



# Latest Results From JLab Longitudinal Spin Experiments

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# Outline

- QCD and spin physics
- Polarized DIS and spin structure functions
- Experiments at Jefferson Lab for  $g_1$  and  $g_2$
- SANE and EG4
- Other experiments for  $g_2$
- Summary

# Nucleon Spin Structure

- Explaining nucleon spin in terms of quarks and gluons (QCD)
- Nucleon spin is  $1/2$ 
  - De-composition is not trivial
  - ~30% from quark spins
  - Little or no polarized gluons

# Solving the Puzzle

- Spin structure functions  $g_1$  and  $g_2$ 
  - Electron scattering on polarized targets ( $p, d, {}^3\text{He}$ )
- Gluon polarization
  - Direct measurement from polarized pp scattering (PHENIX, STAR)
  - QCD evolution from spin structure functions
- Orbital Angular Momentum (OAM)
  - Generalized Parton Distributions



# All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4} \times$$

$$f_1 = \text{[Diagram: Yellow circle with red dot and no arrows]}$$

$$\{ [1 + (1-y)^2] \sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z, P_{h\perp}^2) \}$$

Unpolarized

Boer-Mulders

$$h_1^\perp = \text{[Diagram: Yellow circle with red dot and vertical arrows]} - \text{[Diagram: Yellow circle with red dot and horizontal arrows]}$$

$$+ (1-y) \frac{P_{h\perp}^2}{4z^2 M_N M_h} \cos(2\phi_h^l) \sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$h_{1L}^\perp = \text{[Diagram: Yellow circle with red dot and diagonal arrows]} - \text{[Diagram: Yellow circle with red dot and diagonal arrows]}$$

$$- |S_L| (1-y) \frac{P_{h\perp}^2}{4z^2 M_N M_h} \sin(2\phi_h^l) \sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Transversity

$$h_{1T} = \text{[Diagram: Yellow circle with red dot and vertical arrows]} - \text{[Diagram: Yellow circle with red dot and horizontal arrows]}$$

$$+ |S_T| (1-y) \frac{P_{h\perp}}{zM_h} \sin(\phi_h^l + \phi_S^l) \sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

Polarized target

Sivers

$$f_{1T}^\perp = \text{[Diagram: Yellow circle with red dot and vertical arrows]} - \text{[Diagram: Yellow circle with red dot and horizontal arrows]}$$

$$+ |S_T| (1-y + \frac{1}{2}y^2) \frac{P_{h\perp}}{zM_N} \sin(\phi_h^l - \phi_S^l) \sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z, P_{h\perp}^2)$$

$$h_{1T}^\perp = \text{[Diagram: Yellow circle with red dot and diagonal arrows]} - \text{[Diagram: Yellow circle with red dot and diagonal arrows]}$$

$$+ |S_T| (1-y) \frac{P_{h\perp}^3}{6z^3 M_N^2 M_h} \sin(3\phi_h^l - \phi_S^l) \sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z, P_{h\perp}^2)$$

$$g_{1L} = \text{[Diagram: Yellow circle with red dot and horizontal arrows]} - \text{[Diagram: Yellow circle with red dot and horizontal arrows]}$$

$$+ \lambda_e |S_L| y (1 - \frac{1}{2}y) \sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z, P_{h\perp}^2)$$

Polarized beam and target

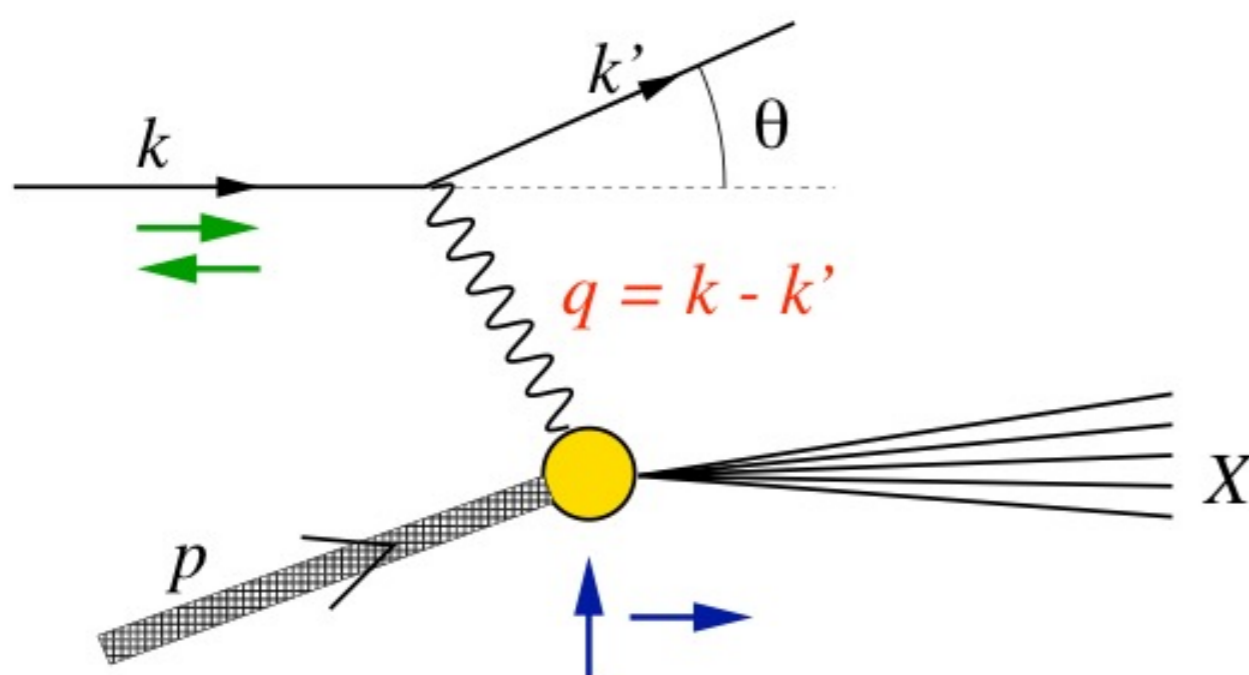
$$g_{1T} = \text{[Diagram: Yellow circle with red dot and diagonal arrows]} - \text{[Diagram: Yellow circle with red dot and diagonal arrows]}$$

$$+ \lambda_e |S_T| y (1 - \frac{1}{2}y) \frac{P_{h\perp}}{zM_N} \cos(\phi_h^l - \phi_S^l) \sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z, P_{h\perp}^2) \}$$

$S_L$  and  $S_T$ : Target Polarizations;  $\lambda_e$ : Beam Polarization

# Inclusive $e$ - $N$ Scattering

## Deep Inelastic Scattering



$$x_{\text{Bjorken}} = \frac{Q^2}{2M_N \nu}$$

- Four-momentum transfer

$$Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$$

- Energy transfer to the hadron

$$\nu = E - E'$$

- Mass of the hadronic residual (or invariant mass)

$$W = \sqrt{(p + q)^2}$$
$$= \sqrt{M_N^2 + 2M_N \nu - Q^2}$$

# Cross Section & Spin Structure Functions

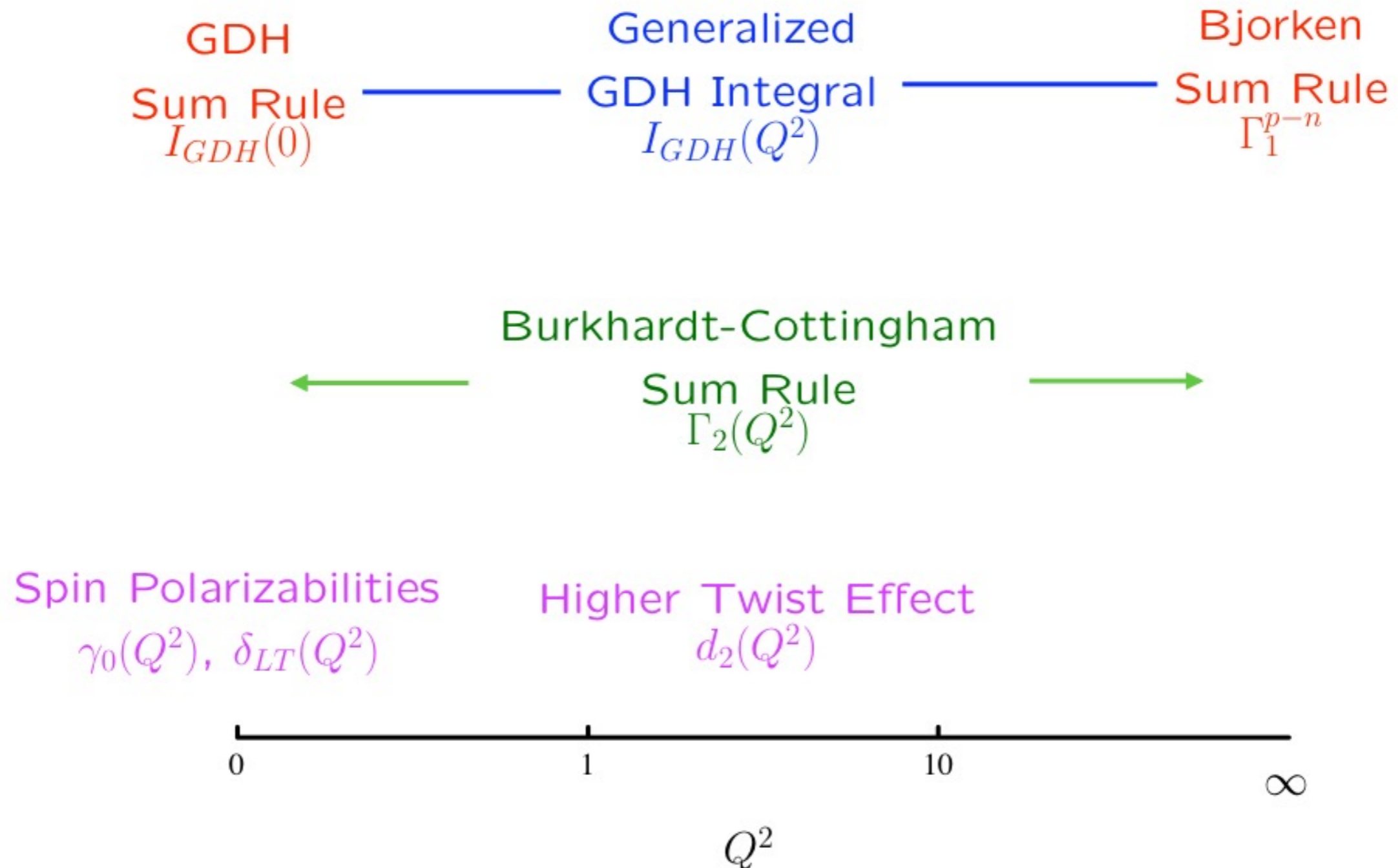
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2 \frac{\theta}{2}}{Q^4} \left[ \frac{F_2}{\nu} + 2 \frac{F_1}{M} \tan^2 \frac{\theta}{2} \right]$$

$$\frac{d^2\sigma}{dE' d\Omega} (\downarrow\uparrow - \uparrow\uparrow) = \frac{4\alpha^2}{MQ^2} \frac{E'}{\nu E} \left[ (E + E' \cos \theta) g_1 - \frac{Q^2}{\nu} g_2 \right]$$

$$\frac{d^2\sigma}{dE' d\Omega} (\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2 \sin \theta}{MQ^2} \frac{E'^2}{E} \frac{1}{\nu^2} (\nu g_1 + 2E g_2)$$

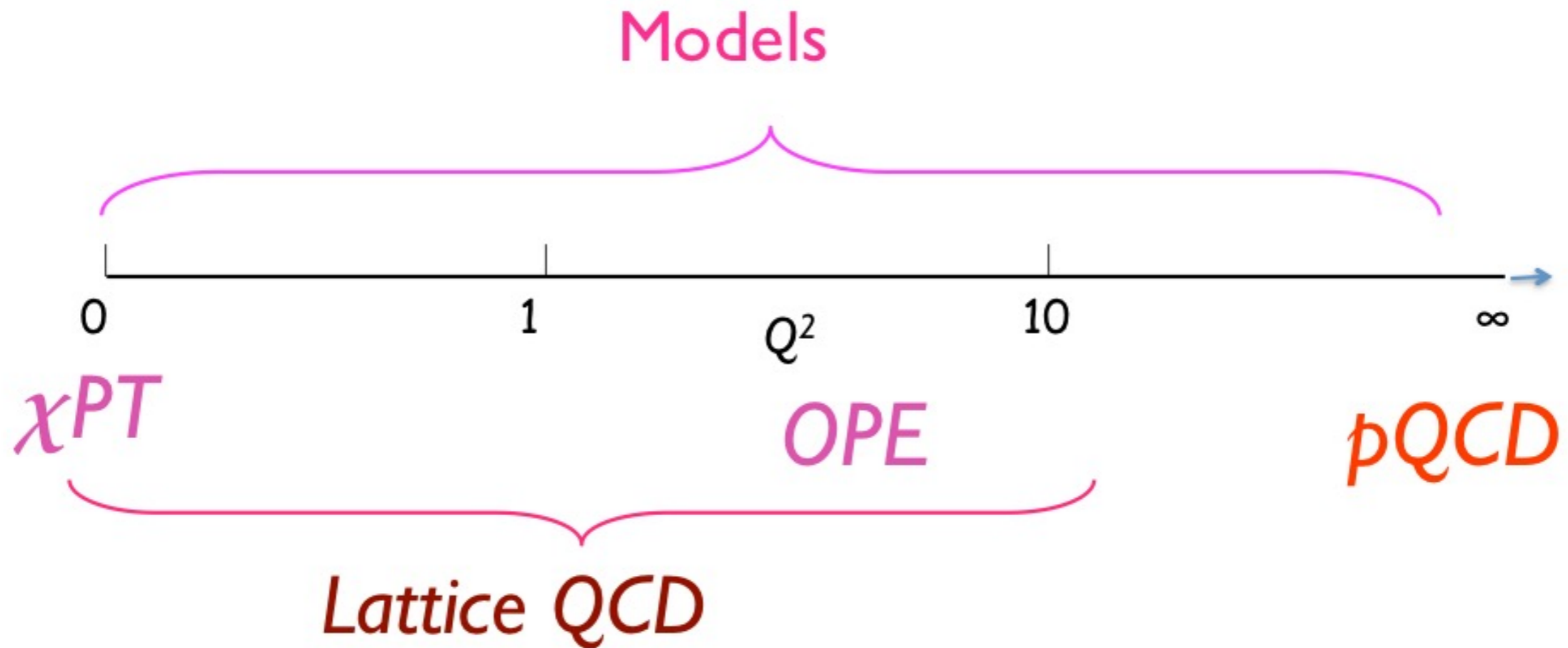


# What to do with $g_1$ and $g_2$





# Probe Resolution and Theory Tools



# Moment of $g_1$

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2) dx$$

- $Q^2 \rightarrow 0$

$$\Gamma_1(Q^2) = -\frac{Q^2}{8M^2} \kappa^2 + O\left(\frac{Q^4}{M^4}\right) \quad (\text{GDH Sum Rule as } Q^2 \rightarrow 0,)$$

- $Q^2 \rightarrow \infty$

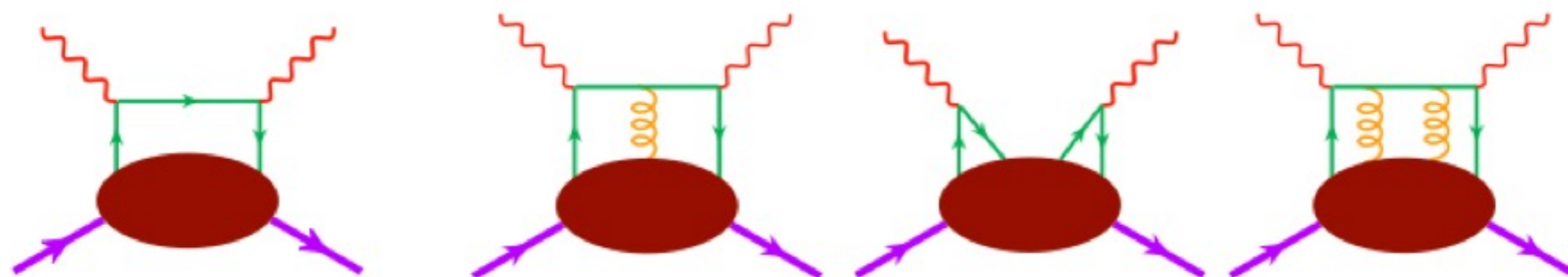
$$\Gamma_1(Q^2) = \frac{1}{2} a^{(0)} + \frac{M^2}{9Q^2} (a^{(2)} + 4d^{(2)} + 4f^{(2)}) + O\left(\frac{M^4}{Q^4}\right)$$

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \quad \text{as } Q^2 \rightarrow \infty \quad (\text{Bjorken Sum Rule})$$

# $g_2$ and Higher Twists

- Decomposition of  $g_2$

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$



single quark  
scattering

$$\tau = 2$$

$qq$  &  $qg$   
correlations

$$\tau > 2$$

# $d_2$ Matrix Element

- Dynamical twist-3 matrix element

$$d_2(Q^2) = 3 \int_0^1 x^2 \bar{g}_2(x, Q^2) dx$$

$$d_2(Q^2) = \int_0^1 x^2 \left[ 3g_2(x, Q^2) + 2g_1(x, Q^2) \right] dx$$



# World Data on $g_1$ and $g_2$

Observable	H target	D target	$^3\text{He}$ target
$g_1, g_2$ at high $Q^2$	SLAC COMPASS HERMES JLab SANE	SLAC COMPASS HERMES	SLAC JLab E97-117 JLab E01-012 JLab E06-014
$g_1, g_2$ at low $Q^2$	COMPASS HERMES JLab RSS	COMPASS HERMES JLab RSS	JLab E94-010 JLab E97-103
$g_1, g_2$ at $Q^2 \sim 0$	COMPASS JLab E08-027	COMPASS	JLab E97-110
$g_1$ at high $Q^2$	SMC, HERMES JLab EGI	SMC, HERMES JLab EGI	HERMES
$g_1$ at low $Q^2$	SLAC, HERMES JLab EGI	SLAC, HERMES JLab EGI	HERMES
$g_1$ at $Q^2 \sim 0$	JLab EG4	JLab EG4	

# JLab Data on $g_1$ and $g_2$

Observable	H target	D target	$^3\text{He}$ target
$g_1, g_2$ at high $Q^2$	JLab SANE		JLab E97-117 JLab E01-012 JLab E06-014
$g_1, g_2$ at low $Q^2$	JLab RSS	JLab RSS	JLab E94-010 JLab E97-103
$g_1, g_2$ at $Q^2 \sim 0$	JLab E08-027		JLab E08-110
$g_1$ at high $Q^2$	JLab EGI		
$g_1$ at low $Q^2$	JLab EGI	JLab EGI	
$g_1$ at $Q^2 \sim 0$	JLab EG4	JLab EG4	

**Hall-C** (Hall-A)

**Focus of This Talk**

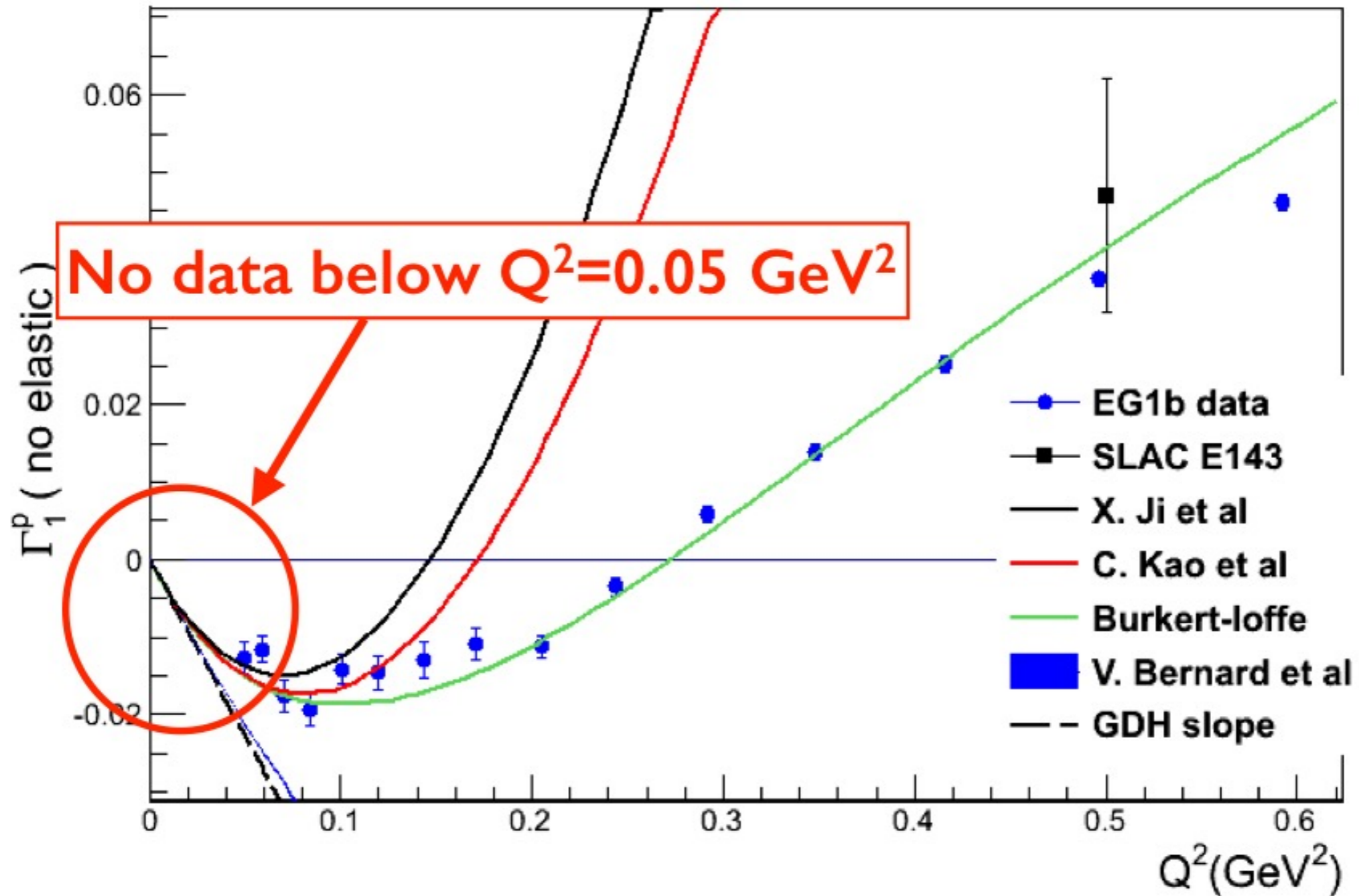
**Will be briefly mentioned**

**Hall-B**

# CLAS eg4

## Proton Spin at Low $Q^2$

# Previous Results

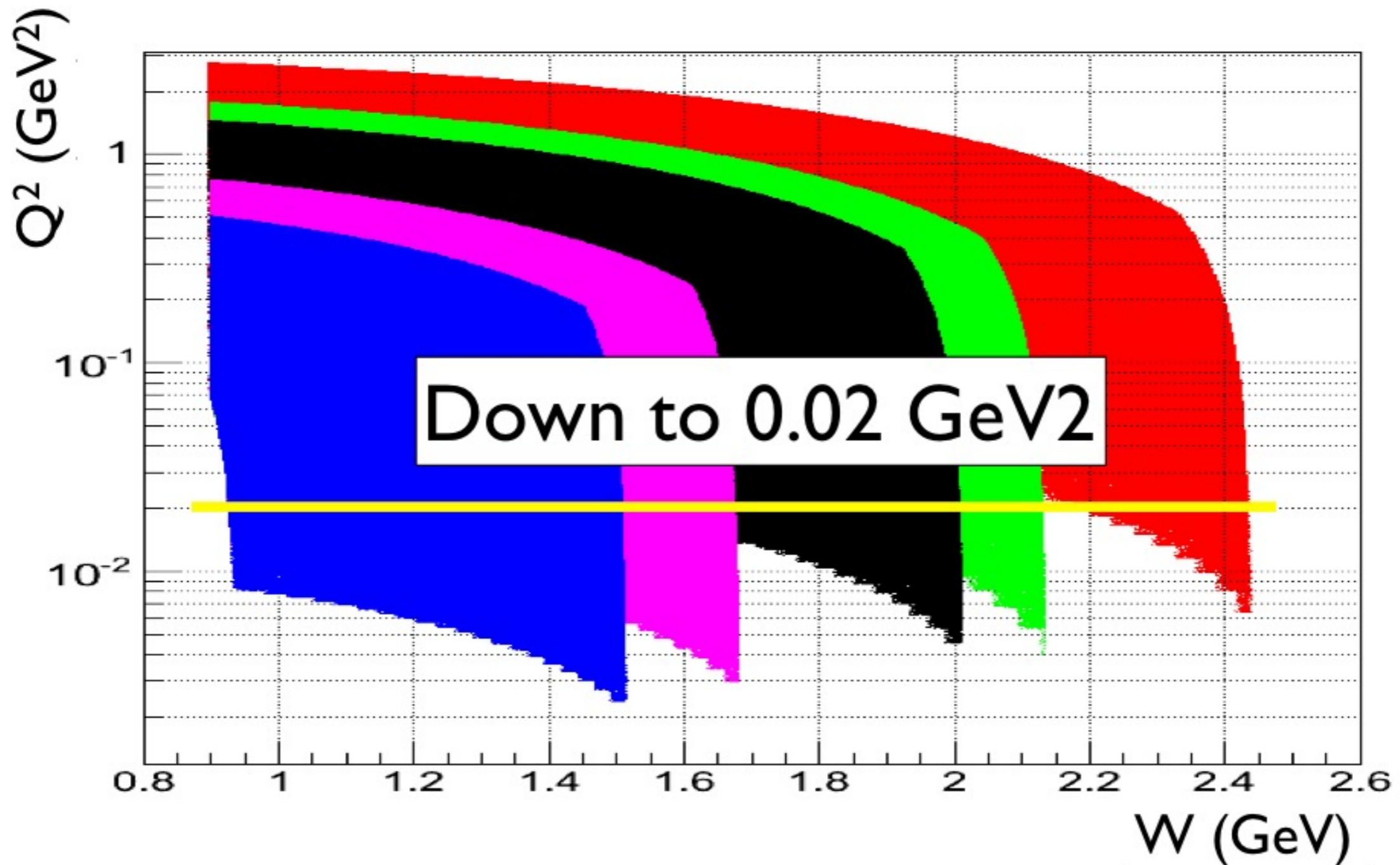




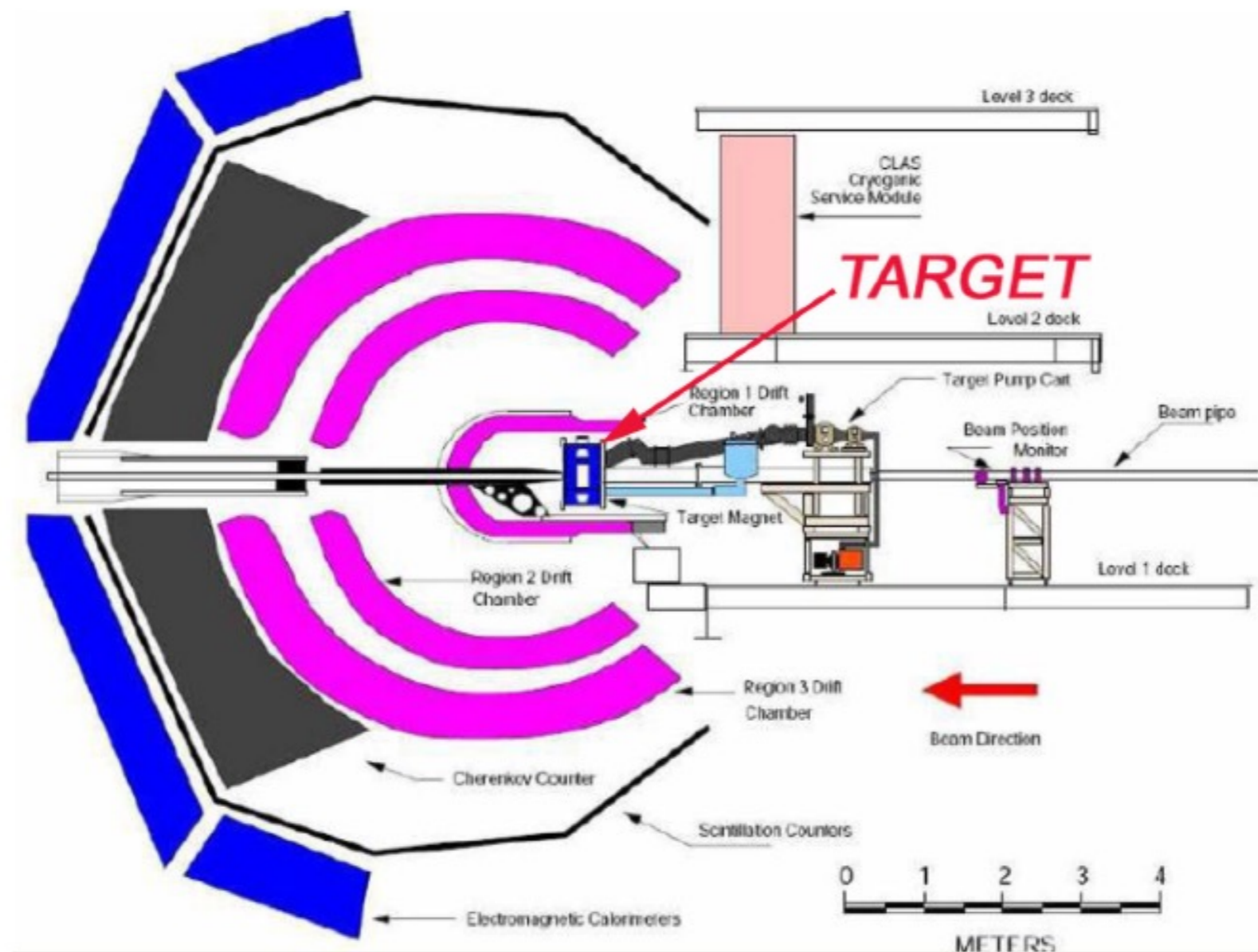
# Experiment Summary

- **Beam**: polarized electron beam (Jefferson Lab) at **1.0, 1.3, 2.0, 2.3** and **3.0** GeV
- **Target**: Polarized **Proton** ( $\text{NH}_3$ ) and **Deuteron** ( $\text{ND}_3$ ) target
  - Orientation: **parallel** ( $180^\circ$ )
- **Detectors**: **CLAS** of Hall-B
- Scattering angle:  $\sim 8^\circ$  to  $\sim 30^\circ$

# Kinematic Coverage

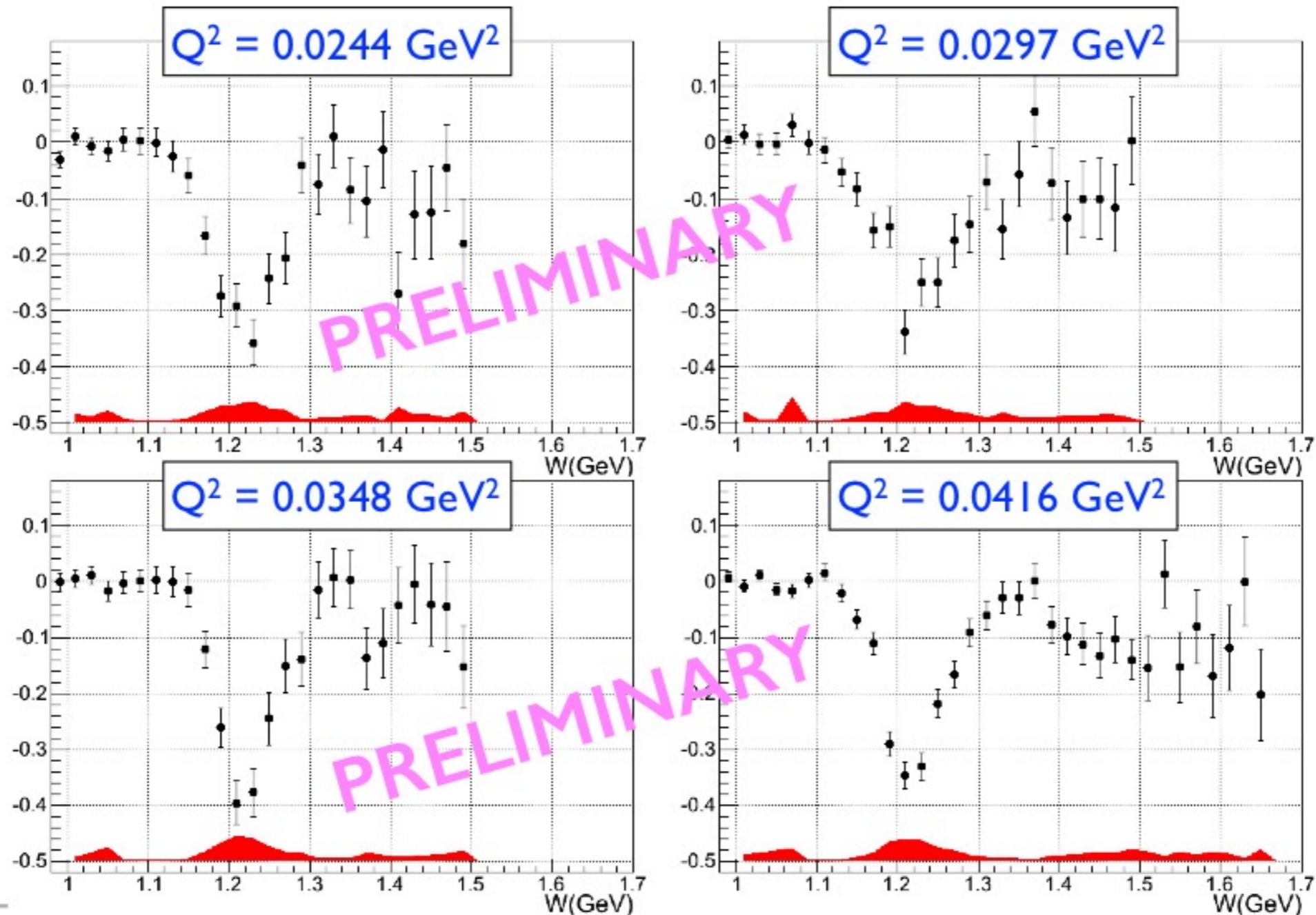


# CLAS at JLab





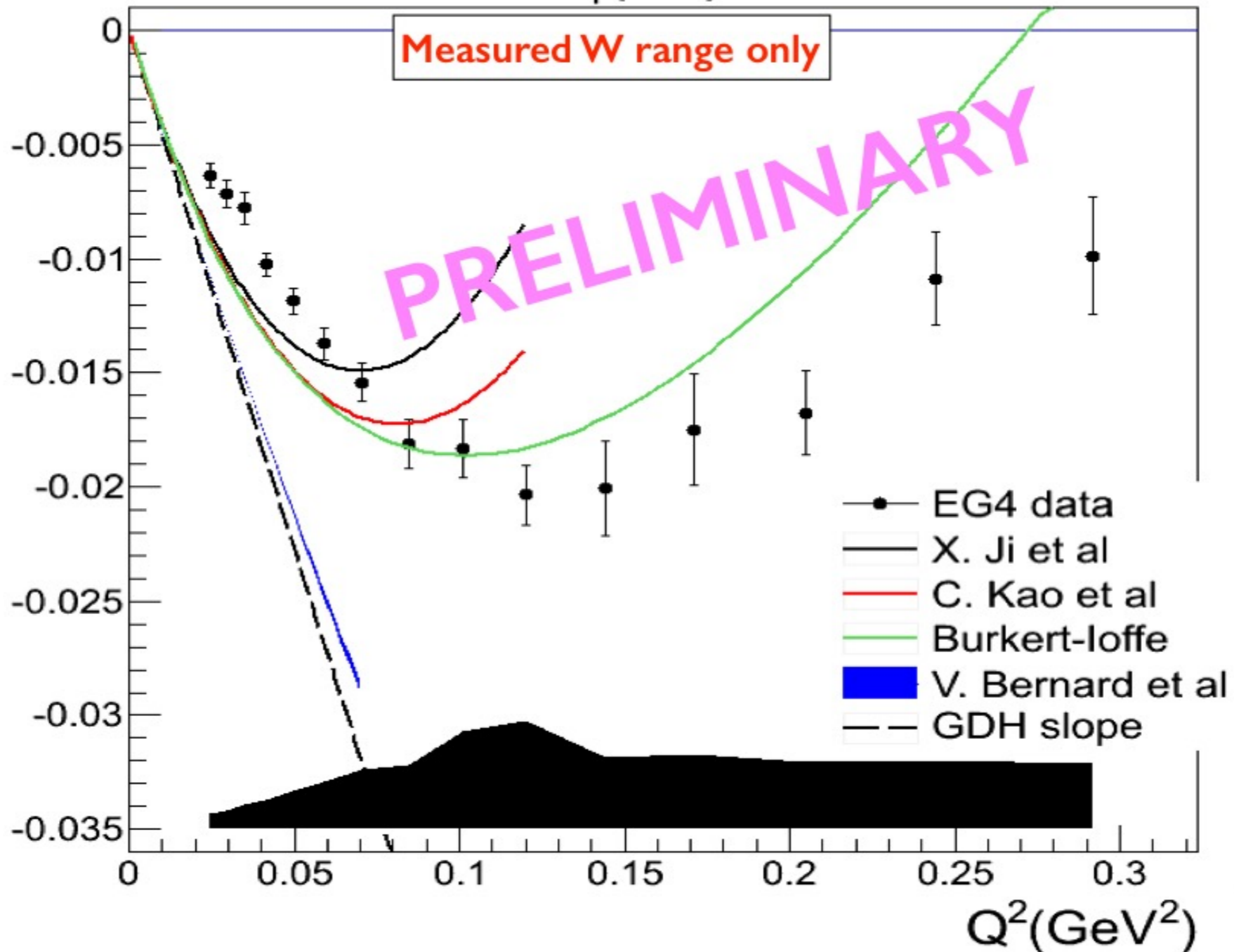
# Spin Structure Function $g_1$





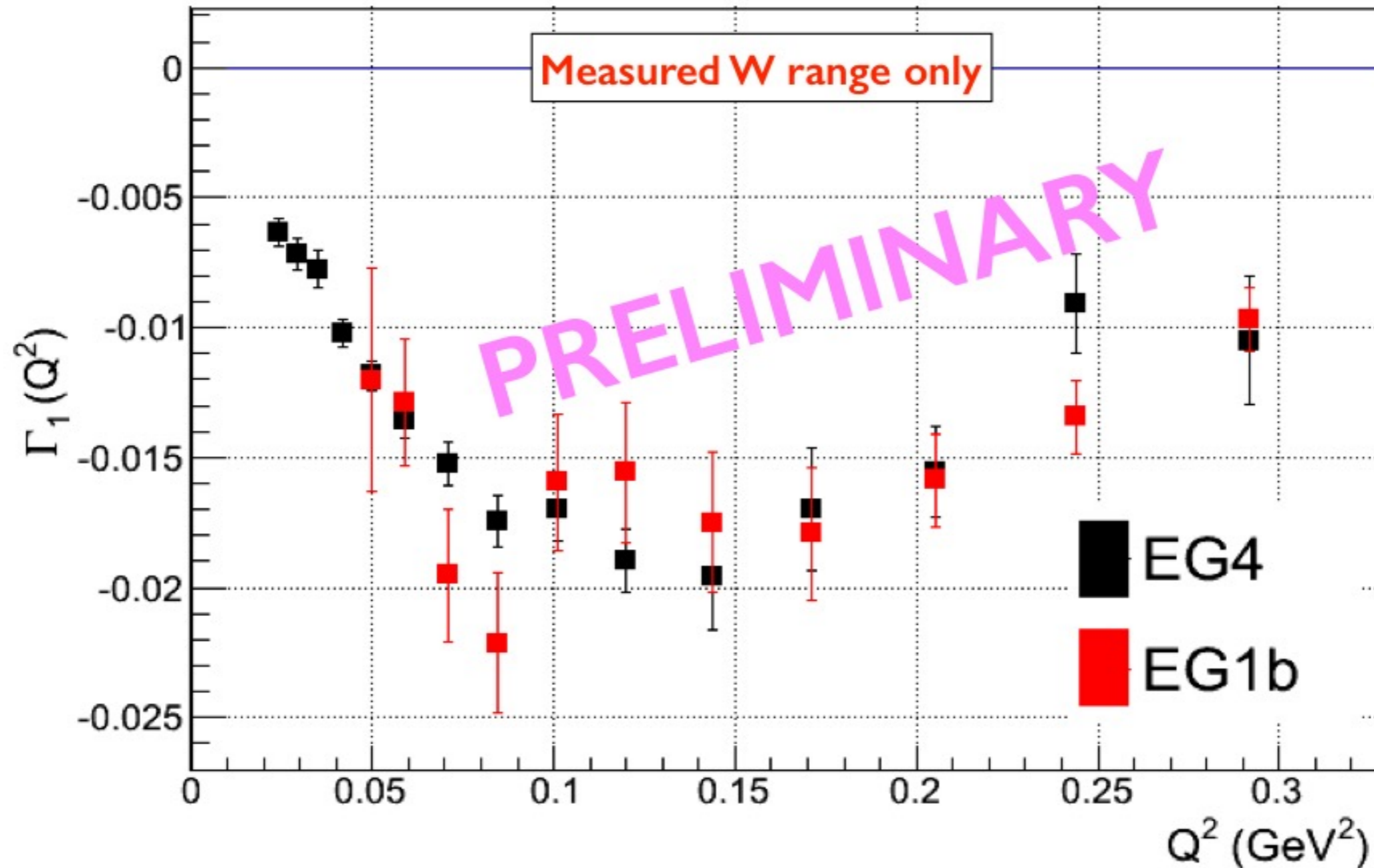
# First Moment

$$\Gamma_1^p(Q^2)$$

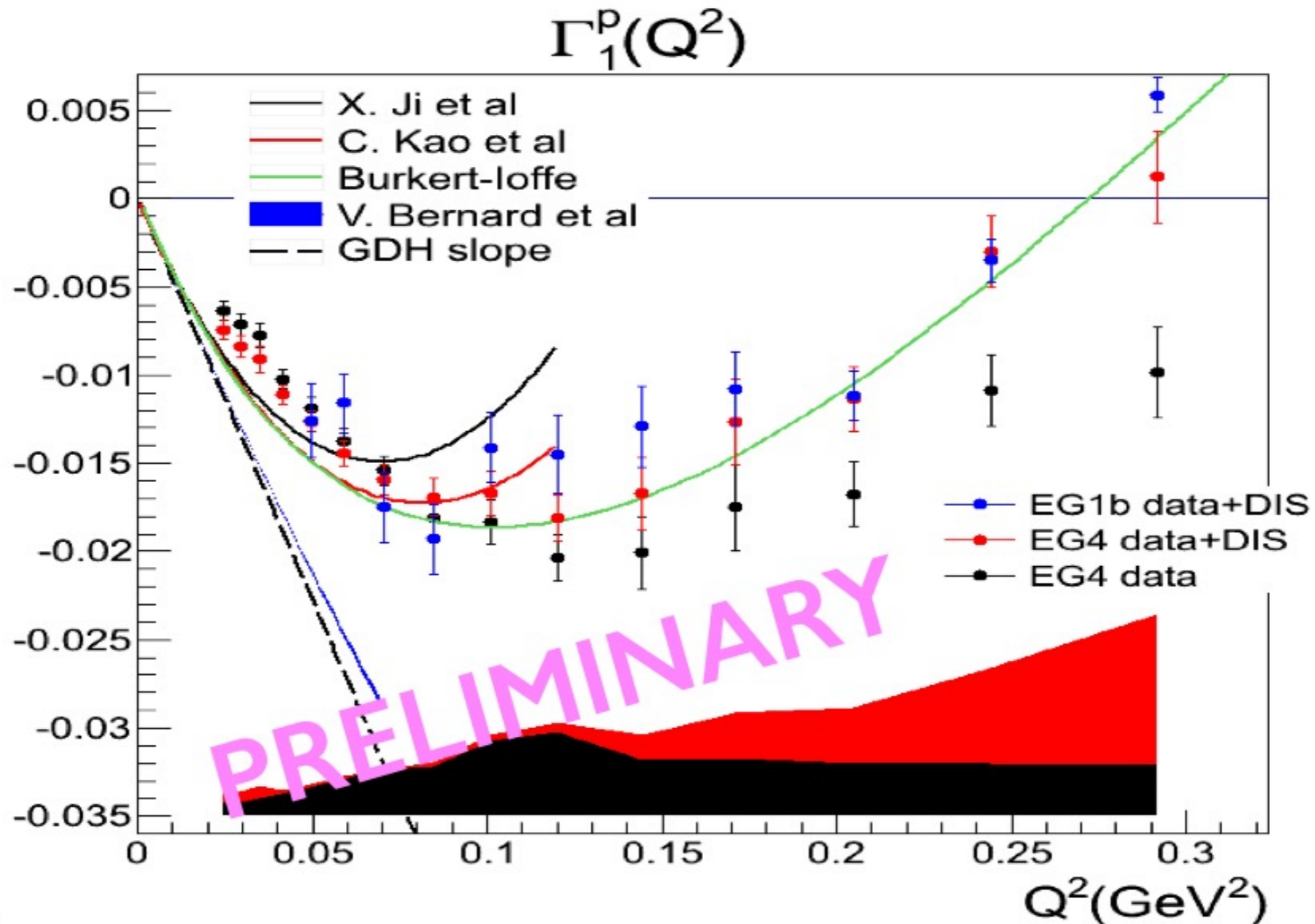


# Comparison with eglb

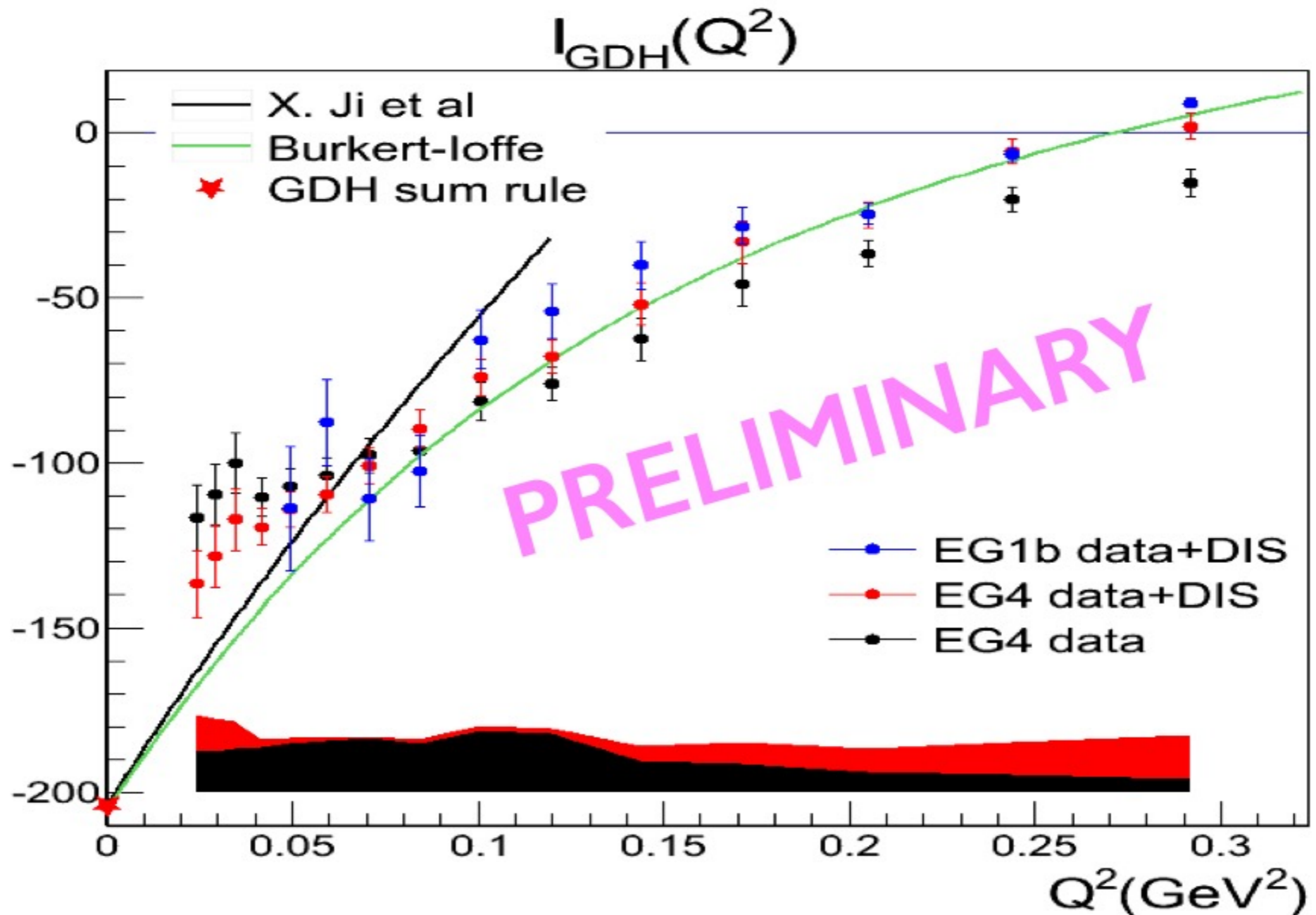
Comparison of  $\Gamma_1$  via the same W range



# First Moment with DIS



# GDH Integral with DIS





# Spin Asymmetries of the Nucleon Experiment

# Experiment Summary

- **Beam:** polarized electron beam (Jefferson Lab) at **4.7** and **5.9** GeV
- **Target:** Polarized **Proton** ( $\text{NH}_3$ ) target
  - Polarization:  $\sim 71\%$
  - Orientation: **parallel** ( $180^\circ$ ) or “**perpendicular**” ( $80^\circ$ )
- **Detectors:** **BETA** and **HMS** of Hall-C
- Scattering angle:  $40^\circ$  for **BETA**,  $15.5^\circ$  or  $20^\circ$  for **HMS**

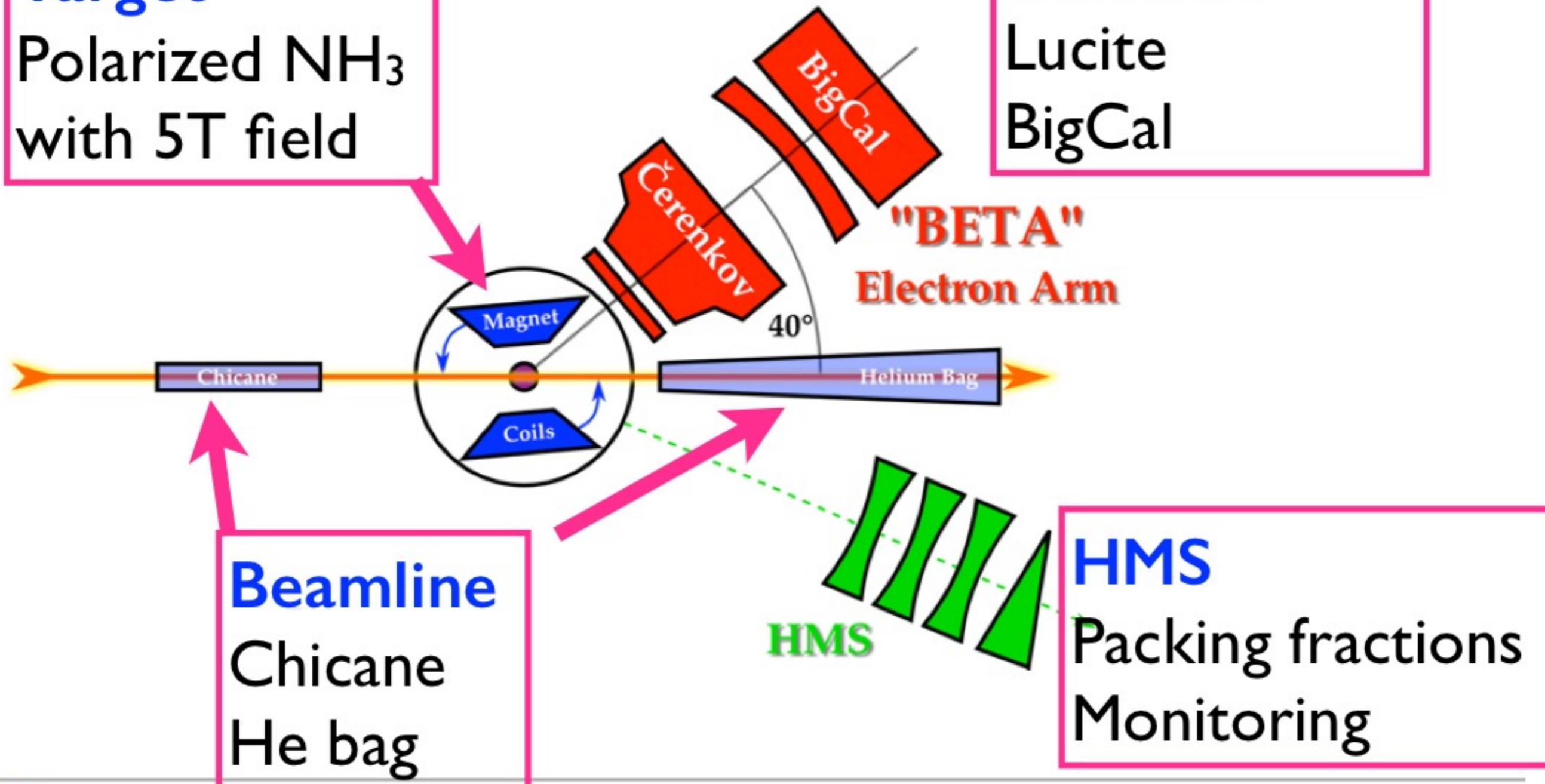
# Setup

## Target

Polarized  $\text{NH}_3$   
with 5T field

## Electron Arm

Tracker  
Cerenkov  
Lucite  
BigCal



## Beamline

Chicane  
He bag

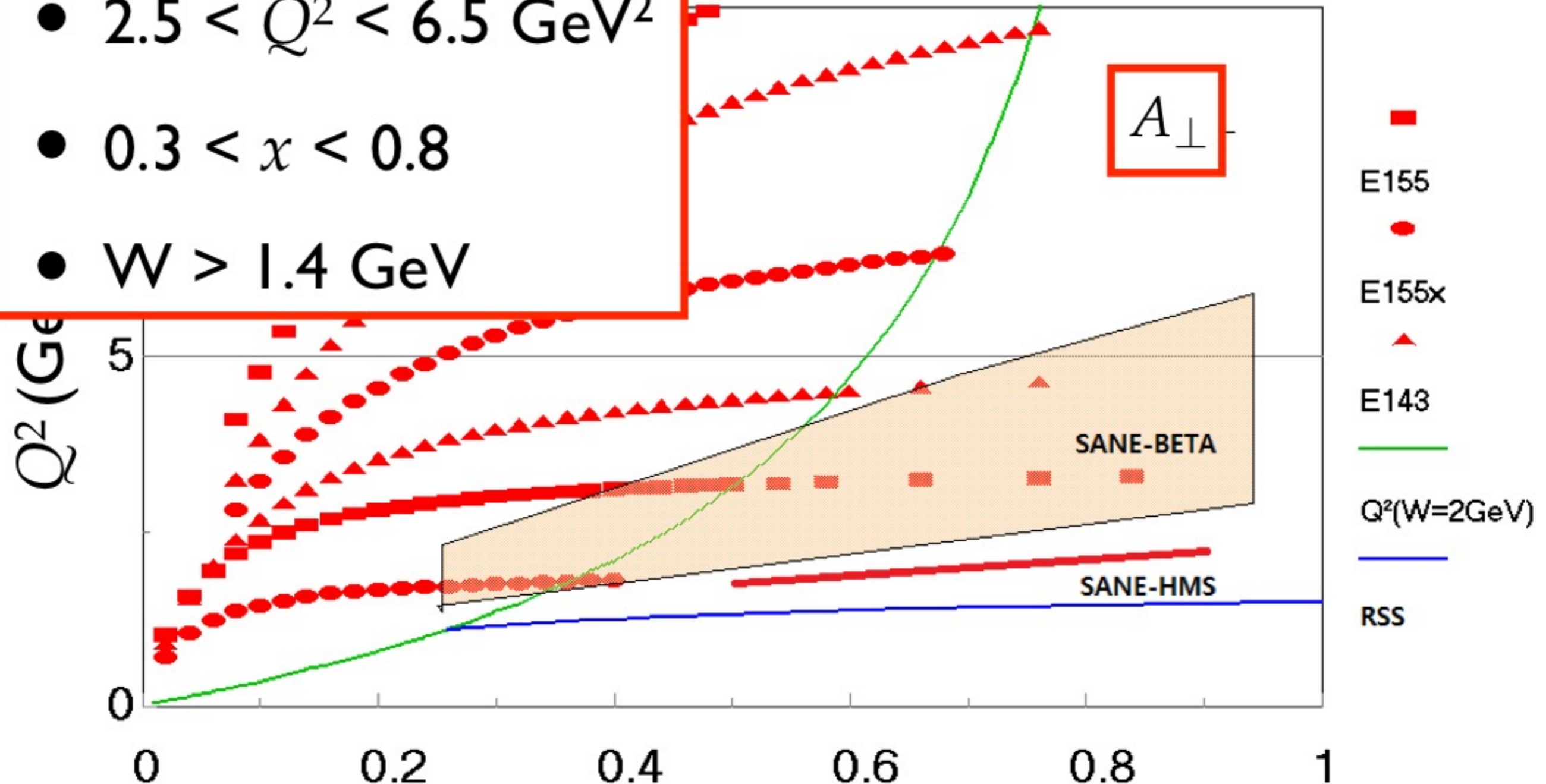
## HMS

Packing fractions  
Monitoring



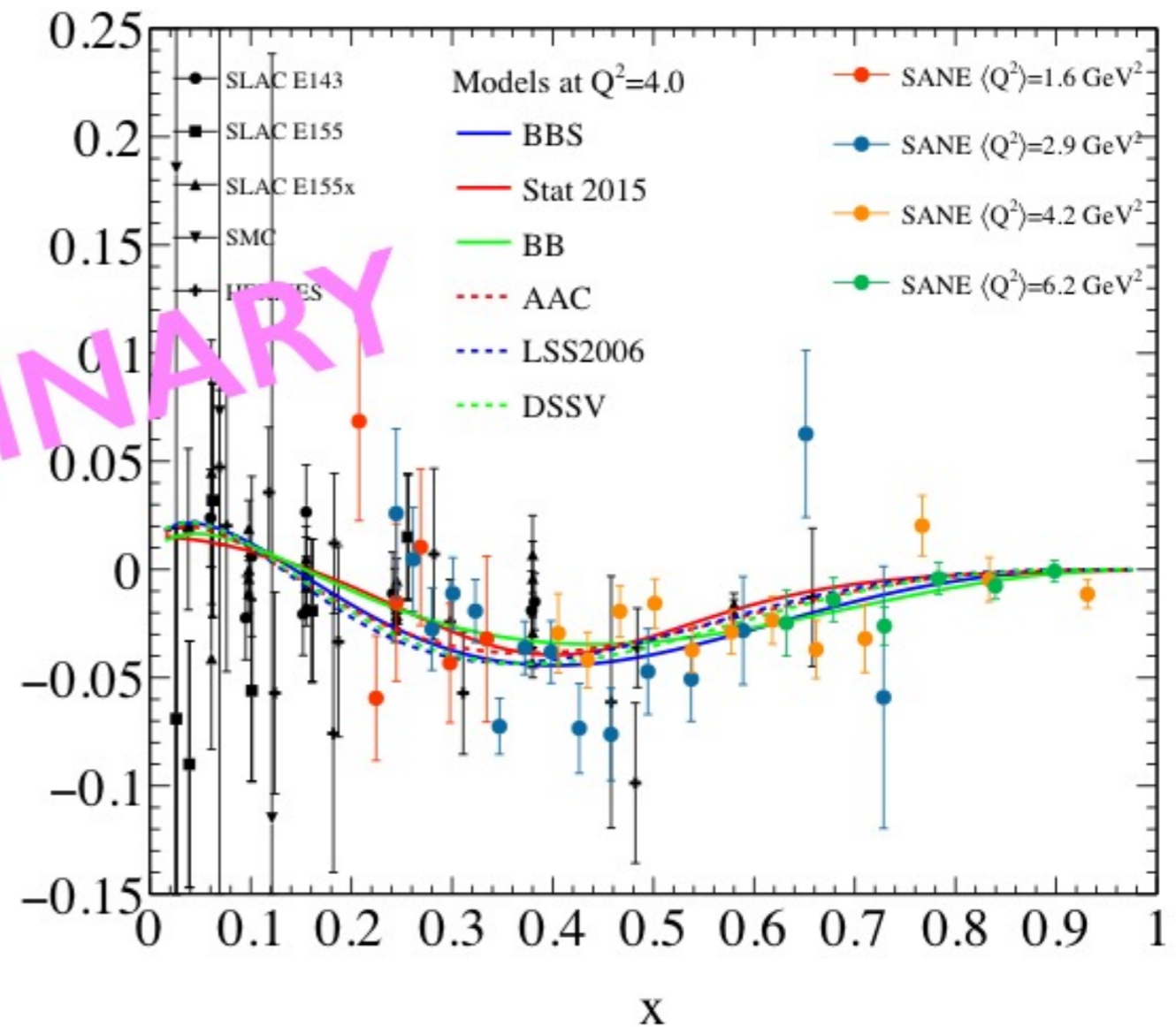
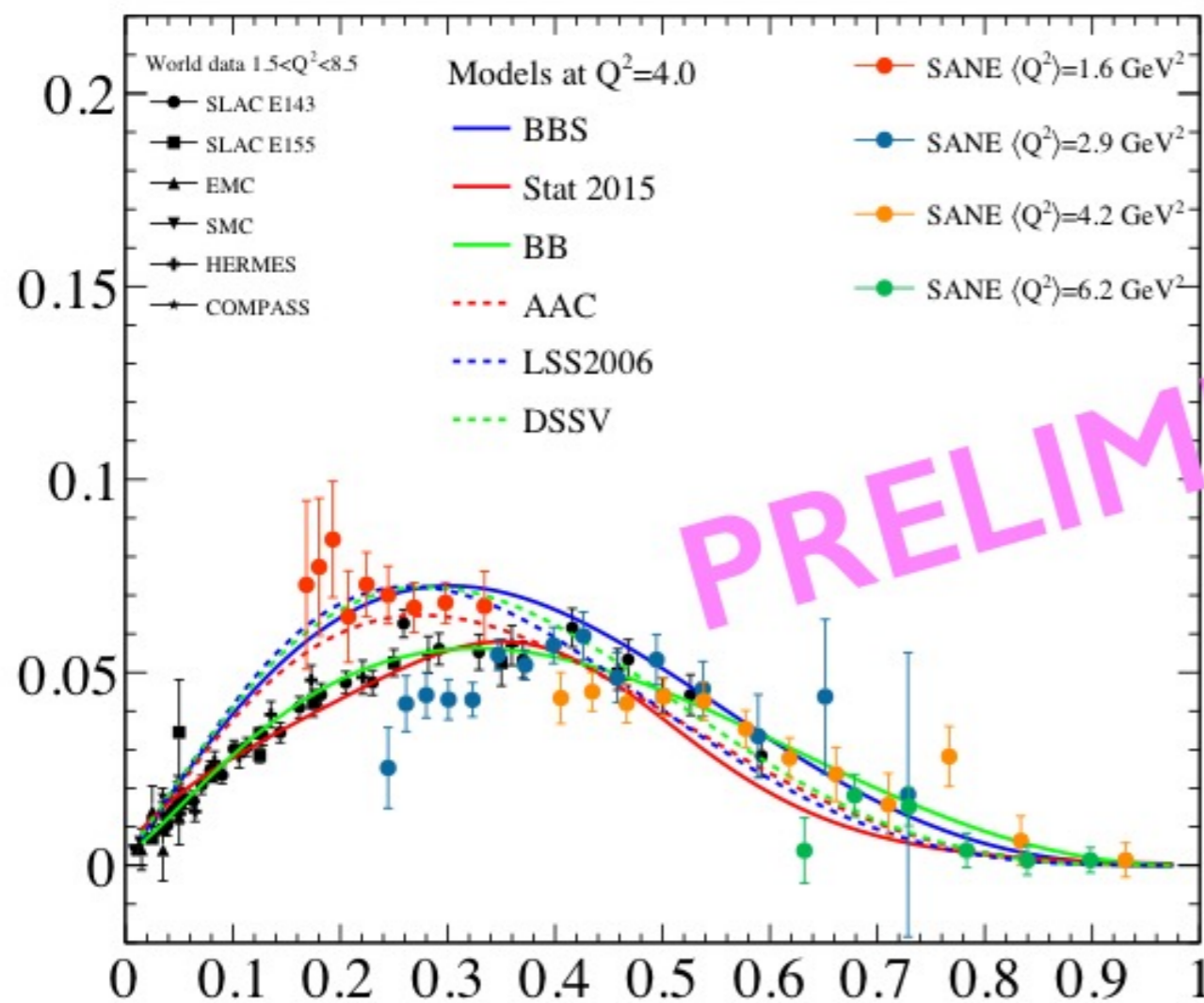
# Kinematic Coverage

- $2.5 < Q^2 < 6.5 \text{ GeV}^2$
- $0.3 < x < 0.8$
- $W > 1.4 \text{ GeV}$



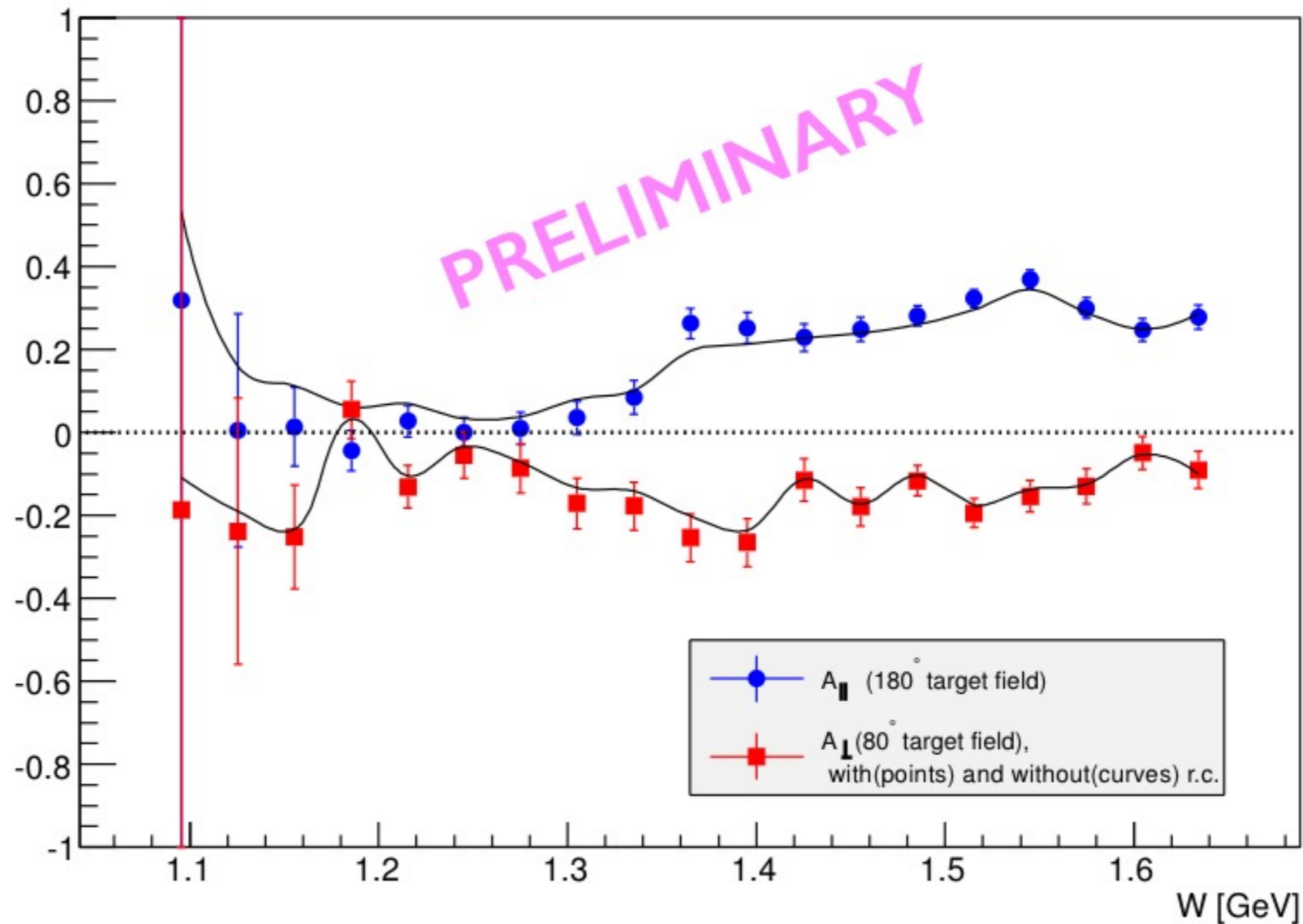


# Proton $g_1$ and $g_2$



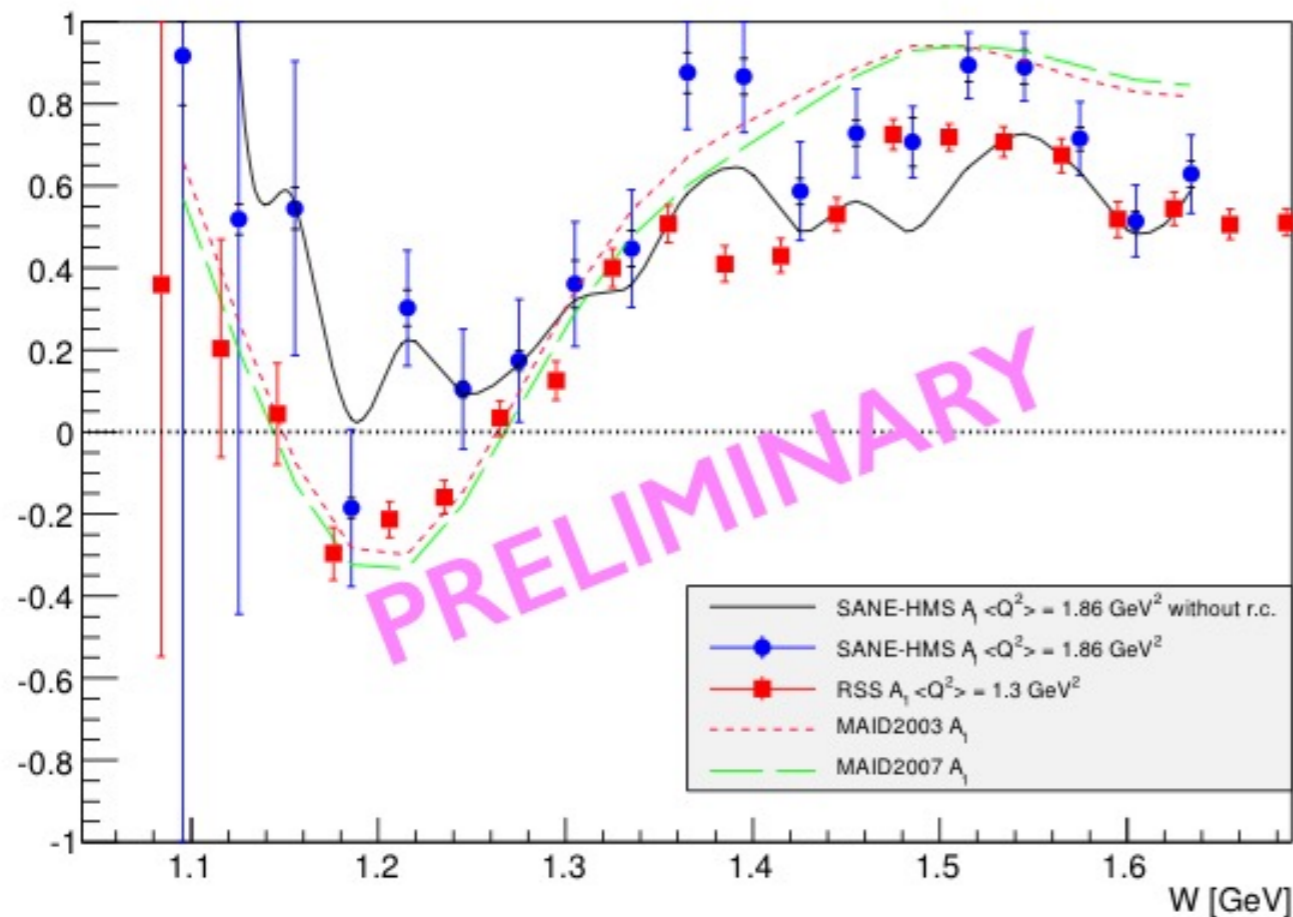
PRELIMINARY

# Parallel & Perpendicular Asymmetries

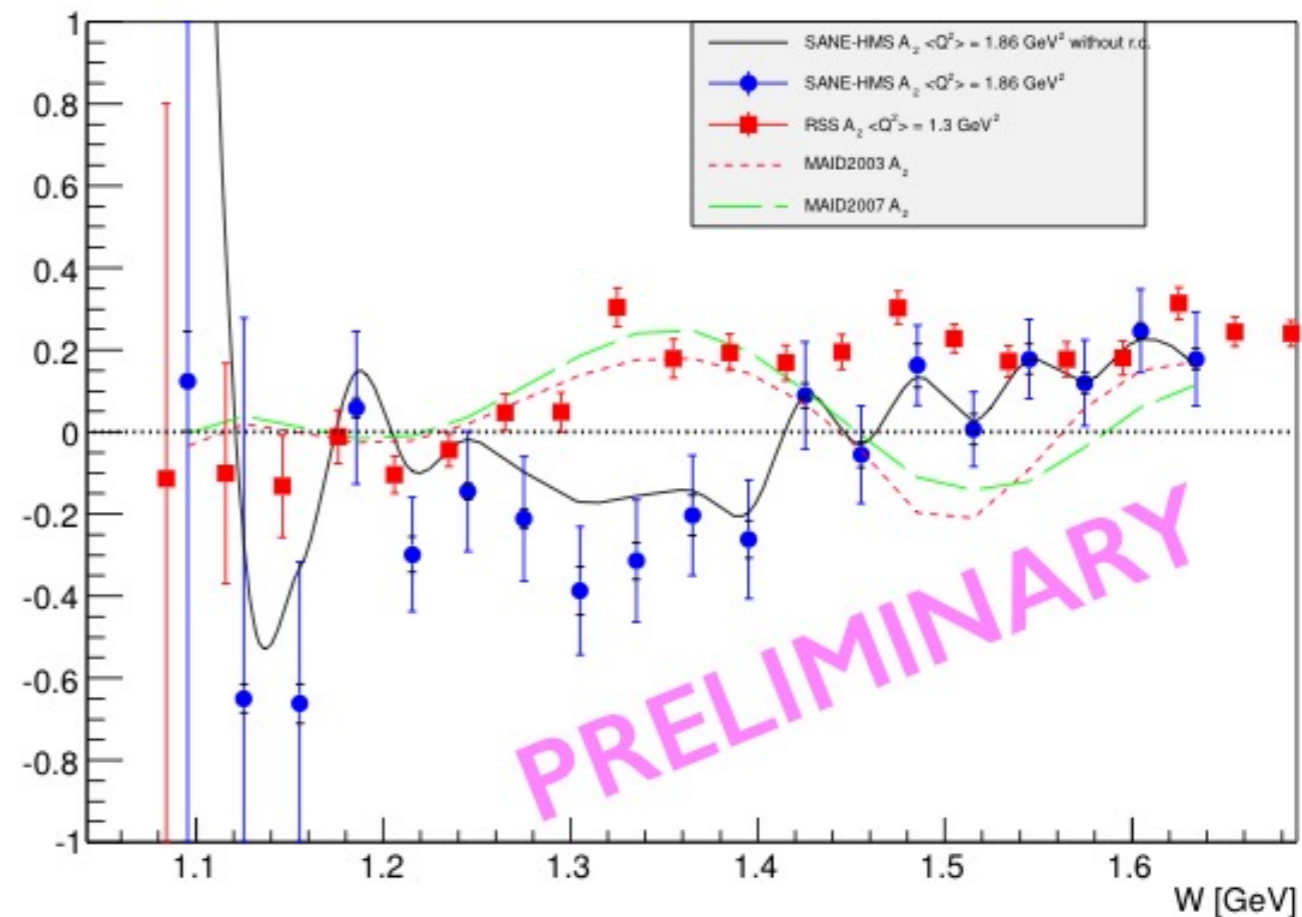


# $A_1$ and $A_2$ with HMS

$A_1$



$A_2$

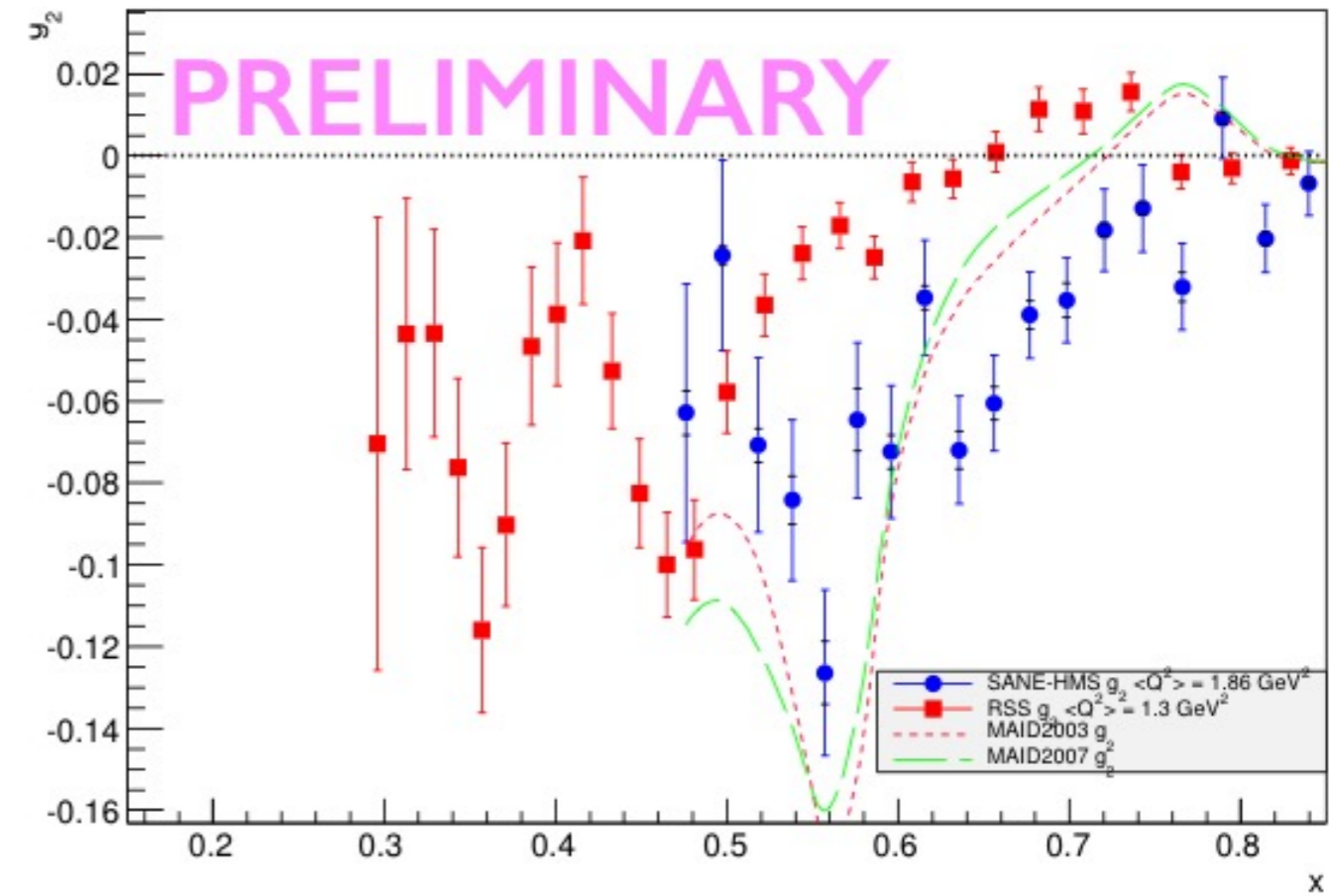
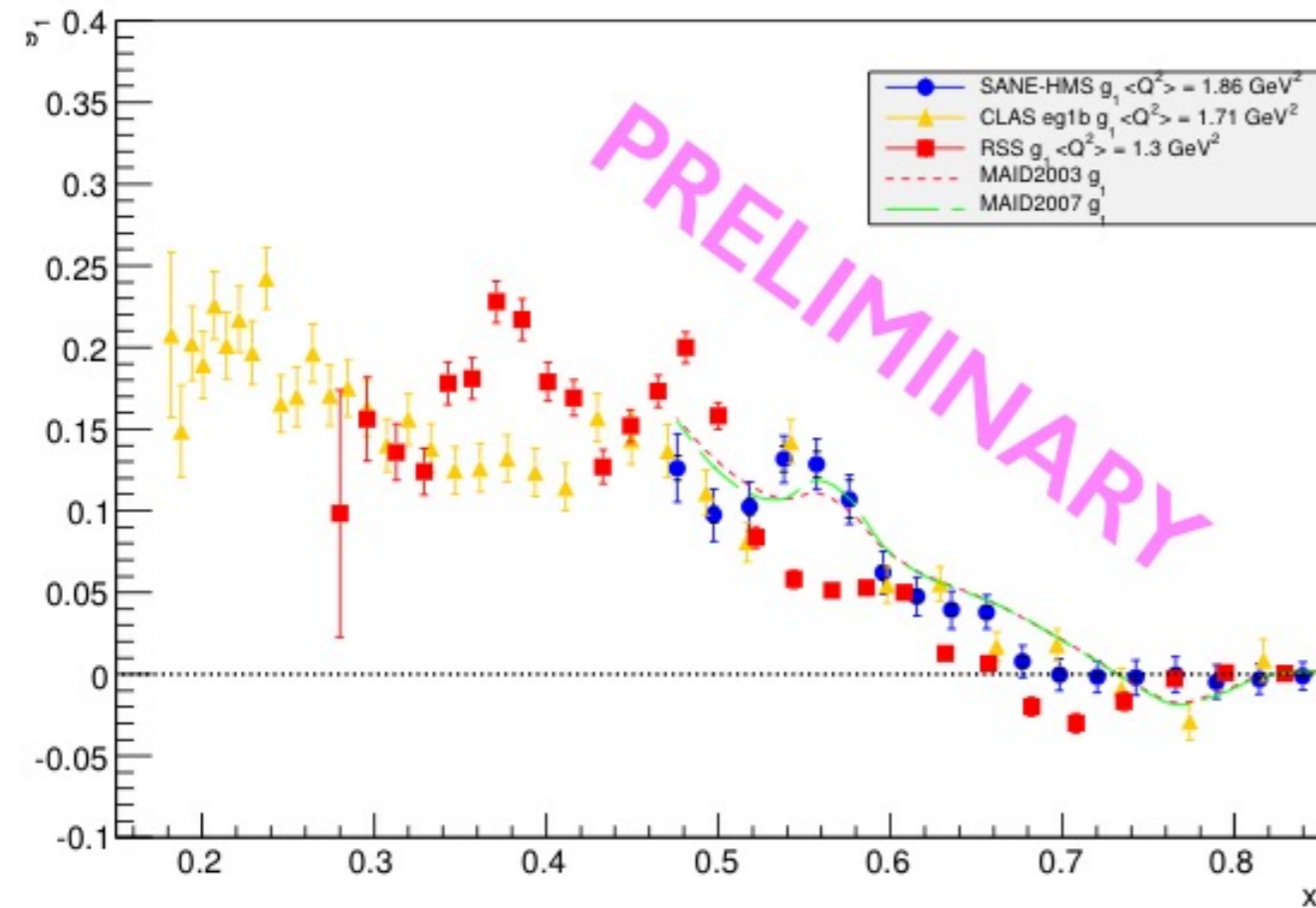




# Proton $g_1$ and $g_2$ with HMS

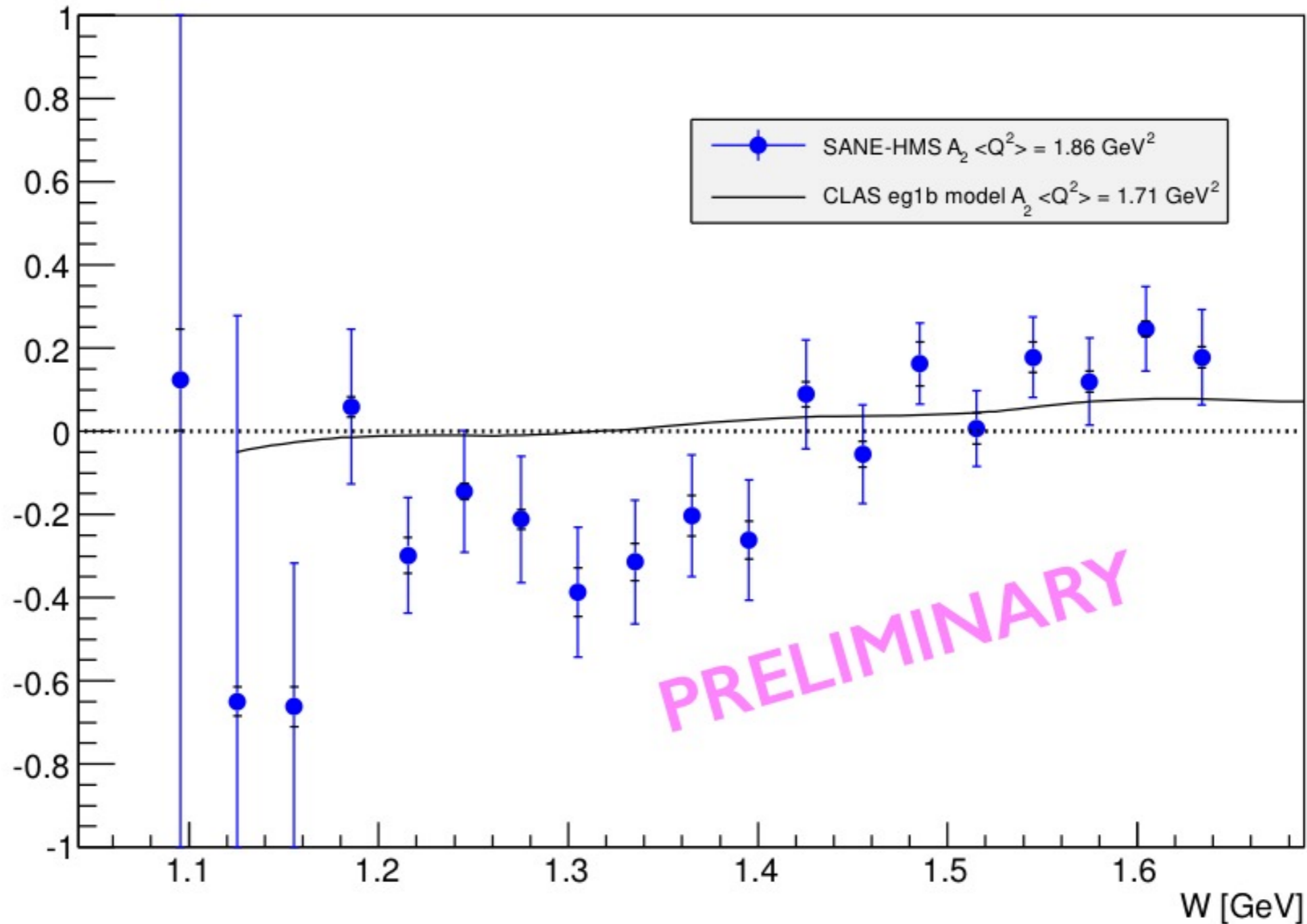
$g_1$

$g_2$





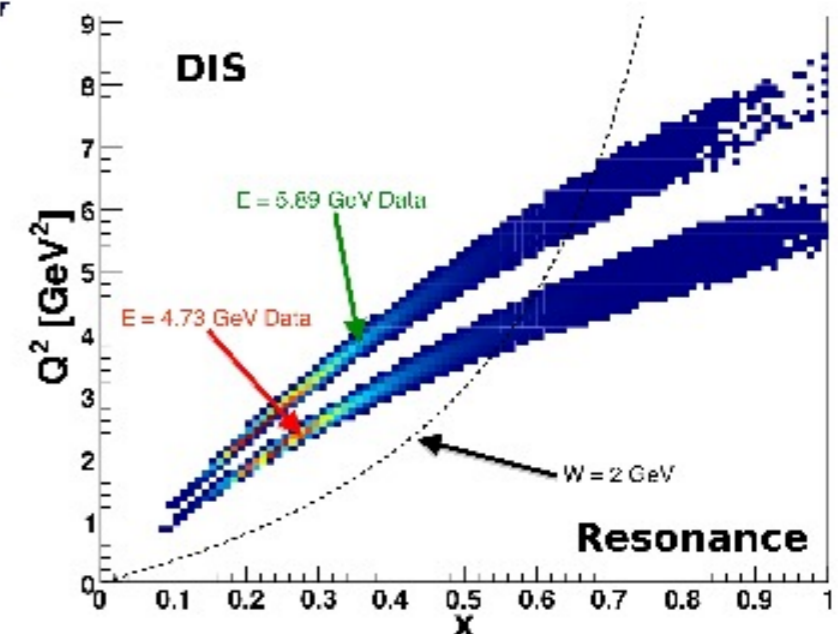
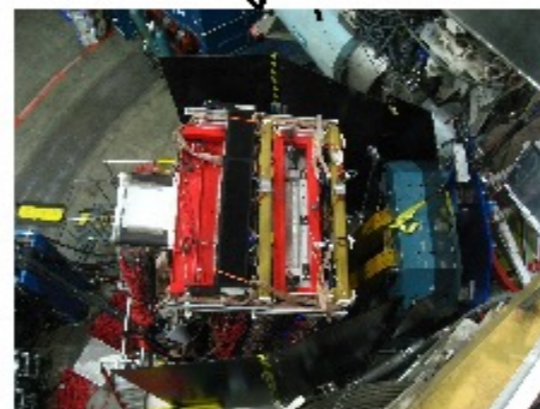
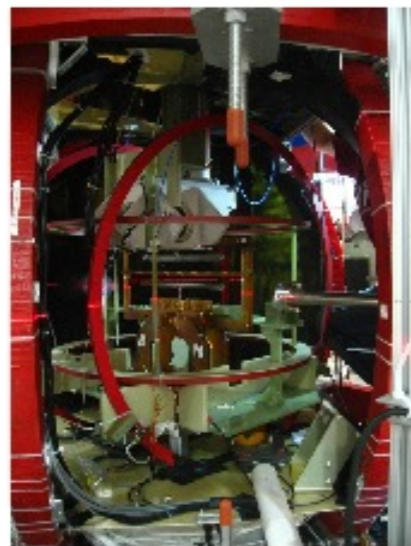
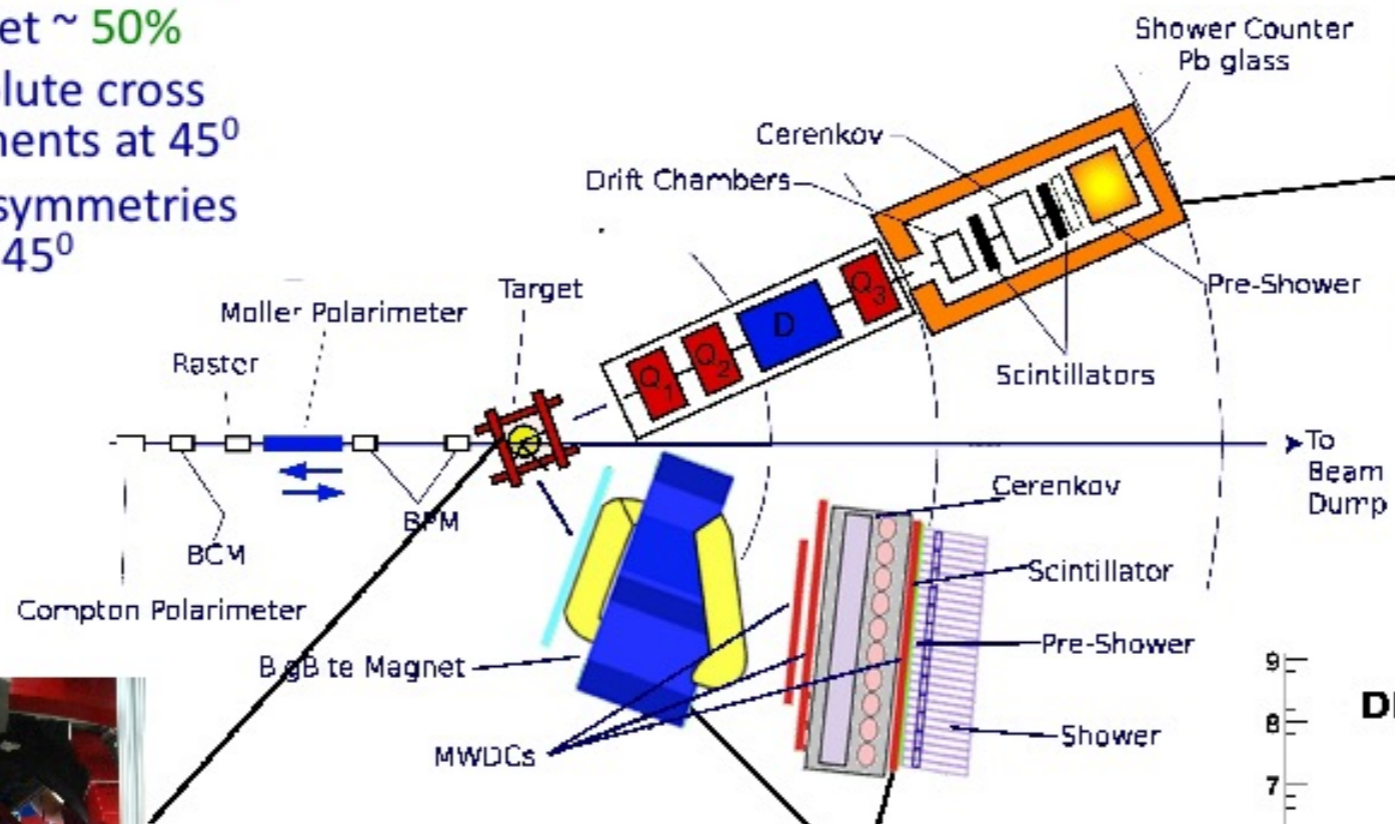
# Proton $A_2$ and Model



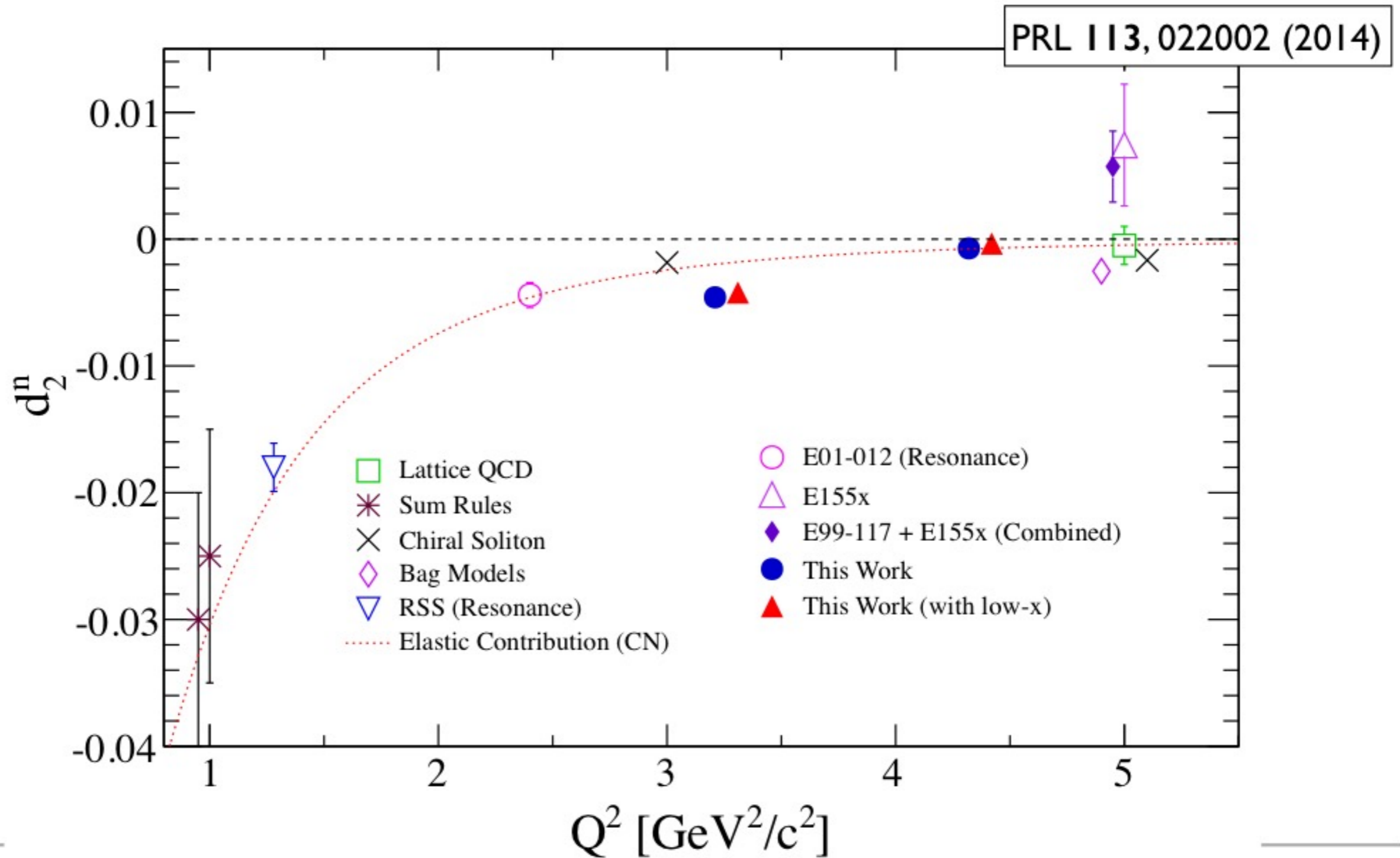
# Precision Measurement of $d_2^n$

# New Experiment at JLab

- ⊙ Polarized electron beam:  $E=4.74, 5.89$  GeV, polarization  $\sim 71\%$
- ⊙ Polarized  $^3\text{He}$  target  $\sim 50\%$
- ⊙ HRS used for absolute cross section measurements at  $45^\circ$
- ⊙ Bigbite used for asymmetries measurements at  $45^\circ$



# $d_2^n$ Results

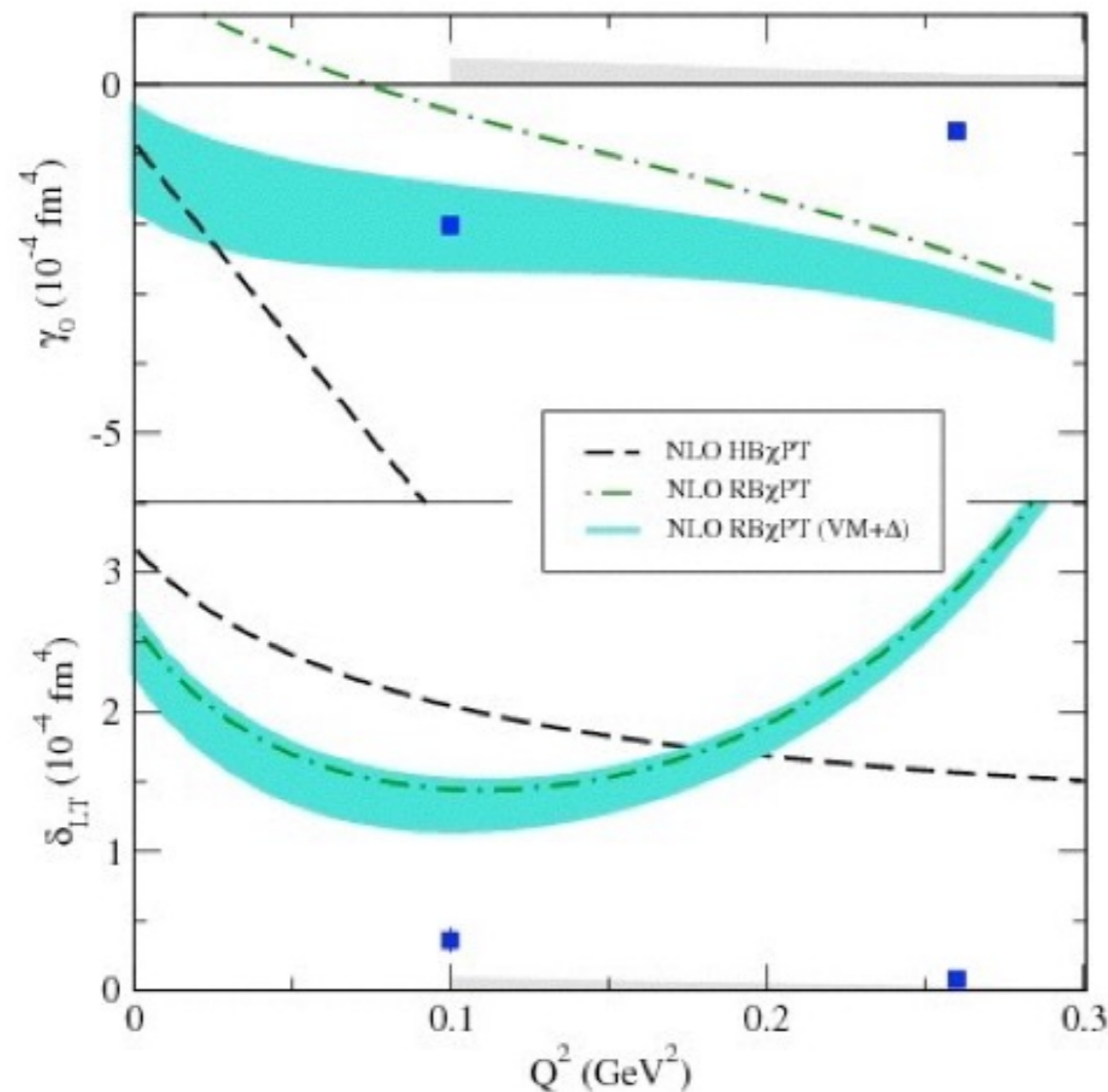




# Spin Polarizabilities at Small $Q^2$

# Neutron Spin Polarizabilities at Low $Q^2$

## Neutron (E94010)



$$\gamma_0 = \frac{16\alpha M^2}{Q^6} \int_x^{x_0} x^2 \left[ g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right]$$

$$\delta_{LT} = \frac{16\alpha M^2}{Q^6} \int_x^{x_0} x^2 [g_1 + g_2]$$

Possible clue from **isospin combination** with similar data on the **proton**

# E08-027 : Proton $g_2$ Structure Function

Fundamental spin observable has never been measured at low or moderate  $Q^2$

A<sup>-</sup> rating by PAC33

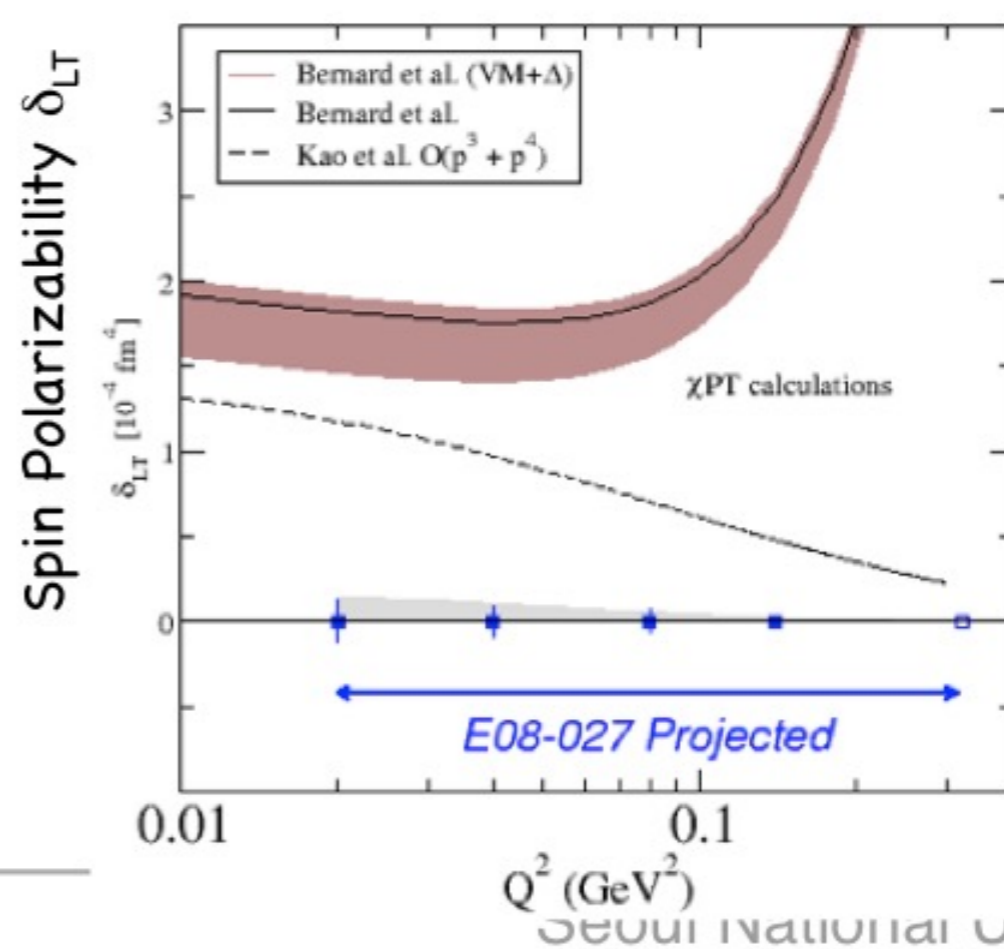
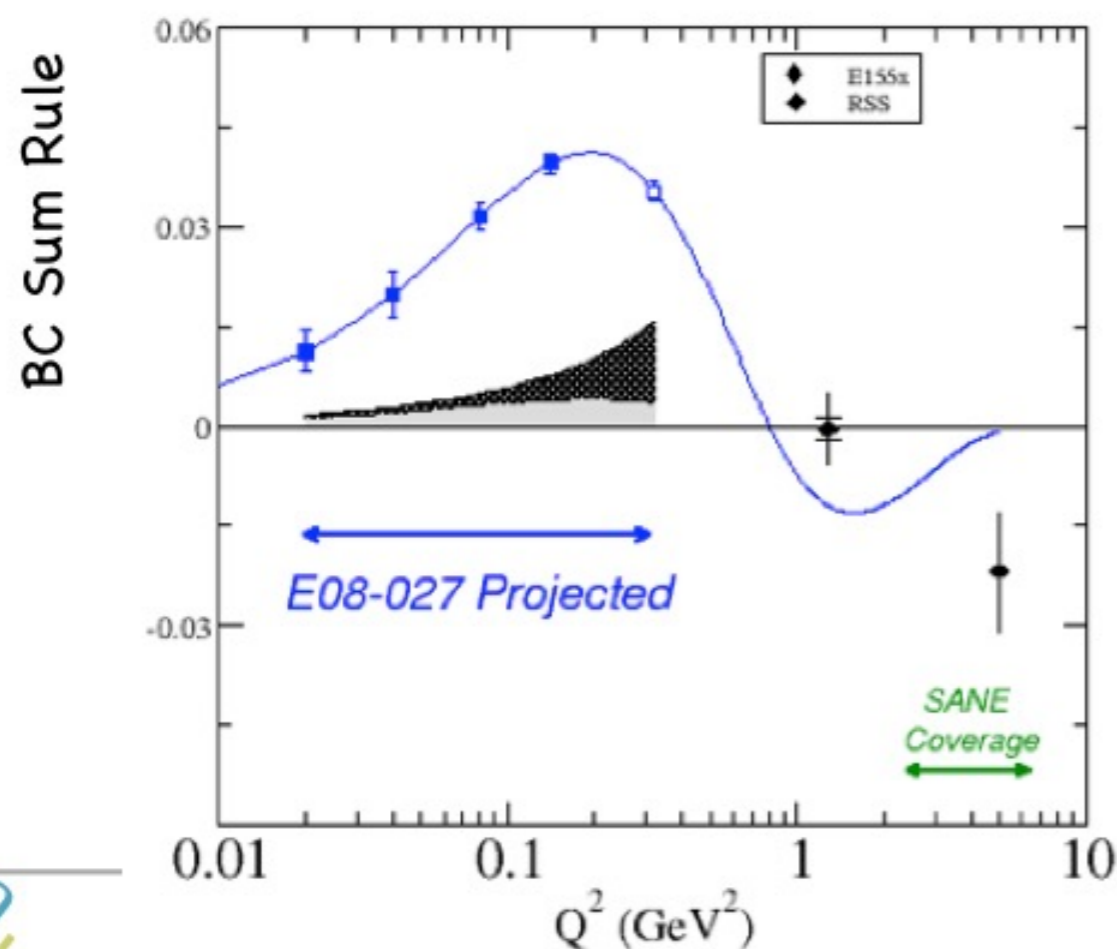
Spokesmen: Camsonne, Crabb, Chen, Slifer

**BC Sum Rule** : violation suggested for proton at large  $Q^2$ , but found satisfied for the neutron &  $^3\text{He}$ .

**Spin Polarizability** : Major failure ( $>8\sigma$ ) of  $\chi\text{PT}$  for neutron  $\delta_{\text{LT}}$ . Need  $g_2$  isospin separation to solve.

**Hydrogen HyperFine Splitting** : Lack of knowledge of  $g_2$  at low  $Q^2$  is one of the leading uncertainties.

**Proton Charge Radius** : one of the leading uncertainties in extraction of  $\langle R_p \rangle$  from  $\mu\text{-H}$  Lamb shift.





# Experiment Overview

## Polarized proton target

upstream chicane

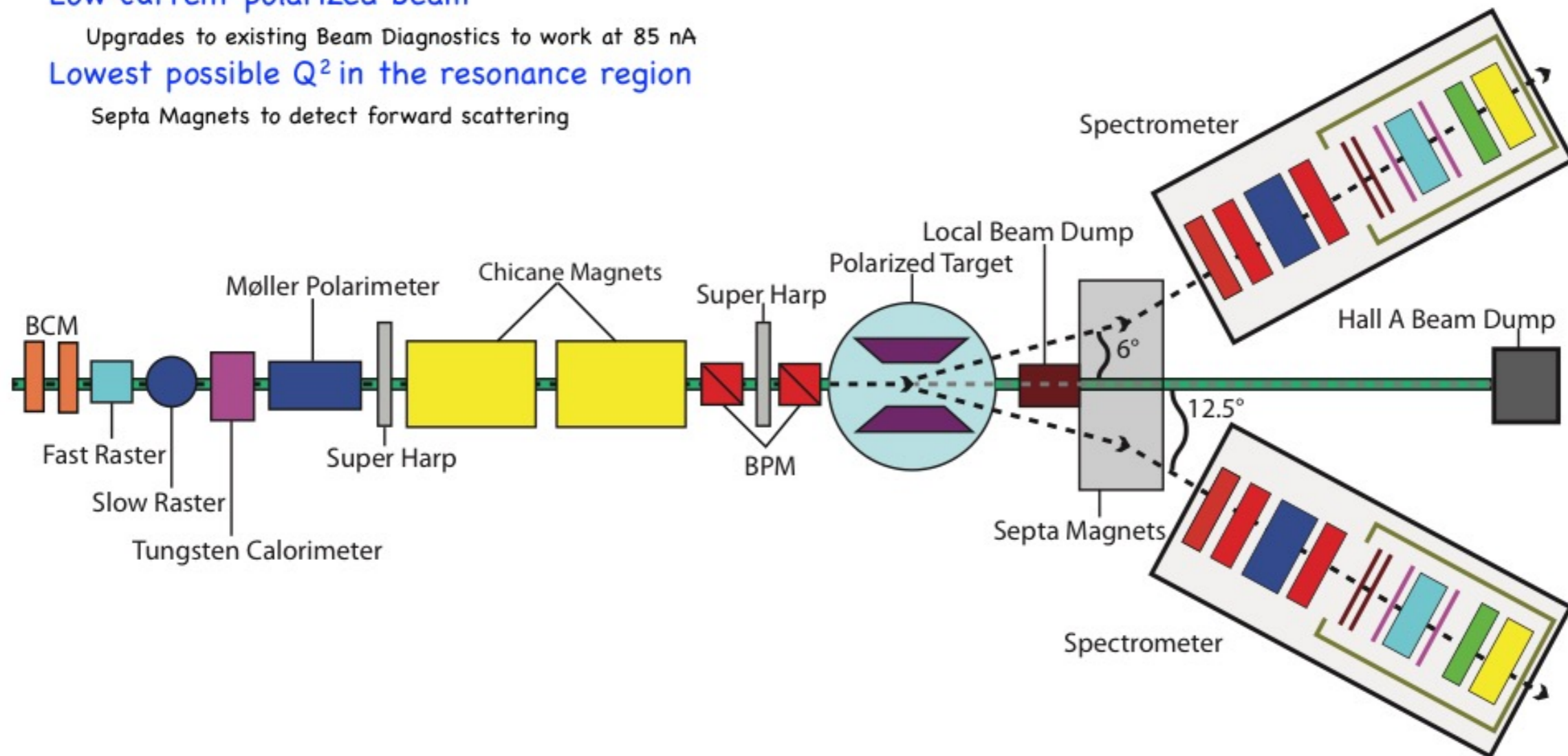
downstream local dump

## Low current polarized beam

Upgrades to existing Beam Diagnostics to work at 85 nA

## Lowest possible $Q^2$ in the resonance region

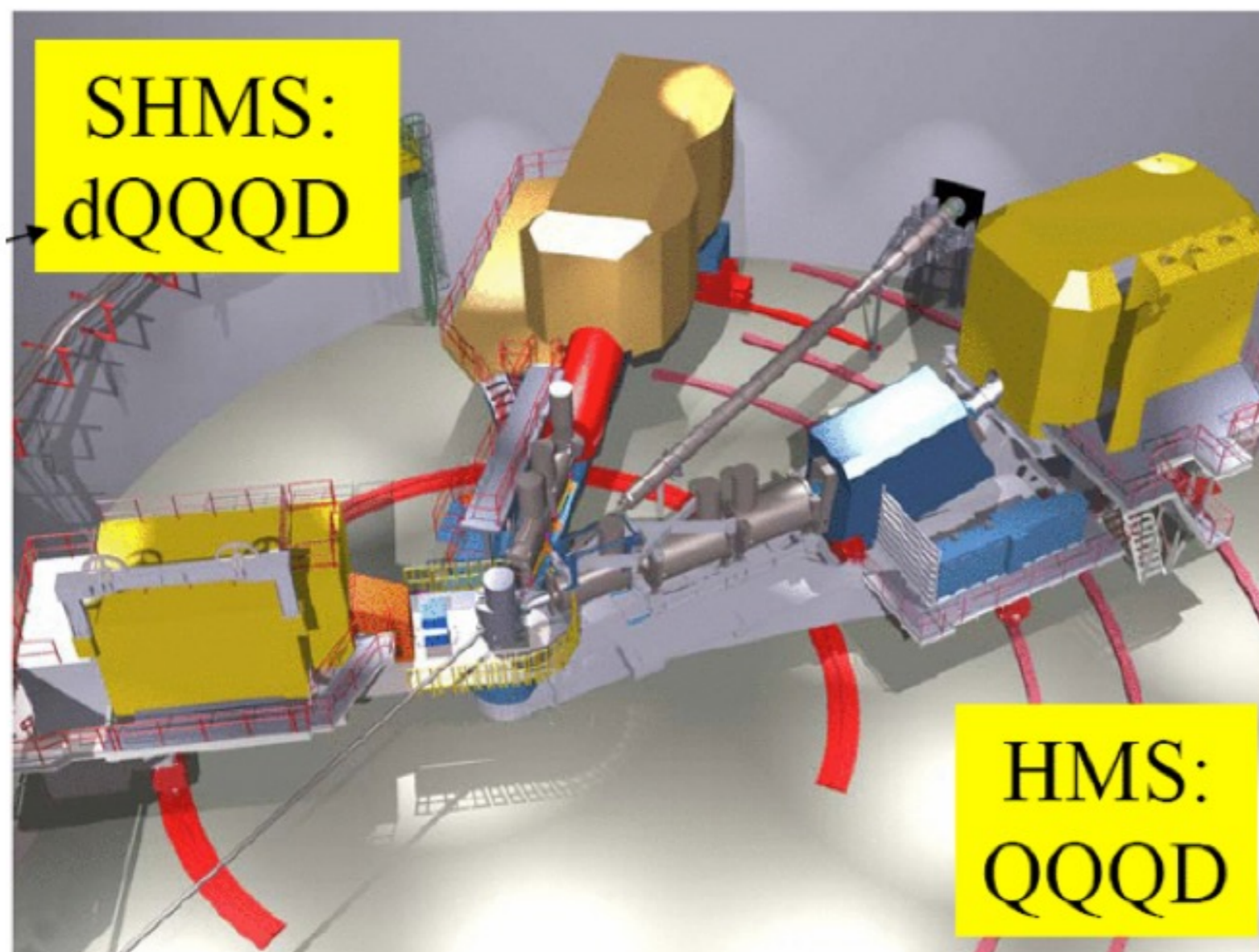
Septa Magnets to detect forward scattering





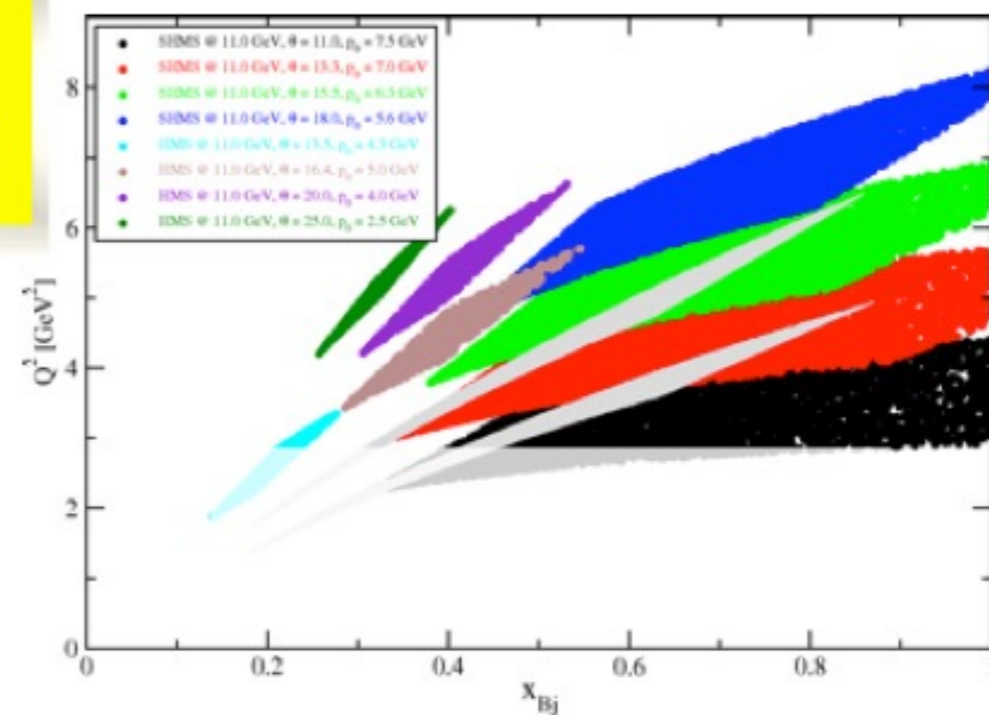
# Spin Structure Functions at 12 GeV

# E12-06-121: $d_2^n, g_2^n$

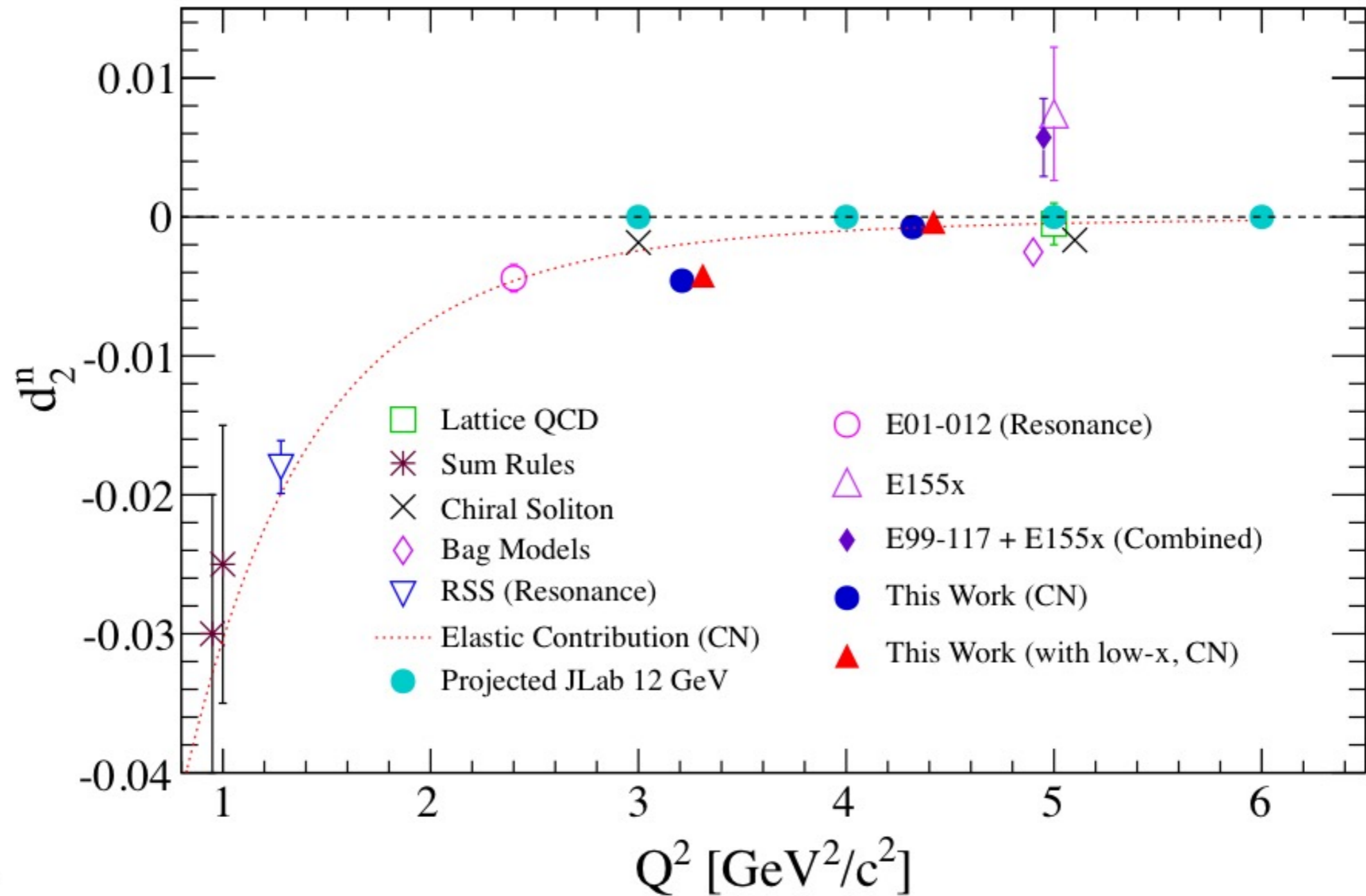


- Hall C: SHMS + HMS
- One beam energy
  - 11 GeV
- Each arm measures a total cross section independent of the other arm.
- Experiment split into **four pairs of 125 hour runs** with spectrometer motion in between.

- SHMS collects data at  $\Theta = 11^\circ, 13.3^\circ, 15.5^\circ$  and  $18.0^\circ$  for 125 hrs each
  - data from each setting divided into 4 bins
- HMS collects data at  $\Theta = 13.5^\circ, 16.4^\circ, 20.0^\circ$  and  $25.0^\circ$  for 125 hrs each



# JLab 12 Projection of $d_2^n$





# Summary

- Extensive measurements for  $g_1$  over large  $Q^2$  region
  - Both for the proton and the neutron
  - New efforts to go down to very low  $Q^2$  (**EG4**)
- Limited data for  $g_2$ , especially for the proton
  - Precision measurements of  $g_2/d_2$ : higher twists
  - Puzzles in generalized spin polarizabilities at low  $Q^2$ 
    - Test of  $\chi$ PT calculations:  $\delta_{LT}$  puzzle
  - New data will be available
    - for the proton (**SANE, E08027**)
    - for the neutron (**E97110, E06014**)
- Continues at 12 GeV