Measurement of parity violation in the resonance region for the proton and deuteron

Mark Dalton, Vincent Sulkosky,
Narbe Kalantarians, Ciprian Gal
for the PVRES Collaboration

Jefferson Lab

Contents

Physics Motivation

Proposed Experiment

Backgrounds

Basic Overview

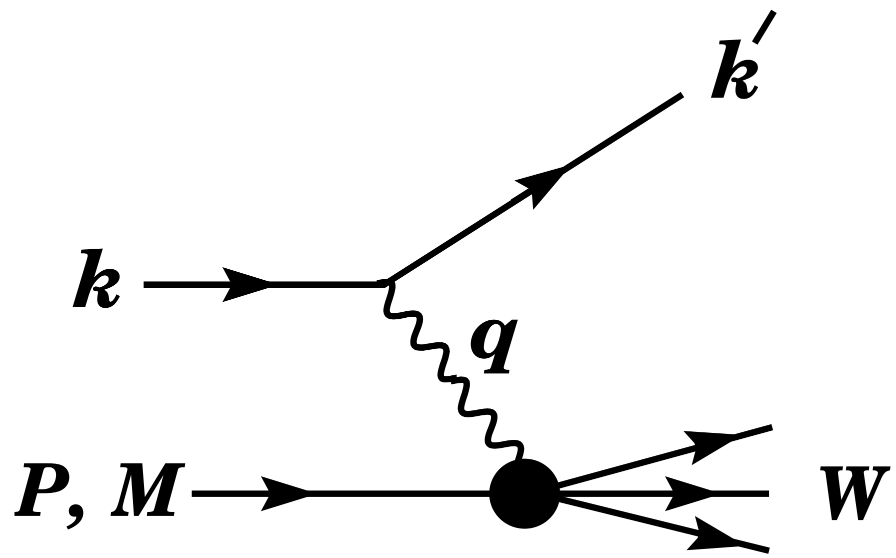
Measure the parity violating asymmetry in electron scattering from hydrogen and deuterium in the nucleon resonance region at low Q^2 ($0.25 < Q^2 < 0.8$ GeV^2)

$$A_{\rm PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

First measurement on a proton target
Increase in precision over existing deuterium data
Push data to Q^2 values where:
- resonances are more pronounced,
- duality is less well established,
- impact on γZ box diagrams is most significant

28 Days in Hall C
4.4 GeV longitudinally polarized electrons up to 80 uA

Structure Functions



$$\frac{d^2\sigma}{dxdy} = \frac{2\pi y\alpha^2}{Q^4} \sum_j \eta_j \, L_j^{\mu\nu} \, W_{\mu\nu}^j$$

$$j \in \{\gamma, \gamma Z, Z, W\}$$

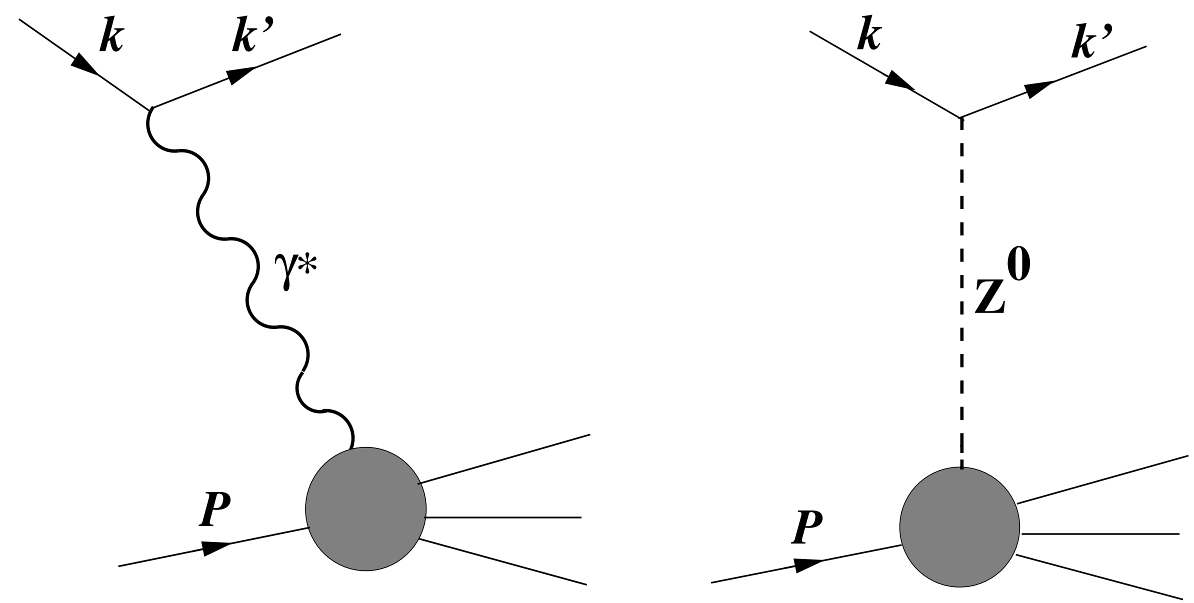
lowest-order perturbation theory

$$\begin{aligned} W_{\mu\nu} = & \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} F_2(x,Q^2) \\ & - i\varepsilon_{\mu\nu\alpha\beta} \frac{q^\alpha P^\beta}{2P\cdot q} F_3(x,Q^2) \\ & + i\varepsilon_{\mu\nu\alpha\beta} \frac{q^\alpha}{P\cdot q} \left[S^\beta g_1(x,Q^2) + \left(S^\beta - \frac{S\cdot q}{P\cdot q} P^\beta \right) g_2(x,Q^2) \right] \\ & + \frac{1}{P\cdot q} \left[\tfrac{1}{2} \left(\hat{P}_\mu \hat{S}_\nu + \hat{S}_\mu \hat{P}_\nu \right) - \frac{S\cdot q}{P\cdot q} \hat{P}_\mu \hat{P}_\nu \right] g_3(x,Q^2) \\ & + \frac{S\cdot q}{P\cdot q} \left[\frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q} g_4(x,Q^2) + \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} \right) g_5(x,Q^2) \right] \end{aligned}$$

Hadronic tensor written in terms of structure functions

Parity Violating Electron Scattering (PVES)

The asymmetry in PVES depends on the γZ and γ structure functions



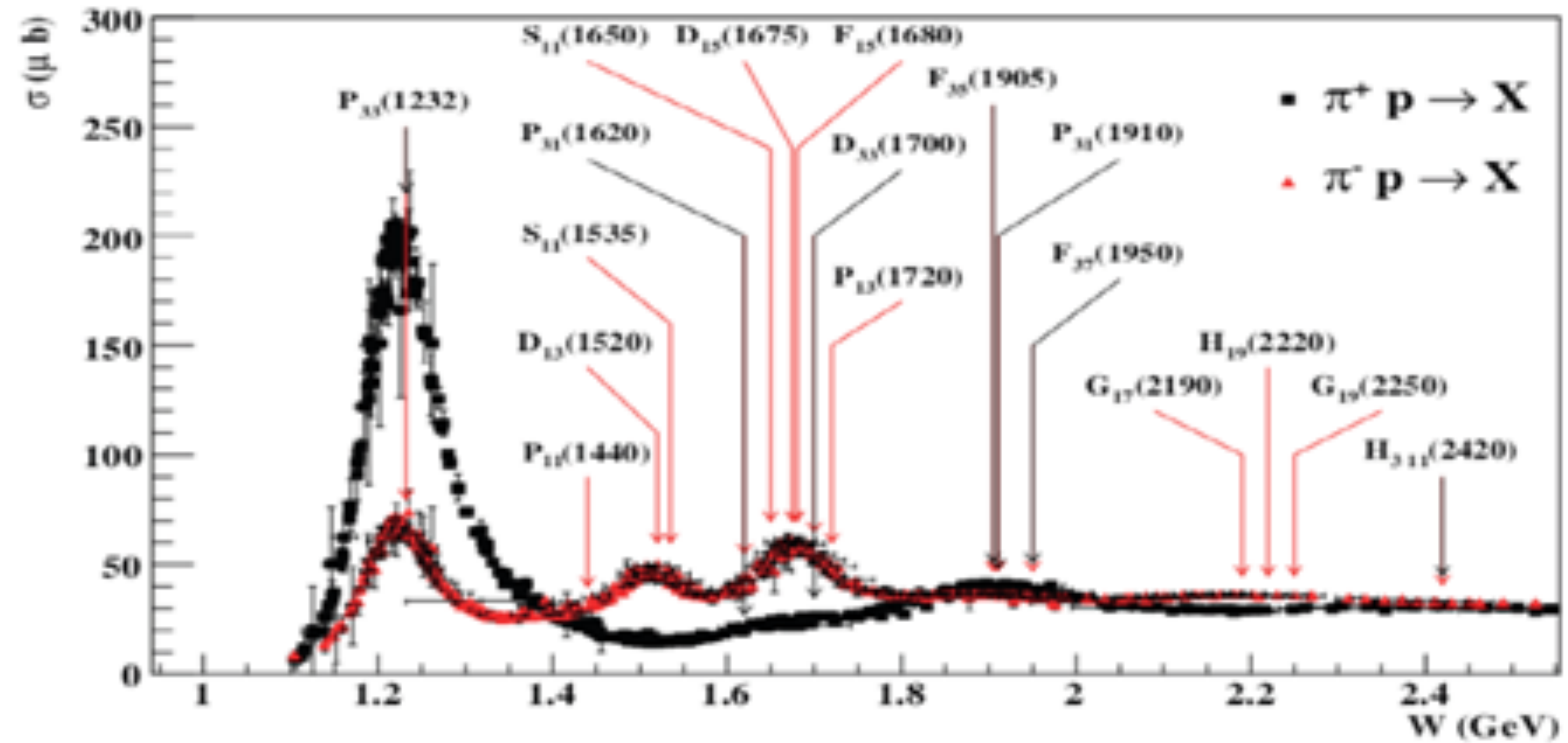
$$A_{PV} = g_A^e \left(\frac{G_F Q^2}{2\sqrt{2}} \pi\alpha \right) \frac{v_1 F_1^{\gamma Z} + v_2 F_2^{\gamma Z} + \frac{g_V^e}{g_A^e} v_3 x F_3^{\gamma Z}}{v_1 F_1^{\gamma} + v_2 F_2^{\gamma}}$$

$$v_1 = x y^2$$

$$v_2 = (1 - y - \frac{x^2 y^2 M^2}{Q^2})$$

$$v_3 = (y - \frac{1}{2} y^2)$$

Resonance Region



Composed of multiple broad and overlapping resonances and a continuum background. (Not separated in a model independent way.)

Not expected to be described by Parton Distribution Functions,

except observations of quark-hadron duality

response averaged over resonances equal that at higher Q^2 (target mass and leading-log corrections)

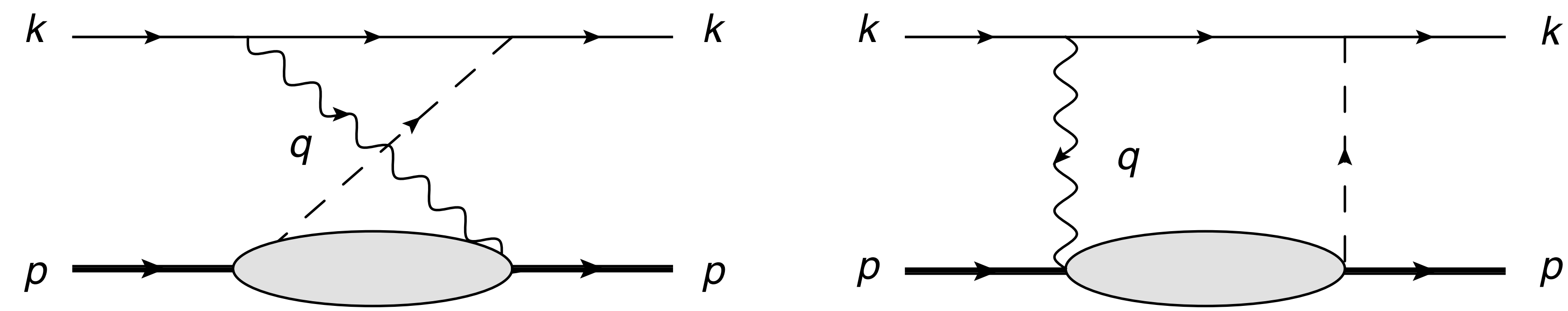
Resonances described in terms of transition form factors to specific resonant states

the weak current will couple to individual resonances differently than the electromagnetic current

The Weak Charge of the Proton

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

Allows the extraction of the weak mixing angle



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

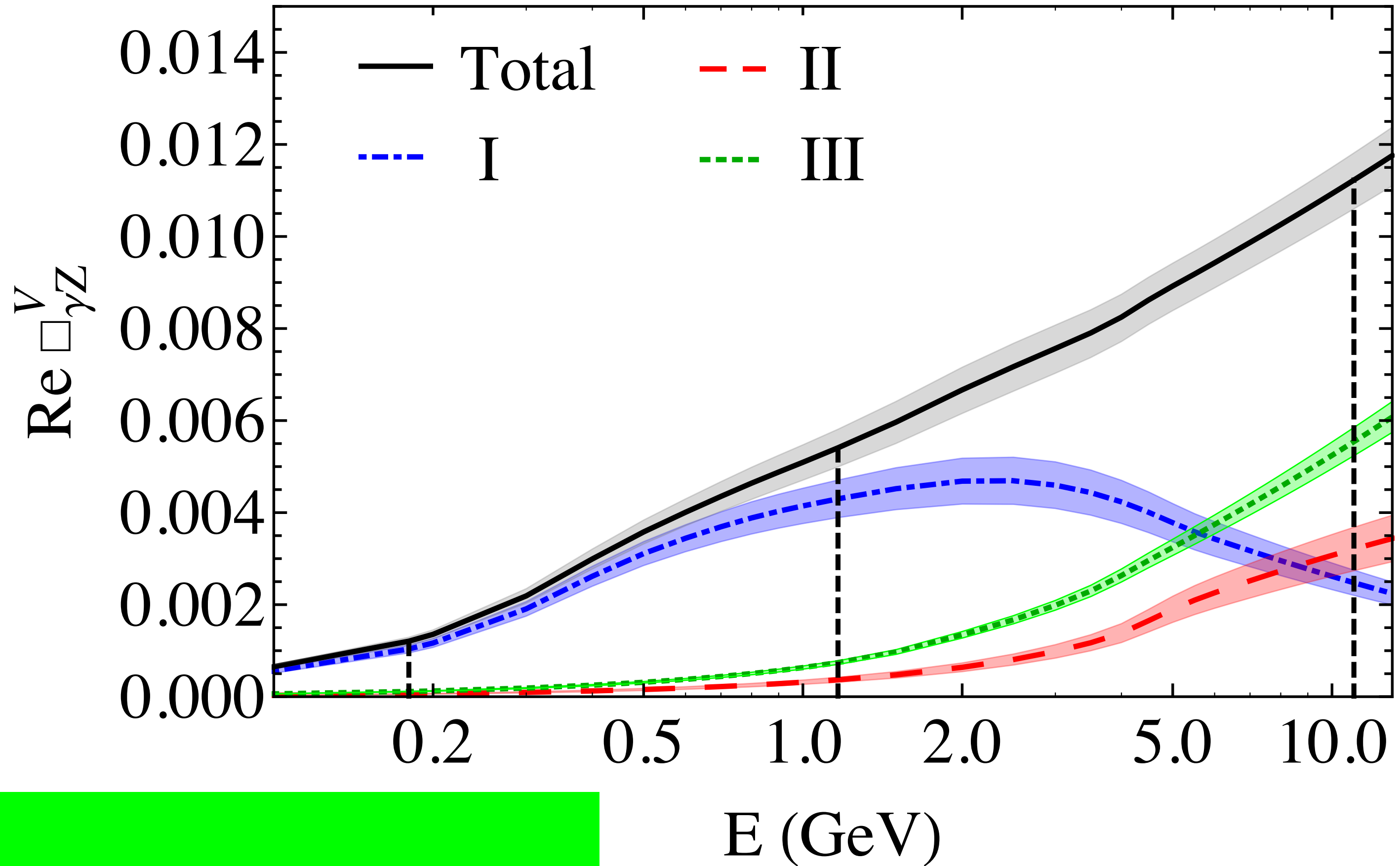
Optical theorem relates γZ box to integral over all phase space of the γZ structure functions

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

Real part obtained using dispersion relations

Parametrizing γZ Structure Functions

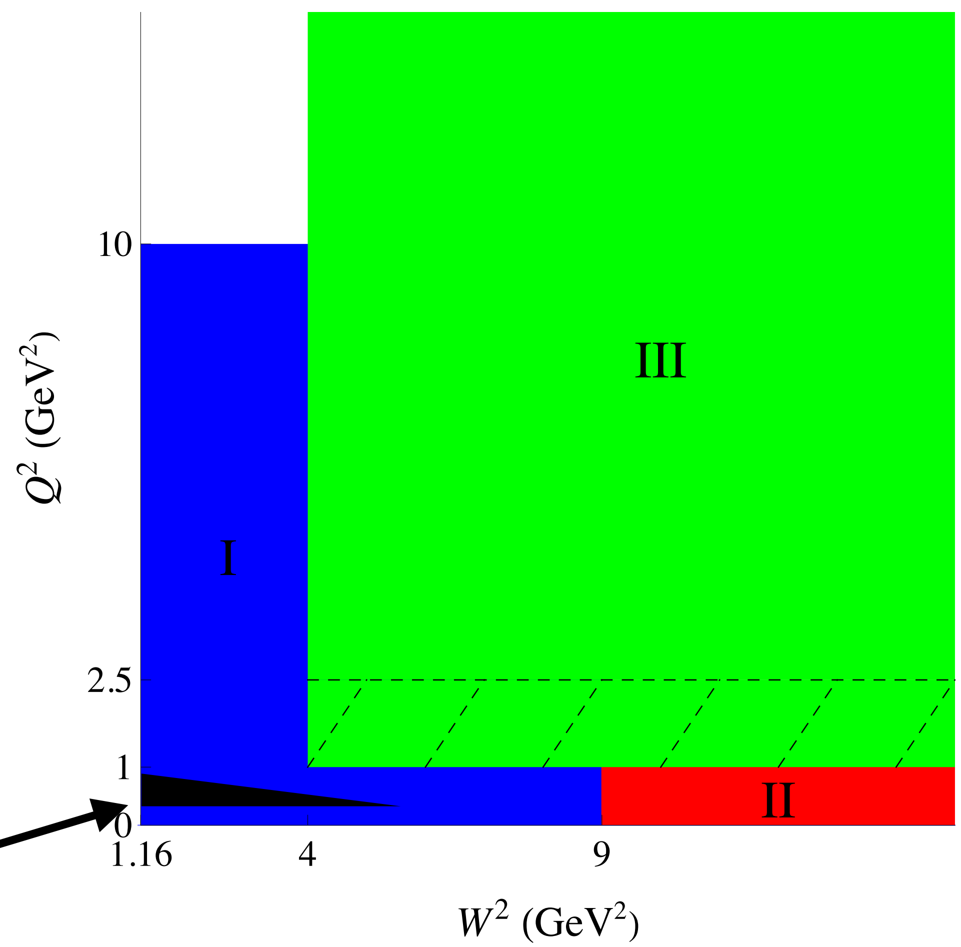
Hall et al, PRD 88, 013011 (2013)



separate resonant and continuum part (model dependent)

Resonances: isospin transformation using CVC and PDG couplings (modest uncertainty)

Continuum: isospin transformation using VMD or color dipole model



PVRES data

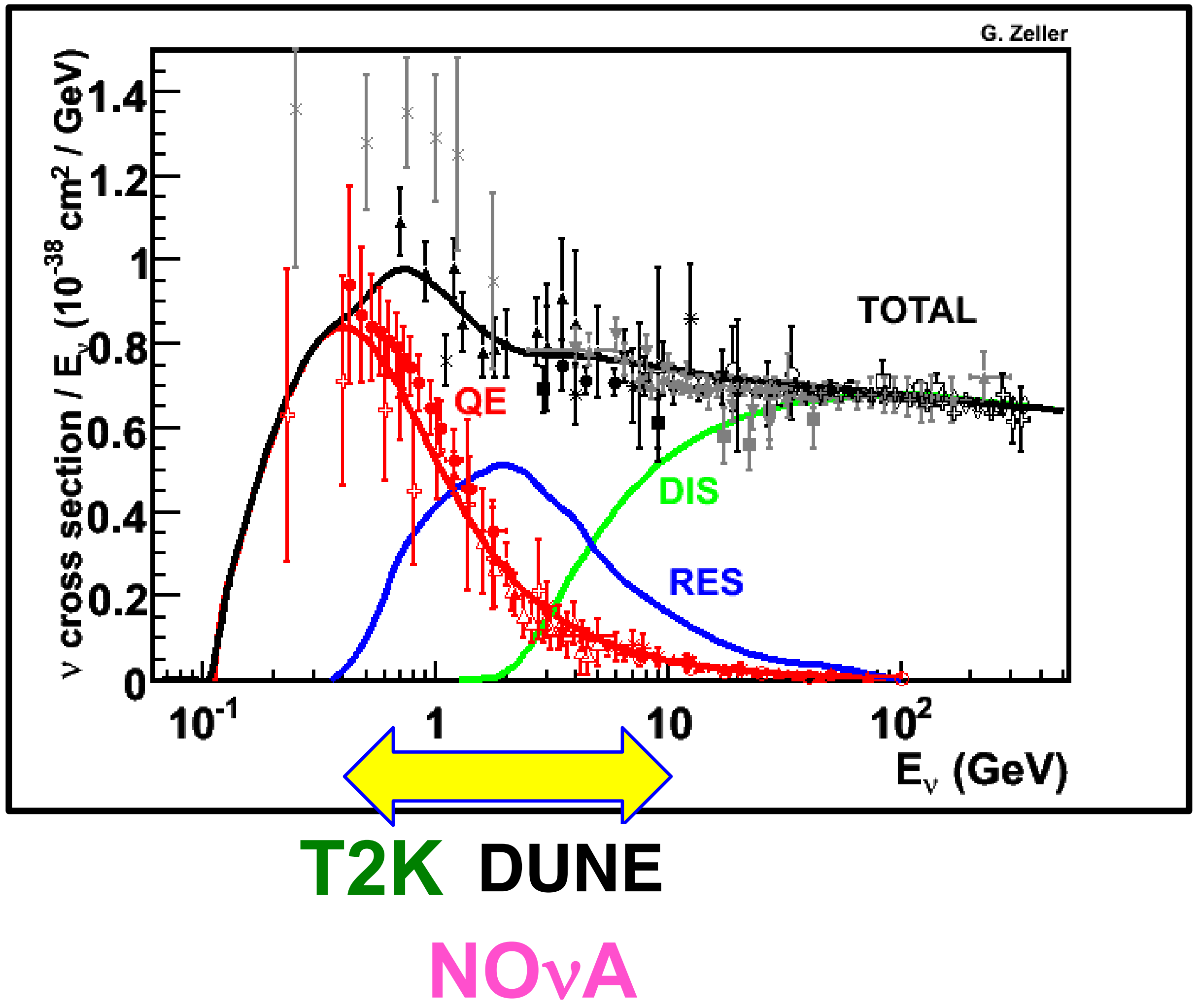
γZ structure functions given from well known parton distribution functions

Alwall & Ingelman, VMD & Regge parametrization

Relationship to Neutrino Experiments

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84, 1307-1341, 2012

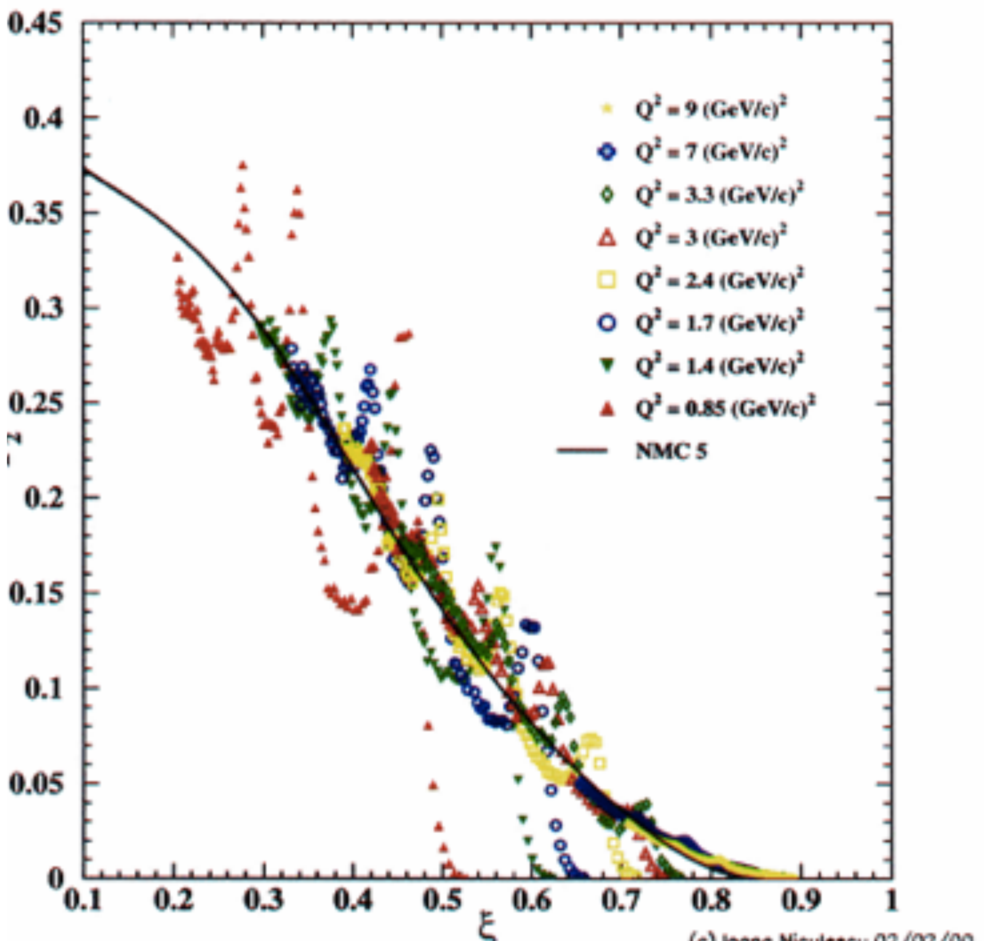
Neutrino Experiments rely heavily on Monte Carlo.
Need accurate predictions for the cross section integrated over the neutrino energy spectrum.
Cross sections and nuclear effects for neutrino interactions in the few GeV region are not well known.
Resonance production very important in for few GeV neutrinos



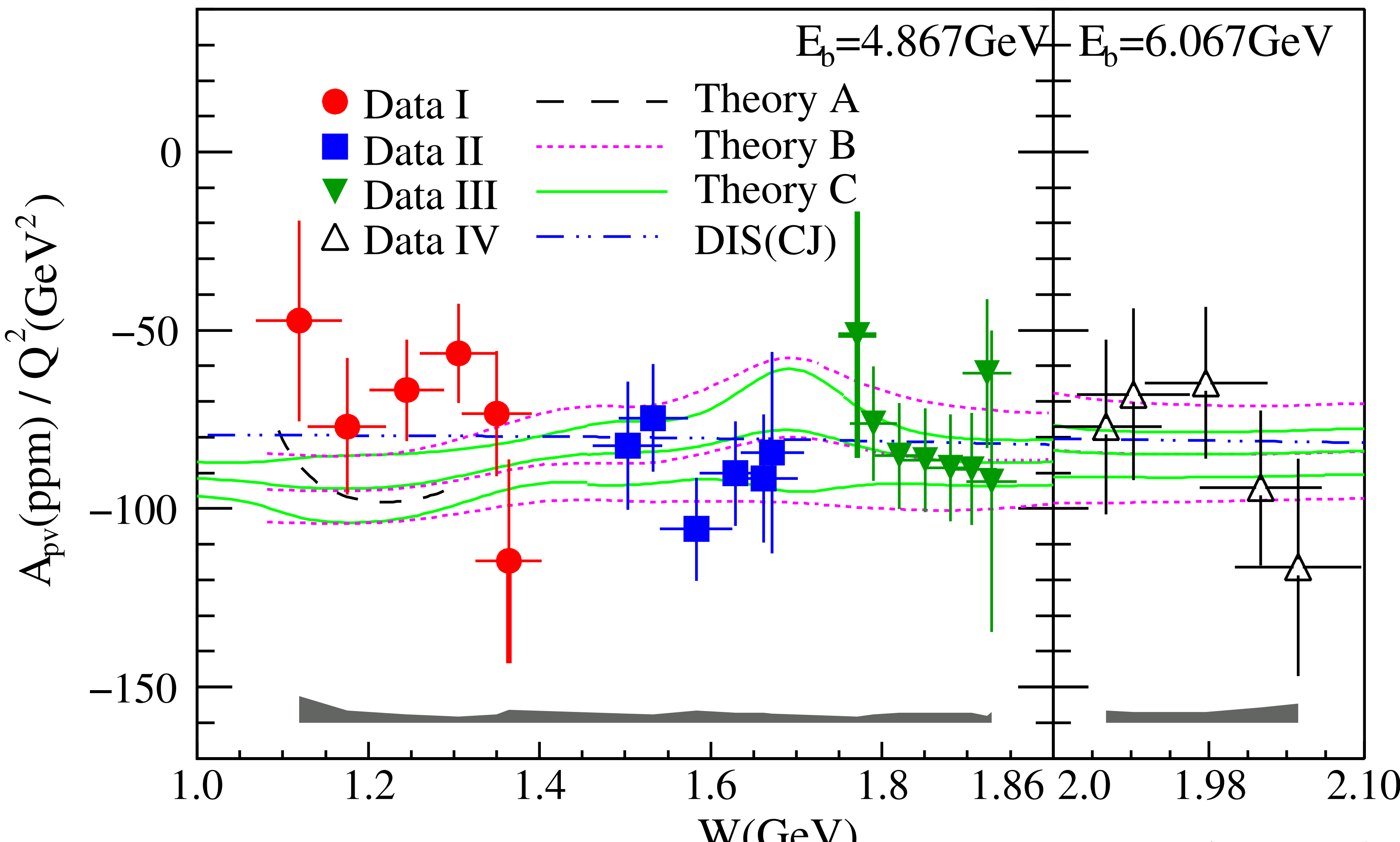
Techniques are similar to γZ structure function models:

use electromagnetic structure functions, form factors or helicity amplitudes
assume conserved vector current (CVC), chiral symmetry, partial conservation of the axial current (PCAC)

Duality



PRL 85, 1186 (2000)



PRL 111, 082501 (2013)

Bloom-Gilman duality shown to hold in electromagnetic:
Unpolarized structure functions ~5%
Polarized structure functions

Duality holds to 15% at Q^2=0.76 GeV^2

PVRES will provide higher precision, better resolution in W, lower Q^2, both proton and isoscaler targets

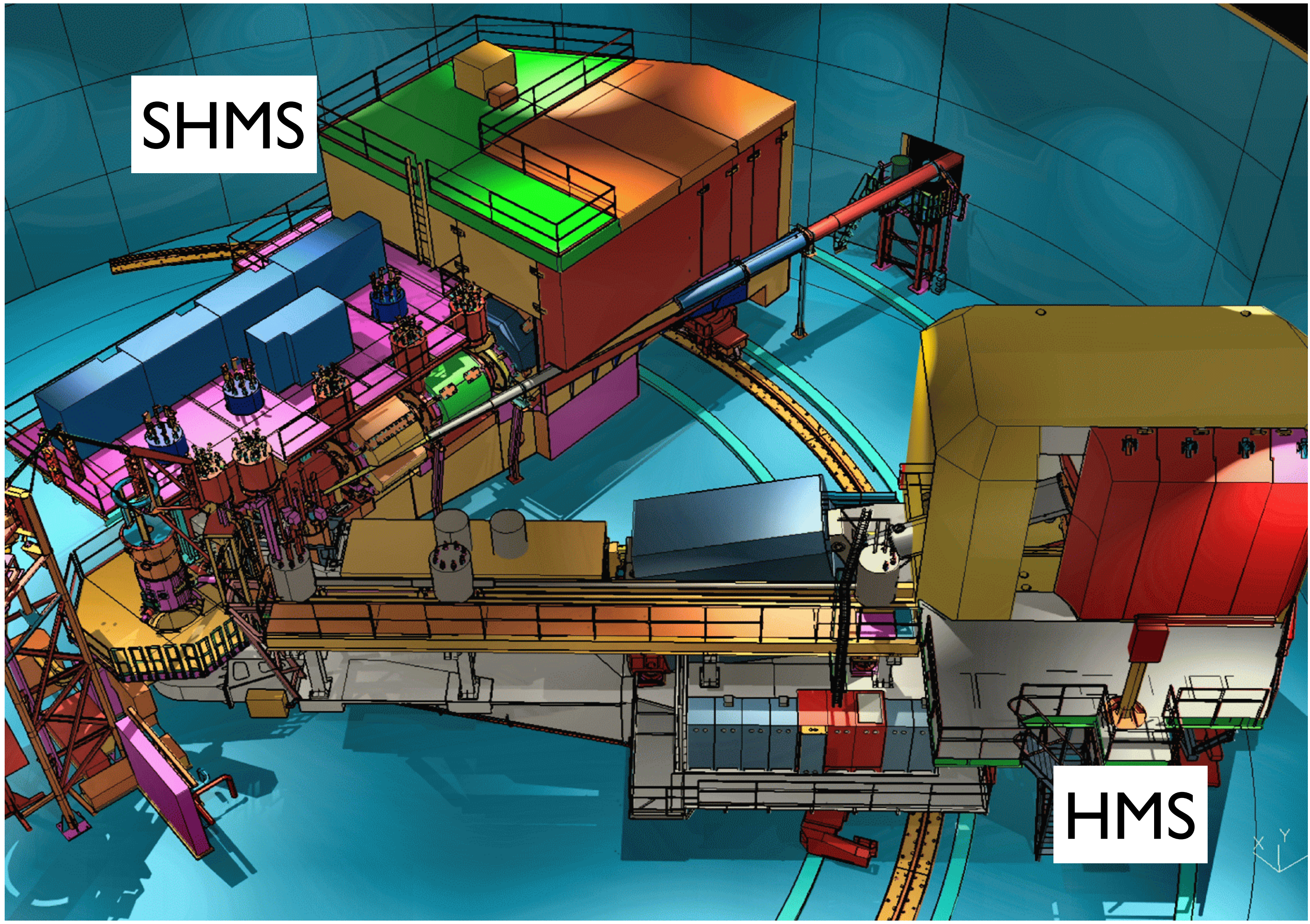
Experiment Details

4.4 GeV beam at 80 uA

Use the HMS and SHMS spectrometers at 10.5 degrees
Solid angles:
  SHMS ~4 msr, HMS ~6 msr
Central momenta:
  2.4 GeV to 4.2 GeV

20 cm LH2 and LD2 targets
High rate requires custom DAQ

Use the existing Compton and Moller polarimeters



Data Acquisition

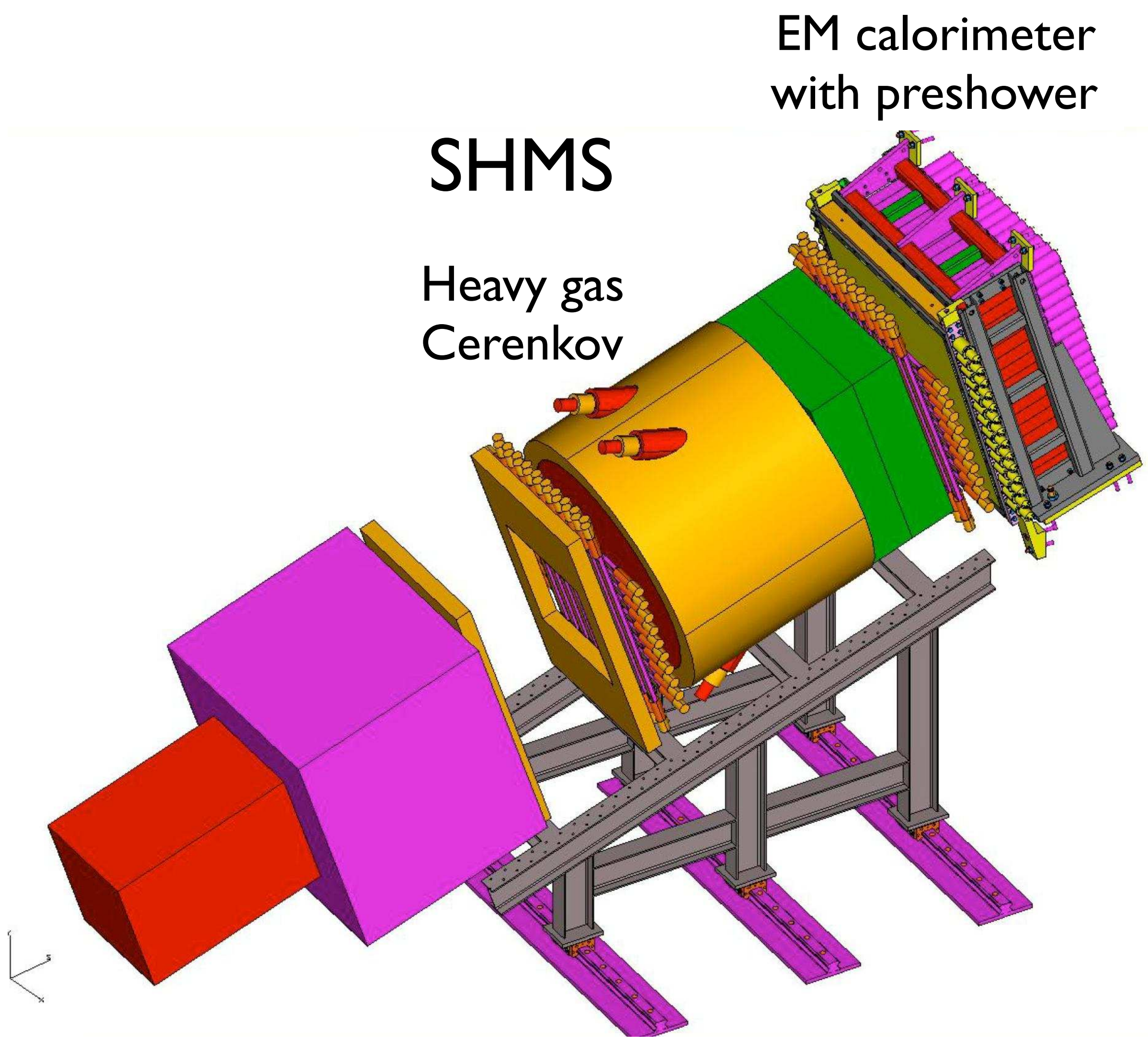
High count rates ~5 MHz with pion/electron separation
Integrate counts for every window and read out at 240 Hz
Parallel redundant DAQ systems: flash ADC pipeline; NIM logic and scalers

event-by-event PID to separate pions and electrons online
Cerenkov and calorimeter
Tracking of individual trajectories with drift chambers
done only in special runs at low current

Relatively modest pion rejection
PVDIS pi/e ~ 3.3
PVRES pi/e < 2.6 at highest W

Pion asymmetry smaller than electrons

PVDIS
pion rejection:
>70 calorimeter, >150 Cerenkov
pion contamination ~10^{-4}



Parallel DAQ Systems

Deadtime affects asymmetry (minimize and carefully measure)
Deadtime effect quantified through pulsing detectors, introducing known dead time, beam current scans, threshold scans
Exploit segmentation in detectors, lower effect rate

Flash ADC pipeline DAQ

F250 hardware standard in Hall C
Requires custom firmware.
Successful in the GlueX experiment.
Logic combinations can be much more sophisticated than practical with NIM
Fill firmware scalers and readout full events for a subset of events,
Full event waveforms in special runs - analyze pileup.

Scaler based DAQ

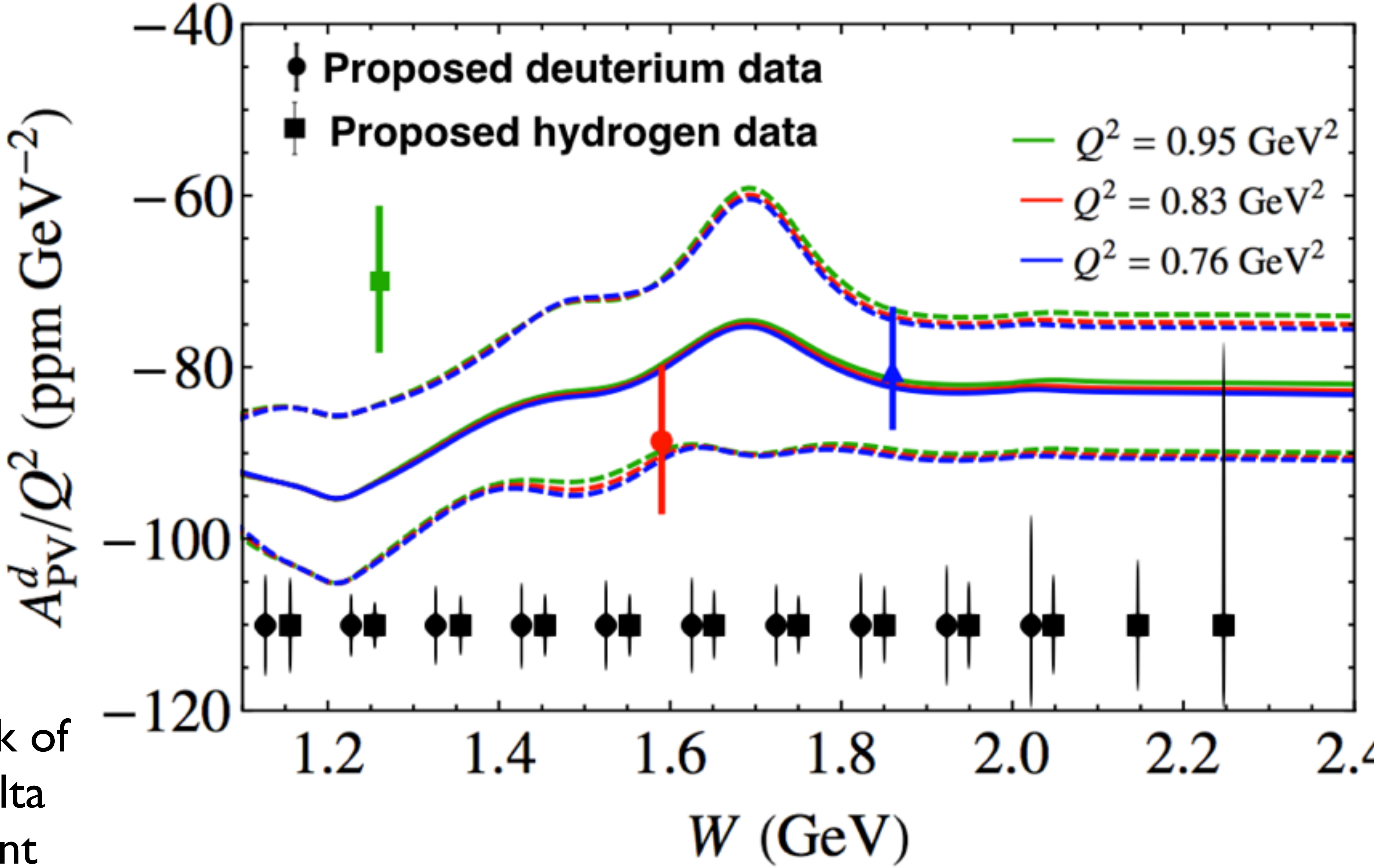
Backup system for online debugging
"Narrow" and "wide" path electronics to measure deadtime effect

Successfully used in PVDIS at 600 kHz

Beam Time Request

Target	P (HMS) [GeV]	HMS time [days]	P (SHMS) [GeV]	SHMS time [days]	Total time [days]
LH2	3.854	4.75	4.149	6.33	
LH2	3.314	4.75	3.208	6.33	
LH2	2.850	4.75	2.480	6.33	
LH2	2.451	4.75			
Total LH2					19
LD2	3.854	1.25	4.149	1.67	
LD2	3.314	1.25	3.208	1.67	
LD2	2.850	1.25	2.480	1.67	
LD2	2.451	1.25			
Total LD2					5
Total Production					24
e^+ background					0.5
Al background					0.58
Carbon optics					0.42
Commissioning					2.5
Total					28

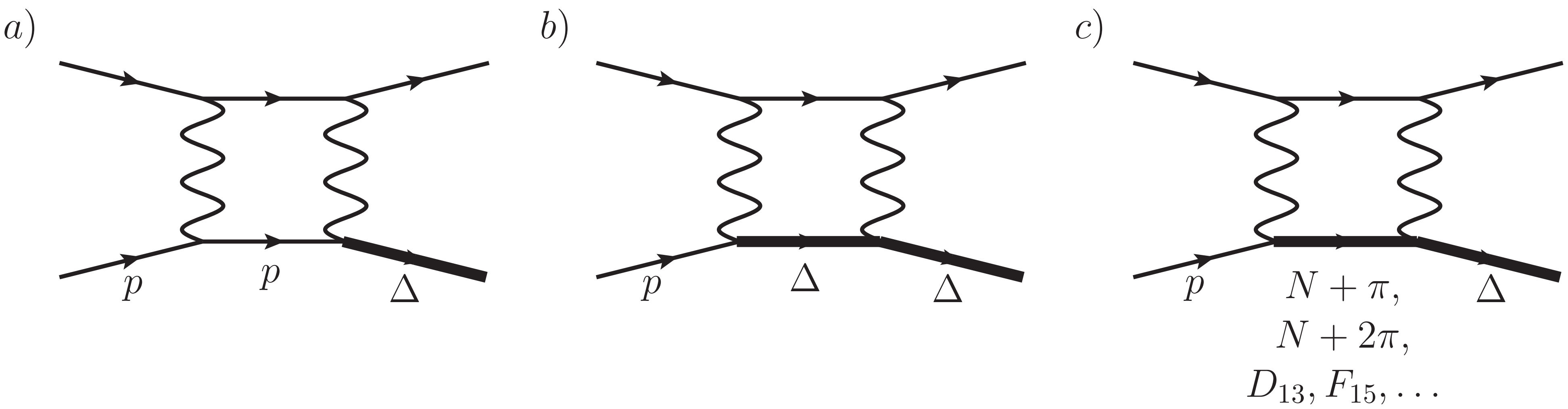
Projected Results



8 sigma check of possible Delta disagreement

Combined statistical uncertainty: 1.5% hydrogen, 1.9% deuterium

Transverse asymmetry background

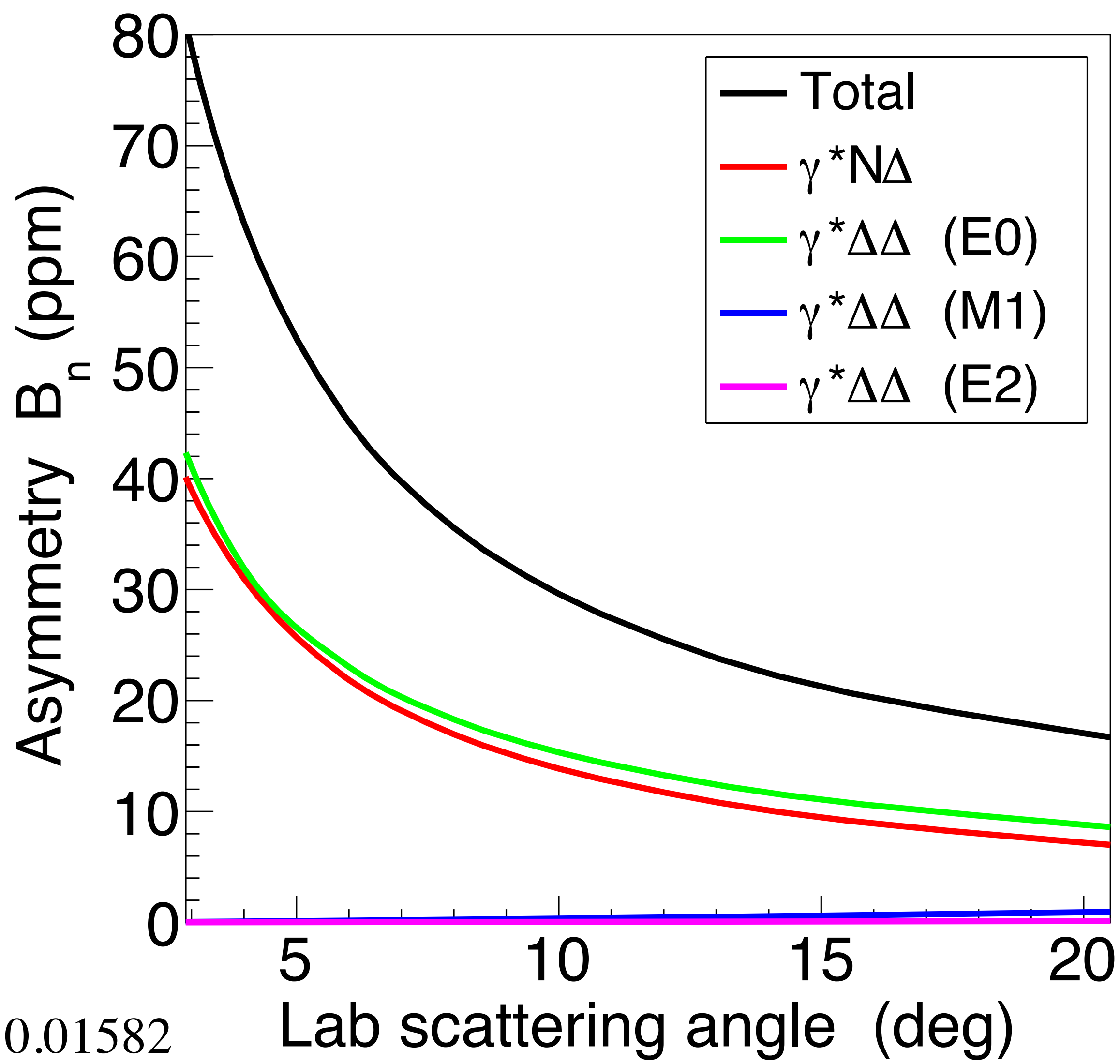


Asymmetry expected to show resonance structure and kinematic dependence.

Sign and magnitude of asymmetry is unknown in resonance region – needs to be measured.

Some estimates exist for the Delta(1232) resonance at lower energy. Asymmetry predicted to decrease with energy and angle.

20 deg, 424 MeV: Bn = ~290 ppm
20 deg, 570 MeV: Bn = ~130 ppm
20 deg, 855MeV: Bn = ~40 ppm
20 deg, 1160 MeV: Bn = ~20 ppm



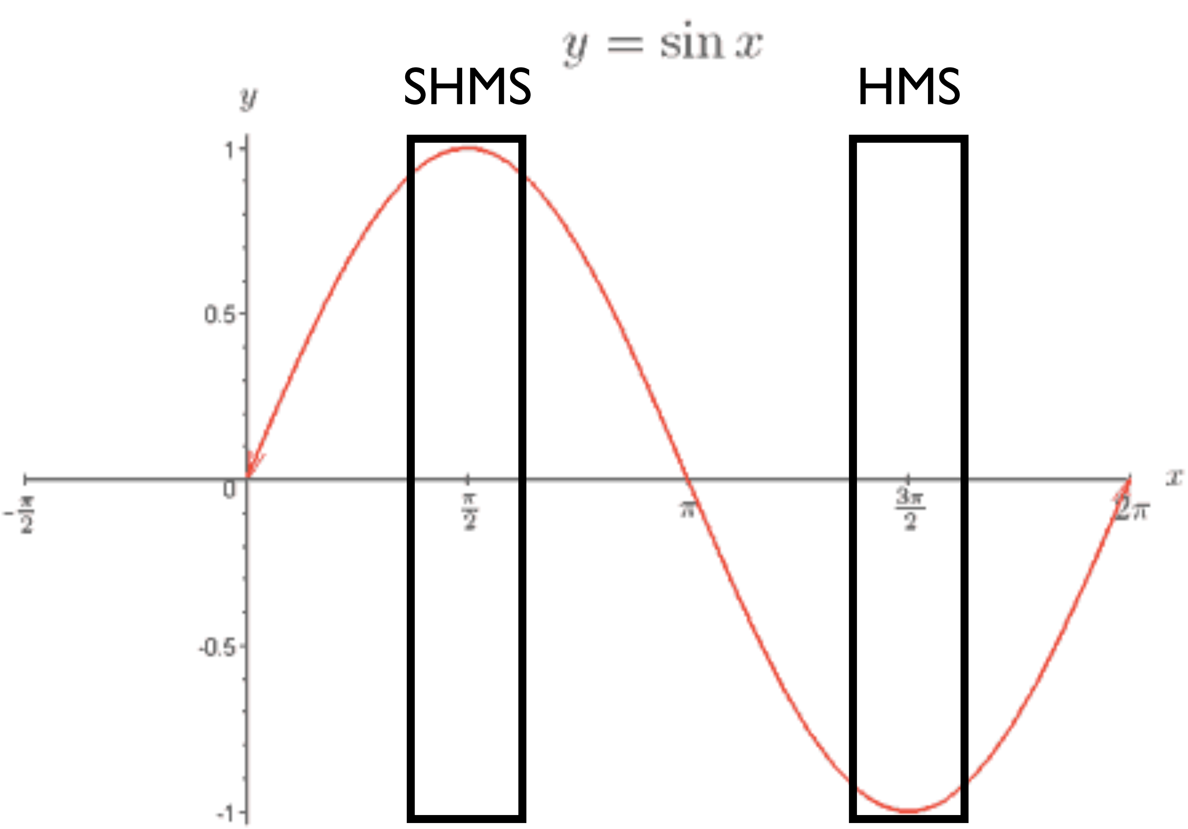
arXiv:1510.01582

Transverse Asymmetry Leakage

Left-Right asymmetry

Vertical polarization:
0.0% ± 2.0% (1.15 degrees)

SHMS and HMS will have opposite central angles and similar momenta. Some degree of first order cancellation.

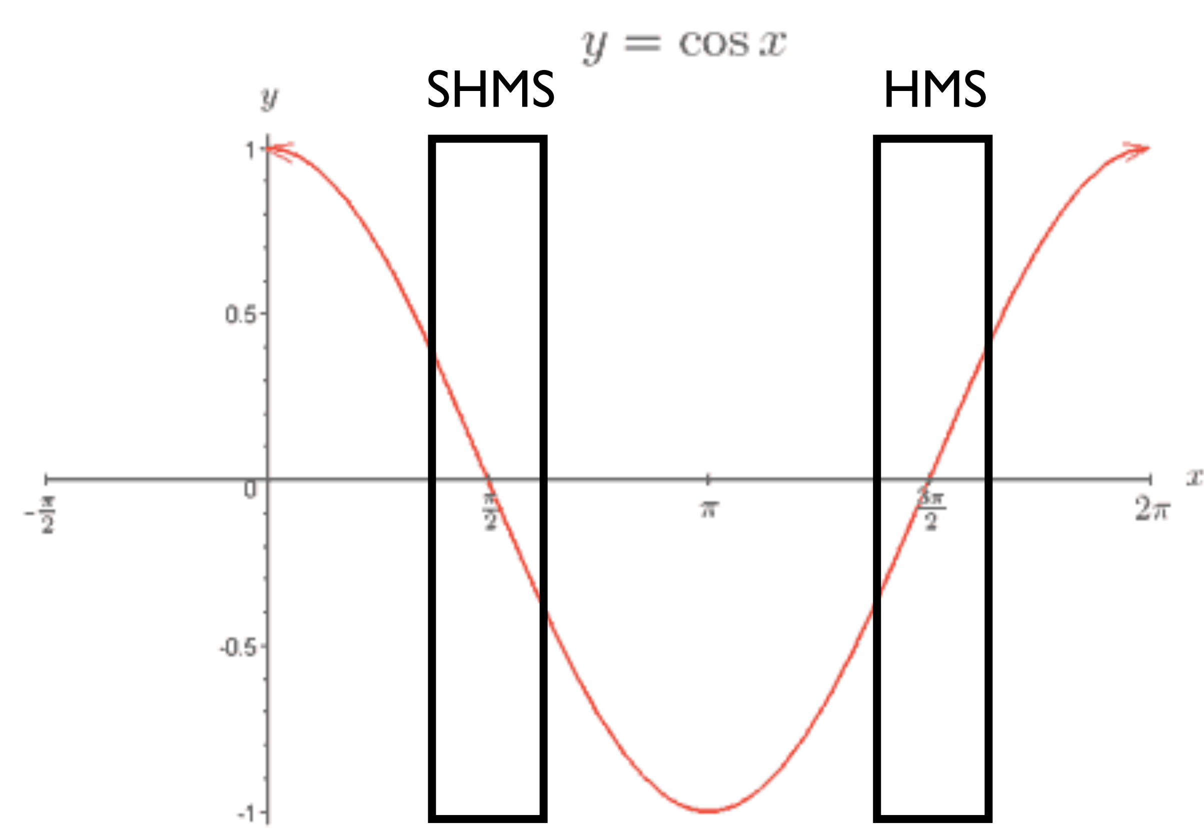


Up-Down asymmetry

Horizontal polarization: ± 4.0% (2.3 degrees)
acceptance around horizontal: -10% to 10%

Acceptance might map to different kinematics, potential non-cancellation must be studied, assume 50%.

50 ppm*4%*10%*50%=0.02 ppm



Polarimetry

Desire <1% polarimetry to match ~1.5% statistical precision

Moller

Achieving <1% with Moller alone requires significant beam time.

~8 measurements
~4 hours per measurement
~32 hours total

Compton

Polarization measured with existing electron detector without modification.

Becomes easier at higher energies.

Setup and commissioning time dominated by beam tuning through the chicane.

Distance from beam	kinematic edge	asymmetry zero
Qweak	17 mm	9 mm
PVRES @ 4.4 GeV	15 mm	7 mm

Response to TAC Comments

Data Acquisition
Polarimetry

→ Already discussed

Helicity Correlated Differences
Spectrometer Backgrounds
Target Window Backgrounds
Target Density Fluctuations

→ Analysis shows little sensitivity. Details in Additional Material.

Systematic Uncertainties

Source	Size
Transverse beam pol. (A_n)	0.2%
Spectrometer re-scattering	0.2%
EM radiative corrections	1%
Q^2 Determination	0.9%
Beam polarization	0.9%
False asymmetries	0.5%
Pair-symmetric background	0.5%
Box diagrams	0.5%
Deadtime corrections	$\leq 0.6\%$
Aluminum endcaps	0.4%
Target purity, density fluctuations	0.2%
Pion contamination	$< 0.05\%$
Total	2.0%

Conclusion

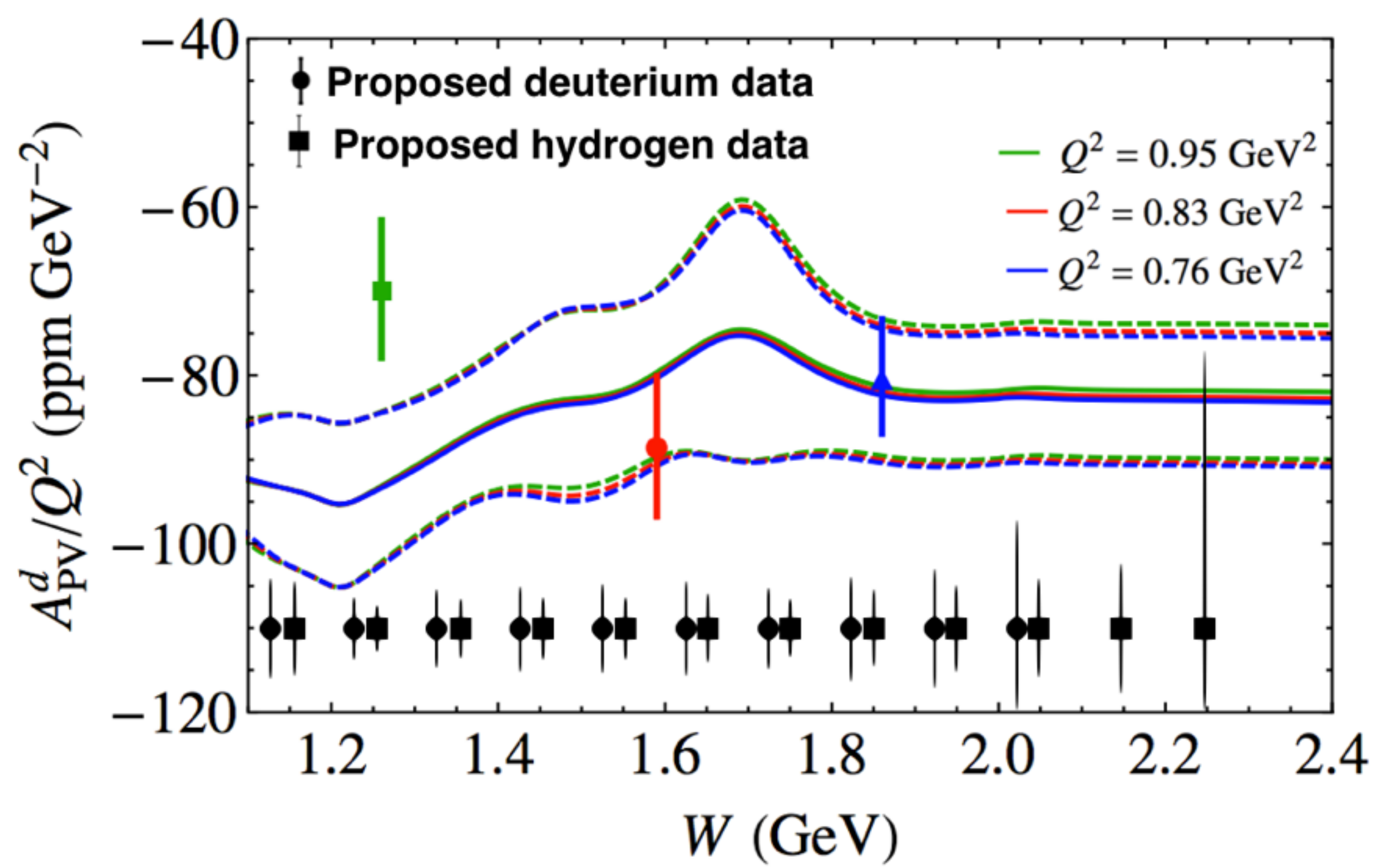
Important data for constraining γZ structure functions in the resonance region.

Will help in modeling neutrino interactions in the resonance region.

Relatively easy experiment: standard equipment, modest requirements for parity quality beam, DAQ represents the biggest challenge.

Can only be done at JLab

Can only be done using magnetic focusing spectrometers.



PVRES Collaboration

F. Benmokhtar
Duquesne University, Pittsburgh, PA 15282, USA

P. Markowitz
Florida International University, Miami, FL 33199, USA

D. Biswas, M. E. Christy, B. Dongwi, T. N. Gautam, N. Kalantarians (co-spokesperson), M. Kohl, A. Liyanage, A. Nadeeshani, J. Nazeer, B. Pandey, L. Tang
Hampton University, Hampton, VA 23668, USA

R. Holmes, P. Souder
Syracuse University, Syracuse, NY 13244, USA

M.M. Dalton (co-spokesperson), D. Gaskell, R. Michaels, B. Sawatzky
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

C. Gal (co-spokesperson), K. Jin, J. Liu, K. Paschke, V. Sulkosky† (spokesperson), N. Ton, X. Zheng
University of Virginia, Charlottesville, VA 22901, USA

M. Pitt
Virginia Polytechnic Institute and State University, VA 24061, USA

Additional Material

Response to TAC Comments

1. Data Acquisition
2. Helicity Correlated Differences
3. Spectrometer Backgrounds
4. Target Window Backgrounds
5. Cooling Requirements
6. Target Density Fluctuations
7. Polarization Uncertainty

Helicity Correlated Differences

Sensitivity to helicity correlated differences will be small
- large physical asymmetries 30-55 ppm
- inelastic scattering more slowly varying with energy and angle

Will perform typical setup of "Parity Quality" beam to minimize differences.

Will not require/request Wien reversal.

Will perform dithering of the beam due to abundance of caution.

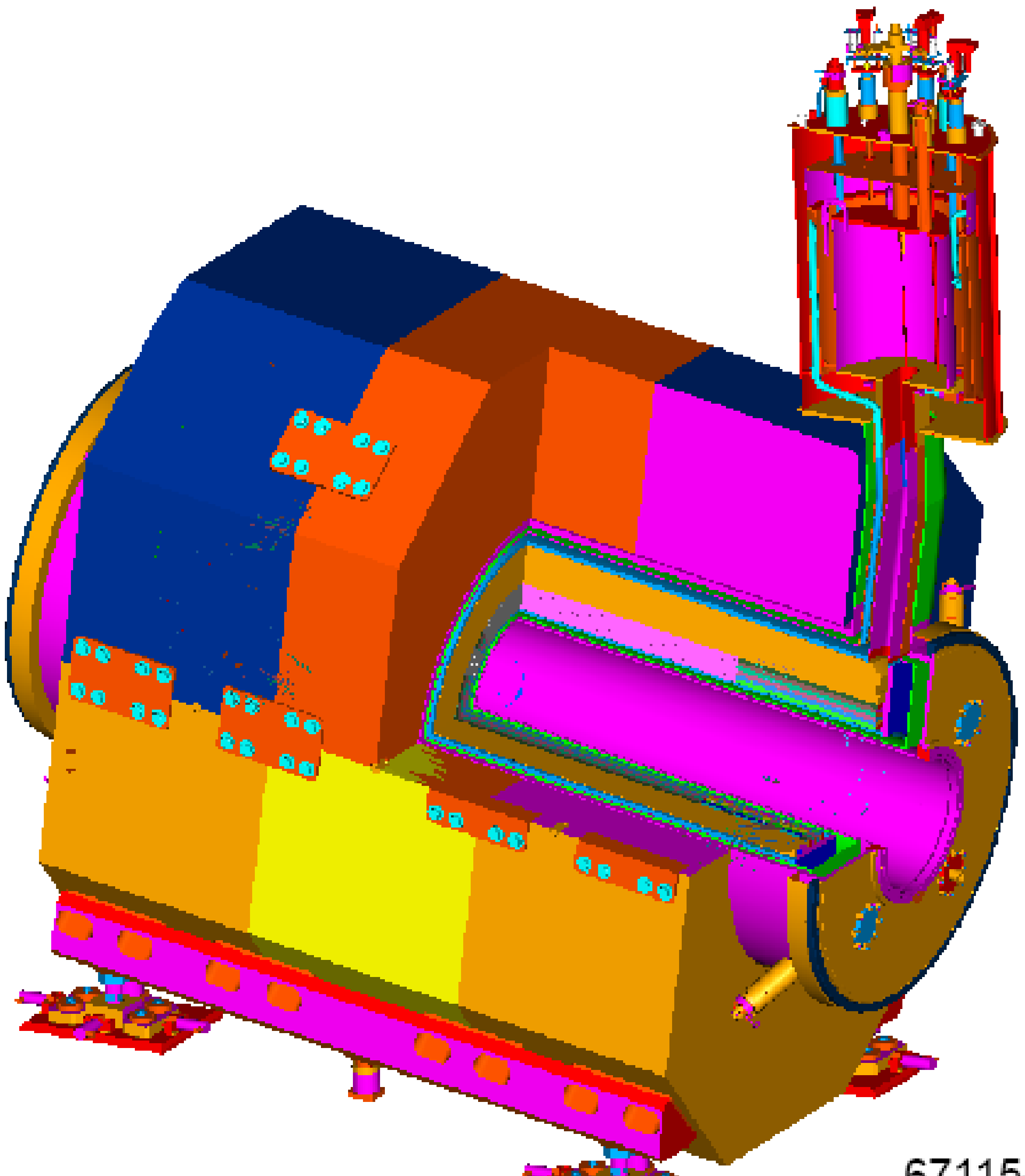
Spectrometer Backgrounds

Re-scattering within the spectrometer may cause background with unknown asymmetry in the acceptance.

No large asymmetry processes contribute.

Unlike HRS dipoles in Hall A there are no magnetized iron “pole tips” to scatter off.

Bounded using a full simulation the spectrometer and tracking data from early 12 GeV experiments. Specific beam based studies might be necessary.



Target Window Background

Scattering from the Aluminum alloy windows causes a background.
Small correction with small additional uncertainty.

Rate

Between 0.8 % and 5.2 % (depending on kinematics) of electron rate will come from 150 um target windows.

Largest correction < 1%

Asymmetry

Expected to be within a few % of deuterium asymmetry and within 20% of the proton asymmetry

If the rate and asymmetry are known to 20% each (possible from models and simulation alone) then the additional uncertainty is 3%.

Target Target Cooling and Density Fluctuations

Density fluctuations a relatively small effect since statistical width is large.
New target design is expected to perform better than previous targets.
Fluctuations can be mitigated by increasing flip rate, raster size, or pump speed.

Experiment	Beam Current	Raster size	Reversal Rate	Width
G0	40 uA	3x3 mm	30 Hz	238 ppm
PVDIS	100 uA	4x4 mm	30 Hz	569 ppm
HAPPEX 3	100 uA		30 Hz	1000 ppm
GMP (opportune)	60 uA	2x2 mm	30 Hz	536 ppm

Conservative Scaling : $(\frac{80\mu A}{60\mu A})^3(\frac{4\text{mm}^2}{16\text{mm}^2})536\text{ ppm} = 318\text{ ppm}.$

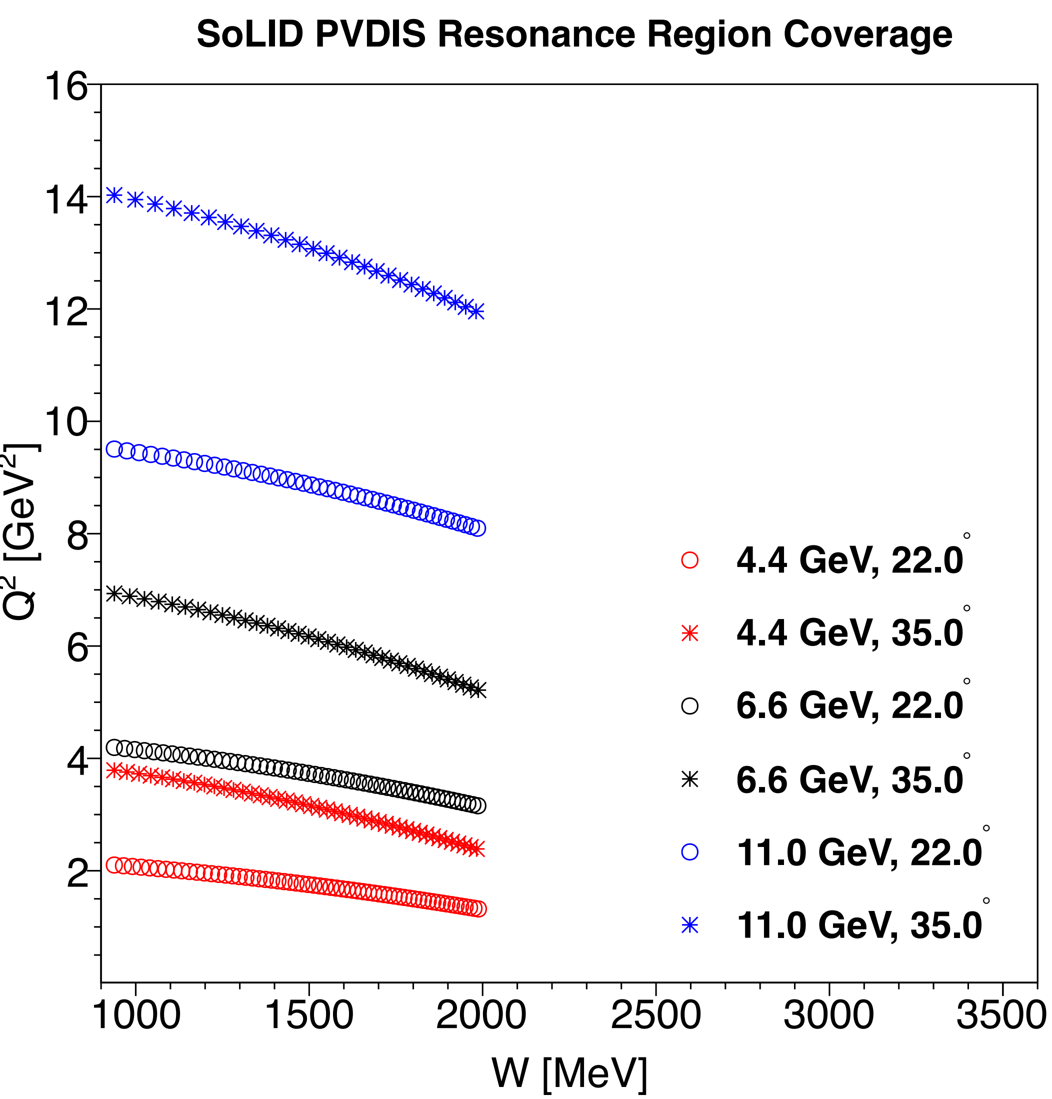
Electron rate	Reversal rate	Statistical noise	Assumed fluctuation noise	Relative noise increase
3.8 MHz	30 Hz	1986 ppm	1000 ppm	12%
3.8 MHz	240 Hz	3970 ppm	1000 ppm	1.6%
3.8 MHz	240 Hz	3970 ppm	318 ppm	0.2%

Working small angle (luminosity) monitors would be useful for helping to understand target density effects early on in the experiment

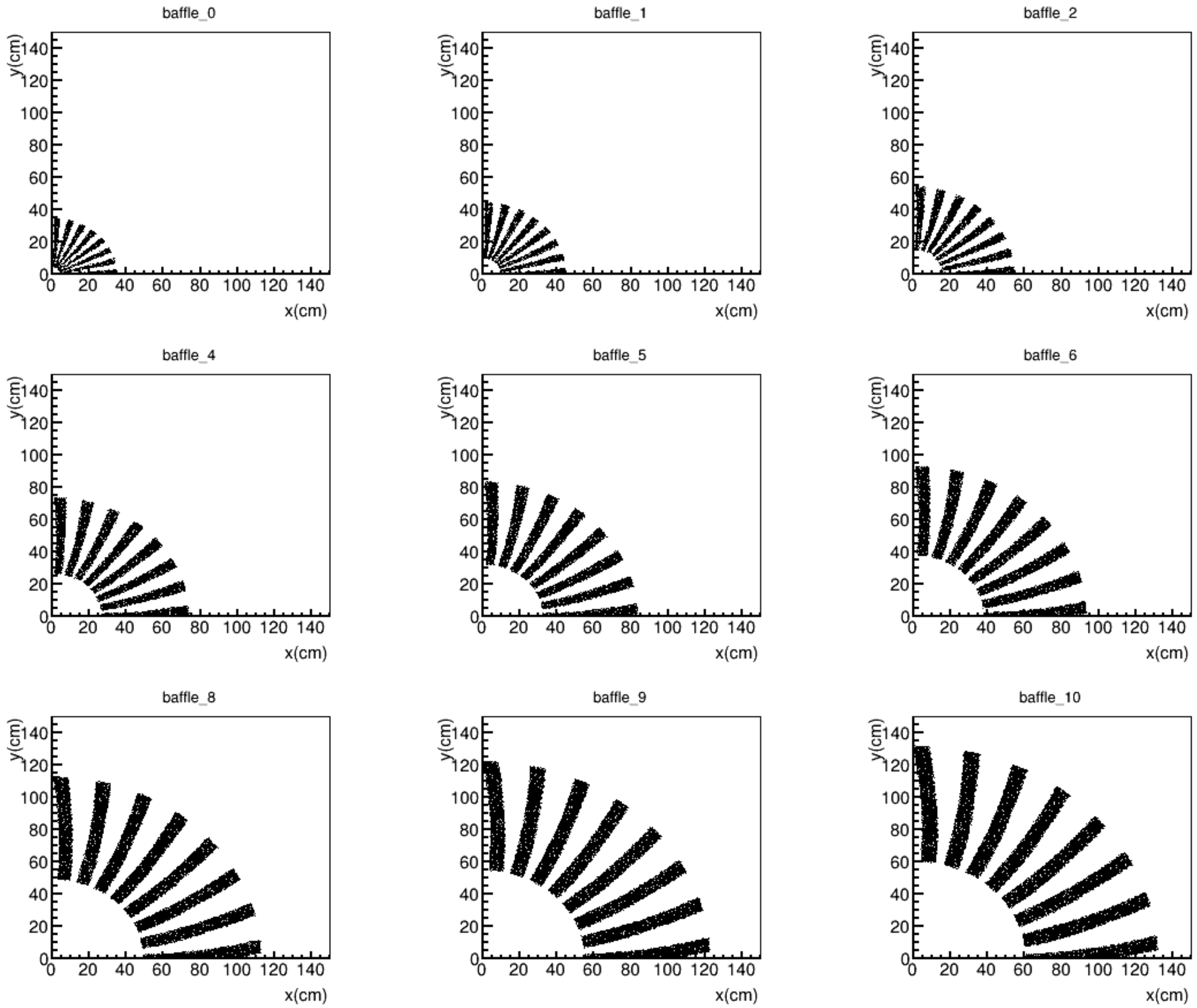
Relationship to SOLID

Low Q^2, resonance-region studies are not possible in SOLID

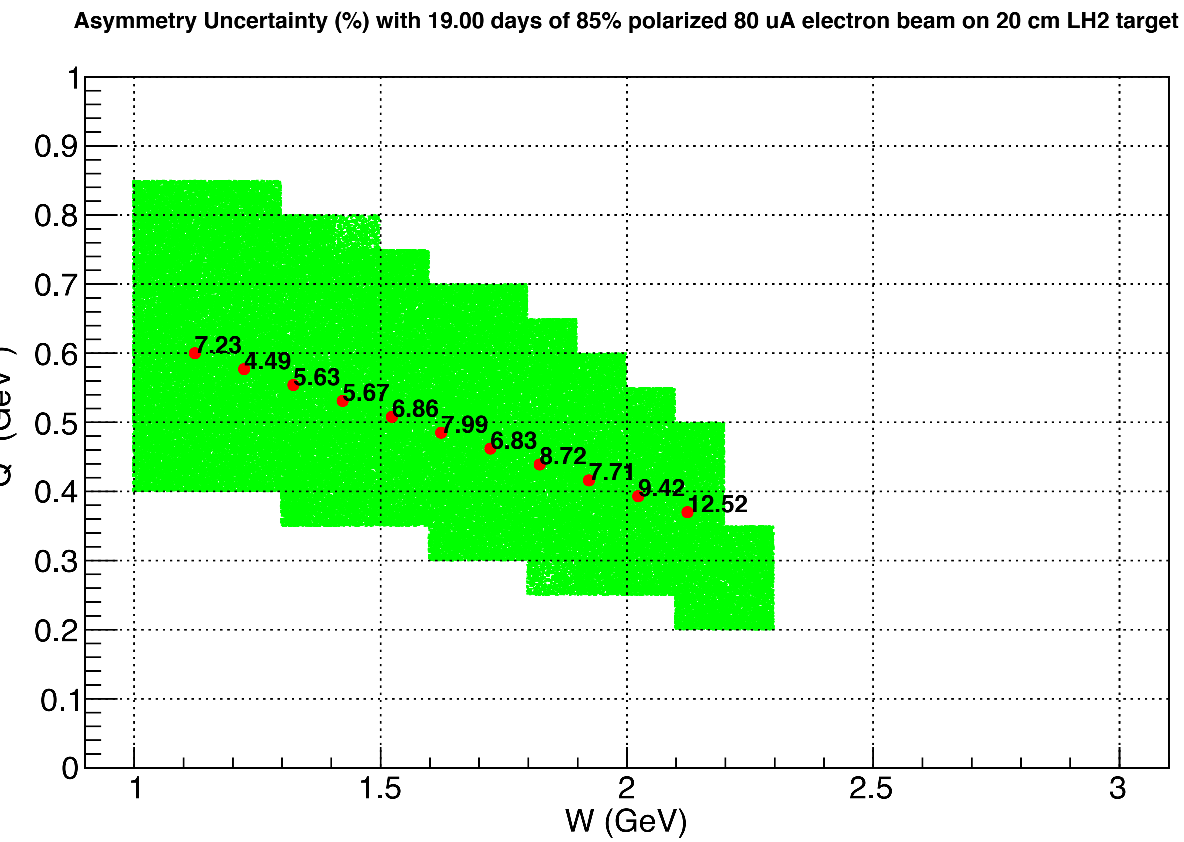
Minimum angle is 22 degrees.



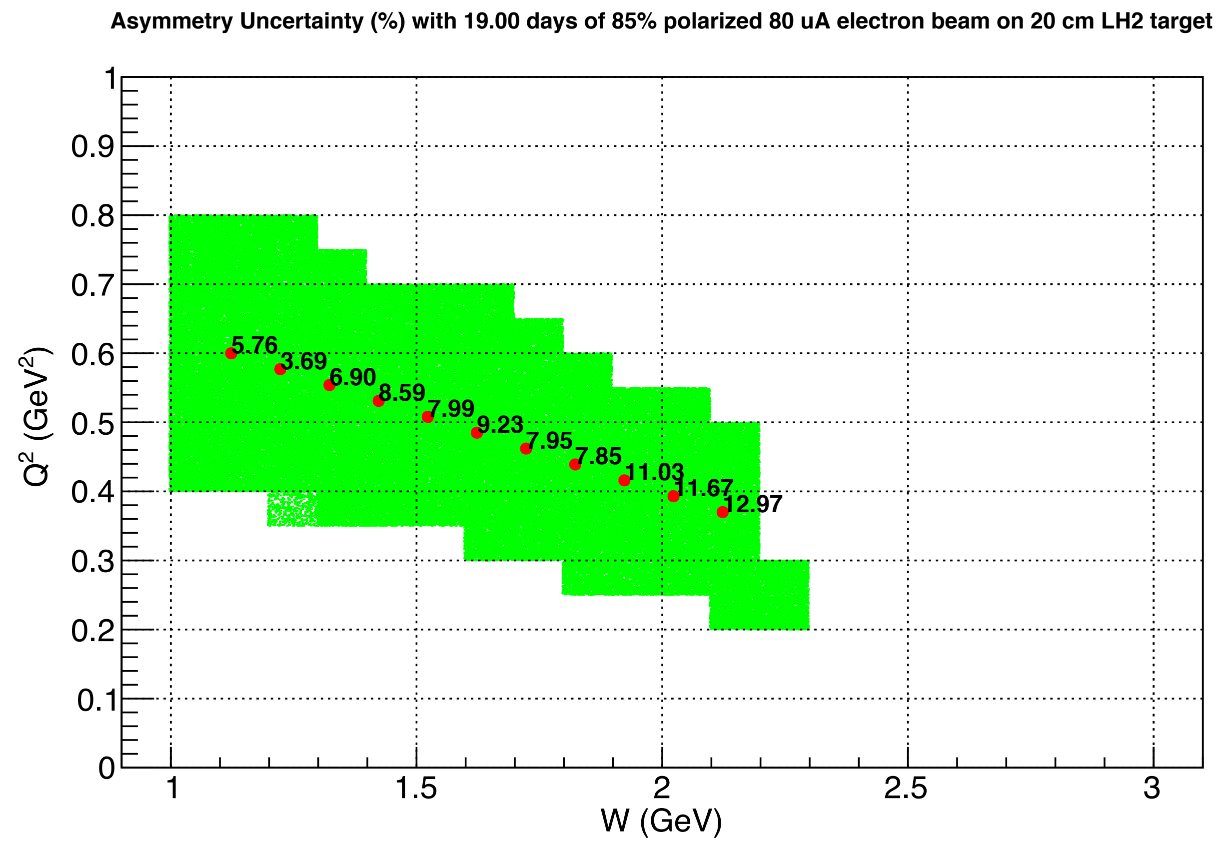
Baffles designed to block low momentum particles



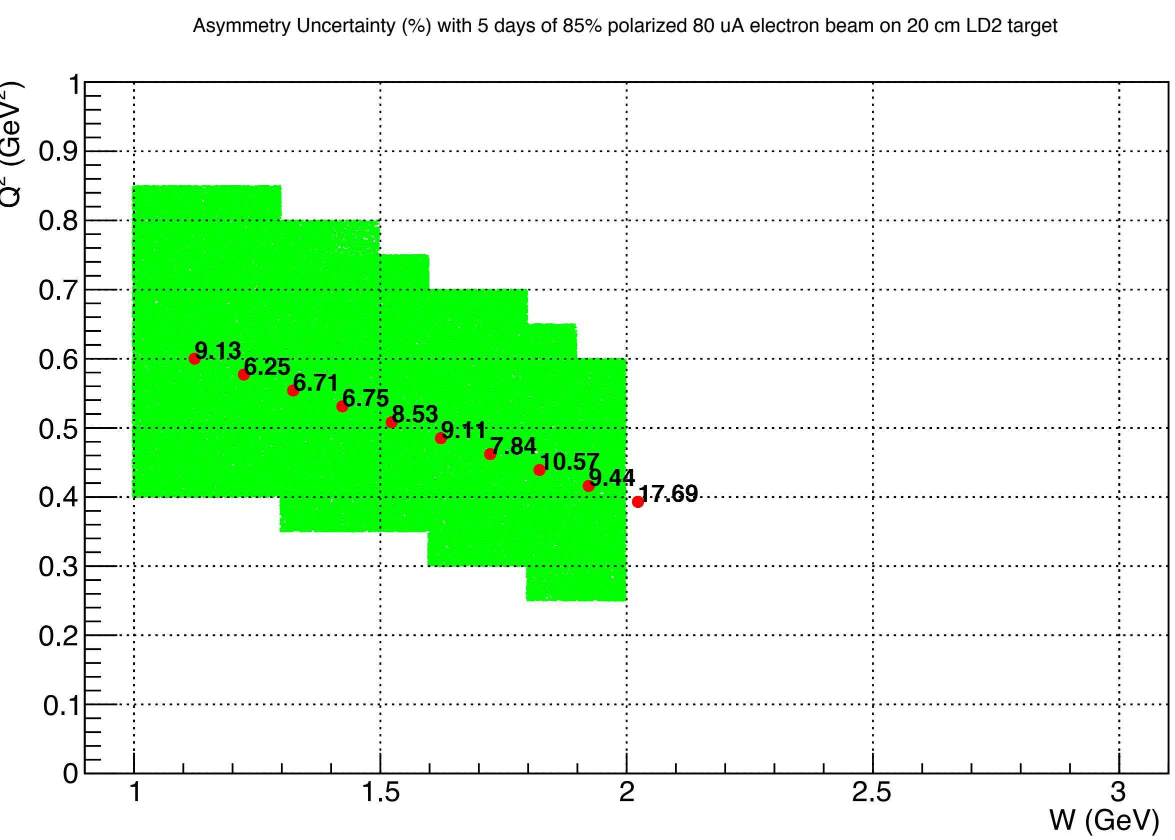
Q2 vs W



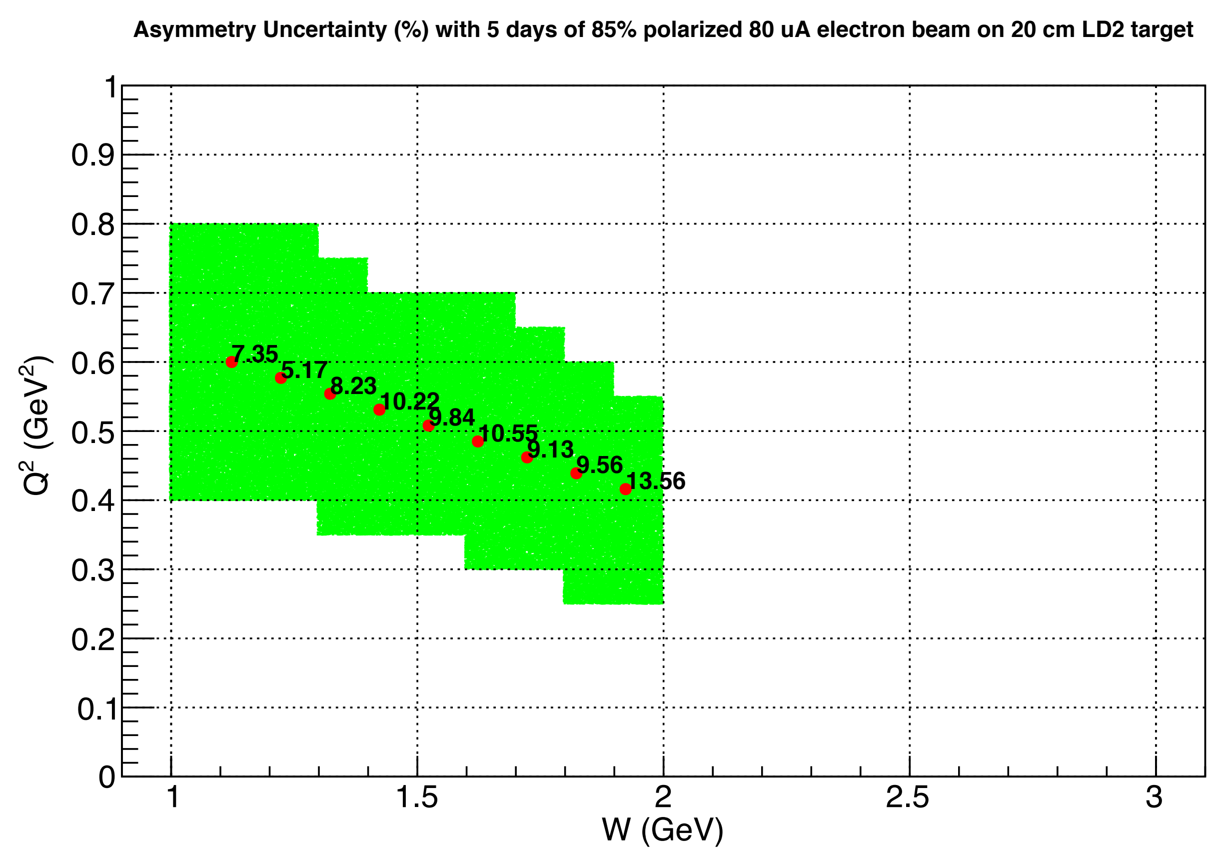
Asymmetry Uncertainty (%) with 19.00 days of 85% polarized 80 uA electron beam on 20 cm LH2 target
7.23
4.49
5.63
5.67
6.86
7.99
6.83
8.72
7.71
9.42
12.52
W (GeV)



Asymmetry Uncertainty (%) with 19.00 days of 85% polarized 80 uA electron beam on 20 cm LH2 target
5.76
3.69
6.90
8.59
7.99
9.23
7.95
7.85
11.03
11.67
12.97
Q2 (GeV2)
W (GeV)



Asymmetry Uncertainty (%) with 5 days of 85% polarized 80 uA electron beam on 20 cm LD2 target
9.13
6.25
6.71
6.75
8.53
9.11
7.84
10.57
9.44
17.69
W (GeV)

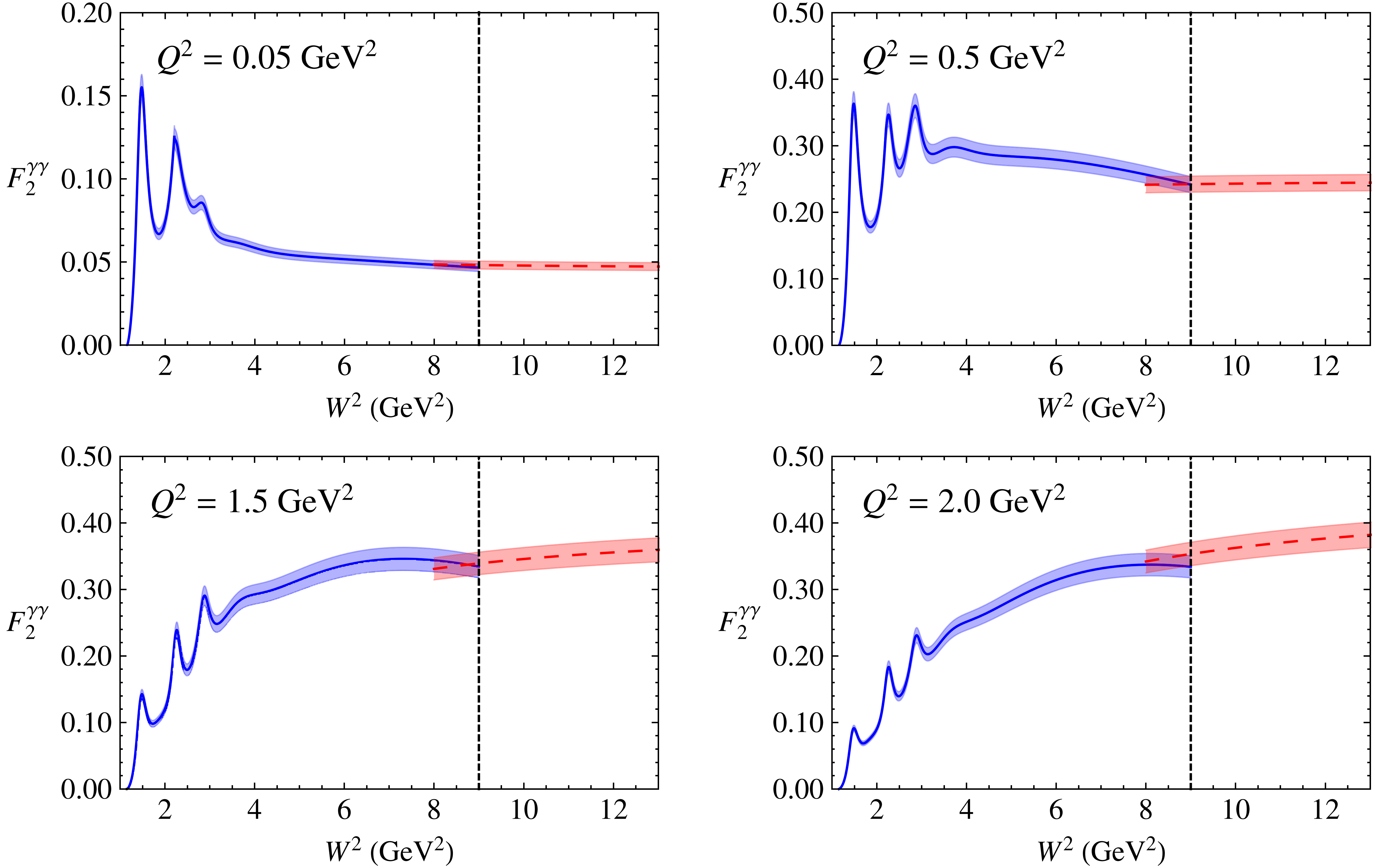


Asymmetry Uncertainty (%) with 5 days of 85% polarized 80 uA electron beam on 20 cm LD2 target
7.35
5.17
8.23
10.22
9.84
10.55
9.13
9.56
13.56
Q2 (GeV2)
W (GeV)

AJM Model

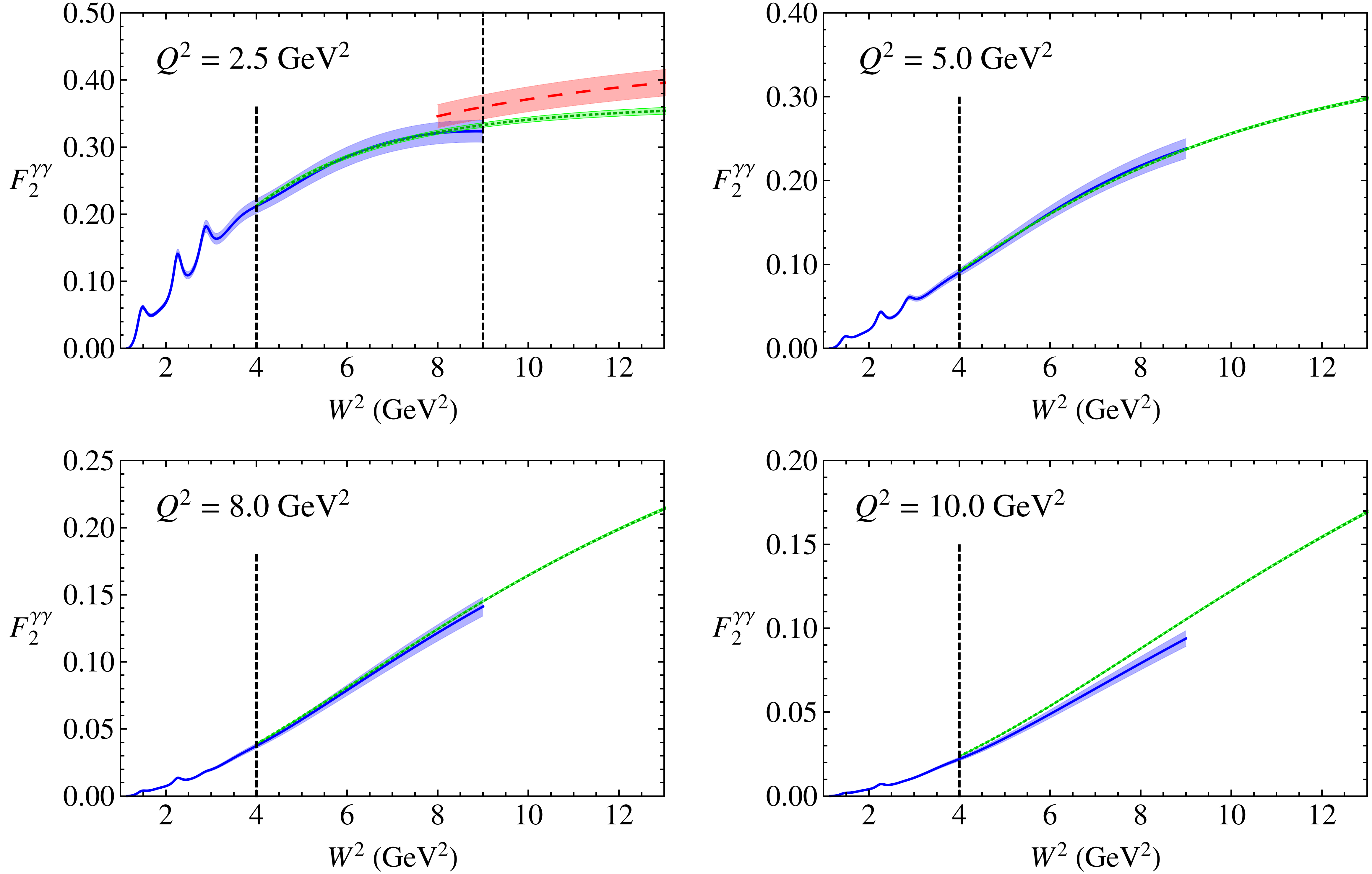
Christy-Bosted parametrization

Alwall & Ingelman,
VMD & Regge parametrization

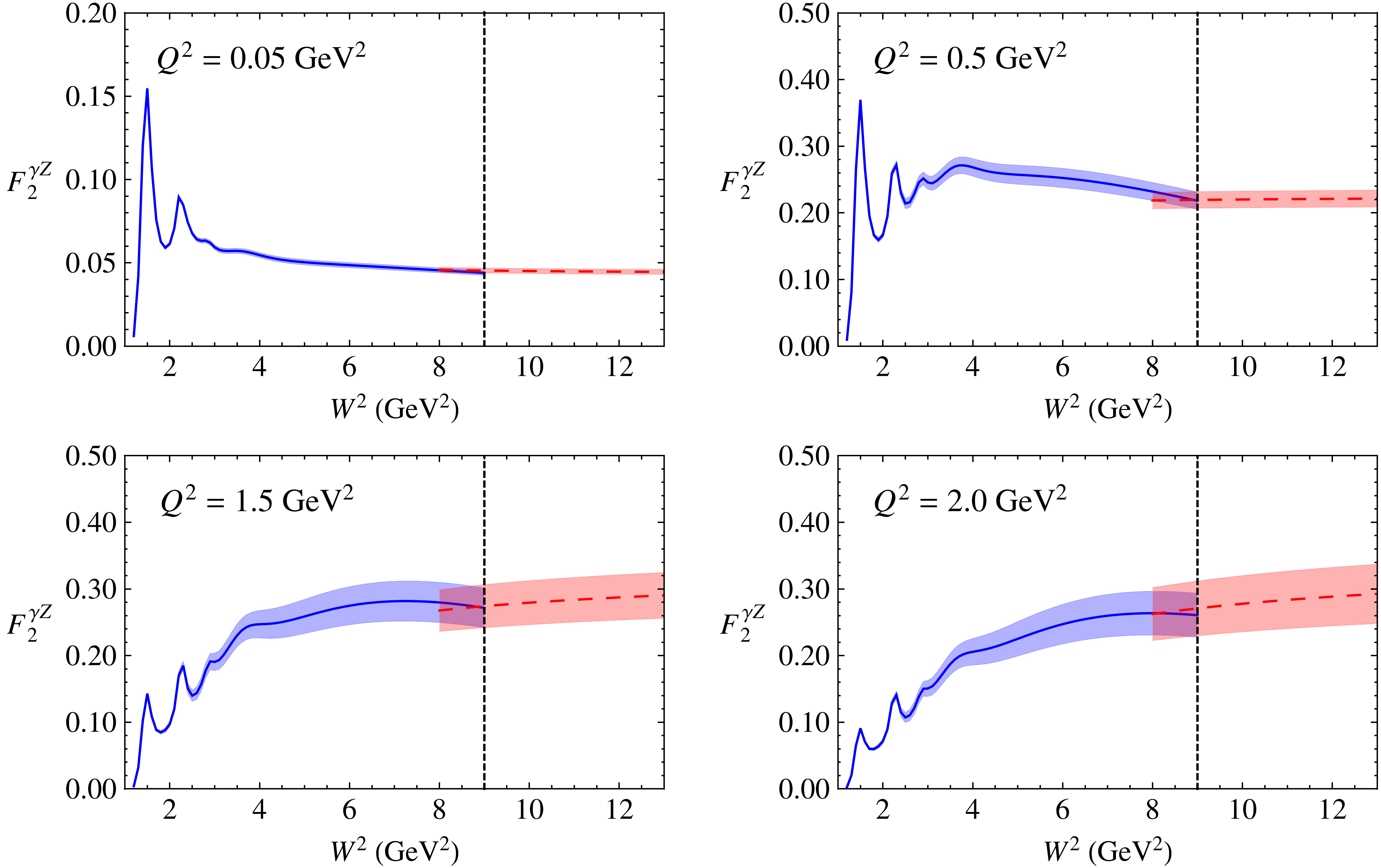


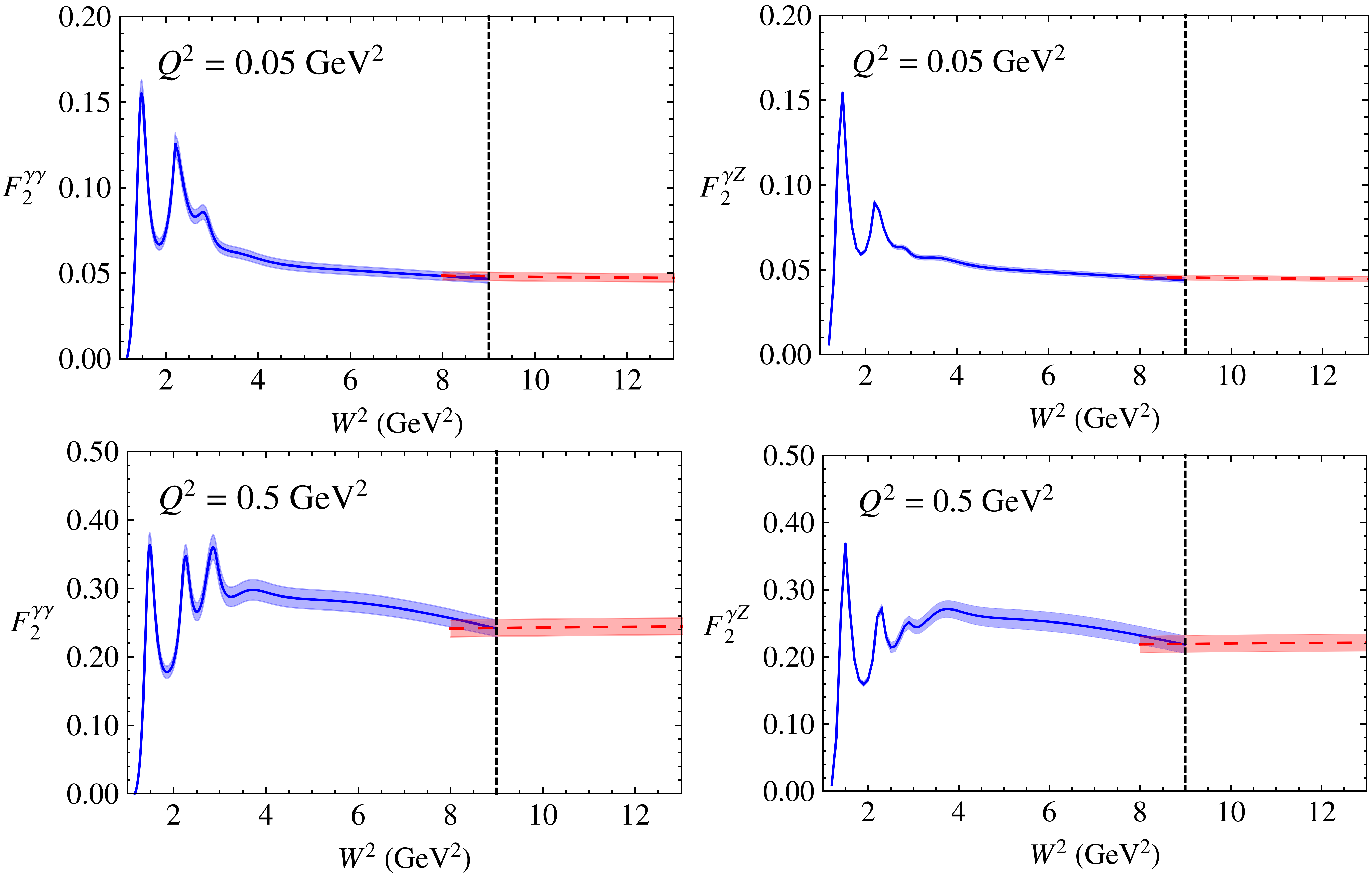
AJM Model

Alekhin, NNLO global PDFs



γZ Structure Functions

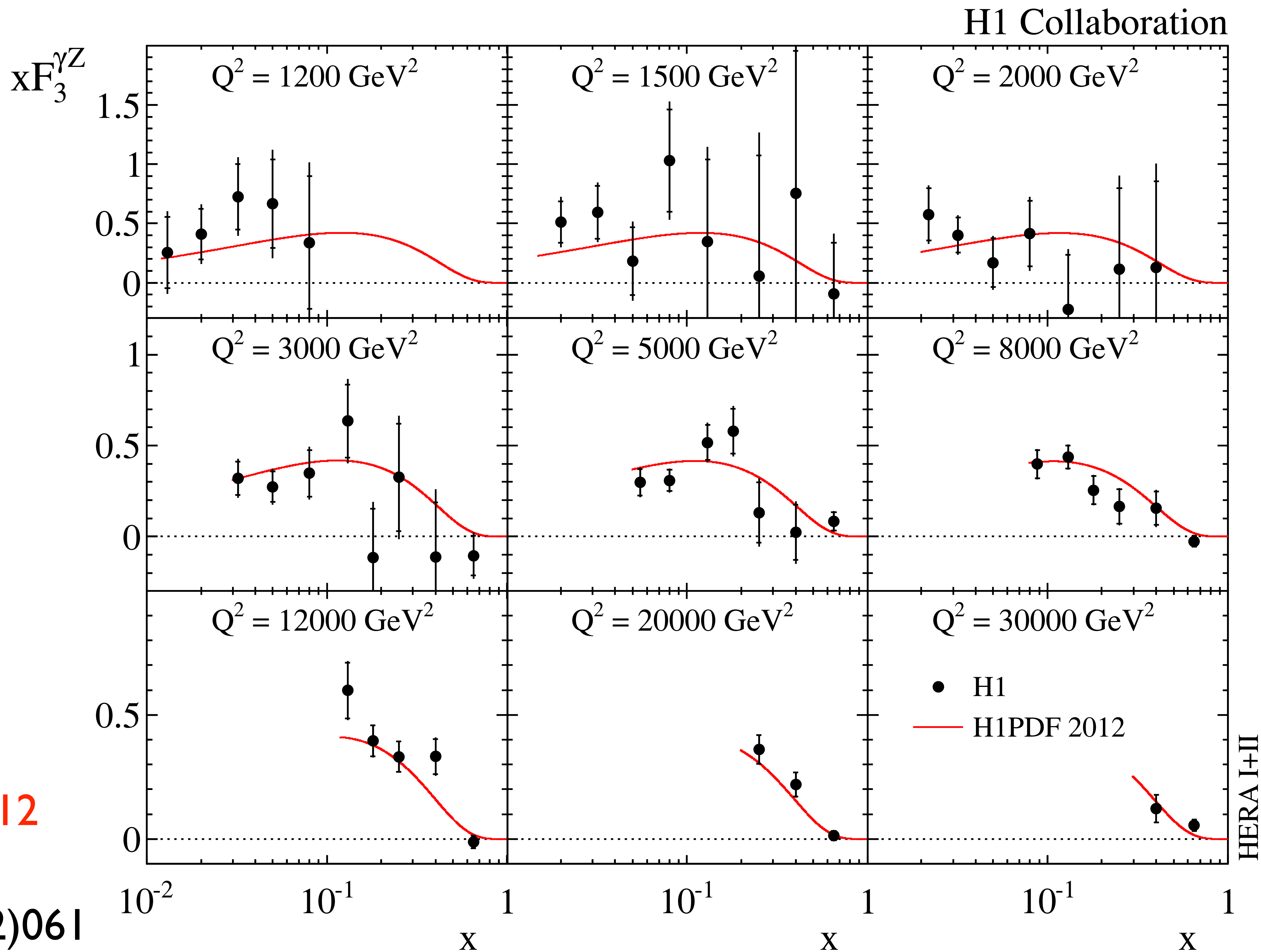




Q^2 = 0.05 GeV^2
F_2^γγ
W^2 (GeV^2)
Q^2 = 0.05 GeV^2
F_2^γZ
W^2 (GeV^2)
Q^2 = 0.5 GeV^2
F_2^γγ
W^2 (GeV^2)
Q^2 = 0.5 GeV^2
F_2^γZ
W^2 (GeV^2)

HERA $xF_3^{\gamma Z}$

60 < Q2 < 50000 GeV2
0.0008 < x< 0.65.

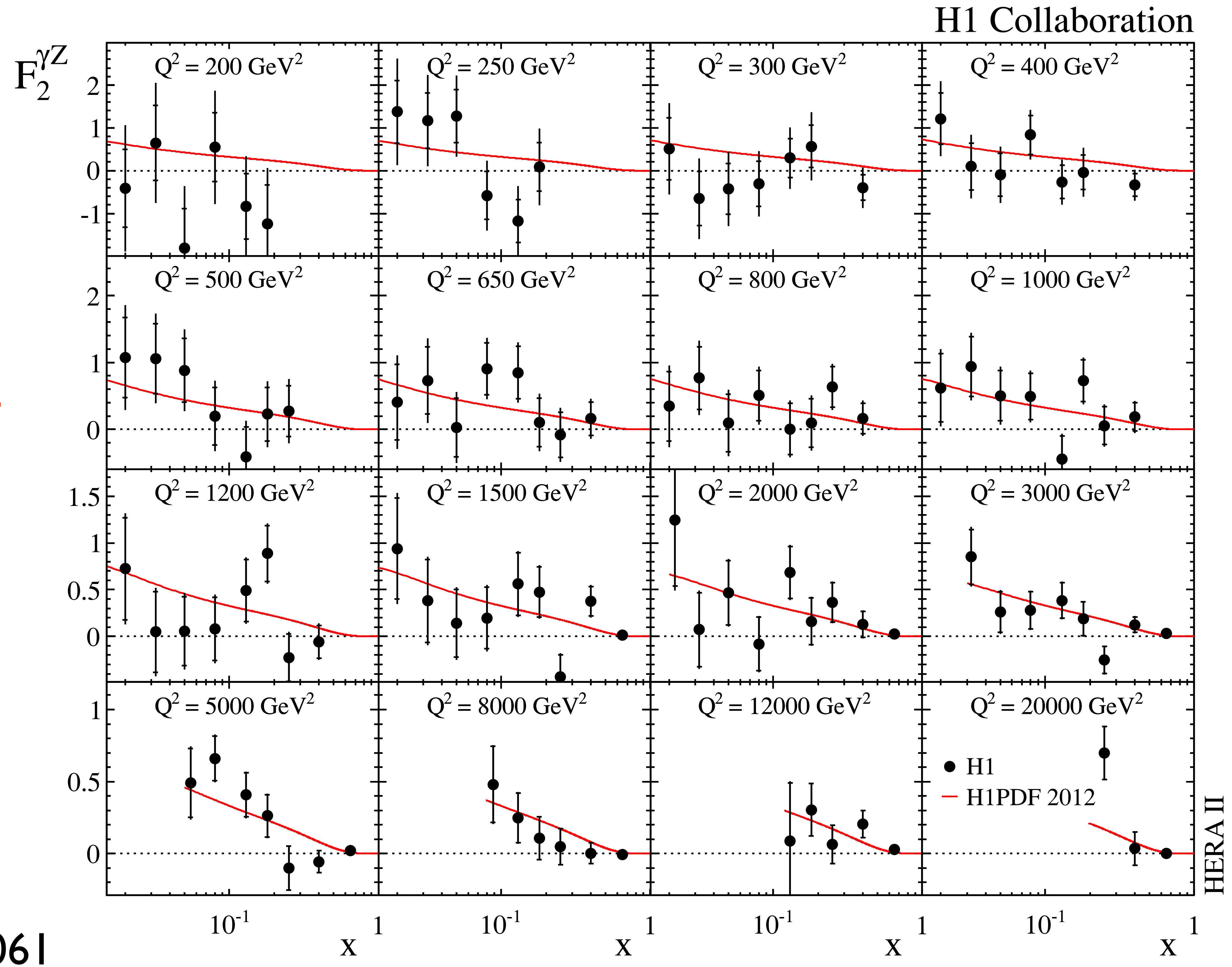


H1PDF2012

JHEP09(2012)061

HERA $F_2^{\gamma Z}$

H1PDF2012



JHEP09(2012)061

Uncertainty band determined using different methods