New Results on Deuteron Spin Structure function g_1 and its moments at low Q^2 from EG4 Experiment

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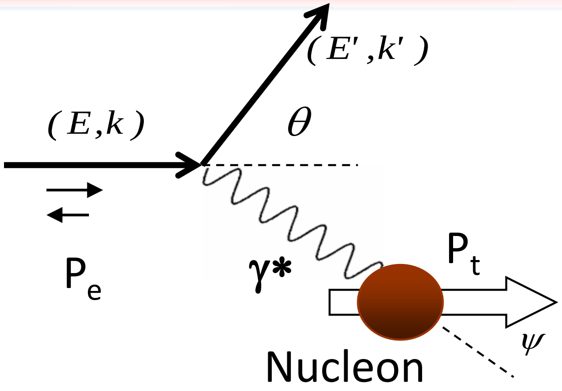
For the CLAS collaboration

- Spin structure at Low Q^2 - Formalism and Motivation
- Experimental Setup
- Data Analysis
- Results

Jefferson Lab
Thomas Jefferson National Accelerator Facility

MISSISSIPPI STATE UNIVERSITY

Inclusive Lepton Scattering & Structure Functions



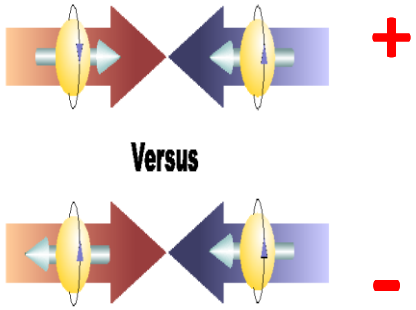
Kinematics

$\nu = \mathrm{E} - \mathrm{E}'$

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

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

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



Cross-section: In the case of a target polarization along the beam:

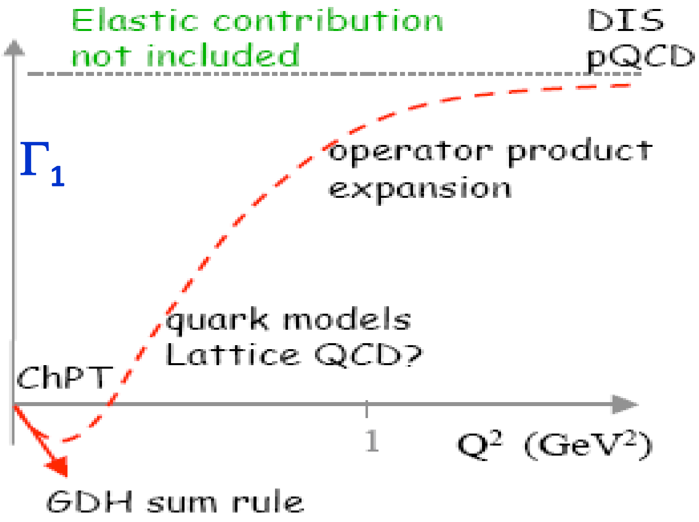
$$\frac{d^2\sigma}{dE'd\Omega} = \sigma_{\text{point}}\left[\overbrace{\frac{2}{M}F_1(Q^2,\nu)\tan^2\frac{\theta}{2} + \frac{F_2(Q^2,\nu)}{\nu}}^{\text{Spin independent}} \pm 2\tan^2\frac{\theta}{2}\left[\left(E + E'\cos\theta\right)\frac{M^2}{\nu}g_1(Q^2,\nu) - \gamma^2 M^2 g_2(Q^2,\nu)\right]\right]$$

With $\gamma^2 = \frac{Q^2}{\nu^2}$ and, **+/- for antiparallel/parallel** beam-target polarizations

In the DIS limit, structure functions are directly related to polarized and unpolarized quark distribution functions

Low Q^2 Motivation - Integrals

- At low momentum transfers (Q^2), one can study the **transition from partonic (quark-gluon) to hadronic (nucleonic) descriptions of Strong interaction by testing & constraining effective theories** based on QCD such as **Chiral Perturbation Theory (χPT).**
- **Test χPT Calculations** (Q^2 <~0.1 GeV^2) :
  - **Relativistic Baryon χPT with Δ,** Bernard, Hemmert, Meissner;
  - **Heavy Baryon χPT,** Ji, Kao, Osborne; Kao, Spitzenberg, Vanderhaeghen
  - Lensky, Alarcón, Pascalutsa, PRC**90**, 055202 (2014).
  - Bernard, Epelbaum, Krebs, Ulf-G. Meißner, Phys. Rev. D **87**, 054032 (2013)
- **Test Phenomenological medels** – Burkert-Ioffe, Soffer-Terayev, MAID, ..



Interesting variation with Q^2

Hadron ⟶ Parton

$$\bar{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x,Q^2\right)dx$$

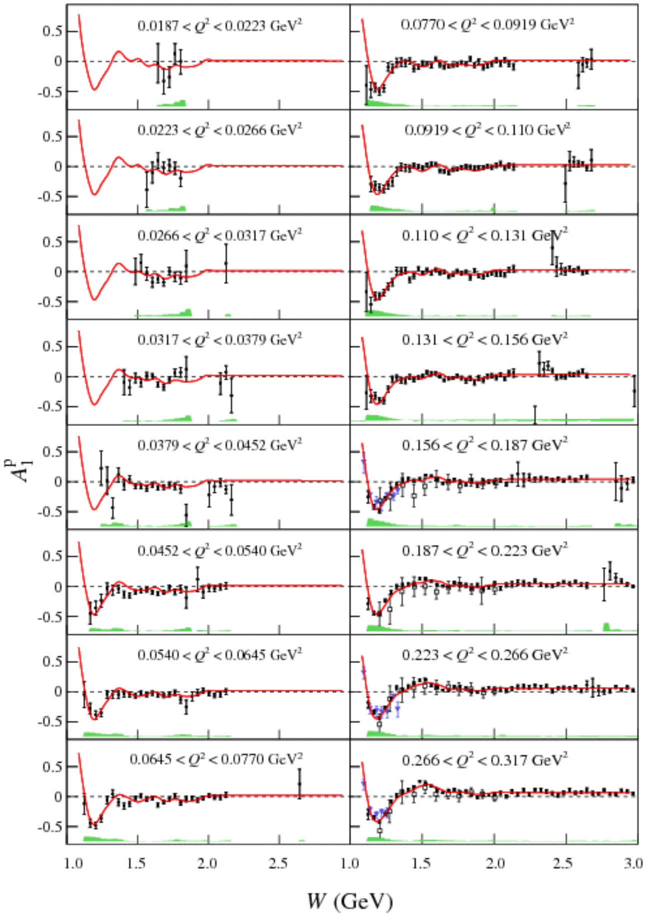
$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_{th}}\left(g_1 - \frac{2M^2x^2}{Q^2}g_2\right)dx \xrightarrow{(Q^2\to 0)} -\frac{\kappa^2}{4}$$

κ = anomalous magnetic moment **GDH**

$$\gamma_0 = \frac{16\alpha M^2}{Q^6}\int_0^{x_{th}}\left(g_1 - \frac{2M^2x^2}{Q^2}g_2\right)x^2dx$$

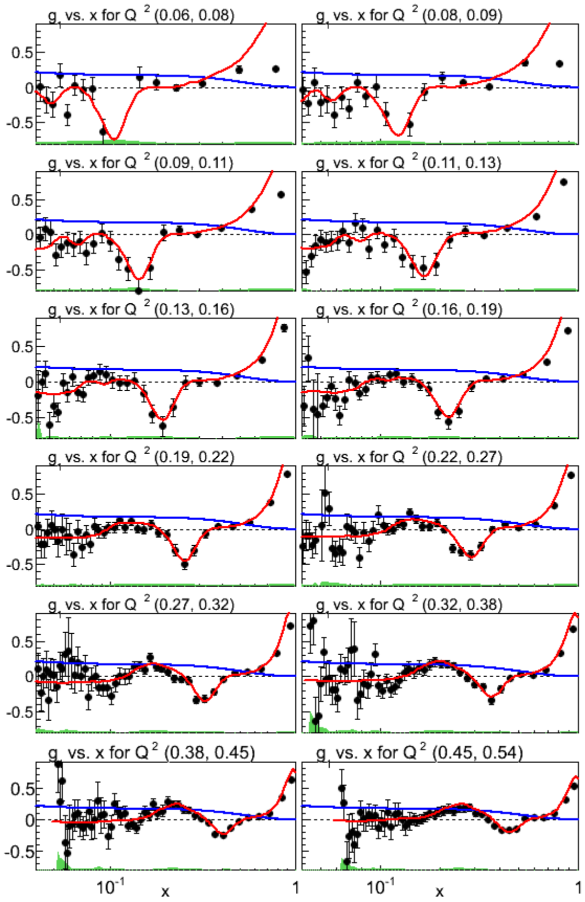
Some Past Data at Low Q^2 : g_1 from EG1b

Proton

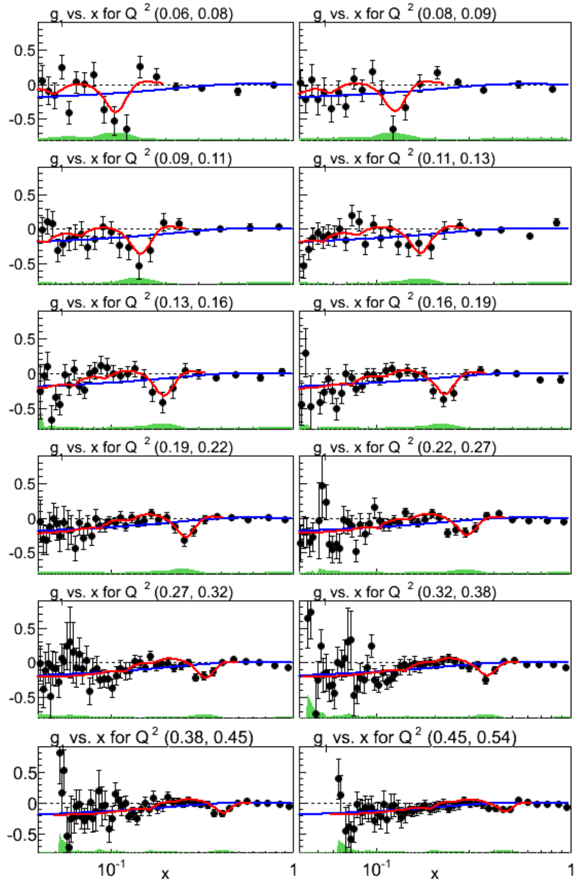


Plots courtesy of R. Fersch

Deuteron



Neutron



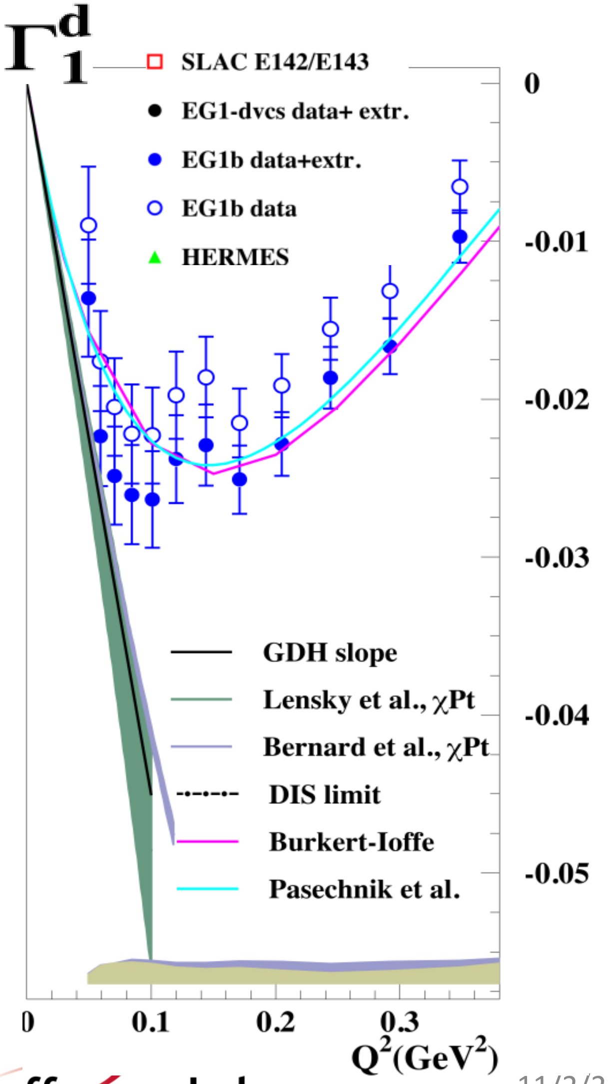
Plots courtesy of N. Guler

Some Past Data – moments from EG1b

$$\Gamma_1 = \int g_1(x,Q^2)dx$$

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} A_1 F_1 x^2 dx$$

Deuteron results from N. Guler



Shows expected trend toward DIS result at high Q^2

At low Q^2 observed a negative slope as expected from GDH Sum Rule.

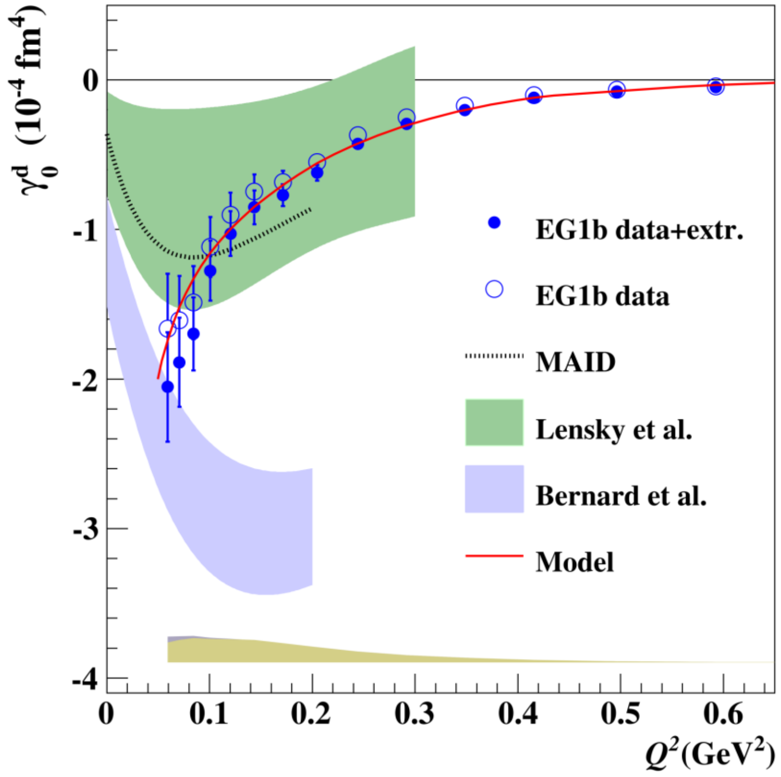
Agreement with χPT at the lowest points.

Deuteron analysis was repeated with full data set and more extended results were obtained for the Γ_1 at low to moderate Q2 region.

F_1 obtained from fit to world data

Discrepancy with MAID - mainly due to parametrizations of F_1.

No agreement with χPT, even at Q^2 = 0.05 GeV^2



Hall B CLAS Experiment: EG4

"EG4"- Similar conditions to EG1

- **Kinematical coverage extended down to $Q^2 = 0.015$ GeV^2 using**
  - **lower beam energies -1.0, 1.3, 2.0, 2.3, 3.0 GeVs**
  - **Target at vz = -101 cm**
  - **electron outbending CLAS configuration**
  - **a new Cerenkov detector in S6**
- **DNP polarized Targets:**

Longitudinally polarized, solid $^{15}NH_3$ (P~85%) & $^{15}ND_3$ (P~35%)

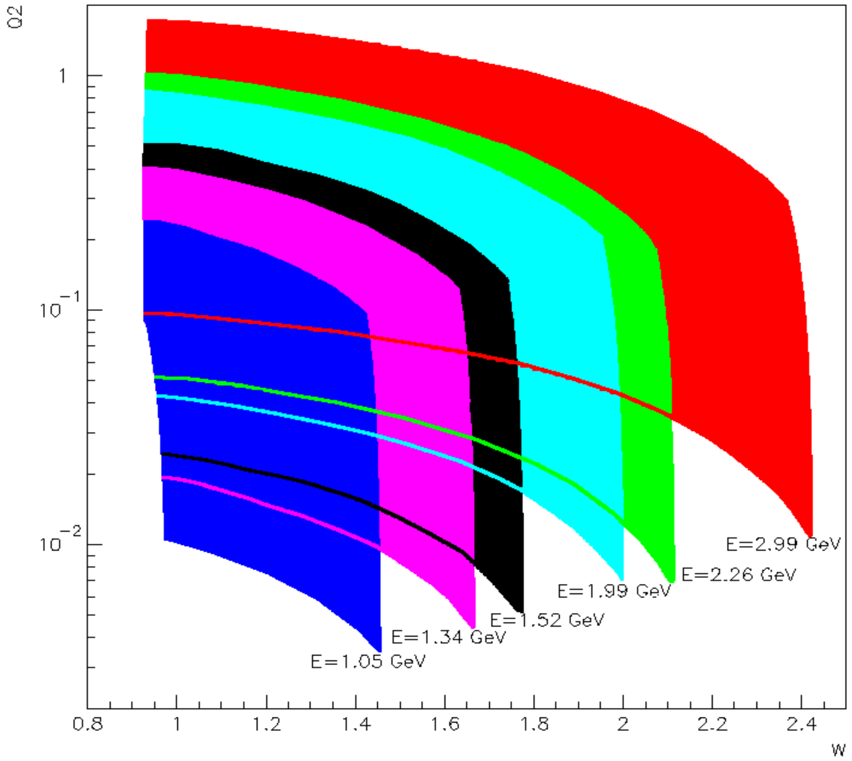
Measurement of g_1 at low Q^2

- **Test of χPT as $Q^2 \to 0$**
- **Measured Absolute XS differences**
- **Goal : Extended GDH Sum Rule on Proton, Deuteron**
- **Ran in 2006**

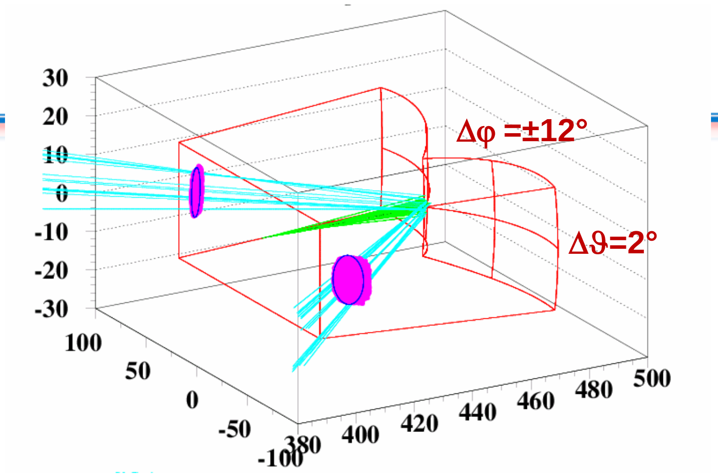
Spokespersons:

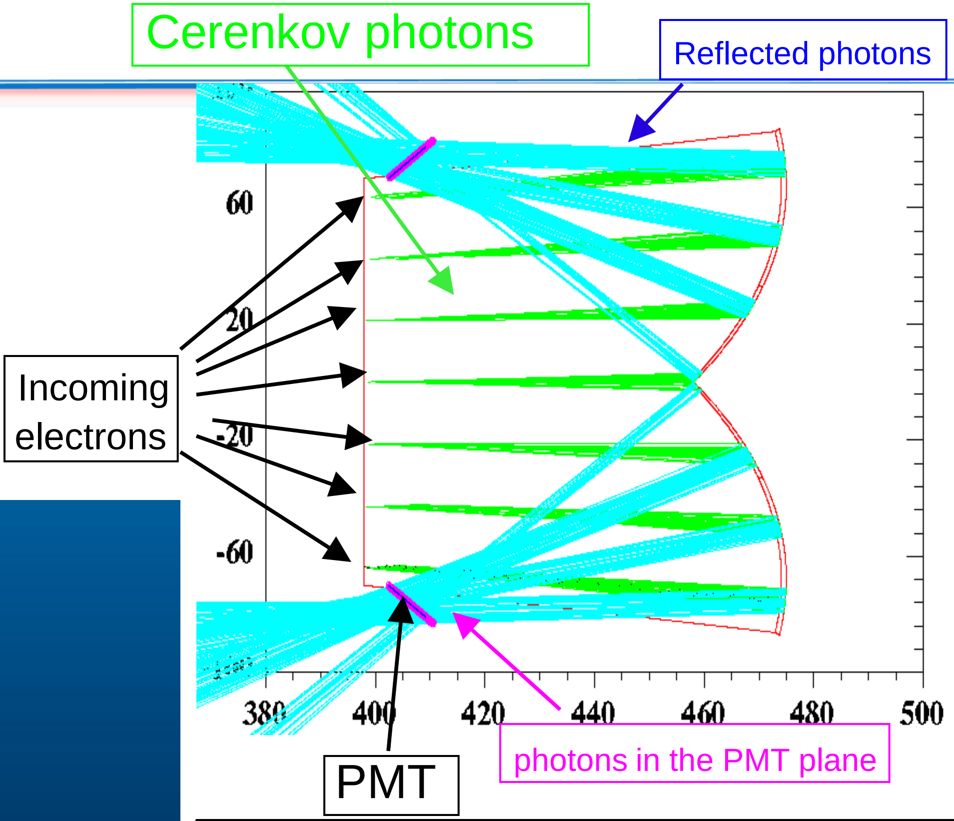
NH_3: M. Battaglieri, A. Deur, R. De Vita, M. Ripani

ND_3: A. Deur, G. Dodge, K. Slifer



New Cerenkov Counter in the 6th sector (INFN Genoa)



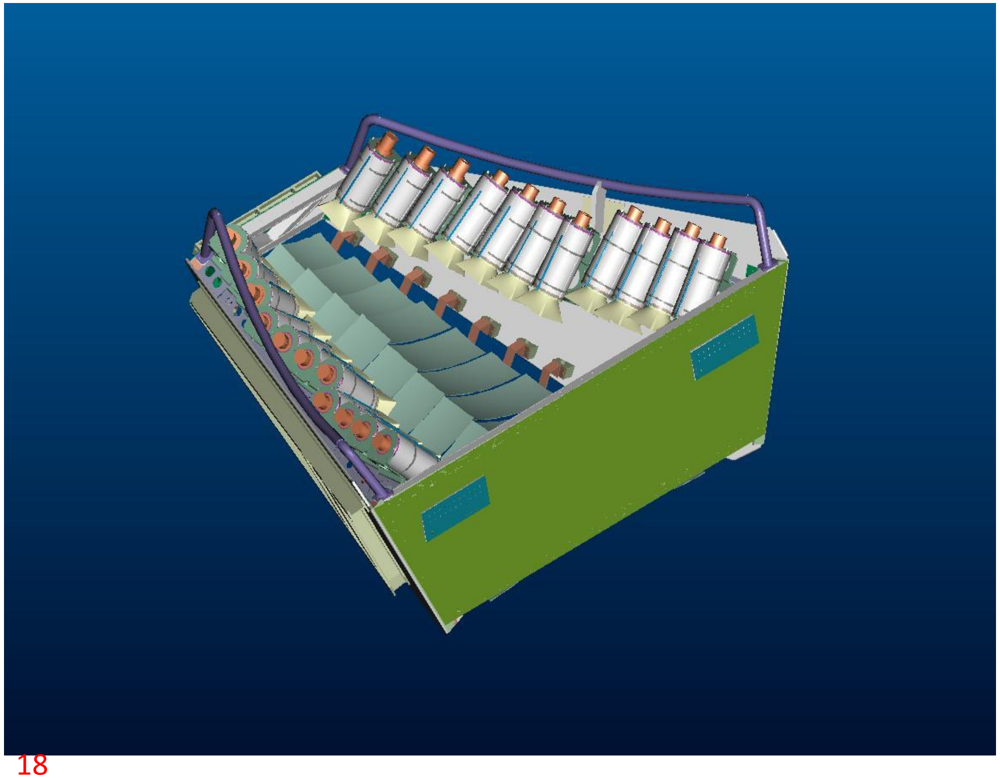

Cerenkov photons

Reflected photons

Incoming electrons

PMT

photons in the PMT plane



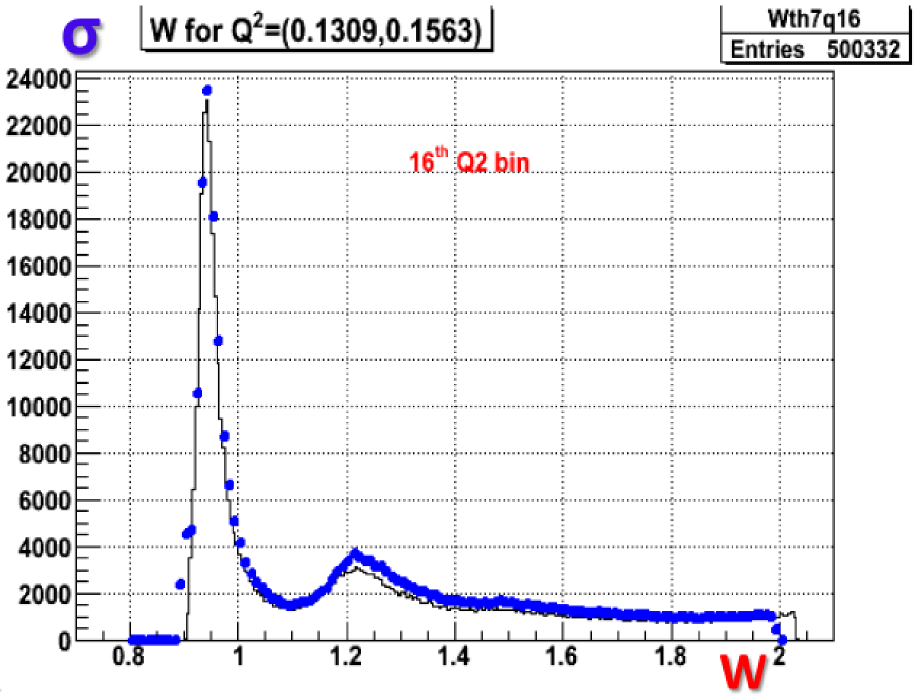
- •Same gas (n=1.00153) and DAQ as before
- •11 modules (15 before) each with
  - • 2 spherical mirrors (R=140 cm)
  - • Δφ =±12° Δϑ=2°
  - •2 PMTs
- •Only one reflection

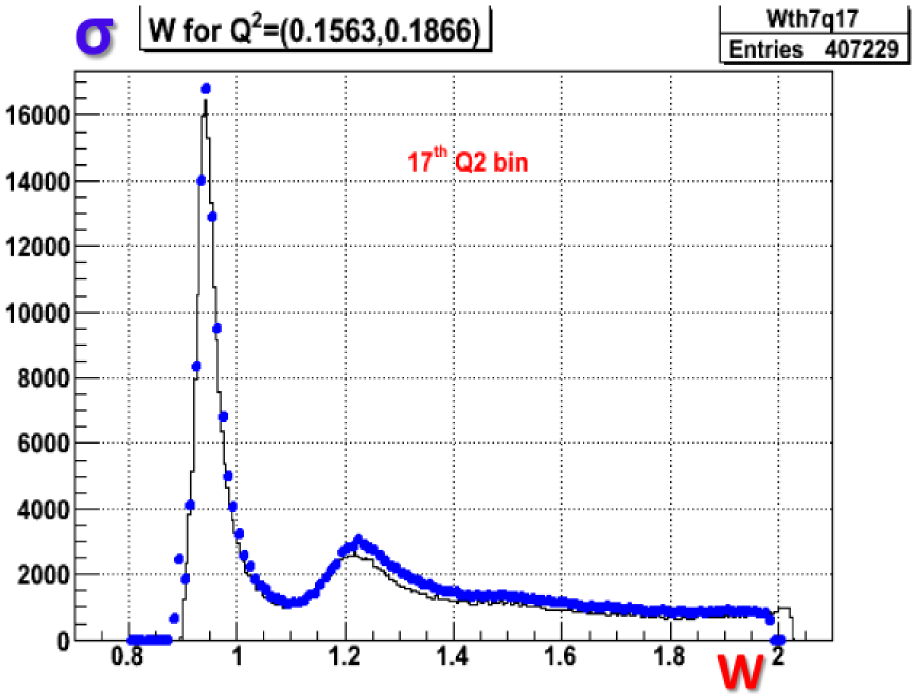
Things done in this Pass2 Analysis

- Pass2 reconstruction (slight changes in RECSIS configuration)
- Repeating the simulation (slight changes in both GSIM and RECSIS configurations)
- Tracking correction (using method developed by Peter Bosted) and momentum correction.
- CC-inefficiency correction
- Redeveloping the following cuts
  - CC-cuts
  - Fiducial cuts
  - Vertex-Z cuts
  - EC-cuts
- Extraction of g_1, A_1F_1 and moments.

Simulation of Deuteron Data

- **RCSLACPOL** program for **Radiated Polarized Cross-sections** for event generator
  - ➢ Uses standard approach by **Shumeiko & Kuchto** *(NP B219, 412 (1983))* and **Mo & Tsai** *(RMP 41, 205 (1969))*, including **external radiation** in the target.
  - ➢ **Updated with latest models** (world data fit) on polarized and un-polarized structure functions over a wide kinematic range.
  - ➢ **Folding algorithm** by **Melnitchouk & Kahn** *(PRC 79 (3), 035205)* for **deuteron structure functions**.
  - ➢ **Extensively tested & used** – at SLAC (E142/143/154/155/155x) & Jlab (EG1a/b).
- **GSIM (& GPP)** for CLAS simulation and **RECSIS** for Data reconstruction



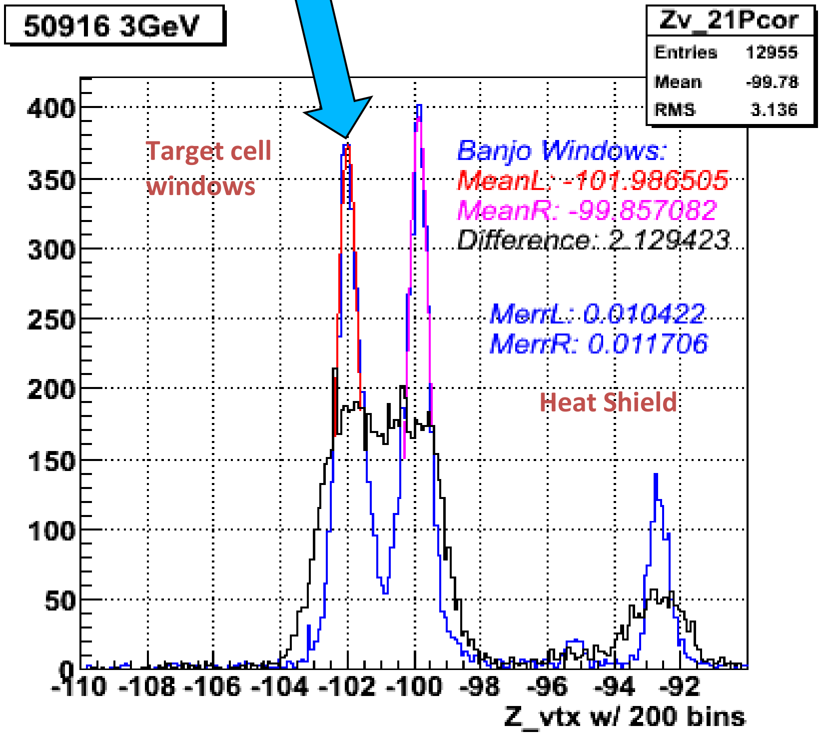


Data Analysis: Kinematic Corrections

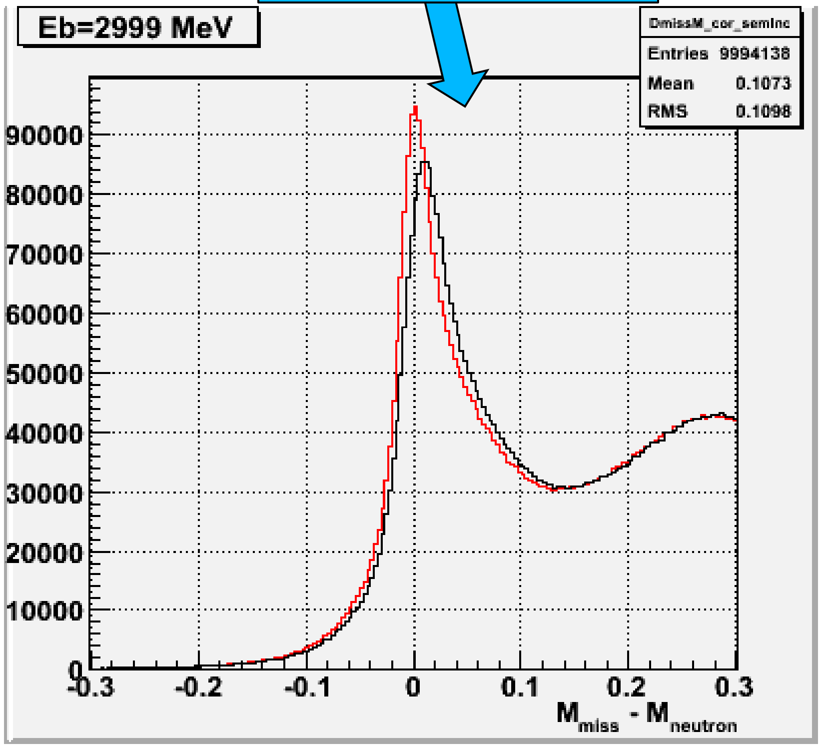
- **Tracking correction:**
  - ➢Swims particles through target field to DC, uses direction cosines at DC and the beam position (x,y) from raster magnets.
  - ➢Improves angles and vz.

- **Energy loss correction**
- **Momentum correction.**

Z-Vertex distribution of scattered electrons from an Empty target run



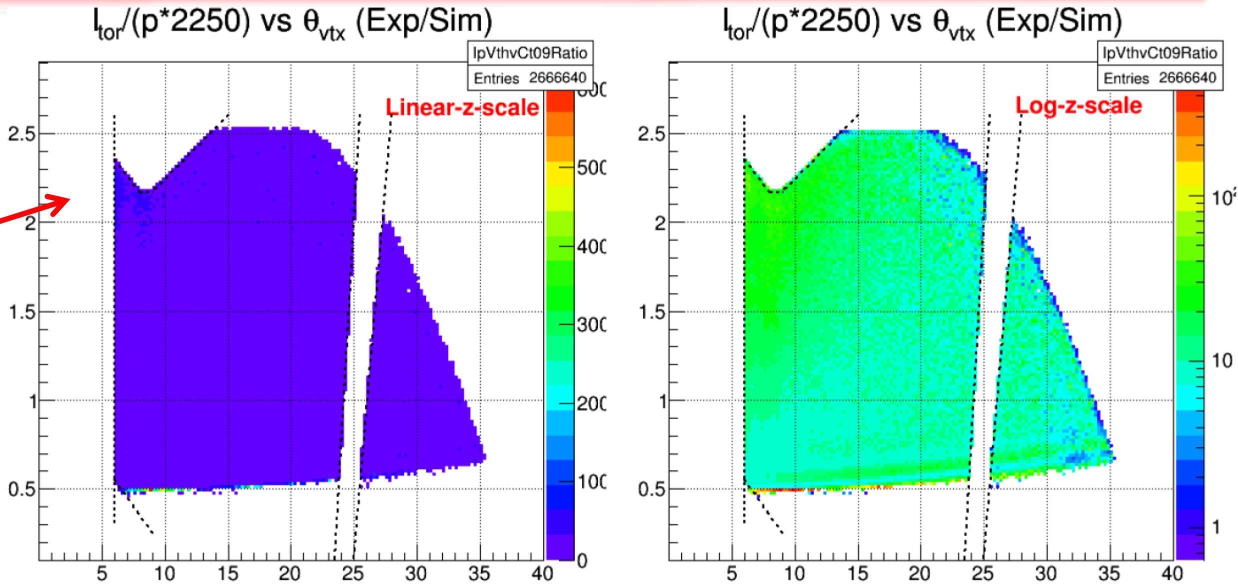
Missing mass (minus $M_{neutron}$) for ($ep \rightarrow e\pi^{+}X$)



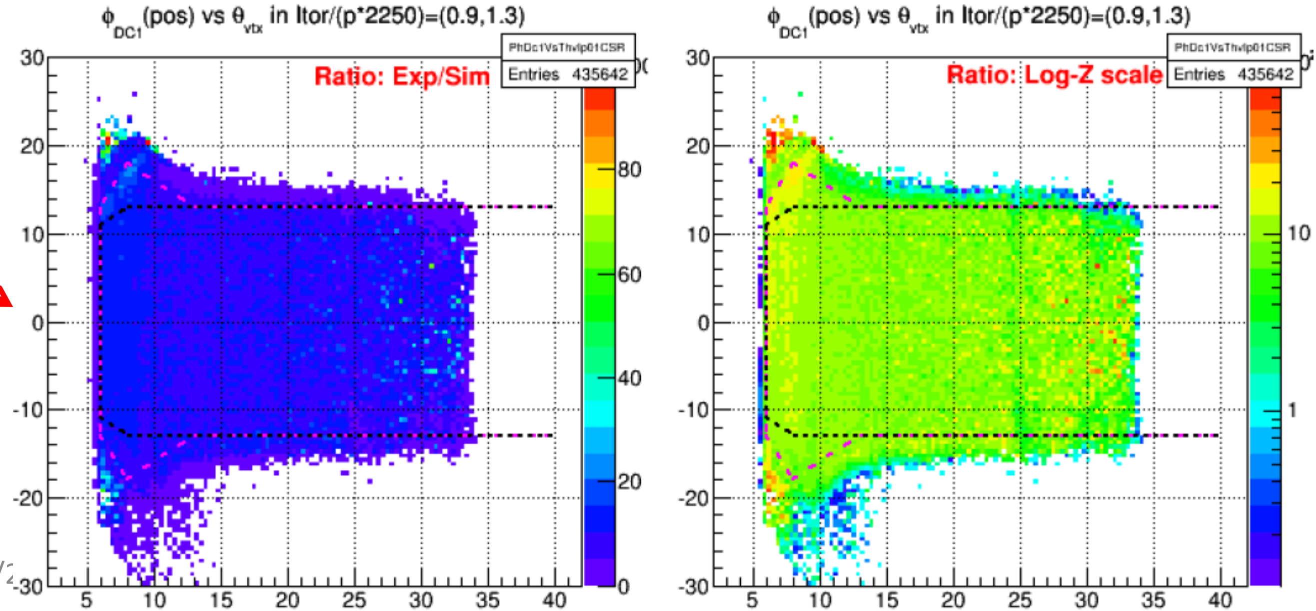
Fiducial cuts

Cuts based on comparing regular run data with the data from EC-calibration runs (with no CC in trigger)

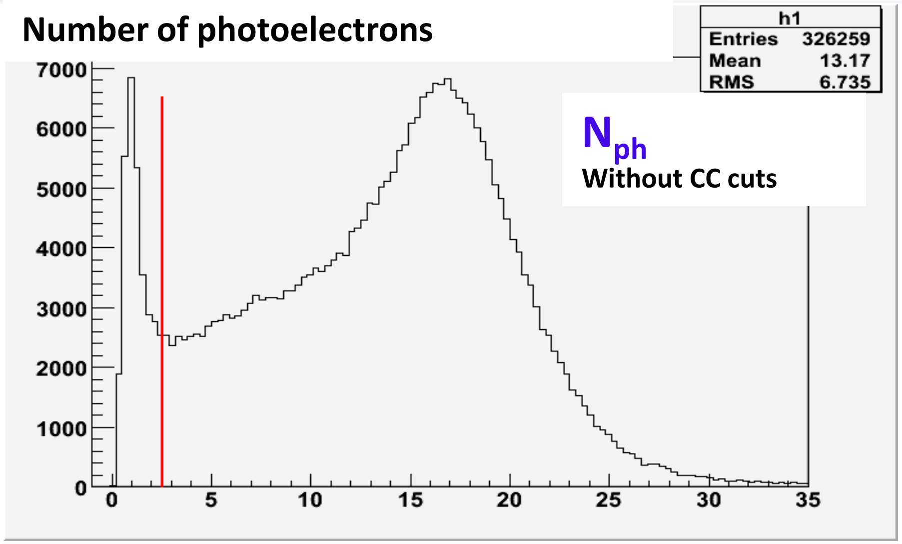
Rejects highly CC-inefficient regions.



Cuts based on comparing experimental and simulated data.



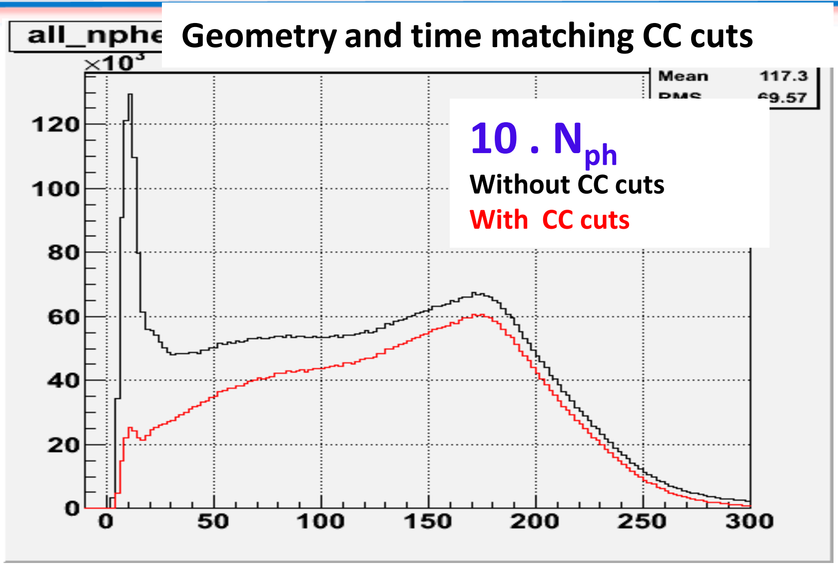
More Particle ID Cuts



Number of photoelectrons

N_{ph}

Without CC cuts

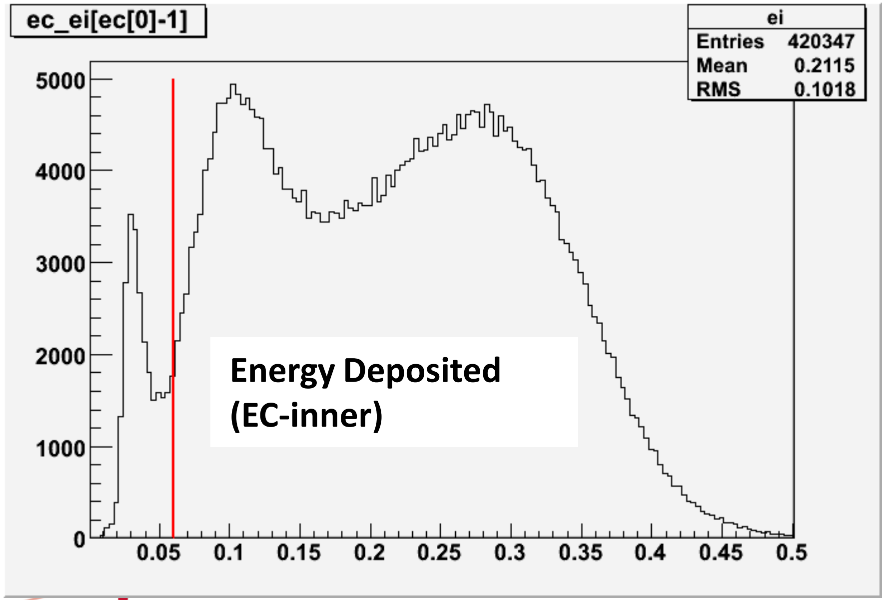


Geometry and time matching CC cuts

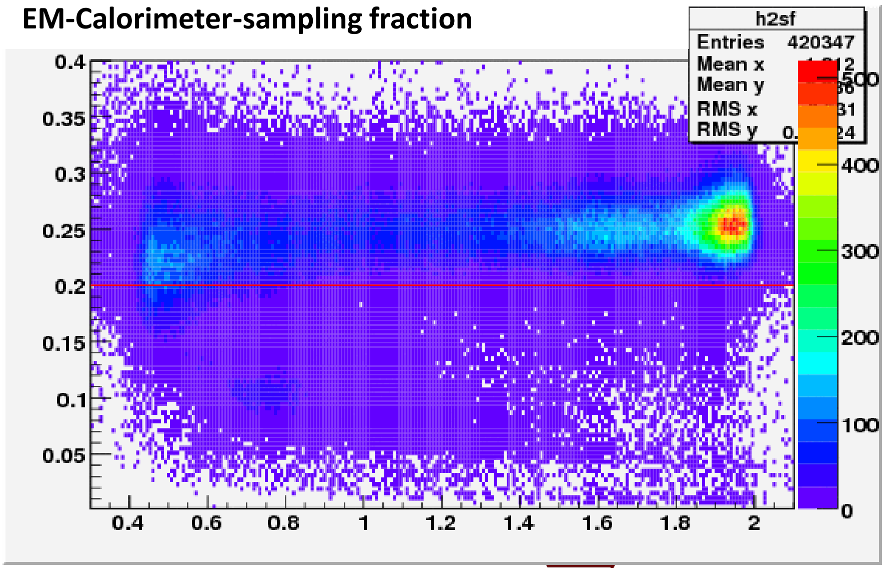
$10 . N_{ph}$

Without CC cuts

With CC cuts

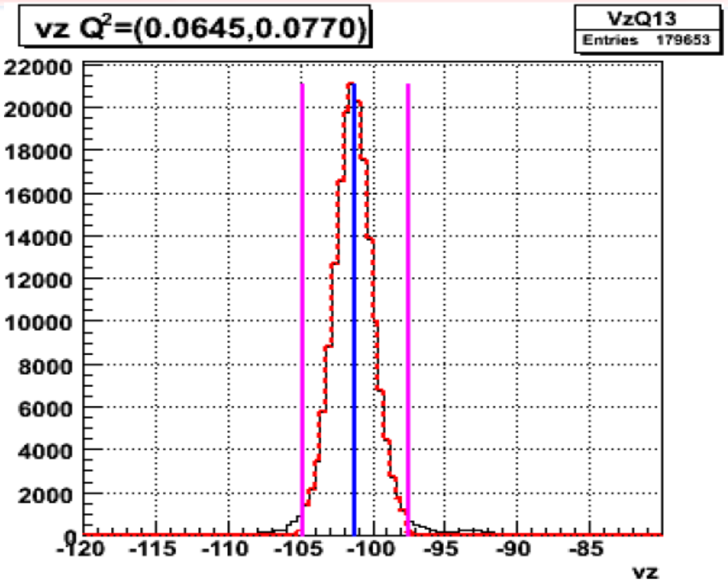


Energy Deposited (EC-inner)

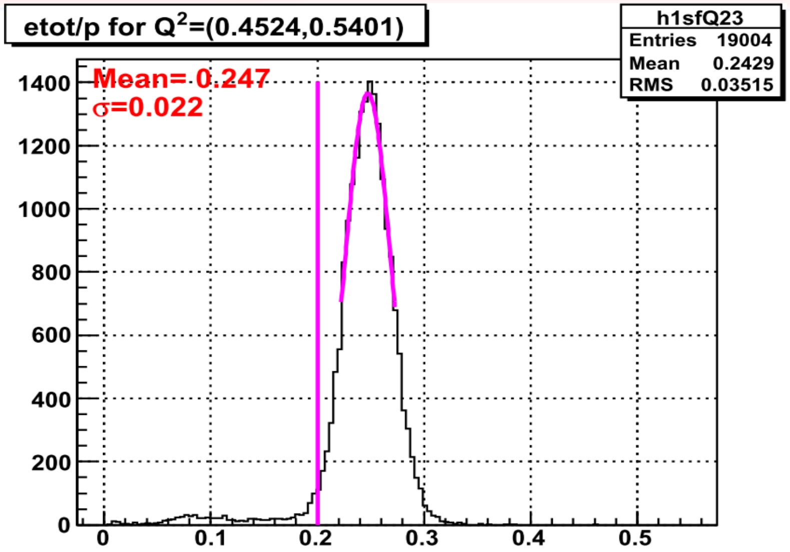


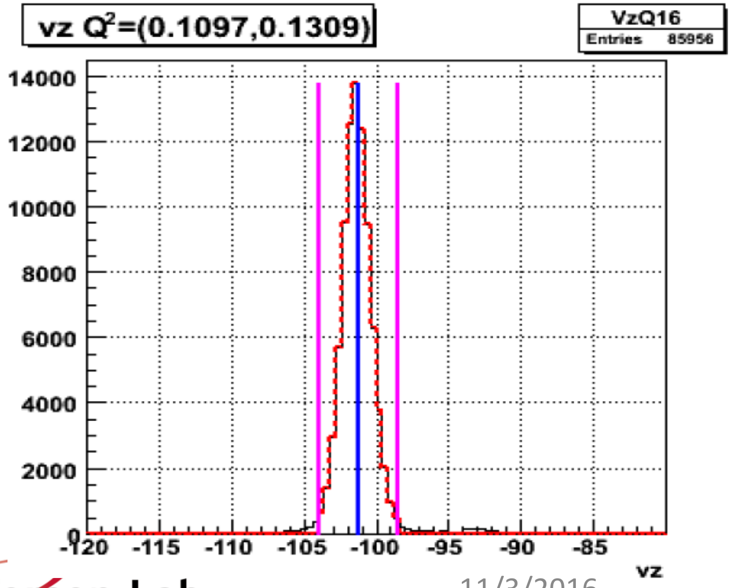
EM-Calorimeter-sampling fraction

Q^2 dependent cuts on Z-vertex & EC-sampling

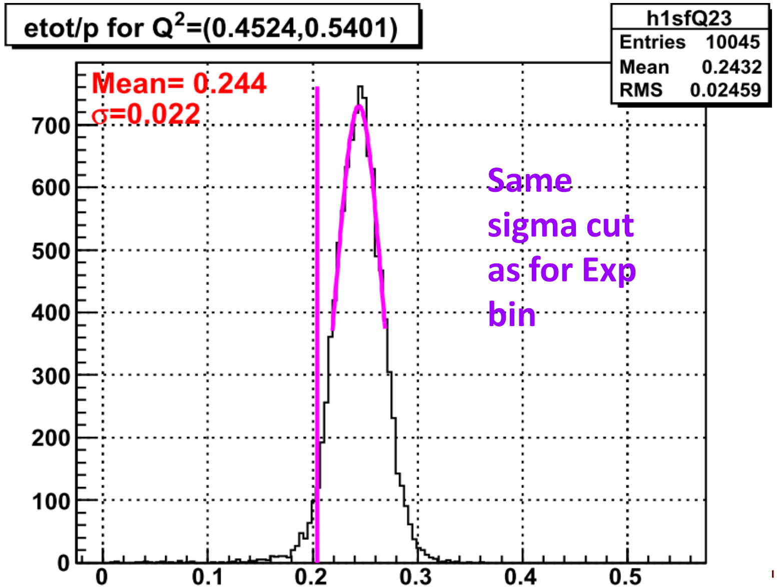


Data





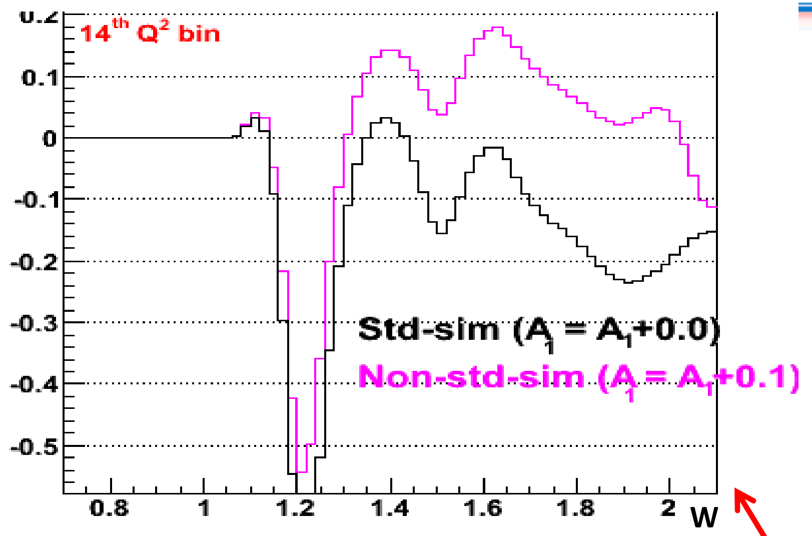
Sim.



Same sigma cut as for Exp bin

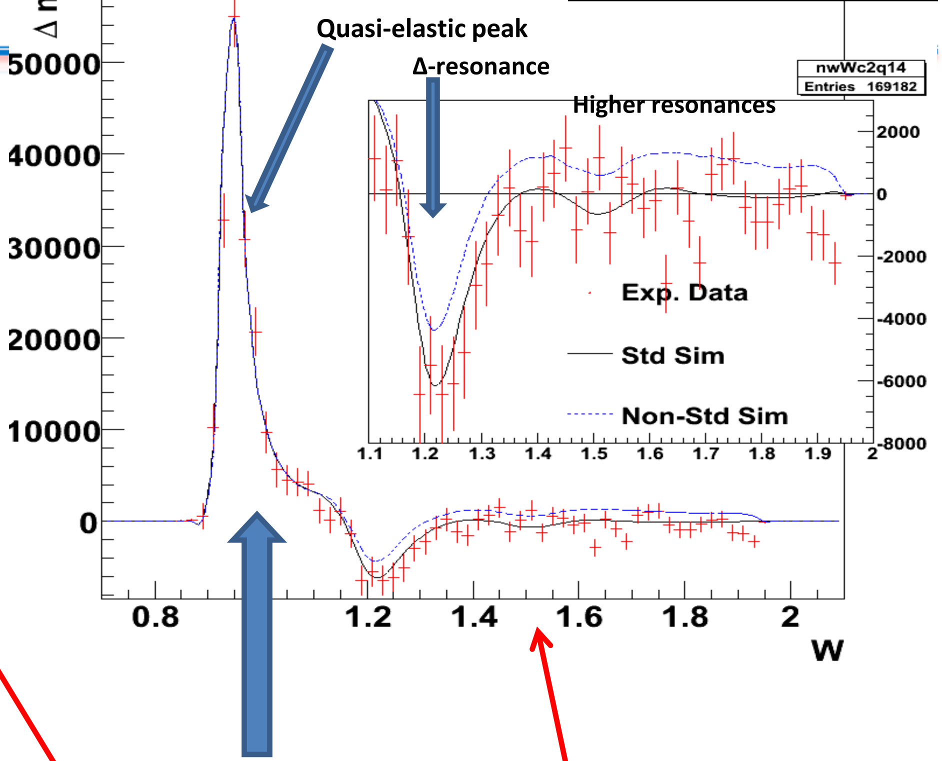
Method for g_1 calculation

Model g_1 in Q^2=(0.092,0.11)

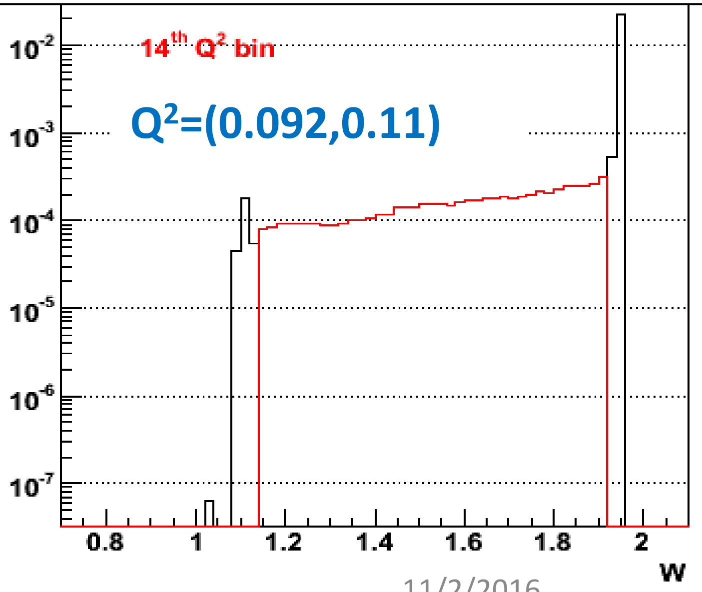


$\Delta n = (n^+ - n^-)$

Q^2=(0.092,0.11)



$B(W,Q^2) = \Delta g_1 / \Delta(\Delta N)$ (proportionality factor)

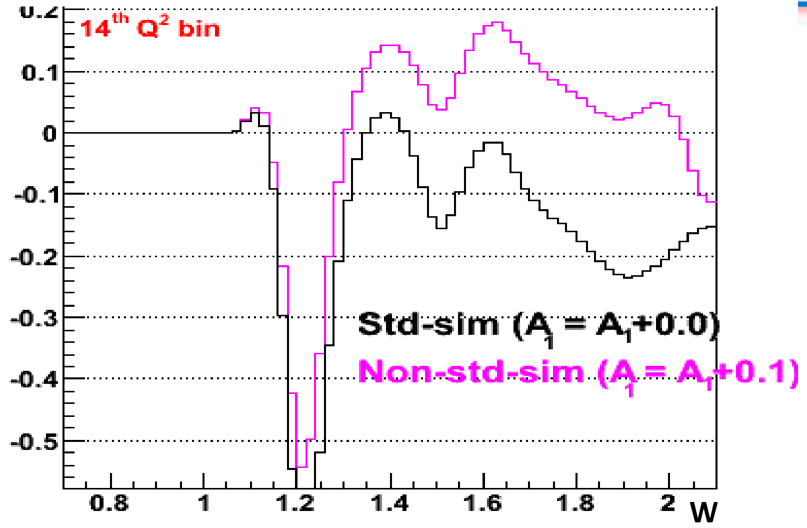


First, simulated data was normalized w.r.t data by comparing in q.e. region.

$$g_1^{extr}(W,Q^2) = g_1^{Standard} + \frac{\Delta n^{data}(W,Q^2) - \Delta n^{standard}(W,Q^2)}{B(W,Q^2)}$$

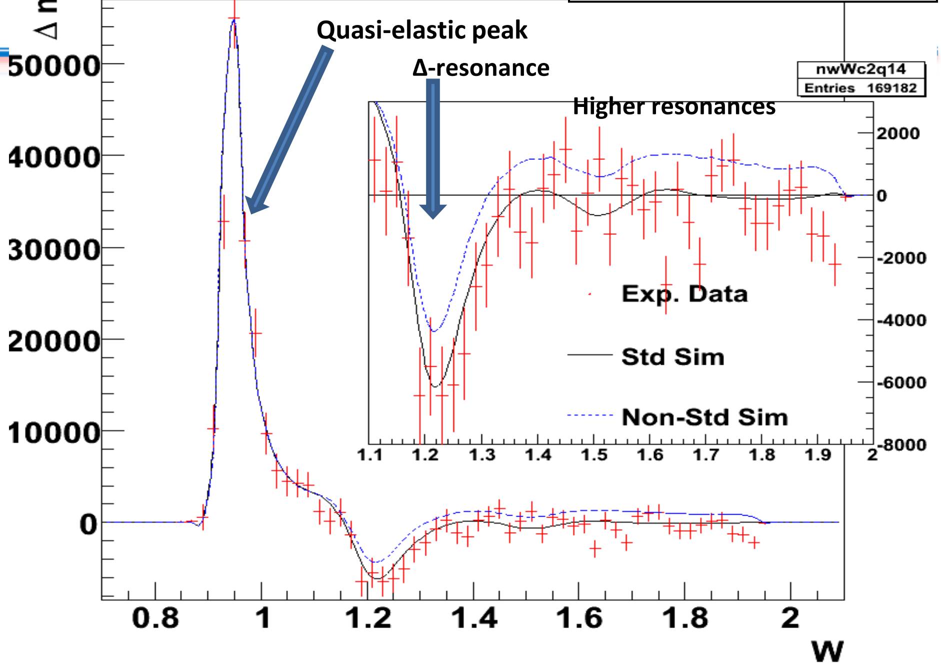
Method for g$_1$ calculation

Model g$_1$ in Q^2=(0.092,0.11)

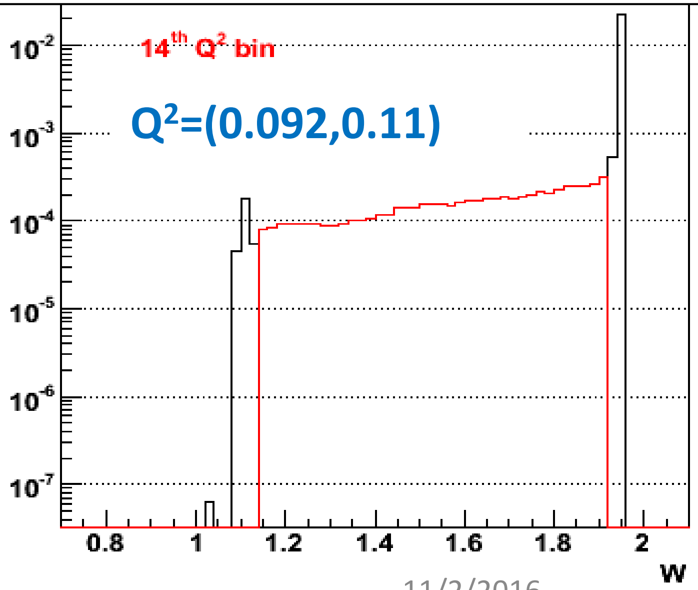


$\Delta n = (n^+ - n^-)$

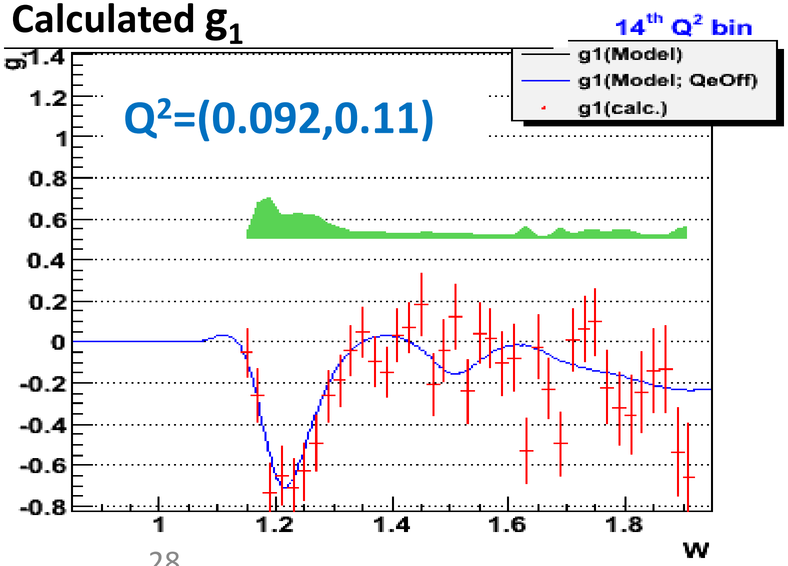
Q^2=(0.092,0.11)



$B(W,Q^2) = \Delta g_1 / \Delta(\Delta N)$ (proportionality factor)

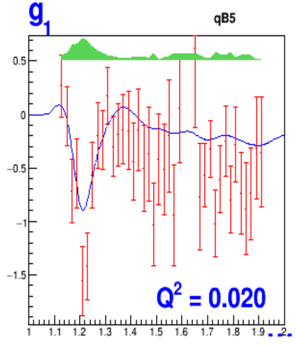


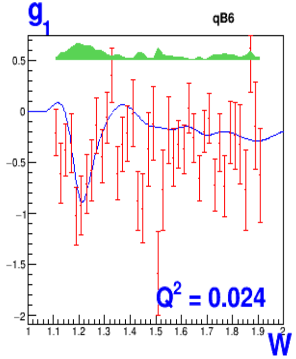
Calculated g$_1$

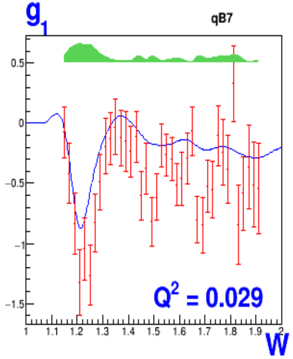


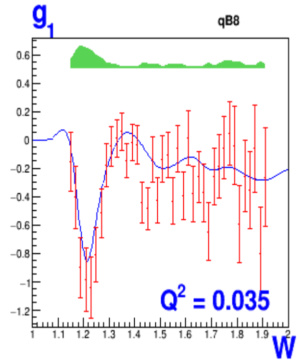
EG4 Results: Extracted g_1 (Deuteron)

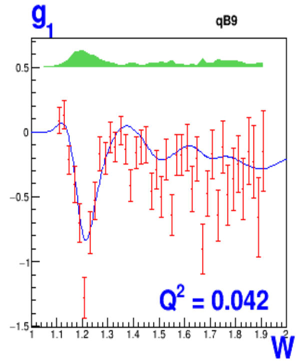
- g_1(Model)
- g_1(comb.)
- 🟩 Sys. Err.

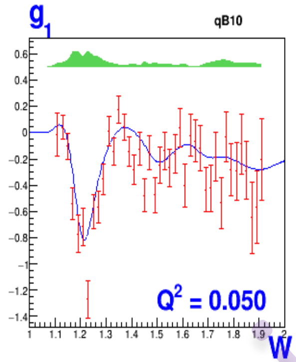


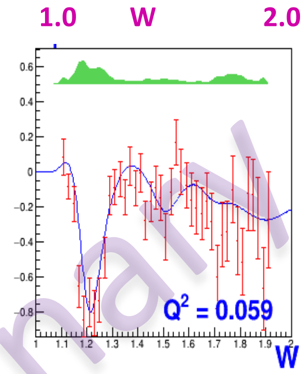


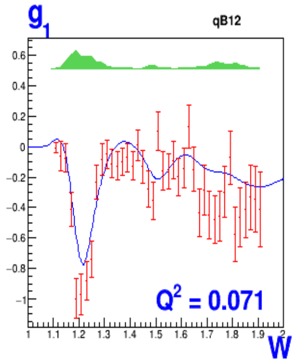


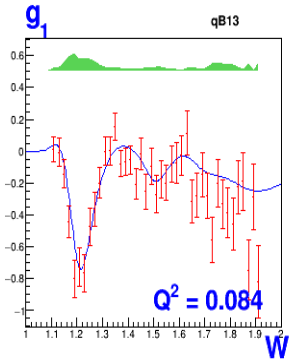


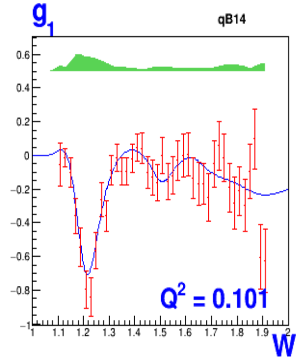


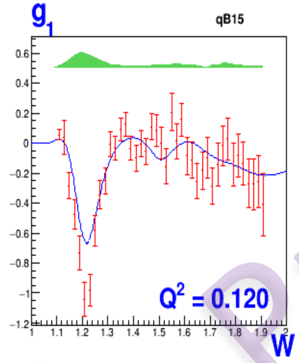


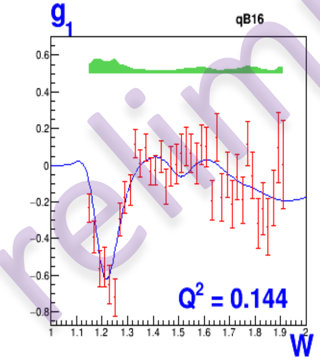


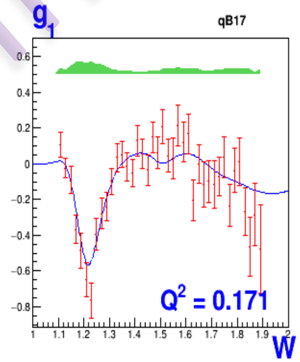


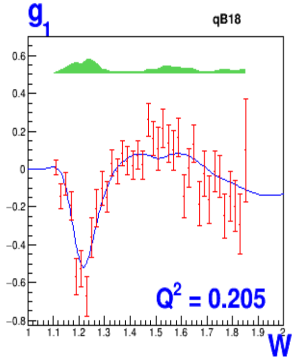


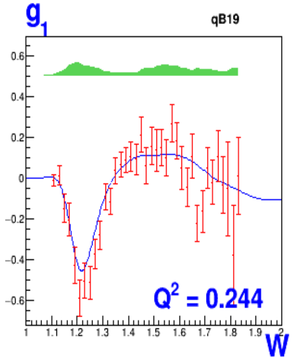


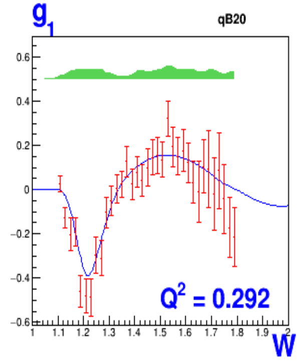


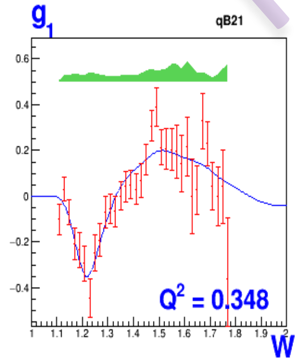


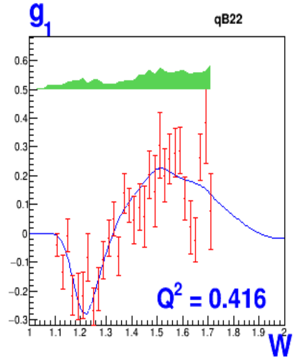


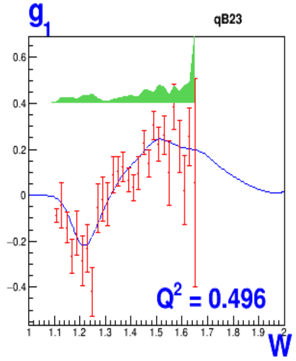


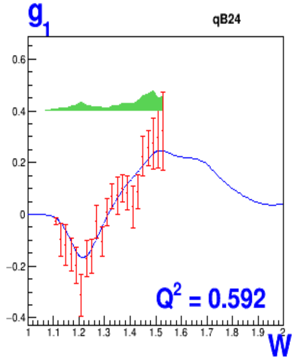


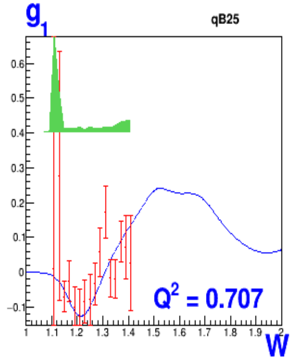








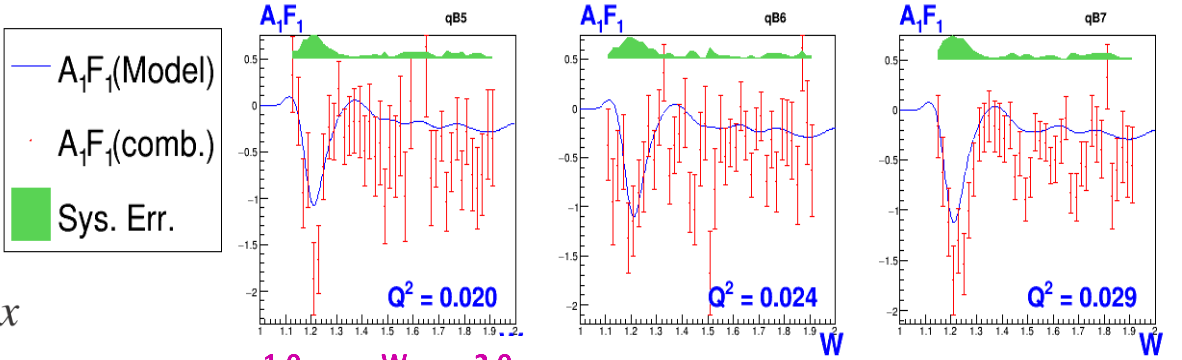


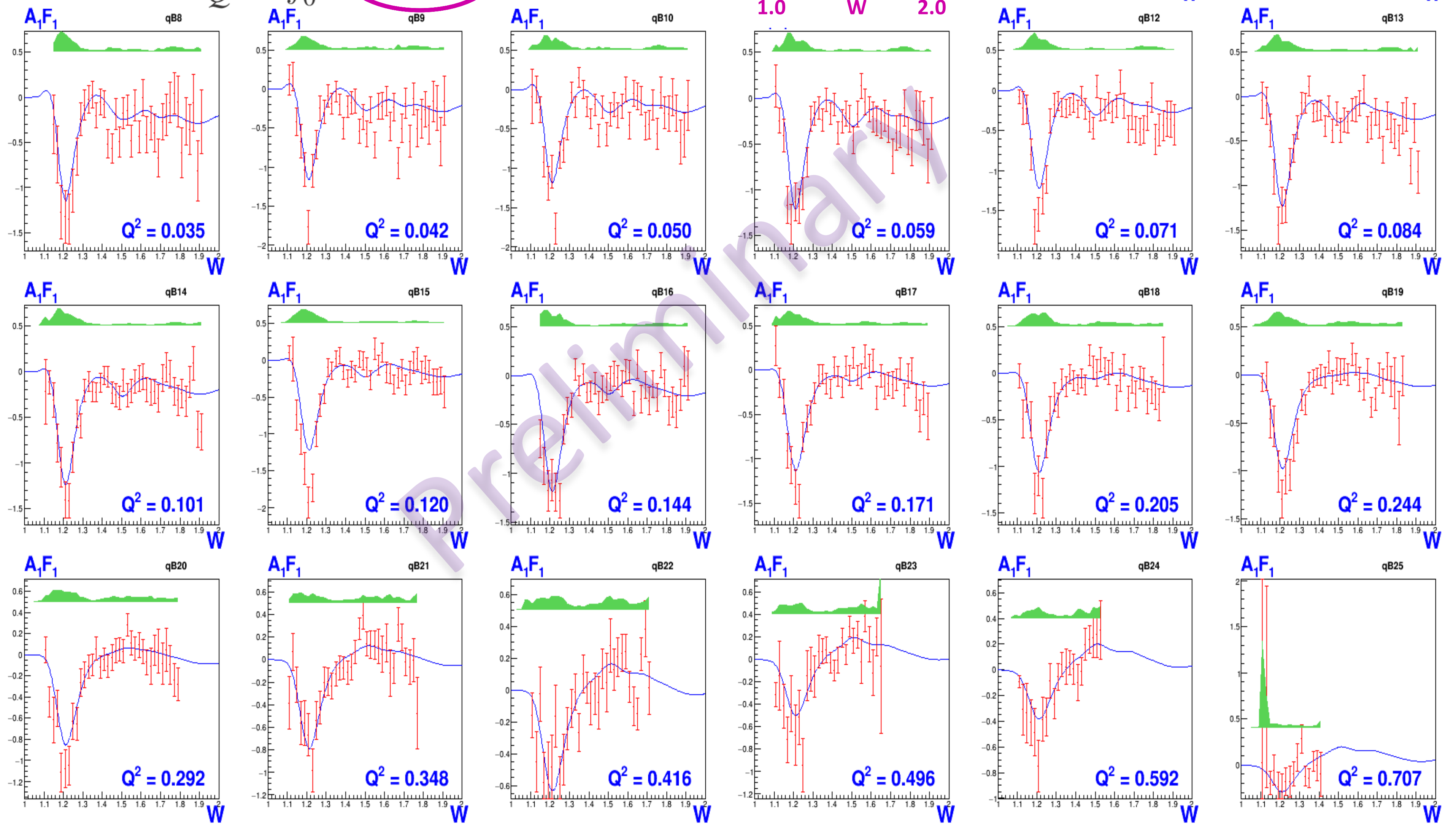


$A_1F_1 = g_1 - (4M^2x^2/Q^2)g_2$

$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_0(Q^2)} dx\, A_1F_1(x,Q^2)$$

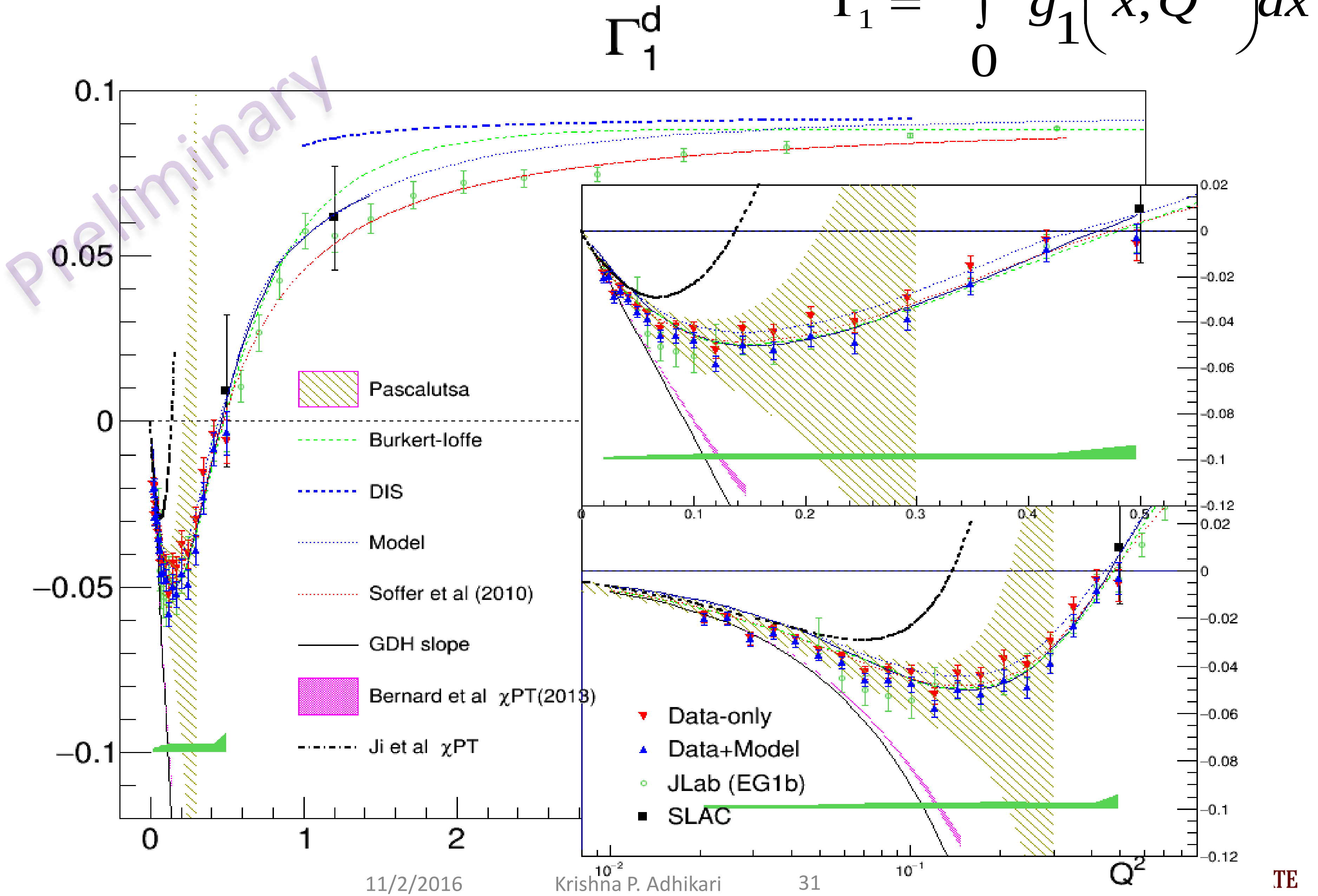
$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} A_1F_1(x,Q^2)\, x^2 dx$$





Results: First Moment

$$\overline{\Gamma}_1 = \int_0^{x_{th}} g_1\left(x, Q^2\right)dx$$

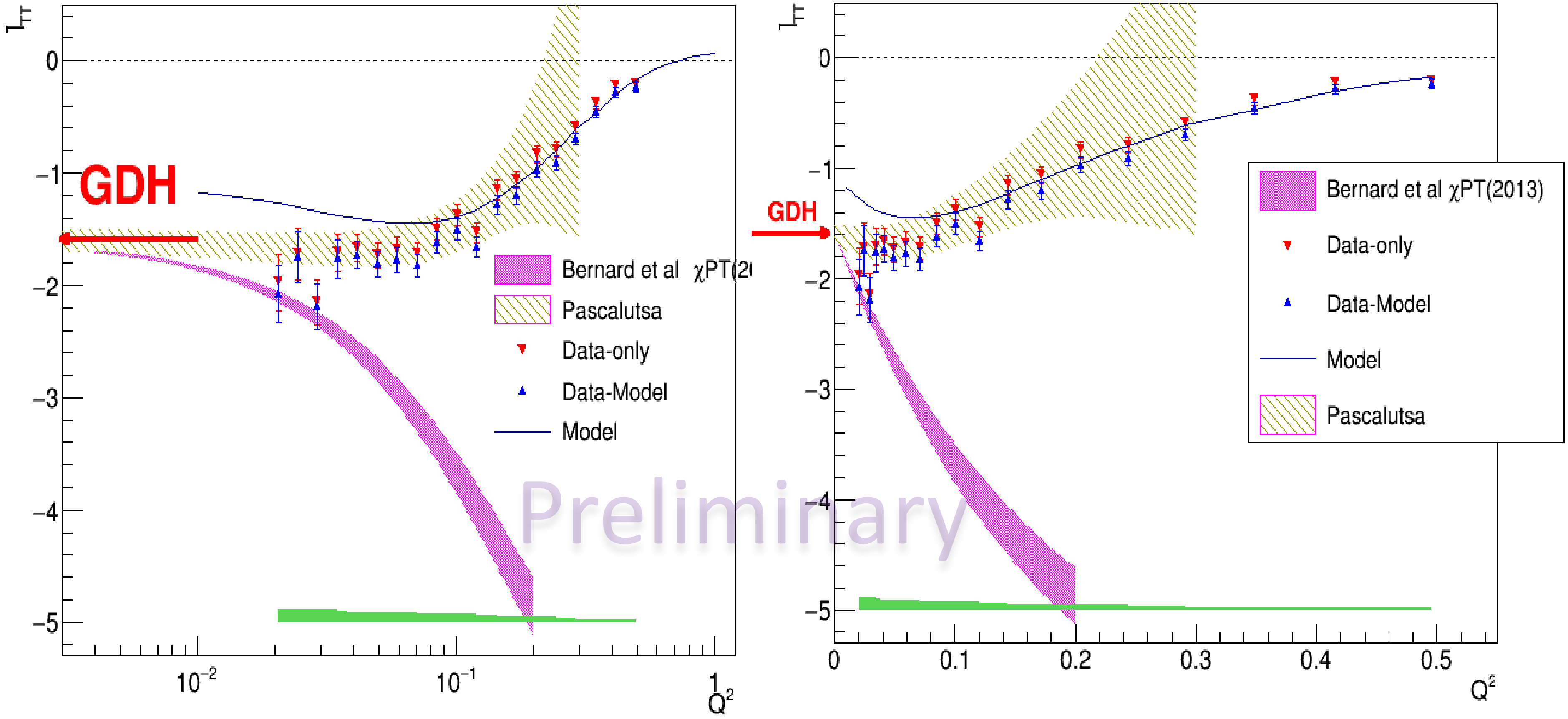


Results: Generalized GDH integral (I_{TT})

$$\bar{I}_{TT} = \frac{2M^2}{Q^2}\int_0^{x_{th}} \left(g_1 - \frac{2M^2 x^2}{Q^2} g_2 \right) dx \xrightarrow{(Q^2 \to 0)} -\frac{\kappa^2}{4}$$

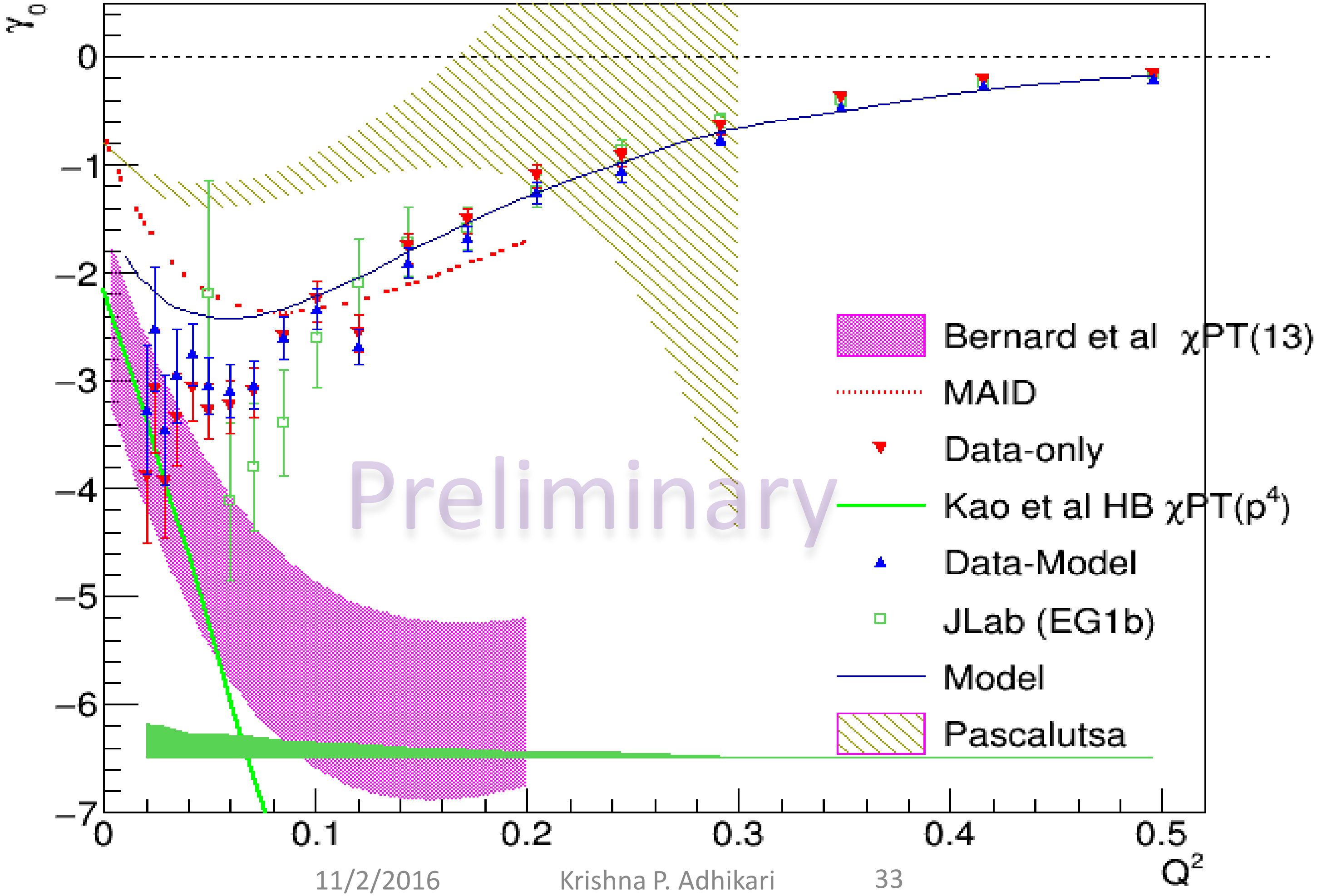
GDH

Generalized GDH integral (I_{TT})



Results: Generalized Forward Spin polarizability (γ_0)

$$\gamma_0 = (16\alpha M^2/Q^6)\int_0^{x_{th}} (g_1 - \frac{2M^2x^2}{Q^2} g_2)x^2dx$$



Summary

- A wealth of new low Q^2 data on the nucleon spin structure in the non-perturbative regime has been produced in Hall A, and B at Jefferson Lab as part of a broad spin physics program
- Measurements of moments of g_1 provide strong tests of χPT.
- Low Q^2 analysis on polarized deuteron target data of EG4 experiment in Hall B are in the final stages.
- At very low Q^2 the EG4 results show good agreement with other Jlab results and with available χPT predictions.
  - ➢Exception – Lensky-Pascalutsca calculation on γ_0
- Proton results and Neutron data extraction from EG4's deuteron and proton data is expected in near future.
- Deuteron analysis is in final stages and first draft of the analysis note will go into circulation next week.
- Ongoing 6 GeV data analyses and the future 12 GeV JLab measurements at low Q^2 are expected to shed more light on the nucleon spin structure in the non-perturbative region.

Thank you!

Sources of Systematic errors

1) **Overall scaling factor** (Mostly due to PbPt and target length)
2) **Radiative corrections**
3) **Model Uncertainties**
4) Contaminations of polarized H in the target and π^- in the scattered electrons.
5) Beam energy measurement
6) CC-efficiency estimation
7) e^+e^- pair symmetric contamination

Estimation of Systematic errors

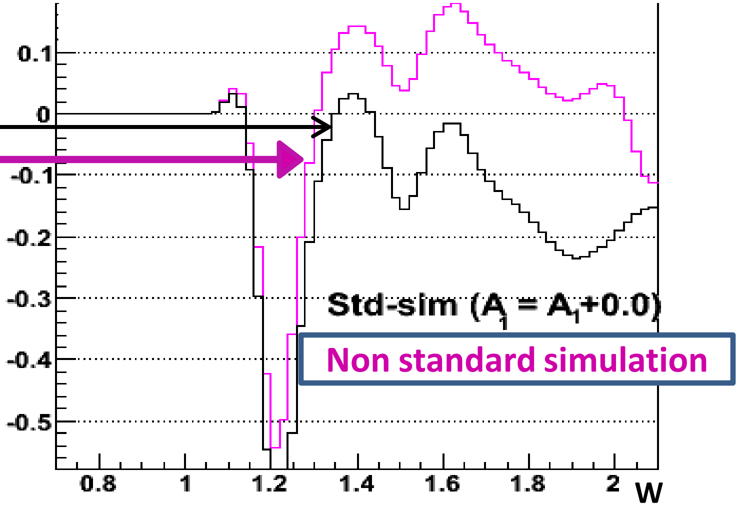
One Example:

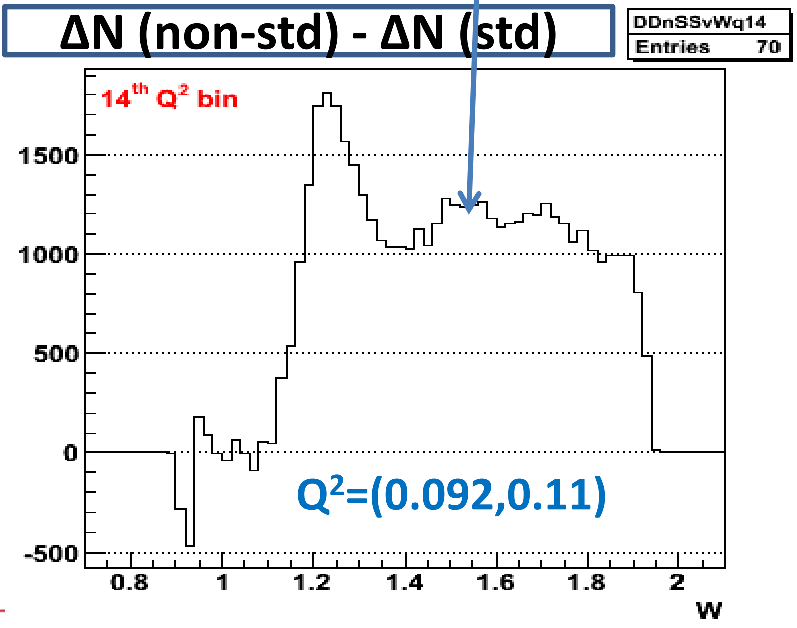
Model Uncertainty Contribution

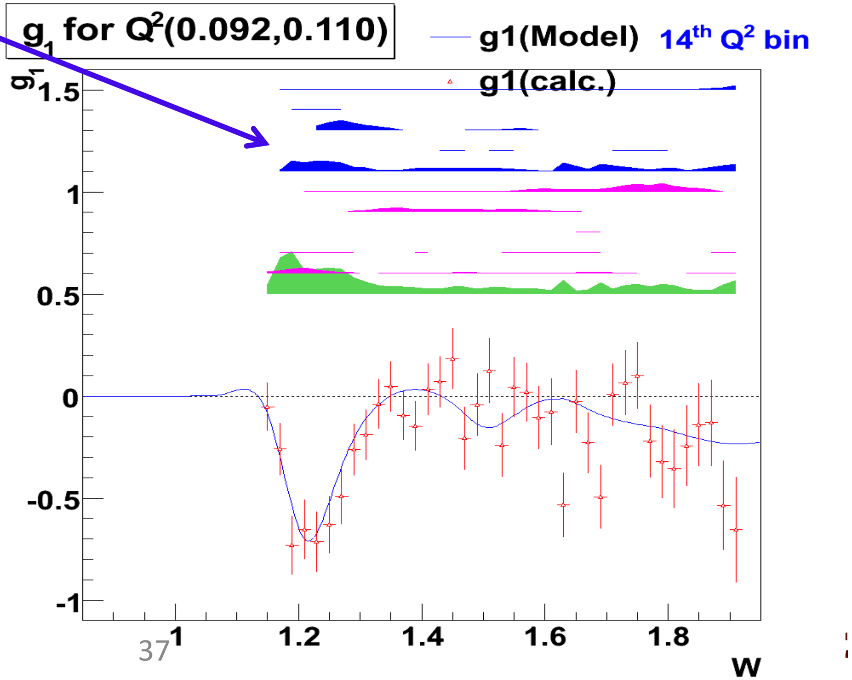
e.g., change $A_1/A_2/F_1/R$ within fit errors

$$\Delta g_1^i(W,Q^2) = \underbrace{g_1^{standard} + \frac{\Delta n^i - \Delta n^{standard}}{B(W,Q^2)} - g_1^i}$$

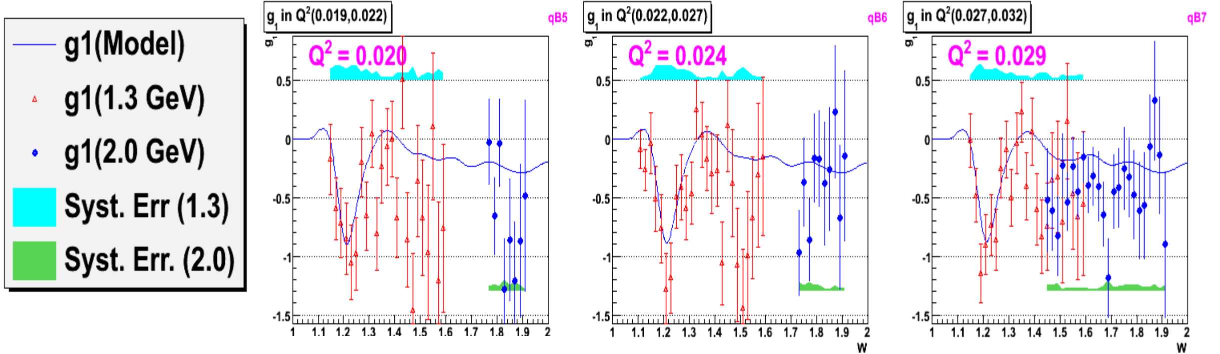
Model g_1 in Q^2=(0.092,0.11)

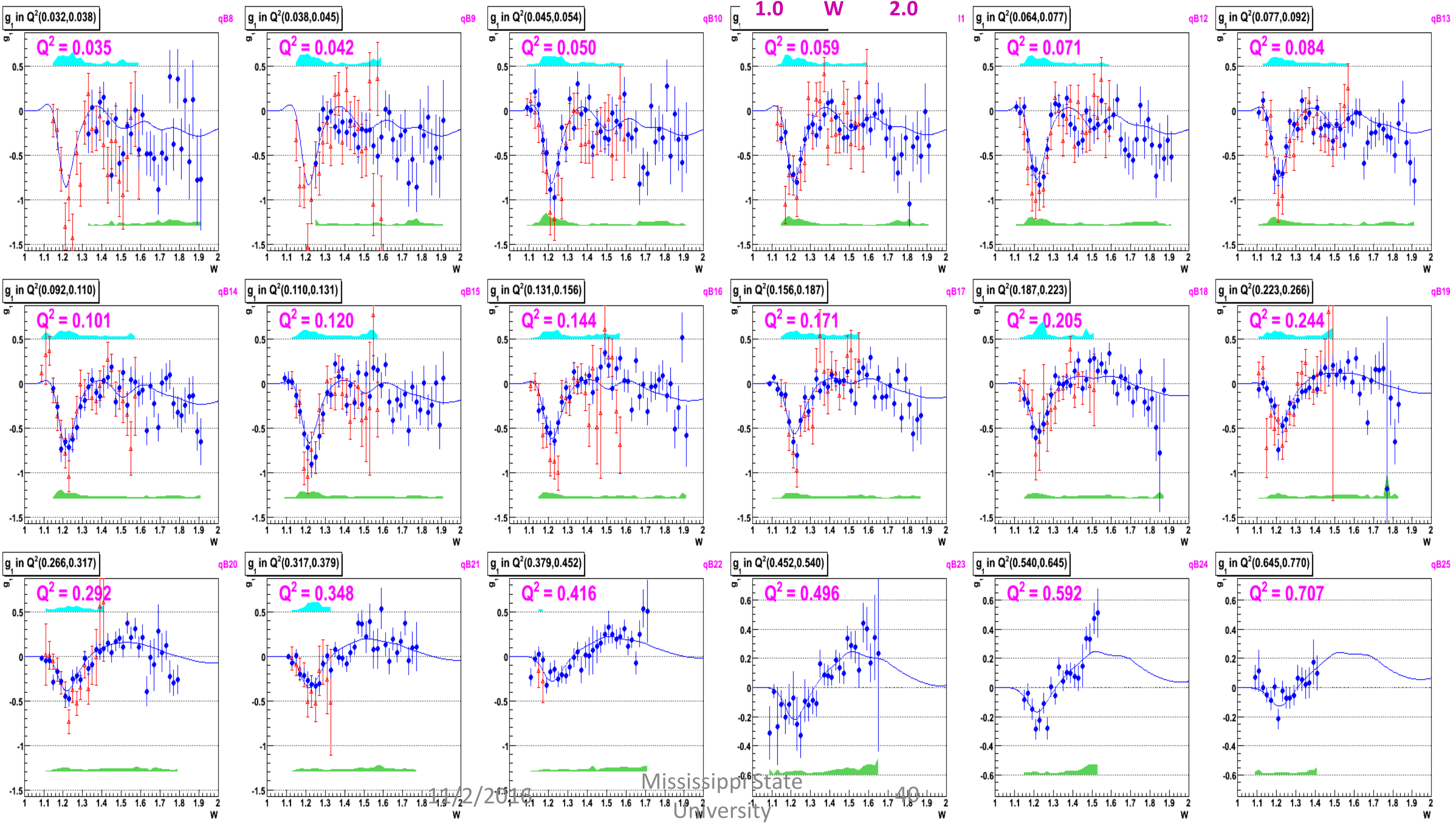



ΔN (non-std) - ΔN (std)


g_1 for Q^2(0.092,0.110)

Extracted g_1





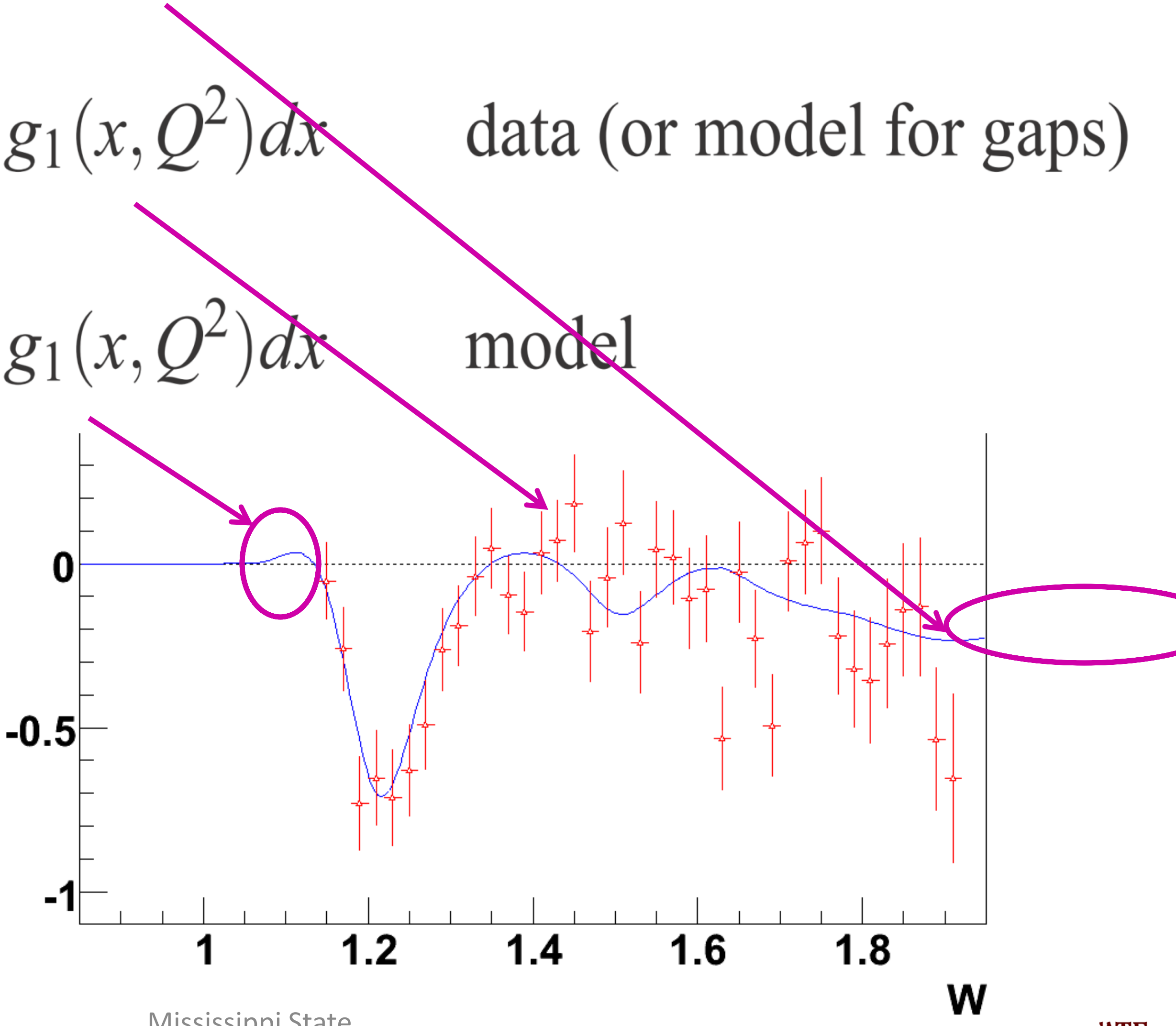
Calculation of Integrals

$$\Gamma_1(Q^2) = \int_{x=0.001}^{x(W_{data})} g_1(x,Q^2)dx \quad \text{model}$$

$$+ \int_{x(W_{data})}^{W=1.15} g_1(x,Q^2)dx \quad \text{data (or model for gaps)}$$

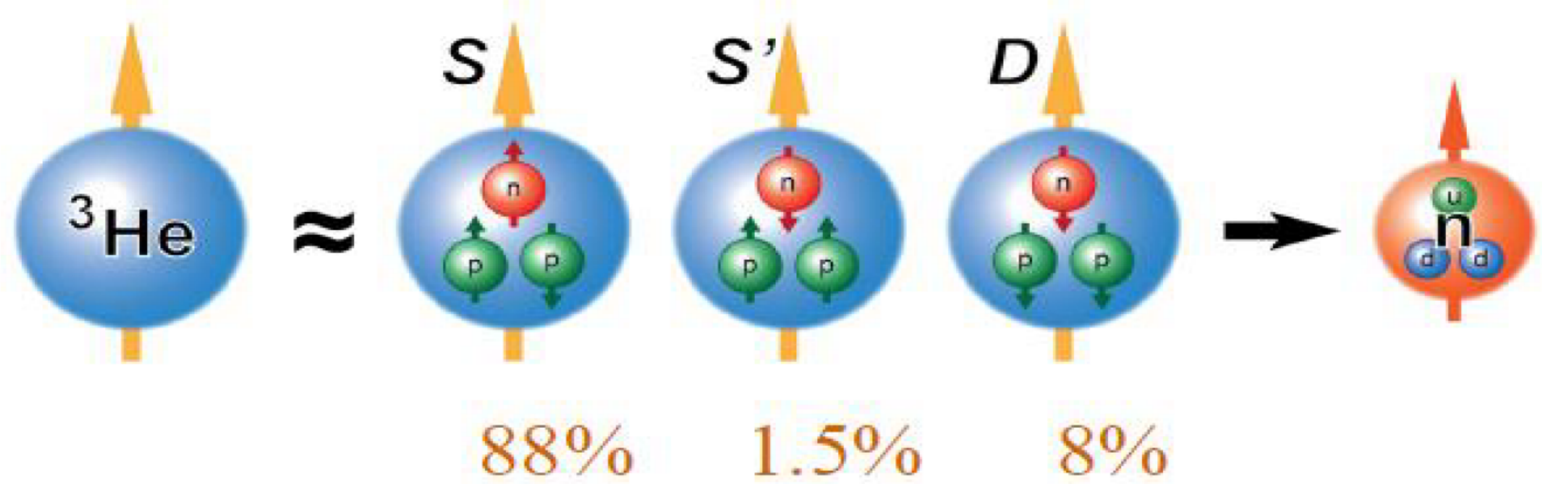
$$+ \int_{W=1.15}^{W=1.08} g_1(x,Q^2)dx \quad \text{model}$$

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



Neutron Target

- Neutron mean lifetime is just under 15 mins.
- ^{3}He nucleus has two protons whose spins are paired, and a single neutron that accounts for most of the nuclear spin.
- So, ^{3}He is an effective polarized neutron target.



F. R. P. Bissey, A. W. Thomas, and I. R. Afnan, Phys. Rev. C64, 024004 (2001)