Overview of
Structure Function Measurements at Jefferson Lab

Wally Melnitchouk

Thomas Jefferson National Accelerator Facility

Outline

- Brief tour of Jefferson Lab
- Unpolarized structure functions
  - → $F_2, F_L,$ "free" neutron, duality, nuclear EMC effect
  - → CTEQ-JLab (CJ) global PDF analysis
- Polarized structure functions → Yelena Prok (Wednesday, 16:30)
  - → longitudinal and transverse structure (DIS & SIDIS)
  - → JLab Angular Momentum (JAM) global PDF analysis
- Outlook
  - → remaining 6 GeV analyses
  - → plans for 12 GeV measurements

CEBAF

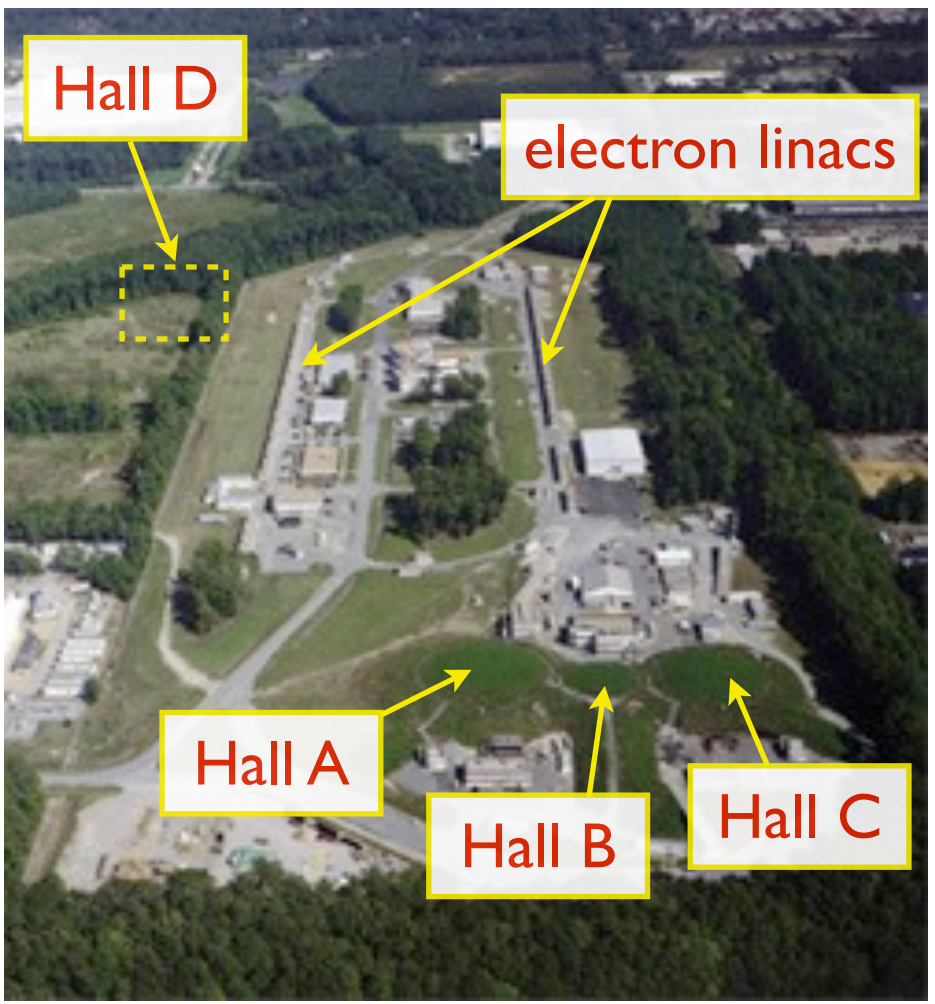
(Continuous Electron Beam Accelerator Facility)

at

Jefferson Lab

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

6 GeV polarized electron beam on (un)polarized targets

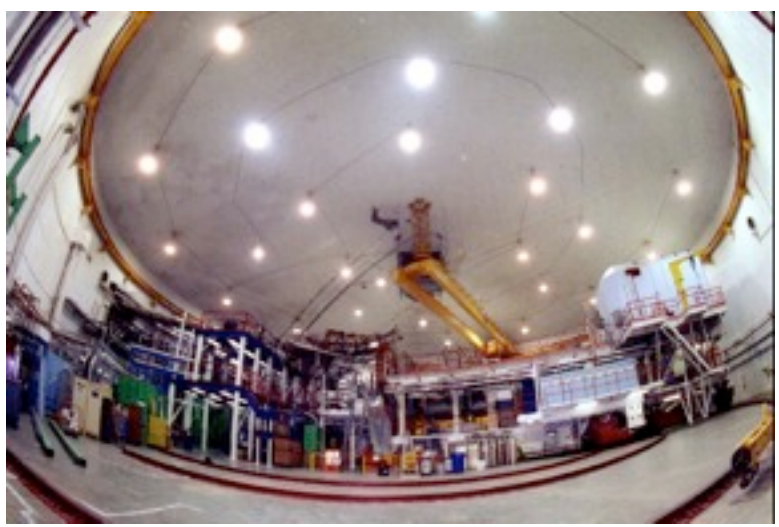


Experimental Halls

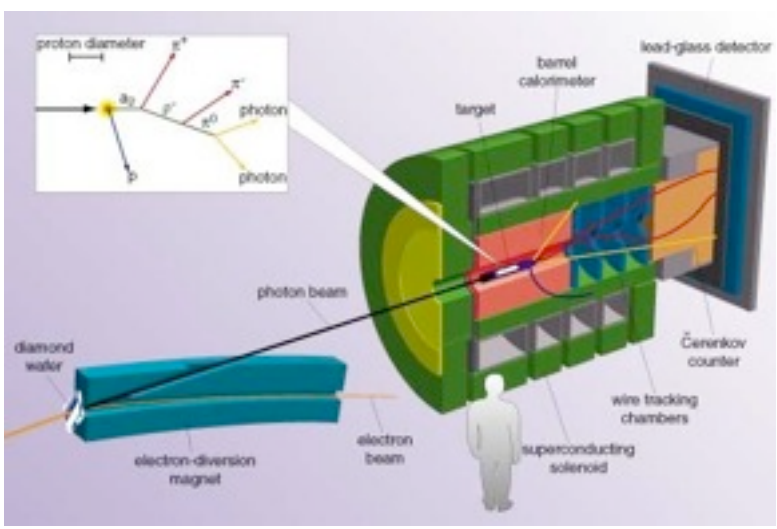
Hall A

Hall B

Hall C



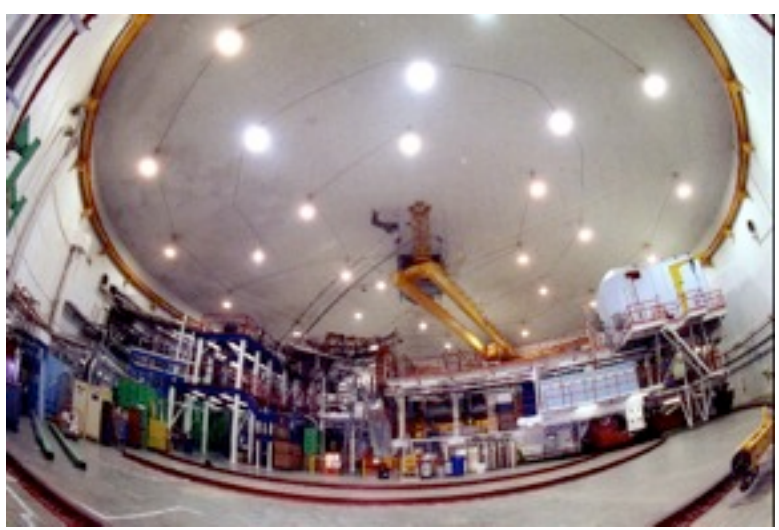
Hall D



Experimental Halls

Hall A

Hall C



- high luminosity
  $> 10^{38}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- very high precision measurements
- precision structure functions, parity-violating e scattering, high Q^2 form factors

Experimental Halls

Hall B

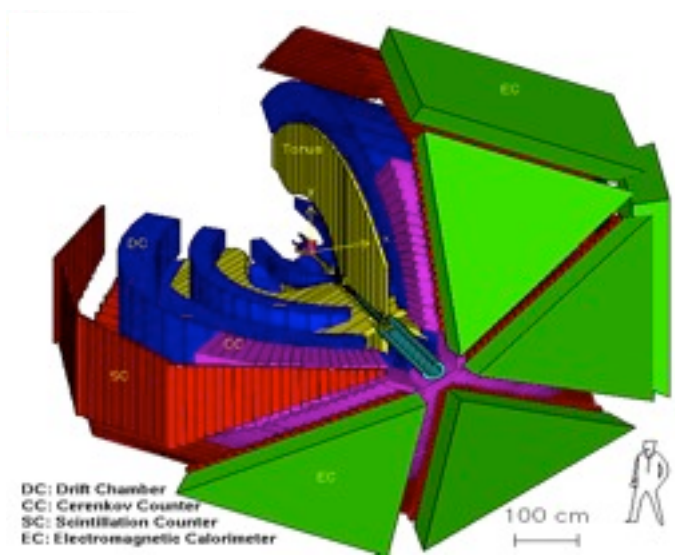
- large acceptance,
  lower luminosity
  $\sim 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

CLAS

(CEBAF Large Acceptance Spectrometer)

- collect all data "at once"

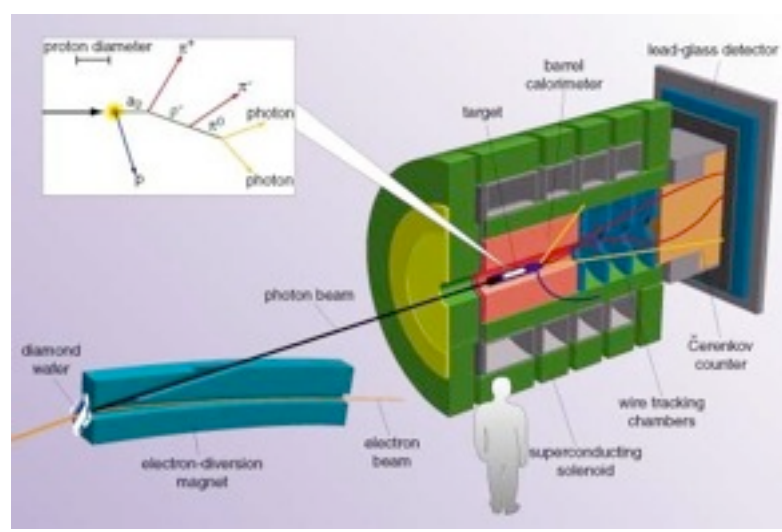
- N^* spectroscopy
  (multi-hadron final states),
  deep exclusive reactions
  (generalized parton distributions),
  structure function moments



Experimental Halls

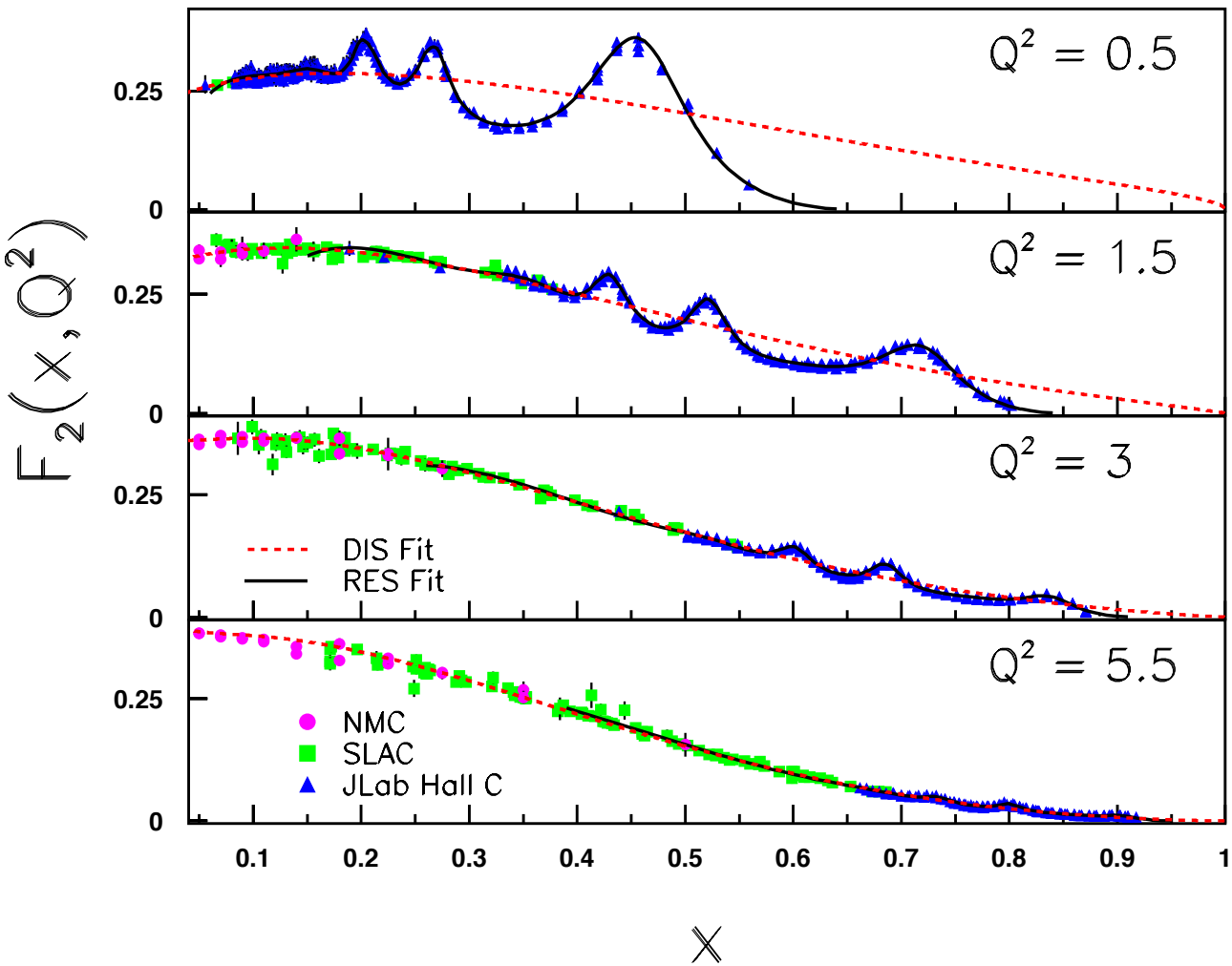
- new Hall just completed,
  as part of 12 GeV Upgrade
- 4π acceptance
- photon beam
- exotic meson spectroscopy
  ($q\bar{q}g$ states)

Hall D



Unpolarized Structure Functions

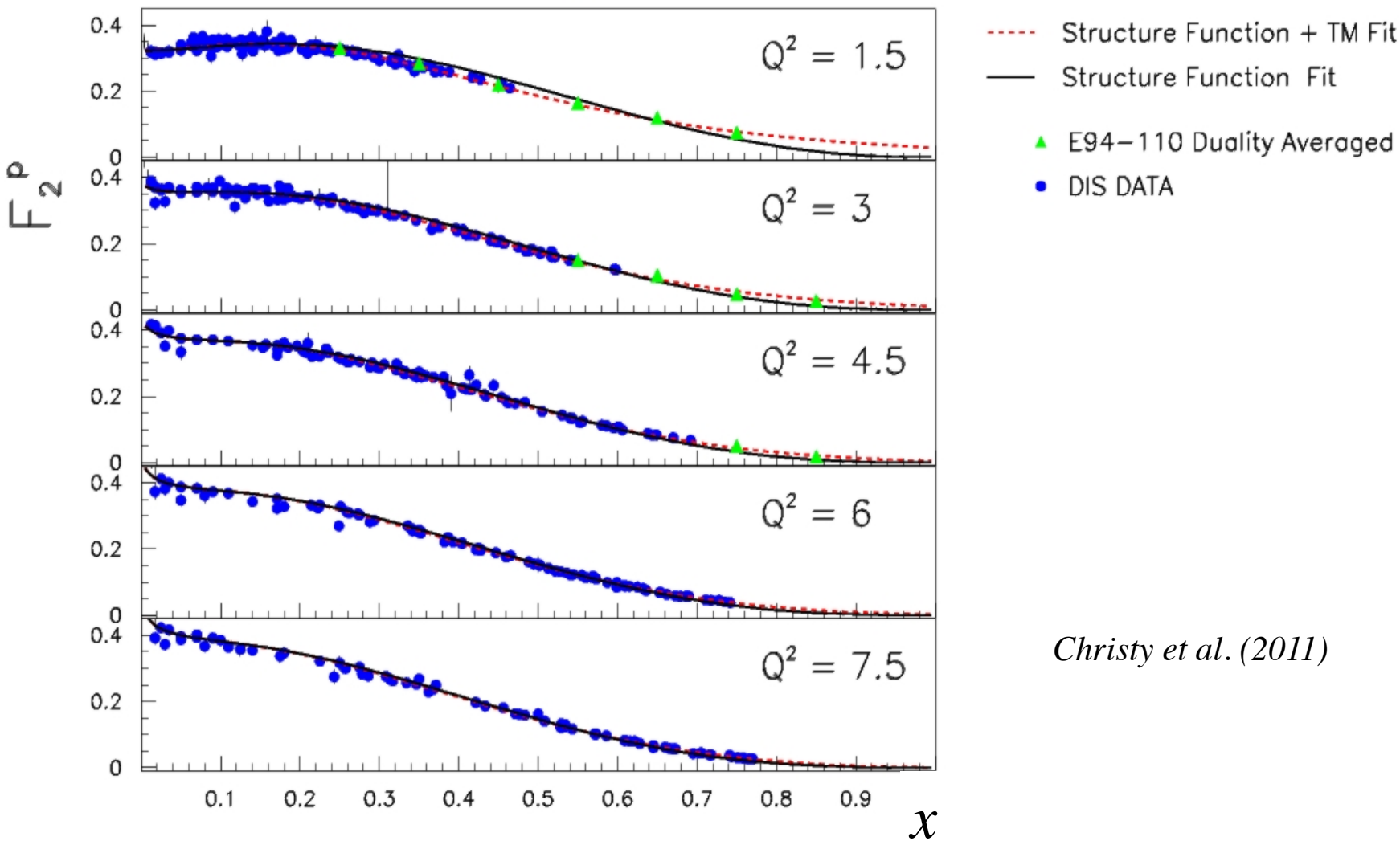
Proton F_2 structure function



Christy, WM
*JPCS **299**, 012004 (2011)*

→ high precision measurements of resonance–DIS transition region (high x, low Q^2)

Proton F_2 structure function



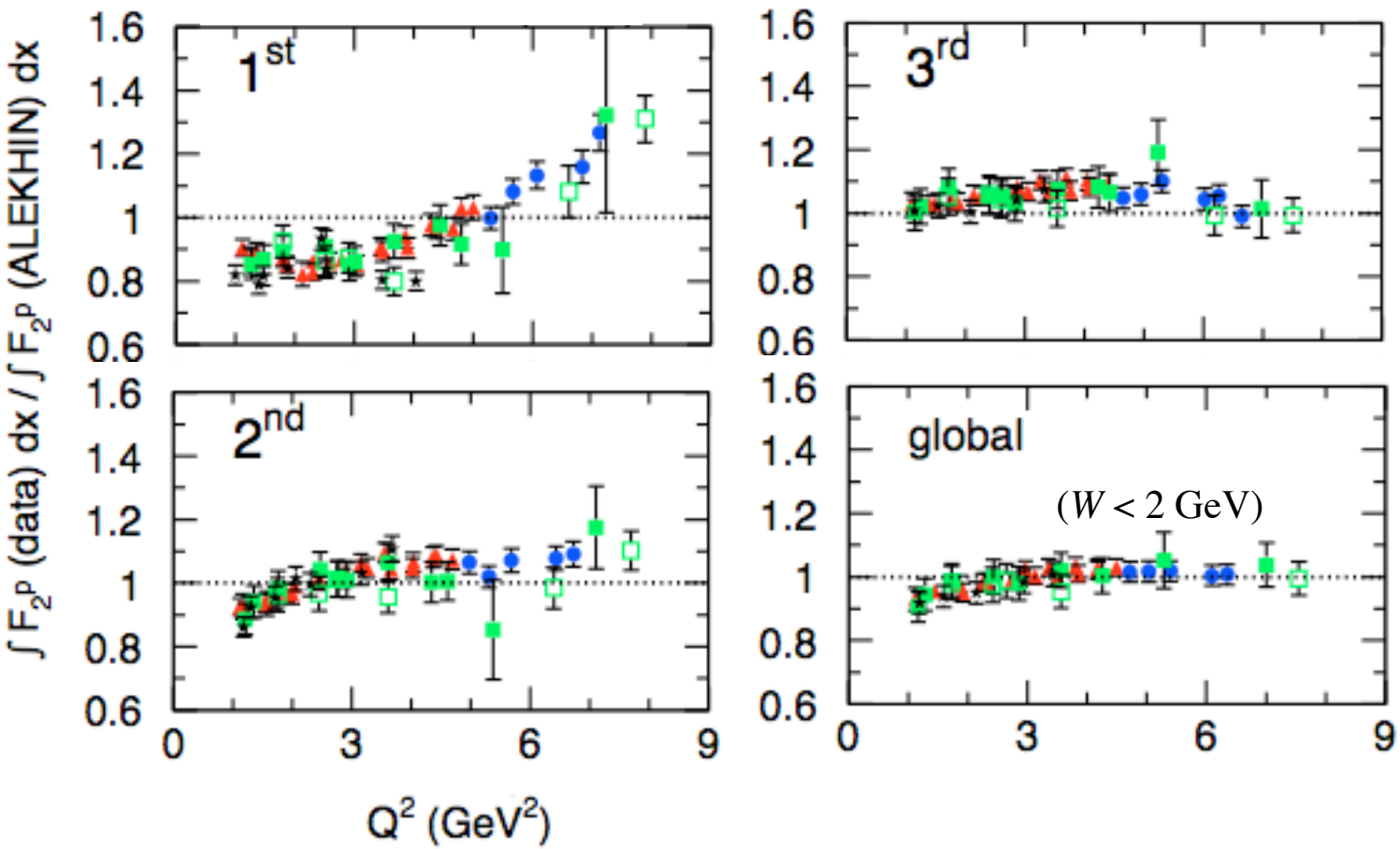
Christy et al. (2011)

→ high precision tests of quark-hadron duality

square of sum ⟷ sum of squares?

"coherent" "incoherent"

Proton F_2 structure function

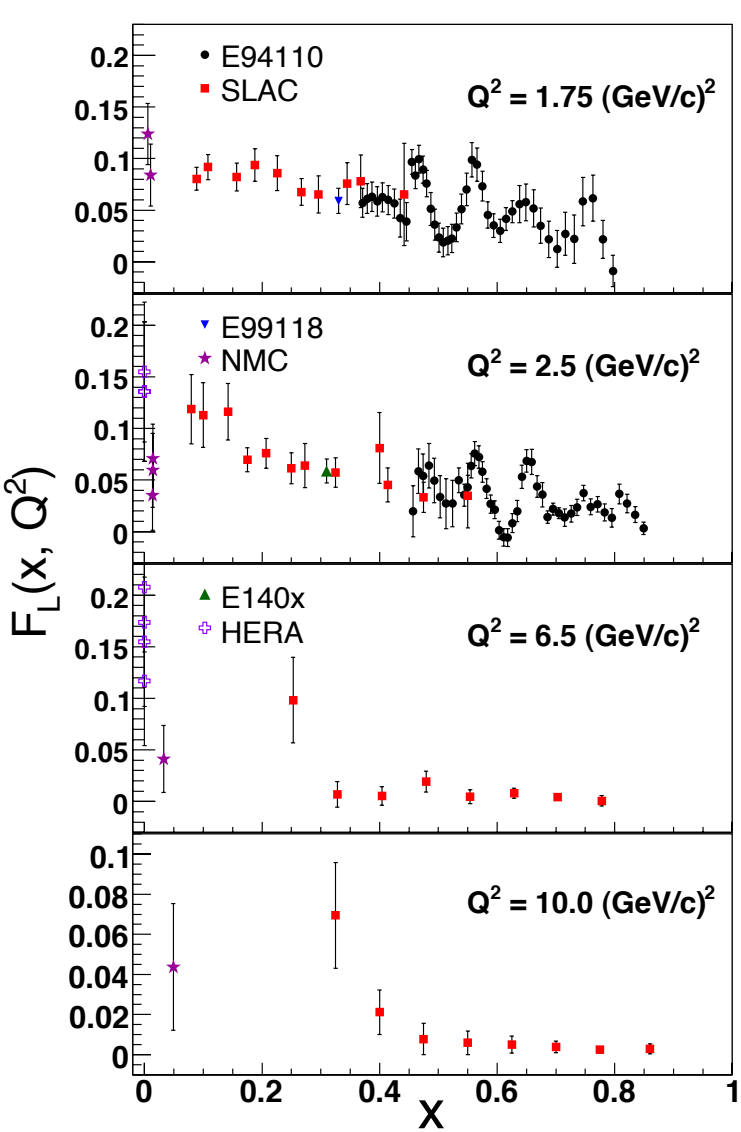


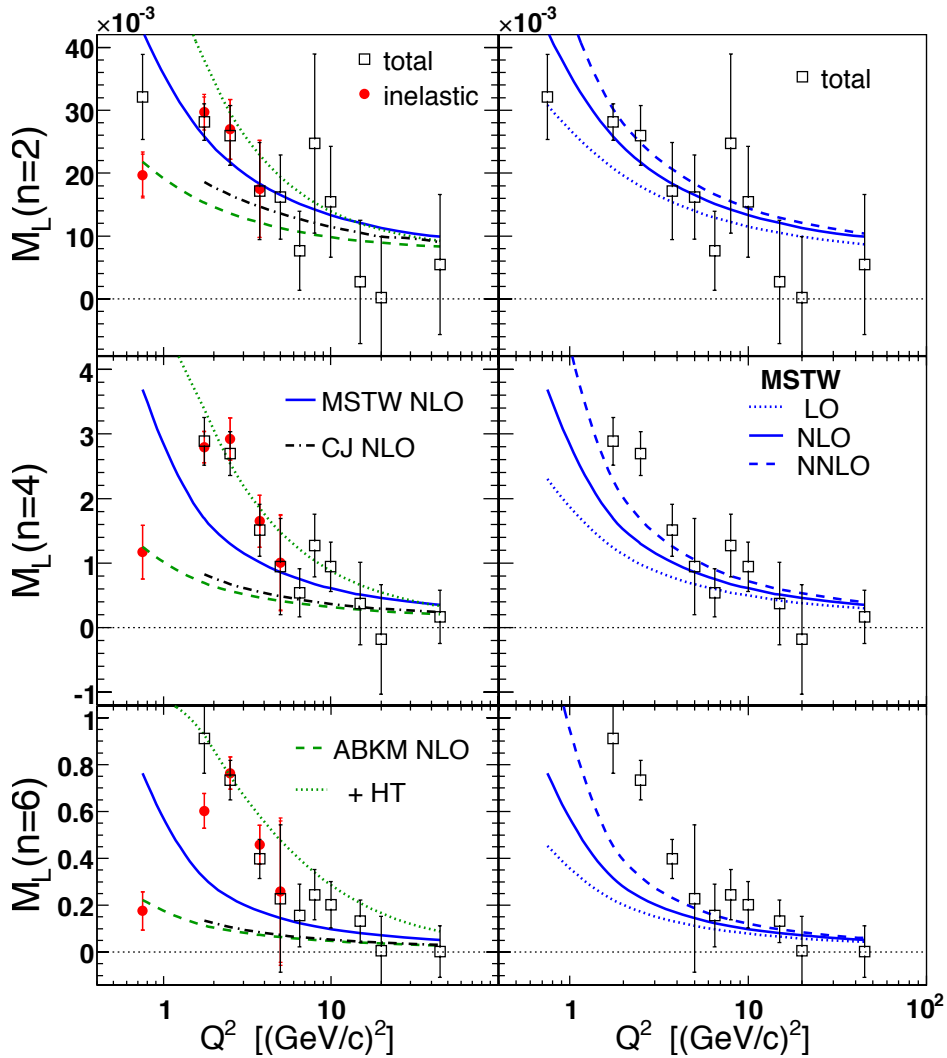
- E00-116 (JLab)
- E94-110 (JLab)
- SLAC
- SLAC (E8920)

Malace et al.
PRC ***80****, 035207 (2009)*

→ higher twists $\lesssim 10\text{–}15\%$ for $Q^2 > 1\ \mathrm{GeV}^2$

Proton F_L structure function





Monaghan et al. (2012)

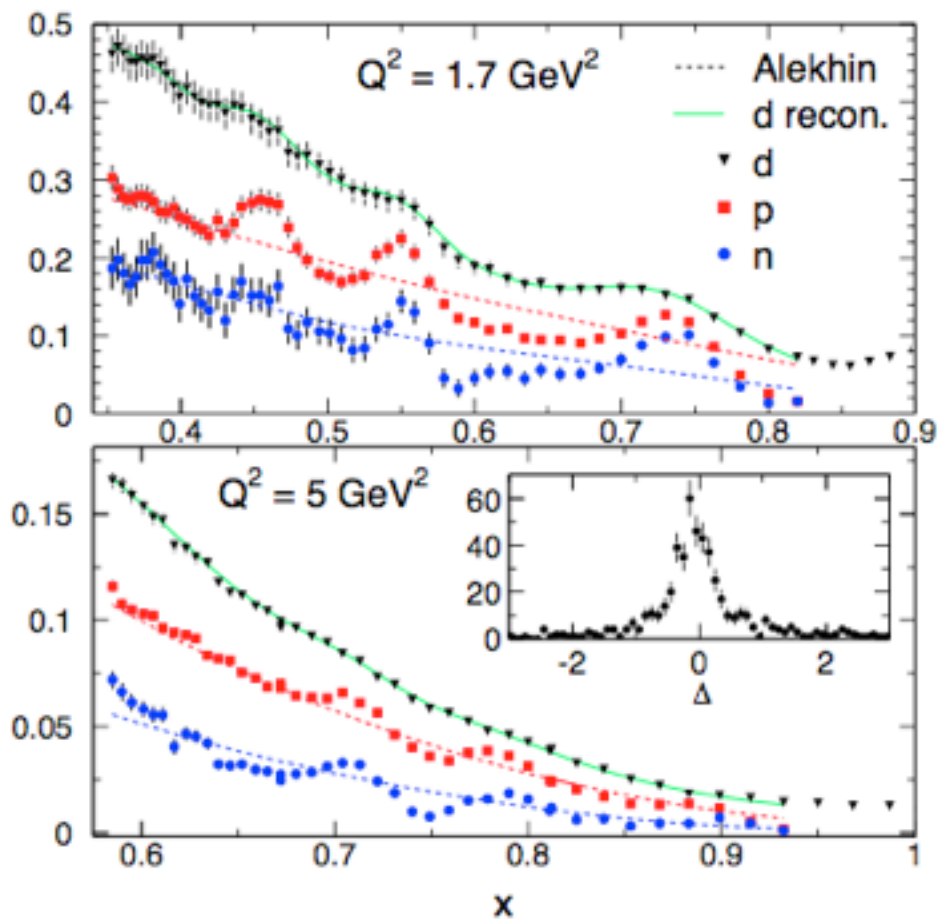
→ moment analysis suggests larger gluon at high x

(or significant higher twists in higher moments)

Neutron F_2 structure function

- Neutron structure more elusive because of absence of free neutron targets

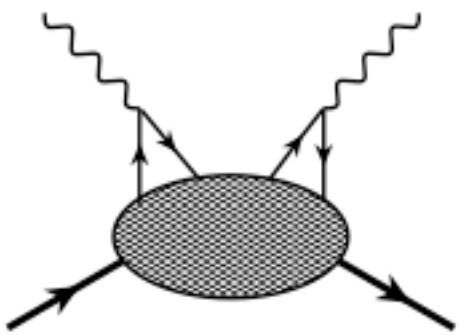
→ new extraction method allows first determination of F_2^n in resonance region



Malace et al., PRL ***104****, 102001 (2010)*

→ test universality of quark-hadron duality!

Duality from accidental cancellations of charges?



cat's ears diagram (4-fermion higher twist $\sim 1/Q^2$)

$$\propto \sum_{i \neq j} e_i \, e_j \;\sim\; \left(\sum_i e_i \right)^2 - \sum_i e_i^2$$

coherent *incoherent*

proton $\quad \mathrm{HT} \sim 1 - \left(2 \times \frac{4}{9} + \frac{1}{9} \right) = 0 \; !$

neutron $\quad \mathrm{HT} \sim 0 - \left(\frac{4}{9} + 2 \times \frac{1}{9} \right) \neq 0$

Brodsky
hep-ph/0006310

→ duality in proton a *coincidence!*

→ should *not* hold for neutron

Neutron F_2 structure function

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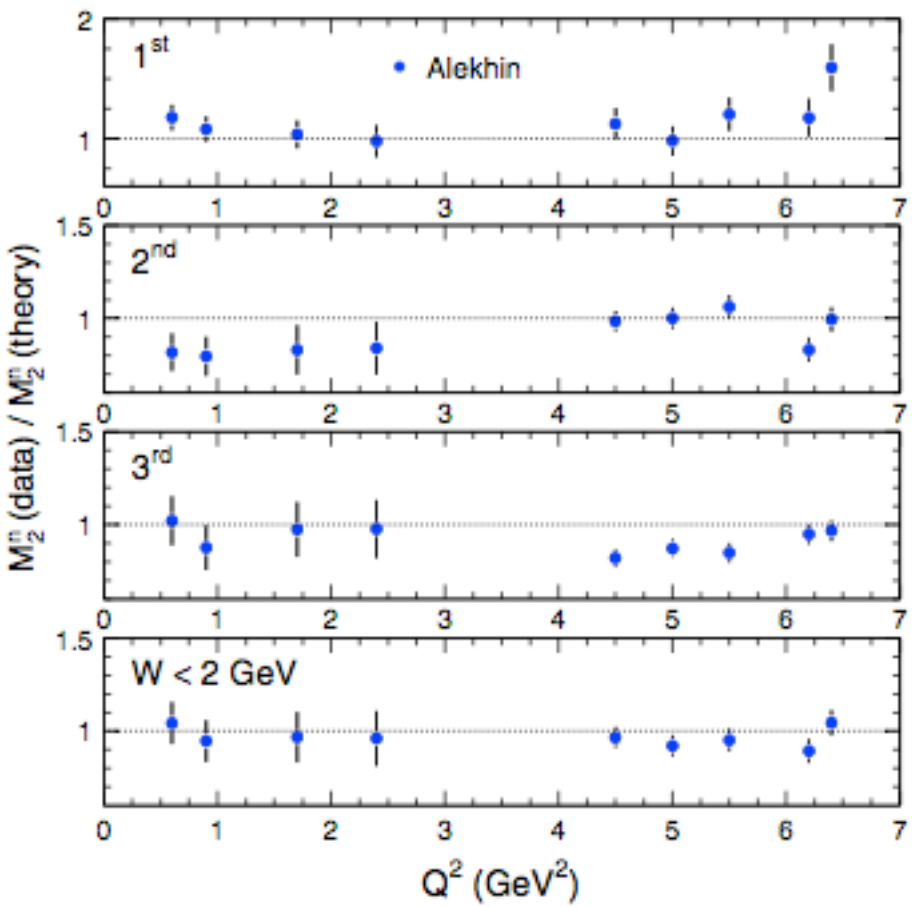


*Malace et al., PRL **104**, 102001 (2010)*

→ "theory": fit to $W > 2$ GeV data
*Alekhin et al., PRD **81**, 014032 (2010)*

→ *locally*, violations of duality in resonance regions < 15–20%

→ *globally*, violations < 10%

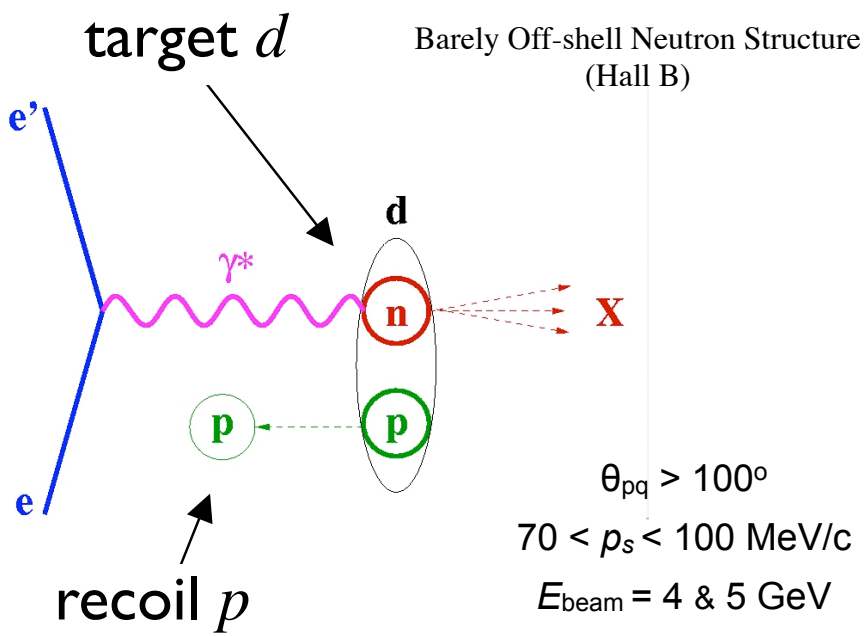
→ duality *not* accidental !

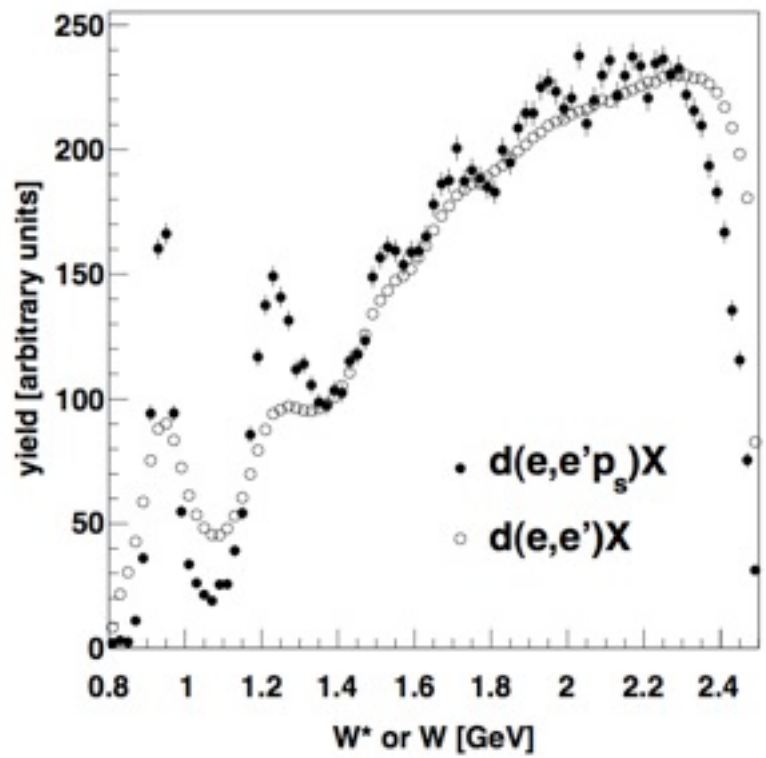
Neutron F_2 structure function

- Model independent confirmation: the BoNuS experiment

→ tag slow, backward proton in SIDIS from deuteron, minimize off-shell extrapolation, rescattering

Ciofi degli Atti, Kopeliovich, Simula, ...





*Baillie et al., PRL **108**, 142001 (2012)*

Neutron F_2 structure function

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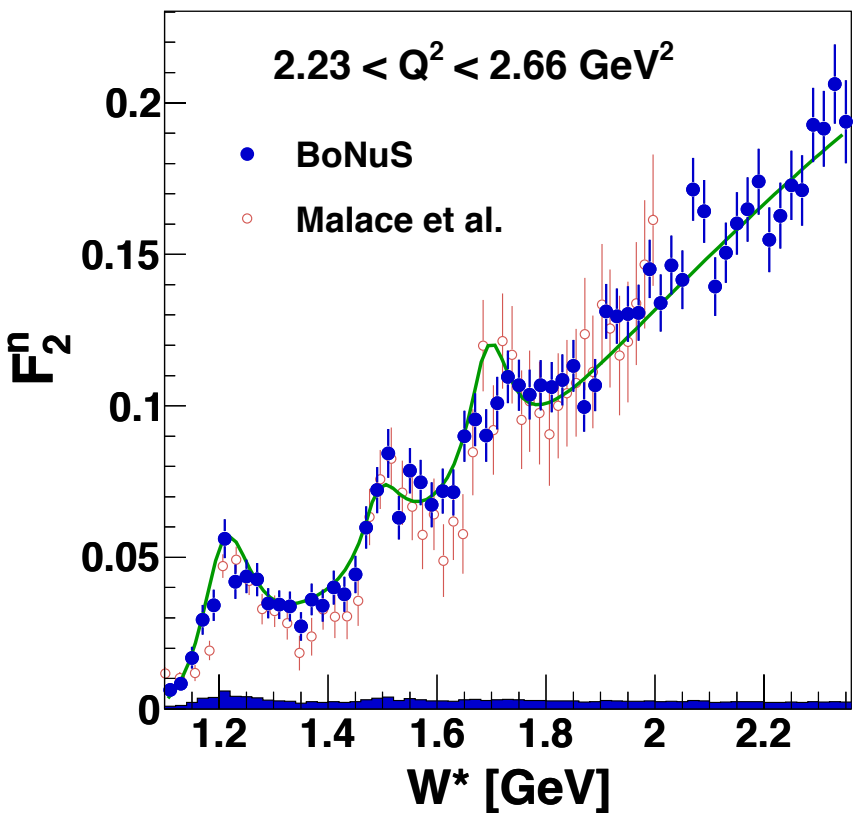
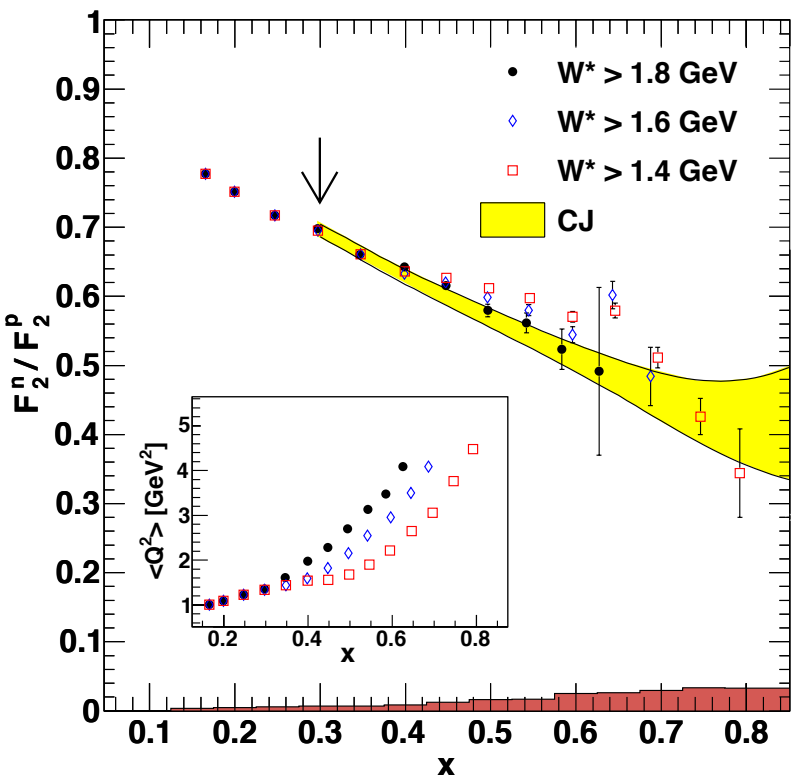




*Baillie et al., PRL **108**, 142001 (2012)*

→ use resonance region data to learn about *leading twist* structure functions?

CTEQ-JLab ("CJ")
Global PDF Analysis

CJ collaboration: A. Accardi, J. Owens, WM (theory)
E. Christy, C. Keppel, P. Monaghan (expt.)

http://www.jlab.org/CJ/

- New global NLO analysis of expanded set of p and d data (DIS, hadronic) including large-x, low-Q^2 region

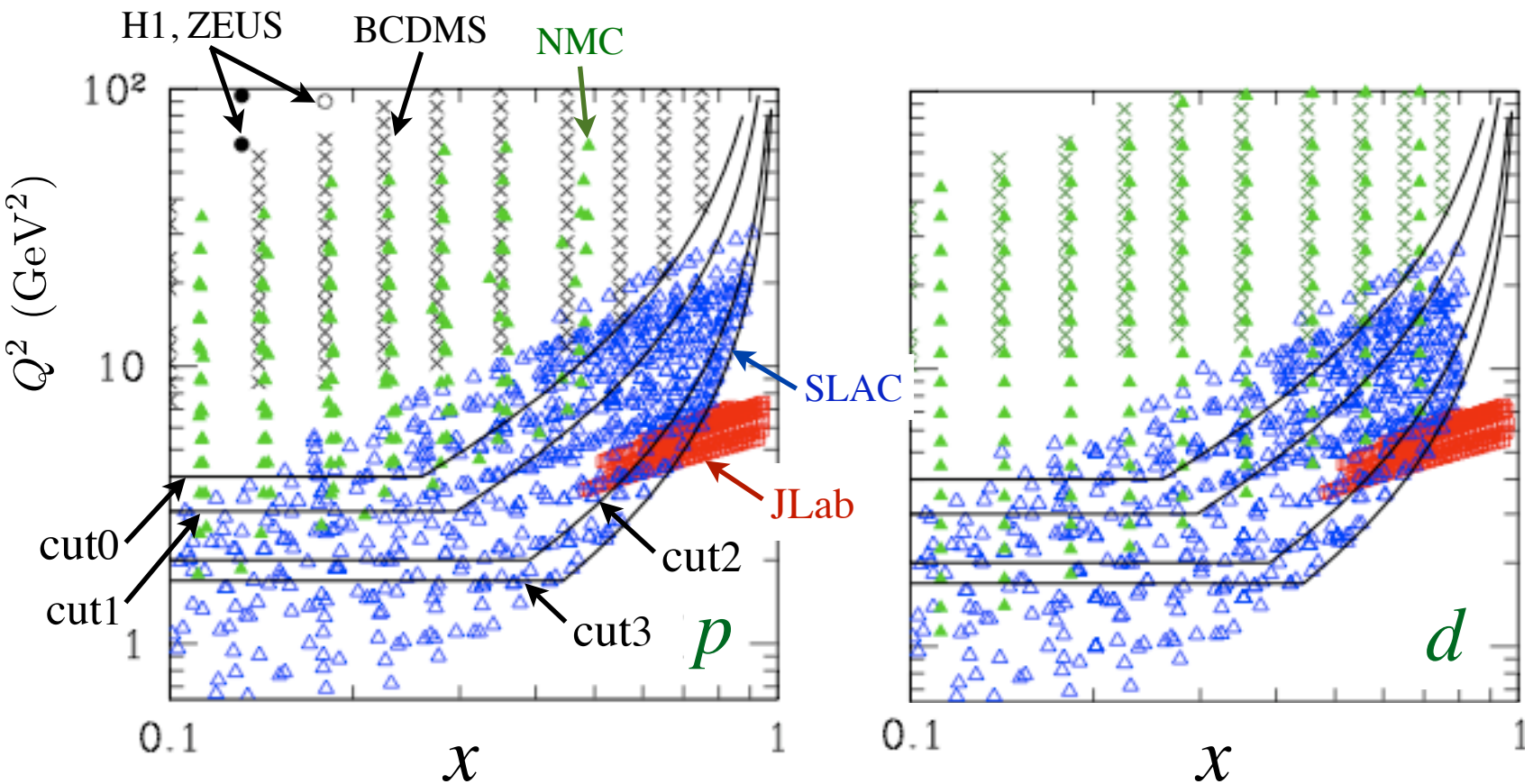
- Systematically study effects of Q^2 & W cuts
  → down to $Q \sim m_c$ and $W \sim 1.7$ GeV

- Include subleading $1/Q^2$ corrections
  → target mass, higher twist effects

- Correct for nuclear smearing effects in the deuteron
  → vital at large x, for all Q^2

- Dependence on choice of PDF parametrization
  → allow nonzero ratio at $x = 1$: $d \to d + a\,x^b\,u$

CJ kinematic cuts



cut0: $Q^2 > 4$ GeV^2, $W^2 > 12.25$ GeV^2

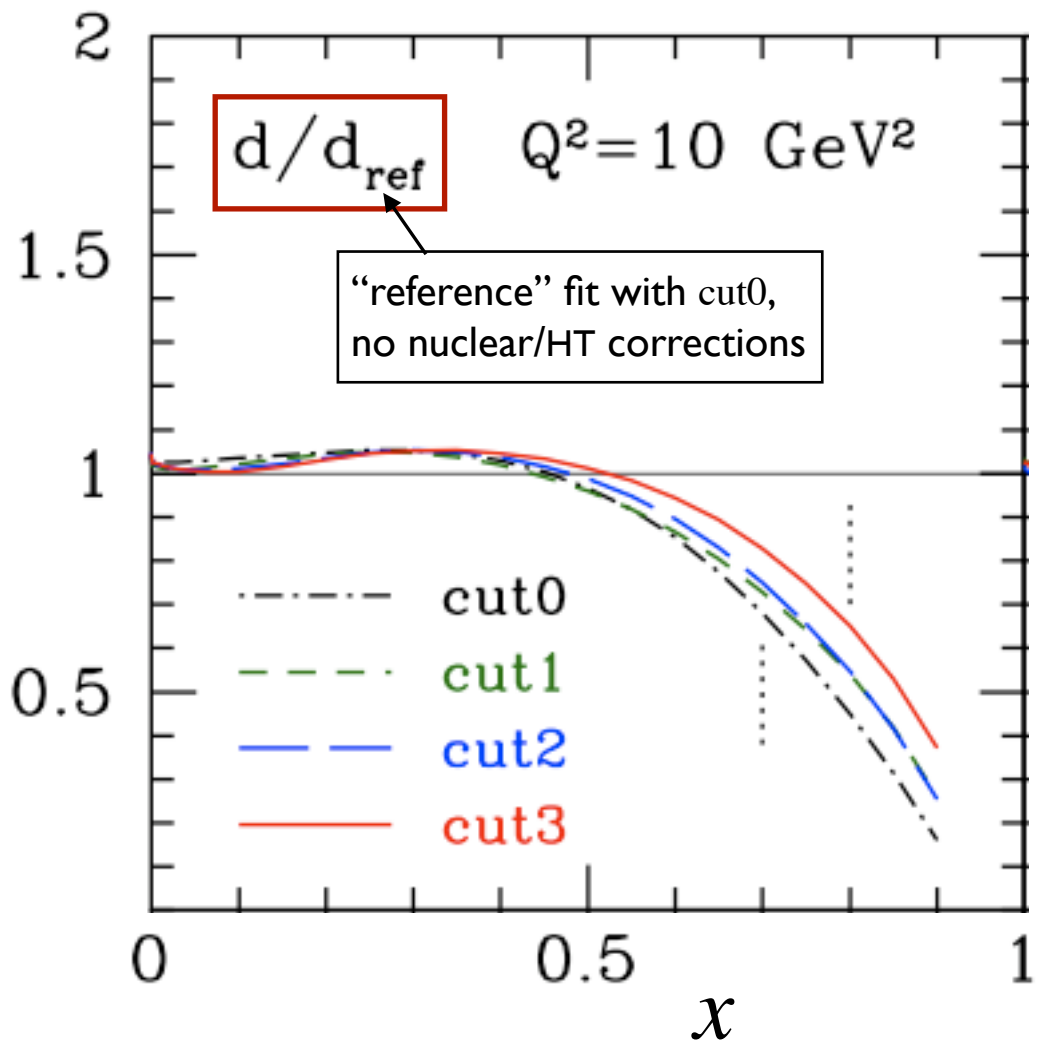
cut1: $Q^2 > 3$ GeV^2, $W^2 > 8$ GeV^2

cut2: $Q^2 > 2$ GeV^2, $W^2 > 4$ GeV^2

cut3: $Q^2 > m_c^2$, $W^2 > 3$ GeV^2

factor 2 increase in DIS data from cut0 → cut3

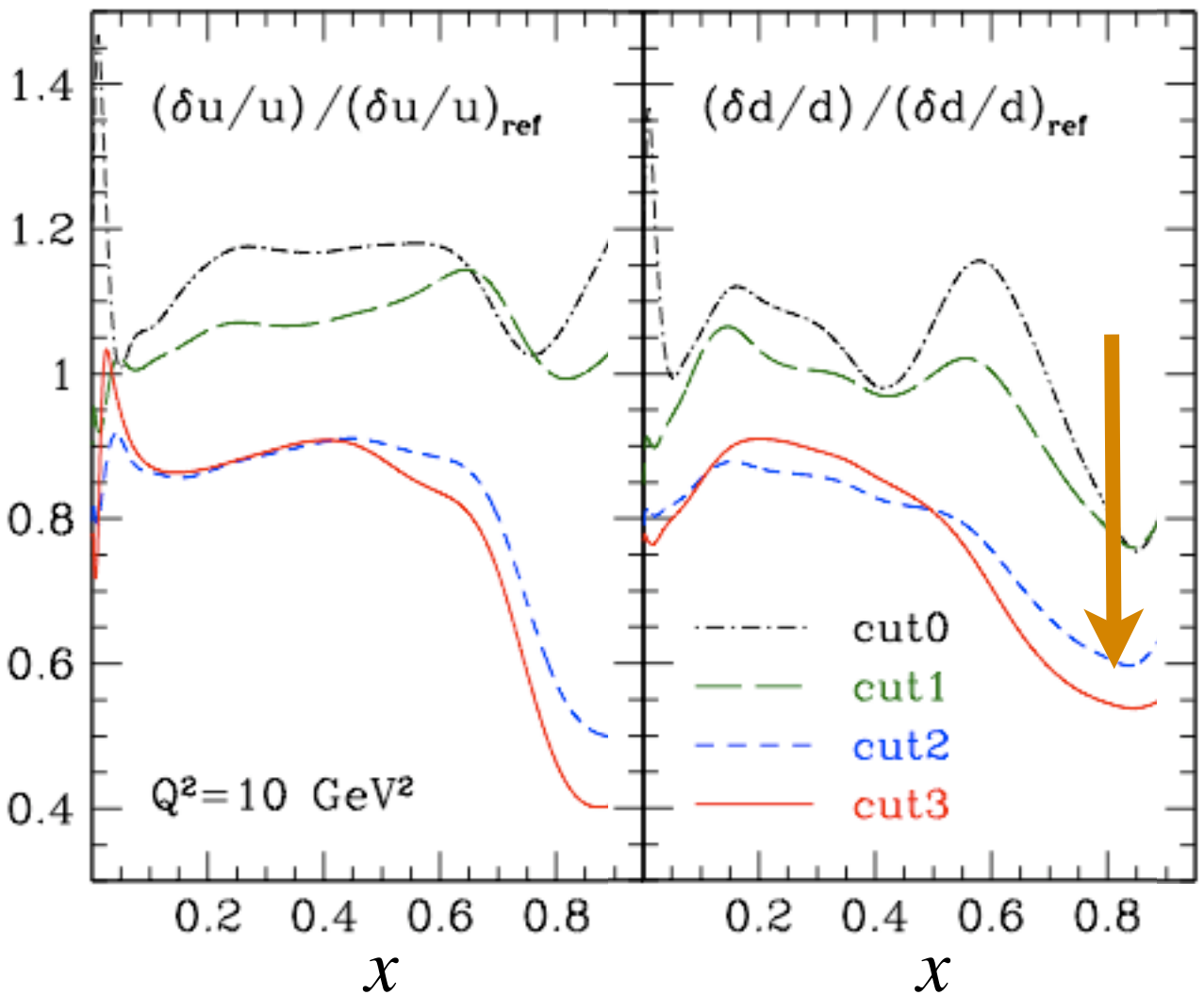
- PDFs remarkably *stable* with respect to cut reduction, as long as finite-Q^2 corrections included



Accardi et al.
PRD ***81****, 034016 (2010)*

→ d quark behavior driven by nuclear corrections at high x

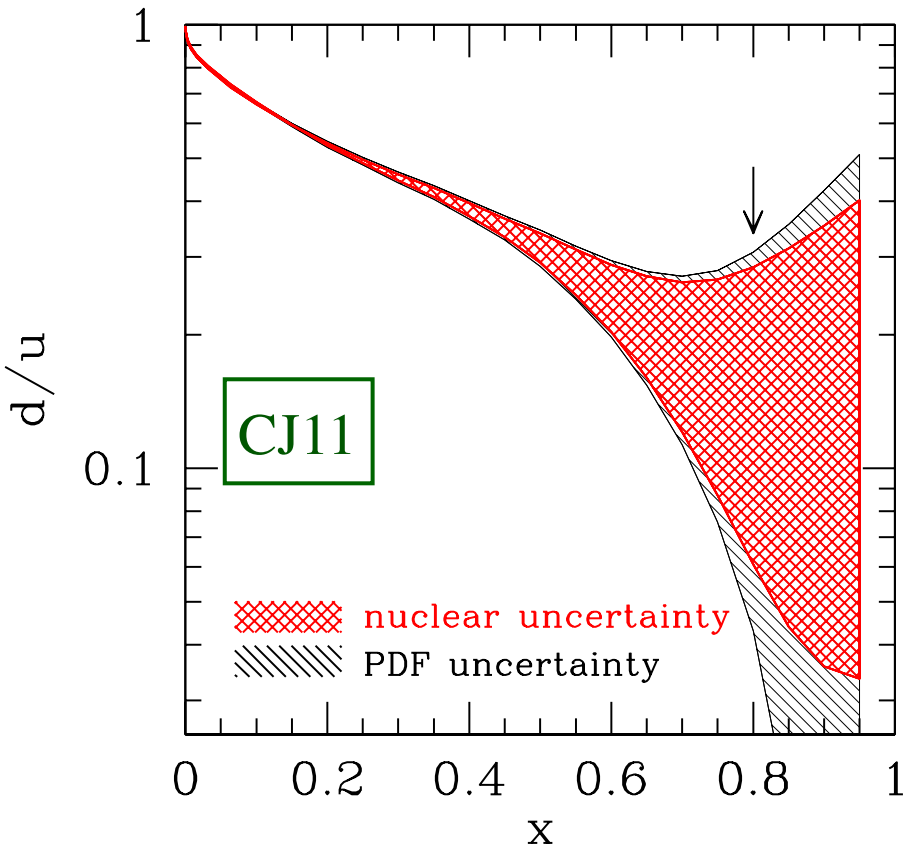
- Larger database with weaker cuts leads to significantly reduced errors, especially at large x

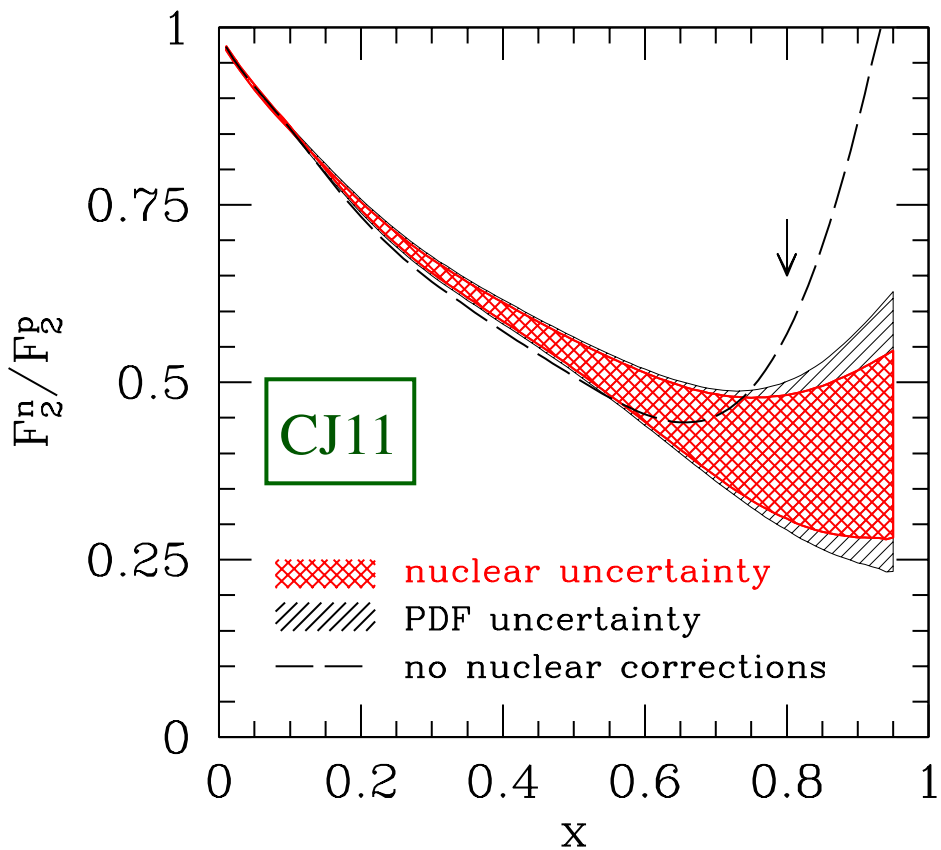


Accardi et al.
PRD ***81****, 034016 (2010)*

→ up to 40–60% error reduction when cuts extended into resonance region

- Vital for large-x analysis, which currently suffers from large uncertainties (mostly due to nuclear corrections)

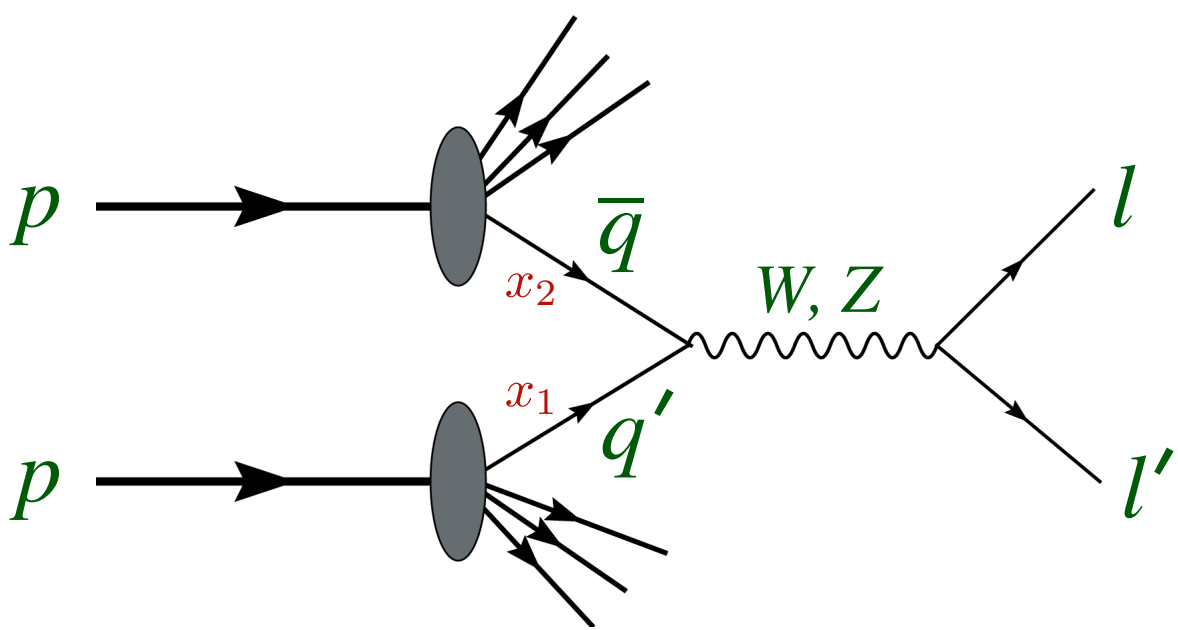




*Accardi et al., PRD **84**, 014008 (2011)*

→ uncertainty in d feeds into larger uncertainty in g at high x (important for LHC physics!)

Impact on collider physics



Heavy Z', W' boson production

- Some extensions of Standard Model predict heavy versions of W, Z bosons

→ Sequential Standard Model (SSM)
(assume same couplings as SM W, Z bosons)

→ Grand Unified Theories $e.g.$ E_6 *London, Rosner (1986)*

$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\psi \times \mathrm{U}(1)_\chi$$

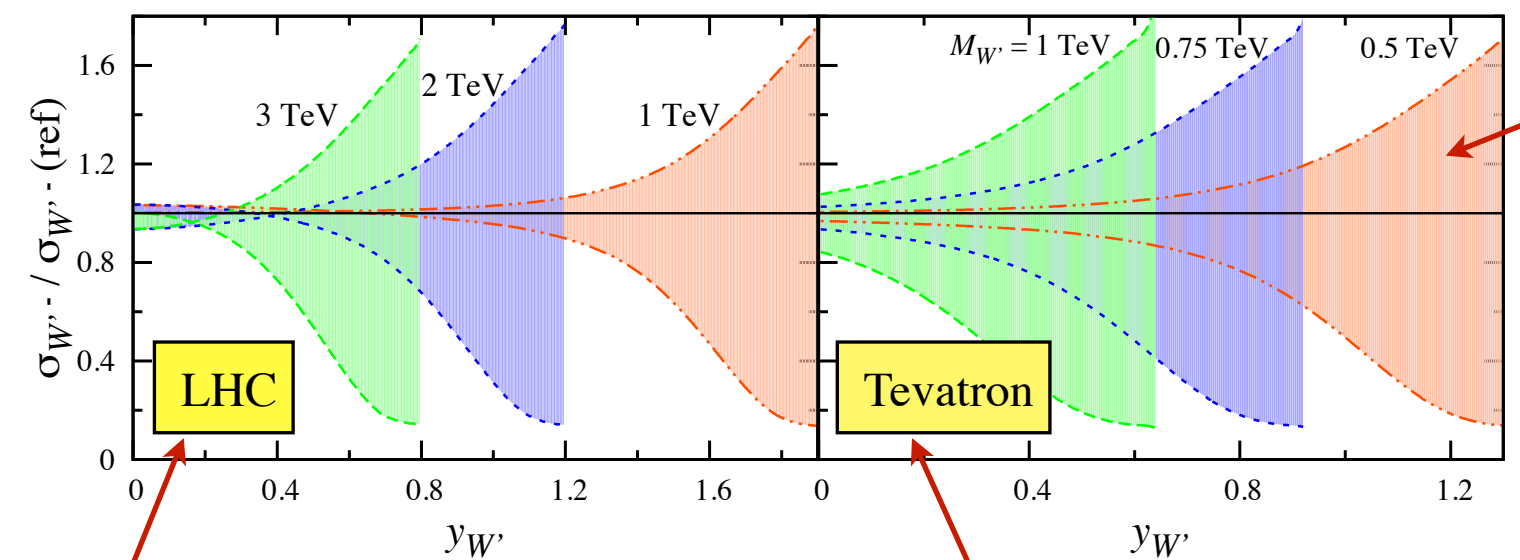
→ more exotic scenarios, $e.g.$

- scalar excitations in R-parity violating supersymmetric models *Hewett, Rizzo (1998)*
- spin-1 Kaluza-Klein excitations of SM bosons in presence of extra dimensions *Antoniadis (1990)*
- spin-2 excitations of the graviton *Randall, Sundrum (1999)*

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

W'^- production



> 100% uncertainty at large y !

Brady et al.
JHEP ***1206***, *019 (2012)*

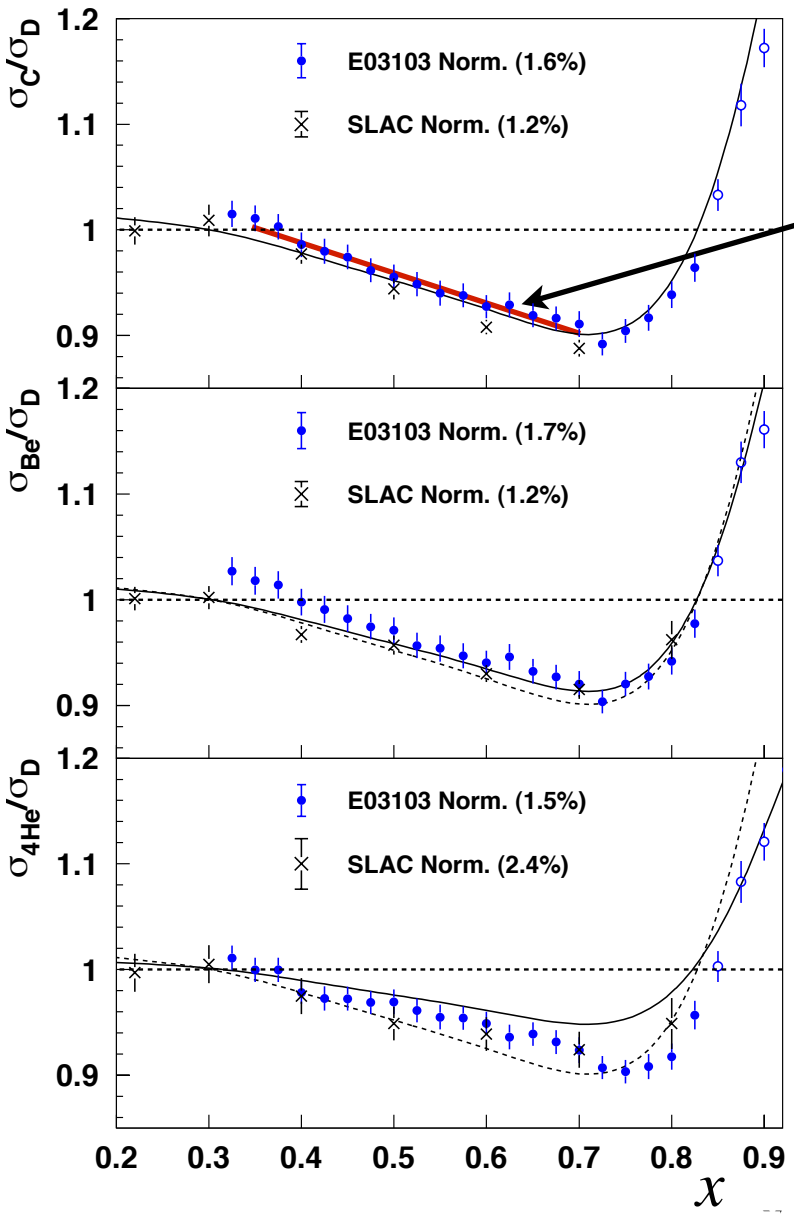
dominated by $d * \bar{u}$

dominated by $d * u + u * d$

→ uncertainty in d PDF at large x and low Q^2 evolves to larger uncertainty at small x and high Q^2

Nuclear Structure Functions

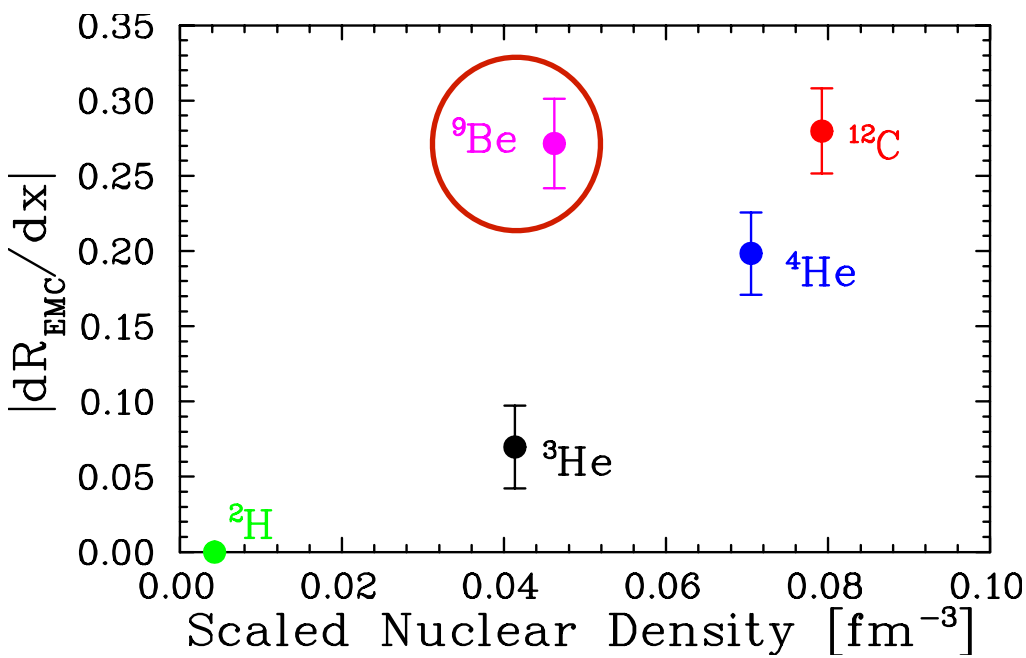
Nuclear EMC effect



slope of EMC ratio

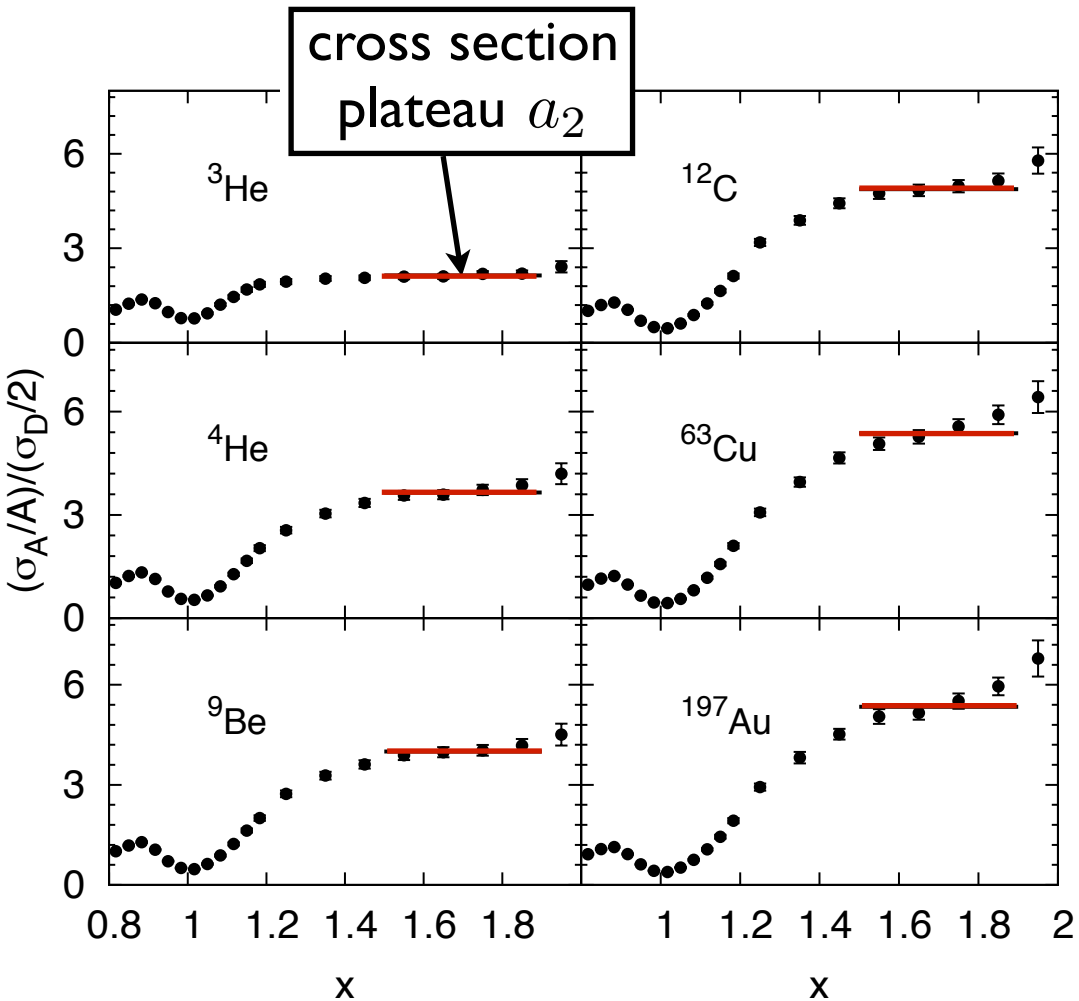
dR_{EMC}/dx

*Seely et al., PRL **103**, 202301 (2009)*

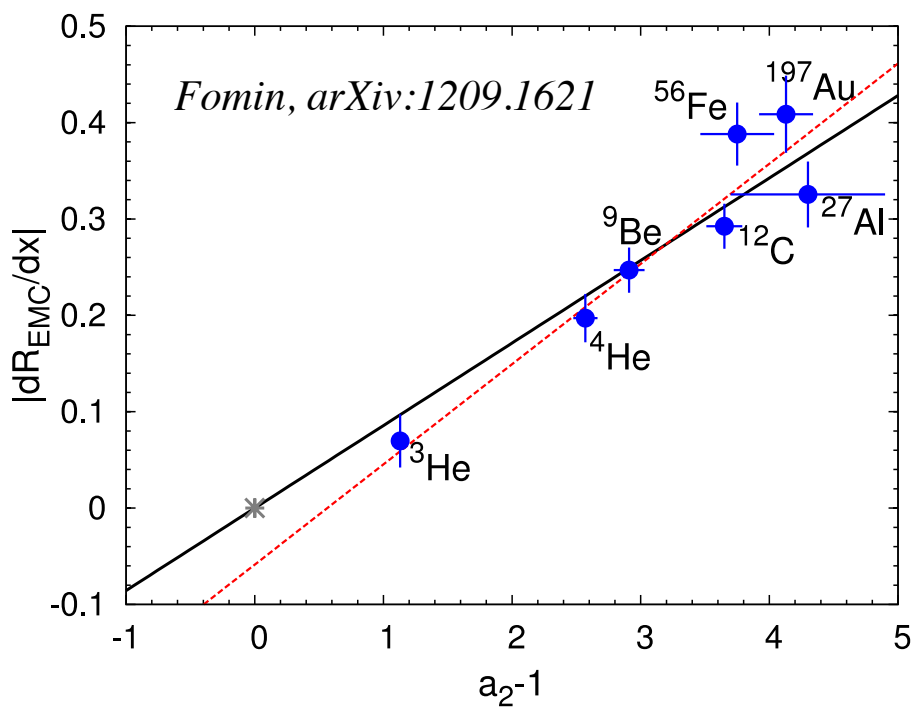


→ ^{9}Be suggests *local density* may provide better scaling

Nuclear EMC effect



Fomin et al.
*PRL **108**, 092502 (2012)*



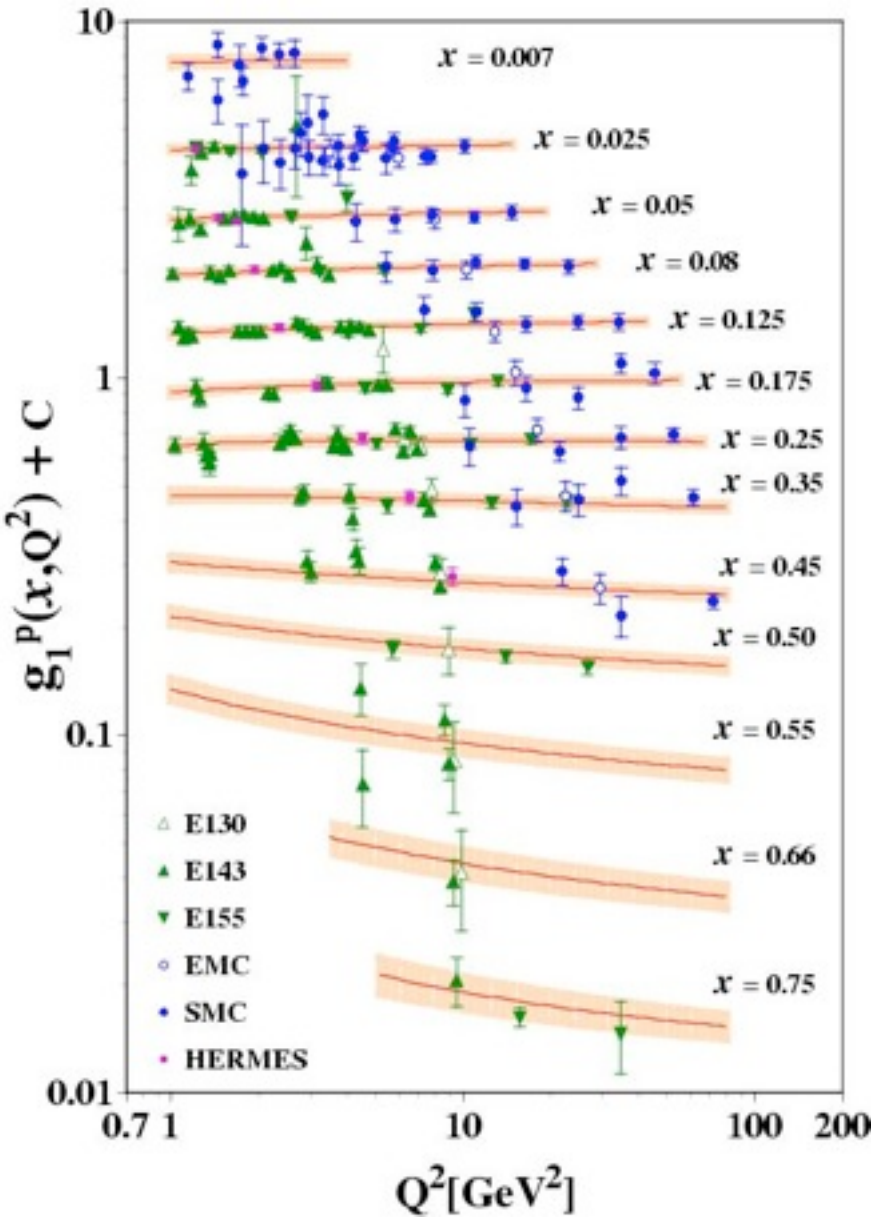
→ intriguing correlation between slope of EMC ratio & nuclear ratio at $x > 1$

Weinstein et al.
*PRL **106**, 052301 (2011)*

→ origin (short-range correlations, local density) being debated

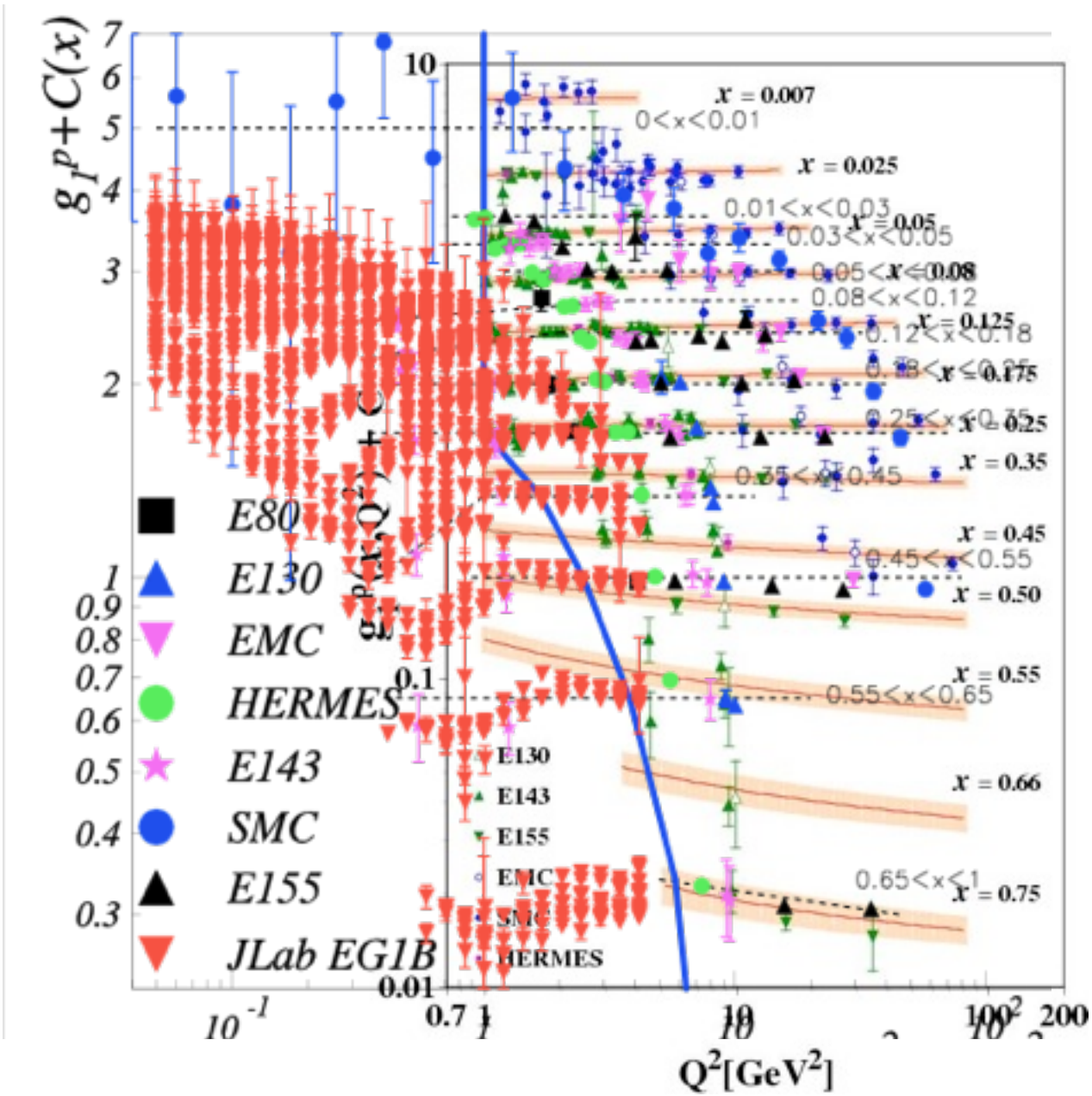
Spin Structure Functions

Proton g_1 structure function



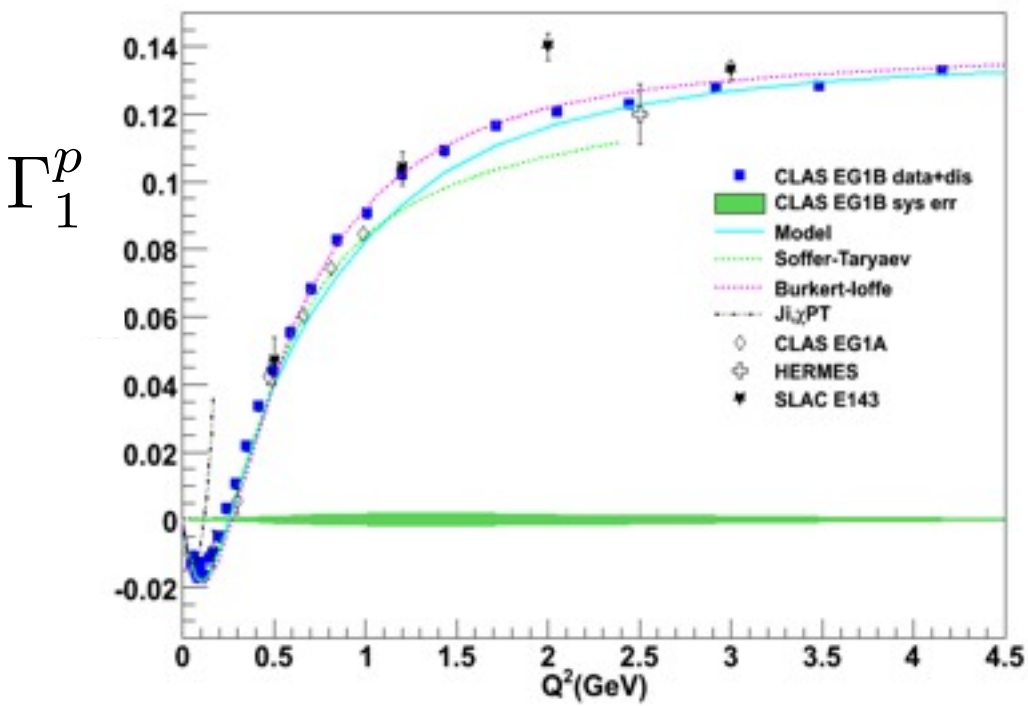
→ world data before JLab

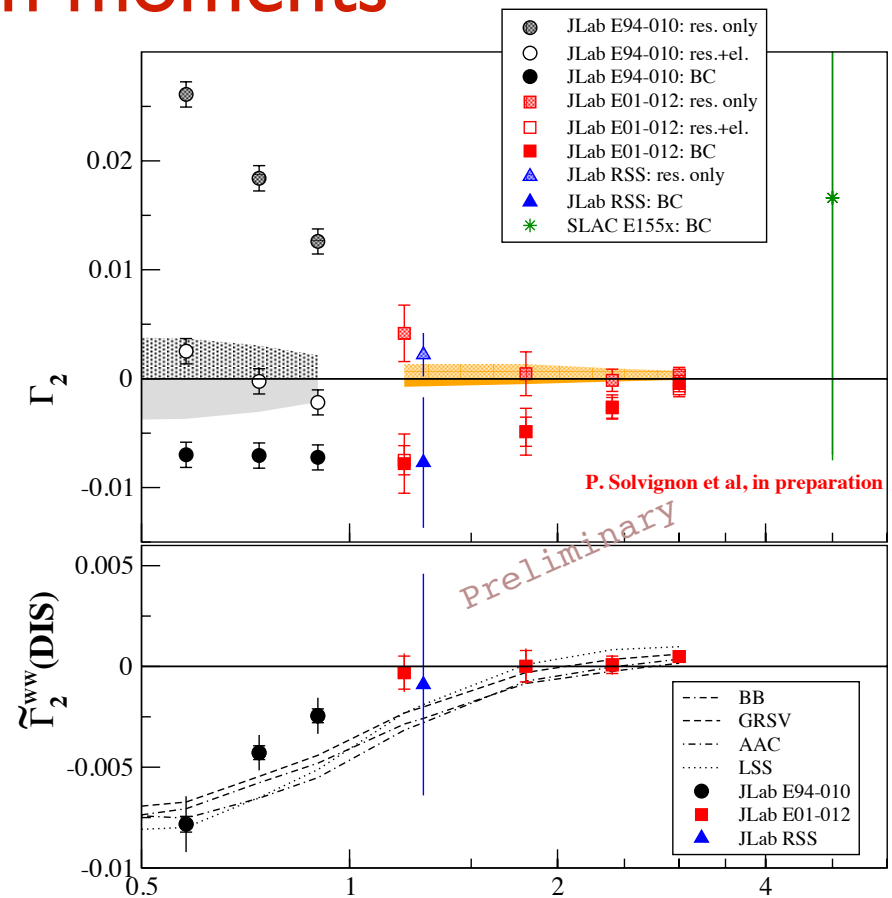
Proton g_1 structure function



→ world data with JLab (up to ~ 2011)

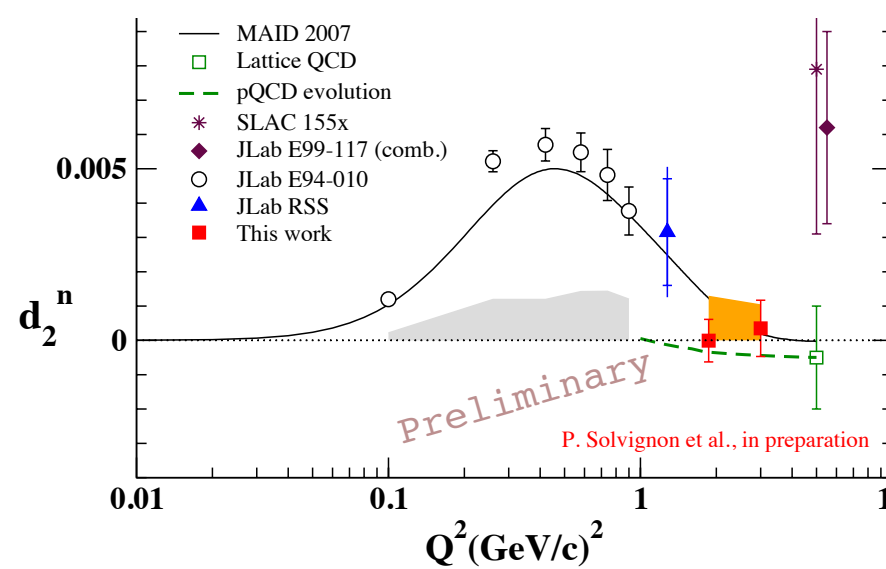
Structure function moments





→ evaluation of moments
(for testing sum rules, or comparison with lattice)
requires data over *all x*

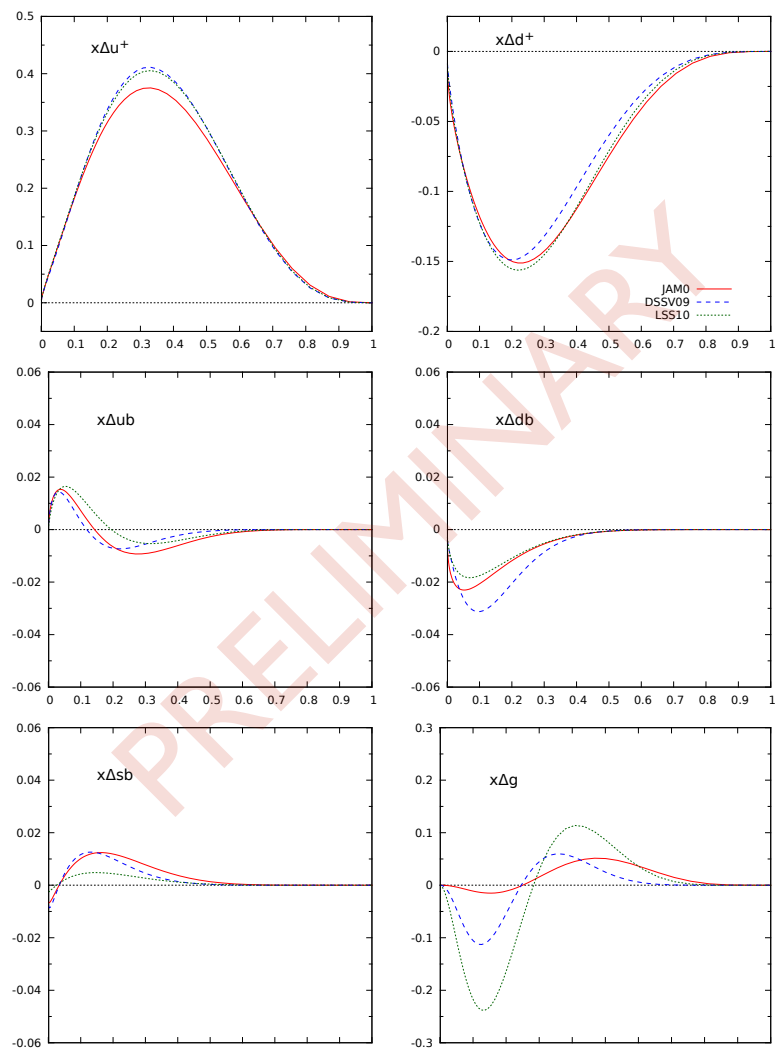
→ JLab maps out transition from pQCD to EFT



JAM global PDF analysis*

- Utilize high-precision low-W, low-Q^2 JLab data to constrain spin PDFs at large x, systematically including
  - → dependence on W & Q^2 cuts
  - → TMC and higher twists
  - → nuclear smearing corrections

- How does $\Delta q/q$ behave as $x \to 1$?
  - → is there evidence for $L_z = 1$ component of wave function from $\Delta d(x)$?



Jimenez-Delgado et al. (2012)

* JLab Angular Momentum collaboration:
P. Jimenez-Delgado, WM, A. Accardi
http://www.jlab.org/JAM

Outlook

- What's still to come from (unpolarized) 6 GeV?
  - → complete analysis of BoNuS F_2^n data (4 and 5 GeV energies)
  - → extraction / fit of neutron F_L^n ; detailed duality studies
  - → inclusion of all 6 GeV cross section data into CJ12 PDF fit

- Plans for 12 GeV measurements
  - → extend measurements of F_2^n to larger x (~ 0.85) with BoNuS12, $^3\mathrm{He}/^3\mathrm{H}$ ratio (determine d/u ratio at $x \to 1$)
  - → parity-violating DIS via γZ interference on p (d/u ratio) and d ($\sin^2\theta_W$) targets
  - → host of spin-dependent inclusive, SIDIS & exclusive measurements
    - → Yelena Prok (Wednesday, 16:30)

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

Jamestown:
1st permanent
English settlement
(1607)

located in Newport News, Virginia

Newport News, Virginia

JLab Kinematic Coverage