The CTEQ Study of Nuclear Parton Distribution Function

NuFact14 – Working Group 2
August 2014

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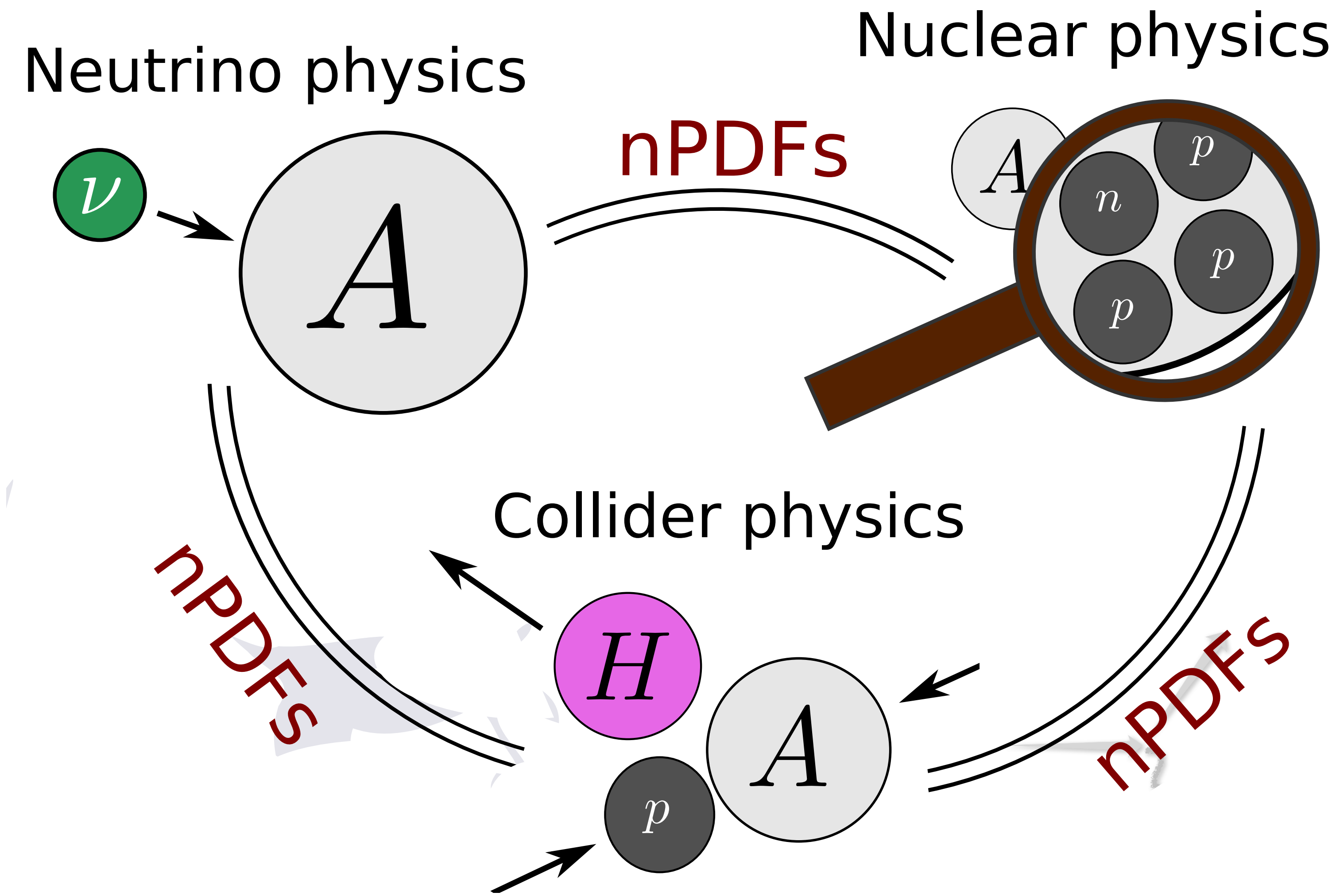
Nuclear Effects in Lepton-nucleus Interactions

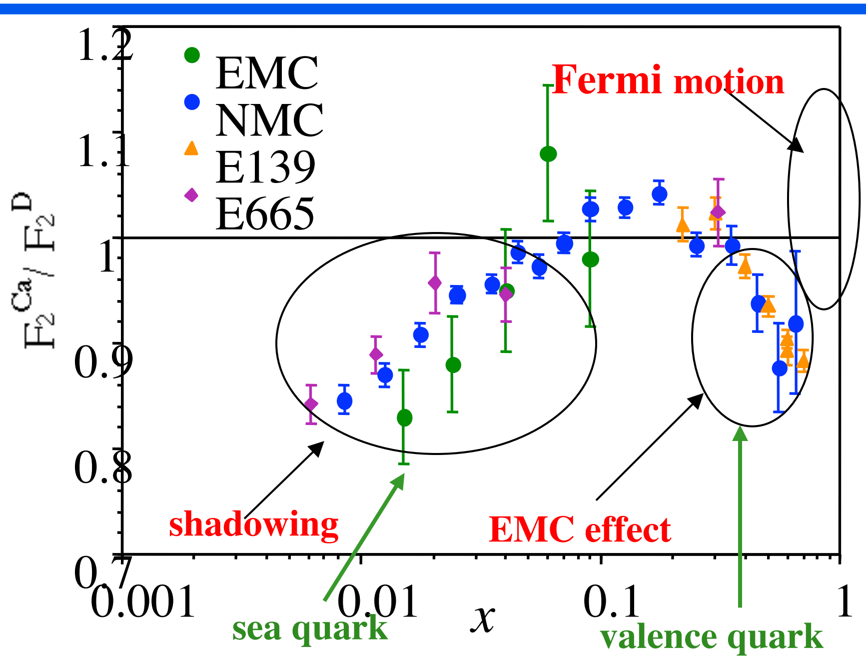
- Target nucleon in motion - spectral functions (Benhar et al.)
- Certain reactions prohibited - Pauli suppression
- Quasi-elastic form factors are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al.)
- SRC and Meson exchange currents: multi-nucleon initial states
- Produced topologies are modified by final-state interactions modifying topologies and reducing detected energy.
  - Convolution of $\delta\sigma(n\pi) \otimes$ formation zone uncertainties $\otimes$ π-absorption uncertainties yield larger oscillation-parameter systematics
- **Cross sections and structure functions are modified and parton distribution functions within a nucleus are different than in an isolated nucleon. Observations from an on-going CTEQ analysis of <u>nuclear parton distributions</u>.**

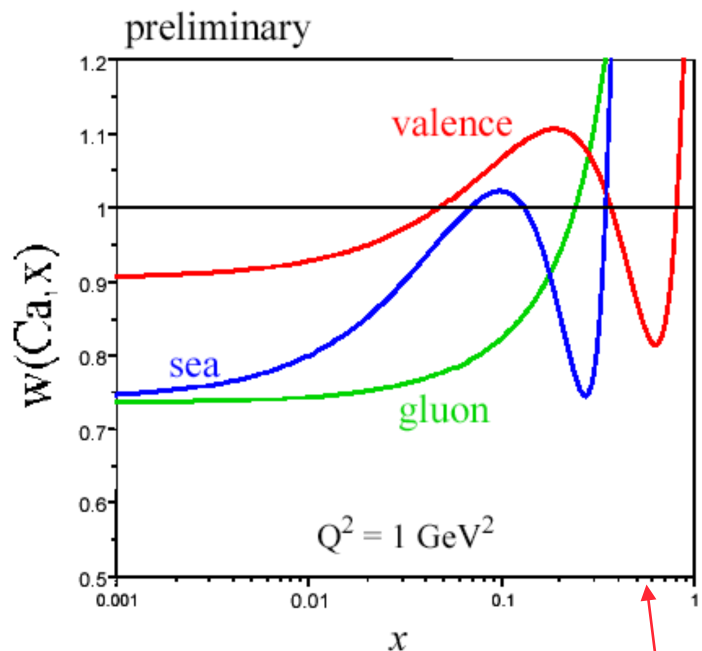
Nuclear PDFS enter many Physics Analyses



Tomáš Ježo Some figures taken from his NuInt14 presentation

Experimental Studies of (Parton-level) Nuclear Effects with Neutrinos: until recently - essentially NON-EXISTENT





- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **SPECULATION: Stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

Two types of nPDF Analyses

- Use multiplicative factors to modify free proton PDFS.

  Such as $f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\, f_i^{free\ proton}(x_N, \mu_0)$ used by

  - Hirai, Kumano, Nagai [PRC 76, 065207 (2007), arXiv:0709.3038]
  - Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065, arXiv:0902.4154]
  - de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012), arXiv:1112.6324]

- Direct nuclear PDF extraction.

  - nCTEQ [PRD 80, 094004 (2009), arXiv:0907.2357]

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

  - The CTEQ nPDF framework is….

nCTEQ Framework

[PRD 80, 094004 (2009), arXiv: 0907.2357]

- Functional form of the bound proton PDF same as for the free proton (∼`CTEQ61` [hep-ph/0702159], x restricted to $0 < x < 1$)

$$x f_i^{p/A}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1}(1-x)^{c_2} + (1+c_3 x)(1-x)^{c_4}$$

- A-dependent fit parameters (reduces to free proton for $A = 1$)

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

- PDFs for nucleus (A, Z)

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

Details of the Fit – First no Neutrino Data

Charged-lepton DIS, DY and RHIC π^0

Fit properties:

- fit @NLO
- $Q_0 = 1.3\text{GeV}$
- using ACOT heavy quark scheme
- kinematical cuts: $Q > 2\text{GeV}$, $W > 3.5\text{GeV}$
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts
- 16 free parameters

7 Gluon
7 Valence
2 Sea

$\chi^2/\text{dof} = 0.85$

Error analysis:

- use Hessian method

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

$$H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}$$

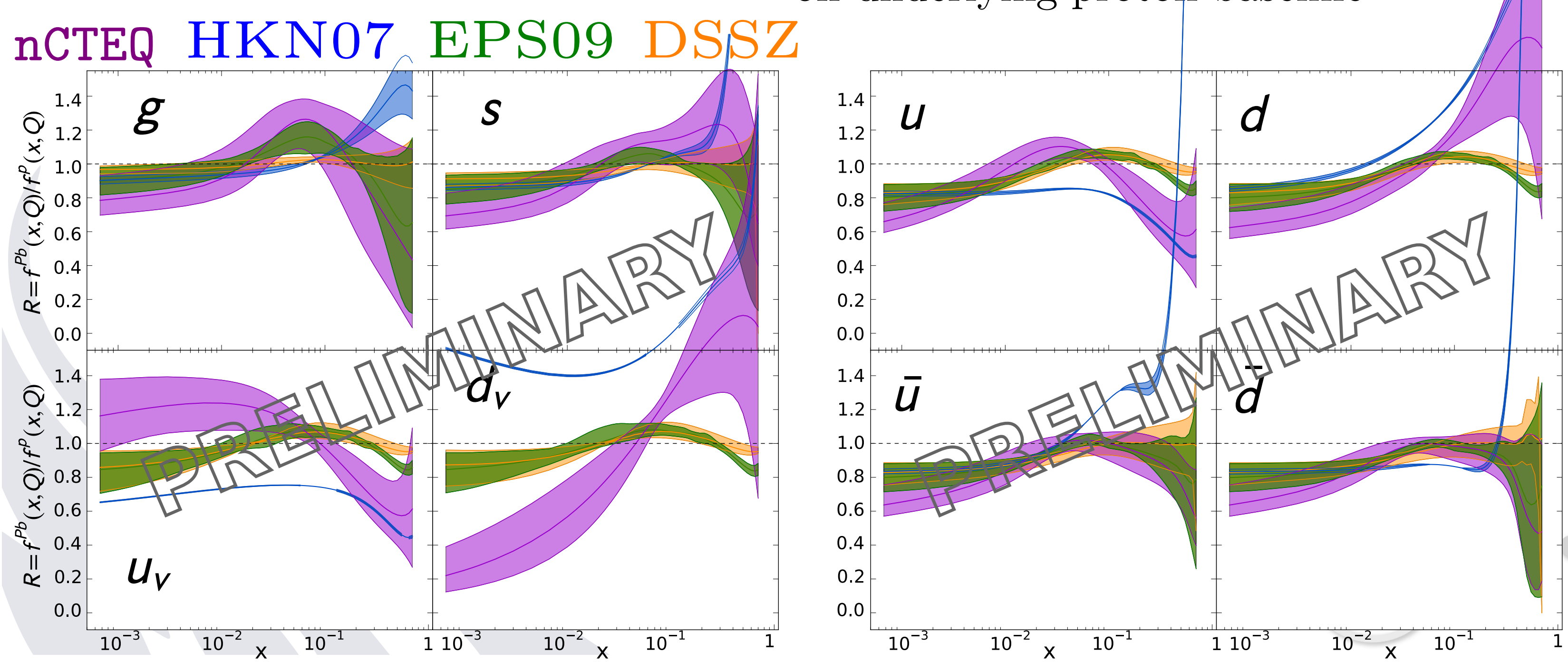
- tolerance $\Delta\chi^2 = 35$ (every nuclear target within 90% C.L.)
- eigenvalues span 10 orders of magnitude → require numerical precision
- use noise reducing derivatives

nCTEQ Results – comparison with other sets

Nuclear correction factors
($Q = 10\text{GeV}$)

$$R_i(Pb) = \frac{f_i^{Pb}(x,Q)}{f_i^{p}(x,Q)}$$

- different solution for d-valence & u-valence compared to EPS09 & DSSZ
- sea quark nuclear correction factors similar to EPS09
- nuclear correction factors depend largely on underlying proton baseline

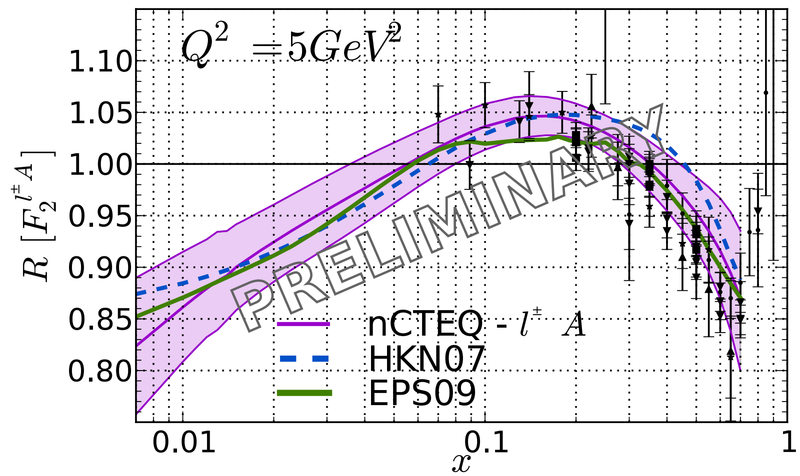


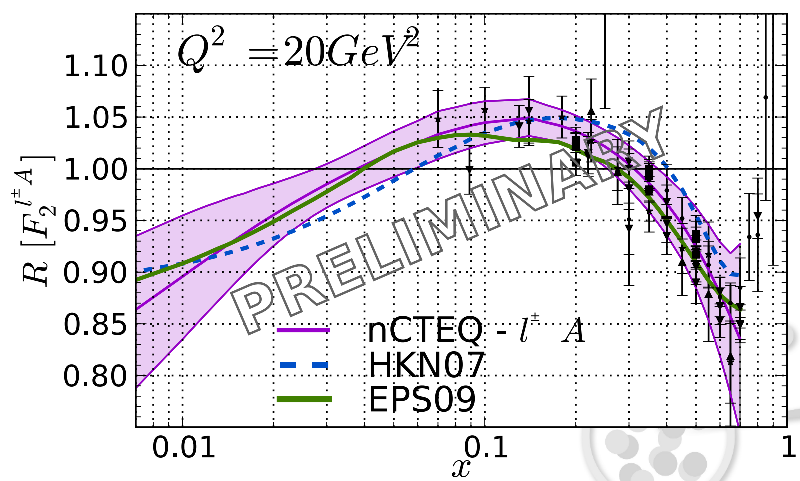
nCTEQ Results - continued

- Structure Function Ratio and comparison with other nPDF sets.

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

- Reasonable agreement of the ratios even though differences in the individual partons





Now bring in Neutrinos
:F_2^{ν} Nuclear Effects Analyses

Nuclear PDFs from neutrino deep inelastic scattering

I. Schienbein (SMU & LPSC-Grenoble, J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Olness (Florida State U)

Also analyses by:
K. Eskola, V. Kolhinen and C. Salgado
and
D. de Florian, R. Sassot, P. Zurita and M. Stratmann

Extraction of Nuclear PDFs and Nuclear Correction Factors from ν–A Scattering

- PDF Parameterized at Q_0 = 1.3 GeV as

$$xf_i(x,Q_0) = \begin{cases} A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5} & : i = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s}\,, \\ A_0 x^{A_1}(1-x)^{A_2} + (1+A_3 x)(1-x)^{A_4} & : i = \bar{d}/\bar{u}\,, \end{cases}$$

- PDFs for a nucleus are constructed as:

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

- Resulting in nuclear structure functions:

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

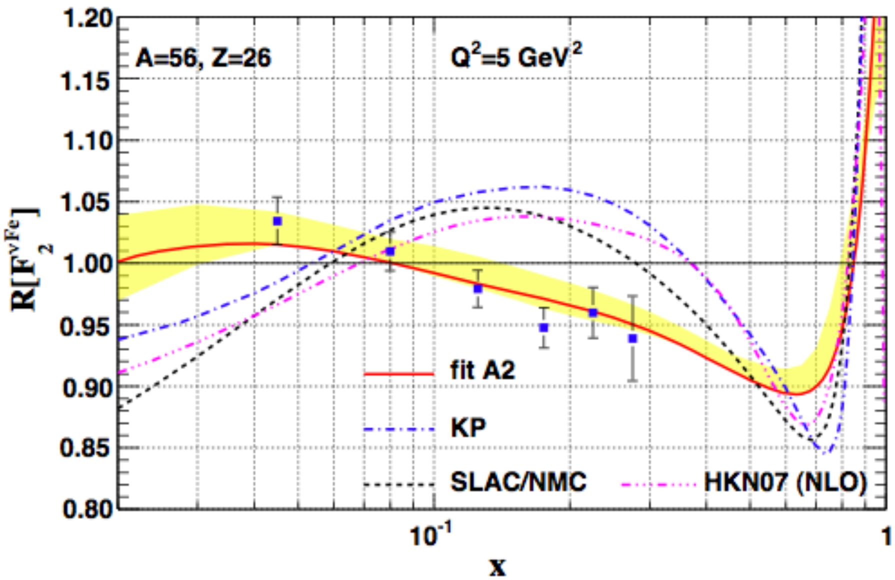
- The differential cross sections for CC scattering off a nucleus::

$$\frac{d^2\sigma}{dx\,dy}^{\overset{(-)}{\nu}A} = \frac{G^2 ME}{\pi}\Big[(1-y-\frac{Mxy}{2E})F_2^{\overset{(-)}{\nu}A} + \frac{y^2}{2} 2xF_1^{\overset{(-)}{\nu}A} \pm y(1-\frac{y}{2})xF_3^{\overset{(-)}{\nu}A}\Big]$$

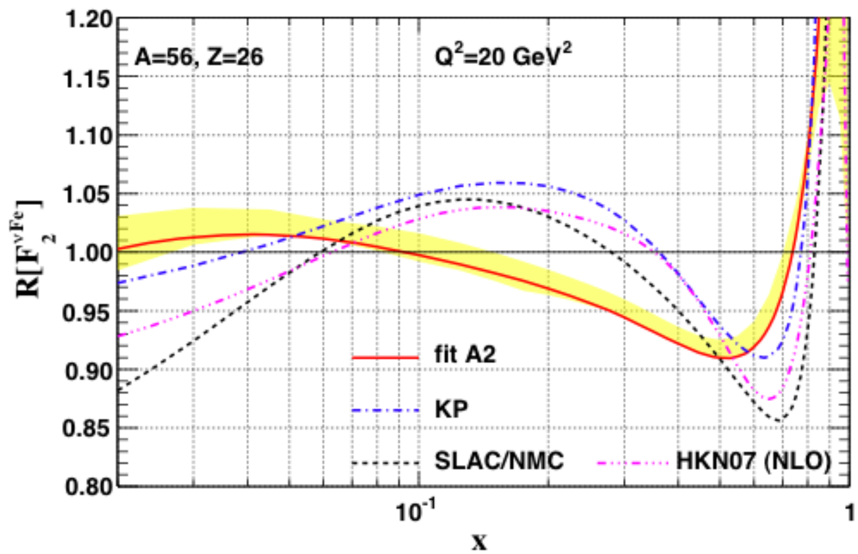
CTEQ High-x Study: nuclear effects
Use nucleon pdf's to form denominator in ratios

- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.
- Correct for deuteron nuclear effects

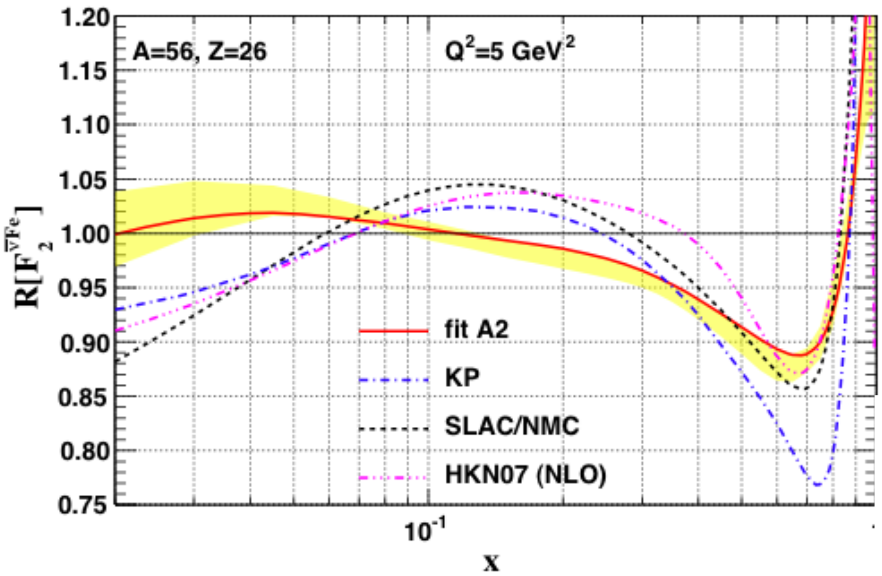
F_2 Structure Function Ratios: ν-Iron



$$\frac{F_2(\nu + Fe)}{F_2(\nu + [n+p])}$$



F_2 Structure Function Ratios: $\overline{\nu}$-Iron



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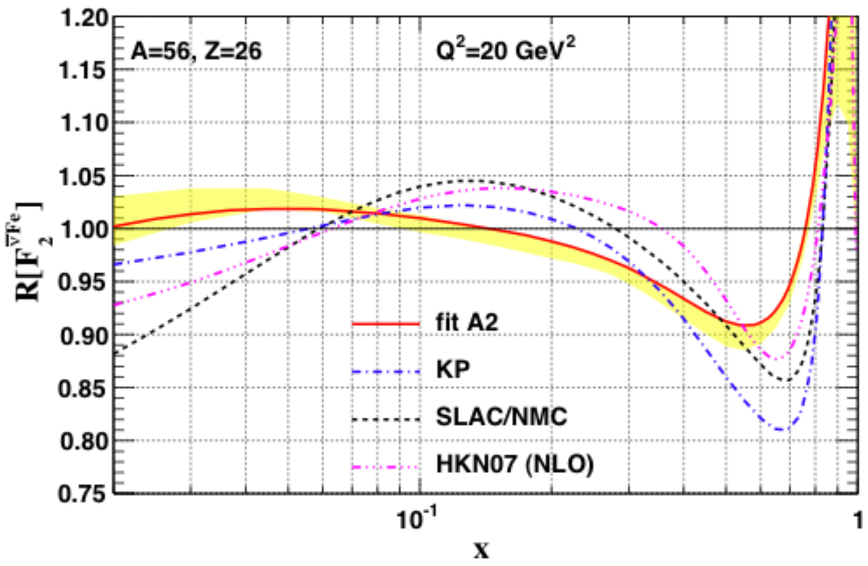
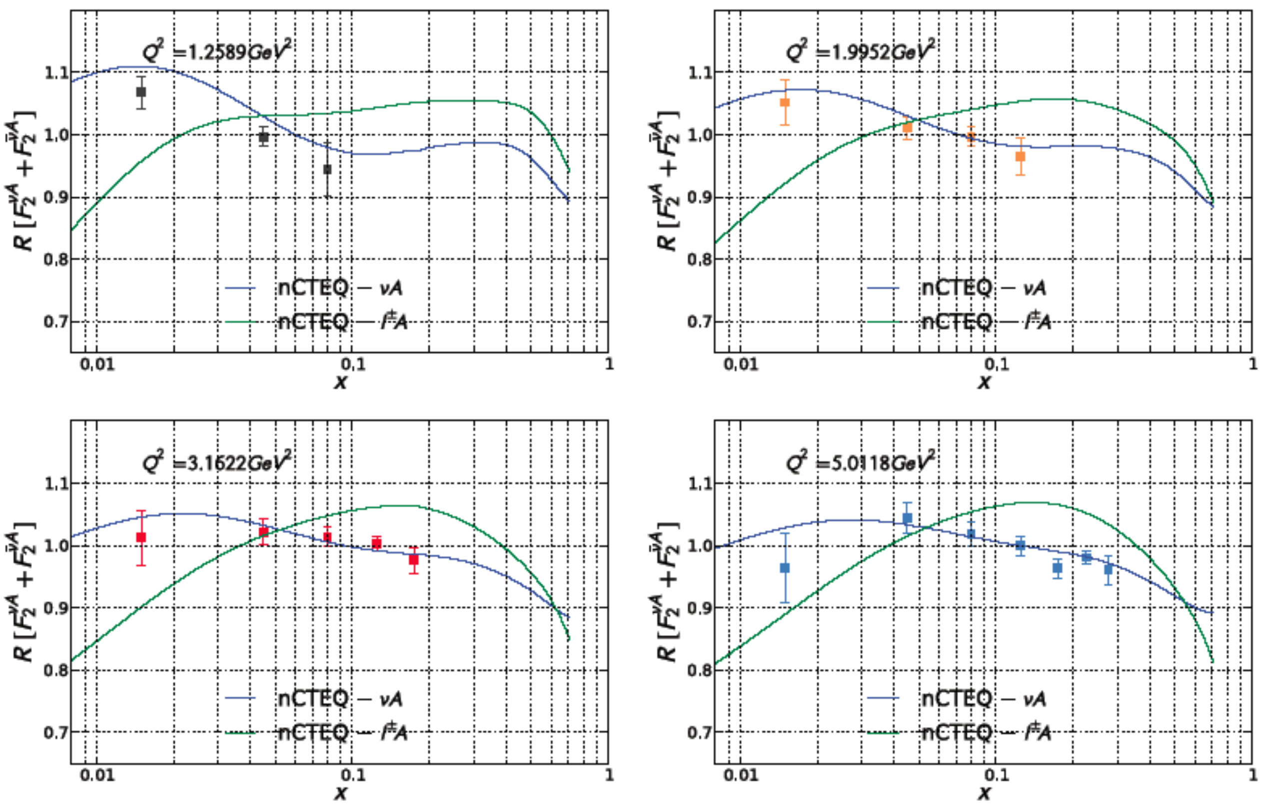


A More-Detailed Look at Differences

- NLO QCD calculation of $\frac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - 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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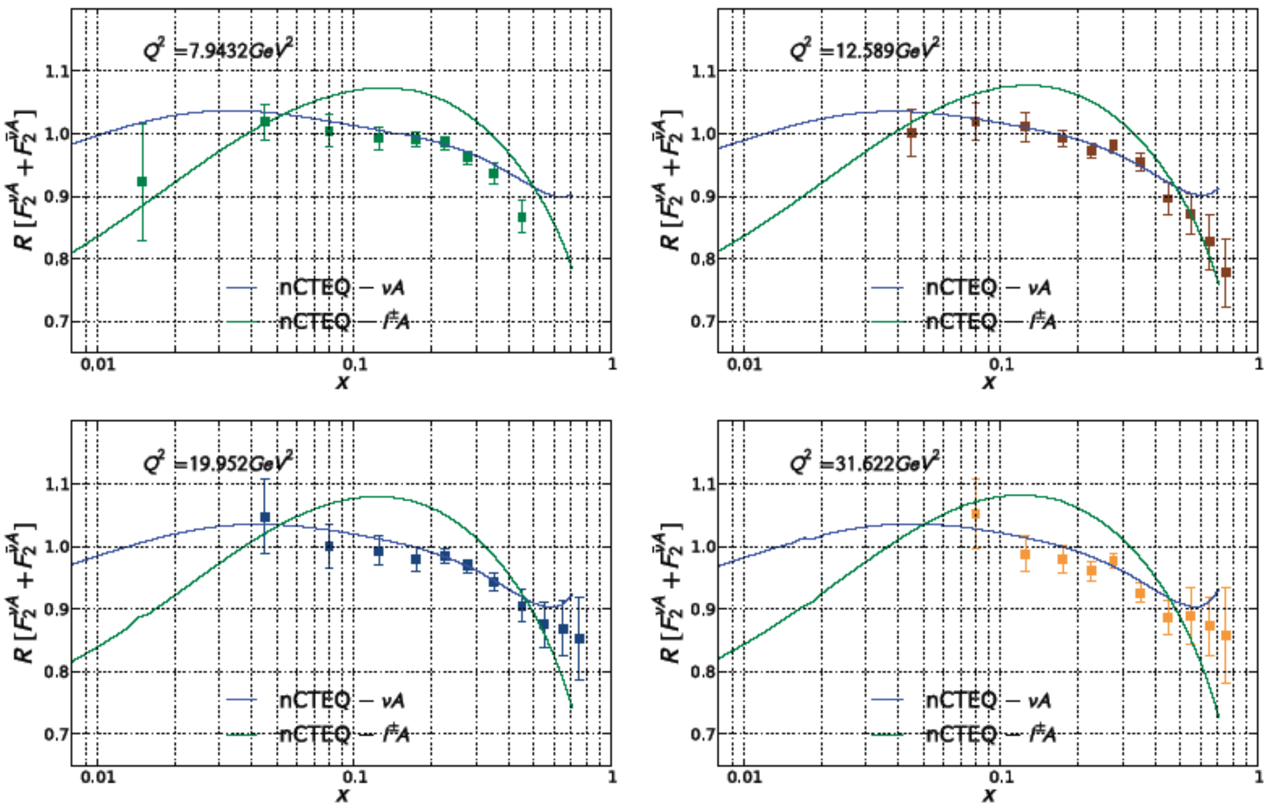

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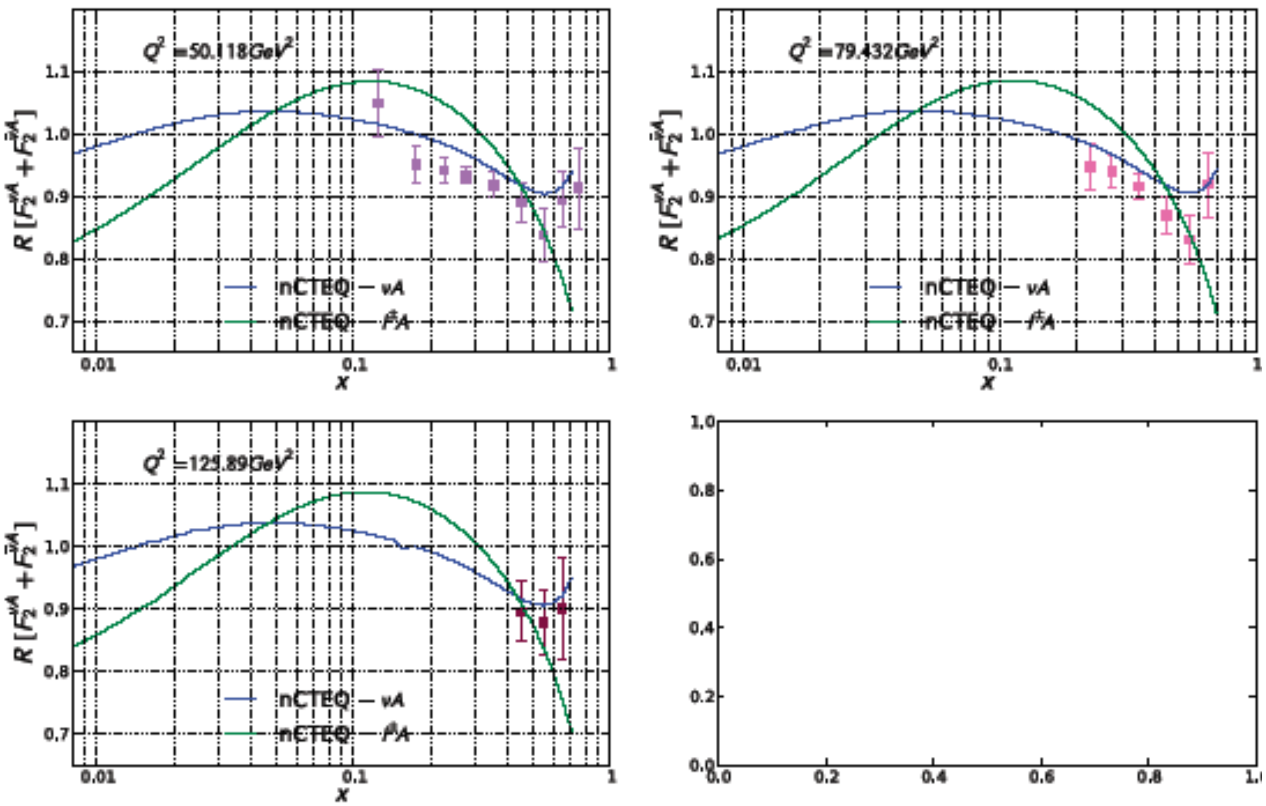


Can we fit the combined ν A, ℓA and DY data ?

Kovarik, Yu, Keppel, Morfin, Olness, Owens, **Schienbein**, Stavreva

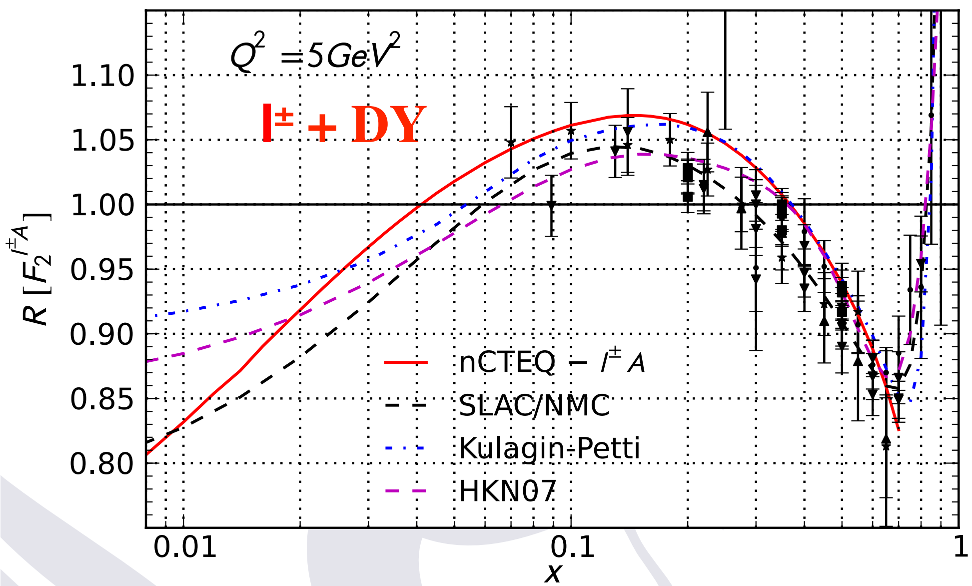
- Take the analysis of $\ell^{\pm}$A data sets (built in A-dependence)
  - Schienbein, Yu, Kovarik, Keppel, Morfin, Olness, Owens,
  - PRD80 (2009) 094004
- For $\ell^{\pm}$A take $F_2(A)/F_2(D)$ and $F_2(A)/F_2(A')$ and DY $\sigma(pA)/\sigma(pA')$
  - 708 Data points with Q > 2 and W > 3.5
- Use **8 Neutrino data sets**
  - NuTeV cross section data: *ν Fe, $\bar{\nu}$ Fe*
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: *ν Pb, $\bar{\nu}$ Pb*
  - CCF*R* dimuon off Fe data
- Initial problem, with standard CTEQ cuts of Q > 2 and W > 3.5 **neutrino data points (3134) far outnumber $\ell^{\pm}$A (708)**.

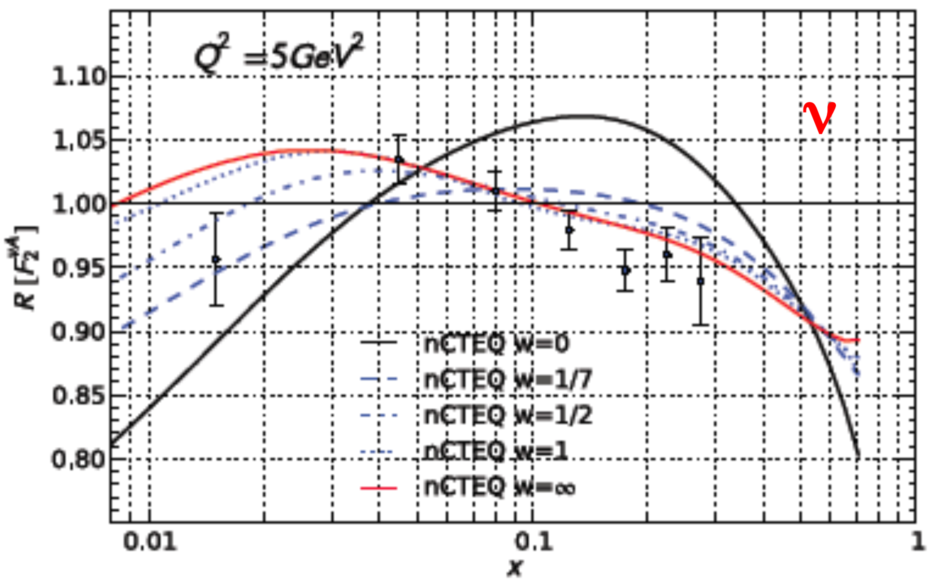
Try to Find a Simultaneous Fit to Both $l^{\pm}$ and ν
Weight the neutrino contribution

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

Weight	Fit name	ℓ data	χ^2 (/pt)	ν data	χ^2 (/pt)	total χ^2 (/pt)
$w = 0$	decut3	708	639 (0.90)	-	-	639 (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)

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





Quantitative χ^2 Analysis of a Combined Fit

- Up to now we are giving a qualitative analysis. Consider next quantitative criterion based on χ^2
- Introduce "tolerance" (T). Condition for compatibility of two fits:

The 2nd fit χ^2 should be within the 90% C.L. region of the first fit χ^2

- Charged: 638.9 ± 45.6 (best fit to charged lepton and DY data)
- Neutrino: 4192 ± 138 (best fit to only neutrino data)

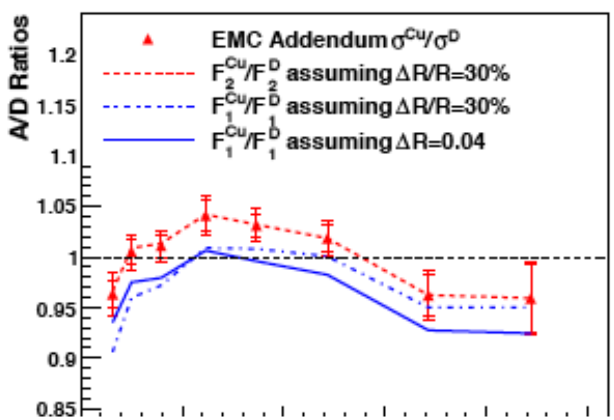
Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)
$w = 1$	global2b	708	736 **NO**	3134	4277 **YES**	5014 (1.30)
$w = \infty$	nuanua1	-	nnn **NO**	3134	4192	4192 (1.33)

Others Do NOT Find this Difference between $l^{\pm}$ and ν

- The analyses of K. Eskola et al. and D. de Florian et al. do not find this difference between $l^{\pm}$–A and ν–A scattering.
- They do not use the full covariant error matrix rather adding statistical and systematic errors in quadrature.
- They do not use the full double differential cross section rather they use the extracted structure functions which involve assumptions:
  - Assume a value for ΔxF_3 (= F_3^{ν} - $F_3^{\bar{\nu}}$) from theory.
  - Assume a value for R = F_L / F_T.
- If nCTEQ makes these same assumptions, than a combined solution of $l^{\pm}$–A and ν–A scattering can be found.

If Difference between both $l^{\pm}$-A and ν–A persists?

- In neutrino scattering, low-Q^2 is dominated by the (PCAC) part of the axial-vector contribution of the longitudinal structure function F_L.
- Shadowing is led by F_T and the shadowing of F_L lags at lower x.



V. Guzey et al. arXiv 1207.0131

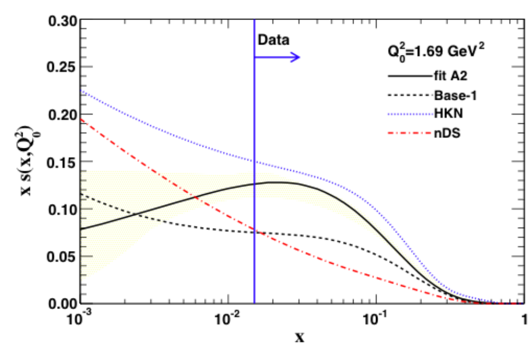
  - F_1 (Blue) is purely transverse and F_2 (Red) is a sum of F_T (F_1) and F_L
  - This could be a contributing factor to such a difference.
- Another idea also from Guzey and colleagues is the observation that

If Difference between both $l^{\pm}$-A and ν–A persists?

- Another idea also from Guzey and colleagues is the observation that (in leading order):

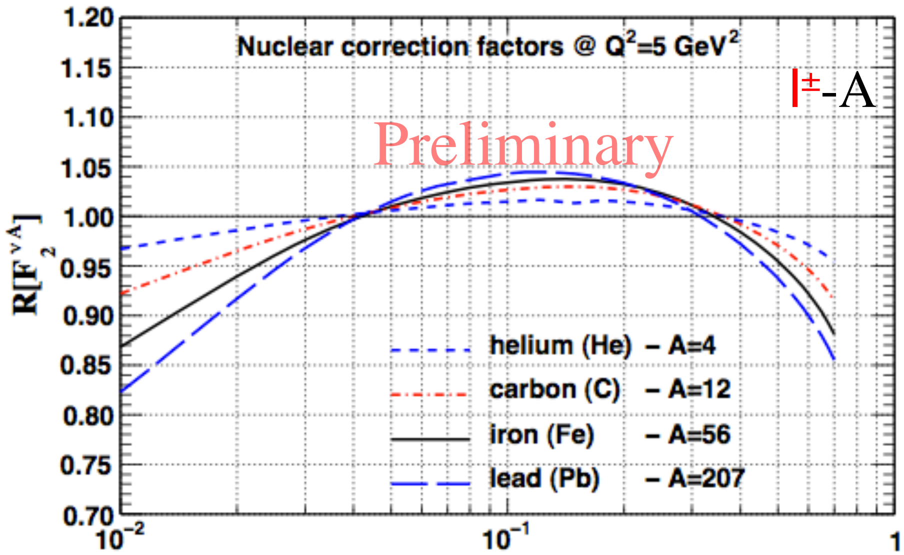
$$\frac{d\sigma^{\nu A}}{dx dy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[d^A + s^A + (1-y)^2(\bar{u}^A + \bar{c}^A)\right]$$
$$\frac{d\sigma^{\bar{\nu} A}}{dx dy} = \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}\frac{ME}{\pi}2x\left[\bar{d}^A + \bar{s}^A + (1-y)^2(u^A + c^A)\right]$$

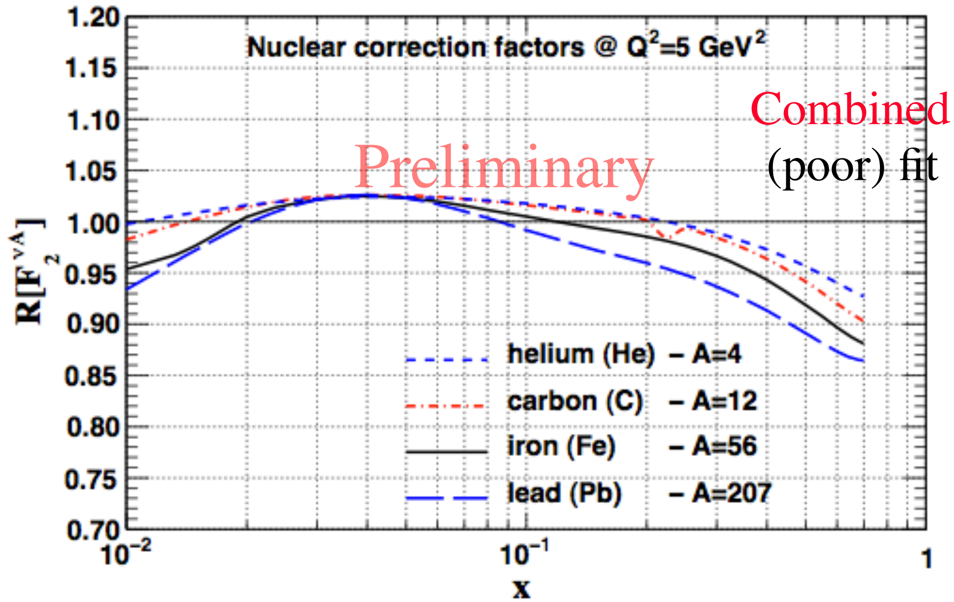
  - In the shadowing region at low-x, y is large and the σ are primarily probing the d- and s-quarks.
- This is very different from $l^{\pm}$ scattering where the d- and s-quarks are reduced by a factor of 4 compared to the u- and c-quarks.
  - If shadowing of the d- or s-quarks is negligible this would explain the NuTeV result.
  - Diminished shadowing of the nuclear s-quark is suggested by early extraction of nPDFs by nCTEQ.

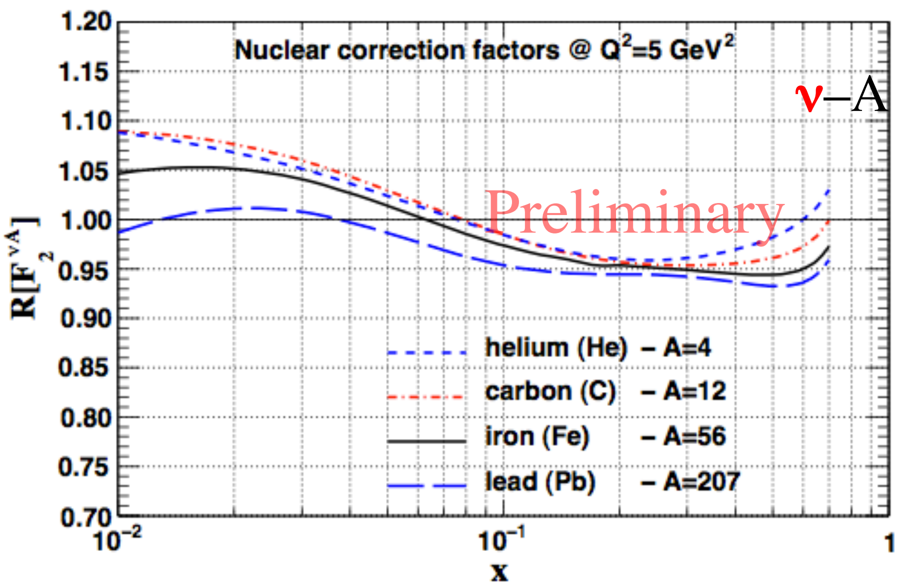


What could MINERνA Contribute?

Preliminary Predictions for MINERνA Targets







Ongoing analysis of MINERνA LE DIS neutrino sample with average Q^2 of 4 GeV^2

Summary and Conclusions

- The CTEQ nPDF fits - without neutrino input - build in the A-dependence and now provide the error associated with each nPDF
- There are indications from **one** experiment using **one** nucleus that **ν-induced parton-level nuclear effects are different** than $\ell^{\pm}$-nuclear effects.
  - Based on nuclear corrections factors R and the tolerance criterion, there is no good compromise fit to the $\ell^{\pm}$A + DY + νA data.
- If these differences between $\ell^{\pm}-$A and ν−A scattering persist, the difference in shadowing, at least, may (partially) be due to the large contribution of F_L at low Q^2 in ν−A scattering and/or shadowing of the strange quark.
- Need systematic **experimental** study of **ν-induced nuclear effects in A and D_2 such as MINERνA in the ME Beam.**

Additional Details

Global Analysis Procedure

1. Parametrize PDFs at low initial scale $\mu = Q_0 = 1.3\text{GeV}$:

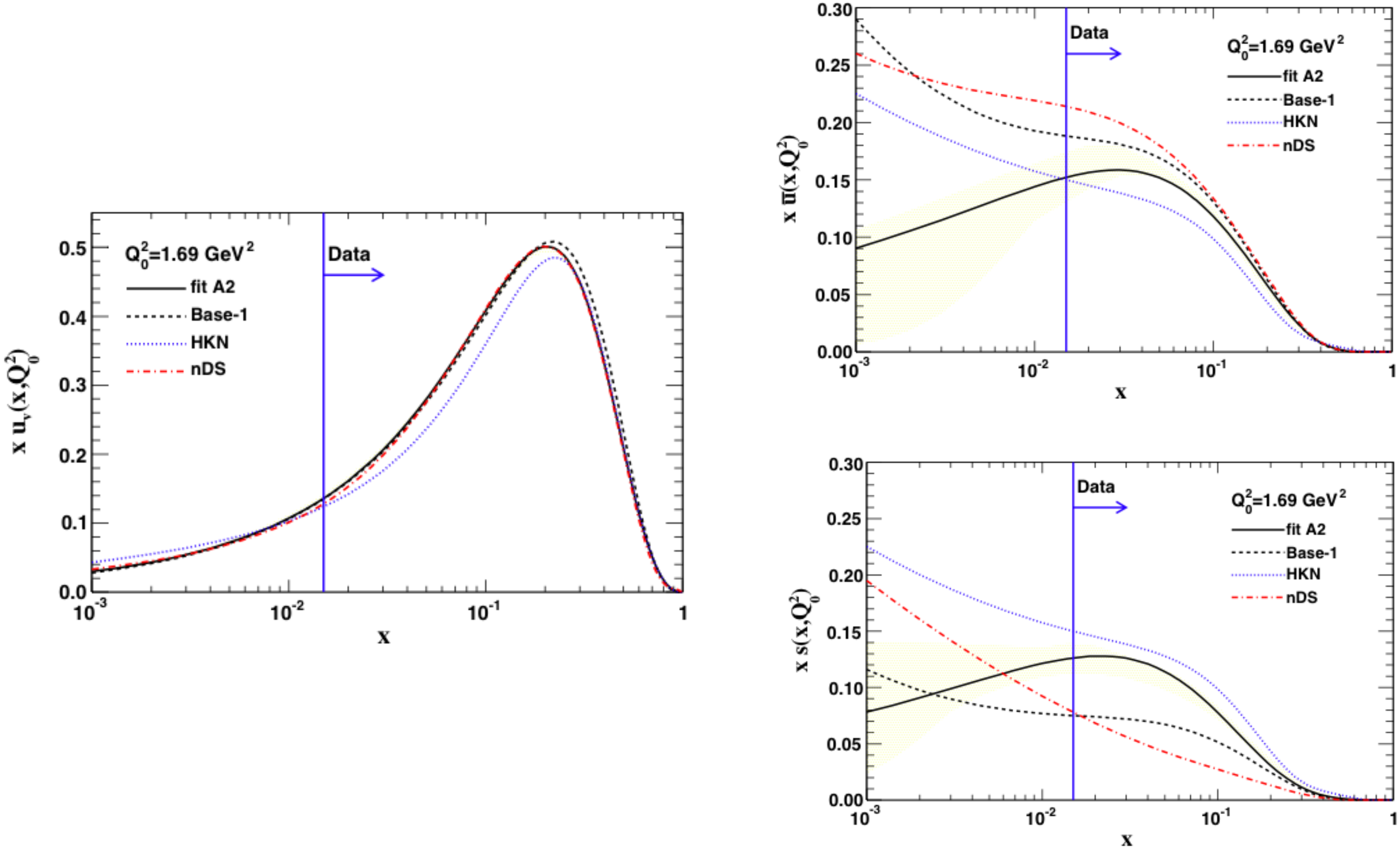
$$f(x, Q_0) = f(x; a_0, a_1, \dots) = a_0 x^{a_1} (1-x)^{a_2} P(x; a_3, \dots)$$

2. Use DGLAP equation to evolve $f(x,\mu)$ from $\mu = Q_0$ to $\mu = Q_{\text{max}}$.
3. Define and minimize appropriate χ^2 function (with respect to parameters $a_0, a_1, \dots$)

$$\chi^2(\{a_i\}) = \sum_{\text{experiments}} w_n \chi^2_n(\{a_i\})$$

$$\chi^2_n(\{a_i\}) = \sum_{\text{data points}} \left(\frac{\text{data} - \text{theory}(\{a_i\})}{\text{uncertainty}} \right)^2$$

Iron PDFs


Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
Data
$x\,u_v(x,Q_0^2)$
$x\,\bar{u}(x,Q_0^2)$
$x\,s(x,Q_0^2)$
x
10^{-3}
10^{-2}
10^{-1}
1

Kulagin-Petti Model of Nuclear Effects

hep-ph/0412425

- Global Approach -aiming to obtain quantitative calculations covering the complete range of x and Q^2 available with thorough physics basis for fit to data.
- Different effects on structure functions (SF) are taken into account:

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\text{coh}}$$

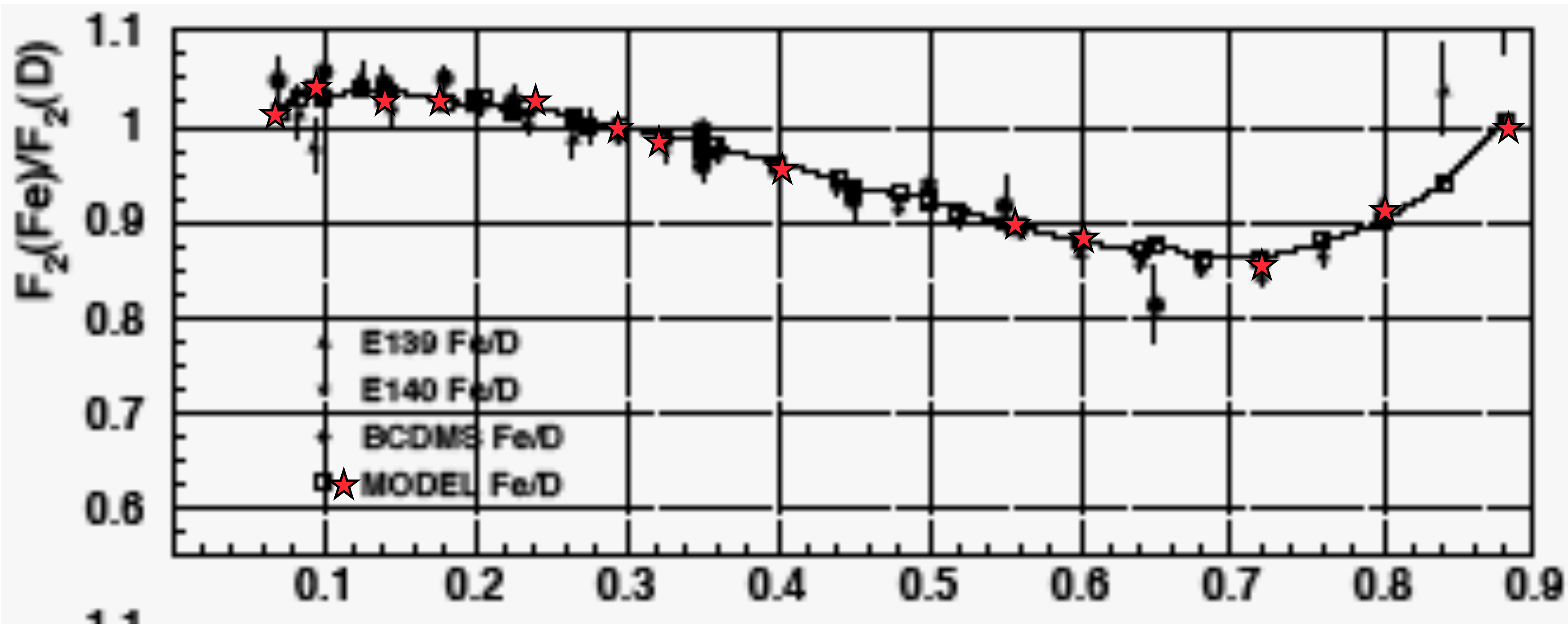
  - $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
  - $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
  - δF_i^{coh} contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **Fermi Motion** and **Binding** in nuclear structure functions is calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:
- Since bound nucleons are off-mass shell there appears dependence on the nucleon virtuality $\kappa^2 = (M + \varepsilon)^2 - k^2$ where we have introduced an **off-shell structure function $\delta f_2(x)$**

$$F_2(x, Q^2, k^2) = F_2(x, Q^2)\left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right)$$

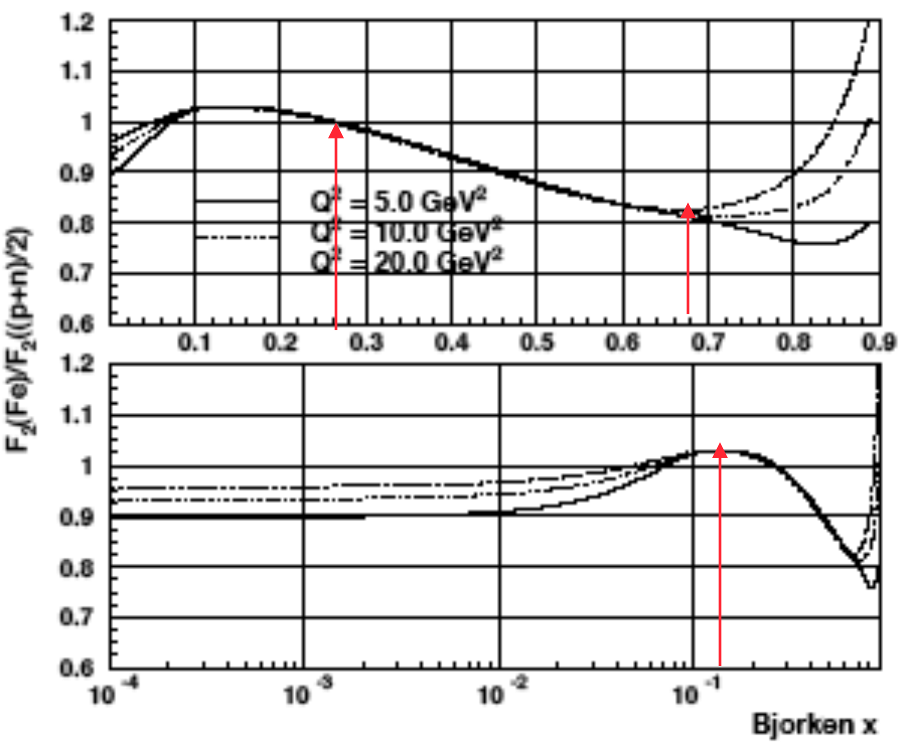
- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

Kulagin-Petti compared to e/μ+Fe data
F_2 (e/μ+Fe) / F_2 (e/μ+D)

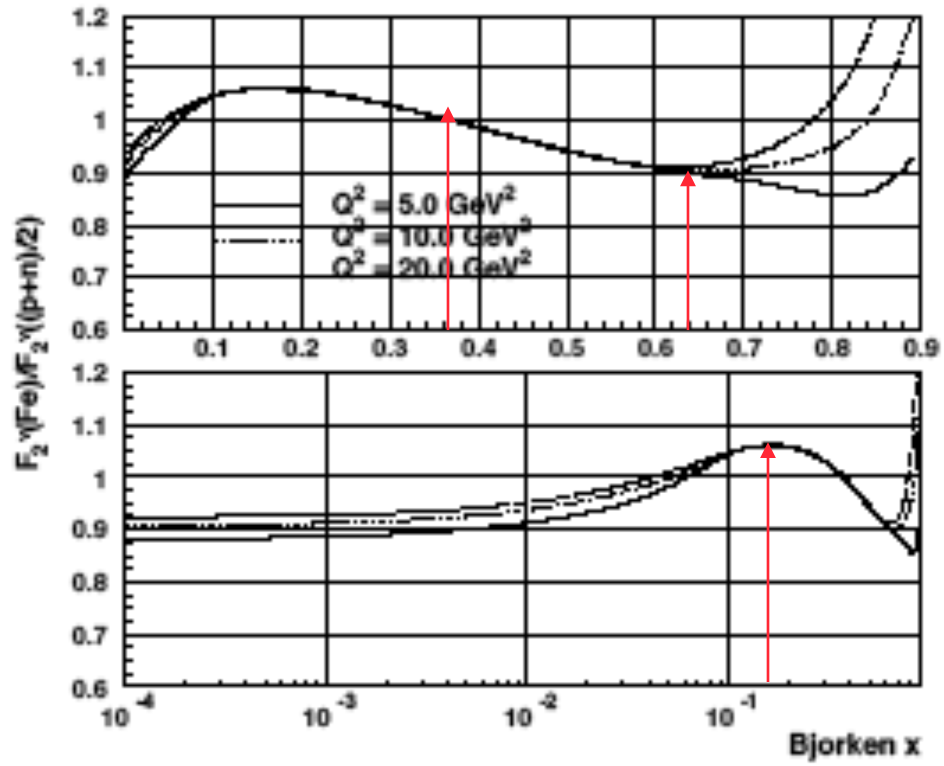


Charged Lepton

F_2 (μ+Fe) / F_2 (μ+N) compared to F_2 (ν+Fe) / F_2 (ν+N)



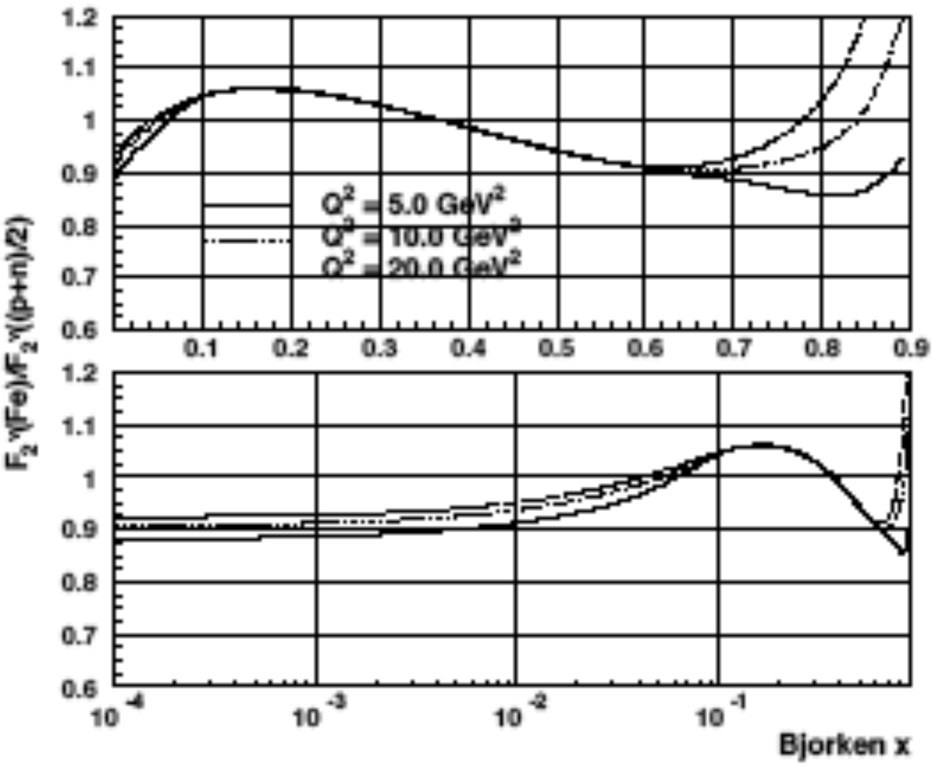
Charged Lepton

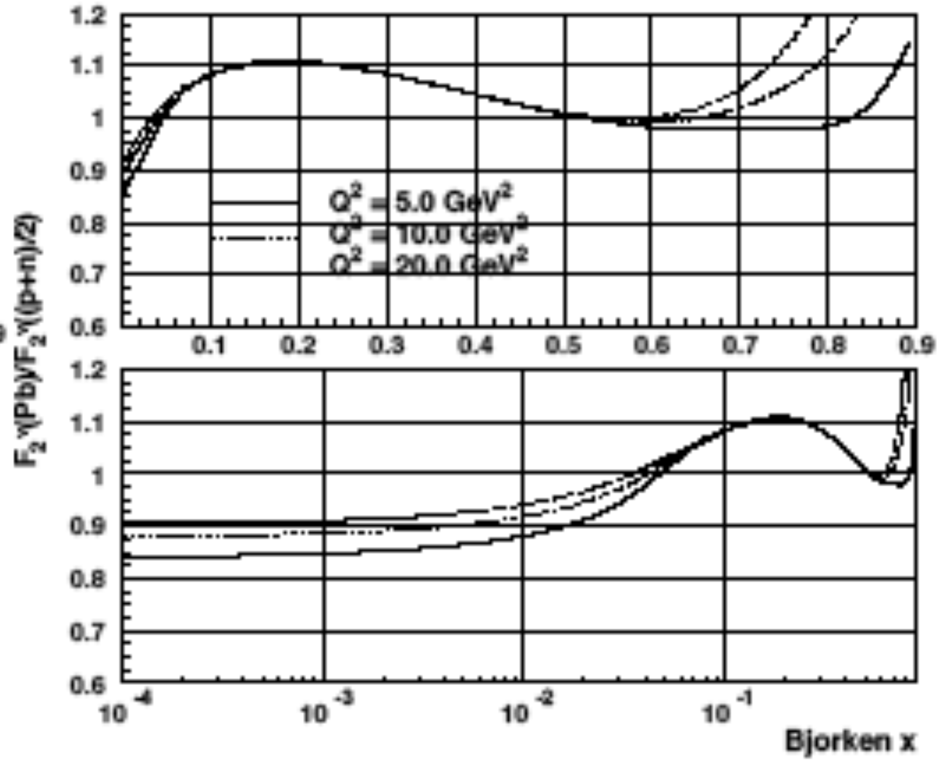


Neutrino

$F_2\,(\nu+A)\,/\,F_2\,(\nu+N)$

(n excess included in effect)

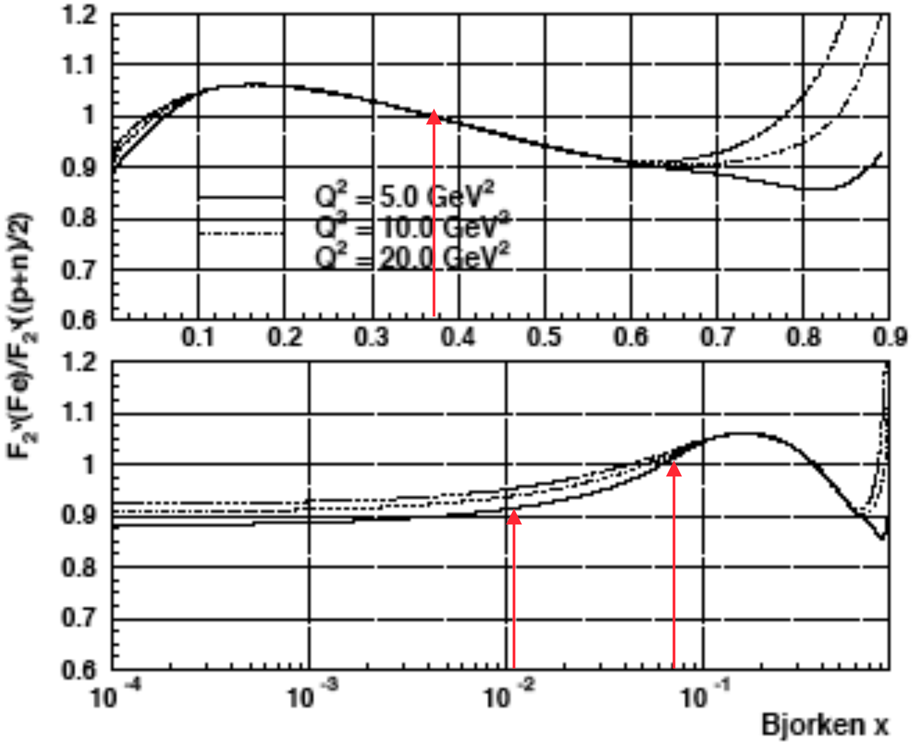




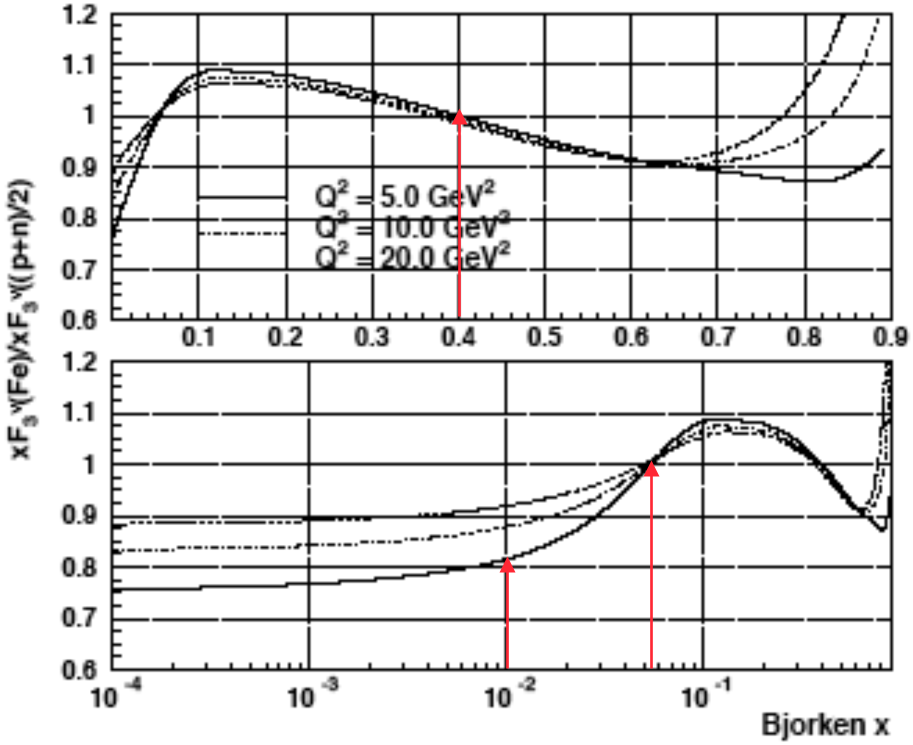
Fe

Pb

Kulagin-Petti: ν-Fe Nuclear Effects

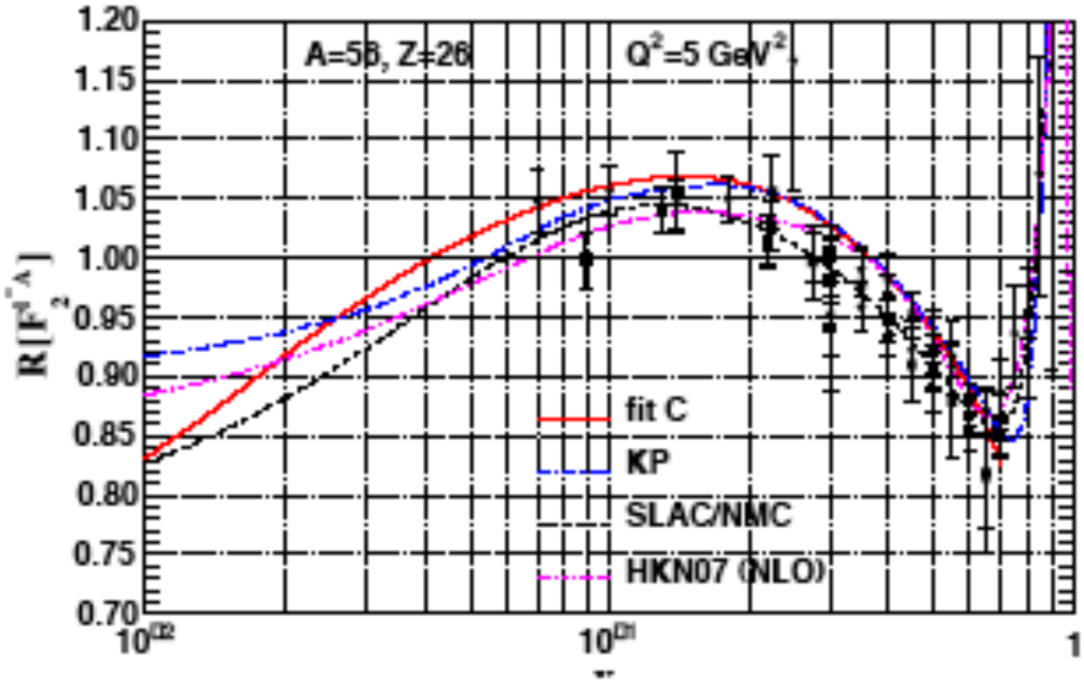


F_2



xF_3

Nuclear Structure Function Corrections
$\ell^{\pm}$ (Fe/D_2)

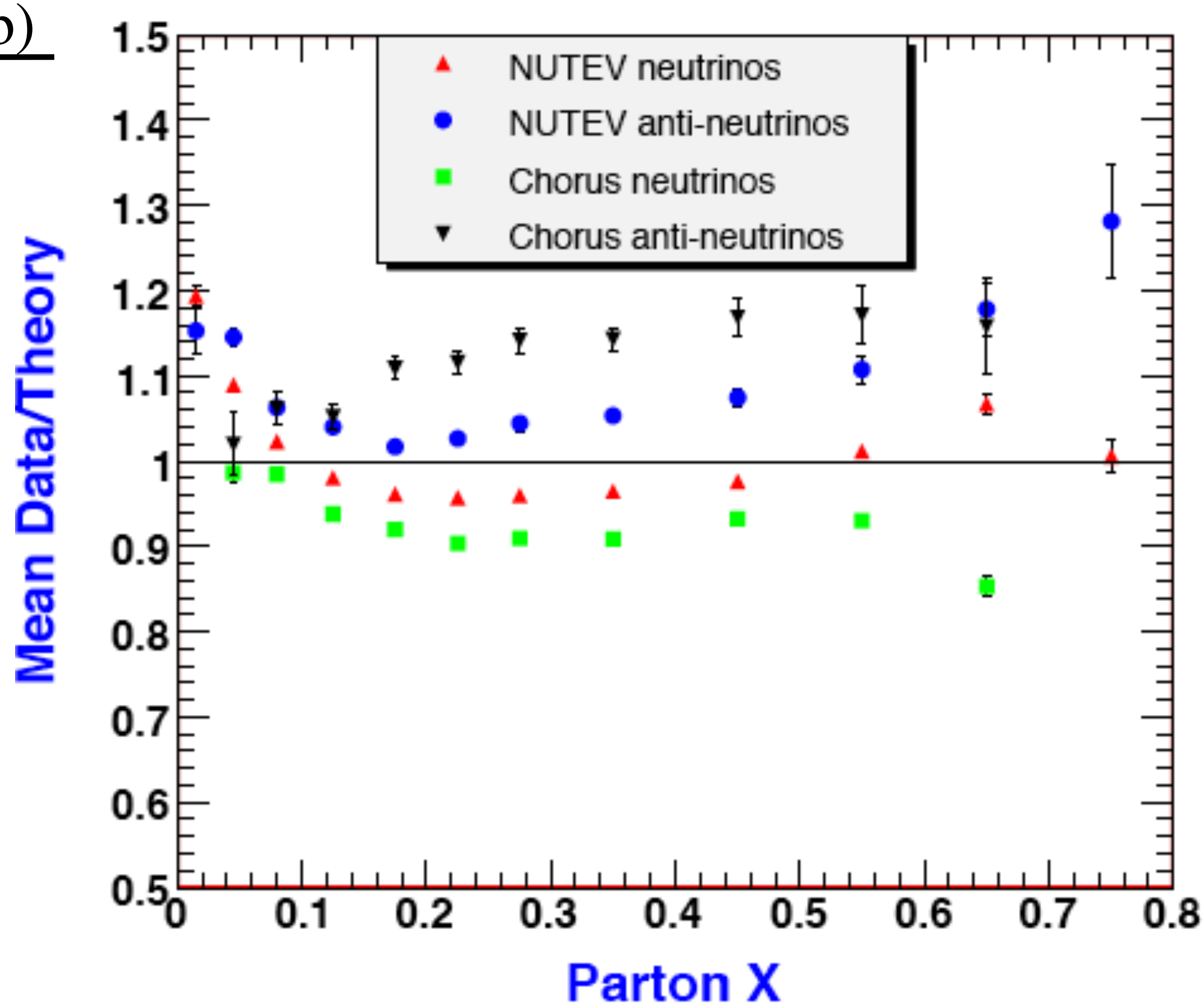


- F_2 / nucleon changes as a function of A. Measured in μ/e - A, **<u>not in ν − A</u>**
- **<u>Good reason to consider nuclear effects are DIFFERENT in ν - A</u>.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**

NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (un-shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

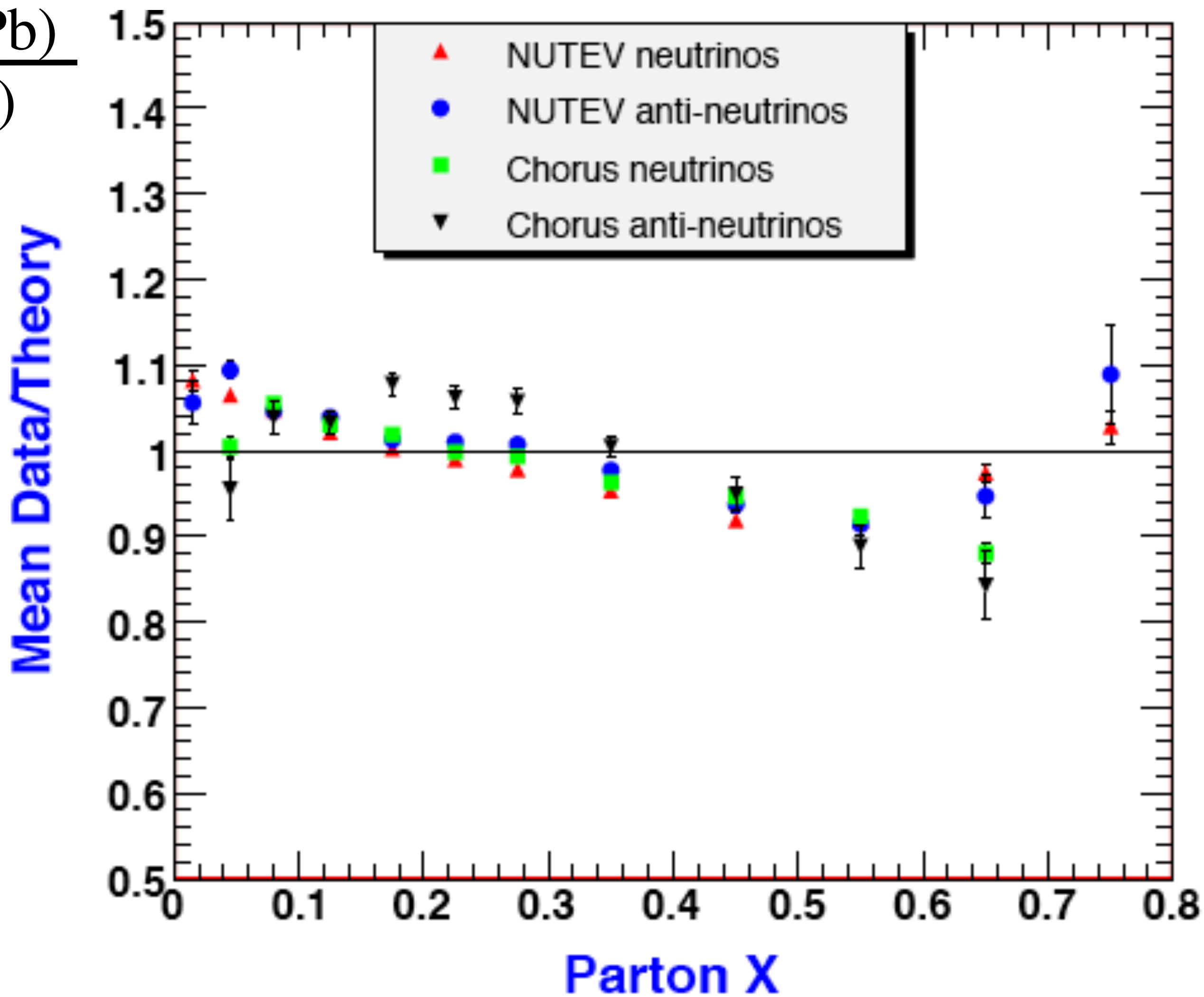
$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



NuTeV(Fe) and CHORUS (Pb) ν scattering (unshifted) σ results compared to reference fit

no nuclear corrections

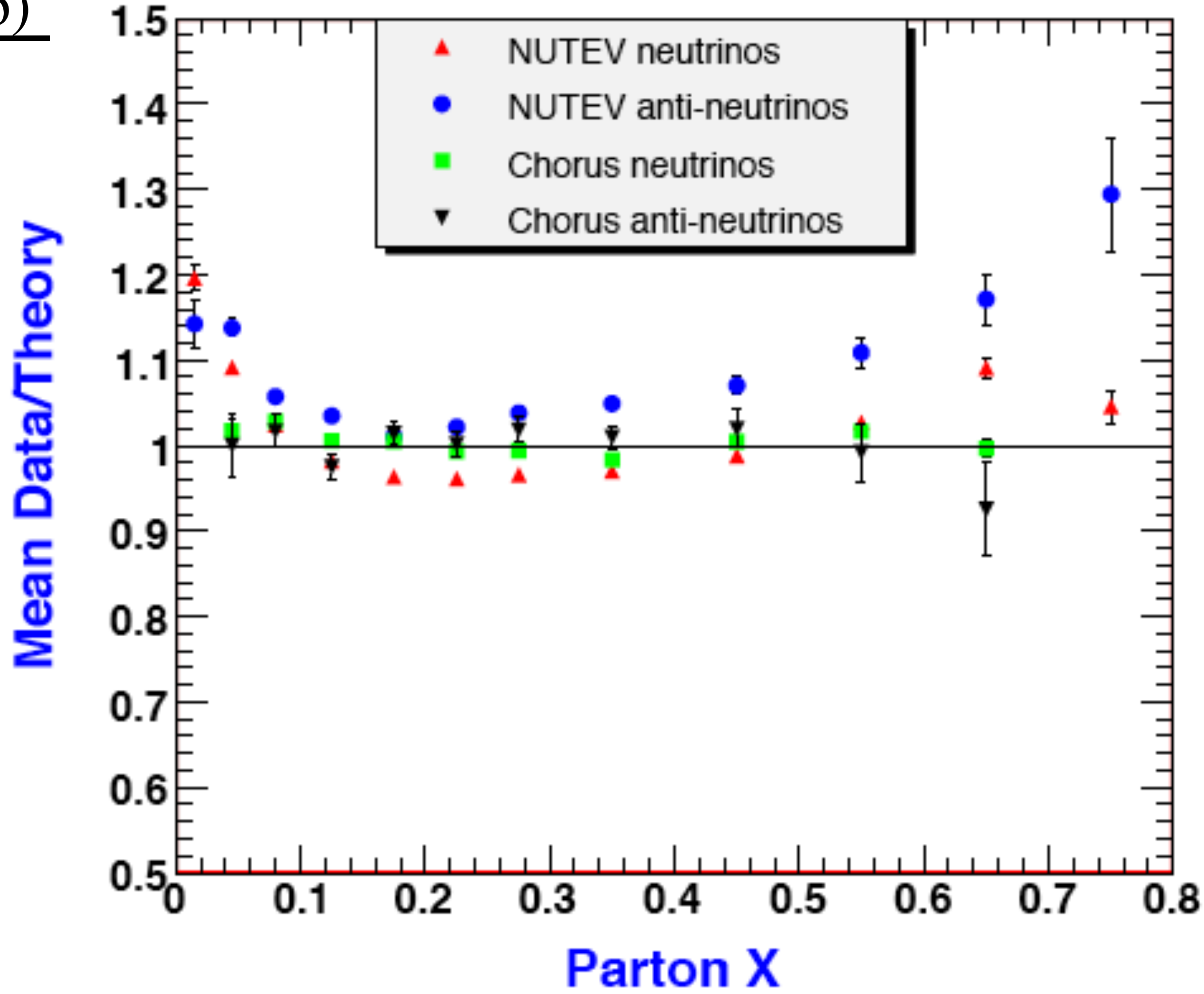
$$\frac{\sigma(\nu\text{Fe or }\nu\text{Pb})}{\sigma(\nu\text{"n+p"})}$$



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering (shifted) results compared to reference fit

Kulagin-Petti nuclear corrections

$$\frac{\sigma(\text{Fe or Pb})}{\sigma(n+p)}$$



Comparison of Data to the Kulagin-Petti Model

thanks to Roberto Petti