PVDIS Collaboration Meeting
Jefferson Lab, January 6, 2012

Finite-Q^2 Corrections to Parity-Violating DIS

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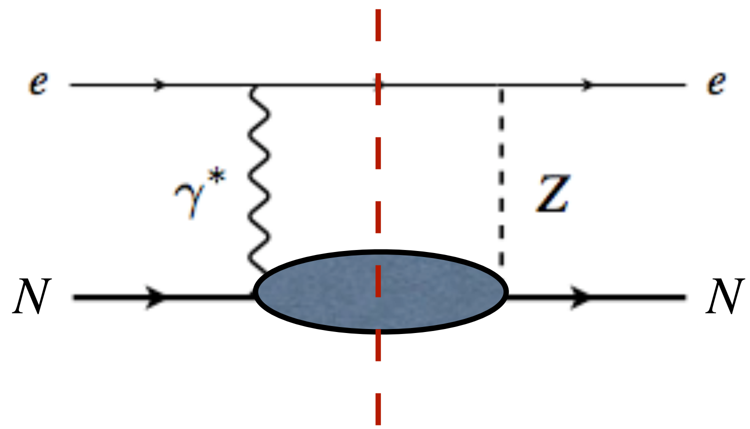
- PVDIS as a tool to measure flavor (p target) and isospin (d target) dependence of nucleon PDFs



imaginary part of γZ interference amplitude

- most analyses assume leading-twist dominance

→ $Q^2 \to \infty$

→ experiments at finite kinematics $(Q^2 \sim 5 - 10\ \mathrm{GeV}^2)$

→ how large are finite-Q^2 corrections?

PVDIS asymmetry in terms of structure functions

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

$$g_A^e = -\frac{1}{2}\ , \quad g_V^e = -\frac{1}{2} + 2\sin^2\theta_W$$

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

$$Y_1 = \frac{1+(1-y)^2 - y^2[1+\rho^2 - 2\rho^2/(R^{\gamma Z}+1)]/2}{1+(1-y)^2 - y^2[1+\rho^2 - 2\rho^2/(R^{\gamma}+1)]/2}\left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right)$$

$$Y_3 = \frac{1+(1-y)^2}{1+(1-y)^2 - y^2[1+\rho^2 - 2\rho^2/(R^{\gamma}+1)]/2}\left(\frac{\rho^2}{1+R^\gamma}\right)$$

with

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

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

- At large Q^2 and W, structure functions given by PDFs

→ electromagnetic (at LO)

$$\boxed{\begin{aligned} F_1^{\gamma}(x) &= \frac{1}{2}\sum_q e_q^2 (q(x) + \bar{q}(x)), \\ F_2^{\gamma}(x) &= 2xF_1^{\gamma}(x), \end{aligned}}$$

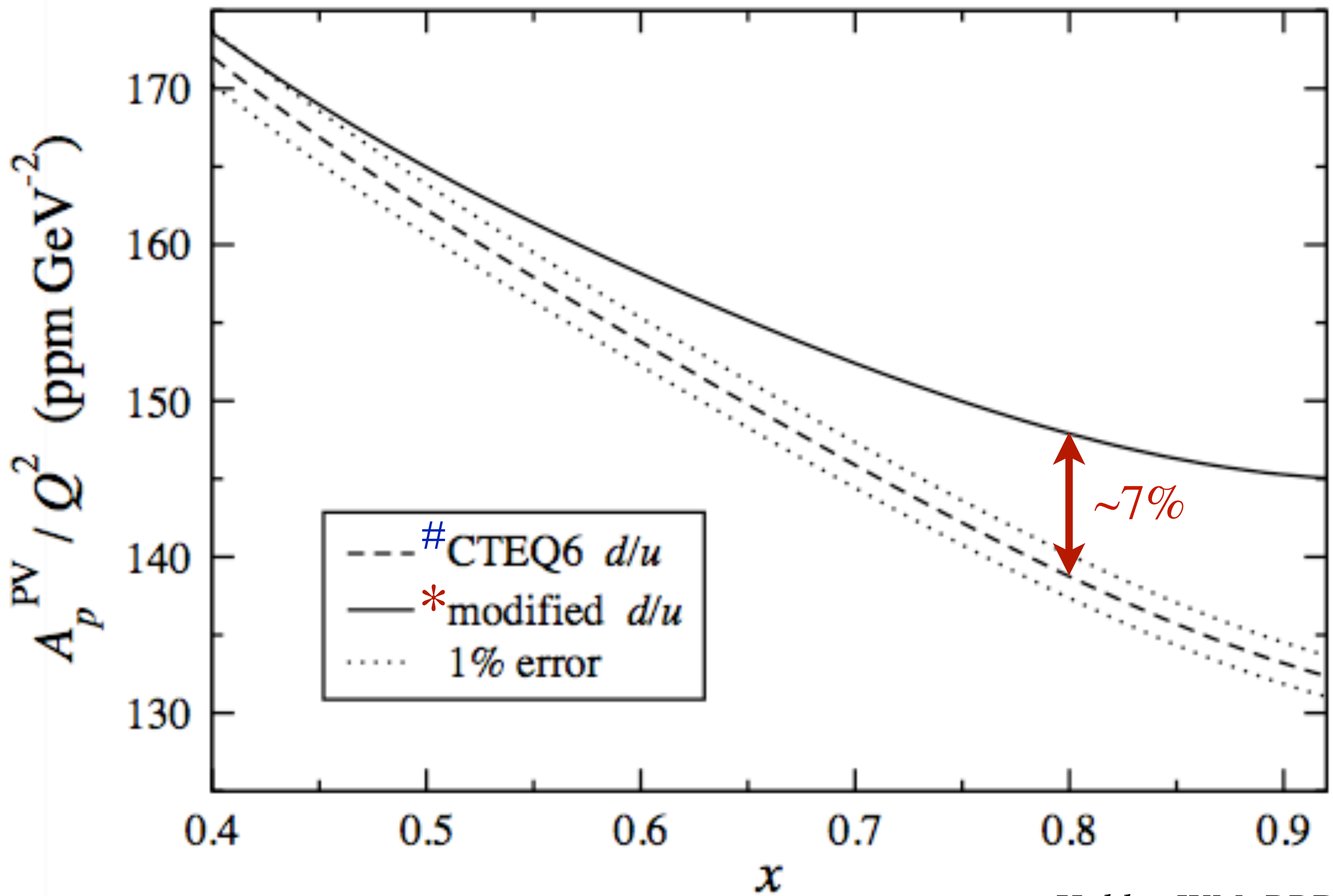
→ γZ interference (at LO)

$$\boxed{\begin{aligned} F_1^{\gamma Z}(x) &= \sum_q e_q g_V^q (q(x) + \bar{q}(x)), \\ F_2^{\gamma Z}(x) &= 2xF_1^{\gamma Z}(x), \\ F_3^{\gamma Z}(x) &= 2\sum_q e_q g_A^q (q(x) - \bar{q}(x)) \end{aligned}}$$

- At low Q^2 or W, structure functions more complicated

■ For *proton* target, direct measure of large-x d/u ratio

→ exploratory study of possible effects: *Hobbs & WM (2008)*

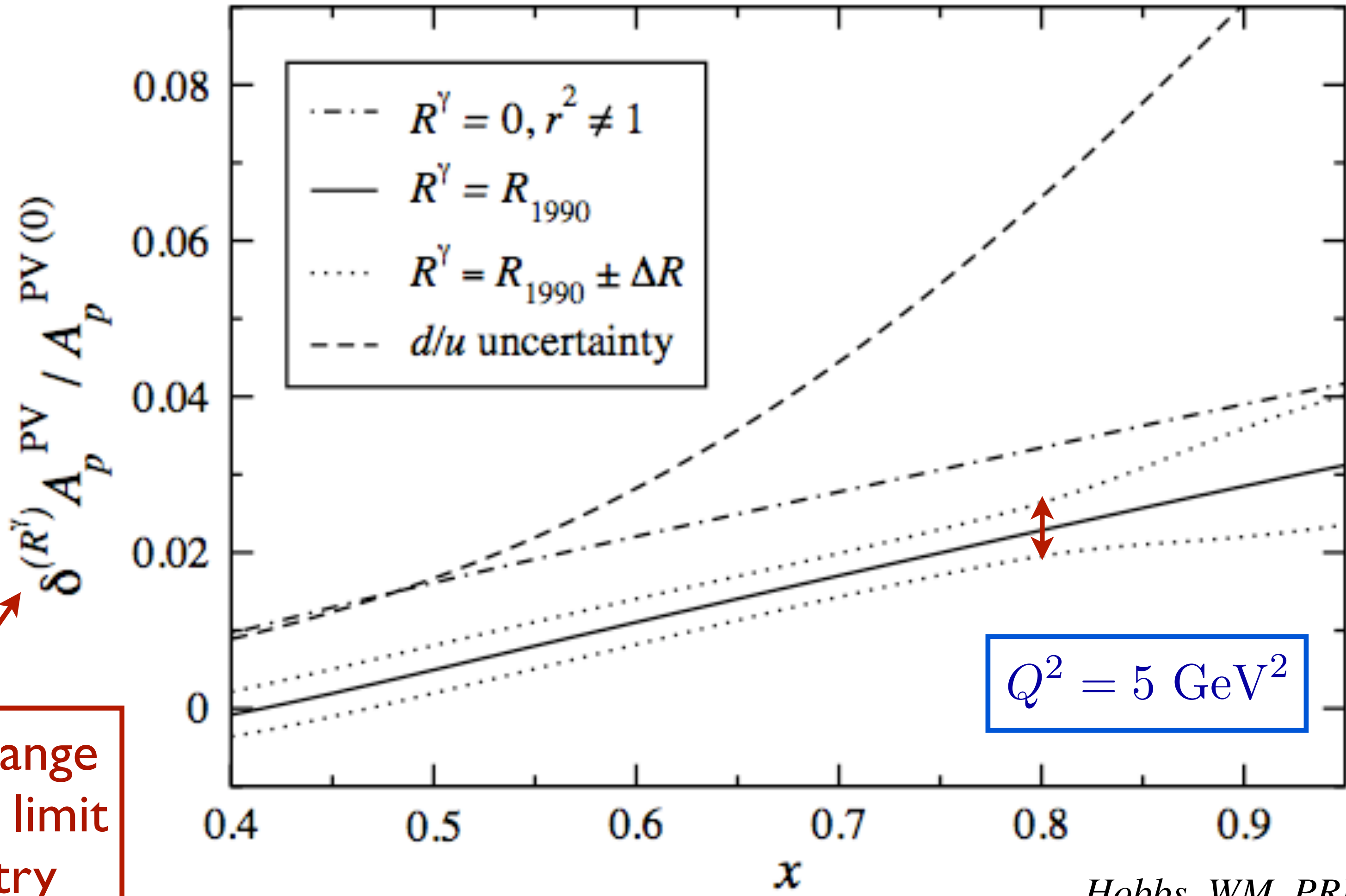


Hobbs, WM, PRD ***77*** *(2008) 114023*

$^{\#}\, d/u \rightarrow 0$ as $x \rightarrow 1$

$*\ d/u \rightarrow 0.2$ as $x \rightarrow 1$

→ sensitivity to ΔR^γ

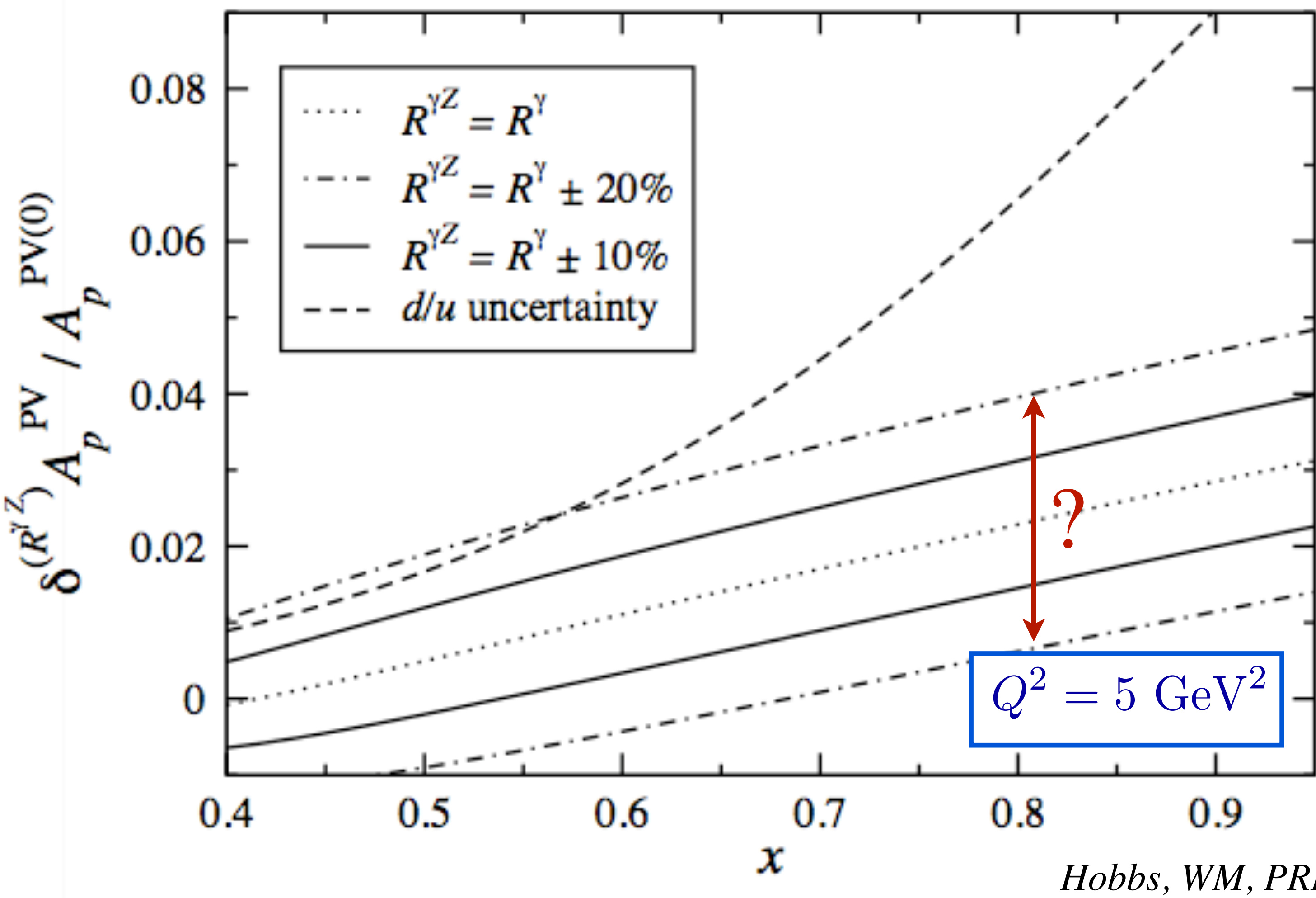


relative change to Bjorken limit asymmetry

*Hobbs, WM, PRD **77** (2008) 114023*

→ uncertainty due to R^γ *smaller* than d/u differences at large x

→ sensitivity to $\Delta R^{\gamma Z}$ – what if $R^{\gamma Z}$ differs from R^{γ} by 10%? 20%?



Hobbs, WM, PRD ***77*** *(2008) 114023*

→ potentially significant if $R^{\gamma Z} \not\approx R^{\gamma}$

→ $R^{\gamma Z}$ needs further investigation!

For *deuteron* (isoscalar) target

→ at LO, in valence region (no sea quarks or gluons), and assuming no charge symmetry violation, PV asymmetry independent of hadronic structure

$$\boxed{A^d_{\rm PV} \approx -\left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{6}{5}\left[g^e_A(2g^u_V - g^d_V) + Y_3 g^e_V(2g^u_A - g^d_A)\right]}$$

$$^* \quad g^u_V = -1/2 + (4/3)\sin^2\theta_W \ , \qquad g^u_A = 1/2$$

$$g^d_V = 1/2 - (2/3)\sin^2\theta_W \ , \qquad g^d_A = -1/2$$

* PDG definitions

For *deuteron* (isoscalar) target

$\longrightarrow$ PV asymmetry sensitive also to CSV (valence approximation)

$$\boxed{(2g^u_{V,A} - g^d_{V,A}) \;\to\; (2g^u_{V,A} - g^d_{V,A})(1 + \Delta_{V,A})}$$

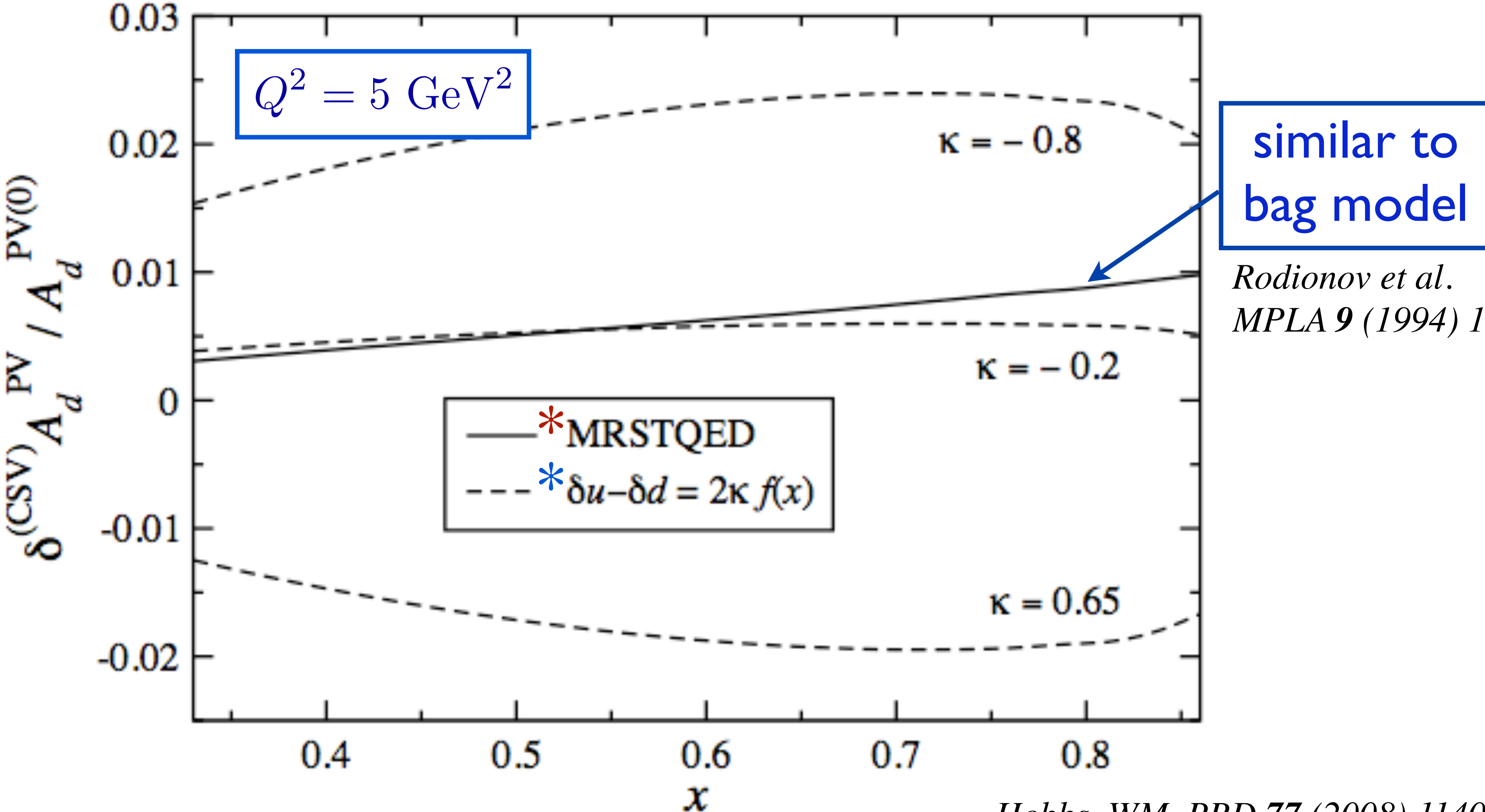
where fractional CSV correction is

$$\boxed{\Delta_{V,A} = \left(-\frac{3}{10} + \frac{2g^u_{V,A} + g^d_{V,A}}{2(2g^u_{V,A} - g^d_{V,A})}\right)\left(\frac{\delta u - \delta d}{u + d}\right)}$$

with CSV PDFs defined by $\delta u = u^p - d^n \;, \quad \delta d = d^p - u^n$

For *deuteron* (isoscalar) target

→ PV asymmetry sensitive also to CSV (valence approximation)



Rodionov et al. MPLA ***9*** *(1994) 1799*

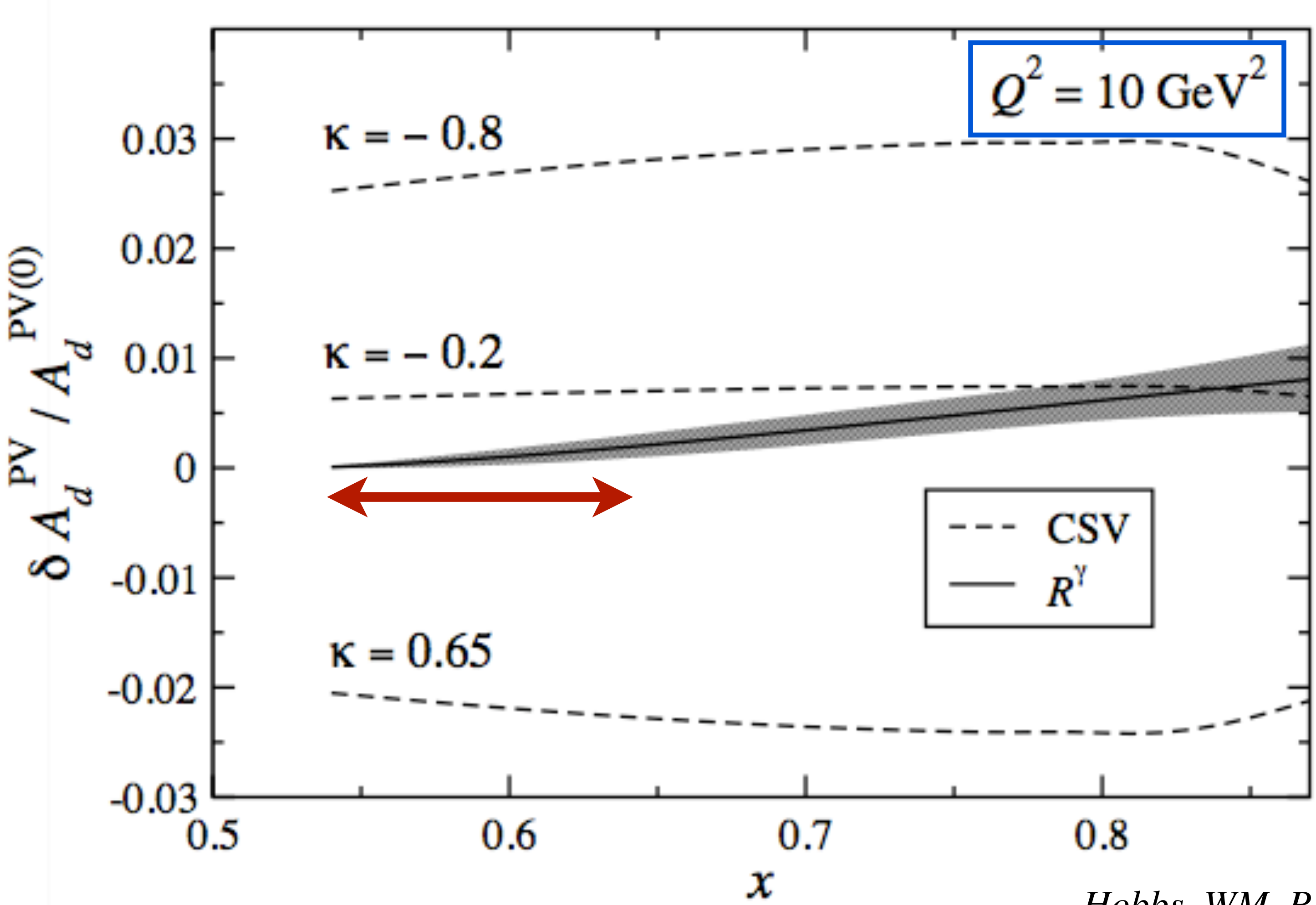
Hobbs, WM, PRD ***77*** *(2008) 114023*

* *MRST, EPJC* ***39*** *(2005) 155*

* *MRST, EPJC* ***35*** *(2004) 325*

- For *deuteron* (isoscalar) target

→ relative sensitivity to ΔR^γ



Hobbs, WM, PRD ***77*** *(2008) 114023*

→ if CSV ~ 0.5%, optimal value $x \sim 0.6$;

(larger CSV could be visible also at higher x)

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 *vs.* without TMC

  $\longrightarrow$ TMCs *not* unique, 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

NLO analysis uses CJ (CTEQ-JLab) PDFs

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

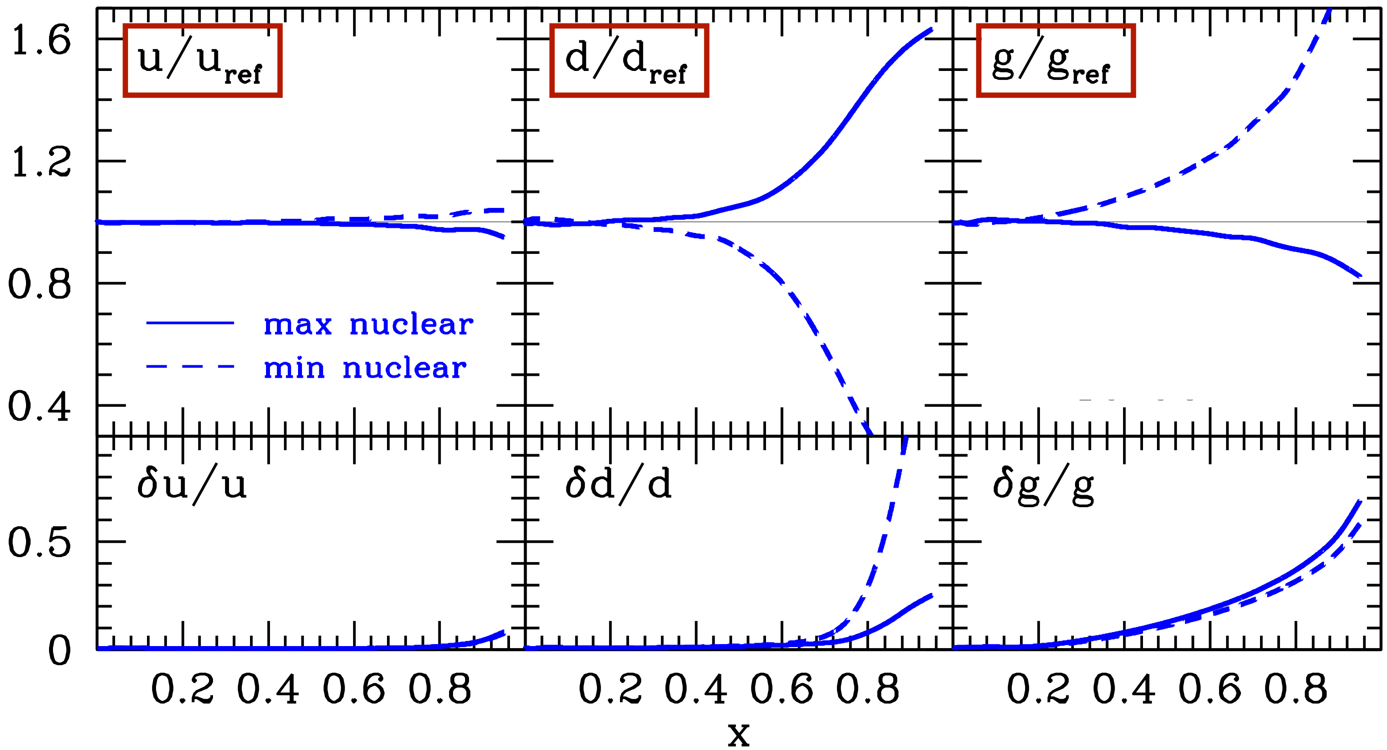
→ dedicated global PDF analysis of p and d data focusing on large-x region (includes low-W and low-Q^2 data)

(→ reduced PDF uncertainty at large x)

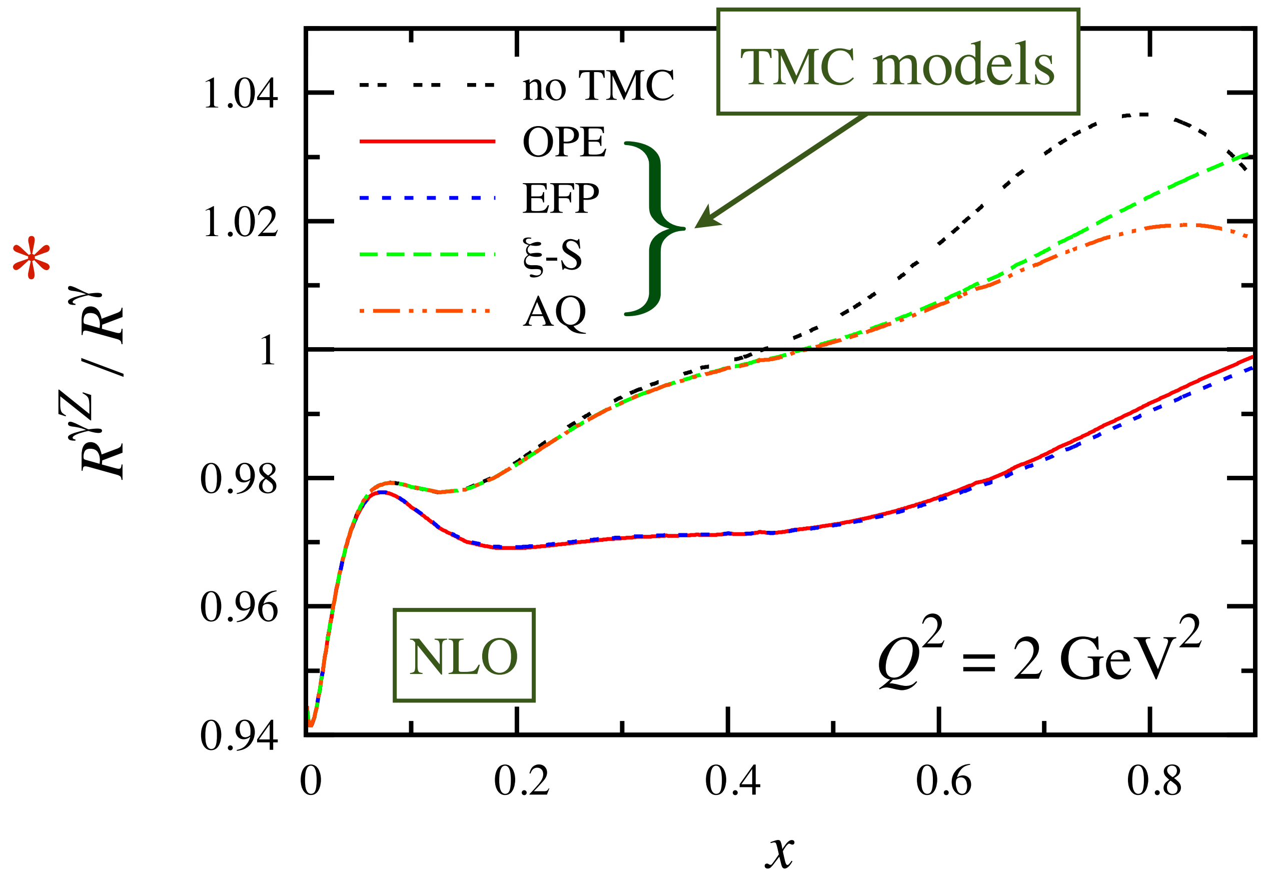
→ includes subleading $1/Q^2$ effects (TMCs & higher twists)

→ corrects for nuclear effects in d, including dependence on wave function and nucleon off-shell corrections

(→ "*max nuclear*" and "*min nuclear*" PDF sets)



pQCD and target mass corrections for *proton*

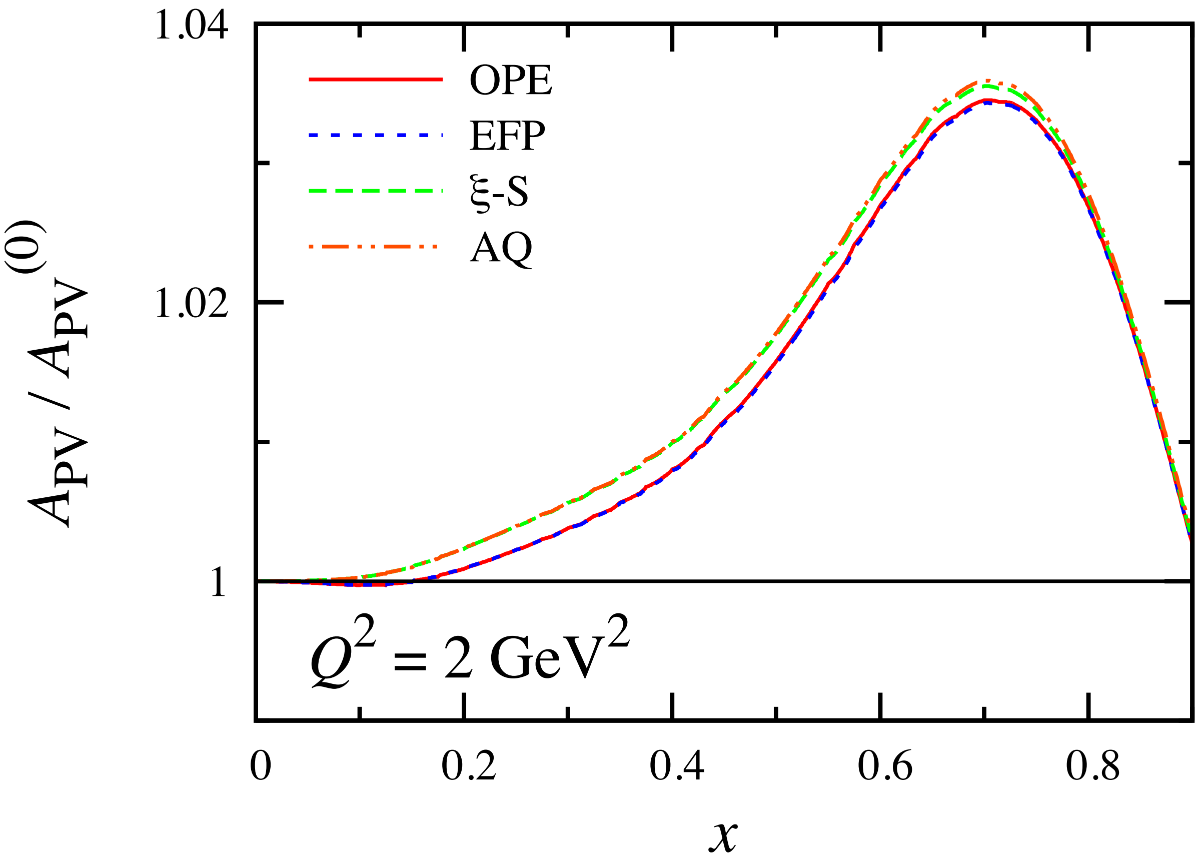


Brady, Accardi, Hobbs, WM
*PRD **84** (2011) 074008*

→ up to ~ 4% TMC and NLO effects *cf.* R^{γ}
(up to ~ 2% at Q^2=10 GeV^2)

* $R^{\gamma,\gamma Z}$ generated perturbatively (no nonperturbative contributions)

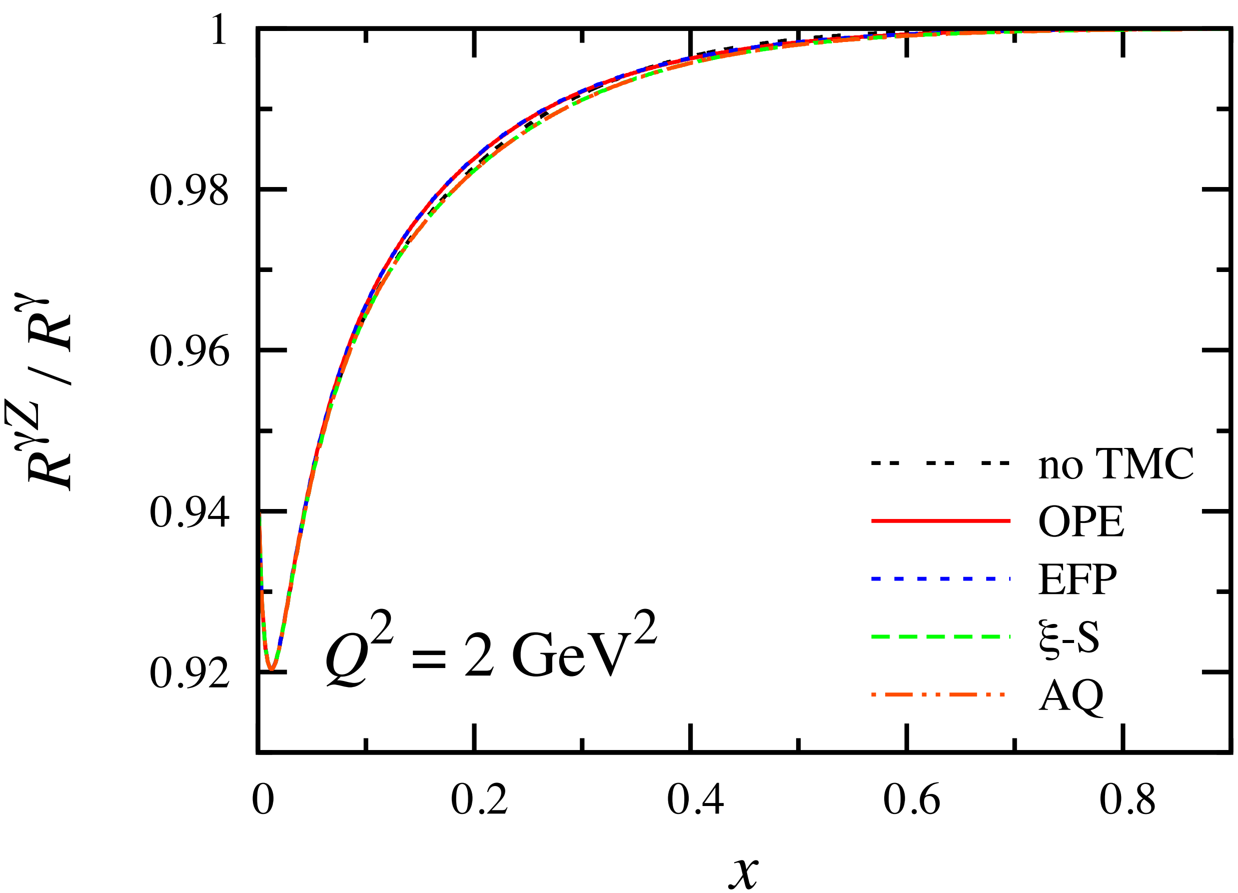
pQCD and target mass corrections for *proton*



→ asymmetry enhanced by $\sim 3–4\%$ at $x \sim 0.7$
(by $\sim 1\%$ at Q^2=10 GeV^2)

→ correction non-negligible, but under control

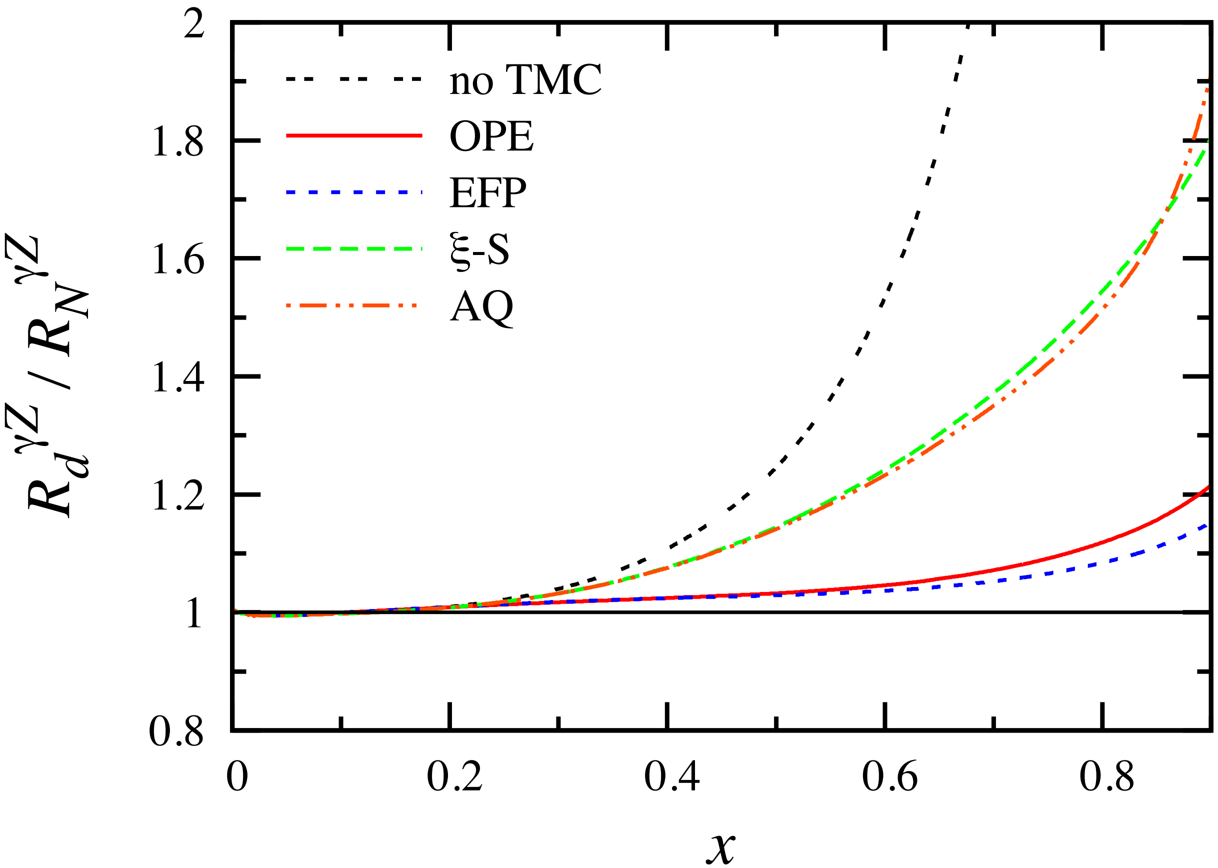
pQCD and target mass corrections for *deuteron*



→ difference between R^{γ} and $R^{\gamma Z}$ is negligible at large x

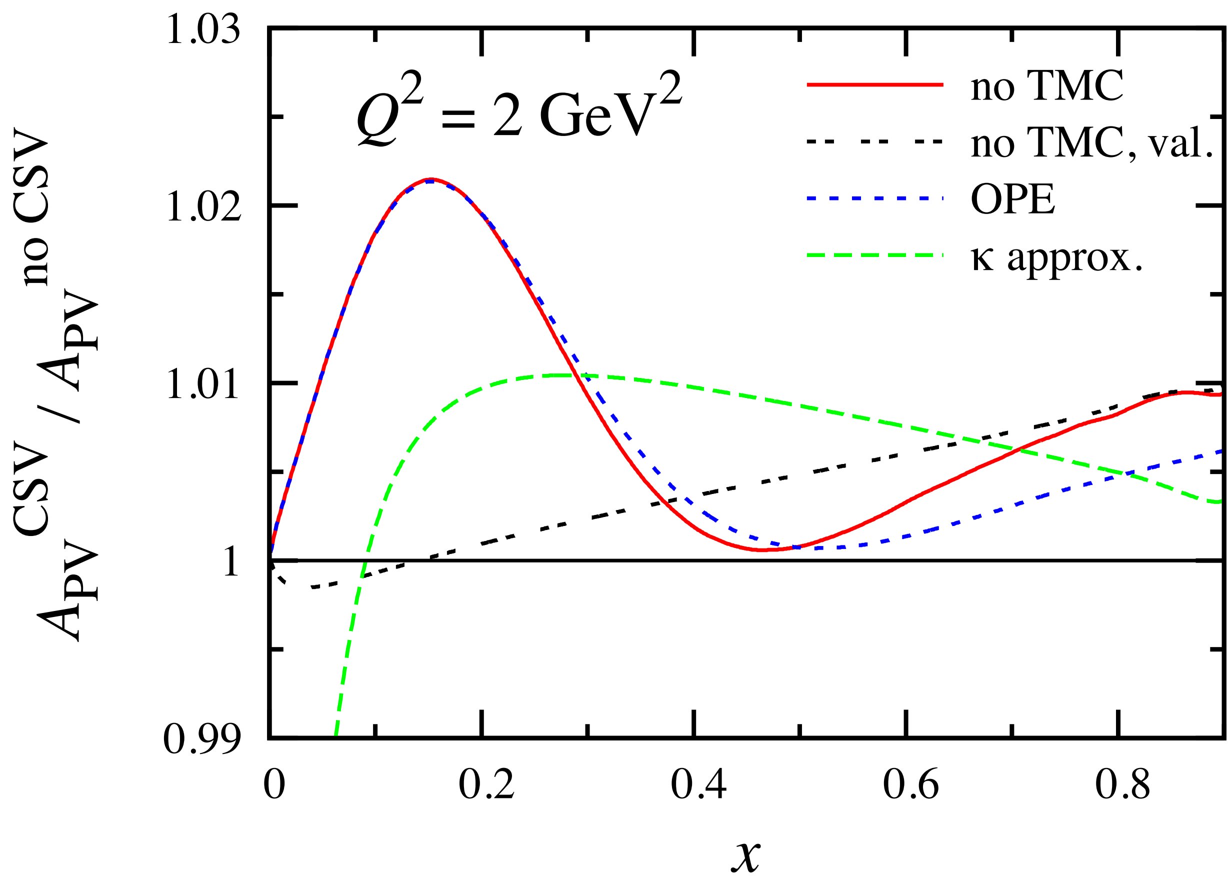
→ dip at low x due to gluons at NLO

pQCD and target mass corrections for *deuteron*



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

pQCD, target mass, and CSV corrections for *deuteron*



→ valence approximation accurate only for $x \gtrsim 0.6$

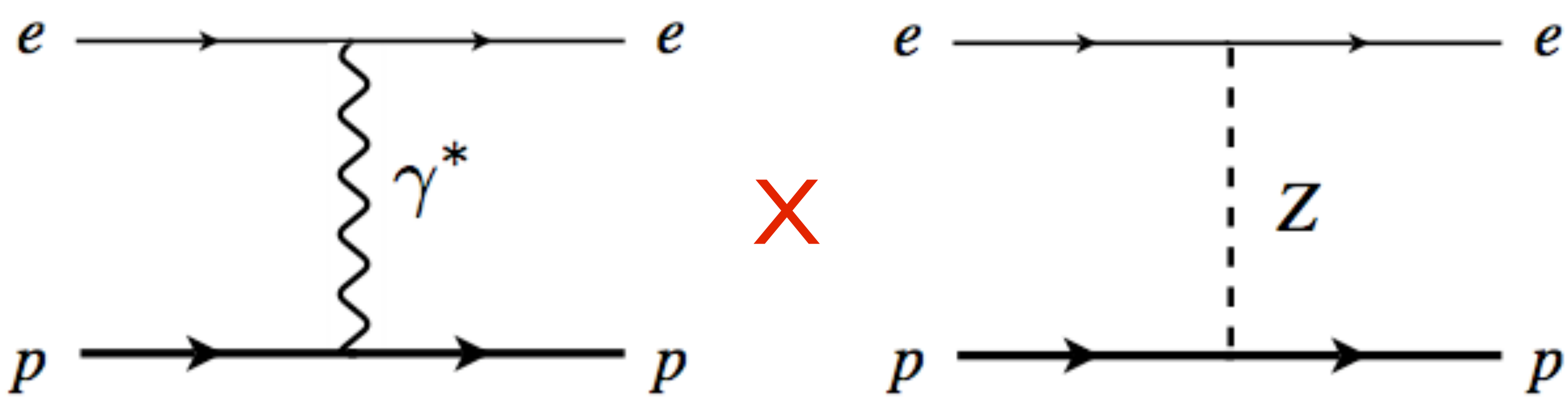
→ effect $< 1\%$ in valence region, but $\sim 2\%$ at $x \sim 0.2$

→ uncertainty arising from TMCs is negligible

Relevance of PVDIS asymmetries for *Qweak* experiment

Parity-violating elastic scattering

- Left-right polarization asymmetry in $\vec{e}\, p \rightarrow e\ p$ scattering

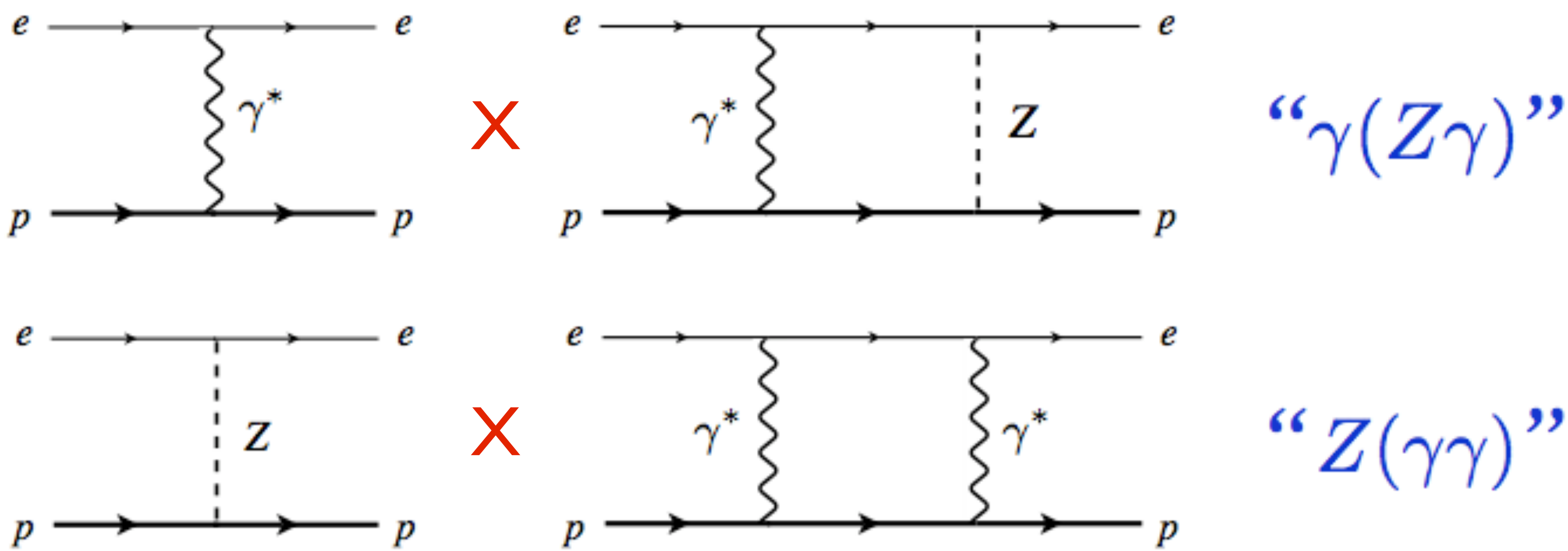


Born (tree) level

$\longrightarrow$ new combination of electroweak form factors, from which <u>strange form factors</u> extracted

Parity-violating elastic scattering

- Two-boson exchange corrections



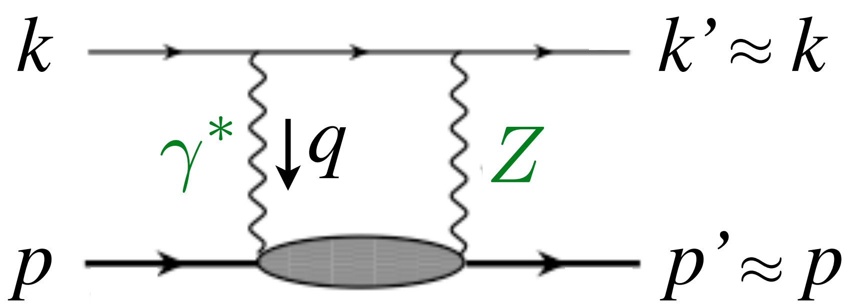
$\longrightarrow$ at low Q^2 dominant correction is from γZ exchange

Parity-violating elastic scattering

- In forward limit $A_{\rm PV}$ measures weak charge of proton Q_W^p

$$A_{\rm PV} \to \frac{G_F\, Q_W^p}{4\sqrt{2}\pi\alpha} t$$

$Q_W^p = 1 - 4\sin^2\theta_W$
at tree level



forward limit

$t = (k - k')^2 \to 0$

$s = (k + p)^2$
$= M(M + 2E)$

- Compute using forward dispersion relations with phenomenological (DIS structure function!) input

e.g. vector part of γZ box

$$\Re e\, \Box_{\gamma Z}^V(E) = \frac{2E}{\pi} \int_0^\infty dE' \frac{1}{E'^2 - E^2}\, \Im m\, \Box_{\gamma Z}^V(E')$$

Parity-violating elastic scattering

- Imaginary part given in terms of $F_{1,2}^{\gamma Z}$ structure functions

$$\Im m \, \square_{\gamma Z}^{V}(E) = \frac{\alpha}{(s-M^2)^2} \int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{\max}} \frac{dQ^2}{1+Q^2/M_Z^2} \times \left(F_1^{\gamma Z} + F_2^{\gamma Z} \frac{s\,(Q^2_{\max}-Q^2)}{Q^2(W^2-M^2+Q^2)} \right)$$

- Structure function inputs
  - DIS part dominated by leading twist PDFs at small x
  - resonance part from transition form factors
  - elastic part given by elastic e.w. form factors

Parity-violating elastic scattering

- Imaginary part given in terms of $F_{1,2}^{\gamma Z}$ structure functions

$$\Im m\,\Box_{\gamma Z}^{V}(E) = \frac{\alpha}{(s-M^2)^2}\int_{W_\pi^2}^{s} dW^2 \int_0^{Q^2_{\max}} \frac{dQ^2}{1+Q^2/M_Z^2} \times \left(F_1^{\gamma Z} + F_2^{\gamma Z}\,\frac{s\,(Q^2_{\max}-Q^2)}{Q^2(W^2-M^2+Q^2)} \right)$$

- Structure function inputs
  - DIS part dominated by leading twist PDFs at small x
  - resonance part from transition form factors
  - elastic part given by elastic e.w. form factors

most uncertain input

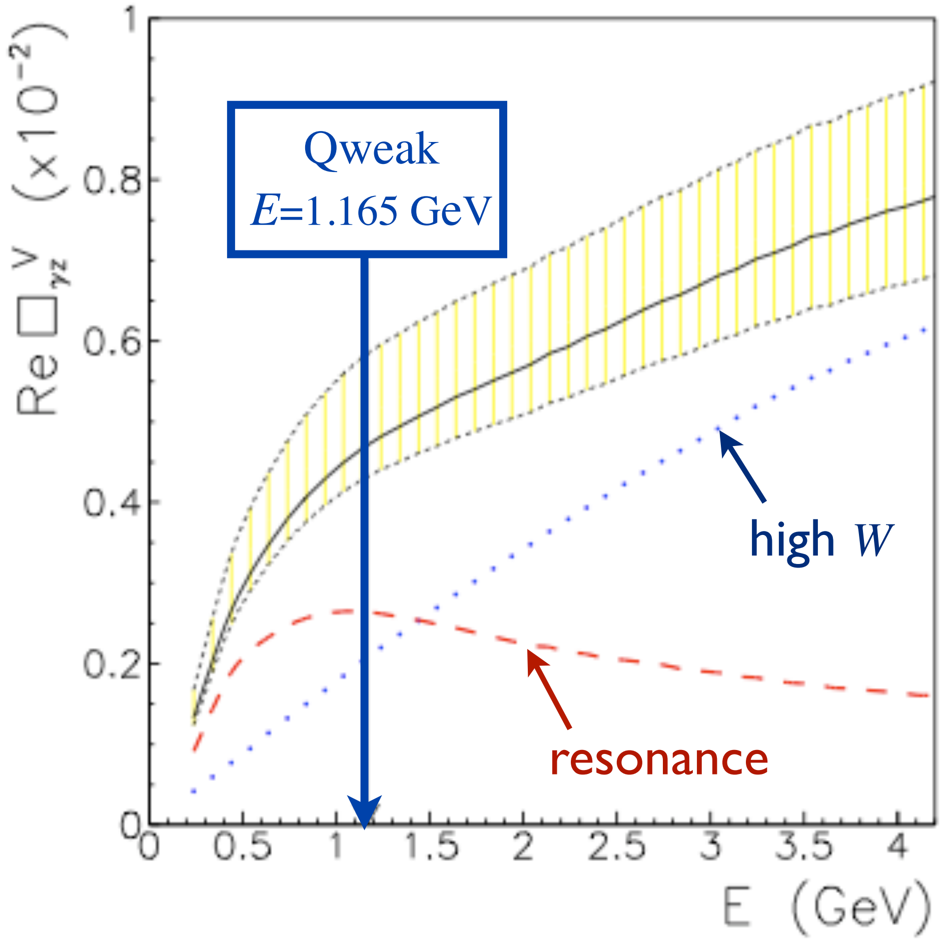
Vector h correction

- Total $\Box^V_{\gamma Z}$ correction:

  $$\Re e\,\Box^V_{\gamma Z} = 0.0047^{+0.0011}_{-0.0004}$$

  Sibirtsev et al., PRD ***82*** *(2010) 013011*

  → similar correction from Rislow & Carlson (2011)



- Recent work of Gorchtein, Horowitz & Ramsey-Musolf *PRC* ***84*** *(2011) 015502* gives

  $$\Re e\,\Box^V_{\gamma Z} = 0.0054 \pm 0.0020$$

  with twice the uncertainty!

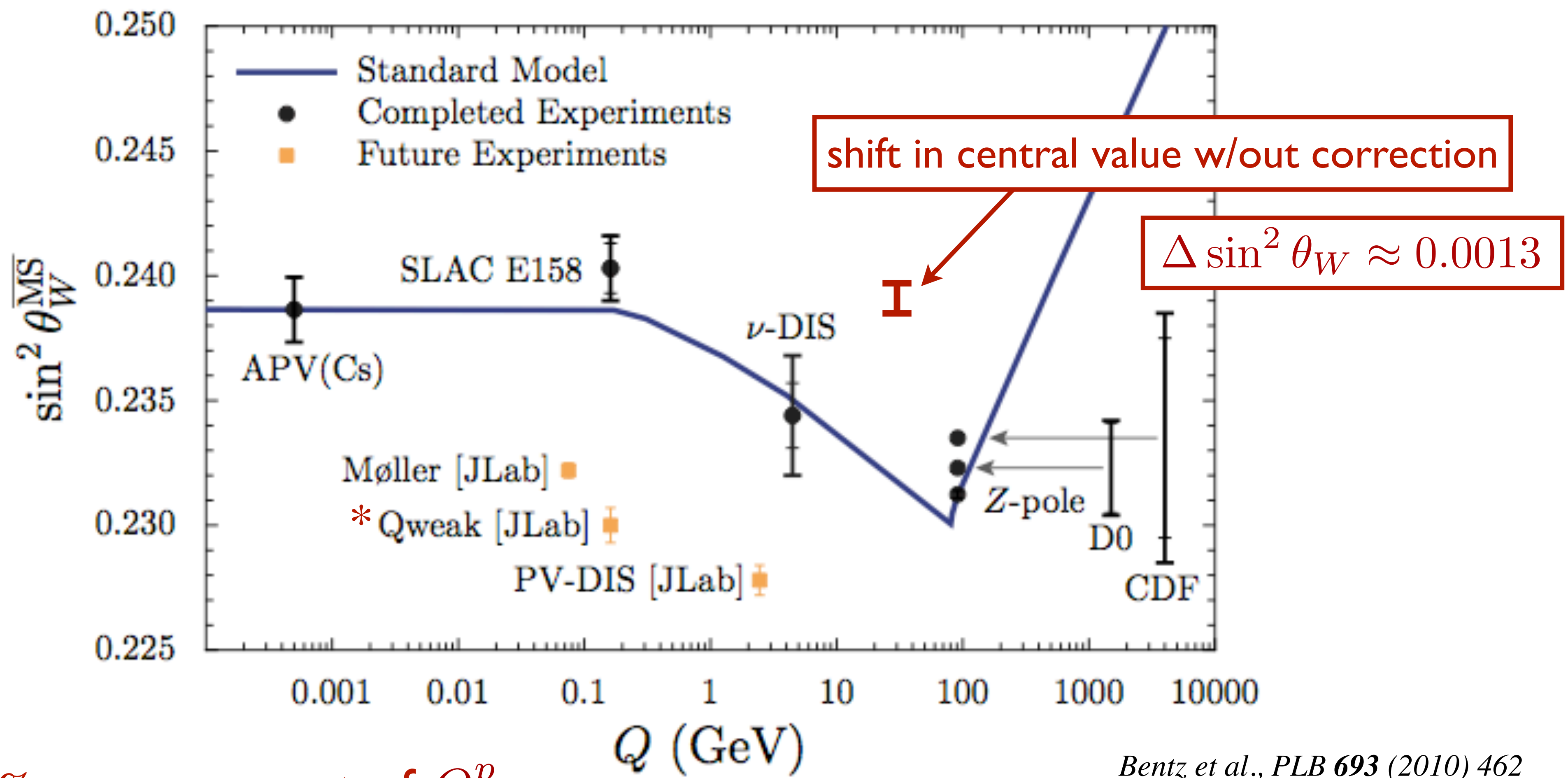
→ would derail interpretation of *Qweak*

→ direct measurement of $F^{\gamma Z}_{1,2,3}$ critical !

Total γZ correction

$$\boxed{Q_W^p = 0.0713(8) \to 0.0765^{+0.0014}_{-0.0009}}$$

→ significant shift in central value, errors within projected experimental uncertainty $\Delta Q_W^p = \pm 0.003$



*Bentz et al., PLB **693** (2010) 462*

* 4% measurement of Q_W^p

Summary

- PVDIS to access CSV (deuteron) or d/u ratio (proton)

  $\longrightarrow$ subleading effects at low Q^2 from pQCD (NLO), TMC are under control

  $\longrightarrow$ higher twists more challenging (especially for p)

- Data on PVDIS asymmetry at low W directly constrains structure function input for γZ correction to $Qweak$ measurement of proton weak charge

  $\longrightarrow$ may be most important constraint on Q_W^p theoretical uncertainty additional slides

higher twist corrections for *deuteron*

→ relevant four-quark operators identified

*Bjorken, PRD **18** (1978) 3239*

*Wolfenstein, NPB **146** (1978) 477*

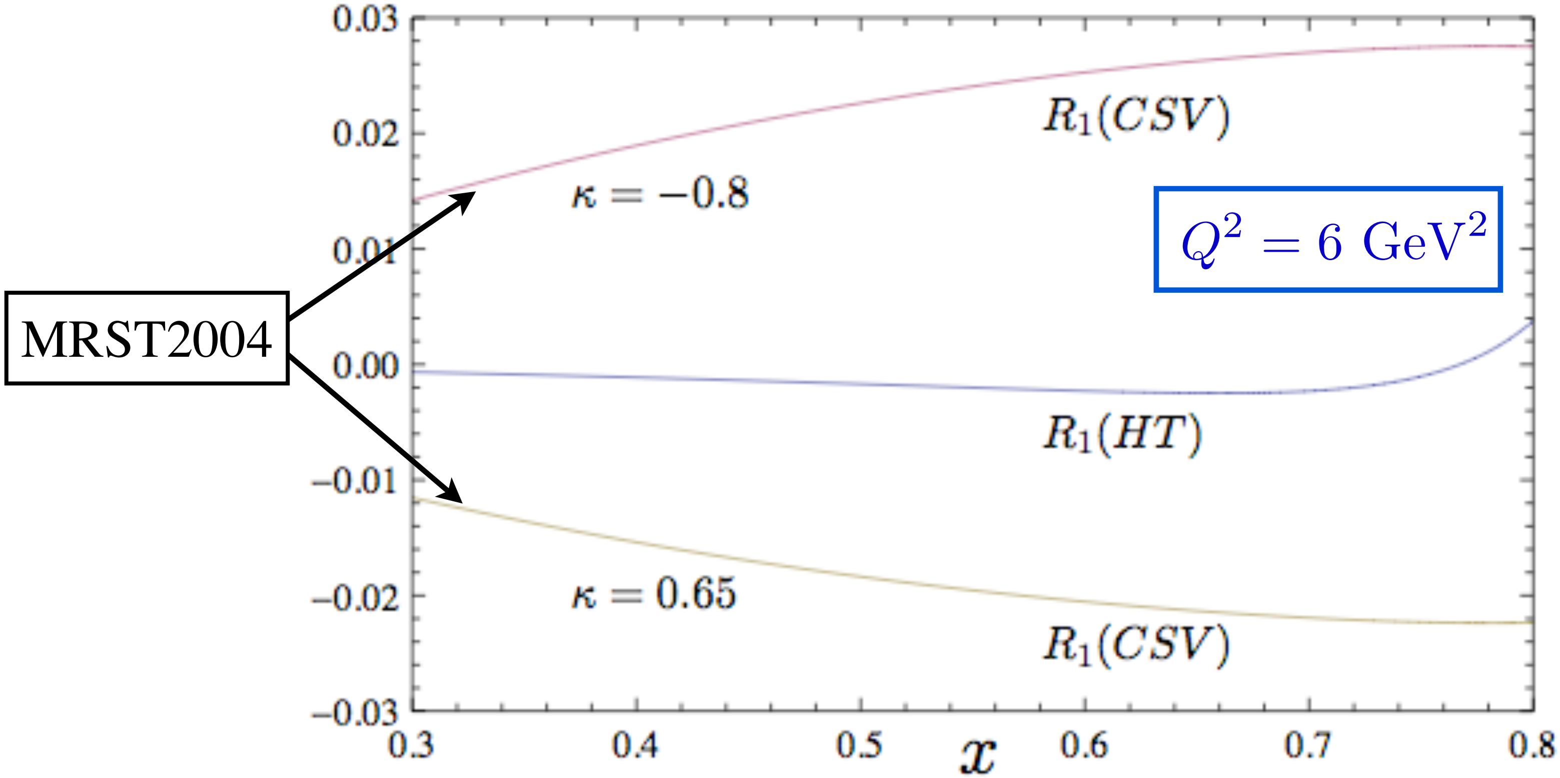
→ matrix elements computed in MIT bag model

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

→ x dependence determined from moments

Mantry, Ramsey-Musolf, Sacco
*PRC **82** (2010) 065205*

higher twist corrections for *deuteron*



Mantry, Ramsey-Musolf, Sacco
PRC ***82*** *(2010) 065205*

→ HT terms $\ll$ MRST2004 bounds on CSV (2−3%)

→ may be comparable if CSV ~ MRSTQED estimate (~ 0.5%)

higher twists for *proton* more complicated