Neutrino Factories, Super Beams and Beta Beams
College of William & Mary / Jefferson Lab
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e and ν scattering synergies

Wally Melnitchouk

Jefferson Lab

Introduction

Many areas of overlap for nucleon (& nuclear) structure studies with neutrino & electron beams, including:

- Parton distributions
  - → flavor separation; implications for LHC
  - → higher twists, resonances & duality
  - → generalized parton distributions
- (Quasi) elastic scattering
  - → strange content of the nucleon
  - → axial form factor
  - → two-boson exchange
- Nuclear targets
  - → nuclear effects on structure functions, form factors

Parton distribution functions

- Vital to have precise ν & $\bar{\nu}$ structure function input into global PDF fits for flavor separation

→ $e.g.$ at leading order in α_s

$$F_2^{ep} = \frac{x}{9}\left[4(u+\bar{u}) + (d+\bar{d}) + (s+\bar{s}) + 4(c+\bar{c})\right]$$

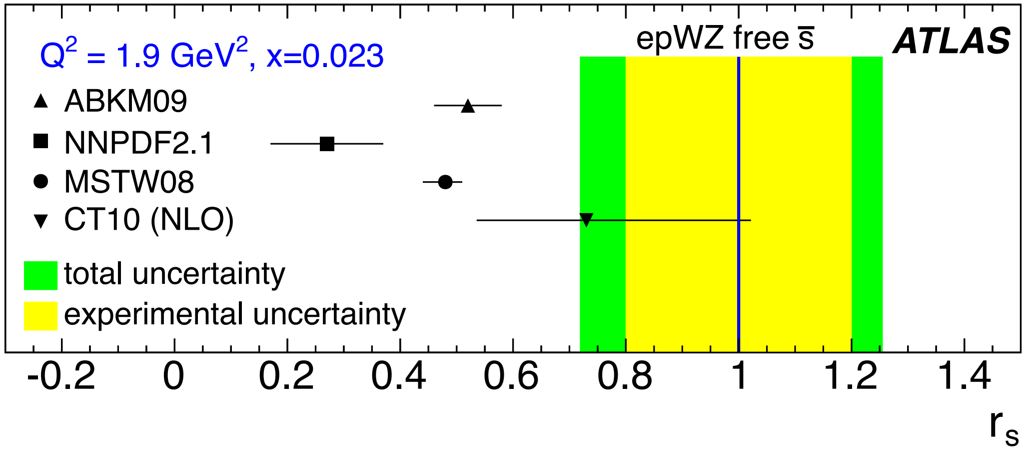
$$F_2^{\nu p} = 2x\left[d+\bar{u}+s+\bar{c}\right] \quad \leftarrow \boxed{d/u,\quad s/\bar{s}}$$

$$xF_3^{\nu p} = 2x\left[d-\bar{u}+s-\bar{c}\right] \quad \leftarrow \boxed{q/\bar{q}}$$

- Most useful if measured on *hydrogen* (or *deuterium*) targets to avoid nuclear correction uncertainties

Parton distribution functions

- Suggestions of larger than expected *strange* quark PDF from $W, Z \to l\,\nu$ at LHC (ATLAS)



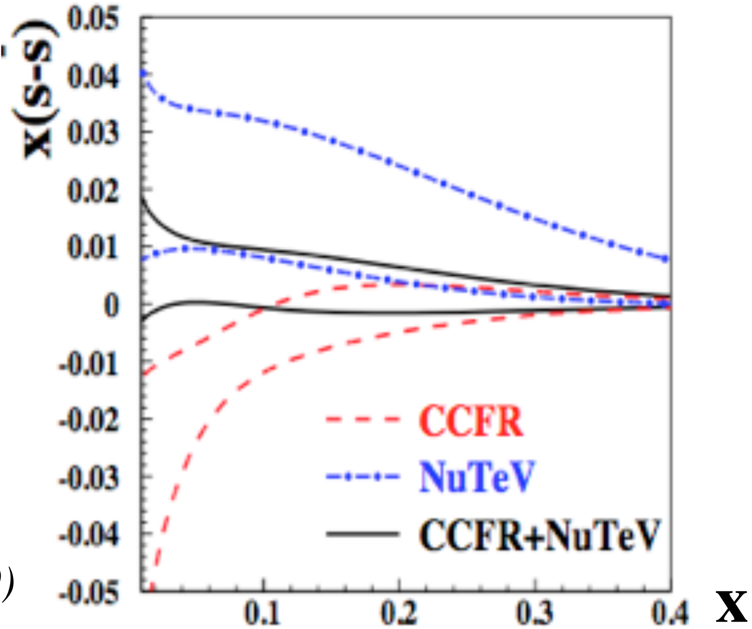
$$r_s = (s + \bar{s})/2\bar{d}$$
$$= 1.00^{+0.25}_{-0.28}$$

ATLAS, PRL ***109****, 012001 (2012)*

- Strange−antistrange asymmetry

  → small but important indicator of nonperturbative physics

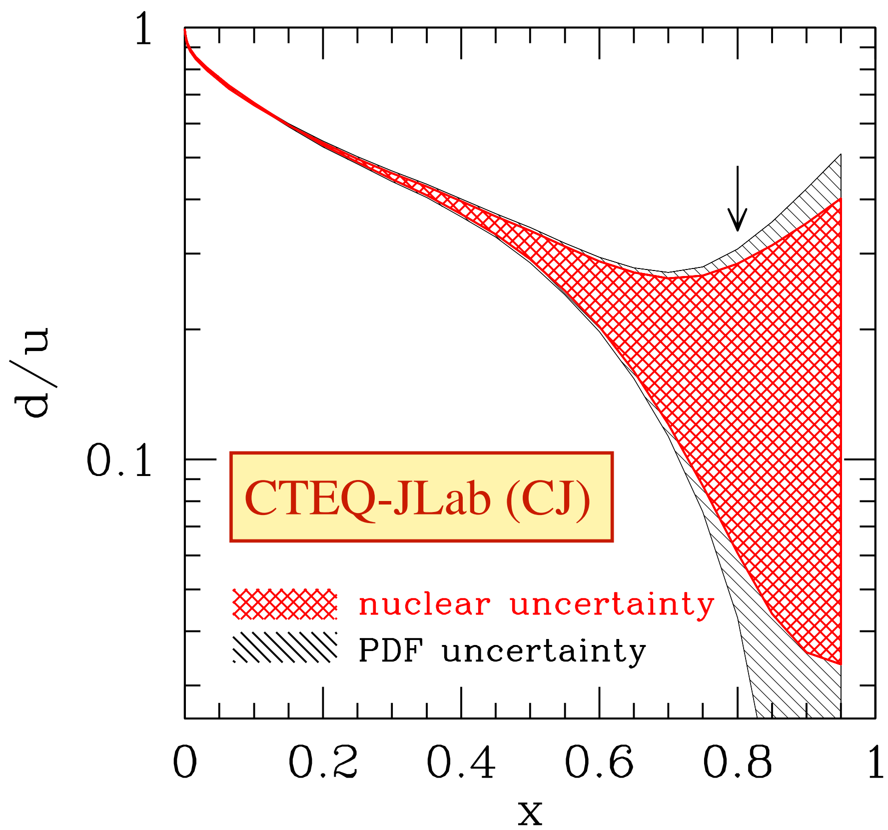
Signal, Thomas, PLB ***191****, 205 (1987)*



Alekhin et al., PLB ***675****, 433 (2009)*

Parton distribution functions

- At large x (> 0.5–0.6) d quark distribution in proton (or d/u ratio) is poorly determined



see talk of C. Keppel

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

→ CJ fit attempts to better constrain d PDF to $x \sim 0.8$

→ limited by *nuclear corrections* in deuteron

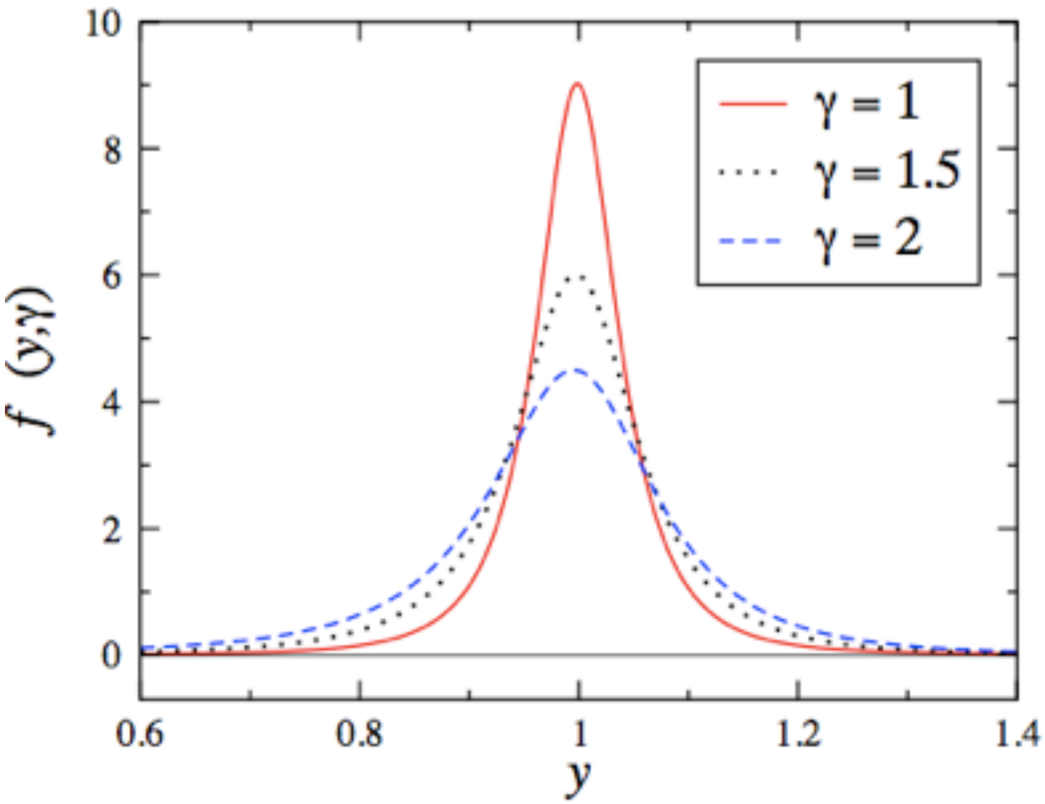
Nuclear effects in deuterium

- In impulse approximation, deuteron structure function computed as convolution:

$$F_2^d(x) = \int dy\, f_{N/d}(y,\gamma)\, F_2^N(x/y) + \delta^{(\mathrm{off})} F_2^d(x)$$

N momentum distribution in D ("smearing function")

N off-shell correction



light-cone momentum fraction

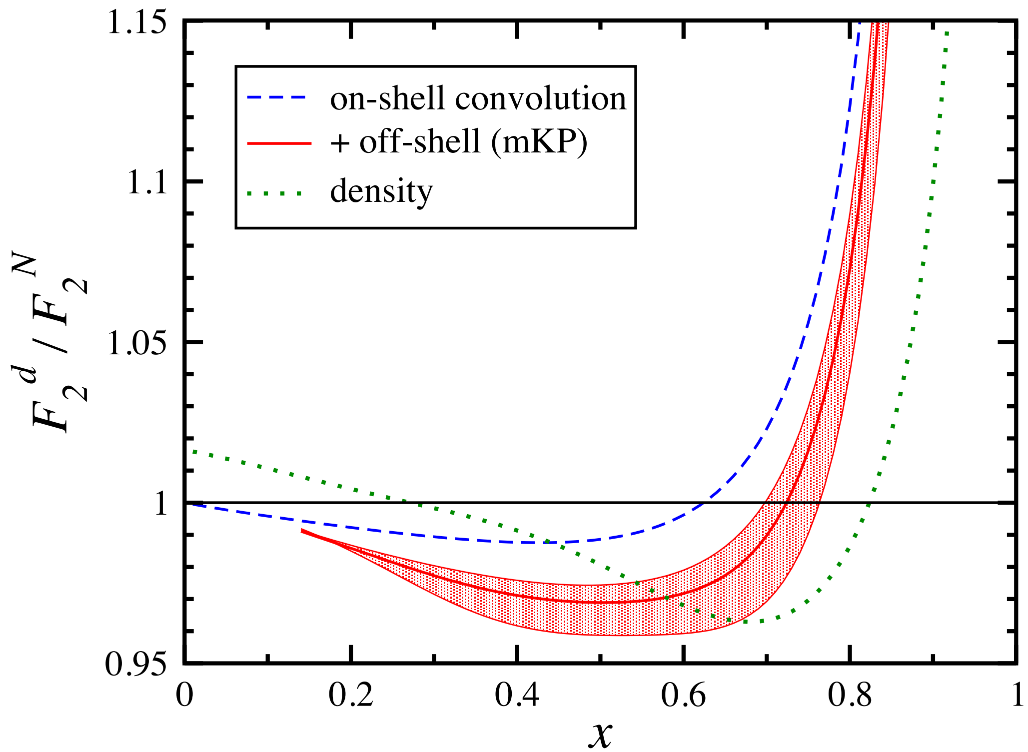
$$y = p_N^+ / P_D^+$$

finite-Q^2 correction

$$\gamma^2 = 1 + 4M^2x^2/Q^2$$

Kahn, WM, Kulagin, PRC ***79****, 035205 (2009)*

Nuclear effects in deuterium

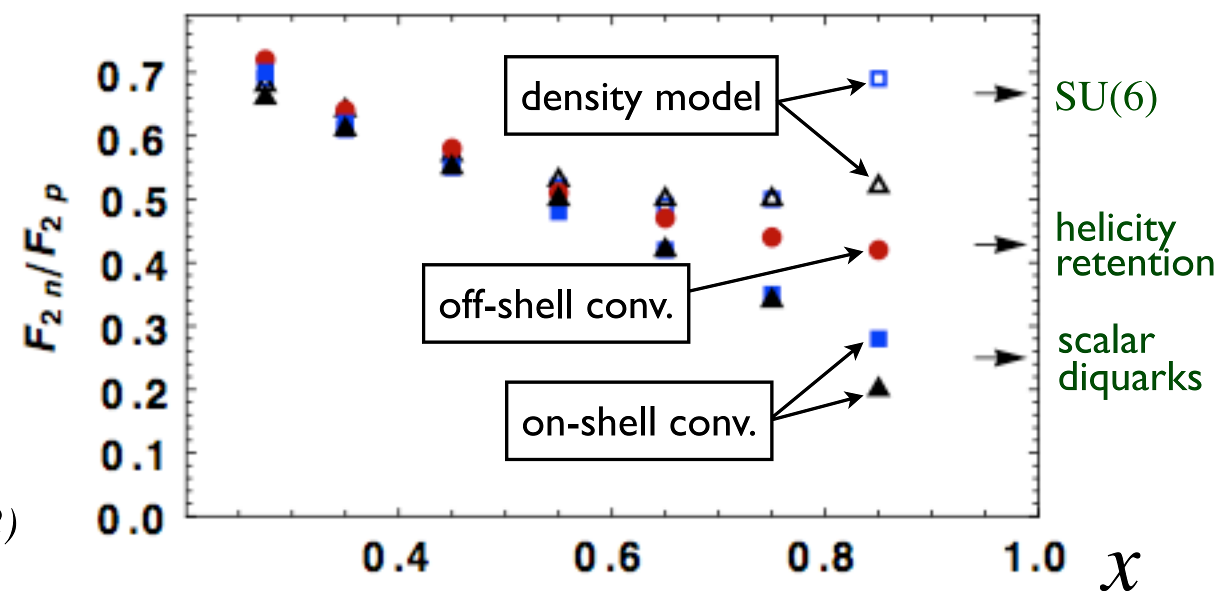


strong dependence of nuclear EMC ratio on deuteron model (wave function, off-shell) at high x ...

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

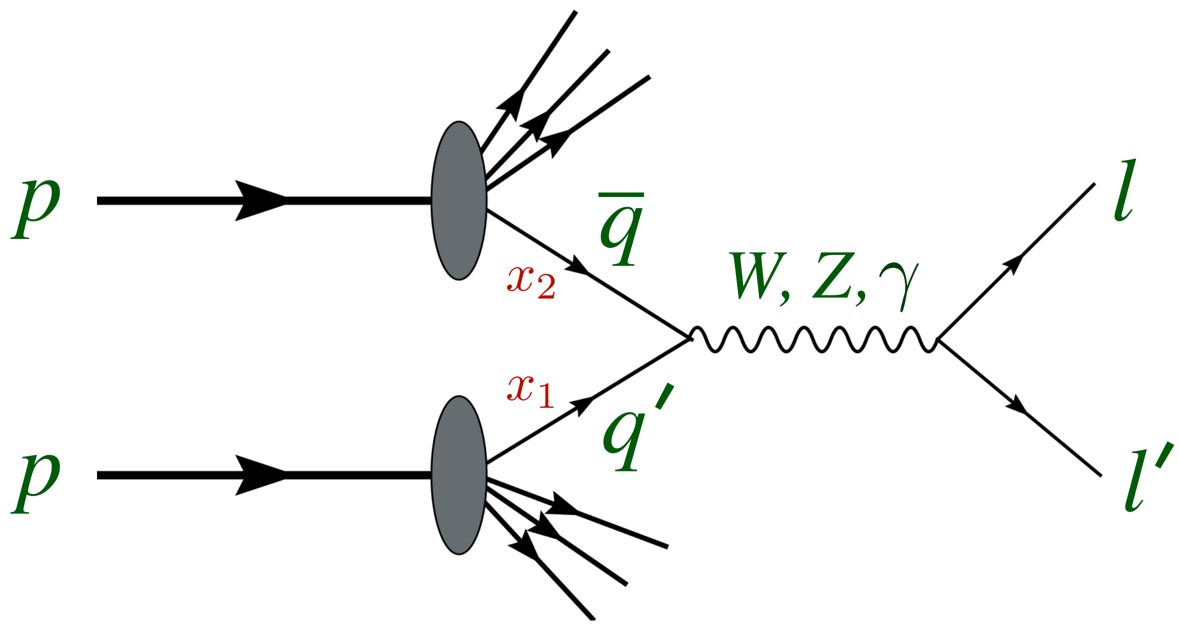
... translates to large uncertainty in n/p ratio, and hence d/u

*Arrington et al., PRL **108**, 252001 (2012)*



Implications for new particle searches

e.g. heavy boson production



Implications for new particle searches

- 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.*

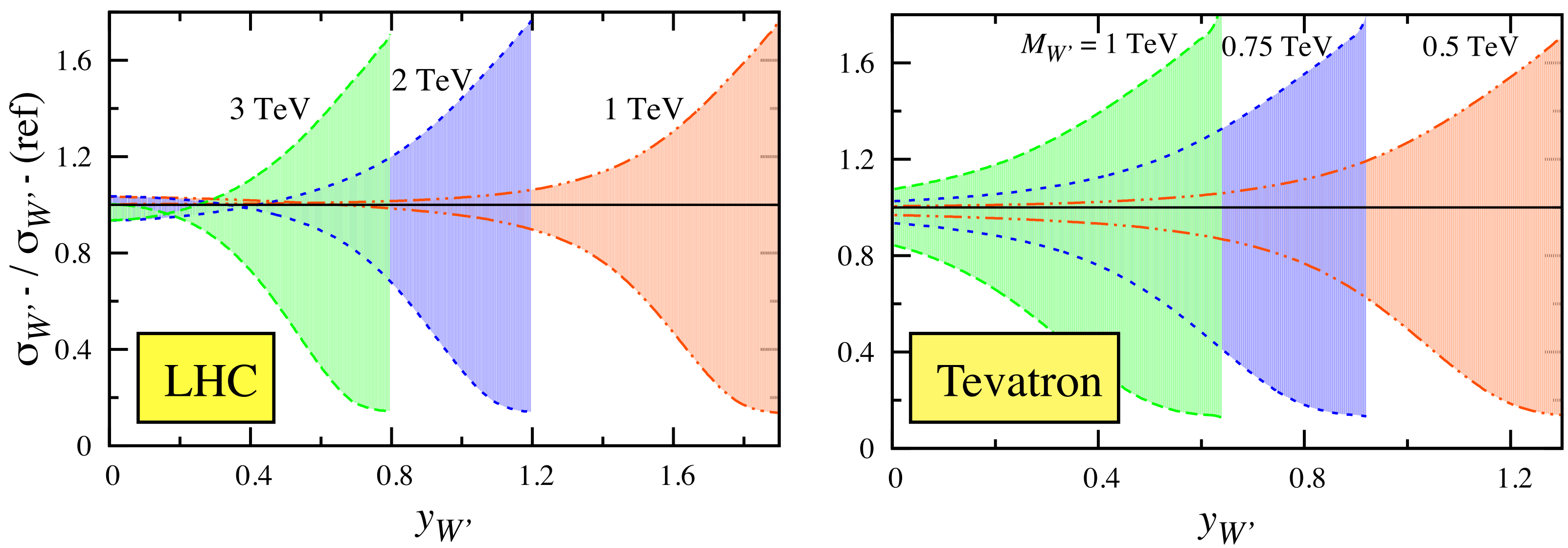
- scalar excitations in R-parity violating supersymmetric models *Hewett, Rizzo (1998)*
- spin-1 Kaluza-Klein excitations of SM bosons in presence of extra dimensions *Antoniadis (1990)*
- spin-2 excitations of the graviton *Randall, Sundrum (1999)*

Implications for new particle searches

- 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!)

  - for W'^{-} production



$\longrightarrow$ dominated by $d * \bar{u}$ $\quad\quad$ $\longrightarrow$ dominated by $d * u + u * d$

$> 100\%$ uncertainties at large y !

Future determinations of d/u

- Several planned experiments at JLab with 12 GeV will measure d/u to $x \sim 0.85$ with minimal nuclear corrections

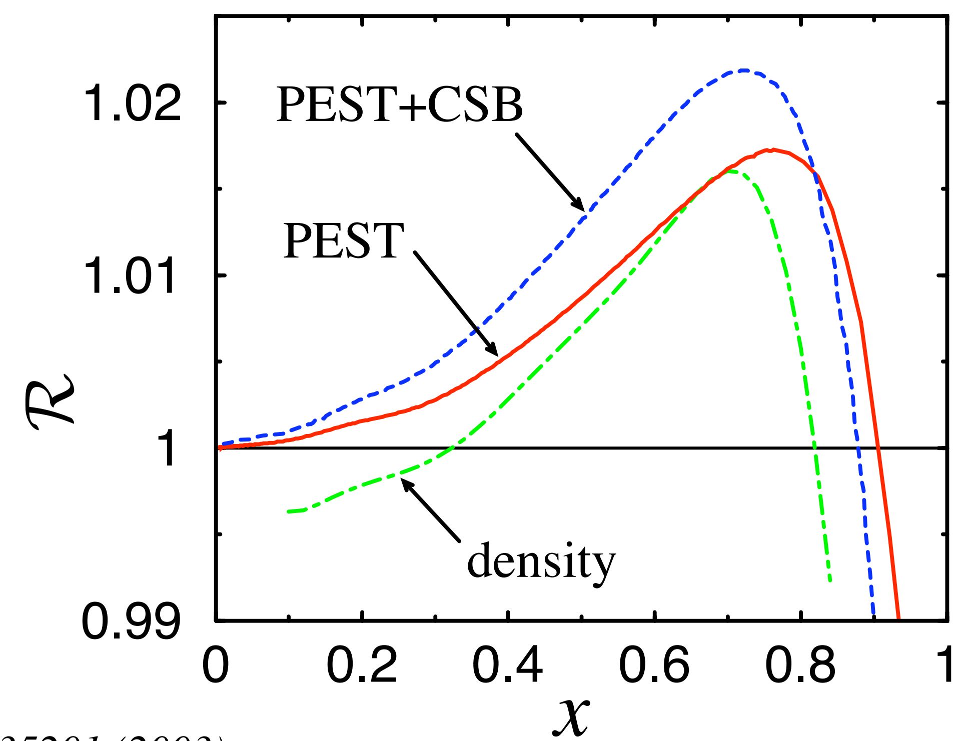
  → SIDIS from D with slow backward proton ("BONUS"); inclusive ^{3}He / ^{3}H ratio; and PVDIS from proton

- Extract n/p ratio from $A = 3$ mirror nuclei

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

$$\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$$

→ need (relative) nuclear corrections to $< 1\%$



*Afnan et al., PRC **68**, 035201 (2003)*

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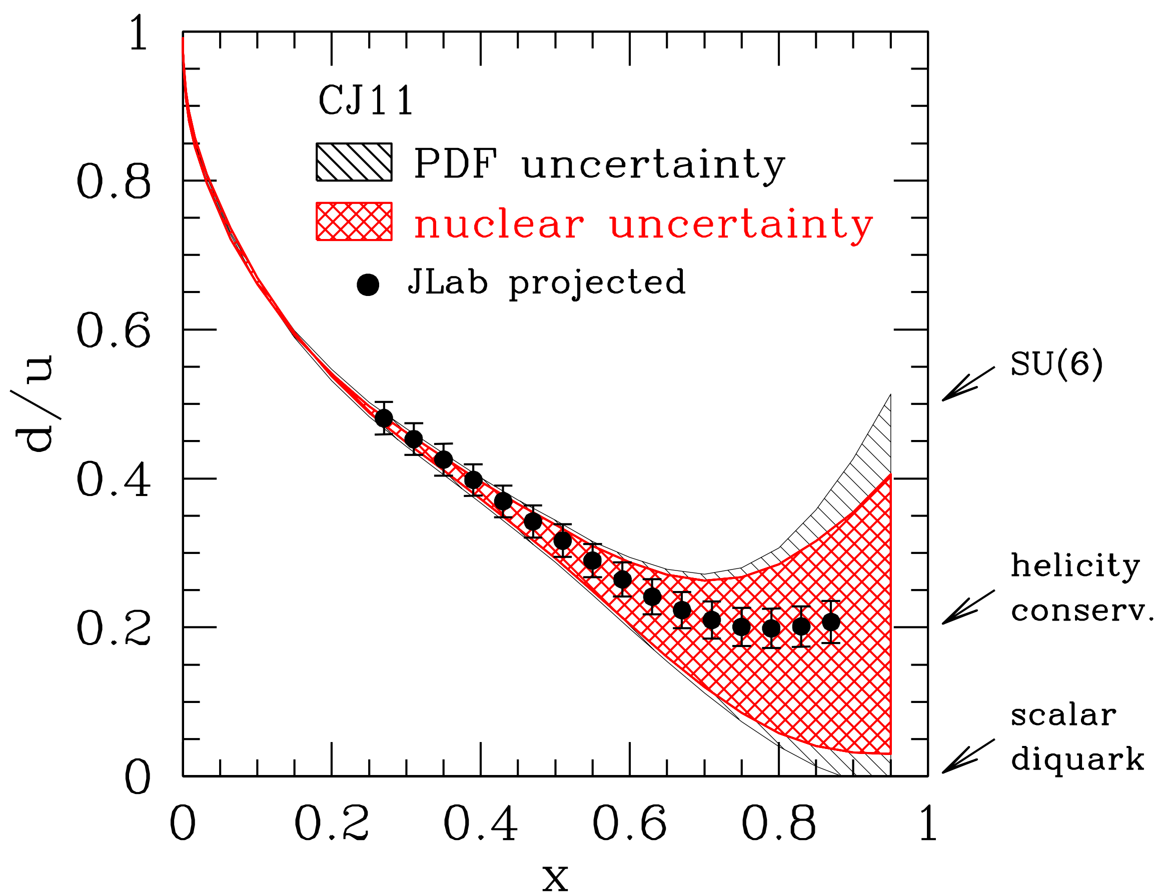

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Future determinations of d/u

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→ SIDIS from D with slow backward proton ("BONUS"); inclusive ^{3}He / ^{3}H ratio; and PVDIS from proton

- Cleanest and most direct method is to use neutrino and antineutrino DIS on hydrogen

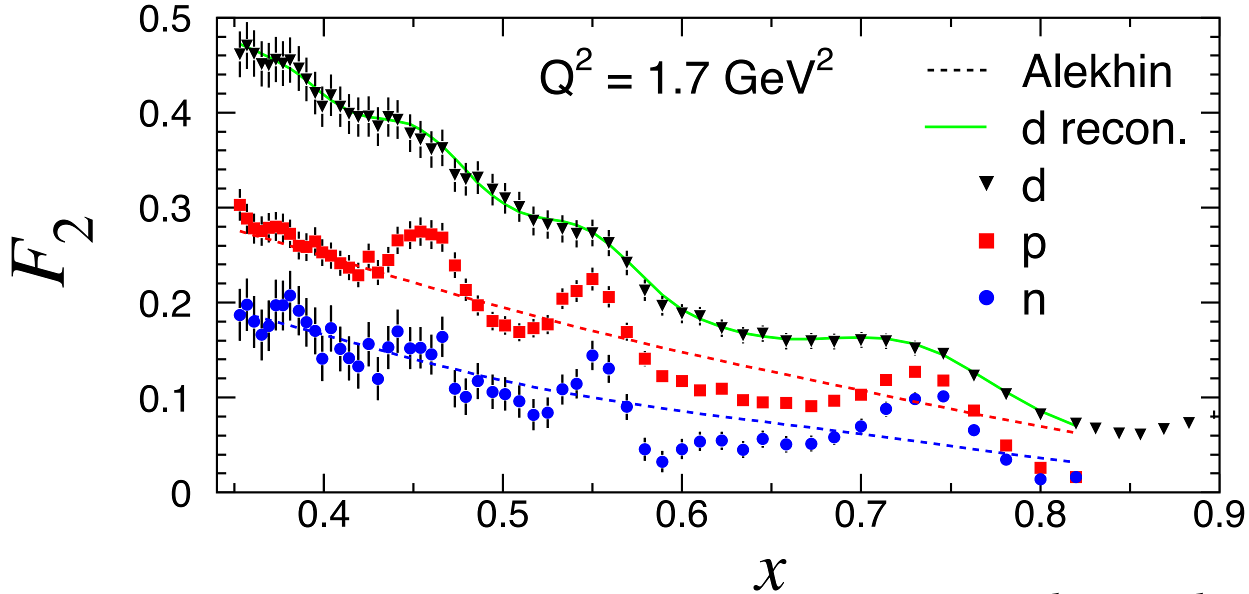
→ selects d and u quark PDFs at large x

$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} \to \frac{d}{u}$$

→ need reach up to $x \sim 0.85$, with large Q^2 range to control for higher twists

Resonances and duality

- Accuracy of *quark-hadron duality* being established in high-precision measurements of electromagnetic structure functions in *resonance* region

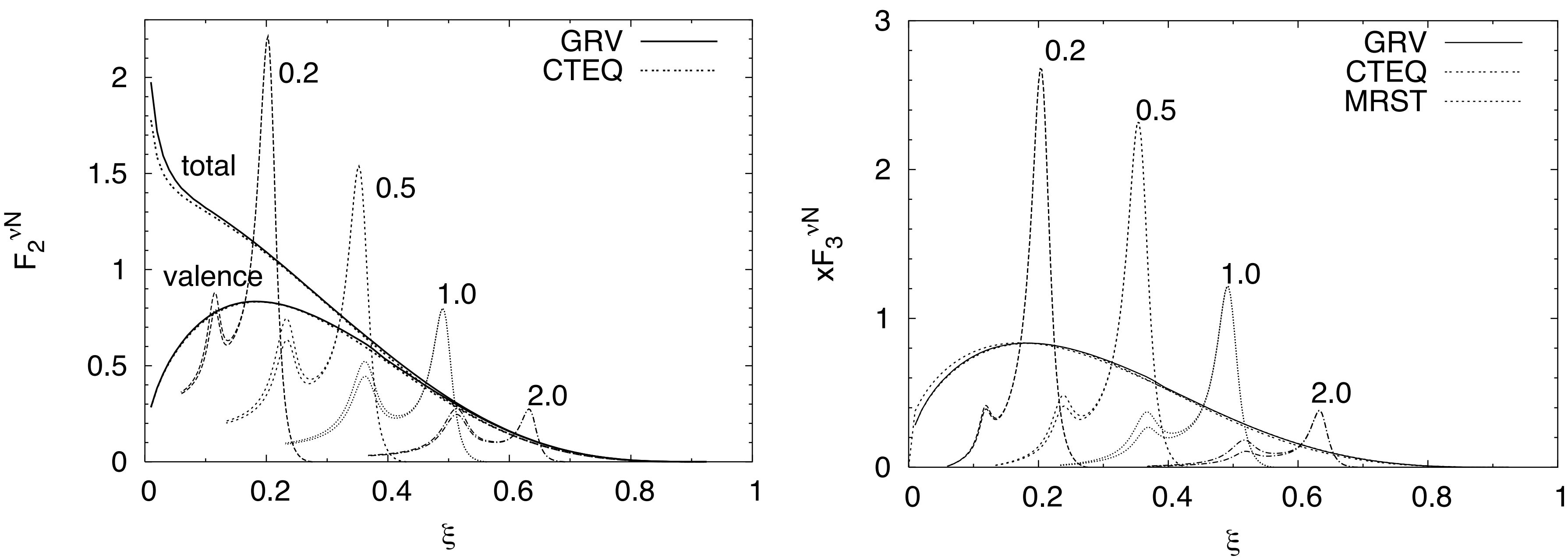


Malace et al., PRL ***104****, 102001 (2010)*

→ higher-twist (duality-violating) corrections appear to be ~10−20% for (low) structure function moments

Resonances and duality

- Neutrino DIS would allow test of universality of duality, and determine size of higher twist matrix elements in P-odd *vs.* P-even structure functions



Lalakulich, Paschos, WM, PRC ***75****, 015202 (2007)*

→ currently resonance form factors poorly constrained
(old ANL/BNL neutrino resonance-production data)

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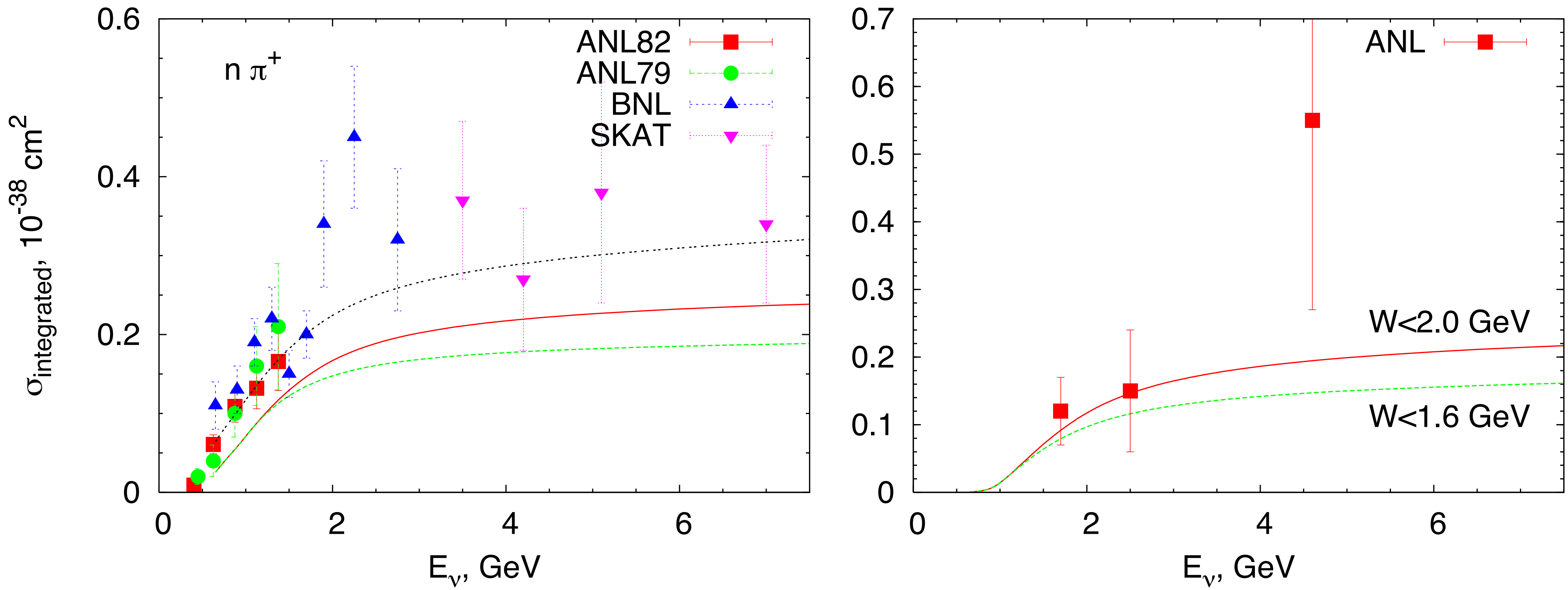
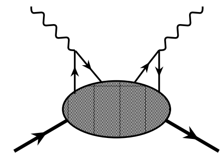


→ currently resonance form factors poorly constrained (old ANL/BNL neutrino resonance-production data)

Twist-four matrix elements

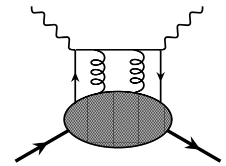
- At twist four, have 3 unique operators

$$\mathcal{O}^V_{\mu\nu} = (\bar{\psi}\gamma_\mu\psi)\,(\bar{\psi}\gamma_\nu\psi)$$



$$\mathcal{O}^A_{\mu\nu} = (\bar{\psi}\gamma_\mu\gamma_5\psi)\,(\bar{\psi}\gamma_\nu\gamma_5\psi)$$

$$\mathcal{O}^g_{\mu\nu} = \bar{\psi}\,\{iD_\mu, \widetilde{F}_{\nu\alpha}\}\gamma_\alpha\gamma_5\,\psi$$



Shuryak, Vainshtein
*NPB **199**, 451 (1982)*

- Higher-twist parts of moments $M_i(Q^2) = \int_0^1 dx\,\mathcal{F}_i(x, Q^2)$ of structure functions $\mathcal{F}_i = F_2, F_L, xF_3$

$$M_i^{\rm HT} = c_i^V \langle \mathcal{O}^V \rangle + c_i^A \langle \mathcal{O}^A \rangle + c_i^g \langle \mathcal{O}^g \rangle$$

→ can solve for matrix elements with precise data on moments in $Q^2 \sim 1\text{–}5~\mathrm{GeV}^2$ region

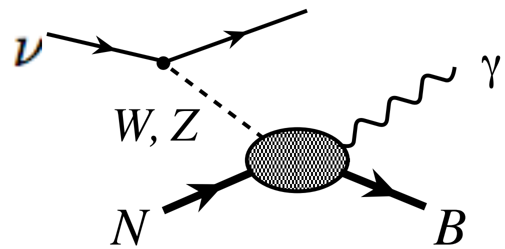
Freid, WM, Steffens (2012)

Generalized parton distributions

- Comprehensive program of hard exclusive reactions ($e.g.$ DVCS) at JLab to extract GPDs

  → determine orbital angular momentum of quarks

  → map out 3D structure of nucleon



- Neutrino DVCS uniquely sensitive to *C*-odd combinations of GPDs, not accessible with e scattering

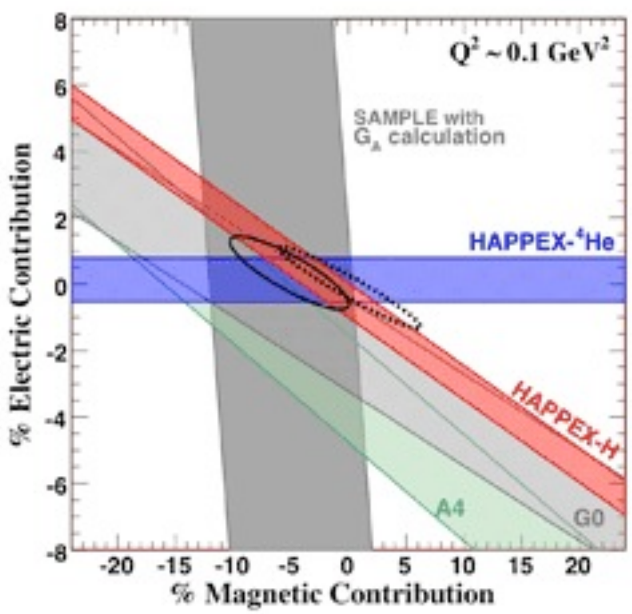
  → flavor decomposition, non-diagonal transitions

  → can extract *spin-dependent* valence & sea distributions with an unpolarized target!

Psaker, WM, Radyushkin
PRD ***75****, 054001 (2007)*

Strange content of the nucleon

- Strange *vector* form factors measured to high precision in parity-violating *e* scattering at JLab, MAMI, ...



$$G_E^s = \rho_s Q^2 + \rho_s' Q^4$$

$$G_M^s = \mu_s + \mu_s' Q^2$$

$$\rho_s = -0.03 \pm 0.63 \text{ GeV}^{-2}$$

$$\mu_s = 0.37 \pm 0.79$$

Young et al., PRL ***99****, 122003 (2007)*

→ strange quark contribution to proton magnetic moment less than 10%

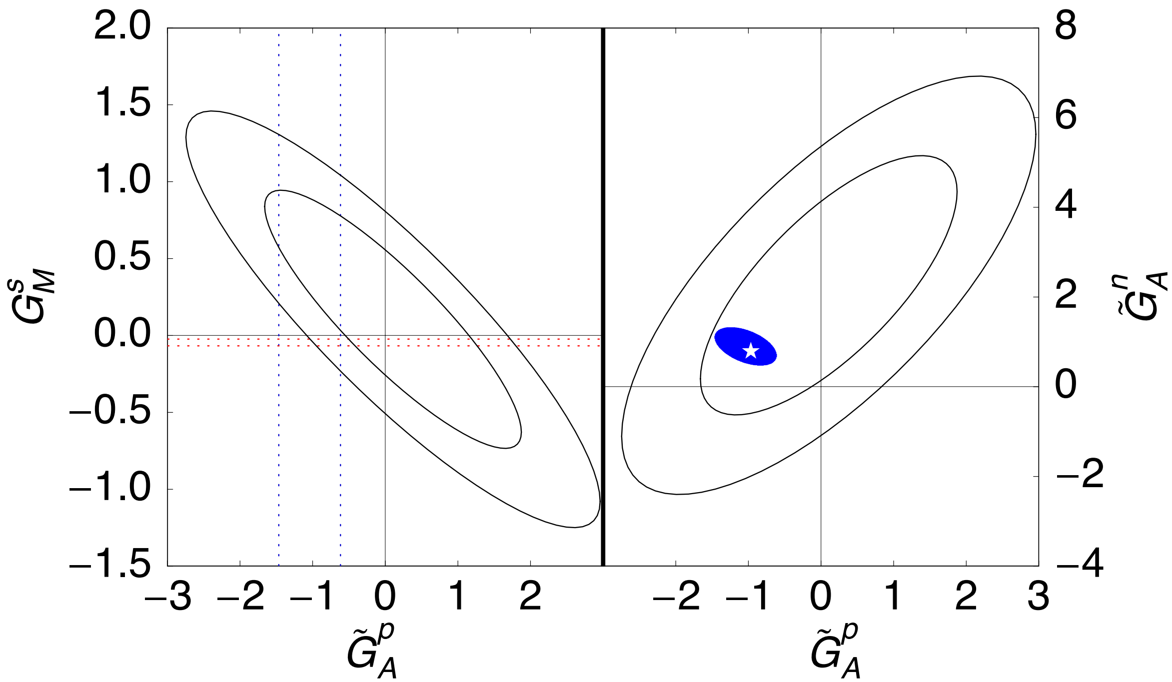
→ strange electric form factor consistent with zero

→ consistent with theory (lattice + phenomenology)

Leinweber et al., PRL ***94****, 212001 (2005)*

Strange content of the nucleon

- Strange *axial* vector form factors not as well determined



$$\tilde{G}^N_A = \tilde{g}^N_A(1 + Q^2/M^2_A)^{-2}$$

$$M_A = 1.026\,\text{GeV}$$

$$\tilde{g}^p_A = -0.80 \pm 1.68$$
$$\tilde{g}^n_A = 1.65 \pm 2.62$$

Young et al., PRL ***99****, 122003 (2007)*

see also Liu, McKeown, Ramsey-Musolf PRC ***76****, 025202 (2007)*

→ includes “anapole” contribution (weak interaction within target)

→ complementary measurement in neutrino-nucleon elastic scattering

Strange content of the nucleon

- Sum rule relates spin-dependent structure function to strange *axial form factor* at $Q^2 = 0$

$$\int_0^1 dx\, g_1^p(x,Q^2) = \left(\frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)}\right) C_{NS}(Q^2) + \frac{1}{9} g_A^{(0)}|_{\rm inv} C_S(Q^2)$$

- From elastic neutrino-proton scattering (NC) measure

$$2 g_A^{(Z)} = (\Delta u - \Delta d - \Delta s)_{\rm inv} + \mathscr{P}\, g_A^{(0)}\big|_{\rm inv} + O(m_{t,b,c}^{-1})$$

→ using $(\Delta u - \Delta d - \Delta s)_{\rm inv} = g_A^{(3)} + \frac{1}{3} g_A^{(8)} - \frac{1}{3} g_A^{(0)}|_{\rm inv}$

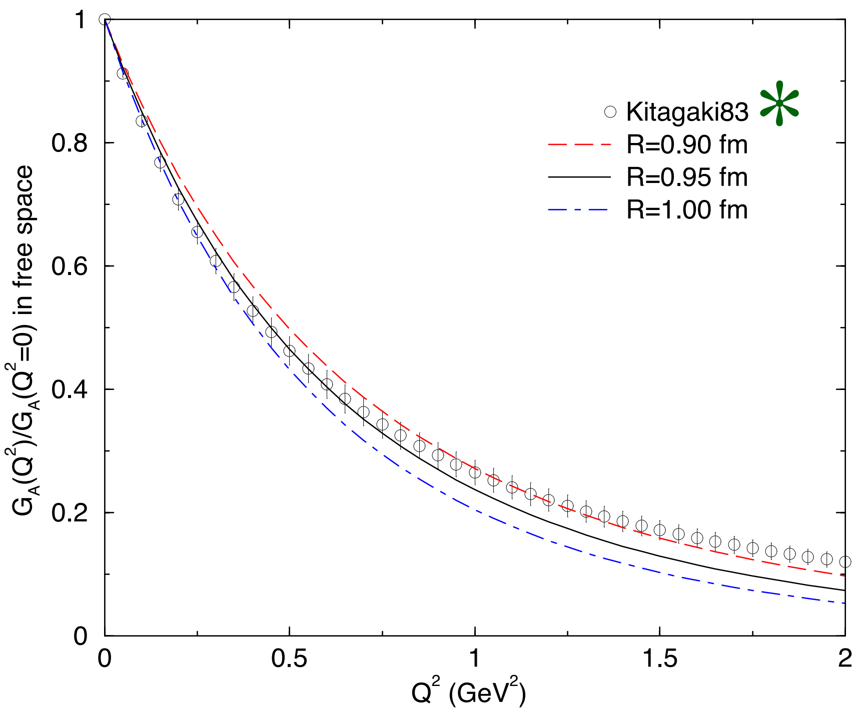
extract $g_A^{(0)}\big|_{\rm inv} = (\Delta u + \Delta d + \Delta s)_{\rm inv}$ to obtain independent determination of Δs

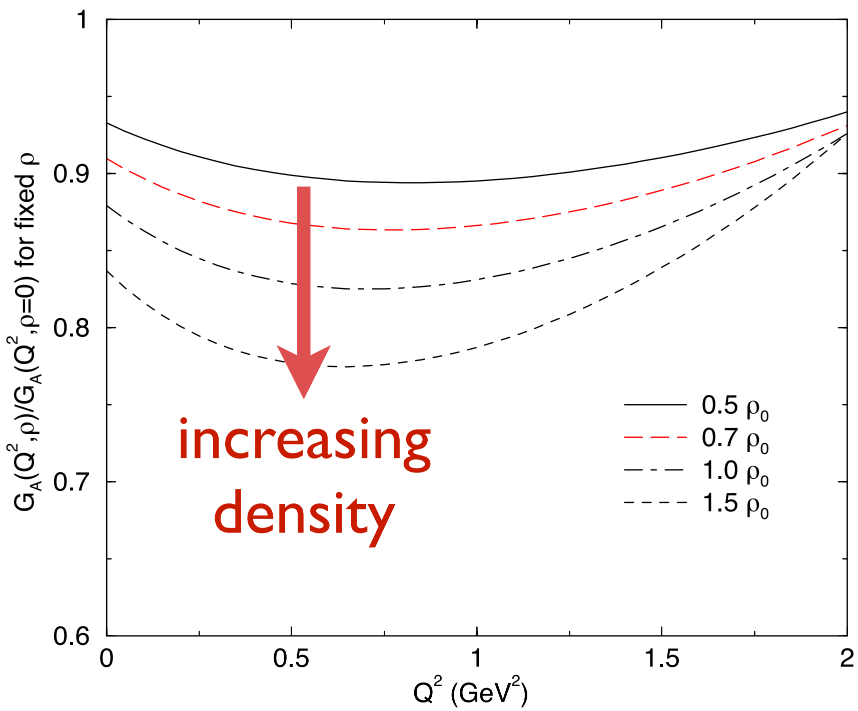
*Bass et al., PRD **66**, 031901 (2002)*

Axial form factor in medium

- Axial form factor expected to be quenched in nuclei

  → $\sim 10\%$ reduction in quark-meson coupling (QMC) model





$$* \quad G_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2}$$

$$M_A = 1.03 \pm 0.04 \text{ GeV}$$

Lu et al., PRC ***60****, 068201 (1999)*
Tsushima et al., nucl-th/0301078

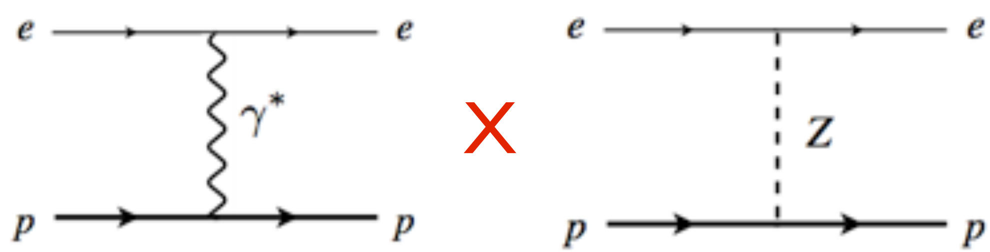
Parity-violating e scattering

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

$$A_{\rm PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \longrightarrow \frac{G_F\, Q_W^p}{4\sqrt{2}\pi\alpha}\, t$$

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

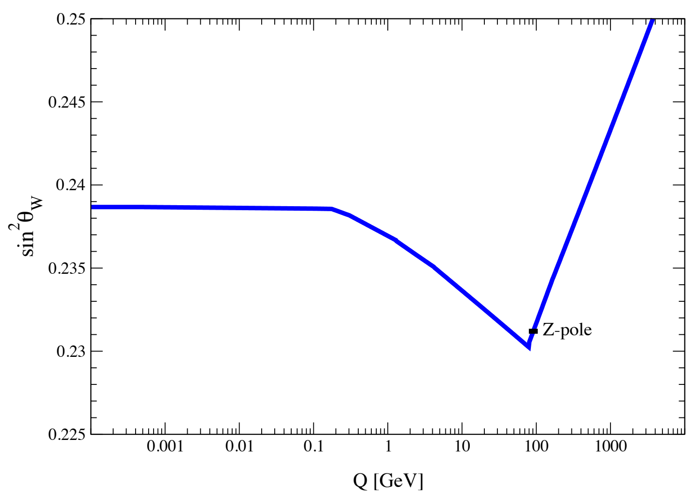
→ measures interference between e.m. and weak currents



→ in forward limit, gives proton weak charge

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

(tree level)



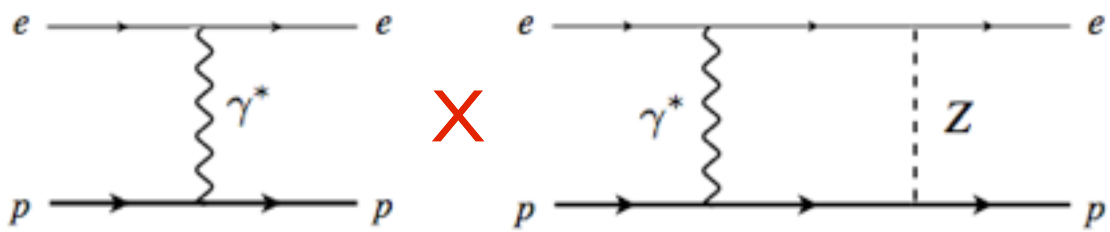
Parity-violating e scattering

- Including higher-order radiative corrections

$$Q_W^p = (1 + \Delta\rho + \Delta_e)(1 - 4\sin^2\theta_W(0) + \Delta_e') + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

Erler et al., PRD ***72****, 073003 (2005)*

"box diagrams"



→ γZ box diagram sensitive to long-distance physics

$$\Box_{\gamma Z} = \Box_{\gamma Z}^A + \Box_{\gamma Z}^V$$

vector e – axial h (finite at E=0)

axial e – vector h (vanishes at E=0)

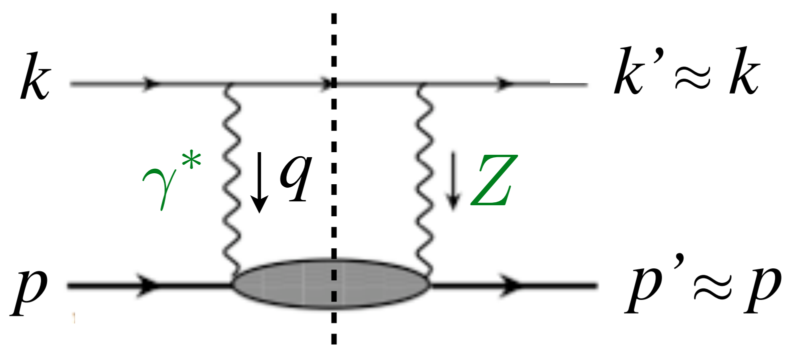
Parity-violating e scattering

- At low energy, dominant $V_e \times A_h$ correction evaluated using forward dispersion relations

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

→ imaginary part given by $F_3^{\gamma Z}$ structure function

$$\Im m\, \Box^{A}_{\gamma Z}(E) = \frac{1}{(2ME)^2} \int_{M^2}^{s} dW^2 \int_0^{Q^2_{\rm max}} dQ^2 \, \frac{v_e(Q^2)\, \alpha(Q^2)}{1 + Q^2/M_Z^2} \times \left(\frac{2ME}{W^2 - M^2 + Q^2} - \frac{1}{2} \right) F_3^{\gamma Z}$$



with $v_e(Q^2) = 1 - 4\kappa(Q^2)\sin^2\theta_W(Q^2)$

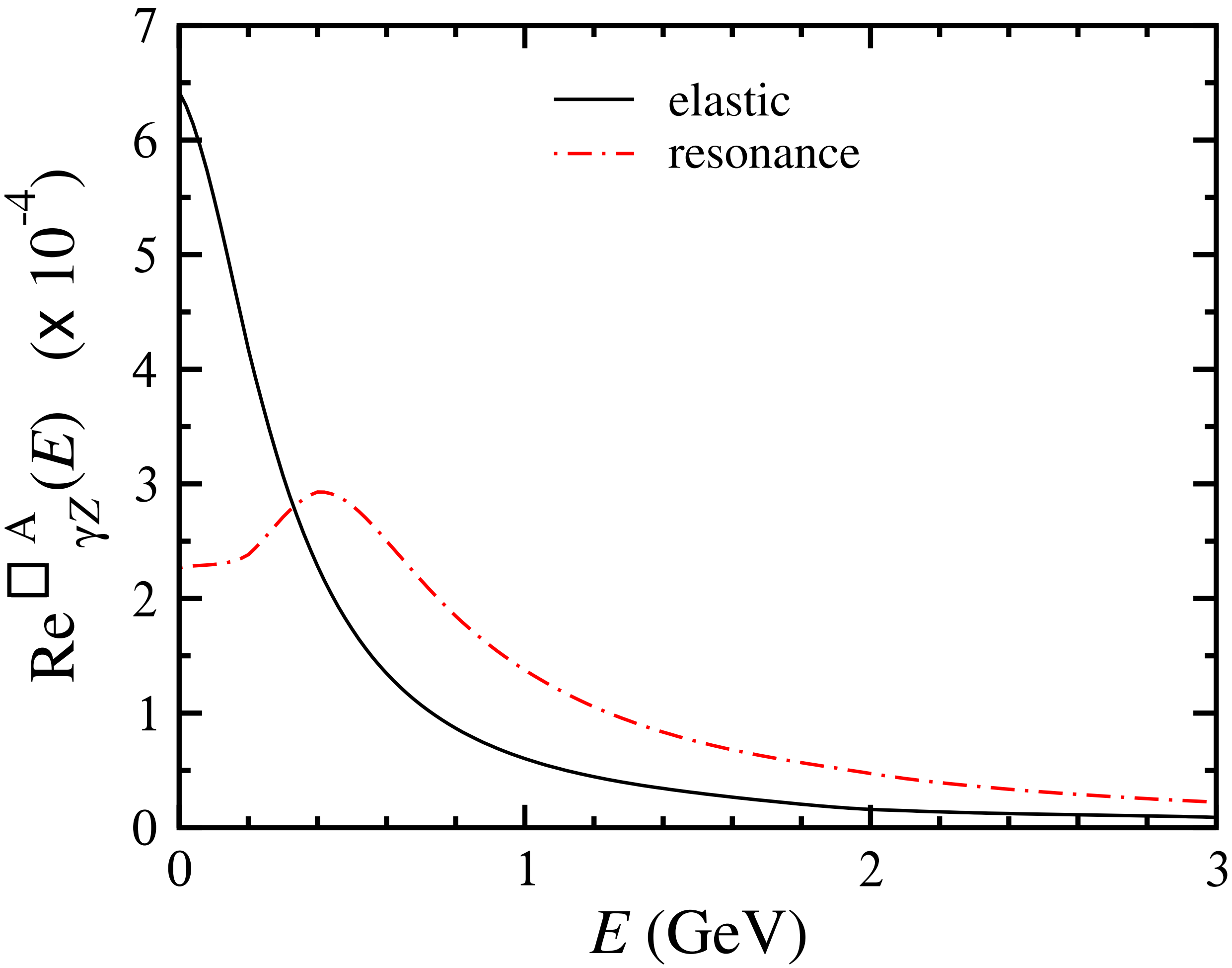
Gorchtein, Horowitz, PRL ***102*** *(2009) 091806*

Parity-violating e scattering

- <u>elastic</u> part $F_3^{\gamma Z(\mathrm{el})} = -Q^2\, G_M^p(Q^2)\, G_A^Z(Q^2)\, \delta(W^2 - M^2)$

- <u>resonance</u> part from parametrization of ν scattering data

Lalakulich, Paschos
*PRD **74**, 014009 (2006)*



Blunden, WM, Thomas
*PRL **107**, 081801 (2011)*

Parity-violating e scattering

★ DIS part dominated by leading twist PDFs

$$F_3^{\gamma Z(\mathrm{DIS})} = \sum_q 2e_q\, g_A^q \left(q(x,Q^2) - \bar{q}(x,Q^2)\right)$$

→ $\Box_{\gamma Z}$ given by moments in $1/Q^2$ expansion

$$\mathcal{R}e\ \Box_{\gamma Z}^{\mathrm{A(DIS)}}(E) = \frac{3}{2\pi}\int_{Q_0^2}^{\infty} dQ^2\, \frac{v_e(Q^2)\,\alpha(Q^2)}{1+Q^2/M_Z^2}$$
$$\times \left[M_3^{\gamma Z(1)} - \frac{2M^2}{9Q^4}(5E^2 - 3Q^2)M_3^{\gamma Z(3)}\right]$$

→ first moment

$$M_3^{\gamma Z(1)}(Q^2) = \frac{5}{3}\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)$$

is γZ analog of Gross-Llewellyn Smith sum rule

Parity-violating e scattering

- "DIS" region at $Q^2 < 1\ \mathrm{GeV}^2$ does not afford PDF description

  $\longrightarrow$ in absence of data, consider models with general constraints

  - $F_3^{\gamma Z}(x_{\max}, Q^2)$ should not diverge in limit $Q^2 \to 0$
  - $F_3^{\gamma Z}(x, Q^2)$ should match PDF description at $Q^2 \sim 1\ \mathrm{GeV}^2$

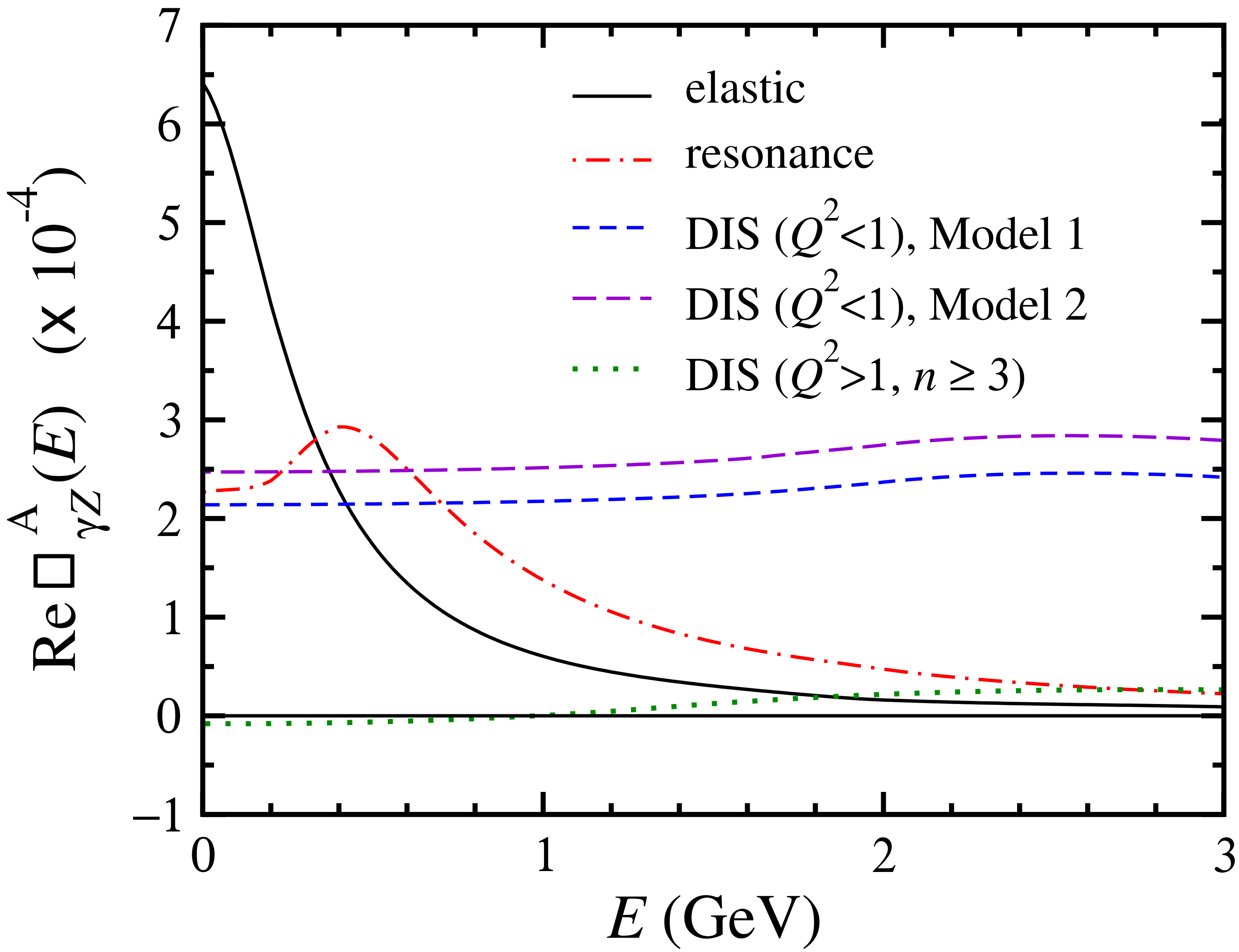
Model 1 $$F_3^{\gamma Z}(x, Q^2) = \left(\frac{1 + \Lambda^2/Q_0^2}{1 + \Lambda^2/Q^2}\right) F_3^{\gamma Z}(x, Q_0^2)$$

$$F_3^{\gamma Z} \sim (Q^2)^{0.3} \text{ as } Q^2 \to 0$$

Model 2 $F_3^{\gamma Z}$ frozen at $Q^2 = 1$ value for all W^2

$$F_3^{\gamma Z} \text{ finite as } Q^2 \to 0$$

Parity-violating e scattering



Blunden, WM, Thomas
PRL ***107****, 081801 (2011)*

→ dominated by $n = 1$ DIS moment: $\underline{32.8 \times 10^{-4}}$
(weak E dependence)

Parity-violating e scattering

- correction at $E = 0$

$$\Re e\,\Box^{A}_{\gamma Z} = 0.00064 + 0.00023 + 0.00350 \to \underline{0.0044(4)}$$

elastic — resonance — DIS

- correction at $E = 1.165$ GeV (Qweak)

$$\Re e\,\Box^{A}_{\gamma Z} = 0.00005 + 0.00011 + 0.00352 = \underline{0.0037(4)}$$

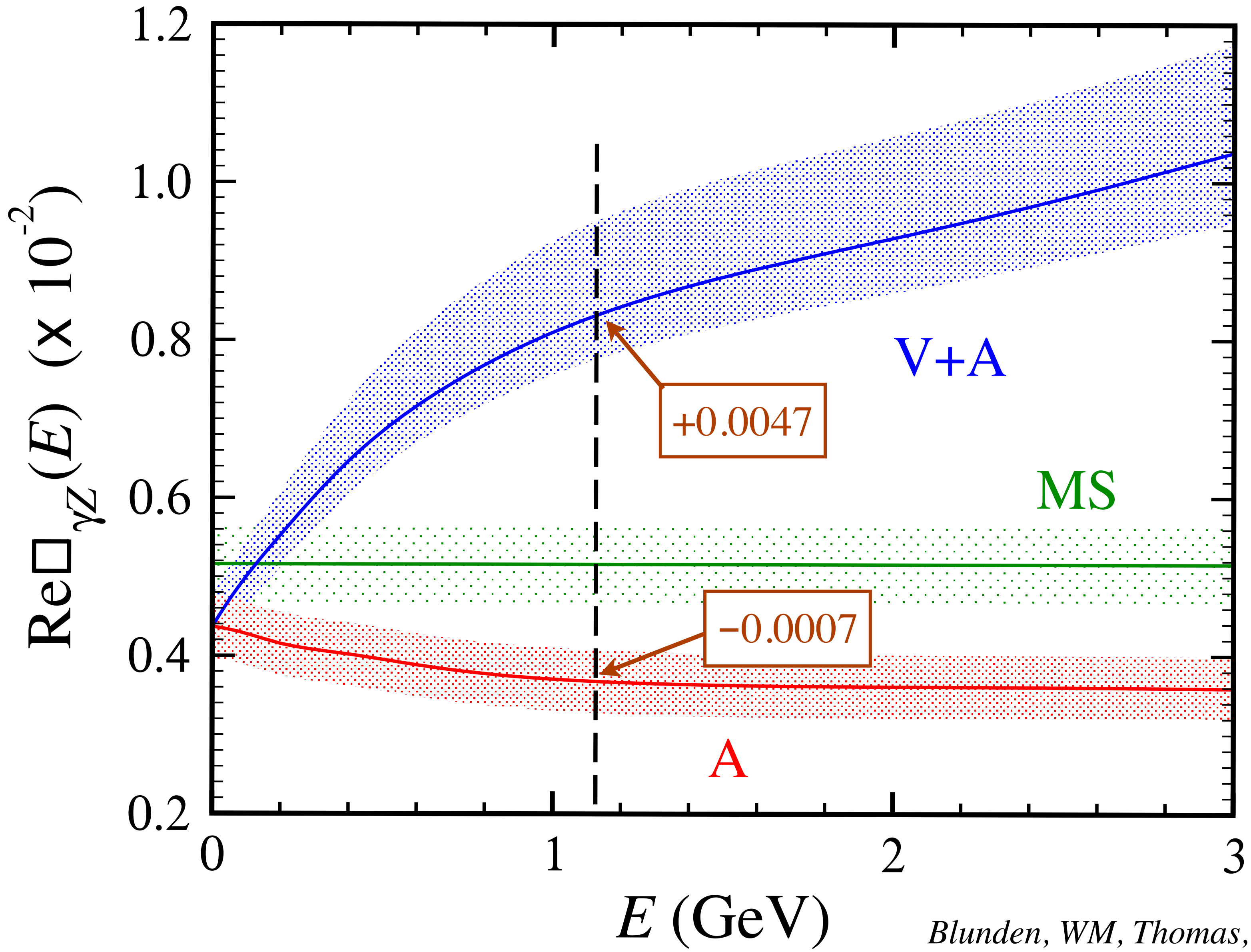
cf. MS* value: 0.0052(5) (~1% shift in Q^p_W)

* *Marciano, Sirlin, PRD* ***29****, 75 (1984)*

- shifts Q^p_W from 0.0713(8) $\longrightarrow$ 0.0705(8)

Combined vector and axial h correction

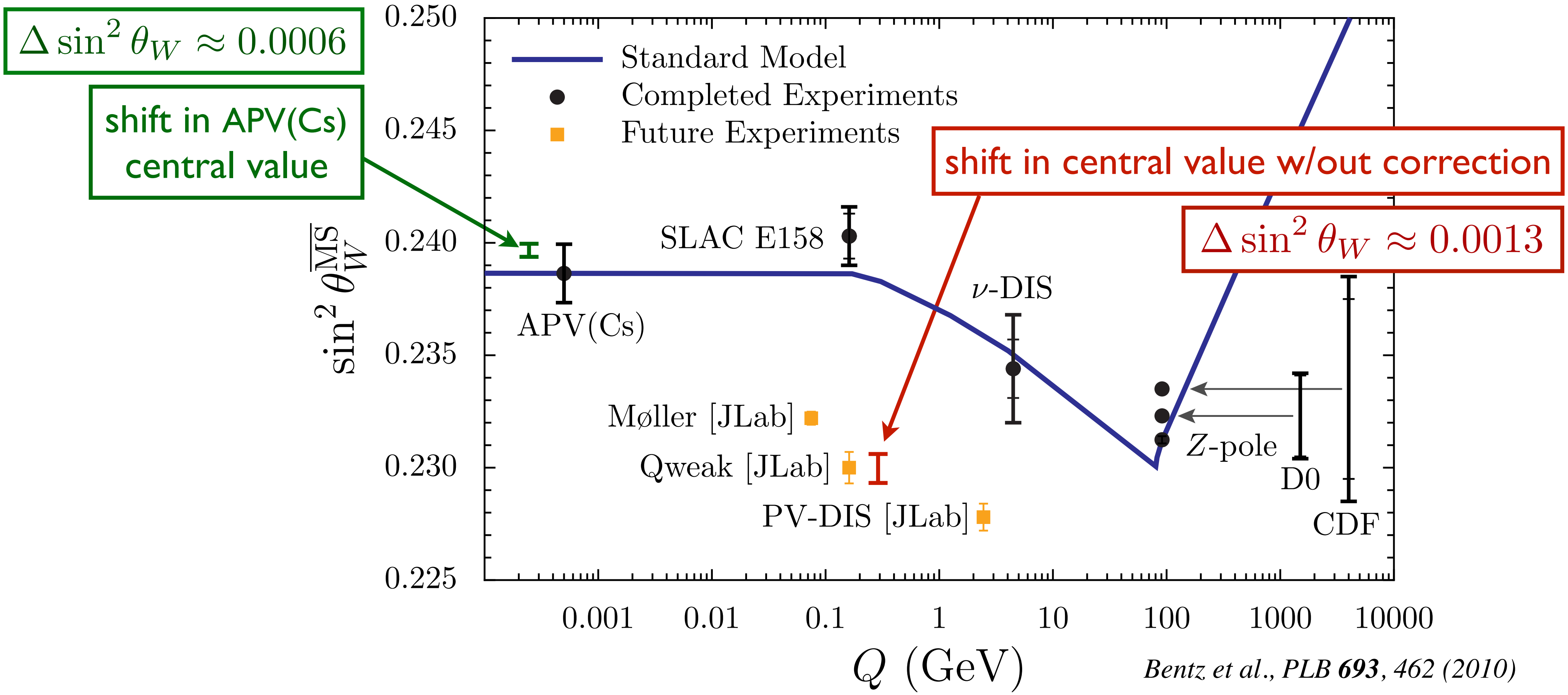
$$Q_W^p = 0.0713 \rightarrow 0.0705$$ (at E=0)



At E=1.165 GeV, E-dependent correction is + 0.0040

*Blunden, WM, Thomas, PRL **107**, 081801 (2011)*

Effect on weak mixing angle



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

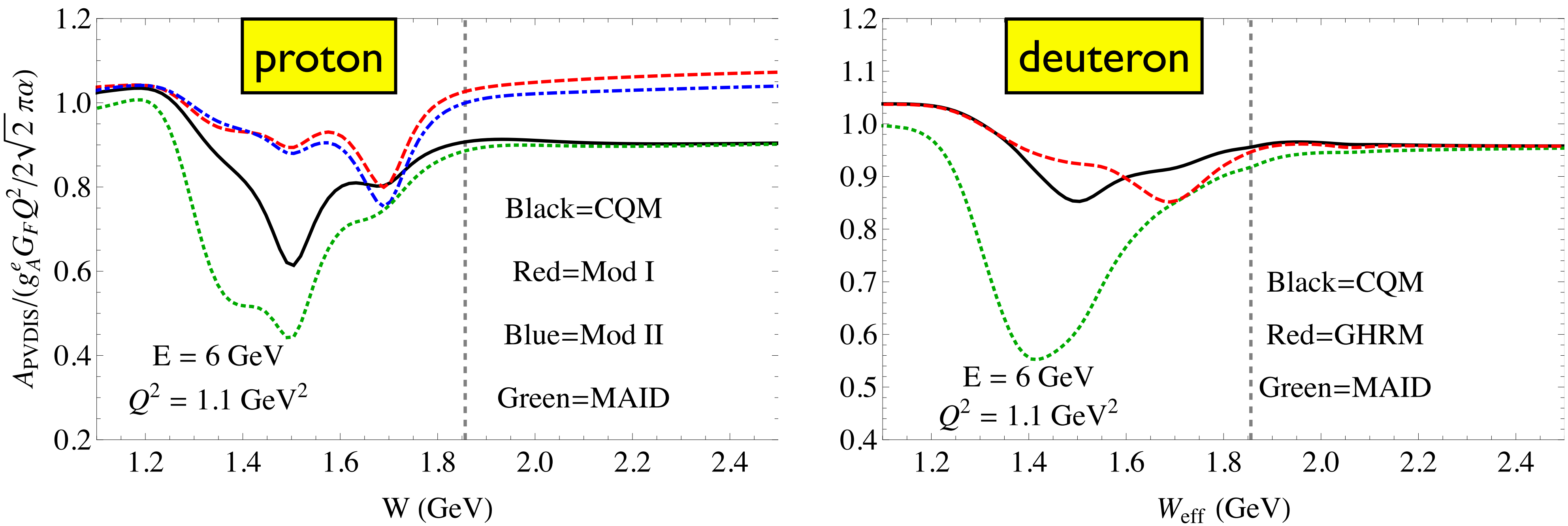
→ Qweak: large shift in central value *cf.* MS

→ APV(Cs): shift in central value *cf.* MS by ~ 1/3 of error bar

Parity-violating DIS

- Constraints from PVDIS asymmetries

$$A_{\rm PV} \;\propto\; \frac{xy^2 F_1^{\gamma Z} + (1-y)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}(y - y^2/2)F_3^{\gamma Z}}{xy^2 F_1^{\gamma\gamma} + (1-y)F_2^{\gamma\gamma}}$$

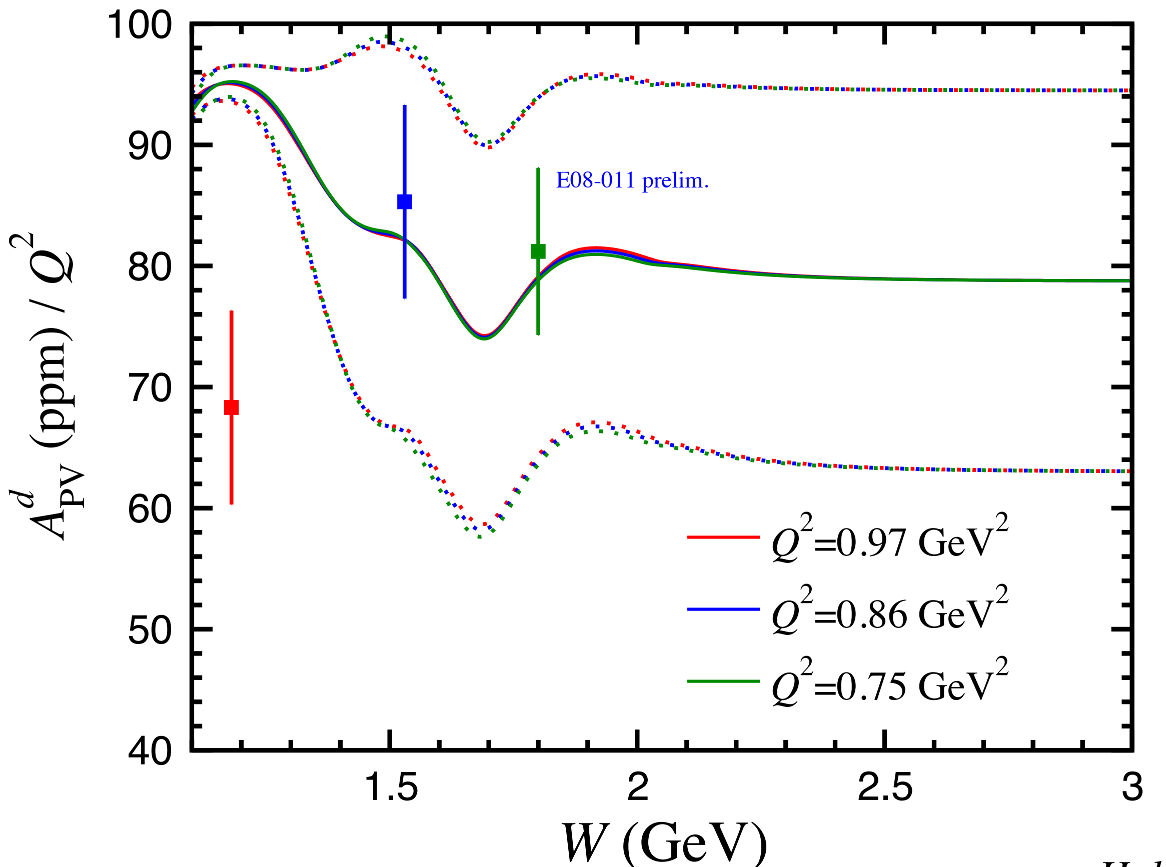


*Carlson, Rislow, PRD **85**, 073002 (2012)*

Parity-violating DIS

- Constraints from PVDIS asymmetries (E08-011 on deuterium)

$$A_{\mathrm{PV}} \;\propto\; \frac{xy^2 F_1^{\gamma Z} + (1-y)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}(y - y^2/2)F_3^{\gamma Z}}{xy^2 F_1^{\gamma\gamma} + (1-y)F_2^{\gamma\gamma}}$$



Hall, Blunden, WM et al. (2012)

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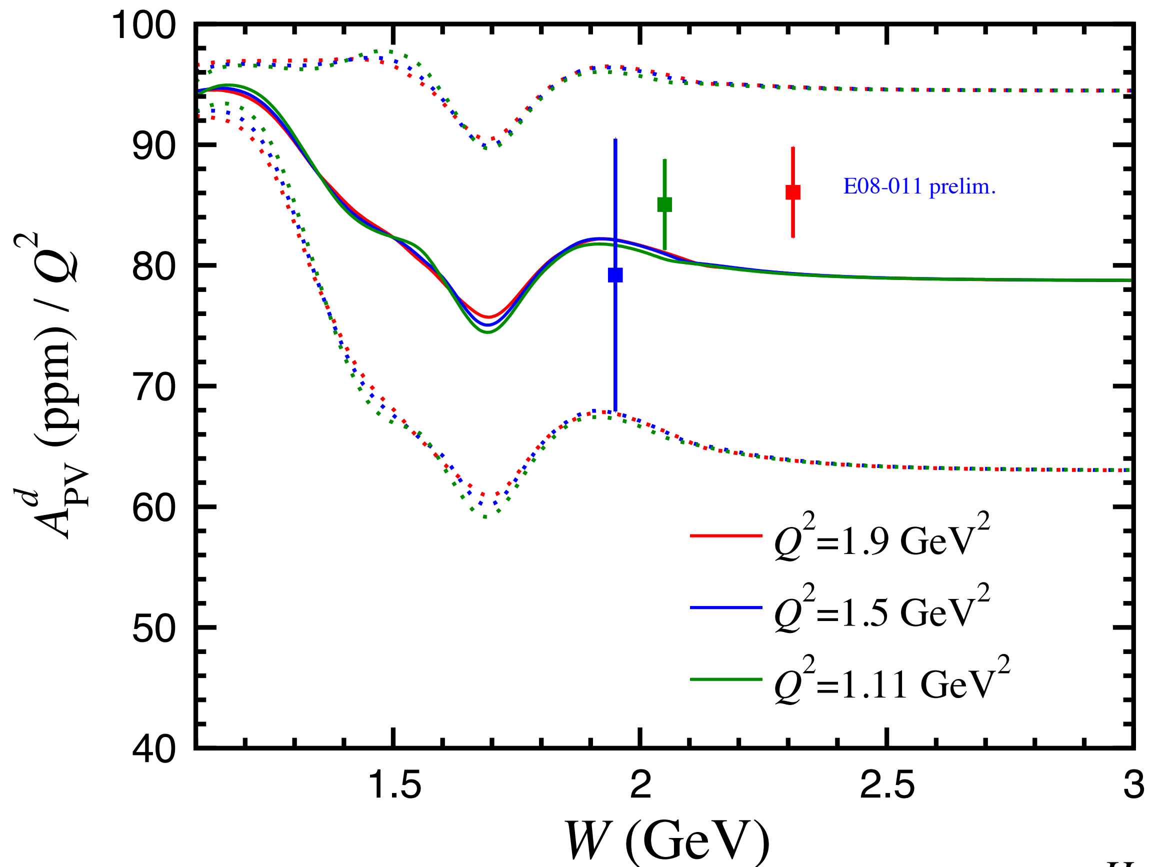
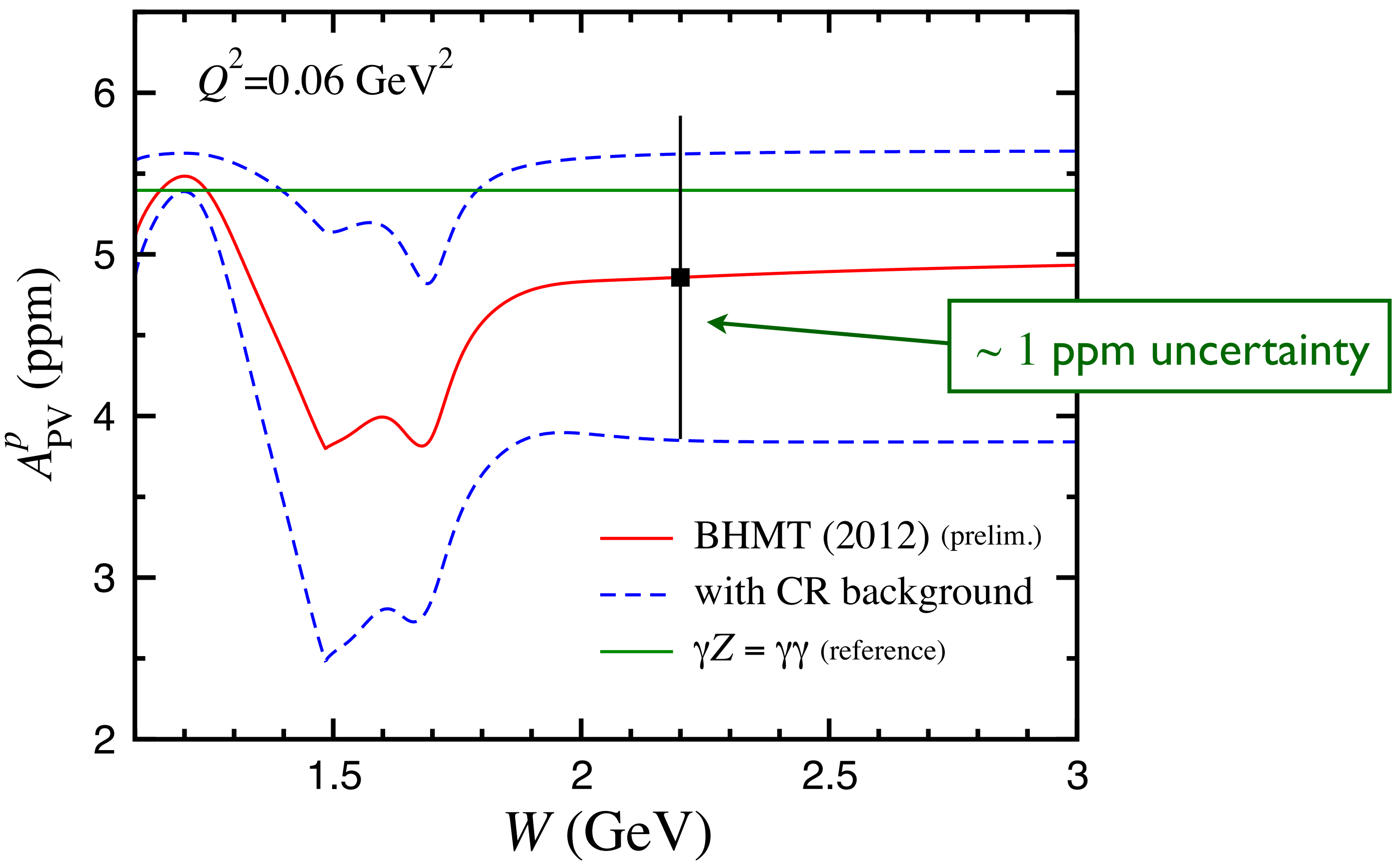


Hall, Blunden, WM et al. (2012)

Parity-violating DIS

- Expected inelastic asymmetry data from Qweak

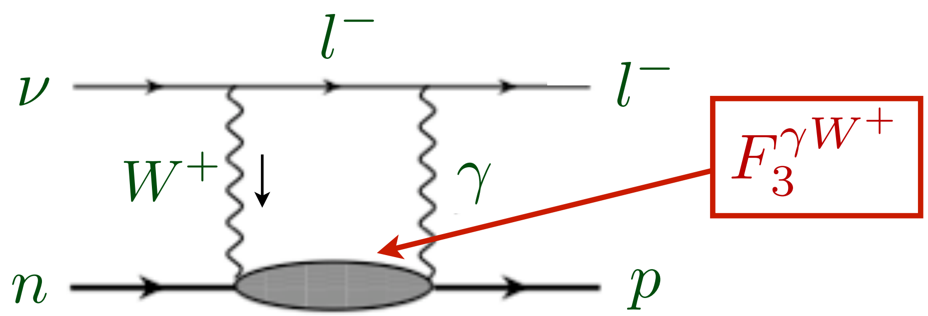


→ constrain input $F_i^{\gamma Z}$ structure functions for $\mathcal{R}e\,\Box_{\gamma Z}$
(updated analysis in progress)

Hall, Blunden, WM et al. (2012)

TBE in neutrino scattering

- May expect similar two-boson exchange (TBE) effects in neutrino scattering (QE, DIS)



- Relevant for n beta decay, extraction of CKM matrix element V_{ud}

$$F(Q^2) \xrightarrow[\text{high } Q^2]{} \frac{1}{Q^2}\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)$$

as in Bjorken & GLS sum rules

$$\xrightarrow[\text{low } Q^2]{} \sum_{V=\rho,A,\rho'} \frac{a_V}{Q^2 + m_V^2}$$

vector meson dominance

Marciano, Sirlin, PRL ***96****, 032002 (2006)*

Structure functions at low Q^2

- Conservation of vector current

  → e.m. structure functions vanish in $Q^2 = 0$ limit

$$F_2^\gamma \sim Q^2\,, \qquad F_L^\gamma \sim Q^4$$

finite photoproduction
cross section

- Axial current not conserved

  → weak structure functions non-zero

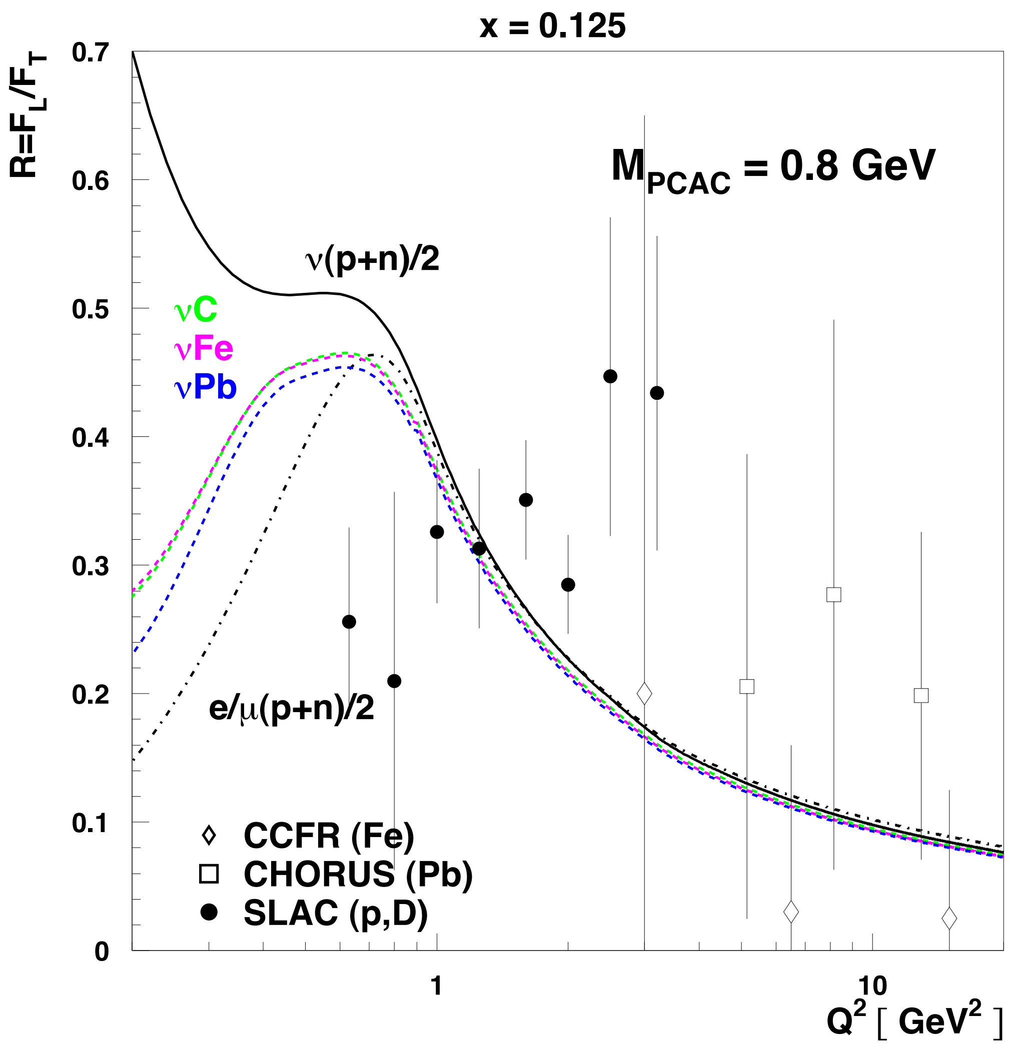
$$F_2^W \sim (V \times V) + (A \times A) \sim 0.2$$ for ν-$^{56}\mathrm{Fe}$

Fleming et al., PRL ***86****, 5430 (2001)*

- Behavior of $V \times A$ interference structure functions $F_3^{W,\,\gamma Z}$ in $Q^2 = 0$ limit not known

  → directly affects TBE correction to $\sin^2\theta_W$ in PVES

Structure functions at low Q^2



Kulagin, Petti
PRD ***76****, 094023 (2007)*

→ dramatically different behavior predicted for electromagnetic and weak $R = \sigma_L/\sigma_T$ ratios

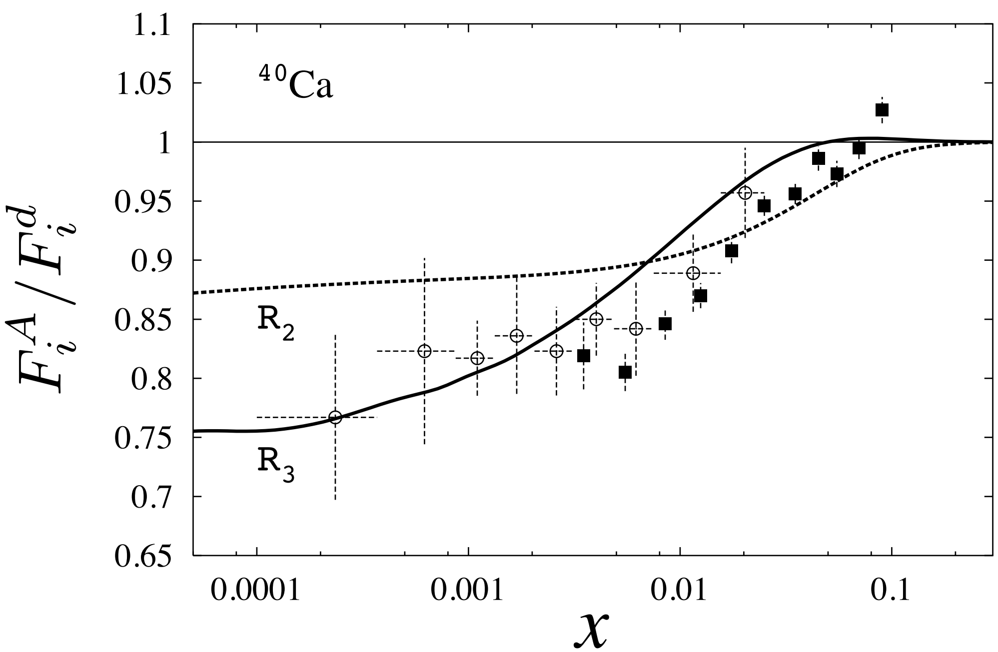
Structure functions at low x

Nuclear shadowing at small x

→ $q, \bar{q} \;\sim\;$ Pomeron ($\mathbf{P}$) + Reggeon ($\mathbf{R}$)

$$F_2 \;\sim\; \mathbf{P} + \mathbf{R}$$

$$xF_3 \;\sim\; \mathbf{P} - \mathbf{R}$$ ← divide by smaller number in EMC ratio



Kulagin, hep-ph/9812532

→ twice as large effect predicted for F_3 than for F_2

Summary

- Many areas of complementarity between physics of e and ν beams

  → cannot have full understanding of nucleon & nuclear structure without input from both

- Need for precision neutrino measurements

  → especially in "nonperturbative" region at low Q^2, W^2

- Nuclear dependence

  → range of nuclei, including deuterium & hydrogen

  (theorists' dream!)

The End