Spin duality on the neutron and ^3He

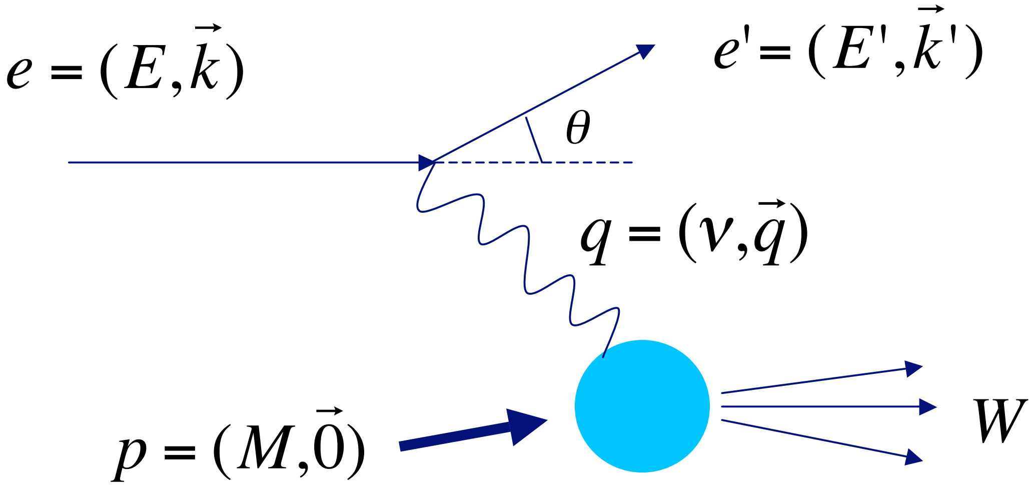
Patricia Solvignon
Temple University

Medium Energy Physics Seminar
Argonne National Laboratory
March 29, 2006

Outlines

- Brief theoretical description of Quark-Hadron Duality
- Experimental setup
- Analysis steps
- Preliminary results on the Spin Structure Functions
- Preliminary test of Quark-Hadron Duality on Neutron and ^3He

Inclusive Electron Scattering



4-momentum transfer squared

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

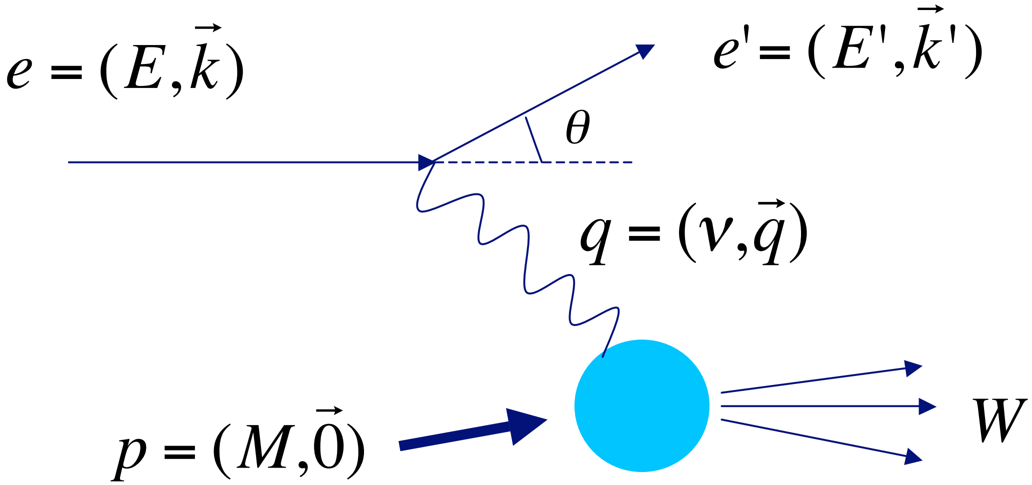
Invariant mass squared

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

Bjorken variable

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

Inclusive Electron Scattering



4-momentum transfer squared

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

Invariant mass squared

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

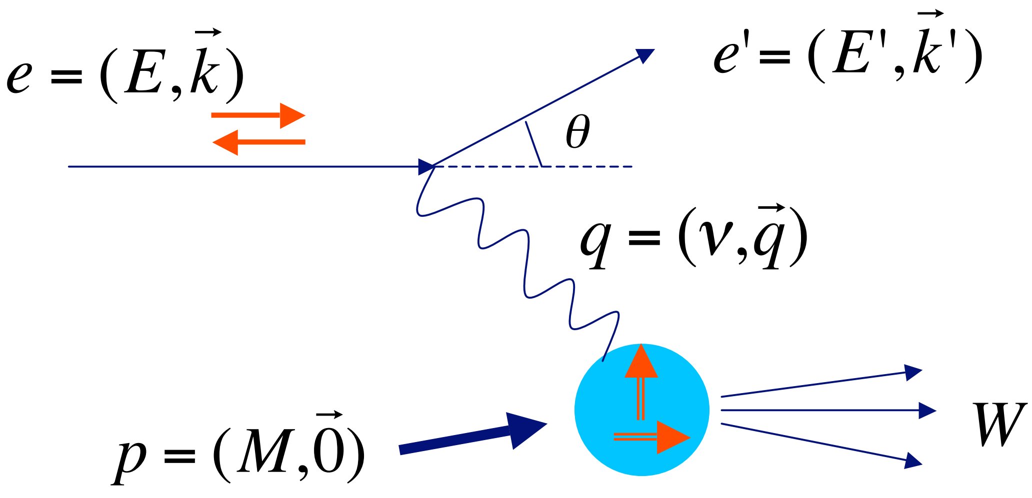
Bjorken variable

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

Unpolarized case

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

Inclusive Electron Scattering



4-momentum transfer squared

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

Invariant mass squared

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

Bjorken variable

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

Unpolarized case

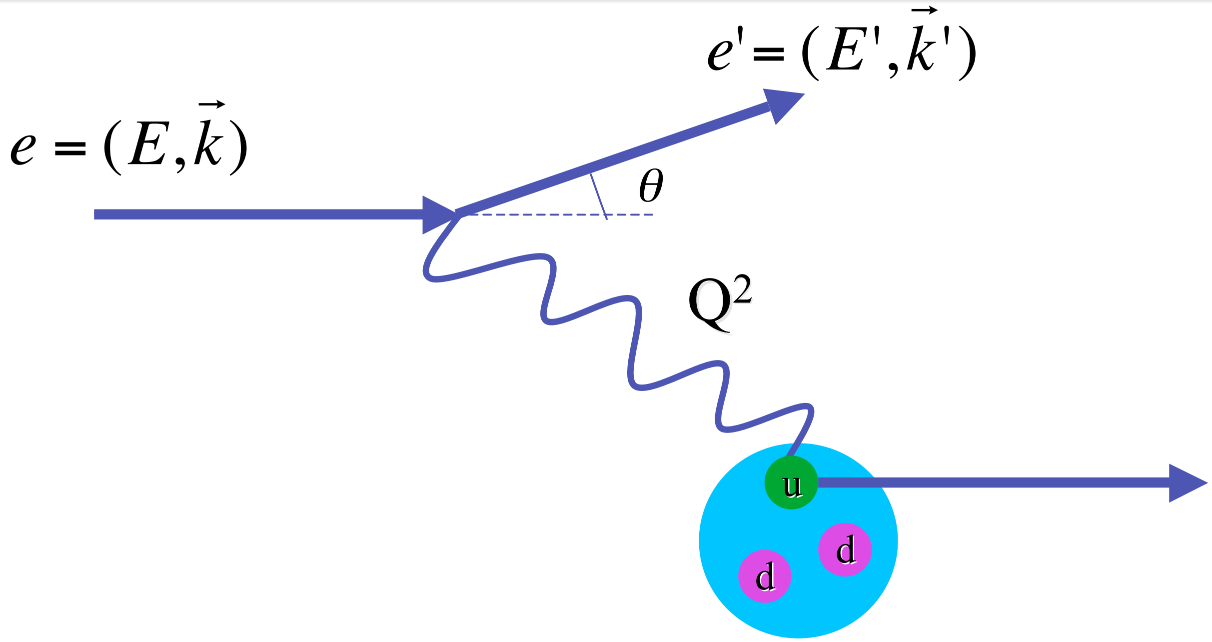
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

Polarized case

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[\left(E + E'\cos\theta\right)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

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

Deep Inelastic Scattering



High Q^2 and W>2GeV: fine resolution → we see partons

→ scaling → asymptotic freedom of the strong interaction

→ 2004 Nobel Prize

D. J. Gross, H. D. Politzer and F. Wilczek

Scaling of F_2

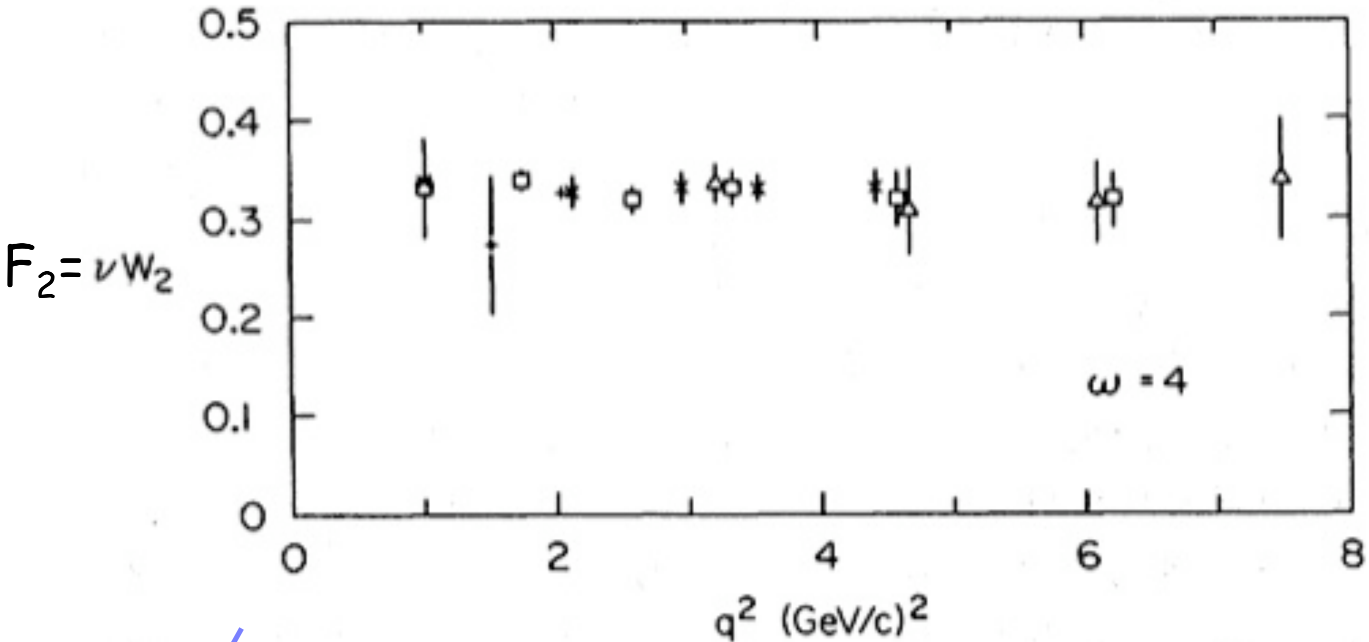


Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

1990 Nobel Prize

J. I. Friedman, H. W. Kendall and R. E. Taylor

Structure functions in the parton model

In the infinite-momentum frame:

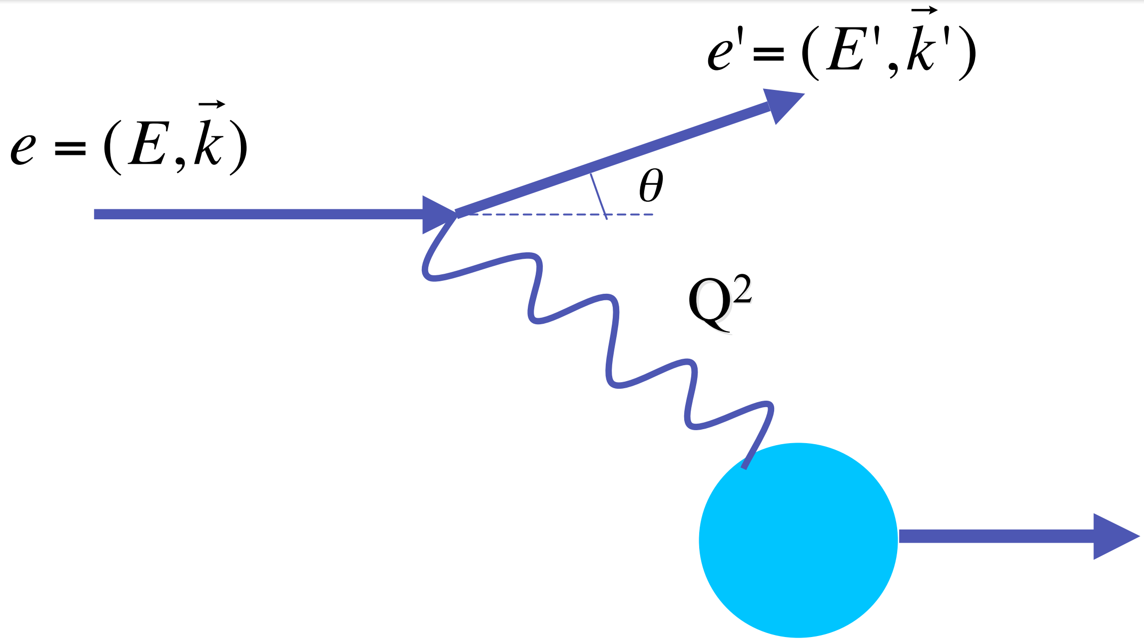
- no time for interactions between partons
- Partons are point-like non-interacting particles: $\sigma_{Nucleon} = \Sigma_i \; \sigma_i$

$$F_1(x) = \frac{1}{2}\sum_i e_i^2 q_i(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)] = \frac{1}{2x} F_2(x)$$

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)]$$

No simple partonic distribution for $g_2(x,Q_2)$

Resonance region



Low Q^2 and $W<2$ GeV : coarse resolution → we don't see partons.

→ The nucleon goes through different excited states: the resonances

DIS versus resonance:

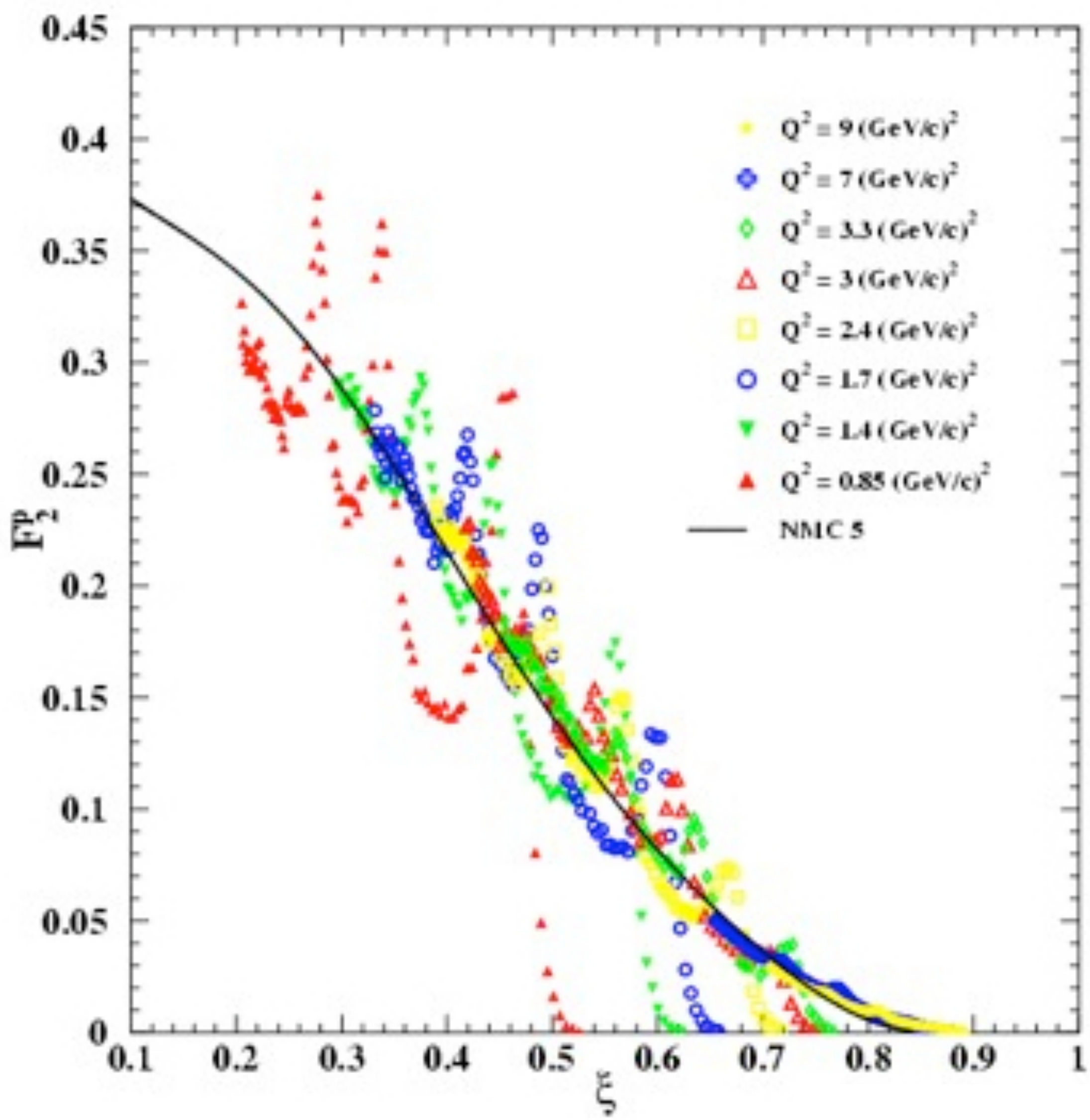
two very different pictures of the nucleon.

Quark-hadron duality

- First observed by Bloom and Gilman in the 1970's on F_2

- Scaling curve seen at high Q^2 is an accurate average over the resonance region at lower Q^2

- Global and Local duality are observed for F_2



I. Niculescu et al., PRL 85 (2000) 1182

Theoretical interpretations

Lattice QCD

χPT Quark models OPE pQCD

$Q^2 = 0$ ⟷ $Q^2 = \infty$

pQCD (Carlson, Mukhopadhyay):

➥ Q^2 dependence of transition form factors vs. x dependence of parton distribution functions

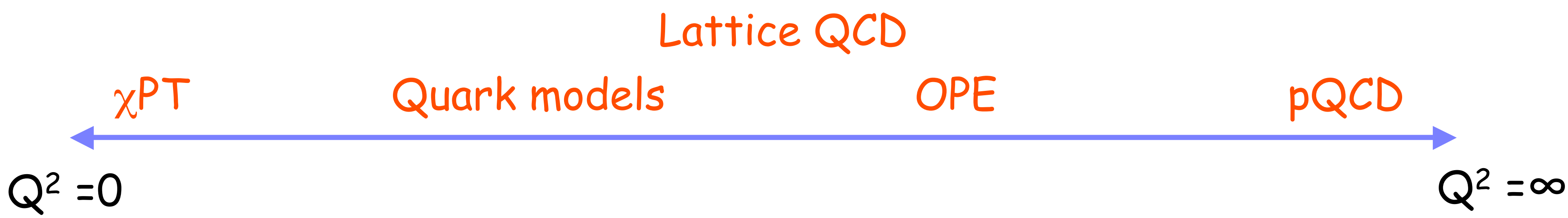
In resonance

$$g_1 = \frac{M_N^2}{\pi M_R \Gamma_R} \frac{g_+^2}{Q^6} = \frac{M_N^2}{\pi M_R \Gamma_R} \frac{g_+^2}{\left(M_R^2 - M_N^2\right)^3} (1-x)^3$$

In DIS

$$\lim_{x \to 1} g_1(x) \propto (1-x)^3$$

Theoretical interpretations



Operator Product Expansion (Rujula, Georgi, Politzer):

➥ Higher twist corrections are small or cancel.

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

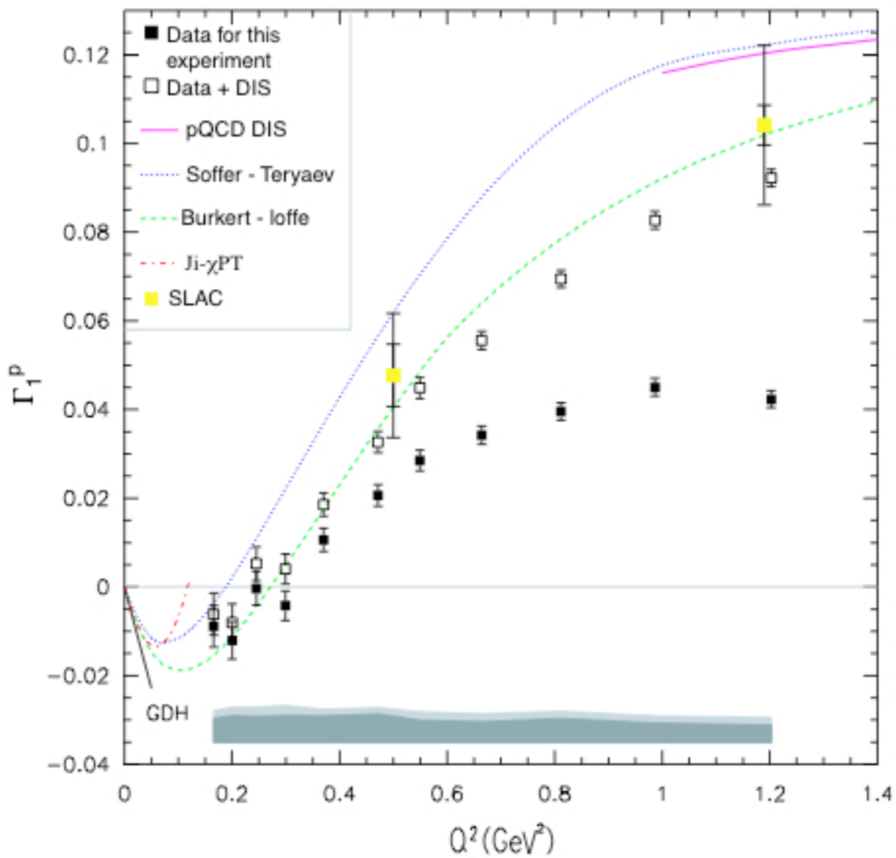
Leading twist: $\mu_2(Q^2)$

Higher twists: $\frac{\mu_4(Q^2)}{Q^2} + \frac{\mu_6(Q^2)}{Q^4} + O\left(\frac{1}{Q^6}\right)$

Scaling of g_1 moments

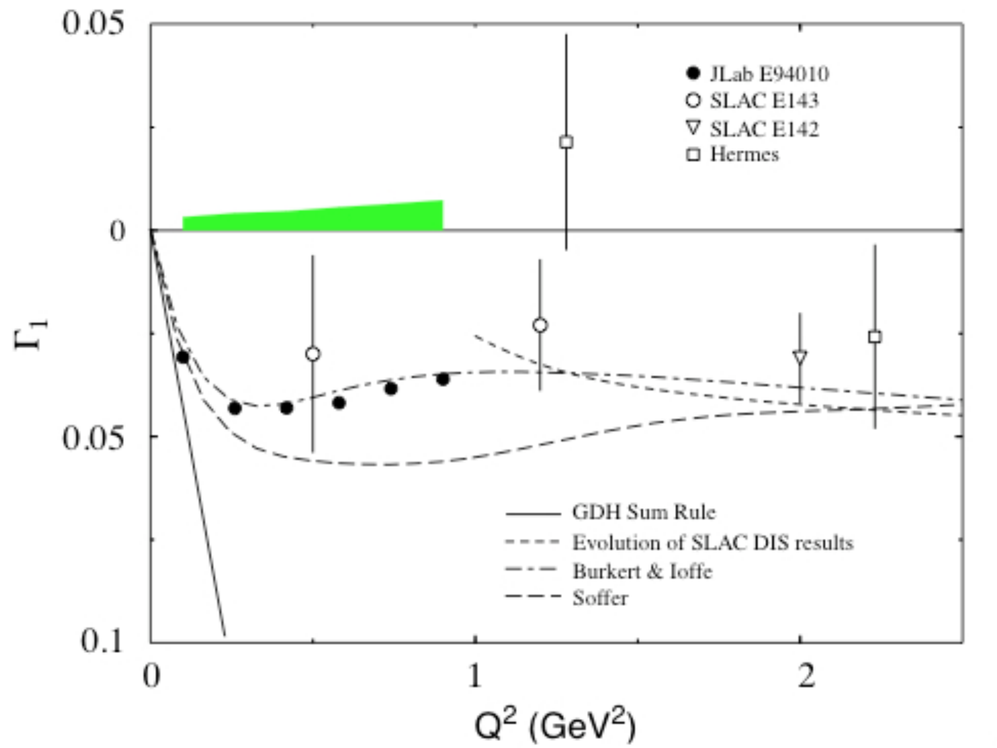
$$\Gamma_1(Q^2) = \int g_1(x,Q^2)dx$$

proton



R. Fatemi et al., PRL 91 (2003) 222002

neutron

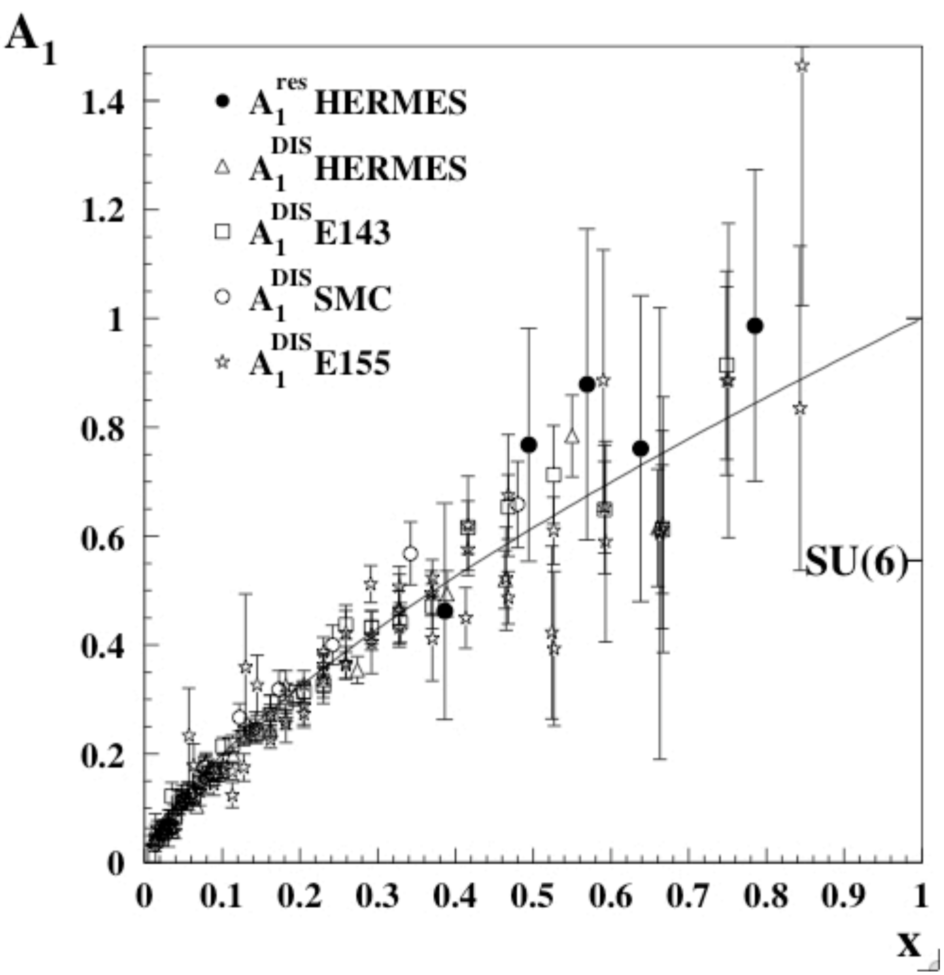


M. Amarian et al., PRL 859(2002) 242301

World data

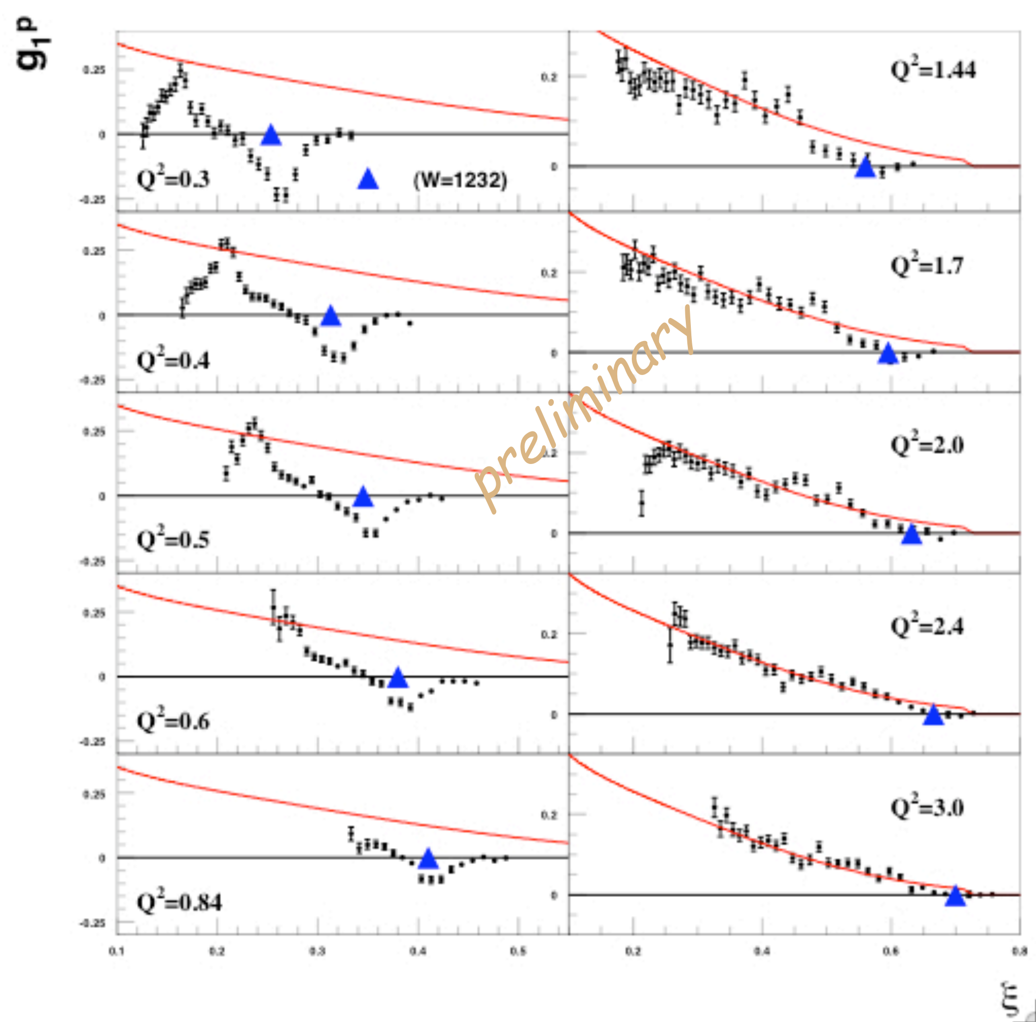
HERMES for A_1^p

A. Airapeian et al., PRL 90 (2003) 092002



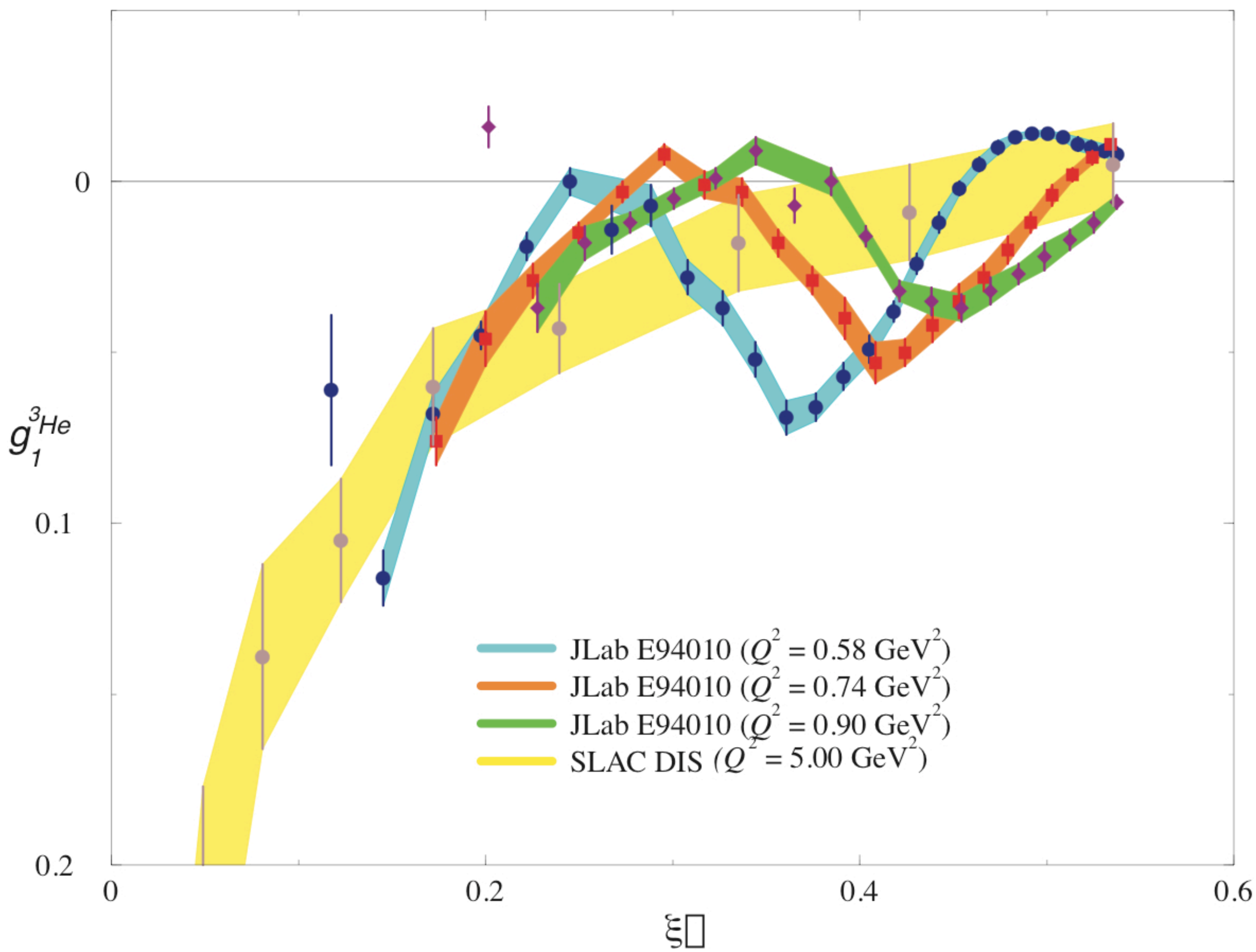
Jlab Hall B for g_1^p

From DIS 2005 proceedings



World data

Indication of duality from Jlab Hall A for g_1^{3He}



Structure functions:

polarized ≠ unpolarized

and

proton ≠ neutron

↓

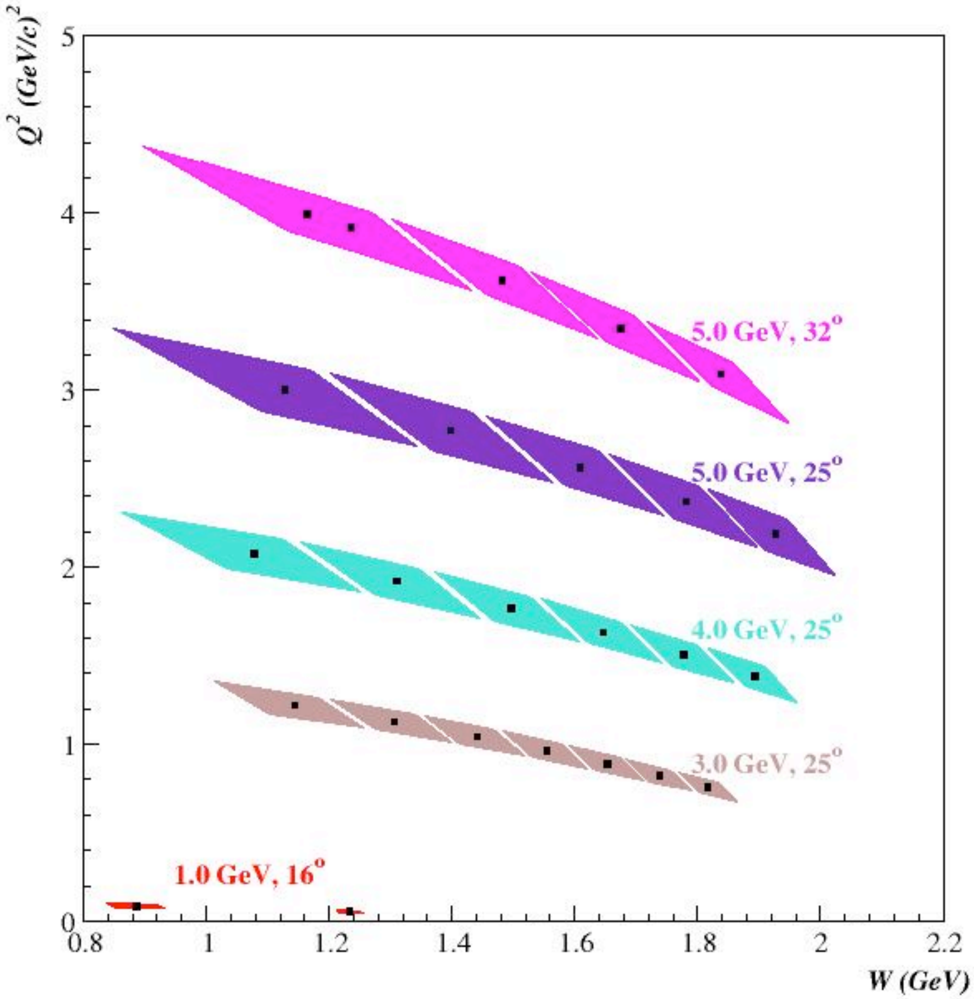
a dedicated experiment to study spin duality on the neutron was necessary

The experiment E01-012

- Ran in Jan.-Feb. 2003
- Inclusive experiment:

$$^3\vec{He}(\vec{e},e')X$$

- Measured polarized cross section differences
- Form g_1 and g_2



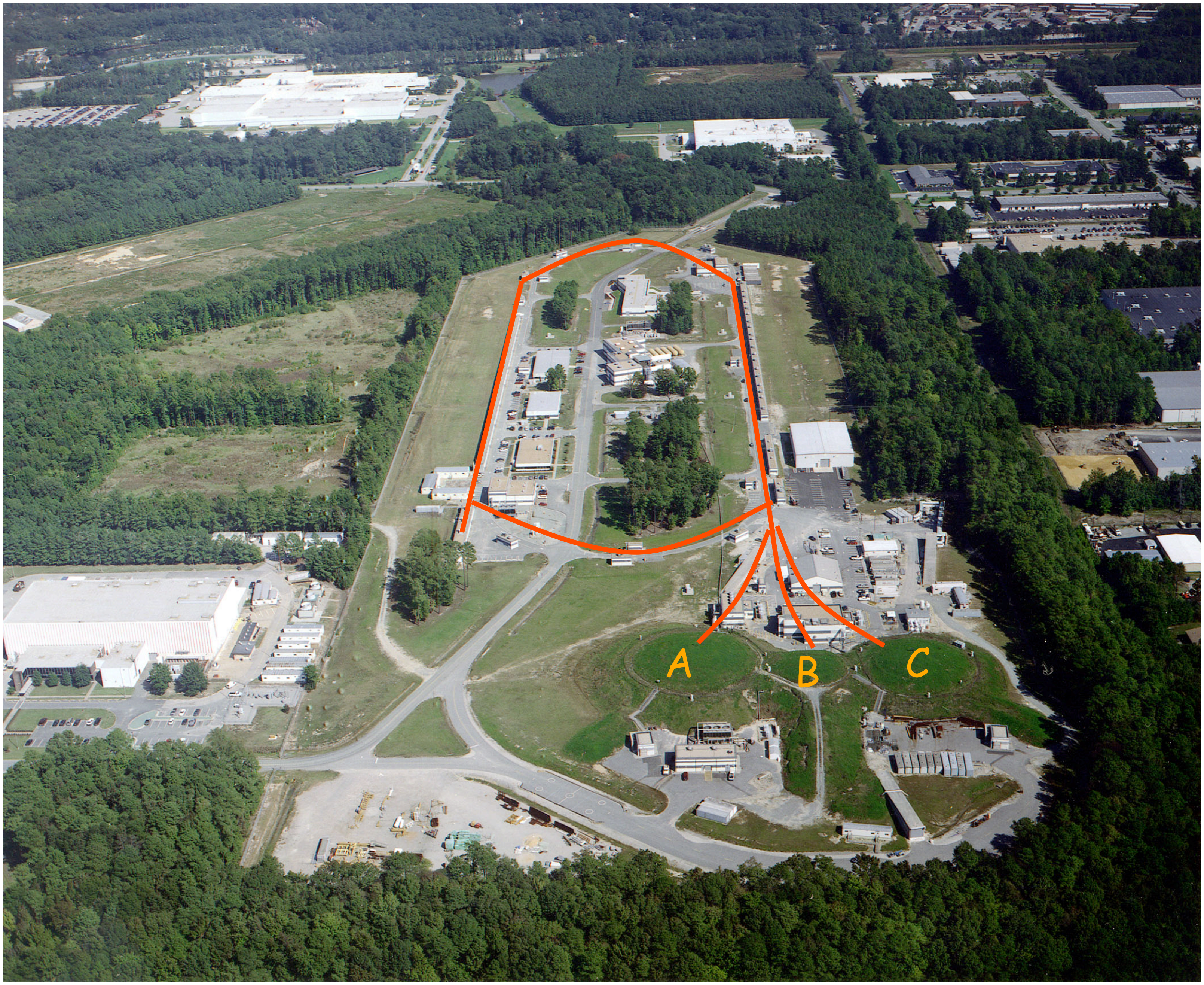
↪ **Test of spin duality on the neutron (and ^{3}He)**

The E01-012 Collaboration

K. Aniol, T. Averett, W. Boeglin, A. Camsonne, G.D. Cates, G. Chang, J.-P. Chen, Seonho Choi, E. Chudakov, B. Craver, F. Cusanno, A. Deur, D. Dutta, R. Ent, R. Feuerbach, S. Frullani, H. Gao, F. Garibaldi, R. Gilman, C. Glashausser, O. Hansen, D. Higinbotham, H. Ibrahim, X. Jiang, M. Jones, A. Kelleher, J. Kelly, C. Keppel, W. Kim, W. Korsch,K. Kramer, G. Kumbartzki, J. LeRose, R. Lindgren, N. Liyanage, B. Ma, D. Margaziotis, P. Markowitz, K. McCormick, Z.-E. Meziani, R. Michaels, B. Moffit, P. Monaghan, C. Munoz Camacho, K. Paschke, B. Reitz, A. Saha, R. Sheyor, J. Singh, K. Slifer, P. Solvignon, V. Sulkosky, A. Tobias, G. Urciuoli, K. Wang, K. Wijesooriya, B. Wojtsekhowski, S. Woo, J.-C. Yang, X. Zheng, L. Zhu

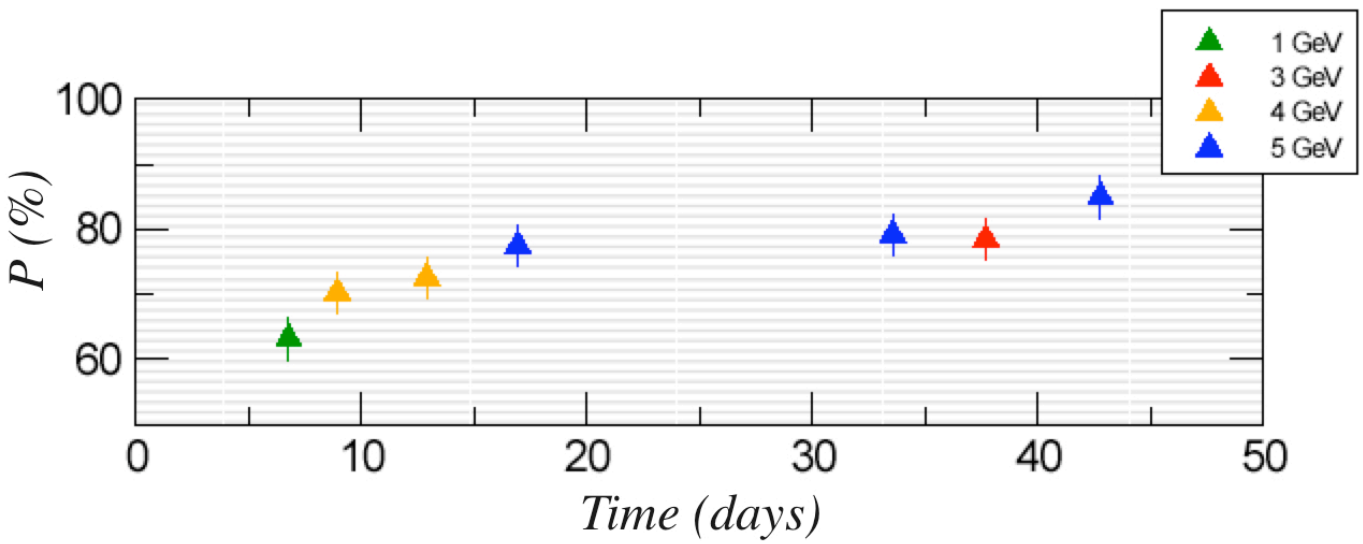
and the Jefferson Lab Hall A Collaboration

The Jefferson Lab Accelerator

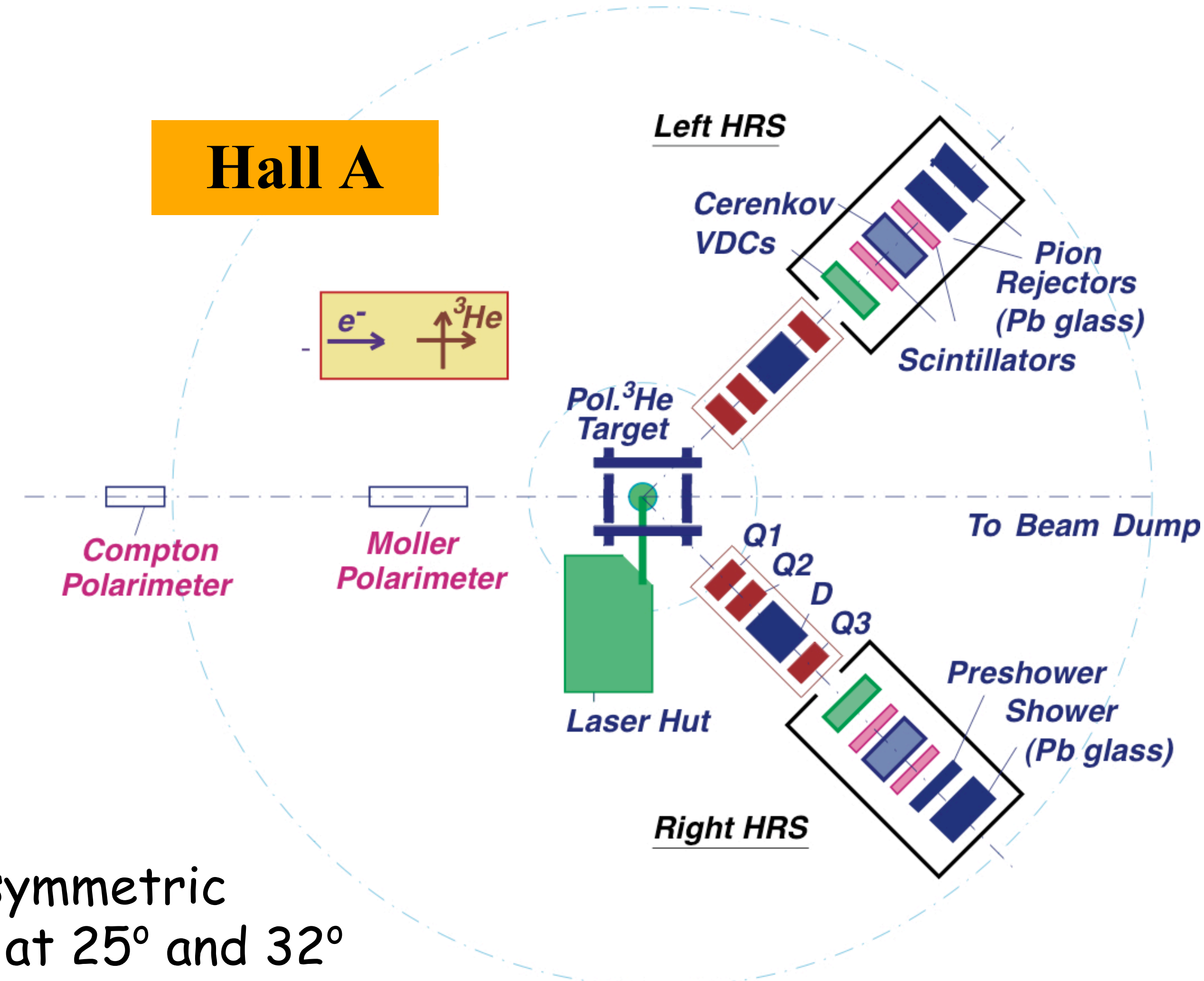


Electron Beam Polarization

- Used Moller Polarimeter
- $70 < P_{beam} < 85\%$ for production data



Experimental setup



Both HRS in symmetric configuration at 25° and 32°

➥ double the statistics

➥ control the systematics

Particle ID = Cerenkov + EM calorimeter

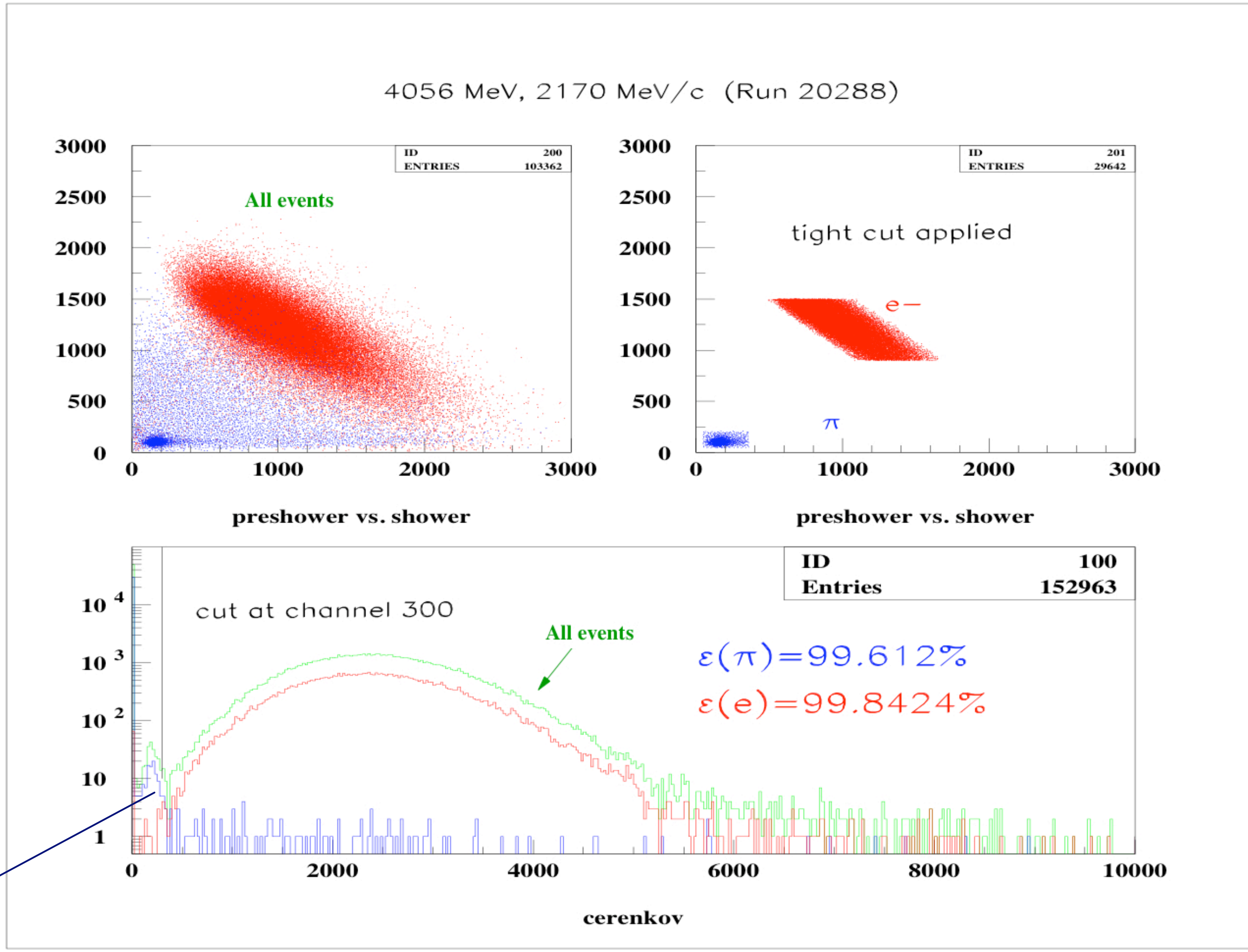
➥ π/e reduced by 10^4

The CO_2 gas Cerenkov counter

Index of refraction:
n = 1.00041

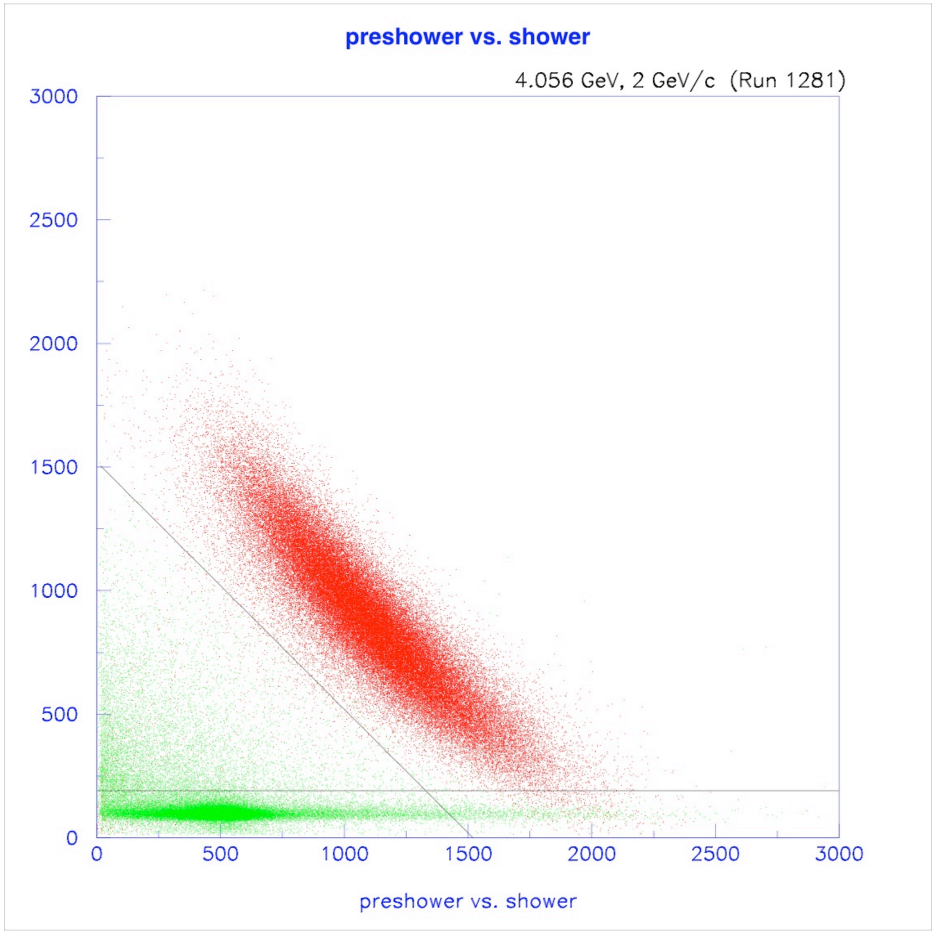
$$P^{e^-}_{thres.} = 18\,MeV$$

$$P^{\pi^-}_{thres.} = 4.9\,GeV$$



Knock-out e⁻
&
Low energy e⁻

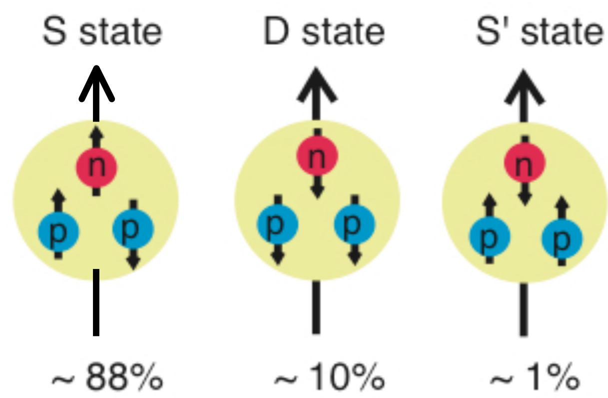
Lead Glass Calorimeter



Cuts applied for electron efficiency > 99%

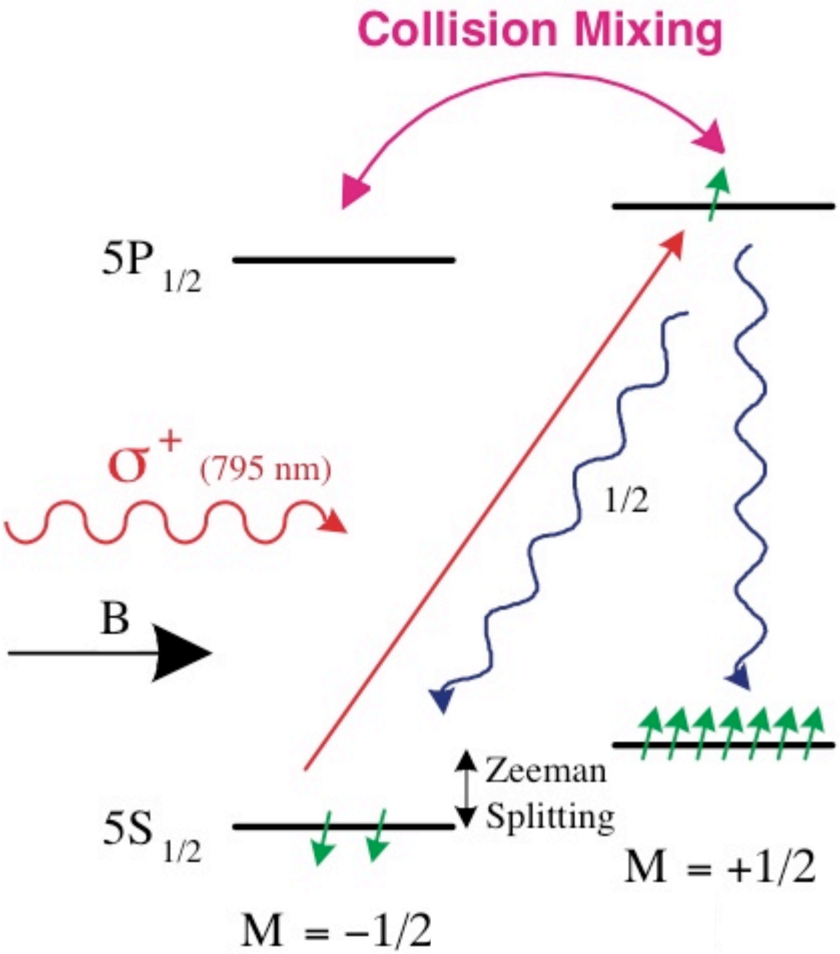
^3He as an effective neutron target

^3He as neutron target



P_n = 86% and P_p = -2.8%

How to polarize ^3He ?



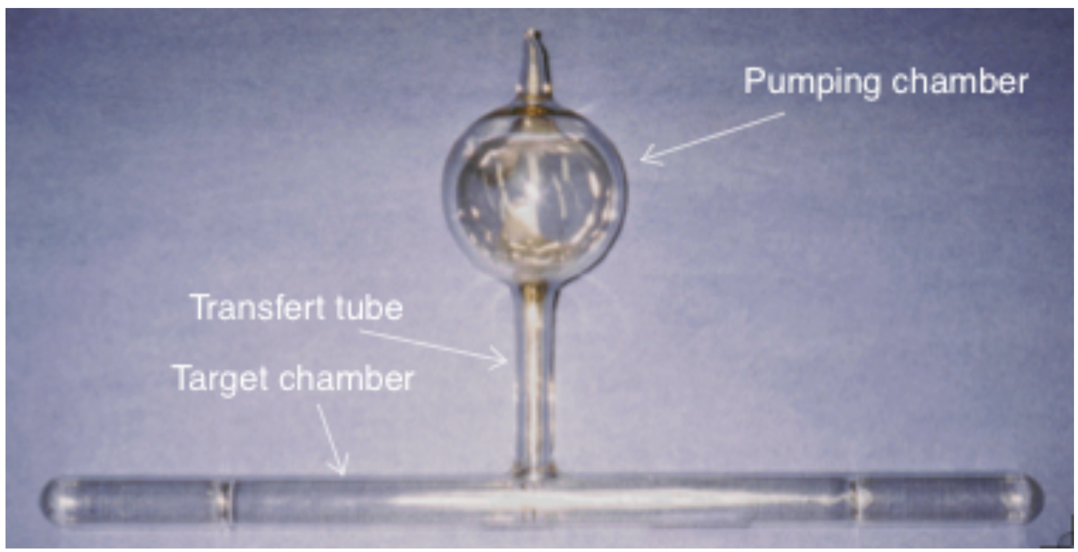
Two step process:

1. Rb vapor is polarized by optical pumping with circularly polarized light
2. Rb e^- polarization is transferred to ^3He nucleus by spin-exchange interaction

A small amount of N_2 is added for quenching

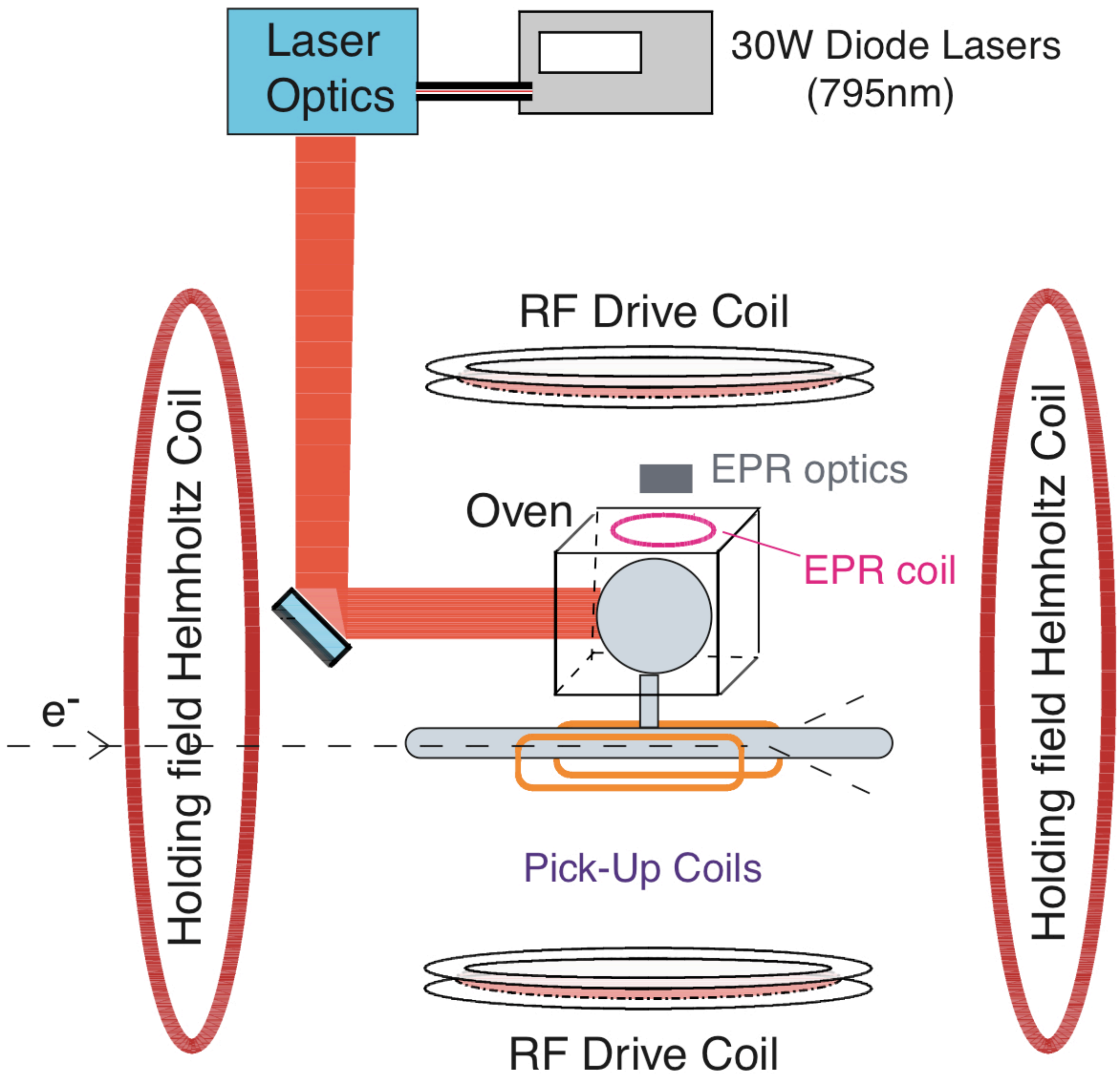
The polarized ^{3}He target

- Two chamber cell
- Pressure ~ 14 atm under running conditions
- High luminosity: $10^{36}\ s^{-1}cm^{-2}$



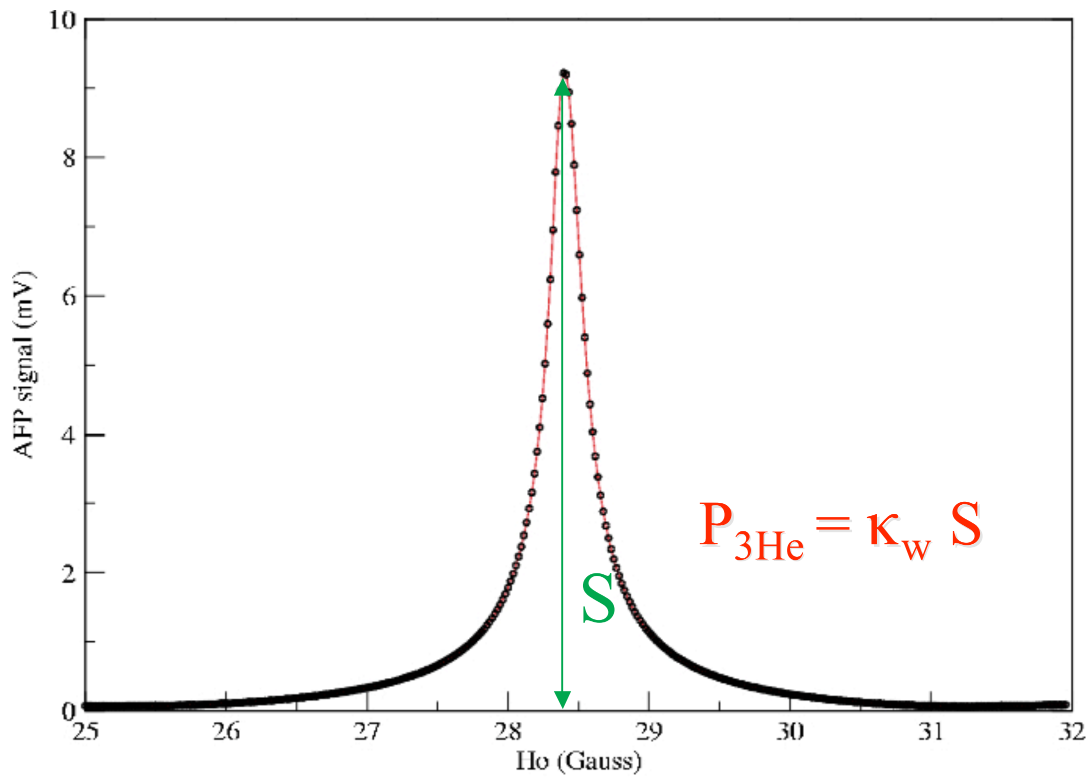
$L_{tg} \sim 40cm$

The polarized ^{3}He system



- ♦ Longitudinal and transverse configurations
- ♦ 2 independent polarimetries: NMR and EPR

Nuclear Magnetic Resonance



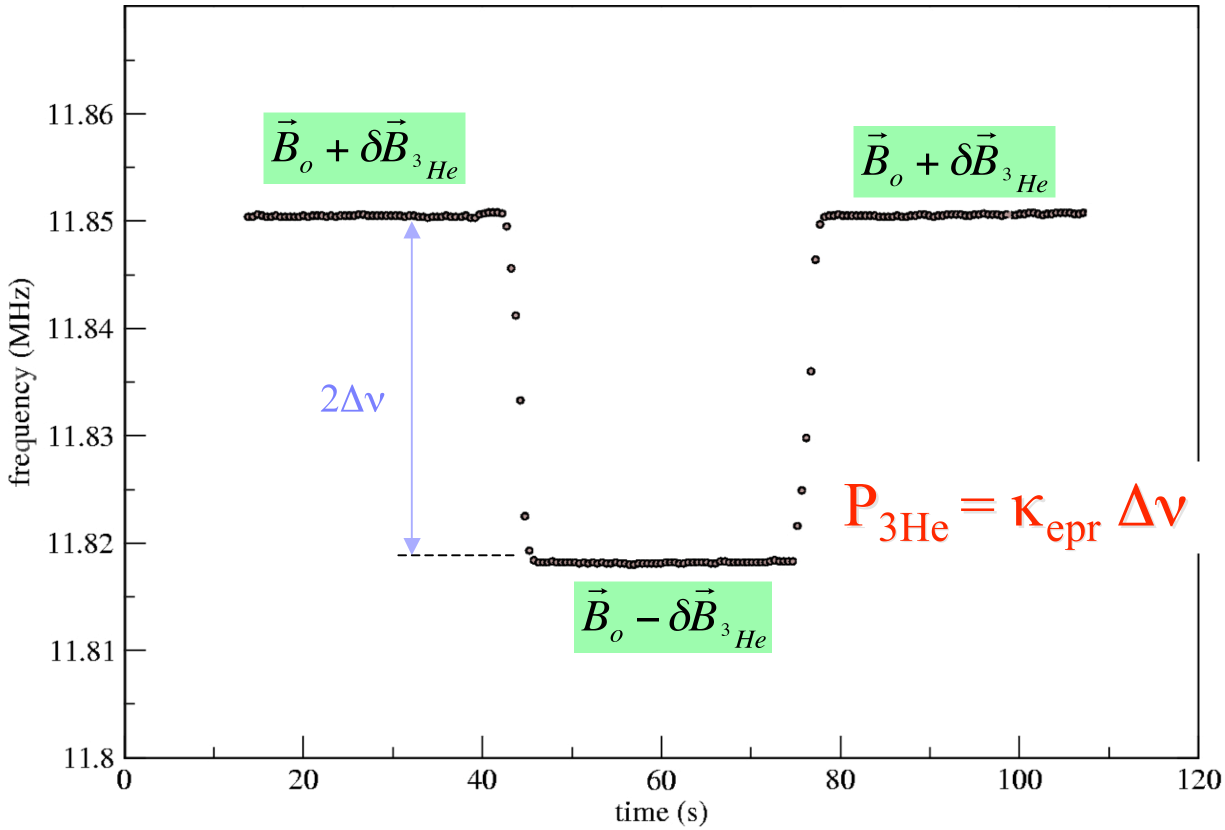
κ_w : from calibration with an identical target cell filled with water

1. Apply perpendicular RF field
2. Ramp holding field (H_0)

} flip the ^{3}He spins under AFP conditions

$$\frac{1}{T_2} << \frac{1}{H_1}\frac{dH_0}{dt} << \gamma H_1$$

Electron Paramagnetic Resonance

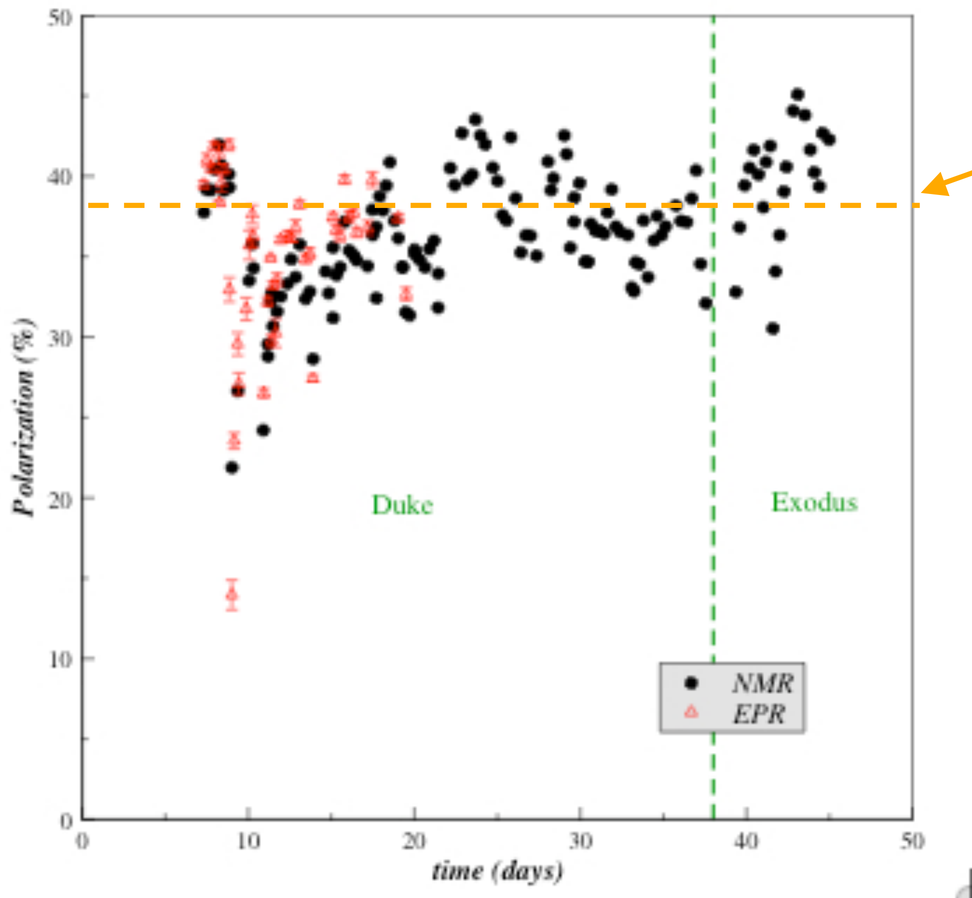


$P_{3He} = \kappa_{epr}\ \Delta\nu$

1. Polarized ^{3}He creates an extra magnetic field: δB_{3He}
2. Measure the Zeeman splitting frequency when B_0 and δB_{3He} are aligned and anti-aligned.

κ_{epr} : depend of cell density and holding field.

Target performance

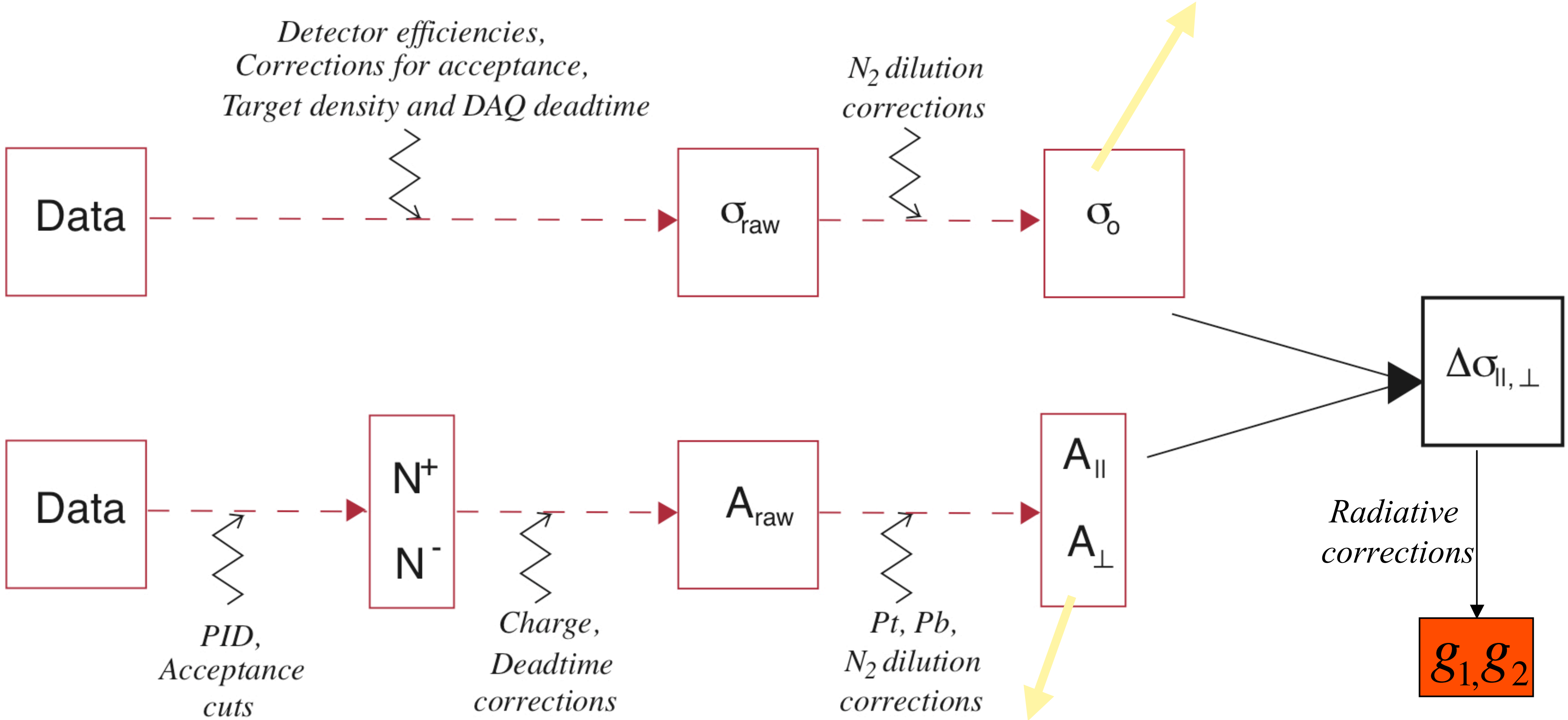


$P_{avg} \sim 37\%$

Statistical errors only

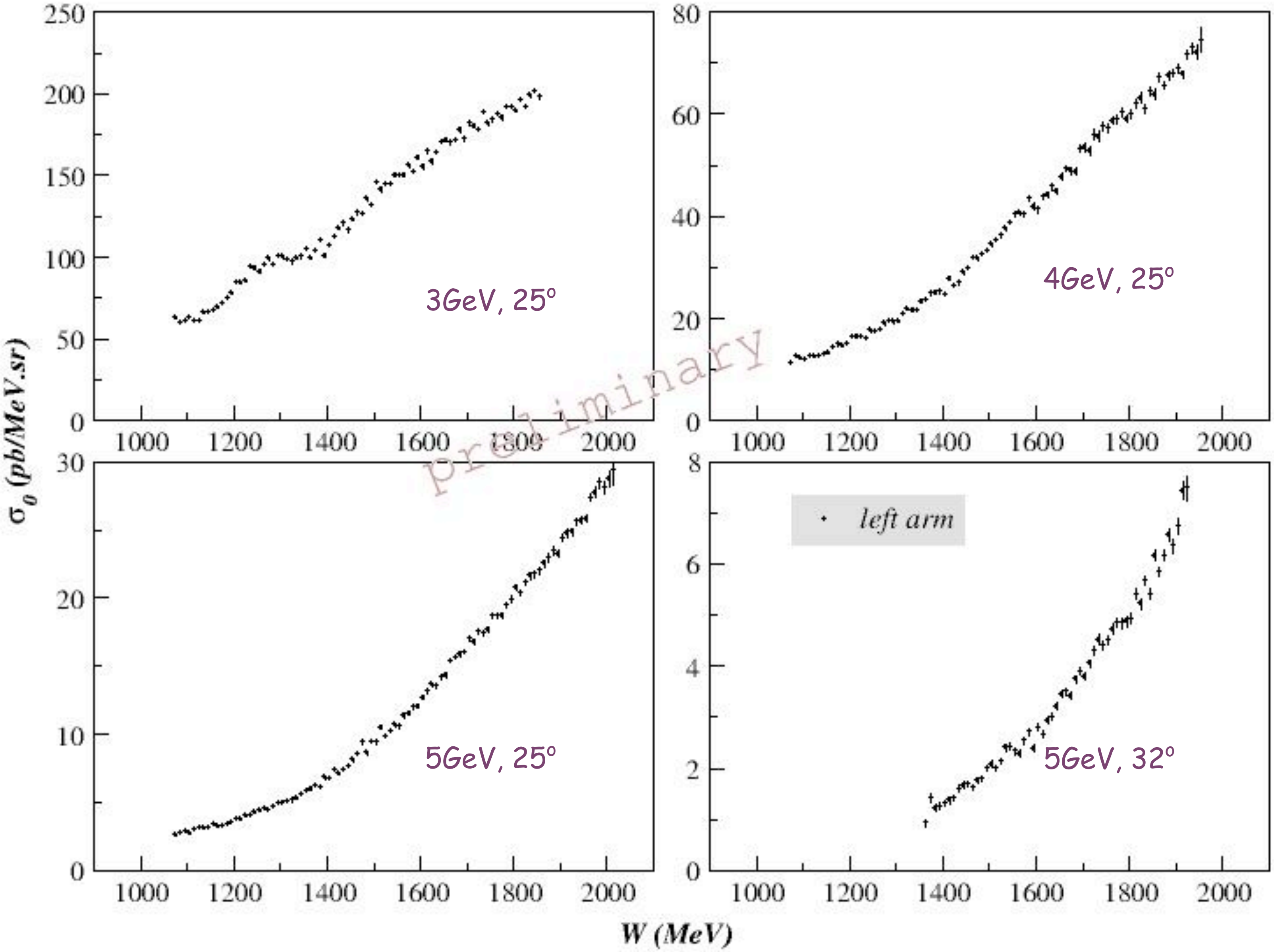
Analysis scheme

$$\sigma_0 = \frac{N_{cuts}}{N_{inc.}\rho\varepsilon_{\det}LT} * Acc. - \frac{2\rho_{N_2}}{\rho + \rho_{N_2}}\sigma_N$$



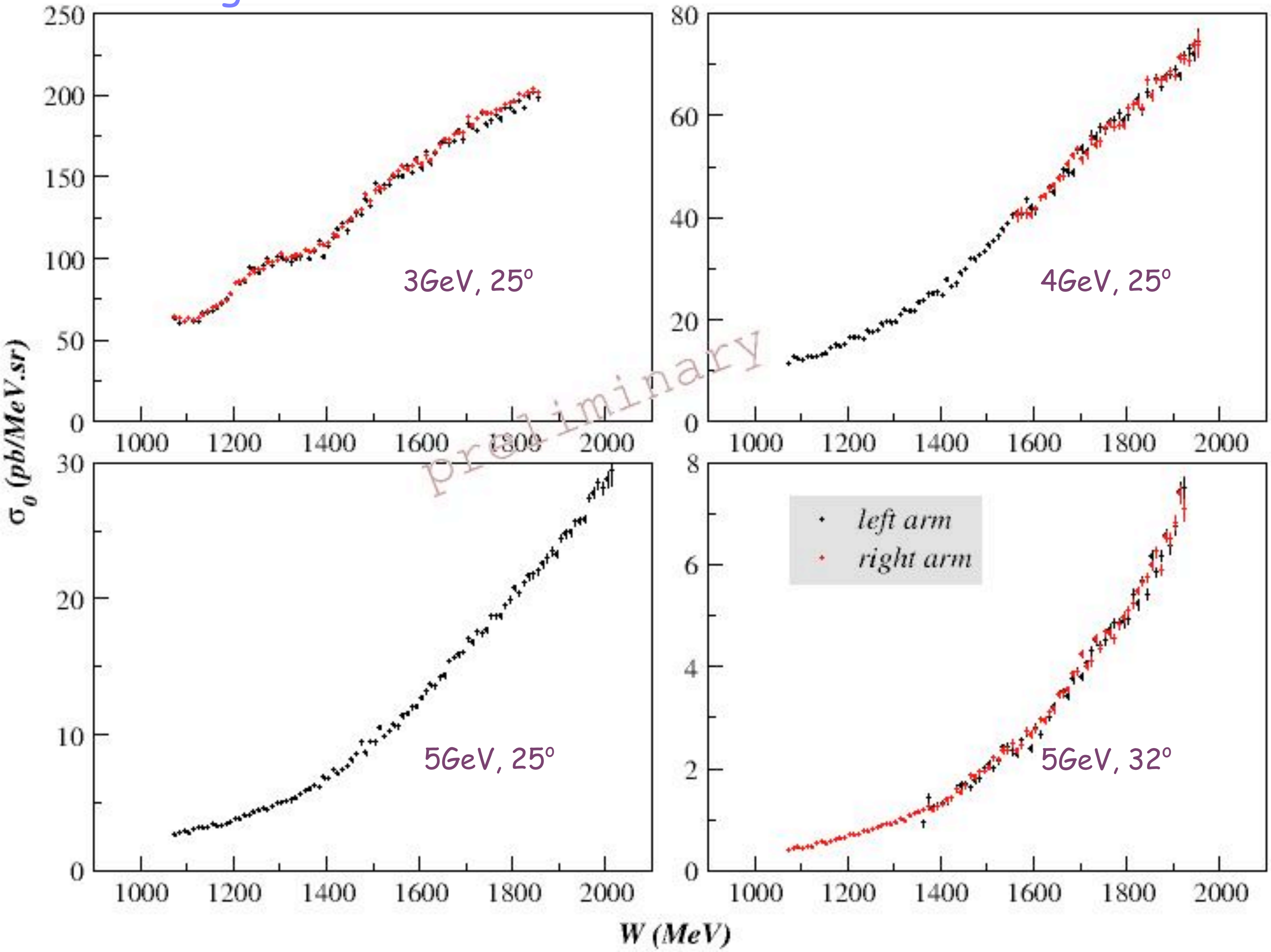
$$A_{\parallel,\perp} = \frac{1}{f_{N_2} P_{tg} P_{beam}} \frac{\dfrac{N^+}{Q^+LT^+} - \dfrac{N^-}{Q^-LT^-}}{\dfrac{N^+}{Q^+LT^+} + \dfrac{N^-}{Q^-LT^-}}$$

Unpolarized cross sections

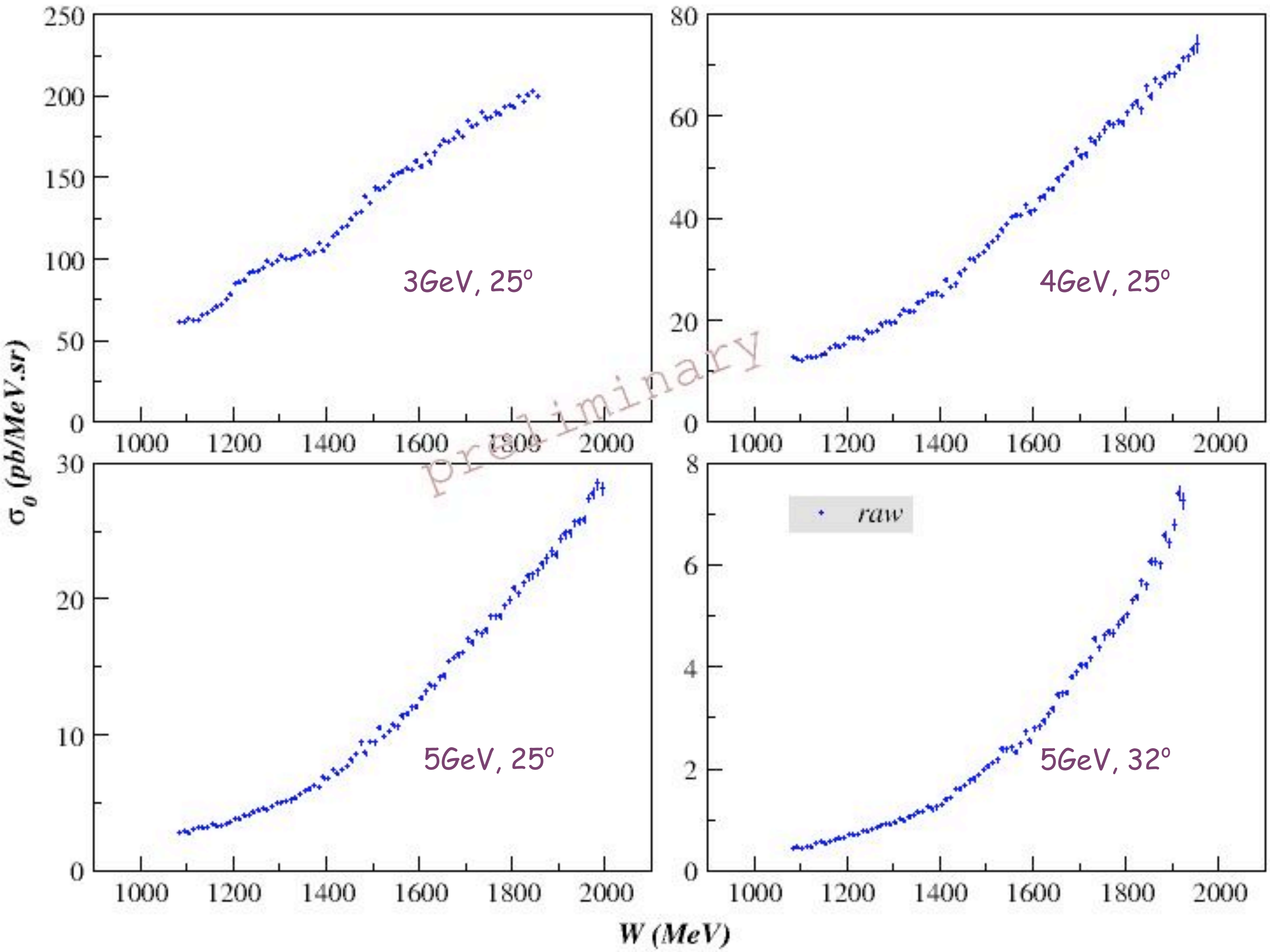


Unpolarized cross sections

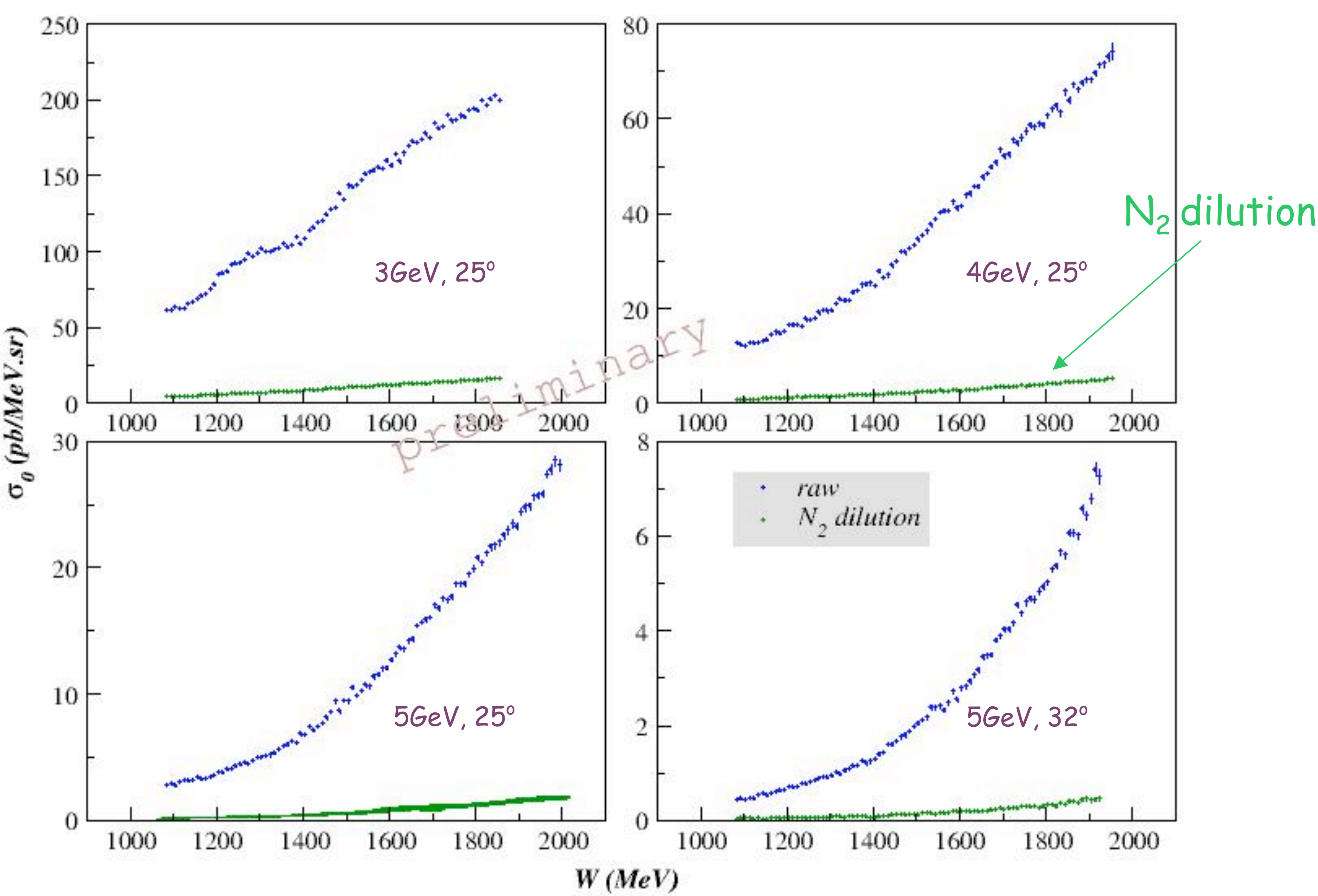
Agreement between both HRS better than 2%



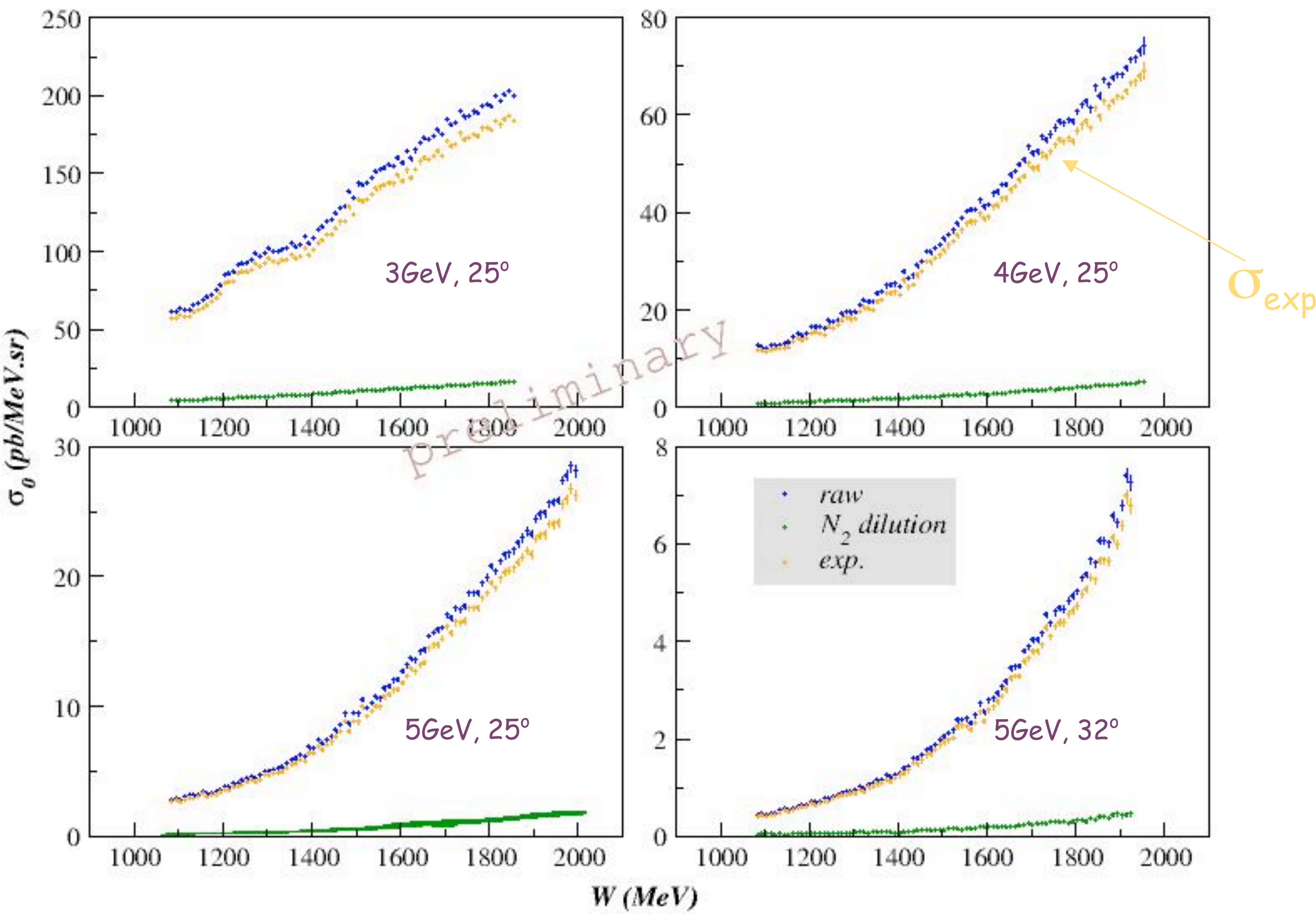
Unpolarized cross sections



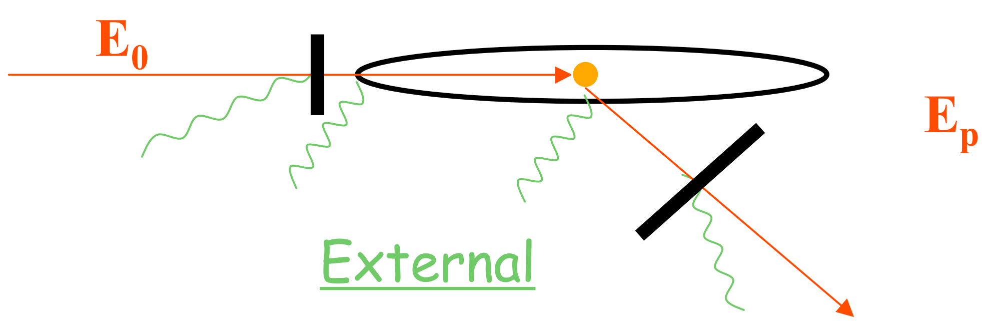
Unpolarized cross sections



Unpolarized cross sections



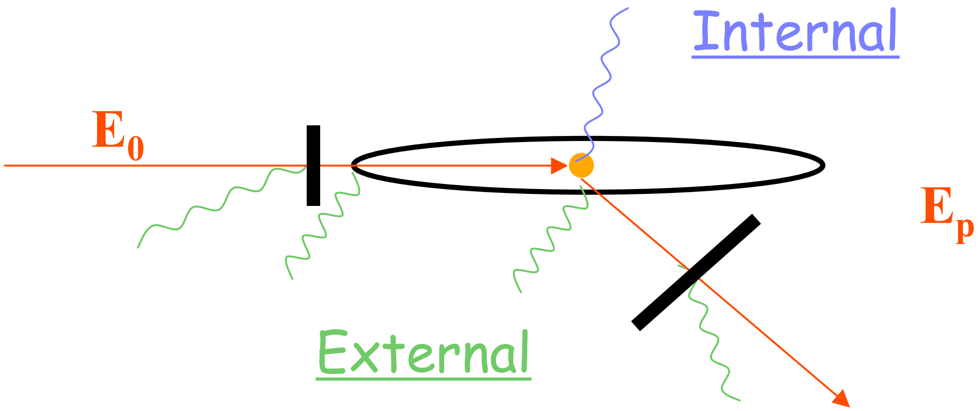
Radiative corrections



At reaction point:

$$E_0^r < E_0$$
$$E_p^r > E_p$$

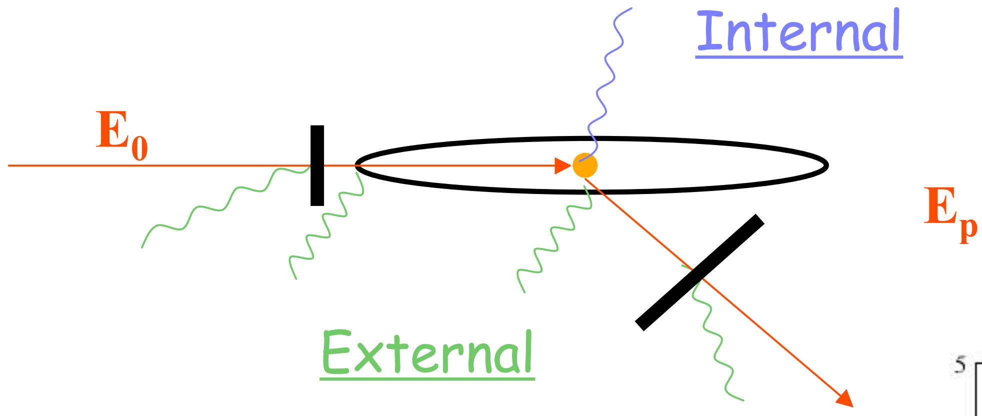
Radiative corrections



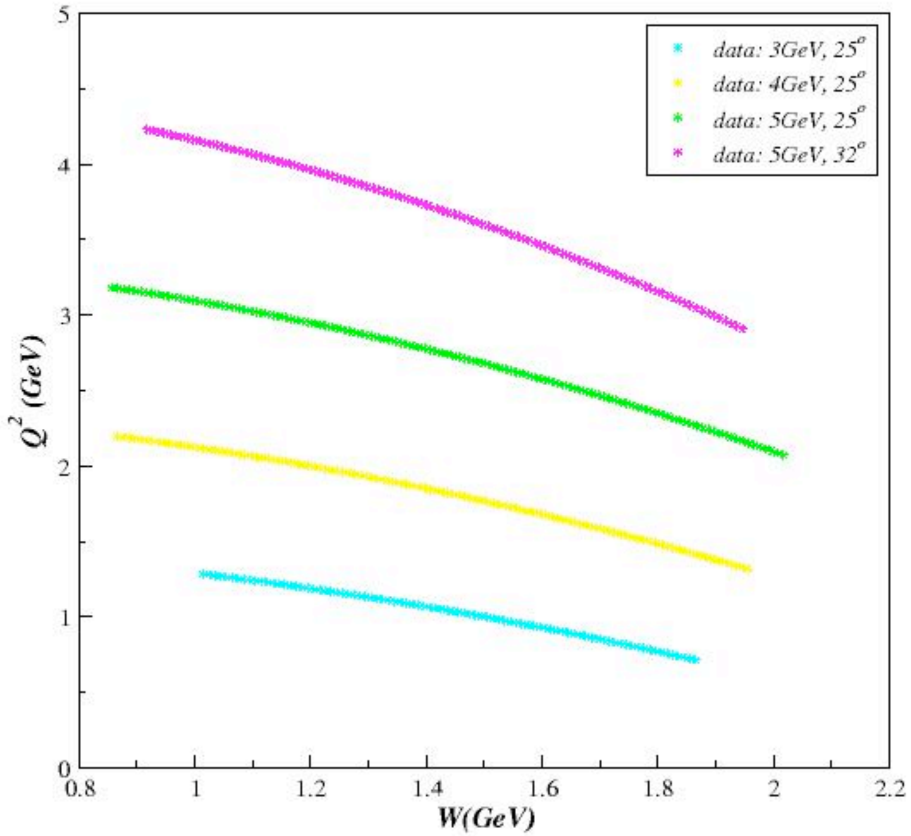
At reaction point:

$$E_0^r < E_0$$
$$E_p^r > E_p$$

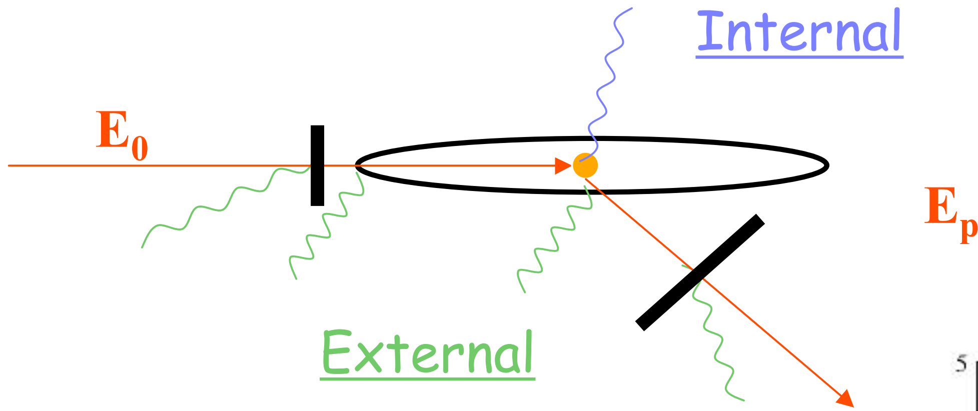
Radiative corrections



At reaction point: $E_0^r < E_0$ $E_p^r > E_p$



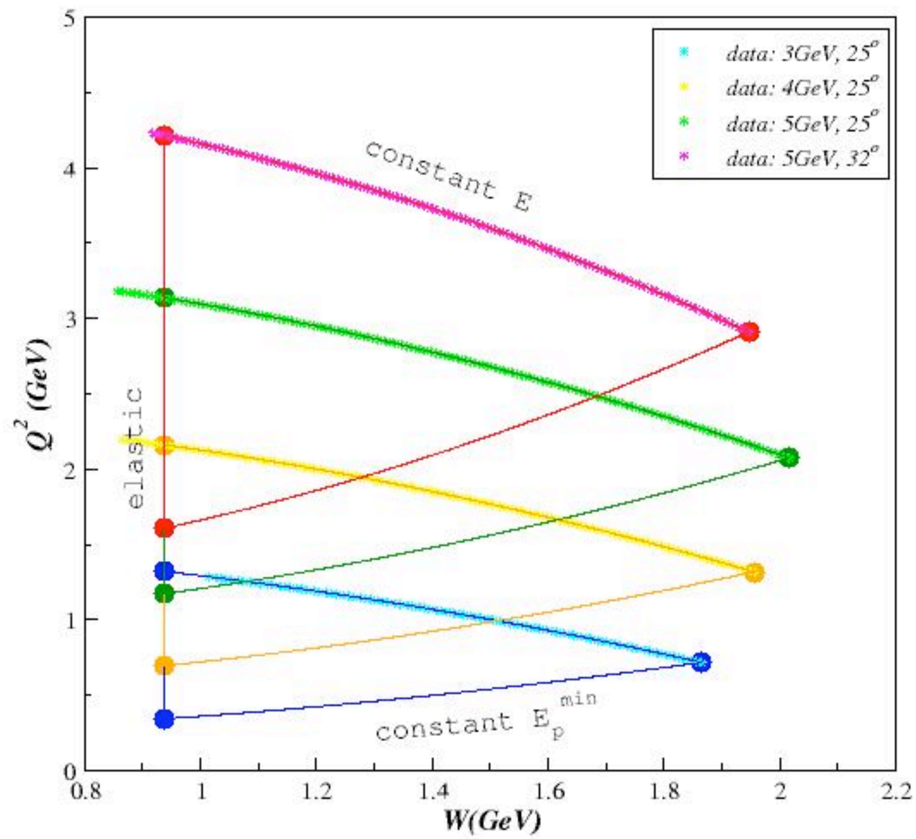
Radiative corrections



At reaction point:

$$E_0^r < E_0$$
$$E_p^r > E_p$$

Computation to get the real reaction



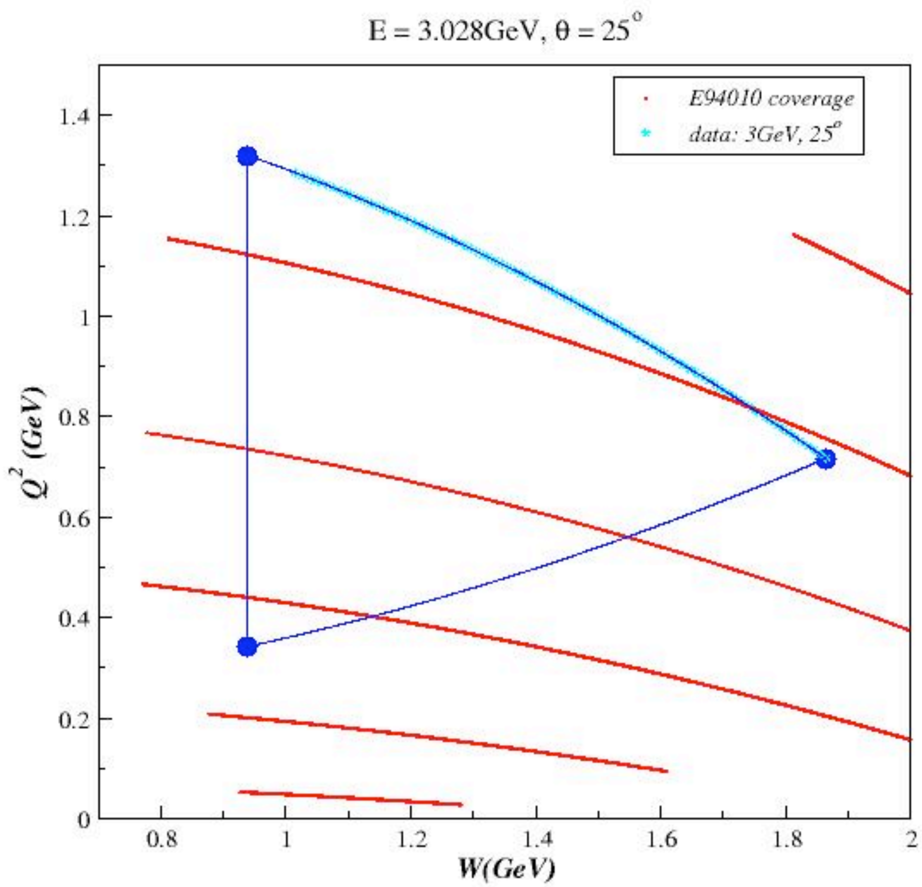
Radiative corrections

♦ Used QFS model for σ_o. Next will use E94-010 data for σ_o:

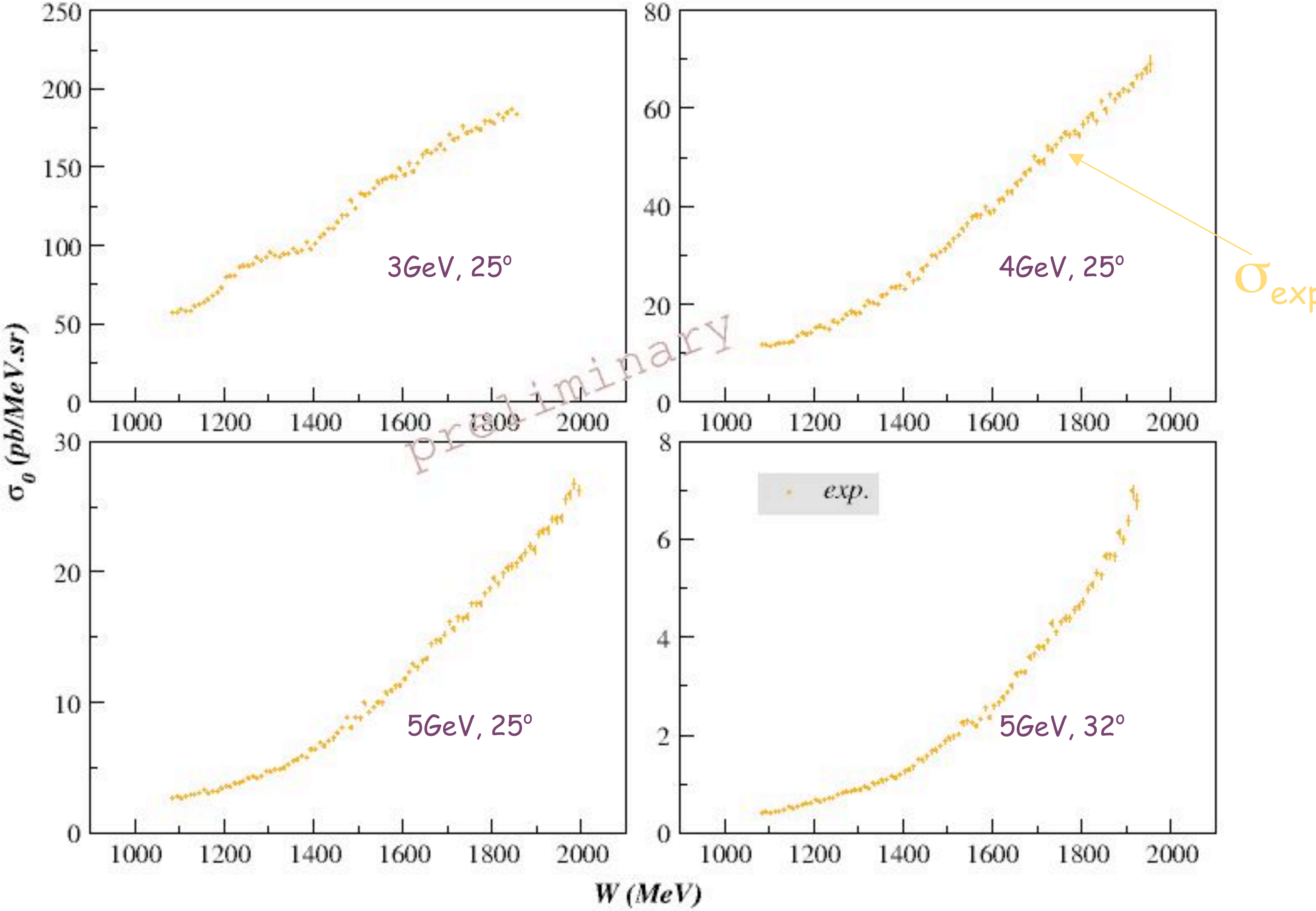
$$F_2(x,Q^2) \rightarrow \sigma_0(E,E',\theta)$$

♦ Used E94-010 data as a model for radiative corrections at the lowest energy:

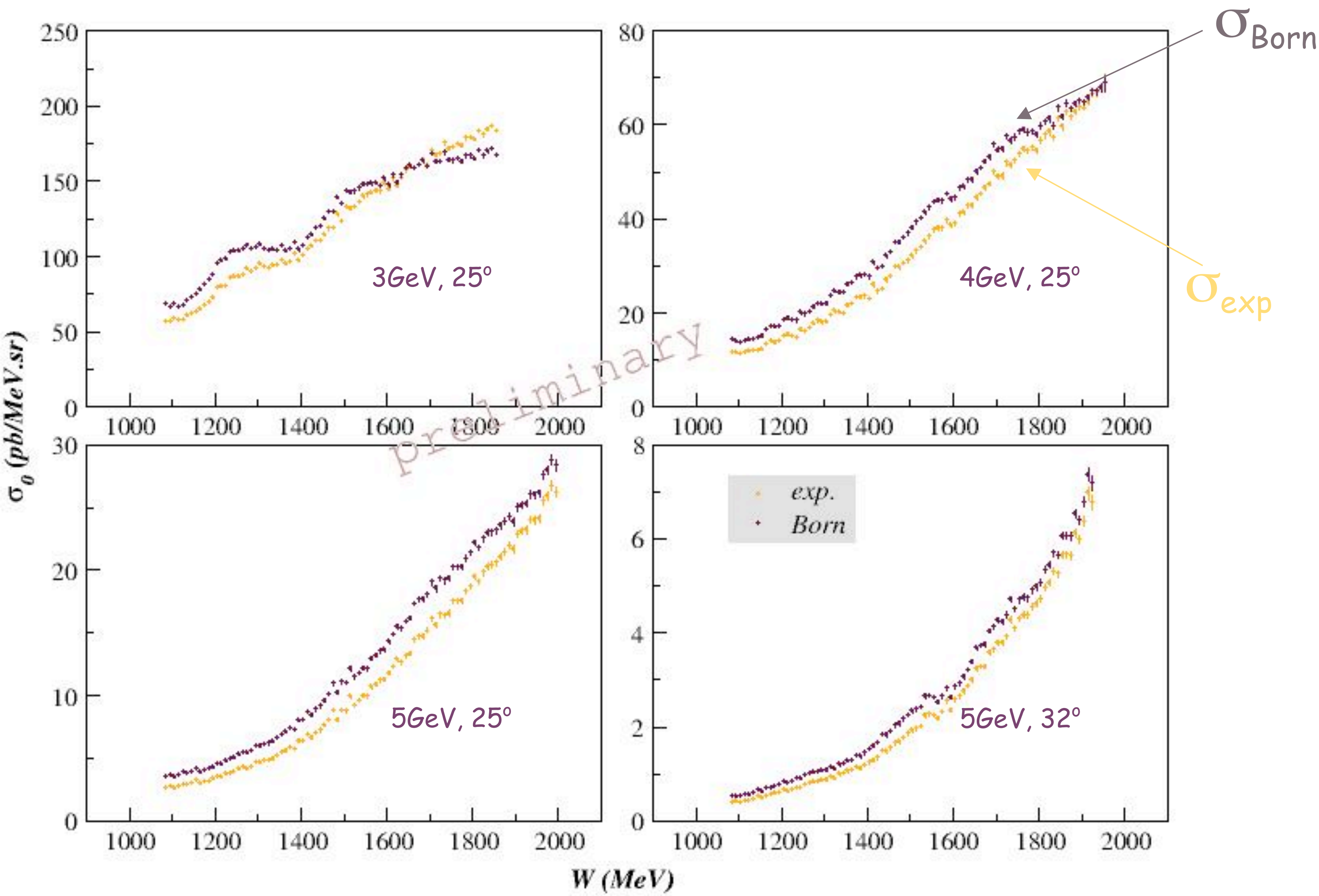
$$g_{1,2}(x,Q^2) \rightarrow \Delta\sigma_{\parallel,\perp}(E,E',\theta)$$



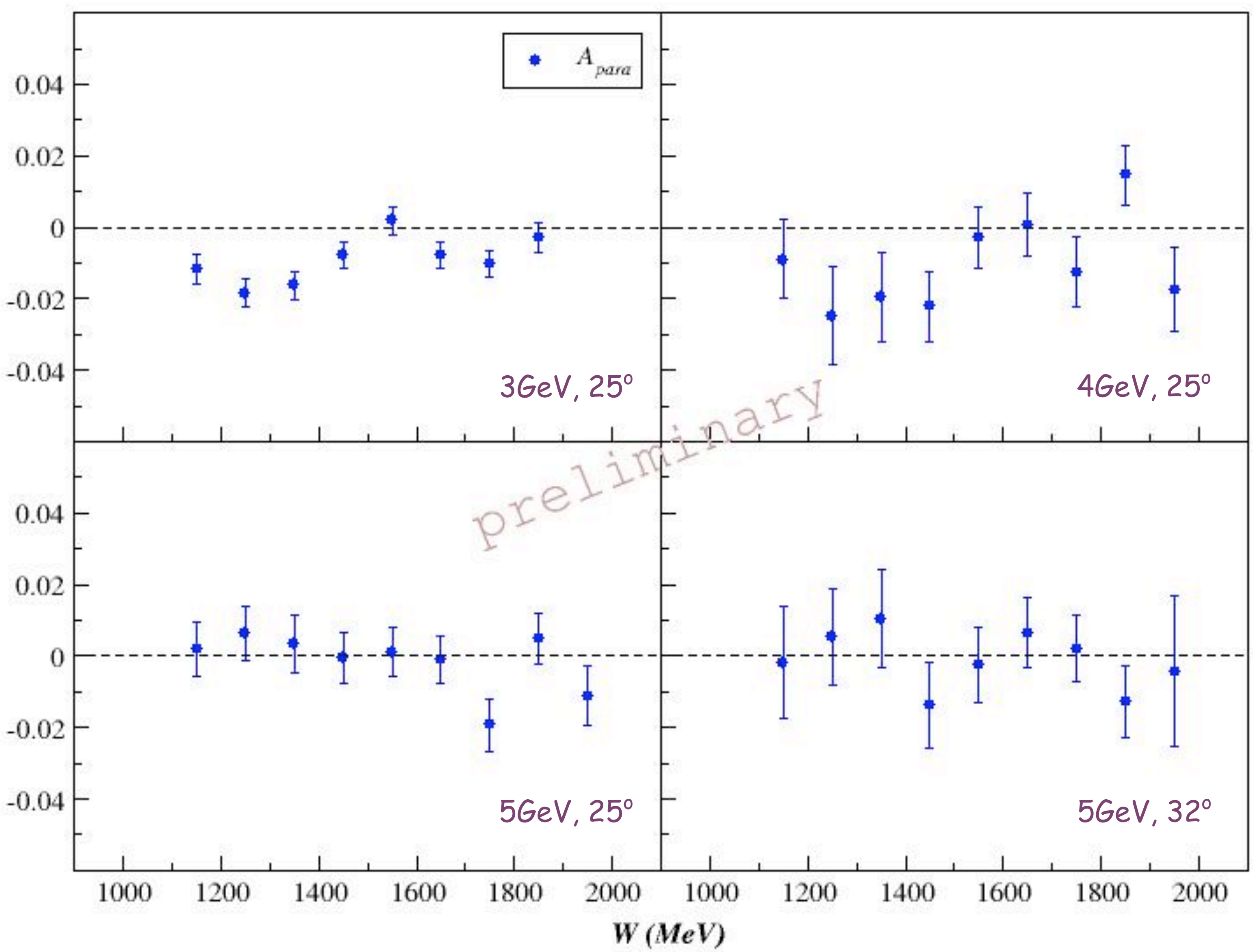
Unpolarized cross sections



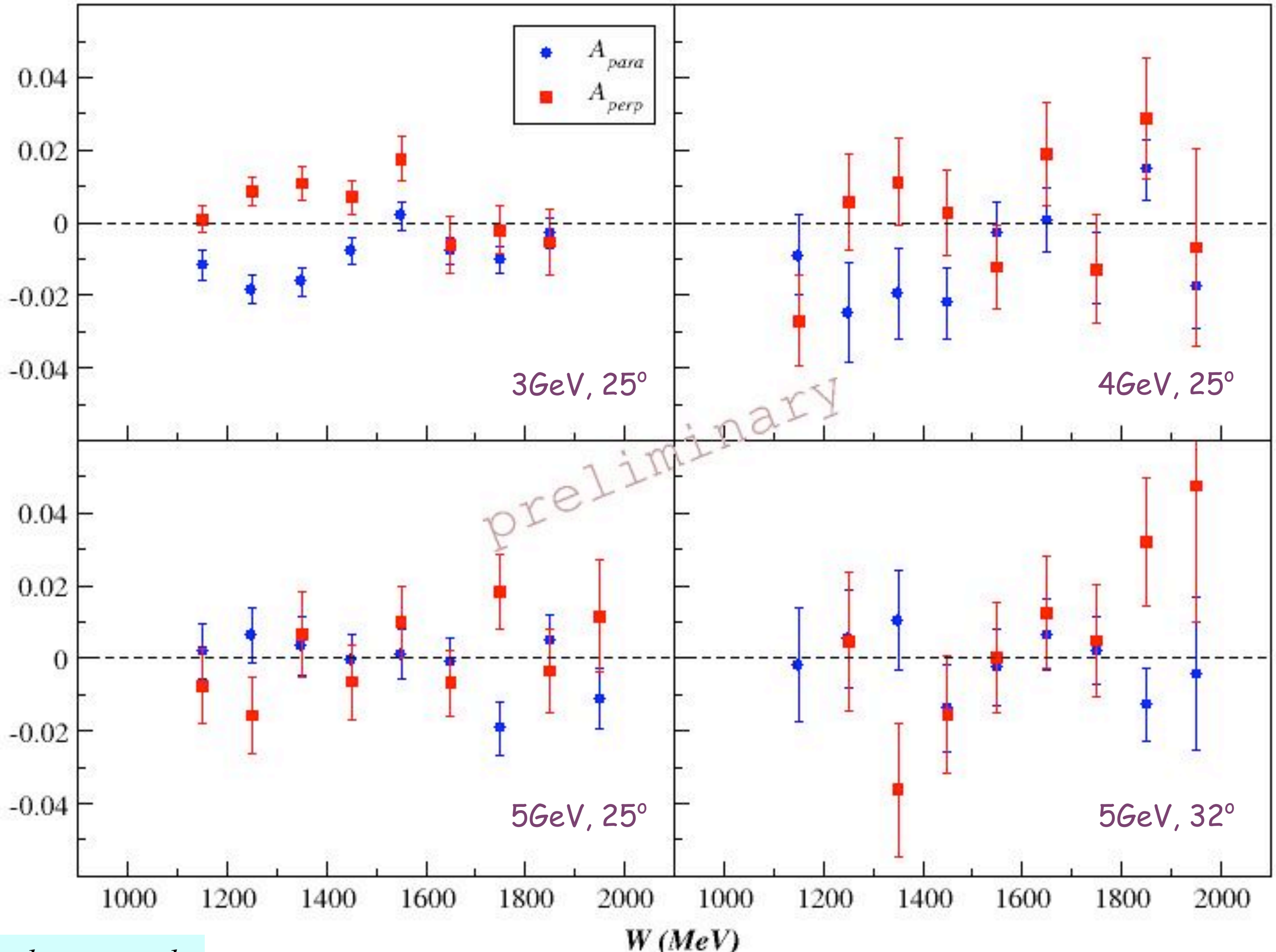
Unpolarized cross sections



Asymmetries

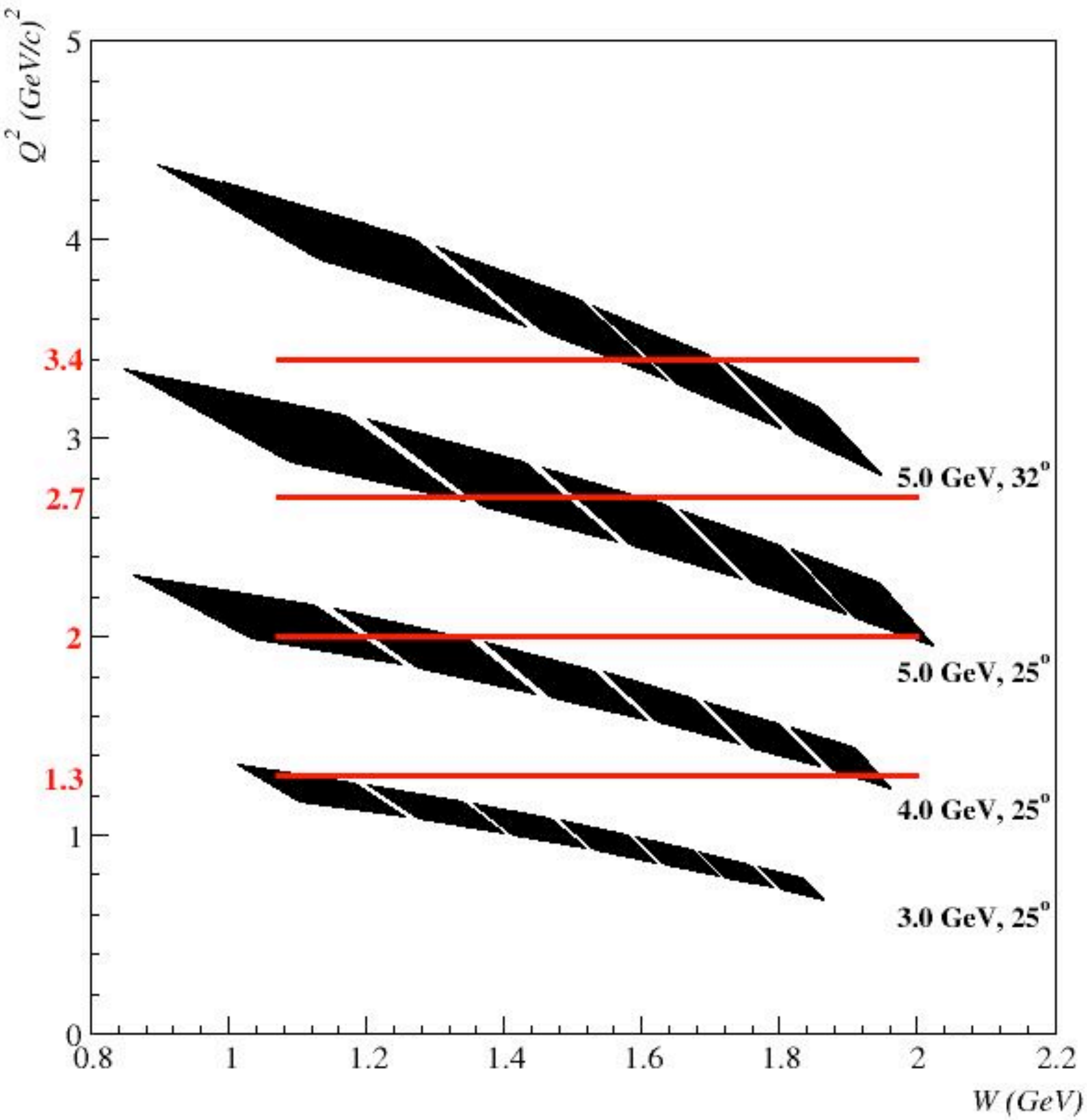


Asymmetries

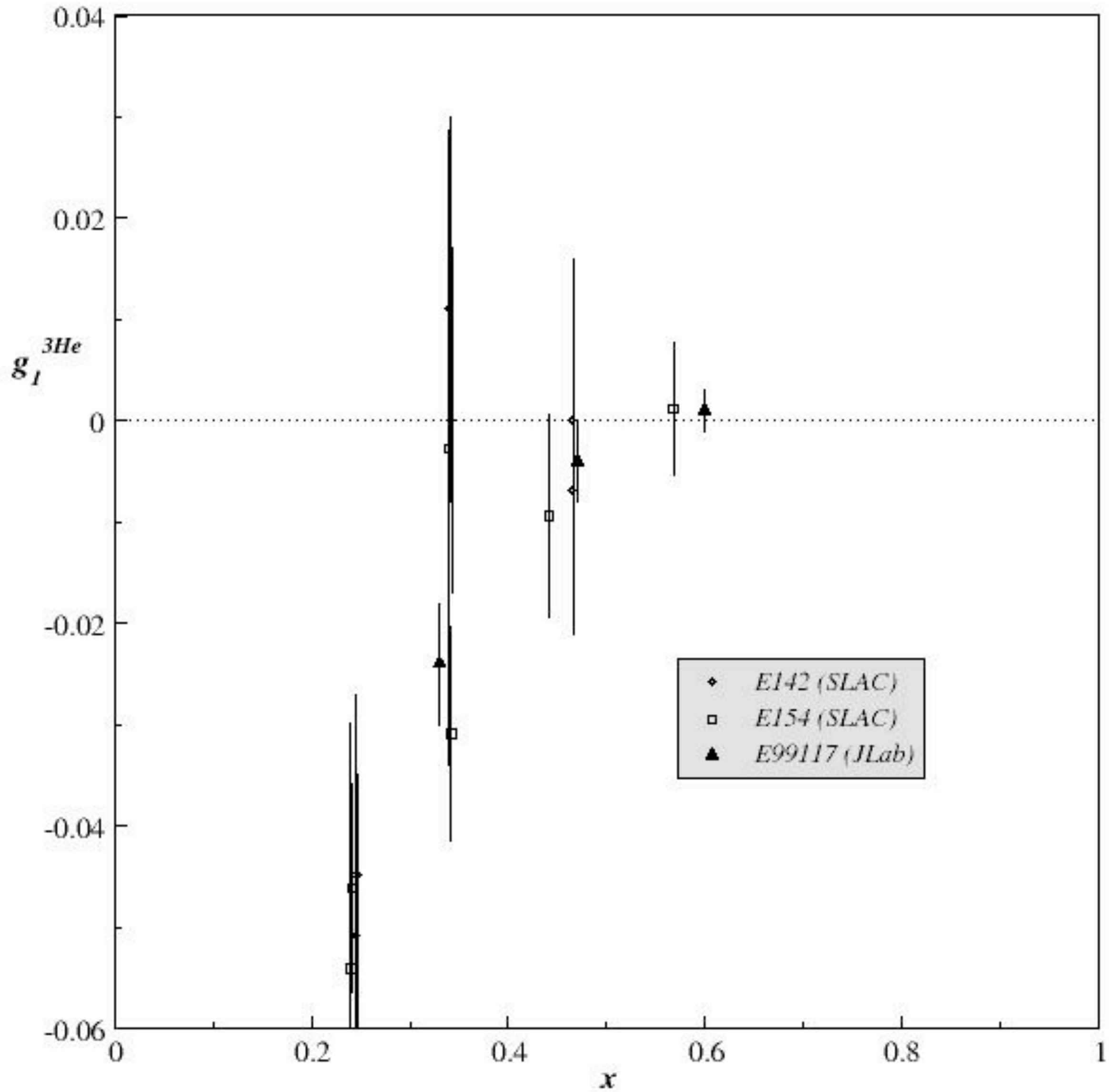


Statistical errors only

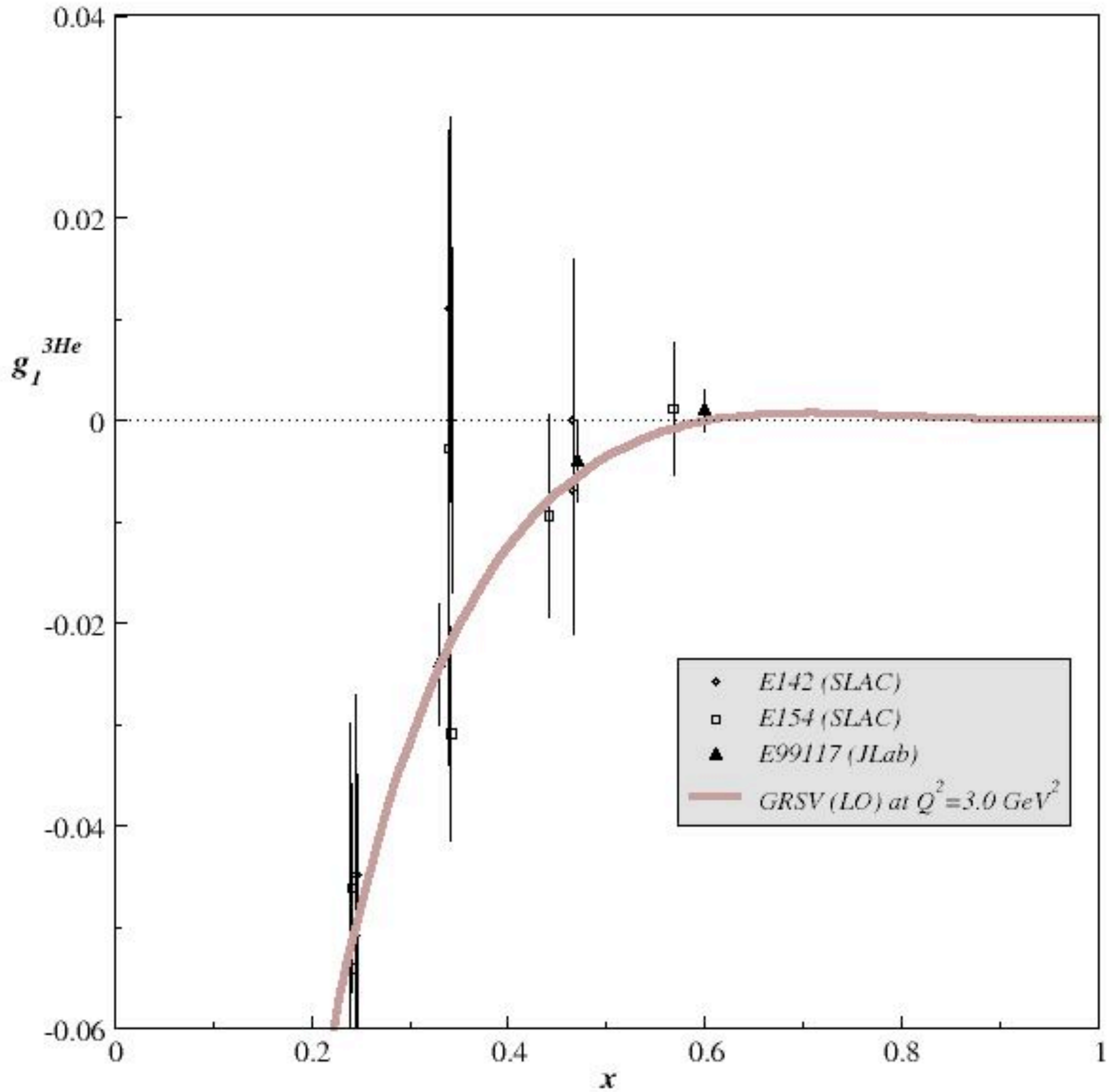
From constant E to constant Q^2



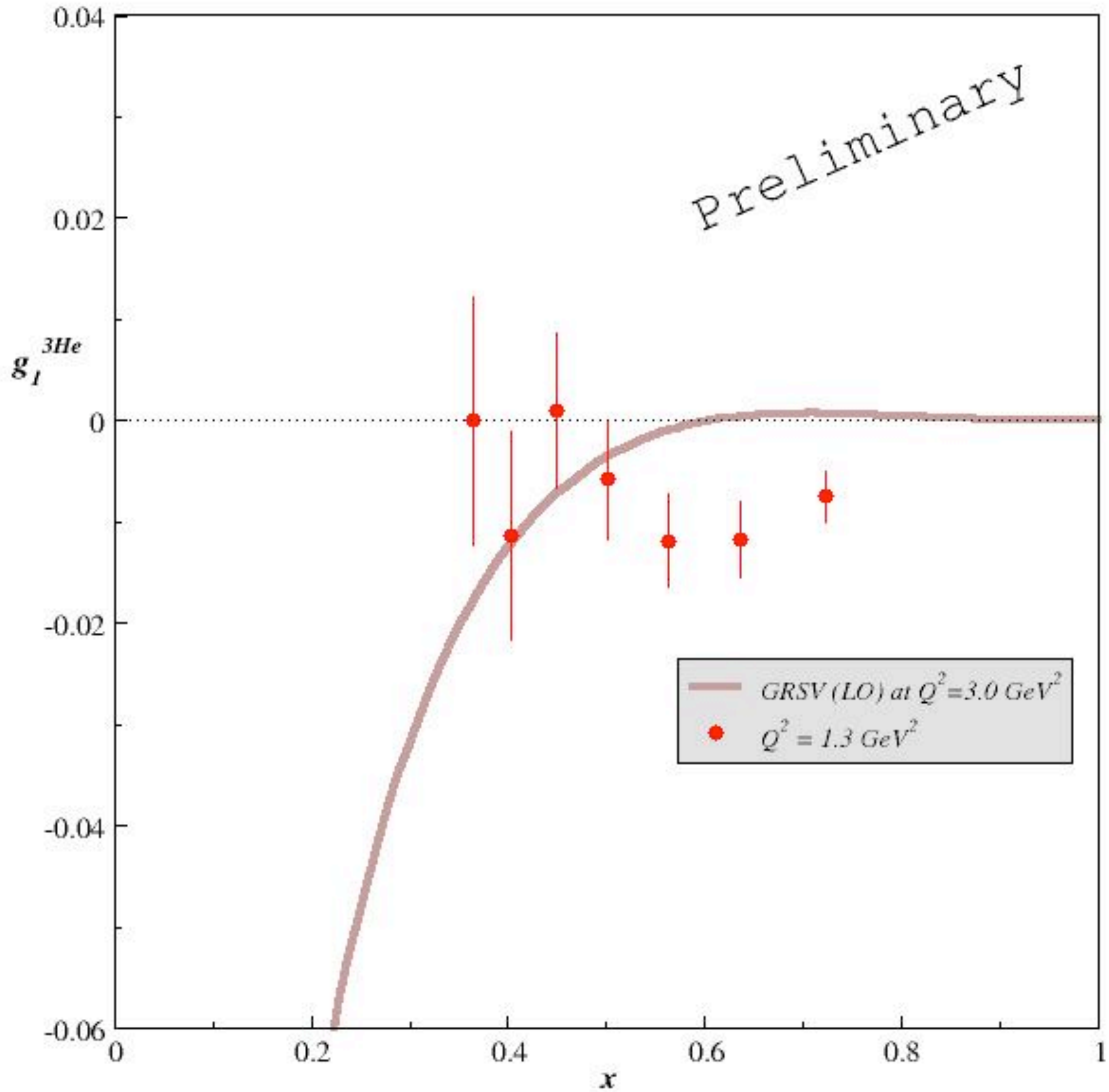
g_1^{3He} at constant Q^2



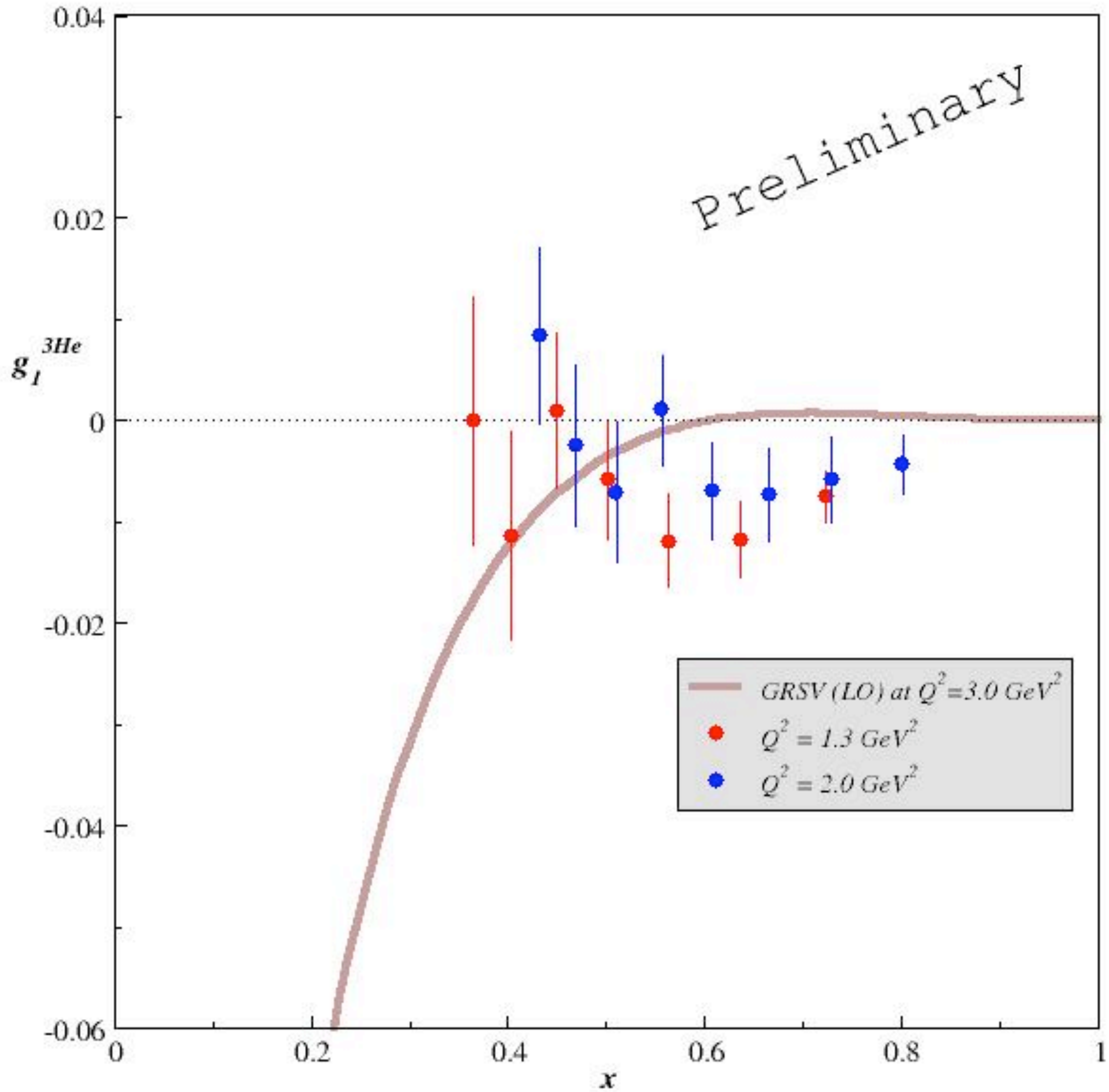
g_1^{3He} at constant Q^2



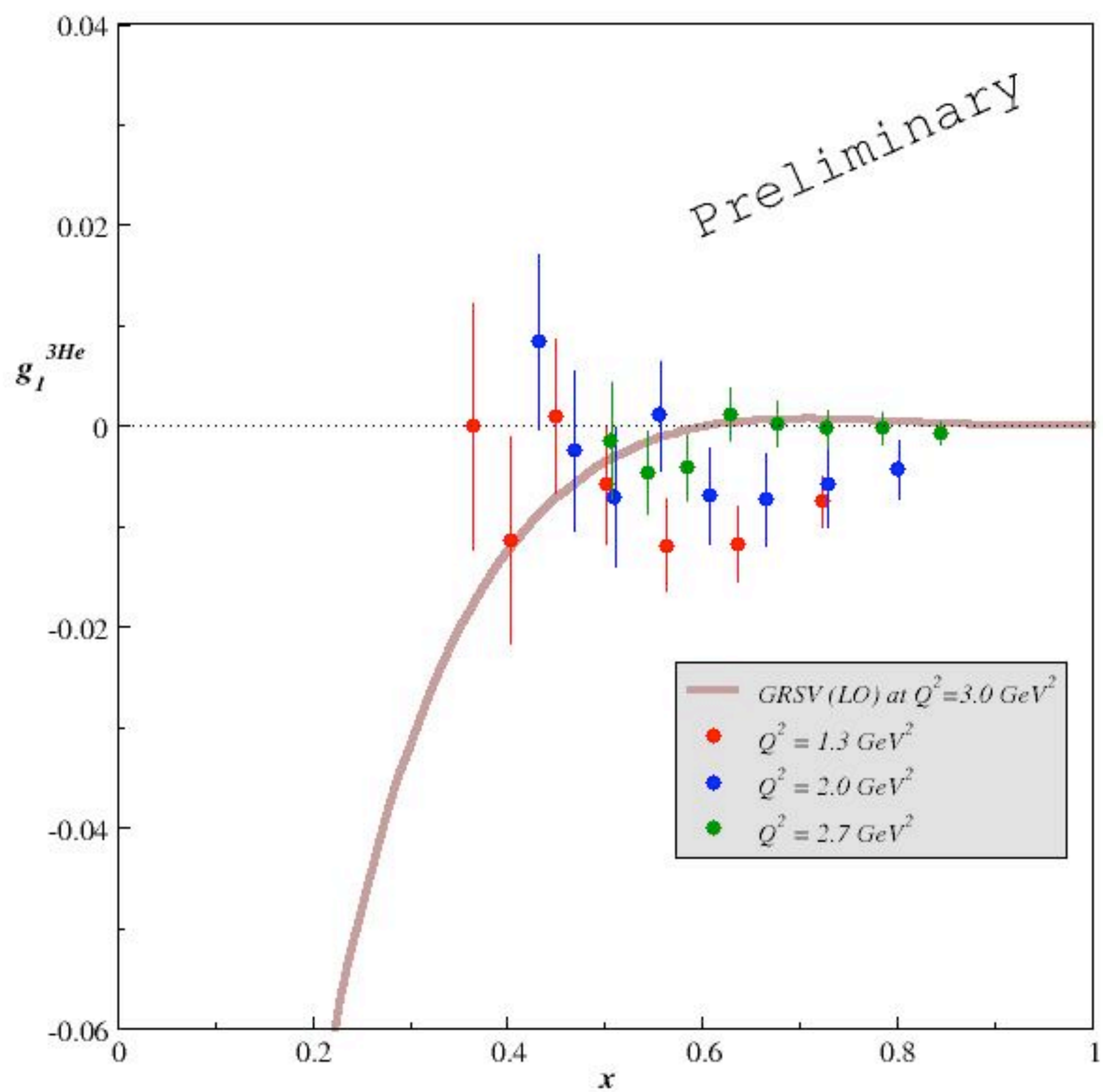
g_1^{3He} at constant Q^2



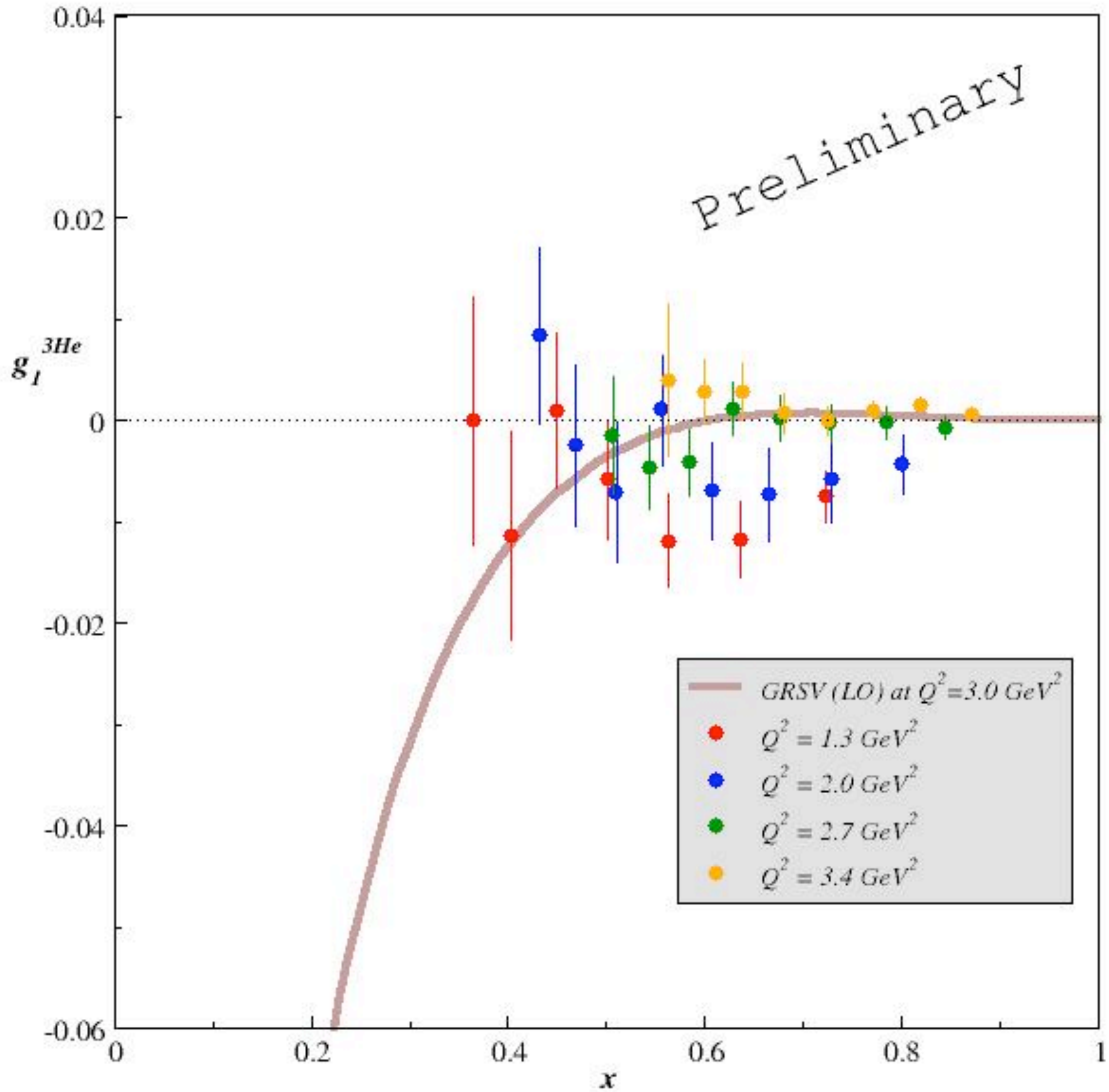
g_1^{3He} at constant Q^2



g_1^{3He} at constant Q^2



g_1^{3He} at constant Q^2

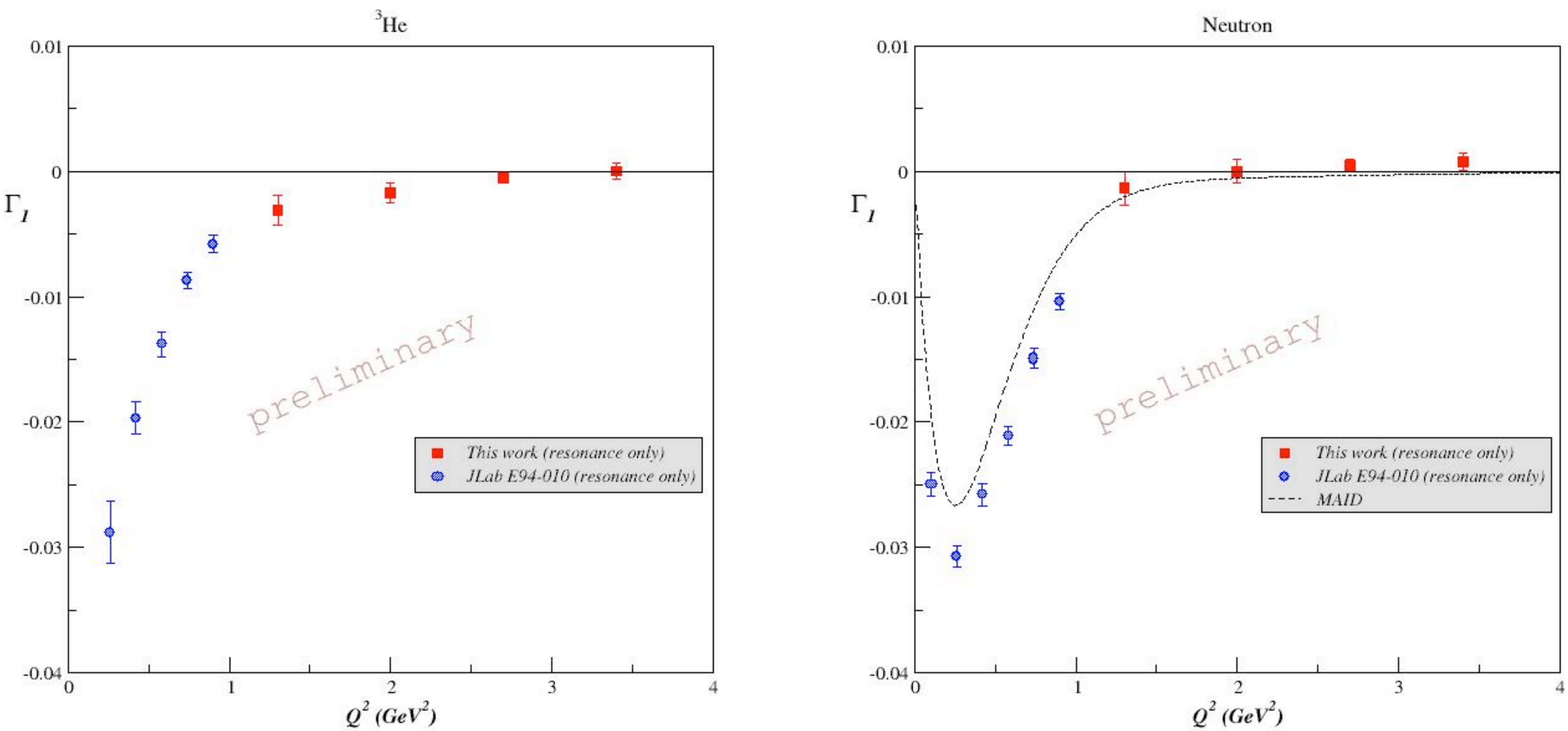


g_1 in the resonance region

Extract the neutron from effective polarization equation:

$$\tilde{\Gamma}_1^{^3He} = P_n \tilde{\Gamma}_1^n + 2P_p \tilde{\Gamma}_1^p$$

P_n=86%
P_p=-2.8%



Statistical errors only

Test of Duality on Neutron and ^{3}He

Used method defined by N. Bianchi, A. Fantoni and S. Liuti on g_1^p PRD 69 (2004) 014505

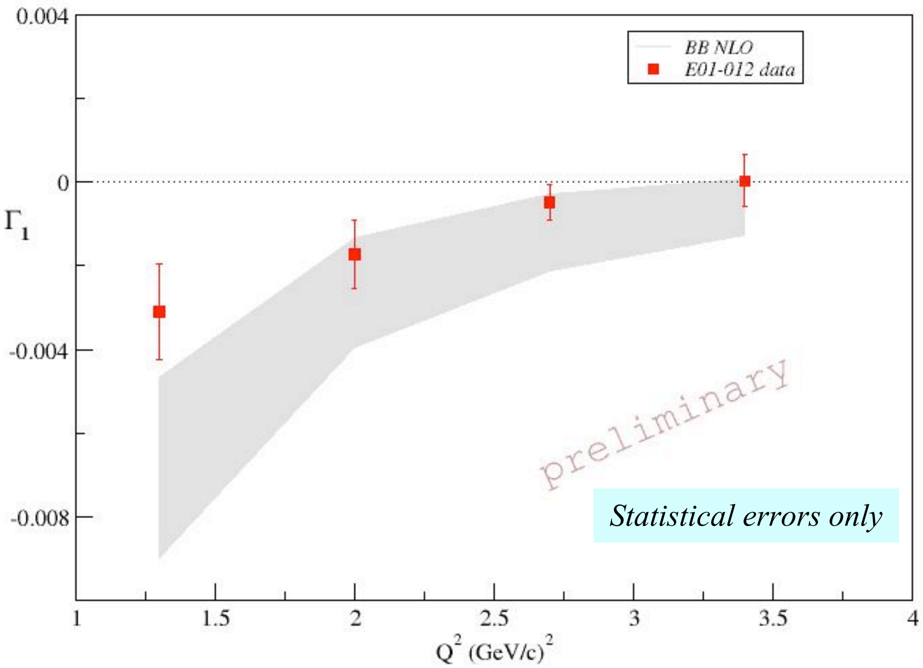
1. Get g_1 at constant Q^2
2. Define integration range in the resonance region in function of W
3. Integrate g_1^{res} and g_1^{dis} over the same x-range and at the same Q^2

$$\tilde{\Gamma}_1^{res} = \int_{x_{min}}^{x_{max}} g_1^{res}(x,Q^2)dx \qquad \tilde{\Gamma}_1^{dis} = \int_{x_{min}}^{x_{max}} g_1^{dis}(x,Q^2)dx$$

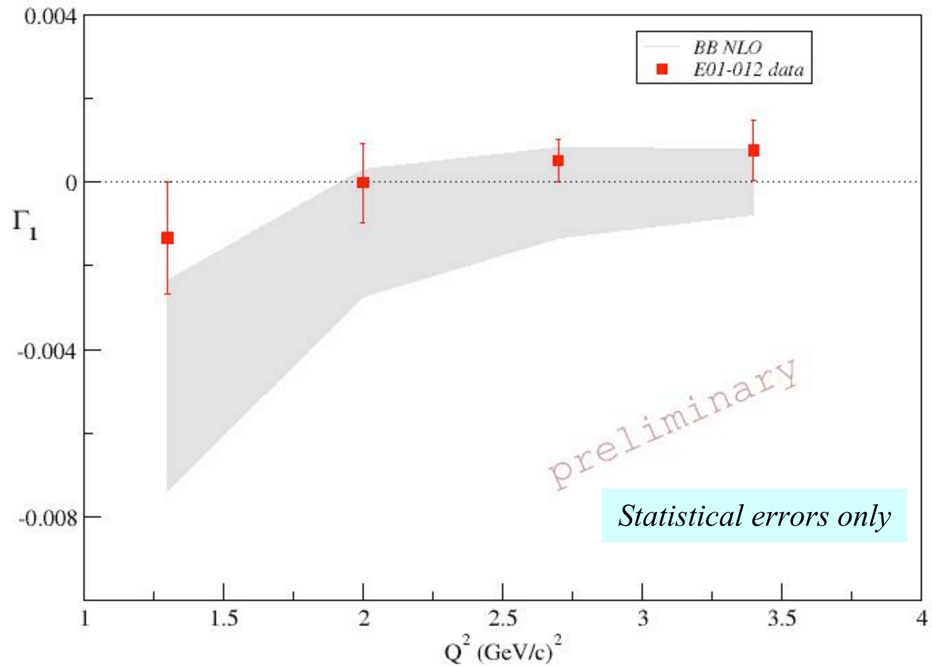
If $\tilde{\Gamma}_1^{res} = \tilde{\Gamma}_1^{dis}$ $\Rightarrow$ **duality is verified**

Test of Duality on Neutron and ^3He

^3He



Neutron



Global duality seems to work for all our Q^2

Virtual Photon-Nucleon Asymmetry

In the parton model:

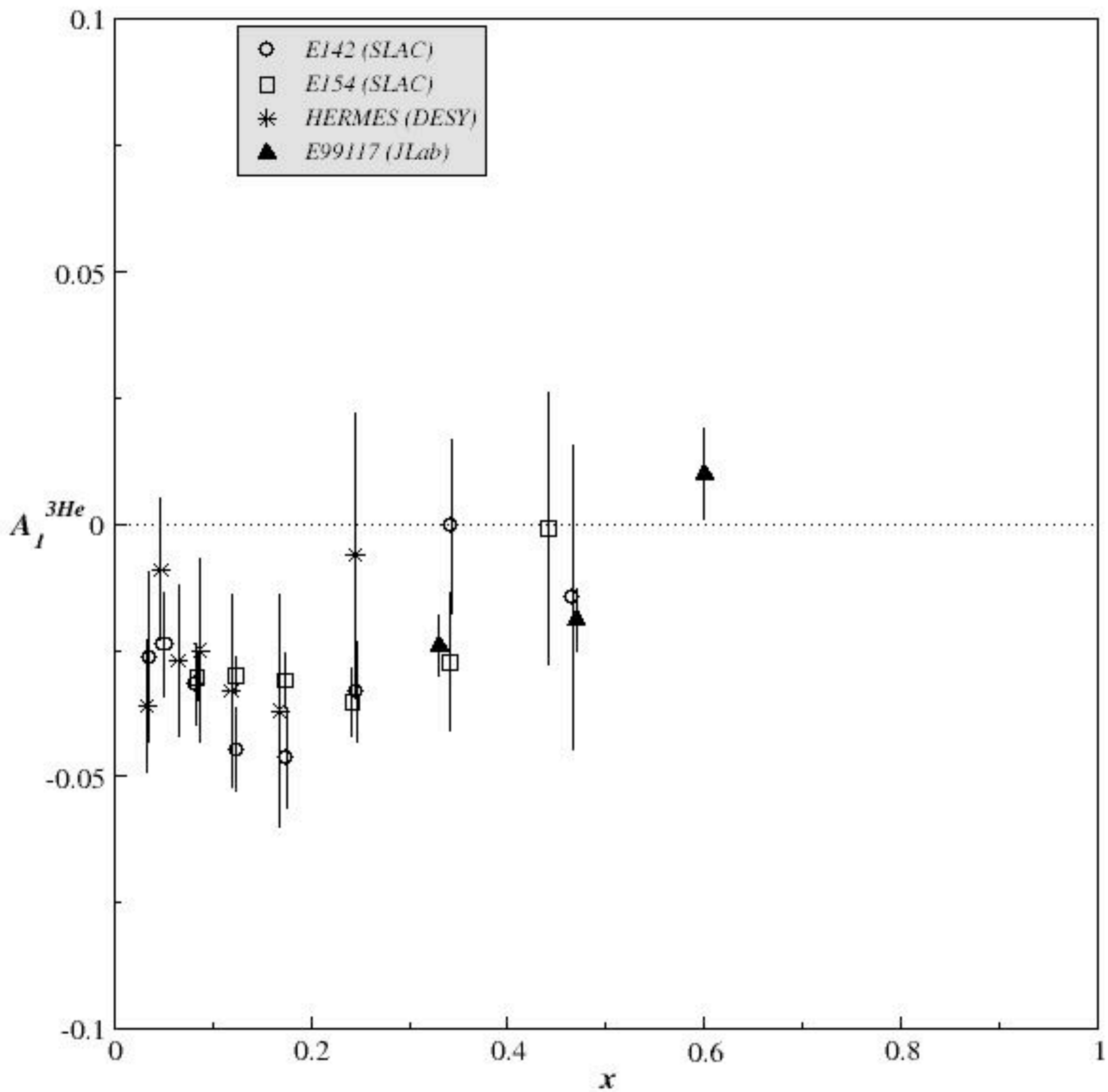
$$A_1(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

If Q^2 dependence similar for g_1 and for F_1 $\Rightarrow$ weak Q^2 dependence of A_1

From the resonance:

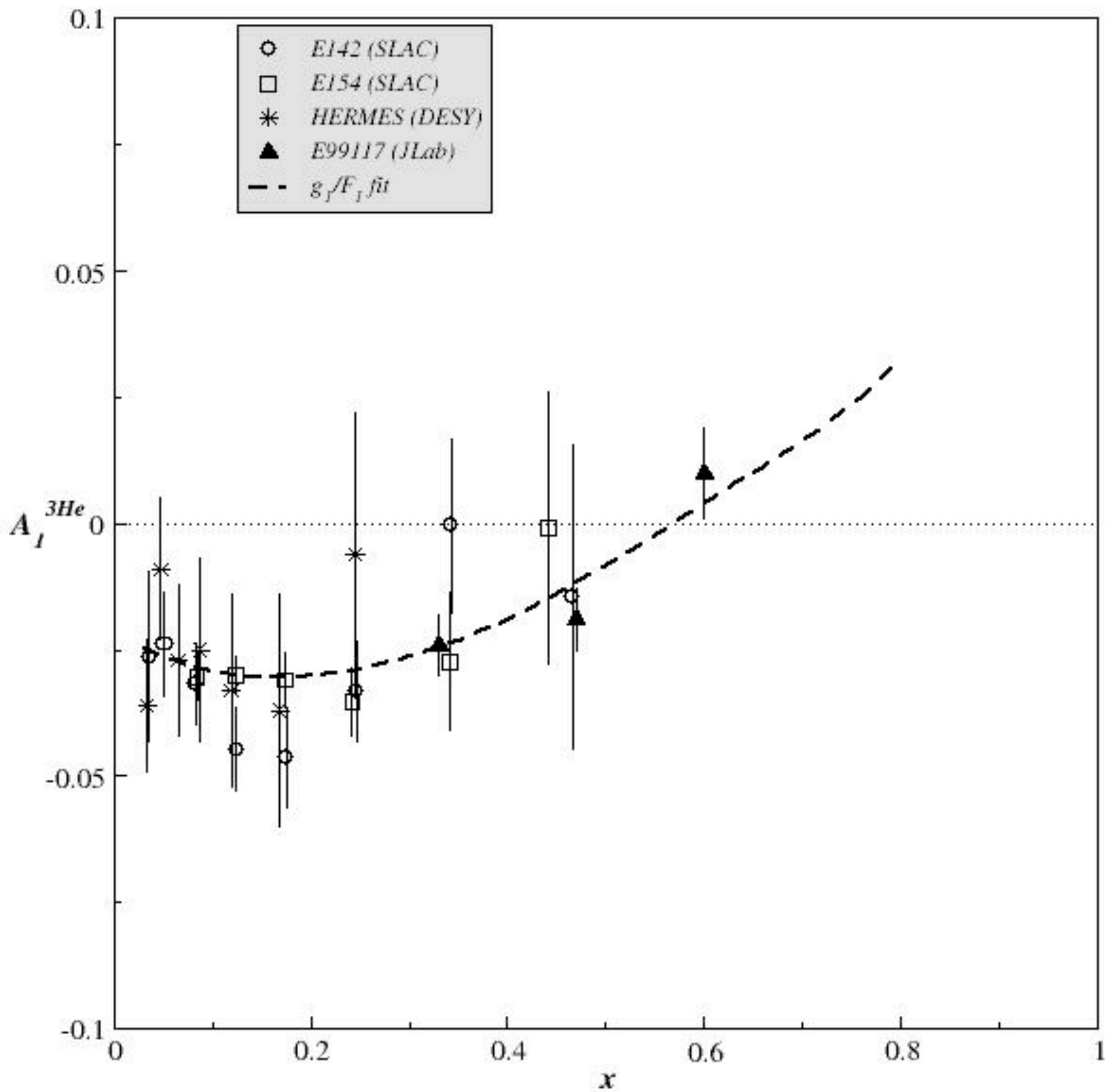
If local duality observed in g_1 and F_1 $\longrightarrow$ $A_1^{res} = A_1^{dis}$

$A_1^{\,3}He$



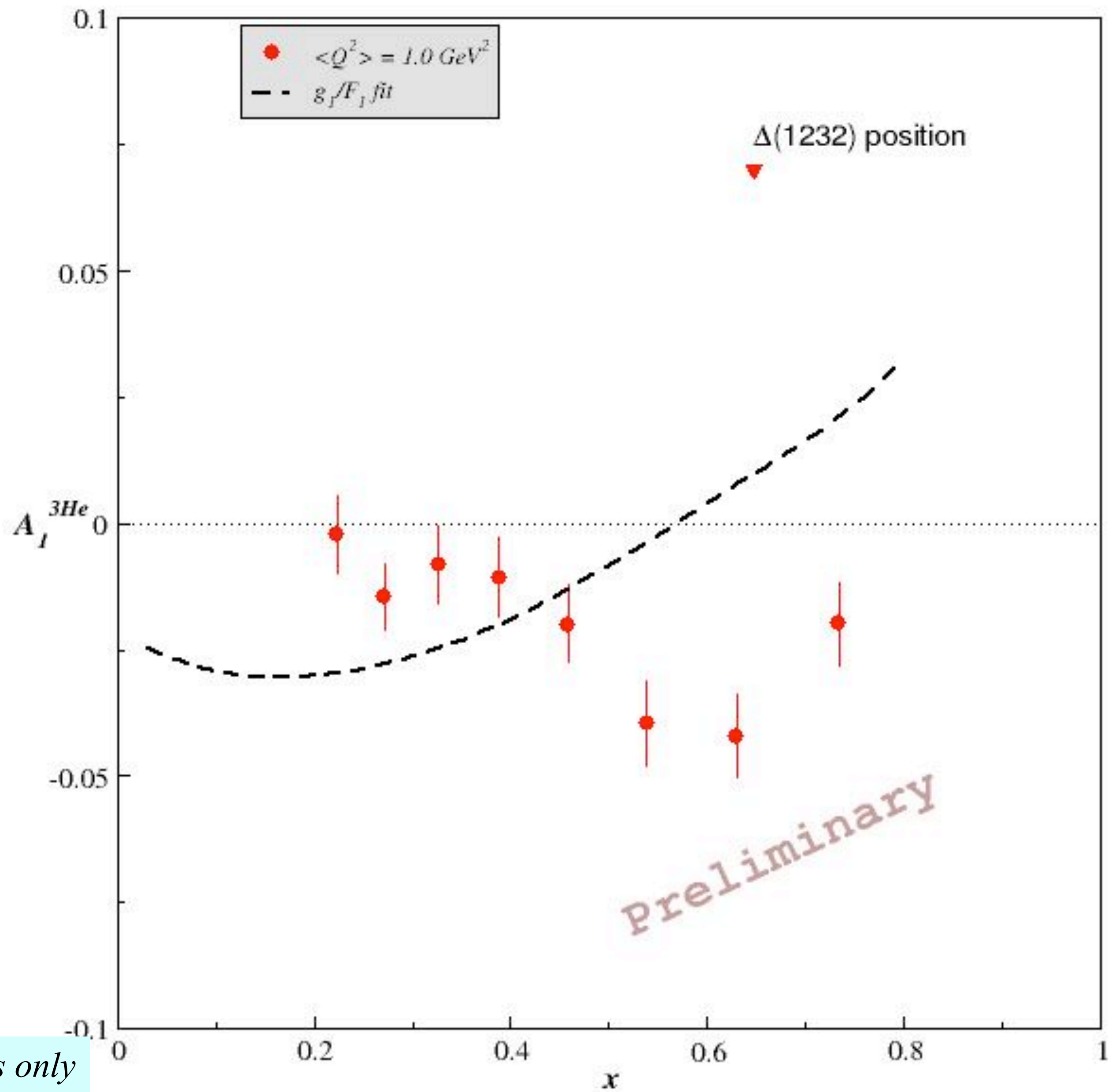
E142 (SLAC)
E154 (SLAC)
HERMES (DESY)
E99117 (JLab)
0.1
0.05
0
-0.05
-0.1
A_1^{3He}
0
0.2
0.4
0.6
0.8
1
x

$A_1{}^{3}He$



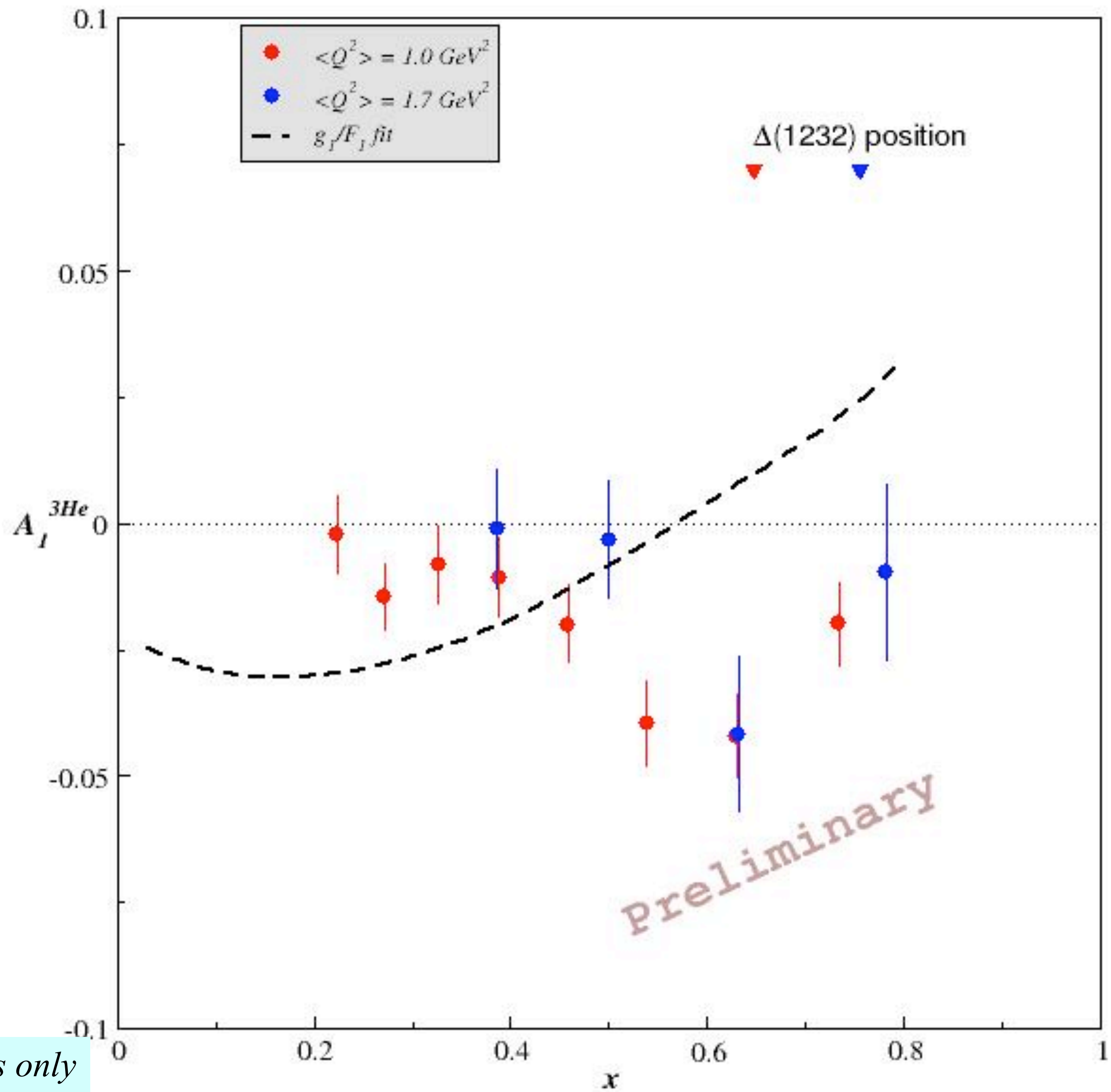
0.1
0.05
0
-0.05
-0.1
A1 3He
E142 (SLAC)
E154 (SLAC)
HERMES (DESY)
E99117 (JLab)
g1/F1 fit
0
0.2
0.4
0.6
0.8
1
x

A_1^{3He}



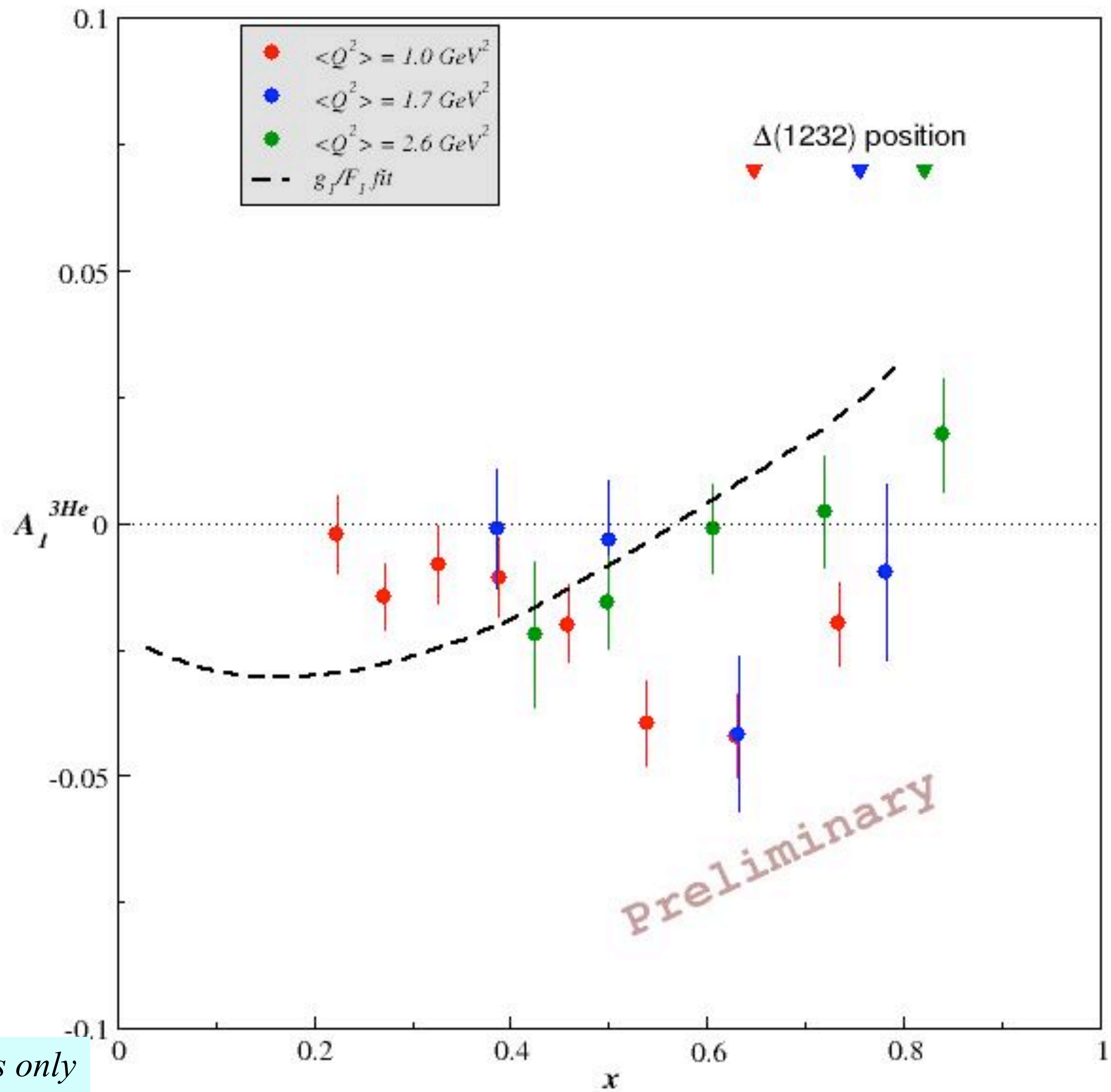
Statistical errors only

A_1^{3He}



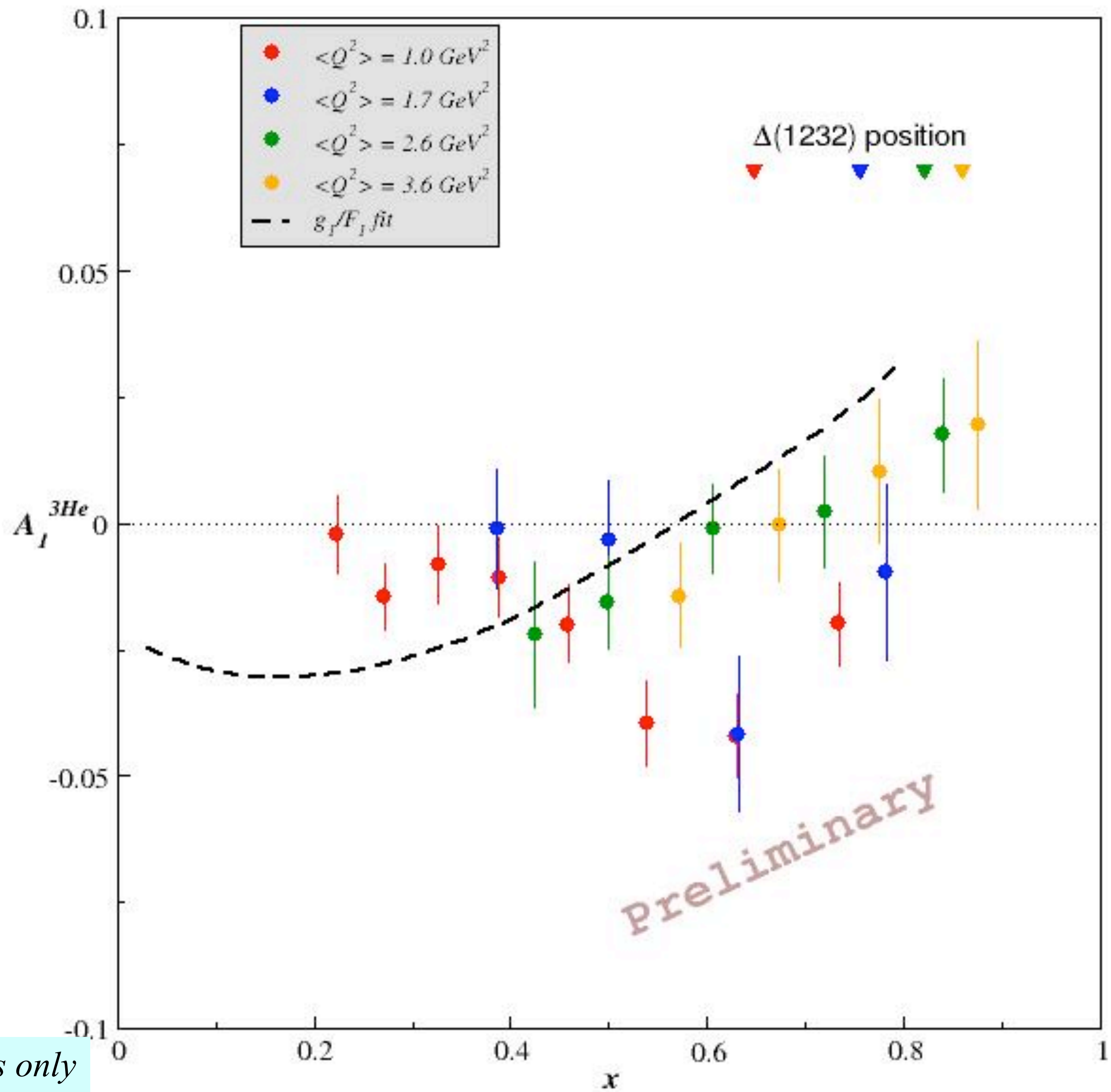
Statistical errors only

$A_1^{\,3He}$



Statistical errors only

A_1^{3He}



Statistical errors only

Summary

- E01-012 provides precision data of Spin Structure Functions on neutron (^{3}He) in the resonance region for $1.0 < Q^2 < 4.0 (GeV/c)^2$

- Direct extraction of g_1 and g_2 from our data

- Overlap between E01-012 resonance data and DIS data

→ First dedicated test of Quark-Hadron Duality for neutron and ^{3}He SSF

→ Global duality seems to work for g_1 for all our Q^2

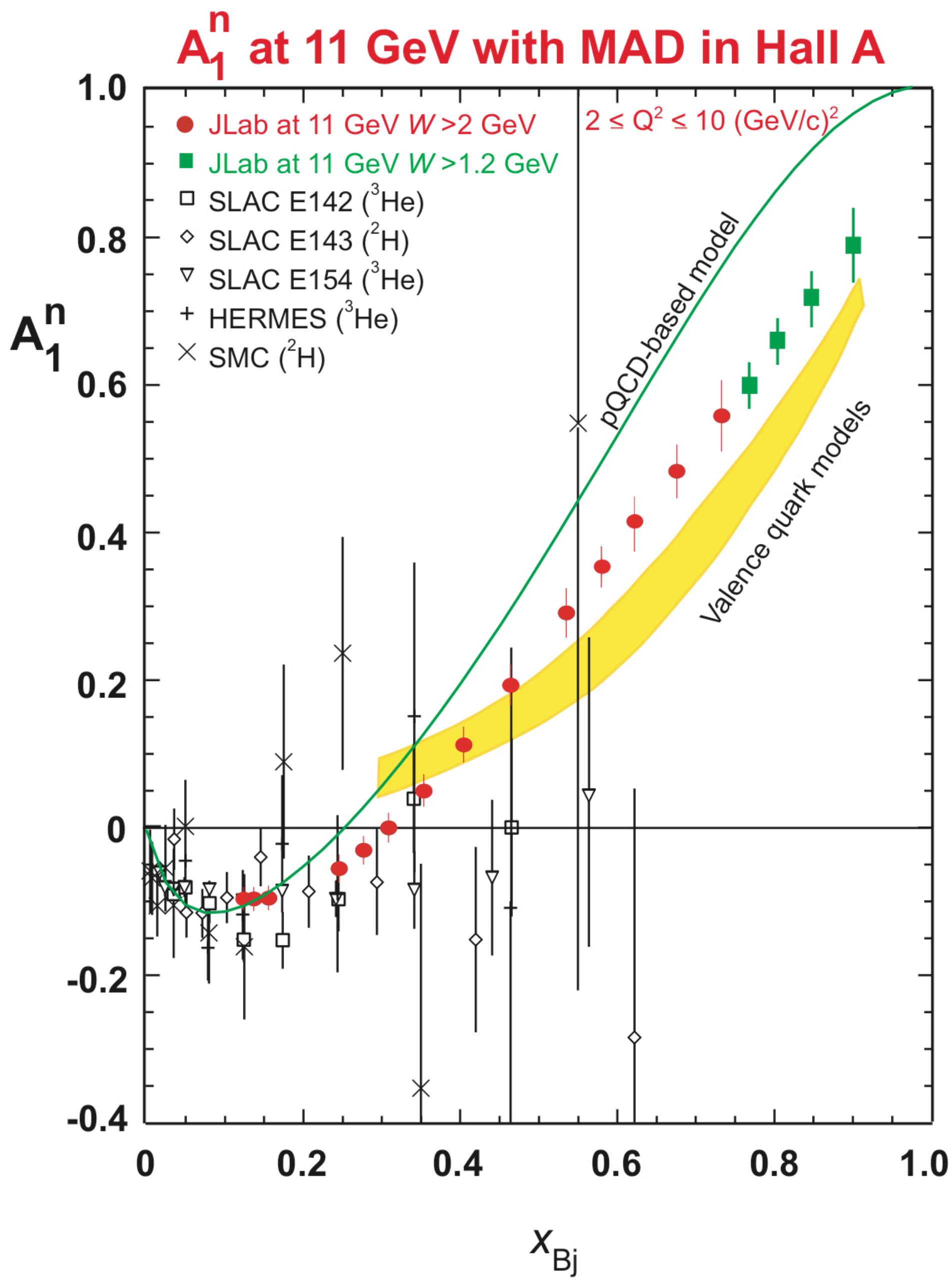
→ Too early to draw conclusions on A_1.

- E01-012 data combined with proton data

→ test of spin and flavor dependence of duality

- Our data can also be used to extract moments of SSF (e.g. Extended GDH Sum Rule, BC Sum Rule)

Jlab at 12 GeV



Extra Slides

Systematics

Target	
density	1.0-2.0%
polarization	3.0-4.0%
Beam	
charge	1.0%
polarization	3.0%
energy	0.5%
N_2 dilution	0.5-1.0%
Detector efficiencies	2.5%
Acceptance	2.0-3.0%
Radiative corrections	?

Theoretical interpretations

Lattice QCD

χPT   Quark models   OPE   pQCD

$Q^2 = 0$ ⟷ $Q^2 = \infty$

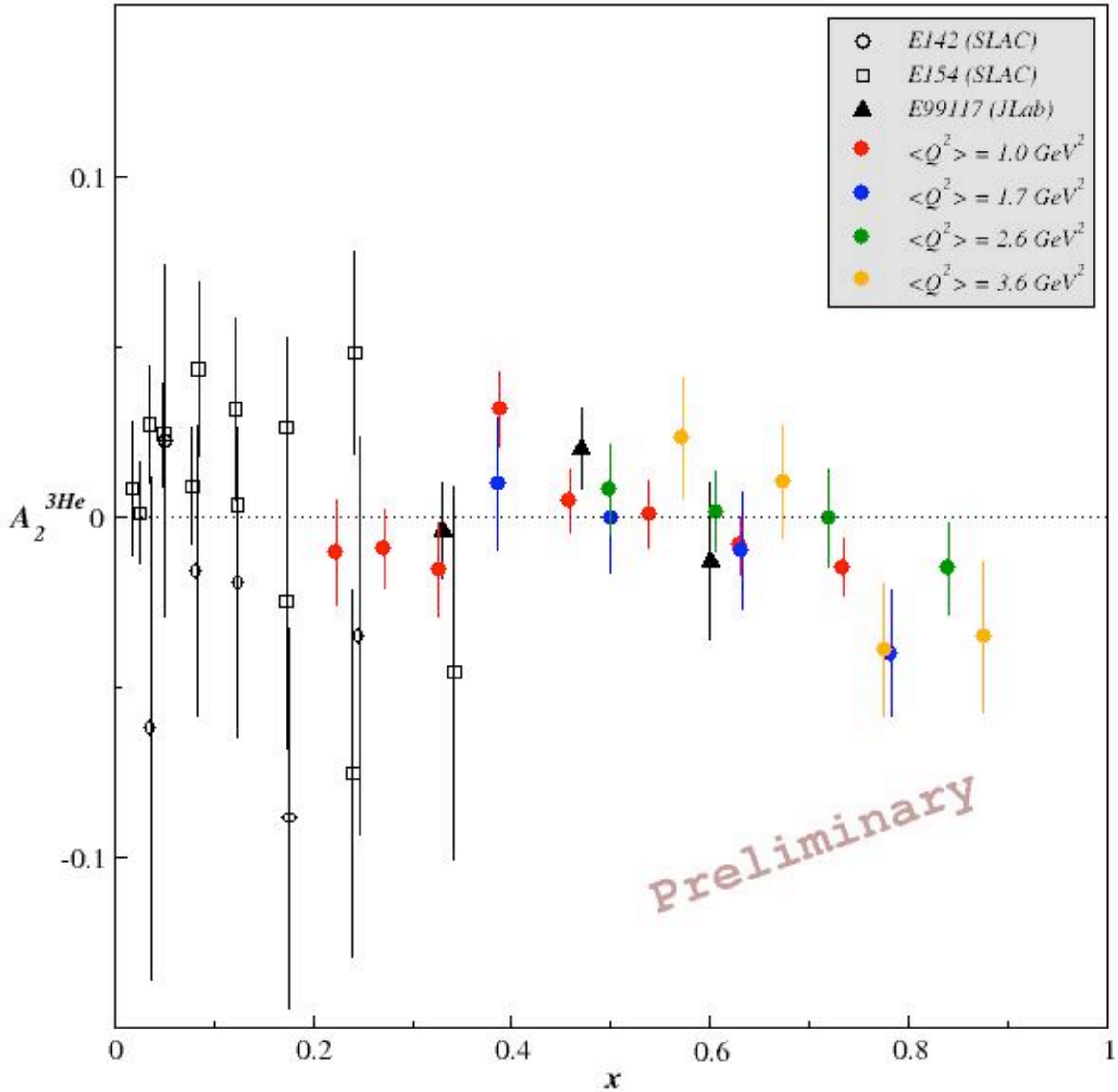
SU(6) symmetry breaking in the quark model (Close, Isgur and Melnitchouk):

➥ investigate several scenarios with suppression of spin-3/2, helicity-3/2 or symmetric wave function

$$|N\rangle = \cos\theta_w |\psi_\rho\rangle + \sin\theta_w |\psi_\lambda\rangle$$

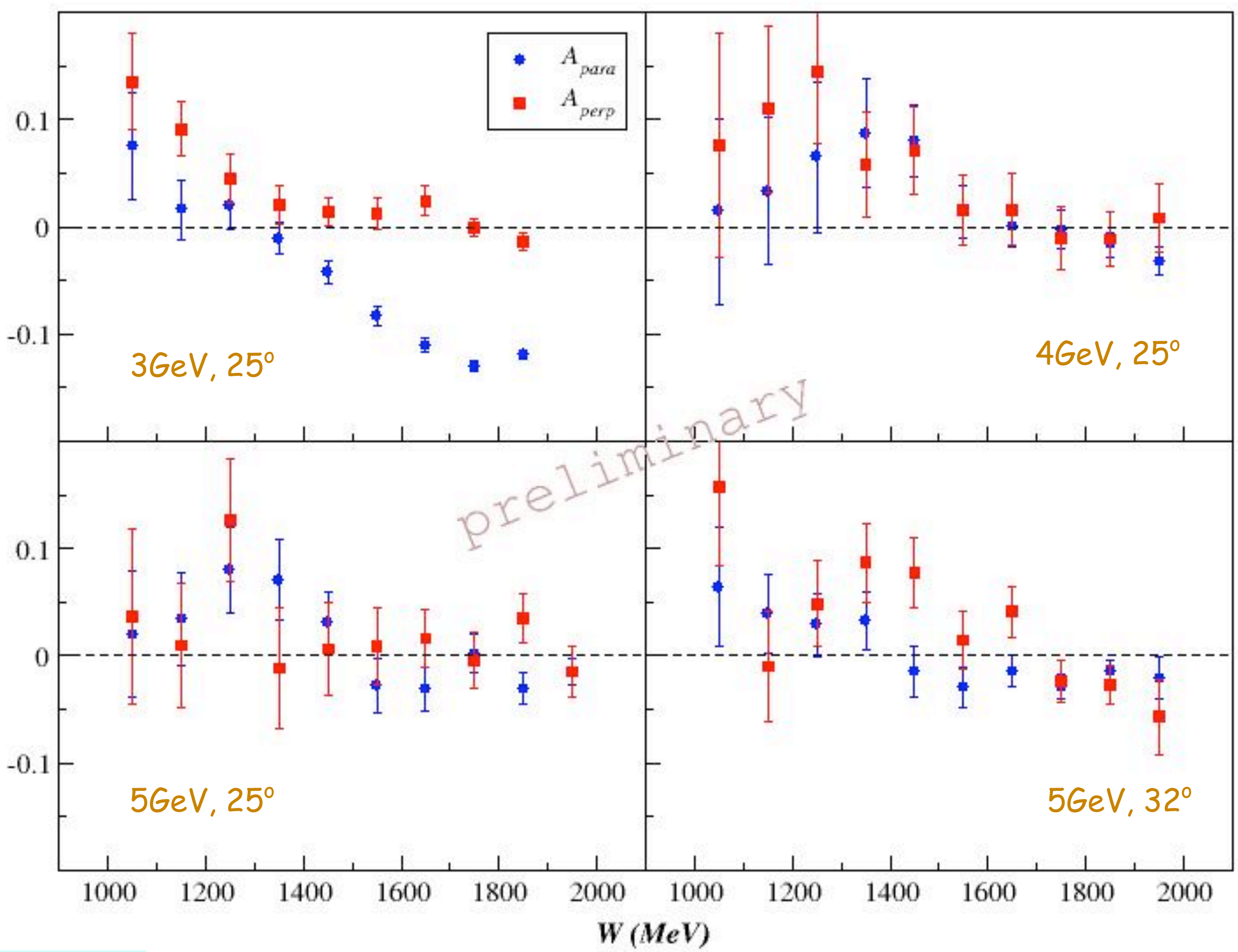
Model	SU(6)	no $^4\mathbf{10}$	no $^2\mathbf{10}$, $^4\mathbf{10}$	no $S_{3/2}$	no $\sigma_{3/2}$	no ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

A_2^{3He}



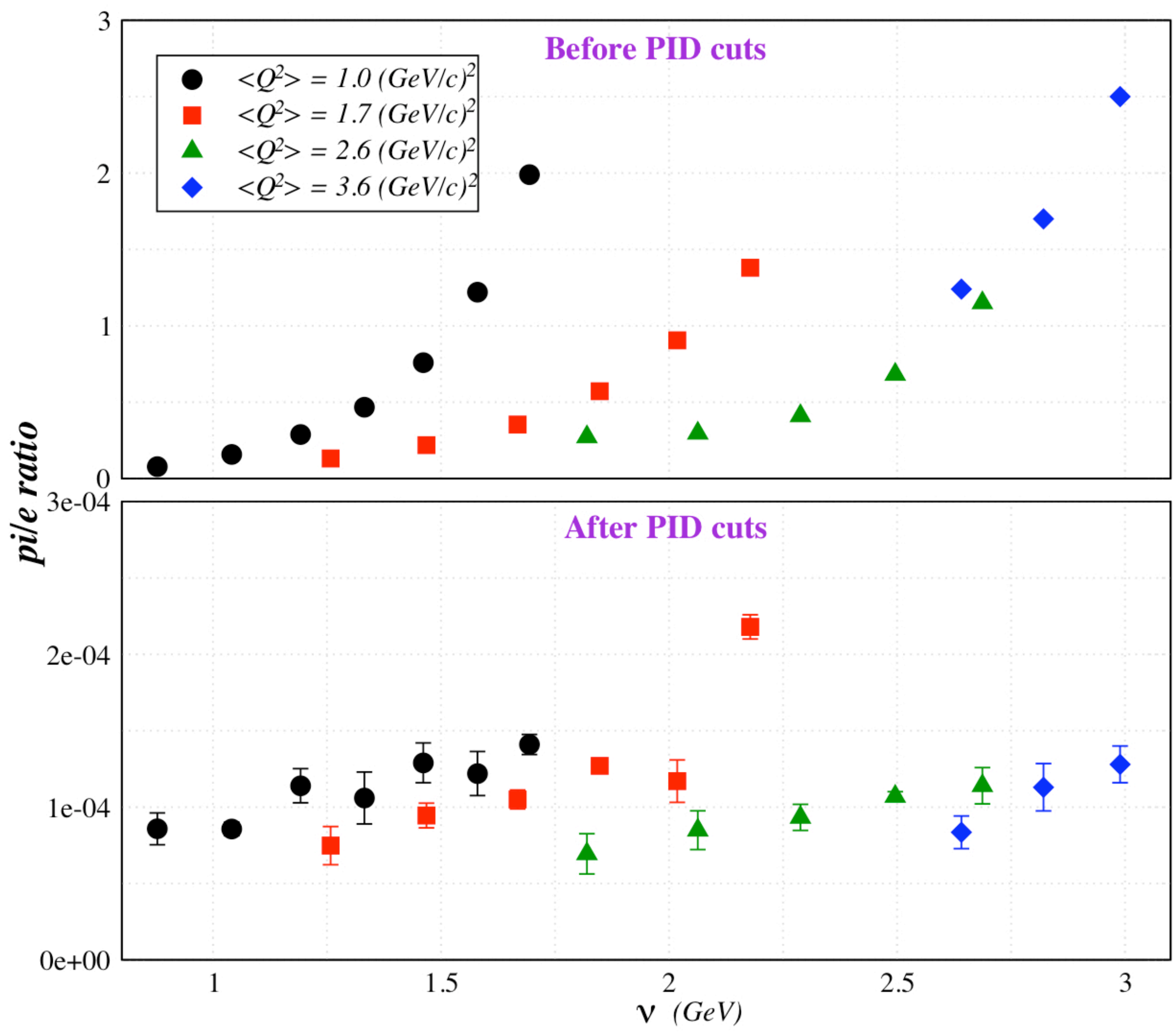
E142 (SLAC)
E154 (SLAC)
E99117 (JLab)
<Q^2> = 1.0 GeV^2
<Q^2> = 1.7 GeV^2
<Q^2> = 2.6 GeV^2
<Q^2> = 3.6 GeV^2
0.1
0
-0.1
A_2^{3He}
0
0.2
0.4
0.6
0.8
1
x
Preliminary

Pion asymmetries



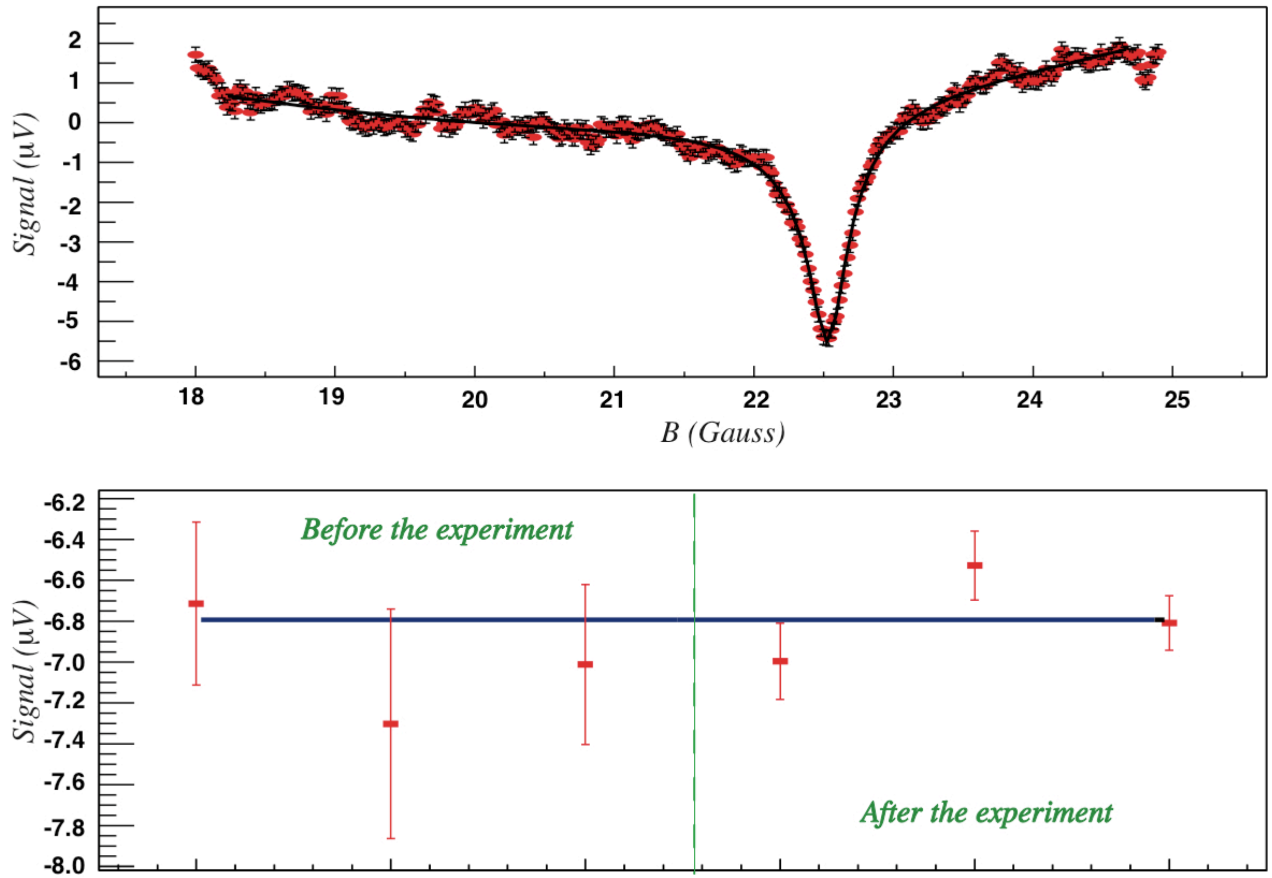
Statistical errors only

Particle identification performance



π/e reduced by 10^4 and electron efficiency kept above 98%

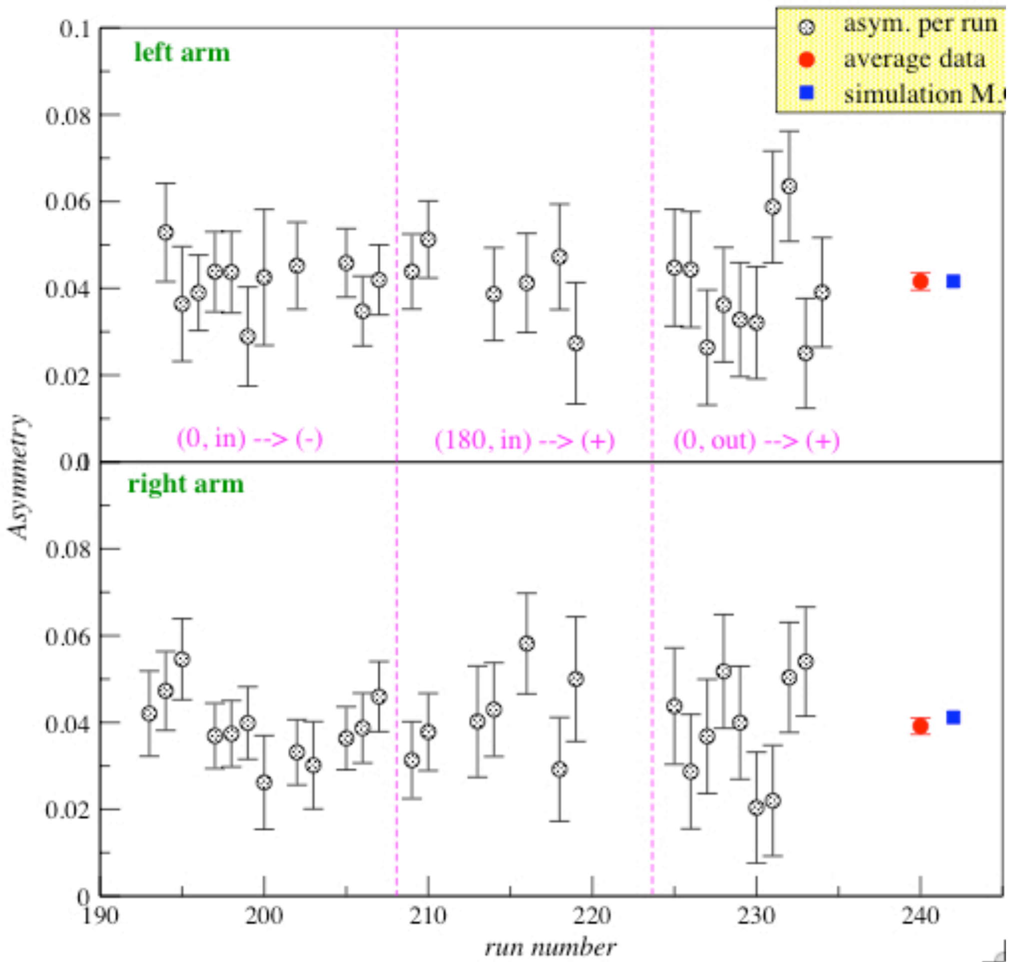
NMR: water calibration



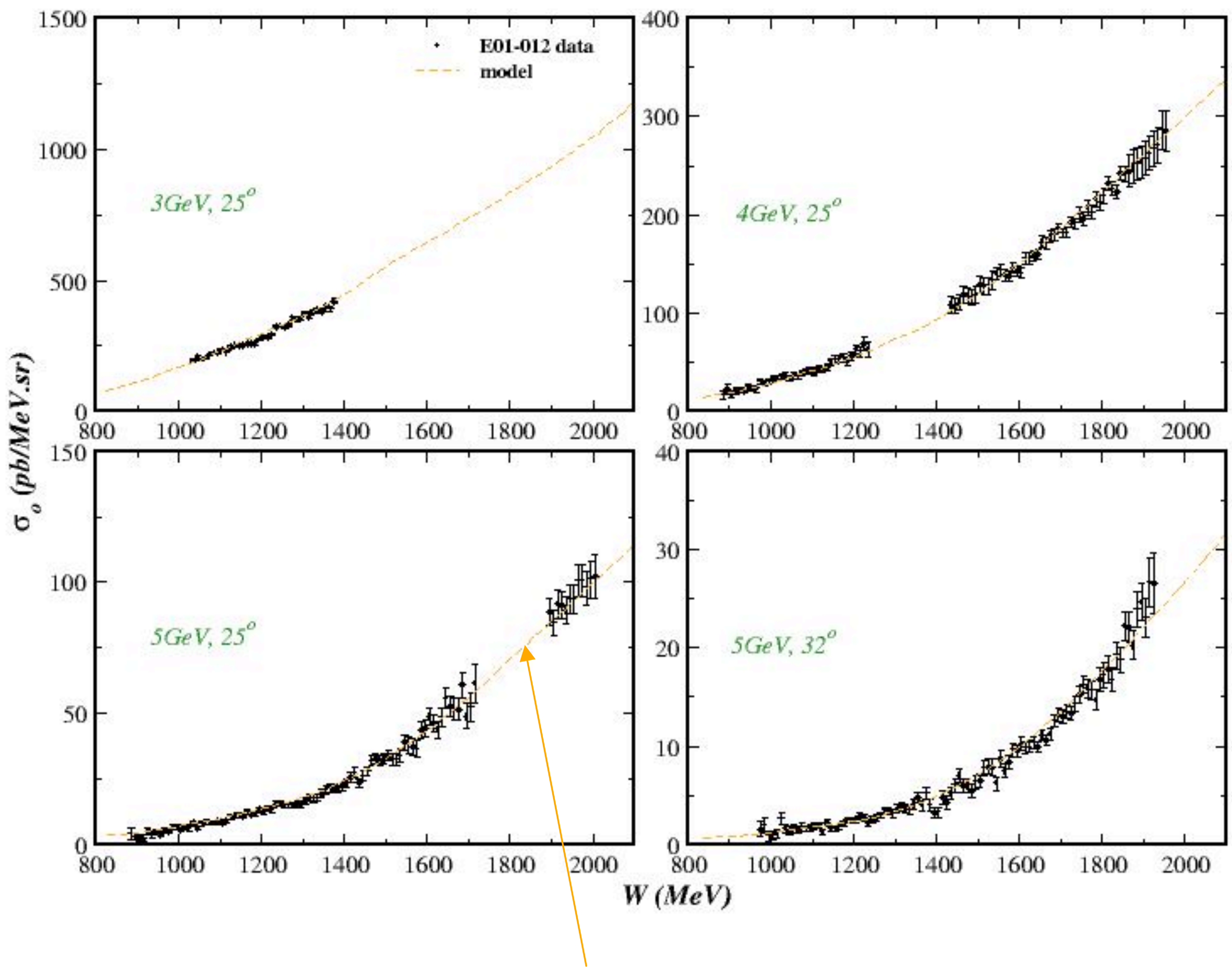
NMR analysis done by Vince Sulkosky

Elastic asymmetry

Check of the product: $f_{N_2} P_{tg} P_{beam}$



Nitrogen cross sections



Modified the QFS model by adding energy dependence to the cross sections