Spin Structure of the Deuteron from the CLAS/EG1b Data

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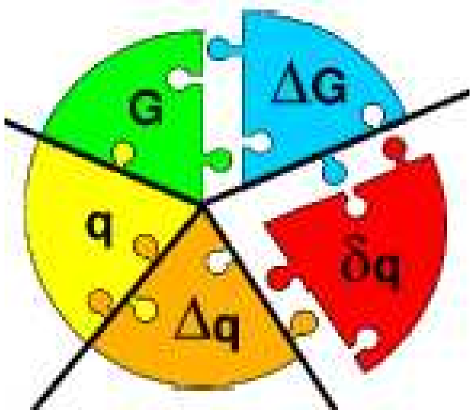
OUTLINE

- **Formalism**
- **Experimental setup**
- **Data analysis**
- **Results**
- **Parameterizations**
- **Conclusion**

Motivation



$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G$$

Quark helicity distribution:

$$\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s + \Delta \bar{u} + \Delta \bar{d} + \Delta \bar{s}$$

$$(\Delta\Sigma \sim 0.2 - 0.3)$$

Simple quark model with relativistic corrections predicts ΔΣ ~ 60%. Experimental results for ΔΣ is generally around 30% ± 10%. Large range of possible values require more precise measurements, possibly by using electron-ion colliders.

Gluon spin distribution:

$$\Delta G$$

topic of active investigation

Orbital angular momenta of quark and gluon:

$$L_q + L_G$$

Can be tackled using GPDs and SIDIS (active at JLab)

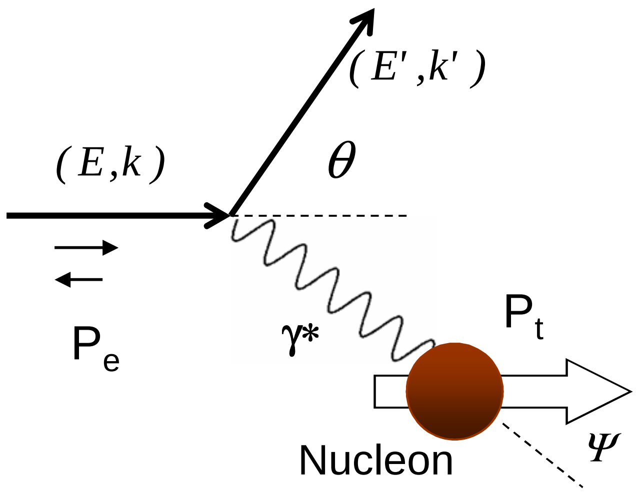
Motivation

- Study valence quark distribution at large x Bjorken.
- Study Q^2 evolution, higher twist contributions, and ChPT limit of sum rules.
- Better understand duality.
- Learn about resonant structure of the nucleon.
- Contribute to our knowledge of $\Delta\Sigma$ and ΔG by providing a low Q^2 anchor point for DGLAP analysis.
- In particular for deuteron: Check neutron SSFs from ^3He data to asses nuclear model dependence.

Experimental Goals

- Measuring the double spin asymmetry for the proton and the deuteron in a very interesting kinematic range that covers the resonance region and extends into the DIS region: from hadronic to quark-gluon degrees of freedom.
- Calculating the virtual photon asymmetry A_1 and the longitudinal spin structure function g_1 as well as the moments of g_1.
- Determining Q^2 evolution of the structure functions and their moments. Compare to the predictions by OPE and χPT and other phenomenological models. Two ends of the kinematic region are constrained by two very important sum-rules: GDH sum rule at $Q^2 = 0$ and Bjorken sum rule at high Q^2.
- Extracting neutron spin structure function from the combined proton and deuteron data.

Lepton – Nucleon Scattering



Kinematics

$$\nu = E - E'$$

$$Q^2 = 4EE'\,Sin^2\left(\frac{\theta}{2}\right)$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$x = \frac{Q^2}{2M\nu}$$

- When an electron scatters from a nucleon, it transfers energy and momentum.

- Theoretically, the interaction occurs by the exchange of a *virtual photon* with energy $\boldsymbol{\nu = E - E'}$ and four-momentum $\boldsymbol{Q^2}$ (virtuality).

- The interaction can be investigated in different regimes according to the transferred energy and momentum.

Lepton – Nucleon Scattering

(Quasi -) Elastic Region:

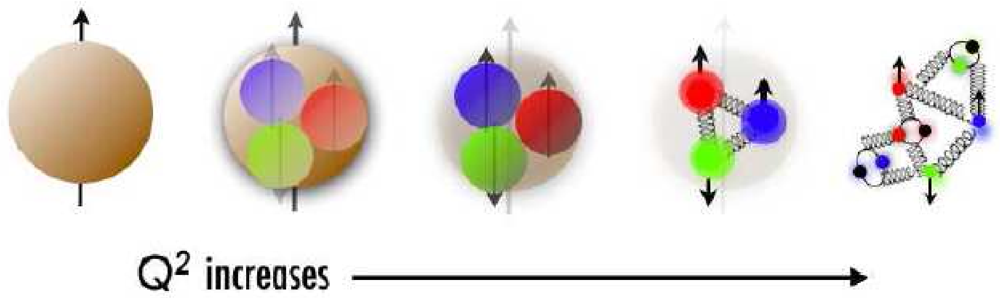
The transferred energy is small (not enough energy to create inner excitations).

Resonance Region:

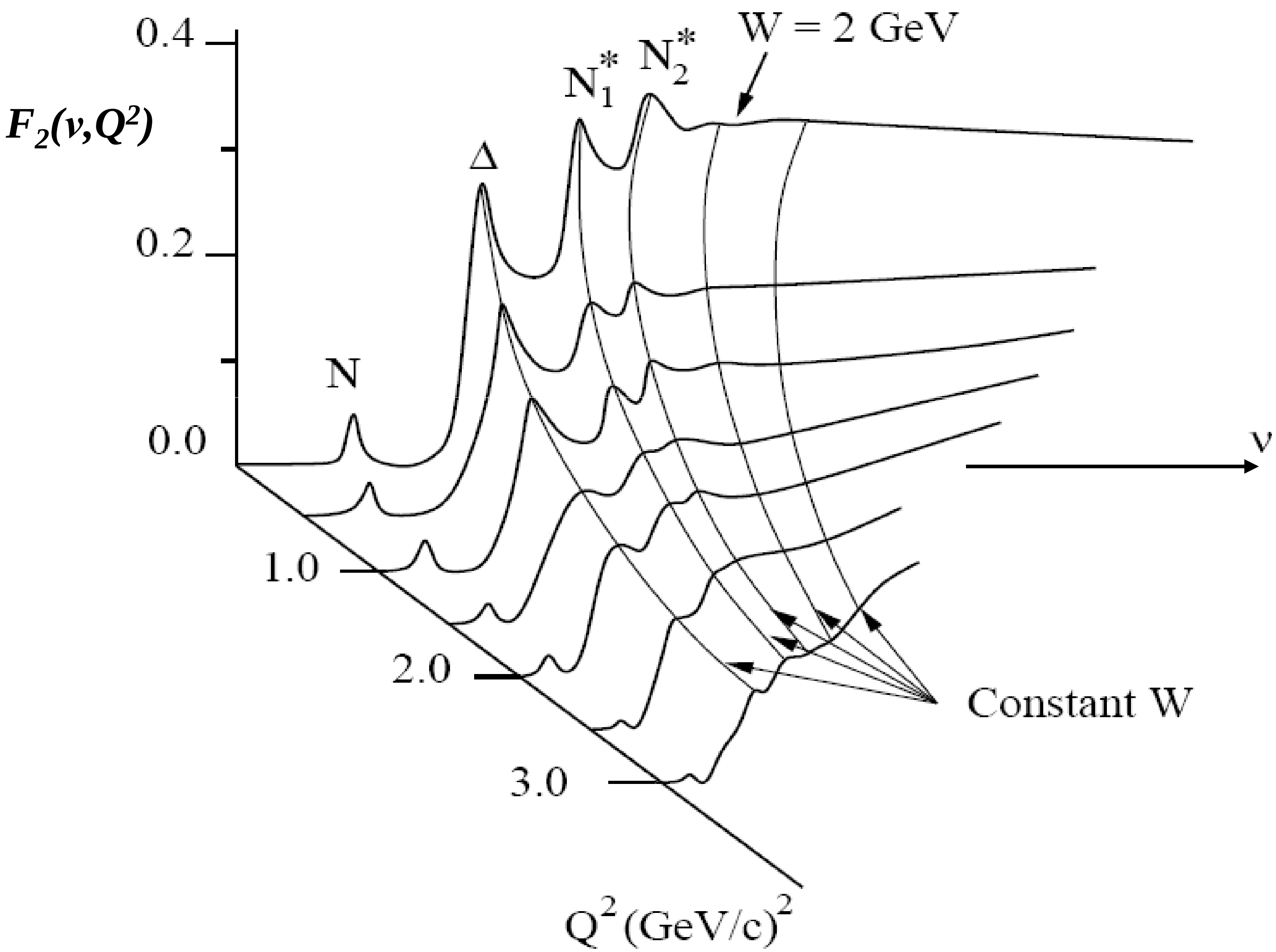
Excited states inside the nucleon (resonances) will be created when the transferred energy is large enough. The mass of a resonance state can be found by $W^2 = (p + q)^2$.

DIS Region:

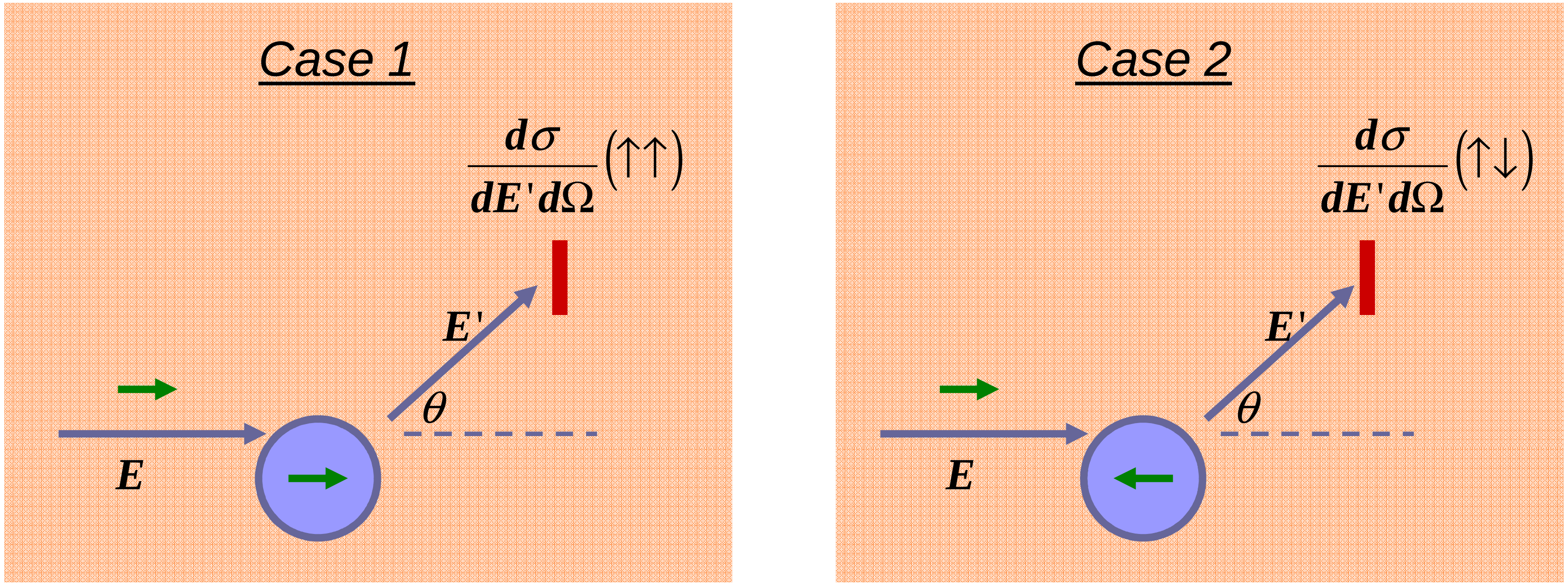
At high energies, the virtual photon can interact with individual partons inside the nucleon. The nucleon breaks apart into pieces and new hadronic states are created.



Lepton – Nucleon Scattering



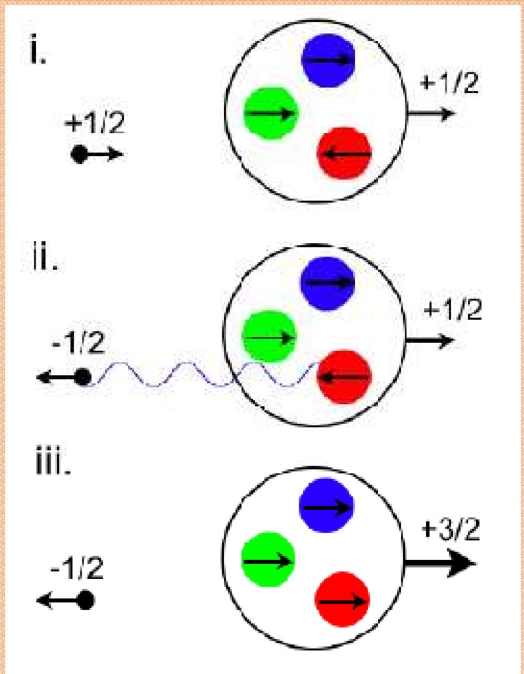
Double polarized inclusive electron scattering



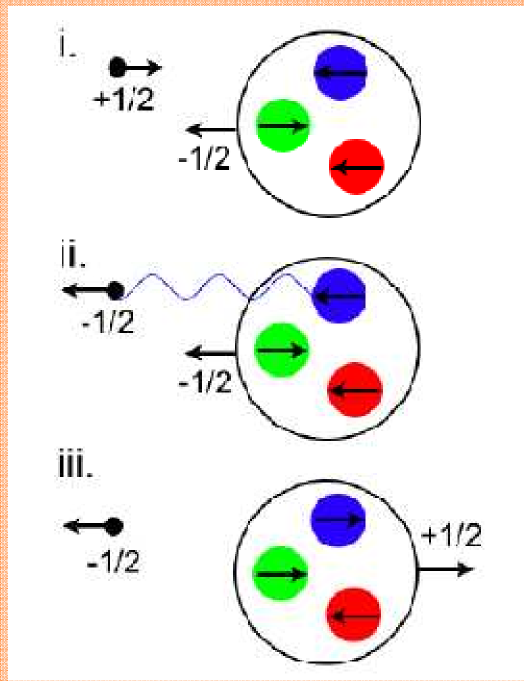
$$A_{\parallel} = \frac{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) - \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)}{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) + \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)}$$

Virtual Photon Asymmetries

In the scaling region at large Q^2 (*kinematic region where you begin to see individual quarks as point particles*), **quarks may be considered almost free** (*by the asymptotic freedom*..), **so the transversely polarized virtual photon interacts with the individual quarks, which are also polarized the same or opposite to the proton's spin. The 1/2 or the 3/2 are the spins of the possible final states**



$\sigma_T^{3/2}$

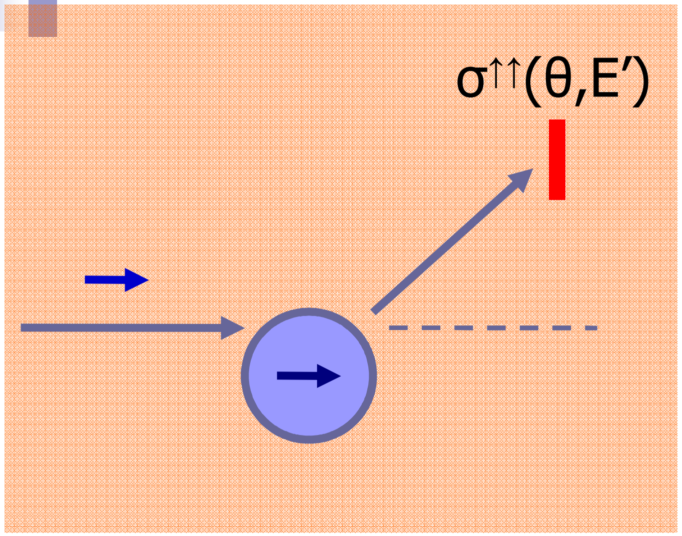


$\sigma_T^{1/2}$

virtual photon asymmetries

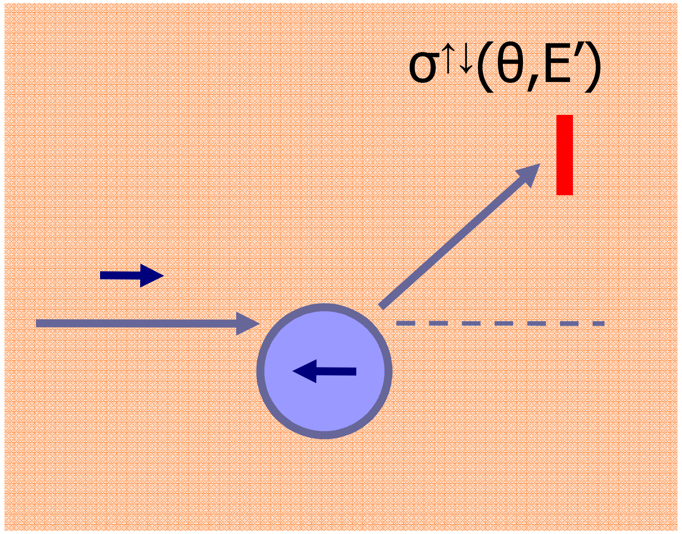
$$A_1 = \frac{\sigma_T^{1/2} - \sigma_T^{3/2}}{\sigma_T^{1/2} + \sigma_T^{3/2}} \qquad A_2 = \frac{2\sigma_{LT}}{\sigma_T^{1/2} + \sigma_T^{3/2}}$$

Double polarized inclusive electron scattering



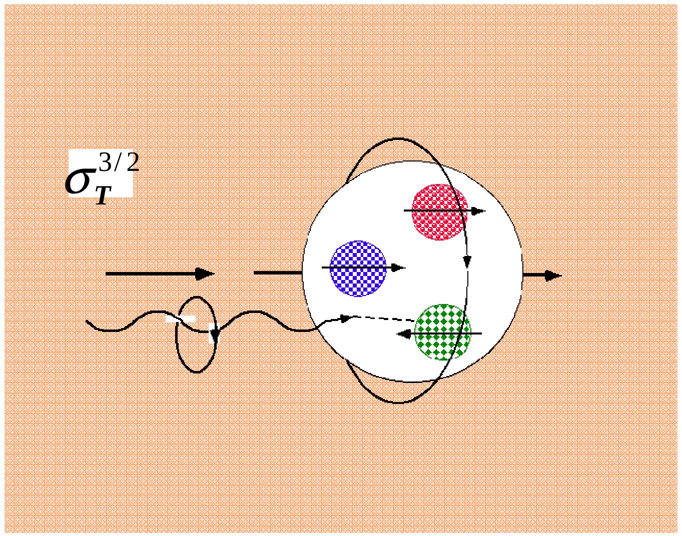
measurable

$$A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$



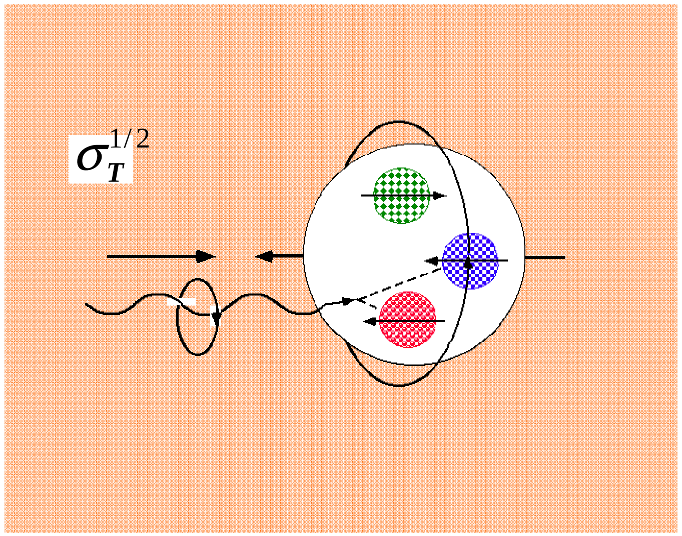
EXPERIMENT

THEORY

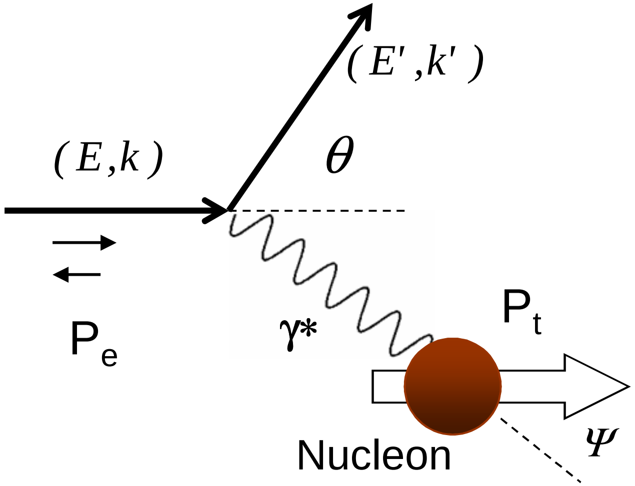


$$A_1 = \frac{\sigma_T^{1/2} - \sigma_T^{3/2}}{\sigma_T^{1/2} + \sigma_T^{3/2}}$$

$$A_2 = \frac{2\sigma_{LT}}{\sigma_T^{1/2} + \sigma_T^{3/2}}$$



Double polarized inclusive electron scattering



Kinematics

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$$Q^2 = 4EE' \, Sin^2\left(\frac{\theta}{2}\right)$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$x = \frac{Q^2}{2M\nu}$$

selected kinematical variables

Cross section can be expressed in terms of the virtual photon asymmetries A_1 and A_2.

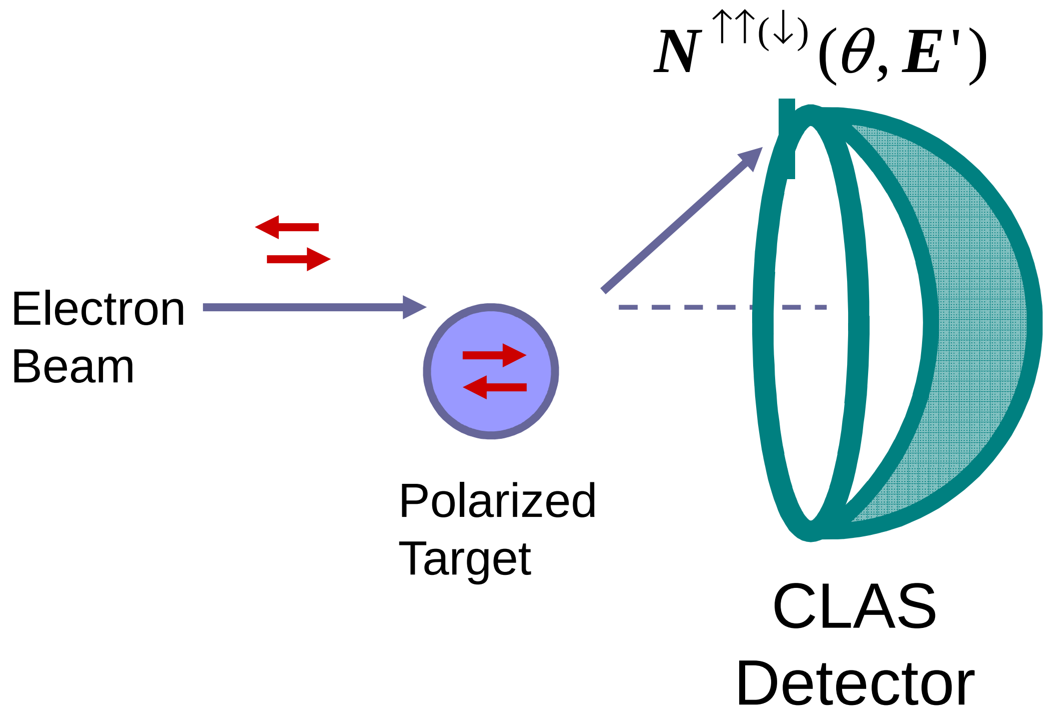
$$\frac{d\sigma}{dE'd\Omega} = \Gamma_\nu \left[\sigma_T + \varepsilon\sigma_L + P_e P_t \left(\sqrt{1-\varepsilon^2} A_1 \sigma_T \cos\theta + \sqrt{2\varepsilon(1-\varepsilon)} A_2 \sigma_T \sin\theta \right) \right]$$

$$A_{||} = \frac{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) - \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)}{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) + \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)} = D(A_1 + \eta A_2)$$

$$D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R} \quad where \quad R = \frac{\sigma_L}{\sigma_T}$$

$$\eta = \frac{\varepsilon\sqrt{Q^2}}{E - E'\varepsilon}$$

Detector



We need to collect huge number of events to get precision results.

Use azimuthal symmetry

Collect data for different kinematics.

Asymmetry Analysis

- raw asymmetry from normalized counts

$$A_{raw} = \frac{N^+/Q^+ - N^-/Q^-}{N^+/Q^+ + N^-/Q^-}$$

- double spin asymmetry

$$A_{\parallel} = \frac{C_1}{f_{RC}}\left(\frac{A_{raw}}{F_D P_b P_t} C_{back} - C_2\right) + A_{RC}$$

- virtual photon asymmetry

$$A_1 = \frac{A_{\parallel}}{D} - \eta A_2$$

model

$$D = \frac{1 - E'\varepsilon/E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon\sqrt{Q^2}}{E - E'\varepsilon}; \quad R = \frac{\sigma_L}{\sigma_T}$$

model

- spin structure function

$$g_1(x, Q^2) = \frac{\nu^2}{Q^2} F_1(x, Q^2)\left(A_1(x, Q^2) + \frac{Q}{\nu} A_2(x, Q^2)\right)$$

model model

Kinematics

- ❑ 12 Different Configurations for Input Beam Energy (MeV) and Magnetic Field (+ or – torus current):

  1606+ 1606- 1723- 2286+
  2561+ 2561- 4238+ 4238-
  5615- 5725+ 5725- 5743-

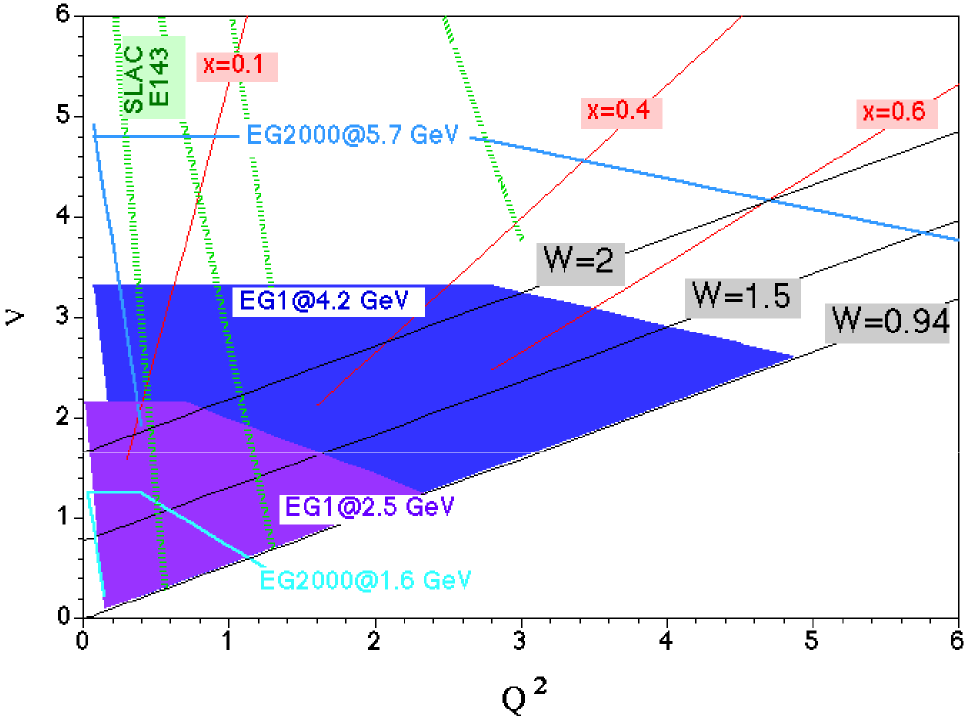
- ❑ 5 Different Targets:

  NH3, ND3, C12, N15 and Empty

- ❑ 23 billion events

1.6 and 5.7 GeV data has been analyzed before and results were published.

Now also analyzed the full data with addition of 2.5 and 4.2 GeV data.



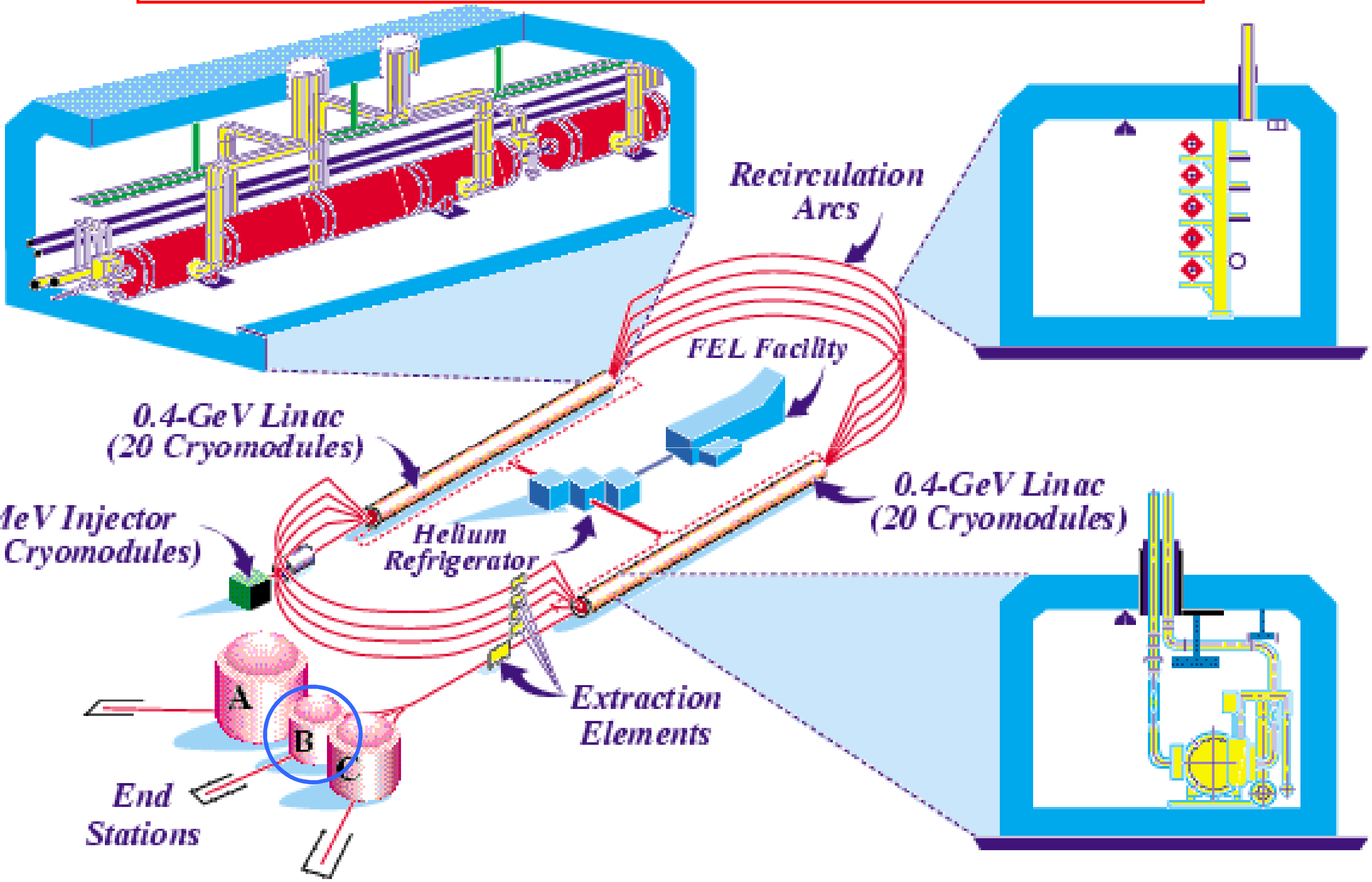
$0.05 < Q^2 < 5.0$ GeV^2 in 39 bins

W < 3.0 GeV in 10 MeV 300 bins

Jefferson Lab

Gwyn Williams
holding a 5-cell cavity.

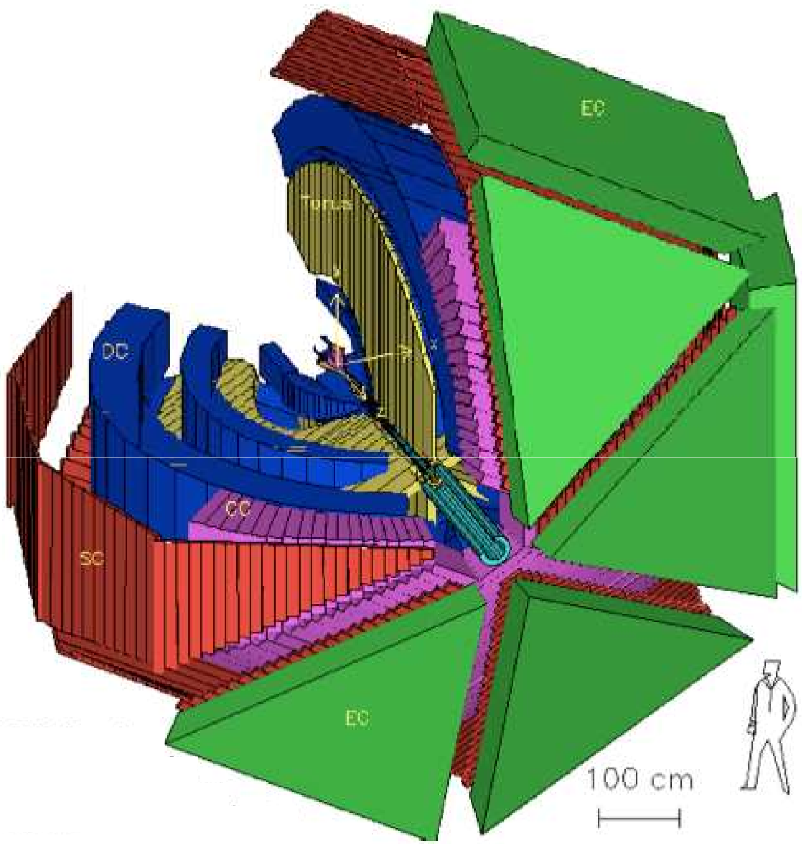
Continuous Electron Beam Accelerator Facility

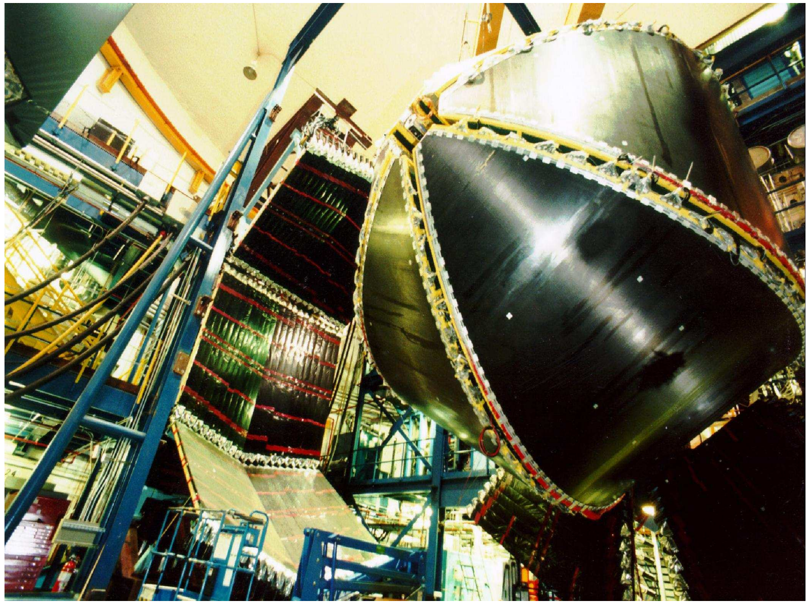


- *Each Cryomodule is made by 8 SRF cavities*
- *Polarized electrons from gallium arsenide (GaAs) cathode*
- *Energies from 800 MeV up to 5.8 GeV*
- *Typical beam polarization ~ 80%*
- *Beam is delivered to three experimental halls in consecutive bunches.*

CLAS Detector

CEBAF Large Acceptance Spectrometer

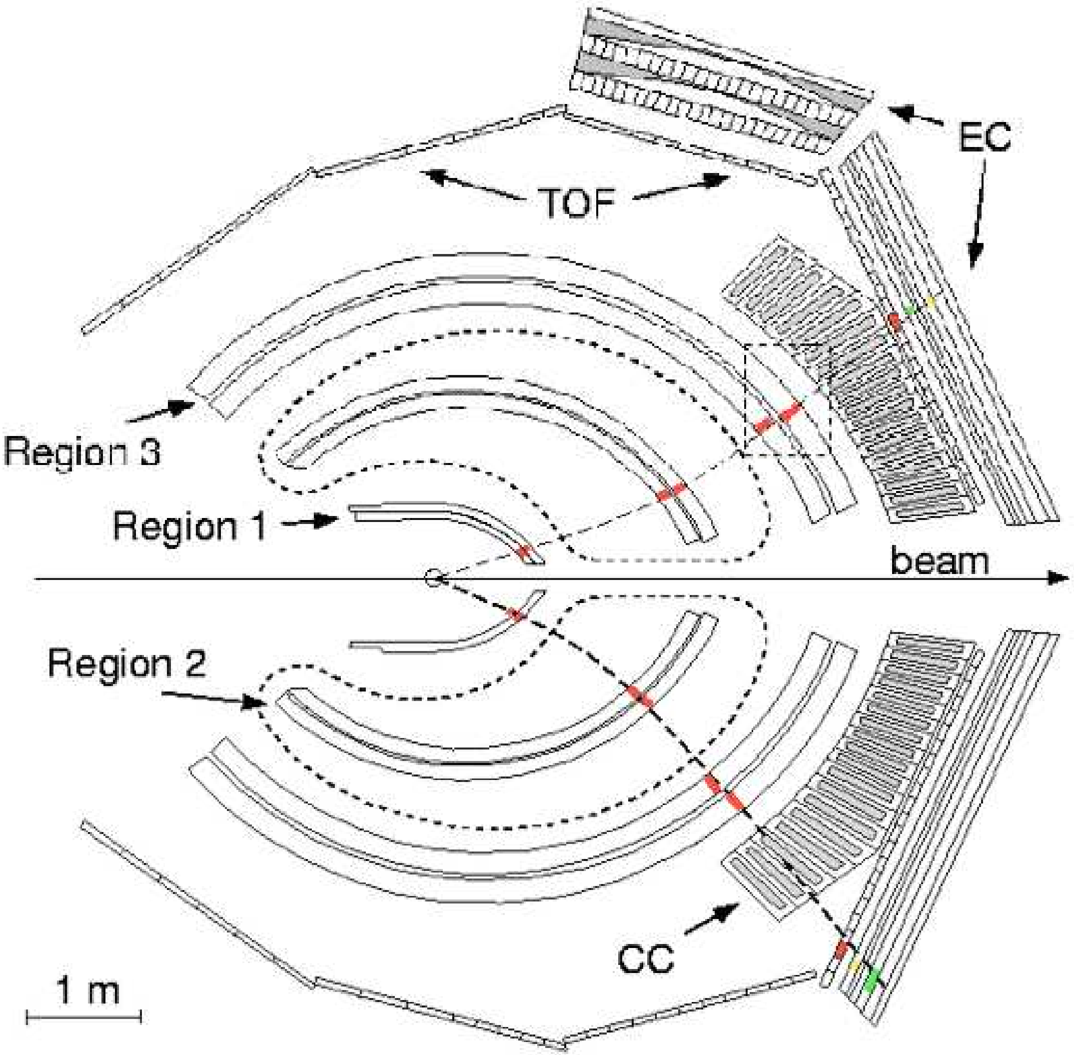




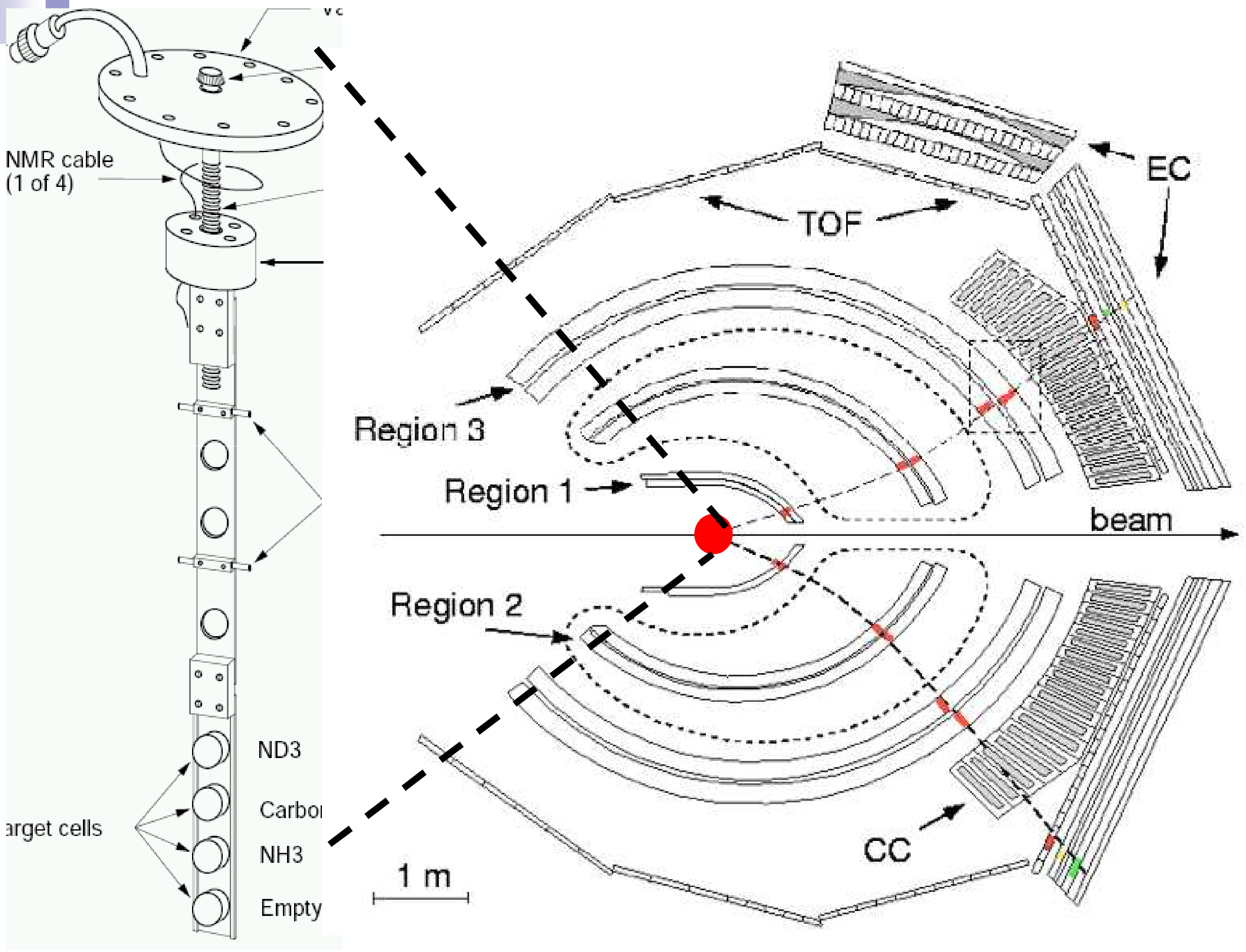
Investigation of quark-gluon structure of the nucleon
Detailed study of spectrum of excited states

- Large kinematic coverage
- Detection of charged and neutral particles
- Multi particle final states
- Polarized NH_3 & ND_3 Targets

CLAS Detector



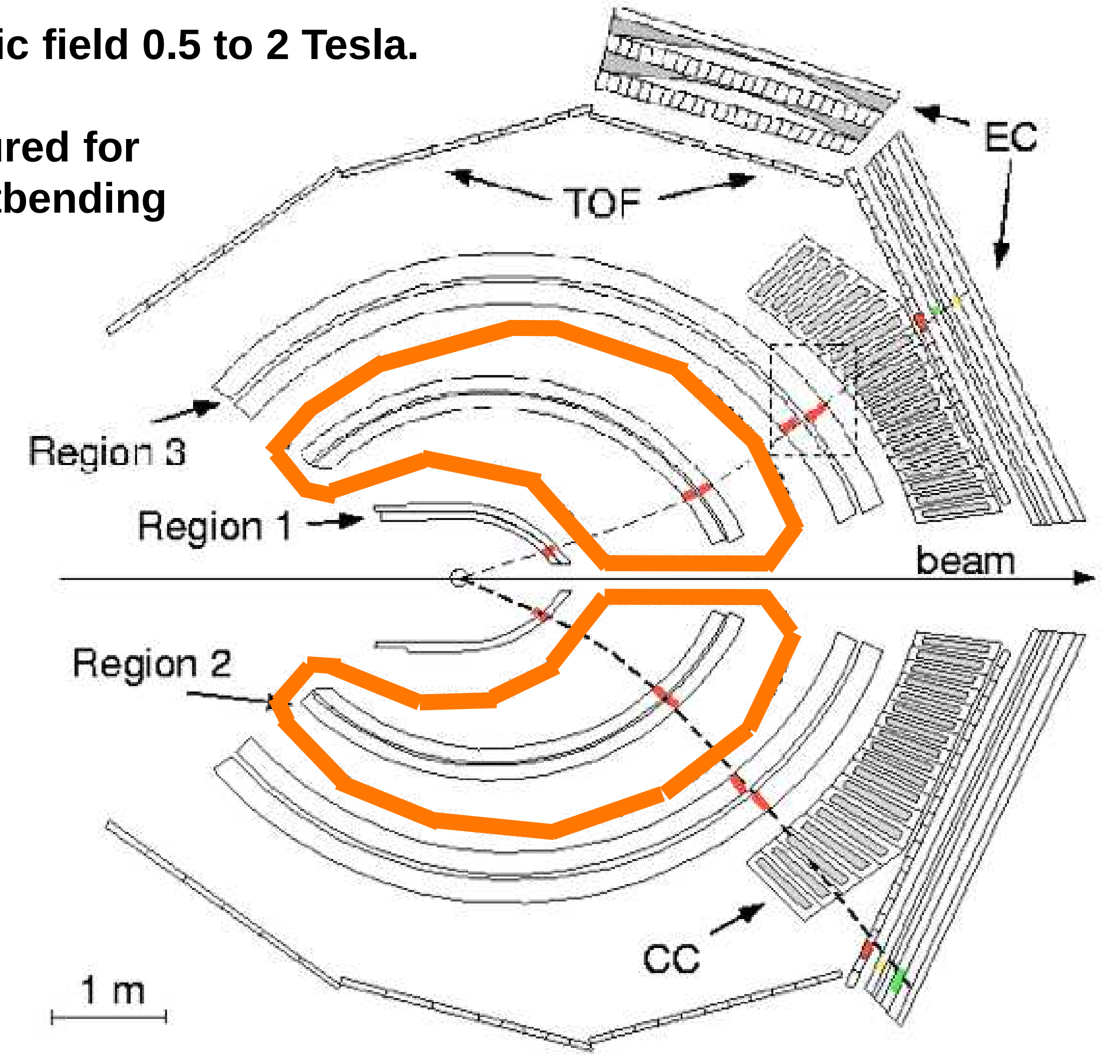
EG1b Polarized Target



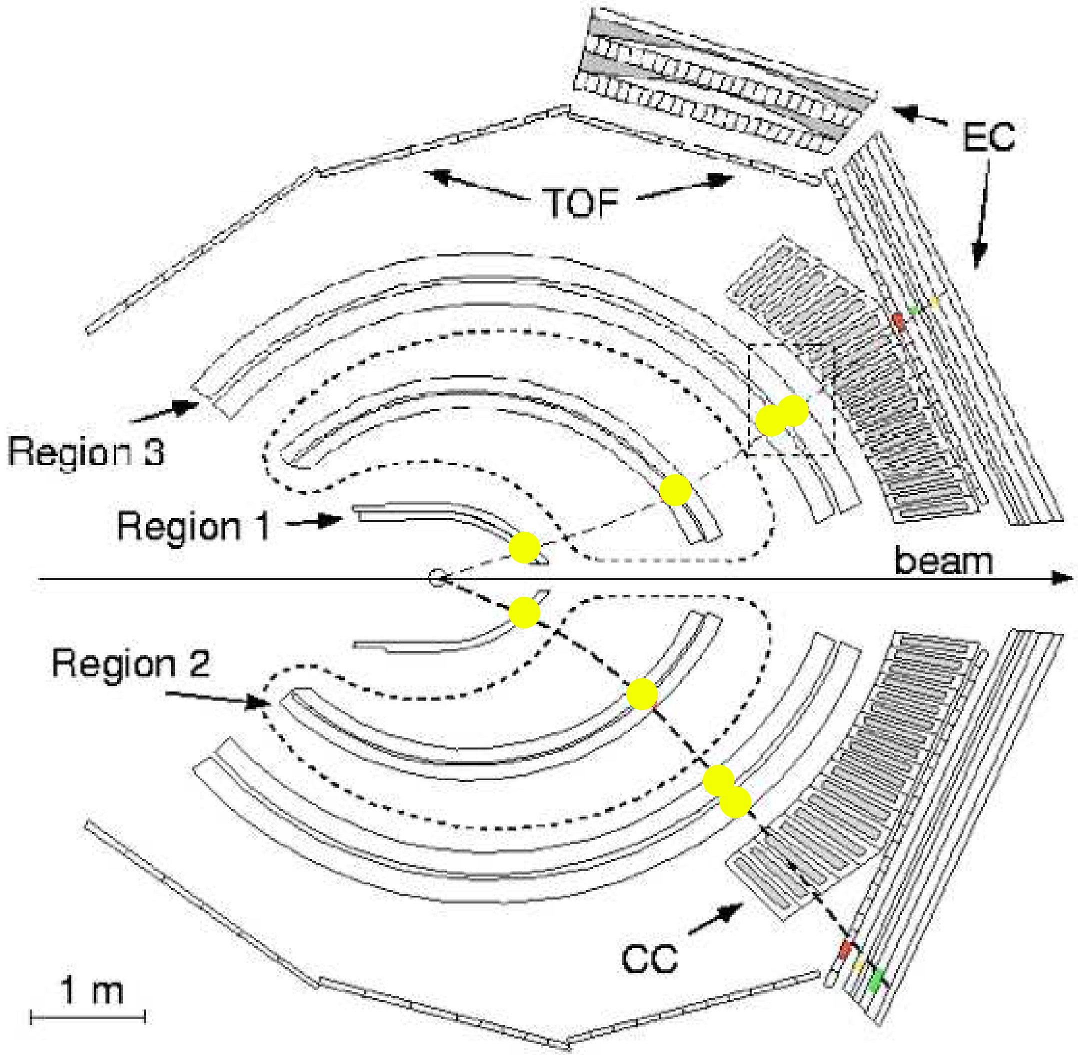
Torus Magnet

Torodial magnetic field 0.5 to 2 Tesla.

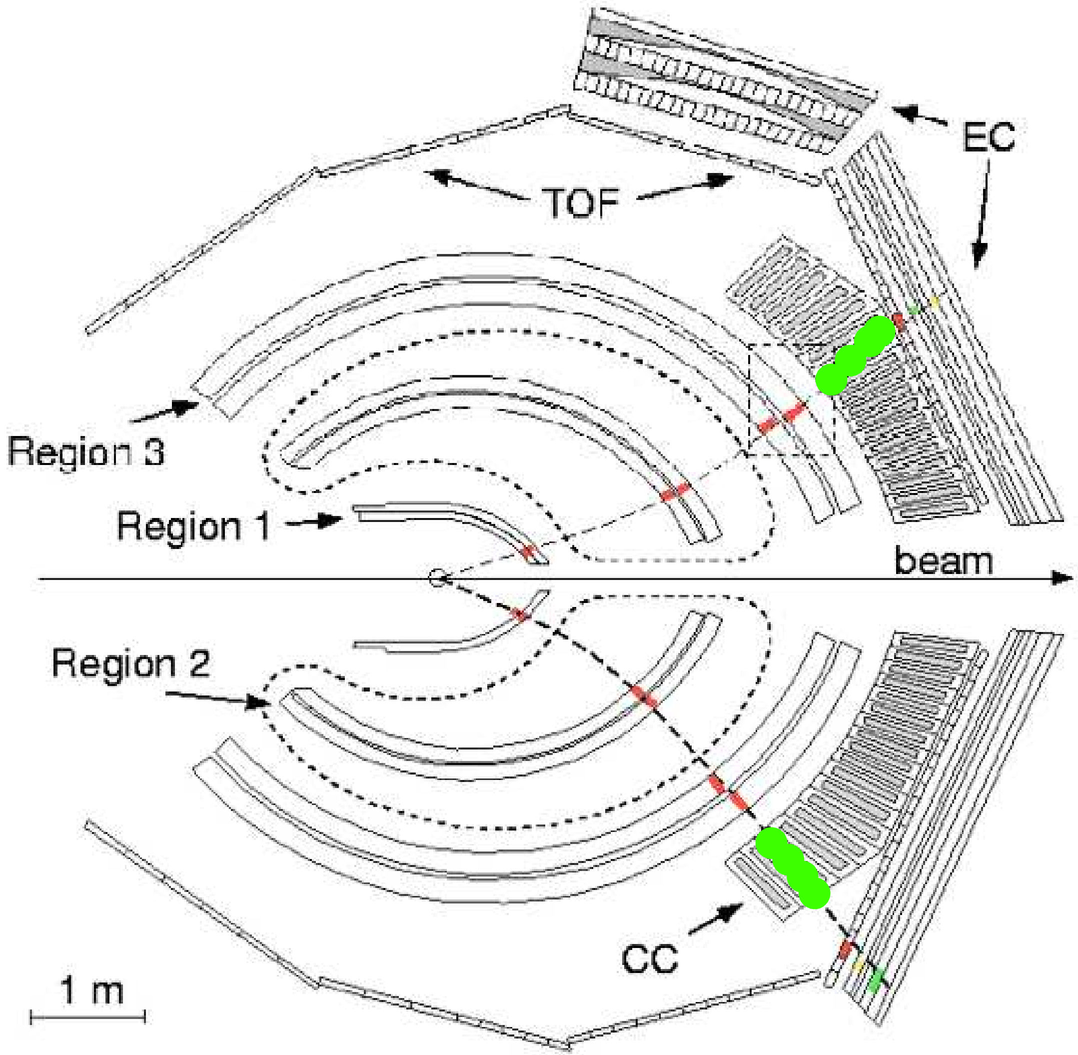
It can be configured for inbending or outbending operations.



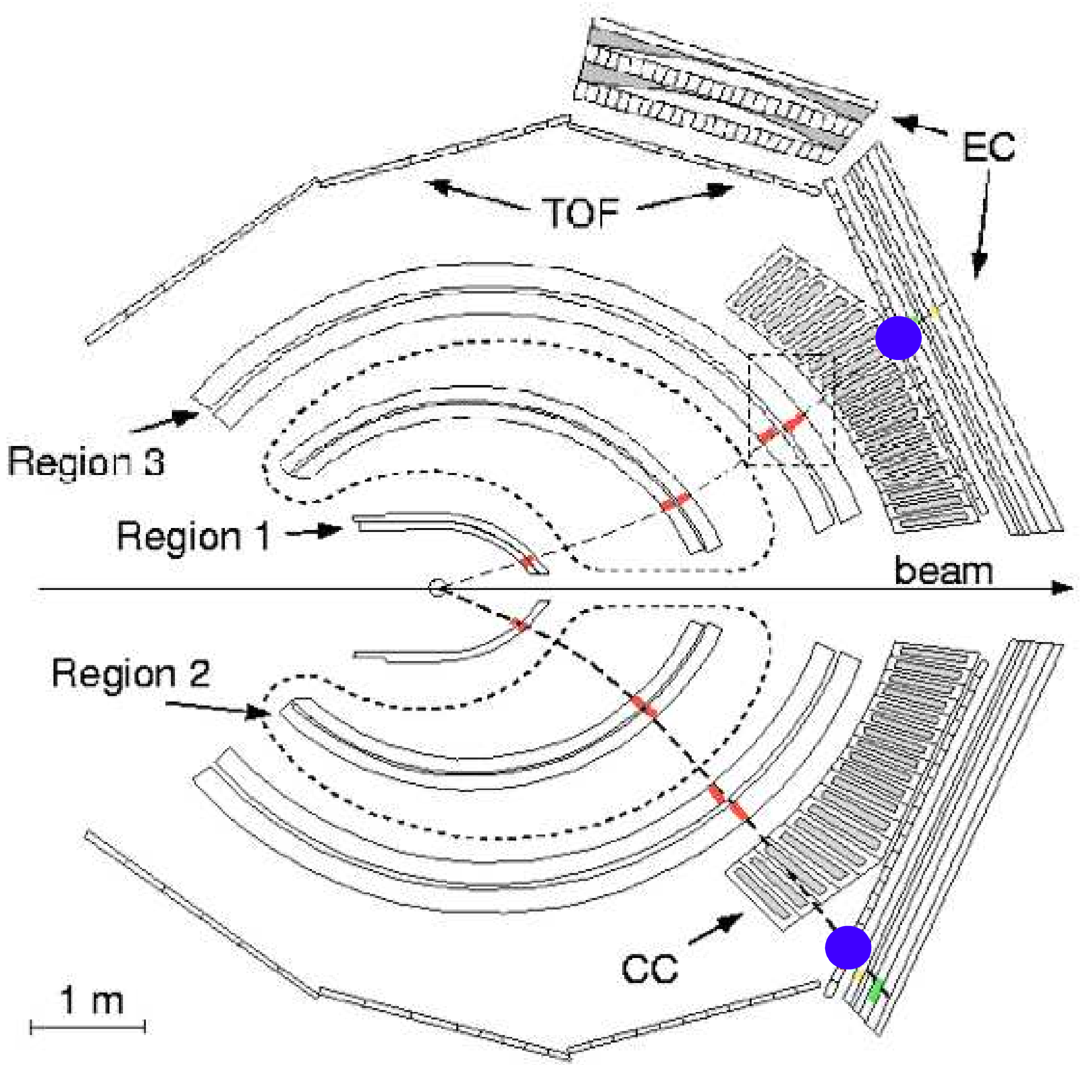
Drift Chambers (DC)



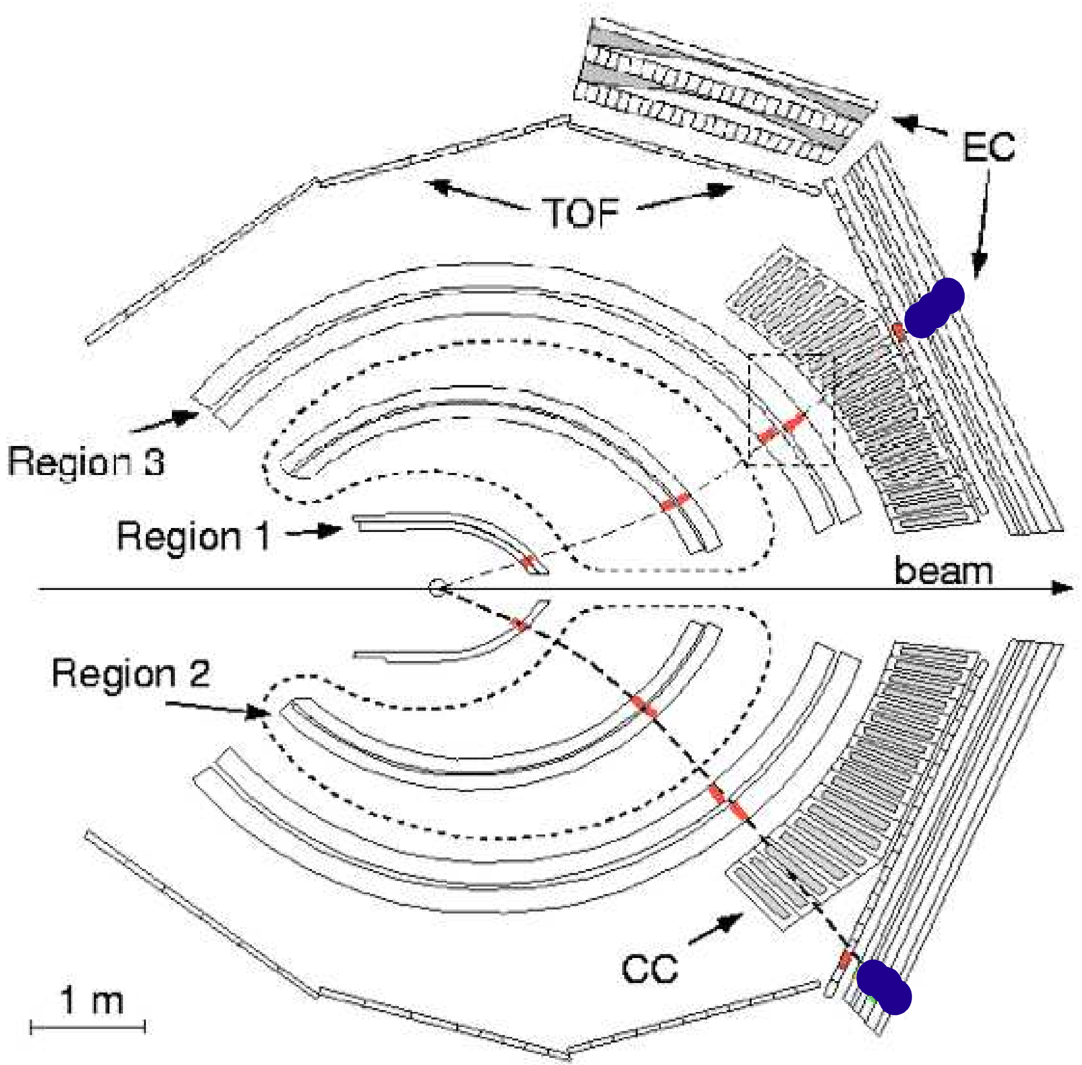
Cherenkov Counters (CC)



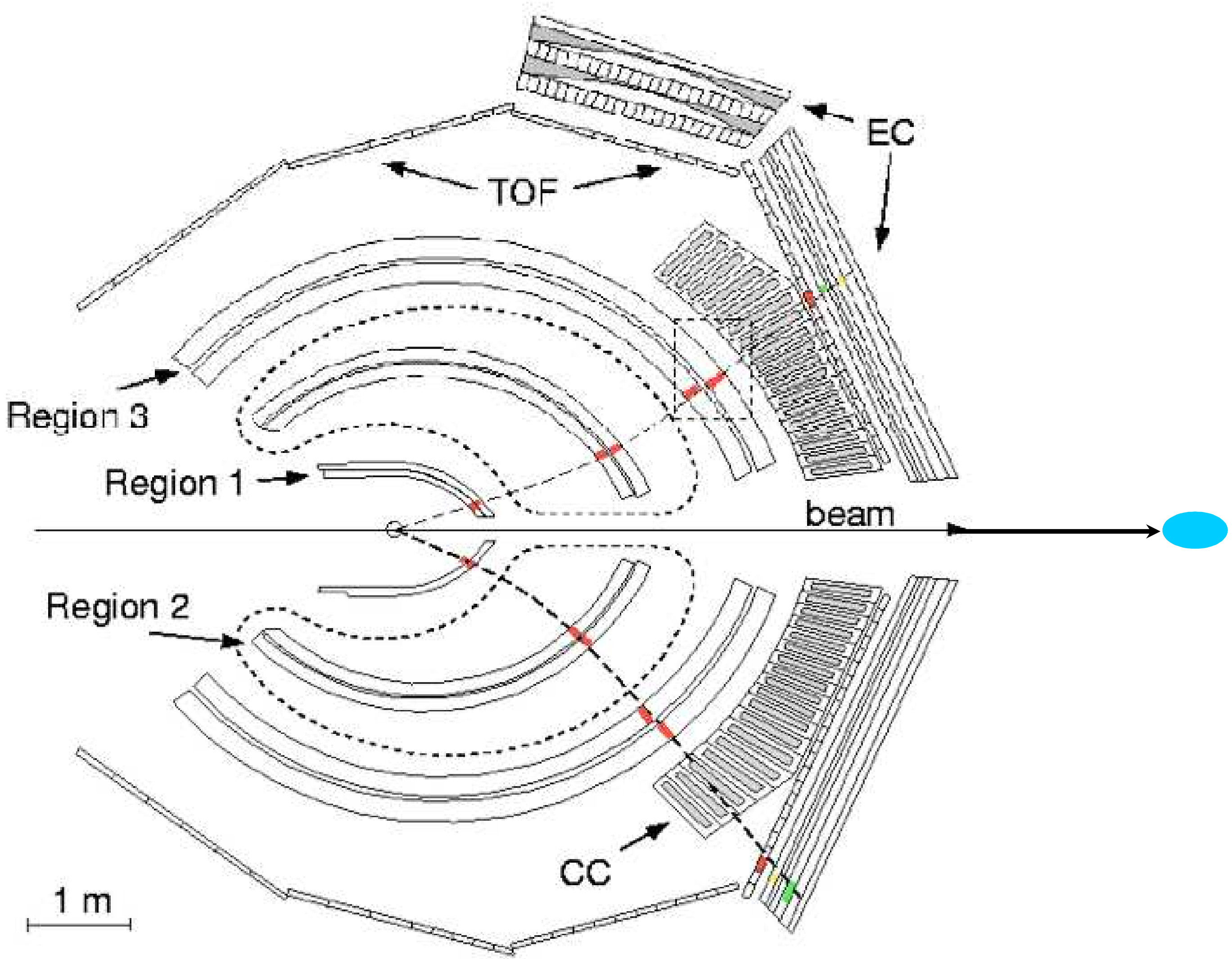
Scintillation Counters (SC)



Electromagnetic Calorimeters (EC)

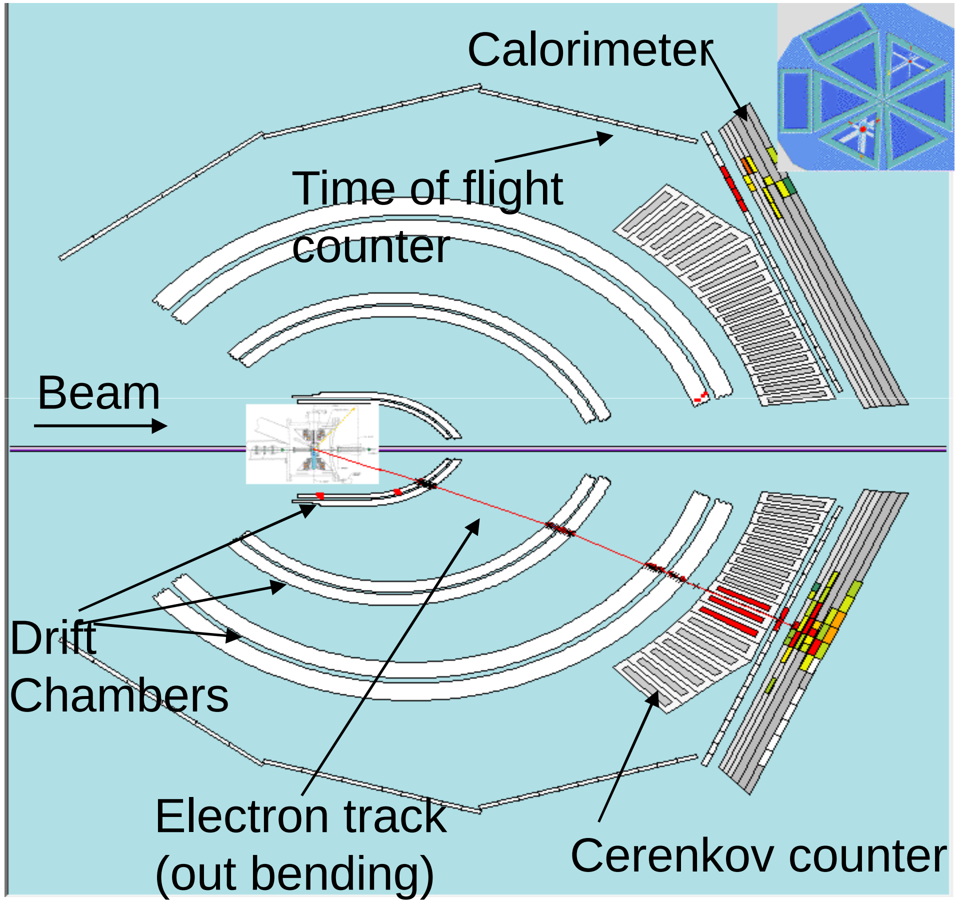


Faraday Cup (FC)



CLAS Detector

- Electrons are detected as a coincidence in the Electromagnetic Calorimeter and the Cherenkov Counter
- Electron momentum is reconstructed from trajectory in Drift chambers
- Dynamically polarized NH_3 and ND_3 targets (along beam direction)
  - NH_3 polarization: 65-75%.
  - ND_3 polarization: 25-35%.
- 1K LHe cooling bath
- ^{12}C,^{15}N and ^{4}He targets to measure background contribution



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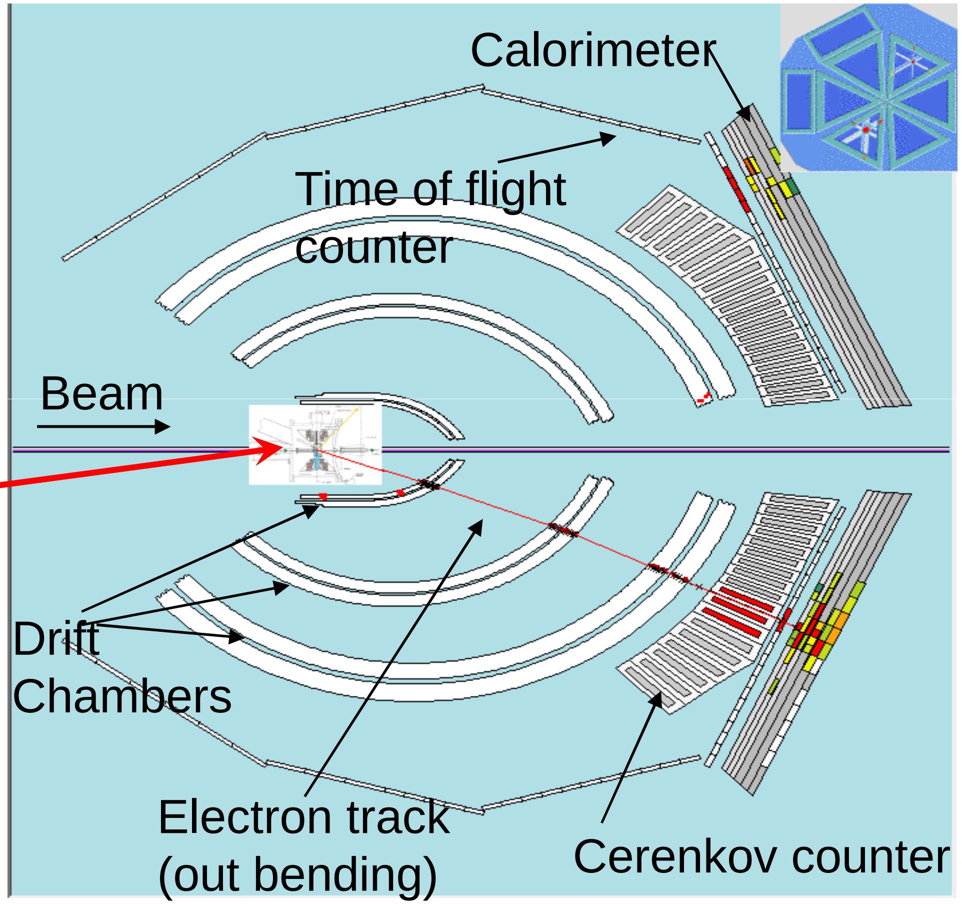
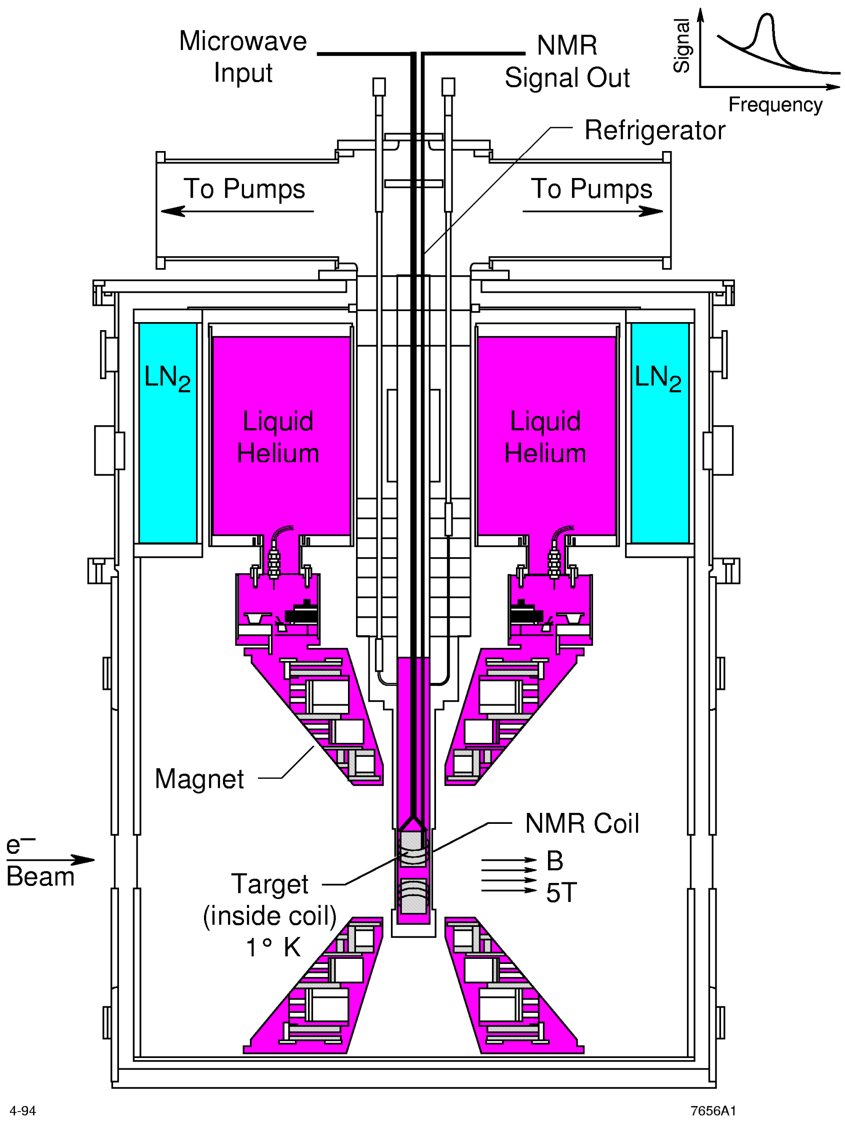


Polarized Solid State Targets



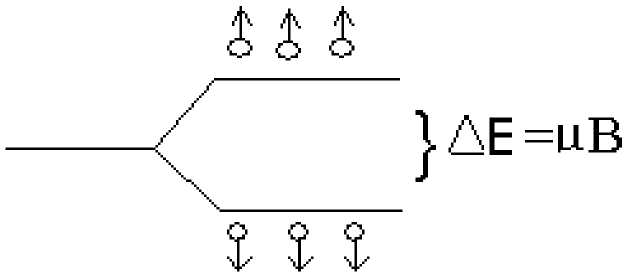
List of Ingredients:

- Polarizable Material (high H content) with paramagnetic centers = unpaired e^- (irradiated or chemically doped):
  - Alcohols (e.g. butanol)
  - Ammonia - $^{15}NH_3$ and $^{15}ND_3$
  - HD ice
- Very Low Temperature:
  - About 1 K for (continuous) dynamic polarization - pumped-on Liquid ^{4}He bath at low pressure
- Dynamic Polarization in high B-field:
  - About 2.5 - 5 T -> unpaired e^- 100% polarized
  - Polarization transferred to nuclei via HF transitions (simultaneous electron and nuclear spin flip); requires 70-140 GHz microwaves
- NMR system to monitor polarization.
- Insulation vacuum, beam and scattered particles ports.

Considerations:

- Possibly significant “dilution” by “inactive” nuclei.
- Beam must be rastered to avoid local depolarization.
- Target must be annealed repeatedly to alleviate radiation damage (due to electron beam).
- Total dose and current limitations (e.g., 100 nA max).
- Transverse DNP targets -> large deflection of electrons.

Dynamic Nuclear Polarization



When we put the target into a static uniform magnetic field, energy level of nucleons will split with respect to their spin configurations.

Large B/T is needed for high polarization.

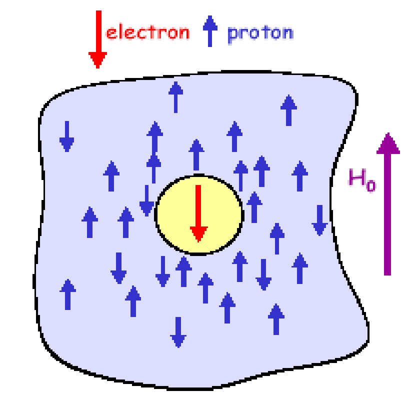
$$P_{1/2} = \frac{N_{1/2} - N_{-1/2}}{N_{1/2} + N_{-1/2}} = \tanh\frac{\mu B}{kT}$$

Because the magnetic moment of the proton (deuteron) is very low, their resulting polarizations will be small.

$$P_1 = \frac{N_1 - N_{-1}}{N_1 + N_0 + N_{-1}} = \frac{4\tanh\frac{\mu B}{2kT}}{3 + \tanh^2\frac{\mu B}{2kT}}$$

At typical settings of B=5Tesla and T=1K, polarization is less than 1%.

Electron’s magnetic moment is larger by a thousand fold. 99% can be reached.



1 - Dope or radiate target with electrons (create radicals)
2 - Polarize the dopant electrons
3 - Transfer the polarization to nucleons by microwave transitions

Dynamic Nuclear Polarization

❑Introduce MW into the system at electron Larmor frequency:

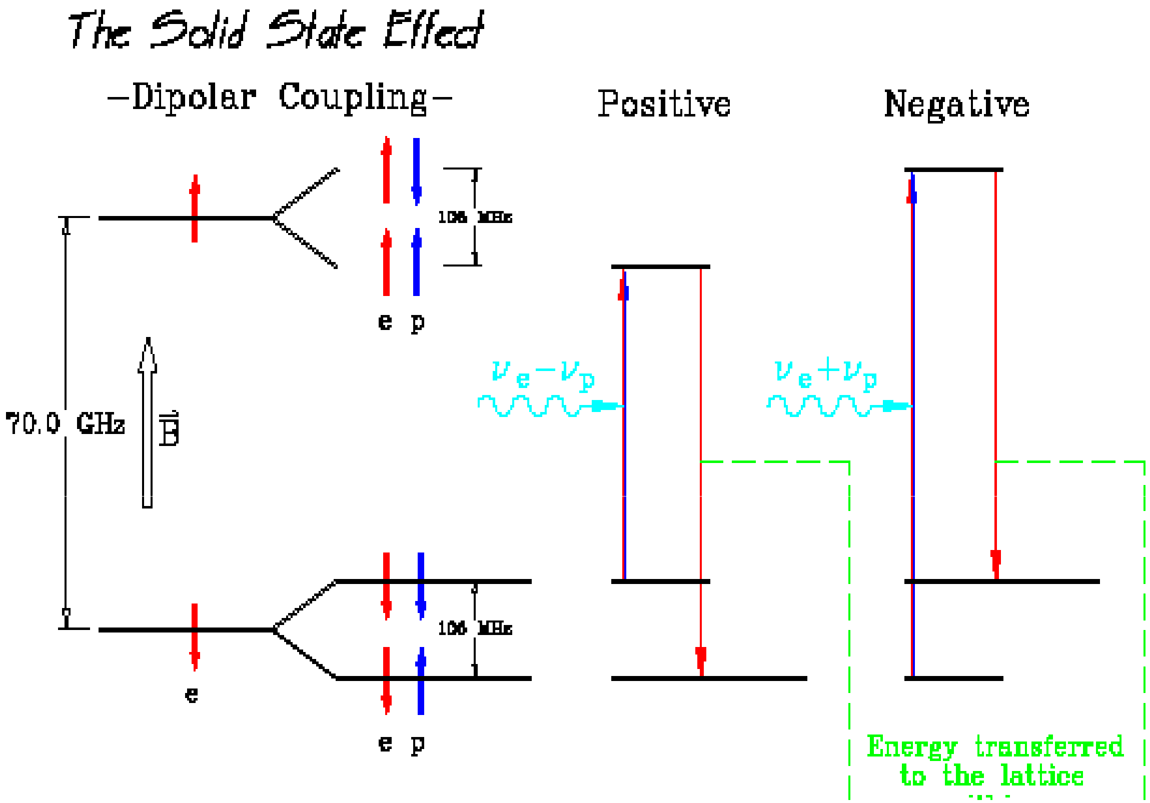
$\nu_e = 2\mu_e B/h$ = 70GHz for 2.5T

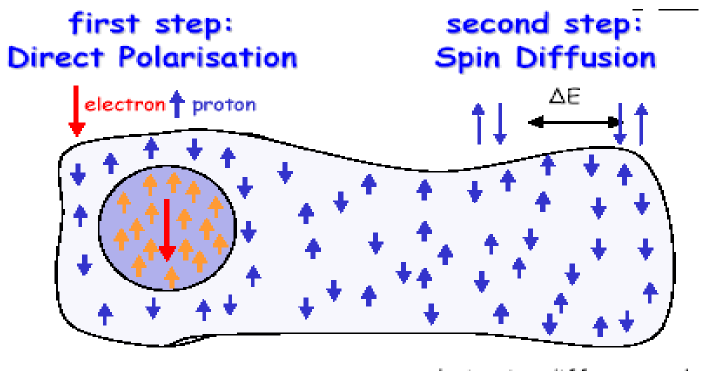
Electron spin flips by MW

❑If the MW frequency is just equal to $\upsilon_e \pm \upsilon_p$, forbidden transitions occur between two nucleon states nucleon spins also flip together with electron spins.

❑ Electron relaxation is fast but nucleons stay much longer.

❑ Nucleon polarizations build up in time. → Solid state effect.





❑ Spin diffusion transfers the polarization to further regions.

Asymmetry Analysis

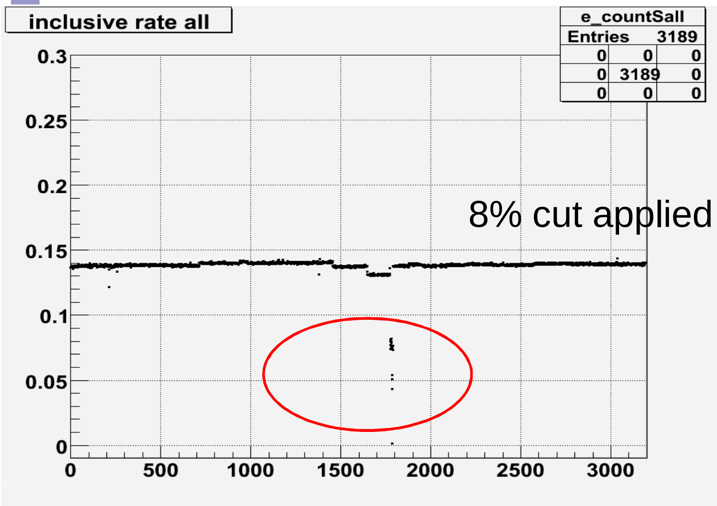
$$A_{\|} = \frac{C_1}{f_{RC}}\left(\frac{\boxed{A_{raw}}}{F_D P_b P_t} C_{back} - C_2\right) + A_{RC}$$

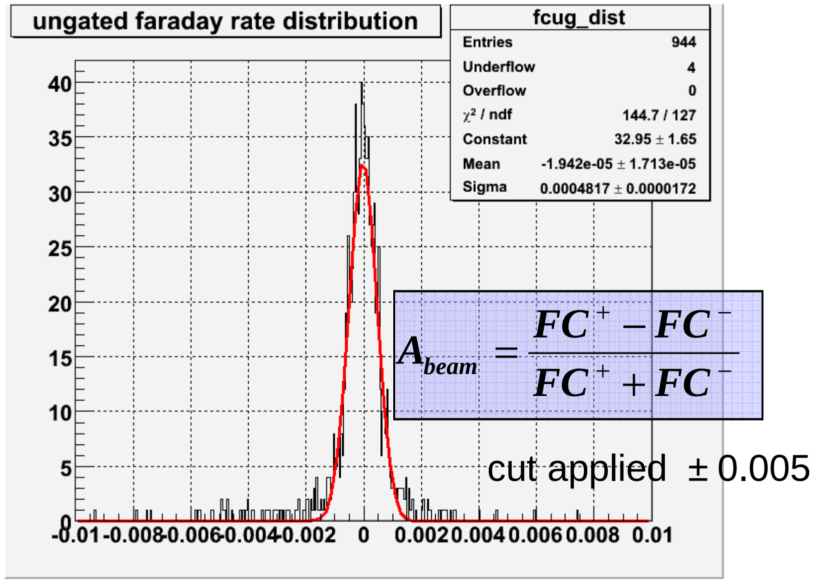
$$A_{raw} = \frac{N^+/Q^+ - N^-/Q^-}{N^+/Q^+ + N^-/Q^-}$$

for each Q^2 and W bins

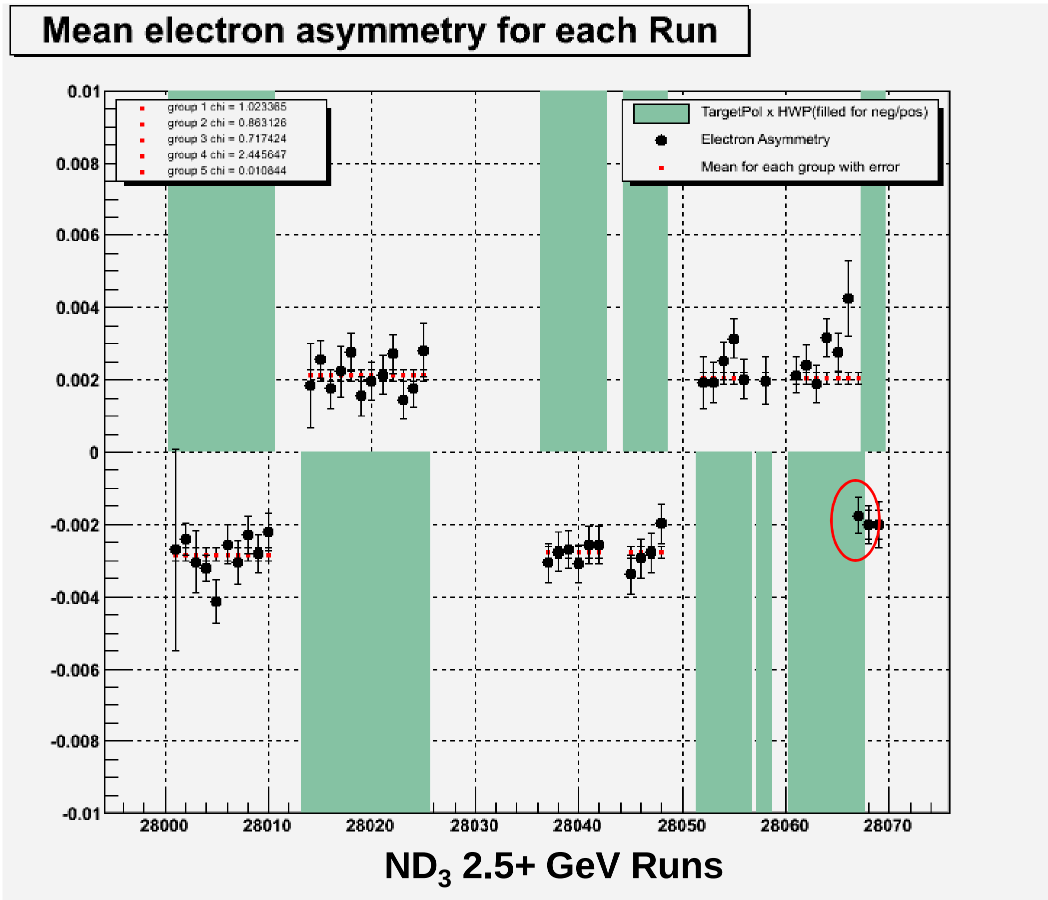
- **Data Calibration and Reconstruction (TOF, DC, EC)**
- **Helicity Studies**
- **Quality Checks and Data File Selections**
- **Particle Selections**
- **Fiducial Cuts**
- **Kinematic Corrections (momentum, energy loss , multiple scattering etc...)**

Quality Checks



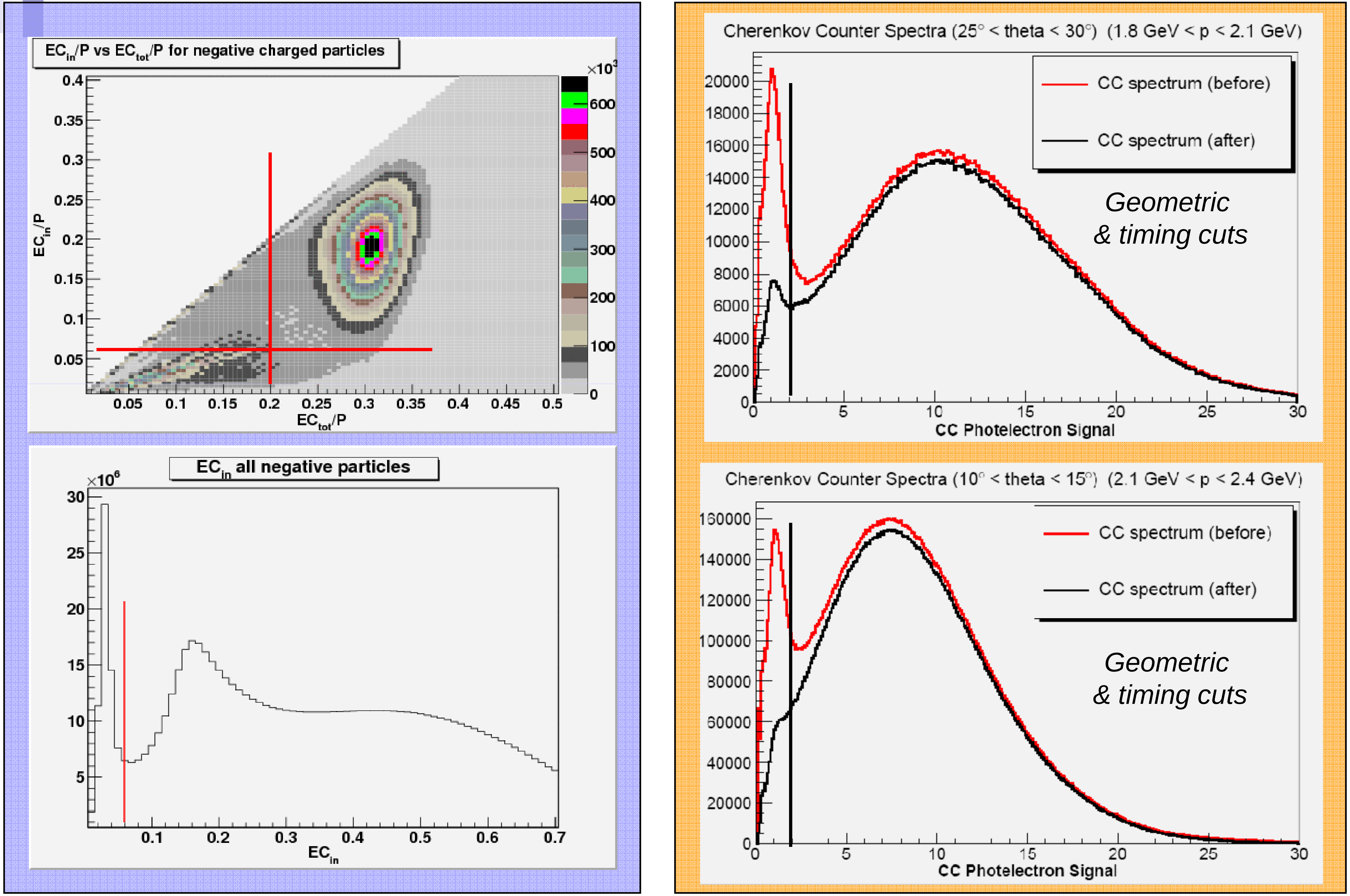


$$A_{beam} = \frac{FC^+ - FC^-}{FC^+ + FC^-}$$



To determine the registered target and beam polarizations are correct.

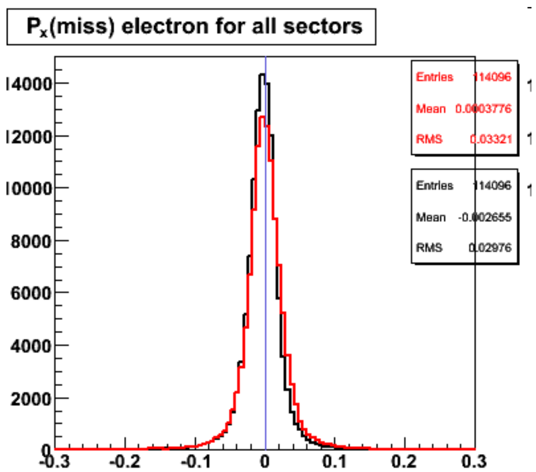
Electron Identification (EM and CC signals)



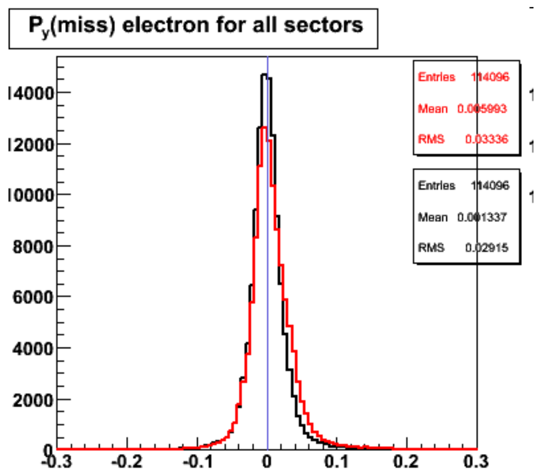
Kinematic Corrections

Mainly based on parameterizations to minimize missing energy and momentum for well identified elastic and multi-particle final states.

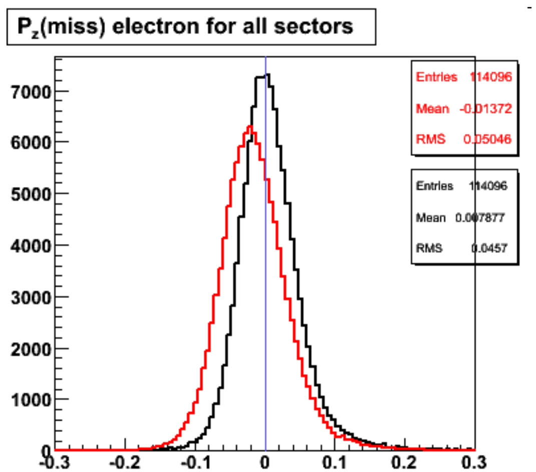
Takes care of the effects from:
- misalignment of DC wires
- complex magnetic fields
- multiple scattering effects
- energy loss inside target



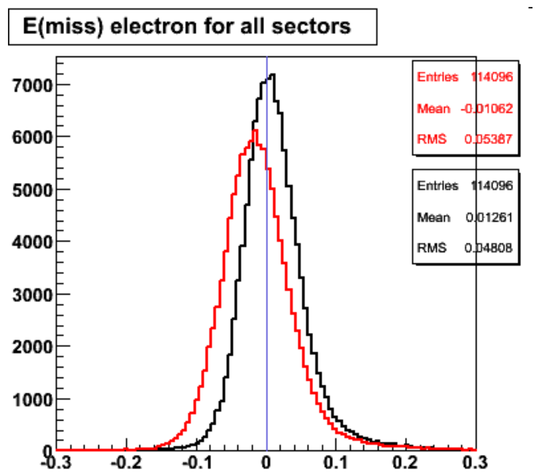
Missing p_{x} Distribution



Missing p_{y} Distribution



Missing p_{z} Distribution



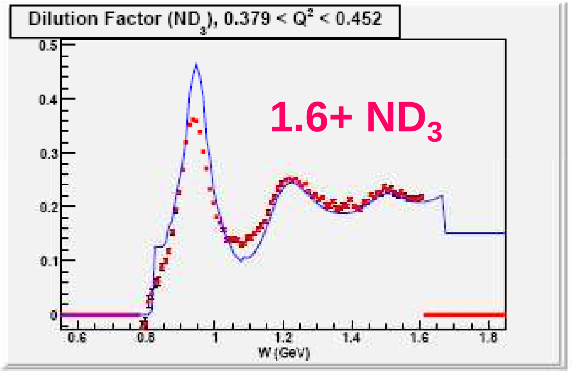
Missing Energy Distribution

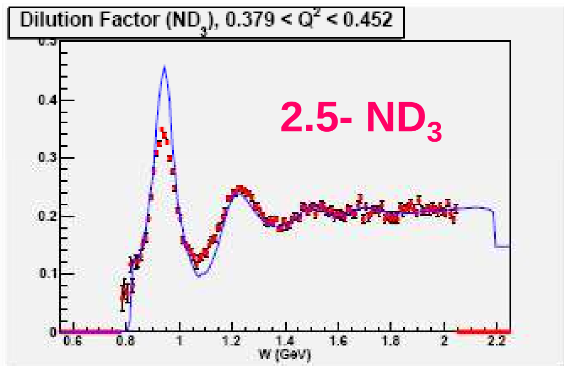
Dilution Factor

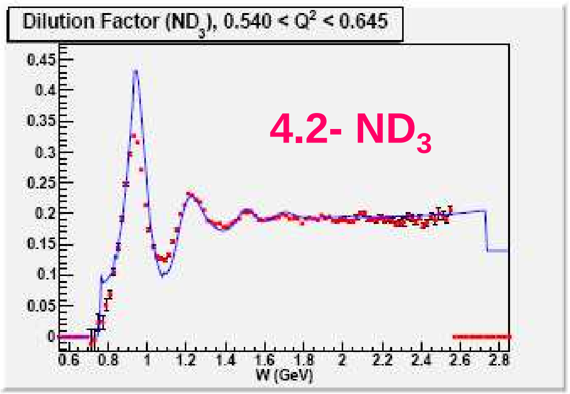
$$A_{\parallel} = \frac{C_1}{f_{RC}}\left(\frac{A_{raw}}{\boxed{F_D} P_b P_t} C_{back} - C_2\right) + A_{RC}$$

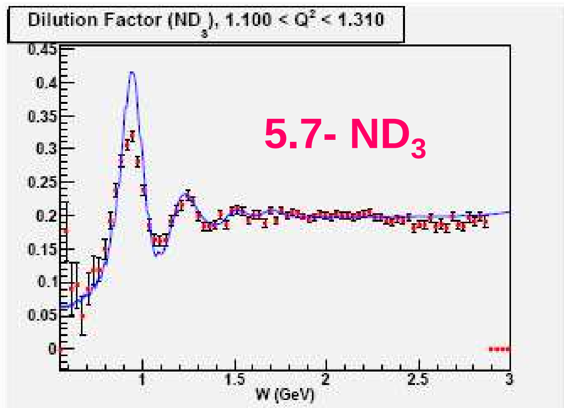
$$A_{undil} = \frac{n^- - n^+}{n^- + n^+ - n_B}$$ (Undiluted asymmetry)

$$F_D = \frac{n^- + n^+ - n_B}{n^- + n^+} = \frac{n_A - n_B}{n_A} = 1 - \frac{n_B}{n_A}$$ so that $$A_{undil} = \frac{A_{raw}}{F_D}$$









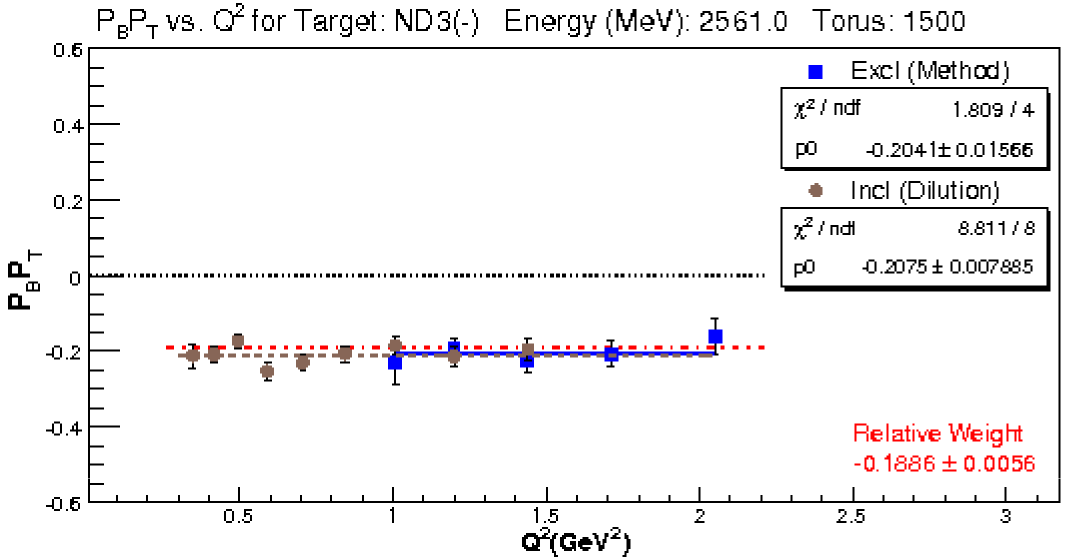
Contributions from unpolarized background are removed by the dilution factor.

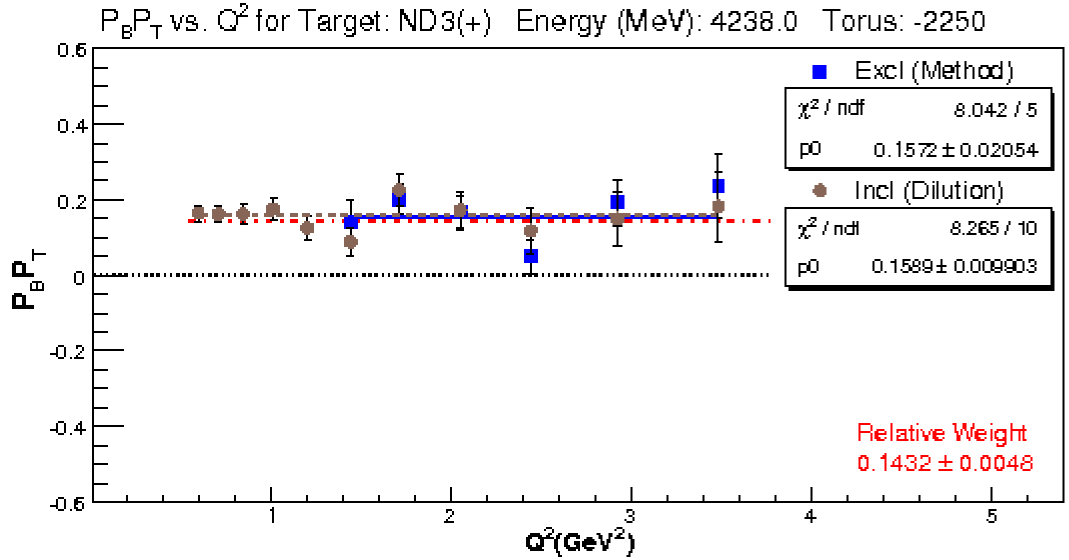
It represents the fraction of truly polarized data to all data.

It was determined using ^{12}C and ^{4}He data. The radiated cross section models for $^{15}N/^{12}C$ ratios generated by P. Bosted and R. Fersch were used.

Polarizations

$$A_{\parallel} = \frac{C_1}{f_{RC}}\left(\frac{A_{raw}}{F_D \boxed{P_b P_t}} C_{back} - C_2\right) + A_{RC}$$





$$P_b P_t = \frac{A^{quasi-el}_{meas}}{F_D\ A^{quasi-el}_{theo}}$$

The elastic events from:

- inclusive events by relying on missing mass cuts (inclusive method)
- exclusive events where corresponding proton is also observed (exclusive method)

$$P_b P_t = \sum_{Q^2} \frac{P_b P_t(Q^2)}{\sigma^2_{P_b P_t}(Q^2)} \Big/ \sum_{Q^2} \frac{1}{\sigma^2_{P_b P_t}(Q^2)}$$

$$\sigma_{P_b P_t} = 1 \Big/ \sum_{Q^2} \frac{1}{\sigma^2_{P_b P_t}(Q^2)}$$

Asymmetry Analysis

$$A_{\parallel} = \frac{C_1}{f_{RC}} \left(\frac{A_{raw}}{F_D P_b P_t} \boxed{C_{back}} - C_2 \right) + A_{RC}$$

- **Dilution factor**
- **Beam and Target polarization**
- **Unpolarized background corrections (pion and pair symmetric electrons)**

Asymmetry Analysis

$$A_{\|} = \frac{\boxed{C_1}}{f_{RC}} \left(\frac{A_{raw}}{F_D P_b P_t} C_{back} - \boxed{C_2} \right) + A_{RC}$$

- **Dilution factor**
- **Beam and Target polarization**
- **Unpolarized background corrections (pion and pair symmetric electrons)**
- **Polarized background correction (very small, well understood correction)**

Asymmetry Analysis

$$A_{\parallel} = \frac{C_1}{\boxed{f_{RC}}}\left(\frac{A_{raw}}{F_D P_b P_t} C_{back} - C_2\right) + \boxed{A_{RC}}$$

- Dilution factor
- Beam and Target polarization
- Background corrections (pion and pair symmetric electrons)
- Polarized background corrections (very small, well understood correction)
- Radiative corrections (RCSLACPOL originated in E143)

Asymmetry Analysis

$$A_{\parallel} = \frac{C_1}{f_{RC}}\left(\frac{A_{raw}}{F_D P_b P_t} C_{back} - C_2 \right) + A_{RC}$$

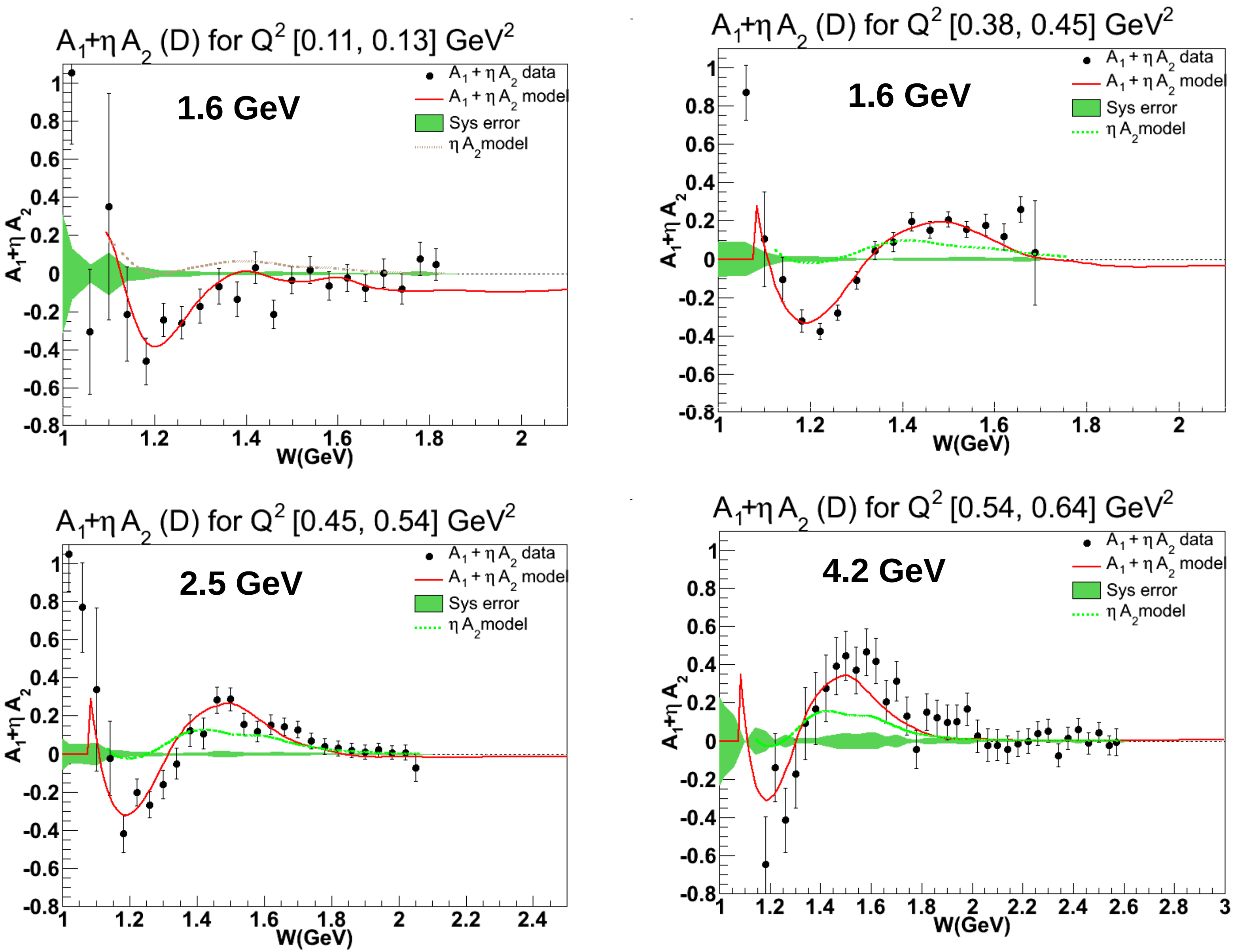
- **Dilution factor**
- **Beam and Target polarization**
- **Background corrections (pion and pair symmetric electrons)**
- **Polarized background corrections (very small, well understood correction)**
- **Radiative corrections (RCSLACPOL originated in E143 at SLAC)**

- **Calculate virtual photon asymmetry**

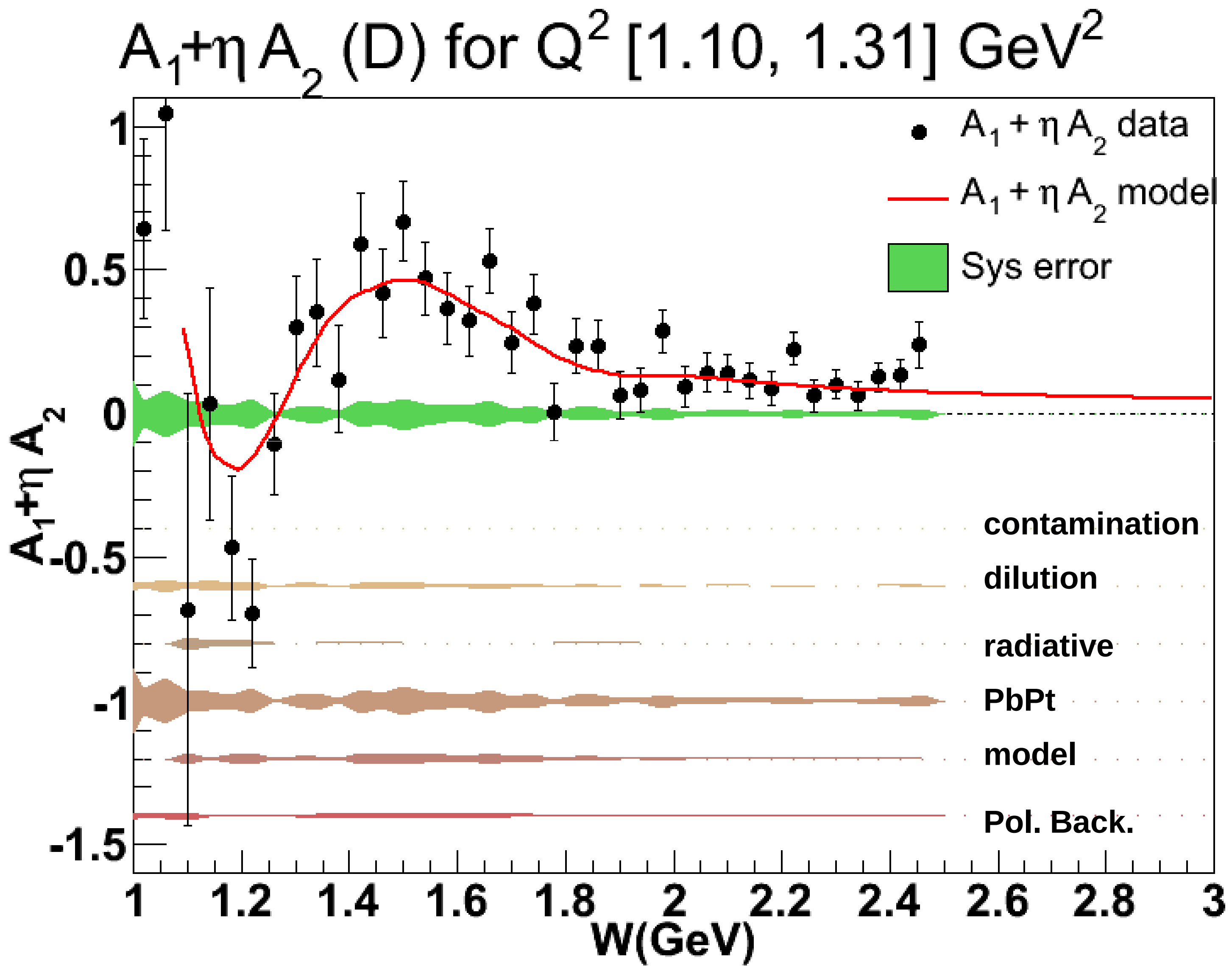
$$A_1 = \frac{A_{\parallel}}{D} - \eta A_{2\,\text{model}}$$

$$D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon\sqrt{Q^2}}{E - E'\varepsilon}; \quad R = \frac{\sigma_L}{\sigma_T}$$

$A_1+\eta A_2$ for the Deuteron

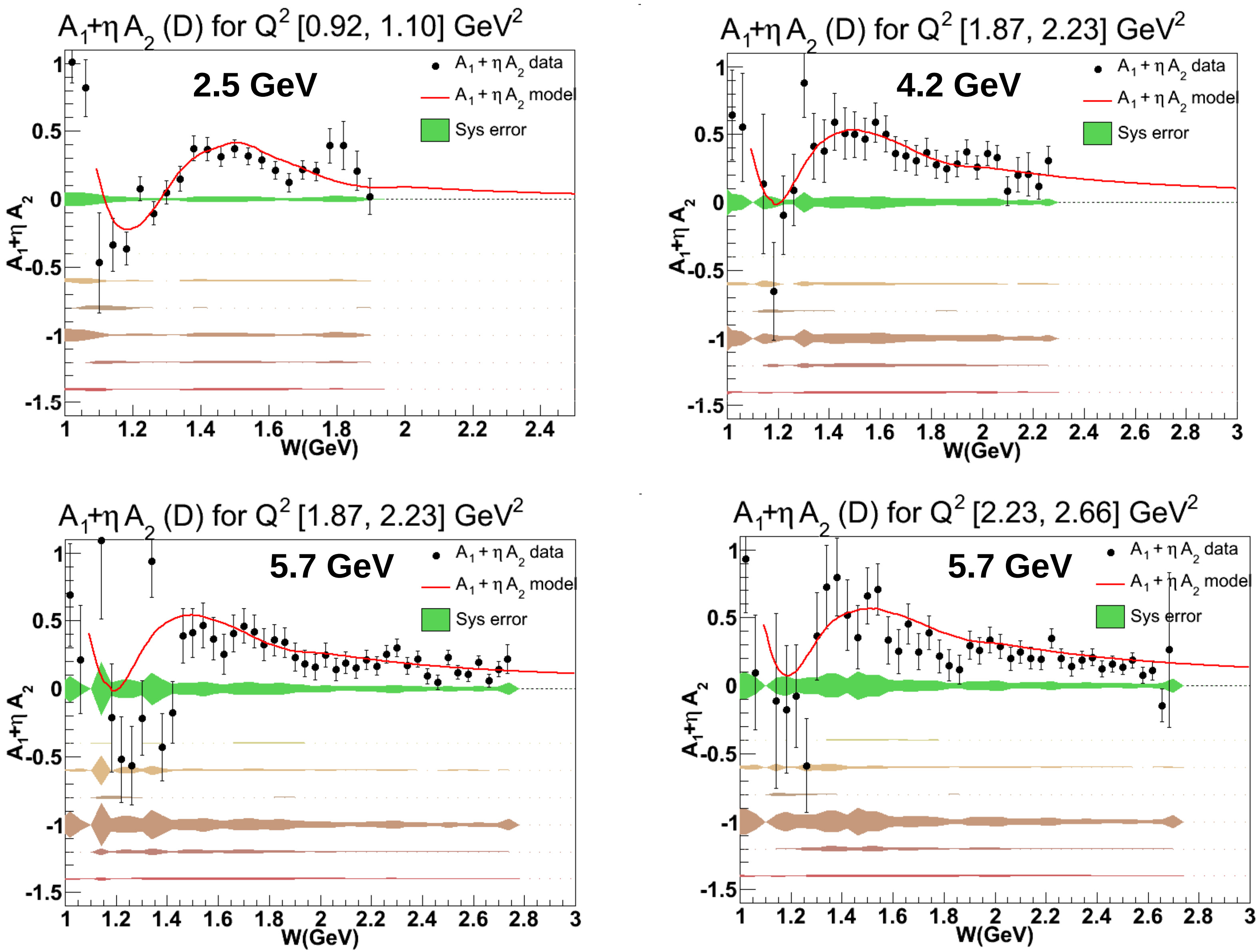


A_1 Deuteron

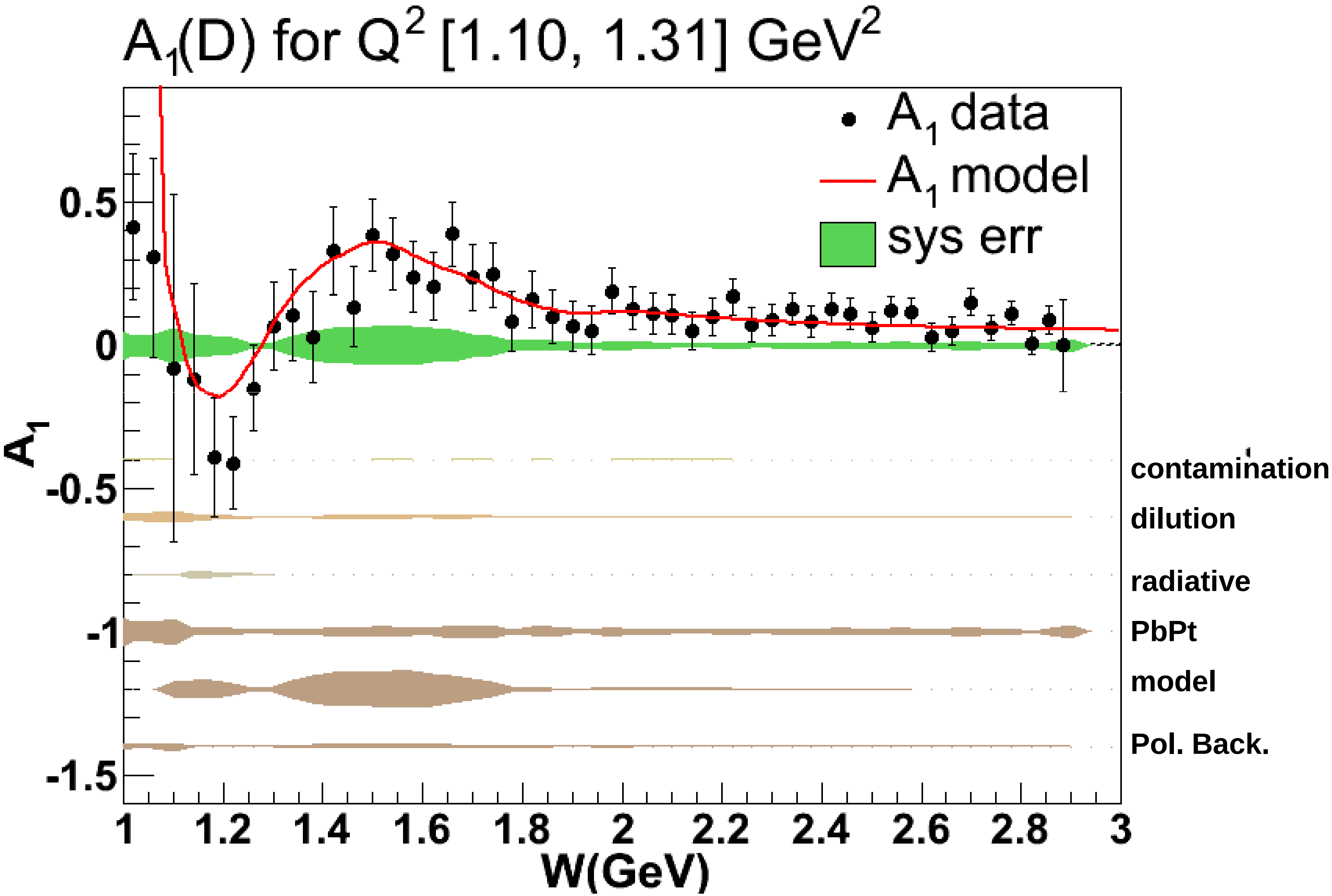


A1+η A2 (D) for Q2 [1.10, 1.31] GeV2
A1 + η A2 data
A1 + η A2 model
Sys error
contamination
dilution
radiative
PbPt
model
Pol. Back.
A1+η A2
W(GeV)
1
0.5
0
-0.5
-1
-1.5
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3

$A_1+\eta A_2$ for the Deuteron



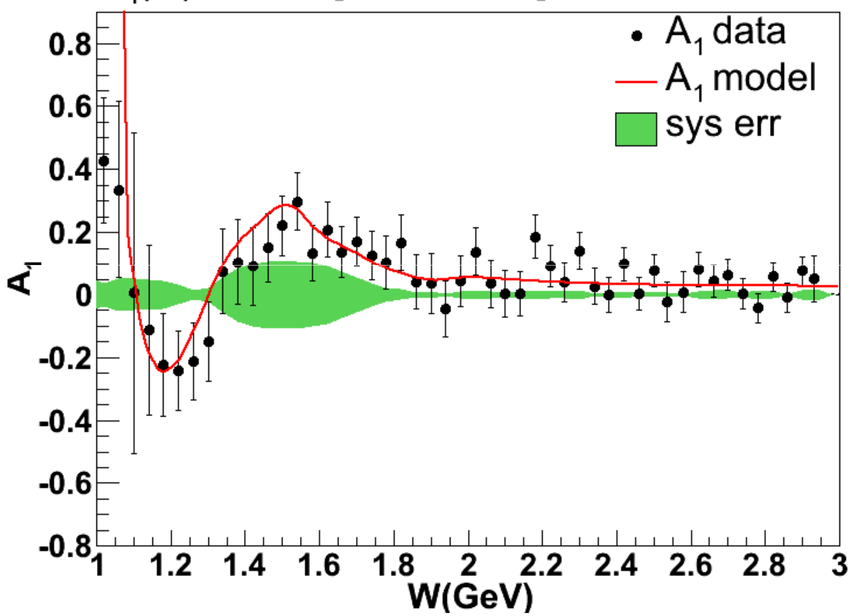
A_1 Deuteron



A1(D) for Q2 [1.10, 1.31] GeV2
A1 data
A1 model
sys err
A1
W(GeV)
0.5
0
-0.5
-1
-1.5
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
contamination
dilution
radiative
PbPt
model
Pol. Back.

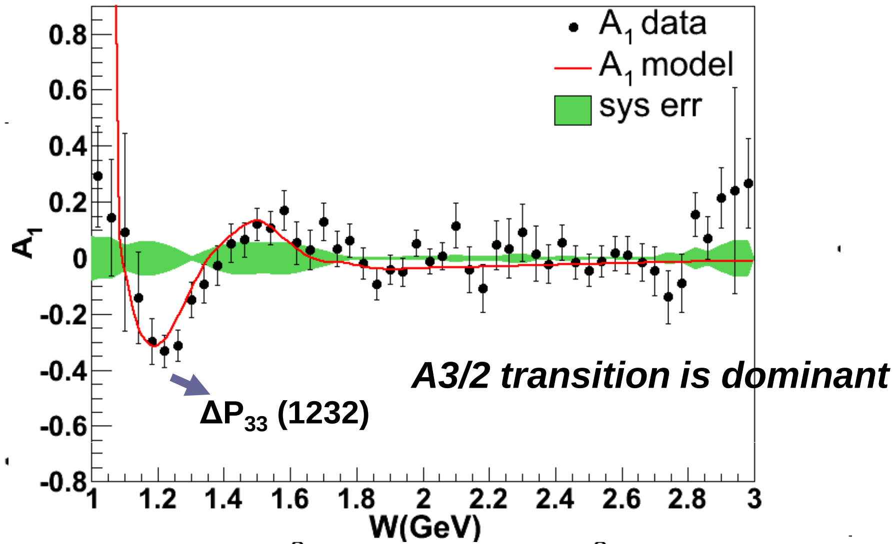
A_1 Deuteron

A1(D) for Q² [0.77, 0.92] GeV²

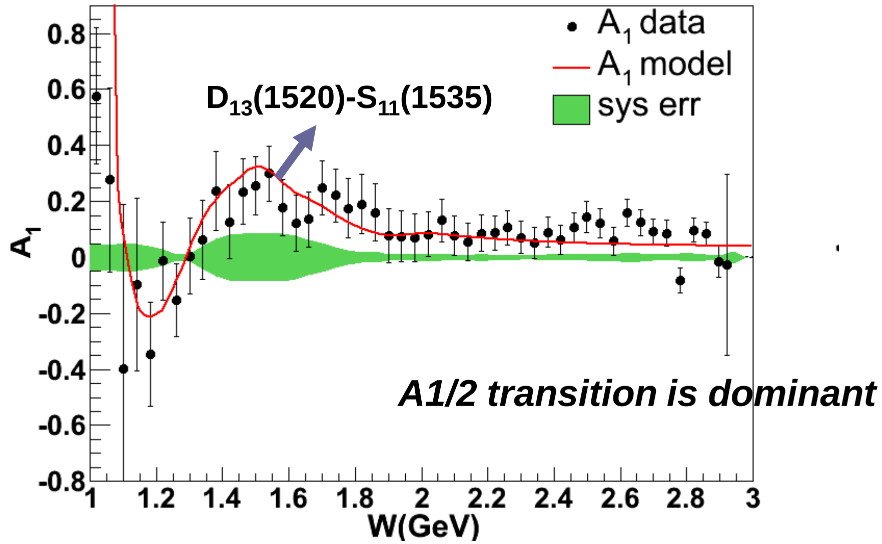


$$A_1 = \frac{\sigma_T^{1/2} - \sigma_T^{3/2}}{\sigma_T^{1/2} + \sigma_T^{3/2}}$$

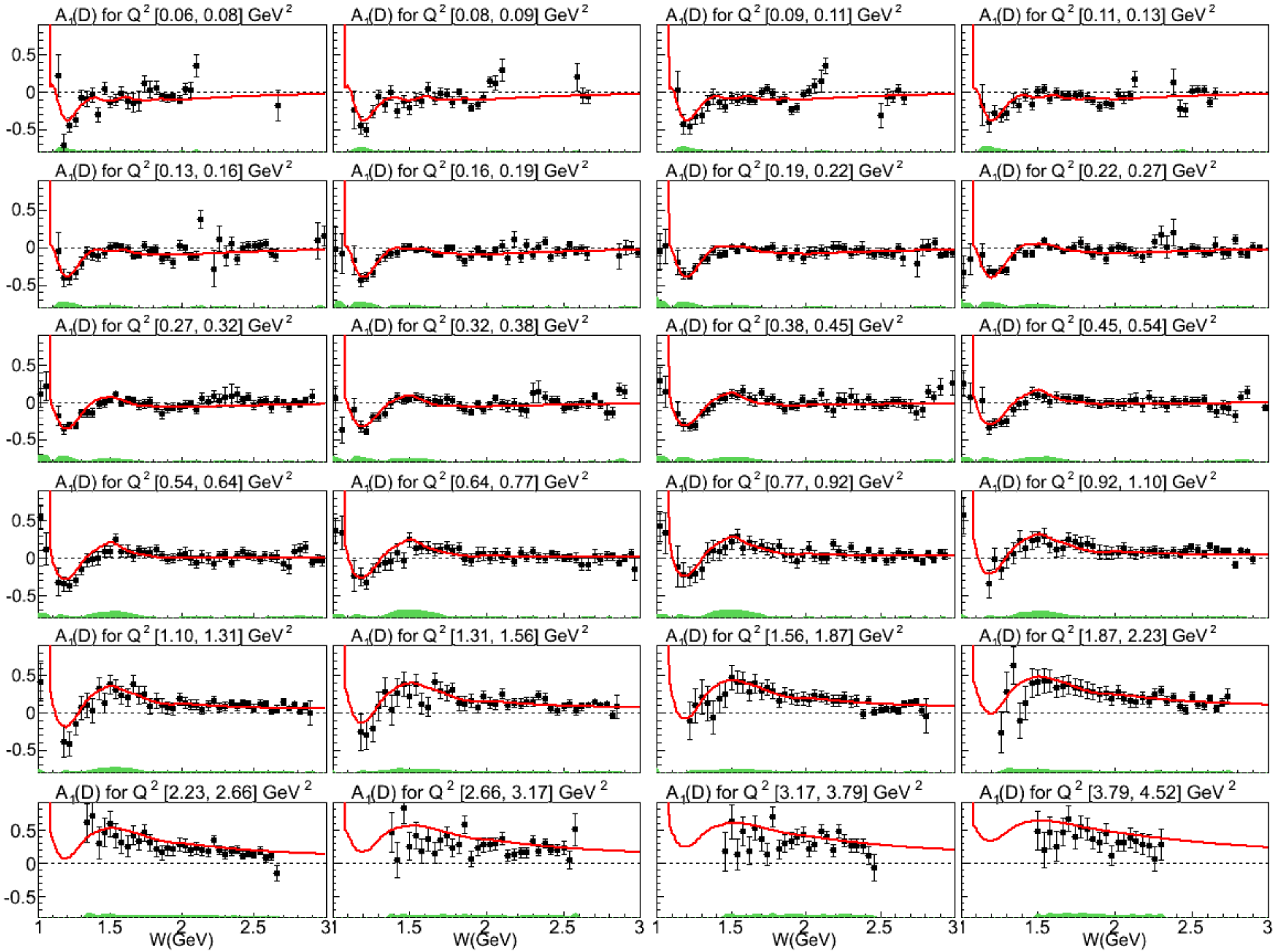
A1(D) for Q² [0.38, 0.45] GeV²



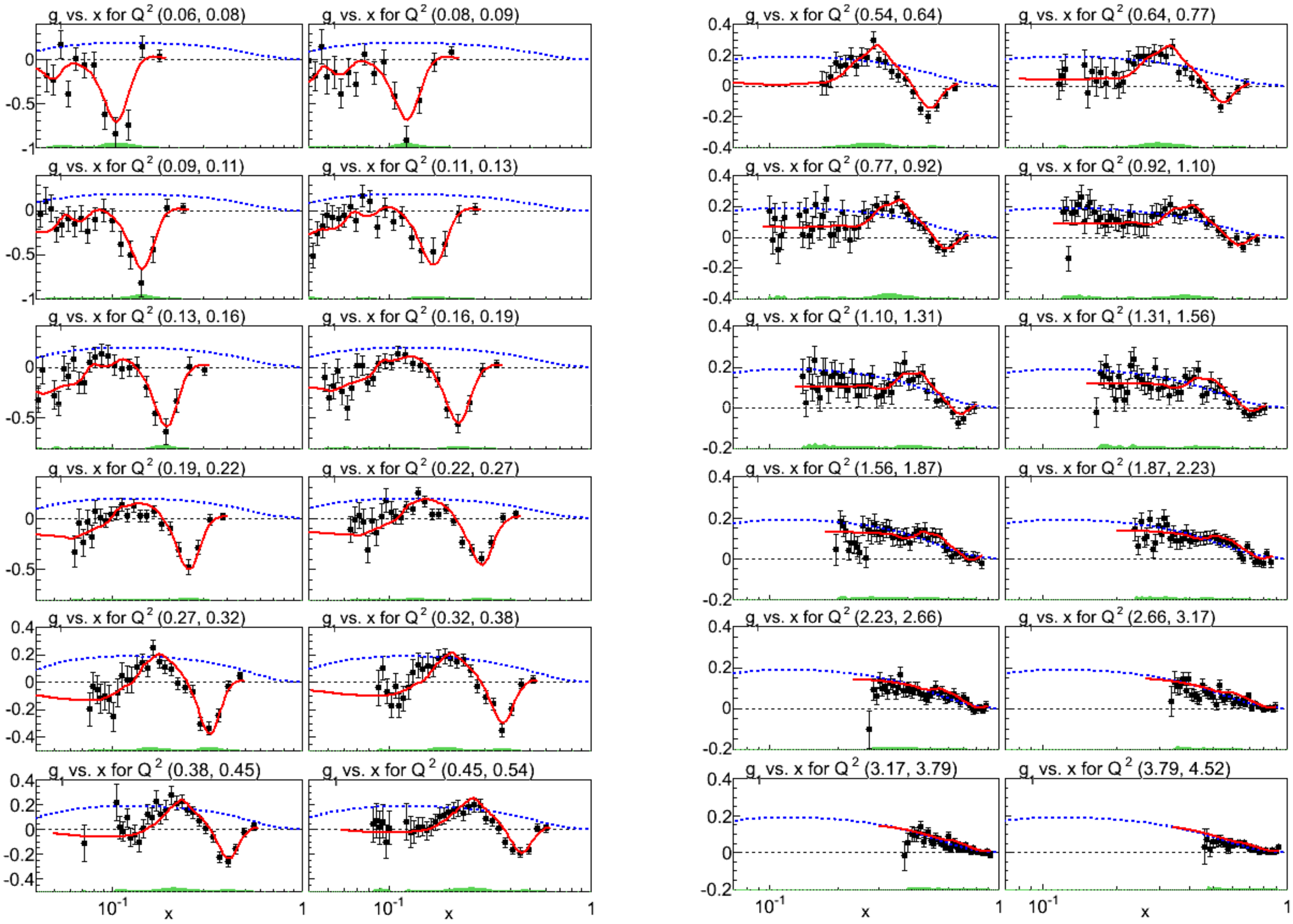
A1(D) for Q² [0.92, 1.10] GeV²



A_1 Deuteron


A1(D) for Q2 [0.06, 0.08] GeV2
A1(D) for Q2 [0.08, 0.09] GeV2
A1(D) for Q2 [0.09, 0.11] GeV2
A1(D) for Q2 [0.11, 0.13] GeV2
A1(D) for Q2 [0.13, 0.16] GeV2
A1(D) for Q2 [0.16, 0.19] GeV2
A1(D) for Q2 [0.19, 0.22] GeV2
A1(D) for Q2 [0.22, 0.27] GeV2
A1(D) for Q2 [0.27, 0.32] GeV2
A1(D) for Q2 [0.32, 0.38] GeV2
A1(D) for Q2 [0.38, 0.45] GeV2
A1(D) for Q2 [0.45, 0.54] GeV2
A1(D) for Q2 [0.54, 0.64] GeV2
A1(D) for Q2 [0.64, 0.77] GeV2
A1(D) for Q2 [0.77, 0.92] GeV2
A1(D) for Q2 [0.92, 1.10] GeV2
A1(D) for Q2 [1.10, 1.31] GeV2
A1(D) for Q2 [1.31, 1.56] GeV2
A1(D) for Q2 [1.56, 1.87] GeV2
A1(D) for Q2 [1.87, 2.23] GeV2
A1(D) for Q2 [2.23, 2.66] GeV2
A1(D) for Q2 [2.66, 3.17] GeV2
A1(D) for Q2 [3.17, 3.79] GeV2
A1(D) for Q2 [3.79, 4.52] GeV2
0.5
0
-0.5
1
1.5
2
2.5
3
W(GeV)

g_1 vs. x for the deuteron



First Moment of $g_1(x,Q^2)$

First moment of g_1^N : $\Gamma_1(Q^2)=\int_0^1 g_1^N(x,Q^2)dx$

at $Q^2 \to 0$

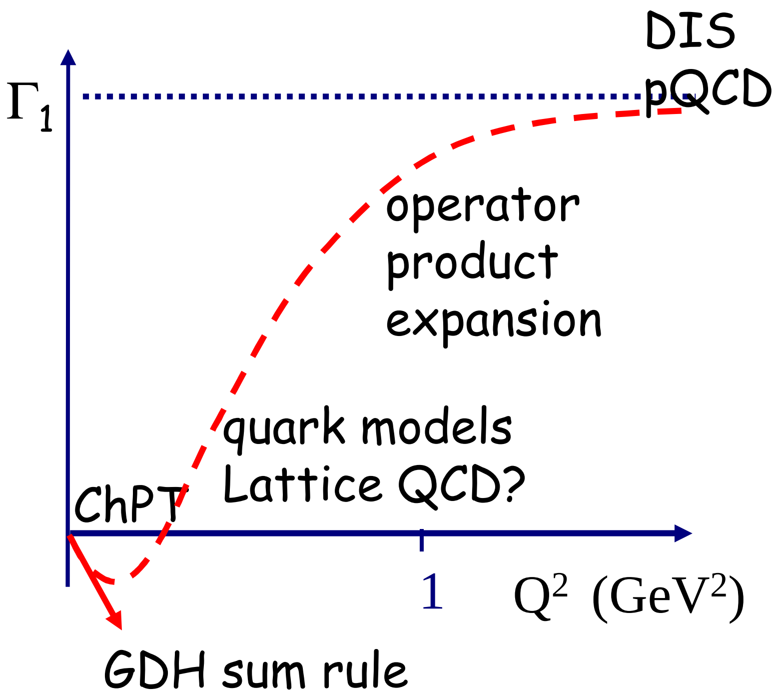
Slope of Γ_1 is constrained by the GDH sum rule

$$I_{GDH}=\frac{M^2}{8\alpha\pi^2}\int_{\nu_{th}}^{\infty}\left(\sigma^{1/2}(\nu)-\sigma^{3/2}(\nu)\right)\frac{d\nu}{\nu}=-\frac{1}{4}\kappa^2$$

$$\Gamma_1 \to \frac{Q^2}{2M^2}I_{GDH}=-\frac{Q^2}{8M^2}\kappa^2$$

at $Q^2 \to \infty$

Closely related to the total spin carried by quarks.



- *Dramatic change of sign of Γ_1 from DIS-regime to the value at the real photon point.*
- *At low Q^2, $g_1(x,Q^2)$ is dominated by resonance excitations.*

Q^2 evolution of the GDH integral

Small Q^2
GDH sum rule
Experiments at Mainz, Bonn
Chiral perturbation theory

?

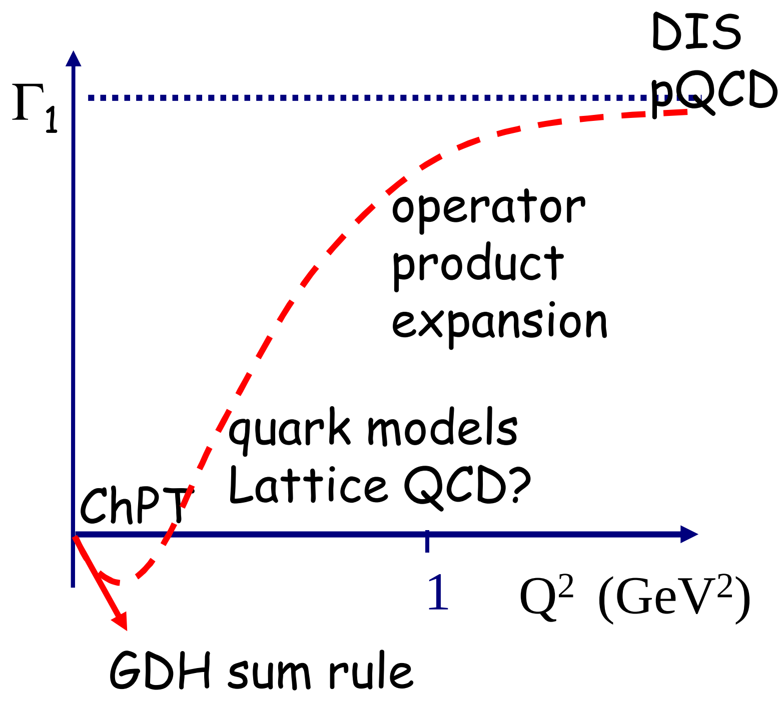
Intermediate Q^2
Extended GDH sum rule

$$I_{GDH}(Q^2) = \frac{M^2}{8\pi^2\alpha}\int_{\nu_{th}}^{\infty}\left(\sigma^{1/2}(\nu,Q^2) - \sigma^{3/2}(\nu,Q^2)\right)\frac{d\nu}{\nu}$$

Several different models
Experiments at JLAB(CLAS/Hall A/Hall C)
A good test of "at what distance scale pQCD corrections and higher twist expansions will break down and physics of confinement dominate".

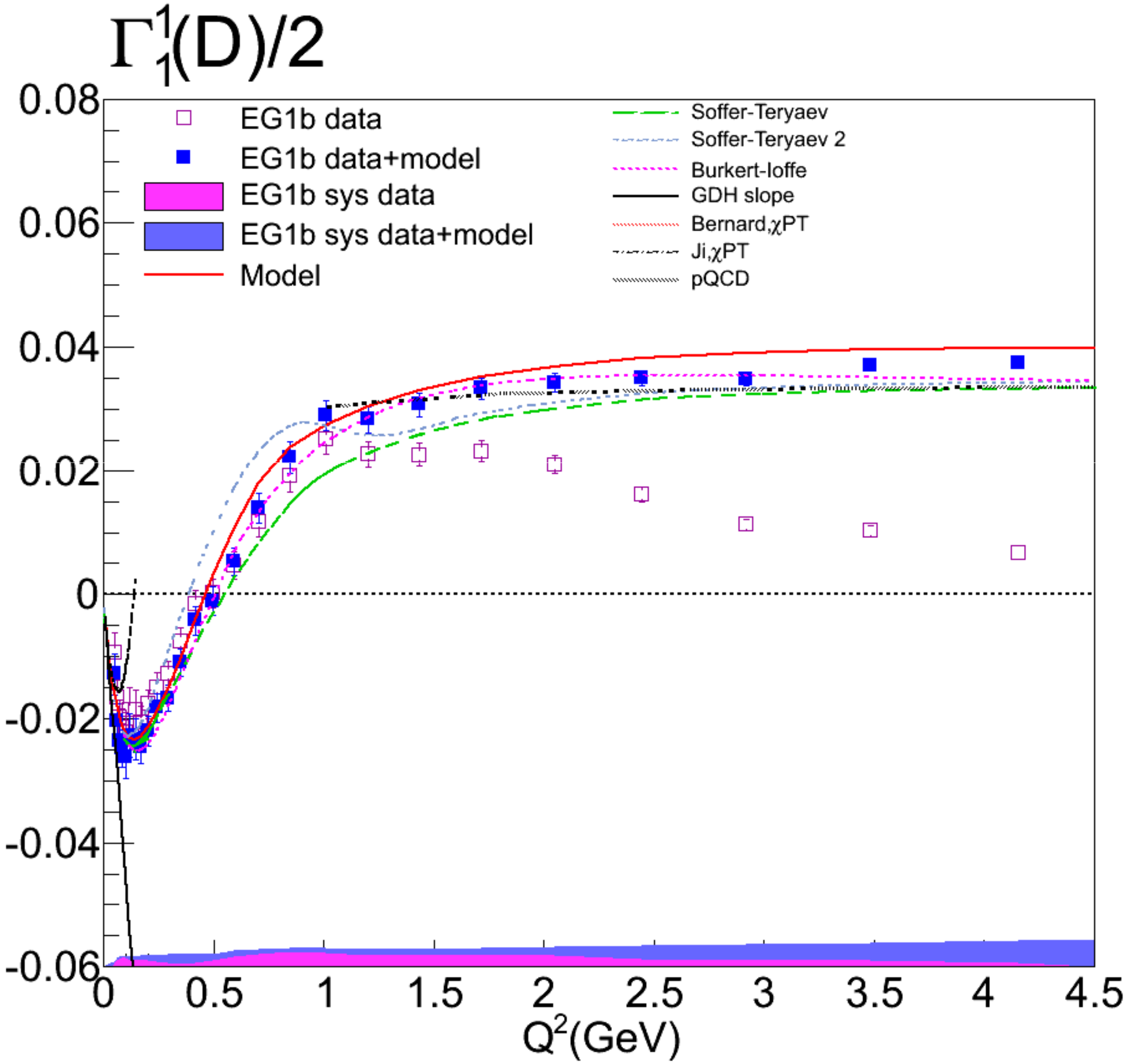
Large Q^2
Bjorken Sum rule
Experiments at CERN,SLAC,DESY
Higher order QCD expansion

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6}g_A\left[1 - \frac{\alpha_S(Q^2)}{\pi} + \ldots\ldots\ldots\right] \xrightarrow{Q^2\to\infty} \frac{1}{6}g_A$$



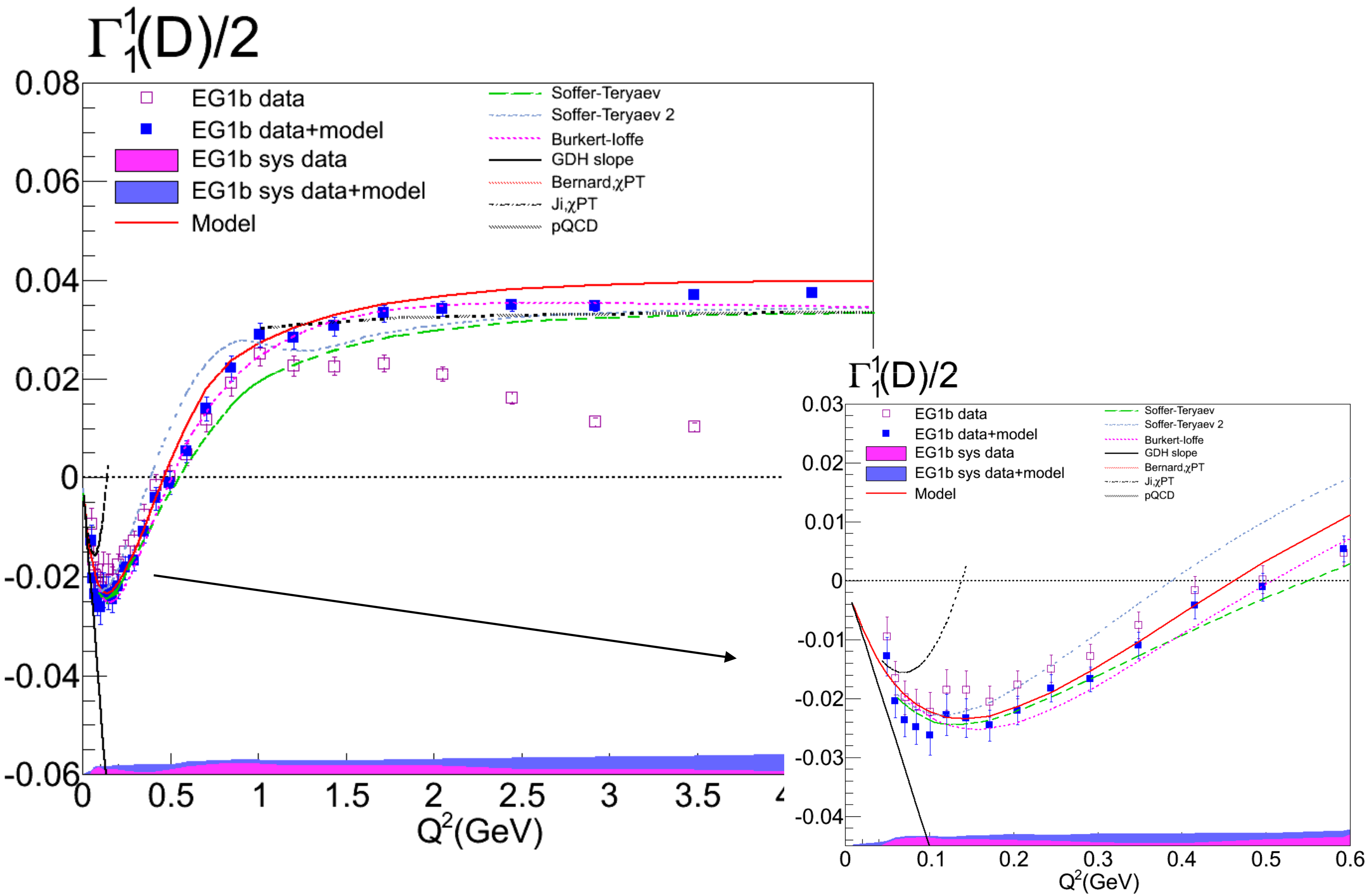
EG1b has a good precision data with wide Q^2 coverage to answer some of these questions.

Γ_1 Deuteron, Data and Data+Model results

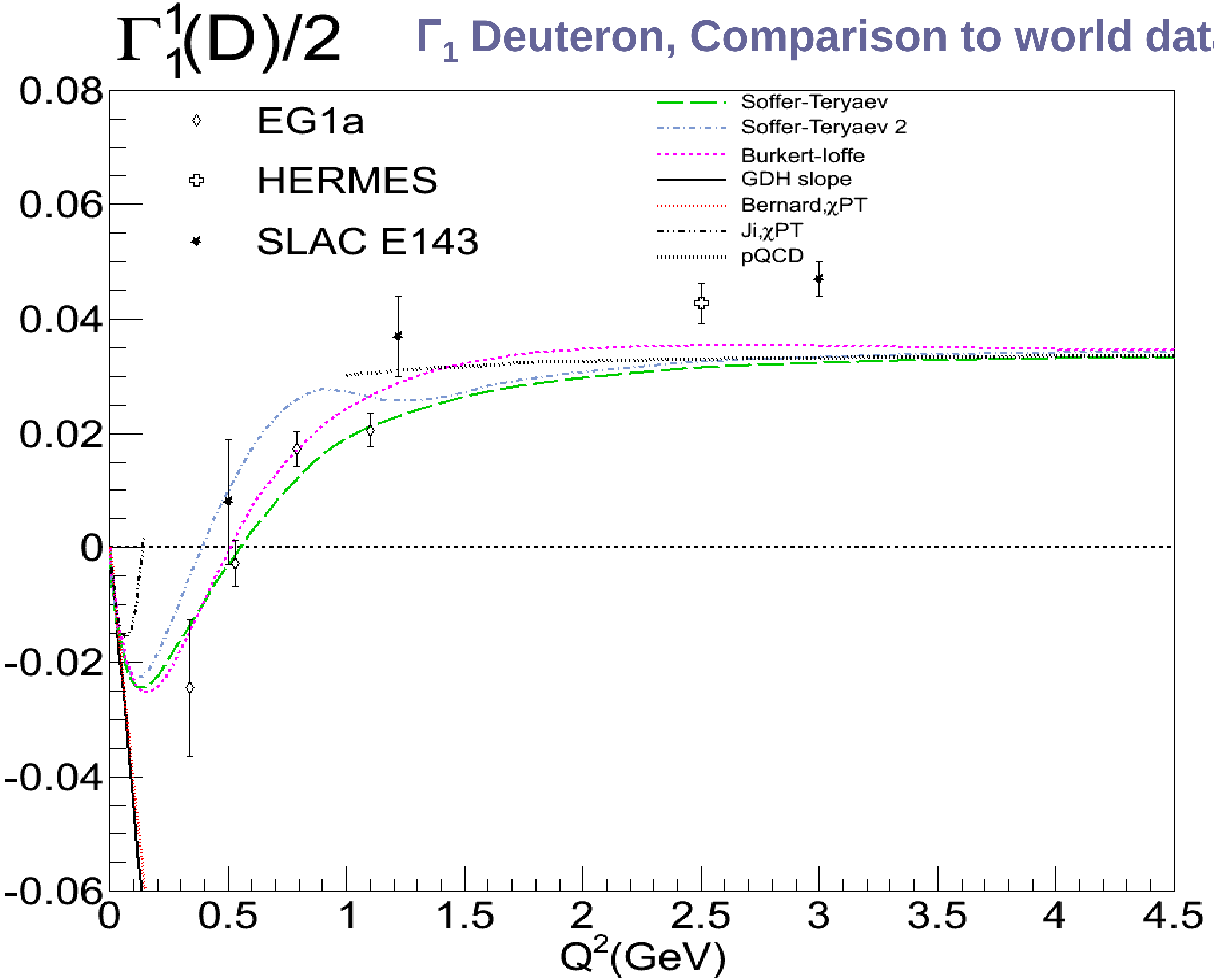


- Γ_{1D}^1 : First moment of g_{1D}
- Strong Q^2 - dependence (zero crossing)
- Well described by some parameterizations such as
  - Burkert-Ioffe: Resonances plus VMD term interpolate GDH to DIS
  - Soffer-Teryaev interpolate g_1+g_2
- χPT calculation works only at smallest Q^2

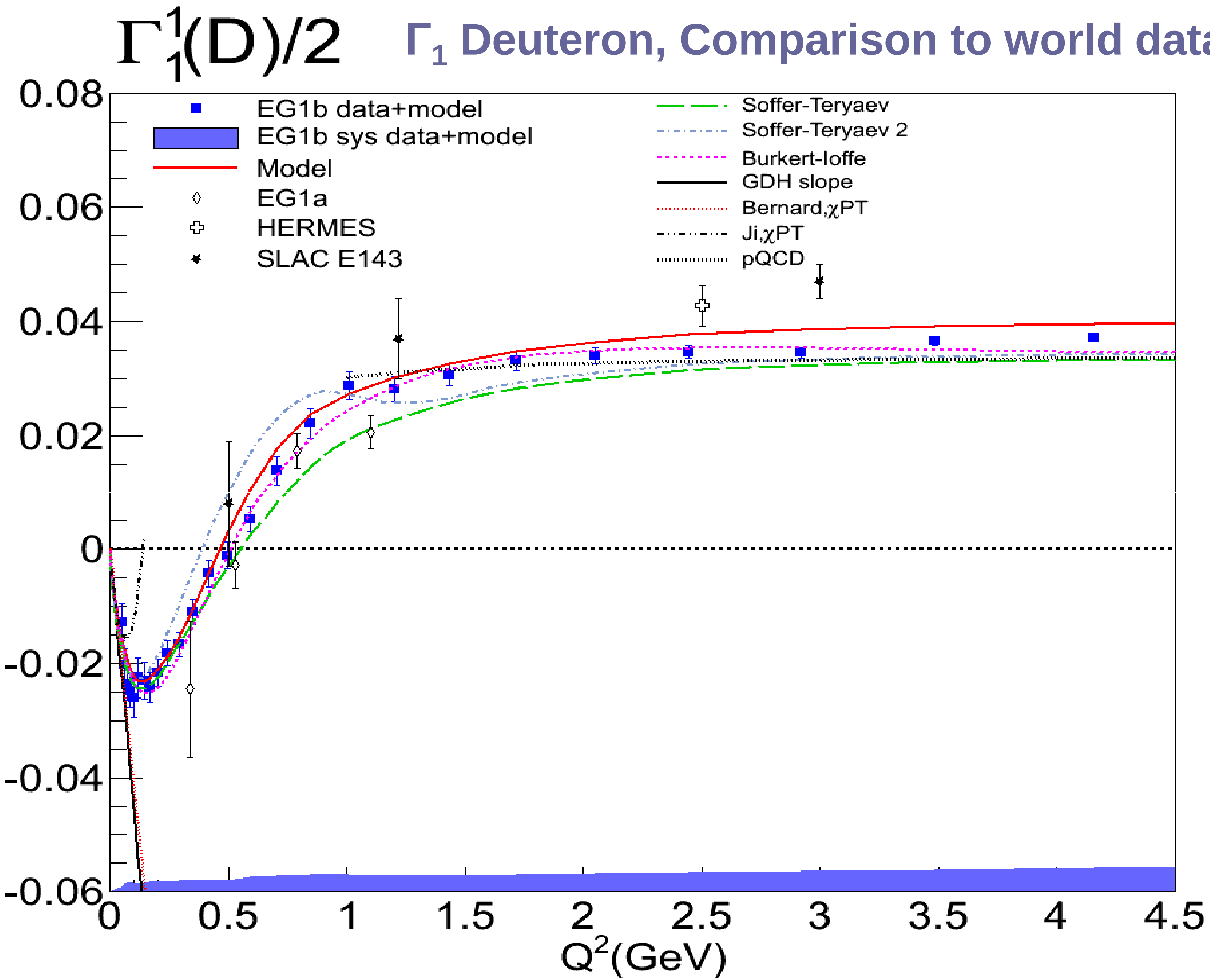
Γ_1 Deuteron, Data and Data+Model results



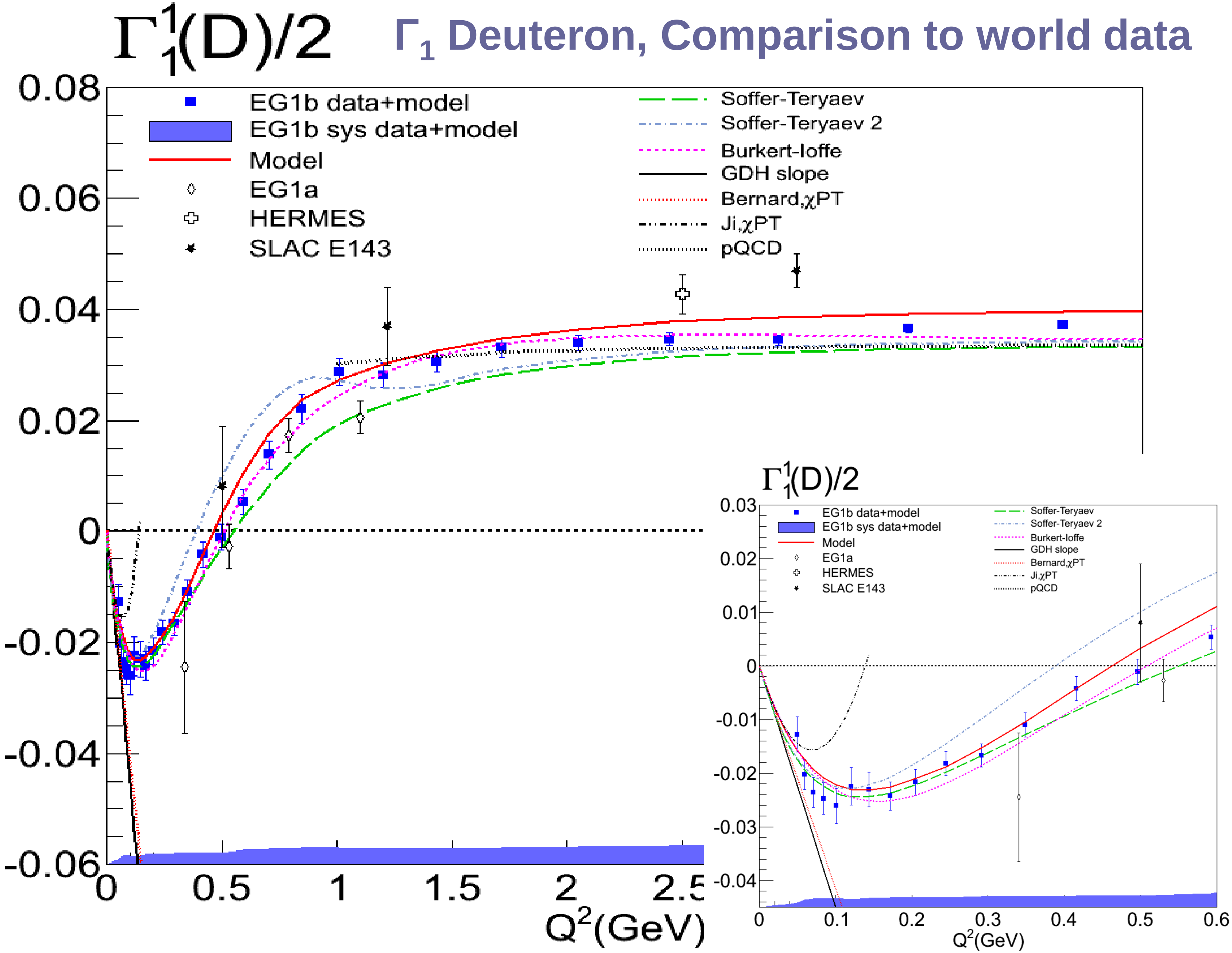
Γ_1 Deuteron, Comparison to world data



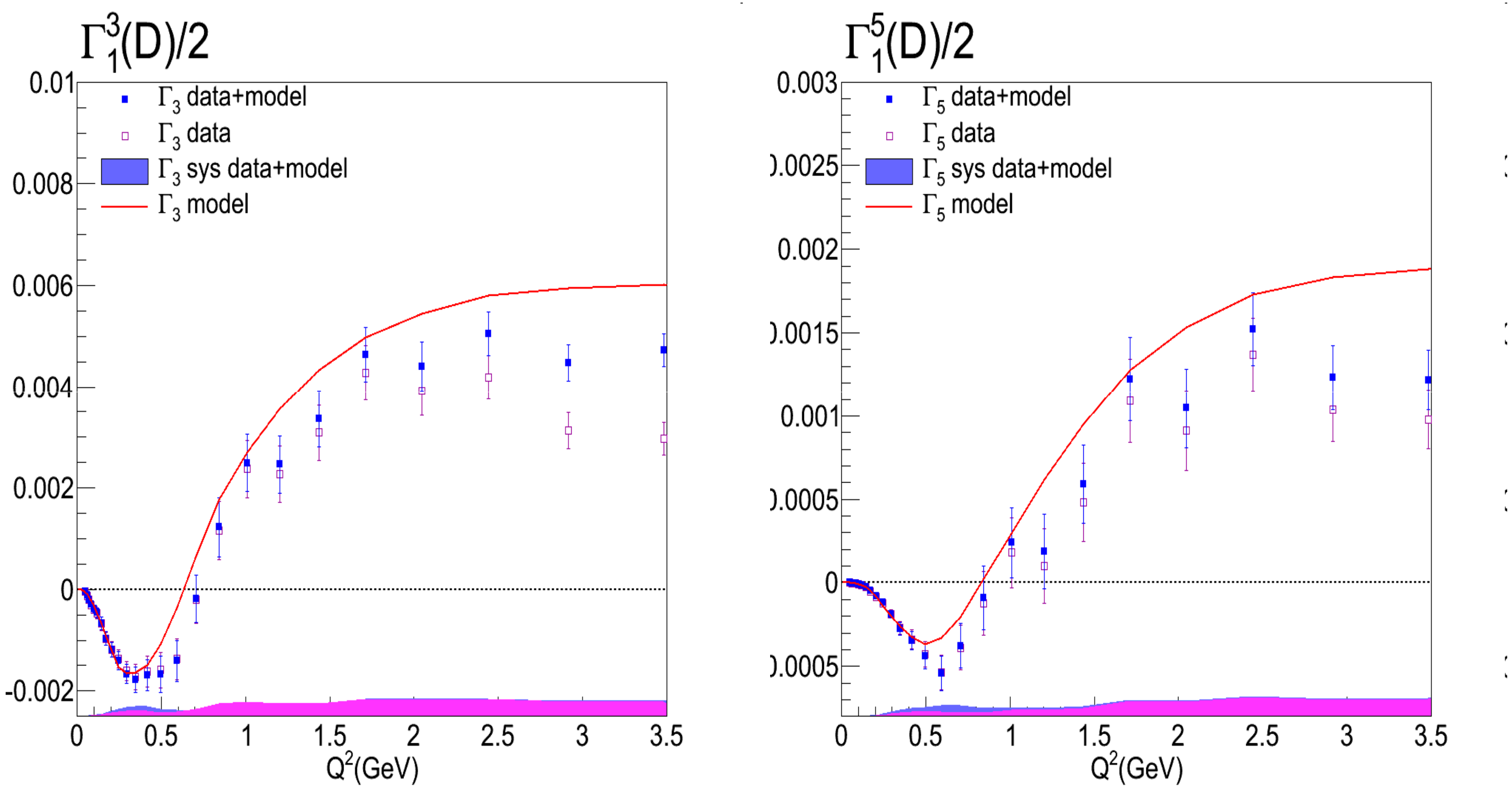
Γ_1 Deuteron, Comparison to world data



Γ_1 Deuteron, Comparison to world data



Γ_3 and Γ_5 Deuteron



Parameterization of the World Data

collect the world data

try different parameterizations

$$\chi^2(Q^2, W) = \sum_n \frac{(A^{data}(Q^2, W) - A^{fit}(Q^2, W))^2}{(\sigma_{A^{data}}(Q^2, W))^2}$$

minimize

Parameterization of the World Data

$$E_1 = P_0 + P_1 \tan^{-1}[(Q^2 - P_2^2)\, P_3^2]$$

$$E_2 = P_4 + P_5 \tan^{-1}[(Q^2 - P_6^2)\, P_7^2]$$

$$E_3 = 1 - E_1 - E_2$$

$$E_4 = P_8 + P_9 \tan^{-1}[(Q^2 - P_{10}^2)\, P_{11}^2]$$

$$E_5 = P_{12} + P_{13} \tan^{-1}[(Q^2 - P_{14}^2)\, P_{15}^2]$$

$$C_1 = 1 - \sin\left(\frac{\pi}{2}\left[\frac{W - 1.08}{2 - 1.08}\right]\right)$$

$$C_2 = C_1^2$$

$$C_3 = \cos\left(\frac{\pi}{2}\left[\frac{W - 1.08}{2 - 1.08}\right]\right)$$

$$C_4 = \begin{cases} \left[\sin\left(\pi\left[\frac{W-1.08}{1.9-1.08}\right]\right)\right]^2 & W \geq 1.9 \\ 0 & W < 1.9 \end{cases}$$

$$C_5 = \begin{cases} \sin\left(\pi\left[\frac{W-1.08}{1.35-1.08}\right]\right) & W < 1.35 \\ 0 & W \geq 1.35 \end{cases}$$

$$\mathcal{M} = E_1 C_1 + E_2 C_2 + E_3 C_3 + E_4 C_4 + E_5 C5$$

$$A_1^{C[1]} = \begin{cases} \mathcal{M} A_1^M + (1 - \mathcal{M}) A_1^{DIS} & W \leq 2 \\ A_1^{DIS} & W > 2 \end{cases}$$

$$Q_{ph}^2 = \begin{cases} 0 & Q^2 \leq 0.01 \text{ GeV}^2 \\ \frac{1}{3\pi}\left(\frac{\log(Q^2)}{\log(10)} + 2\right) & Q^2 > 0.01 \text{ GeV}^2 \\ 1 & Q^2 > 10 \text{ GeV}^2 \end{cases}$$

$$W_{ph} = \pi \frac{(W - 1.08)}{(2.04 - 1.08)}$$

$$D_0 = P_0 + P_1 \cos\left(Q_{ph}^2\right) + P_2 \cos\left(2Q_{ph}^2\right)$$

$$D_1 = P_3 + P_4 \cos\left(Q_{ph}^2\right) + P_5 \cos\left(2Q_{ph}^2\right)$$

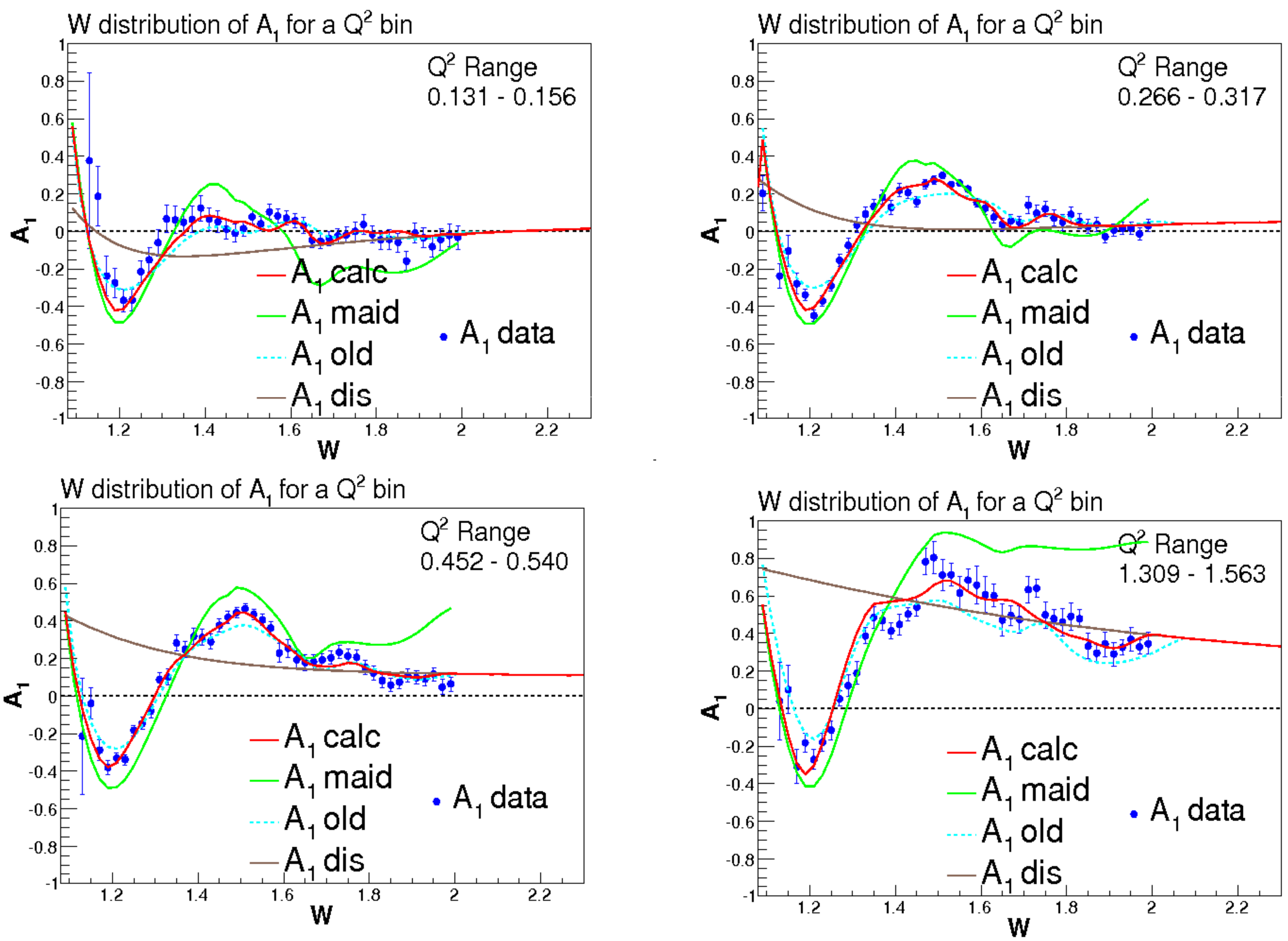
$$D_2 = P_6 + P_7 \cos\left(Q_{ph}^2\right) + P_8 \cos\left(2Q_{ph}^2\right)$$

$$D_3 = P_9 + P_{10} \cos\left(Q_{ph}^2\right) + P_{11} \cos\left(2Q_{ph}^2\right)$$

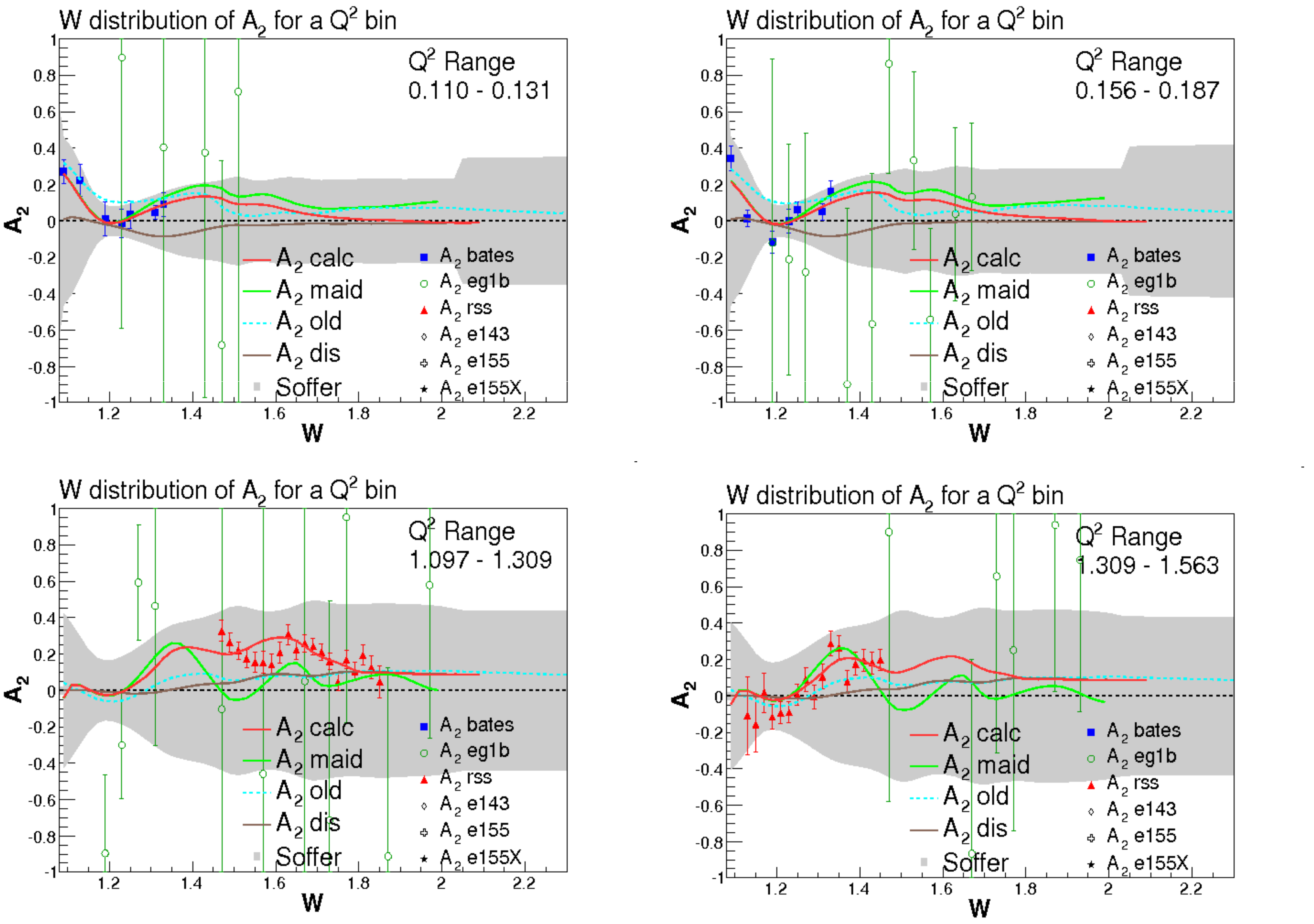
$$\mathcal{B} = \begin{cases} D_0 \sin(12 W_{ph}) + D_1 \sin(W_{ph}) & \\ \quad + D_2 \sin(2W_{ph}) + D_3 \sin(4W_{ph}) & W < 2.04 \text{ GeV} \\ 0 & W \leq 2.04 \text{ GeV} \end{cases}$$

$$A_1^C = (1 - \mathcal{B})\, A_1^{C[1]} + \mathcal{B} A_1^{OM}$$

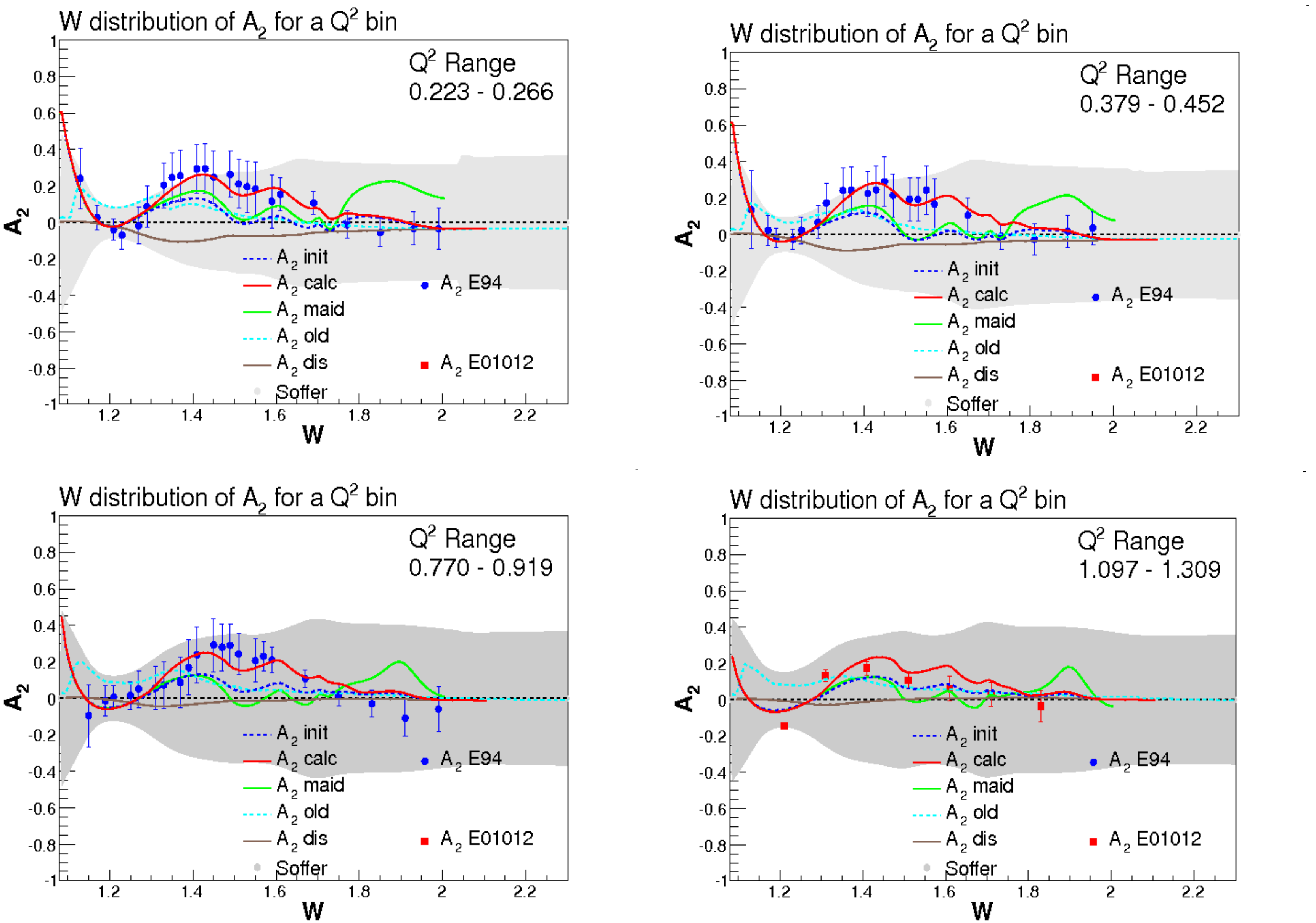
Parameterization of A_1^p



Parameterization of A_2^p

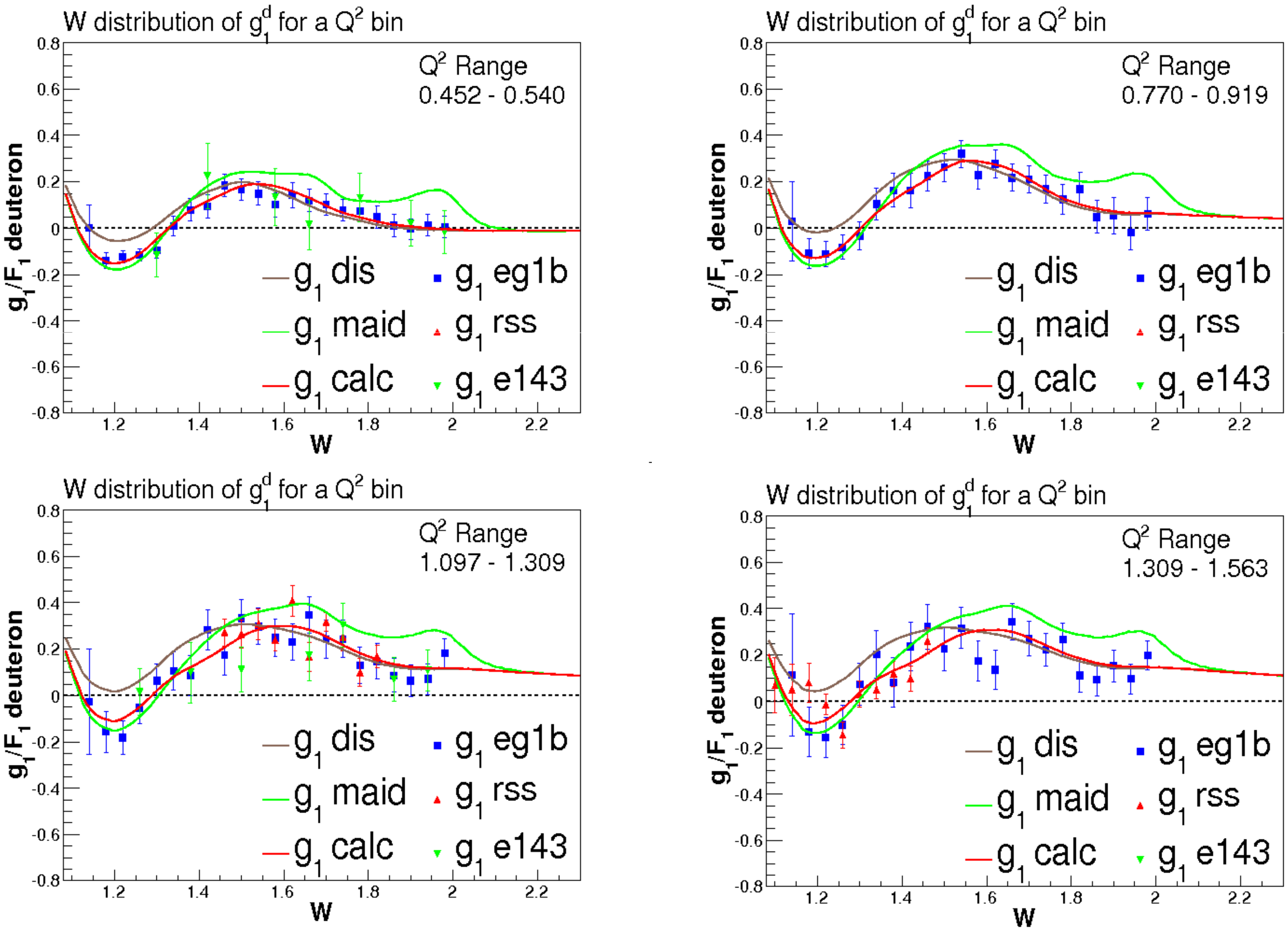


Parameterization of A_2^n

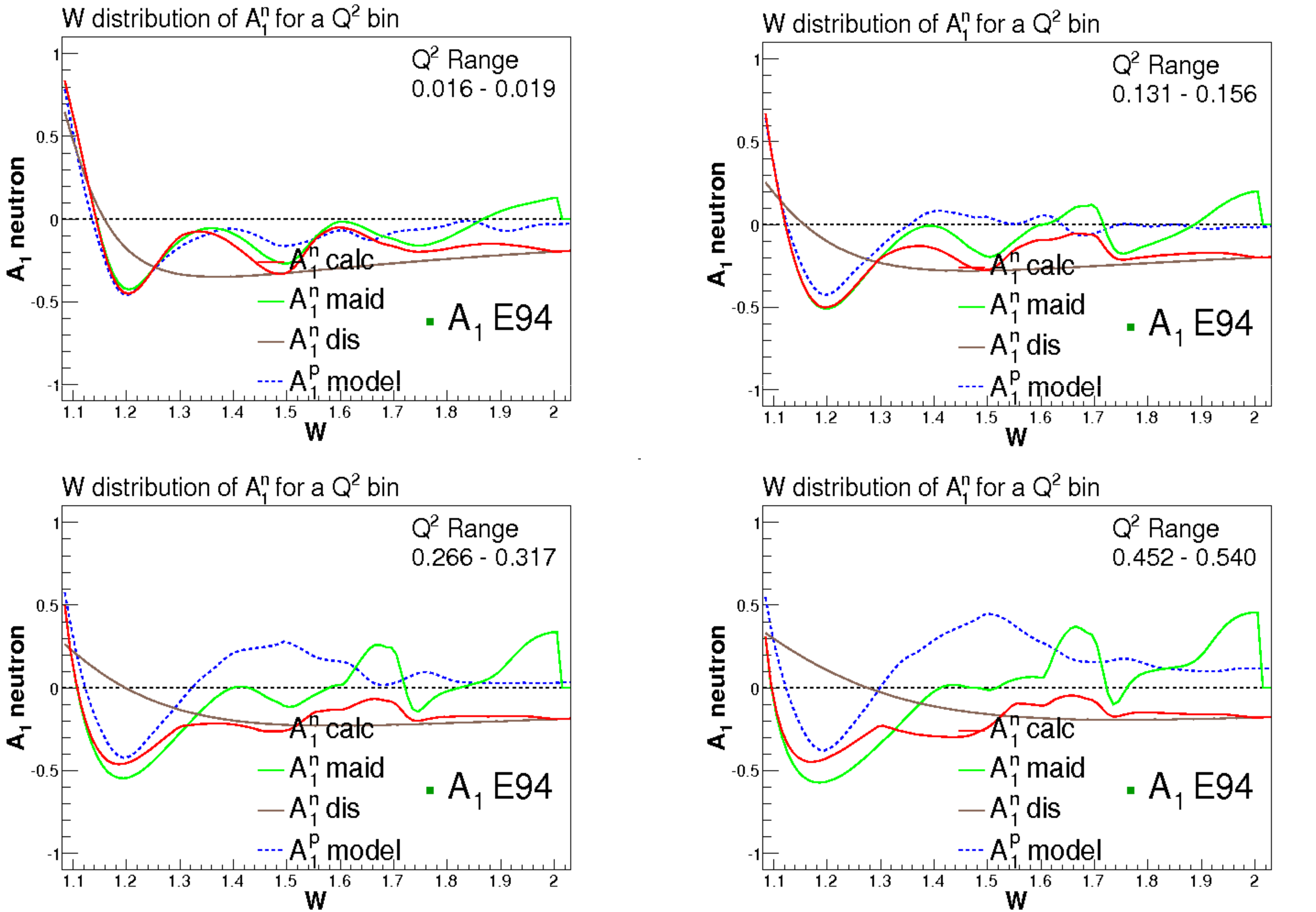


Parameterization of A_1^n

Parameterize the neutron**;** use the proton and neutron models with ***smearing*** function and calculate deuteron g1**;** then compare to the data to determine the fit parameters for neutron

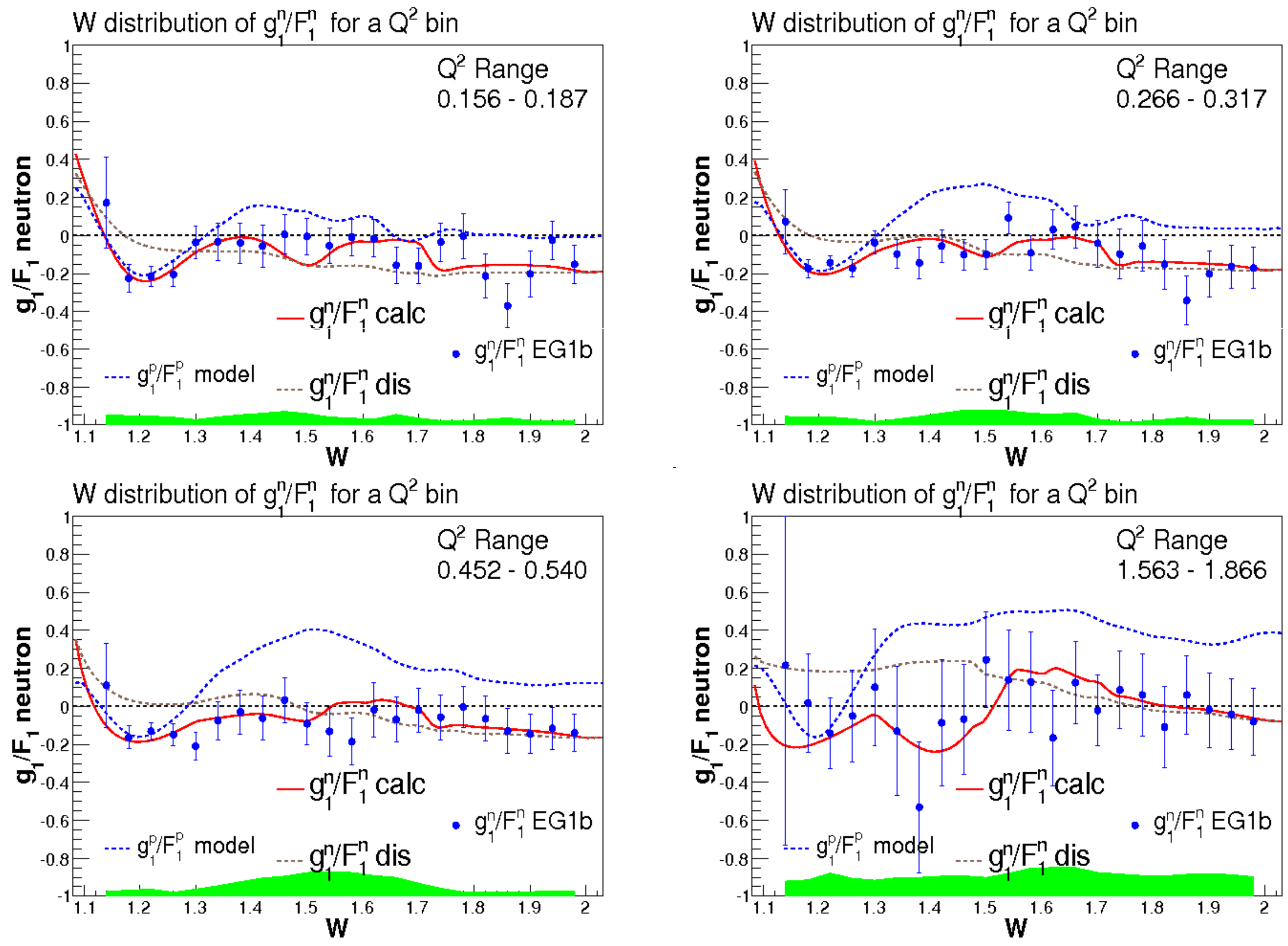


Parameterization of A_1^n



Extraction of the g_1^n

$$g_1^{n[data]} = \frac{1}{1-1.5w_D}\left(g_1^{d[data]} - g_1^{d[model]}\right) + g_1^{n[model]}$$



Conclusions

- Inclusive SSFs for both the proton and the deuteron have been measured with unprecedented statistics and coverage in the low – to moderate Q^2 region. The data cover both the resonance region and the onset of the DIS region.

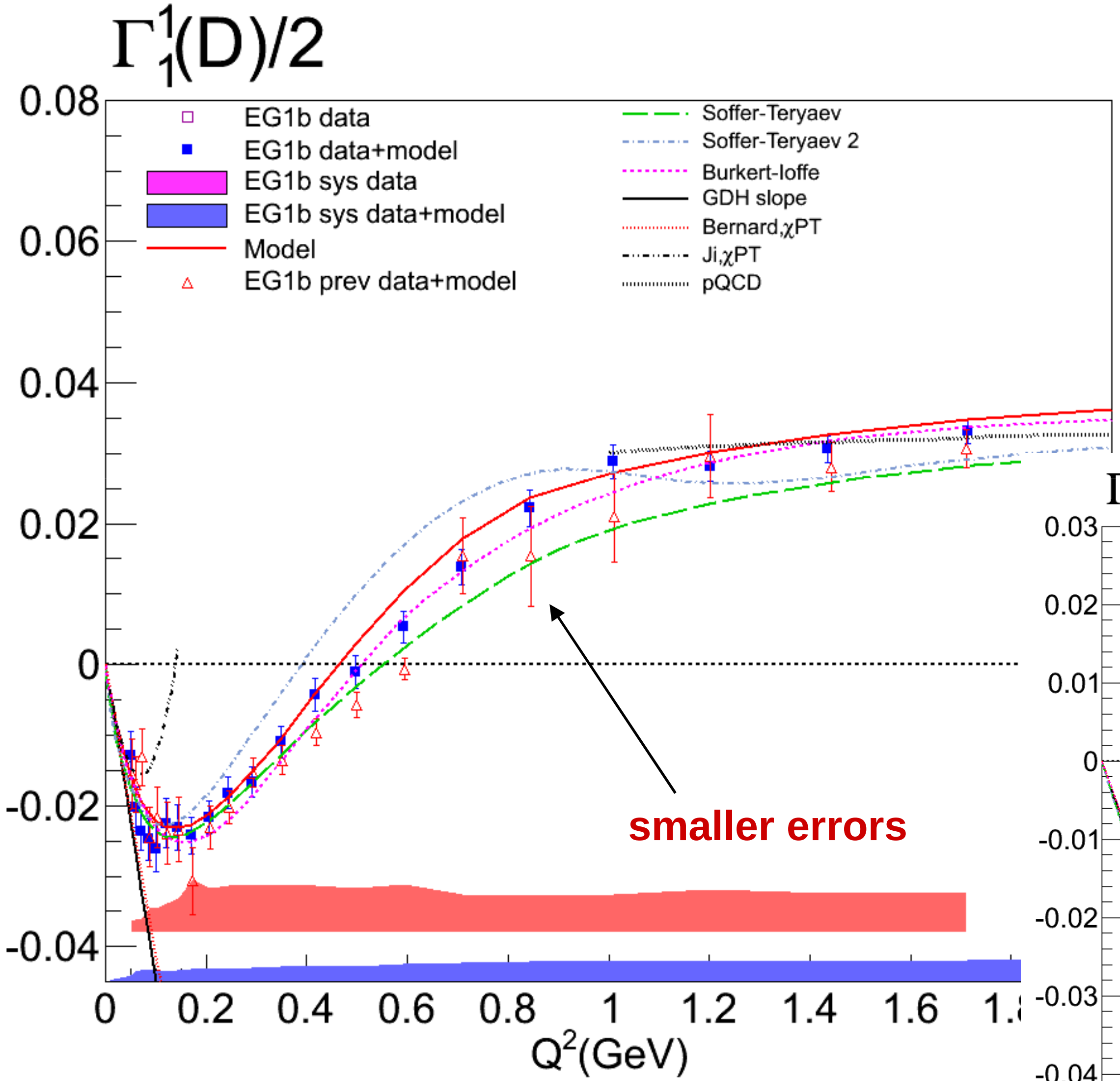
- The structure function g_1 is deeply affected by the resonance contribution. Hence, the moments of g_1 also show strong variation with Q^2. Some phenomenological calculations describe the experimental results well. The data will be useful for future Lattice QCD calculations, extraction of higher twist coefficients and to study duality.

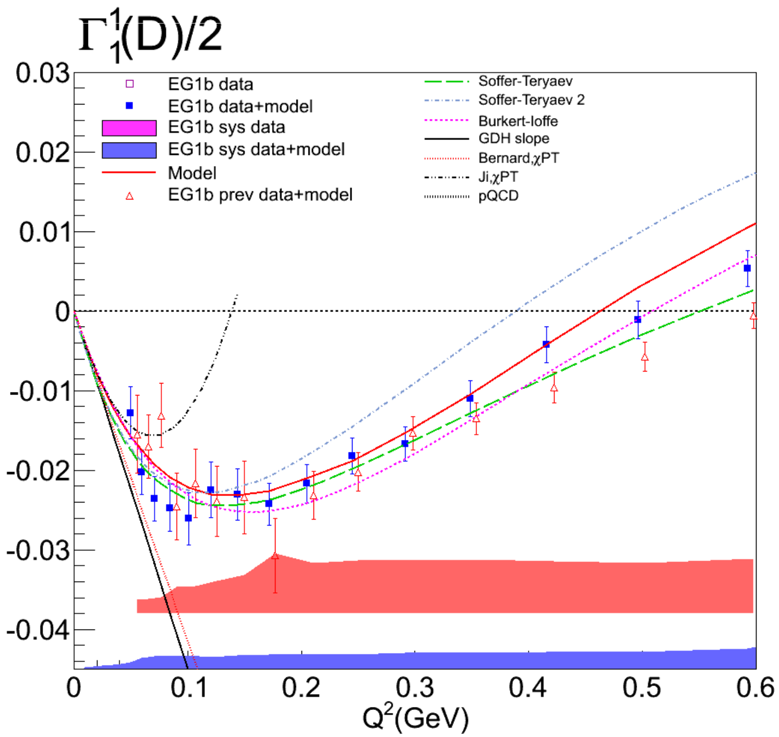
- World data on the virtual photon asymmetries were parameterized. High precision data from the EG1b experiment played a key role. By using these parameterizations and the deuteron data, spin structure function g_1 of the neutron was extracted.

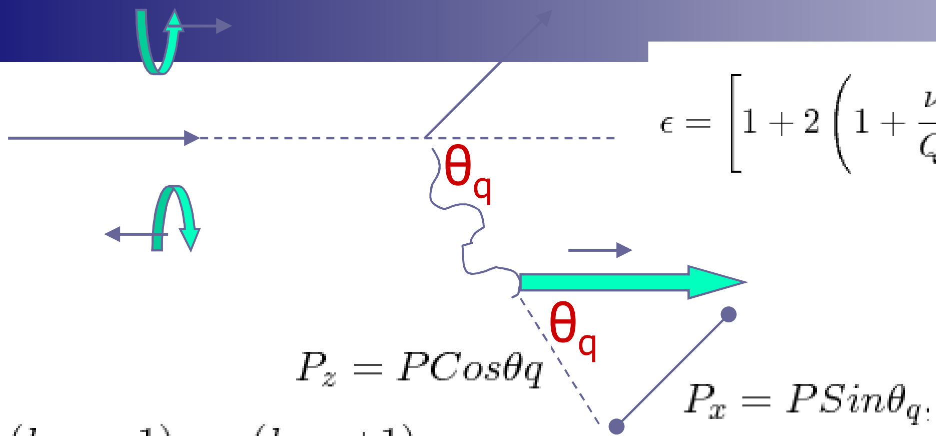
- A wealth of semi-inclusive and exclusive data were also collected simultaneously and have been analyzed.

- A follow-up experiment (EG1-DVCS) at the highest beam energy available at JLab (6 GeV) will improve significantly the precision of the data at the highest Q^2.

Γ_1 Deuteron, Comparison to previous analysis







$$\epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right) tan^2(\theta/2)\right]^{-1}$$ virtual photon polarization

a path from experiment to theory is established!

$$A_{\parallel} = \frac{\sigma(h=-1) - \sigma(h=+1)}{\sigma(h=-1) + \sigma(h=+1)}$$ experimental quantity

$$\sigma = \sigma_T + \epsilon\sigma_L + hP_z\sqrt{1-\epsilon^2}\sigma_{TT'} + hP_x\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'} + P_y\sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}$$

$$A_{\parallel} = \frac{-2P_z\sqrt{1-\epsilon^2}\sigma_{TT'} - 2P_x\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}}{2\sigma_T + 2\epsilon\sigma_L}$$

$$A_1 = \frac{\sigma_{TT'}}{\sigma_T}, A_2 = \frac{\sigma_{LT'}}{\sigma_T}$$

$$\sigma_T = \frac{\sigma_{3/2} + \sigma_{1/2}}{2}, \sigma_{TT'} = \frac{\sigma_{3/2} - \sigma_{1/2}}{2}$$

$$A_{\parallel} = \left(\frac{Cos\theta_q\sqrt{1-\epsilon^2}}{1+\epsilon R}\right)\frac{\sigma_{TT'}}{\sigma_T} + \left(\frac{Sin\theta_q\sqrt{2\epsilon(1-\epsilon)}}{1+\epsilon R}\right)\frac{\sigma_{LT'}}{\sigma_T}$$

$$A_{\parallel} = -D\left(\frac{\sigma_{TT'}}{\sigma_T} + \eta\frac{\sigma_{LT'}}{\sigma_T}\right) = -D(-A_1 - \eta A_2)$$ theoretical quantities

$$R = \frac{\sigma_L}{\sigma_T}, D = \frac{1 - E'\epsilon/E}{1+\epsilon R}, \eta = \frac{\epsilon\sqrt{Q^2}}{E - E'\epsilon}$$

Structure functions

Scattering cross-section for electrons:

$$\frac{d\sigma}{dE'\,d\Omega} = \frac{\alpha^2}{Q^4}\frac{E'}{E} L^{\mu\nu} W_{\mu\nu}$$

Hadronic tensor

$$W_{\mu\nu} = \quad g^{\mu\nu} \boxed{F_1(x,Q^2)} + \frac{p^\mu p^\nu}{\nu} \boxed{F_2(x,Q^2)}$$

unpolarized

$$+i\varepsilon^{\mu\nu\lambda\sigma}\frac{q_\lambda}{\nu}\left(S_\sigma \boxed{g_1(x,Q^2)} + \frac{1}{\nu}\left([p\times qS]_\sigma - [S\times qp]_\sigma\right)\boxed{g_2(x,Q^2)}\right)$$

polarized

$$g_1 = \frac{\tau}{1+\tau}\left(A_1(x,Q^2) + \frac{1}{\sqrt{\tau}}A_2(x,Q^2)\right)\boxed{F_1(x,Q^2)}$$

$$g_2 = \frac{\tau}{1+\tau}\left(\sqrt{\tau}A_2(x,Q^2) - A_1(x,Q^2)\right)\boxed{F_1(x,Q^2)}$$

Modeled by world data

$\tau = \nu^2/Q^2$ Objective of EG1 inclusive analysis

Structure Functions in the Scaling Limit

By considering not only the valence quarks (uud for the proton; udd for the neutron) but also the quark-antiquark sea in the nucleon, general expression for the structure functions in the scaling limit can be written:

$$F_1(x) = \tfrac{1}{2}\sum_i e_i^2 q_i(x) \qquad g_1(x) = \tfrac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

$$F_2(x) = x\sum_i e_i^2 q_i(x) = 2xF_1(x) \qquad g_2(x) = 0$$

Infinite Momentum Frame

$x = Q^2/2M\nu$
i = quark flavor
e_i = quark charge
q(x) = prob. dist.
$\Delta q(x) = q\uparrow - q\downarrow$

F_1 is defined as sum of the distribution of quark flavors inside the nucleon weighted by their squared charges.

F_2 is the total four-momentum carried by the quarks which carry the momentum fraction x of the nucleon. It can be understood as spatial current density of the nucleon.

g_1 is the sum of the helicity distributions of the quark flavors which have their spins aligned or anti-aligned with respect to the spin of the nucleon.

g_2 represents the quark flavors with transverse spin components to the nucleon spin. In the scaling limit, it is considered as zero.

Γ_1 (The First Moment of g_1)

Most of the spin dependent sum rules can be written in terms of the first moment of g_1.
It represents the total spin carried by the quarks inside the nucleon.

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{2}\int_0^1 \sum_i e_i^2 \Delta q_i(x)dx$$

For a simple model of proton from uud quarks and sea quarks (s)

$$\Gamma_1^p = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)$$

In the scaling limit
(large Q2, free quarks)

Experimental results from neutron beta decay predicts $\Delta u - \Delta d = 1.26$
Hyperon beta decay predicts $\Delta u + \Delta d - 2\Delta s = 0.58$

Assuming $\Delta s = 0$ gives $\Gamma_1^p \sim 0.186$ & $\Gamma_1^n \sim -0.024$: larger than experimental limits

Comparing with $\Gamma_1^p(Q^2 \rightarrow \text{big}) \sim 0.14$ from experiments give
$\Delta u \approx 0.81$, $\Delta d \approx -0.46$, $\Delta s \approx -0.12$ (nonzero and negative)

spin of the d quark is mostly opposite to that
of the nucleon, same is true for sea quarks

$$\int_{\nu_0}^{\infty}\frac{d\nu}{\nu}\left[\sigma_{1/2}(\nu)-\sigma_{3/2}(\nu)\right]=-\frac{2\pi^2\alpha_{em}}{M^2}\kappa^2$$

For real photon ($Q^2 = 0$)

photo-absorption threshold

Anomalous magnetic moment of the nucleon

$$\boxed{\begin{aligned}\sigma_T^{1/2}(\nu,Q^2)&=-\frac{4\pi^2\alpha}{MK}\left(F_1+g_1-\frac{2Mx}{\nu}g_2\right)\\ \sigma_T^{3/2}(\nu,Q^2)&=-\frac{4\pi^2\alpha}{MK}\left(F_1-g_1+\frac{2Mx}{\nu}g_2\right)\end{aligned}}$$

$\gamma^2 = Q^2/\nu^2$

$$I(Q^2)=\int_{Q^2/2M\nu}^{\infty}\frac{d\nu}{\nu}\left[\sigma_{1/2}(\nu,Q^2)-\sigma_{3/2}(\nu,Q^2)\right]=-\frac{8\pi^2\alpha}{M}\int_0^{x_0}\frac{dx}{x}\left[\frac{g_1(x,Q^2)-\gamma^2 g_2(x,Q^2)}{K}\right]$$

Generalized GDH Sum Rule

$K = \nu(1-x)$

Determining Q^2 evolution of the GDH integral is one of the aims of the EG1 experiment

Axial vector coupling constant
Current value

$$\frac{g_A}{g_V} = -1.2670 \pm 0.0035$$

$$\int_0^1 \left[g_1^p\left(x,Q^2\right) - g_1^n\left(x,Q^2\right) \right] dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| f\left(Q^2\right) + HT$$

Bjorken Limit

$$f\left(Q^2\right) = 1 - \frac{\alpha_s\left(Q^2\right)}{\pi} - 3.58\left(\frac{\alpha_s\left(Q^2\right)}{\pi}\right)^2 - 20.21\left(\frac{\alpha_s\left(Q^2\right)}{\pi}\right)^3 + \ldots\ldots\ldots \equiv \mu_2^{p-n}\left(Q^2\right)$$

Leading Twist
(DGLAP egn.)

Radiative corrections from higher order Feynman diagrams

$$HT = \frac{\mu_4^{p-n}\left(Q^2\right)}{Q^2} + \frac{\mu_6^{p-n}\left(Q^2\right)}{Q^4} + O\left(\frac{1}{Q^6}\right)$$

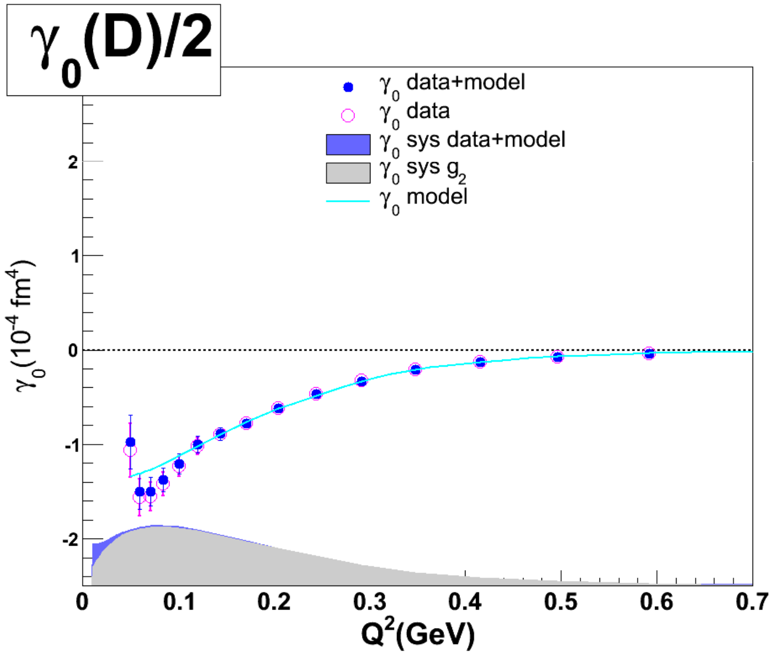
Higher Twist terms

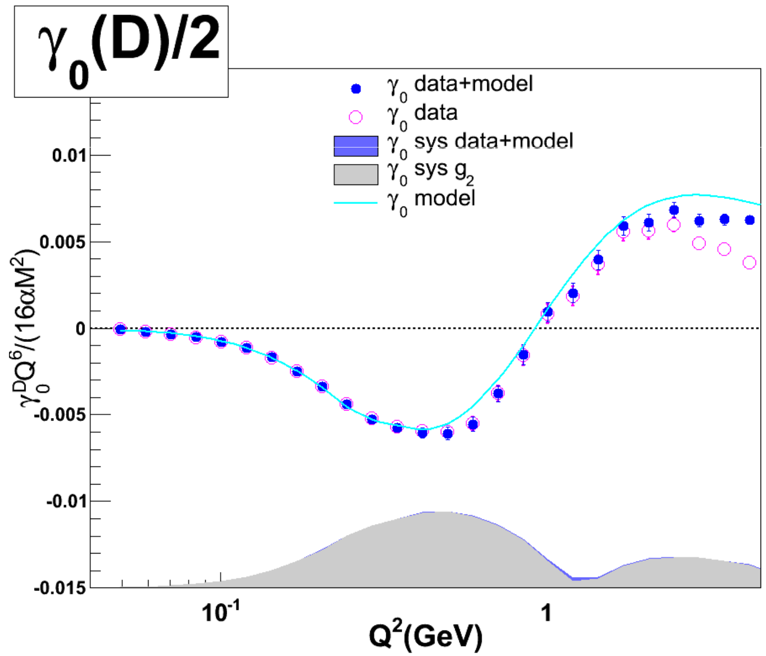
Forward Spin Polarizability γ_0 for the Deuteron

$$\gamma_0(Q^2) = C(Q^2)\int_0^{x_0} x^2\left\{g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2 g_2(x,Q^2)\right\}dx$$

Model

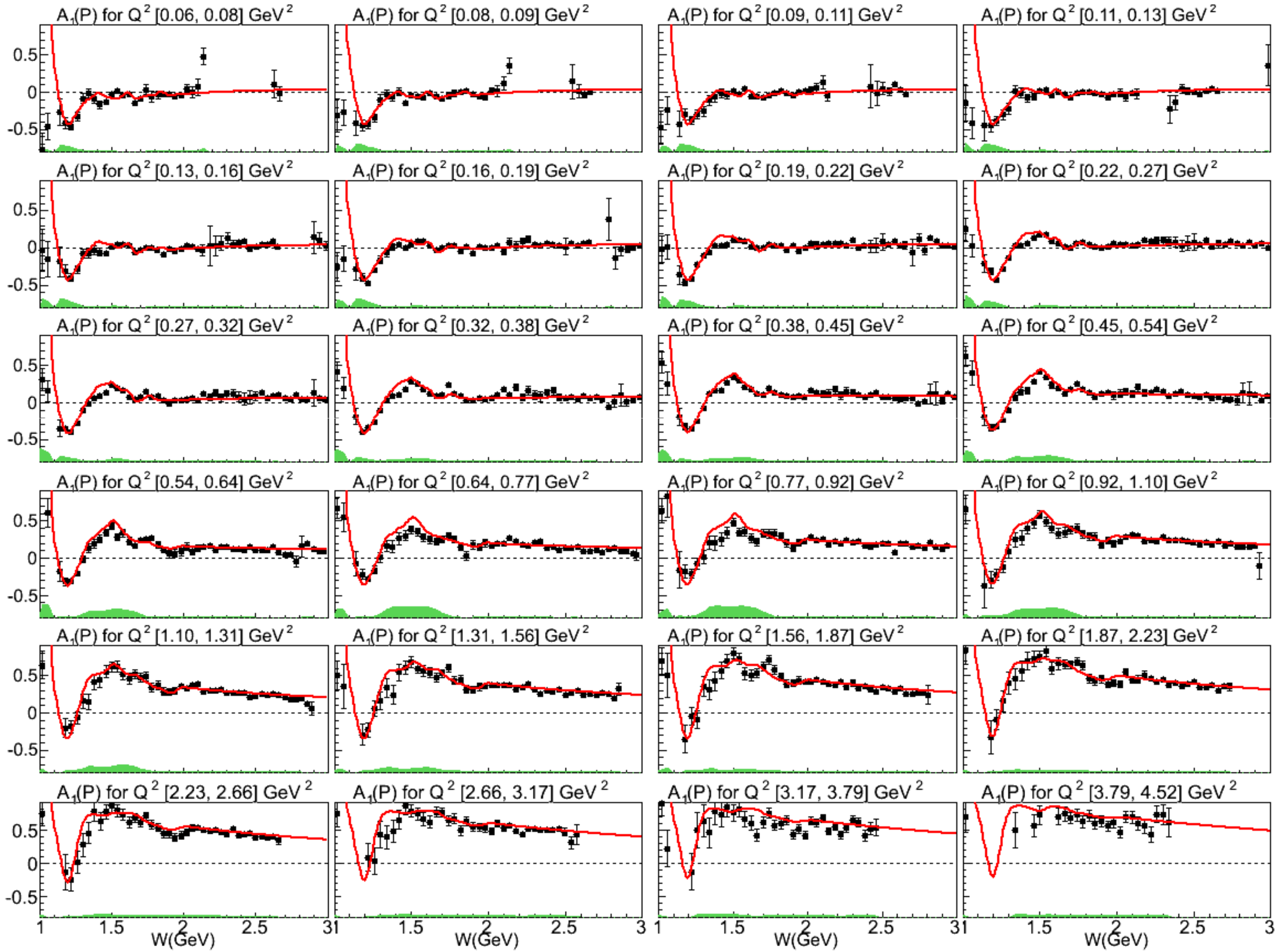
$$C(Q^2) = 16\alpha M^2/Q^6$$





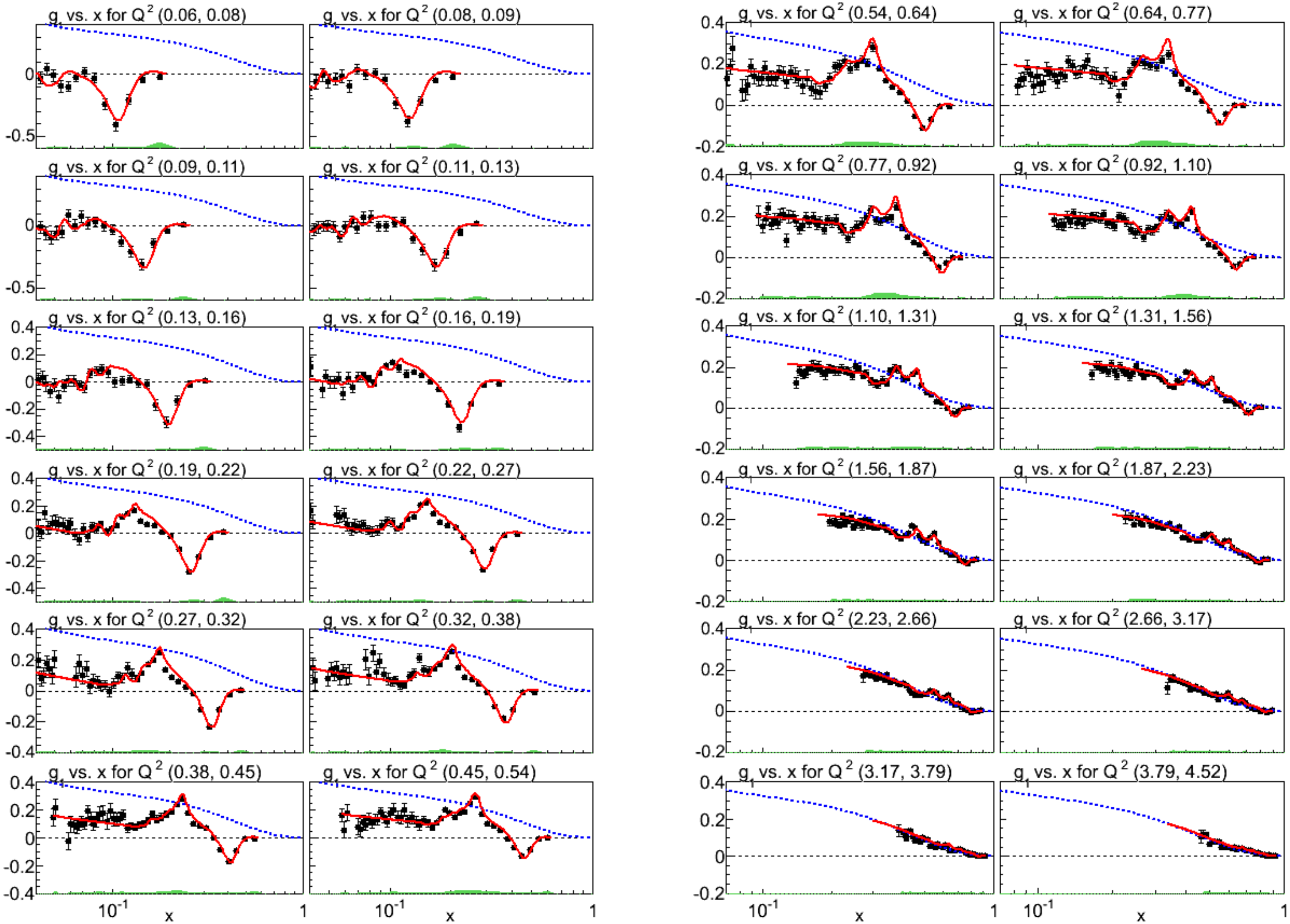
There is also multiplication factor 15.134 to convert to [10^{-4} fm^4] unit

A_1 Proton



A1(P) for Q2 [0.06, 0.08] GeV2
A1(P) for Q2 [0.08, 0.09] GeV2
A1(P) for Q2 [0.09, 0.11] GeV2
A1(P) for Q2 [0.11, 0.13] GeV2
A1(P) for Q2 [0.13, 0.16] GeV2
A1(P) for Q2 [0.16, 0.19] GeV2
A1(P) for Q2 [0.19, 0.22] GeV2
A1(P) for Q2 [0.22, 0.27] GeV2
A1(P) for Q2 [0.27, 0.32] GeV2
A1(P) for Q2 [0.32, 0.38] GeV2
A1(P) for Q2 [0.38, 0.45] GeV2
A1(P) for Q2 [0.45, 0.54] GeV2
A1(P) for Q2 [0.54, 0.64] GeV2
A1(P) for Q2 [0.64, 0.77] GeV2
A1(P) for Q2 [0.77, 0.92] GeV2
A1(P) for Q2 [0.92, 1.10] GeV2
A1(P) for Q2 [1.10, 1.31] GeV2
A1(P) for Q2 [1.31, 1.56] GeV2
A1(P) for Q2 [1.56, 1.87] GeV2
A1(P) for Q2 [1.87, 2.23] GeV2
A1(P) for Q2 [2.23, 2.66] GeV2
A1(P) for Q2 [2.66, 3.17] GeV2
A1(P) for Q2 [3.17, 3.79] GeV2
A1(P) for Q2 [3.79, 4.52] GeV2
0.5
0
-0.5
1
1.5
2
2.5
3
W(GeV)

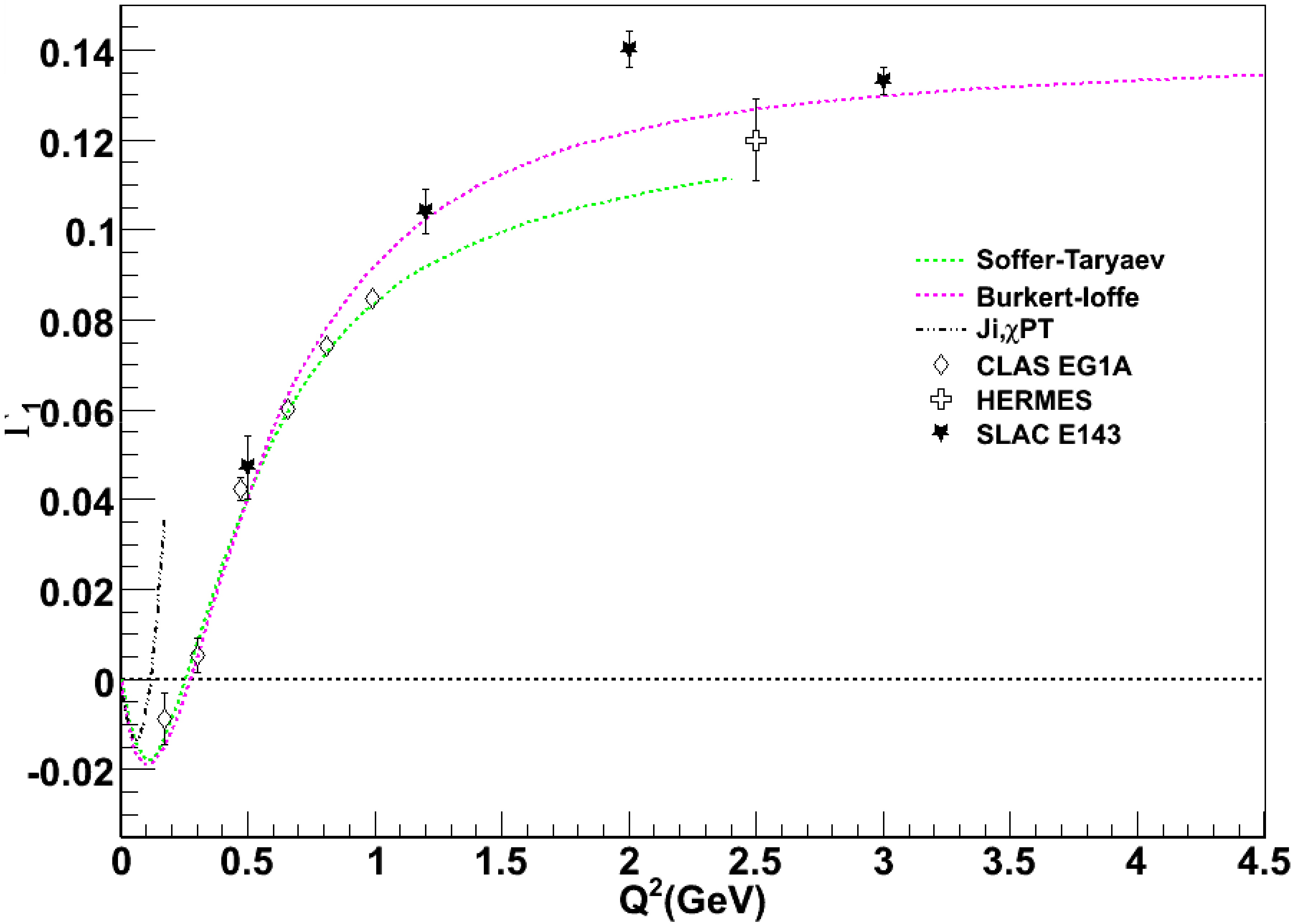
g_1 Proton



g1 vs. x for Q2 (0.06, 0.08)
g1 vs. x for Q2 (0.08, 0.09)
g1 vs. x for Q2 (0.09, 0.11)
g1 vs. x for Q2 (0.11, 0.13)
g1 vs. x for Q2 (0.13, 0.16)
g1 vs. x for Q2 (0.16, 0.19)
g1 vs. x for Q2 (0.19, 0.22)
g1 vs. x for Q2 (0.22, 0.27)
g1 vs. x for Q2 (0.27, 0.32)
g1 vs. x for Q2 (0.32, 0.38)
g1 vs. x for Q2 (0.38, 0.45)
g1 vs. x for Q2 (0.45, 0.54)
g1 vs. x for Q2 (0.54, 0.64)
g1 vs. x for Q2 (0.64, 0.77)
g1 vs. x for Q2 (0.77, 0.92)
g1 vs. x for Q2 (0.92, 1.10)
g1 vs. x for Q2 (1.10, 1.31)
g1 vs. x for Q2 (1.31, 1.56)
g1 vs. x for Q2 (1.56, 1.87)
g1 vs. x for Q2 (1.87, 2.23)
g1 vs. x for Q2 (2.23, 2.66)
g1 vs. x for Q2 (2.66, 3.17)
g1 vs. x for Q2 (3.17, 3.79)
g1 vs. x for Q2 (3.79, 4.52)
x

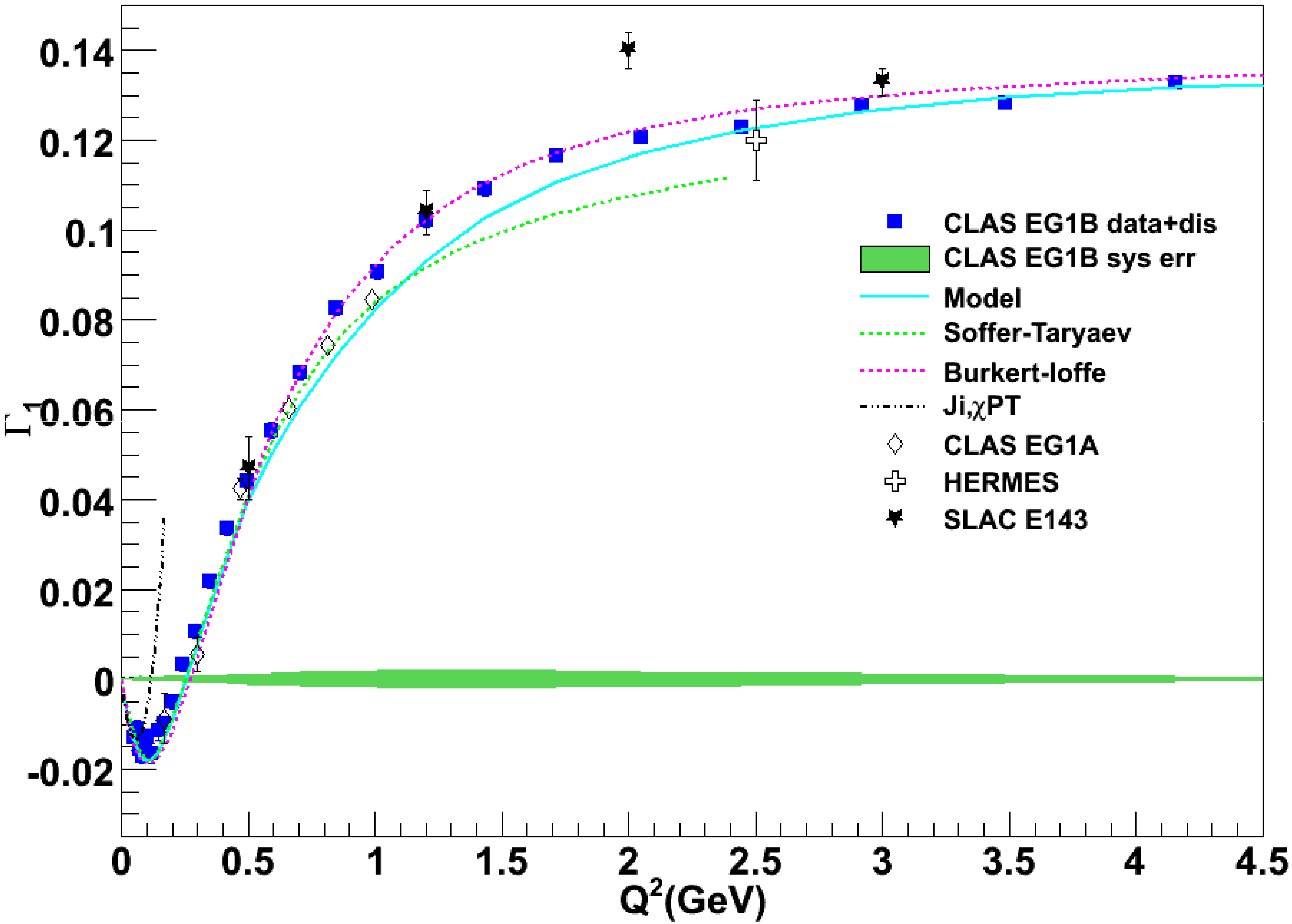
$\Gamma_1(P)$

Γ_1 Proton, Comparison to world data

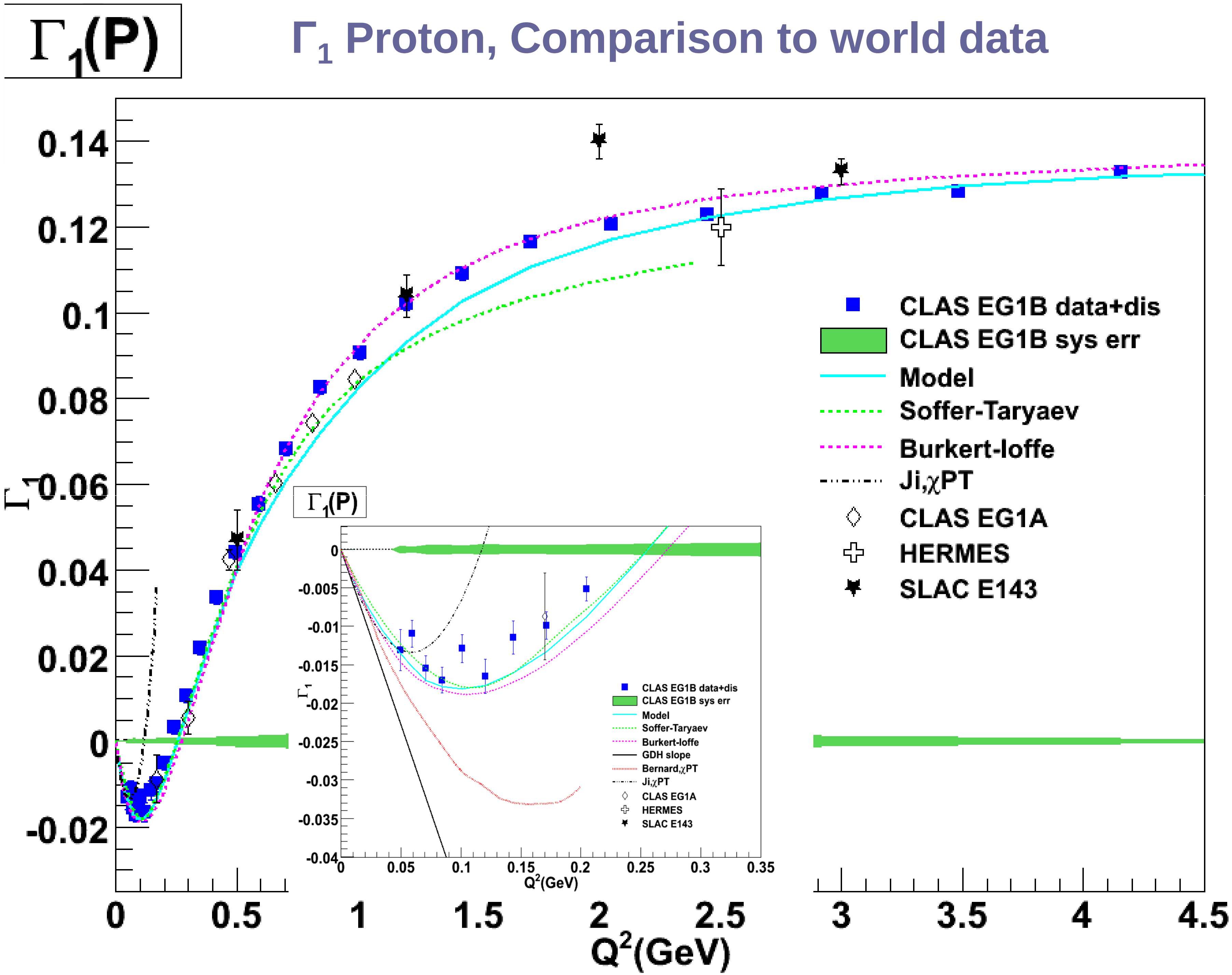


$\Gamma_1(P)$

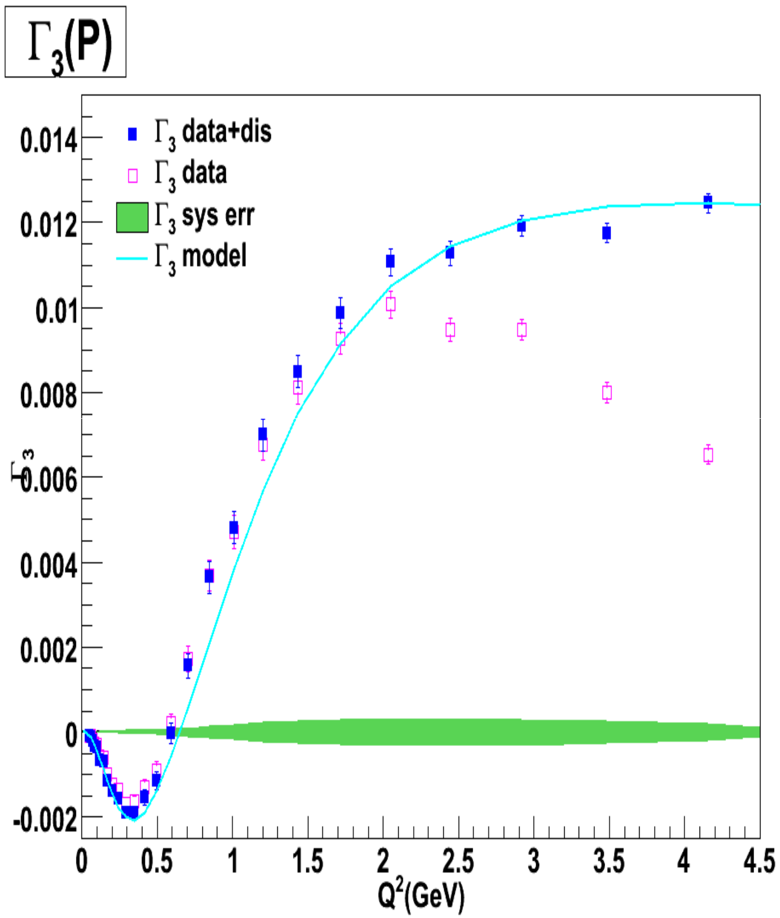
Γ_1 Proton, Comparison to world data

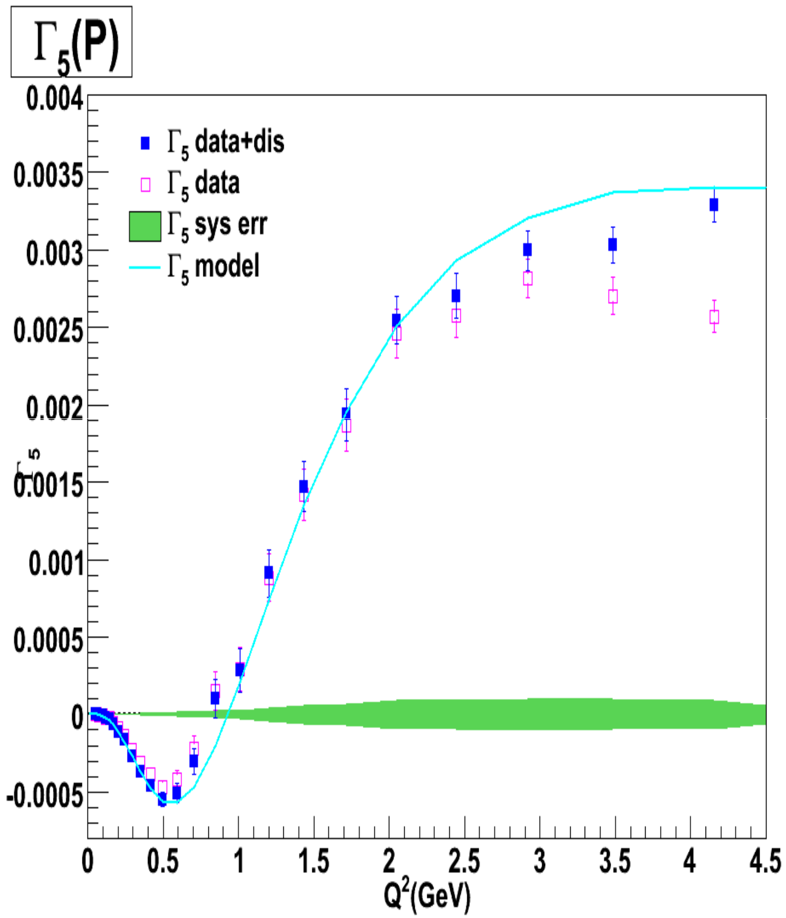


Γ_1 Proton, Comparison to world data



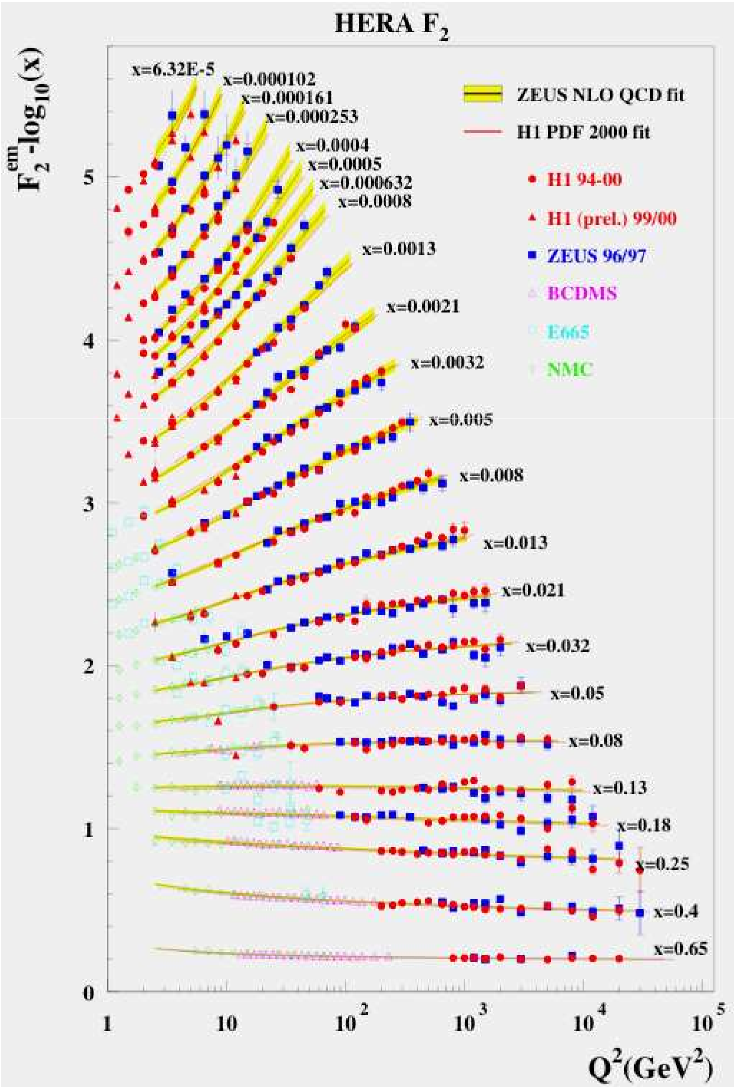
Γ_3 and Γ_5 Proton





Scaling Violations

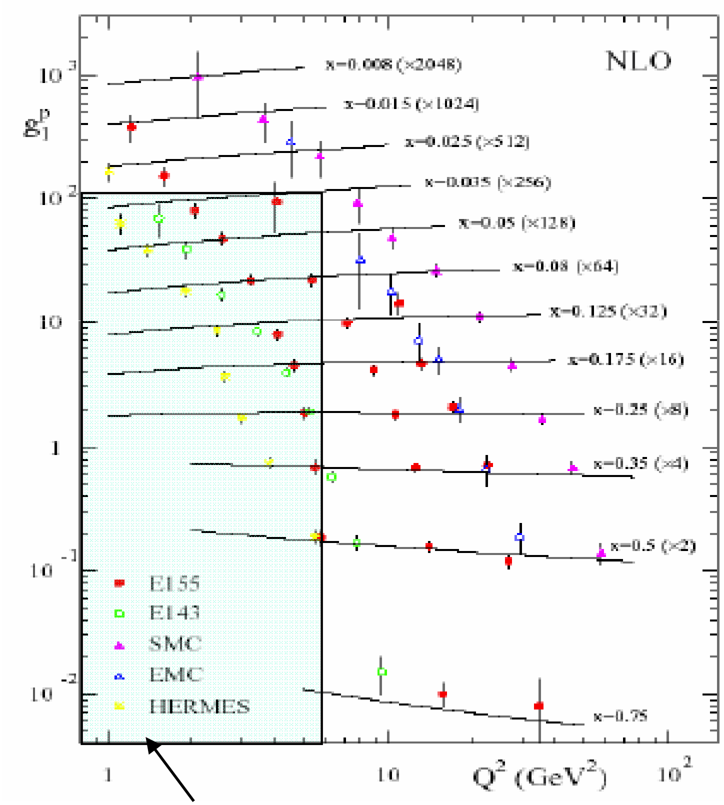
F2



g_1^p

Lot's of work to do for g1

Current data on scaling violation for g_1^p



EG1b can fill this region

Operator Product Expansion (OPE)

$$\Gamma_1^N(Q^2) \equiv \int_0^1 dx\, g_1^N(x,Q^2) = \sum_{\tau=2,4,\dots} \frac{\mu_\tau^N(Q^2)}{Q^{\tau-2}} = \mu_2^N(Q^2) + \frac{\mu_4^N(Q^2)}{Q^2} + \frac{\mu_6^N(Q^2)}{Q^4} + \dots$$

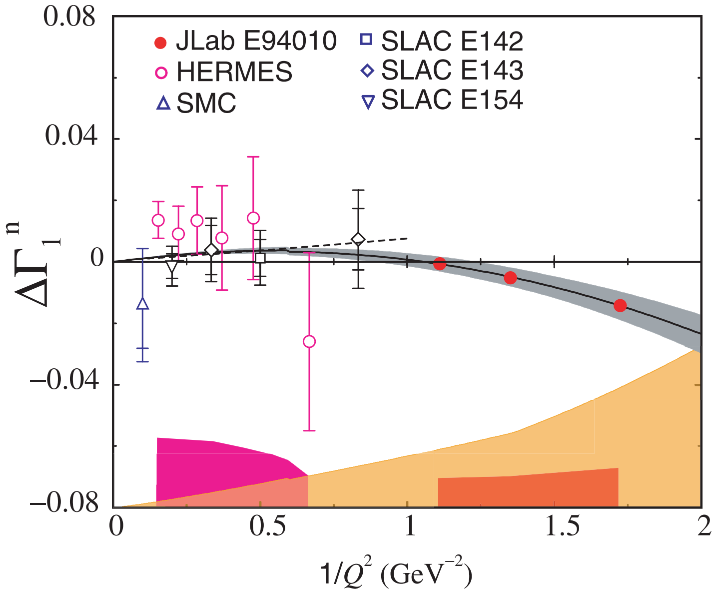
Single Parton Behavior

Higher Twist Terms

(quark-quark and quark-gluon correlations)

Higher Twist Contribution to the first moment of g_1

$$\Delta\Gamma_1^n(Q^2) \equiv \Gamma_1^n(Q^2) - \mu_2^n(Q^2) = \frac{\mu_4^n(Q^2)}{Q^2} + \frac{\mu_6^n(Q^2)}{Q^4} + \mathcal{O}\left(\frac{1}{Q^6}\right)$$



- Higher twist contributions become important at low Q^2 regions.

- To understand the dynamics of quark-gluon interactions at large distances, this region should be studied carefully.

- This is important to understand the CONFINEMENT, a weird property of QCD.

- Also important to calculate the color polarizabilities for the nucleon

$$\mu_4 = \frac{1}{9} M^2 \left(a_2 + 4d_2 + 4 f_2\right)$$

Target mass correction

$$\chi_E = \frac{2}{3}\left(2d_2 + f_2\right)$$ Color electric

$$\chi_B = \frac{1}{3}\left(4d_2 - f_2\right)$$ Color magnetic

MODEL DEPENDENT PROPERTIES!

- Complementarity between quark and hadron descriptions of observables.
  Physical phenomena can be described by using either of the definitions: hadronic or partonic pictures of the nucleon;

either set of basis states should work.

$$\sum_{hadronic\ \ states} = \sum_{partonic\ \ states}$$

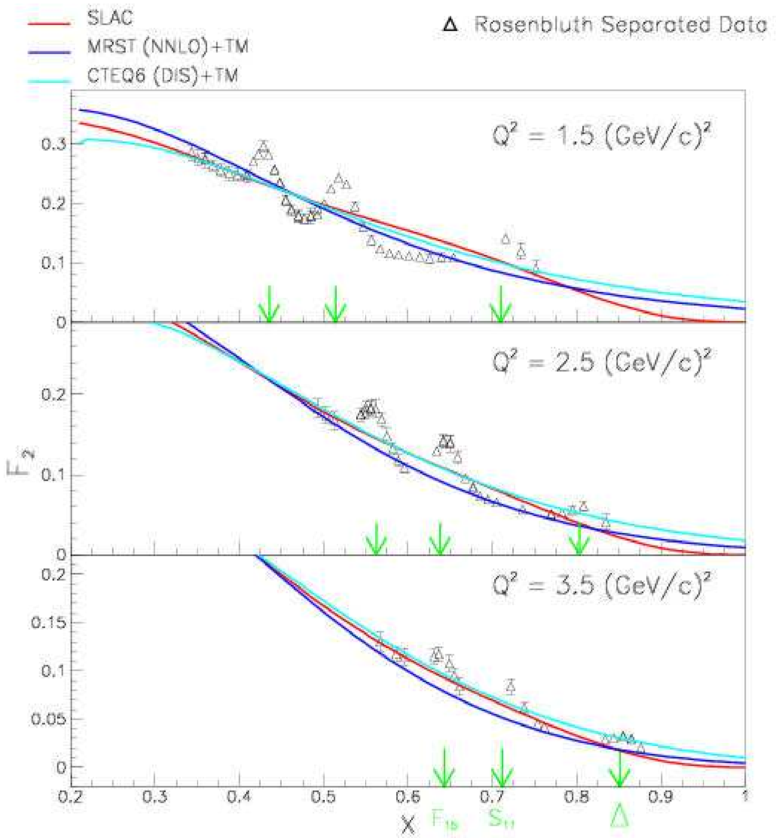
pQCD should be able to describe the average behavior of hadronic observables.

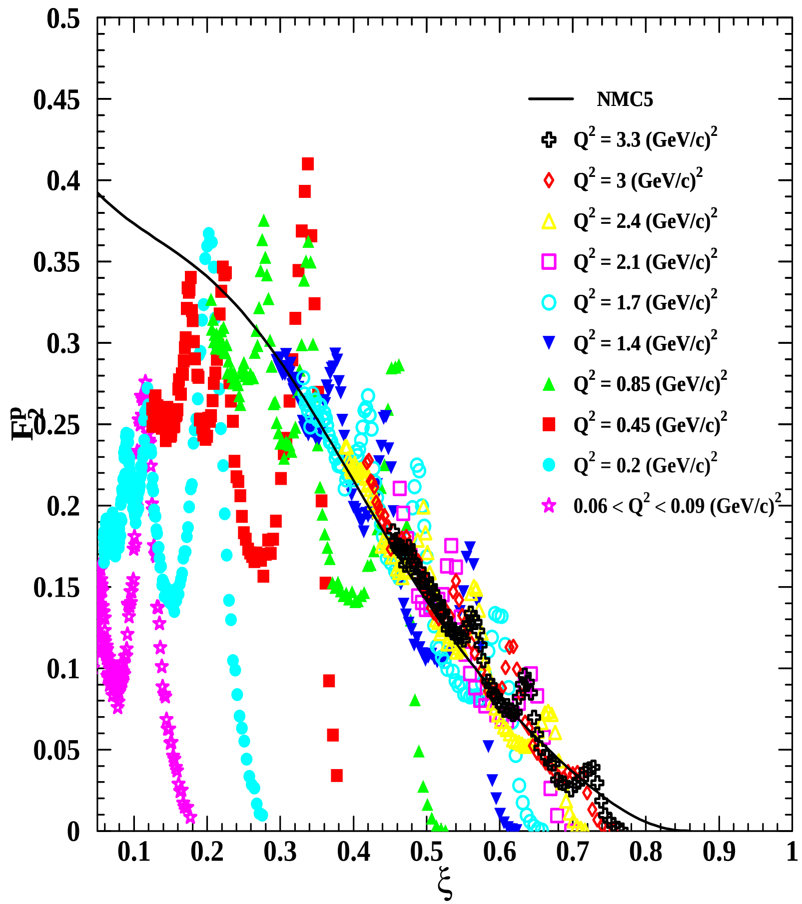
Connection between low and high Q^2 regions

- A universal curve should define hadronic cross sections averaged over appropriate energy range and partonic cross sections at the same time.

- Duality should break down as $Q^2 \rightarrow 0$: Total charge obtained from partonic picture by combining the squared charges of the valence quarks does make up the proton charge but does not make up the neutron charge.

- Where is the break down point of quark-hadron duality?

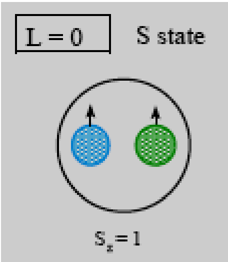




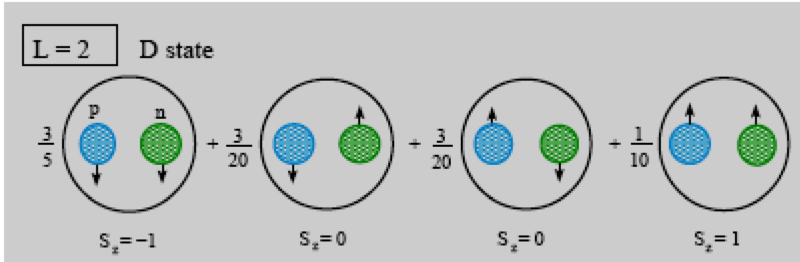
Q^2>1.5GeV^2 Duality holds for entire resonance region (Global Duality) and also for individual resonances (Local Duality)

Neutron (D-State Correction)

L=0 and L=2 configurations for the deuteron



Probability of finding the deuteron in D-state is $\omega_D \sim 0.056$



Probability of finding a nucleon with spin opposite to the spin of the deuteron: $\left(\frac{1}{2} * \frac{3}{10} + \frac{3}{5}\right)\omega_D = \frac{3}{4}\omega_D$

$$\sigma_D^{\uparrow\downarrow} = \left(1 - \frac{3}{4}\omega_D\right)\sigma_N^{\uparrow\downarrow} + \frac{3}{4}\omega_D \sigma_N^{\uparrow\uparrow}$$

$$\sigma_D^{\uparrow\uparrow} = \frac{3}{4}\omega_D \sigma_N^{\uparrow\downarrow} + \left(1 - \frac{3}{4}\omega_D\right)\sigma_N^{\uparrow\uparrow}$$

$$\sigma_D = \frac{1}{2}\left(\sigma_p + \sigma_n\right)$$

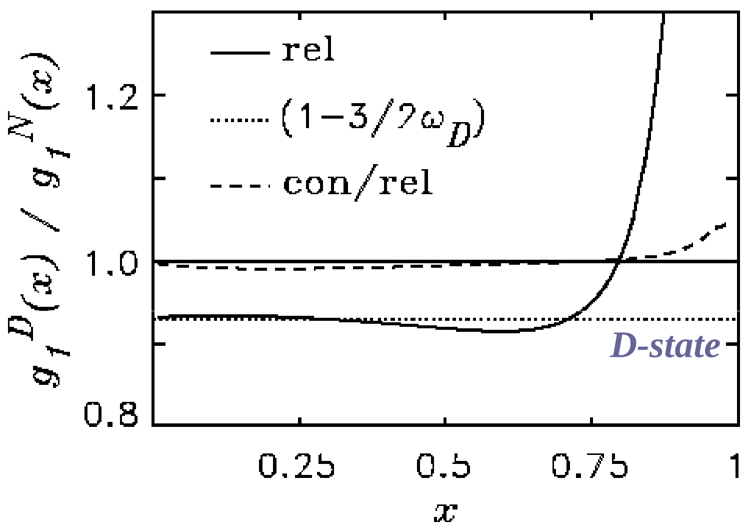
- Deuteron cross sections can be written in terms of proton and neutron cross sections
- Then asymmetries and structure functions can be calculated for the deuteron in terms of the proton and the neutron structure functions

Neutron (D-State Correction)

$$g_1^D\left(x,Q^2\right)=\left[g_1^p\left(x,Q^2\right)+g_1^n\left(x,Q^2\right)\right]\left(1-\frac{3}{2}\omega_D\right)$$

$$\Gamma_1^D=\left[\Gamma_1^p+\Gamma_1^n\right]\left(1-\frac{3}{2}\omega_D\right)$$

Full Model



D-state correction works for x < 0.7

Other corrections required for Fermi motion and binding effects

Nuclear Corrections

1) EMC Effect: This effect takes into account the distortion of the free-nucleon structure function by a nuclear medium.

2) Fermi Motion: Bound nucleons are moving inside the nucleus and this causes kinematic shifts and Doppler broadening of peaks in the cross section.

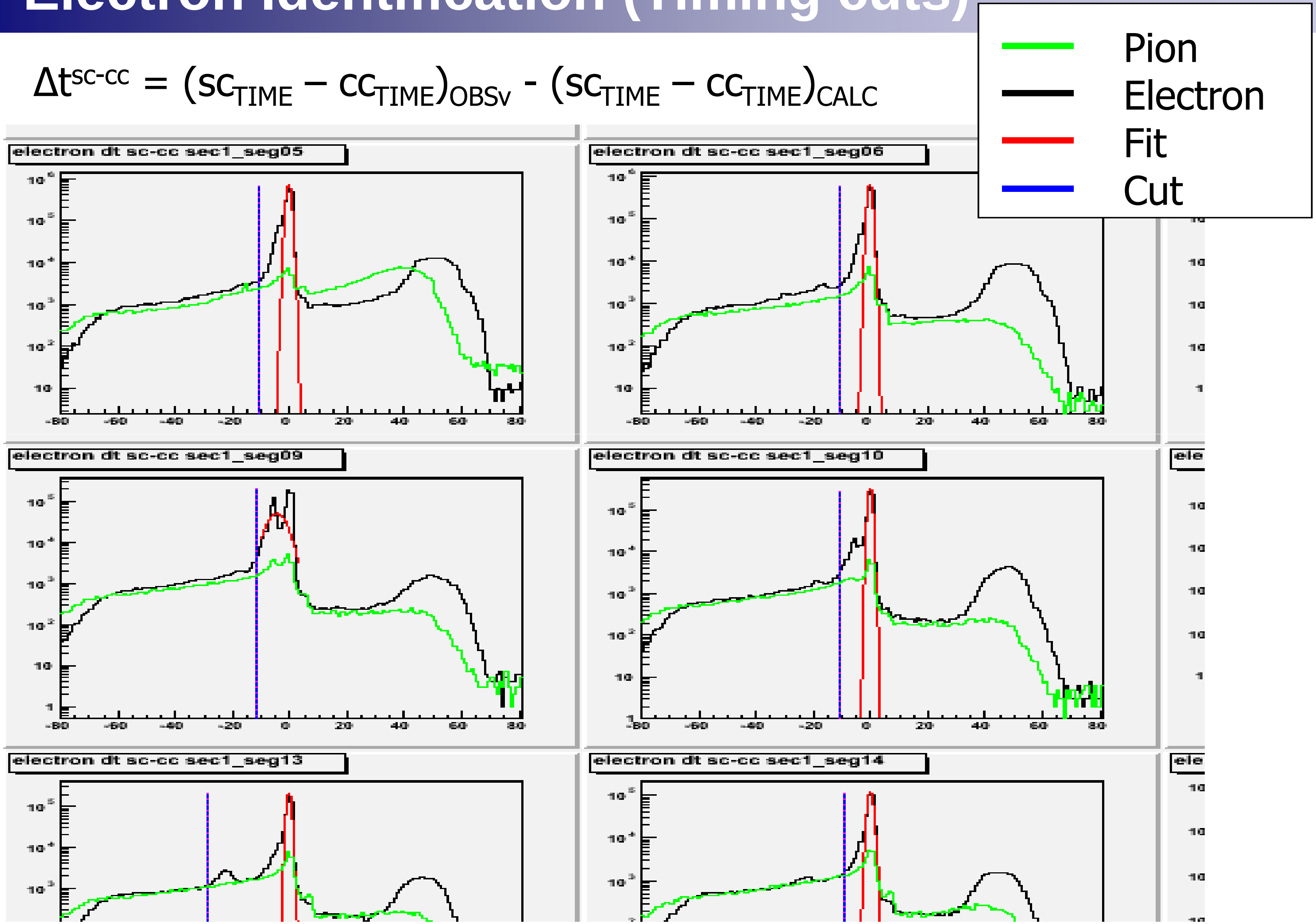
3) Off-Shell Mass Effects: A correction is required for the virtual photon interaction with an off-shell nucleon. (Because of the negative contribution coming from the binding energy to the overall mass of deuterium, both nucleons cannot be on the mass shell at the same time.)

4) Effects of non-nucleonic states:

- Effects of nucleonic resonance states and pions (meson exchange currents).
- According to the six quark bag model of the deuteron, one should also include direct correlations between quarks and gluons in the proton and neutron.
- Nuclear shadowing (rescattering of the lepton from both nucleons in the deuteron or from the meson cloud within the nucleus.)

Electron Identification (Timing cuts)

$$\Delta t^{SC\text{-}CC} = (SC_{TIME} - CC_{TIME})_{OBSv} - (SC_{TIME} - CC_{TIME})_{CALC}$$

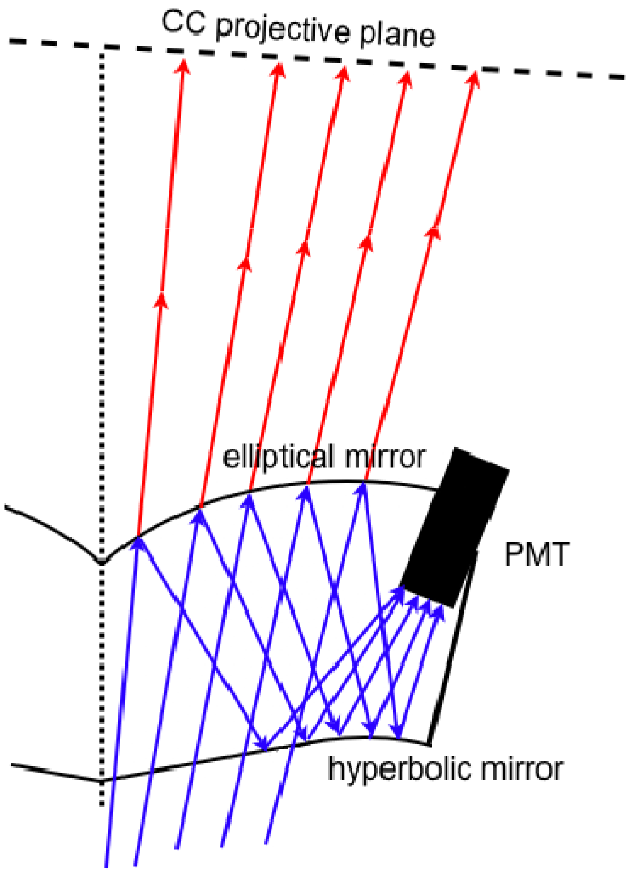


Δt Distribution For Each Sector And Segment

Electron Identification (Geometric cuts)

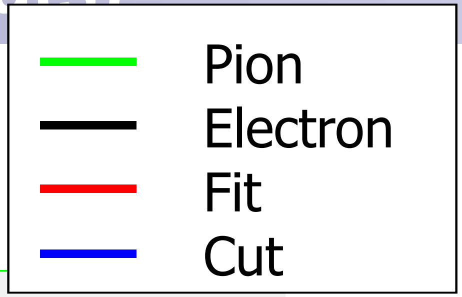
Polar angle θ_{proj} of the particle is calculated assuming particle continues on a straight line, but travels the same amount of path length

The polar angle is θ_{proj} should be a narrow distribution around the center of the cc segment

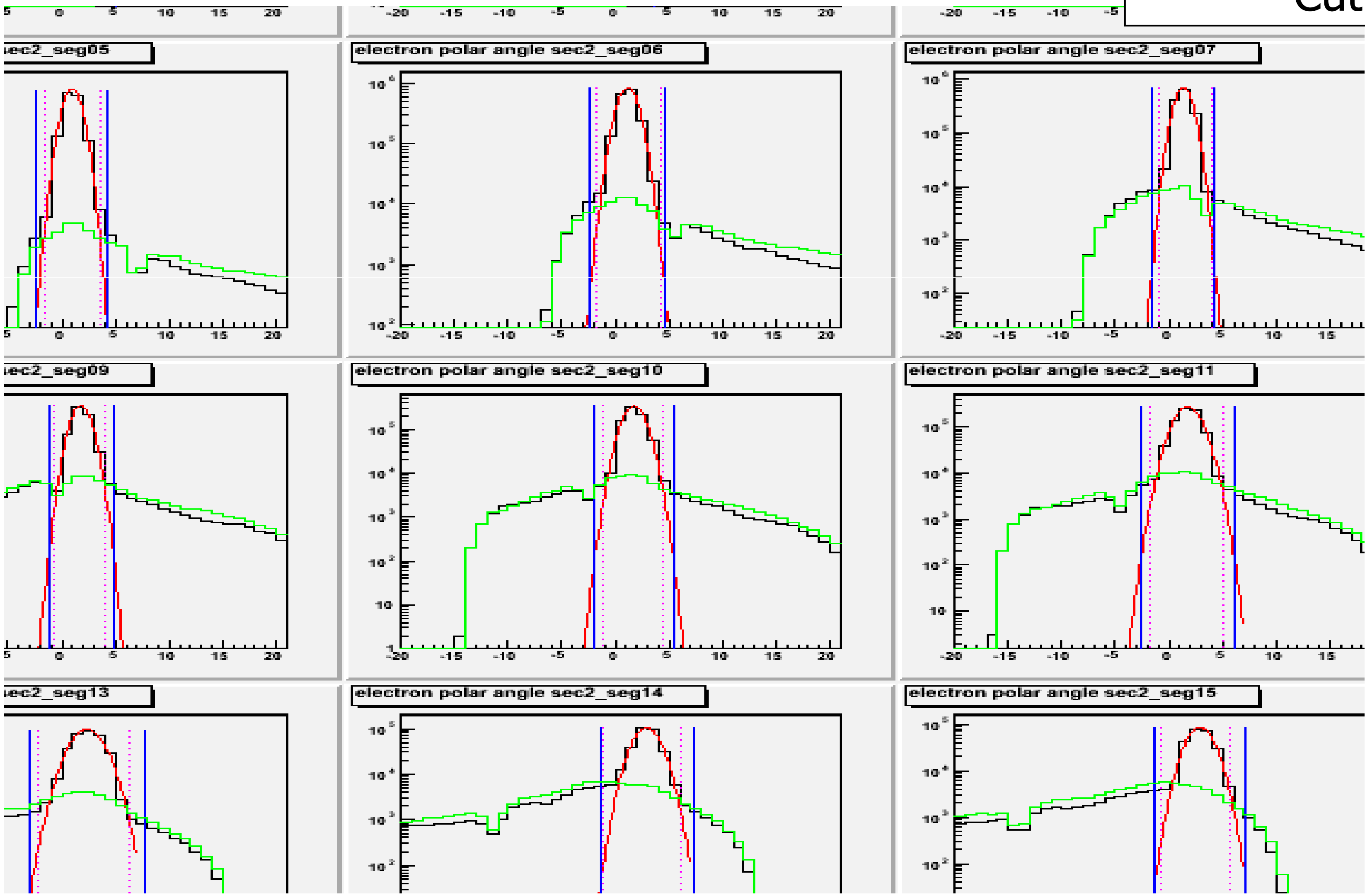


Electron Identification (Geometric cuts)

$(\theta_{proj} - \theta_{seg\_centr}) < 3\sigma$

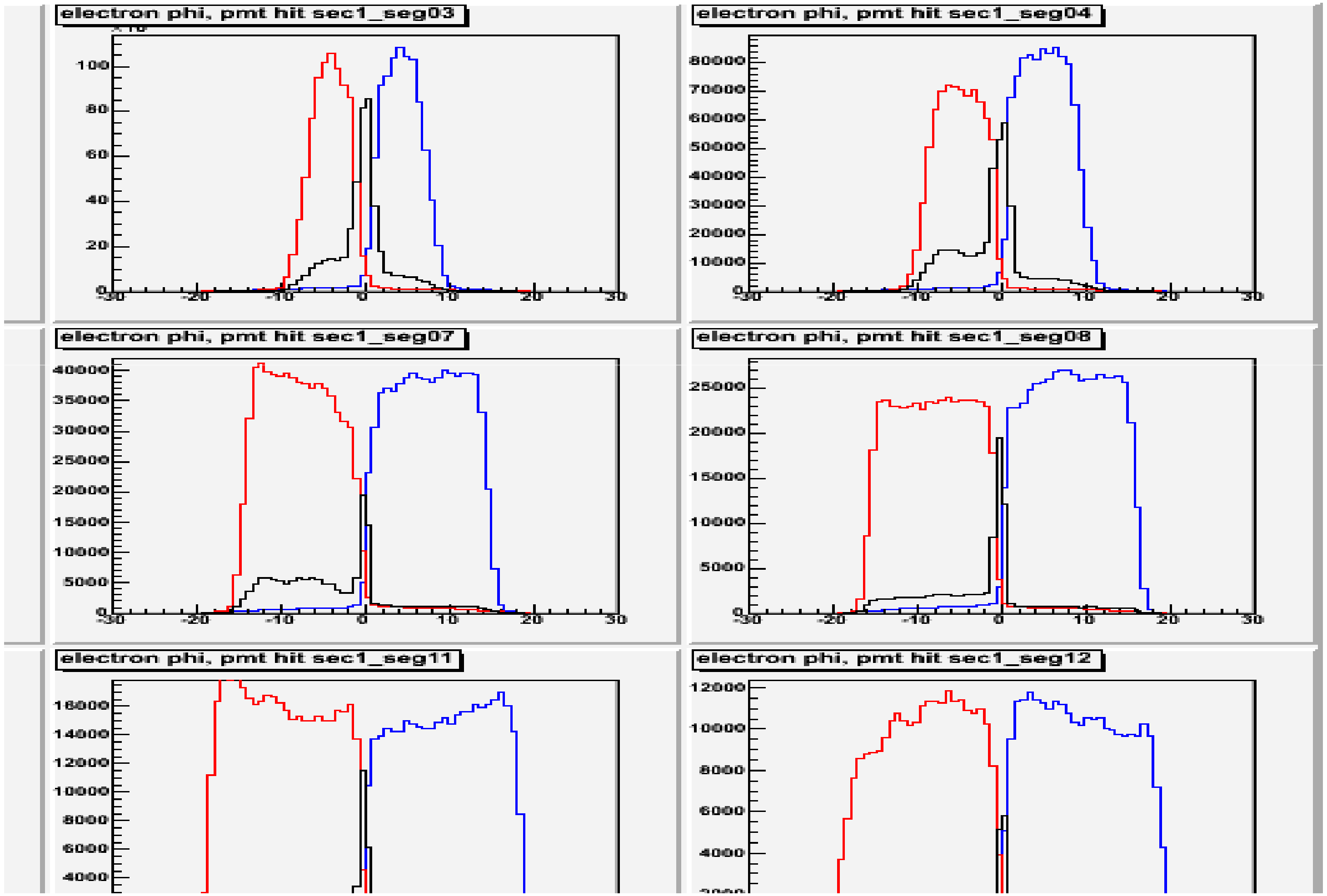


Δθ Distribution For Each Sector And Segment



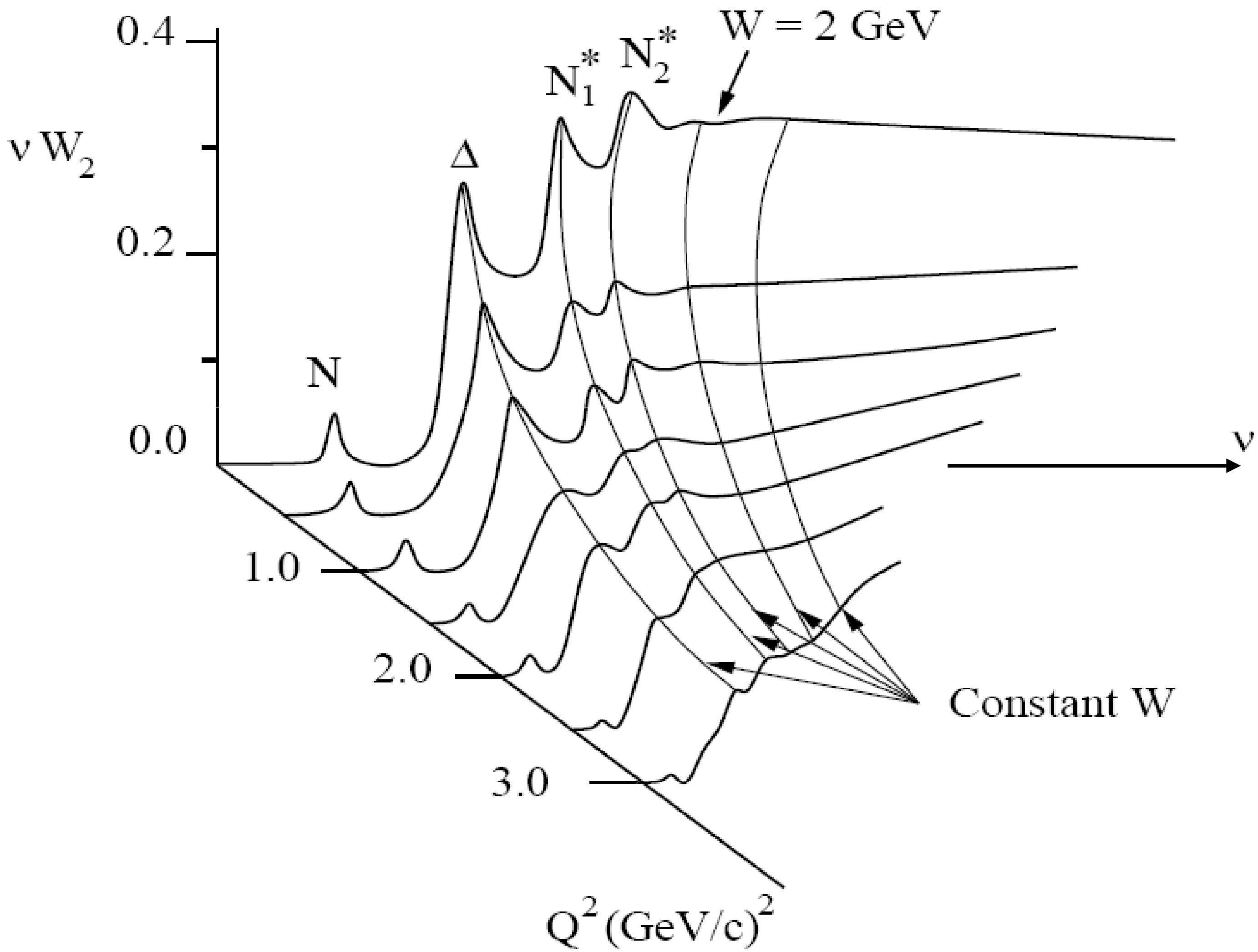
Electron Identification (Geometric cuts)

PMT signal (left, right) vs. azimuthal angle (-30 < Φ< 30) examined.



If Φ< 0 → Left PMT signals If Φ< 0 → Right PMT signals

Resonance excitations

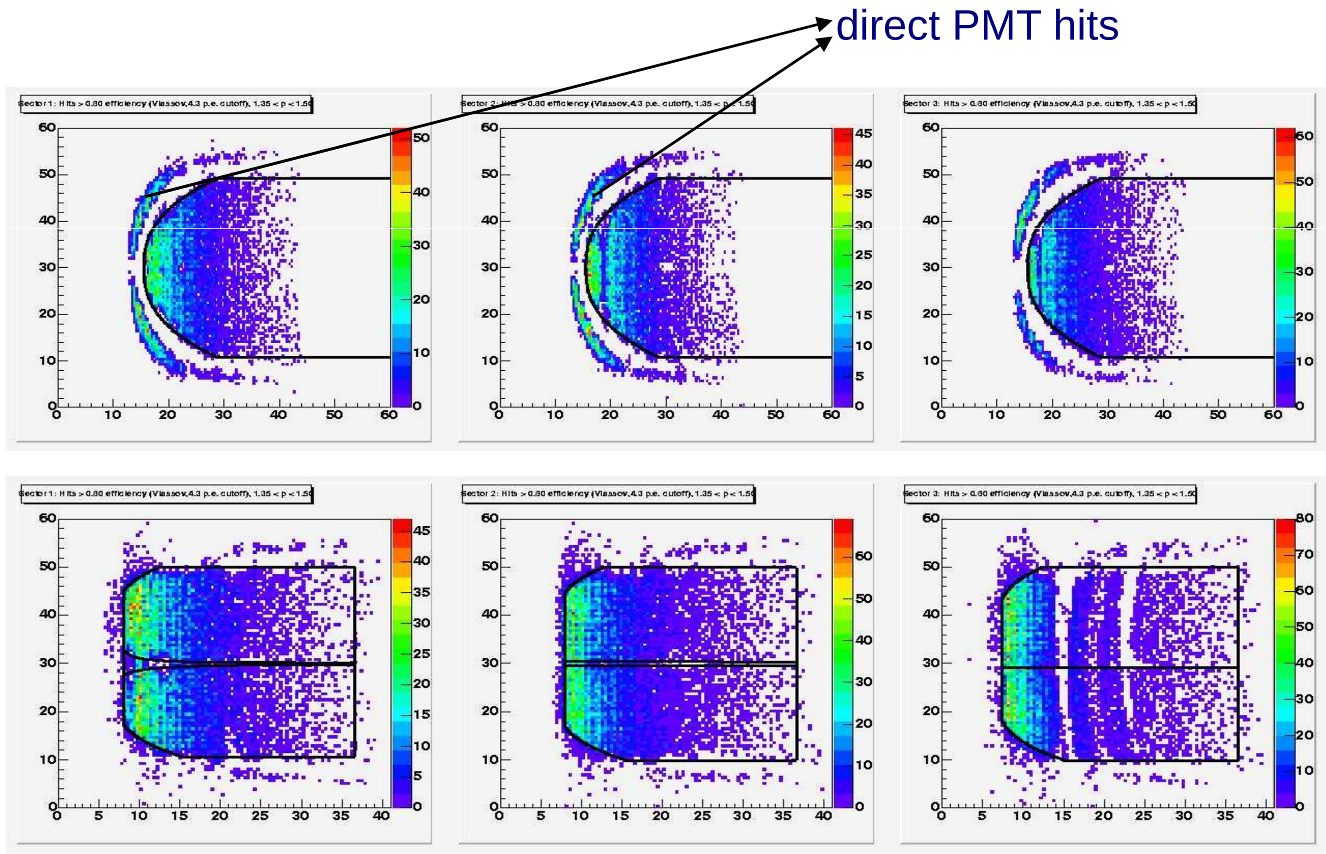


Fiducial cuts

Data from inefficient regions of the detector (the fringes at the edge of CC detector) are removed. Acceptance is not important for the asymmetry itself but it is important to estimate the background (where ^{12}C target is used and the acceptance of ^{12}C and ND_3 (or NH_3) must be the same).

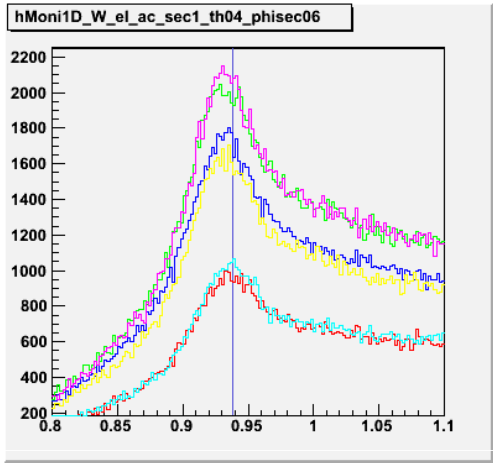
2.3 +I
Data

2.5 -I
Data

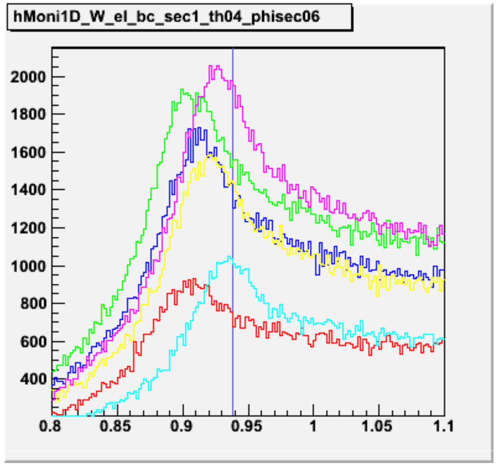


Kinematic Corrections

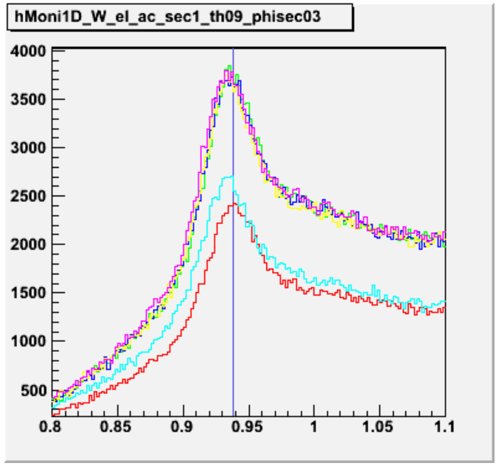
Elastic Invariant Mass Distributions for Different Azimuthal Angles



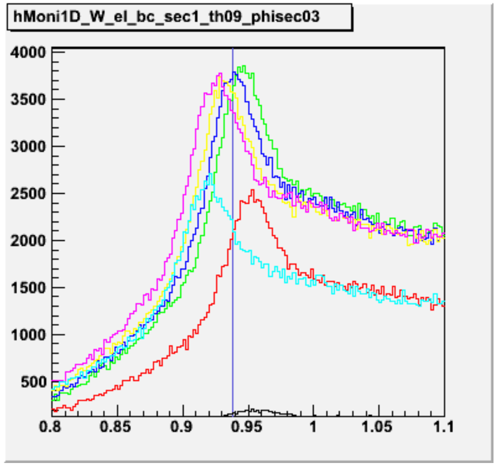
4.2 GeV Outb After Corr



4.2 GeV Outb Before Corr



2.3 GeV Inb After Corr



2.3 GeV Inb Before Corr

Kinematic Corrections