Spin physics with CLAS and CLAS12

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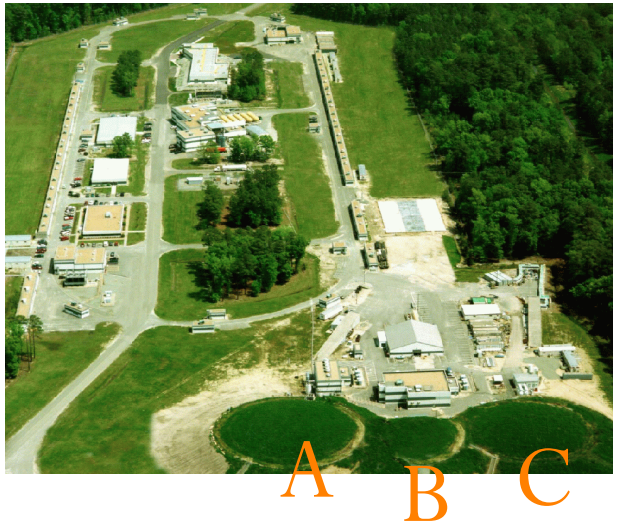
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Fairfield
UNIVERSITY

Overview

- Experiments EG1, EG4 with CLAS
- Nucleon Structure Functions results
- EG1-DVCS experiment with CLAS
- DVCS results
- Future experiments with CLAS12
- Summary

Jefferson Laboratory and CLAS



CEBAF
Large
Acceptance
Spectrometer

- Six individually instrumented sectors
- Toroidal magnetic field
- Multi-particle final state
- Large acceptance

CEBAF is a superconductive electron accelerator

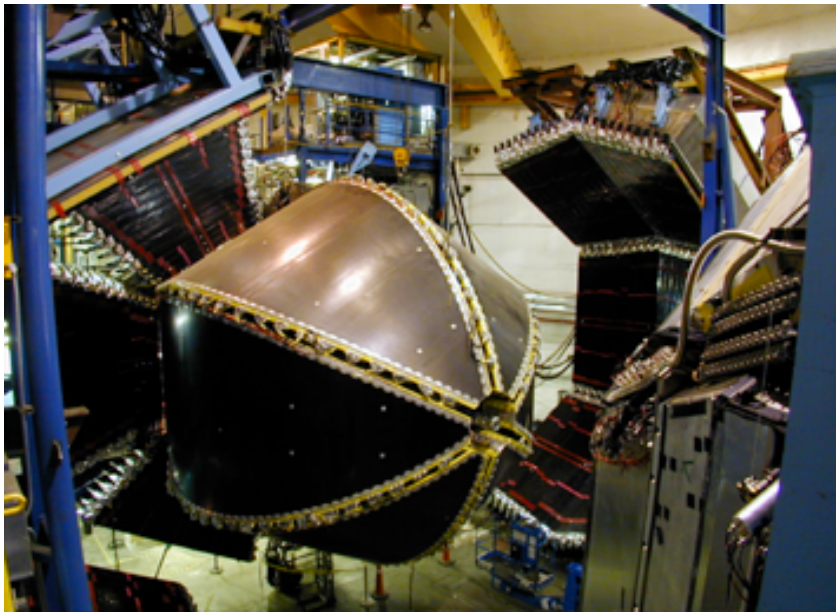
→ **continuous beam**

→ **high longitudinal polarization**

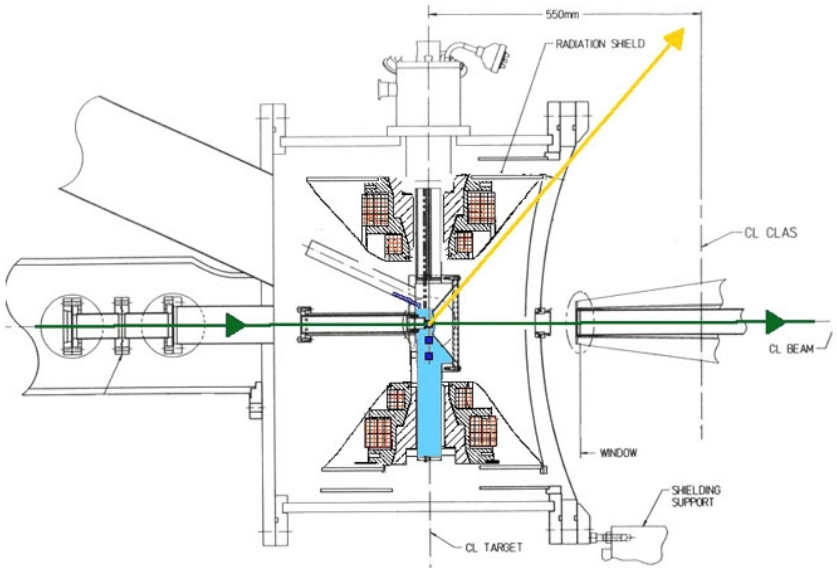
→ **energy range → 0.75 –5.9 GeV**

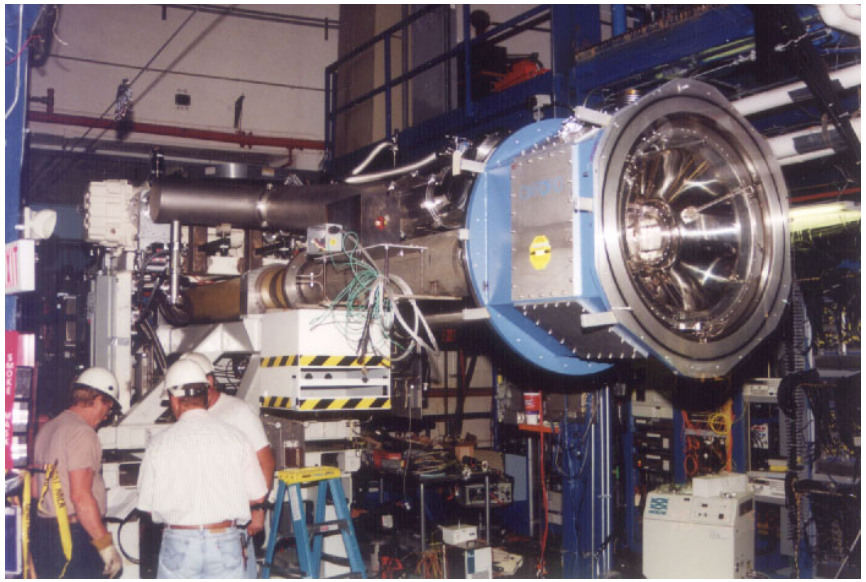
→ **current range → 0.1 nA –200mA**

→ **Beam polarization 80-90%**

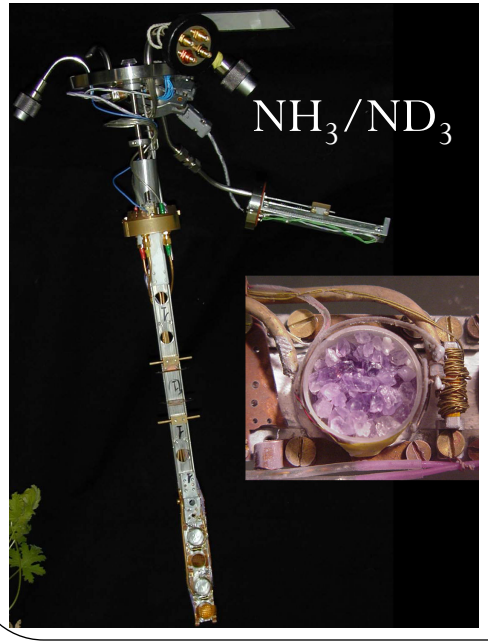


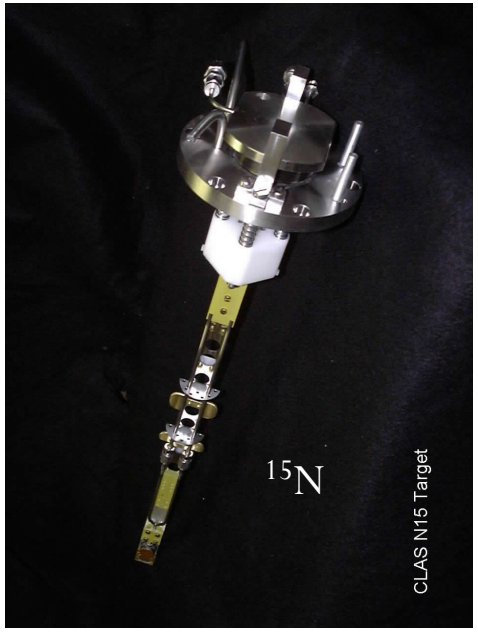
The polarized target





EG1/EG4 target (CLAS):
Polarization up to 0.9 (p) or 0.4 (d)





Experiments EG1 and EG4 with CLAS

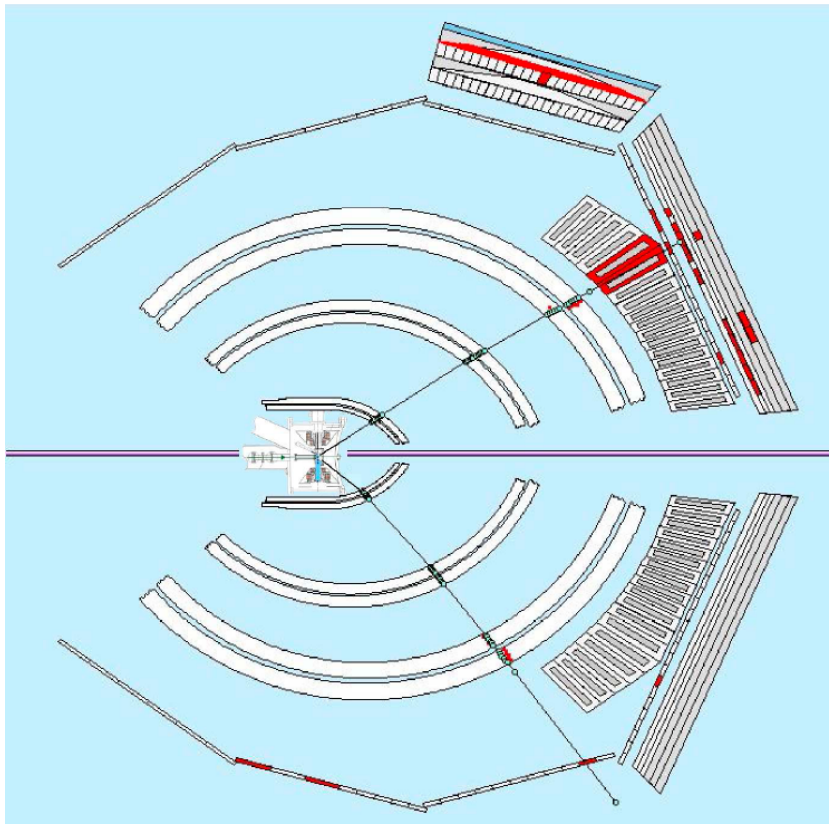
EG1: $Q^2 = 0.05\ldots5$ GeV^2

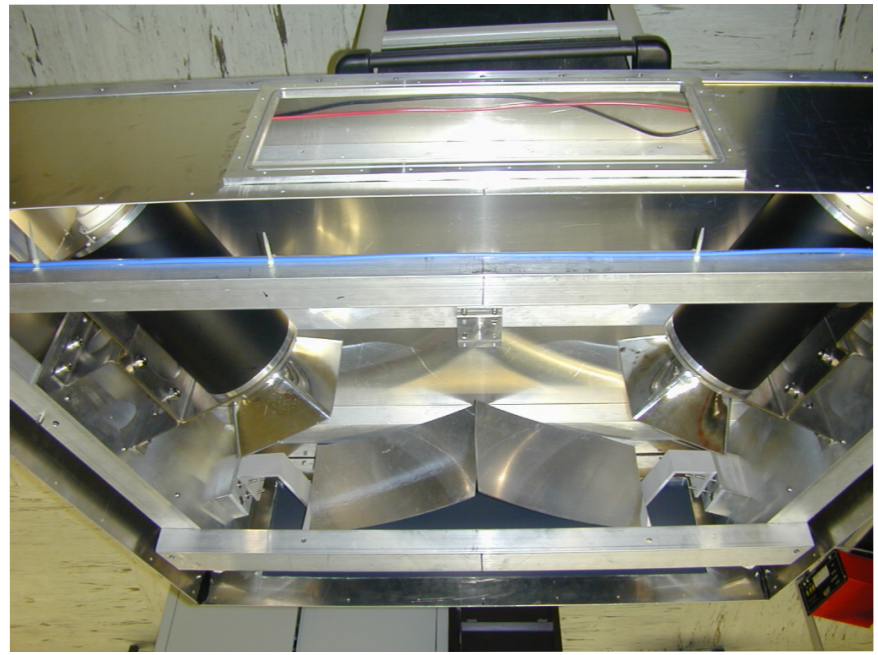
EG4: $Q^2_{min}=0.015$ GeV^2

note: $m_\pi^2 = 0.02$ GeV^2

Largest possible kinematic coverage
→ inbending and outbending configuration, E = 1.6…5.8 GeV

1998 - 2001





Focus on low Q^2 (GDH, χPT) => lower beam energies (up to 3 GeV), new Cherenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

2006

JLab experiments

"Everything"

Sum Rules at low Q^2

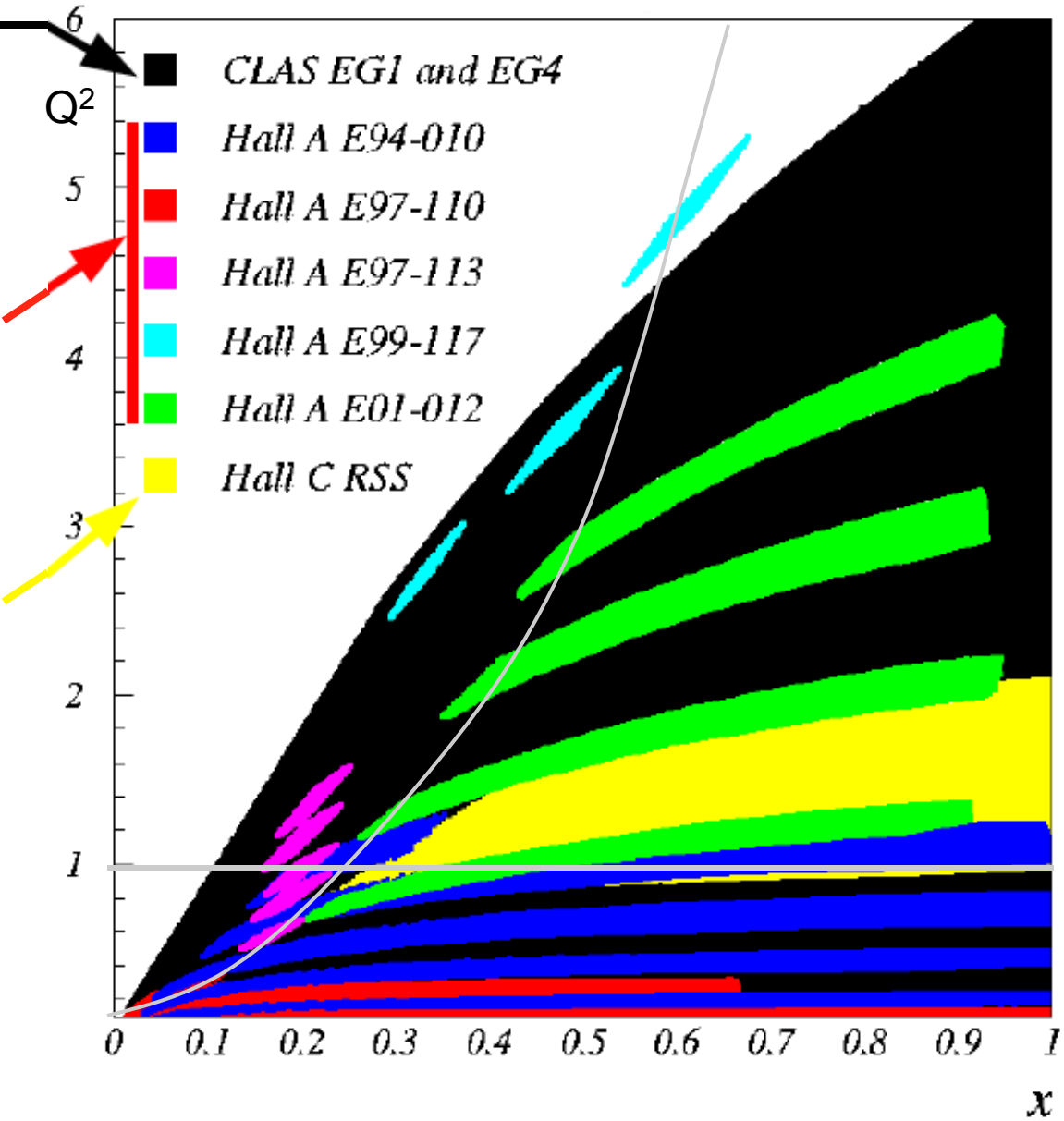
very low Q^2 - χPT

Q^2-dep. of g_2

A_{1n} at high x

Duality

Res. Region, Duality

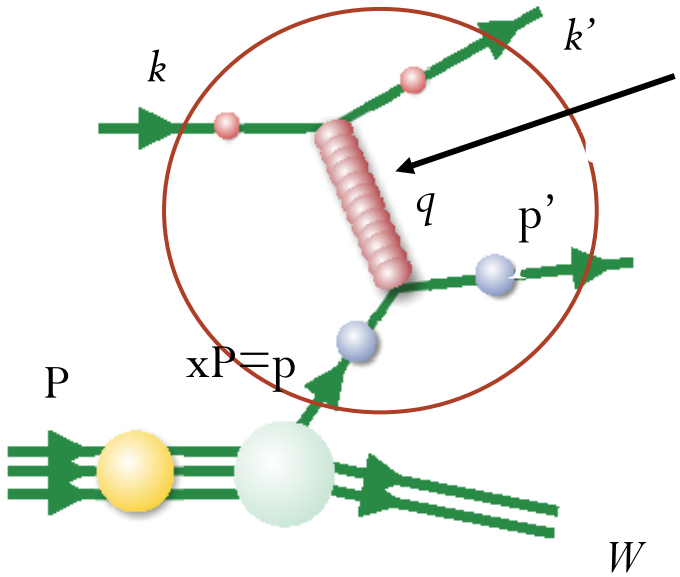


✓8 completed experiments

3 (+3) approved with 6 GeV JLab

3 (+1) approved with 12 GeV (A/B/C)

DIS of lepton off nucleon



Virtual photon probes the structure

Important variables:

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

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

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

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

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

Virtual photon asymmetries

Experimentally: $$A_{\parallel} = \frac{d\sigma^{\uparrow\Uparrow} - d\sigma^{\downarrow\Uparrow}}{2d\sigma_{unpol}} = D\left(A_1 + \eta A_2\right)$$

$$A_{\perp} = \frac{d\sigma^{\uparrow\Rightarrow} - d\sigma^{\downarrow\Leftarrow}}{2d\sigma_{unpol}} = d\left(A_1 + \zeta A_2\right)$$

D, η, d, ζ are functions of Q^2, E', E, $R=\sigma_L/\sigma_T$....

$$\gamma^2 = \frac{4M^2x^2}{Q^2}$$

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \gamma^2 \frac{g_1 + g_2}{F_1}$$

The virtual photon asymmetries **A_1** and **A_2** can be extracted by varying the *direction of the nucleon polarization*

or by varying the *beam energy* at fixed Q^2, ν

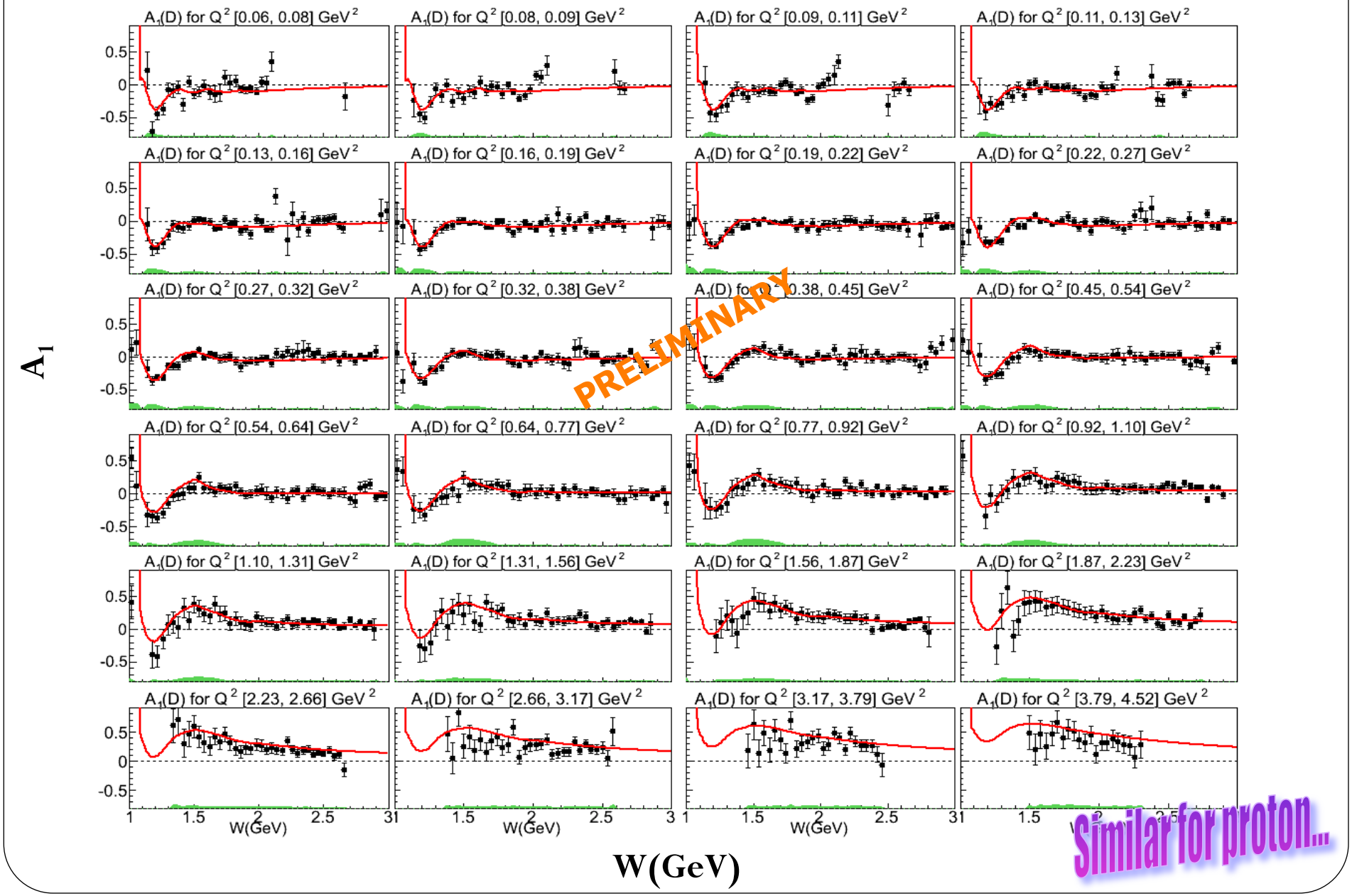
Large-x behavior of the A_1 asymmetry

- SU(6) ➔ $A_1^p = \frac{5}{9}$, $A_1^n = 0$
- Hyperfine perturbed QM
  - ✓ makes S=1 pairs more energetic than S=0 pairs ➔ A_1 → 1
- In DIS, and in pQCD
  - ✓ Minimal gluon exchanges
  - ✓ Spectator pair: quarks have opposite helicities
  - ✓ At large x struck quark carries the helicity of the nucleon
  - ✓ A_1 → 1

Isgur, PRD 59, 034013 (1999)

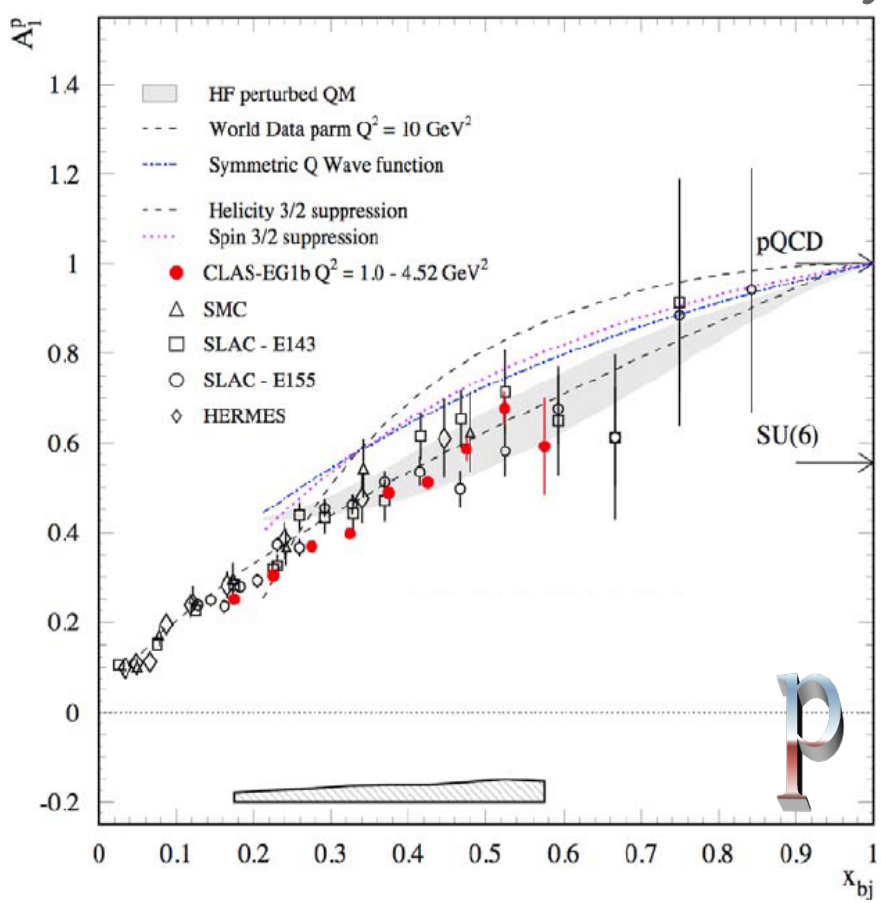
Farrar and Jackson, PRL 35, 1416 (1975)

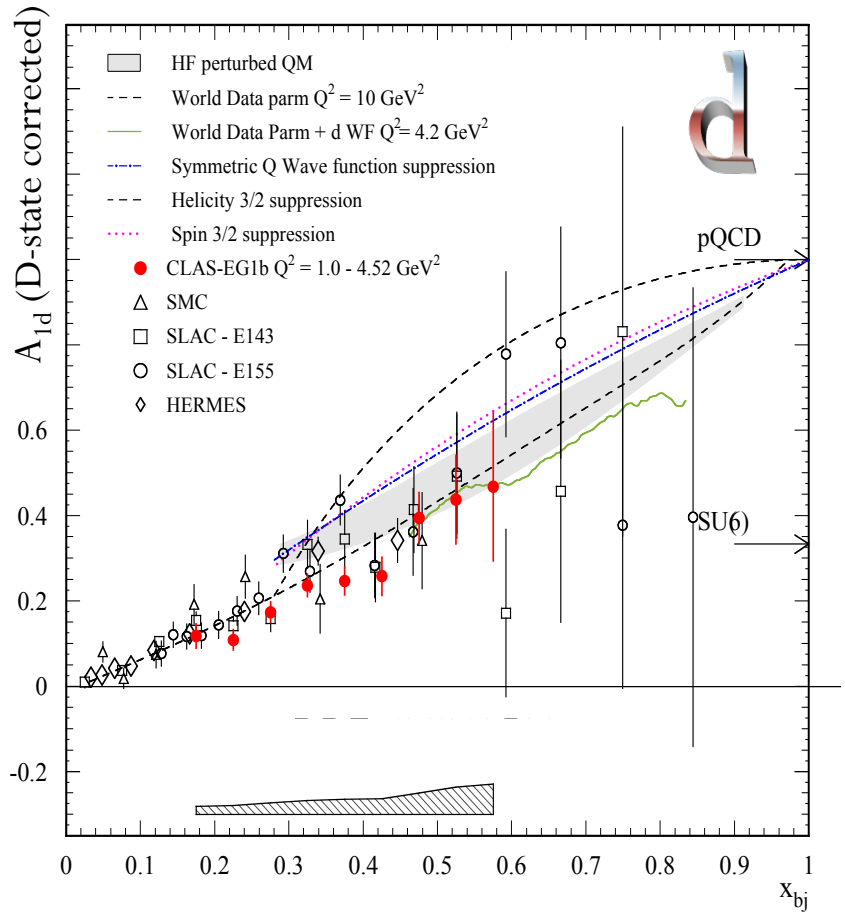
A_1 deuteron for different Q^2 bins



Similar for proton...

Virtual Photon Asymmetry A_1





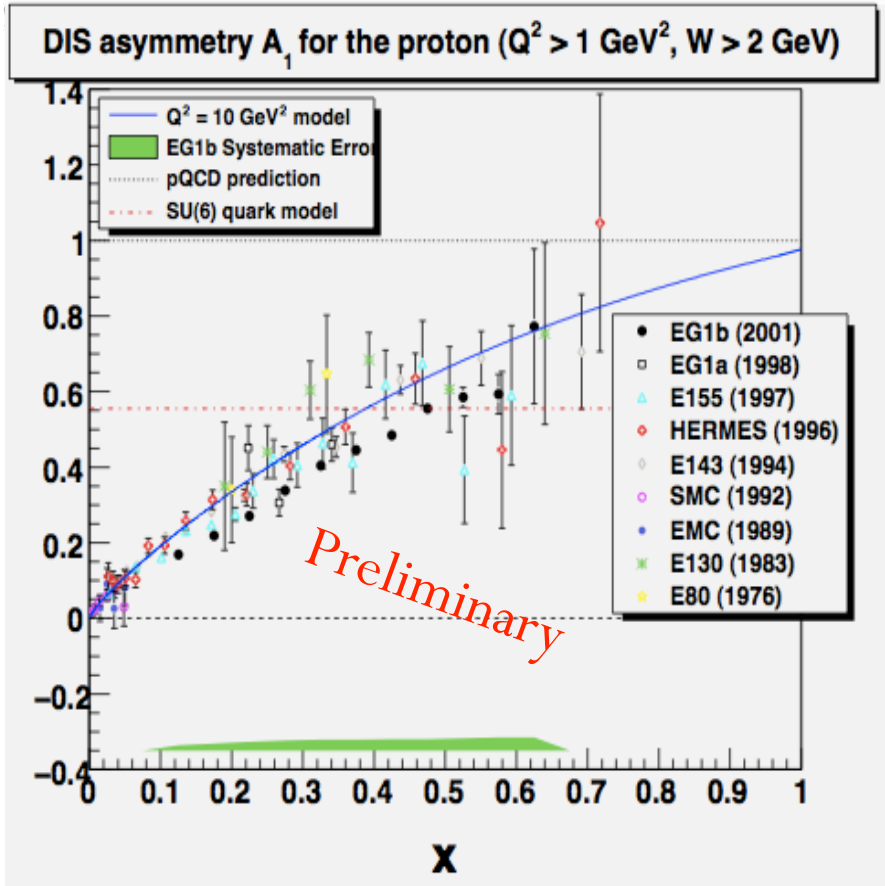
- p and d results fall below parameterization of world data at 10 GeV^2 → include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region
- p and d results are in better agreement with the HFP quark model

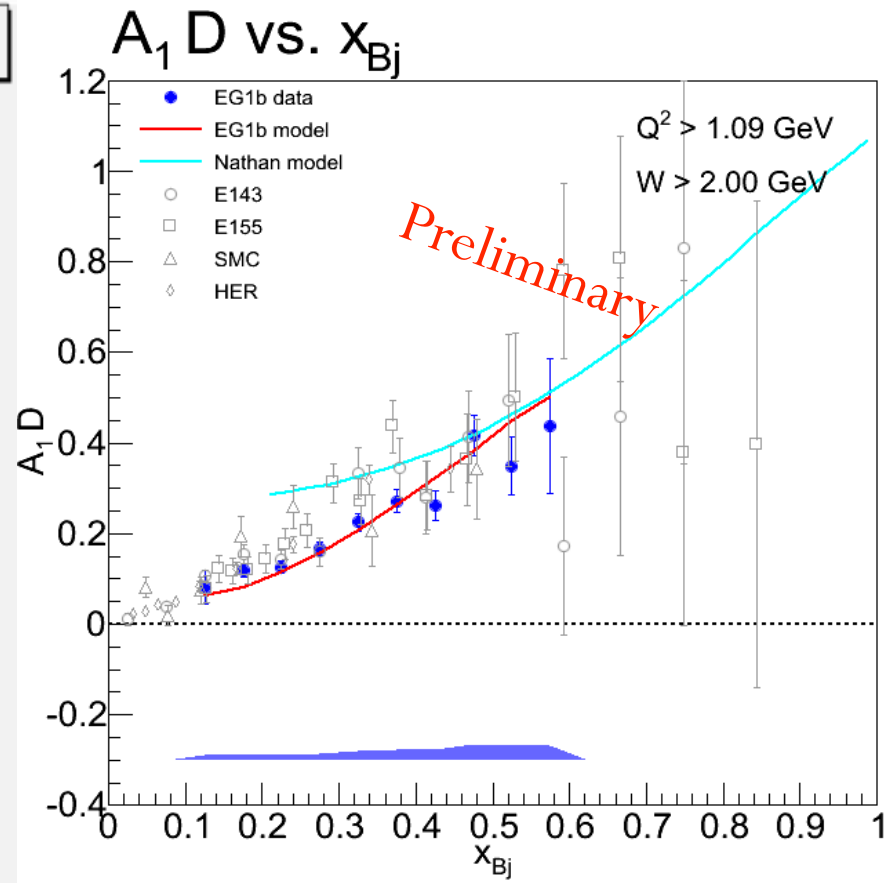
Hall B CLAS, Phys.Lett. B641 (2006) 11

HP perturbed QM N. Isgur, Phys. Rev. D 59, 34013

F. Close and W. Melnitchouk, Phys. Rev. C 68, 035210

Virtual Photon Asymmetry A_1

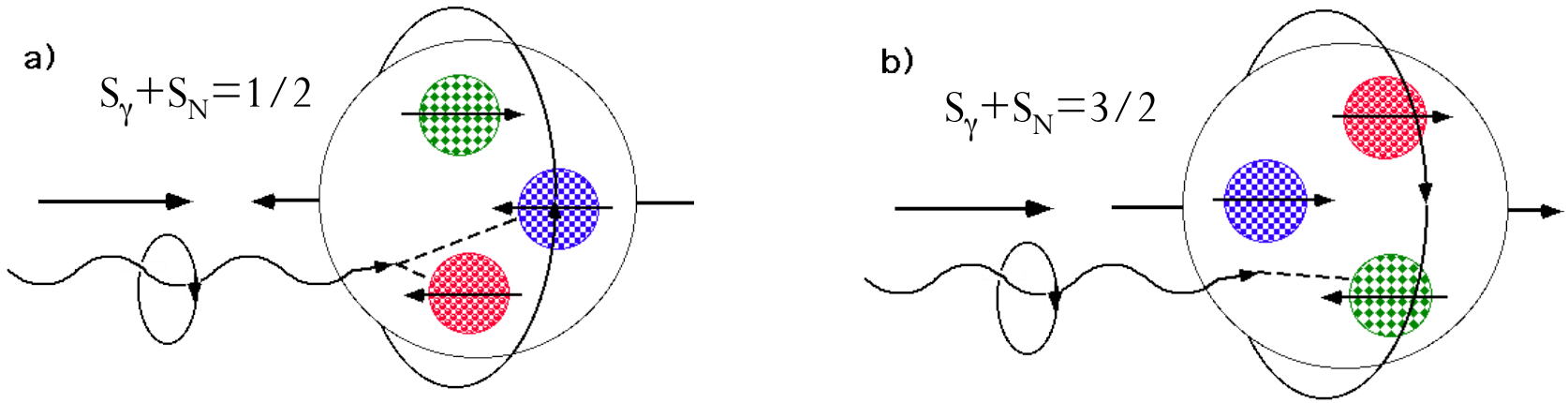




- New results from CLAS eg1b
- Better statistical precision
- Better systematic errors

Spin Structure Function g_1

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\ \Delta q + \Delta\bar{q} = \frac{1}{2}\sum_q e_q^2\left(q^+(x) - q^-(x)\ + \bar{q}^+(x) - \bar{q}^-(x)\right)$$

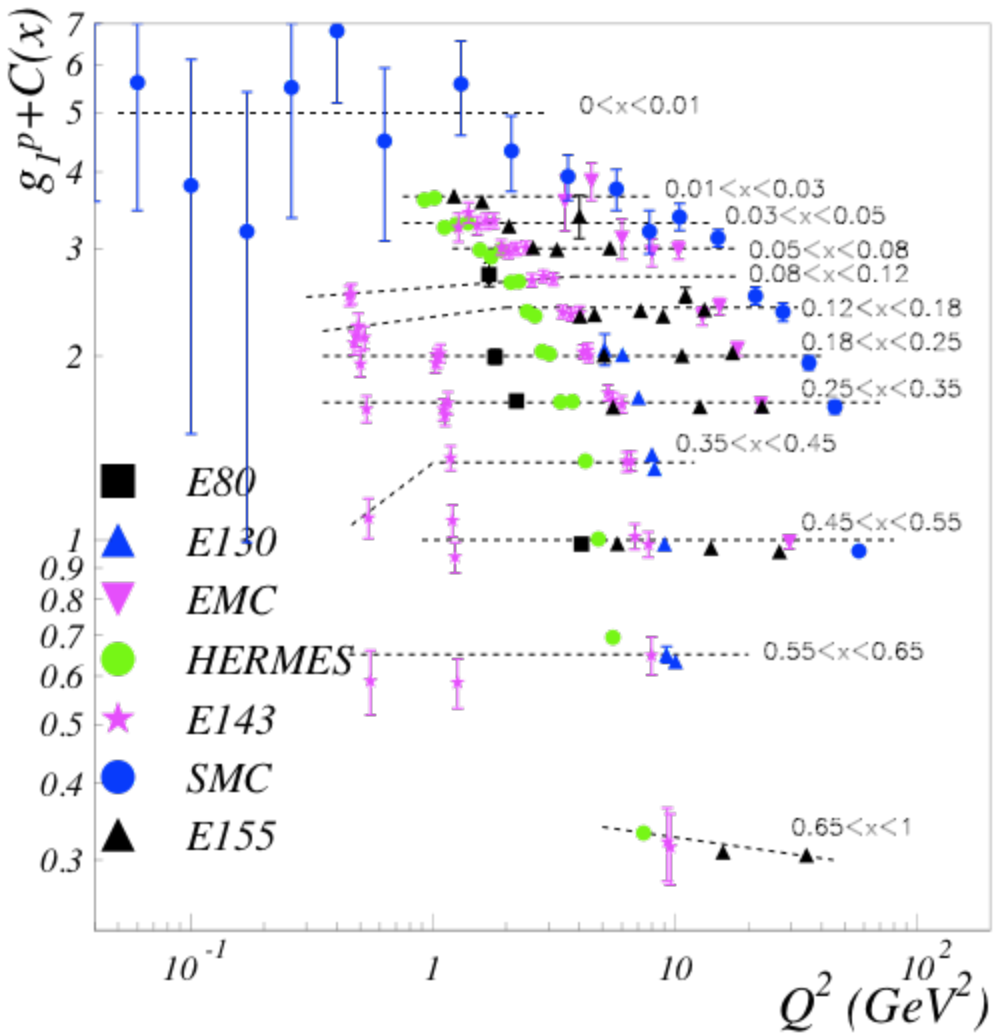


$\sigma_{1/2} \approx q^+(x)$ $\qquad$ $\sigma_{3/2} \approx q^-(x)$

- Virtual photon couples to quarks of opposite helicity
- $q^+(x)$ or $q^-(x)$ are chosen by changing the configuration of the incident lepton and target nucleon spin
- $g_1(x) \sim \sigma_{1/2} - \sigma_{3/2}$

g_1^p @ Jefferson Lab

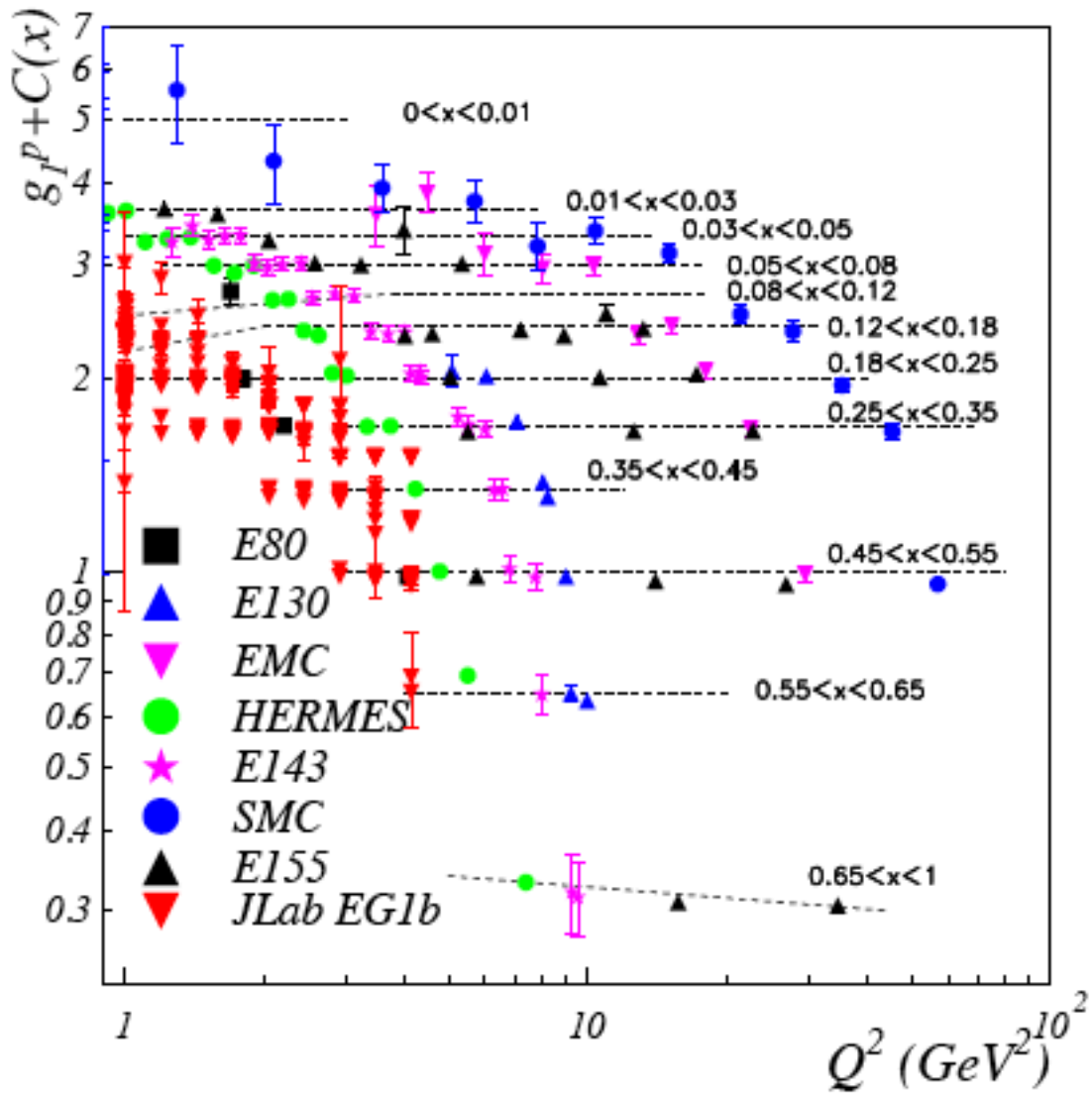
World data on the proton before JLab (without COMPASS)



g_1^p @ Jefferson Lab

World data on the proton before JLab (without COMPASS)

World data on the proton including EG1

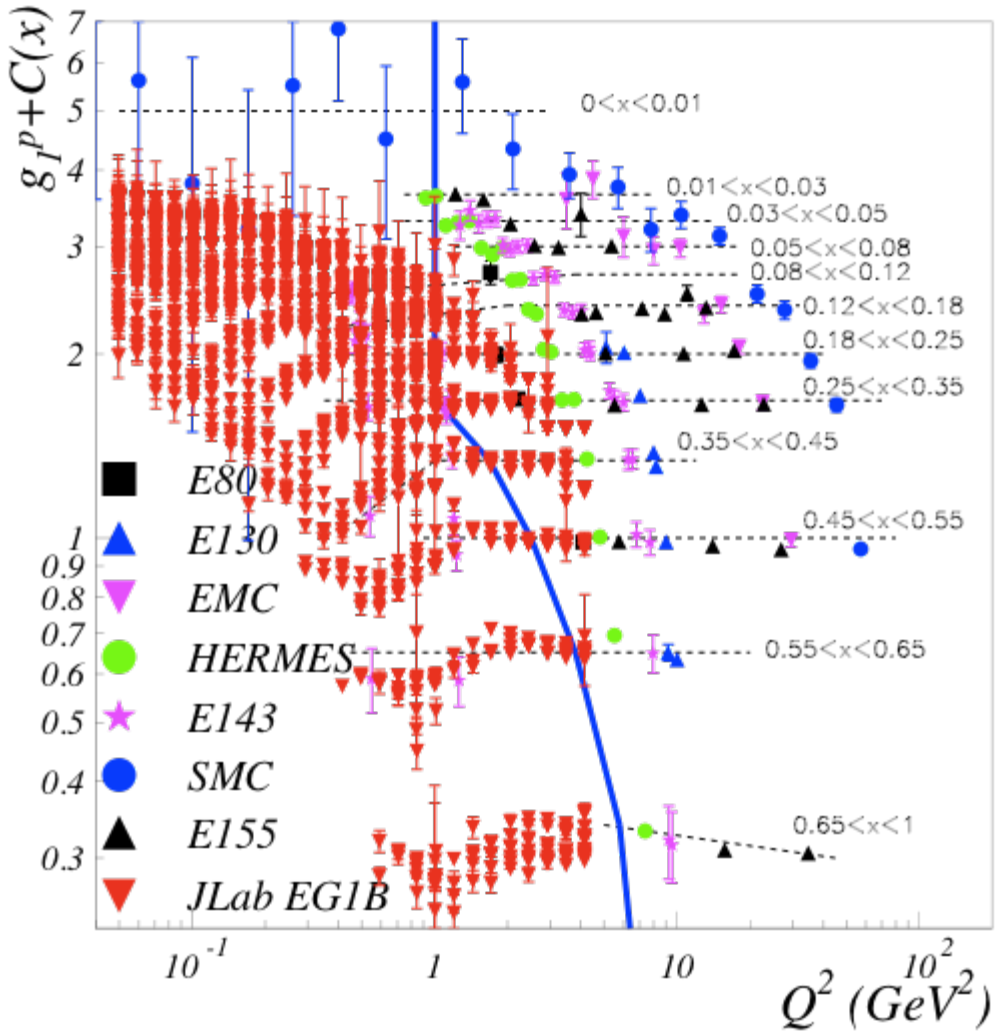


g_1^p @ Jefferson Lab

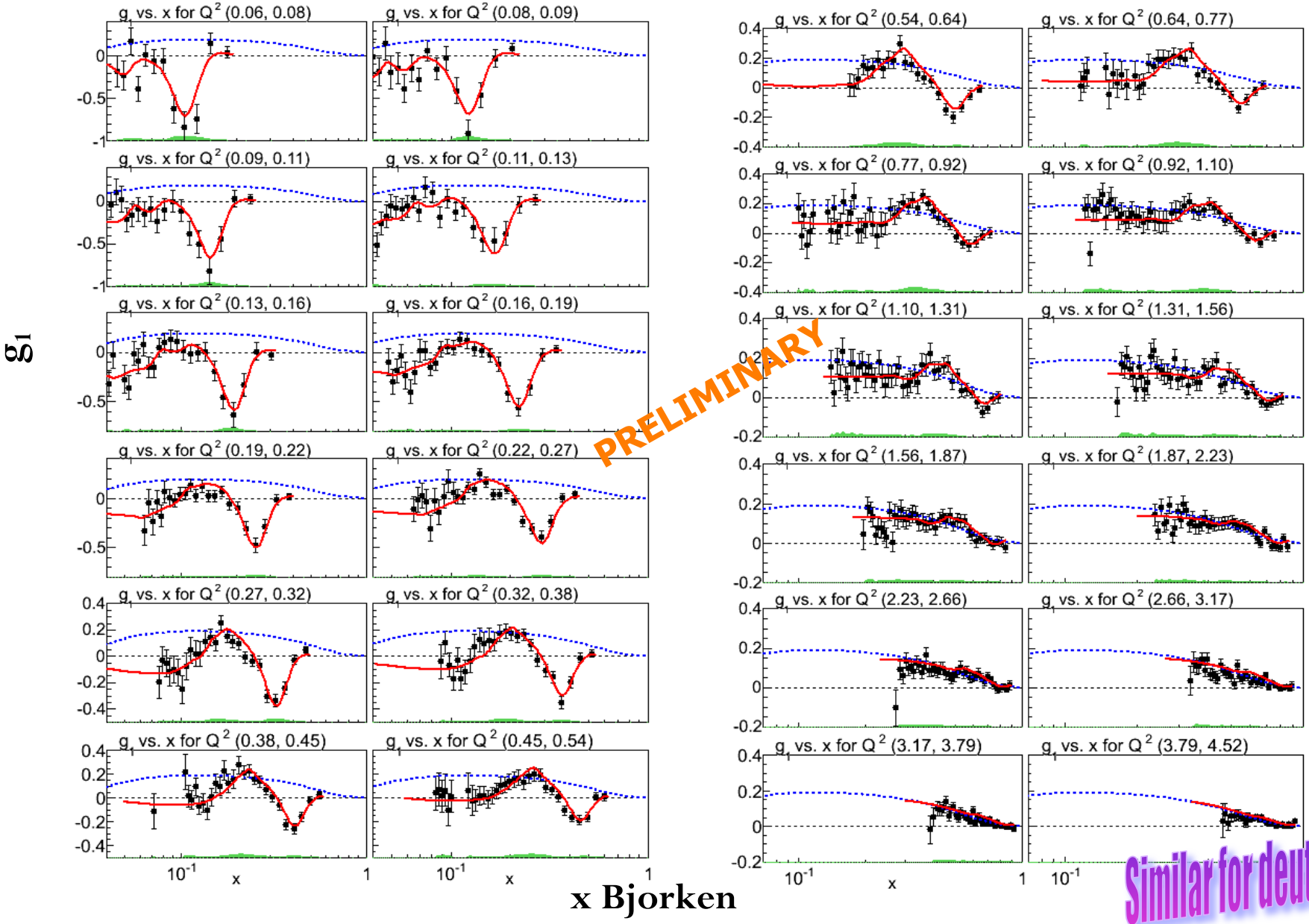
World data on the proton before JLab (without COMPASS)

World data on the proton including EG1

…including resonance region data!



$g_1(x,Q^2)$ proton for different Q^2 bins – eg1



Similar for deuteron...

First moment Γ_1 and GDH

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx$$

Net Quark Spin

At high Q^2 - QPM $\quad g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$

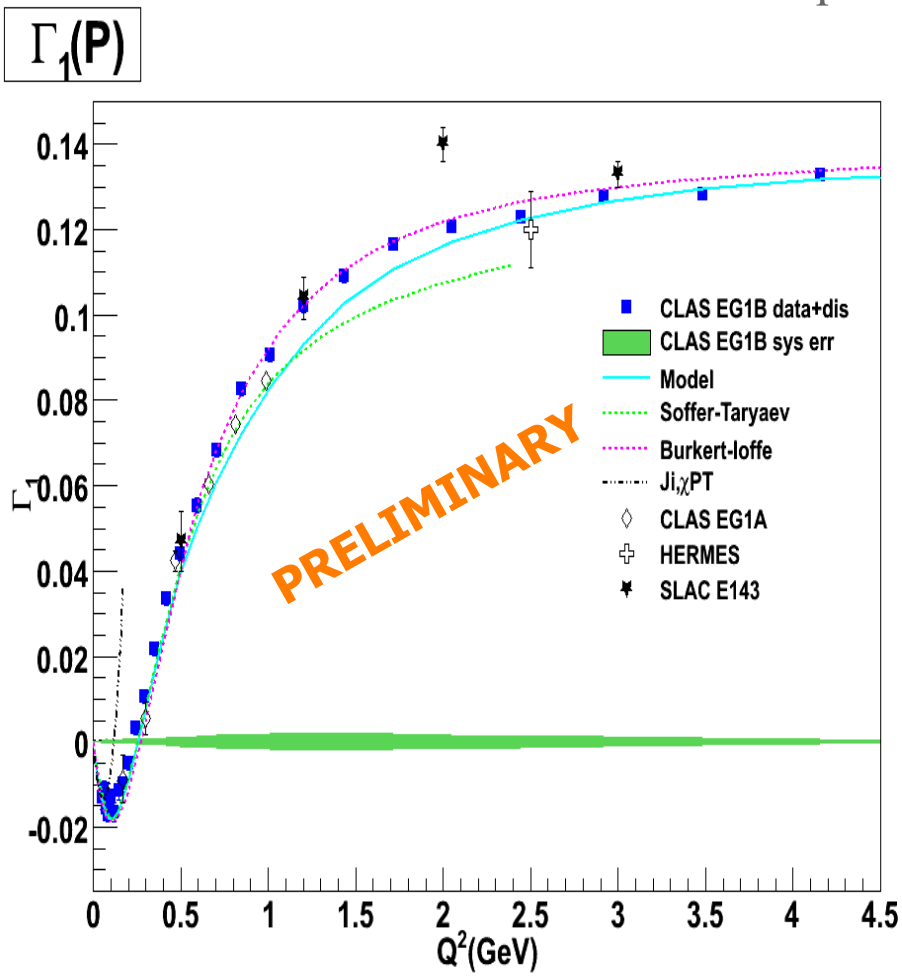
$$\Gamma_1^p = \frac{1}{9}\left(\frac{3}{4}a_3 + \frac{1}{4}a_8 + a_0\right) \qquad a_0 = \Delta\Sigma$$

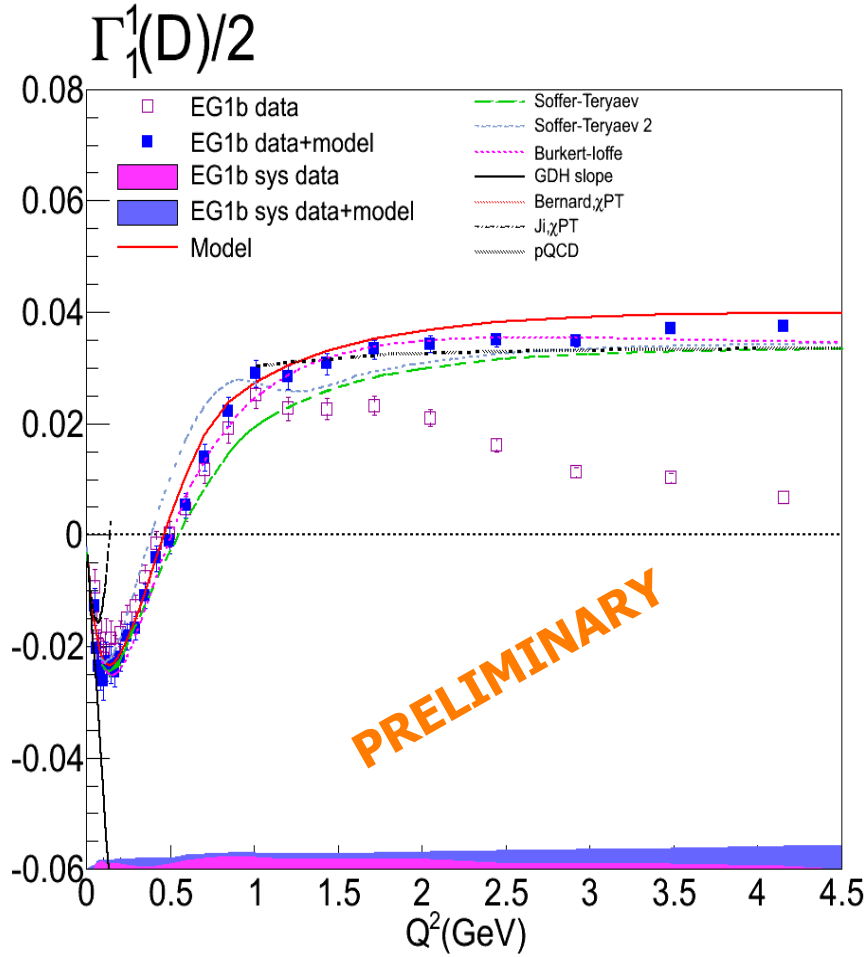
$Q^2 \to 0$ - GDH $\quad \Gamma_1 = \int g_1\left(x,Q^2\right)\, dx \xrightarrow[Q^2\to 0]{} \frac{Q^2}{2M^2} I_{GDH}$

$$I_{GDH} = \frac{M^2}{8\alpha\pi^2}\int_{thr}^{\infty}\left(\sigma_{1/2} - \sigma_{3/2}\right)\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

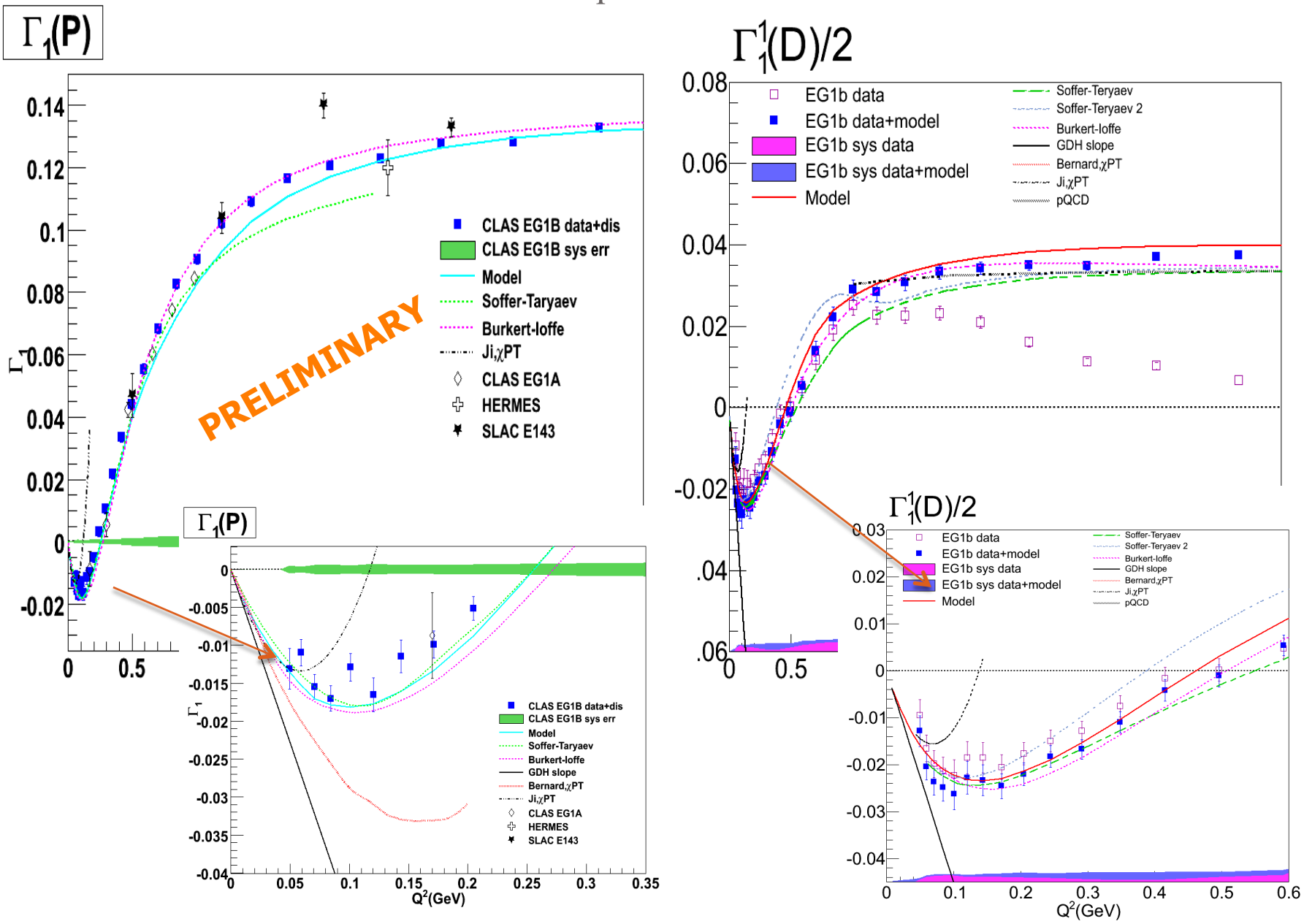
A connection between dynamic and static properties.

First moment Γ_1 and GDH - CLAS



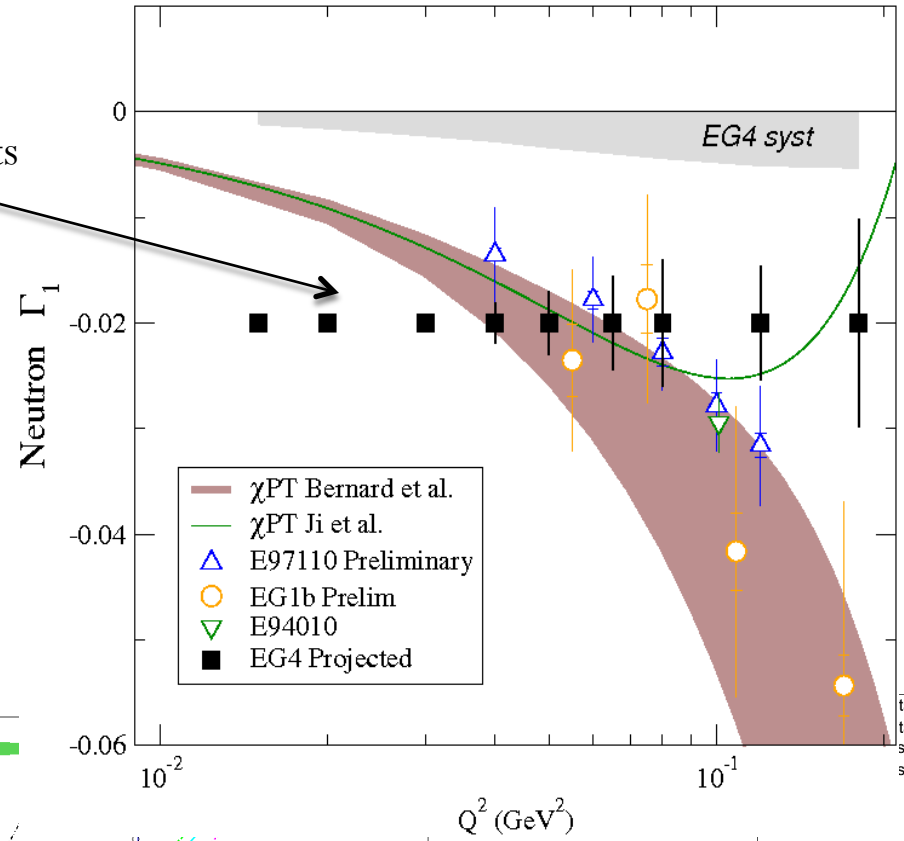


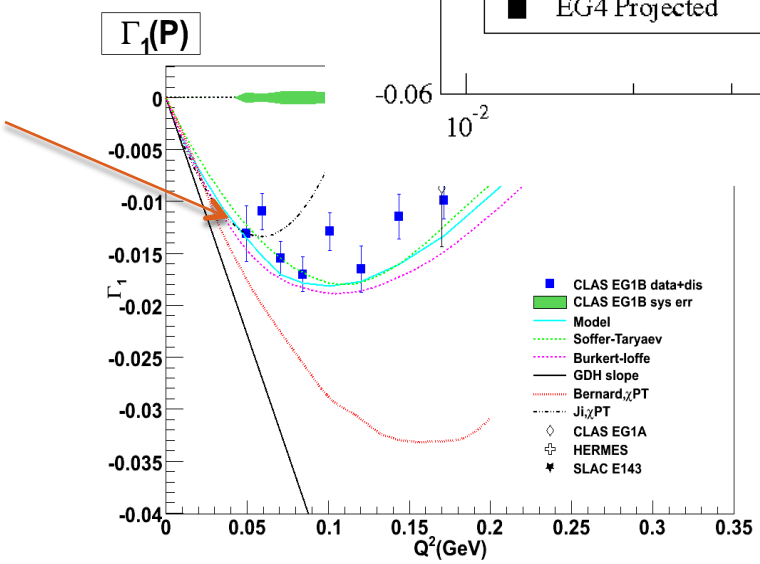
First moment Γ_1 and GDH - CLAS

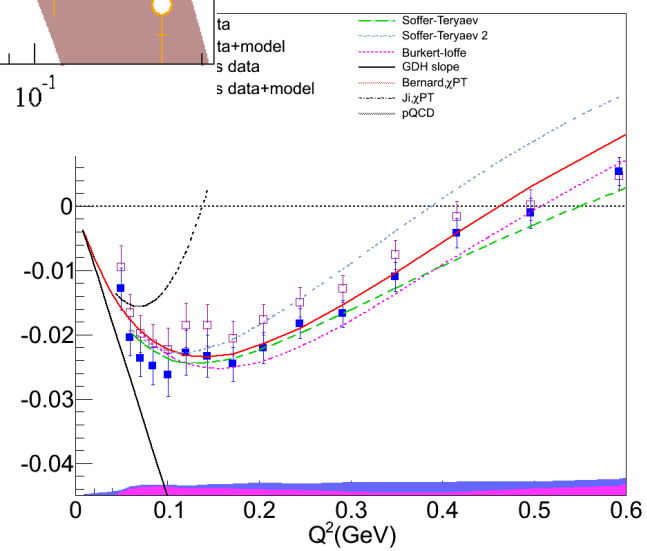


First moment Γ_1 and GDH - CLAS

EG4 expected results



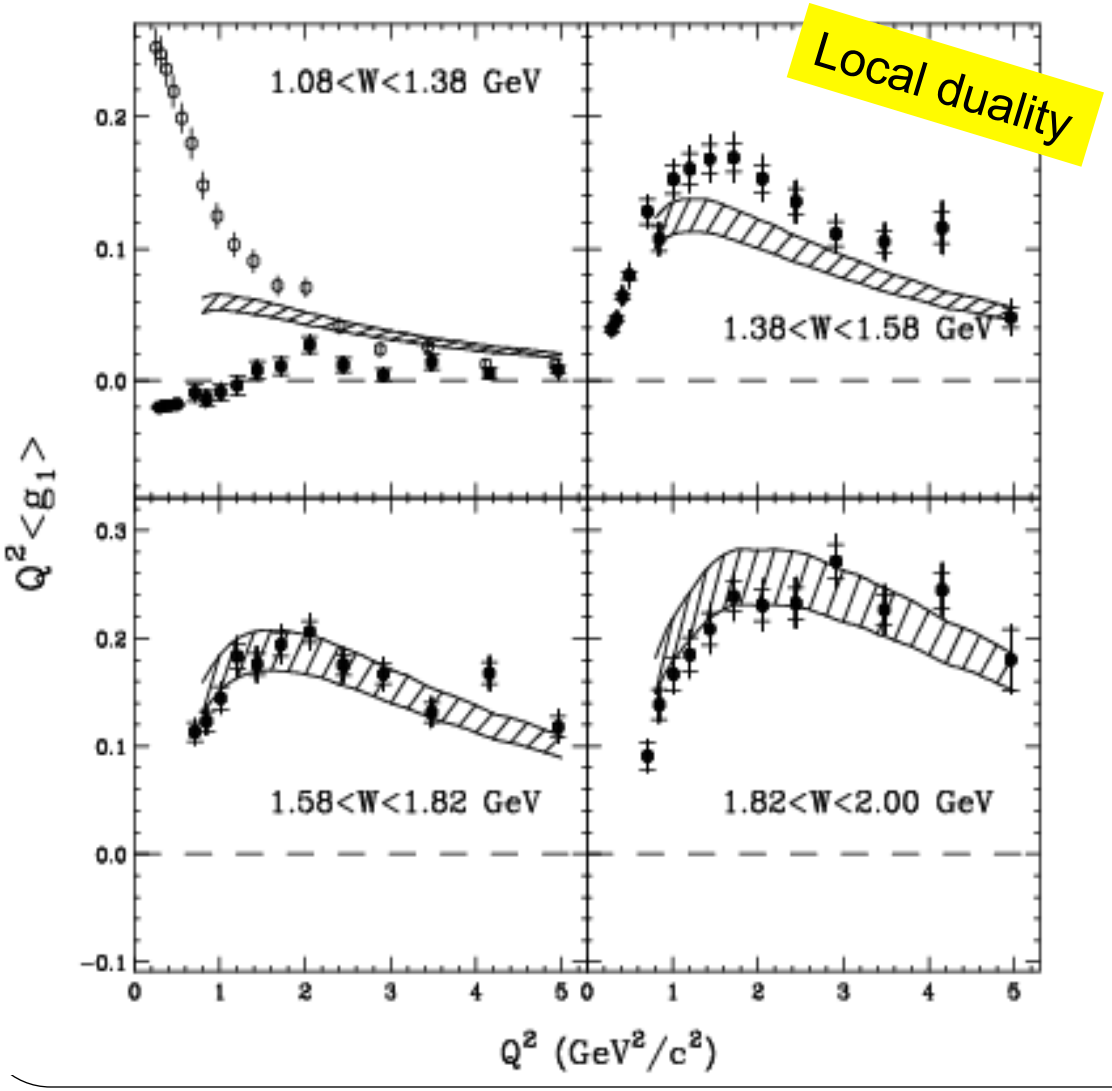


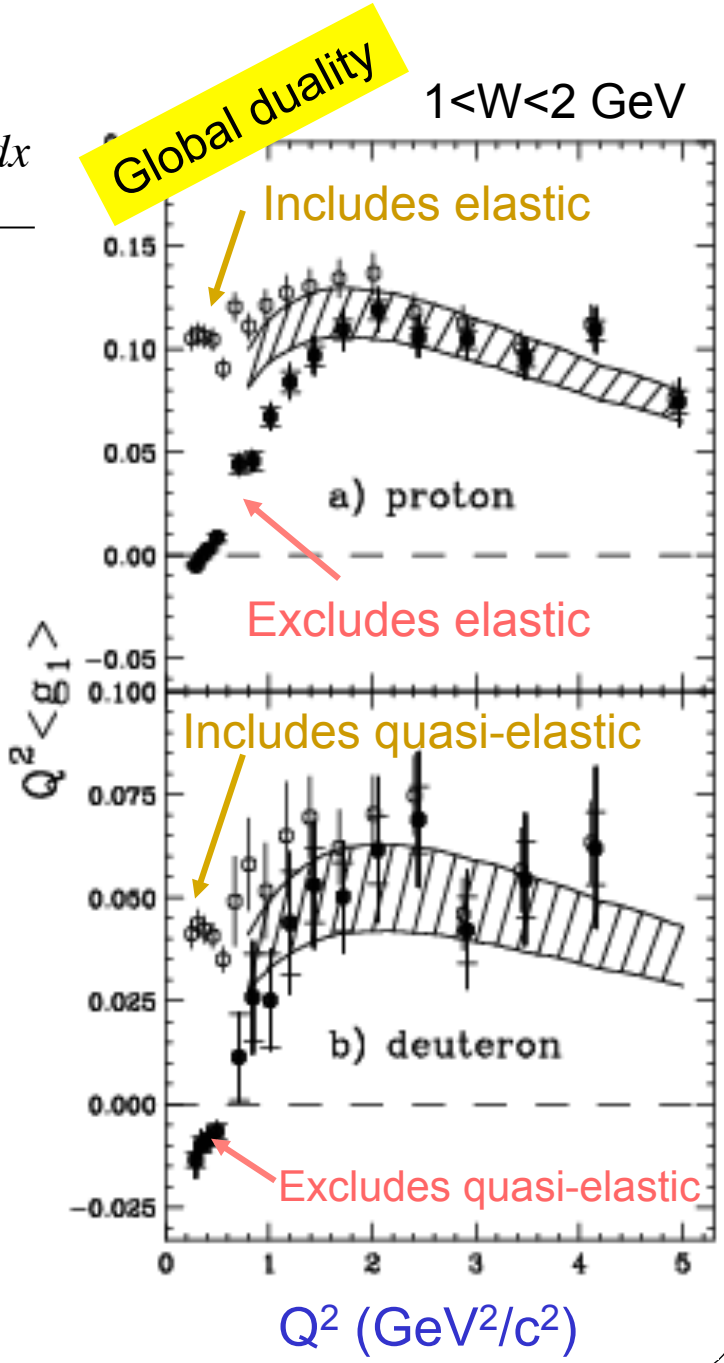


Duality

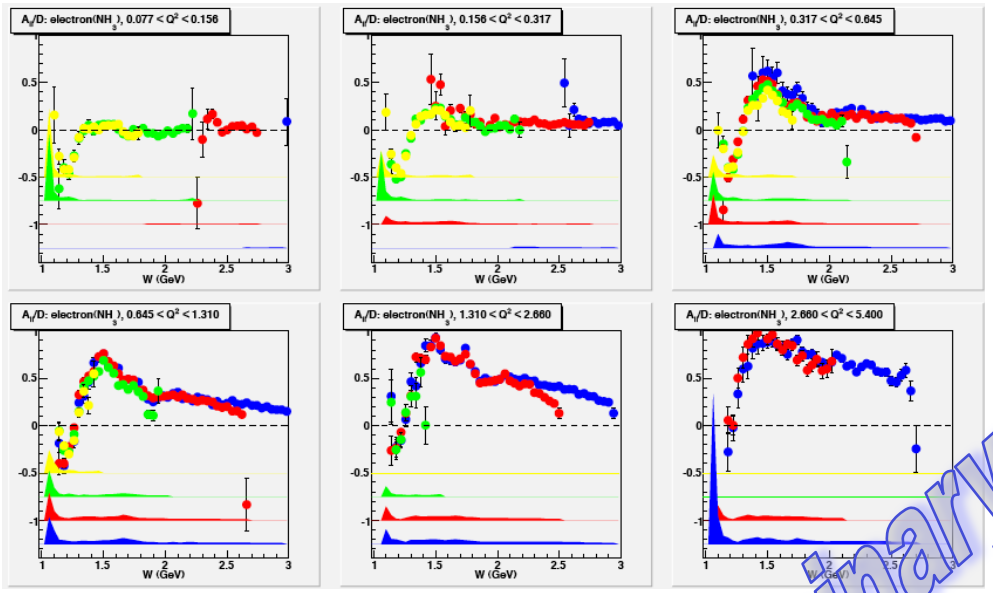
Structure functions averaged over resonances behave like DIS

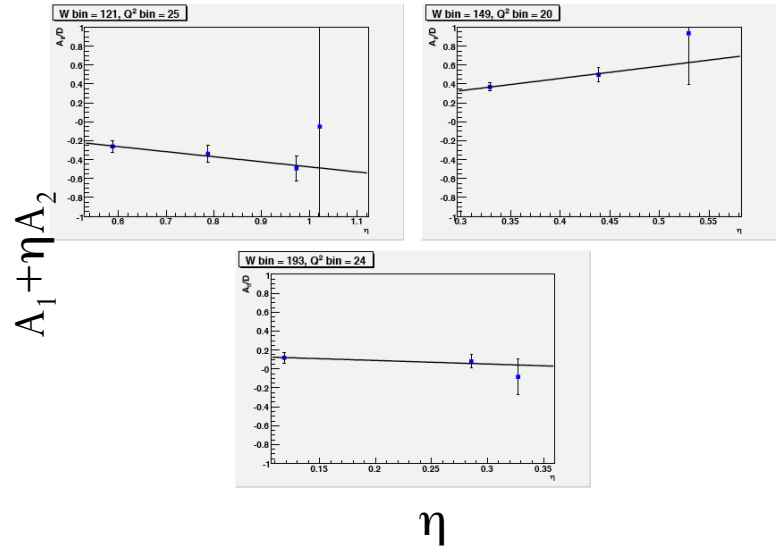
$$\left\langle g_1\left(Q^2\right)\right\rangle = \frac{\int_{x_l}^{x_h} g_1(x,Q^2)\,dx}{x_h - x_l}$$

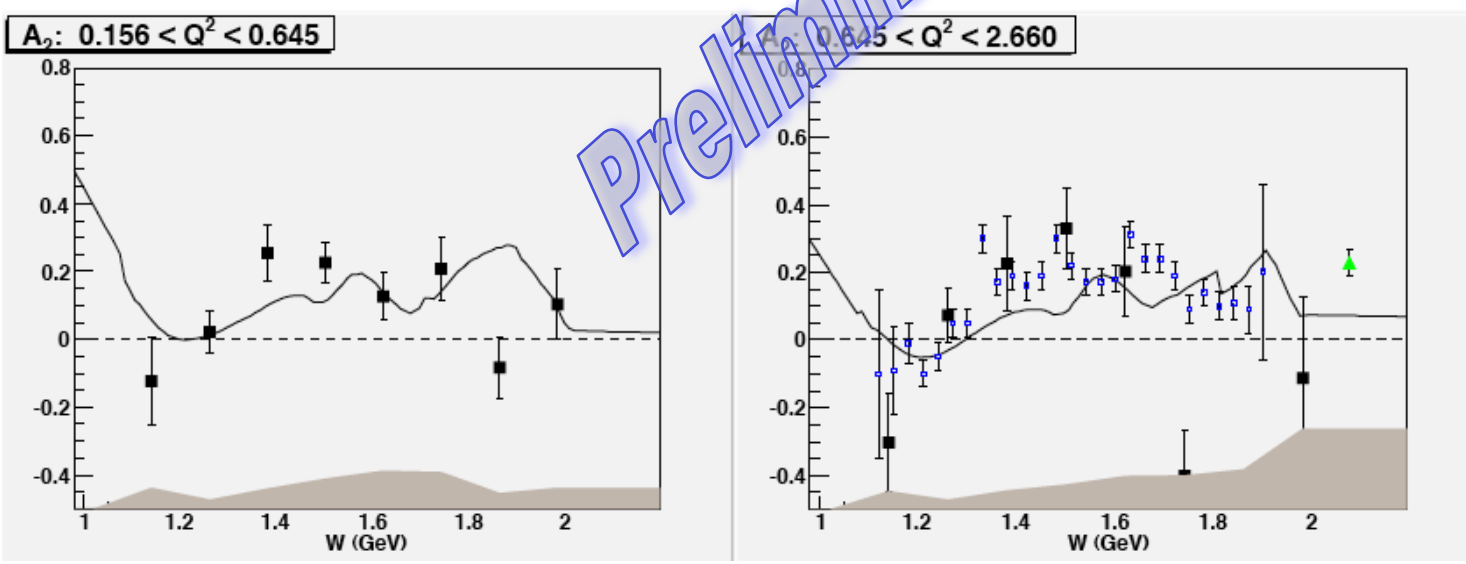




Extracting A_2 / g_2

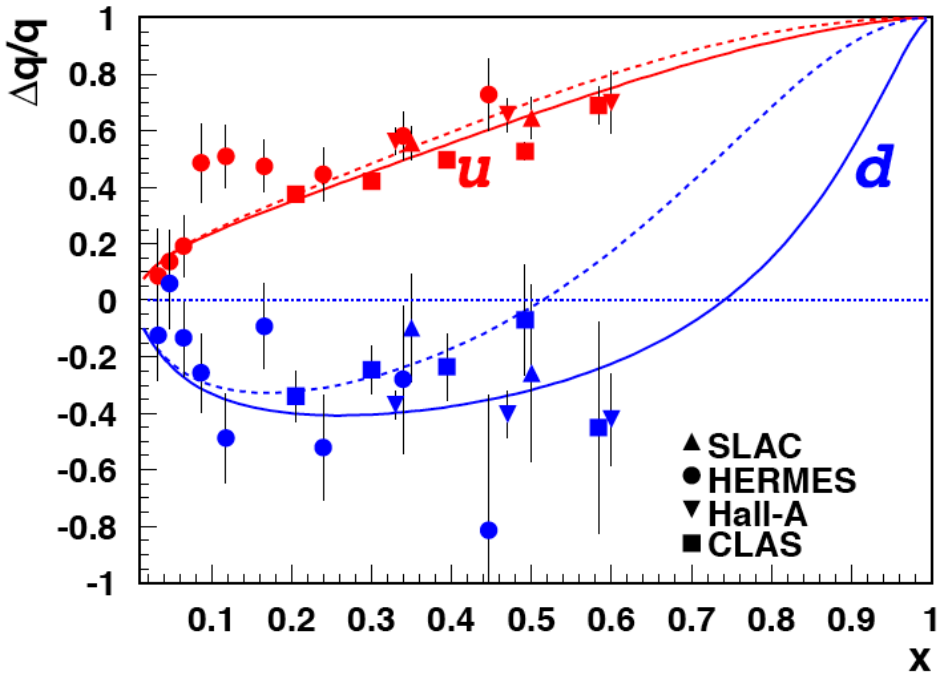




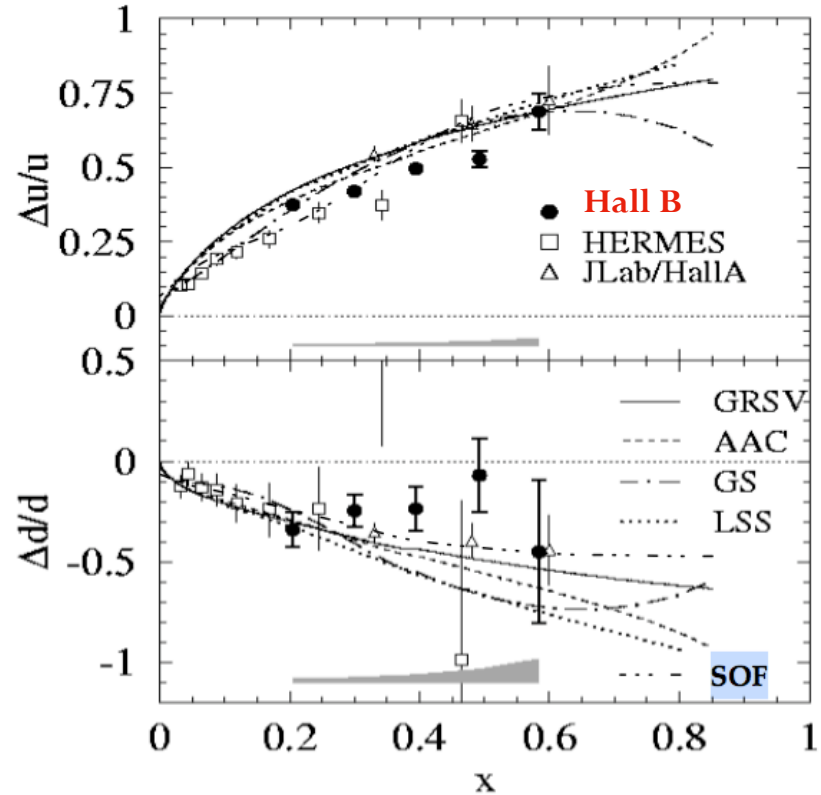


Black points:
EG1b data
Blue points:
RSS data
Line: EG1b model for A_2

Polarized quark distribution functions



Avakian et al., Phys.Rev.Lett.99:082001,2007



Dharmawardane et al., Phys.Rev.Lett. B641,2006

Assuming the naïve parton model with no sea contribution, quark polarizations in the valence region can be estimated directly from the data:

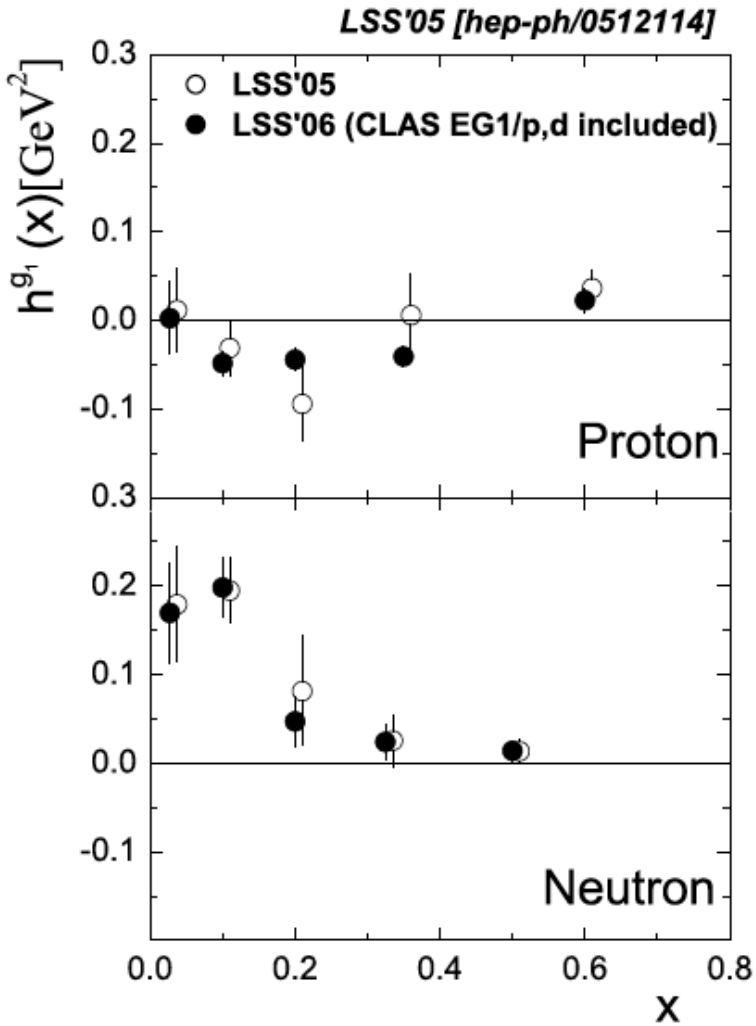
$$\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d/(1-1.5\omega_D)}{5F_1^p - 2F_1^d}$$

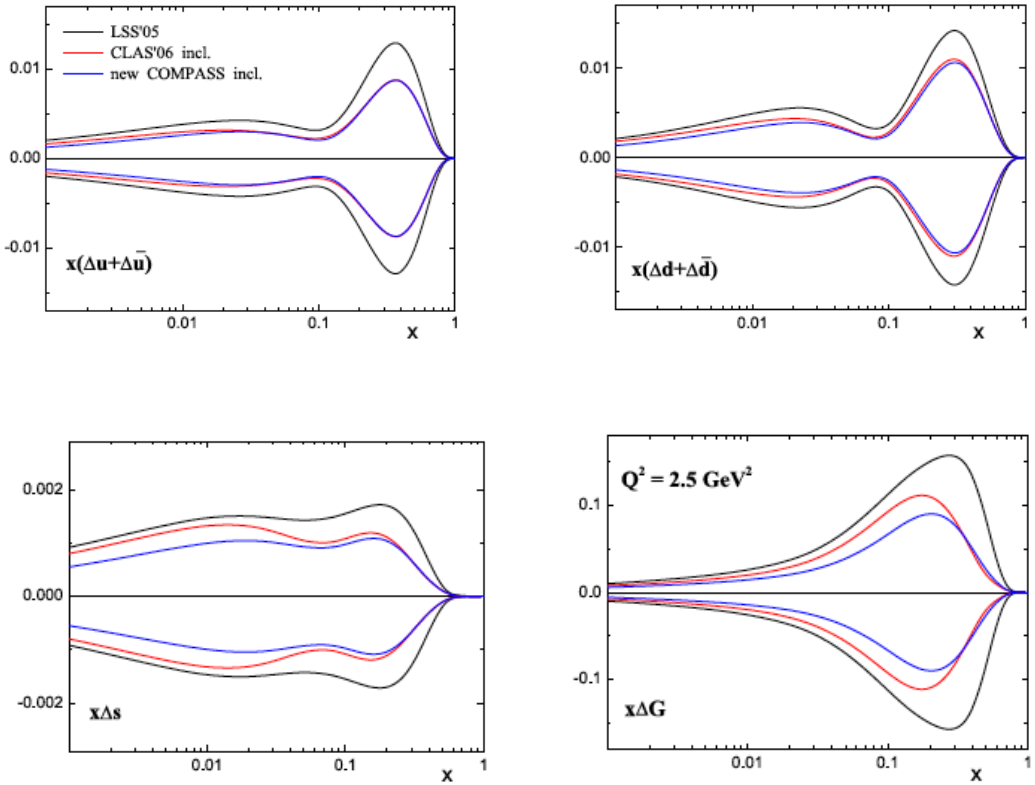
$$\frac{\Delta d}{d} \approx \frac{8g_1^d/(1-1.5\omega_D) - 5g_1^p}{8F_1^d - 5F_1^p}$$

- Also NLO analysis on this data
- New results for recent data coming soon!

Orbital angular momentum may change this picture

Effect of CLAS data on NLO fits of PDFs





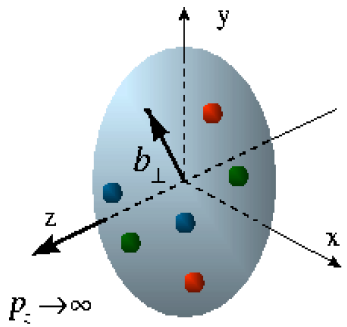
$$g_1(x,Q^2)_{\rm exp} = g_1(x,Q^2)_{LT} + h^{g_1}(x)/Q^2$$

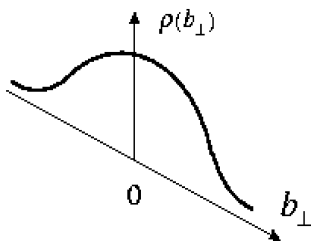
NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron

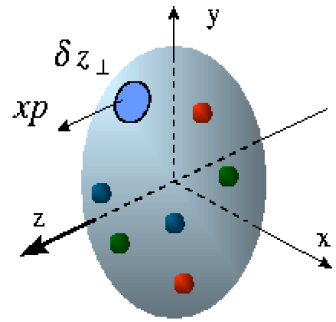
Higher Twist contribution to g_1

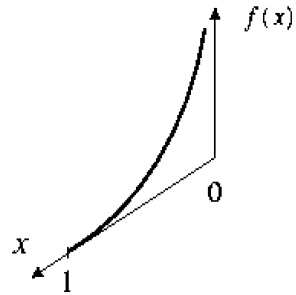
Generalized Parton Distributions (GPD)

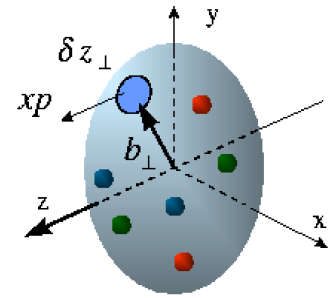
3-dimensional quark structure of nucleon

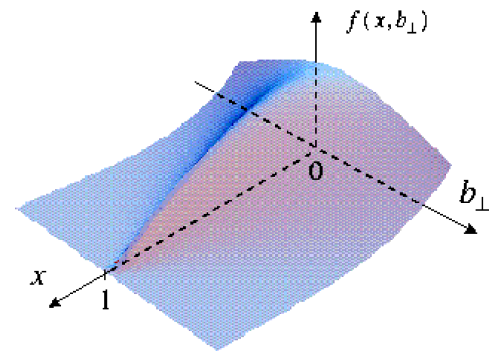












Elastic Scattering
transverse quark distribution in coordinate space

Deep inelastic scattering
Longitudinal quark Distribution in momentum space

Deep exclusive scattering
Fully-correlated quark distribution in both coordinate and momentum space - GPDs

Deeply Virtual Compton Scattering and GPDs

- DVCS is the cleanest process to access GPDs

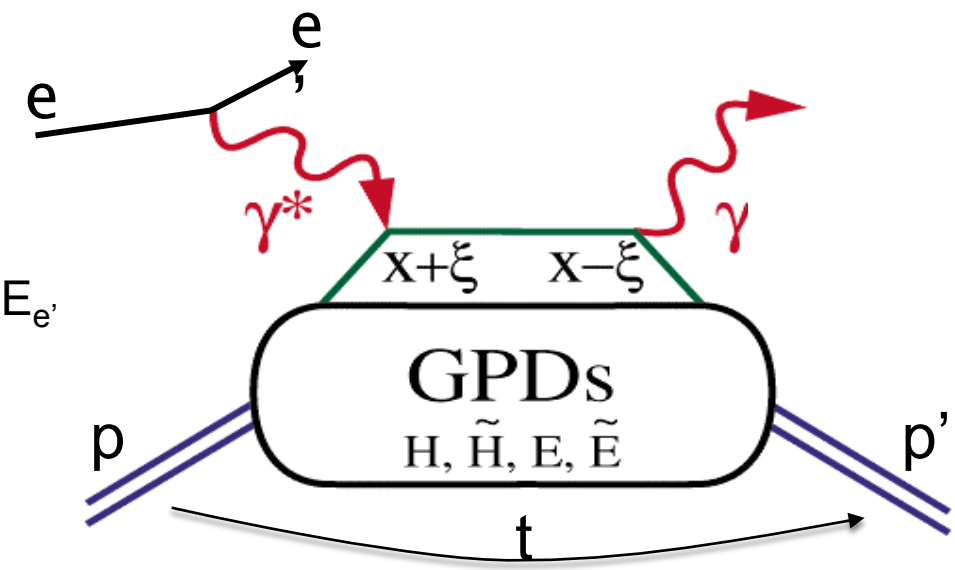
Handbag mechanism: the exclusive process can be factorized into a hard scattering part and a nucleon structure part parameterized via GPDs

$Q^2 = -(e-e')^2$

$x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$

$t = (p-p')^2$

$\xi \cong x_B/(2-x_B)$



x longitudinal quark momentum fraction

2ξ longitudinal momentum transfer

GPD (x, ξ ,t)

DIS at t=ξ=0: parton distributions

$$H^q(x,\xi=0,t=0) = q(x)$$

$$\tilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

$$E^q, \tilde{E}^q$$

new information

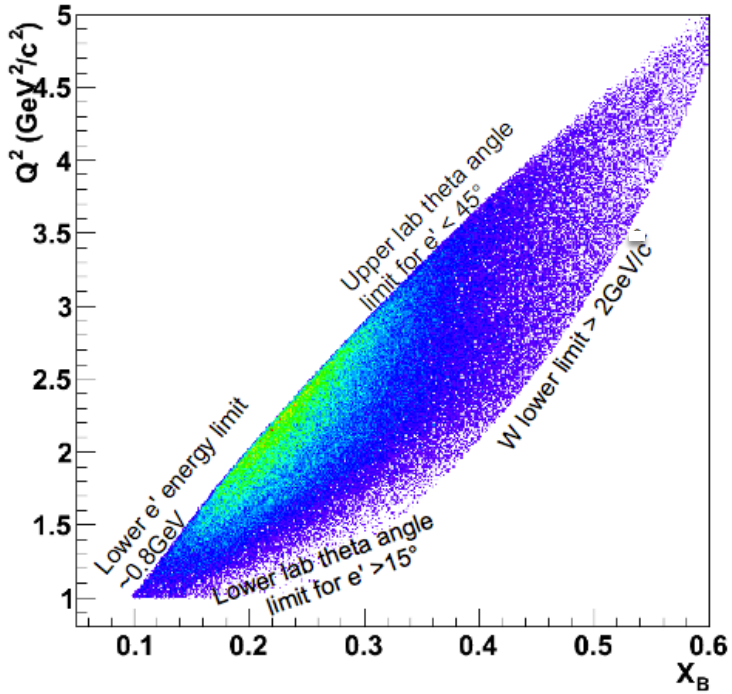
First moments: form factors

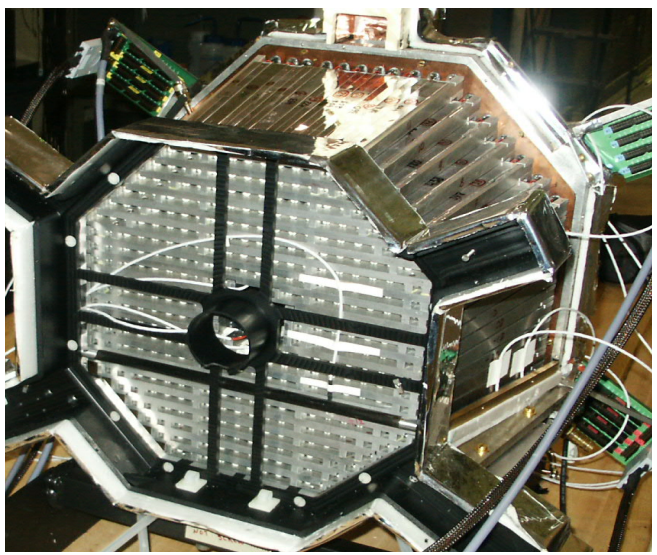
$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

$$\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$$

The eg1-dvcs experiment

- eg1 configuration + IC calorimeter
- 6 GeV beam energy
- NH3 and ND3 targets
- DVCS Target and double spin asymmetry
- Semi-inclusive
- Uses 2π inner calorimeter for γ/π^0 coverage



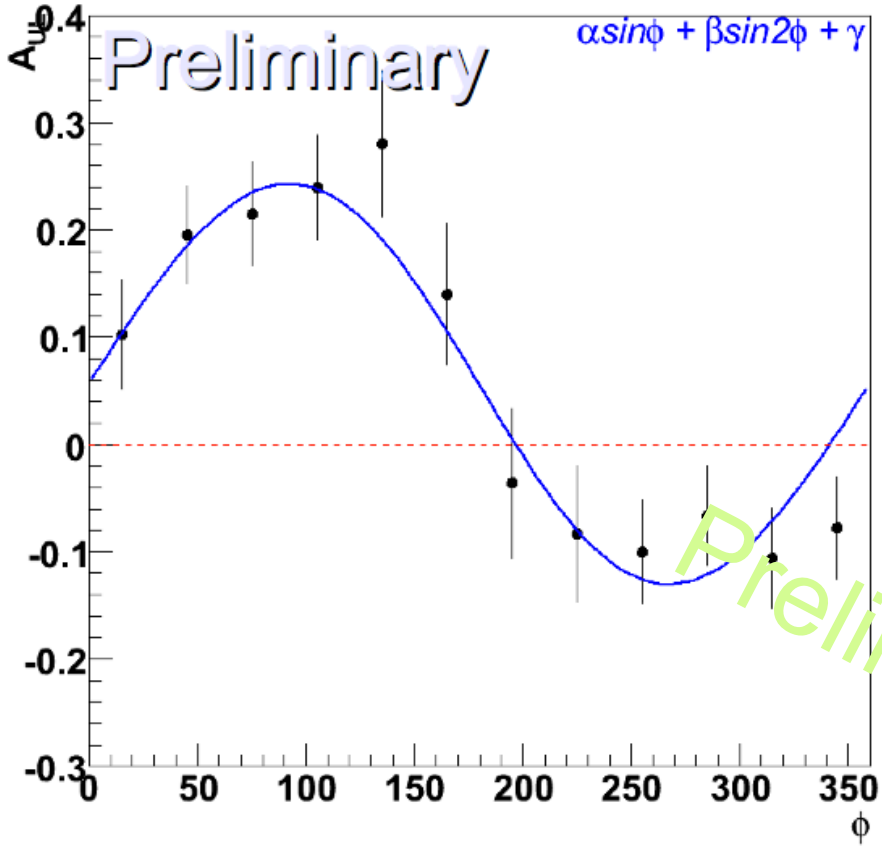


IC calorimeter to

- increase γ acceptance
  - EC: $17^o<\theta<43^o$
  - IC: $4^o<\theta<15^o$
- Better resolution

- 424 $PbWO_4$ crystals
- 16 cm x 1.3 cm x 1.3 cm
- Pointing geometry
- ~1.2 degree/crystal
- 18 radiation lengths
- APD readout

DVCS preliminary results



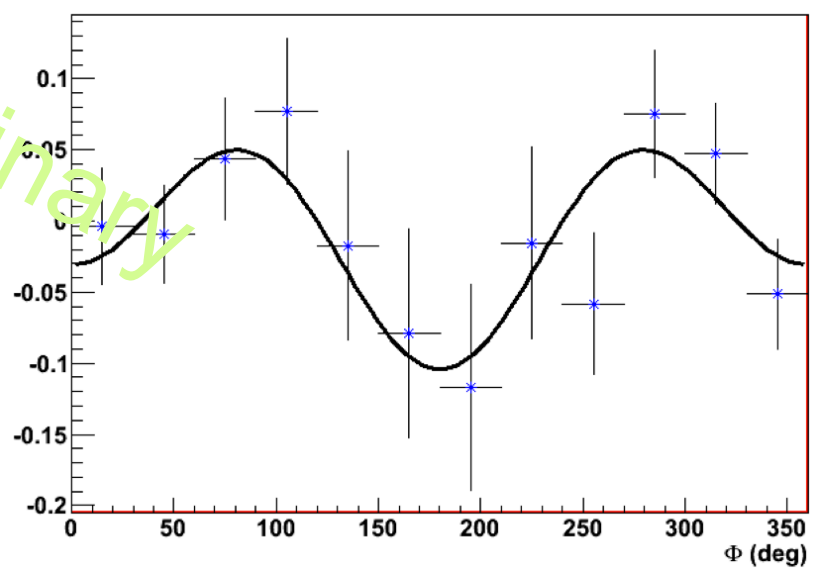
Target asymmetry

$$\Delta\sigma_{UL} \sim \sin\phi \,\mathrm{Im}\left\{F_1\tilde{H} + \xi\left(F_1 + F_2\right)\left(H + ..\right)\right\} d\phi$$

Double spin asymmetry

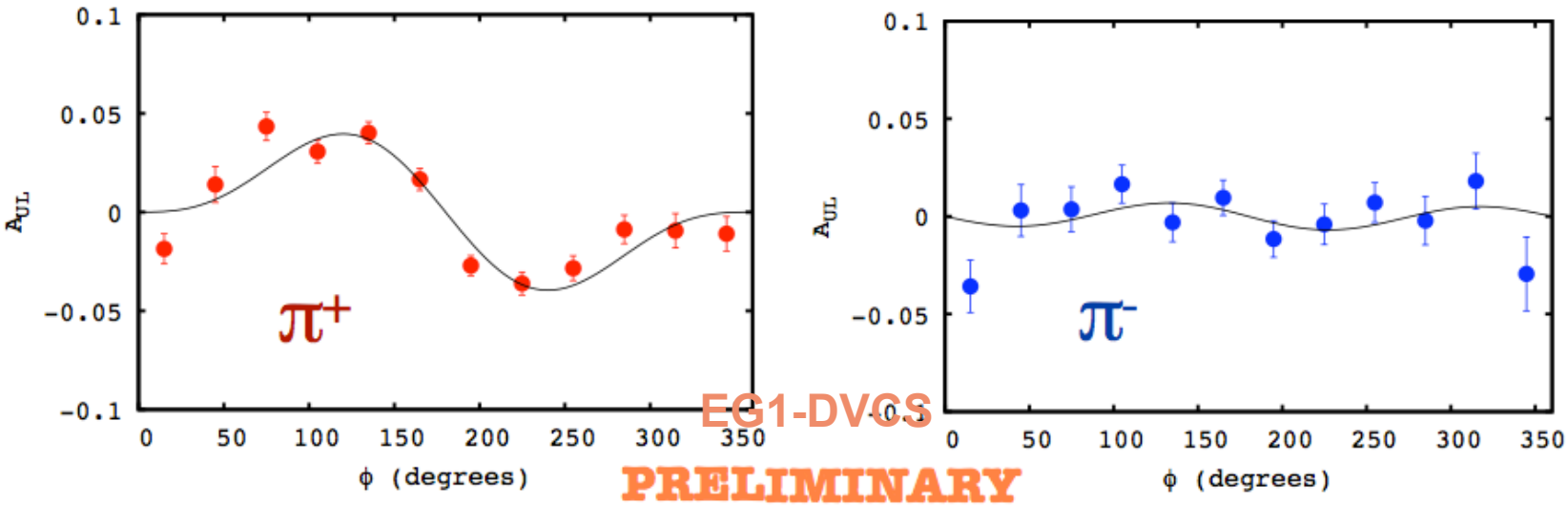
$$\Delta\sigma_{LL} \sim \cos\phi \,\mathrm{Re}\left\{F_1\tilde{H} + \xi\left(F_1 + F_2\right)\left(H + ..\right)\right\} d\phi$$

- No π^0 corrections
- Estimated dilution factor of 0.8

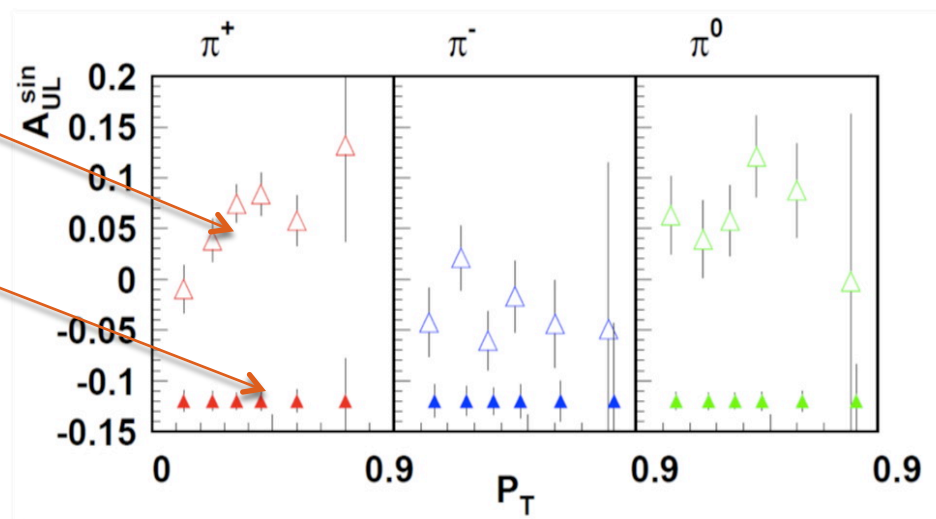


Semi-inclusive pion production

TMDs and Collins fragmentation function



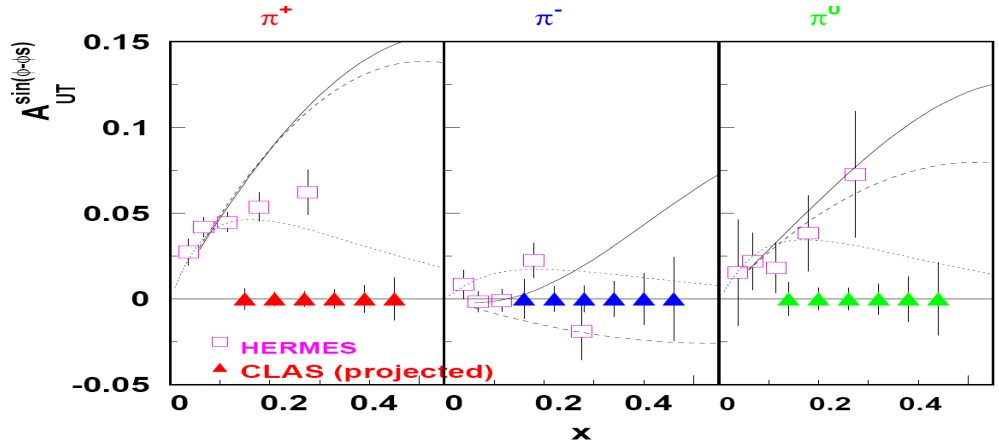
Data: eg1 run Avakian et al arXiv:1003.4549
Expected Precision for sinϕ and sin2ϕ moments of target SSA

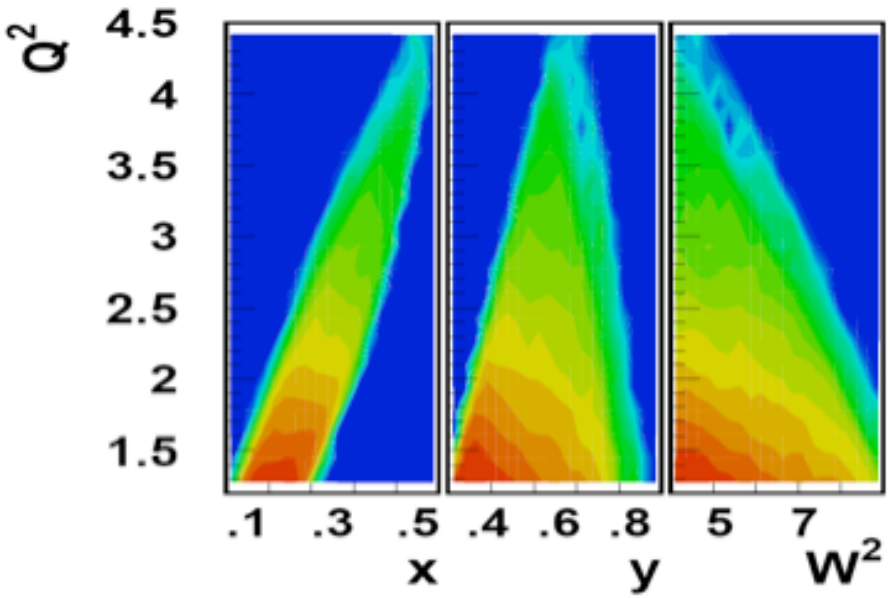


See talks by Harut Avakian and Patrizia Rossi on Friday!

Study of spin orbit correlations in semi inclusive DIS and Sivers distribution function (E08-015 – running in 2011)

HD target



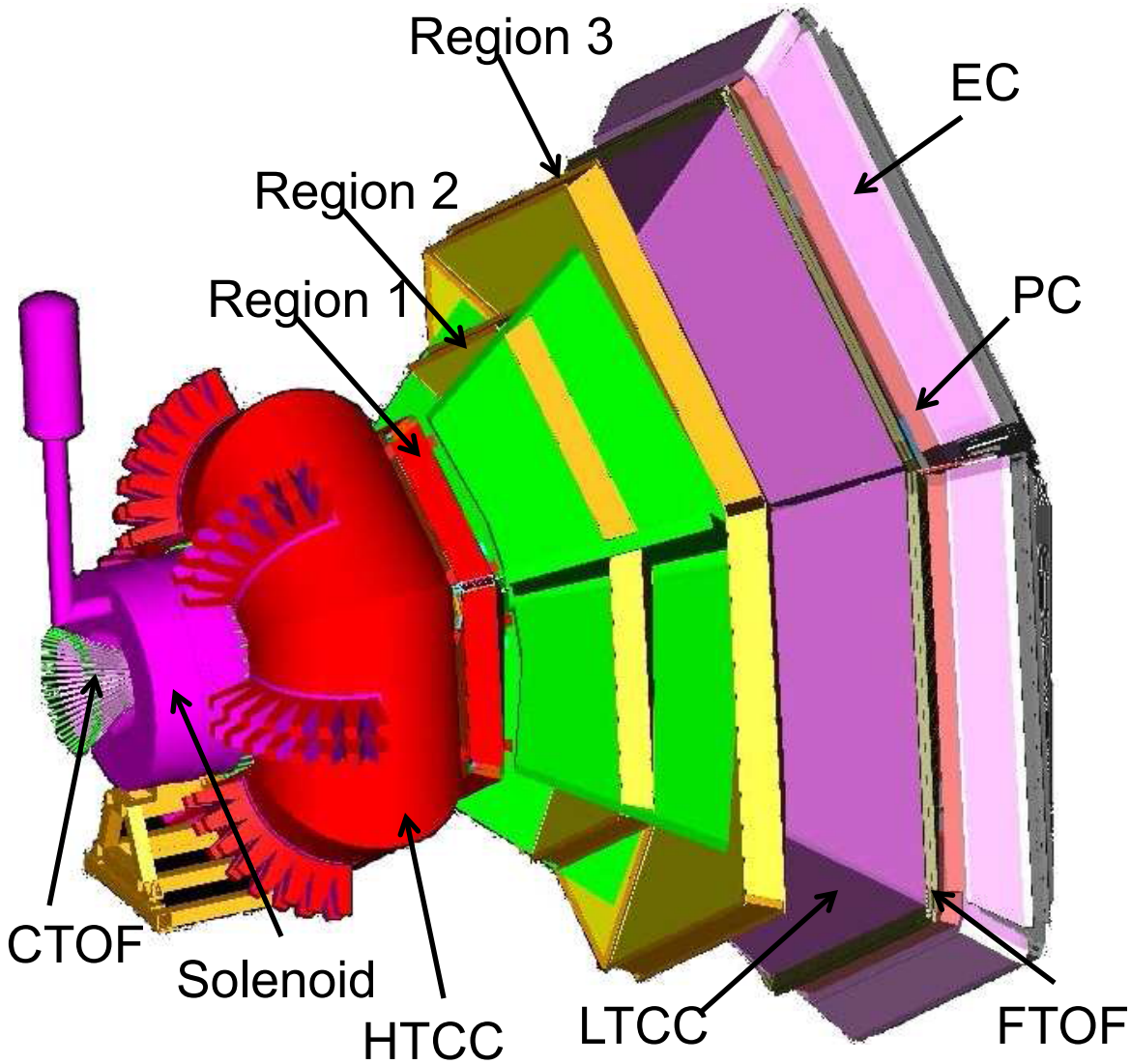


E_{beam} = 6 GeV

25 days (P_H=75% P_D=25%)

Potential to add to world data on g_2 and A_2

12 GeV program: CLAS12



Superconducting coils for toroidal magnetic field

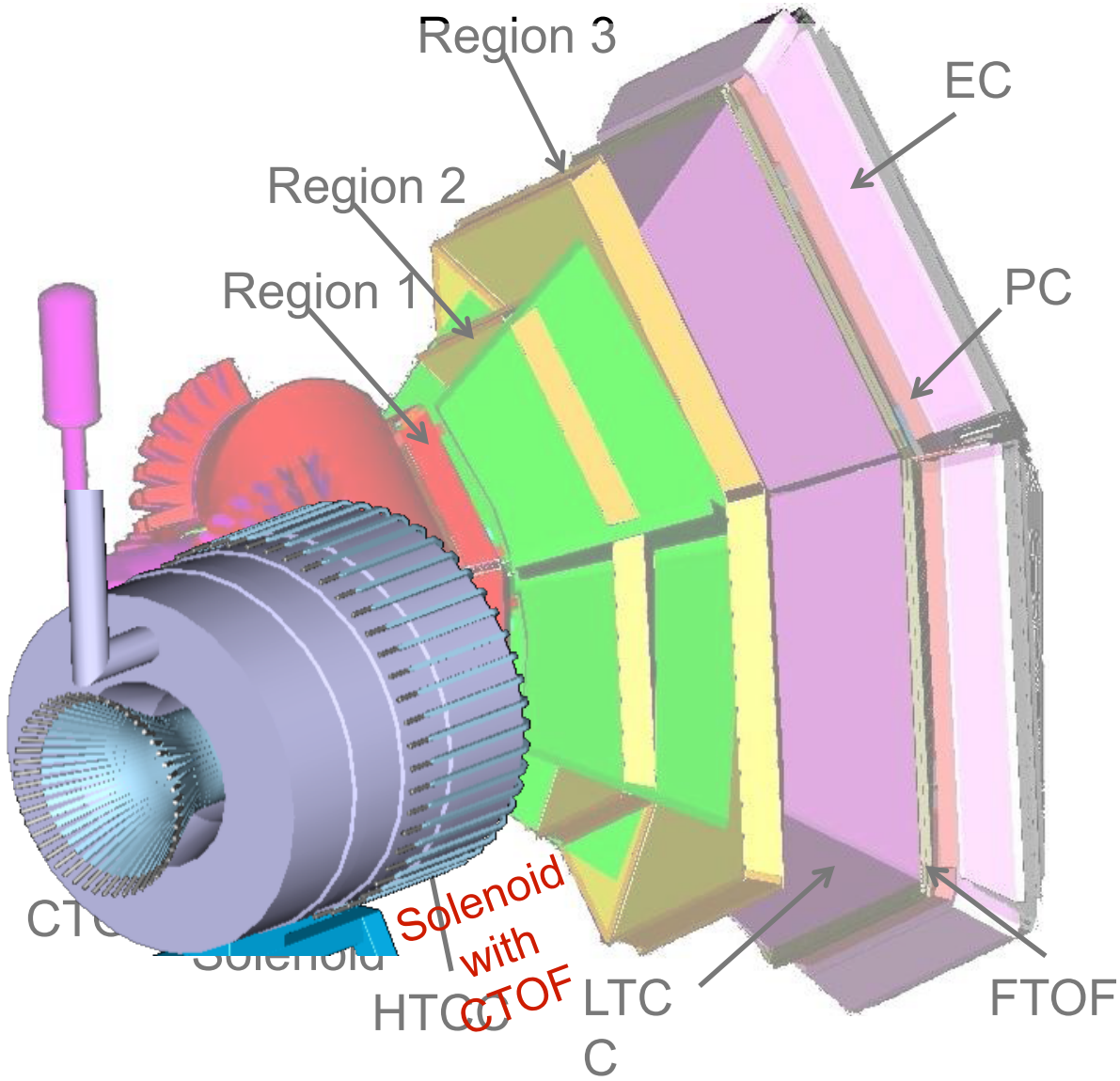
Drift Chambers are for tracking of the forward going charged particles

Cherenkov Counters and Time-of-Flight system are for Particle Identification

Central detector for large angle particle detection and identification

Electromagnetic Calorimeter and Preshower Calorimeter for neutral particle detection, triggering and electron identification

12 GeV program: CLAS12



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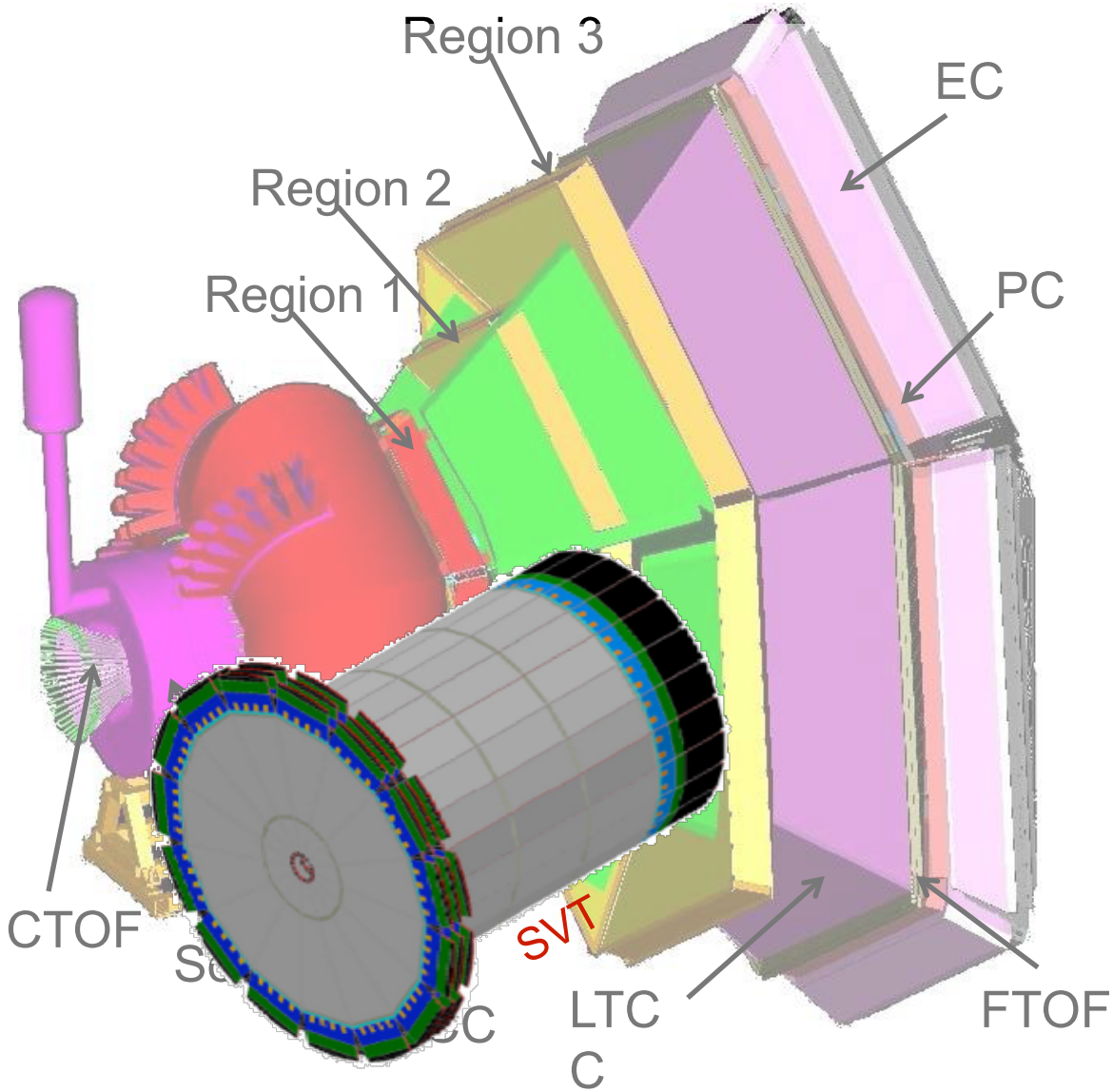

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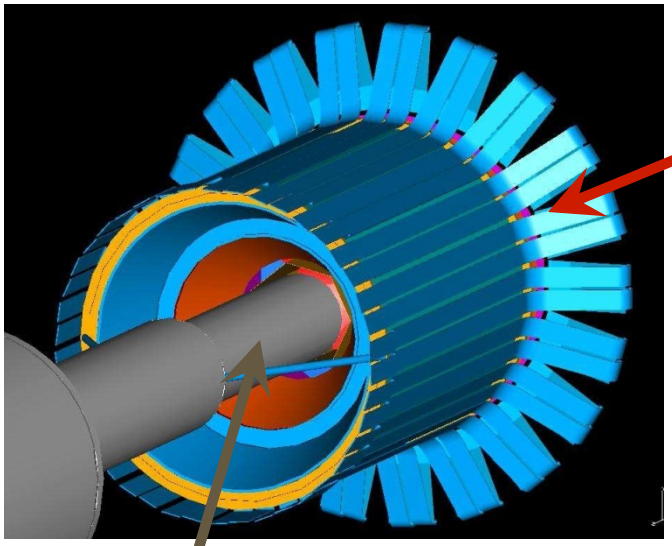
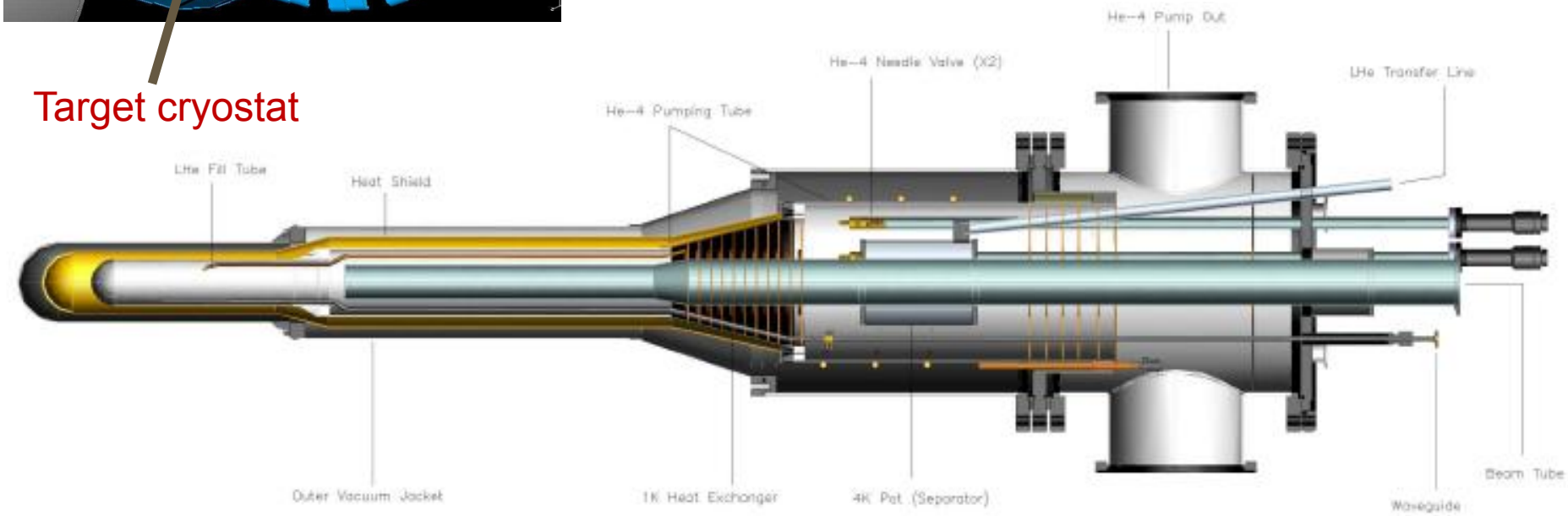
The polarized target



Silicon Vertex Tracker

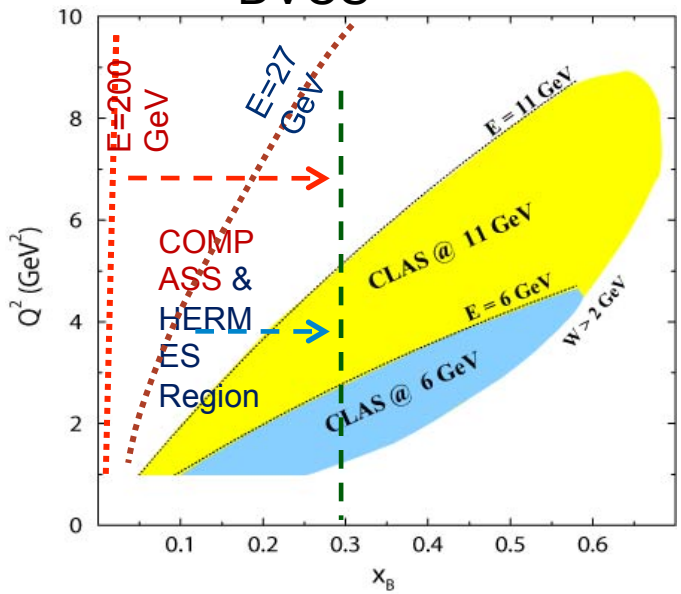
Target cryostat

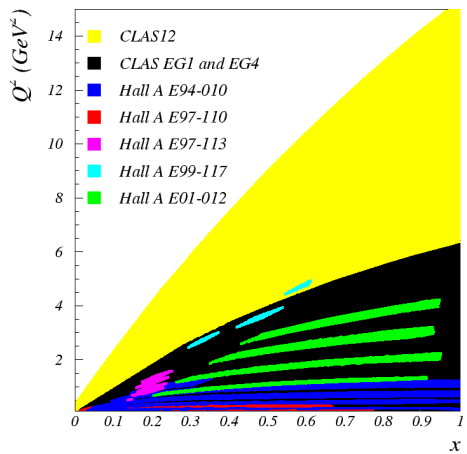
Chemical Structure: NH_3
Length: 3.3 cm
Diameter: 3.0 cm
Polarization: 85%
Dilution Factor: 0.15
Luminosity: 2×10^{35} cm^{-2} s^{-1}



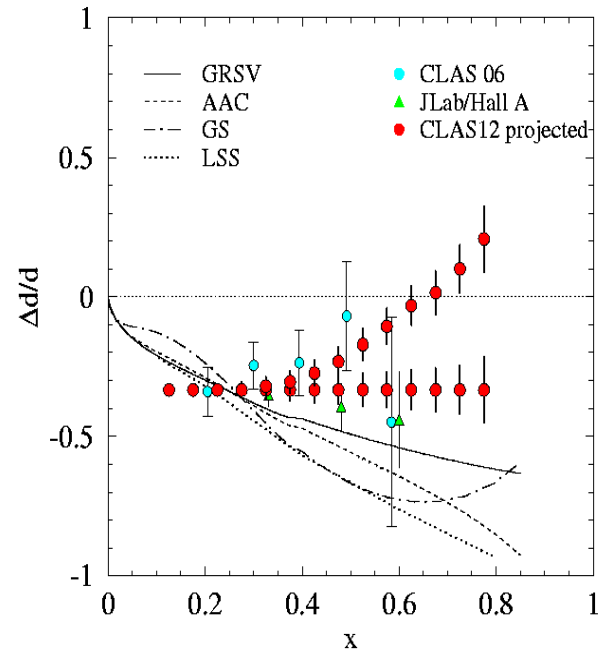
12 GeV program

DVCS

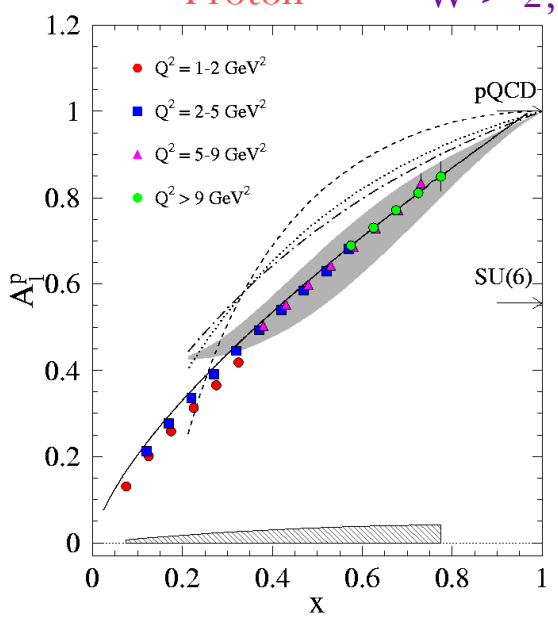


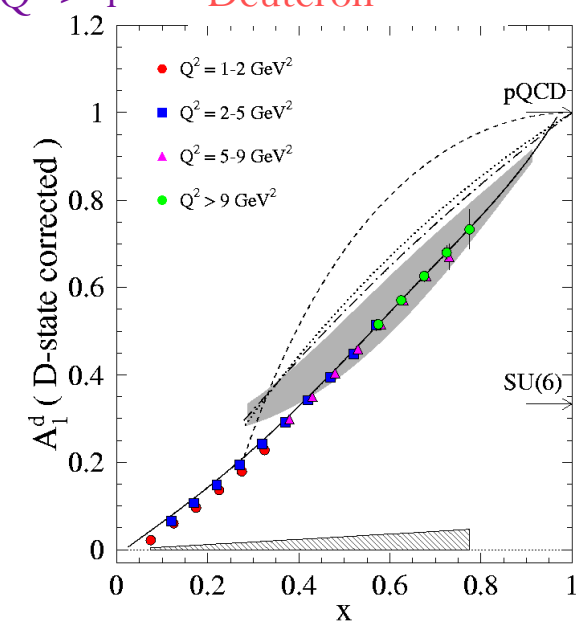


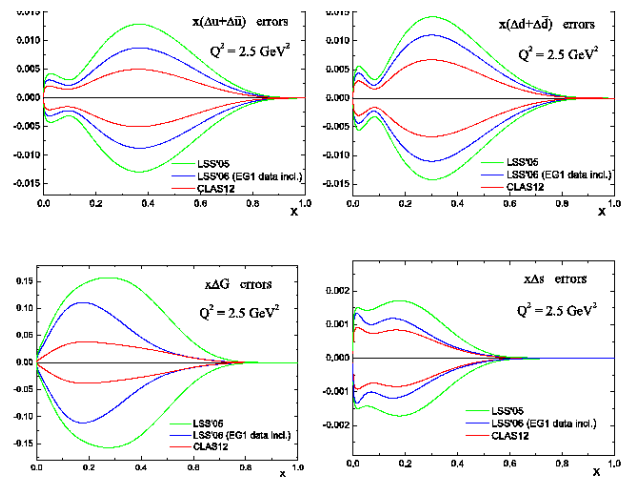
DIS



Proton $W > 2$; $Q^2 > 1$ Deuteron







Also Semi-inclusive

Conclusions

- Broad spin program at Jefferson Lab.
- Complex look at the structure of the nucleon.
- Many observables asymmetries, structure functions, sum rules, moments, GPDs, TMDs
- New information to understand the transition between hadron and partonic degrees of freedom
- Plenty results from Jefferson Lab, large acceptance and access to resonance region
- Much more to come **JLab @ 12 GeV**: DIS, SIDIS, DVCS
- Also COMPASS+RHIC, Spring8, J-PARC, FAIR, … EIC?

Thanks to Sebastian Kuhn, Nevtzat Guler, Yelena Prok, Keith Griffioen, Peter Bosted, Erin Seder, Silvia Pisano, Sucheta Jawalkar

Additional results

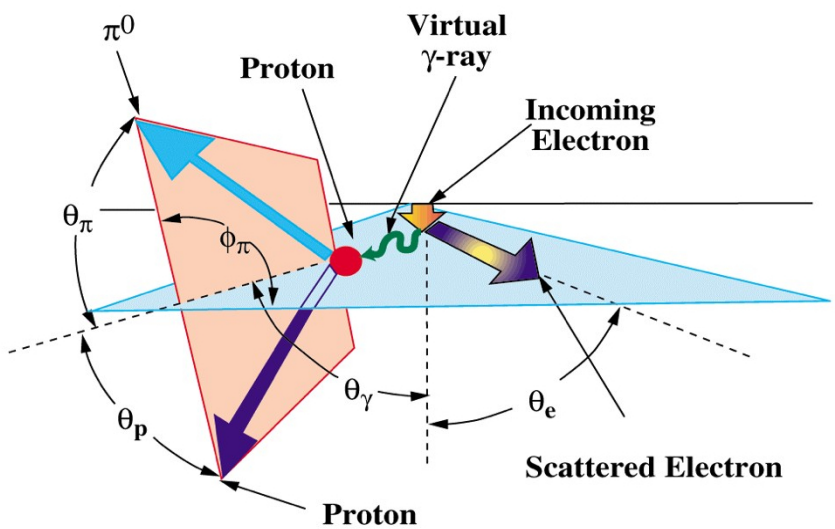
- NLO PDF fit
- A2/g2
- Duality
- Two particle channel

2 particles final state

H(e,e'π^0)p
H(e,e'π^+)n
D(e,e'pπ^-)p
rho production
eta production

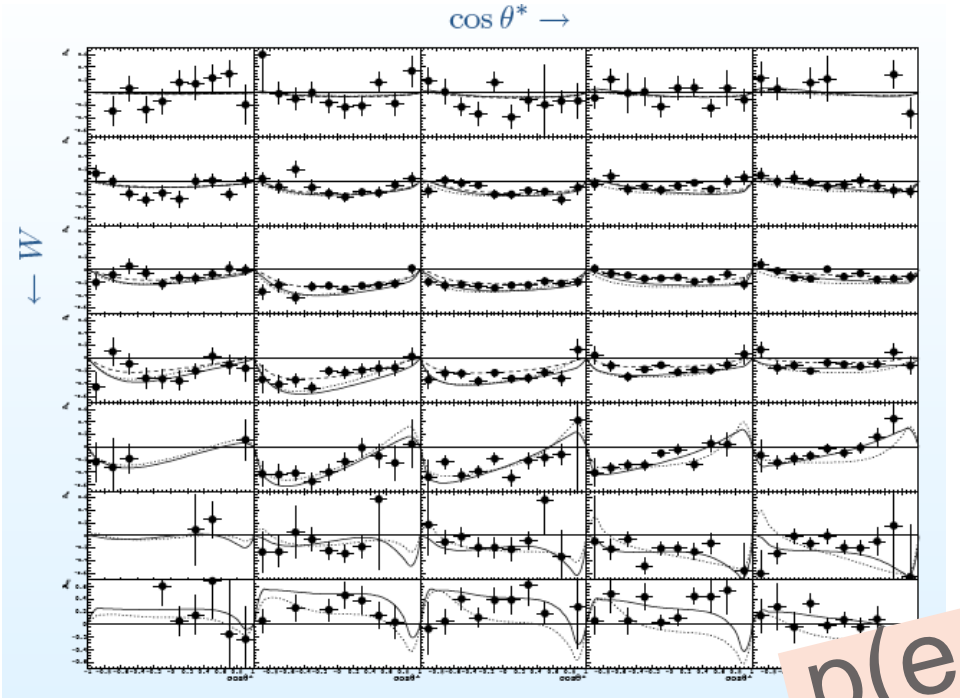
$$\sigma(W,Q^2,\vartheta^*,\phi^*) \propto \sigma_o + P_e\sigma_e + P_t\sigma_t + P_eP_t\sigma_{et}$$

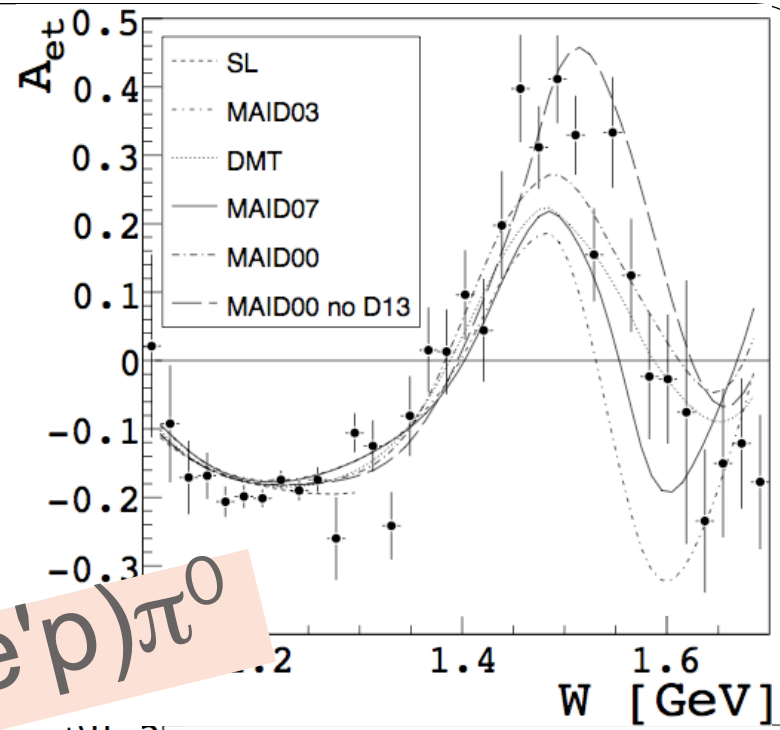
- Different sensitivities to resonant and non resonant contributions for the double (σ_{et}) and target (σ_t) polarization terms
- Polarized measurements to provide new constraints to phenomenological models which are based on previous unpolarized photo- and electro-production data



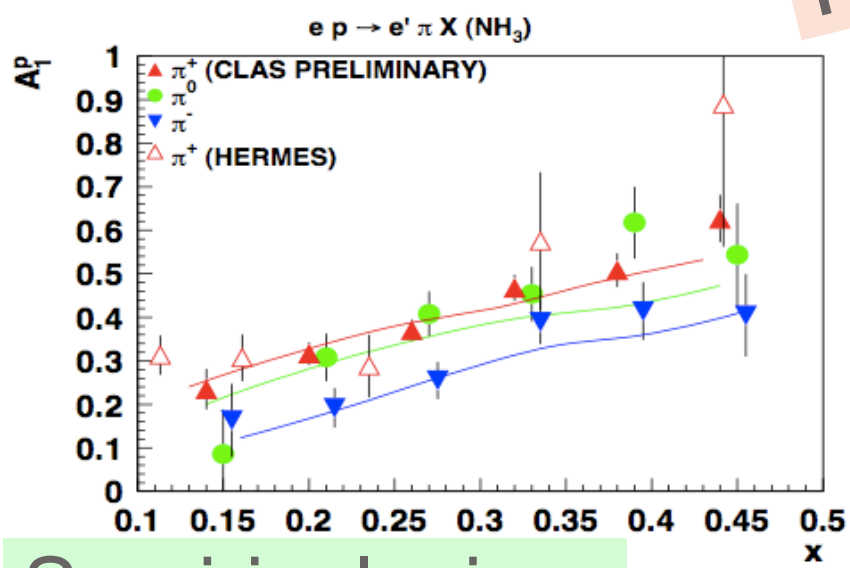
Semi-inclusive

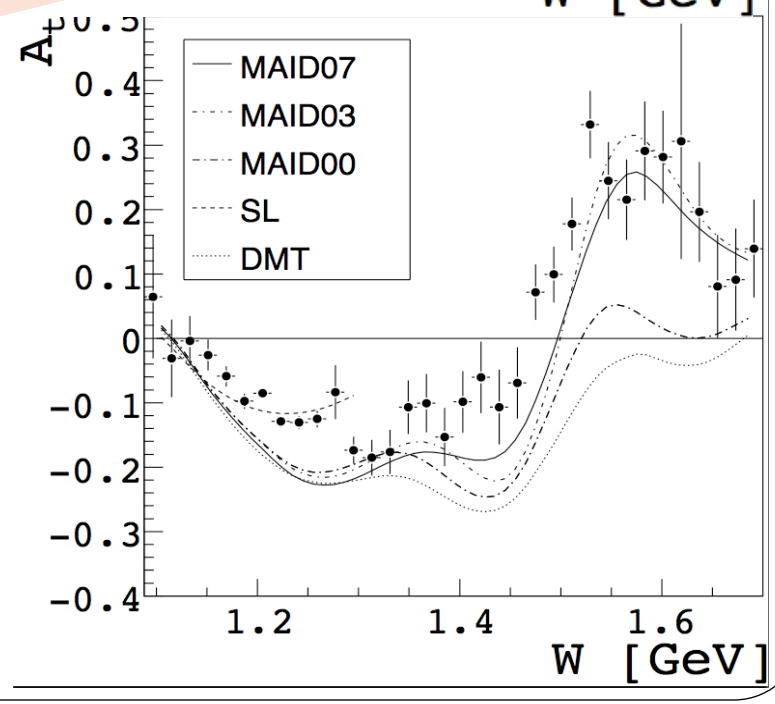
- e p $\longrightarrow$ e' p X
- Struck quark of different flavors produce the hadron with different probabilities $\longrightarrow$ SIDIS can help to separate contributions from quark flavors
- Access to orbital angular momentum of quarks
- Transverse momentum distributions





p(e,e'p)π⁰





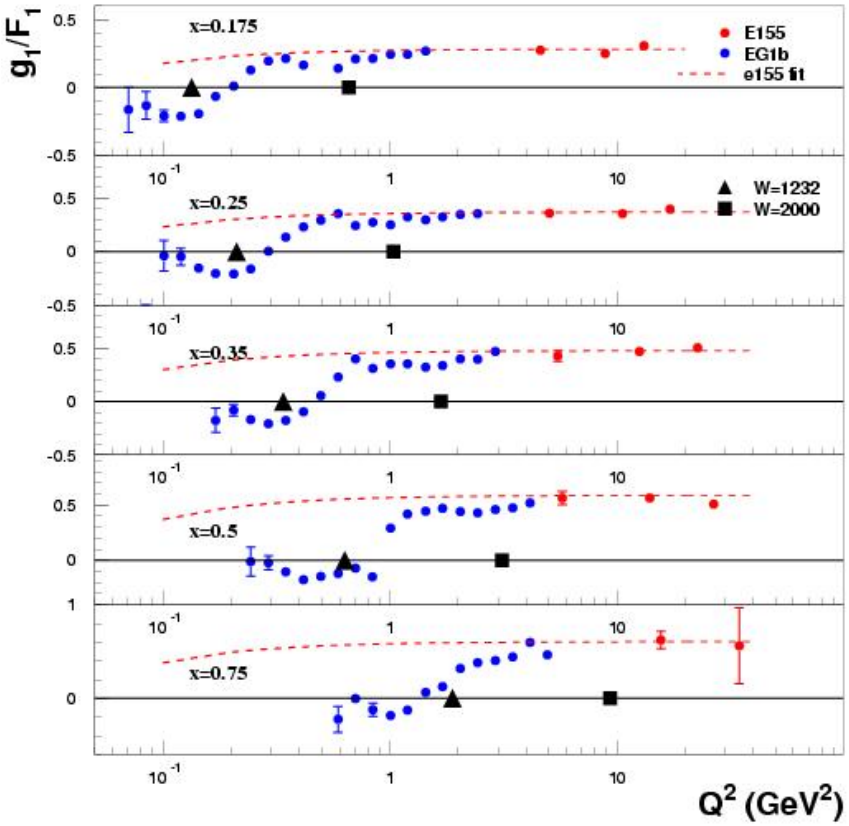
Semi-inclusive

Outlook: The Future at JLab

- Remaining experiments at 6 GeV
  - Hall A
    - E-06-010: Transverse target single spin asymmetry in $n\uparrow(e,e'\pi^-)$
    - E-06-011: Transverse target single spin asymmetry in $n\uparrow(e,e'\pi^+)$
    - E-06-014: Precision measurement of d_2 on the neutron
    - E-08-027: g_{2p} and δ_{LT}
  - Hall B
    - E-05-113: Semi-inclusive pion production (and DVCS) on $p\rightarrow$
    - E-08-015: Semi-inclusive pion production (and DVCS) on $p\uparrow$
  - Hall C
    - E-07-011: High precision g_{1d} in DIS region
    - E-07-003: SANE (SSFs on p, with emphasis on g_2)
- Approved experiments for 12 GeV
  - Hall A/C
    - E12-06-122: A_{1n} at high x with 8.8 GeV and 6.6 GeV beam in Hall A
    - E12-06-121: Precision measurement of g_2 and d_2 on the neutron
  - Hall B
    - E12-06-10: SSFs on longitudinal target with CLAS12
    - E12-07-107: Semi-inclusive pion production on $p\rightarrow$

Running now!

g_1/F_1



- g_1/F_1 falls below the DIS extrapolation at low Q2 (dashed curve)

Large-x behavior of the A_1 asymmetry

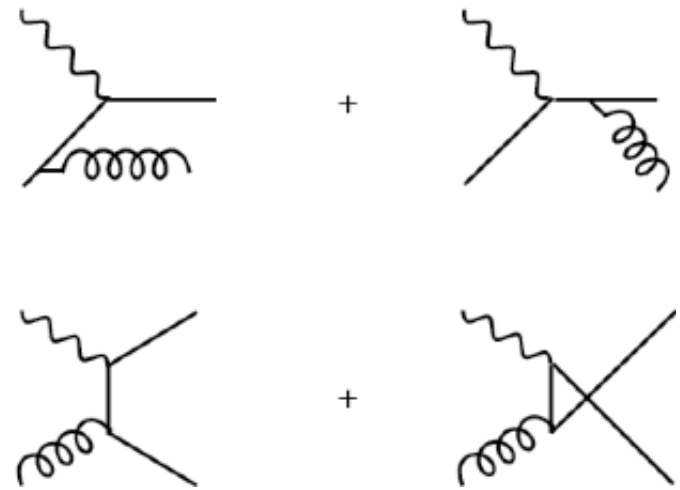
Large x region dominated by valence quarks→ can test quark models

- SU(6) QM: Exact SU(6) symmetry
  Equal probability for S=0 and S=1 di-quark configuration
- Hyperfine perturbed QM **Isgur, PRD 59, 034013 (2003)**
  makes S=1 pairs more energetic than S=0 pairs
- Duality **Close and Melnitchouk, PRC 68, 035210 (2003)**
  Suppress transitions to specific resonances (56^+ and 70^-)
- In DIS, pQCD: Minimal gluon exchanges
  Spectator pair: quarks have opposite helicities **Farrar and Jackson, PRL 35, 1416 (1975)**

Model for x --> 1	A_1^p	A_1^n	d/u	Δu/u	Δd/d
SU(6)	5/9	0	1/2	2/3	-1/3
w/ hyperfine ($E_{S=0} < E_{S=1}$)	1	1	0	1	-1/3
One gluon exchange	1	1	0	1	-1/3
Suppressed symmetric WF	1	1	0	1	-1/3
S=1/2 dominance	1	1	1/14	1	1
$\sigma_{1/2}$ dominance	1	1	1/5	1	1
pQCD (conserved helicity)	1	1	1/5	1	1

Parton Distributions Functions and NLO pQCD

- Two effects modify simple parton picture:
  - pQCD evolution makes PDFs Q^2-dependent (NLO DGLAP equations) – mild logarithmic dependence
  - (Gluon) radiative corrections change elementary cross section generating a contribution to g1 due to the gluon polarization

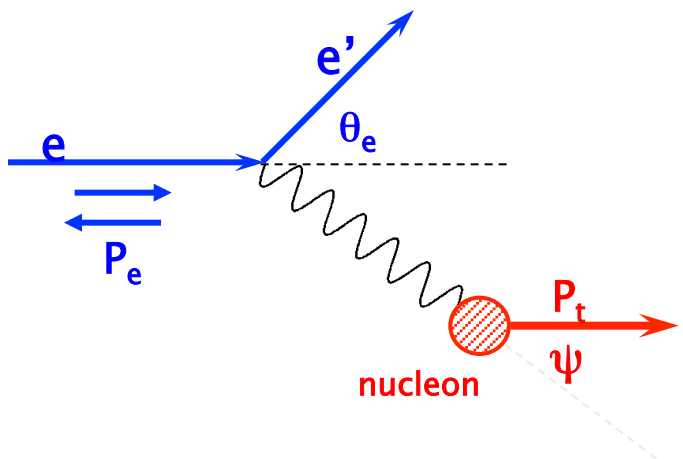


$$g_1^{\mathrm{NLO}}(\mathrm{x},\mathrm{Q}^2) = g_1^{\mathrm{LO}} + \frac{1}{2}\langle e^2\rangle \sum_{\mathrm{q}} \mathrm{e}_{\mathrm{q}}^2 [\Delta \mathrm{q}(\mathrm{x},\mathrm{Q}^2) \otimes C_{\mathrm{q}} + \Delta \mathrm{g}(x,\mathrm{Q}^2) \otimes C_{\mathrm{g}}]$$

we can extract information on the gluon from DIS

Virtual photon asymmetries

$$\frac{d\sigma}{dE'\,d\Omega} = \Gamma_v\left[\sigma_T + \varepsilon\sigma_L + P_e P_t\left(\sqrt{1-\varepsilon^2}\,A_1\sigma_T\cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}\,A_2\sigma_T\sin\psi\right)\right]$$



$$A_1 \approx \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)}$$

$$\mathbf{A_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \qquad \mathbf{A_2} = \frac{\sigma_{LT'}}{\sigma_T}$$

the asymmetries $\mathbf{A_1}$ and $\mathbf{A_2}$ can be extracted by varying the *direction of the nucleon polarization* or by varying the *beam energy* at fixed Q^2, ν

$$A_{\parallel} = D(A_1 + \eta A_2)$$
$$A_{\perp} = d(A_1 + \zeta A_2)$$

[where D, η, d, ζ are functions of Q^2, E′, E, R, e.g.:

$$D = \frac{1-\varepsilon E'/E}{1+\varepsilon R}$$

$$\eta = \frac{\varepsilon\sqrt{Q^2}}{E-\varepsilon E'} \qquad R = \frac{\sigma_L}{\sigma_T}$$]

EG1 used parameterization of world data on A_2 to extract A_1 (η is usually small)

The asymmetry analysis

$$A_{raw} = \frac{N^-/Q^- - N^+/Q^+}{N^-/Q^- + N^+/Q^+}$$

- $N^{+/-}$ Yield for electron/target spins
- antiparallel (-) or parallel (+)
- $Q^{+/-}$ gated FC

Physics asymmetry $A_{||}$

$$A_{||} = \frac{C_{back} A_{raw}}{P_e P_t \times DF}$$

- P_e Beam polarization
- P_t Target polarization
- DF Dilution factor
- C_{back} Background processes (pion contamination & pair symmetric)

$$\boxed{A_1 + \eta A_2 = \frac{A_{//}}{D}}$$

$$D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon\sqrt{Q^2}}{E - E'\varepsilon} \quad R = \frac{\sigma_L}{\sigma_T}$$

A_1, g_1 can be extracted

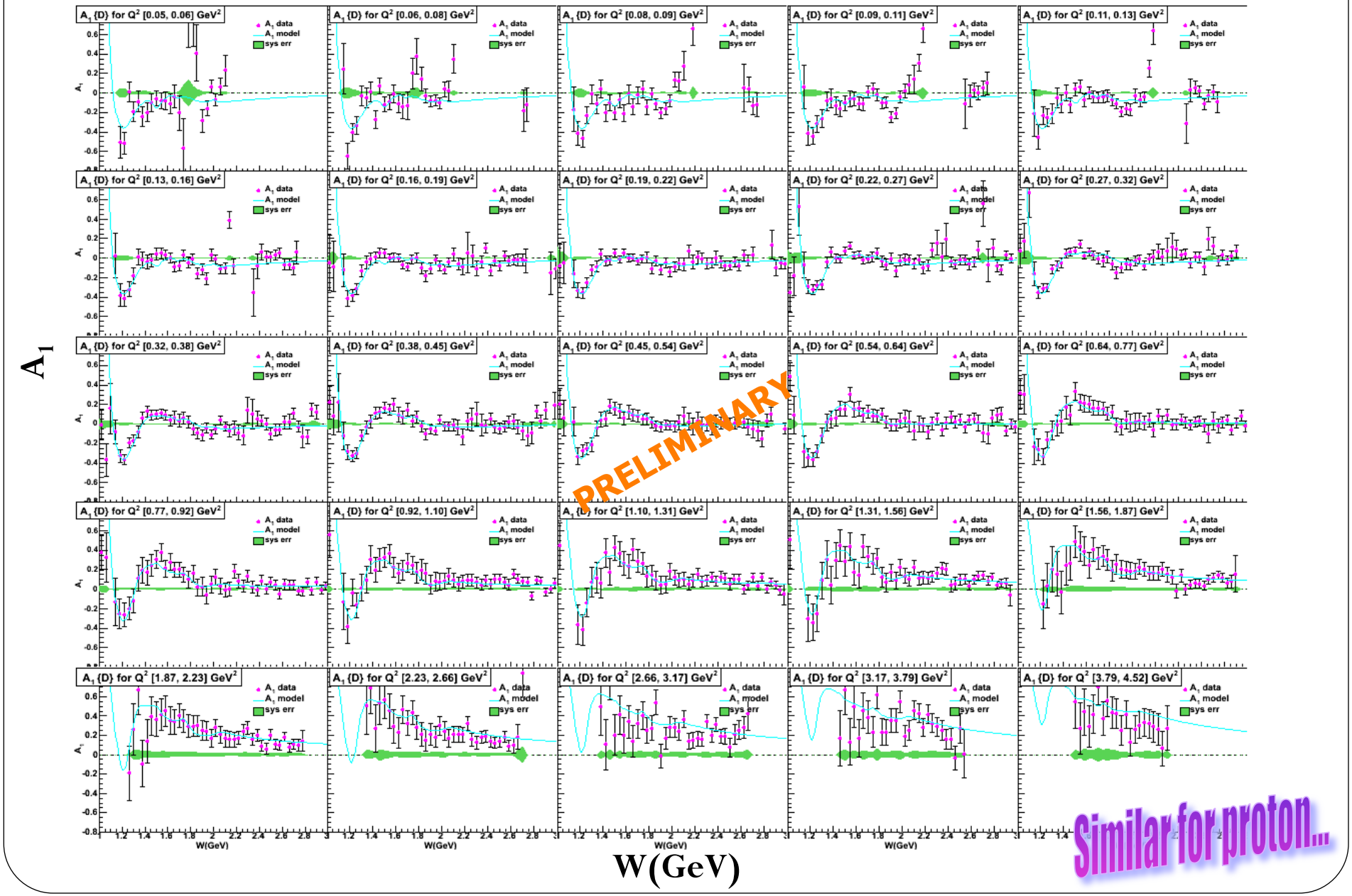
the structure functions g_1 and g_2 are linear combinations of A_1 and A_2

$$g_1(x,Q^2) = \frac{\tau}{1+\tau}(A_1 + \tfrac{1}{\sqrt{\tau}} A_2)F_1 = \frac{\tau}{1+\tau}\left(\frac{A_{||}}{D} + \left(\tfrac{1}{\sqrt{\tau}} - \eta\right)A_2\right)F_1$$

$$g_2(x,Q^2) = \frac{\tau}{1+\tau}(\sqrt{\tau} A_2 - A_1)F_1$$

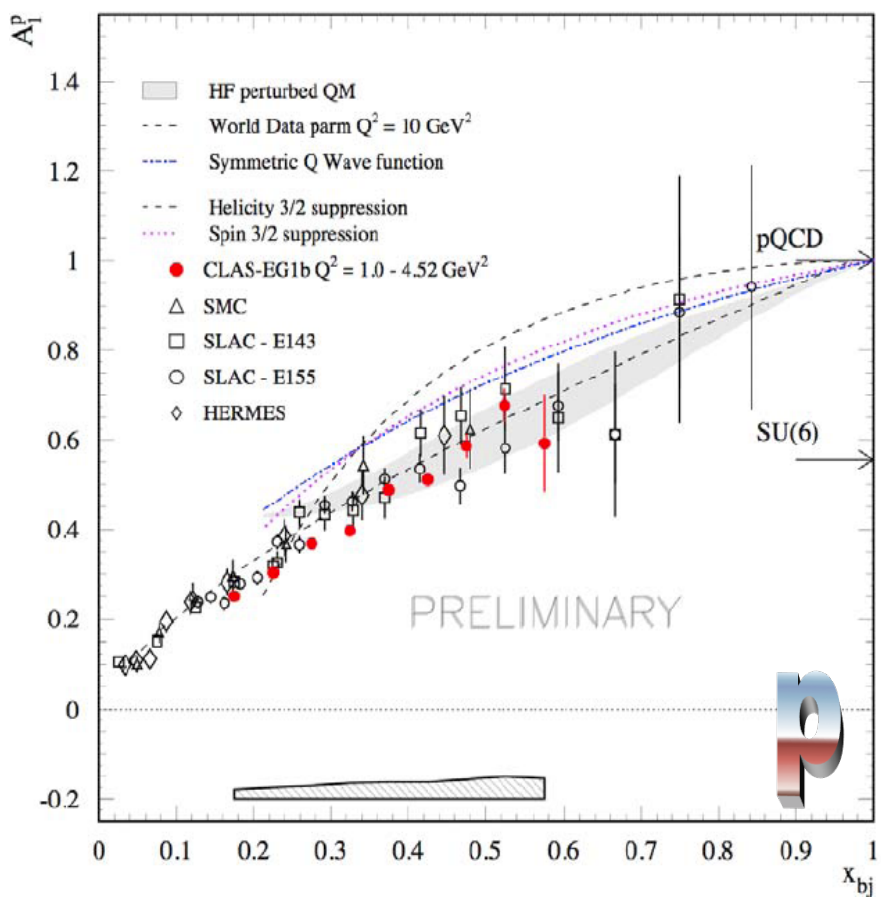
$$\tau = \frac{\nu^2}{Q^2}$$

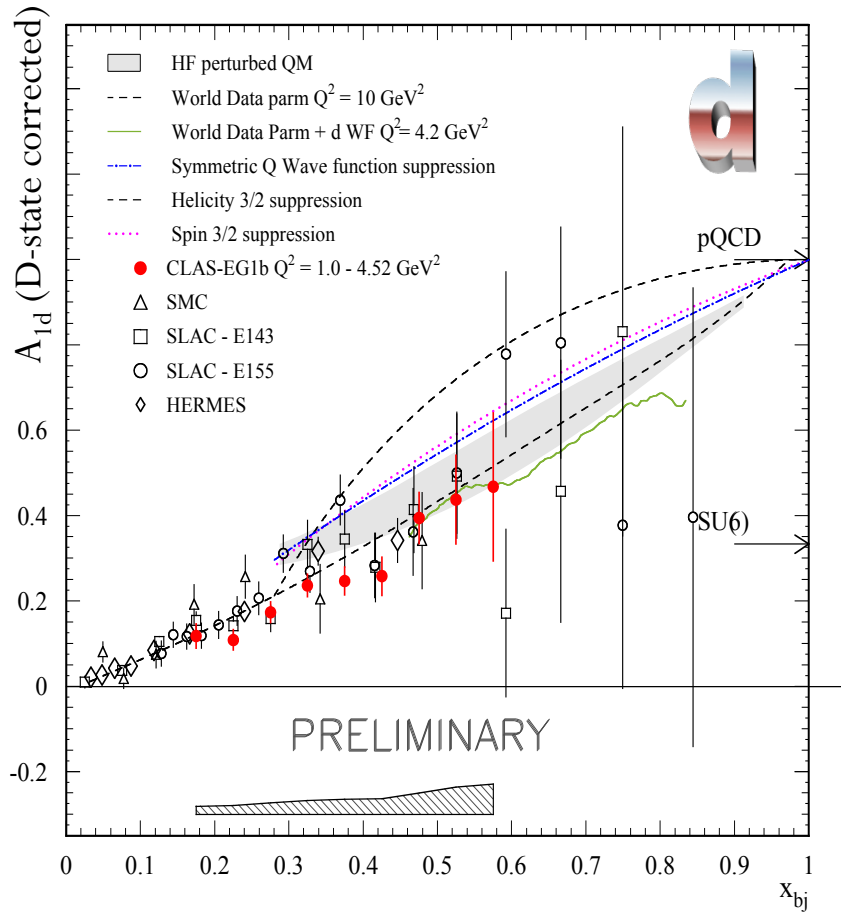
A_1 proton for different Q^2 bins



Similar for proton...

Virtual Photon Asymmetry A_1



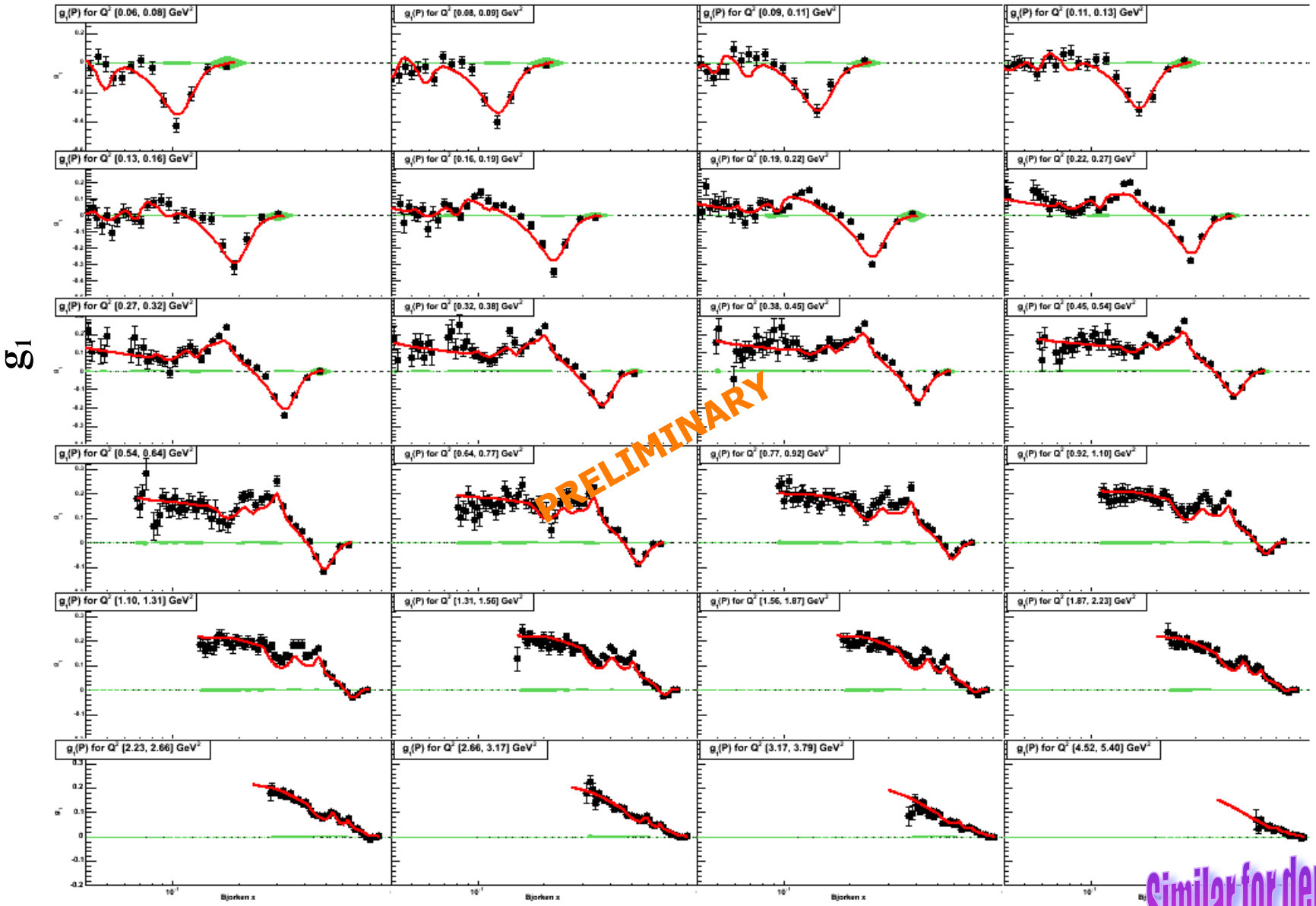


- P and d results fall below parameterization of world data at 10 GeV^2 → include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region
- P and d results are in better agreement with the HFP quark model

HP perturbed QM N. Isgur, Phys. Rev. D 59, 34013

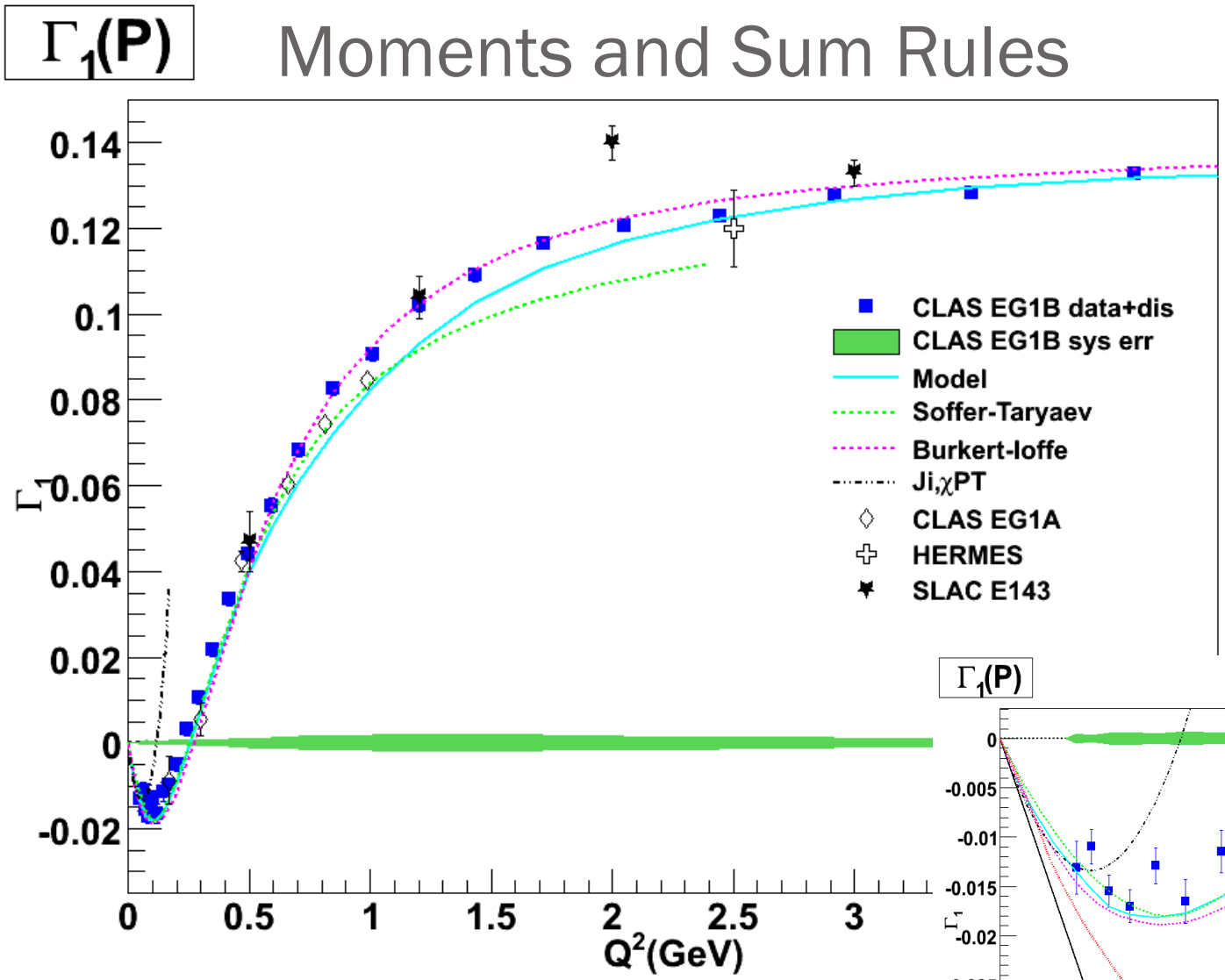
F. Close and W. Melnitchouk, Phys. Rev. C 68, 035210

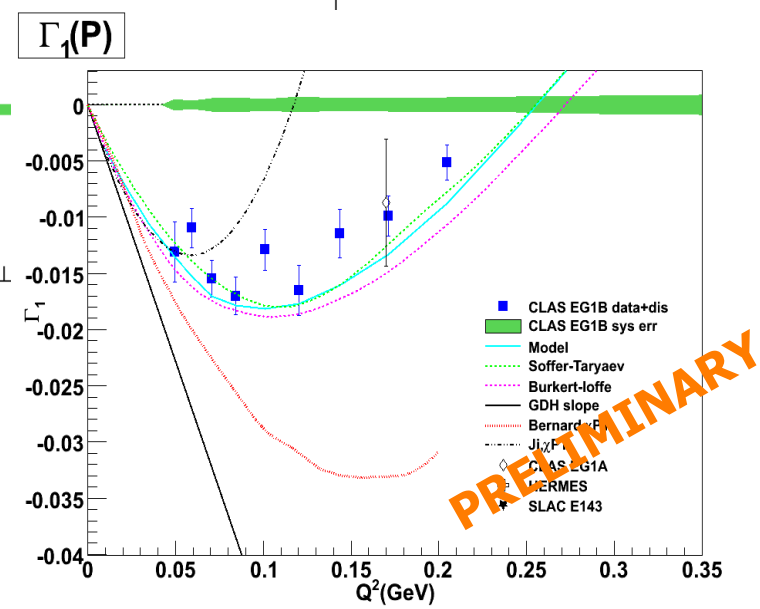
$g_1(x,Q^2)$ proton for different Q^2 bins



Similar for deuteron...

Moments and Sum Rules





Similar for deuteron...

Link between GPDs, DIS and form factors

- DIS at t=ξ=0: ordinary parton distributions

$$H^q(x,\xi=0,t=0)=q(x)$$ unpolarized quark distributions

$$\tilde{H}^q(x,\xi=0,t=0)=\Delta q(x)$$ polarized quark distributions

$$E^q,\tilde{E}^q$$ new information

- First moments: form factors

Dirac

$$\int_{-1}^{1} dx H^q(x,\xi,t)=F_1^q(t)$$

axial

$$\int_{-1}^{1} dx \tilde{H}^q(x,\xi,t)=G_A^q(t)$$

Pauli

$$\int_{-1}^{1} dx E^q(x,\xi,t)=F_2^q(t)$$

pseudo-scalar

$$\int_{-1}^{1} dx \tilde{E}^q(x,\xi,t)=G_P^q(t)$$