Recent Results in DIS from JLab

Dave Gaskell

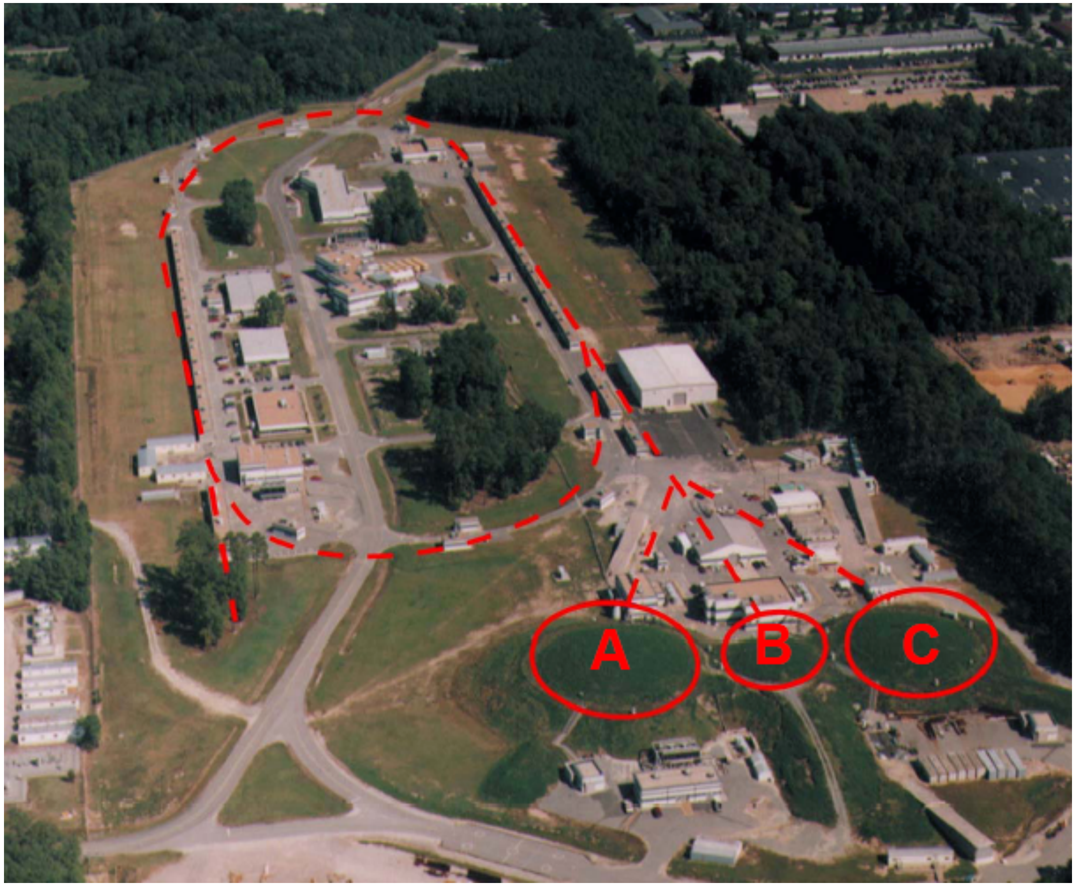
Jefferson Lab

18th International Workshop on Deep-Inelastic Scattering

April 19, 2010

"Beam in 30 minutes or it's free"

CEBAF at Jefferson Lab



"CW" electron accelerator

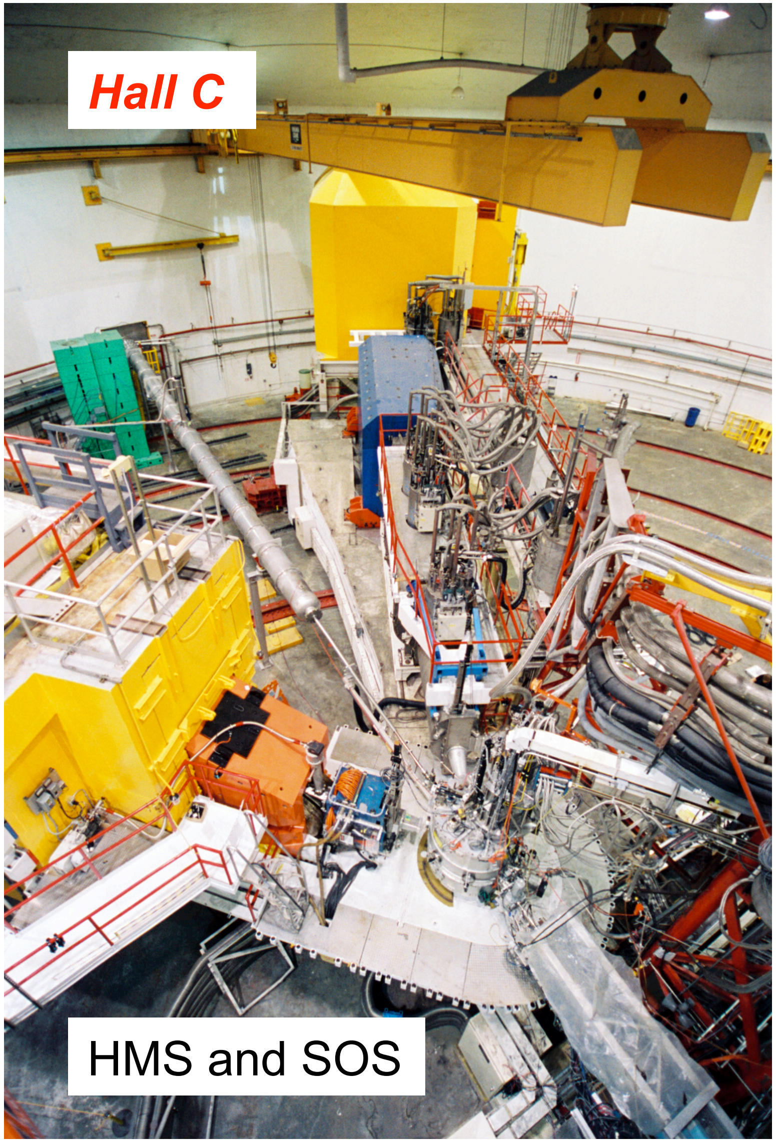
→2 superconducting RF cavity based linacs

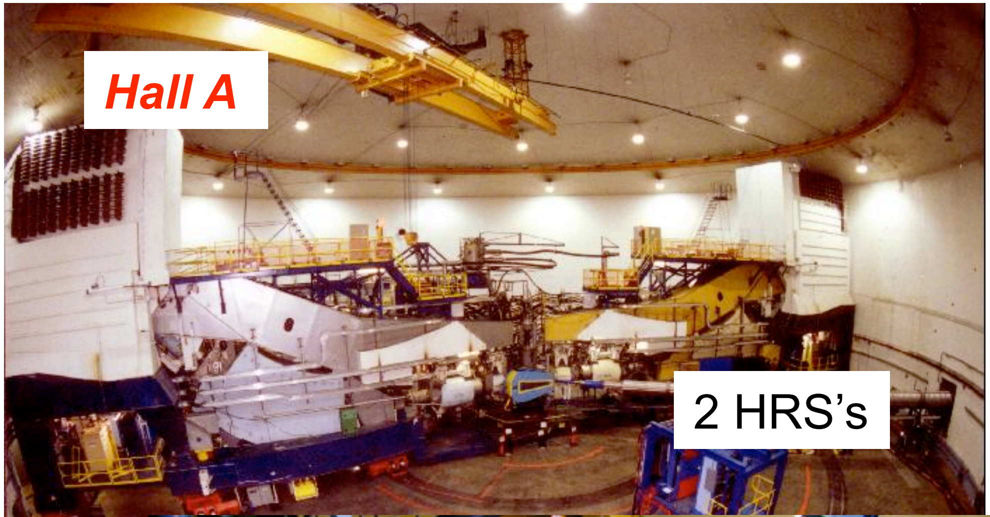
→Maximum beam energy = 6 GeV

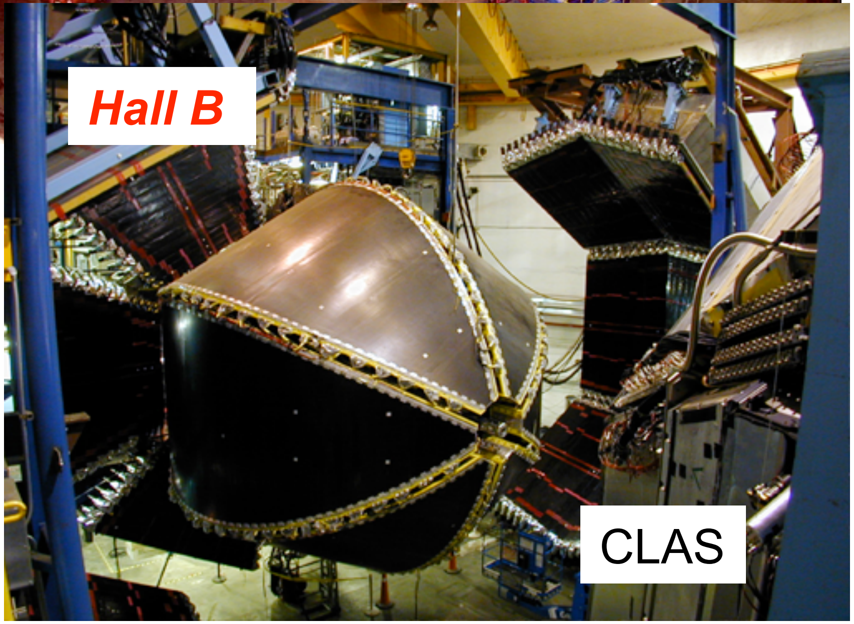
→Routinely deliver beam with polarization > 80%

→3 experimental halls; in principle can deliver beam to all 3 at once

JLab’s Experimental Halls

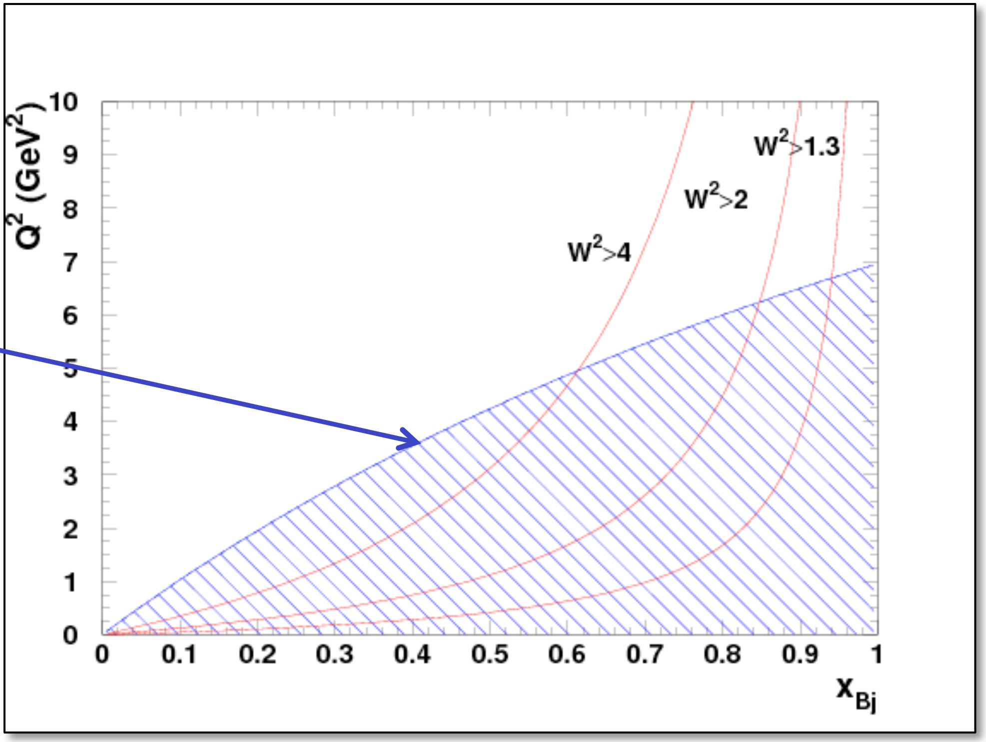






“DIS” and Jefferson Lab

- Relatively “low” beam energy limits JLab’s reach in the canonical DIS regime
  - for W>2 GeV, Q^2>1 GeV^2, limited to x~0.2-0.6, modest Q^2 range
  - This will grow to x=0.1 to 0.8 after 12 GeV upgrade
- High luminosity in part compensates for this kinematic “limitation”



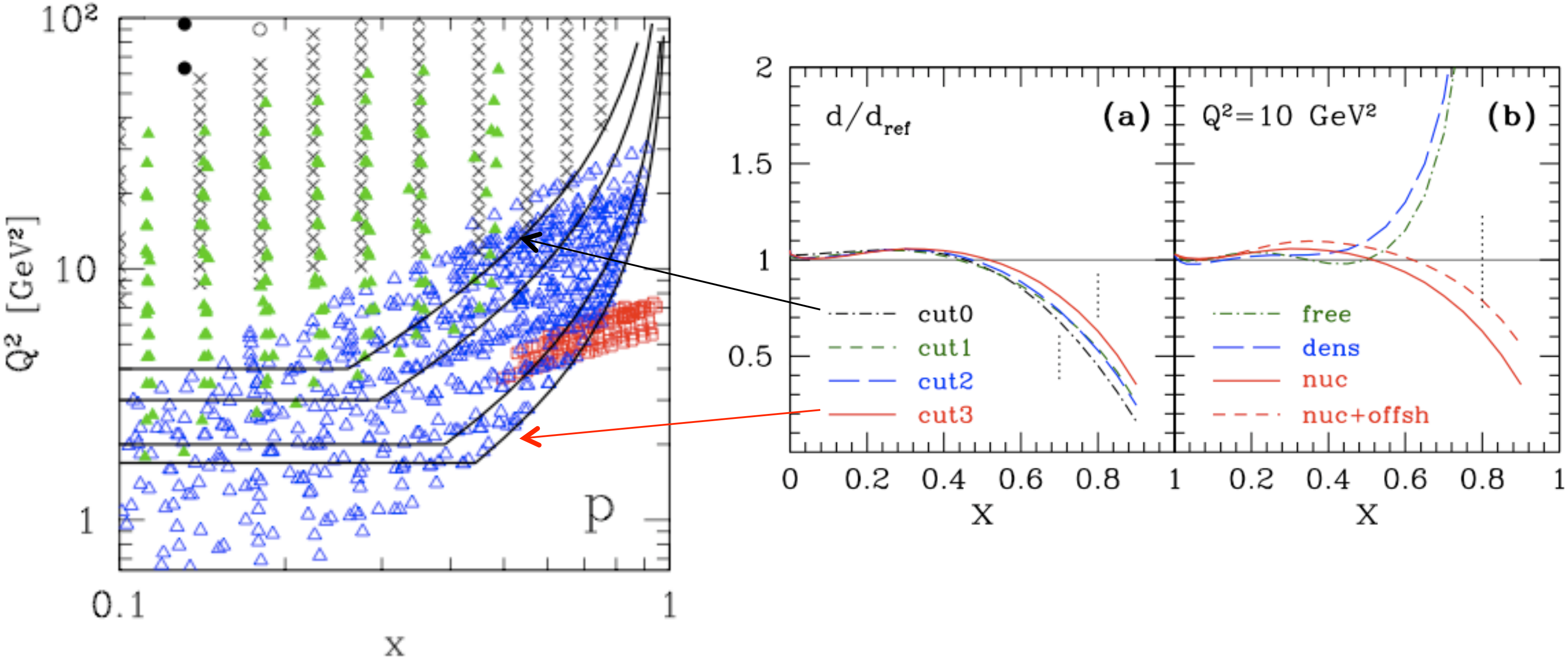
“Easily” accessible kinematics at JLab → larger Q^2 accessible with infinite time!

Topics of Interest

- Inclusive reactions
  - Unpolarized structure functions (F_2,F_L); duality
  - Nuclear dependence (EMC effect)
  - Polarized structure functions (g_1,g_2)
- Semi-inclusive reactions
  - Factorization studies at low energies
  - Transverse momentum dependent distributions
  - Flavor tagging polarized PDFs
- Exclusive reactions
  - Deeply virtual meson, photon production
  - Factorization, GPDs

PDFs at Large x – CTEQ6x

Parton distribution functions at large x poorly constrained
→ Data typically limited to large Q^2, W^2 for fits (W^2>12.25 GeV^2, Q^2>4 GeV^2)
→Higher twist effects significant
→Nuclear corrections important for neutron extraction from deuterium



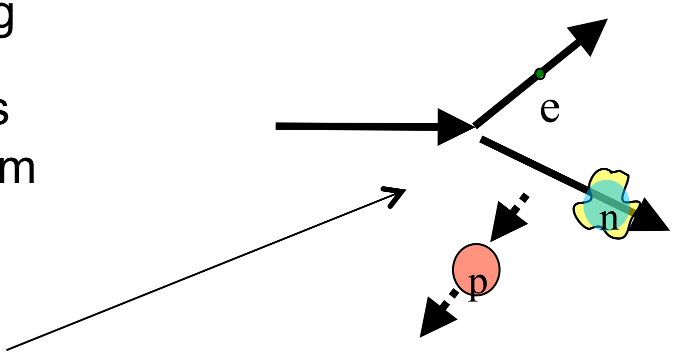
CTEQ6x (CTEQ, Hampton U., JLab) – improve large x fits relaxing kinematic constraints via better control of Target Mass Corrections (TMC) and higher twist

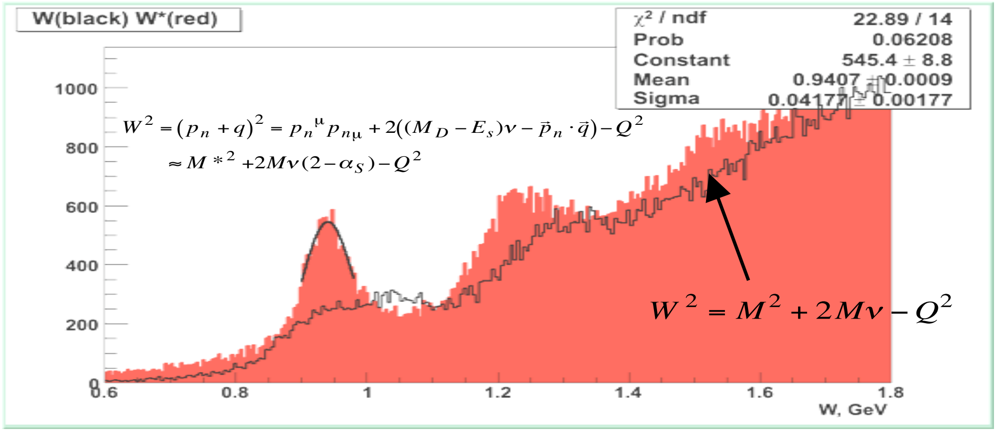
BONUS – d/u via Spectator Tagging

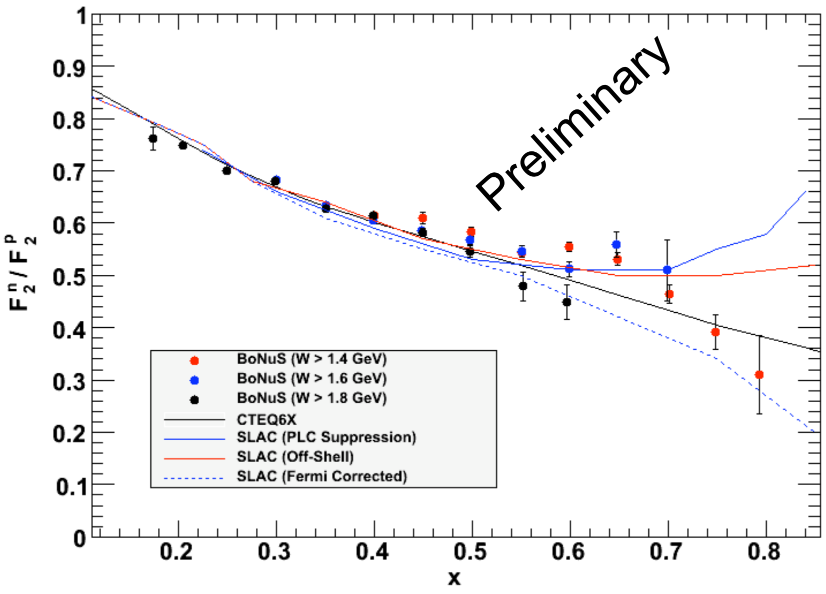
BONUS = Barely Offshell Neutron Scattering

Nuclear corrections lead to large uncertainties when extracting neutron structure function from deuterium data

→ Tag low momentum “spectator” protons at backward angles; struck neutron almost on-shell







EMC Effect in Light Nuclei

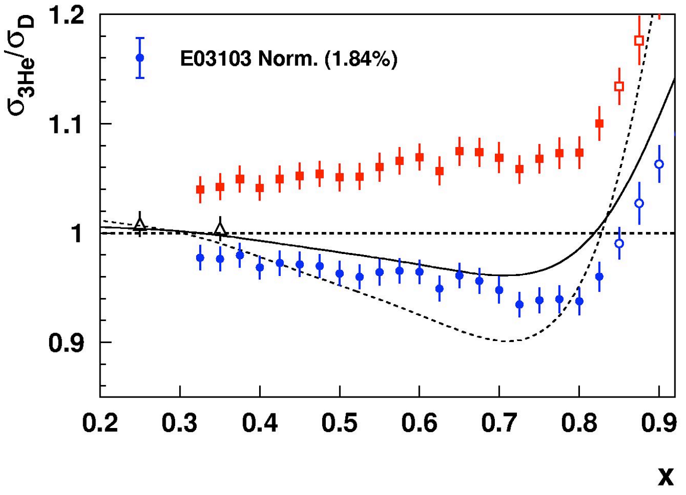
New measurement of the EMC effect in light nuclei in Hall C

→Both A and density dependent fits fail

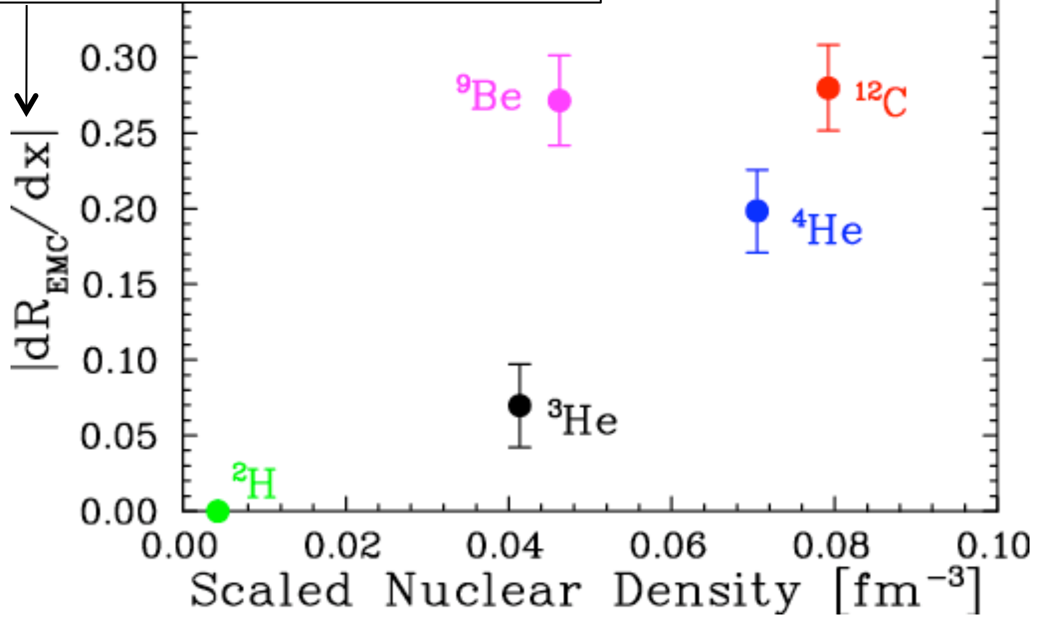
→ Be structure suggests "local density" picture

Cluster structure dominated by $2\alpha+n$

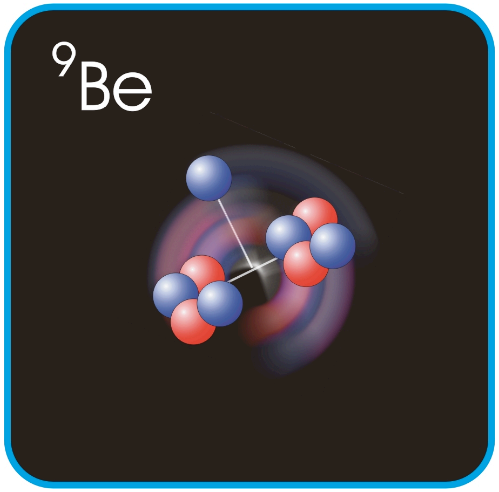
Ave. density low, but all protons in α-like clusters



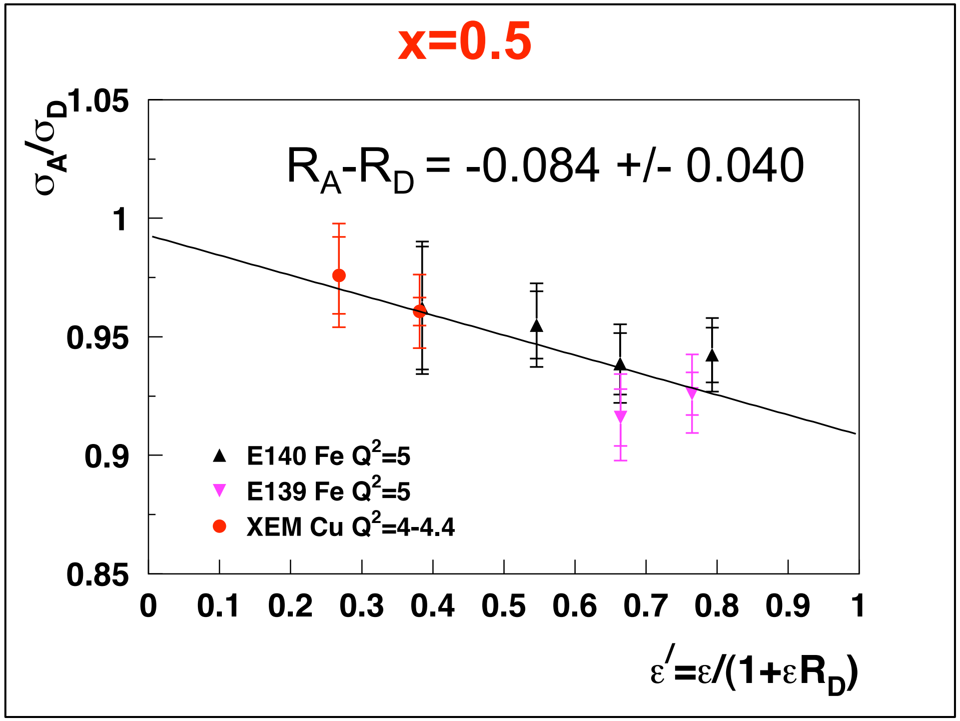
Linear fit between x=0.3-0.7



[J. Seely et al, 103:202301 (2009)]



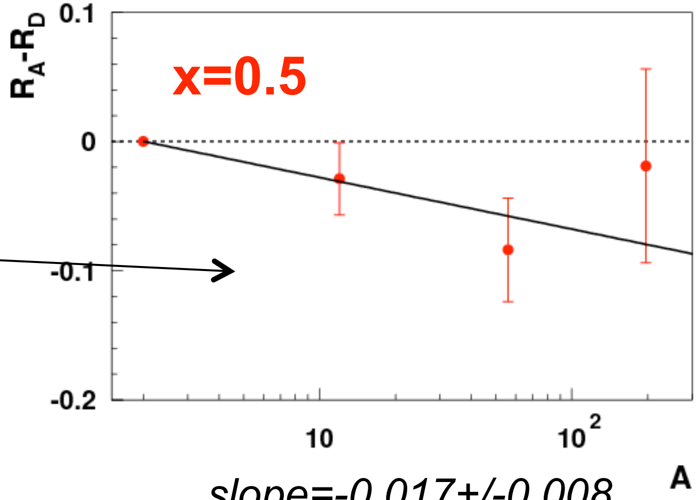
Nuclear Dependence of R?



SLAC E140 results demonstrated no evidence for nuclear dependence of $R=\sigma_L/\sigma_T$ at large x(>0.2)

→ Applying *Coulomb corrections* to SLAC data and combining with Hall C data suggest non-trivial nuclear dependence at large x

SLAC E139/E140, Hall C combined for carbon, Fe/Cu, gold



slope=-0.017+/-0.008

[P. Solvignon et al, arXiv:0906.2839 (AIP Conf. Proc.)]

→ *longer publication in progress*

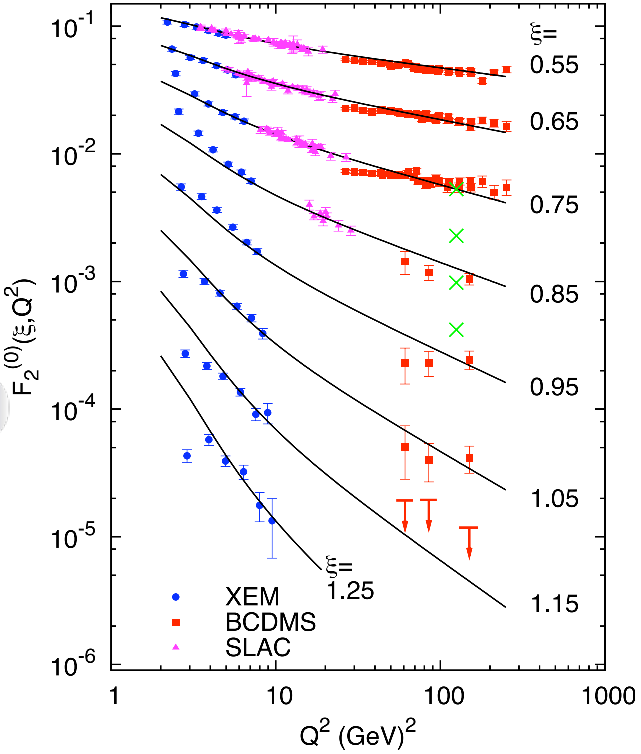
Quark Distributions at x>1

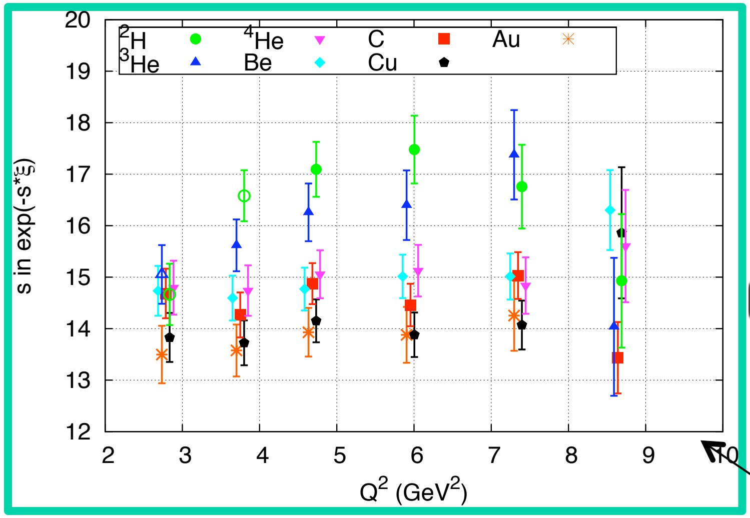
E02-109 measured A(e,e') at x>1 for variety of nuclei

→Short-range correlations lead to "super-fast quarks" in the nucleus

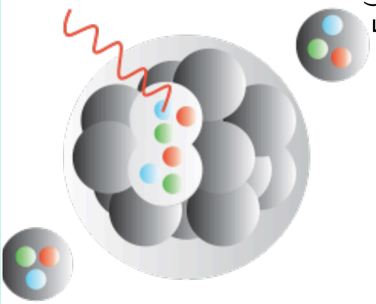
→Target mass corrections applied to F_2 "inelastic" structure function

Target mass corrected $F_2(x,Q^2)$





[N. Fomin et al, in preparation]



$F_2 \sim e^{-s\xi}$ predicted by multi-quark cluster, NN correlation models

Fit to form $e^{-s\xi}$ for ξ=1-1.25

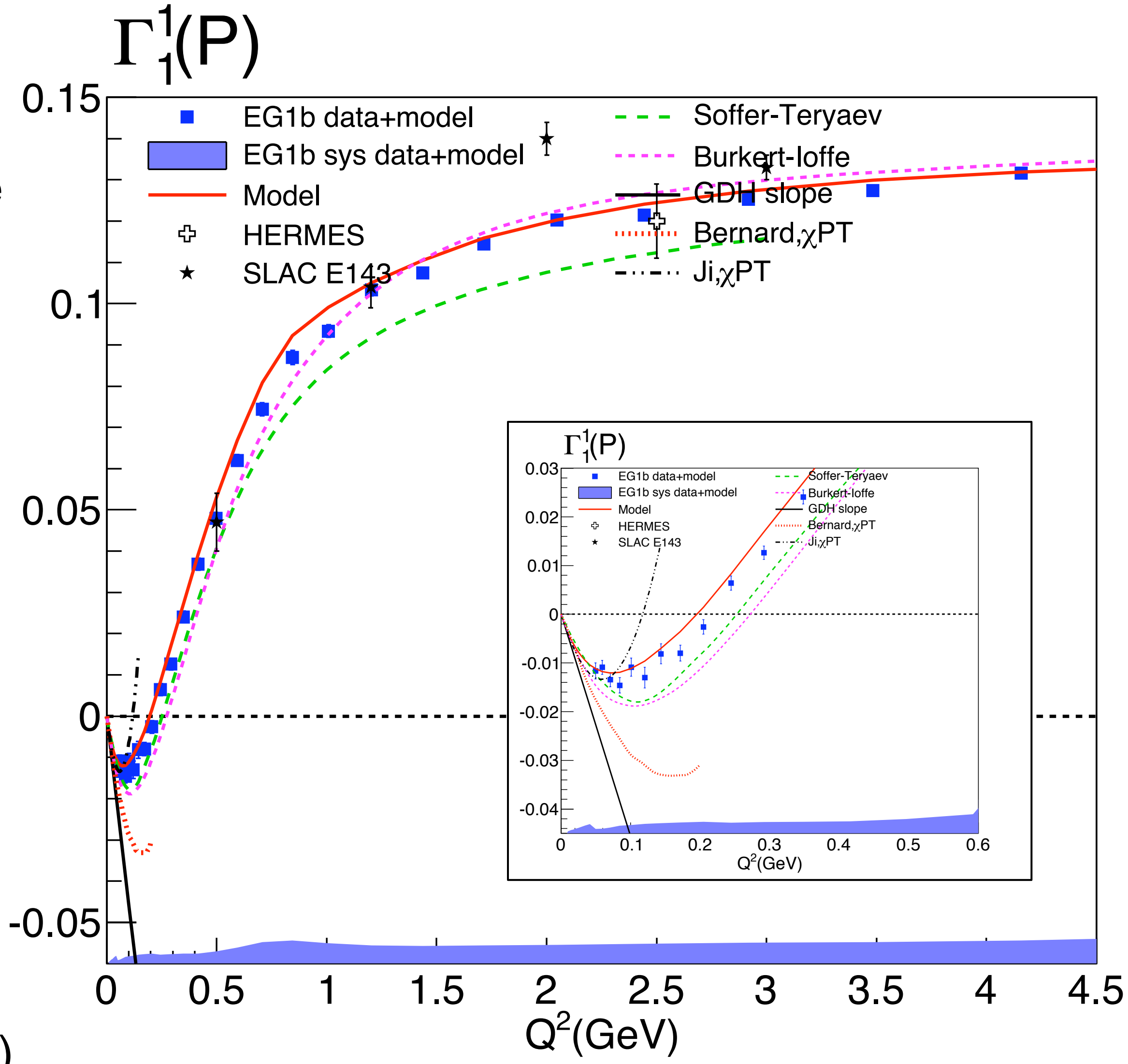
→Q^2 independent

→Saturates quickly for medium-heavy nuclei

$\Gamma_1^p(Q^2)$ x-Moment of $g_{1p}(x,Q^2)$

JLab measurements have added large body of precise polarized target data

2010 results include four energies in the range of 1.5 – 5.7 GeV. They extend the Q^2 range, and have higher statistics and smaller systematic uncertainties.



Similar data for $g_{1d}(x,Q^2)$

g_2(x,Q) and d_2

- $g_2(x,Q^2)$ provides unique access to higher twist contributions

$$\begin{aligned} g_2(x,Q^2) &= g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2) \\ &= -g_1(x,Q^2) + \int_x^1 g_1(x',Q^2)\frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'}\left[\frac{m}{M}h_T(x',Q^2) + \xi(x',Q^2)\right]\frac{dx'}{x'} \end{aligned}$$

Twist-3 – quark-gluon correlations

- 2nd moment of g_2-g_2^{WW} → d2; twist-3 matrix element

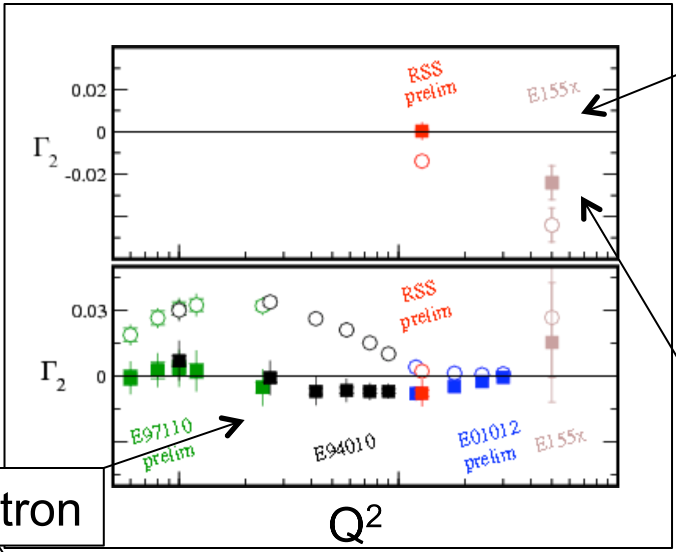
$$\boxed{\begin{aligned} d_2(Q^2) &= 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx \\ &= \int_0^1 [2g_1(x,Q^2) + 3g_2(x,Q^2)]dx \end{aligned}}$$

→ "Color polarizabilities", provide benchmark for lattice QCD

Moments of $g_2(x,Q^2)$

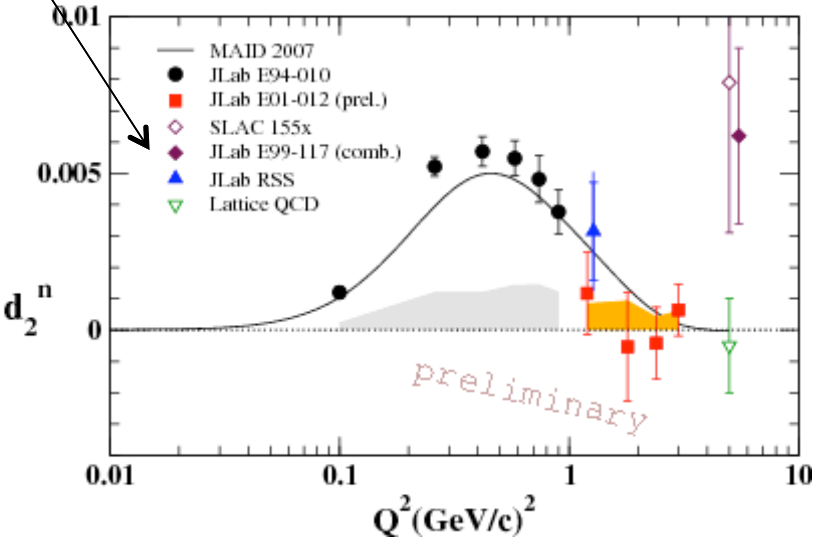
Burkhardt-Cottingham sum-rule → $\int_0^1 g_2(x,Q^2) = 0$

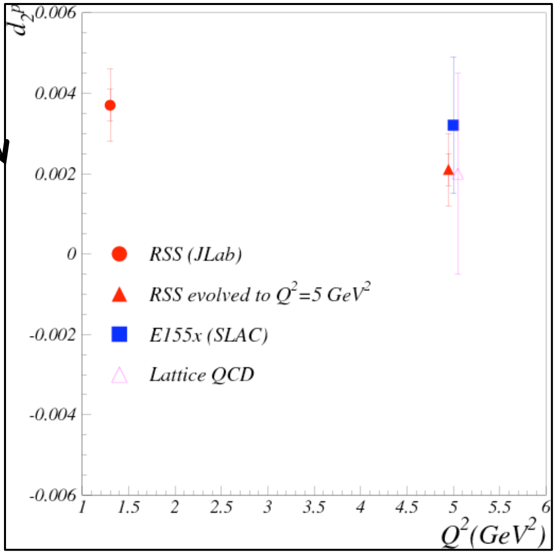
$$d_2 = 3\int_0^1 x^2(g_2(x,Q^2) - g_2^{WW}(x,Q^2))dx$$



Neutron

Proton





$g_2(x,Q^2)$ and d_2 Measurements

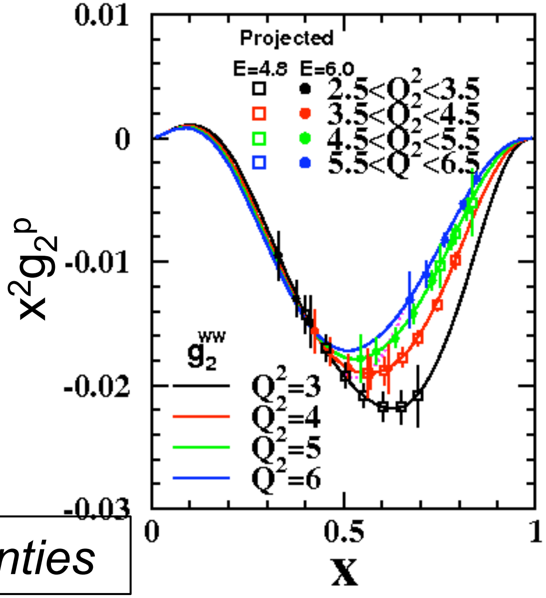
Proton: Spin Asymmetries of the Nucleon Experiment (SANE) in Hall C → polarized NH_3

Neutron: d_2n Experiment in Hall A → polarized ^{3}He

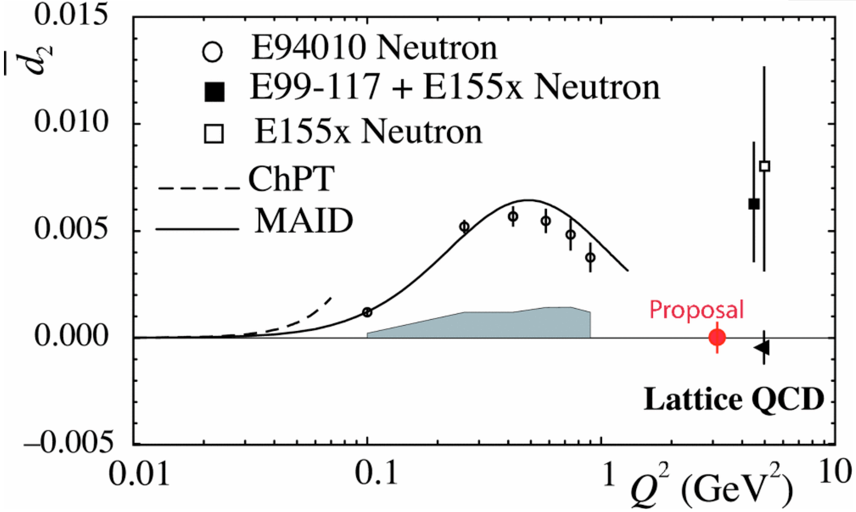
Ran almost concurrently in 2008

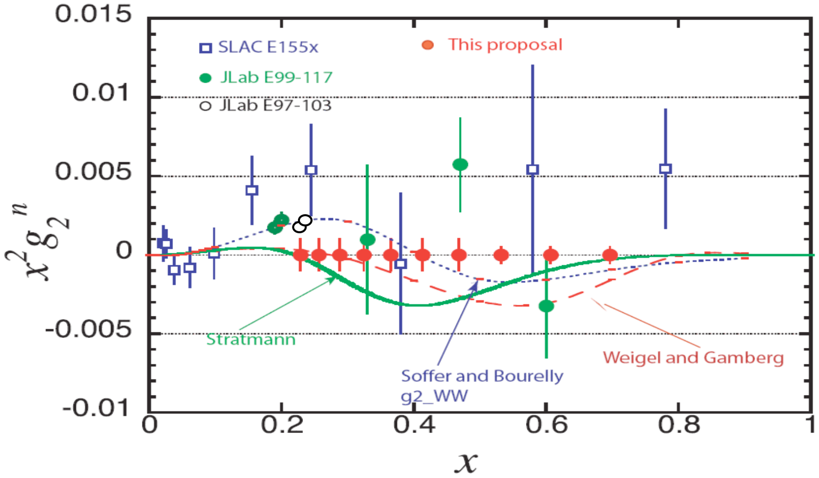
→Each used novel large acceptance "spectrometers" (BETA and Big Bite)

→ Multiple beam energies allow extraction of d_2 with minimal Q^2 interpolation



Projected uncertainties

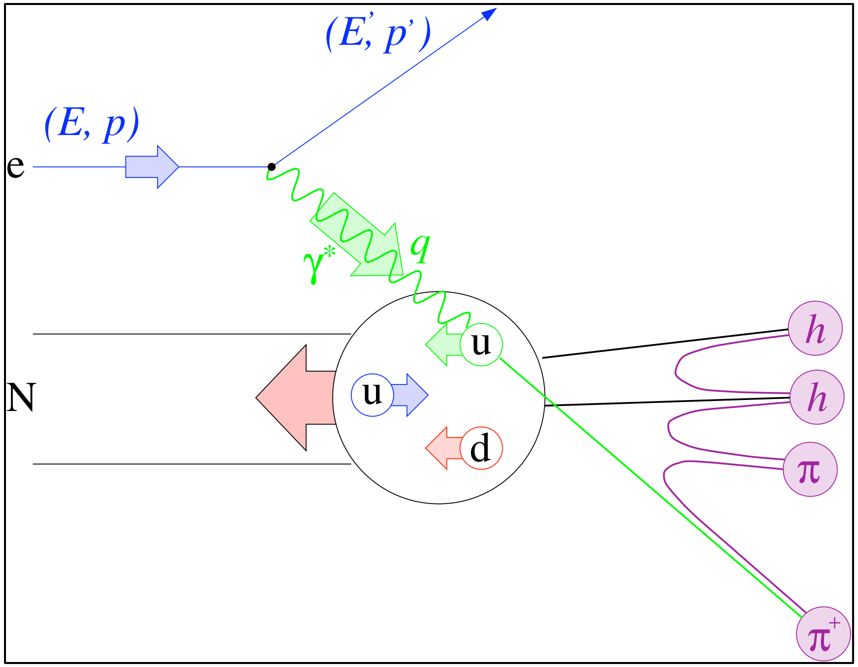




Semi-inclusive Processes

Interest in semi-inclusive processes dominated originally by potential use in “flavor” tagging
→ deconvolution of polarized PDFs
→ constraints on unpolarized sea

More recently, interest has grown in azimuthal asymmetries
→Transversity distribution
→ Transverse Momentum Distributions (TMDs)



$$d\sigma^h \propto \sum f^{H\to q}(x)\,\mathbf{d}\sigma_q(y)\,D^{q\to h}(z)$$

$$\downarrow$$

$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathbf{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

Distribution Functions

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1 \, h_{1T}^\perp$

quarks

nucleon

U=unpolarized
L=long. polarized
T=trans. polarized

Diagonal elements = usual PDFs

Off-diagonal elements = transverse momentum distributions, require non-zero angular momentum

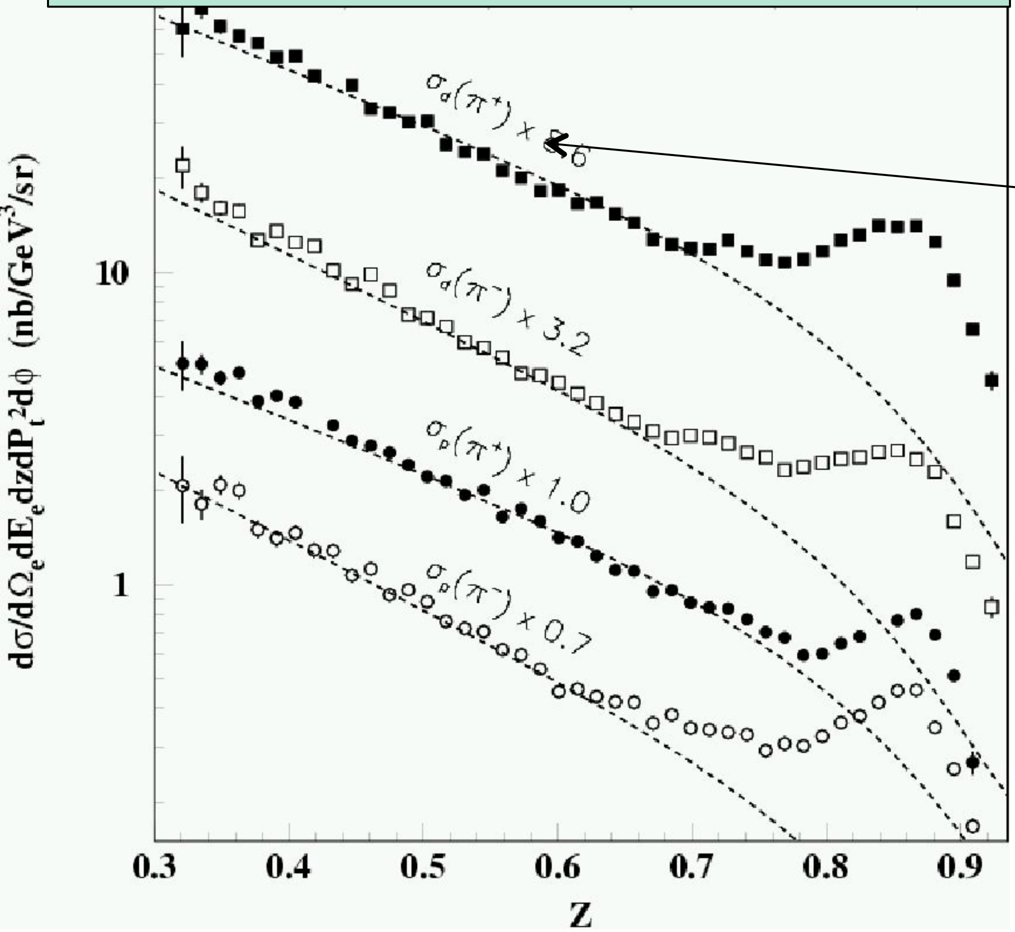
$f_{1T}^\perp$ → Sivers function, describes unpolarized quark in trans. pol. nucleon

$h_1^\perp, h_{1L}^\perp, h_{1T}^\perp$ → Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon

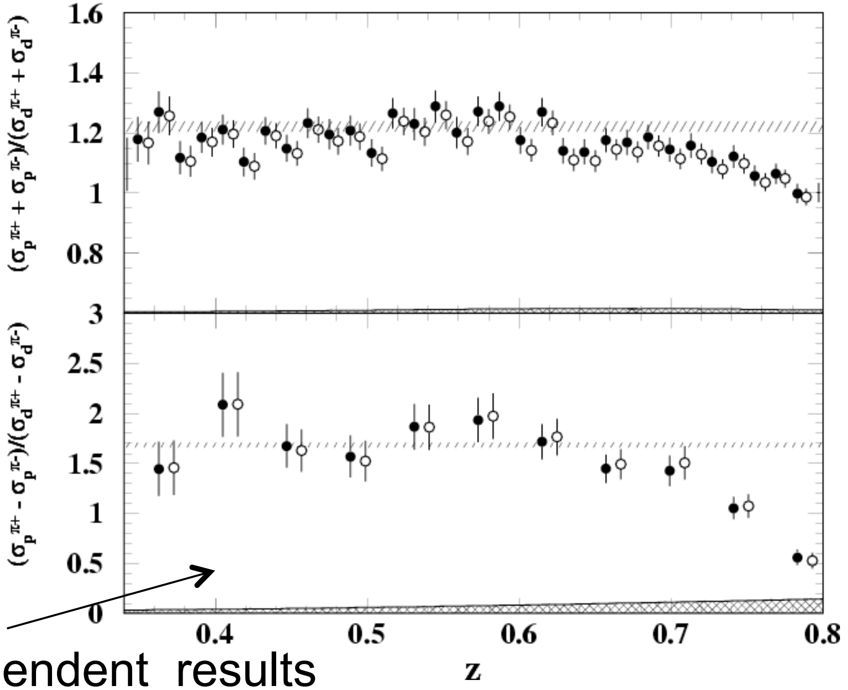
Unpolarized SIDIS in Hall C

Cross sections and ratios consistent with naïve factorization expectations

ep,d→e'$\pi^{+/-}$X in Hall C



Low energy semi-inclusive cross sections consistent with calculation using high energy params. of frag. functions and cteq PDFs (z<0.7)



Combinations of D/p,π^+/π^- yields give z-independent results

Unpolarized SIDIS – P_T Dependence

Constrain k_T dependence of up and down quarks *separately*

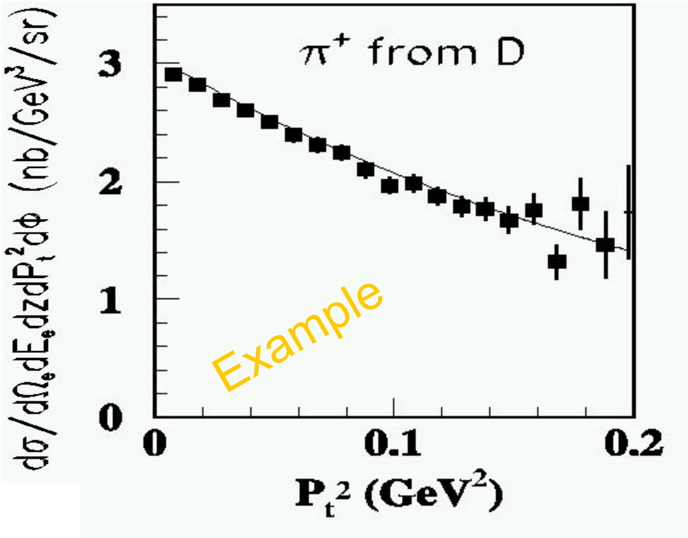
1) Probe π^+ and π^- final states

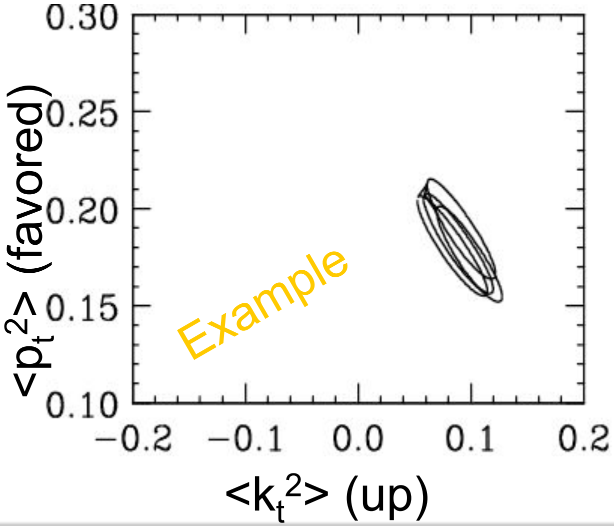
2) Use both **proton** and neutron (**d**) targets

3) Combination allows, in principle, separation of quark width from fragmentation widths *(if sea quark contributions small)*

1st example: Hall C, PL B665 (2008) 20

Simple model, with several assumptions:
→ factorization valid
→ fragmentation functions do not depend on quark flavor
→ transverse momentum widths of quark and fragmentation functions are gaussian and can be added in quadrature
→ more …





A_1 P_T-Dependence in SIDIS

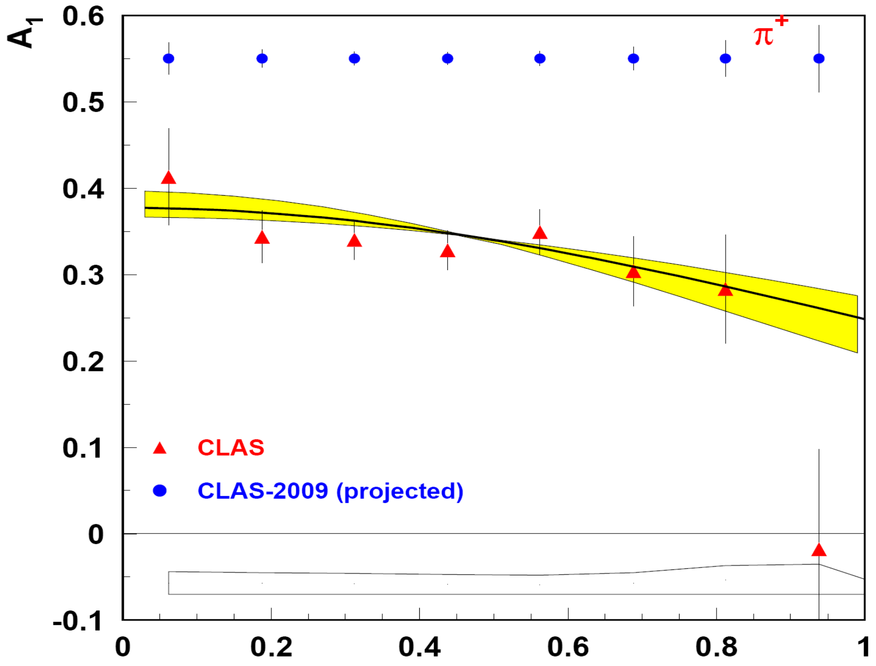
$$A_1 \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \quad e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2
M.Anselmino et al
hep-ph/0608048

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

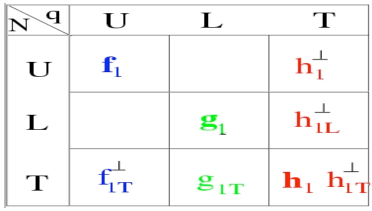


New eg1dvcs data allow multidimensional binning to study k_T-dependence for fixed x

In perturbative limit predicted to be constant

π+ A_{LL} can be explained in terms of broader k_T distributions for f_1 compared to g_1

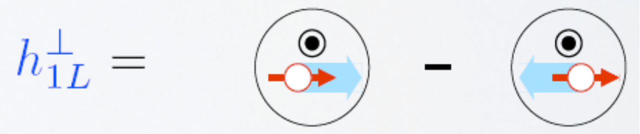
Proton Single-Spin Asymmetries with CLAS

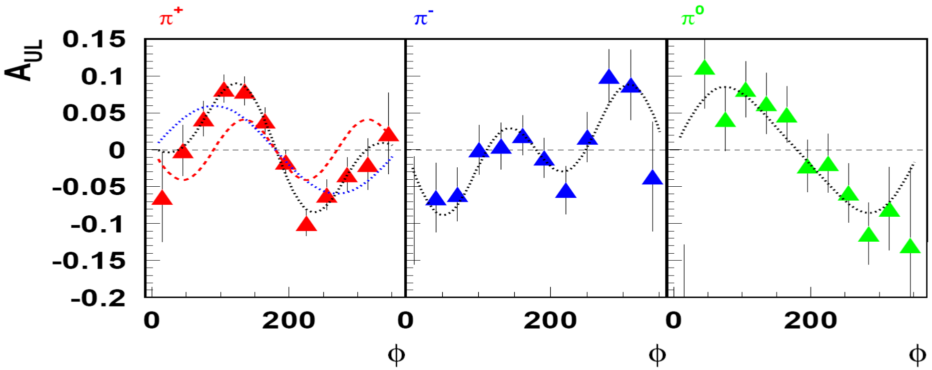


N q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$$\rightarrow A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp}$$

Transversely polarized quarks in the longitudinally polarized nucleon





$W^2>4$ GeV^2

$Q^2>1.1$ GeV^2

$y<0.85$

$0.4<z<0.7$

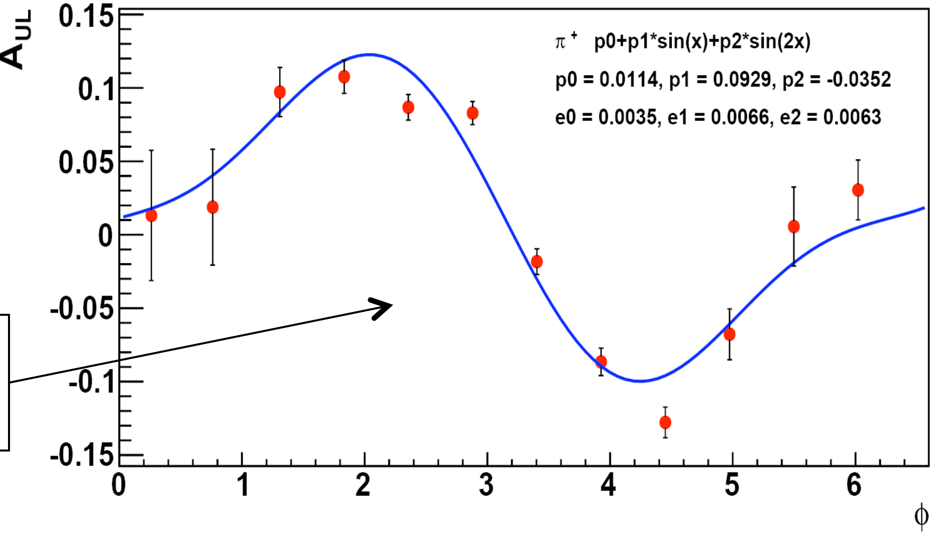
$M_X>1.4$ GeV

$P_T<1$ GeV

$0.12<x<0.48$

ep→e'πX

~10% of E05-113 data

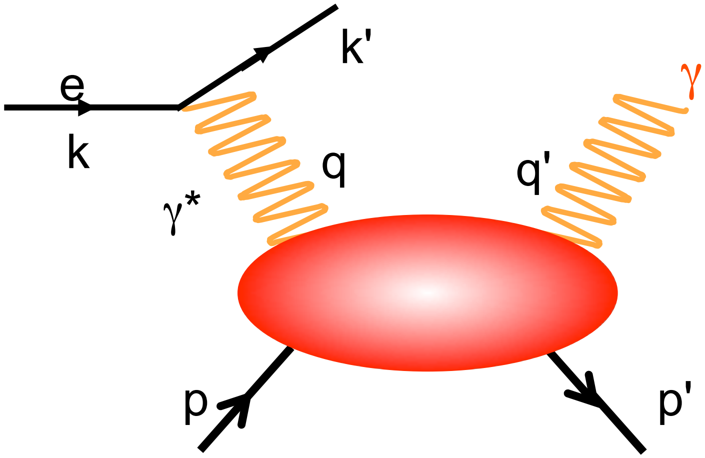


Much higher statistics from 2009 run

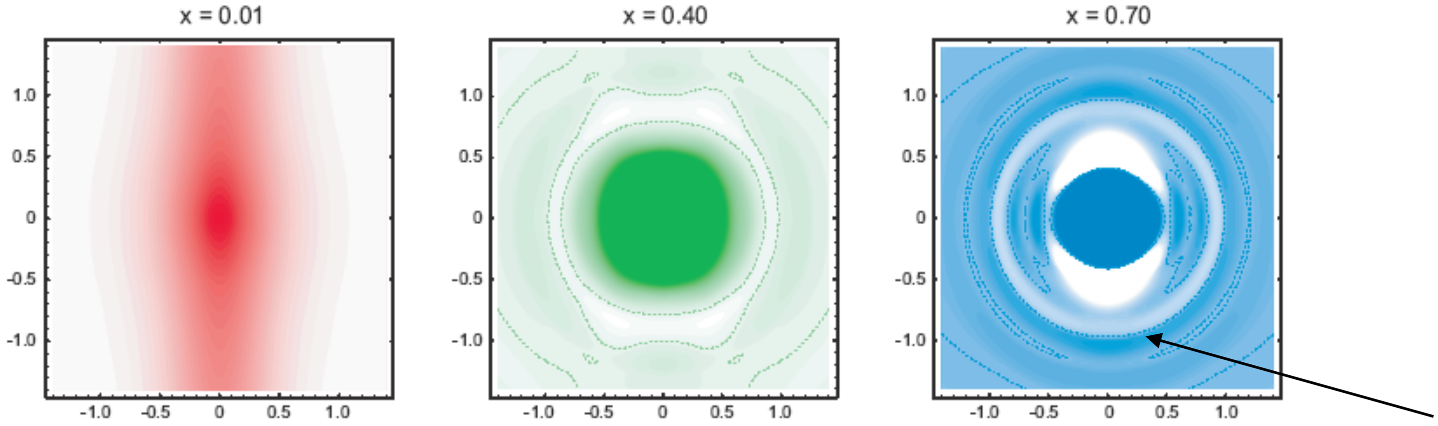
Generalized Parton Distributions

A major new direction in Hadron Physics aimed at the 3-D mapping of the quark structure of the nucleon.

→ JLab is just beginning the first stages of a large program of exclusive reactions to access GPDs



x = Longitudinal momentum fraction



interference pattern

Charge density distributions for u-quarks

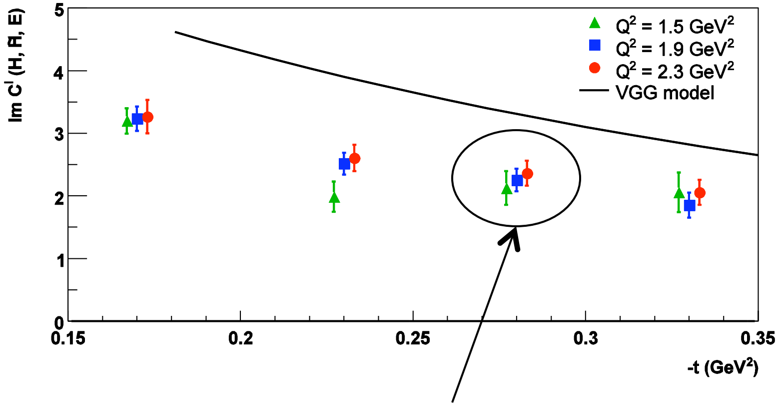
3D image is obtained by rotation around the z-axis

DVCS Beam Spin Asymmetries

Initial round of dedicated DVCS experiments focused on beam-spin asymmetry

Hall A: BSA + absolute cross sections

$$F_1(t)\mathcal{H} + \frac{x_B}{2 - x_B}[F_1(t) + F_2(t)]\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}$$

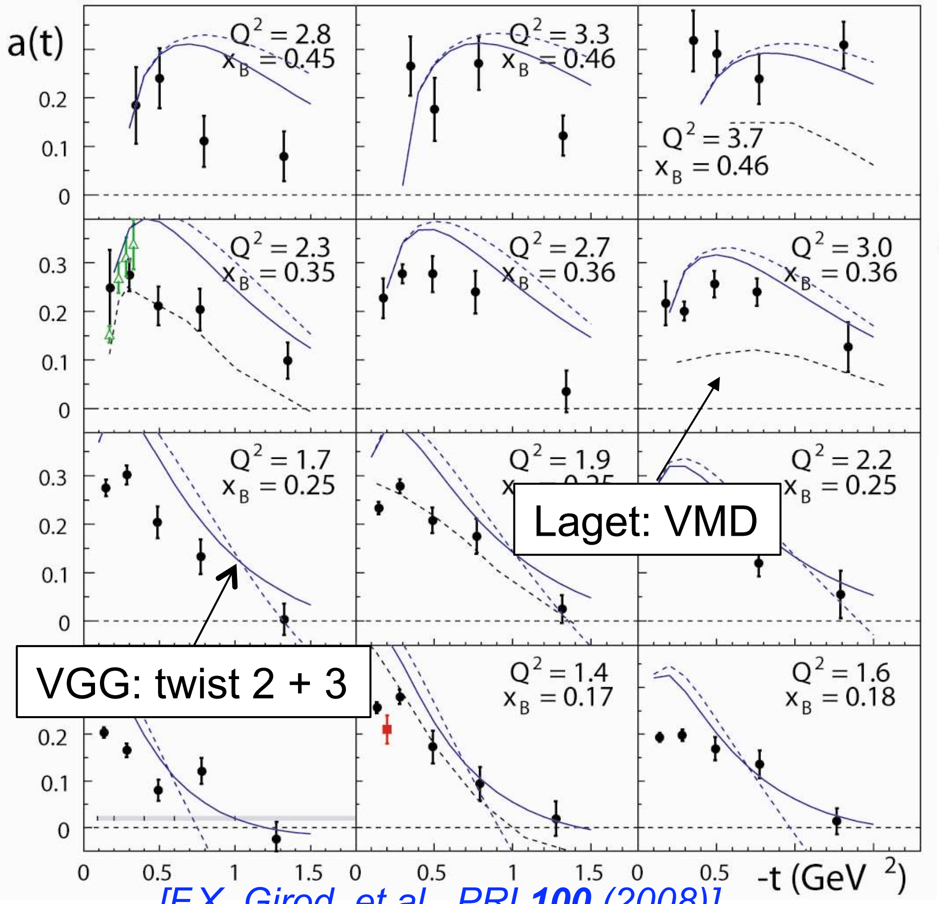


Q^2 – dependence tests factorization

*[C. Muñoz Camacho et al., PRL**97**, 262002 (2006)]*

Also: “neutron” data via Deuterium

CLAS: Emphasis on asymmetries over wide range of x, Q^2 ,t



Laget: VMD

VGG: twist 2 + 3

*[F.X. Girod et al., PRL**100** (2008)]*

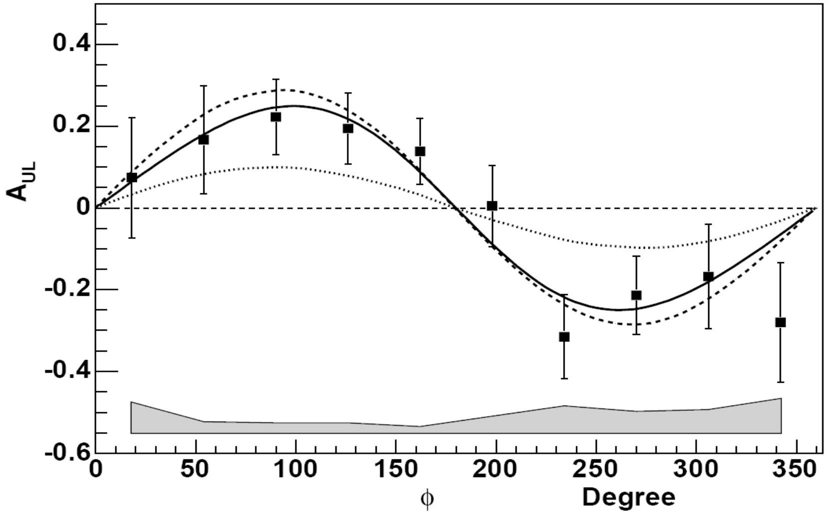
DVCS Target Spin Asymmetries

$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1 \tilde{H} + \xi(F_1+F_2)(H + .. \}$$
$$\Delta\sigma_{LL} \sim \cos\phi \, \mathrm{Re}\{F_1 \tilde{H} + \xi(F_1+F_2)(H + .. \}$$

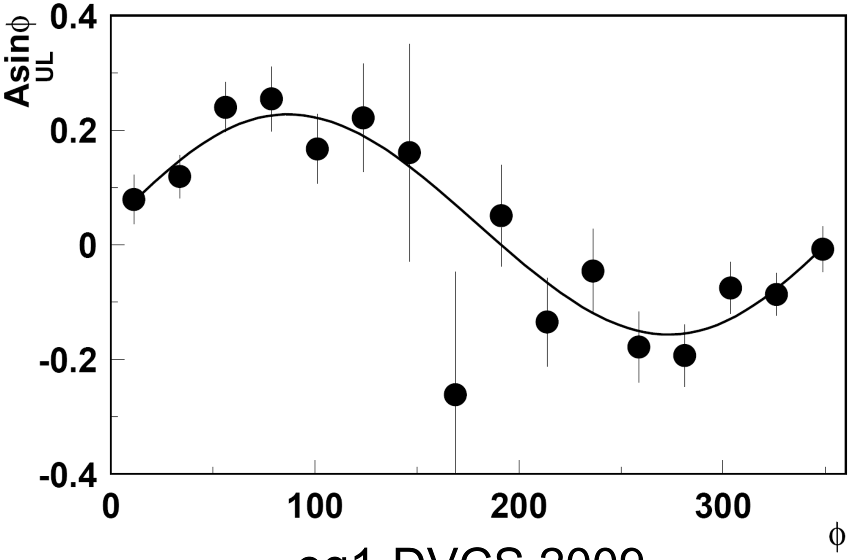
Kinematically suppressed

Measurements with polarized target will constrain the polarized GPDs and combined with beam SSA measurements would allow precision measurement of unpolarized GPDs.

(order of magnitude more data to analyze)

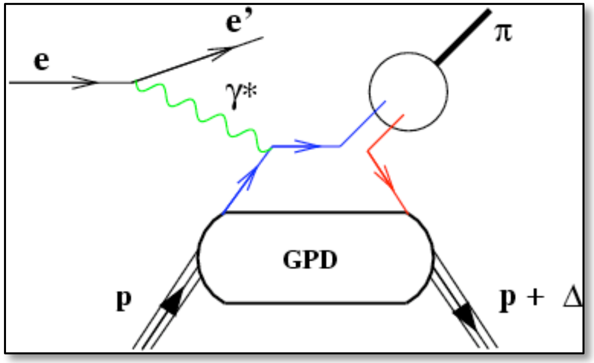


S.Chen et al. Phys.Rev.Lett.97:072002,2006



eg1-DVCS 2009

Deep Exclusive π^0 Production with CLAS

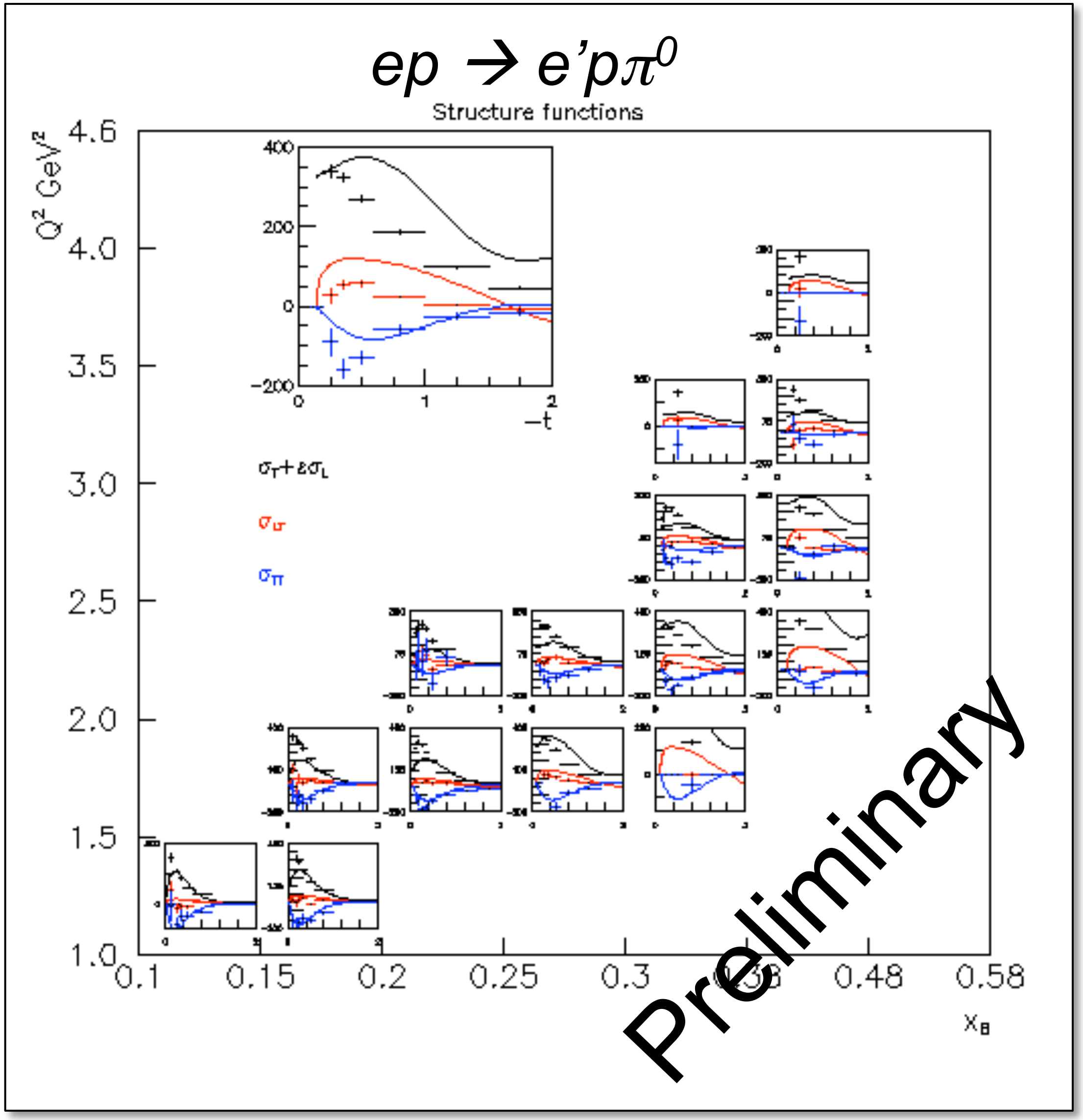


- Reaction complicated by meson structure
- Factorization only for σ_L
- Large data set from CLAS

→Good agreement with Laget's "Regge"-like model

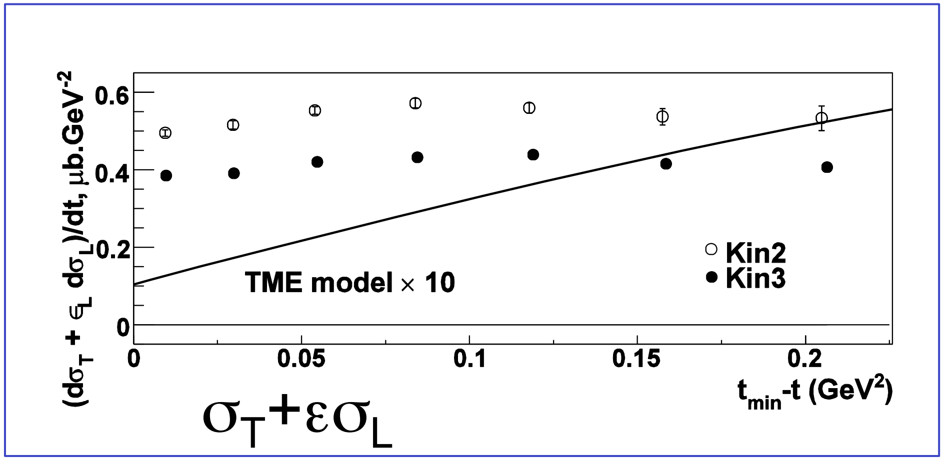
→No L-T separation

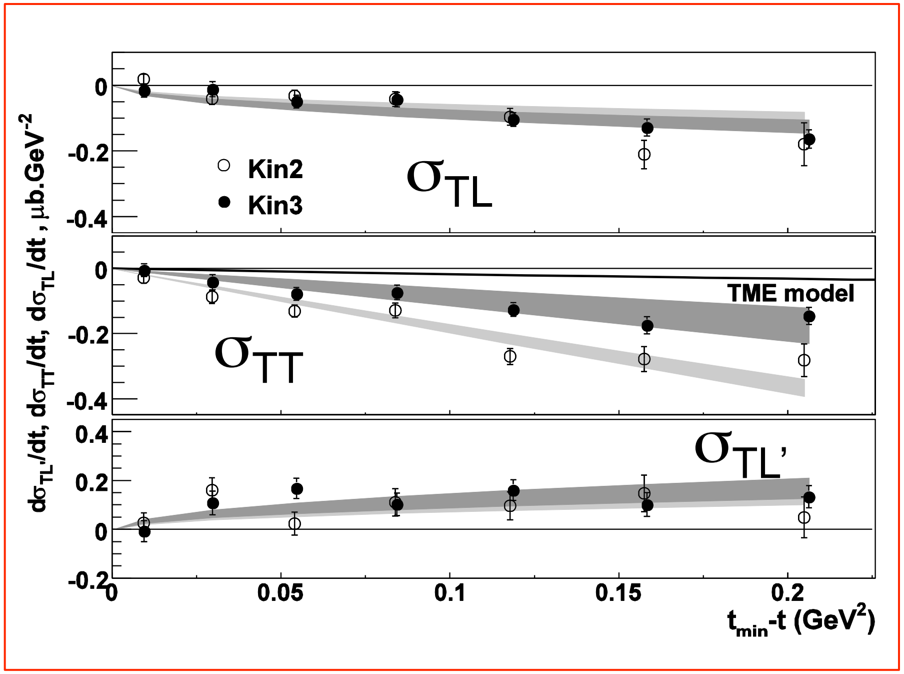
→Similar data set for η production also exists



Deep Exclusive π^0 Production in Hall A

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon_L \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon_L(1+\varepsilon)}\frac{d\sigma_{TL}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \lambda\sqrt{2\varepsilon_L(1-\varepsilon)}\frac{d\sigma_{TL'}}{dt}\sin\phi$$





arXiv:1003.2938 [nucl-ex]

- Very soft Q^2-dependence:

$$\sigma_T + \varepsilon_L\sigma_L \approx \left(Q^2\right)^{-1.3\pm0.1}$$

- *Far from the asymptotic pQCD prediction* $\sigma_L \approx Q^{-6}$ *and* $\sigma_T \approx Q^{-8}$

Even Laget model breaks down at this low *-t*

Follow-up experiment E07-007 runs fall 2010 – full L-T separation

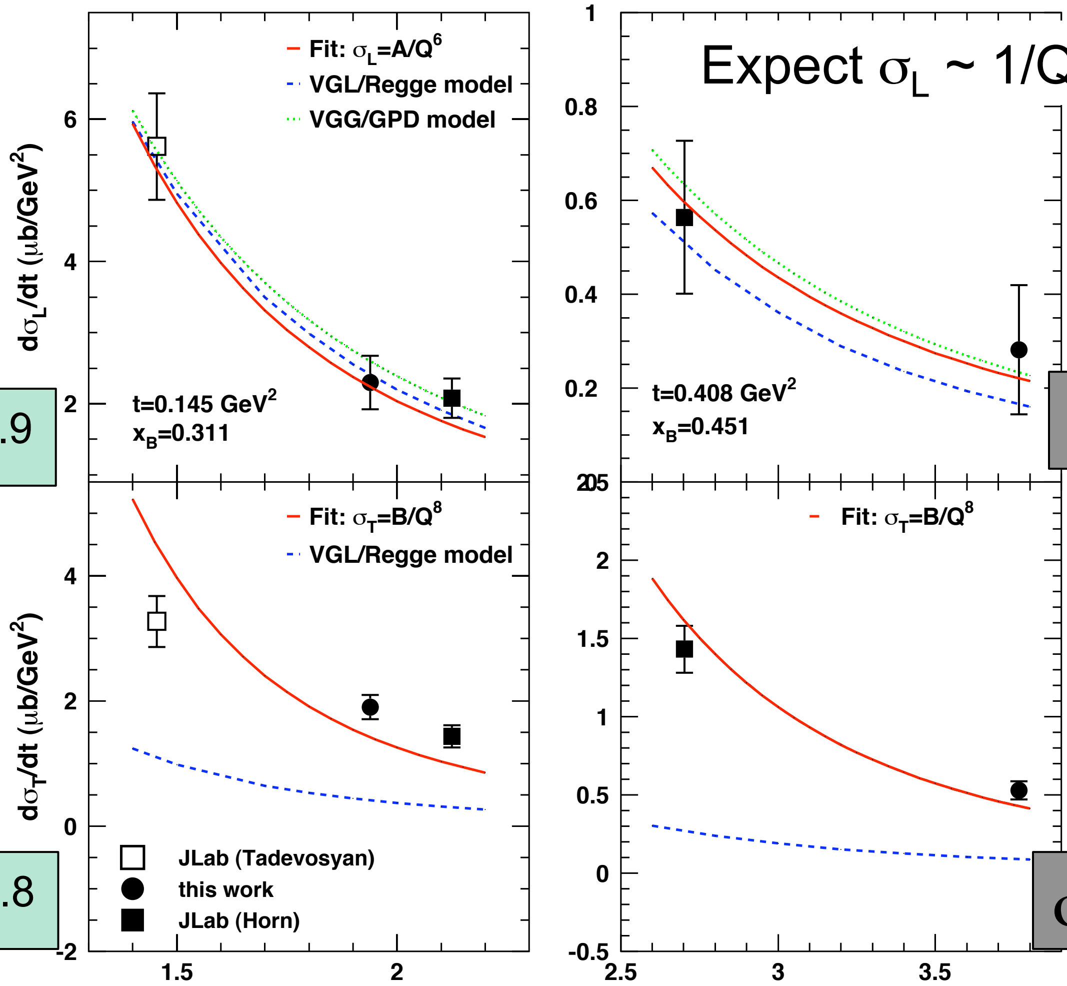
Q^2 dependence of π^+ σ_L,σ_T

Hall C: *Horn et al*

x=0.31 x=0.41

Large contribution from pole process

Expect $\sigma_L \sim 1/Q^6$ for factorization



$\sigma_L \sim 1/Q^{5.1+/-0.9}$

$\sigma_L \sim 1/Q^{4.2+/-2.9}$

$\sigma_T \sim 1/Q^{4.2+/-0.8}$

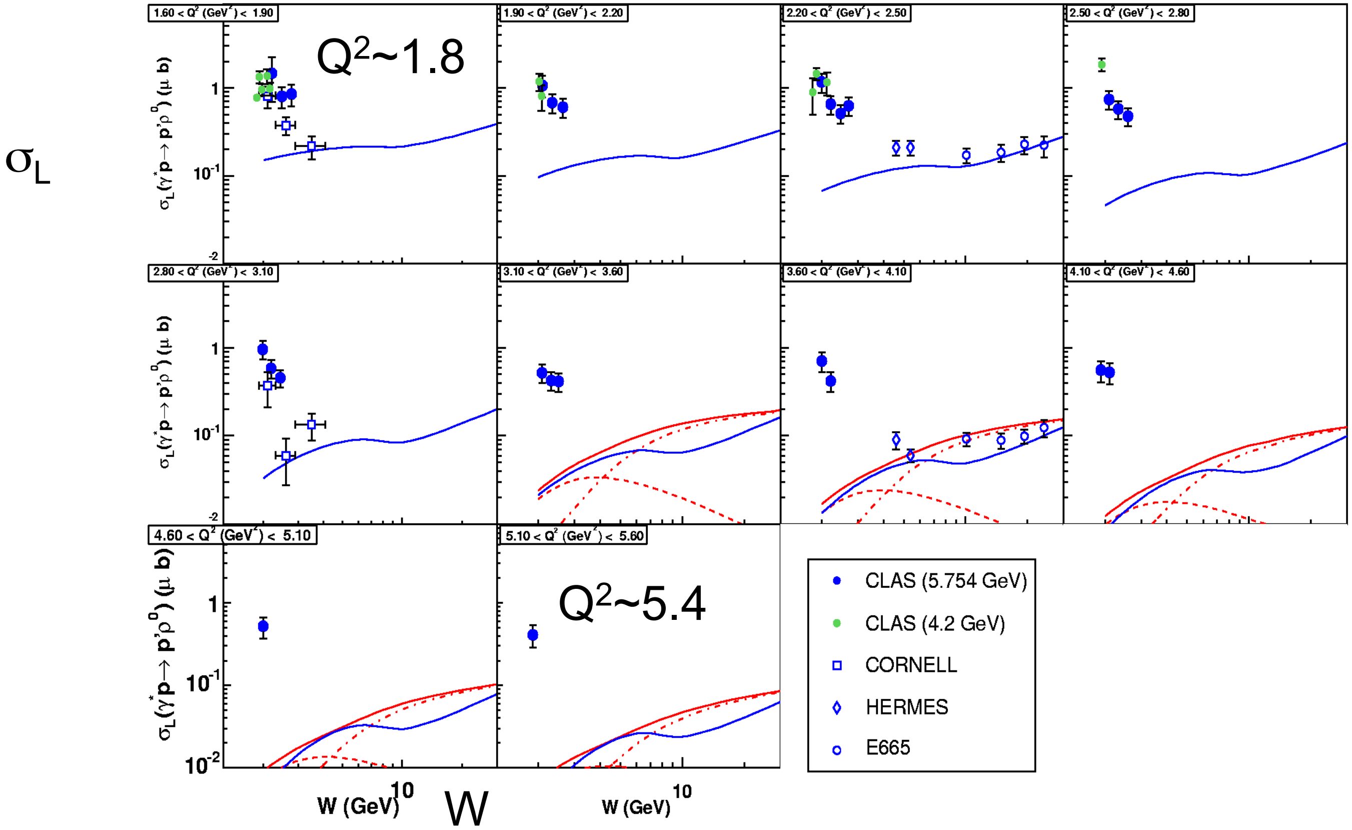
$\sigma_T \sim 1/Q^{6.0+/-0.9}$

For π^+, σ_L is not even close to dominating at Q^2=4 GeV^2

Vector Mesons with CLAS: ρ^0

Longitudinal cross section in $ep \rightarrow ep\rho^0$ → extracted using decay angular distributions

→ Similar data sets exist for ω, ϕ, and $\rho+$ (preliminary)



S. Morrow et al, EPJA 39, 5-31(2009)

Poor agreement with "standard" GPD-based models

Deep Exclusive Processes at JLab

- Initial indications are that quantities extracted in the DVCS reaction appear to scale like expected if one is really sensitive to GPDs
- Situation for mesons more complicated
  - σ_L does not dominate (in experiments where L-T separation is done)
  - Charged pions display expected Q^2 dependence in longitudinal cross section
  - Vector mesons situation is less clear → data consistent with Regge-based model and certain class of GPD-based models
- Major thrust of program at 12 GeV

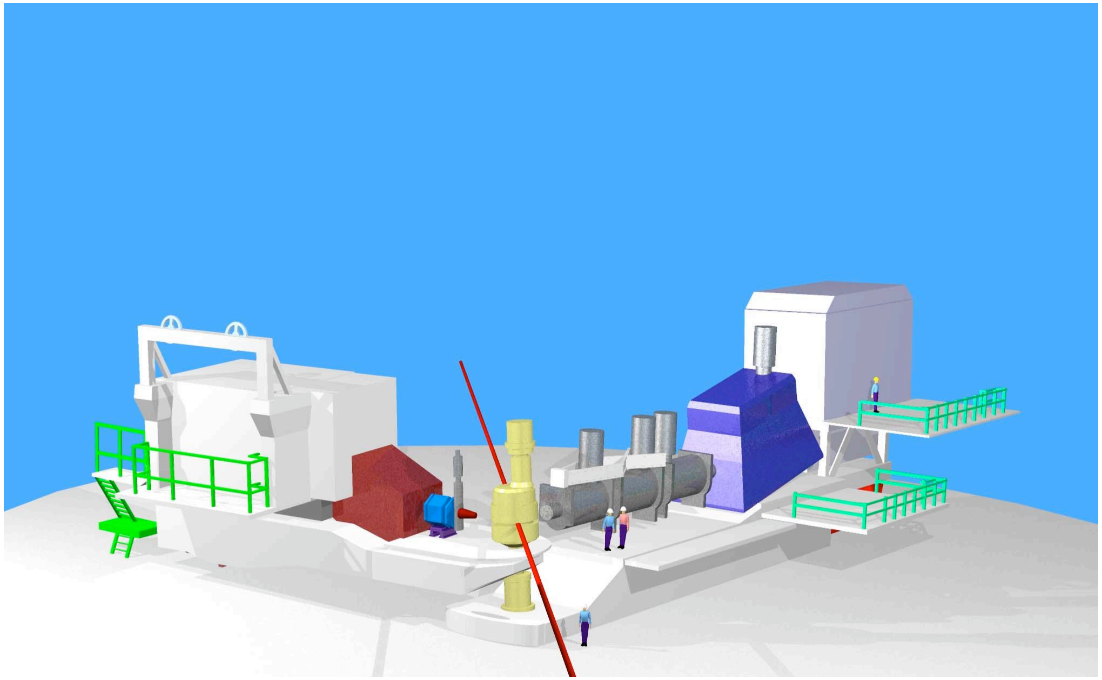
Summary

- JLab experimental program makes significant contributions in the realm of DIS and nucleon structure
- High luminosity allows measurement of low-rate processes (e.g., exclusive reactions, large P_T)
- Access to spin observables with high beam polarization, high performance polarized targets
- Access to large Q^2 at high x (low W) allows us to explore higher twist, moments
- JLab 12 GeV upgrade will allow unprecedented access to large x in the DIS regime

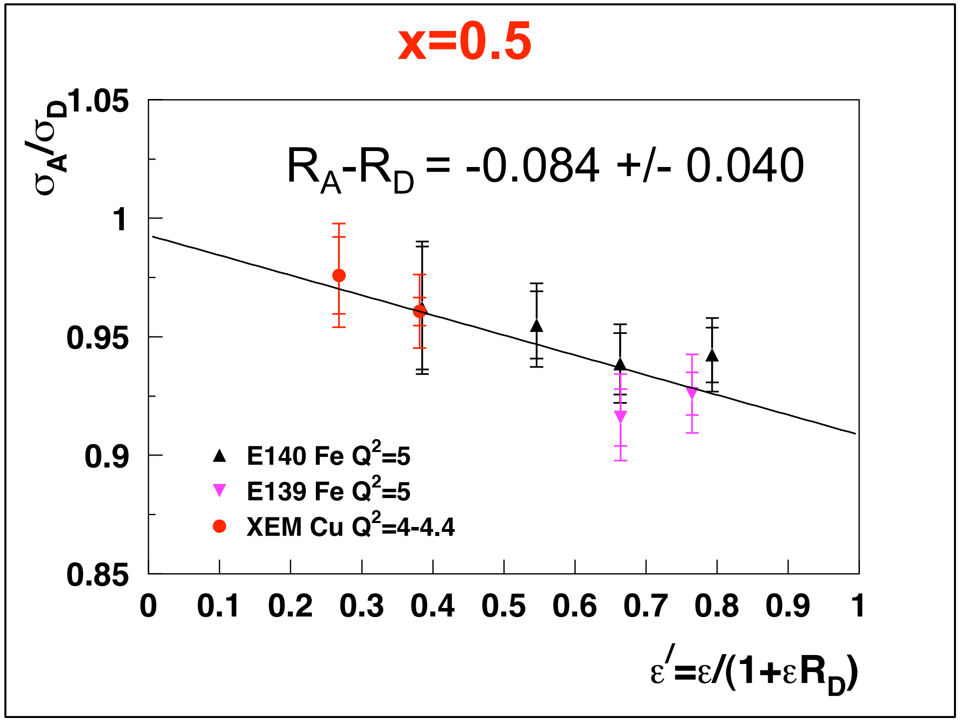
Related talks

- More details
  - CTEQx and BONUS: C. Keppel
  - DVCS with CLAS: F.-X. Girod
  - Deep Exclusive Reactions in Hall A: C. Munoz-Camacho
  - SANE (g_2^p): N. Kalantarians
  - EMC Effect: D. Gaskell
- Not discussed in this talk
  - Neutron Transversity: E. Cisbani
  - Hadronization in Nuclei: A. Daniel
  - DVCS on Nuclei: H. Egiyan

Extra/Other



Nuclear Dependence of R?



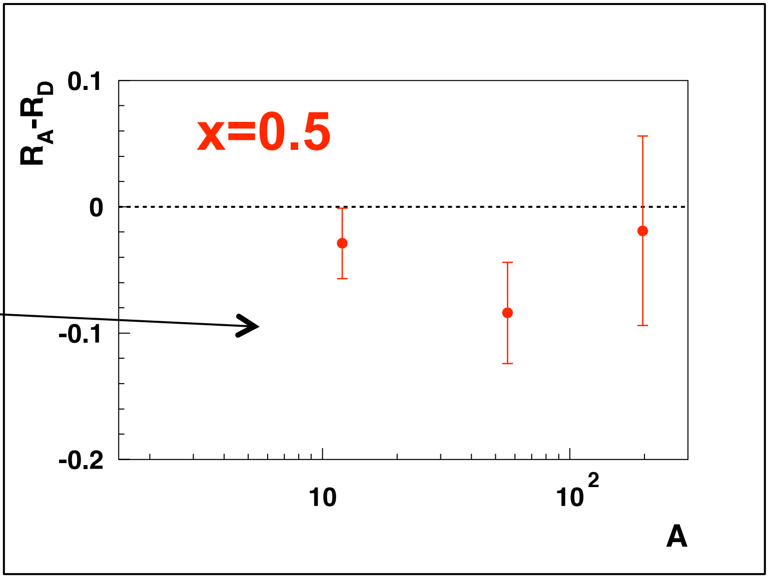
SLAC E140 results demonstrated no evidence for nuclear dependence of $R=\sigma_L/\sigma_T$ at large x(>0.2)

→ Applying *Coulomb corrections* to SLAC data and combining with Hall C data suggest non-trivial nuclear dependence at large x

SLAC E139/E140, Hall C combined for carbon, Fe/Cu, gold

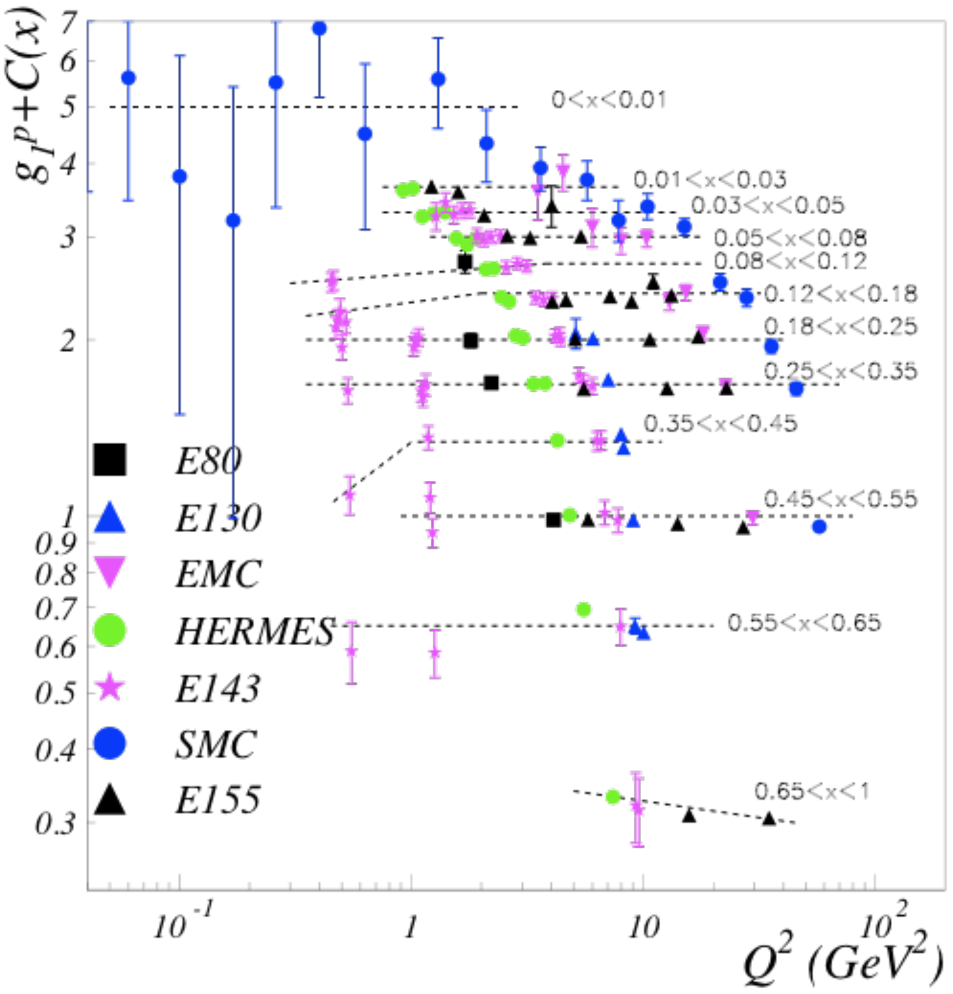
[P. Solvignon et al, arXiv:0906.2839 (AIP Conf. Proc.)]

→ *longer publication in progress*



The $g_1(x,Q^2)$ landscape

World data on the proton before JLab

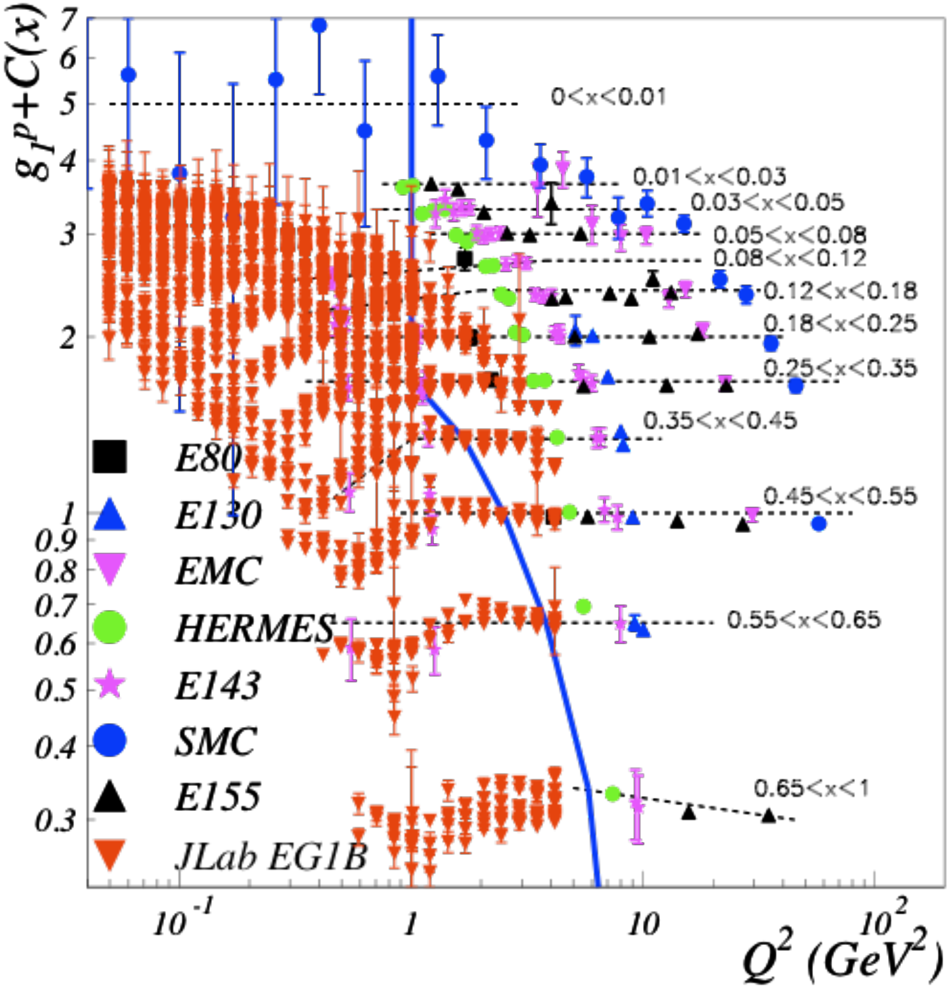


The $g_1(x,Q^2)$ landscape

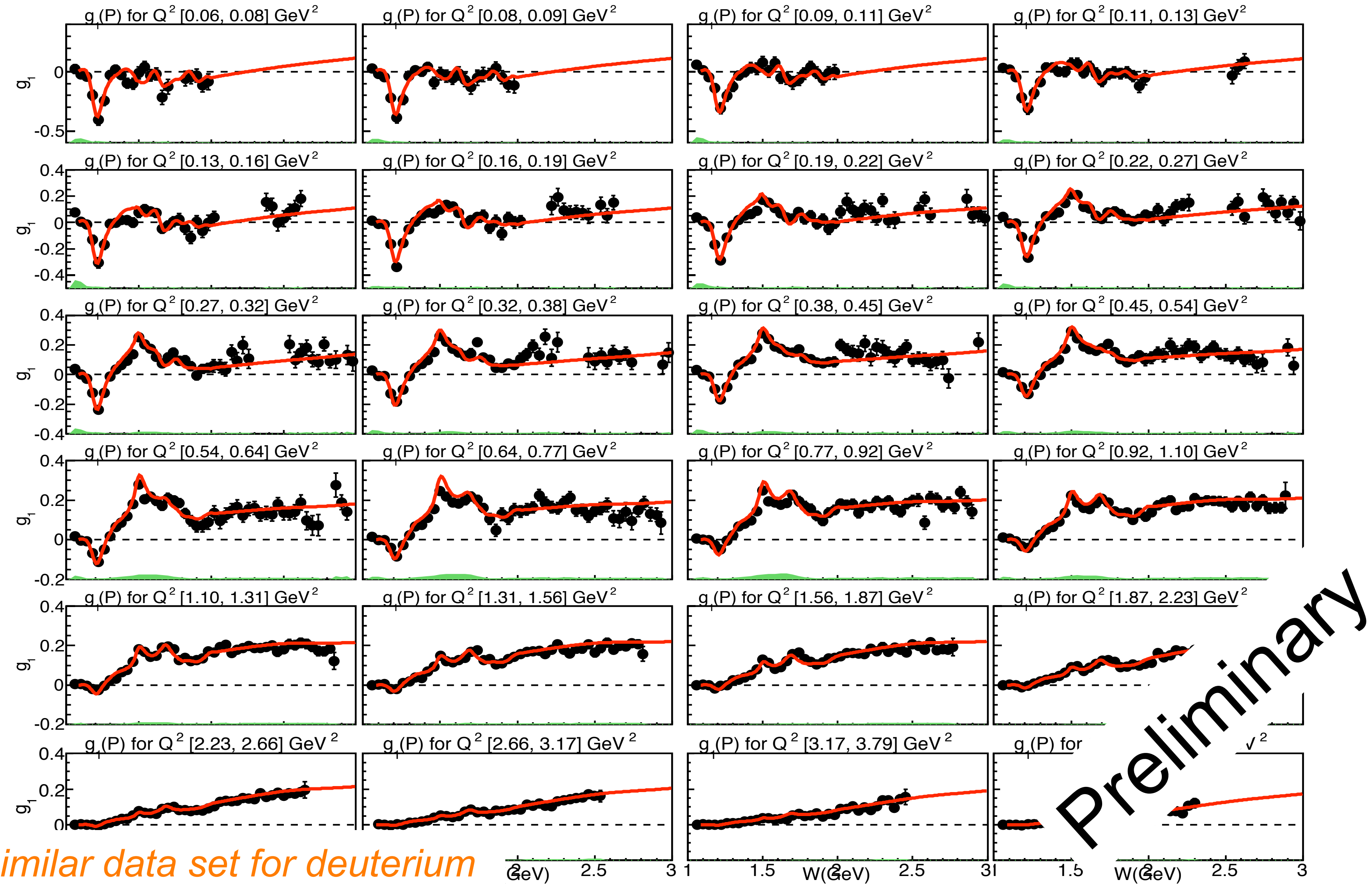
World data on the proton before JLab

World data on the proton including Jlab data from CLAS and Hall C covering the resonance region and overlapping with the DIS domain

Same coverage for ^{2}H, and data on ^{3}He from Hall A.

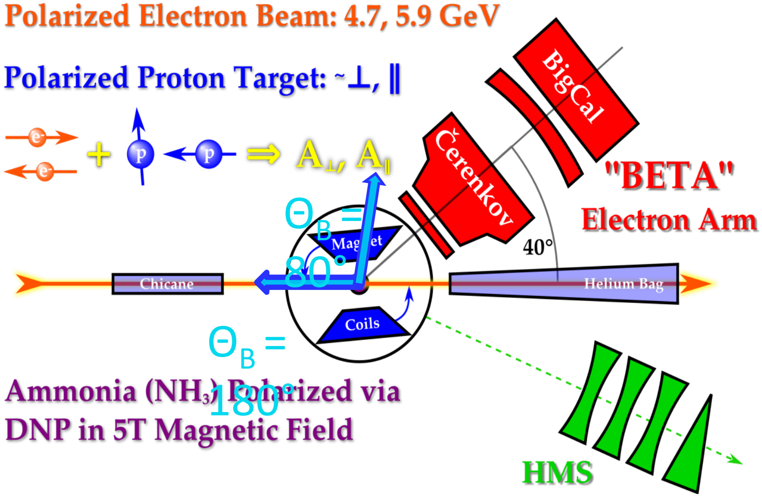


CLAS Structure function $g_{1p}(W,Q^2)$



Similar data set for deuterium

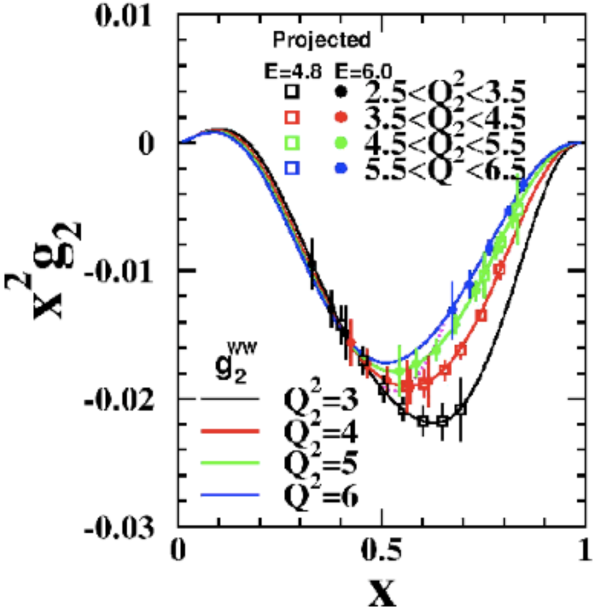
SANE Experiment in Hall C

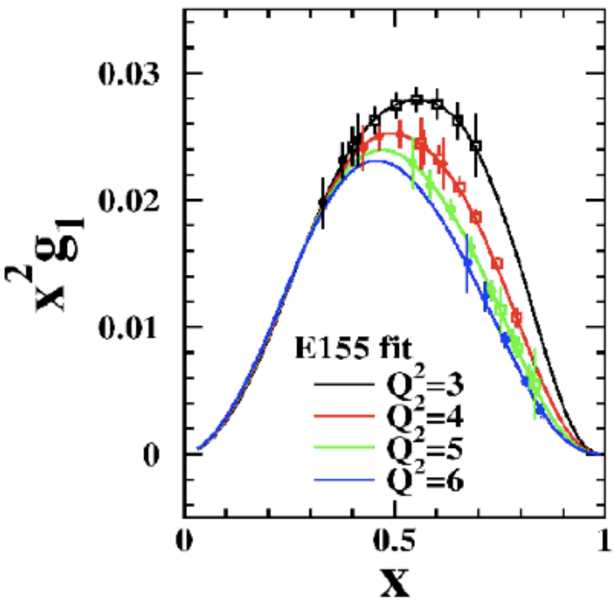


Data taken Feb-March 2008 for 4.7 & 5.9 GeV with polarized beam and target in parallel and perpendicular fields.

*See Narbe Kalantarians talk

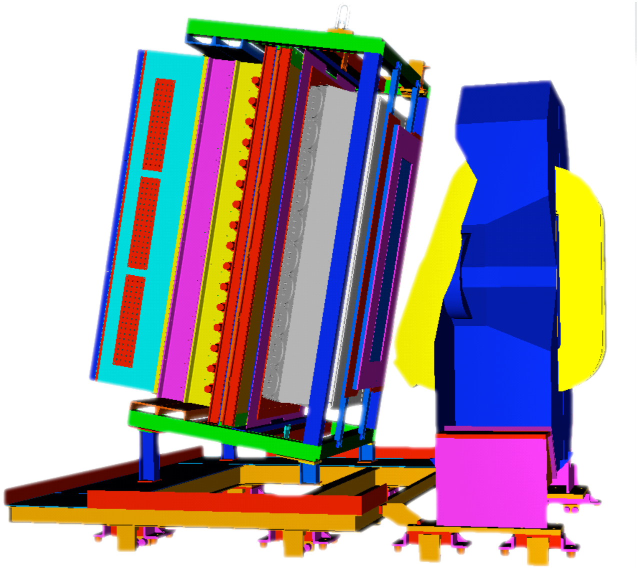
Projected uncertainties





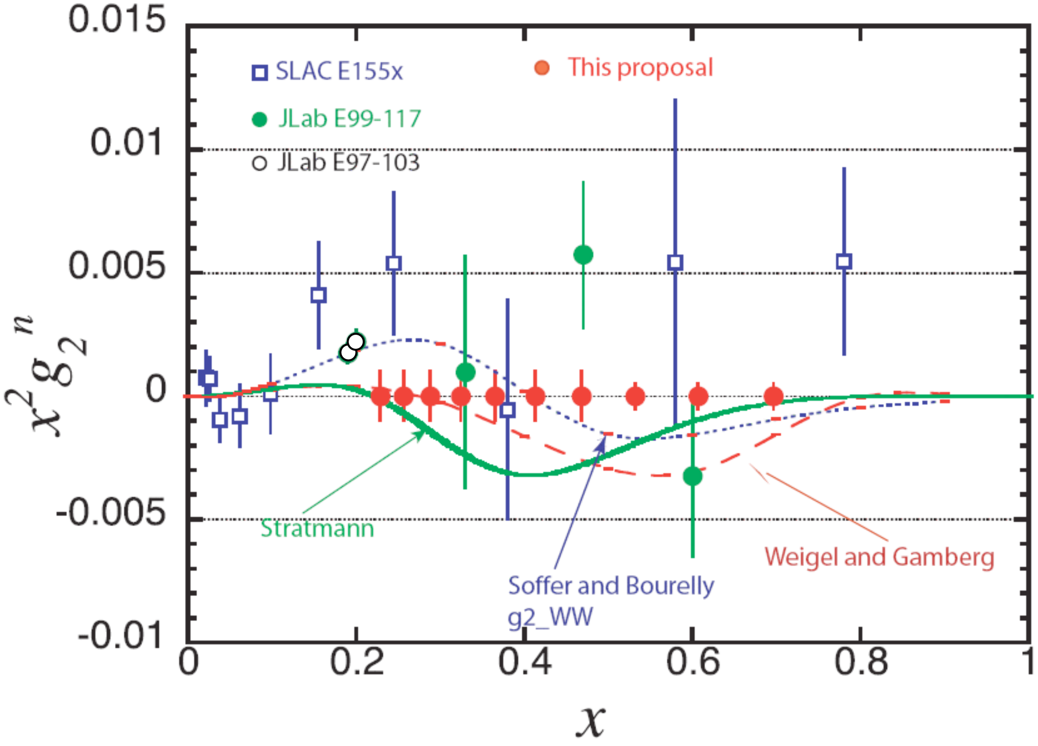
g_2 proton

d_2^n in Hall A



Used polarized ^{3}He target with "Big Bite" spectrometer

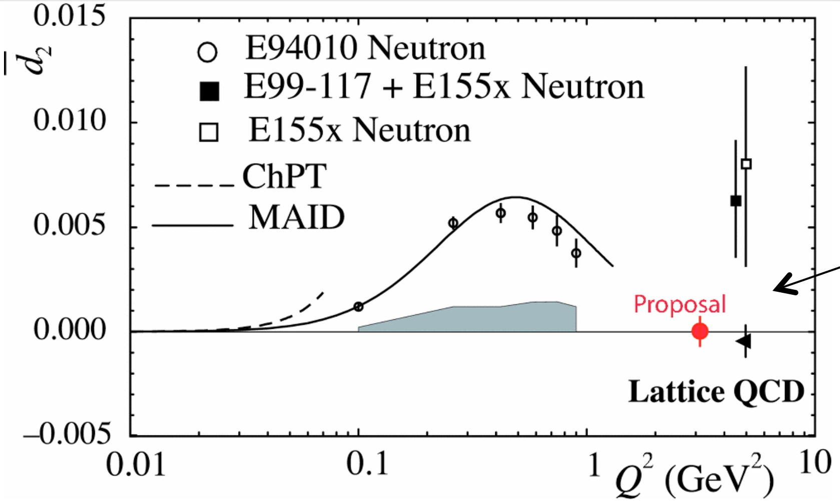
→ Ran in spring of 2008



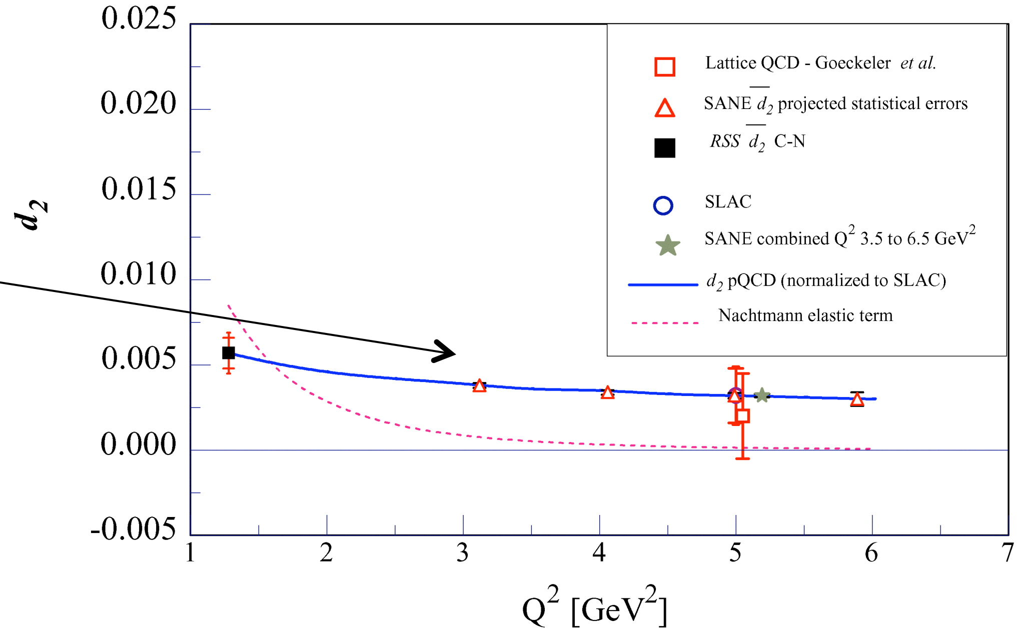
Two beam energies: 4.75 and 5.9 GeV (4 pass, 5 pass)

→ provides a handle on the Q^2 dependence of g_2

d_2 Projected Uncertainties

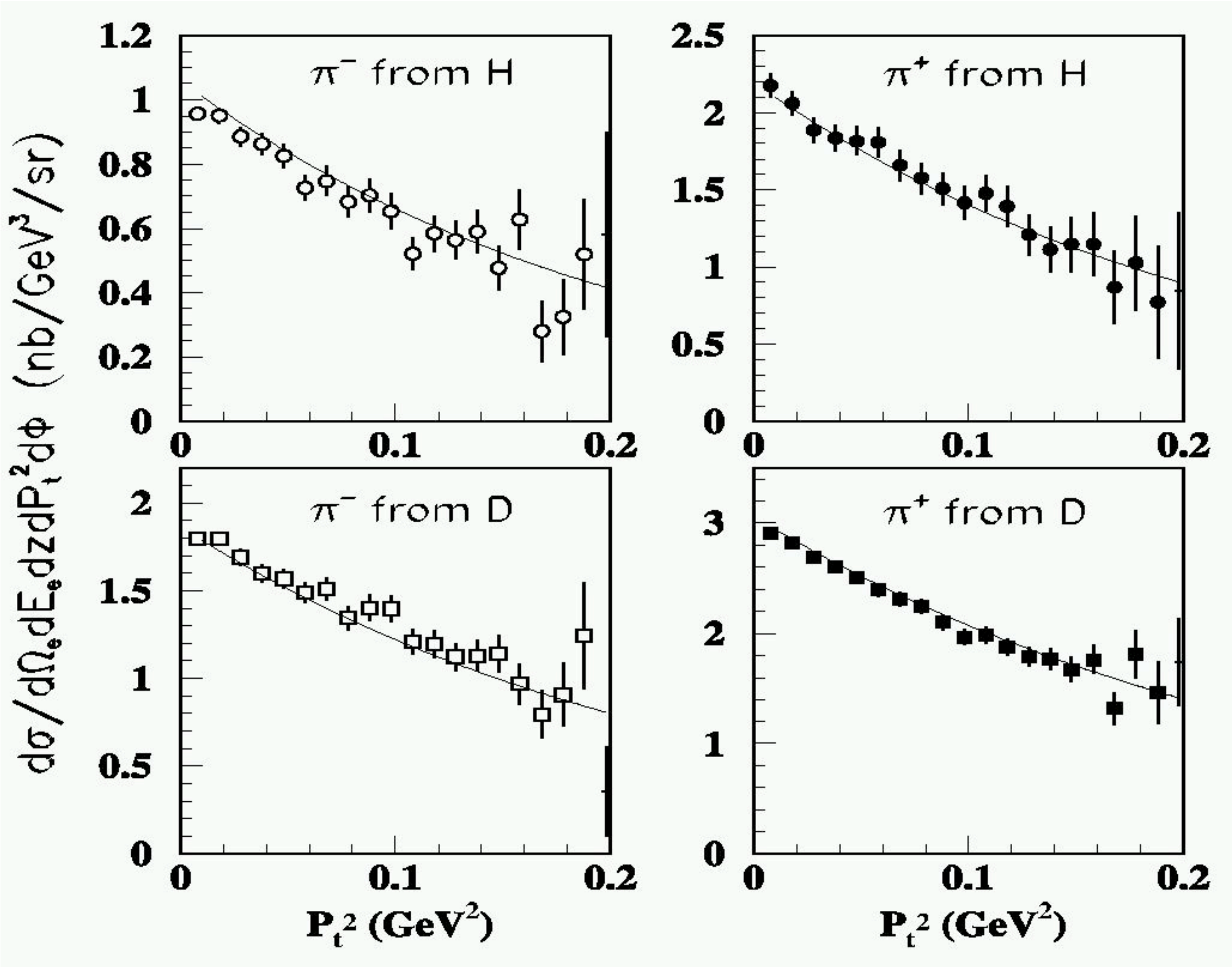


Neutron, Hall A



Proton, Hall C

Transverse momentum dependence of SIDIS



E00-108

Recent analysis of same data examined P_t dependence of π^-, π^+, from H and D

x=0.32 z=0.5

P_t dependence very similar for proton and deuterium targets

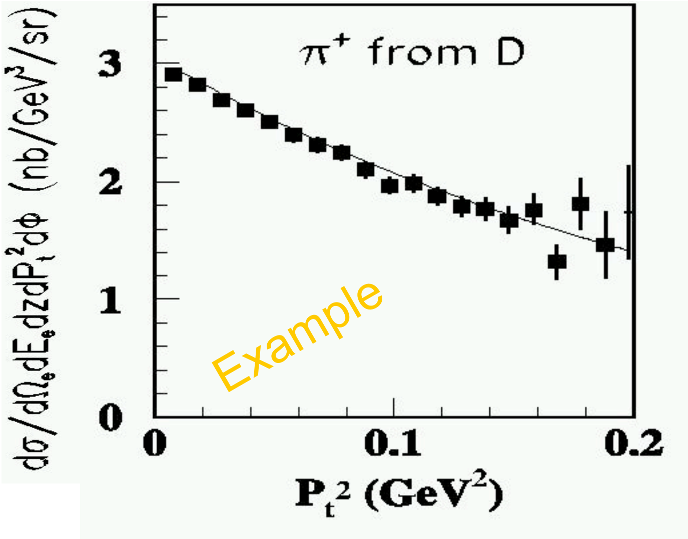
Unpolarized SIDIS – P_T Dependence

Constrain k_T dependence of up and down quarks *separately*

1) Probe π^+ and π^- final states

2) Use both **proton** and neutron (**d**) targets

3) Combination allows, in principle, separation of quark width from fragmentation widths *(if sea quark contributions small)*



1st example: Hall C, PL B665 (2008) 20

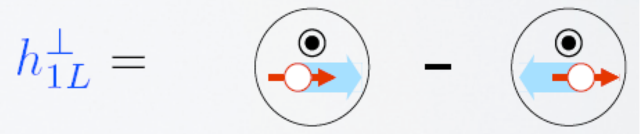
Simple model, host of assumptions (factorization valid, fragmentation functions do not depend on quark flavor, transverse momentum widths of quark and fragmentation functions are gaussian and can be added in quadrature, sea quarks are negligible, assume Cahn effect, etc.) →

Proton SSA measurements with CLAS

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$$\longrightarrow A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp}$$

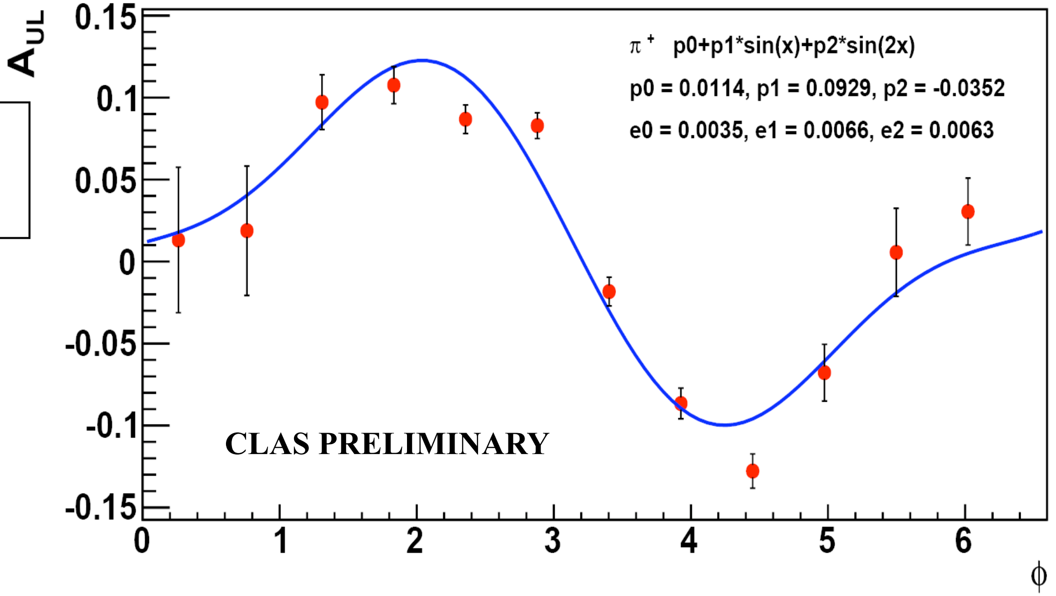
Transversely polarized quarks in the longitudinally polarized nucleon



~10% of
E05-113 data

CLAS-2009
(E05-113)

ep→e’πX



$W^2>4$ GeV^2

$Q^2>1.1$ GeV^2

$y<0.85$

$0.4<z<0.7$

$M_X>1.4$ GeV

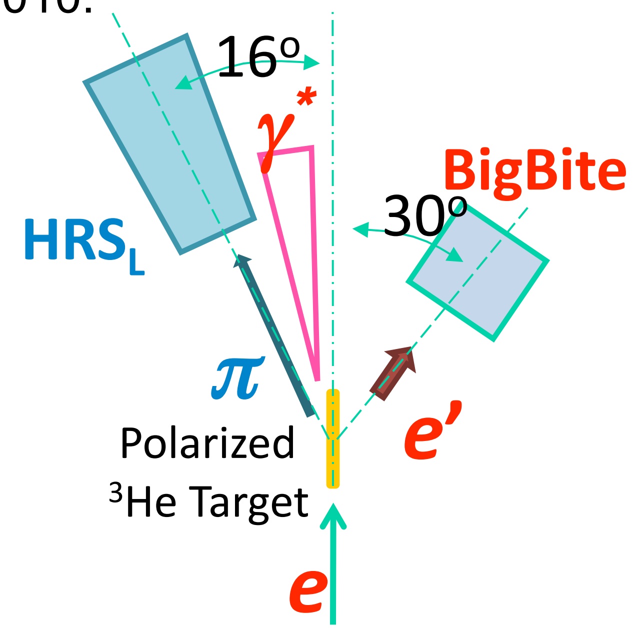
$P_T<1$ GeV

$0.12<x<0.48$

Much higher statistics from 2009 run

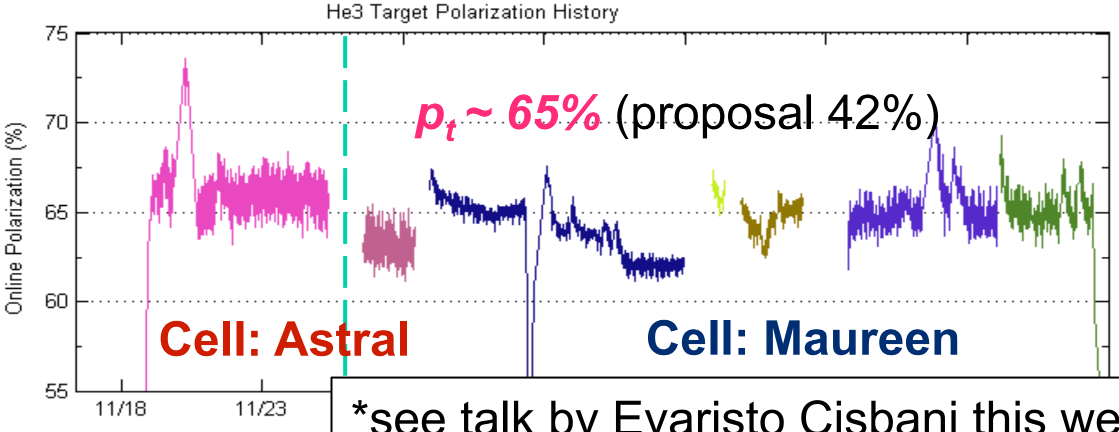
Neutron Single-Spin Asymmetry in Semi-Inclusive $n^{\uparrow}(e, e'\pi^{+/-})$

E06-010:



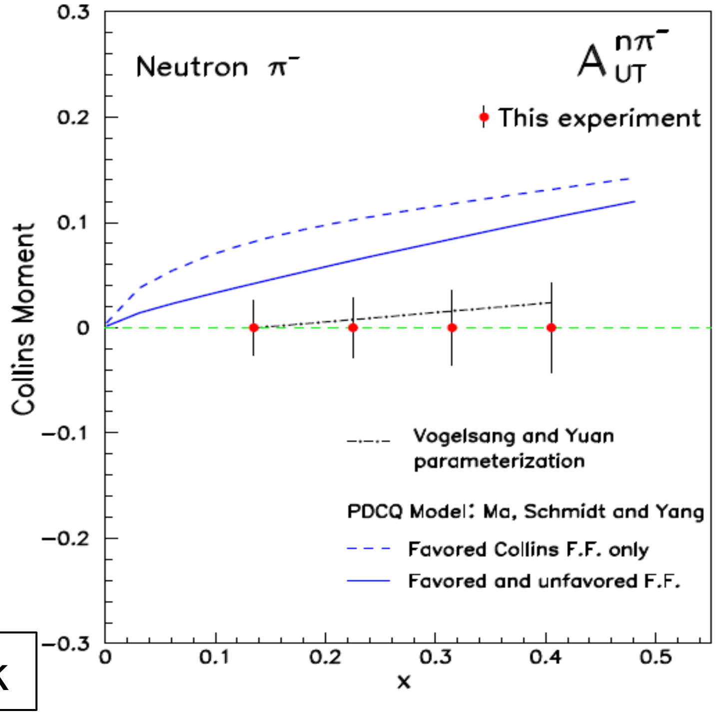
Reaction on a Transversely Polarized ^{3}He Target

- **First measurement of the neutron Collins and Sivers asymmetries in SIDIS.**
- **High density polarized ^{3}He target.**
- **Run in Hall A from 10/24/08-2/5/09.**
  110 shift workers, 6 Ph.D. students.



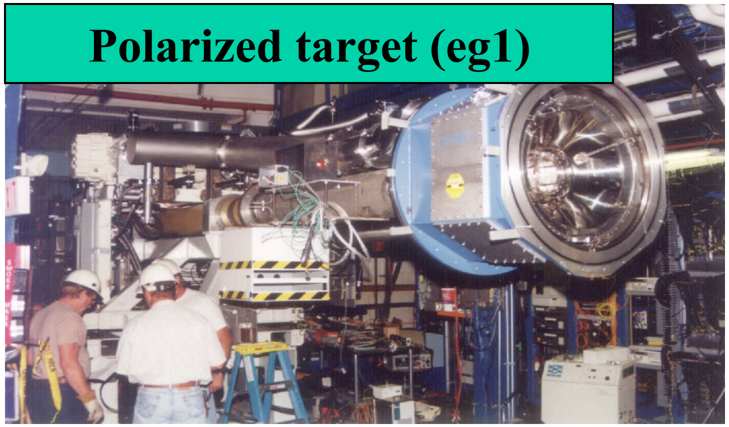
p_t ~ 65% (proposal 42%)

*see talk by Evaristo Cisbani this week



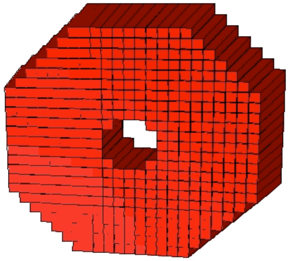
CLAS EG1-DVCS

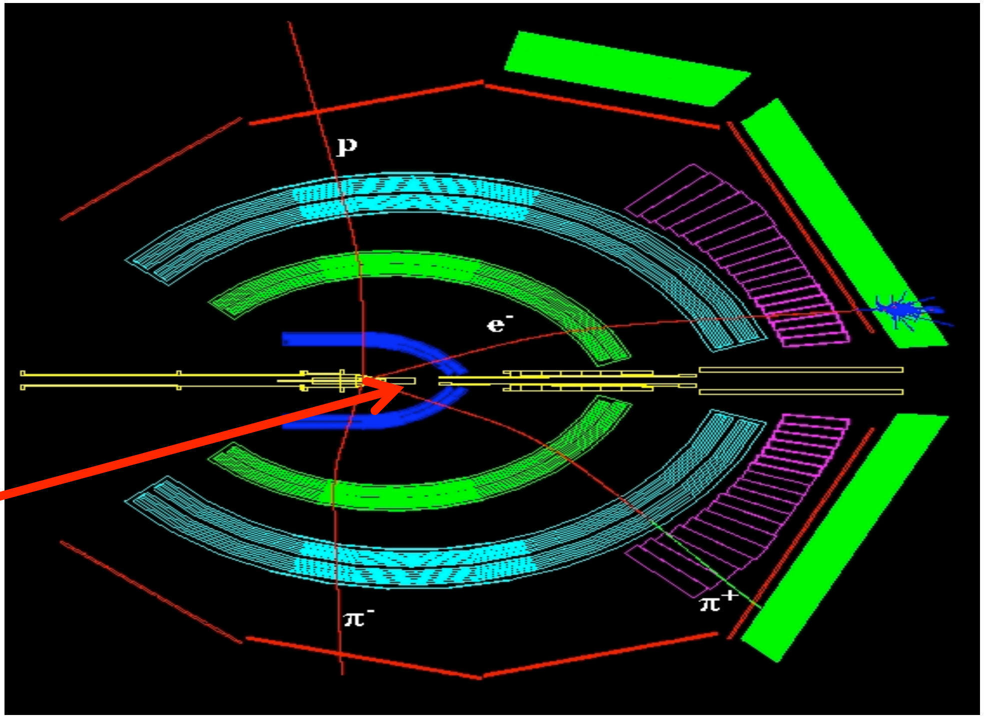
Polarized target (eg1)



Ran in spring and summer of 2009

- **solid NH_3 polarized target**
- **proton polarization >75%**
- **high luminosity ~ 2×10^{34} $s^{-1}cm^{-2}$**

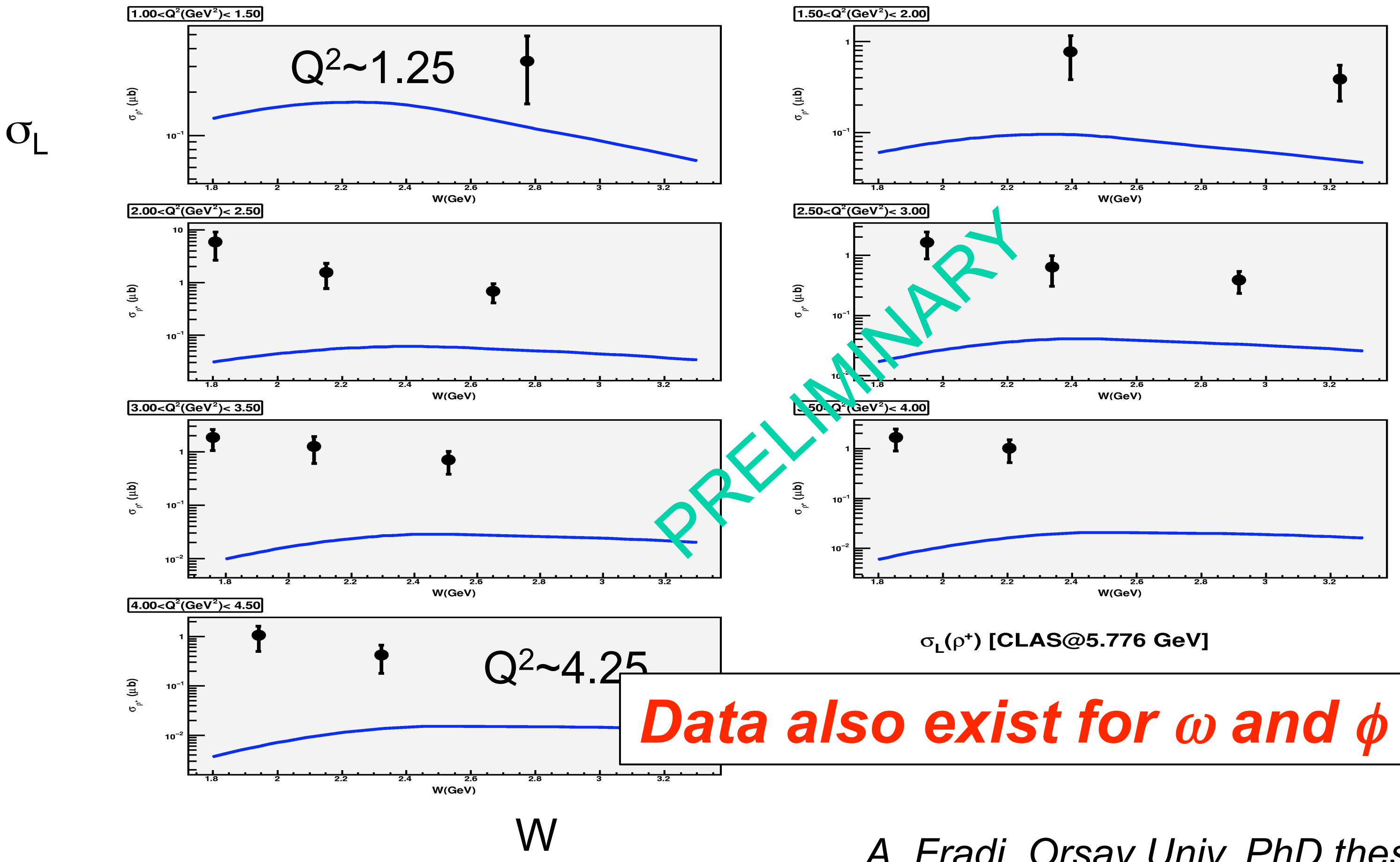




Inner Calorimeter (424 $PbWO_4$ crystals) for the detection of high energy photons at forward lab angles (e1-DVCS).

Vector Mesons with CLAS: ρ^+

New results on ρ^+ production at 5.75 GeV



Data also exist for ω and ϕ

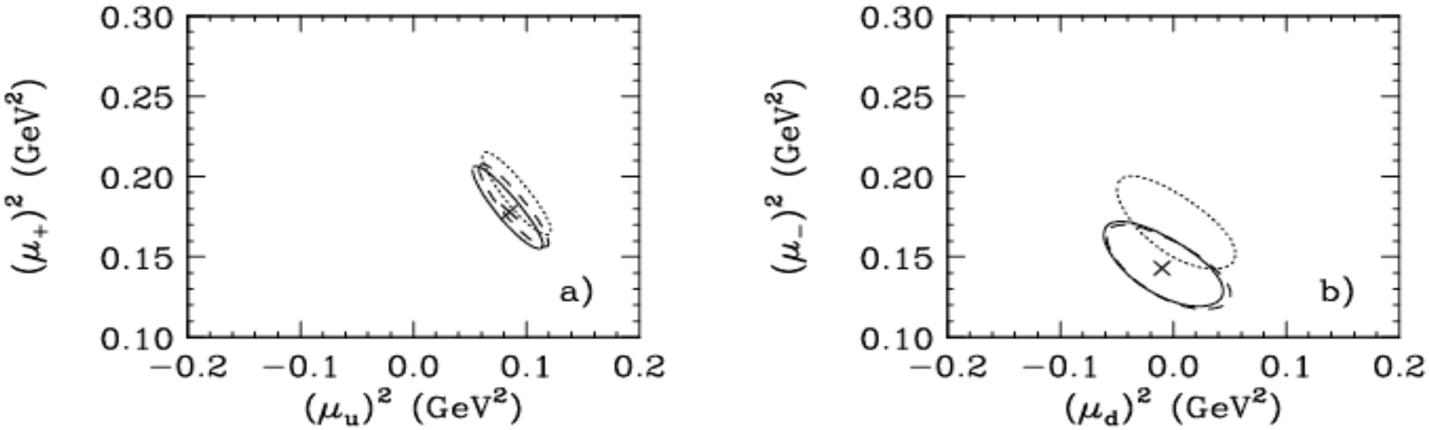
A. Fradi, Orsay Univ. PhD thesis (2009)

Like ρ^0 – GPD-based approach yields poor agreement with data

Transverse momentum dependence of SIDIS

Simple model, host of assumptions (factorization valid, fragmentation functions do not depend on quark flavor, transverse momentum widths of quark and fragmentation functions are gaussian and can be added in quadrature, sea quarks are negligible, assume Cahn effect, etc.) →

$(\mu_+)^2$ → width of $D^+(z,p_t)$, $(\mu_-)^2$ → width of $D^-(z,p_t)$,
$(\mu_u)^2$ → width of $u(x,k_t)$, $(\mu_d)^2$ → width of $d(x,k_t)$

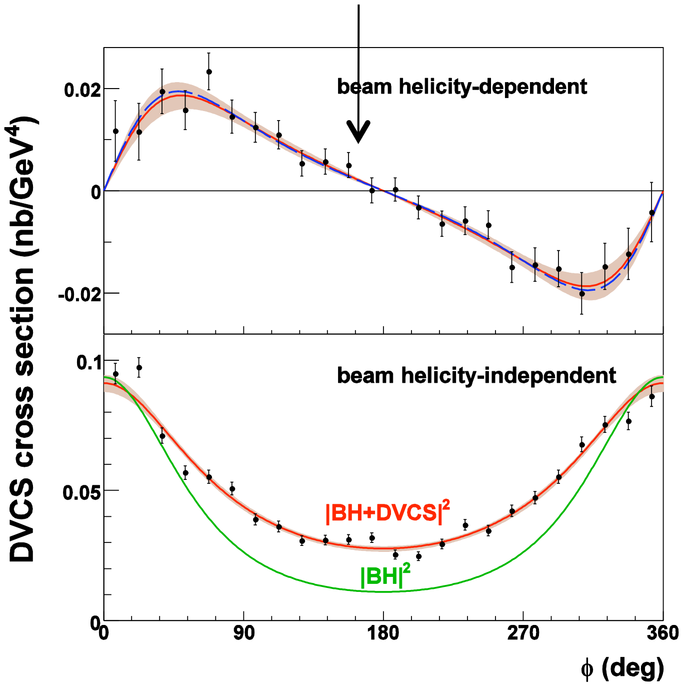


$(\mu_u)^2 = 0.09$ +/- 0.03 GeV^2, $(\mu_d)^2$ consistent with 0
Consistent w/di-quark model where d quarks only in axial di-quark, u quarks predominantly in scalar di-quark

DVCS beam spin asymmetries

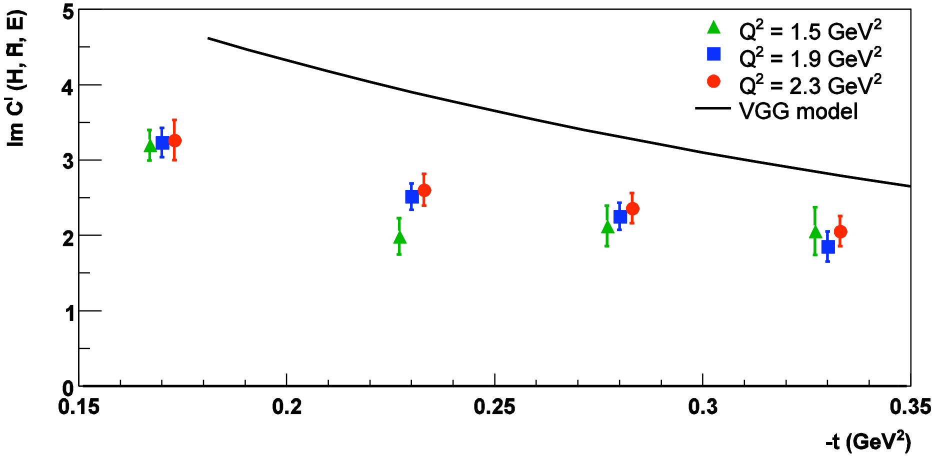
Initial round of dedicated DVCS experiments focused on beam-spin asymmetry

Hall A E00-110: BSA + absolute cross sections



Well described by leading twist contribution

$$F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}$$



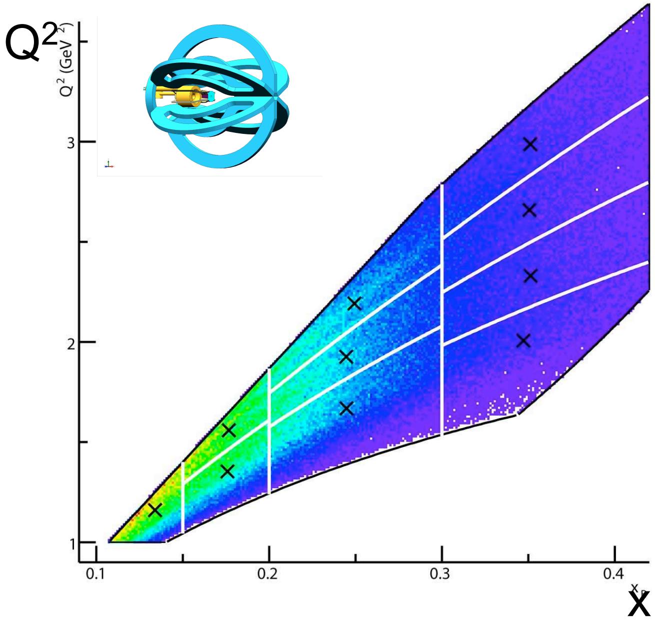
***Q^2* – dependence tests factorization**

[C. Muñoz Camacho *et al.*, PRL**97**, 262002 (2006)]

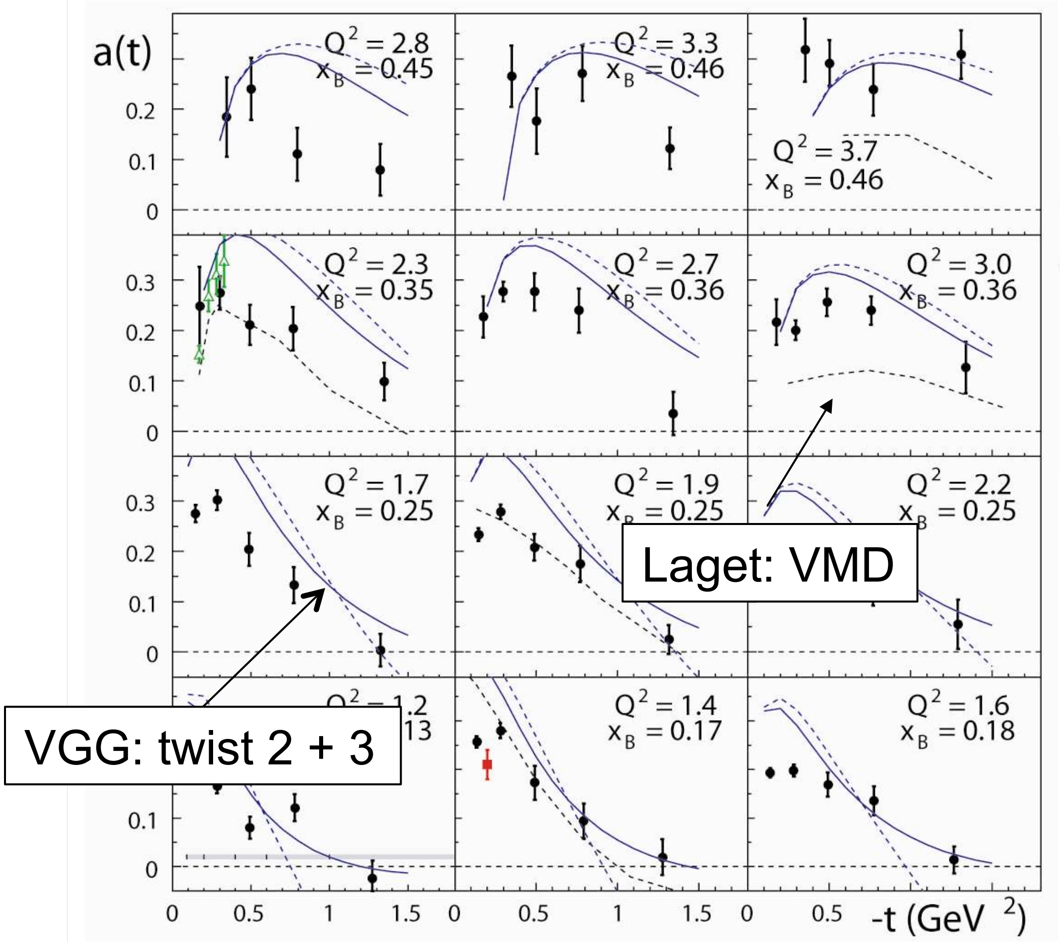
Also: “neutron” data via Deuterium

DVCS beam spin asymmetries

Initial round of dedicated DVCS experiments focused on beam-spin asymmetry



CLAS: Large phase space
→ emphasis on asymmetries
over wide range of x, Q^2 ,t



Laget: VMD

VGG: twist 2 + 3

[F.X. Girod *et al.*, PRL**100** (2008)]