International Workshop on Diffraction in High-Energy Physics
September 11, 2012

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

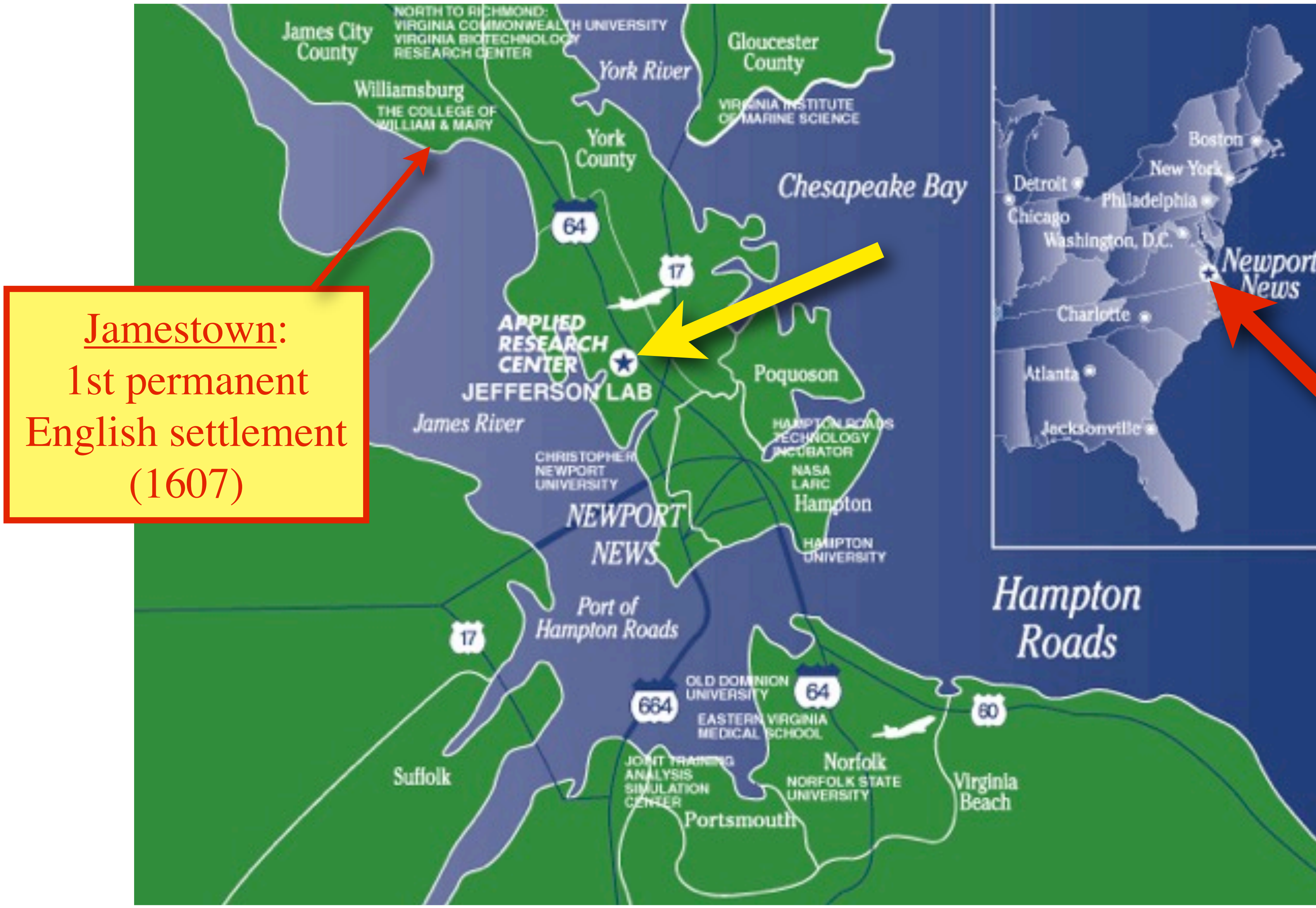
CEBAF

(Continuous Electron Beam Accelerator Facility)

at

Jefferson Lab

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

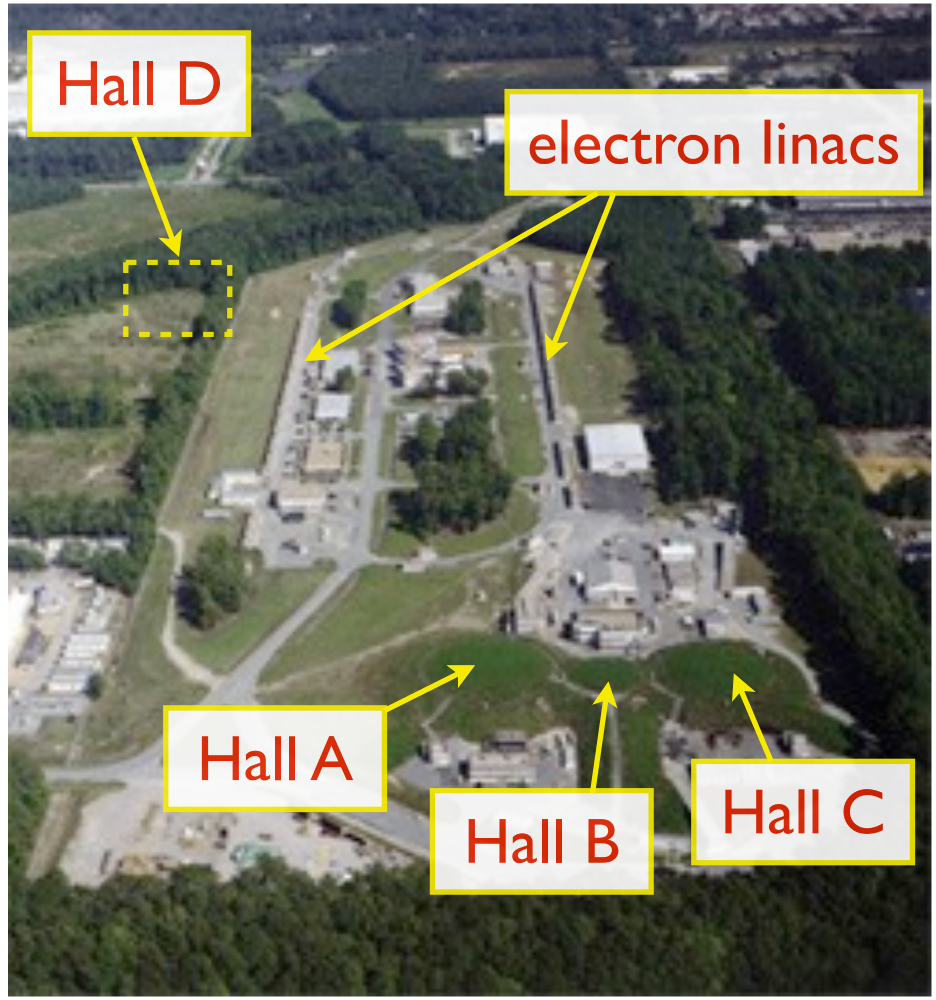


located in Newport News, Virginia

Newport News, Virginia

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

6 GeV polarized electron beam
on (un)polarized targets



6 GeV program ended in May, 2012

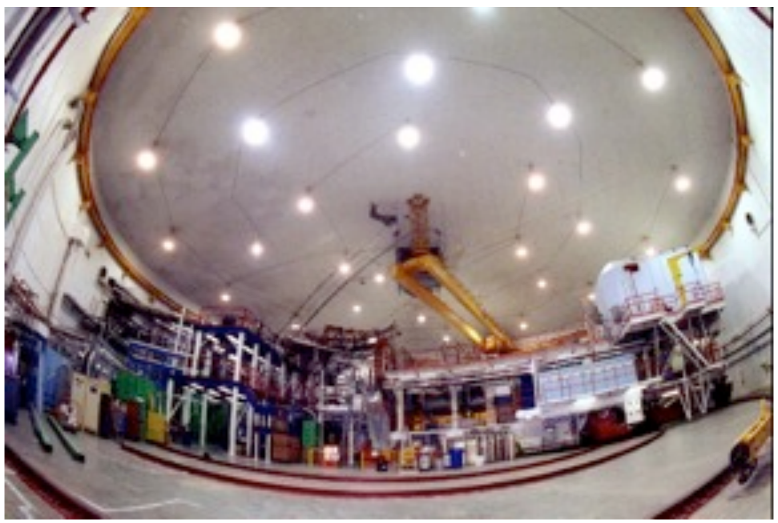
Upgrade to 12 GeV under way
(restart ~ 2014–2015)

Experimental Halls

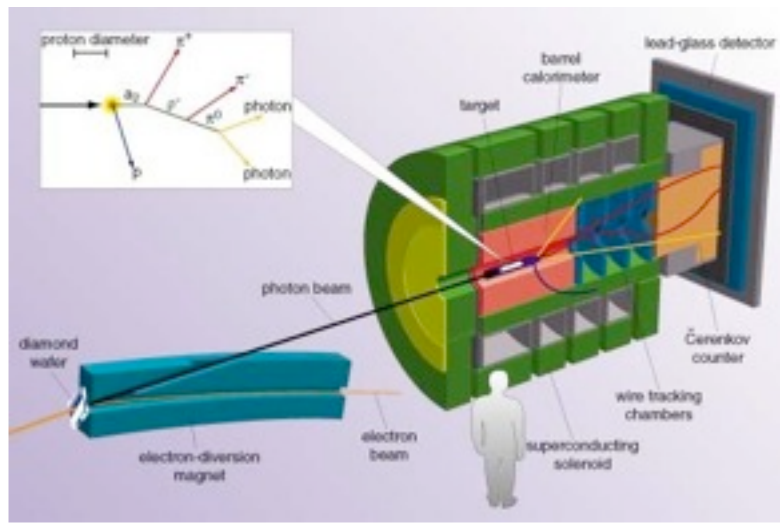
Hall A

Hall B

Hall C



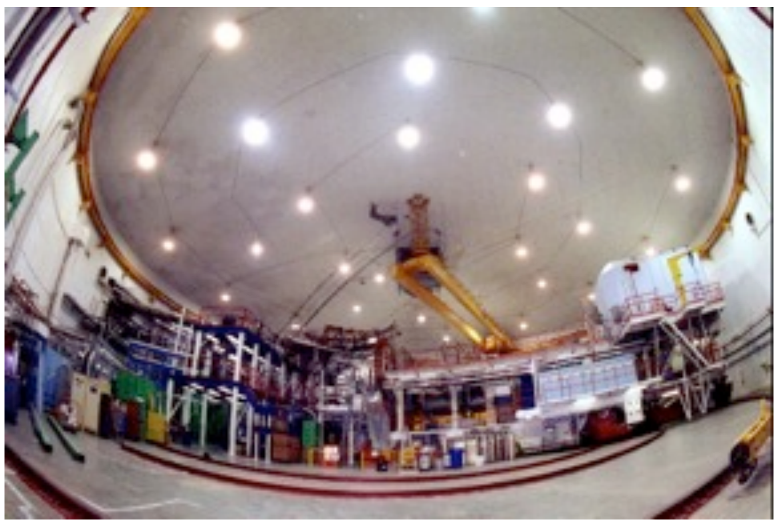
Hall D



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

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

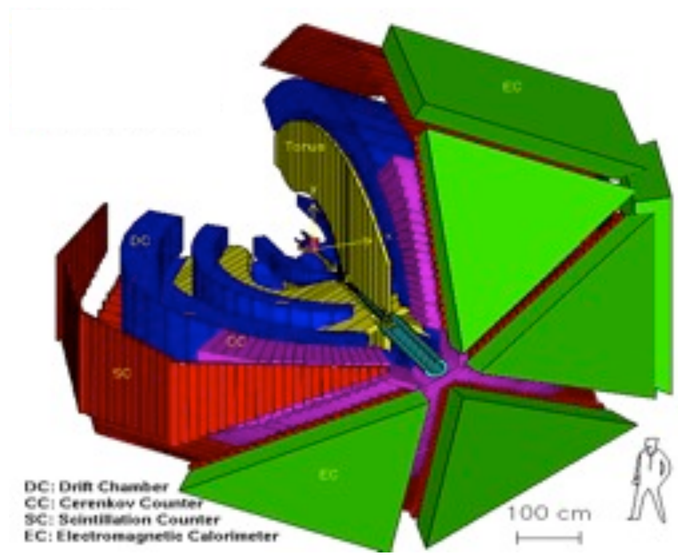
- collect all data "at once"

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

Hall B

CLAS

(CEBAF Large Acceptance Spectrometer)



Experimental Halls

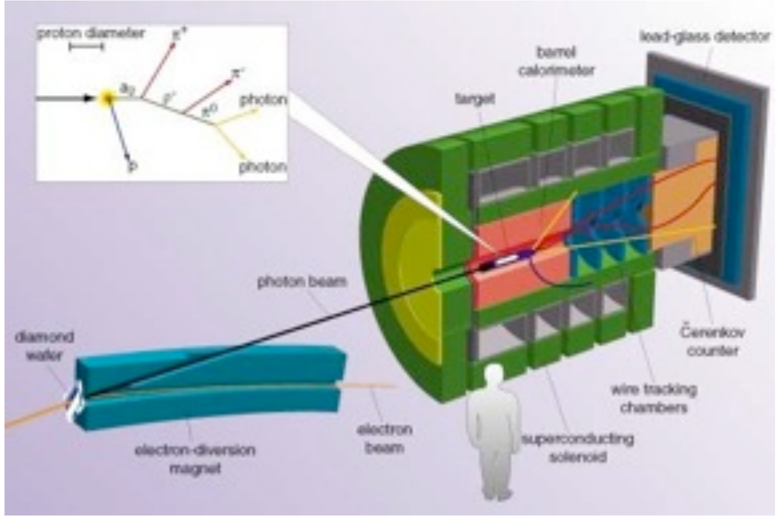
- new Hall just completed, as part of 12 GeV Upgrade

- 4π acceptance

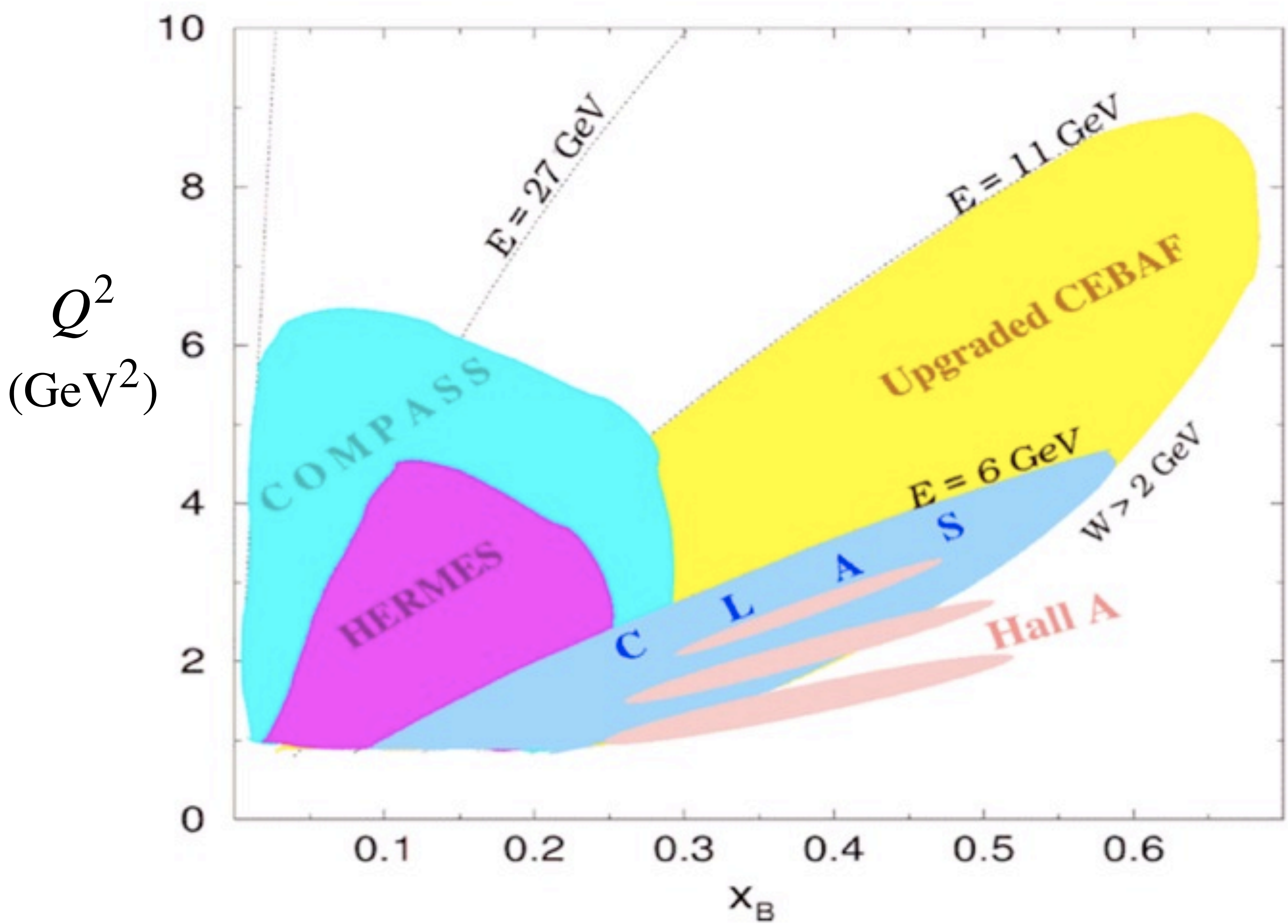
- photon beam

- exotic meson spectroscopy ($q\bar{q}g$ states)

Hall D

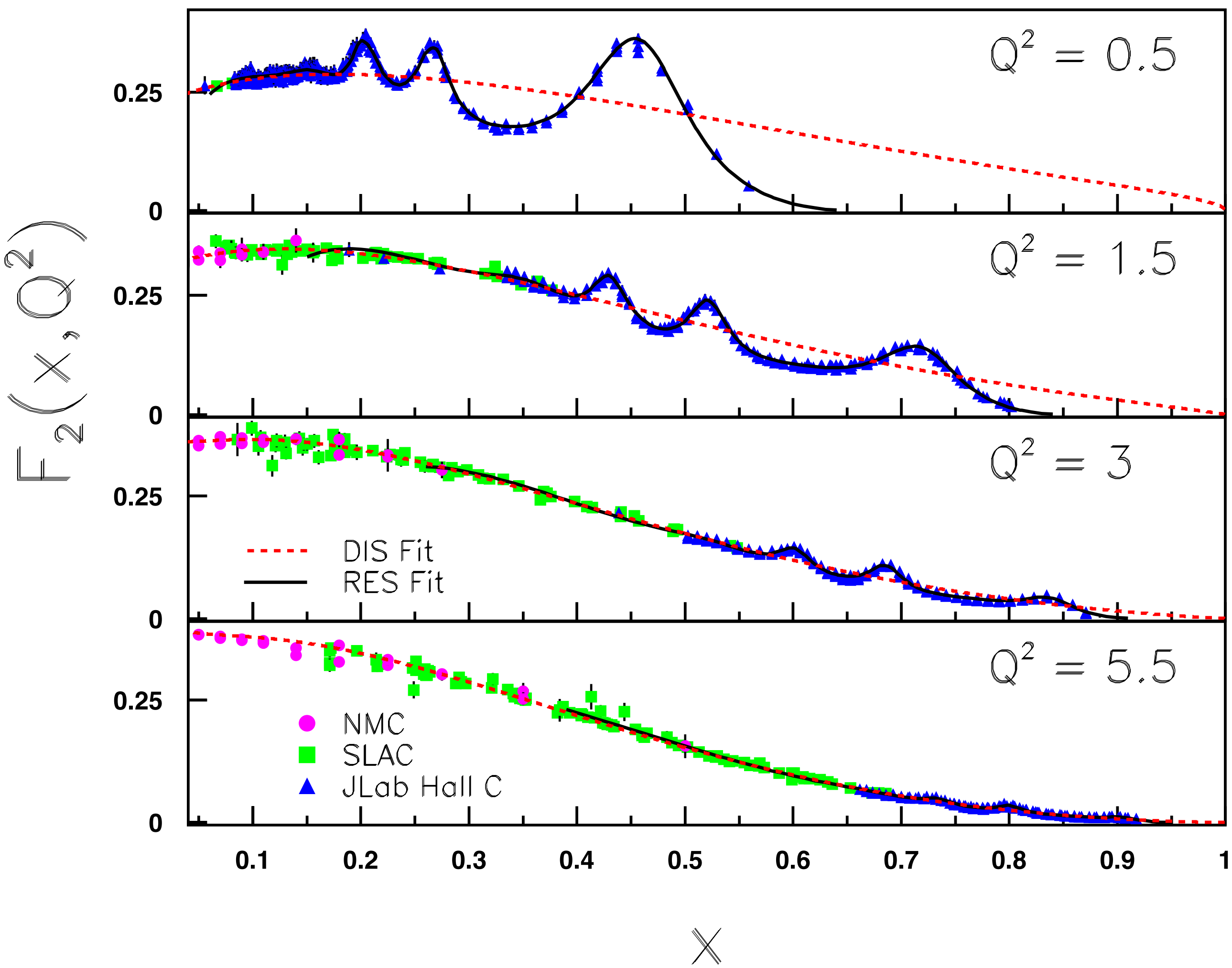


JLab Kinematic Coverage



Unpolarized Structure Functions

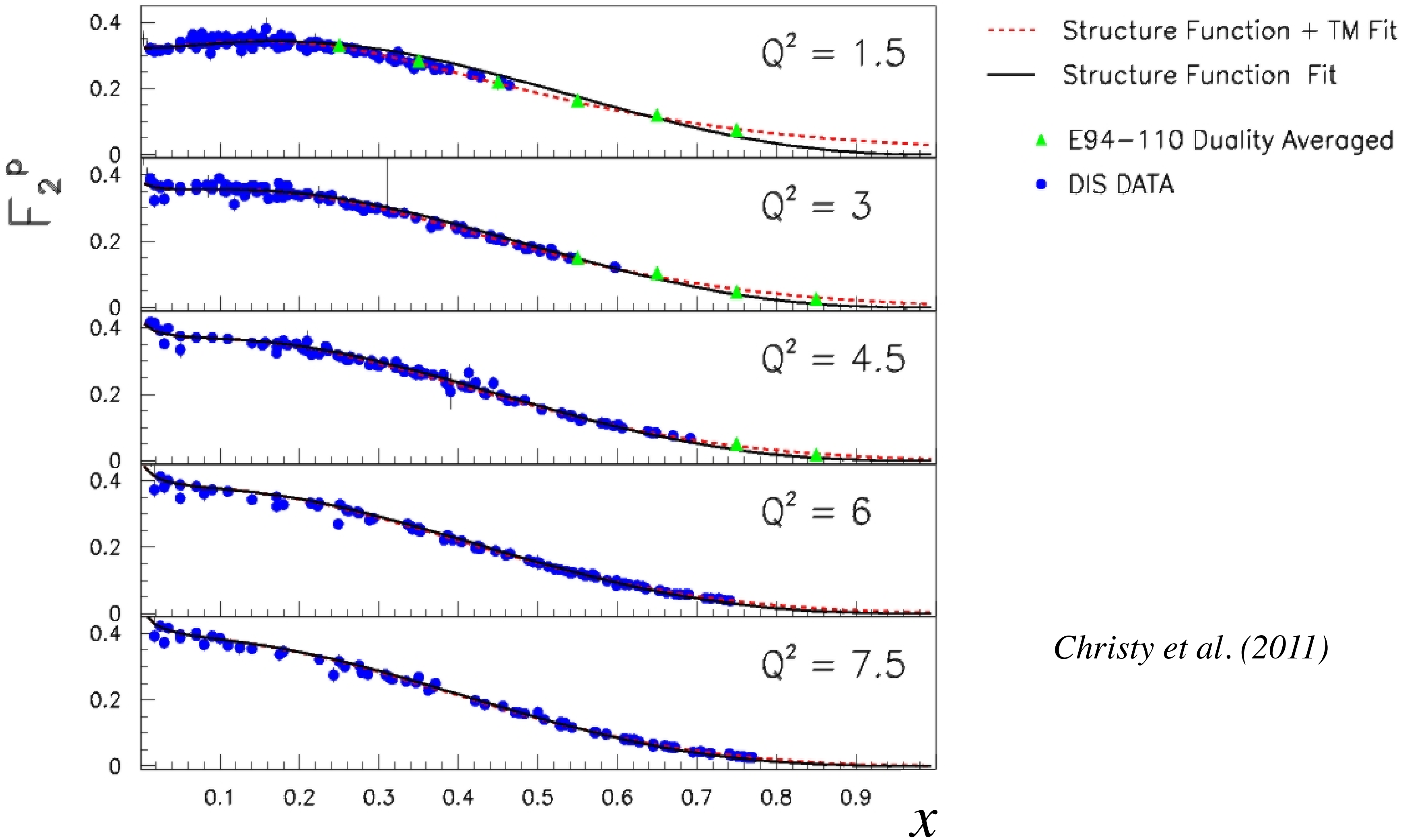
Proton F_2 structure function



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

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

Proton F_2 structure function



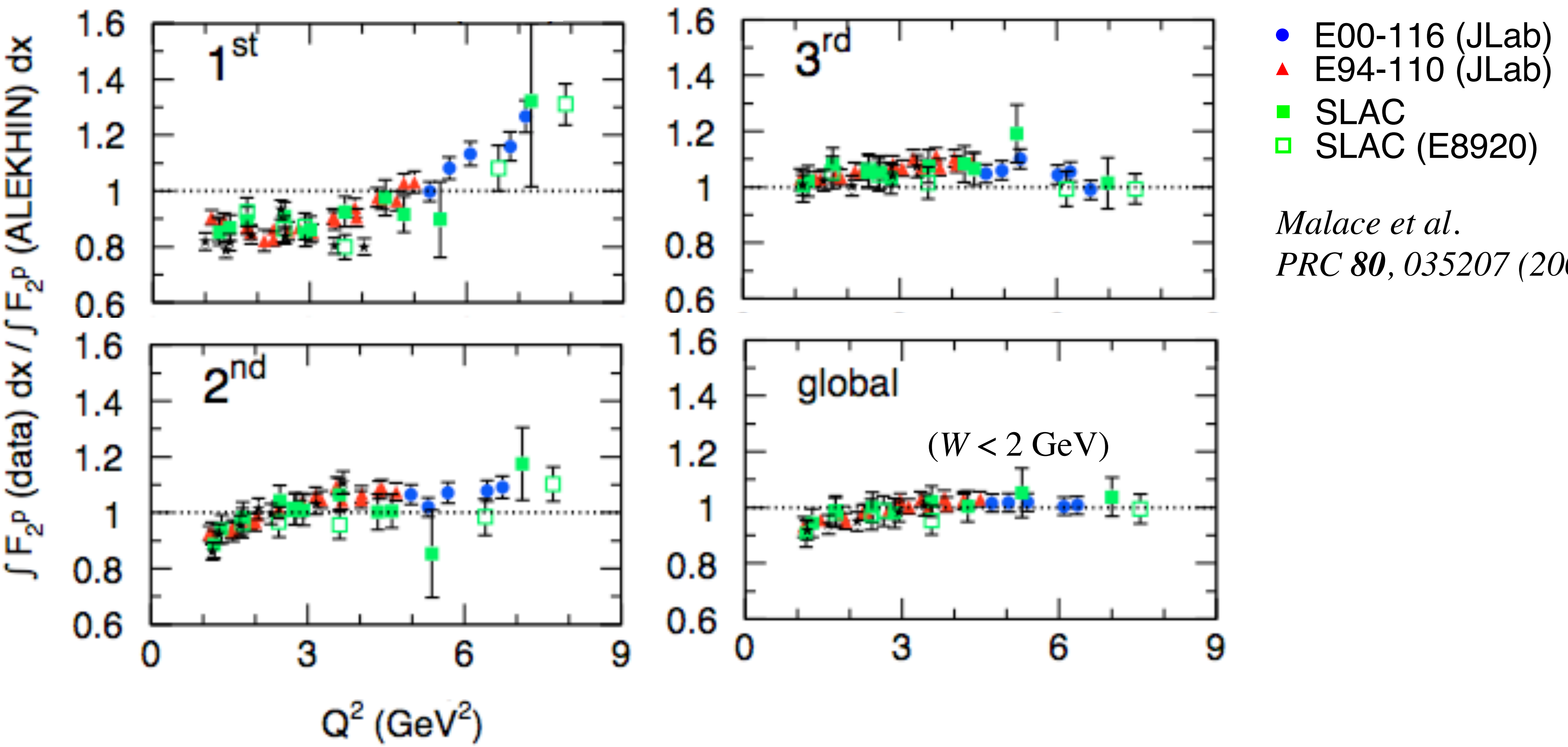
Christy et al. (2011)

→ high precision tests of quark-hadron duality

square of sum ⟷ sum of squares?

"coherent" "incoherent"

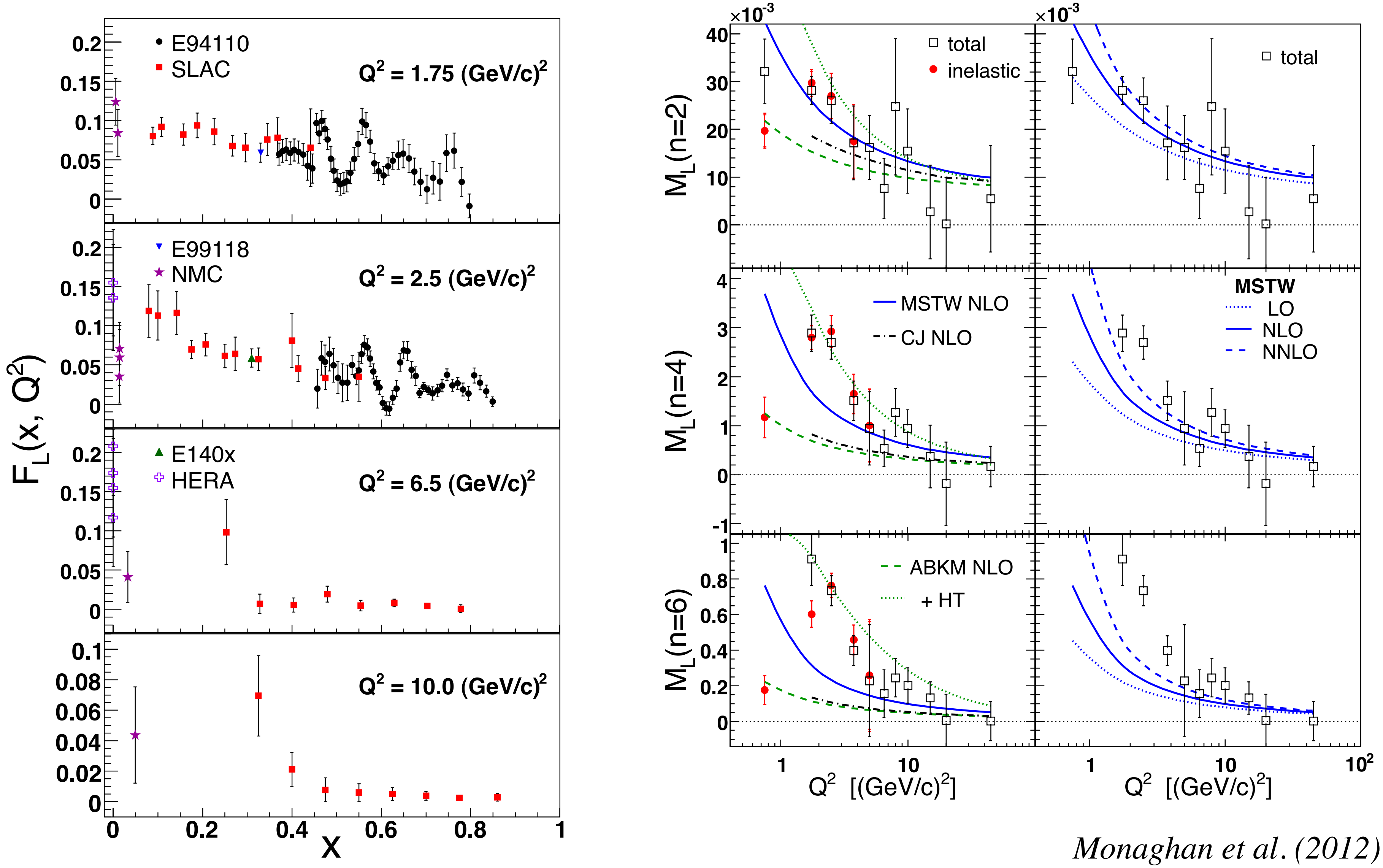
Proton F_2 structure function



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)

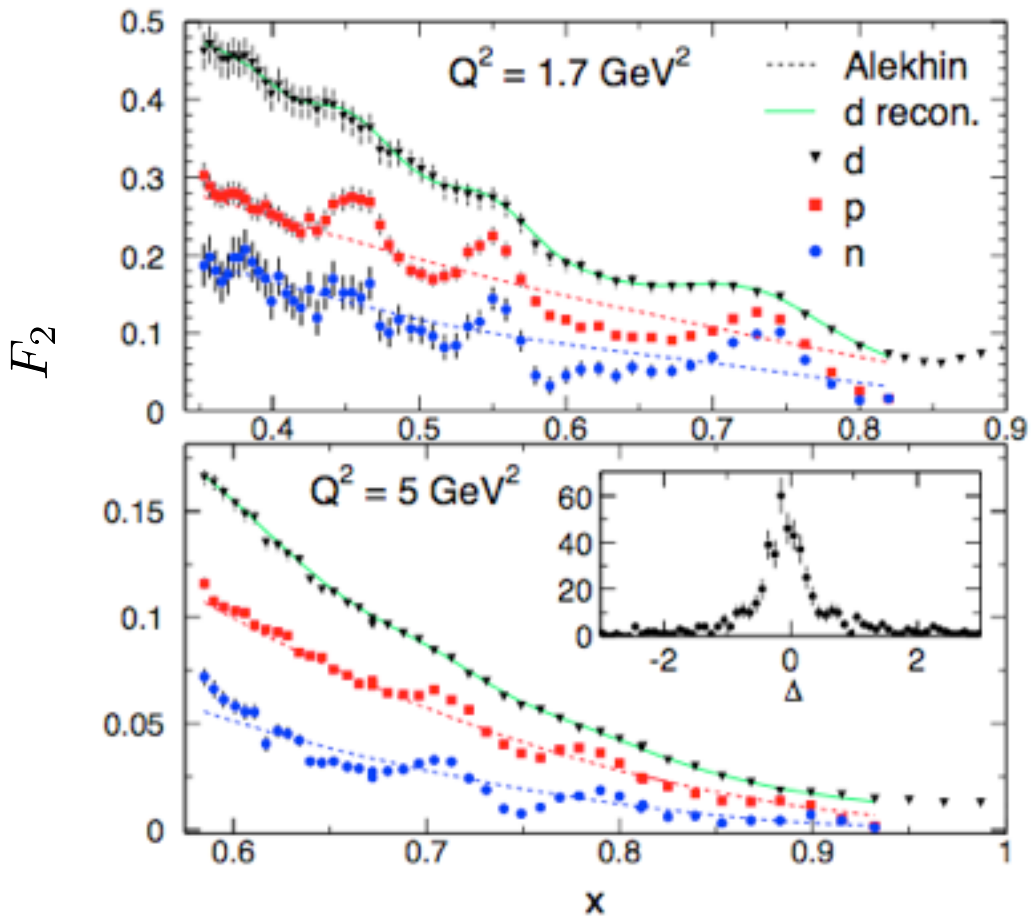
→ moment analysis suggests larger gluon at high x

(or significant higher twists in higher moments)

Neutron F_2 structure function

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

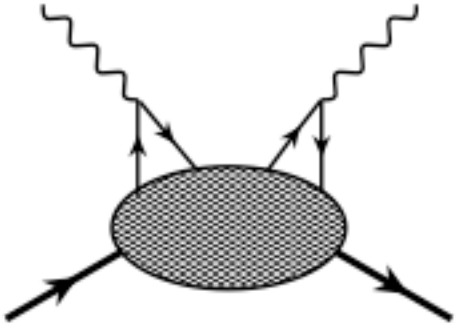
  → new extraction method allows first determination of F_2^n in resonance region



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

→ test universality of quark-hadron duality!

Duality from accidental cancellations of charges?



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

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

coherent (first term) *incoherent* (second term)

<u>*proton*</u> $\quad \mathrm{HT} \sim 1 - \left(2 \times \frac{4}{9} + \frac{1}{9}\right) = 0 \, !$

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

Brodsky
hep-ph/0006310

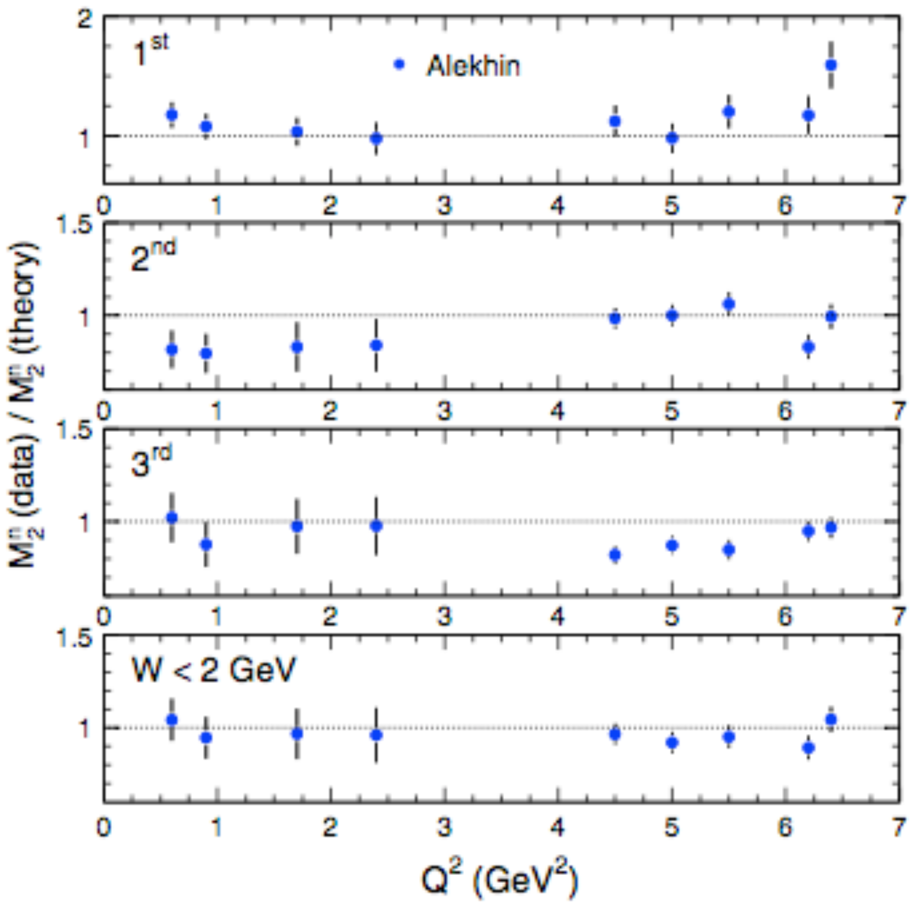
→ duality in proton a *coincidence!*

→ should <u>*not*</u> hold for neutron

Neutron F_2 structure function

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

  $\longrightarrow$ new extraction method allows first determination of F_2^n in resonance region



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

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

$\longrightarrow$ *locally*, violations of duality in resonance regions < 15–20%

$\longrightarrow$ *globally*, violations $< 10\%$

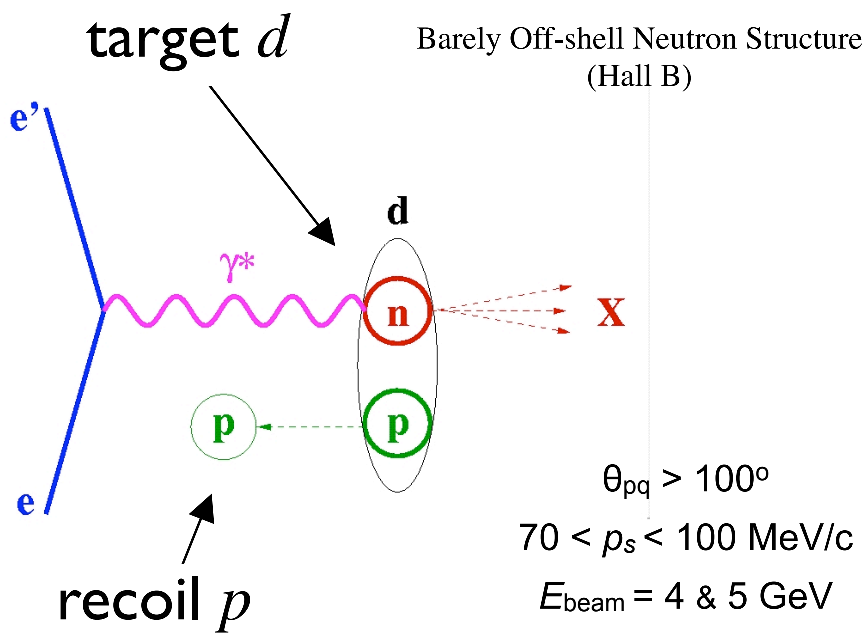
$\longrightarrow$ duality *not* accidental !

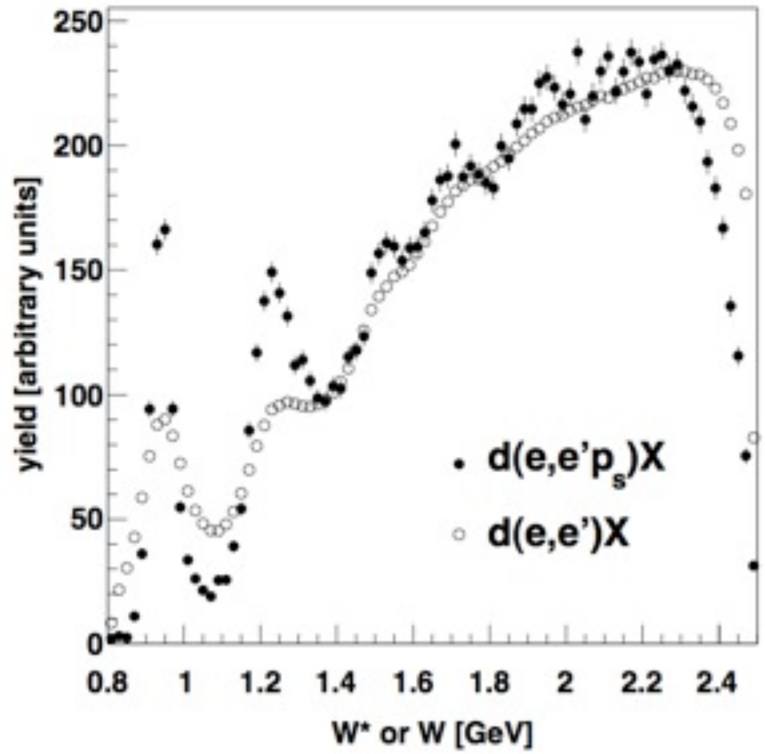
Neutron F_2 structure function

- 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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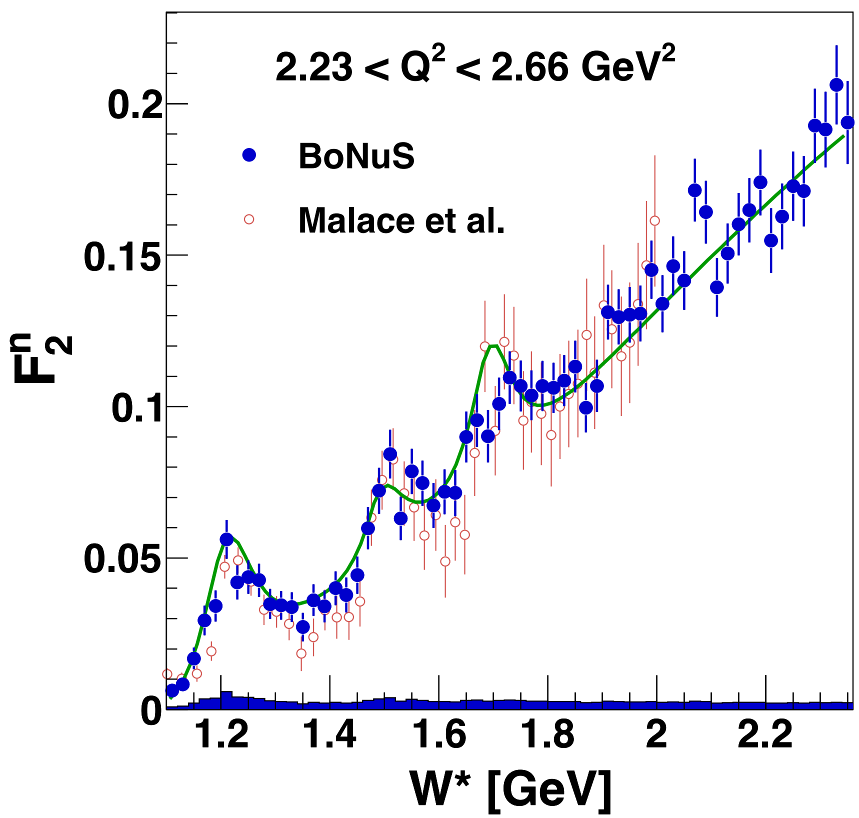
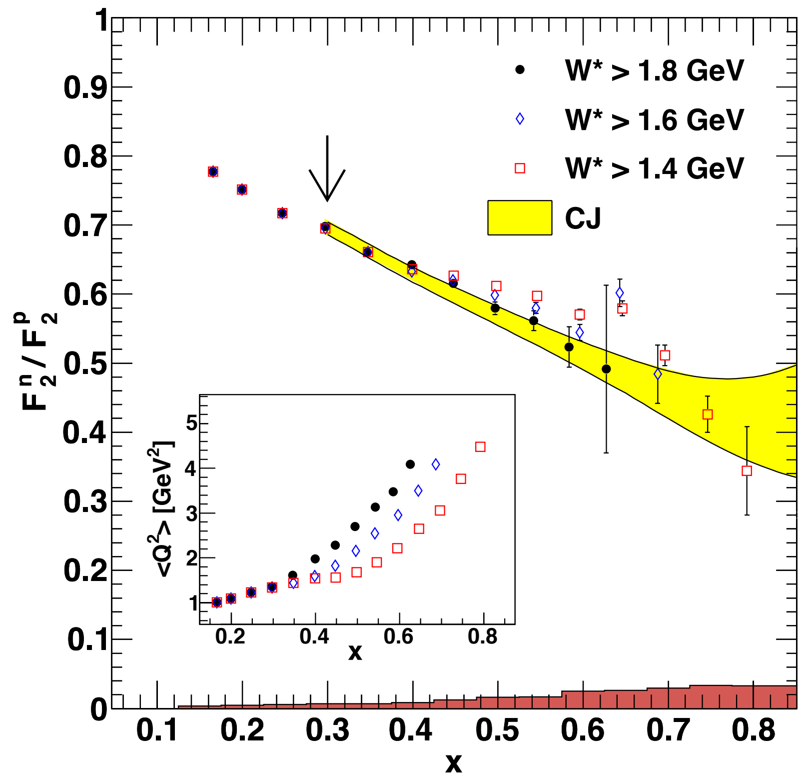




*Baillie et al., PRL **108**, 142001 (2012)*

→ 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

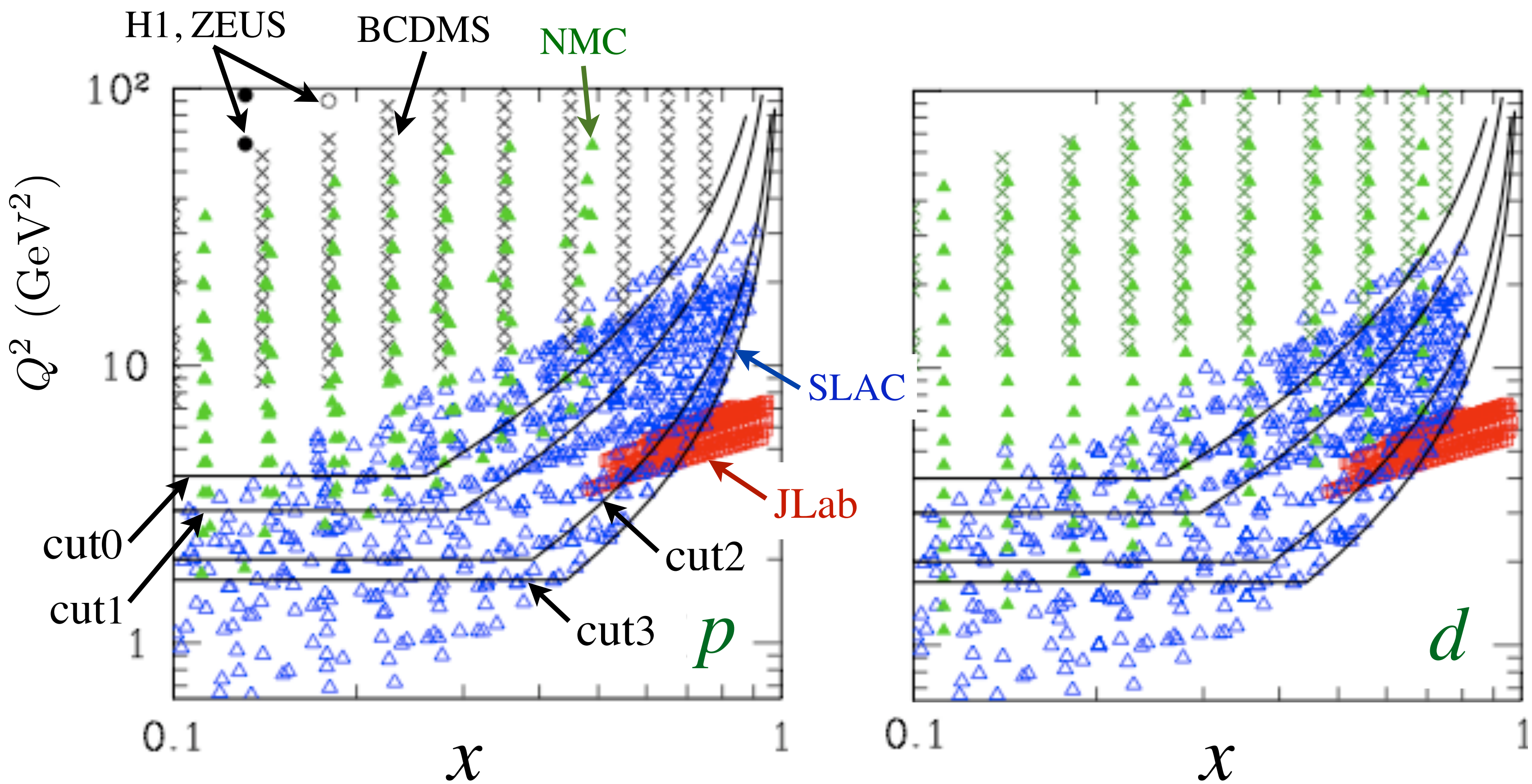
- Systematically study effects of Q^2 & W cuts
  → down to $Q \sim m_c$ and $W \sim 1.7$ GeV

- 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 $x = 1$: $d \;\rightarrow\; d + a\,x^b\,u$

CJ kinematic cuts



cut0: $Q^2 > 4\ \text{GeV}^2,\quad W^2 > 12.25\ \text{GeV}^2$

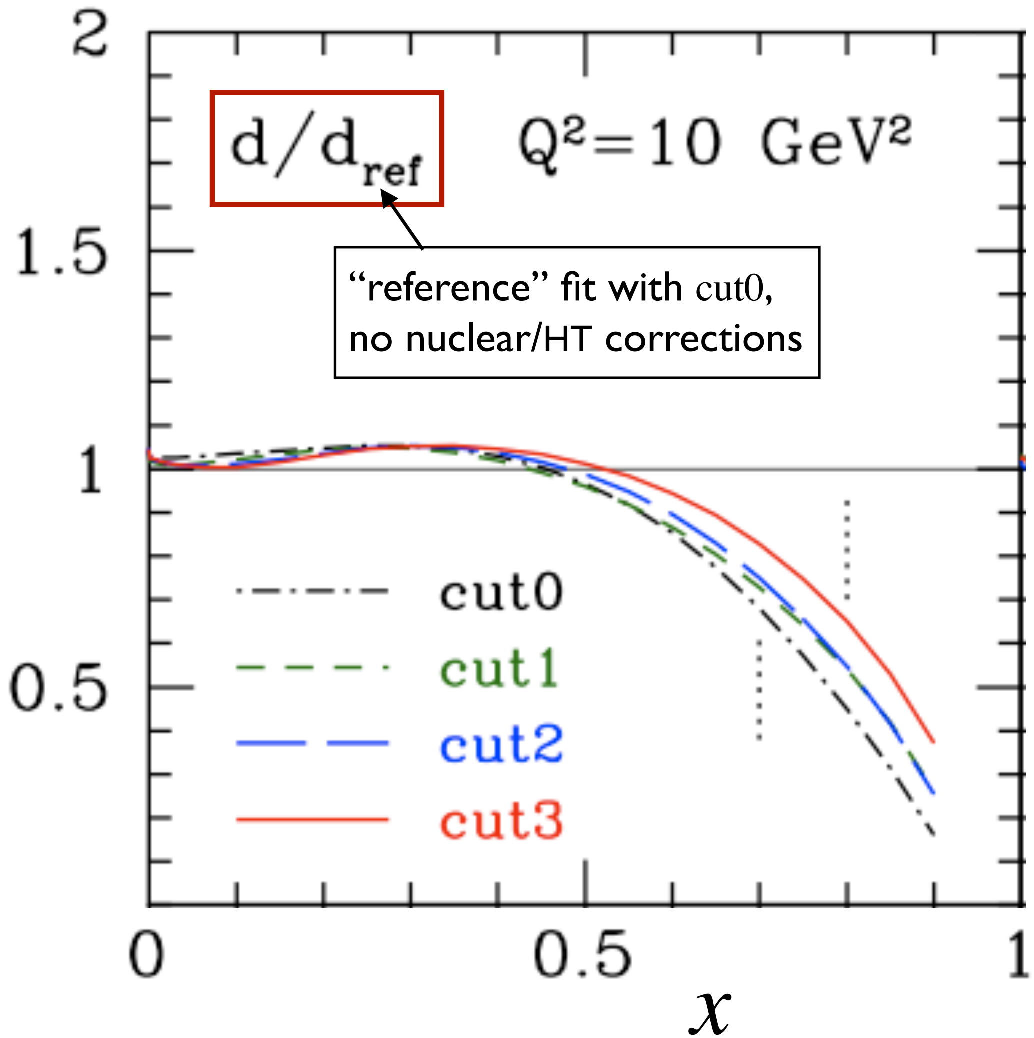
cut1: $Q^2 > 3\ \text{GeV}^2,\quad W^2 > 8\ \text{GeV}^2$

cut2: $Q^2 > 2\ \text{GeV}^2,\quad W^2 > 4\ \text{GeV}^2$

cut3: $Q^2 > m_c^2\ ,\quad W^2 > 3\ \text{GeV}^2$

factor 2 increase in DIS data from cut0 → cut3

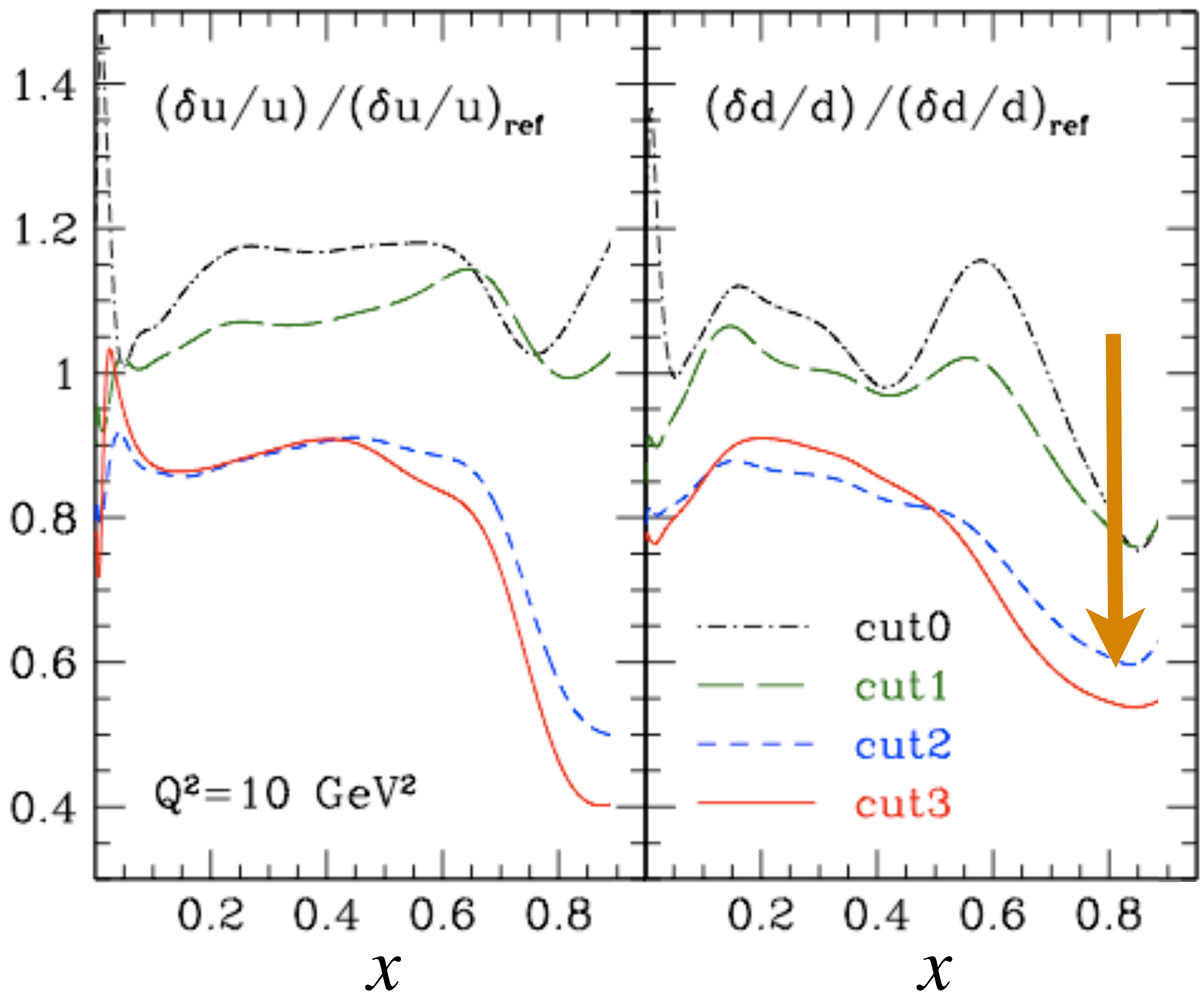
- PDFs remarkably *stable* with respect to cut reduction, as long as finite-Q^2 corrections included



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

→ d quark behavior driven by nuclear corrections at high x

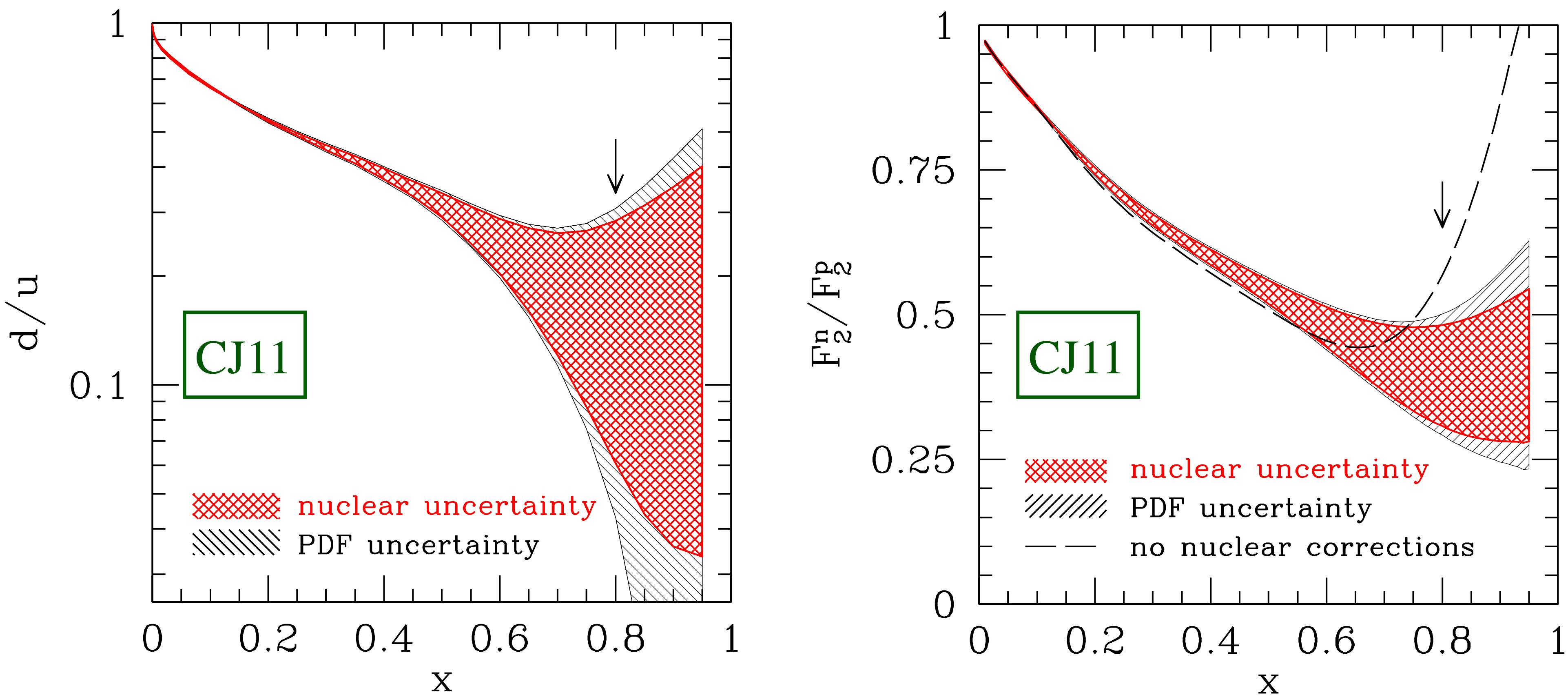
- Larger database with weaker cuts leads to significantly reduced errors, especially at large x



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

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

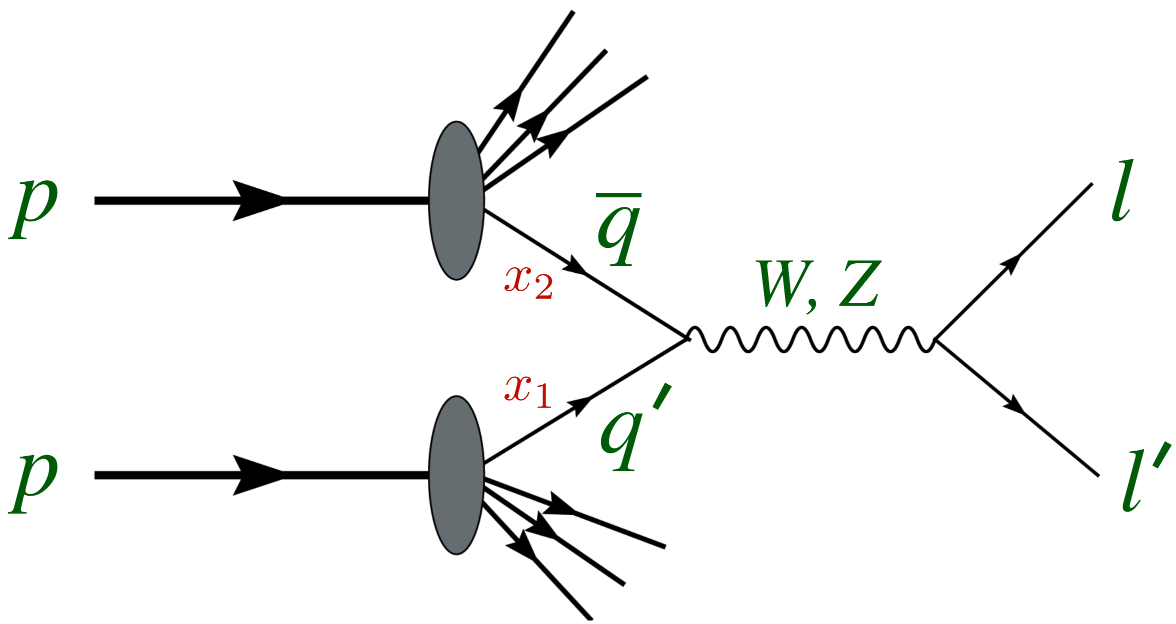
- Vital for large-x analysis, which currently suffers from large uncertainties (mostly due to nuclear corrections)



*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)*

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

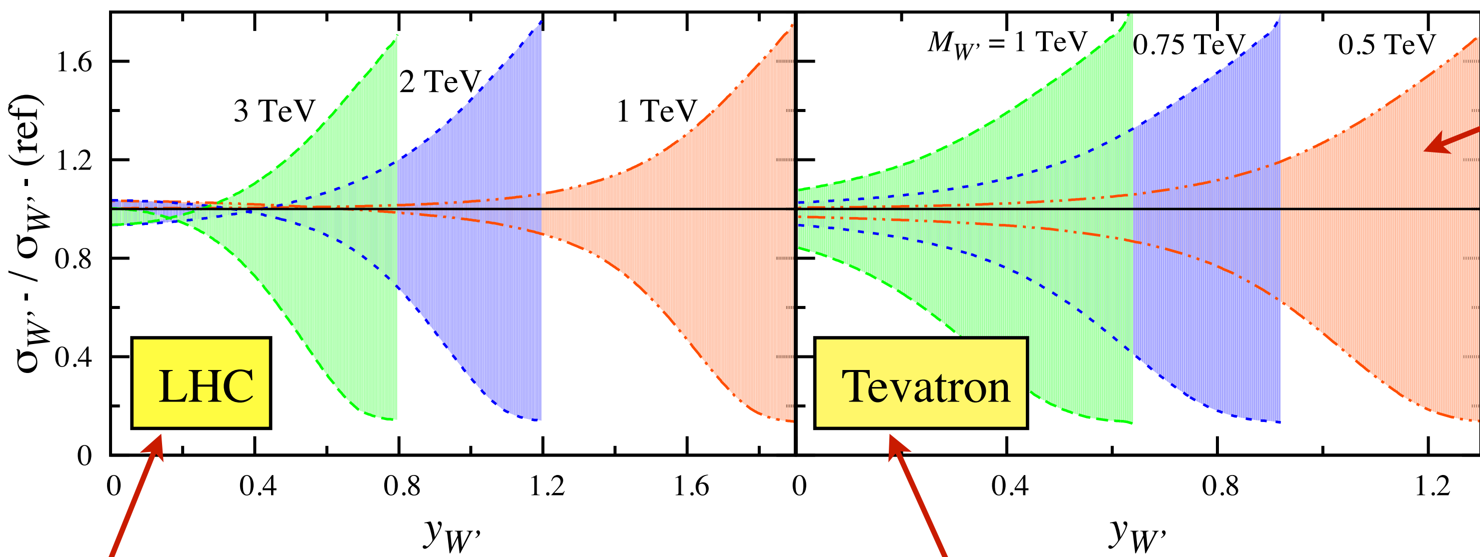
→ more exotic scenarios, *e.g.*

- 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)*

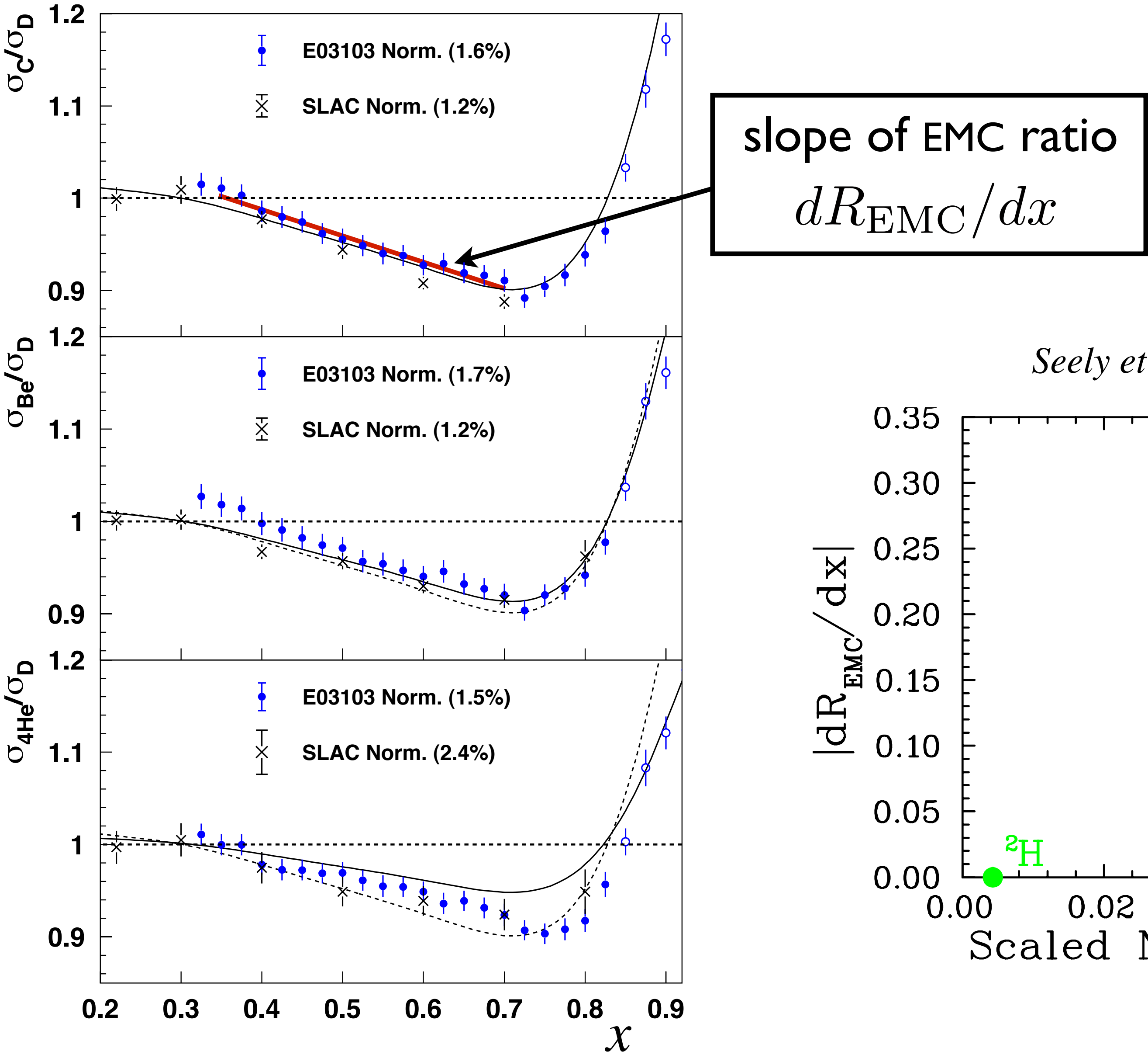
dominated by $d * \bar{u}$

dominated by $d * u + u * d$

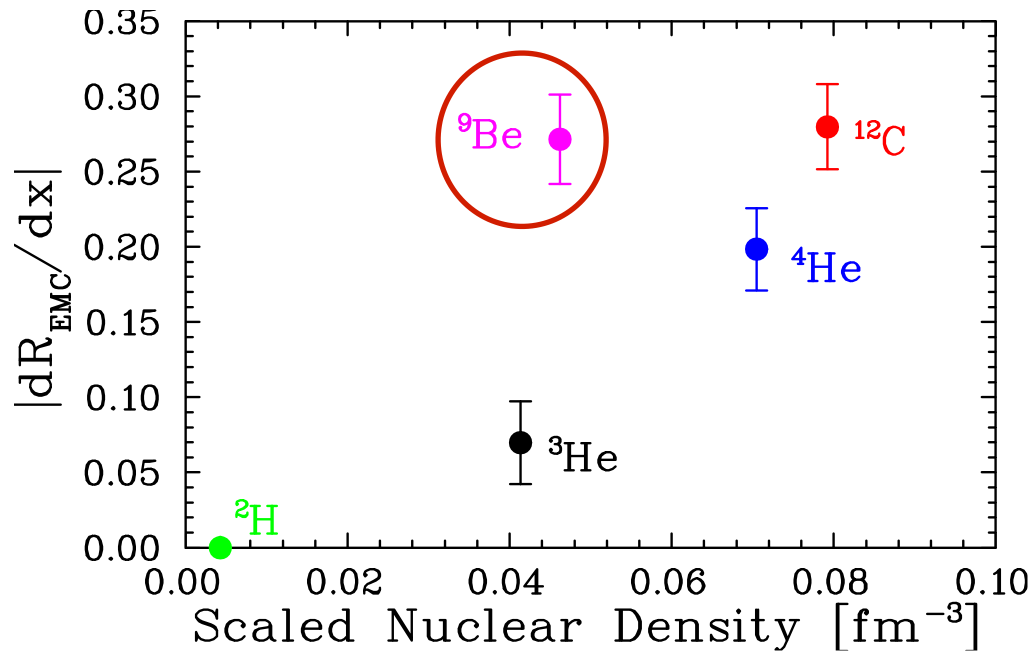
→ uncertainty in d PDF at large x and low Q^2 evolves to larger uncertainty at small x and high Q^2

Nuclear Structure Functions

Nuclear EMC effect

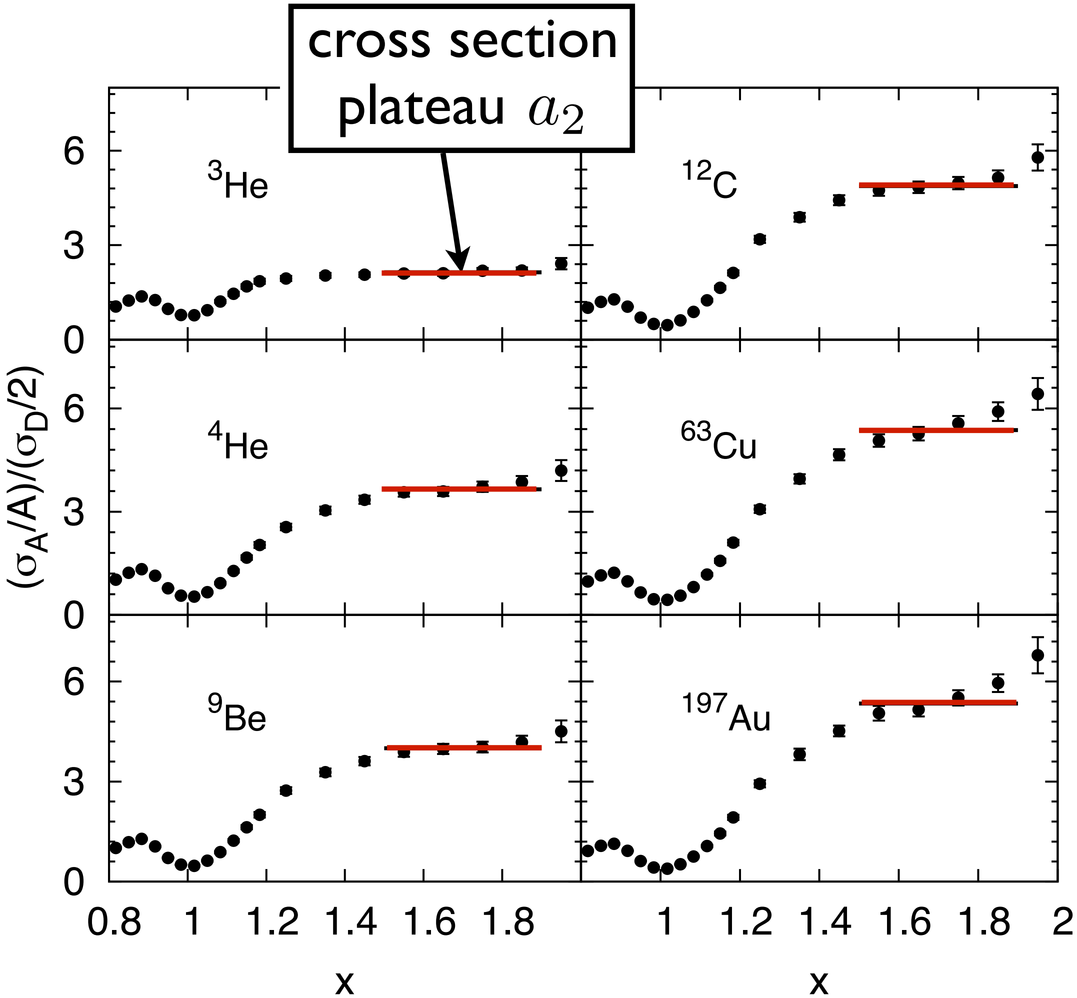


Seely et al., PRL ***103***, *202301 (2009)*

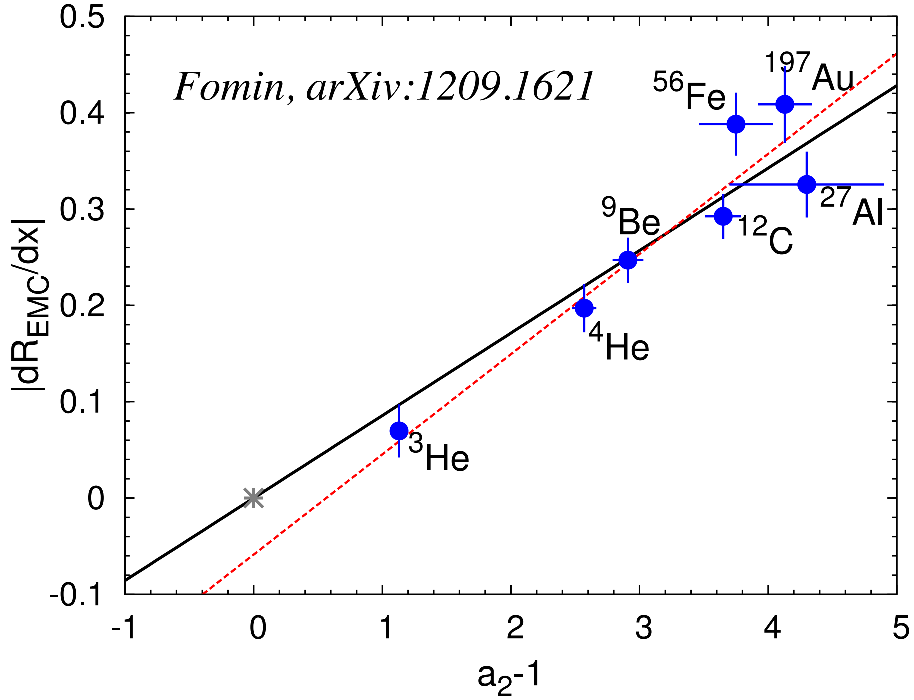


→ ^{9}Be suggests *local density* may provide better scaling

Nuclear EMC effect



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



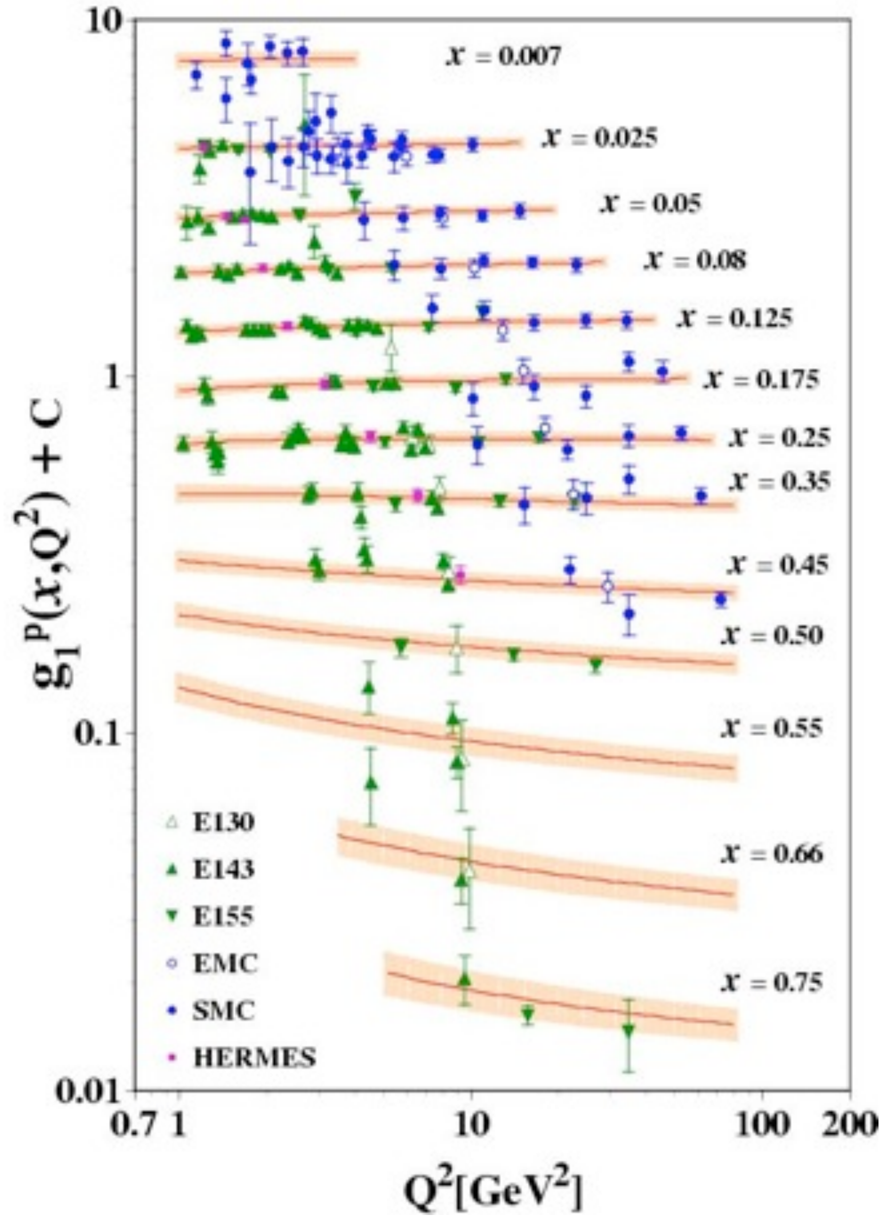
→ intriguing correlation between slope of EMC ratio & nuclear ratio at $x > 1$

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

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

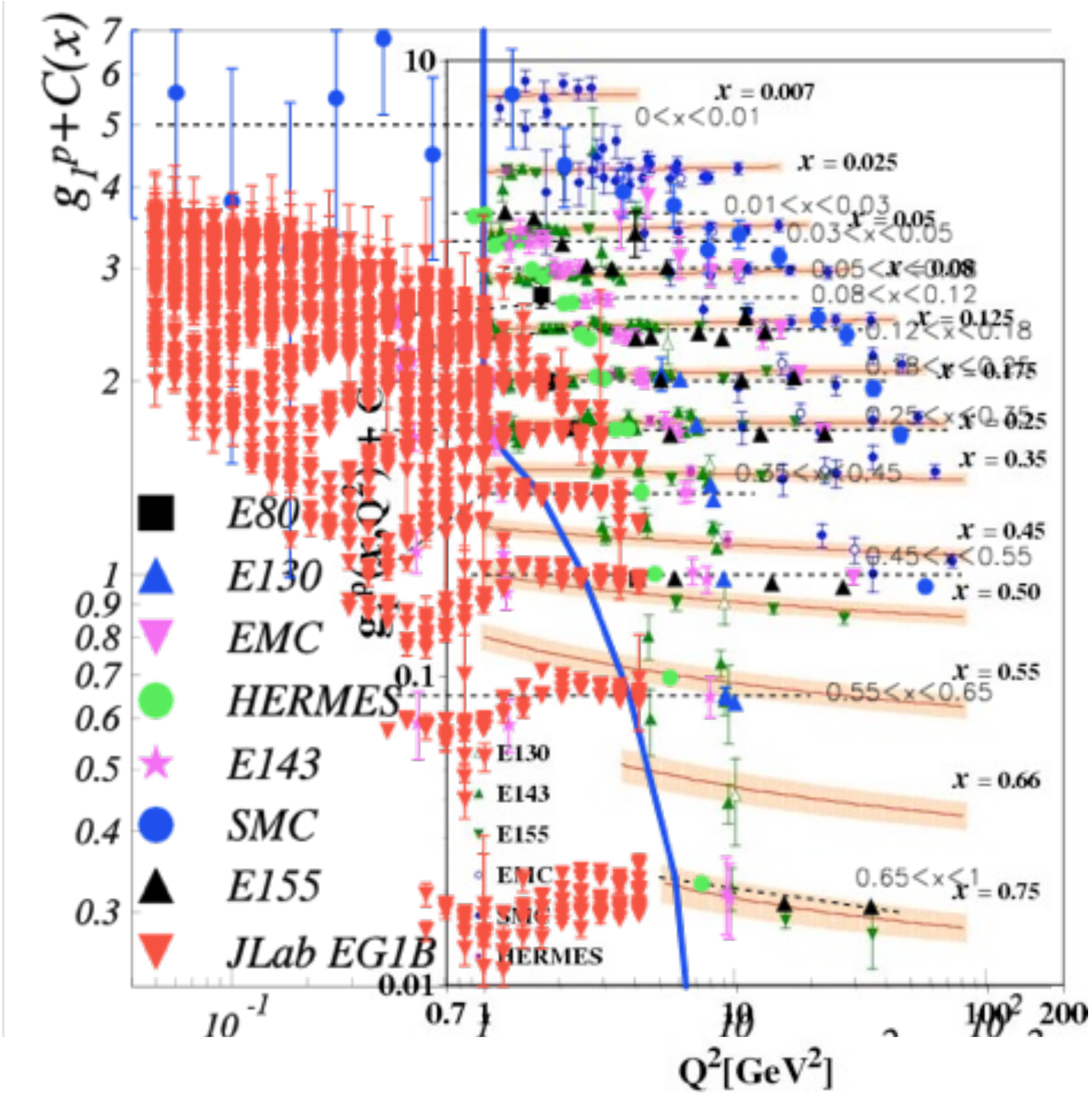
Spin Structure Functions

Proton g_1 structure function



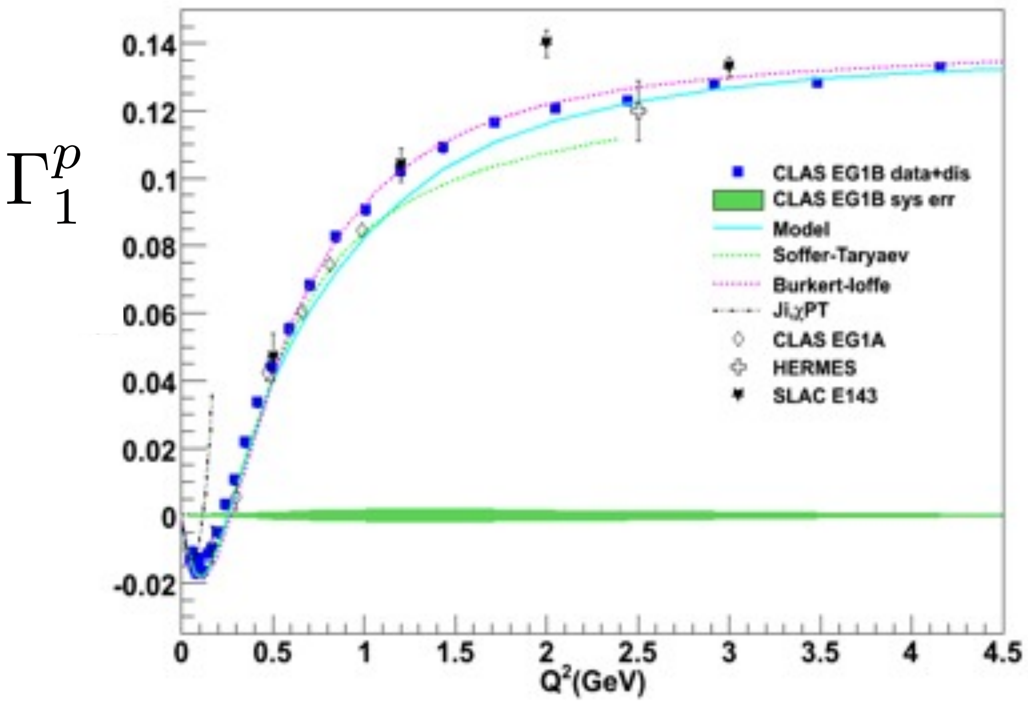
→ world data before JLab

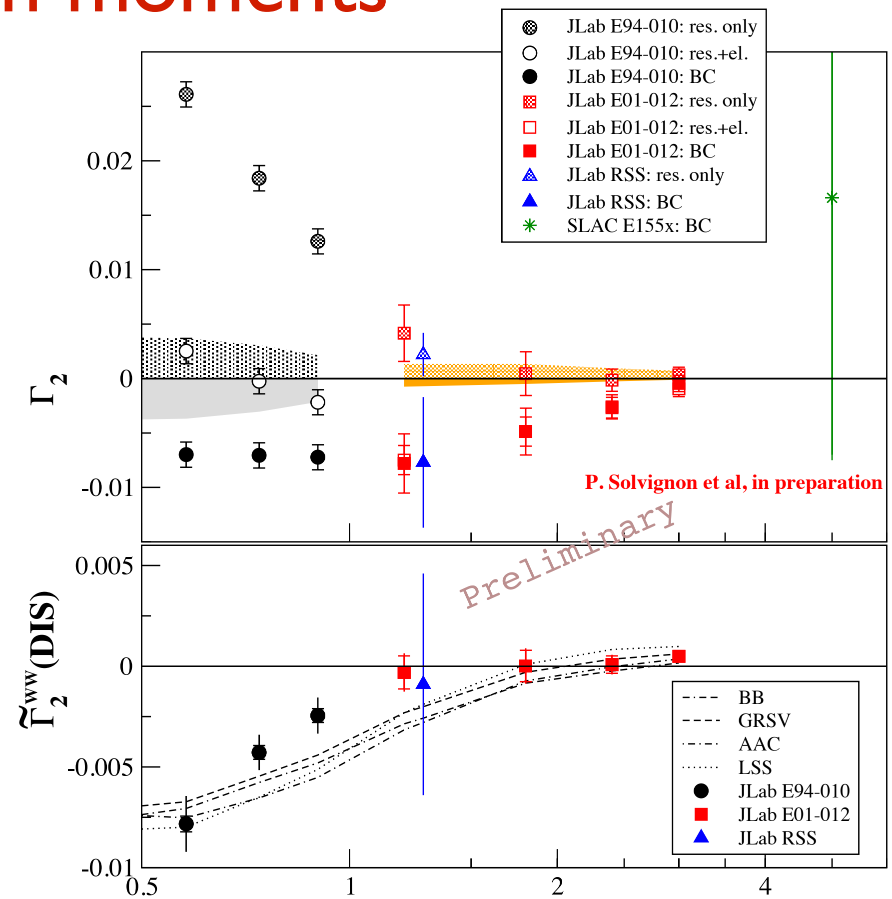
Proton g_1 structure function



→ world data with JLab (up to ~ 2011)

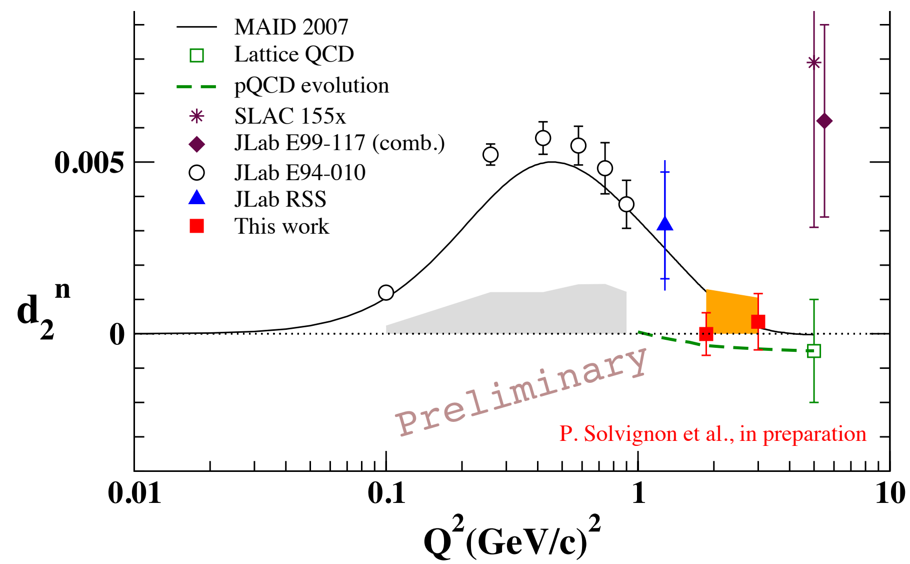
Structure function moments





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

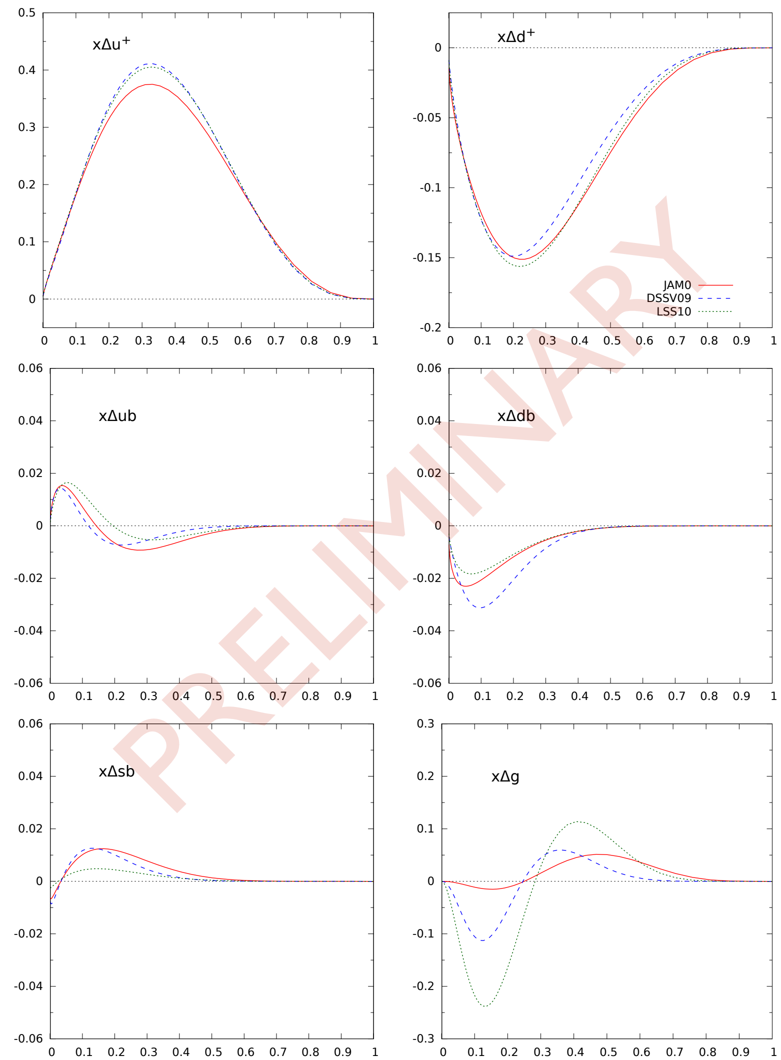
- → JLab maps out transition from pQCD to EFT



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) $6\ \mathrm{GeV}$?
  - → 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 $6\ \mathrm{GeV}$ cross section data into CJ12 PDF fit

- Plans for $12\ \mathrm{GeV}$ 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)