

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

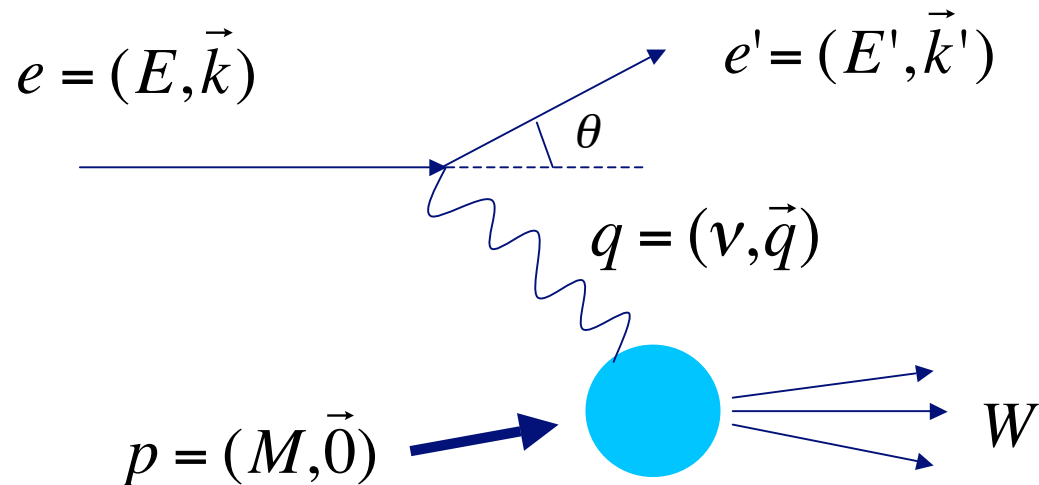
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Temple University

Nuclear Physics Seminar
University of Illinois at Urbana-Champaign
March 8, 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



Photon momentum transfer

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

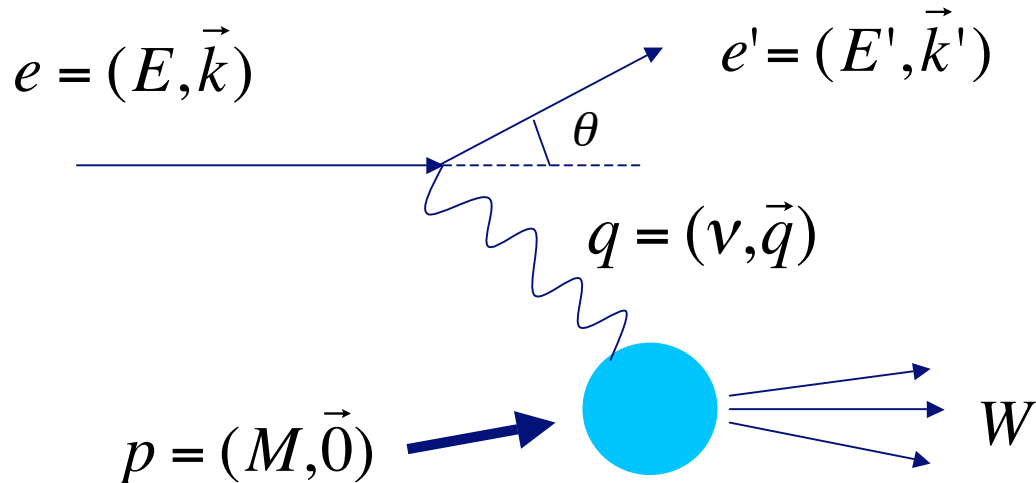
Invariant mass squared

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

Bjorken variable

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

Inclusive Electron Scattering



Photon momentum transfer

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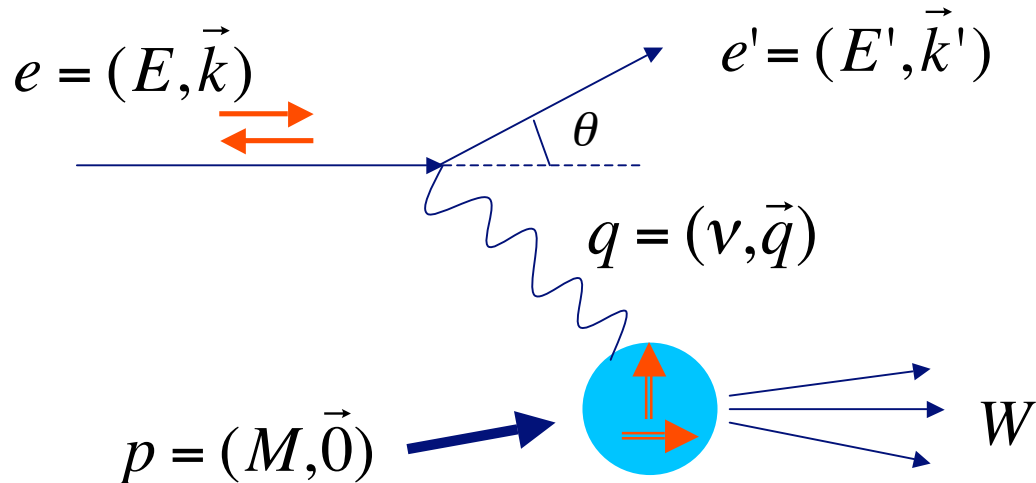
$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable

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

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

Inclusive Electron Scattering



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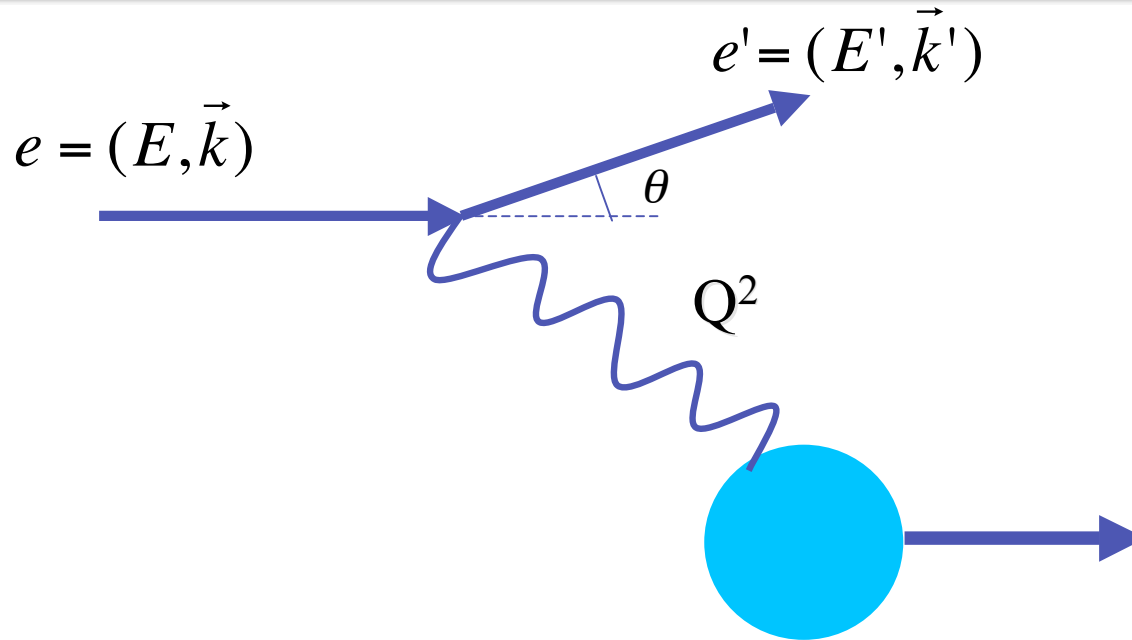
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Polarized case $\left\{ \begin{aligned} \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\uparrow}}{d\Omega dE'} &= \frac{4\alpha^2 E'}{\nu EQ^2} \left[(E + E' \cos \theta) g_1(x, Q^2) - 2Mx g_2(x, Q^2) \right] \\ \frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} &= \frac{4\alpha^2 E'}{\nu EQ^2} \sin \theta \left[g_1(x, Q^2) + \frac{2ME}{\nu} g_2(x, Q^2) \right] \end{aligned} \right.$

Resonance region

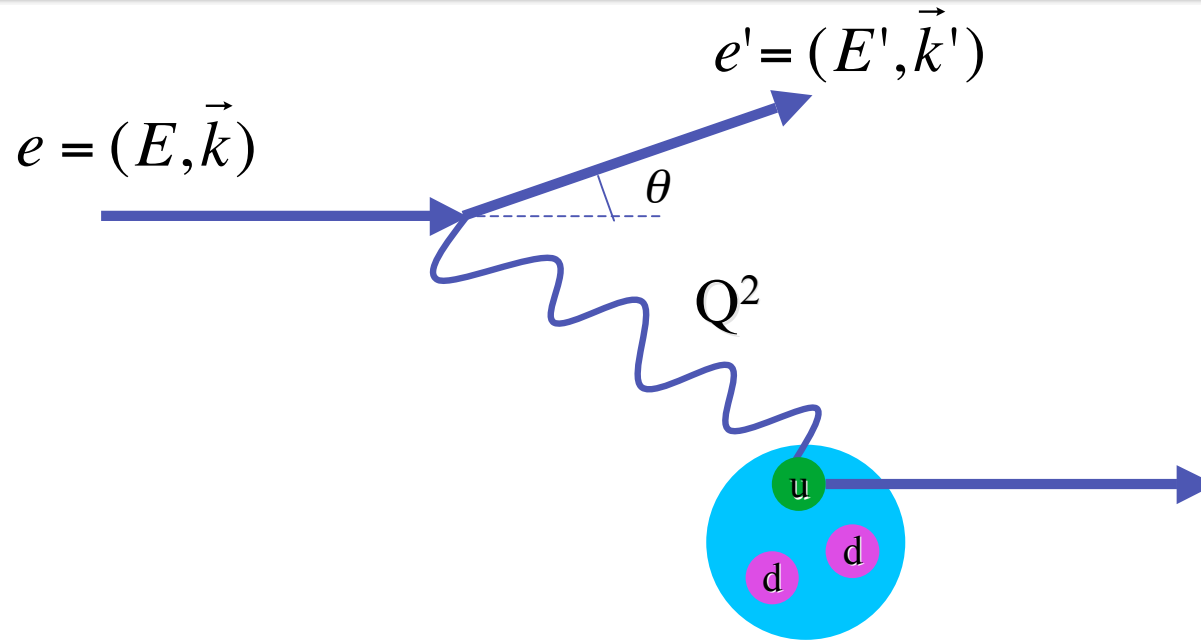


Low Q^2 and $W < 2 \text{ GeV}$: coarse resolution \rightarrow we don't see structure.



The nucleon goes through different excited states:
the resonances

Deep Inelastic Scattering



High Q^2 and $W > 2\text{GeV}$: fine resolution \rightarrow we see partons



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

Scaling of F_2

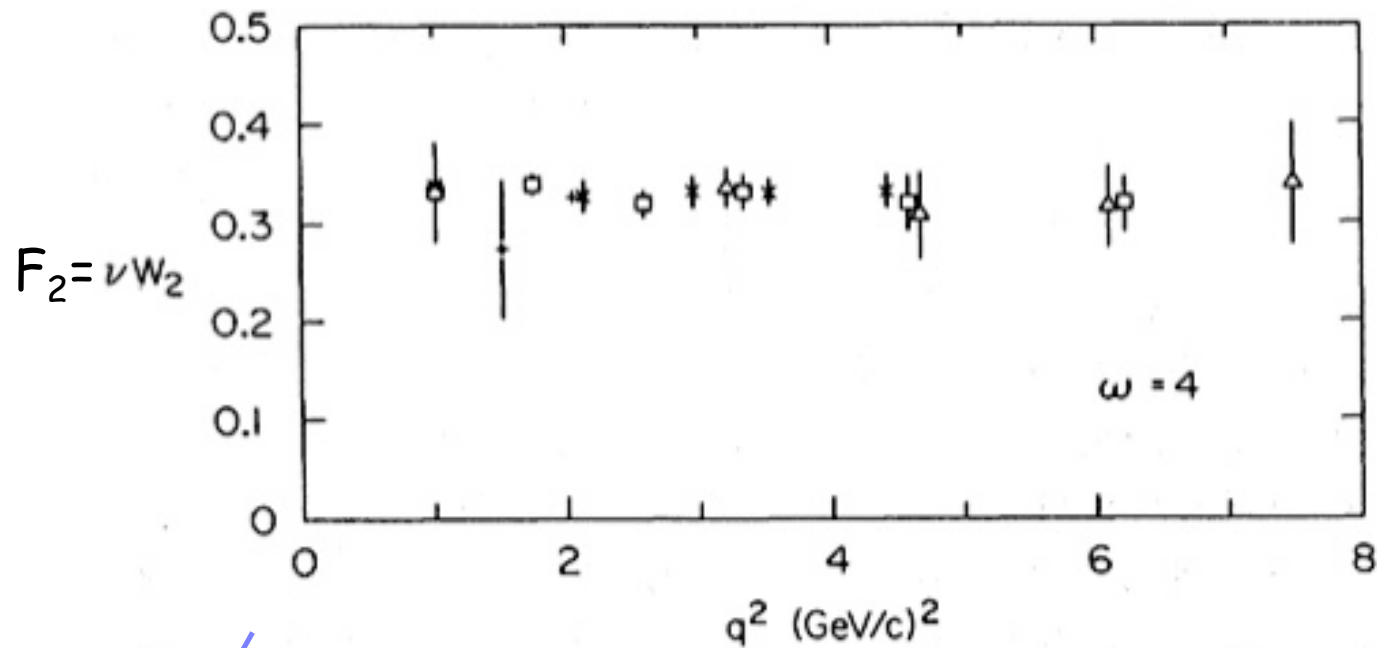


Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

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: $\sigma_{\text{Nucleon}} = \sum_i \sigma_i$

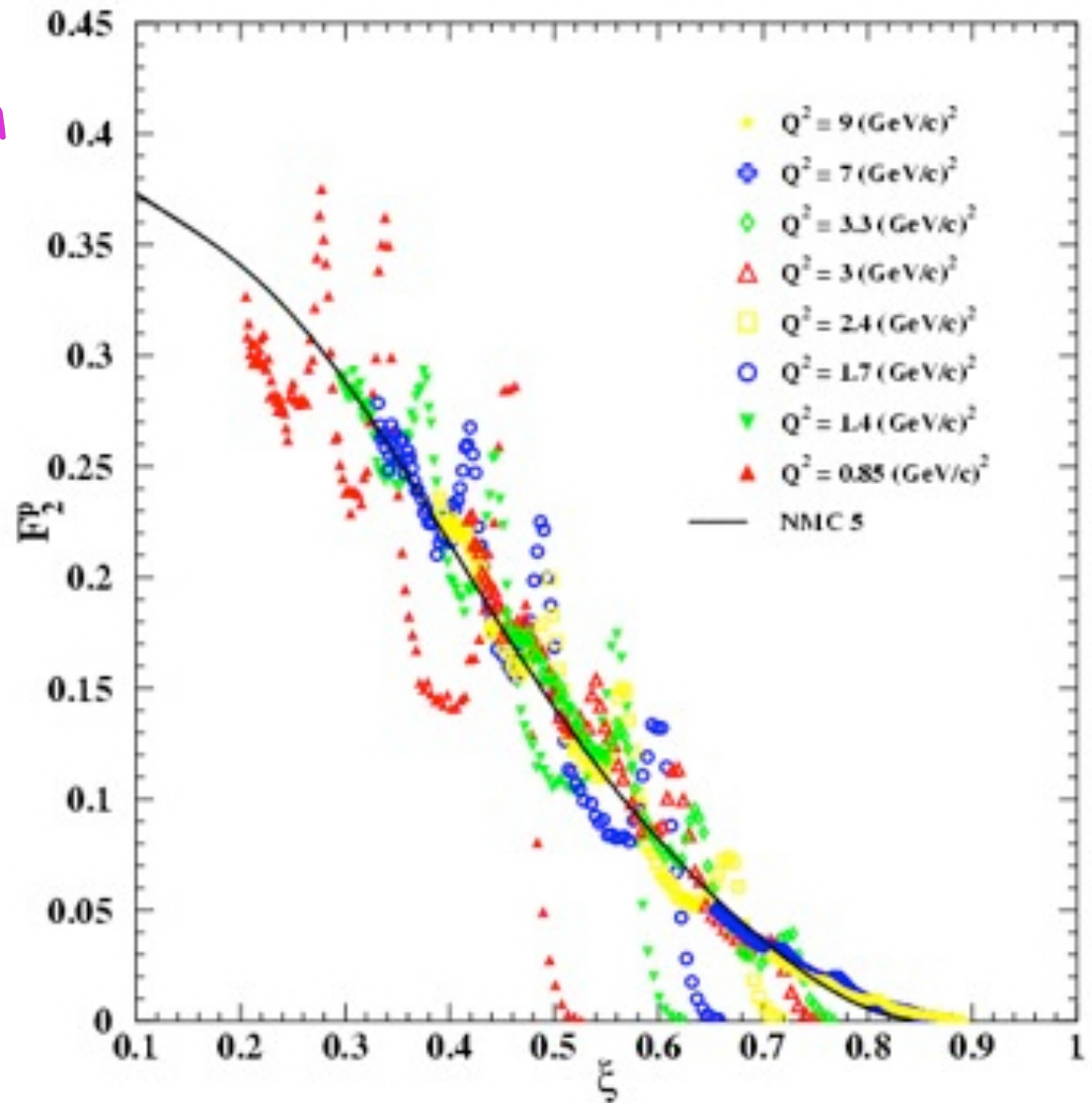
$$F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) + q_i^\downarrow(x)] = \frac{1}{2x} F_2(x)$$

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

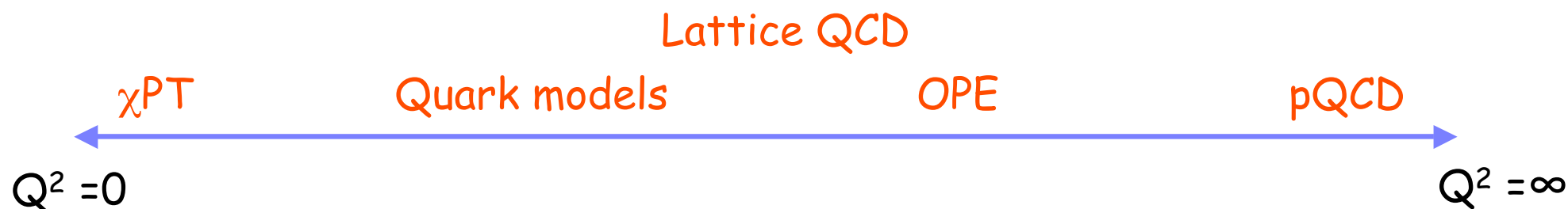
No simple partonic distribution for $g_2(x, Q_2)$

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



Theoretical interpretations



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:

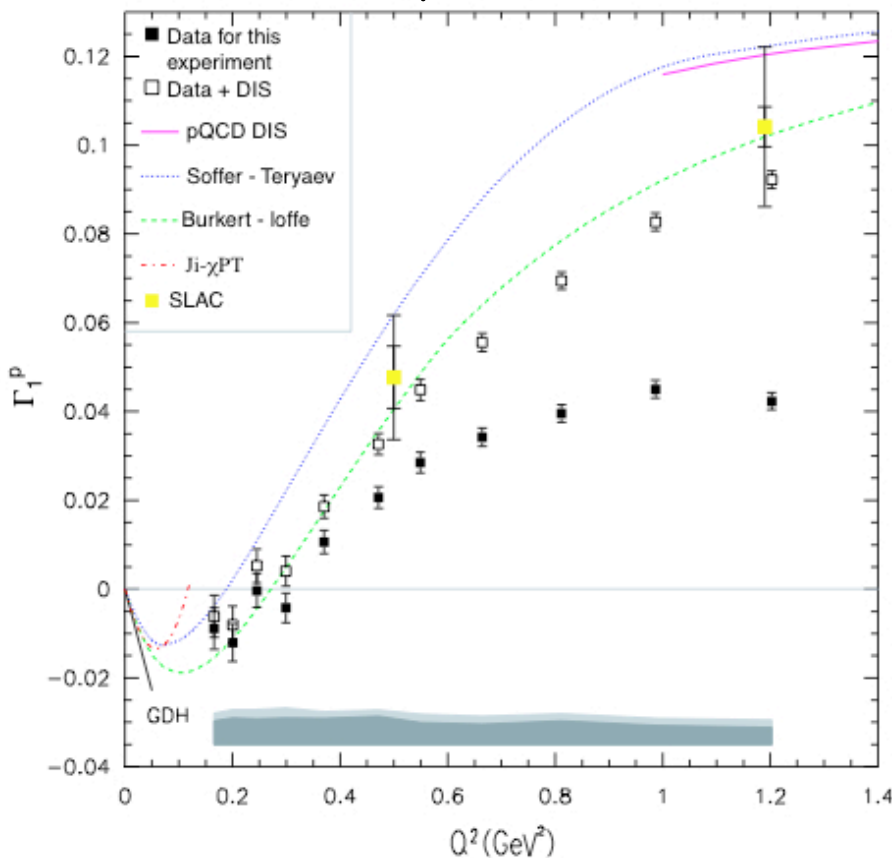
- spin-3/2
- helicity-3/2
- symmetric wave function

Scaling of g_1 moments

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

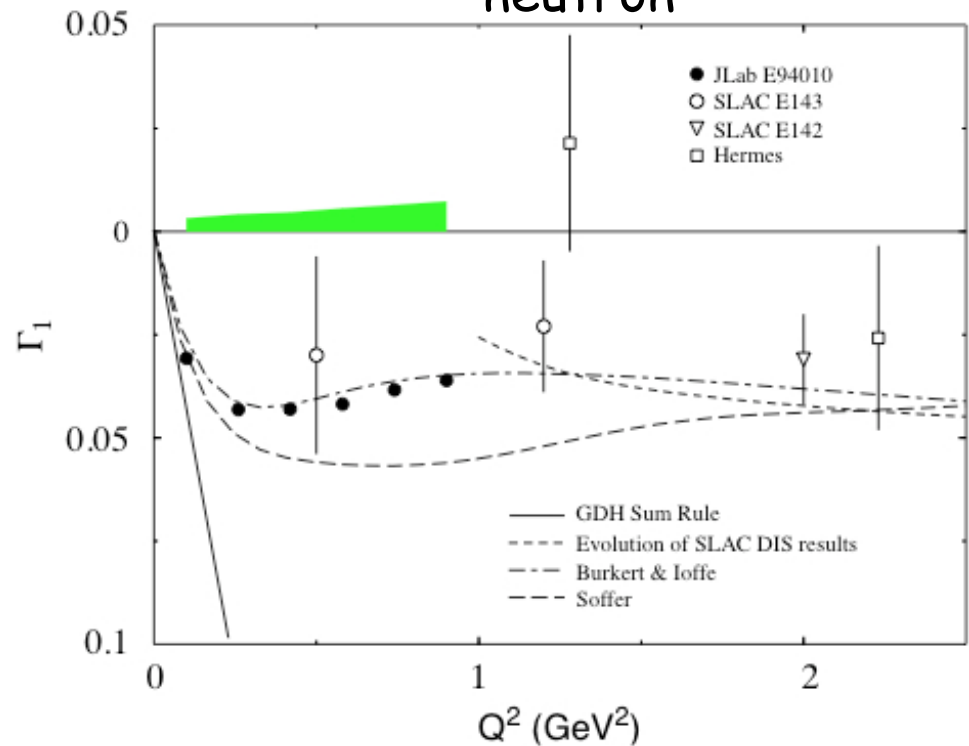
$$\Gamma_1(Q^2) = \int g_1(x, Q^2) dx$$

proton



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

neutron

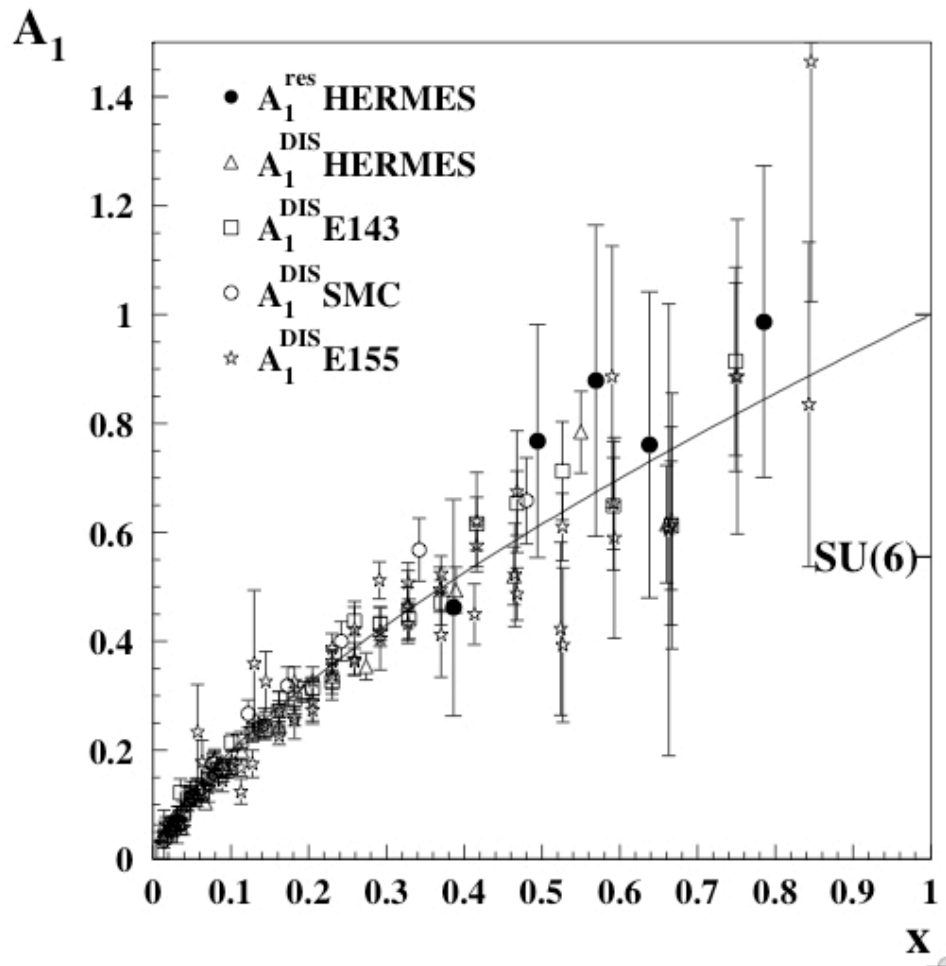


M. Amerian et al., PRL 85(2002) 242301

World data

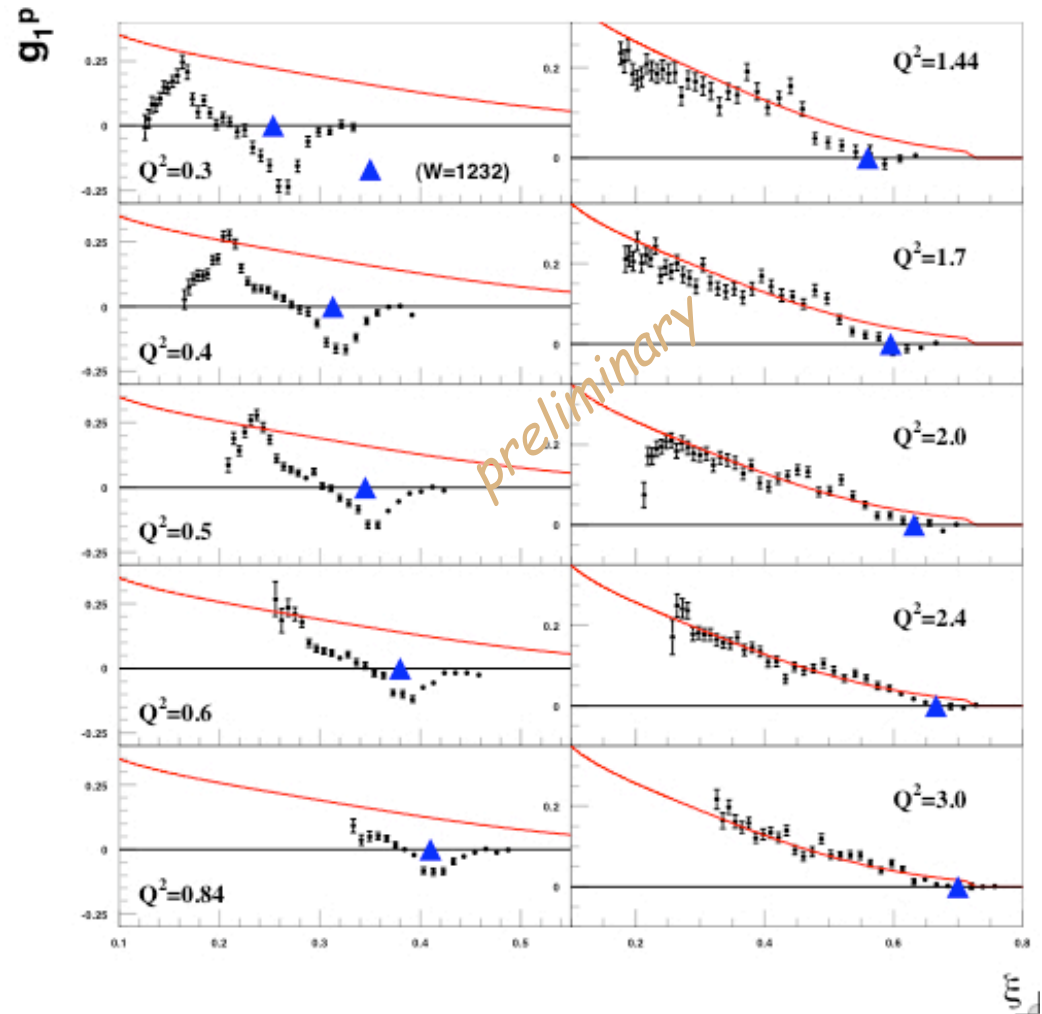
HERMES for A_1^p

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



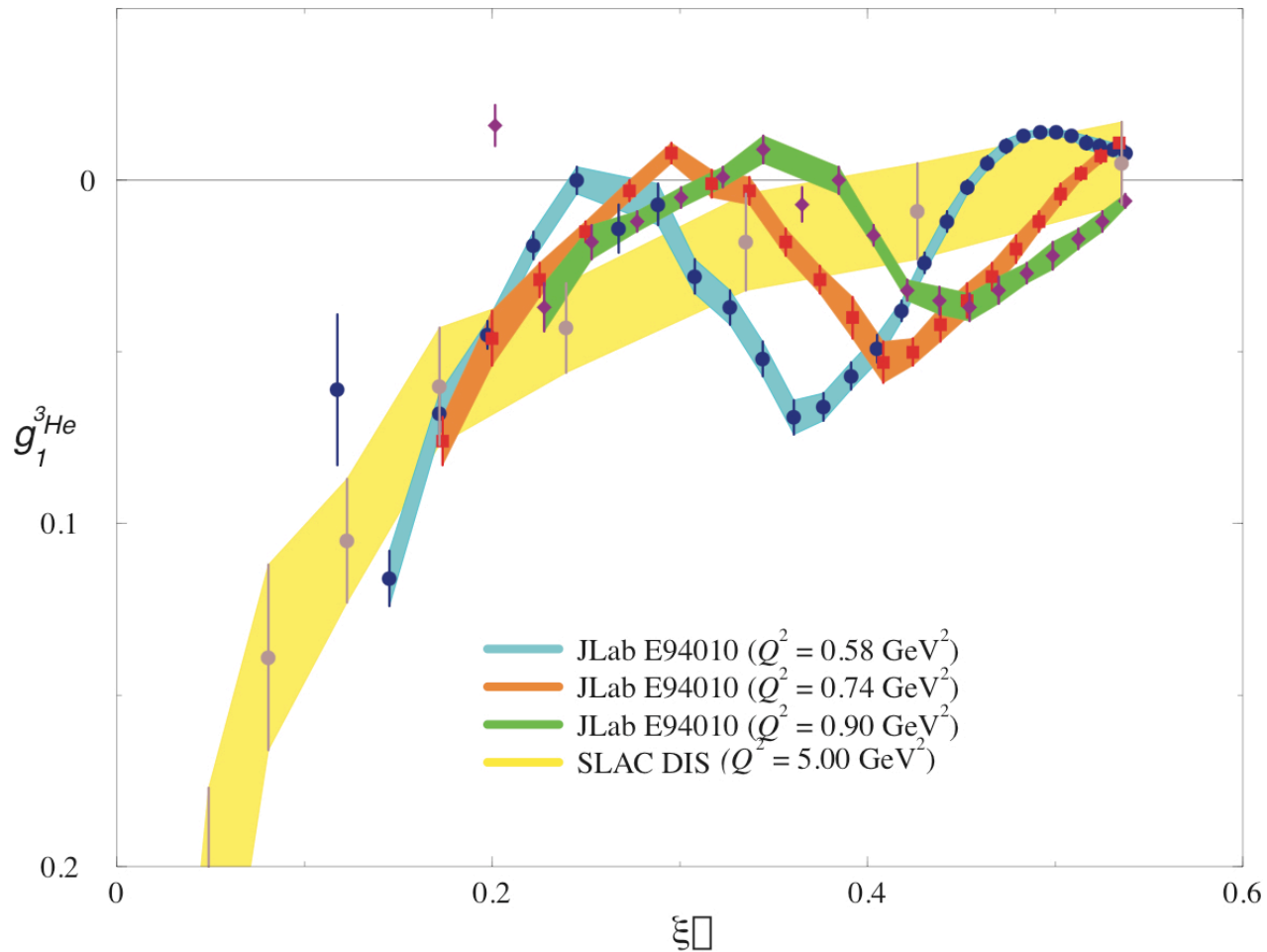
Jlab Hall B for g_1^p

From DIS 2005 proceedings



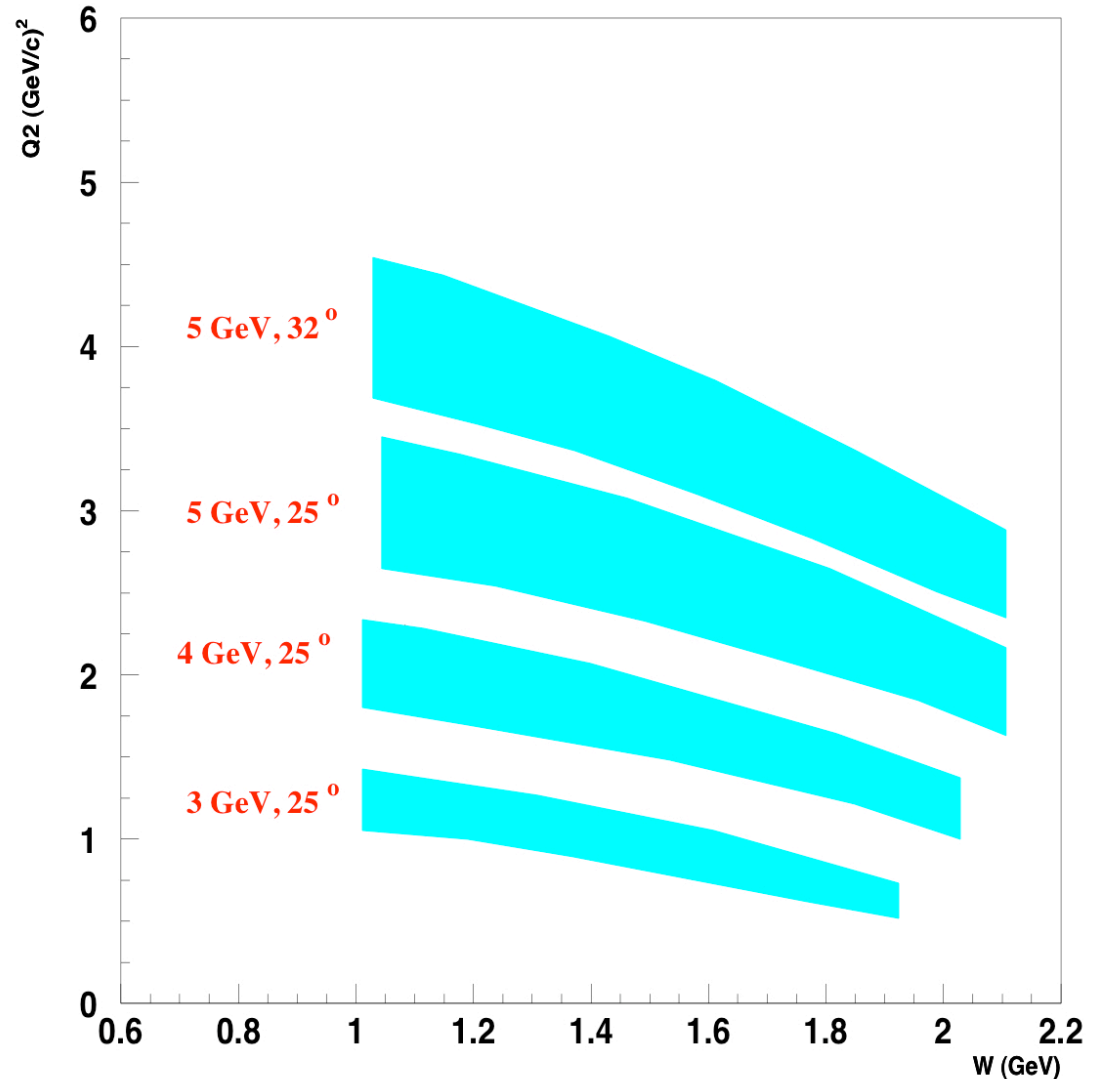
World data

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



The experiment E01-012

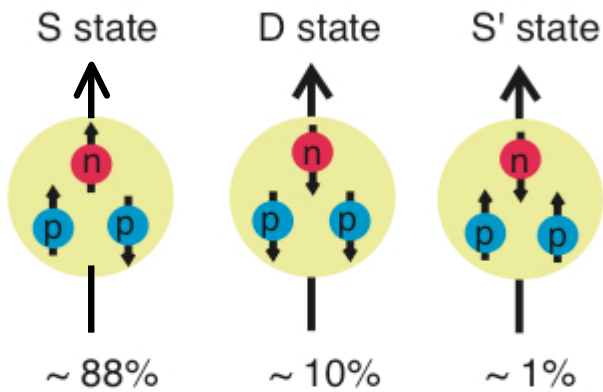
- Ran in Jan.-Feb. 2003
- Inclusive experiment:
 ${}^3\vec{\text{He}}(\vec{e}, e')X$
- Measured polarized cross section differences
- Form g_1 and g_2



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

^3He as an effective neutron target

^3He as neutron target



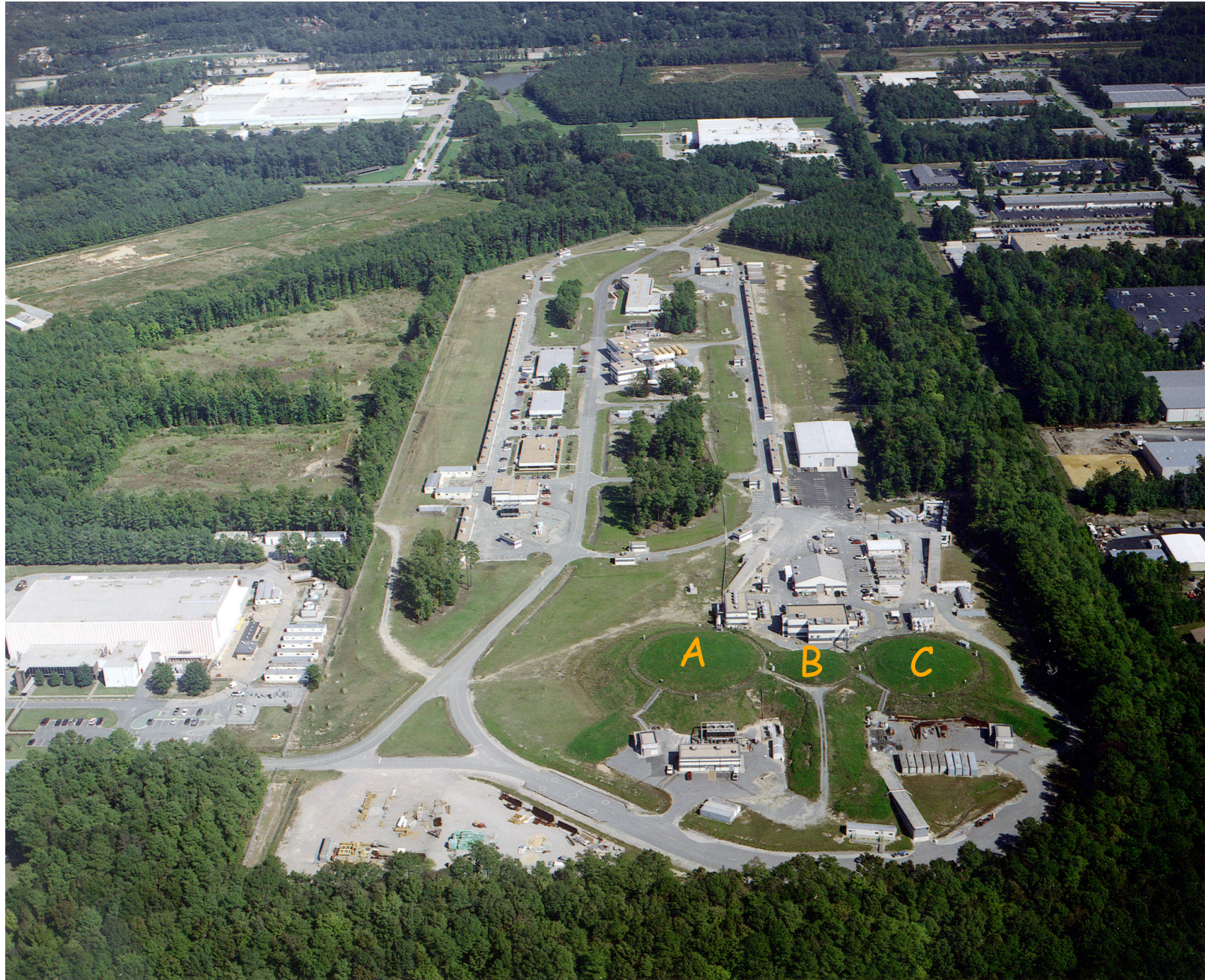
$$R_n = 86\% \text{ and } R_p = -2.8\%$$

The E01-012 Collaboration

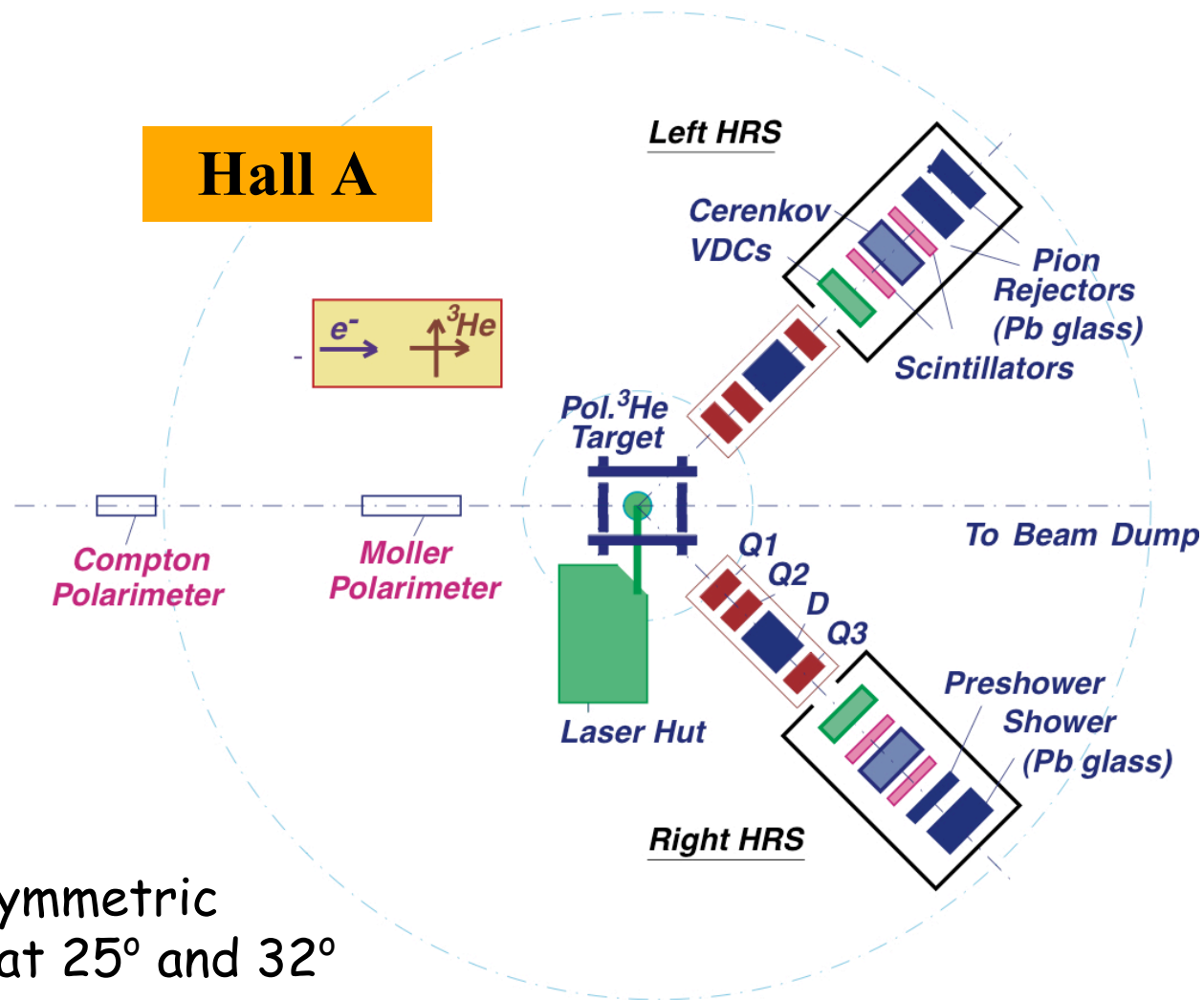
K. Aniol, T. Averett, W. Boeglin, A. Camsonne, G.D. Cates, G. Chang, J.-P. Chen, Seonho Choi, E. Chudakov, B. Craver, F. Cusanno, A. Deur, D. Dutta, R. Ent, R. Feuerbach, S. Frullani, H. Gao, F. Garibaldi, R. Gilman, C. Glashausser, O. Hansen, D. Higinbotham, H. Ibrahim, X. Jiang, M. Jones, A. Kelleher,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

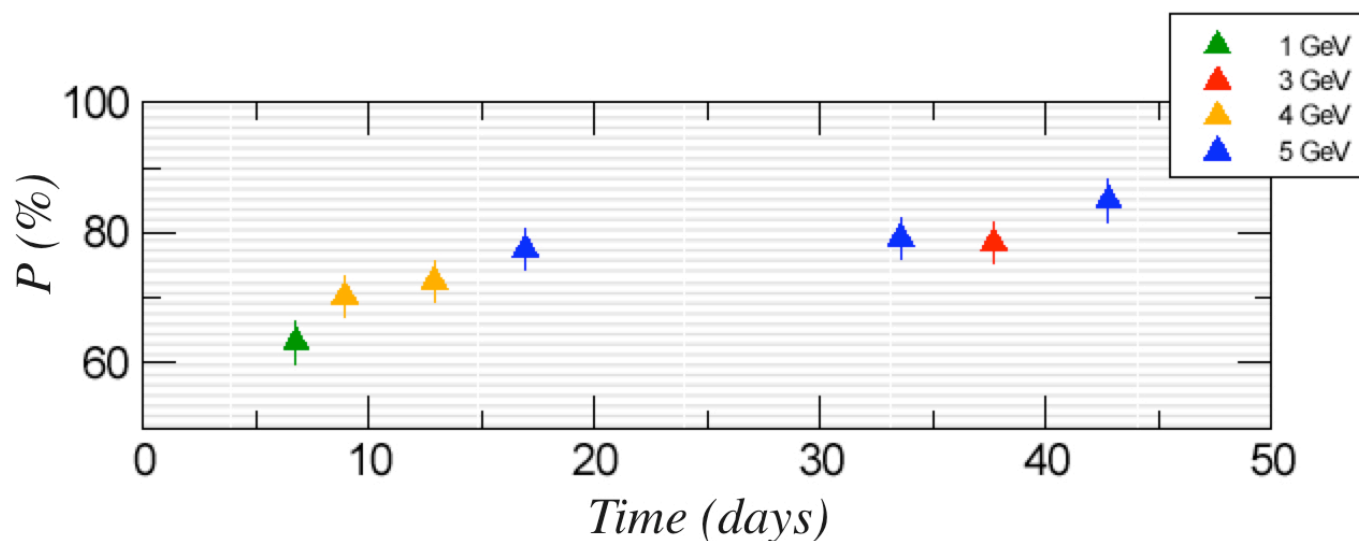
- double the statistics
- control the systematics

Particle ID = Cerenkov + EM calorimeter

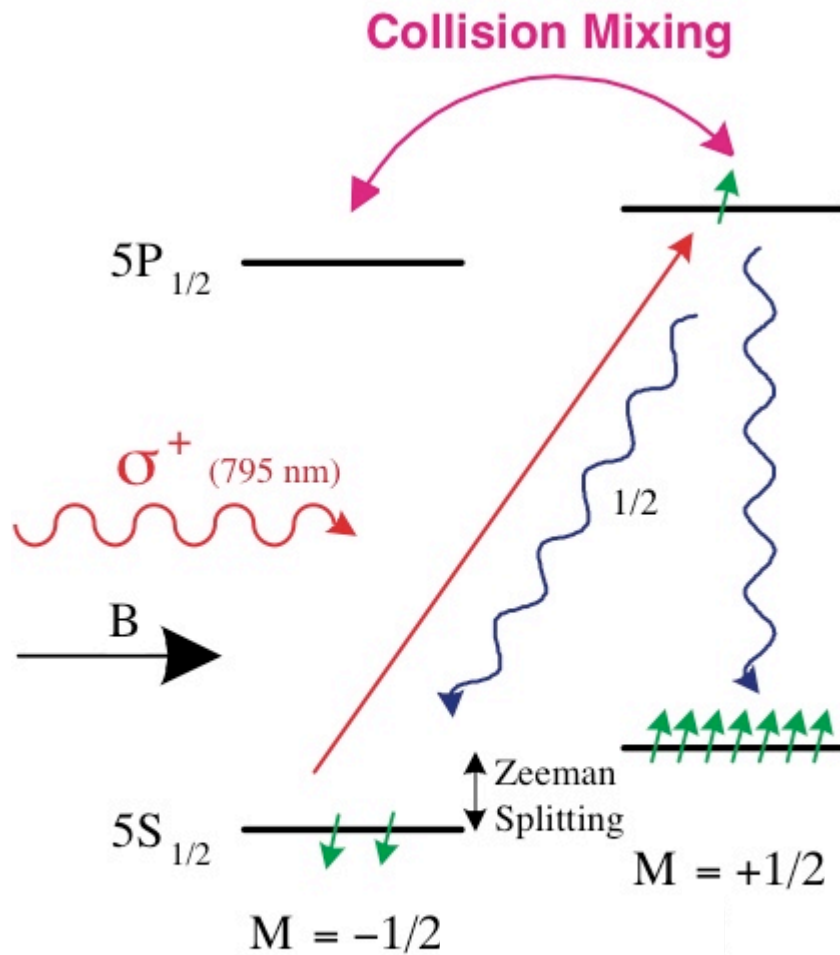
→ π/e reduced by 10^4

Electron Beam Polarization

- ◆ Used Moller Polarimeter: measurements performed by E. Chudakov et al.
- ◆ $70 < P_{\text{beam}} < 85\%$ for production data



How to polarize ^3He ?



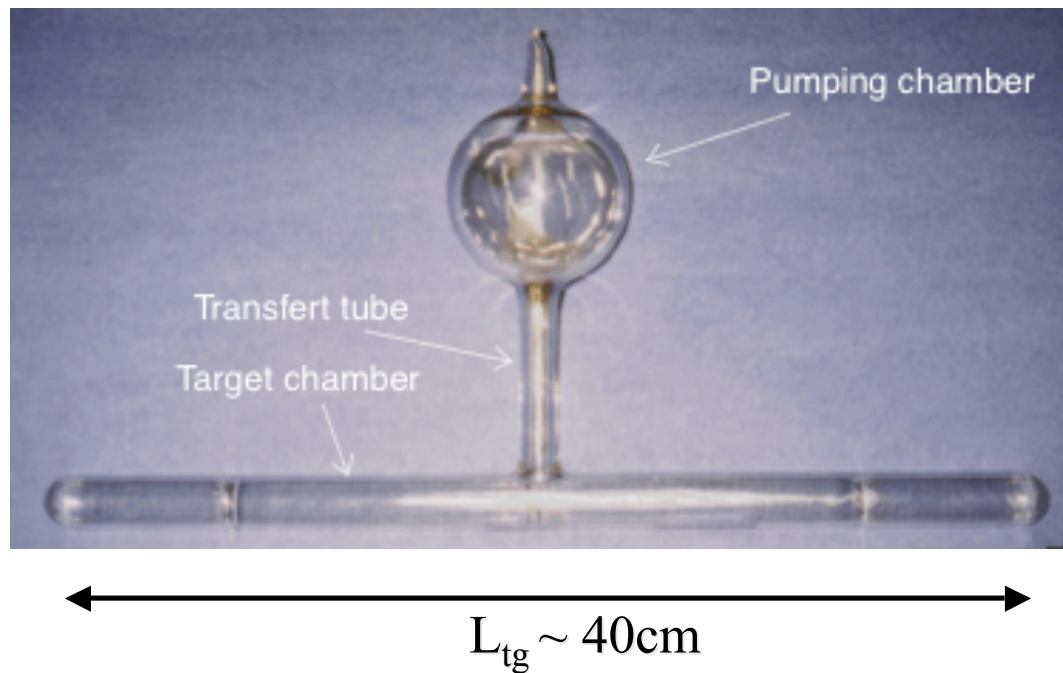
Two step process:

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

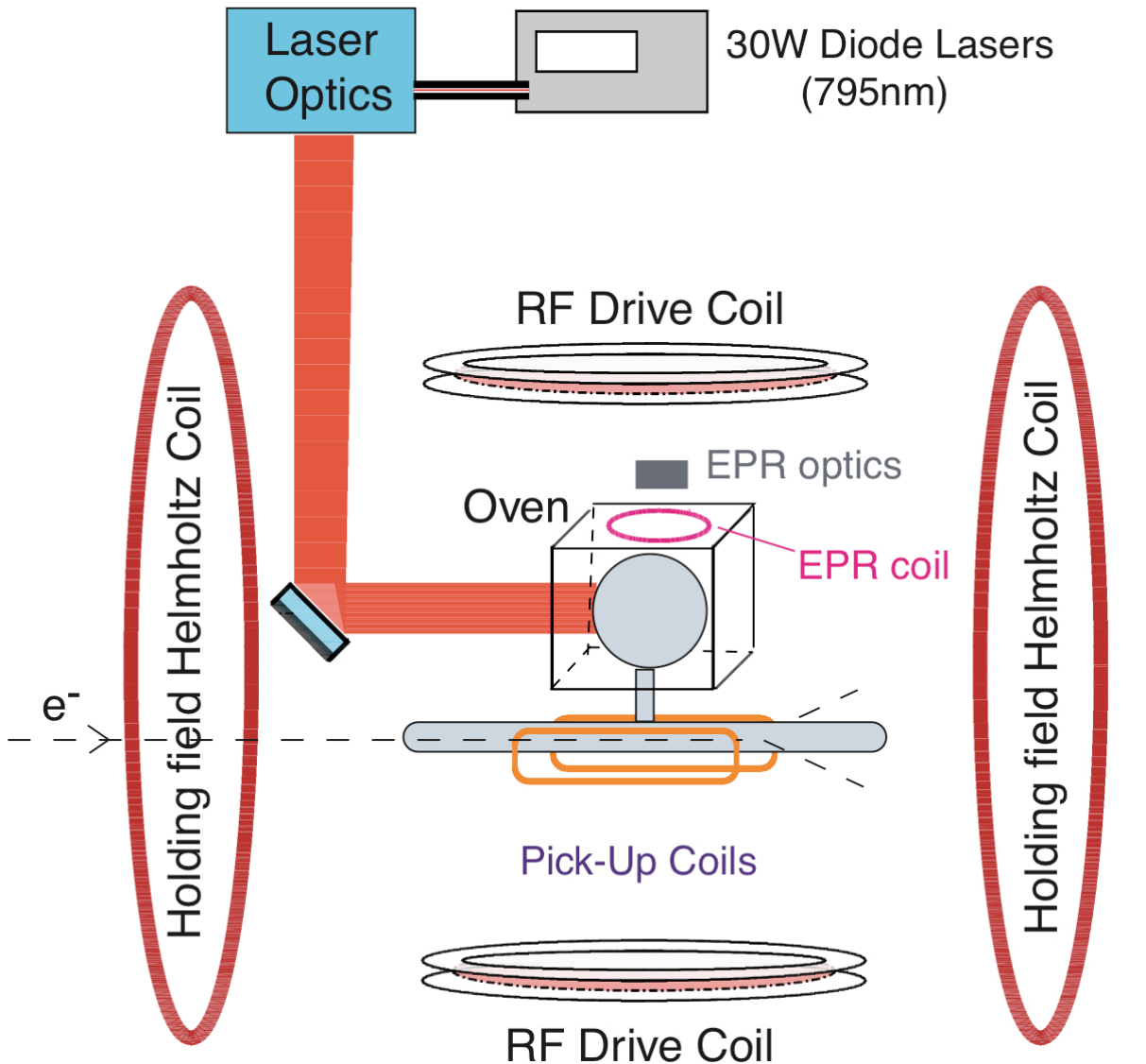
A small amount of N_2 is added for quenching

The polarized ^3He target

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



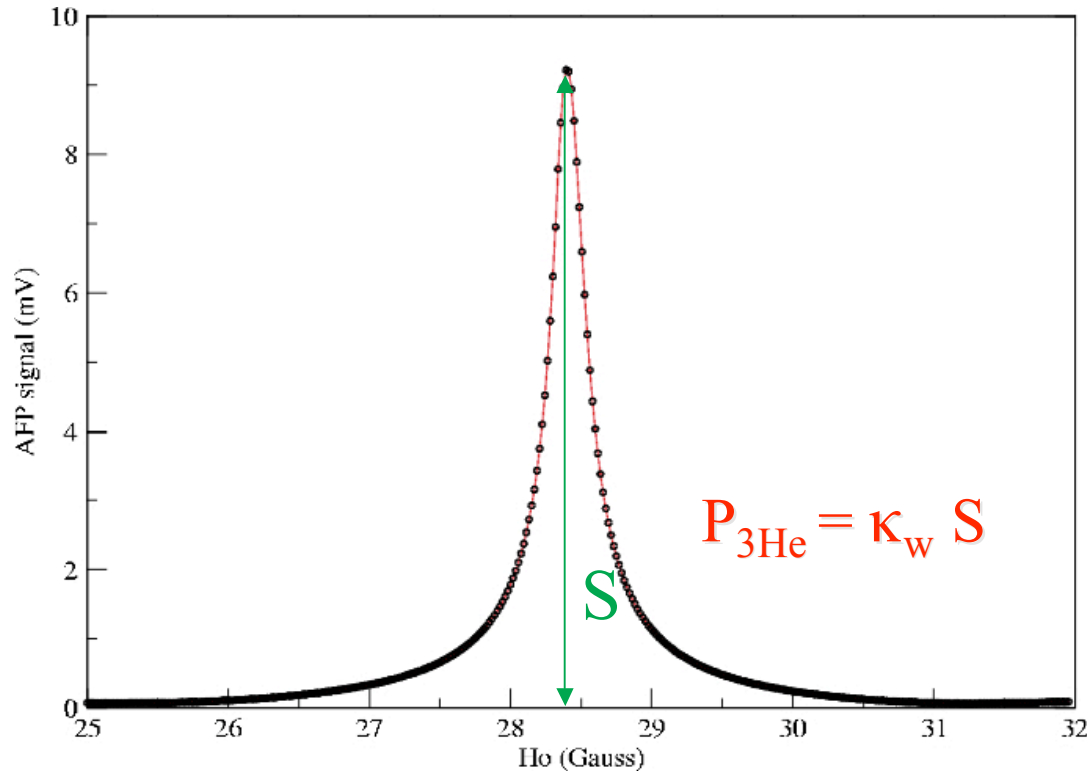
The polarized ^3He system



◆ Longitudinal and transverse configurations

◆ 2 independent polarimetrys:
NMR and EPR

Nuclear Magnetic Resonance



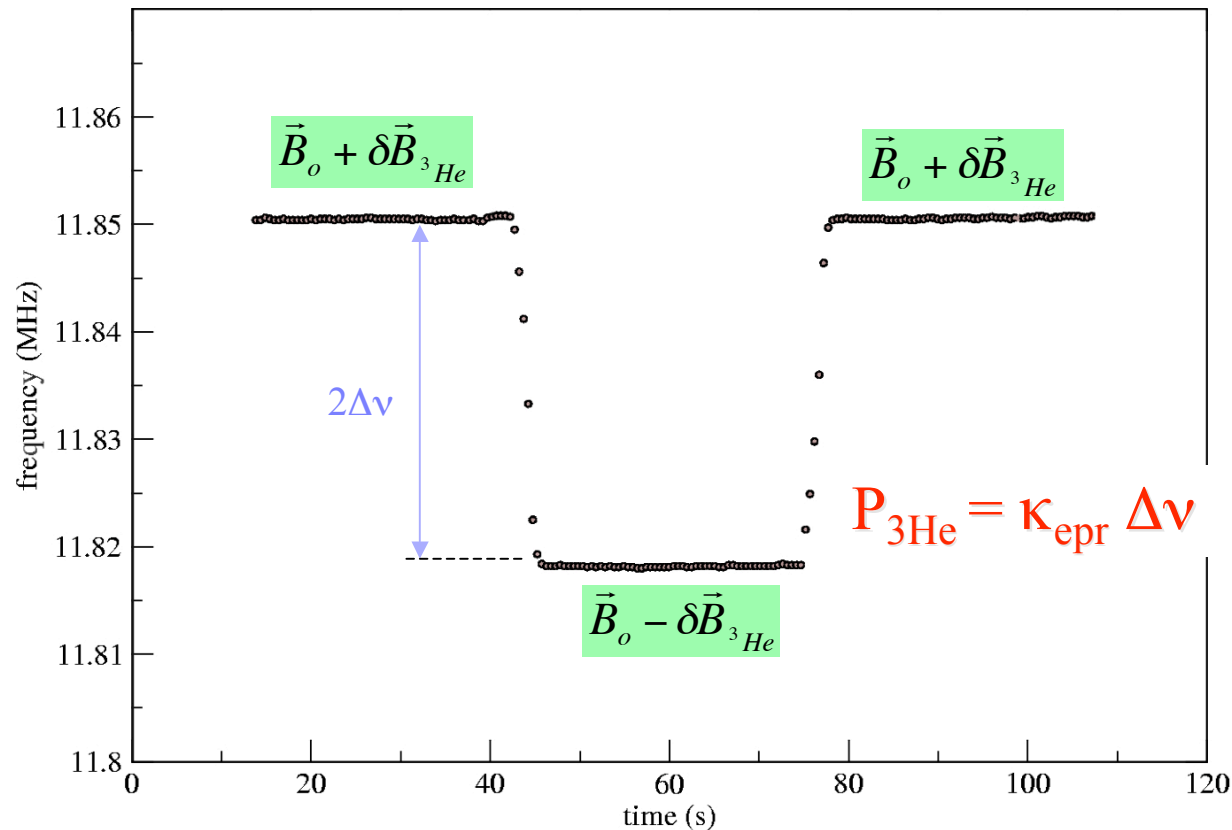
κ_w : from calibration with an identical target cell filled with water

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

} flip the ^3He spins under AFP conditions

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

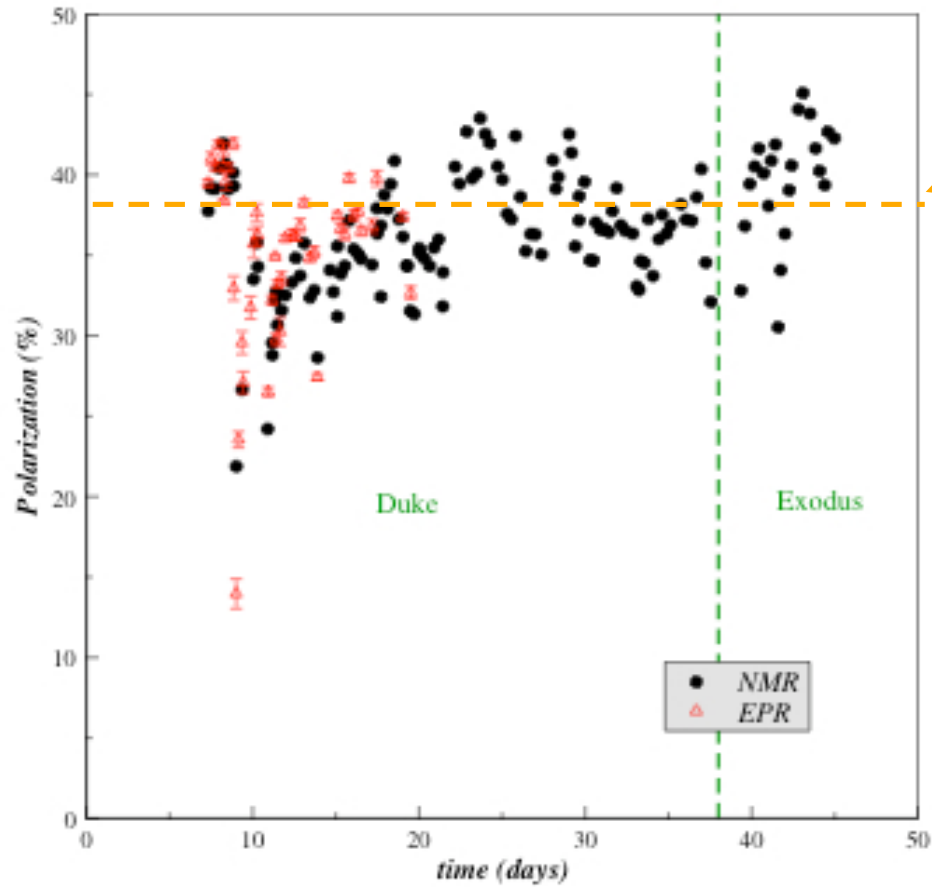
Electron Paramagnetic Resonance



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

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

Target performance

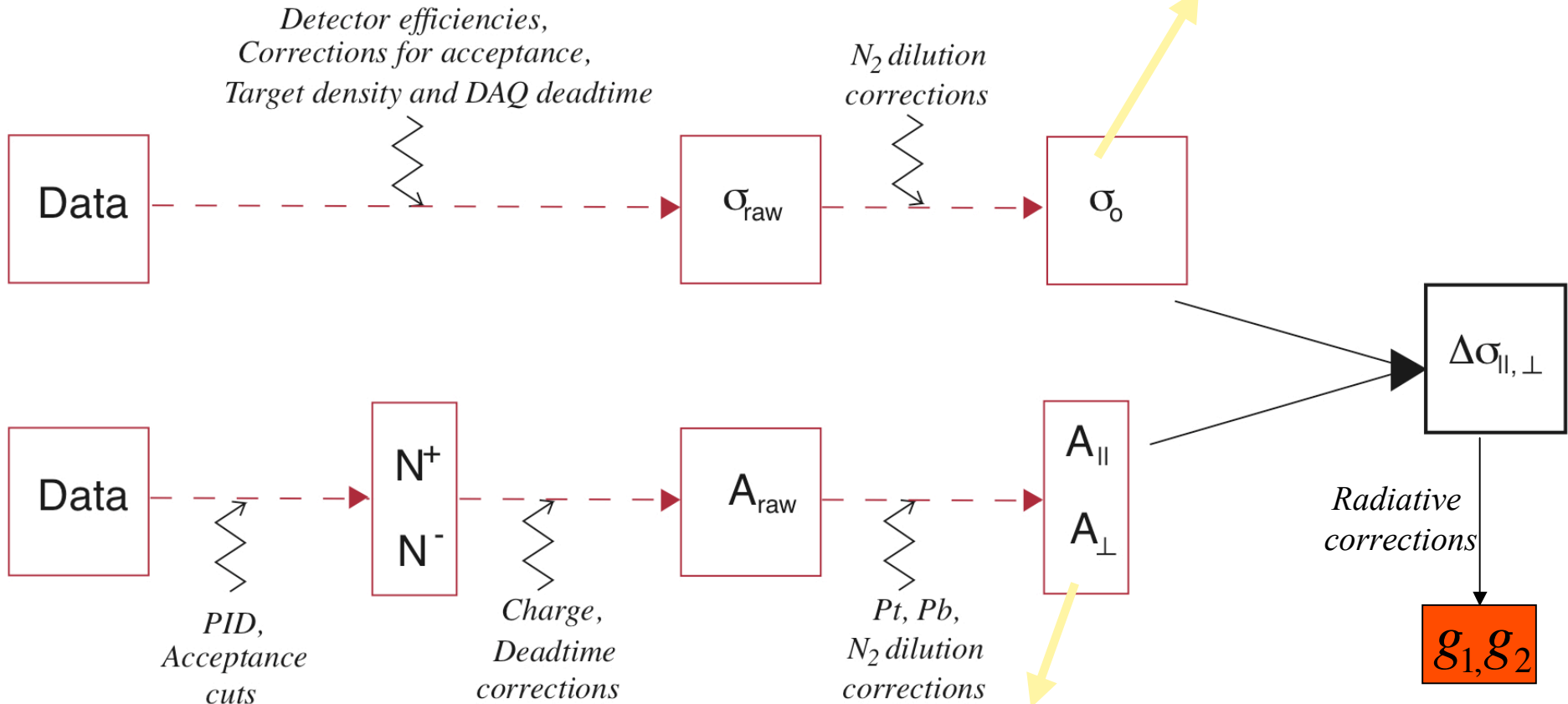


$P_{\text{avg}} \sim 37\%$

Statistical errors only

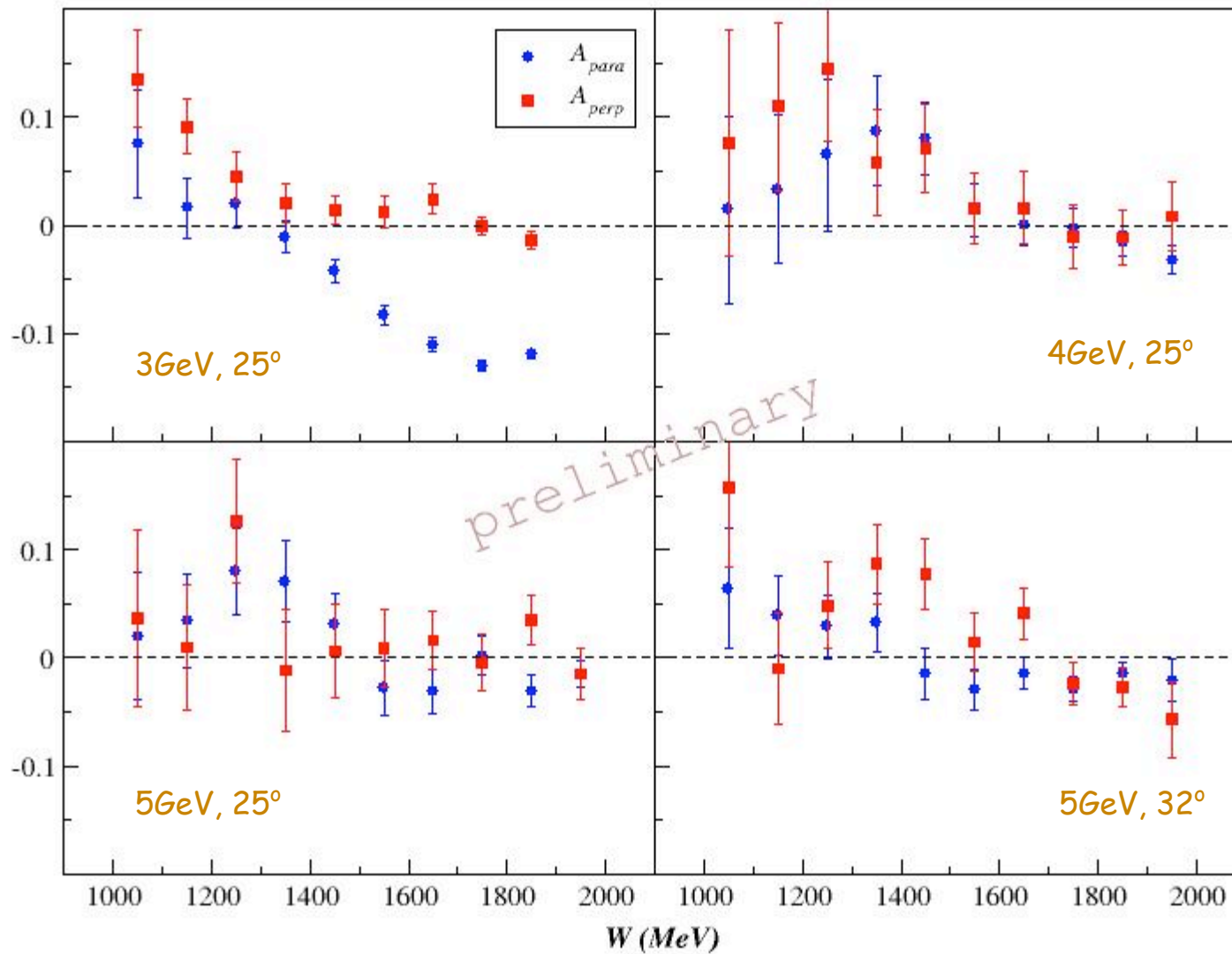
Analysis scheme

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



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

Pion asymmetries



Statistical errors only

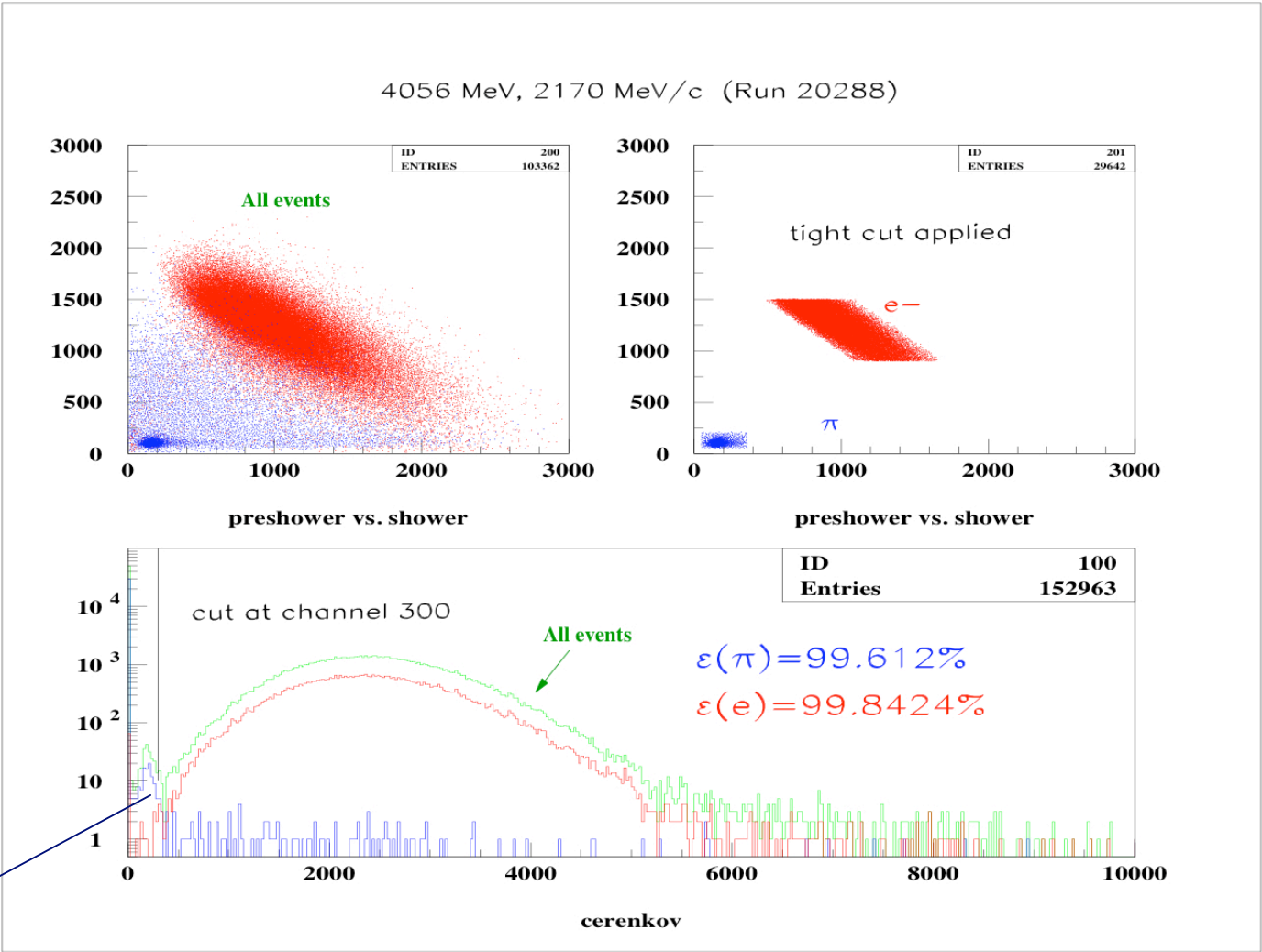
The CO₂ gas Cerenkov counter

Index of refraction:
 $n = 1.00041$



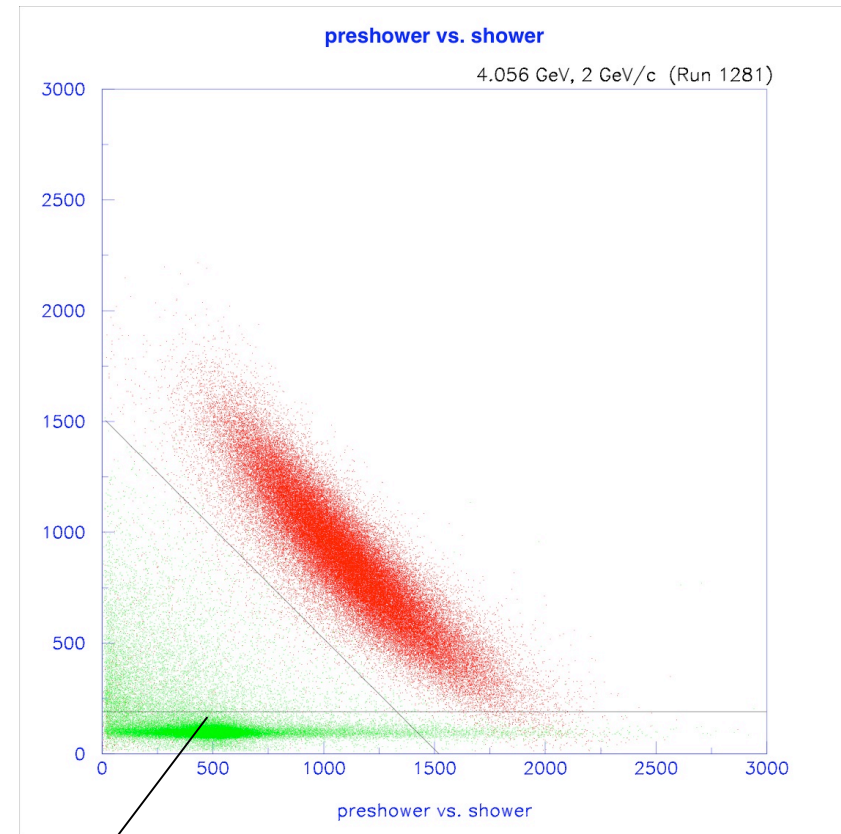
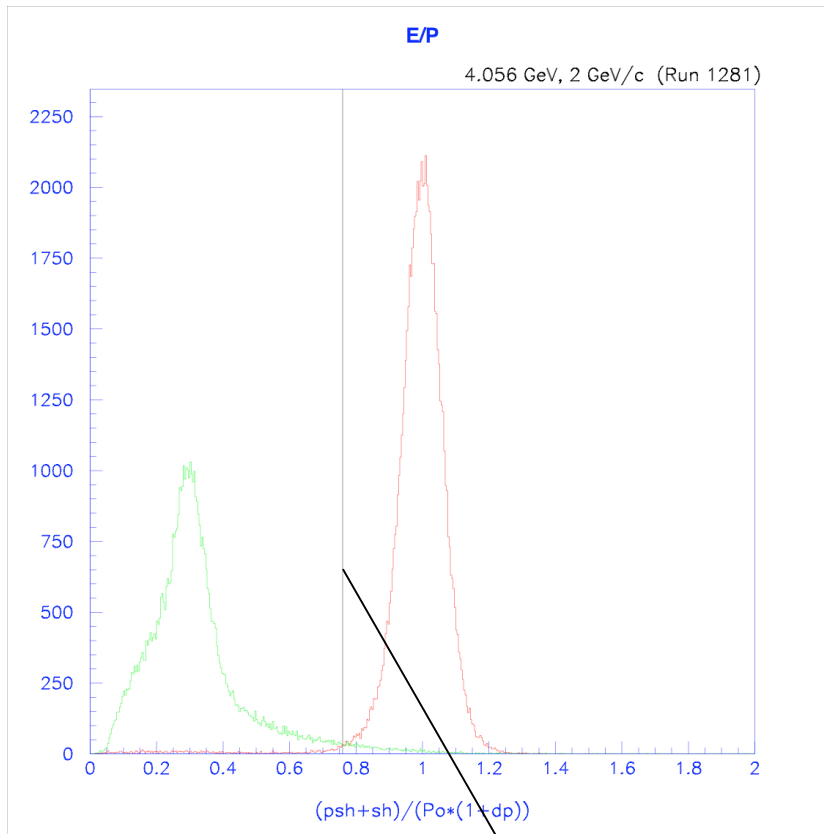
$P_{thres.}^{e^-} = 18 MeV$

$P_{thres.}^{\pi^-} = 4.9 GeV$



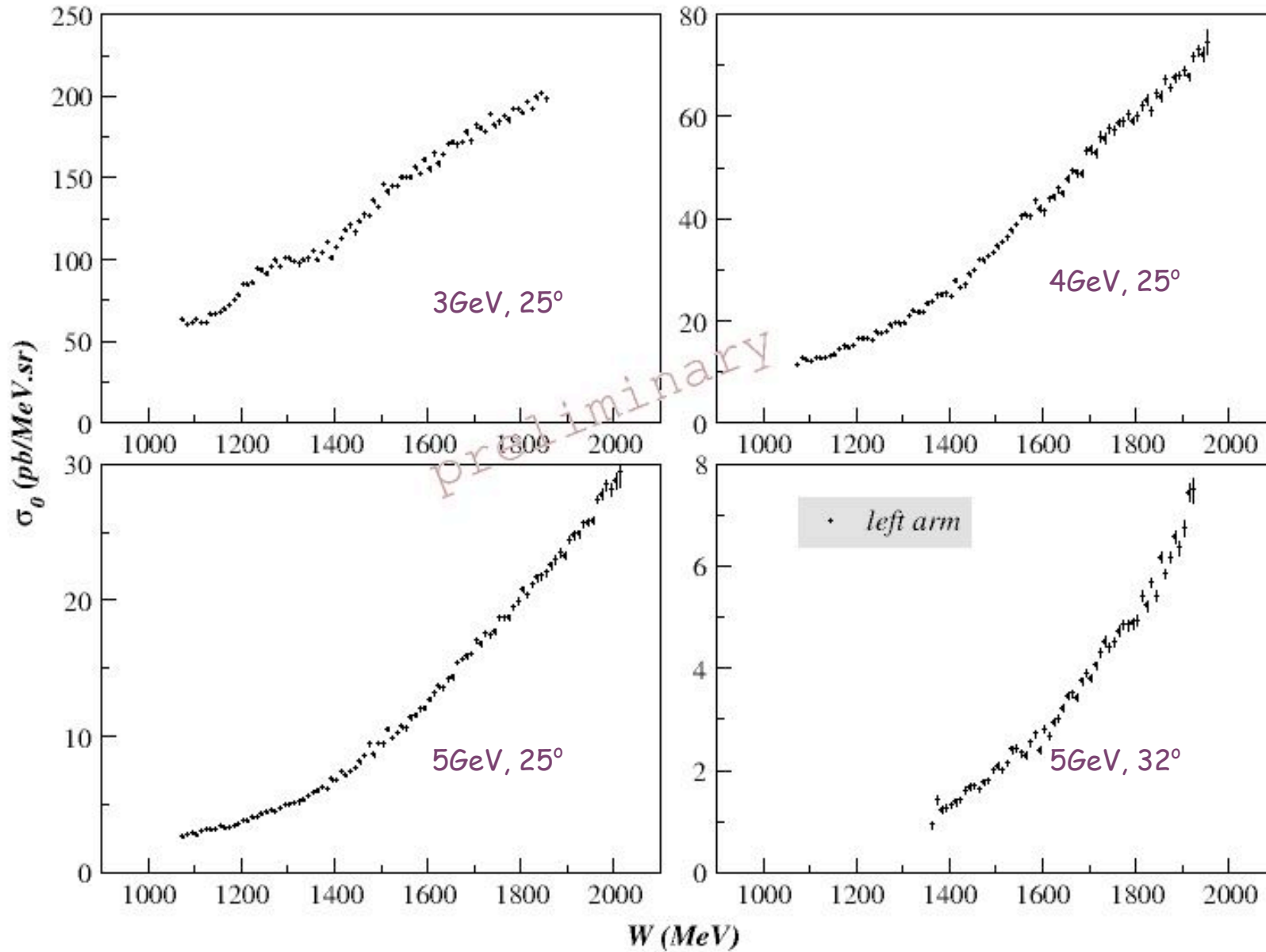
Knock-out e^-
 &
 Low energy e^-

Lead Glass Calorimeter

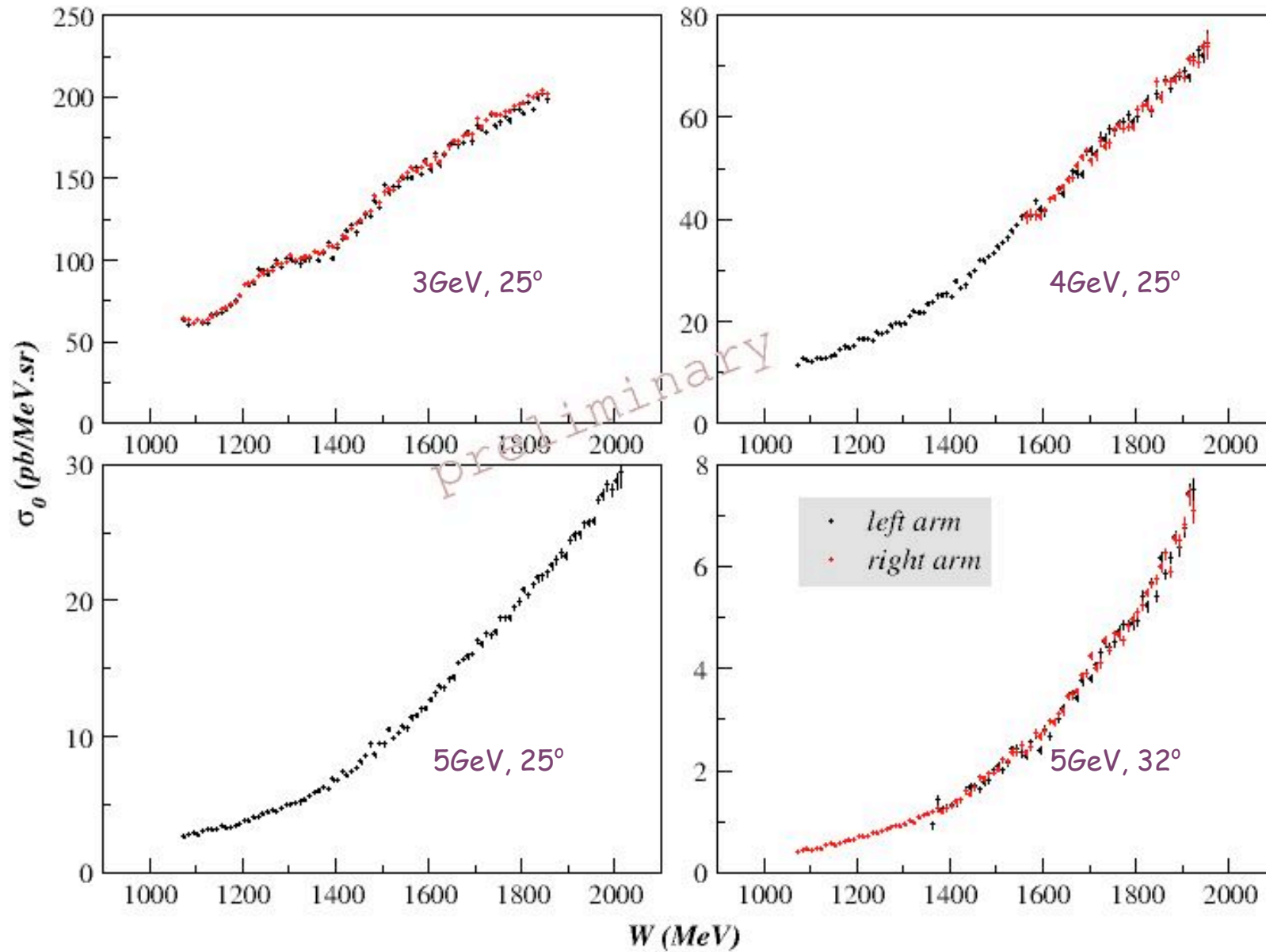


Cuts applied for electron efficiency > 99%

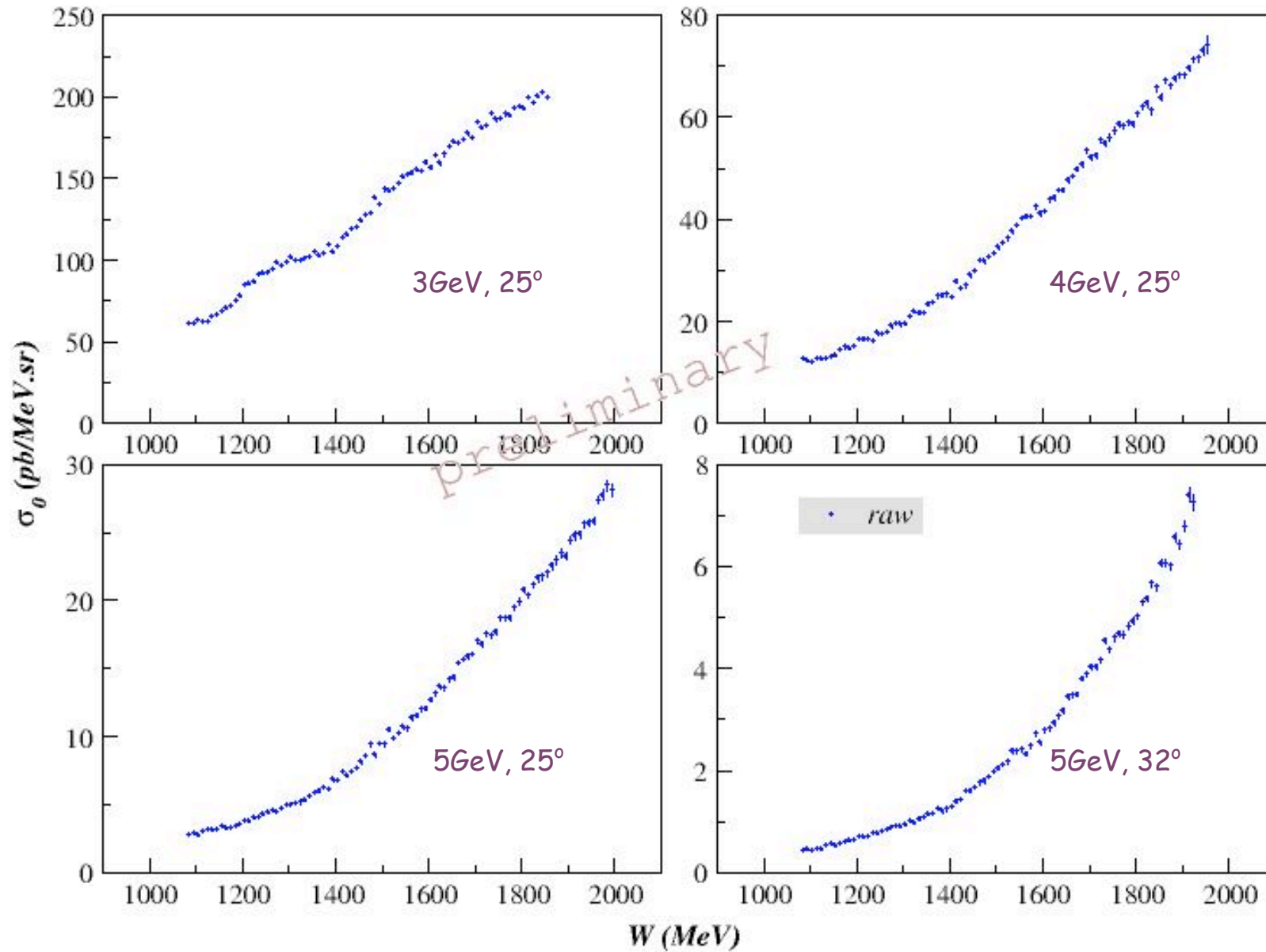
Unpolarized cross sections



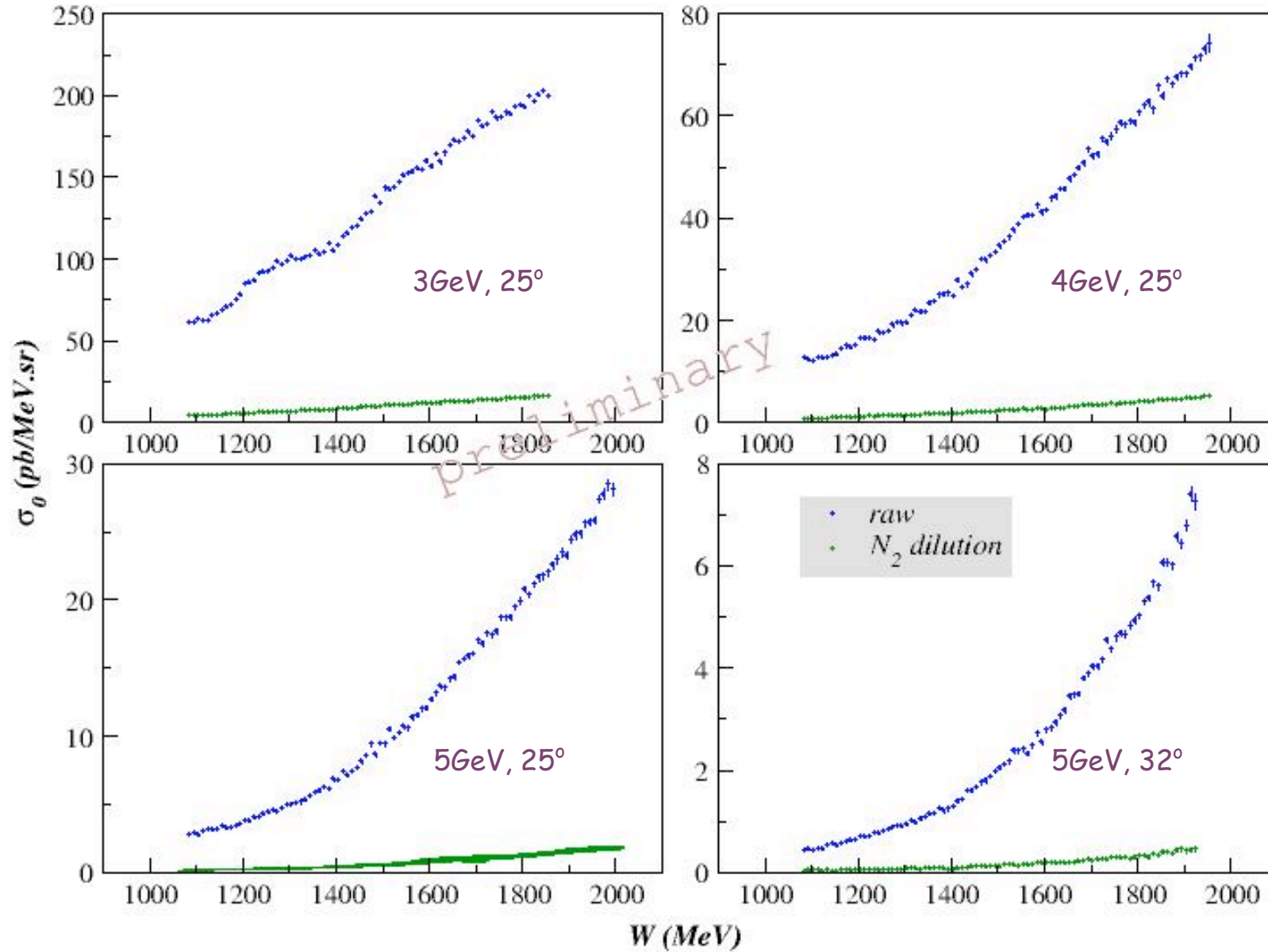
Unpolarized cross sections



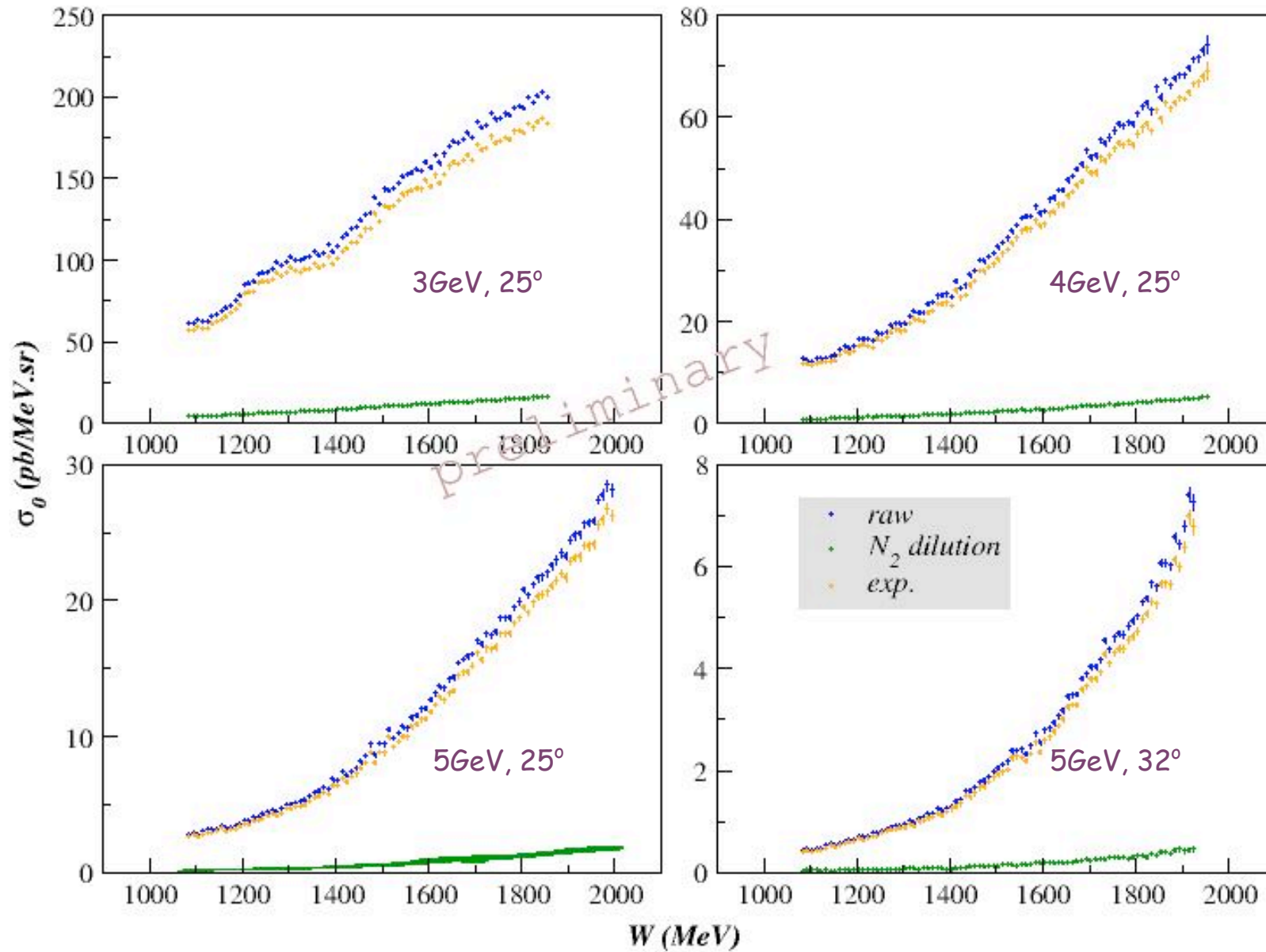
Unpolarized cross sections



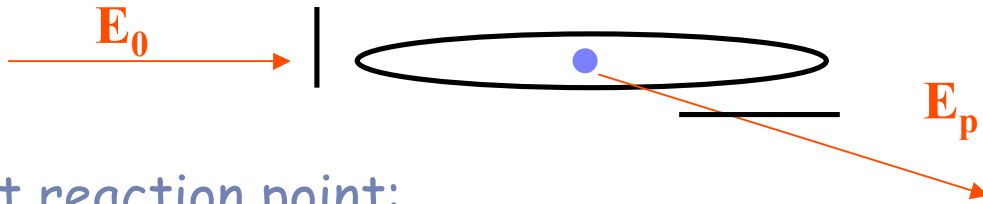
Unpolarized cross sections



Unpolarized cross sections



Radiative corrections

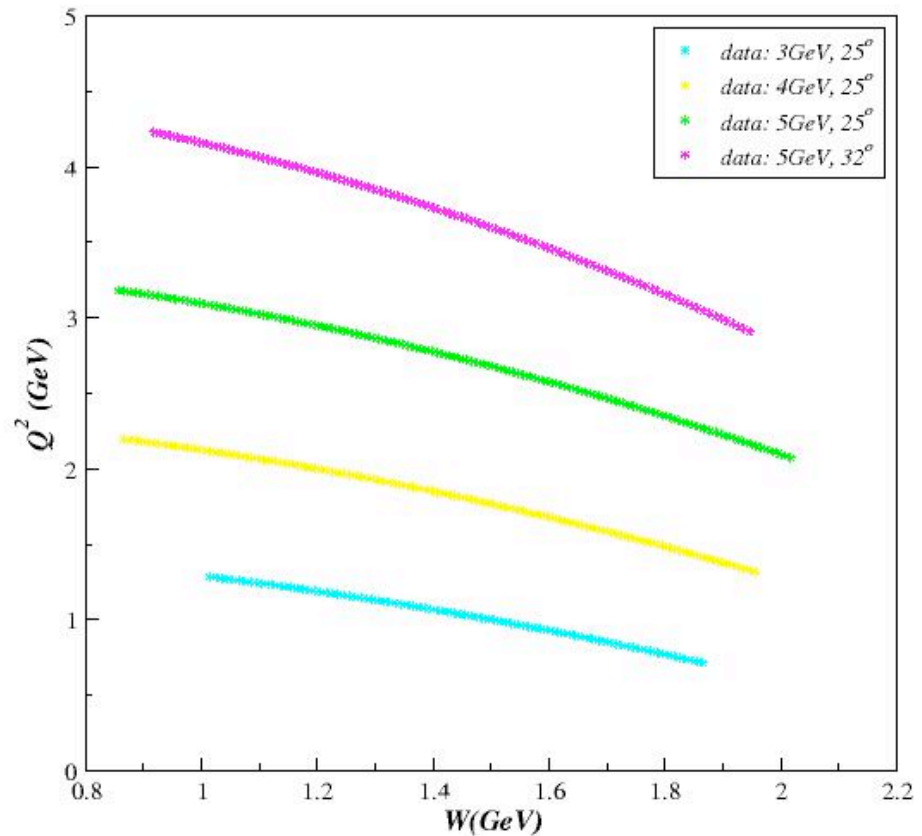


At reaction point:

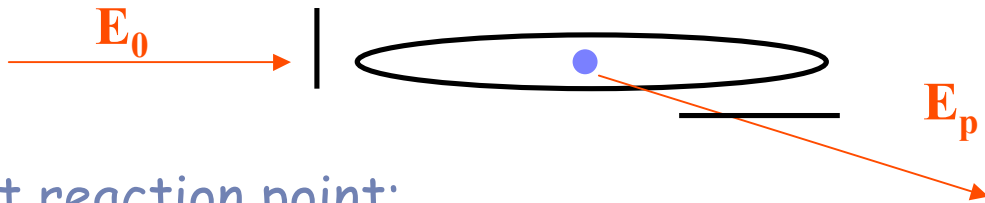
$$E_0^r < E_0$$

$$E_p^r > E_p$$

Computation to get the
real reaction



Radiative corrections

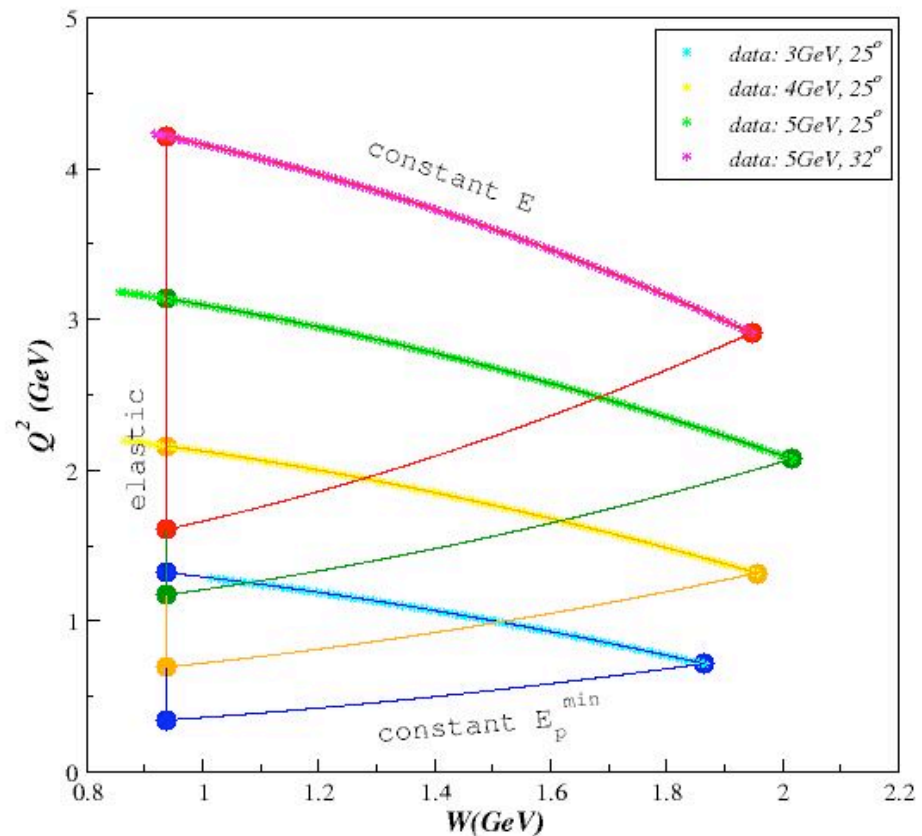


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Computation to get the
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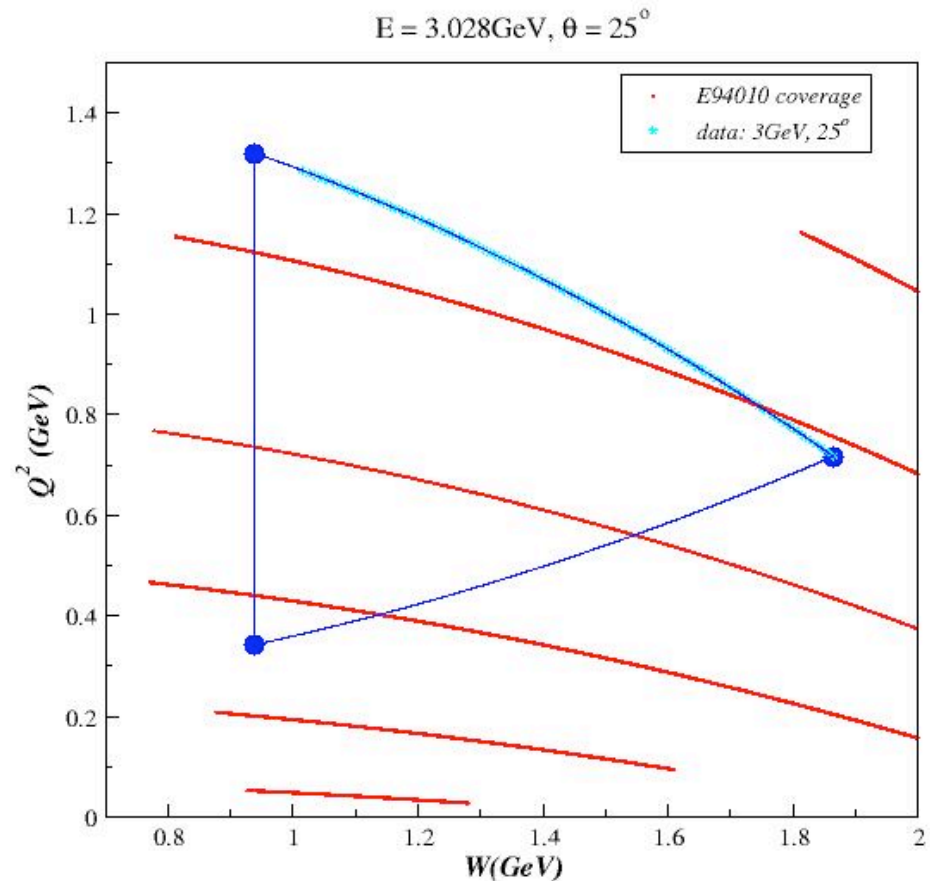
Radiative corrections

- ◆ Used QFS model for σ_0 . Next will use E94-010 data for σ_0 :

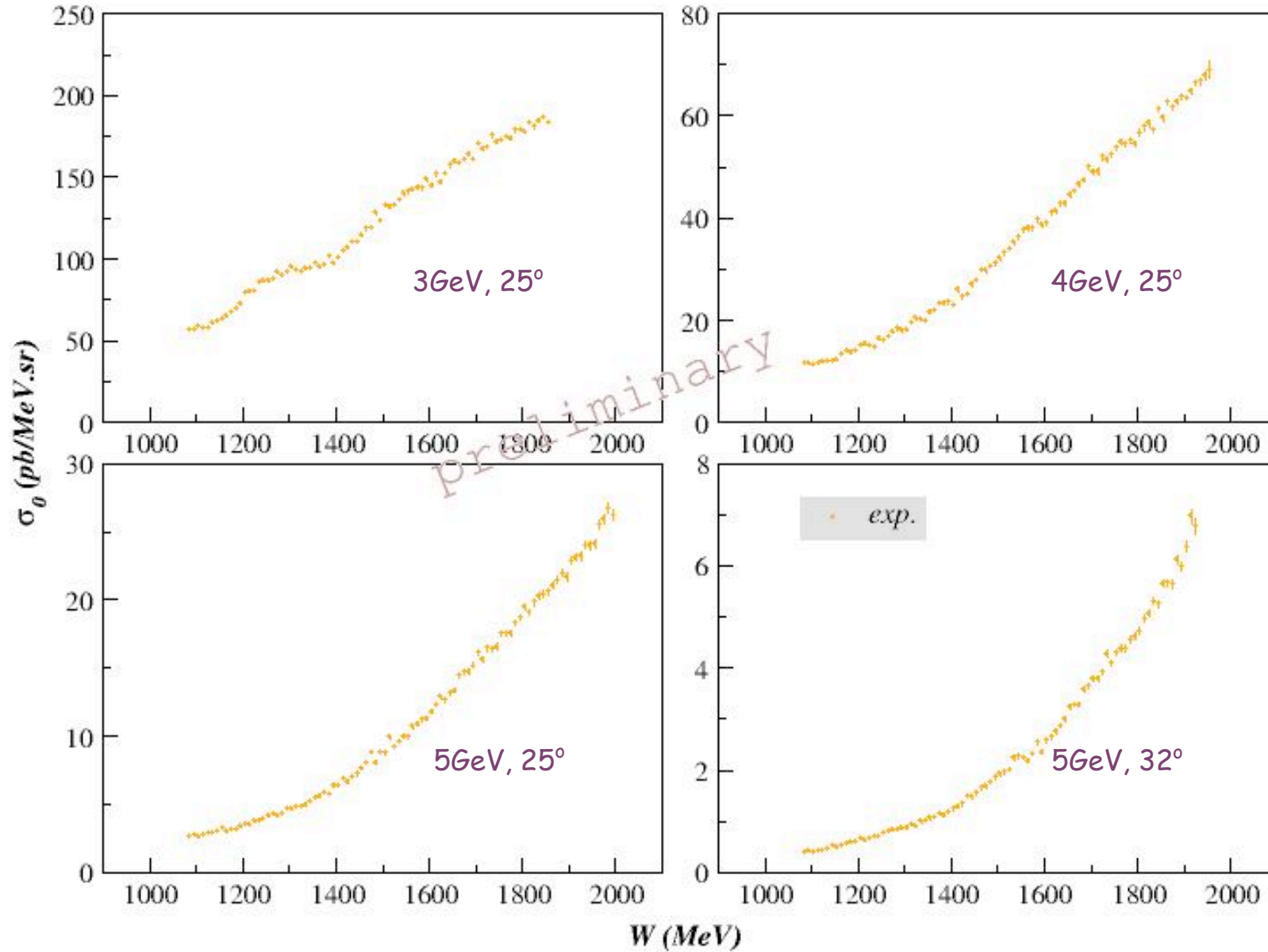
$$F_2(x, Q^2) \rightarrow \sigma_0(E, E', \theta)$$

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

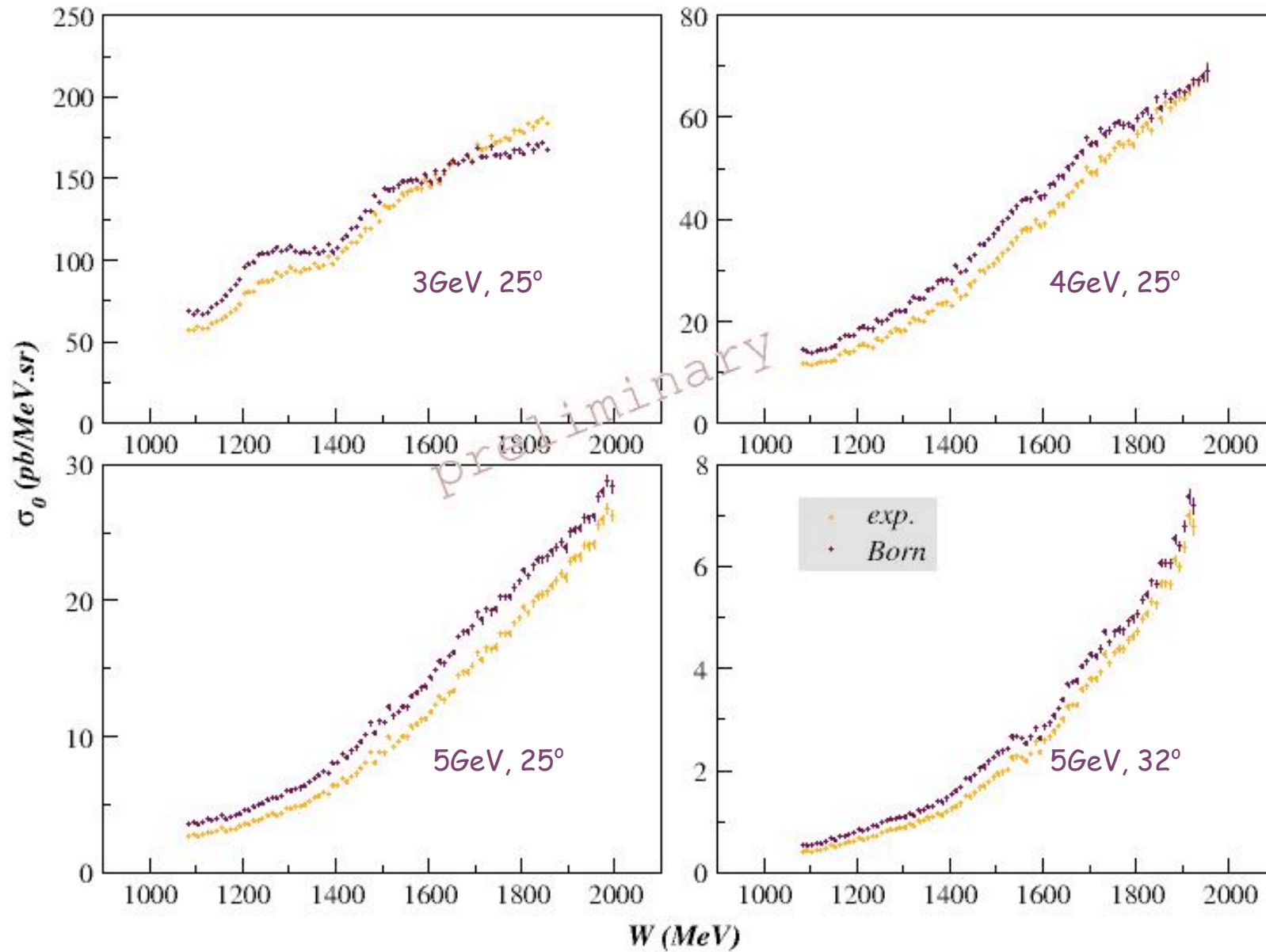
$$g_{1,2}(x, Q^2) \rightarrow \Delta\sigma_{\parallel, \perp}(E, E', \theta)$$



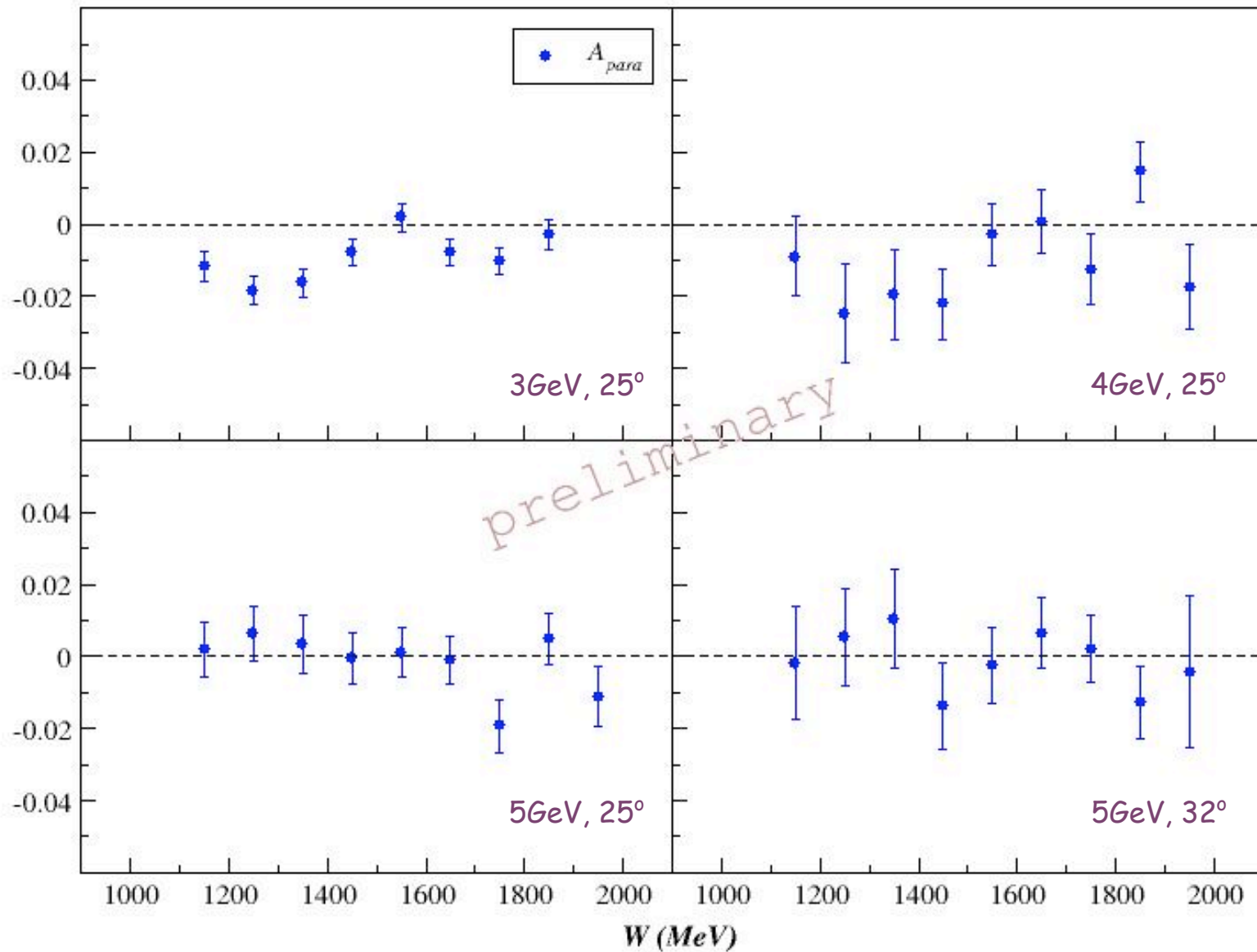
Unpolarized cross sections



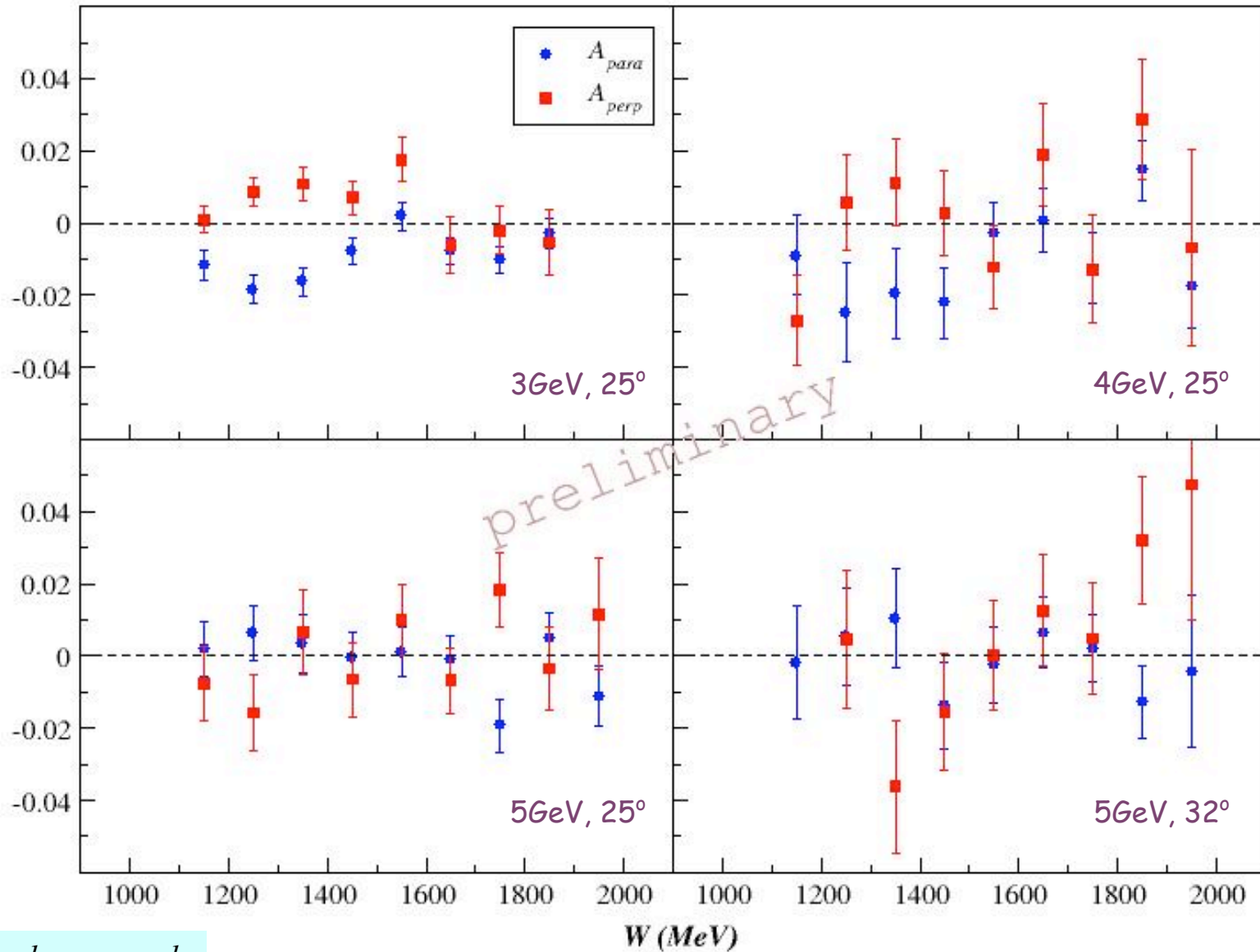
Unpolarized cross sections



Asymmetries

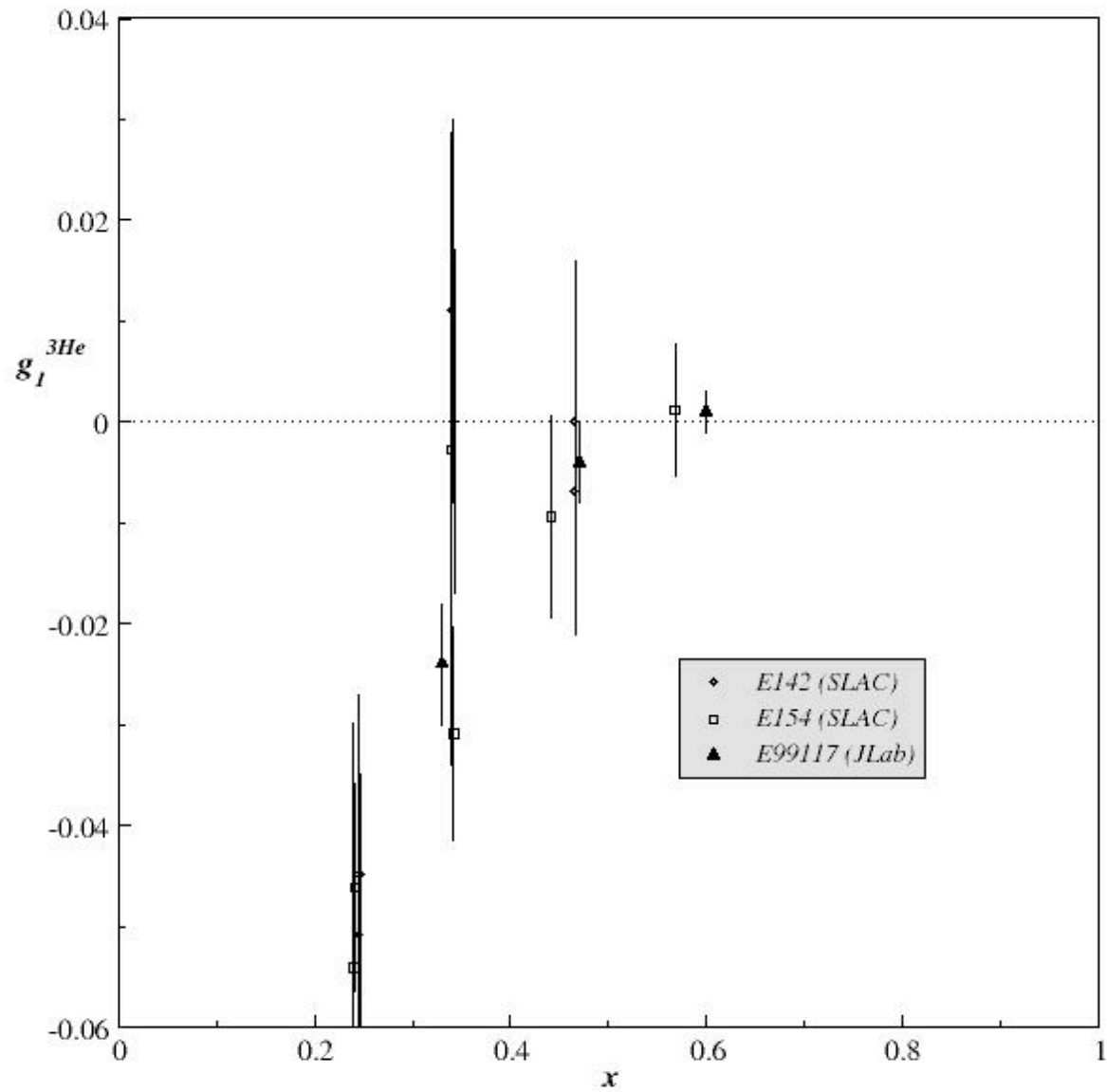


Asymmetries

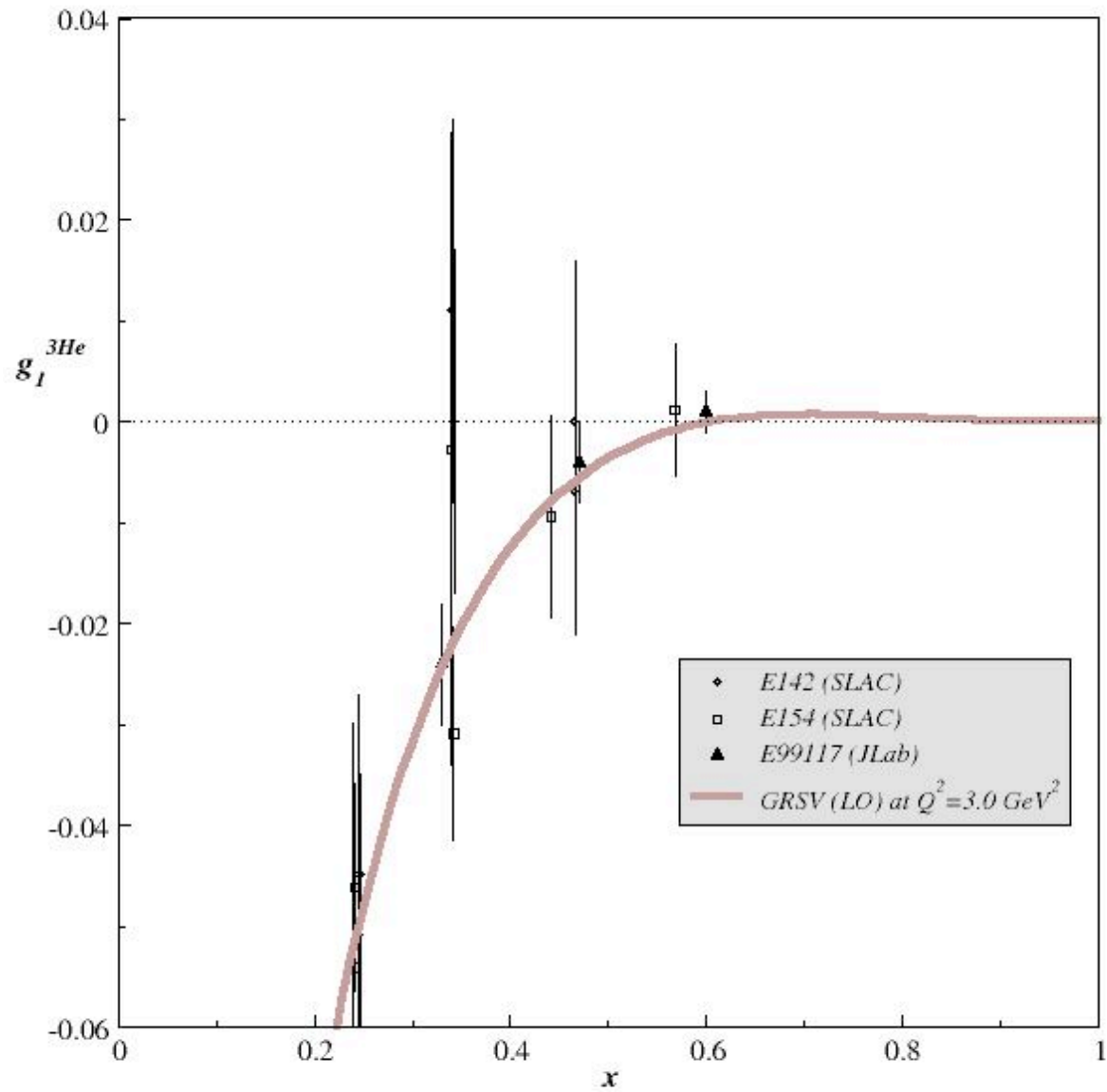


Statistical errors only

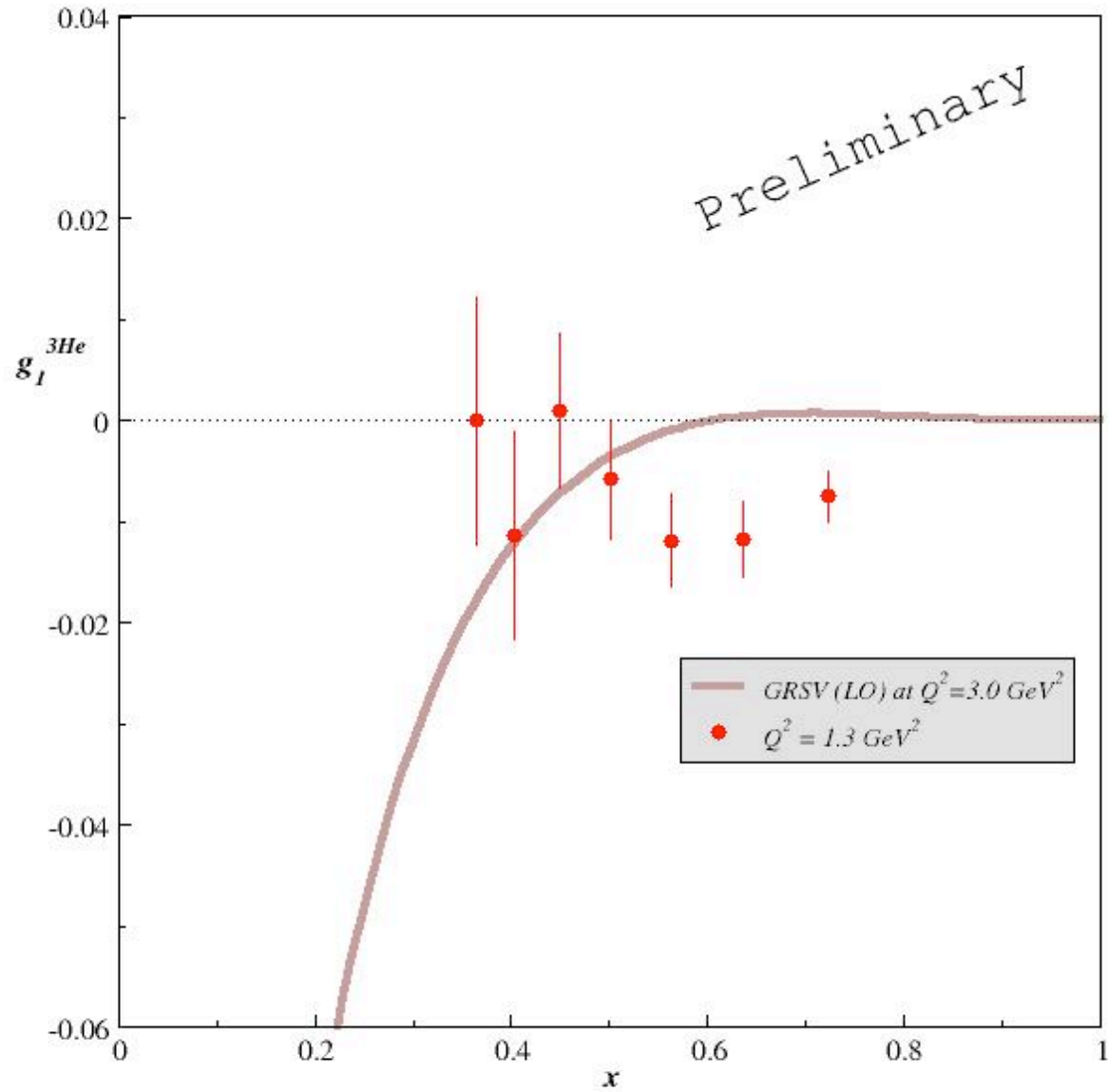
$g_1^{3\text{He}}$ at constant Q^2



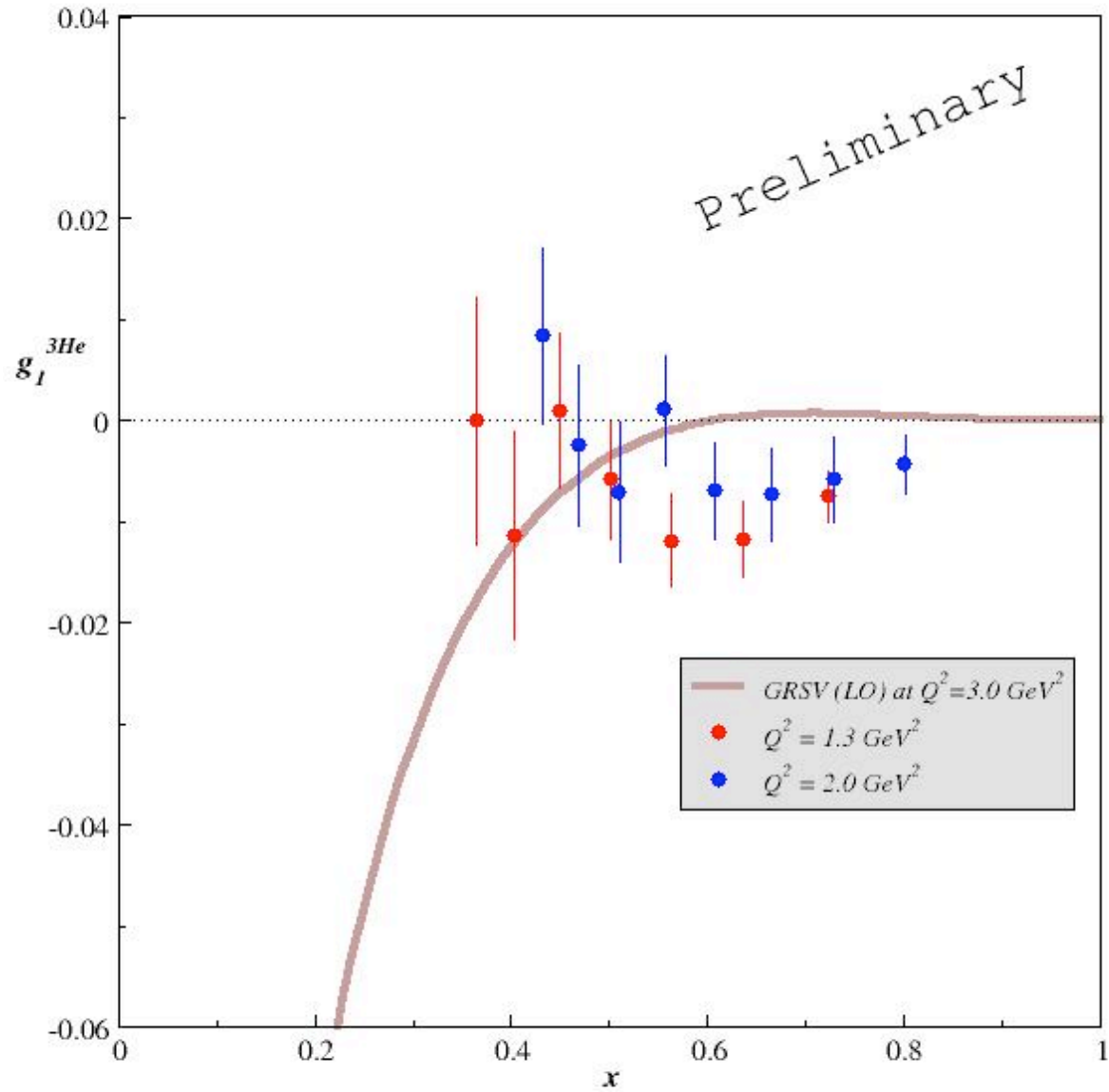
$g_1^{3\text{He}}$ at constant Q^2



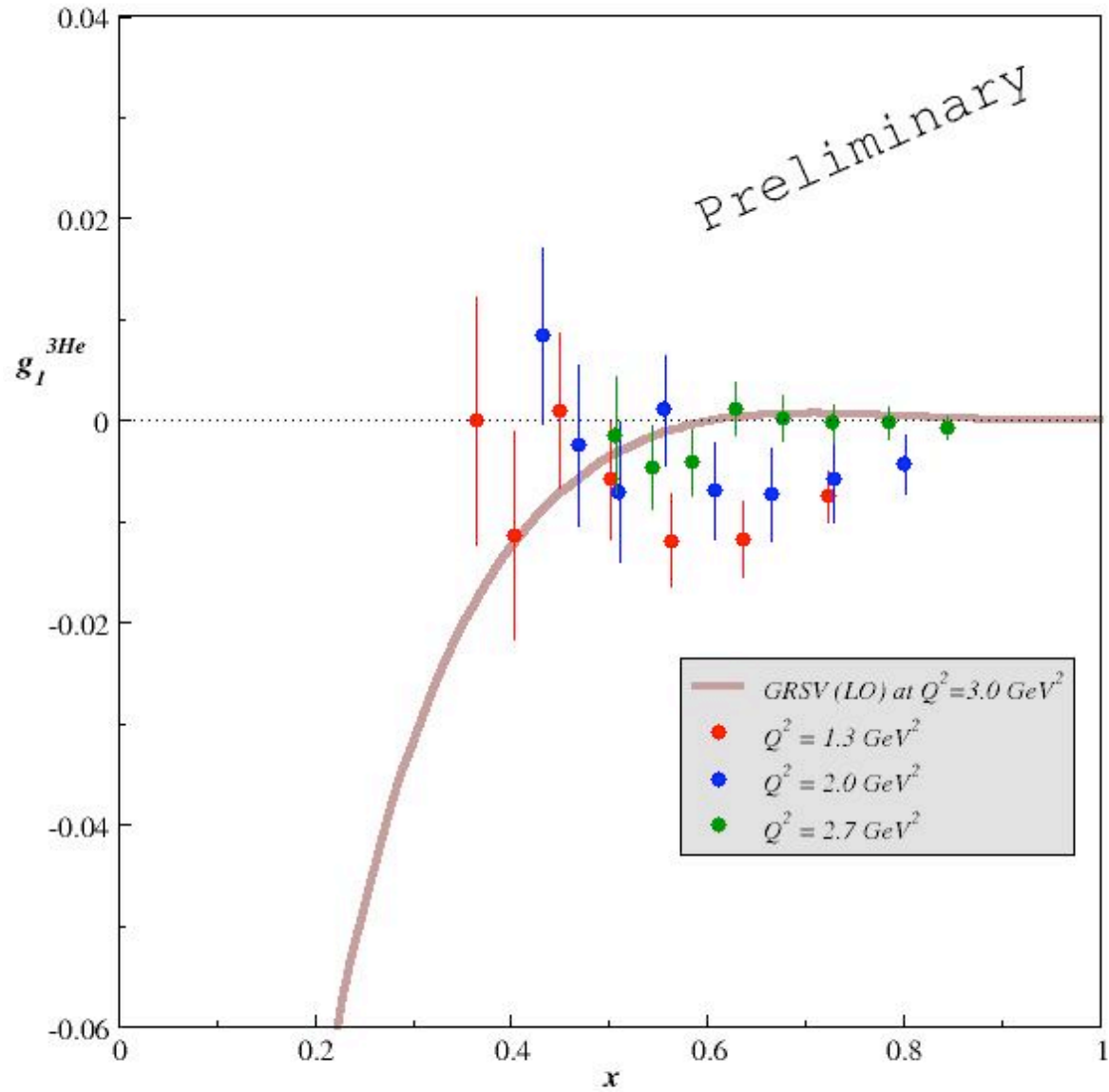
$g_1^{3\text{He}}$ at constant Q^2



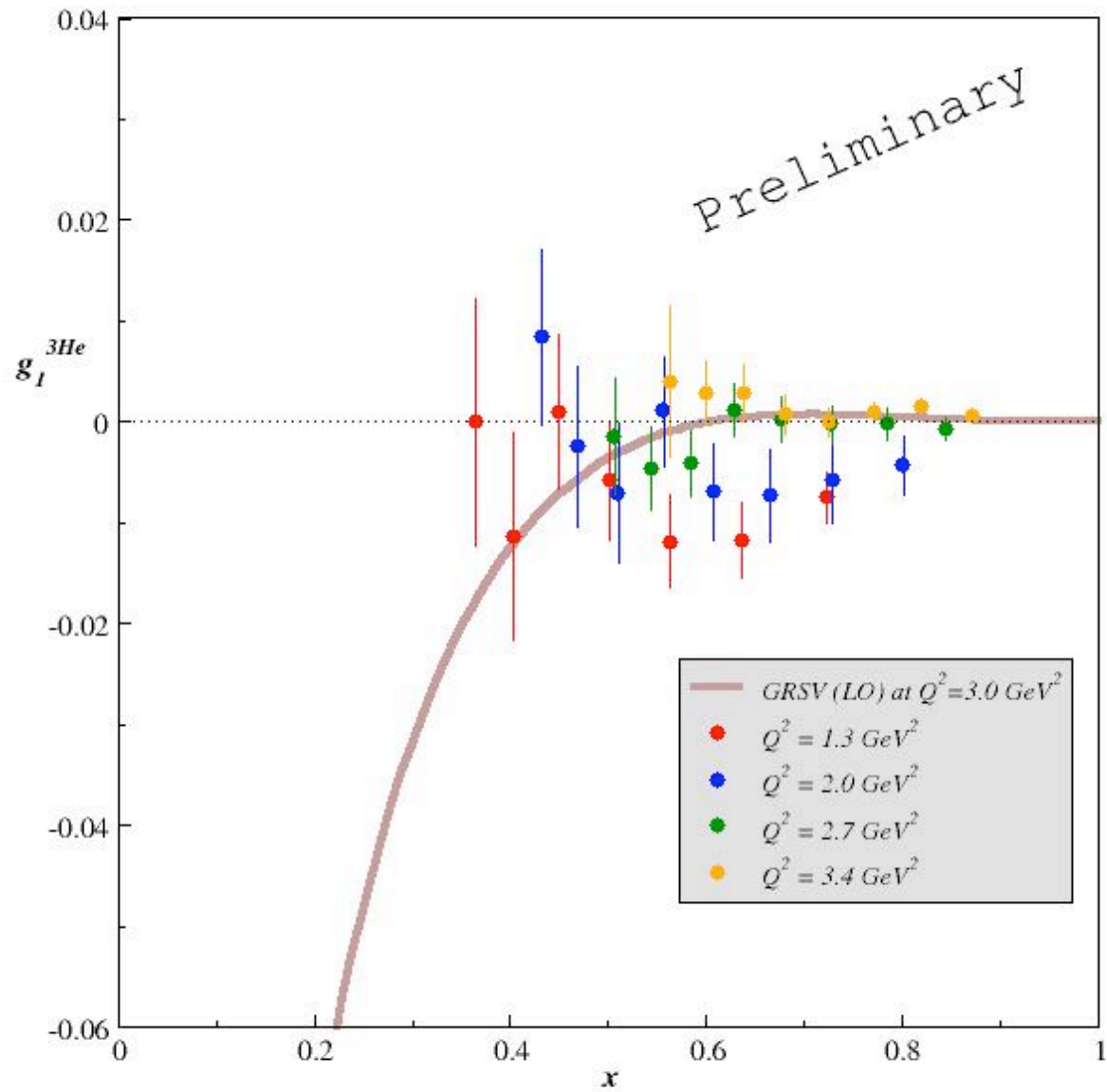
$g_1^{3\text{He}}$ at constant Q^2



$g_1^{3\text{He}}$ at constant Q^2



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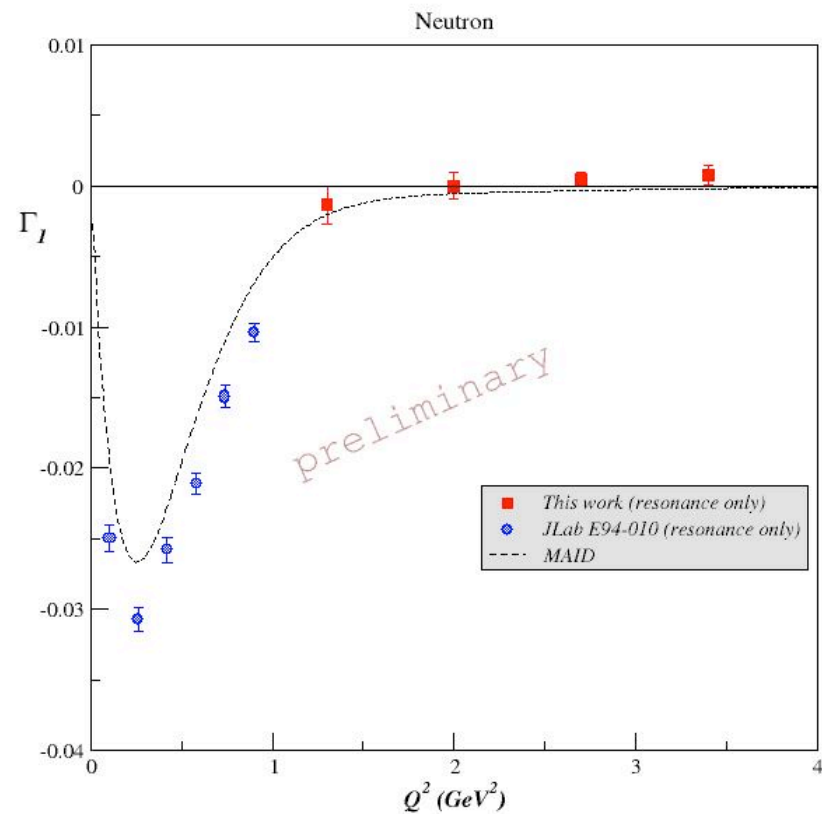
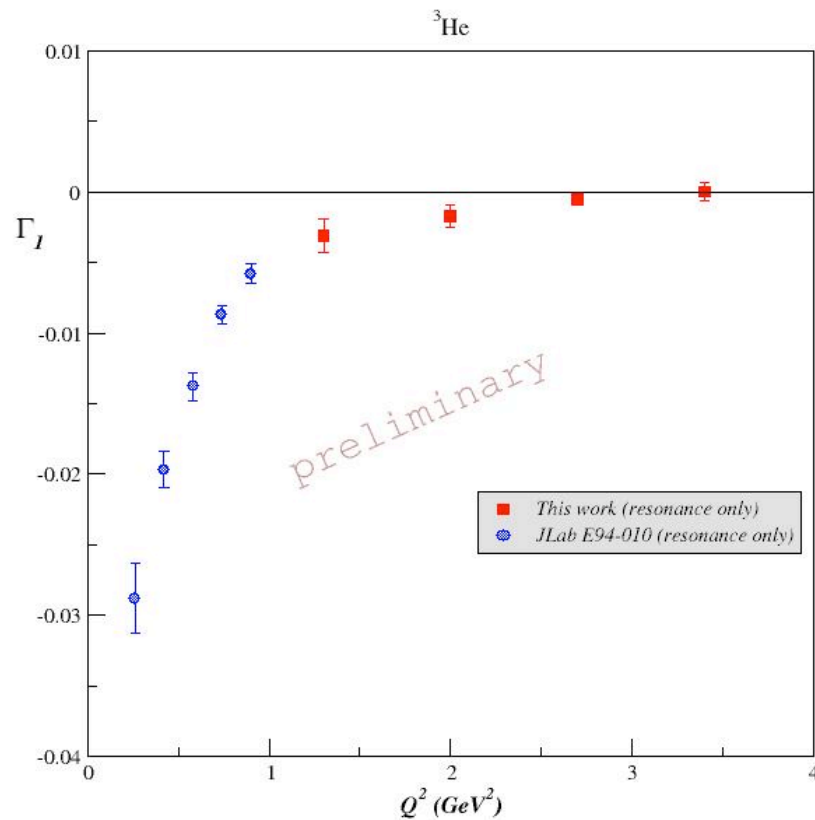


Γ_1 in the resonance region

Extract the neutron from effective polarization equation:

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

$$P_n = 86\% \\ P_p = -2.8\%$$



Statistical errors only

Test of Duality on Neutron and ^3He

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

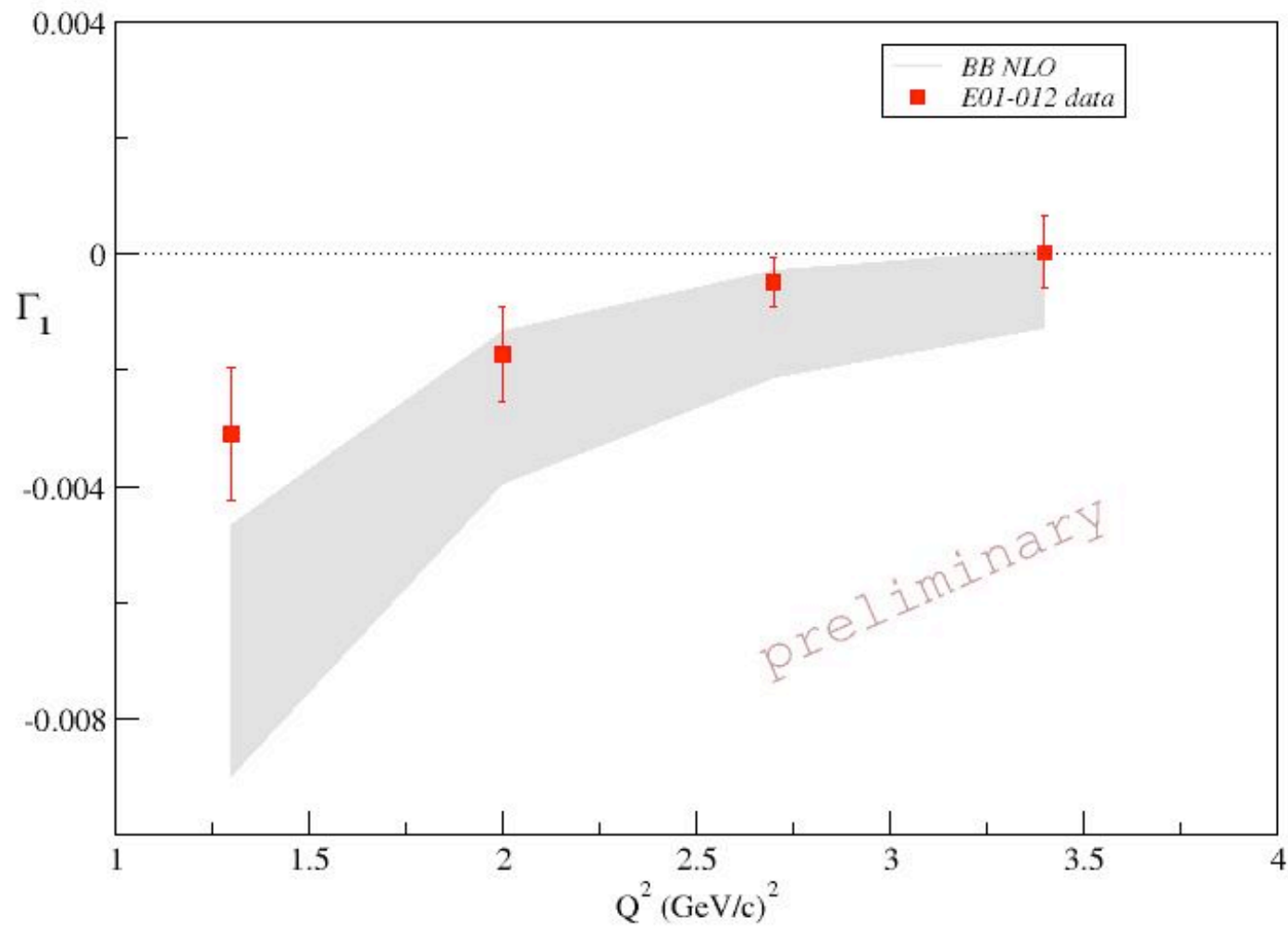
$$\tilde{\Gamma}_1^{res} = \int_{x_{min}}^{x_{max}} g_1^{res}(x, Q^2) dx$$

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

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

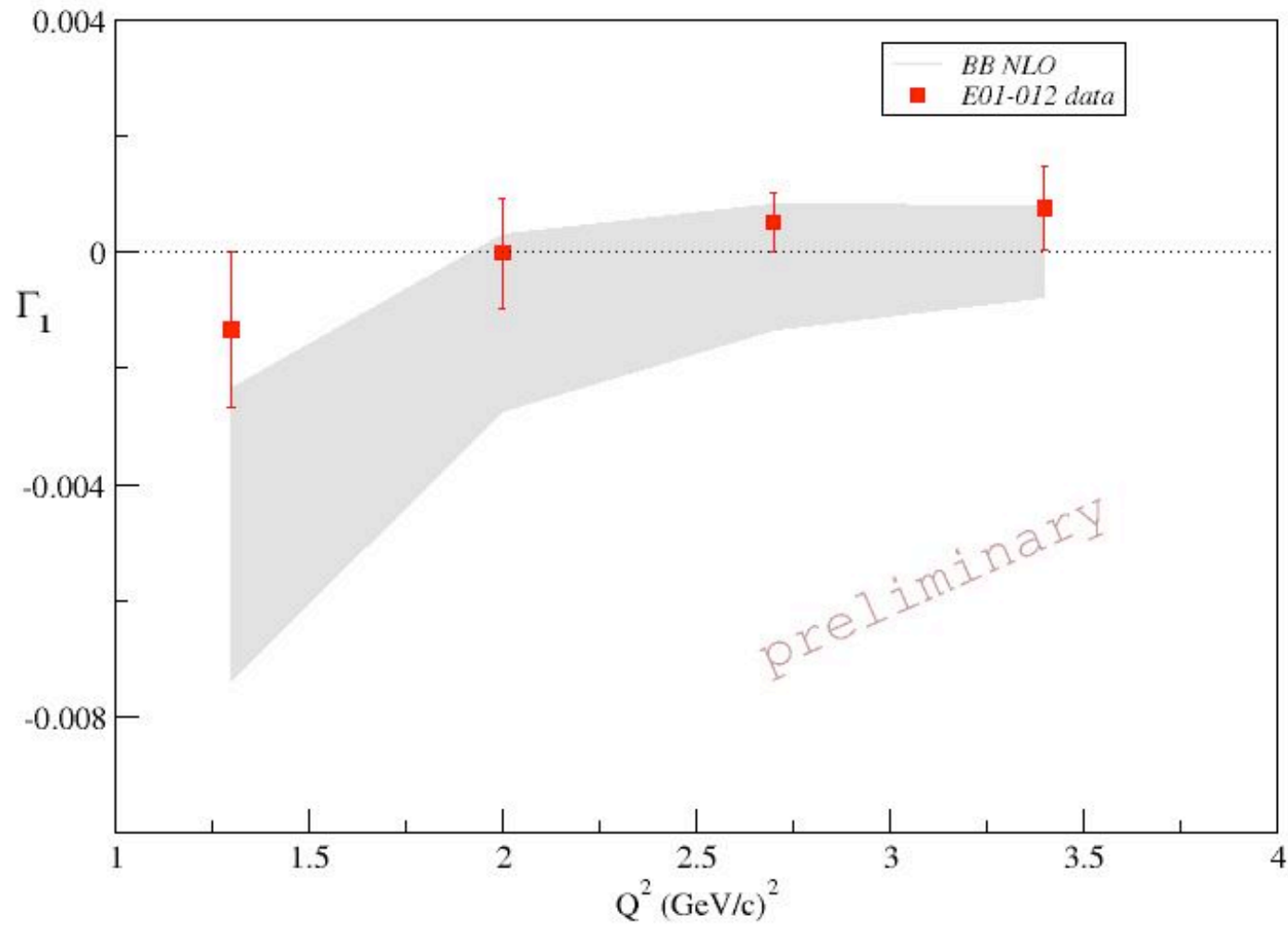
if unity \Rightarrow duality is verified

Test of duality on ^3He



Statistical errors only

Test of duality on neutron



Statistical errors only

Spin asymmetries

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

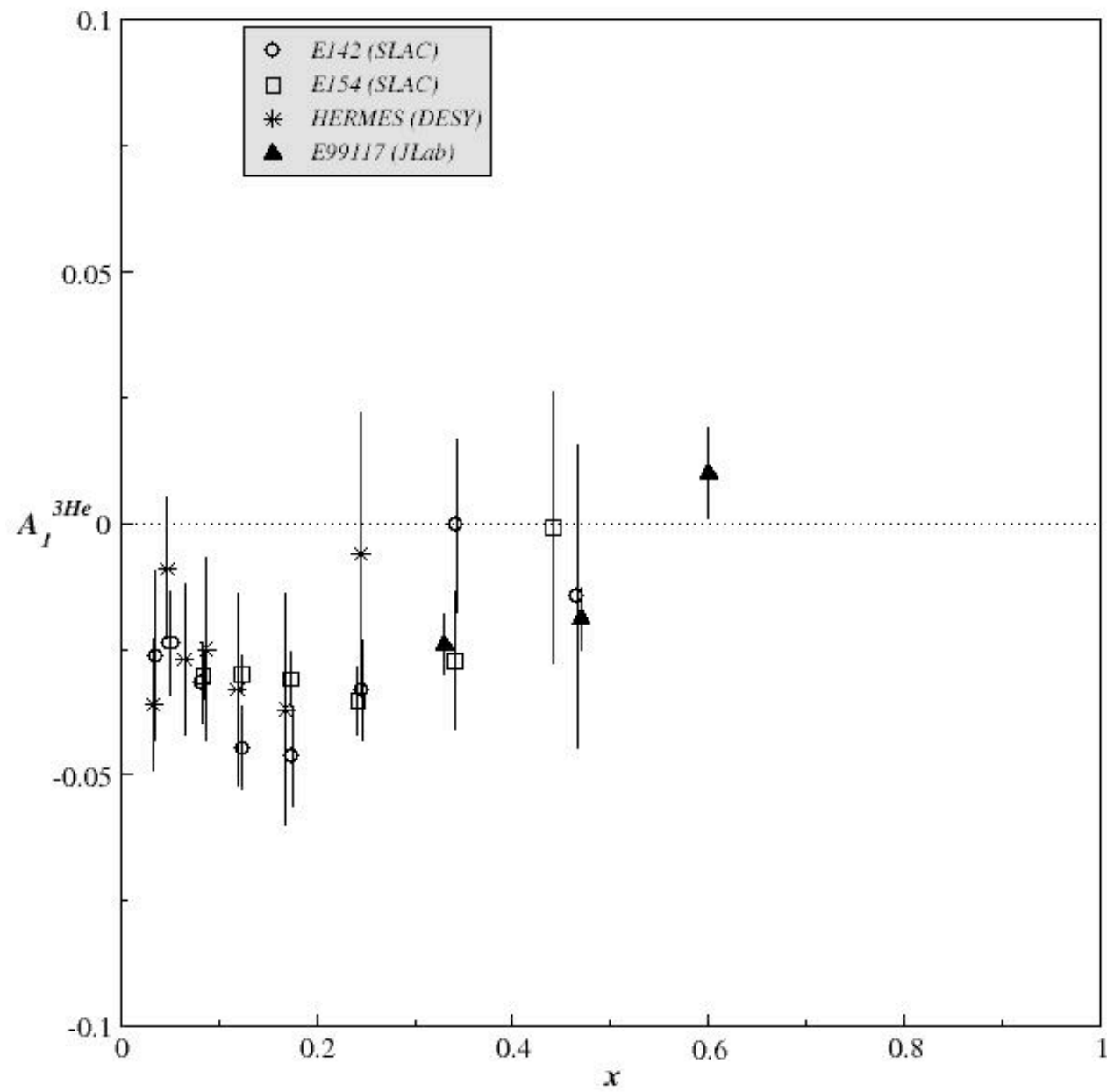
η and ξ depend on kinematic variables
 D and d depend on $R = \sigma_L / \sigma_T$ for ${}^3\text{He}$

In the parton model:

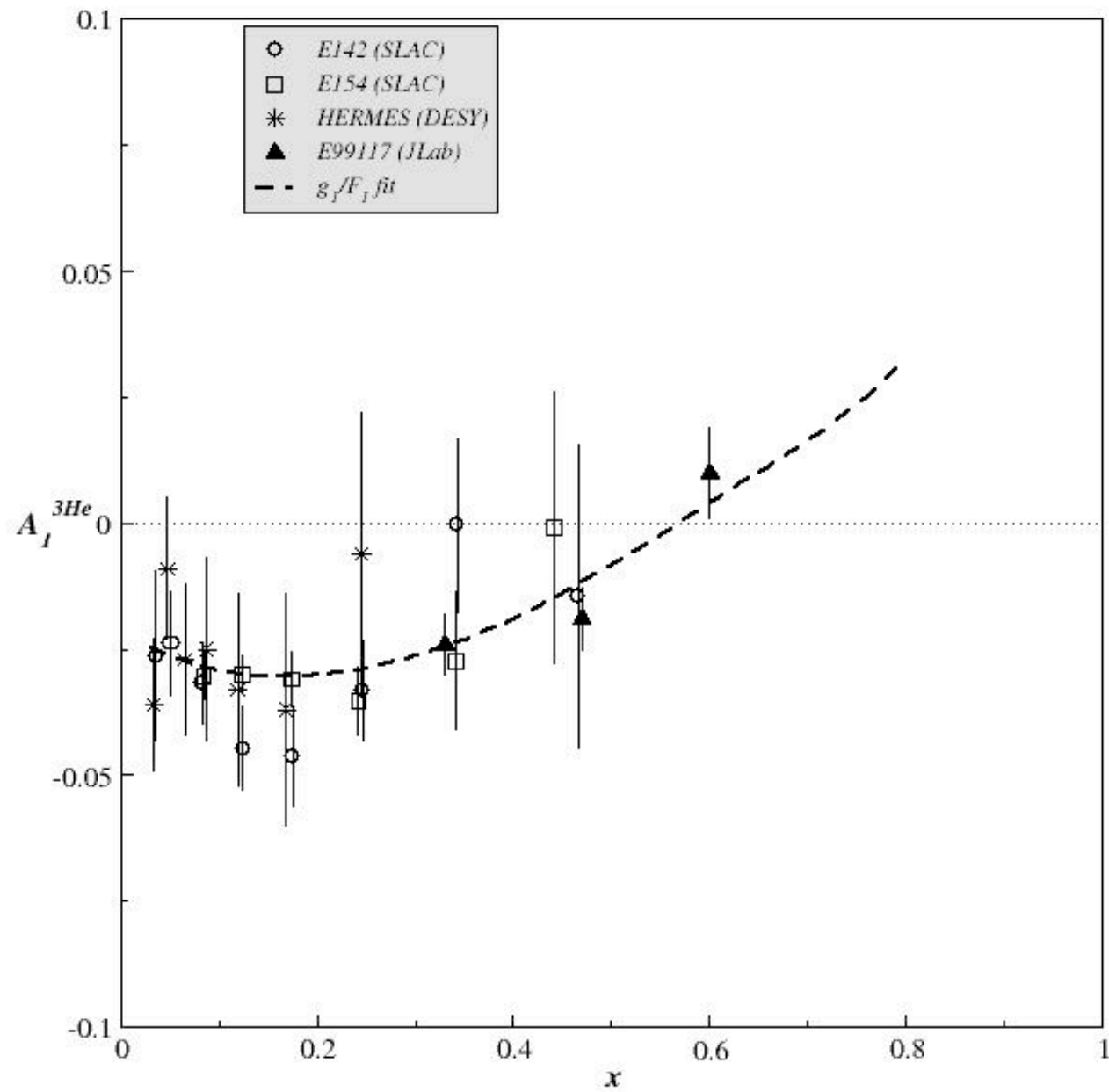
$$A_1(x, Q^2) \approx \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

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

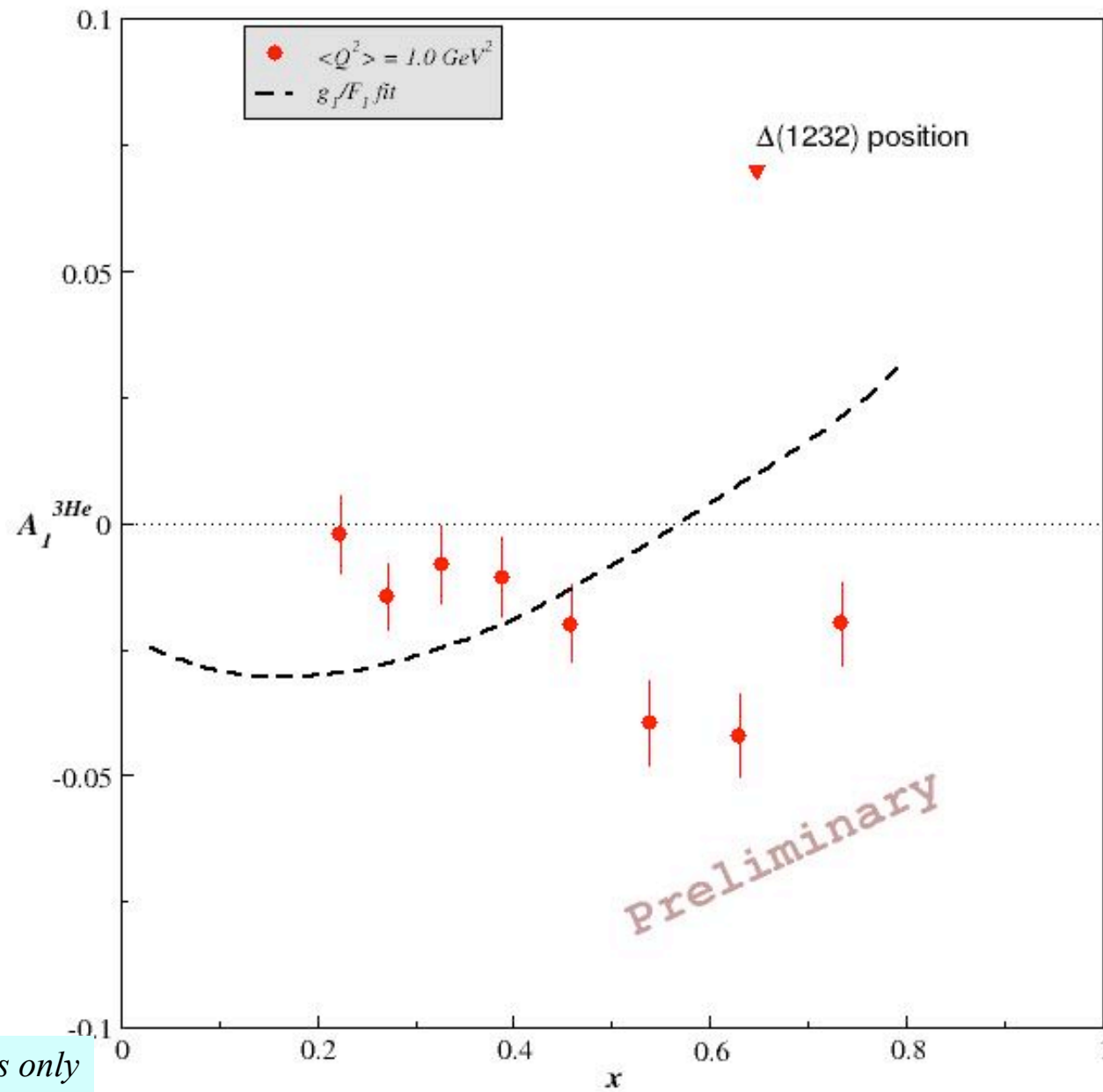
$A_1^{3\text{He}}$



$A_1^{3\text{He}}$

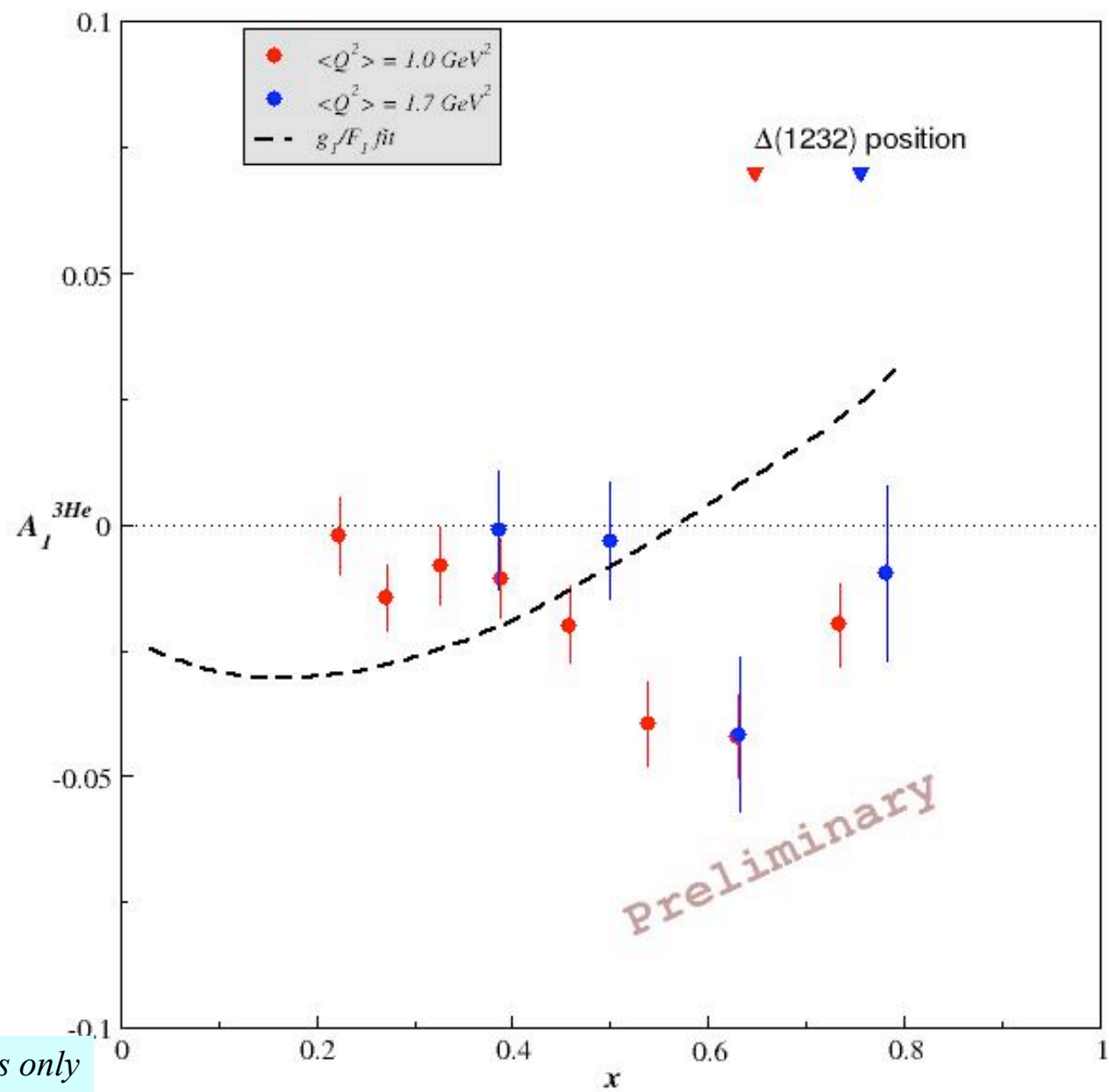


$A_1^{3\text{He}}$



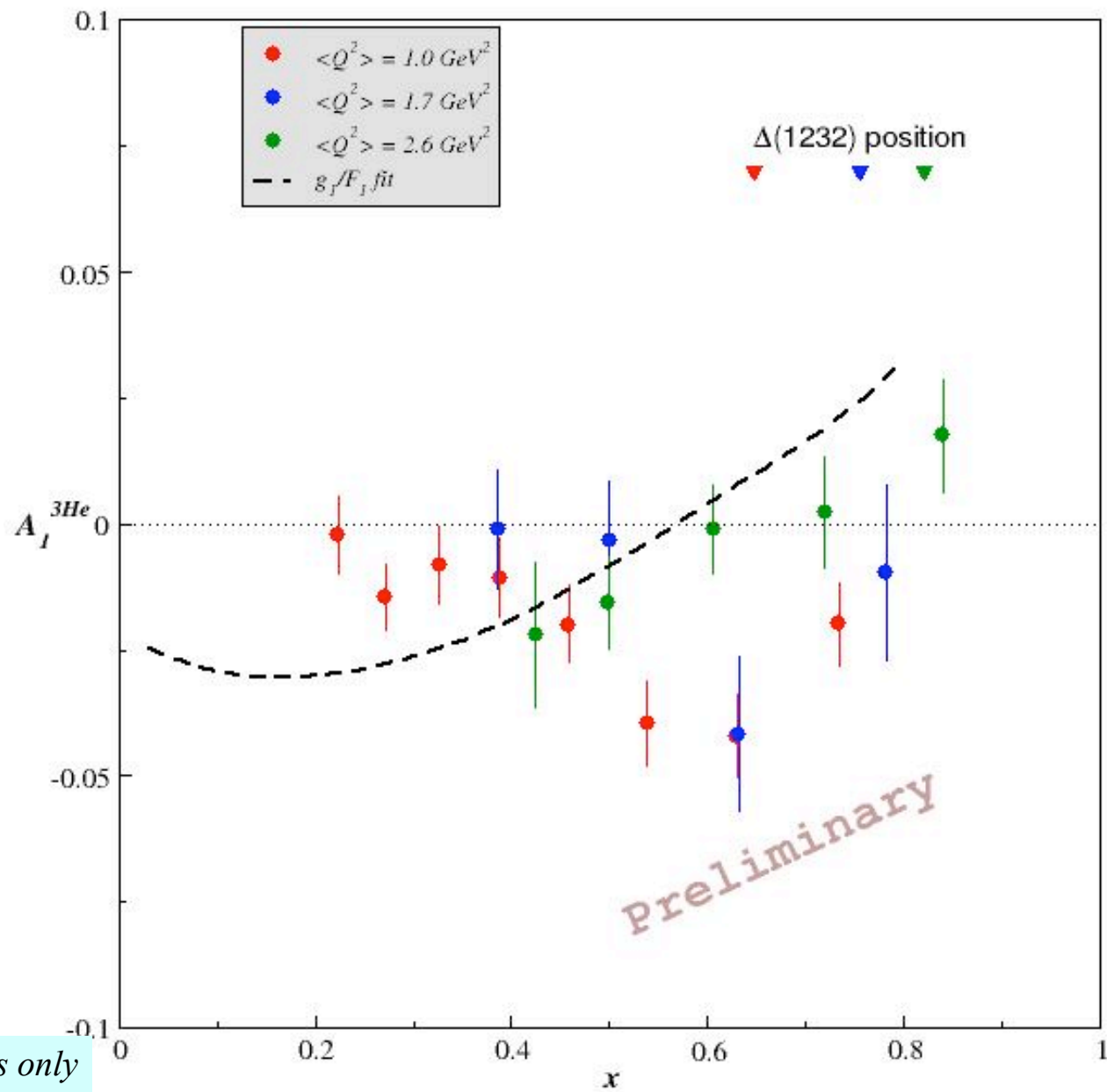
Statistical errors only

$A_1^{3\text{He}}$



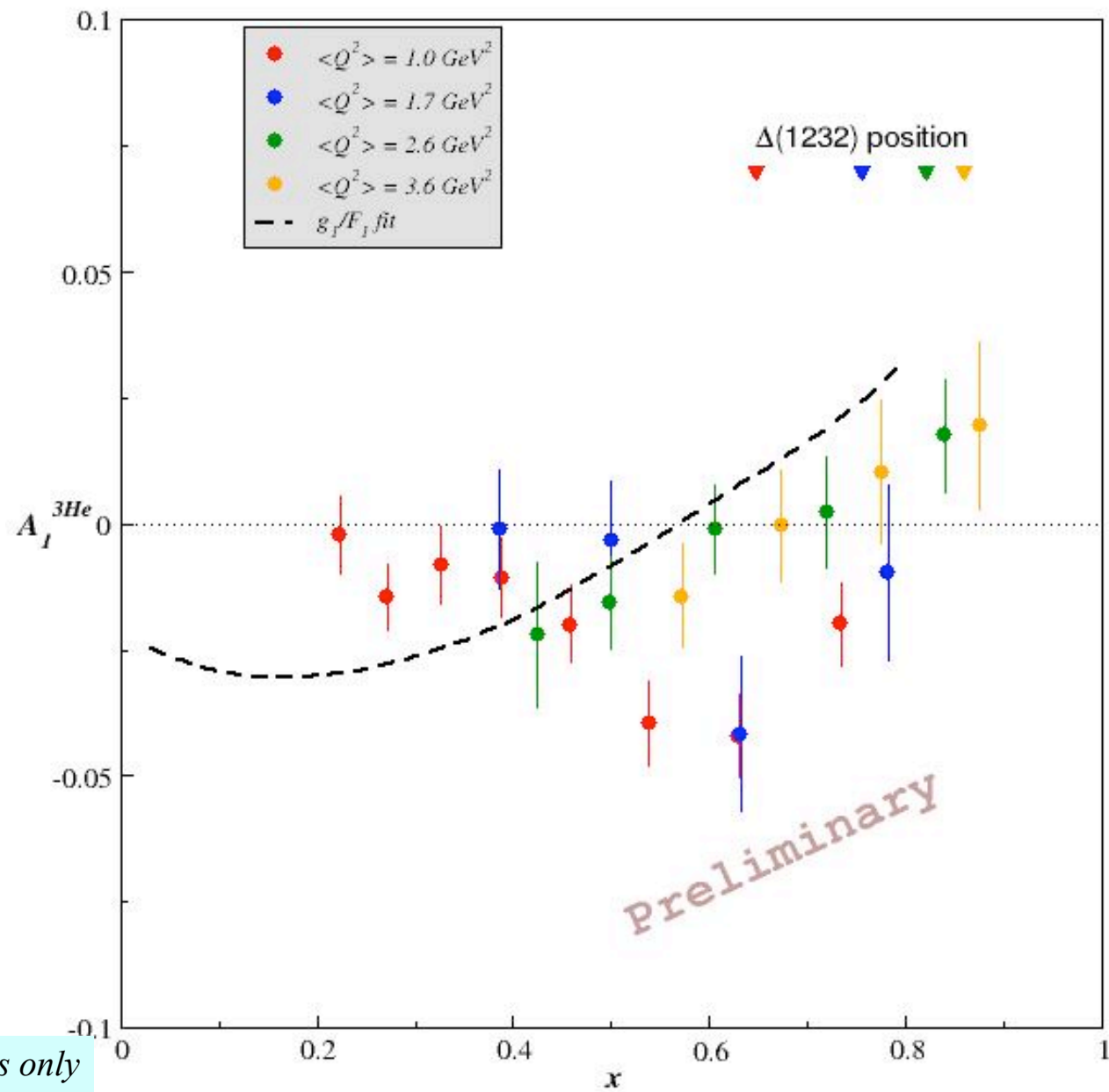
Statistical errors only

$A_1^3\text{He}$



Statistical errors only

$A_1^3\text{He}$

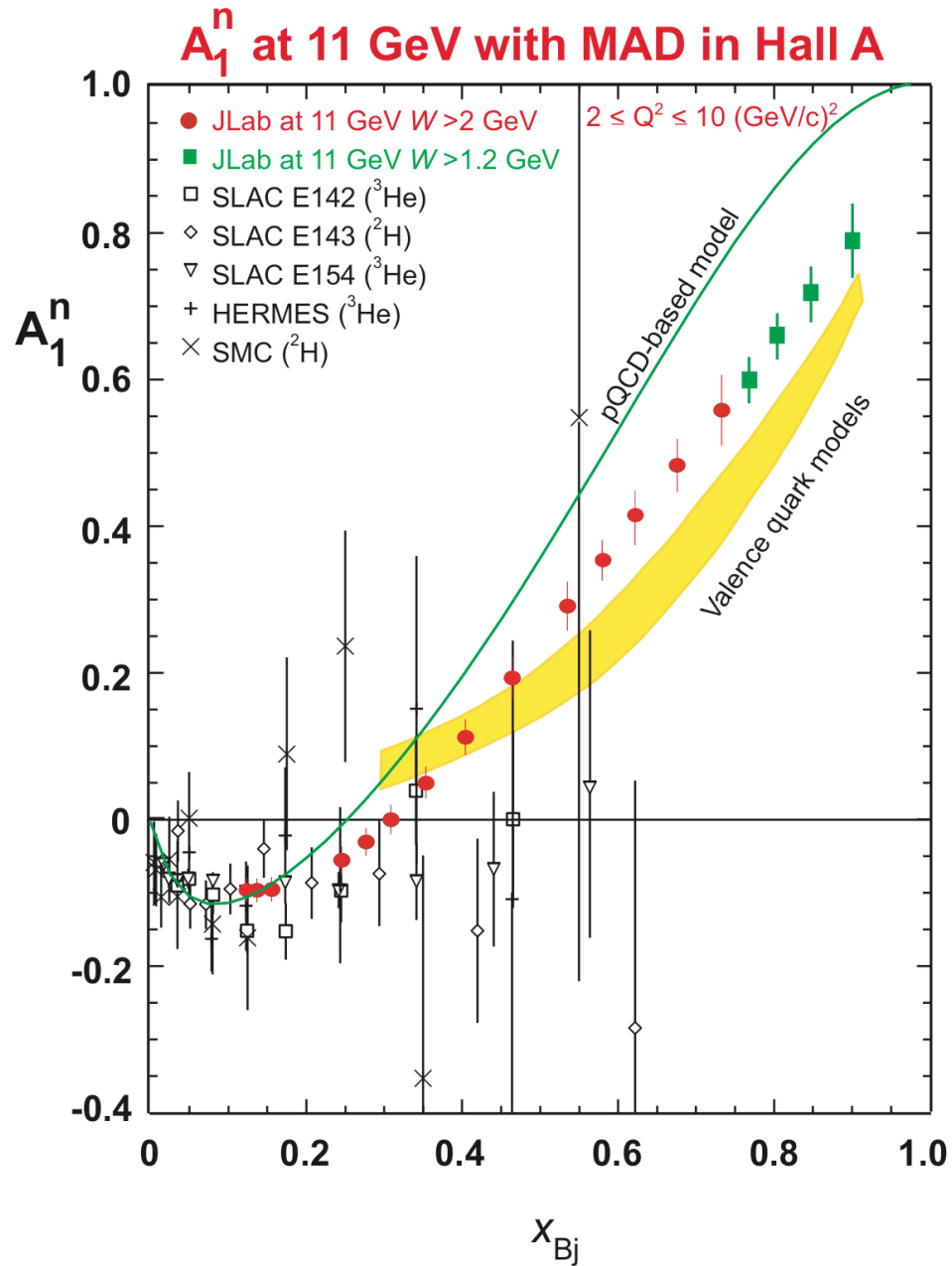


Statistical errors only

Summary

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

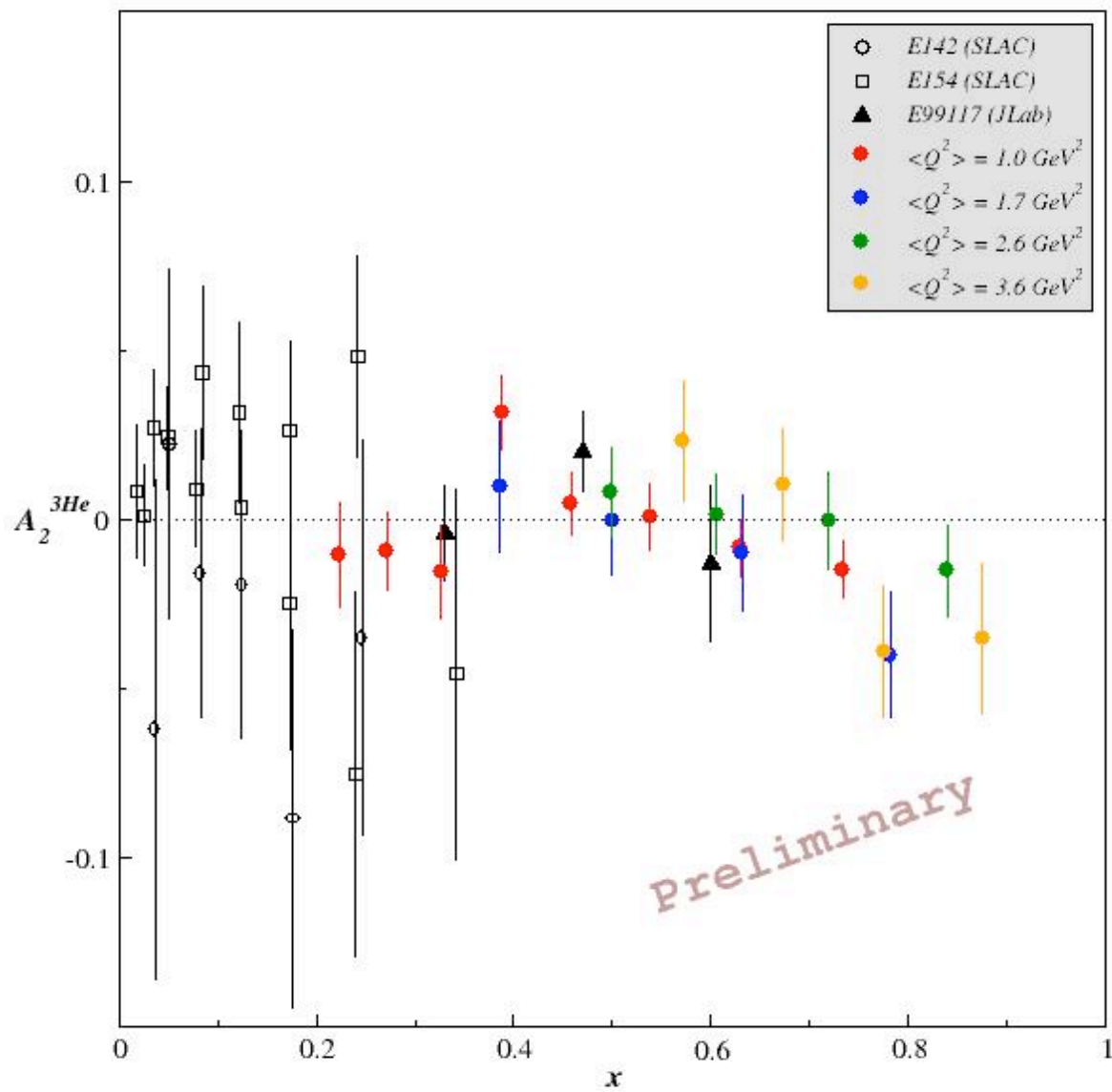


Extra Slides

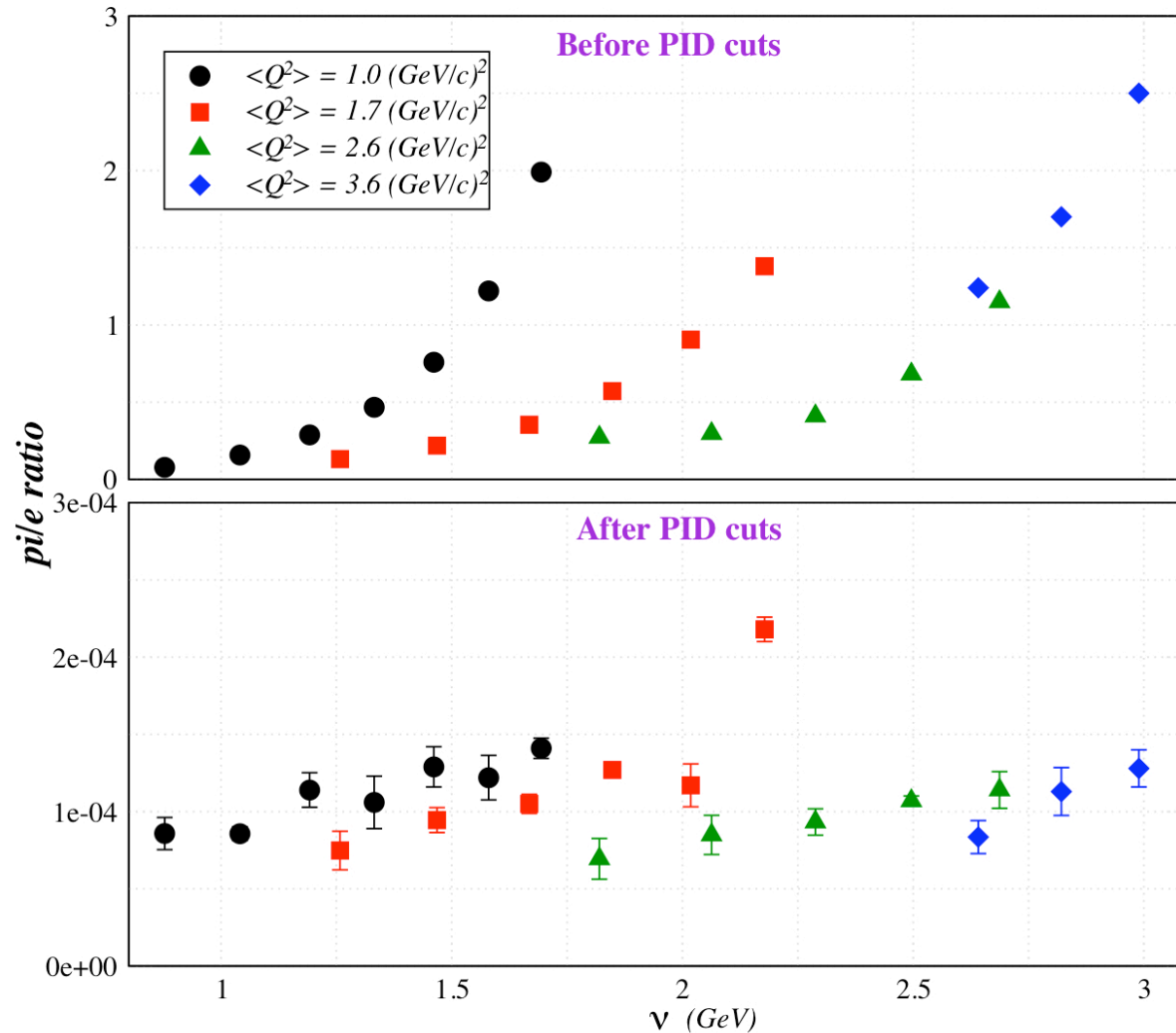
Systematics

Target	
density	1.0-2.0%
polarization	3.0-4.0%
Beam	
charge	1.0%
polarization	3.0%
energy	0.5%
N₂ dilution	0.5-1.0%
Detector efficiencies	2.5%
Acceptance	2.0-3.0%
Radiative corrections	?

$A_2^{3\text{He}}$

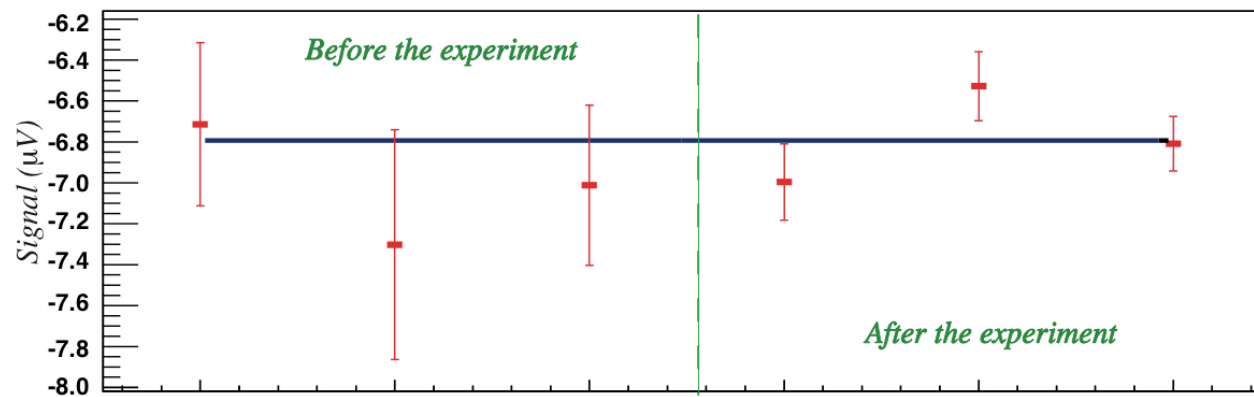
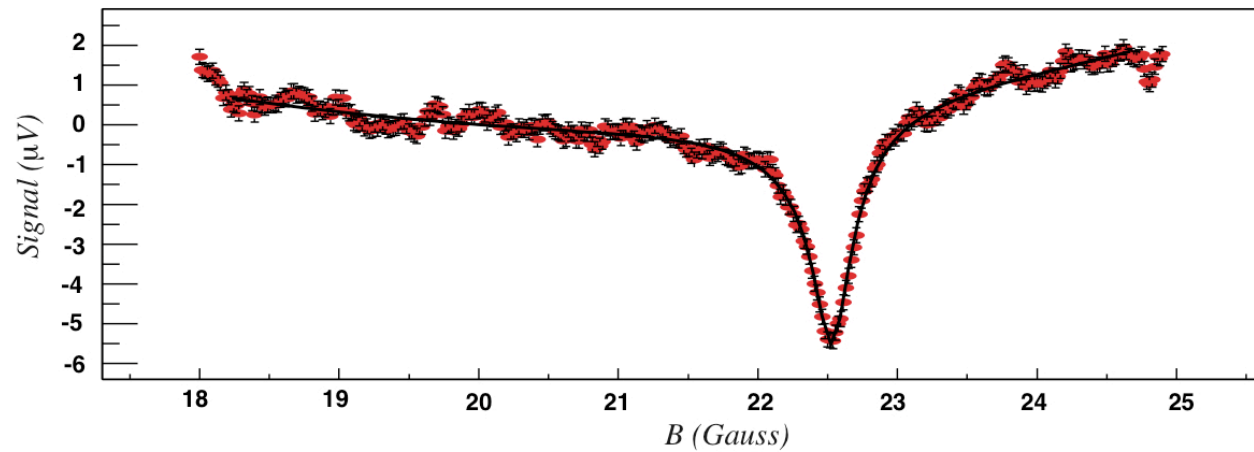


Particle identification performance



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

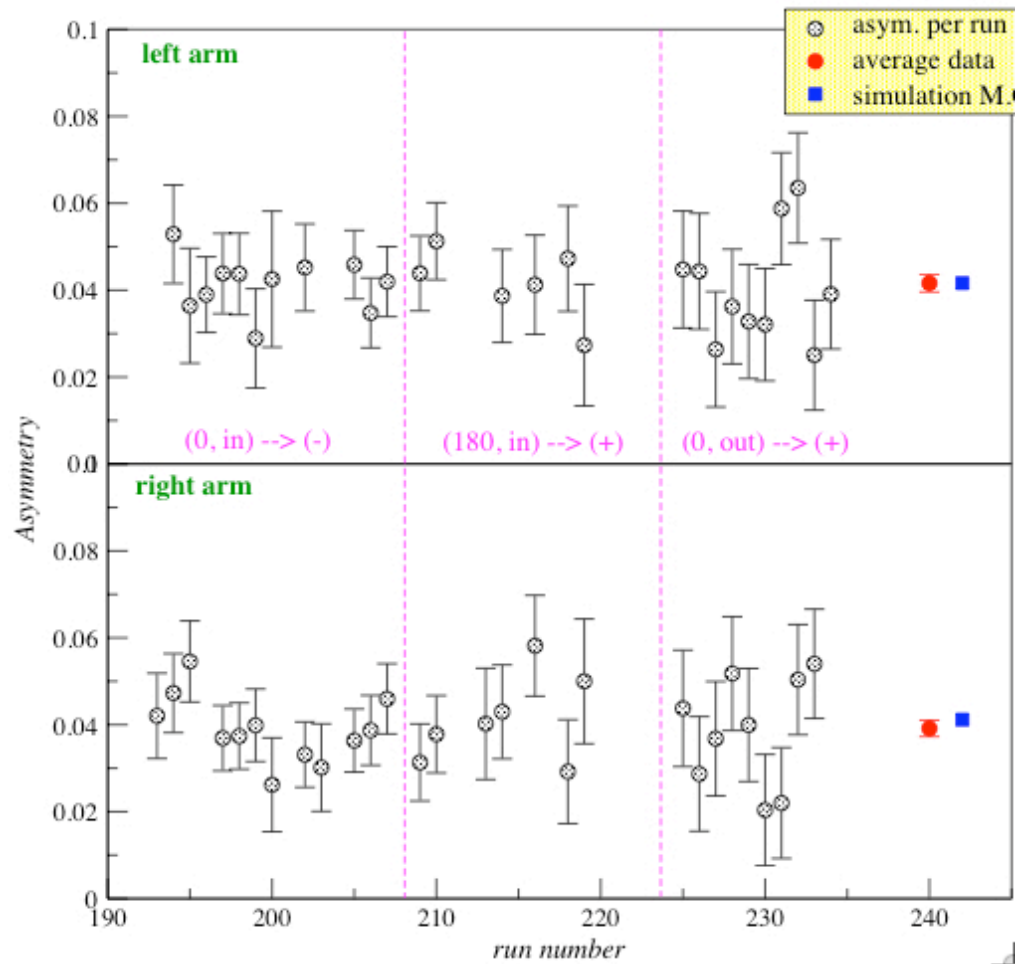
NMR: water calibration



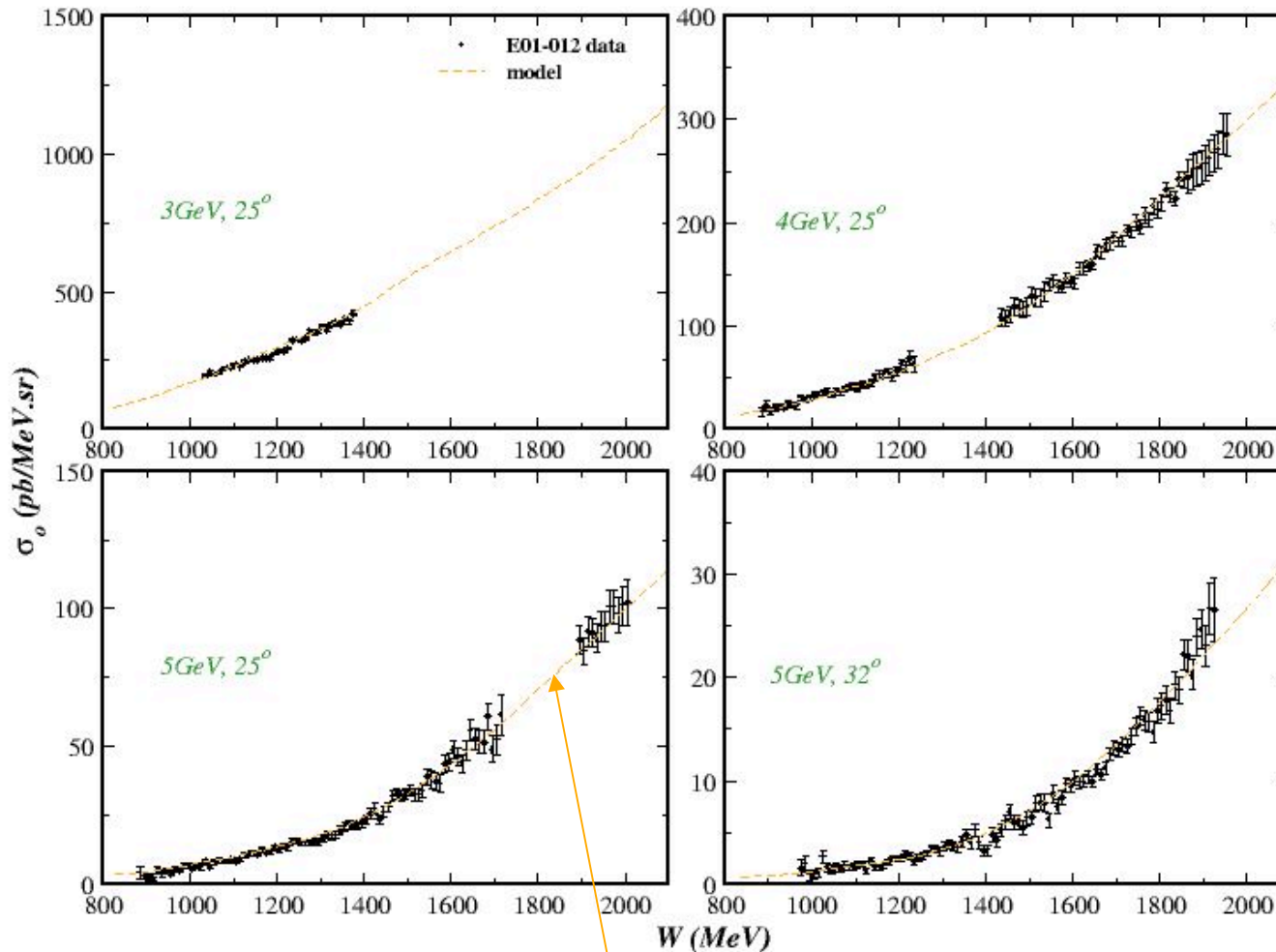
NMR analysis done by Vince Sulkosky

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