nCTEQ Parton Distributions

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

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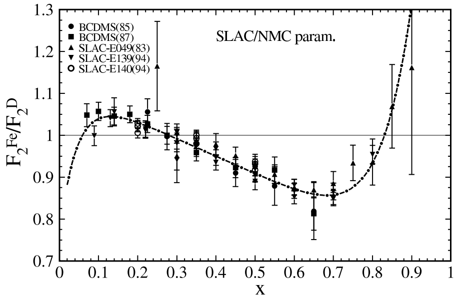
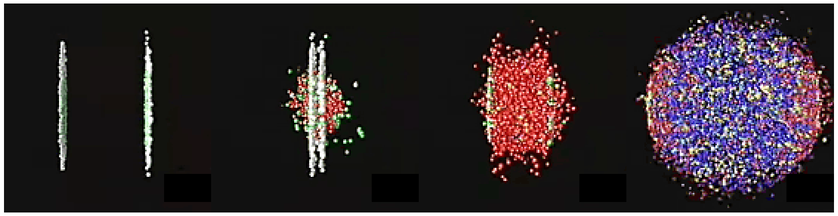
With thanks to A. Kusina for figures

Why do we need **nuclear** Parton Distribution Functions?

- What are PDFs of bound protons/neutrons?



- Heavy ion collisions in LHC and RHIC



- Differentiate flavors in free-proton PDFs (e.g. strange)

charged lepton DIS

$$F_2^{l^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d+s] + \left(\tfrac{2}{3}\right)^2 [u+c]$$

neutrino DIS

$$F_2^{\nu} \sim \left[d+s+\bar{u}+\bar{c}\right]$$
$$F_2^{\bar{\nu}} \sim \left[\bar{d}+\bar{s}+u+c\right]$$
$$F_3^{\nu} \sim 2\left[d+s-\bar{u}-\bar{c}\right]$$
$$F_3^{\bar{\nu}} \sim 2\left[u+c-\bar{d}-\bar{s}\right]$$

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 ∈ (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.

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]

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

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

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)

$$xf_i^{p/A}(x,Q_0) = x^{c_1}(1-x)^{c_2}e^{c_3x}(1+e^{c_4}x)^{c_5}, \qquad i = u_v, d_v, g, \ldots$$
$$\bar{d}(x,Q_0)/\bar{u}(x,Q_0) = x^{c_1}(1-x)^{c_2} + (1+c_3x)(1-x)^{c_4}$$

- 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)

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

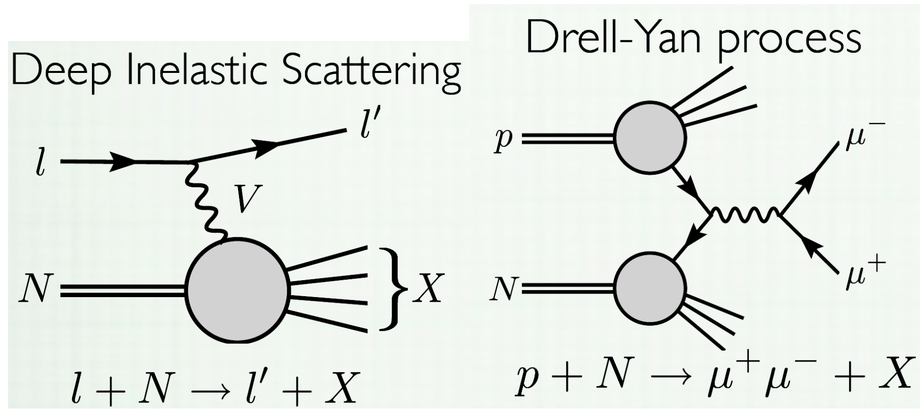
  - Bound neutron PDFs $f_i^{n/A}$ by isospin symmetry

Data Sets Used in this nCTEQ Analysis

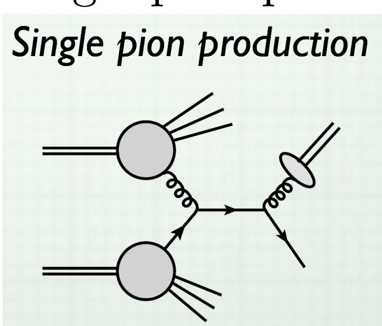
No Neutrino Data Here

- NC 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)



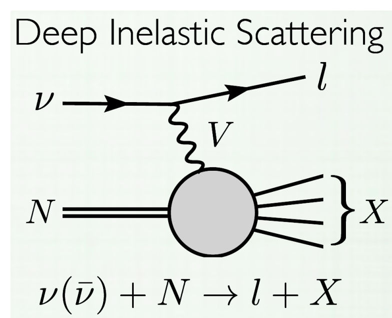
- Single pion production (new)



RHIC - PHENIX & STAR

N = Au

- Neutrino (to be included later)



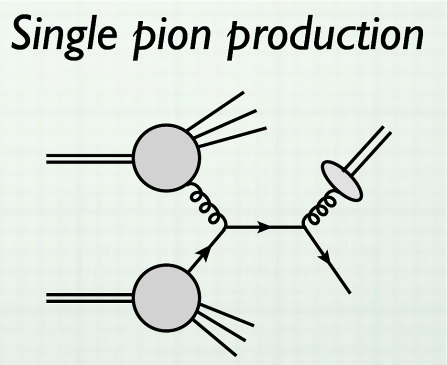
CHORUS CCFR & NuTeV

N = Pb N = Fe

Recently Added – single pion production

RHIC - PHENIX & STAR

(N = Au)



PHENIX Collaboration:

[Phys.Rev.Lett. 98 (2007) 172302, nucl-ex/0610036]

STAR Collaboration:

[Phys.Rev. C81 (2010) 064904, arXiv:0912.3838]

- Theory calculation:

  P. Aurenche, M. Fontannaz, J.-Ph. Guillet, B. A. Kniehl, M. Werlen

  [Eur. Phys. J. C13, 347-355, (2000), arXiv:hep-ph/9910252]

- Fragmentation functions:

  J. Binnewies, Bernd A. Kniehl, G. Kramer

  [Z. Phys. C65 (1995) 471-480, arXiv:hep-ph/9407347]

Fit Details

- Fit @ NLO with Q_0 =1.3GeV
- 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
- $\chi^2 = 611$, giving $\chi 2/\mathrm{dof} = 0.85$
- Error analysis – use Hessian method

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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

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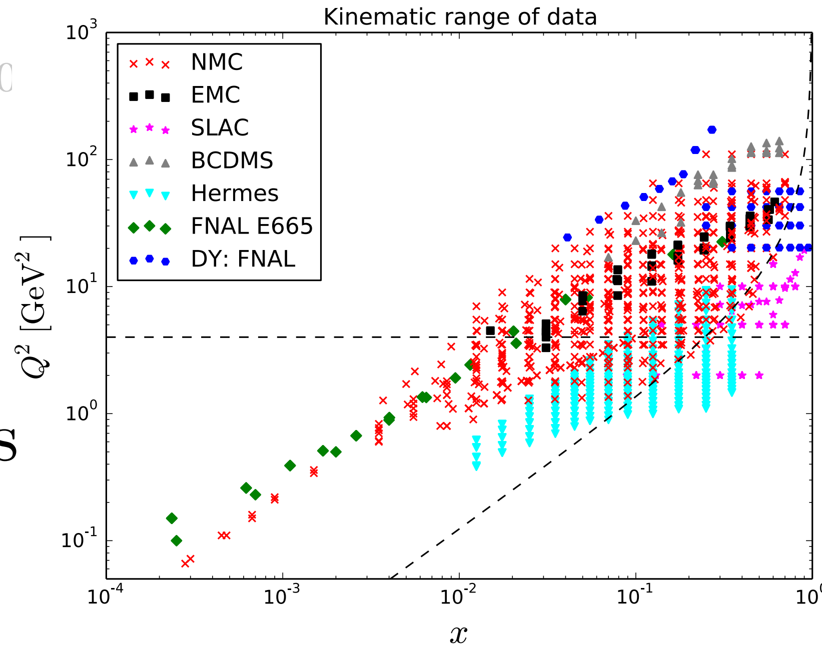
- **nCTEQ: 740** data points
- **EPS09: 929** data points

reducing derivatives



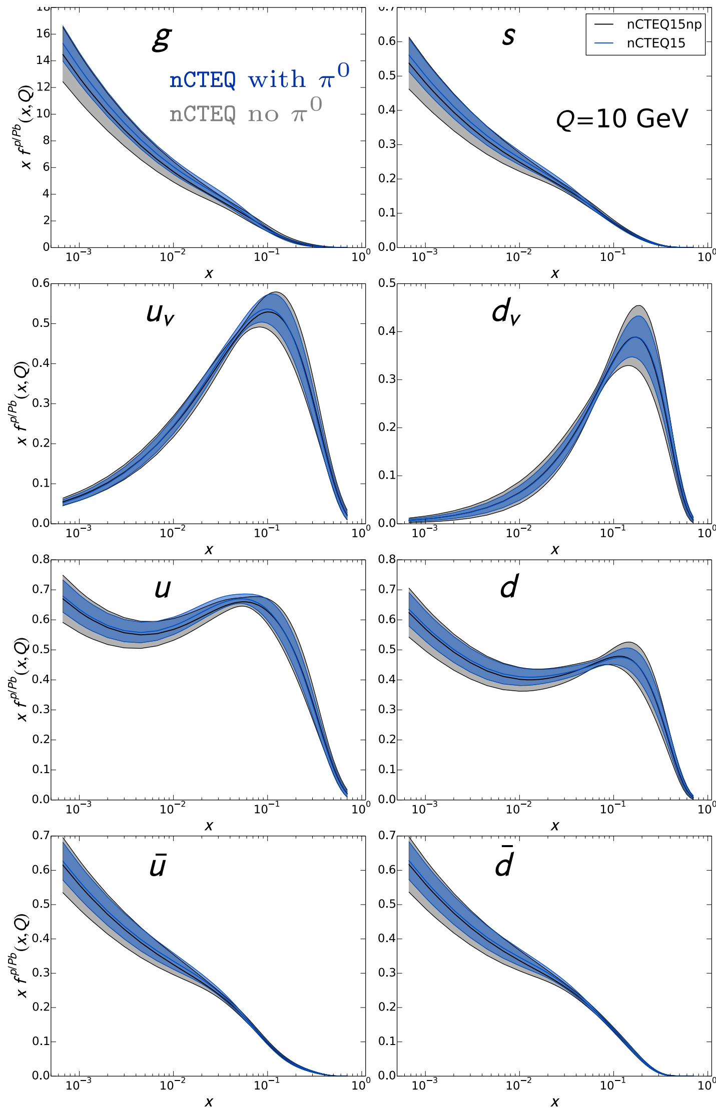
nCTEQ Results

Nuclear PDFs ($Q = 10$ GeV)

$$x f_i^{p/Pb}(x,Q)$$

Compare `nCTEQ` fits:

- `nCTEQ15` with π^0 data
- `nCTEQ15wp` without π^0 data



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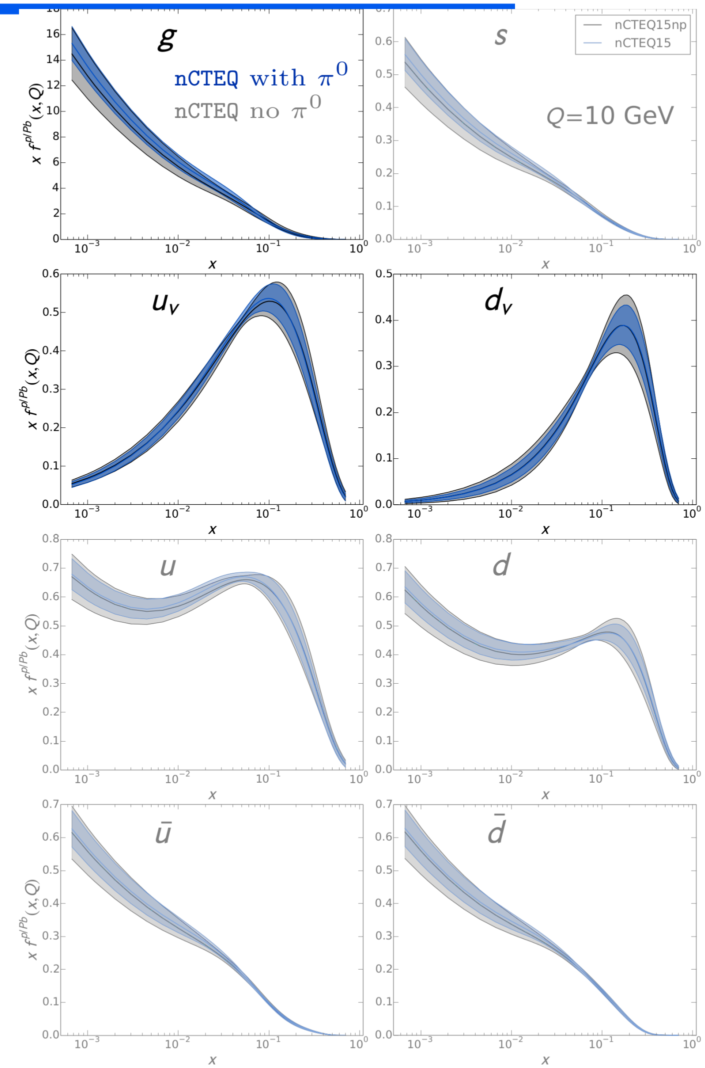

nCTEQ Results

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

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

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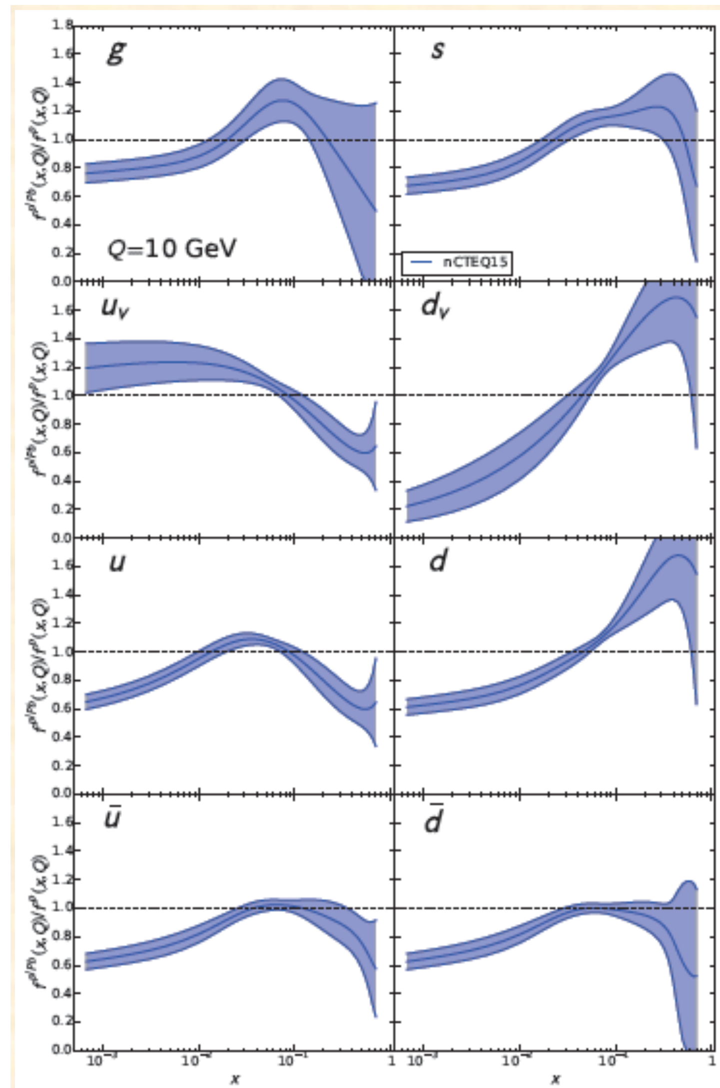

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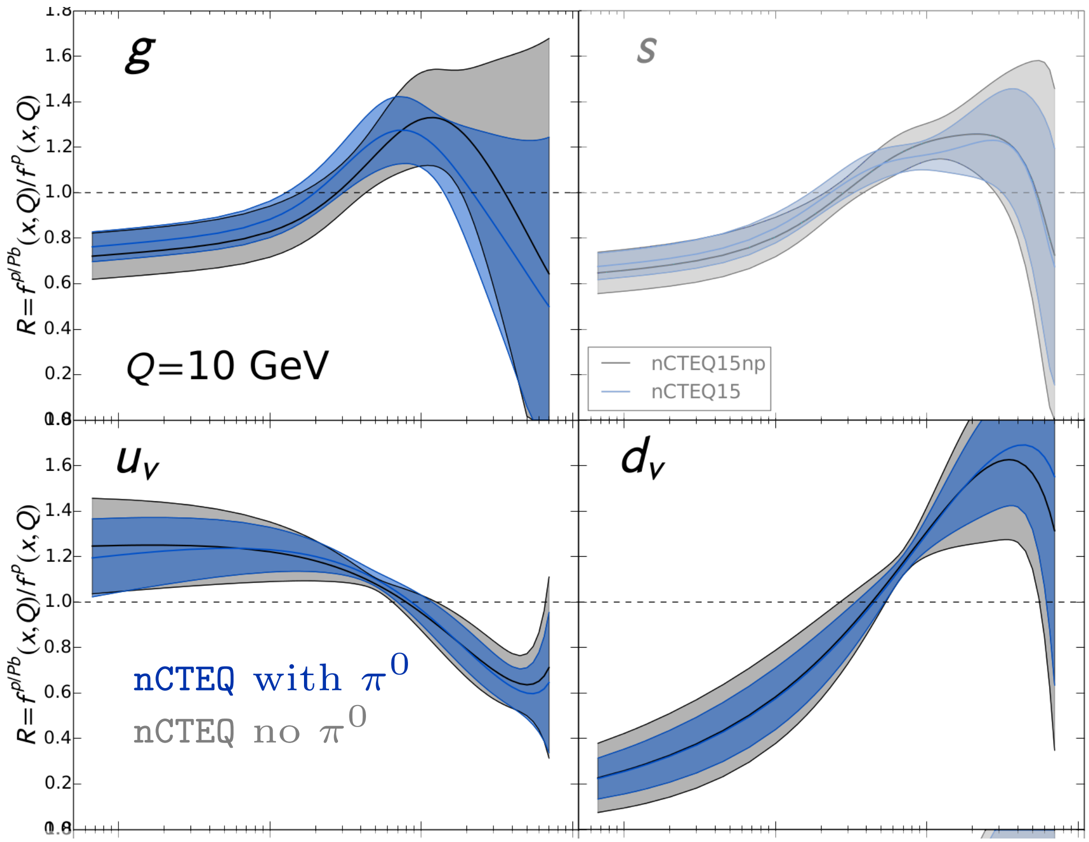

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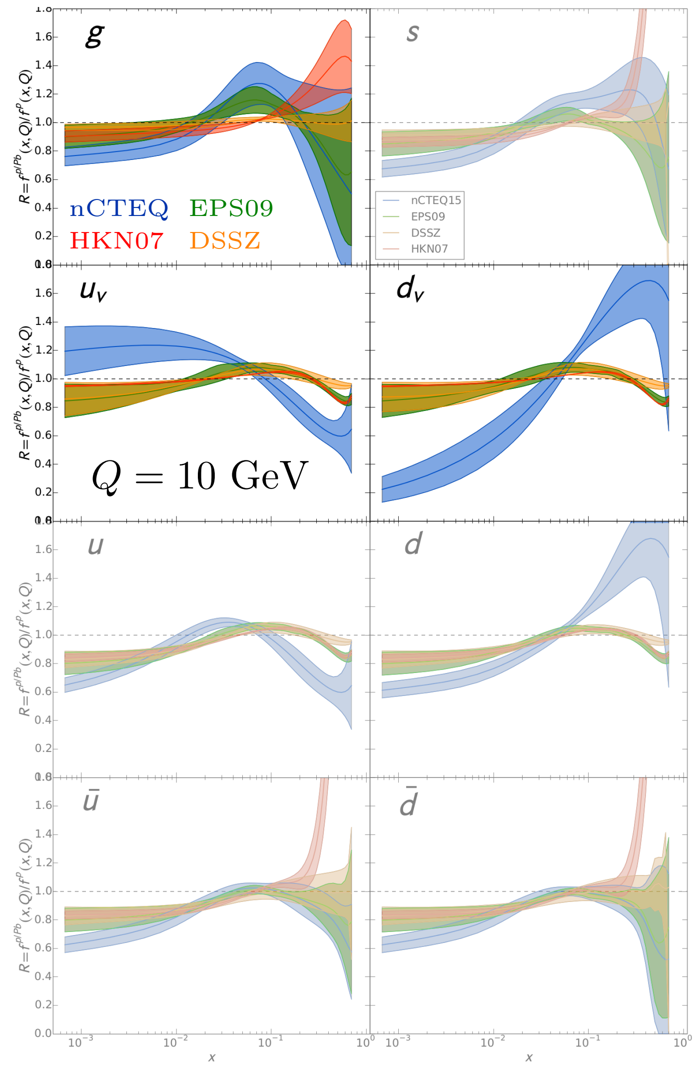
$$R_i(Pb) = \frac{f_i^{p/Pb}(x,Q)}{f_i^p(x,Q)}$$

- 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



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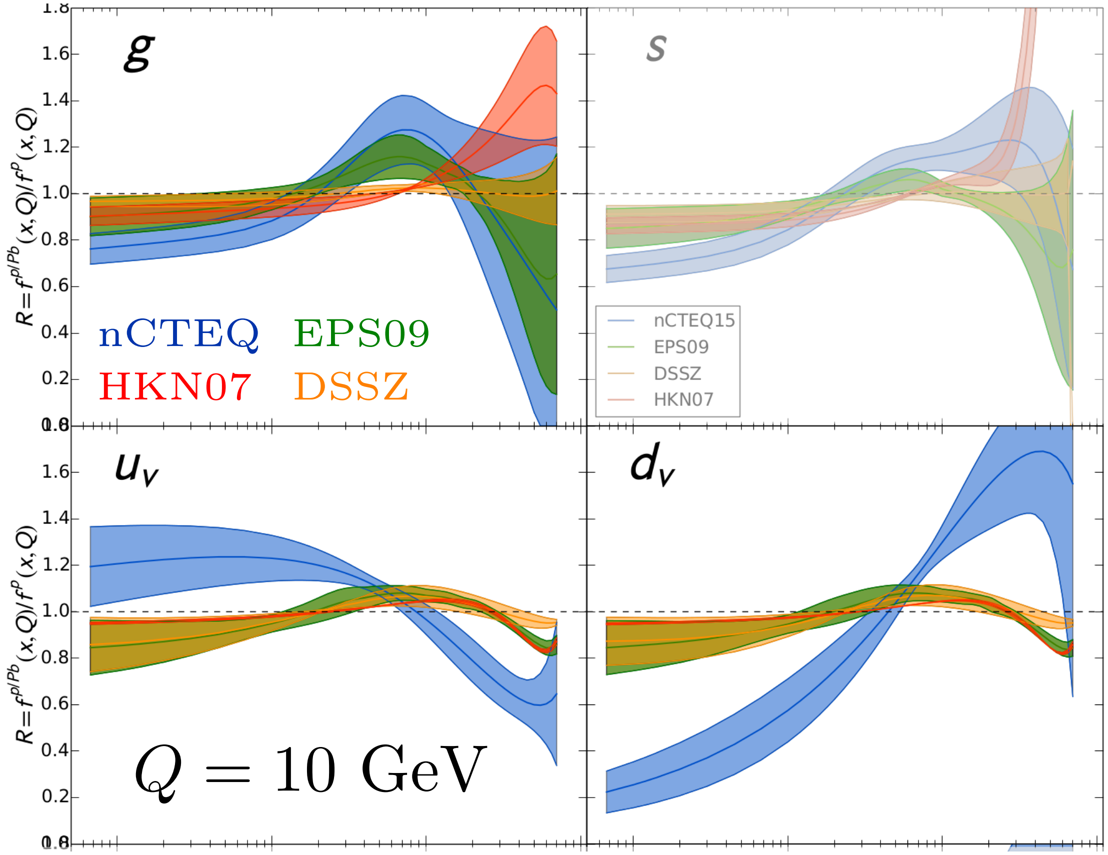


nCTEQ compared to EPS09 – u_v and d_v (same vs independent nuclear effects)

nCTEQ

$$xu_v^{p/A}(Q_0) = x^{c_1^u}(1-x)^{c_2^u} e^{c_3^u x}(1+e^{c_4^u}x)^{c_5^u}$$

$$xd_v^{p/A}(Q_0) = x^{c_1^d}(1-x)^{c_2^d} e^{c_3^d x}(1+e^{c_4^d}x)^{c_5^d}$$

$$c_k^{u_v} = c_{k,0}^{u_v} + c_{k,1}^{u_v}\left(1 - A^{-c_{k,2}^{u_v}}\right)$$

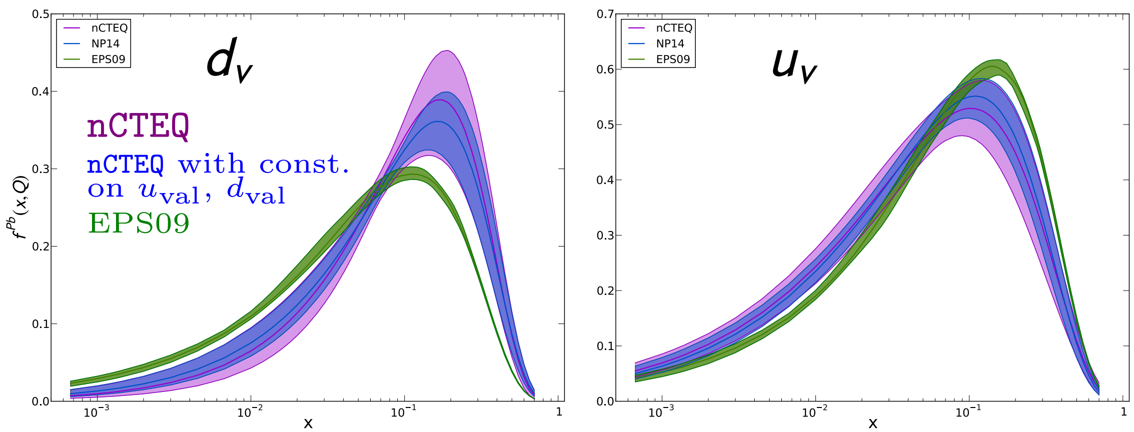
$$c_k^{d_v} = c_{k,0}^{d_v} + c_{k,1}^{d_v}\left(1 - A^{-c_{k,2}^{d_v}}\right)$$

EPS09

$$u_v^{p/A}(Q_0) = R_v(x, A, Z)\, u(x, Q_0)$$

$$d_v^{p/A}(Q_0) = R_v(x, A, Z)\, d(x, Q_0)$$

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



we set:

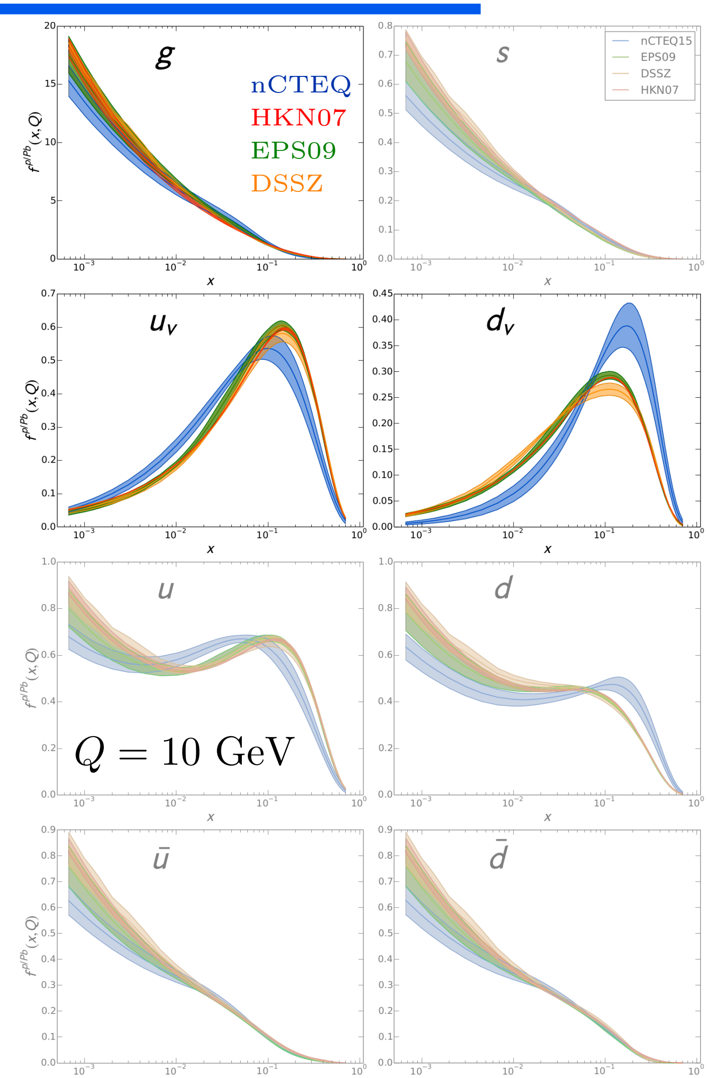
$$\begin{cases} c_1^{d_v} = c_1^{u_v} \\ c_2^{d_v} = c_2^{u_v} \end{cases}$$

nCTEQ Results

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

$$x\, f_i^{p/Pb}(x, Q)$$

- nCTEQ features larger uncertainties than previous nPDFs
- better agreement between different groups (nPDFs don't depend on proton baseline)

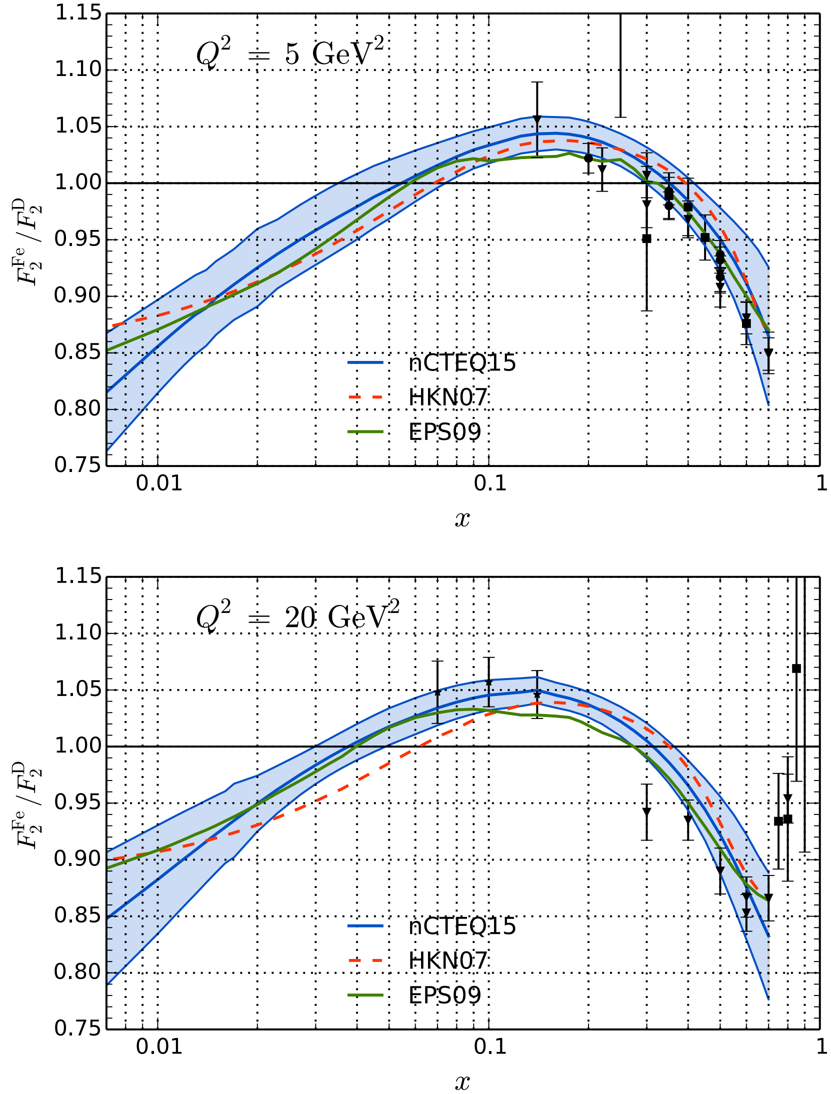


nCTEQ results: F_2 ratios

Structure function ratio

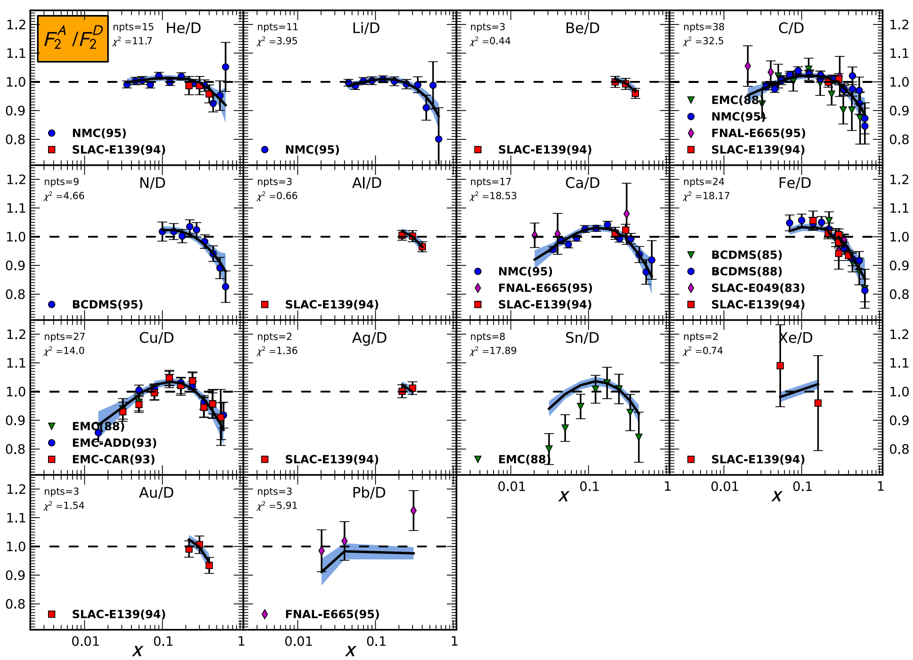
$$R = \frac{F_2^{Fe}(x,Q)}{F_2^D(x,Q)}$$

- good data description
- despite different u-valence & d-valence ratios are similar to EPS09



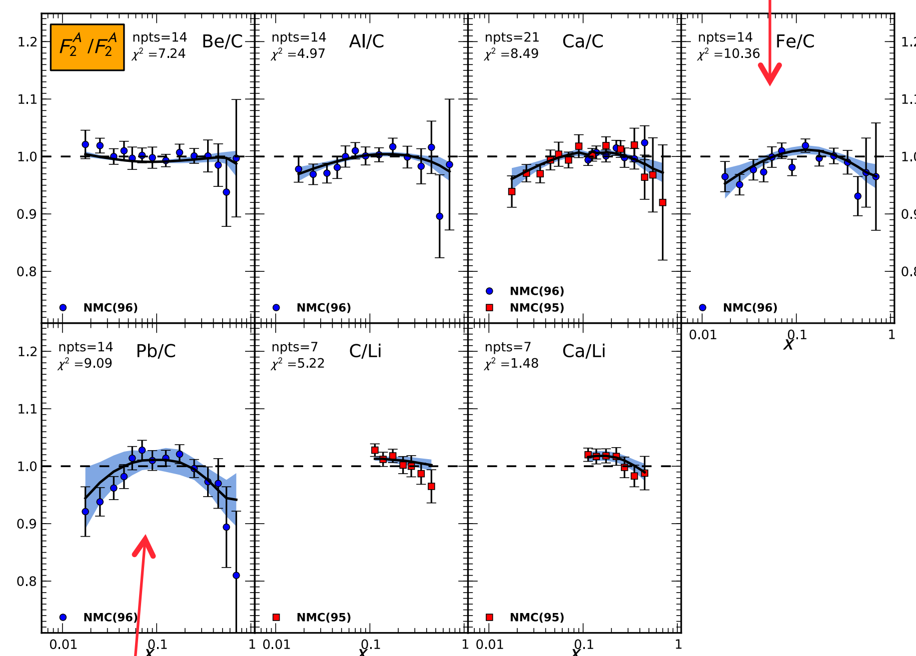
F_2 ratios: continued

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



$$R = \frac{F_2^A(x,Q)}{F_2^{A'}(x,Q)}$$

Fe/C goes < 1.0 at x ≈ 0.06

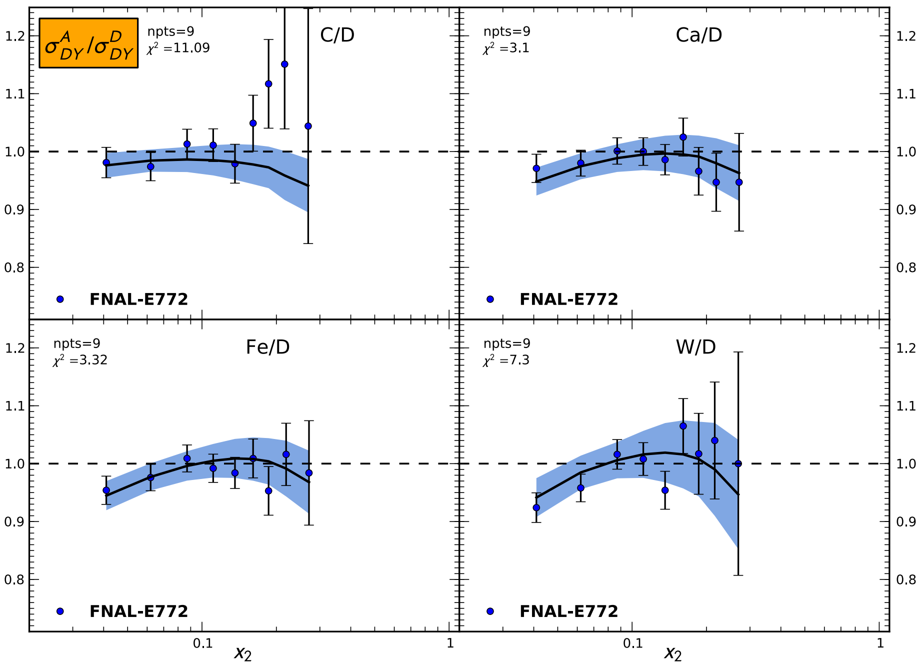


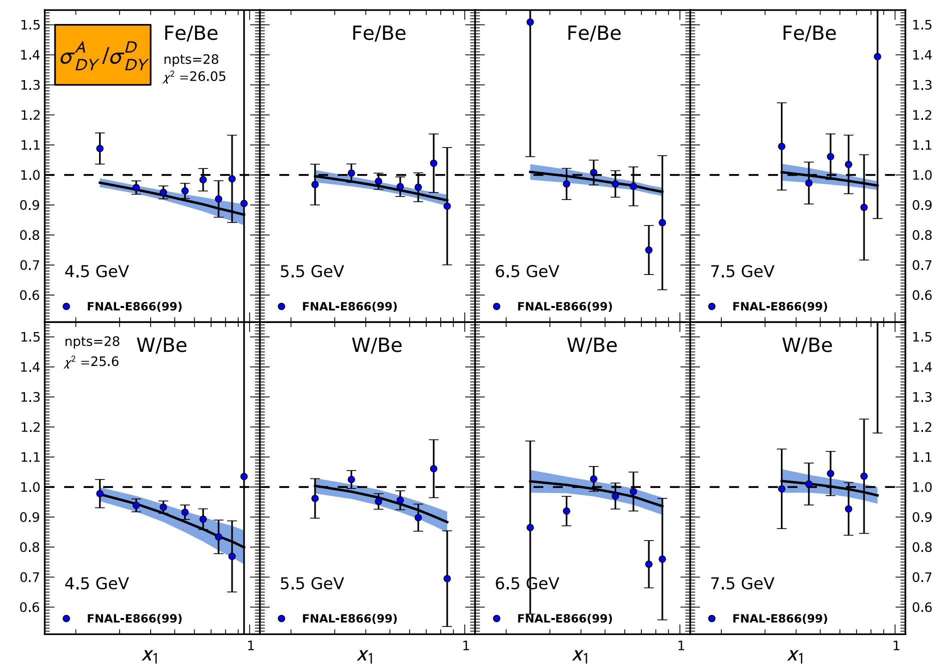
Pb/C goes < 1.0 at x ≈ 0.05

nCTEQ Results : Drell-Yan ratios

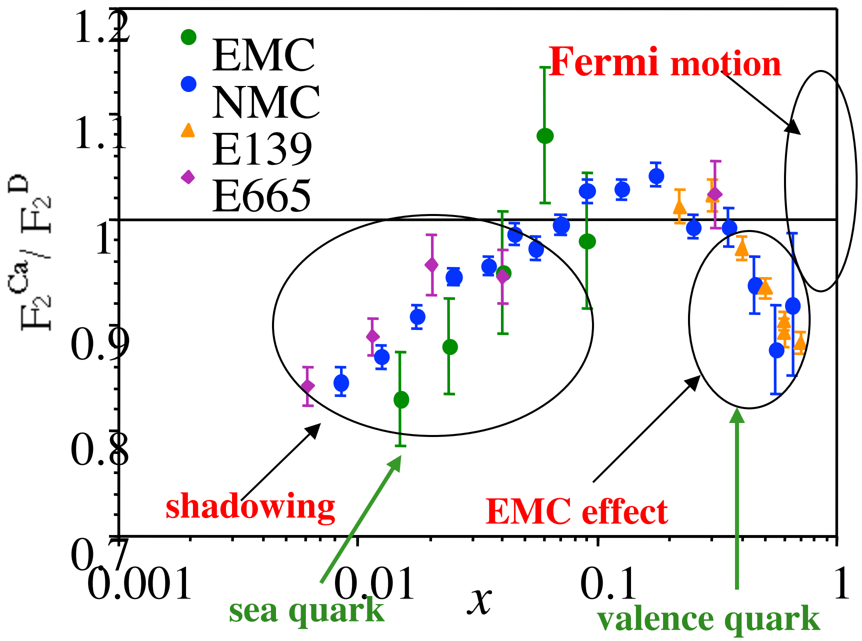
$$R = \frac{\sigma_{DY}^{A}(x,Q)}{\sigma_{DY}^{D}(x,Q)}$$

$$R = \frac{\sigma_{DY}^{A}(x,Q)}{\sigma_{DY}^{A'}(x,Q)}$$





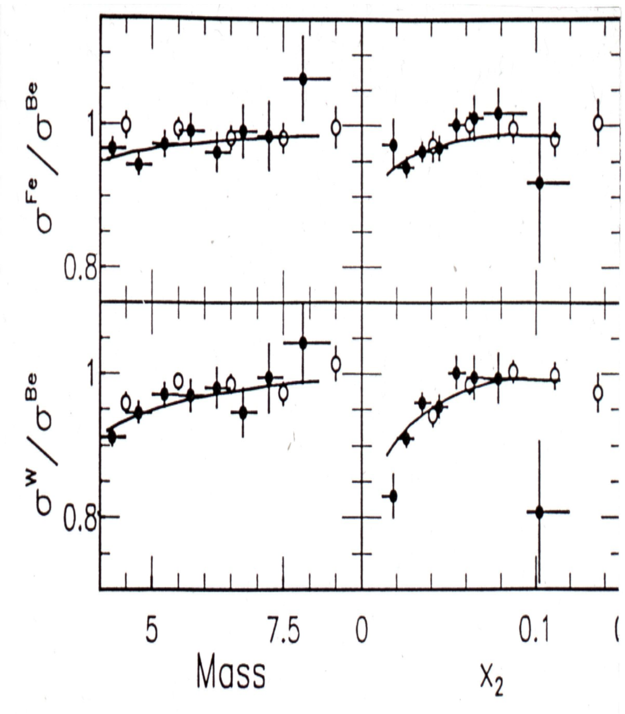
What about Neutrinos?

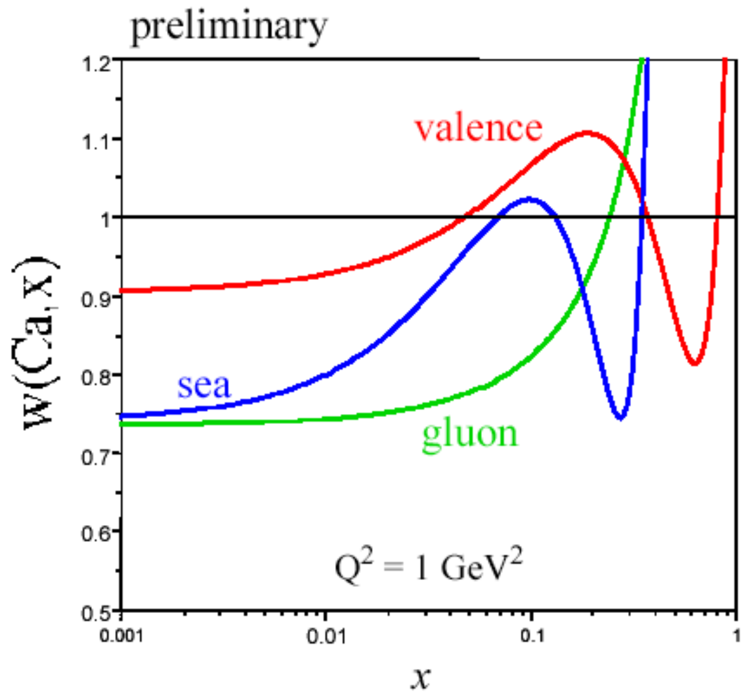


- **Good reason to consider nuclear effects are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **Different nuclear effects for valance and sea --> for example different shadowing for xF_3 compared to F_2.**

Nuclear Effects

A Difference in Nuclear Effects of Valence and Sea Quarks?





- Nuclear effects similar in Drell-Yan and DIS for x < 0.1. Then no "anti-shadowing" in D-Y while "anti-shadowing" seen in DIS (5-8% effect in NMC).

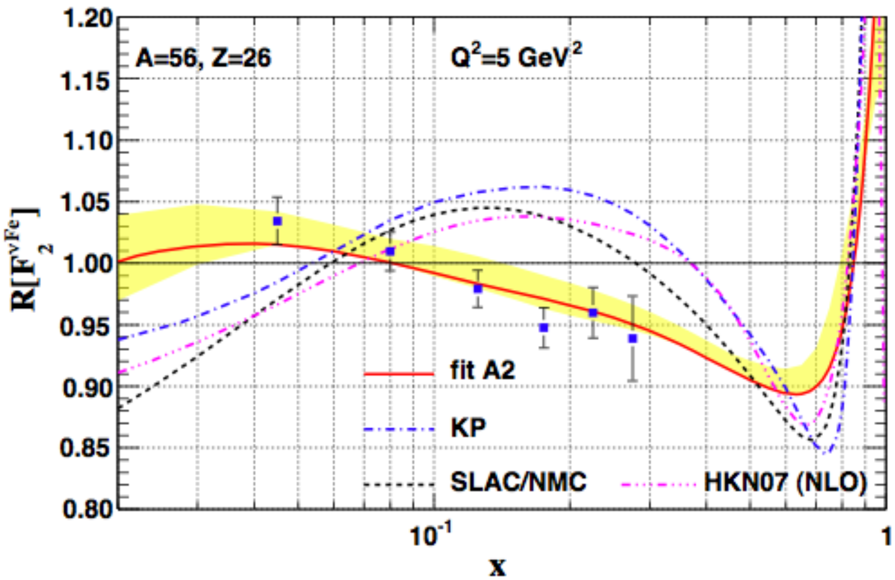
Neutrino: CTEQ vs. Other nPDF sets

- CTEQ uses the double differential cross sections NOT the structure functions F_2 and xF_3 that require additional theoretical assumptions to extract.

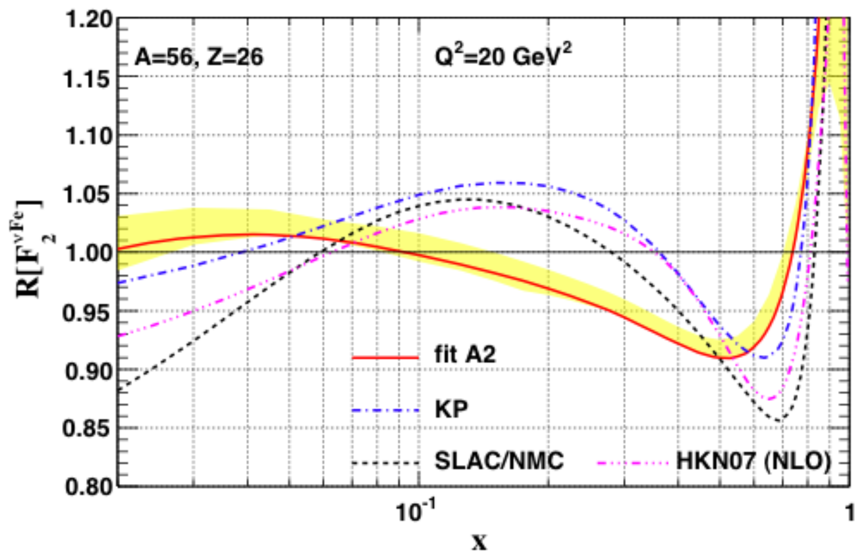
- CTEQ uses the full NuTeV covariant error matrix rather than adding systematics and statistical errors in quadrature.

- Use **8 Neutrino data sets**
  - NuTeV cross section data: $\nu\ Fe,\ \nu\ Fe$
  - NuTeV dimuon off Fe data
  - CHORUS cross section data: $\nu\ Pb,\ \nu\ Pb$
  - CCF*R* dimuon off Fe data

F_2 Structure Function Ratios: ν-Iron



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



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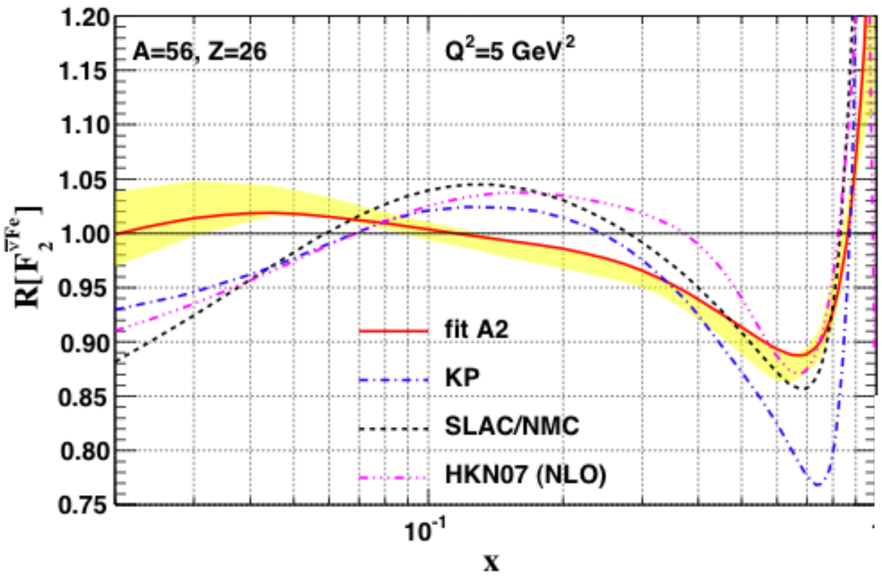

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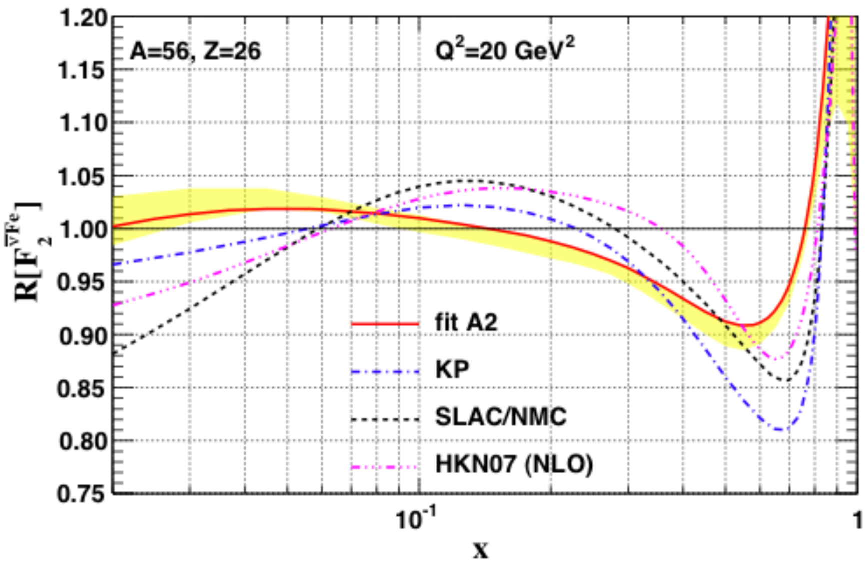
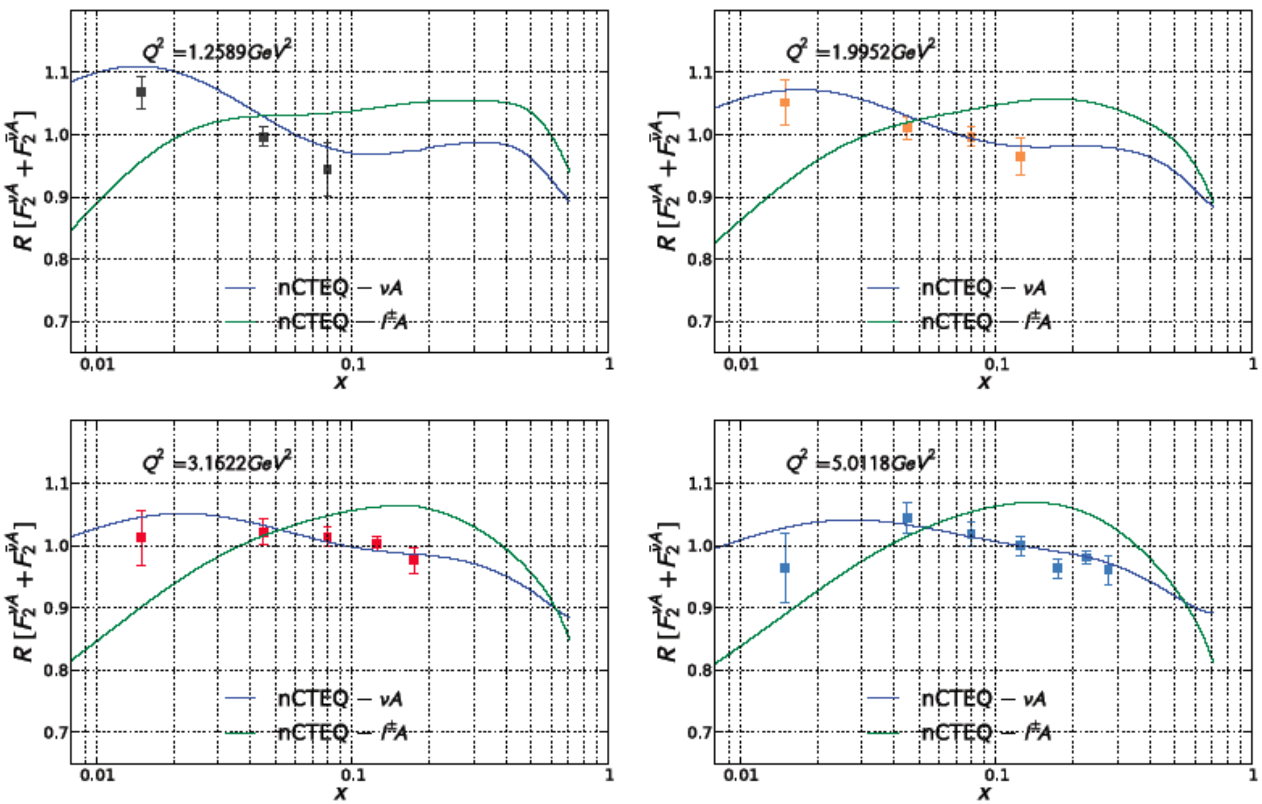


A More-Detailed Look at Differences

- NLO QCD calculation of $\dfrac{F_2^{\nu A}+F_2^{\bar{\nu} A}}{2}$ 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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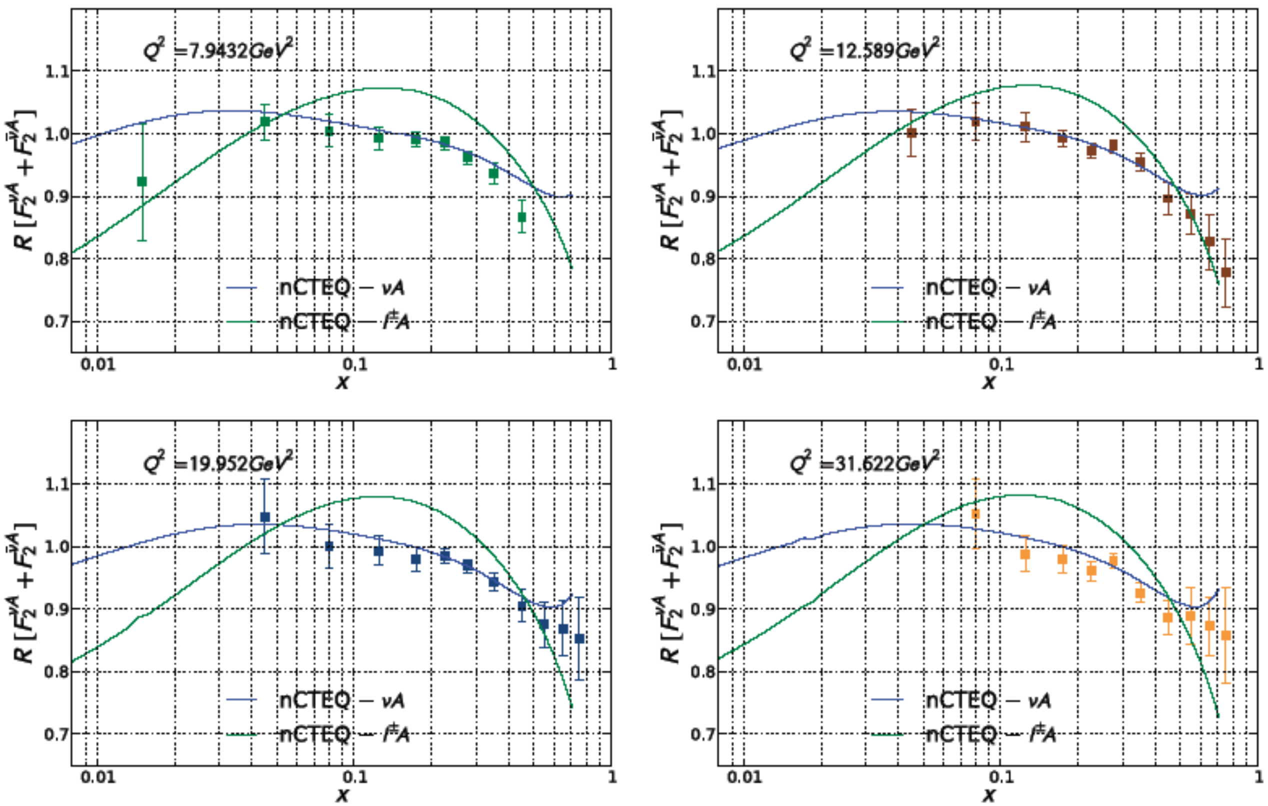
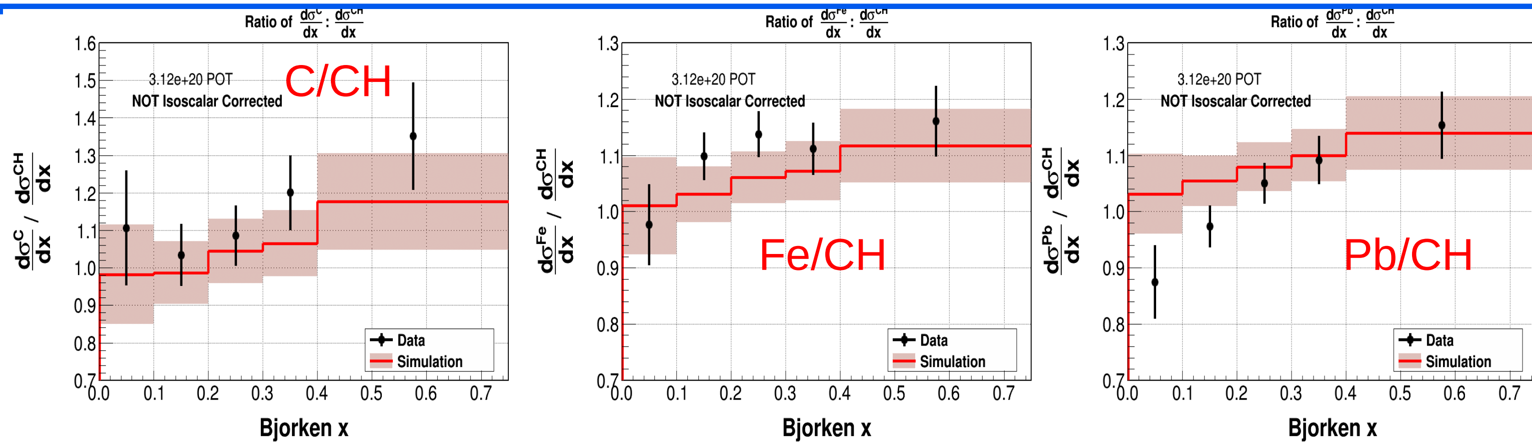


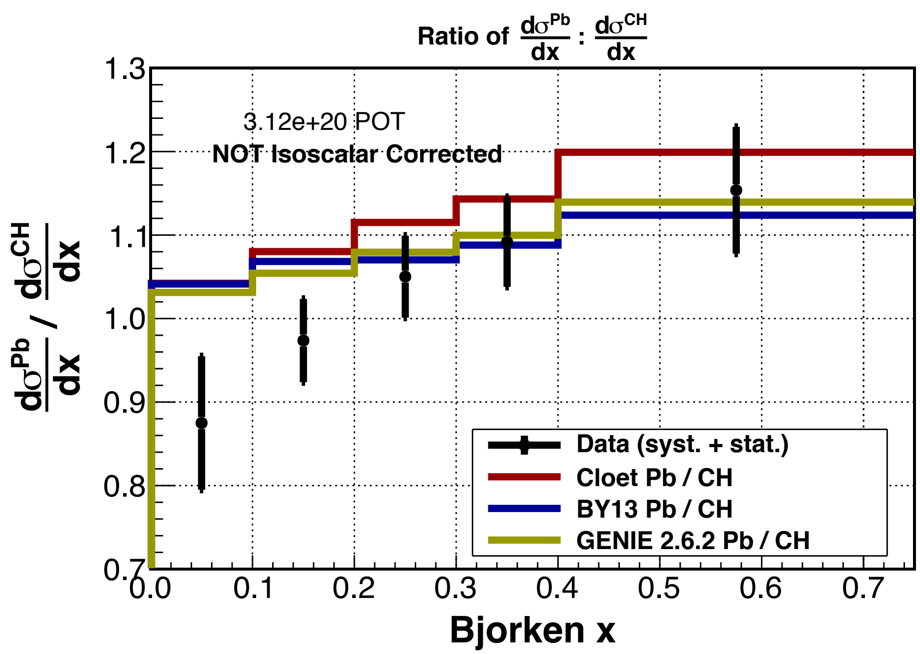
We Now Have A New DIS Player - What does MINERvA see?

DIS Cross Section Ratios – $d\sigma/dx$



J. Mousseau

- The shape of the data at low x, especially with lead is consistent with additional nuclear shadowing. **at an <x>** (0.07) **& <Q^2 >** (2 GeV^2) - **where negligible shadowing is expected with l±.**

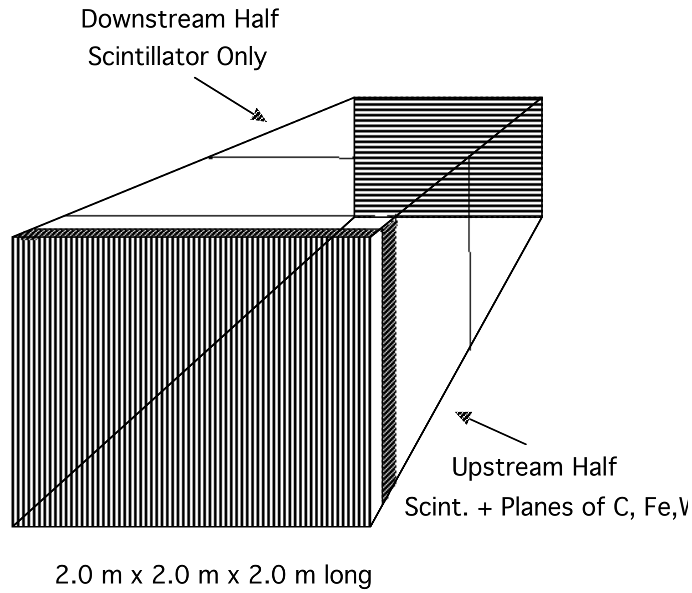


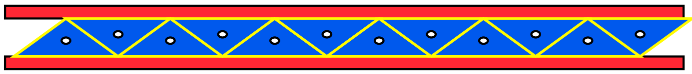
Before MINERνA there was MIDIS
and a High-energy Configuration of NuMI

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.



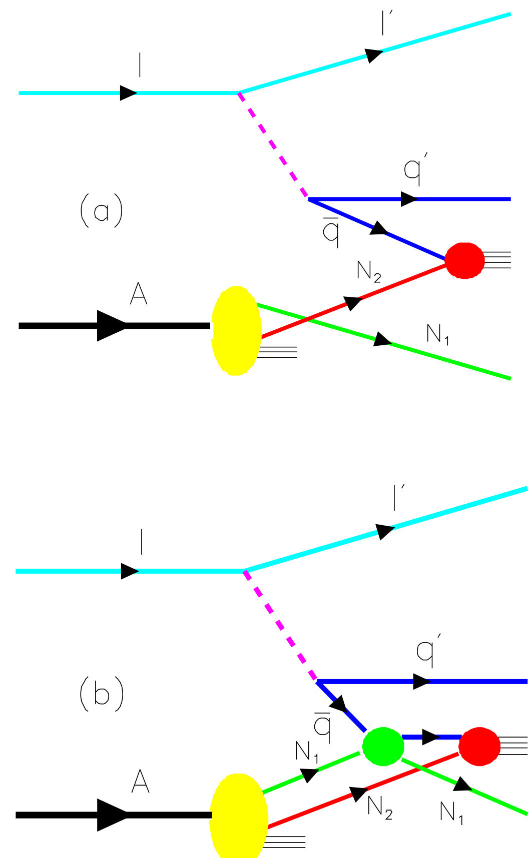


Triangles:1 cm base and transverse segmentation.
Yields about 1 mm position resolution for mips
From D0 pre-shower test data

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

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

- Several theoretical models successfully describe the shadowing effects observed in charged-lepton nucleus scattering.
- Most 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 multiple scatters interfere destructively leading to no flux making it to downstream nucleons resulting in a depletion of cross section at low values of x.



Shadowing - continued

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

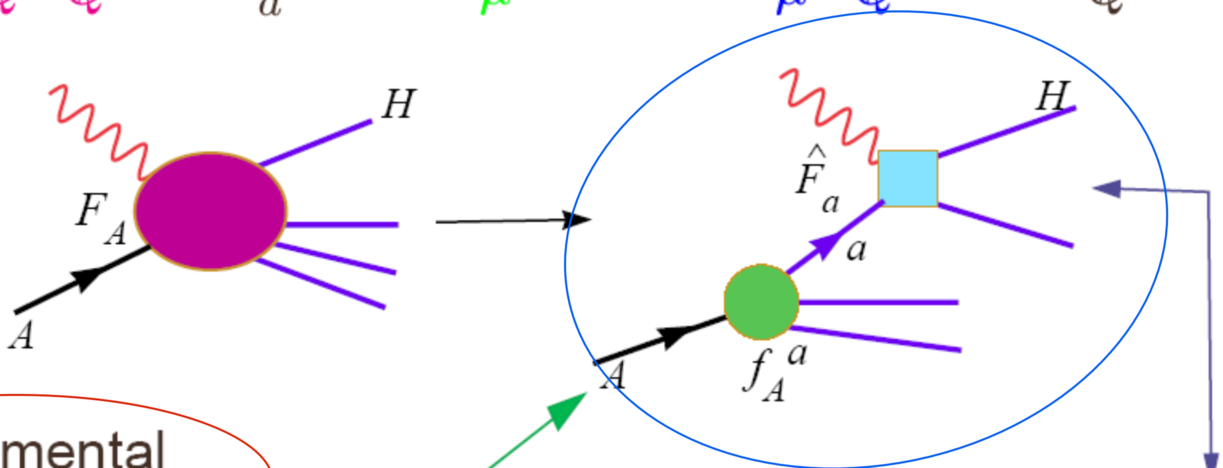
$$t_c = 2E_{had} \,/\, (Q^2 + m^2)$$

- 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 $\rightarrow$ 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

Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model
– the Factorization Theorem

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



Experimental Input

Theoretical Calculations

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

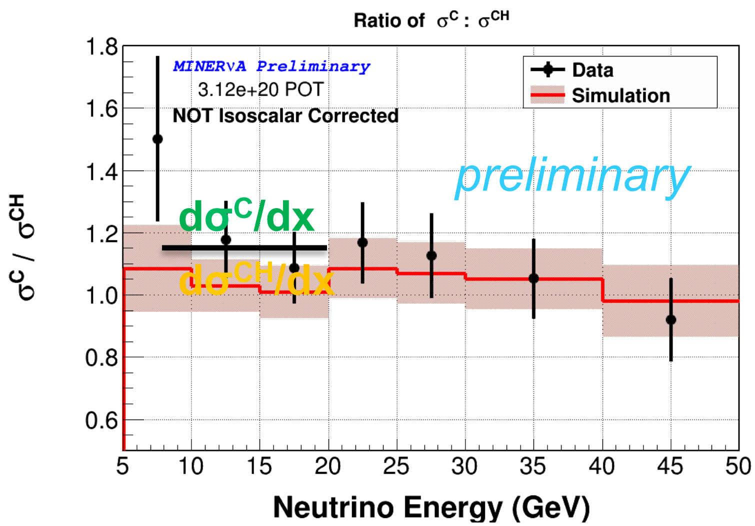
What do the concepts of "factorization" and "universal (nuclear) parton distributions" mean in the nuclear environment?

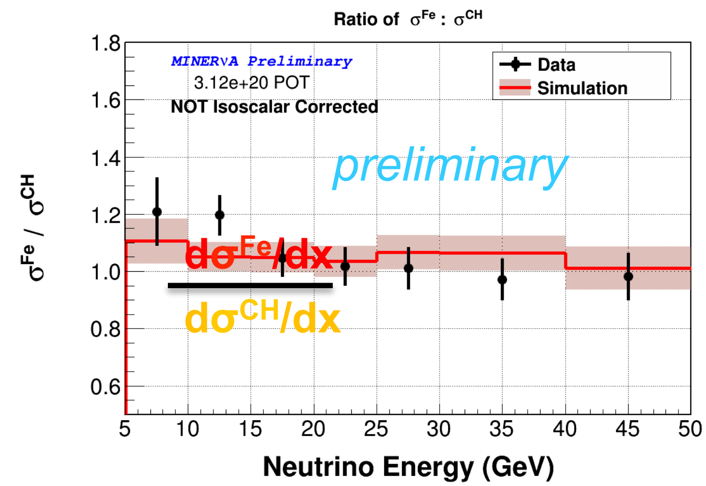
Summary and Conclusions

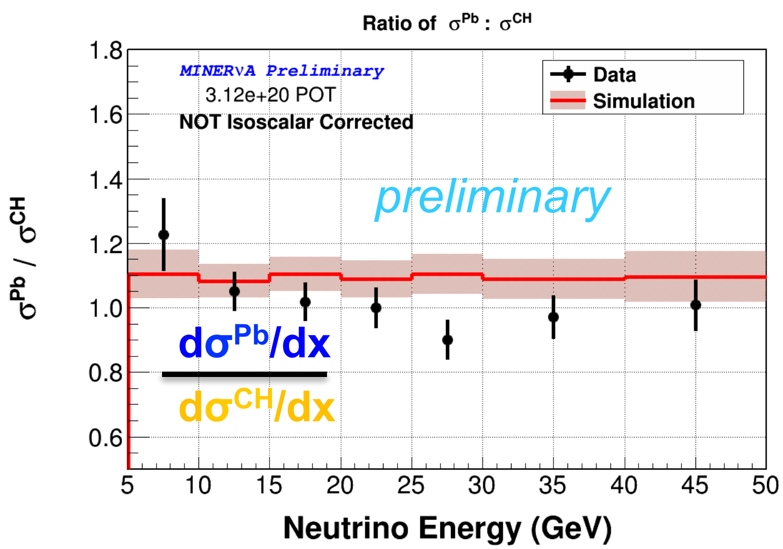
- We have updated the nCTEQ nuclear PDFs and errors w/o neutrino:
  (Referee comments on our full PRD article received yesterday!)
- In spite of our very different valence quark distributions compared to other nPDF fits – we fit u_v and d_v separately - we have good fits to data. Update: re-evaluation of fit suggests we do not yet have sufficient data to say separate u_v and d_v give a better fit!
- Our study suggests that uncertainties on these nPDF fits are underestimated.
- We are turning back to neutrino nPDFs with extended data sets.
- Our current nPDFs from neutrino data inconsistent with charged lepton nPDFs.
- The very first MINERvA results on nuclear target ratio are not yet statistically significant but promising! (Pb/CH) at $x < 0.1$ is consistent with shadowing at a higher x than would be expected with $l^{\pm}$.

Backup

DIS Cross Section Ratios – dσ/dE







DIS cross section ratios on C, Fe, and Pb compared to CH as a function of E_ν

"Simulation" based on nuclear effects observed with electromagnetic probes

Ratios of the heavy nuclei to lighter CH are evidence of nuclear effects

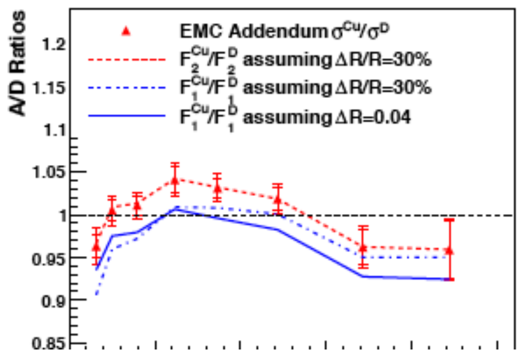
Observe no neutrino energy dependent nuclear effect

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 1207.013

  - 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 (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_ν are primarily probing the d- and s-quarks. If shadowing of the d and/or s quark negligible could contribute to the result.

Combined Analysis of ν A, ℓA and DY data

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

- Take an 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)**.

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

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:

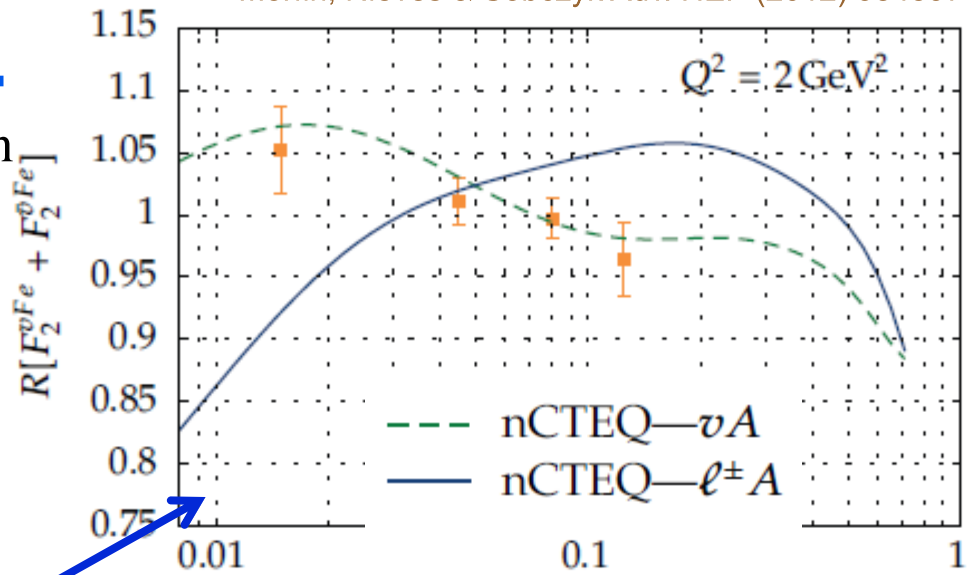
The 2nd fit χ^2 should be within the 90% C.L. region of the first fit χ^2

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

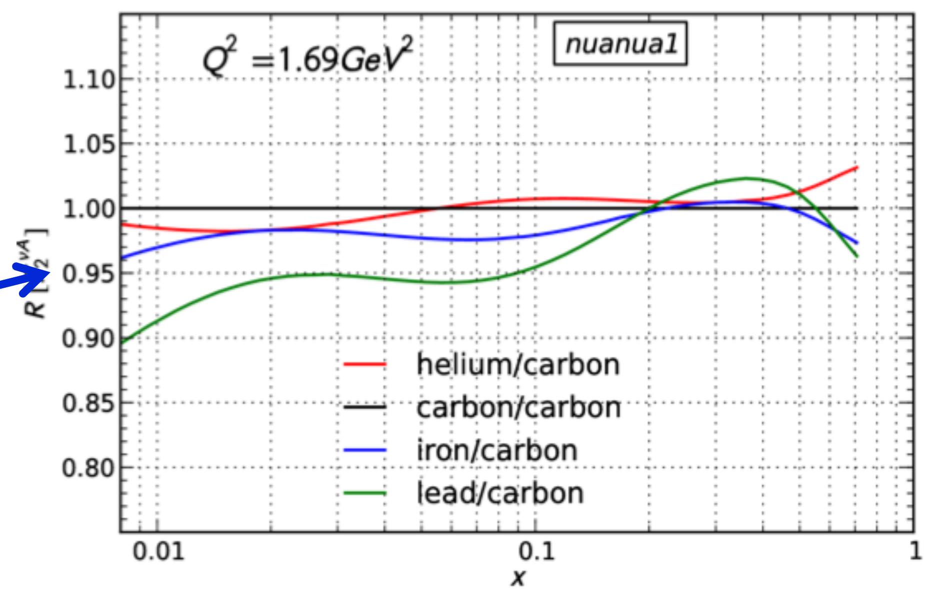
Weight	Fit name	ℓ data	χ^2	ν data	χ^2	total χ^2 (/pt)
$w = 0$	decut3	708	639	-	nnnn **NO**	639 (0.90)
$w = 1/7$	glofac1a	708	645 **YES**	3134	4710 **NO**	5355 (1.39)
$w = 1/4$	glofac1c	708	654 **YES**	3134	4501 **NO**	5155 (1.34)
$w = 1/2$	**glofac1b**	708	680 **YES**	3134	4405 **NO*** **	5085 (1.32)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

CTEQ Predictions for MINERνA

Morfin, Nieves & Sobczyk Adv. HEP (2012) 934597



Kovarik PRL106 (2011) 122301



General strategy has been to adapt electron scattering effects into neutrino scattering theory.

Neutrino event generators rely on measurements from charged leptons

CTEQ fit for neutrino nuclear effects by comparing NuTeV structure functions on iron to predicted "n+p" structure functions. Compared to predictions from l± scattering.

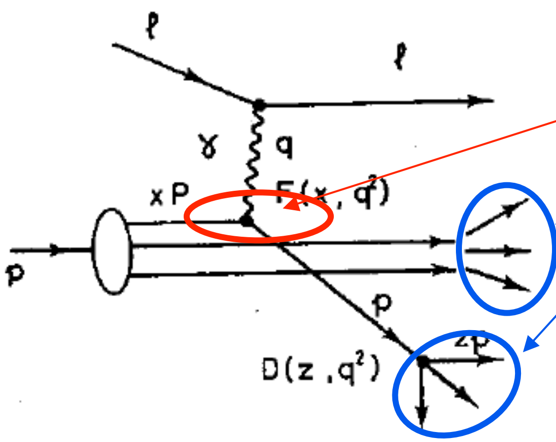
CTEQ prediction for the structure function ratios MINERνA can measure 5% to 10% effects predicted for Pb / C.

Should be also studied using deuterium targets!

DIS Formalism

- QCD Factorization means that we can treat the scattering and later processes separately, they occur on very different timescales:

$$A(l+h \rightarrow l+X) = \sum_q \int dx A(l+q(x) \rightarrow l+X) q_h(x)$$



hard scatter: fast

fragmentation: slow

Justification for summing probabilities rather than amplitudes for ν−q scattering.

Justification for QCD factorization and other aspects of the parton model come from formal approaches, namely the operator product expansion of the hadronic tensor.

What about Neutrinos?

- After improving methods for nuclear parton function extraction using charged-lepton and Drell-Yan data we will turn back to nuclear parton distributions from neutrino nucleus scattering.

- Will include CCFR, CDHSW and MINERvA results in addition to the NuTeV and CHORUS results already included.

- We are starting from our published values shown several times at this workshop.