NUCLEAR CORRECTION FACTORS FROM NEUTRINO DIS

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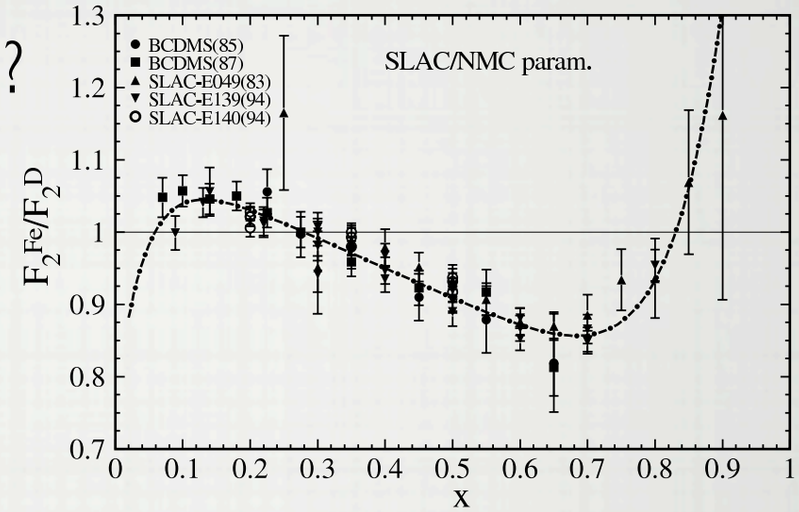
Karlsruhe Institute of Technology

OUTLINE

1. Global nPDF analysis & new CTEQ framework
2. Neutrino DIS vs. nPDF
3. Conclusions and Outlook

NUCLEAR PDFS

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



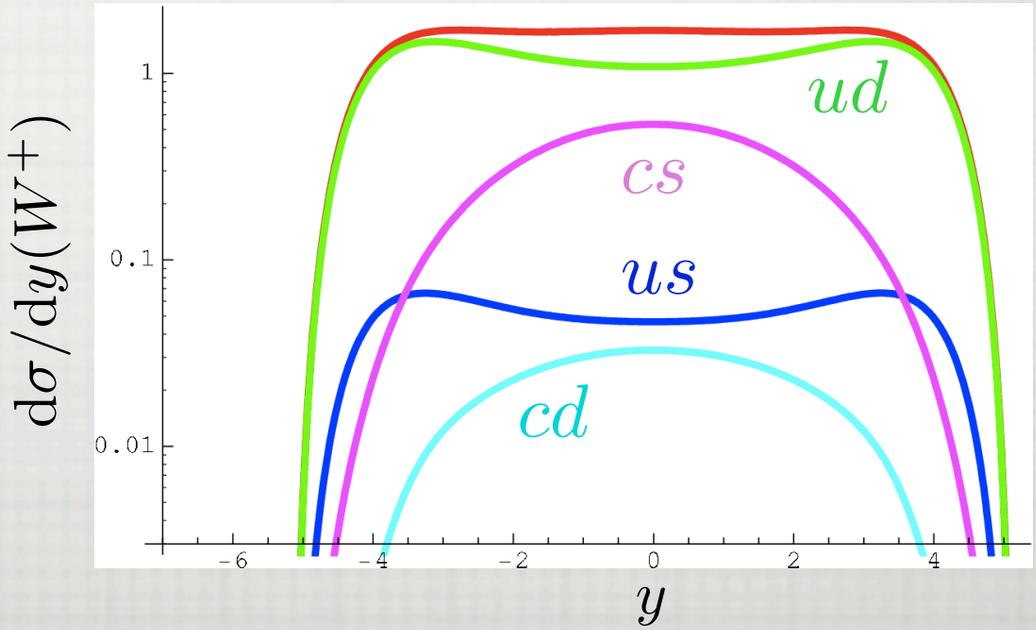
- Where are nuclear parton density functions useful ?

  1. Strange quark content of the proton

  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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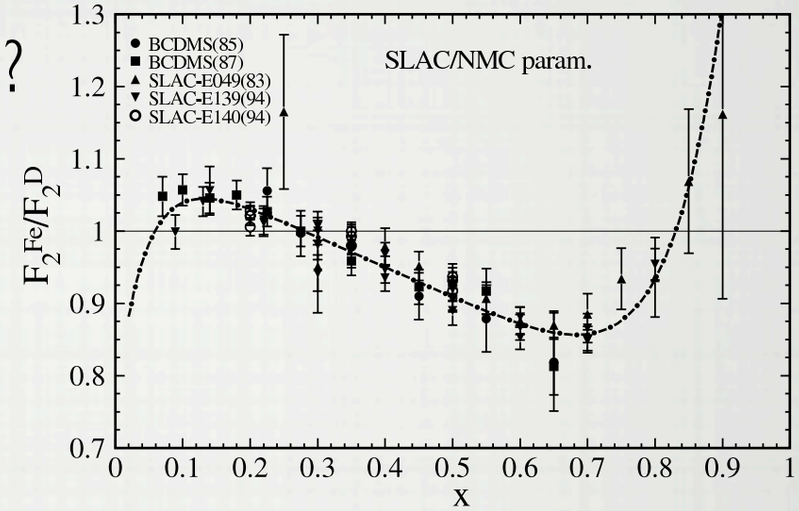


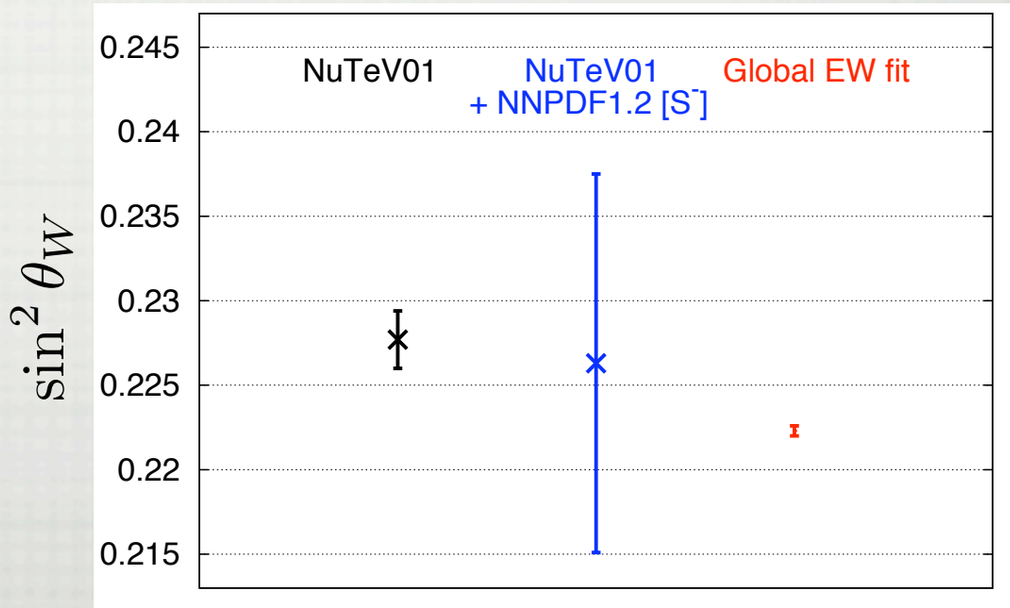
- Where are nuclear parton density functions useful ?

  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



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

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

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

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

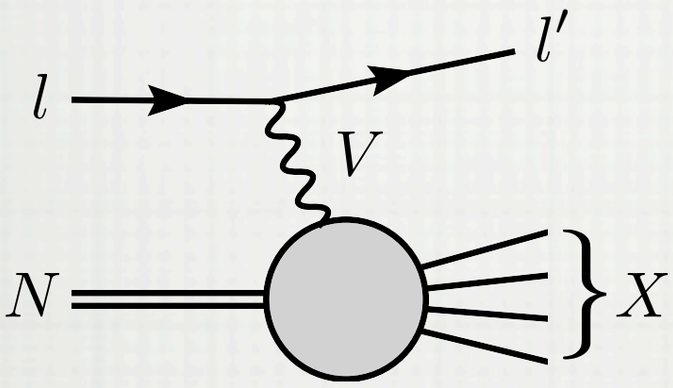
  - Input scale and other input parameters as in CTEQ6M proton analysis

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

NUCLEAR CTEQ

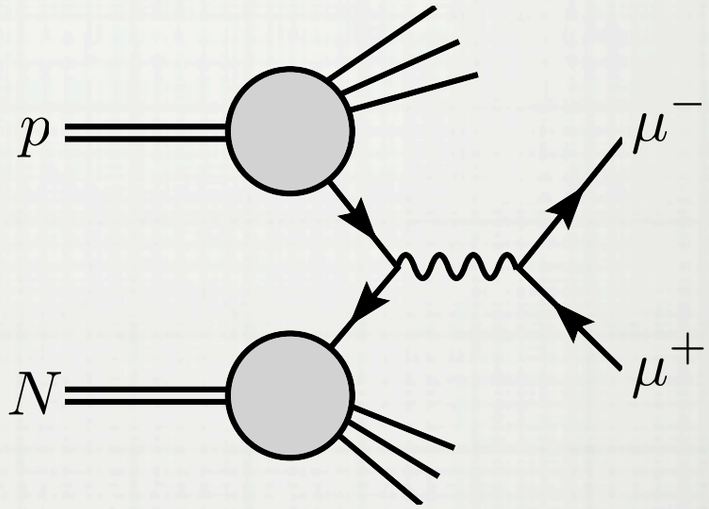
- Experiments included in the analysis:

Deep Inelastic Scattering



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

Drell-Yan process



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

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

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

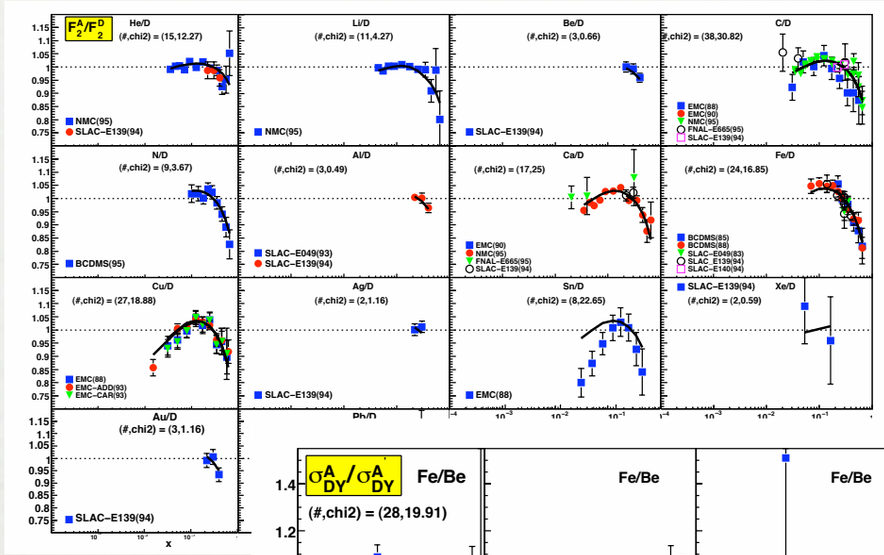
FNAL E-772 & E-886

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

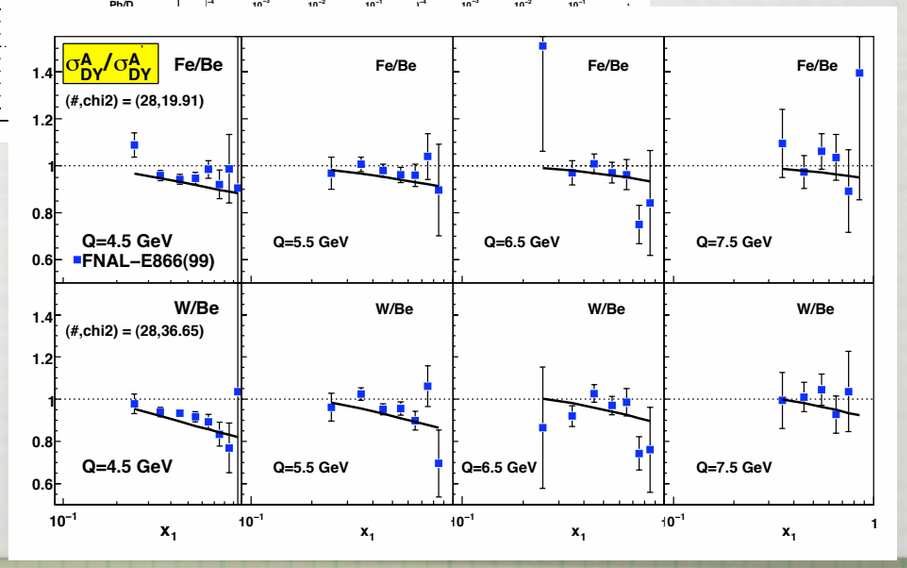
NUCLEAR CTEQ

- 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



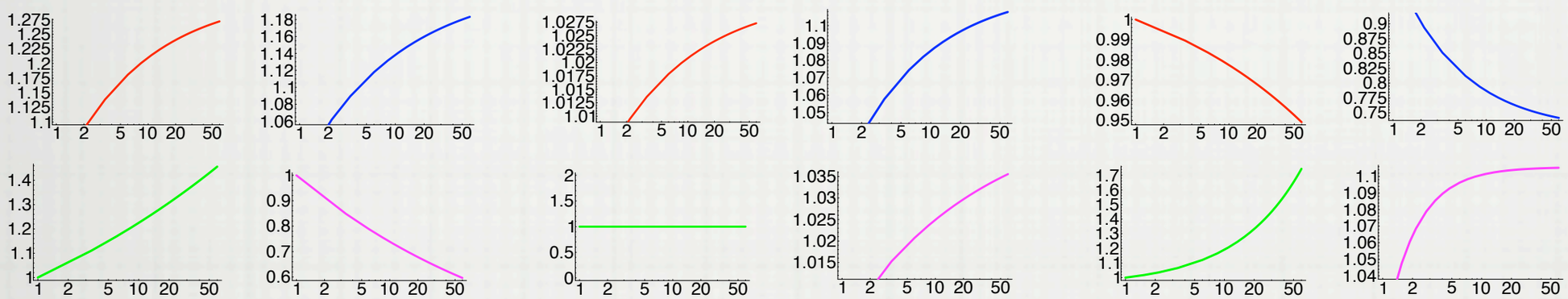
- NPDF fit results:
  - 708 (1233) data points after (before) cuts
  - 32 free parameters - 675 degrees of freedom
  - overall χ^2/dof = 0.95
  - individually for different data sets
    - for F_2^A/F_2^D χ^2/pt=0.92
    - for $F_2^A/F_2^{A'}$ χ^2/pt=0.69
    - for $\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$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



NUCLEAR CTEQ

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

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



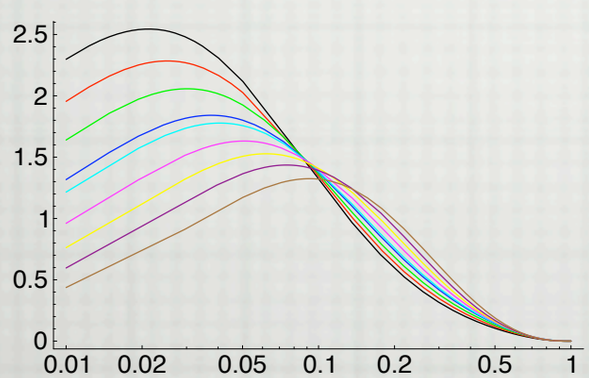
$$\begin{pmatrix} d_v & u_v \\ g & \bar{u}+\bar{d} \end{pmatrix}$$

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

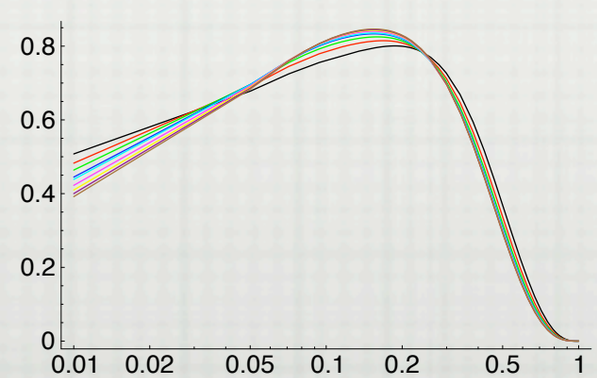
black yellow brown

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

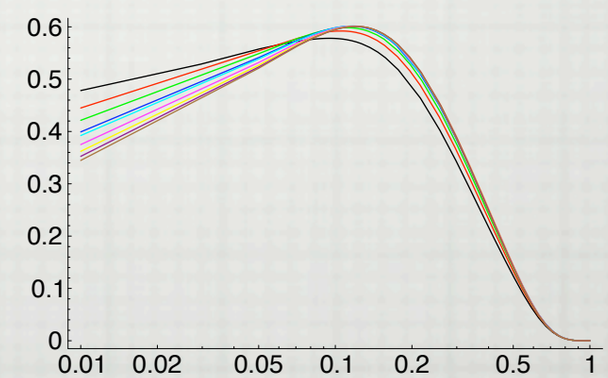
red purple



gluon



total up-quark

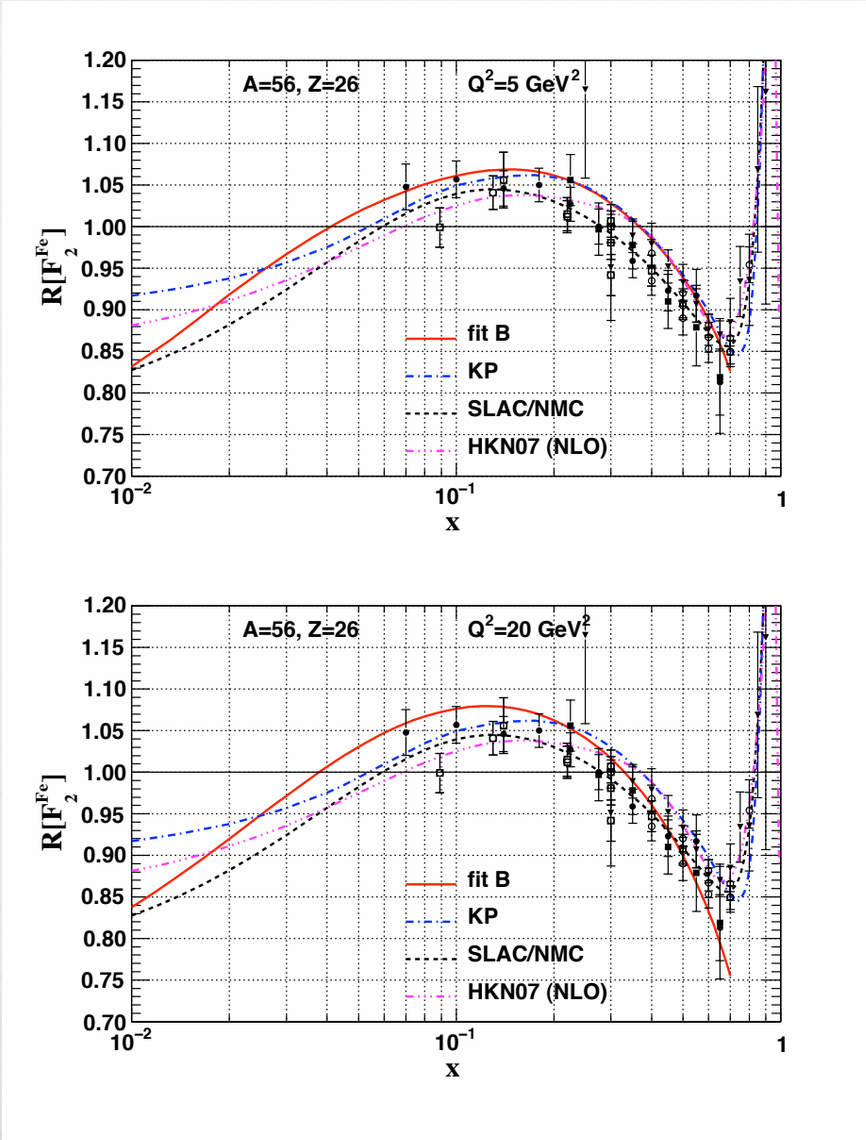


total down-quark

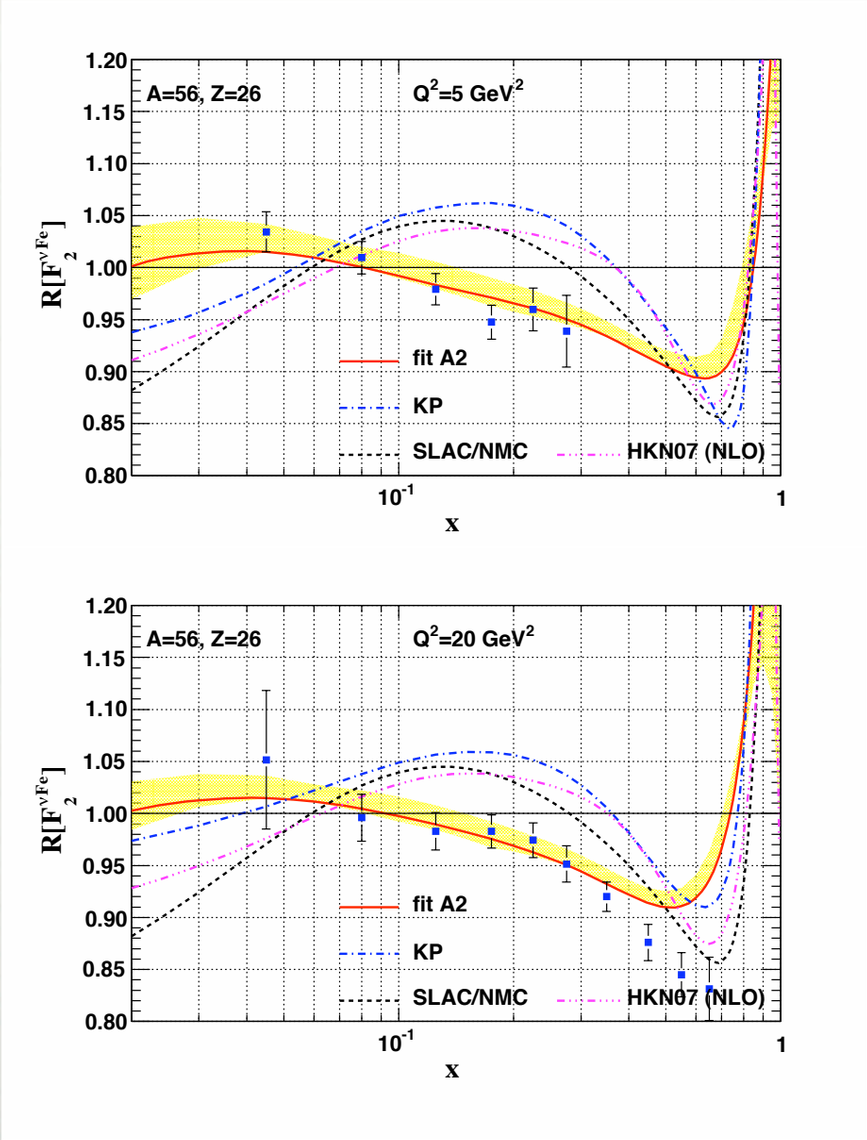
NEUTRINO DIS

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

Phys.Rev.D80 094004, 2009

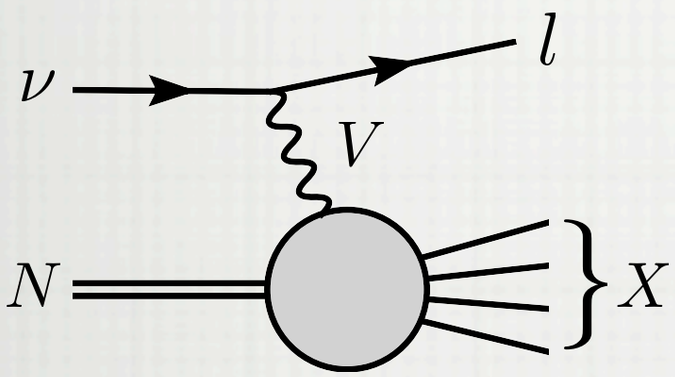


Phys.Rev.D77 054013, 2008



NEUTRINO DIS

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



$\nu + N \rightarrow l + X$

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 ?

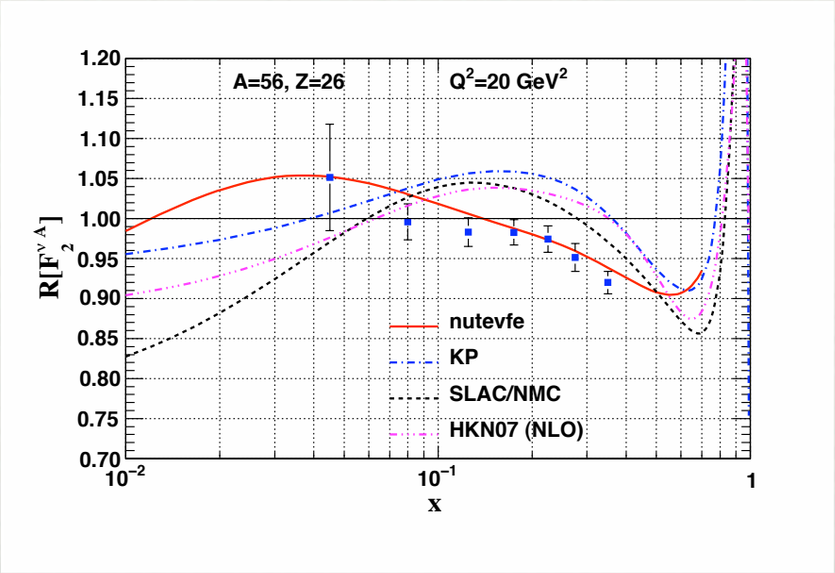
NEUTRINO DIS

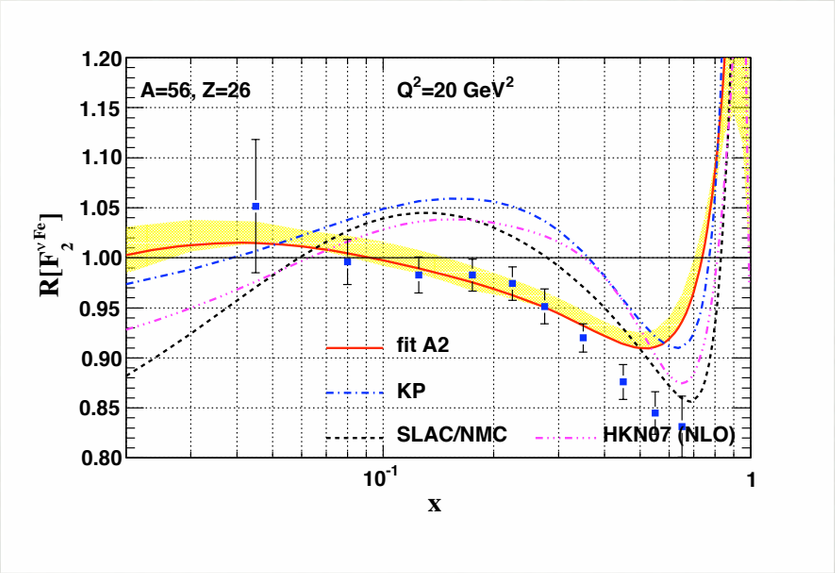
- Properties of neutrino fits
  - CHORUS data are in good agreement with the charged lepton data

    combined: χ^2/pt=1.03
  - NuTeV data (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



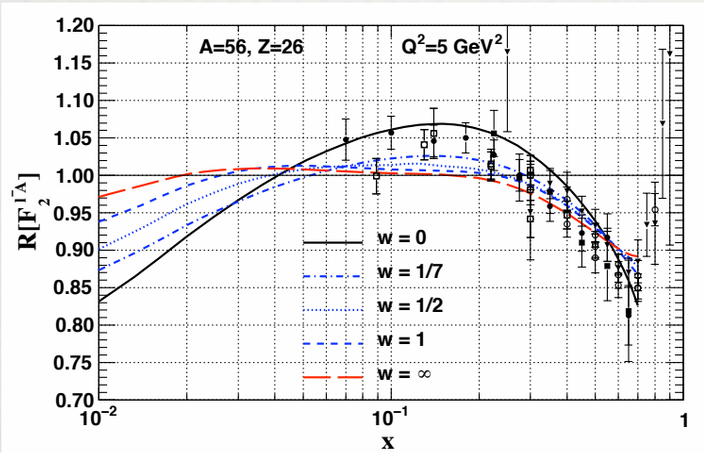


NEUTRINO DIS

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

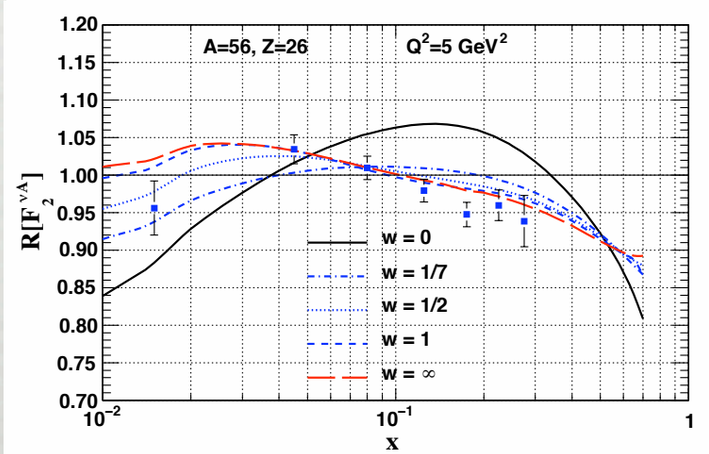
- Nuclear correction factors - $R = F_2^{Fe}/F_2^{Fe,0}$

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)



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

$Q^2 = 5GeV^2$



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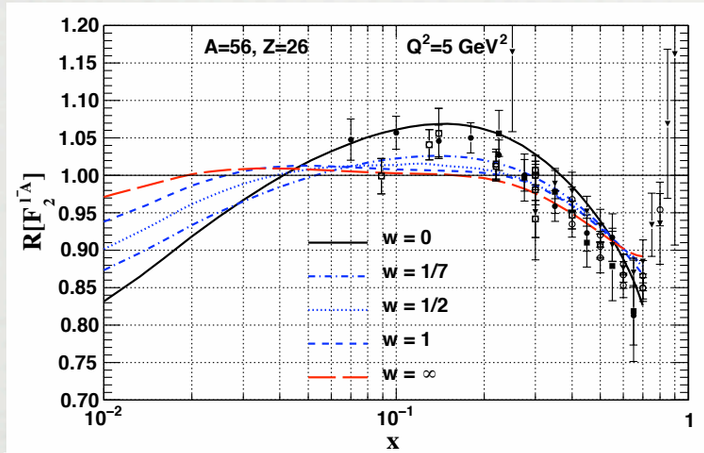
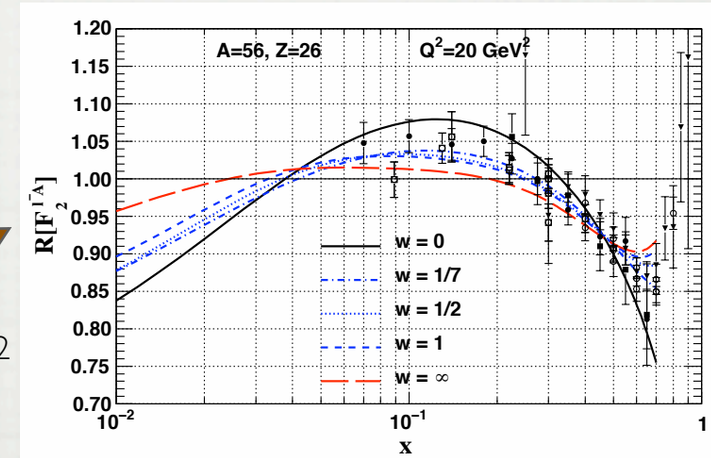
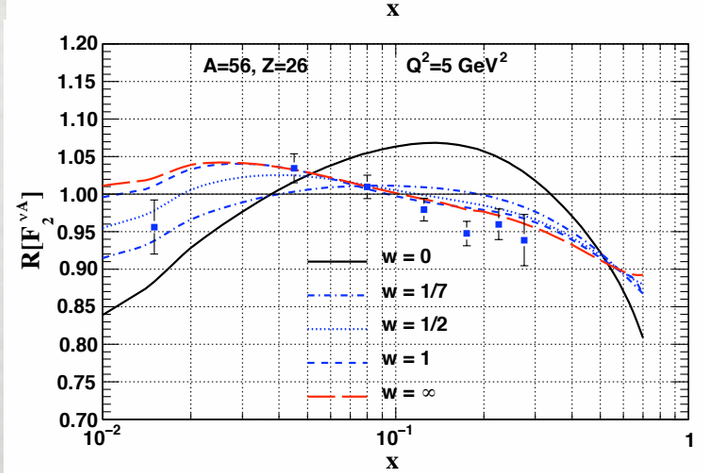


$R\left[F_2^{l^{\pm}A}\right]$

$Q^2 = 5\text{GeV}^2$

$Q^2 = 20\text{GeV}^2$

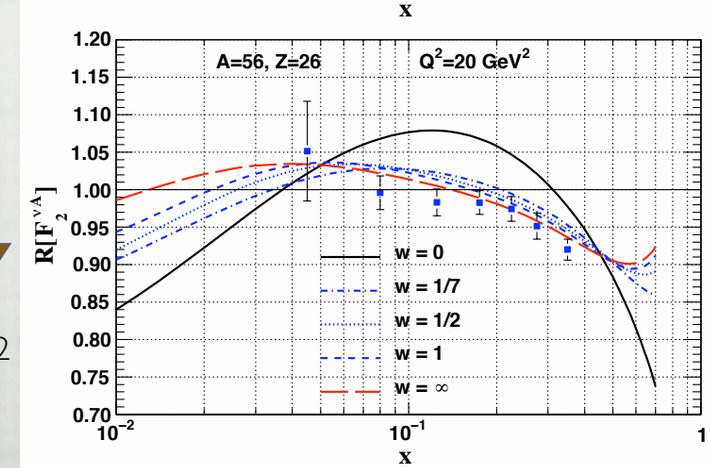




$R\left[F_2^{\nu A}\right]$

$Q^2 = 5\text{GeV}^2$

$Q^2 = 20\text{GeV}^2$



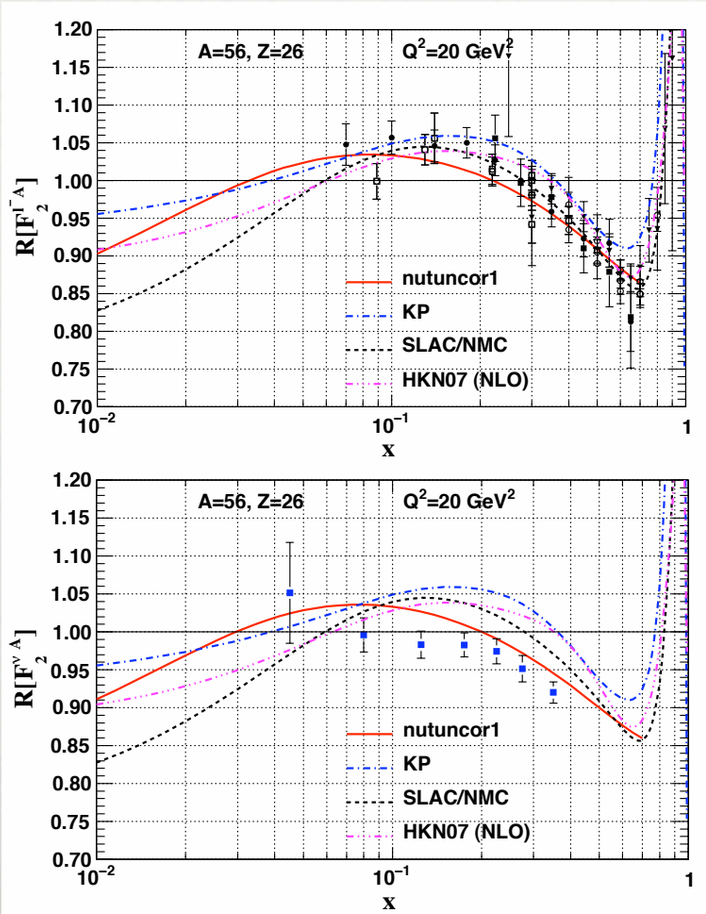
NEUTRINO DIS

- Analysis of fits with neutrino DIS (uncorrelated errors)

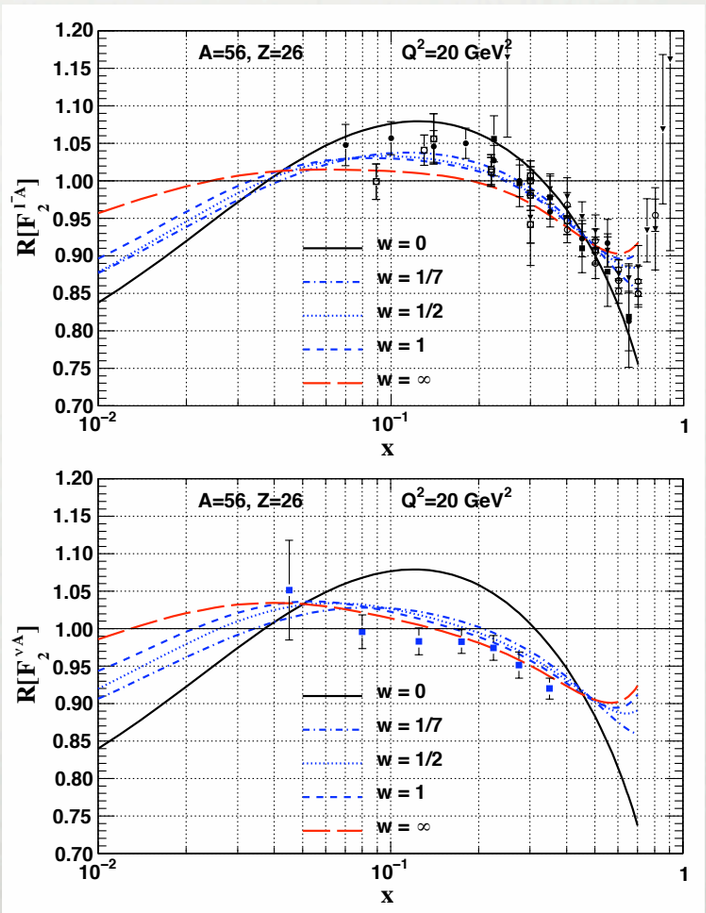
- Nuclear correction factors - $R = F_2^{Fe}/F_2^{Fe,0}$

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



NEUTRINO DIS

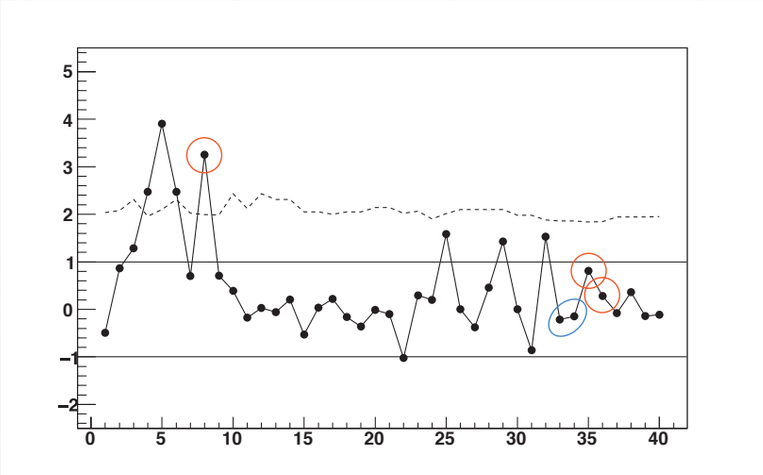
- Analysis of fits with different weights of neutrino DIS (corr. errors)

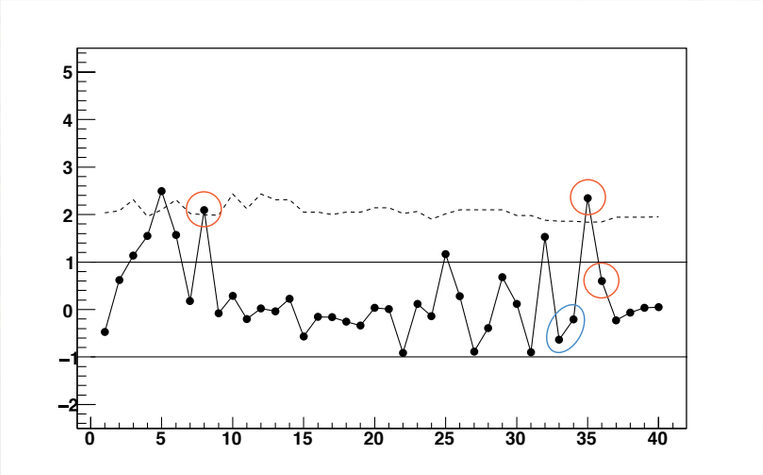
- χ^2- distribution criterion

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

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

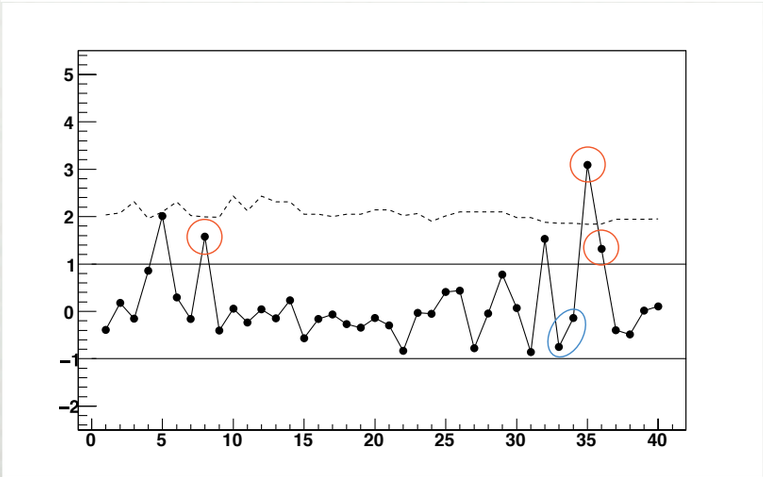
(w=1)

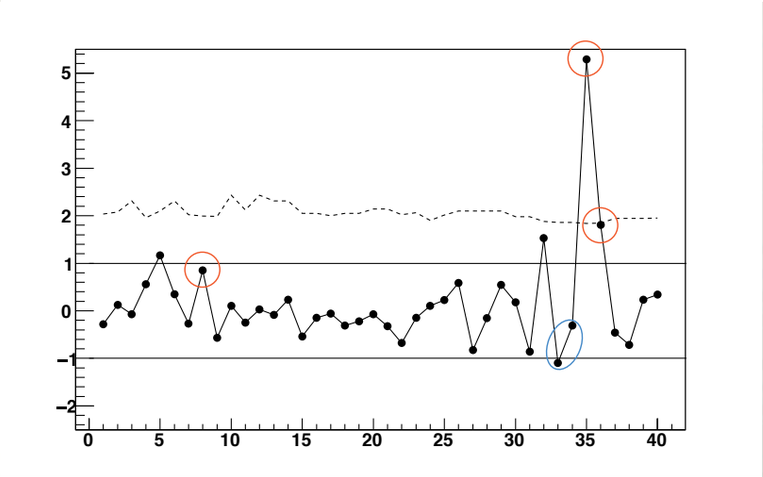




(w=1/2)

(w=1/4)





(w=1/7)

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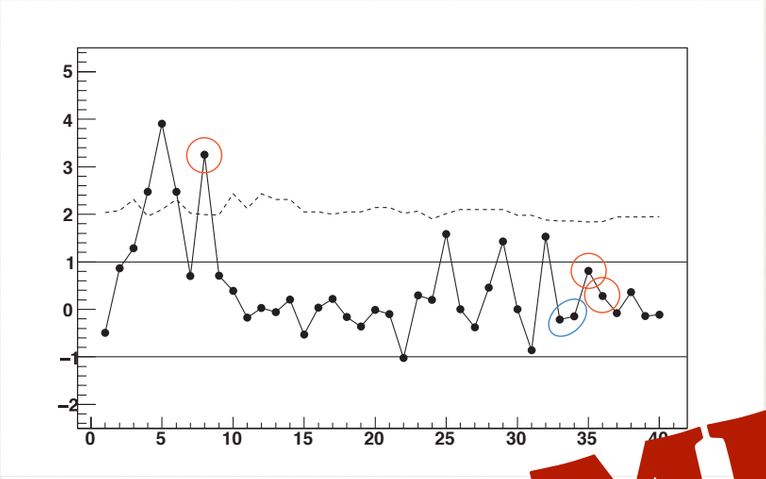
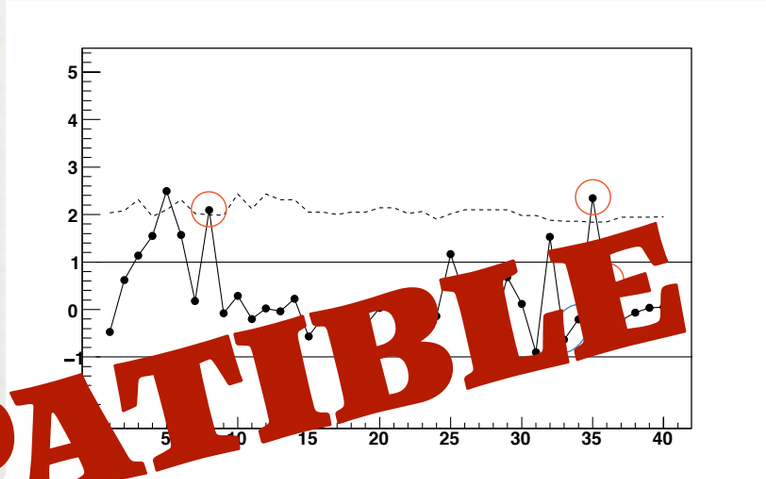
(w=1)

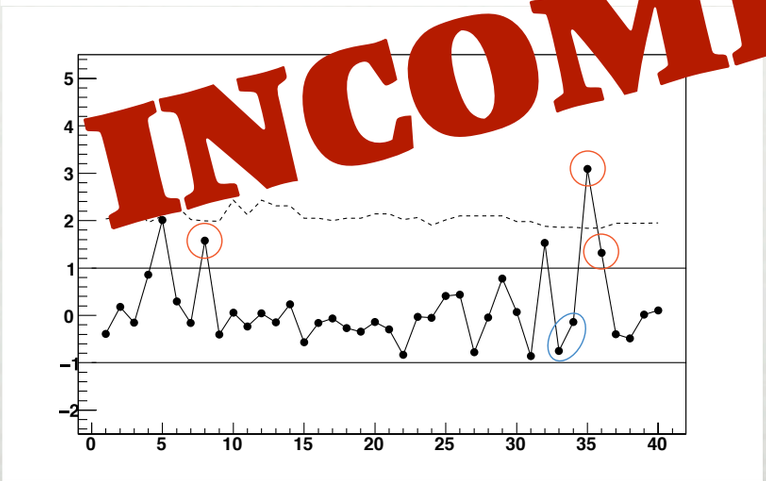


(w=1/2)



INCOMPATIBLE

(w=1/4)



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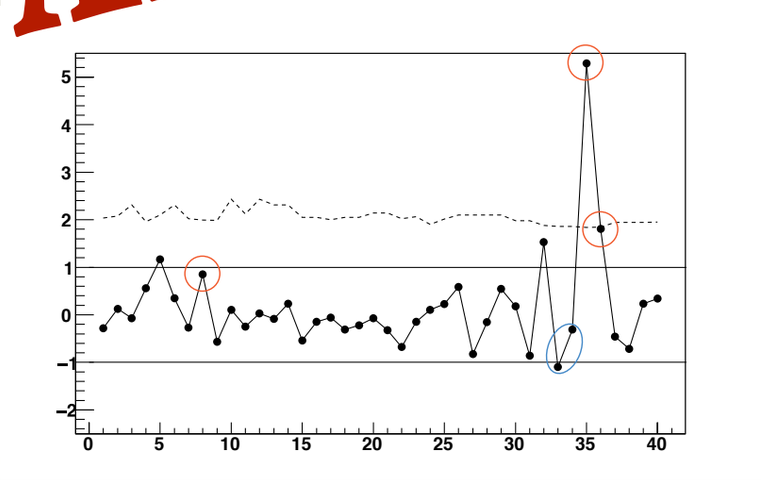

CONCLUSIONS

- 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

- 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 ?