NUCLEAR PARTON DISTRIBUTION FUNCTIONS

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OUTLINE

1. Nuclear effects in PDFs
2. Overview of global nPDF analysis
3. Generalized CTEQ framework
4. Neutrino DIS data
5. Outlook

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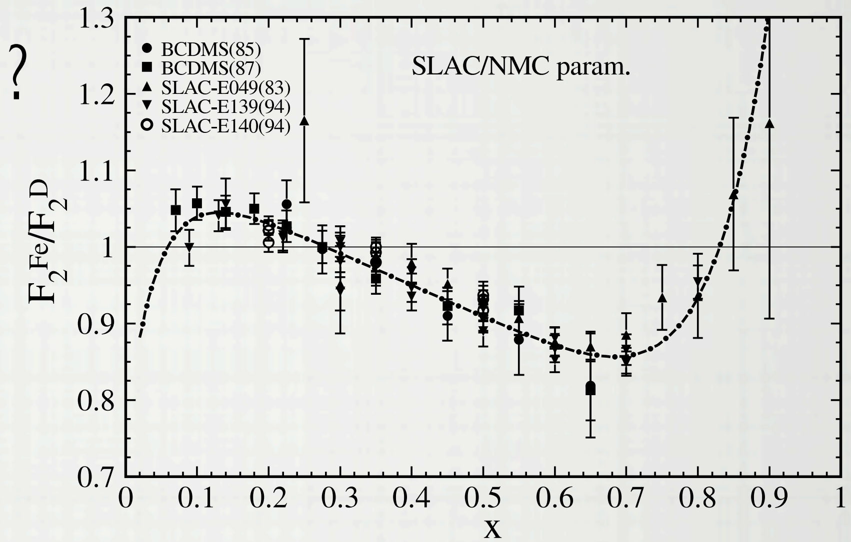
NUCLEAR EFFECTS

- What are nuclear parton density functions (nPDF) ?

  - parton densities for partons in bound proton & neutron



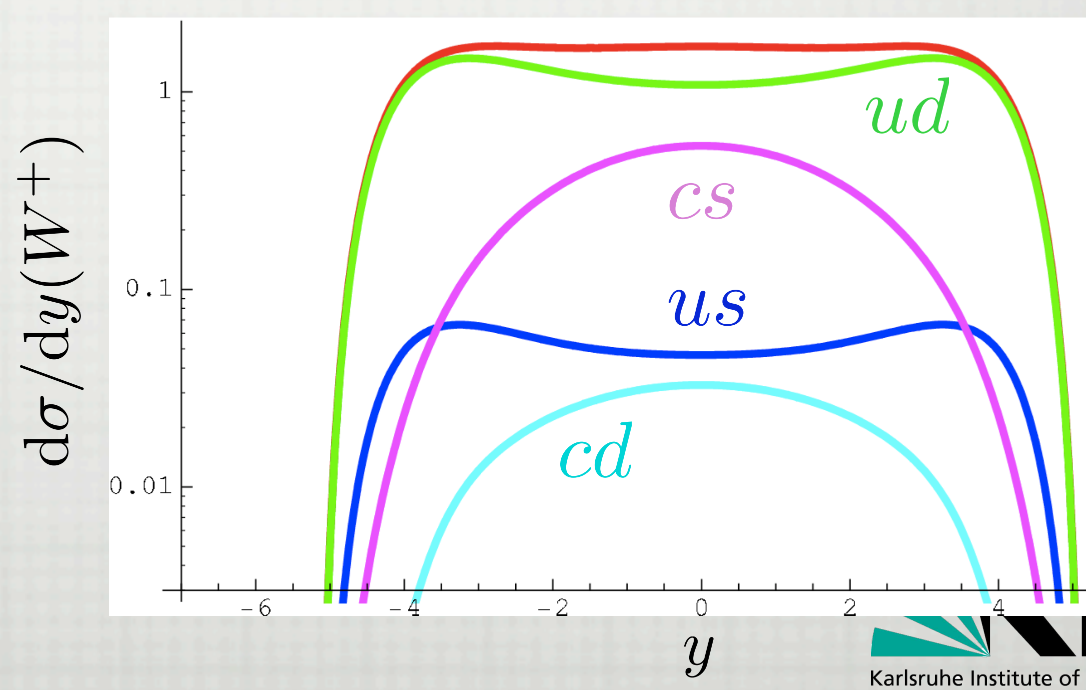
- Where are nuclear parton density functions useful ?

  1. Strange quark content of the proton

  strange PDF from neutrino DIS with heavy nuclei - nuclear effects very important

crucial for: W-boson production at the LHC

(standard candle process)



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NUCLEAR EFFECTS

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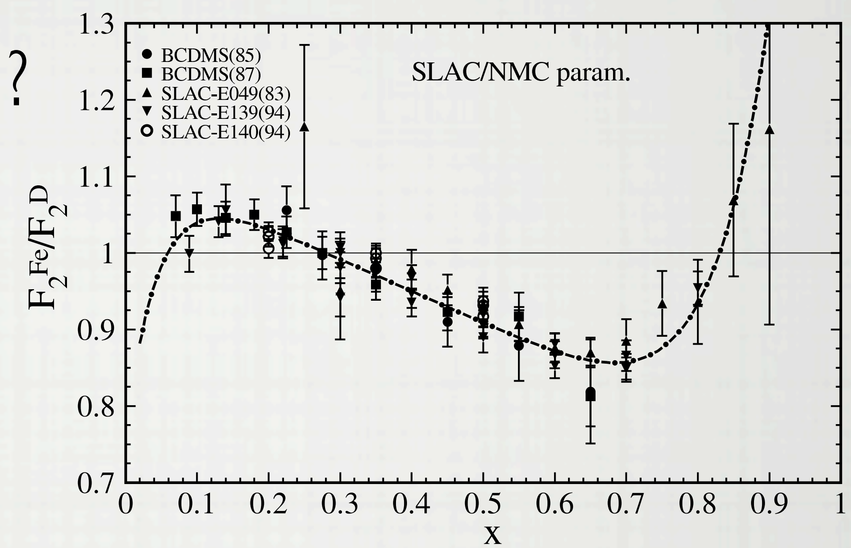


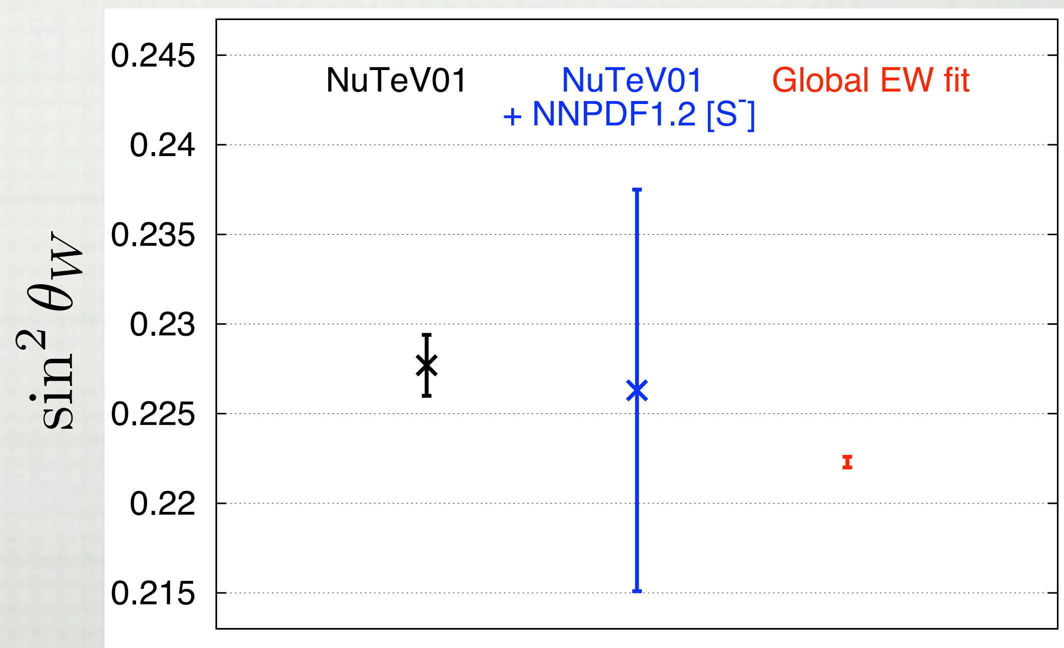
- Where are nuclear parton density functions useful ?

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

     strange PDF from neutrino DIS with heavy nuclei - nuclear effects very important

crucial for: determining weak mixing angle

from NuTeV experiment



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NUCLEAR EFFECTS

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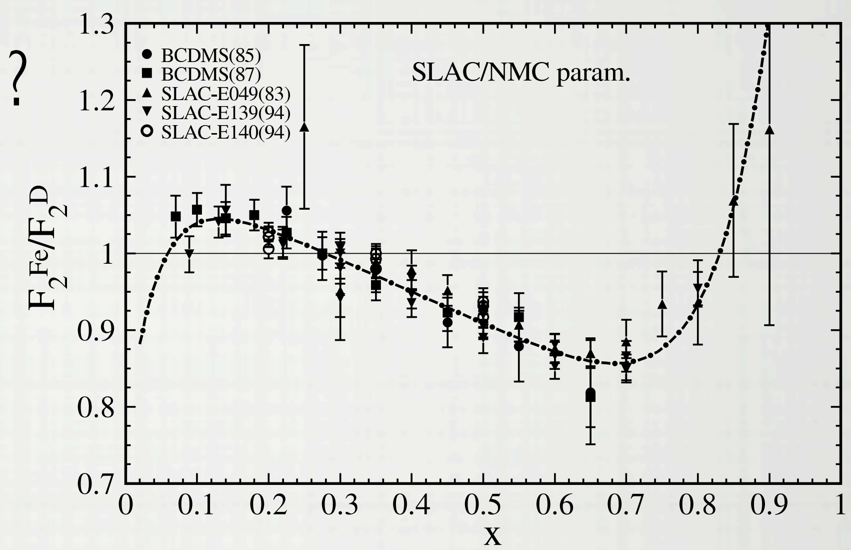

- Where are nuclear parton density functions useful ?

1. Strange quark content of the proton
2. Collisions of protons and nuclei at RHIC, ALICE & CMS
3. Neutrino scattering experiments e.g. MINERvA
4. Neutrino oscillations experiments e.g. MINOS

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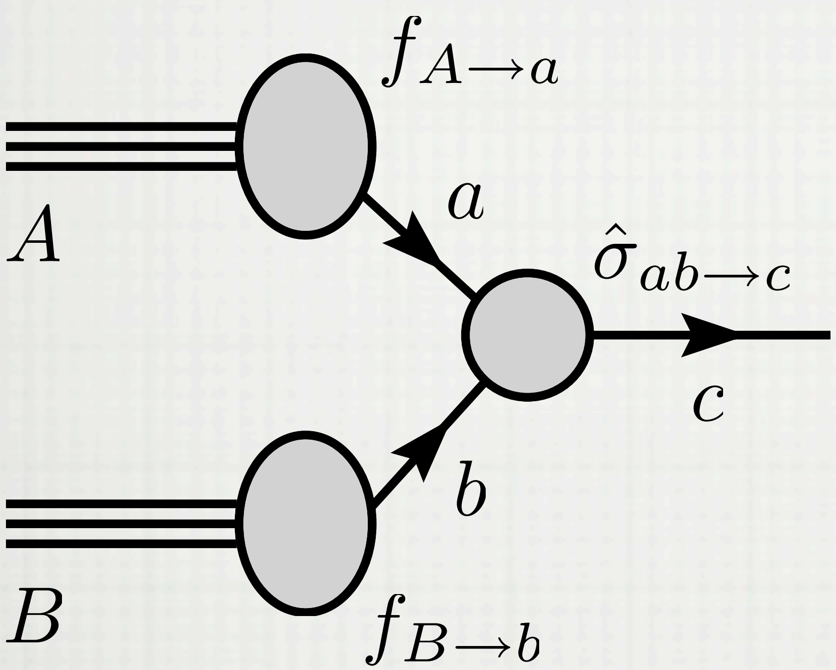
OVERVIEW NPDF

- Factorization & PDFs



$$\sigma = f_{A\to a} \otimes f_{B\to b} \otimes \hat{\sigma}_{ab\to c}$$

from experiment   from pQCD

Parton distribution functions (PDFs)

$$f_{A\to a}(x, \mu_F)$$

- universal, non-perturbative objects
- describe the structure of hadrons (in terms of partons - quarks & gluons)
- obey DGLAP evolution equations

The hard cross-section $\hat{\sigma}_{ab\to c}$

- free of long distance effects
- calculable in pQCD
- process dependant

Collins, Soper, Sterman hep-ph/0409313

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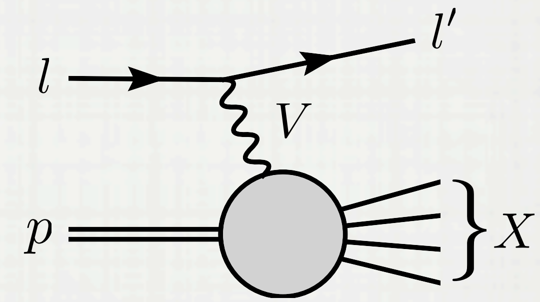
OVERVIEW NPDF

- Universality of PDFs - same parton distribution functions for all processes

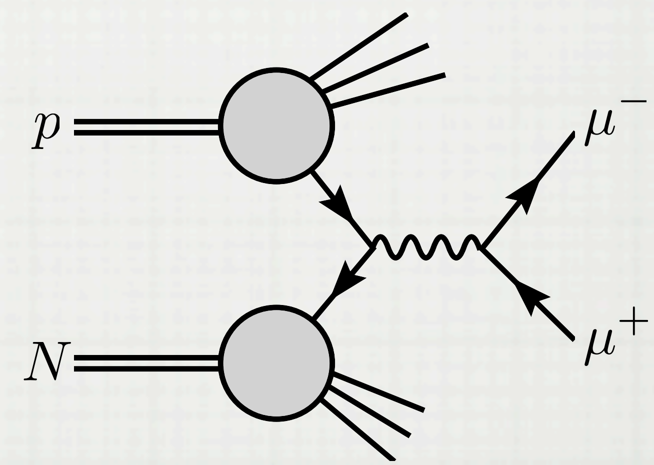
  - Deep Inelastic Scattering (DIS)

$$F_2^A(x,\mu^2) = \sum_i \left[f_i^A \otimes C_{2,i}\right](x,\mu^2)$$



  - Drell-Yan processes (DY)

$$\sigma_{A+B\to l^+ + l^- + X} = \sum_{i,j} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to l^+ + l^- + X}$$



  - hadron production

$$\sigma_{A+B\to H+X} = \sum_{i,j,k} f_i^A \otimes f_j^B \otimes \hat{\sigma}^{i+j\to k+X} \otimes D_k^H$$

- PDFs give predictions for unexplored kinematic regions and for new physics at the LHC

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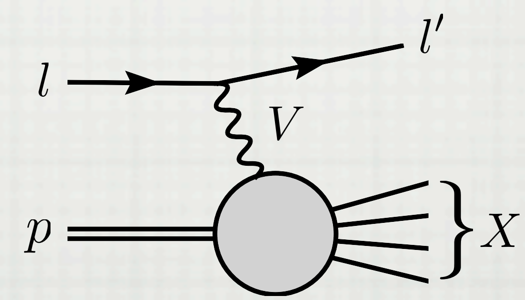
OVERVIEW NPDF

- CTEQ framework to fit PDFs from experimental data — CTEQ6M hep-ph/0201195
  - the input scale set to $\mu_0 = Q_0 = 1.3\,\mathrm{GeV}$
  - parameterization of the PDFs in x

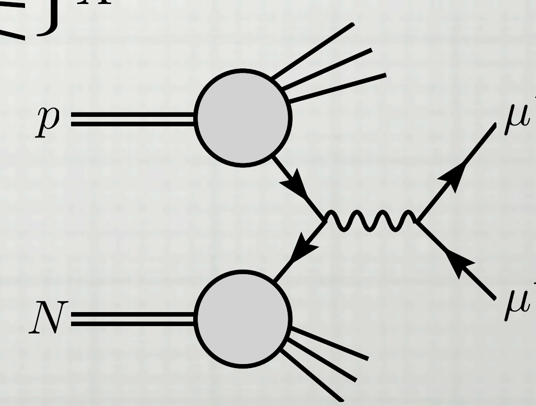
$$x\,f_k(x,Q_0) = c_0\,x^{c_1}(1-x)^{c_2}e^{c_3 x}(1+e^{c_4}x)^{c_5} \qquad k = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}$$

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

  - make sure # of free parameters not too high - CTEQ approx. 20 free params
  - carefully choose data sets & kinematic cuts to constrain free parameters
  - perform χ^2 fit to data



- Which data sets are included ?
  - Deep Inelastic Scattering ($l^{\pm}p, l^{-}d, \nu N, \bar{\nu}N$)
  - Neutrino DIS di-muon production
  - Drell-Yan & vector boson production ($W^{\pm}, Z^0, \gamma$)
  - hadronic jet data



OVERVIEW NPDF

- Review of existing global analyses of nuclear PDF

  - first differentiating factor - how to relate nuclear PDF to proton 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

    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

  - second differentiating factor - data sets included in the analysis

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OVERVIEW NPDF

- Review of existing global analyses of nuclear PDF

DE FLORIAN, SASSOT'04 [PRD69(2004)074028]
LO, NLO

χ^2/dof = 0.76

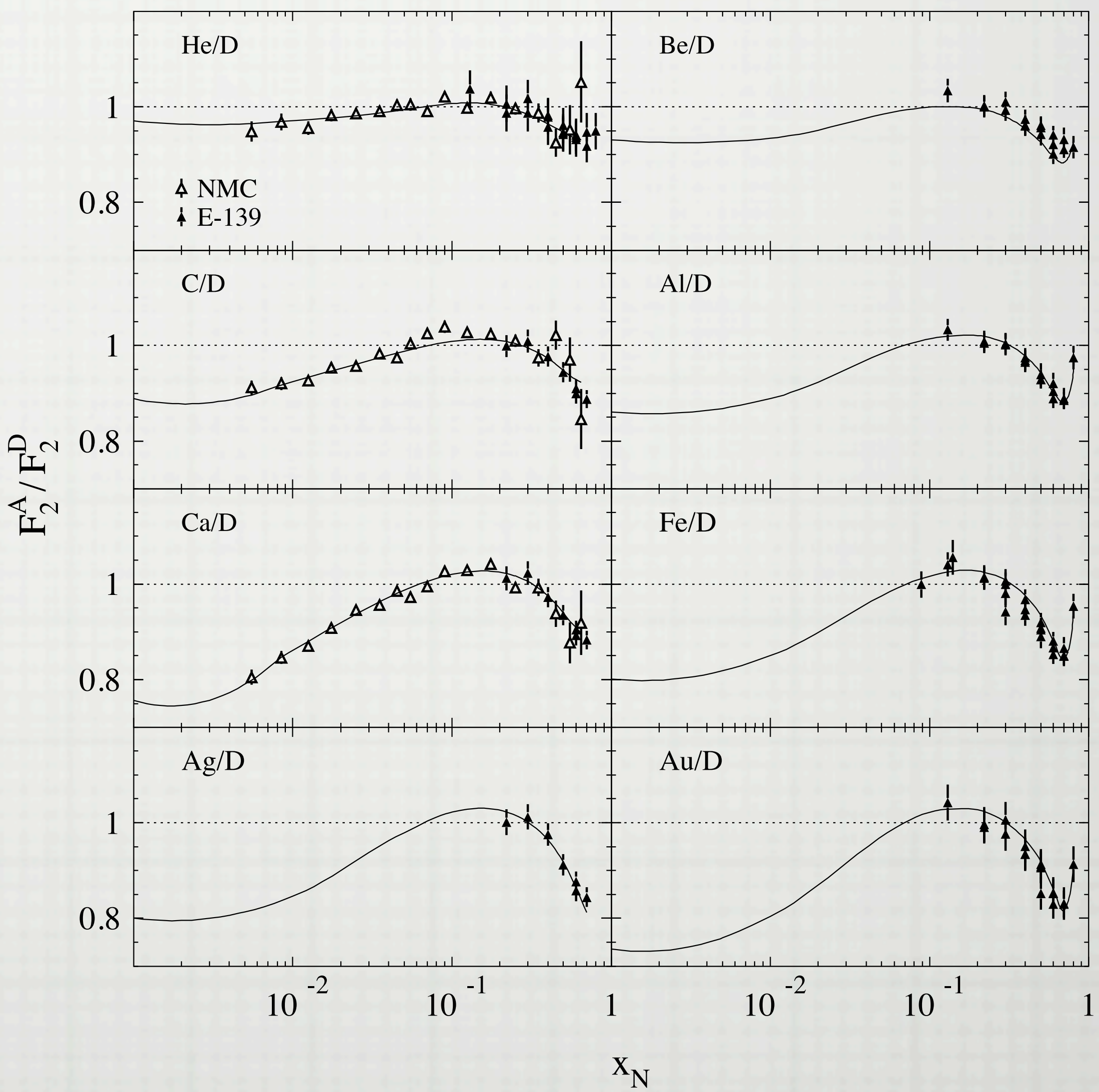
- first NLO analysis of nuclear data
- the only group using convolution relation

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

- typical nucleon density for valence quarks

$$W_v(y, A, Z) = A[a_v \delta(1 - \epsilon_v - y) + (1 - a_v)\delta(1 - \epsilon_{v'} - y)] + n_v \left(\frac{y}{A}\right)^{\alpha_v} \left(1 - \frac{y}{A}\right)^{\beta_v} + n_s \left(\frac{y}{A}\right)^{\alpha_s} \left(1 - \frac{y}{A}\right)^{\beta_s}$$

- the only framework using evolution in Mellin space & have PDFs also for $x_N > 1$
- only standard DIS data sets (semi-global)
- no error analysis



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OVERVIEW NPDF

- 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

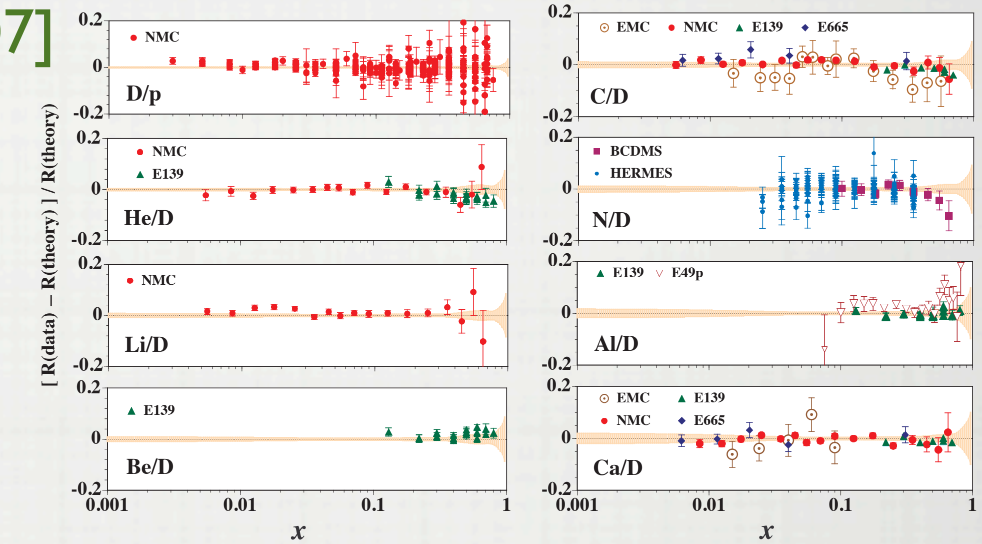
$$R_i(x, A, Z) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$

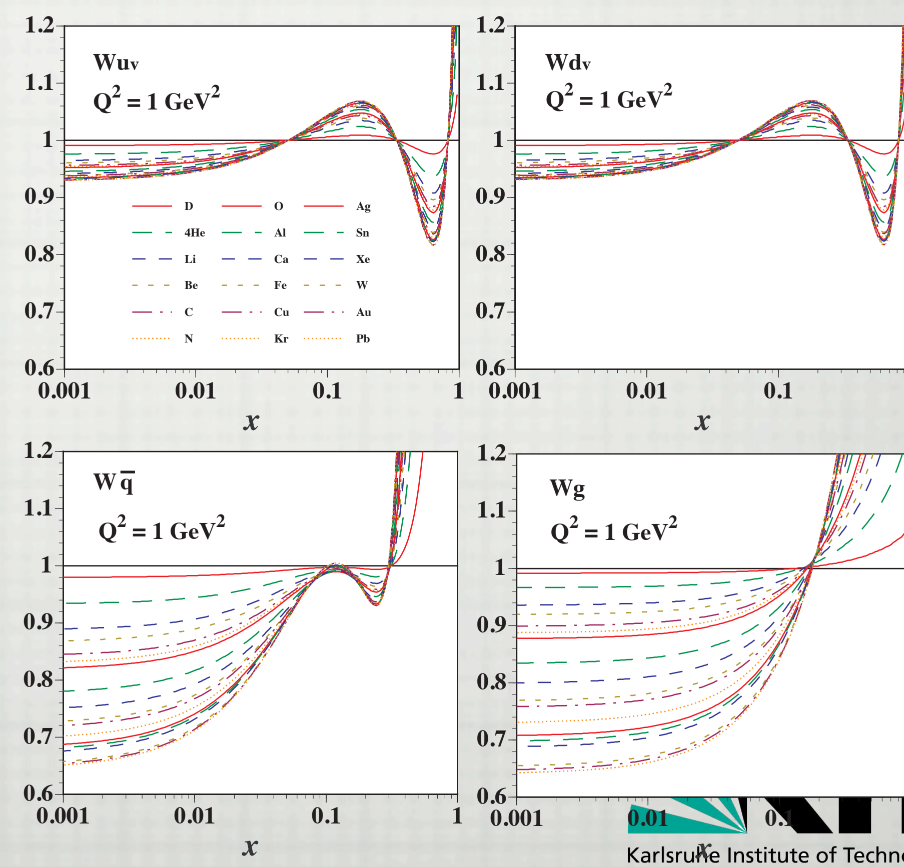
- neglects region x>1

- 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





OVERVIEW NPDF

- 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

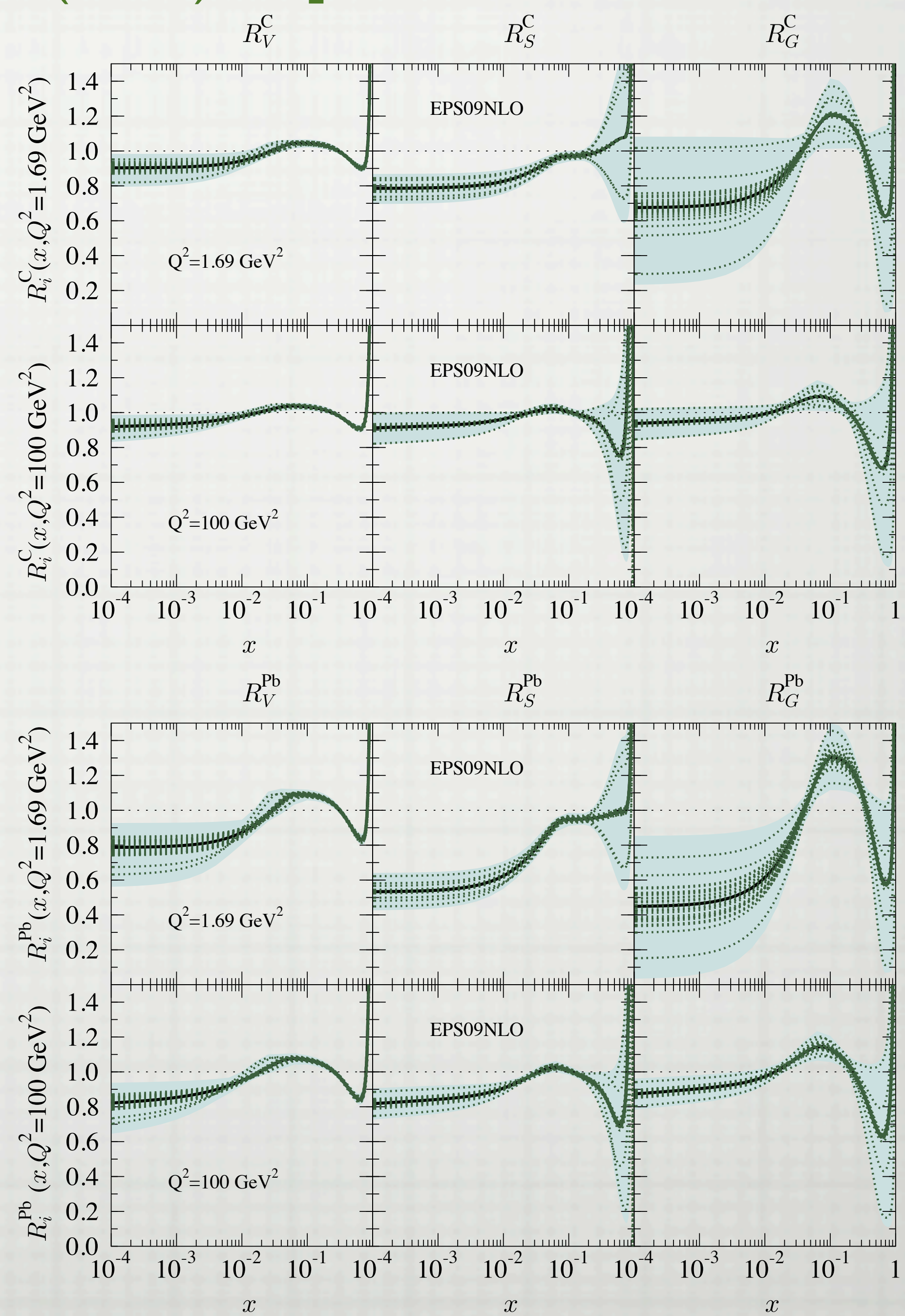
$$R_i(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

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



OVERVIEW NPDF

- Why another set of NPDFs ?

  - nuclear PDFs different from proton PDFs - PDF parameters contain more information but the fit has less data to constrain them

  - big source of uncertainty - systematic uncertainty connected to assumptions made about PDF parameters & the parametric form of the PDF at Q_0

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OVERVIEW NPDF

- Why another set of NPDFs ?

  - nuclear PDFs different from proton PDFs - PDF parameters contain more information but the fit has less data to constrain them

  - big source of uncertainty - systematic uncertainty connected to assumptions made about PDF parameters & the parametric form of the PDF at Q_0

1. nCTEQ framework entirely different from previous nPDF frameworks - useful to study parameterization dependence & estimate systematic uncertainty

2. nCTEQ analysis is in a close relation to the existing CTEQ proton analysis - allows to calculate nuclear correction factors in a flexible way (Q dependent & based on global analysis)

3. Our analysis aims at including also neutrino DIS data

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NUCLEAR CTEQ

- nCTEQ 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)

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

  - PDF for a nucleus with A-nucleons out of which Z-protons

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

Note: PDF of neutron are related to the proton by isospin symmetry

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

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

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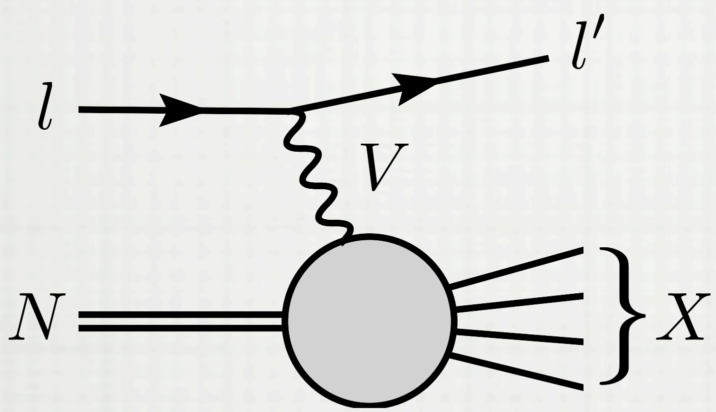
NUCLEAR CTEQ

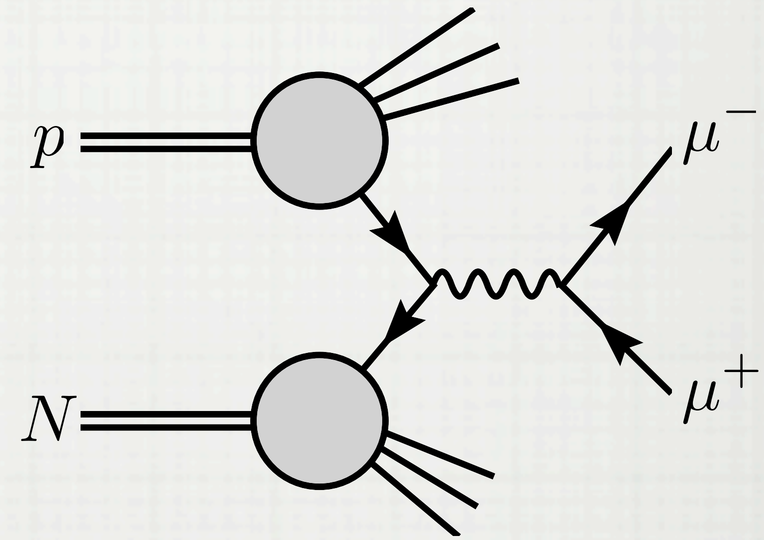
- Experiments included in the analysis:

Deep Inelastic Scattering



$$l + N \rightarrow l' + X$$

Drell-Yan process



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

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

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

FNAL E-772 & E-886

$N = (\mathrm{D, C, Ca, Fe, W})$

NUCLEAR CTEQ

- NPDF fit properties:
  - we fit nuclear data with NLO QCD predictions & include heavy quark effects (ACOT)
  - added nuclear observables to CTEQ fitting routines (need to treat 2 nuclei at once)

    DIS: $F_2^A/F_2^{A'}$ Drell-Yan: $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$
  - applied standard CTEQ kinematical cuts Q>2GeV & W>3.5GeV

- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 32 free parameters - 675 degrees of freedom
  - overall χ^2/dof = 0.95
  - individually for different data sets
    - for F_2^A/F_2^D χ^2/pt=0.92
    - for $F_2^A/F_2^{A'}$ χ^2/pt=0.69
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$ χ^2/pt=1.08

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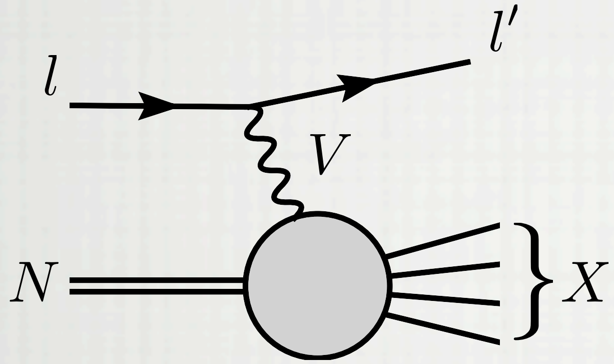
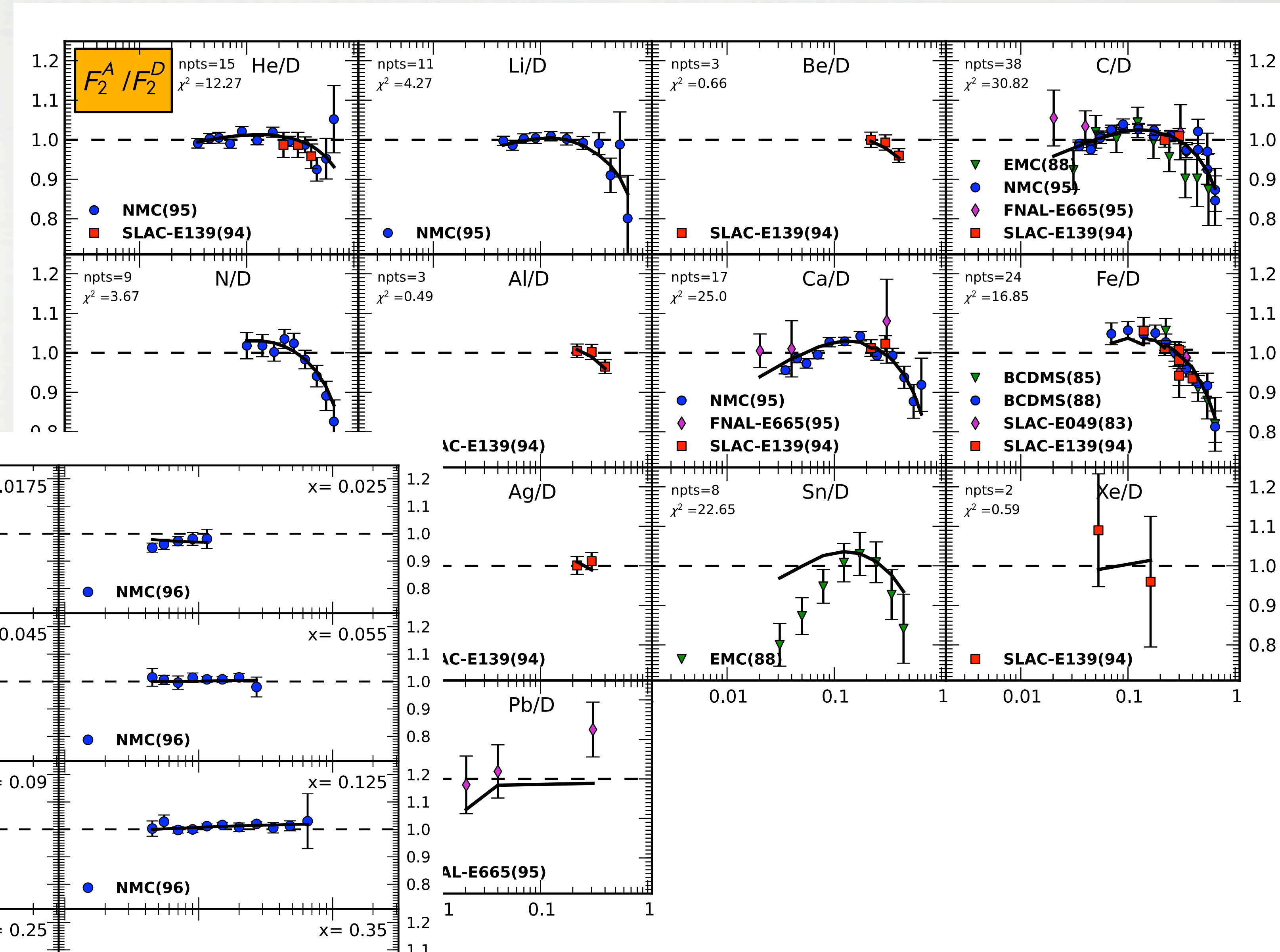
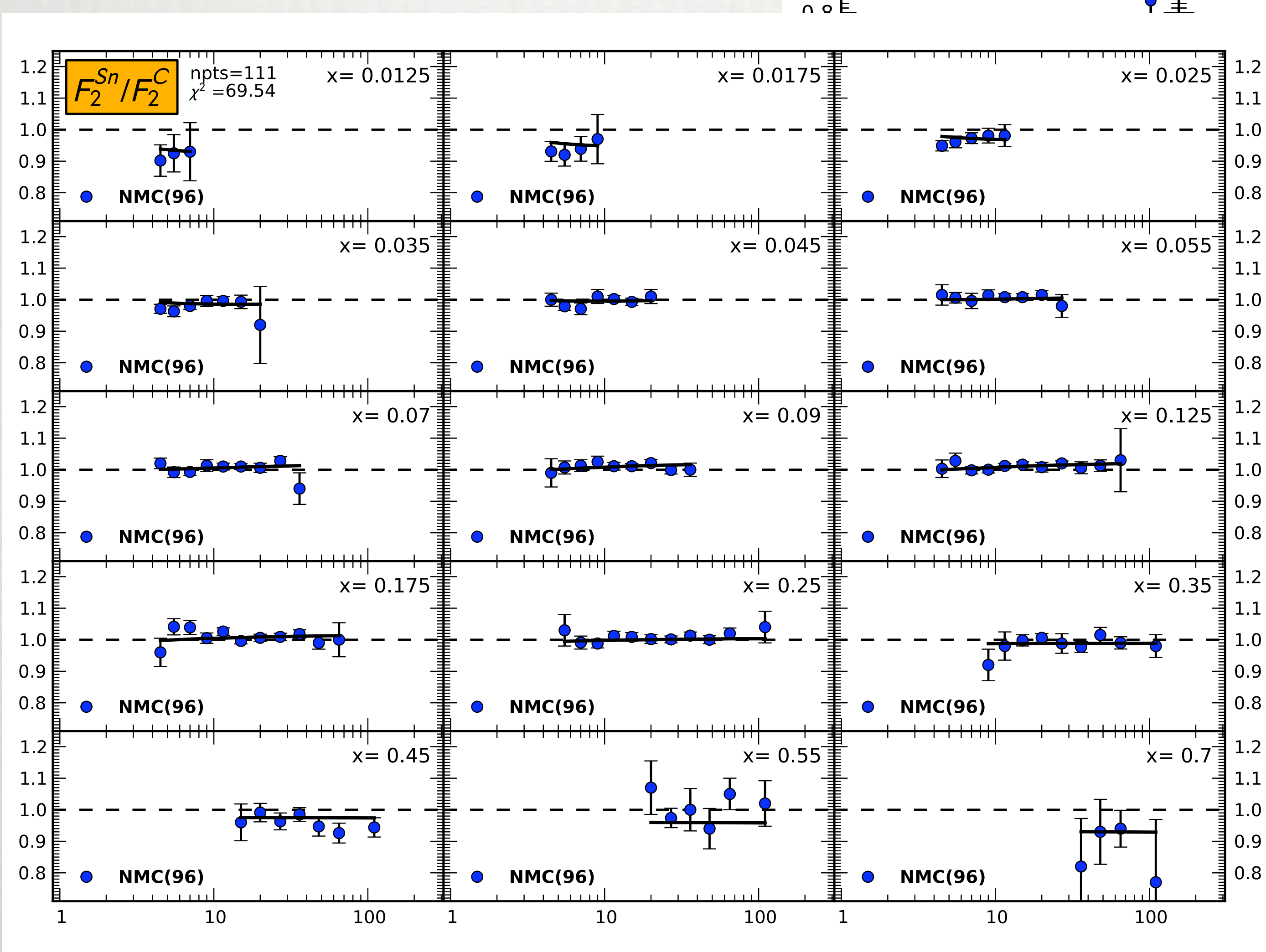
NUCLEAR CTEQ

Deep Inelastic Scattering







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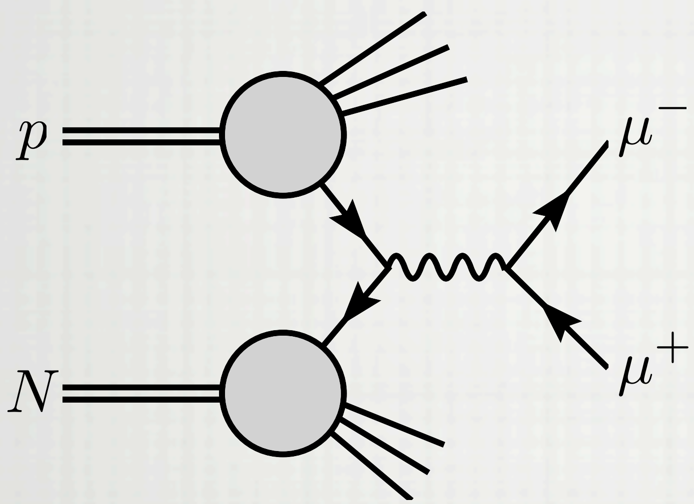
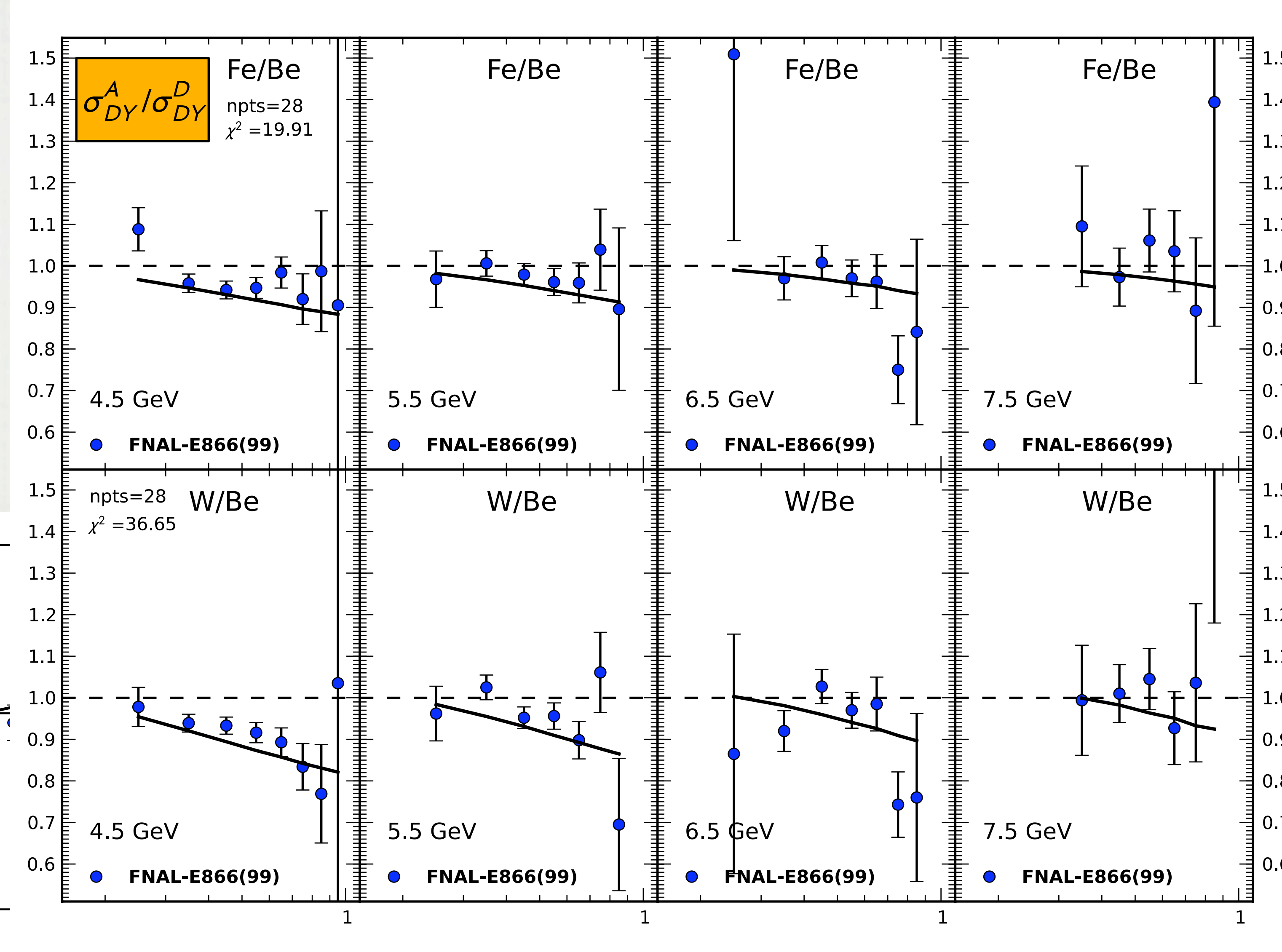
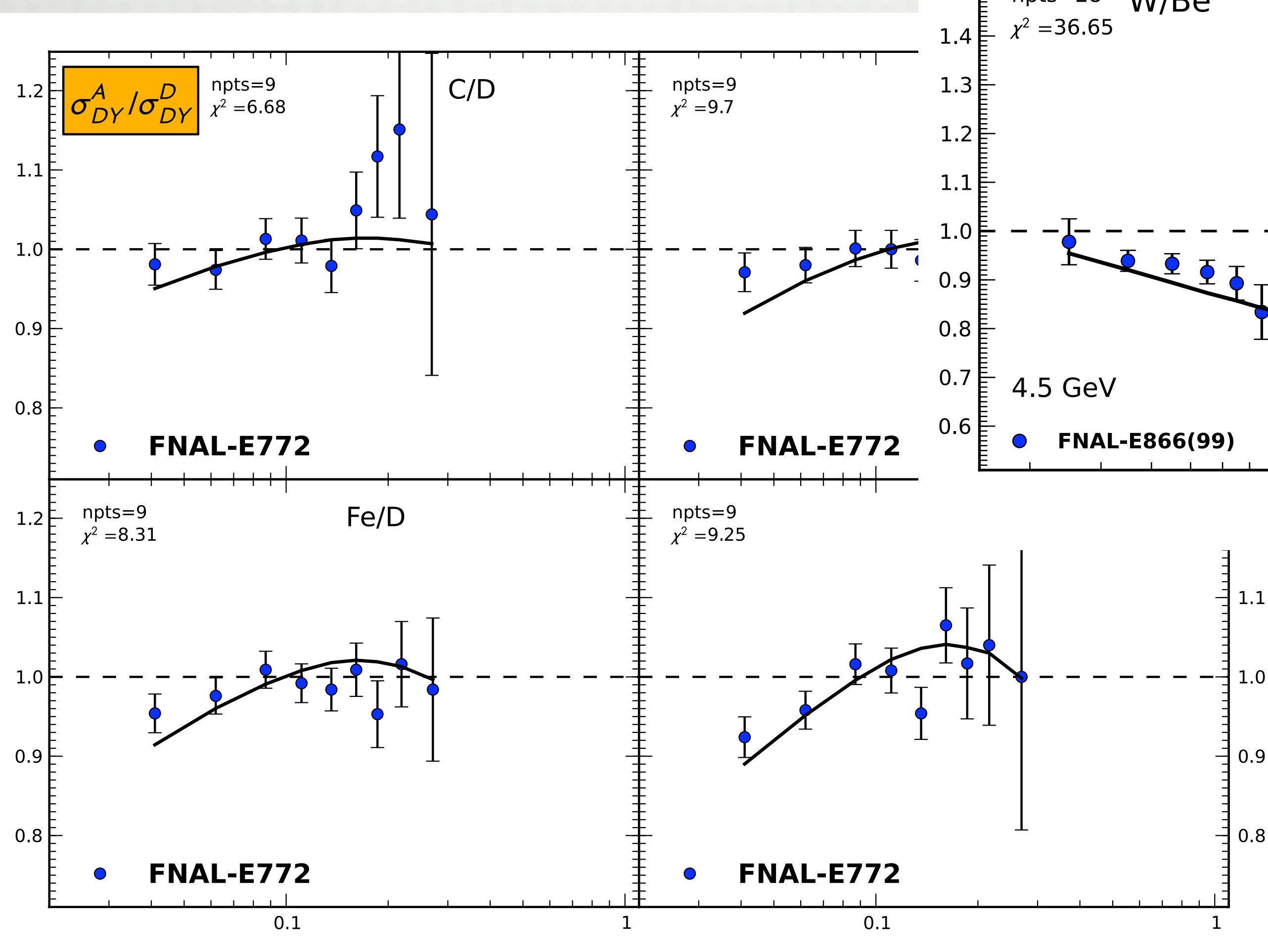
NUCLEAR CTEQ

Drell-Yan process







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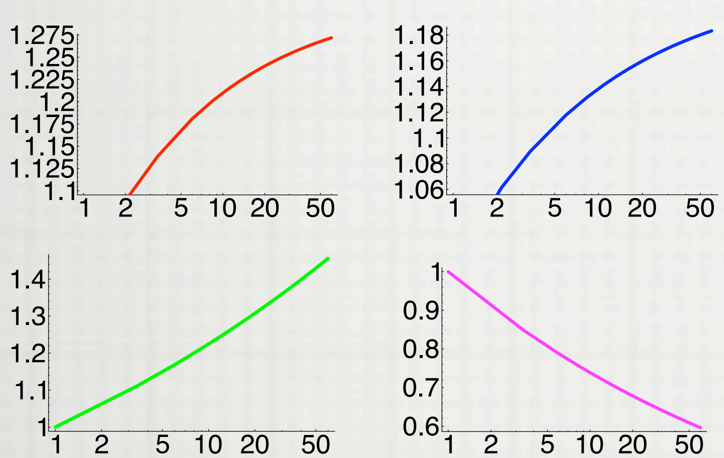
NUCLEAR CTEQ

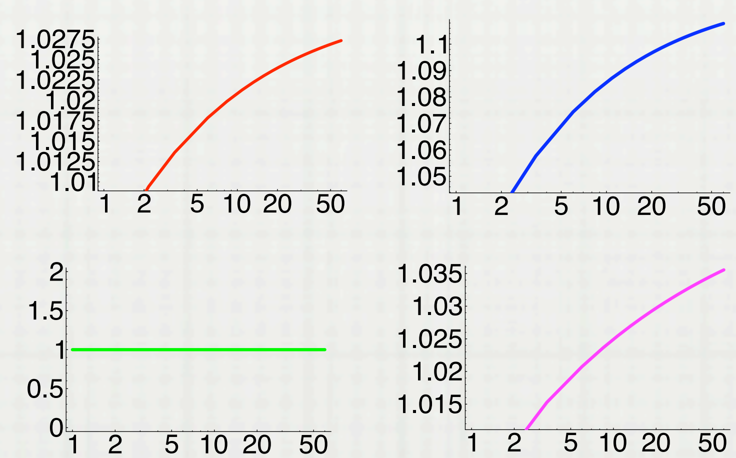
- CTEQ parameters dependent on atomic number A - $c_k(A)/c_{k,0}$

  for parton distributions $\begin{pmatrix} d_v & u_v \\ g & \bar{u}+\bar{d} \end{pmatrix}$

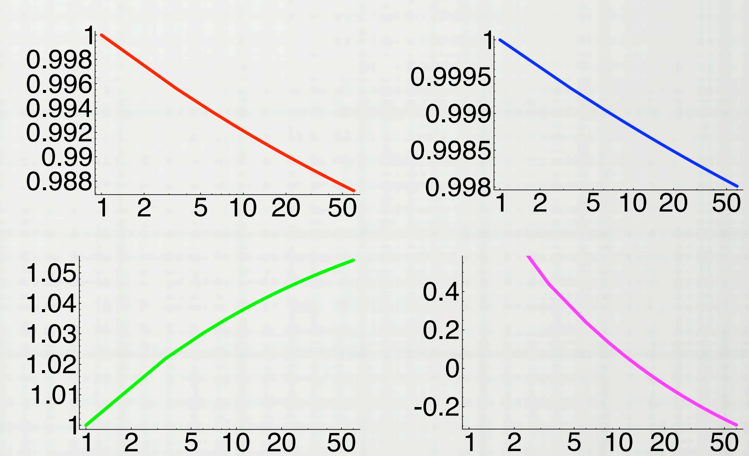
$c_1(A)/c_{k,0}$



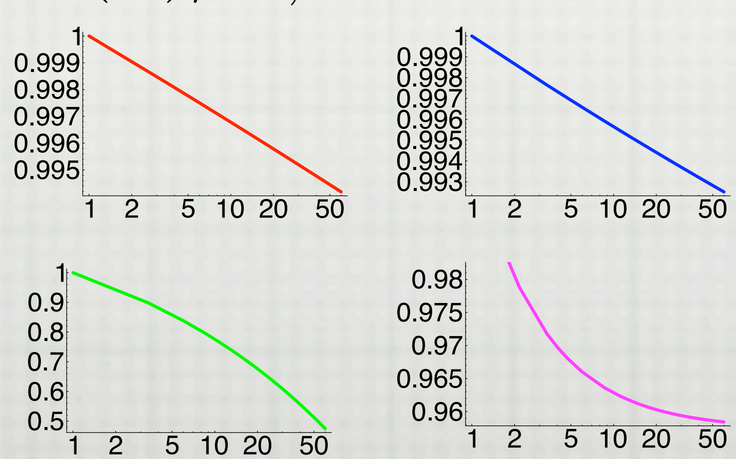
$c_2(A)/c_{k,0}$



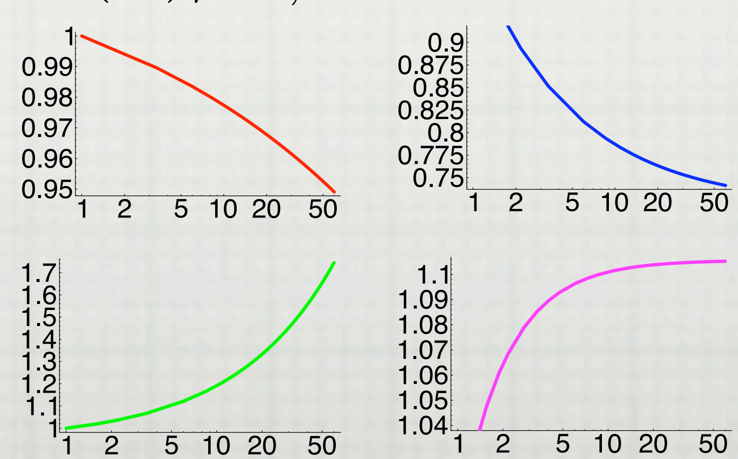
$c_3(A)/c_{k,0}$



$c_4(A)/c_{k,0}$



$c_5(A)/c_{k,0}$



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NUCLEAR CTEQ

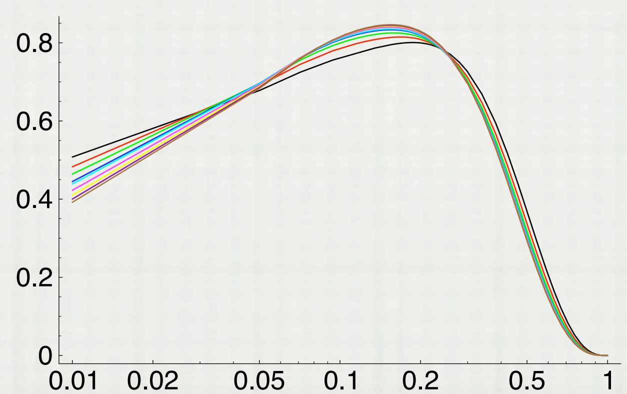
- Parton density functions for bound partons as a function of x

black yellow brown

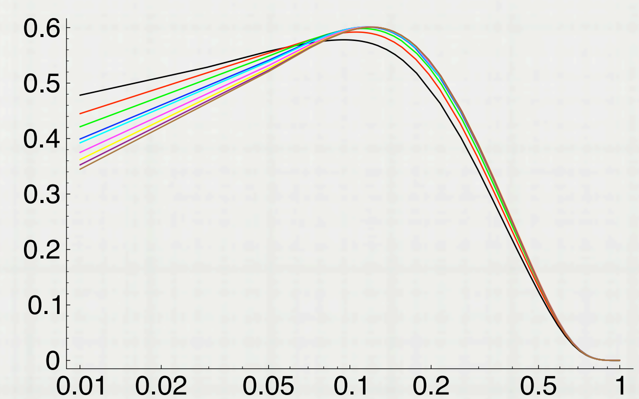
$$x\, f_k^A(x,Q) \quad \text{for} \quad A = (1, 2, 4, 9, 12, 27, 56, 108, 207)$$

red purple

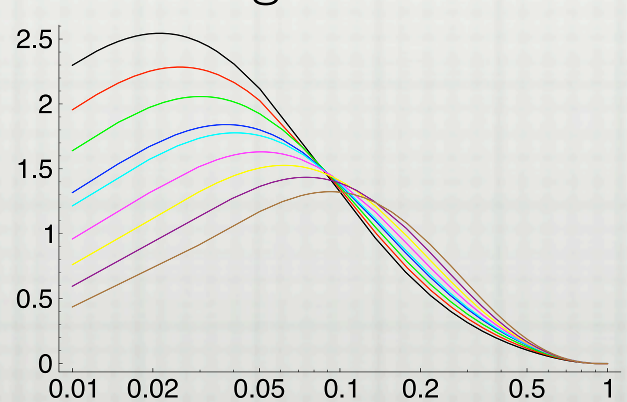
total up-quark



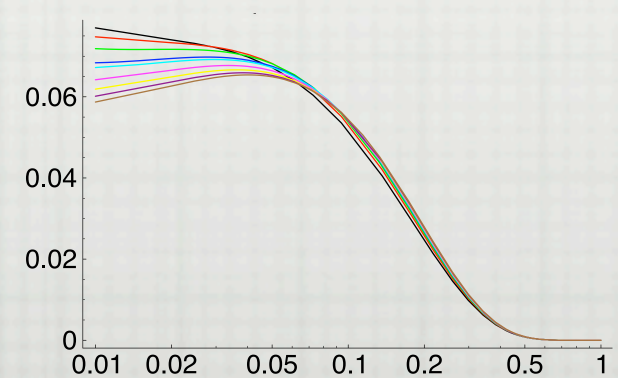
total down-quark



gluon



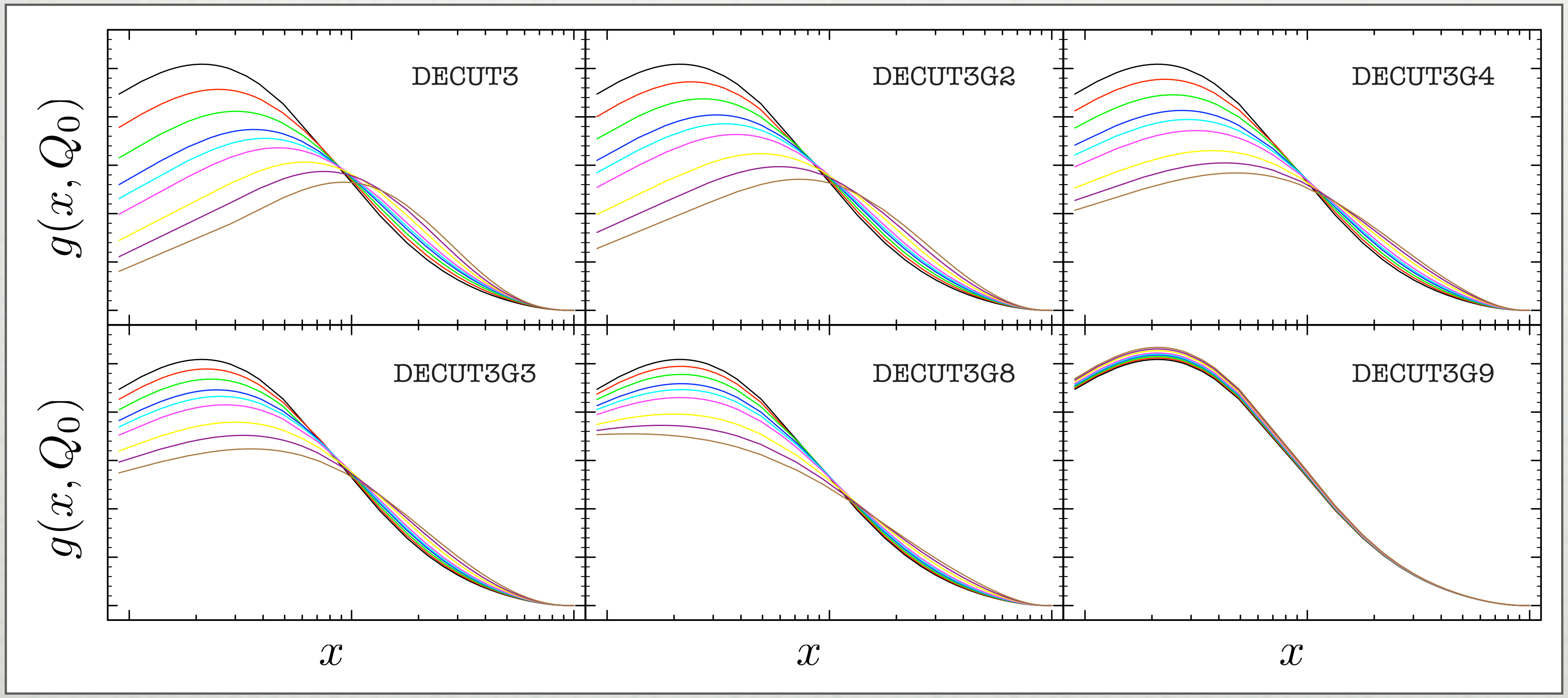
strange-quark



NUCLEAR CTEQ

- Example of different assumptions in nuclear gluon PDF
- nCTEQ estimate of gluon nPDF uncertainty
  - vary gluon nPDF assumptions & parametrizations
  - large uncertainty for low x<0.1 in nCTEQ framework
  - need further data to constrain gluon nPDF

JHEP 1101 (2011) 152



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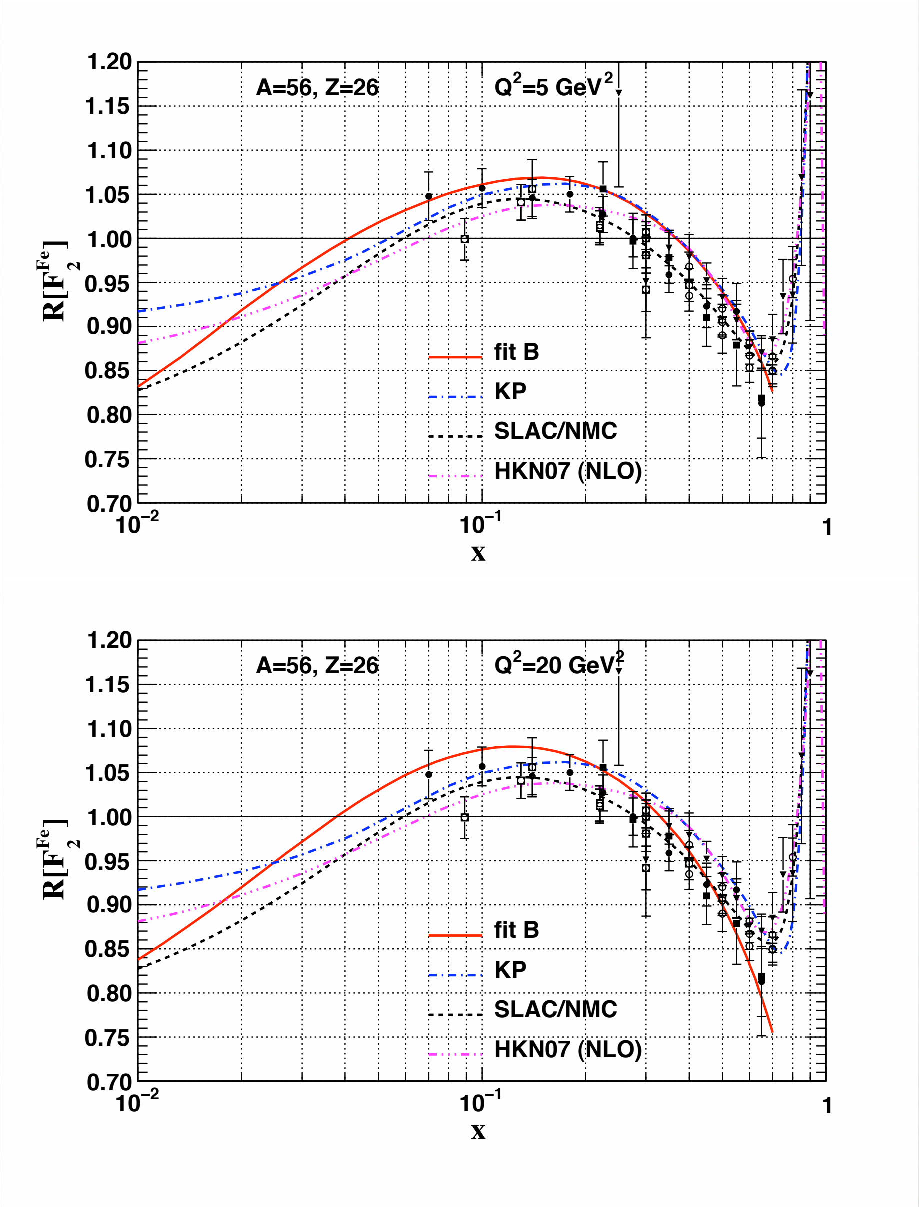
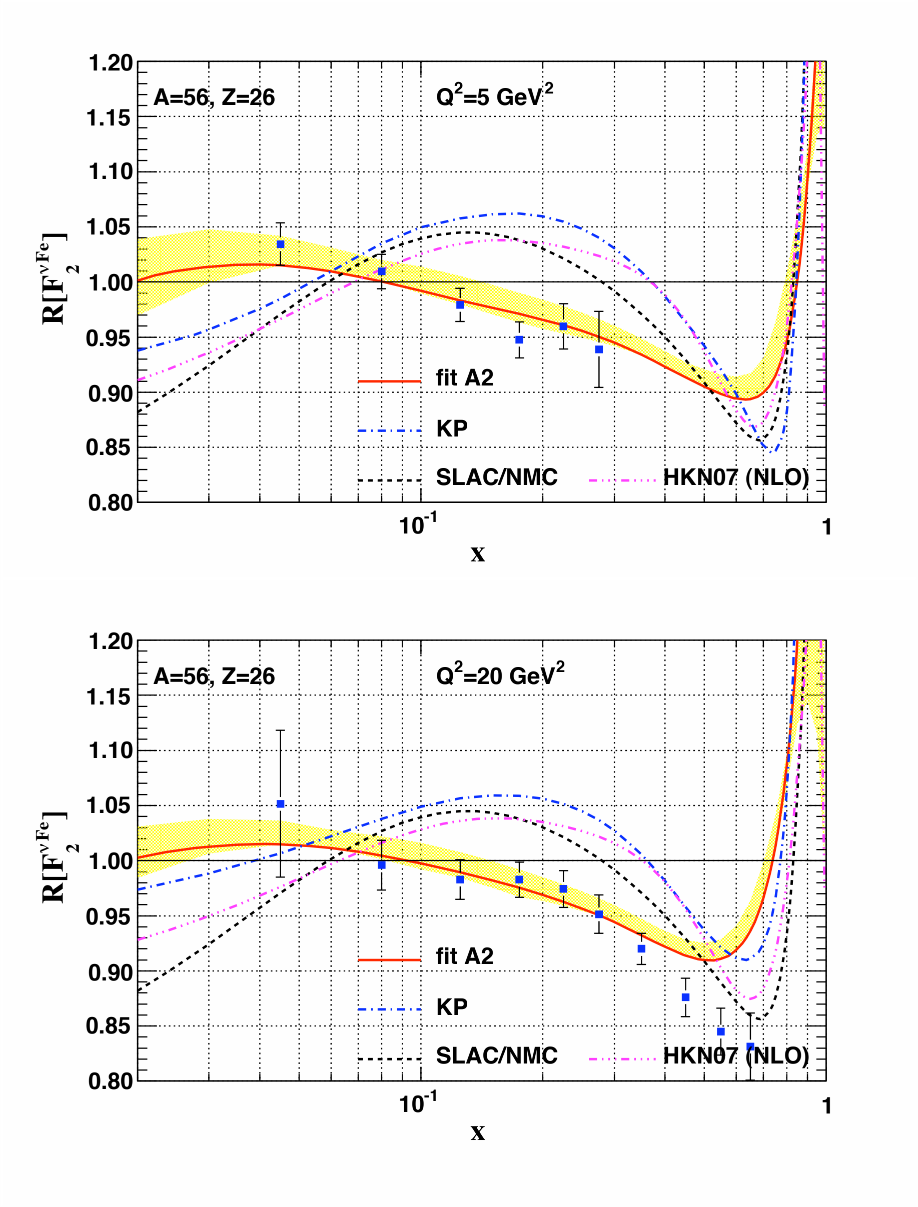
NEUTRINO DIS

- Comparison of iron F_2 from neutrino and charged lepton DIS $R[F_2^{Fe}] = F_2^{Fe}/F_2^D$

Phys.Rev.D80 094004, 2009

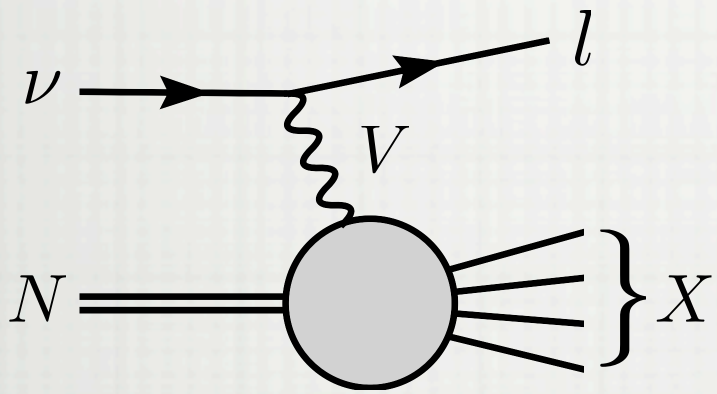


Phys.Rev.D77 054013, 2008



NEUTRINO DIS

- Re-analyze neutrino data within the same framework as for charged lepton
- 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 ?

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NEUTRINO DIS

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

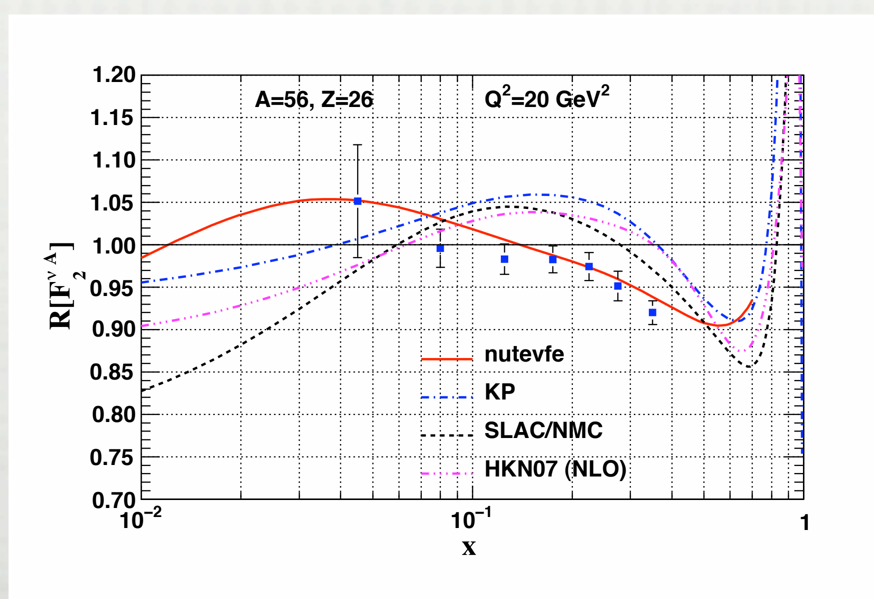
    combined: χ^2/pt=1.03

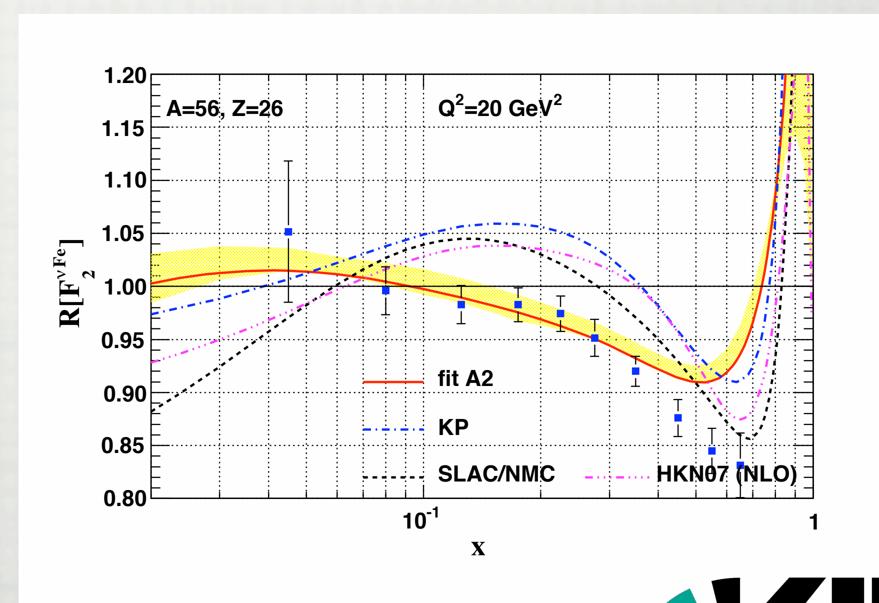
  - NuTeV data (with correlated errors) difficult to fit alone or with the charged lepton data

    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

Consistency check with only NuTeV





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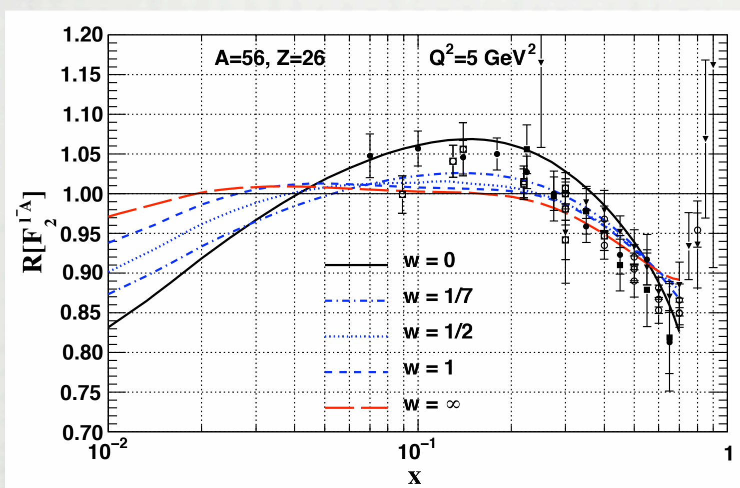
NEUTRINO DIS

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

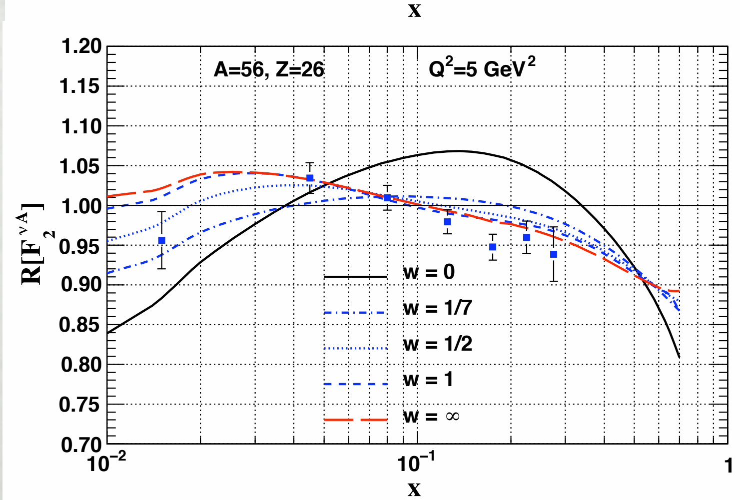
- Nuclear correction factors - $R = F_2^{Fe} / F_2^{Fe,0}$

w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
0	708	638 (0.90)	-	-	638 (0.90)
1/7	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
1/2	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
1	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
∞	-	-	3134	4192 (1.33)	4192 (1.33)



$R[F_2^{l^{\pm}A}]$

$Q^2 = 5 GeV^2$



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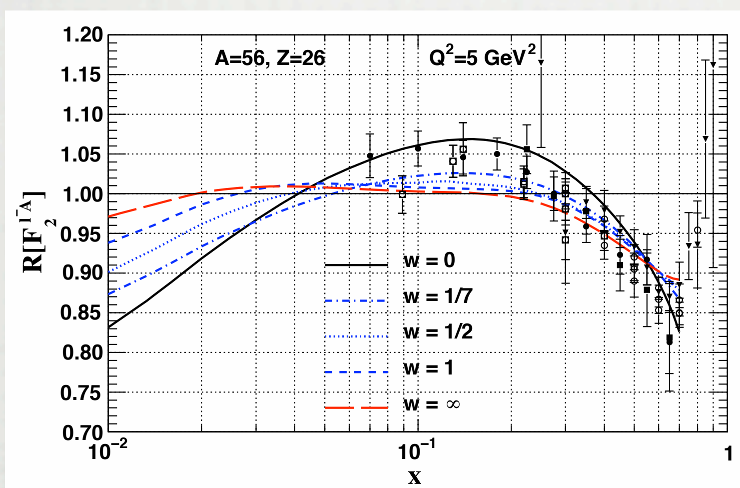
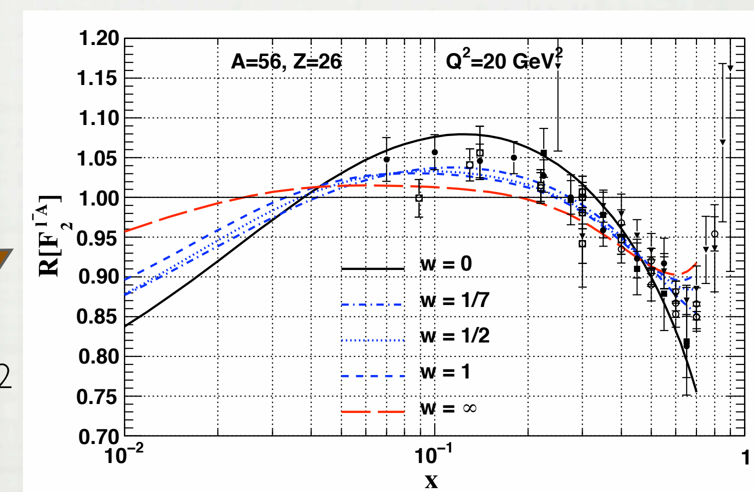
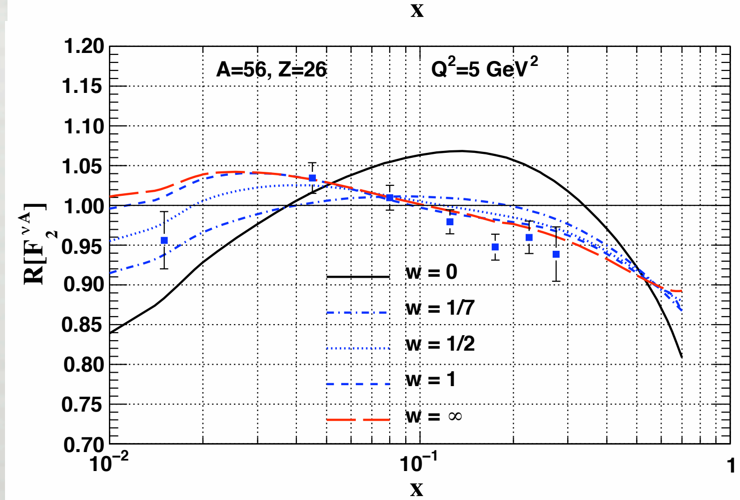


$R[F_2^{l^{\pm}A}]$

Q^2 = 5GeV^2

Q^2 = 20GeV^2

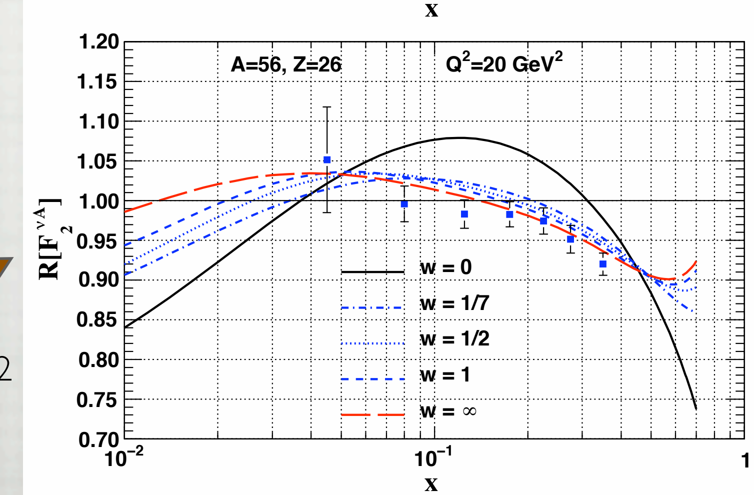




$R[F_2^{\nu A}]$

Q^2 = 5GeV^2

Q^2 = 20GeV^2



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NEUTRINO DIS

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

- χ^2- distribution criterion

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

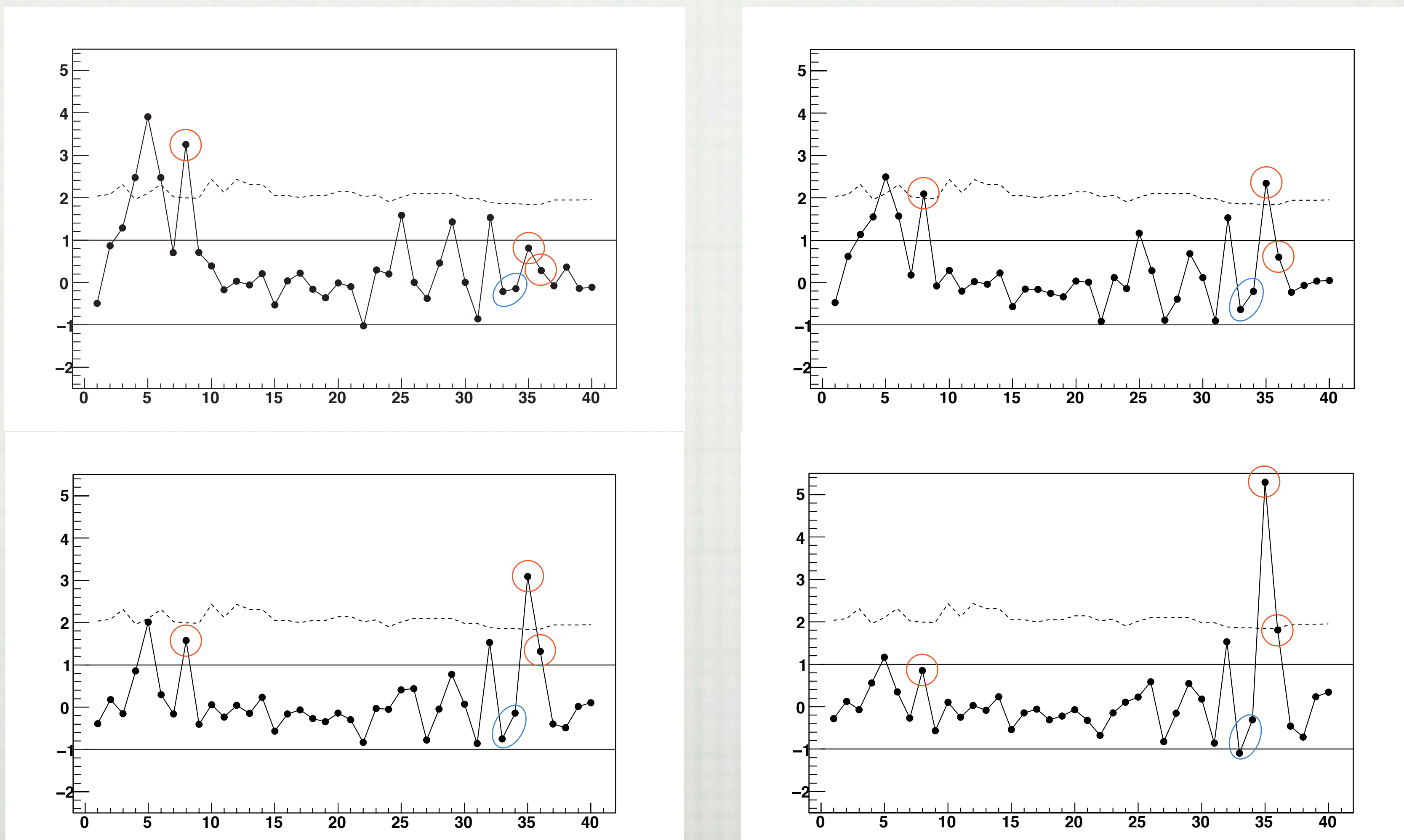
CTEQ hep-ph/0101051

MSTW arXiv:0901.0002 [hep-ph]

error PDFs defined as 90% C.L. $\longrightarrow \int_0^{\xi_{90}} P(\chi^2, N) d\chi^2 = 0.90$

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

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



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NEUTRINO DIS

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

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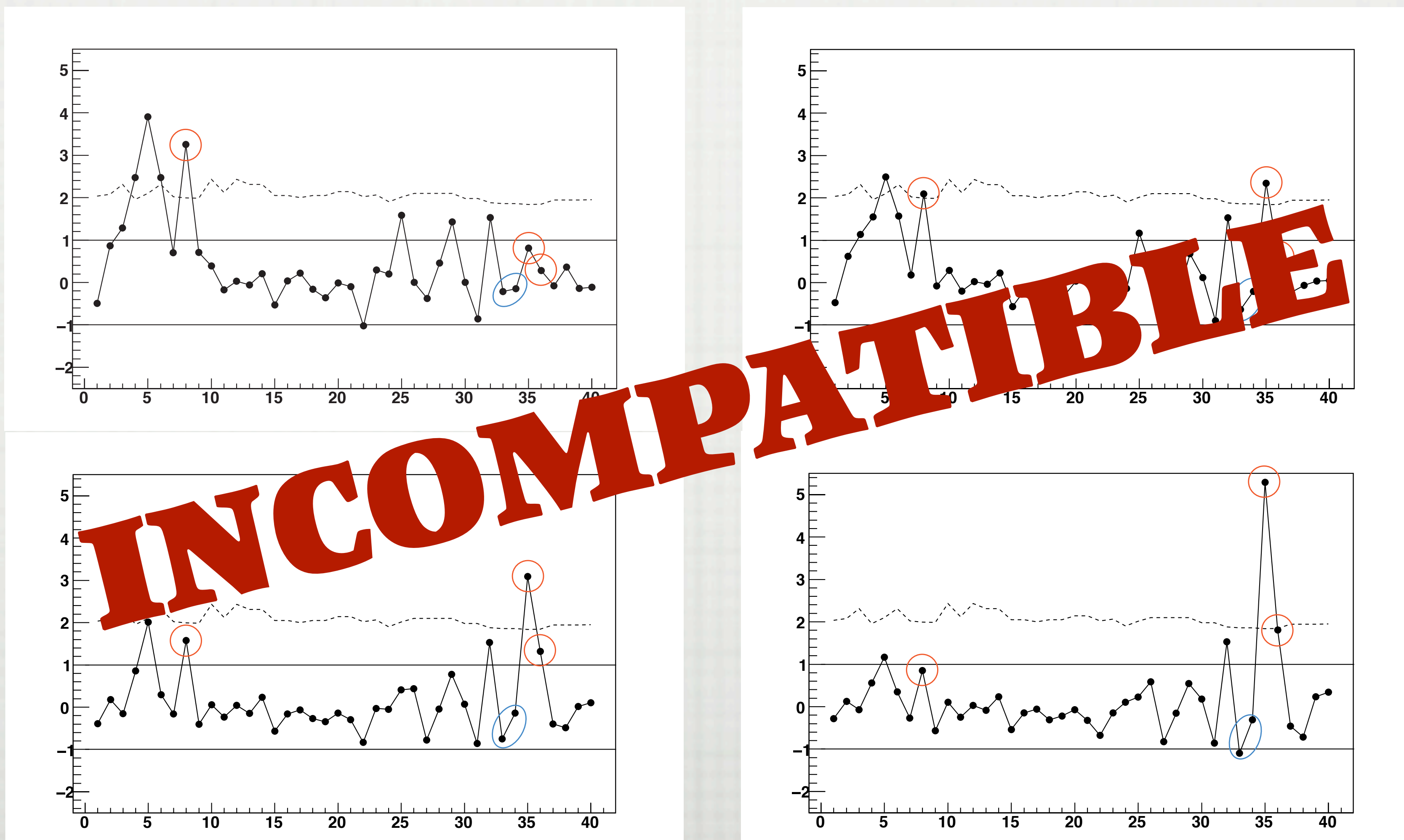

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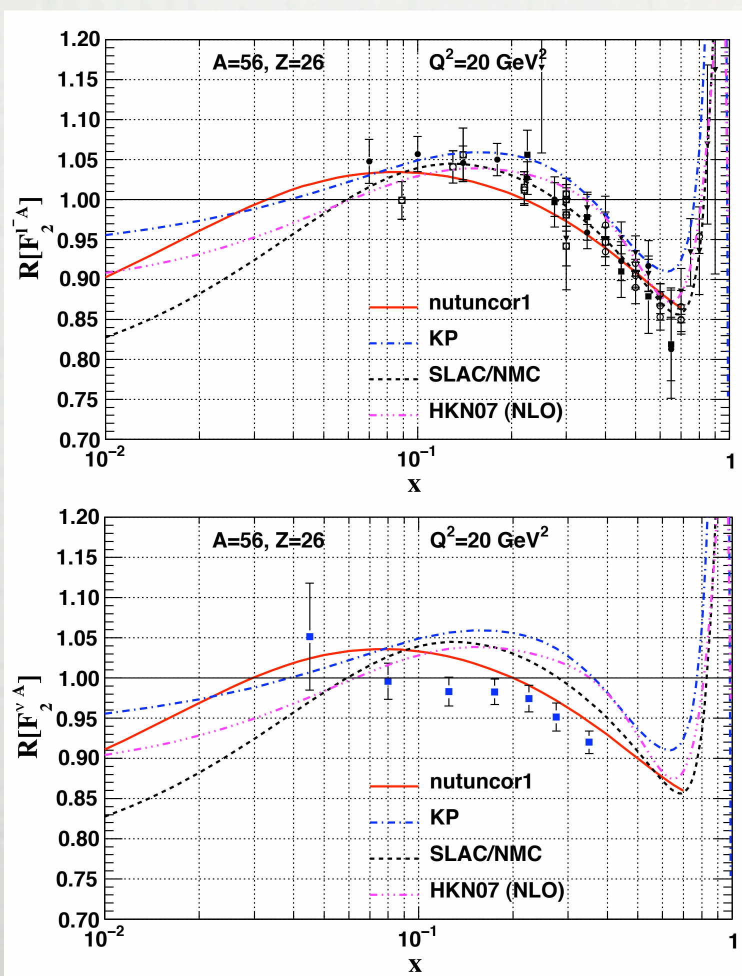
NEUTRINO DIS

- Analysis of fits with neutrino DIS (uncorrelated errors)

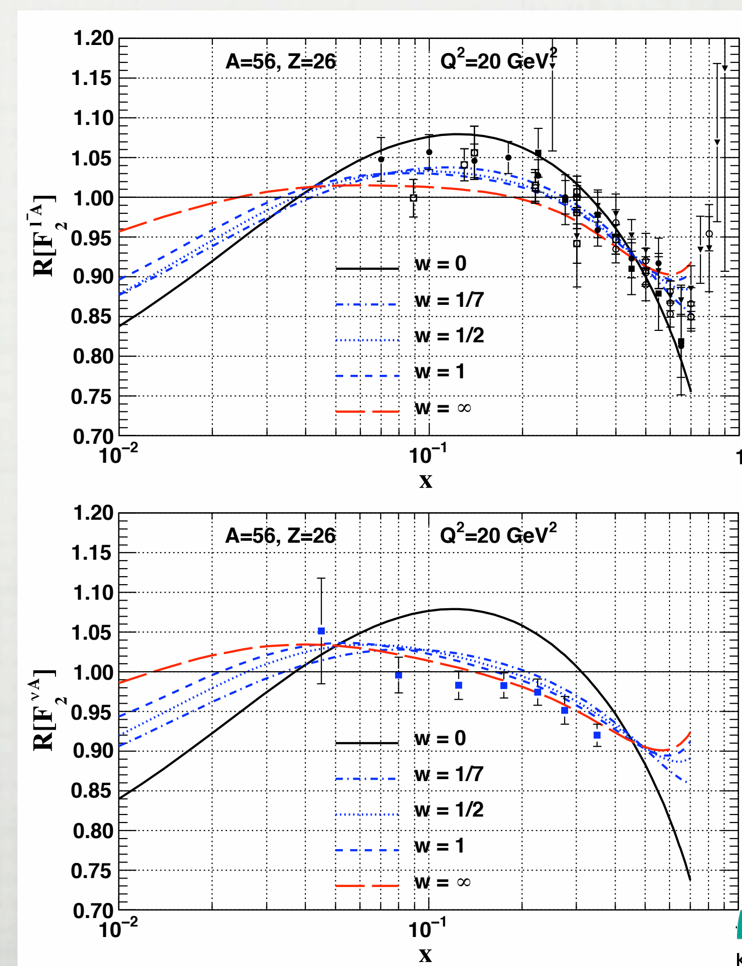
- Nuclear correction factors - $R = F_2^{Fe}/F_2^{Fe,0}$

w	$l^{\pm}A$	χ^2 (/pt)	νA	χ^2 (/pt)	total χ^2(/pt)
1-uncorr	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
1-corr	708	809 (1.14)	3110	3115 (1.00)	3924 (1.02)

uncorrelated errors



correlated errors



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OUTLOOK

- Global nuclear CTEQ fit is able to describe the charged lepton data well
  - some challenges on the way to a comprehensive public nPDF release
  - relax kinematical cuts and fit Fermi motion peak in a natural way
  - error PDFs & realistic estimate of uncertainty
- Incompatibility of neutrino DIS with charged lepton DIS
  - incompatibility a "precision" effect - the result changes 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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