NPDF FOR NEUTRINO & CHARGED LEPTON DATA

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arXiv:0710.4897 [hep-ph]   arXiv:0907.2357 [hep-ph]

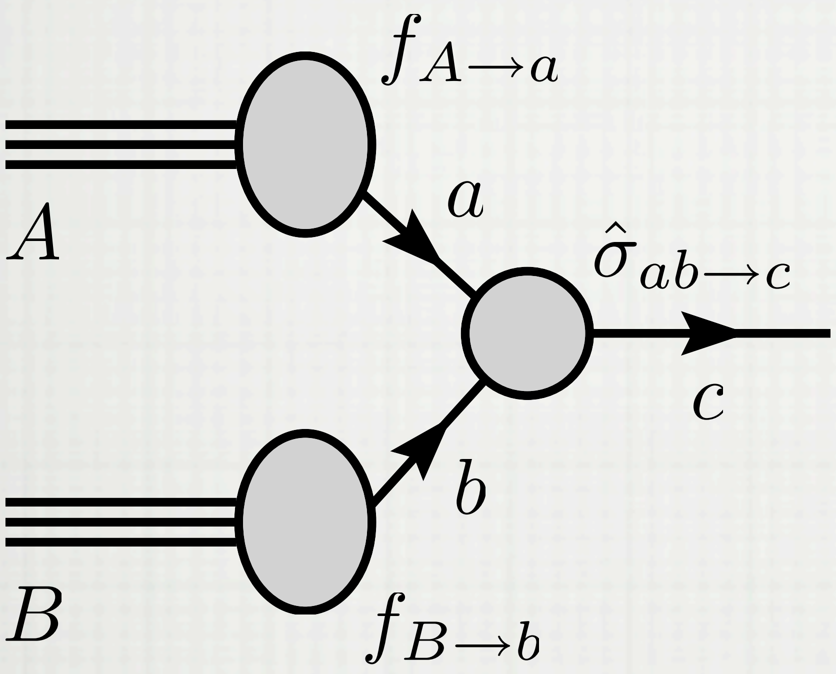
Karlsruhe Institute of Technology

OUTLINE

1. Introduction to parton distribution functions
2. Nuclear effects in PDFs
3. Global nPDF analysis & new CTEQ framework
4. Neutrino DIS vs. nPDF
5. Conclusions and Outlook

INTRO TO PDFS

- Factorization & PDFs



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

from experiment

from pQCD

Collins, Soper, Sterman hep-ph/0409313

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

INTRO TO PDFS

- How to determine PDFs $f_{A\to a}(x,\mu_F)$ from experimental data ?
- Scale dependence of PDFs obeys the DGLAP equations

$$\frac{\mathrm{d}f_i(x,\mu_F)}{\mathrm{d}\ln\mu_F^2} = \frac{\alpha_S(\mu_F)}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y} P_{ij}(y) f_j(x/y,\mu_F)$$

- The set of equations can be solved exactly in momentum space

  - **BUT** one needs the knowledge of initial PDFs at scale μ_0 for all values of $x \in (0,1)$

- Current global analysis - CTEQ, MRST etc...

  - solve set of DGLAP equations numerically
  - input needed only for as low x as needed
  - at the input scale one chooses a parameterization in x to fit data

INTRO TO PDFS

- CTEQ framework to fit PDFs from experimental data

CTEQ6M hep-ph/0201195

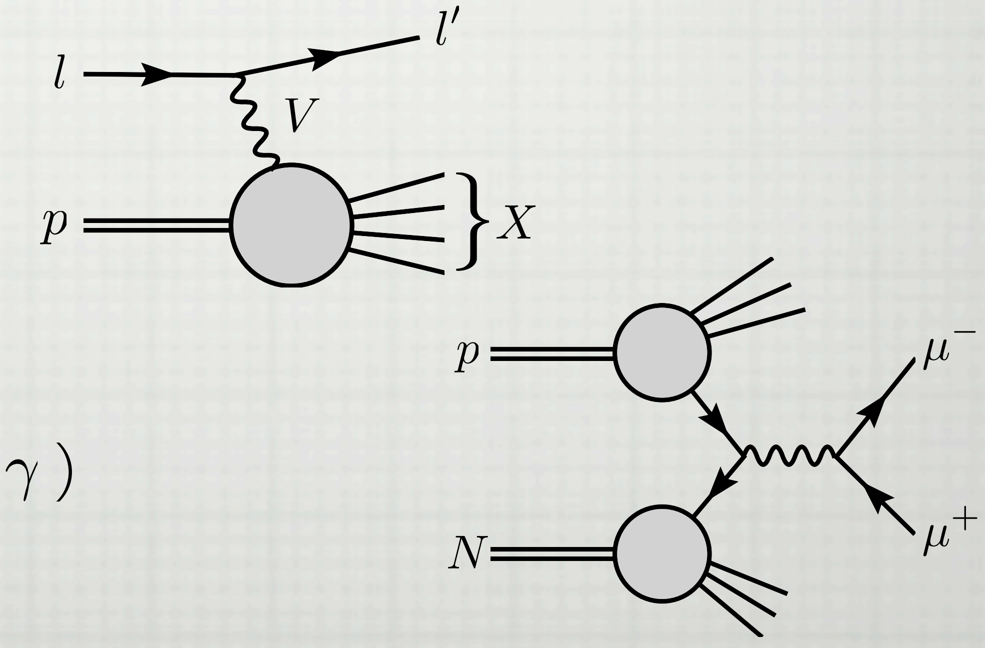
  - the input scale set to $\mu_0 = Q_0 = 1.3\,\mathrm{GeV}$
  - parameterization of the PDFs in x

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

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

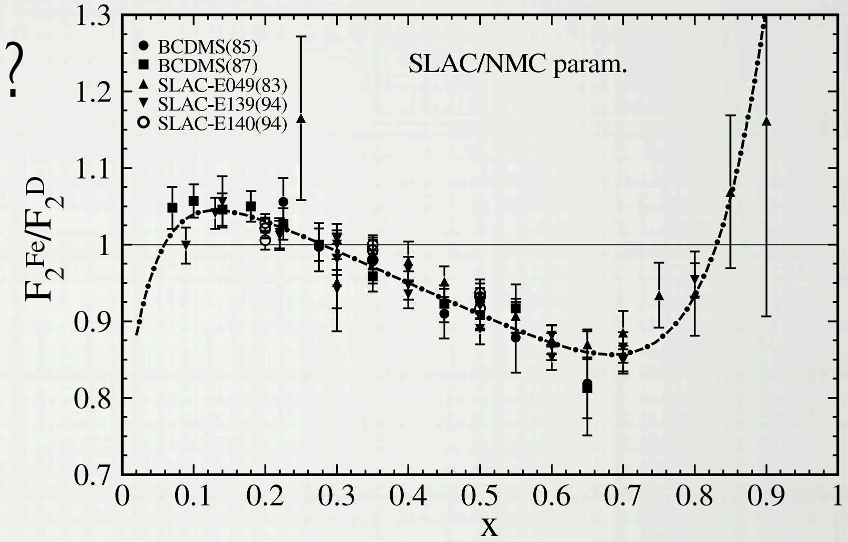
  - make sure # of free parameters not too high - CTEQ approx. 20 free params
  - carefully choose data sets & kinematic cuts to constrain free parameters
  - perform χ^2 fit to data

- 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



NUCLEAR PDFS

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



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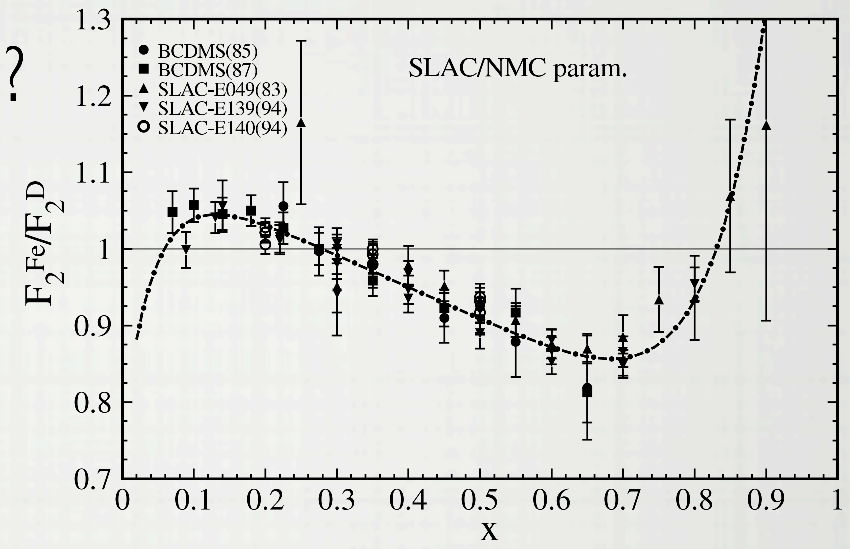


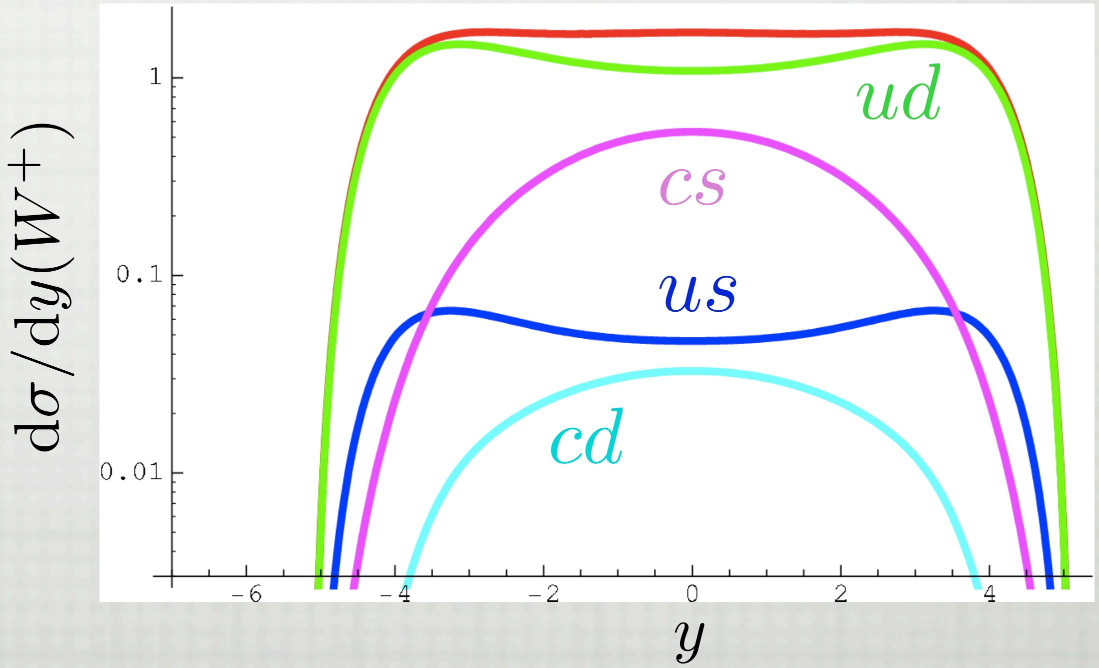
- Where are nuclear parton density functions useful ?

  1. Strange quark content of the proton

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

crucial for: W-boson production at the LHC

(standard candle process)



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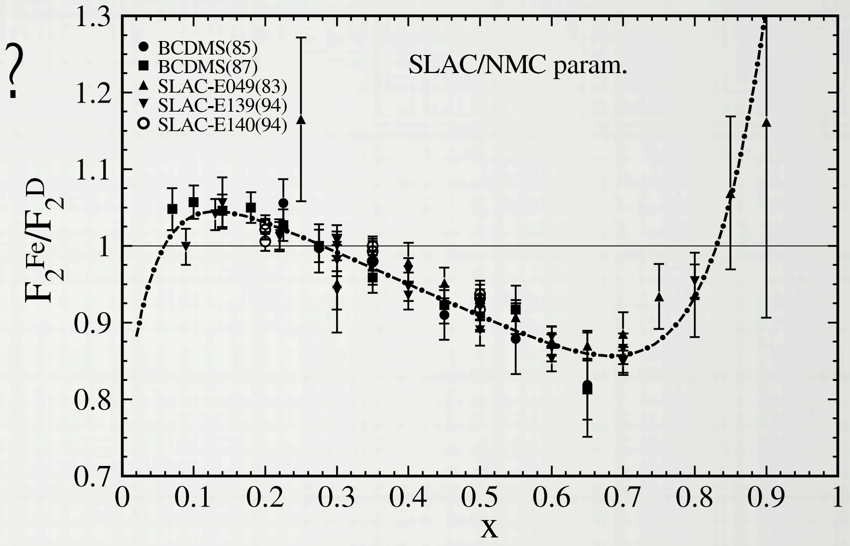


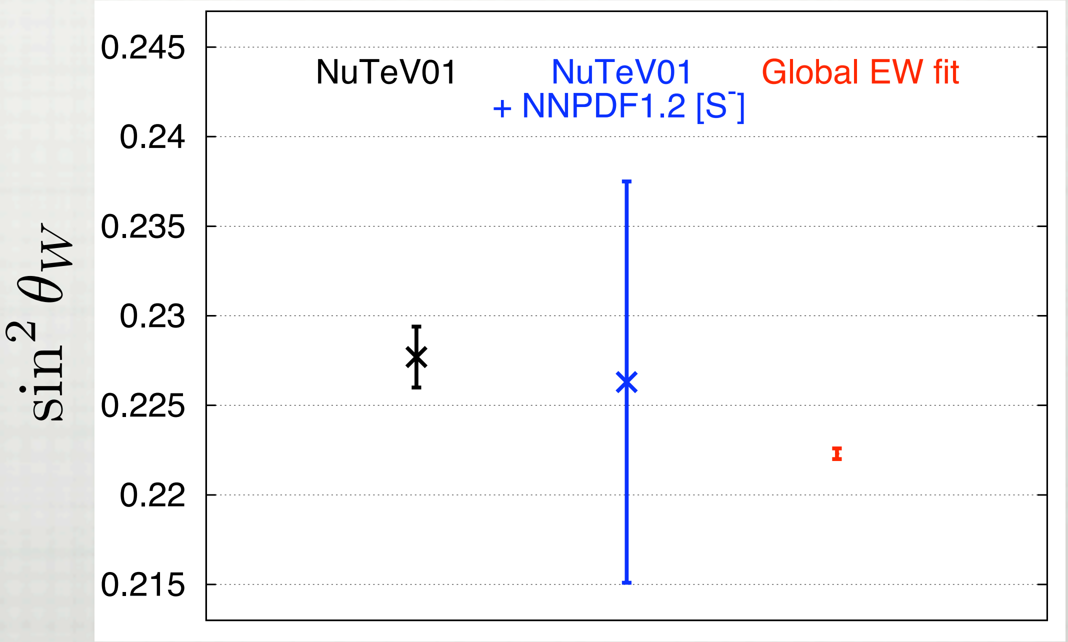
- Where are nuclear parton density functions useful ?

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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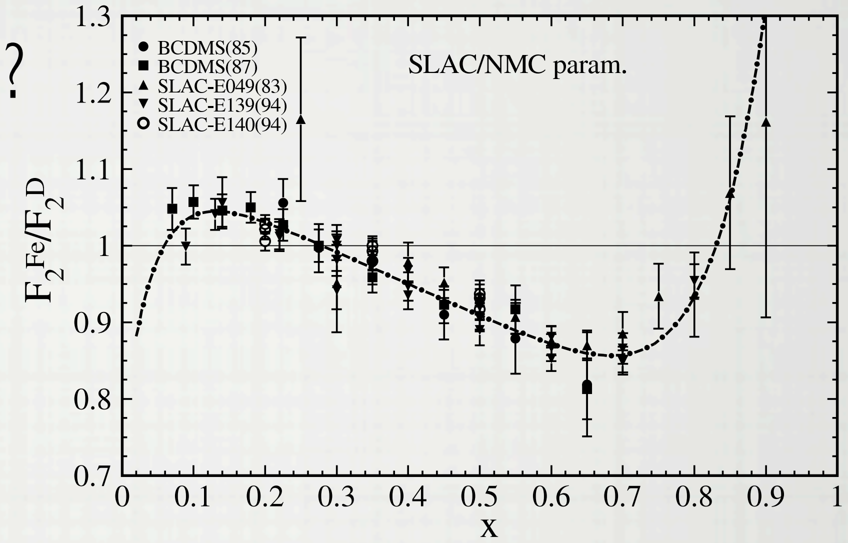


- Where are nuclear parton density functions useful ?

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

5. Even new physics - direct detection of dark matter

NUCLEAR PDFS

- Review of existing global analyses of nuclear PDF

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

    1. Multiplicative nuclear correction factor

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

$$\underset{\text{bound parton density}}{\uparrow} \qquad\qquad \underset{\text{free parton density}}{\nwarrow}$$

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

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

2. Convolution relation

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

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

NUCLEAR PDFS

- 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

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

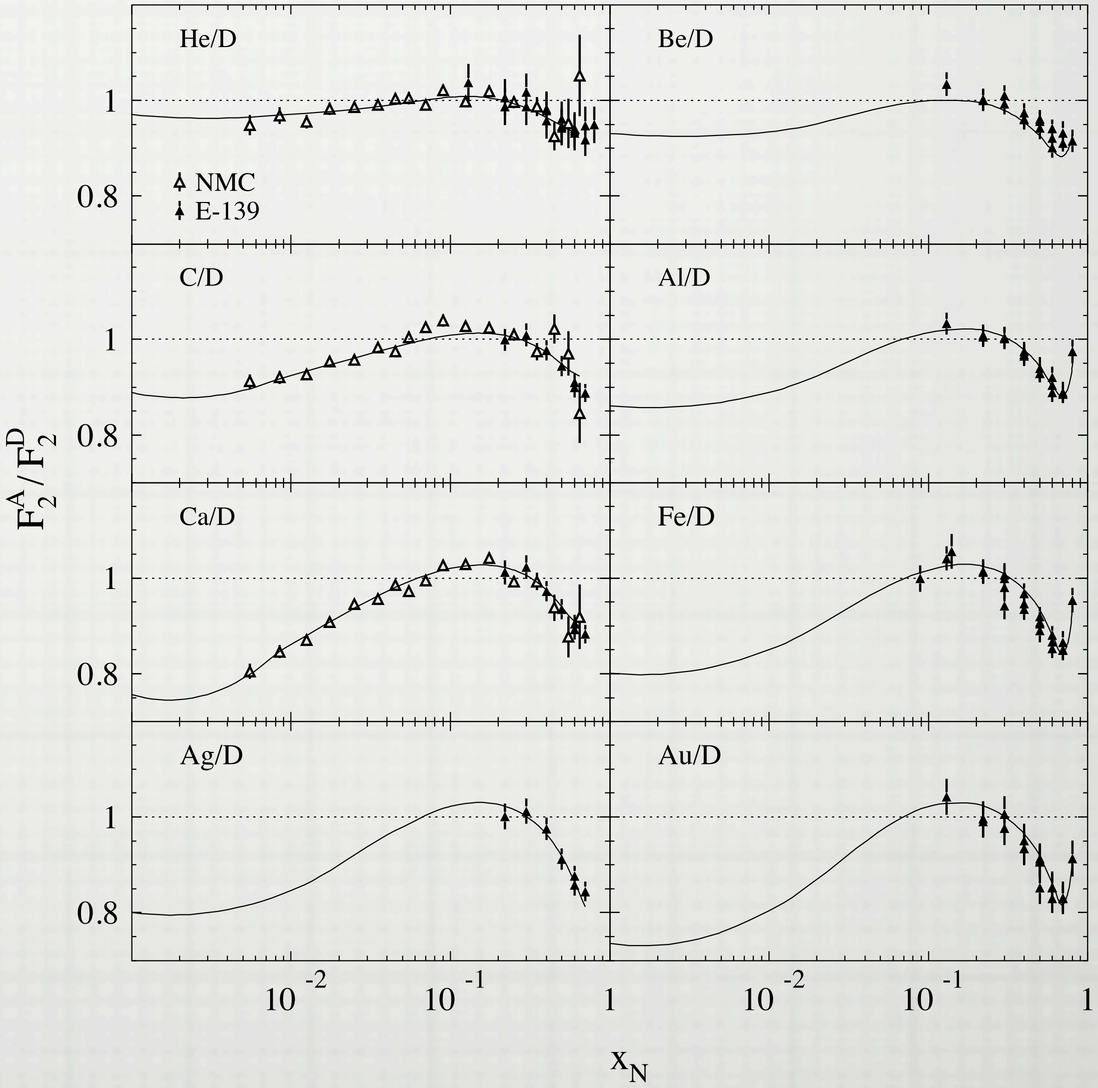
- typical nucleon density for valence quarks

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

- 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



NUCLEAR PDFS

- 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

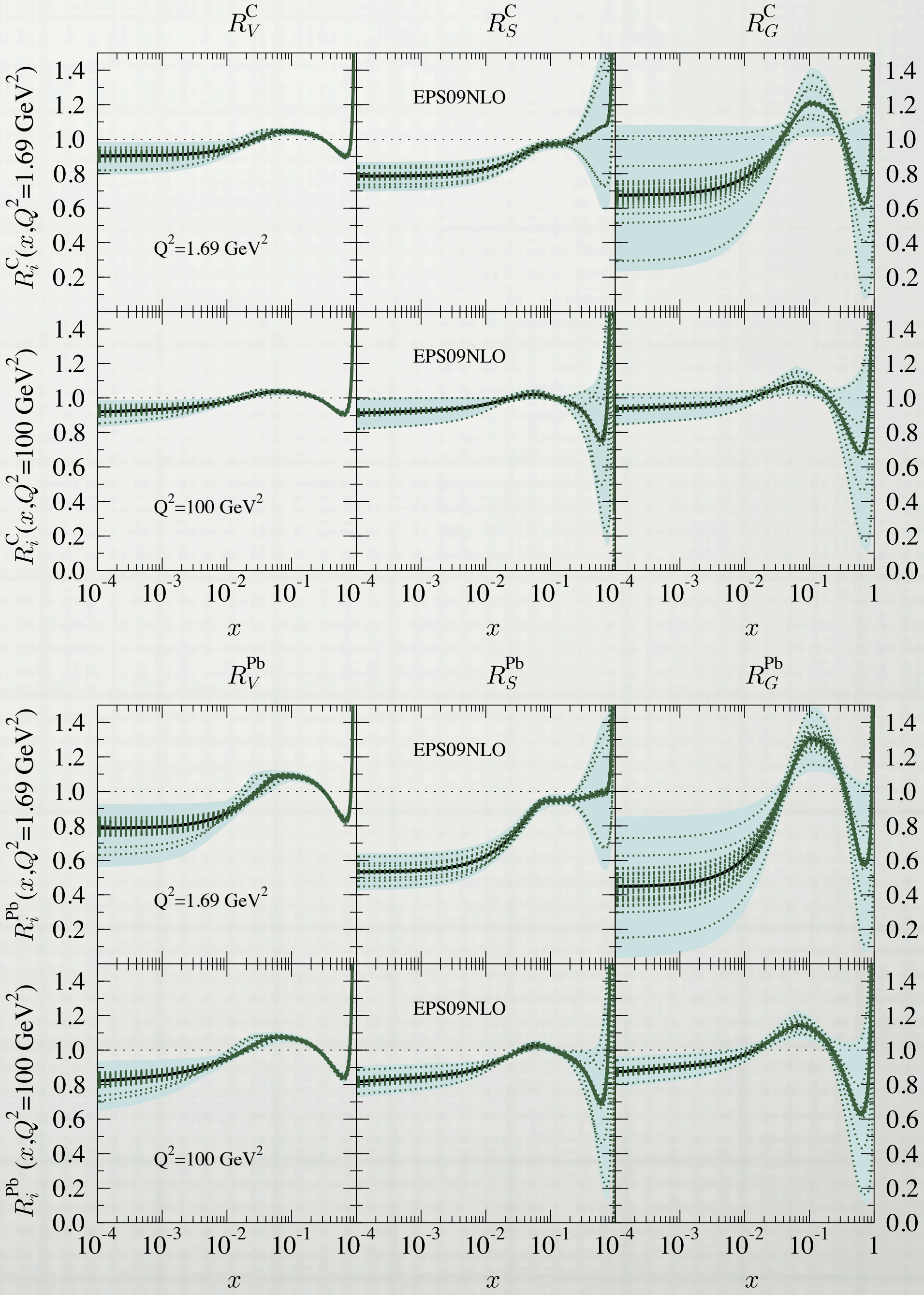
$$R_i(x,A,Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1-x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

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



NUCLEAR PDFS

- Why another set of NPDFs ?

1. Better estimate of the nPDF uncertainty

- PDFs underestimate the true error since they do not take into account the variation of the framework (parameterization) & all other physical assumptions & technical details

2. Flexible CTEQ nuclear correction factor

- we would like a NPDF analysis with 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. Include neutrino DIS data in the fit

NUCLEAR CTEQ

- 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)

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

  - 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

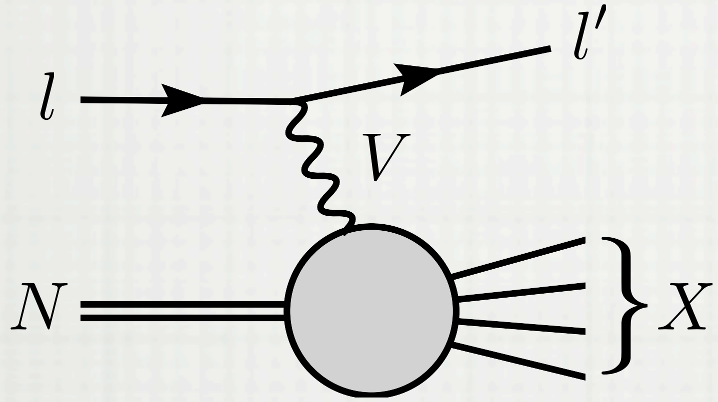
  - Input scale and other input parameters as in CTEQ6M proton analysis

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

NUCLEAR CTEQ

- Experiments included in the analysis:

Deep Inelastic Scattering



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

CERN BCDMS & EMC & NMC

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

FNAL E-665

$N = (\mathrm{D, C, Ca, Pb, Xe})$

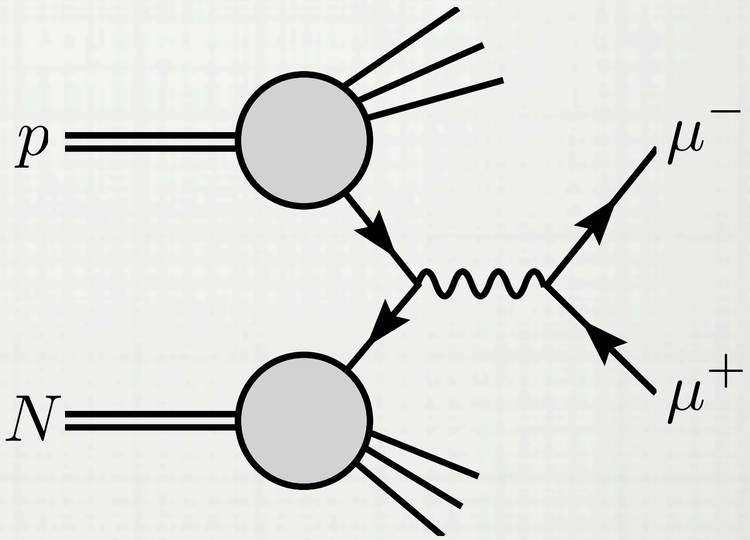
DESY Hermes

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

SLAC E-139 & E-049

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

Drell-Yan process



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

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)

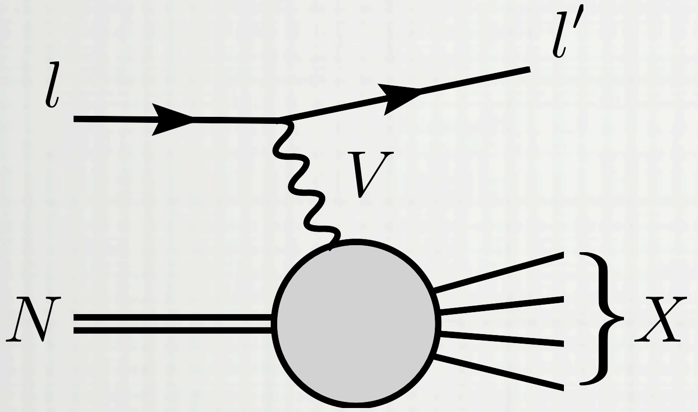
    DIS: $F_2^A/F_2^{A'}$ Drell-Yan: $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$

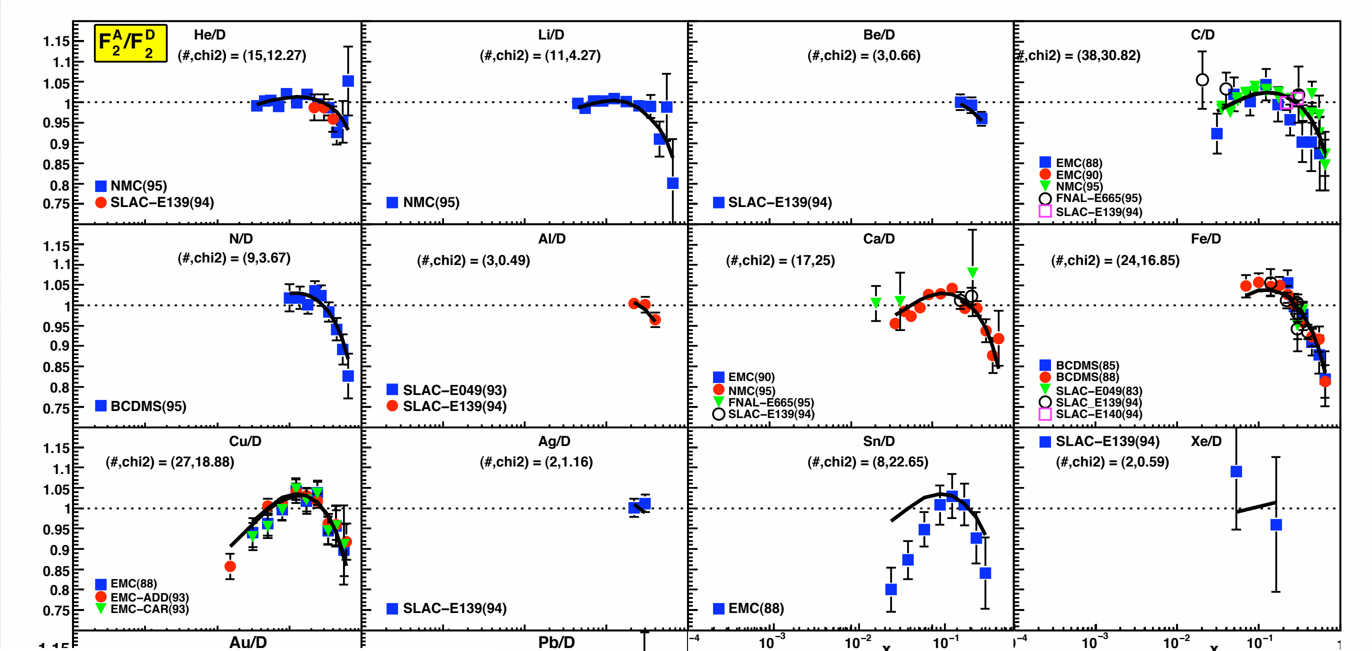
  - applied standard CTEQ kinematical cuts Q>2GeV & W>3.5GeV

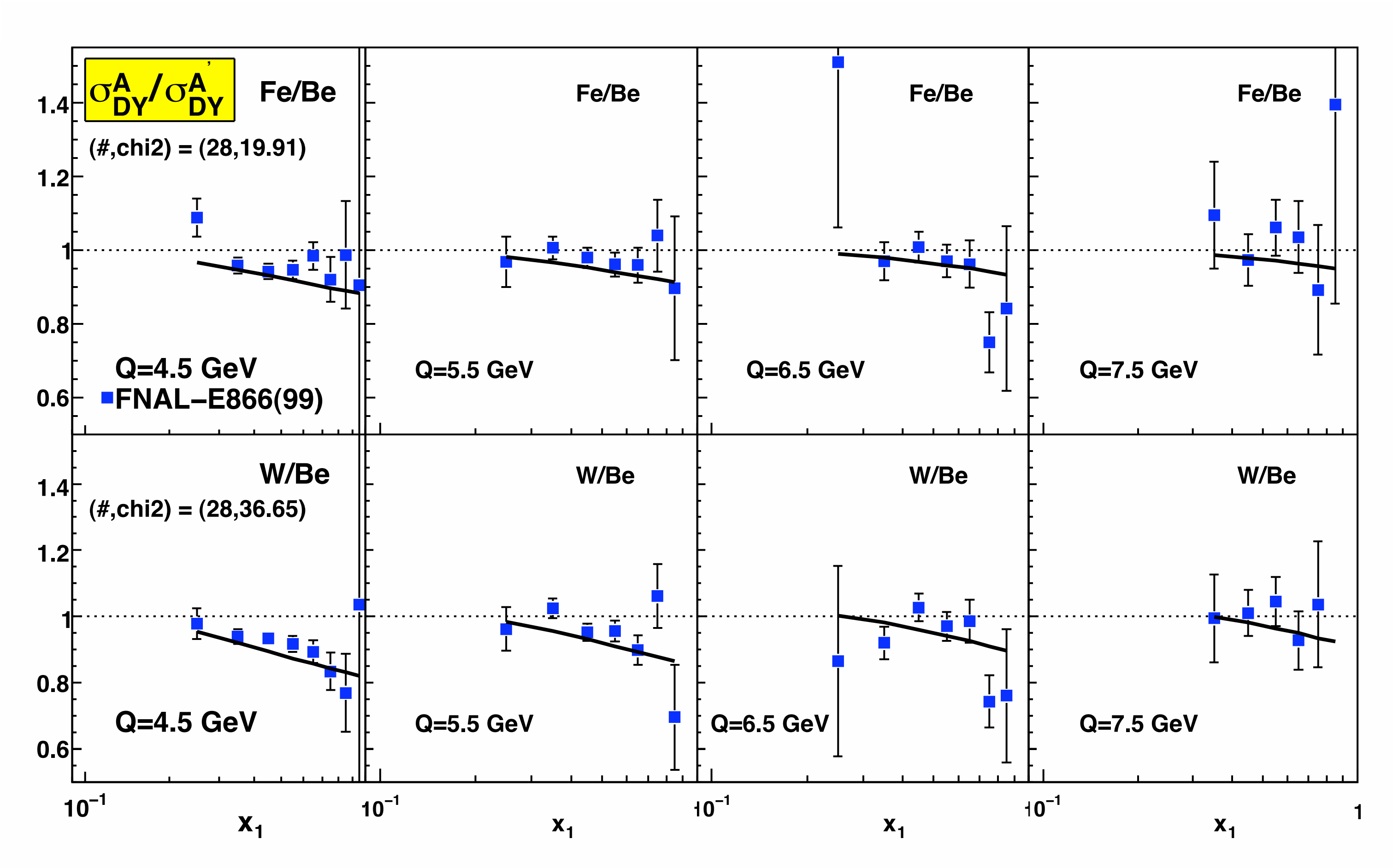
- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 32 free parameters - 675 degrees of freedom
  - overall χ^2/dof = 0.95
  - individually for different data sets
    - for F_2^A/F_2^D χ^2/pt=0.92
    - for $F_2^A/F_2^{A'}$ χ^2/pt=0.69
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$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

NUCLEAR CTEQ

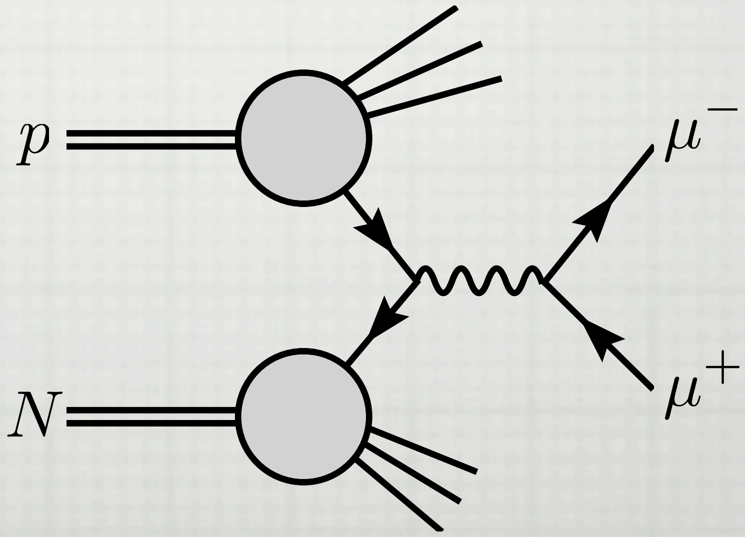
Deep Inelastic Scattering





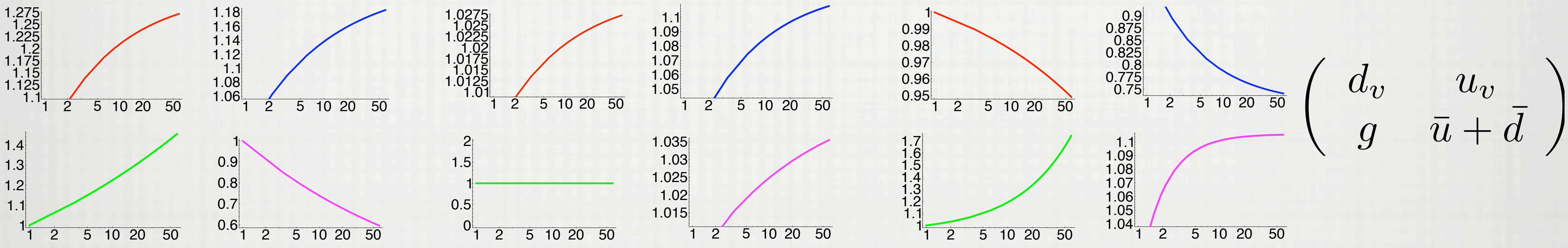


Drell-Yan process



NUCLEAR CTEQ

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



$c_1(A)/c_{k,0}$ $c_2(A)/c_{k,0}$ $c_5(A)/c_{k,0}$

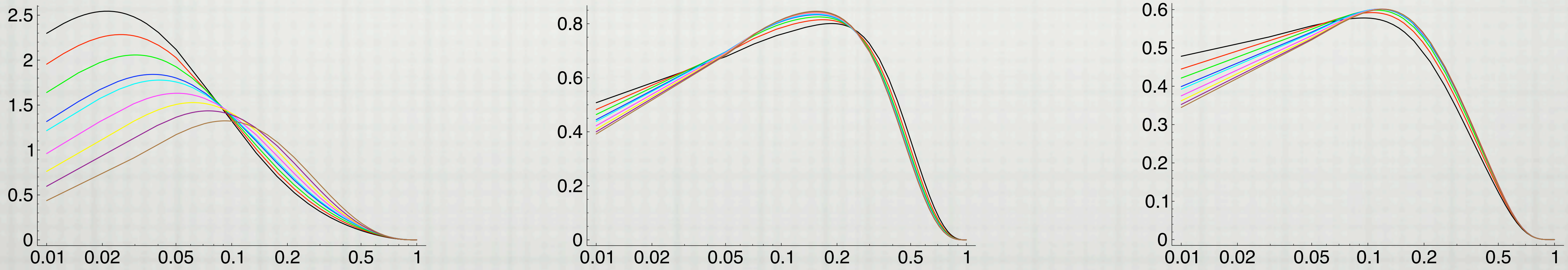
$$\begin{pmatrix} d_v & u_v \\ g & \bar{u}+\bar{d} \end{pmatrix}$$

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

black yellow brown

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

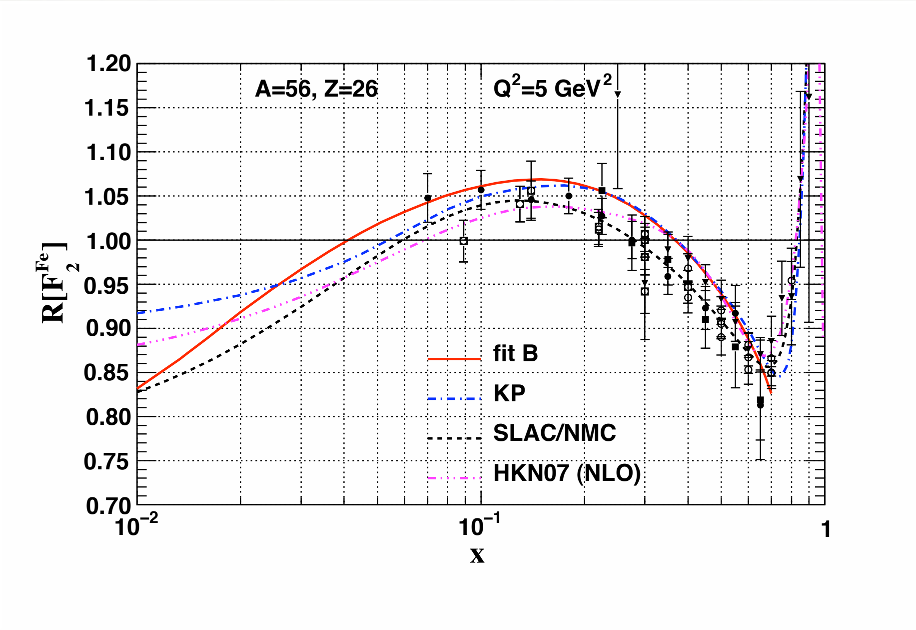
red purple

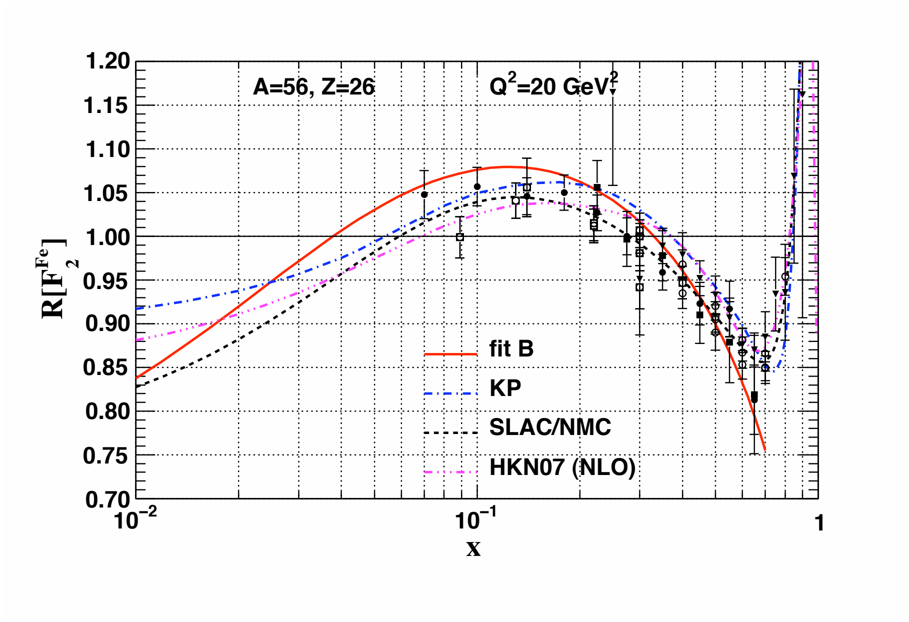


gluon total up-quark total down-quark

NEUTRINO DIS

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





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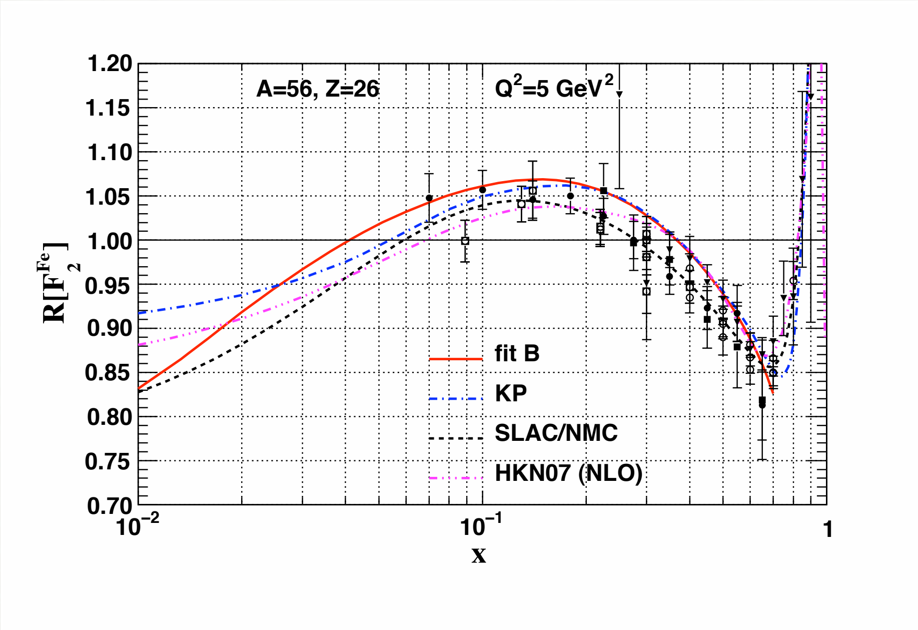

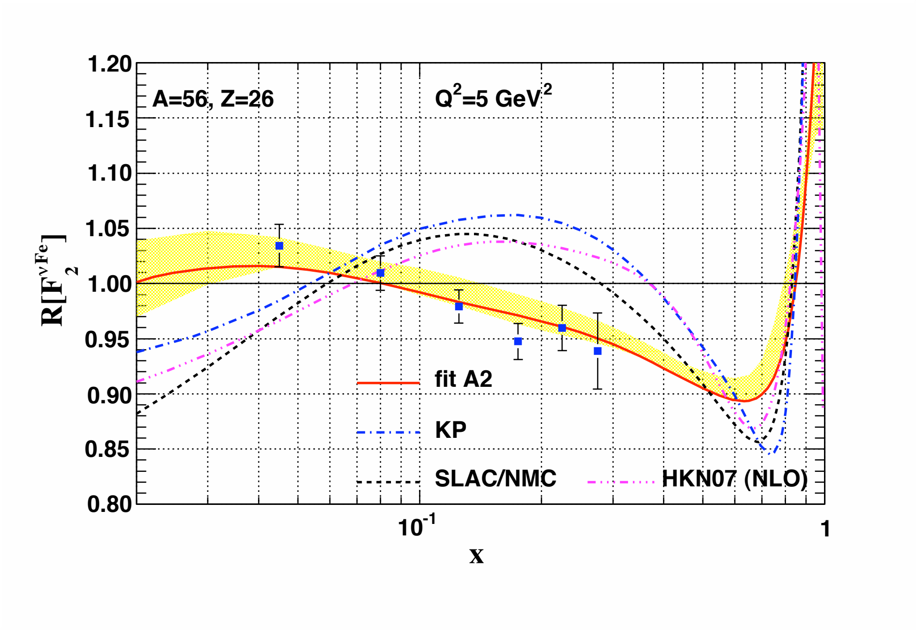

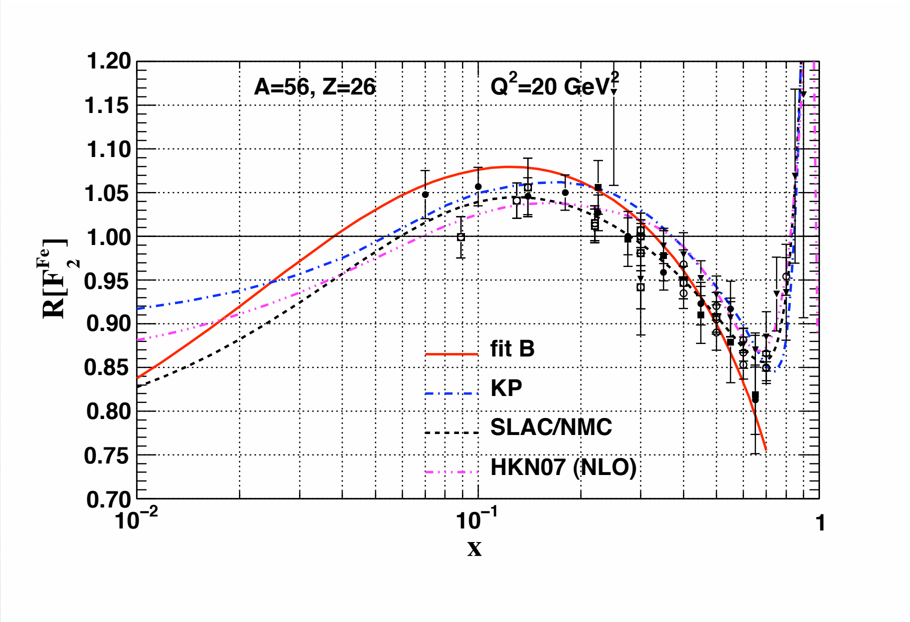

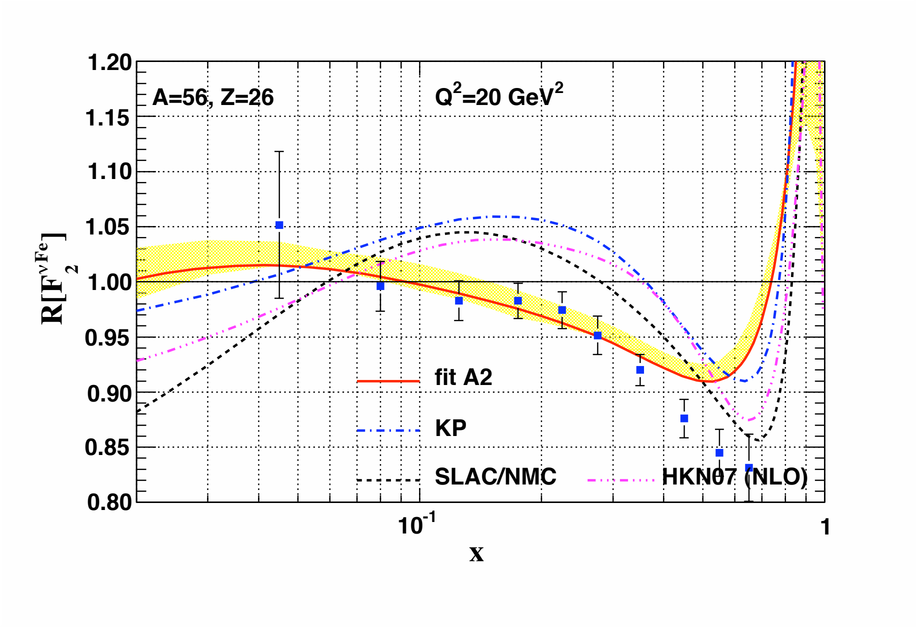

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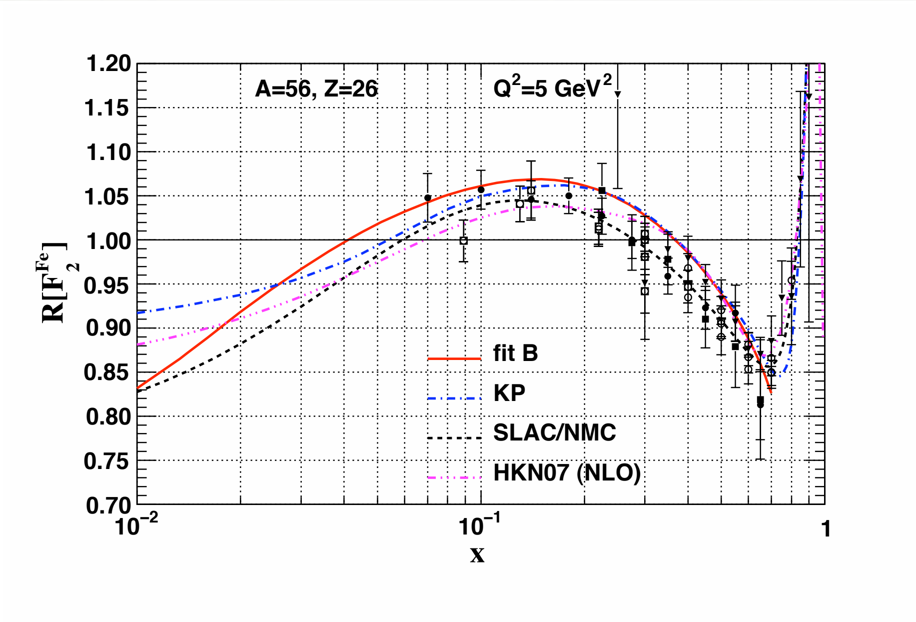
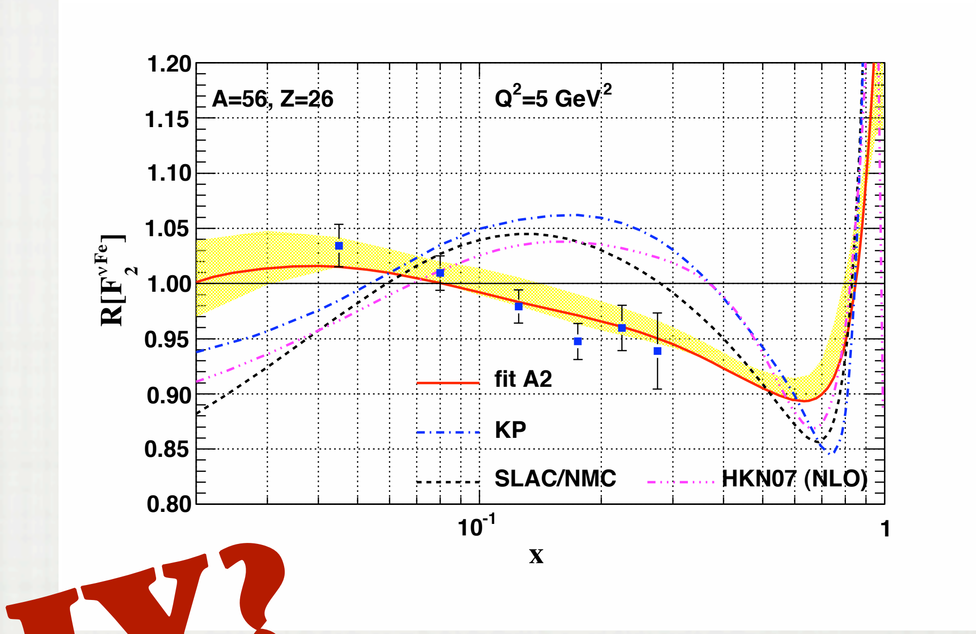
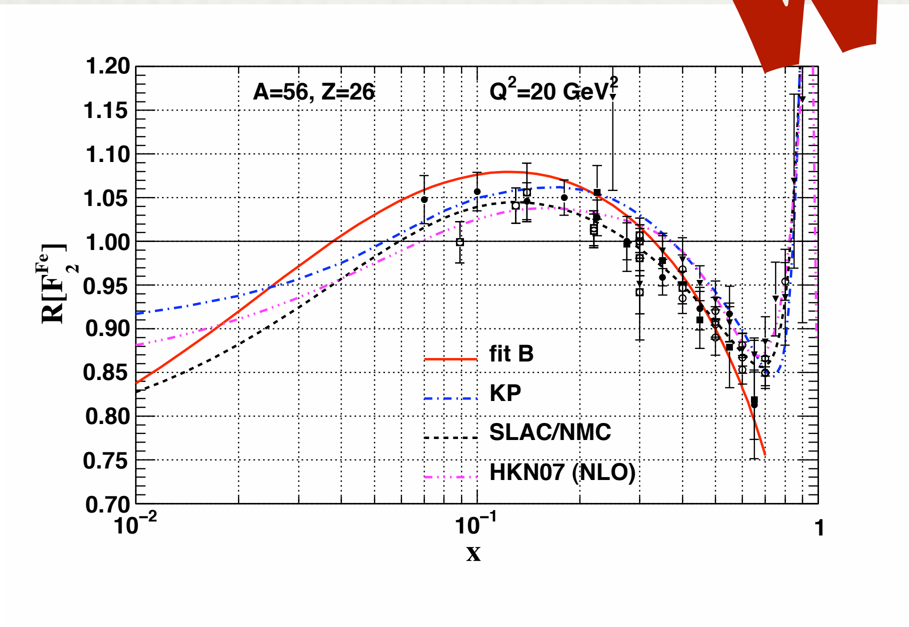
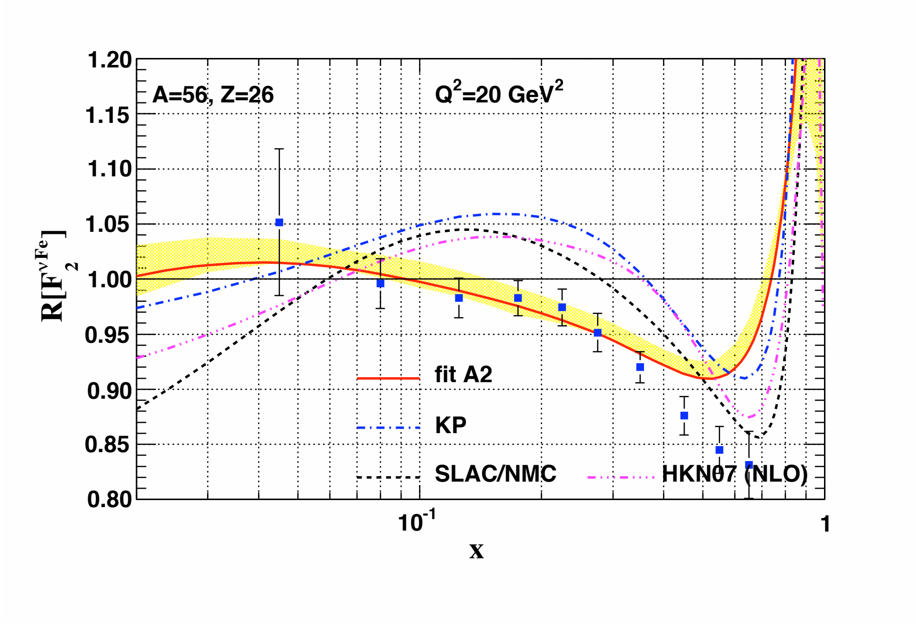




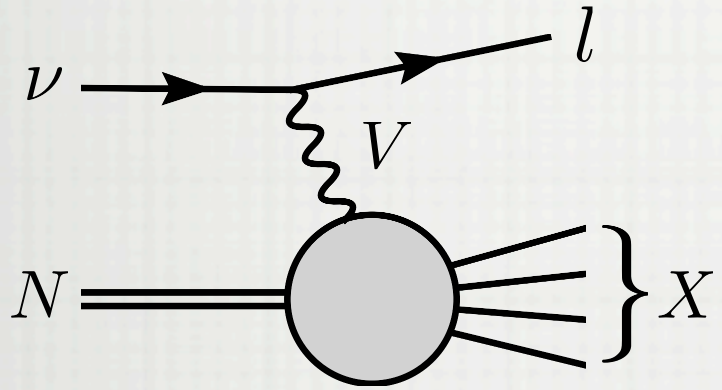
WHY?





NEUTRINO DIS

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

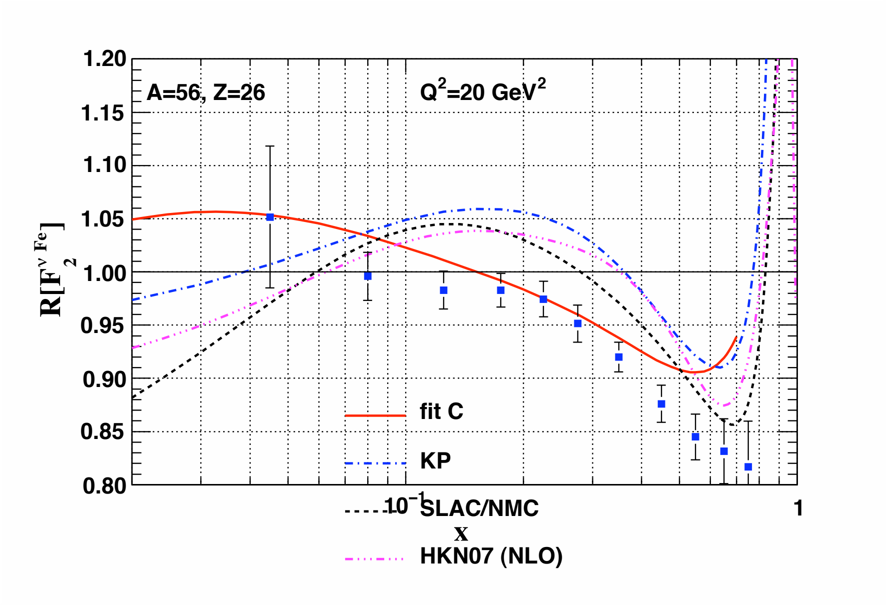
NEUTRINO DIS

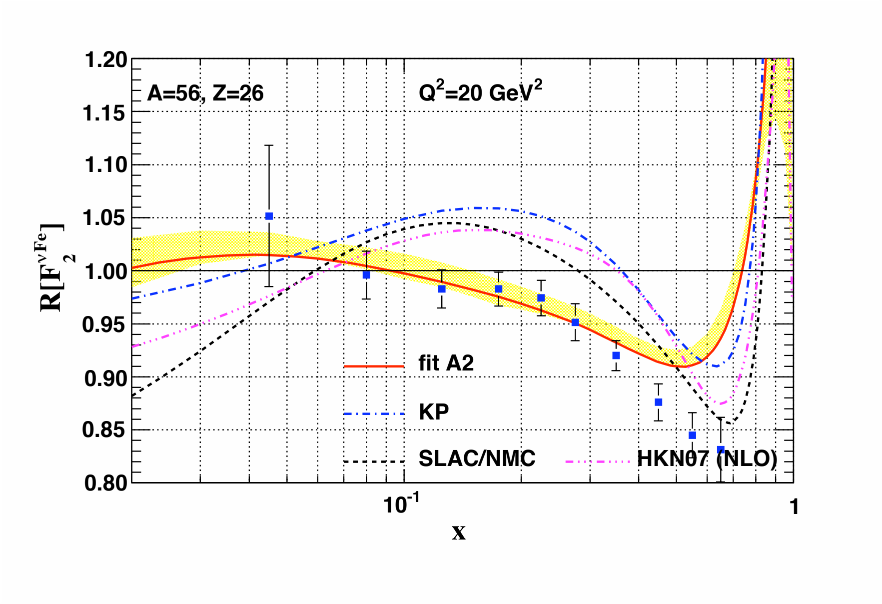
- Properties of neutrino fits
  - CHORUS data are in good agreement with the charged lepton data

    combined: χ^2/pt=1.03
  - NuTeV data difficult to fit alone or together 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



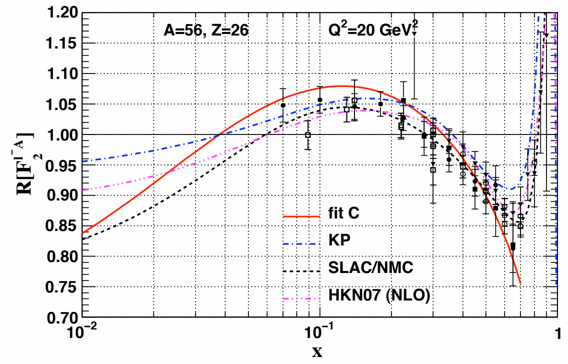


NEUTRINO DIS

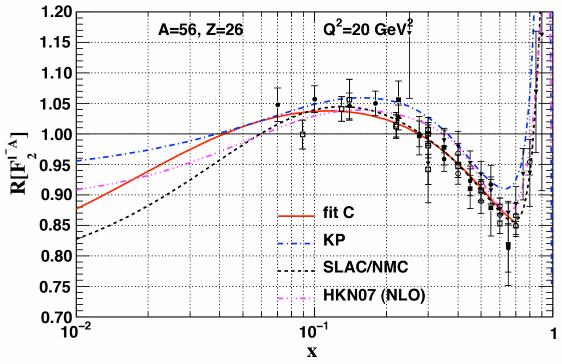
- Analysis of fits with different weights of neutrino DIS

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

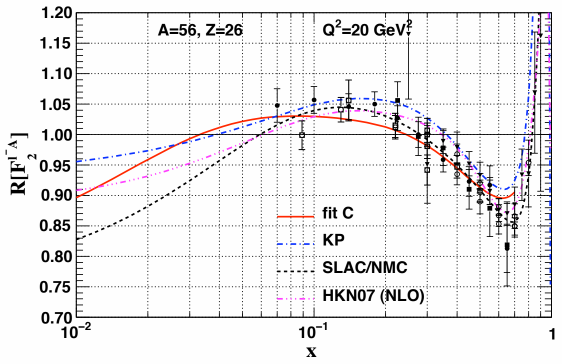
Weight	Name of fit	$l^{\pm}A$ data	χ^2 (/pt)	νA data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	decut3	708	638 (0.90)	-	-	638 (0.90)
$w = 1/7$	glofac1a	708	645 (0.91)	3134	4710 (1.50)	5355 (1.39)
$w = 1/4$	glofac1c	708	654 (0.92)	3134	4501 (1.43)	5155 (1.34)
$w = 1/2$	glofac1b	708	680 (0.96)	3134	4405 (1.40)	5085 (1.32)
$w = 1$	global2b	708	736 (1.04)	3134	4277 (1.36)	5014 (1.30)
$w = \infty$	nuanua1	-	-	3134	4192 (1.33)	4192 (1.33)



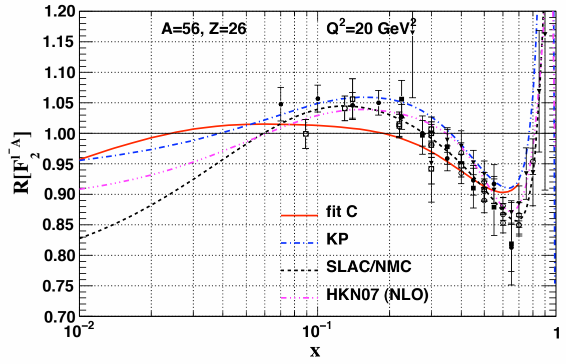
decut3 (w=0)



glofac1a (w=1/7)



global2b (w=1)



nuanua1 - only neutrino DIS

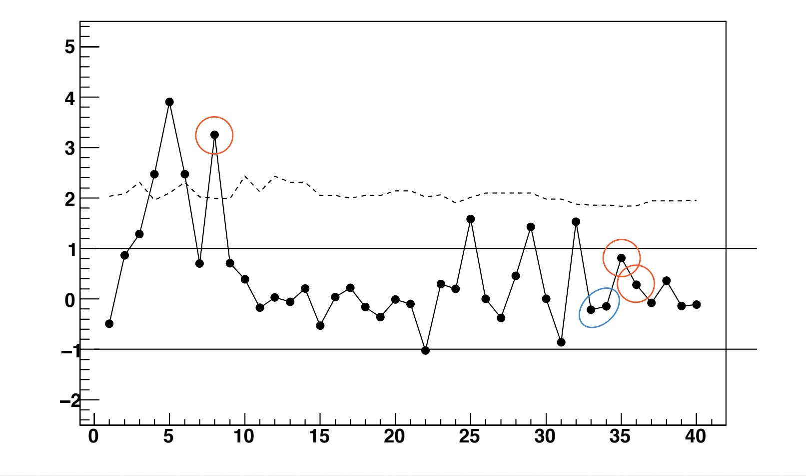
NEUTRINO DIS

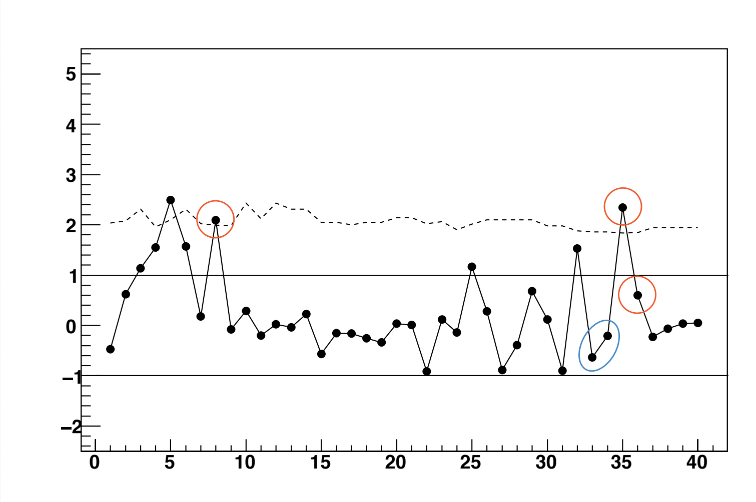
- Analysis of fits with different weights of neutrino DIS

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

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

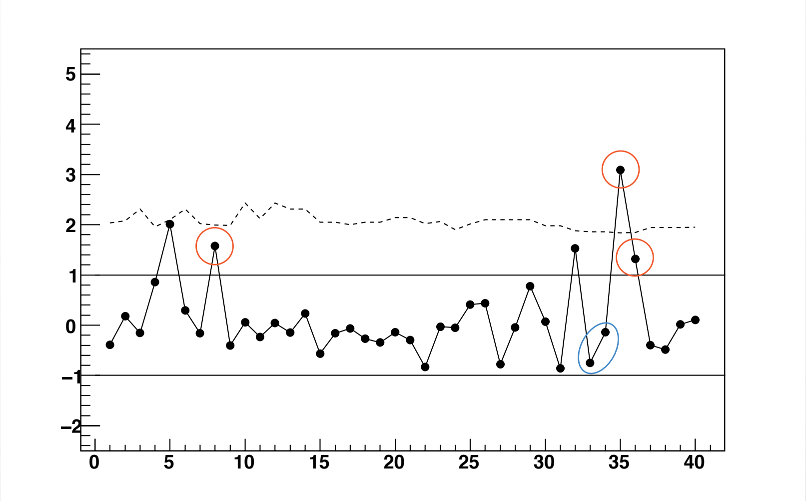
(w=1)

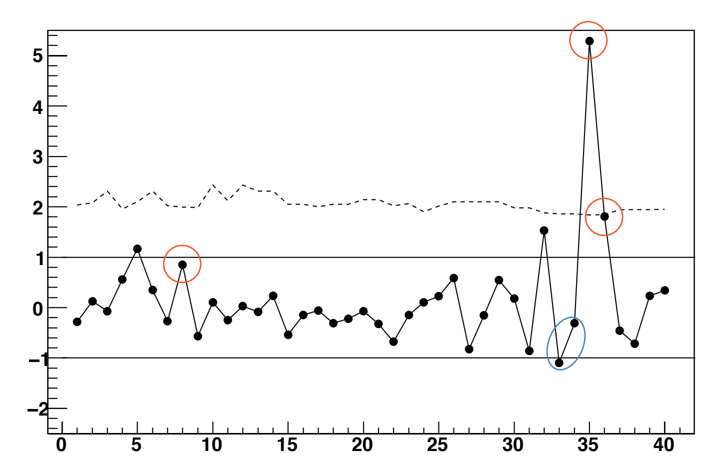




(w=1/2)

(w=1/4)





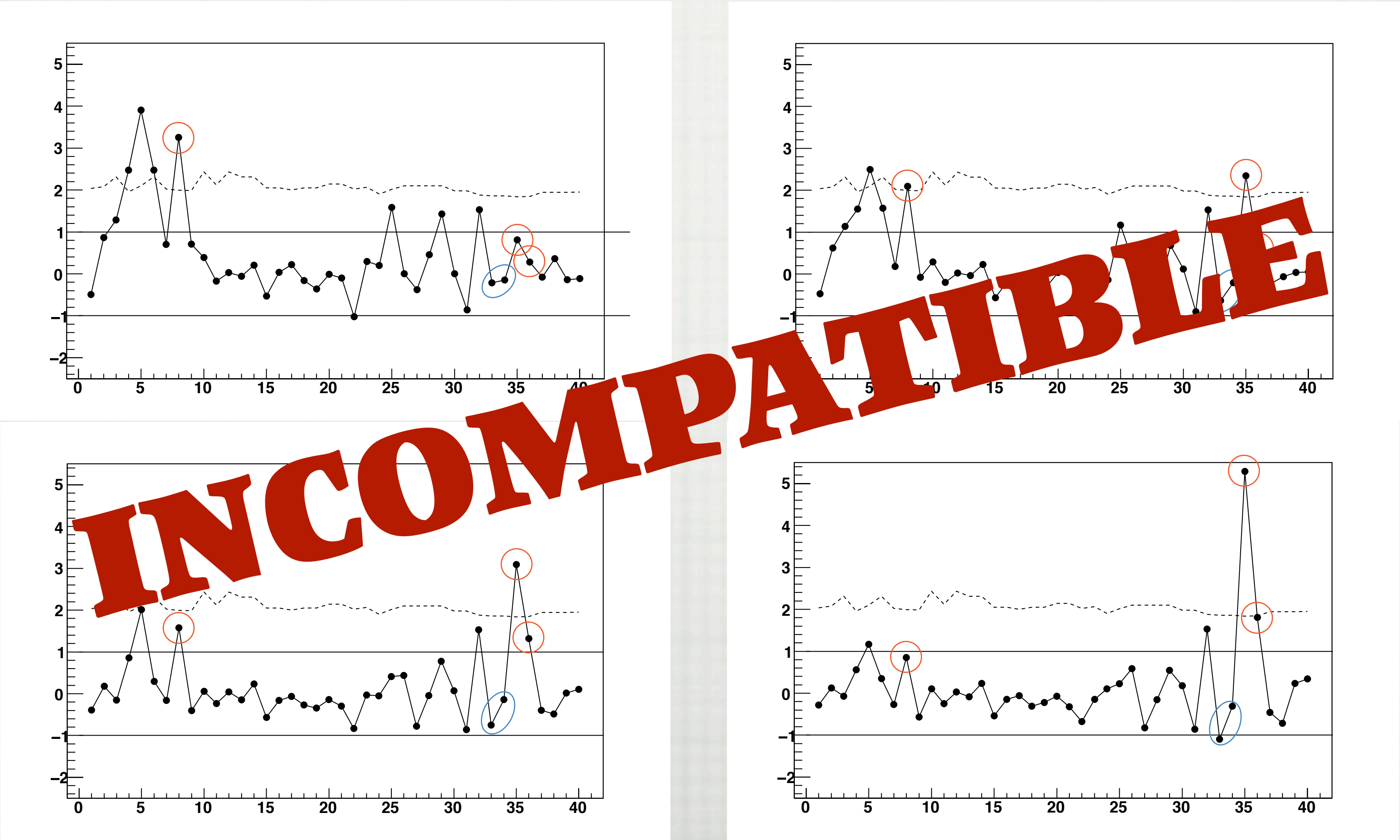
(w=1/7)

NEUTRINO DIS

- Analysis of fits with different weights of neutrino DIS

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

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)

CONCLUSIONS

- Global nuclear CTEQ fit is able to describe the charged lepton data well

  - hope to release a first public nPDF set in not so distant future

- Greatest challenges on the way to public nPDFs

  - relax kinematical cuts and fit Fermi motion peak in a natural way
  - error PDFs and an error estimate of PDF
  - find a way how to constrain the gluon

- Incompatibility of neutrino DIS with charged lepton DIS

  - incompatibility a "precision" effect - the result changes when using uncorrelated errors
  - understand the high χ^2 of the NuTeV data
  - can NOMAD data help ?