Overview of γZ box corrections in PVES

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Bridging the Standard Model to New Physics with the Parity Violation Program at MESA, May 3, 2018

†in collaboration with AJM Collaboration (Hall, Melnitchouk, Ross, Thomas), and K. Shiells

Outline

- γZ box contributions to PV electron scattering
  - amenable to dispersion analysis in forward limit ($Q^2 \to 0$)
  - distinction between axial and vector hadron coupling
  - use of inelastic PV data in resonance and DIS regions

- From Thomson to scattering limits: a few issues
  - Vertex diagrams
  - Elastic γZ contribution (Coulomb distortions)

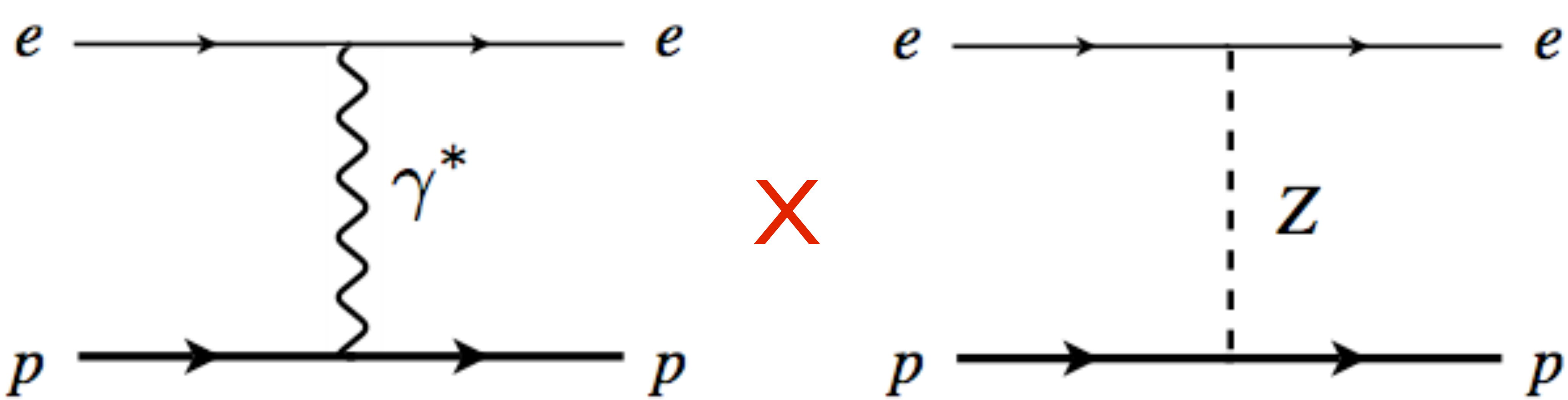
Parity-violating *e*-*p* scattering

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

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

Forward limit:

$$Q^2 = -(k-k')^2 \to 0$$
$$s = (k+p)^2$$
$$= M^2 + 2ME$$



$\longrightarrow$ in forward limit, gives proton "weak charge"

A(e) x V(h)

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

(tree level only)

Correction to proton weak charge

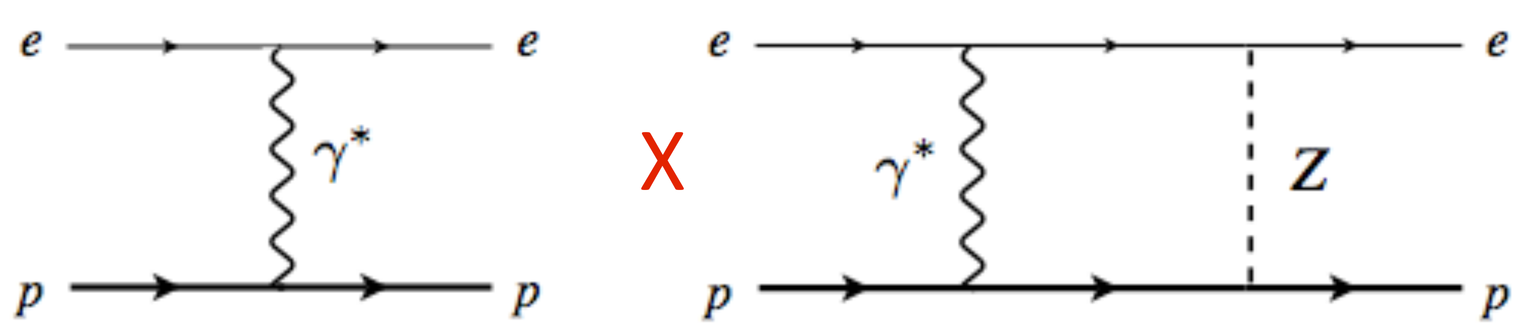
- including one-loop radiative corrections

e.w. vertex corrections

$$Q_W^p = \rho\left(1 - 4\kappa_{\rm PT}(0)\hat{s}^2 + \Delta_e' + \Delta_W\right)$$
$$+ \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$$

box diagrams

Box corrections



→ WW and ZZ box diagrams large but dominated by short distances; can be evaluated perturbatively

→ γZ box diagram sensitive to long distance physics, has two contributions: $\Box_{\gamma Z} = \Box_{\gamma Z}^A + \Box_{\gamma Z}^V$

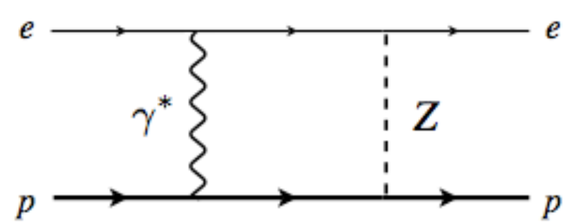
V(e) x A(h)
(finite at E=0)

A(e) x V(h)
(inelastic vanishes at E=0)

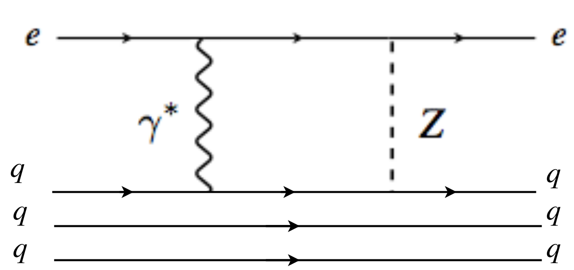
Axial h correction

- <u>axial</u> h correction $\Box^A_{\gamma Z}$ dominant γZ correction in atomic parity violation at very low (zero) energy

$\longrightarrow$ computed by Marciano & Sirlin in 1983 as sum of two parts:



★ low-energy part approximated by *Born* contribution (elastic intermediate state)



★ high-energy part (above scale $\Lambda \sim 1$ GeV) computed perturbatively in terms of scattering from *free quarks*

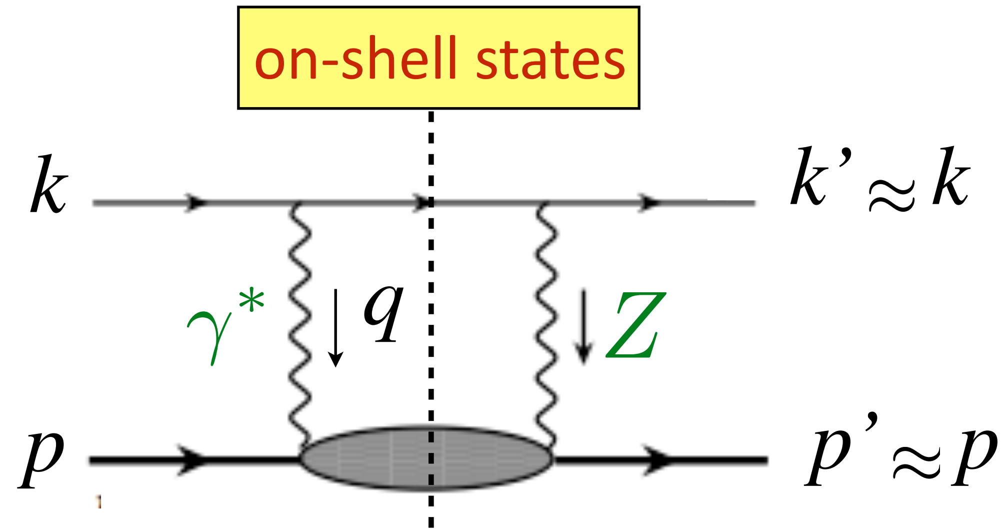
$$\Box^A_{\gamma Z} = (1 - 4\hat{s}^2)\,\frac{5\alpha}{2\pi}\underbrace{\int_{\Lambda^2}^{\infty}\frac{dQ^2}{Q^2(1+Q^2/M_Z^2)}\left(1-\frac{\alpha_s(Q^2)}{\pi}\right)}_{\sim \log\frac{M_Z^2}{\Lambda^2}+c}$$

Marciano, Sirlin, PRD ***29*** *(1984) 75; Erler et al., PRD* ***68*** *(2003) 016006*

Forward angle dispersion method

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

$$S = 1 + i\mathcal{M}$$
$$S^\dagger = 1 - i\mathcal{M}^\dagger$$
$$SS^\dagger = 1$$



Unitarity $\rightarrow \quad -i\left(\mathcal{M} - \mathcal{M}^\dagger\right) = 2\Im m\, \mathcal{M} = \mathcal{M}^\dagger \mathcal{M}$

$$\boxed{\Im m\, \langle f|\mathcal{M}|i\rangle = \frac{1}{2}\int d\rho\, \sum_n \langle f|\mathcal{M}^*|n\rangle\langle n|\mathcal{M}|i\rangle}$$

Forward scattering amplitude: $|\, f\,\rangle \approx |\, i\,\rangle$

$$\Im m \langle i|\mathcal{M}|i\rangle = \frac{1}{2}\int d\rho \sum_n |\langle n|\mathcal{M}|i\rangle|^2 \sim \int d^3k_1\; \frac{L_{\mu\nu}W^{\mu\nu}}{q^2(q^2 - M_Z^2)}$$

vector *h*

axial *h*

hadronic tensor: $\quad MW^{\mu\nu}_{\gamma Z} = -g^{\mu\nu} F_1^{\gamma Z} + \frac{p^\mu p^\nu}{p\cdot q} F_2^{\gamma Z} - i\varepsilon^{\mu\nu\lambda\rho}\frac{p_\lambda q_\rho}{2p\cdot q} F_3^{\gamma Z}$

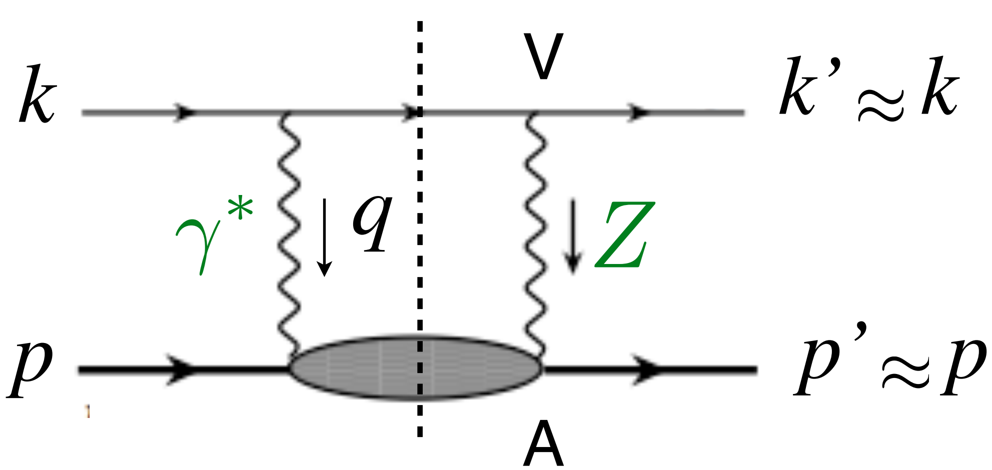
Axial h correction

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

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

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

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



with $v_e(Q^2) = 1 - 4\kappa(Q^2)\hat{s}^2$

Axial h correction DIS part (dominant contribution)

- DIS part dominated by leading twist PDFs at small x

(MSTW, CTEQ, Alekhin parametrizations)

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

$\longrightarrow$ in DIS region ($Q^2 \gtrsim 1\ \mathrm{GeV}^2$), expand integrand in powers of x

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

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

Axial h correction

- structure function moments

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

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

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

$\longrightarrow$ precisely result from Marciano & Sirlin! $\sim \log\frac{M_Z^2}{Q_0^2}$

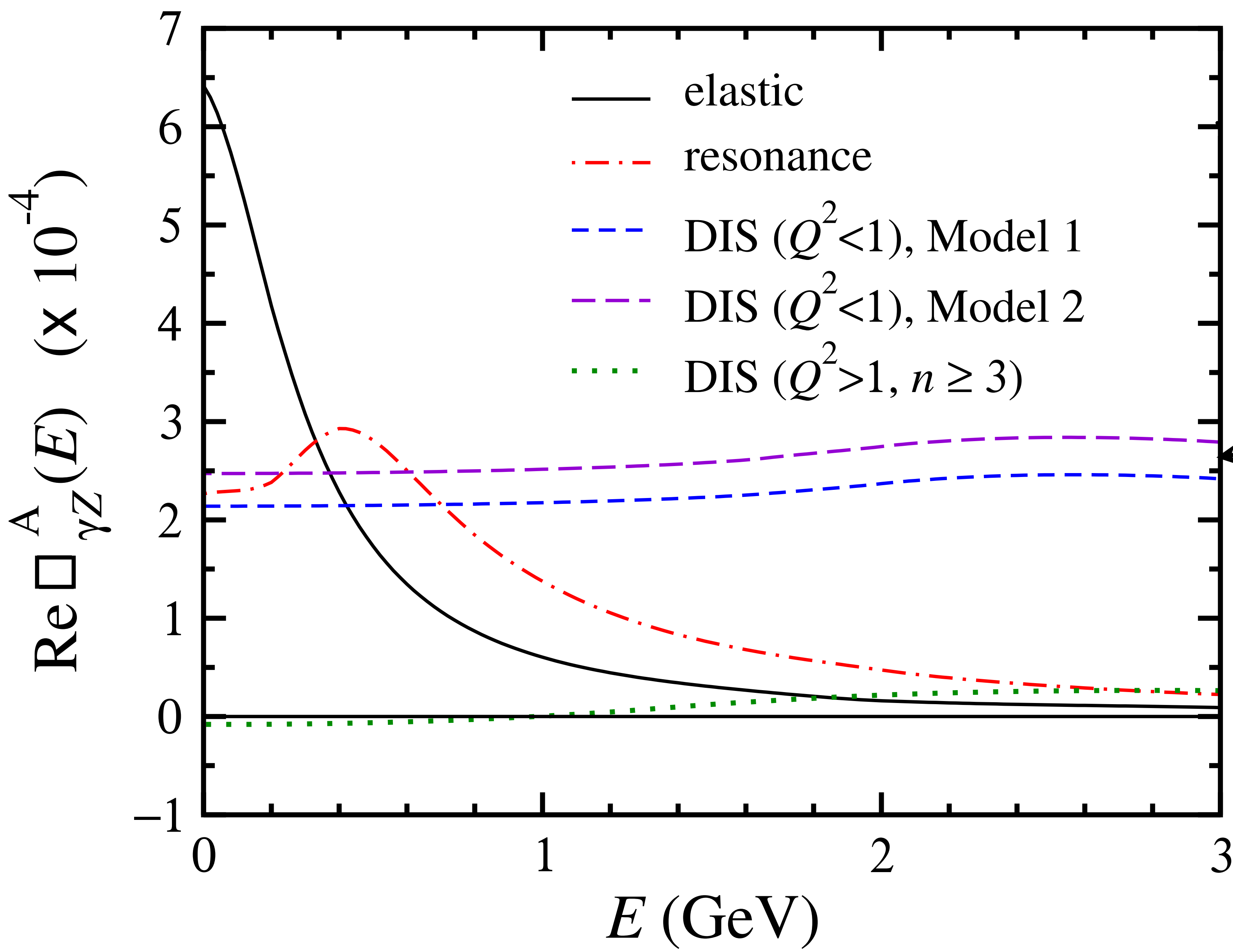
$\underline{n=3}$ $$M_3^{\gamma Z(3)}(Q^2) = \frac{1}{3}\left(2\langle x^2\rangle_u + \langle x^2\rangle_d\right)\left(1 + \frac{5\alpha_s(Q^2)}{12\pi}\right)$$

$\longrightarrow$ related to x^2-weighted moment of valence quarks

Axial h elastic + resonance correction

- elastic part: $F_3^{\gamma Z(\mathrm{el})}(Q^2) = -Q^2 G_M^p(Q^2) G_A^Z(Q^2)\delta(W^2 - M^2)$
- resonance part from parametrization of ν scattering data; includes lowest four spin 1/2 and 3/2 resonances

[$P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$] *Lalakulich, Paschos PRD **74**, 014009 (2007)*



$n = 1$ moment gives 32.8×10^{-4} (no E dependence)

Take this as estimate of uncertainty

*Blunden et al., PRL **107**, 081801 (2011)*

Axial h correction

- correction at $\underline{E = 0}$

$$\Re e \Box^{A}_{\gamma Z} = \underset{\uparrow\ \text{elastic}}{0.00063} + \underset{\uparrow\ \text{resonance}}{0.00023} + \underset{\uparrow\ \text{DIS}}{0.00350} \rightarrow 0.0044(2)$$

- correction at $\underline{E = 1.165\ \mathrm{GeV}}$ (Qweak)

$$\Re e \Box^{A}_{\gamma Z} = 0.00005 + 0.00011 + 0.00352 \rightarrow 0.0037(2)$$

cf. MS value: $\underline{0.0052(5)}$ ($\sim$1% shift in Q^p_W)

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

- shifts Q^p_W by -0.0008

Vector h correction

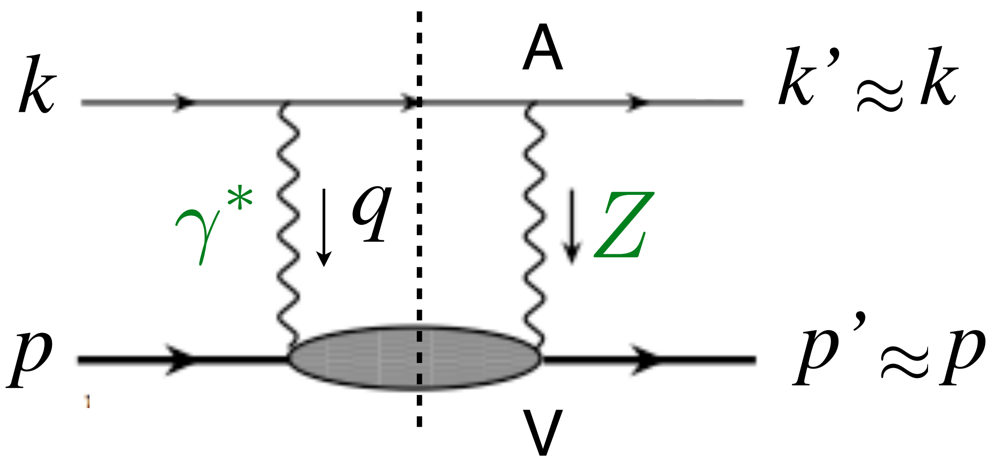
- vector h correction $\Box^V_{\gamma Z}$ vanishes at $E = 0$ (inelastic only), but experiment has $E \sim 1$ GeV. What is energy dependence?

$\longrightarrow$ forward dispersion relation

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

$\longrightarrow$ inelastic imaginary part given by

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



γZ box: Vector h correction

- Several groups doing independent analyses

- At $\mathrm{Q_{weak}}$ energy $E = 1.165$ GeV (relative to weak charge of 0.0713)

Gorchtein/Horowitz (2009)	
Sibirtsev *et al.* (2010)	$(4.7^{+1.1}_{-0.4}) \times 10^{-3}$
Gorchtein *et al.* (2011)	$(5.4 \pm 2.0) \times 10^{-3}$
Rislow/Carlson (2011)	$(5.7 \pm 0.9) \times 10^{-3}$
AJM-I: Hall *et al.* (2013)	$(5.6 \pm 0.4) \times 10^{-3}$
Gorchtein *et al.* (2015)	$(5.6 \pm 1.4) \times 10^{-3}$
AJM-II: Hall *et al.* (2016)	$(5.4 \pm 0.4) \times 10^{-3}$

new results

- Mainly different treatments of low Q^2, low W region background contributions

- Agree on overall magnitude, but disagree on errors and details

AJM structure function model

- Accurate knowledge of $\gamma\gamma$ and γZ structure functions (at all kinematics) vital for determination of radiative corrections

- Wealth of data on $F_i^{\gamma\gamma}$ structure functions over large range of kinematics in Q^2 and W (or x) – with some gaps

- Relatively little known about $F_i^{\gamma Z}$ interference structure functions below HERA measurements, with $Q^2 \geq 1500\ \mathrm{GeV}^2$

- Fit $F_i^{\gamma\gamma}$ over all kinematics in Q^2 and W, then "rotate" to $F_i^{\gamma Z}$ using available theoretical/phenomenological constraints

→ *e.g.* isospin symmetry

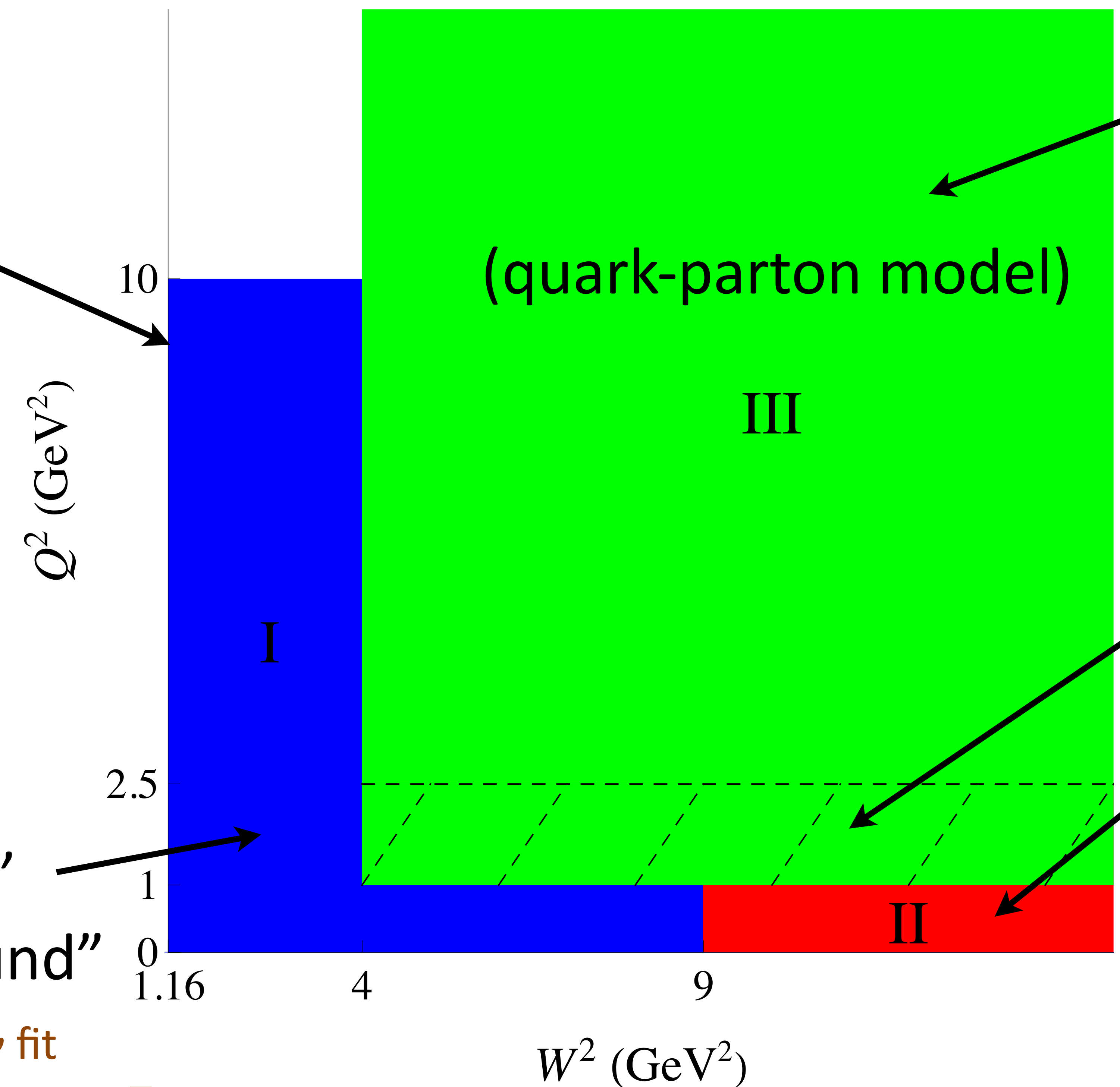
$$\langle N^*|J_Z^\mu|p\rangle = (1 - 4\sin^2\theta_W)\langle N^*|J_\gamma^\mu|p\rangle - \langle N^*|J_\gamma^\mu|n\rangle$$

Integration region (structure function map)

“DIS”

Leading twist PDFs

“elastic”



Matching range

“Regge” +
“background”

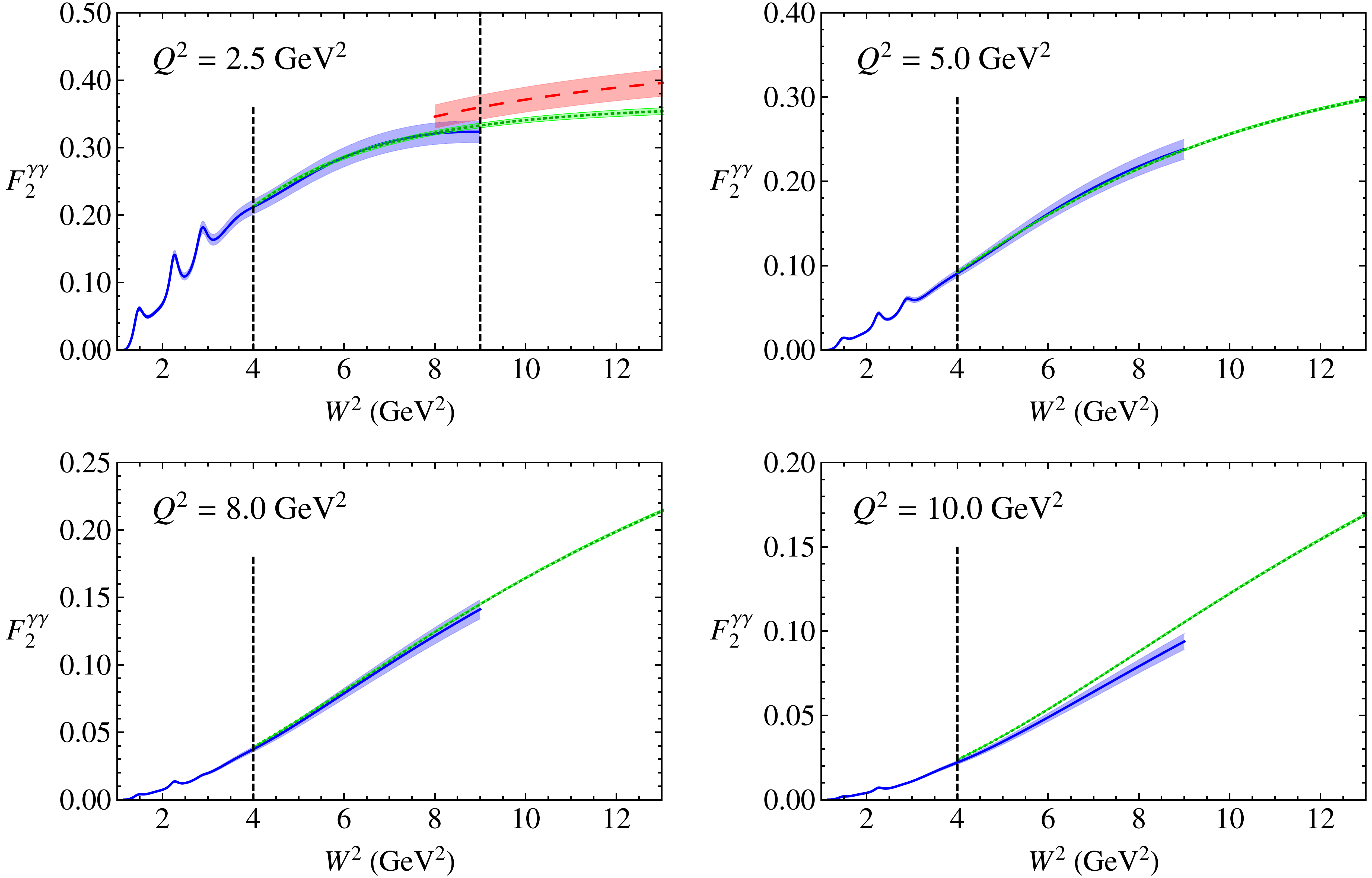
Pomeron and
Reggeon exchange

“resonance”
+ “background”

Bosted-Christy $\gamma\gamma$ fit
+ isospin rotation to γZ

VMD model for “background”

$\gamma\gamma$ structure function matching



Basic issue: how to relate $F_{1,2}^{\gamma Z}$ to $F_{1,2}^{\gamma}$?

Scaling region III

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

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

$$x = \frac{Q^2}{W^2 - M^2 + Q^2}$$

Resonance region I largest contribution (unlike $F_3^{\gamma Z}$)

For $\gamma\gamma$ use Christy-Bosted (CB) fit to e-p cross sections

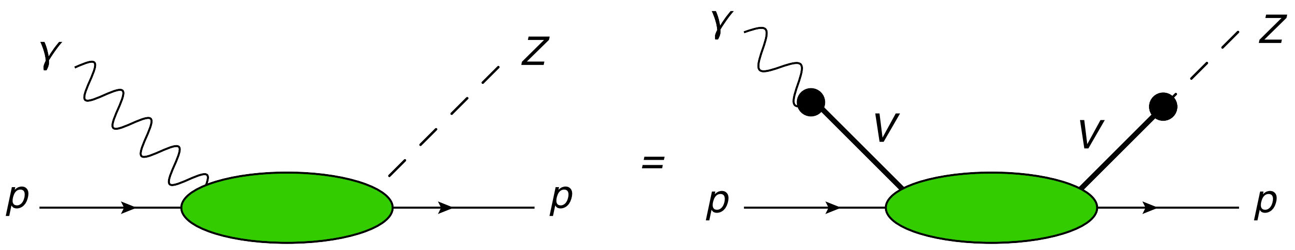
$$\sigma_{T,L} = \sigma_{T,L}(\mathrm{res}) + \sigma_{T,L}(\mathrm{bg})$$

$\sigma_{T,L}(\mathrm{res})$

- Includes 7 most prominent N* resonances below 2 GeV.
- Generally agrees with data to $\sim 5\%$
- For γZ modify fit by ratio of weak to e.m. transition amplitudes.

Background $\sigma_{T,L}(\mathrm{bg})$

- Use Vector Meson Dominance (VMD) models fit to high energy data, plus isospin rotations



V = ρ, ω, φ + continuum

$$\sigma_V^{\gamma Z} = \kappa_V \, \sigma_V^{\gamma\gamma} \qquad \frac{\sigma^{\gamma Z}}{\sigma^{\gamma\gamma}} = \frac{\kappa_\rho + \kappa_\omega R_\omega + \kappa_\phi R_\phi + \kappa_C R_C}{1 + R_\omega + R_\phi + R_C}$$

Isospin rotation: $\kappa_\rho = 2 - 4\sin^2\theta_W, \;\; \kappa_\omega = -4\sin^2\theta_W, \;\; \kappa_\phi = 3 - 4\sin^2\theta_W$

$\longrightarrow$ continuum parameter κ_C not constrained in VMD

- GHRM: assign 100% uncertainty on continuum contribution (dominates errors)

- AJM model: constrain continuum (higher Q^2) contribution by matching with PDF ratios (γZ to $\gamma\gamma$) across boundaries of Regions I, II and III.

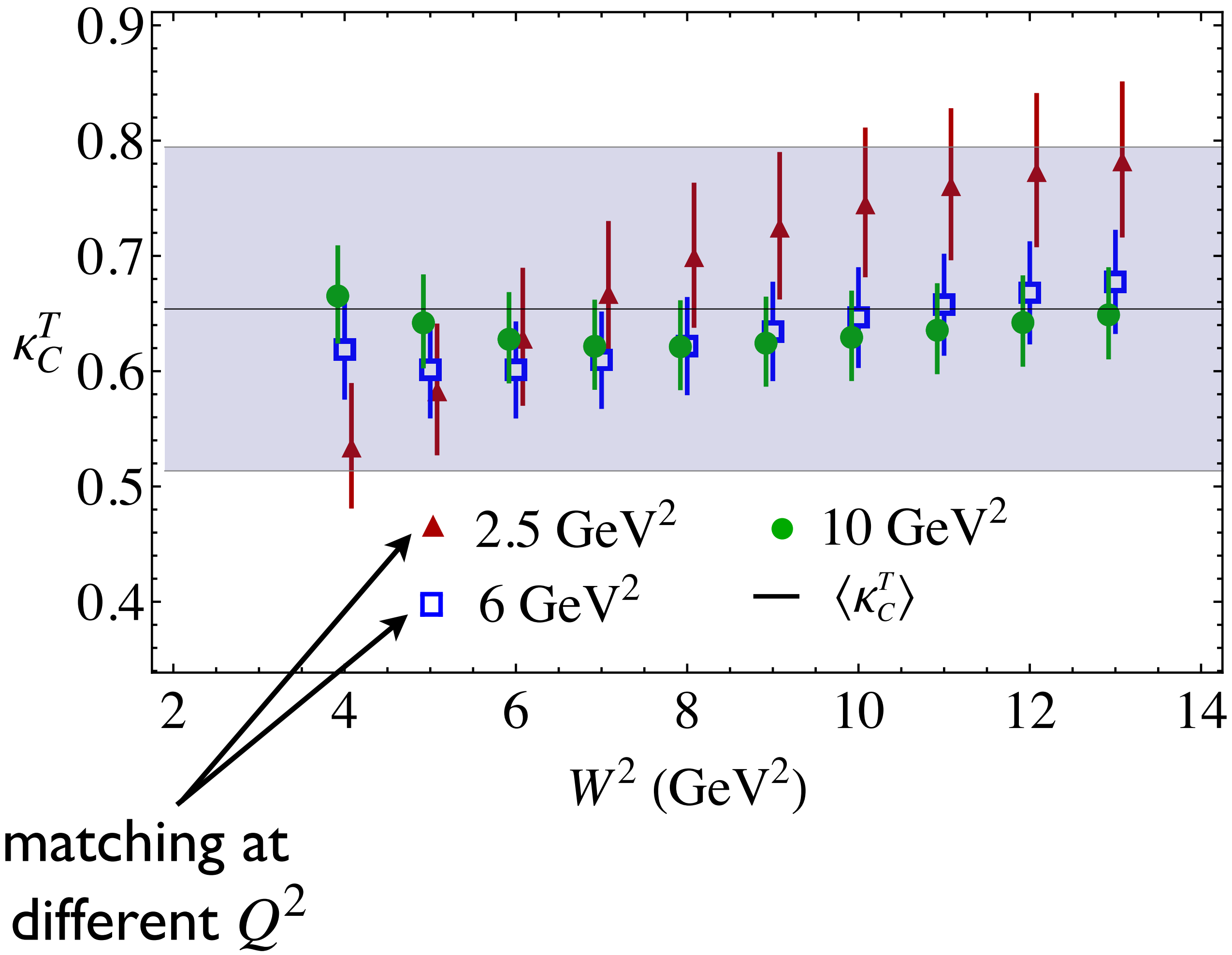
AJM γZ model

- Region where continuum contributions are relevant overlaps with typical reach of global PDF fits

→ constrain κ_C using PDF parametrizations by requiring matching of $F_{1,2}^{\gamma Z}$ to DIS structure functions:

$$\frac{\sigma_T^{\gamma Z}(\kappa_C^T)}{\sigma_T^{\gamma\gamma}} = \left.\frac{F_1^{\gamma Z}}{F_1^{\gamma\gamma}}\right|_{\mathrm{LT}}$$

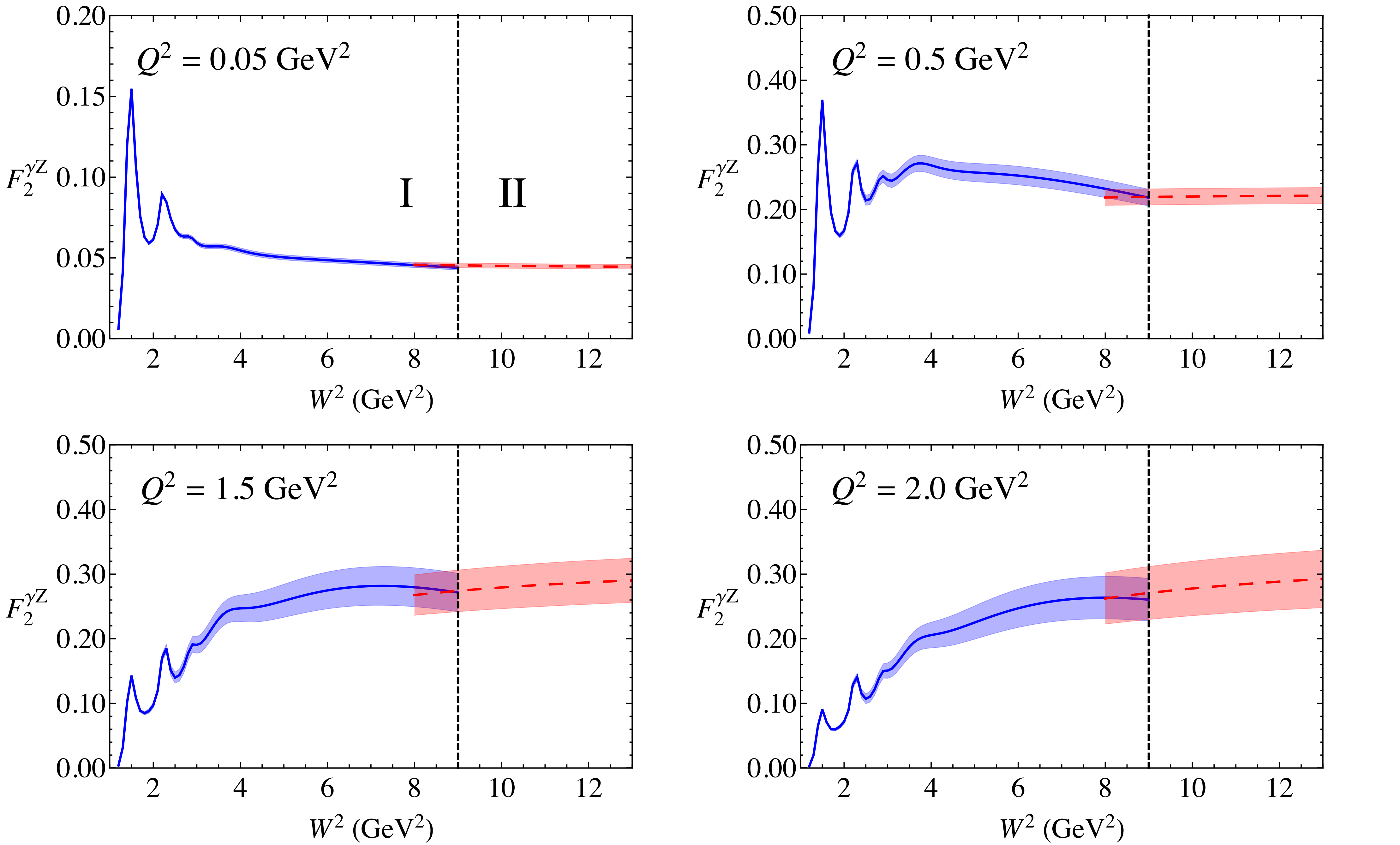
$$\frac{\sigma_L^{\gamma Z}(\kappa_C^T)}{\sigma_L^{\gamma\gamma}} = \left.\frac{F_L^{\gamma Z}}{F_L^{\gamma\gamma}}\right|_{\mathrm{LT}}$$



→ $\boxed{\kappa_C^T = 0.65 \pm 0.14, \quad \kappa_C^L = -1.3 \pm 1.7}$

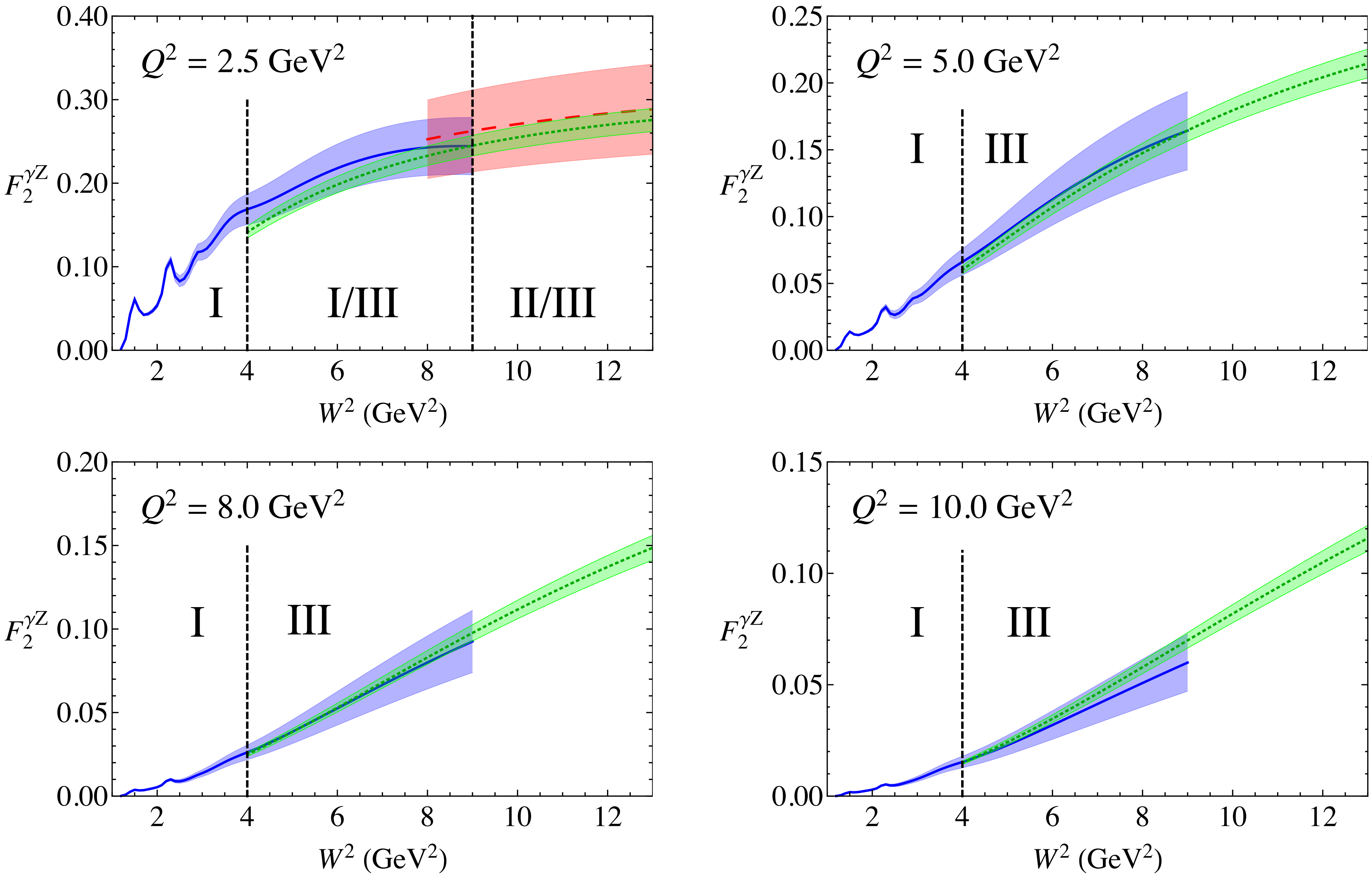
(small contribution to asymmetry)

γZ structure function matching



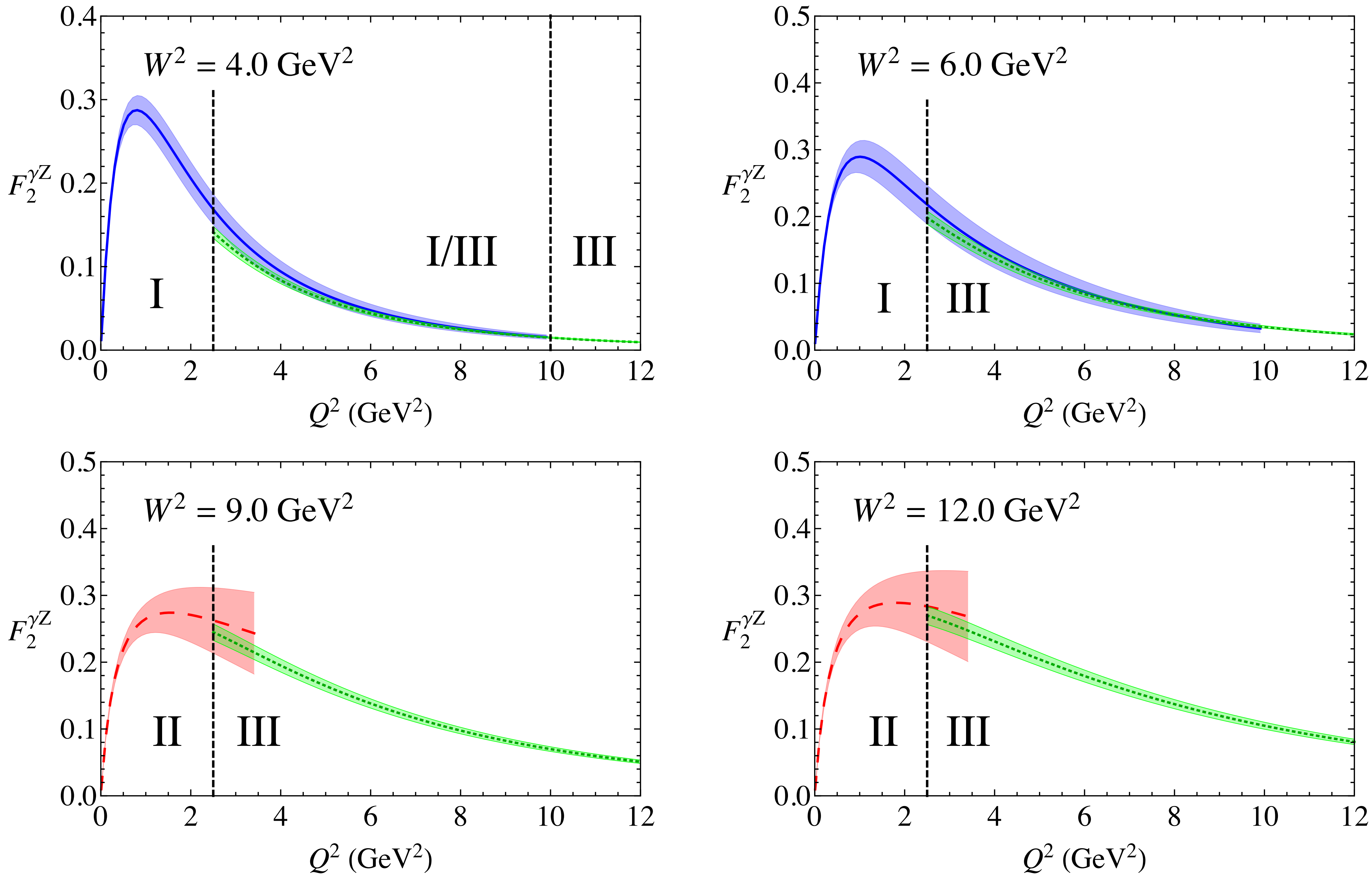
→ structure functions well matched at boundary of regions I and II, within larger errors *cf.* $\gamma\gamma$ functions

γZ structure function matching



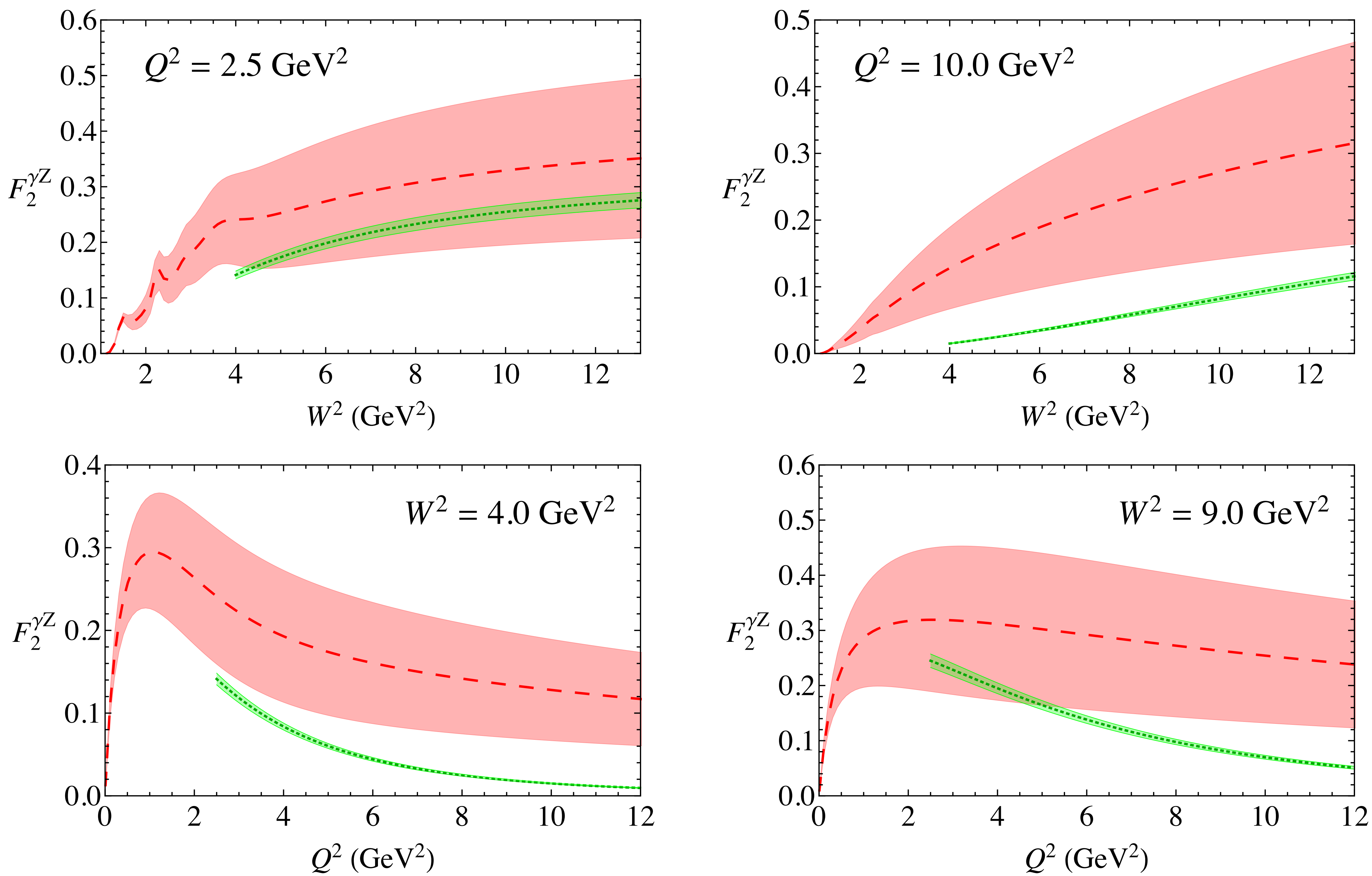
→ structure functions well matched at boundaries of regions I, II and III

γZ structure function matching



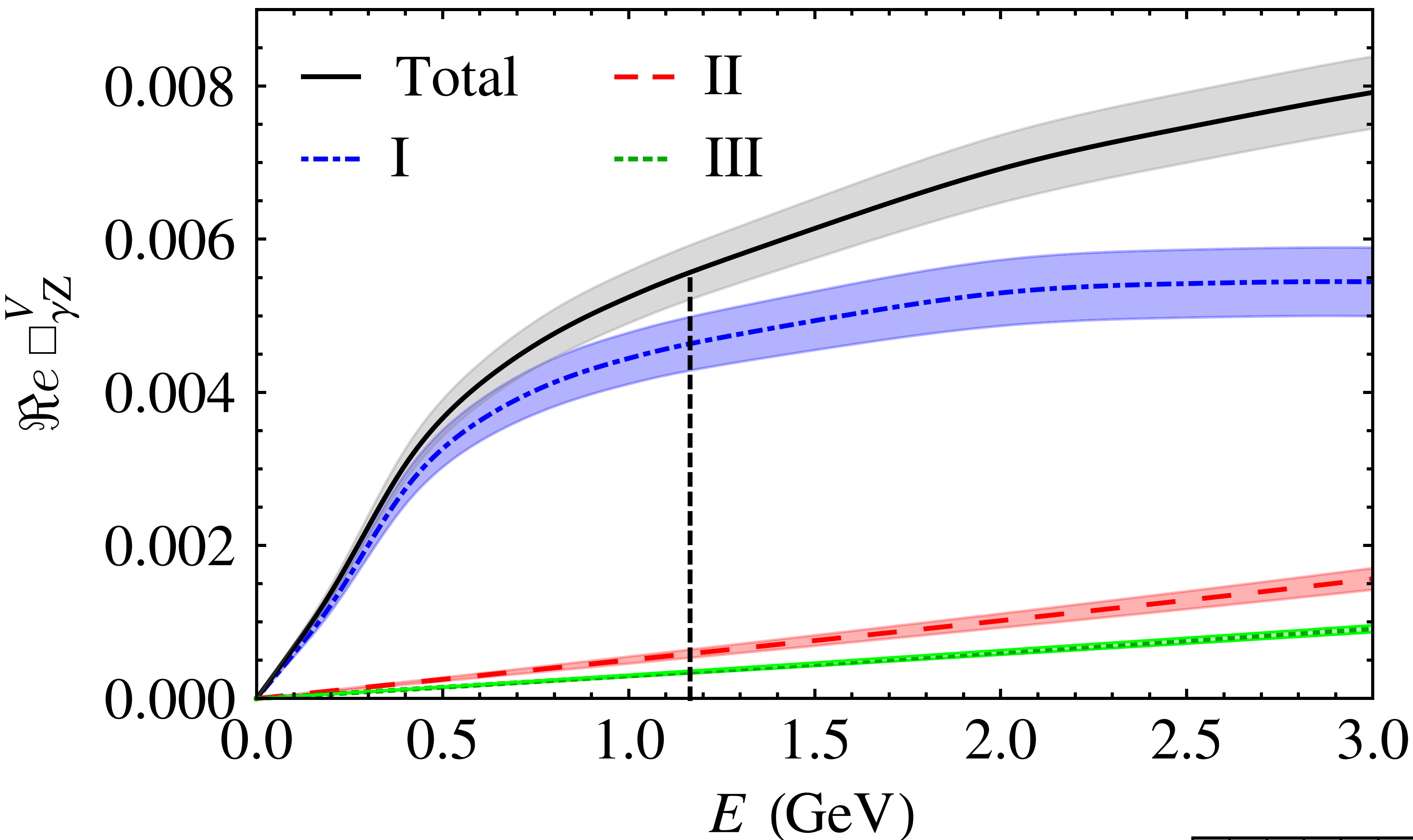
→ structure functions well matched at boundaries of regions I, II and III

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

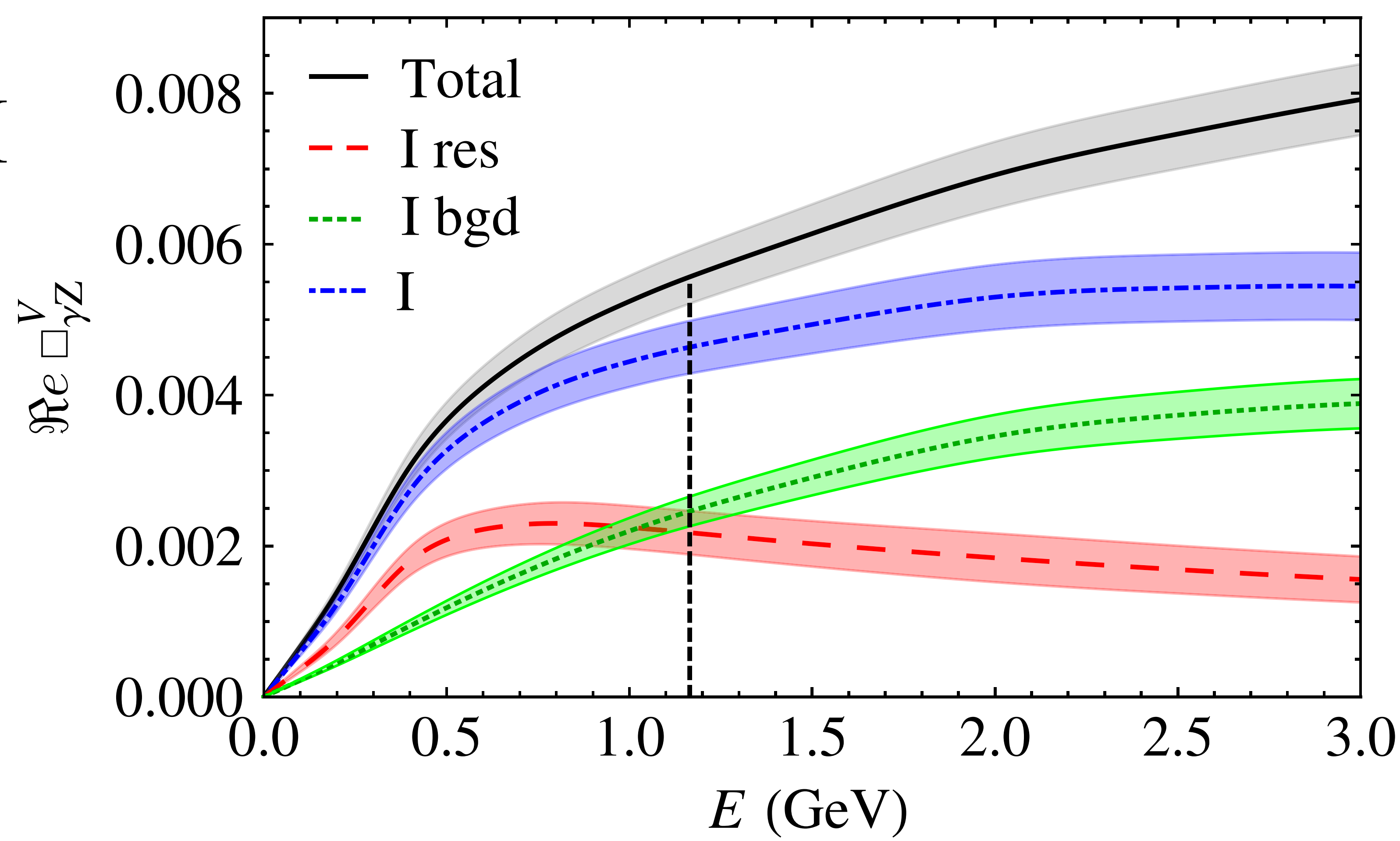
Contribution from different regions to $\Box^V_{\gamma Z}$



(relative to weak charge of 0.0713)

Breakdown of region I res + bgd

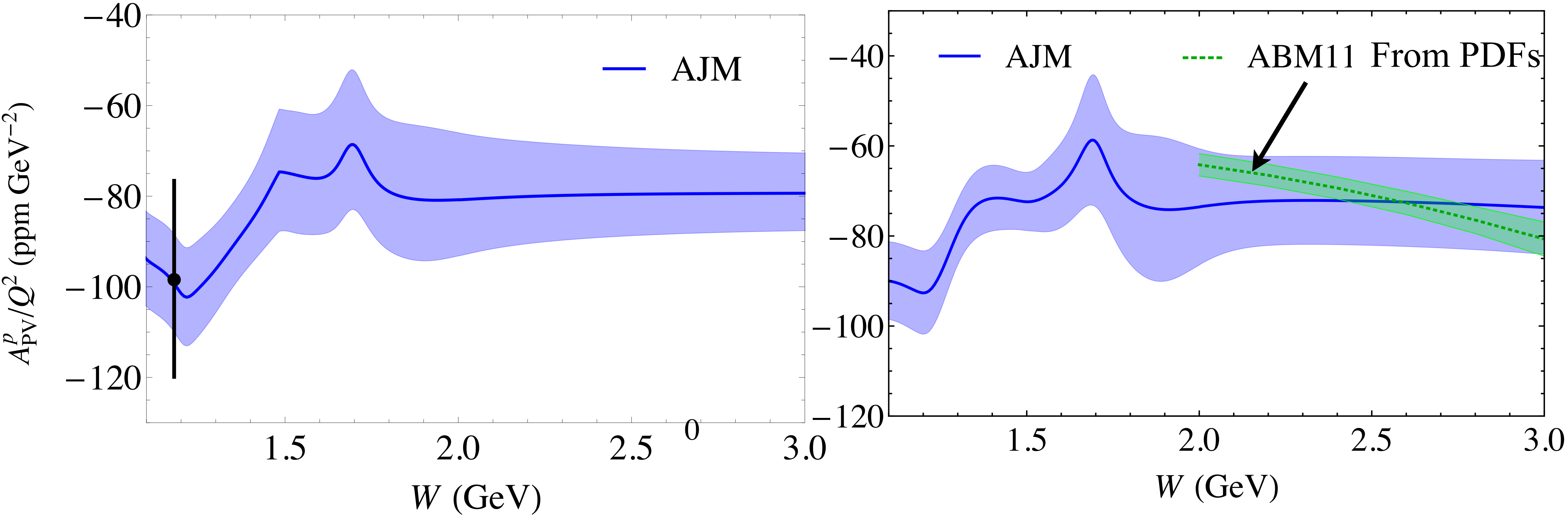
Region	$\Box_{\gamma Z}$ $(\times 10^{-3})$
I (res)	2.18 ± 0.29
I (bgd)	2.46 ± 0.20
I (total)	4.64 ± 0.35
II	0.59 ± 0.05
III	0.35 ± 0.02
Total	5.57 ± 0.36



AJM γZ model direct test

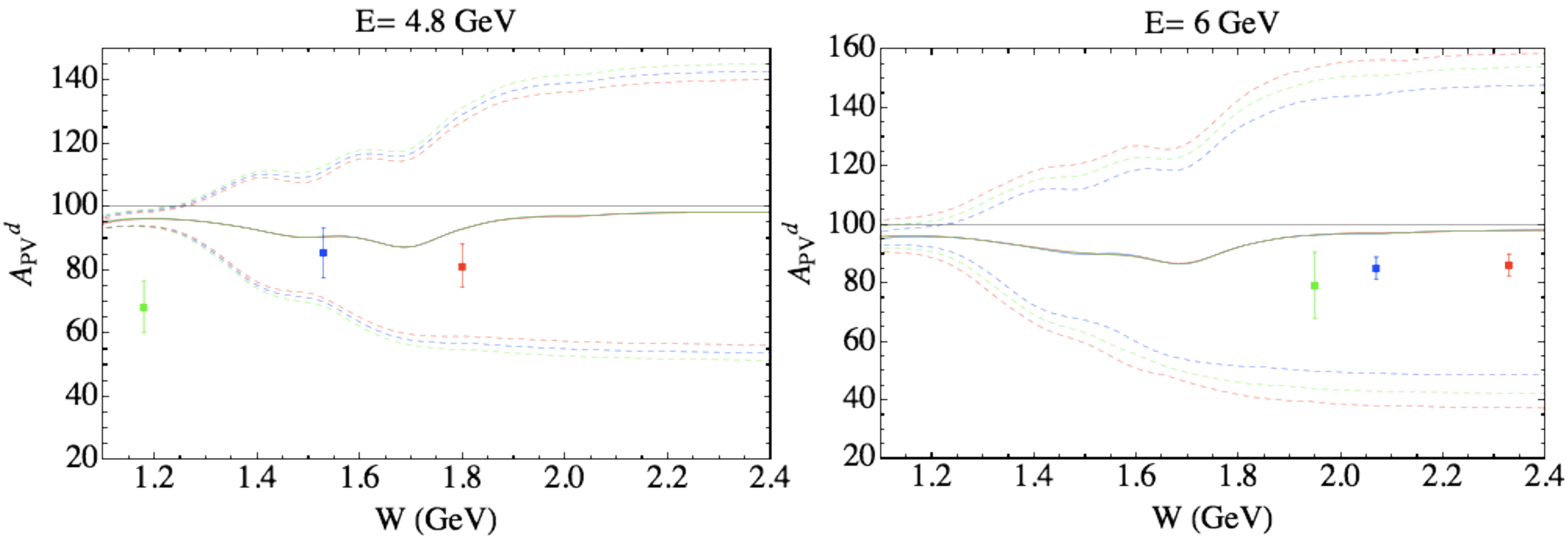
- Parity-violating Deep Inelastic Scattering (PVDIS) asymmetry allows a direct measurement of the γZ structure functions

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



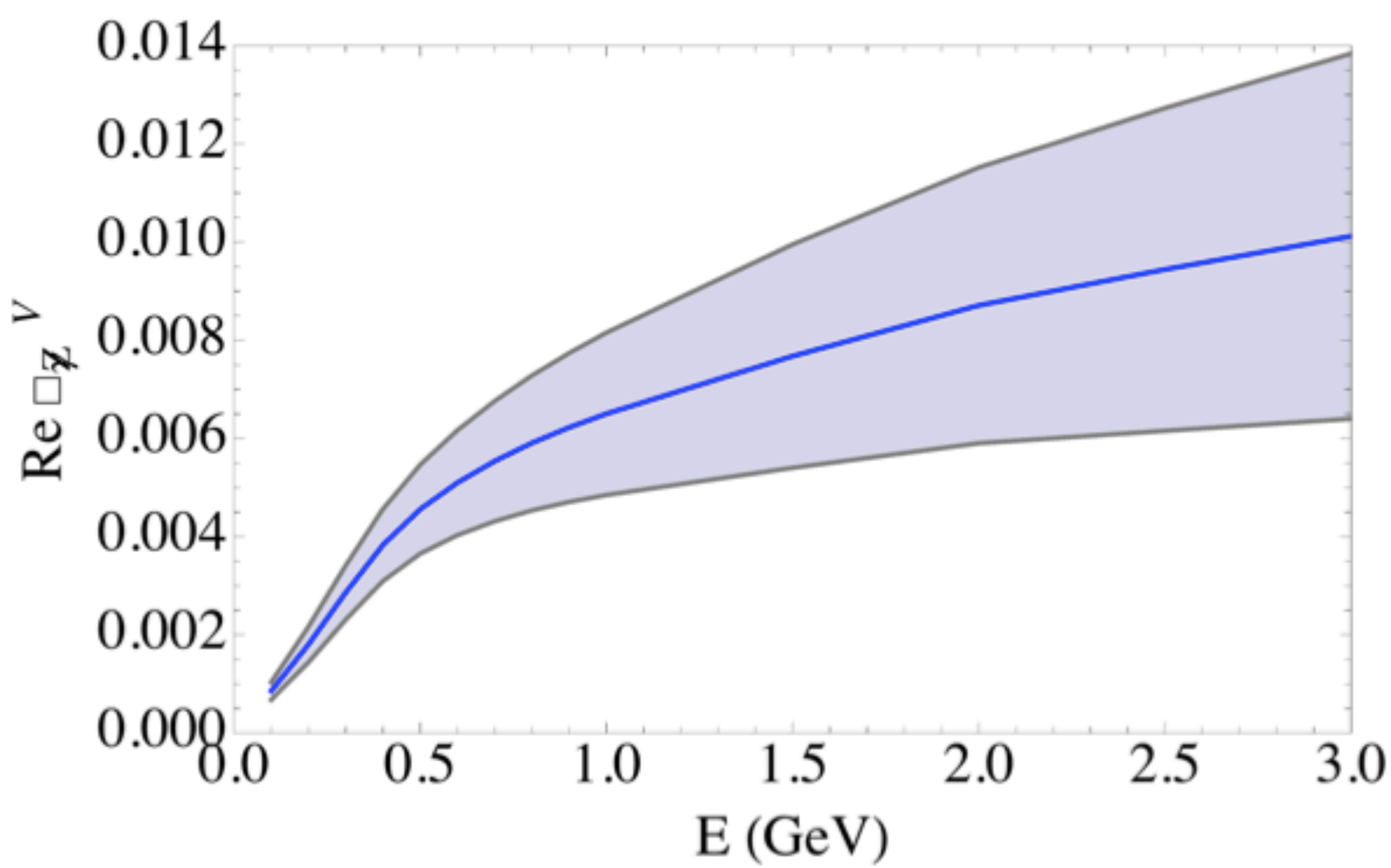
Q^2=0.34 GeV^2, E=0.69 GeV $\qquad$ Q^2 = 2.5 GeV^2, E = 6 GeV

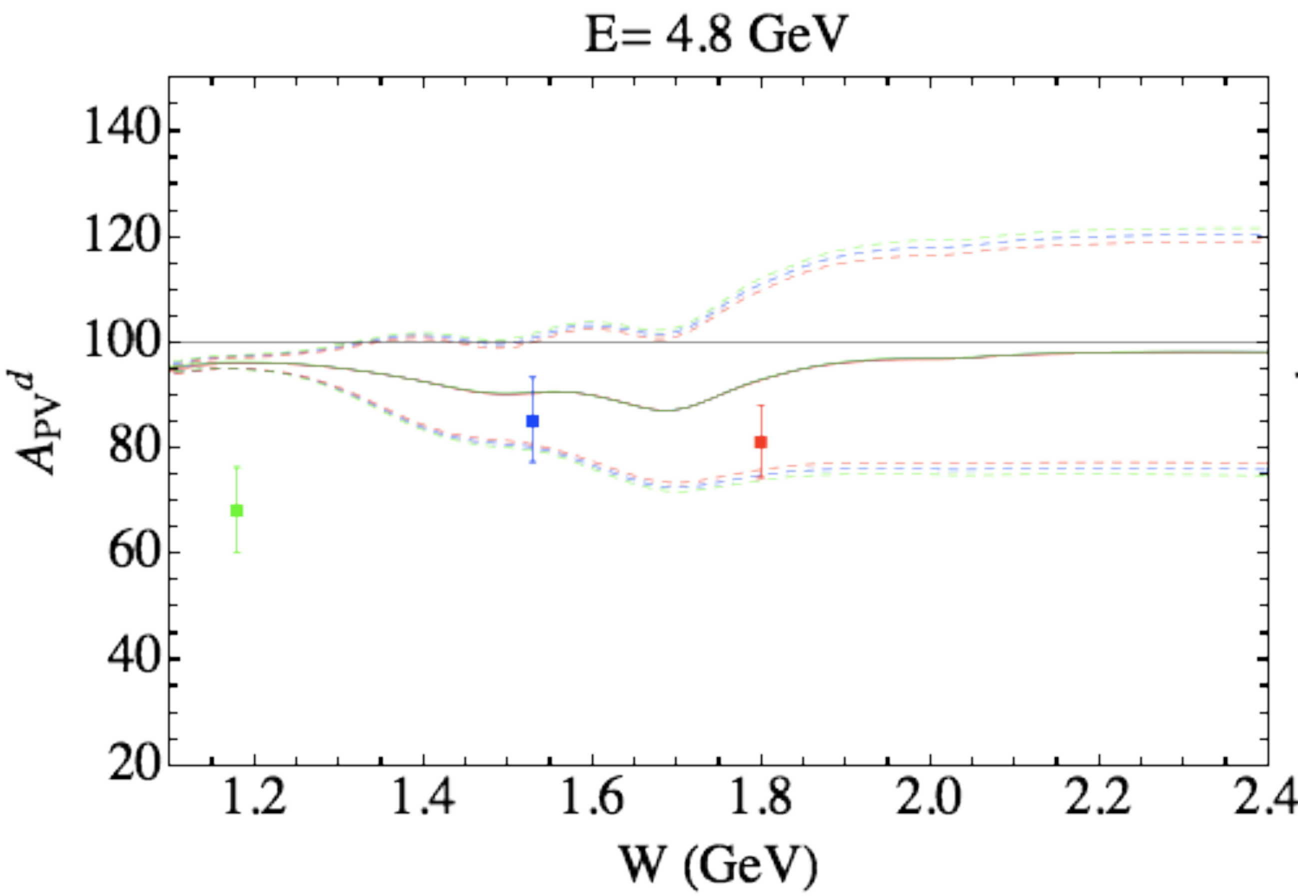
Androic et al. (G0 collaboration), arXiv:1212.1637

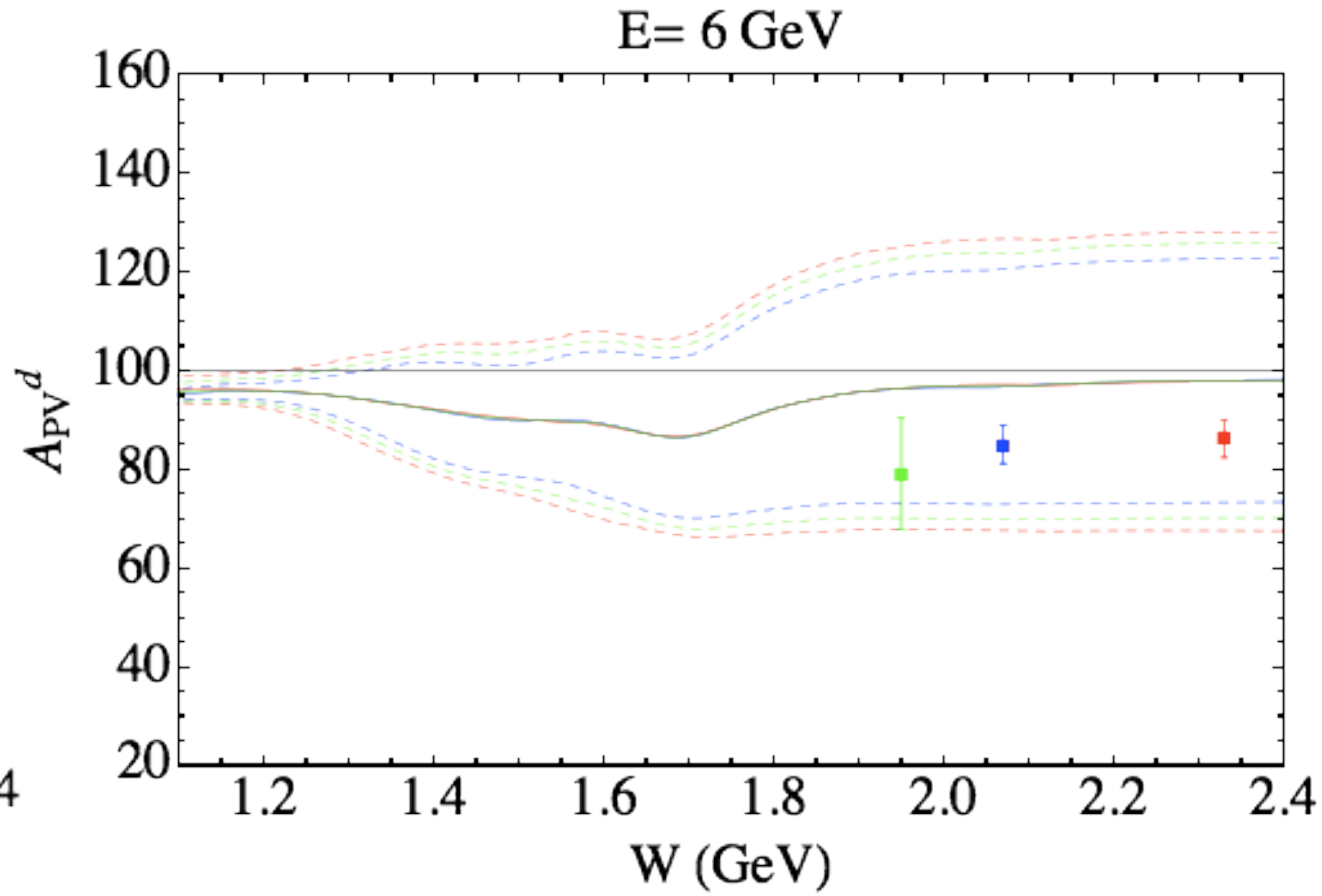


Potential impact of constraints from <u>deuteron</u> PV inelastic asymmetries

100% uncertainty on continuum background

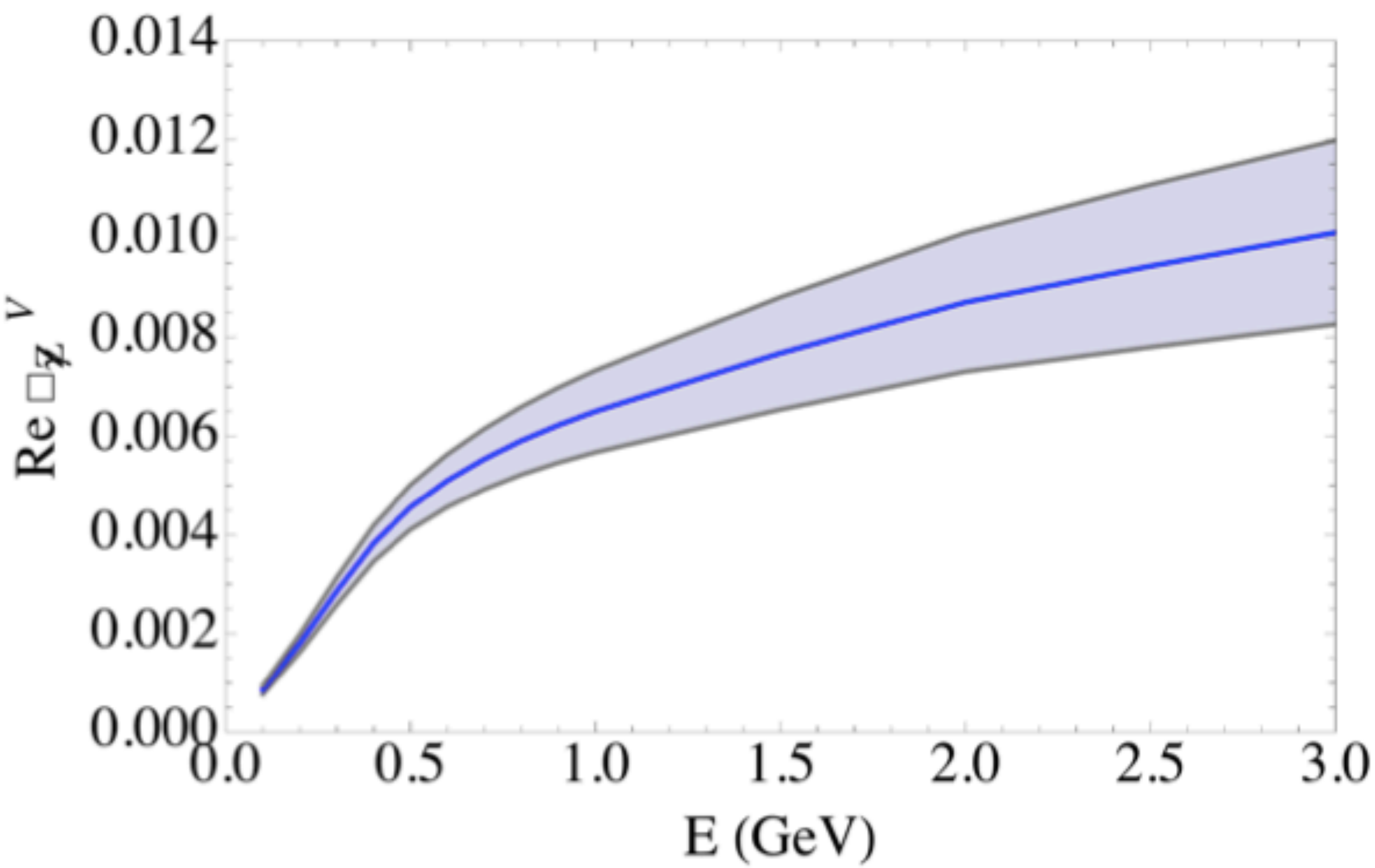


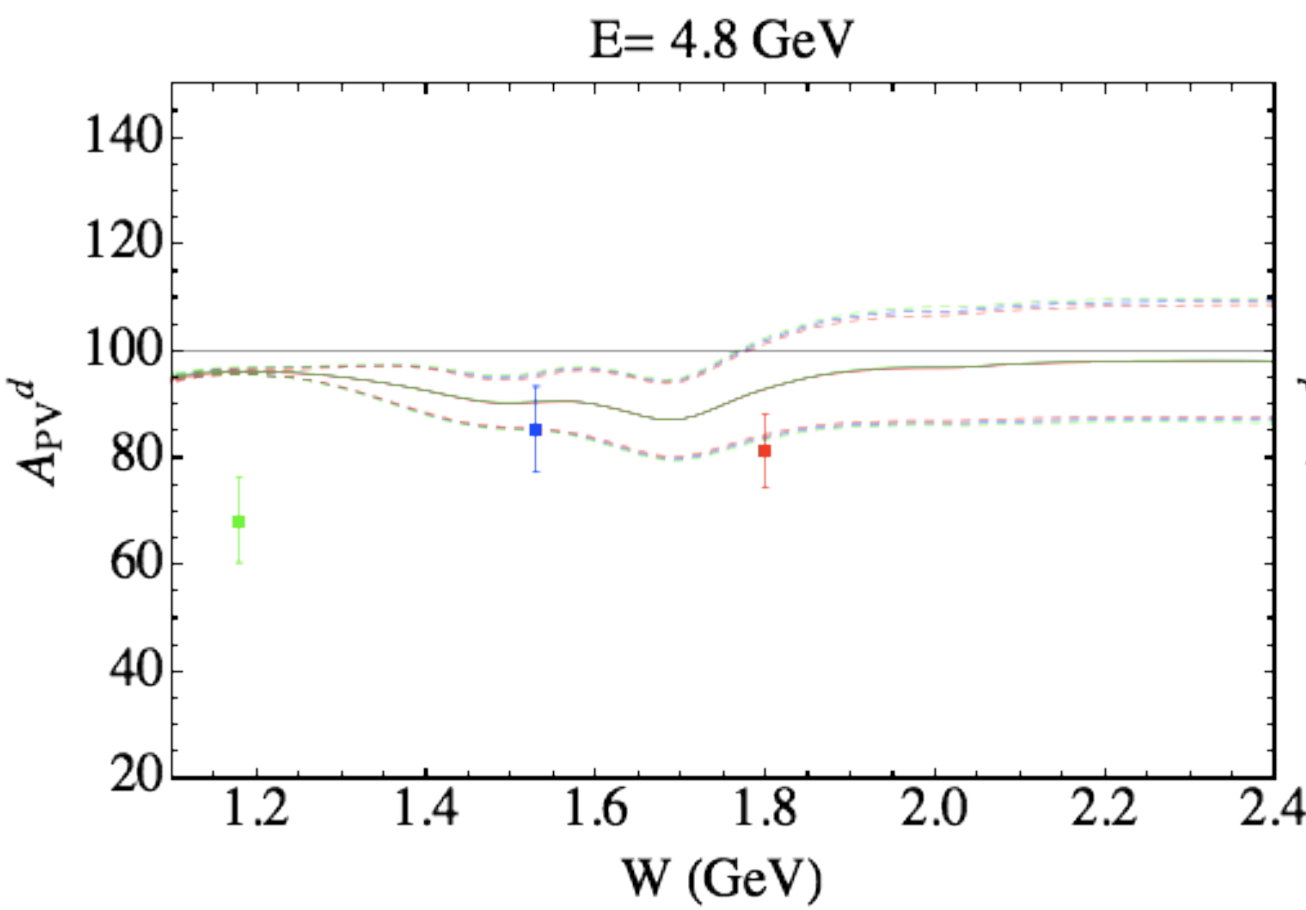


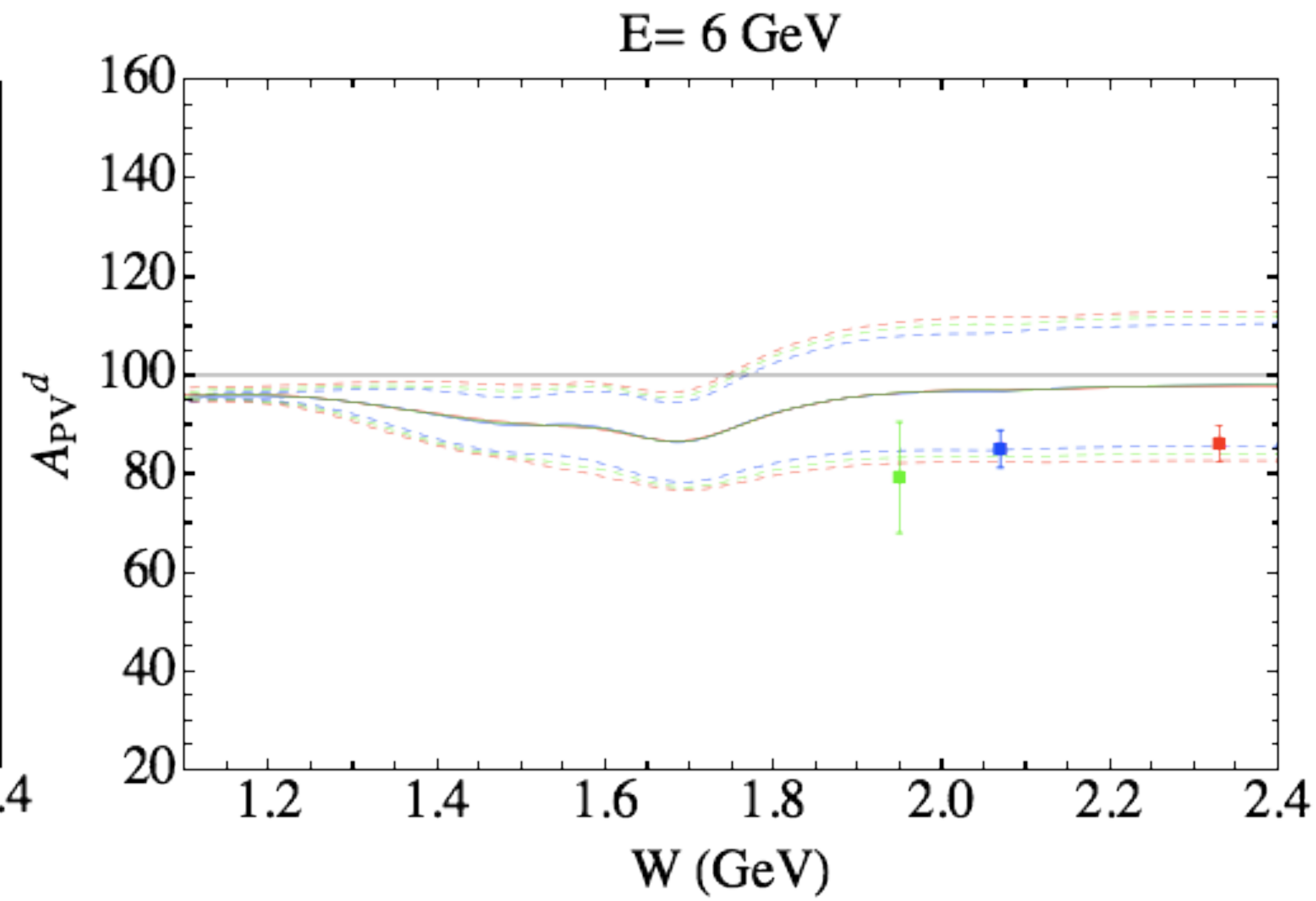


Potential impact of constraints from <u>deuteron</u> PV inelastic asymmetries

50% uncertainty on continuum background

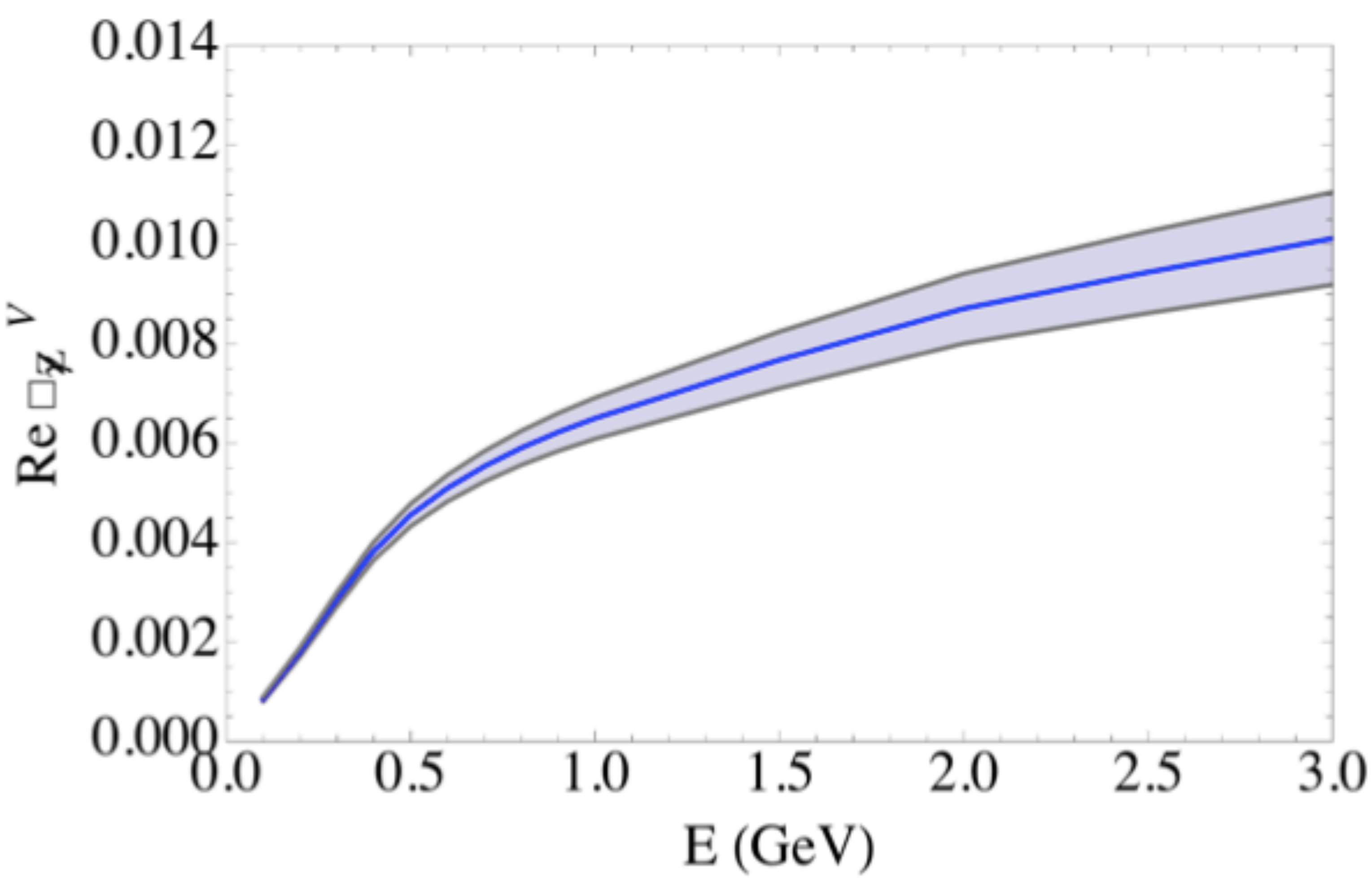






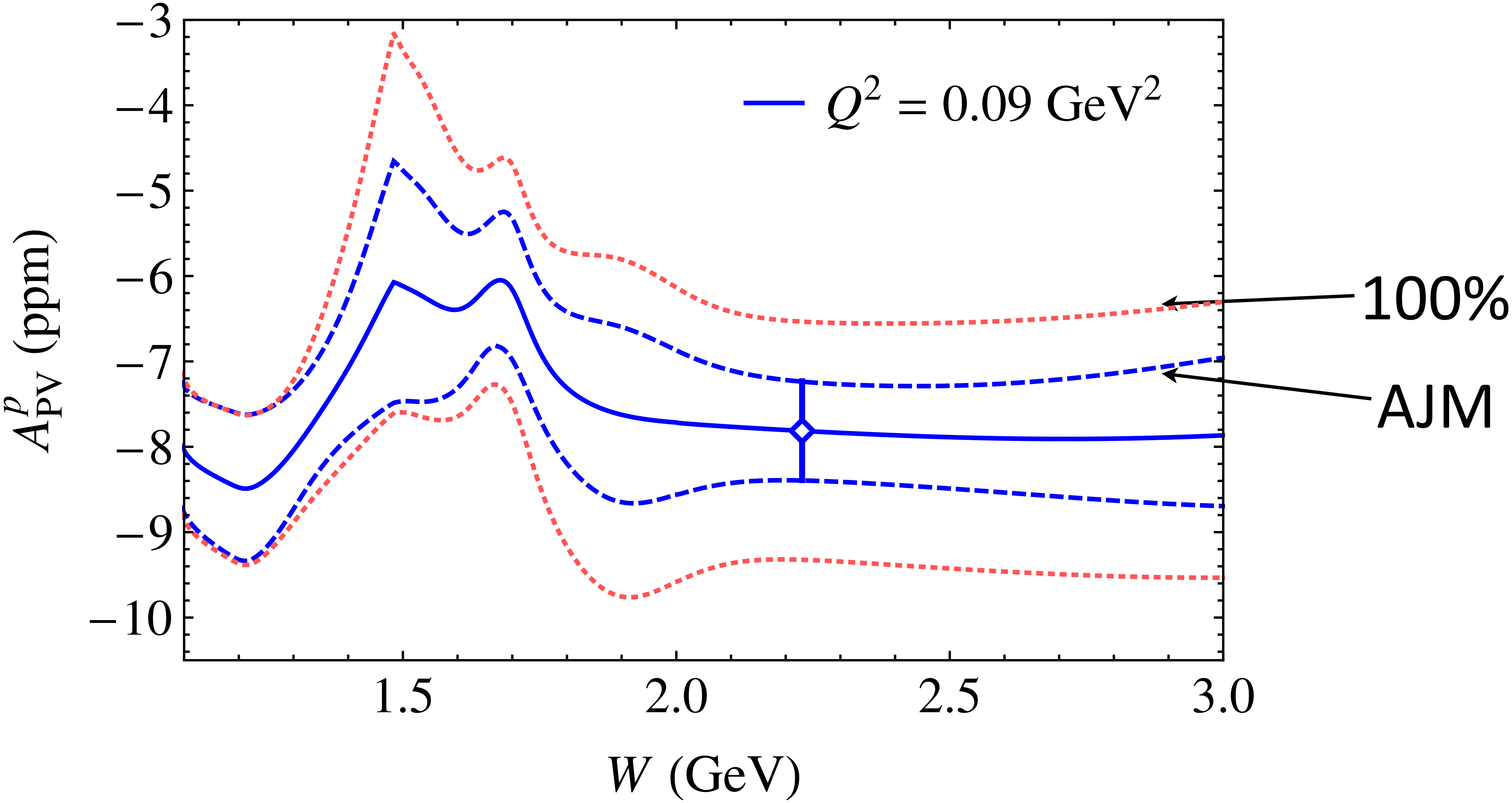
Potential impact of constraints from deuteron PV inelastic asymmetries

25% uncertainty on continuum background



Parity-violating inelastic asymmetries

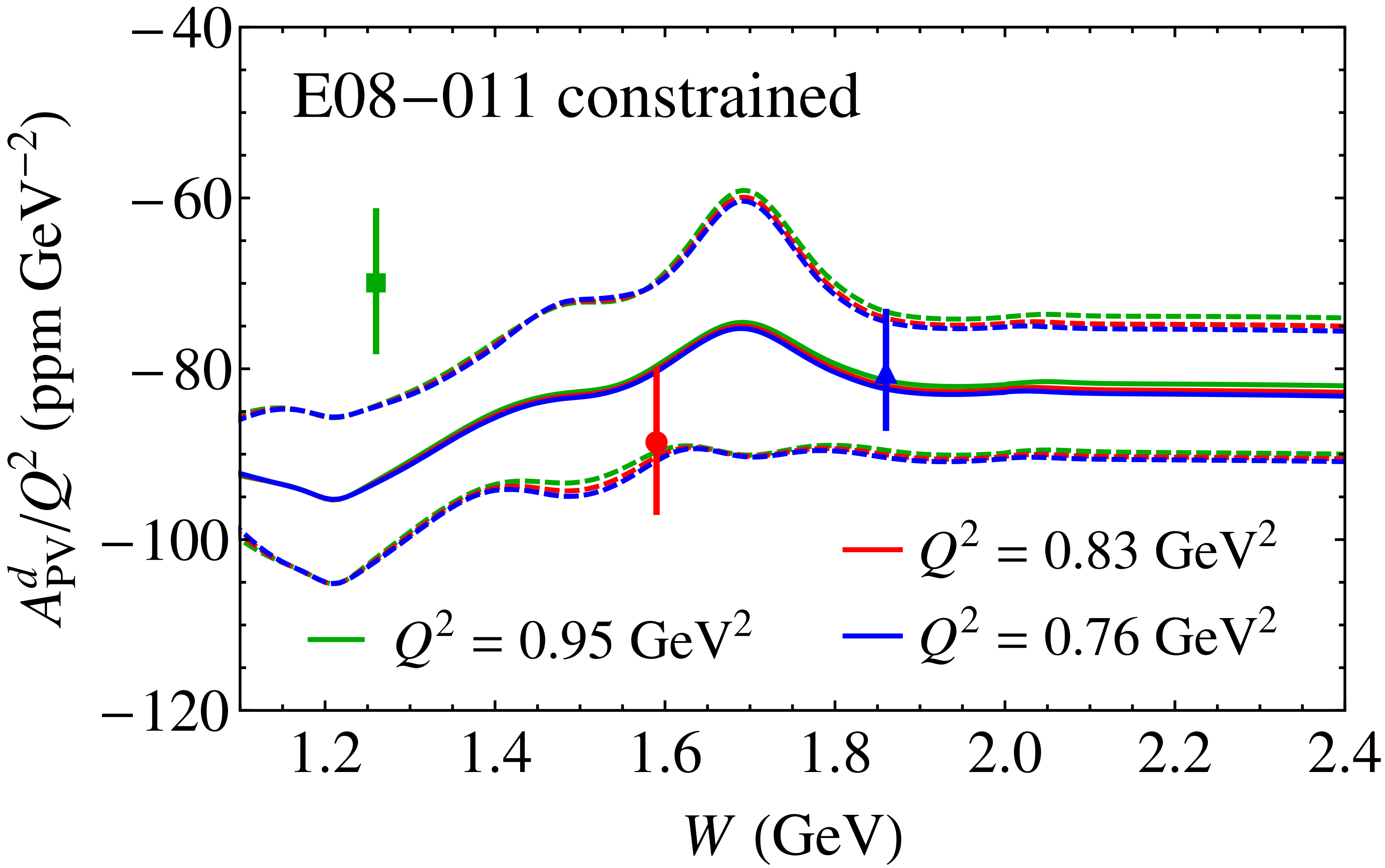
- Expected inelastic asymmetry data from Qweak



→ AJM model uncertainties compared with 100% on continuum contribution

Hall et al. (2013)

Constraints from PV inelastic asymmetries in the resonance region

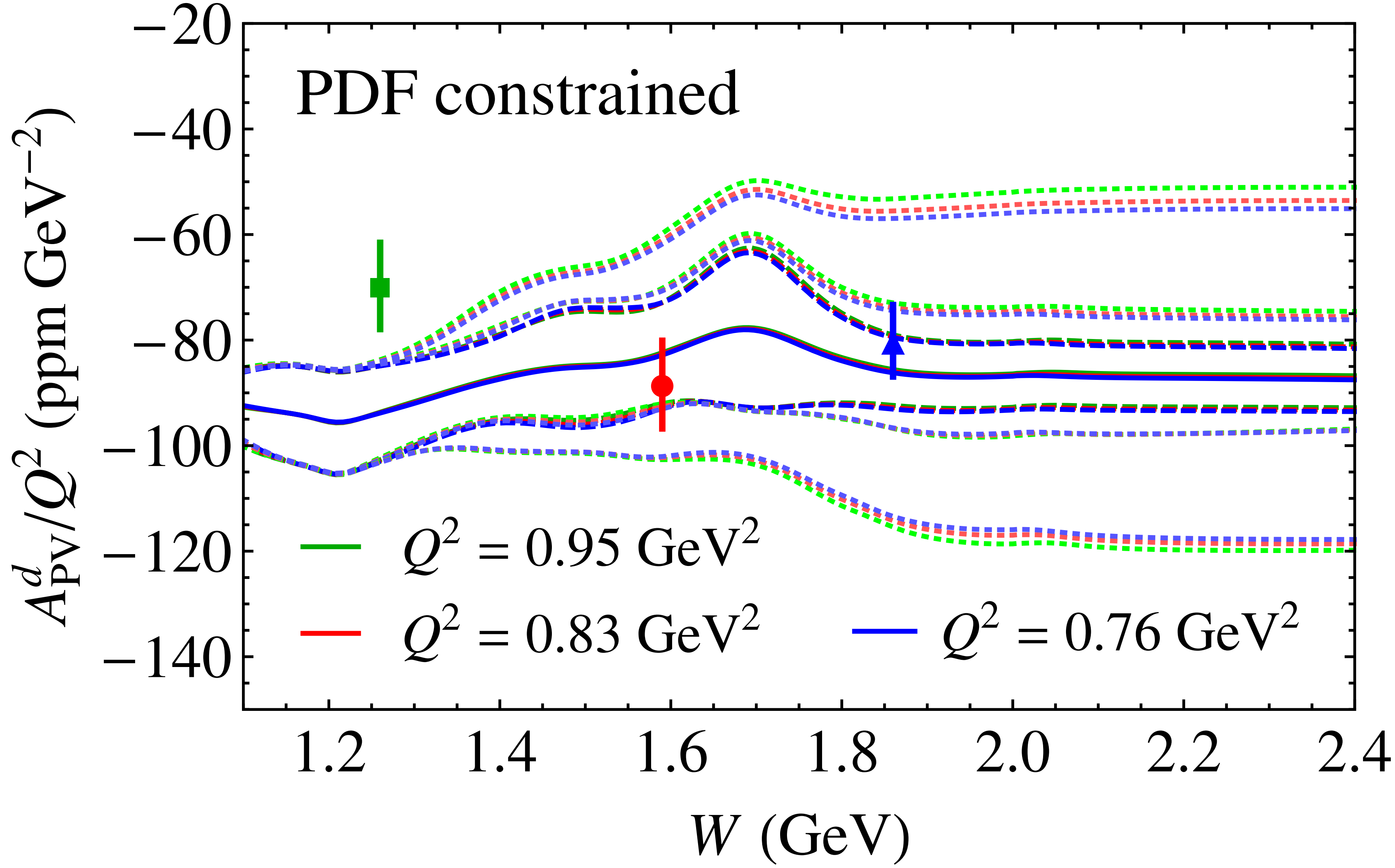


*Wang et al. PRL **111**, 082501 (2013)*

AJM model asymmetries and uncertainties for PV deuteron asymmetry constrained by fit to E08-011 data

Hall et al. (2013)

Predictions for PV deuteron asymmetry in DIS kinematics



Prediction: *Hall et al. (2013)*

$A_{\rm PV} = -92.4 \pm 6.8$ ppm

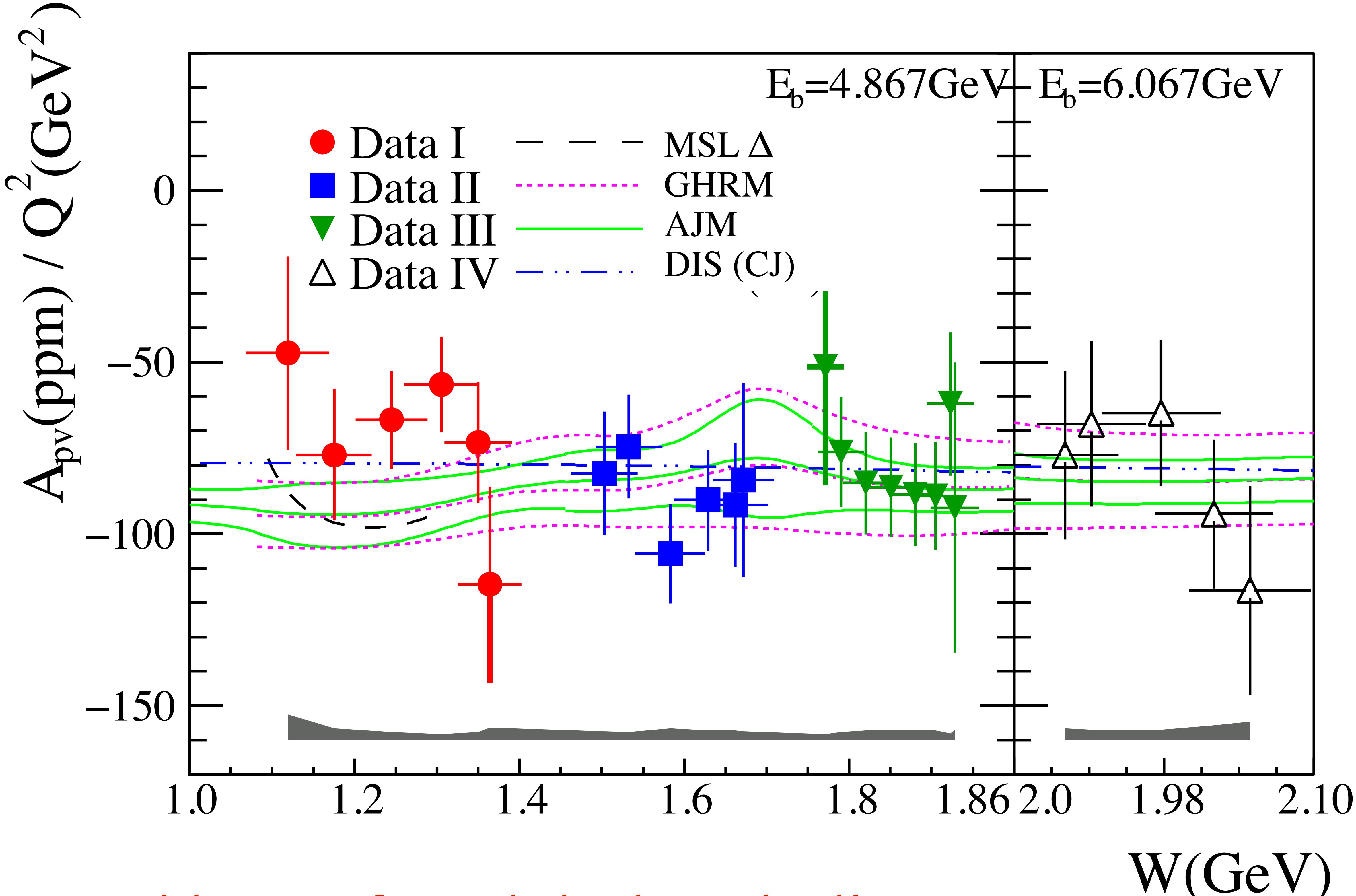
$A_{\rm PV} = -157.2 \pm 12.2$ ppm

E08-011: *Wang et al. Nature* ***506****, 67 (2014)*

$A_{\rm PV} = -91.1 \pm 4.3$ ppm

$A_{\rm PV} = -160.8 \pm 7.1$ ppm

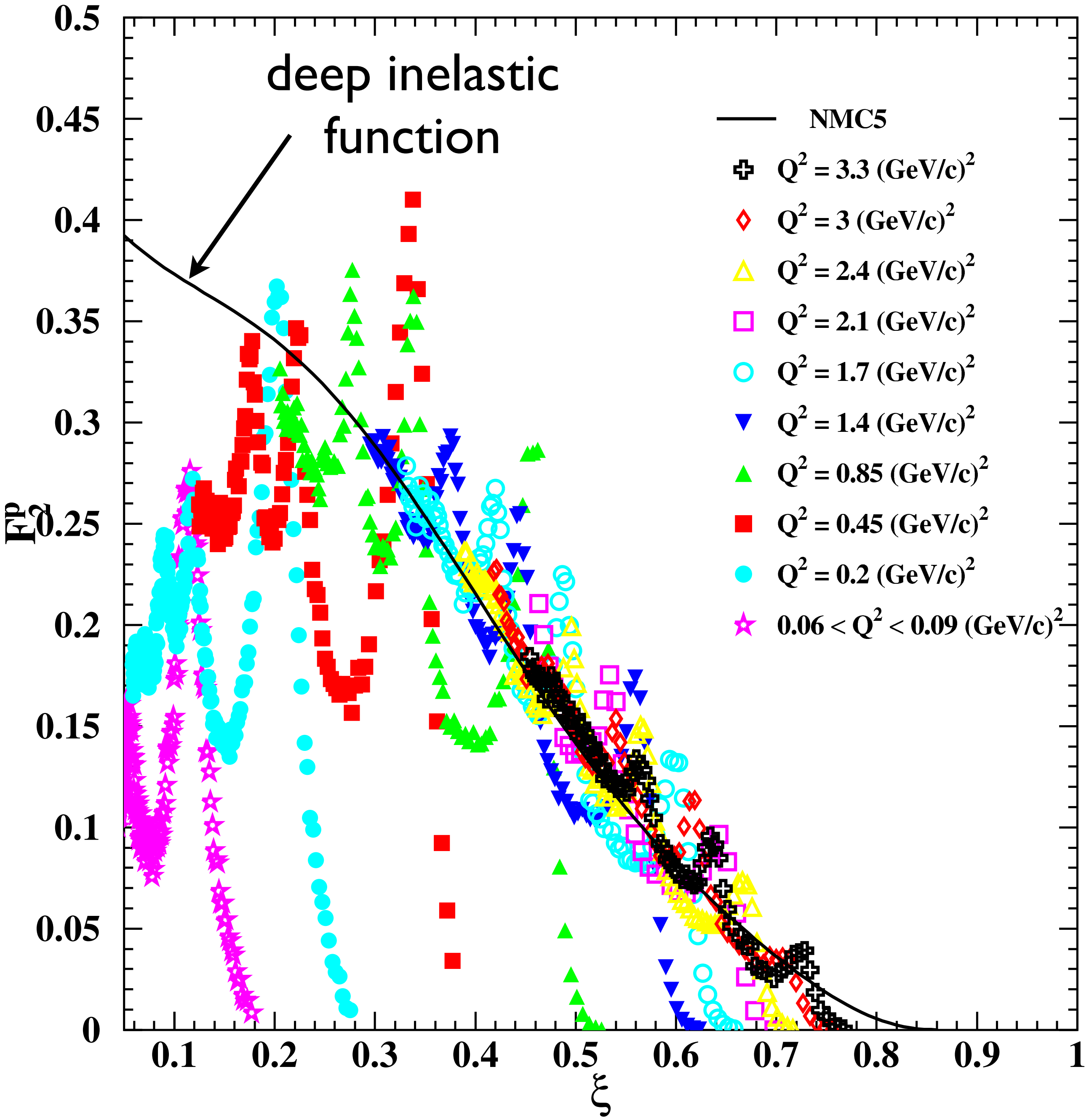
PV deuteron asymmetry in DIS kinematics



Evidence of quark-hadron duality at the 10-15% level

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

Duality in electron-nucleon scattering



Niculescu et al., PRL ***85****, 1182 (2000)*
Melnitchouk, Ent, Keppel, PRep. ***406****, 127 (2005)*

Empiral observation

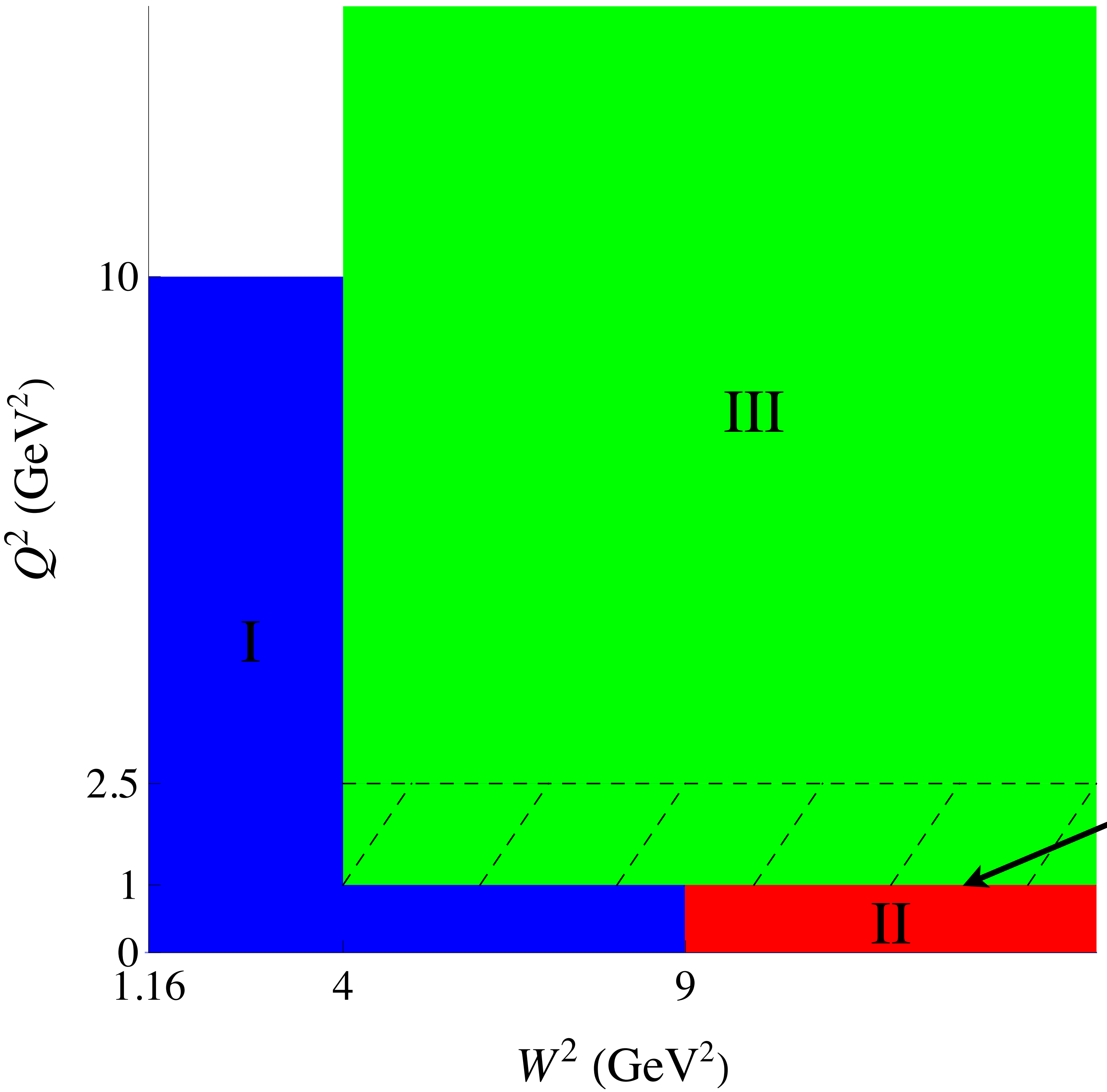
average over
(strongly Q^2-dependent)
resonances
$\approx Q^2$ independent
scaling function

"Nachtmann" scaling variable

$$\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$

Separates higher twist (HT) effects from target mass corrections to leading twist (LT)

Using Quark-Hadron Duality in Resonance Region

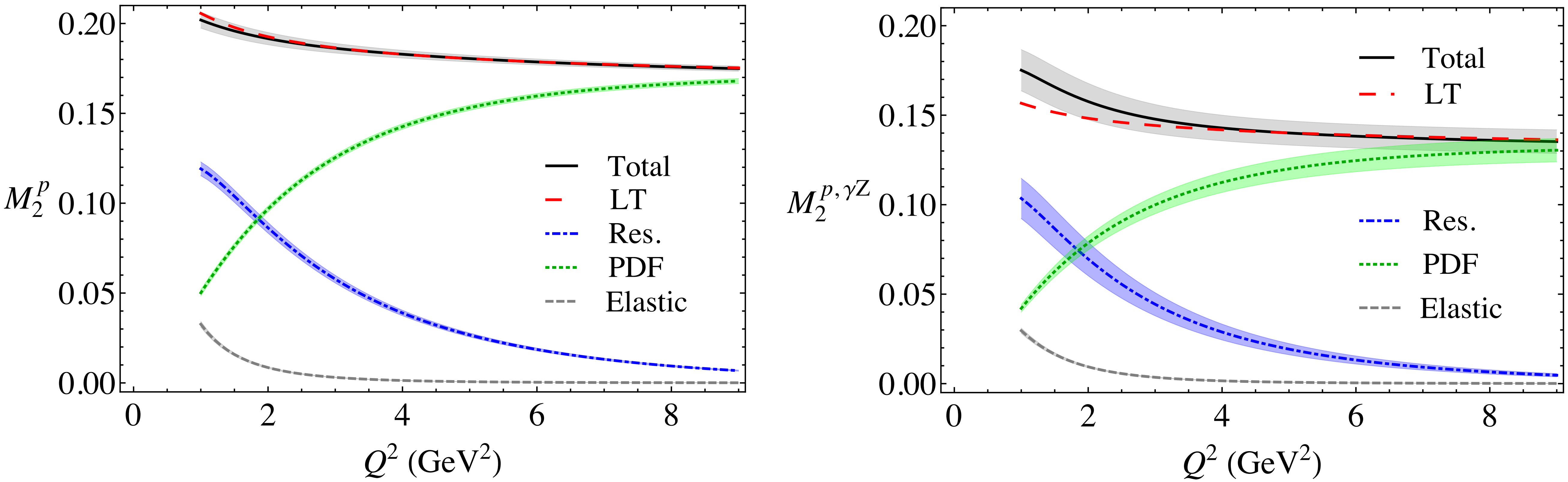


Shift down to
$Q^2 = 1$ GeV^2

- Estimate higher twist corrections using AJM model

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

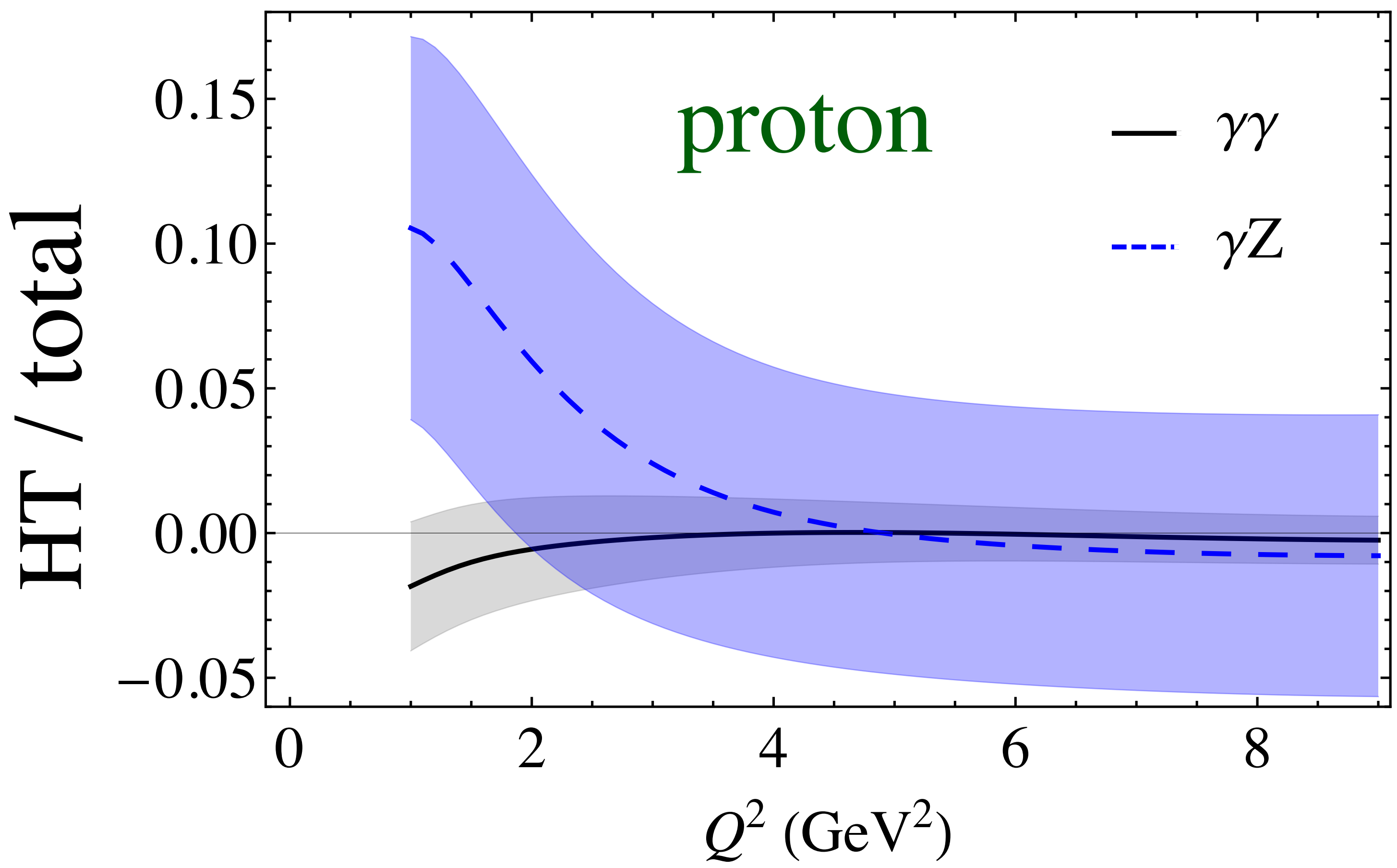
e.g. for F_2^p moment



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

- Estimate higher twist corrections using AJM model

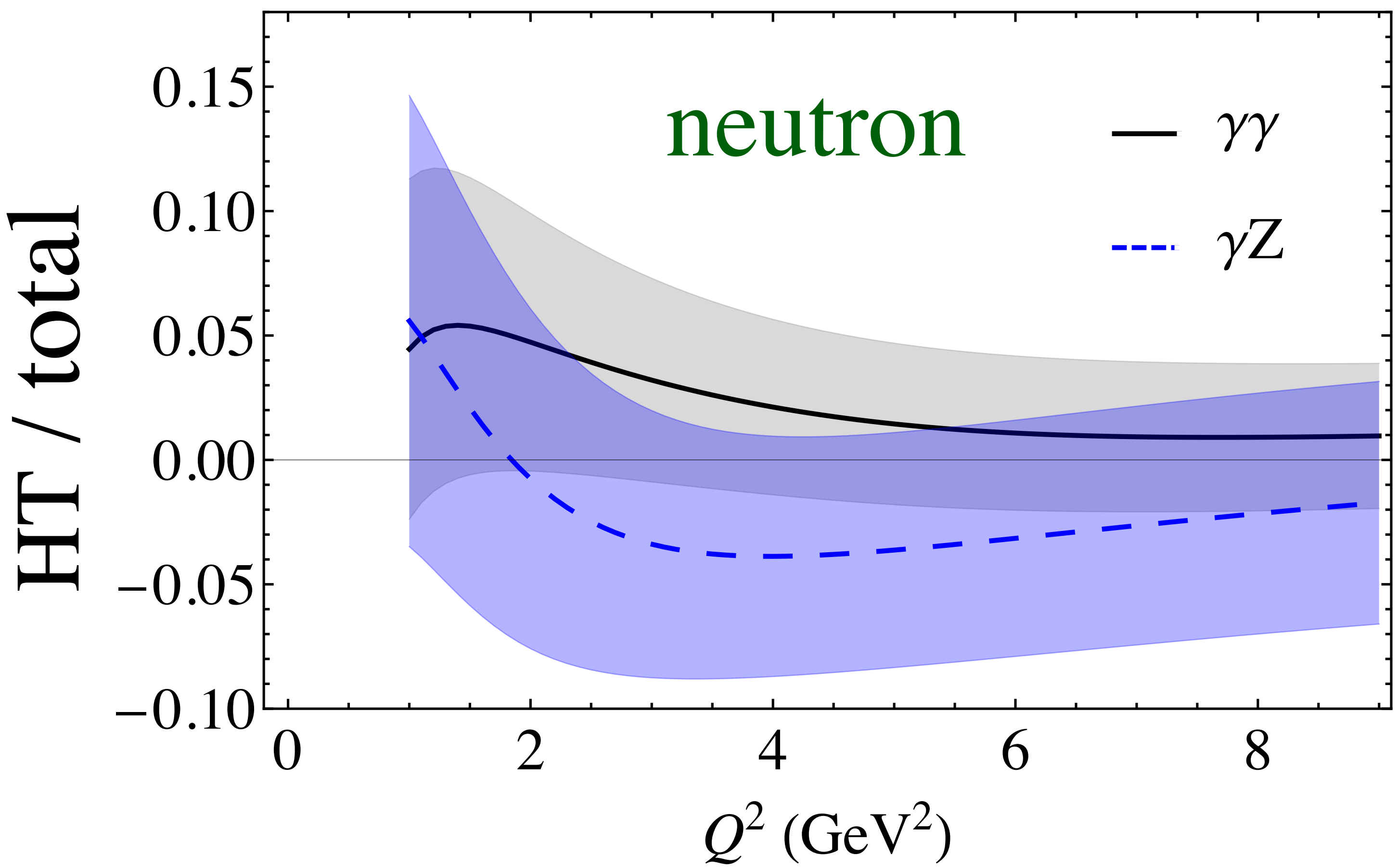
→ define HT as difference between *total* structure function and leading twist contribution



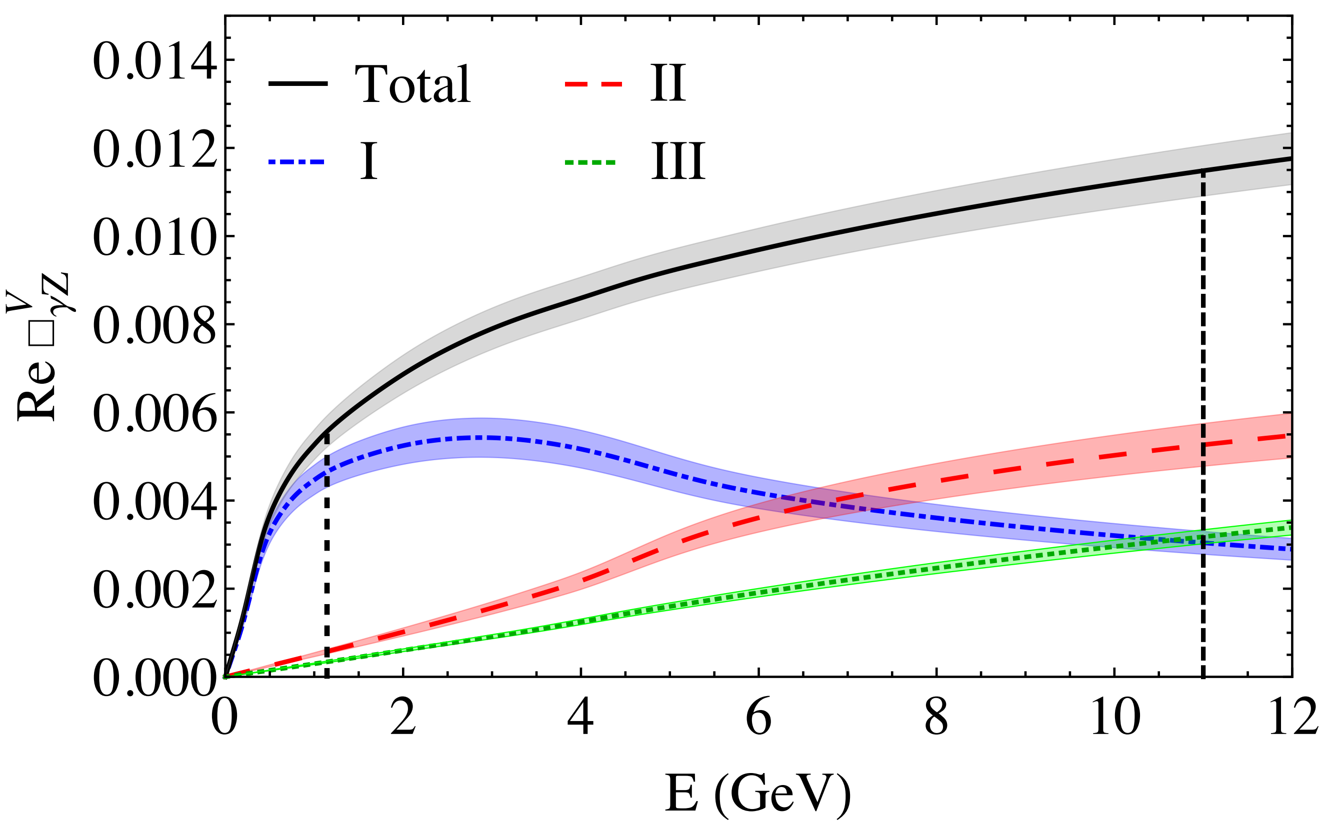
→ HT in γZ for proton larger than in $\gamma\gamma$ but still ~10% at $Q^2 \sim 1\,\mathrm{GeV}^2$

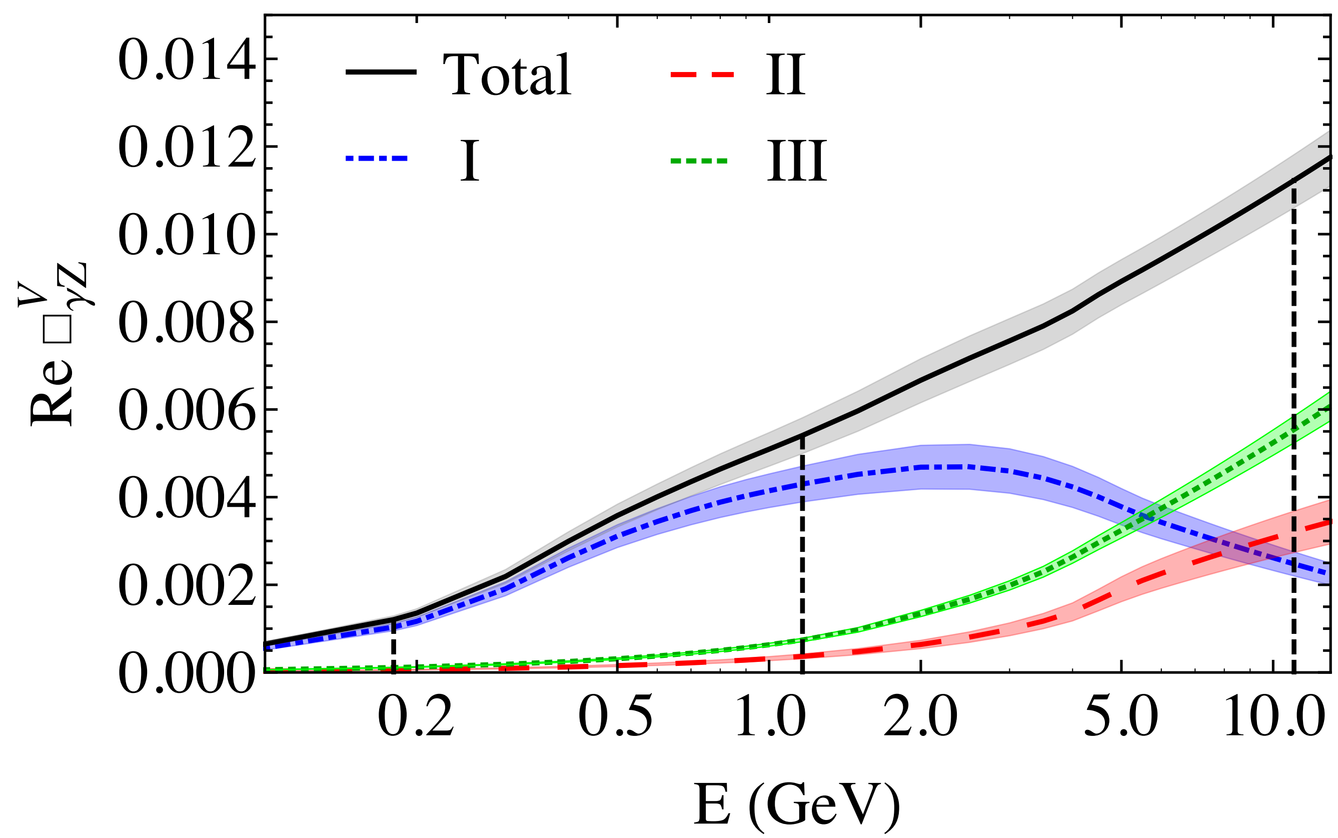
- Estimate higher twist corrections using AJM model

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



→ for neutron HTs are comparable, within larger uncertainties





Match at $Q^2 = 2.5$ GeV²

(rel to $Q_W^p = 0.0713$)

Region	$\Re e\,\Box^V_{\gamma Z}$ ($\times 10^{-3}$) $Q_{\rm weak}$	MOLLER
I	4.64 ± 0.35	3.04 ± 0.26
II	0.59 ± 0.05	5.26 ± 0.49
III	0.35 ± 0.02	3.18 ± 0.16
total	5.57 ± 0.36	11.5 ± 0.6

Using duality down to $Q^2 = 1$ GeV²

Region	$\Re e\,\Box^V_{\gamma Z}$ ($\times 10^{-3}$) $Q_{\rm weak}$ ($E = 1.165$ GeV)	MOLLER ($E = 11$ GeV)	MESA ($E = 0.18$ GeV)
I	4.3 ± 0.4	2.5 ± 0.3	1.0 ± 0.1
II	0.4 ± 0.05	3.2 ± 0.5	0.06 ± 0.01
III	0.7 ± 0.04	5.5 ± 0.3	0.1 ± 0.01
Total	5.4 ± 0.4	11.2 ± 0.7	1.2 ± 0.1

A few comments on Thomson (atomic) versus scattering limits

Thompson limit ($Q^2 \ll m_e{}^2$):

$$Q_W^p = (\rho + \Delta_e)\left(1 - 4\kappa^{\mathrm{PT}}(0)\hat{s}^2 + \Delta_e' + \Delta_W\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$$

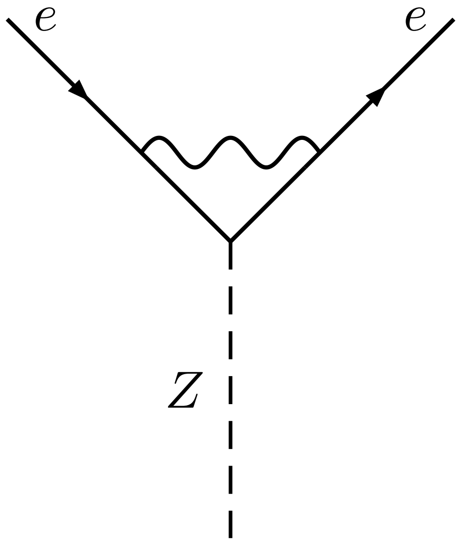
Scattering ($Q^2 \gg m_e{}^2$):

$$\mathcal{A}_{ep} = \mathcal{A}_0\left[Q_W^p(ep) + Q^2 B(Q^2, E)\right], \quad \mathcal{A}_0 \equiv -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

$$Q_W^p(ep) = \lim_{E\to 0}\lim_{Q^2\to 0}\frac{\mathcal{A}_{ep}}{\mathcal{A}_0}$$

Vertex correction: $Q_W^p = (\rho + \Delta_e)\left(1 - 4\kappa^{\rm PT}(0)\hat{s}^2 + \Delta_e' + \Delta_W\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$

Electromagnetic: $\Delta_e = -\frac{\alpha}{2\pi} \sim 0.00116$ (0.1% of 0.0708)



$$\gamma_\mu \to \gamma_\mu(1 + \delta f_1) + \frac{\delta f_2}{2m_e}\sigma_{\mu\nu}(-q^\nu)$$

$$\gamma_\mu\gamma_5 \to \gamma_\mu\gamma_5(1 + \delta g_1) + \cancel{\frac{\delta g_2}{m_e}\gamma_5(-q_\mu)}$$

Thompson limit ($Q^2 \ll m_e^2$): $\delta f_1 = 0; \quad \delta f_2 = \frac{\alpha}{2\pi}; \quad \delta g_1 = -\frac{\alpha}{2\pi}$

Scattering ($Q^2 \gg m_e^2$): $\delta f_1 \sim \log\frac{Q^2}{m_e^2} \times \log\frac{\lambda^2}{m_e^2}; \quad \delta f_2 \to 0; \quad \delta g_1 \to \delta f_1$

IR divergent
(cancelled by soft photon emission)

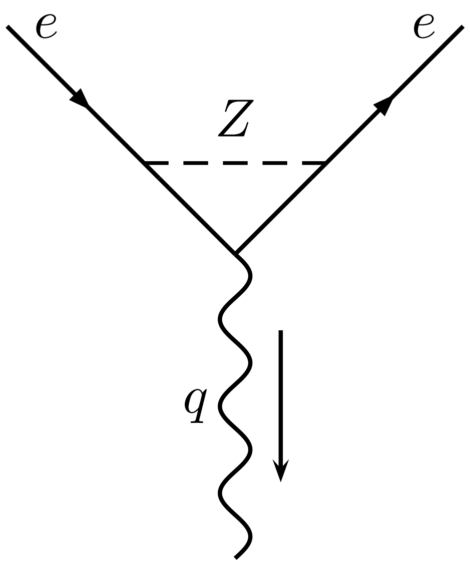
Overall Zee vertex has same (divergent) factor as γee

$\longrightarrow$ Cancels in $A_{\rm PV}$ (or include with standard rad. corr.).

Therefore take $\Delta_e = 0$ for scattering.

Vertex correction: $$Q_W^p = (\rho + \Delta_e)\left(1 - 4\kappa^{\mathrm{PT}}(0)\hat{s}^2 + \Delta_e' + \Delta_W\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$$

Electroweak: $\Delta_e' = -0.0014$ (1.9% of 0.0708)

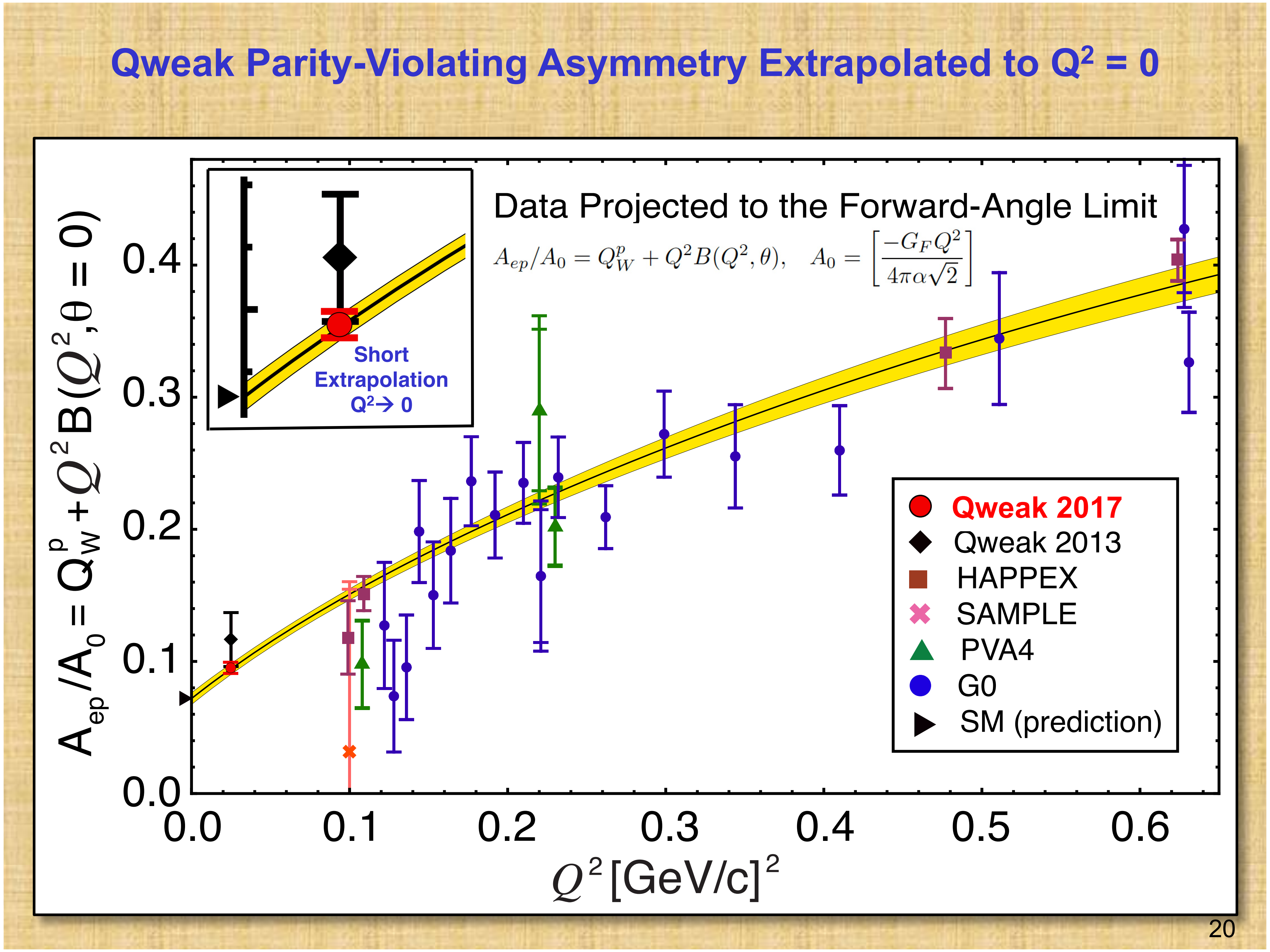


Thompson limit ($Q^2 \ll m_e^2$): $$\Delta_e'(0) = -\frac{\alpha}{3\pi}(1 - 4\hat{s}^2)\left(\log\frac{M_z^2}{m_e^2} + \frac{1}{6}\right)$$

Scattering ($Q^2 \gg m_e^2$): $$\Delta_e'(Q^2) = -\frac{\alpha}{3\pi}(1 - 4\hat{s}^2)\left(\log\frac{M_z^2}{Q^2} + \frac{11}{6}\right)$$

$$\Delta_e'(Q^2) = \Delta_e'(0) + \underbrace{\frac{\alpha}{3\pi}(1 - 4\hat{s}^2)\left(\log\frac{Q^2}{m_e^2} - \frac{5}{3}\right)}_{+0.0006 \text{ at } Q^2 = 0.025 \text{ GeV}^2}$$

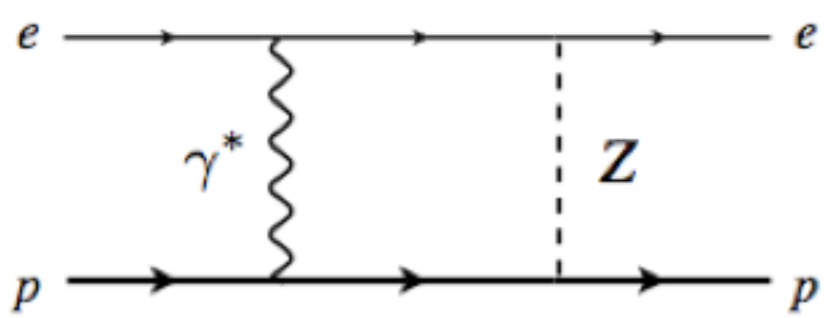
Same size as electron contribution from running of $\sin^2\theta_W$

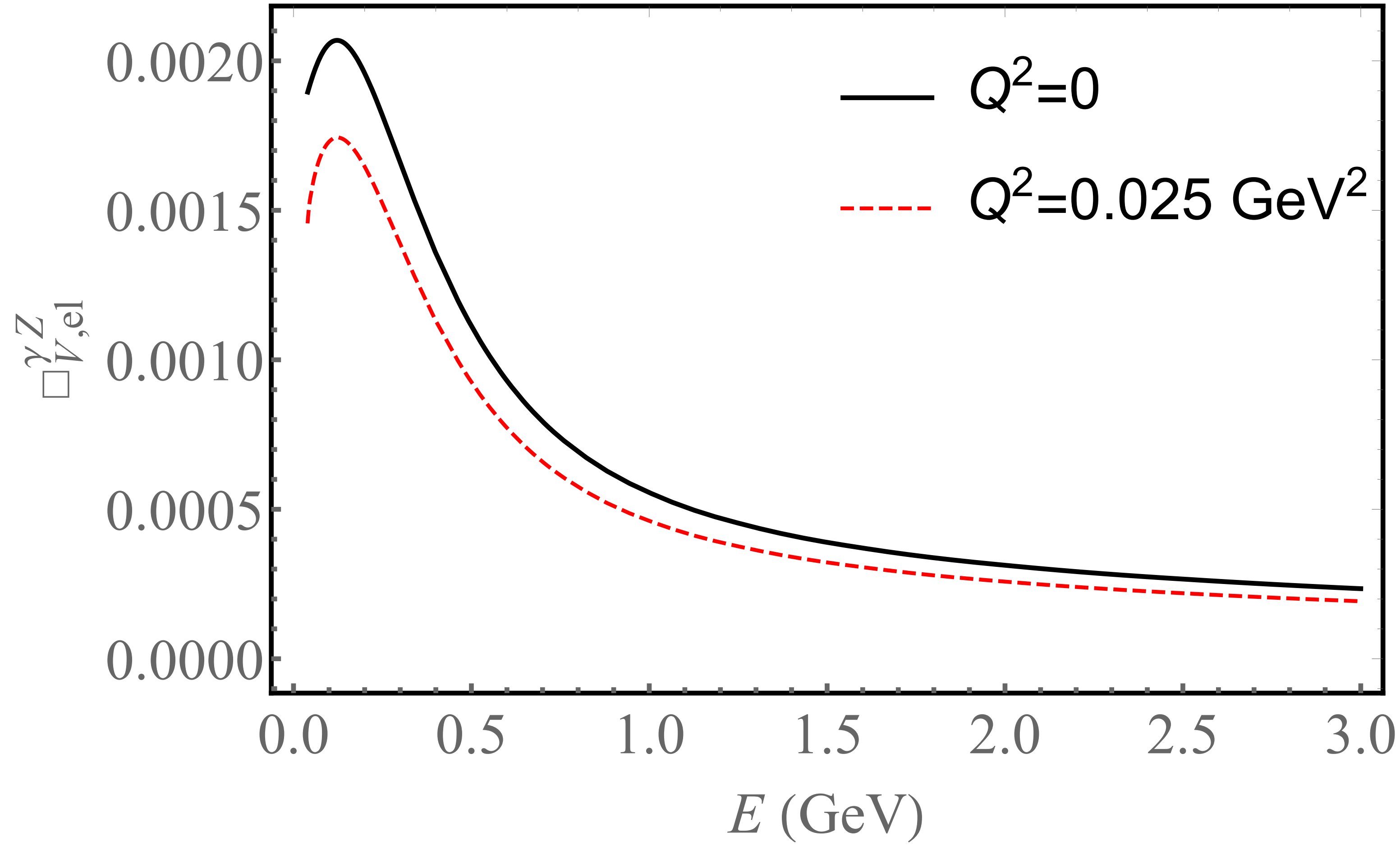


Assumption: $$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left(Q_W^p + Q^2 B(Q^2, \theta_e)\right)$$

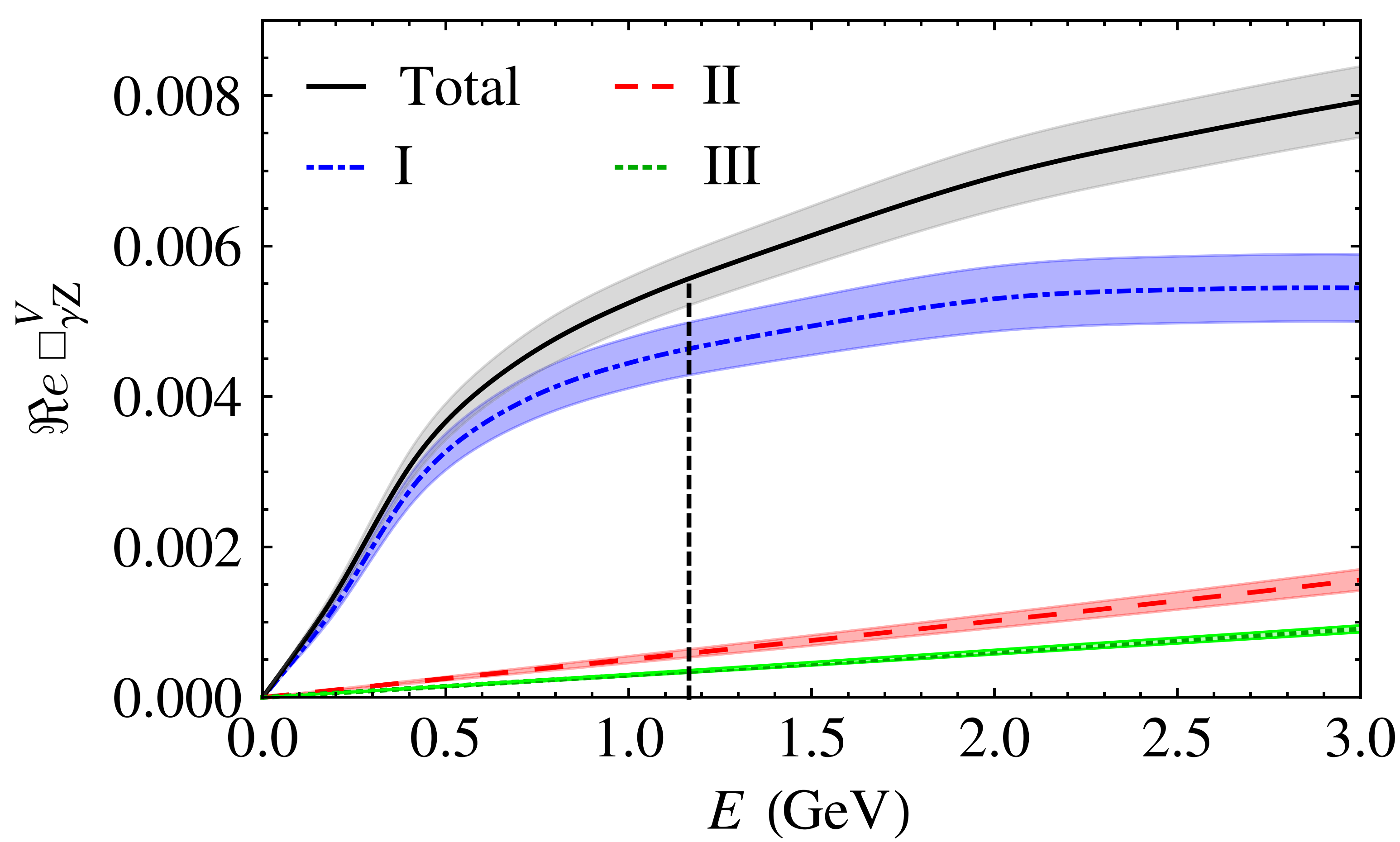
Log terms most likely to affect extraction of additional parameters from fit, not extracted value of Q_W

Elastic part of Vector *h* correction





- Can be considered a "Coulomb distortion" effect
- Relatively insensitive to choice of nucleon form factors
- Equal to $\alpha\pi(1\text{-}4s^2)$ as $E\rightarrow 0$ independent of structure
- Does <u>not</u> cancel in A_{PV} ratio
- Excluded by Marciano-Sirlin in atomic systems (bound states)
- More important for P2 than Qweak



Summary

- Dispersion approach significant improvement over old methods
- PDF region provides some constraints on model-dependence of isospin rotation
- Direct comparison with PV inelastic data in resonance and DIS regions
- e-d PVDIS asymmetry strongly constrains the uncertainty
- checking Δ region for inelastic A_{PV} at Mainz or JLab would be useful
- quark-hadron duality approach allows further constraints on uncertainties