Neutrino Scattering and Nuclear Parton Distributions

What do the concepts of "Factorization" and "Universal" Parton Distributions mean in the Nuclear Environment

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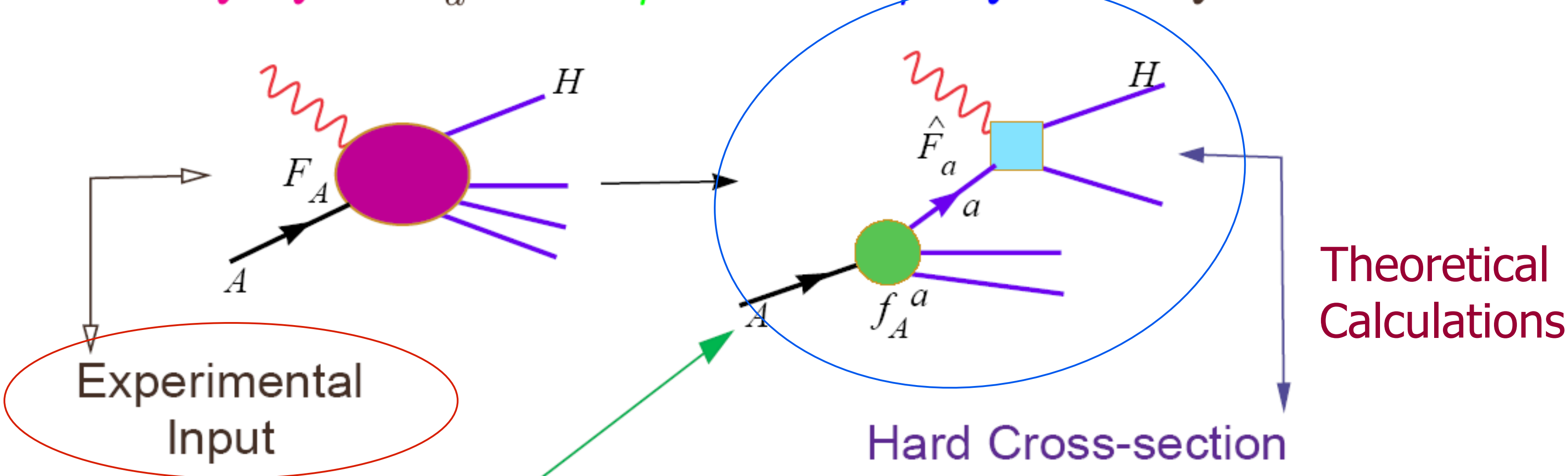
Fermilab

Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model – the Factorization Theorem

$$F_A^\lambda\left(x, \frac{m}{Q}, \frac{M}{Q}\right) = \sum_a f_A^a\left(x, \frac{m}{\mu}\right) \otimes \hat{F}_a^\lambda\left(x, \frac{Q}{\mu}, \frac{M}{Q}\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$



Hard Cross-section
perturbative calculable
(may contain $\alpha_s^n \mathrm{Log}^n(M/Q)$)

universal Parton Dist. Fn.
Non-Perturbative Parametrization at Q_0
GLAP Evolution to Q

extracted by applying global analysis methods

What do the concepts of "factorization" and "universal (nuclear) parton distributions" mean in the nuclear environment?

The Nuclear Environment
Nuclear Effects in lepton nucleus Interactions

- Target nucleon in motion - spectral functions (Benhar et al.).
- Certain reactions prohibited - Pauli suppression.
- Form factors are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al.).
- Interactions with correlated 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>**

Assumptions entering the nuclear PDF Analysis

- **Factorization** & DGLAP evolution
  - allow for definition of universal PDFs
  - make the formalism predictive
- Isospin symmetry
  - $$\begin{cases} u^{n/A}(x) = d^{p/A}(x) \\ d^{n/A}(x) = u^{p/A}(x) \end{cases}$$
- $x \in (0, 1)$ like in free-proton PDFs [instead of (0, A)]
- The observables O^A can be calculated as:

$$O^A = Z\, O^{p/A} + (A-Z) O^{n/A}$$

- With the above assumptions we can use the free proton framework to analyze nuclear data.

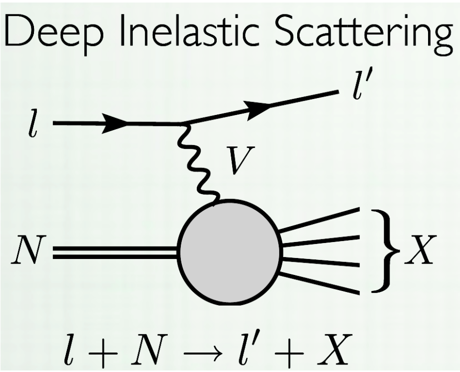
First: nCTEQ Analysis based on Charged Lepton + D-Y

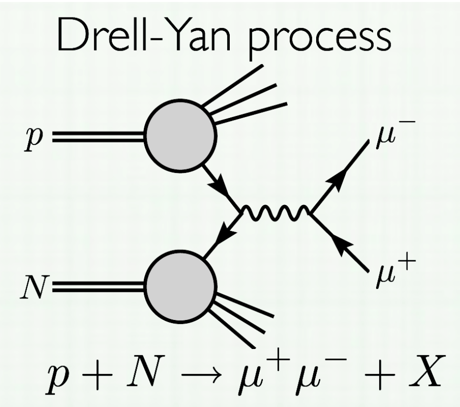
No Neutrino Data Here

Long publication describing details out shortly

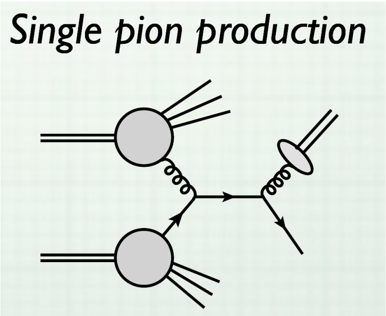
- $L^{\pm}$ DIS & DY

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)
FNAL E-665
N = (D, C, Ca, Pb, Xe)
DESY Hermes
N = (D, He, N, Kr)
SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)
FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)





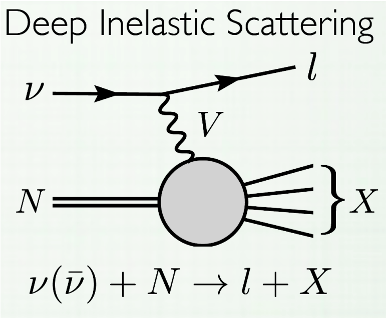
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

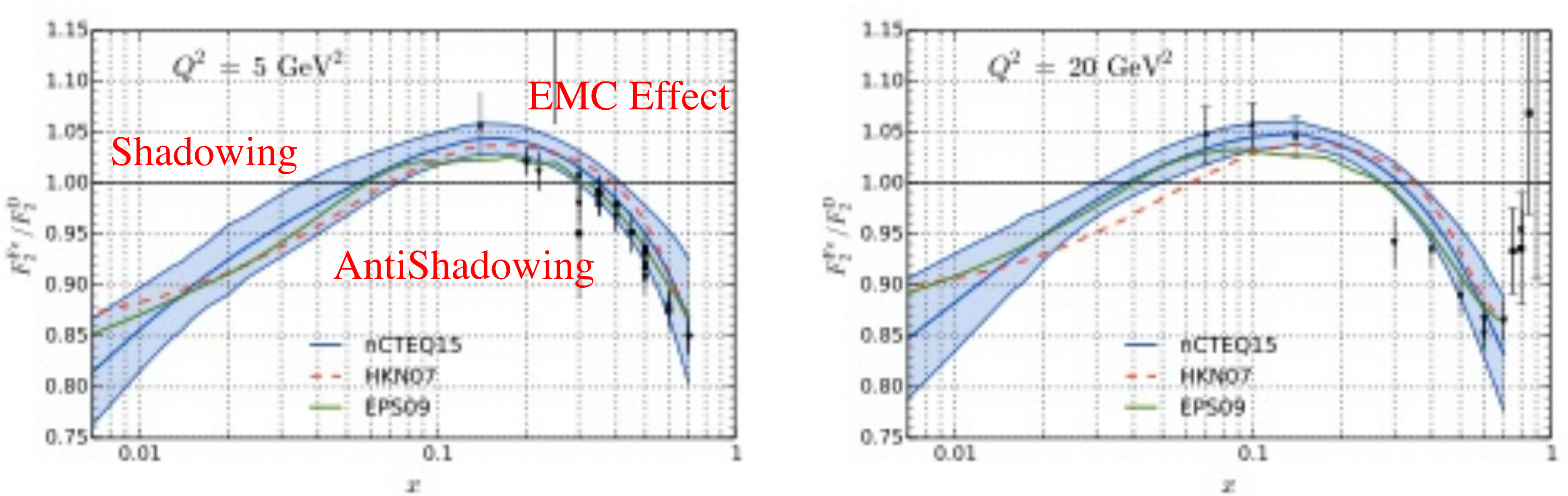
- Neutrino (to be included later)



CHORUS CCFR & NuTeV

N = Pb N = Fe

nCTEQ results – charged lepton: F_2 ratios for Fe/D



Now for Neutrinos

- F_2 / nucleon changes as a function of A. Measured in μ/e - A <u>**not yet 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.**
  - **All flavor dependent nuclear effects will be different for <u>ν - A.</u>**

Addressing the lack of F_2^{ν} Nuclear Effects Analyses

Nuclear PDFs from neutrino deep inelastic scattering Using NuTeV ν-Fe and CHORUS ν-Pb Data

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, Paukkunen and C. Salgado

and

D. de Florian, R. Sassot, P. Zurita and M. Stratmann

and

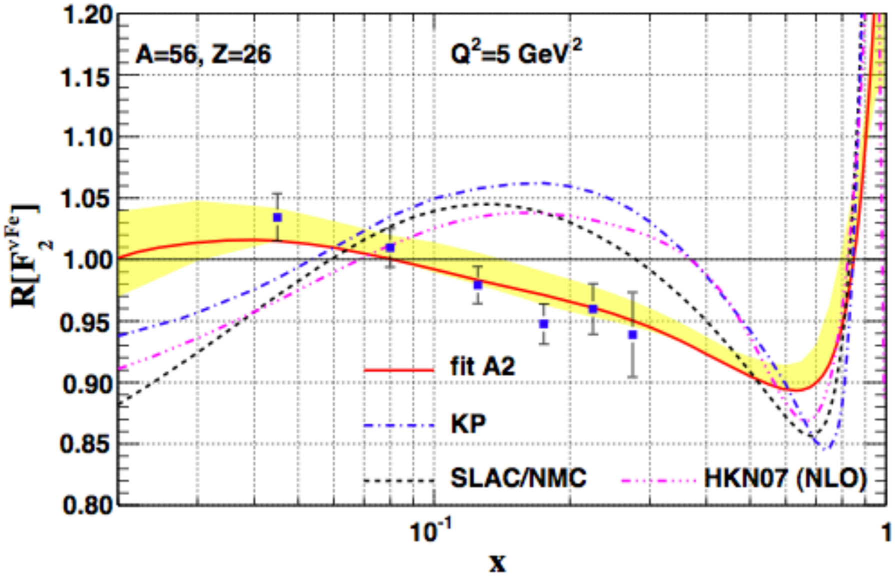
M.Hirai, S. Kumano and T.-H. Nagai

CTEQ ν nuclear effects study
No high-statistics D_2 data – "make it" from PDFs

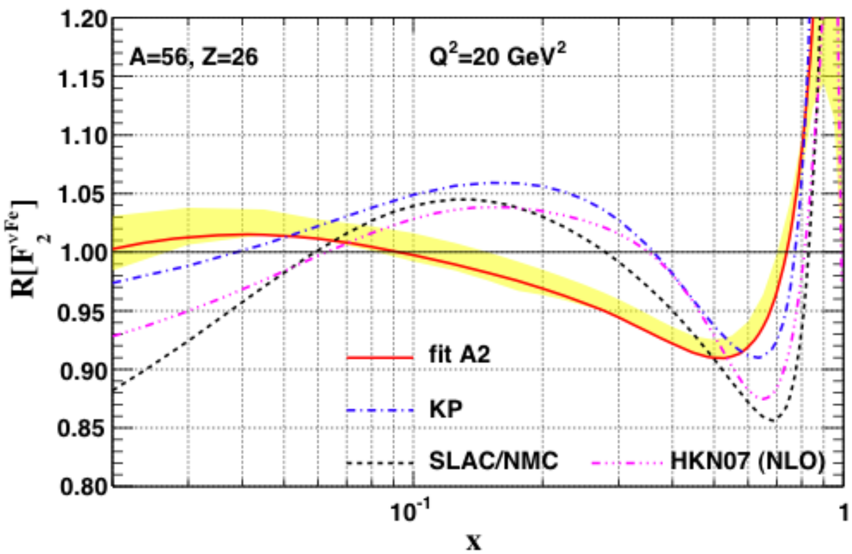
- Form reference fit with nucleon (as opposed to nuclear A>2) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results 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

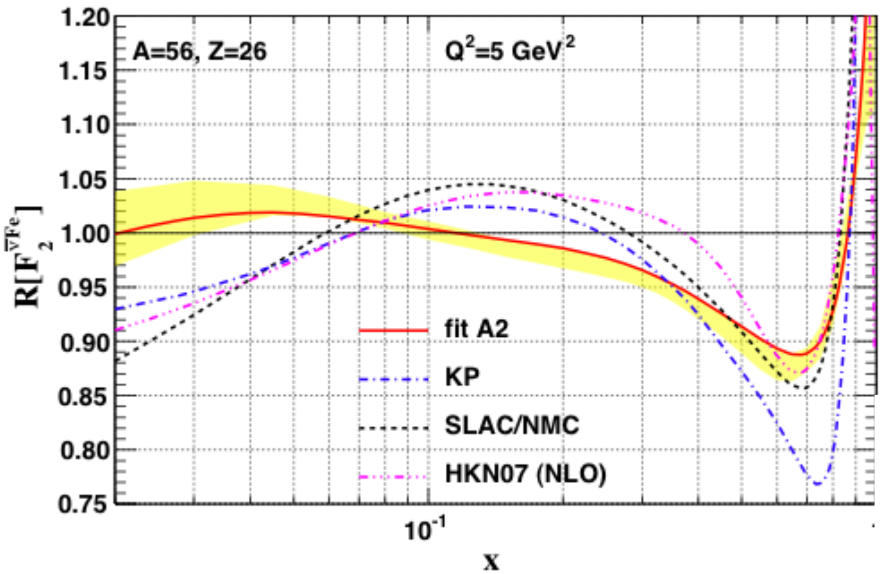
Using NuTeV ν-Iron double differential cross sections



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



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



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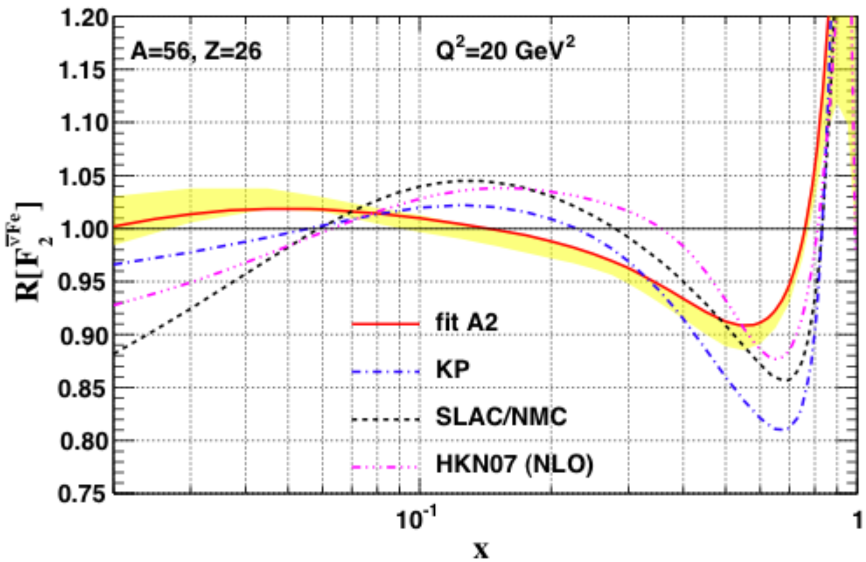
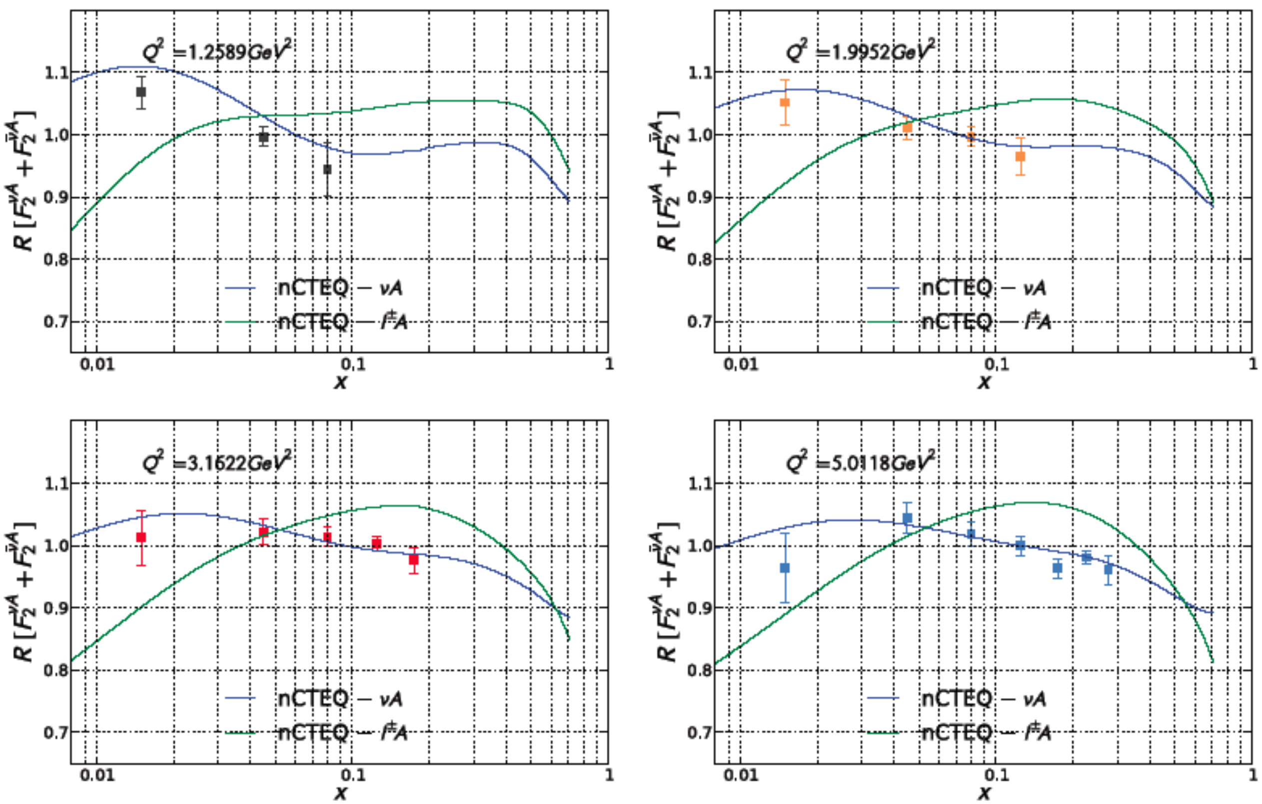


A More-Detailed Look at Differences

- 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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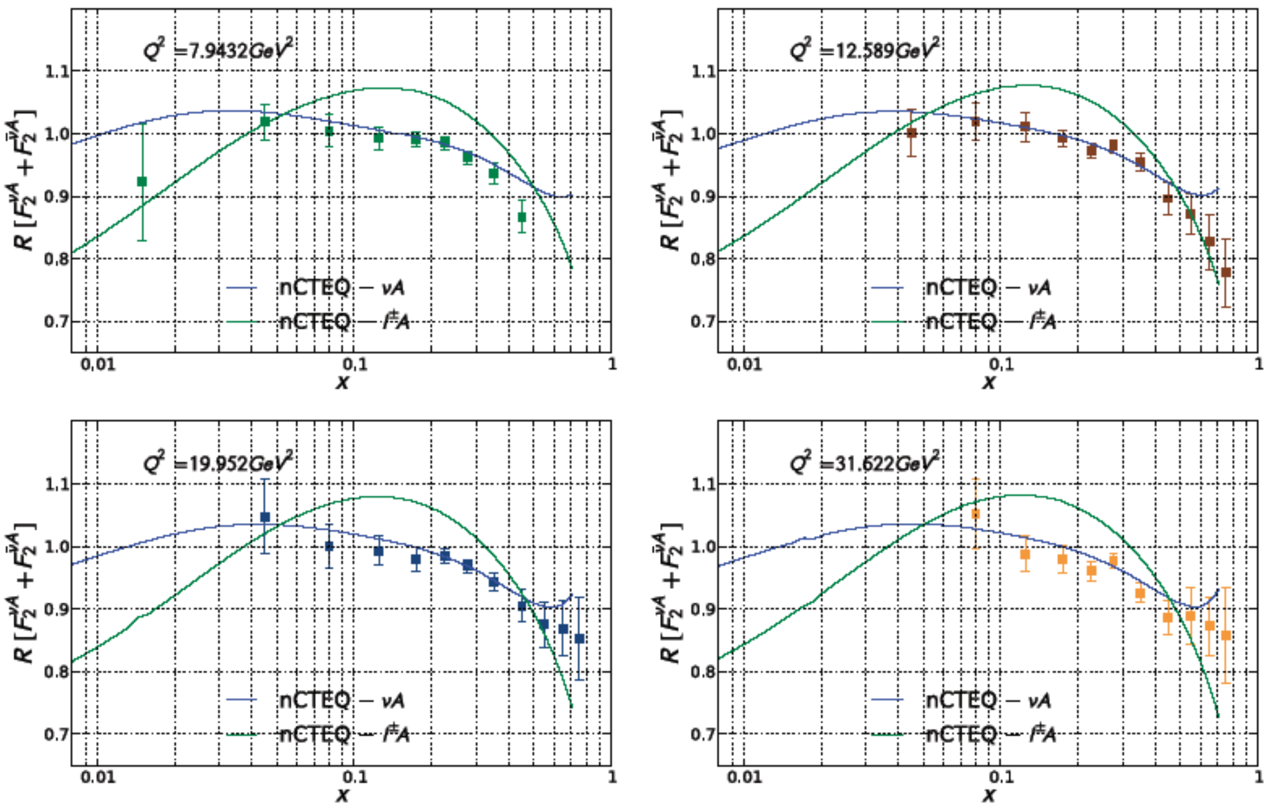

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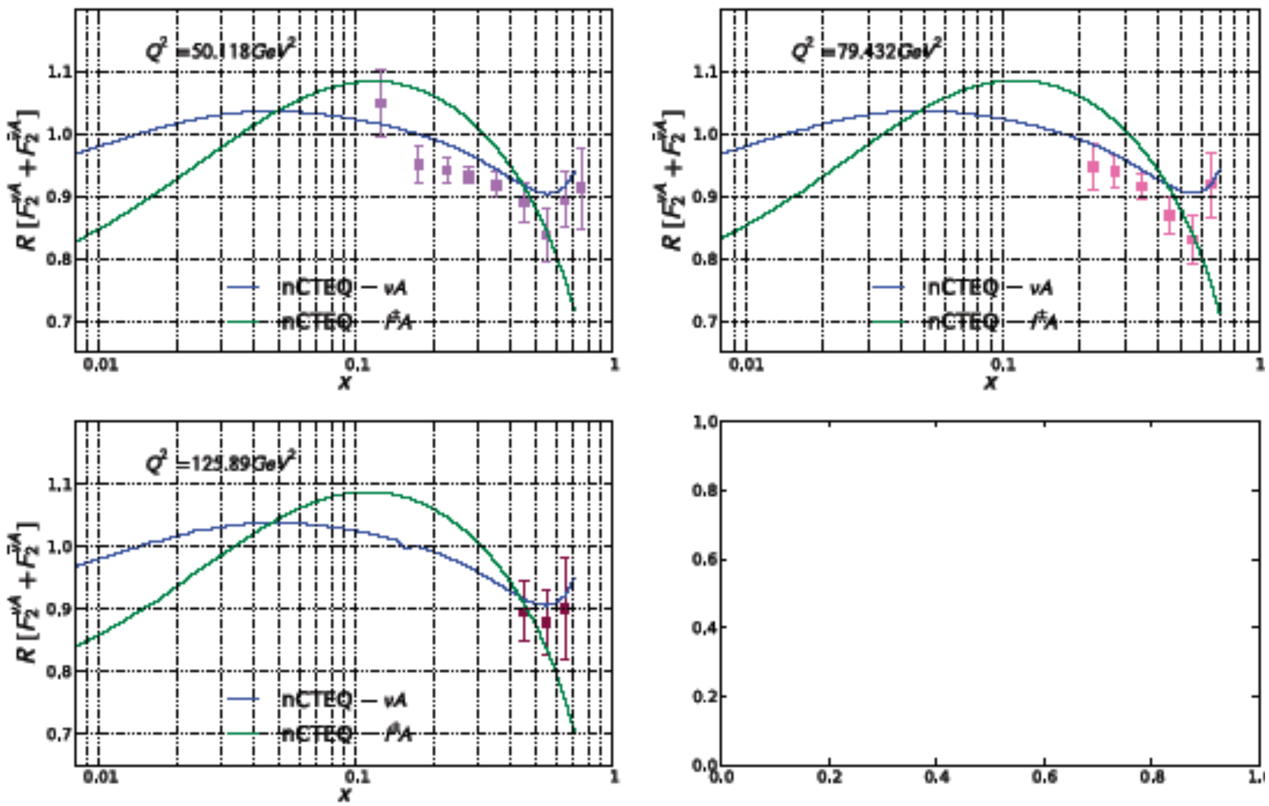


Can we get a reasonable **combined** fit of ν A, ℓA and DY

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

- Take the earlier 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: $\nu\, Fe$, $\bar{\nu}\, Fe$
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: $\nu\, Pb$, $\bar{\nu}\, Pb$
  - 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)**. Multiply neutrino results by weight w.

Quantitative χ^2 Analysis of a Combined Fit:

<u>No</u> combination satisfies tolerance requirement

- 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)

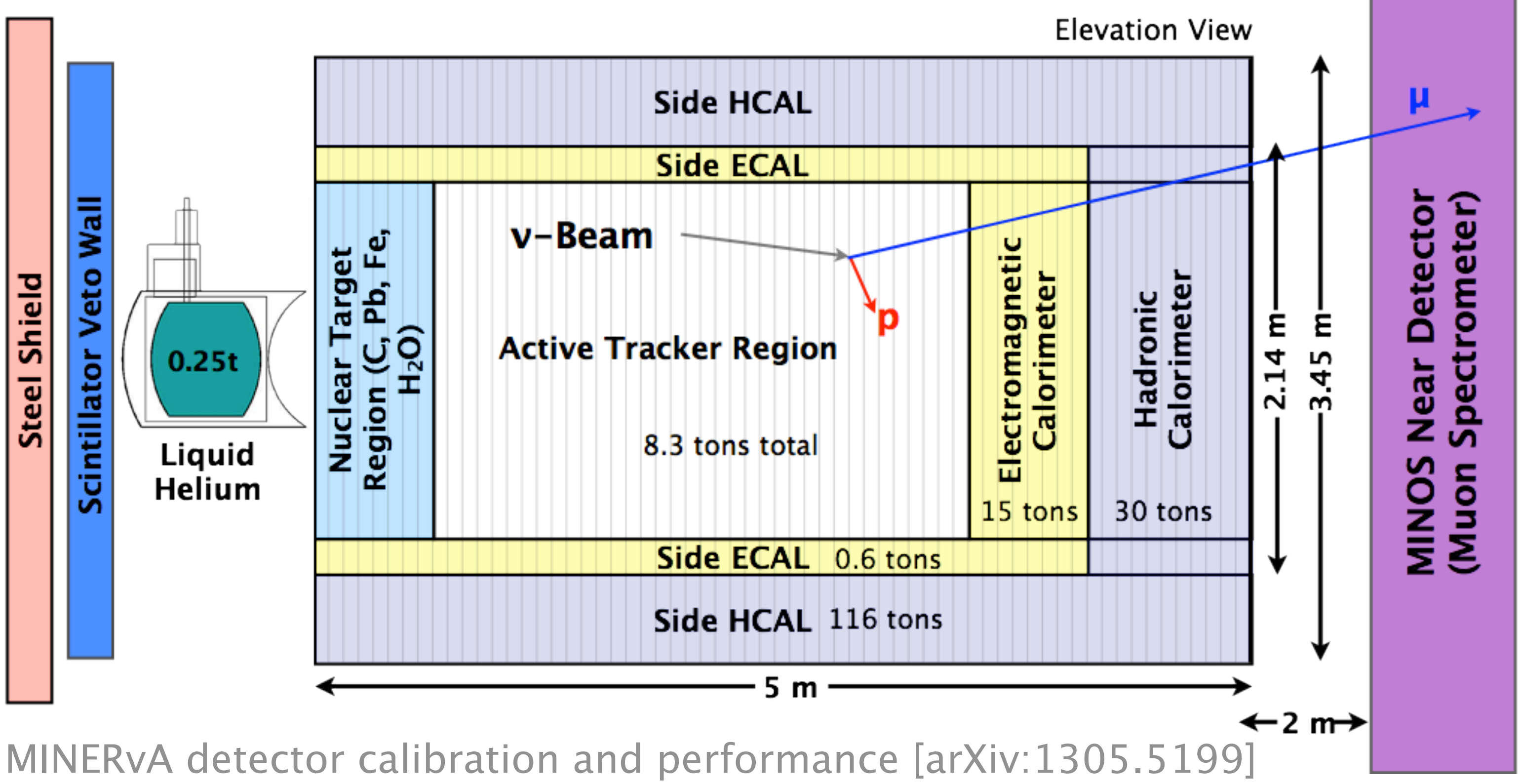
Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO** T?	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)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

- **We need a fresh look with direct measurements of nuclear target ratios in a neutrino experiment!**

A new direct look at ν A scattering
Then MINERνA Experiment

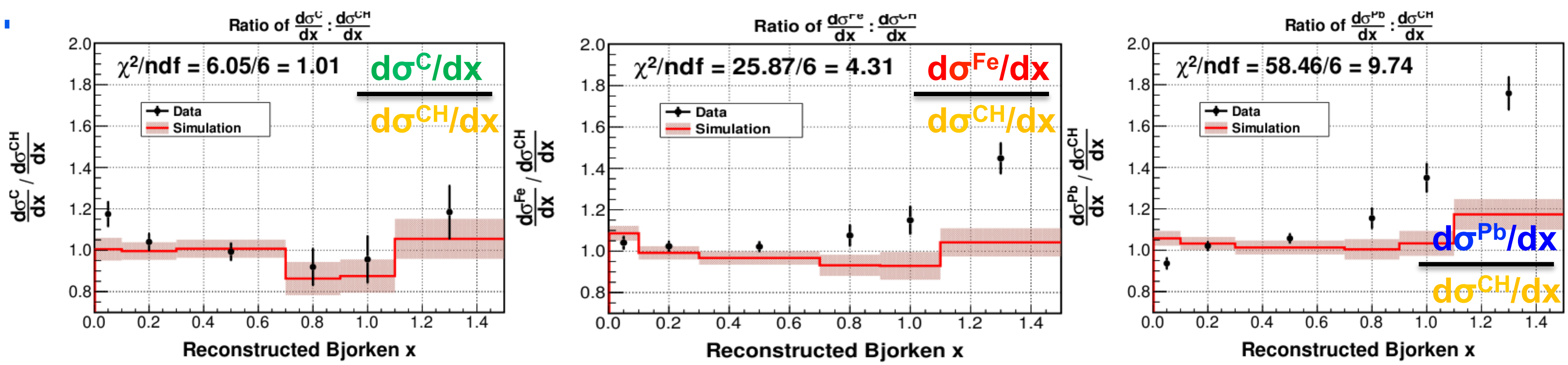
See Chris Marshall's talk tomorrow for details

- 120 modules for tracking and calorimetry (~32k channels)
  - Active element is polystyrene (extruded plastic scintillator)
- Fully commissioned in Spring 2010
- MINOS Near Detector provides a muon spectrometer



The MINERvA detector calibration and performance [arXiv:1305.5199]

Inclusive Cross Section Ratios – $d\sigma / dx_{Bj}$
Compared to the GENIE Event Generator Predictions



Reconstructed *x* (no correction for detector smearing) Tice et al., PRL 112 (2014) 231801

Taking ratios removes uncertainties due to the neutrino flux, acceptance, …

At low x, $x < 0.1$, observe a *deficit* that increases with the size of the nucleus
(possibly additional nuclear shadowing in ν scattering, study more directly in DIS)

At high x, $x > 0.7$, observe an *excess* that grows with the size of the nucleus
(events are dominated by CCQE and resonances)

These effects are not reproduced by current neutrino interaction models

GENIE assumes an x dependent effect from charged lepton scattering on nuclei
but ν sensitive to xF_3 and also to the axial part of F_2

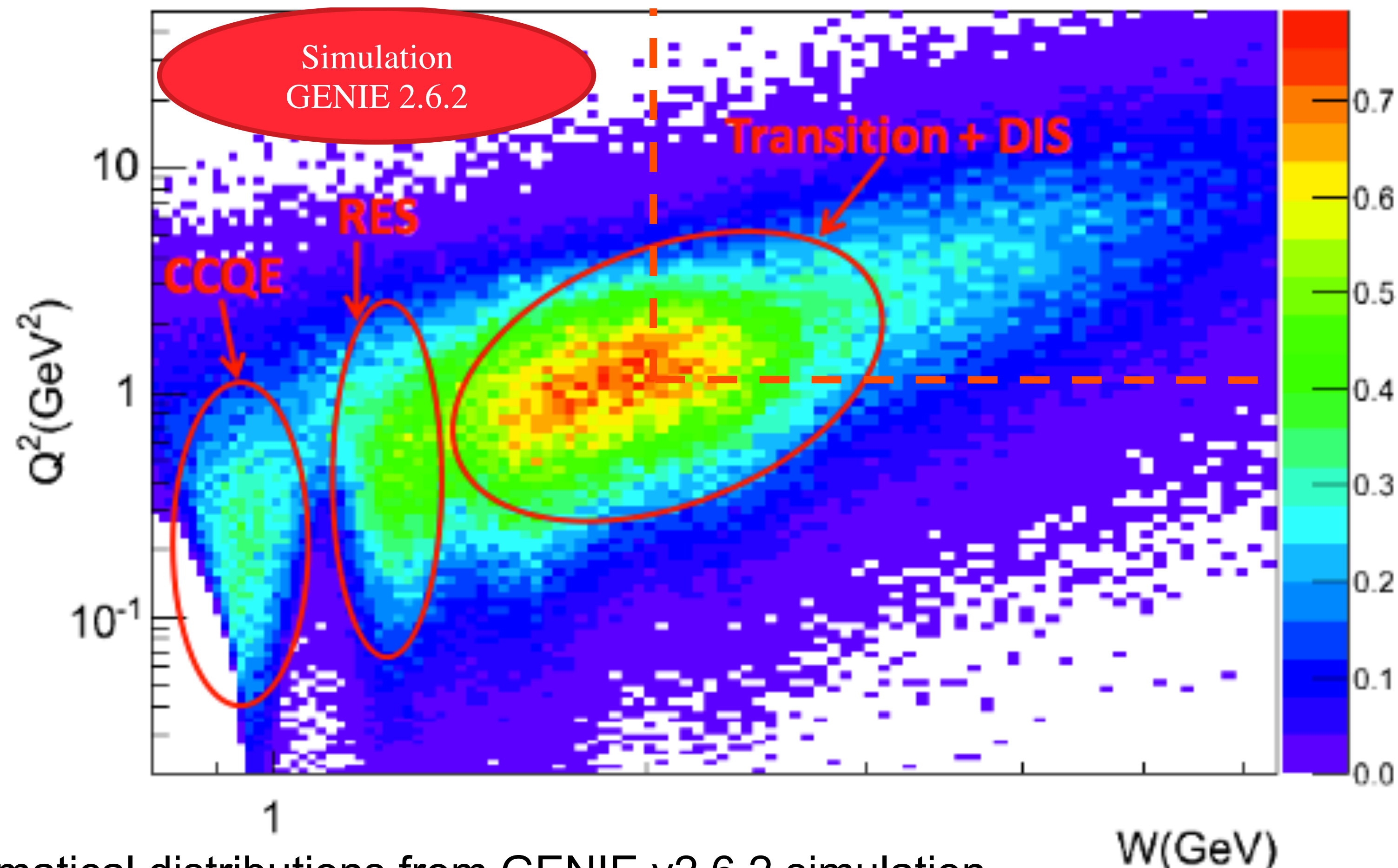
When studied as a function of E_ν:
no evidence of tension between MINERνA data and GENIE 2.6.2 simulations

W – Q^2 Kinematical Region in LE Beam

Select **DIS** sample by requiring $Q^2 > 1.0$ GeV^2 and $W > 2.0$ GeV

Extend E_ν to 50 GeV : $5 < E_\nu < 50$ GeV

z axis : 10^3 events / 3 x 10^3 kg of C / 5e20POT

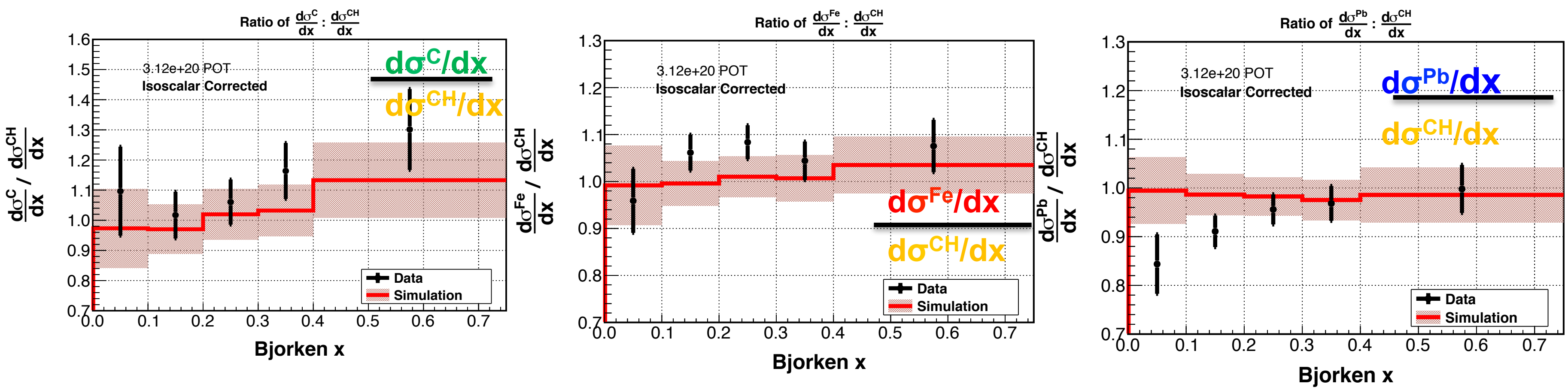


kinematical distributions from GENIE v2.6.2 simulation
events shown have muon tracked in MINOS

We Now Have A New DIS Player - What does MINERvA see?

DIS Cross Section Ratios – $d\sigma$ / dx_{Bj}

J. Mousseau, PhD thesis



Unfolded x (detector smearing)

$$x_{Bj} = \frac{Q^2}{2ME_{had}}$$

DIS: interpret data at partonic level

x dependent ratios directly translates to *x* dependent nuclear effects

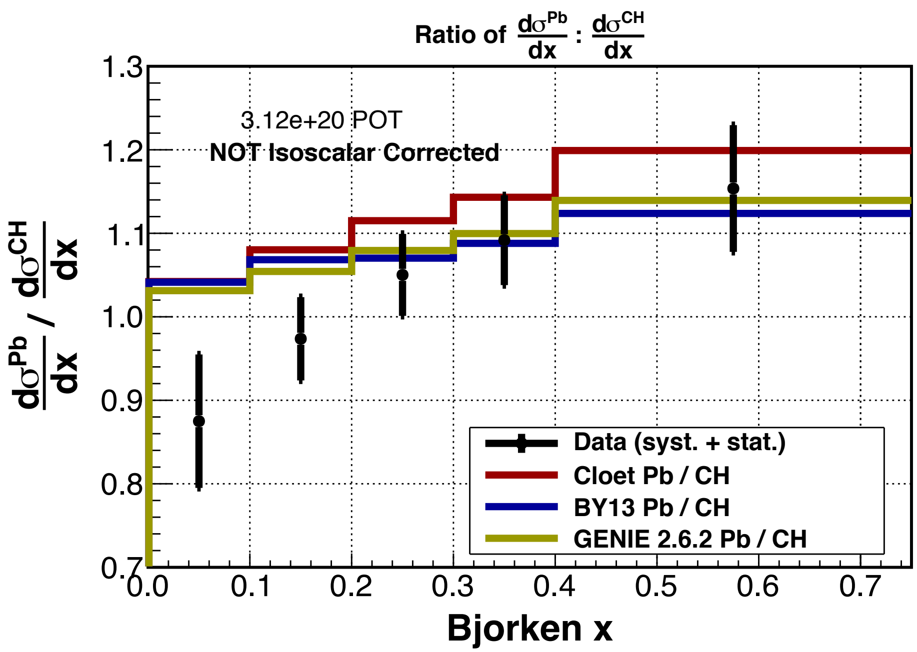
(cannot reach the high-*x* with LE data sample)

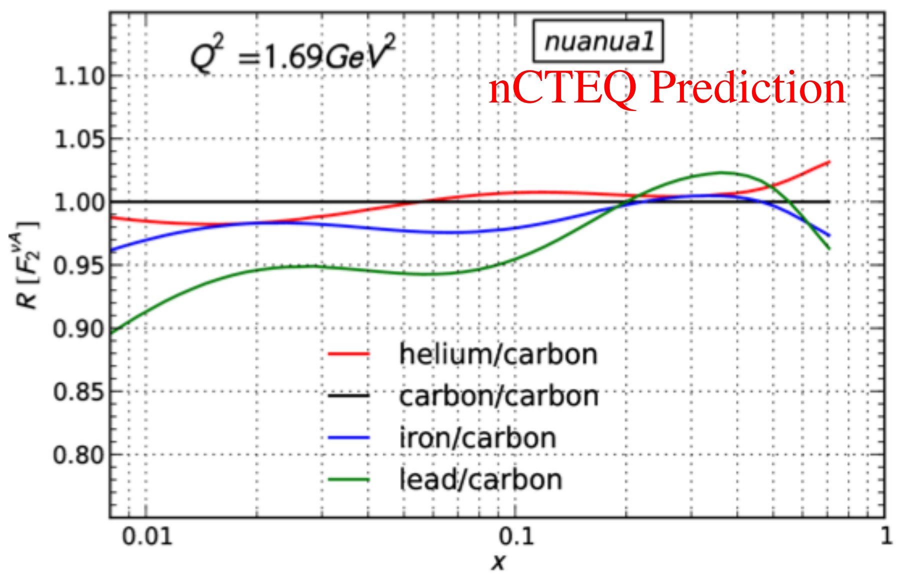
MINERνA data suggests additional nuclear shadowing in the lowest *x* bin

($\langle x \rangle = 0.07$, $\langle Q^2 \rangle = 2$ GeV^2)

In EMC region ($0.3 < x < 0.7$) agreement between data and models

Shadowing in Neutrino Interactions: Pb / CH



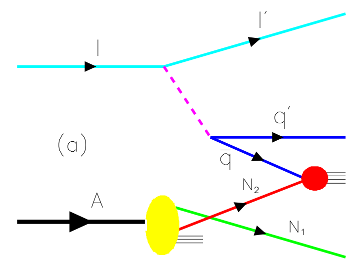


- Although not yet statistically significant the trend is certainly suggestive of something interesting happening in the low-x region of Pb/CH.
- **The data is consistent with nuclear shadowing at an <x>** (0.07) **& <Q^2>** (2 GeV^2) **where negligible shadowing is expected with $l^{\pm}$.**

Shadowing in Neutrino Interactions
Difference expected compared to $l^{\pm}$ A

Nuclear Shadowing in Electro-Weak Interactions - Kopeliovich, JGM and Schmidt arXiv:1208.6541

- Most successful theoretical models of shadowing are based on hadronic fluctuations of the γ (or W/Z for neutrinos)
- These fluctuations then undergo multiple diffractive scattering off leading nucleons in the the nucleus.

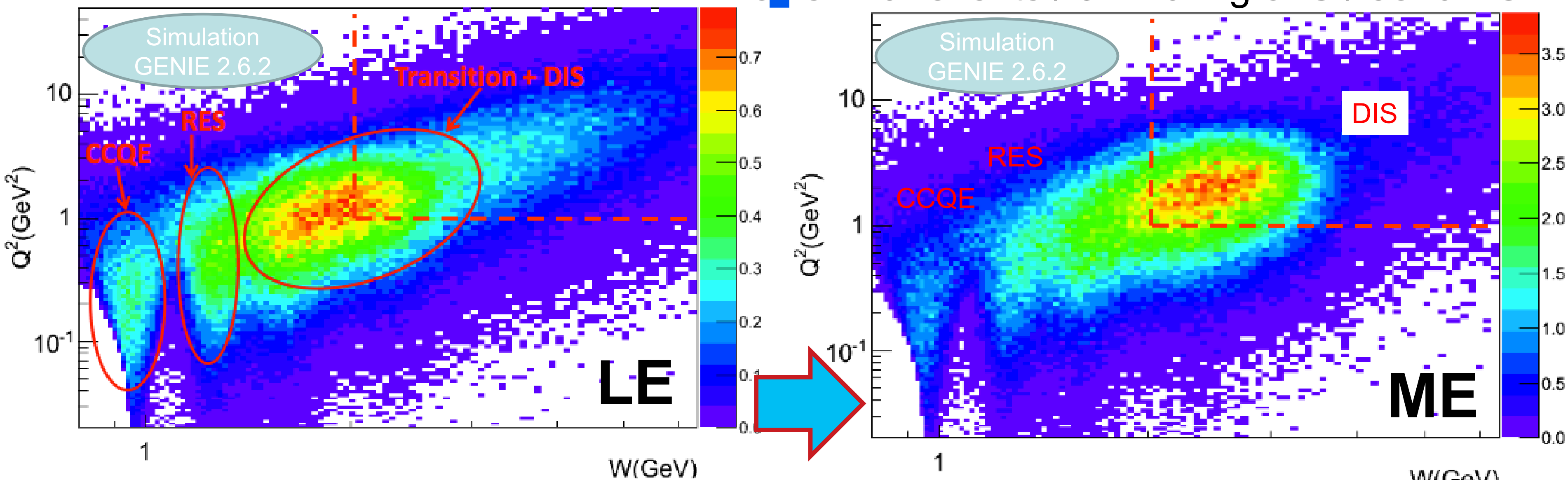


- The lifetime t_c of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters.
- For a given Q^2 need large E_{had} to yield sufficient t_c which implies small x.
- For a given Q^2 you need more E_{had} for the vector current than the axial vector current to have sufficient $t_{c.}$
- **This implies you can have shadowing at higher x with neutrinos than with charged leptons**

Need Higher Statistics: Prospects for DIS with ME Beams

W – Q^2 Kinematical Region in LE and ME

z axis : 10^3 events / 3 x 10^3 kg of C / 5e20 POT



Many more neutrino interactions in DIS regime

→ higher beam energy

→ increased statistics (beam intensity, energy) and kinematic reach

→ improve on systematical uncertainties

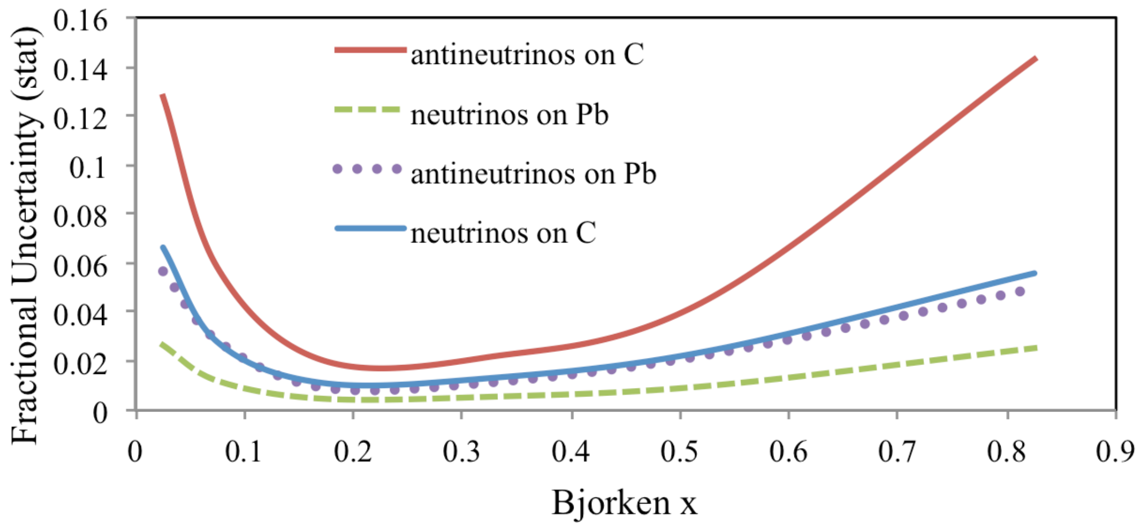
→ structure function measurements on different nuclei

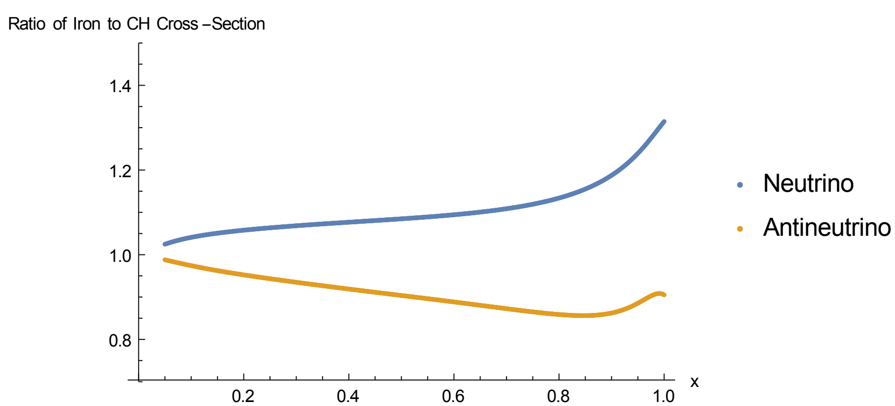
→ probe quark flavor dependence of nuclear effects

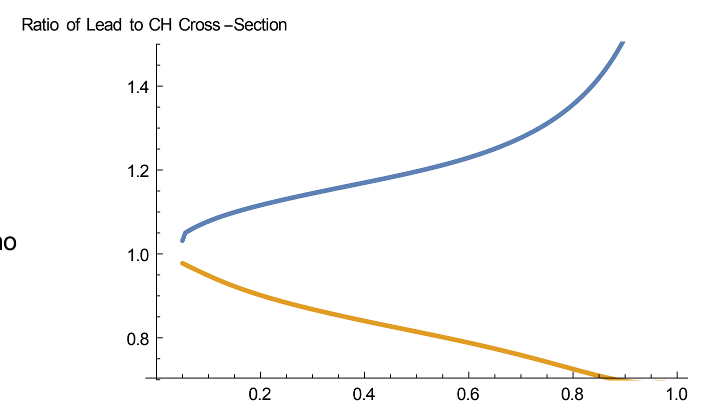
Requested 10 x 10^{20} POT in neutrino and
12 x 10^{20} POT in antineutrino mode

ME Physics Reach on Nuclear Effects

Assume 10×10^{20} POT in neutrino mode, 12×10^{20} POT in antineutrino mode







Prediction from Cloet model described in PRL 109, 182301

Summary and Conclusions

- There are indications from the nCTEQ analysis of **one** experiment using **one** nucleus that **ν-induced parton-level nuclear effects are quite different** than ℓ±-nuclear effects.
- MINERνA has performed a systematic study of nuclear medium modifications of hadronic structure using different nuclear targets in the same detector exposed to the same neutrino beam. **First measurement of ratios of neutrino cross sections on nuclei in the DIS regime.**
- **In the lowest *x* bin MINERνA data suggests nuclear shadowing at an <x> (**0.07) **& $\langle Q^2 \rangle$ (**2 GeV^2**)where negligible shadowing is expected with l±. This is consistent with axial-vector expectations but different thaN nCTEQ claims.**
- Need systematic high-statistics **experimental** study of **ν-induced nuclear effects in A (and D_2)such as MINERνA in the ME Beam.**
- **SO WHAT ABOUT THE CONCEPTS OF FACTORIZATION AND UNIVERSAL PDFS IN THE NUCLEAR ENVIRONMENT**

Additional Details

Fit Details

- Fit @ NLO with Q_0 =1.3 GeV
- Using ACOT heavy quark scheme
- Kinematic cuts:
  - Q > 2 GeV, W > 3.5 GeV
  - p_T > 1.7 GeV
- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts
- 16 free parameters
  - 7 gluon, 7 valence and 2 sea
- χ^2 = 611, giving χ 2/dof = 0.85
- Error analysis – use Hessian method

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::

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

Available nuclear PDF sets

- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\; f_i^{free\ proton}(x_N, \mu_0)$$

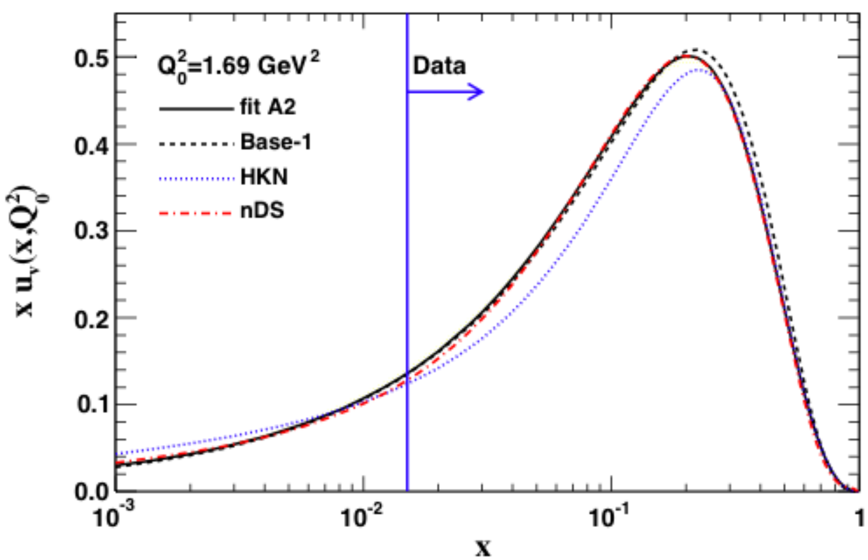
  - Hirai, Kumano, Nagai [PRC 76, 065207 (2007), arXiv:0709.3038]
  - Eskola, Paukkunen, Salgado [JHEP 04 (2009) 065, arXiv:0902.4154]
  - de Florian, Sassot, Stratmann, Zurita [PRD 85, 074028 (2012), arXiv: 1112.6324]

- **Native nuclear PDFs**
  - nCTEQ [PRD 80, 094004 (2009), arXiv:0907.2357]

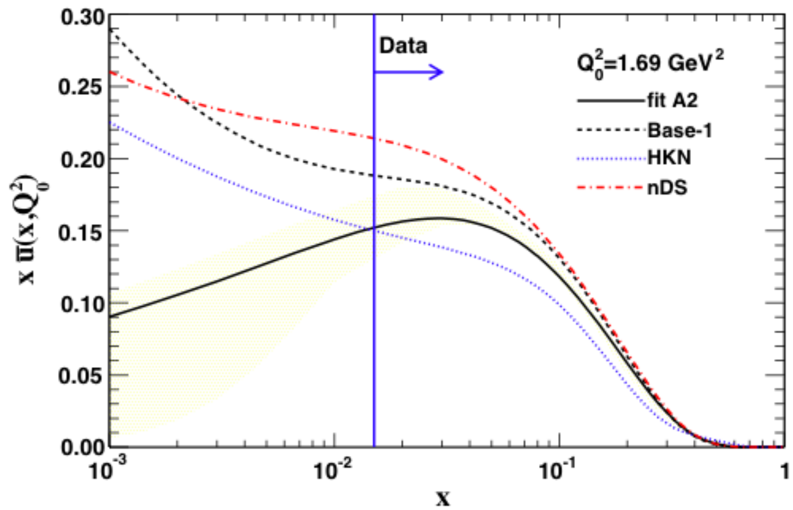
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f_i(x_N, A = 1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

Iron PDFs



Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
Data
$x\,u_v(x,Q_0^2)$
x



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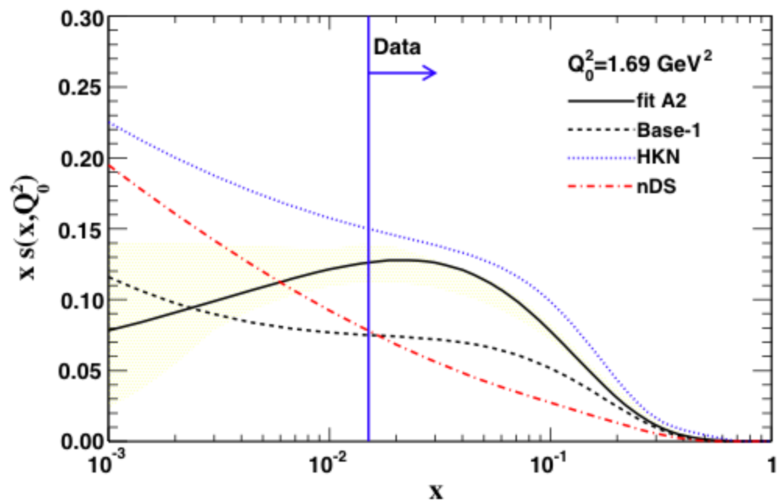


Data
Q_0^2=1.69 GeV^2
fit A2
Base-1
HKN
nDS
$x\,s(x,Q_0^2)$
x

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:

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

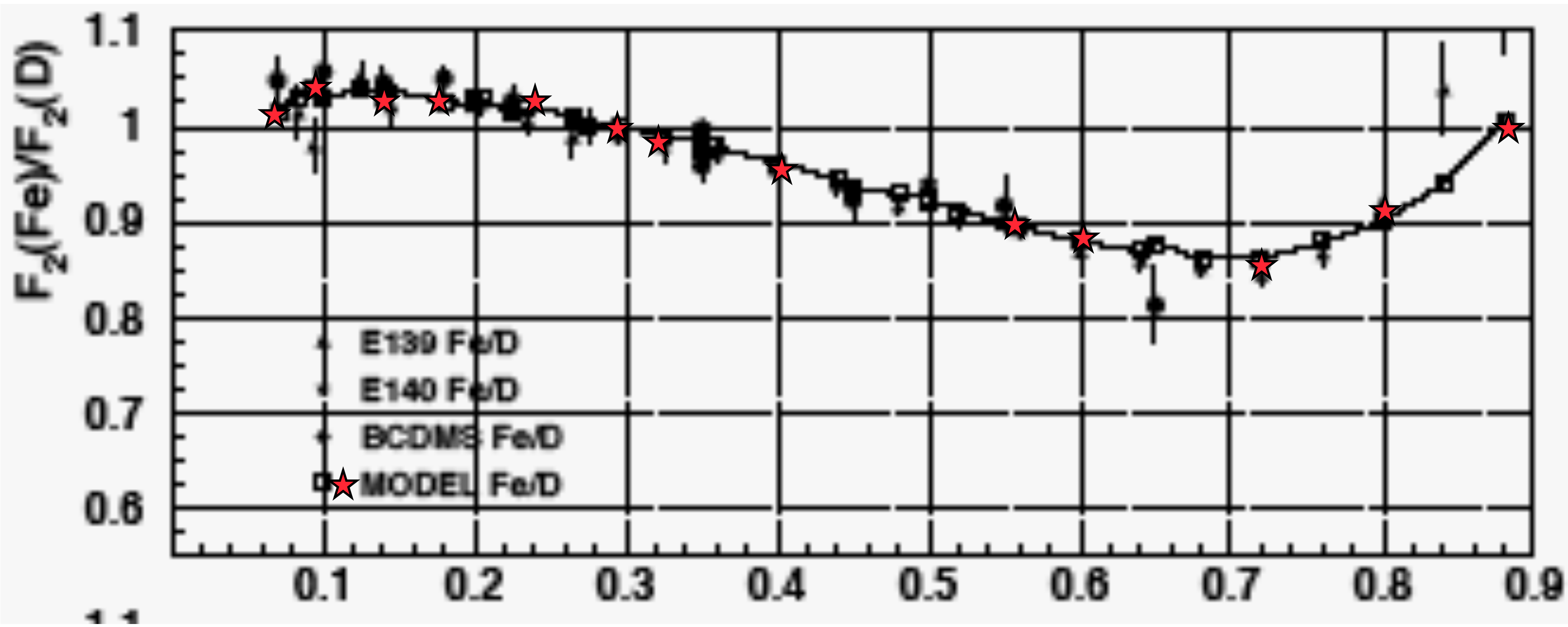
  - $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
  - $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
  - δF_i^{coh} contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **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 $\delta f_2(x)$**

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

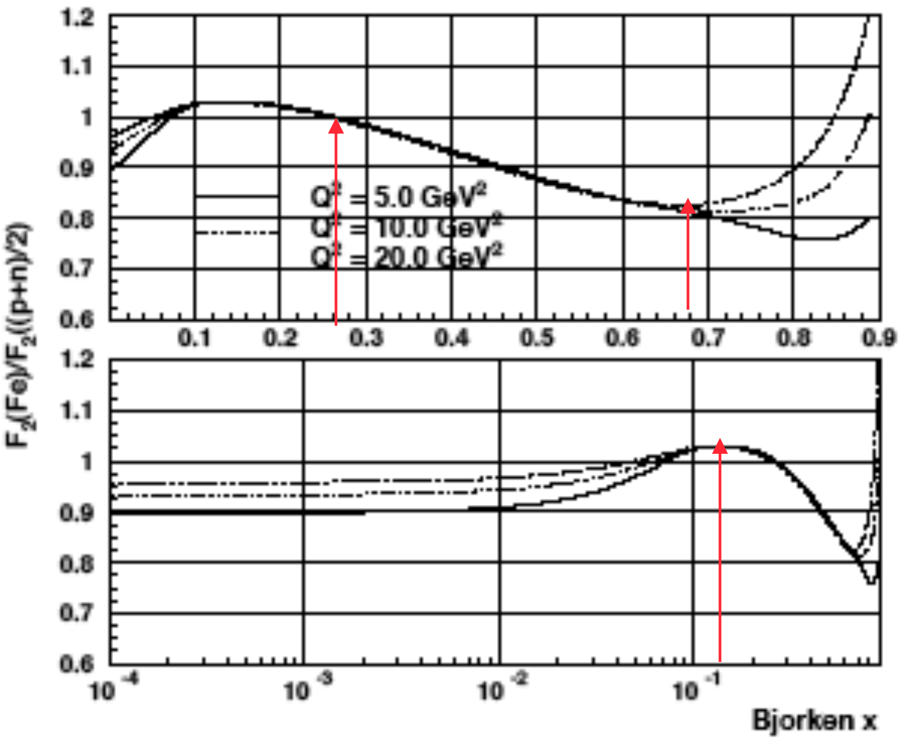
- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

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

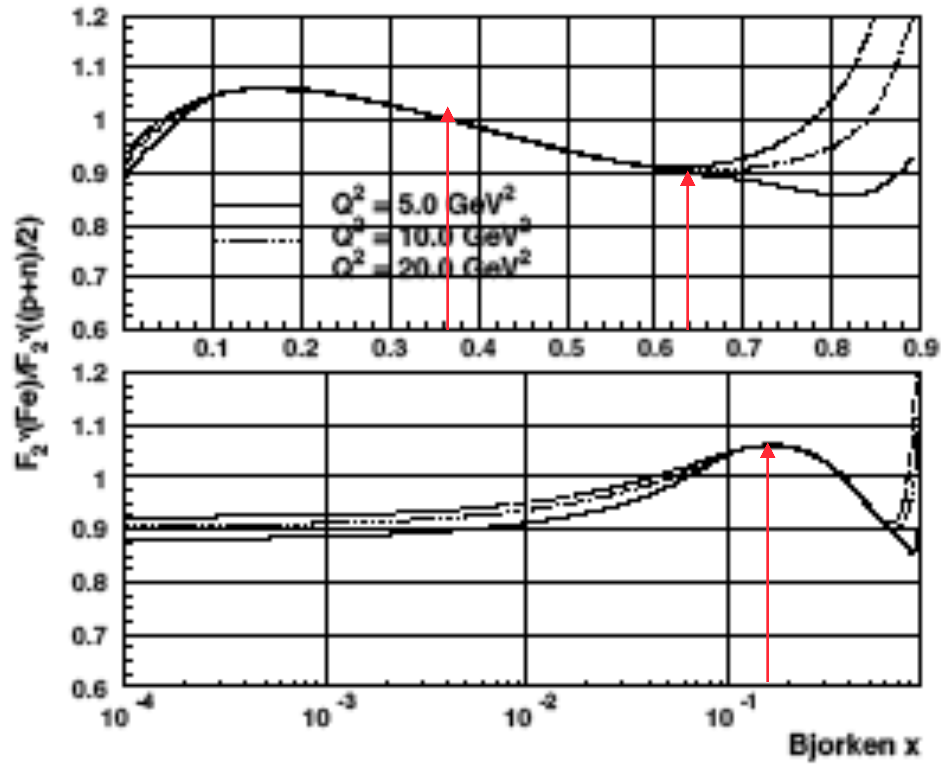


Charged Lepton

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



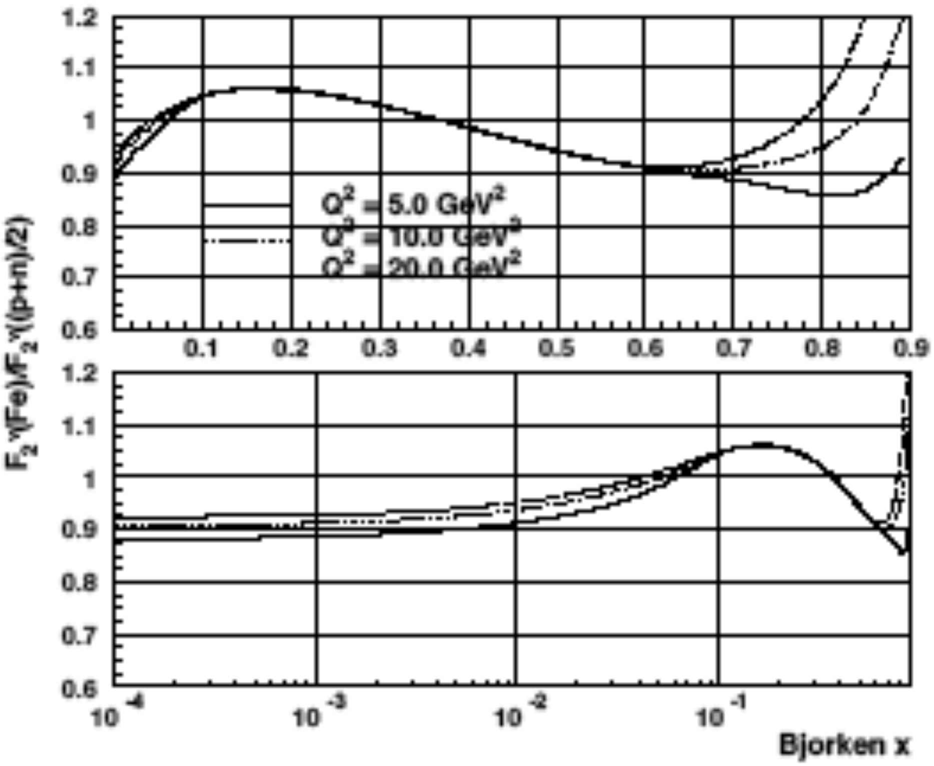
Charged Lepton



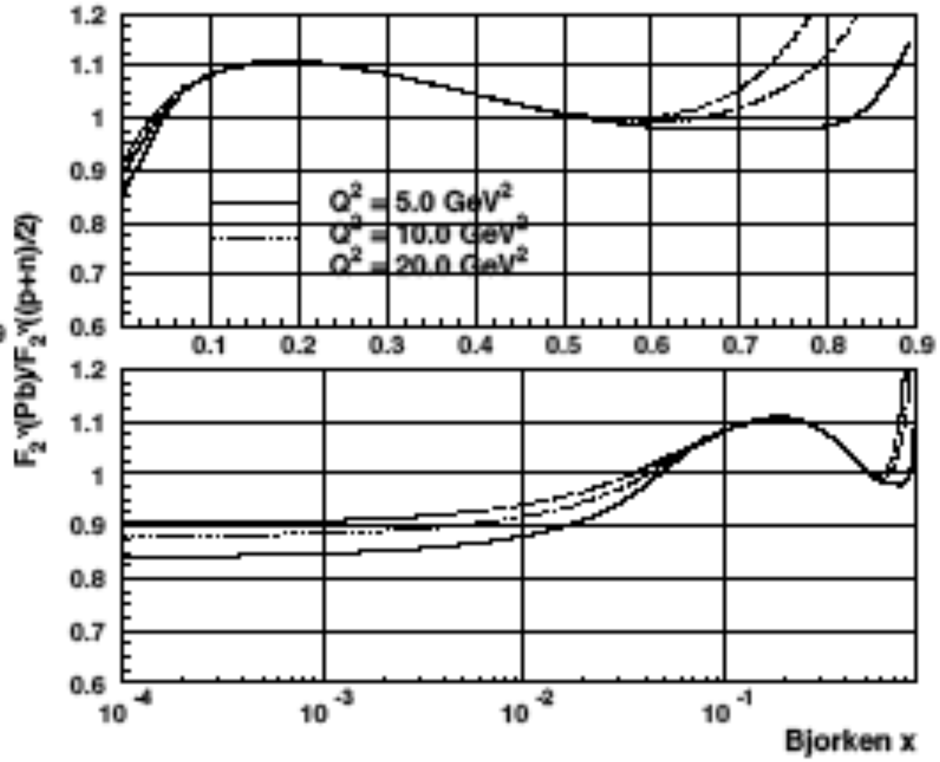
Neutrino

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

(n excess included in effect)

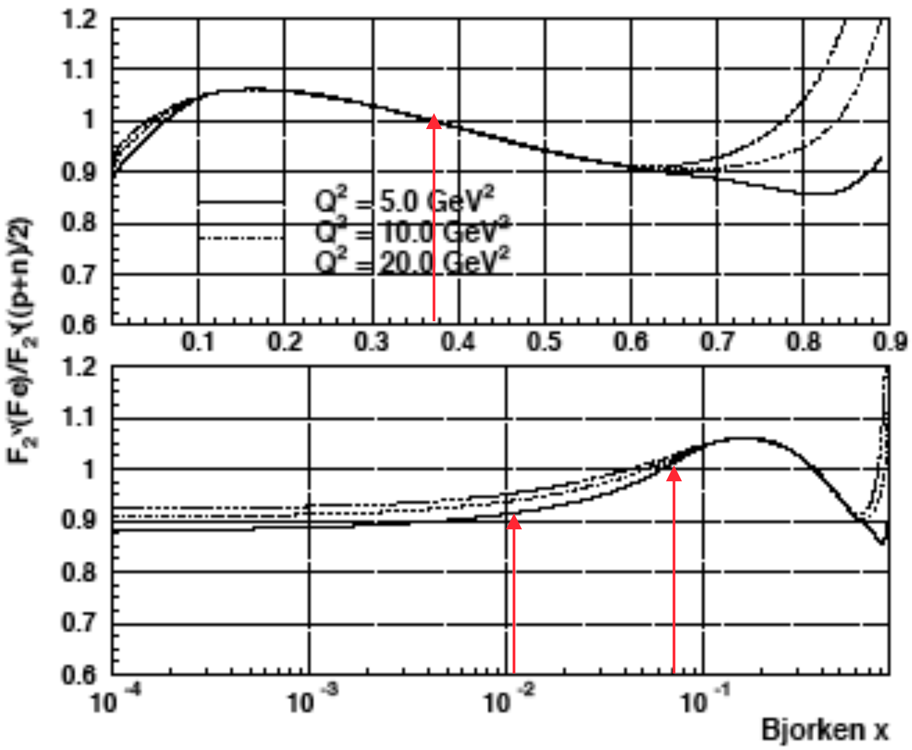


Fe

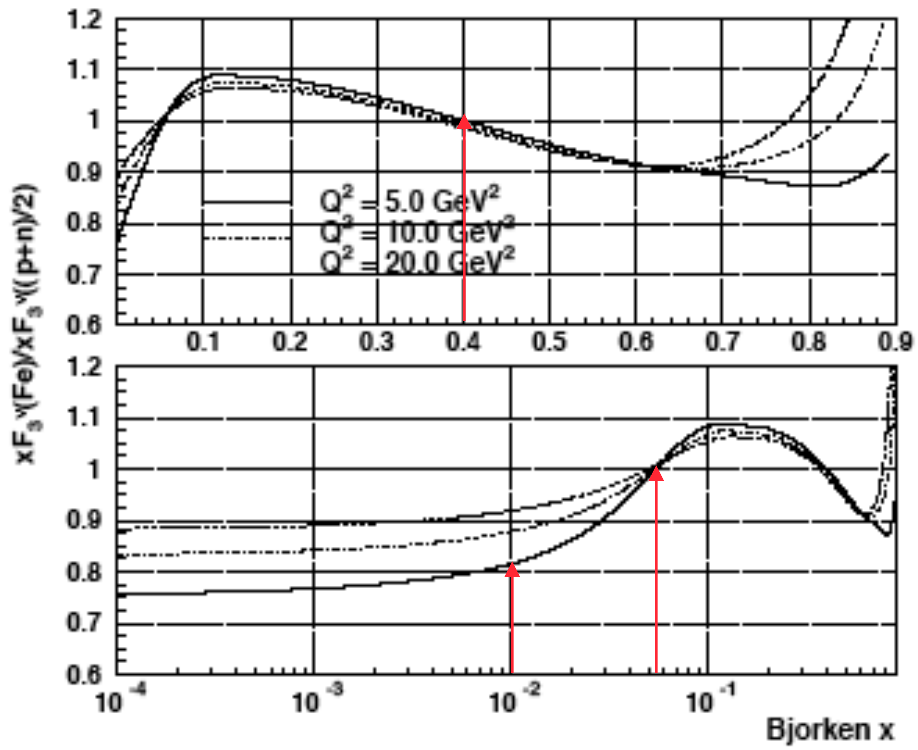


Pb

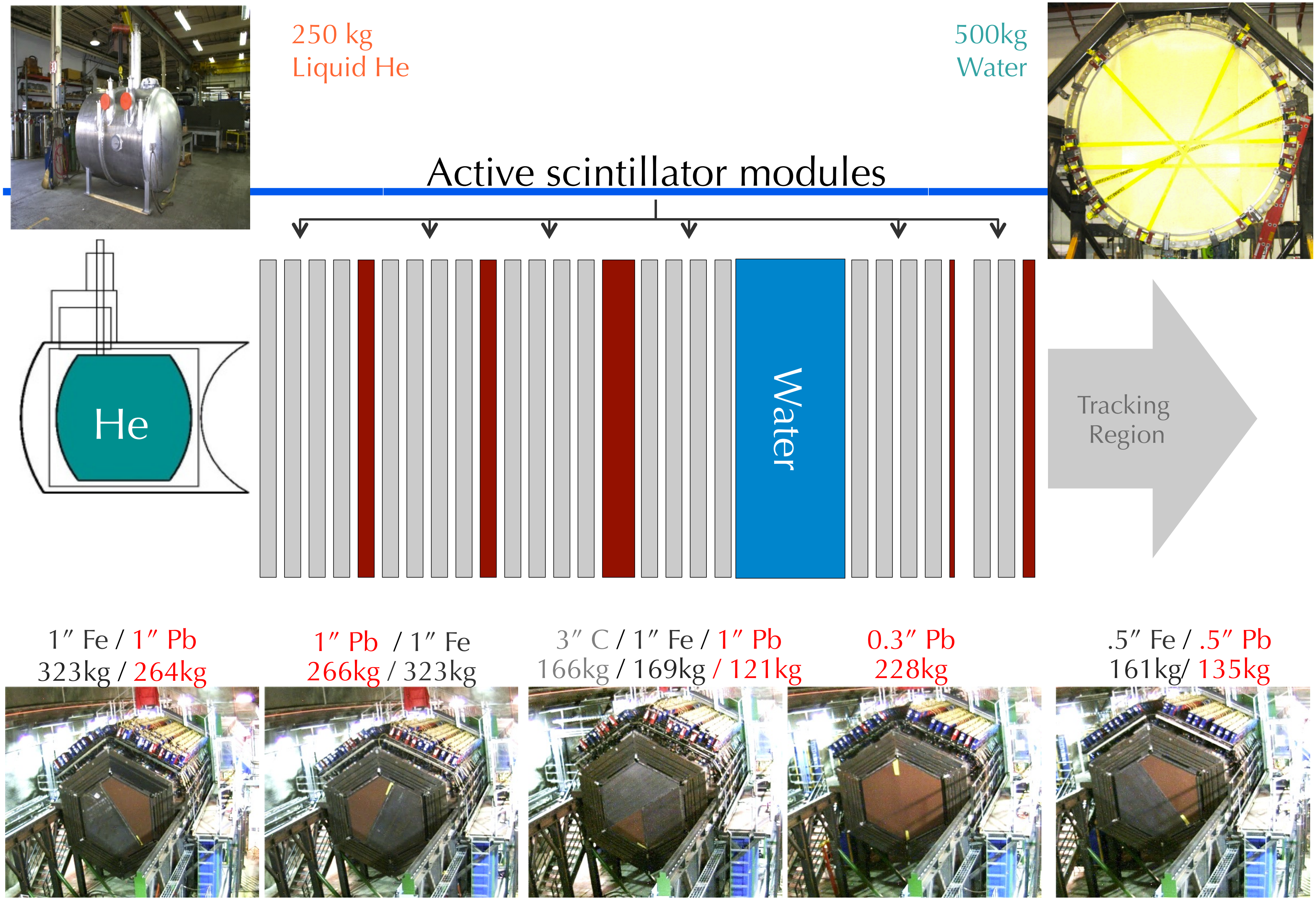
Kulagin-Petti: ν-Fe Nuclear Effects



F_2

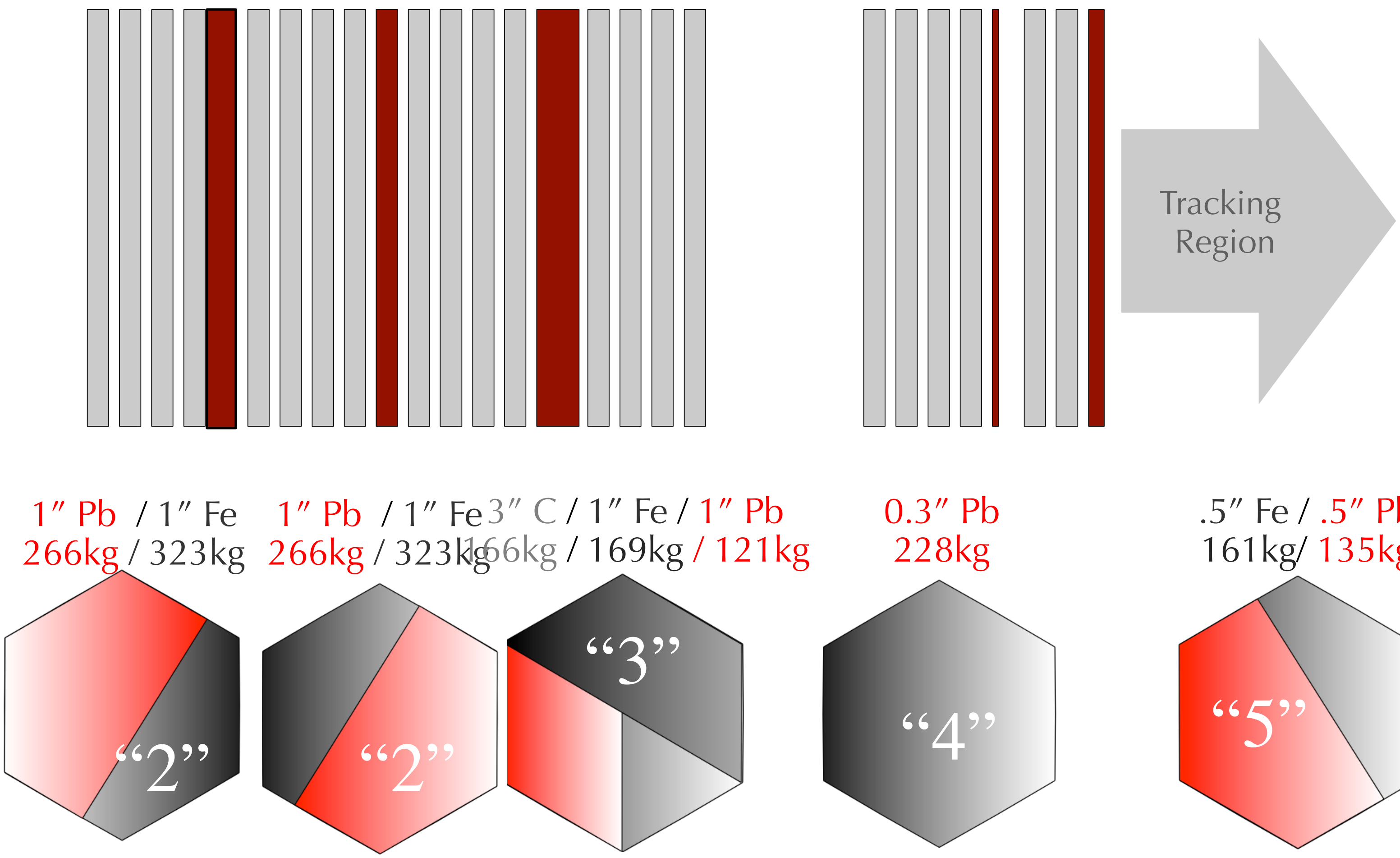


xF_3



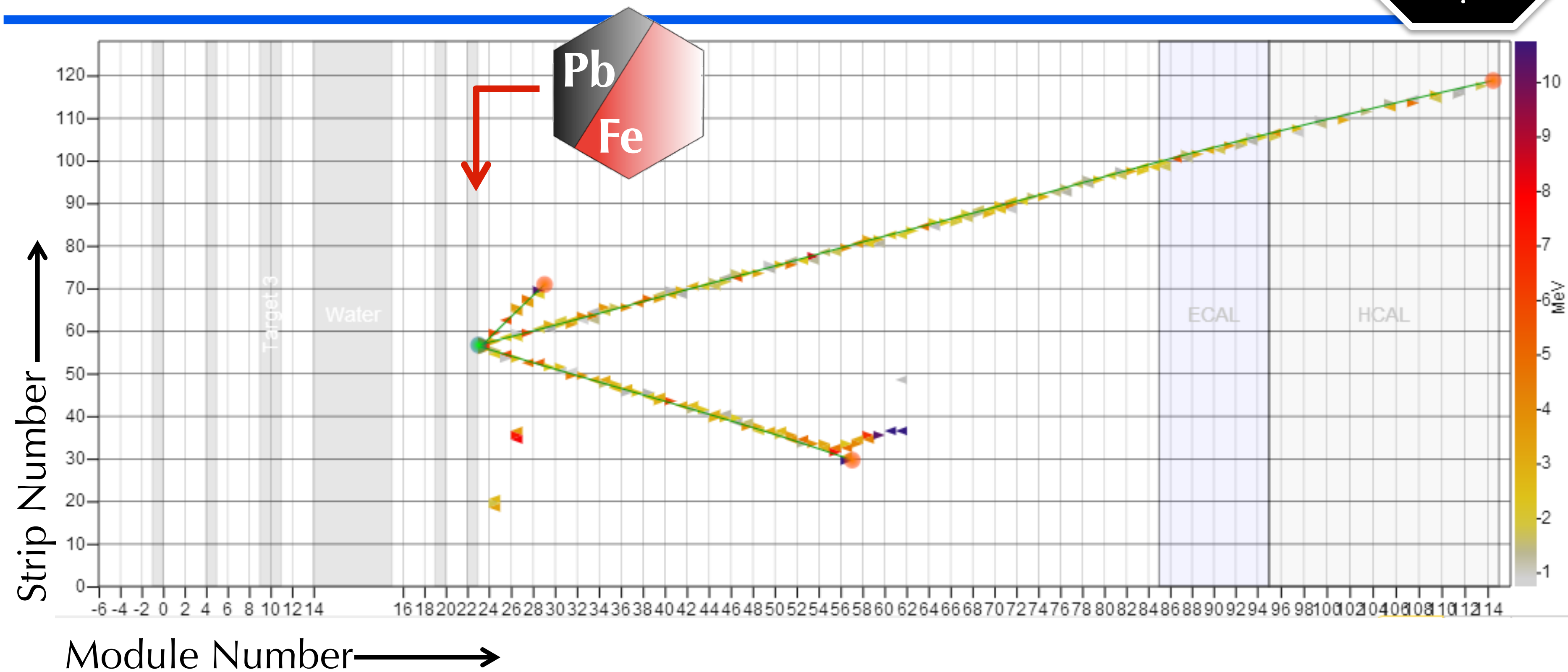
250 kg
Liquid He
500kg
Water
Active scintillator modules
He
Water
Tracking
Region
1″ Fe / 1″ Pb
323kg / 264kg
1″ Pb / 1″ Fe
266kg / 323kg
3″ C / 1″ Fe / 1″ Pb
166kg / 169kg / 121kg
0.3″ Pb
228kg
.5″ Fe / .5″ Pb
161kg/ 135kg

Targets used for these results



Event selection (1)

Thanks MINOS !



Event topology

Muon must be matched to a muon in MINOS

Resulting kinematic region

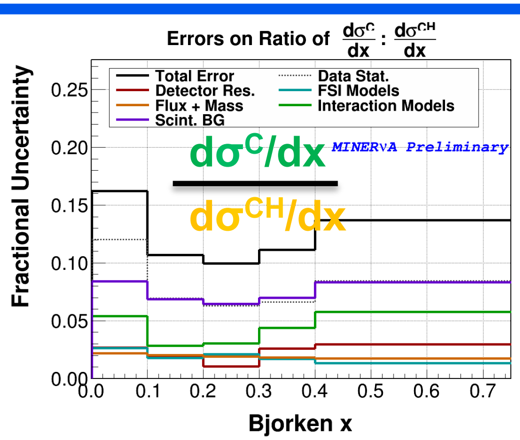
2 < Neutrino Energy < 20 GeV

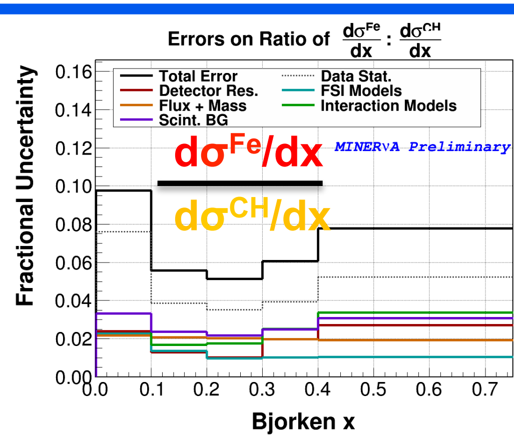
0 < Muon Angle < 17°

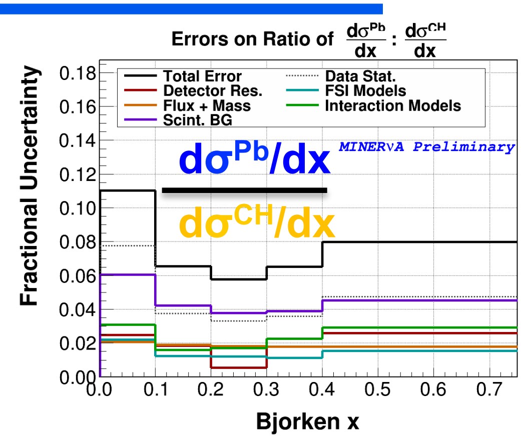
Nuclear target sample

Vertex must be in passive target or an adjacent downstream scintillator plane

Cross Section Ratios Uncertainties (x_{Bj})







Taking ratios removes large uncertainties due to the neutrino flux

Uncertainties similar across different targets, all targets in same beam
→ flux largely cancels
→ similar acceptance and reconstruction
(however efficiency correction introduces cross section model uncertainties)

Most of the uncertainty stems from data statistics
(higher intensity, higher energy ME beam will improve this substantially)

"Plastic" background subtraction introduces a larger uncertainty in *x* (not in E_ν)

Fit Details

- Fit @NLO with Q_0 =1.3GeV
- Using ACOT heavy quark
- Kinematic cuts:
  - $Q > 2$ GeV, $W > 3.5$ GeV
  - $p_T > 1.7$ GeV

Kinematic cuts

nCTEQ:

$$\begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$$

EPS: $Q > 1.3$ GeV

HKN: $Q > 1$ GeV

DSSZ: $Q > 1$ GeV

- 708 (DIS & DY) + 32 (single π^0) = 740 data points after cuts
- 16 free parameters
  - 7 gluon, 7 valence and 2 sea
- $\chi^2 = 611$, giving χ^2/dof = 0.85
- Error analysis – use Hessian method

Fit Details

- Fit @NLO with Q_0 =1.3GeV
- Using ACOT heavy quark
- Kinematic cuts:
  - Q > 2 GeV, W > 3.5 GeV
  - p_T > 1.7 GeV
- 708 (DIS & DY) + 32 (single π^0
- 16 free parameters
  - 7 gluon, 7 valence and 2 sea
- **nCTEQ: 740** data points
- **EPS09: 929** data points
  - reducing derivatives

Kinematic cuts

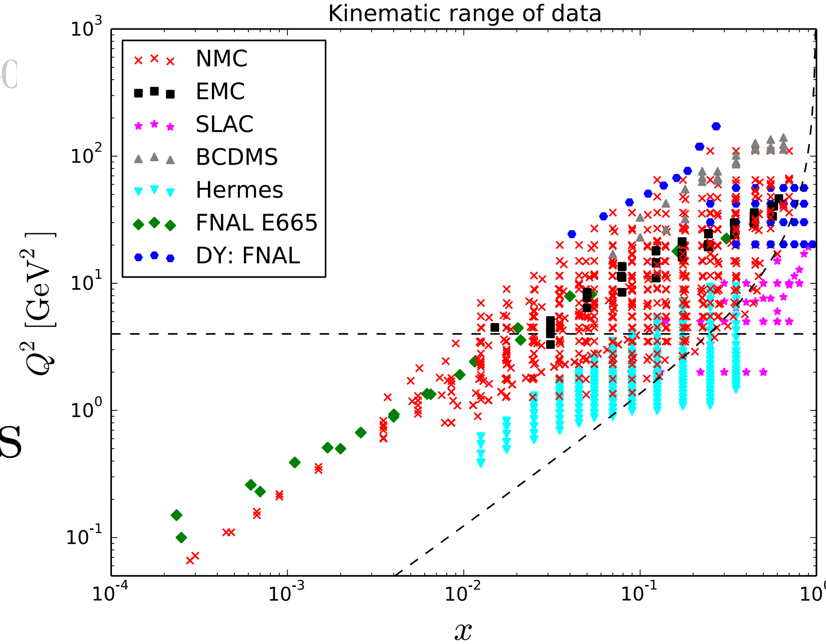
nCTEQ:

$$\begin{cases} Q > 2 \text{ GeV} \\ W > 3.5 \text{ GeV} \end{cases}$$

EPS: $Q > 1.3$ GeV

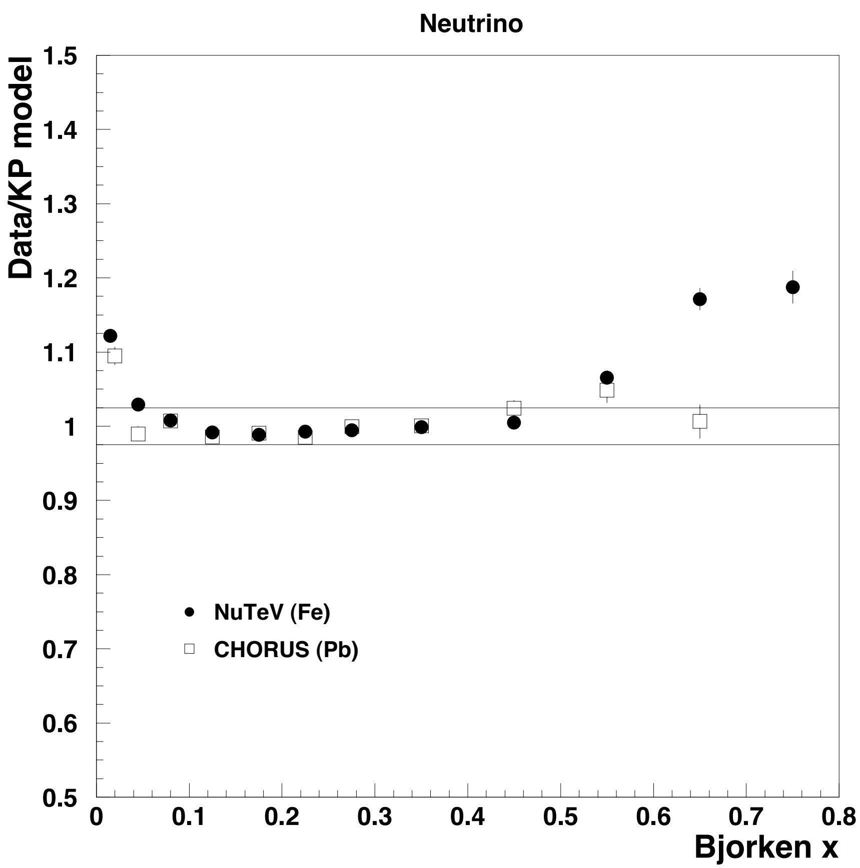
HKN: $Q > 1$ GeV

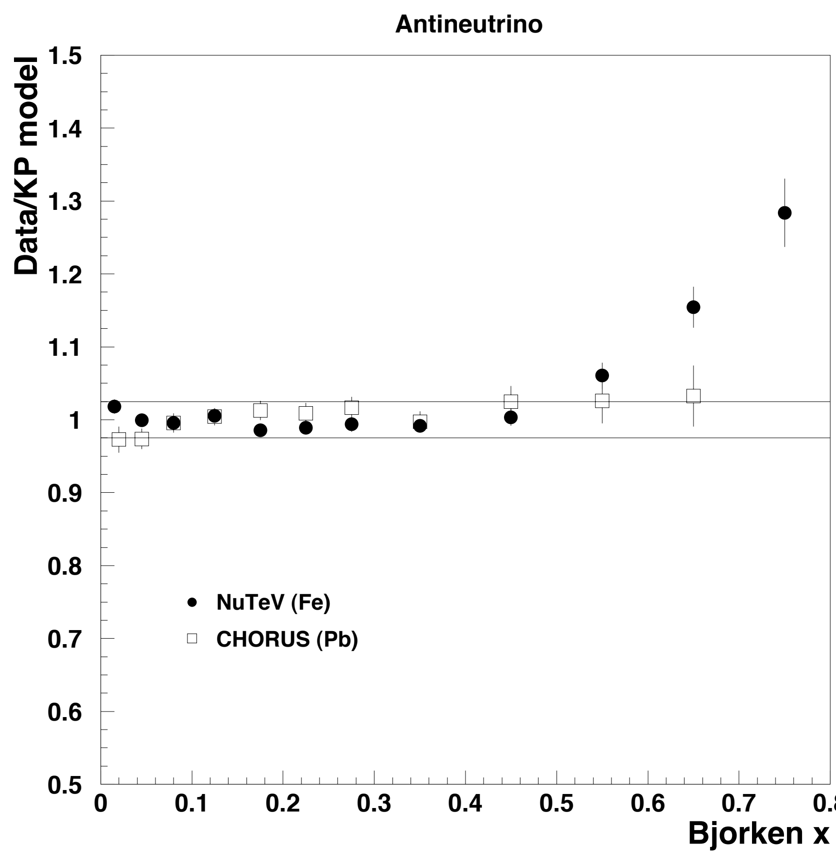
DSSZ: $Q > 1$ GeV



Comparison of Data to the Kulagin-Petti Model

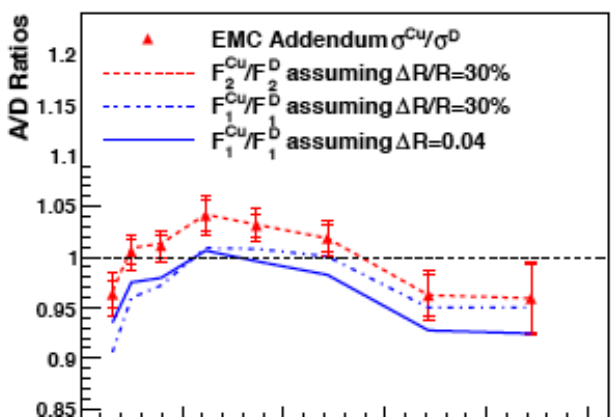
thanks to Roberto Petti





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

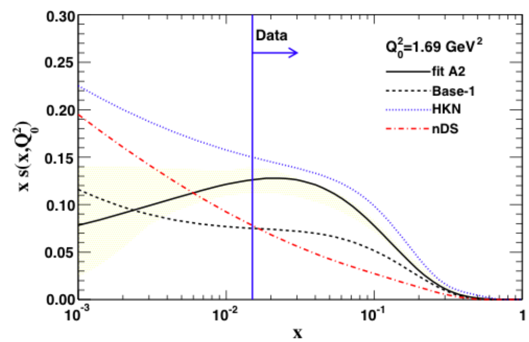
If Difference between both $l^{\pm}$-A and ν–A persists?

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

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

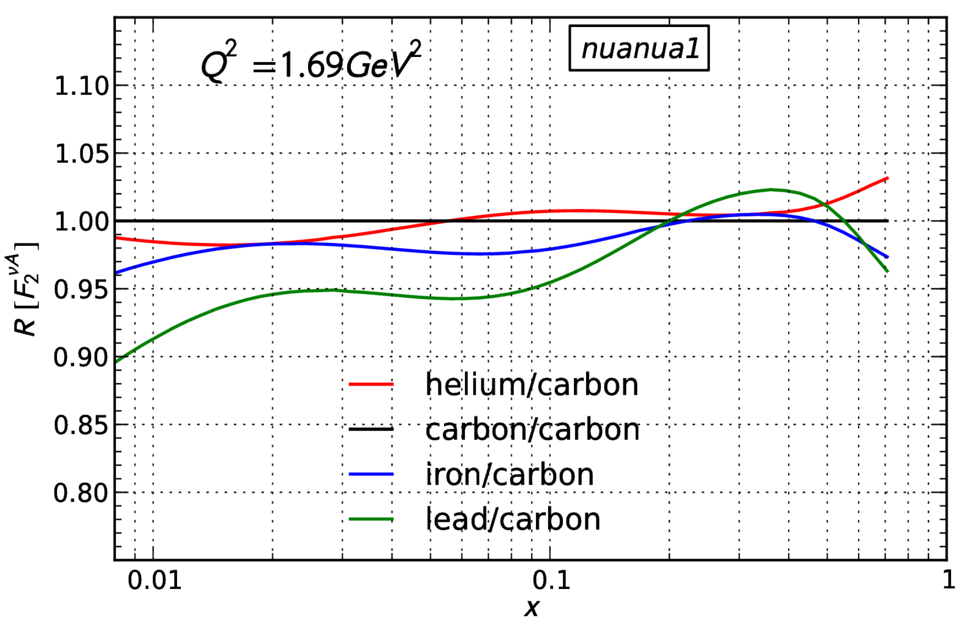
$$\frac{d\sigma^{\bar{\nu} A}}{dxdy} = \frac{G_F^2 M_W^4}{(Q^2 + M_W^2)^2} \frac{ME}{\pi} 2x \left[\bar{d}^A + \bar{s}^A + (1-y)^2(u^A + c^A)\right]$$

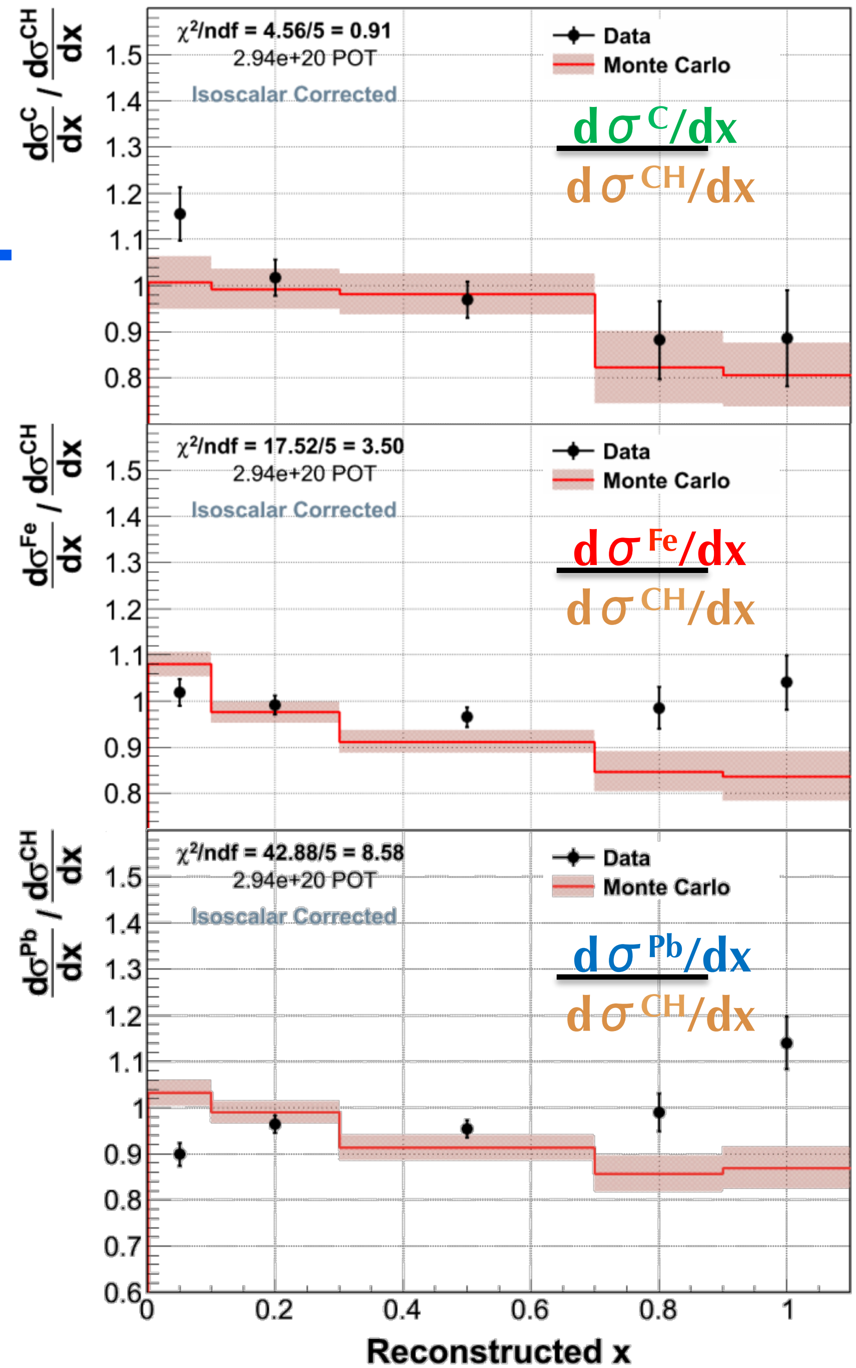
  - In the shadowing region at low-x, y is large and the σ are primarily probing the d- and s-quarks.
- This is very different from $l^{\pm}$ scattering where the d- and s-quarks are reduced by a factor of 4 compared to the u- and c-quarks.
  - If shadowing of the d- or s-quarks is negligible this would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



High x summary
INCLUSIVE RATIOS

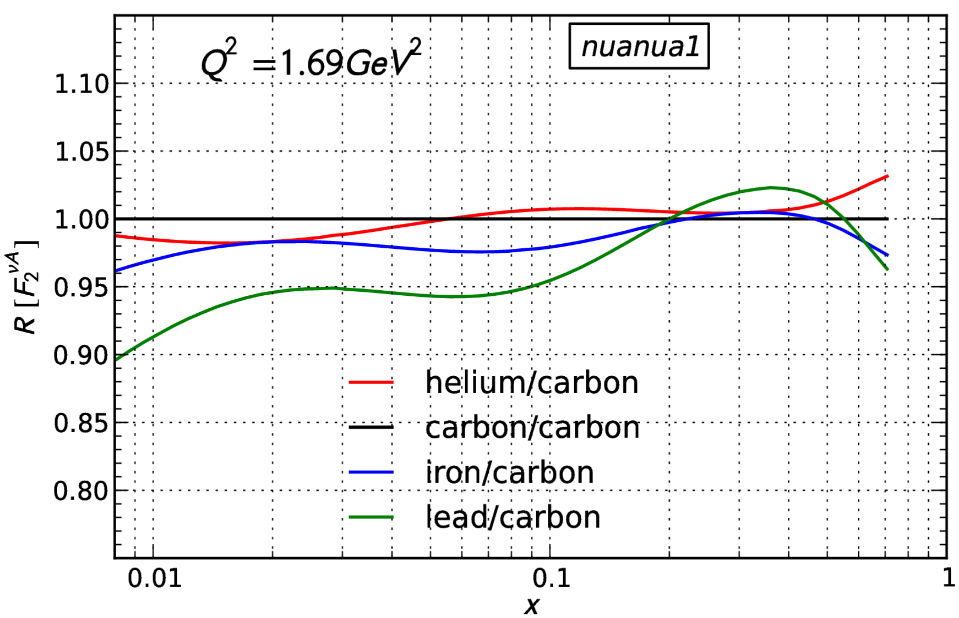
- At x = [0.7,1.1], we observe an **excess** that grows with the size of the nucleus
- This effect is not modeled in simulation

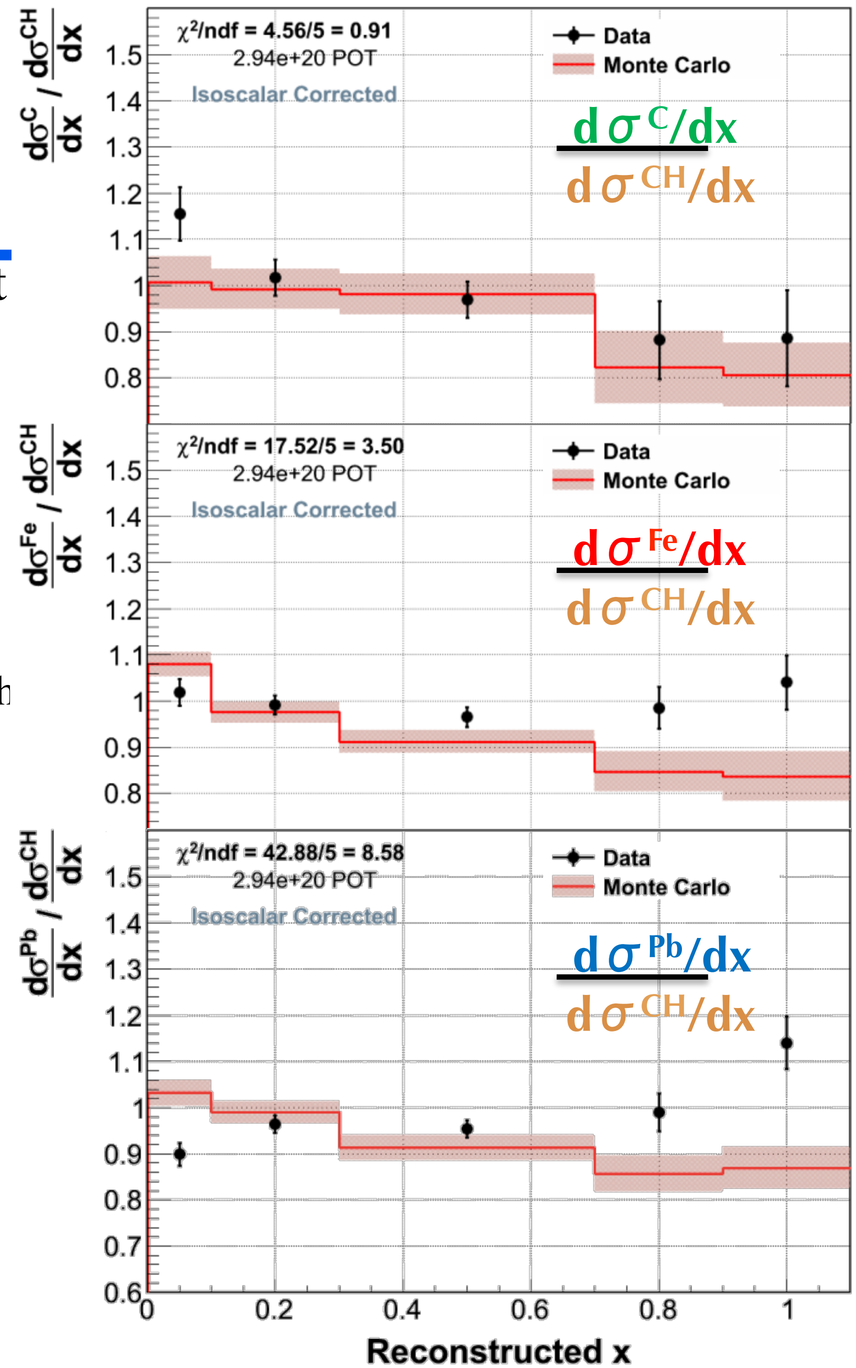




Low x summary
INCLUSIVE RATIOS

- At x = [0.0,0.1], we observe a **deficit** that increases
  with the size of the nucleus
- This effect is not modeled in simulation
- Expected Neutrino Differences
  - Neutrino sensitive to xF_3
  - Axial-vector current different coherence length





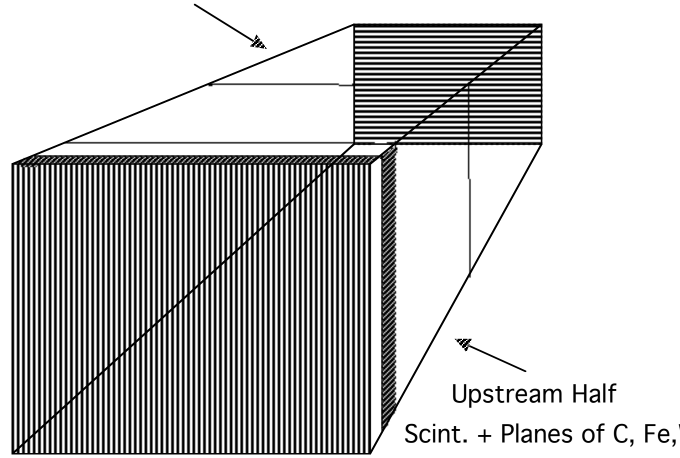
Before MINERνA there was MIDIS

and a High-energy Configuration of NuMI

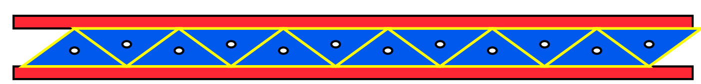
MIDIS: Central Detector, Conceptual Design

ANL: John Arrington, Roy Holt, Dave Potterveld and Paul Reimer - FNAL: JGM
Fermilab Bright Booster Study - Spring 2001

- 2m x 2 cm x 2cm scintillator (CH) strips with fiber readout.
- Fiducial volume: r = .8m L = 1.5:
  3 tons of scintillator
- Downstream half: pure scintillator
- Upstream half: scintillator plus 2 cm thick planes of C, Fe and W.
  - 11 planes C = 1.0 ton (+Scintillator)
  - 3 planes Fe = 1.0 ton (+MINOS)
  - 2 planes Pb = 1.0 ton
- Readout: mainly VLPC, perhaps also multi-anode PMT for TOF.
- Use MINOS near detector as muon identifier / spectrometer.



2.0 m x 2.0 m x 2.0 m long



Triangles:1 cm base and transverse segmentation.
Yields about 1 mm position resolution for mips
From D0 pre-shower test data

Shadowing - continued

- Why low x?
- The lifetime of the hadronic fluctuation has to be sufficient to allow for these multiple diffractive scatters:

$$t_c \approx 2E_{had} \,/\, (Q^2 + m^2)$$

- For a given Q^2 need large E_{had} to yield sufficient t_c which implies small x.
- m is larger for the vector current than the axial vector current → for a given Q^2 you need more E_{had} for the vector current than the axial vector current to have sufficient t_c.
- This implies you can have shadowing at higher x with neutrinos than with charged leptons

Conclusions

MINERνA performs a systematic study of nuclear medium modifications of hadronic structure using different nuclear targets in the same detector exposed to the same neutrino beam

First measurement of ratios of neutrino cross sections on nuclei in the DIS regime

Observe no significant E_ν dependences compared to theory

These measurements may be interpreted directly as *x* dependent nuclear effects

(GENIE assumes an *x* dependent effect from charged lepton scattering on nuclei)

** **In the EMC region ($0.3 < x < 0.7$) good agreement between data and models within errors**

** **In the lowest *x* bin ($x < 0.1$) MINERνA data suggests nuclear shadowing at an <x>** (0.07) **& $<Q^2>$** (2 GeV^2) **where negligible shadowing is expected with $l^\pm$.**

Data taking with a "Medium Energy" ν beam started in fall 2013

E_ν peak ~6 GeV, already more POT (6×10^{20}) than LE data taking

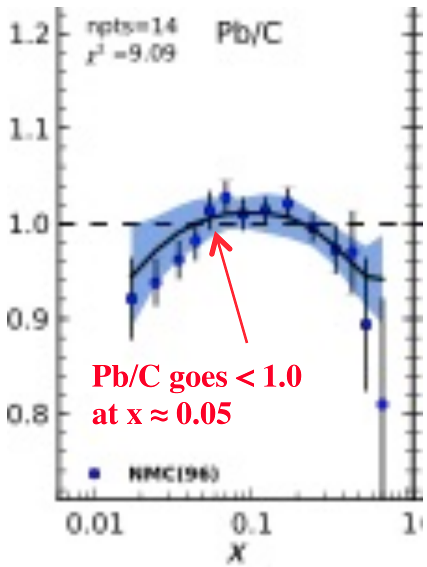
The higher neutrino beam energy allow us to access the DIS region and study quark distributions over a broad x_{Bj} range

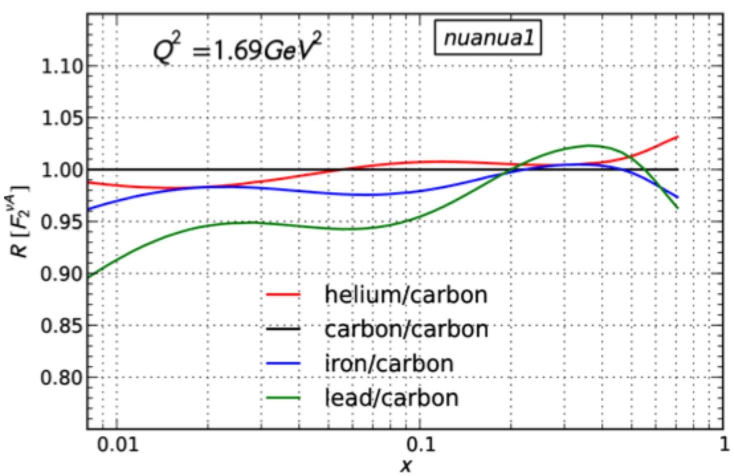
Increased statistics gives nuclear target ratios for all interactions

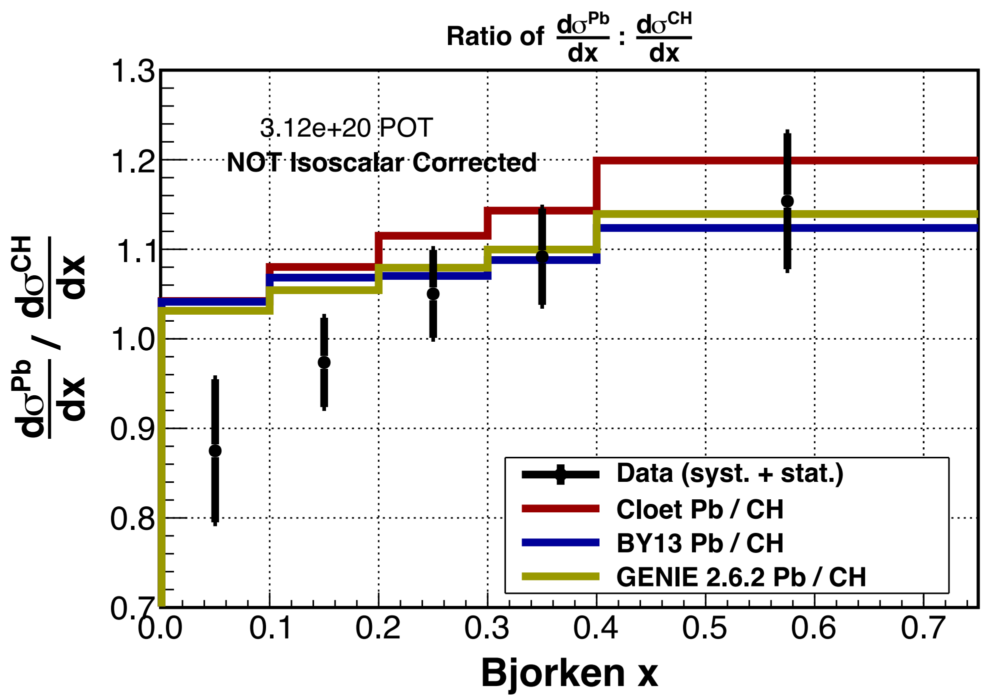
Others Do NOT Find this Difference between $l^{\pm}$ and ν

- 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.
- **What's next?**

Charged lepton F_2 Pb/C ratio & nCTEQ Prediction







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

- Functional form of the bound proton PDF same as for the free proton (~CTEQ6.1 [hep-ph/0702159], x restricted to 0 < x < 1)

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

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

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

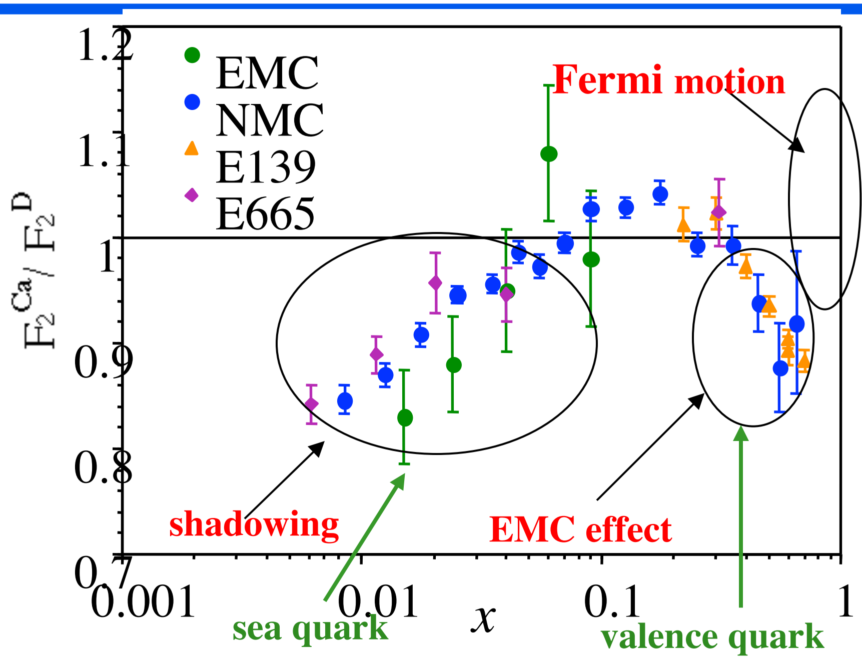
- PDFs for nucleus (A, Z)

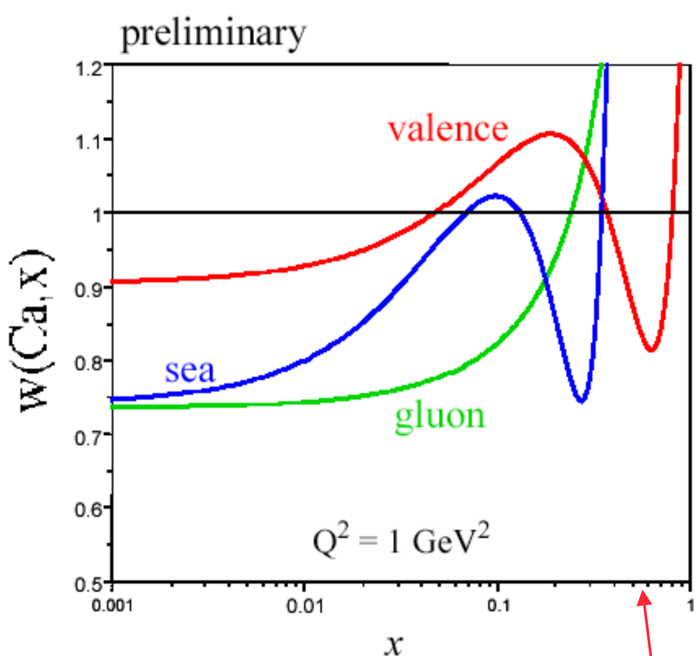
$$f_i^{(A,Z)}(x, Q) = \frac{Z}{A} f_i^{p/A}(x, Q) + \frac{A-Z}{A} f_i^{n/A}(x, Q)$$

  - Bound neutron PDFs $f_i^{n/A}$ by isospin symmetry

Now for Neutrinos

Experimental Studies of (Parton-level) Nuclear Effects with Neutrinos: limited to early Bubble Chamber studies and, now, MINERvA

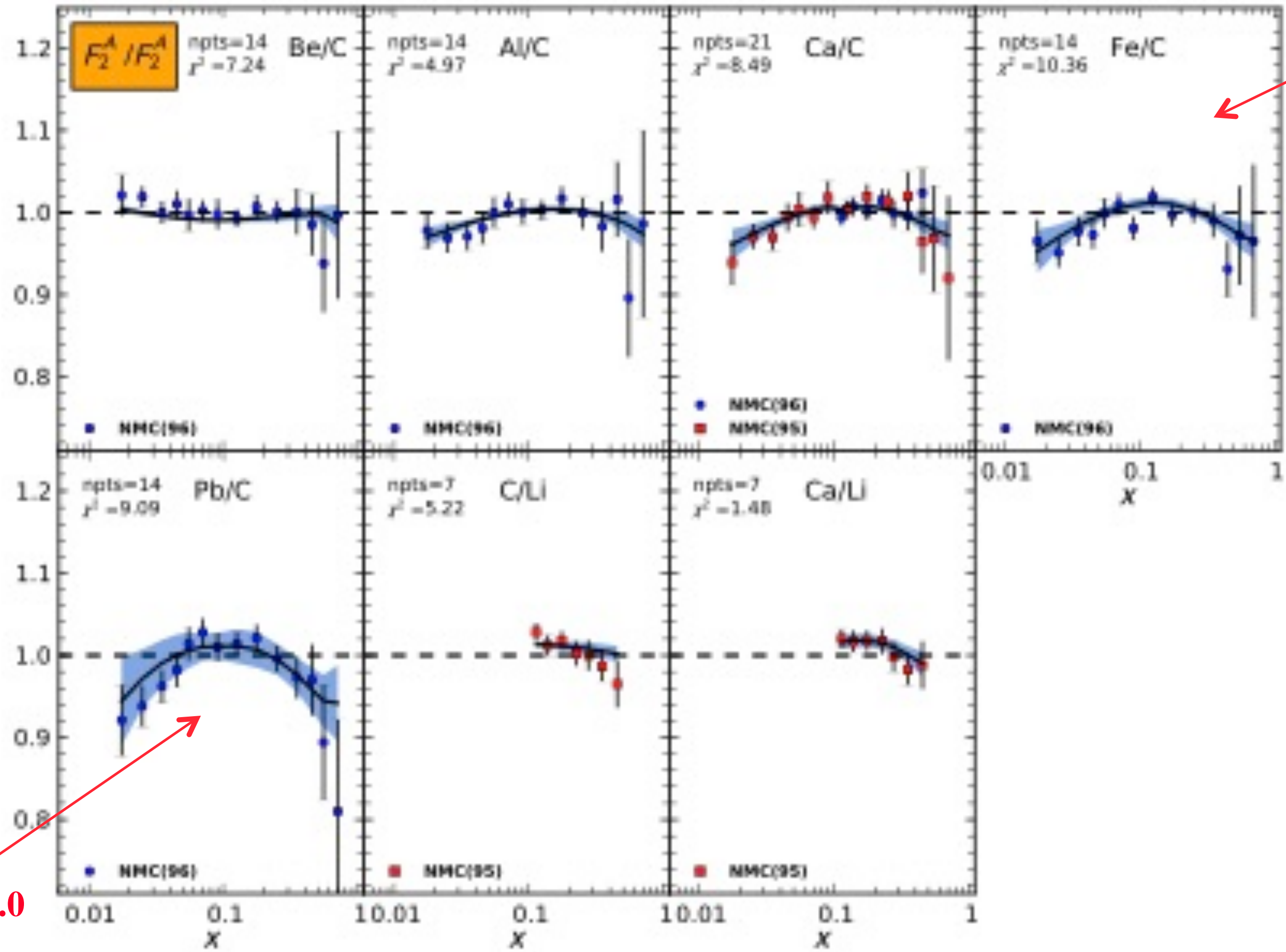




- F_2 / nucleon changes as a function of A. Measured in μ/e - A **not yet in ν − A**
- **Good reason to consider nuclear effects are DIFFERENT in ν - A**.
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**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

charged lepton F_2 ratios: continued

Fe/C goes < 1.0
at x ≈ 0.06



Pb/C goes < 1.0
at x ≈ 0.05