The 3D nucleon imaging program at JLab 12 GeV

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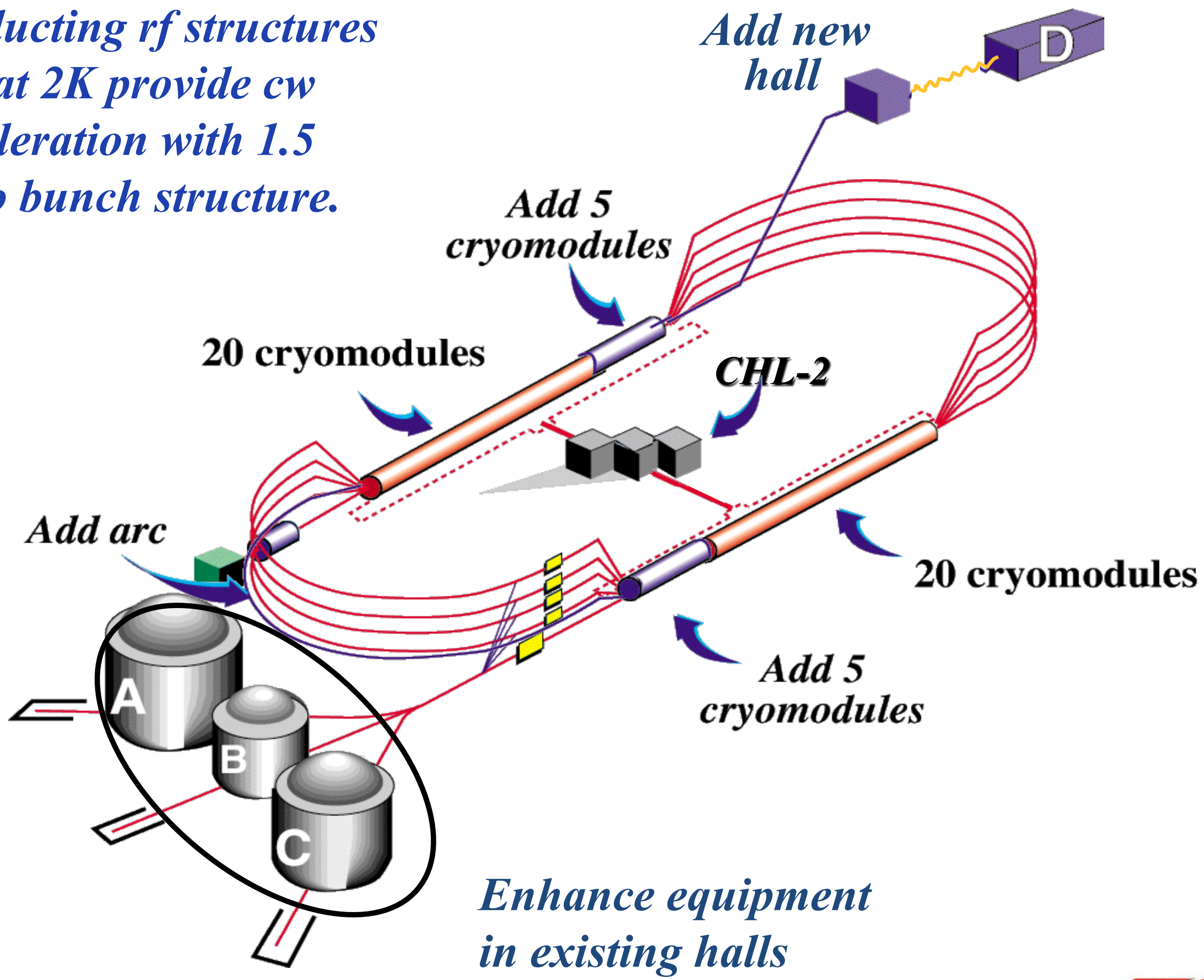
Jefferson Lab

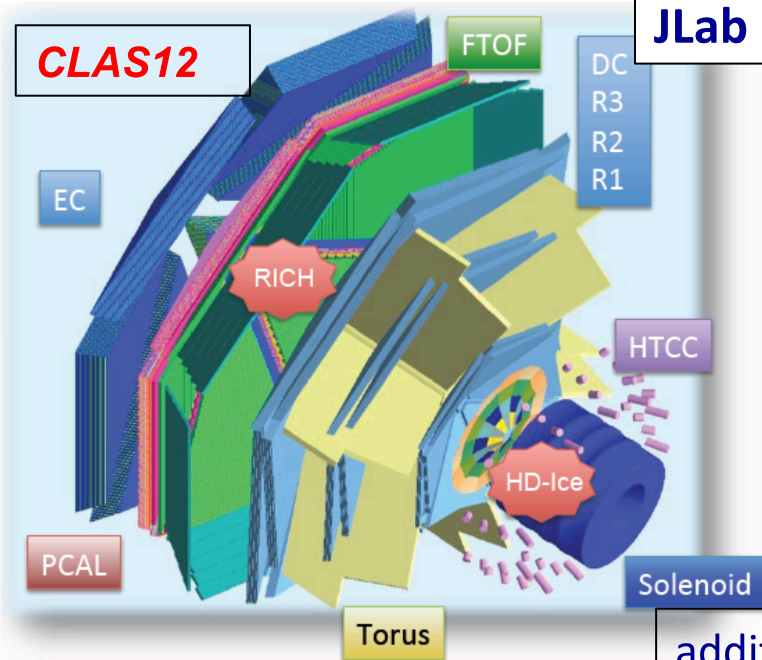
CEBAF energy doubling from 6 GeV to 12 GeV

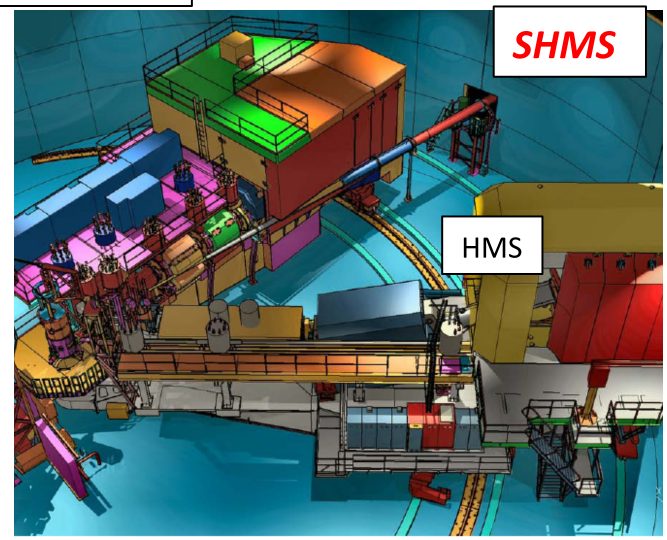
Superconducting rf structures operating at 2K provide cw beam acceleration with 1.5 GHz micro bunch structure.



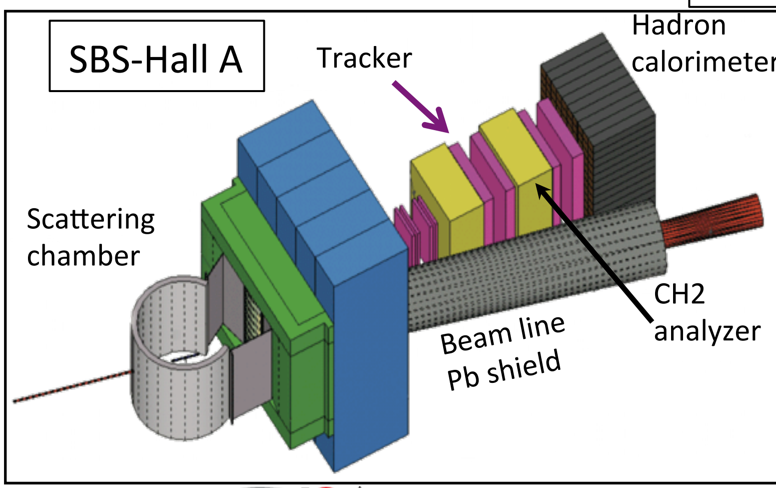
Base equipment & proposed equipment

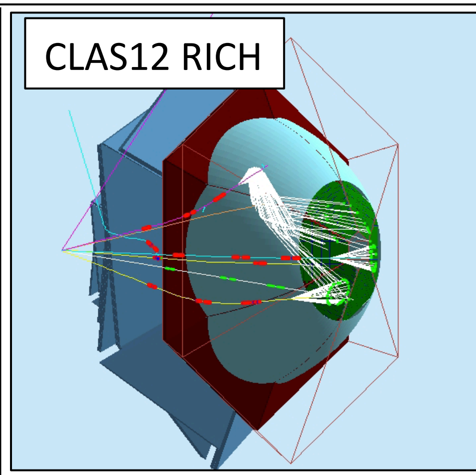
JLab 12 GeV base equipment





additional equipment (proposed)





Wigner Function - GPDs and TMDs

(Quantum phase-space quark distribution in the nucleon)

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over ***spatial*** dimensions

Integrate over ***momentum*** space

Transverse Momentum-dependent Distributions (TMD)

Generalized Parton Distributions (GPD)

3D imaging of the nucleon in momentum space

3D nucleon imaging in transverse coordinate and longitudinal momentum space.

Physical content of GPDs *H, E*

Nucleon energy-momentum tensor of *q* flavored quarks:

$$\langle p_2 | \hat{T}^q_{\mu\nu} | p_1 \rangle = \bar{U}(p_2) \left[M_2^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{\imath(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{5M} \right] U(p_1)$$

To measure gravitational FFs : graviton scattering or GPDs identities :

$$J^q(t) = \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, x \left[H^q(x, \xi, t) + E^q(x, \xi, t) \right] , \quad M_2^q(t) + \frac{4}{5} d_1(t) \xi^2 = \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, x H^q(x, \xi, t)$$

(Ji's sum for t=0)

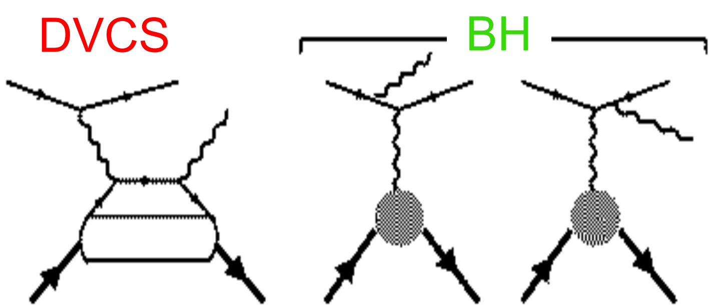
Fourier transformation relates *J(t)* to the quark angular momentum distribution in b_T space.

$M_2(t)$: Mass distribution in b_T space
$d_2(t)$: Pressure and force distribution on quarks.

K. Goeke et al., PRD75, 2094021 (2007)

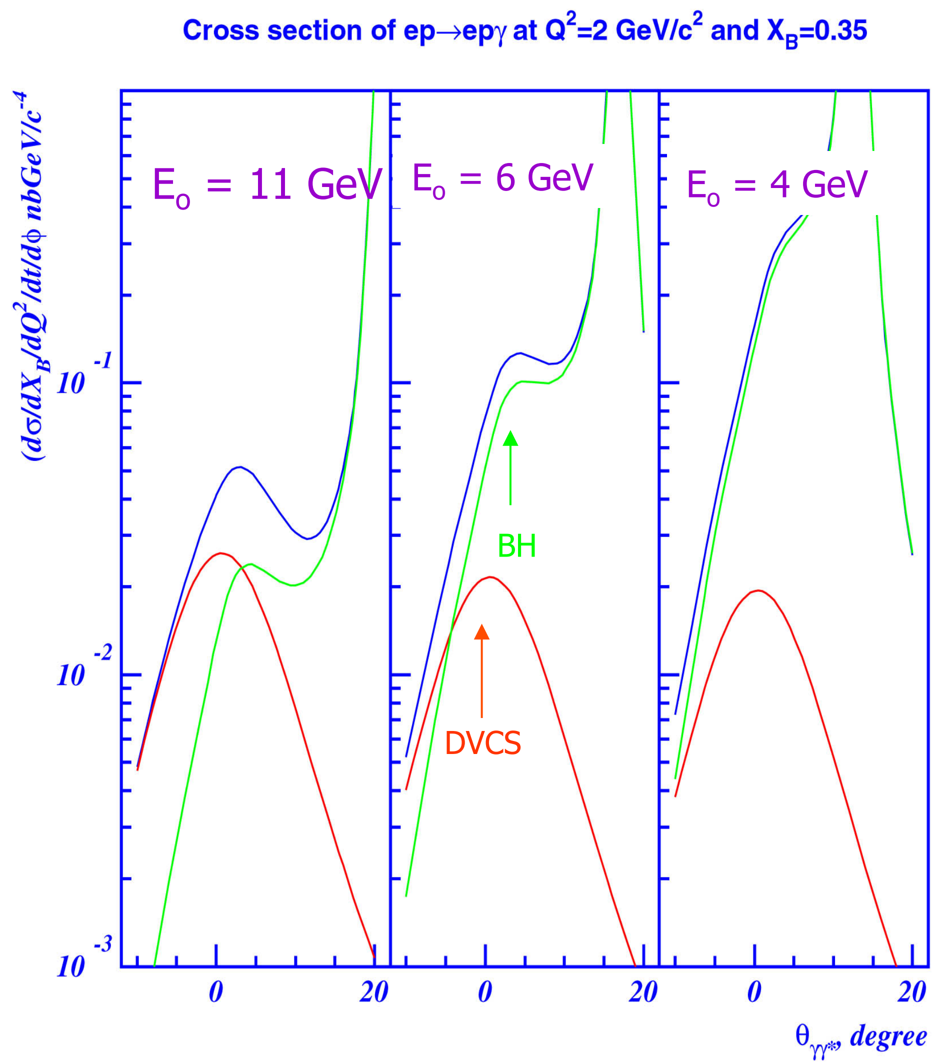
DVCS and Bethe-Heitler Process

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$



T^{BH}: given by elastic form factors
T^{DVCS}: determined by GPDs

BH-DVCS interference generates beam and target polarization asymmetries that encode the nucleon structure content.

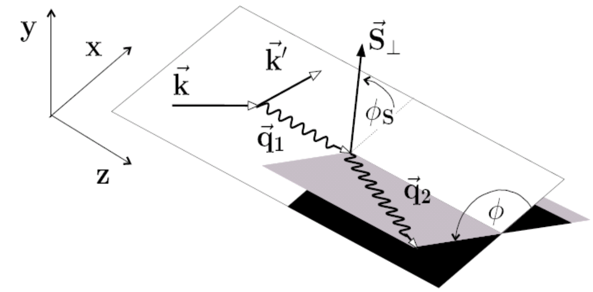


A path towards extracting GPDs

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

$\xi \sim x_B/(2\text{-}x_B)$

$k = t/4M^2$



Polarized beam, unpolarized target:

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

⇒ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi \, \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$$

⇒ $\tilde{H}(\xi,t)$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s-\phi)\{k(F_2 H - F_1 E)\}d\phi$$

⇒ $E(\xi,t)$

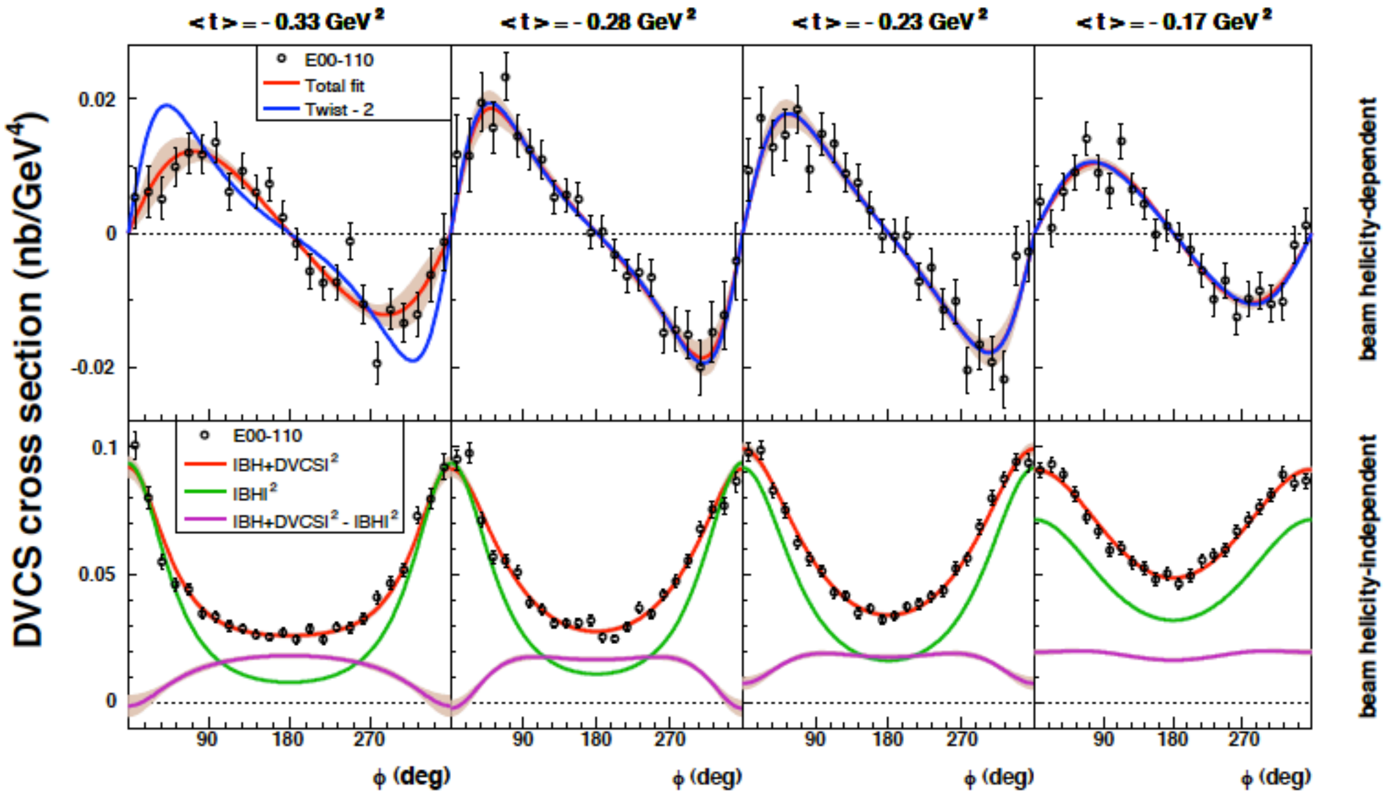
Unpolarized total cross section:

Separates h.t. contributions to DVCS

⇒ $\mathcal{Re}(T^{DVCS})$

Hall A DVCS/BH cross section on proton

C. Muñoz et al., Phys. Rev. Lett. 97 (2006) 262002



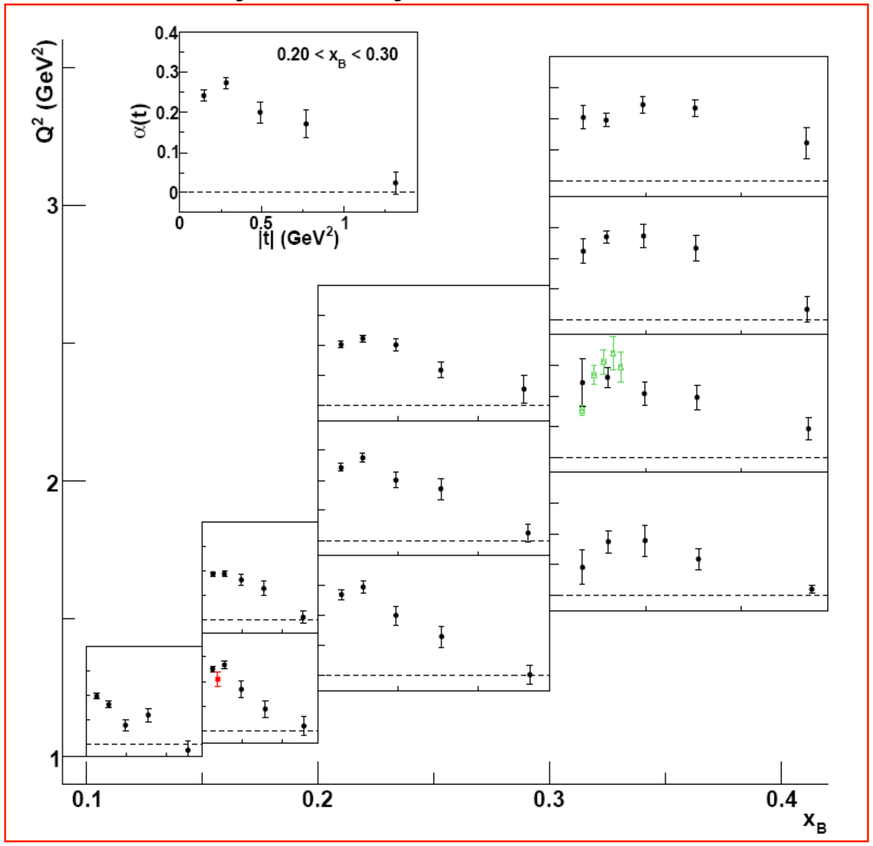
High statistics in small range in Q^2, x_B, t

Verify Bjorken scaling in small Q^2 range

New data taken 2010 on hydrogen and deuterium at two beam energies

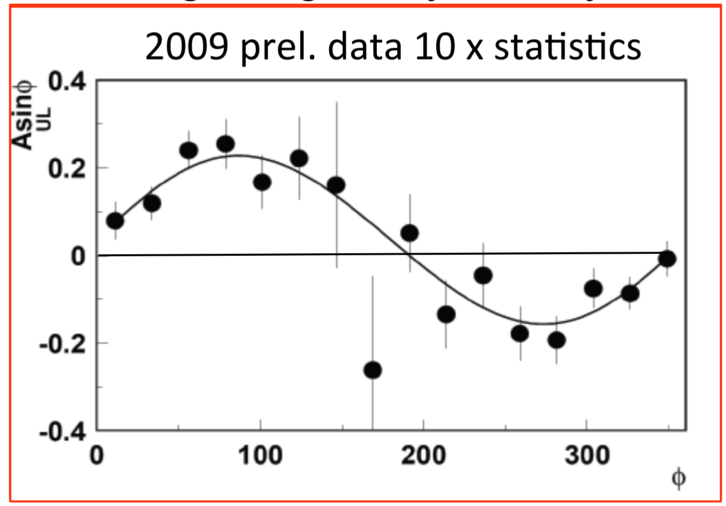
Extraction of GPDs $H, \tilde{H}$ at 6 GeV

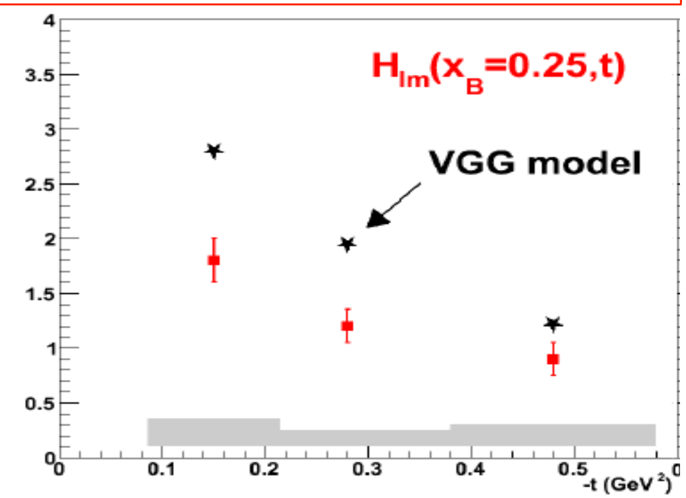
Beam asymmetry



F.X. Girod et al. (CLAS), Phys.Rev.Lett100:162002,2008
S. Chen et al. (CLAS), Phys.Rev.Lett97:072002,2006

Long. Target asymmetry



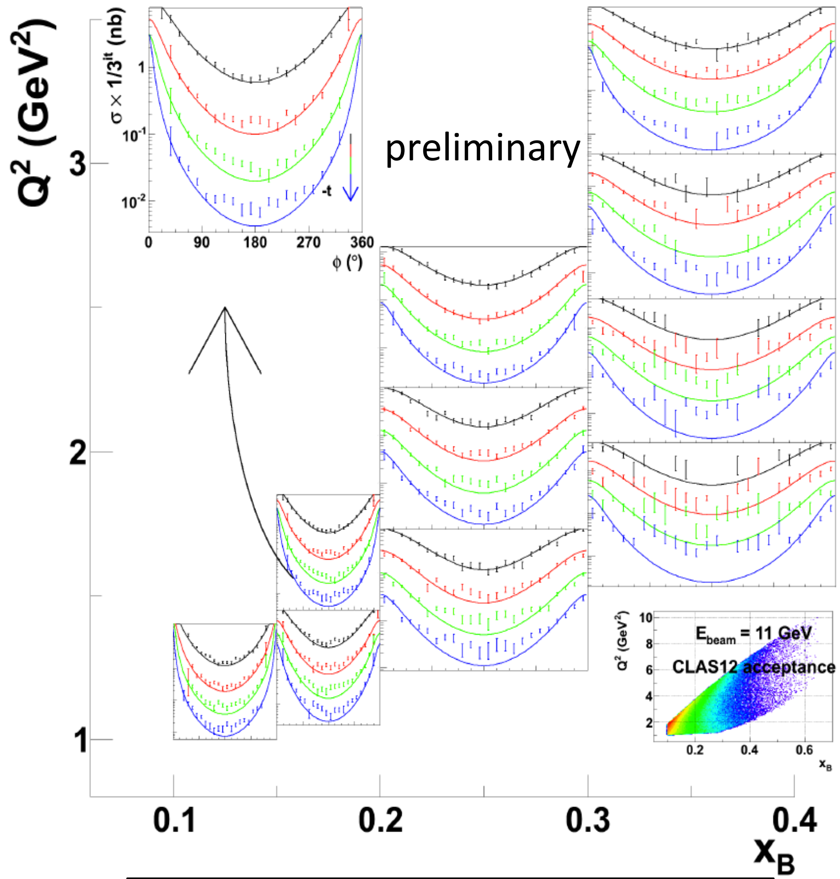


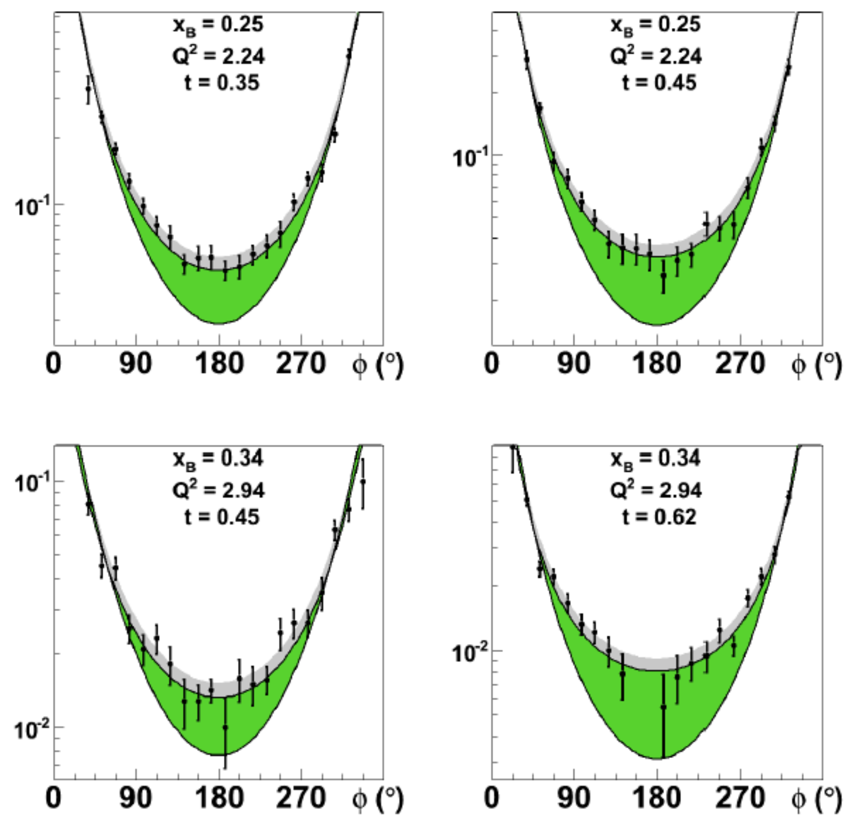
M. Guidal, Phys.Lett.B689, 156-162,2010

CLAS DVCS/BH cross sections

Large kinematical range in Q^2, x_B, t

E01-113, σ_{DVCS}, $F_1\mathcal{H} + \xi G_M \tilde{\mathcal{H}} - F_2 \frac{t}{4M^2}\mathcal{E} + \cdots$





Full exclusivity by detecting all particles (e, p, γ) in the final state.

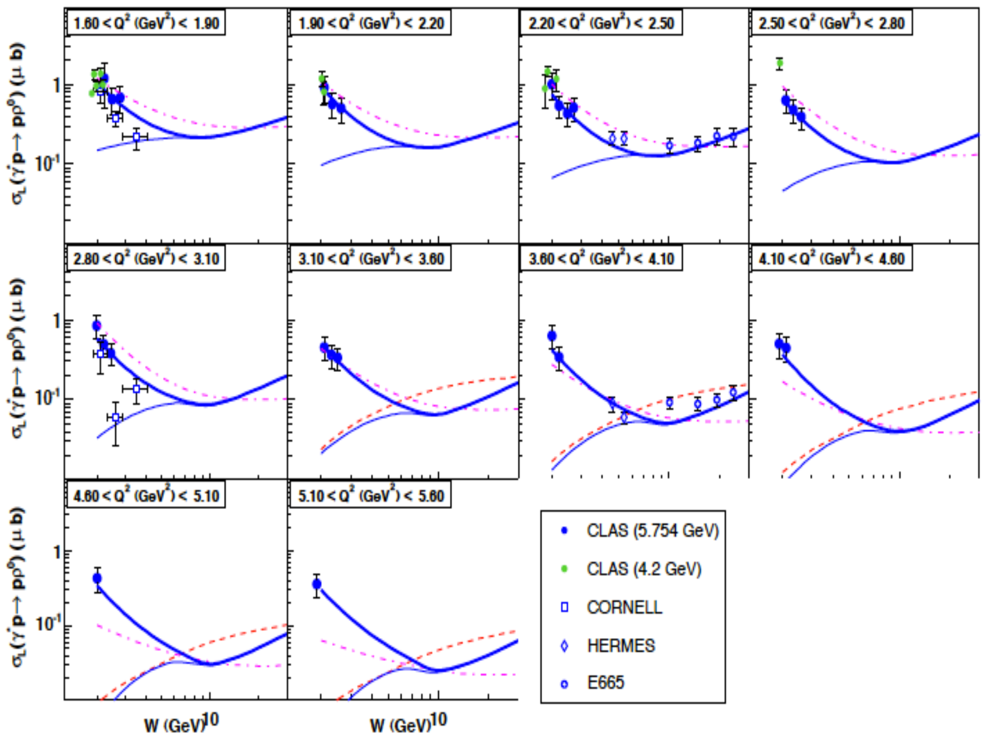
2009 data will double statistics

Office of Science
U.S. DEPARTMENT OF ENERGY

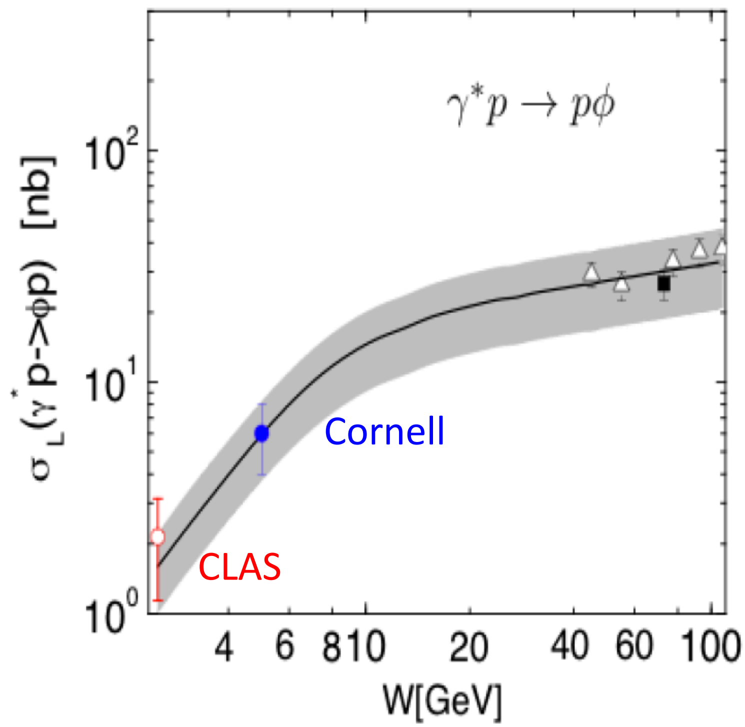
CLAS Exclusive vector mesons

ρ^0 helps the flavor separation of GPDs: 2u + d

Longitudinal cross-section separated by angular analysis in the C.O.M.
Missing strength at low W : higher-twist or missing contribution in the D-term



Gluon-GPD handbag works for ϕ's



Also longitudinal cross section data for ρ^+ production.

GPDs in DVCS experiments at JLab12

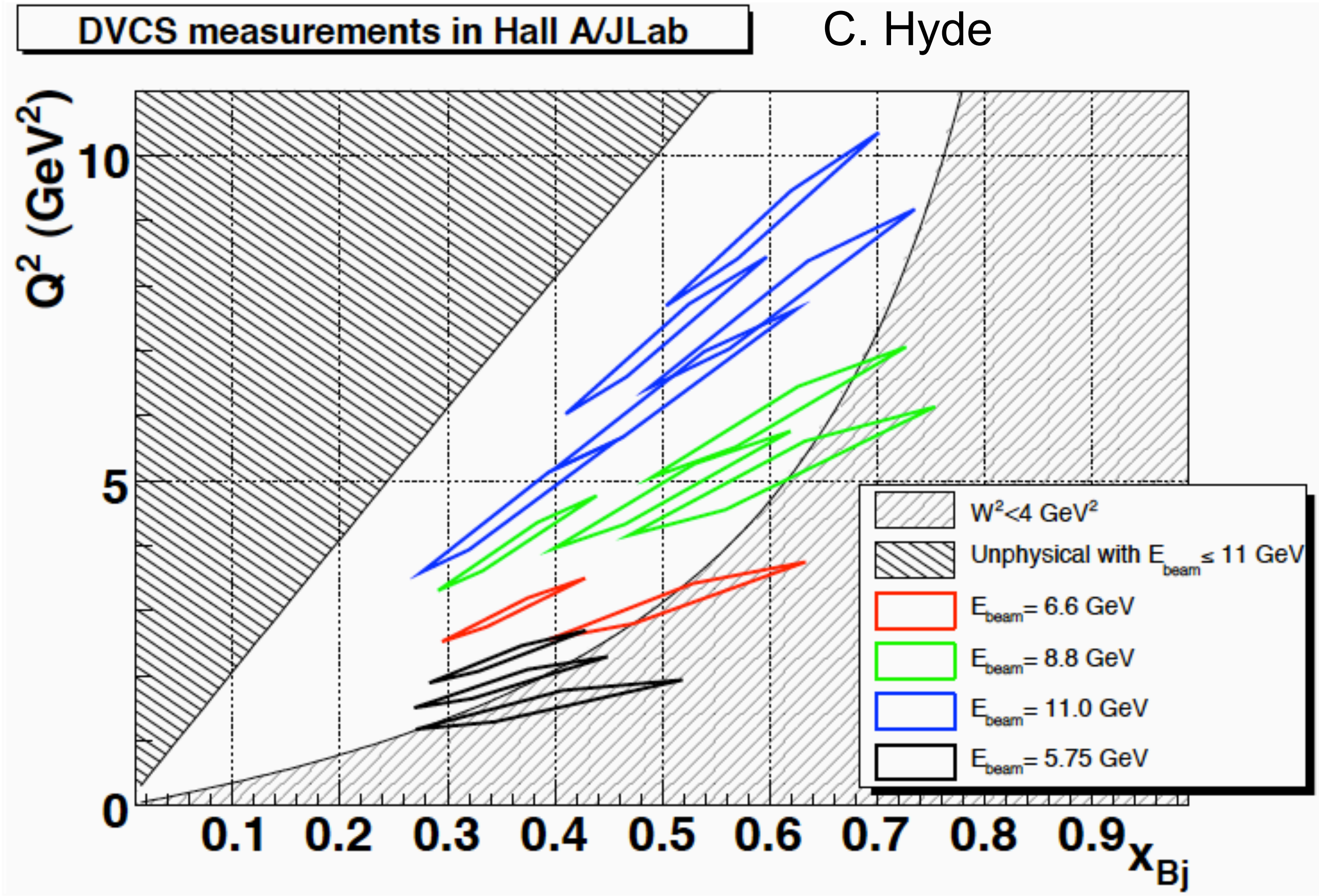
Nucleon polarization	Sensitivity to GPDs	Experiments
UP	$H, \tilde{H}, E$	E12-06-114 : γ, π^0 (A) proton E12-06-119 : γ, π^0 (B) proton E12-11-003: γ, π^0 (B) neutron
LP	$\tilde{H}, H, E$	E12-06-119 : γ, π^0 **(NH_3)** (B) proton
TP	E, H	LOI12-11-105 : γ, π^0 **(HD)** (B) proton

The JLab DVCS program will be carried out in two experimental Halls: **A & B (CLAS12)**

Hall A DVCS at 12 GeV

E12-06-114

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

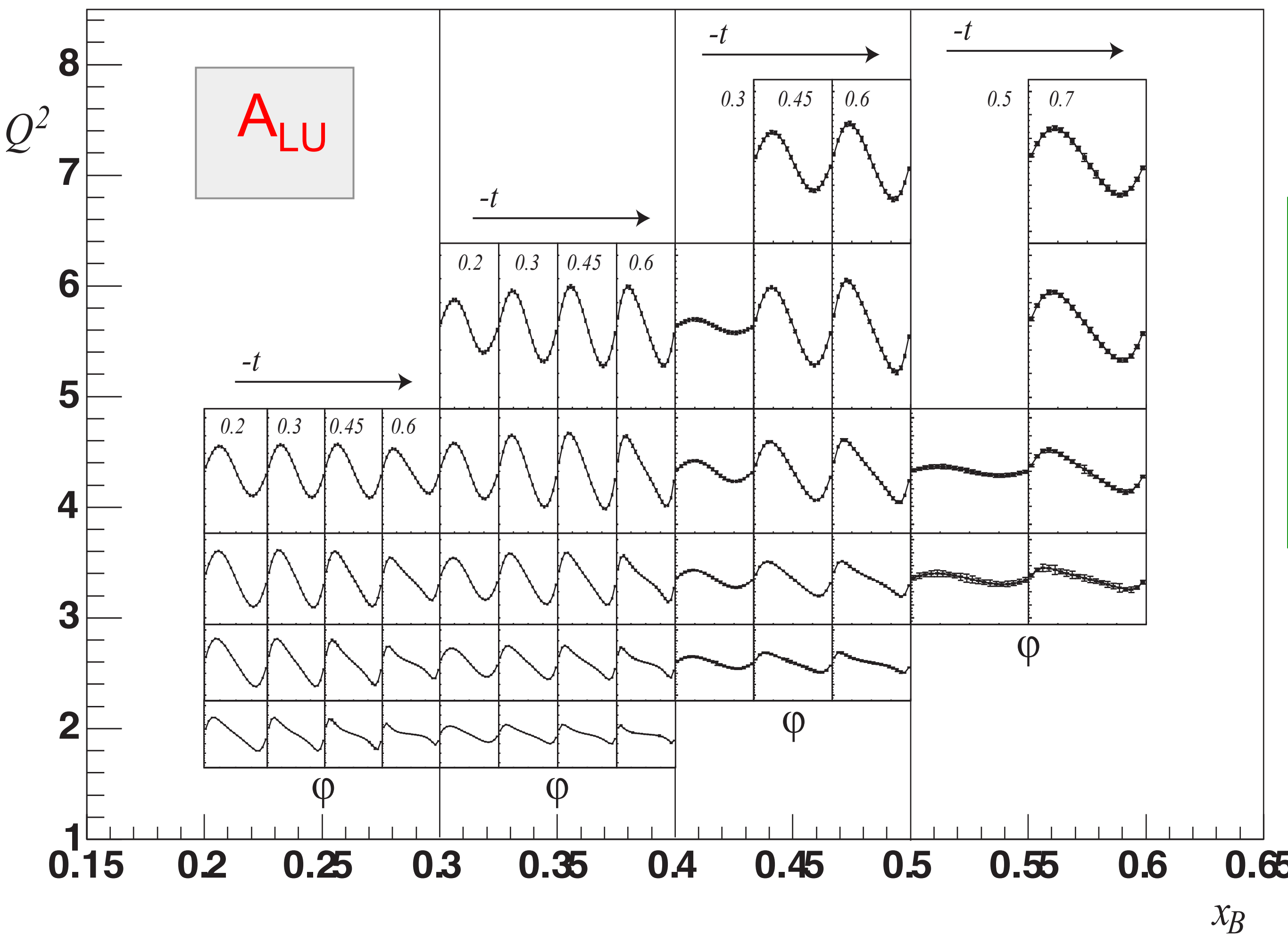


DVCS/BH A_{LU} projections on protons

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

F. Sabatié, C. Hyde

E12-06-119/CLAS12
E12-06-114/Hall A



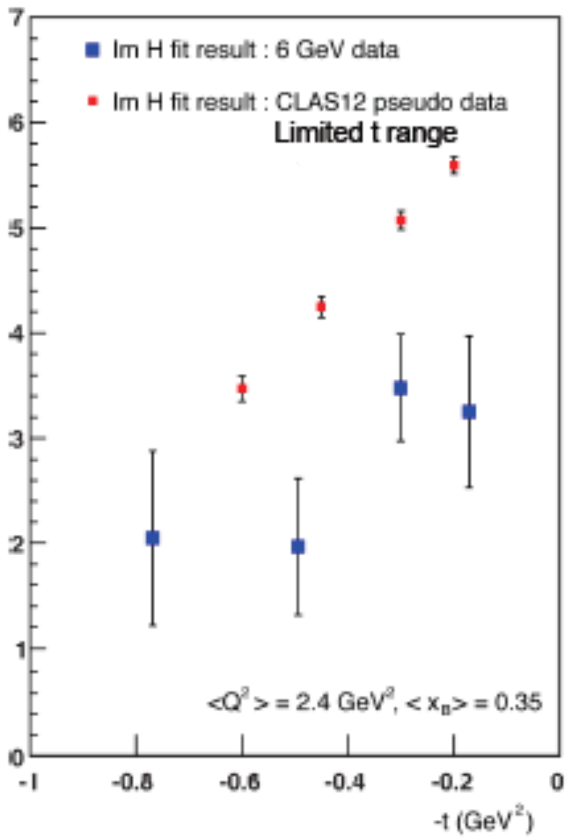
With large acceptance measure large Q^2, x_B, t ranges simultaneously.

$A_{LU}(Q^2,x_B,t)$
$\Delta\sigma(Q^2,x_B,t)$
$\sigma(Q^2,x_B,t)$

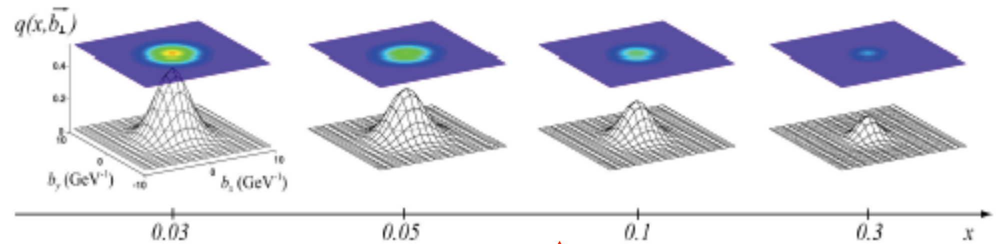
GPDs from simulated CLAS12 data

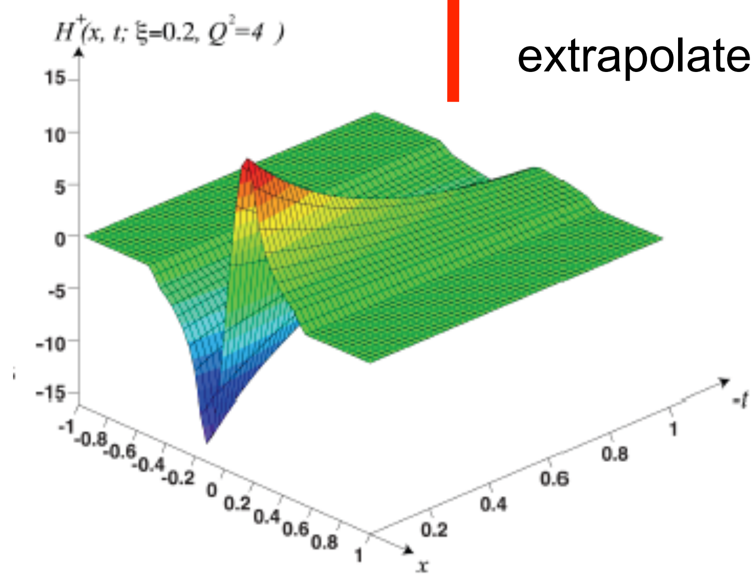
E12-06-119

GPD H only contribution



$$q(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} H(x,\xi=0,-\Delta_\perp^2)$$



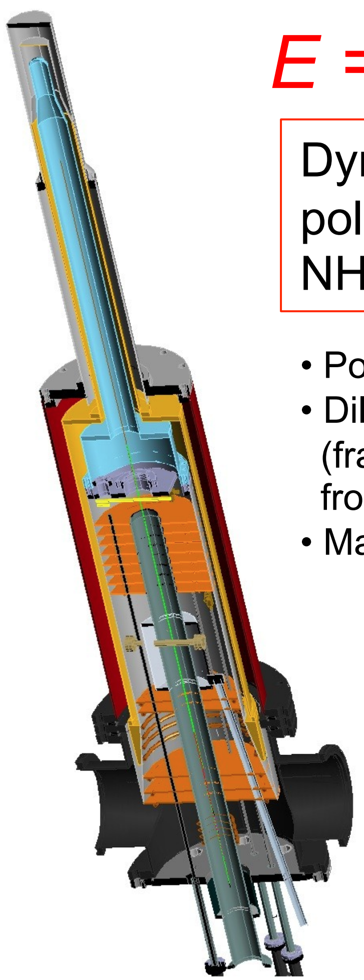


extrapolate to ξ=0

CLAS12 DVCS/BH A_{UL} on protons

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

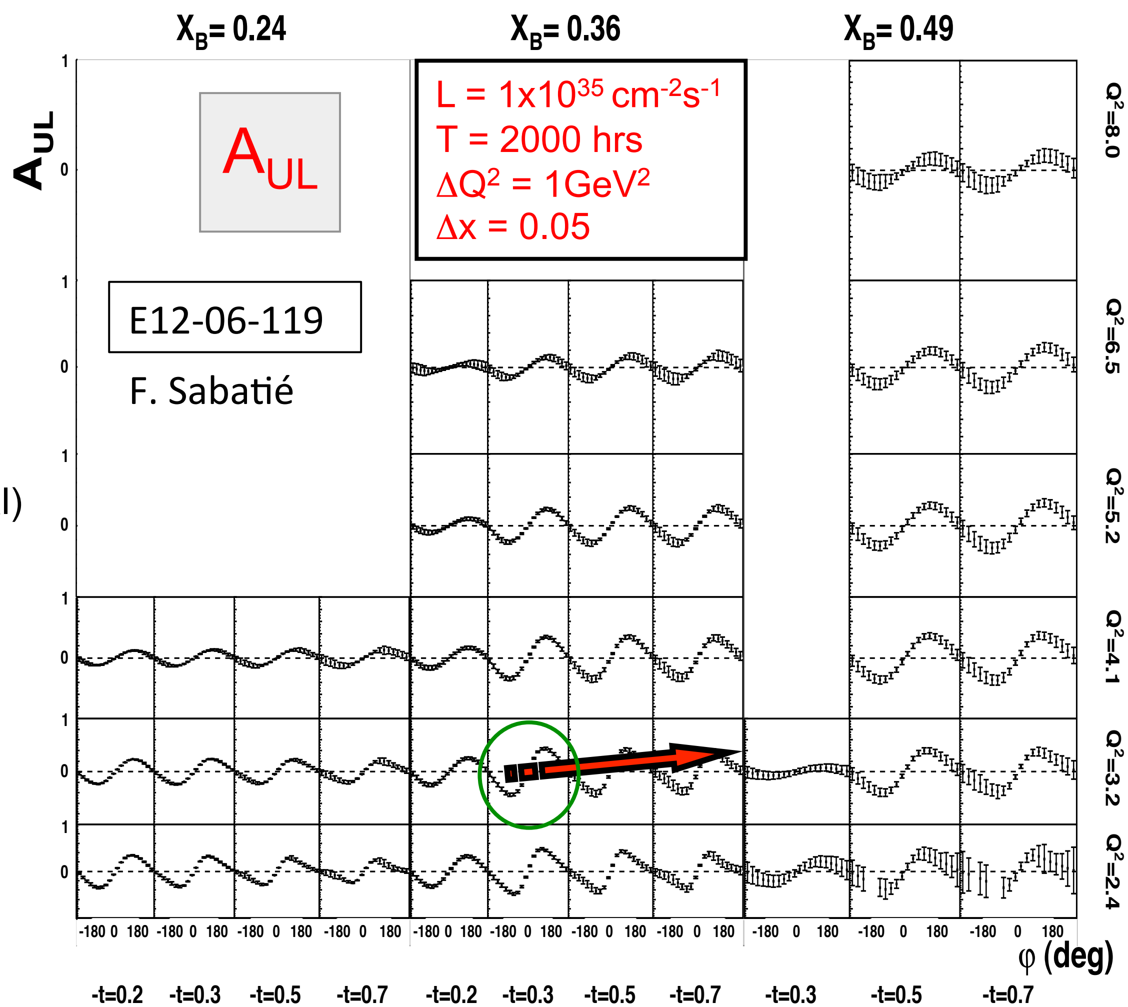
$\Delta\sigma_{UL} \sim \sin\phi \, \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$



E = 11 GeV

Dynamically polarized target NH_3, ND_3

- Polarization: 0.8
- Dilution factor: 0.15 (fraction of events from polarized material)
- Magnetic field: 5T

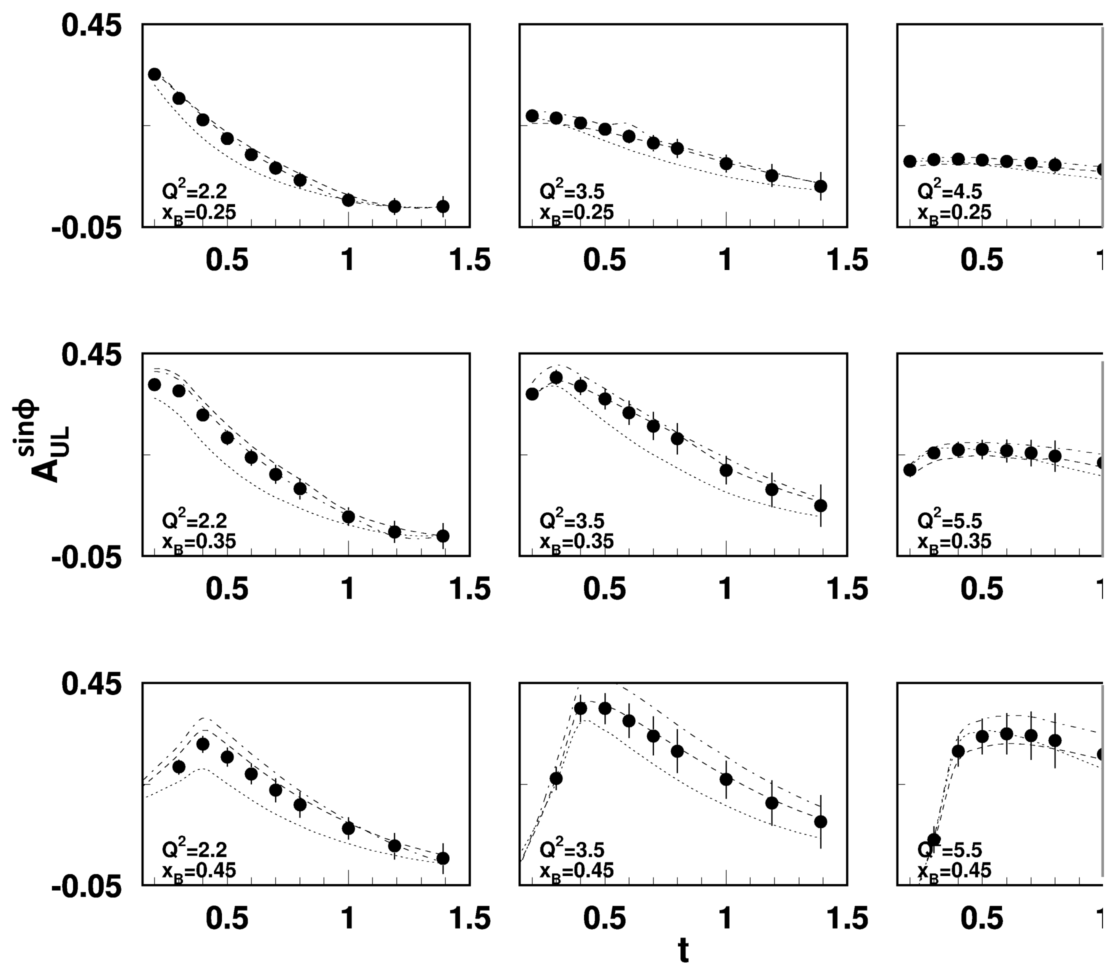


CLAS12 A_{UL} sinϕ moment on protons

E12-06-119

F. Sabatié

Spin asymmetry with longitudinally polarized proton target

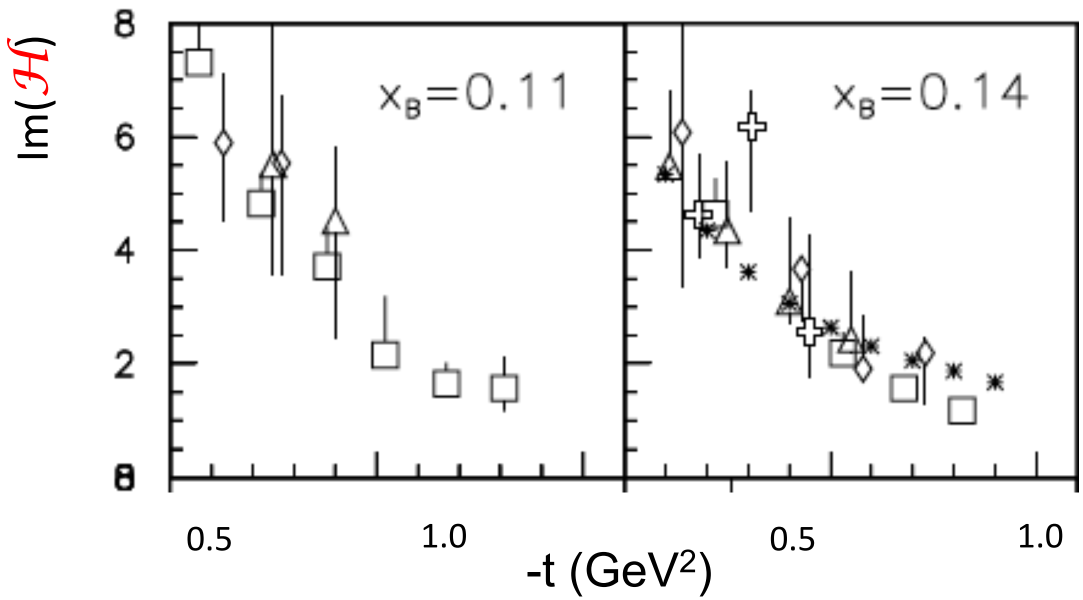


Extraction of $\mathcal{H}$ & $\tilde{\mathcal{H}}$ from A_{LU} and A_{UL}

Q^2=1.5-7.5 GeV^2

3% of expected statistics

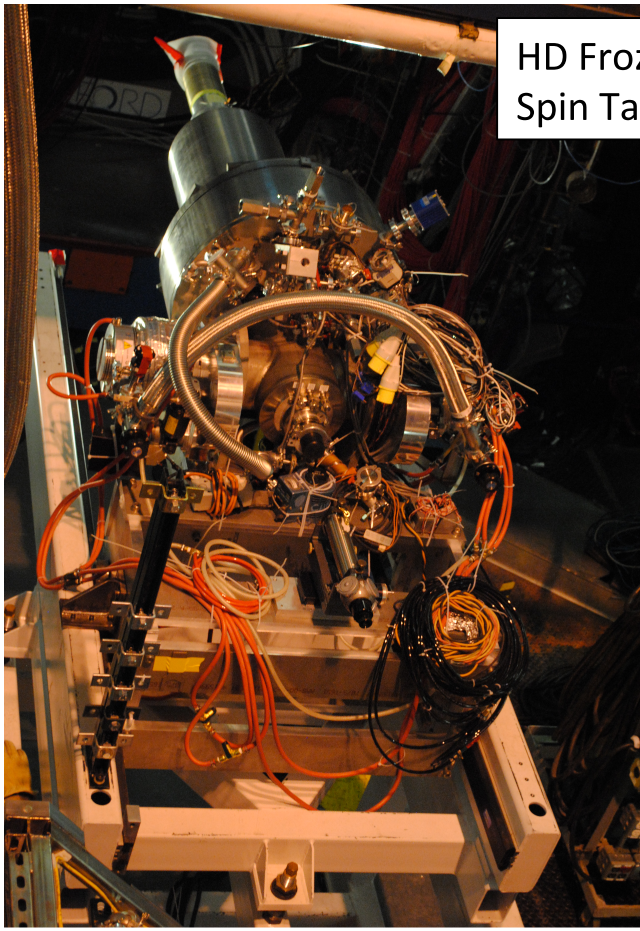
E12-06-119



M. Guidal: Model-independent analysis in leading twist

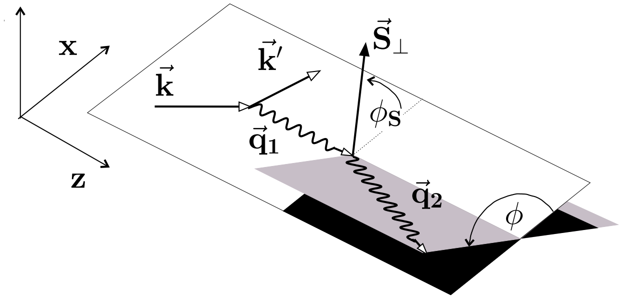
CLAS12 Target spin asymmetry A_{UT}

$\Delta\sigma \sim \cos\phi \sin(\phi-\phi_s) \mathrm{Im}\{k_1(F_2 \mathcal{H} - F_1 \mathcal{E})\} d\phi$



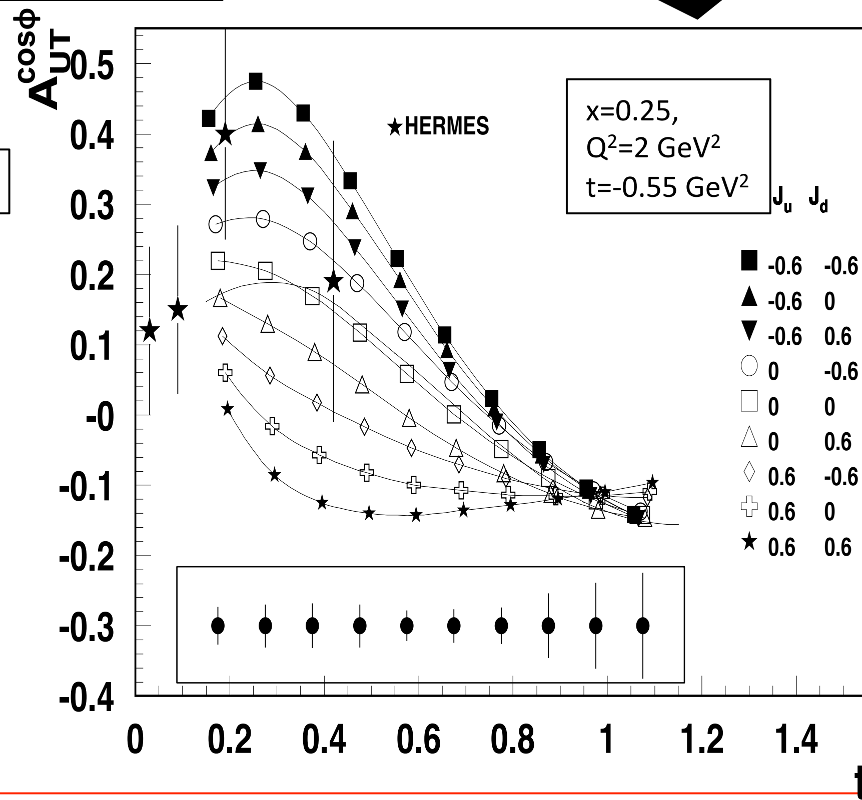
HD Frozen Spin Target

P_p=0.75
$L=10^{34} cm^{-2}s^{-1}$
2000 hrs



LOI12-11-105

L. Elouadrhiri



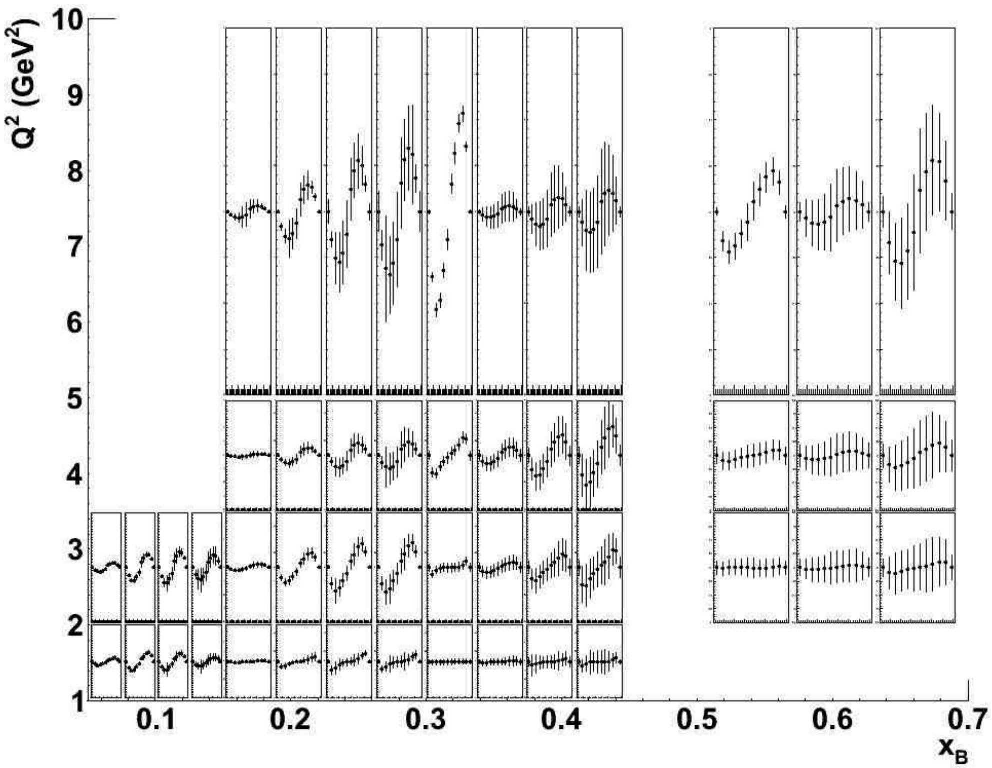
A_{UT} and A_{LT} are sensitive to the u and d-quark helicity content of the proton spin

CLAS12 DVCS/BH Beam asymmetries A_{LU} neutrons

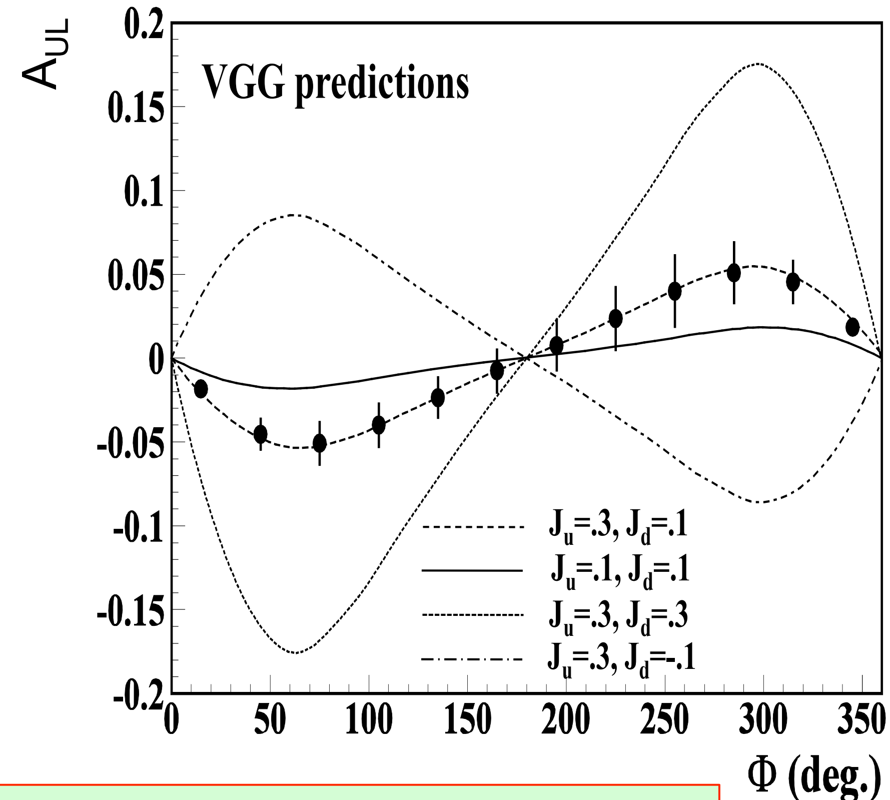
E12-11-003

S. Niccolai

Total of 588 bins in t, Q^2, x_B, ϕ



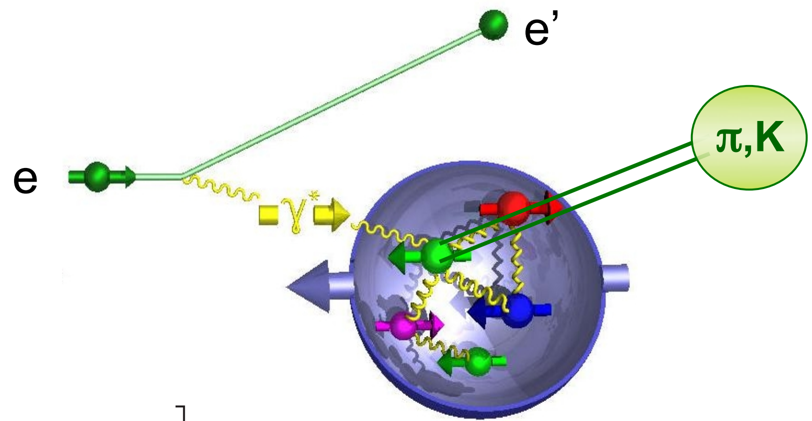
t=-0.35GeV²
Q²=2.75GeV²
x_B=0.225



A_{LU} is highly sensitive to d-quark helicity content of the neutron.

SIDIS and Transverse Momentum Distribution

SIDIS cross section in leading twist:



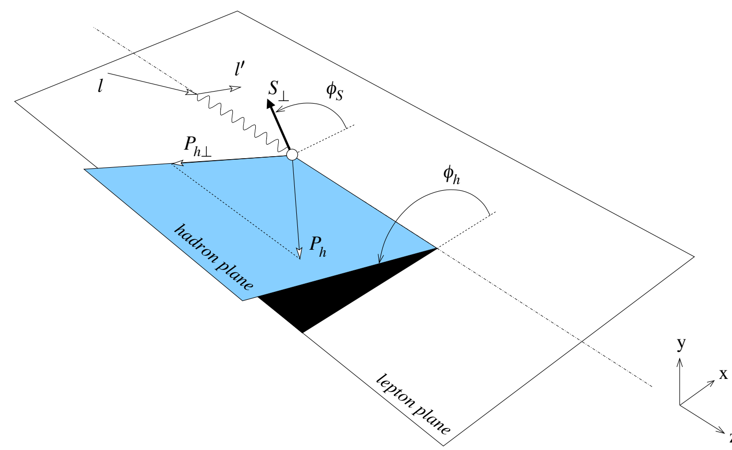
$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\,\frac{y}{2\,(1-\varepsilon)}$$

$$\times\Big\{ F_{UU,T} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + S_L\,\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}$$

$$+ S_L\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL} + |\boldsymbol{S}_T|\Big[\sin(\phi_h-\phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)}$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_T|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big]\Big\},$$



The 8 structure functions factorize into TMD parton distributions, fragmentation functions, and hard parts:

$$F_{UU} \propto f_1(x,k_\perp)\,D_1(z_h,p_\perp)\,H_{UU}(Q^2)$$
$$F_{LL} \propto g_{1L}(x,k_\perp)\,D_1(z_h,p_\perp)\,H_{LL}(Q^2)$$
$$F_{UL} \propto h_{1L}^\perp(x,k_\perp)\,H_1^\perp(z_h,p_\perp)\,H_{UL}(Q^2),$$

Integrals over transverse momentum of initial and scattered parton

A full program to extract L.T. TMDs from measurements requires separation of the structure function using polarization, and coverage of a large range in x, z, P_T along with sensitivity to Q^2, and the flavor separation in u, d, s quarks.

JLab TMD Proton Program @ 12 GeV

Leading twist TMD parton distributions:
information on correlations between
quark orbital motion and *spin*

CLAS12

- E12-06-112: π^+,π^-,π^0
  E12-09-008: K^+, K^-, K^0
- E12-07-107: π^+,π^-,π^0
  E12-09-009: K^+,K^-,K^0
- C12-11-111: π^+,π^-,π^0
  K^+, K^-

H_2, NH_3, HD

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

Hall C | **Hall A**

- E12-09-017: π^+,π^-, K^+,K^-
  C12-11-102: π^0 — HMS SHMS
- C12-11-108: π^+,π^- — Solid

H_2 | NH_3

The TMD program will map the 4D phase space in Q^2, x, z, P_T

CLAS12 A_{UU} for pions on unpolarized protons.

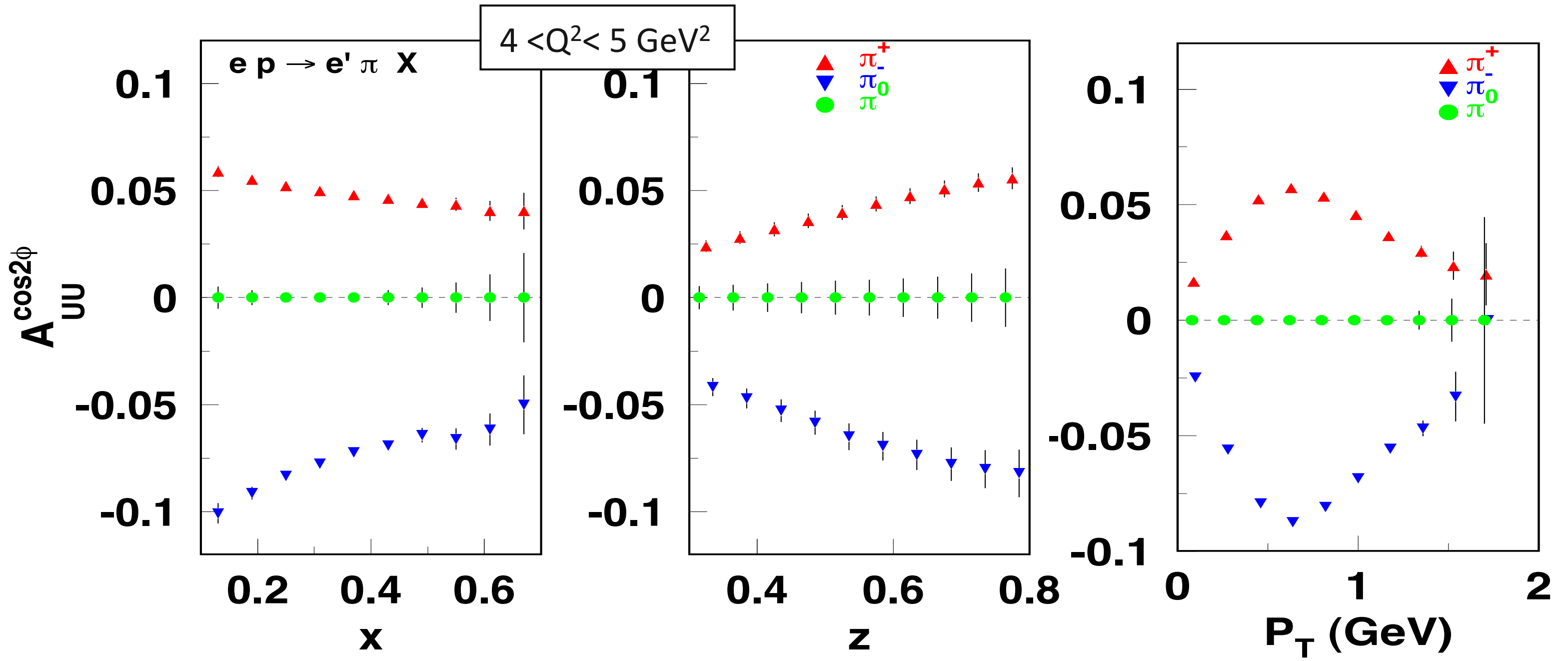
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

E12-06-112

H. Avakian

$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h}\Big\},$$

Measures momentum distribution of trans. pol. quarks in unpol. nucleon



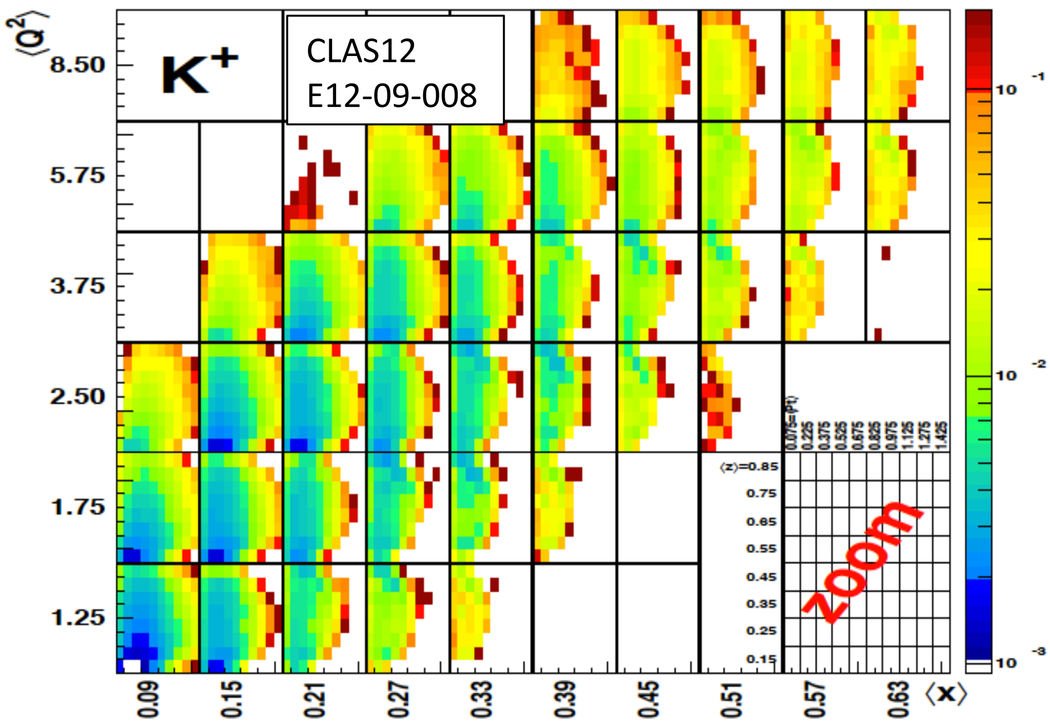
Wide x and P_T range needed to map out phase space in longitudinal and transverse quark momentum

SIDIS pion/kaon on unpolarized protons.

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 $h_{1T}^\perp$

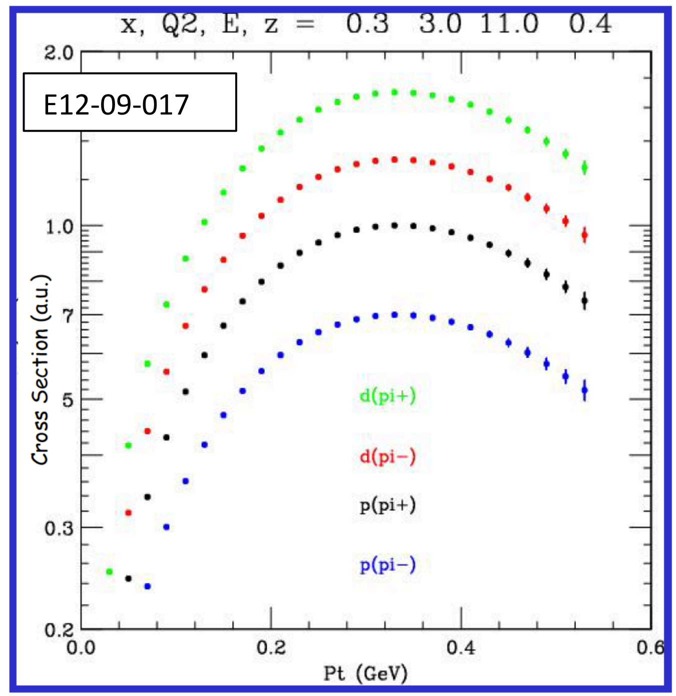
$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \right\},$$

E12-09-008	H. Avakian, P. Rossi
E12-09-017	R. Ent



Hall C: Precise measurement in small P_T range

(Kinematics II, z = 0.4 bin only)



Extraction of $f_1\,(x,z^2,b_T^2)$

Project x-section onto b_T-space to avoid convolution + Bessel weighting

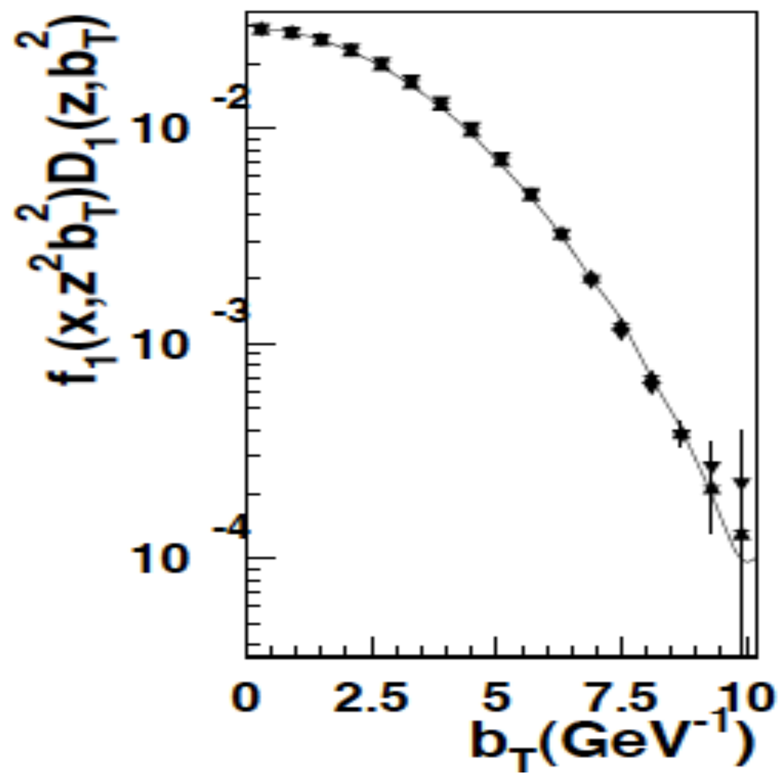
$$\int_0^\infty d|\boldsymbol{P}_{h\perp}|\;|\boldsymbol{P}_{h\perp}|\,J_0(|\boldsymbol{P}_{h\perp}||\boldsymbol{b}_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|\boldsymbol{P}_{h\perp}|d|\boldsymbol{P}_{h\perp}|}\right]$$

Boer, Gamberg, Musch, Prokudin, arXiv:1107.5294

$$\tilde{f}_1^q(x, z^2 b_T^2)\,\tilde{D}_1^{q\to\pi}(z, b_T^2)$$

- provides a model independent way to study kinematical dependences of TMDs
- requires wide range in hadron P_T

Example of simulated data with CLAS12



CLAS12 A_{UL} on longitudinally polarized target

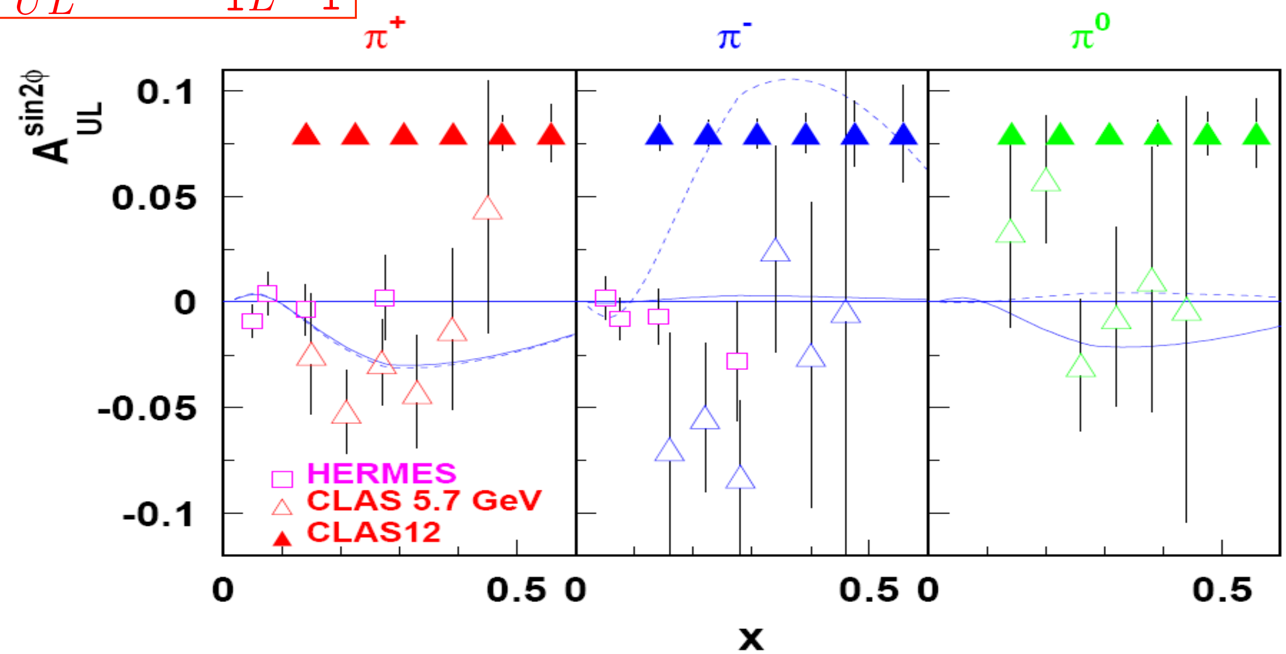
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

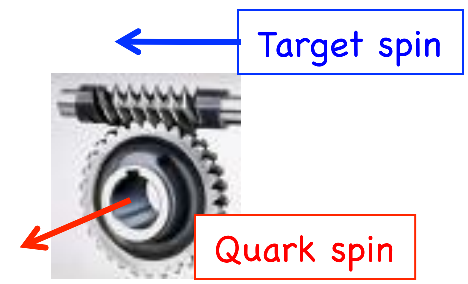
$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp}$$

The Kotzinian-Mulders function measures the momentum distribution of transversely polarized quarks in a longitudinally polarized nucleon.

E12-09-008

H. Avakian





- This is the only leading twist azimuthal moment for longitudinally polarized target. The sin2ϕ moment is sensitive to spin-orbit correlations.

CLAS12 A_{LL} in double polarization

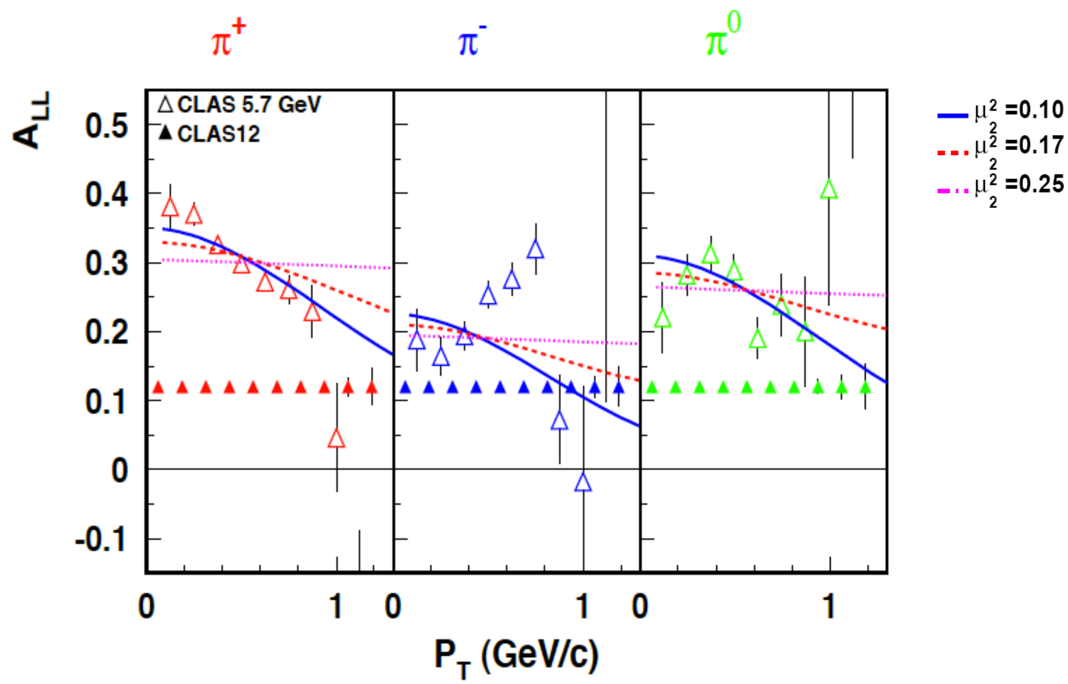
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Transverse momentum dependence of longitudinally polarized quarks in longitudinally polarized protons.

M.Anselmino et al Phys.Rev.D74:074015,2006

E12-07-107

H. Avakian
P. Rossi



H. Avakian et al, (CLAS), Phys.Rev.Lett. 105 (2010) 262002

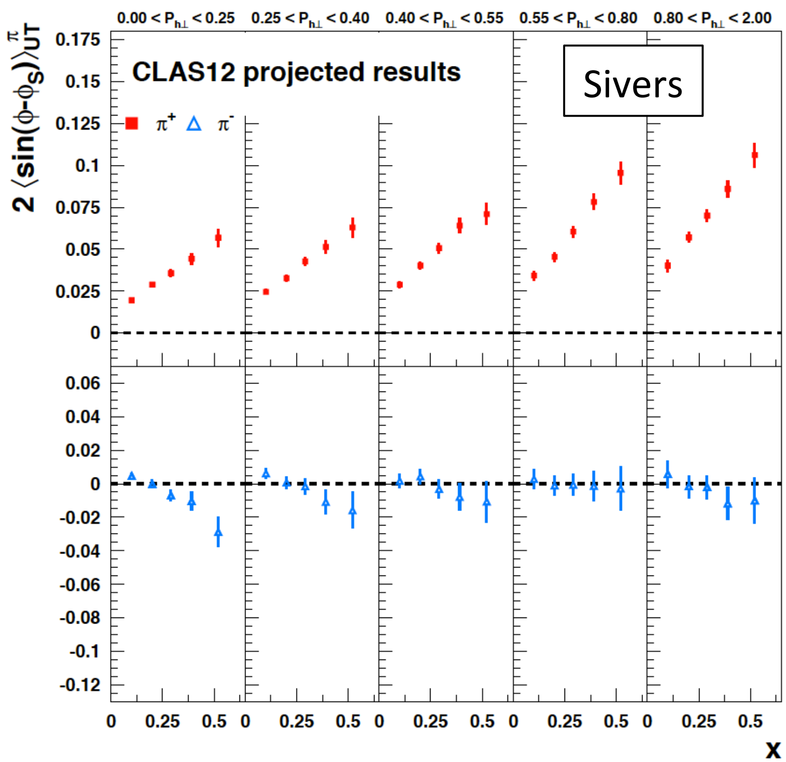
The double polarization asymmetry is sensitive to the difference in the k_T distribution of quarks with spin orientation parallel and anti-parallel to proton spin.

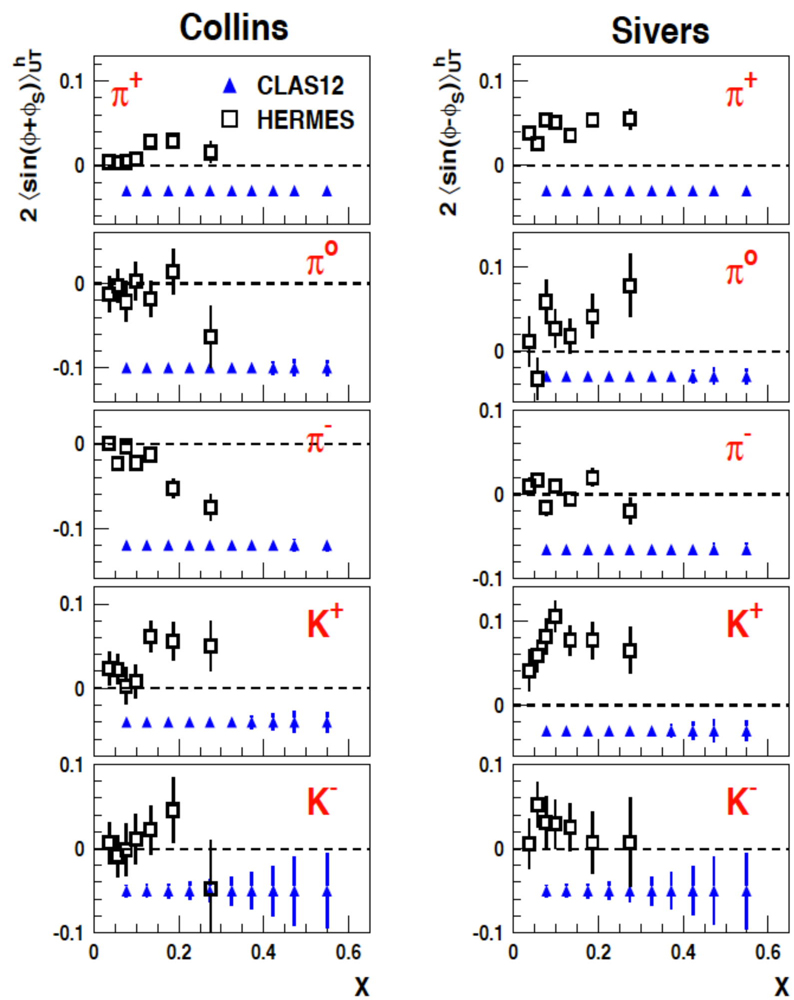
CLAS12 A_{UT} with transverse proton target

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 $h_{1T}^{\perp}$

C12-11-111

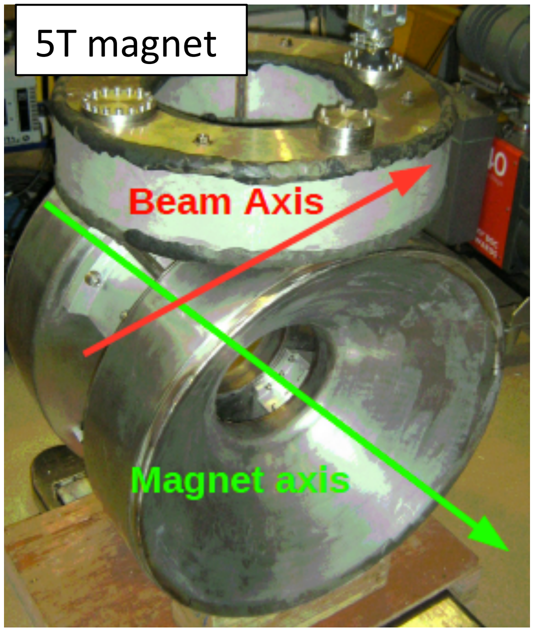
M. Contalbrigo





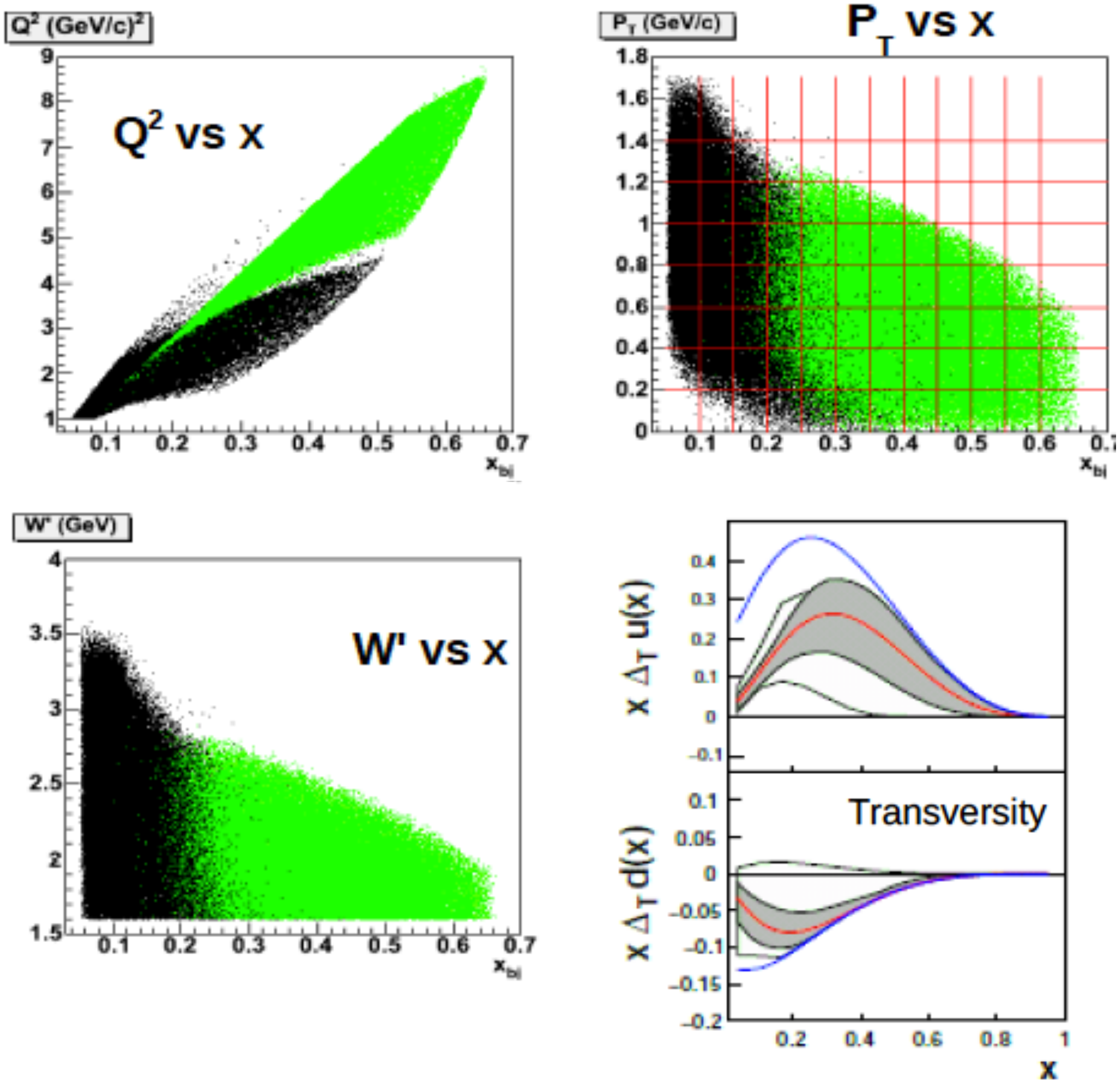
The high statistics allows for x-P⊥ bins

SOLID A_{UT} with transverse proton target



E12-11-108

K. Allada



JLab TMD ^{3}He Program @ 12 GeV

Leading twist TMD parton distributions:
information on correlations between
quark orbital motion and *spin*

Quark spin polarization

Nucleon polarization

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 $h_{1T}^{\perp}$

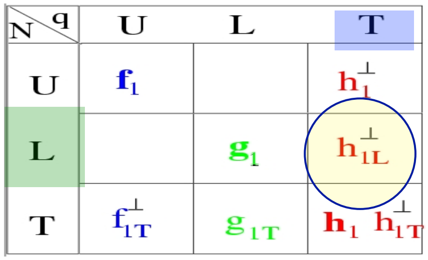
Hall A

E12-07-007: π^+, π^- — Solid

E10-006: π^+,π^- — Solid
E12-09-018: π^+,π^- , K^+,K^- — SBS

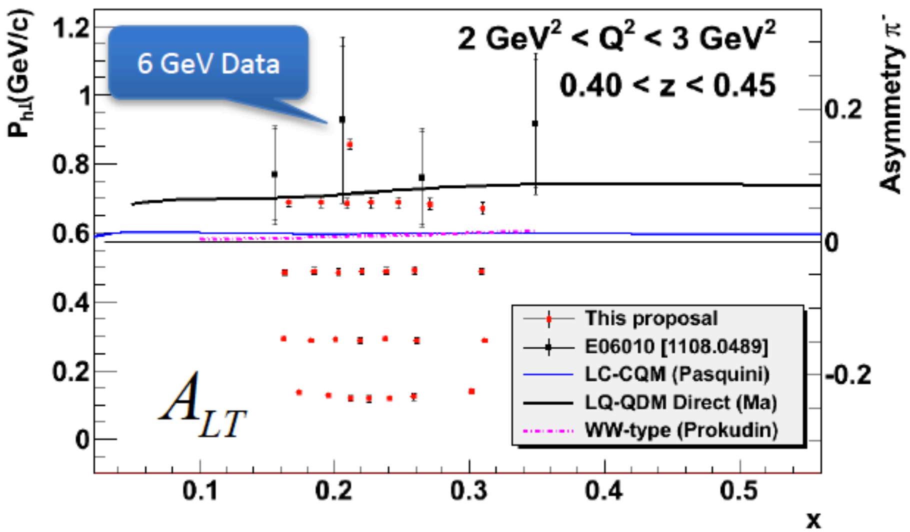
^{3}He

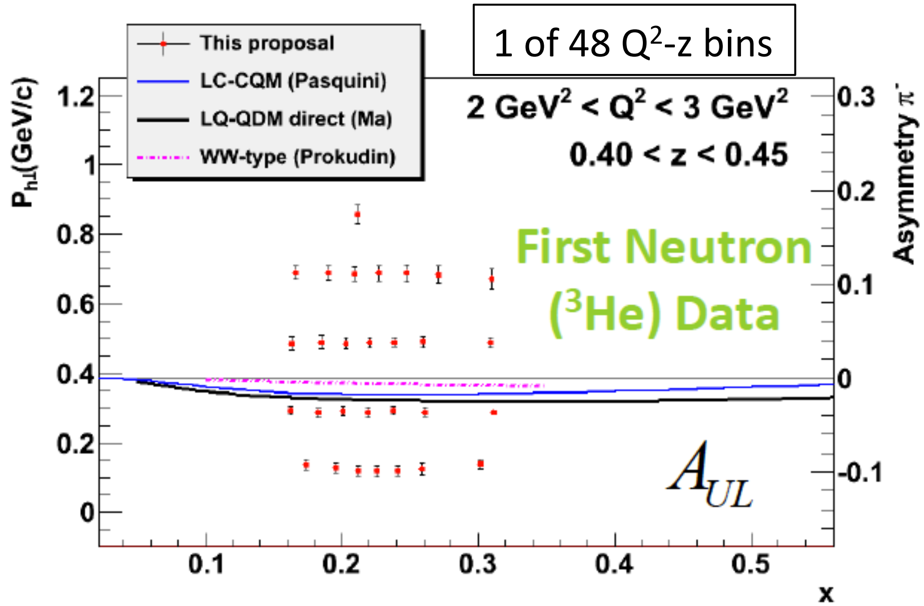
SOLID A_{UL} on ^{3}He



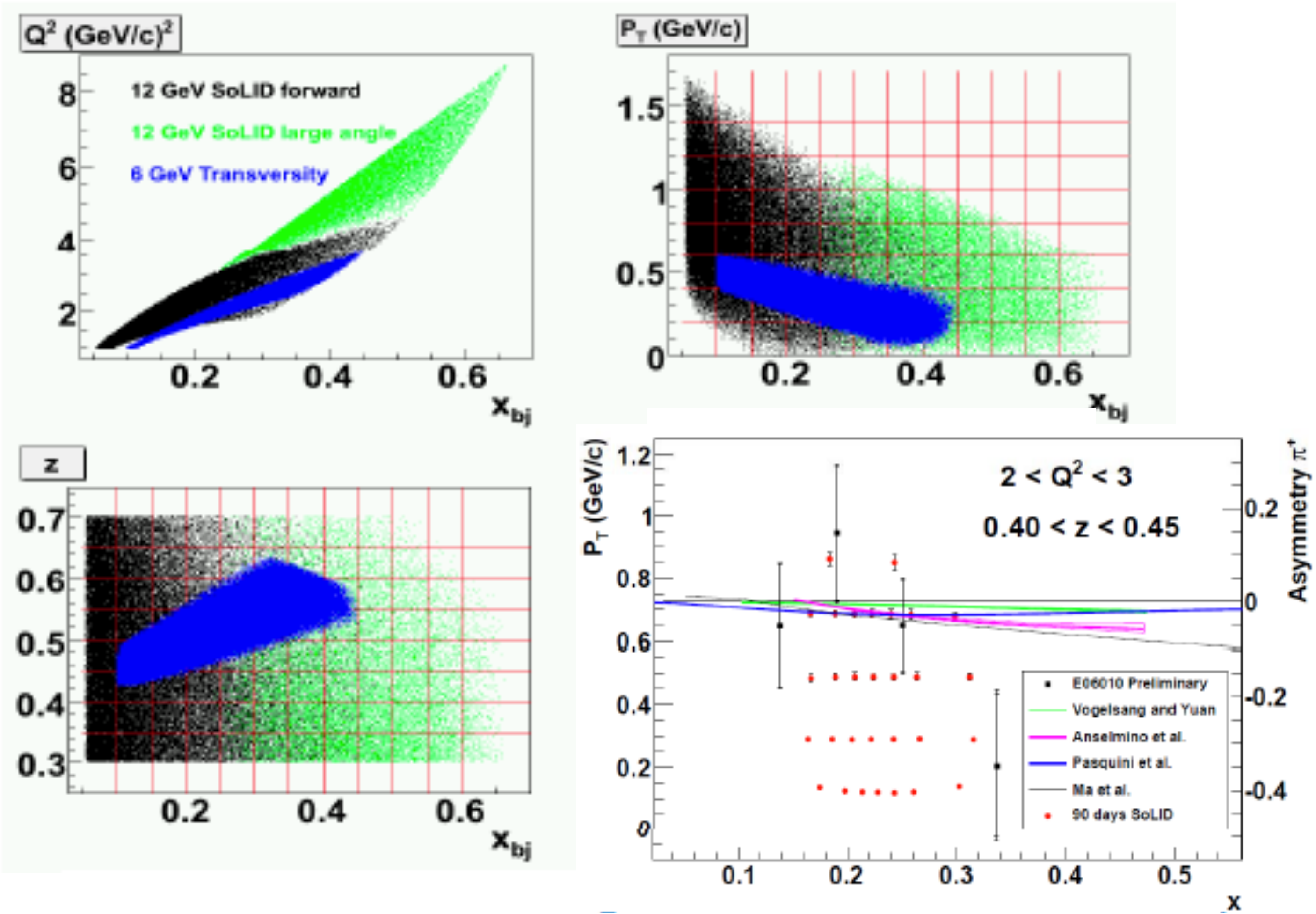
E12-11-007

$e^3He \rightarrow e\pi^- X$





SOLID A_{UT} on ^{3}He Target

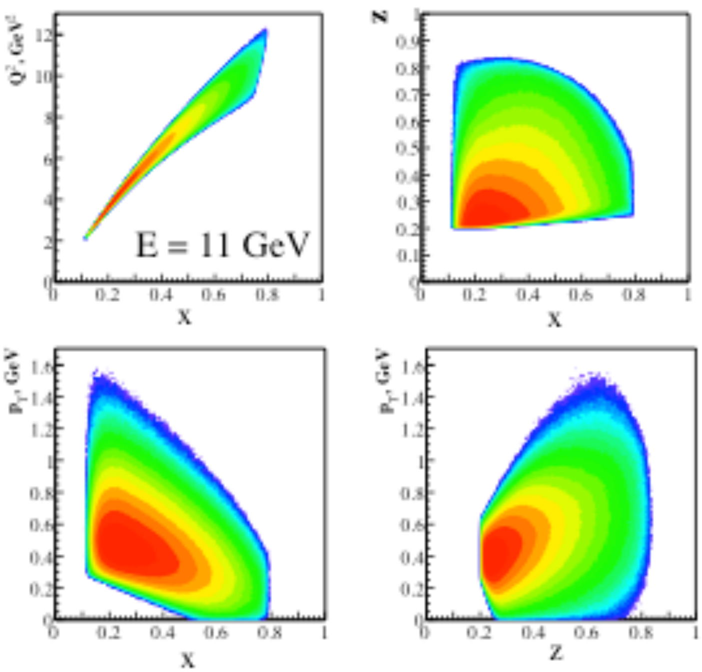


1/48 bins in Q^2,z

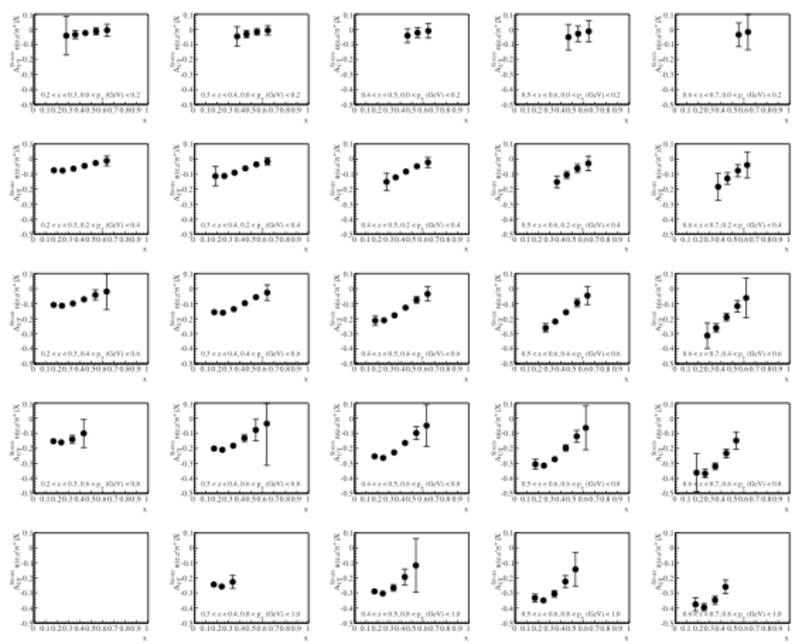
Office of Science
U.S. DEPARTMENT OF ENERGY

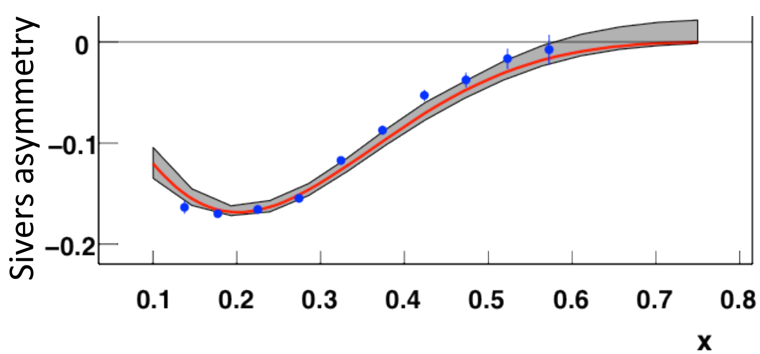
SBS/BB A_{UT} on ^{3}He Target

^{3}He(e,e'$\pi^{+,-,o}$), ^{3}He(e,eK$^{+,-}$)



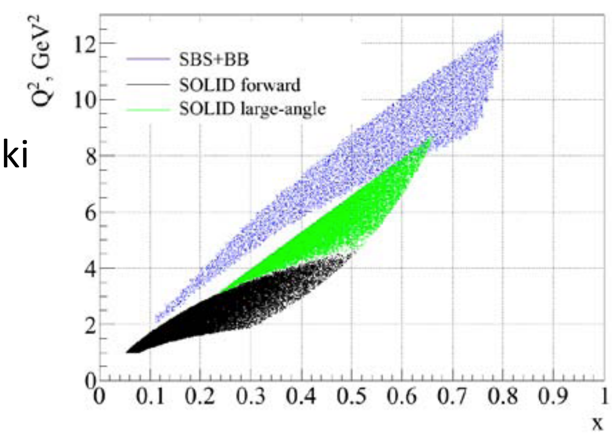
n(e,e'π^+)





C12-09-018

B. Wojtsekhowski



JLab TMD D_2 Program @ 12 GeV

Leading twist TMD parton distributions:
information on correlations between
quark orbital motion and *spin*

CLAS12

E09-008: π^+, π^-, π^0 K^+, K^-, K^0

E07-107: π^+, π^-, π^0
E09-009: K^+, K^-, K^0

D_2, ND_3

Quark spin polarization (columns) / Nucleon polarization (rows)

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 $h_{1T}^\perp$

Hall C

E12-09-017: π^+, π^-, K^+, K^-
C12-11-102: π^0

HMS
SHMS

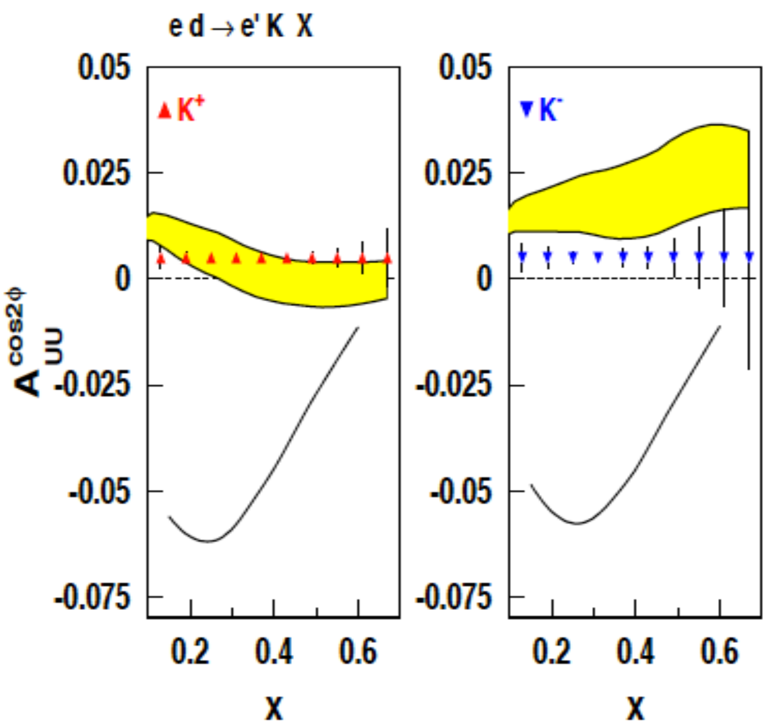
D_2

The JLab TMD program will chart the 4D phase space in Q^2, x, z, P_T

CLAS12 Kaon A_{UU} on unpolarized D_2

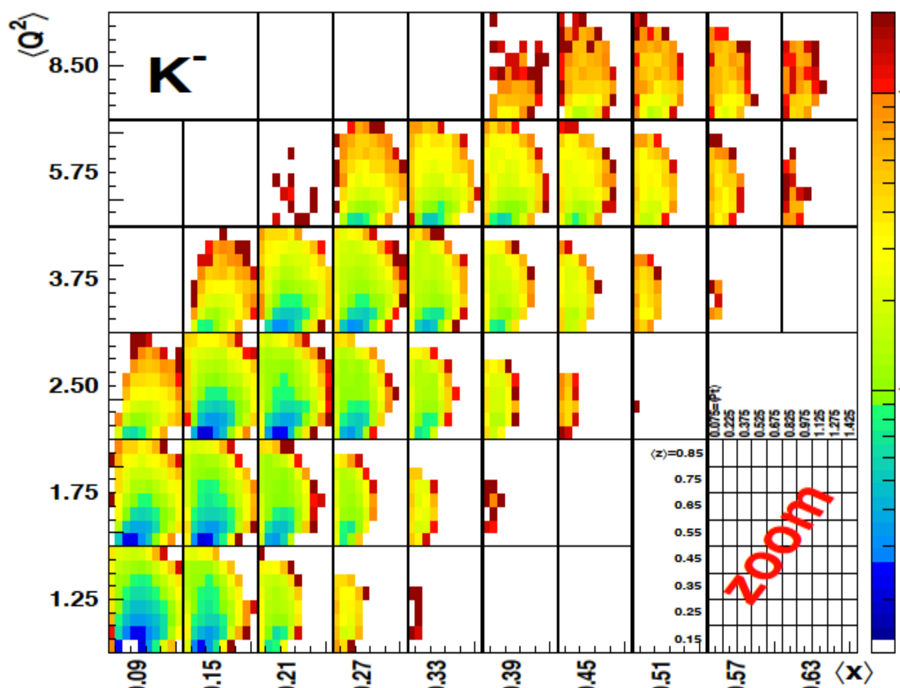
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h}\right\},$$



CLAS12 acceptance

P. Rossi

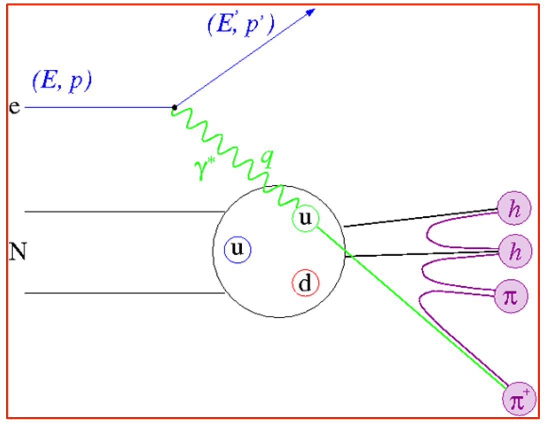


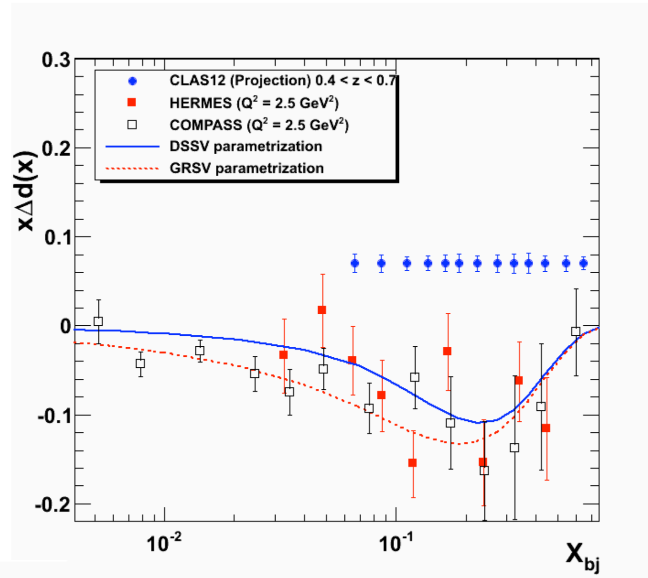
CLAS12 PDFs in π/K SIDIS

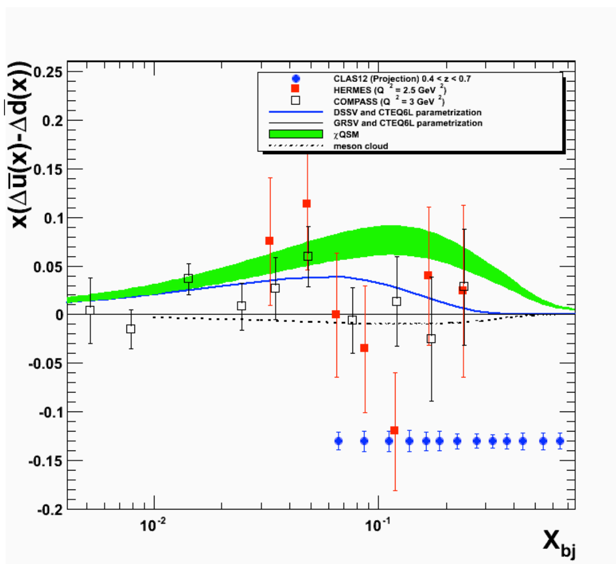
Extraction of the individual contributions of quarks and anti-quarks to the nucleon spin. Use polarized & unpolarized proton and deuteron targets.

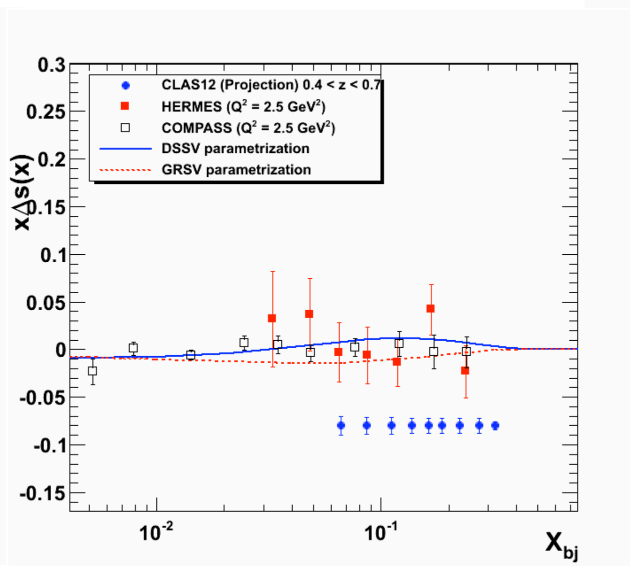
E12-09-002

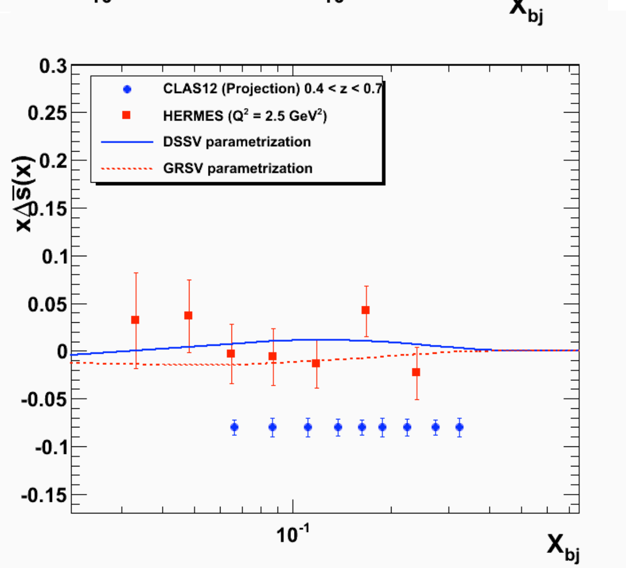
K. Hafidi











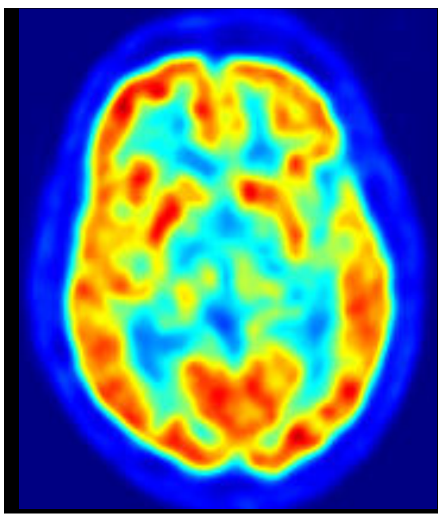
Conclusions

- Several detectors under construction or proposed – CLAS12, SBS, SOLID to carry out 3D nucleon imaging program
- Jlab12 has a well defined and broad experimental program to measure DVCS in the full phase space available at 12 GeV: $Q^2 < 9GeV^2$, $0.5<x_B< 0.7$, $-t < 2.5GeV^2$.
- CLAS12 is the major detector system to measure DVCS cross section and target polarization observables
- High statistics data are expected from Hall A for DVCS cross sections in reduced kinematics
- JLab12 has a broad program defined to measure TMDs in 4D phase space Q^2, x_B, z, P_T
- Use of full acceptance detectors with excellent Kaon identification essential for complete program
- Use of polarized proton (NH_3) and neutron (ND_3, ^3He) targets with longitudinal and transverse polarization are available for complete program

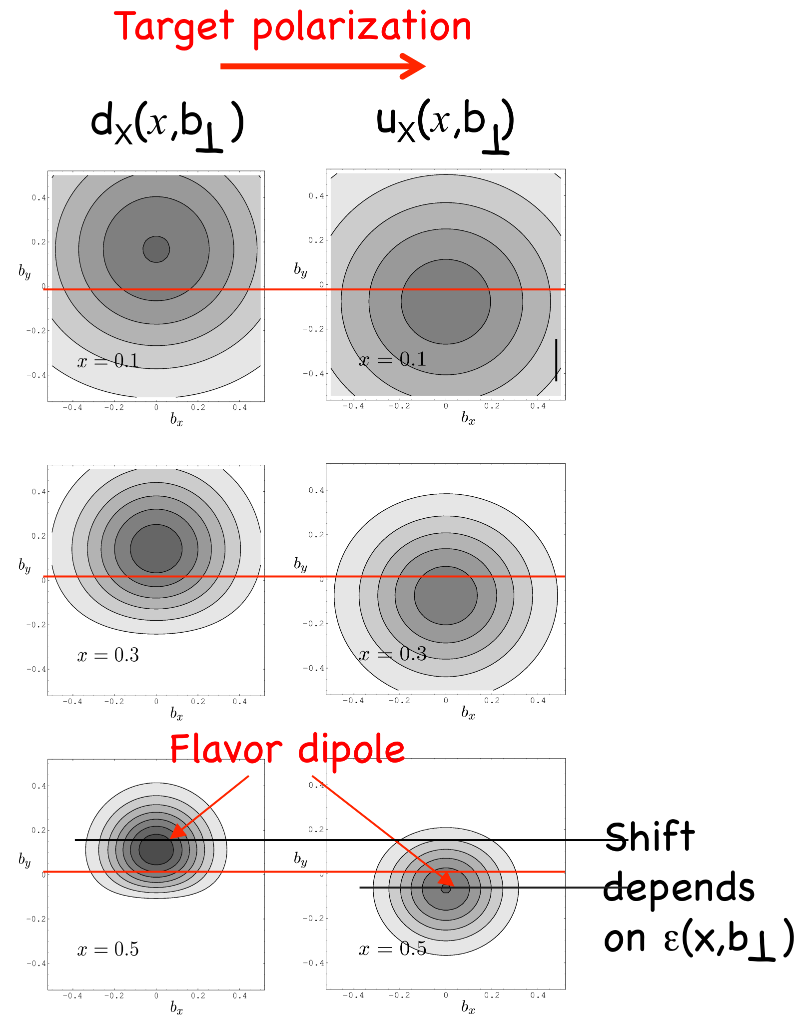
Promise of GPDs & TMDs: Imaging of the Proton

$$\varepsilon(x,\mathrm{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp b_\perp} E_q(x,\Delta_\perp)$$

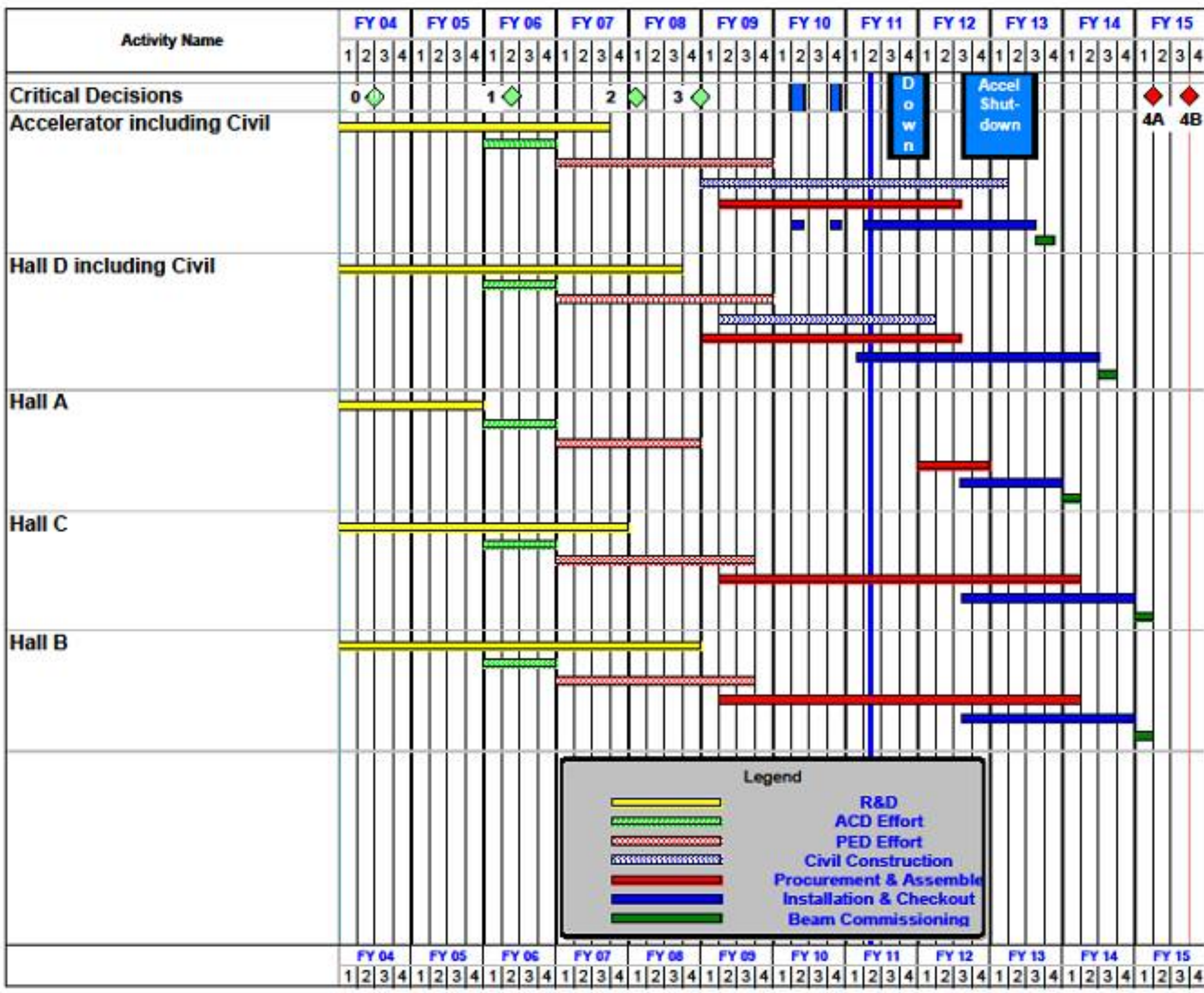
Cat scan of the human brain



TMDs extend the image to include the quarks orbital motion.



12 GeV Upgrade Schedule



Two short parasitic installation periods in FY10

6-month installation May – Oct 2011

12-month installation May 2012 – May 2013

Hall A commissioning start October 2013

Hall D commissioning start April 2014

Halls B/C commissioning start October 2014

Project Completion June 2015