Test of Quark-Hadron Duality on Neutron and ^{3}He Spin Structure Functions

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Nuclear Physics Seminar
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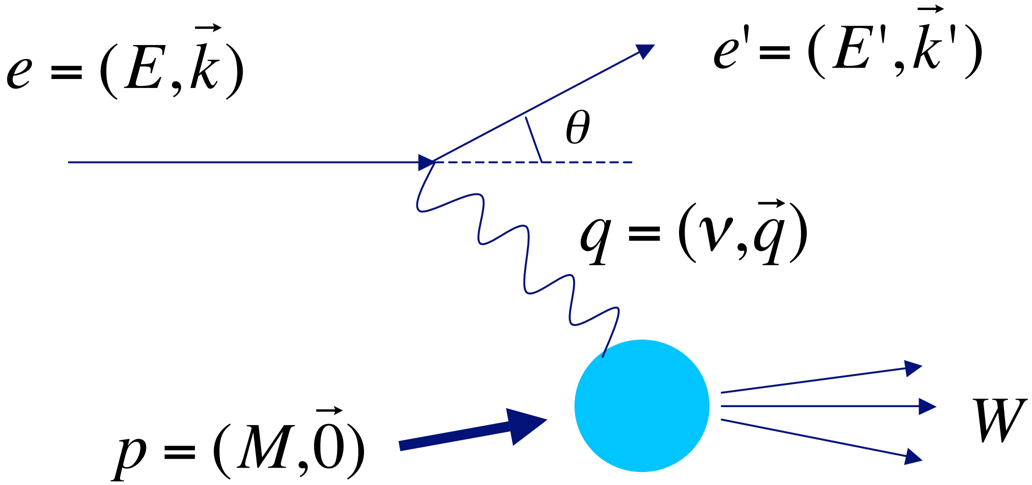
Outlines

- 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 ^{3}He

Inclusive Electron Scattering



<u>Photon momentum transfer</u>

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

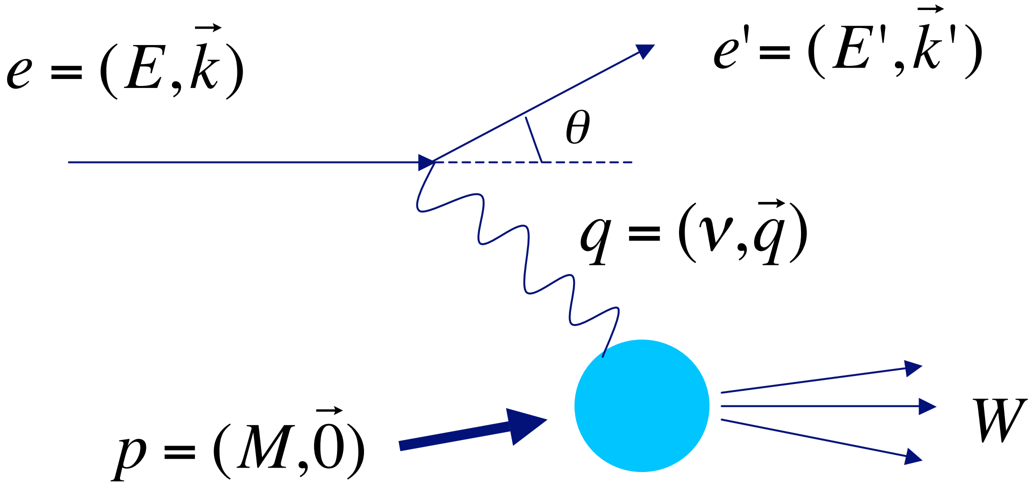
<u>Invariant mass squared</u>

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

<u>Bjorken variable</u>

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

Inclusive Electron Scattering



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Unpolarized case

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

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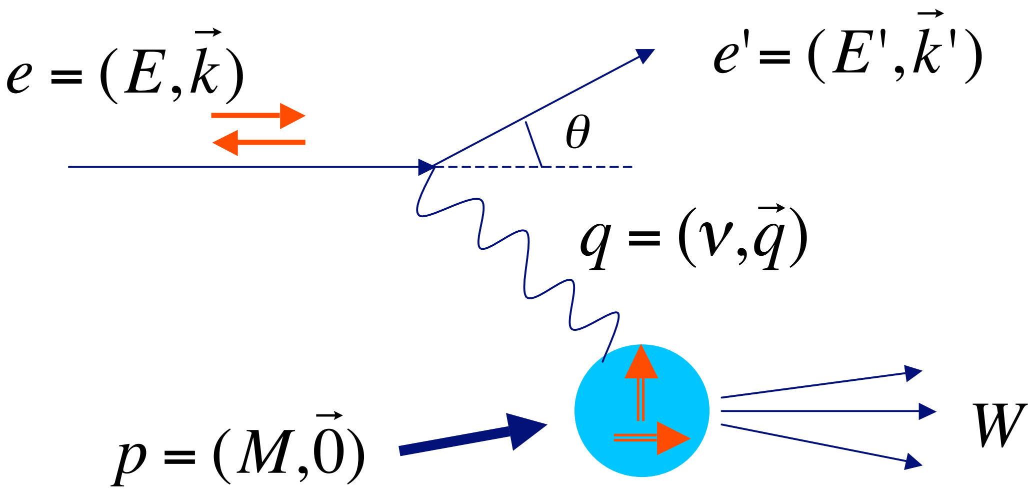

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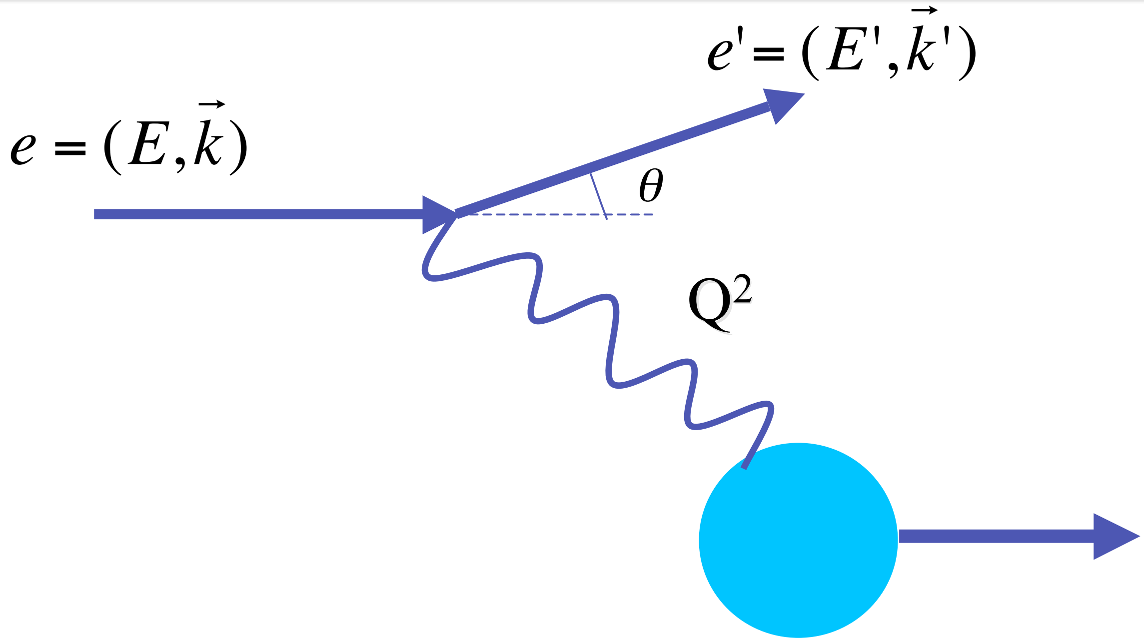
Polarized case

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

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

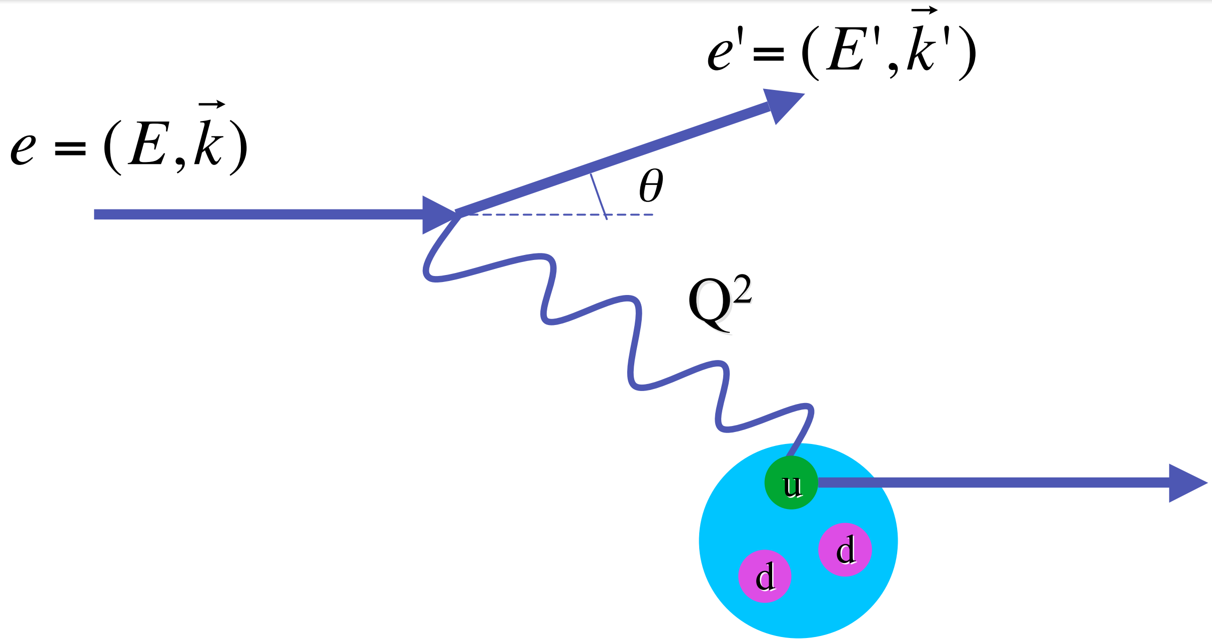
Resonance region



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

→ The nucleon goes through different excited states: the resonances

Deep Inelastic Scattering



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

Parton model: scaling → asymptotic freedom of the strong interaction

↓

2004 Nobel Prize

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

Scaling of F_2

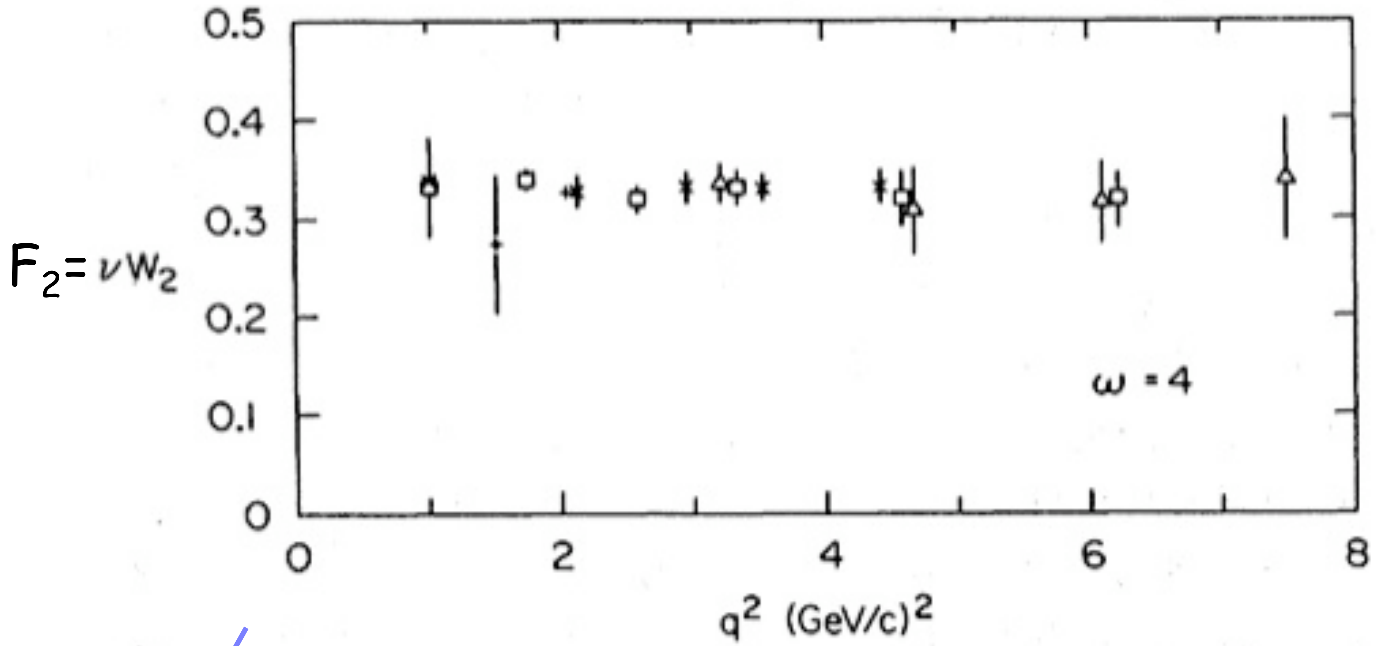


Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

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: $\sigma_{Nucleon} = \Sigma_i \; \sigma_i$

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

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

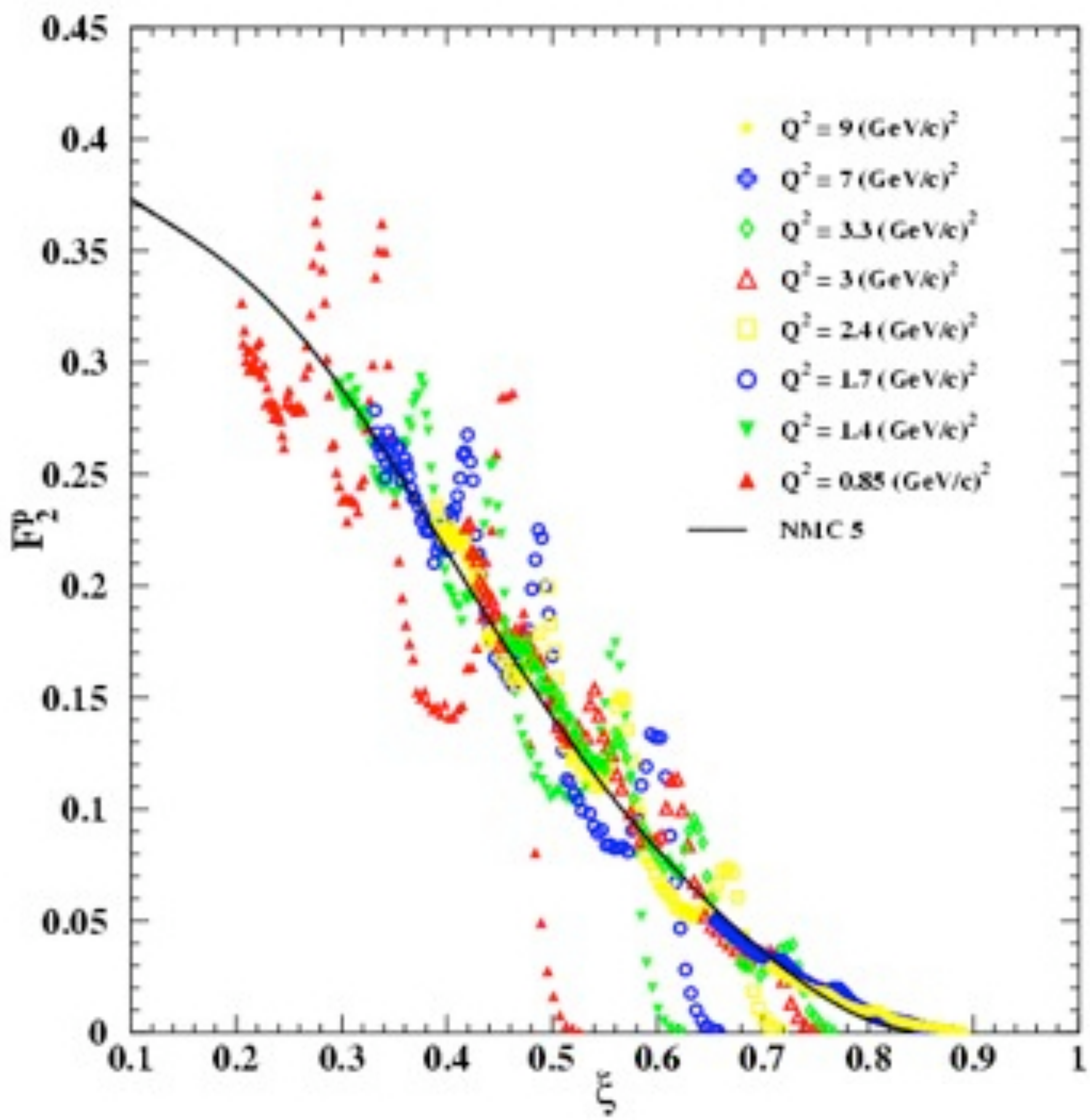
No simple partonic distribution for $g_2(x,Q_2)$

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

$Q^2 = 0$ ⟷ $Q^2 = \infty$

Operator Product Expansion (Rujula, Georgi, Politzer):

➥ Higher twist corrections are small or cancel.

pQCD (Carlson, Mukhopadhyay):

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

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

➥ investigate several scenarios with suppression of:

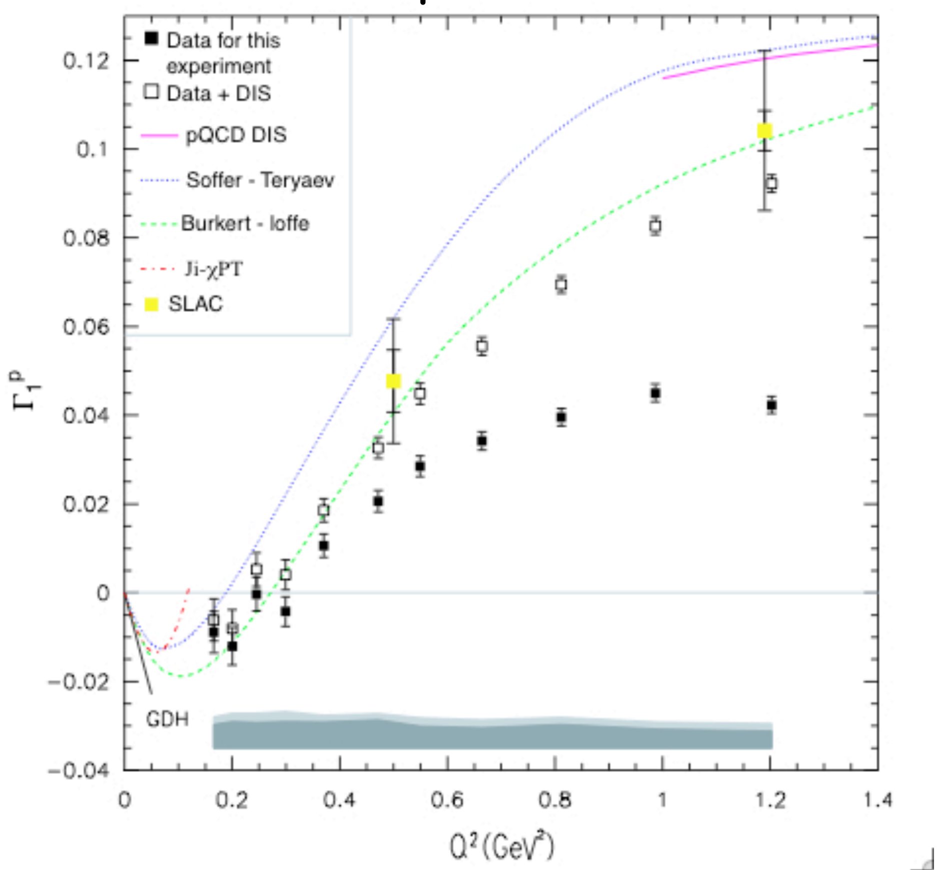
- spin-3/2
- helicity-3/2
- symmetric wave function

Scaling of g_1 moments

Scaling = Q^2 independence of structure function moments
When moments scaled $\Rightarrow$ resonance region scales too.

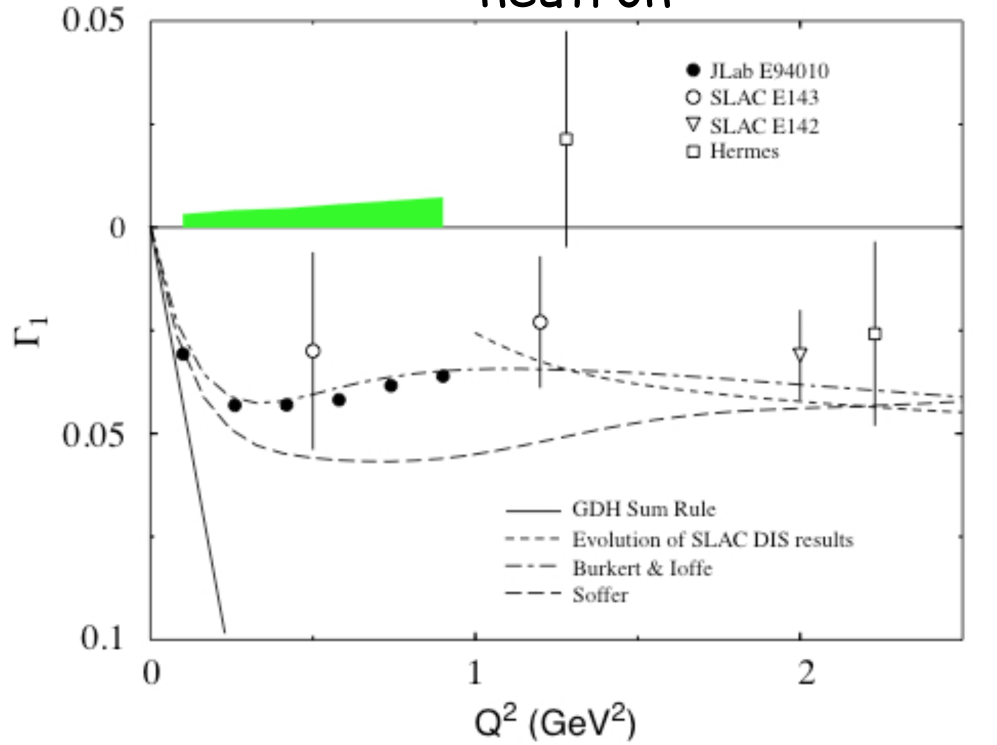
$$\Gamma_1(Q^2) = \int g_1(x,Q^2)dx$$

proton



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

neutron

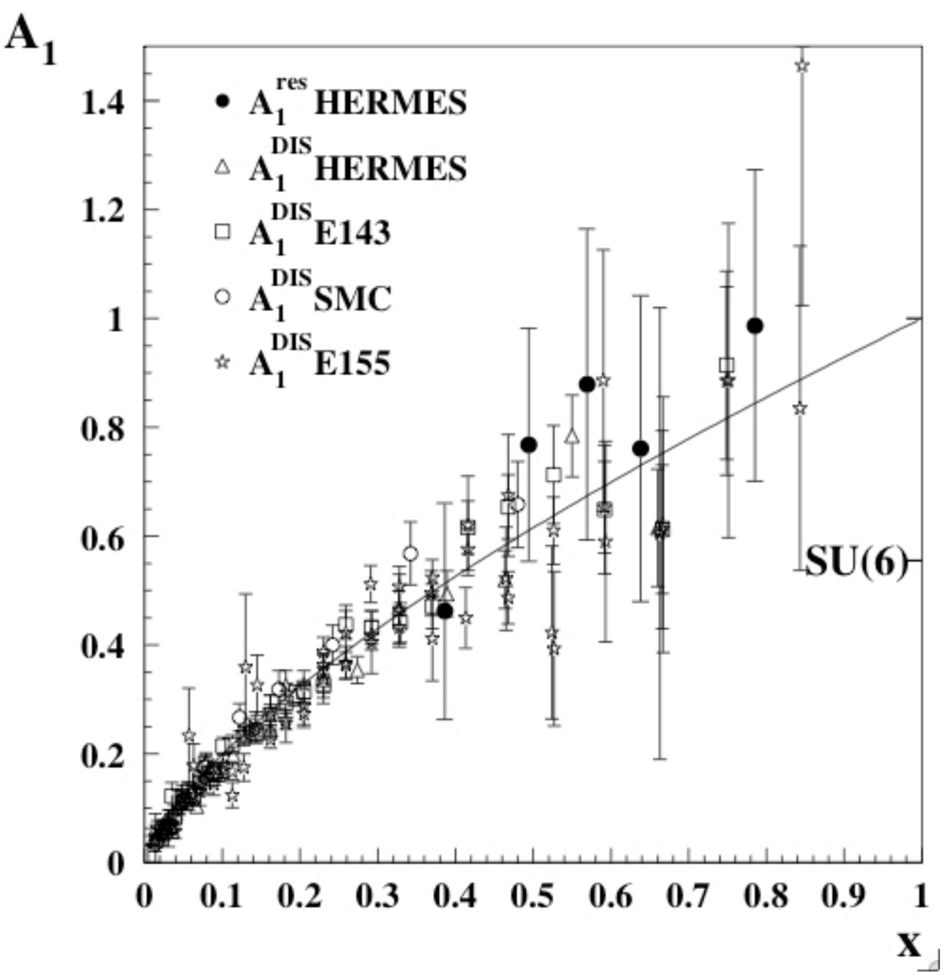


M. Amerian et al., PRL 859(2002) 242301

World data

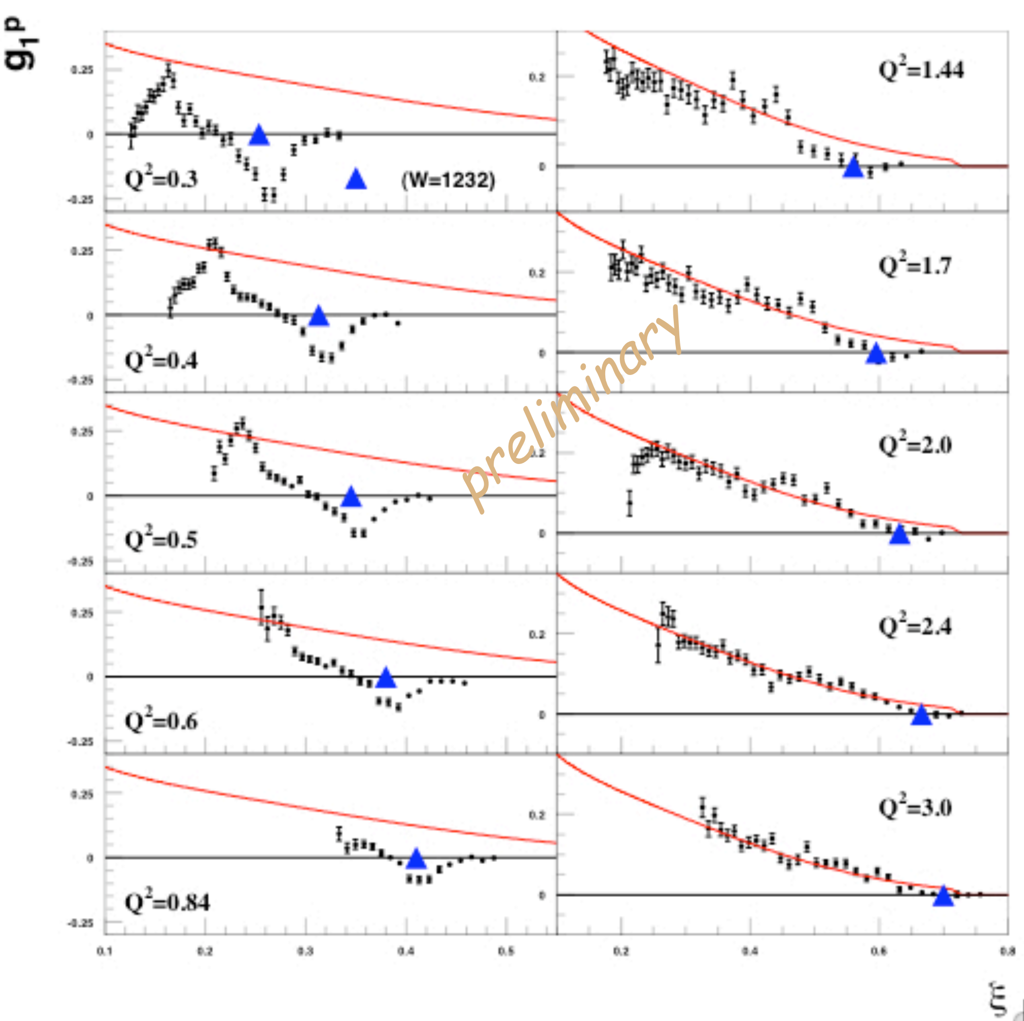
HERMES for A_1^p

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



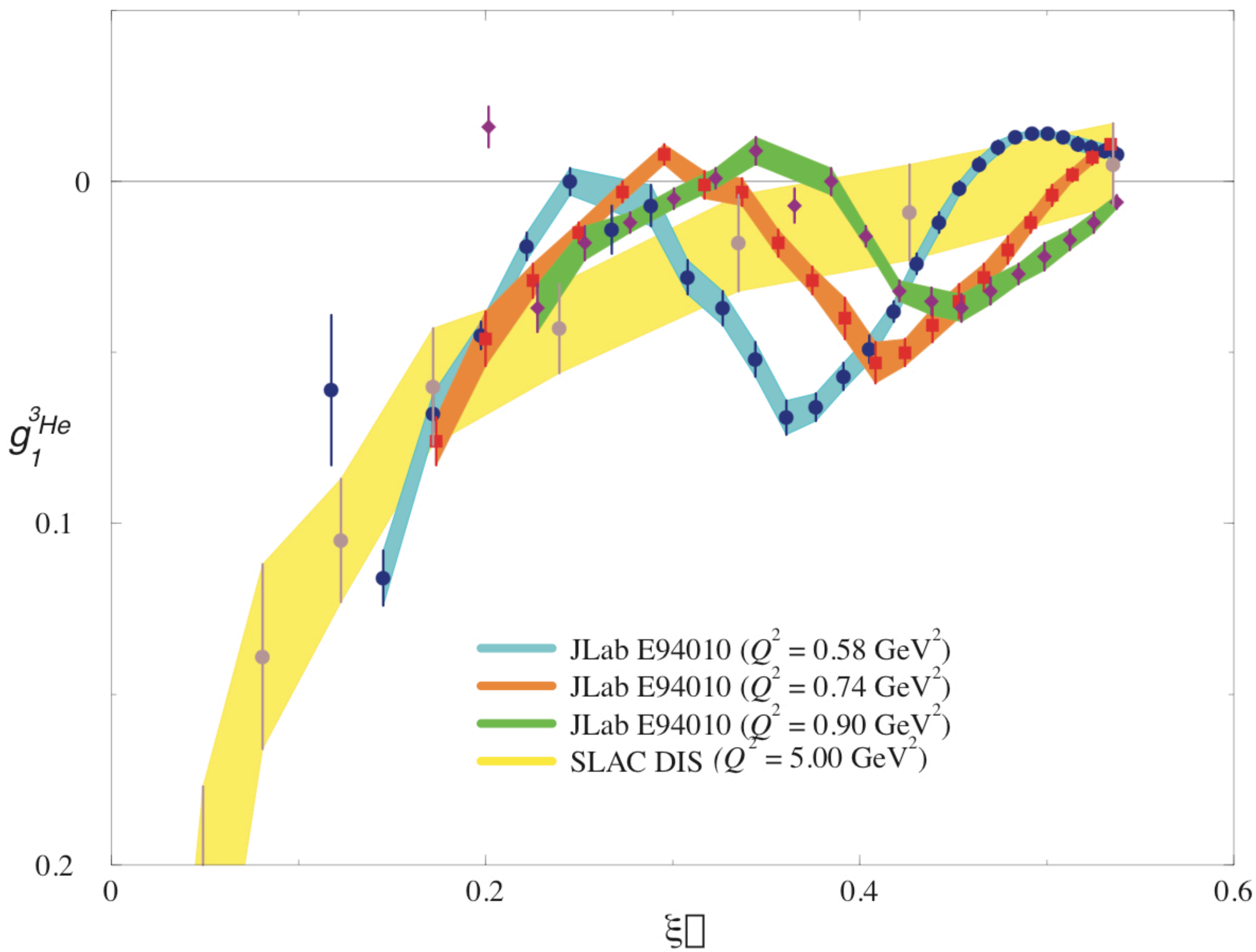
Jlab Hall B for g_1^p

From DIS 2005 proceedings



World data

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



The experiment E01-012

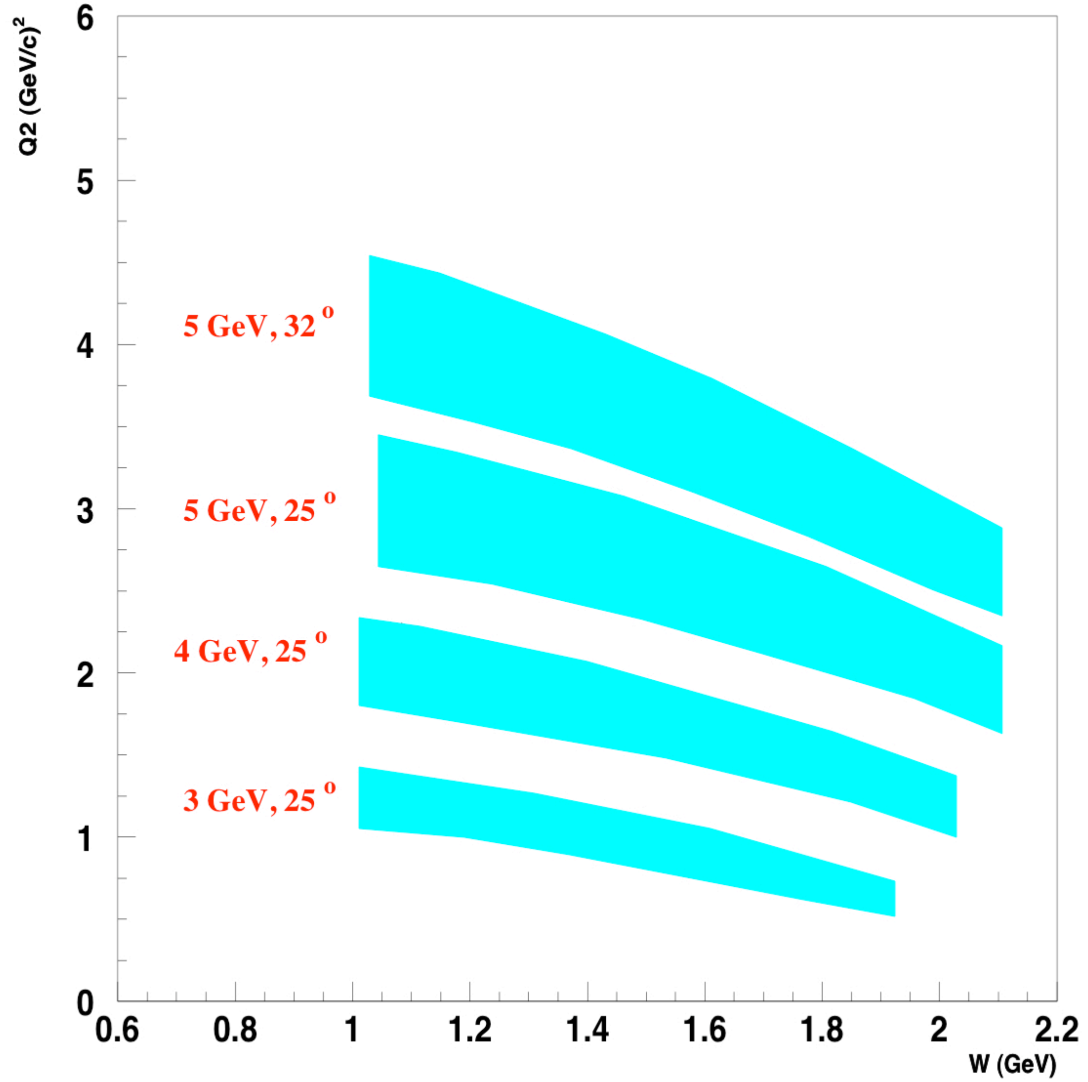
- Ran in Jan.-Feb. 2003

- Inclusive experiment:

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

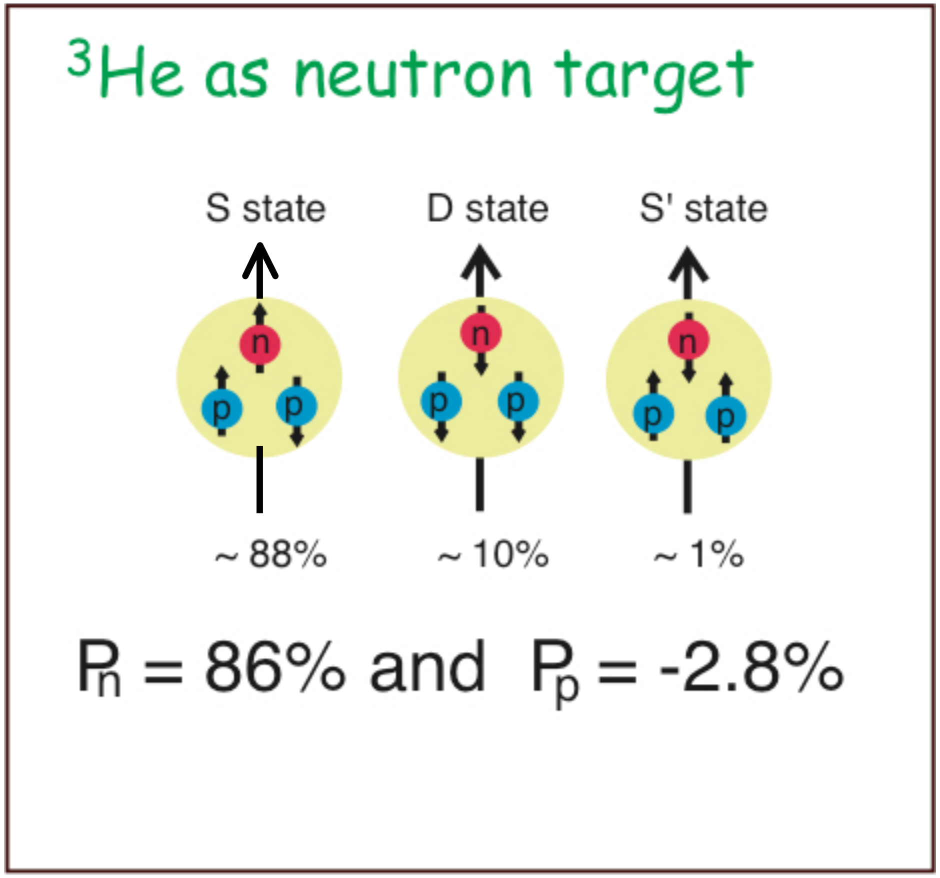
- Measured polarized cross section differences

- Form g_1 and g_2



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

^{3}He as an effective neutron target

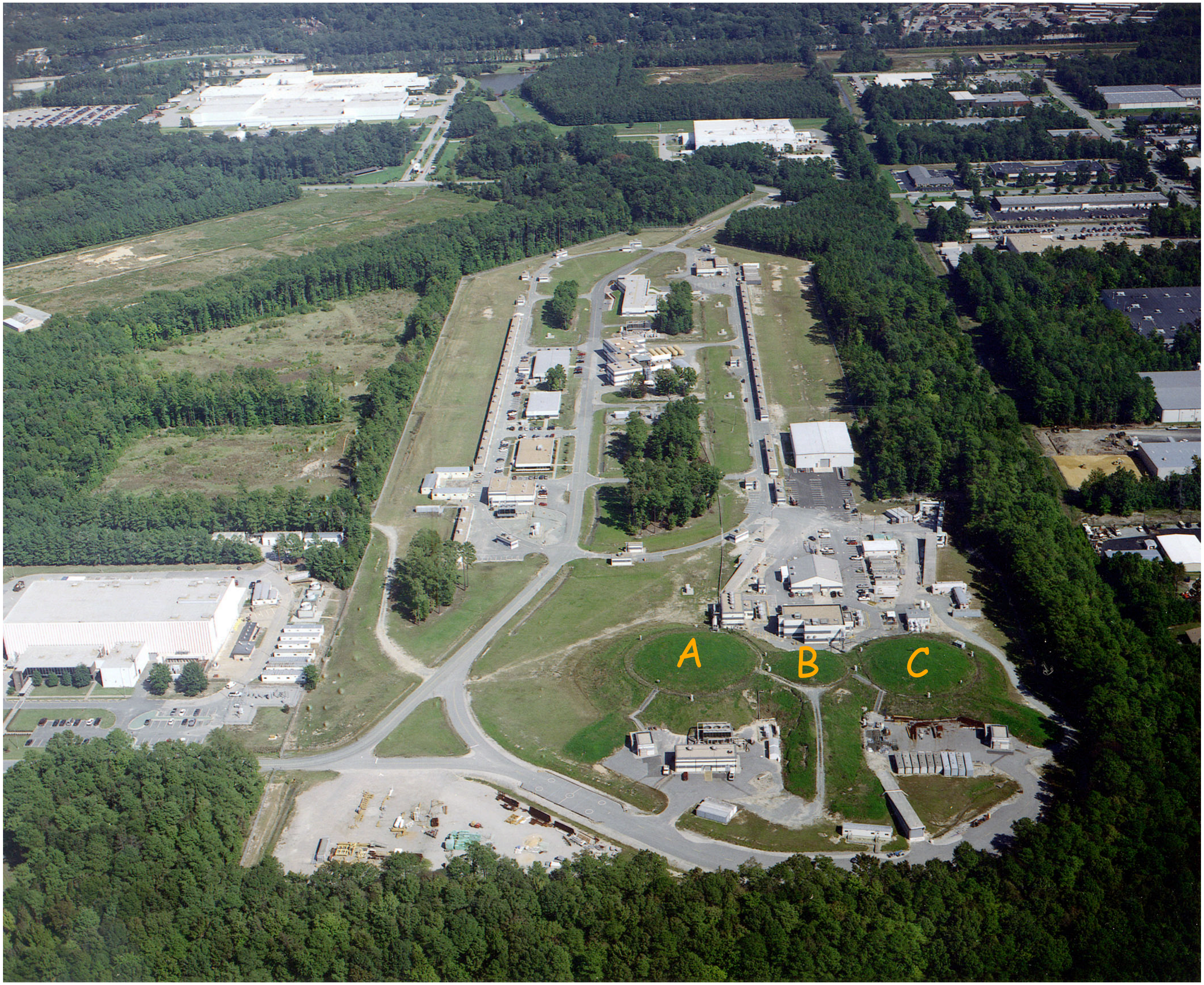


The E01-012 Collaboration

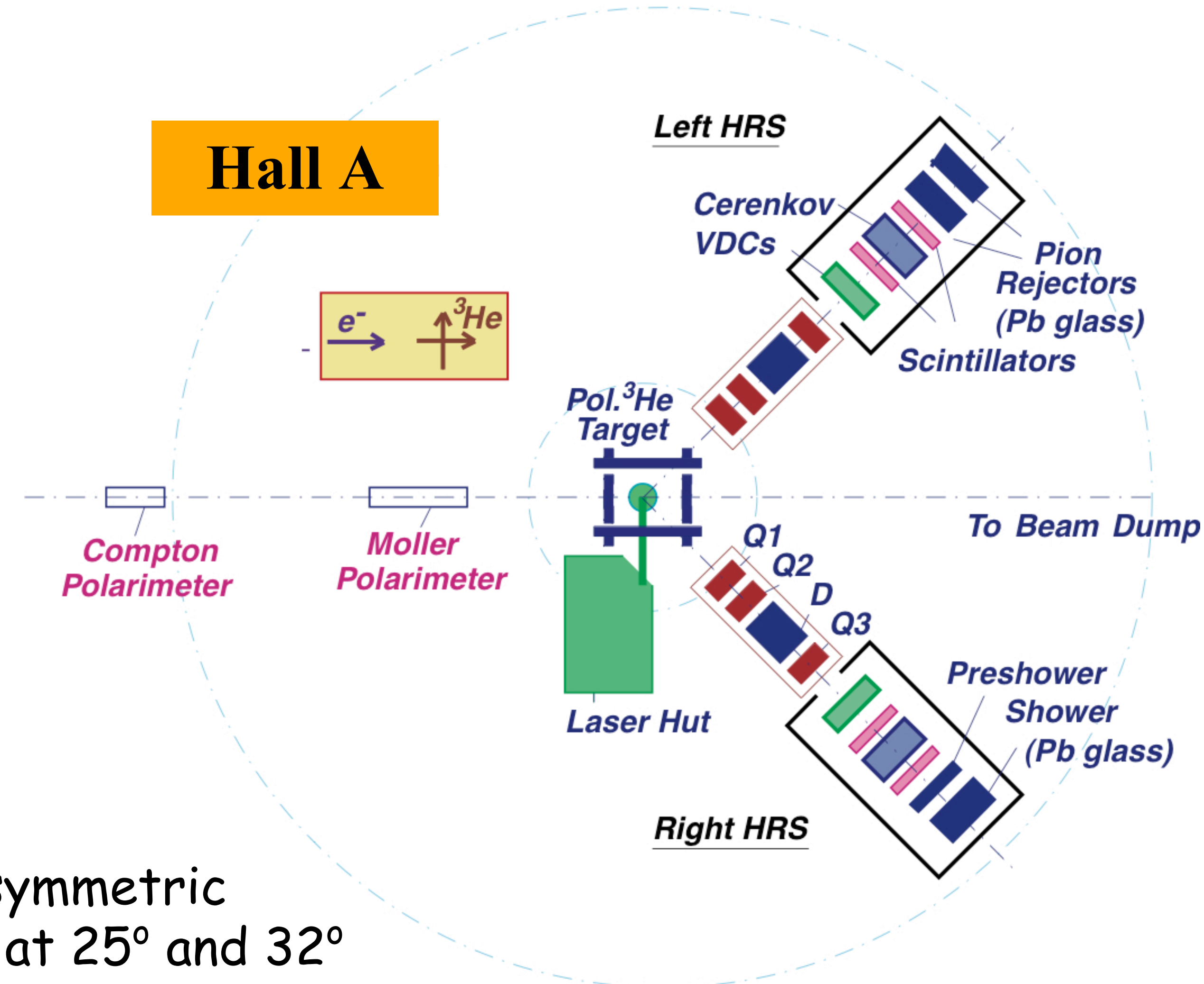
K. Aniol, T. Averett, W. Boeglin, A. Camsonne, G.D. Cates, G. Chang, J.-P. Chen, Seonho Choi, E. Chudakov, B. Craver, F. Cusanno, A. Deur, D. Dutta, R. Ent, R. Feuerbach, S. Frullani, H. Gao, F. Garibaldi, R. Gilman, C. Glashausser, O. Hansen, D. Higinbotham, H. Ibrahim, X. Jiang, M. Jones, A. Kelleher, 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



Experimental setup



Both HRS in symmetric configuration at 25° and 32°

➥ double the statistics

➥ control the systematics

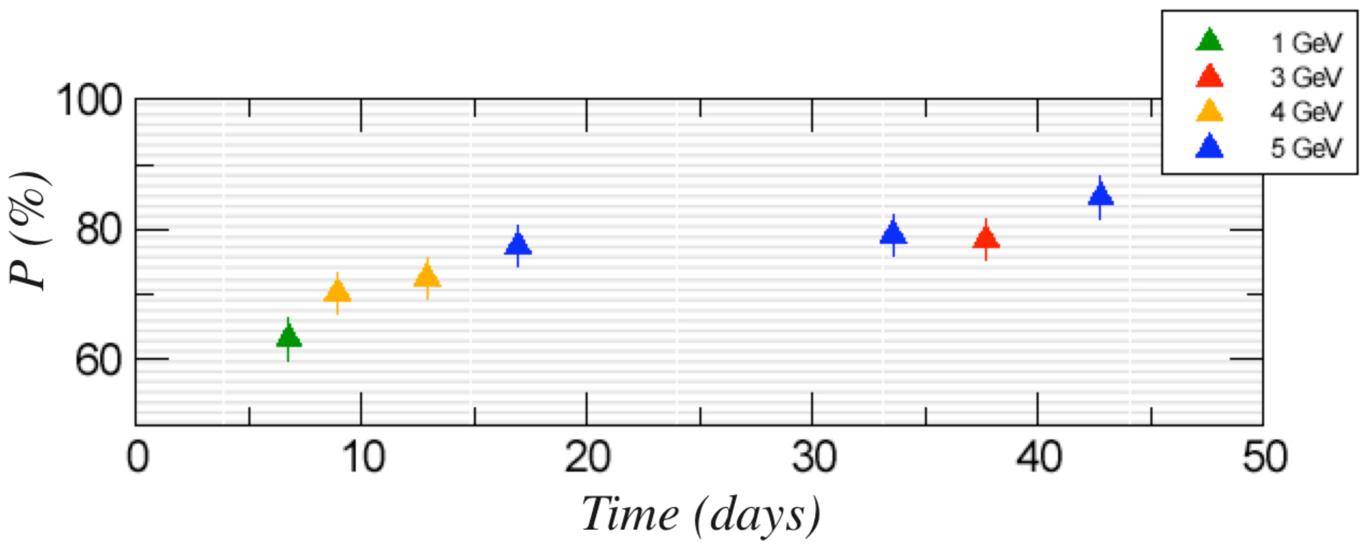
Particle ID = Cerenkov + EM calorimeter

➥ π/e reduced by 10^4

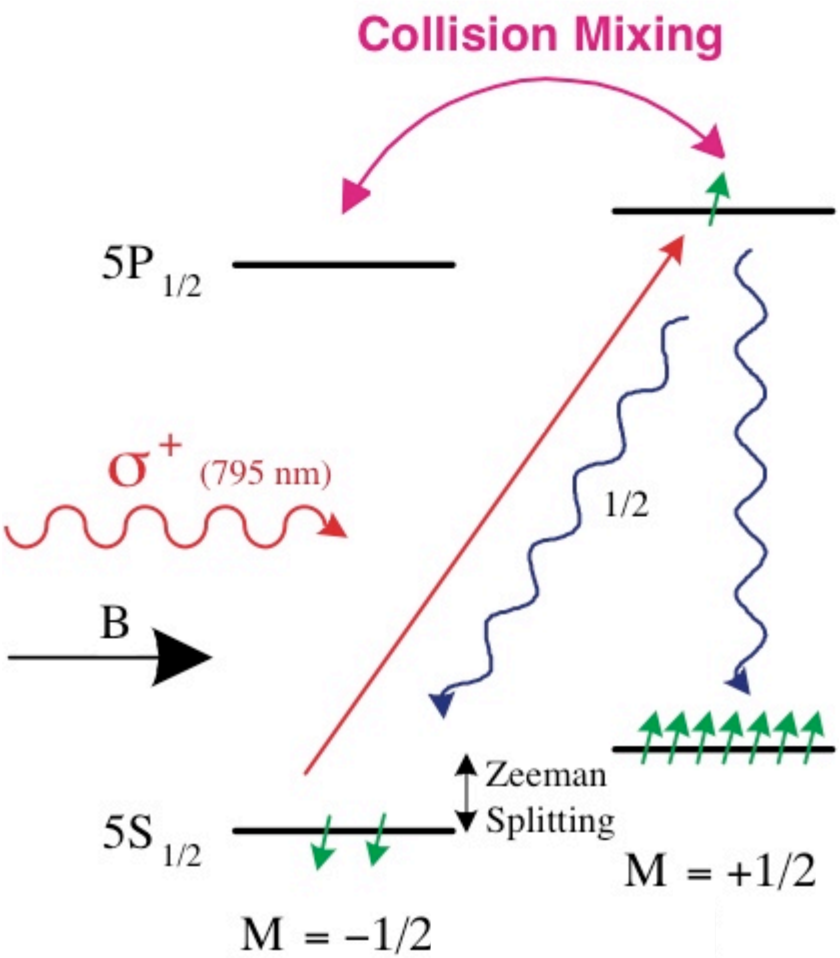
Electron Beam Polarization

- Used Moller Polarimeter: measurements performed by E. Chudakov et al.

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



How to polarize ^3He ?



Two step process:

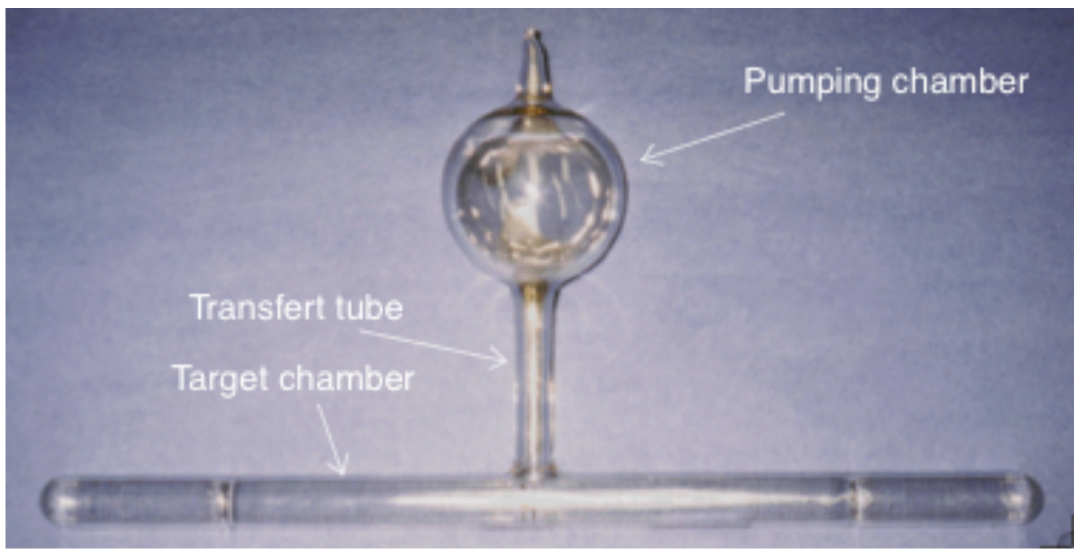
1. Rb vapor is polarized by optical pumping with circularly polarized light

2. Rb e^- polarization is transferred to ^3He nucleus by spin-exchange interaction

A small amount of N_2 is added for quenching

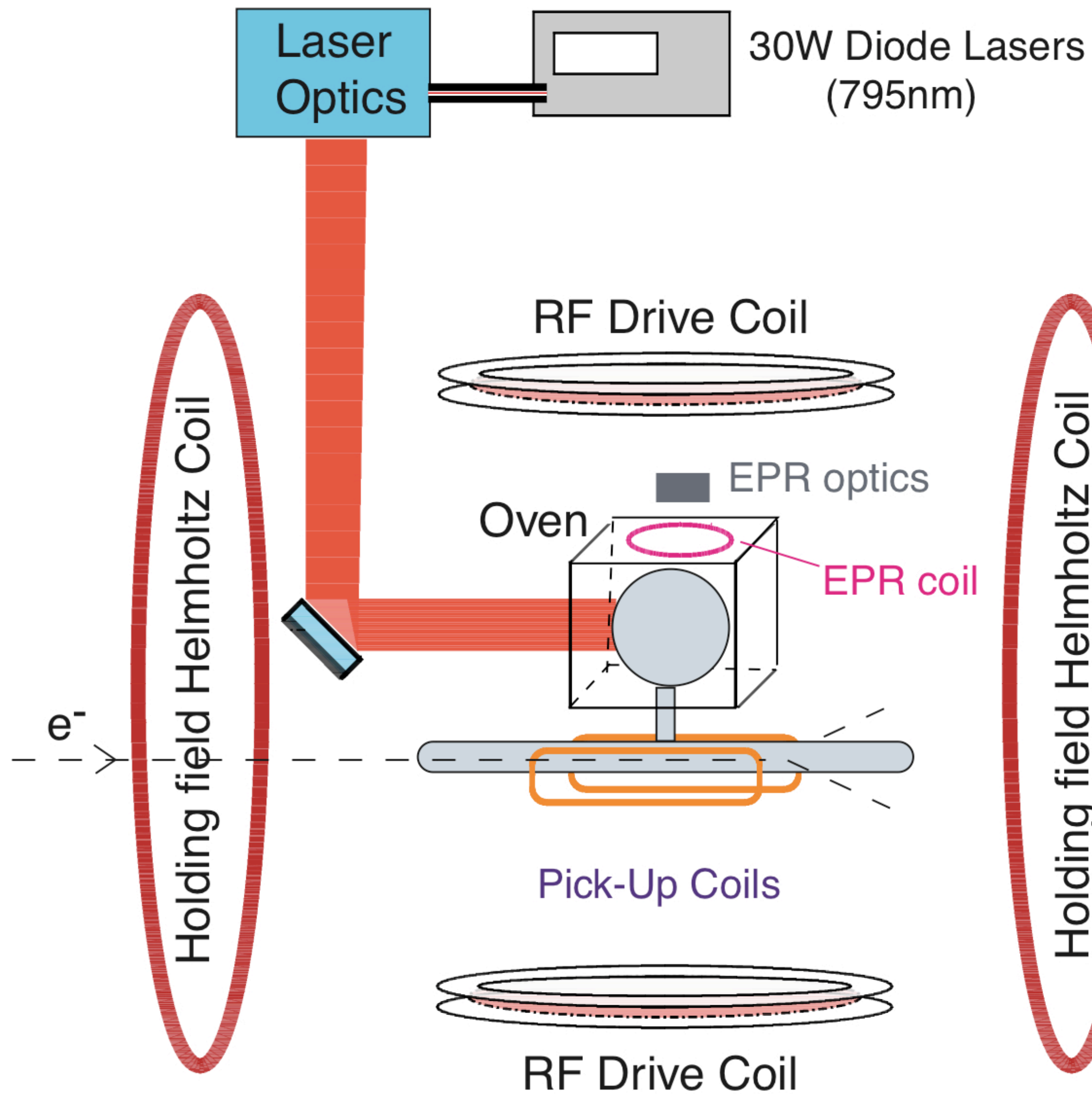
The polarized ^{3}He target

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



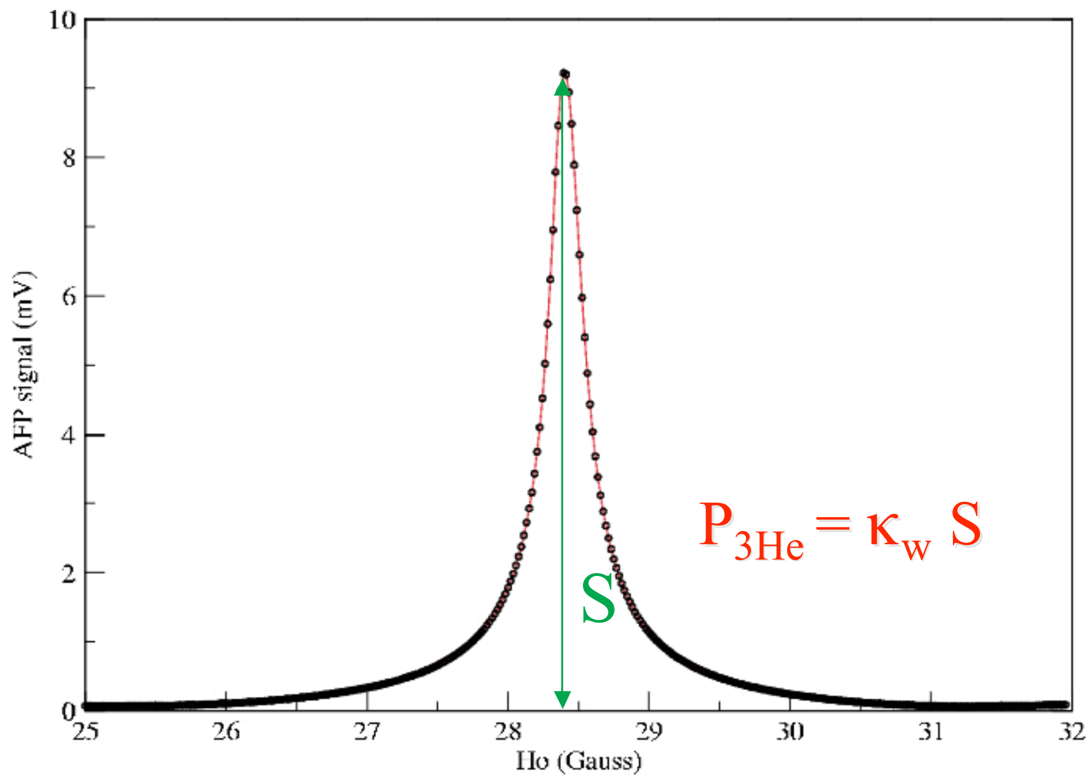
$L_{tg} \sim 40cm$

The polarized ^{3}He system



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

Nuclear Magnetic Resonance



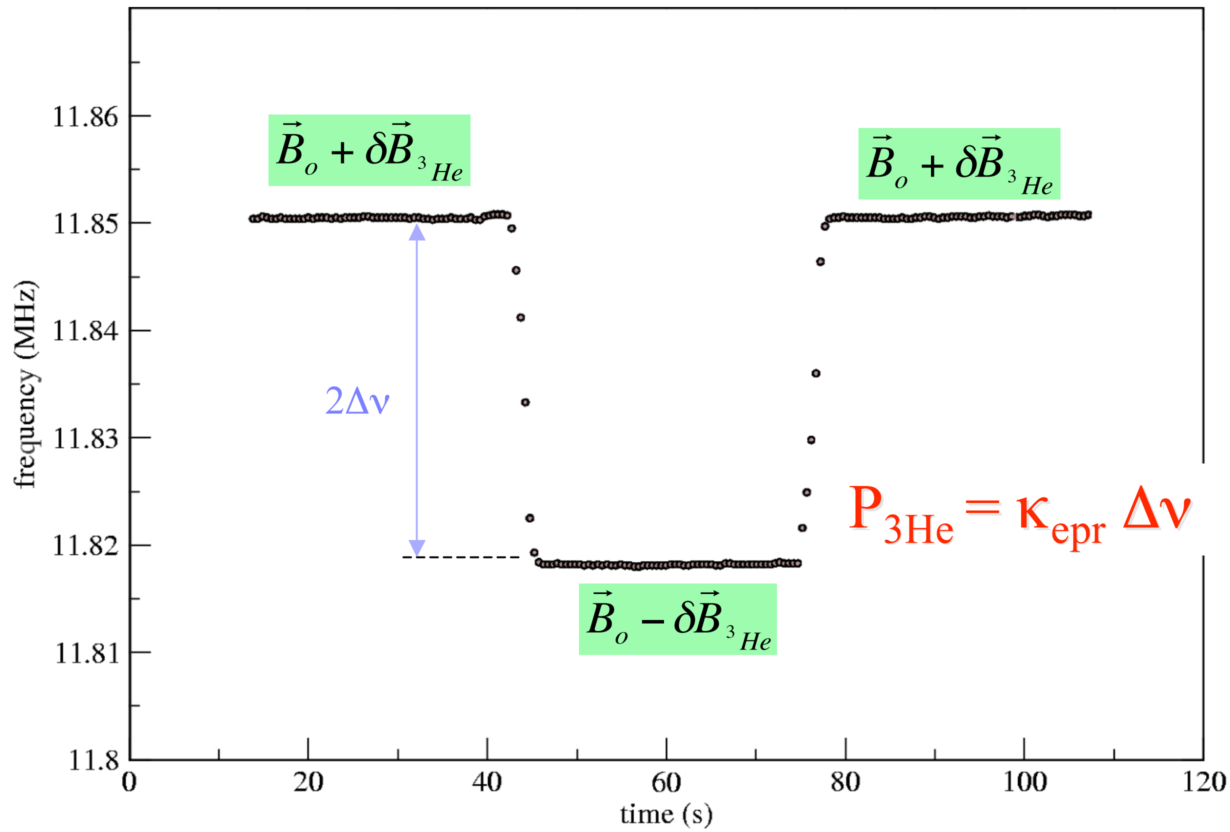
κ_w : from calibration with an identical target cell filled with water

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

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

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

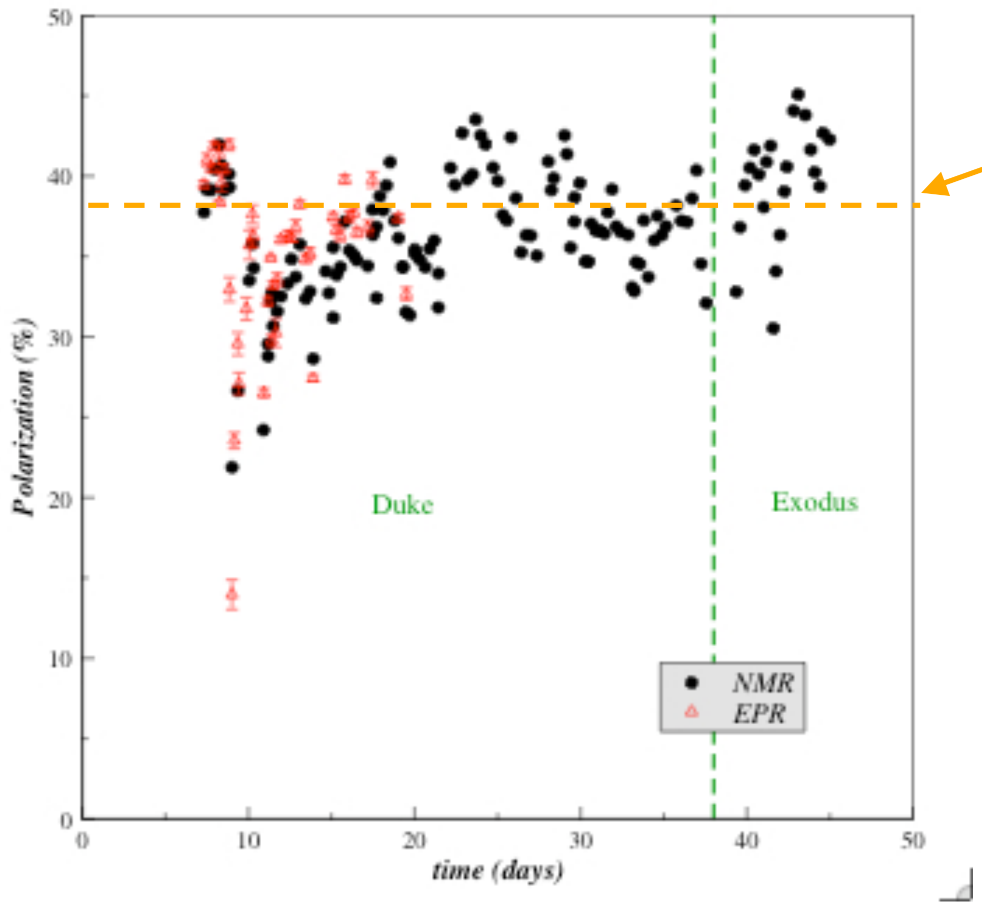
Electron Paramagnetic Resonance



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

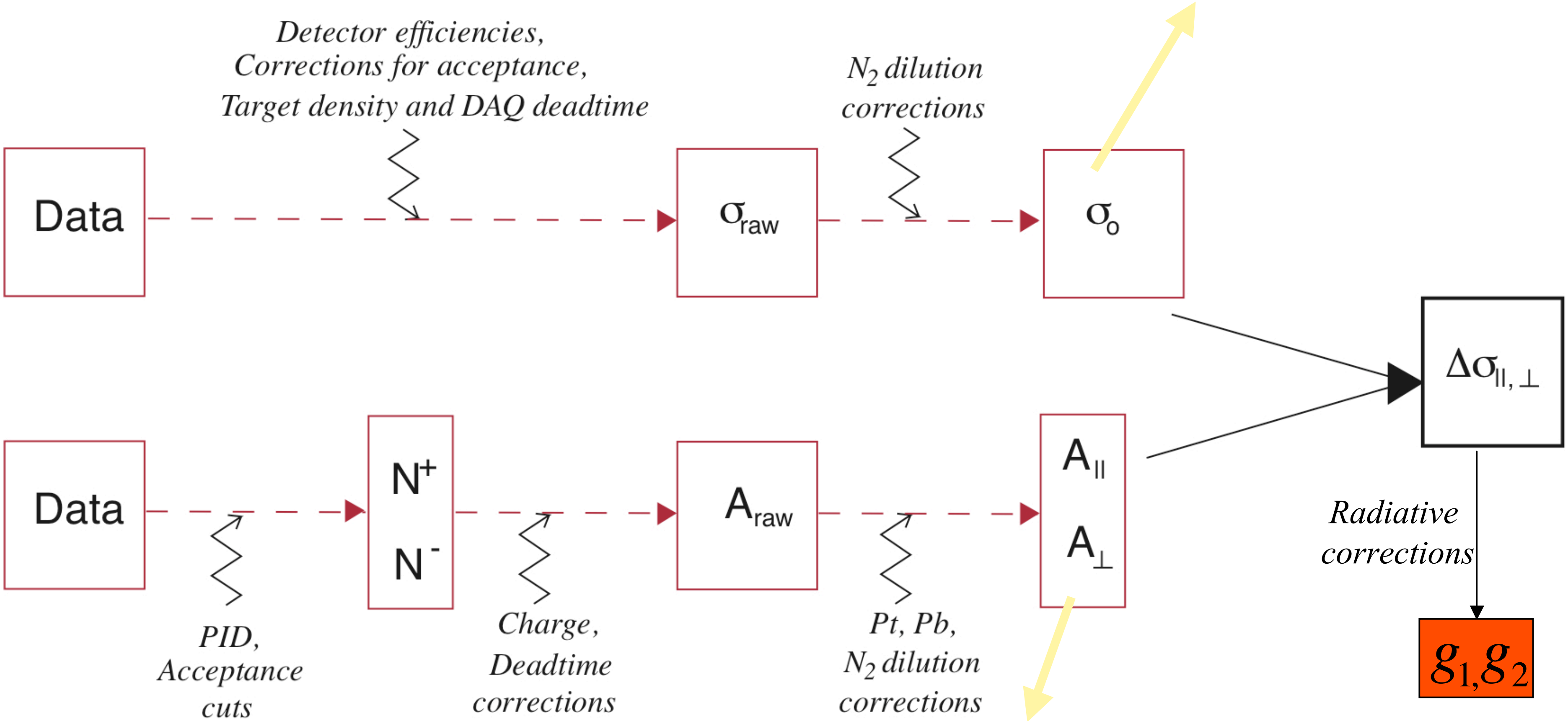


$P_{avg} \sim 37\%$

Statistical errors only

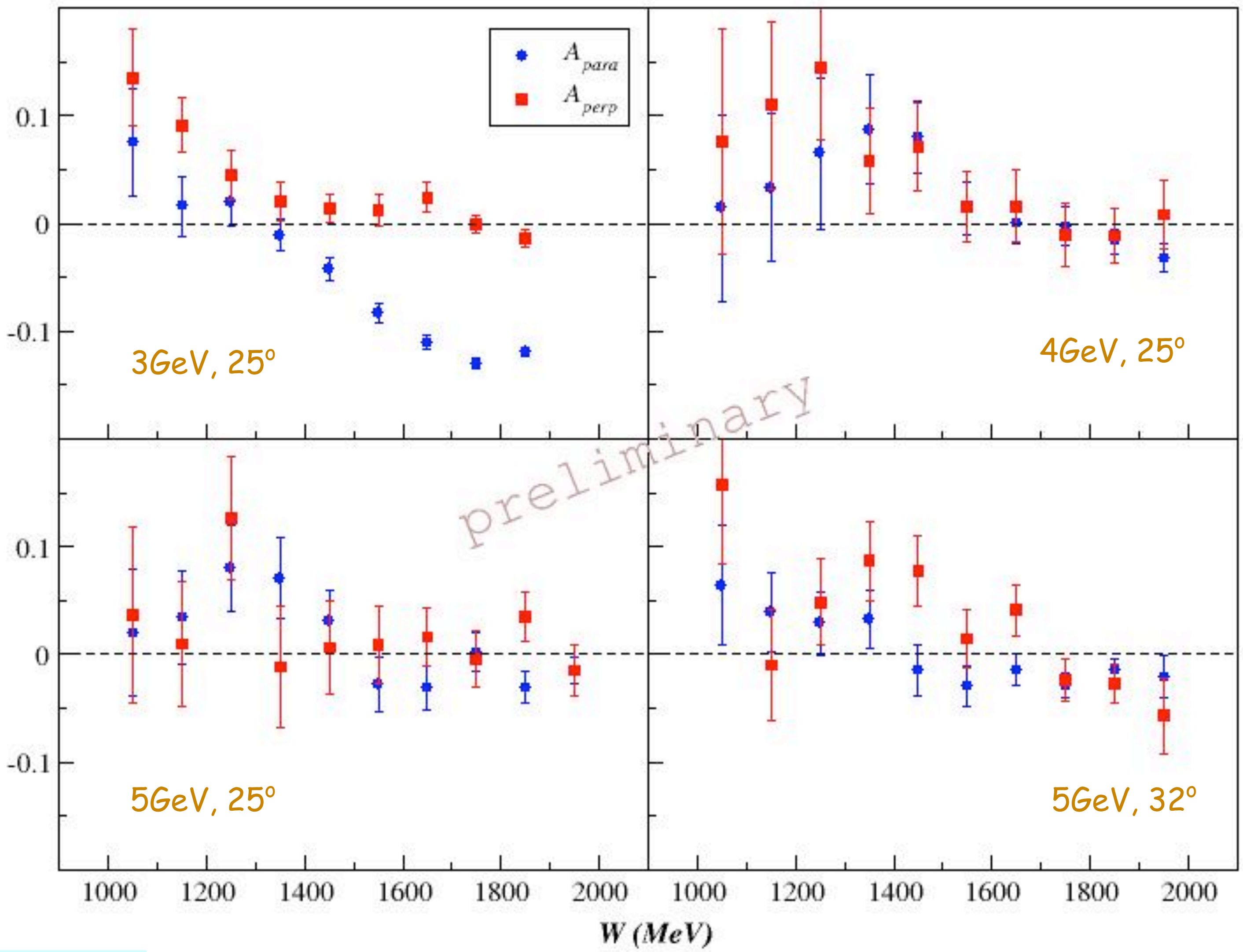
Analysis scheme

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



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

Pion asymmetries



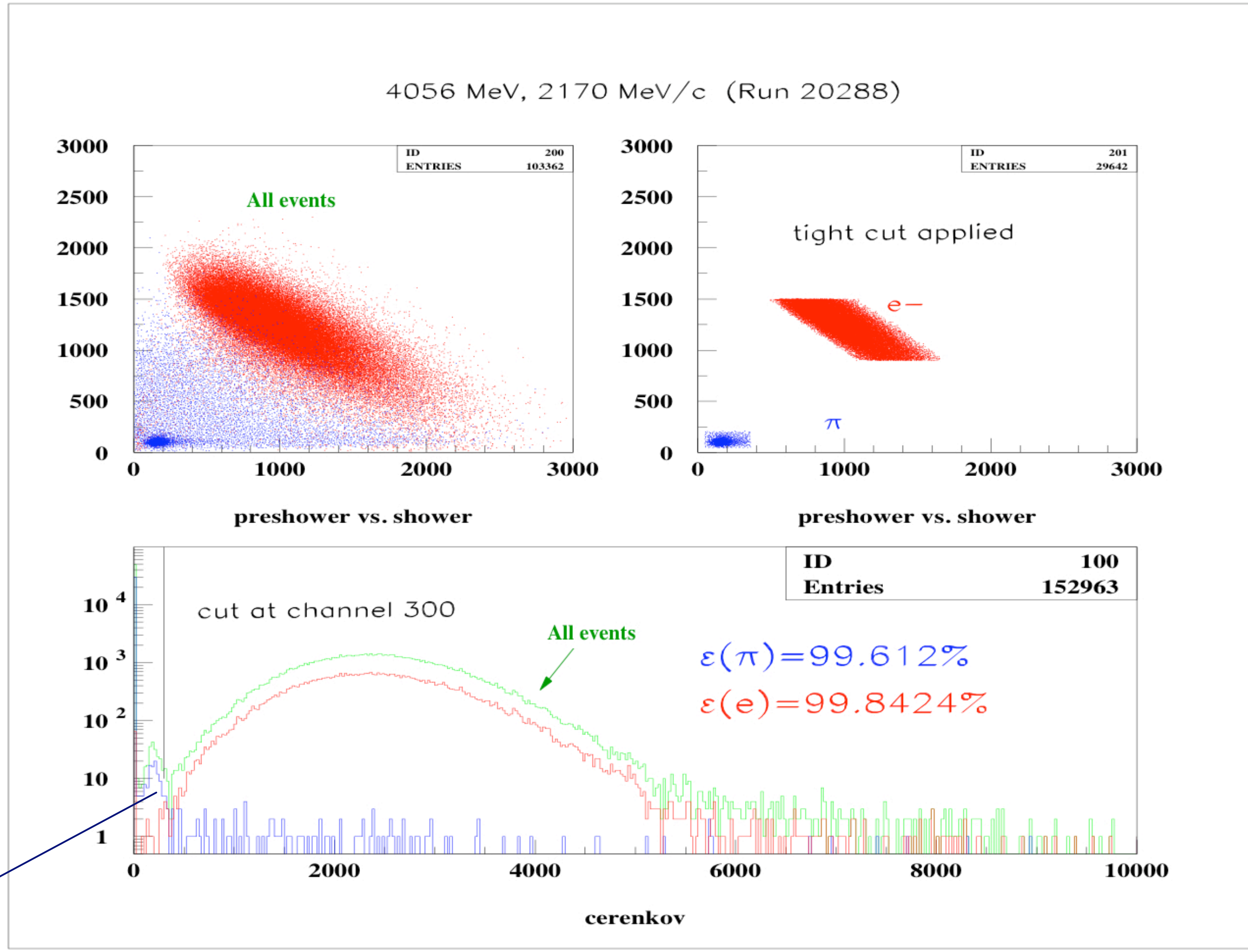
Statistical errors only

The CO_2 gas Cerenkov counter

Index of refraction:
n = 1.00041

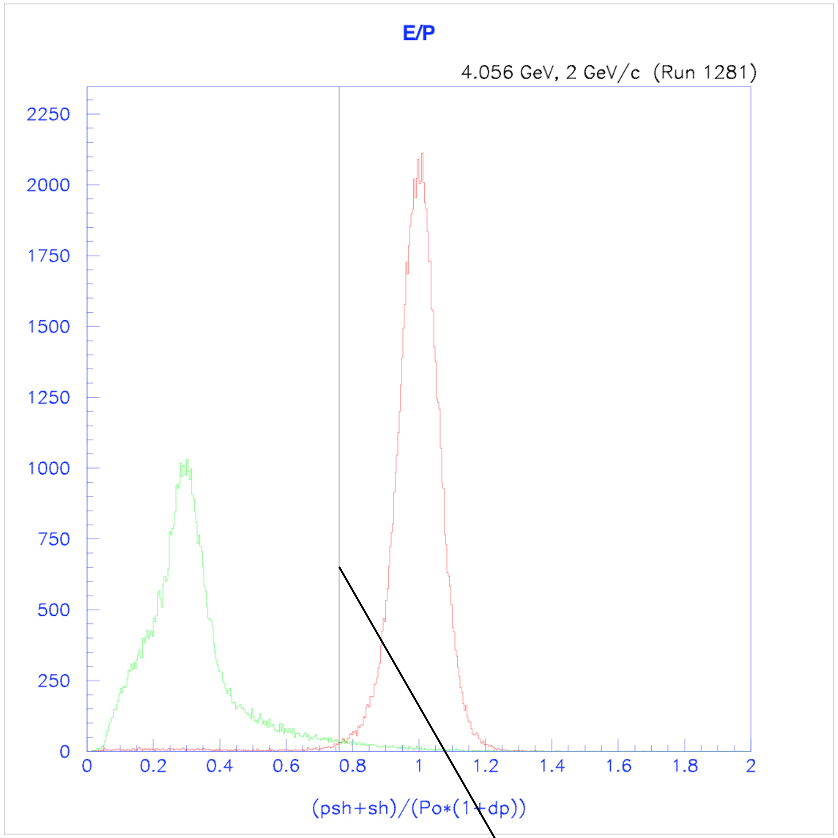
$$P^{e^-}_{thres.} = 18\,MeV$$

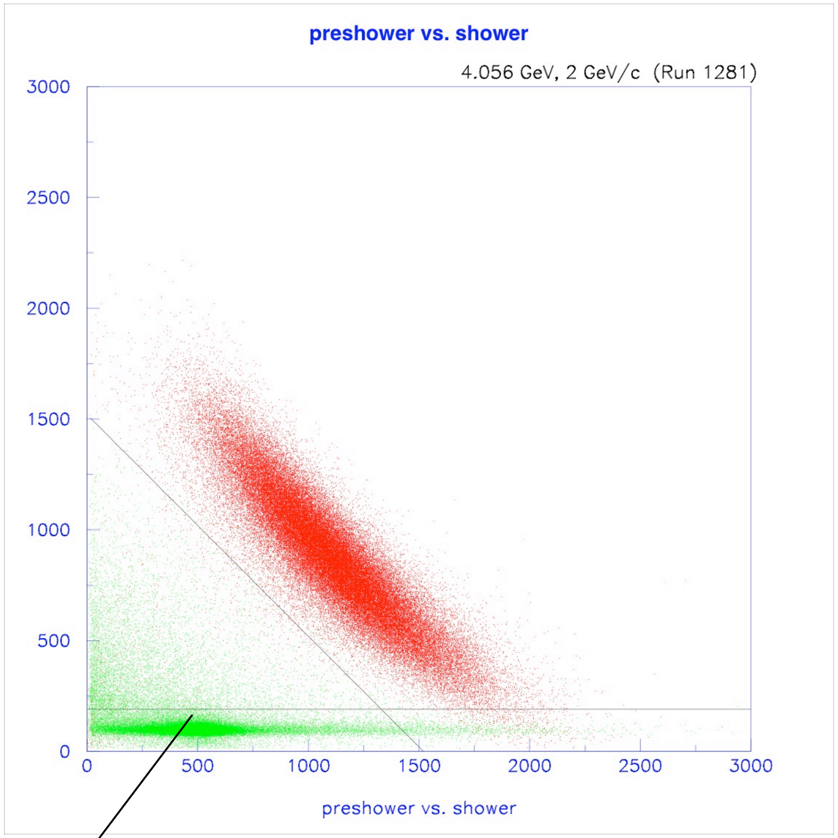
$$P^{\pi^-}_{thres.} = 4.9\,GeV$$



Knock-out e-
&
Low energy e-

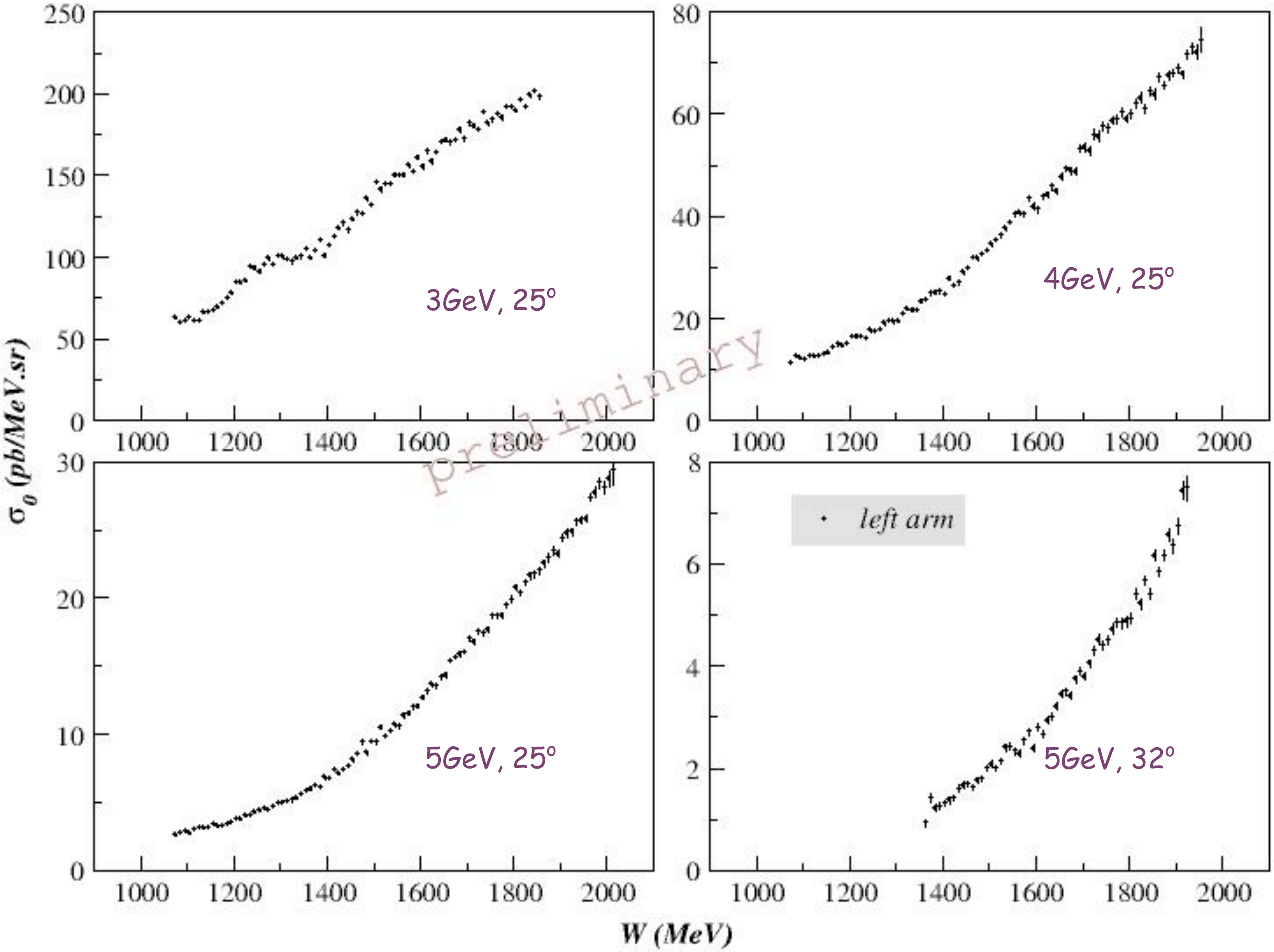
Lead Glass Calorimeter





Cuts applied for electron efficiency > 99%

Unpolarized cross sections



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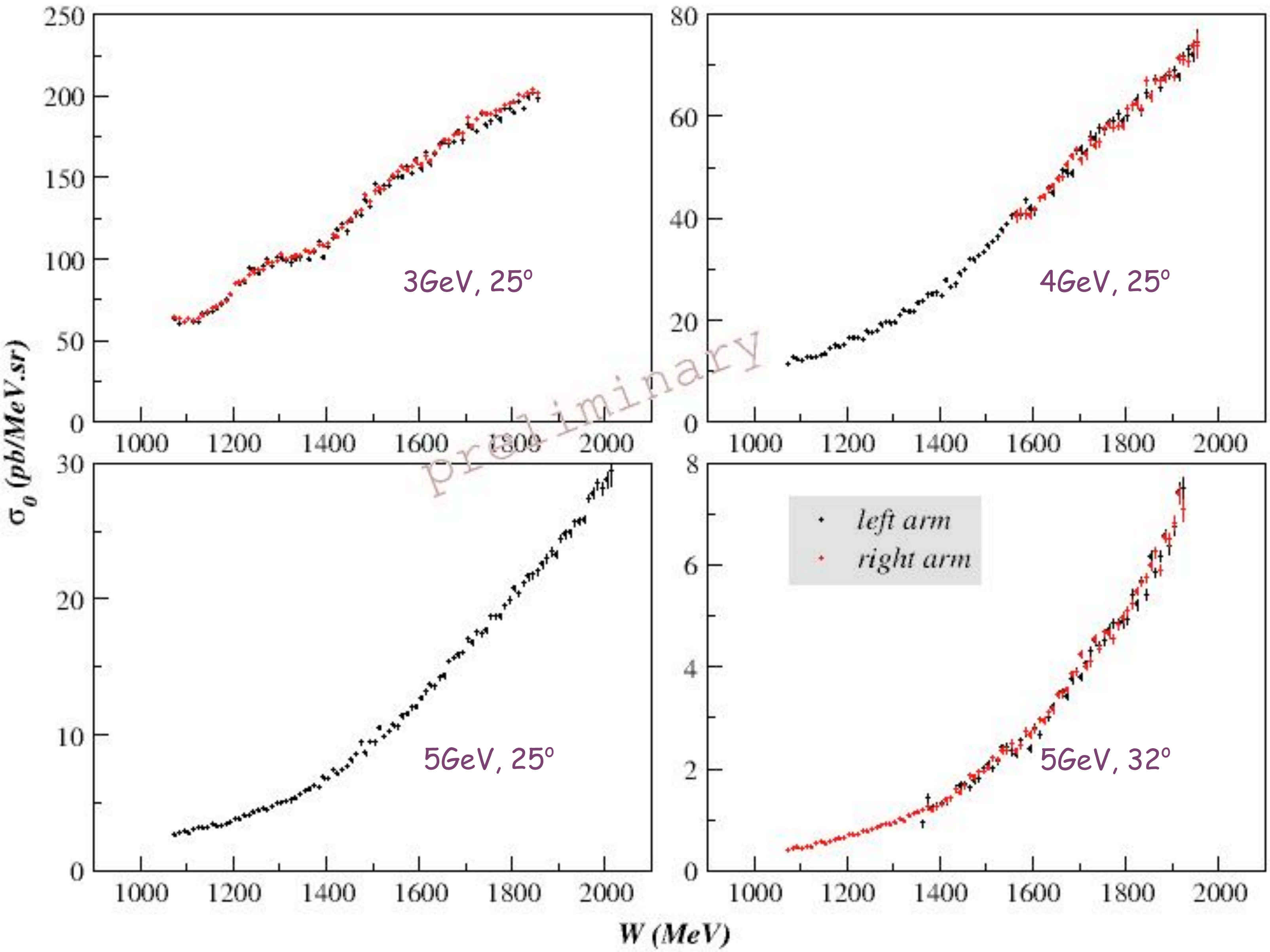

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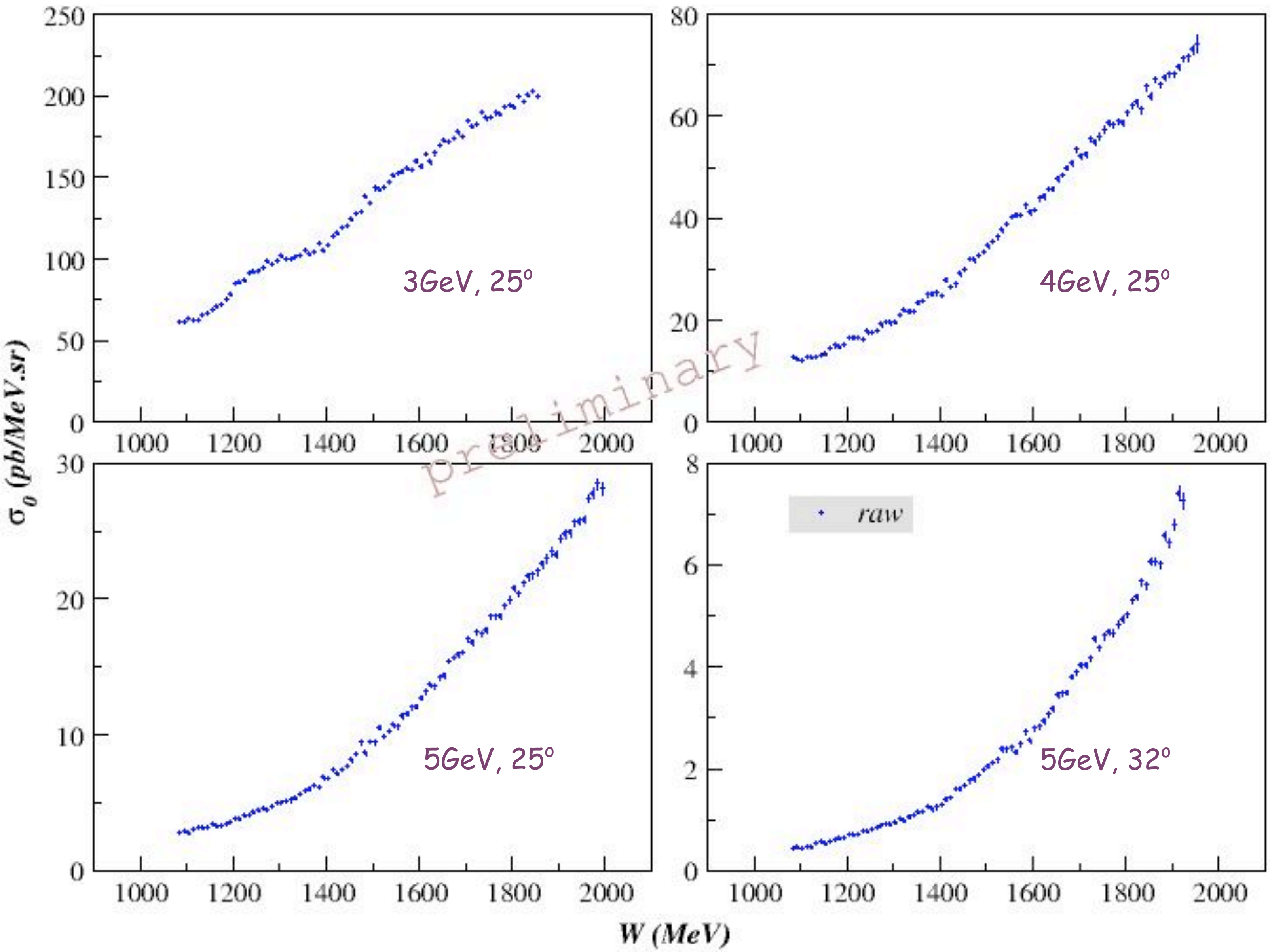

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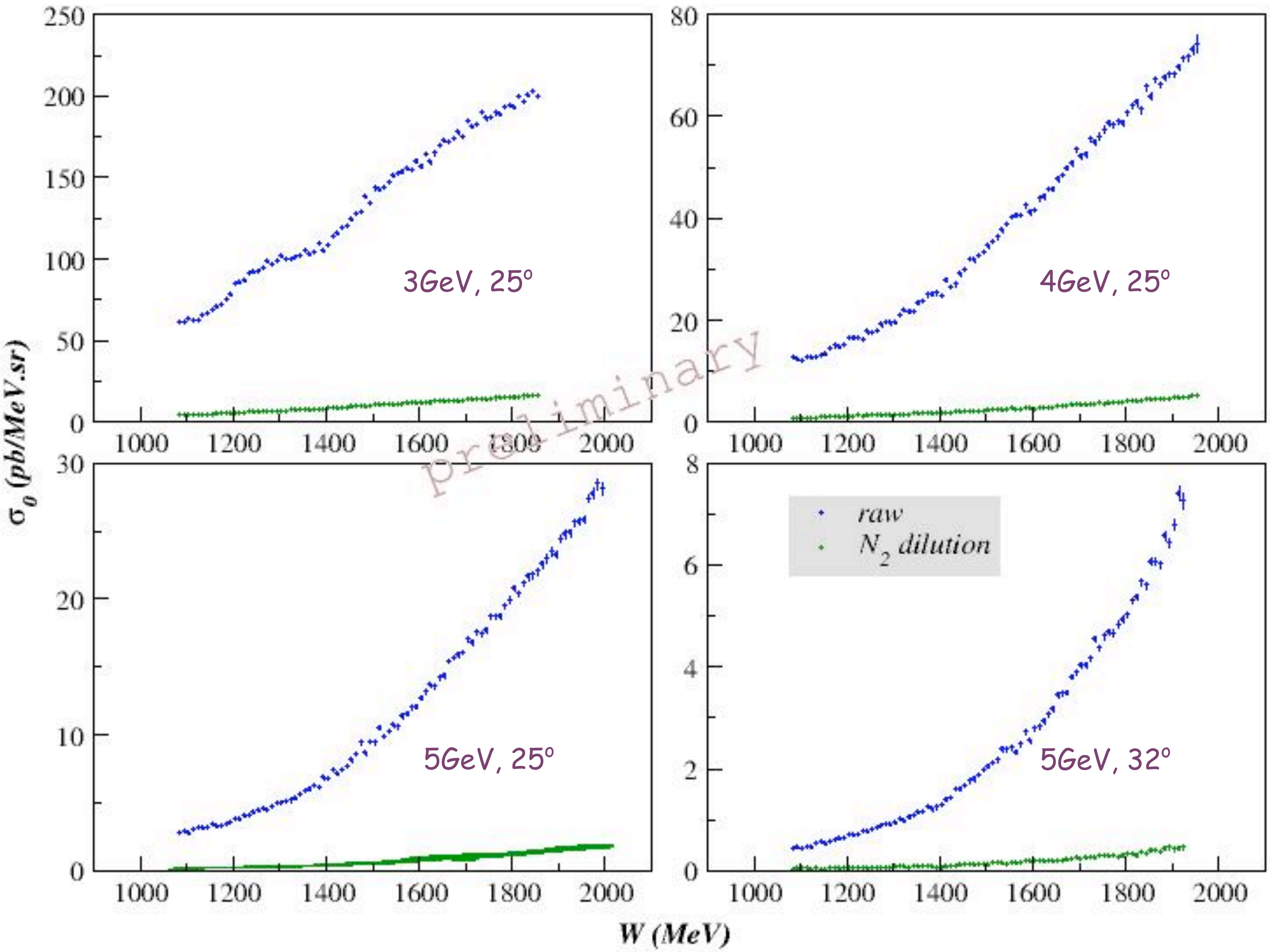

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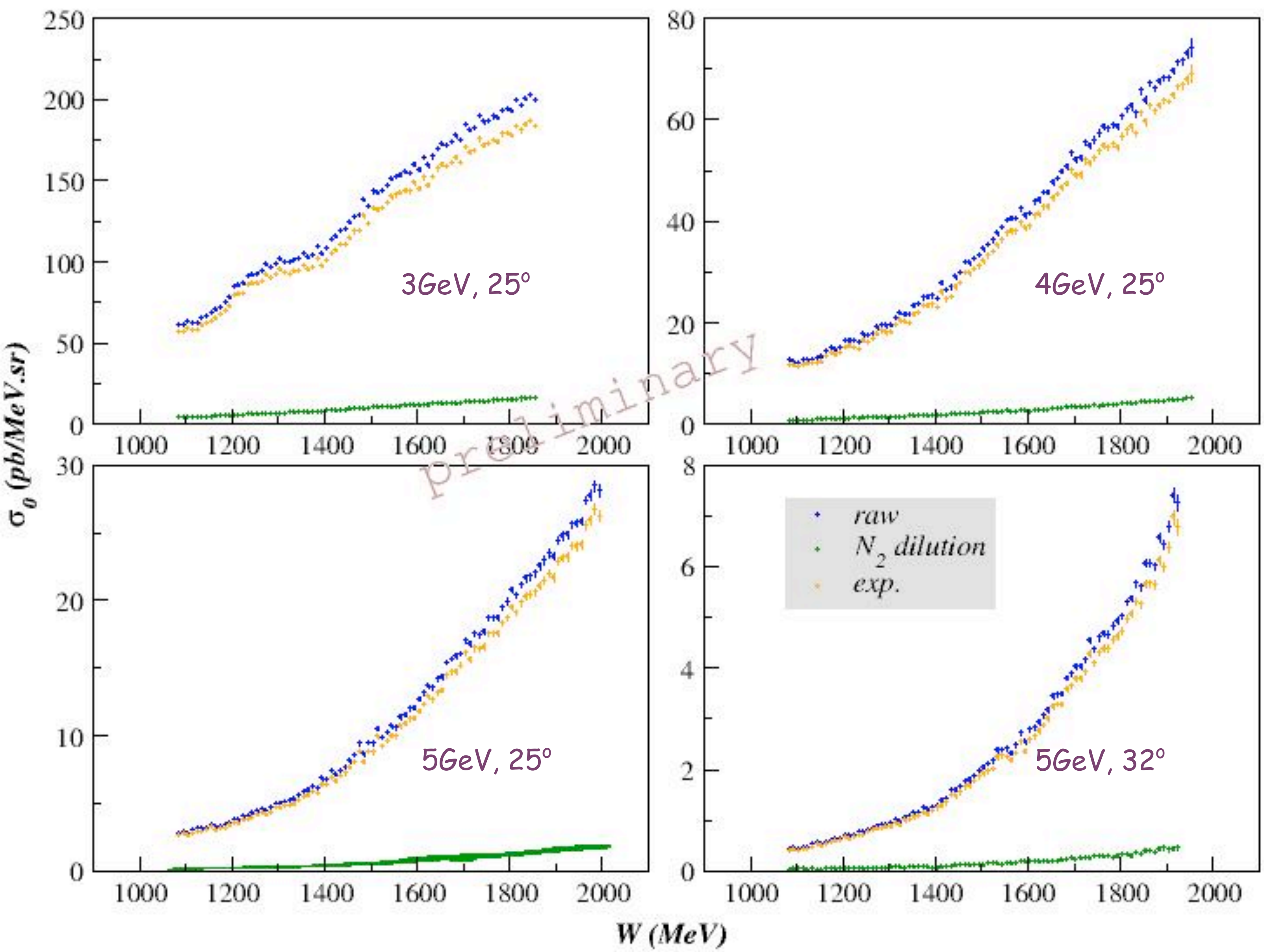
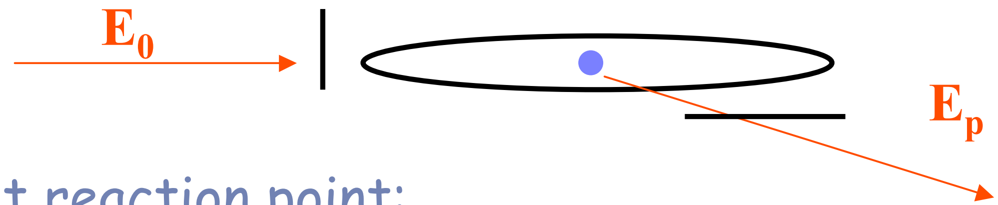


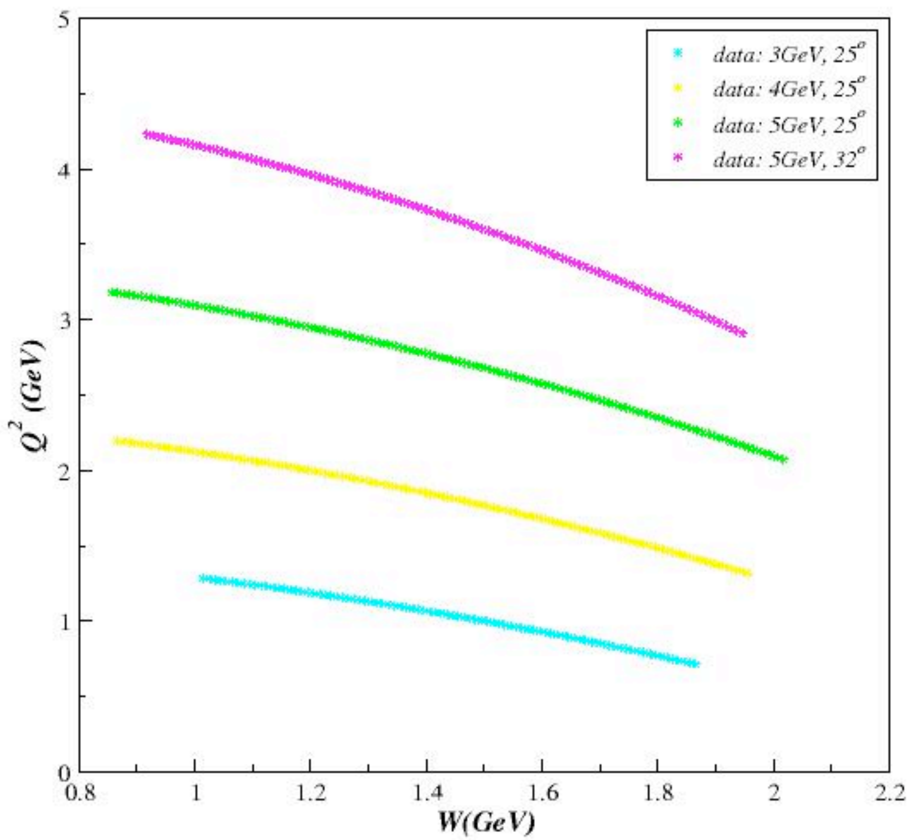
Radiative corrections



At reaction point:

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

Computation to get the real reaction



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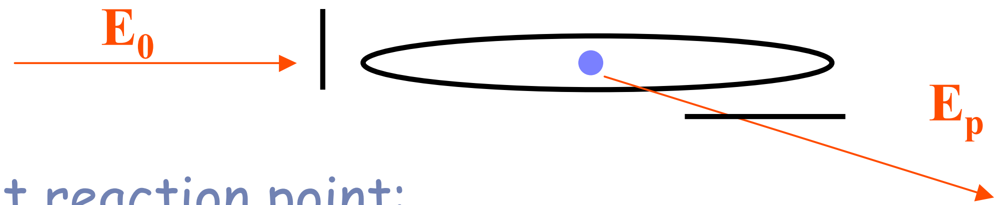

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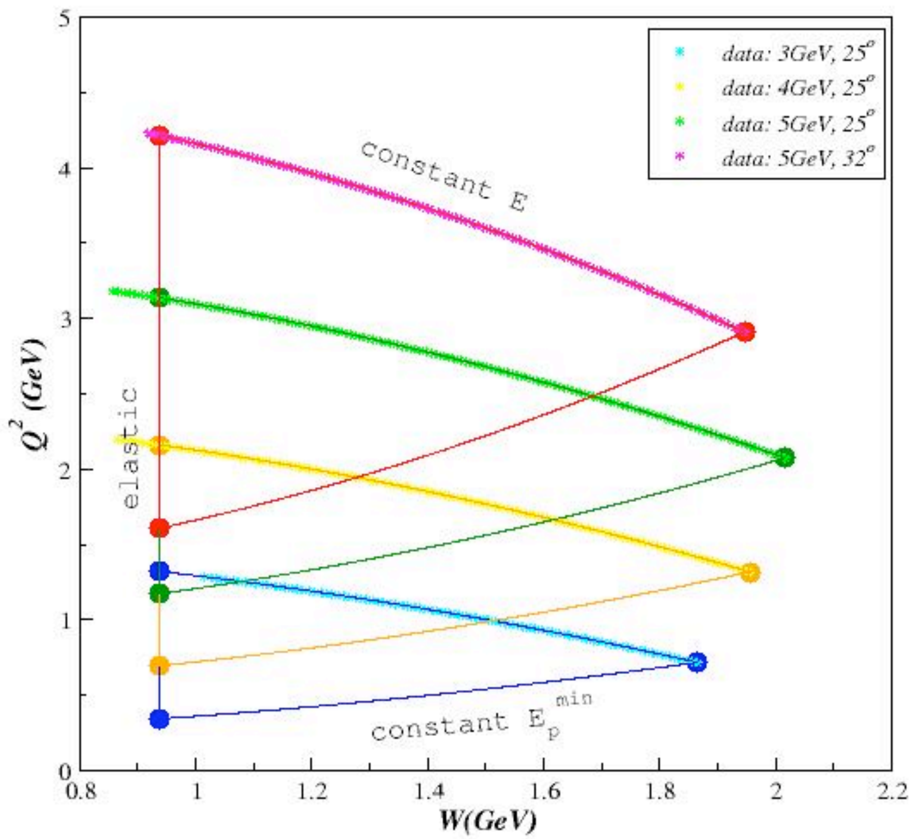


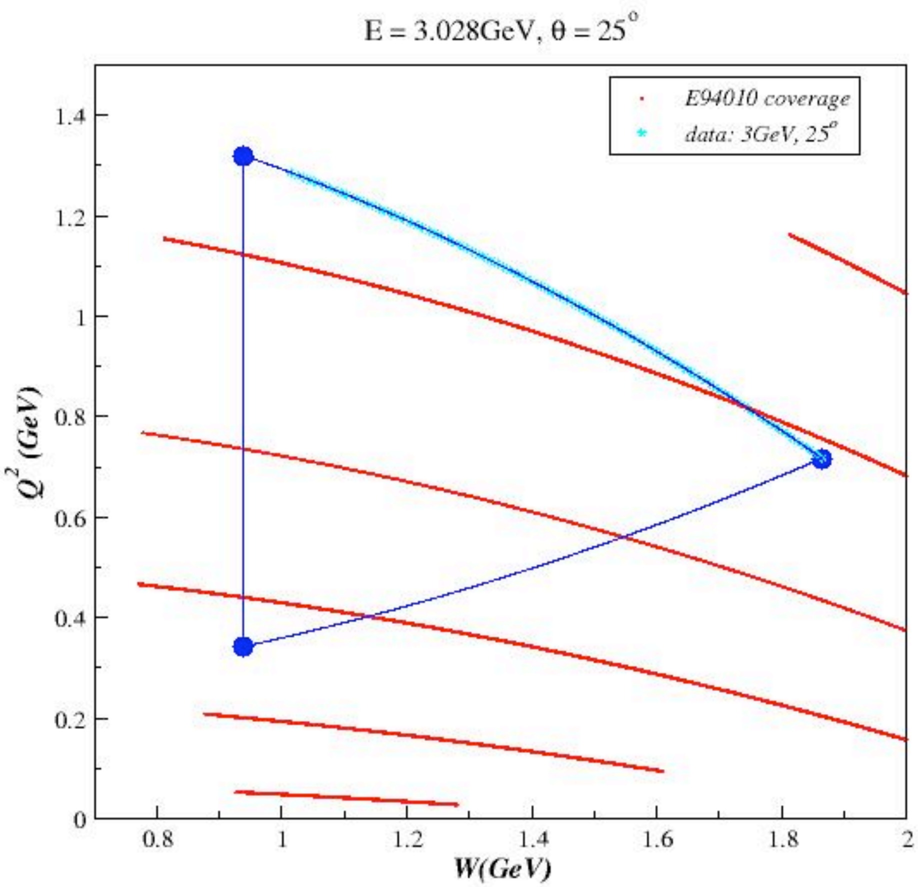
Radiative corrections

♦ 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:

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



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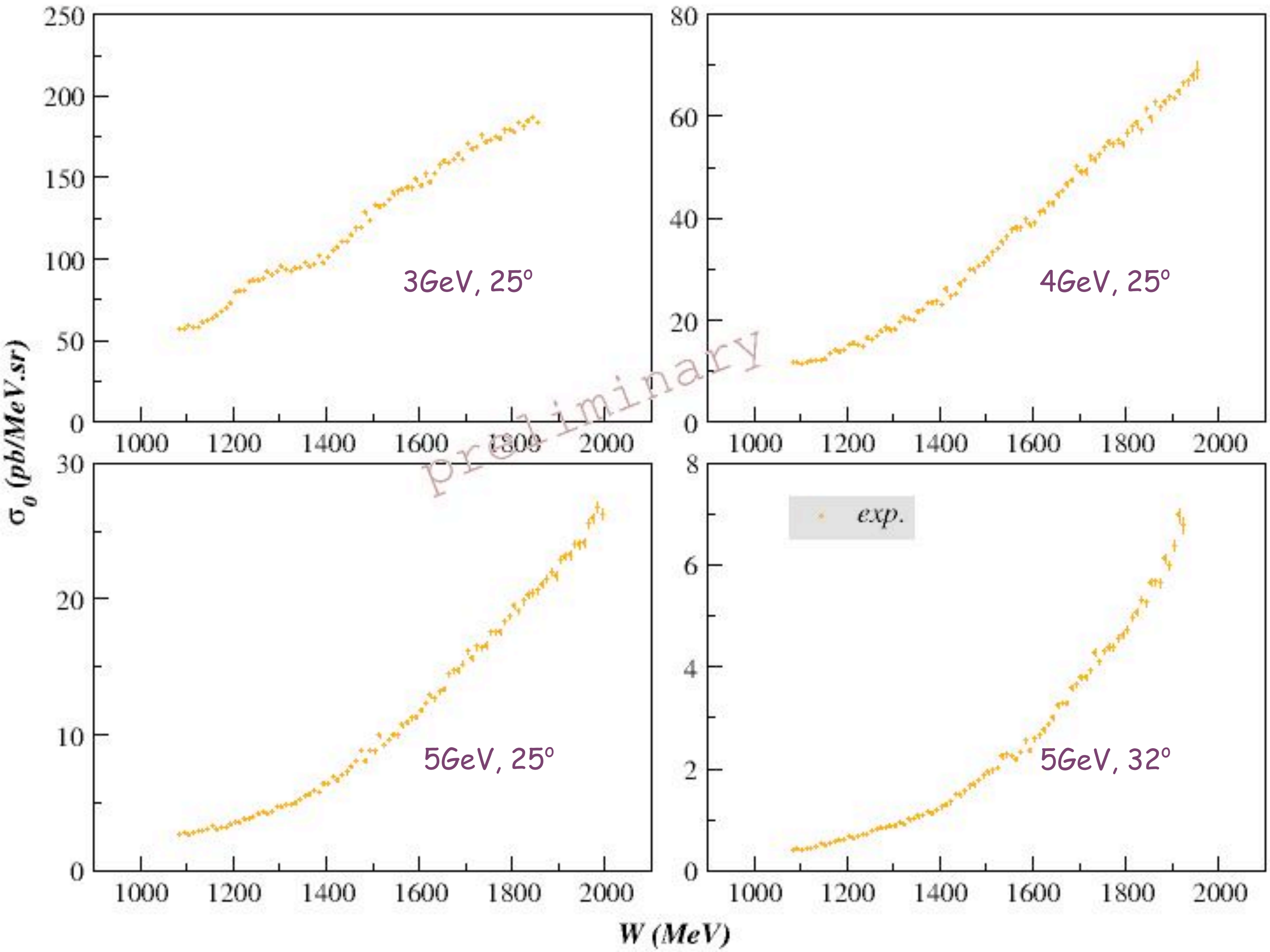

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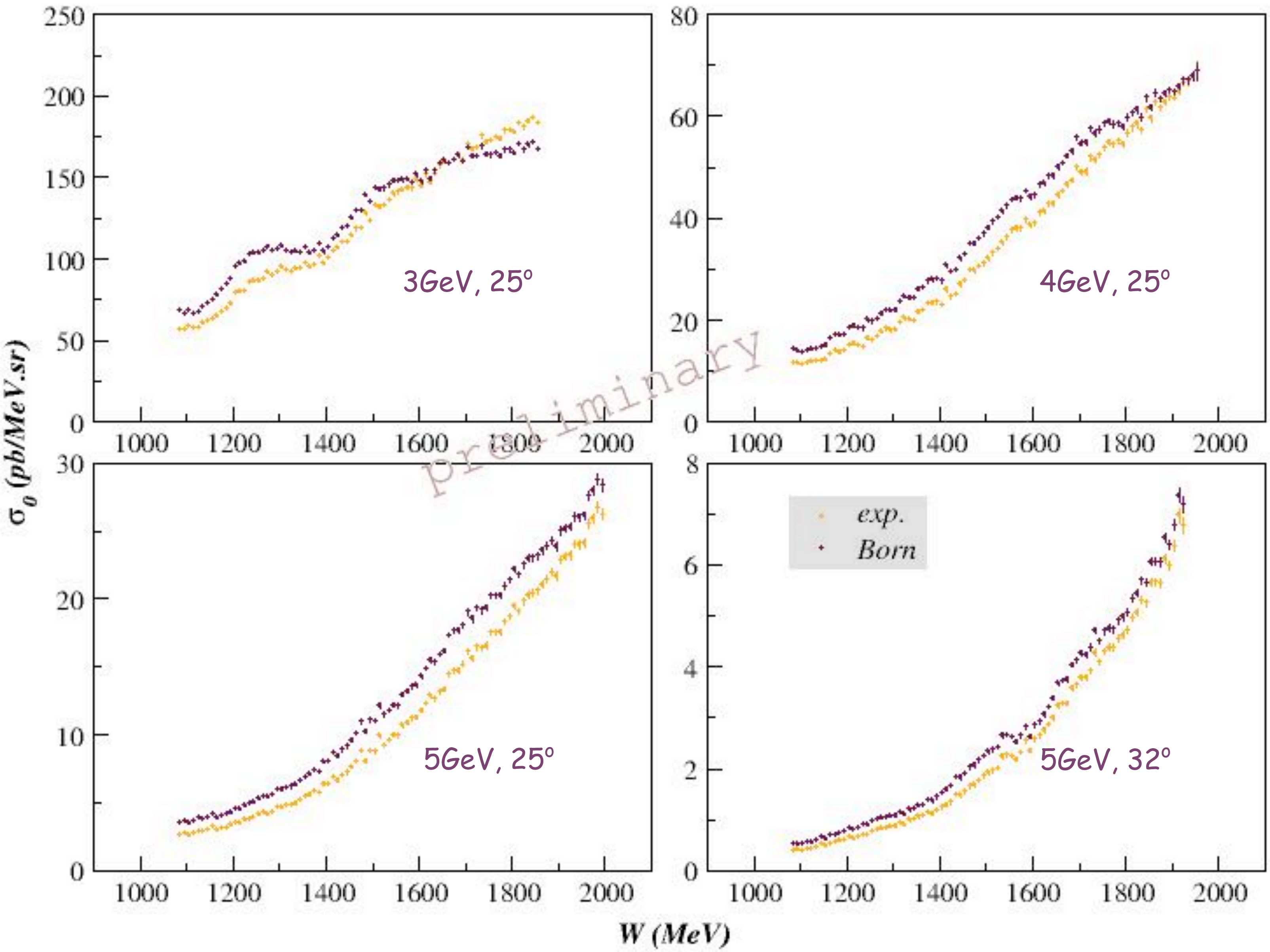
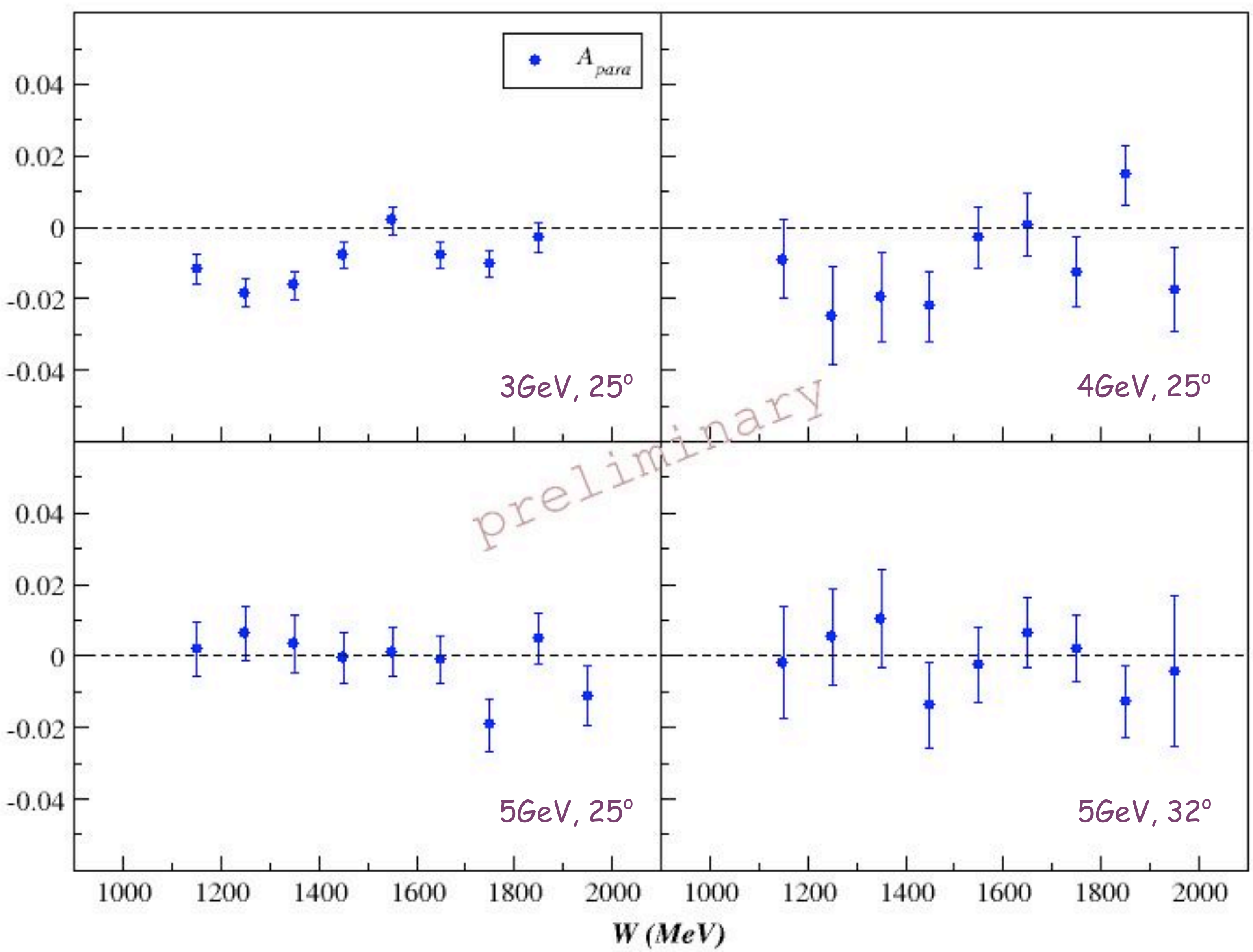


Asymmetries



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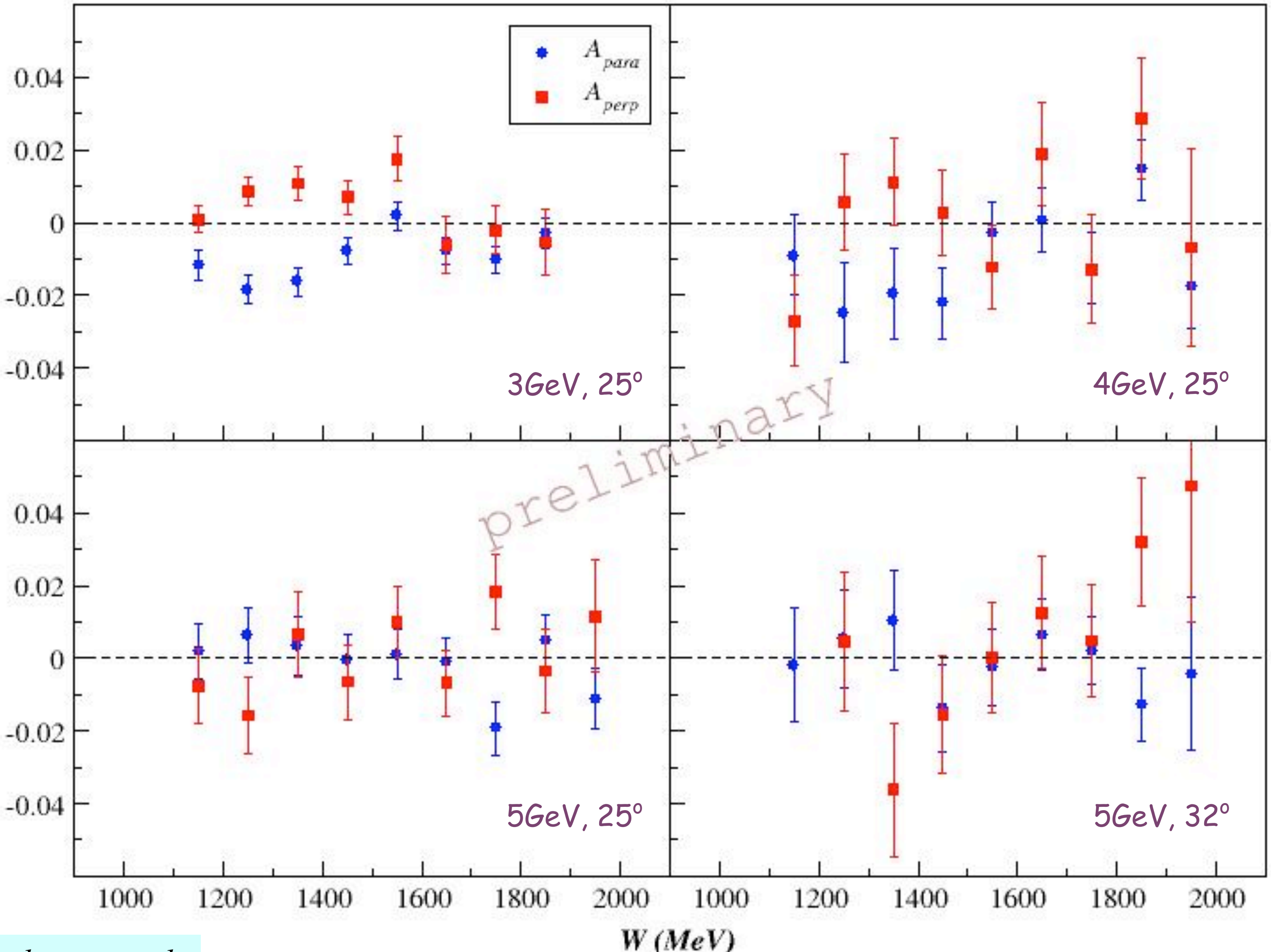
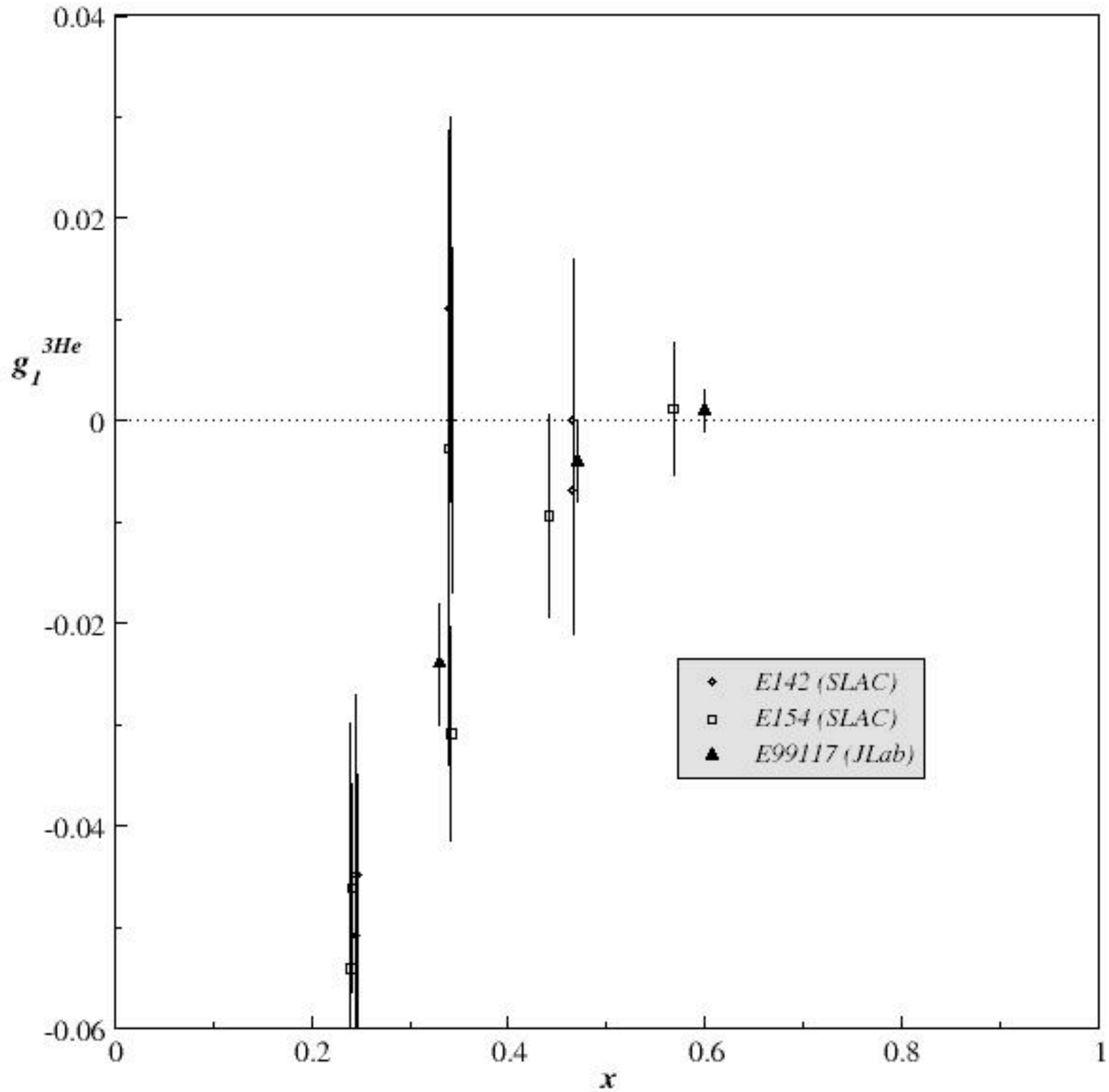


Statistical errors only

g_1^{3He} at constant Q^2



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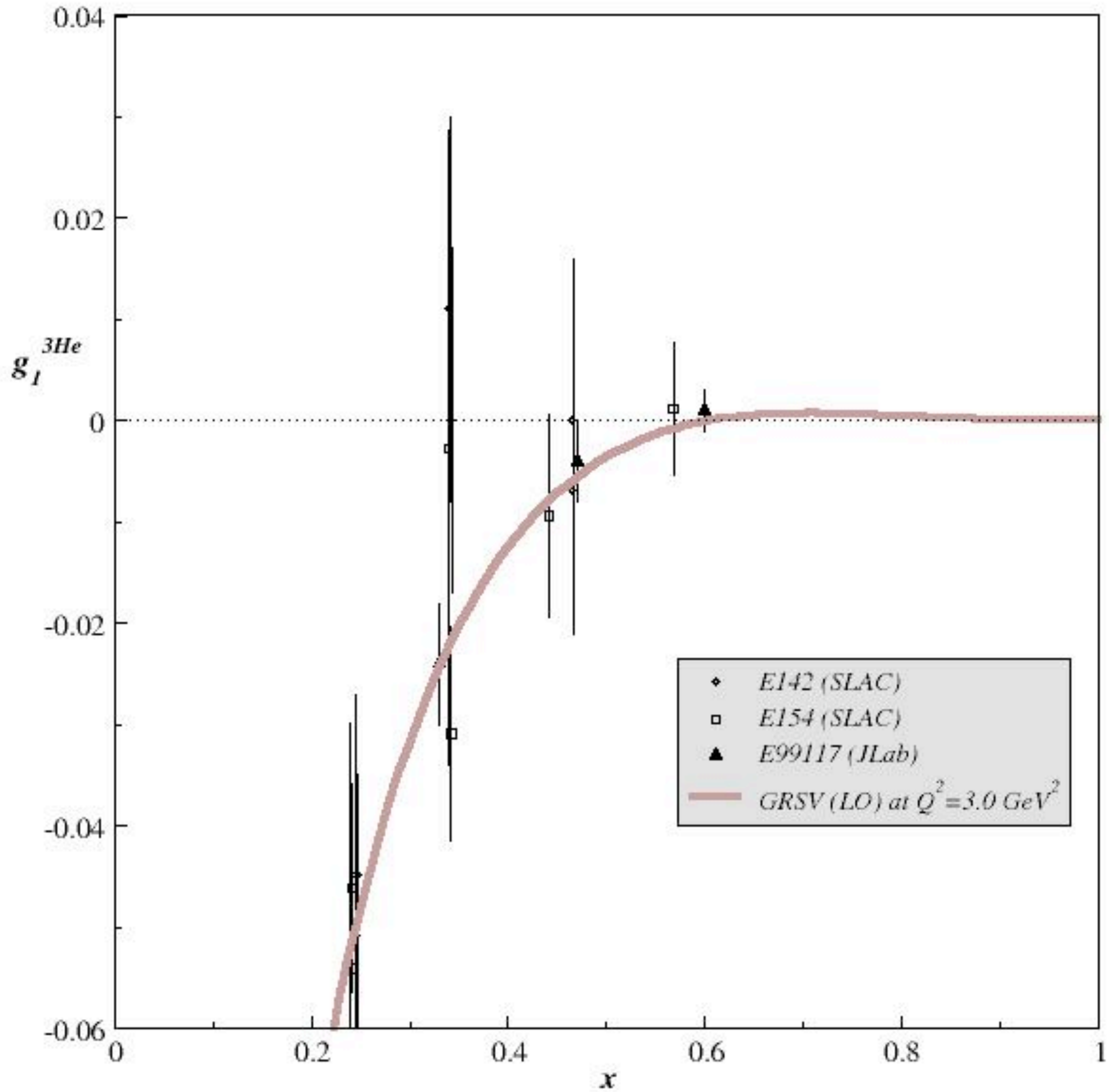

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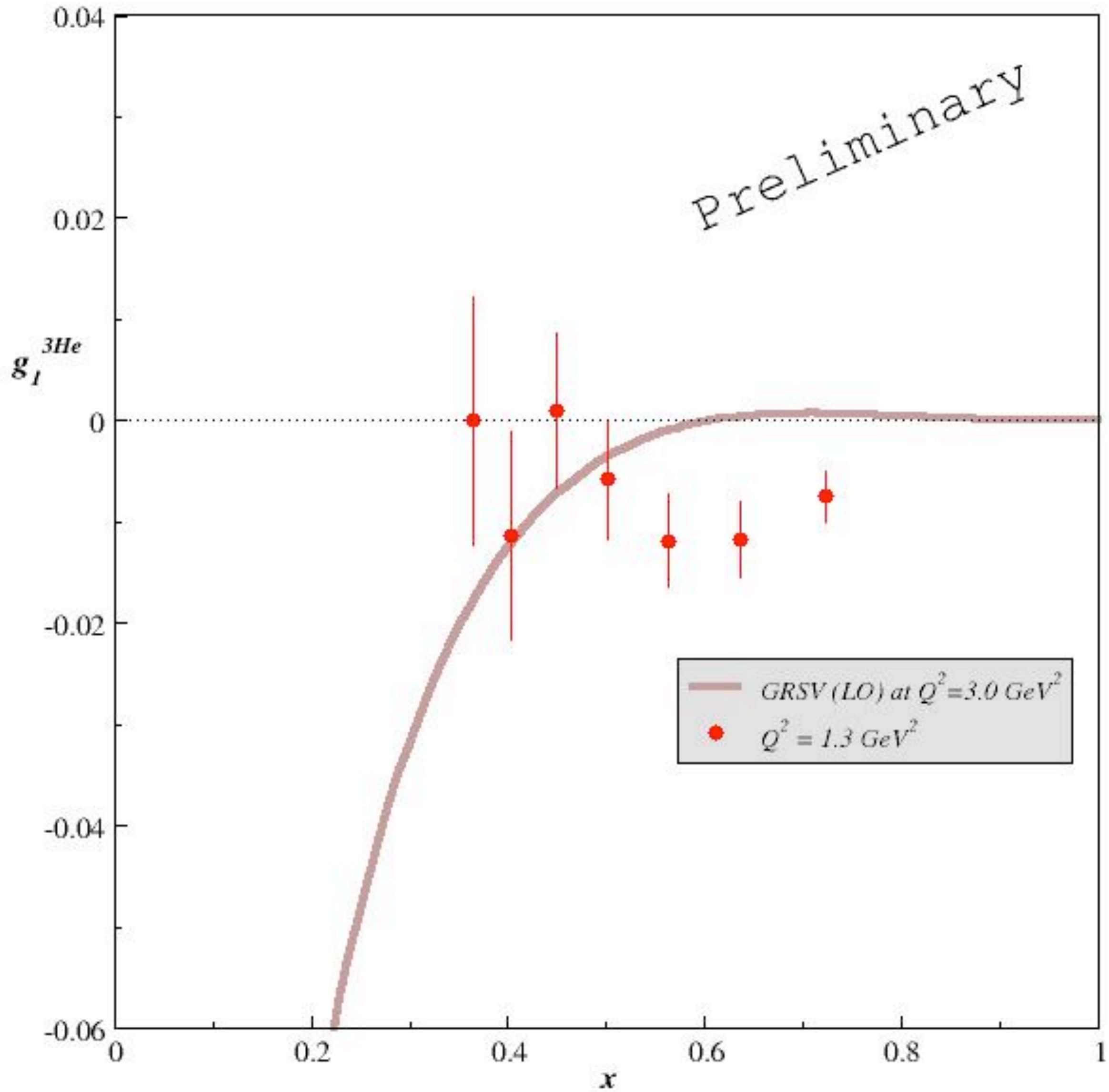

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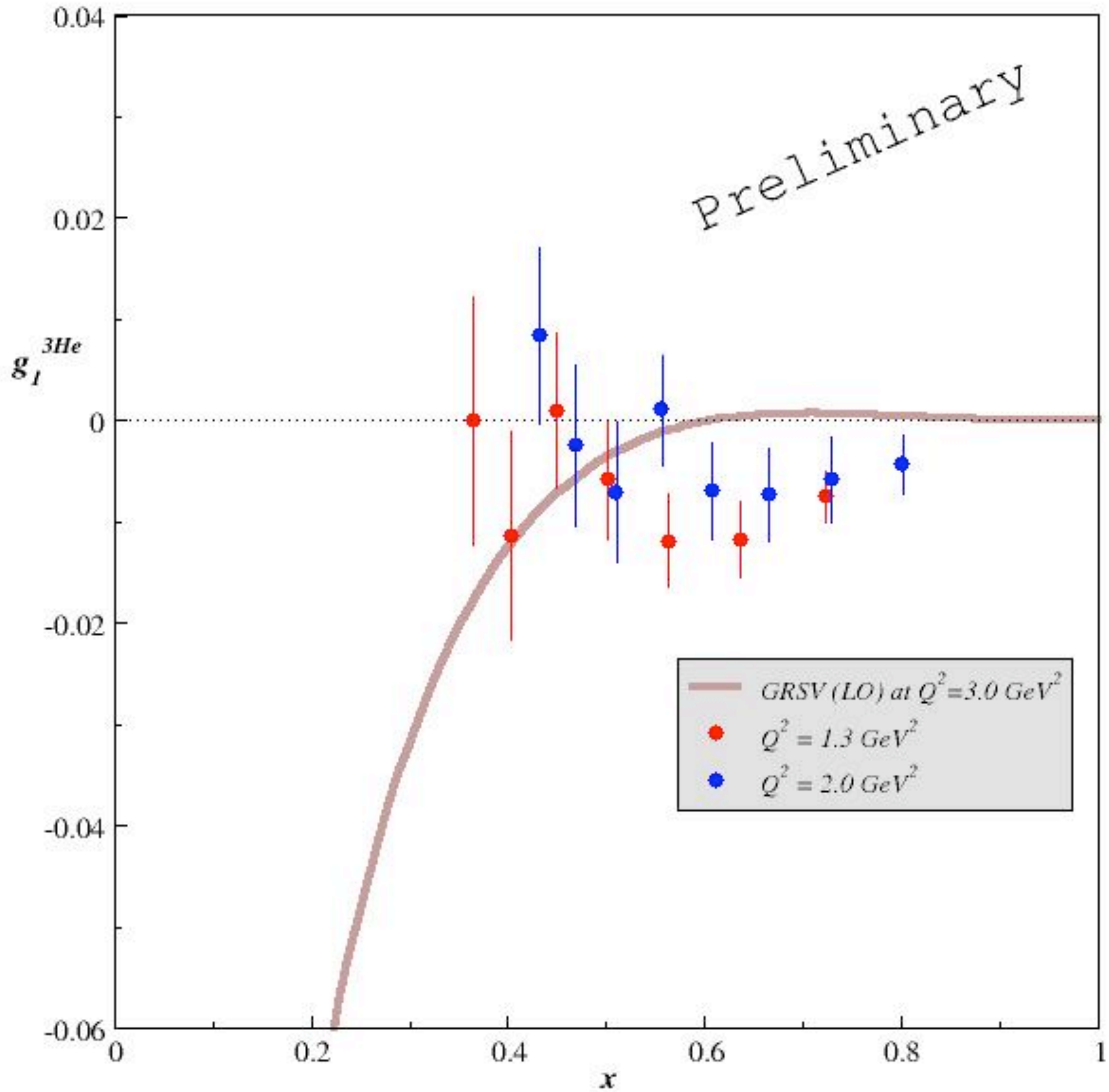

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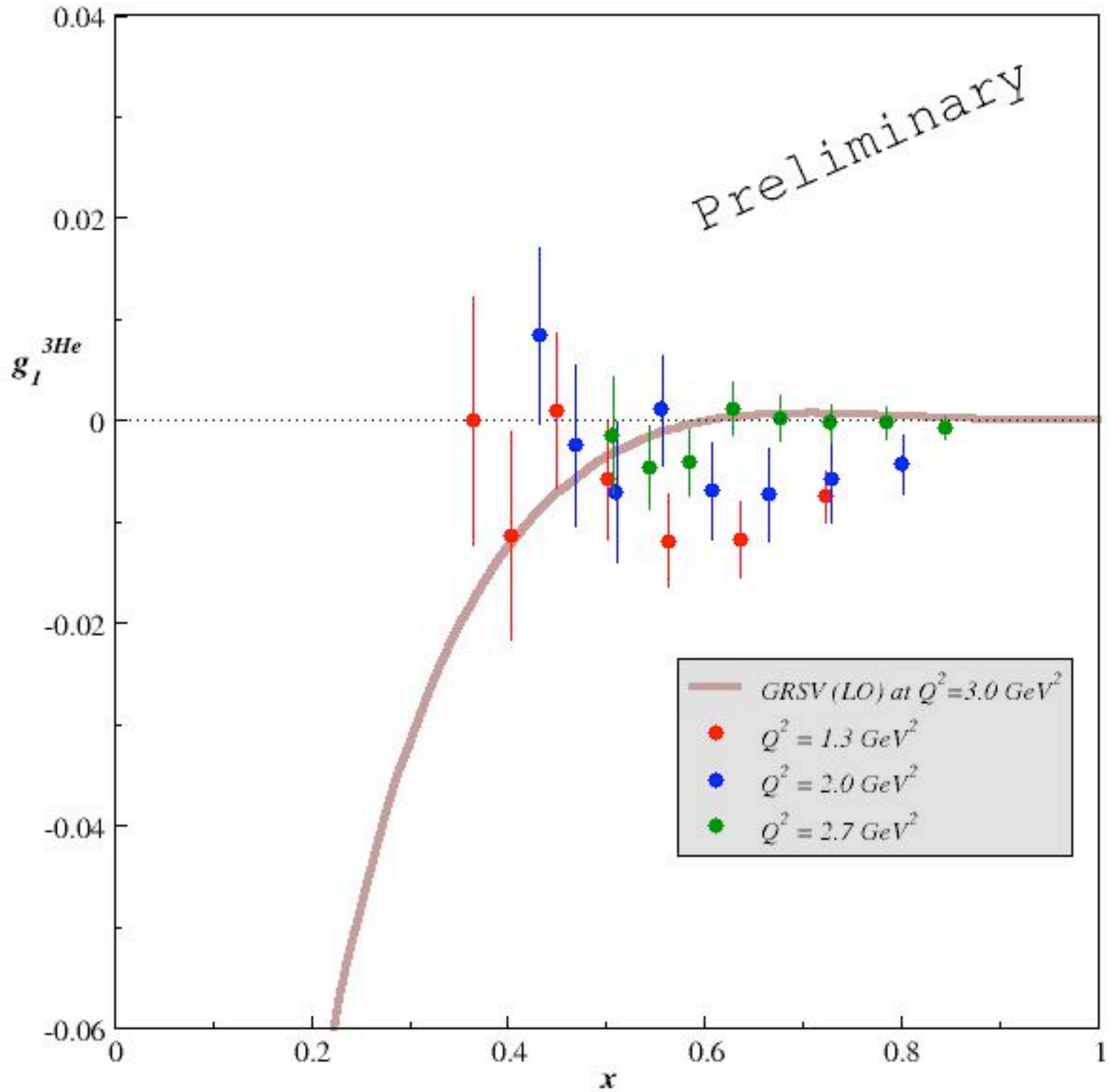

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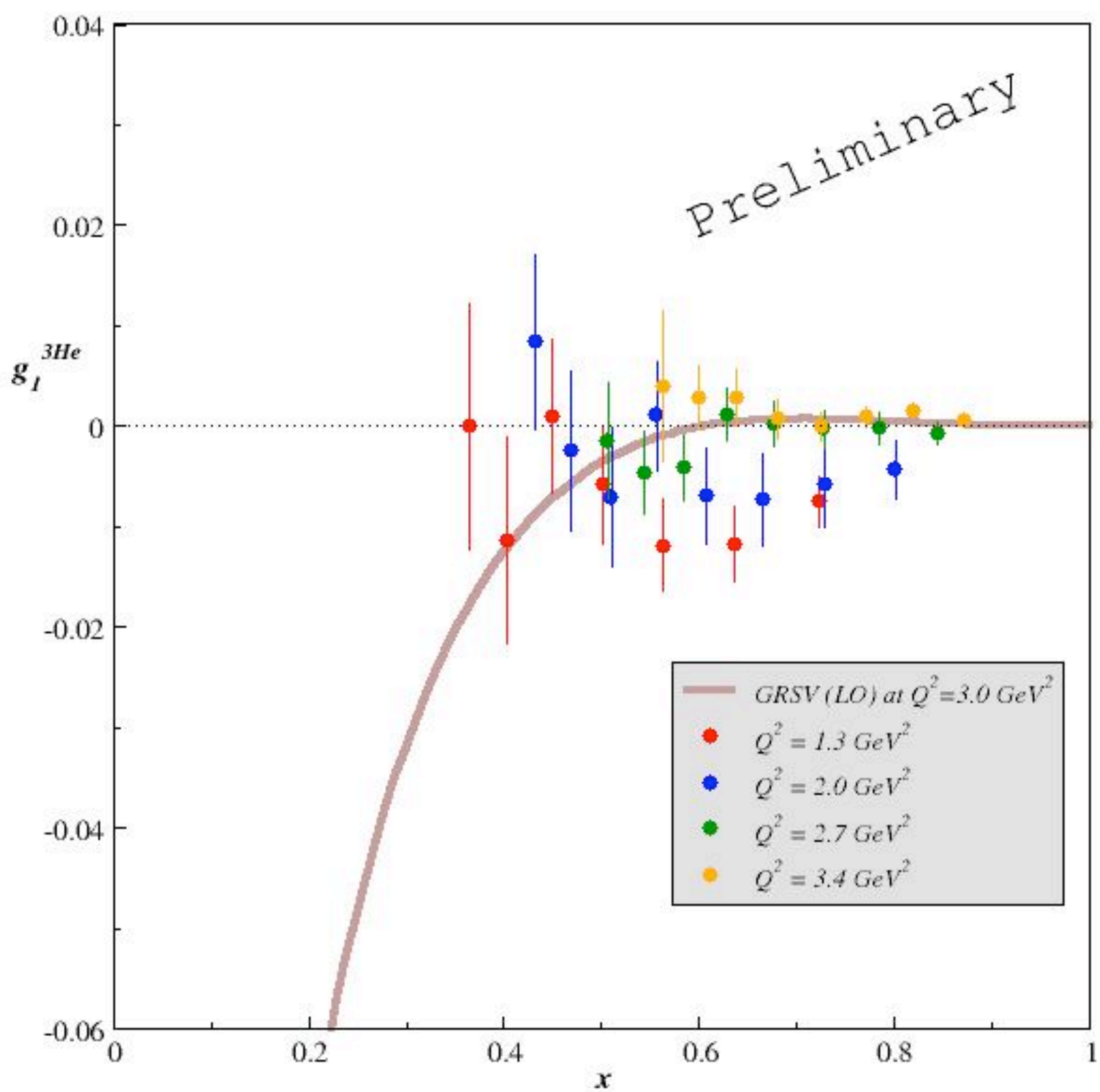
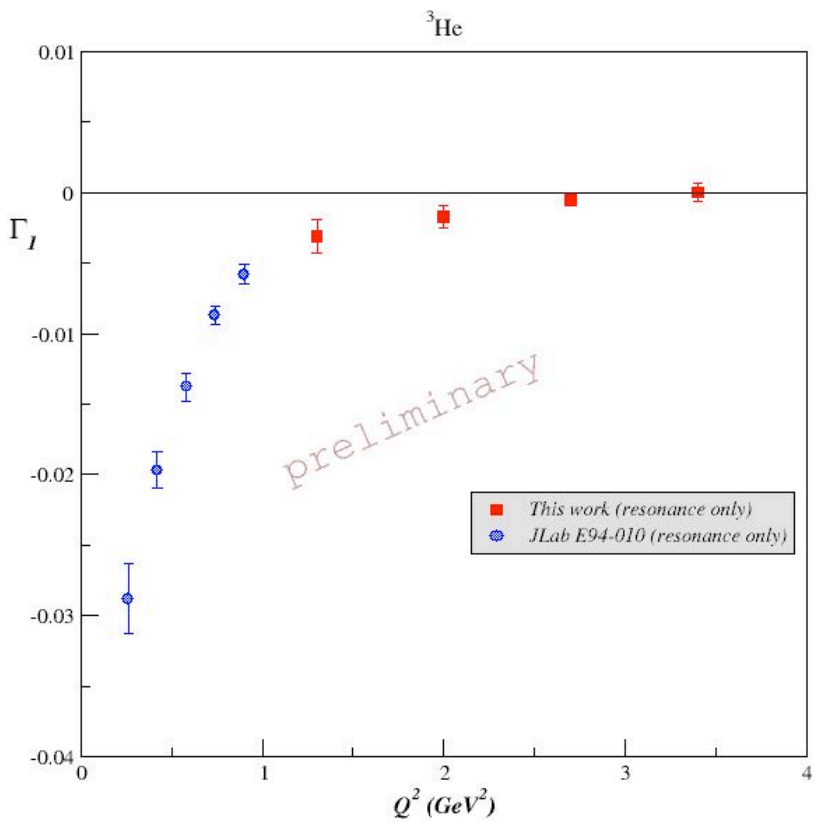


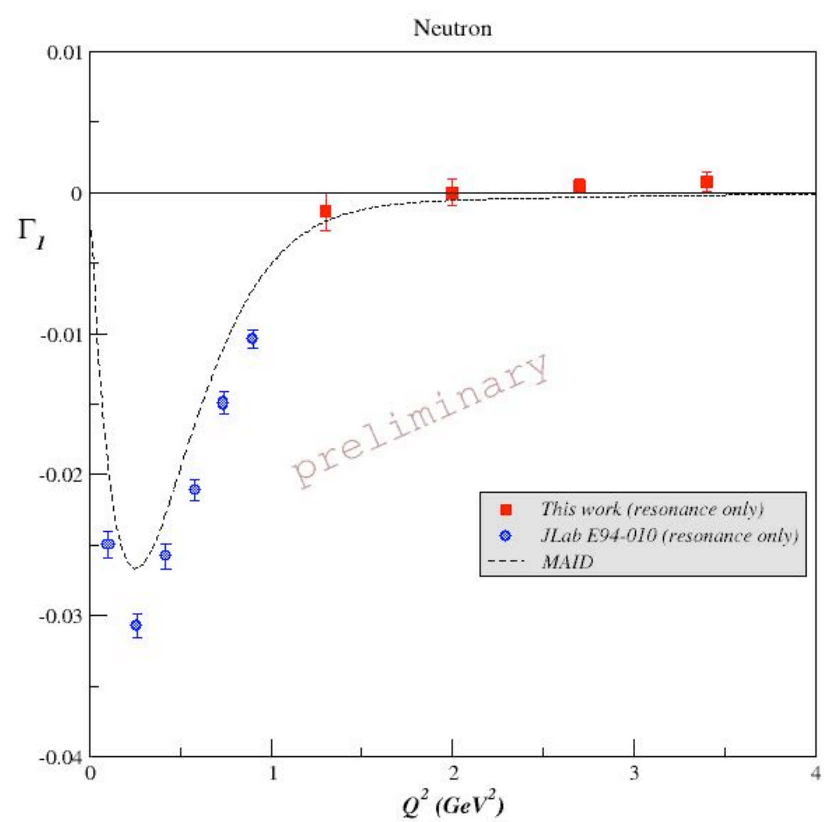
Γ_1 in the resonance region

Extract the neutron from effective polarization equation:

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

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

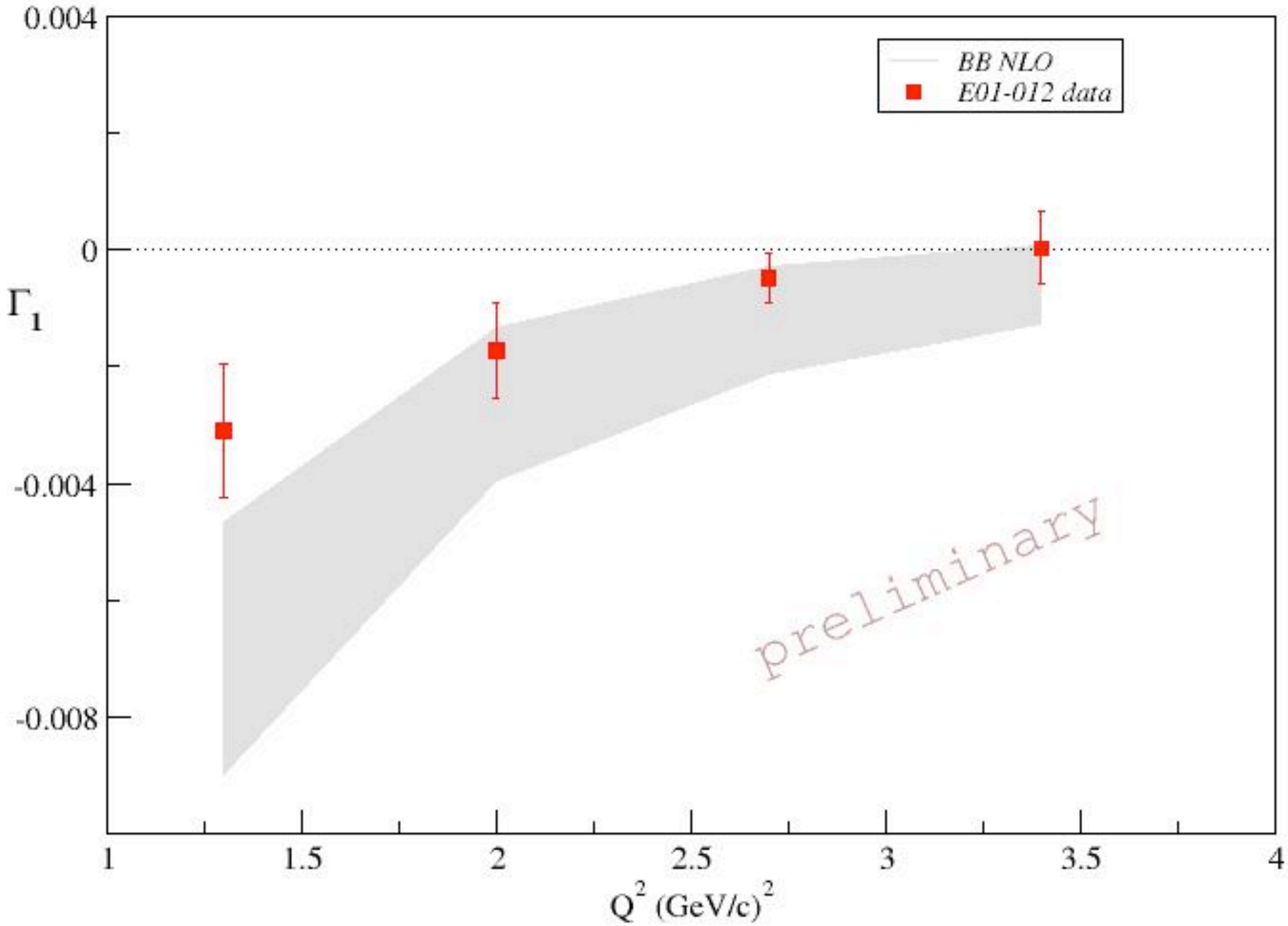
1. Get g_1 at constant Q^2
2. Define integration range in the resonance region in function of W
3. Integrate g_1^{res} and g_1^{dis} over the same x-range and at the same Q^2

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

$$R = \frac{\tilde{\Gamma}_1^{res}}{\tilde{\Gamma}_1^{dis}}$$

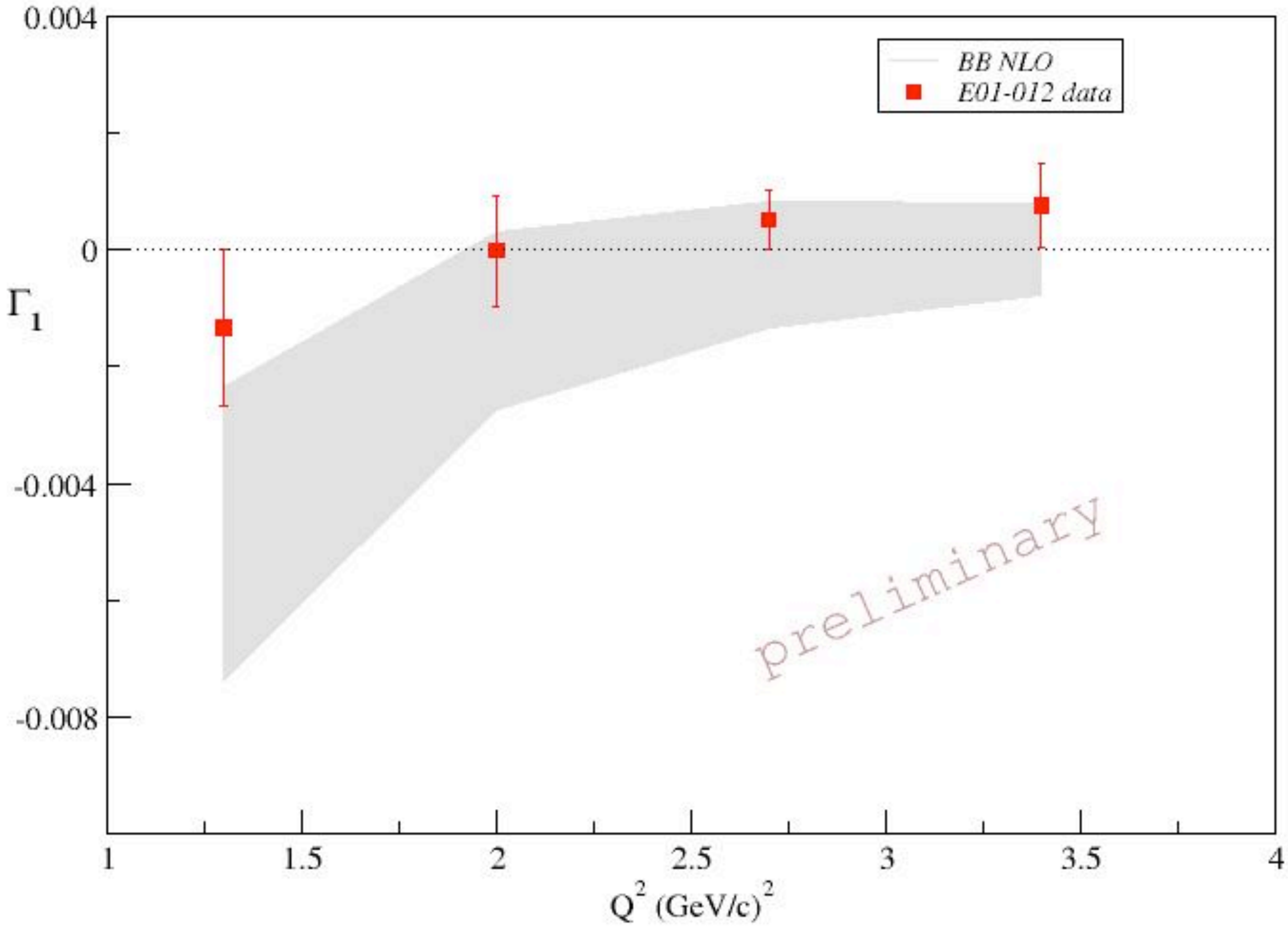
if unity ⇒ duality is verified

Test of duality on ^3He



Statistical errors only

Test of duality on neutron



Statistical errors only

Spin asymmetries

$$A_1(x,Q^2) = \frac{A_{//}}{D(1+\eta\xi)} - \frac{\eta A_\perp}{d(1+\eta\xi)}$$

η and ξ depend on kinematic variables

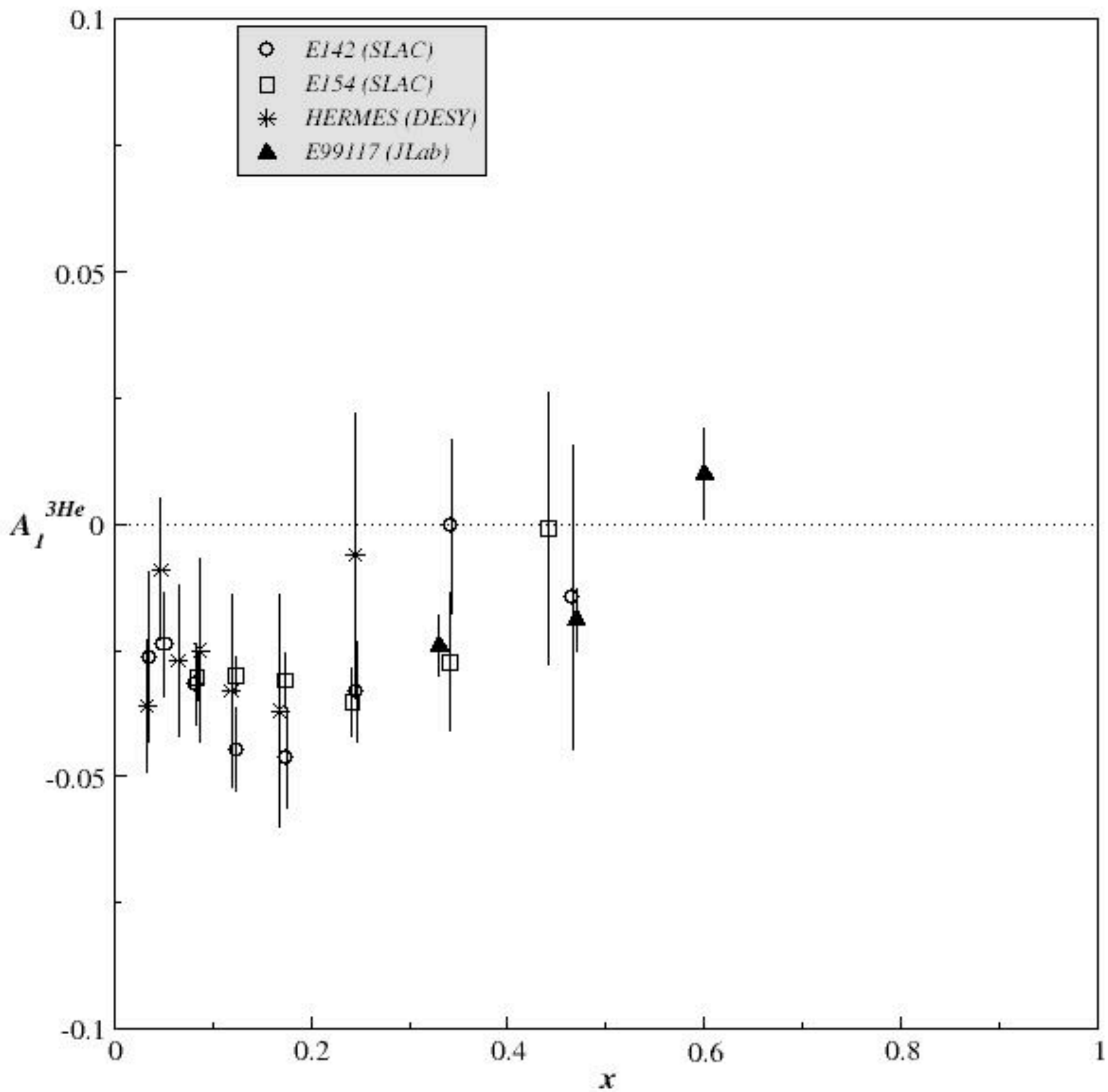
D and d depend on $R=\sigma_L/\sigma_T$ for ^3He

In the parton model:

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

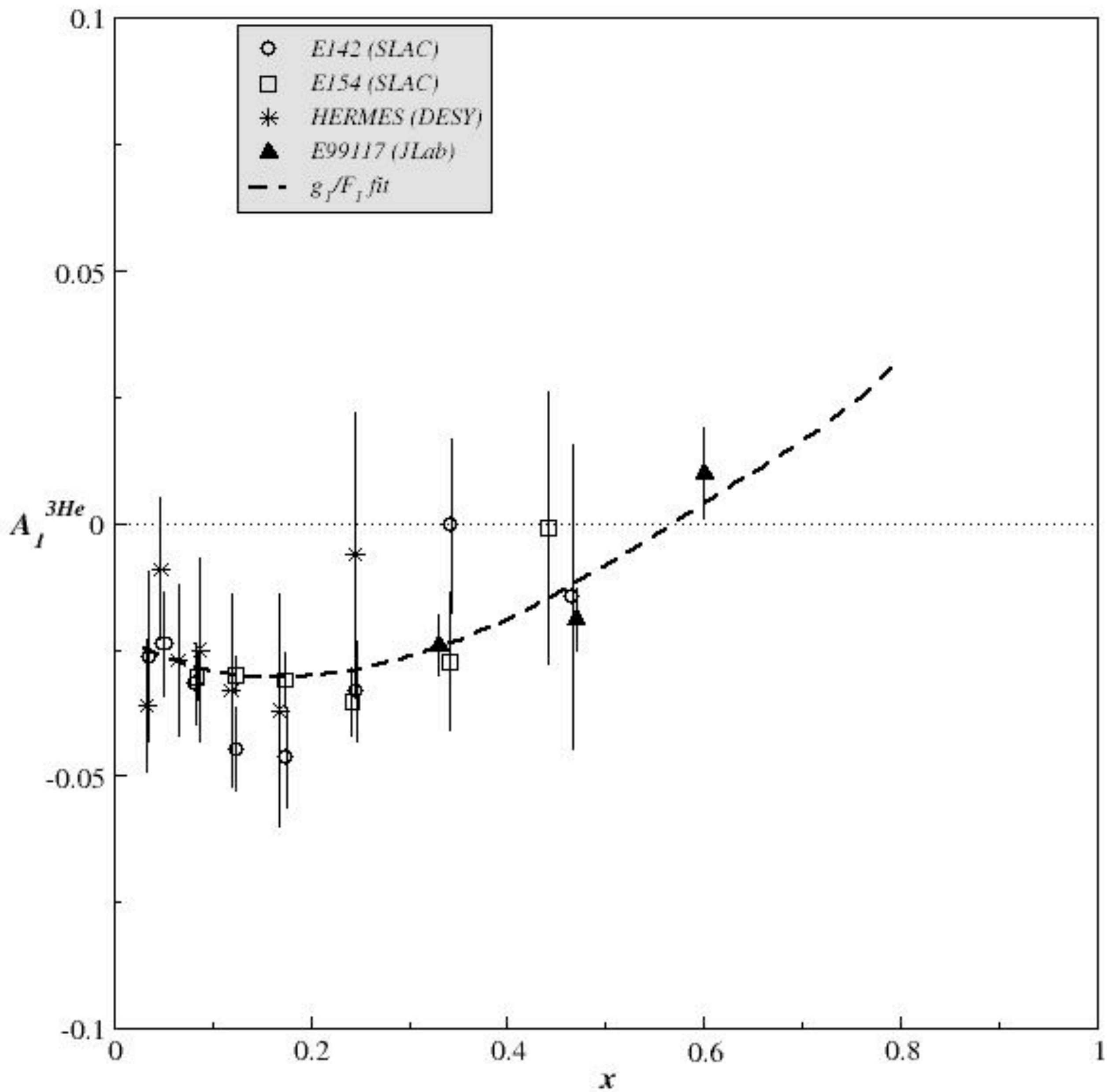
If Q^2 dependence similar for g_1 and for $F_1 \Rightarrow$ weak Q^2 dependence of A_1

$A_1^{3}He$



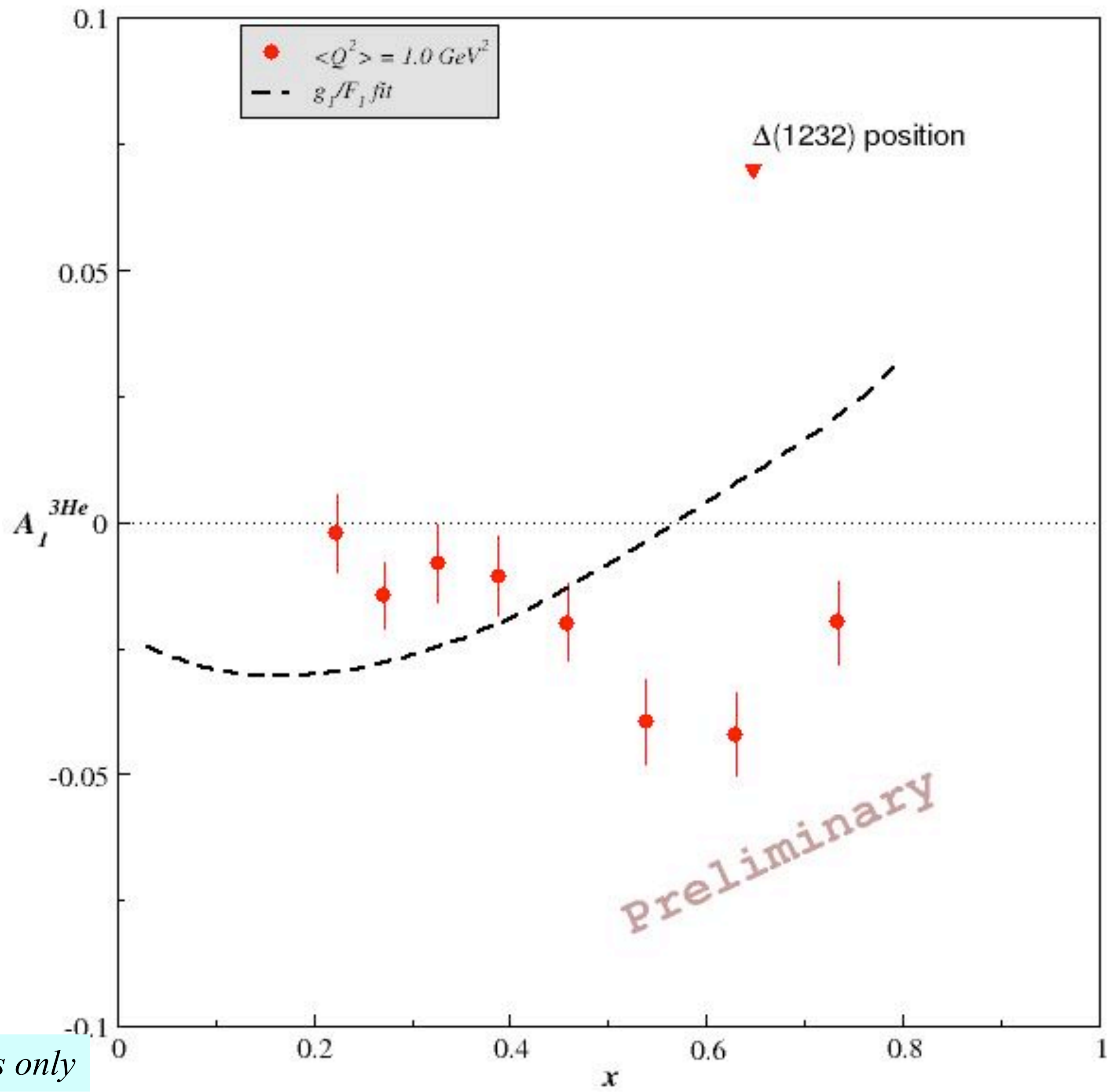
E142 (SLAC)
E154 (SLAC)
HERMES (DESY)
E99117 (JLab)
A_1^{3He}
x
0.1
0.05
0
-0.05
-0.1
0
0.2
0.4
0.6
0.8
1

A_1^{3He}



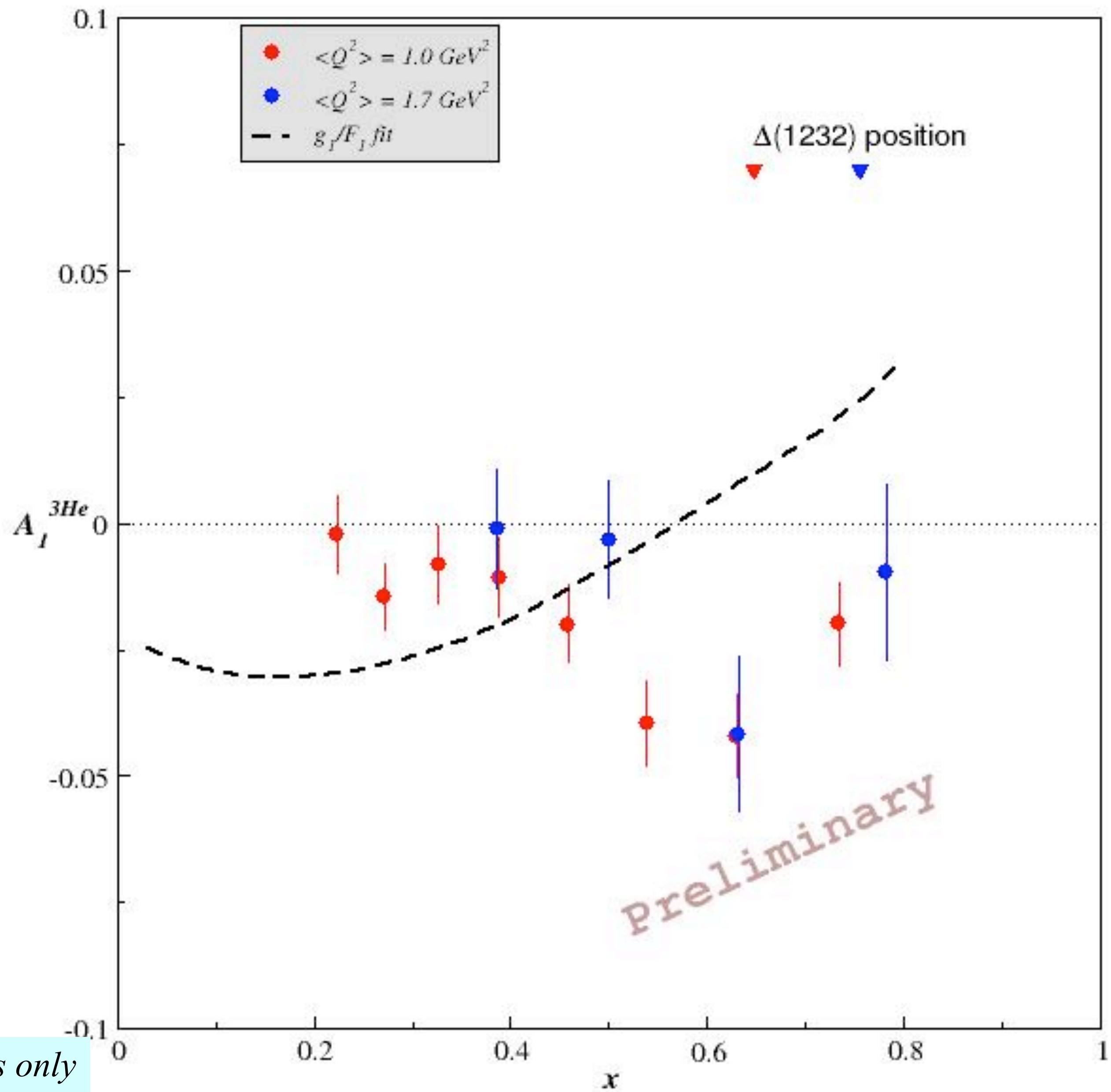
E142 (SLAC)
E154 (SLAC)
HERMES (DESY)
E99117 (JLab)
g1/F1 fit
A1 3He
0.1
0.05
0
-0.05
-0.1
0
0.2
0.4
0.6
0.8
1
x

$A_1^{\,3}He$



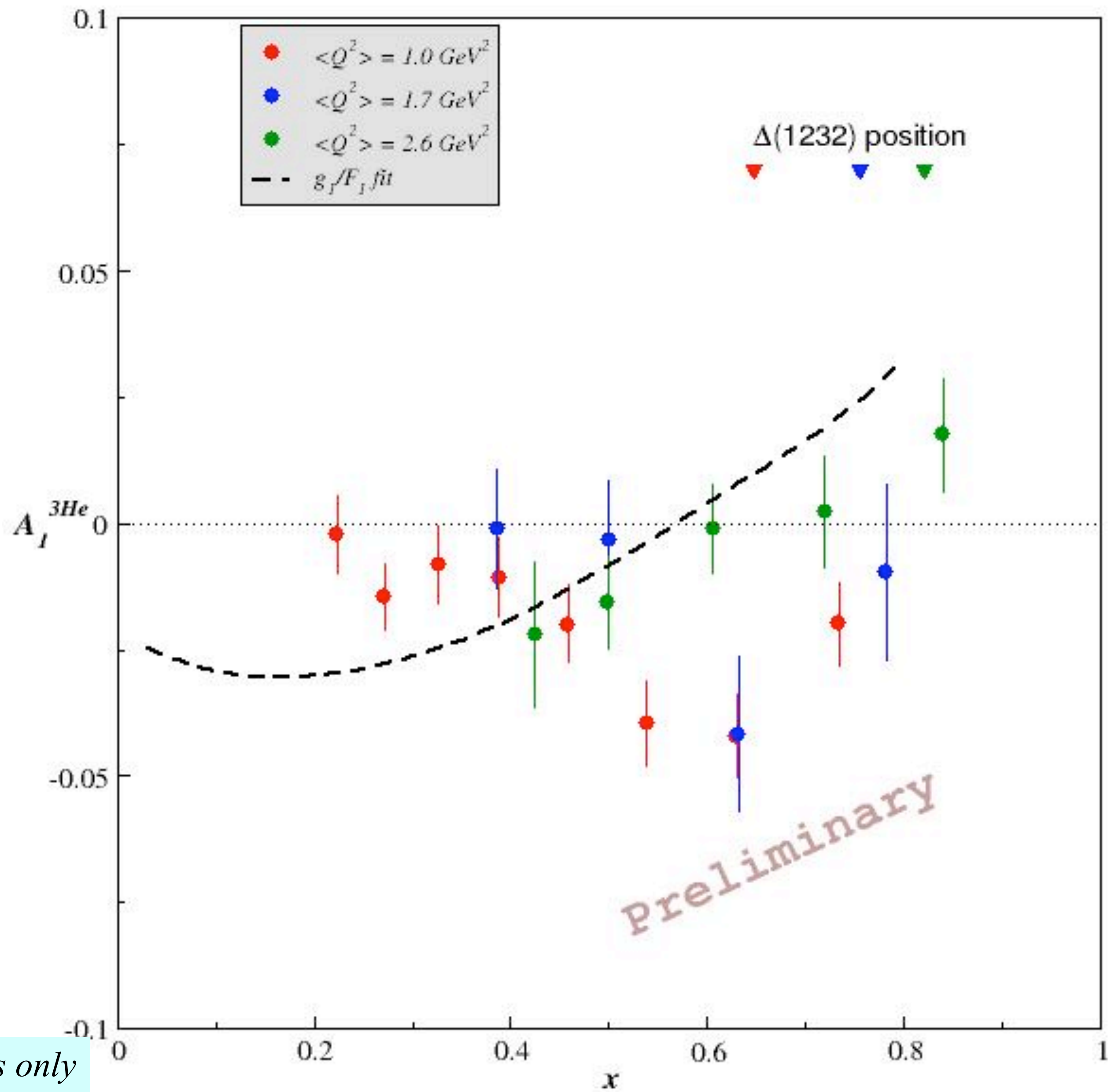
Statistical errors only

$A_1^{3}He$



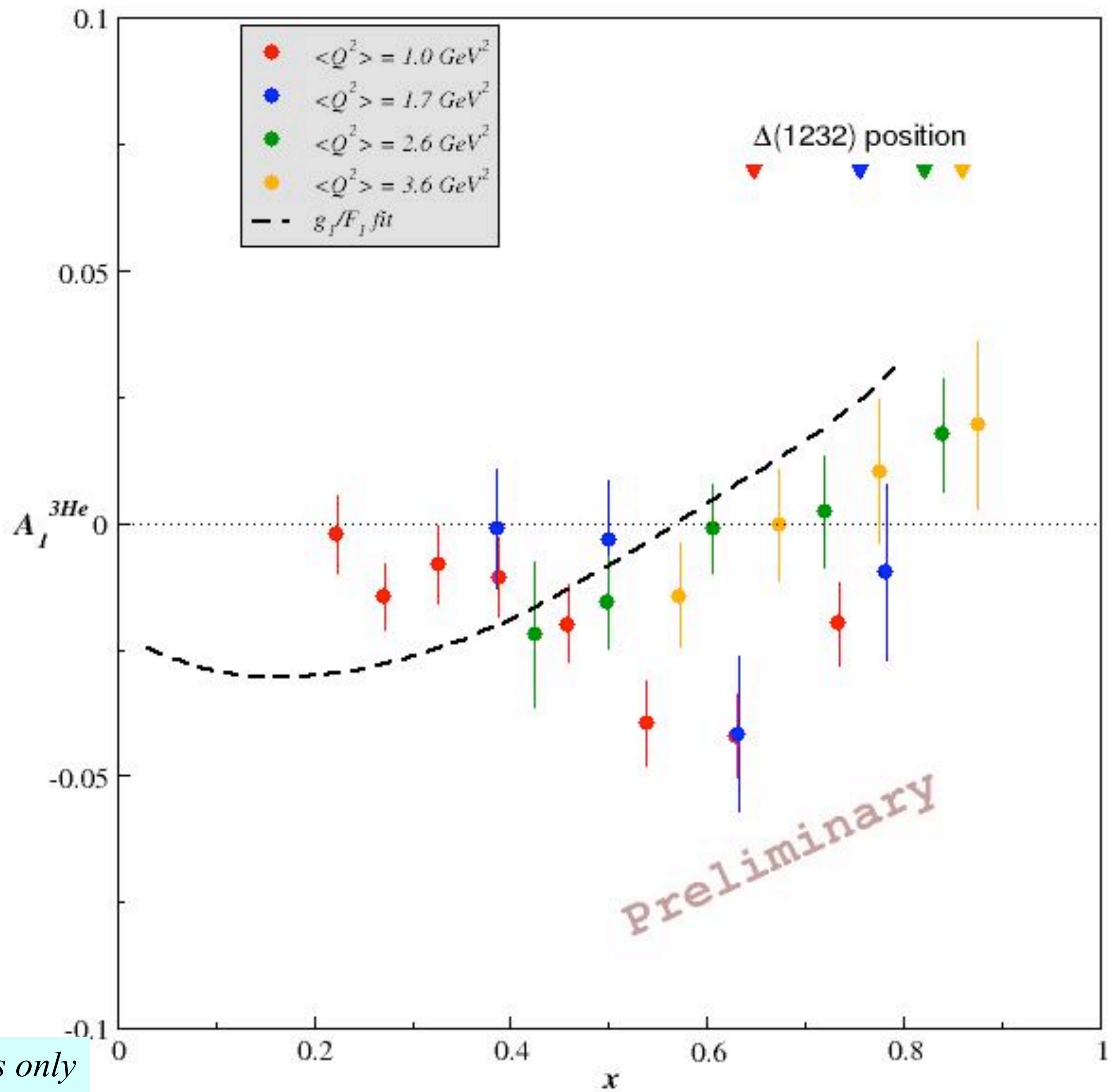
Statistical errors only

$A_1^{3}He$



Statistical errors only

$A_1^{3}He$



Statistical errors only

Summary

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

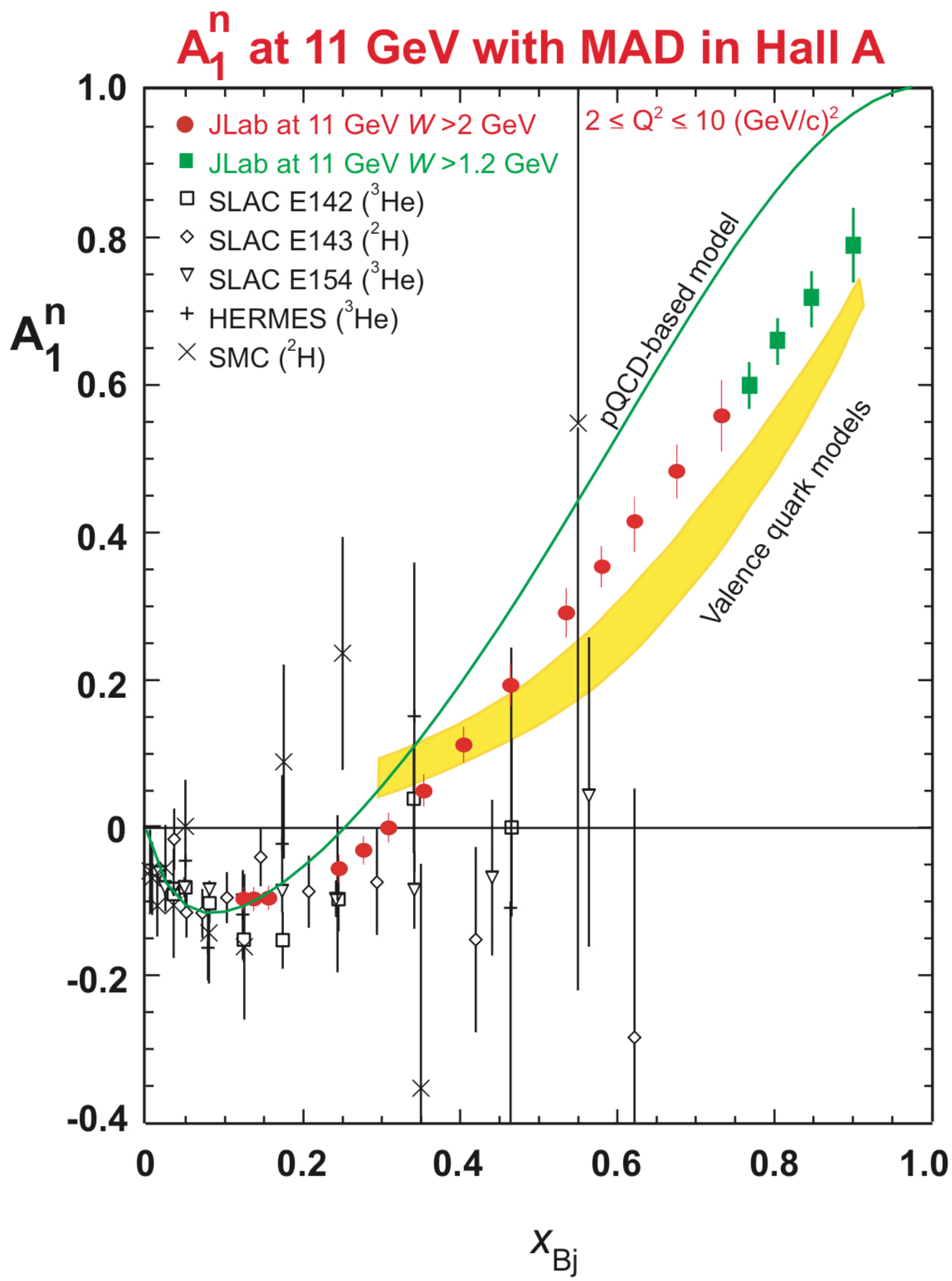
- Direct extraction of g_1 and g_2 from our data

- Overlap between E01-012 resonance data and DIS data
→ First precise test of Quark-Hadron Duality for neutron and nuclei SSF
→ Global duality seems to work for g_1 for all our Q^2
→ Too early to draw conclusions on duality in 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

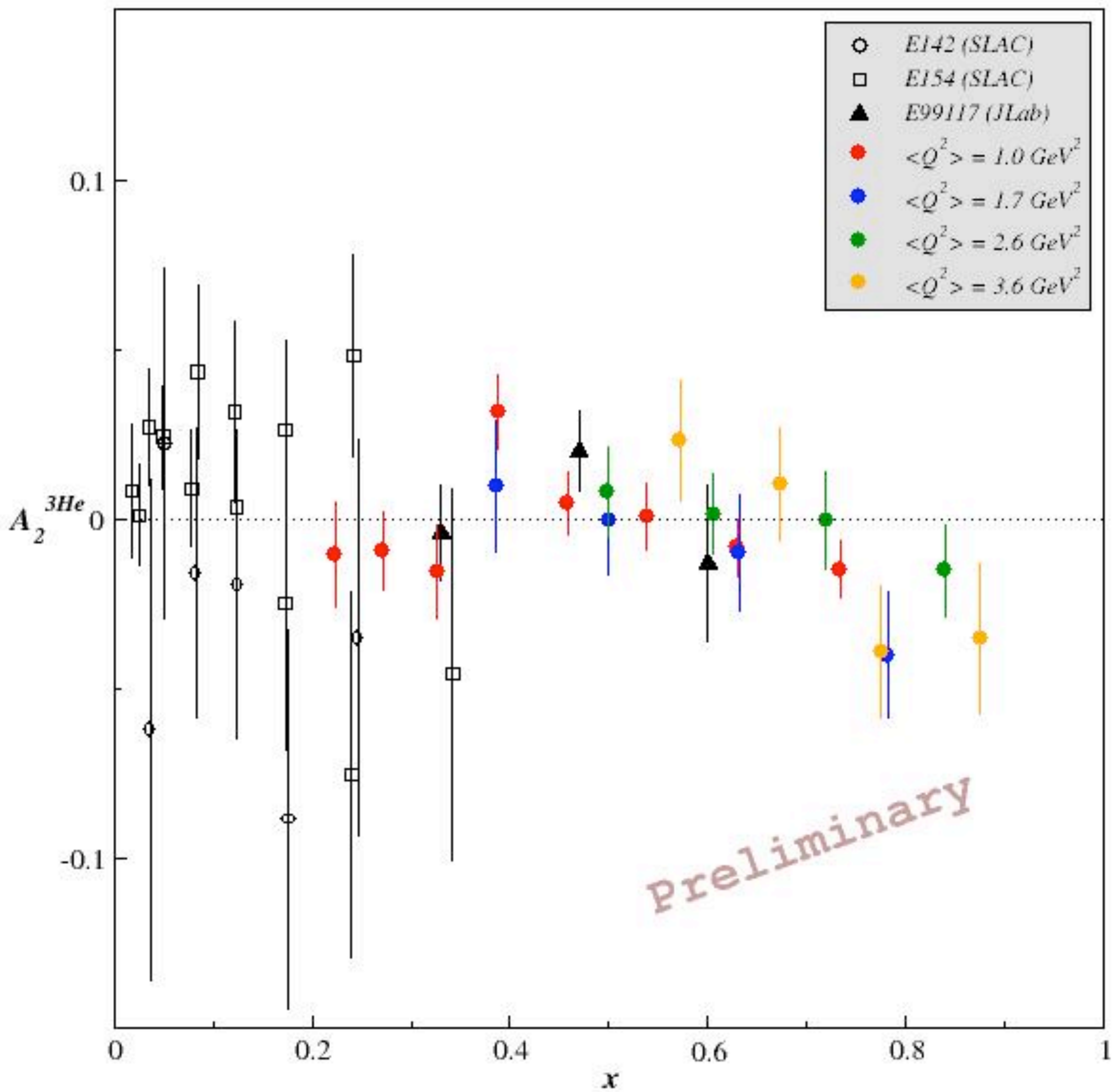


Extra Slides

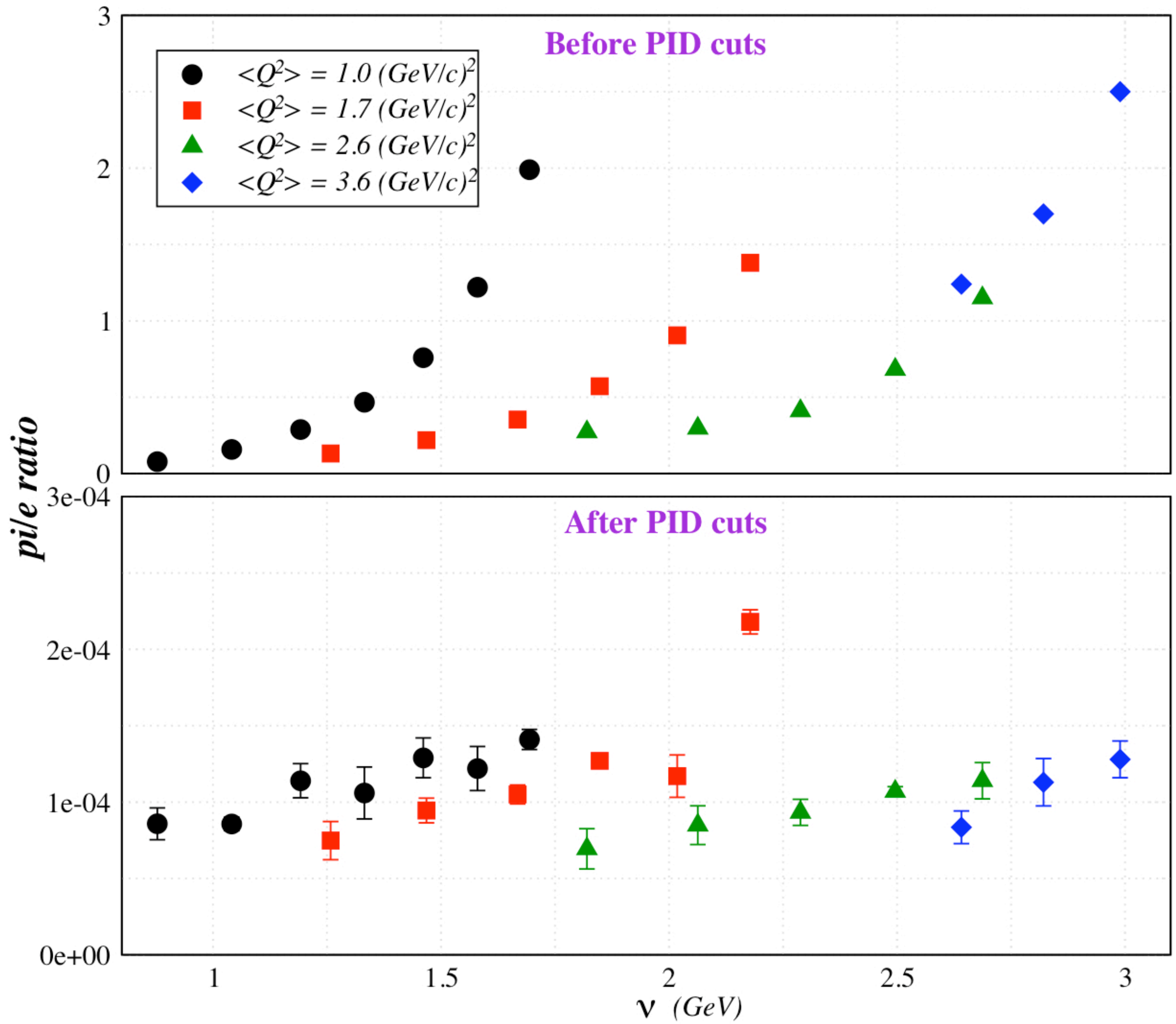
Systematics

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	?

A_2^{3He}

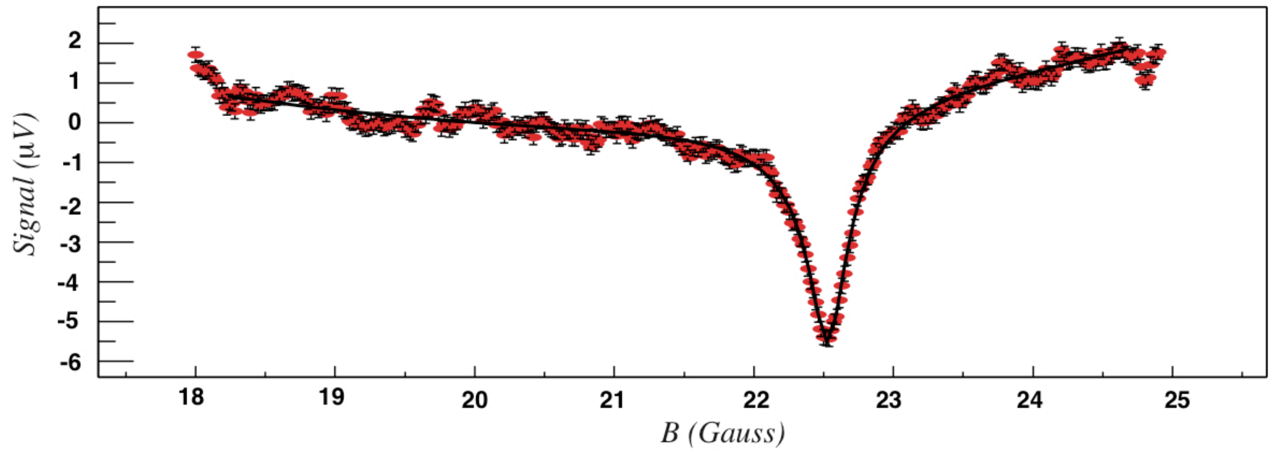

E142 (SLAC)
E154 (SLAC)
E99117 (JLab)
<Q^2> = 1.0 GeV^2
<Q^2> = 1.7 GeV^2
<Q^2> = 2.6 GeV^2
<Q^2> = 3.6 GeV^2
A_2^{3He}
0.1
0
-0.1
0
0.2
0.4
0.6
0.8
1
x
Preliminary

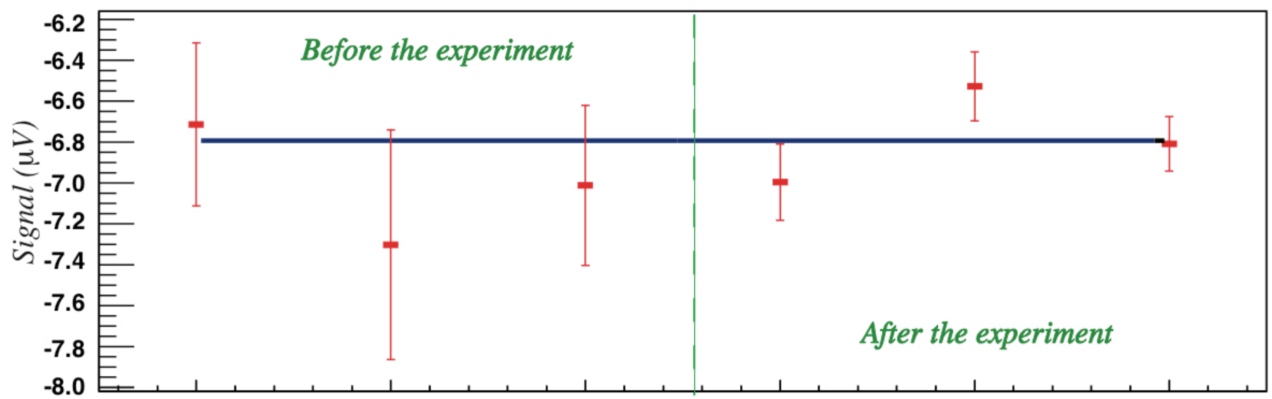
Particle identification performance



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

NMR: water calibration

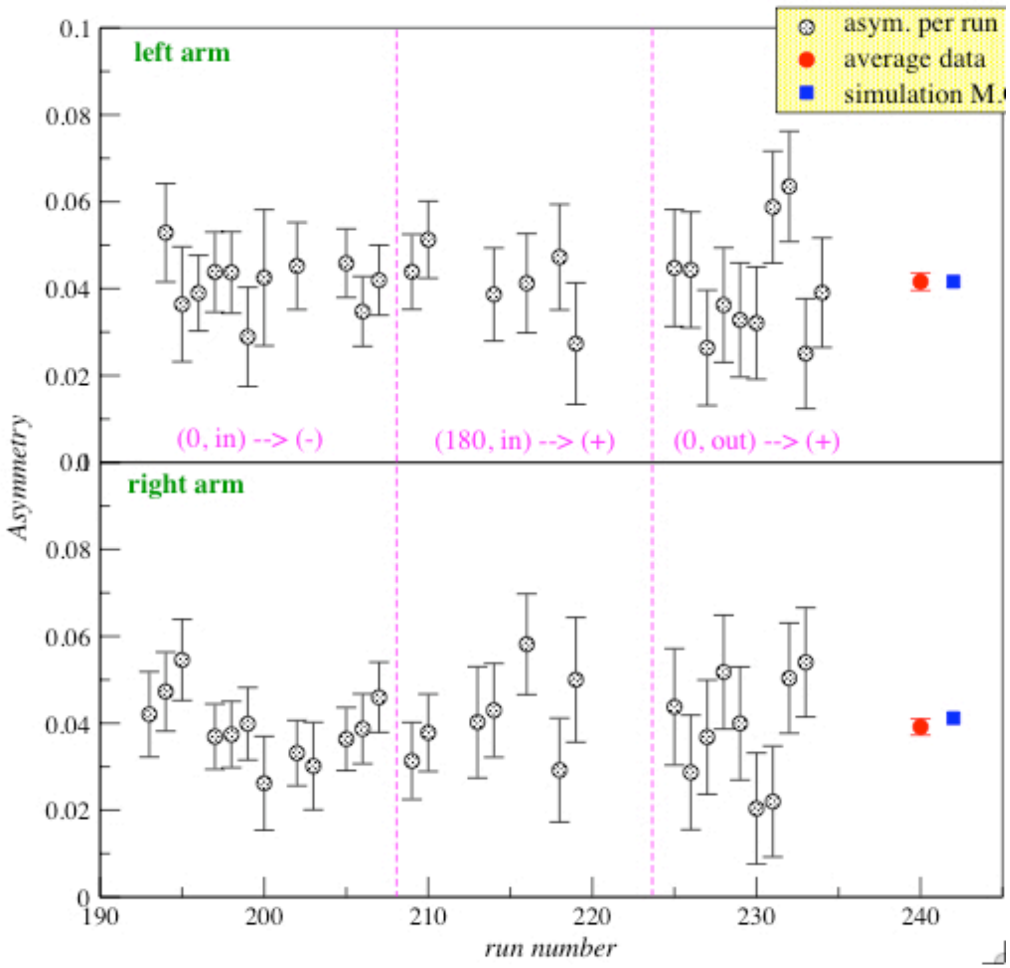




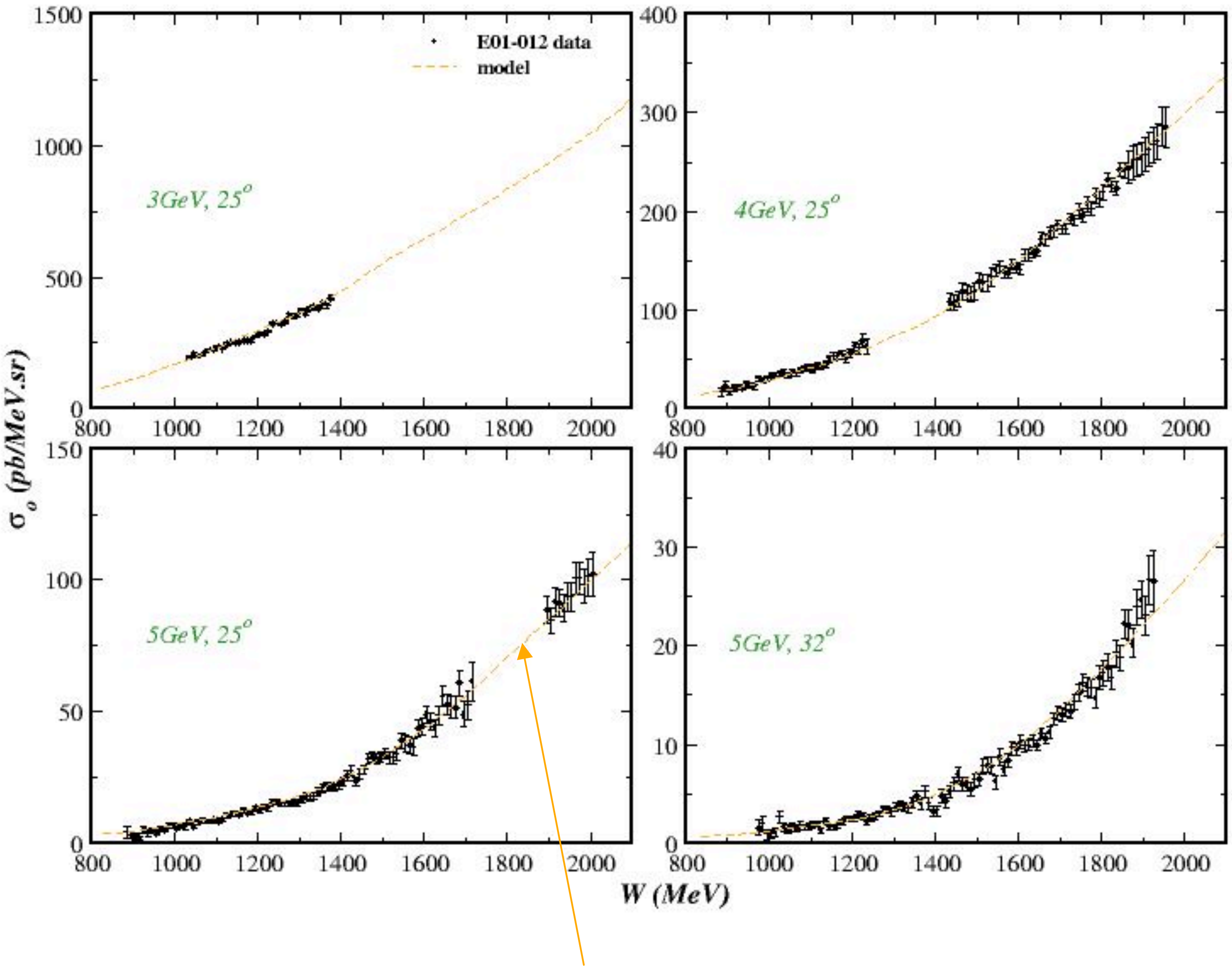
NMR analysis done by Vince Sulkosky

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