Jlab 12 GeV: Large x,Spin/Flavour and GPDs

Zein-Eddine Meziani

Temple University

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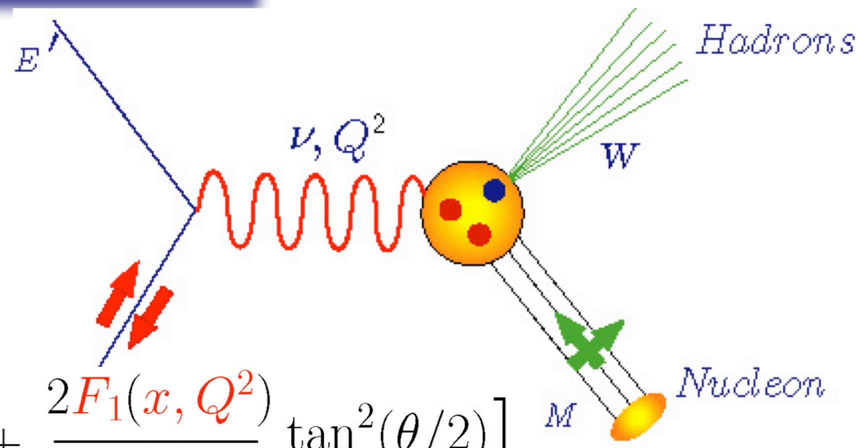
Inclusive DIS

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$
  - ➡ Proton & neutron measurements provide d/u distributions ratio



U $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Polarized structure functions

  $g_1(x,Q^2)$ and $g_2(x,Q^2)$
  - ➡ Proton & neutron measurements combined with d/u provide the spin-flavor distributions $\Delta u/u$ & $\Delta d/d$

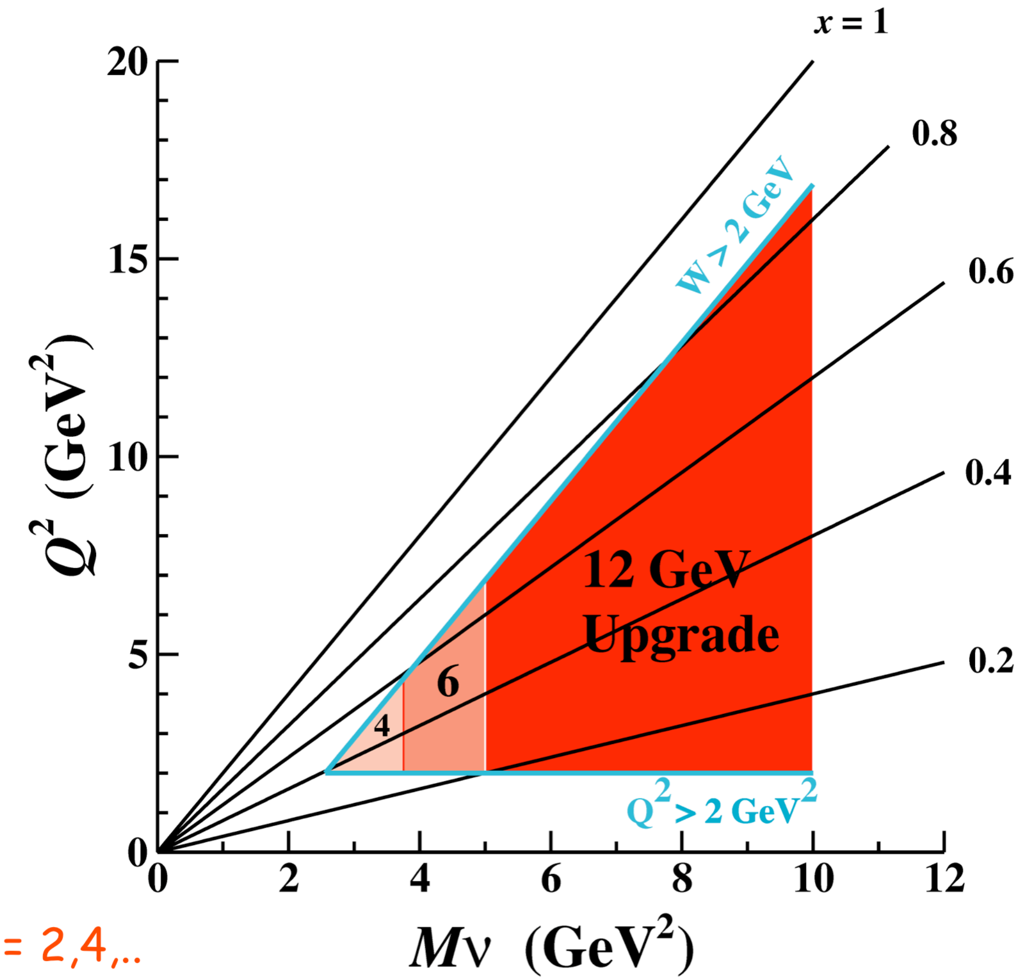
Q^2 :Four-momentum transfer
x : Bjorken variable
ν : Energy transfer
M : Nucleon mass
W : Final state hadrons mass

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

T $$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right]$$

12 GeV upgrade kinematical reach

- Access to very large x (x > 0.4)
  - Clean region
    - No strange sea effects
    - No explicit hard gluons to be included
- Quark models can be a powerful tool to investigate the structure of the nucleon
- Comparison with lattice QCD is possible for higher moments of structure functions.

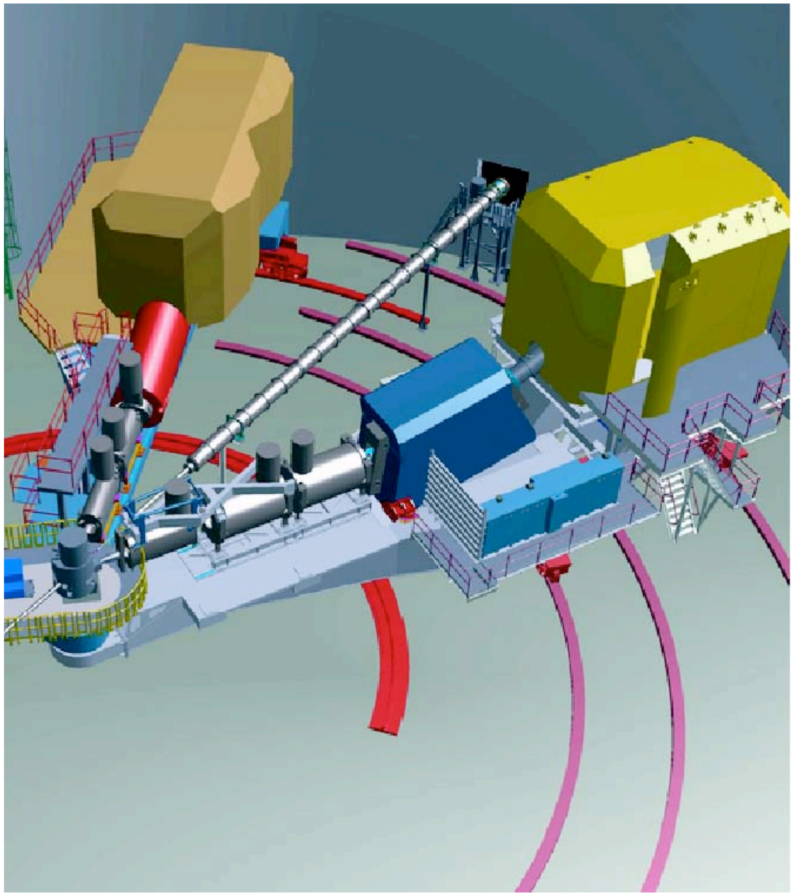


$$M_n(Q^2) = \int_0^1 dx\, x^{n-2}\, F_2(x, Q^2) \qquad n = 2,4,\ldots$$

$$M_n(Q^2) = \int_0^1 dx\, x^{n-1}\, g_1(x, Q^2), \qquad n = 1, 3, 5\ldots$$

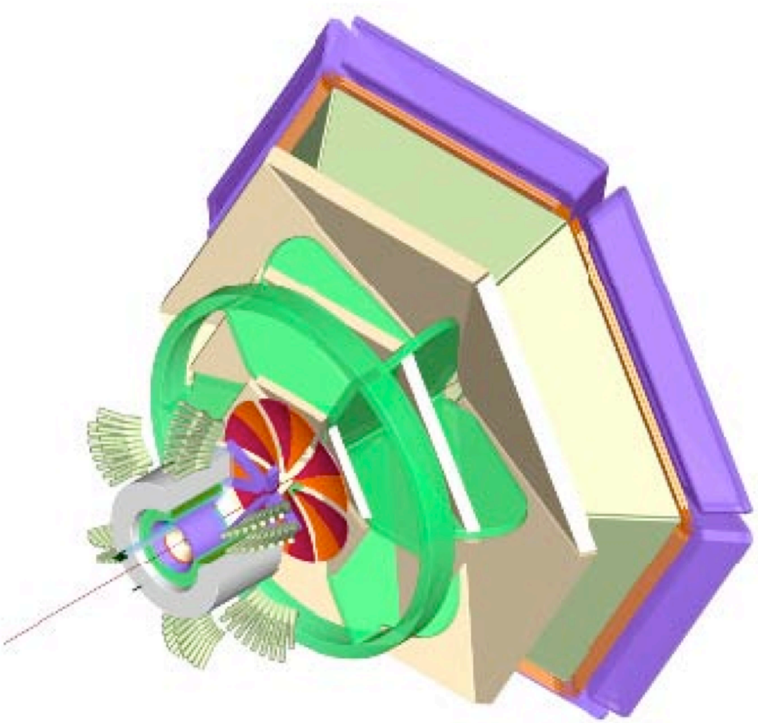
The tools

- A high duty cycle, high current, polarized 12 GeV electron beam
- A high luminosity Hall.



The tools

- A high duty cycle, high current, polarized 12 GeV electron beam
- A high luminosity Hall.
- A large acceptance Hall.
- Polarized targets



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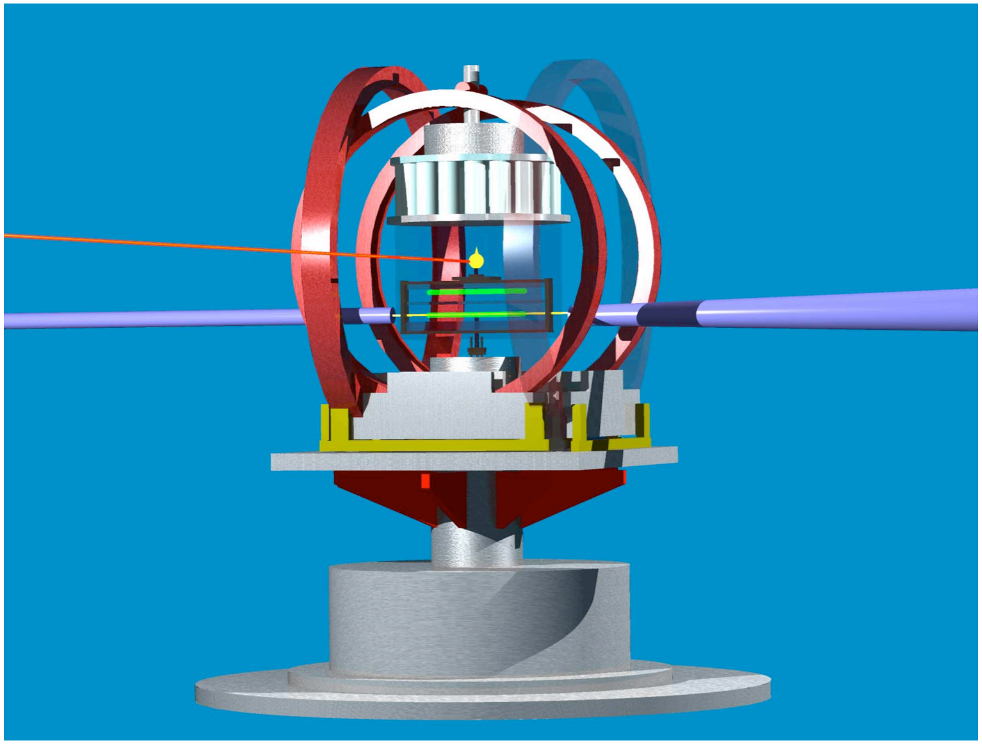
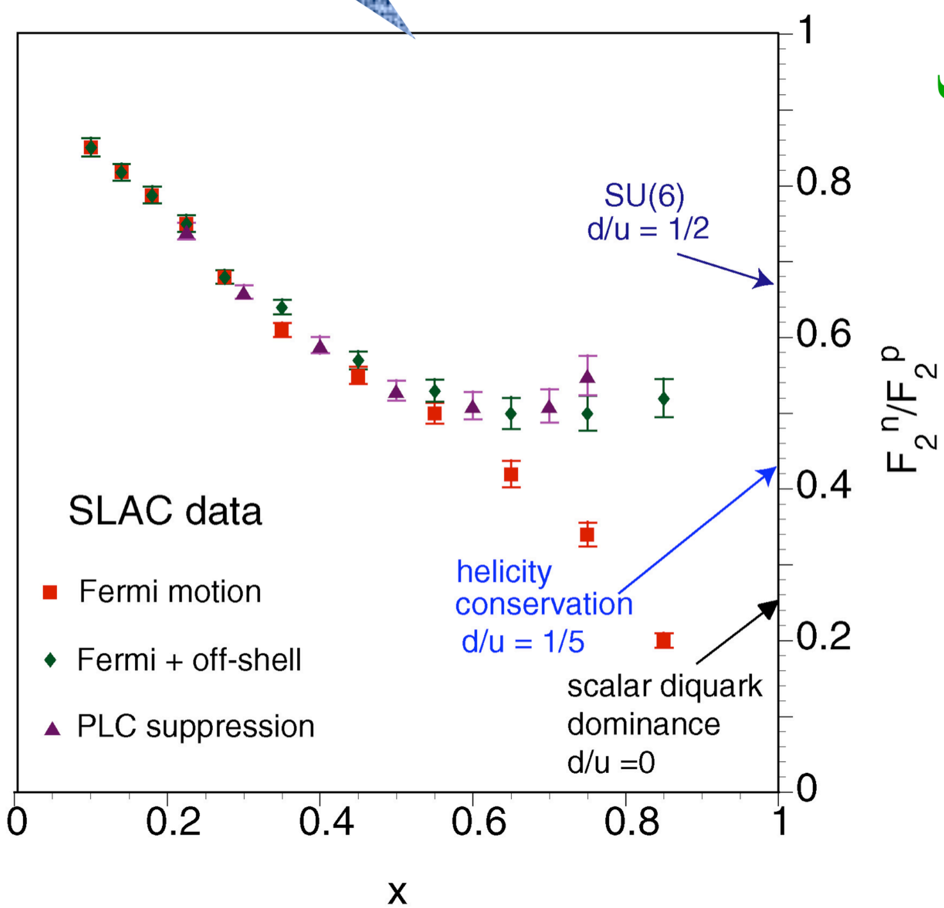
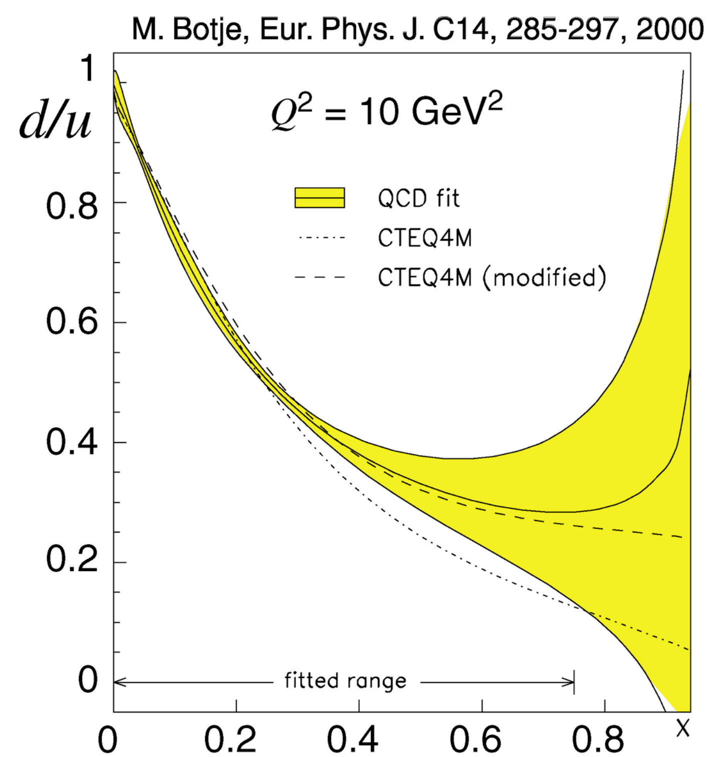


Unpolarized Neutron to Proton ratio

- In the large x region (x>0.5) the ratio F_2^n/F_2^p is not well determined due to the lack of free neutron targets



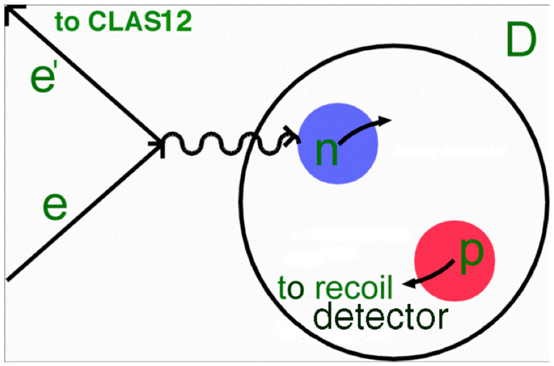
- Impact:
  - determine valence *d* quark momentum distribution
  - extract helicity dependent quark distributions through inclusive DIS
  - high x and Q^2 background in high energy particle searches.
  - construct moments of structure functions



Unpolarized Neutron to Proton ratio

Spectator tagging

- Nearly free neutron target by tagging low-momentum proton from deuteron at backward angles



- Small p (70-100 MeV/c)
  - Minimize on-shell extrapolation (neutron only 7 MeV off-shell)
- Backward angles (θ_{pq}> 110°)
  - Minimize final state interactions

DIS from A=3 nuclei

- Mirror symmetry of A=3 nuclei
  - Extract F_2^n/F_2^p from ratio of $^3He/^3H$ structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathcal{R}}$$

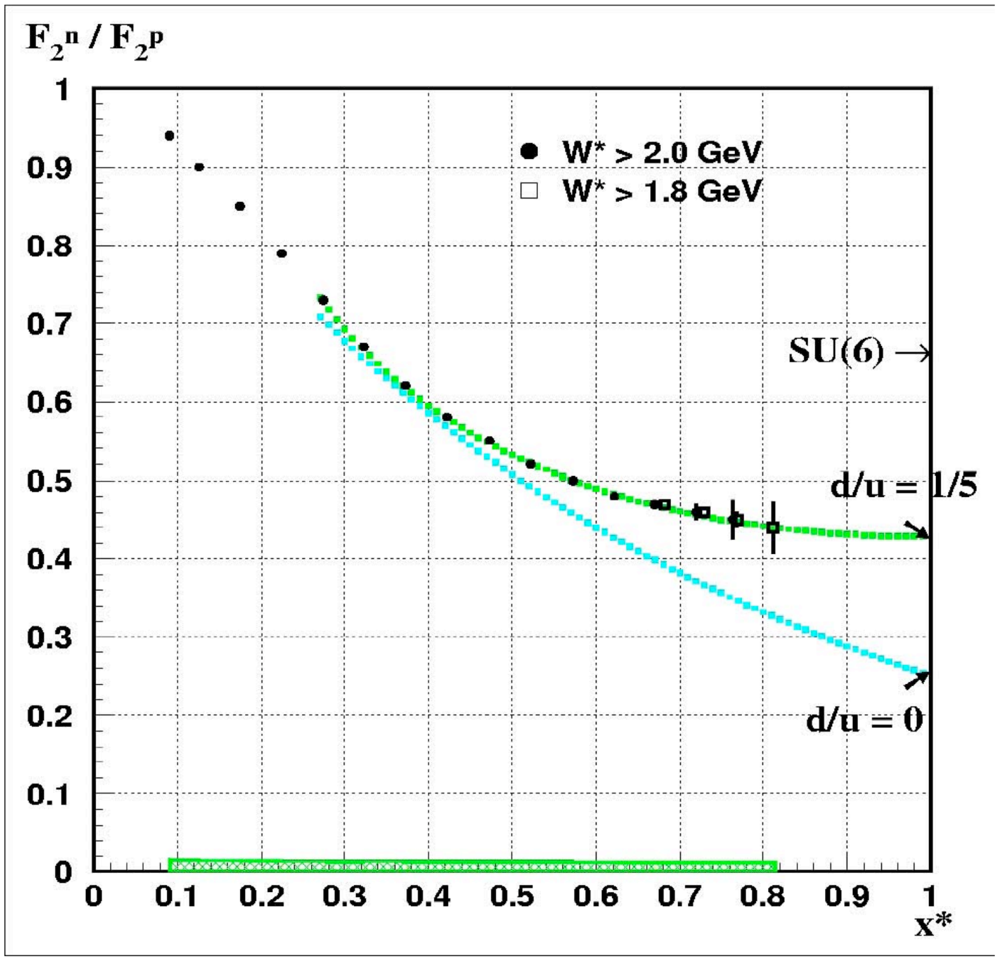
  - Super ratio
    $\mathcal{R}$ = ratio of "EMC ratios" for ^{3}He and ^{3}H

calculated to within 1%

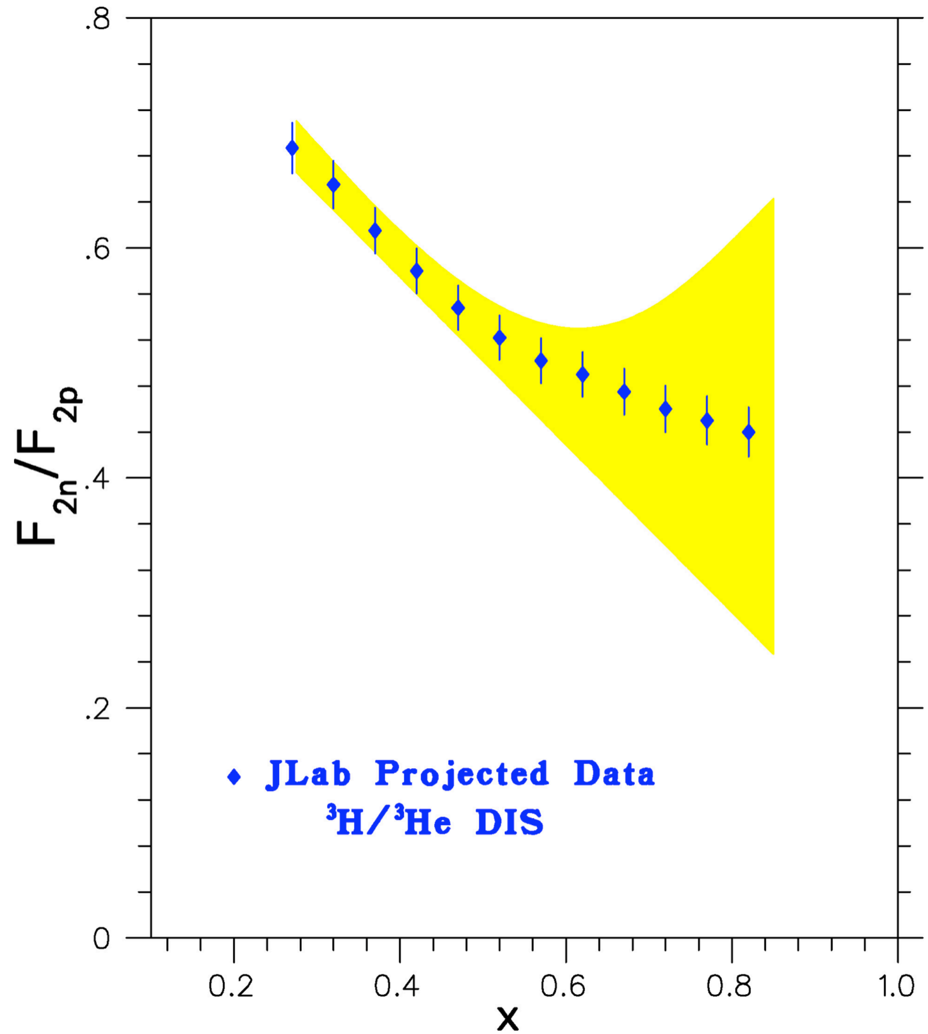
- Most systematic and theoretical uncertainties cancel

Unpolarized Neutron to Proton Ratio

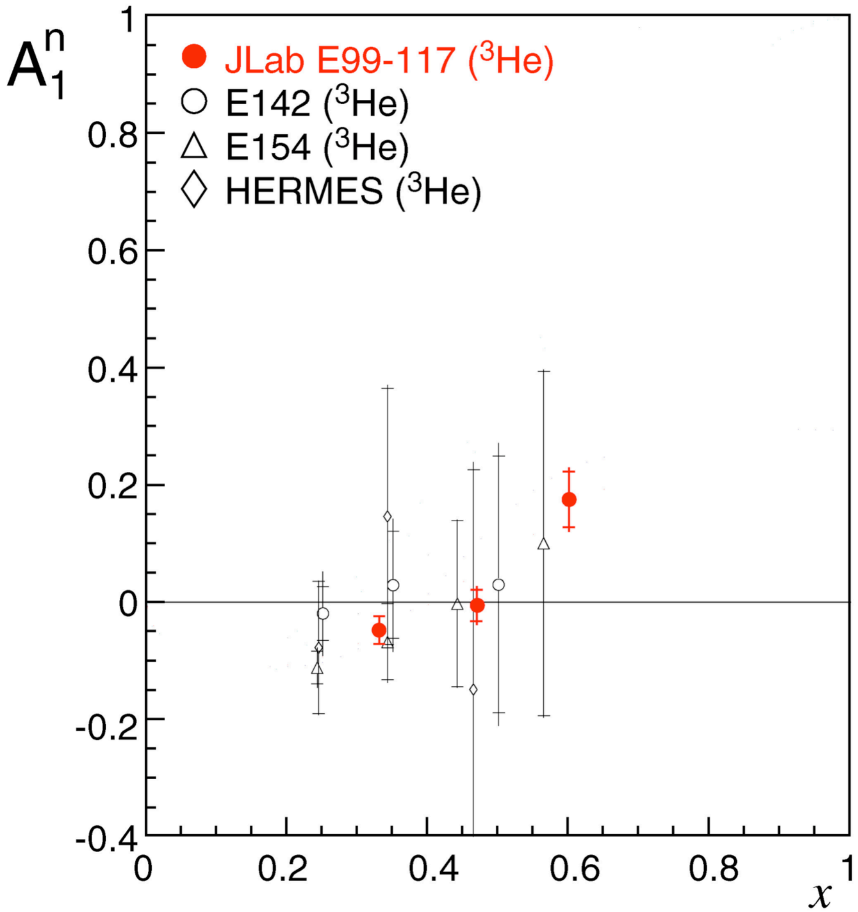
HallB 11 GeV with CLAS12

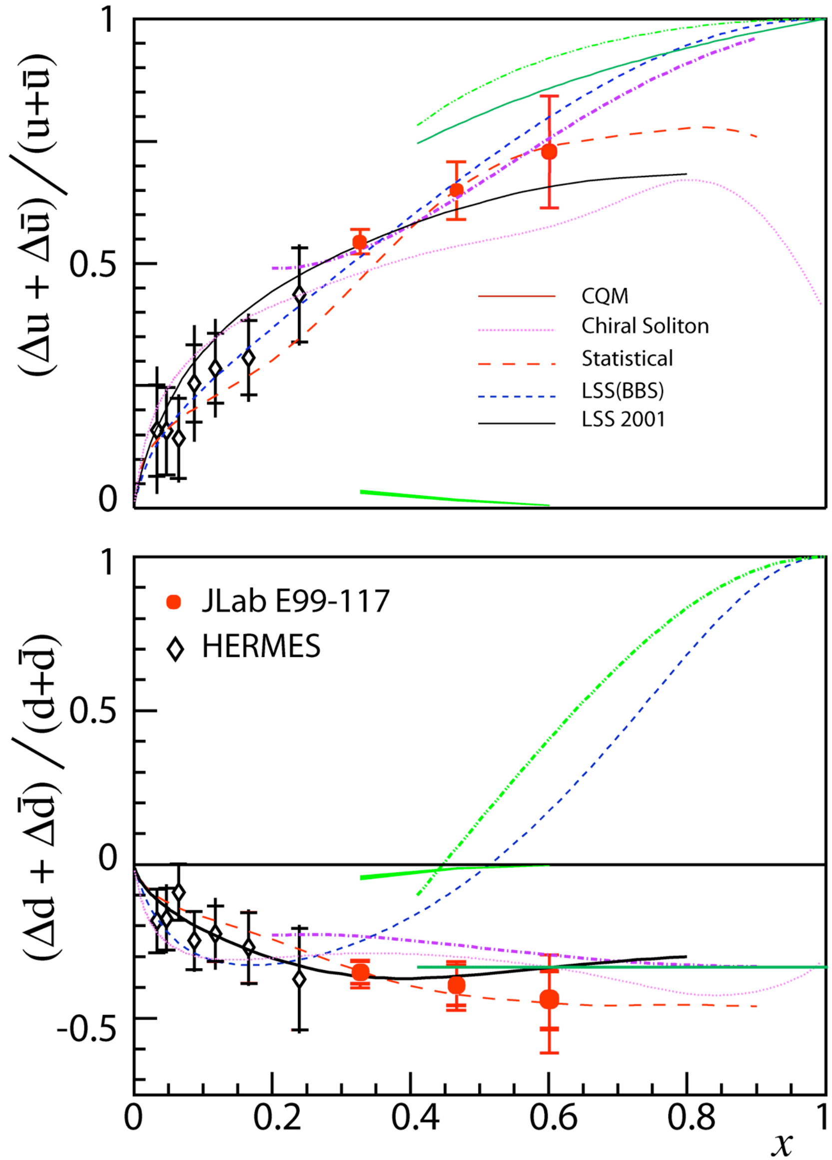


Hall C 11 GeV with HMS



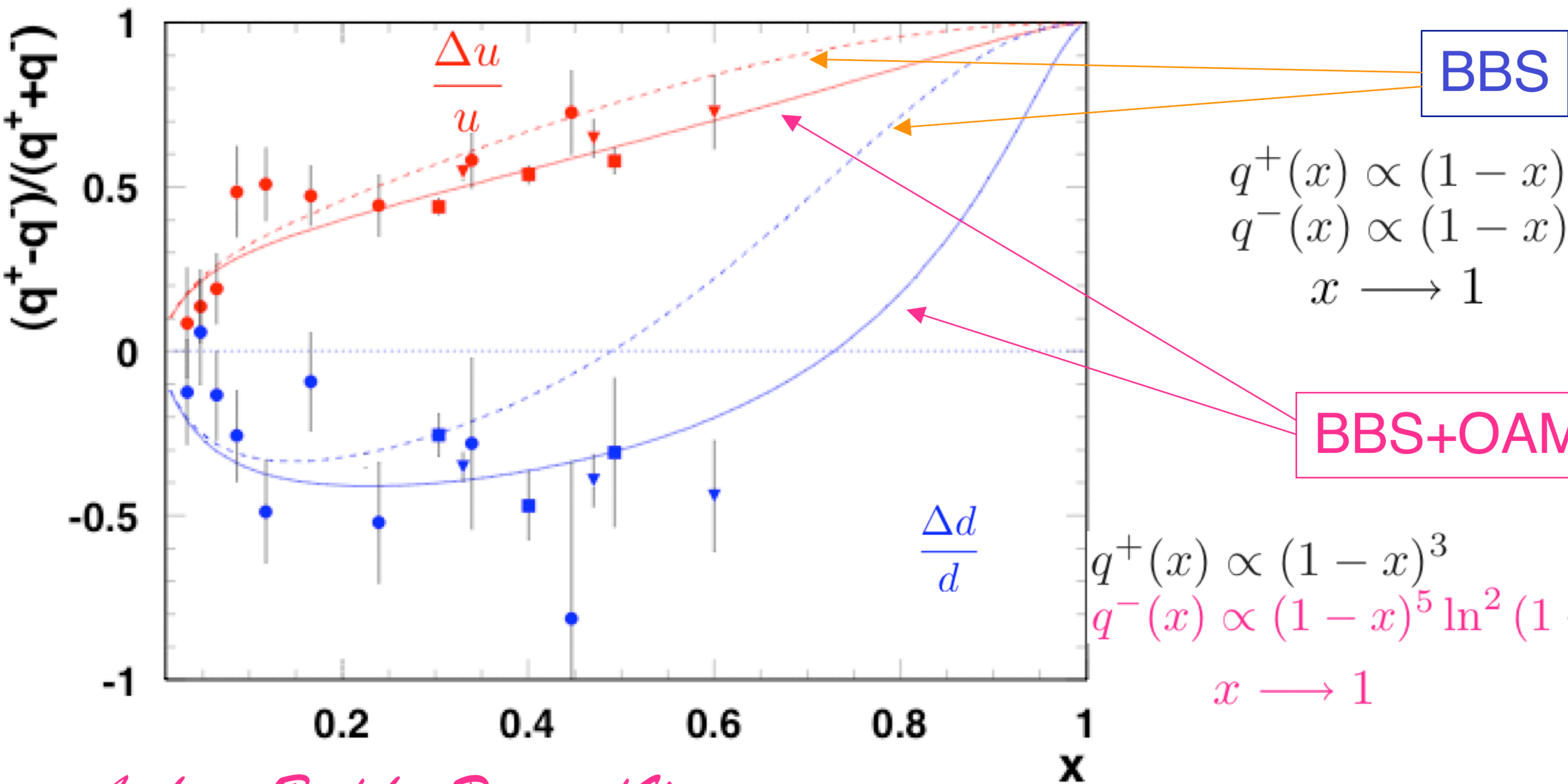
A_1^n and Helicity-Flavor Decomposition





Effect of quark orbital angular momentum

Inclusive Hall A and B and Semi-Inclusive Hermes



$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5$$
$$x \longrightarrow 1$$

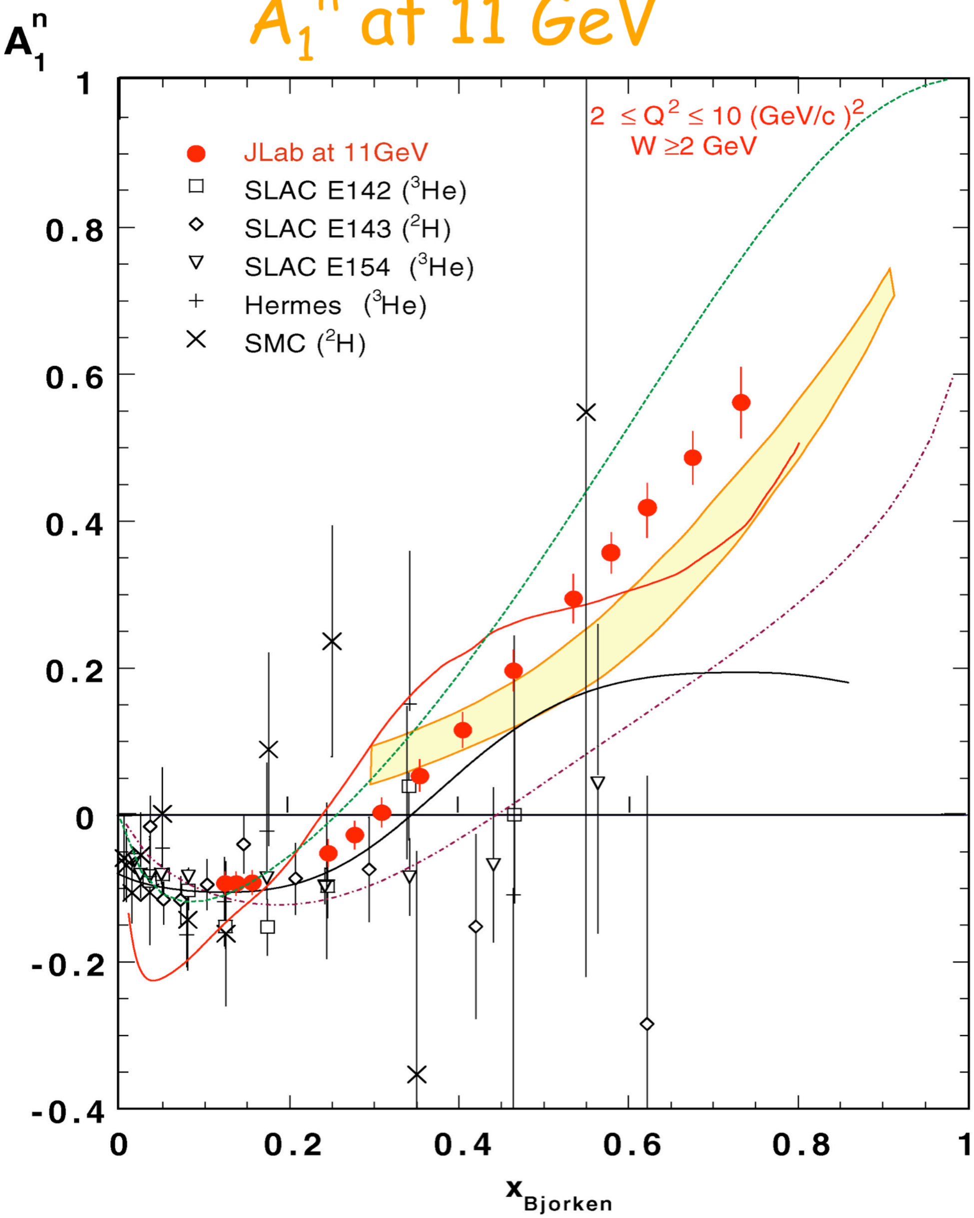
$$q^+(x) \propto (1-x)^3$$
$$q^-(x) \propto (1-x)^5 \ln^2(1-x)$$
$$x \longrightarrow 1$$

Avakian, Brodsky, Deur and Yuan

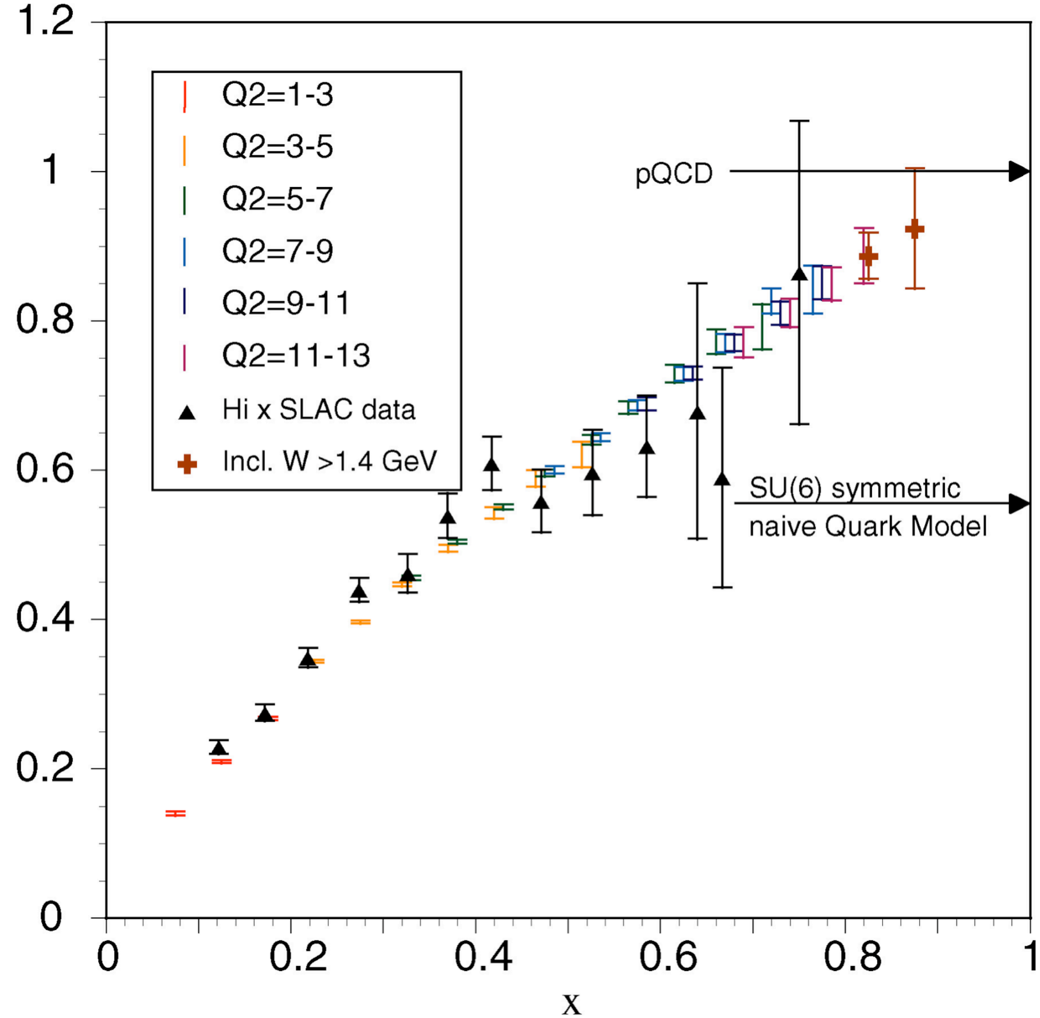
To be submitted to PRL

Inclusive measurements of asymmetries

A_1^n at 11 GeV

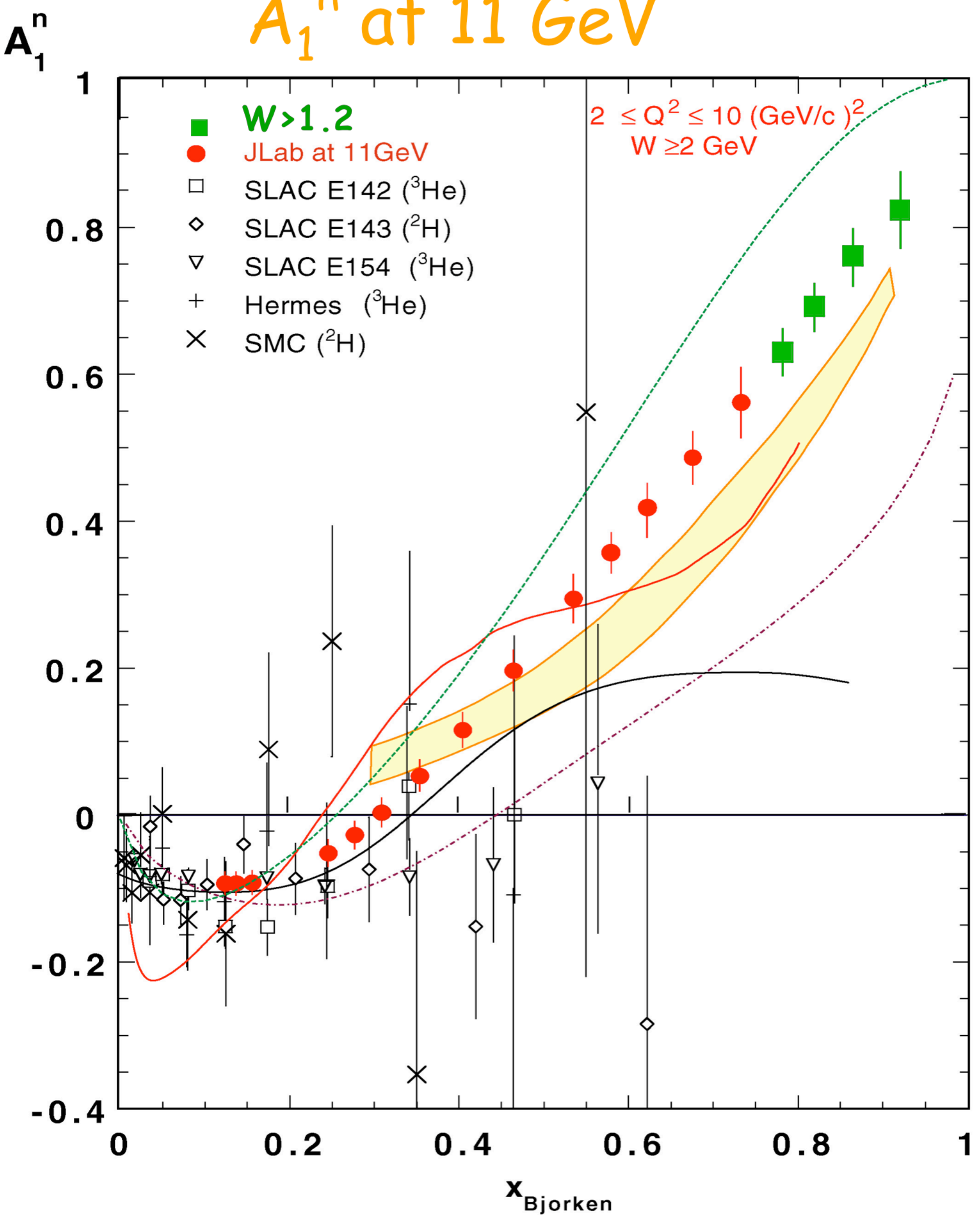


A_1^p at 11 GeV

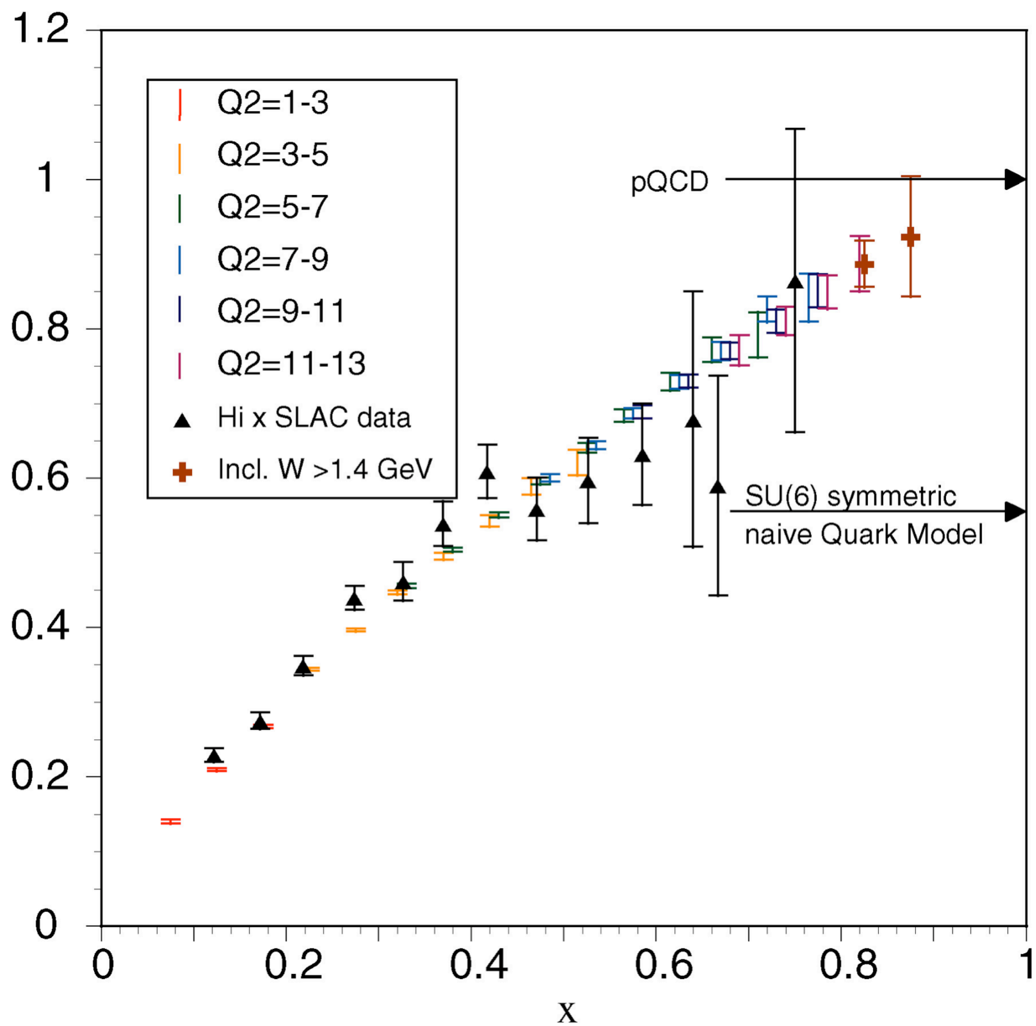


Inclusive measurements of asymmetries

A_1^n at 11 GeV



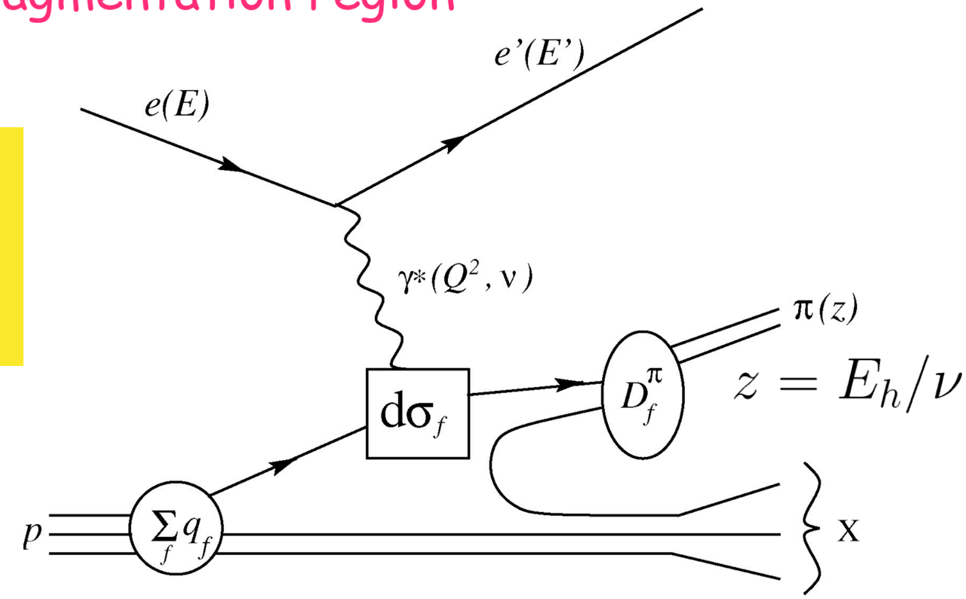
A_1^p at 11 GeV



Semi-inclusive DIS

- Spin-flavor decomposition of valence and sea quarks by tagging hadron (e.g. π, K) in current fragmentation region

$$\boxed{d\sigma = \sum_f e_f^2 q_f(x) D_f^h(z)}$$

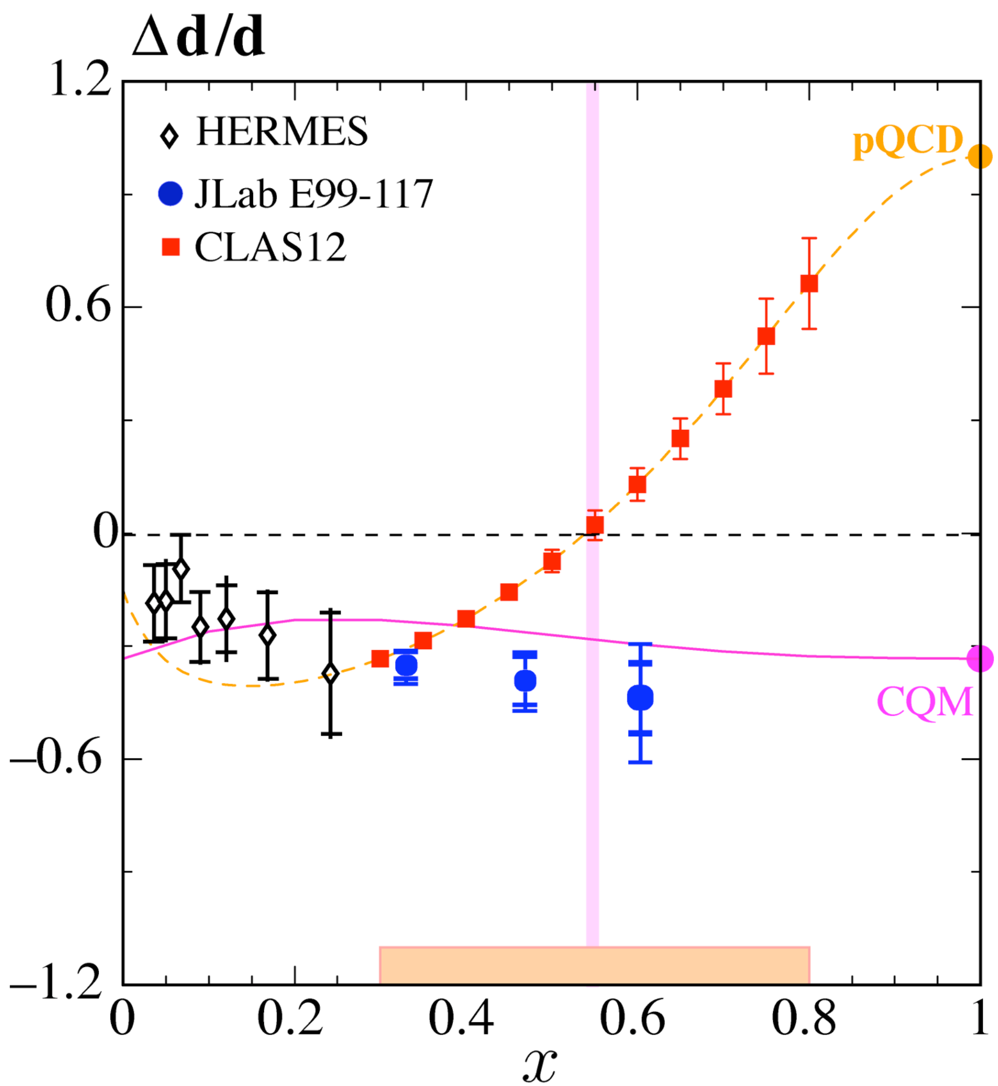


$D(z)$ quark--> hadron fragmentation function

- unpolarized or polarized beam and target
- mass of unobserved X system, W_X > 2 GeV

Flavor decomposition (2)

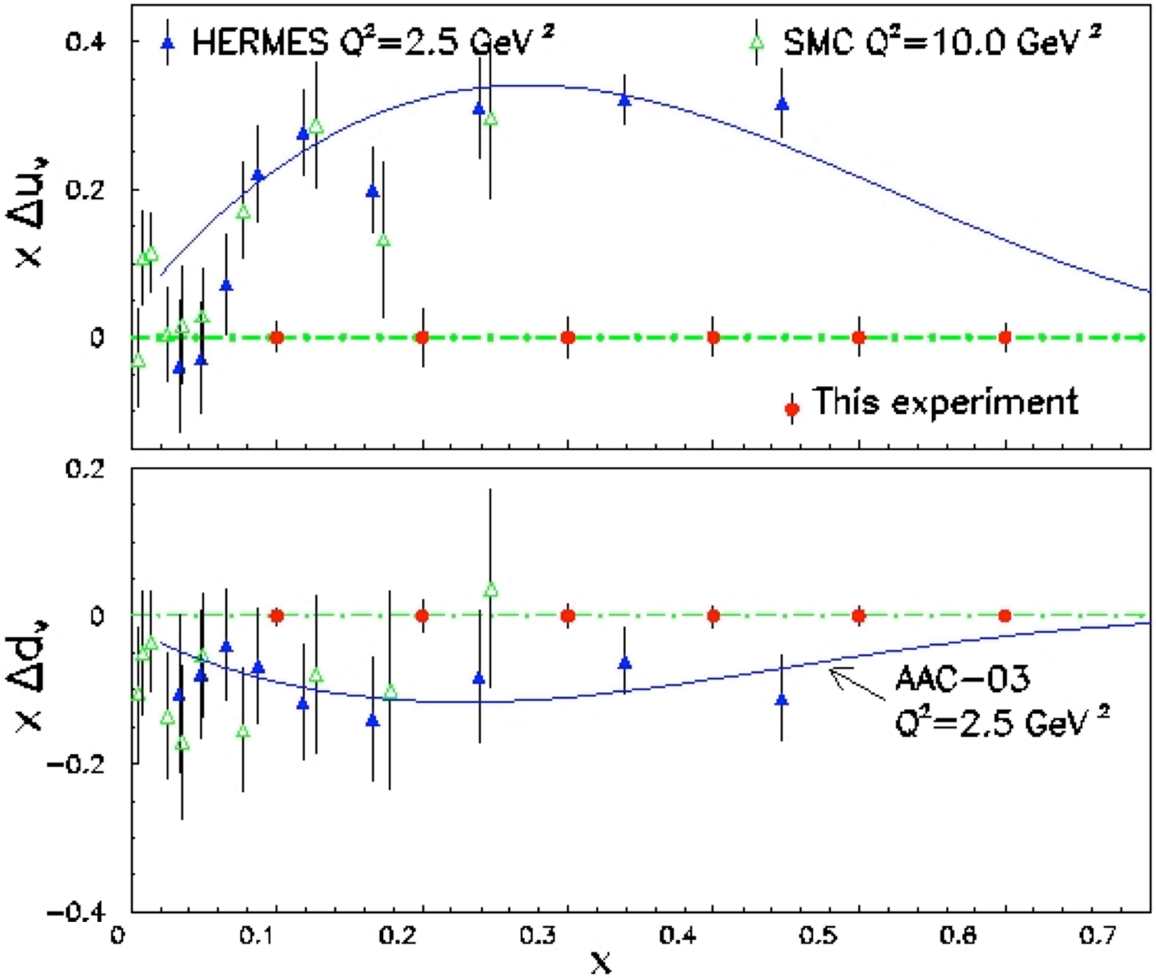
At JLab 12 GeV with SIDIS



Flavor decomposition (2)

E_e =11 GeV NH_3 and ^3He

- Asymmetry measurements with different hadrons (π+, π−) and targets (p,n) allow flavor separation



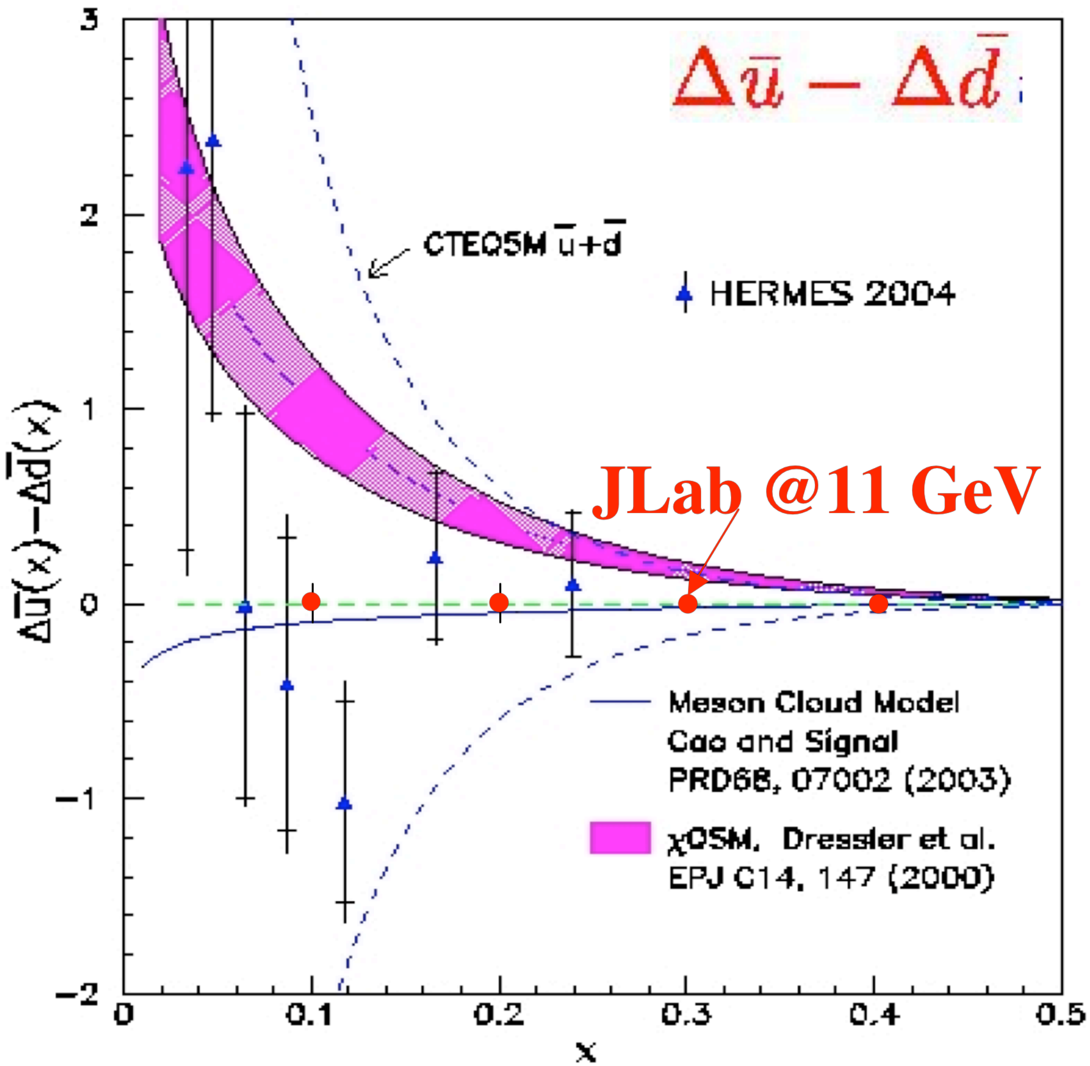
Flavor decomposition: polarized sea

- Predictions:
  - Instantons (χQSM):

$$\Delta\bar{u} \approx -\Delta\bar{d}$$

- First data from HERMES

$$\Delta\bar{u} - \Delta\bar{d} \approx 0$$



Color "Polarizabilities"

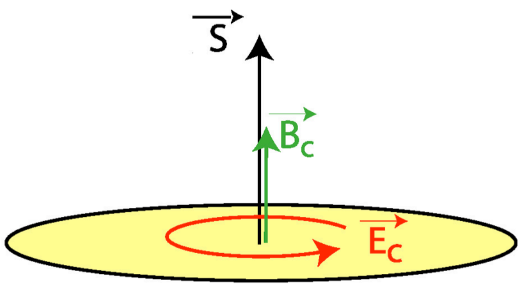
How does the gluon field respond when
a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E} 2M^2 \vec{S} = \langle PS | \vec{O}_{B,E} | PS \rangle$$

where $\vec{O}_B = \psi^\dagger g \vec{\boldsymbol{B}} \psi$

$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{\boldsymbol{E}} \psi$$



$$d_2 = (\chi_E + 2\chi_B)/8$$

$$f_2 = (\chi_E - \chi_B)/2$$

d_2 and f_2 represent the response of the color $\vec{B}$ & $\vec{E}$ fields
to the nucleon polarization

Moments of Structure Functions

$$\Gamma_1(Q^2) \equiv \int_0^1 \mathrm{d}x\, g_1(x,Q^2)$$
$$= \Gamma_1^{\mathrm{twist-2}}(Q^2) + \frac{M_N^2}{9\,Q^2}\left[a_2(Q^2) + 4\,d_2(Q^2) + 4\,f_2(Q^2)\right] + \mathcal{O}\left(\frac{M_N^4}{Q^4}\right)$$

$$a_2(Q^2) \equiv 2\int_0^1 \mathrm{d}x\, x^2\, g_1^{\mathrm{twist-2}}(x,Q^2) \rightarrow$$ target mass correction term

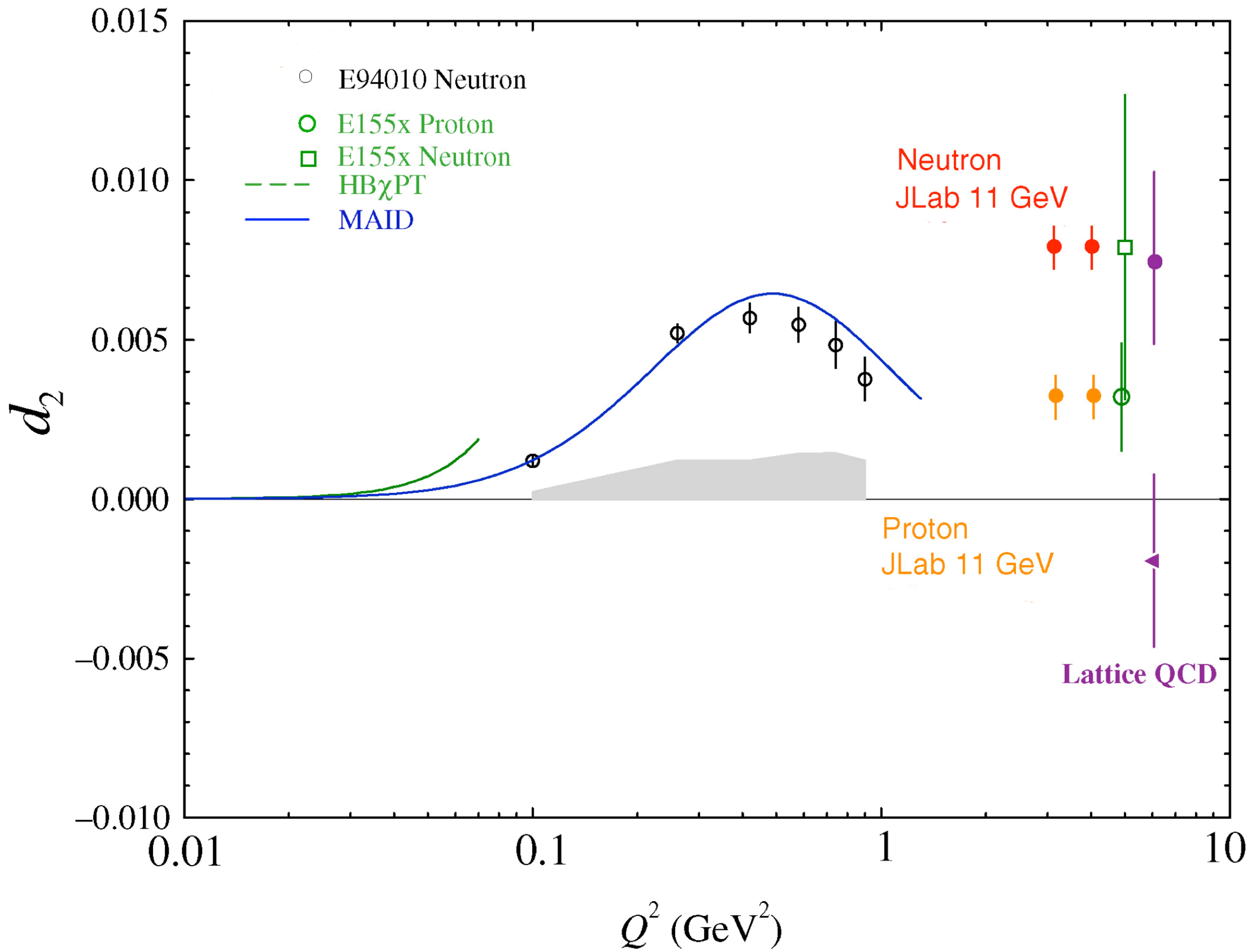
$d_2(Q^2) \rightarrow$ dynamical twist-3 matrix element

$$d_2(Q^2) \equiv \int_0^1 \mathrm{d}x\, x^2 \left\{3\,g_2(x,Q^2) + 2\,g_1(x,Q^2)\right\}$$

$f_2(Q^2) \rightarrow$ dynamical twist-4 matrix element

- Both d_2 and f_2 are required to determine the color polarizabilities
- To extract f_2, d_2 needs to be determined first.

d_2 with 11 GeV at JLab



All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$

f_1 =

Boer-Mulders $h_1^\perp$ =

$h_{1L}^\perp$ =

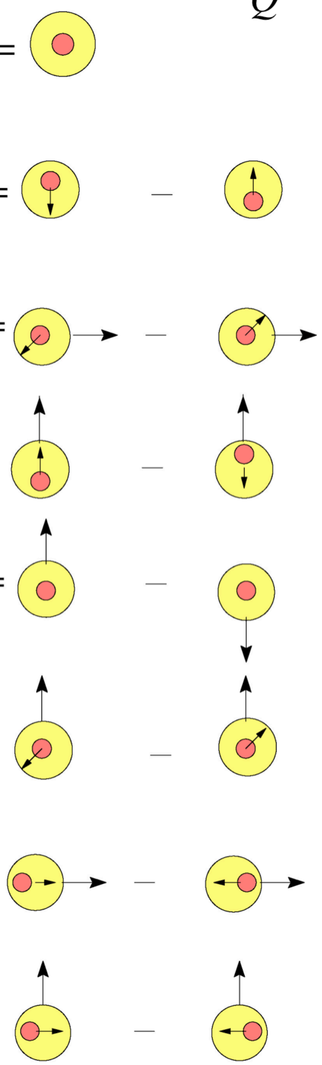
Transversity h_{1T} =

Sivers $f_{1T}^\perp$ =

$h_{1T}^\perp$ =

g_{1L} =

g_{1T} =



Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized beam and target

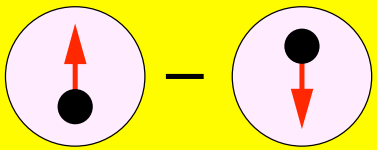
$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λ_e: Beam Polarization

Collins asymmetry & Boer-Mulders Effect

(PR12-06-112)

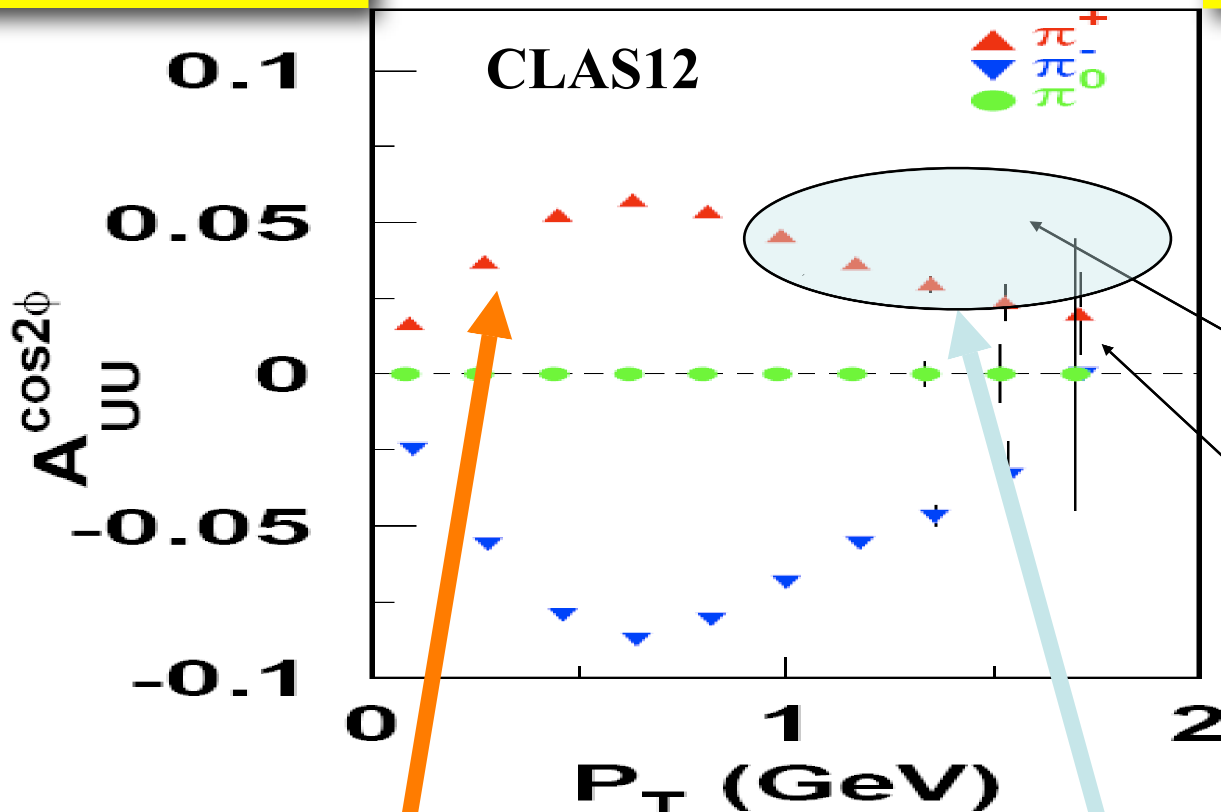


$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$

Transversely polarized quarks in the unpolarized nucleon

$s_T(p \times k_T) \leftrightarrow h_1^{\perp}$

$\sin(\phi_C) = \cos(2\phi_h)$



In the perturbative limit $1/P_T^2$ behavior expected (F.Yuan)

quark-scalar diquark model (L.Gamberg)

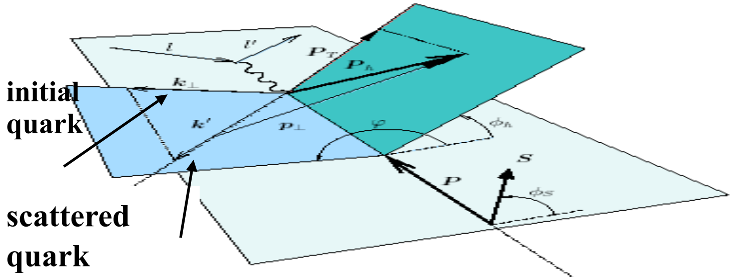
$4<Q^2<5$ (2000h @ 11 GeV with 10^{35}sec^{-1}cm^{-2})

Non-perturbative TMD

Perturbative region

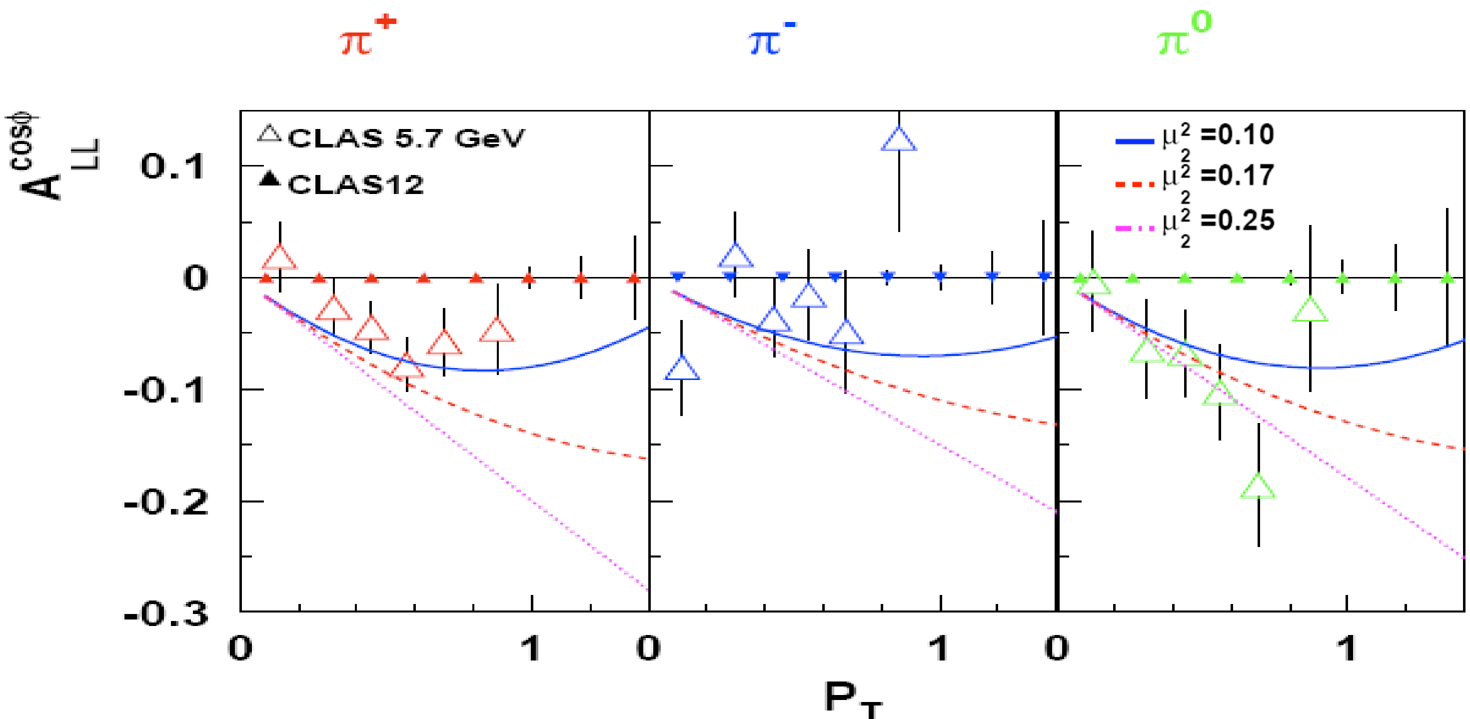
$$\Lambda_{QCD} \ll P_T \ll Q$$

•BM cos2ϕ moment, sensitive to spin-orbit correlations: the only leading twist azimuthal moment for unpolarized target
•P_T-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).
•More info will be available from SIDIS (HERMES,COMPASS,ZEUS,EIC) and DY (RHIC,GSI)



A_1-P_T-dependence

hep-ph/0608048
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2



$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\frac{1}{\mu_D^2+z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_0^2}\right)\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

$$\Delta\sigma_{LL}^{\cos\phi_h} = -4\frac{\sqrt{1-y}}{xy}\frac{z\,\mu_2^2\, P_{hT}}{Q\,(\mu_D^2+z^2\mu_2^2)^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2\, g_1^q(x)\, D_q^h(z)$$

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

$$D_q^h(z,p_\perp) = D_q^h(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_\perp^2}{\mu_D^2}\right)$$

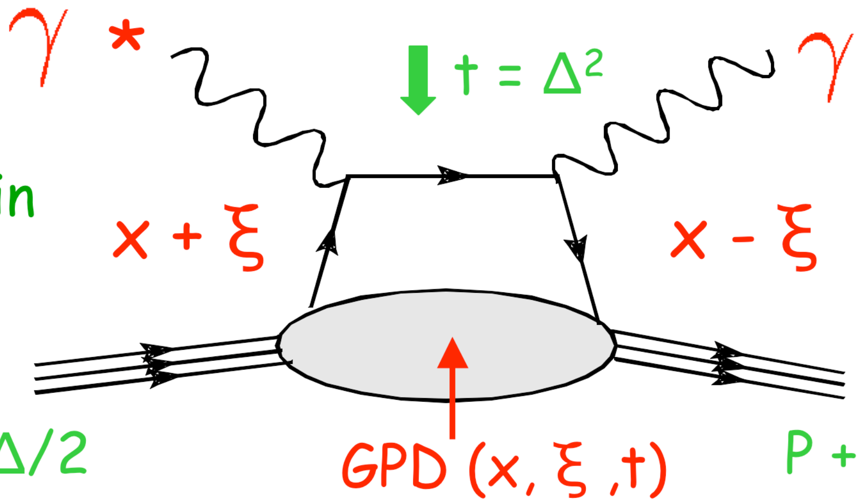
$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

P_T-dependence of the cosϕ moment of double spin asymmetry is consistent with ***significant difference in k_T-distributions of polarized and unpolarized quarks***

Generalized Parton Distributions

➡ Q_{hard}^2 large

Ji , Radyushkin (1996)



low $-t$ process :
$-t \ll Q_{hard}^2$

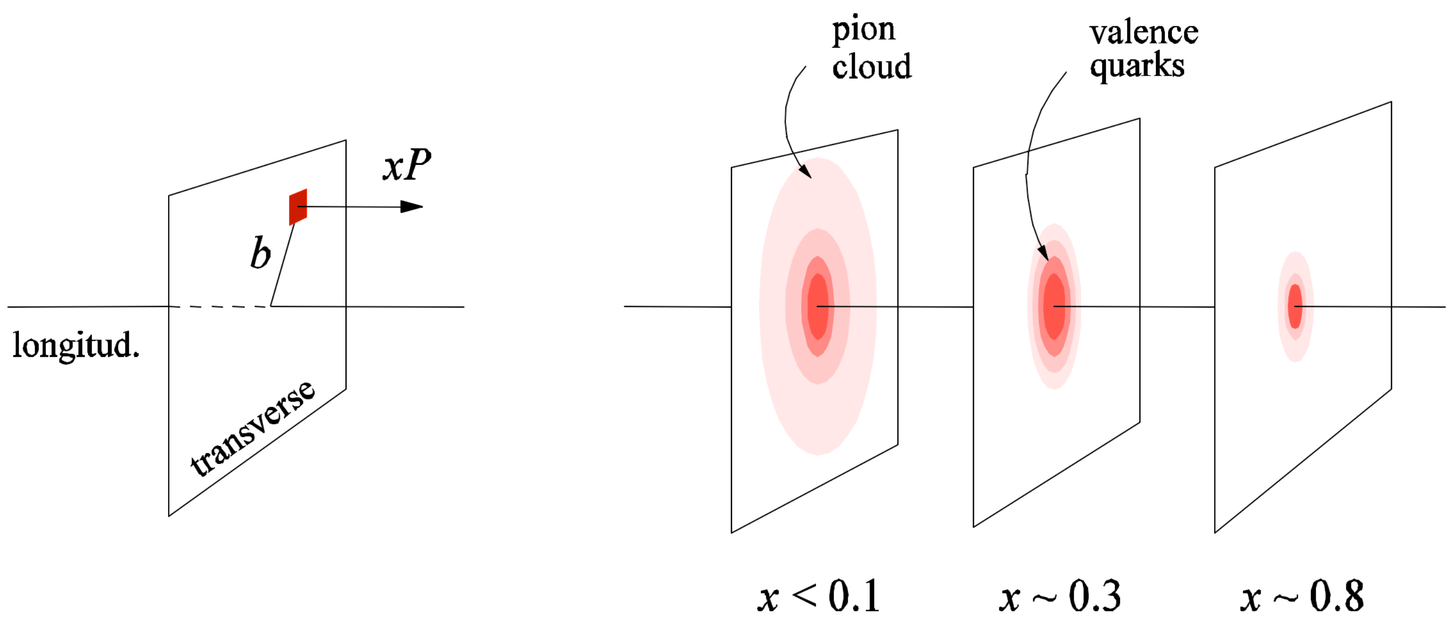
$(x + \xi)$ and $(x - \xi)$: longitudinal momentum fractions of quarks

➡ at large Q^2 : QCD factorization theorem ➡ hard exclusive process can be described by 4 transitions (GPDs) :

Vector : $H(x, \xi, t)$ **Axial-Vector** : $\tilde{H}(x, \xi, t)$

Tensor : $E(x, \xi, t)$ **Pseudoscalar** : $\tilde{E}(x, \xi, t)$

GPDs : 3D quark/gluon imaging of nucleon



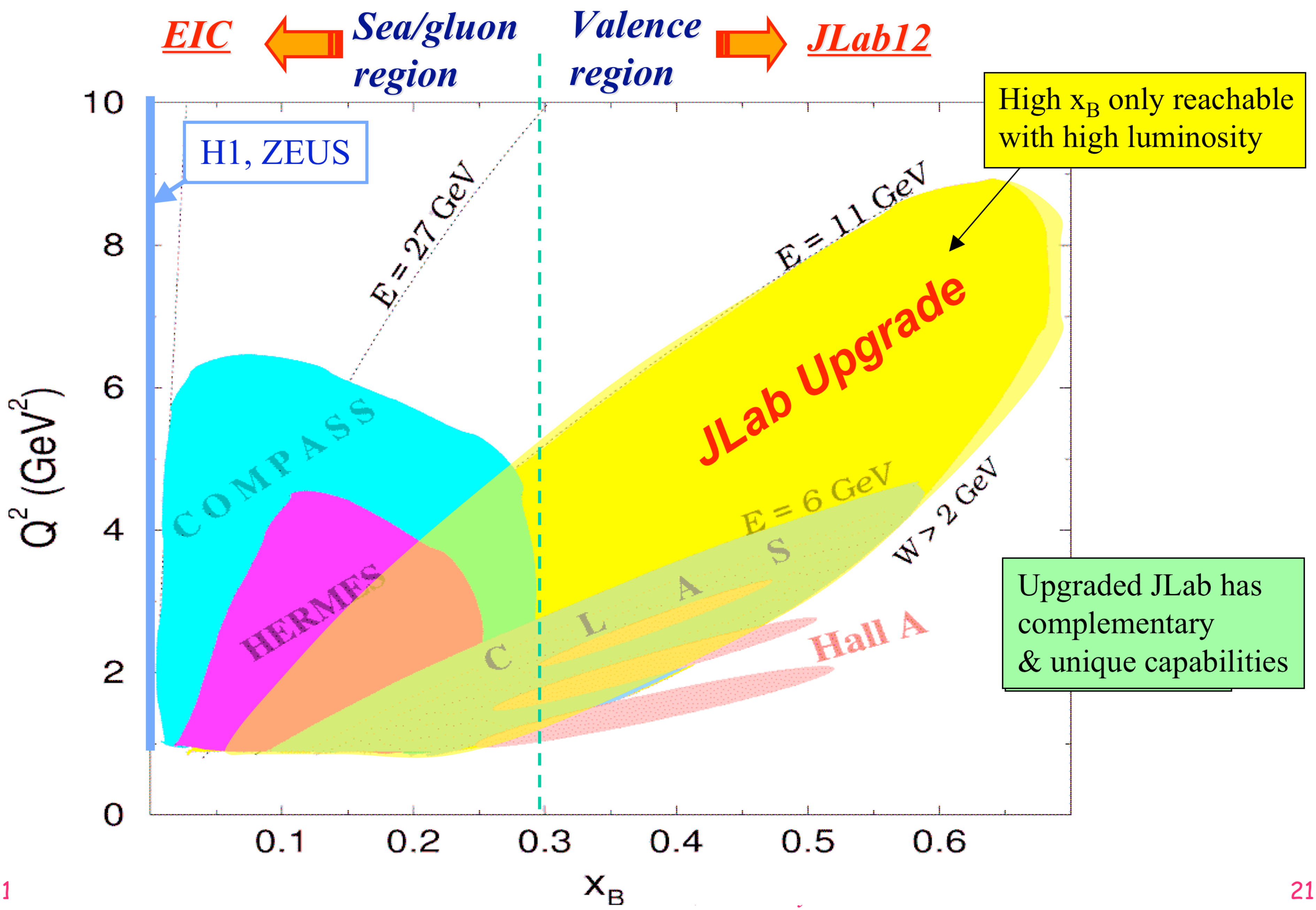
Fourier transform of GPDs :

simultaneous distributions of quarks w.r.t. longitudinal momentum x P and transverse position b (Burkardt)

⇨ theoretical parametrization needed :

double distributions, dual param. (Guzey), conformal param. (Müller)

Large phase space (ξ,t,Q^2) and High luminosity required



Extracting GPDs from data

global analysis : X-sec, asymm, (p,n), (g,M)

ep $\longrightarrow$ epγ

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\xi = x_B/(2-x_B)$$
$$k = -t/4M^2$$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

(BSA)

Kinematical suppression

$\Rightarrow$ $H(\xi,\xi,t)$, $\tilde{H}(\xi,\xi,t)$, $E(\xi,\xi,t)$

Unpolarized beam, long. pol. target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \dots\}d\phi$$

(l)TSA

$\Rightarrow$ H, $\tilde{H}$

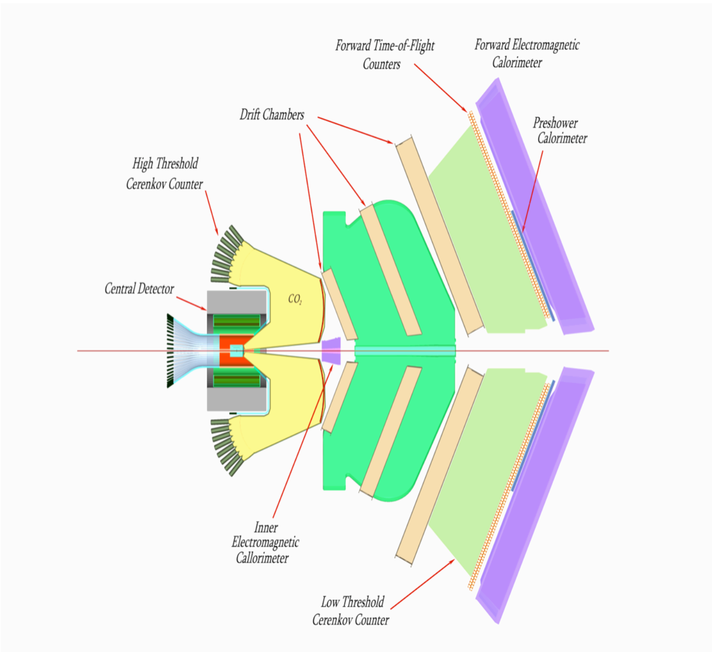
Unpolarized beam, trans. pol. target:

$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \dots..\}d\phi$$

(t)TSA

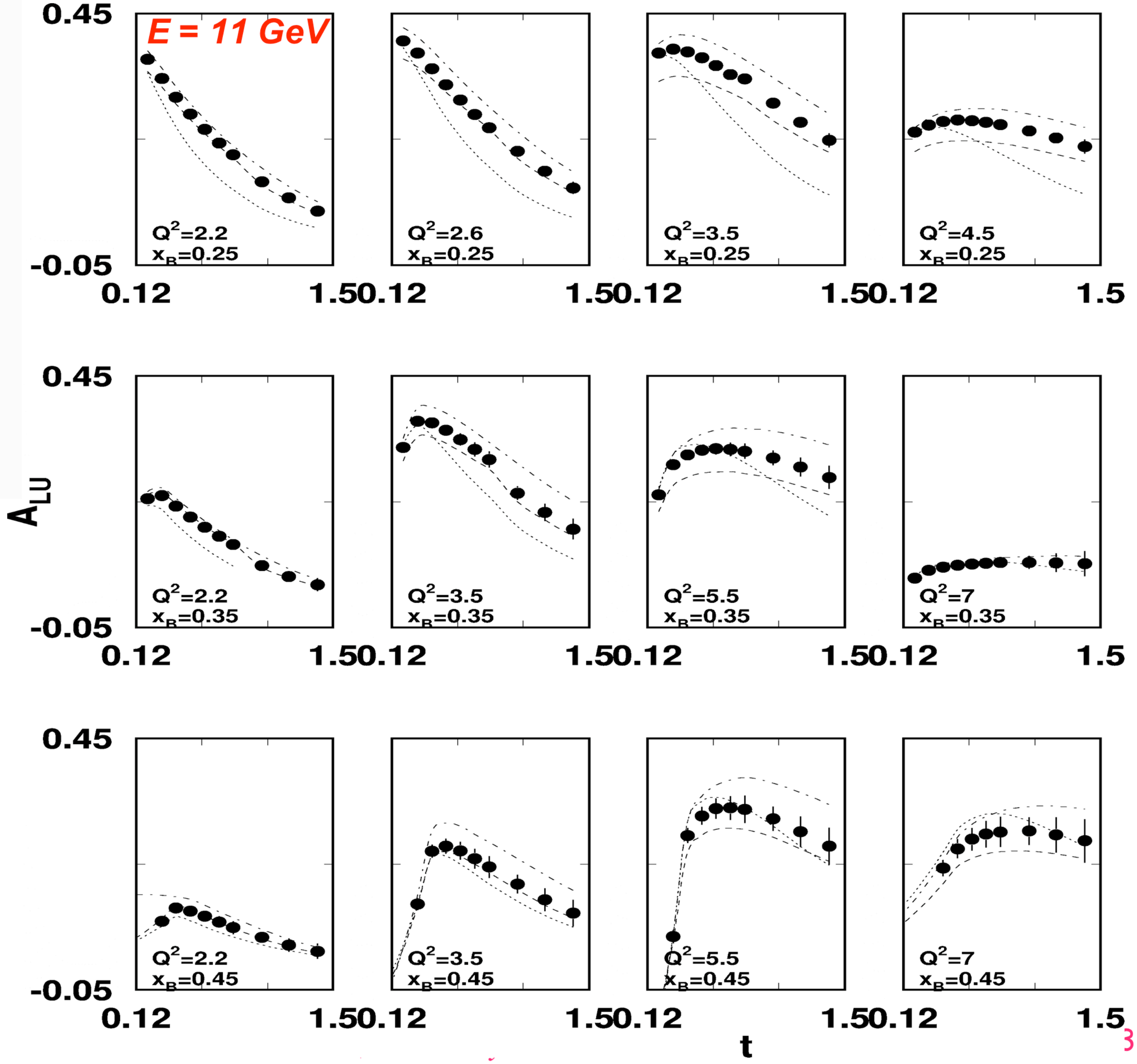
$\Rightarrow$ H, E

exclusive DVCS : BSA @ JLab 12 GeV



$$\vec{e}\,p \longrightarrow ep\gamma$$

Projected results



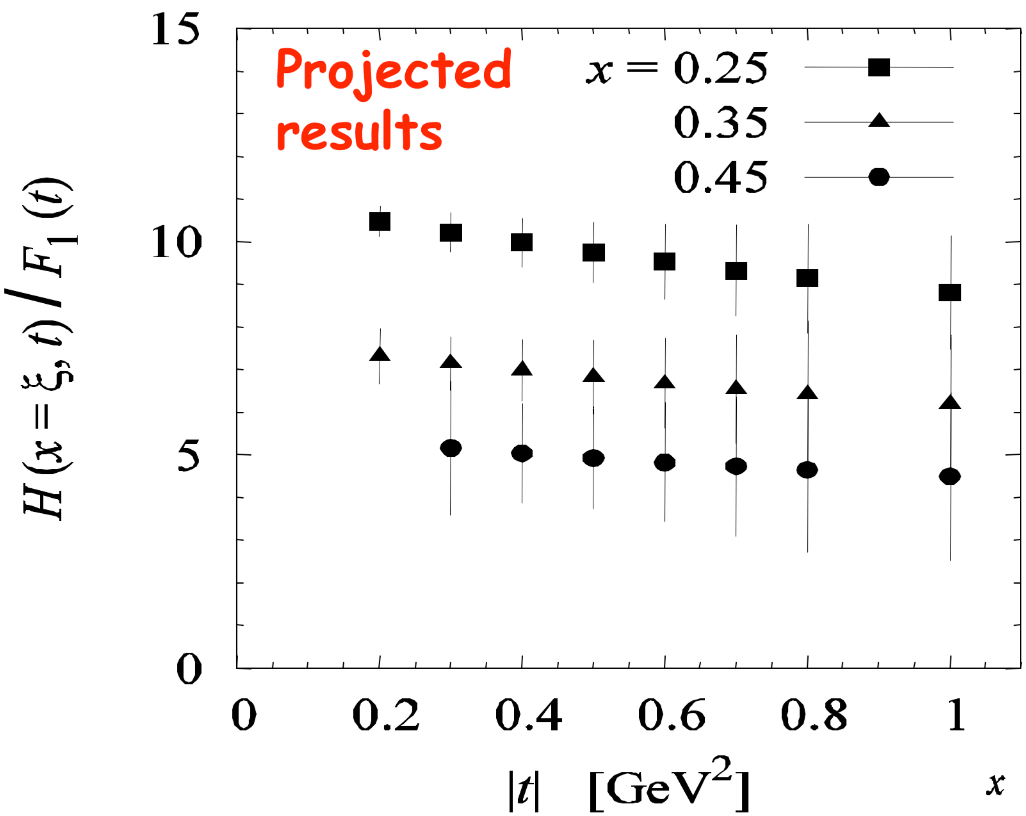
$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + ..\} d\phi$$

Selected Kinematics

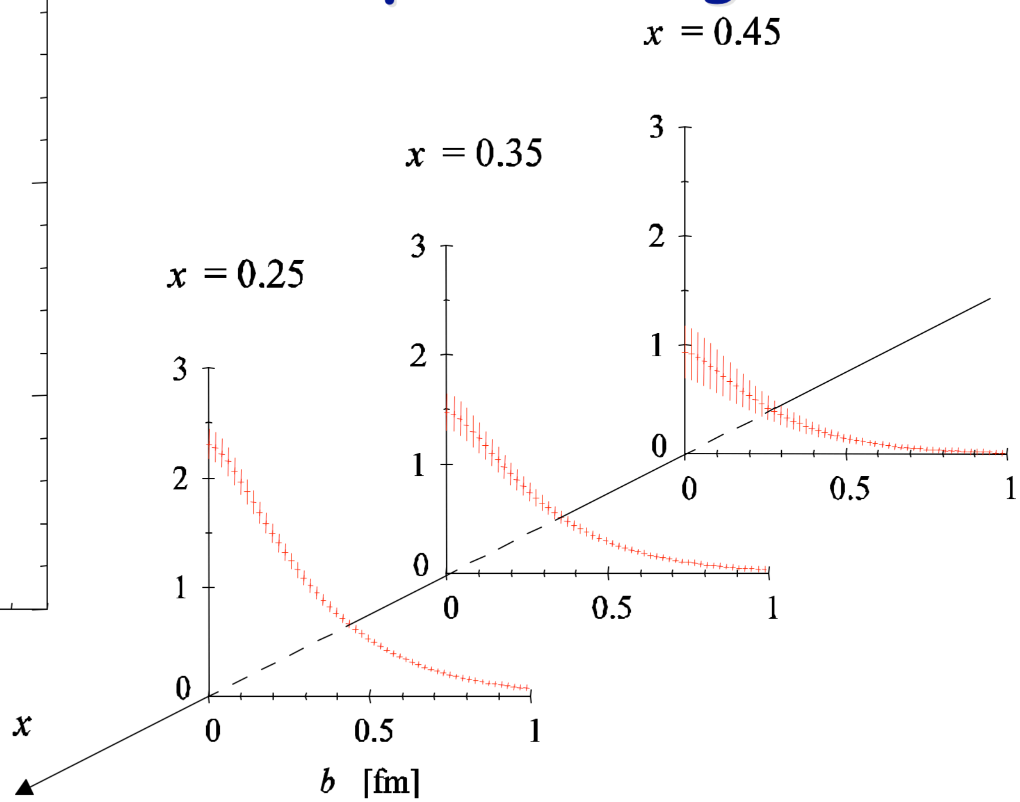
$L = 1\mathrm{x}10^{35}$
$T = 2000$ hrs
$\Delta Q^2 = 1\ \mathrm{GeV}^2$
$\Delta x = 0.05$

Avakian

Projected precision in extraction of GPD H at $x = \xi$



spatial image



upgraded CLAS @ JLab12GeV

Avakian, Weiss

Exclusive DVCS on *longitudinal* target @ JLab 12 GeV

$e\vec{p} \longrightarrow ep\gamma$

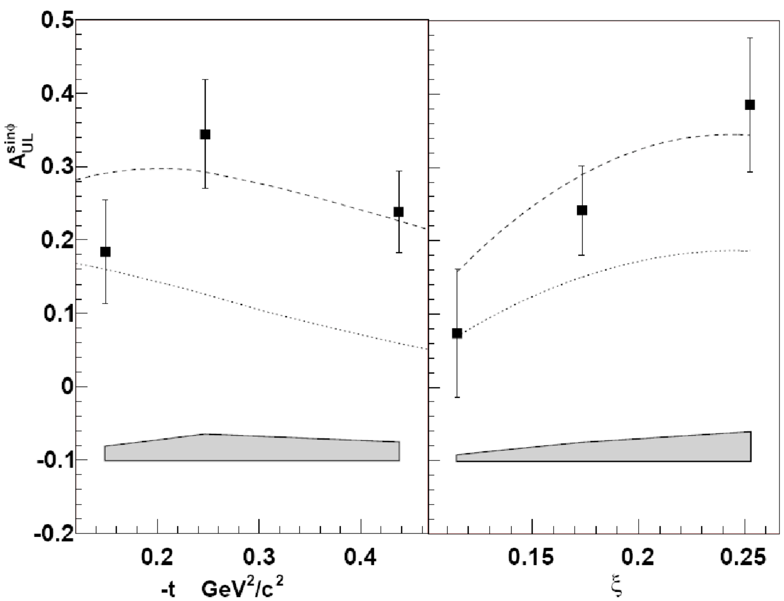
L = 2x10^{35} cm^{-2}s^{-1}
T = 1000 hrs
ΔQ^2 = 1GeV^2
Δx = 0.05

Longitudinally polarized target

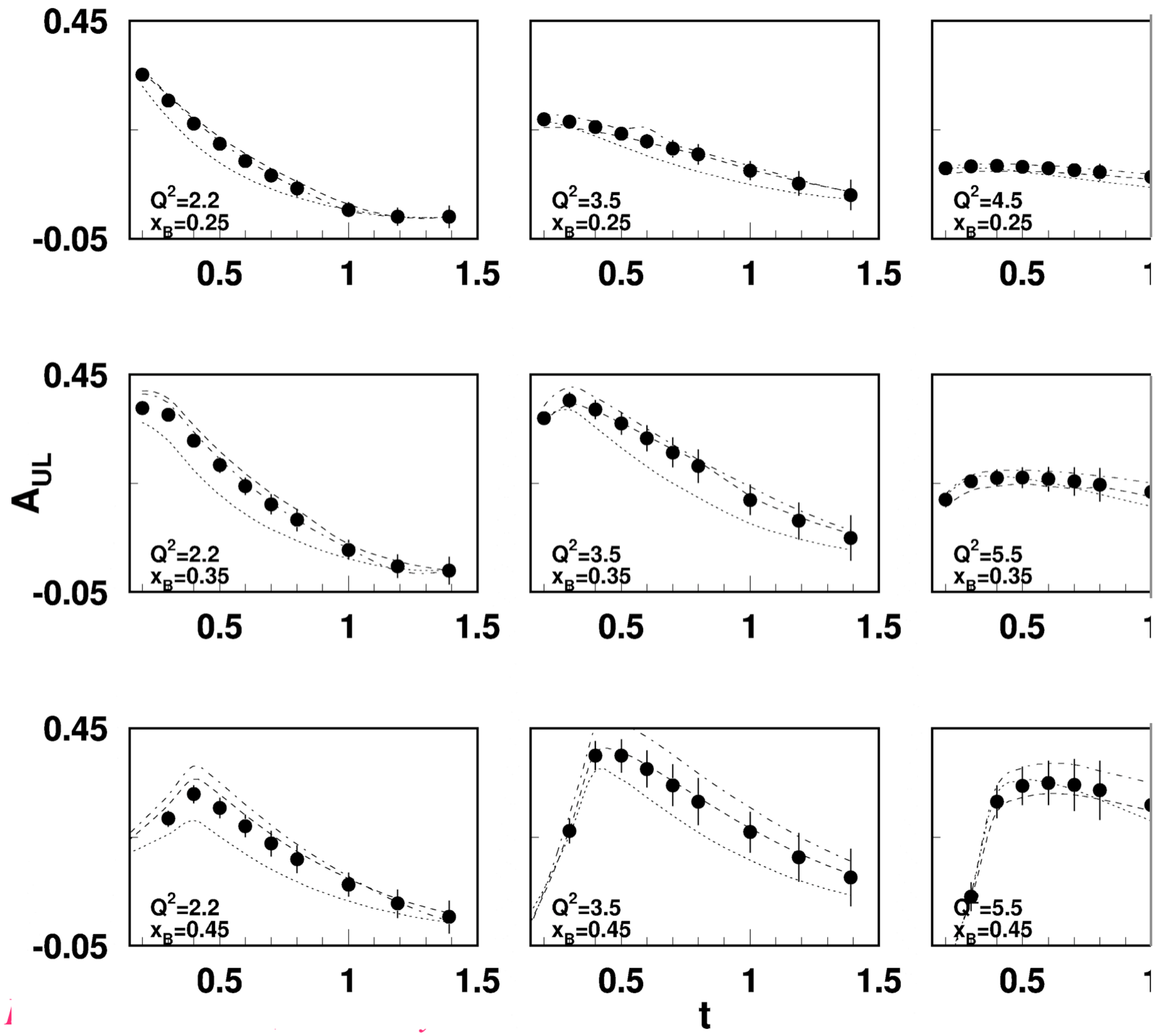
$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$$

CLAS exclusive DVCS data

PRL97, 072002 (2006)



Projected results



Exclusive DVCS on *transverse* target @ JLab 12 GeV

$e\,p^{\uparrow} \longrightarrow e p \gamma$

E = 11 GeV

Projected results

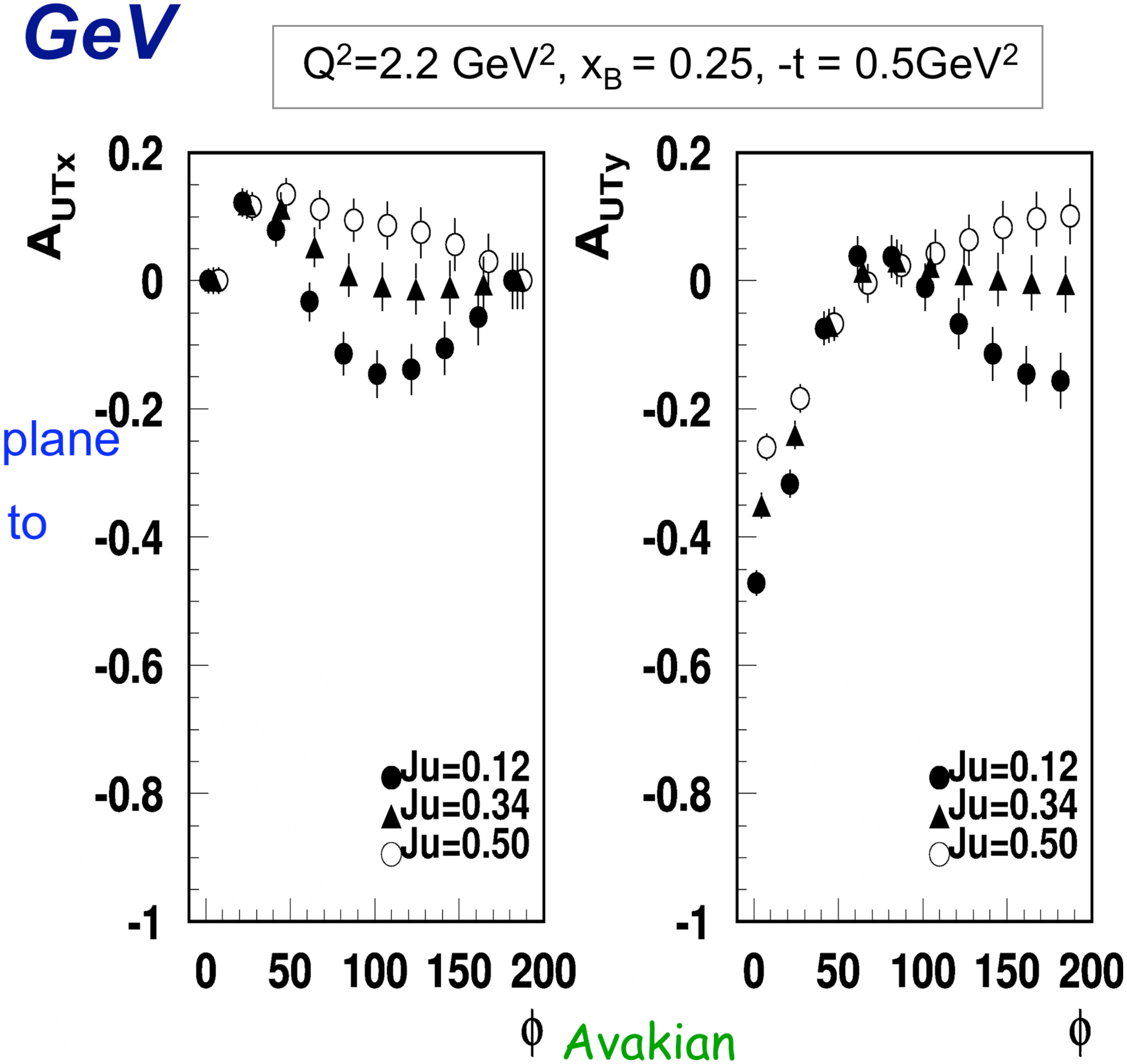
Transverse polarized target

$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\phi$

A_{UTx} Target polarization in scattering plane

A_{UTy} Target polarization perpedicular to scattering plane

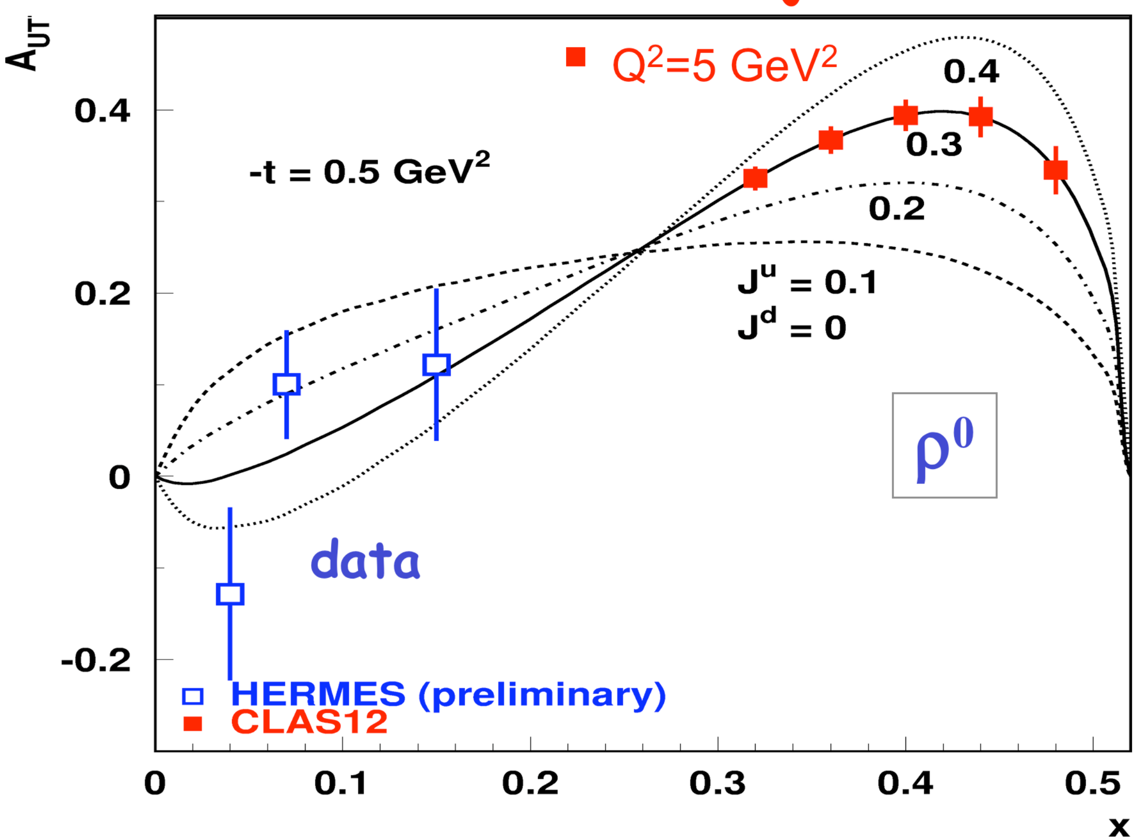
- Asymmetry highly sensitive to the u-quark contributions to proton spin.



exclusive ρ^0 production on *transverse* target

$$A_{UT} = -\frac{2\Delta_\perp (\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2 + t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

Projected results



ρ^0: $A \sim 2H^u + H^d$, $B \sim 2E^u + E^d$

ρ^+: $A \sim H^u - H^d$, $B \sim E^u - E^d$

E^u, E^d needed for angular momentum sum rule.

Goeke, Polyakov, Vdh (2001)

Conclusion

JLab at 12 GeV will provide for a true revolution of our knowledge of the nucleon structure in the valence region