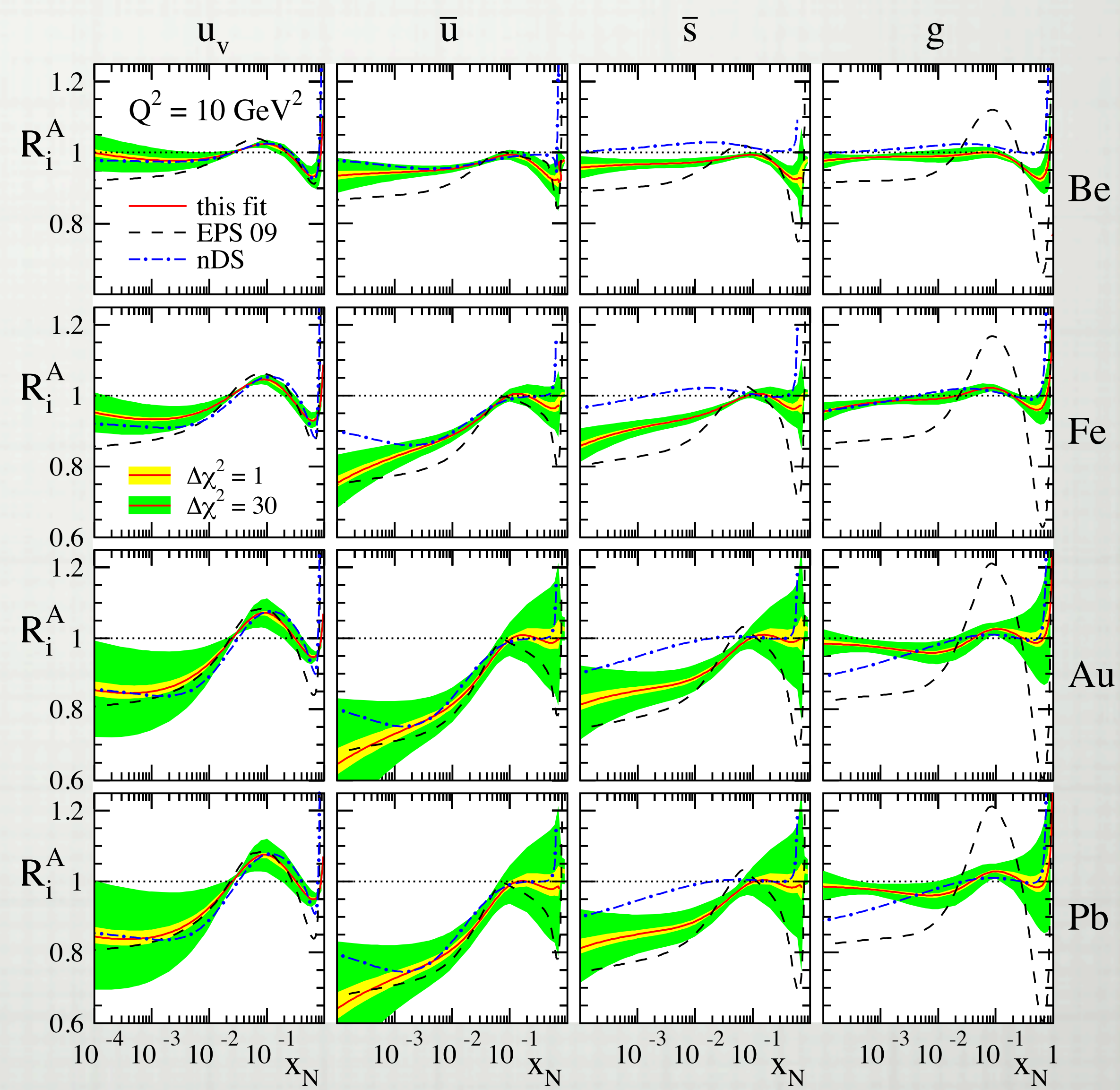
where proton PDF in MSTW08 and factor is a complicated function different for each flavour

$$R_v^A(x, Q_0^2) = \epsilon_1\, x^{\alpha_v}(1-x)^{\beta_1}\left(1+\epsilon_2(1-x)^{\beta_2}\right)\times$$
$$\times\left(1+a_v(1-x)^{\beta_3}\right)$$

$$R_s^A(x, Q_0^2) = R_v^A(x, Q_0^2)\,\frac{\epsilon_s}{\epsilon_1}\,\frac{1+a_s x^{\alpha_s}}{a_s+1}$$

$$R_g^A(x, Q_0^2) = R_v^A(x, Q_0^2)\,\frac{\epsilon_g}{\epsilon_1}\,\frac{1+a_g x^{\alpha_g}}{a_g+1}$$

- includes all current DIS & DY data set & π^0 RHIC data and $F_2^{\nu A}$ from neutrino data
- use Hessian method to produce error PDFs



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nCTEQ

- CTEQ framework for nuclear PDF - based on CTEQ6M proton fit
  - functional form for bound protons same as for free proton PDF (restrict x to 0<x<1)

$$x\, f_k(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5} \qquad k = u_v, d_v, g, \bar{u} + \bar{d}, s, \bar{s}$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0\, x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

  - coefficients with A-dependance (reduces to proton for A=1)

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

  - proton coefficients $c_{k,0}$ fixed to special CTEQ6M fit without much of nuclear data
  - PDF for a nucleus with A-nucleons out of which Z-protons

$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A - Z}{A} f_i^{n/A}(x, Q)$$

  - Input scale and other input parameters as in CTEQ6M proton analysis

$$Q_0 = m_c = 1.3\mathrm{GeV} \qquad m_b = 4.5\,\mathrm{GeV} \qquad \alpha_s(m_Z) = 0.118$$

  - Kinematic cuts on data

$$Q > 2\,\mathrm{GeV} \qquad W > 3.5\,\mathrm{GeV}$$

nCTEQ [PRD80(2009)094004] arXiv: 0907.2357

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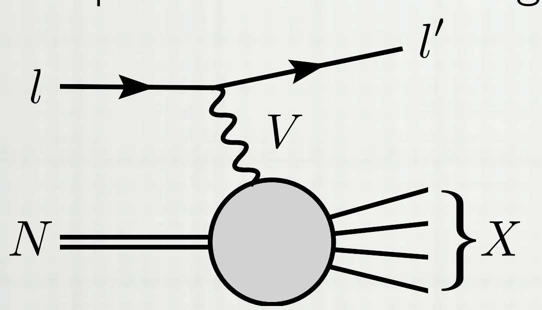
nCTEQ

- Experiments included in the analysis

NOT (YET) INCLUDED

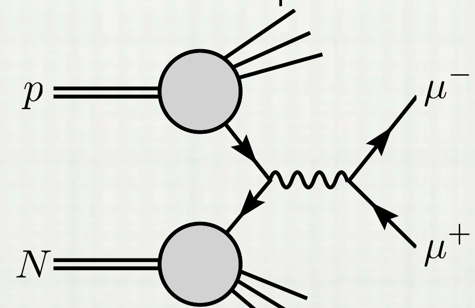
Charged lepton

Deep Inelastic Scattering



$l + N \to l' + X$

Drell-Yan process



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

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
$N = (\mathrm{D, Ag, Al, Au, Be, C, Ca, Fe, He})$

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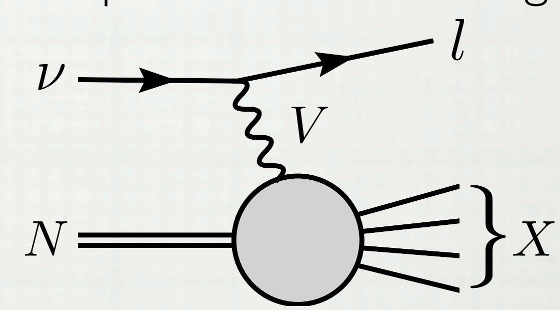
1233 data points (708 after cuts)

Neutrino

Deep Inelastic Scattering

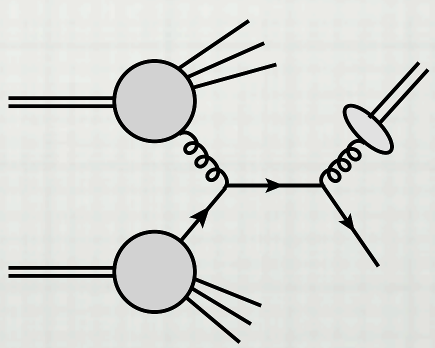


$\nu(\bar{\nu}) + N \to l + X$

CHORUS
$N = \mathrm{Pb}$

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

Single pion production



RHIC - PHENIX & STAR
$\mathrm{N = Au}$

nCTEQ

- NPDF fit properties:
  - we fit nuclear data with NLO QCD predictions
  - we include heavy quark effects (ACOT)
  - applied standard CTEQ kinematical cuts **Q>2GeV & W>3.5GeV**

- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 17 free parameters - 691 degrees of freedom
  - overall χ^2/dof = 0.87
  - individually for different data subsets
    - for F_2^A/F_2^D χ^2/pt = 0.80
    - for $F_2^A/F_2^{A'}$ χ^2/pt = 0.51
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$ χ^2/pt = 0.85

$\mathbf{F_2^A/F_2^{A'}}$: Observable	Experiment	# data
Be/C	NMC-96	15
Al/C	NMC-96	15
Ca/C	NMC-95	20
	NMC-96	15
Fe/C	NMC-95	15
Sn/C	NMC-96	144
Pb/C	NMC-96	15
C/Li	NMC-95	20
Ca/Li	NMC-95	20
Total:		279

$\mathbf{\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}}$: Observable	Experiment	# data
C/D	FNAL-E772-90	9
Ca/D	FNAL-E772-90	9
Fe/D	FNAL-E772-90	9
W/D	FNAL-E772-90	9
Fe/Be	FNAL-E866-99	28
W/Be	FNAL-E866-99	28
Total:		92

$\mathbf{F_2^A/F_2^D}$: Observable	Experiment	# data
D	NMC-97	275
He/D	SLAC-E139	18
	NMC-95,re	16
	Hermes	92
Li/D	NMC-95	15
Be/D	SLAC-E139	17
C/D	EMC-88	9
	EMC-90	2
	SLAC-E139	7
	NMC-95,re	16
	NMC-95	15
	FNAL-E665-95	4
N/D	BCDMS-85	9
	Hermes	92
Al/D	SLAC-E049	18
	SLAC-E139	17
Ca/D	EMC-90	2
	SLAC-E139	7
	NMC-95,re	15
	FNAL-E665-95	4
Fe/D	BCDMS-85	6
	BCDMS-87	10
	SLAC-E049	14
	SLAC-E139	23
	SLAC-E140	6
Cu/D	EMC-88	9
	EMC-93(addendum)	10
	EMC-93(chariot)	9
Kr/D	Hermes	84
Ag/D	SLAC-E139	7
Sn/D	EMC-88	8
Xe/D	FNAL-E665-92	4
Au/D	SLAC-E139	18
Pb/D	FNAL-E665-95	4
Total:		862

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- NPDF Hessian analysis:

$$\chi^2 = \chi_0^2 + \frac{1}{2} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \qquad H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

  - 17 free parameters - 7 gluon parameters
    - 8 valence parameters
    - 2 sea parameters
  - Eigenvalues span 10 orders of magnitude → numerical precision required
  - Use improved derivatives - less sensitive to noise

$$\frac{\partial f}{\partial x} = \frac{f_1 - f_{-1}}{2h}$$

central differences

$$\frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3})}{28h}$$

noise robust Lanczos 3, 5-point derivative

$$\frac{f_1 - f_{-1} + 2(f_2 - f_{-2}) + 3(f_3 - f_{-3}) + 4(f_4 - f_{-4}) + 5(f_5 - f_{-5})}{110h}$$

  - $\Delta\chi^2 = 35$ determined so that every nuclear target is described within 90% C.L.

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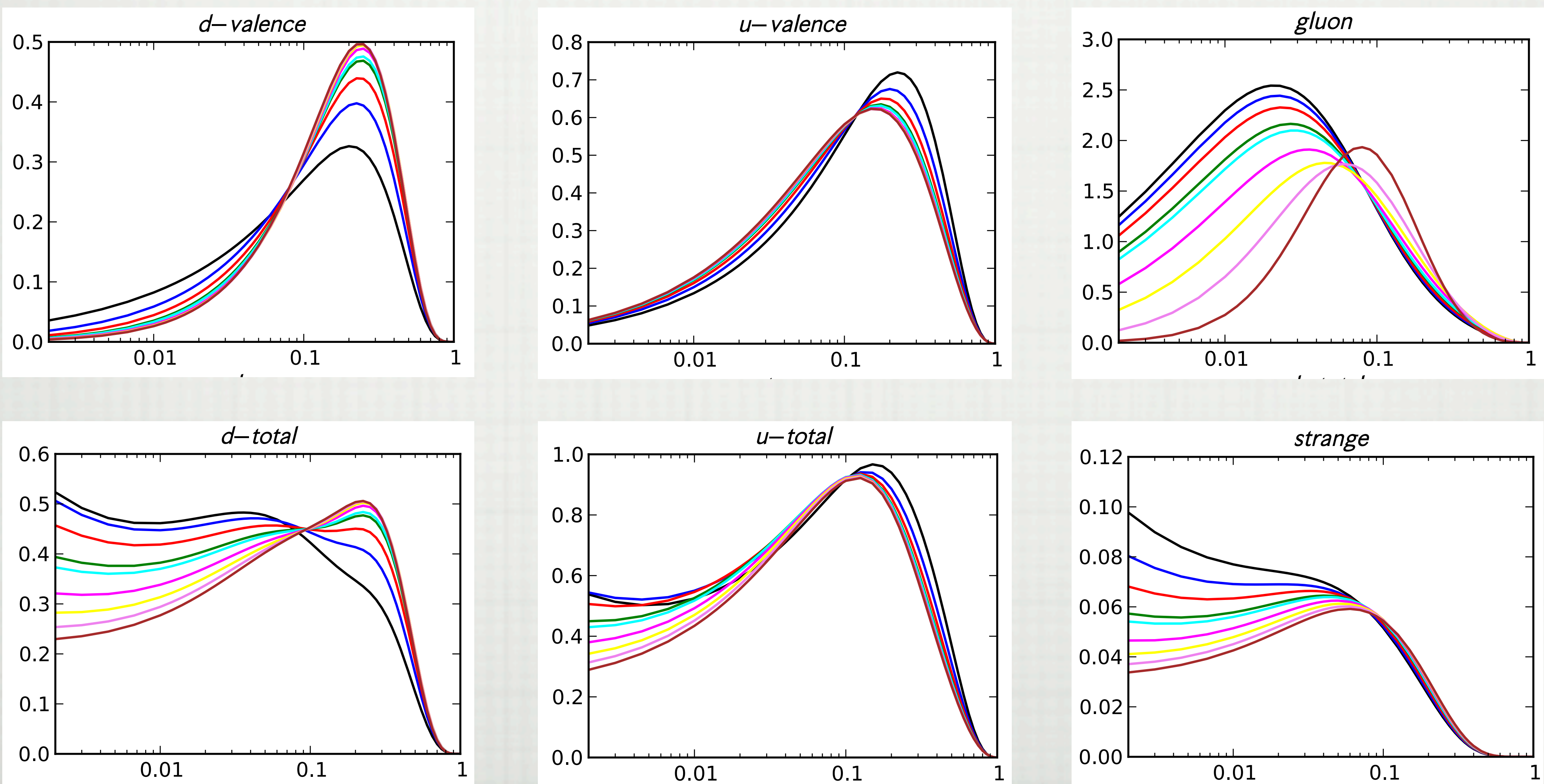
nCTEQ

- Parton density functions for bound partons as a function of x

black yellow brown

$$x\, f_k^A(x,Q) \text{ for } A = (1, 2, 4, 9, 12, 27, 56, 108, 207)$$

red purple



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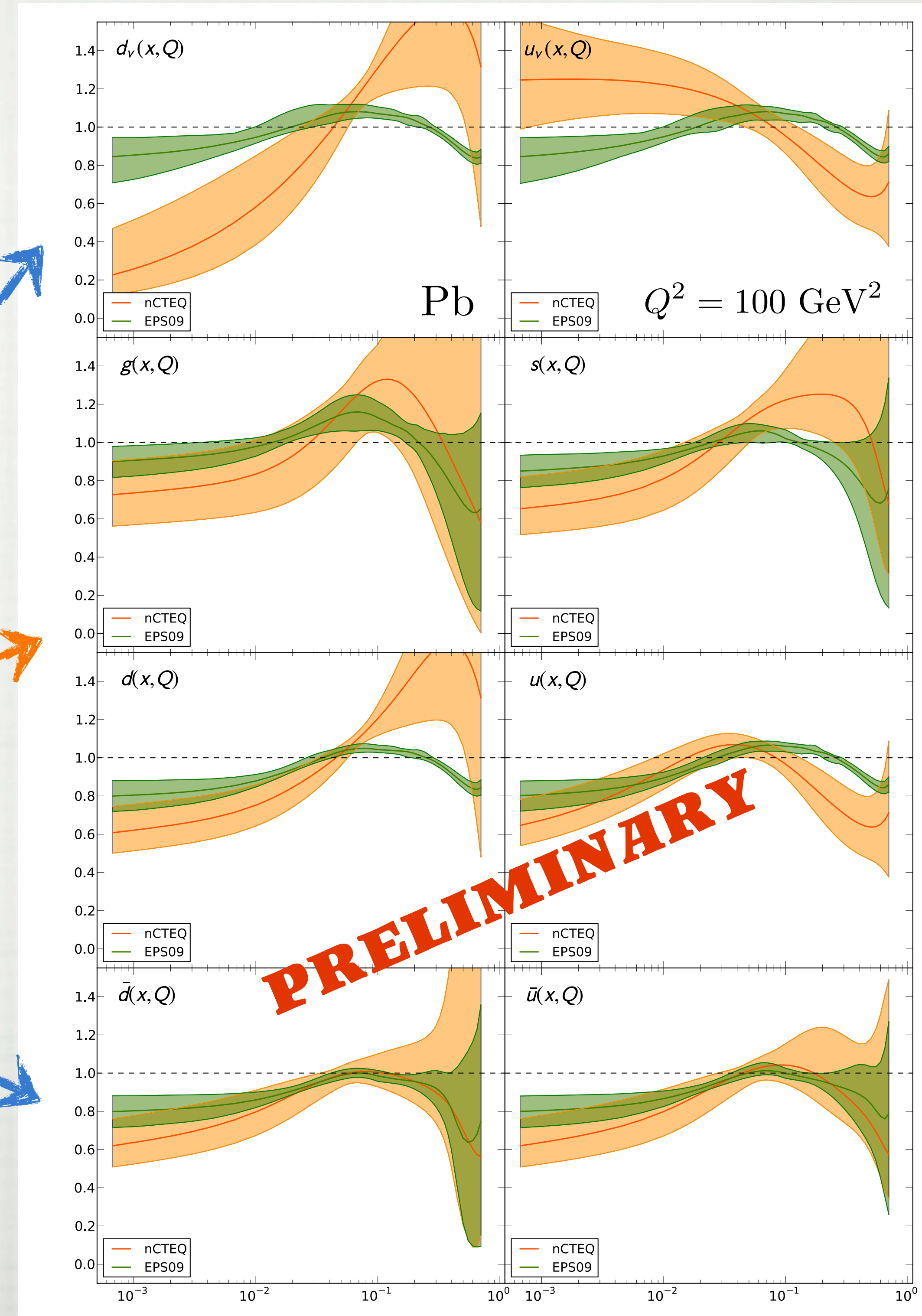
- nCTEQ nuclear correction factors with uncertainties

$$R_i(\mathrm{Pb}) = \frac{f_i^{Pb}(x,Q)}{f_i^{p}(x,Q)} \quad @ \;\; Q^2 = 100\ \mathrm{GeV}^2$$

  - different solution for d-valence & u-valence compared to EPS09
  - larger uncertainty @ gluon nuclear correction factor & bigger low-x suppression
  - sea quark nuclear correction factors similar to EPS09
  - nuclear correction factors depend largely on underlying proton baseline

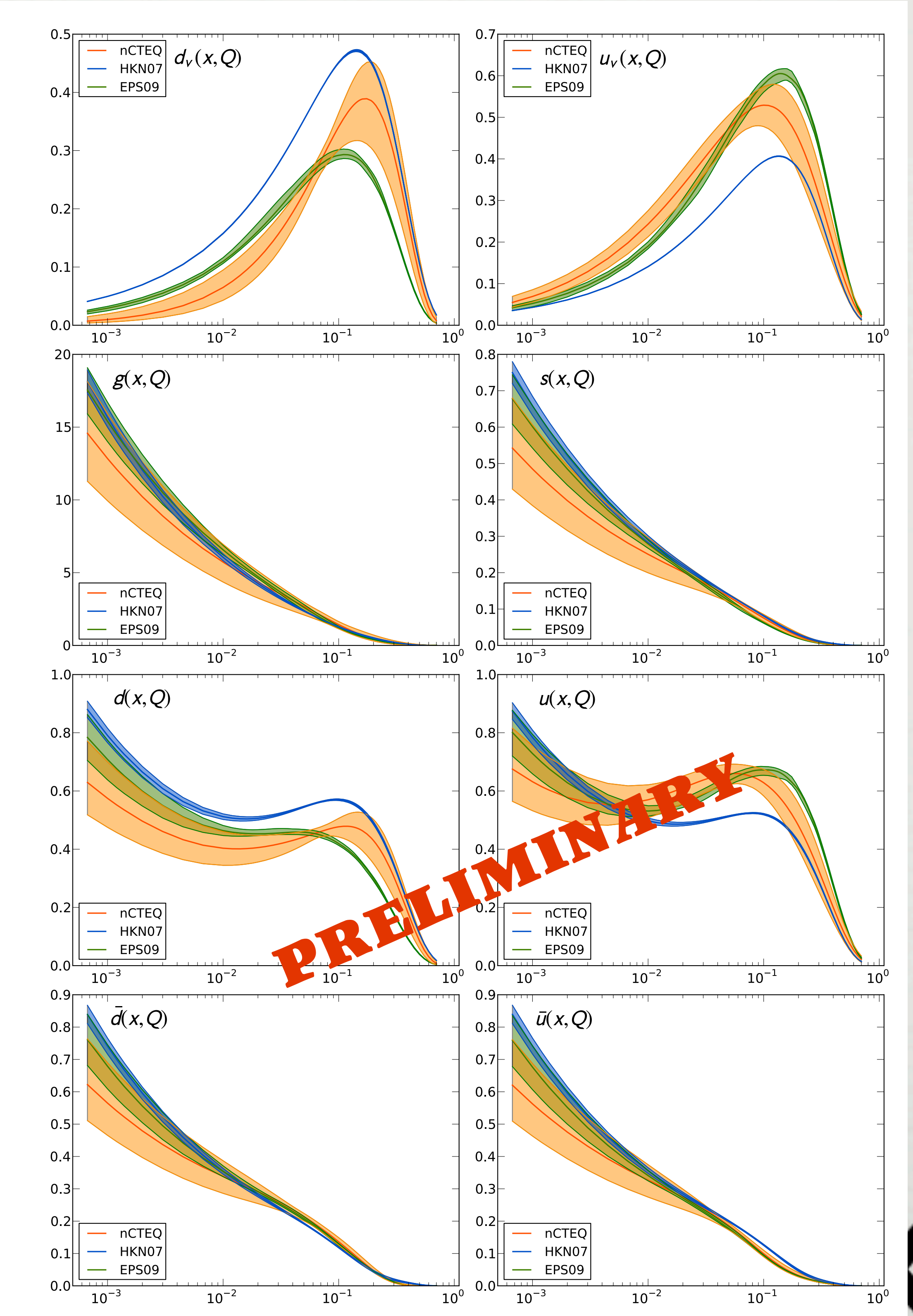


nCTEQ

- nCTEQ nuclear PDFs with uncertainties

$$xf_i^{\mathrm{Pb}}(x,Q) \quad @ \quad Q^2 = 100\ \mathrm{GeV}^2$$

  - nCTEQ d-valence & u-valence solution between HKN07 & EPS09
  - nCTEQ nuclear uncertainties larger than previous nPDF analyses
  - nPDFs not dependant on proton baseline - better agreement between different nPDFs
  - Results still very preliminary



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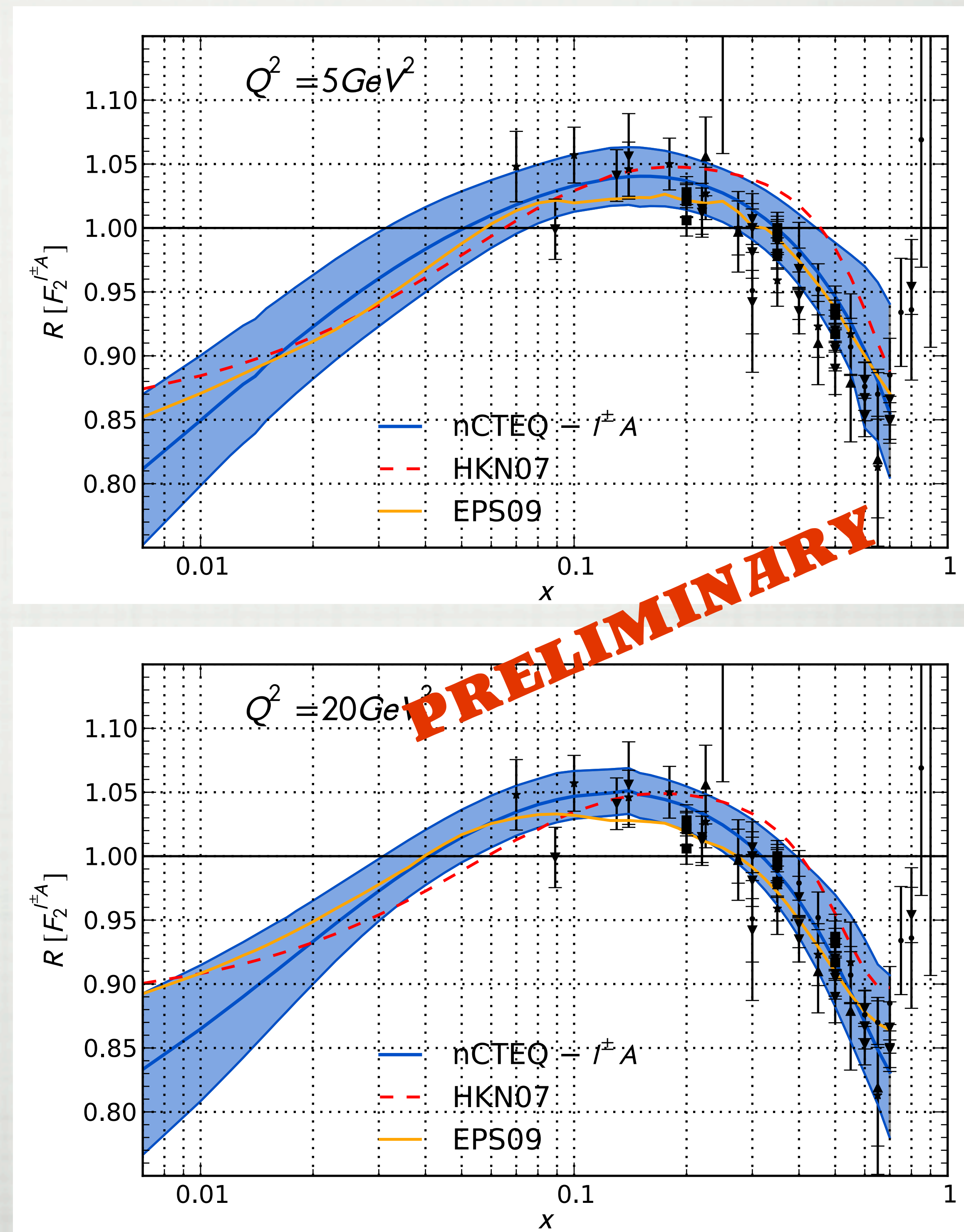
- nCTEQ structure function ratios with uncertainties

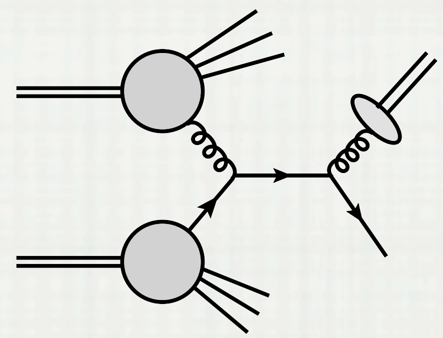
$$R = \frac{F_2^{Fe}(x,Q)}{F_2^{D}(x,Q)}$$



- Structure function ratios are fitted observables
- Despite different d-valence & u-valence solutions - ratio of structure functions remain very similar
- Good description of data & differences between nCTEQ and other nPDFs appear at low-x where there's no data

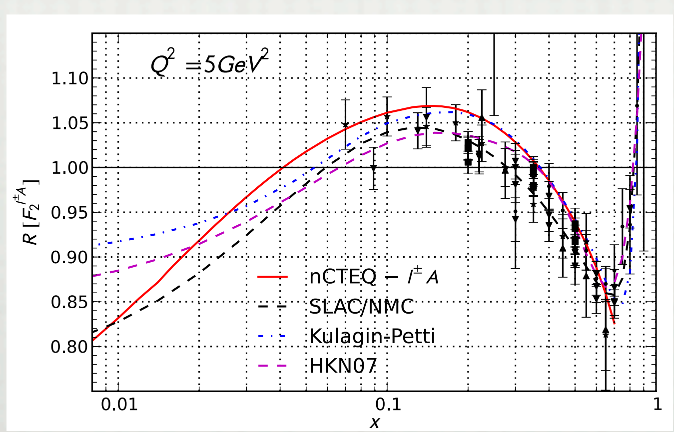
nCTEQ

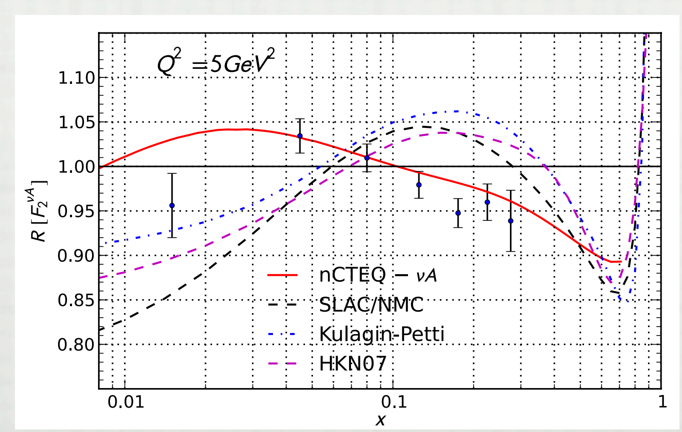
- Why is the nCTEQ analysis still **PRELIMINARY ?**
  - On-going work - inclusion of single inclusive pion production data from d-Au from RHIC



  - more realistic estimate of the nuclear gluon correction factor @ intermediate & high-x

- In discussion - inclusion of neutrino DIS data (inconsistencies within NuTeV data)





  - better flavour separation for nuclear effects

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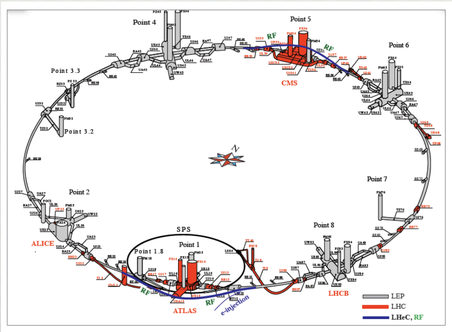
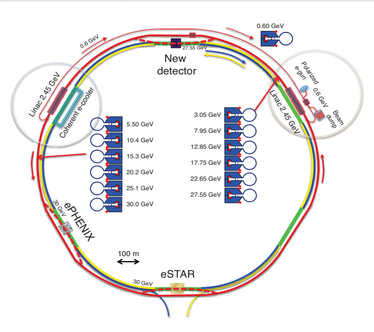
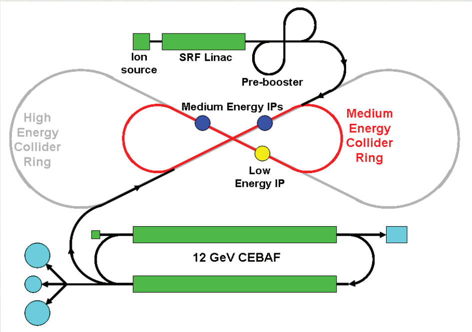
Conclusions & Outlook

- nCTEQ analysis still preliminary - RHIC data being included & analysed at the moment
- nCTEQ has larger uncertainties & larger nuclear suppression for gluon @ low-x
- LHC pPb data have a large potential to constrain nPDF
  - need baseline w/o LHC data first
- Next-generation colliders LHeC or EIC would be a game-changer for nPDFs







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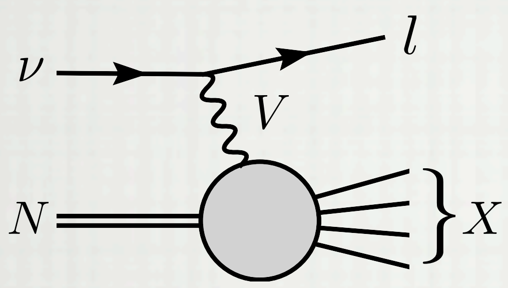
THANK YOU

BACKUP SLIDES

NEUTRINO DIS

- Neutrino DIS cross-section data



$\nu + N \to l + X$

NuTeV & di-muon $N = \mathrm{Fe}$ → 2310 data points

CHORUS $N = \mathrm{Pb}$ → 824 data points

All charged lepton DIS & Drell-Yan data → 708 data points

- Challenges in combining the neutrino & charged lepton data
  - deal with the disparity of number of data points - assigning weights to neutrino data
  - neutrino DIS data only with 2 heavy nuclei - insufficient to get a reliable A-dependance
  - do all neutrino data show the different behavior or only NuTeV ?
- Different neutrino observables

$$\frac{d\sigma^{\nu A}}{dx dQ^2} \;\&\; \frac{d\sigma^{\bar{\nu} A}}{dx dQ^2} \quad \text{vs.} \quad F_2^{\nu+\bar{\nu}}(x,Q^2) \;\&\; xF_3^{\nu+\bar{\nu}}(x,Q^2)$$

needs theory assumptions to extract

- Nuclear correction factors
  - we show correction factors defined e.g. as $R[F_2^{\nu}] = F_2^{\nu A} / F_2^{\nu A,\mathrm{free}}$

from free proton PDF

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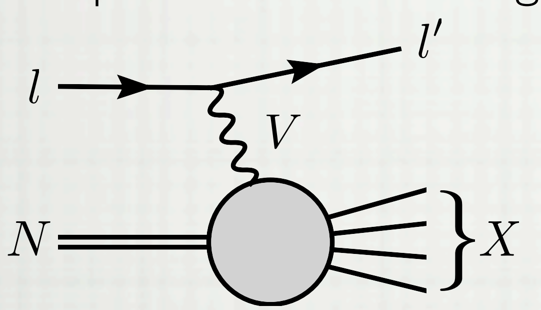
NEUTRINO DIS

- Experiments included in the analysis

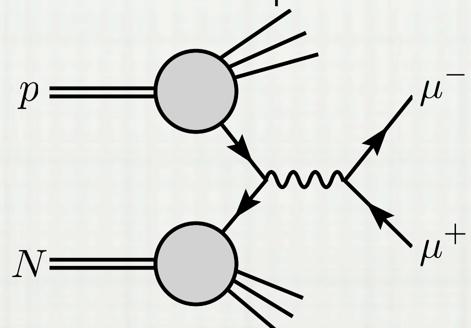
Charged lepton

Deep Inelastic Scattering



$l + N \to l' + X$

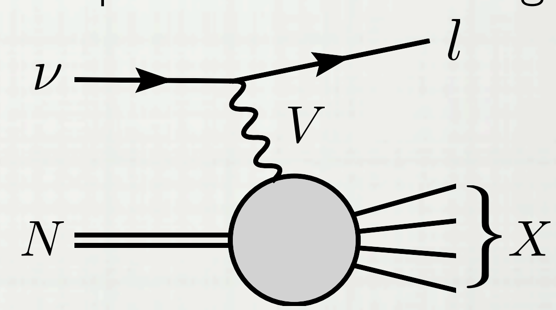
Drell-Yan process



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

Neutrino

Deep Inelastic Scattering



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

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

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

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

SLAC E-139 & E-049
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FNAL E-772 & E-886
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CHORUS
$N = \mathrm{Pb}$

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

1233 data points (708 after cuts)

3832 data points (3134 after cuts)

NEUTRINO DIS

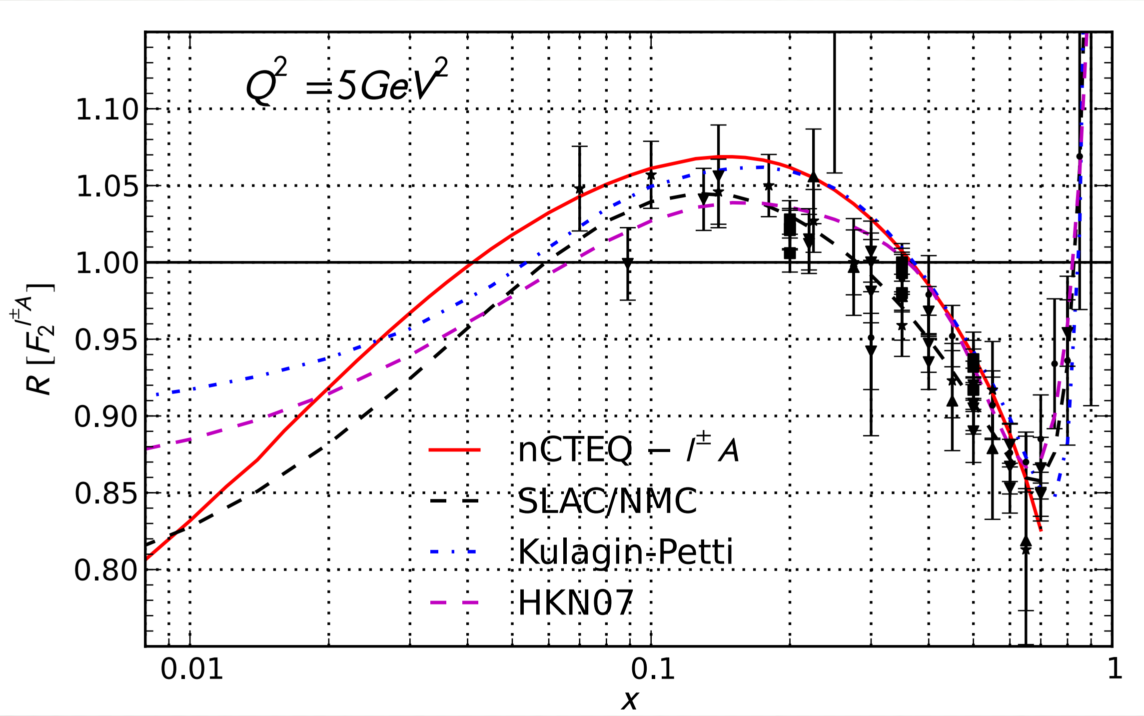
- Comparison of charged lepton and neutrino fits

KK et al.
[Phys.Rev.Lett. 106(2011) 122301] arXiv: 1012.1178

Fit to charged lepton data

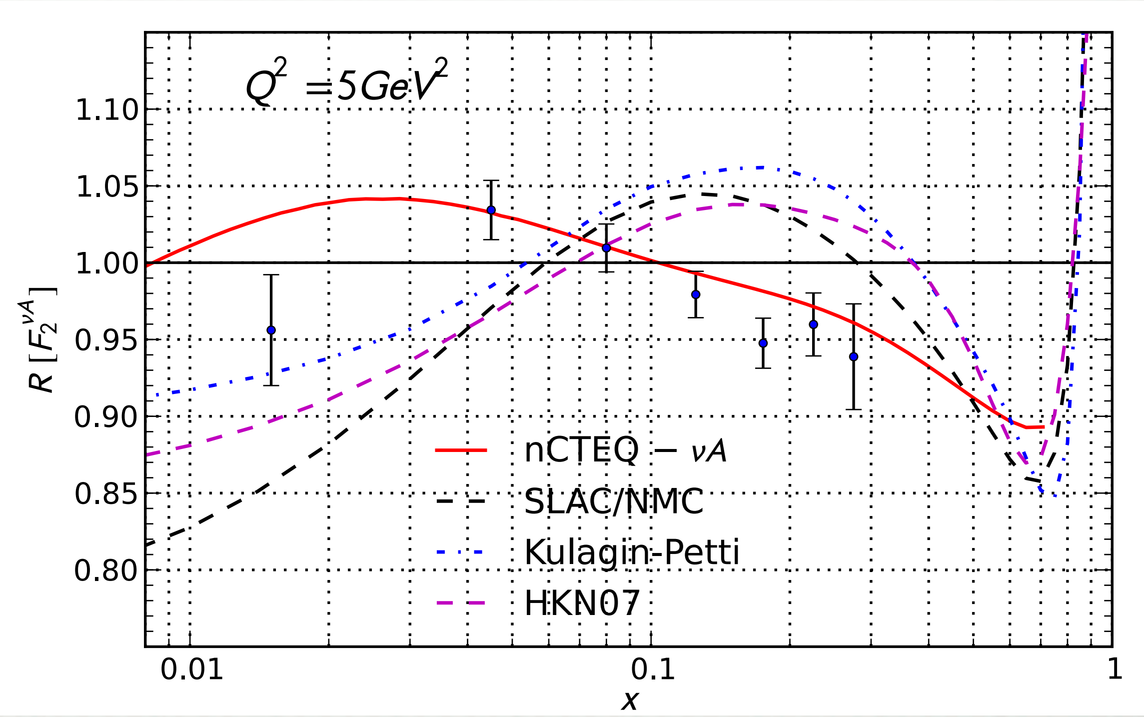
DIS & DY

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



Fit to only neutrino DIS

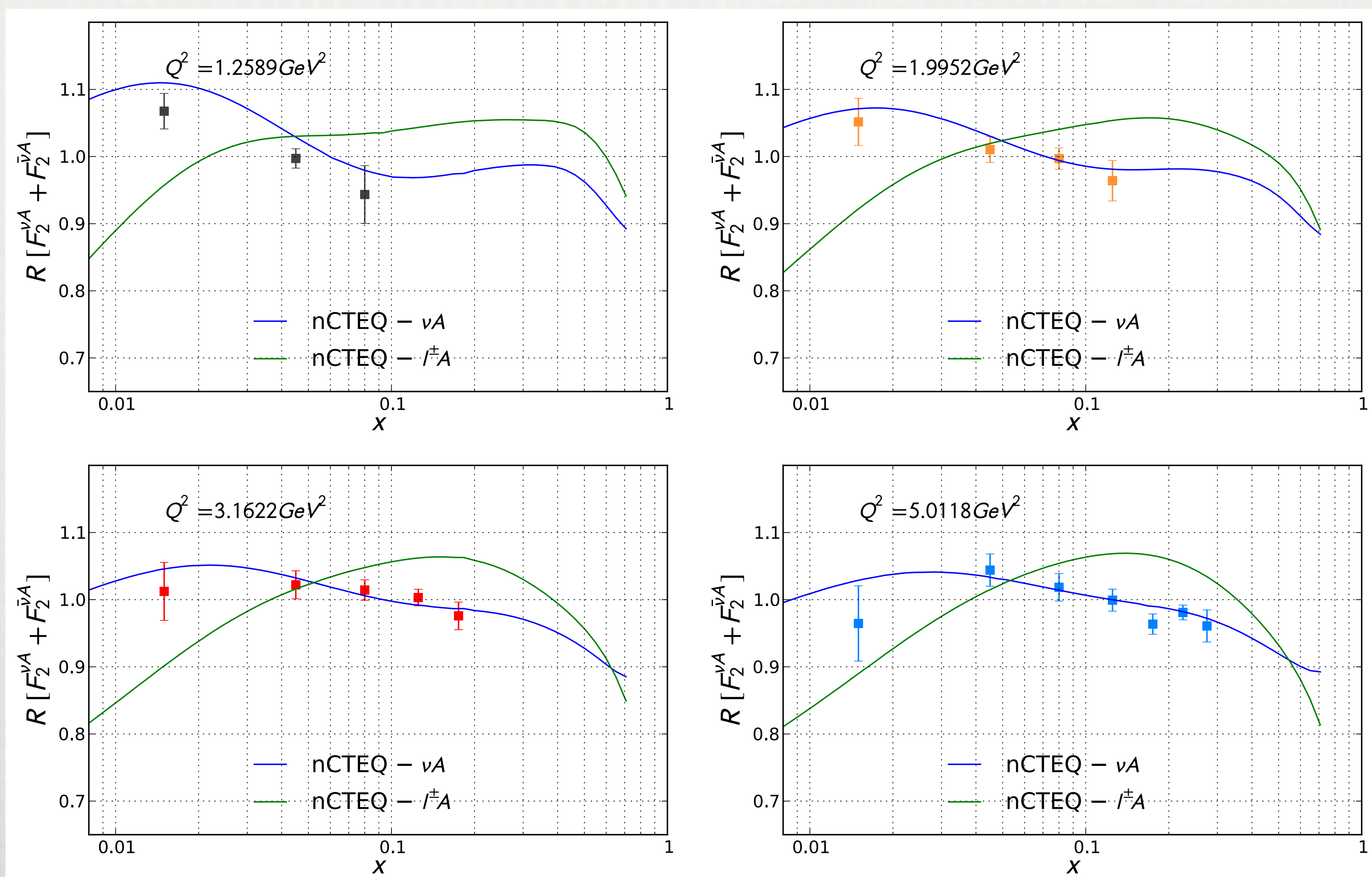
$\chi^2/\mathrm{d.o.f} = 1.33$



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

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 small-x data cause tension with the shadowing observed in charged lepton data



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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
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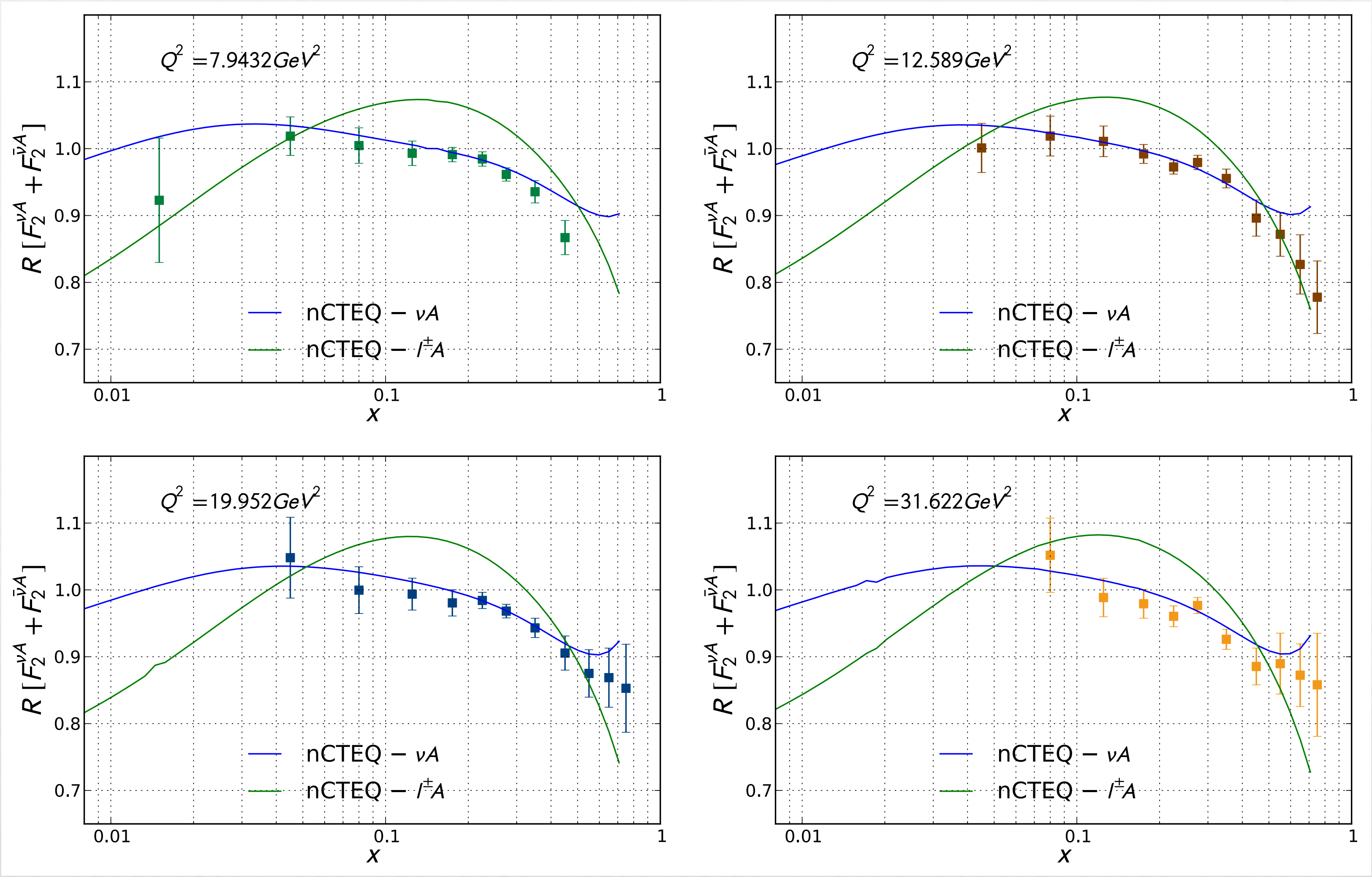

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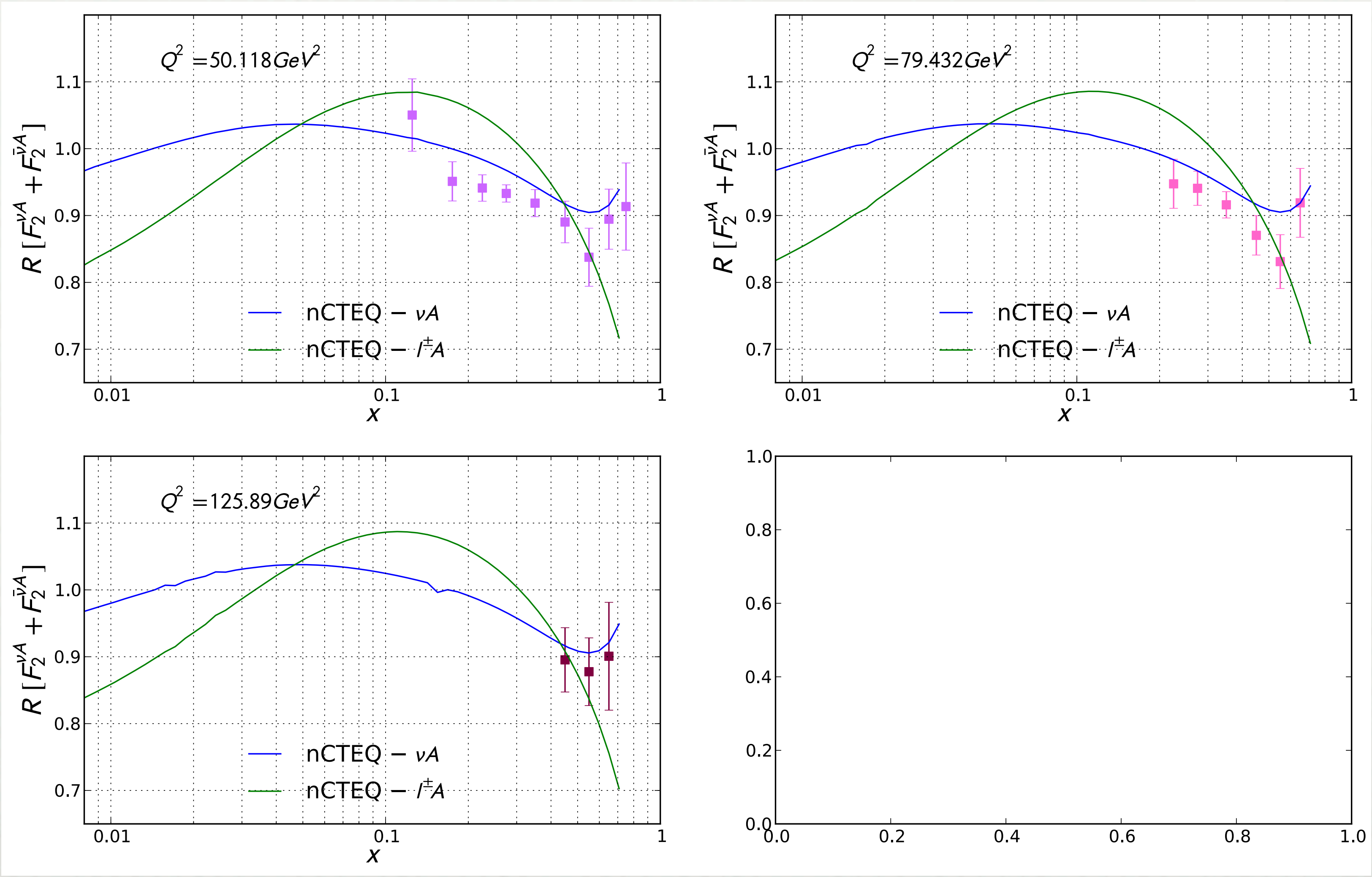

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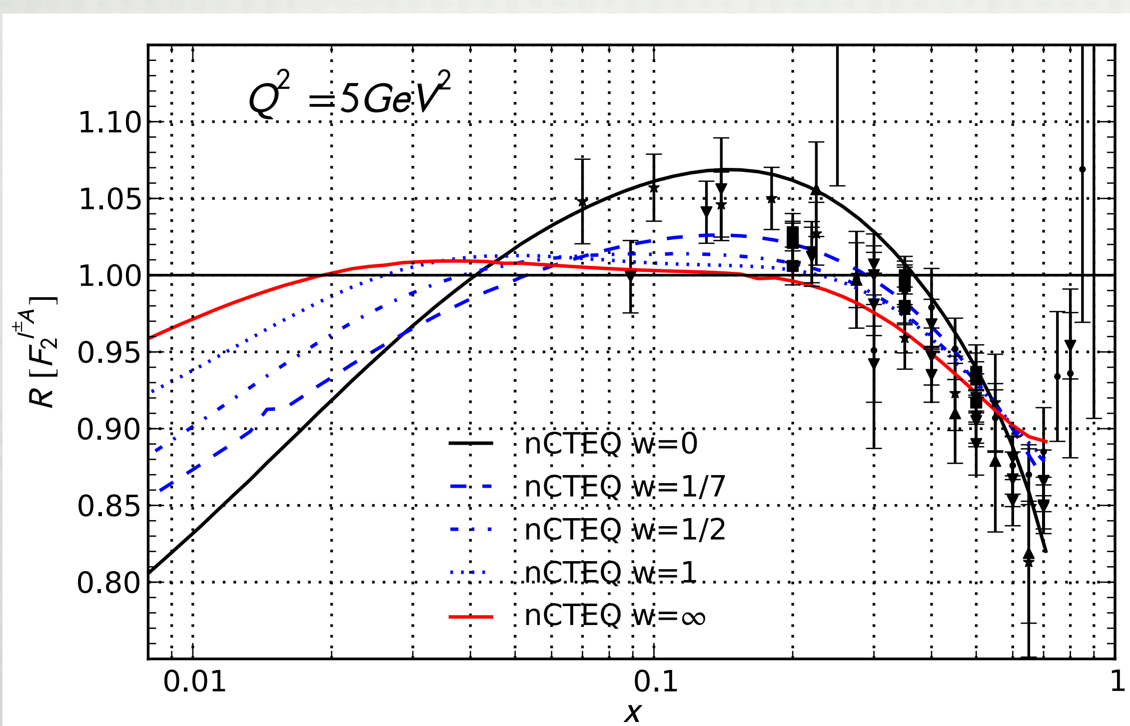
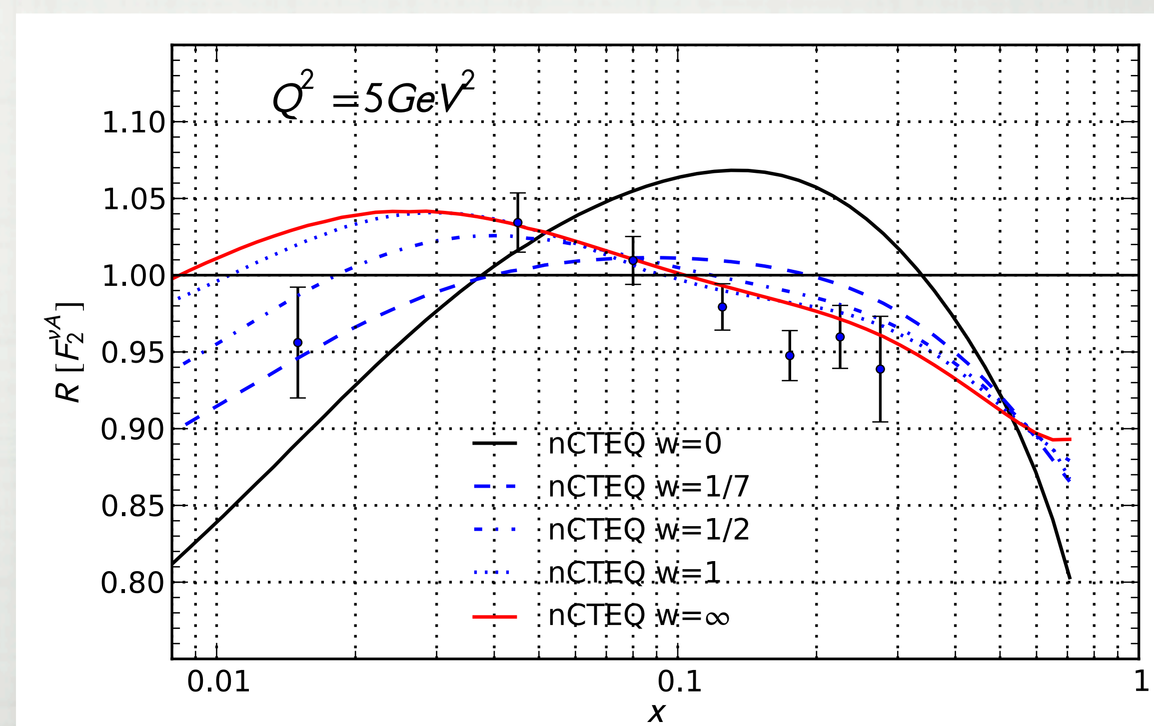
NEUTRINO DIS

- 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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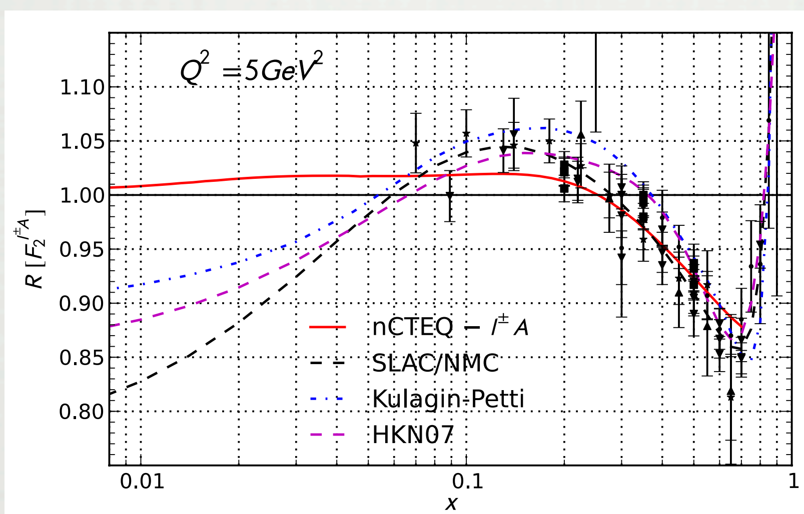
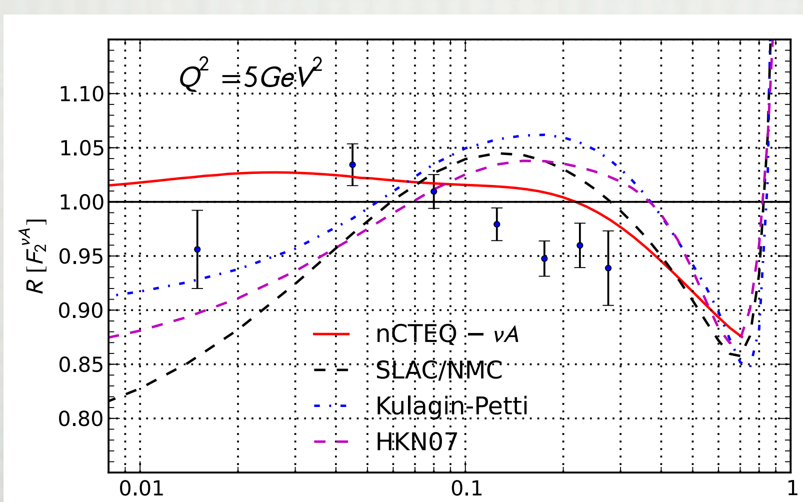
NEUTRINO DIS

- Analysis of fits with neutrino DIS (uncorrelated errors)

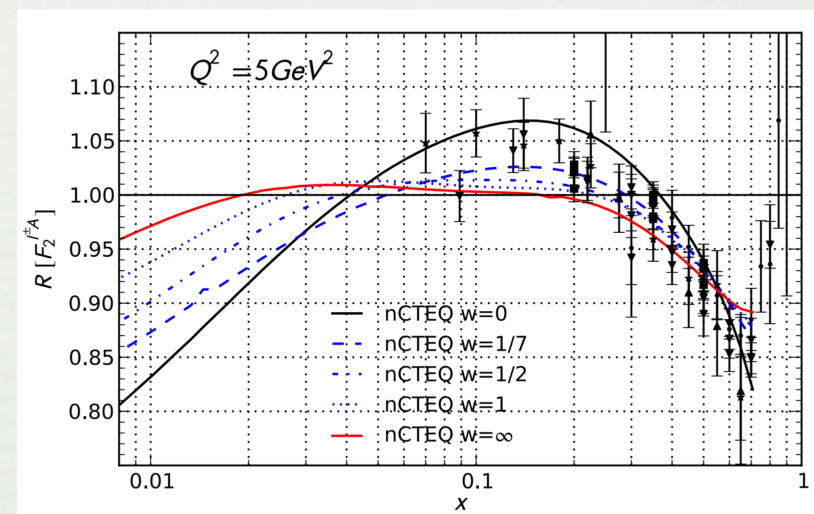
w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
1-corr	708	736 (1.04)	3134	4246 (1.36)	4983 (1.30)
1-uncorr	708	809 (1.14)	3110	3115 (1.00)	3924 (1.02)

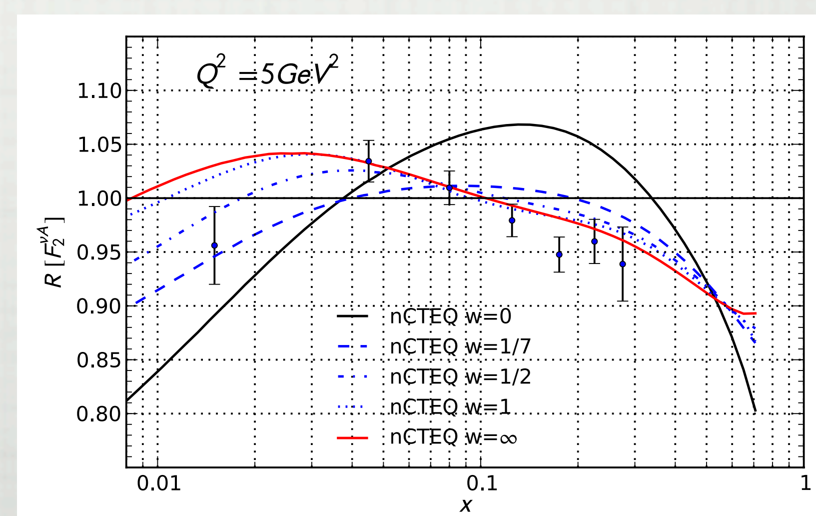
uncorrelated errors





correlated errors





NEUTRINO DIS

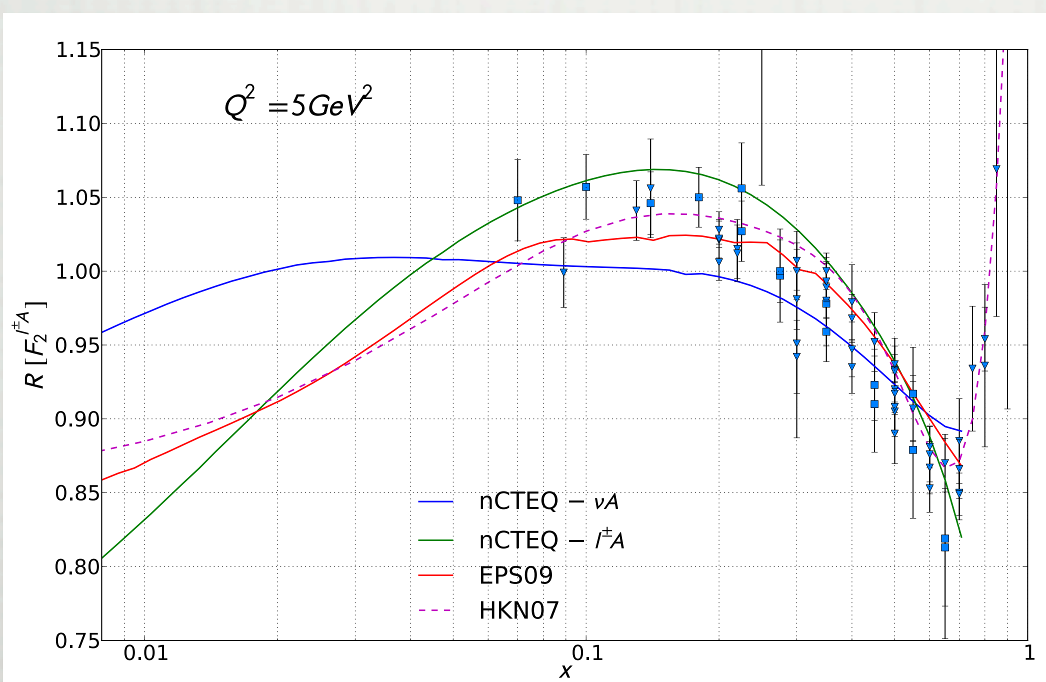
- Properties of neutrino fits
  - CHORUS data are in good agreement with the charged lepton data

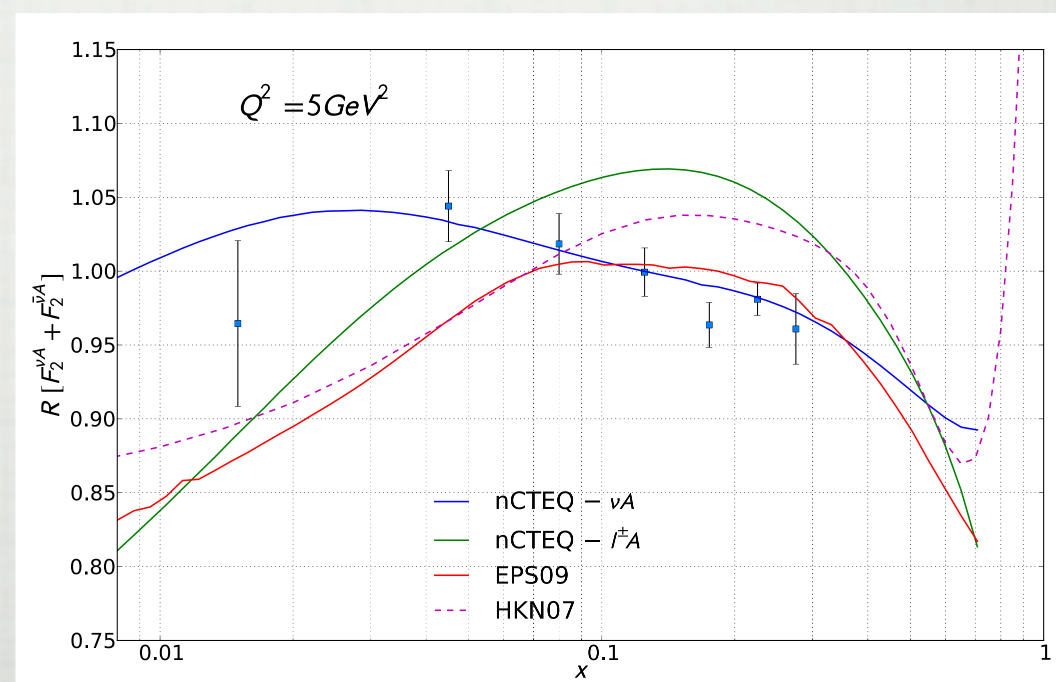
    combined: χ^2/pt=1.03

  - 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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