Measurement of the Q^2-dependence of the Neutron Spin Structure Function g_2^n in the Range

$$0.57\ \mathrm{GeV}^2 \leq Q^2 \leq 1.34\ \mathrm{GeV}^2$$

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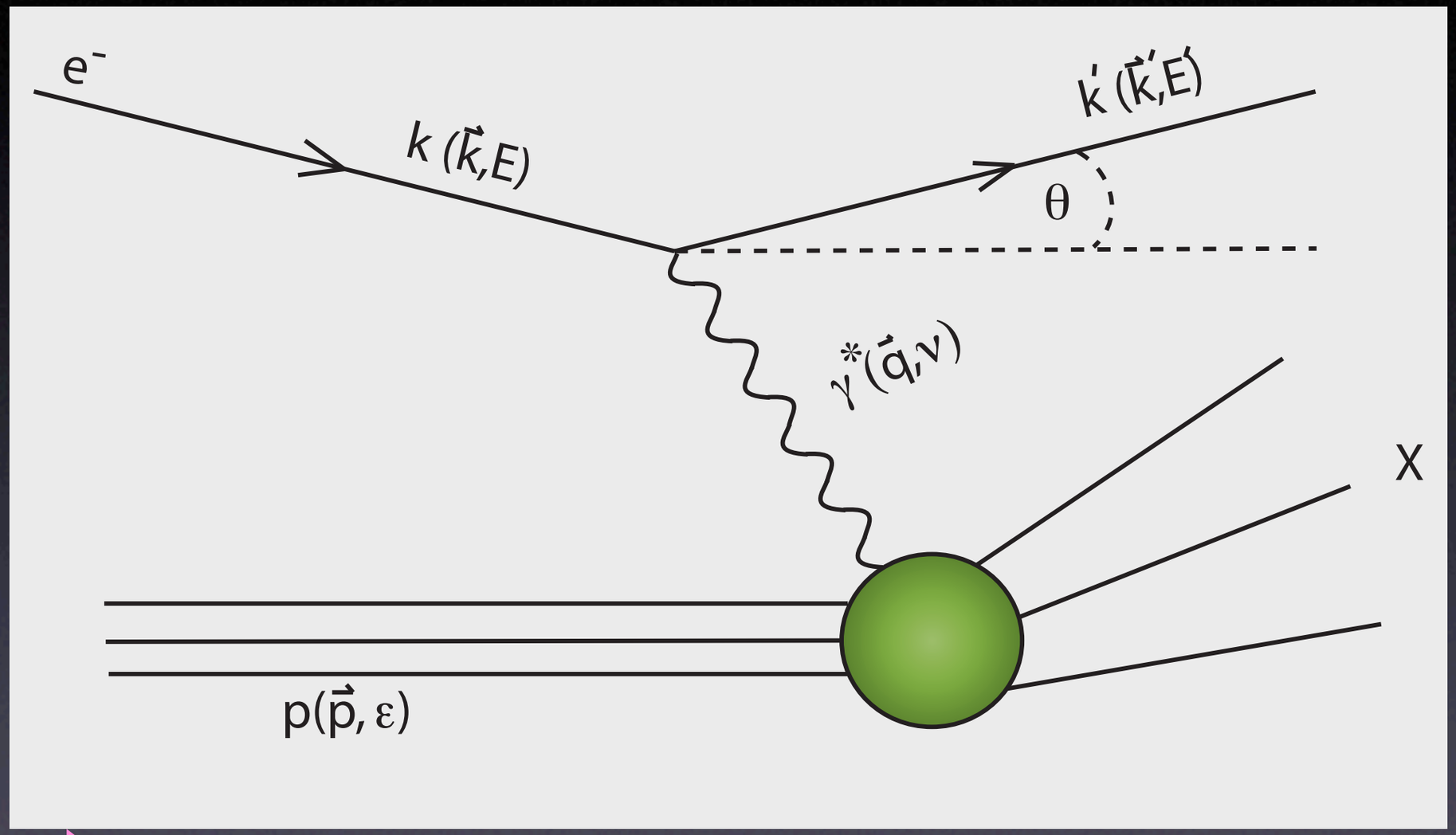
Jefferson Lab Seminar

A Brief Summary of Spin-Structure Studies using Deep-Inelastic Scattering

- Deep-Inelastic Scattering measurements use high-energy leptons to probe asymptotically free quarks
- In the mid-80s, physicists became interested in the distribution of spin in nucleon (quarks? gluons? angular momentum?)
- Double-polarization inclusive DIS experiments can be used to isolate the spin-dependent properties of quarks

Deep-Inelastic Scattering Terminology



$Q^2 = -q^2 =$ virtual four – momentum squared

$x = \dfrac{Q^2}{2M\nu} =$ Bjorken scaling parameter

$W^2 = M^2 + 2M\nu - Q^2 =$ Invariant mass squared of final hadronic system

The Structure of the DIS Cross-section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{q^4}\frac{E'}{E}L_{\mu\nu}W^{\mu\nu}$$

$L_{\mu\nu}$ Leptonic Tensor calculable from QED

$W^{\mu\nu} = W_S^{\mu\nu} + W_A^{\mu\nu}$ Hadron Tensor is the nucleon structure and can be seperated into spin-independent and spin-dependent parts

Spin-independent cross-section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{F_2(x,Q^2)}{\nu}\cos^2\frac{\theta}{2} + \frac{2F_1(x,Q^2)}{M}\sin^2\frac{\theta}{2}\right)$$

$F_1(x,Q^2)$ and $F_2(x,Q^2)$ are the spin-independent structure functions

- In the DIS region ($W \geq 2.0$ GeV), these functions are characterized by Bjorken Scaling
- Functions are essentially dependent only on scaling parameter *x*, with only a slowly evolving dependence on Q^2

Spin-Dependent Cross-section

Target polarized parallel to beam :

$$\frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 EM\nu}\left[\left(E + E'\cos\theta\right) g_1(x,Q^2) - 2xMg_2(x,Q^2)\right]$$

Target polarized perpendicular to beam :

$$\frac{d^2\sigma^{\downarrow\Leftarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Leftarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 EM\nu} E'\sin\theta\left[g_1(x,Q^2) + \frac{4xEM}{Q^2} g_2(x,Q^2)\right]$$

g_2 is sometimes known as the transverse spin-structure function

Understanding the Spin-Structure Functions

- The Quark-Parton Model provides a useful interpetive framework for answering the initial questions about the distribution of spin in the nucleon

$$g_1^p = \frac{4}{18}\Delta u(x,Q^2) + \frac{1}{18}\Delta d(x,Q^2) + \frac{1}{18}\Delta s(x,Q^2)$$

$$g_1^n = \frac{4}{18}\Delta d(x,Q^2) + \frac{1}{18}\Delta u(x,Q^2) + \frac{1}{18}\Delta s(x,Q^2)$$

The polarized parton functions are mostly functions of x with the Q^2 evolution described by the DGLAP equations

Physics beyond naive QPM

QPM obviously lacks important physics (quark-gluon interactions!)

The naive model even predicts:

$$g_2 = 0$$

A QPM with some transverse momentum predicts:

$$g_2 = \frac{1}{2} \sum_q e_q^2 \left(\frac{m_q}{xM} - 1 \right)$$

Operator Product Expansion

The operator product expansion (OPE) can deconstruct the spin-structure functions using the formalism of QCD

$$\lim_{q\to\infty}\int d^4z e^{iq\cdot z} O_a(z) O_b(0) = \sum_k c_{abk}(q) O_k(0)$$

expands the product of operators into a sum of over a set of coefficients and operators

Applying OPE to Electron Scattering

The scattering matrix is a product of two current operators

$$T_{\mu\nu} = i \int d^4 z e^{iq\cdot z} \langle N | \mathcal{T}(j_\mu(z) j_\nu(0)) | N \rangle$$

and can be written using OPE as

$$T_{\mu\nu} = \sum_k c_{\mu_1..\mu_n k} O_{k,V}^{\mu_1 \ldots \mu_n}$$

Operators in OPE

Operator of an asymptotically free quark

$$O_{V,a}^{\mu_1 \ldots \mu_n} = \frac{1}{2}\left(\frac{i}{2}\right)^{n-1} S\left\{\overline{\psi_a}\gamma^{\mu_1} D^{\mu_1} \ldots D^{\mu_n} \psi_a\right\}$$

Operator with gluon fields

$$O_{V,a}^{\mu_1 \ldots \mu_n} = -\frac{1}{2}\left(\frac{i}{2}\right)^{n-2} S\left\{G_a^{\mu_1 \alpha}\gamma^{\mu_1} D^{\mu_1} \ldots D^{\mu_n} G_{a\alpha}^{\mu_n}\right\}$$

The dimension and spin of the operator is determined by the fields

The Concept of Twist

The spin and dimension of the operator determine how the momentum vectors contract

$$c_{\mu_1 \ldots \mu_n} O_{d,n}^{\mu_1 \ldots \mu_n} \rightarrow \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2+n-d} = \left(\frac{1}{x}\right)^n \left(\frac{Q}{M}\right)^{2-t}$$

$$\text{twist } = t = d - n$$

Operators in the OPE will group by twist and the therefore can be separated by Q^2 evolution! Useful!

Wandzura-Wilczek Relation

- Leading order twist term (twist=2) in g_2 can be written in terms of g_1

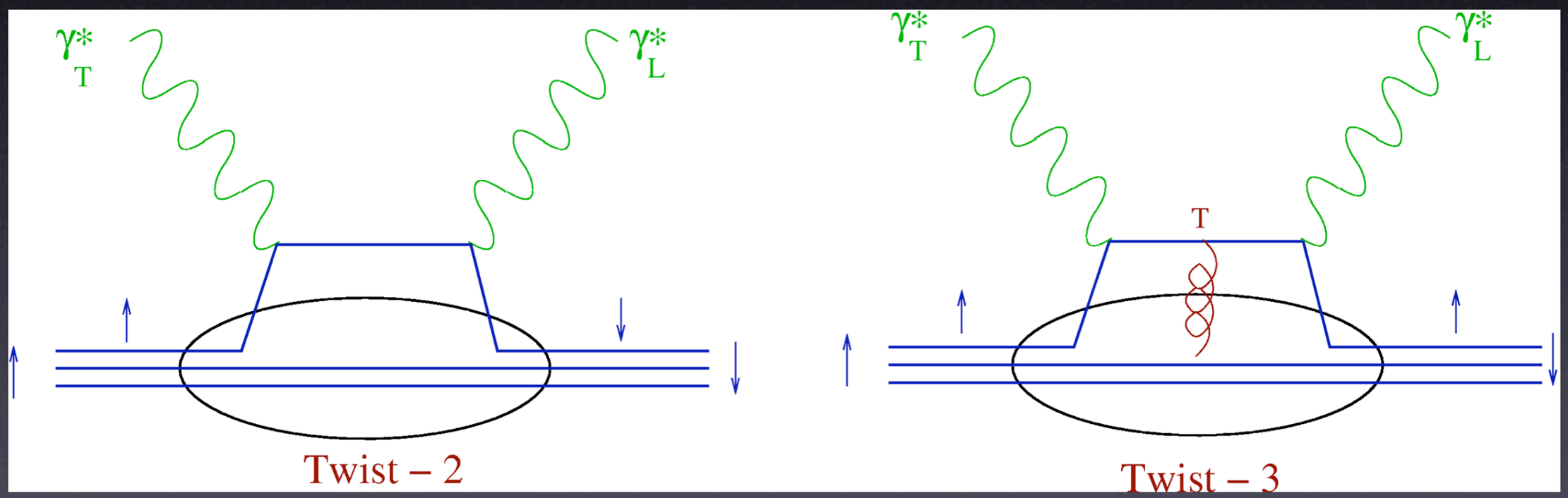
$$g_2^{\mathrm{WW}}(x) = -g_1(x) + \int_x^1 g_1(x')\frac{dx'}{x'}$$

Can be derived from OPE by dropping all non-leading order terms

$$g_2(x) = g_2^{\mathrm{WW}}(x) + g_2^{\mathrm{ht}}(x)$$

The purpose of this experiments is to measure these higher twist terms

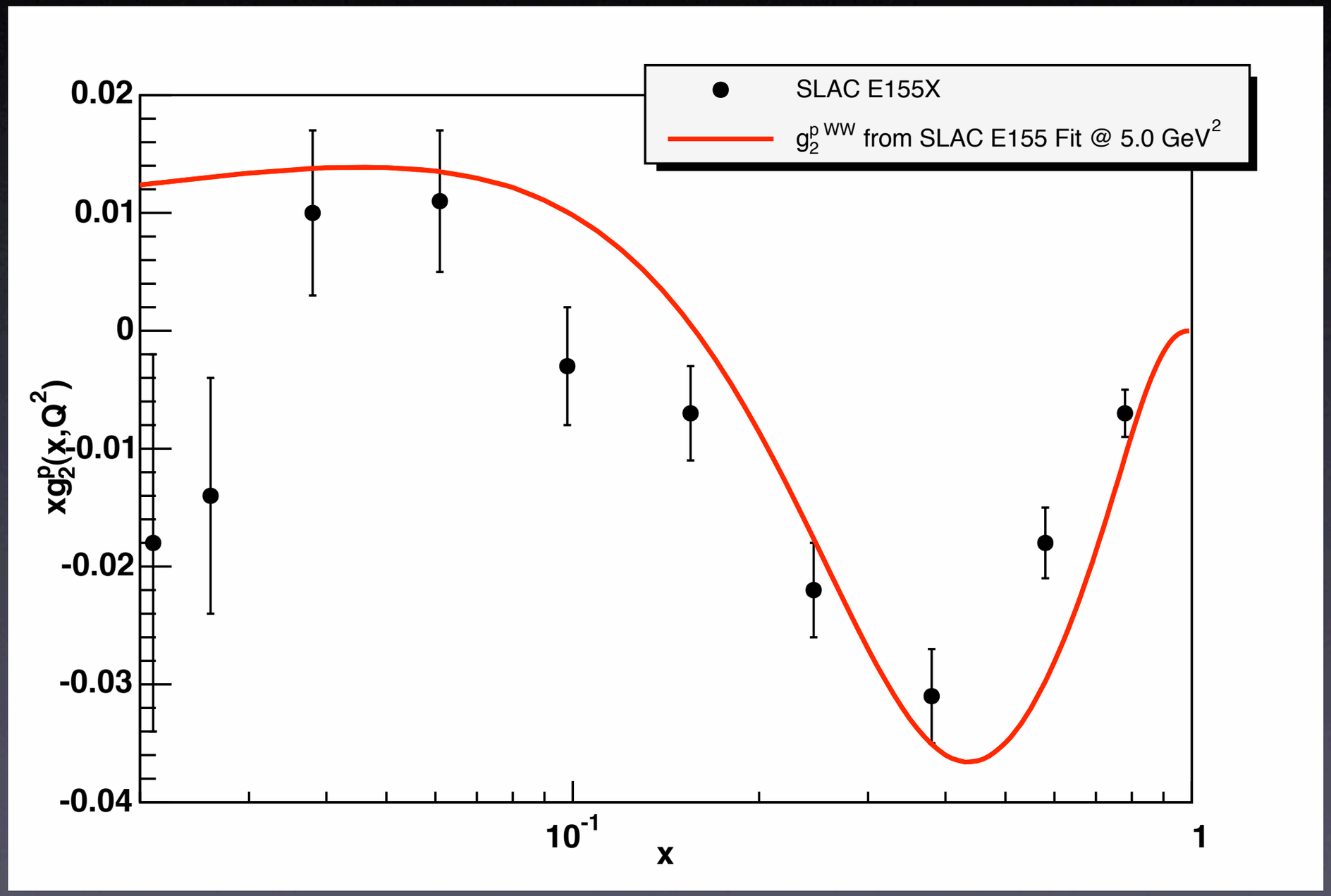
Example of Twist-2 and Twist-3 OPE Terms



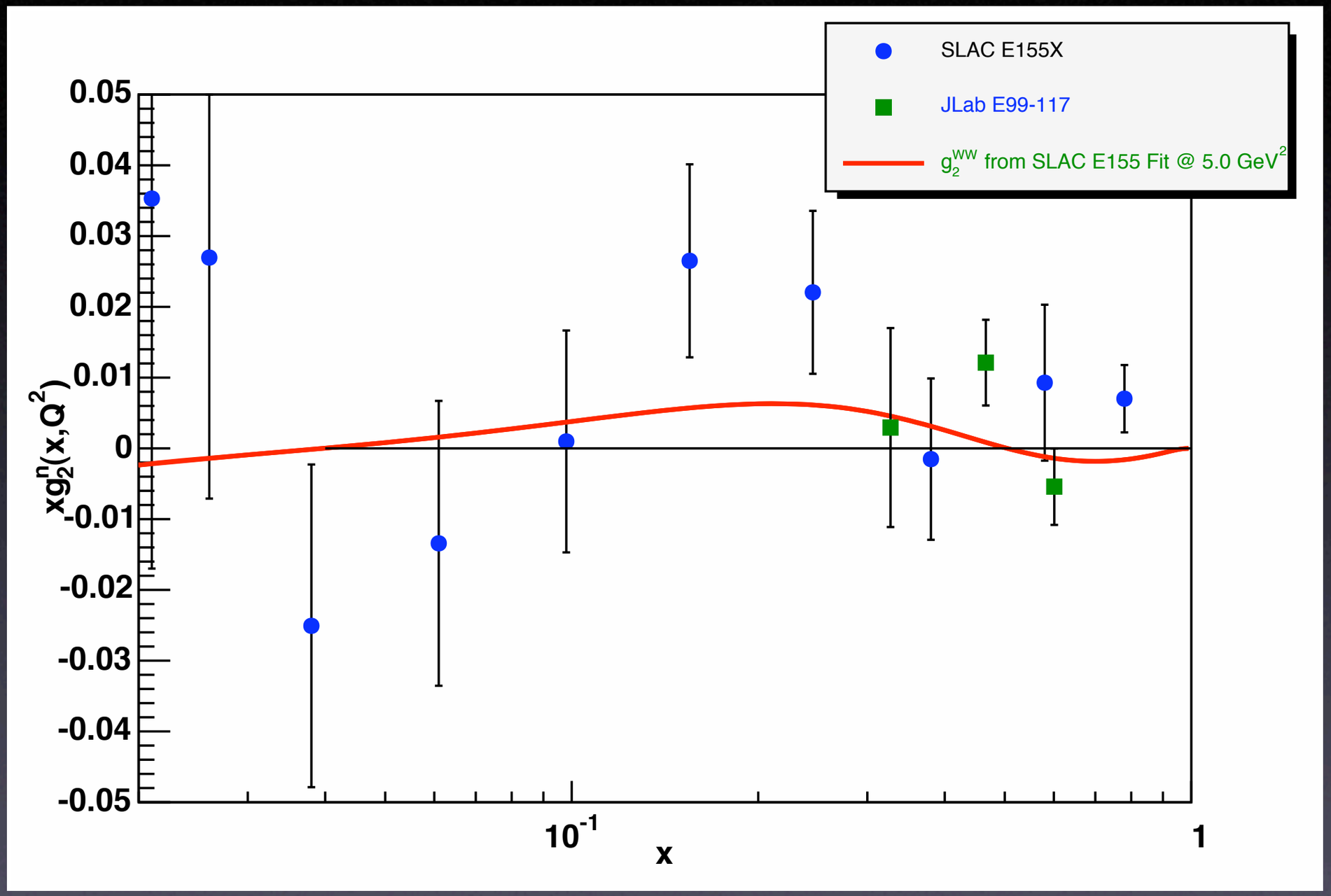
Where to Measure Higher Twists Terms?

- Lower Q^2 to see higher twists
- Not too low or into resonance region
- g_1 larger for proton than neutron, so easier to measure on neutron
- Experiment needs to be at constant x to see Q^2 evolution

World Data on g_2^p



World Data on g_2^n

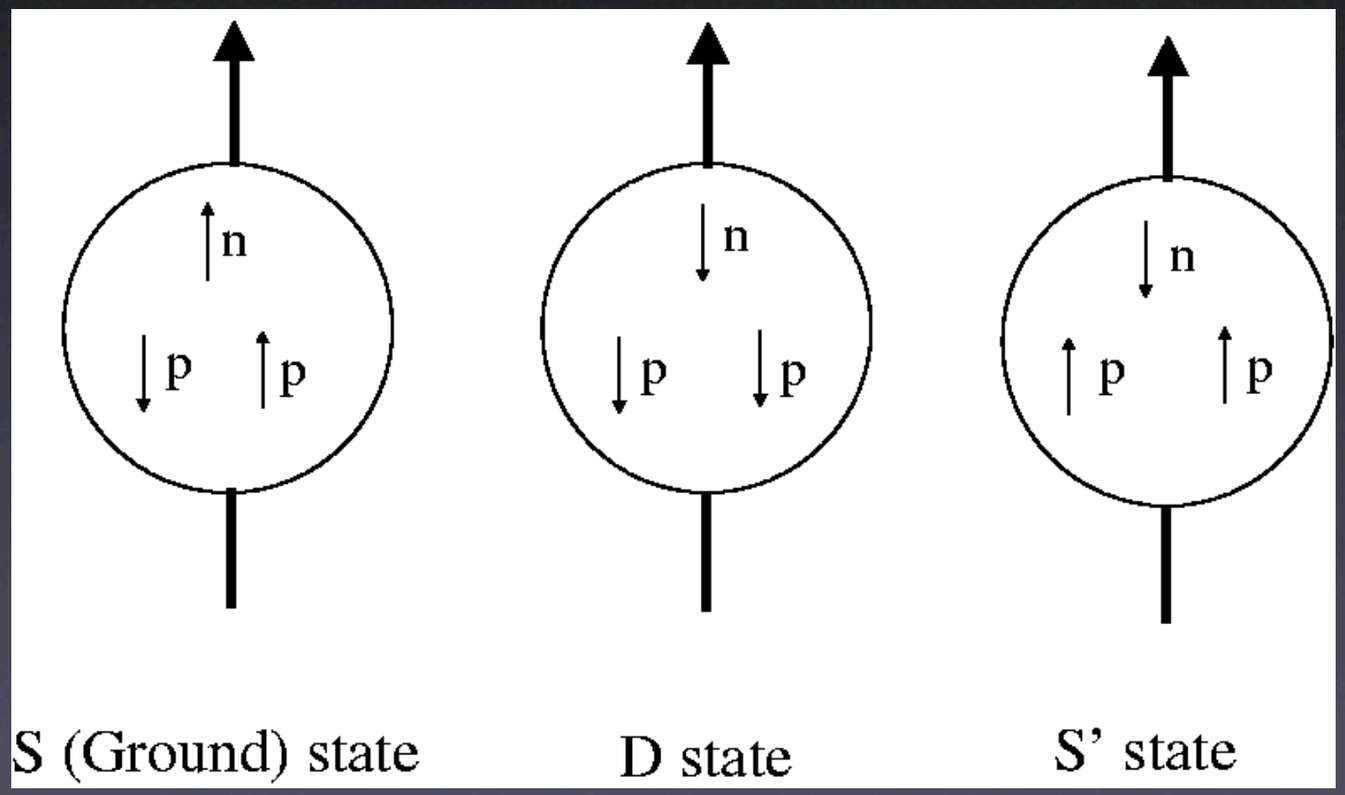


Measuring g_2^n

- Need both polarized target and polarized beam
- Measure cross-section differences
- Luminosity on polarized ^{3}He target superior to other polarized targets

Why use Polarized ^{3}He Target?

- No practical pure neutron target!
- Use polarized ^{3}He target as effective neutron target (86% of polarization comes from neutron)

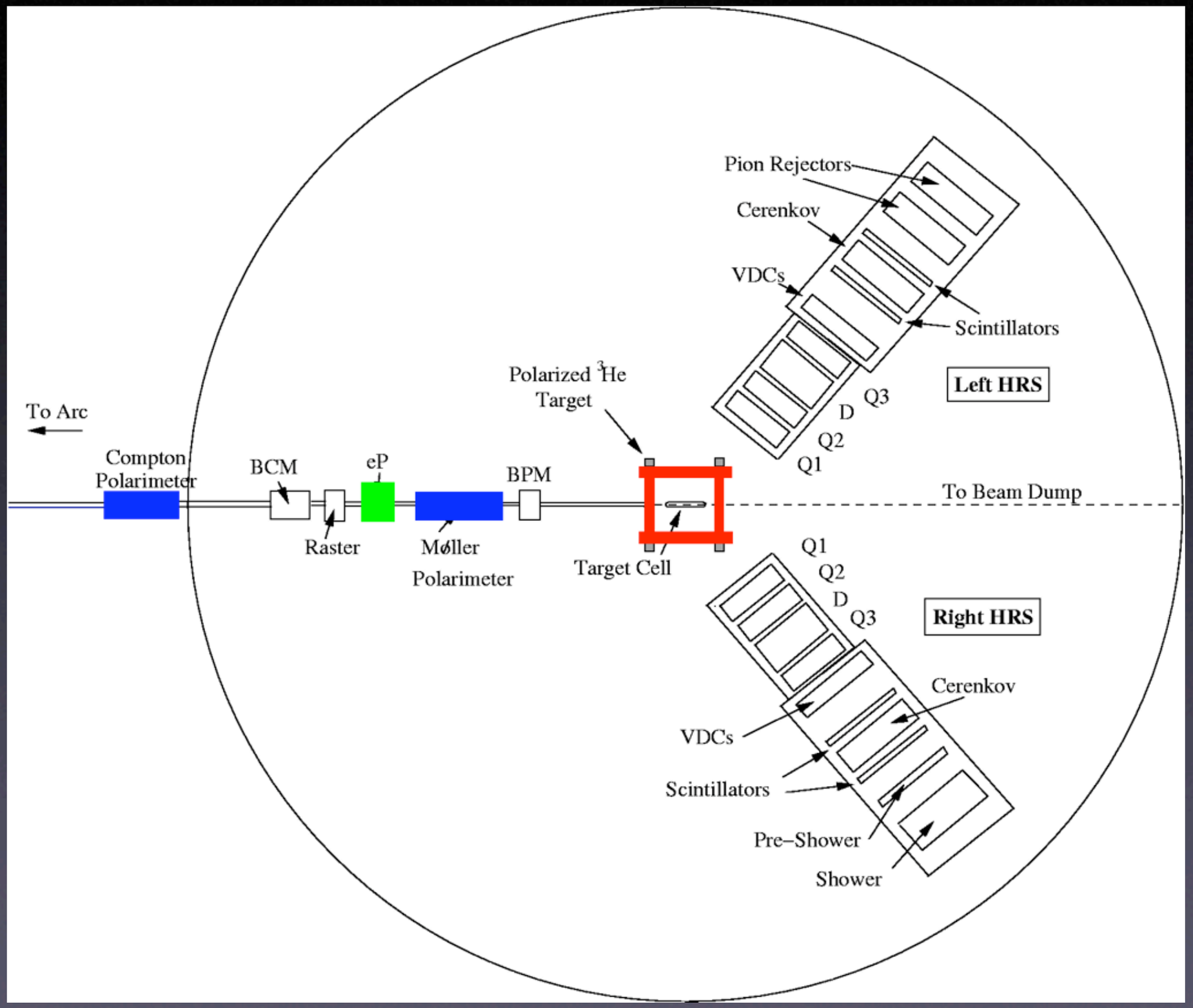


Jefferson Lab Experiment E97-103

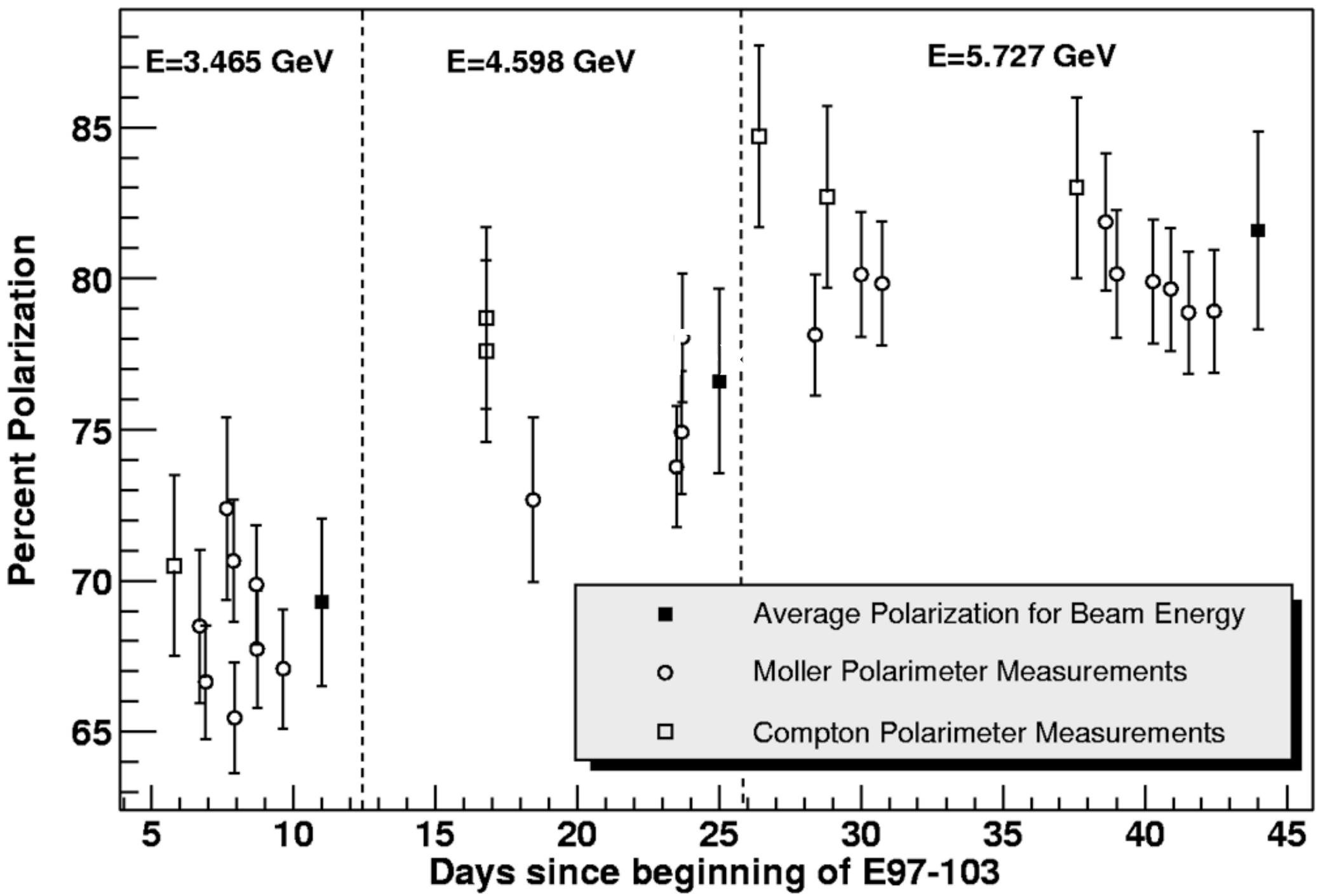
- Ran from 1 Aug 2001 - 17 Sep 2001
- Took place in experimental Hall A at JLab
- Used the Jefferson Lab polarized

E(GeV)	E'(GeV)	θ(degrees)	Q^2(GeV^2)	x	W(GeV)
3.465	1.600	18.6	0.571	0.163	1.95
4.598	2.290	15.8	0.781	0.188	2.10
4.598	1.990	18.6	0.942	0.192	2.20
5.727	2.630	15.8	1.127	0.194	2.36
5.727	2.270	18.6	1.341	0.202	2.46

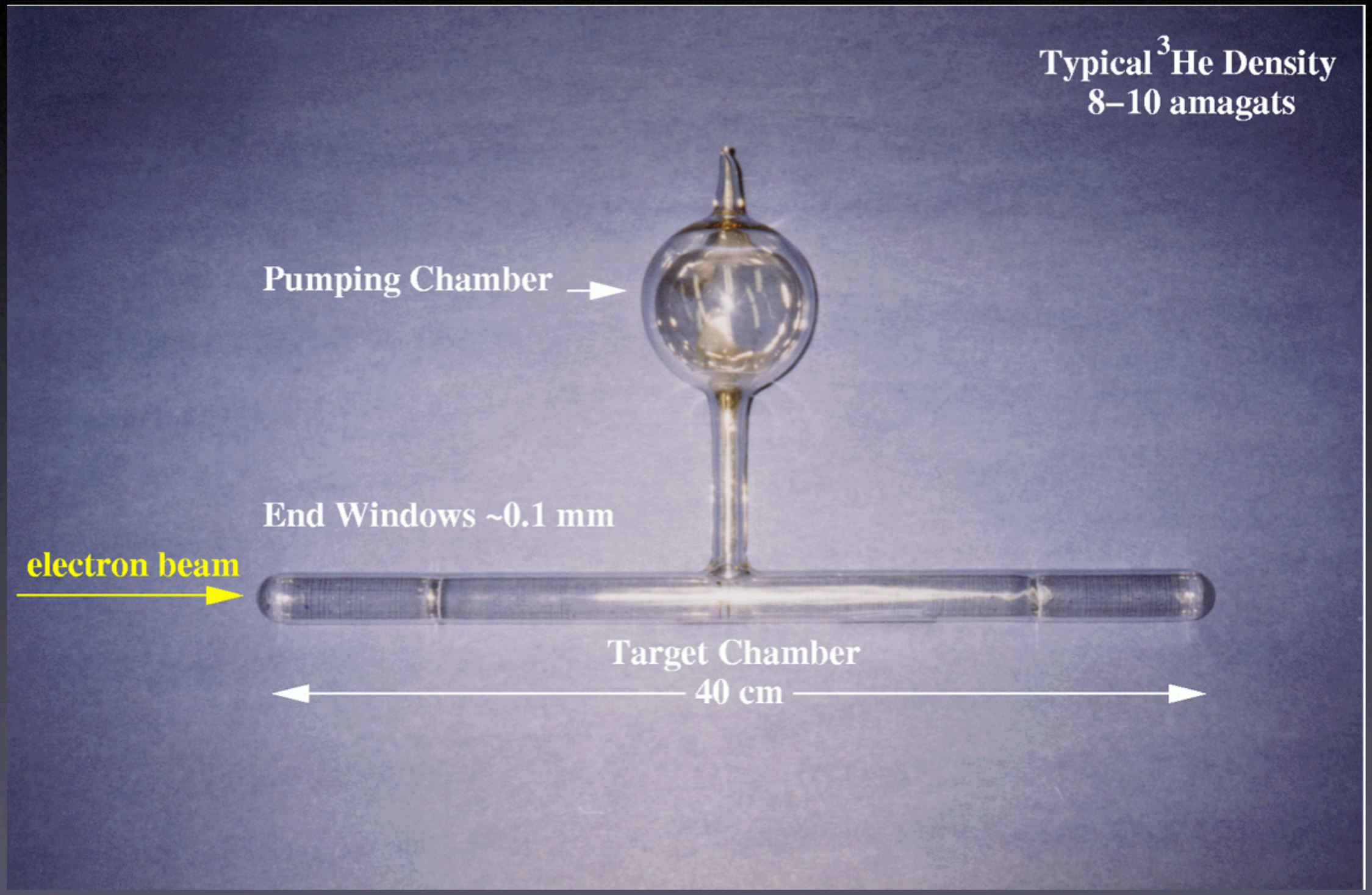
Hall A Configuration



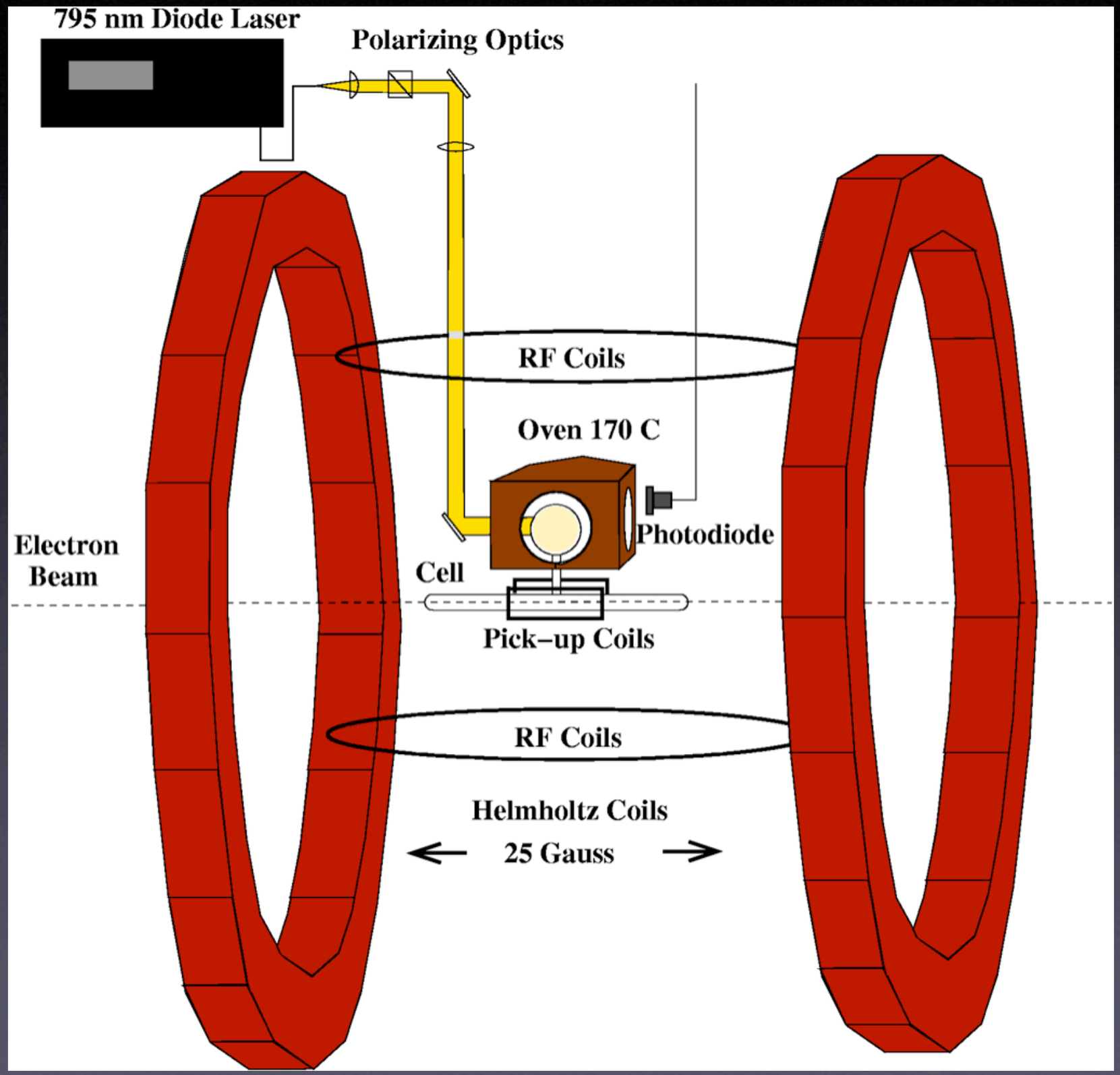
Beam Polarization in E97-103



Polarized ^{3}He Target Cell



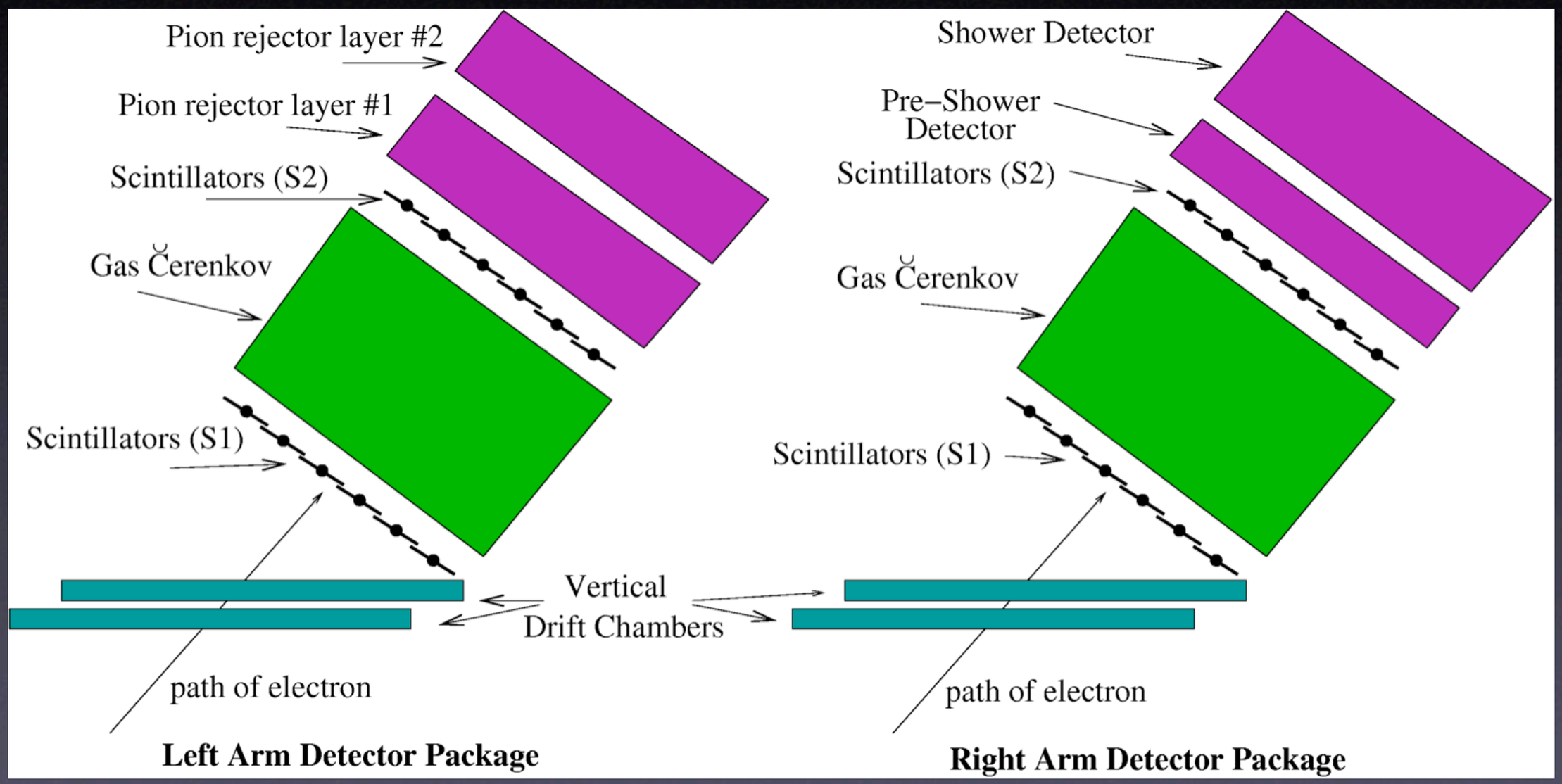
Polarized ^{3}He Target



Measuring Target Polarization

- Two Polarimetry Systems to reduce systematic error in the target polarization
- One measured nuclear magnetic resonance (NMR) of ^{3}He nuclei
- The other measures the electron paramagnetic resonance (EPR) of rubidium

Detector Package for E97-103



Detector Efficiencies

- **Vertical Drift Chambers -** 95-99% tracking effiency depending on rates
- **Scintillators -** Trigger efficiency of > 99.8%
- **Cerenkov -** Electron efficiency 99.9% (l), 99%(r), Pion Rejection factor 770 (l), 900 (r)
- **Lead Glass Detectors -** Electron efficiency 98% (l), 98% (r), Pion Rejection factor 38(l), 182(r)
- Pion rate 1x-4x electron rate, asymmetry larger

Raw Cross-Section Analysis

$$\sigma = \frac{N^{\text{data}}}{(Q/e)\eta_{\text{dt}}\eta_{\text{pid}}\eta_{\text{track}}\eta_{\text{trig.}}} \frac{N^{\text{MC}}_{\text{tot.}}}{N^{\text{MC}}_{\text{accp.}}\rho_{\text{tgt}}d_{\text{tgt,il}}\Delta\phi_{\text{il}}\Delta\theta_{\text{il}}}$$

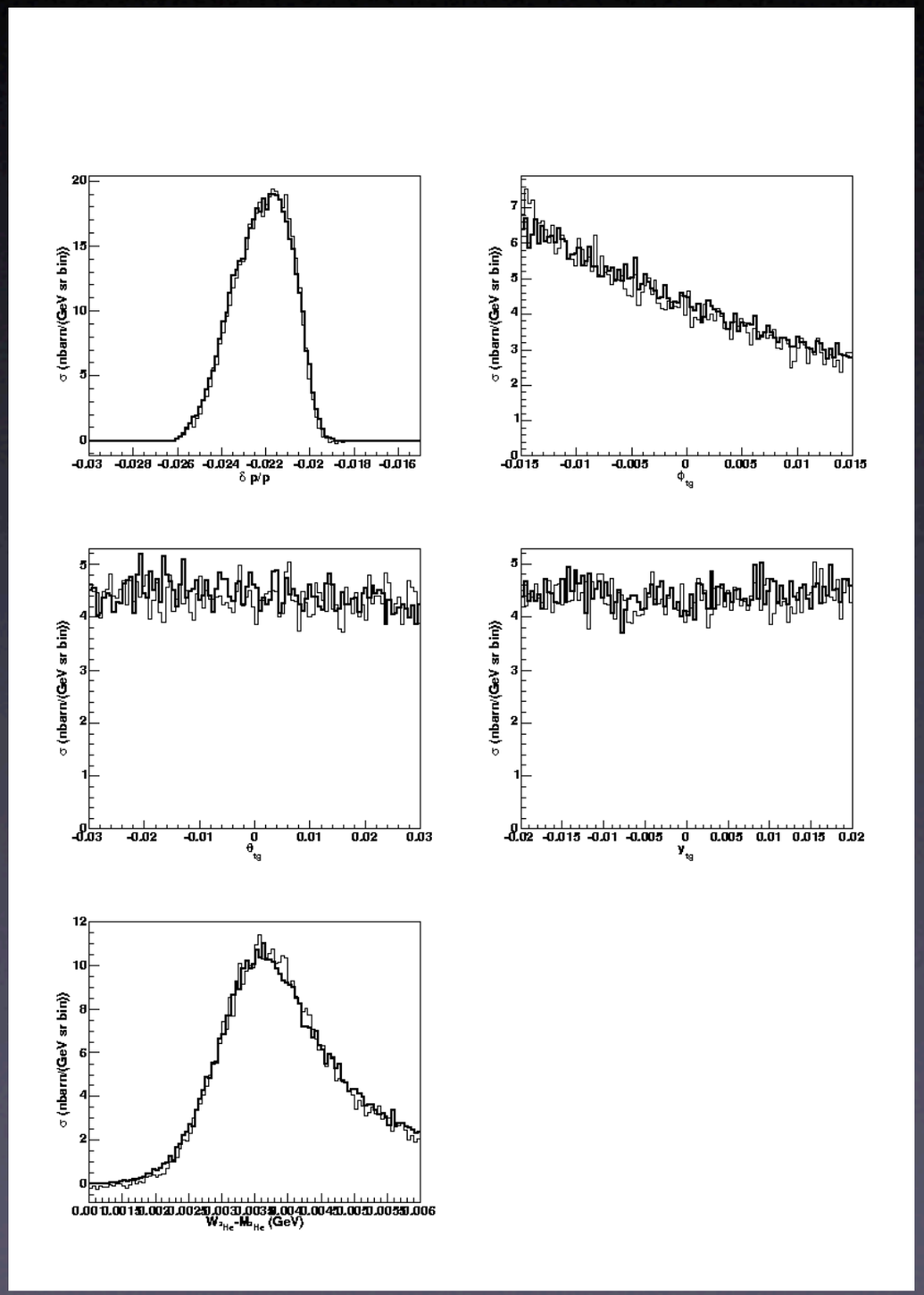
- Used SAMC Monte Carlo (A. Deur) with J. LeRose Spectrometer Optics Functions
- Checked Monte Carlo with ^{3}He Elastic Analysis

Comparison of Monte Carlo and Data

$\delta p/p$ →

θ_{tg} →

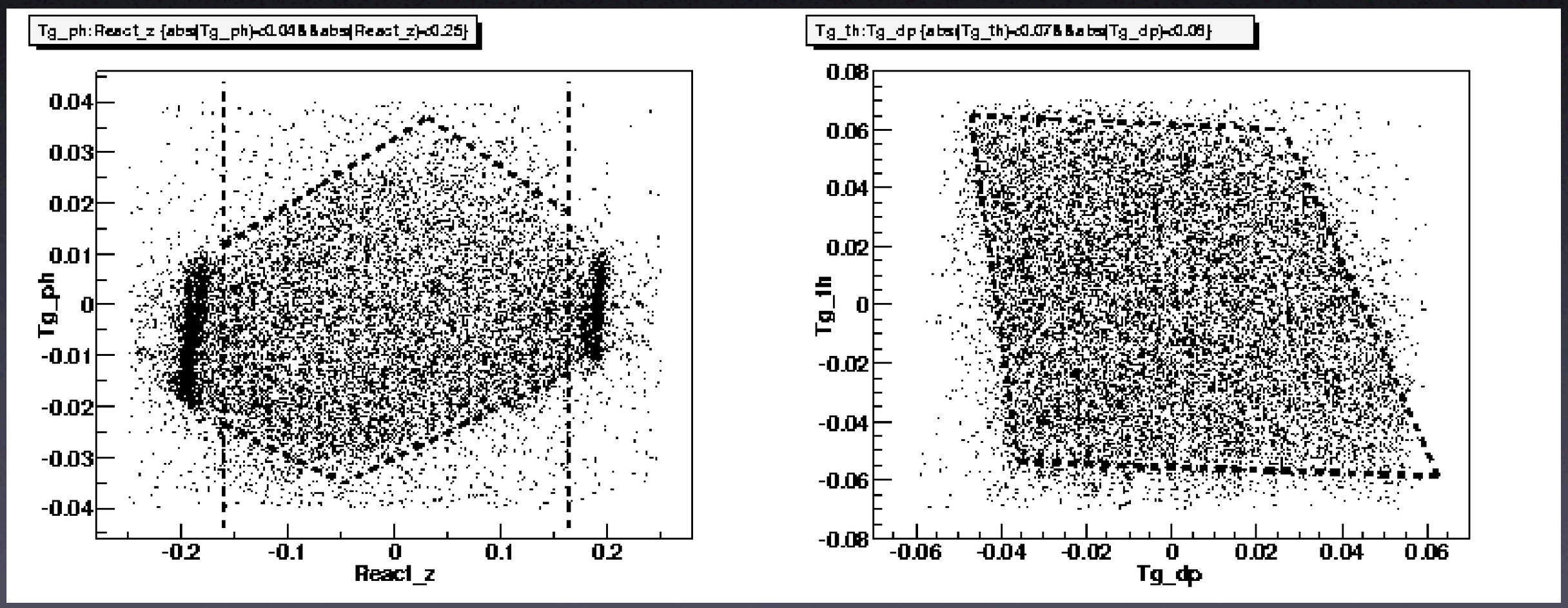
$W_{^3\mathrm{He}} - M_{^3\mathrm{He}}$ →



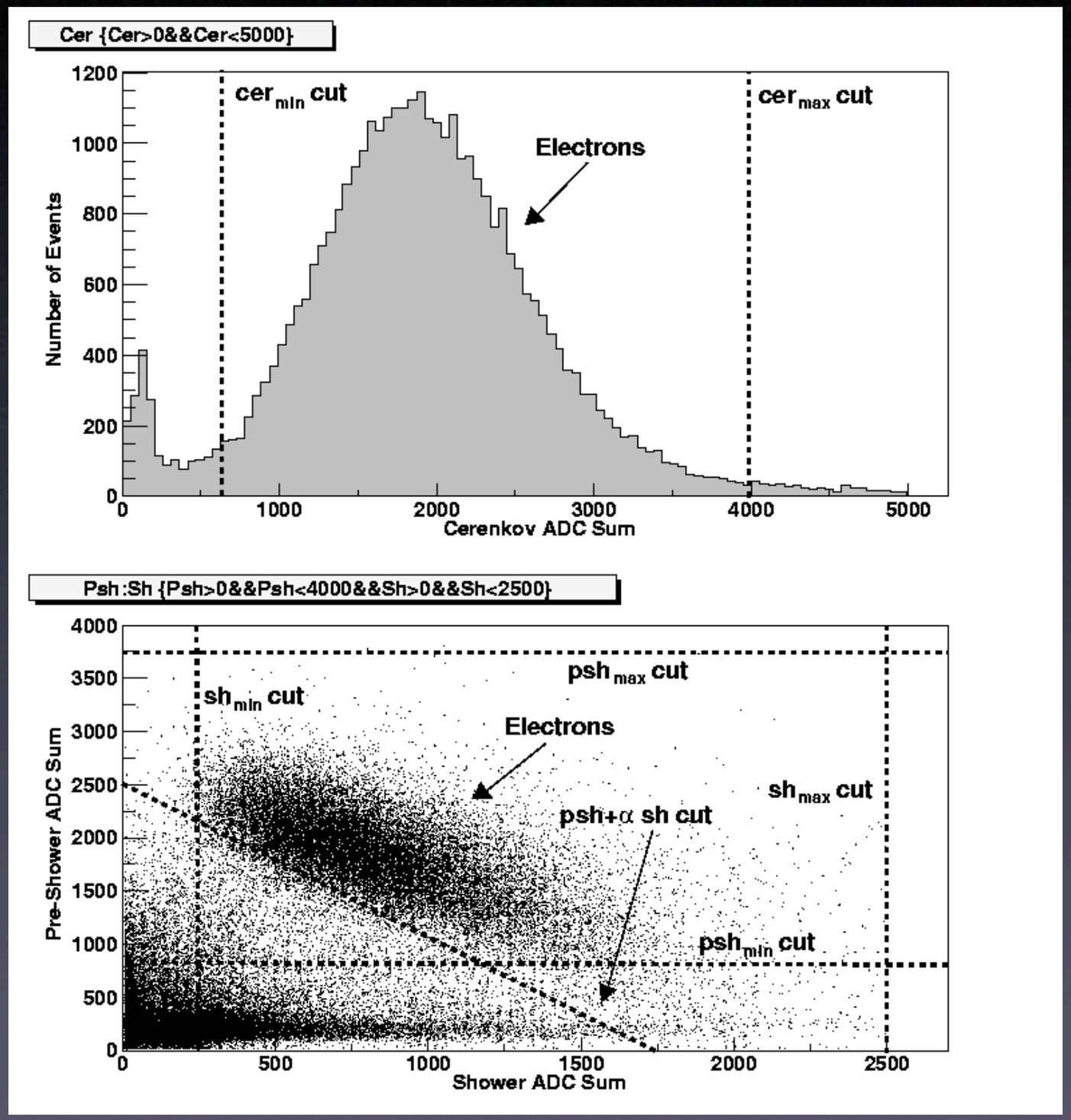
← ϕ_{tg}.

← y_{tg}

Acceptance Cuts

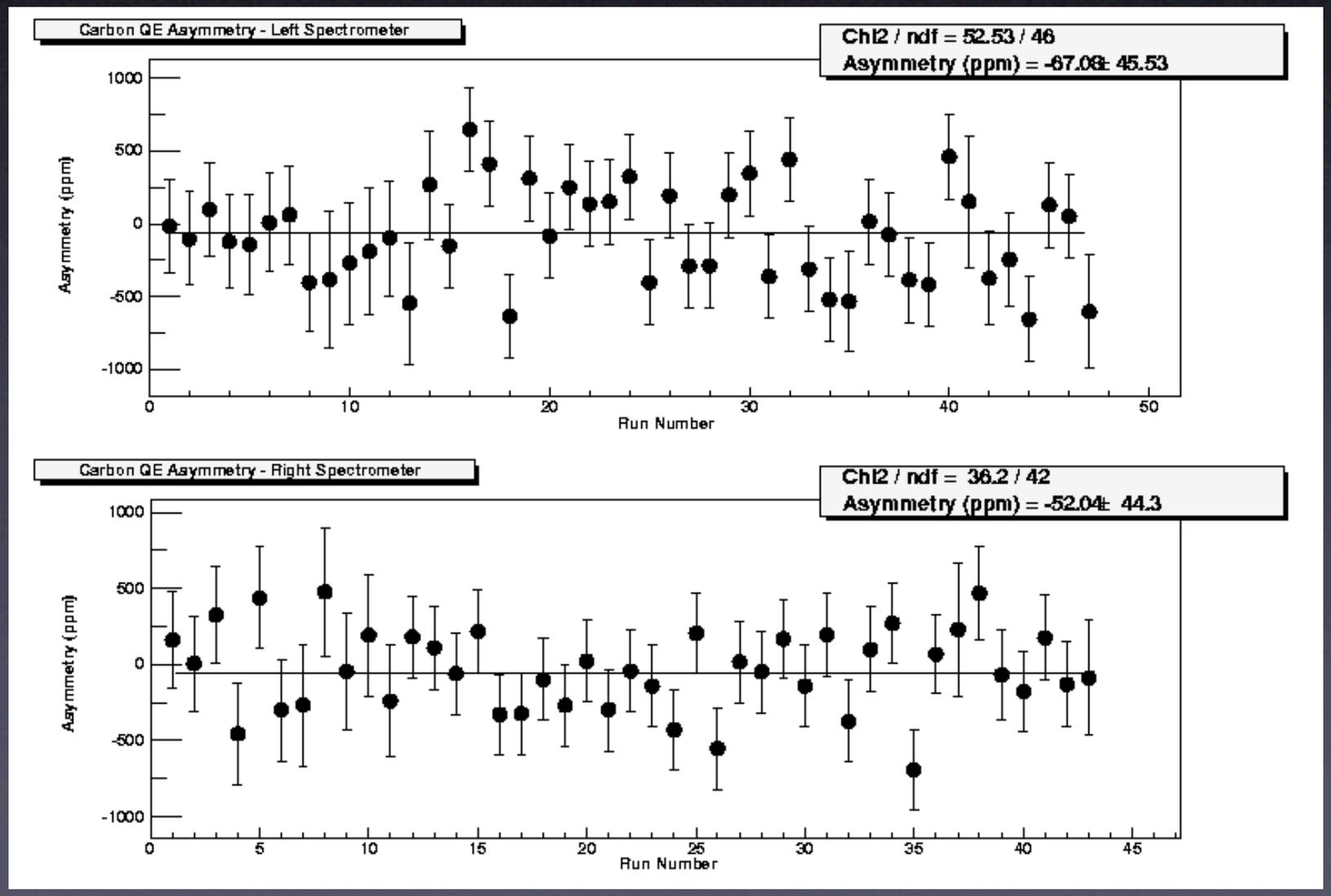


Particle Identification Analysis

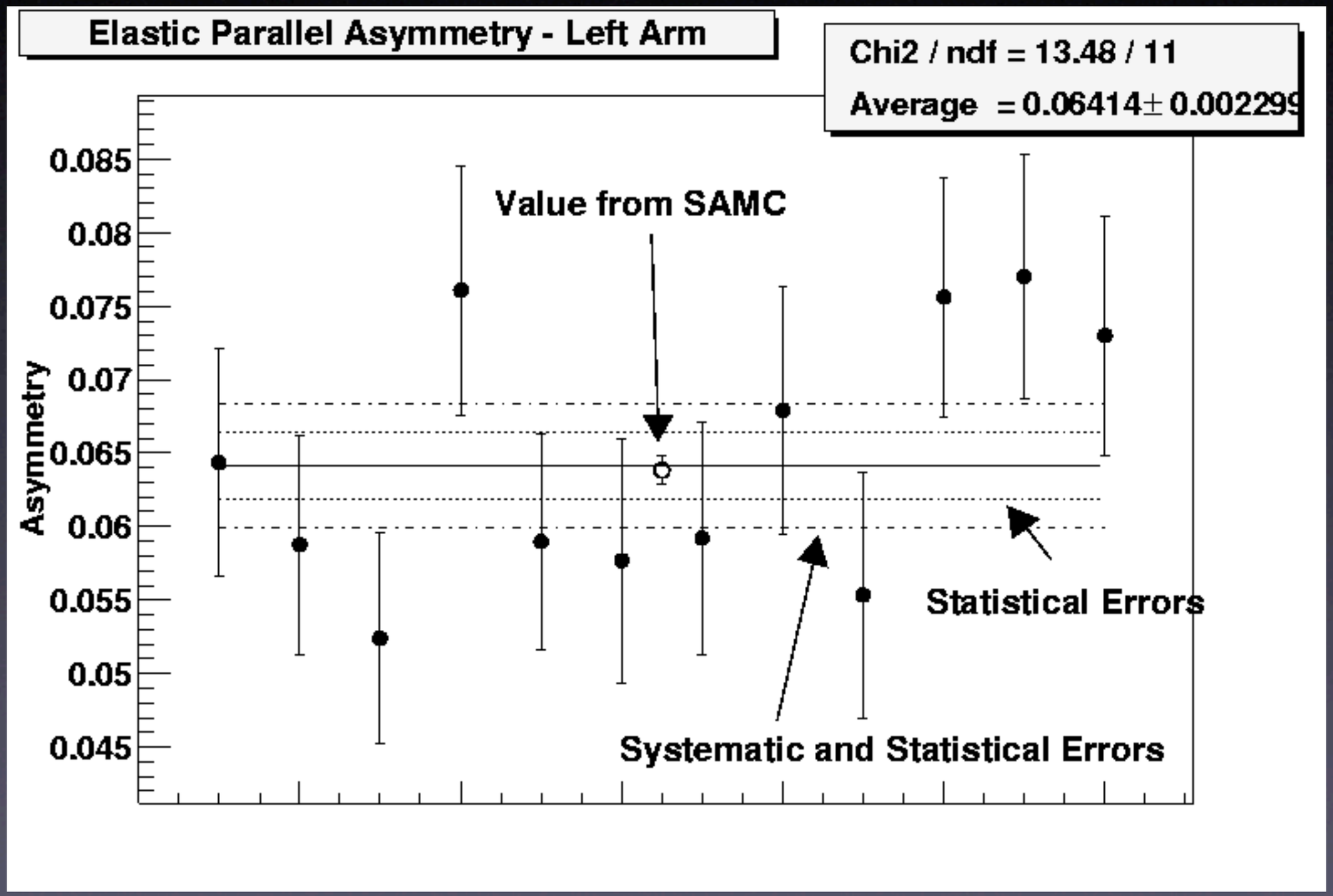


False Asymmetries

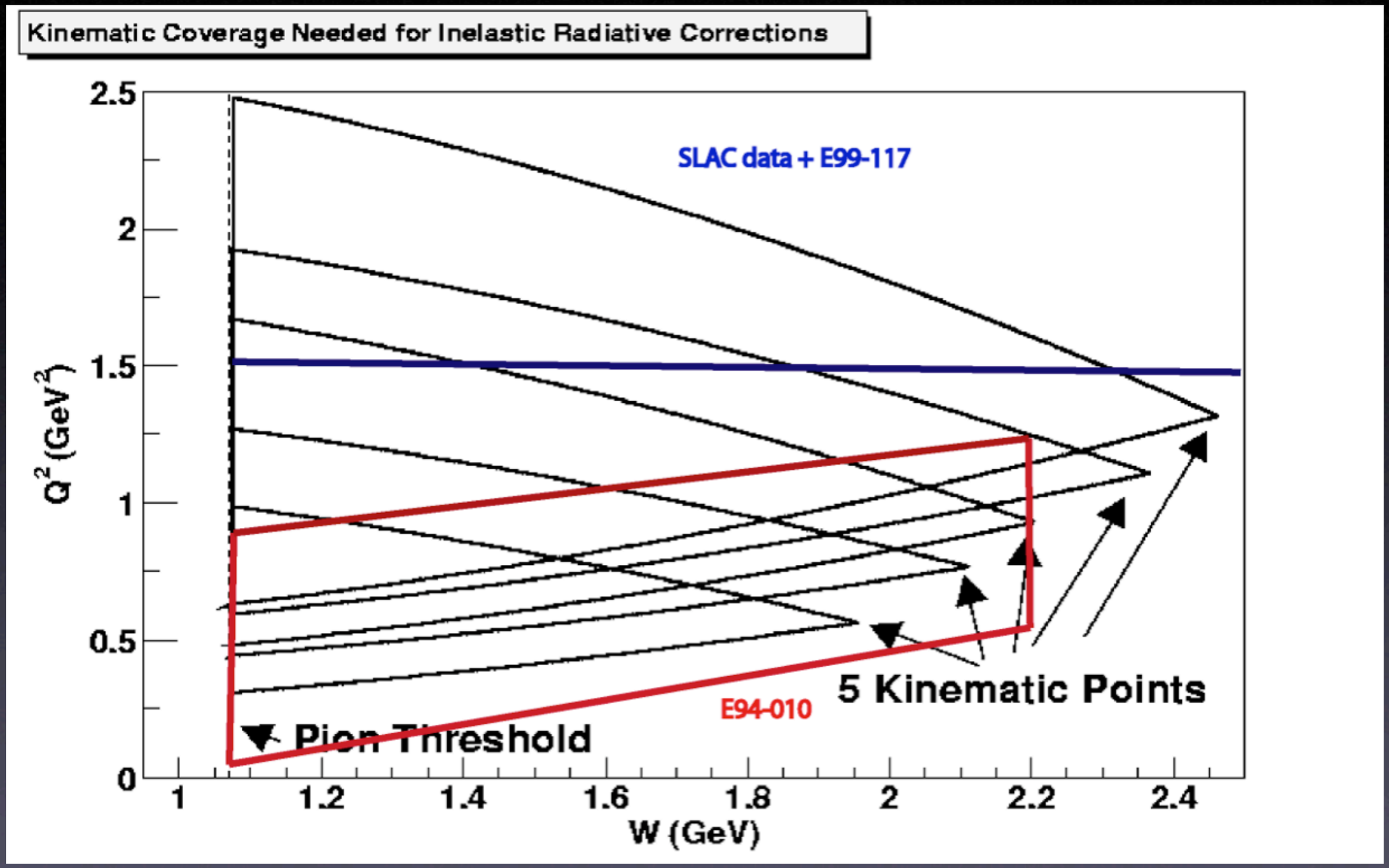
Measured Asymmetries were 500 -1000 ppm +/- 100-150 ppm



Elastic Asymmetry



Radiative Corrections



Radiative Corrections

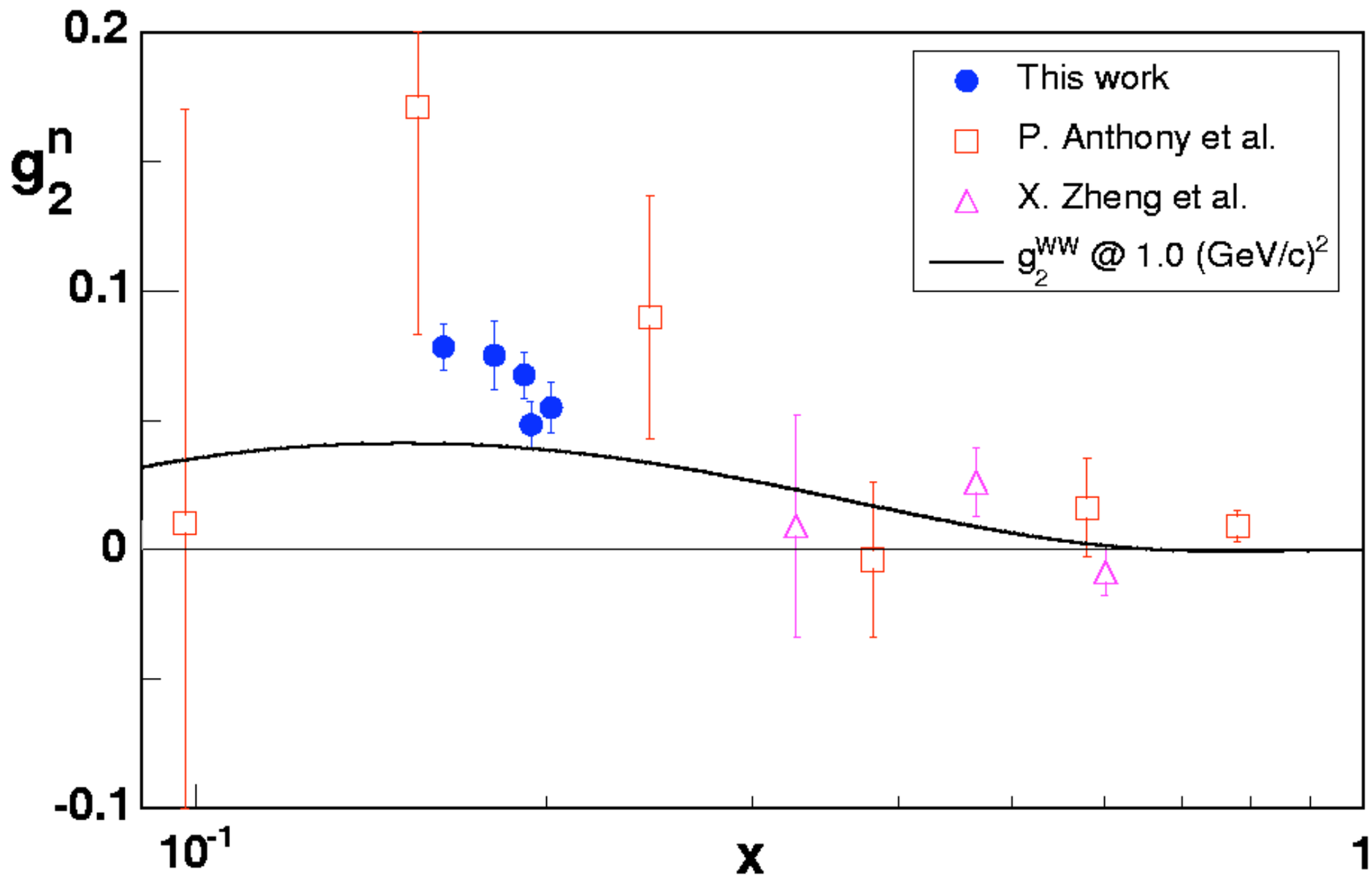
- Radiative corrections from kinematics above pion-threshhold range from 30-50% of polarized cross-section
- Quasi-elastic tail corrections range also from 20-50%
- Quasi-elastic corrections and above pion-threshhold corrections have opposite sign
- Corrections from Elastic scattering are 1-3% of cross-section

Nuclear Corrections

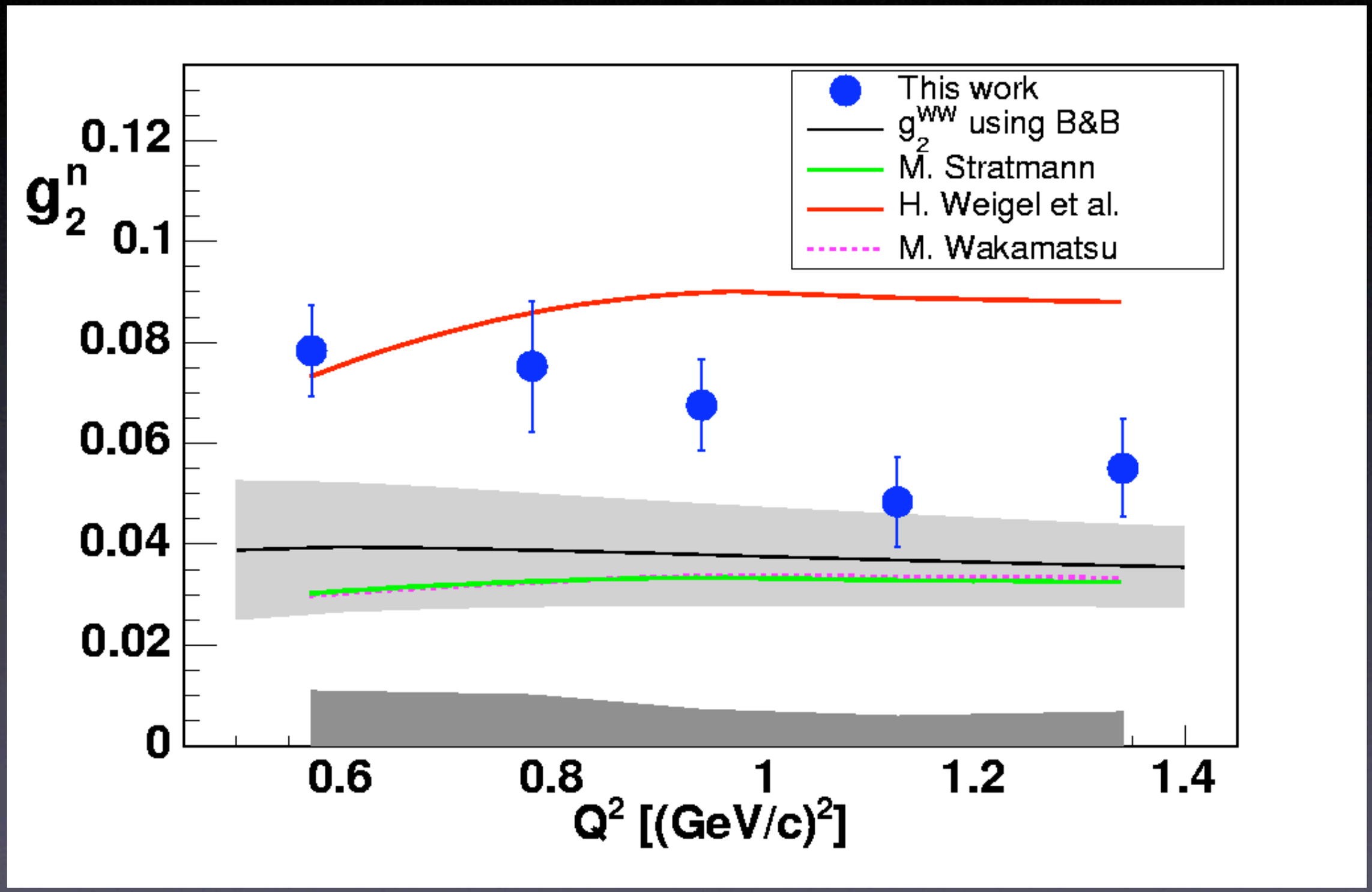
- Need to correct for the fact that we used an effective neutron target
- Correction straight-forward at our kinematics

$$g_1^n = \frac{1}{P_n + 0.056}\left[g_1^{^3\mathrm{He}} + (0.014 - 2P_p)g_1^p\right]$$
$$g_2^n = \frac{1}{P_n + 0.056}\left[g_2^{^3\mathrm{He}} + (0.014 - 2P_p)g_2^p\right]$$

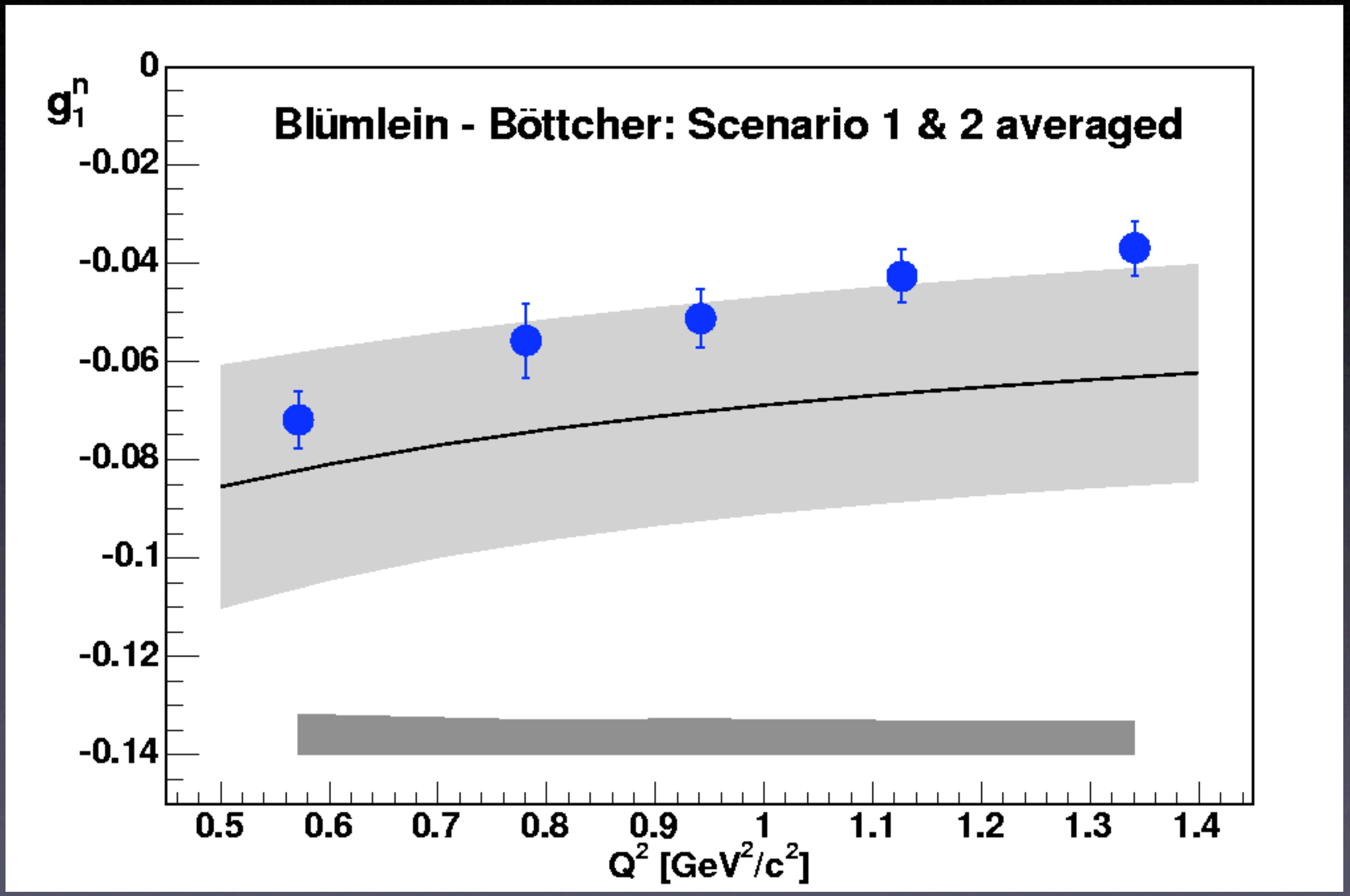
g_2^n vs. x


0.2
0.1
0
-0.1
g_2^n
10^{-1}
x
1
This work
P. Anthony et al.
X. Zheng et al.
g_2^{WW} @ 1.0 (GeV/c)^2

g_2^n vs. Q^2


This work
g_2^{WW} using B&B
M. Stratmann
H. Weigel et al.
M. Wakamatsu
g_2^n
0.12
0.1
0.08
0.06
0.04
0.02
0
0.6
0.8
1
1.2
1.4
Q^2 [(GeV/c)^2]

g_1^n vs. Q^2


Blümlein - Böttcher: Scenario 1 & 2 averaged
g_1^n
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
Q^2 [GeV^2/c^2]

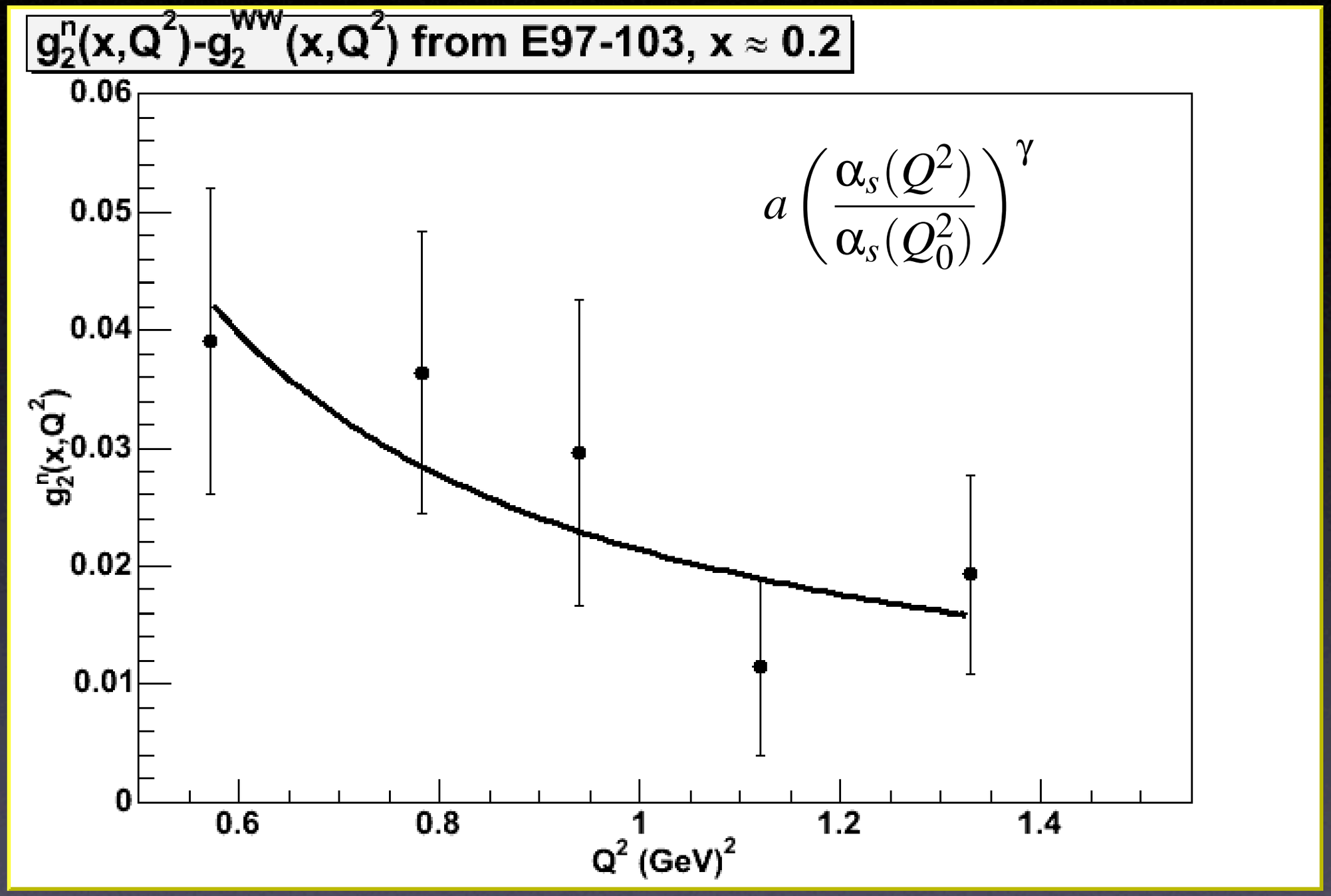
Average Systematic Errors on g_2^n

Transverse QE Tail	6.0%
Raw Cross-Section	6.0%
Transverse above pion threshhold RC	4.5%
Nuclear Correction	4.4%
False Asymmetry	4.2%
Beam Polarization	4.0%
Target Polarization	3.6%
Others	2.0%
Total	13.6%

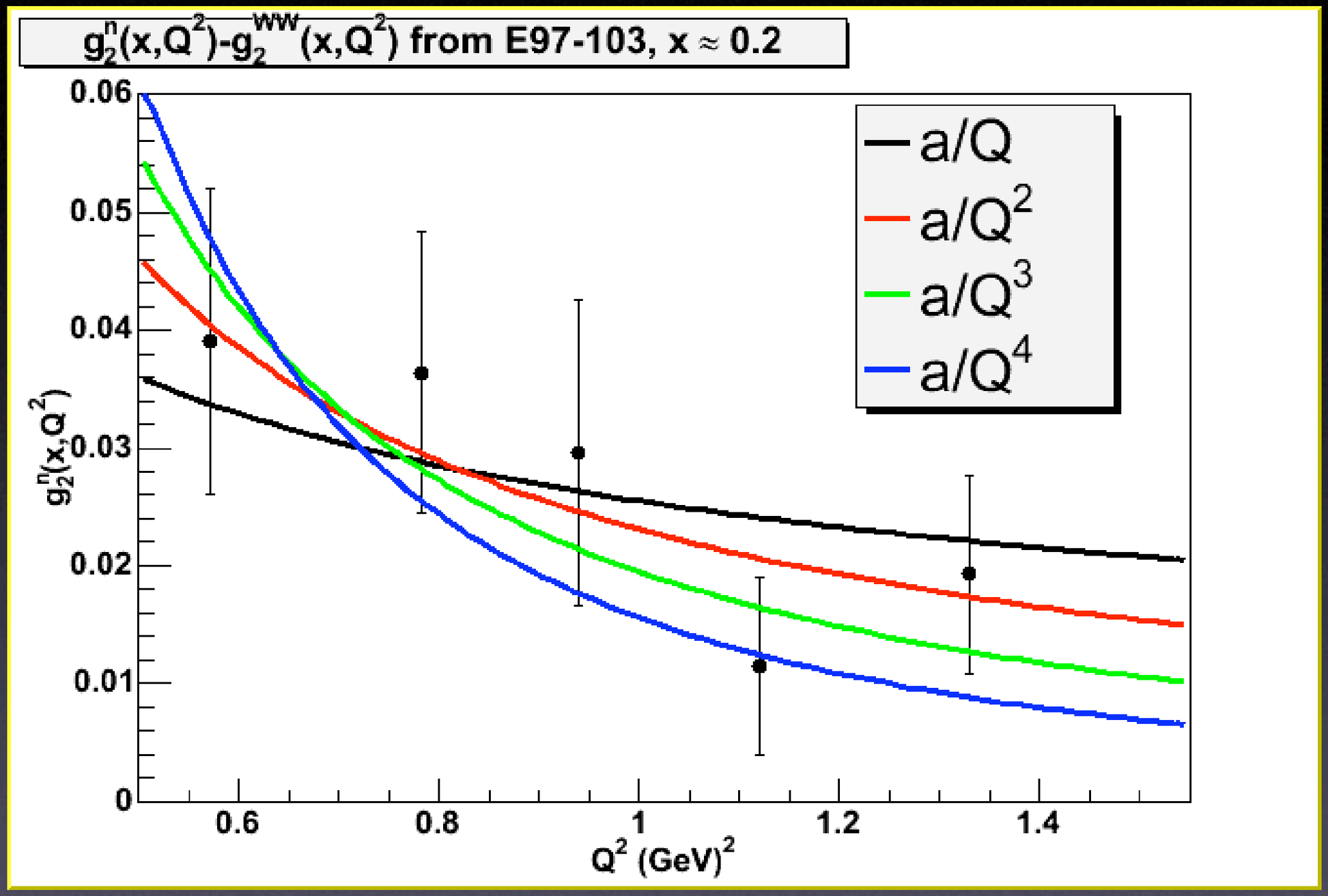
Interpreting Q^2 evolution of g_2-g_2^{WW}

- Several effects convoluted on top of one another
  - Q^2 evolution of operator according to DGLAP
  - $(1/Q)^{2-t}$ dependence of expansion terms
- Not really enough points to make clear statement which effect is dominate
- However clear separation between g_2 and g_2^{WW}

Fit of g_2-g_2^{WW} assuming only twist-three



Fit of g_2-g_2^{WW} assuming $1/Q^n$ form



Conclusions

- Clear indication of physics beyond leading order twist
- Need further experimental input to differentiate different orders of twist
- Further theoretical work to interpret and model data
- Publication Imminent!