AJM structure functions:

precise inputs for radiative corrections

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Motivation

- Accurate knowledge of electroweak structure functions (at all kinematics) vital for determination of two-boson exchange (TBE) radiative corrections

  → *P. Blunden talk*

- Wealth of data on e.m. F_1, F_2 structure functions over large range of kinematics – with some notable gaps!

  → *A. Accardi, B. Badelek, J. Soffer talks*

- Relatively little known about interference γZ structure functions, especially at low Q and W (outside pQCD region)

  → Adelaide-JLab-Manitoba model aims to fill this gap using various nonperturbative phenomenology

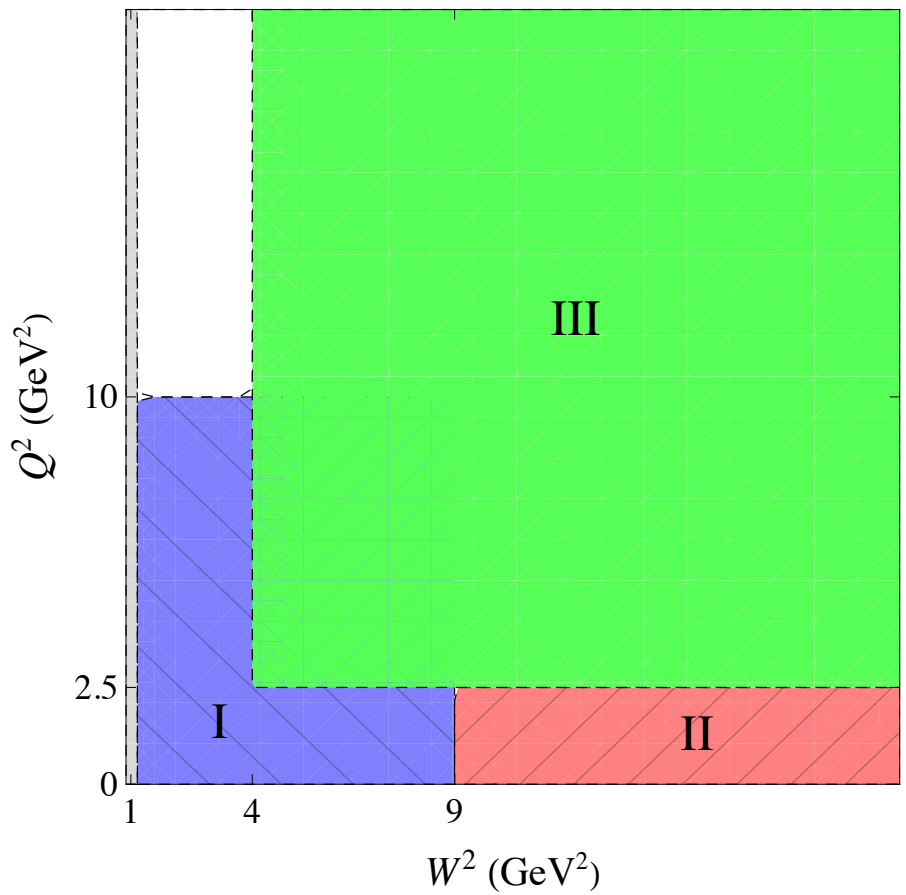
Kinematic landscape

- Convenient to separate (W, Q) space into 3 distinct regions:

  - region I – "resonance"
    low W, low Q^2

  - region II – "Regge"
    high W, low Q^2

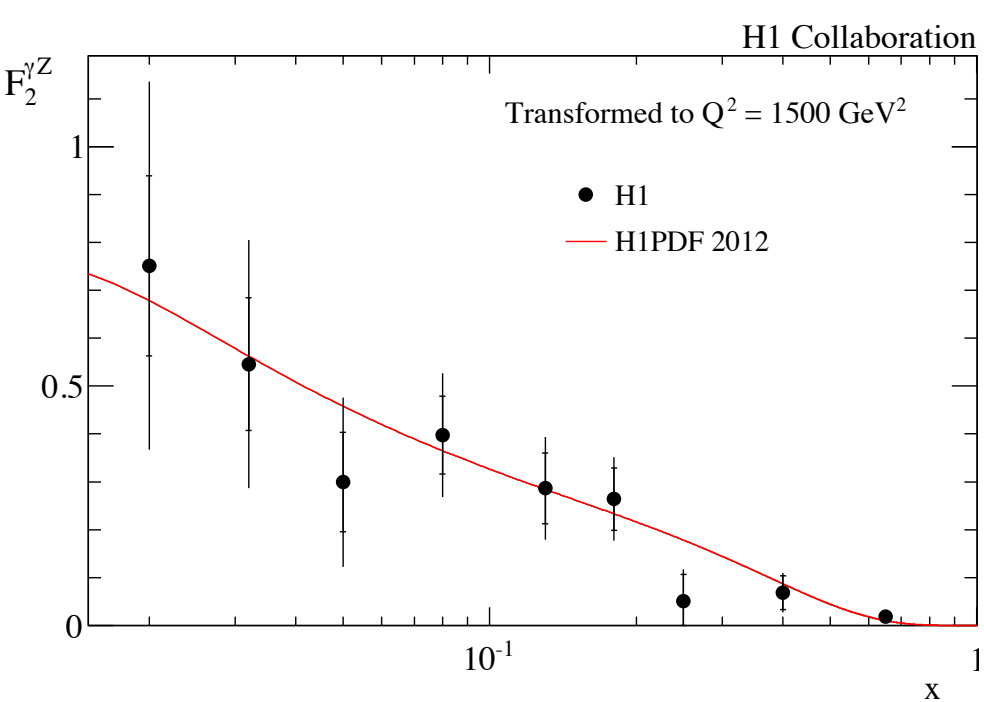
  - region III – "DIS"
    high W, high Q^2

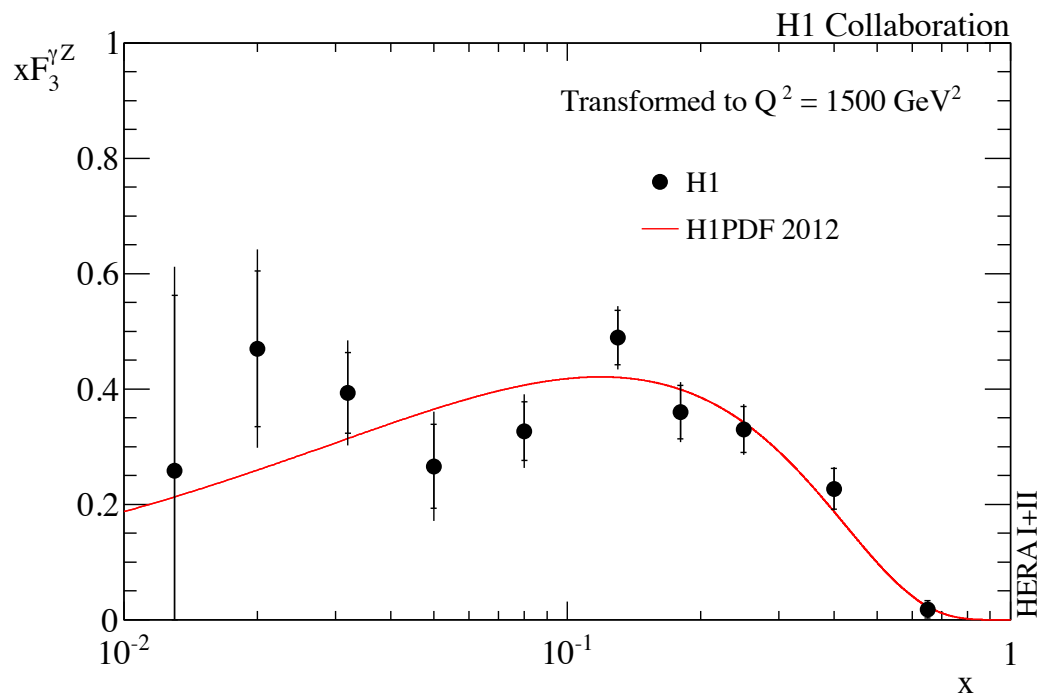


- Need V-V ($F_{1,2}$ or $F_{T,L}$) and V-A (F_3) structure functions

Kinematic landscape

- Currently only measurements of $F_i^{\gamma Z}$ are from HERA at very high Q^2 and W





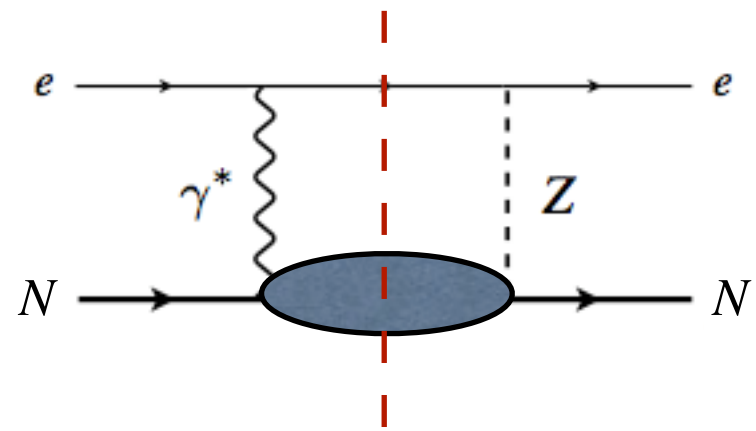
→ essentially no data at lower Q^2 and higher x

AJM γZ model

- General strategy: where data absent, start from appropriate $F_i^{\gamma\gamma}$ structure function, then "rotate" to γZ using available theoretical / phenomenological constraints

  → *e.g.* use isospin symmetry to relate matrix elements of vector currents

$$\langle X|J_Z^\mu|p\rangle = (1 - 4\sin^2\theta_W)\langle X|J_\gamma^\mu|p\rangle - \langle X|J_\gamma^\mu|n\rangle$$



- Isolate resonant vs. nonresonant physics by separating cross sections into "resonance" and "background" contributions

$$\sigma_i = \sigma_i^{(\mathrm{res})} + \sigma_i^{(\mathrm{bgd})}$$

→ *note*: separation <u>*not*</u> unique!

"Resonance" region

- For $\gamma\gamma$ structure functions, use empirical fit by Christy & Bosted (CB), valid for $W_{\rm thr} < W < 3$ GeV and $0 \leq Q^2 \leq 10$ GeV^2

  PRC ***81***, *055213 (2010)*

  → includes 7 most prominent N^* resonances

  $[P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535), S_{15}(1650), F_{15}(1680), F_{37}(1950)]$

  plus smooth function of (W, Q^2) for background

  – generally agrees with data to ~5%

- For each resonance R, define ratio of $\gamma Z/\gamma\gamma$ cross sections

$$\frac{\sigma_R^{\gamma Z}}{\sigma_R^{\gamma\gamma}} = (1 - 4\sin^2\theta_W) - y_R$$

with

$$y_R = \frac{A^p_{R,\frac{1}{2}} A^{n^*}_{R,\frac{1}{2}} + A^p_{R,\frac{3}{2}} A^{n^*}_{R,\frac{3}{2}}}{|A^p_{R,\frac{1}{2}}|^2 + |A^p_{R,\frac{3}{2}}|^2}$$

$A^N_{R,\lambda}$ is $N \to R$ transition amplitude for helicity λ

"Resonance" region

- For transitions to $\underline{I = 3/2}$ states $(e.g.\,\Delta)$, use CVC & isospin symmetry to give $F_i^{\gamma Z} = (1 + Q_W^p) F_i^{\gamma\gamma}$, with $Q_W^p = 1 - 4\sin^2\theta_W$ the proton's weak charge (at tree level)

- For transitions to $\underline{I = 1/2}$ states, $\gamma\gamma \to \gamma Z$ rotations fixed by CVC and p, n helicity amplitudes from latest PDG

TABLE I. Electromagnetic to γZ resonance cross section transformation ratios y_R from Eq. (17) for the proton, neutron and deuteron in the AJM model, compared with the proton ratio in the GHRM model [14]. The AJM model values in parentheses use helicity amplitudes from the earlier 2010 PDG [32], as utilized by GHRM. The errors labeled with the asterisks (*) are values corrected [46] from those in Ref. [14].

	$P_{33}(1232)$	$P_{11}(1440)$	$D_{13}(1520)$	$S_{11}(1535)$	$S_{11}(1665)$	$F_{15}(1680)$	$F_{37}(1950)$
p (AJM)	-1.0 ± 0.1	-0.67 ± 0.17	-0.84 ± 0.17	-0.51 ± 0.35	-0.28 ± 0.41	-0.27 ± 0.08	-1 ± 1
		(-0.62 ± 0.16)	(-0.77 ± 0.08)				
p (GHRM)	-1.0 ± 0.1	$-0.62^{+0.19}_{-0.20}$	$-0.77^{+0.122}_{-0.125}$ (*)	$-0.51^{+0.35}_{-0.71}$	$-0.28^{+0.45}_{-0.69}$ (*)	$-0.27^{+0.10}_{-0.12}$	-1 ± 1
n (AJM)	-1.0 ± 0.1	-1.50 ± 0.39	-0.85 ± 0.15	-1.96 ± 1.32	-3.53 ± 5.06	-2.50 ± 1.01	-1 ± 1
d (AJM)	-1.0 ± 0.1	-0.92 ± 0.27	-0.85 ± 0.14	-0.81 ± 0.64	-0.52 ± 0.78	-0.49 ± 0.14	-1 ± 1

"Resonance" region

- For nonresonant background in low-W region, rotate $\gamma\gamma$ to γZ using vector meson dominance (VMD) model and weak isospin

$\longrightarrow$ for given vector meson V, cross sections related by

$$\sigma_V^{\gamma Z} = \kappa_V \, \sigma_V^{\gamma\gamma}$$

where

$$\kappa_\rho = 2 - 4\sin^2\theta_W \qquad \text{"isovector"}$$

$$\kappa_\omega = -4\sin^2\theta_W \qquad \text{"isoscalar"}$$

$$\kappa_\phi = 3 - 4\sin^2\theta_W \qquad \text{"strange"}$$

"Resonance" region

- Generalizing to include high-virtuality "continuum" component,

$$\frac{\sigma^{\gamma Z}_{\rm bgd}}{\sigma^{\gamma\gamma}_{\rm bgd}} = \frac{\kappa_\rho + \kappa_\omega\, R_\omega(Q^2) + \kappa_\phi\, R_\phi(Q^2) + \kappa_C\, R_C(Q^2)}{1 + R_\omega(Q^2) + R_\phi(Q^2) + R_C(Q^2)}$$

where ratio of production cross sections for vector meson V to ρ meson is

$$R_V = \frac{\sigma^{\gamma^* p \to V p}}{\sigma^{\gamma^* p \to \rho p}} = \frac{f_\rho^2}{f_V^2}\left(\frac{1 + Q^2/m_\rho^2}{1 + Q^2/m_V^2}\right)^2$$

- Corresponding ratio of continuum C to ρ contributions is

$$R_C = \frac{r_C}{r_\rho}\left(\frac{1 + Q^2/m_\rho^2}{1 + Q^2/m_0^2}\right)^2$$

where $r_C = 1 - \sum_V r_V$ and $r_{\rho,\omega,\phi} = \{67\%,\ 6.2\%,\ 5.9\%\}$

"Resonance" region

- Continuum parameter κ_C not constrained in VMD, represents largest source of uncertainty in determination of γZ background

  → GHRM* model assumes $\kappa_C = 1$ with 100% uncertainty

  → in AJM model κ_C fitted by matching structure functions at boundaries between different regions

*Gorchtein, Horowitz, Ramsey-Musolf
PRC **84**, 015502 (2011)

"Regge" region

- At higher W (> 3 GeV), but not too high Q^2, cross section can be parametrized within Regge theory in terms of Pomeron & Reggeon exchanges

→ *e.g.* electromagnetic VMD cross sections

$$\sigma_T^{\rm VMD} = \sigma_{\gamma N}\left[\sum_V r_V \frac{1}{(1+Q^2/m_V^2)^2} \;+\; r_C\,\frac{1}{1+Q^2/m_0^2}\right]$$

$$\sigma_L^{\rm VMD} = \sigma_{\gamma N}\left[\sum_V r_V\,\xi_V\,\frac{Q^2/m_V^2}{(1+Q^2/m_V^2)^2} + r_C\,\xi_C\left(\frac{m_0^2}{Q^2}\ln\left(1+\frac{Q^2}{m_0^2}\right) - \frac{m_0^2}{m_0+Q^2}\right)\right]$$

Alwall, Ingelman, PLB ***596****, 77 (2004)*

where high-energy photoproduction cross section given by

$$\sigma_{\gamma N} = A_\gamma\, s_\gamma^{\epsilon} + B_\gamma\, s_\gamma^{-\eta} \qquad (s_\gamma = W^2)$$

Donnachie, Landshoff, PLB ***296****, 227 (1992)*

"Regge" region

- At higher W (> 3 GeV), but not too high Q^2, cross section can be parametrized within Regge theory in terms of Pomeron & Reggeon exchanges

→ $e.g.$ electromagnetic VMD cross sections

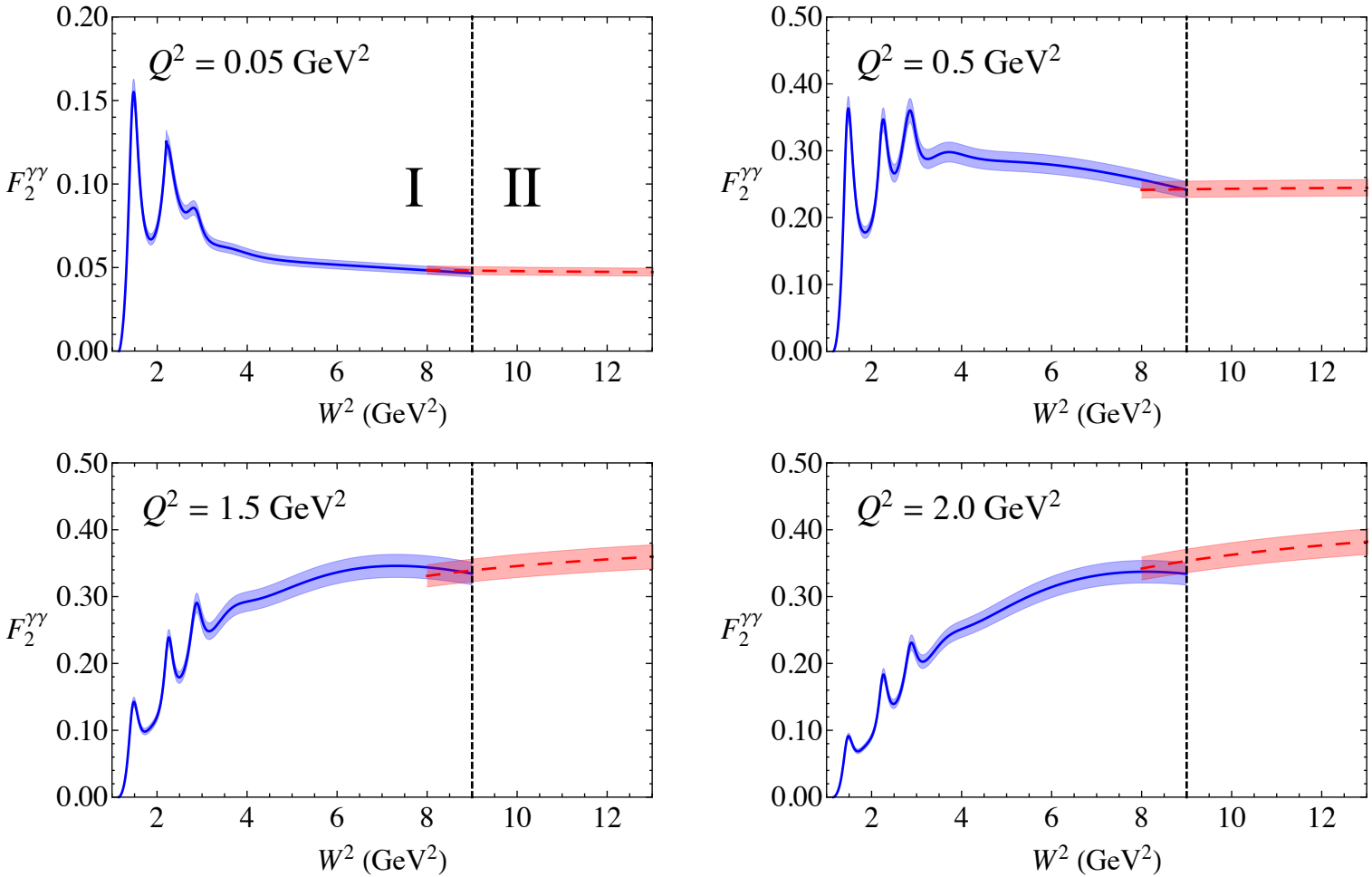
$$\sigma_T^{\rm VMD} = \sigma_{\gamma N} \left[\sum_V r_V \frac{1}{(1+Q^2/m_V^2)^2} \; + \; r_C \, \frac{1}{1+Q^2/m_0^2} \right]$$

$$\sigma_L^{\rm VMD} = \sigma_{\gamma N} \left[\sum_V r_V \, \xi_V \, \frac{Q^2/m_V^2}{(1+Q^2/m_V^2)^2} + r_C \, \xi_C \left(\frac{m_0^2}{Q^2} \ln\left(1+\frac{Q^2}{m_0^2}\right) - \frac{m_0^2}{m_0+Q^2} \right) \right]$$

→ for γZ, transform Regge cross sections according to background ratio (with parameter κ_C)

$$\sigma^{\gamma Z} = \left(\frac{\sigma_{\rm bgd}^{\gamma Z}}{\sigma_{\rm bgd}^{\gamma\gamma}} \right) \sigma^{\gamma\gamma}$$

$\gamma\gamma$ structure function matching



Hall et al., PRD ***88****, 013011 (2013)*

→ matching of the CB ("low-W") and Regge ("high-W") regions at fixed Q^2 values

"DIS" region

- At high W and high Q^2, structure functions are parametrized in terms of PDFs from global QCD analyses of high-energy data (including leading- and higher-twist contributions)

  → at leading order in strong coupling,

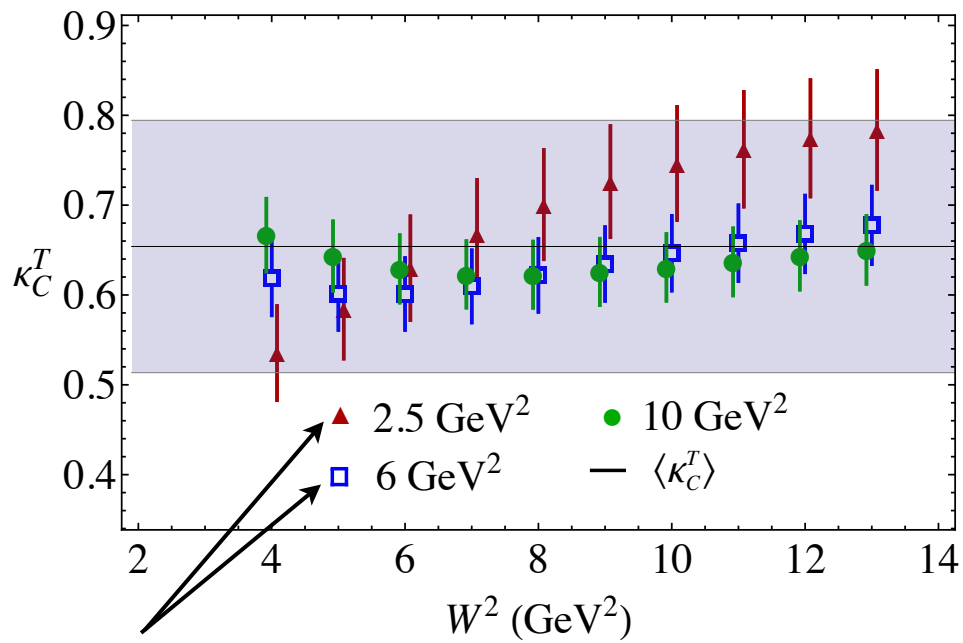
$$F_1^{\gamma Z} = \sum_q e_q \, g_V^q \, (q + \bar{q})$$

$$F_2^{\gamma Z} = 2x \, F_1^{\gamma Z}$$

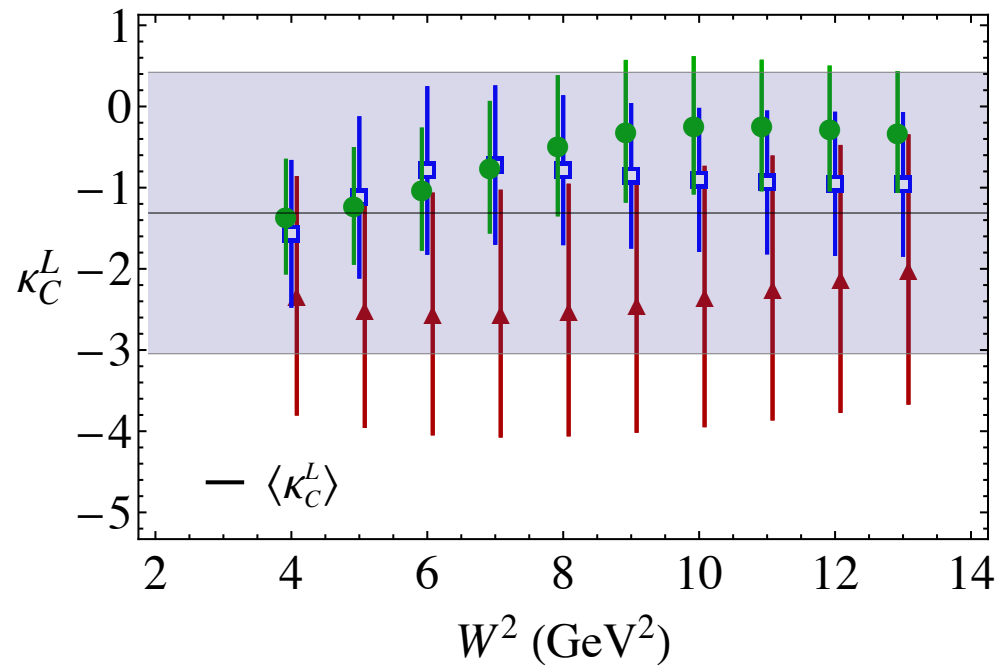
- Parameter κ_C fitted by matching to DIS structure function ratios

$$\frac{\sigma_{T,L}^{\gamma Z}}{\sigma_{T,L}^{\gamma\gamma}} = \left. \frac{F_{1,L}^{\gamma Z}}{F_{1,L}^{\gamma\gamma}} \right|_{\mathrm{DIS}}$$

γZ structure function matching



matching at different Q^2

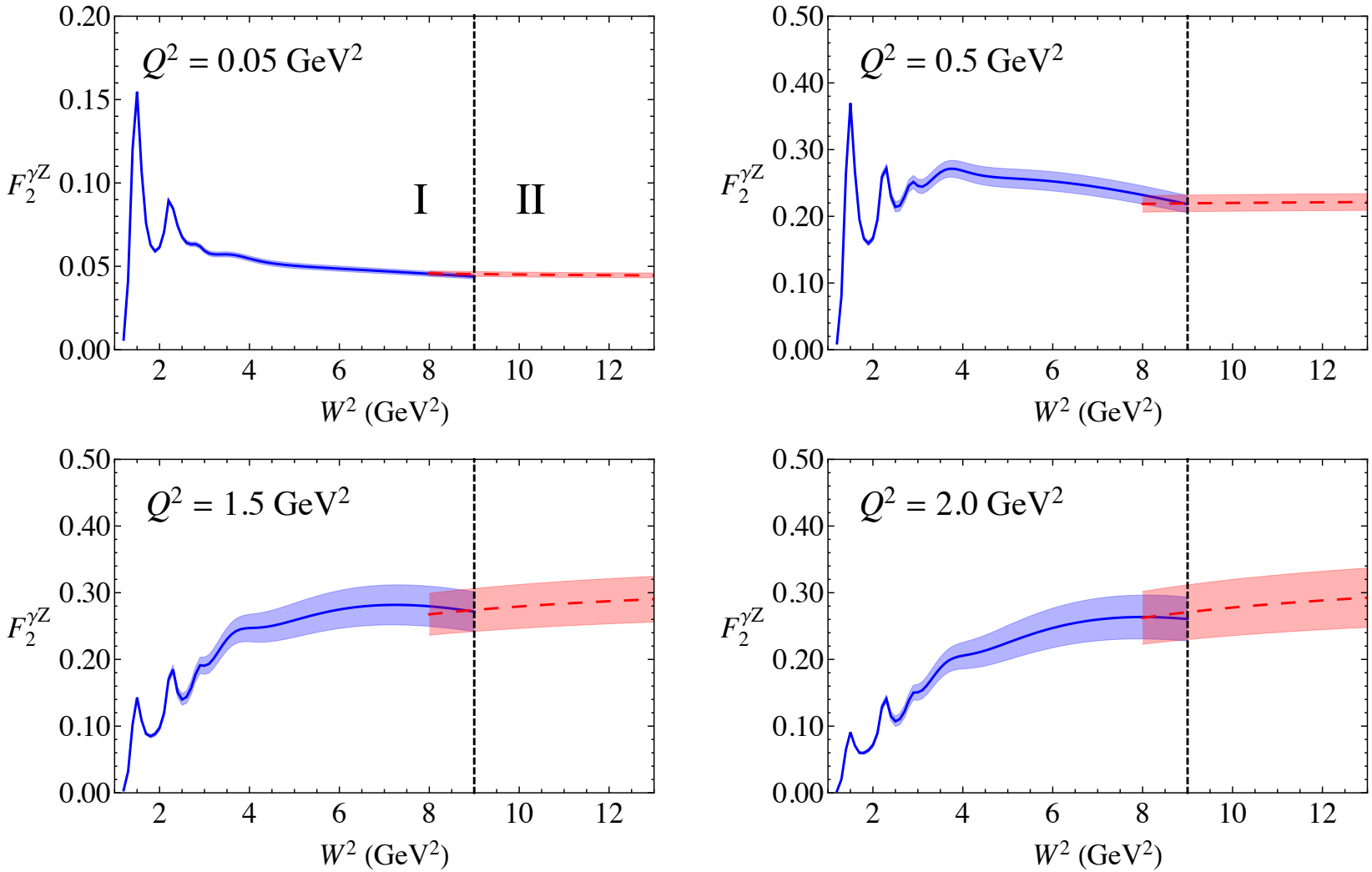


→ averaging over several Q^2 values gives best fit parameters

$$\kappa_C^T = 0.65 \pm 0.14$$

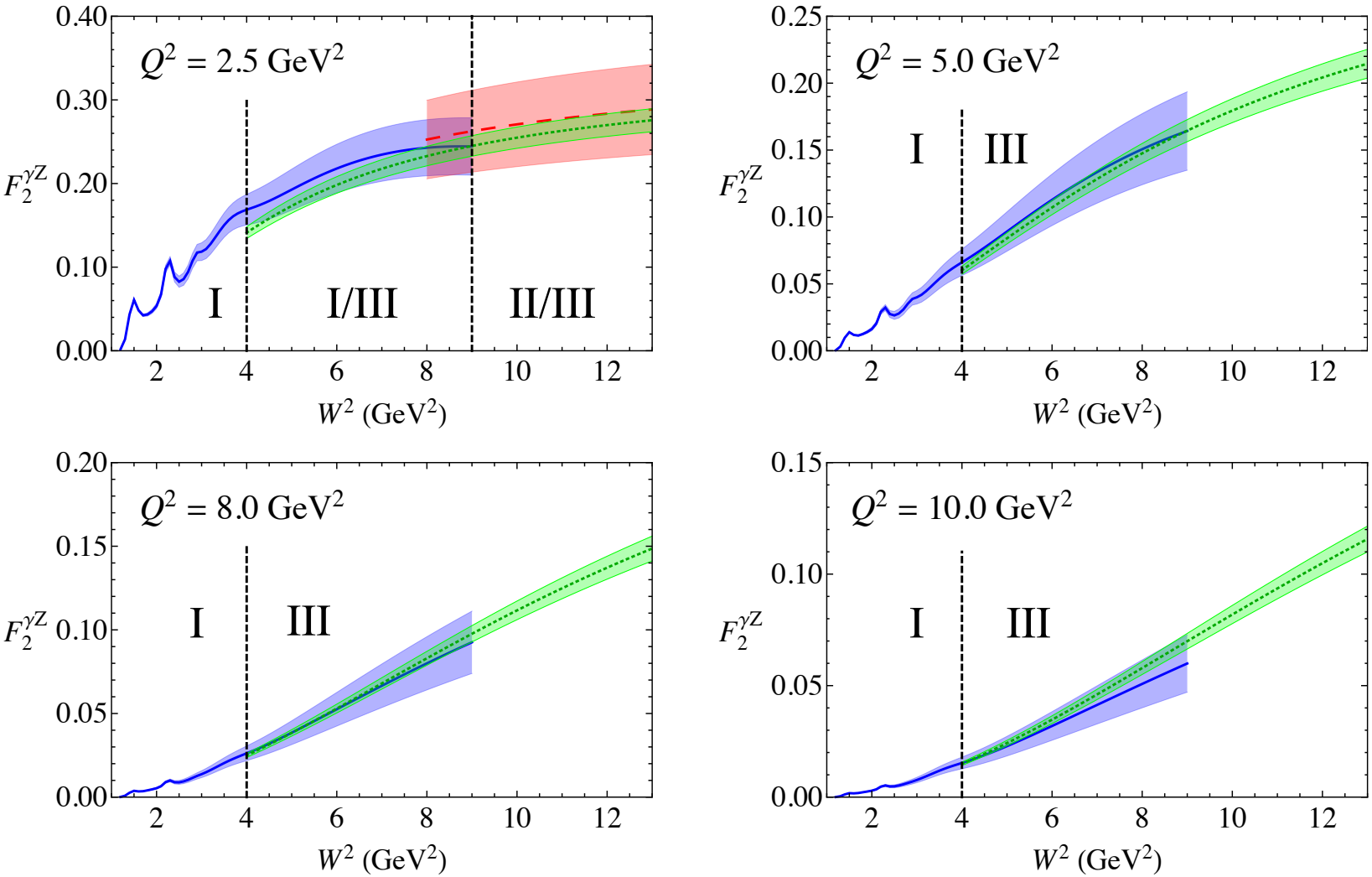
$$\kappa_C^L = -1.3 \pm 1.7$$

γZ structure function matching



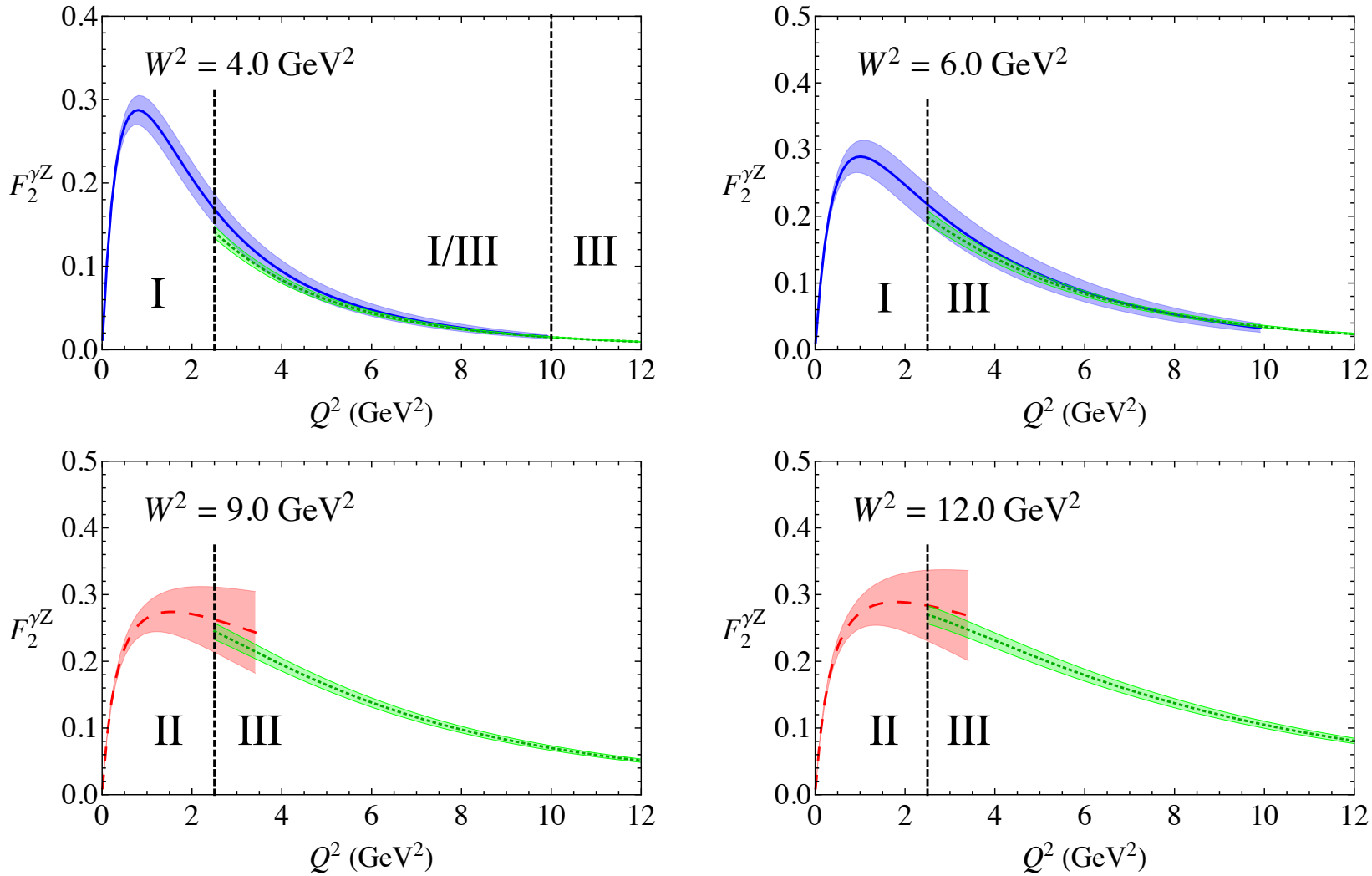
→ structure functions well matched at boundary of regions I and II, within larger errors *cf.* $\gamma\gamma$ functions

γZ structure function matching



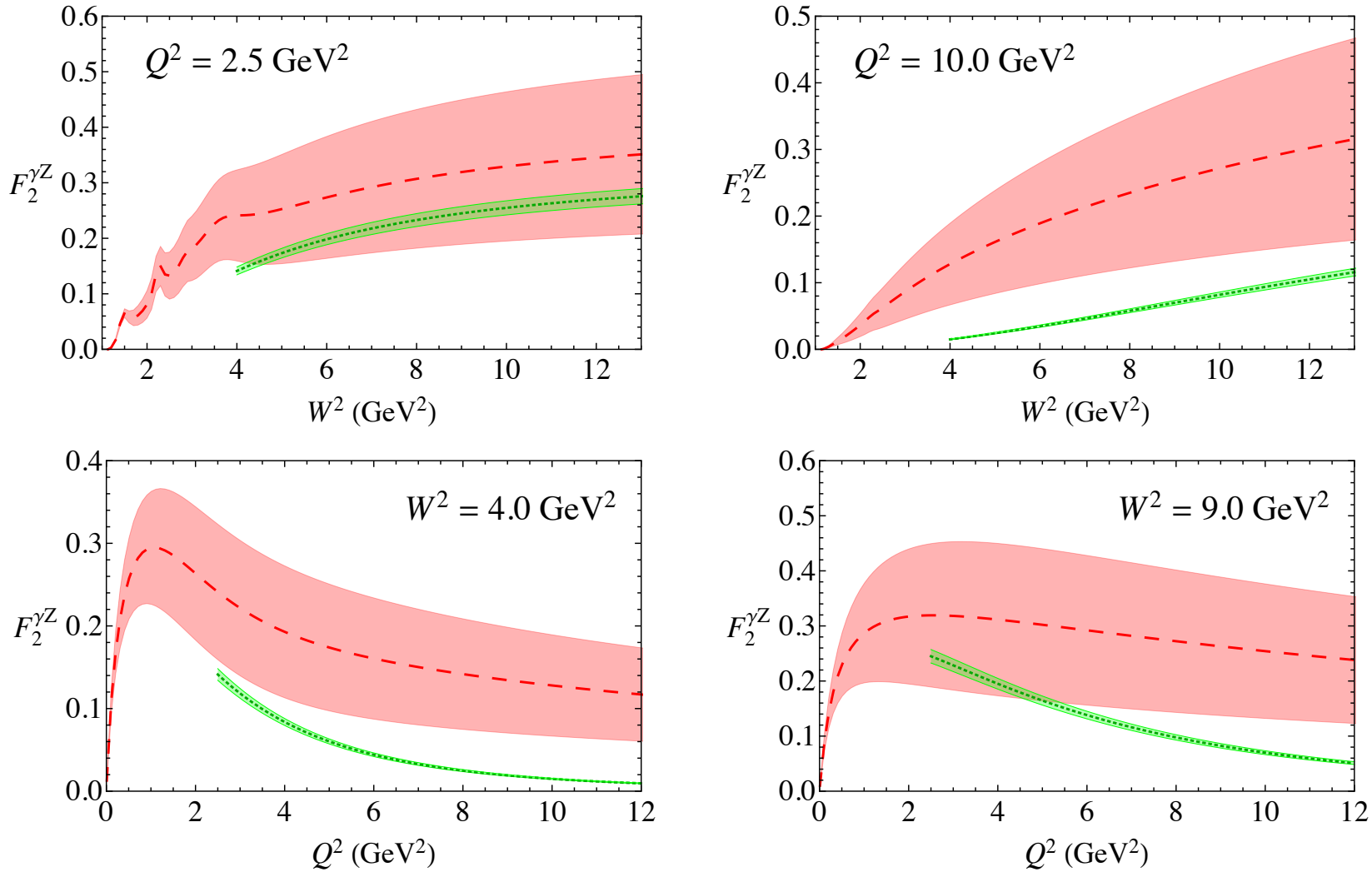
→ structure functions well matched at boundaries of regions I, II and III

γZ structure function matching



→ structure functions well matched at boundaries of regions I, II and III

γZ structure function matching



→ if do *not* impose any constraint on κ_C (*e.g.* GHRM model), have far greater mismatch between Regge and DIS regions

Applications of γZ structure functions

- Vector part of box correction $\Box^V_{\gamma Z}$ from dispersion relations

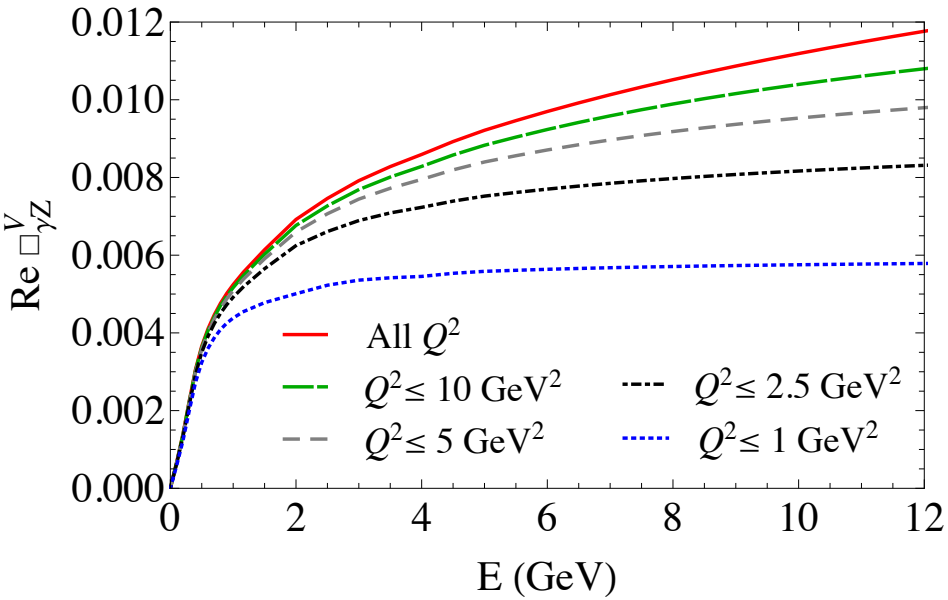
$$\Re e\, \Box^V_{\gamma Z}(E) = \frac{2E}{\pi} \int_0^\infty dE' \frac{1}{E'^2 - E^2}\, \Im m\, \Box^V_{\gamma Z}(E')$$

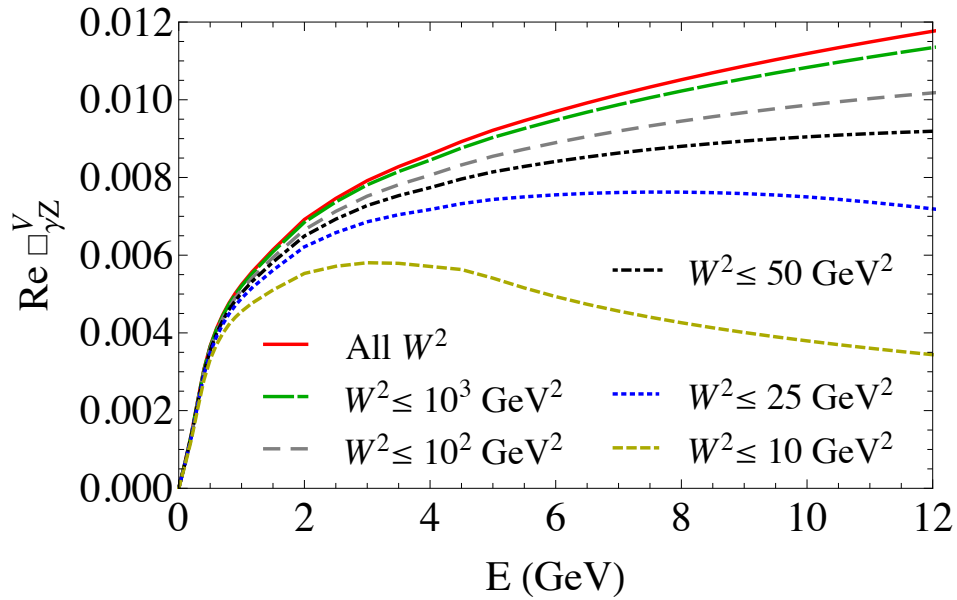
where imaginary part given in terms of $F^{\gamma Z}_{1,2}$

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

Applications of γZ structure functions

- Integral emphasizes low-W, low-Q^2 part of spectrum

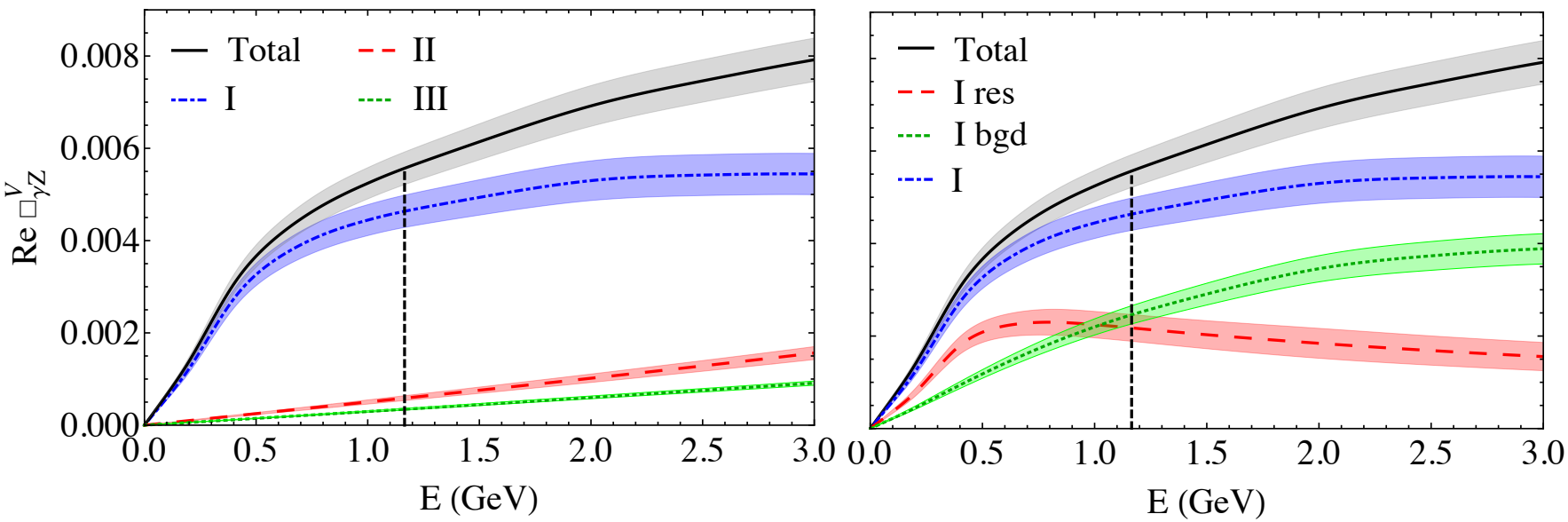




→ at $E \sim 1$ GeV, integral dominated by $Q^2 \lesssim 1\ \mathrm{GeV}^2,\ \ W \lesssim 3\ \mathrm{GeV}$ region

Applications of γZ structure functions

- Integral emphasizes low-W, low-Q^2 part of spectrum



→ region I dominates correction & its uncertainty

→ resonance & background similar at $E \sim 1$ GeV

Axial γZ structure function

- Axial part of box correction $\Box^A_{\gamma Z}$ important for atomic parity violation at very low energy

→ dispersion relation

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

with imaginary part given in terms of $F_3^{\gamma Z}$

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

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

→ integral emphasizes different kinematical regions

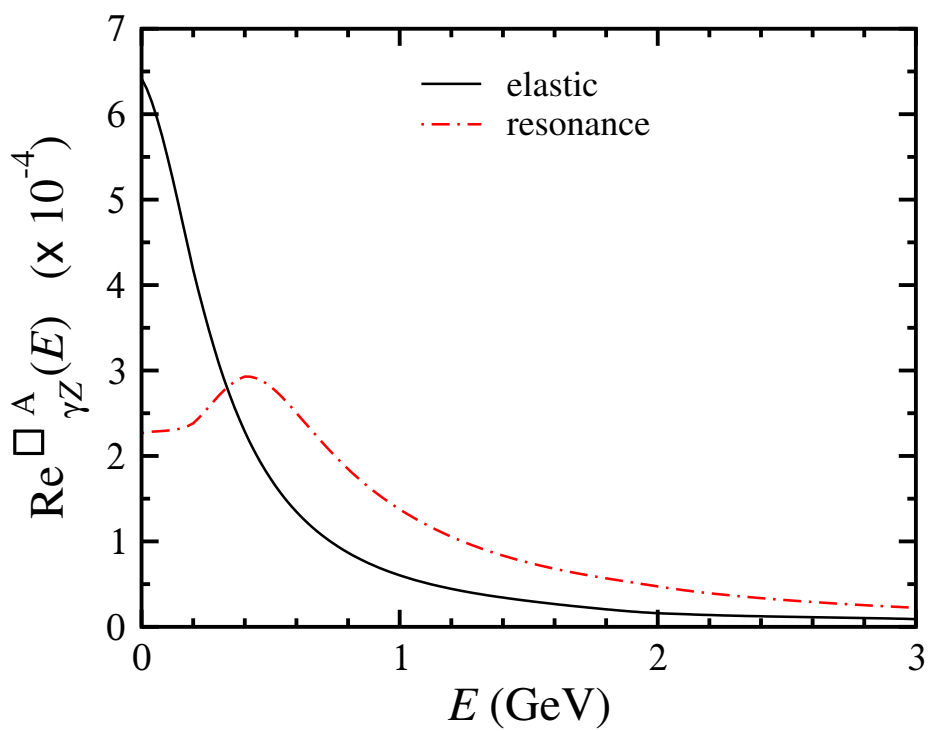
Axial γZ structure function

- $F_3^{\gamma Z}$ structure function has no e.m. analog

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

  → resonance part from parametrization of ν scattering data $e.g.$ model of Lalakulich & Paschos, with 4 lowest-mass resonances $[P_{33}(1232), P_{11}(1440), D_{13}(1520), S_{11}(1535)]$

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



Axial γZ structure function

- $F_3^{\gamma Z}$ structure function has no e.m. analog

→ DIS part dominated by PDFs at high W (small x)

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

→ Low-Q^2, high-W region from 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 $Q^2 = 1\,\mathrm{GeV}^2$

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

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

Axial γZ structure function

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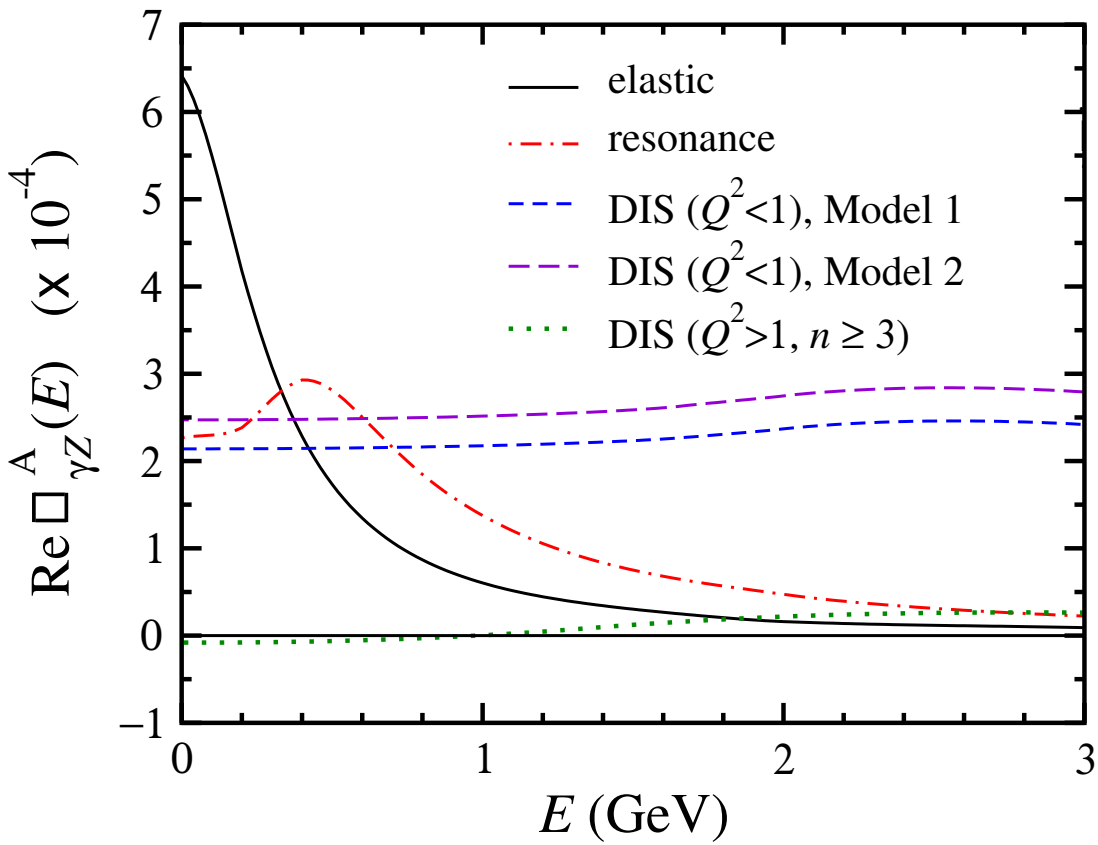
- ★ $F_3^{\gamma Z}(x_{\max}, Q^2)$ should not diverge in limit $Q^2 \to 0$
- ★ $F_3^{\gamma Z}(x, Q^2)$ should match PDF description at $Q^2 = 1\,\mathrm{GeV}^2$

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

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

Axial γZ box correction



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

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

Axial γZ box correction

- Note that in DIS region, can expand integrand in dispersion relation in $1/Q^2$

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

where moments $M_3^{\gamma Z(n)}(Q^2) = \int_0^1 dx\,x^{n-1}F_3^{\gamma Z}(x,Q^2)$

- Structure function lowest moments

<u>$n = 1$</u> $\quad M_3^{\gamma Z(1)}(Q^2) = \frac{5}{3}\left(1-\frac{\alpha_s(Q^2)}{\pi}\right)$

$\longrightarrow$ γZ analog of Gross-Llewellyn Smith sum rule

<u>$n = 3$</u> $\quad M_3^{\gamma Z(3)}(Q^2) = \frac{1}{3}\left(2\langle x^2\rangle_u + \langle x^2\rangle_d\right)\left(1+\frac{5\alpha_s(Q^2)}{12\pi}\right)$

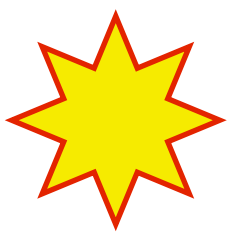
Axial γZ box correction

- Note that in DIS region, can expand integrand in dispersion relation in $1/Q^2$

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

where moments $M_3^{\gamma Z(n)}(Q^2) = \int_0^1 dx\,x^{n-1}F_3^{\gamma Z}(x,Q^2)$

$$\mathcal{R}e\,\Box_{\gamma Z}^{A(\mathrm{DIS})} \approx (1-4\hat{s}^2)\frac{5\alpha}{2\pi}\int_{Q_0^2}^{\infty}\frac{dQ^2}{Q^2(1+Q^2/M_Z^2)}\left(1-\frac{\alpha_s(Q^2)}{\pi}\right)$$



→ precisely result from Marciano & Sirlin!

(result depends on lowest moment of *valence* PDF, with <u>model-independent normalization</u>!)

Axial γZ box correction

- correction at $E = 0$

$$\Re e\,\Box^A_{\gamma Z} = \underset{\text{elastic}}{0.00064} + \underset{\text{resonance}}{0.00023} + \underset{\text{DIS}}{0.00350} \rightarrow \underline{0.0044(4)}$$

- 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: $\underline{0.0052(5)}$ (~1% shift in Q^p_W)

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

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

APV in ^{133}Cs

- Parity violating dipole transition $6\,\mathrm{S}_{1/2} - 7\,\mathrm{S}_{1/2}$ sensitive to weak mixing angle $(E \sim 0)$

  → weak charge of Cs

$$Q_W(\mathrm{Cs}) \;=\; 55\,\widetilde{Q}_W^p \;+\; 78\,\widetilde{Q}_W^n$$

weak charge of *bound* p in Cs nucleus

- Nuclear effect on elastic N contribution – Pauli blocking

  → intermediate state N (in target rest frame) must have momentum above Fermi level

$$|\mathbf{q}| > p_F \approx 260\,\mathrm{MeV}$$

$$\Rightarrow \quad Q^2 > Q^2_{\mathrm{min}} = 2M^2\left(\sqrt{1 + p_F^2/M^2} - 1\right) \approx p_F^2$$

APV in ^{133}Cs

- Significantly reduced elastic contribution

$$\Box_{\gamma Z}^{p\,(\mathrm{el})} \;:\; 0.00064 \;\rightarrow\; 0.00029, \qquad \Box_{\gamma Z}^{n\,(\mathrm{el})} \;:\; 0.00044 \;\rightarrow\; 0.00020$$

- Total γZ corrections dominated by DIS contributions

	p	n
total	0.0040(4)	0.0032(4)
MS	0.0052(5)	0.0040(4)
$\Delta\widetilde{Q}_W^N$	−0.0012	−0.0008
$\Delta Q_W(\mathrm{Cs})$	−0.065	−0.060

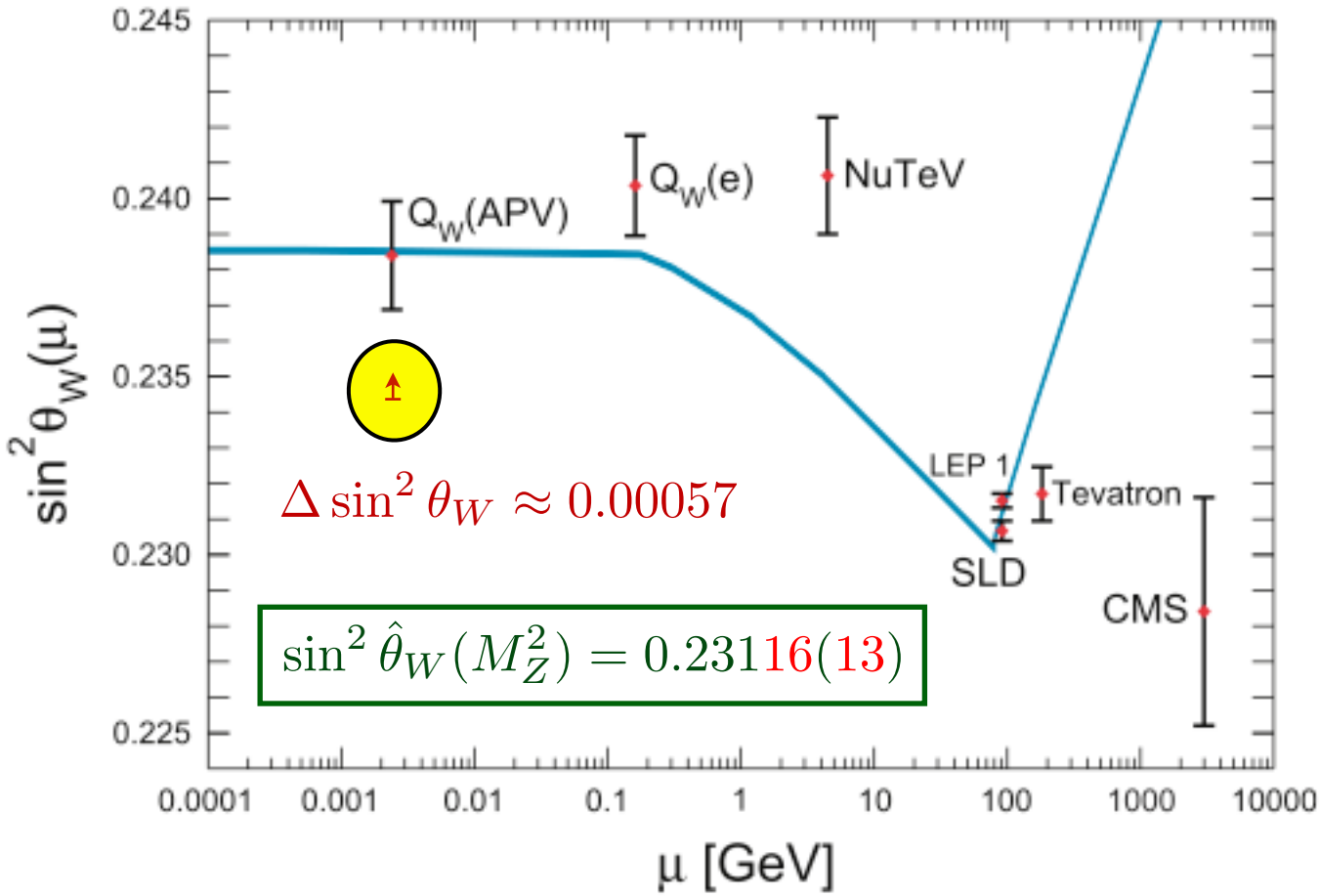
Blunden, WM, Thomas
*PRL **109**, 262301 (2012)*

→ overall shift (relative to MS): $\Delta Q_W(\mathrm{Cs}) = -0.126$

or $\boxed{-\,0.16\% \;\text{ of }\; \mathrm{Q_W^{exp}}(\mathrm{Cs}) = -73.20(35)}$

→ 4 times larger than current SM uncertainty on $\sin^2\theta_W$

APV in ^{133}Cs



Particle Data Group
PRD ***86****, 010001 (2012)*
[*June 18, 2012*]

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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

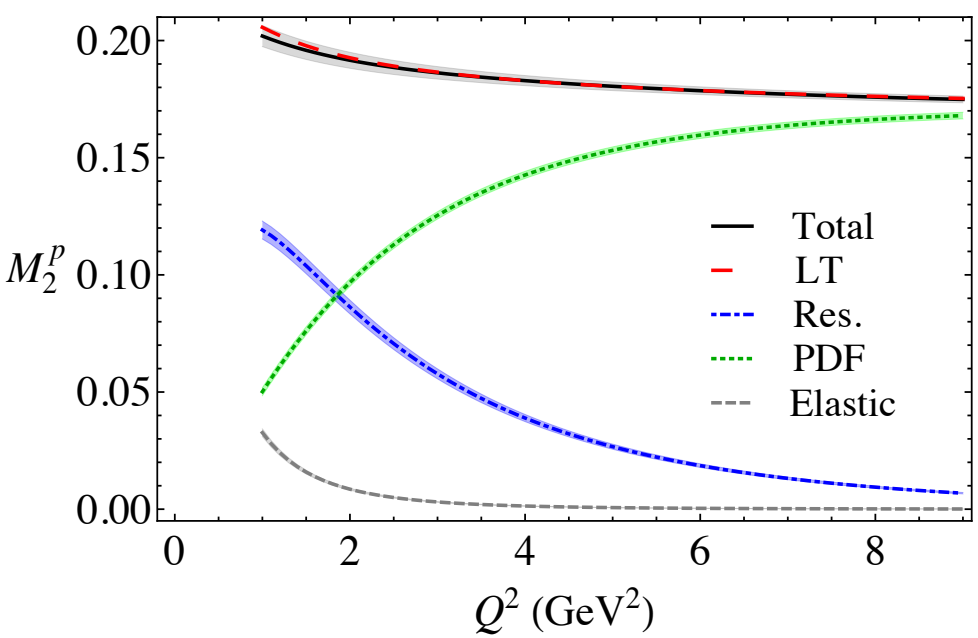
  *Belitsky, Manashov, Schaefer, PRD **84**, 014010 (2011)*

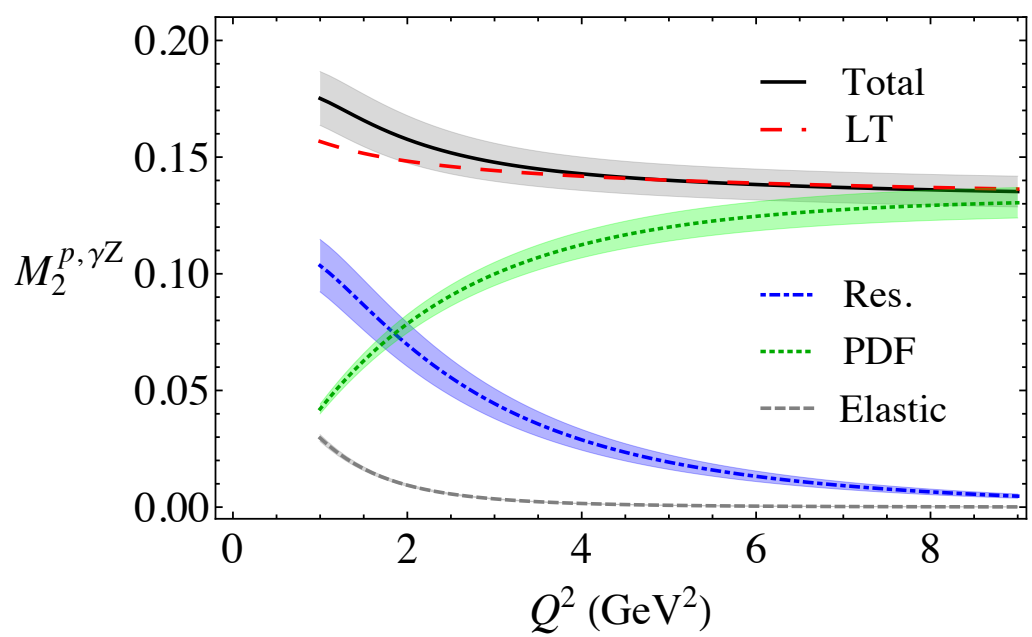
- Alternatively, estimate higher twist contribution to structure functions phenomenologically

- Estimate higher twist corrections using AJM model

→ define HT as difference between *total* structure function and leading twist contribution

e.g. for F_2^p moment

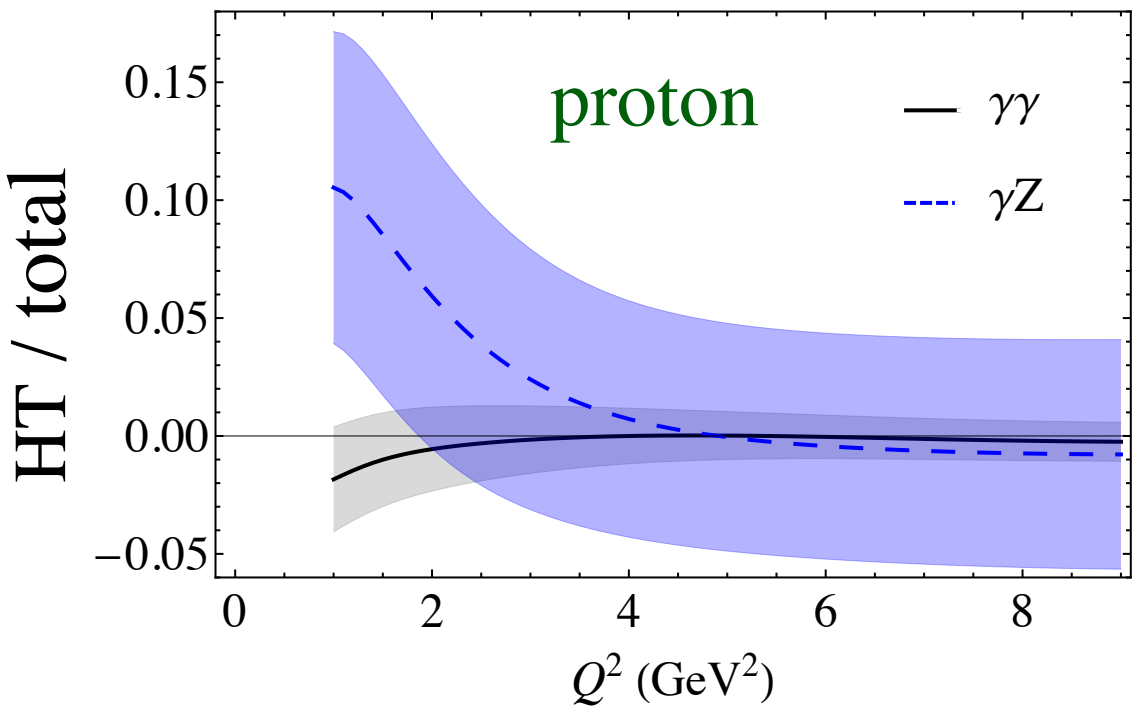




→ total moment is sum of resonance (low W), "PDF" (high W), and elastic contributions

- Estimate higher twist corrections using AJM model

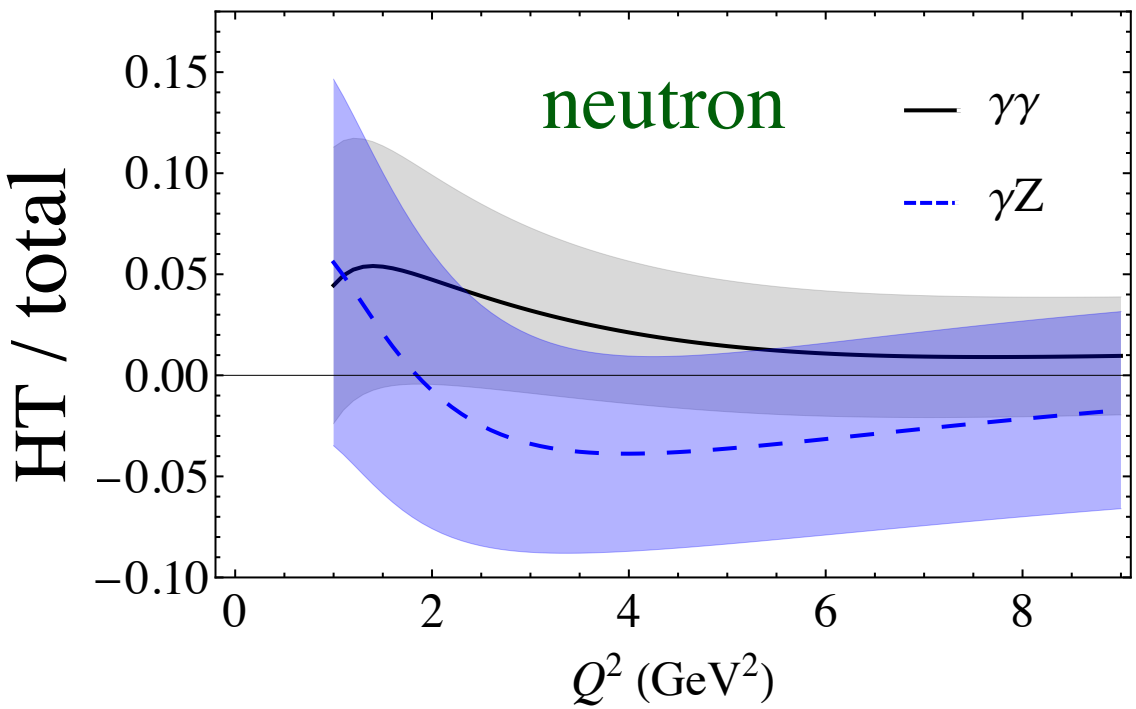
→ define HT as difference between *total* structure function and leading twist contribution



→ HT in γZ for proton larger than in $\gamma\gamma$ but still ~10% at $Q^2 \sim 1\,\mathrm{GeV}^2$

- Estimate higher twist corrections using AJM model

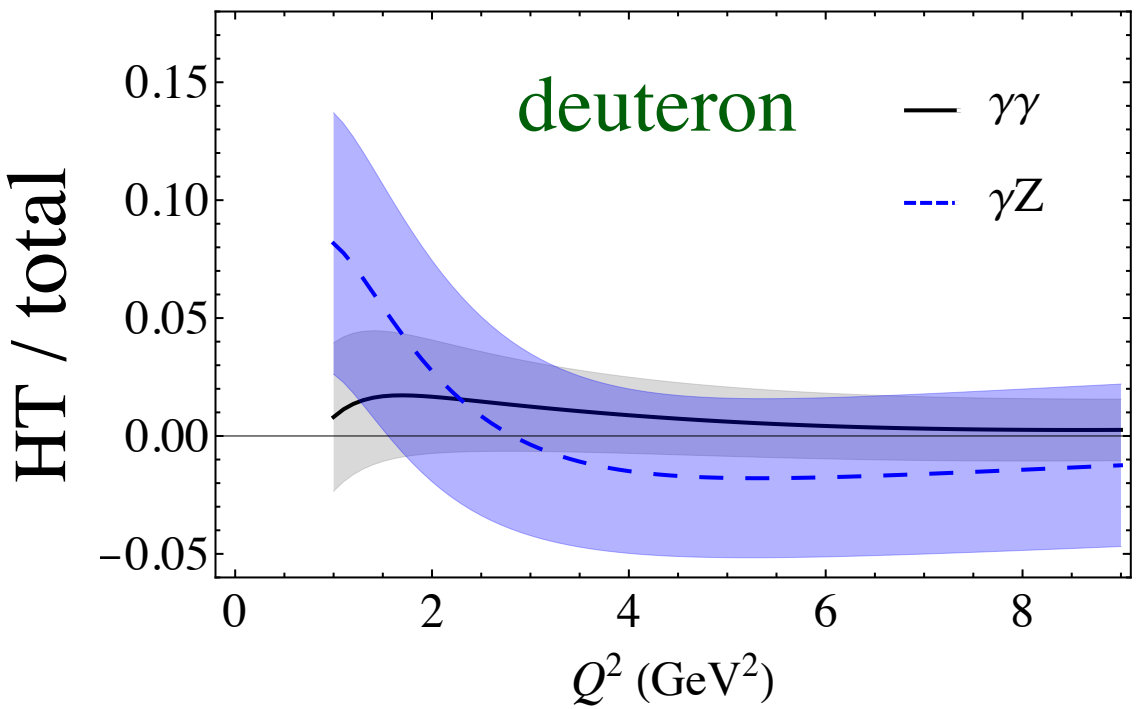
→ define HT as difference between *total* structure function and leading twist contribution



→ for neutron HTs are comparable, within larger uncertainties

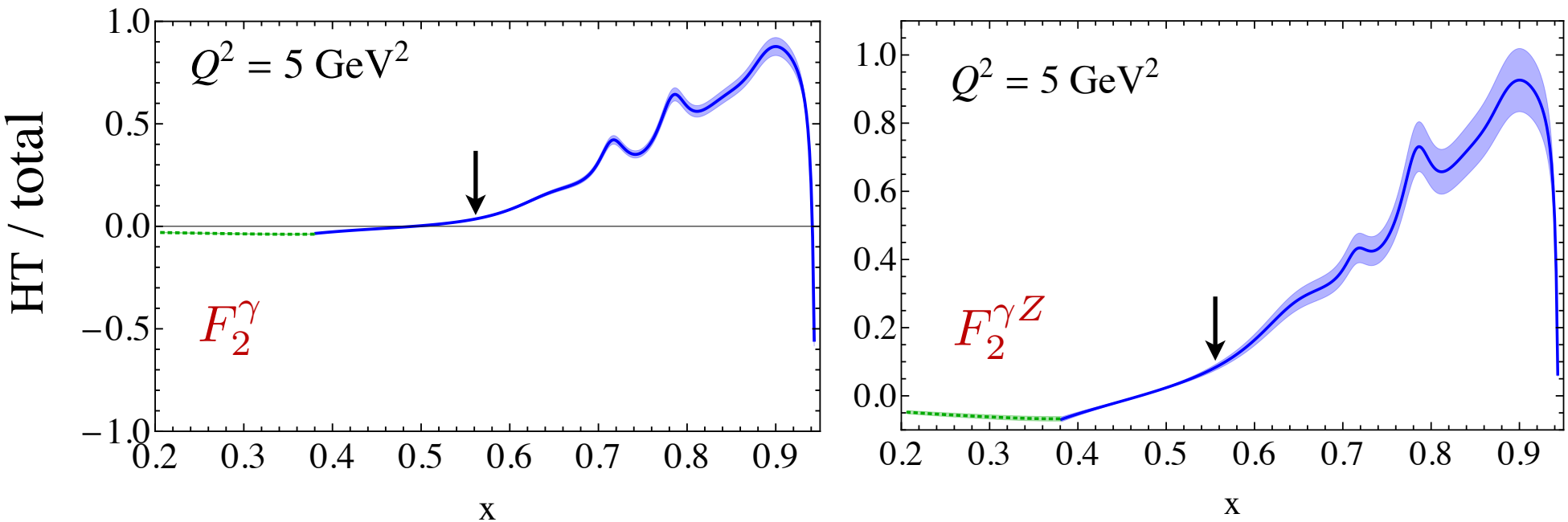
- Estimate higher twist corrections using AJM model

→ define HT as difference between *total* structure function and leading twist contribution



→ for deuteron, HTs are again larger for γZ but decrease rapidly for $Q^2 \gtrsim 2\,\mathrm{GeV}^2$

Map out x dependence of HTs (twist-4 + higher) directly



→ in DIS region ($W < 2$ GeV), HTs $\lesssim 5\%$ for F_2^γ, and $\lesssim 10\%$ for $F_2^{\gamma Z}$

→ increase rapidly at higher x (lower W)

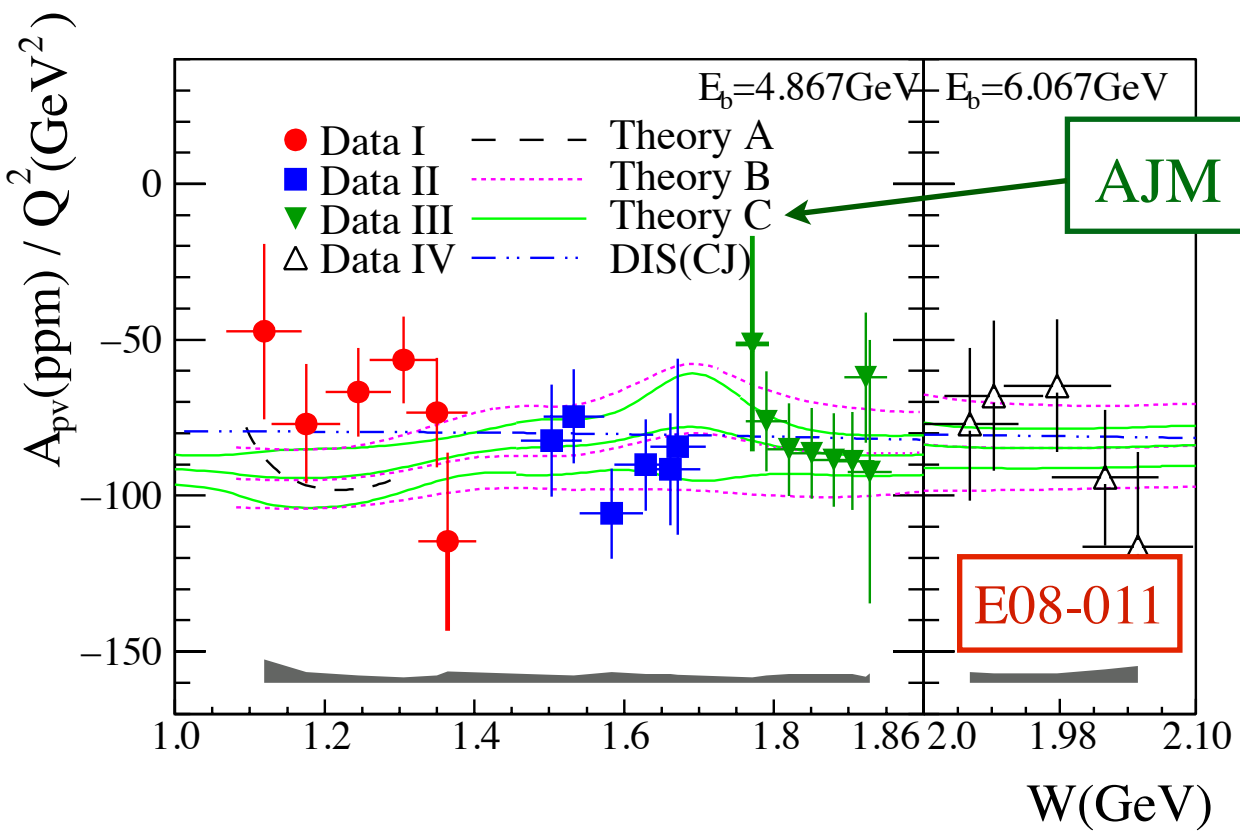
Outlook

- γZ structure functions vital $e.g.$ for box corrections to PVES
  - → AJM model provides phenomenological basis for computations, in absence of direct measurements
  - → important corrections to proton weak charge

- Low-W, low-Q region least constrained
  - → important constraints from recent Hall A PVDIS experiment E08-011

Parity-violating DIS

$$A_{\rm PV} = g_A^e \left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right) \frac{xy^2 F_1^{\gamma Z} + (1-y)F_2^{\gamma Z} + \frac{g_V^e}{g_A^e}(y - y^2/2)xF_3^{\gamma Z}}{xy^2 F_1^{\gamma\gamma} + (1-y)F_2^{\gamma\gamma}}$$



AJM model

E08-011

Wang et al.
PRL ***111***, *013011 (2013)*

→ first evidence of quark-hadron duality for γZ

Outlook

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- Low-W, low-Q region least constrained
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- New proposal to PAC44 (V. Sulkosky, X. Zheng *et al.*) to measure PVDIS for p and d in resonance region