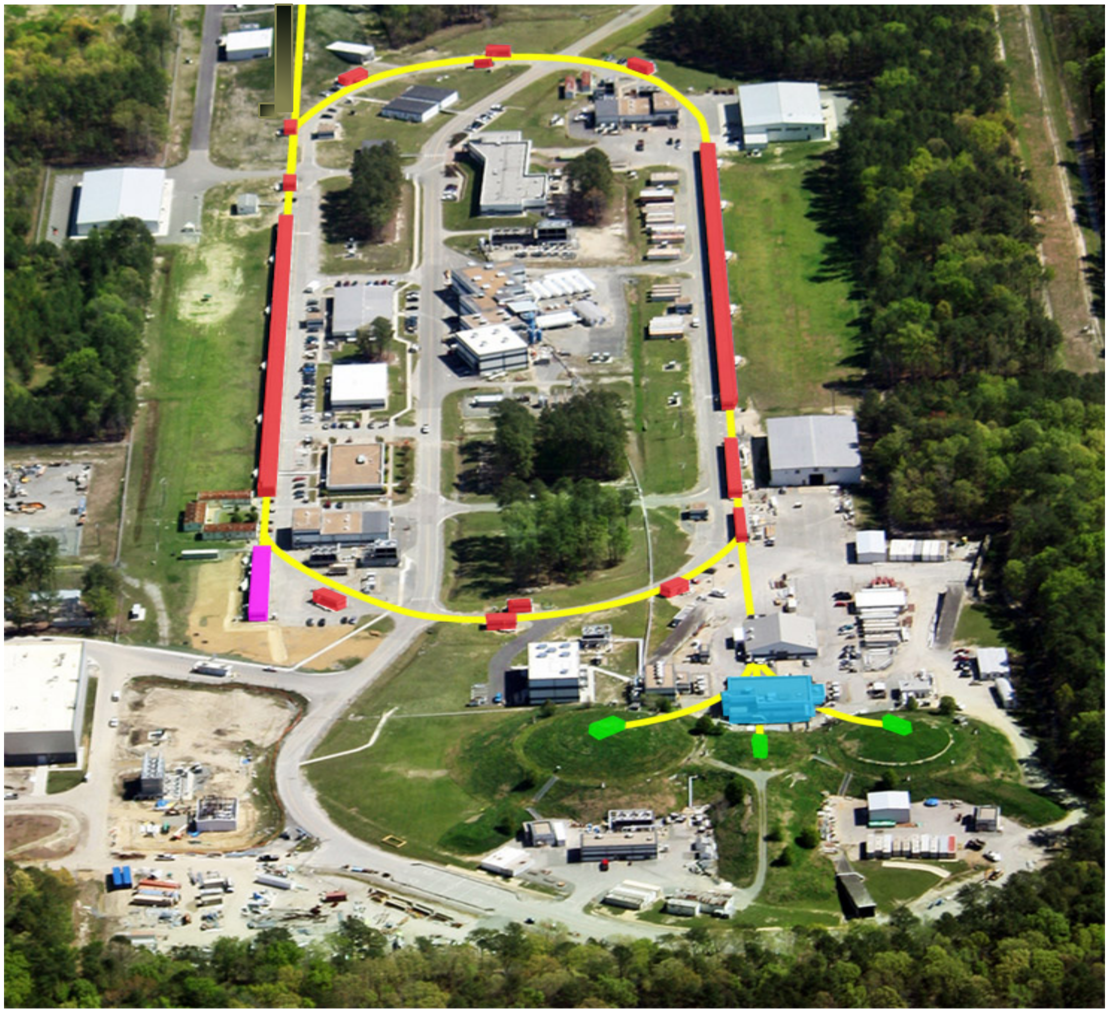
e-A Community Studies of the SIS/DIS Region

Cynthia Keppel

NuSTEC Workshop on Shallow and Deep Inelastic Scattering

11-13 October 2018
Gran Sasso Science Institute (GSSI)



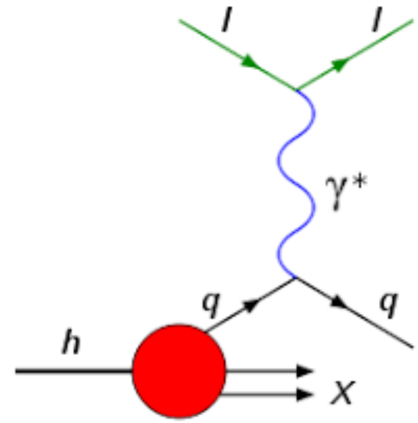
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Electron Scattering Measurements Applied to Neutrino Interactions on Nuclei

- Precision measurements of vector components of cross sections
  - Nucleons and nuclei, A-dependence
  - Form factors
  - Resonances
  - Deep Inelastic Scattering
  - Quark-hadron duality studies



- Parity violating electron scattering
  - As above!
- Precision decomposition of nuclear effects – within nuclei
  - Smearing/momentum distributions
  - Including short range correlations
  - Additional two body effects (meson exchange currents)
  - EMC effect
  - Shadowing and anti-shadowing

- Nuclear interactions
  - Hadronization
  - Final state interactions

Electron Scattering Measurements Applied to Neutrino Interactions on Nuclei

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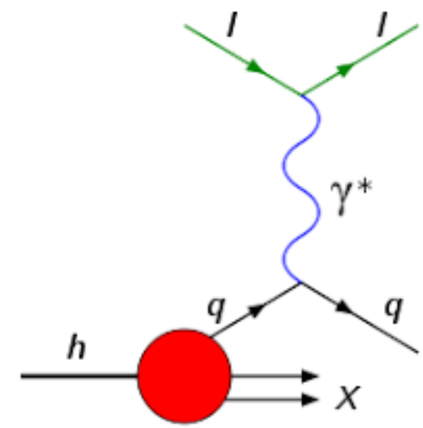

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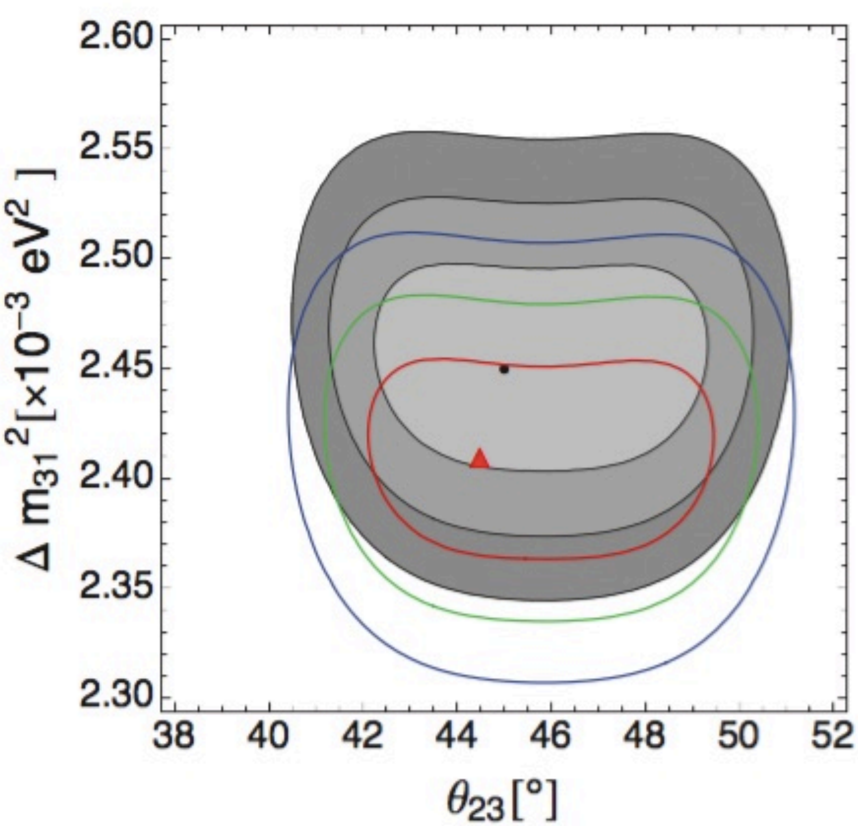
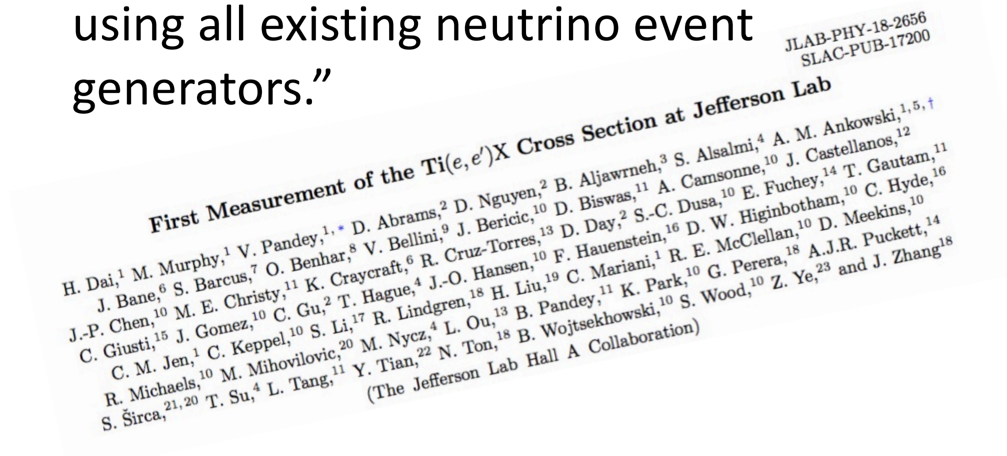
Direct measurements of initial state nucleon momentum distributions (Spectral Functions)

Effect of ^{40}Ar spectral function versus Relativistic Fermi Gas for simulated analysis (using GENIE) of DUNE



C.M. Jen, A. M. Ankowski, O. Benhar, A. P. Furmanski, L. N. Kalousis, and C. Mariani, Phys.Rev. D90 (2014) no.9, 093004 :

"We note that the large body of precise electron scattering data should be exploited to perform similar comparisons using all existing neutrino event generators."



JLAB-PHY-18-2656
SLAC-PUB-17200

First Measurement of the Ti(e,e')X Cross Section at Jefferson Lab

H. Dai,[1] M. Murphy,[1] V. Pandey,[1,*] D. Abrams,[2] D. Nguyen,[2] B. Aljawrneh,[3] S. Alsalmi,[4] A. M. Ankowski,[1,5,†] J. Bane,[6] S. Barcus,[7] O. Benhar,[8] V. Bellini,[9] J. Bericic,[10] D. Biswas,[11] A. Camsonne,[10] J. Castellanos,[12] J.-P. Chen,[10] M. E. Christy,[11] K. Craycraft,[6] R. Cruz-Torres,[13] D. Day,[2] S.-C. Dusa,[10] E. Fuchey,[14] T. Gautam,[11] C. Giusti,[15] J. Gomez,[10] C. Gu,[2] T. Hague,[4] J.-O. Hansen,[10] F. Hauenstein,[16] D. W. Higinbotham,[10] C. Hyde,[16] C. M. Jen,[1] C. Keppel,[10] S. Li,[17] R. Lindgren,[18] H. Liu,[19] C. Mariani,[1] R. E. McClellan,[10] D. Meekins,[10] R. Michaels,[10] M. Mihovilovic,[20] M. Nycz,[4] L. Ou,[13] B. Pandey,[11] K. Park,[10] G. Perera,[18] A.J.R. Puckett,[14] S. Širca,[21,20] T. Su,[4] L. Tang,[11] Y. Tian,[22] N. Ton,[18] B. Wojtsekhowski,[10] S. Wood,[10] Z. Ye,[23] and J. Zhang[18]
(The Jefferson Lab Hall A Collaboration)

Jefferson Lab Hall A Experiment E12-14-012:

Measurement of the Spectral Function of 40Ar through the (e,e'p) Reaction

Ran 2017

First publication Phys.Rev. C98 (2018) 014617

Draft Ar pubication now with collaboration!

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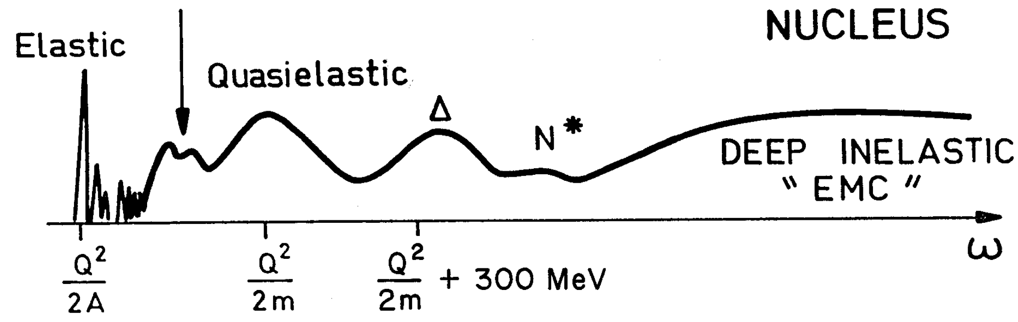
  - **Quark-hadron duality studies**



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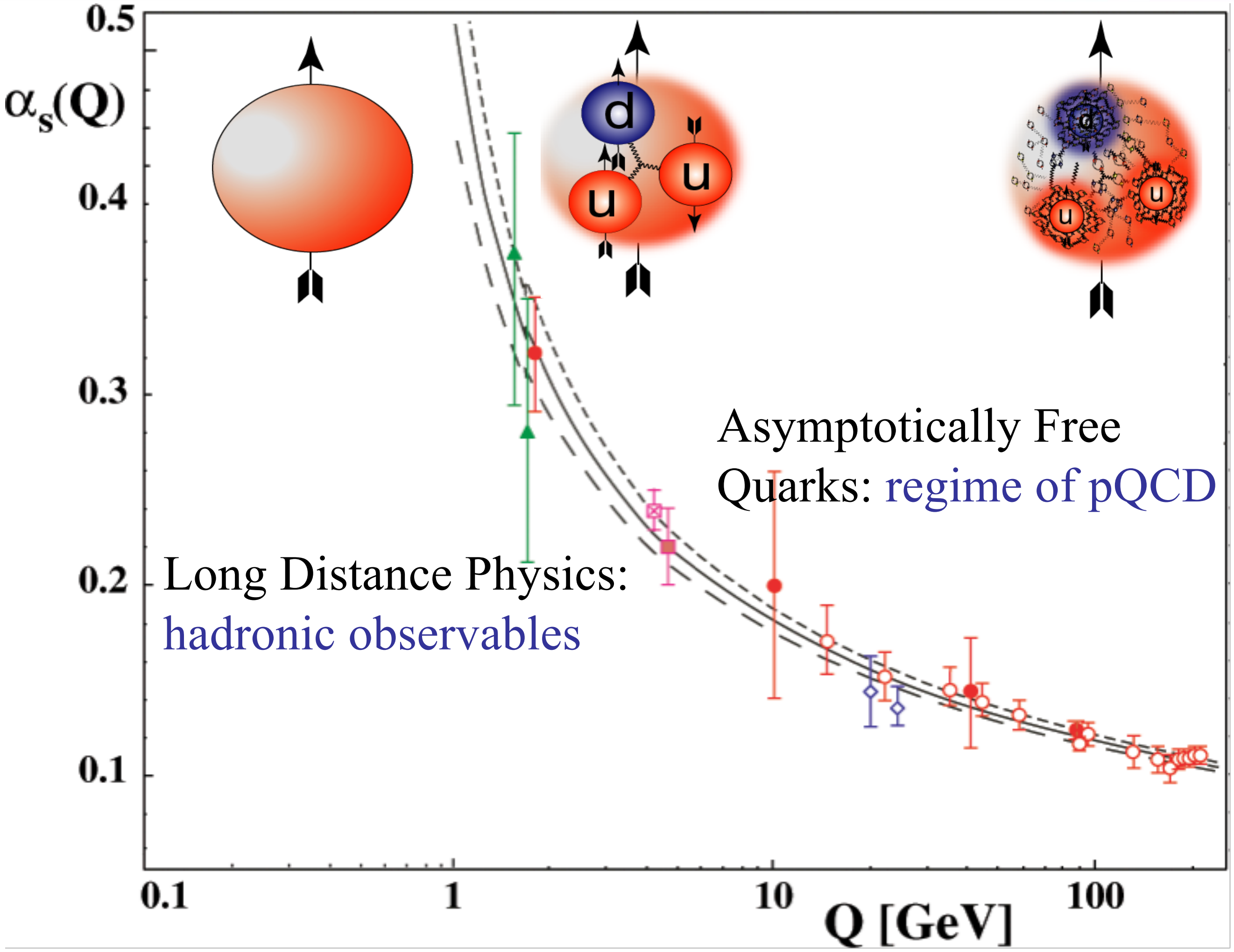
See E. Christy, H. Haider, E. Paschos talks!

Jefferson Lab

What is duality?

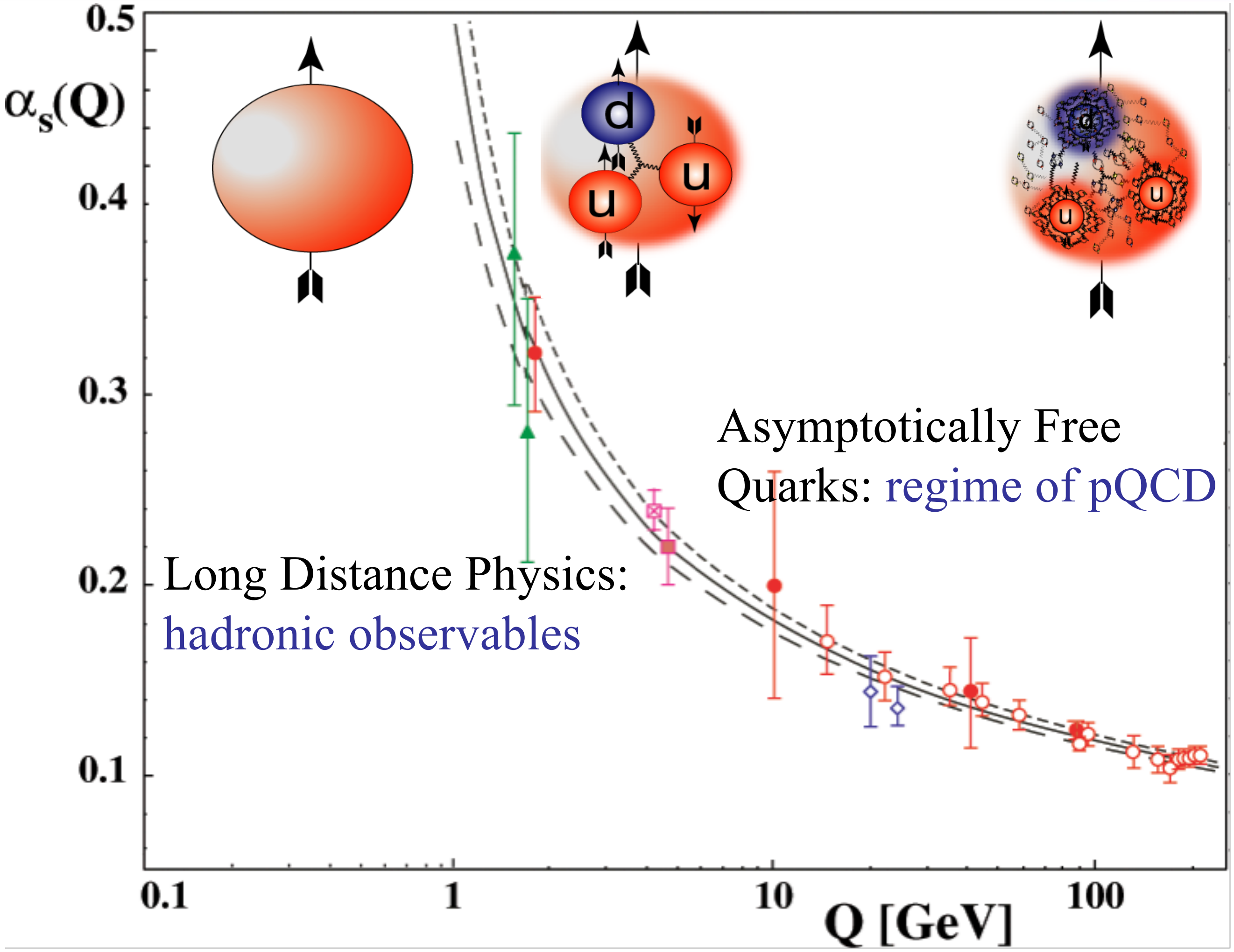


pQCD is well defined and calculable in terms of *asymptotically free* quarks and gluons, yet…

confinement ensures that hadrons are observed – pions, protons,…

Duality is an apparent experimental bridge between free and confined partons

What is duality?



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confinement ensures that hadrons are observed – pions, protons,…

Duality is an apparent experimental bridge between free and confined partons, i.e. between (perturbatively) calculable and difficult-to-calculate regimes

"Duality"

From J. Morfin talk at Jefferson Lab October 2018

- Relationships between meson–hadron and quark- … of freedom.
- Quark–hadron duality is a general feature of strongly interacting landscape.
- There exist examples where low-energy hadronic phenomena, averaged over appropriate energy intervals, closely resemble those at higher energies, calculated in terms of quark-gluon degrees of freedom.
- Duality is an important ingredient for the Bodek-Yang model that the neutrino event generators GENIE, NEUT, NuWro employ.
- Originally studied and confirmed in e-N scattering – how about ν-N scattering? There is essentially no high-statistics ν-N experimental data with W>1.4 GEV for tests! Rely on **models** for resonances and essentially **ONE** theoretical look at duality in ν-N scattering.

See U-K Yang talk!

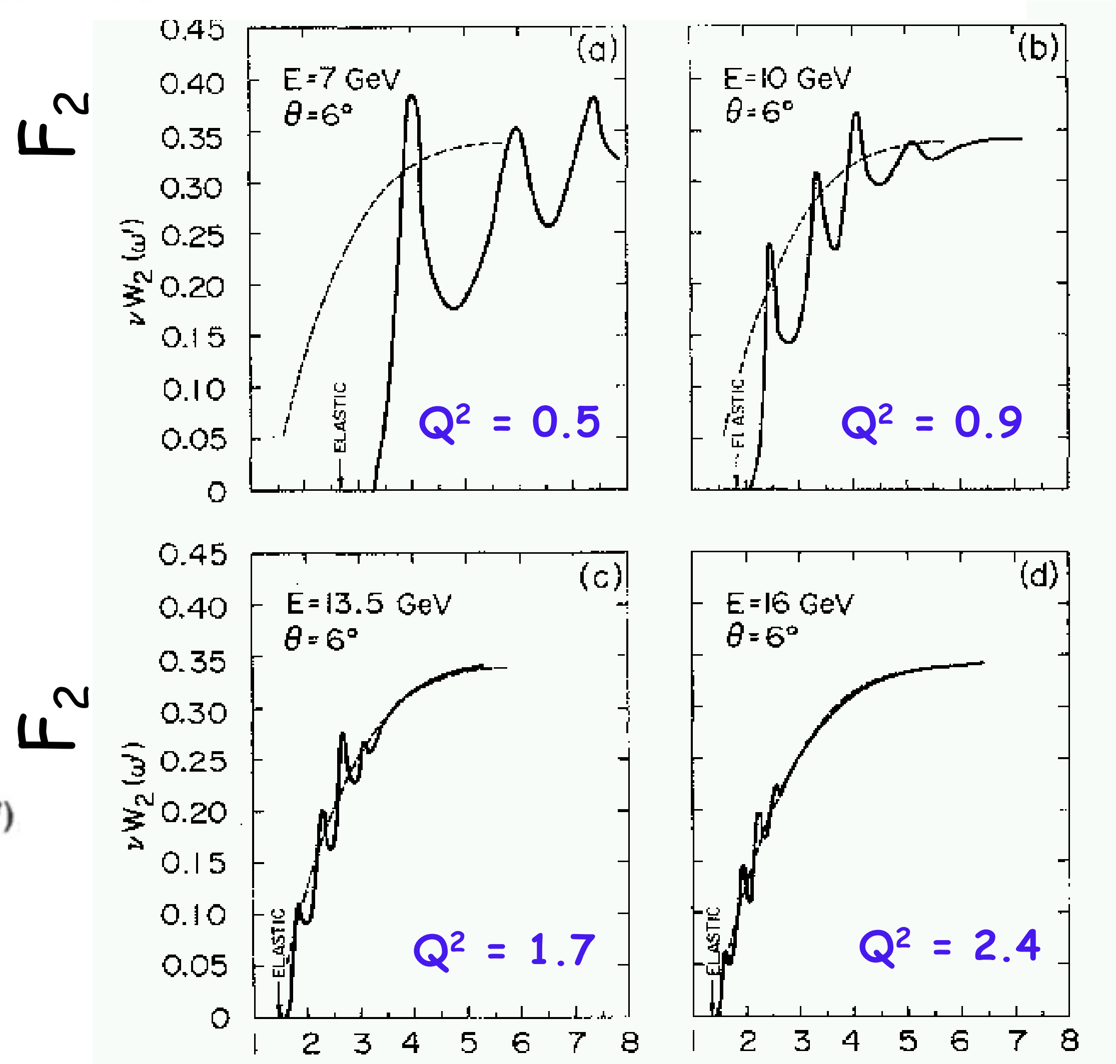
Electron Scattering: "Bloom-Gilman" Duality

photon mass in electroproduction and have scaling, we can directly measure a smooth curve which averages the resonances in the finite energy sum rule and

- 1970s: Bloom and Gilman at SLAC compared resonance production data with deep inelastic scattering data using ad hoc variable
- Integrated F_2 strength in nucleon resonance region equals strength under scaling curve.
- Finite energy sum rule:

$$\frac{2M}{q^2}\int_0^{\nu_m} d\nu\, \nu W_2(\nu,q^2) = \int_1^{(2M\nu_m+m^2)/q^2} d\omega'\, \nu W_2(\omega')$$

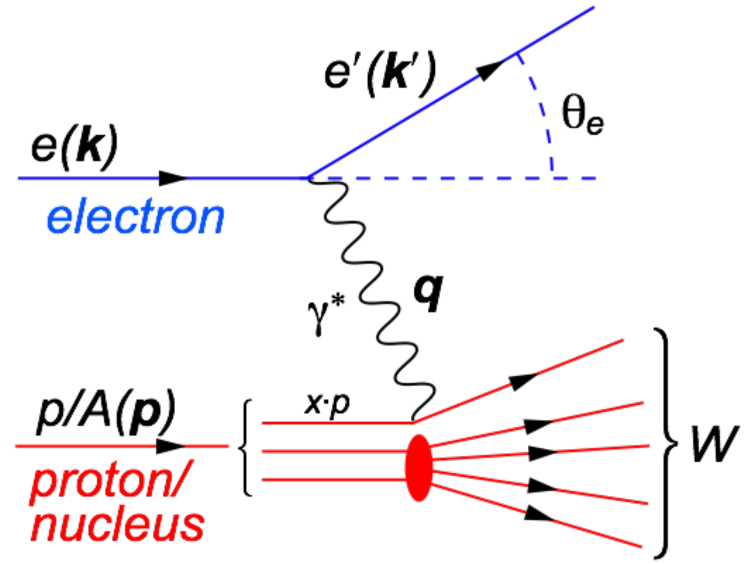
- Resonances oscillate around curve *at all Q^2*

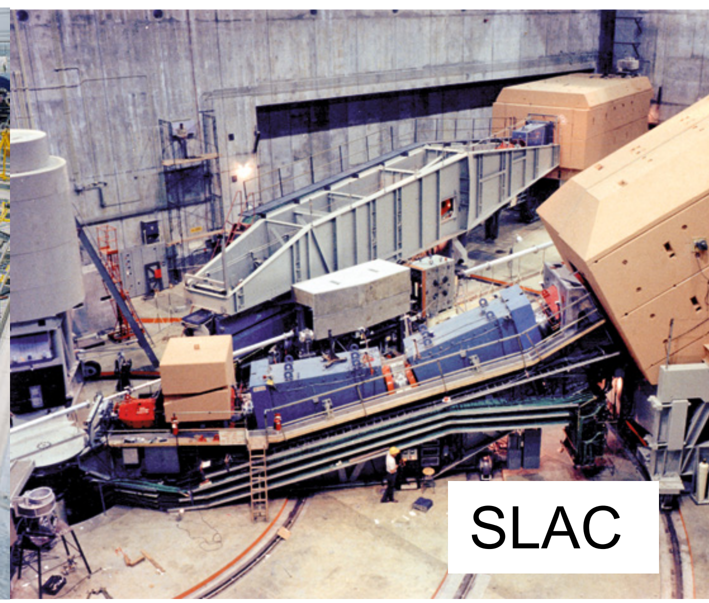


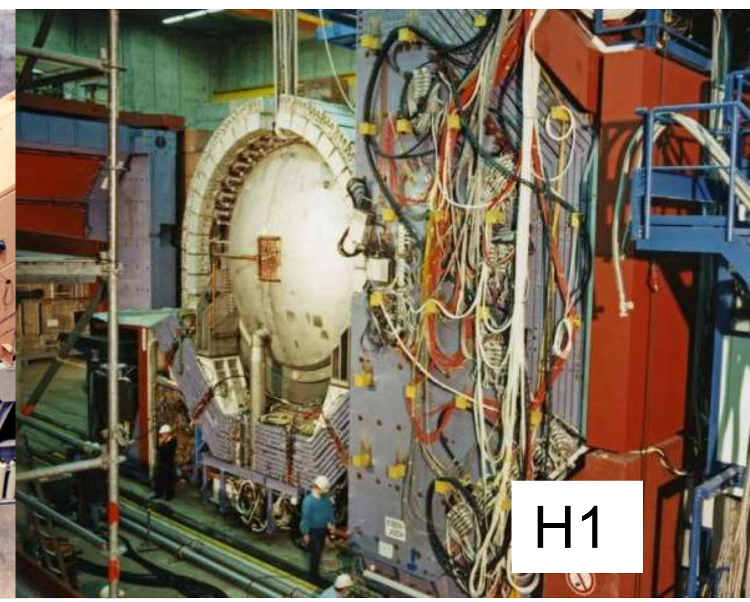
$\omega' = 1 + W^2/Q^2$

Three Decades Later….

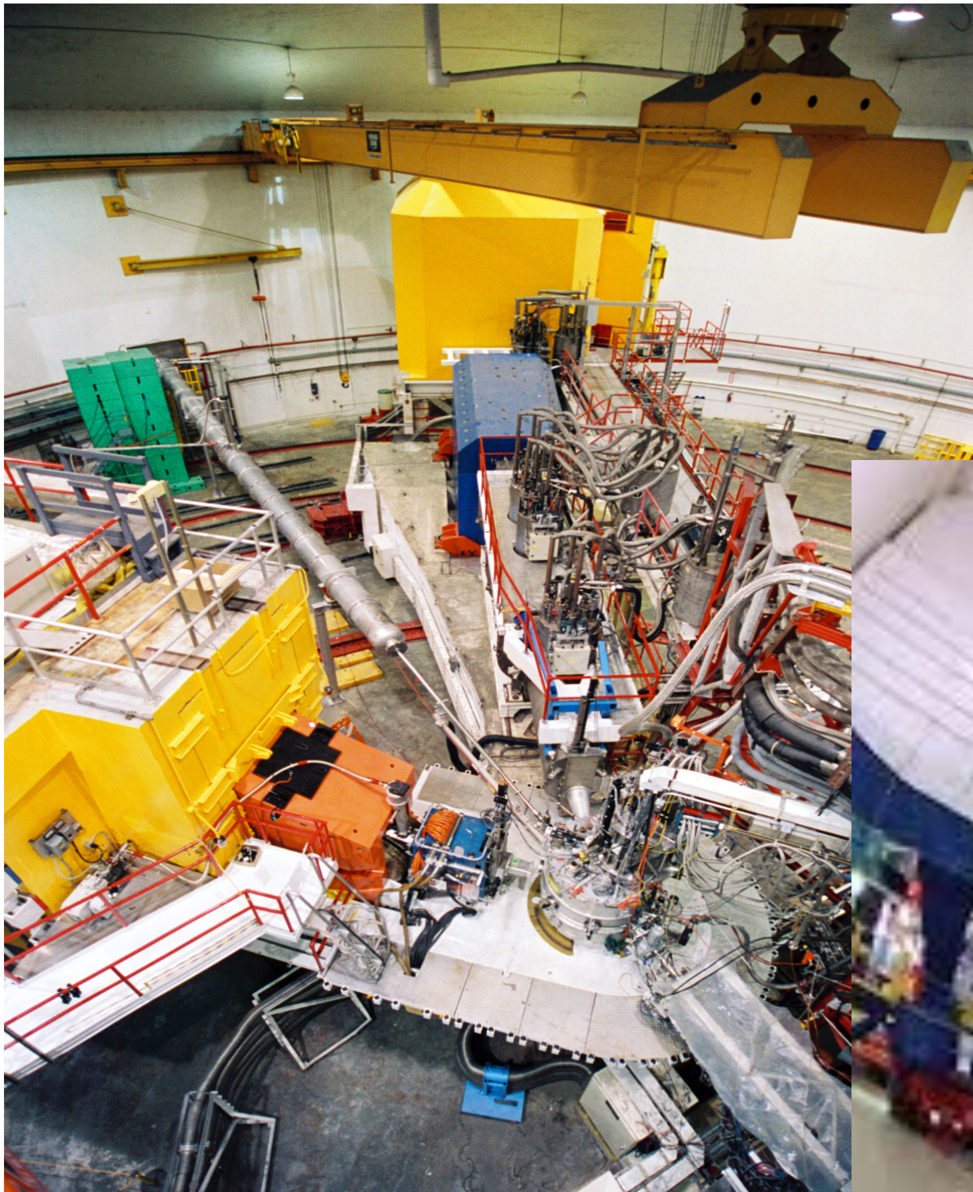
- 30+ years of charged lepton DIS at *multiple* laboratories
- Nucleon structure function well measured over broad range in x,Q^2
- DGLAP evolution equations for the parton densities, success of QCD
- It was time to revisit the resonances…..

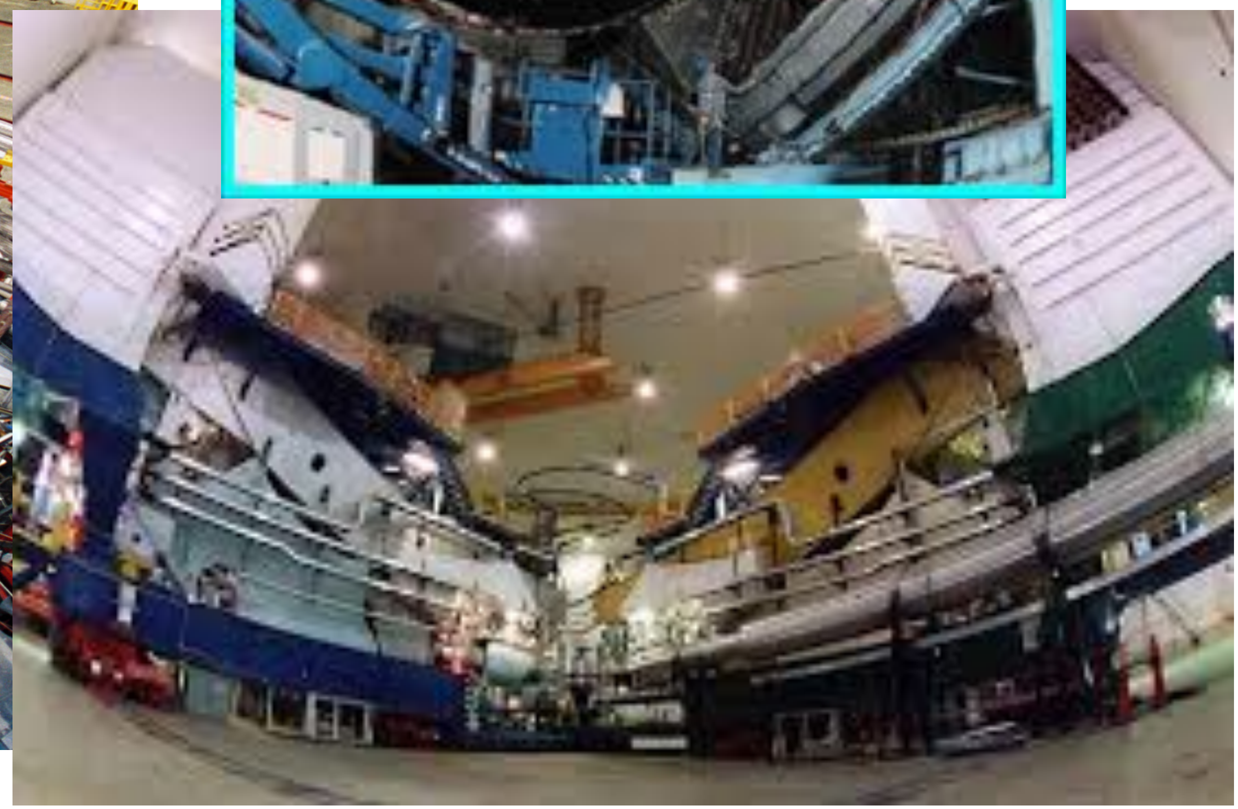




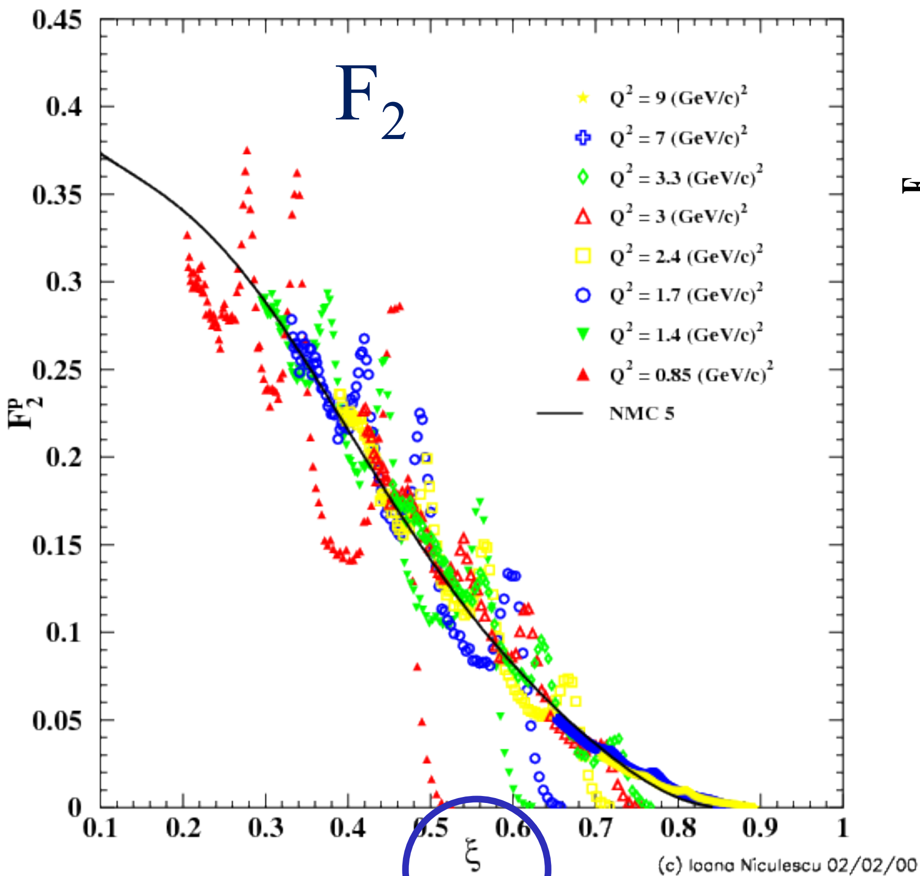


Precision Resonance Data from Multiple Experiments in Jefferson Lab in 6 GeV Era

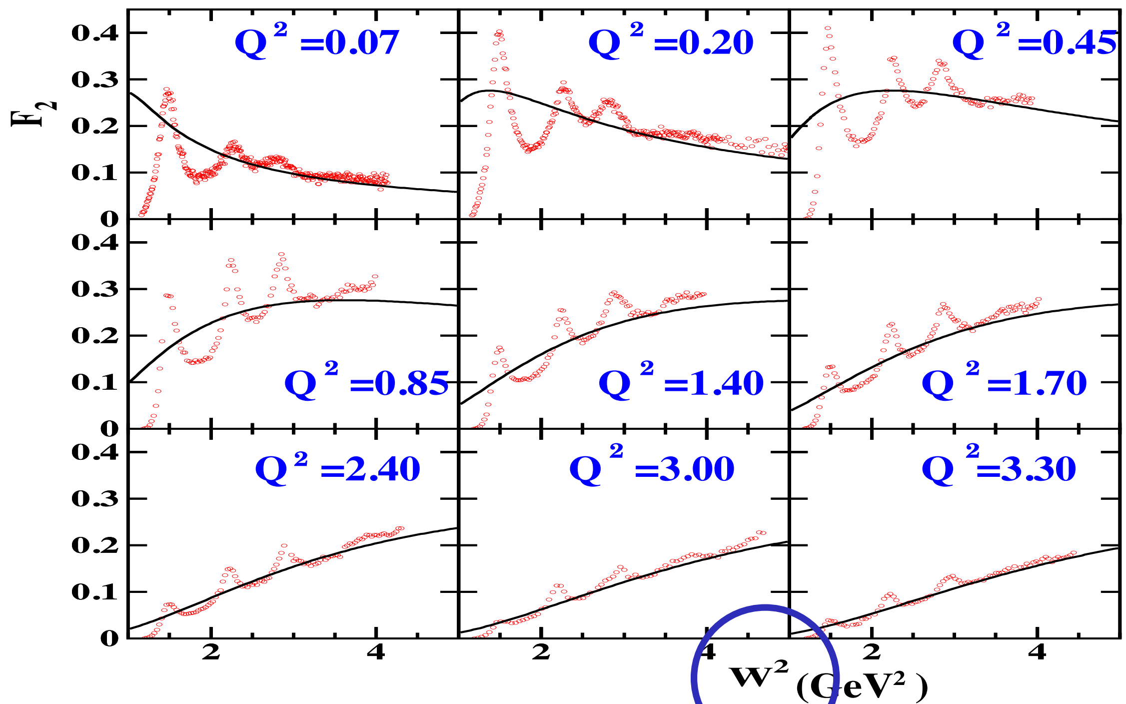




Duality Re-observed



I. Niculescu, et al., PRL 85 (2000), 1186 and 1182



$\xi = 2x/[1 + (1+4x^2M^2/Q^2)^{1/2}]$

One of the first Jefferson Lab 6 GeV era measurements

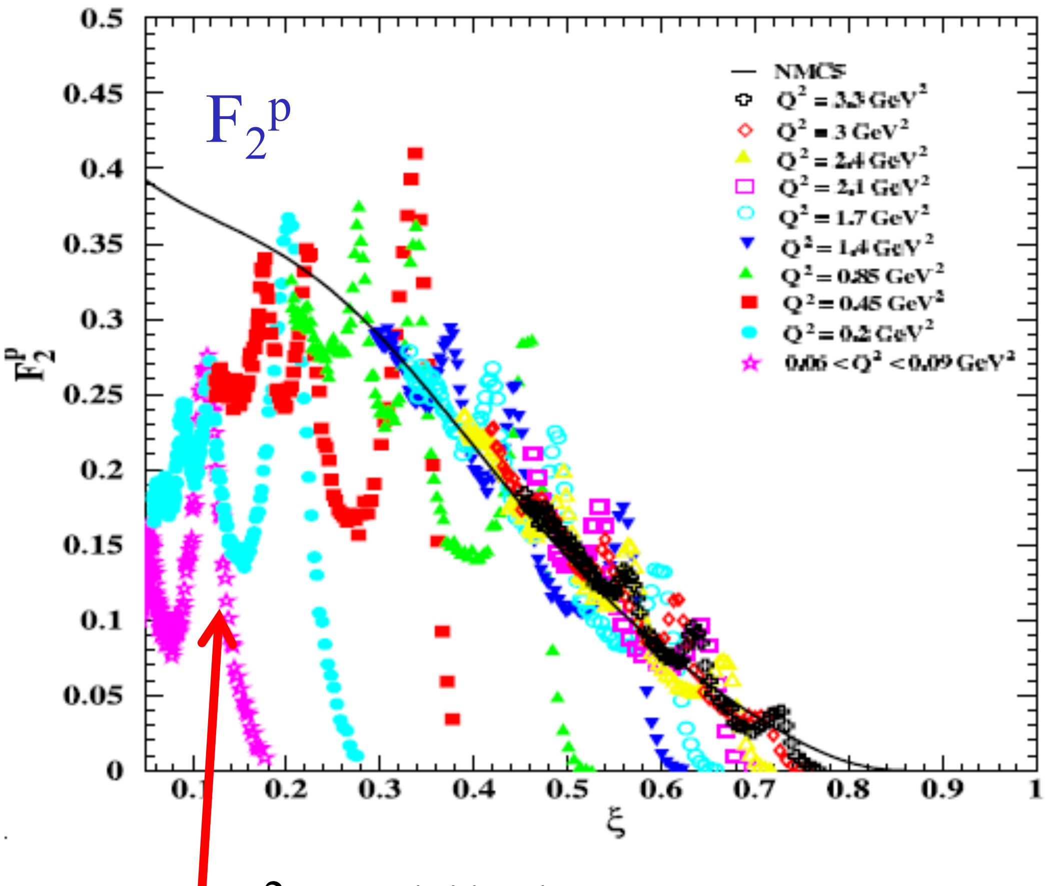
Duality clearly observed, but…

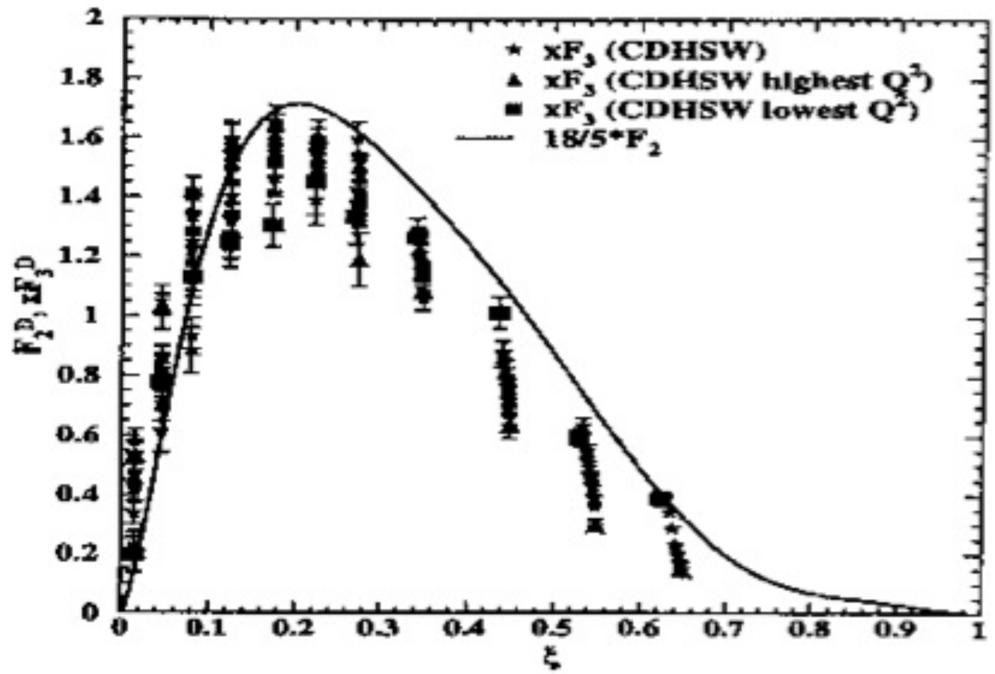
What to use for curve(s)? What to use for variable?

How to test precisely?

See E. Christy talk

What is the average curve? Is it the pure valence distribution?



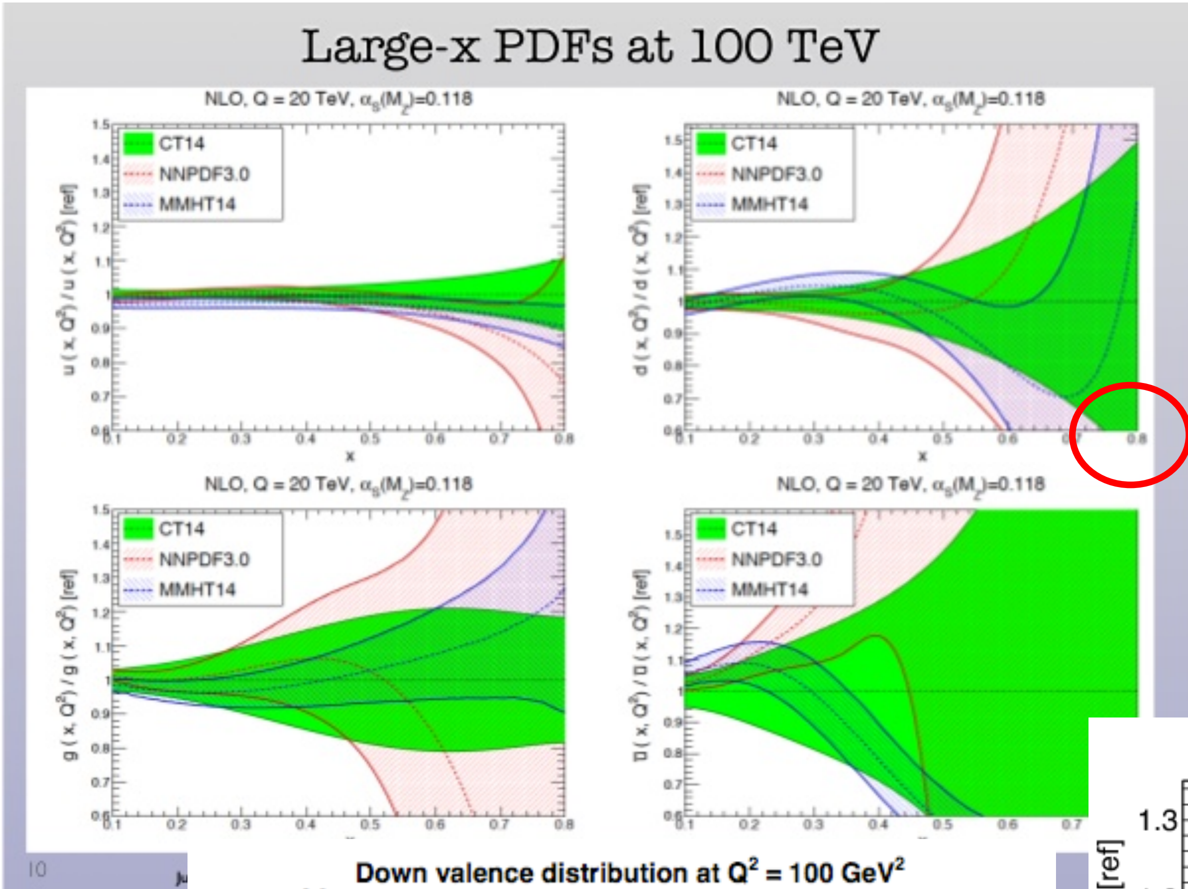


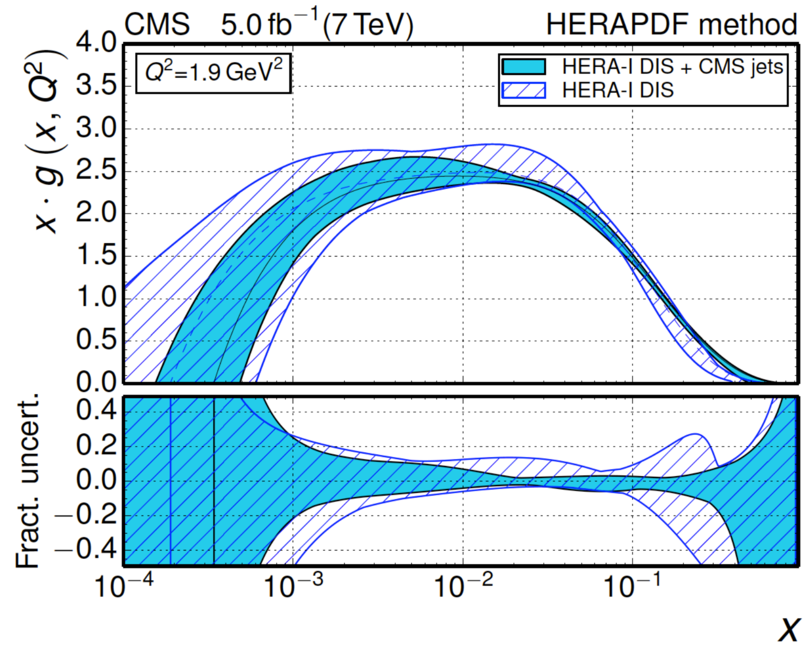
Low Q^2 – while low x, perhaps wavelength such that sea quarks “invisible”??

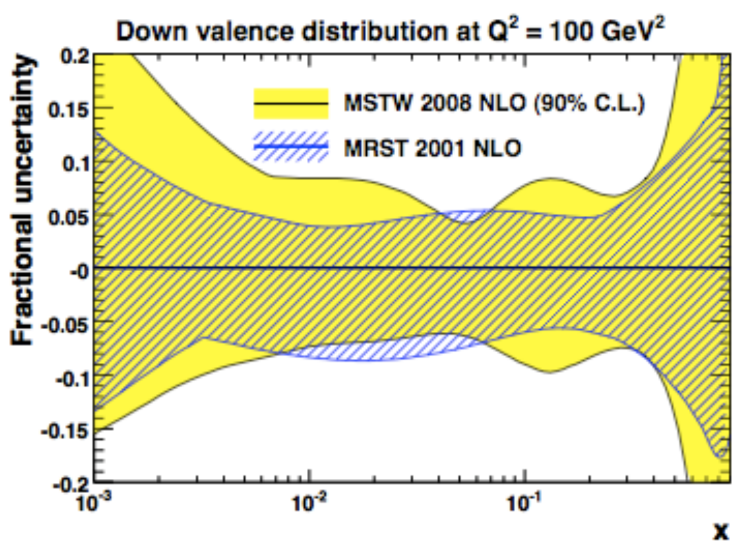
Curve = average electron scattering D data * 18/5

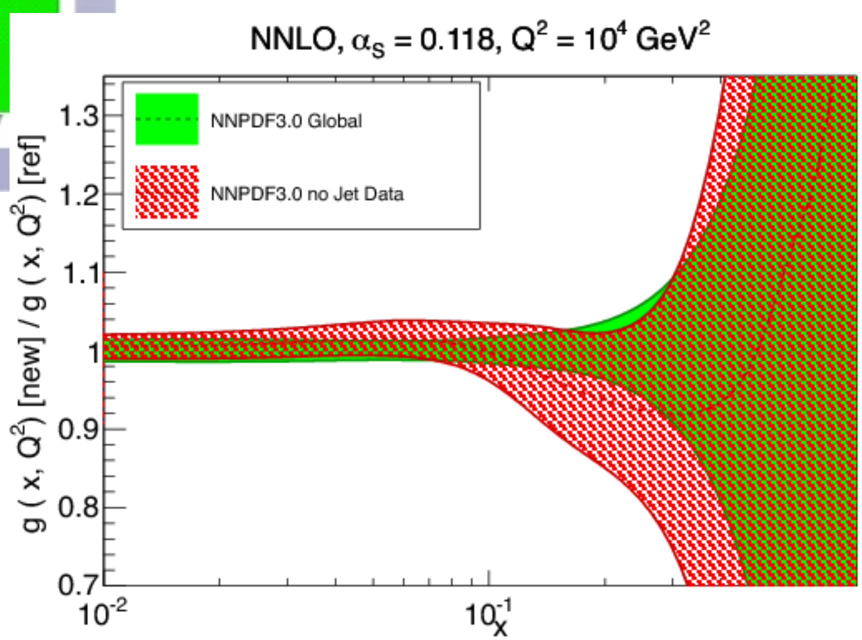
Data = DIS neutrino xF_3 (nuclear averaged to D), valence sensitive only

Present status: large uncertainties on PDFs at large x



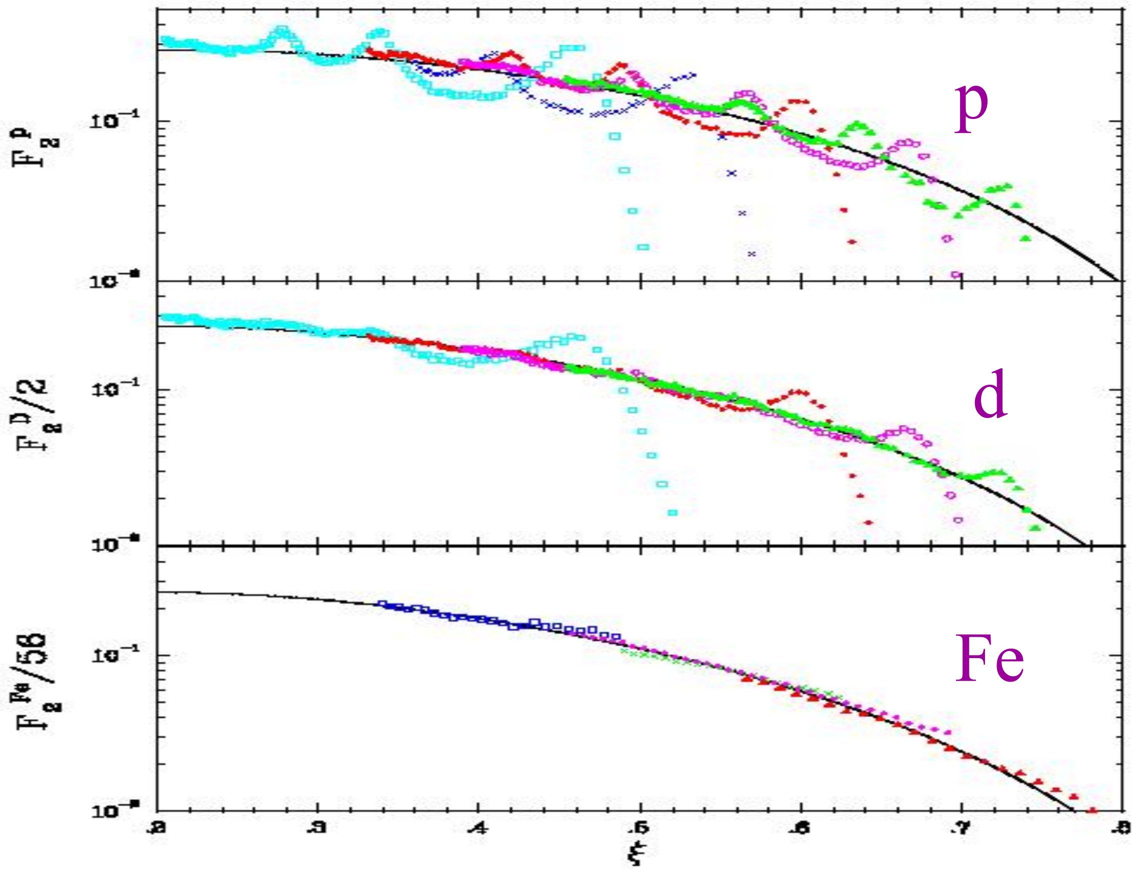






Duality also tested in higher mass nuclei

- Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2
- GRV scaling curve
- The nucleus (Fermi smearing) does the averaging!
- For larger A, resonance region indistinguishable from DIS

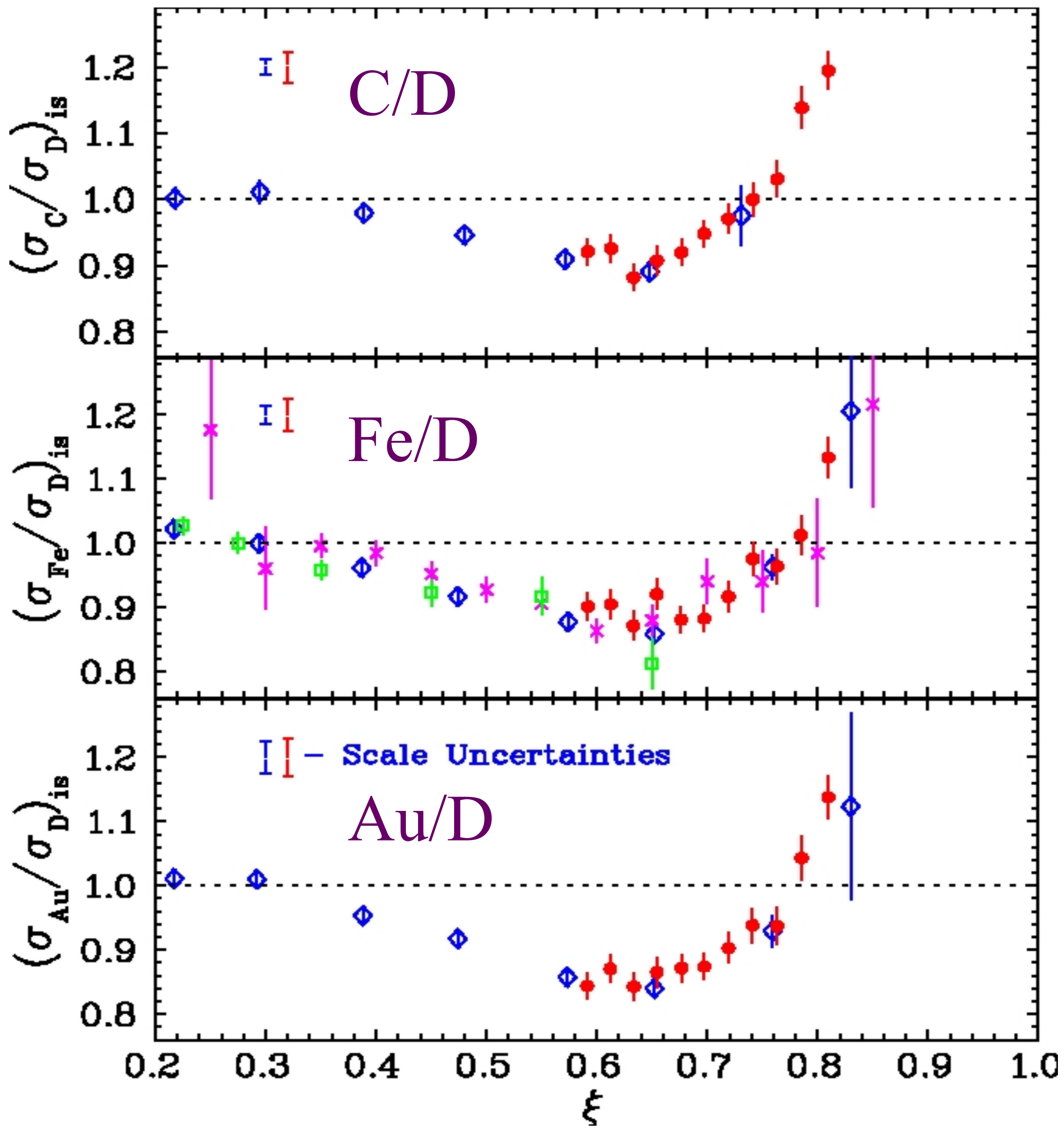


$$\xi = 2x\left[1 + (1 + 4M^2x^2/Q^2)^{1/2}\right]$$

J. Arrington, R. Ent, CK, J. Mammei, I. Niculescu, **Phys.Rev. C73 (2006) 035205**

Duality and the EMC Effect

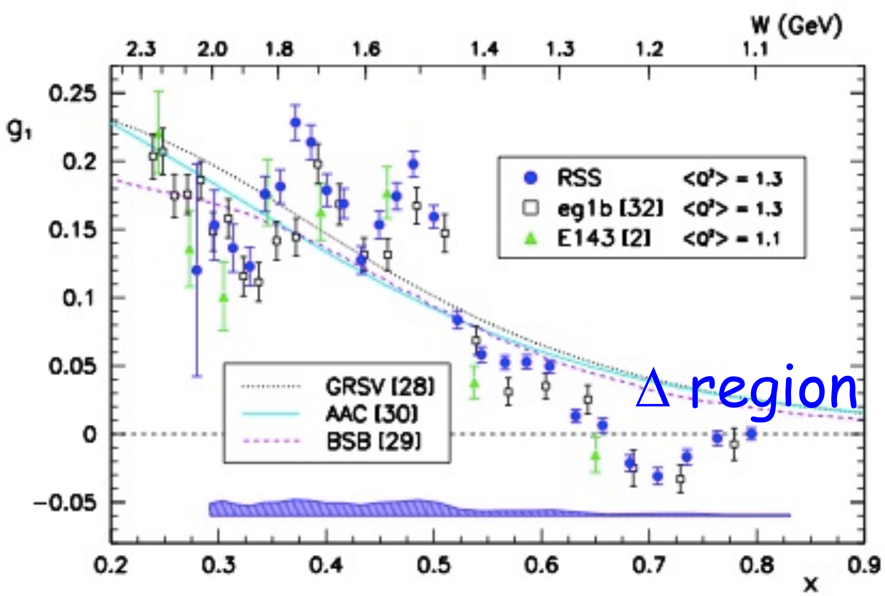
- Red = resonance region data
- Blue, purple, green = deep inelastic data from SLAC, EMC
- Medium modifications to the structure functions ***are the same*** in the resonance region as in the DIS
- Duality observed in nuclei

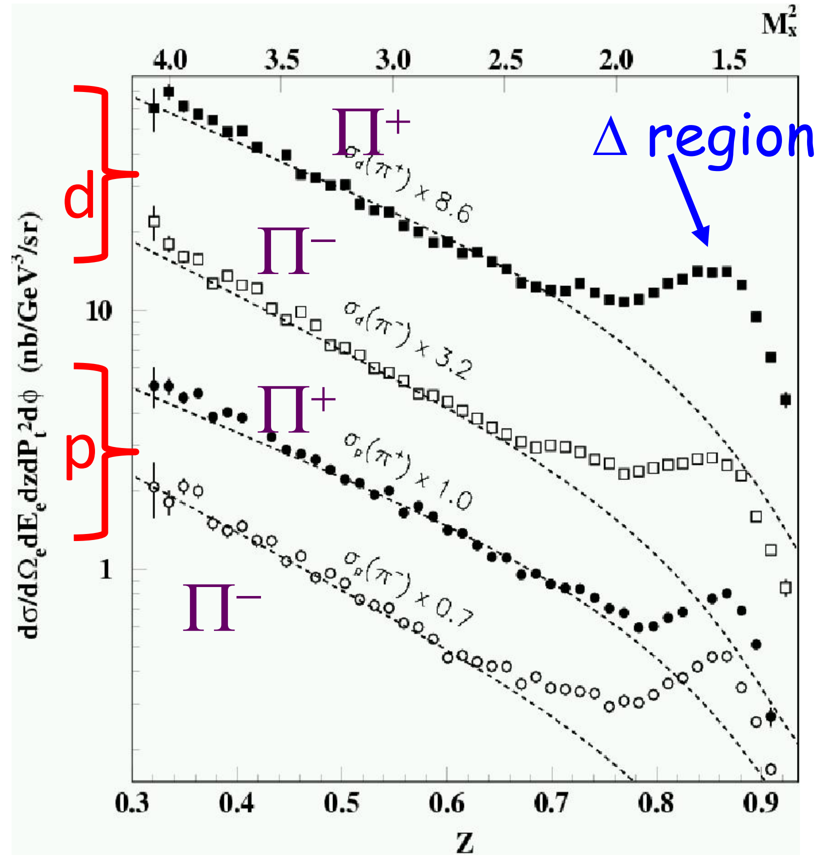


Duality observed for ***multiple*** observables…

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p
- ✓ F_2^n
- ✓ F_2^d
- ✓ F_2^C
- ✓ F_2^{Fe}
- ✓ F_2^{Au}
- ✓ A_1^p
- ✓ g_1^p
- ✓ g_1^d
- ✓ g_1^n
- ✓ g_1^{3He}

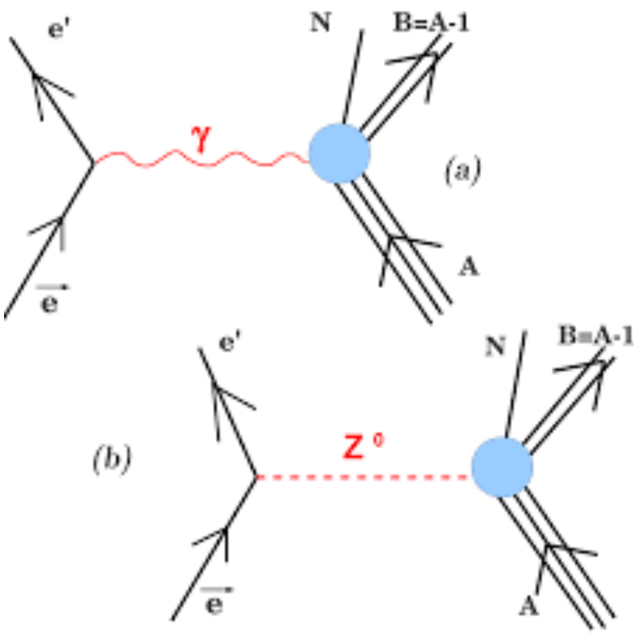
- ✓ SIDIS p π^+
- ✓ SIDIS p π^-
- ✓ SIDIS d π^+
- ✓ SIDIS d π^-



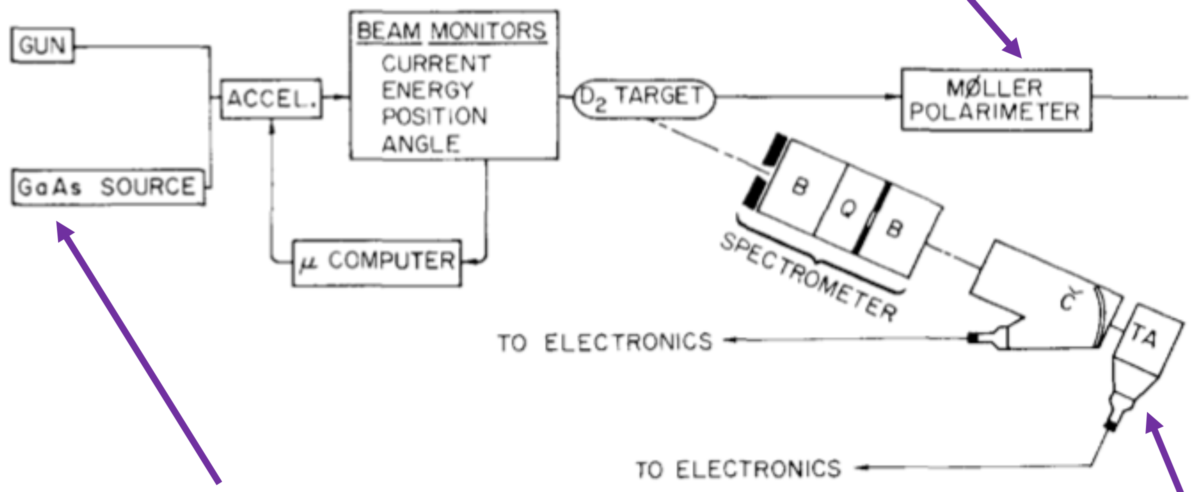


Also parity violating electron scattering….

Parity Violation Electron Scattering



Precision polarimetry



Rapid helicity-flip (sign of e- polarization) at beam source

Integrating detectors

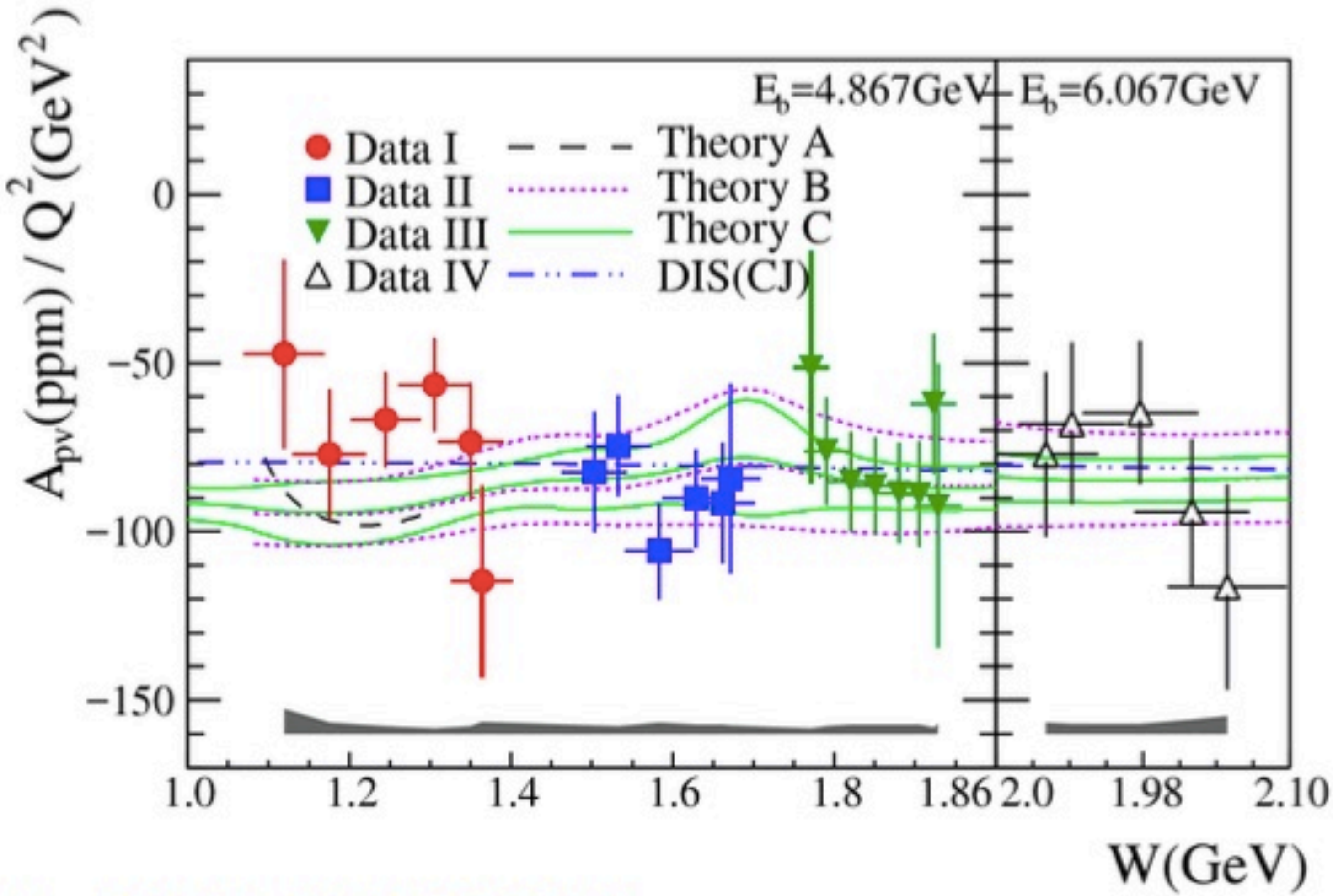
$$\sigma_{\pm} \propto [M_{EM} \pm M_{NC}]^2 = |M_{EM}|^2 \pm 2Re(M_{EM}^* M_{NC}) + |M_{NC}|^2$$

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx \frac{2Re(M_{EM}^* M_{NC})}{|M_{EM}|^2 + \cdots}$$

$$\Rightarrow \frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \frac{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_A^e A_\mu^{NC,e} V_\mu^{NC,N} + Q_e V_\mu^{EM,e} V_\mu^{EM,N} g_V^e V_\mu^{NC,e} A_\mu^{NC,N}\right)}{\left(Q_e V_\mu^{EM,e} V_\mu^{EM,N}\right)^2}$$

Resonance PV Asymmetry Results

Theory A: Matsui, Sato, Lee, PRC72,025204(2005)
Theory B: Gorchtein, Horowitz, Ramsey-Musolf, PRC84,015502(2011)
Theory C: Hall, Blunden, Melnitchouk, Thomas, Young, PRD88, 013011 (2013)
DIS (CJ): using DIS PDFs (and ignored the W and Q2 limits of the code)

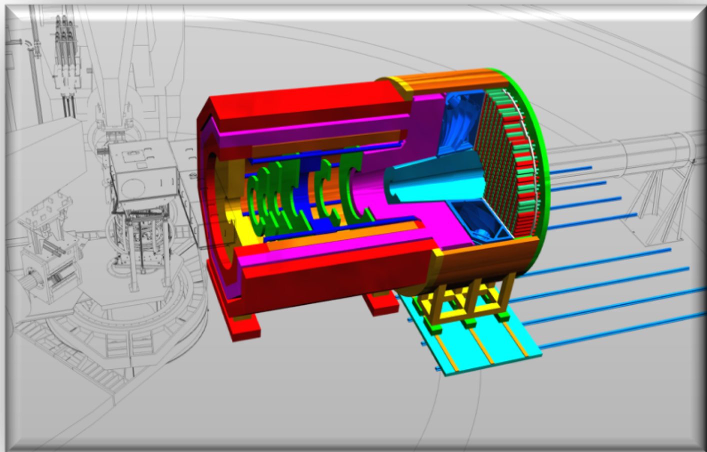


Wang et al., PRL 111, 082501 (2013);

Future Studies: Solenoidal Large Intensity Device

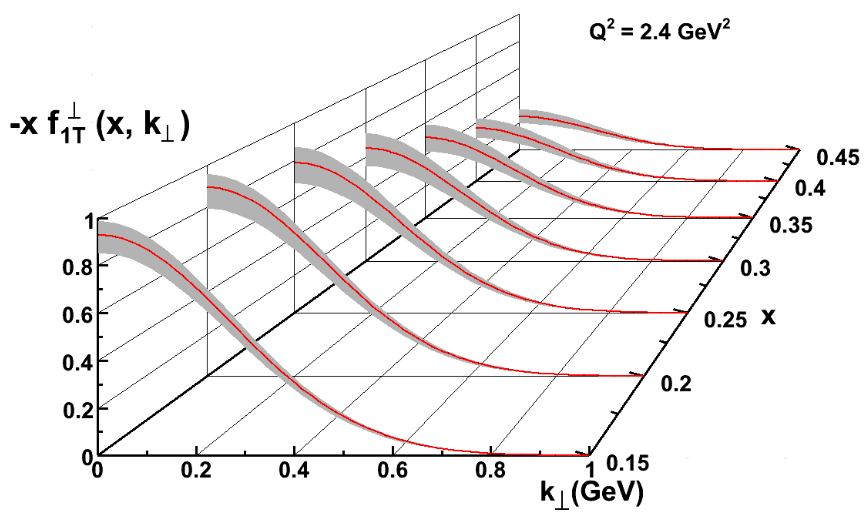
SoLID provides unique capability:

- ✓ high luminosity ($10^{37\text{-}39}$)
- ✓ large acceptance with full ϕ coverage

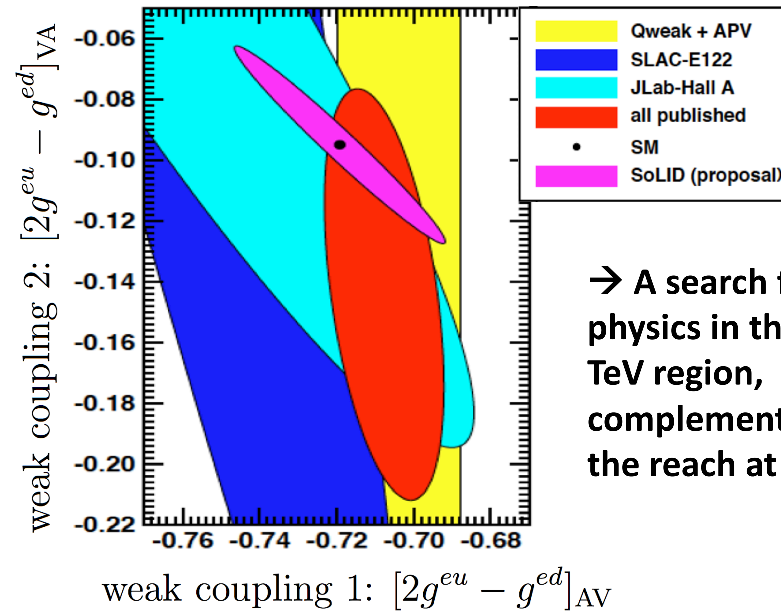


→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

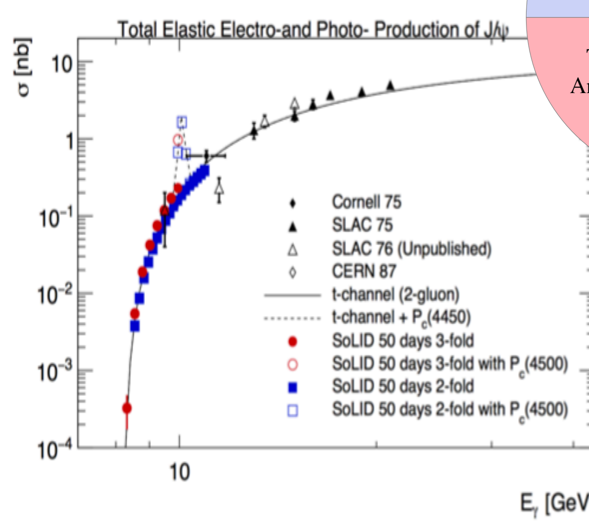


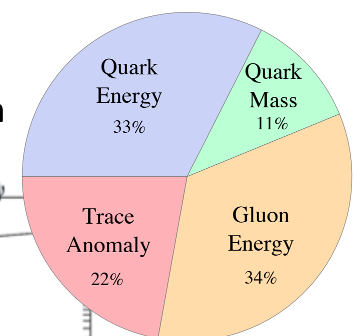
2) Precise determination of the electroweak couplings



→ A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.

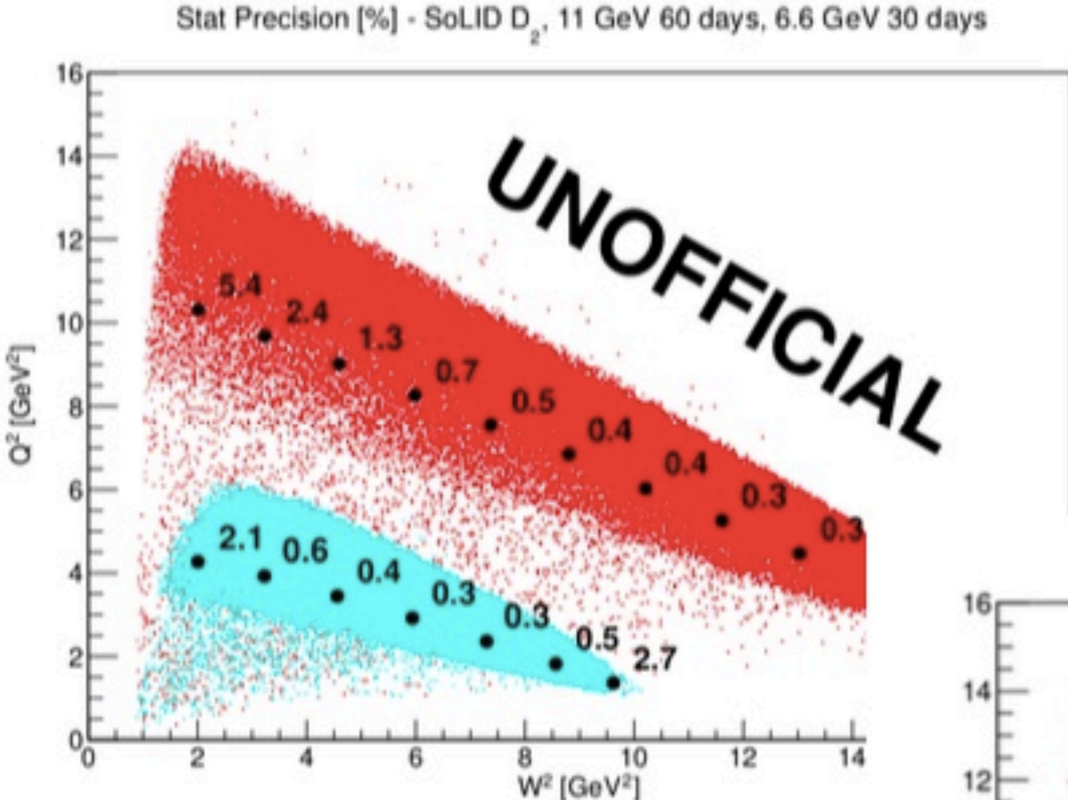
3) J/ψ production cross section

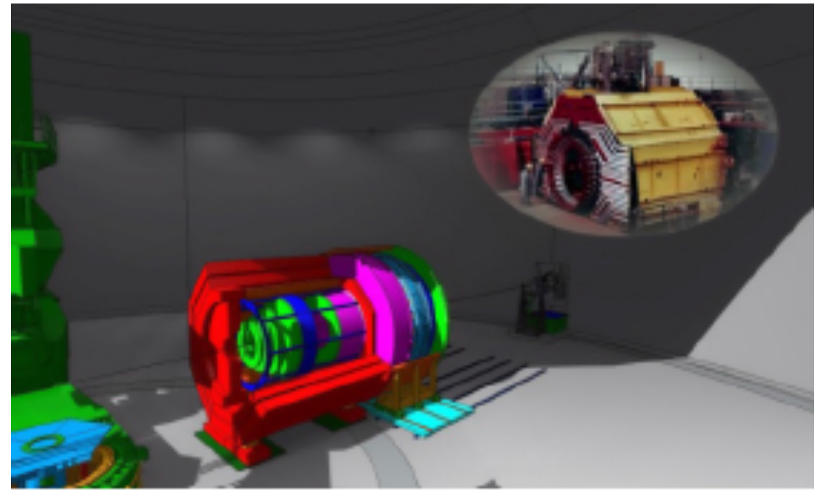


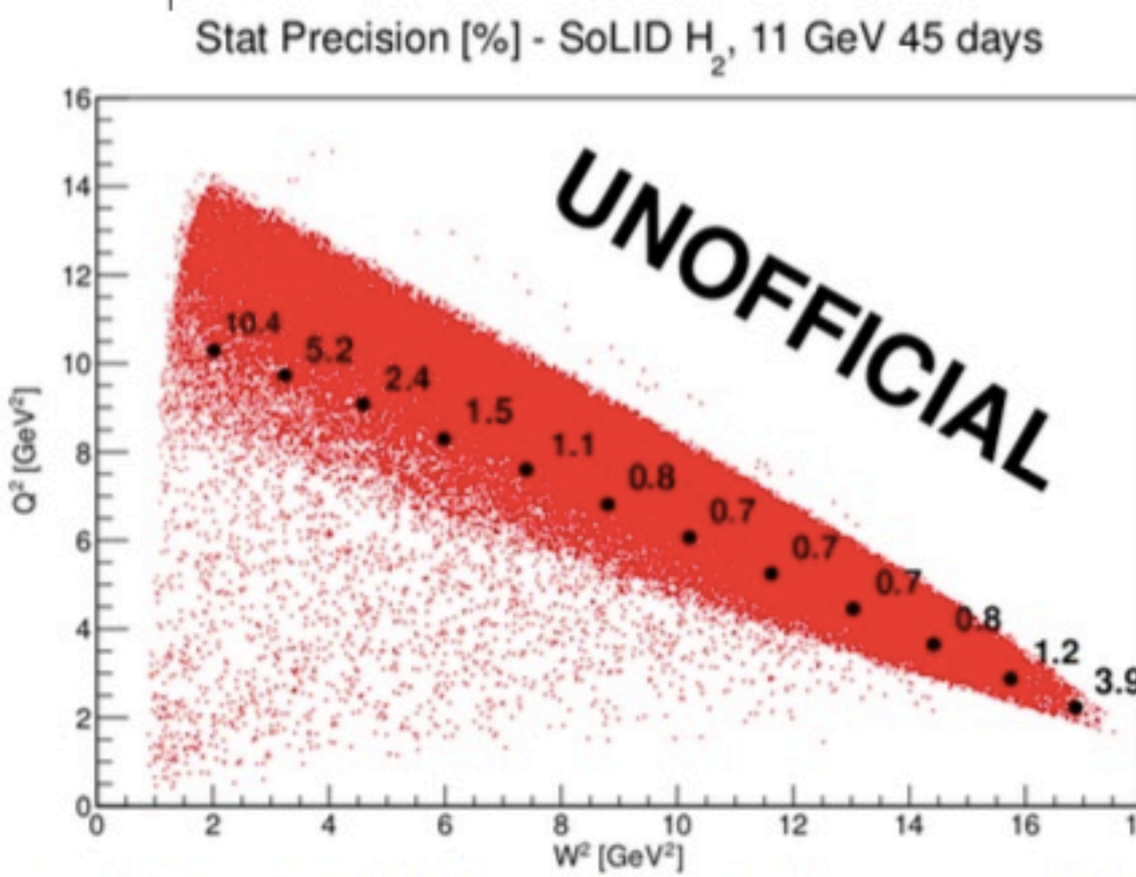


→ Constrain the QCD trace anomaly, Proton mass, LHCb charmed pentaquark

Data in the resonance region (W<2) with no addition beam time







- **Quark-hadron duality is apparently a fundamental property of nucleon structure**
  - Works to ~5-10% above Q^2 ~1 GeV^2
  - Multiple processes studied
  - Studies now *quite* numerous!
- Seems to need >1 state for averaging
  - Elastic add to moments
  - Delta alone a problem
- Challenges to quantifying experimentally
  - pQCD predictions for large x, low Q have large uncertainties
- *If* understood better, a powerful tool to understand confinement
- Lacks fundamental theoretical understanding

Time to revisit! New studies underway!

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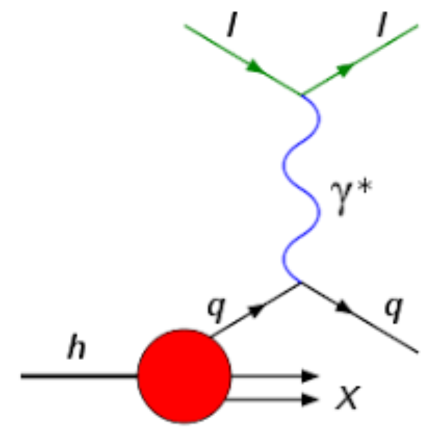
  - **Deep Inelastic Scattering**
  - Quark-hadron duality studies
- Parity violating electron scattering
  - As above!



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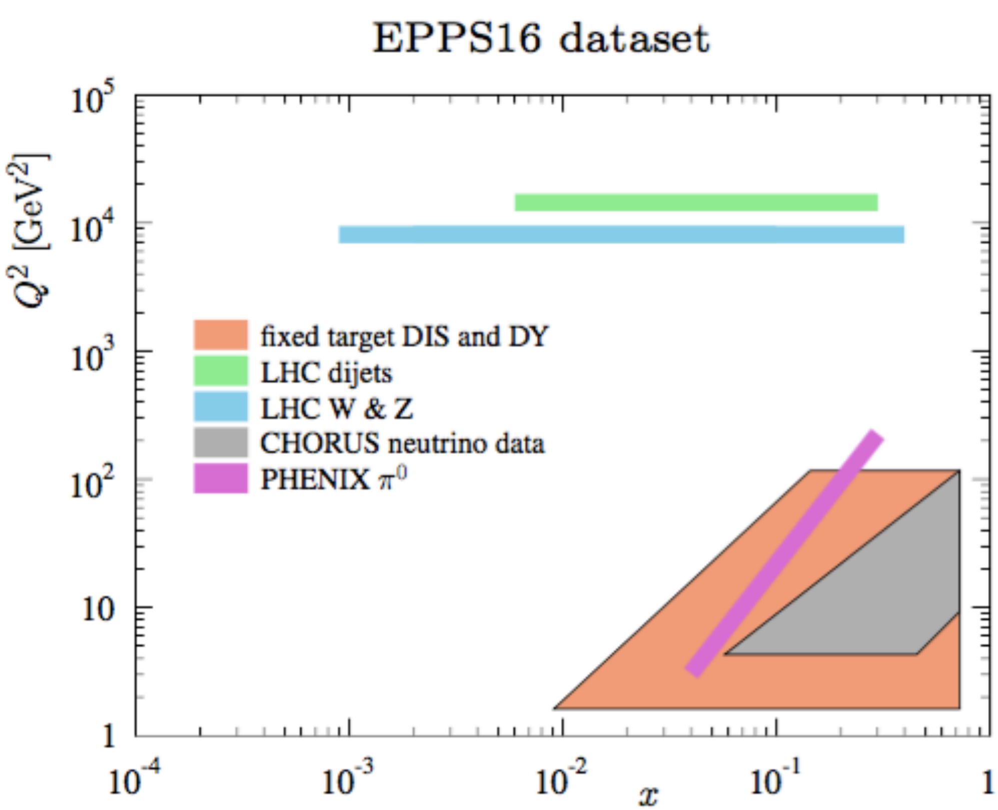
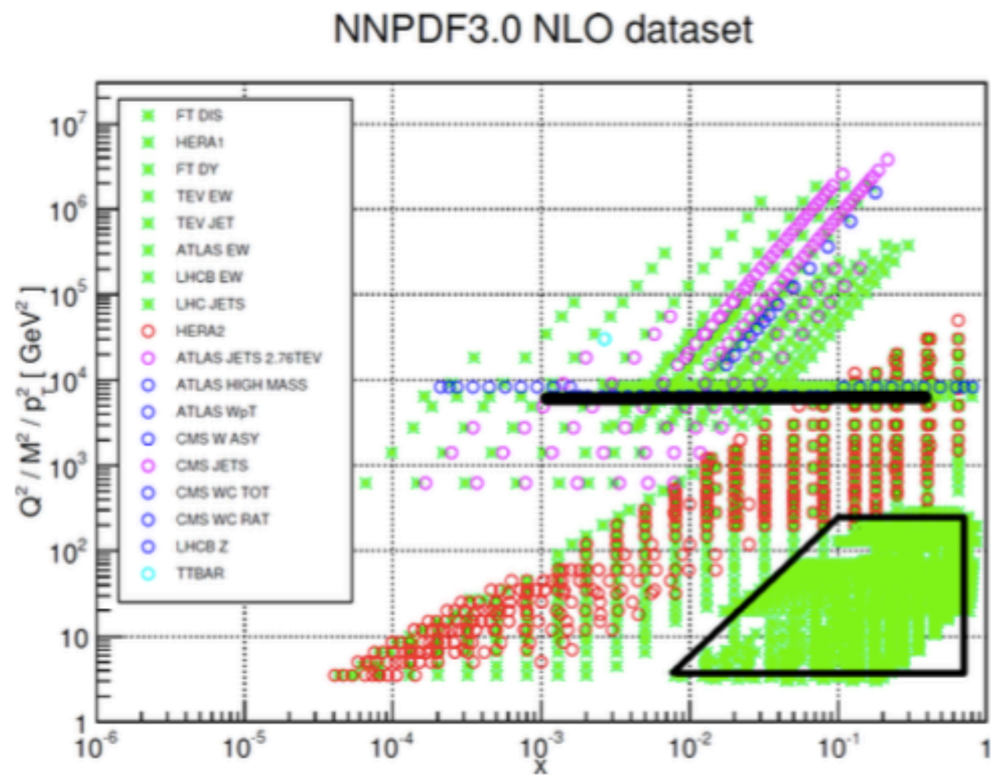
Nuclear PDFs Compared to Free Proton PDFs

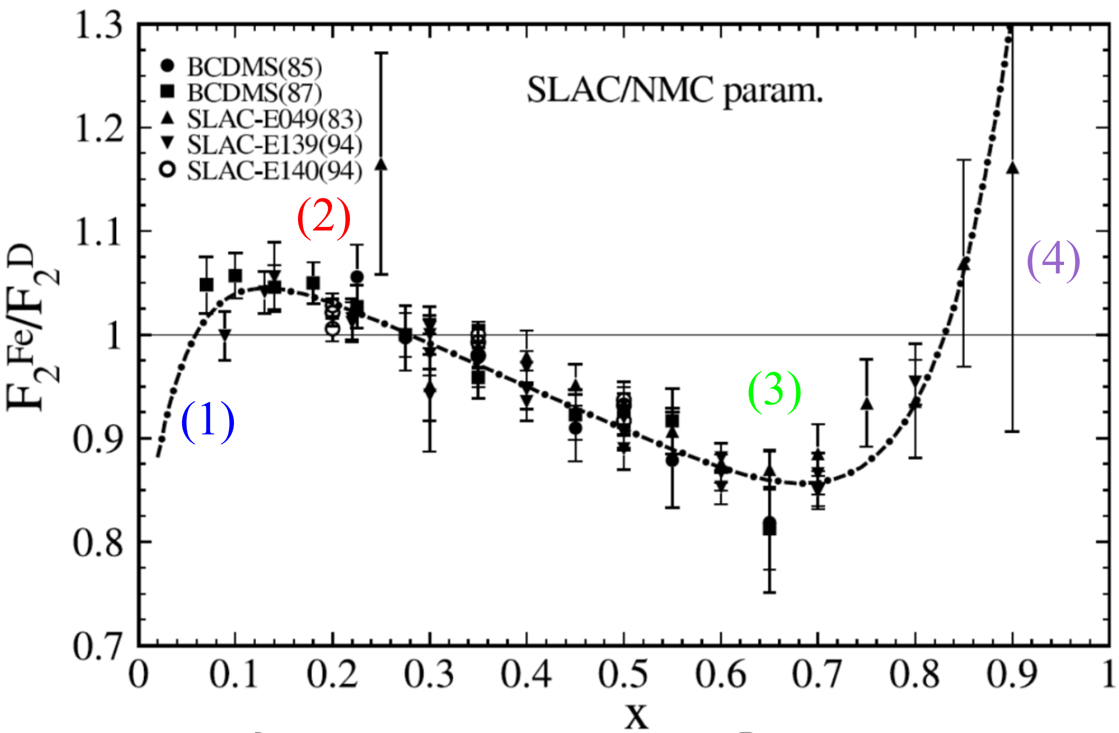
- Theoretical status of factorization
- More parameters to model A-dependence
- Different data sets – much less data:



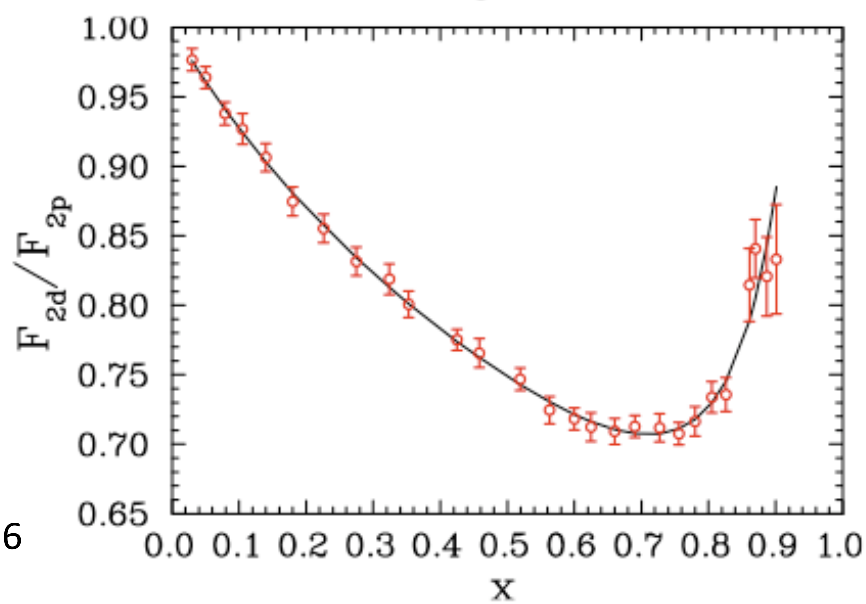


- Less data → less constraining power → more assumptions
- 740 nuclear points for nCTEQ15 vs 2947 protons points for CT14

Nuclear PDFs



F_2^d/F_2^p



J. Arrington, F. Coester, R.J. Holt, T.-S.H. Lee, J.Phys. G36 (2009) 025005

- Nuclear corrections are needed for A>1!
- Parton momentum distributions broadened
- Historically nuclear effects are described in regions of x
  - (1) Shadowing
  - (2) Anti-Shadowing
  - (3) EMC Effect
  - (4) Fermi Motion

Available Nuclear PDFs

- **Multiplicative nuclear correction factors**

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

  - **HKN**: Hirai, Kumano, Nagai
    [PRC 76, 065207 (2007), arXiv:0709.3038]
  - **DSSZ**: de Florian, Sassot, Stratmann, Zurita
    [PRD 85, 074028 (2012), arXiv:1112.6324]
  - **EPS**: Eskola, Paukkunen, Salgado
    [JHEP 04 (2009) 065, arXiv:0902.4154]
    EPPS16: Eskola, Paakkinen, Paukkunen, Salgado
    [arXiv:1612.05741]
  - **KT16** H.Khanpour, S.A.Tehrani
    [PRD 93, 014026 (2016), arXiv:1601.00939]

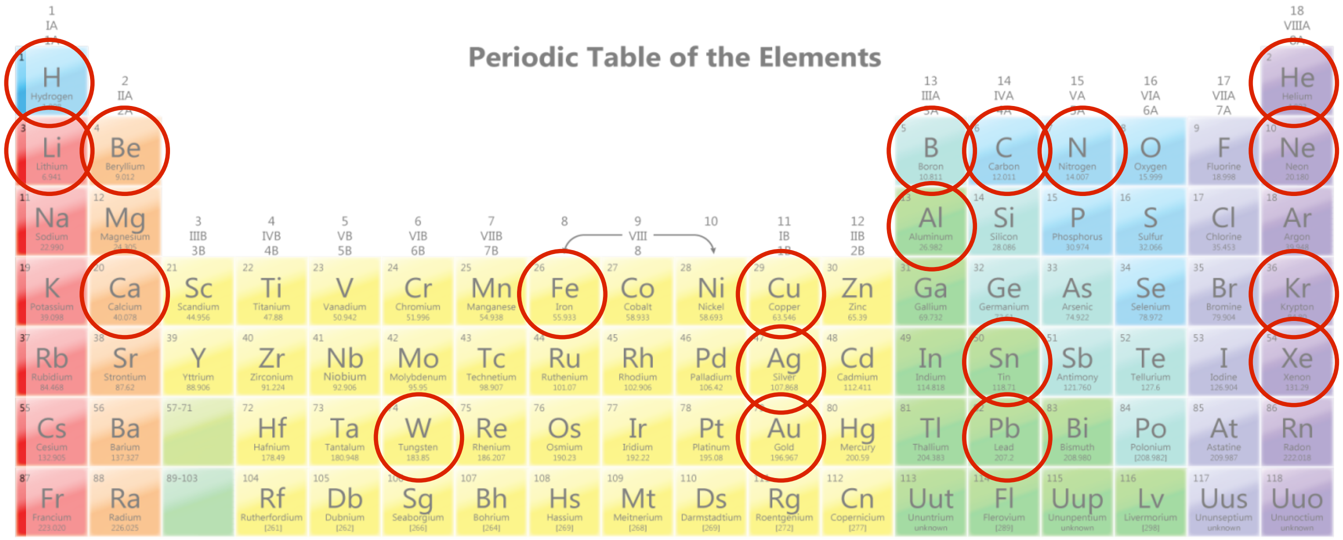
- **Native nuclear PDFs**
  - **nCTEQ15** [PRD 93, 085037 (2016), arXiv:1509.00792]

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

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

nCTEQ PDFs

See A. Kusina talk!



Nuclei with DIS data included in nCTEQ15 – generalized A parametrization

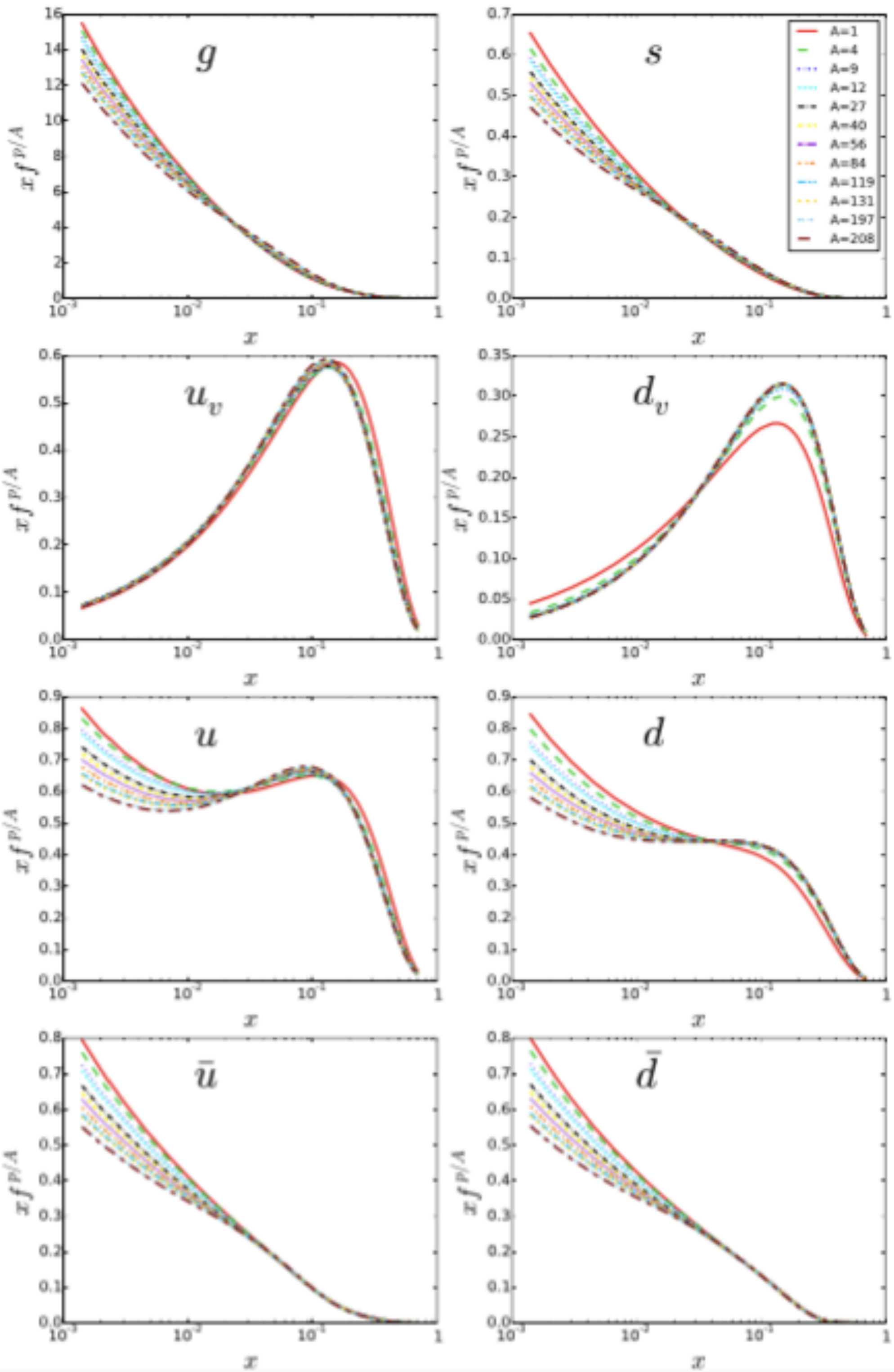
$$f_i^{(A,Z)}(x,Q) = \frac{Z}{A} f_i^{p/A}(x,Q) + \frac{A-Z}{A} f_i^{n/A}(x,Q)$$

$$x f_i^{p/A}(x,Q^2) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1+e^{c_4} x)^{c_5}$$

$$c_k \to c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

- Bound neutron PDFs ($f_i^{n/A}$) constructed assuming isospin symmetry
- Bound proton PDFs parametrized
- ~3 x more parameters than nucleon fits – assumptions needed!

nCTEQ Results: Bound Proton PDFs



Range of nuclei from the free proton (A = 1) to lead (A = 208)

Q = 10 GeV

The gluon and sea-distributions decrease at small x values with increasing A

nPDF nuclear correction factors for uv and dv treated as independent

- uv is suppressed and dv is enhanced in the EMC region.
- Flavor dependent EMC effect*?

Can be tested with Jefferson Lab Hall A ^{3}H/^{3}He data being obtained now!

*I. C. Cloet, W. Bentz, and A. W. Thomas (Phys. Rev. Lett. 102 (2009) 252301)

*D. Dutta, J. C. Peng, I. C. Cloet, and D. Gaskell, Phys. Rev. C83 (2011) 042201

JEFFERSON LAB HALL A TRITIUM TARGET

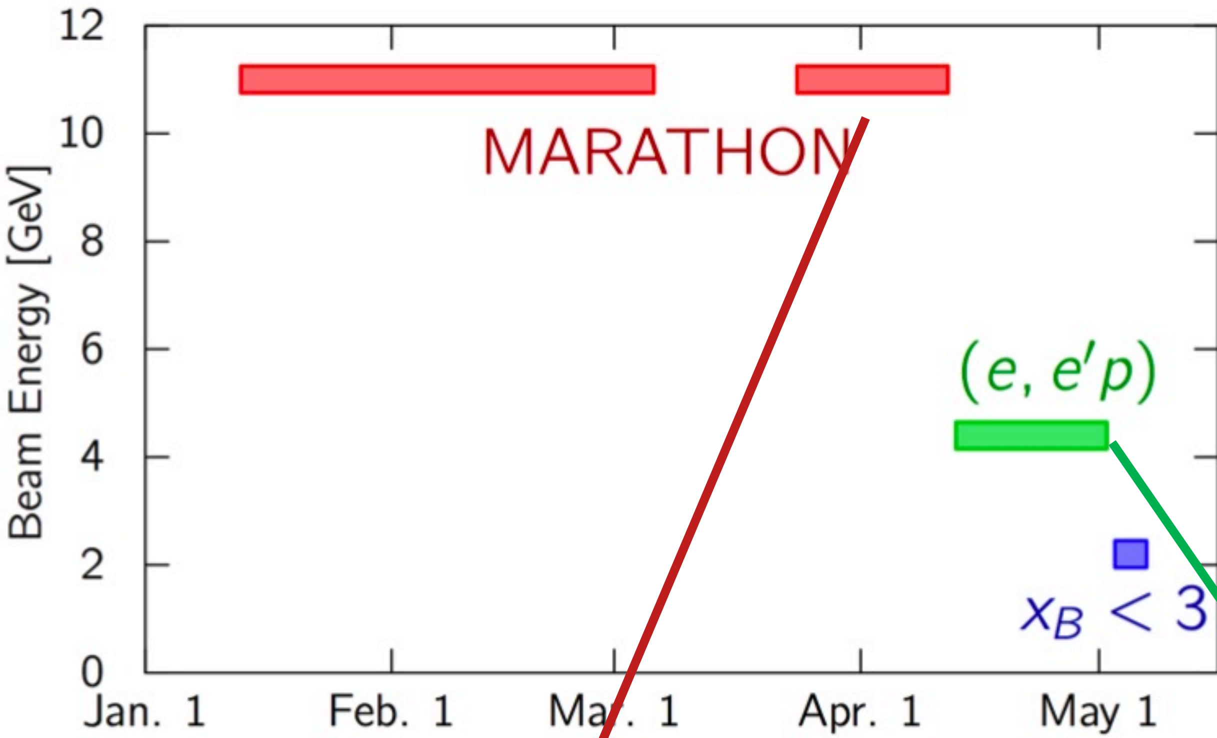
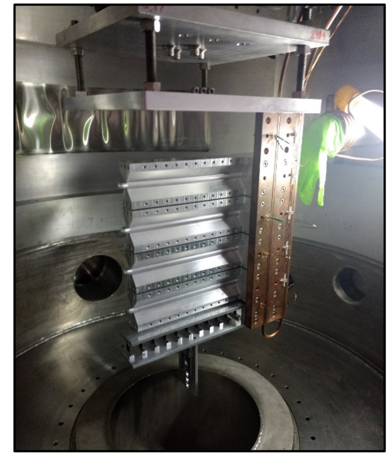
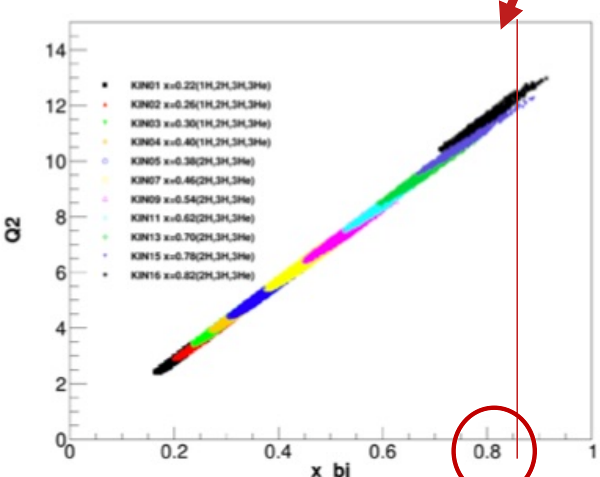


Figure by A.Schmidt



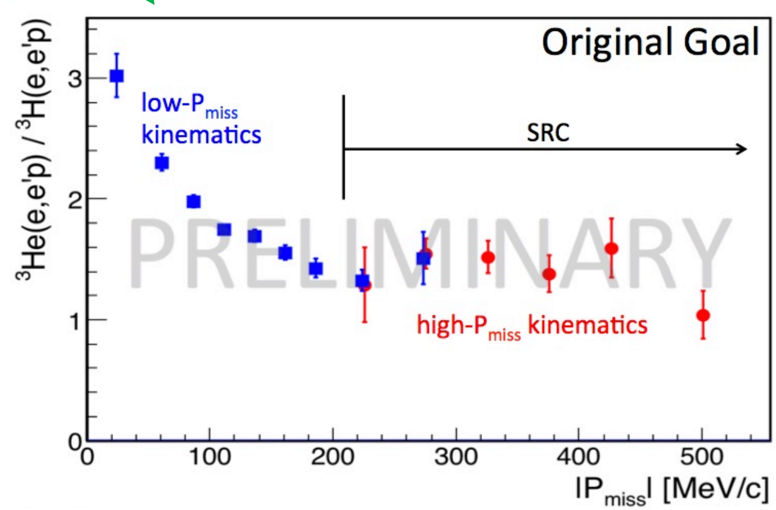
The first tritium target for electron scattering in 3 decades!



MARATHON kinematics plot from T. Su

Running tritium family of 5 experiments in 2018 – 3 already complete

Preliminary results plot from R. Cruz Torres



nCTEQ15 PDFs

The compatibility of neutrino and charged lepton nuclear DIS data has been studied independently by several nPDF groups.

nCTEQ:

Phys. Rev. D **77**, 054013 (2008)
Phys. Rev. D **80**, 094004 (2009)
Phys. Rev. Lett. **106**, 122301 (2011)
K. Kovarik *et al.*. Phys.Rev. D **93** 8, 085037 (2016)

Q > 2.0 GeV, W > 3.5 GeV
(standard CTEQ cuts)

A-dependence introduced directly into distributions at input scale Q = 1.3 GeV

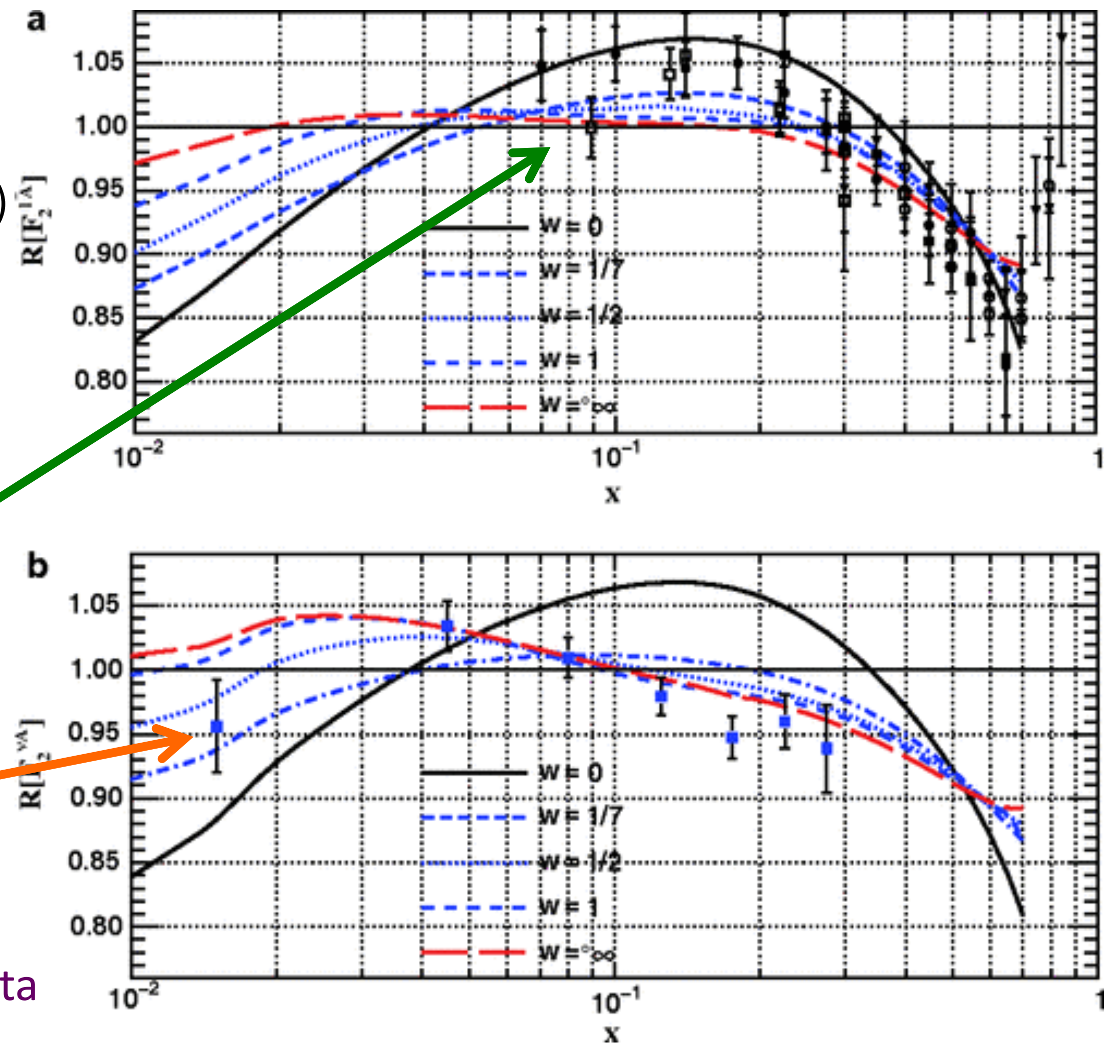
Use ACOT - heavy quark mass effects - in NLO QCD

Charged lepton data

Neutrino data

Fits with different weighting of neutrino data

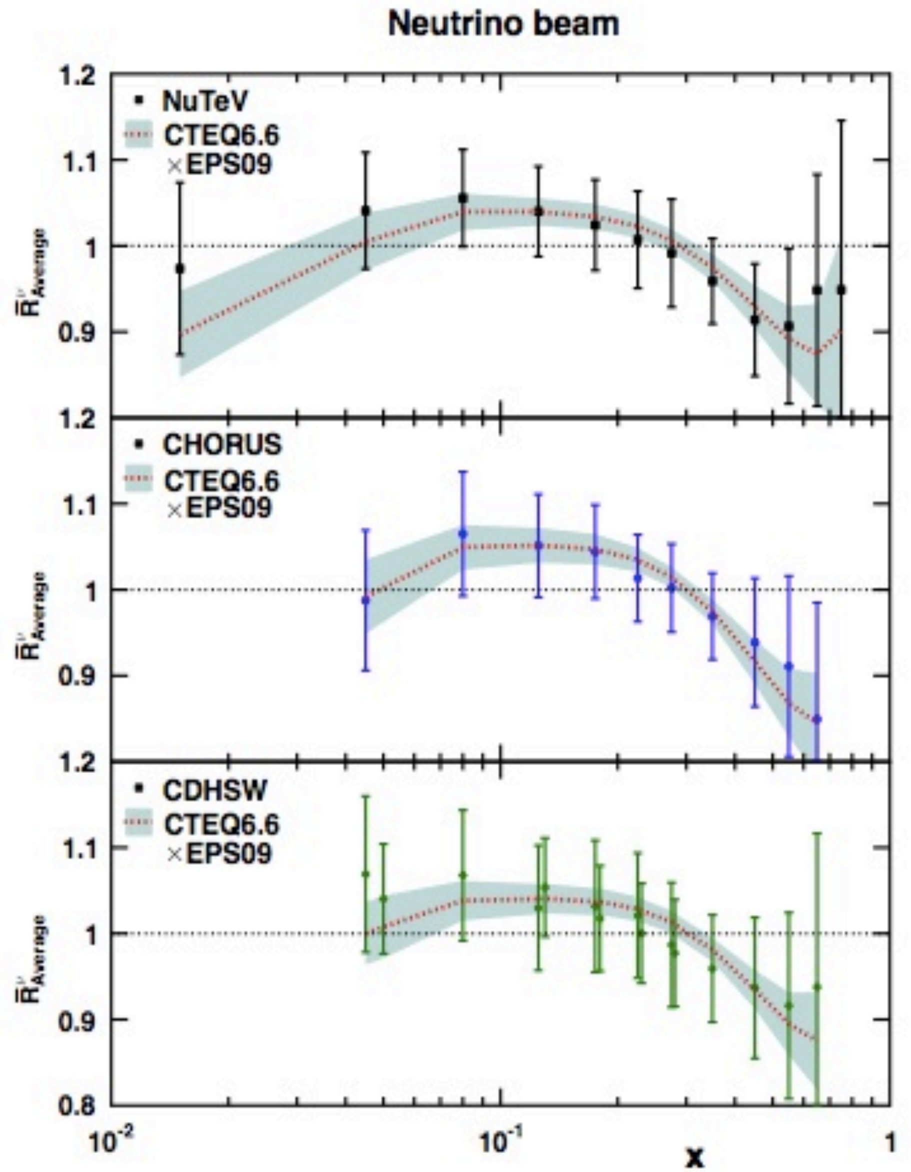
$Q^2 = 5\ GeV^2$



ν-A dependence different from *e/μ-A*

BUT…

- Conclusions from different groups are contradictory, ranging from a violation of the universality up to a good agreement



Example:
H. Paukkunen, C. Salgado, Phys. Rev. Lett. 110:212301 (2013)

Consider non-negligible differences in the absolute normalization between different neutrino data sets… procedure to accommodate this.

With the normalization procedure, the NuTeV data seem to display tension with the other neutrino data.

ν-A dependence **compatible** with e/μ-A

What's going on?

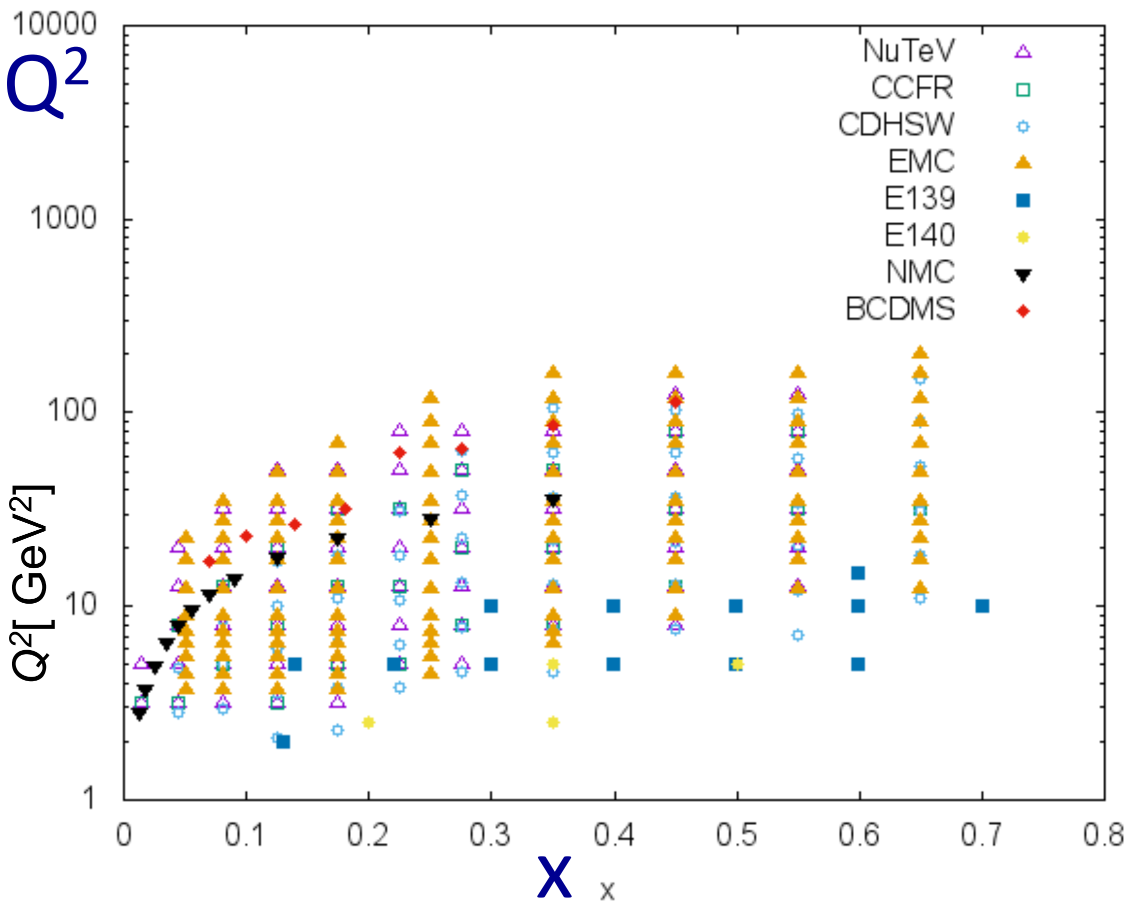
The nPDF efforts fit nuclear effects using the canonical F_2^A/F_2^D ratios as a function of x

However, there are essentially NO neutrino F_2^D data!

Comparisons are necessarily to *modeled* deuterium data

We decided to try and compare only F_2^A data
- start with Fe, largest data set covering both charged lepton and neutrino data over a range of x,Q….

World F^{Fe}_2 Data



Wide range in x, Q^2!

x

Neutrino Expts ***(open symbols)***:
CCFR, CDHSW, NuTeV

Charged Lepton (e/μ) Expts:
BCDMS, EMC, E140, E139,NMC

Most available at Durham data base:

http://hepdata.cedar.ac.uk/review/f2/

E139 cross sections available at:
slac/stanford.edu/exp/e139/
- used parameterization of R to get F_2

BCDMS and NMC were available in ratios of Fe to D
- used fit of F_2^D from NMC to obtain F_2^{Fe}

Evaluated model dependence of the above

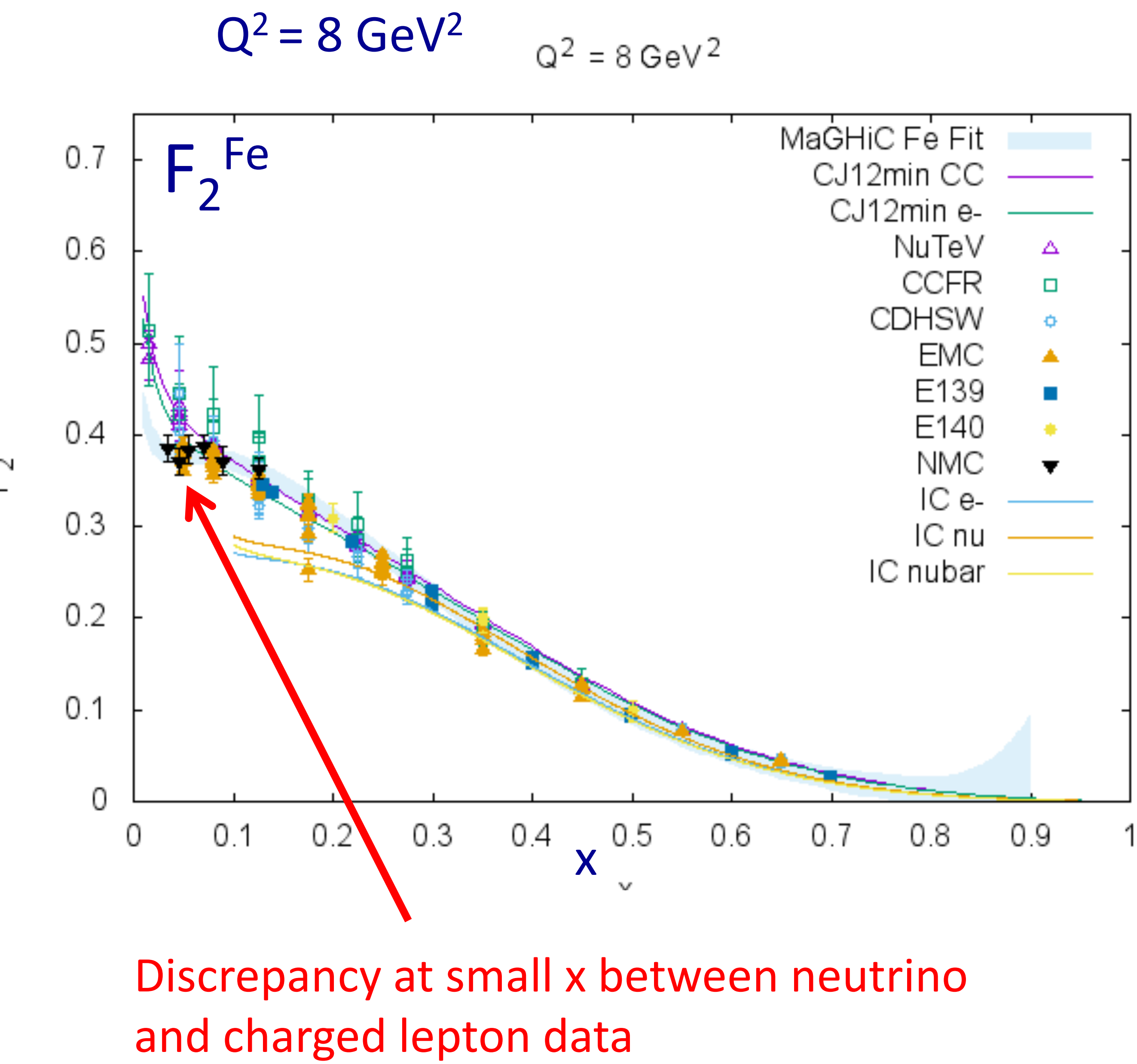
Analysis

- All data used were isoscalar corrected when published. We did not alter these corrections, used data as presented.
  - Large at small *x* for neutrino, and large x for charged leptons
  - Correction is SMALL for Fe

- Applied "DIS" cuts; $Q^2 > 2$, $W^2 > 4$ GeV^2
- Set F^{Fe}_2 data to a common Q^2 (bin-centering) using NMC fit*, checked for dependence on this fit
- Neutrino data are a flux-weighted average of nu, nu_bar data
- Multiply neutrino data by 5/18 to account for quark charges.

*H.Abramowicz, A.Levy, hep-ph/9712415,
Q^2 dependent, with F2n/F2p added by A. Bruell

Results: F_2^{Fe} Data – NOT a ratio to deuterium!



Neutrino data open symbols, charged lepton closed

$2 < Q^2 < 20$ GeV^2, bin-centered to 8 GeV^2

MaGHiC fit is to charged lepton data (Malace, Gaskell, Higinboham, Cloet, Int. J. Mod. Phys. E 23 (2014) 1430013)

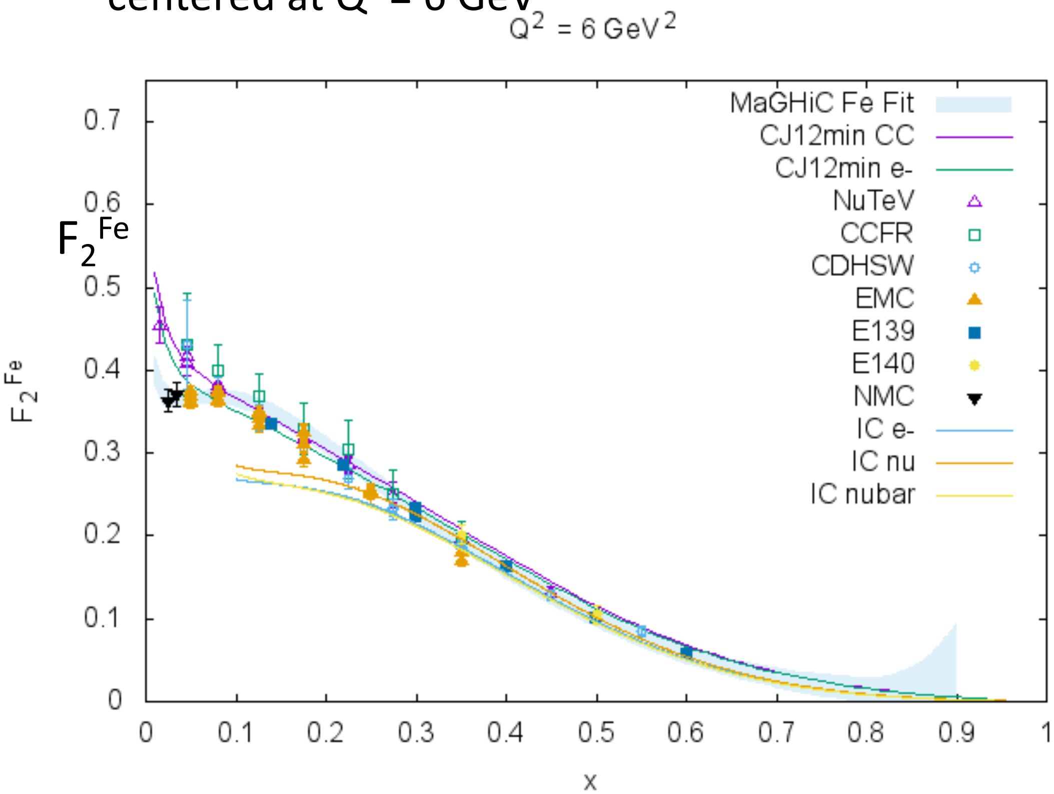
Cloet fit is valence only
- good agreement!

Charged lepton data agree with charged lepton and neutrino data with neutrino, no normalizaions applied

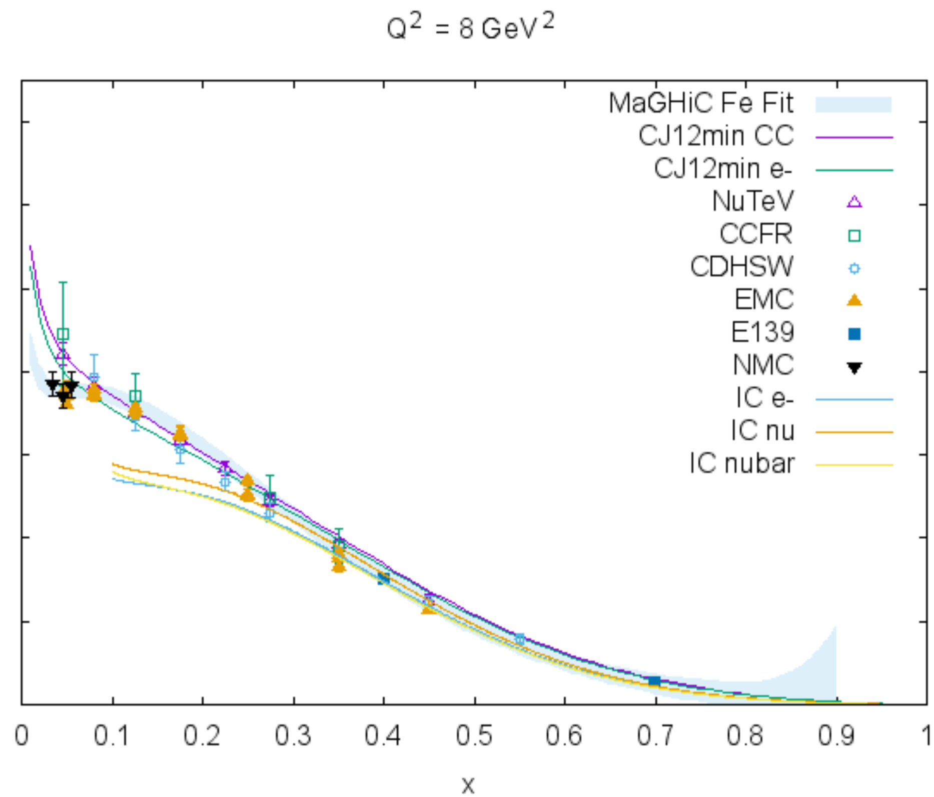
Remarkable agreement of all data at x > 0.1, 18/5 works within ~5%

Smaller bins in Q^2

$4 < Q^2 < 8$
centered at $Q^2 = 6\ GeV^2$



$6 < Q^2 < 10$
centered at $Q^2 = 8\ GeV^2$

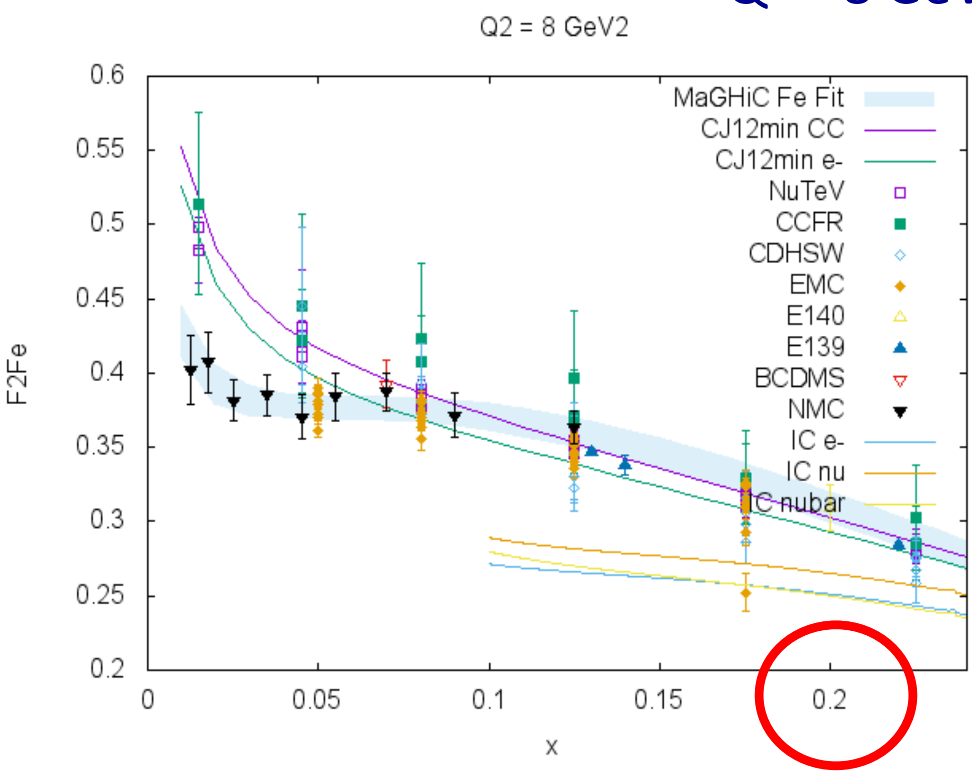


- Same observations:
  - remarkably good agreement of neutrino, charged lepton at large x
  - surprisingly bad at small x
- Both CJ and Cloet theory curves are shown with both electron and CC
  - Should depict size of strangeness difference
  - Does not account for large discrepancy at low x
- Charged lepton data agree with MaGHiC fit – not surprising
- Neutrino data seem to be in agreement with CJ12min fit (Phys. Rev. D **87** 094012 (2013))
  - no nuclear effects taken in to account, just add free neutrons and protons

Look closer

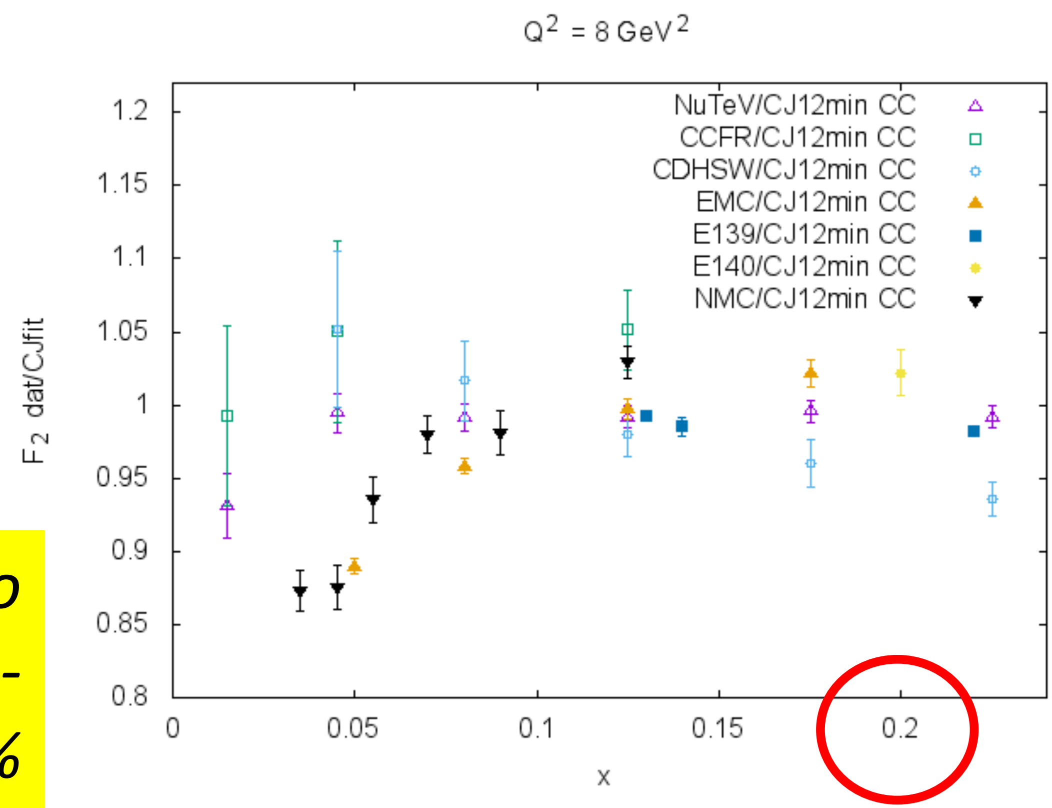
F_2^{Fe} zoom

Q^2 = 8 GeV^2



Ratio to CJ electron, at lowest x:

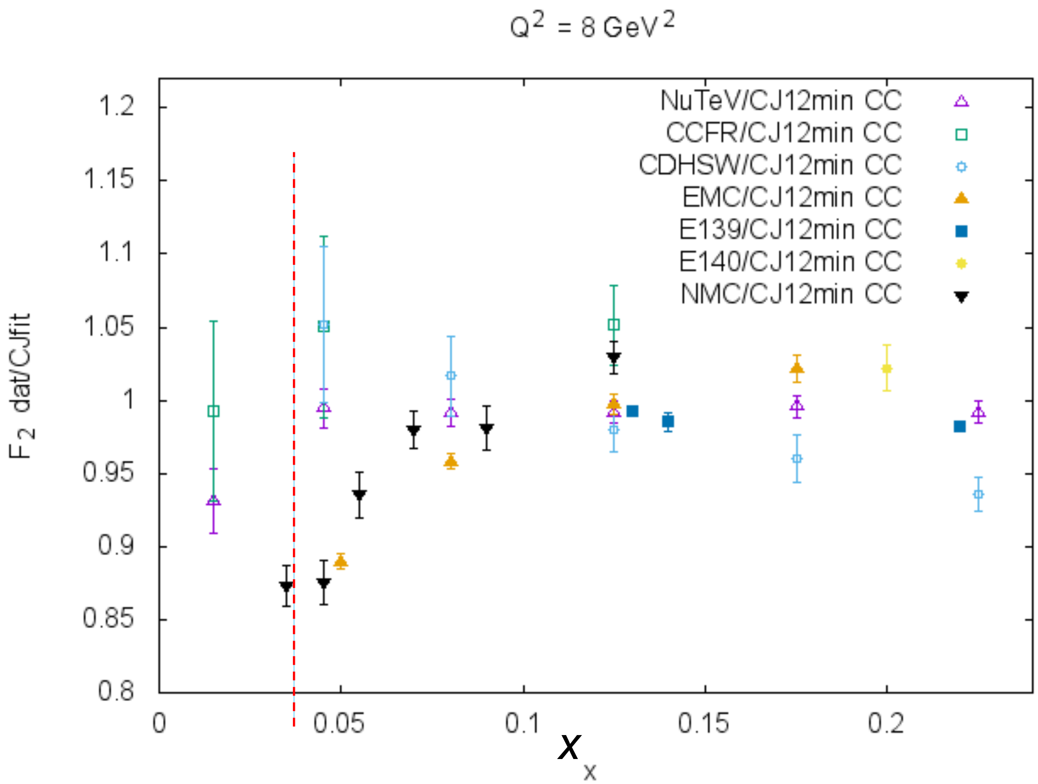
- Neutrino data ratio ~1
- Charged lepton ratio < 0.9

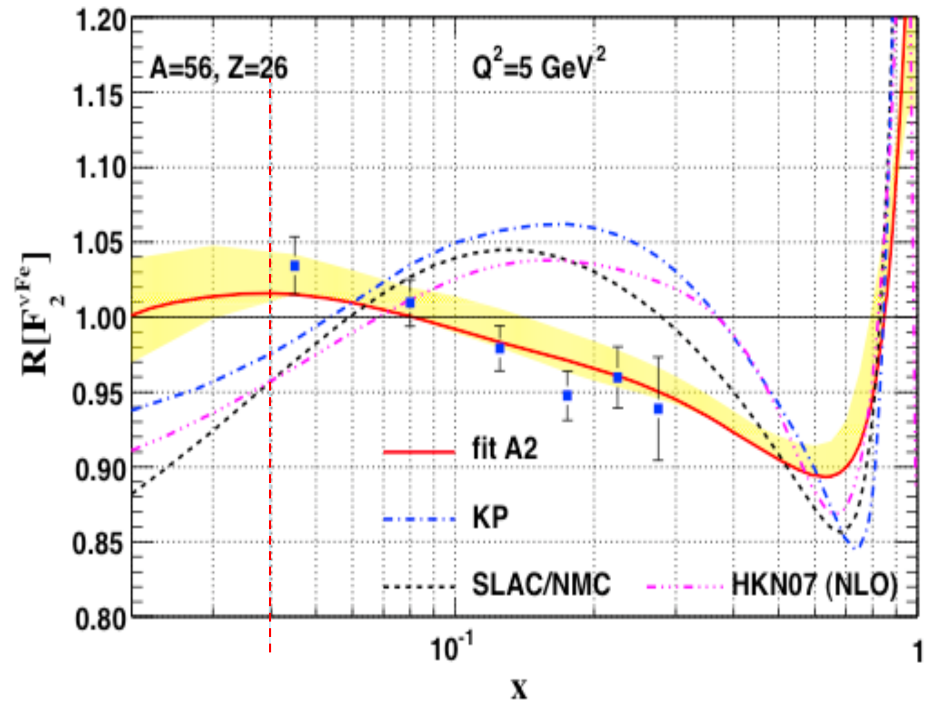


N. Kalantarians, CK, M.E. Christy Phys.Rev. C96 (2017) no.3, 032201

Looks to be ~10-15% effect

Compare with nCTEQ





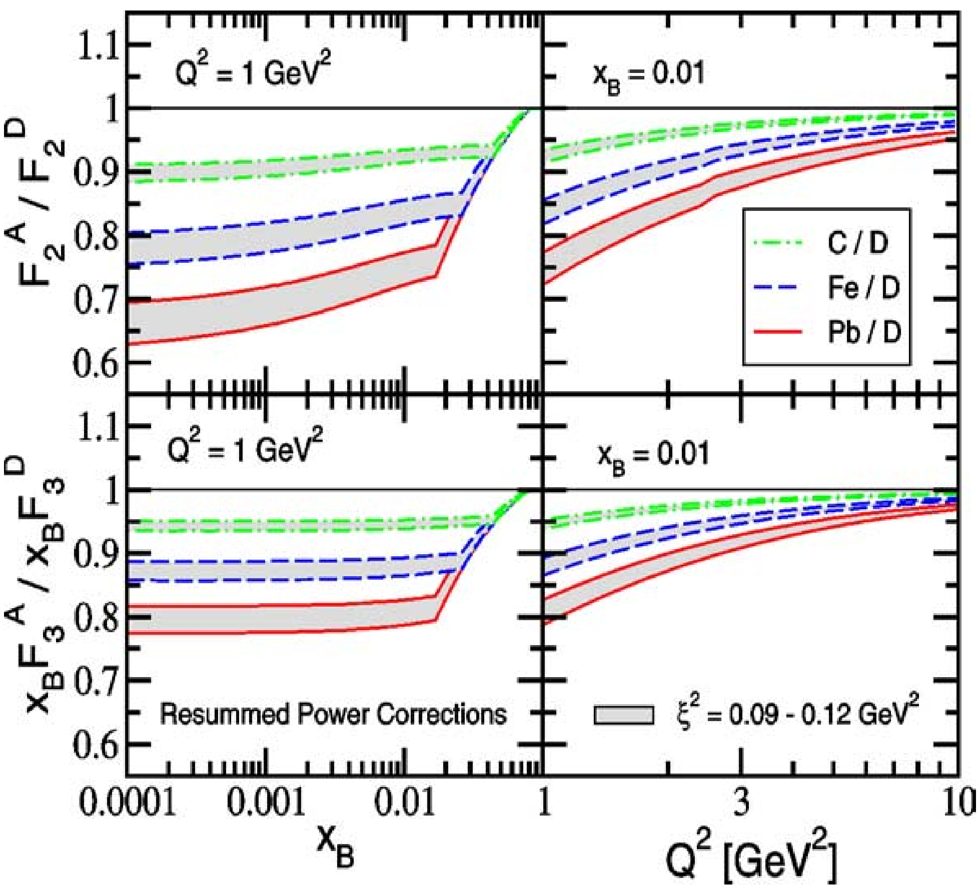
- *Same trend*, perhaps somewhat larger effect in data
- Deuteron model in nCTEQ could be moderating

Not completely new..

- C. Boros, J.T. Londergan, A.W. Thomas, Phys.Rev.Lett. 81 4075 *(1998!)*
- CCFR and NMC only, smaller data set available
- *Ascribed discrepancy to CSV*

Many theory predictions for different e-A, ν-A effects…

Qiu and Vitev, Phys. Lett. B **587**, 52 (2004)



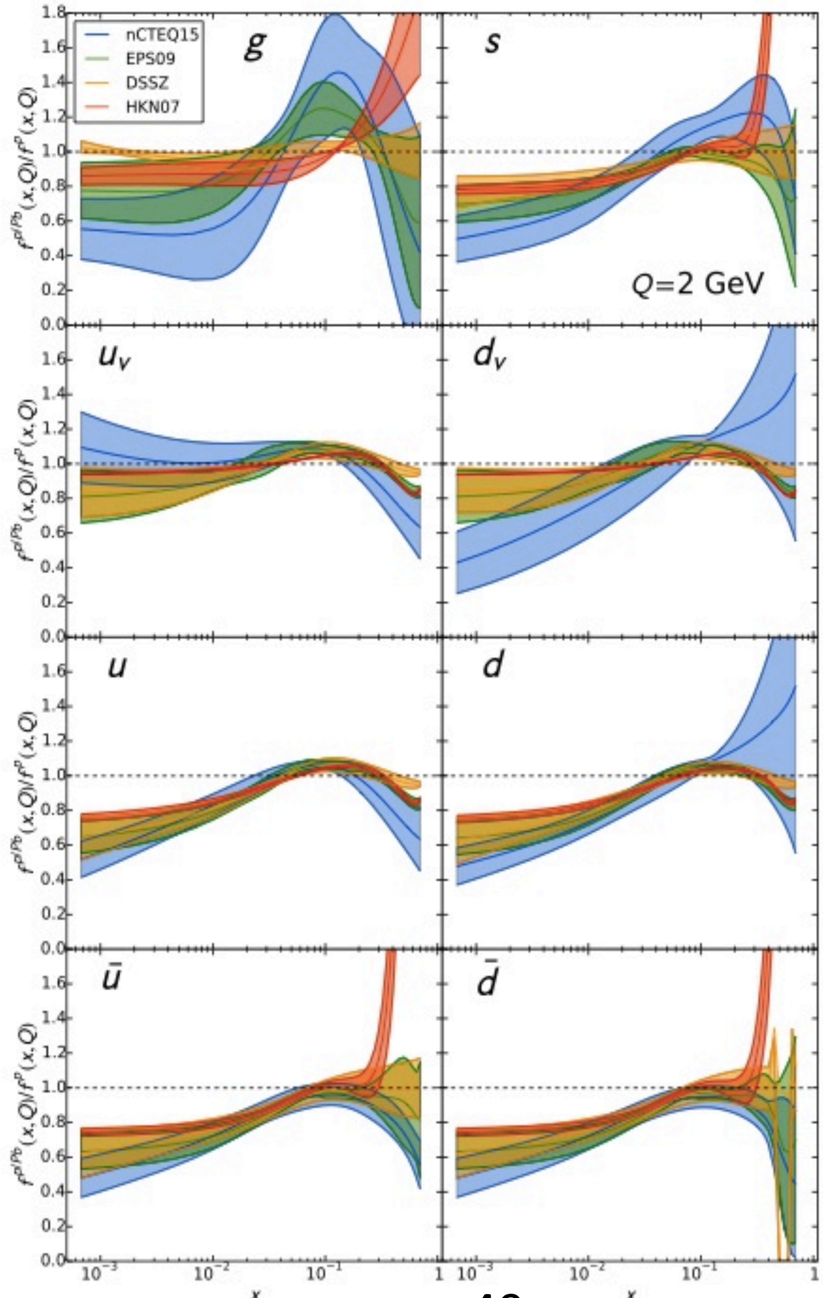
And More… *please accept my apologies for not mentioning all!*

- Sizeable, A-dependent effects in shadowing region (Frankfurt, V. Guzey, M. Strikman, Phys. Rept. 512, 255 (2012))
- Isospin-dependent nuclear forces lead to flavor-dependence of nuclear PDFs (Cloet, Bentz, Thomas, Phys.Rev.Lett. 109 (2012) 182301)
- Nuclear medium effects important, meson cloud contributions (Haider, Simo, Athar, and Vacas, Phys. Rev. C 84, 054610 Phys. Rev. C **84** 054610 (2011))
- Global analysis including nucleon binding, Fermi motion, off-shell effects,.. (Kulagin and Petti, Phys. Rev. D76:094023, Phys. Rev. C 90, 045204 2007)
- The axial-vector current allows shadowing *at lower n* than the vector current (B. Kopeliovich, Nucl. Phys. Proc. Suppl. 139: 219-225, 2005)

Good reasons to consider nuclear effects may be DIFFERENT in e-A and ν - A:

- Shadowing effects ~similar in Drell-Yan and DIS for x < 0.1, *BUT,* no Anti-Shadowing in Drell-Yan (in DIS 5-8% effect)
- Different probes sensitive to different partons
  - Global nuclear PDF fits suggest different nuclear effects for valence and sea
  - Presence of axial-vector current
  - Coherence length differences for vector, axial vector masses
  - F_L dominance in low Q neutrino due to PCAC term, vanishes for charged lepton

- Can measure F_L in electron scattering by performing Rosenbluth separtions to extract $R = \sigma_L / \sigma_T$ and $FL \sim \sigma_L$



nCTEQ15 PDFs

Nuclear Dependence of R: Experimental Status

Published/Preliminary extractions from **JLab**

→ L/T separations on proton and deuteron at low Q^2

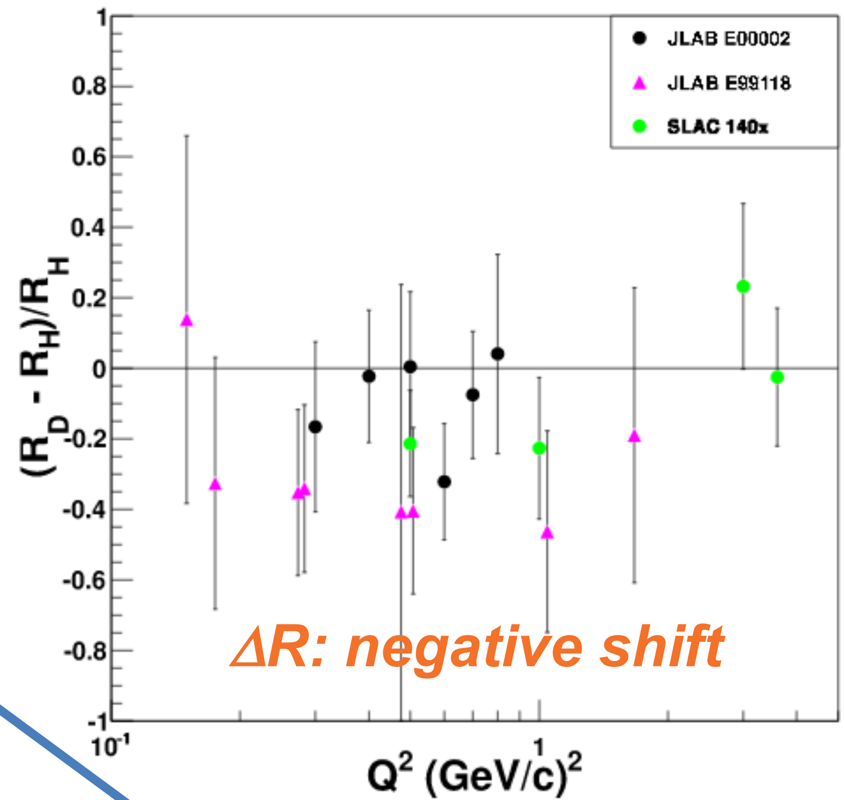
E99-118 (Hall C): *PRL 98 142301 (2007)*

$$R_D - R_H = -0.054 \pm 0.029$$

E00-002 (Hall C): PRC 97, 045204 (2018)

$$R_D - R_H = -0.042 \pm 0.018$$

Conclusion: **~20% effect in deuterium**



Low Q^2 (R larger)

The only previous model-independent extraction

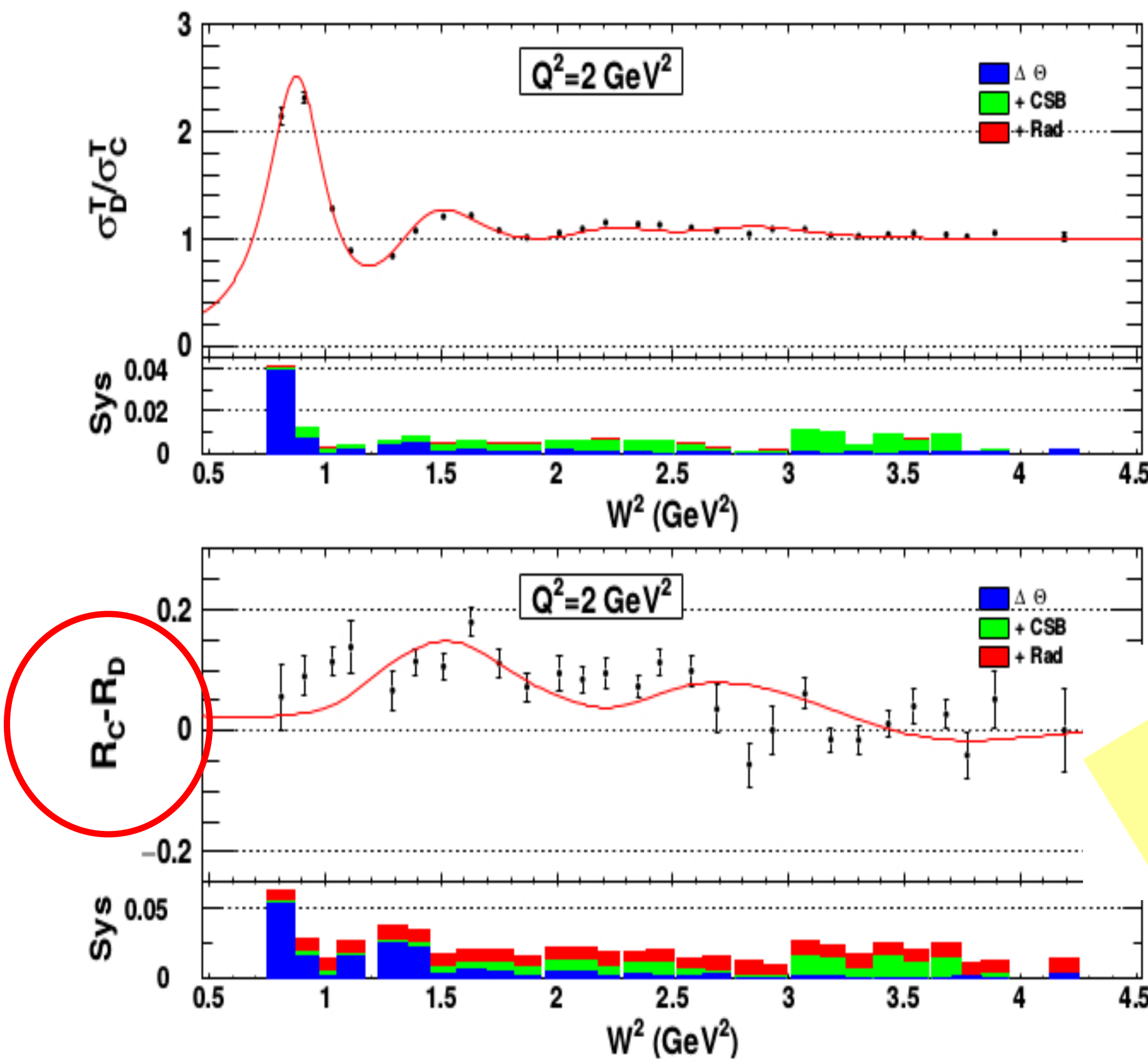
- **SLAC (E140):** *Phys. Lett. D 49 (1993)*

$$x = 0.2 - 0.5 \quad Q^2 = 1 - 5\ GeV^2$$
$$R_{Fe} - R_D \quad R_{Au} - R_D$$

ΔR consistent with zero?

High Q^2 (R smaller)

E04-001/E06-109 (JLab Hall C): final analysis, expect publication in ~months



Resonance "SIS" Region

→L/T separations on D and Al, C, Cu, Fe in the resonance region

Preliminary: $R_{Al,Cu,C} - R_D$ non-zero

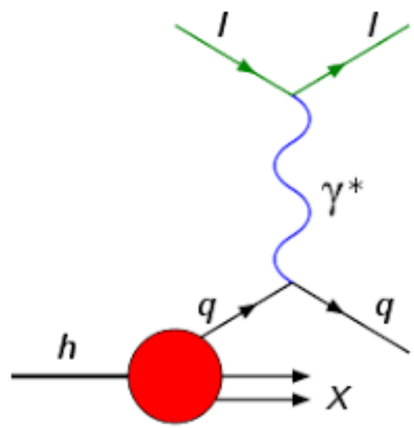
Note: R ~ 0.2, so this is a >20% effect

There appears to be a nuclear dependence to F_L in the SIS regime

Precision electron cross sections also facilitate improved modeling for vector component (in resonance region) of neutrino cross sections – see for example Bodek, Christy, Coopersmith, **Nucl. Part. Phys. Proc. 273-275 (2016) 1705-1710**

Electron Scattering Measurements Applied to Neutrino Interactions on Nuclei

- Precision measurements of isovector components of cross sections
  - Nucleons and nuclei, A-dependence
  - Form factors
  - Resonances
  - Deep Inelastic Scattering
  - Quark-hadron duality studies
- Parity violating electron scattering
  - As above!

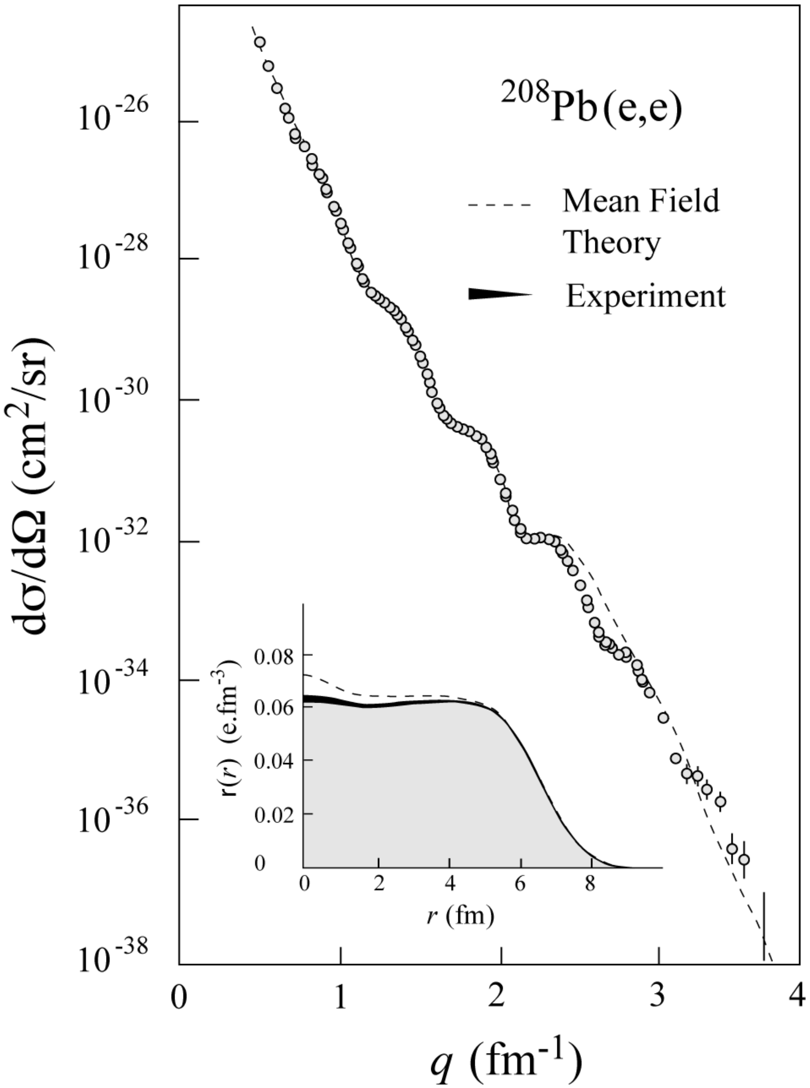


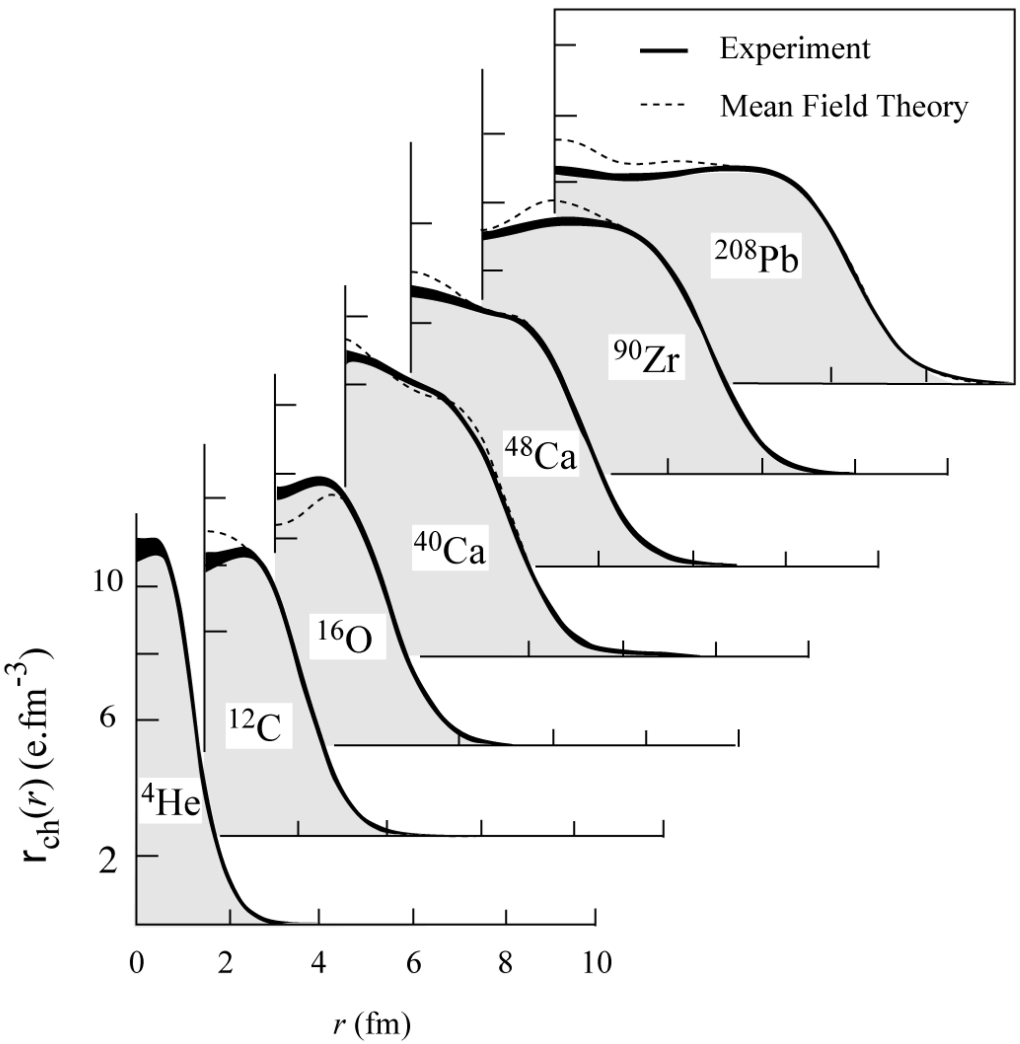
- Precision decomposition of nuclear effects – within nuclei
  - Smearing/momentum distributions
  - **Including short range correlations**
  - Additional two body effects (meson exchange currents)
  - **EMC effect**
  - Shadowing and anti-shadowing

- Nuclear interactions
  - Hadronization
  - Final state interactions

Inclusive Electron-Nucleus Scattering – historical example

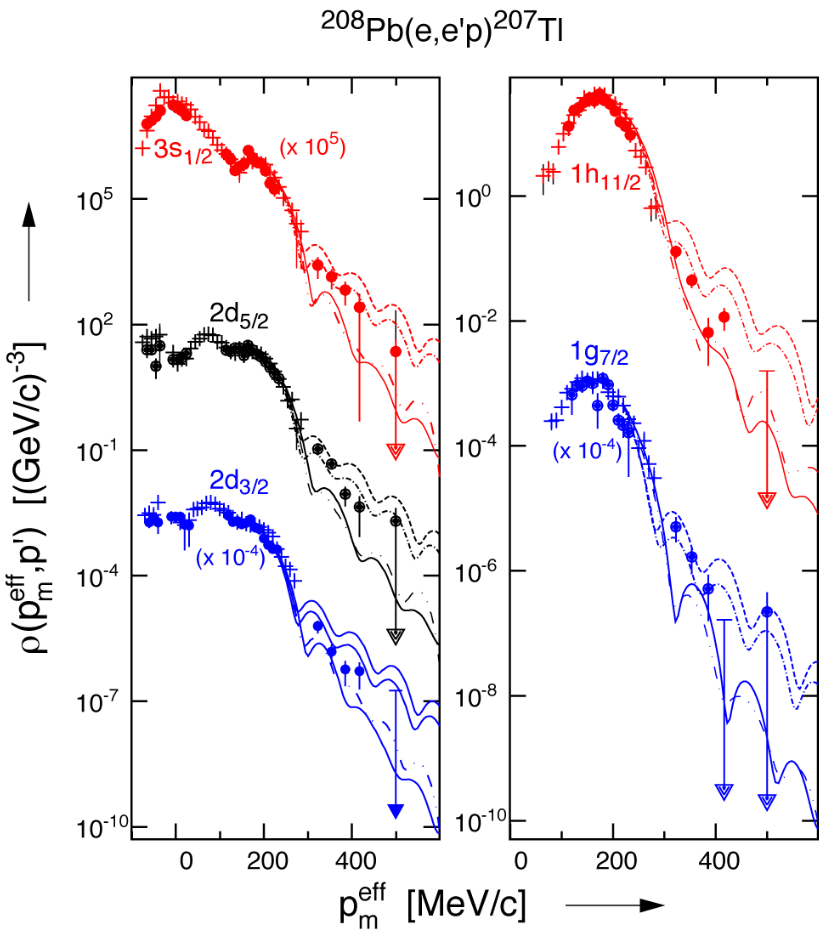
Elastic Scattering → Charge Distributions

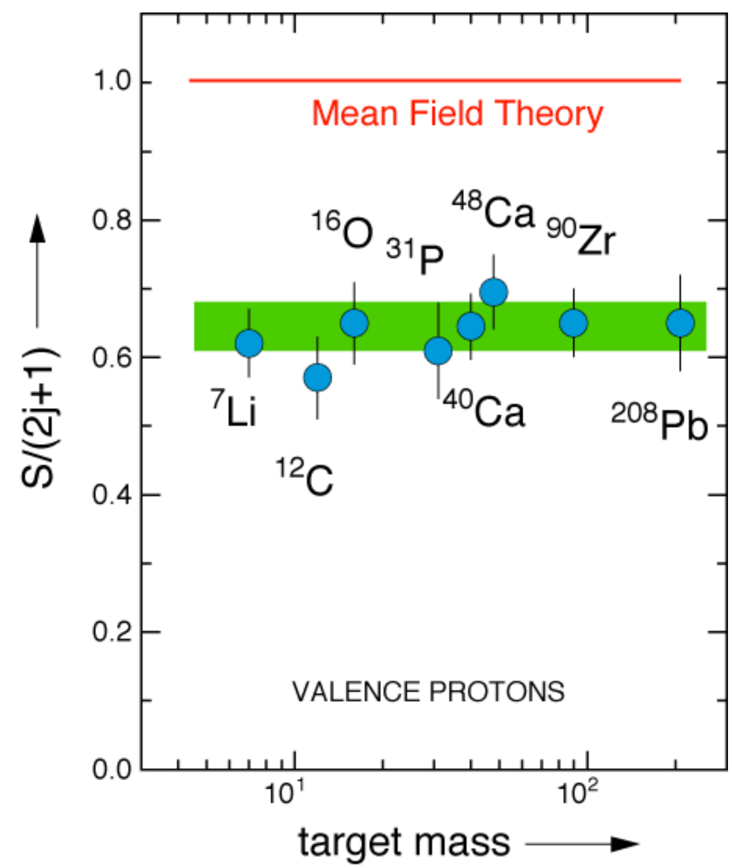




The Classic A(e,e'p)A-1 Problem

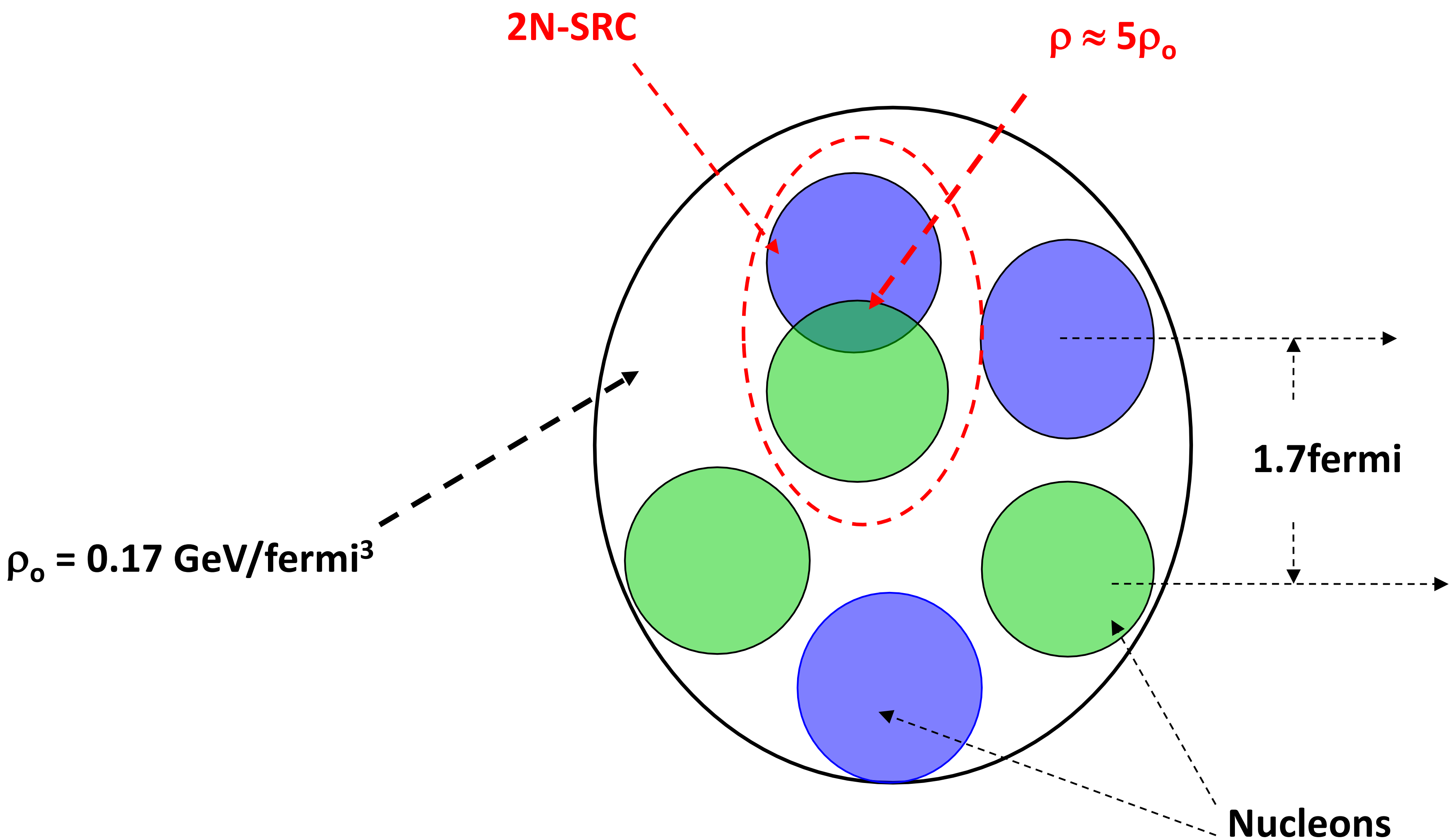
Independent-Particle Shell-Model
is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons





The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.

Possible Answer: *Short-Range Correlations*

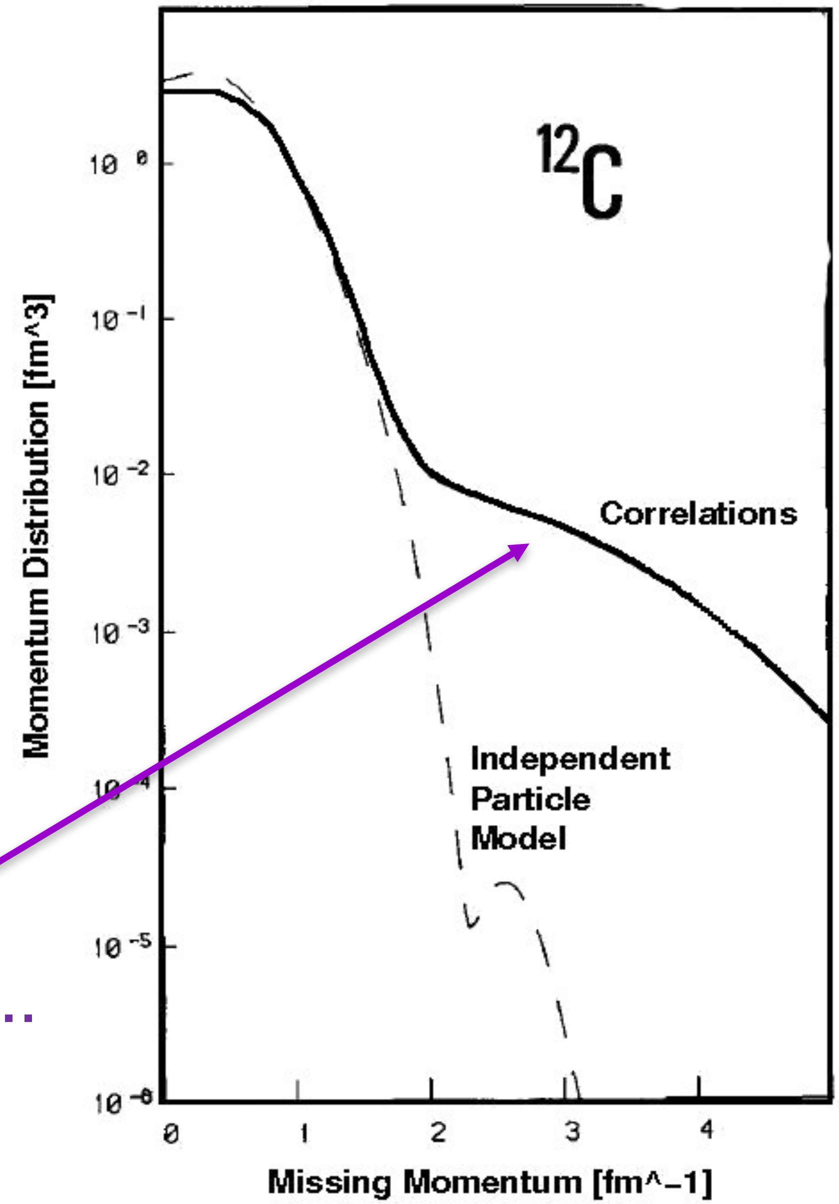


Nucleons are made up of quarks, so does NOT violate Pauli exclusion principle

If Correct Raises More Questions

- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

Benhar et al., Phys. Lett. **B** 177 (1986) 135.

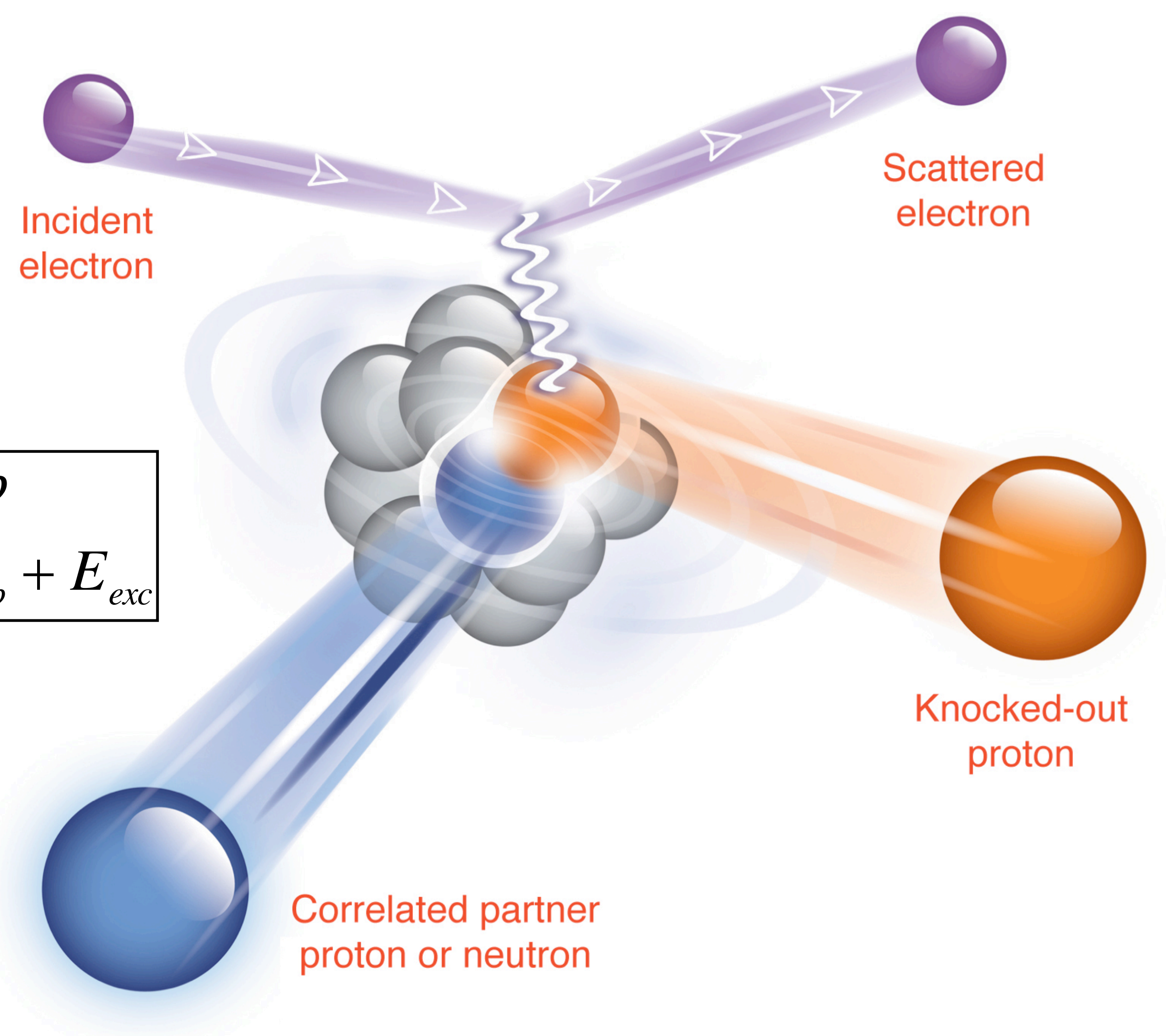


Measure out here…!...

Coincidence (e,e'pN) Exclusive Measurement

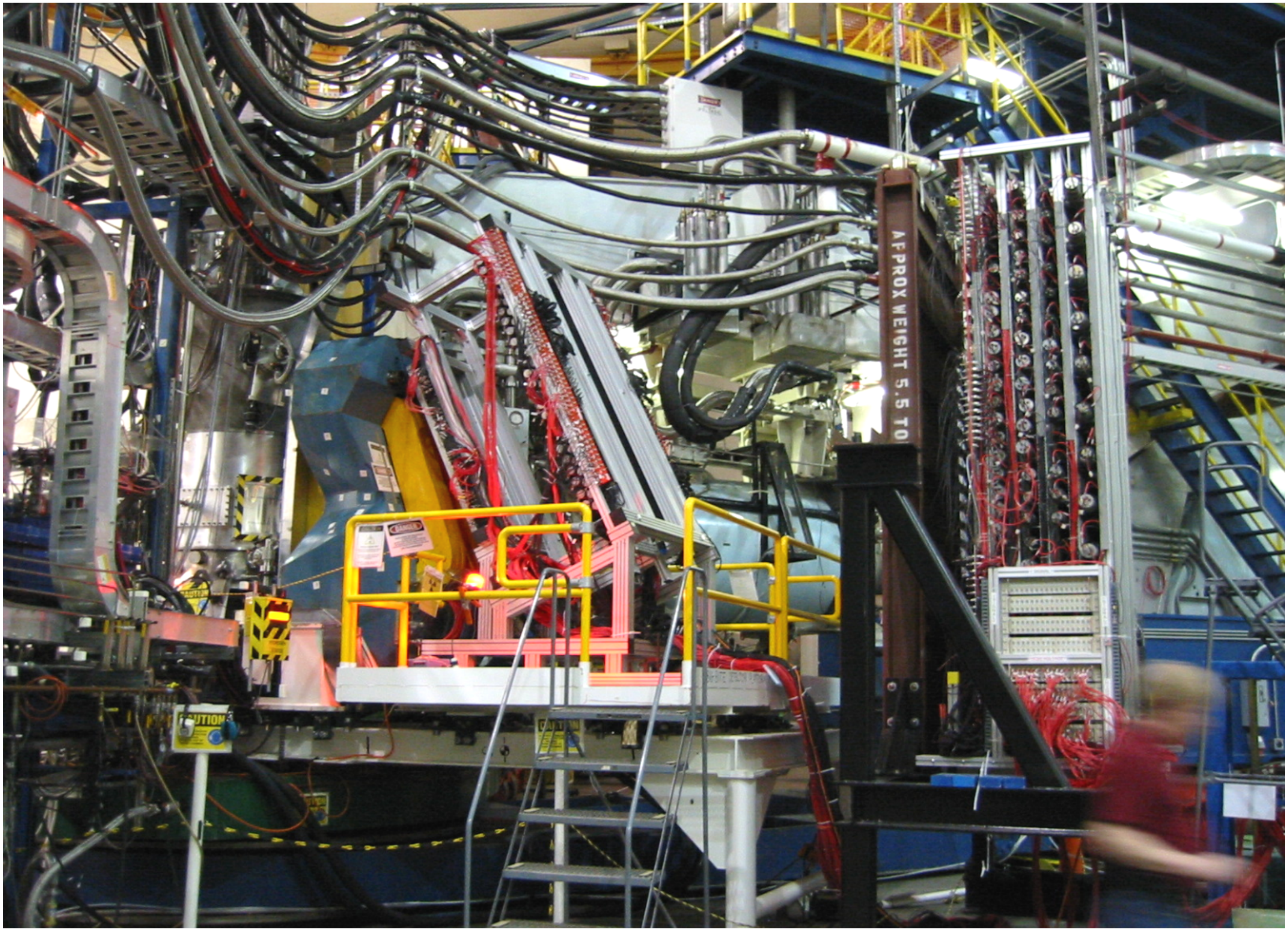
Study nucleon pairs and the fraction that contribute to momentum tail.

$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$



x > 1 , Q^2 = 1.5 $[GeV/c]^2$ and missing momentum of 500 MeV/c

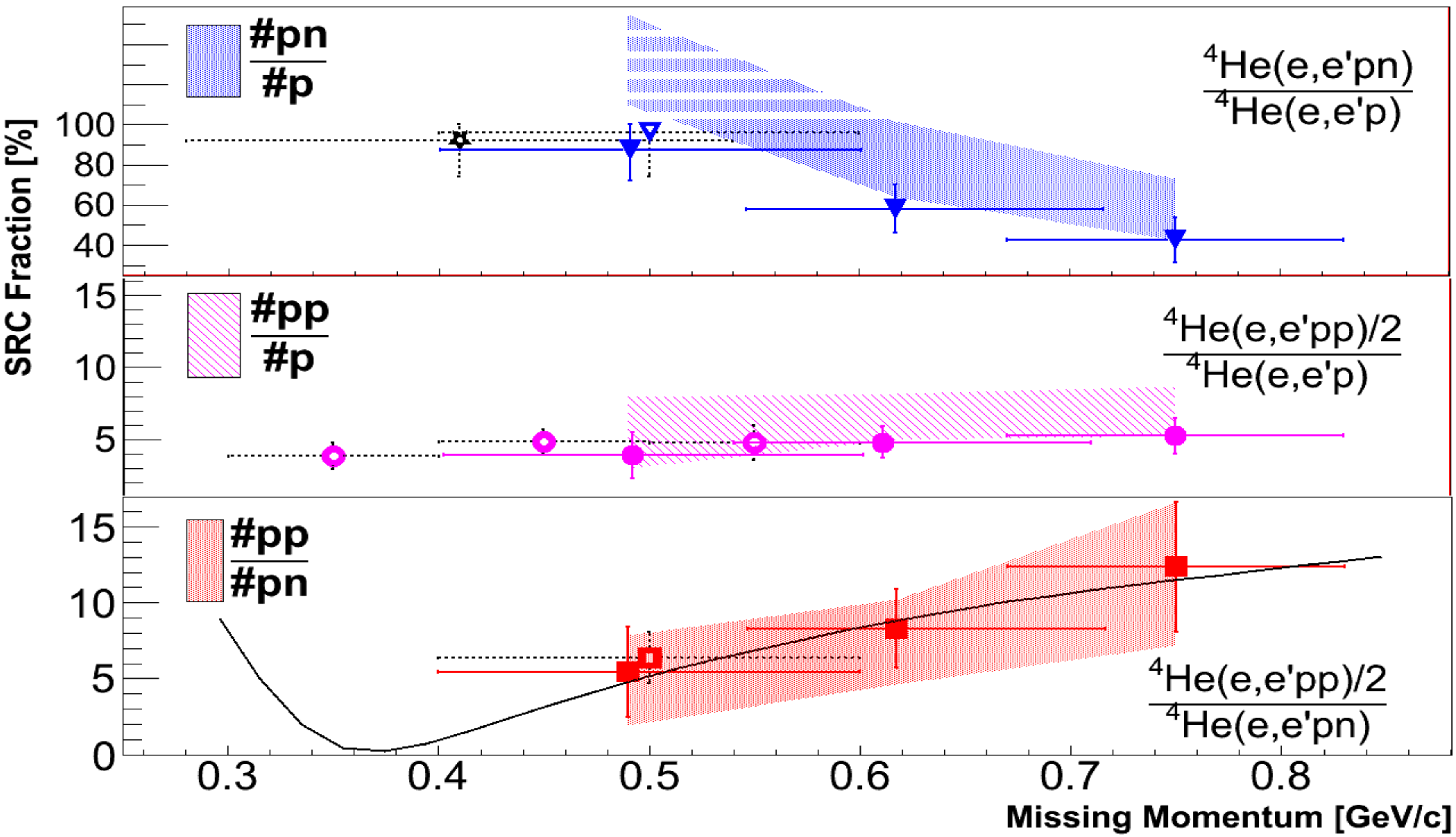
BigBite and Neutron Detector in Hall A



First step along the way to many successful high luminosity, large acceptance measurements.

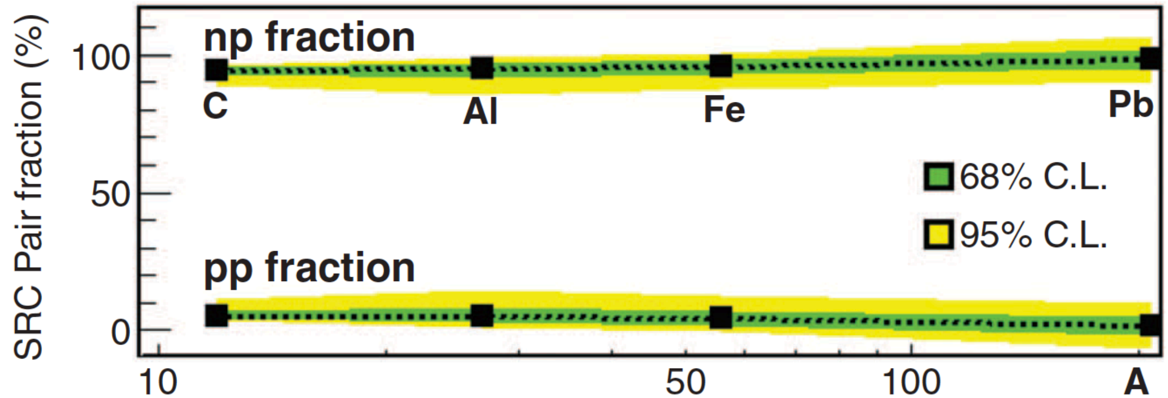
^{4}He(e,e'pN) Results – recoiling neutrons favored

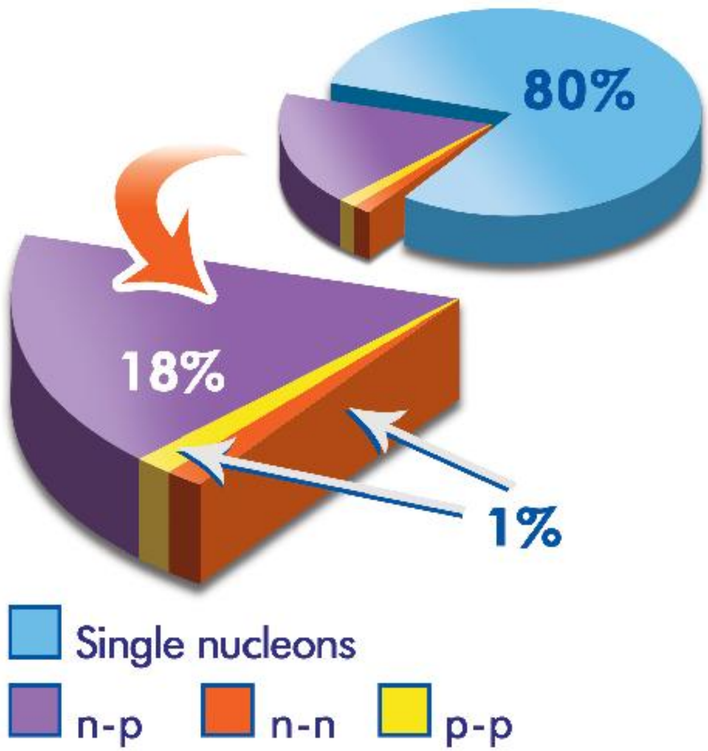
I. Korover *et al.*, Phys. Rev. Lett. **113** (2014) 022501.

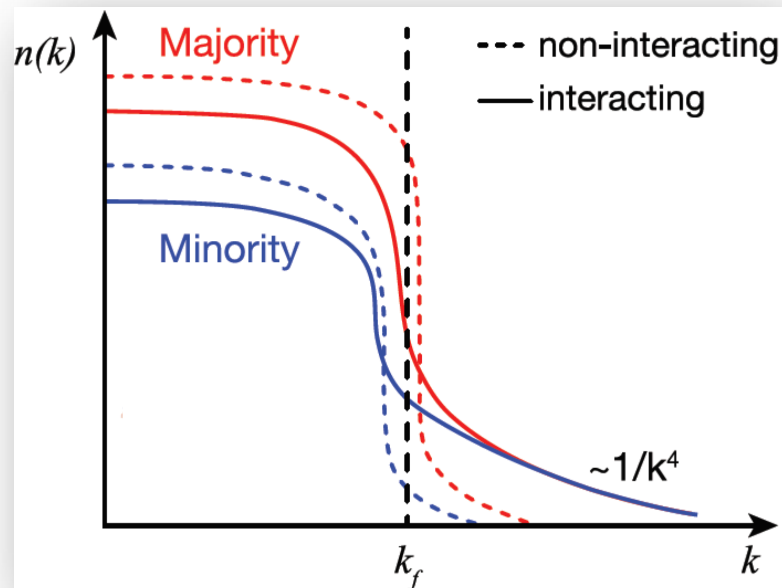


Proton-Neutron Pairing In All Nuclei

Or Hen *et al.* (Jefferson Lab CLAS Collaboration) Science 346 (2014) 614.

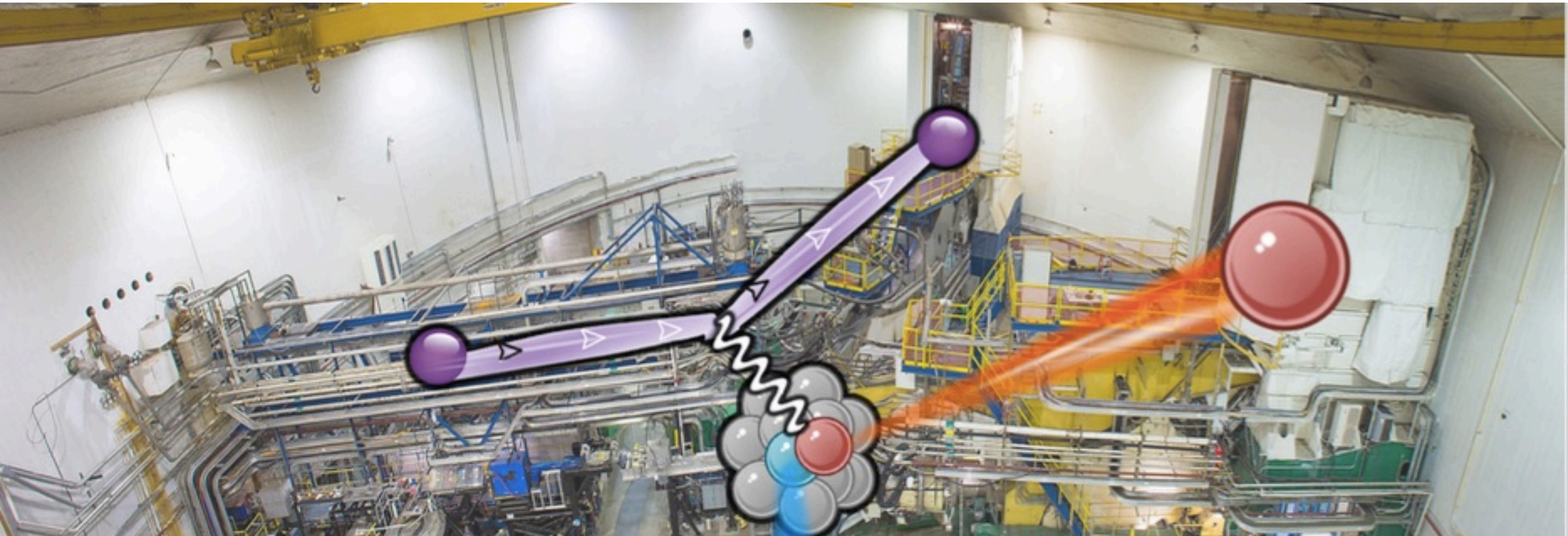




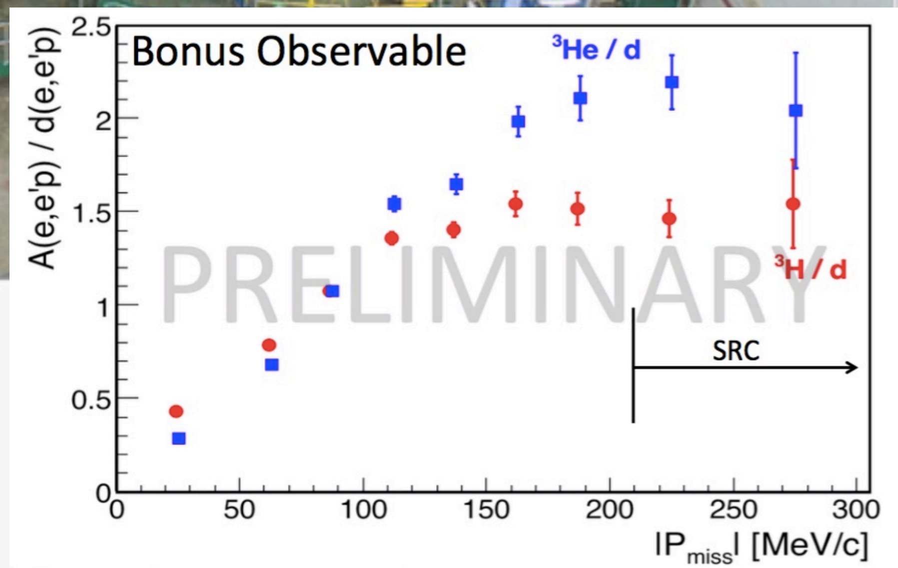


The minority particle will have a higher average kinetic energy then the majority particle.

Preliminary Results from Spring Running in Hall A
(R. Cruz Torres, MIT Hen lab at Hall A Collaboration, June 2018)

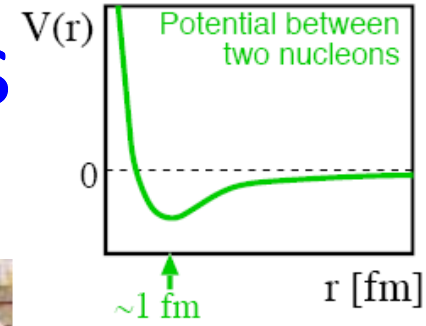


Hall A **(e, e' p) on tritium and 3He**

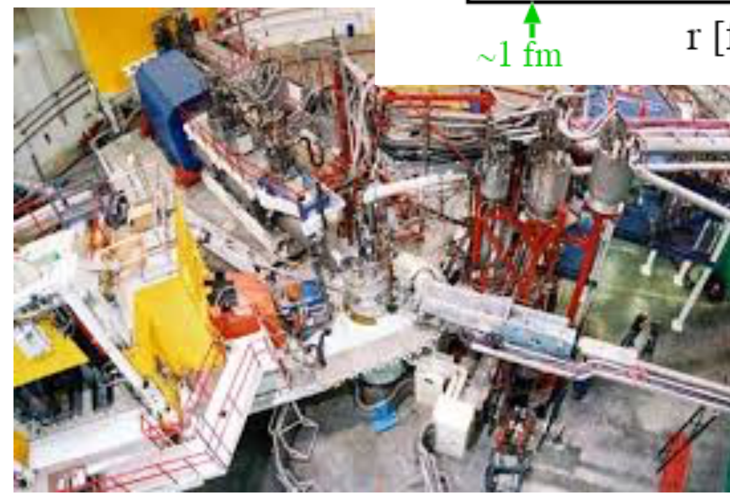


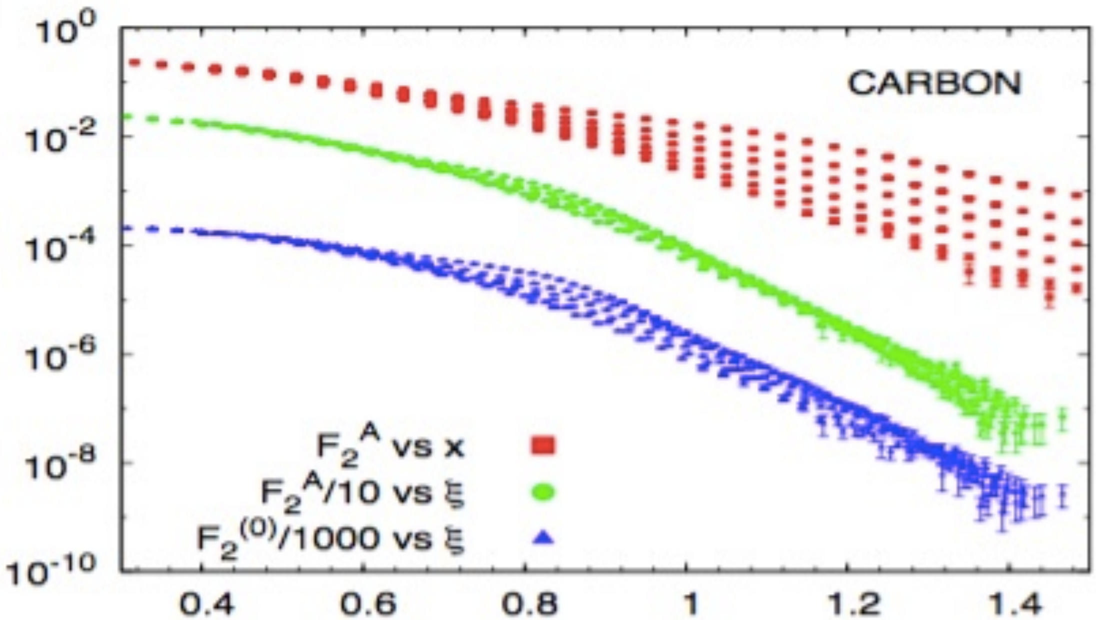
Precision (e,e’) x>1 Cross Sections

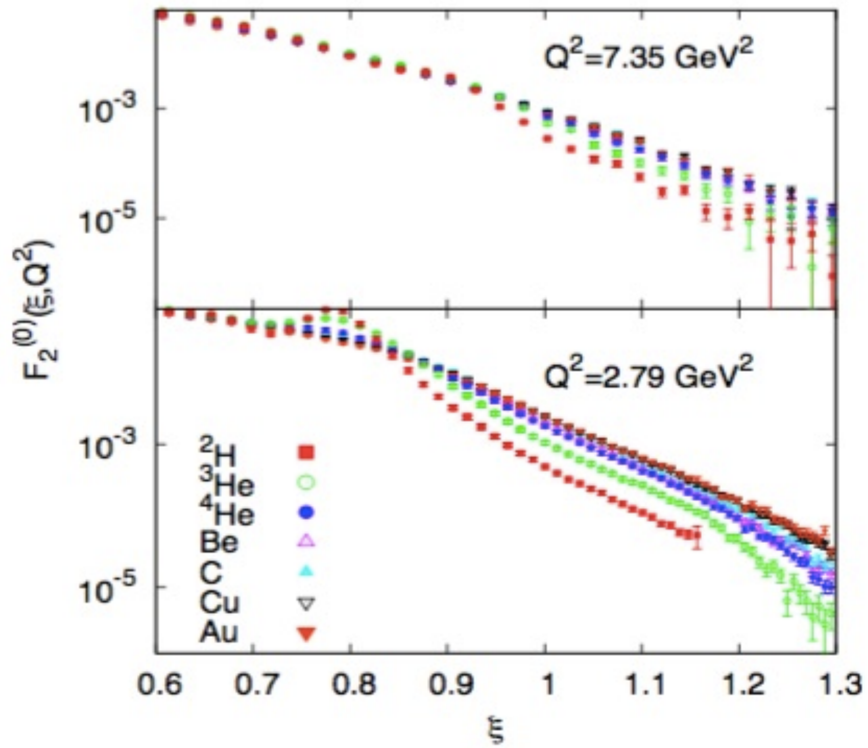
N. Fomin *et al.*, Phys. Rev. Lett. **105** (2010) 212502 – JLab Hall C



- Electron-nucleus scattering allows for F_2 structure functions above x = 1
- Nucleons are close together and interact via the (poorly-constrained) repulsive core of the N–N interaction, yielding high momentum nucleons.
- Deuteron limited to x < 2, etc.
- Deep inelastic probe of very high momentum “superfast” quarks

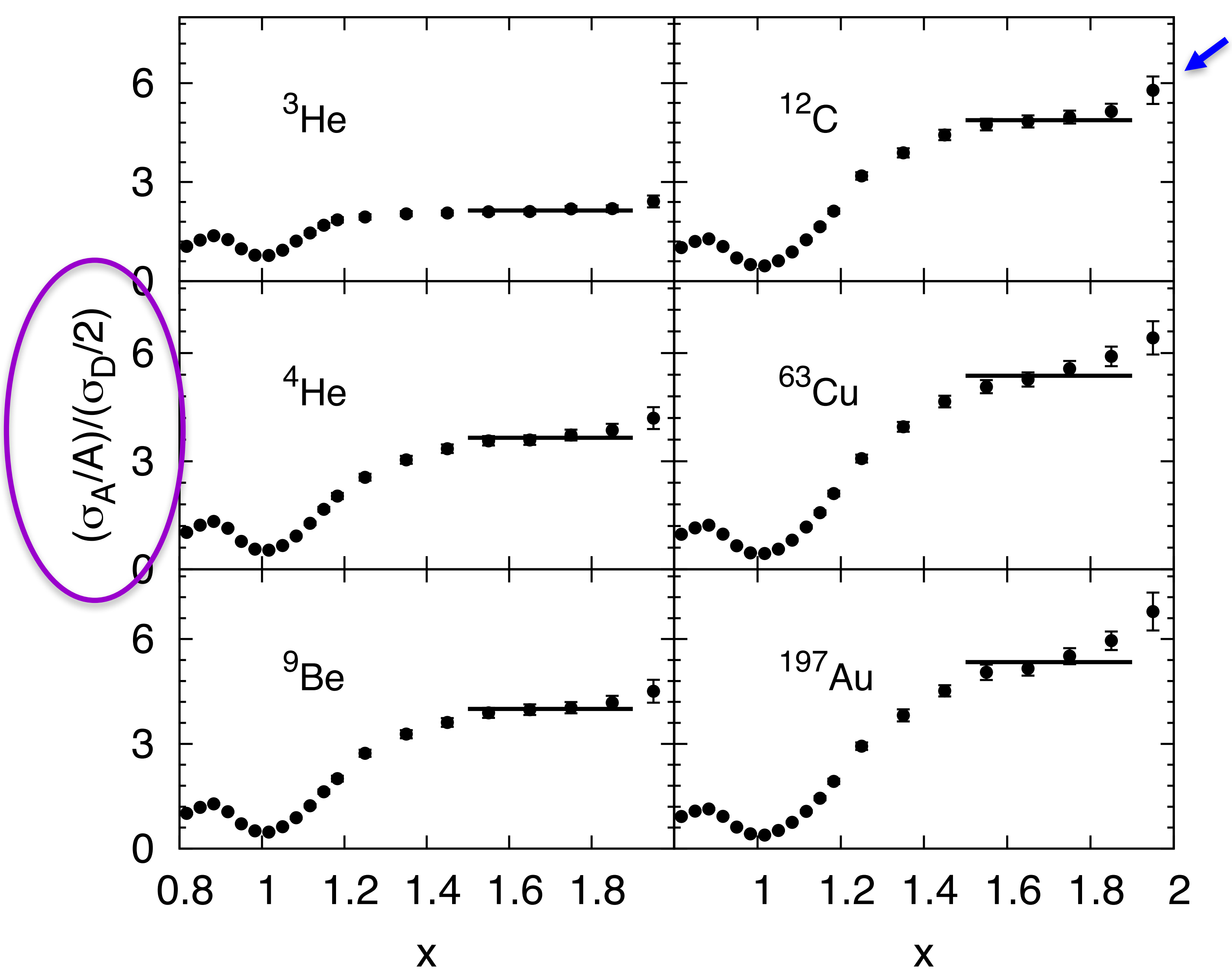






Precision (e,e') *x>1* Cross Section Ratios

N. Fomin *et al*., Phys. Rev. Lett. **108** (2012) 092502.



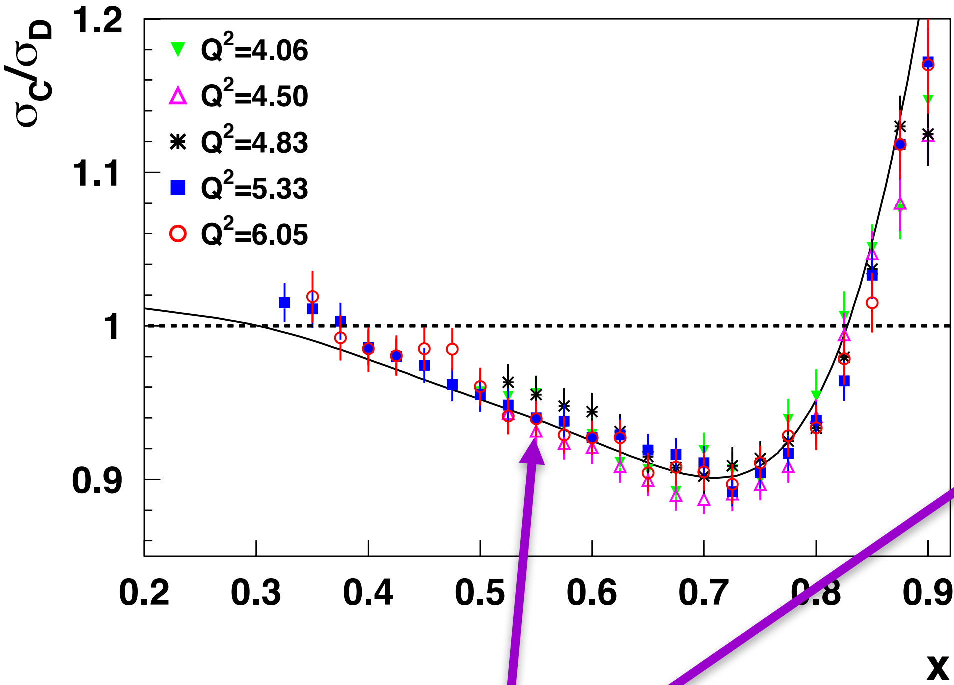
Plateaus seen in the ratio $(\sigma_A/A)/(\sigma_D/2)$

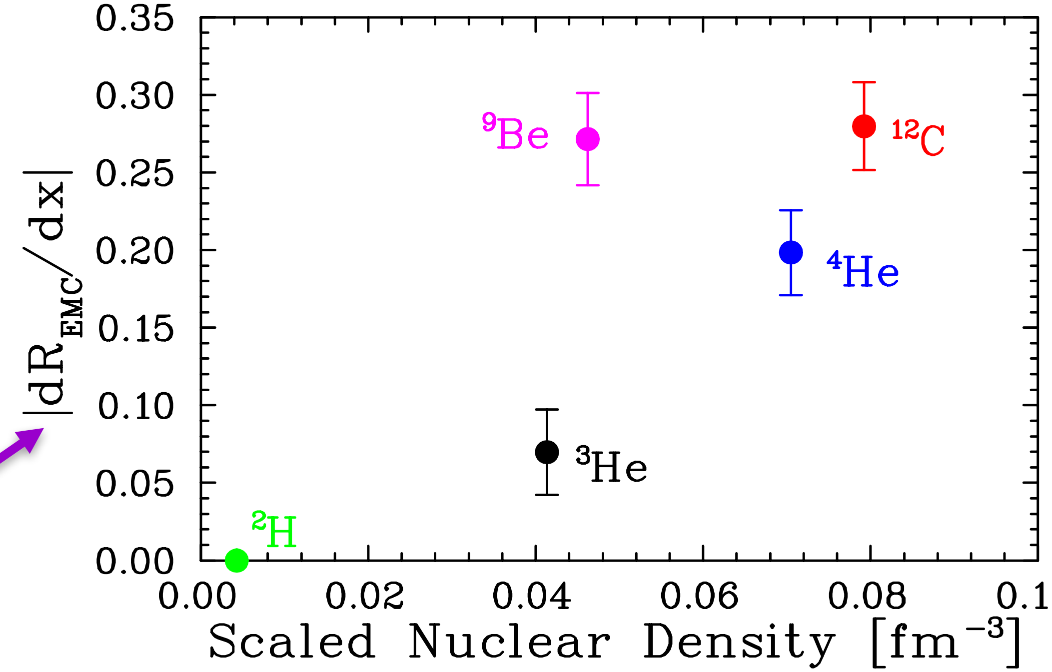
Roughly A independent

Understood as evidence for 2N short range correlations

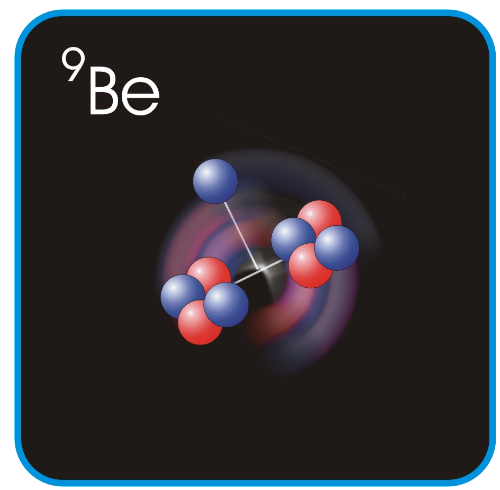
Jefferson Lab EMC Effect Data

J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.



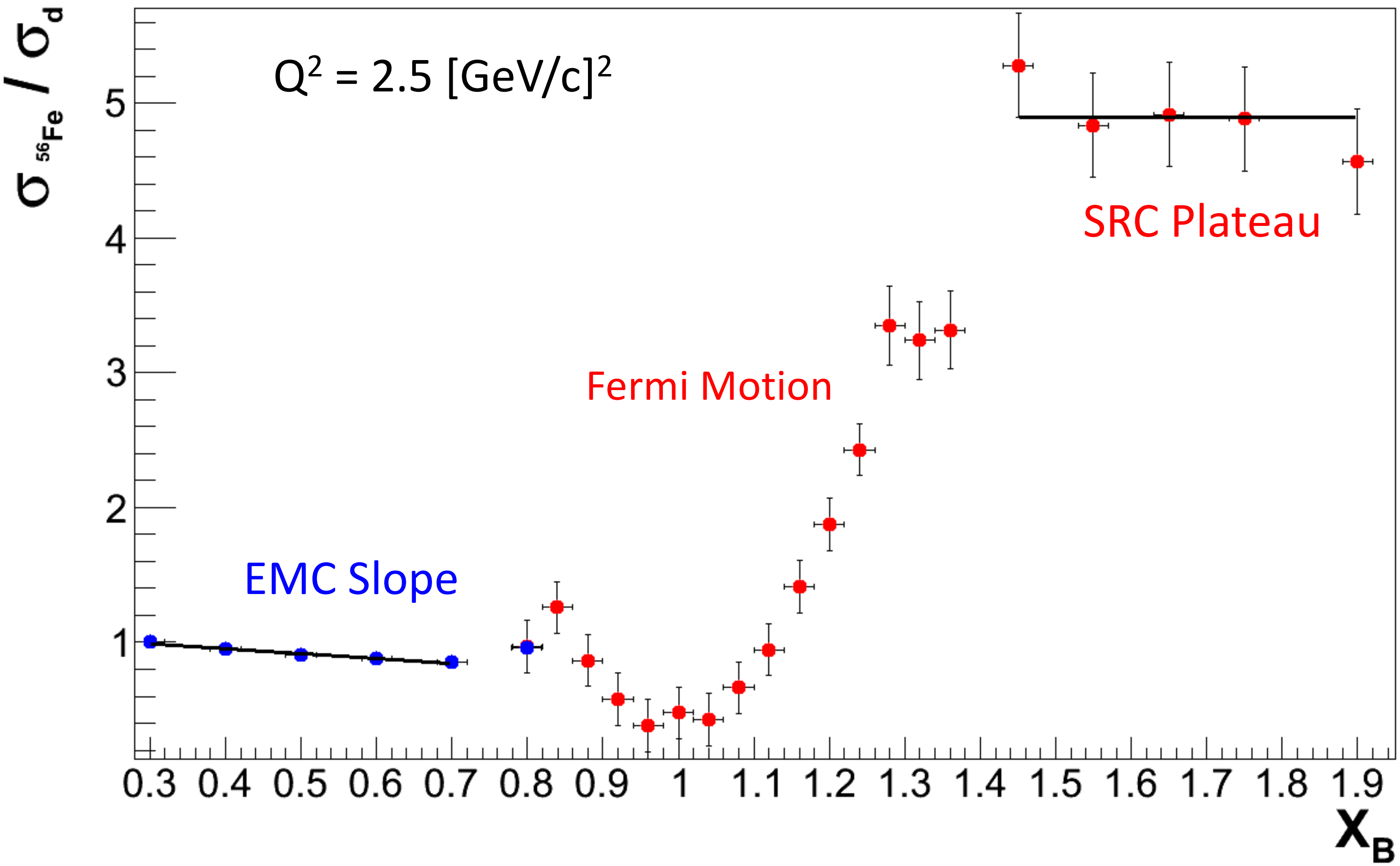


- Slope of ratio σ_A/σ_D at EMC region.
- *EMC effect correlated with* ***local density*** *not average density.*



Holistic View of inclusive EMC & SRC Data

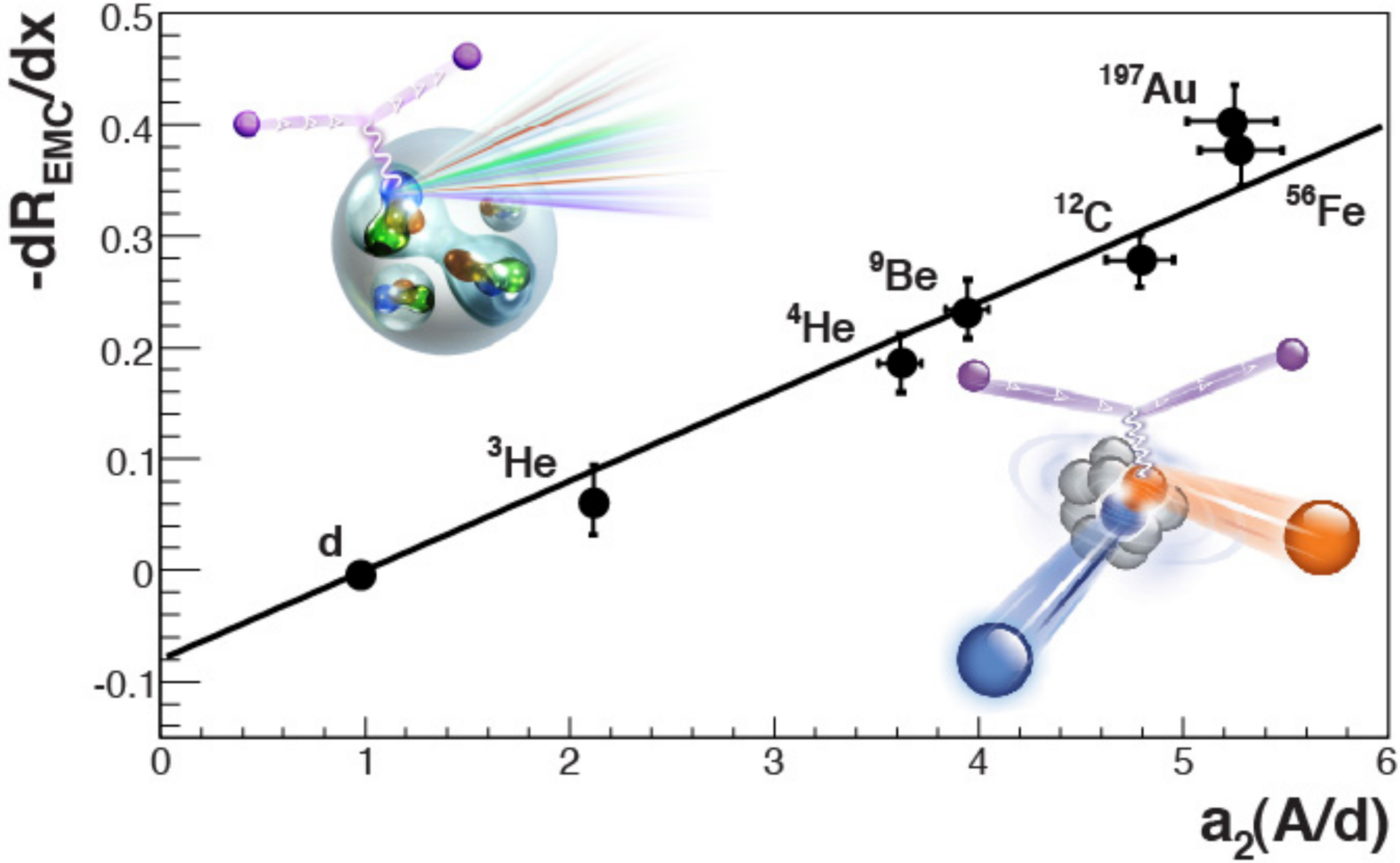
S. Malace, D. Gaskell, D.H., I. Cloet, Int. J. Mod. Phys. E **23** (2014) 1430013



- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC** slopes (x_B<0.7) and **SRC plateaus** (x_B>1.5) correlated?!

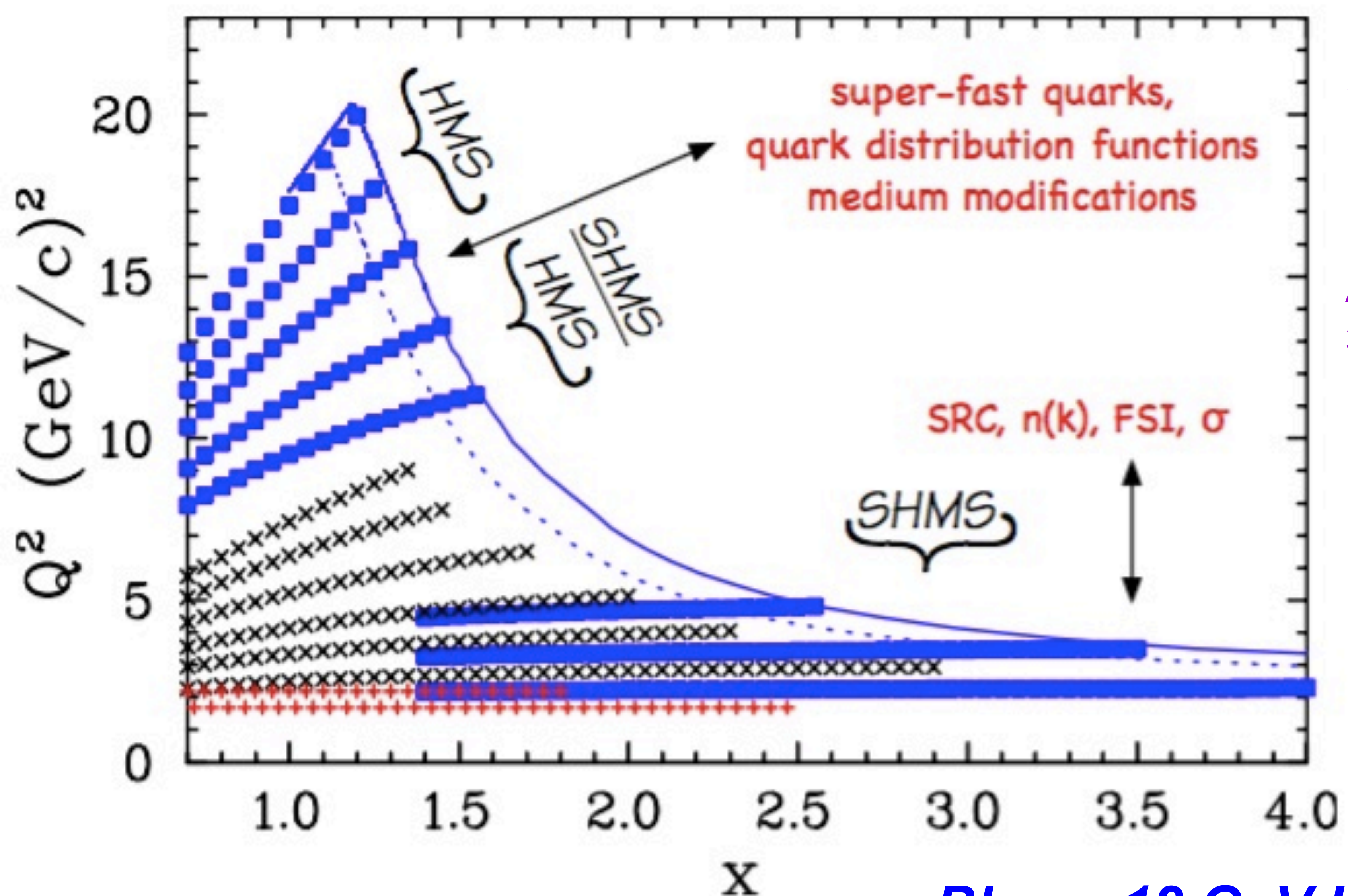
x>1 Ratios and EMC Slope Correlation

L. Weinstein, E. Piasetzky, DH, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. 106 (2011) 052301.



Origin of the EMC effect? Not a smoking gun, but highly suggestive….

EMC, x>1 experiments ran/running in JLab Halls A,C *this year*!



3N plateau?

Also ^{3}H, ^{3}He (e,e'p) in Hall A

More!

Black = 6 GeV Hall C

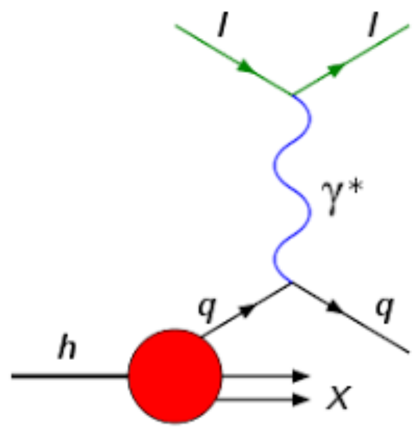
Red = 6 GeV Hall B

Blue = 12 GeV Hall C!!

(push up in x, Q^2, range of A)

Electron Scattering Measurements Applied to Neutrino Interactions on Nuclei

- Precision measurements of isovector components of cross sections
  - Nucleons and nuclei, A-dependence
  - Form factors
  - Resonances
  - Deep Inelastic Scattering
  - Quark-hadron duality studies
- Parity violating electron scattering
  - As above!
- Precision decomposition of nuclear effects – within nuclei
  - Smearing/momentum distributions
  - Including short range correlations
  - Additional two body effects (meson exchange currents)
  - EMC effect
  - Shadowing and anti-shadowing
- **Nuclear interactions**
  - **Hadronization**
  - **Final state interactions**



Jefferson Lab

Jefferson Lab — Thomas Jefferson National Accelerator Facility | MIT | Old Dominion University | Michigan State University | Tel Aviv University

Electrons for Neutrinos: Addressing Critical Neutrino-Nucleus Issue

Proposal C12-17-006

e4ν Spokespersons:

O. Hen (MIT), A. Ashkenazi (MIT),
K. Mahn (MSU), E. Piasetzky (TAU),
S. Stepanyan (JLab) and L.B. Weinstein (ODU).

✓ *Approved with A priority 2018*

Jefferson Lab PAC-46, July 17th, 2018

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