

# **Study of Quark-Hadron Duality on Neutron and $^3\text{He}$ Spin Structure Functions**

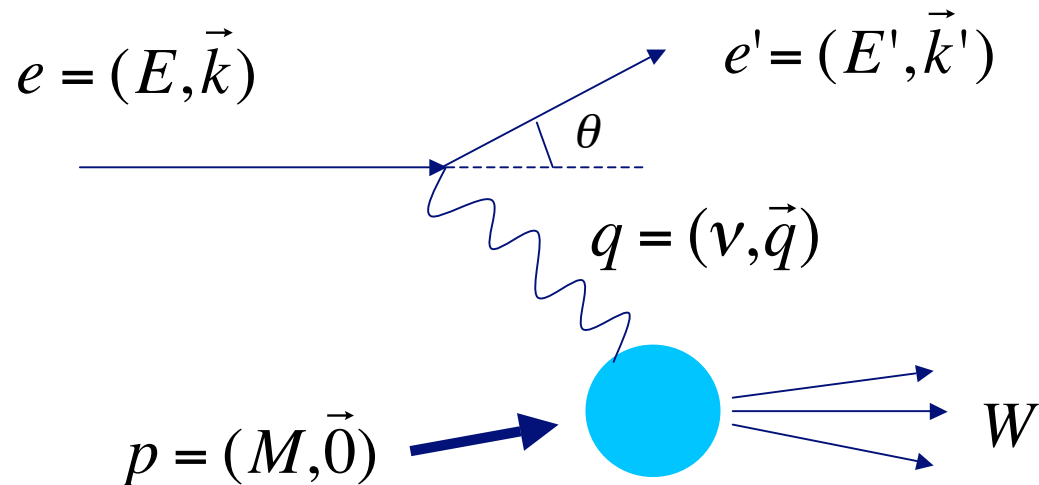
**Patricia Solvignon**  
Temple University

**Hall A Interview Seminar**  
Jefferson Lab, Newport News  
March 24, 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  $^3\text{He}$

# Inclusive Electron Scattering



Photon momentum transfer

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

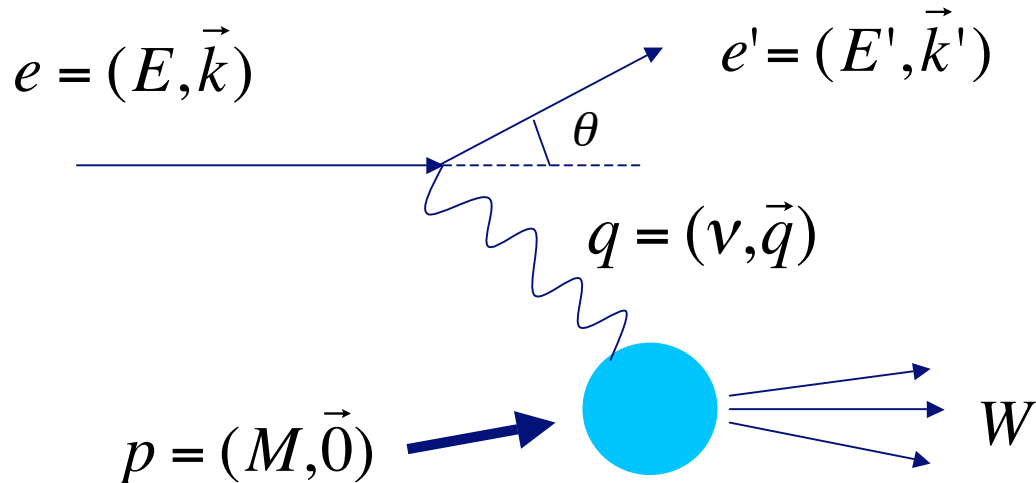
Invariant mass squared

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

Bjorken variable

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

# Inclusive Electron Scattering



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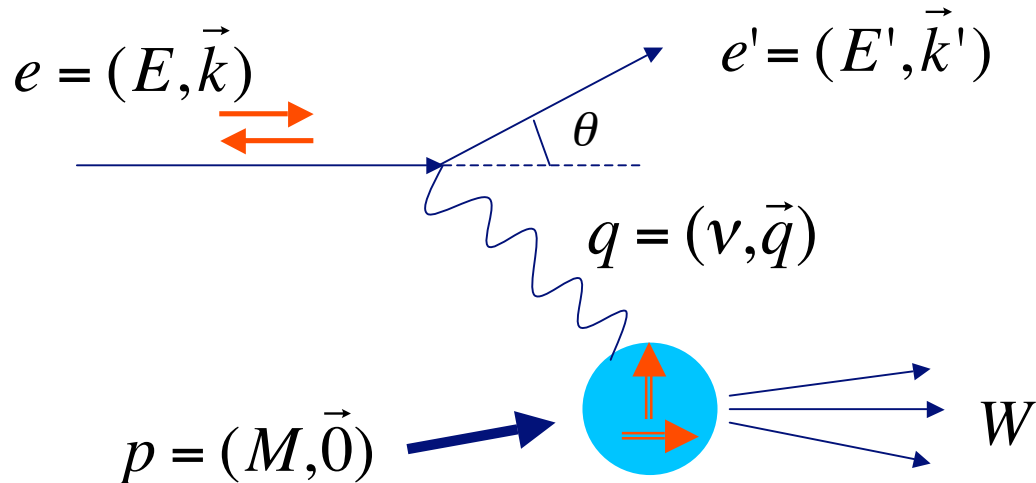
$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable

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

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

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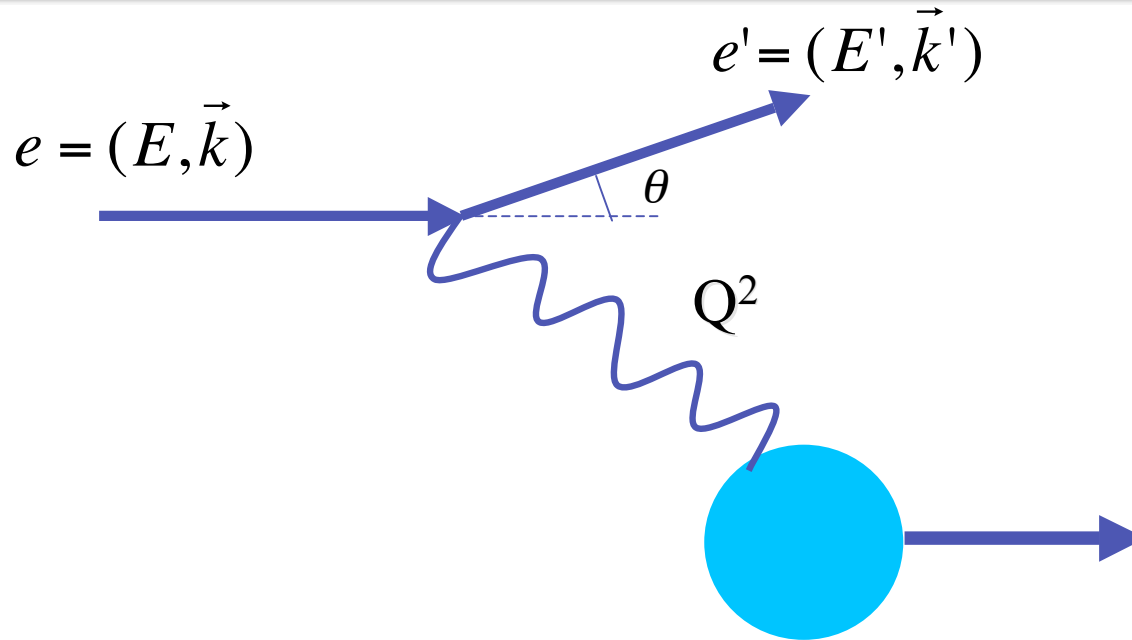
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*Polarized case*  $\left\{ \begin{aligned} \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\uparrow}}{d\Omega dE'} &= \frac{4\alpha^2 E'}{\nu EQ^2} \left[ (E + E' \cos \theta) g_1(x, Q^2) - 2Mx g_2(x, Q^2) \right] \\ \frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega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

# Resonance region

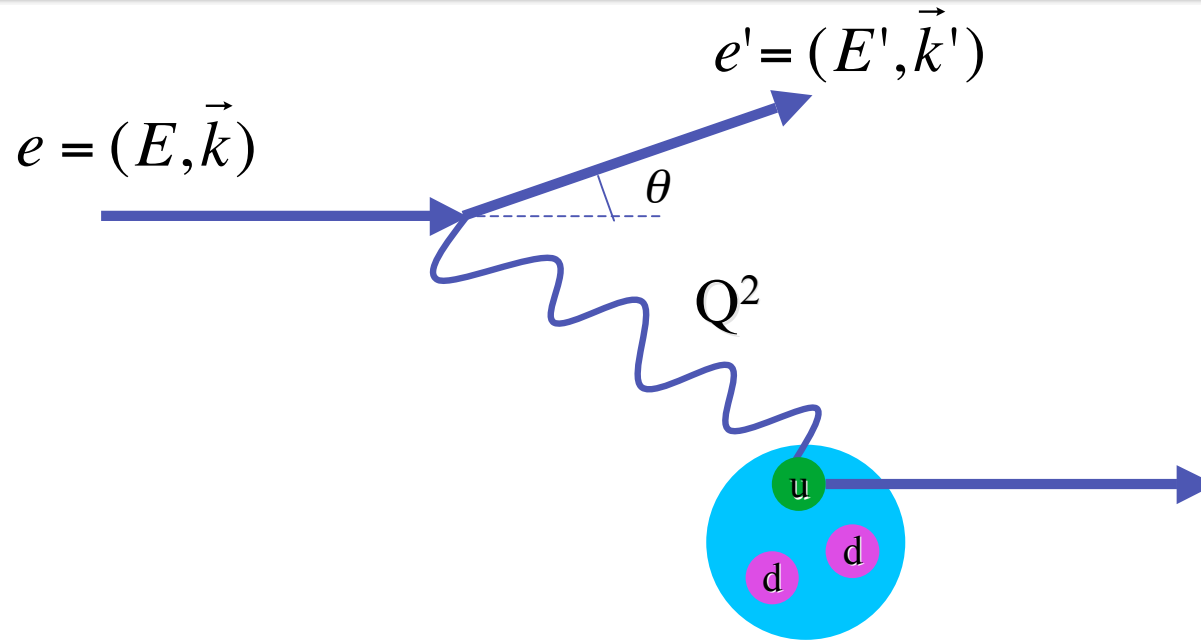


Low  $Q^2$  and  $W < 2 \text{ GeV}$ : coarse resolution  $\rightarrow$  we don't see partons.

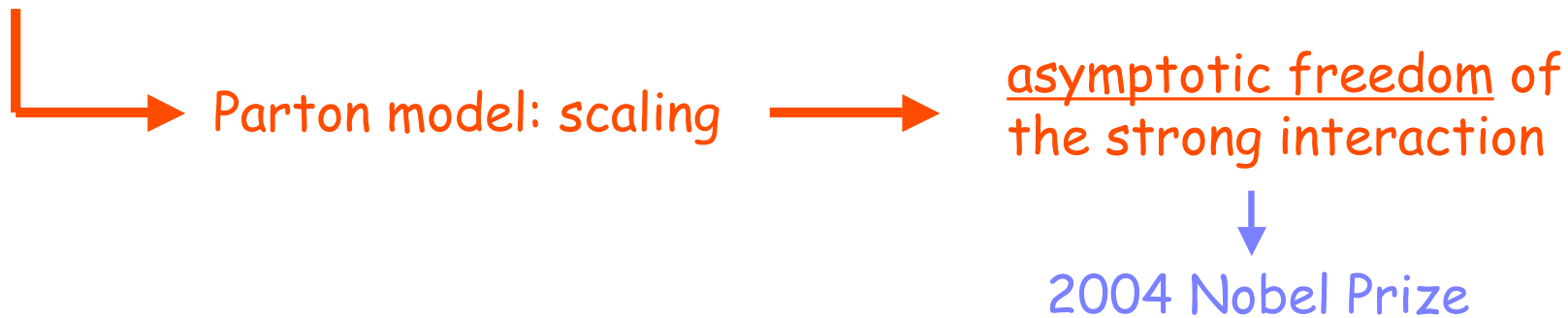


The nucleon goes through different excited states:  
the resonances

# 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 $F_2$

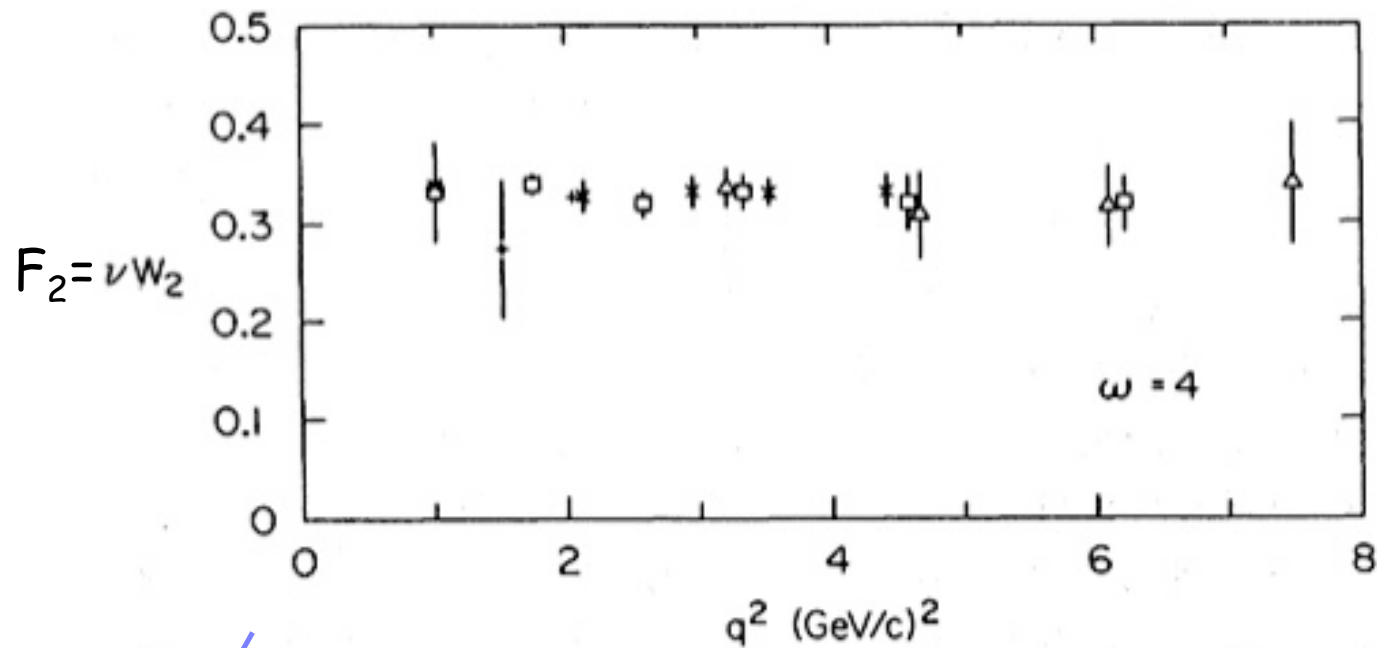


Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

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

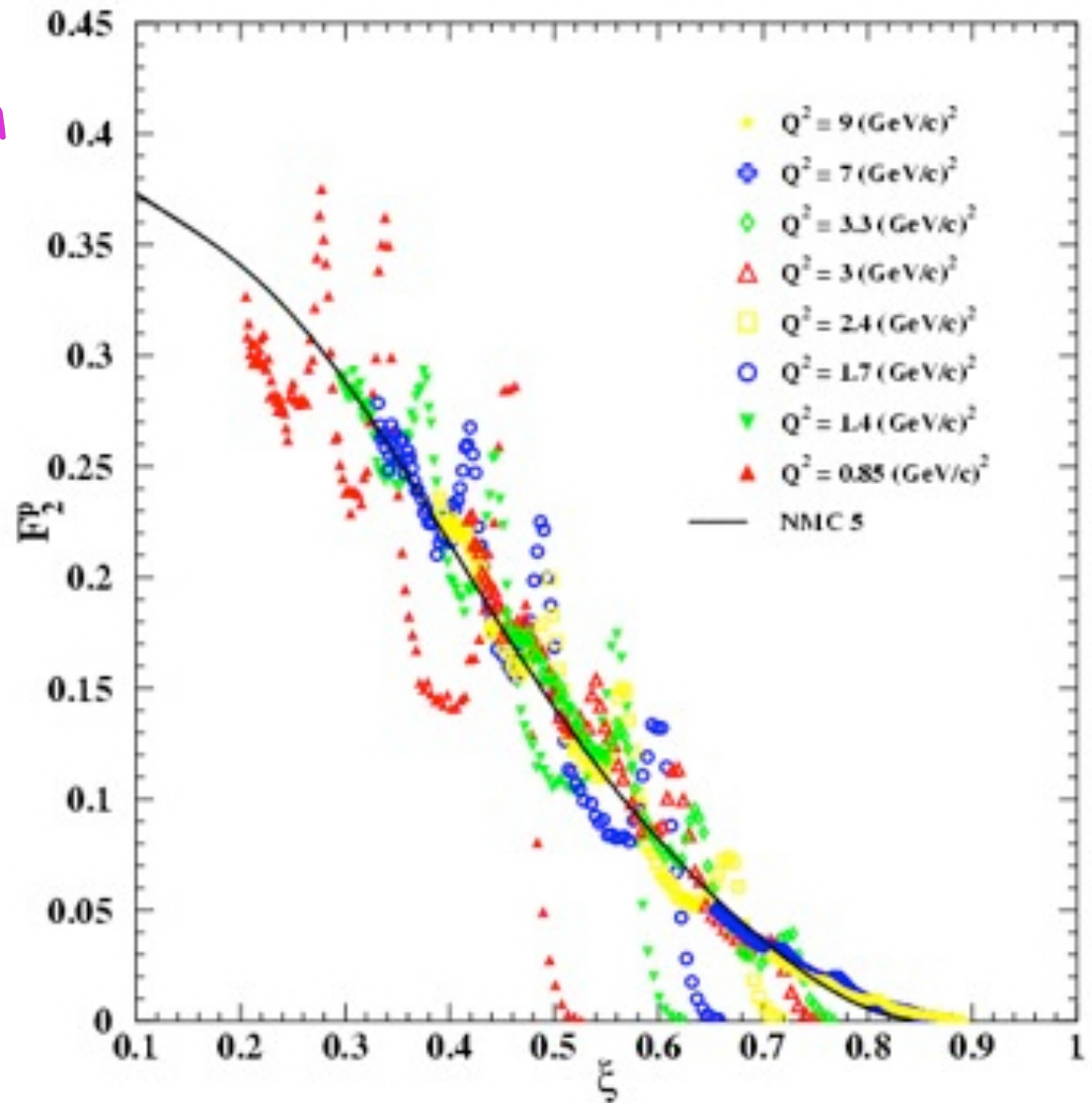
$$F_1(x) = \frac{1}{2} \sum_i e_i^2 q_i(x) = \frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) + q_i^\downarrow(x)] = \frac{1}{2x} F_2(x)$$

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

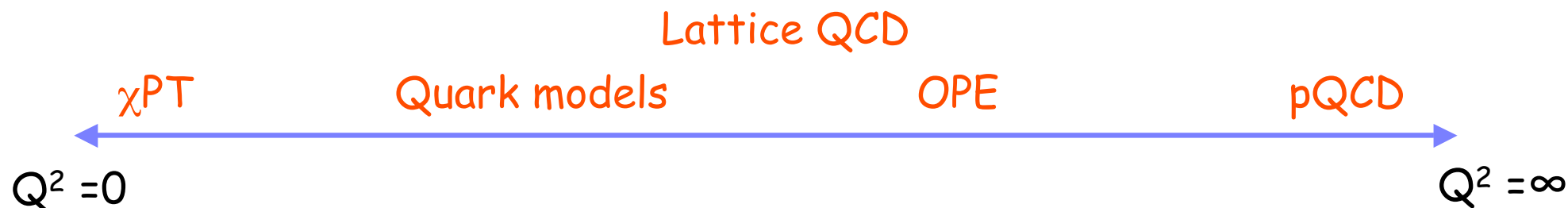
No simple partonic distribution for  $g_2(x, Q_2)$

# 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):

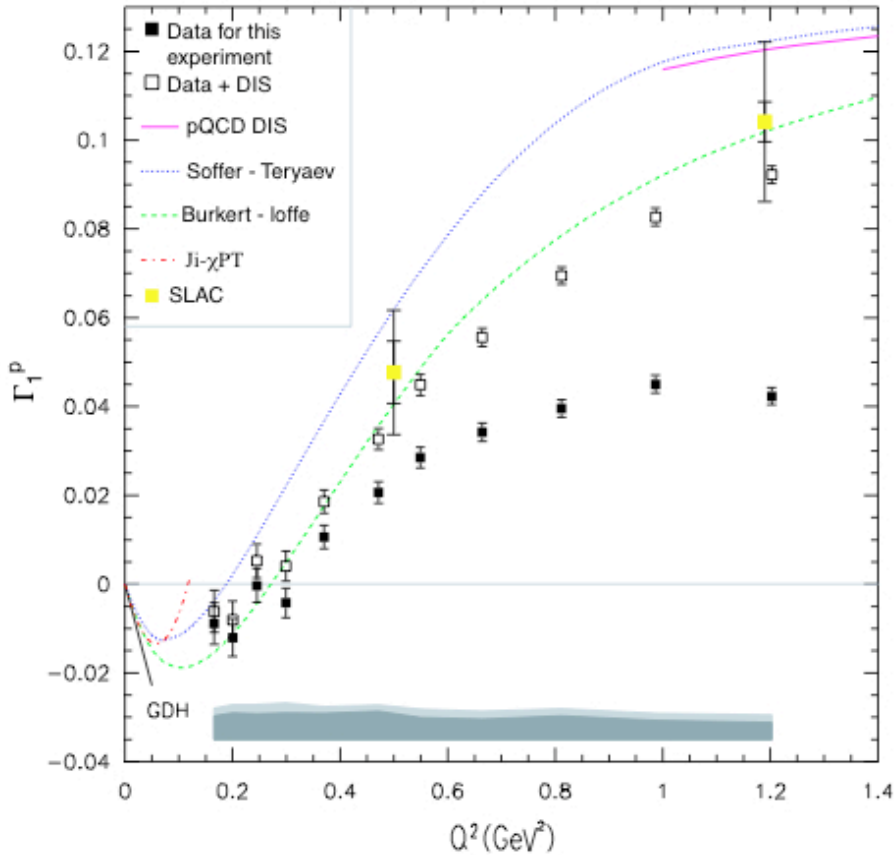
→ investigate several scenarios with suppression of:

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

# Scaling of $g_1$ moments

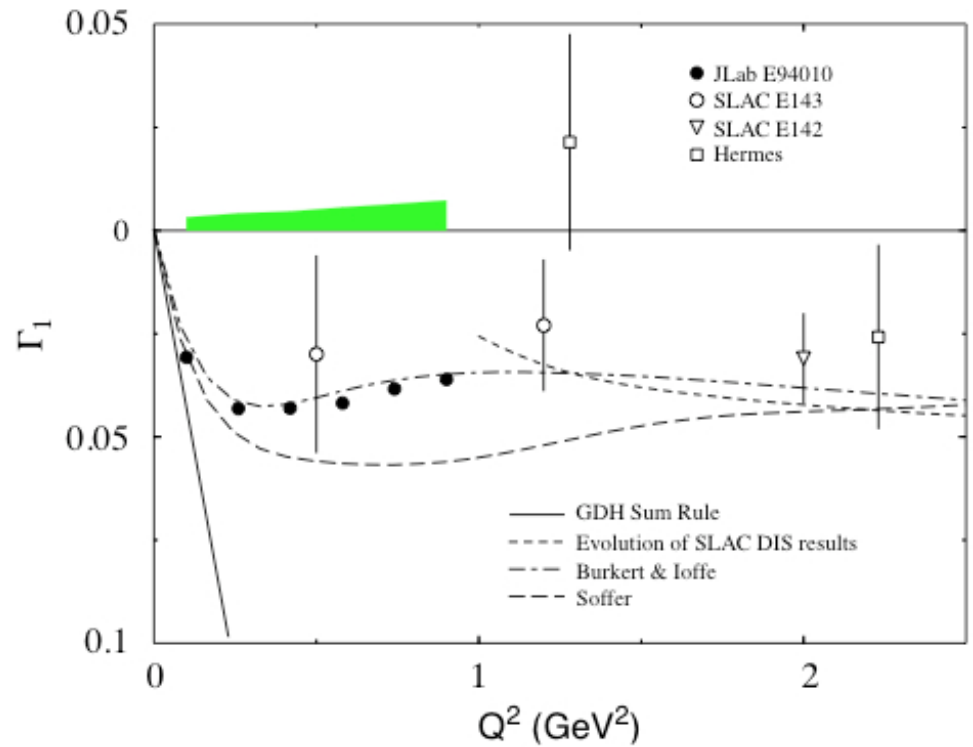
$$\Gamma_1(Q^2) = \int g_1(x, Q^2) dx$$

proton



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

neutron

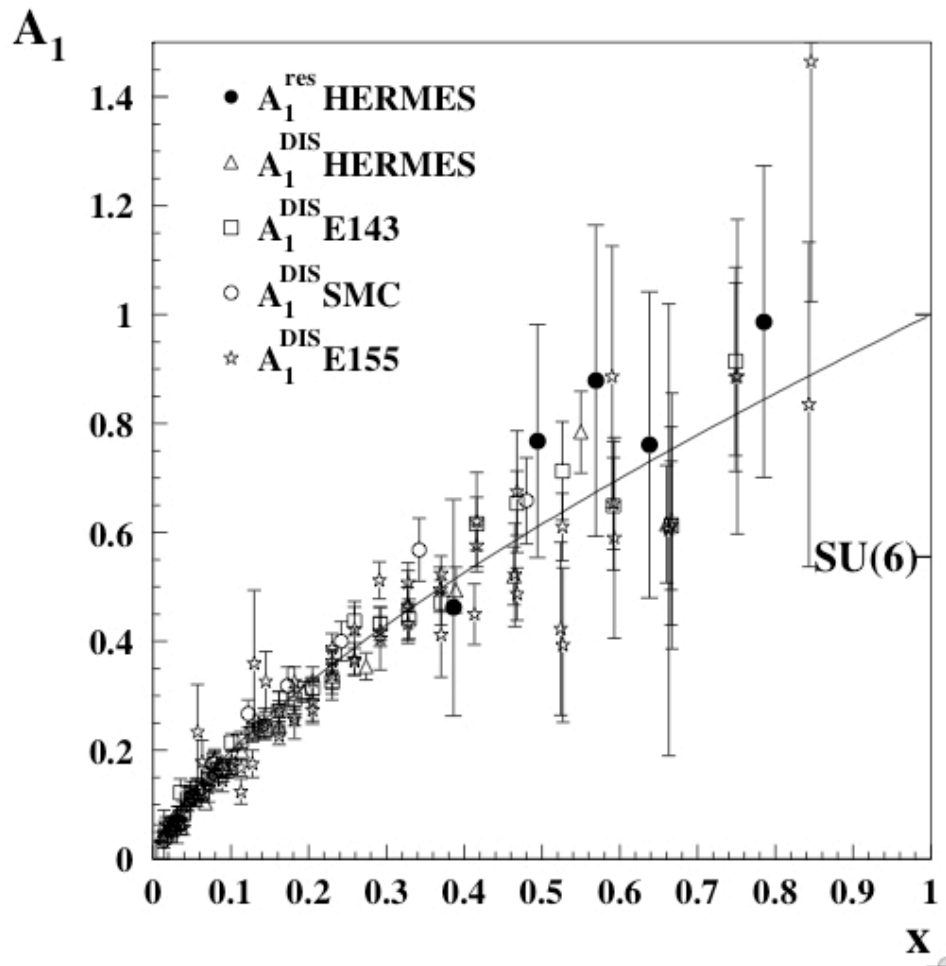


M. Amerian et al., PRL 859(2002) 242301

# World data

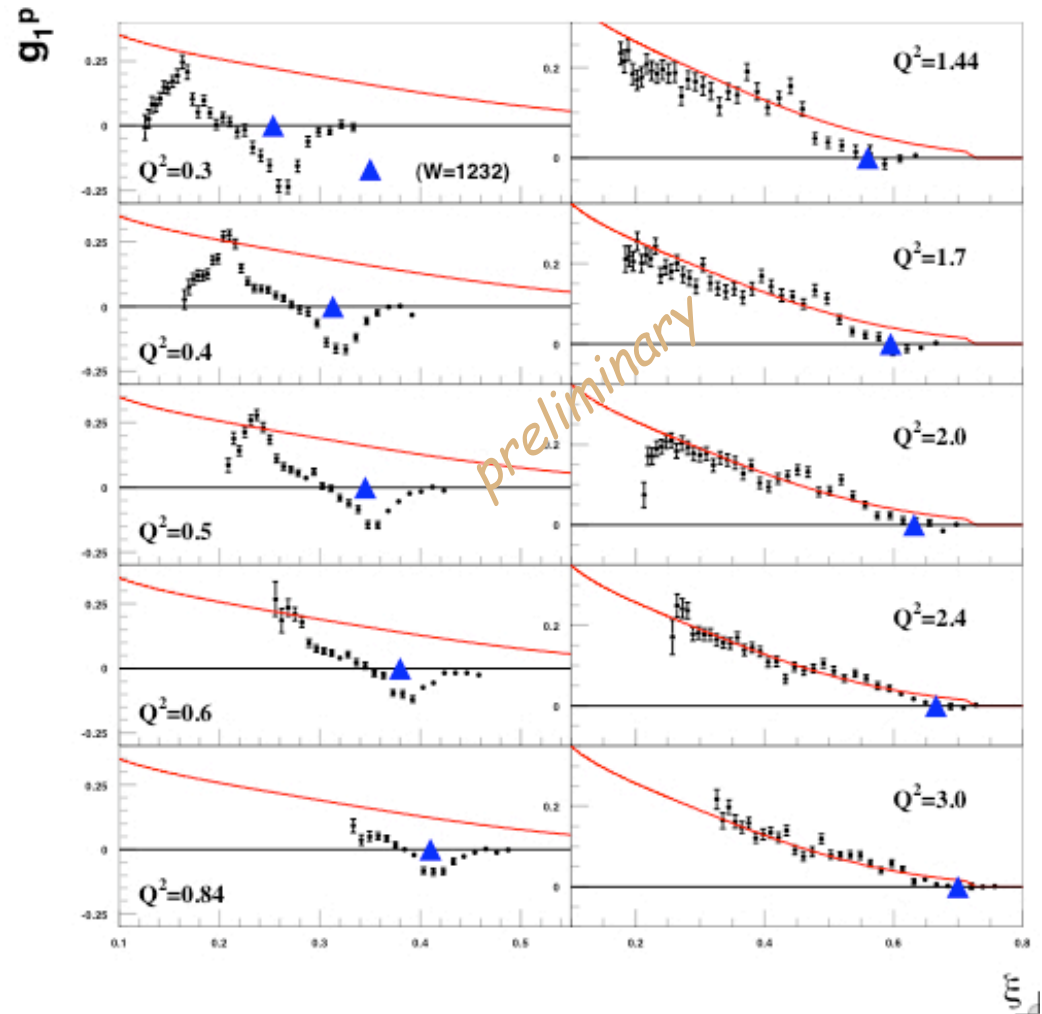
## HERMES for $A_1^p$

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



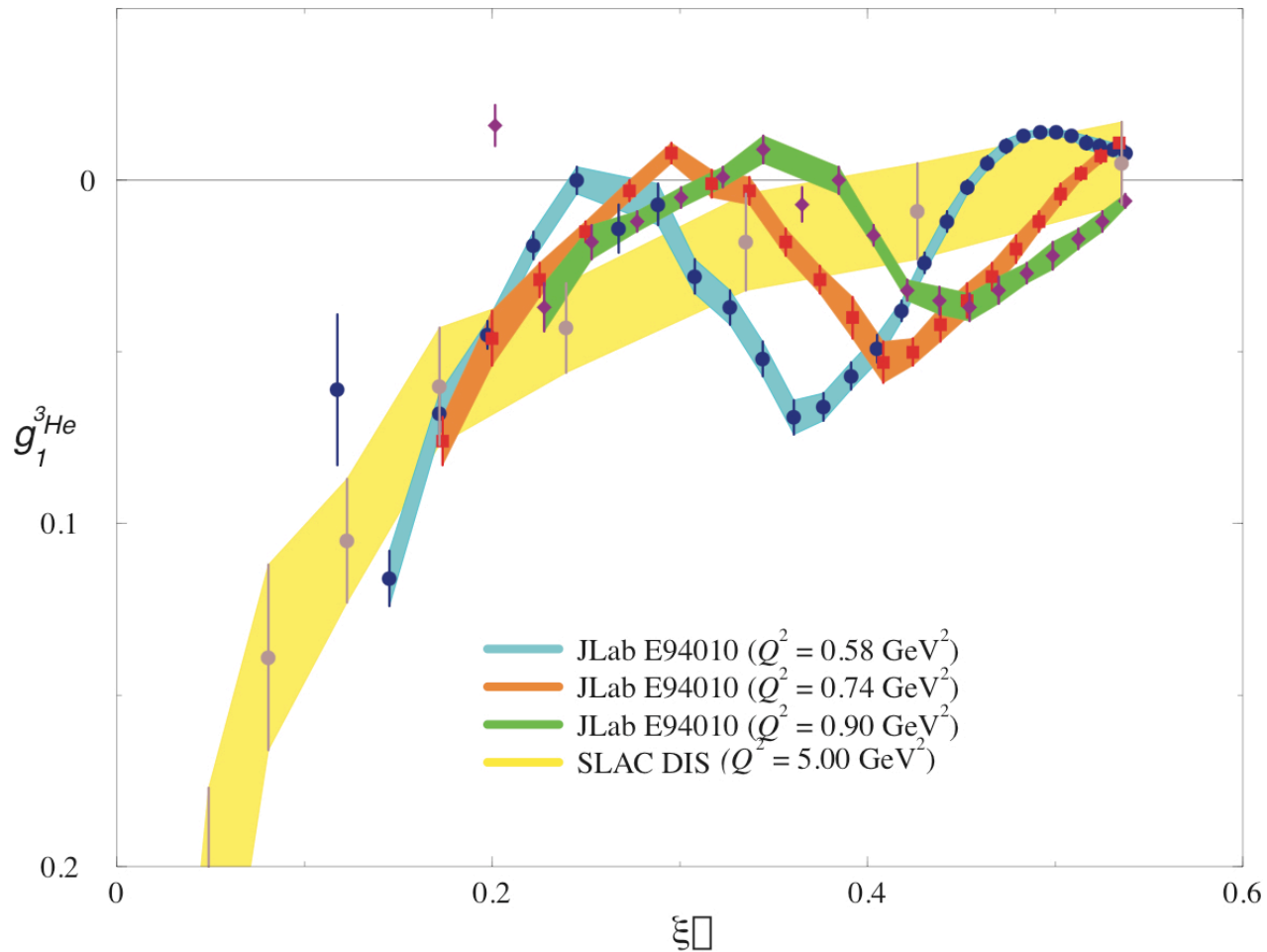
## Jlab Hall B for $g_1^p$

From DIS 2005 proceedings



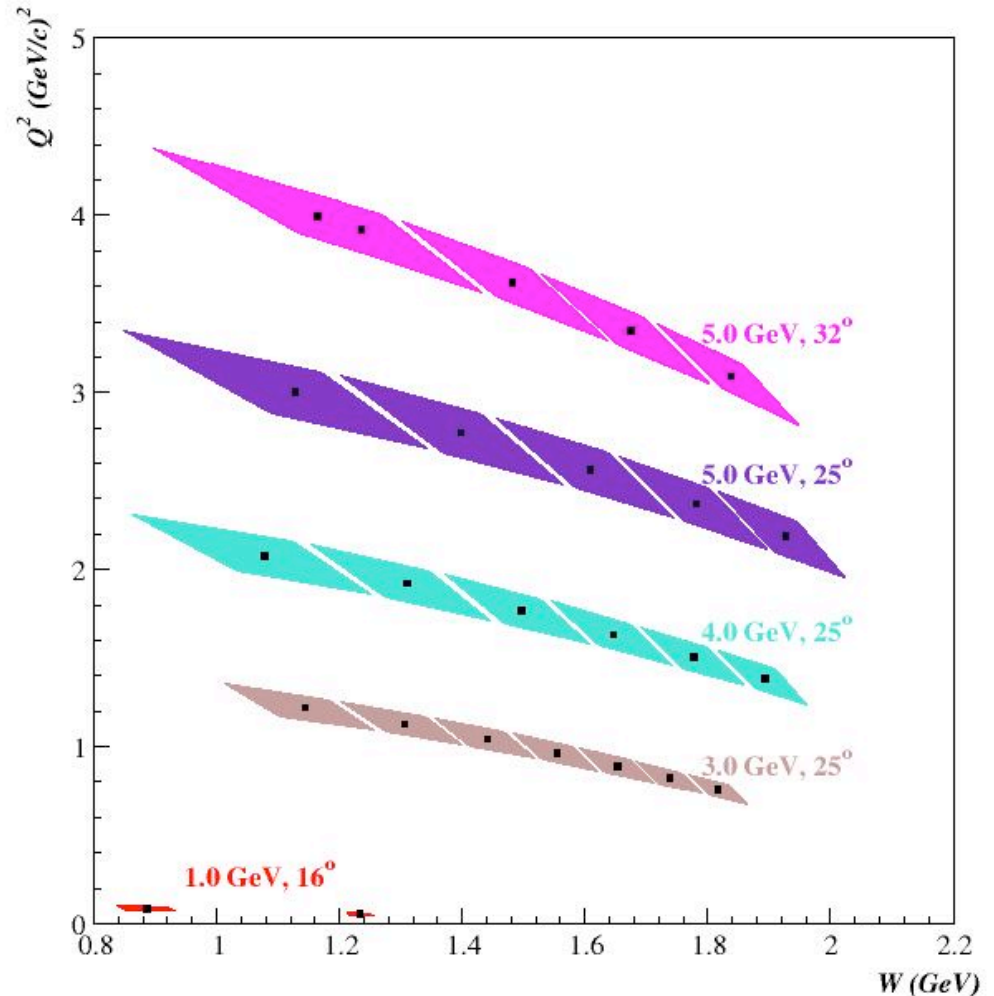
# World data

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



# The experiment E01-012

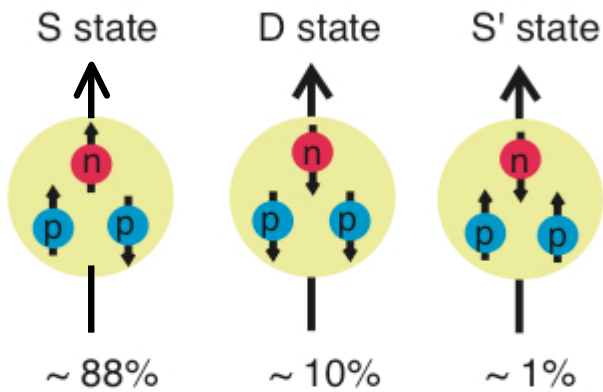
- Ran in Jan.-Feb. 2003
- Inclusive experiment:  
 ${}^3\vec{He}(\vec{e}, e')X$
- Measured polarized cross section differences
- Form  $g_1$  and  $g_2$



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

# $^3\text{He}$ as an effective neutron target

## $^3\text{He}$ 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

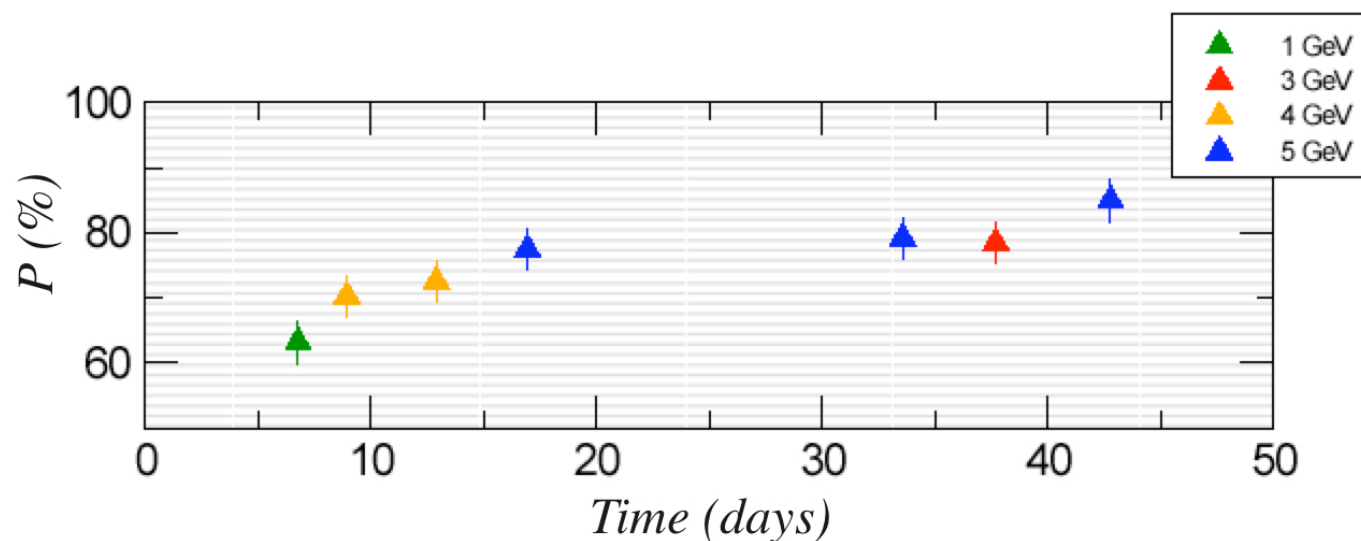
*and the Jefferson Lab Hall A Collaboration*

# Experimental setup

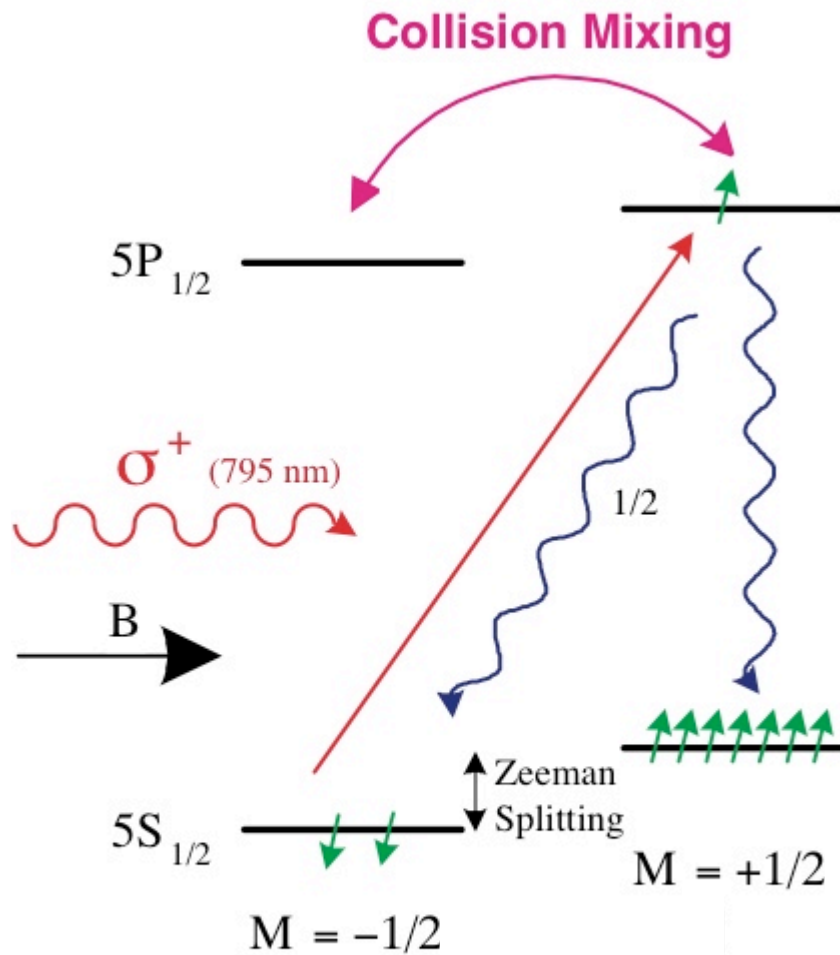
- Polarized electron beam
- Standard Hall A equipment:
  - Both HRS in symmetric configuration
    - ↳ double the statistics
    - ↳ control the systematics
  - Particle ID = Cerenkov + EM calorimeter
    - ↳  $\pi/e$  reduced by  $10^4$
- Polarized  $^3\text{He}$  target

# Electron Beam Polarization

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



# How to polarize $^3\text{He}$ ?



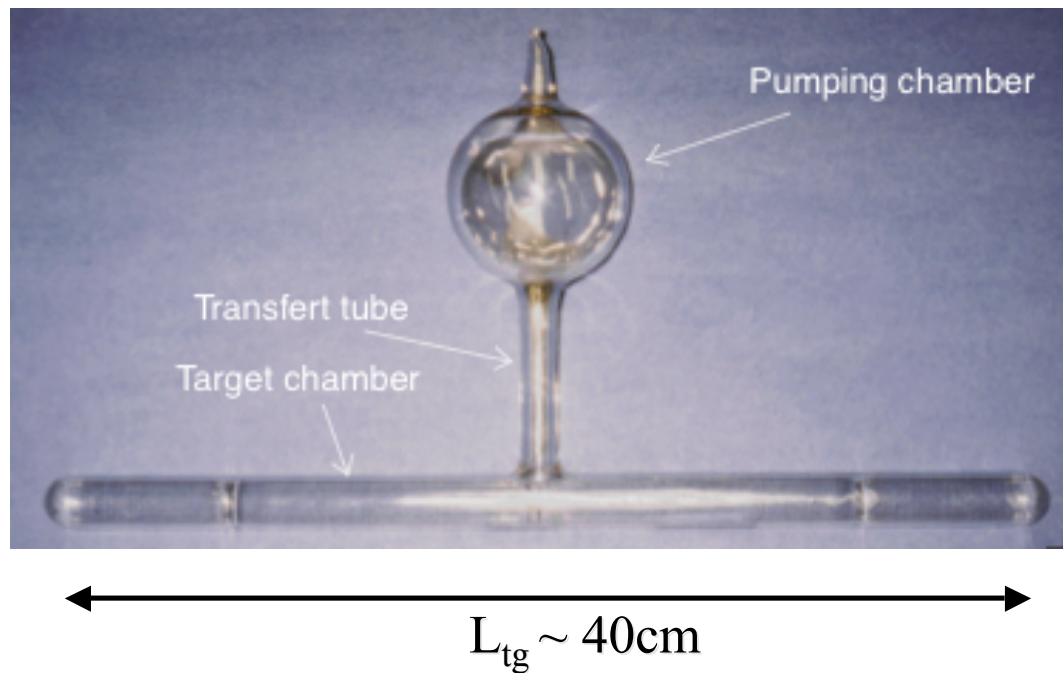
Two step process:

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

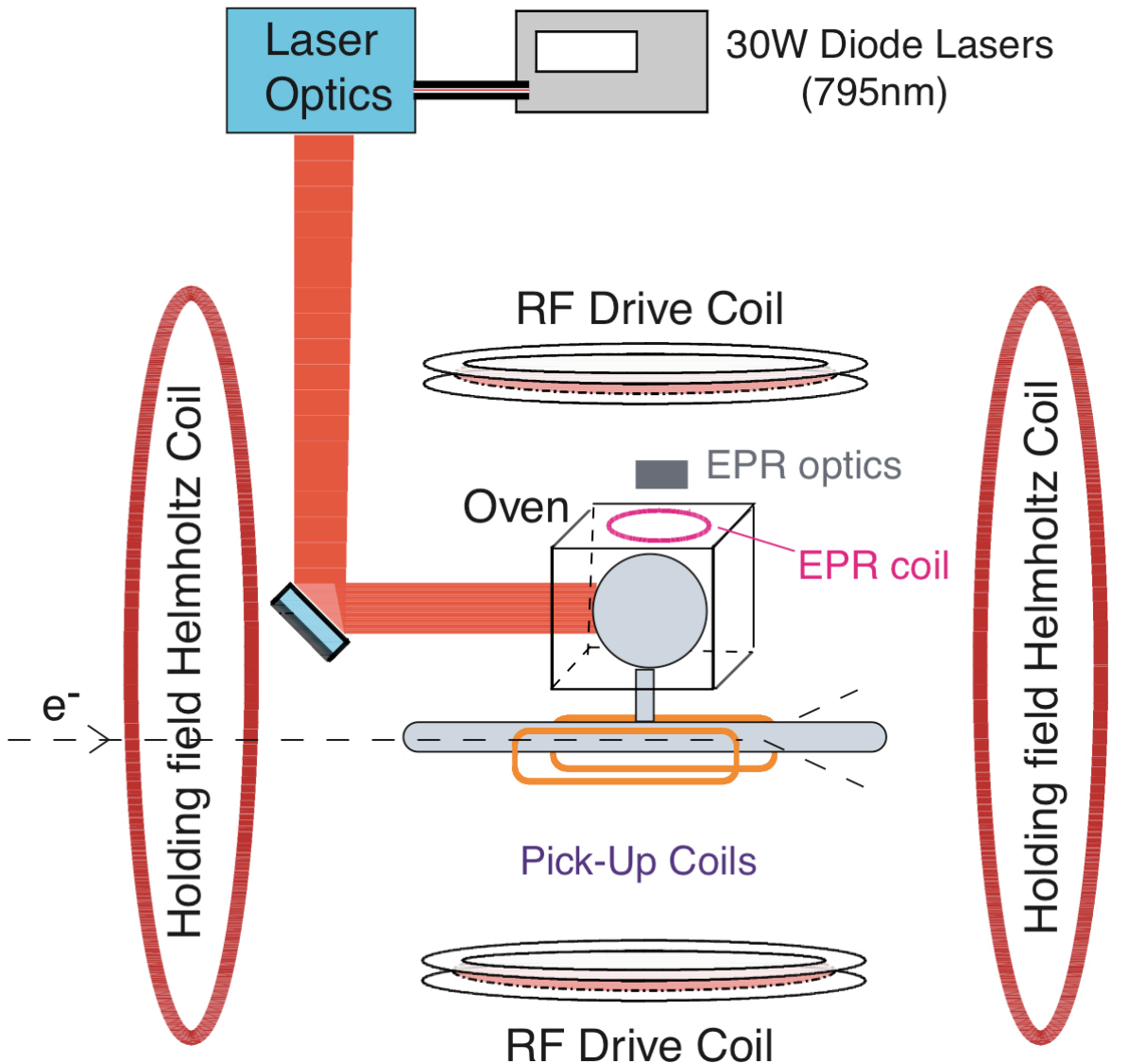
A small amount of  $\text{N}_2$  is added for quenching

# The polarized $^3\text{He}$ target

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



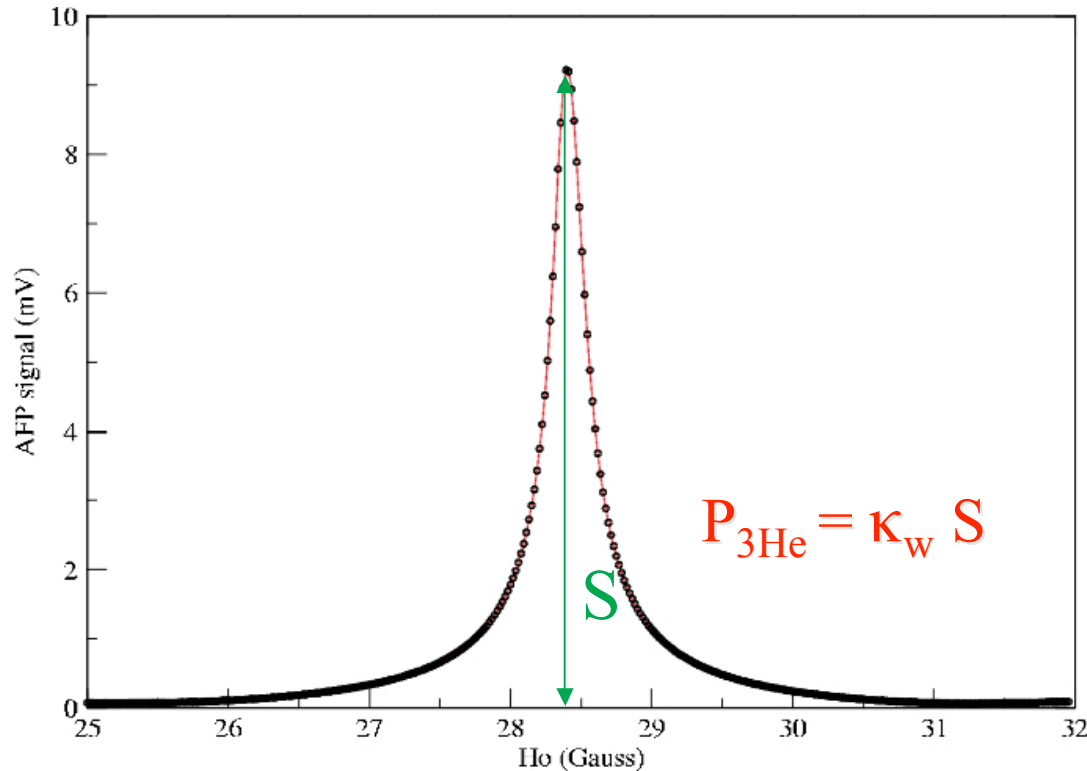
# The polarized $^3\text{He}$ system



◆ Longitudinal and transverse configurations

◆ 2 independent polarimetrys:  
NMR and EPR

# Nuclear Magnetic Resonance



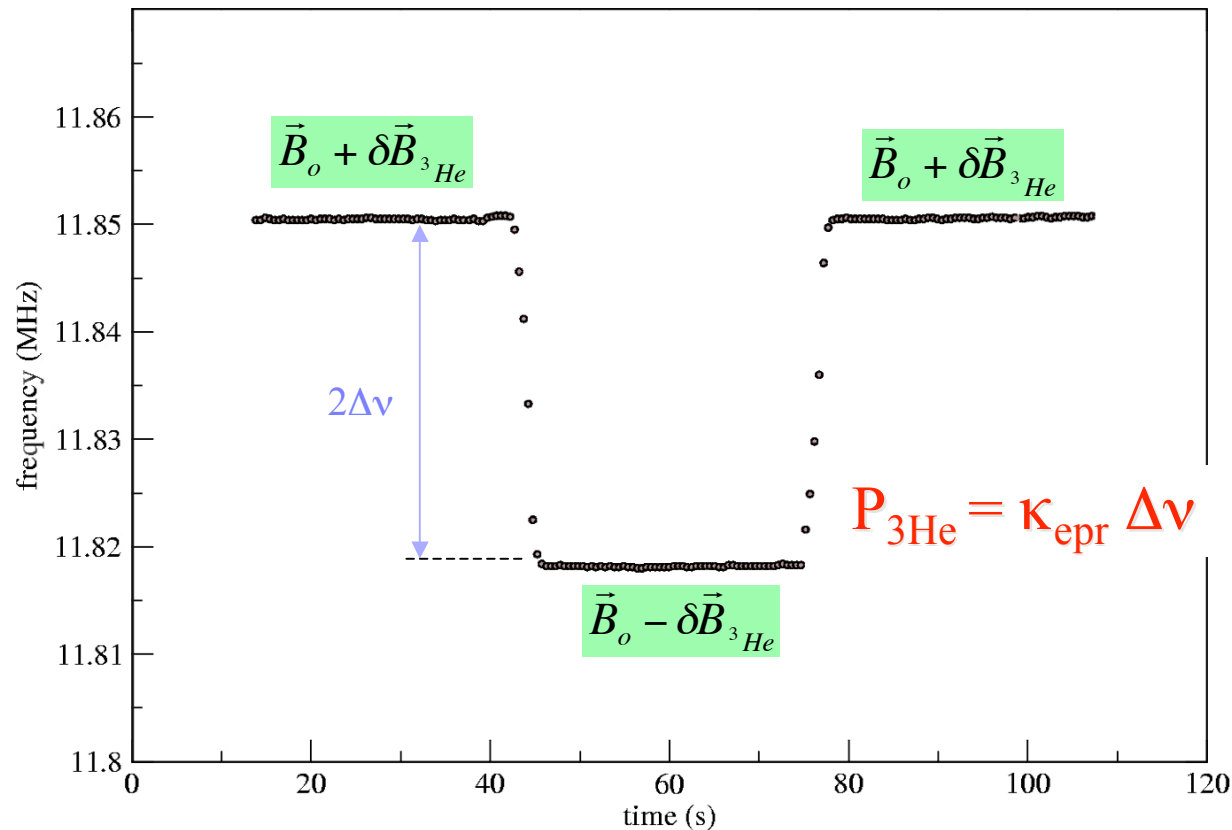
$\kappa_w$ : from calibration with an identical target cell filled with water

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

} flip the  $^3\text{He}$  spins under AFP conditions

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

# Electron Paramagnetic Resonance

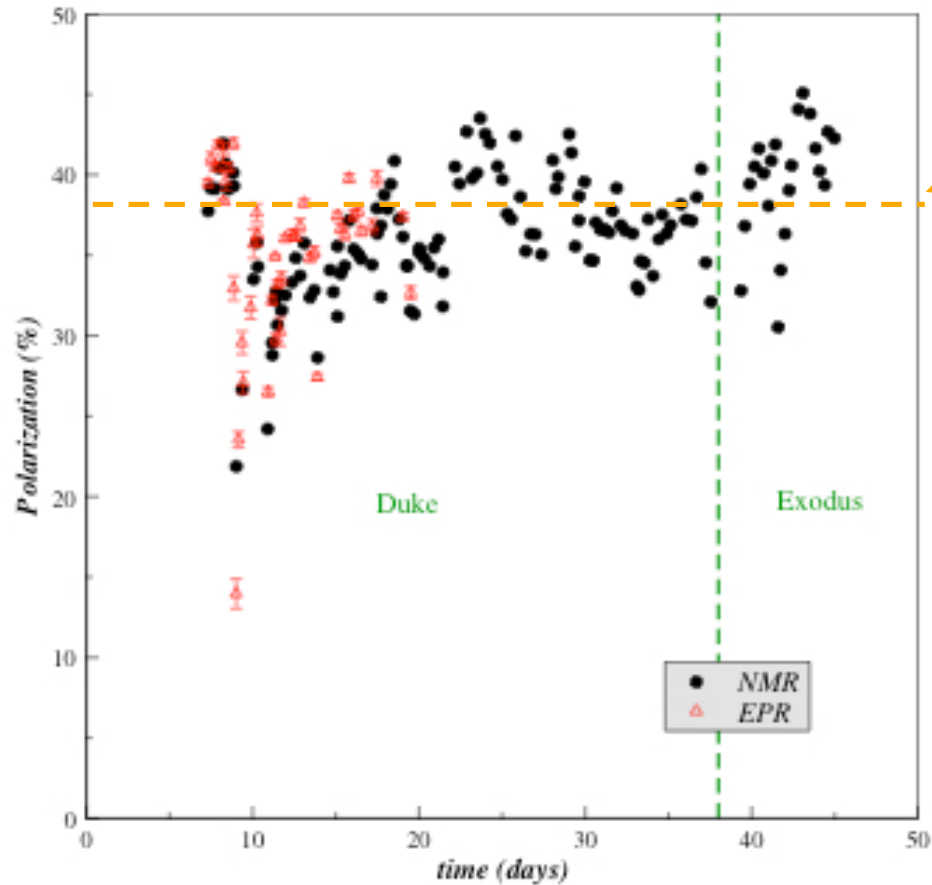


1. Polarized  $^3\text{He}$  creates an extra magnetic field:  $\delta B_{3\text{He}}$
2. Measure the Zeeman splitting frequency when  $B_0$  and  $\delta B_{3\text{He}}$  are aligned and anti-aligned.

$\kappa_{\text{epr}}$  : depend of cell density and holding field.



# Target performance

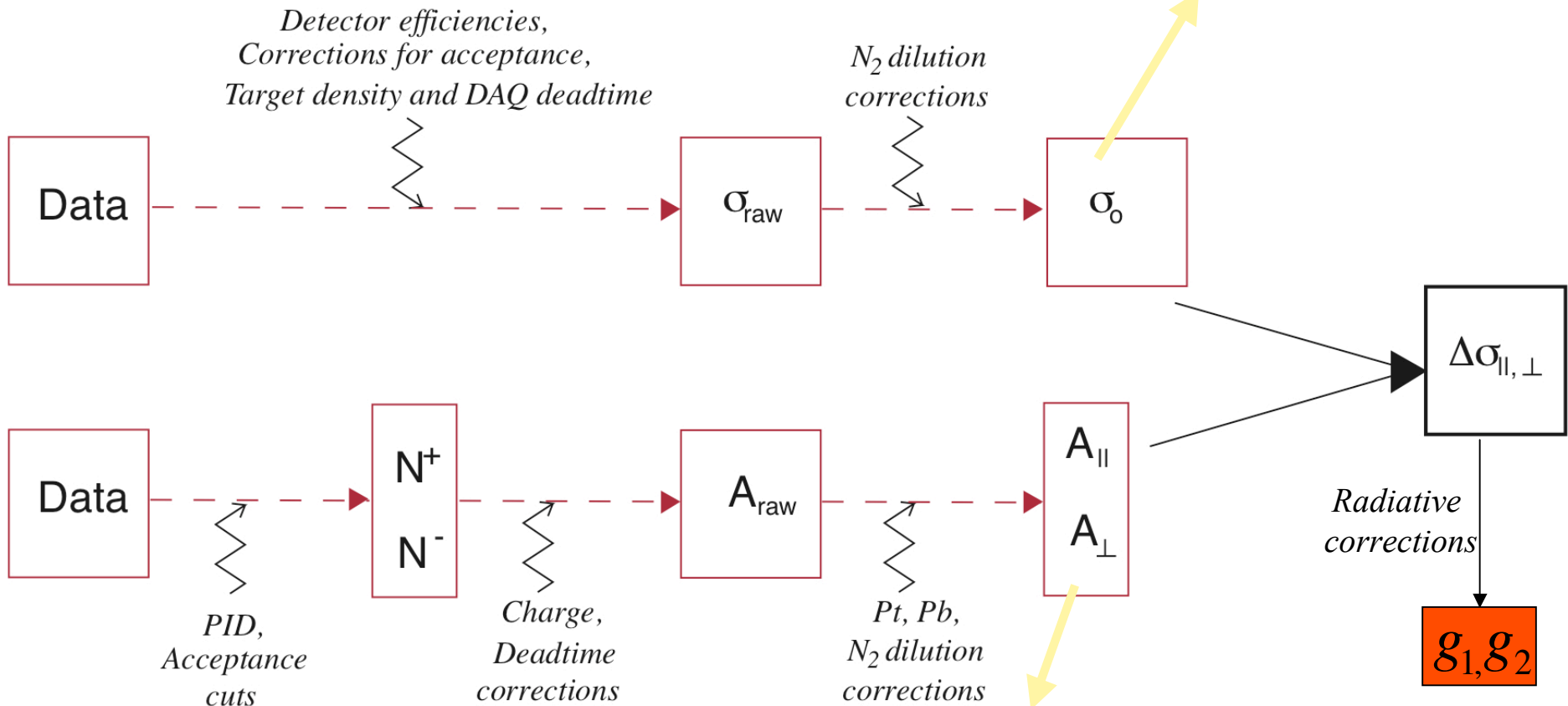


$P_{avg} \sim 37\%$

Statistical errors only

# Analysis scheme

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

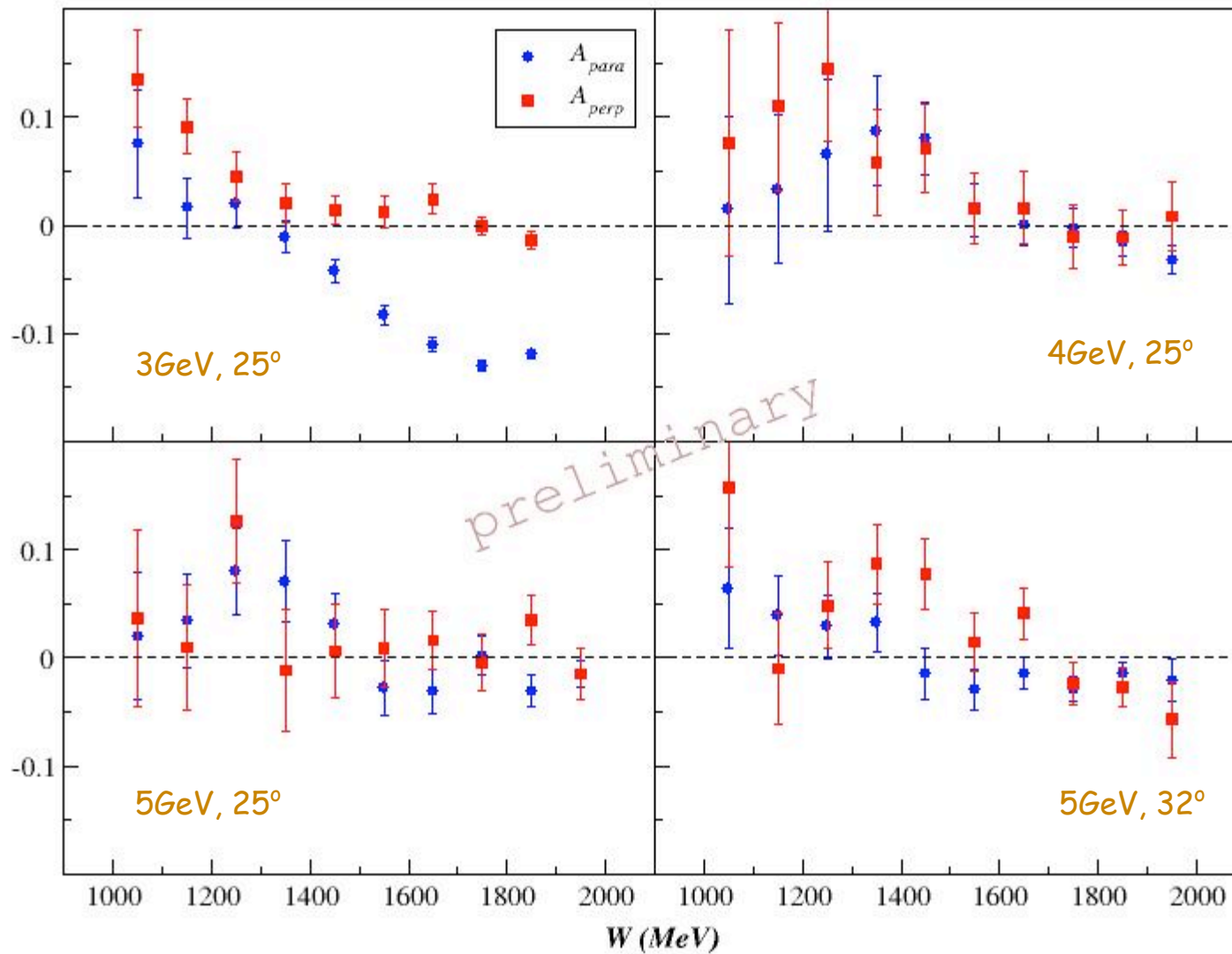


$$A_{||,\perp} = \frac{1}{f_{N_2} P_{tg} P_{beam}} \frac{\frac{N^+}{Q^+ LT^+} - \frac{N^-}{Q^- LT^-}}{\frac{N^+}{Q^+ LT^+} + \frac{N^-}{Q^- LT^-}}$$

Radiative corrections

$g_1, g_2$

# Pion asymmetries



Statistical errors only

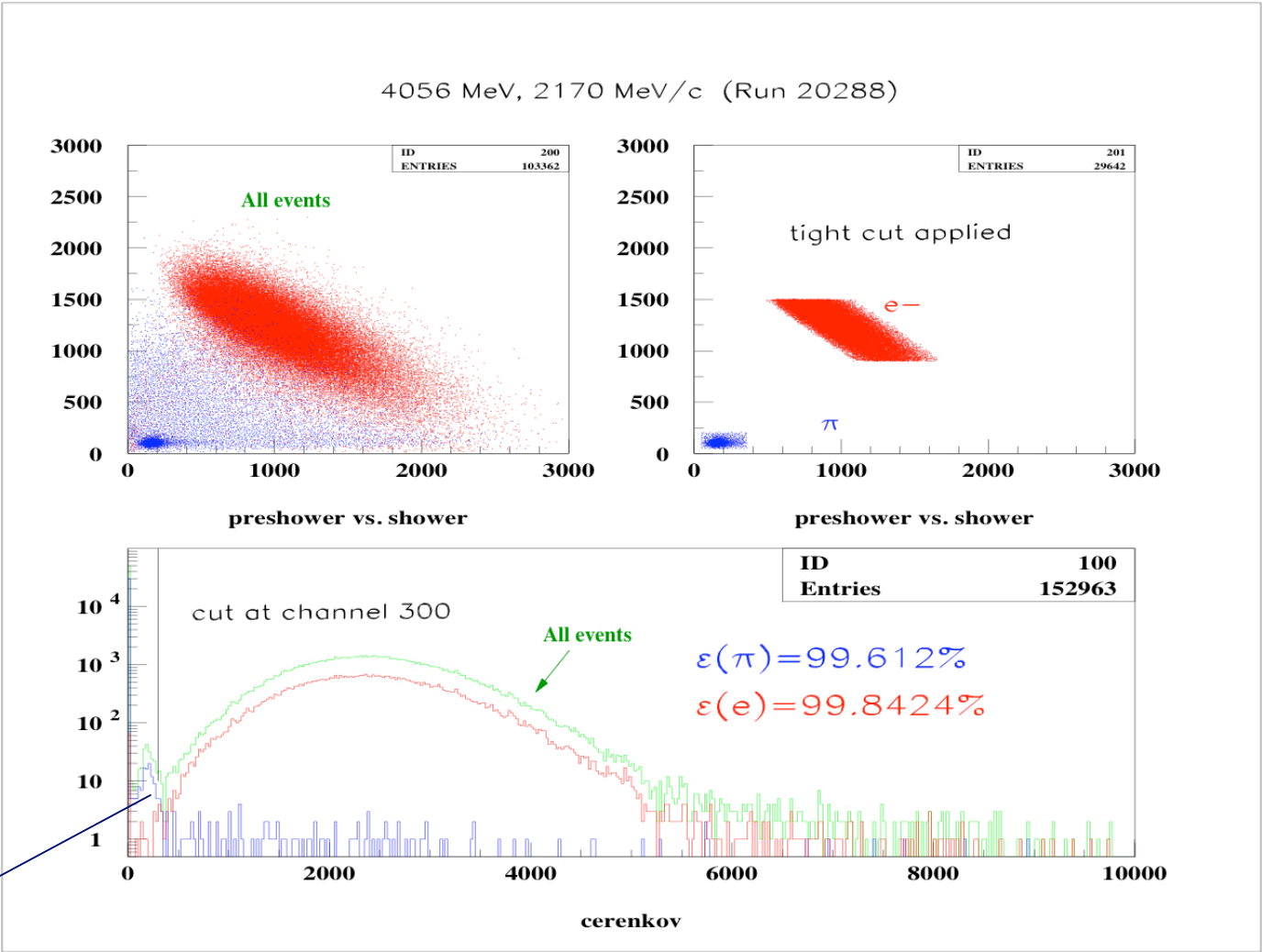
# The CO<sub>2</sub> gas Cerenkov counter

Index of refraction:  
 $n = 1.00041$



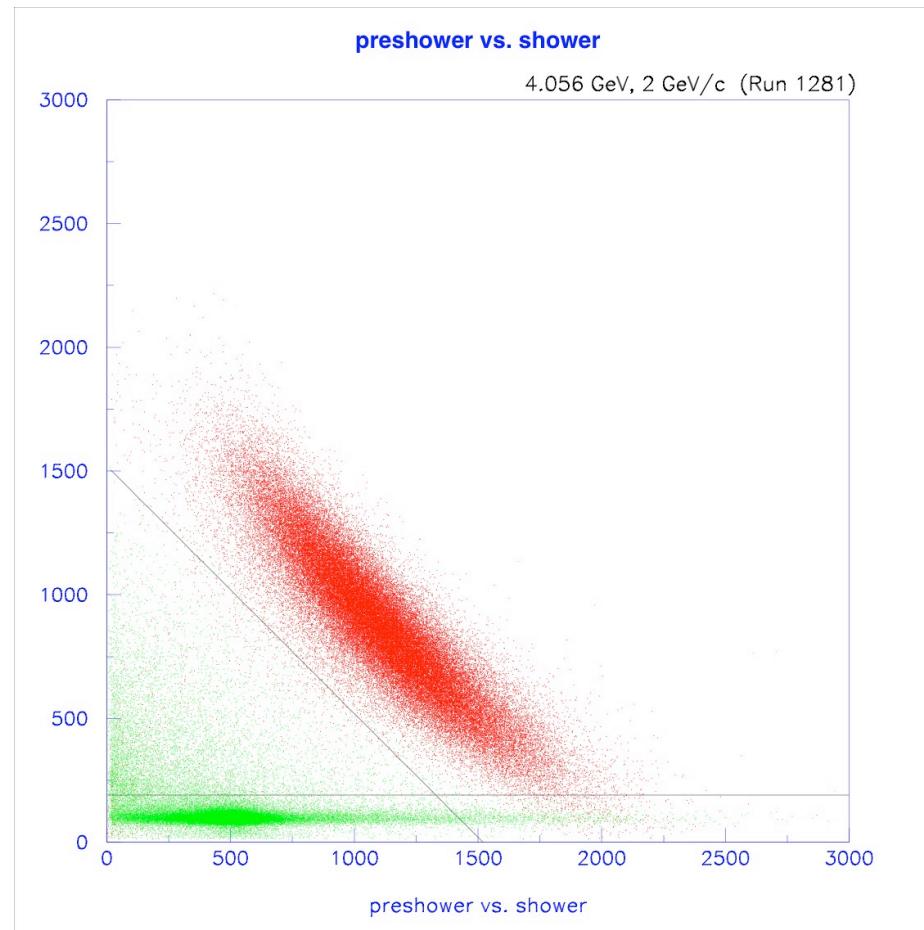
$P_{thres.}^{e^-} = 18 MeV$

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



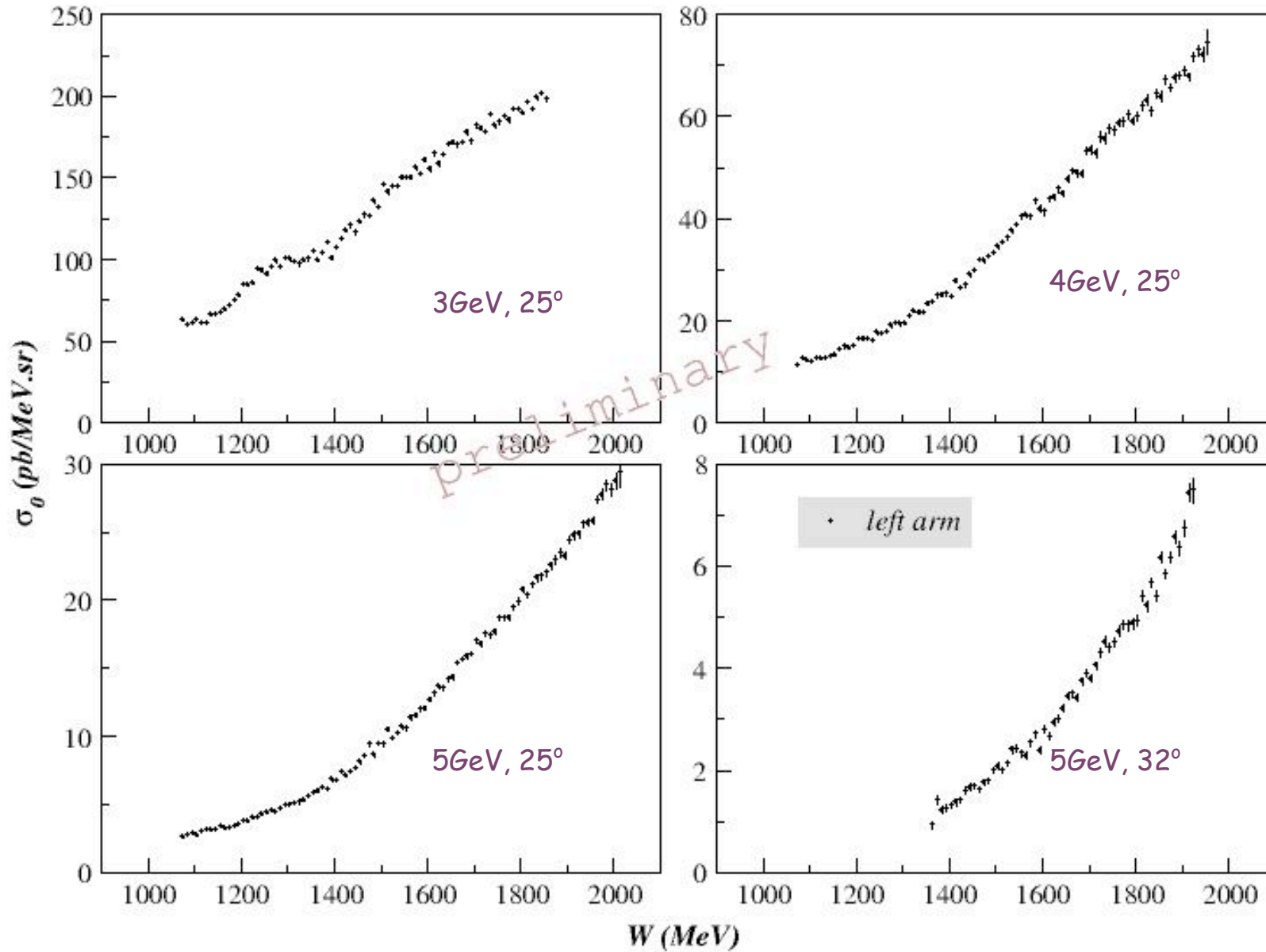
Knock-out  $e^-$   
 &  
 Low energy  $e^-$

# Lead Glass Calorimeter

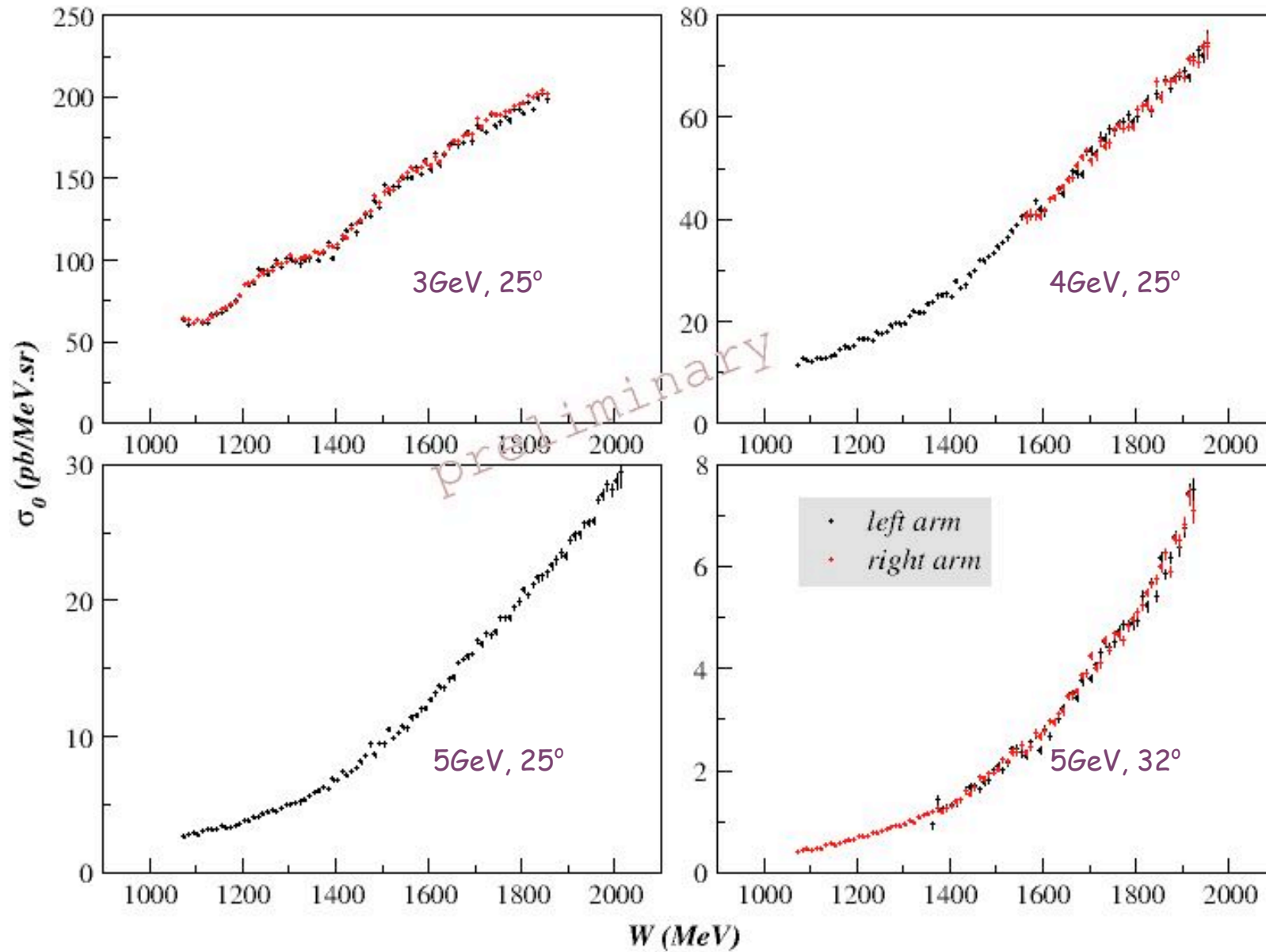


Cuts applied for electron efficiency > 99%

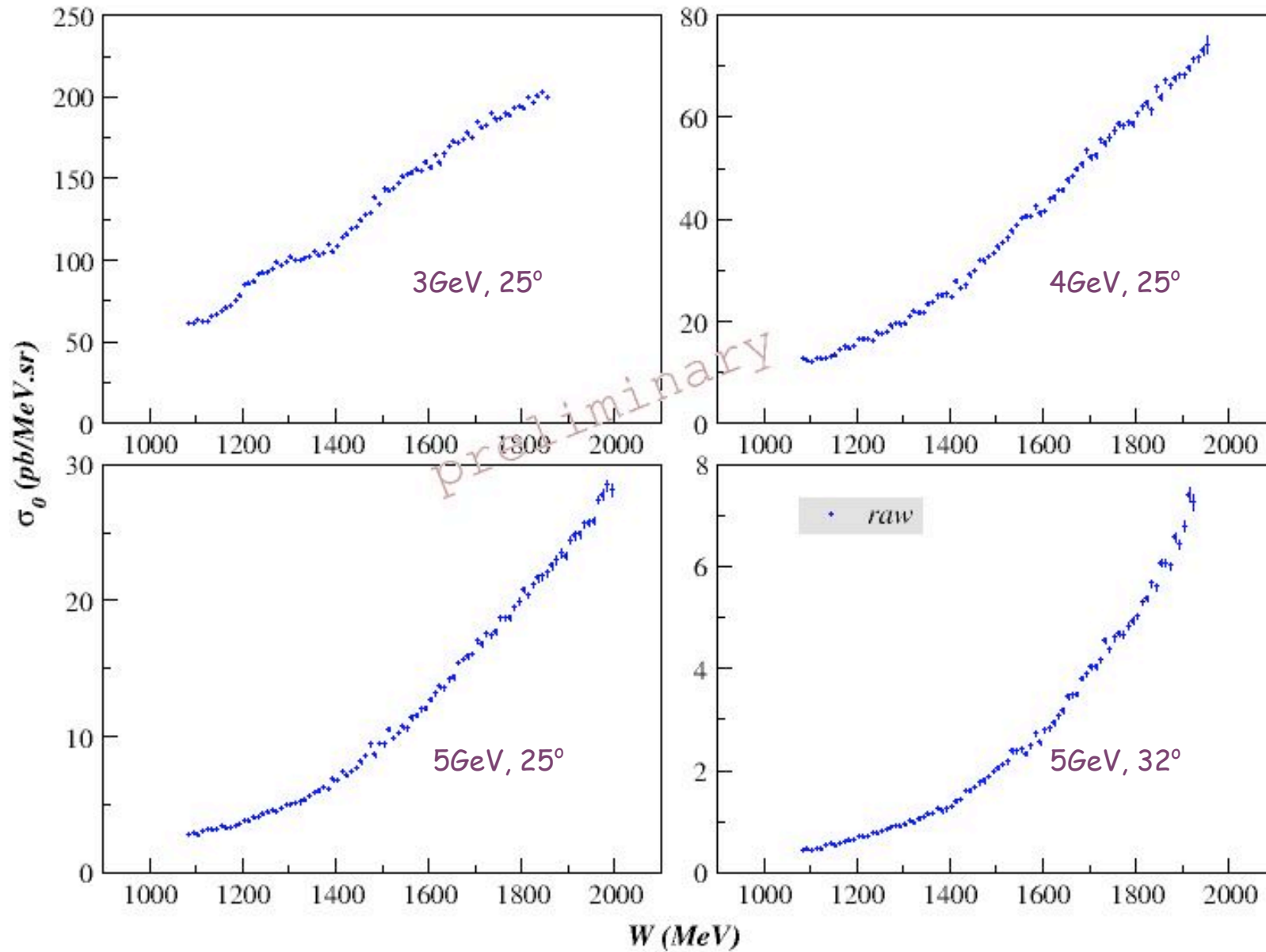
# Unpolarized cross sections



# Unpolarized cross sections

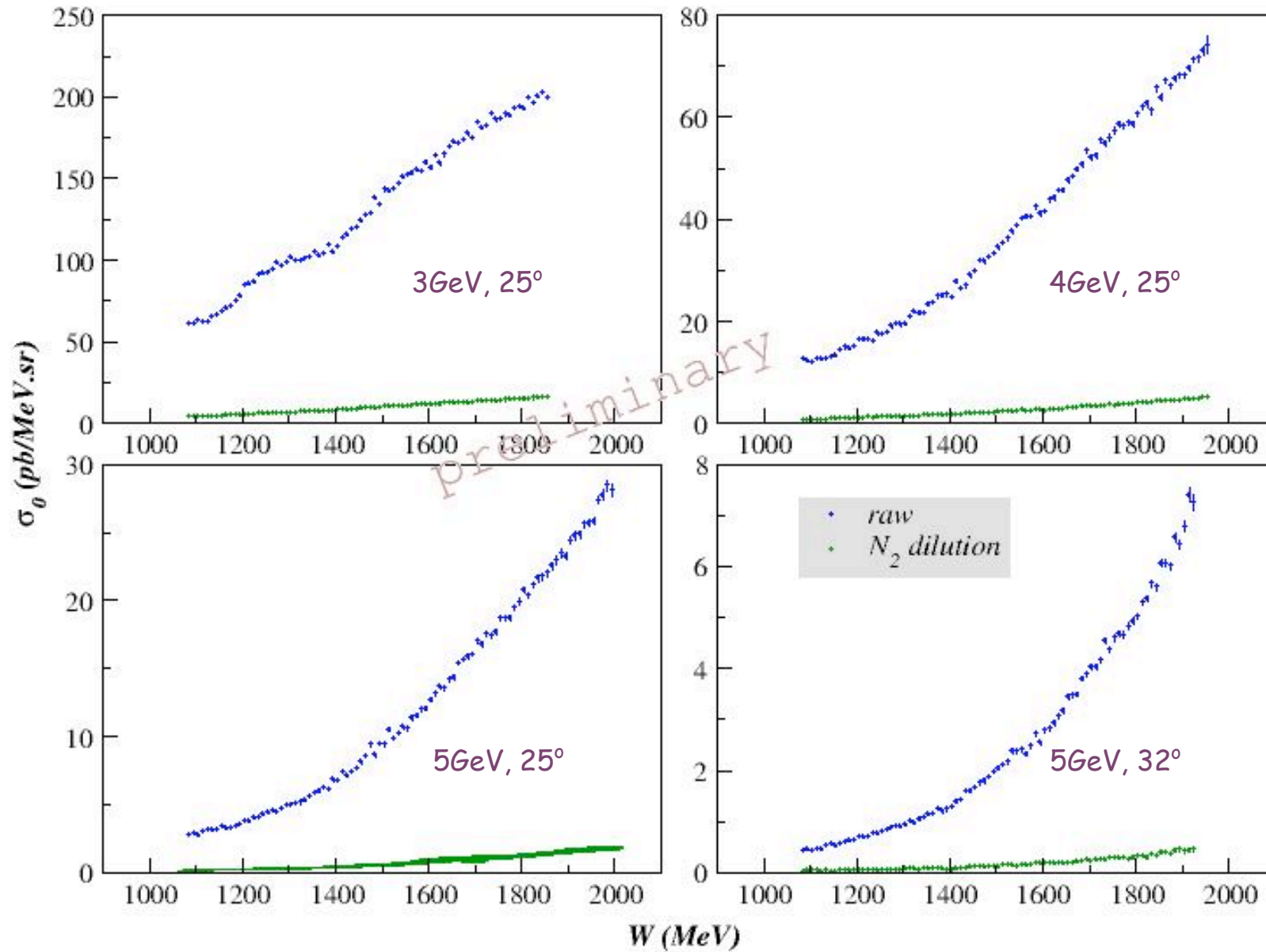


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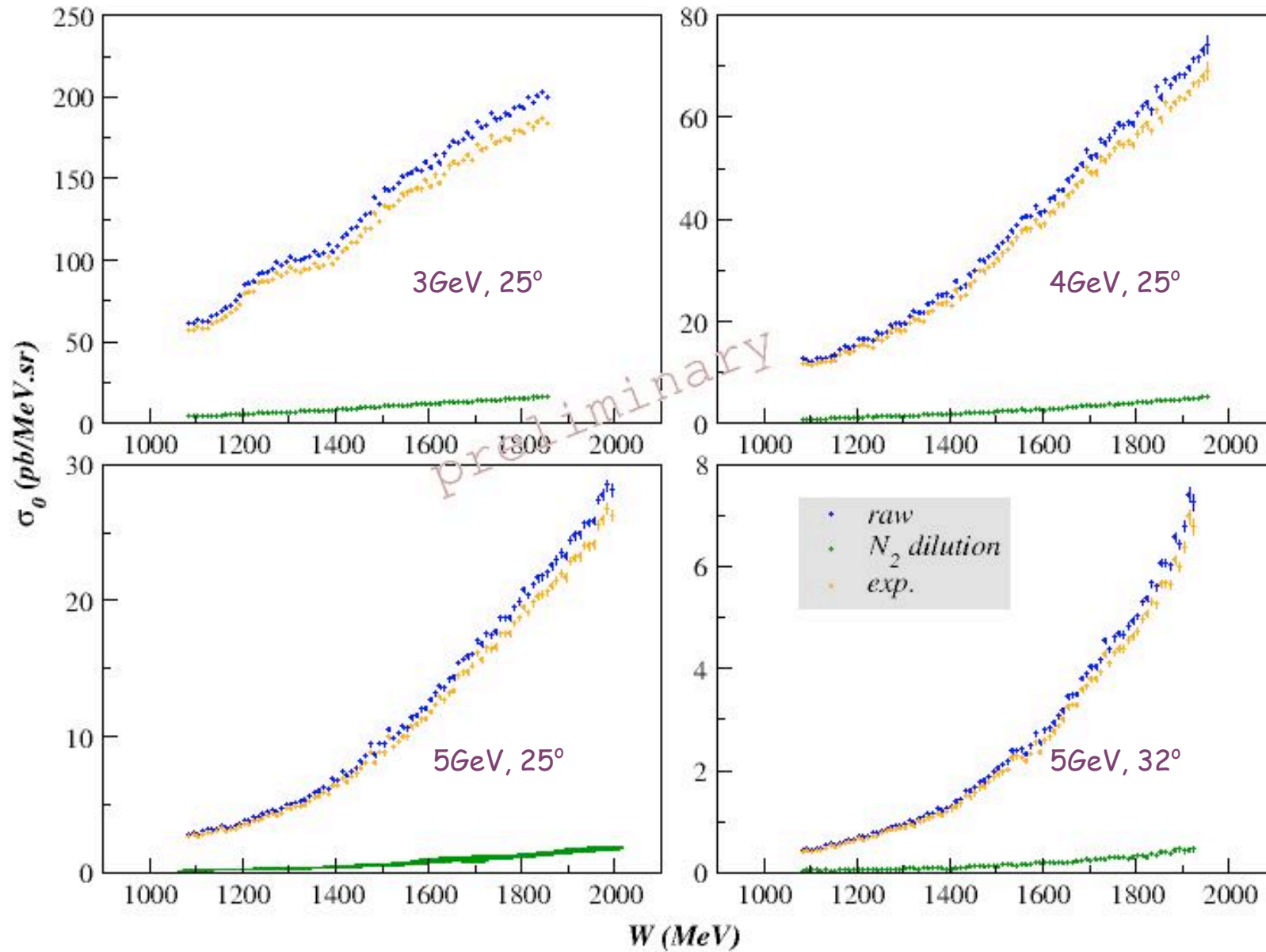




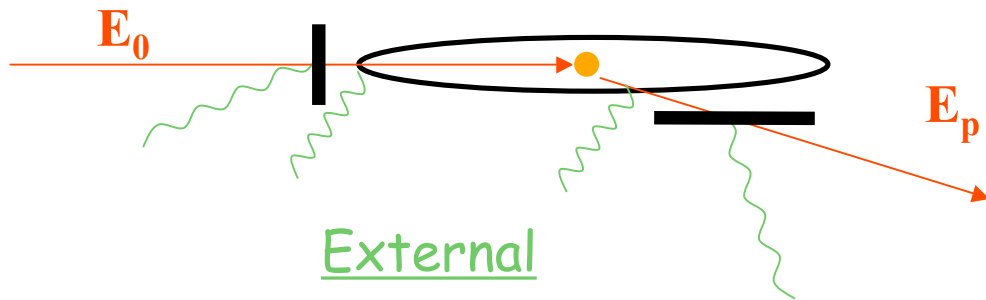
# Unpolarized cross sections



# Unpolarized cross sections



# Radiative corrections

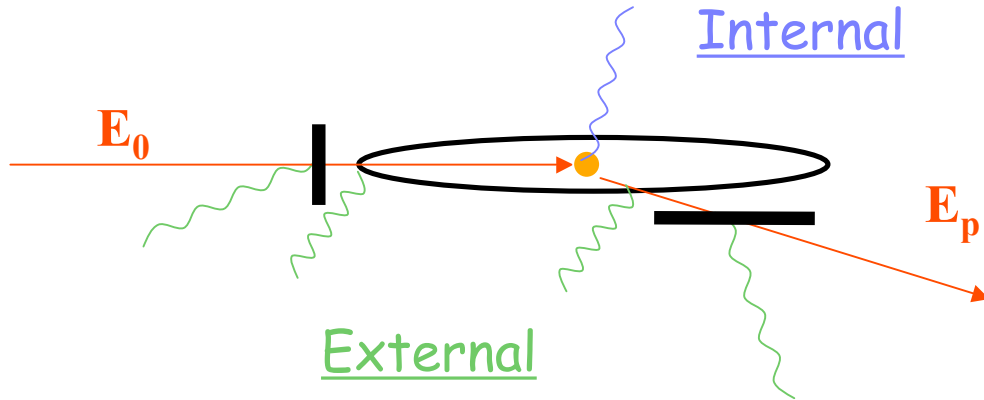


At reaction point:

$$E_0^r < E_0$$

$$E_p^r > E_p$$

# Radiative corrections

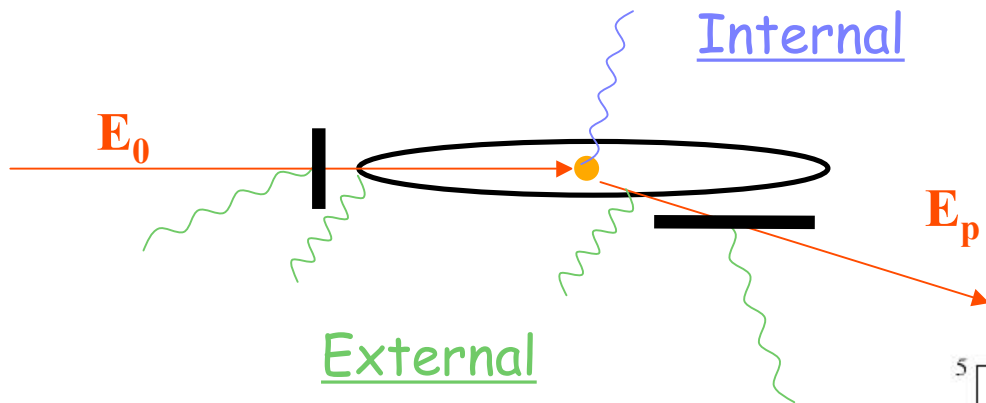


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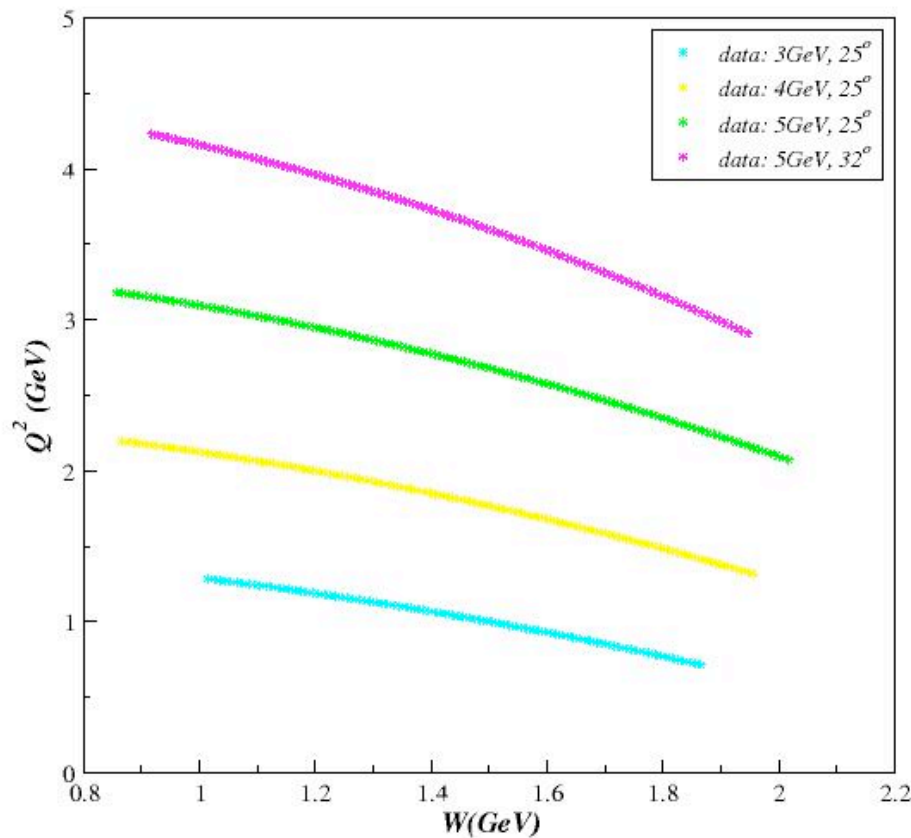
# Radiative corrections



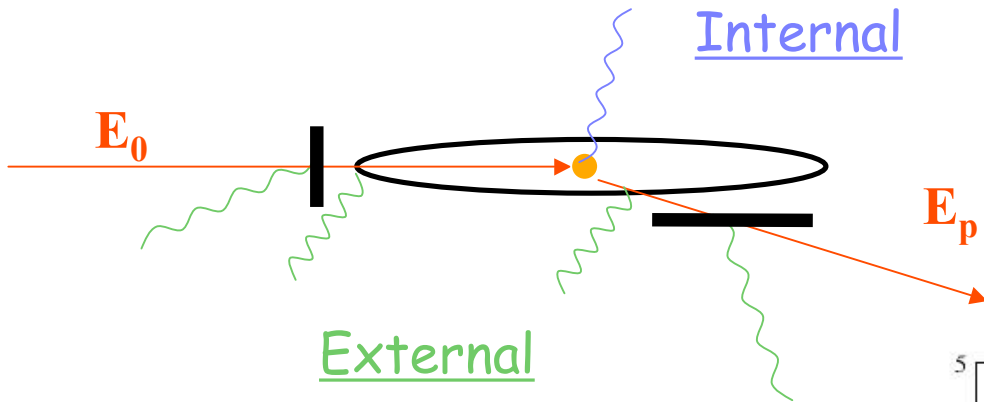
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# Radiative corrections

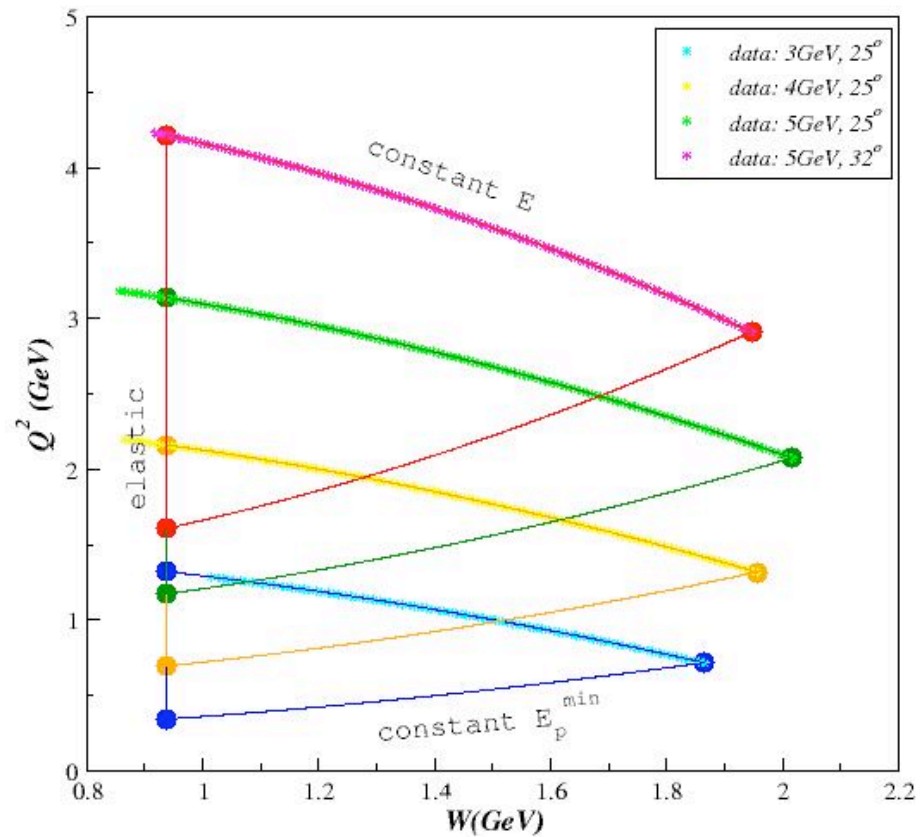


At reaction point:

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Computation to get the real reaction



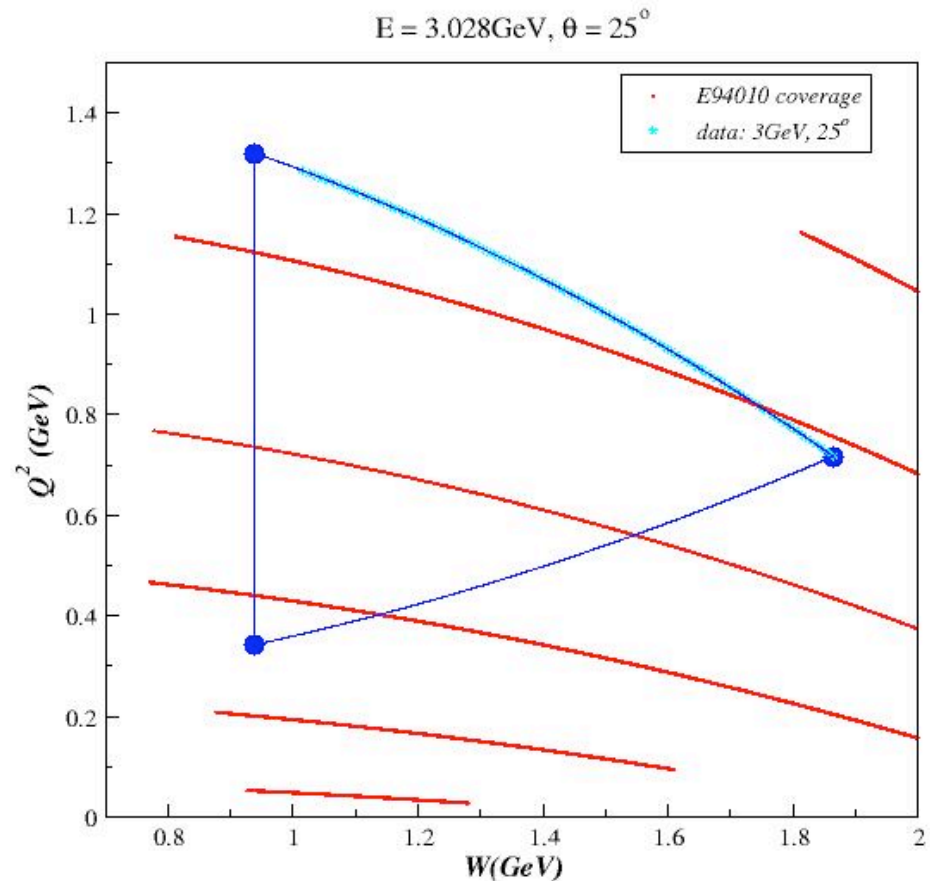
# Radiative corrections

- ◆ Used QFS model for  $\sigma_0$ . Next will use E94-010 data for  $\sigma_0$ :

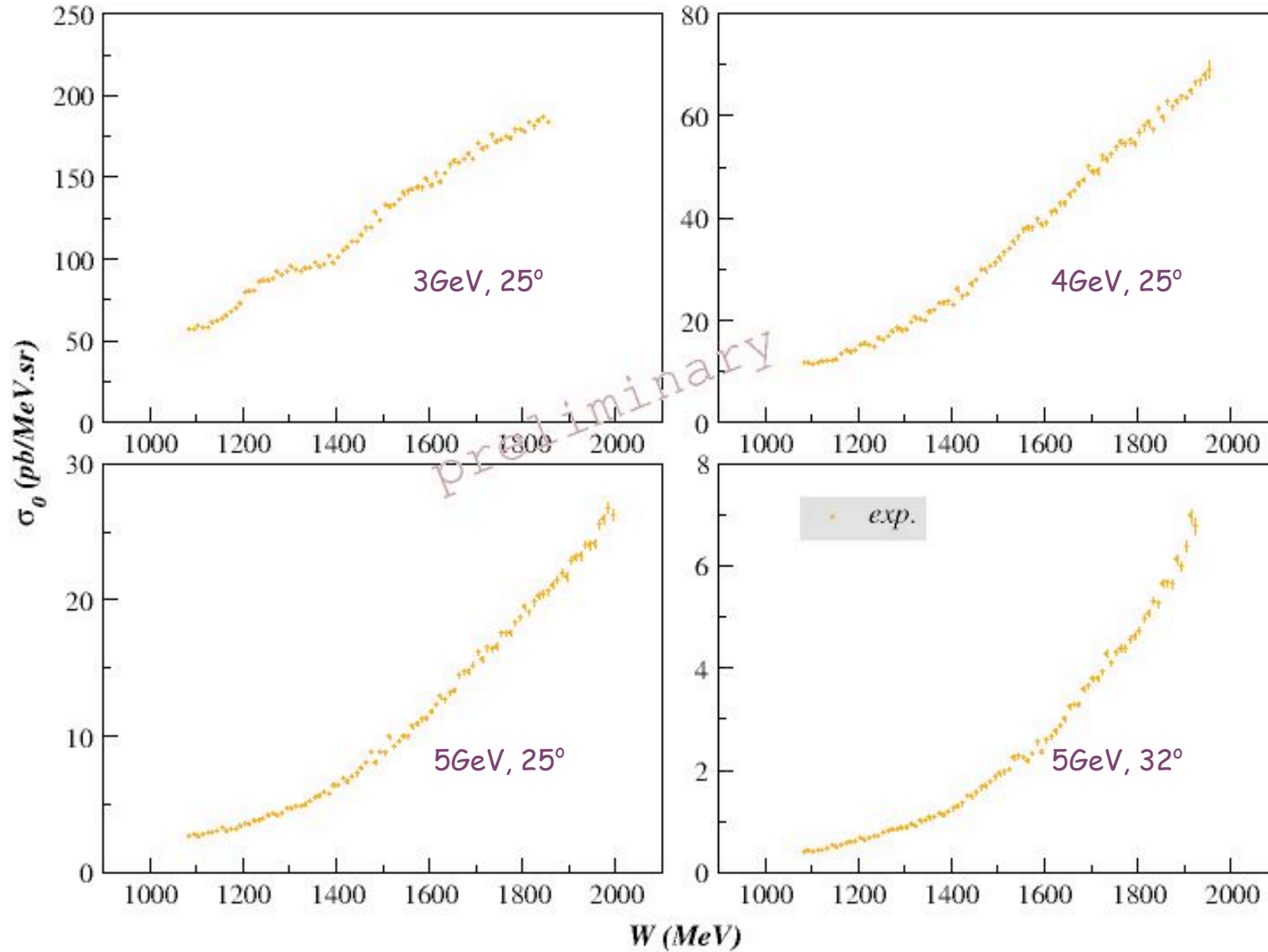
$$F_2(x, Q^2) \rightarrow \sigma_0(E, E', \theta)$$

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

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

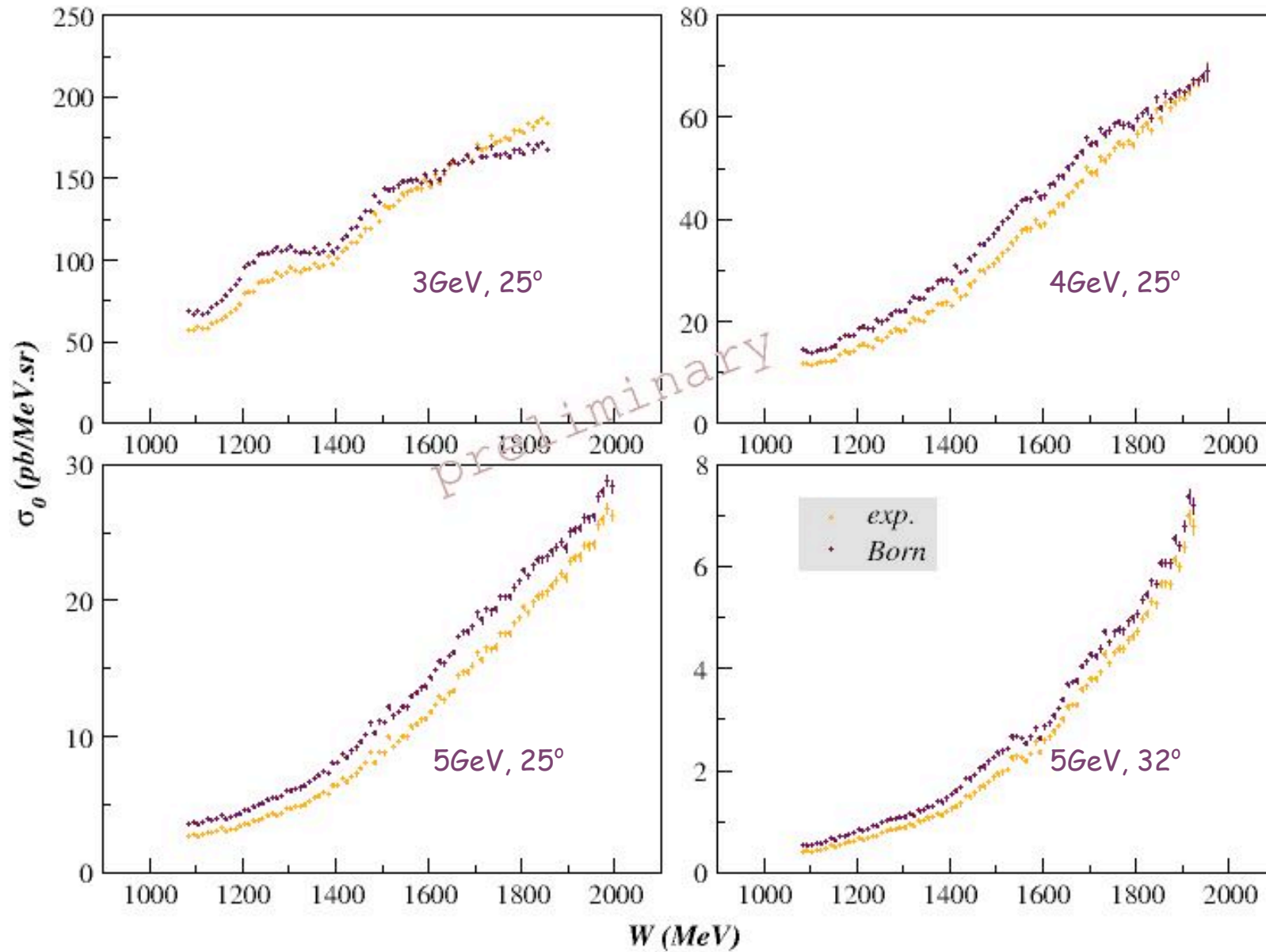


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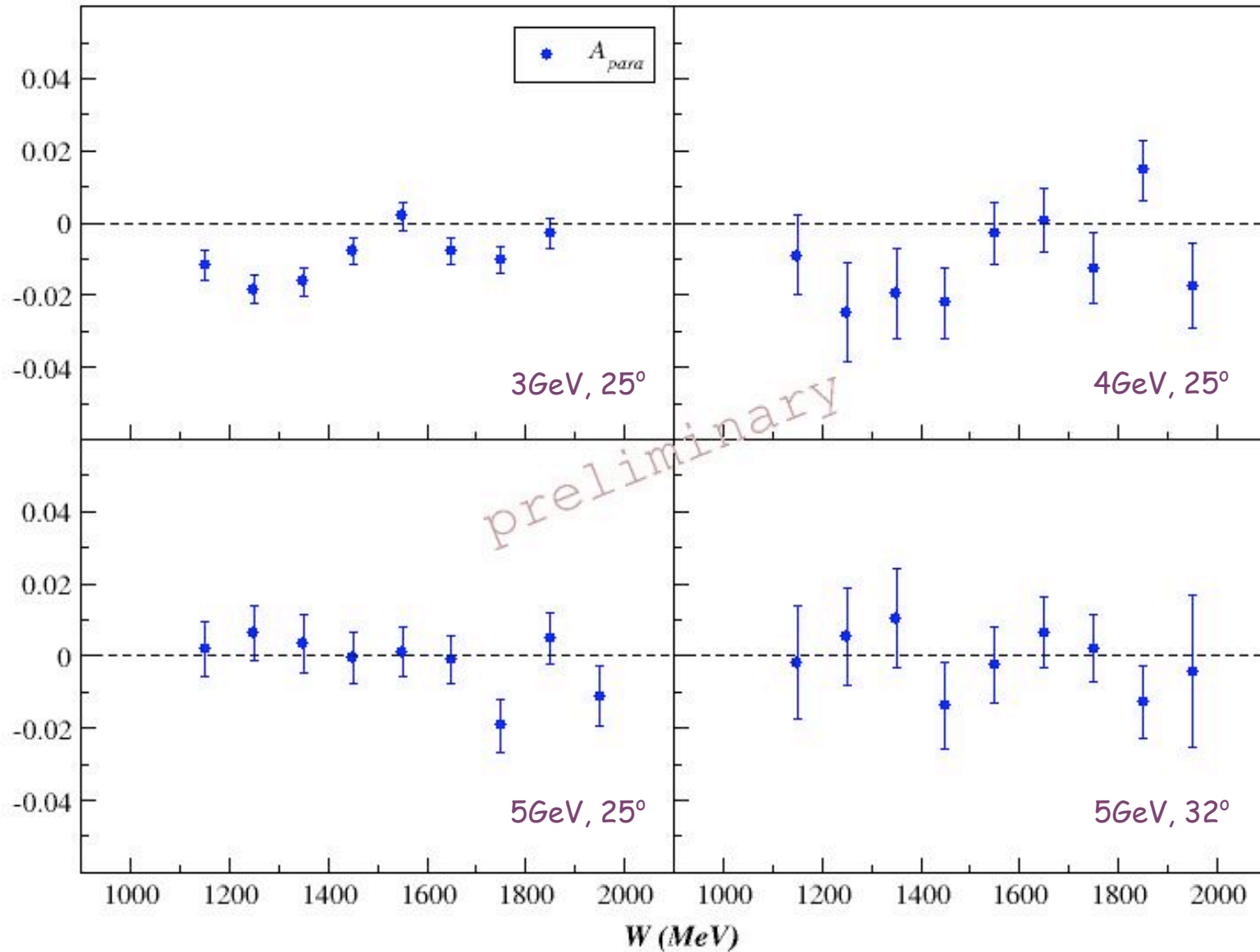




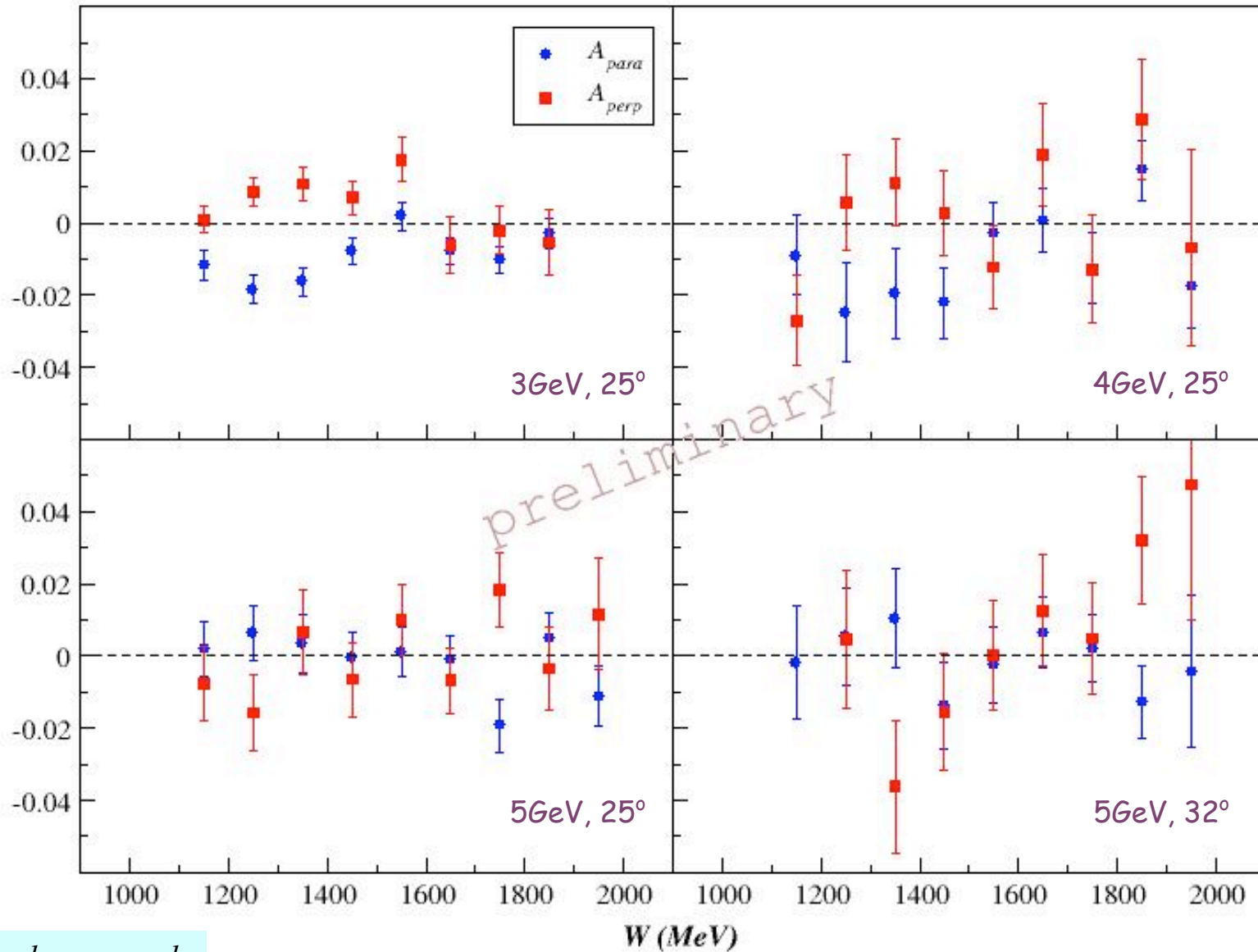
# Unpolarized cross sections



# Asymmetries

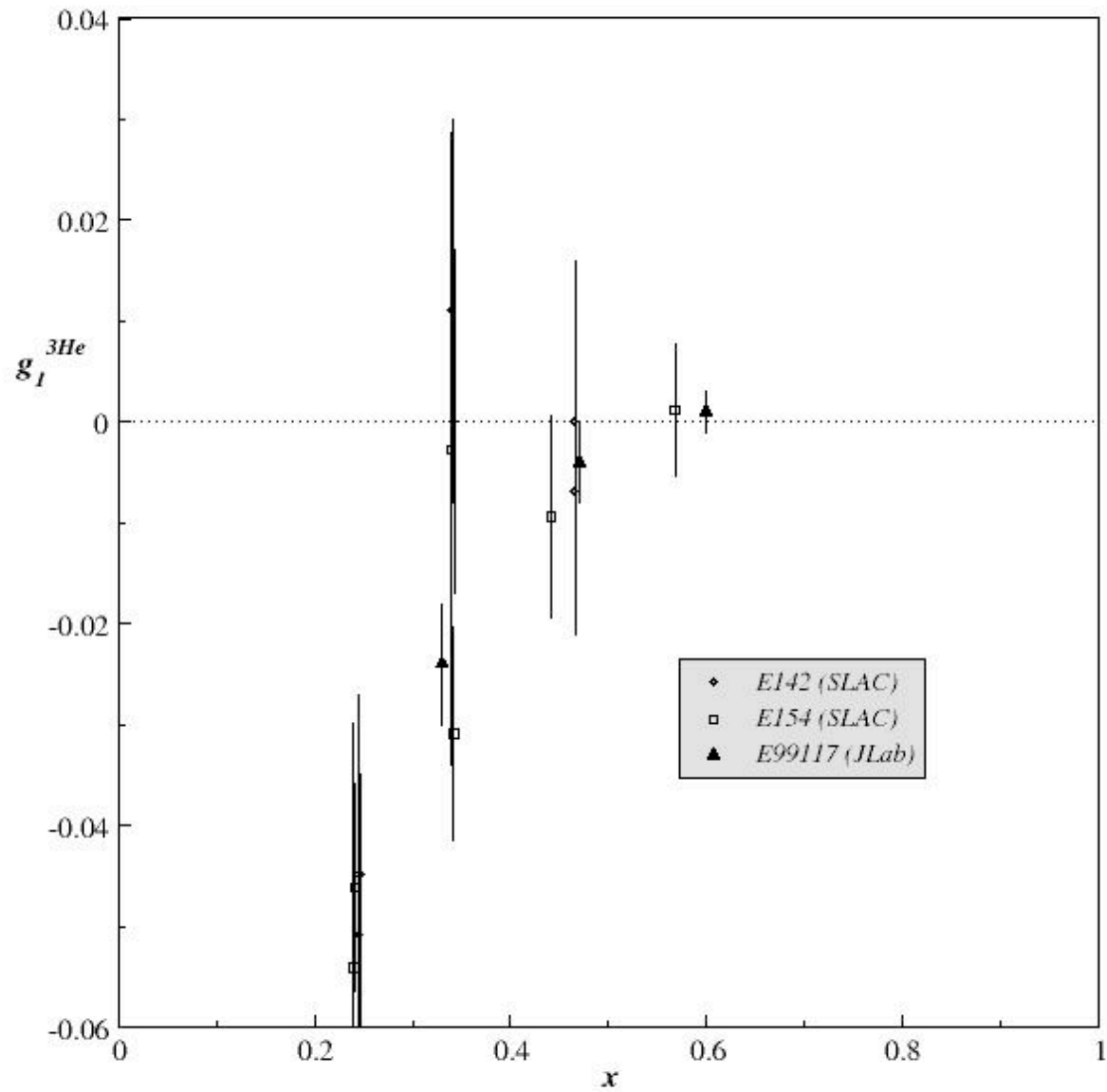


# Asymmetries

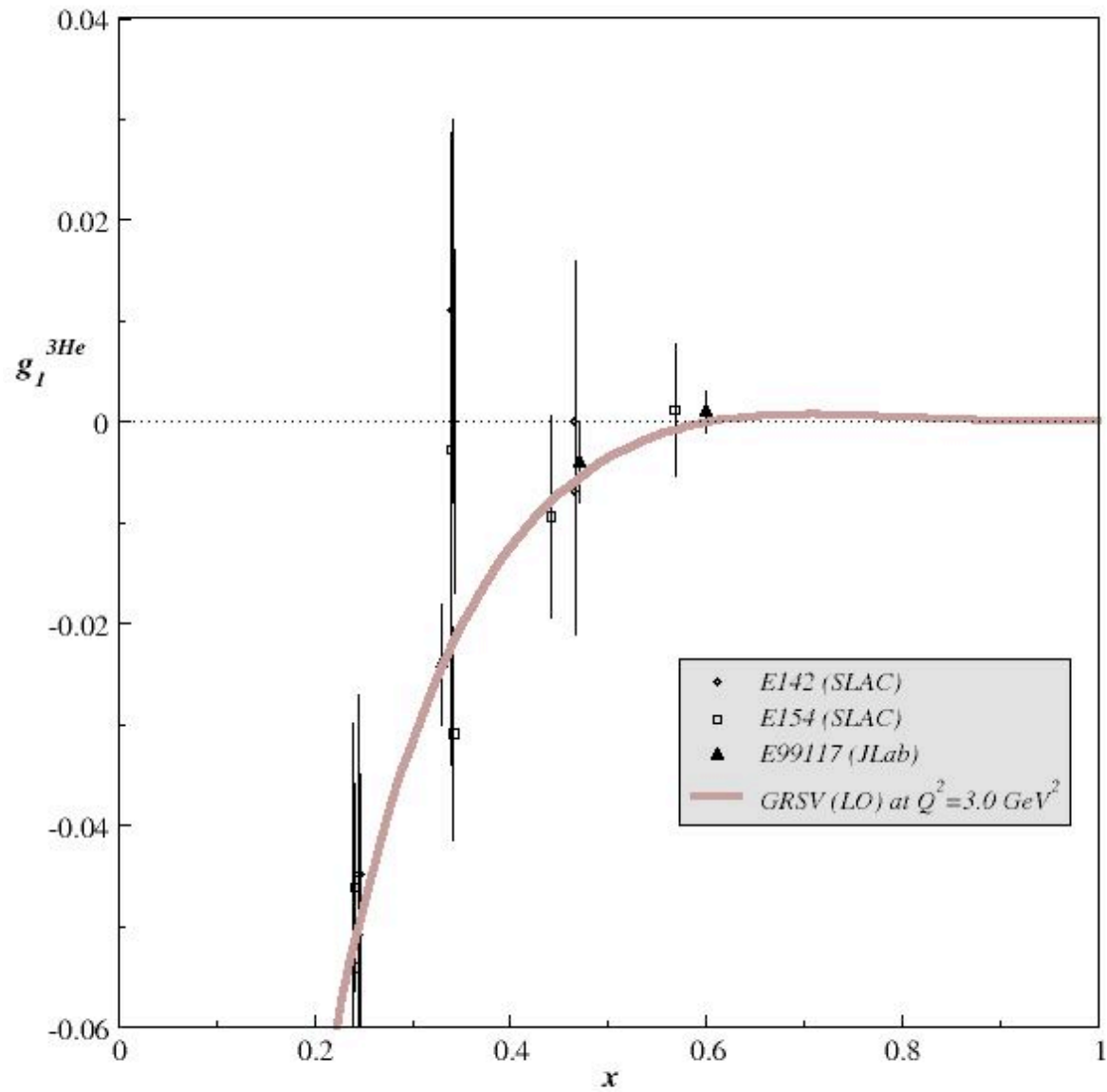


Statistical errors only

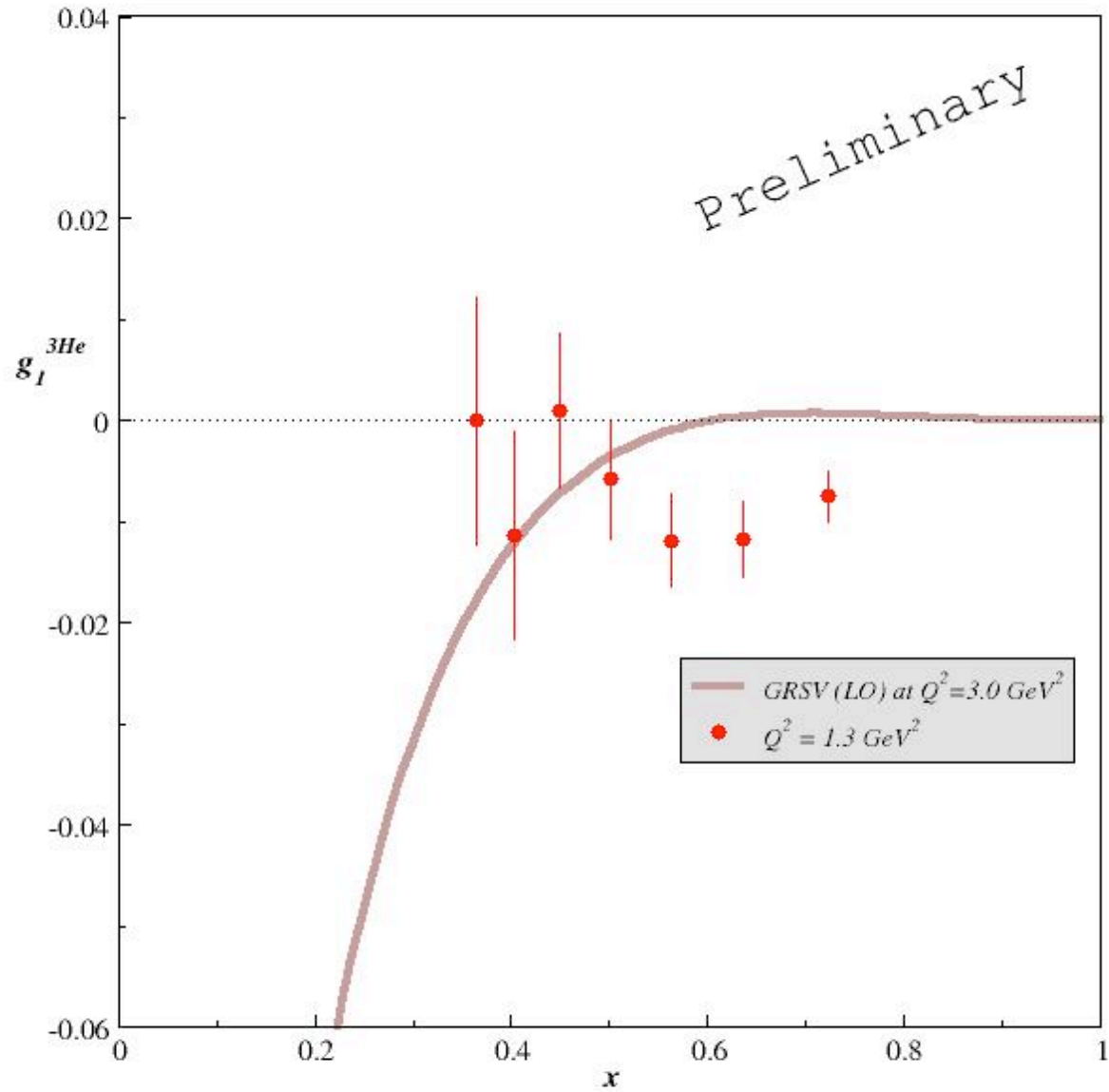
# $g_1^{3\text{He}}$ at constant $Q^2$



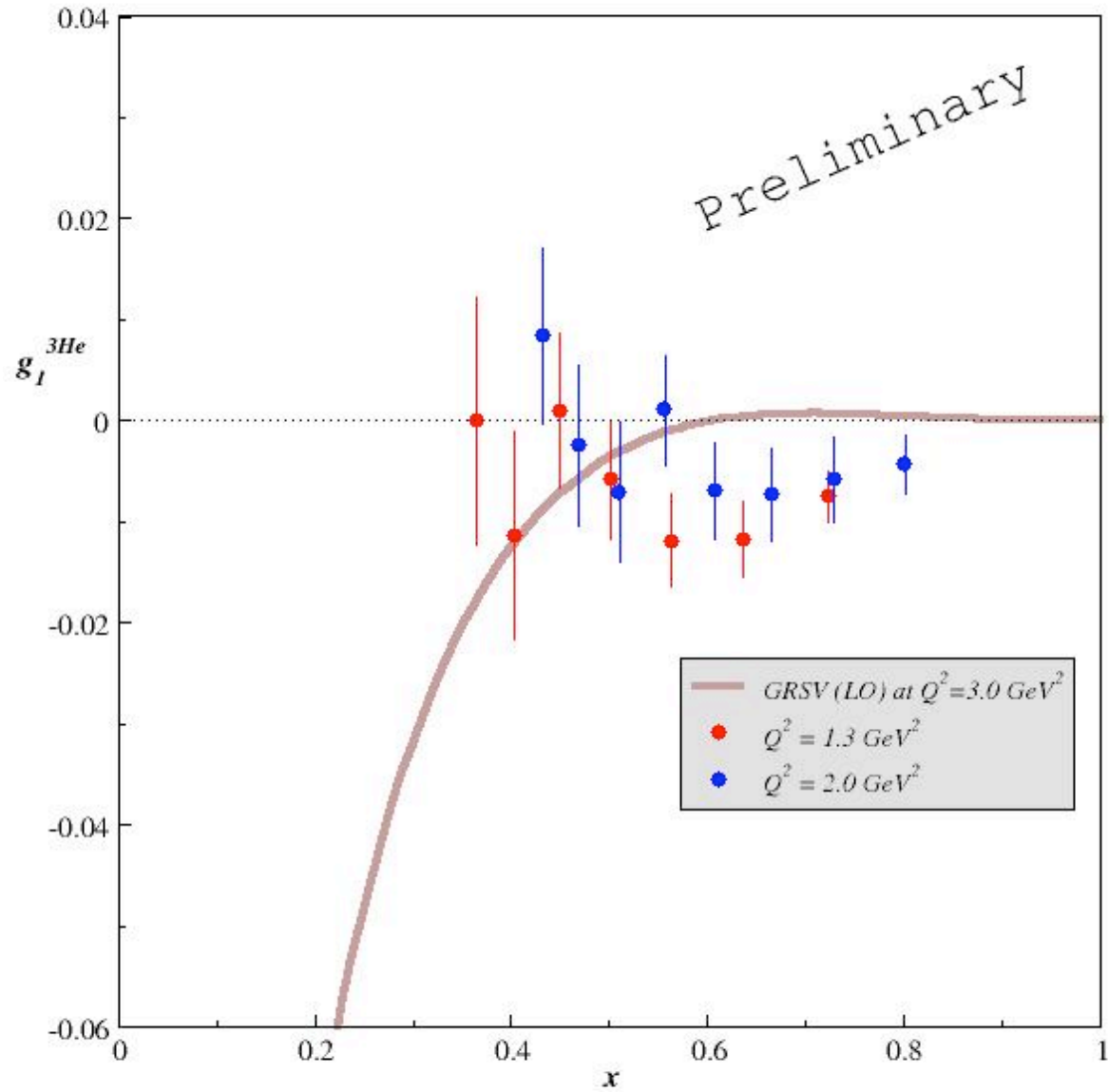
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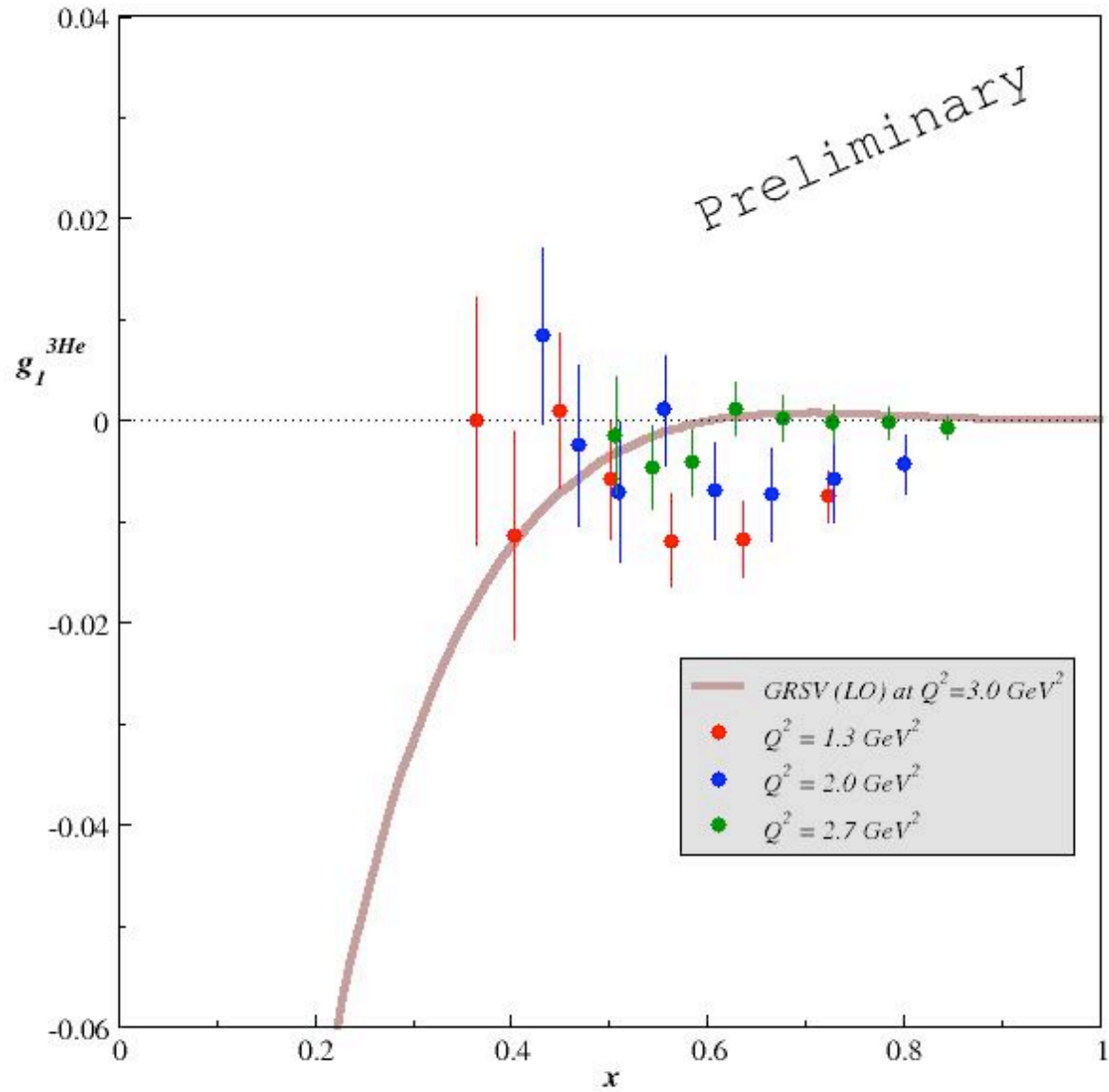
# $g_1^{3\text{He}}$ at constant $Q^2$



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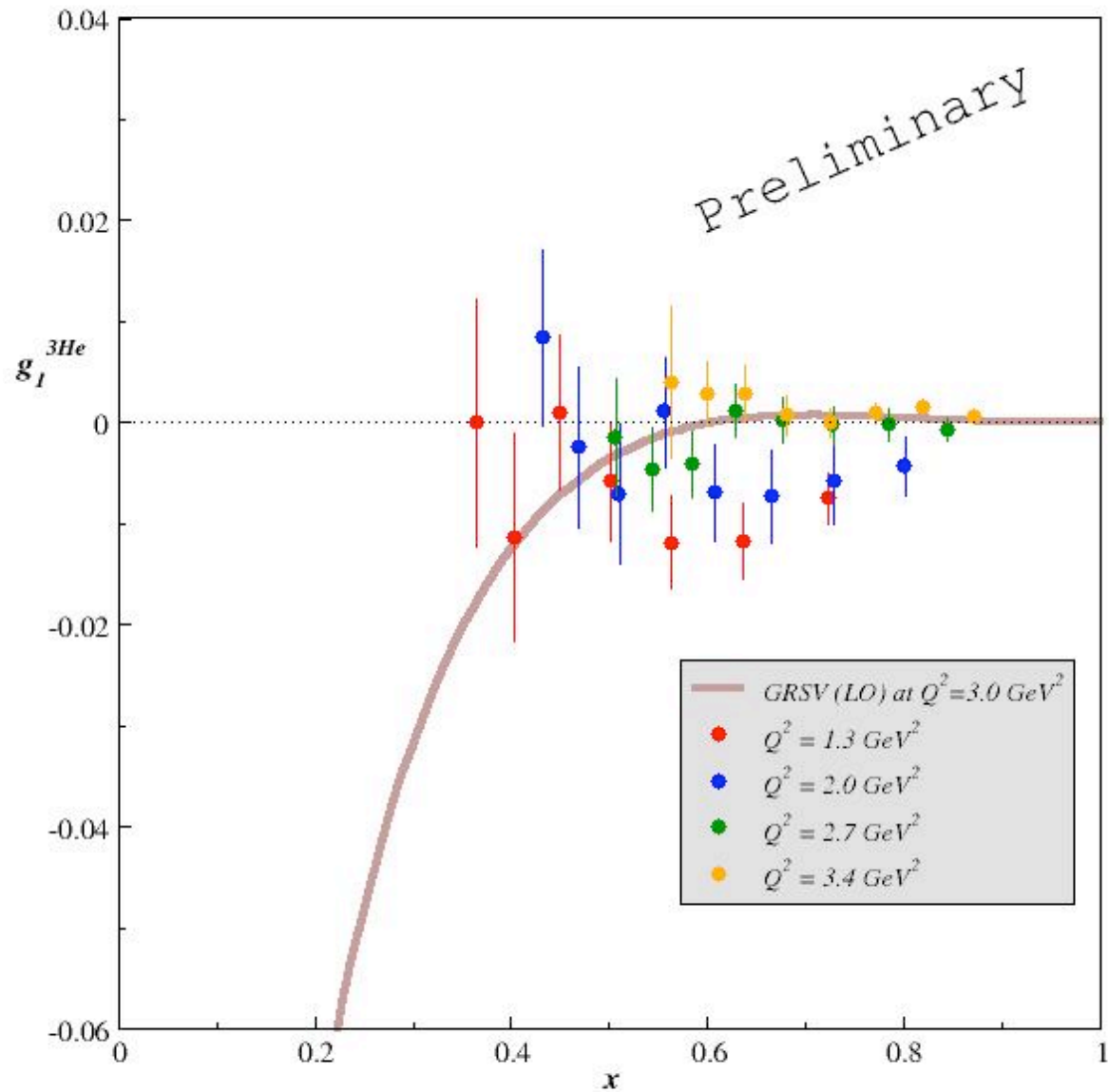


# $g_1^{3\text{He}}$ at constant $Q^2$





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

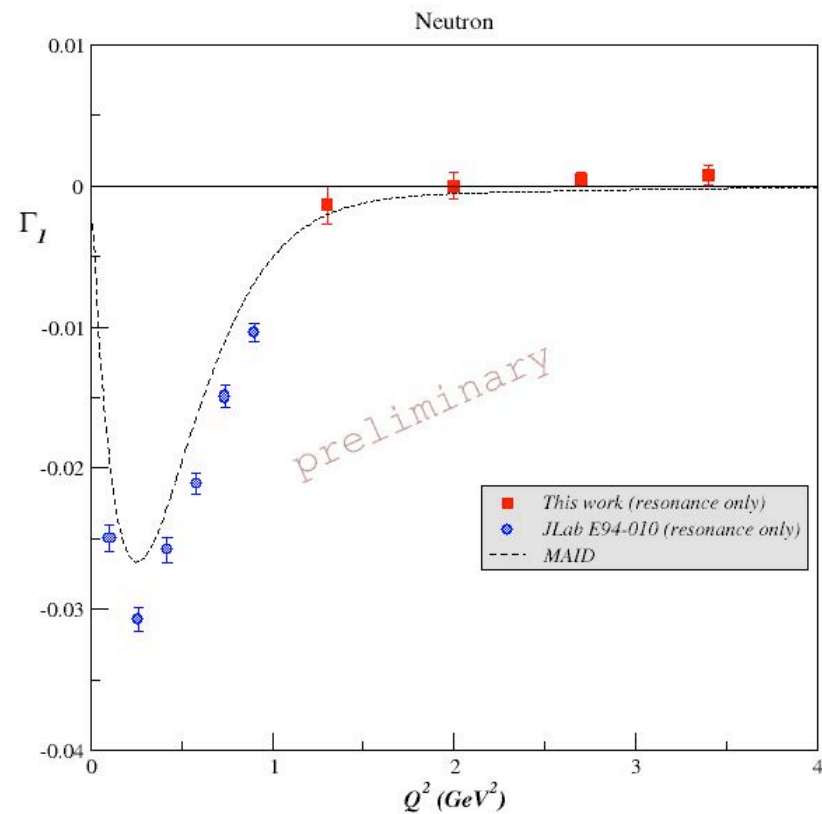
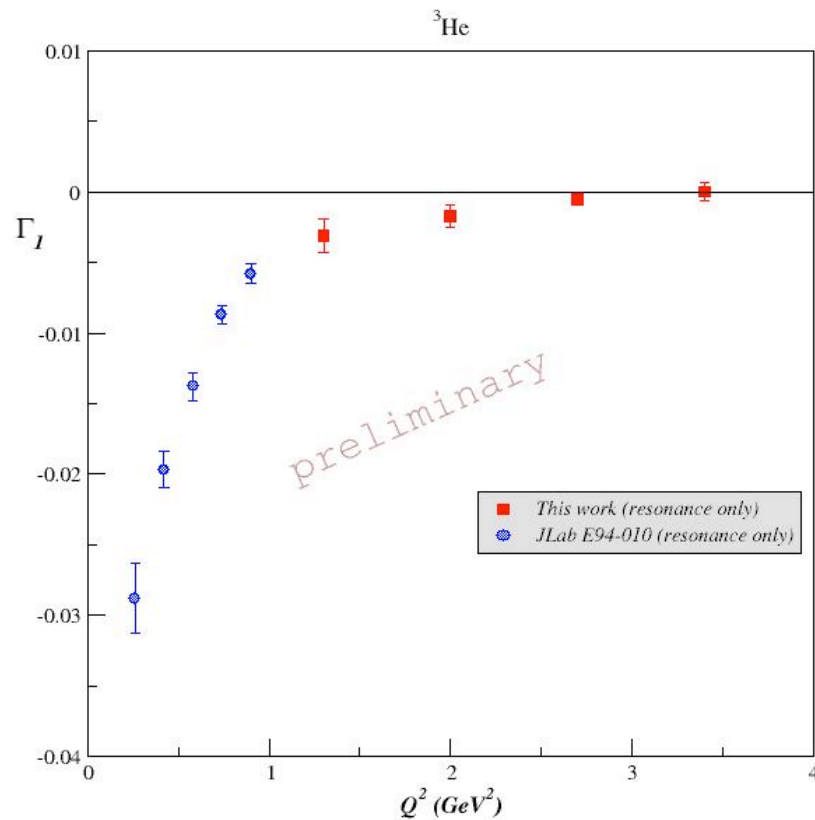


# $\Gamma_1$ in the resonance region

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 $^3\text{He}$

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

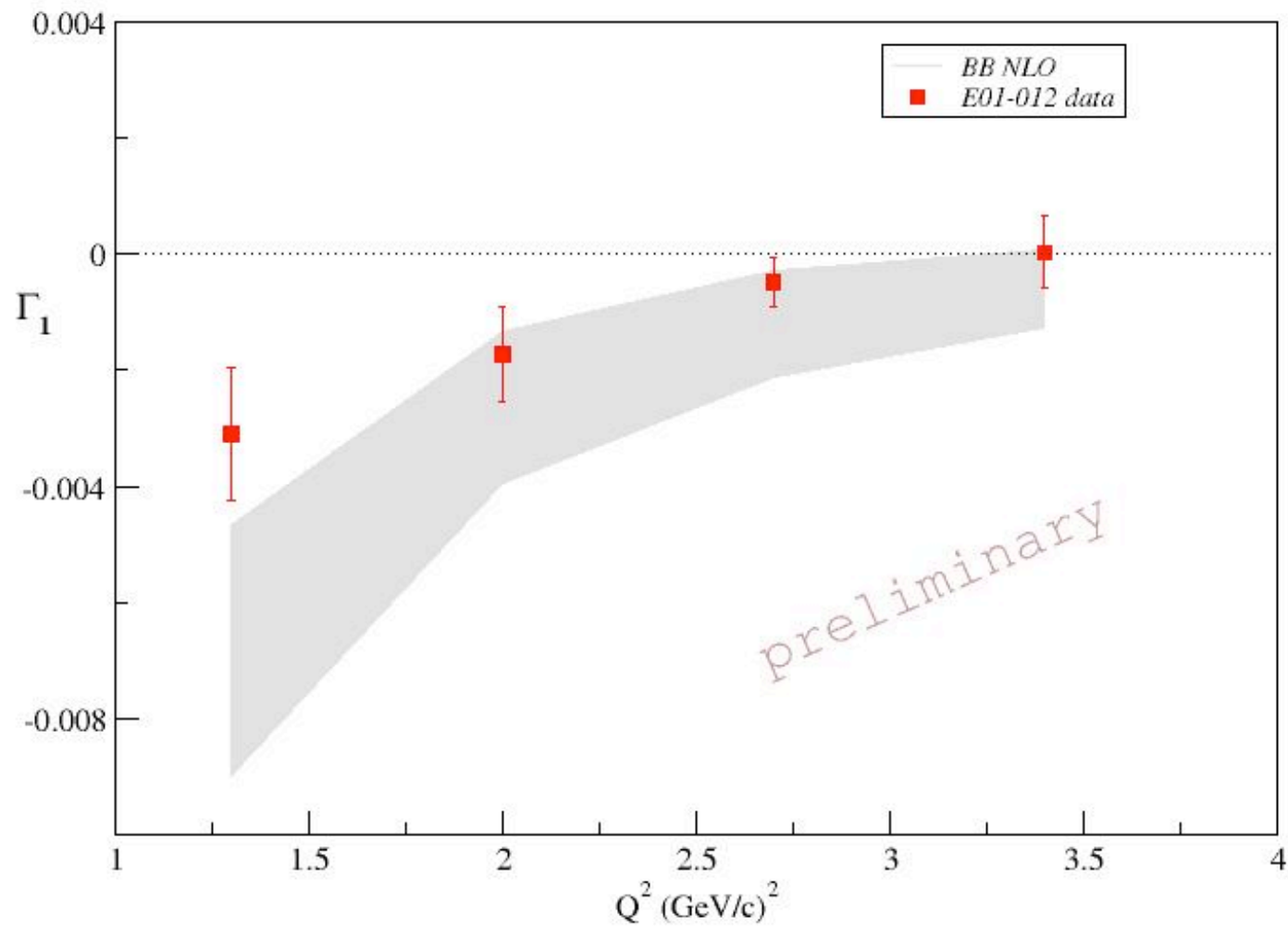
1. Get  $g_1$  at constant  $Q^2$
2. Define integration range in the resonance region in function of  $W$
3. Integrate  $g_1^{res}$  and  $g_1^{dis}$  over the same  $x$ -range and at the same  $Q^2$

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

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

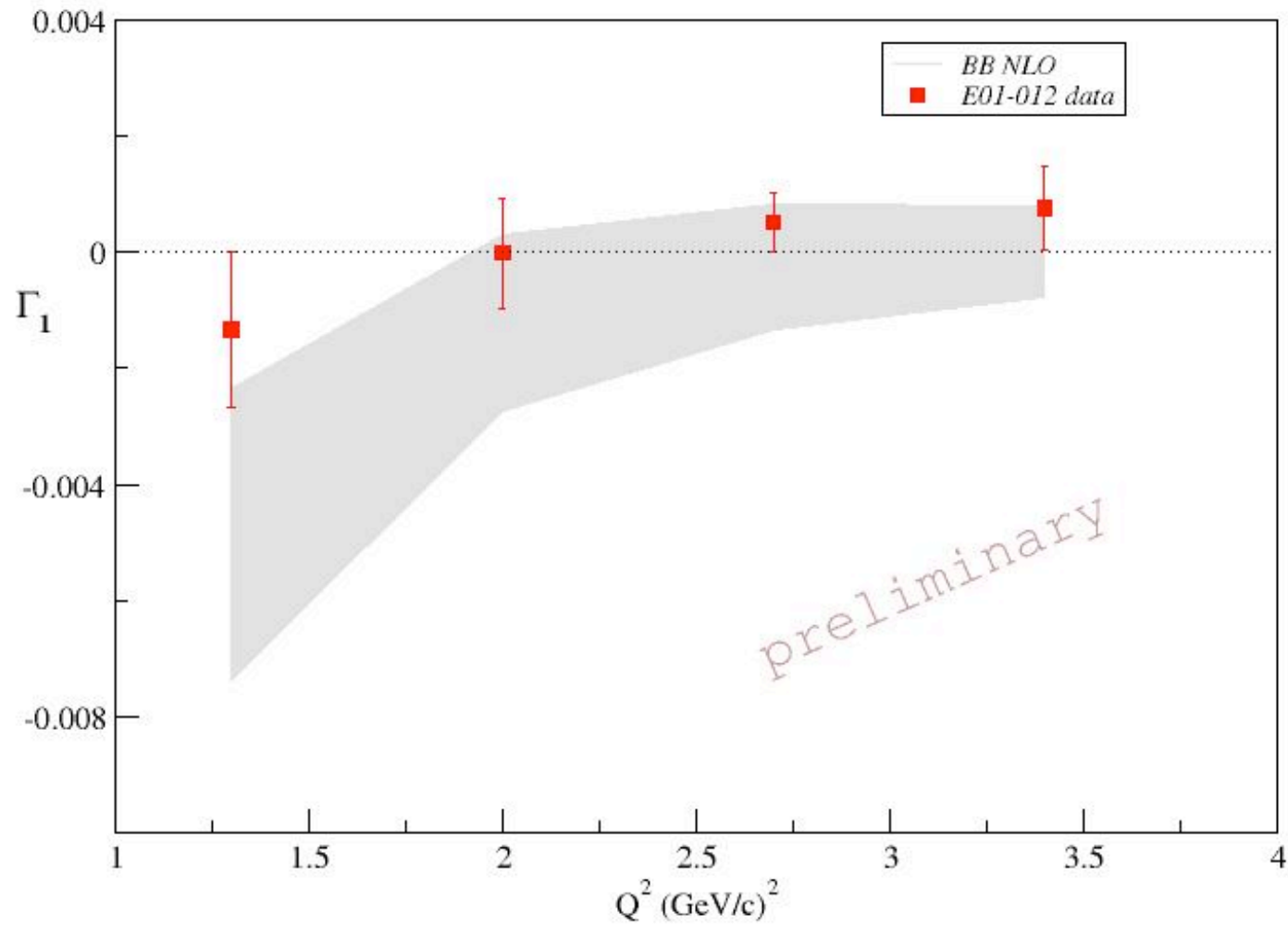
If  $\tilde{\Gamma}_1^{res} = \tilde{\Gamma}_1^{dis} \Rightarrow$  duality is verified

# Test of duality on $^3\text{He}$



Statistical errors only

# Test of duality on neutron



Statistical errors only

# Spin asymmetries

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

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

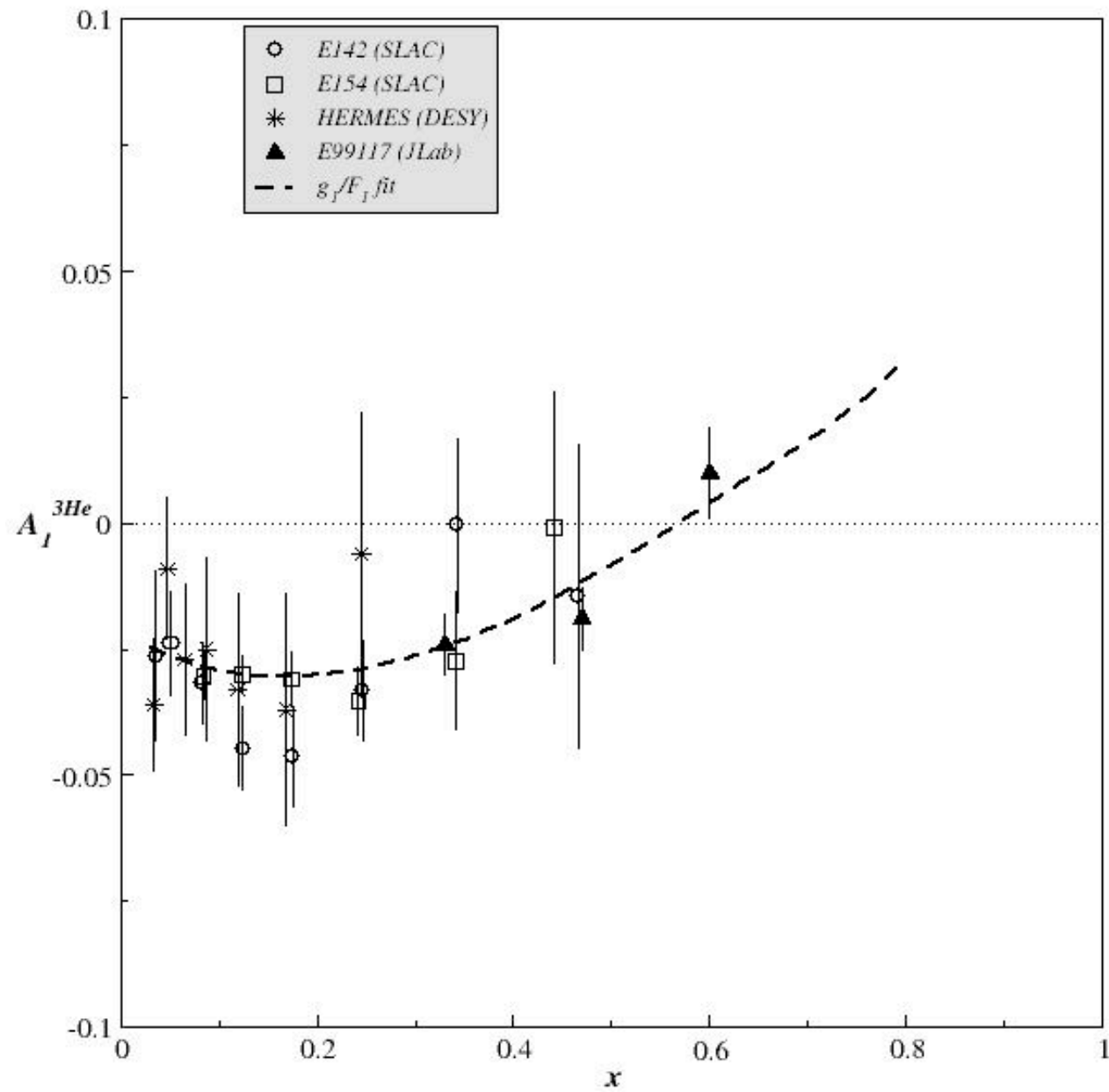
In the parton model:

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

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

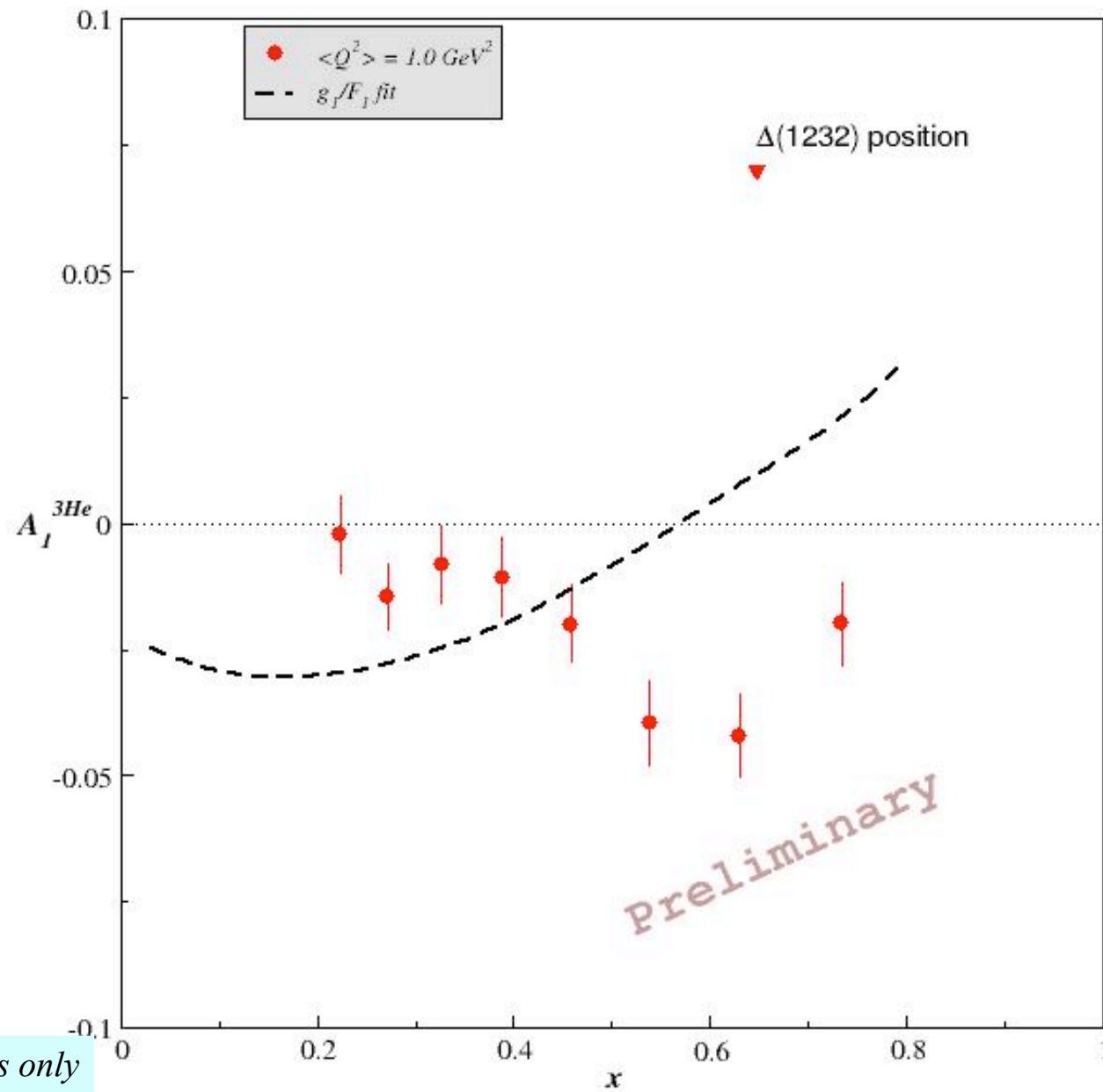


# $A_1^{3\text{He}}$



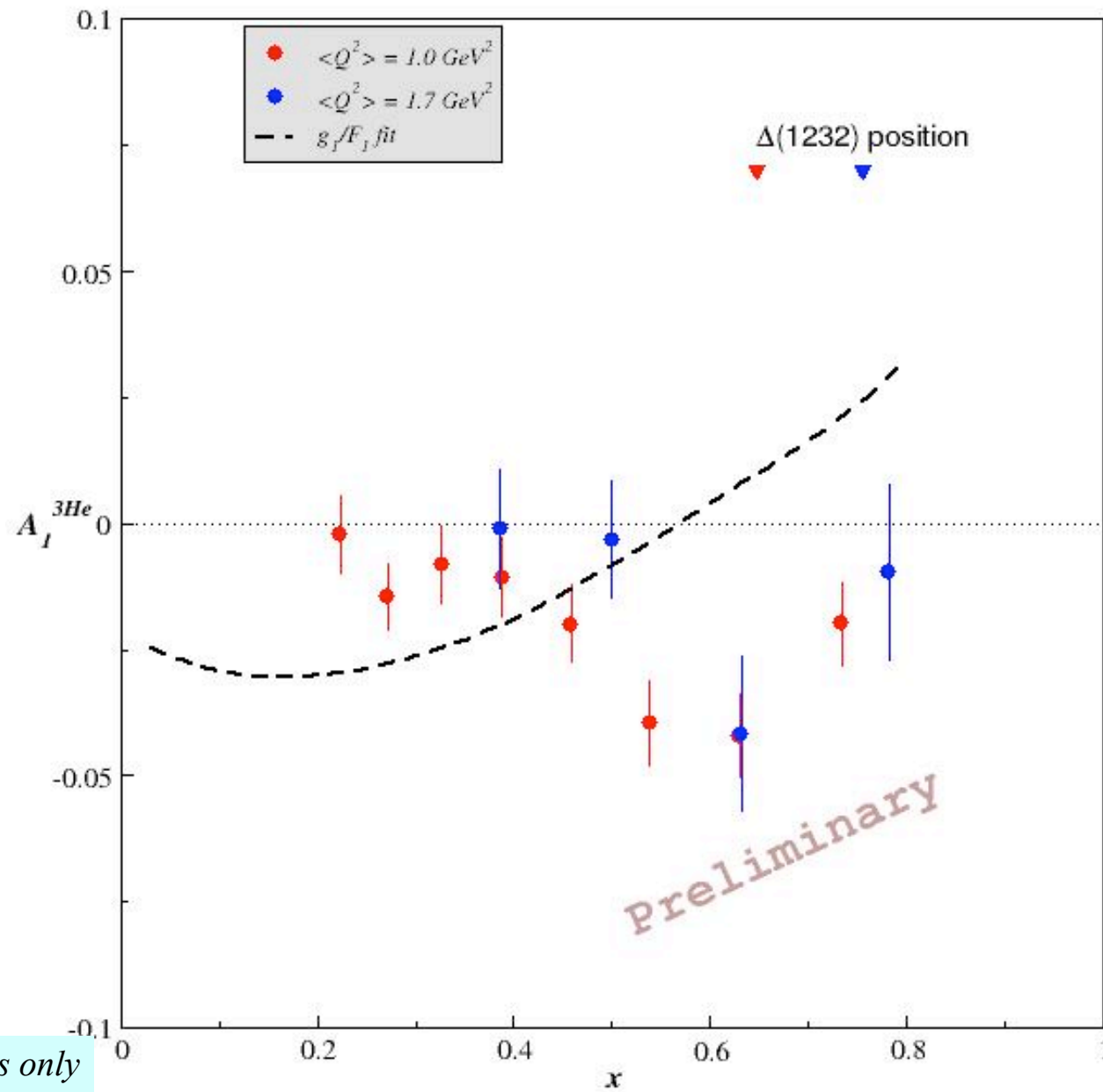


# $A_1^{3\text{He}}$



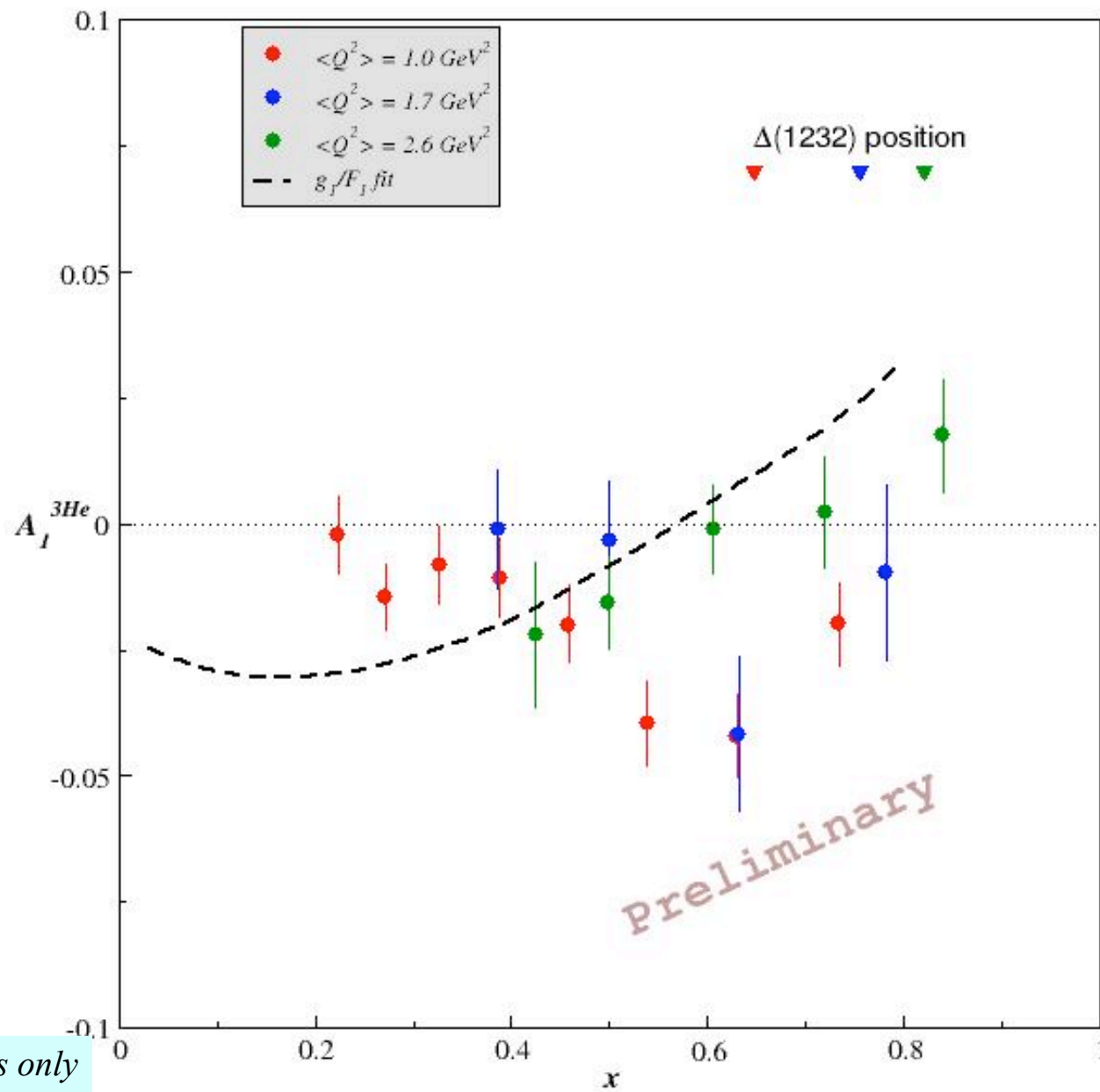
Statistical errors only

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



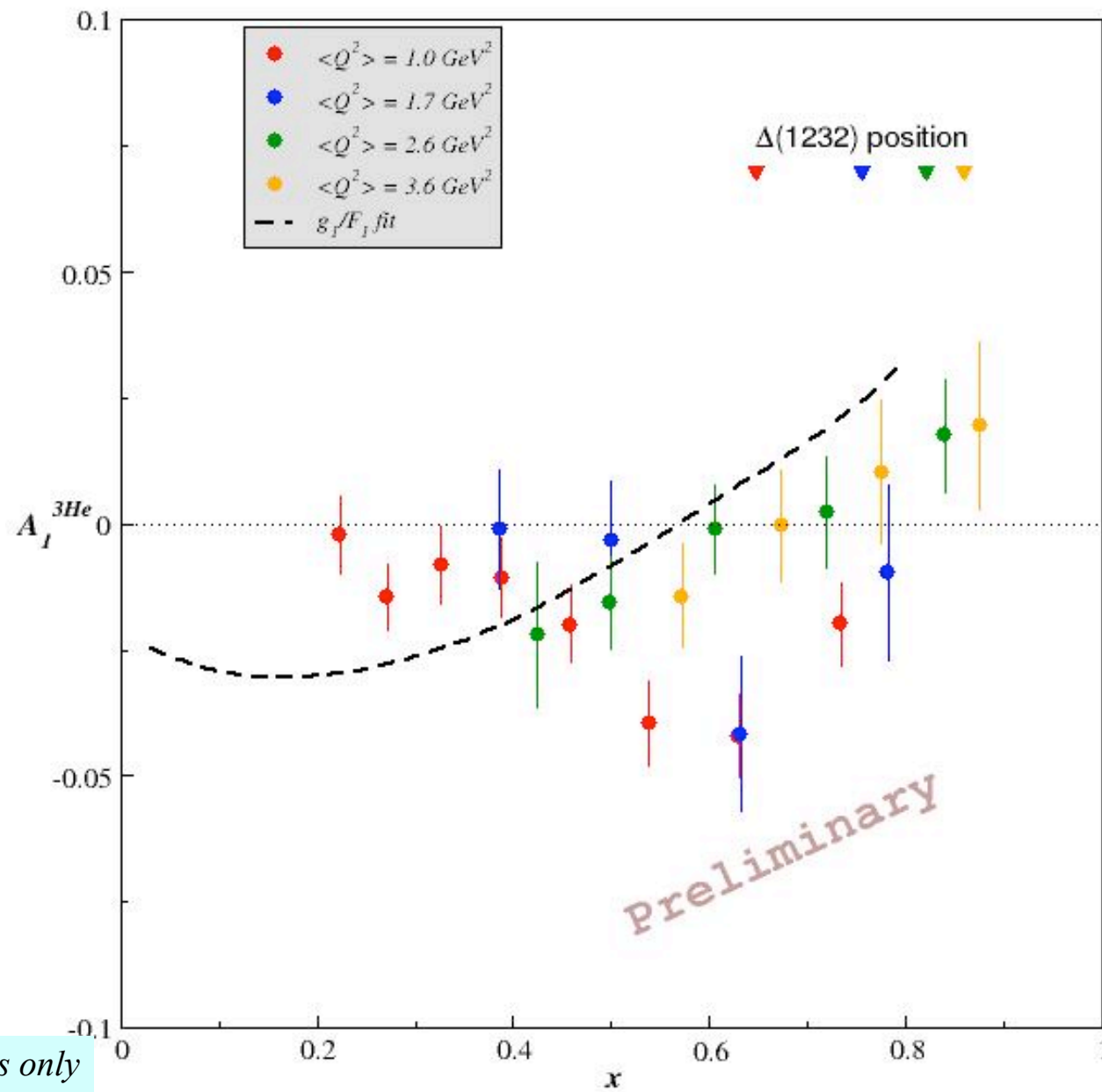
Statistical errors only

# $A_1^3\text{He}$



Statistical errors only

# $A_1^3\text{He}$

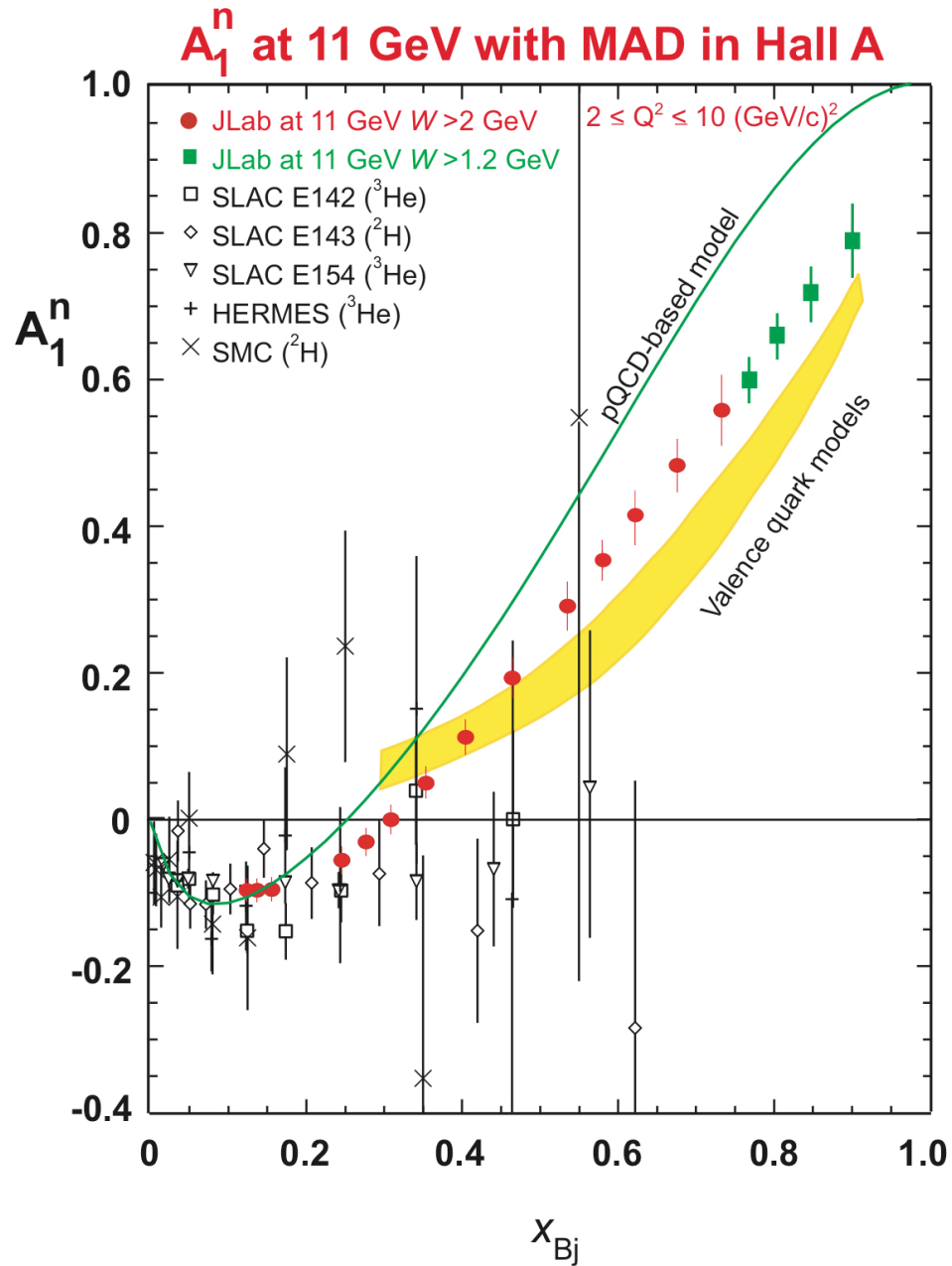


Statistical errors only

# Summary

- E01-012 provides precision data of **Spin Structure Functions** on **neutron ( $^3\text{He}$ )** 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  $^3\text{He}$  SSF**
  - **Global duality seems to work for  $g_1$  for all our  $Q^2$**
  - **Too early to draw conclusions on  $A_1$  behavior.**
- 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



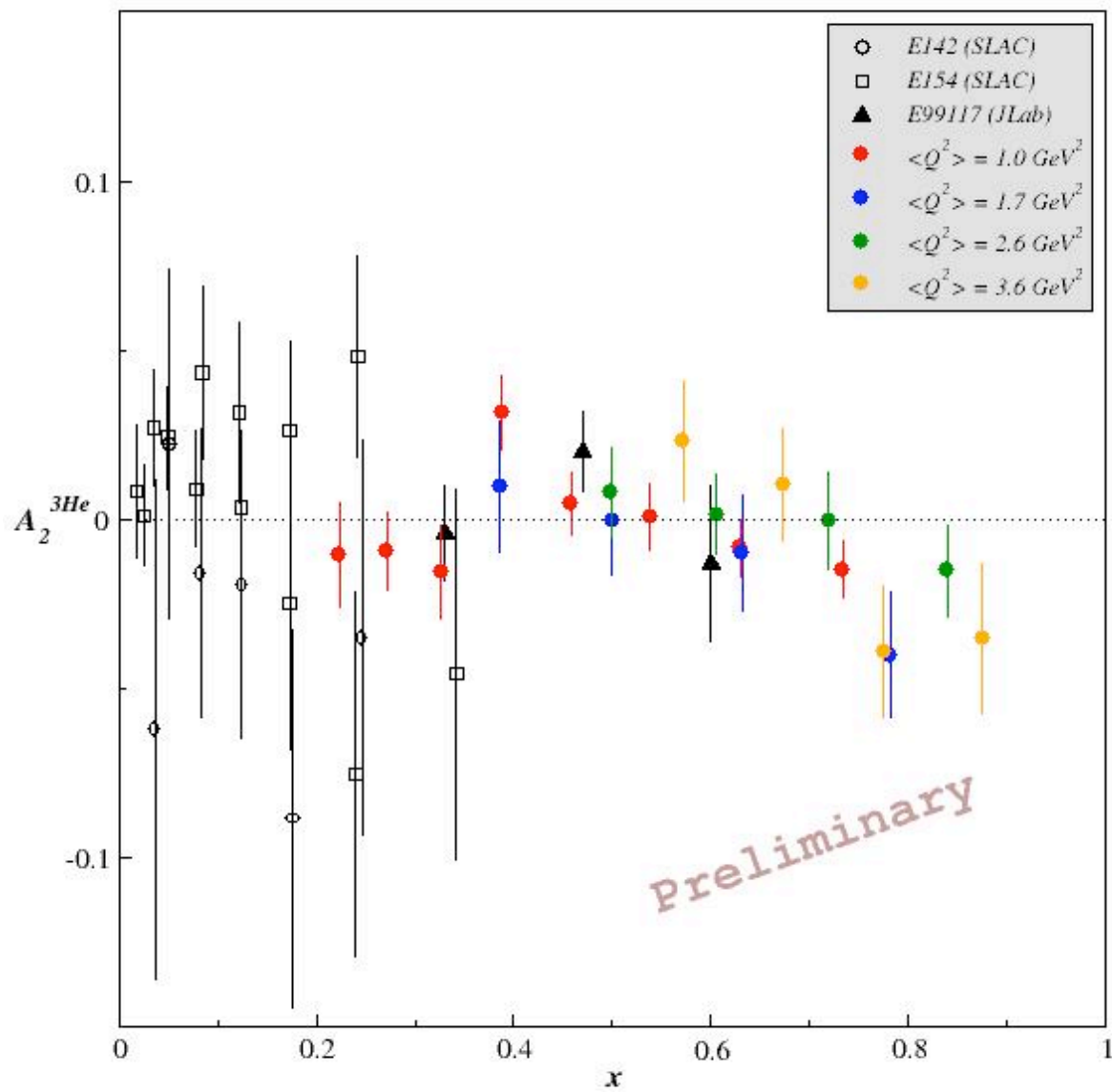
**Extra Slides**

# Systematics

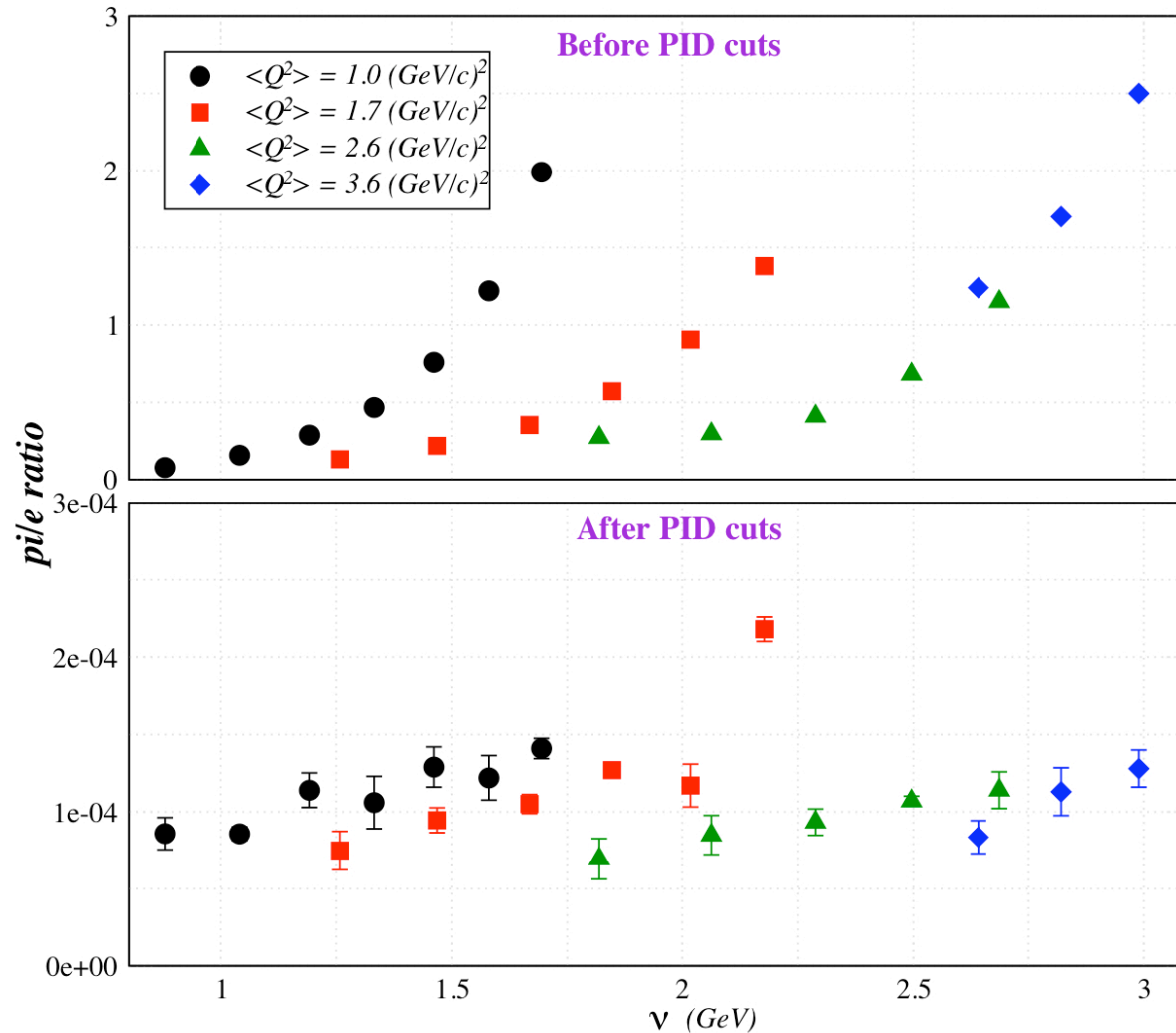
<b>Target</b>	
density	1.0-2.0%
polarization	3.0-4.0%
<b>Beam</b>	
charge	1.0%
polarization	3.0%
energy	0.5%
<b>N<sub>2</sub> dilution</b>	0.5-1.0%
<b>Detector efficiencies</b>	2.5%
<b>Acceptance</b>	2.0-3.0%
<b>Radiative corrections</b>	?



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

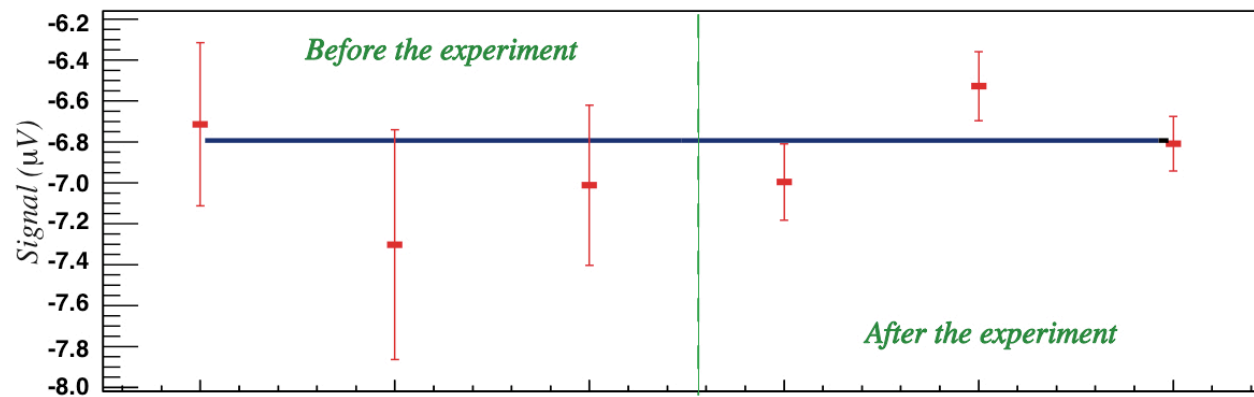
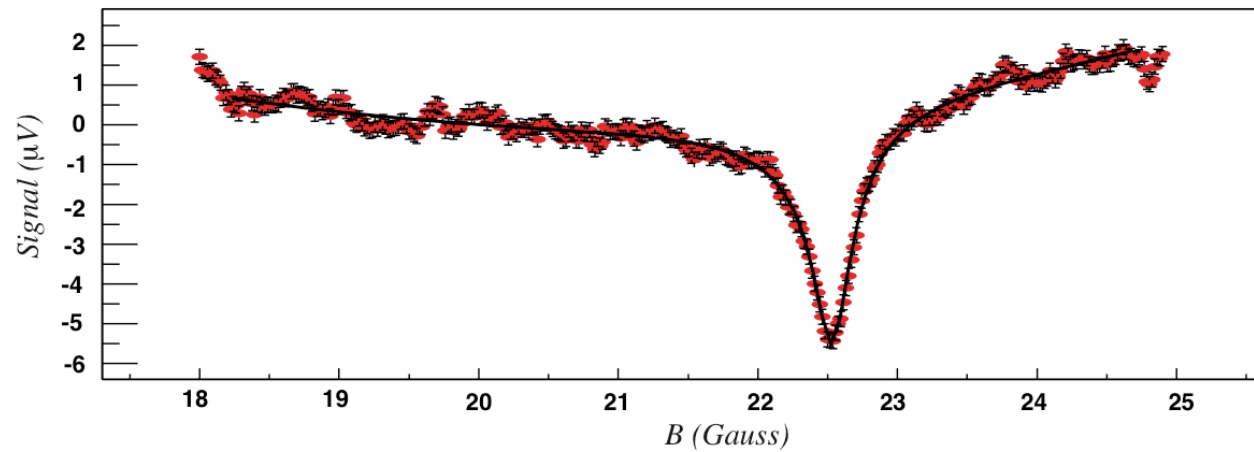


# Particle identification performance



$\pi/e$  reduced by  $10^4$  and electron efficiency kept above 98%

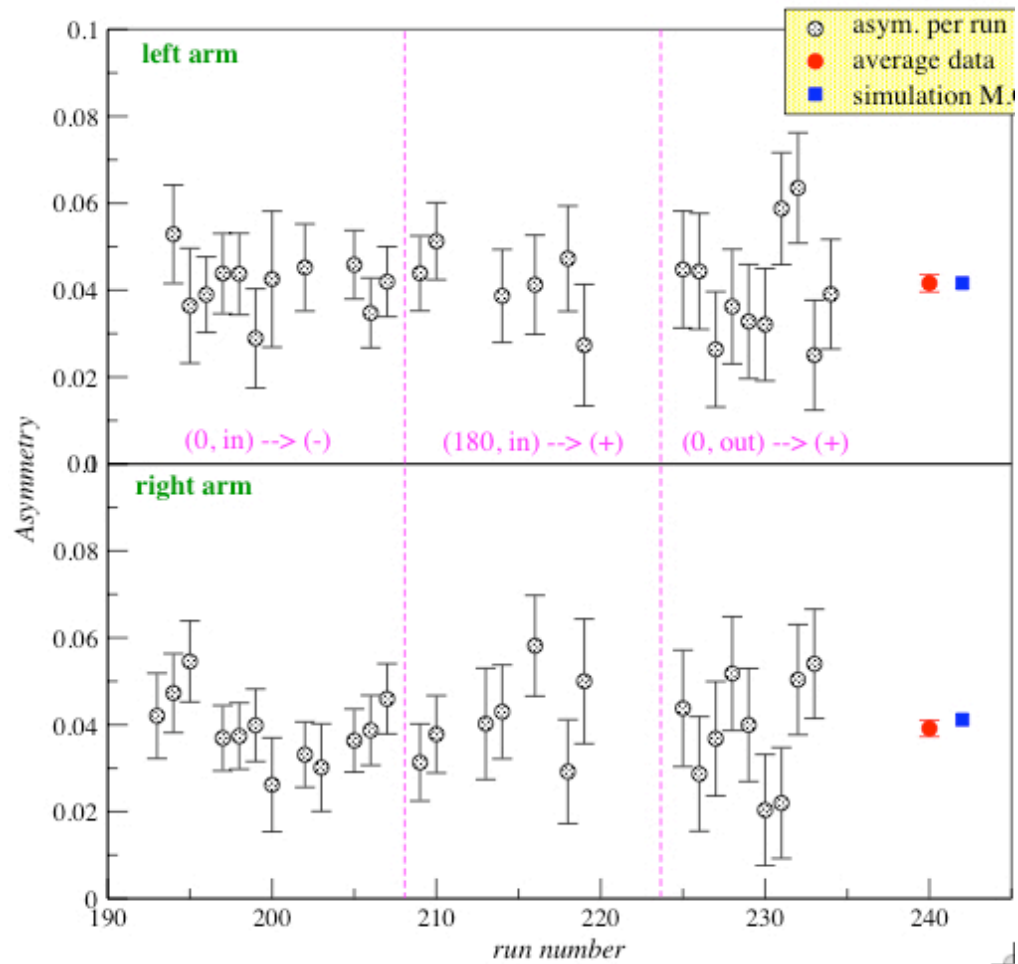
# NMR: water calibration



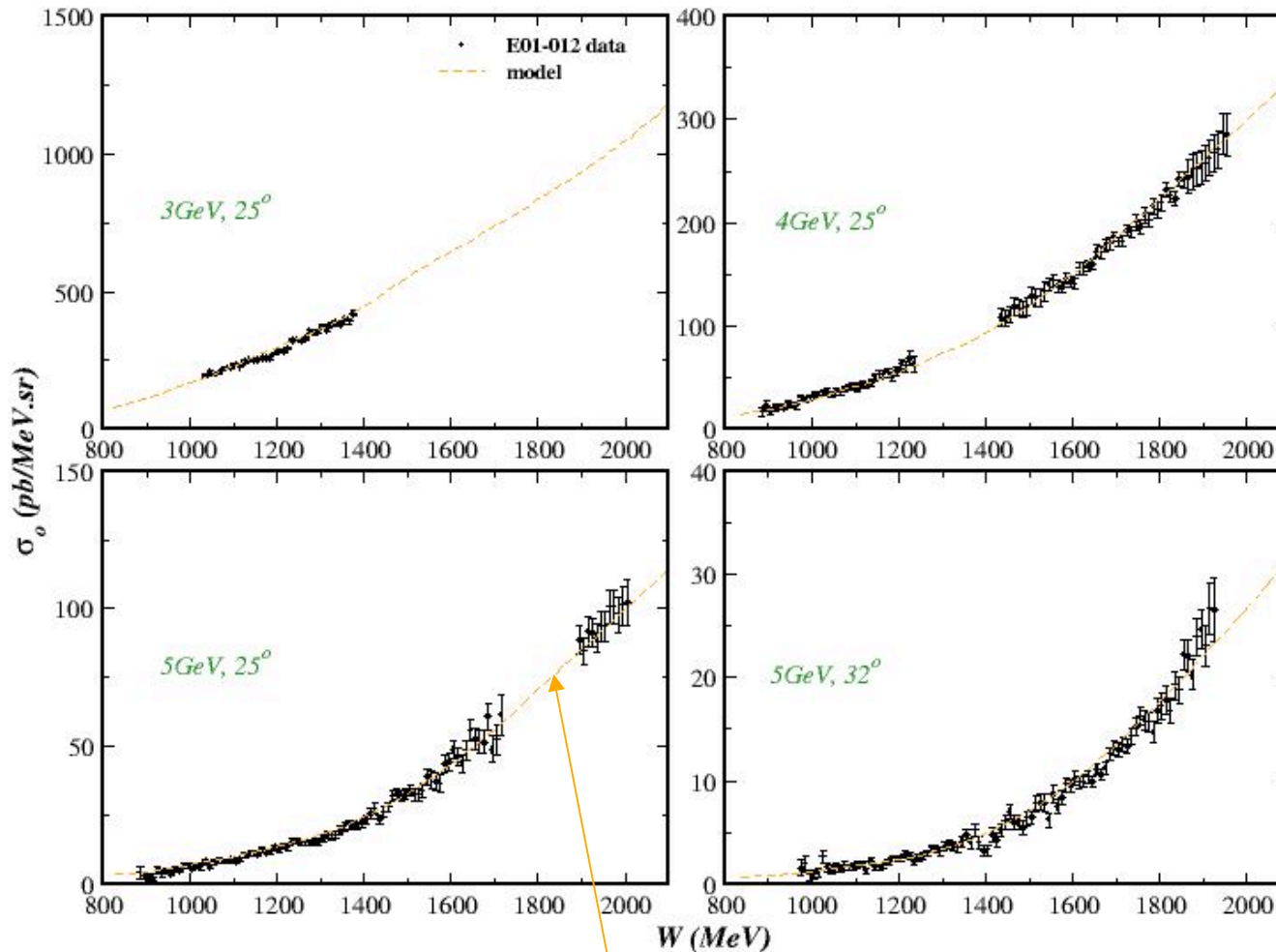
NMR analysis done by Vince Sulkosky

# 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