Physics Beyond the SM and Precision Nucleon Structure with PVES
ECT Trento, August 2, 2016*

PVDIS and nucleon structure

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Outline

- PVDIS $(\vec{e}N \to eX)$ is a valuable tool to study flavor and spin dependence of nucleon PDFs

  $\longrightarrow$ establish accurate baseline from which to explore BSM physics

- PVDIS at lower Q^2 and W^2 ($e.g.$ resonance region) provides vital input for estimates of γZ interference corrections ($e.g.$ for Qweak)

  P. Blunden, M. Gorshteyn talks

- Extraction of PDF information requires various subleading, finite-Q^2 corrections to be understood

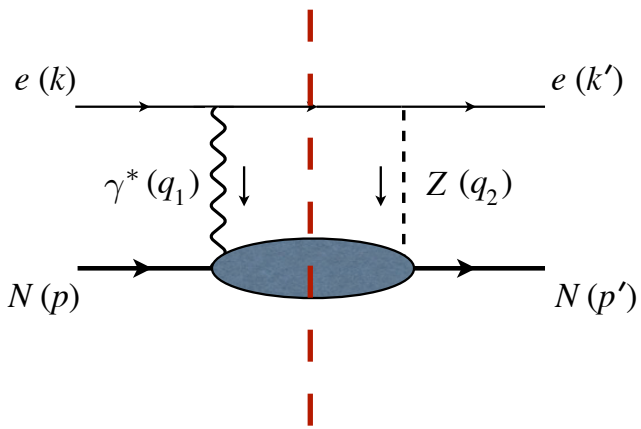
  - α_s corrections (NLO), σ_L/σ_T ratio
  - target mass corrections
  - higher twists *C. Seng talk*

PVDIS at leading twist

- Asymmetry between left- and right-handed inclusive electron-nucleon cross sections

$$A^{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

→ for $Q^2 \ll M_Z^2$ numerator sensitive to γZ interference only



$$Q^2 = -(q_1 + q_2)^2$$

→ denominator dominated by electromagnetic component

- In terms of structure functions,

$$A^{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(g_A^e\, Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e\, \frac{Y_3}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right)$$

→ $Y_{1,3}$ parameterize dependence on $y = \nu/E$

$$Y_1 = \frac{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma Z})) - 2xyM/E}{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma})) - 2xyM/E}\left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right)$$

$$Y_3 = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma})) - 2xyM/E}\left(\frac{r^2}{1+R^{\gamma}}\right)$$

with

$$r^2 = 1 + \frac{Q^2}{\nu^2} = 1 + \frac{4x^2M^2}{Q^2}$$

$$R^{\gamma(\gamma Z)} = \frac{\sigma_L^{\gamma(\gamma Z)}}{\sigma_T^{\gamma(\gamma Z)}} = r^2\frac{F_2^{\gamma(\gamma Z)}}{2xF_1^{\gamma(\gamma Z)}} - 1$$

Leading twist electroweak structure functions
(at leading order in α_s)

→ electromagnetic

$$F_2^\gamma = 2xF_1^\gamma(x) = \sum_q e_q^2\, x\,\big(q(x) + \bar{q}(x)\big)$$

$V \times V$

→ interference

$$F_2^{\gamma Z} = 2xF_1^{\gamma Z}(x) = \sum_q e_q\, g_V^q\, x\,\big(q(x) + \bar{q}(x)\big)$$

$V \times V$

$$F_3^{\gamma Z} = 2\sum_q e_q\, g_A^q\,\big(q(x) - \bar{q}(x)\big)$$

$V \times A$

$$g_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad g_A^u = \frac{1}{2} = -g_A^{d,s}$$

$$g_V^{d,s} = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$$

Leading twist electroweak structure functions

$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma n} = \frac{4}{9}x(d+\bar{d}) + \frac{1}{9}x(u+\bar{u}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma Z,p} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right)x(u+\bar{u}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(d+\bar{d}+s+\bar{s}) + \cdots$$

$$\approx \frac{1}{9}x(u+\bar{u}+d+\bar{d}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

$$F_2^{\gamma Z,n} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right)x(d+\bar{d}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(u+\bar{u}+s+\bar{s}) + \cdots$$

$$\approx \frac{1}{9}x(d+\bar{d}+u+\bar{u}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

$\longrightarrow$ strange quark sensitivity enhanced relative to e.m. case

Leading twist electroweak structure functions

$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

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$$\approx \frac{1}{9}x(d+\bar{d}+u+\bar{u}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

$$F_3^{\gamma Z,p} = \frac{2}{3}(u-\bar{u}) + \frac{1}{3}(d-\bar{d}+s-\bar{s}) + \cdots$$

$$F_3^{\gamma Z,n} = \frac{2}{3}(d-\bar{d}) + \frac{1}{3}(u-\bar{u}+s-\bar{s}) + \cdots$$

$\longrightarrow$ sensitivity to strange-antistrange asymmetry

PV asymmetry in terms of PDFs

$$A^{\mathrm{PV}} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)(Y_1\, a_1 + Y_3\, a_3)$$

(hadronic) *vector* term

$$a_1 = \frac{2\sum_q e_q C_{1q}(q+\bar{q})}{\sum_q e_q^2 (q+\bar{q})}$$

$$C_{1q} = 2 g_A^e\, g_V^q$$

(hadronic) *axial-vector* term

$$a_3 = \frac{2\sum_q e_q C_{2q}(q-\bar{q})}{\sum_q e_q^2 (q+\bar{q})}$$

$$C_{2q} = 2 g_V^e\, g_A^q$$

→ simplified y dependence

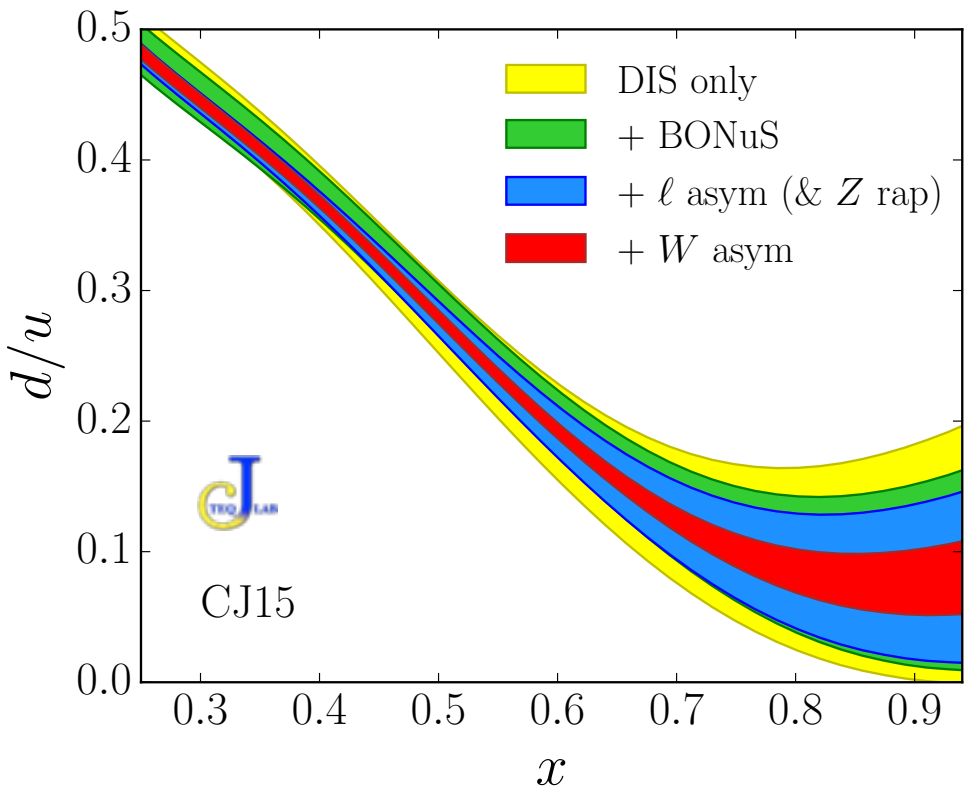
$$Y_1 \to 1$$

$$Y_3 \to \frac{1-(1-y)^2}{1+(1-y)^2}$$

At large x proton asymmetry sensitive to d/u ratio

$$a_1 = \frac{12C_{1u} - 6C_{1d}\, d/u}{4 + d/u}$$

$$a_3 = \frac{12C_{2u} - 6C_{2d}\, d/u}{4 + d/u}$$



Accardi, Brady, WM, Owens, Sato
*PRD **93**, 114017 (2016)*

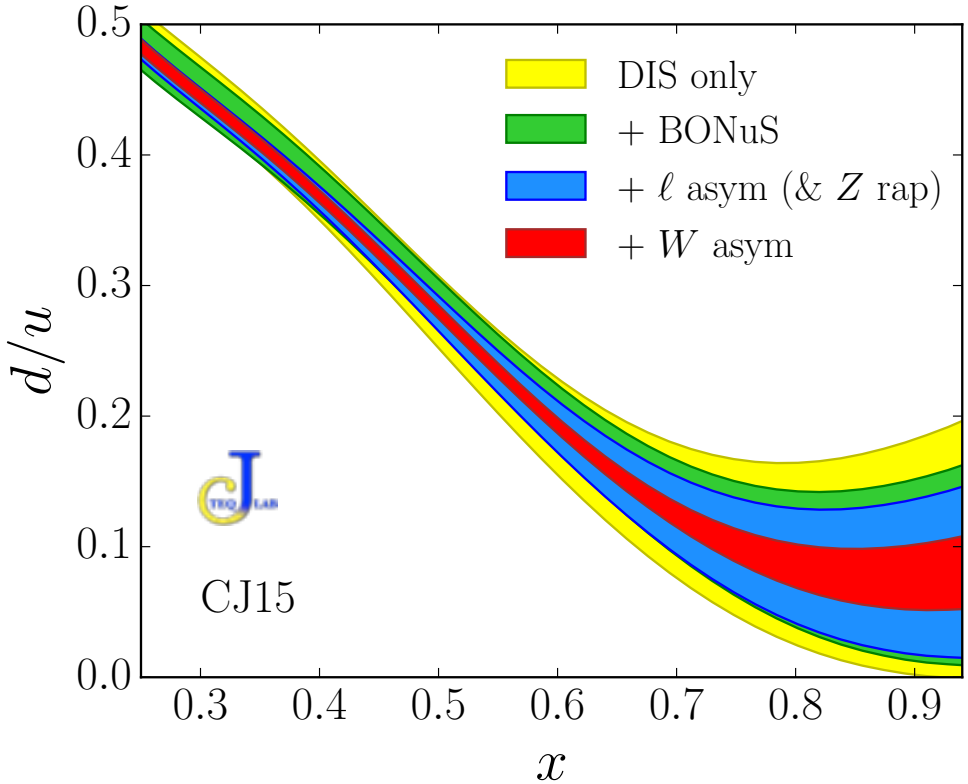
→ ~1% error on d/u expected in SoLID up to $x \sim 0.7$

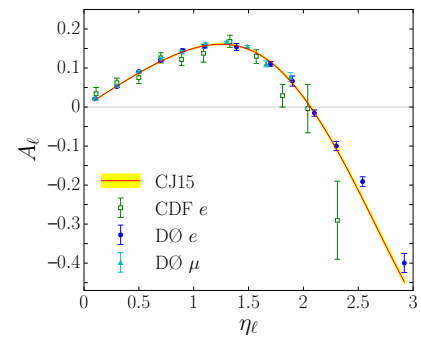
(note: different PDF uncertainty definitions in different analyses!!)

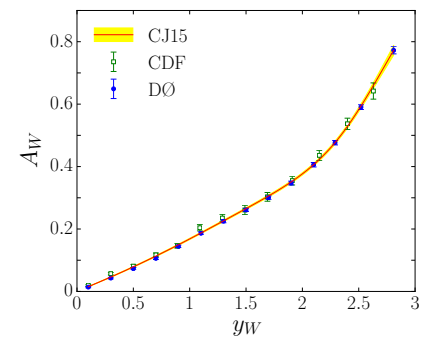
At large x proton asymmetry sensitive to d/u ratio

$$a_1 = \frac{12C_{1u} - 6C_{1d}\, d/u}{4 + d/u}$$

$$a_3 = \frac{12C_{2u} - 6C_{2d}\, d/u}{4 + d/u}$$

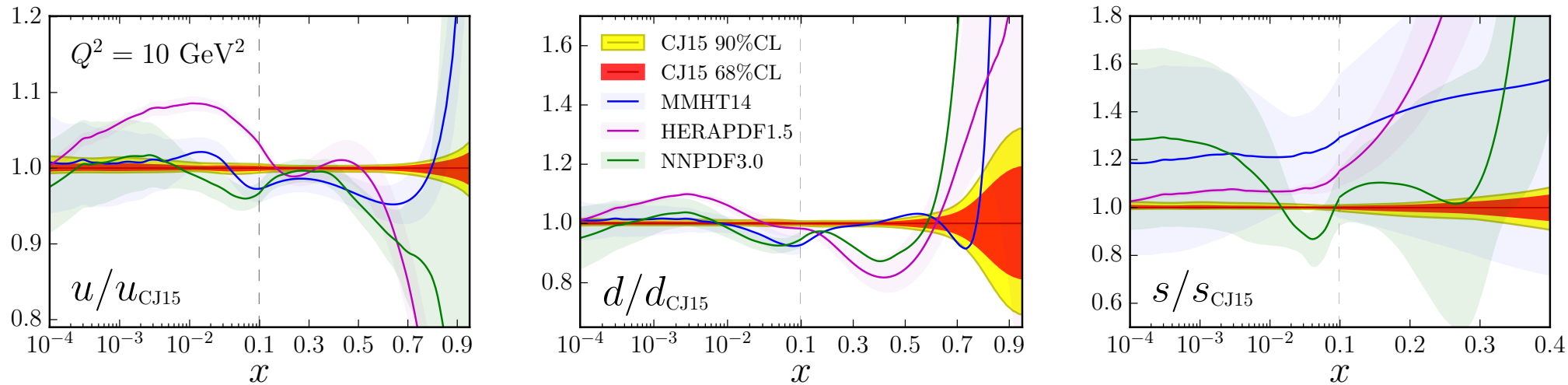




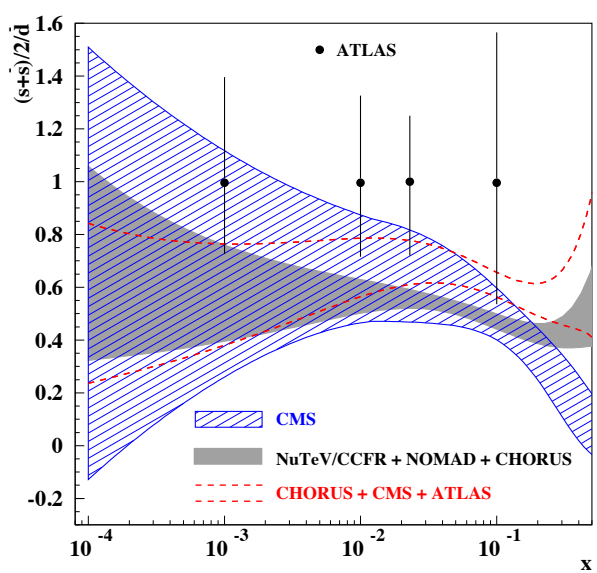


→ error reduced by recent W asymmetry data
– but rely on reconstruction from $W \to \ell\, \nu$ decays

- At smaller x, have order of magnitude greater sensitivity of $F_2^{\gamma Z,p}$ to strange-quark PDF than of e.m. $F_2^{\gamma p}$



Accardi et al, PRD ***93****, 114017 (2016)*



Alekhin et al, PRD ***91****, 094002 (2015)*

→ currently relatively large uncertainties on $s(x)$ at intermediate x

– most information obtained from charm production in neutrino-nucleus DIS

- Deuteron target – dependence on PDFs cancels at high Q^2

$$a_1 = \frac{6}{5}(2C_{1u} - C_{1d})$$

$$a_3 = \frac{6}{5}(2C_{2u} - C_{2d})$$

→ PV asymmetry independent of hadronic structure

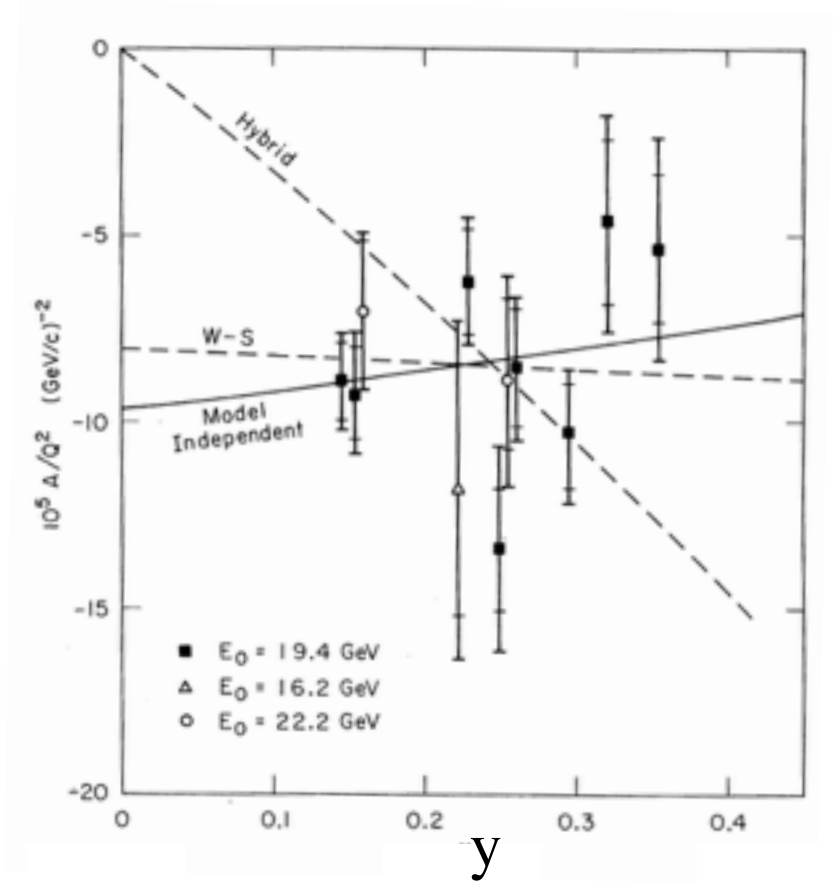
$$A^{\mathrm{PV}} = -\left(\frac{3G_F Q^2}{10\sqrt{2}\pi\alpha}\right)\left(Y_1(2C_{1u} - C_{1d}) + Y_3(2C_{2u} - C_{2d})\right)$$

→ sensitivity to electroweak couplings

→ alternatively, could probe charge symmetry violation (CSV) in PDFs

I. Cloet talk

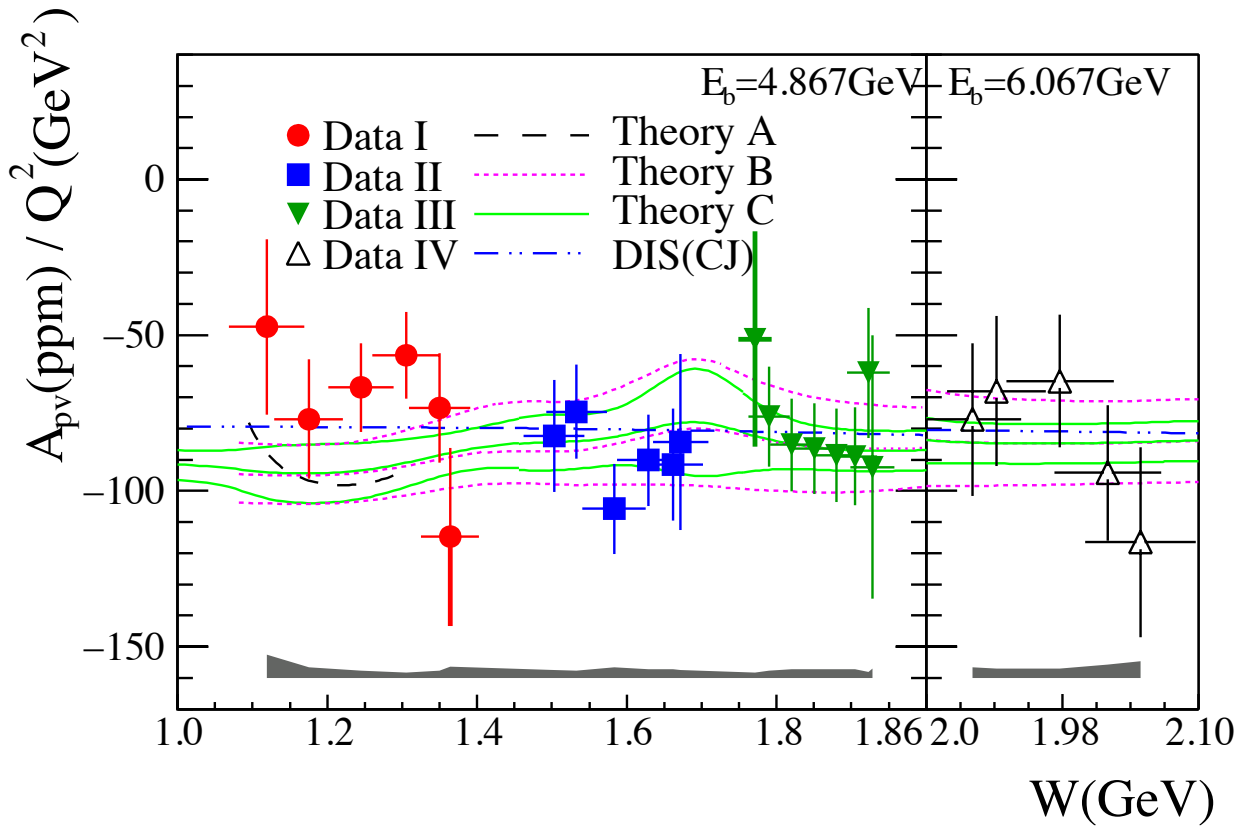
- Historically, PVDIS was first measured at SLAC (on deuterium) at $Q^2 \sim 1\ \mathrm{GeV}^2$ and $W \sim 3\ \mathrm{GeV}$



Prescott et al, PLB 77, 347 (1978)

→ important for testing SM, but not for PDF determination

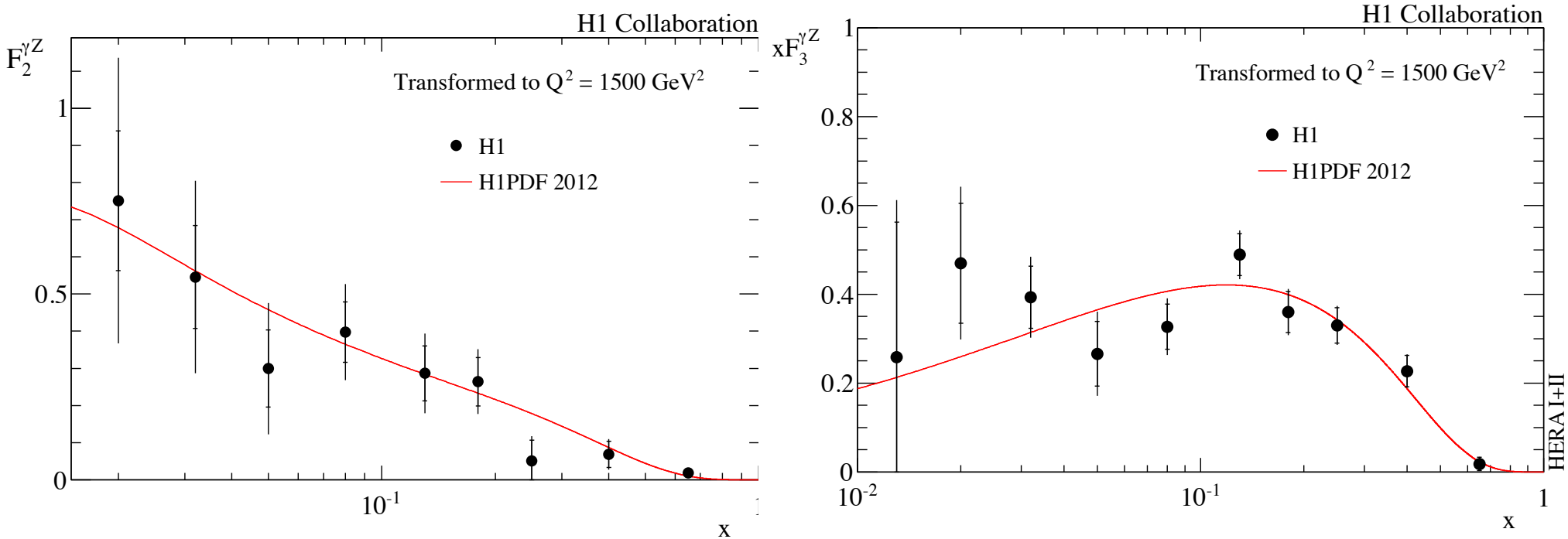
- More recently, PVDIS measured more precisely at Jefferson Lab E08-011 at lower W



Wang et al, PRL ***111****, 082501 (2013)*

→ indication of quark-hadron duality in γZ structure functions in the nucleon resonance region

γZ structure functions measured at HERA at very high Q^2 & W

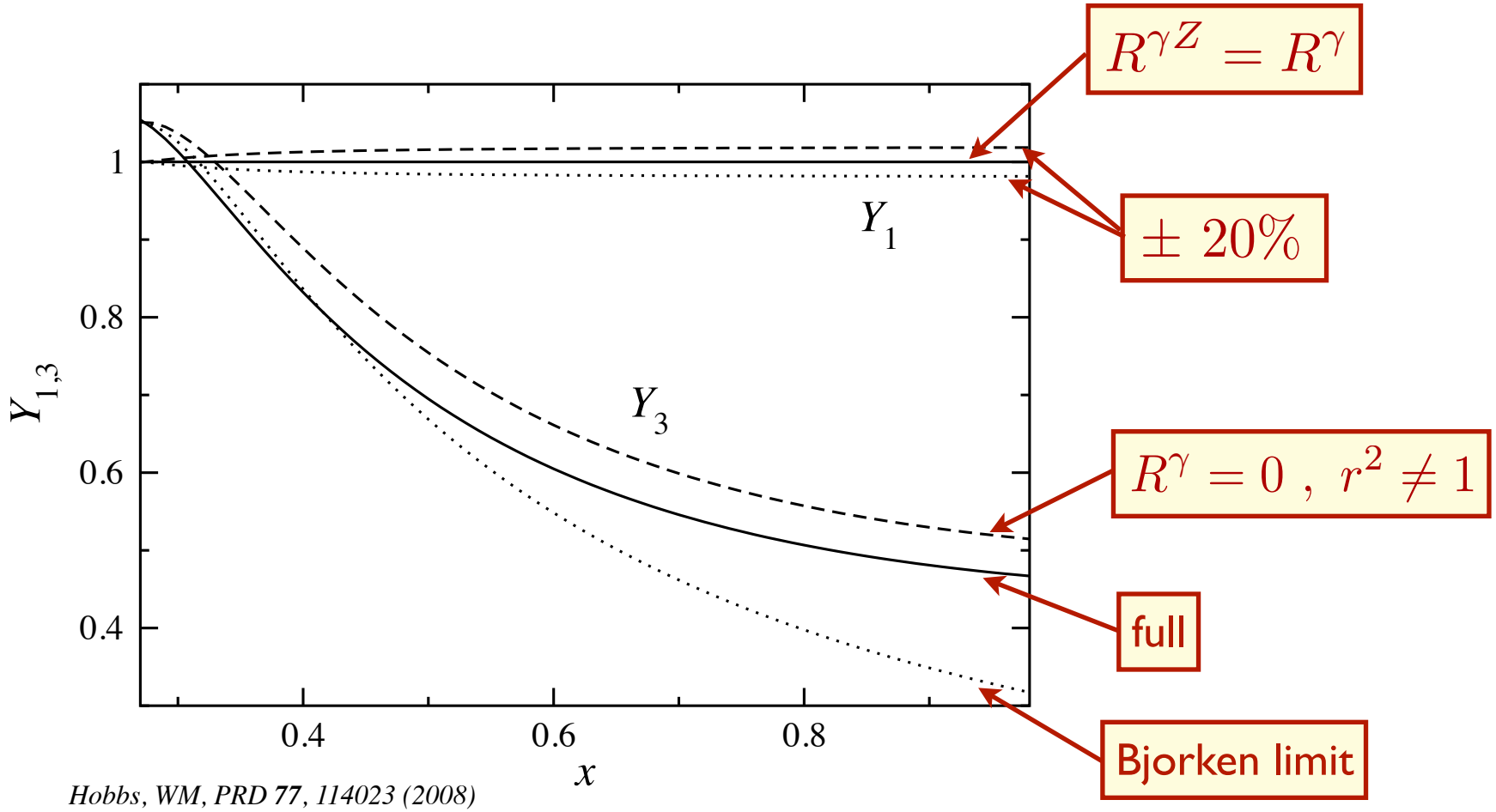


*H1 Collaboration, JHEP **09** (2012) 61*

→ essentially no proton PVDIS data at lower Q^2

Finite-Q^2 corrections

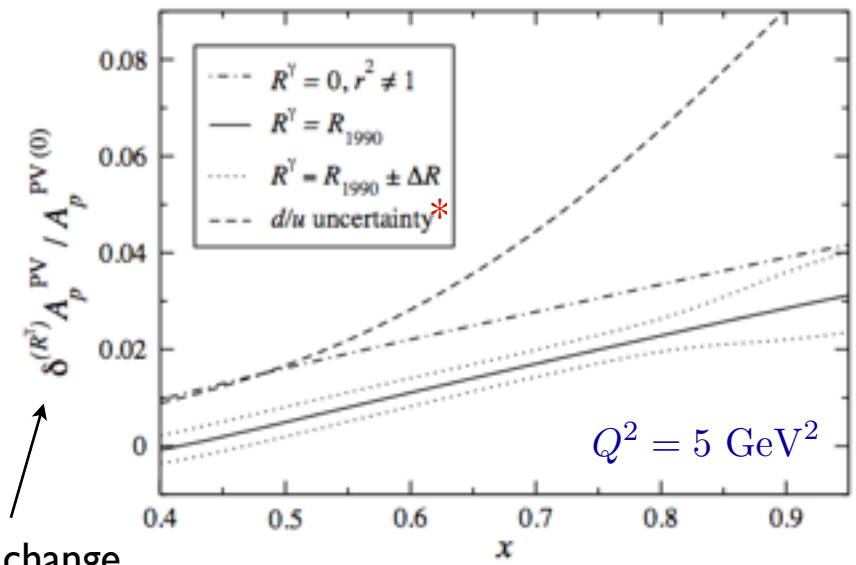
Contribution from axial-vector term

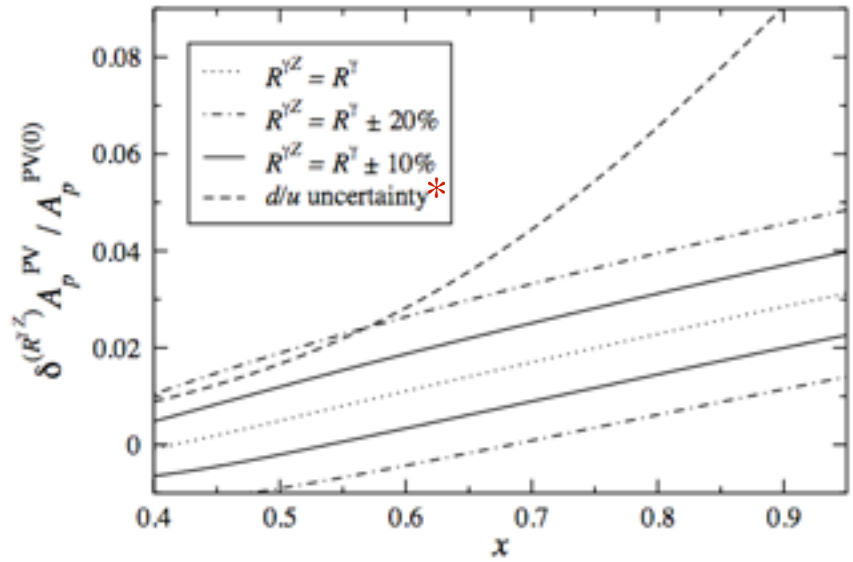


Hobbs, WM, PRD 77, 114023 (2008)

→ hadronic axial-vector term relatively more important at finite Q^2

Sensitivity to $R^\gamma = \sigma_L^\gamma / \sigma_T^\gamma$ and $R^{\gamma Z} = \sigma_L^{\gamma Z} / \sigma_T^{\gamma Z}$





relative change to Bjorken limit asymmetry

→ uncertainty due to R^γ smaller than d/u error* at high x

→ need estimate for $R^{\gamma Z}$ to determine impact on asymmetry uncertainty

* assuming $d/u \to 0$ or 0.2 at $x = 1$; uncertainty smaller with new W asymmetry data

What could break $R^{\gamma Z} = R^{\gamma}$?

- higher order pQCD corrections

  $\longrightarrow$ $R^{\gamma(\gamma Z)} = 0$ at leading order (perturbatively);
  at NLO different γ/Z couplings induce $R^{\gamma} \neq R^{\gamma Z}$

- target mass corrections ("kinematical" $1/Q^2$ corrections)

  $\longrightarrow$ since TMCs for F_L and F_T are different, differences in ratios will be different with & without TMC
  (depend on treatment of struck parton – off-shell, collinear, ...)

- dynamical higher twist

  $\longrightarrow$ Λ^2/Q^2 corrections from multi-parton correlations

- nuclear effects in deuteron

Target mass corrections

- operator product expansion (Georgi, Politzer) *PRD* ***14***, *1829 (1976)*

  → standard approach, uses inverse Mellin transform; "threshold problem" at $x = 1$

- collinear factorization (Ellis, Furmanski, Petronzio) *NP* ***B212***, *29 (1983)*

  → diagrammatic approach, impose $x < 1$ by definition; include parton virtuality & k_T; to $\mathcal{O}(1/Q^2)$ only

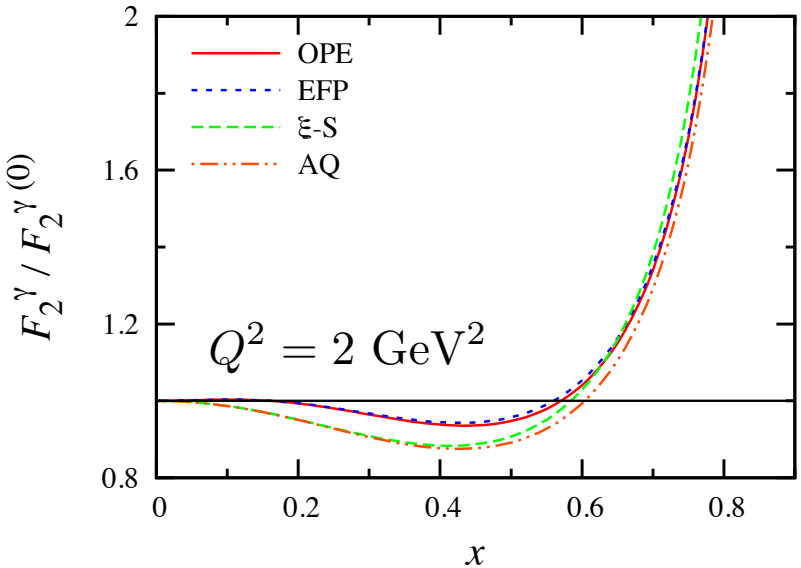
- collinear factorization (Accardi, Qiu) *JHEP* ***07***, *090 (2008)*

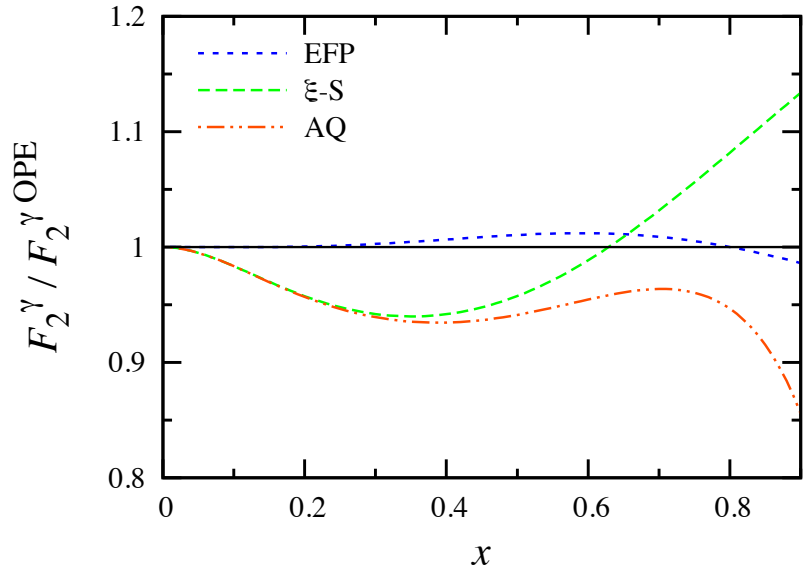
  → similar to EFP, but include only 2-leg ($cf.$ 4-leg) diagrams; allow for jet-mass corrections, NLO effects

- ξ-scaling (Aivazis *et al.*, Kretzer-Reno) *PRD* ***69***, *034002 (2004)*

  → similar to AQ, but at leading order

Target mass corrections

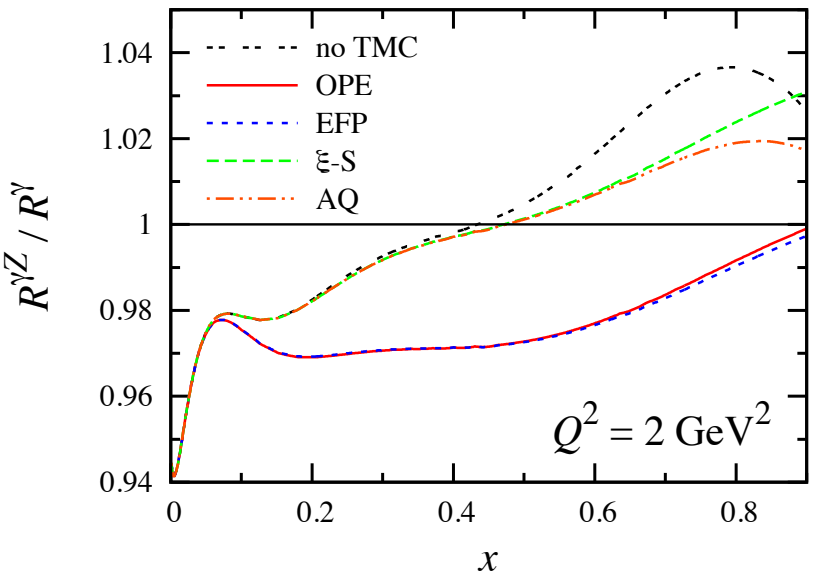


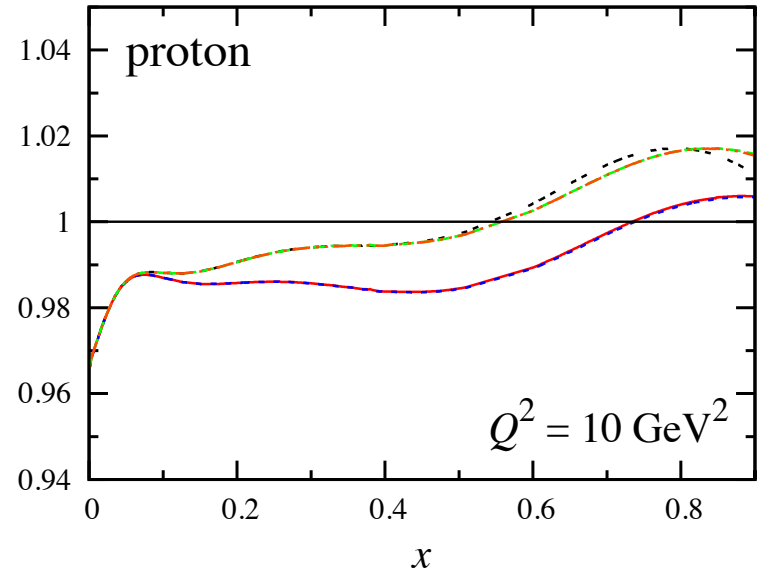


→ effects large at high x (and low Q^2)

→ up to ~10% model dependence in structure functions

Target mass corrections

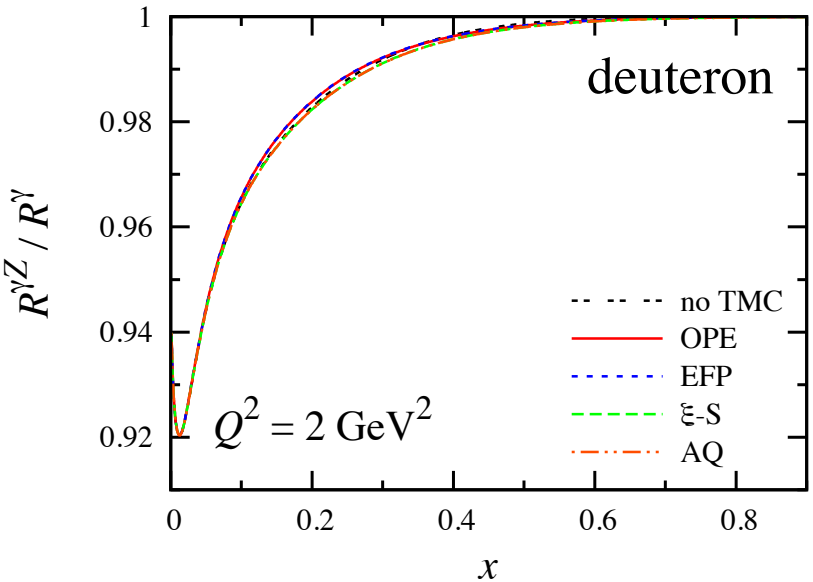


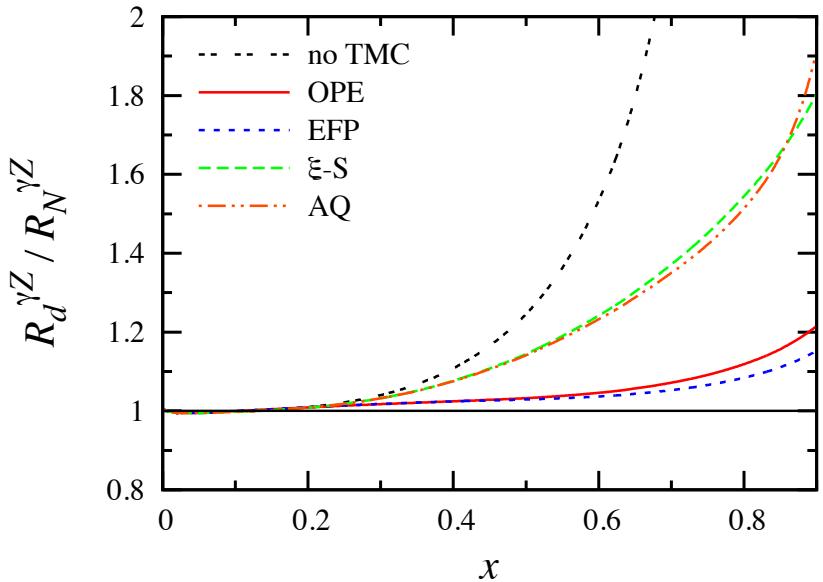


→ less than $\sim 4\%$ TMC and NLO effects $cf.\ R^{\gamma}$

→ reduced to $\sim 2\%$ at Q^2=10 GeV^2

Target mass corrections





→ differences between R^{γ} & $R^{\gamma Z}$ small at high x

→ significant nuclear effect in $R^{\gamma Z}$ ratio
– reduced with inclusion of TMCs

Dynamical higher twists

- $\Lambda^2_{\rm QCD}/Q^2$ corrections from multi−parton correlations

  → for deuterium, only one twist-4 (four-quark) operator

  $$\bar{u}(z)\gamma^\mu u(z)\, d(0)\gamma^\nu d(0) + (u \leftrightarrow d)$$

  *Bjorken, PRD **18**, 3239 (1978)*
  *Wolfenstein, NP **B146**, 477 (1978)*

  → MIT bag model estimate of matrix elements

  *Castorina, Mulders, PRD **31**, 2760 (1985)*

  → extension to x dependence *Mantry, Ramsey-Musolf, Sacco, PRC **82**, 065205 (2010)*

  → estimate using multi-parton light-cone wavefunctions

  *Belitsky, Manashov, Schaefer, PRD **84**, 014010 (2011)*

  → matrix elements sensitive to OAM in initial state

  *Seng, Ramsey-Musolf, PRC **88**, 015202 (2013)*

  C.-Y. Seng talk

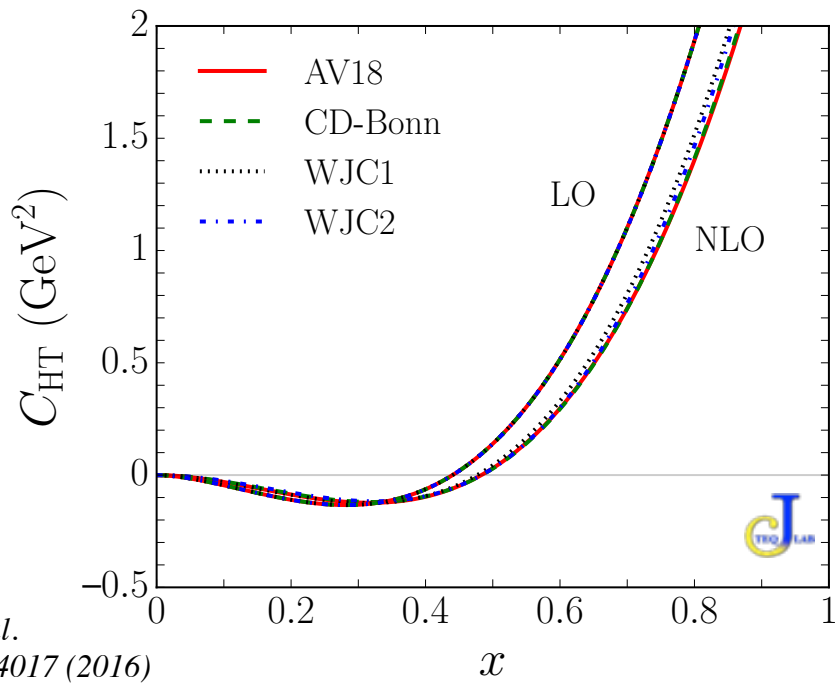
- Alternatively, estimate HT contribution phenomenologically

Dynamical higher twists

- In global QCD analyses parametrize structure function as

$$F_2(x,Q^2) = F_2^{(\mathrm{LT})}(x,Q^2)\left(1+\frac{C_{\mathrm{HT}}(x)}{Q^2}\right)$$

$$C_{\mathrm{HT}} = h_0\, x^{h_1}(1+h_2 x)$$



Accardi et al.
PRD ***93****, 114017 (2016)*

→ cannot accommodate Q^2 dependence of data without power corrections

→ crucial for extracting correct PDFs at high x

→ can do the same with PVDIS data, especially with sufficient Q^2 coverage – isolate isospin dependence of higher twists vs. x!

Polarized PVDIS

PVDIS from a polarized target

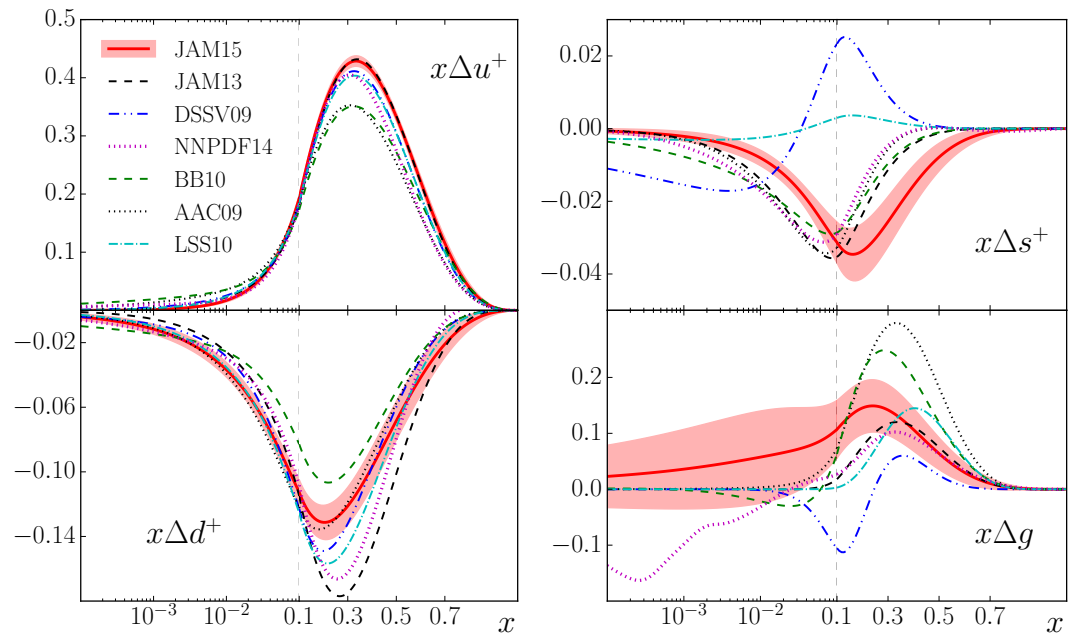
- LOI 12-16-007 to JLab PAC44 for *"PVDIS from polarized ^3He"*
- Just as with sensitivity to s in $F_2^{\gamma Z}$, the spin-dependent $g_1^{\gamma Z}$ structure function has enhanced sensitivity to Δs

$$g_1^{\gamma Z,p} = \frac{1}{2}\sum_q e_q g_V^q \left(\Delta q + \Delta\bar{q}\right) \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}) + \cdots$$
$$\approx g_1^{\gamma Z,n}$$

→ significant uncertainty exists for $\Delta s(x)$, even in sign!

→ most PDF analyses assume flavor SU(3) symmetry for hyperon decay constants

→ polarized PVDIS would be first ever test of SU(3) in DIS



Nobuo Sato et al, PRD ***93****, 074005 (2016)*
Jefferson Lab Angular Momentum (JAM) Collaboration

Summary

- PVDIS offers unique window on nucleon structure, with unambiguous flavor separation (u, d and s)

- Corrections to leading-twist PVDIS from finite Q^2 effects identified and quantified

- PVDIS data (unpolarized and polarized) can be included in global QCD analyses (CJ, JAM) that are continuously being improved and developed