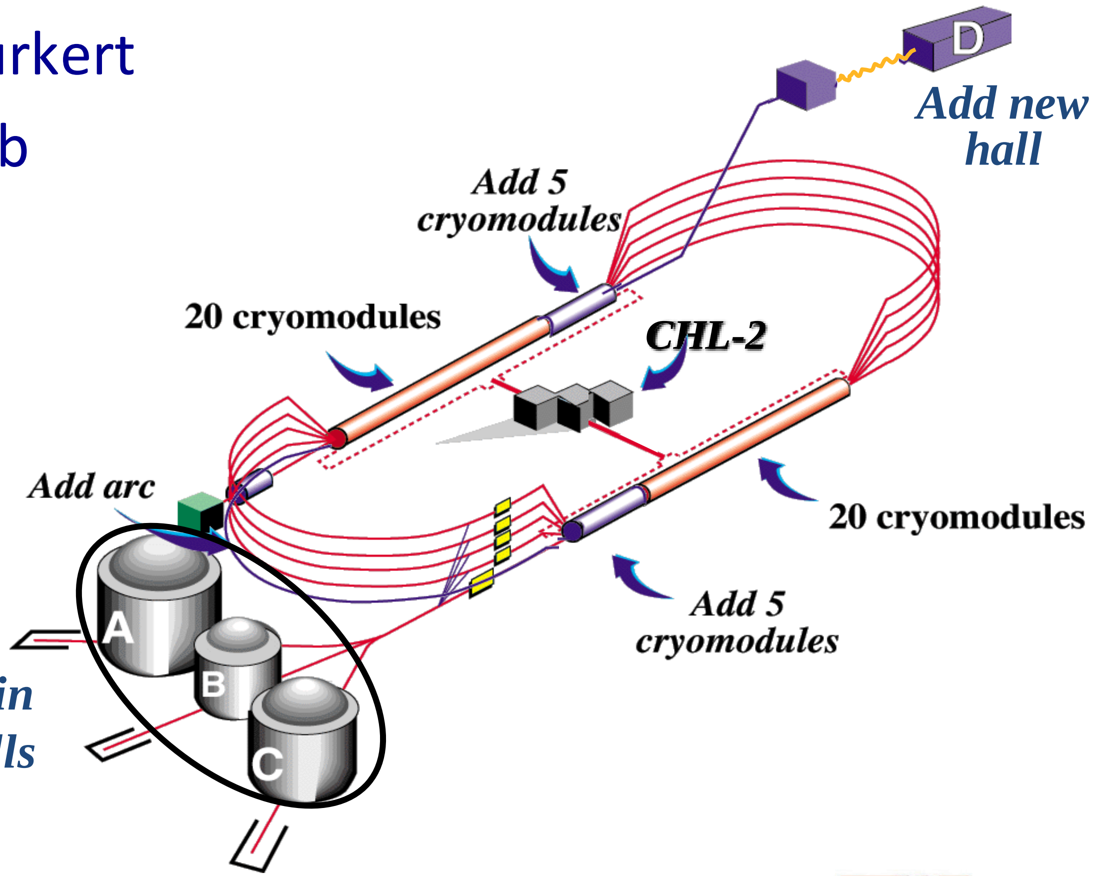
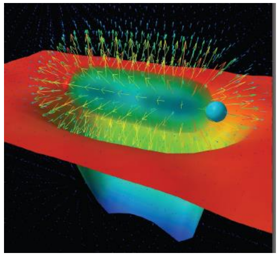
The JLab 12 GeV Project

Volker D. Burkert
Jefferson Lab

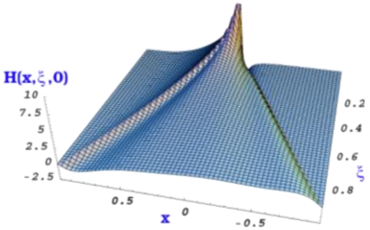


The science program at JLab @ 12GeV

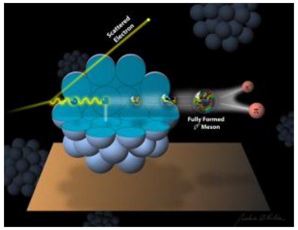
- Quark confinement and the role of the glue in meson and baryon spectroscopy



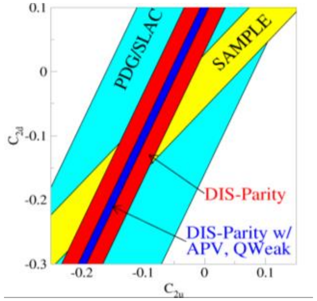
- The 3D structure of the nucleon – from form factors and PDFs to GPDs and TMDs



- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons



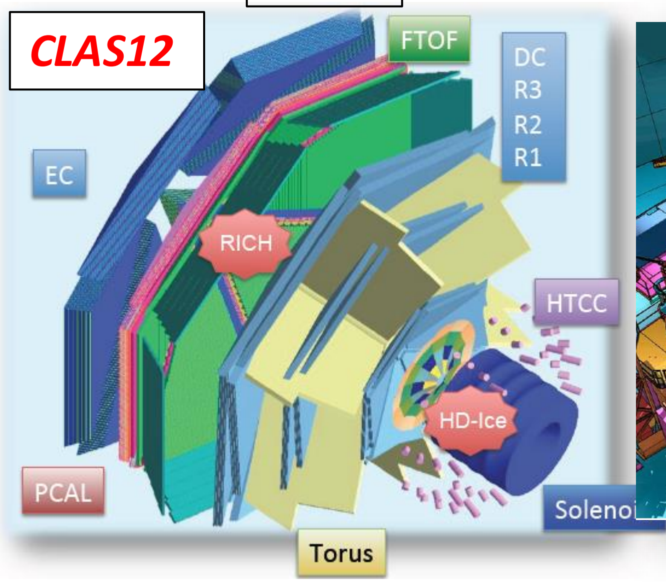
- Search for science beyond the Standard Model – precision and intensity frontiers



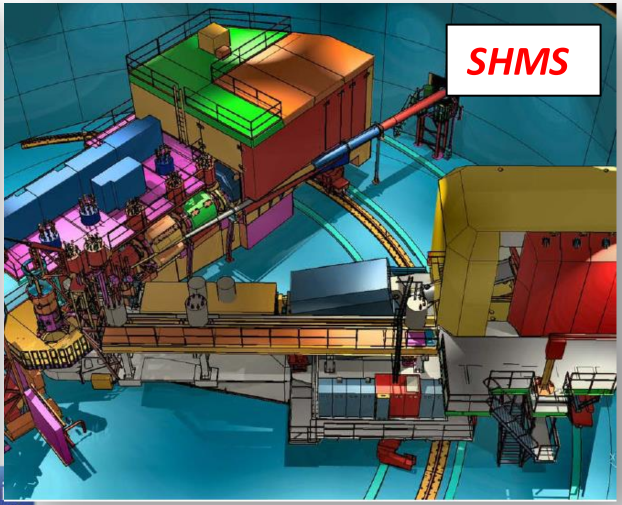
Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab, J. Dudek et al., EPJ A48 (2012) 187

Base equipment & proposed equipment

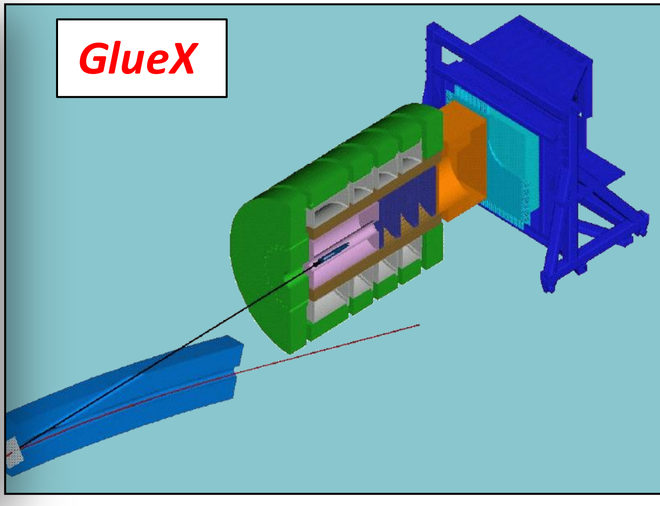
Hall B



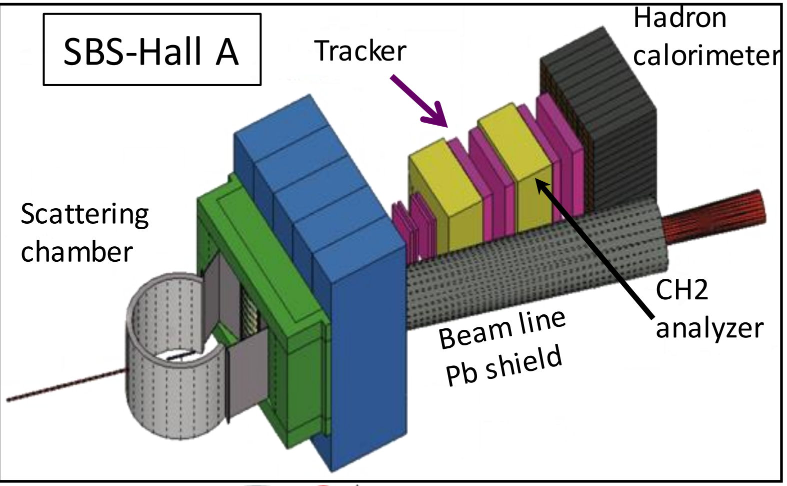
Hall C

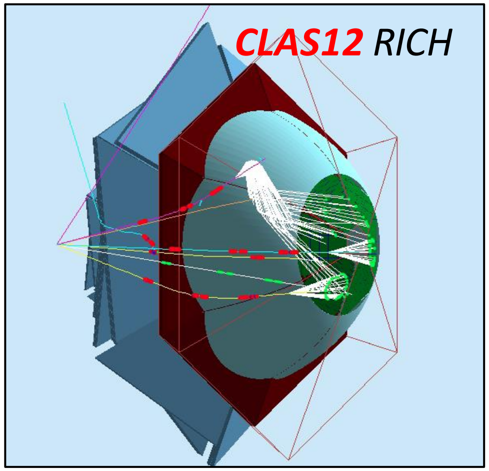


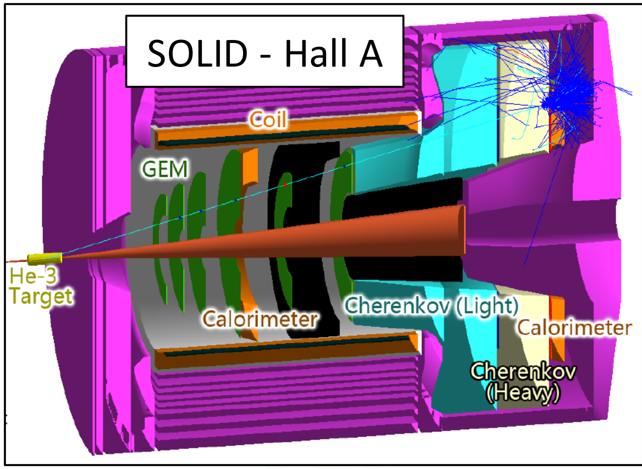
Hall D



additional equipment (proposed)







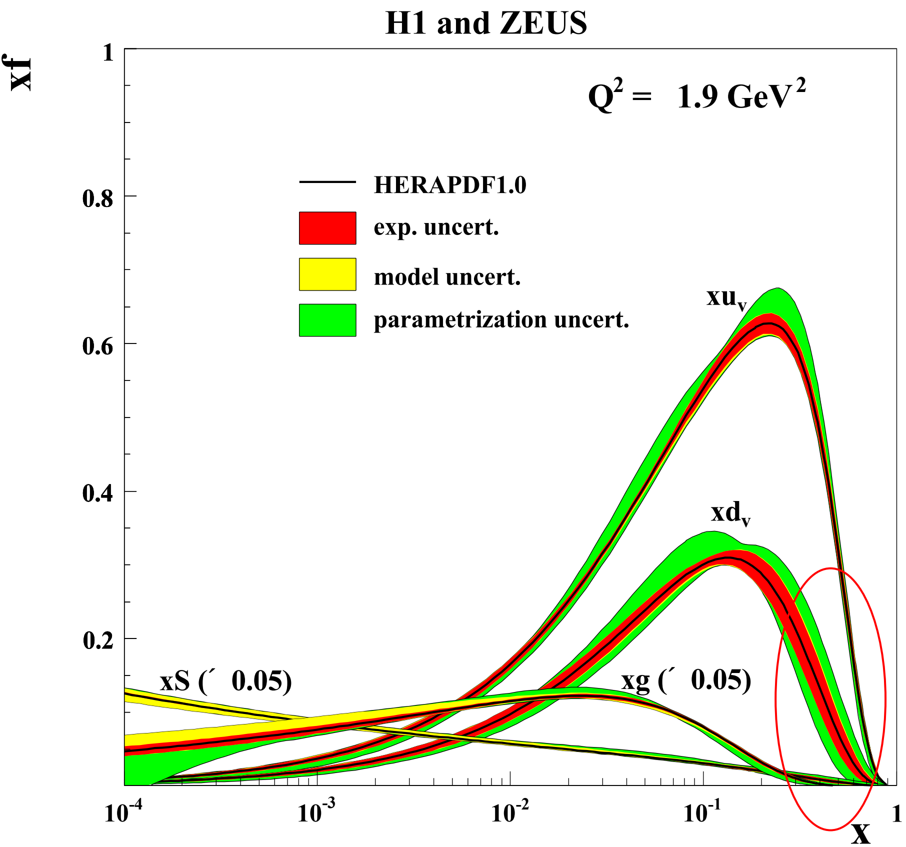
12 GeV Experiments by Physics Topics

Updated PAC40, June 2013

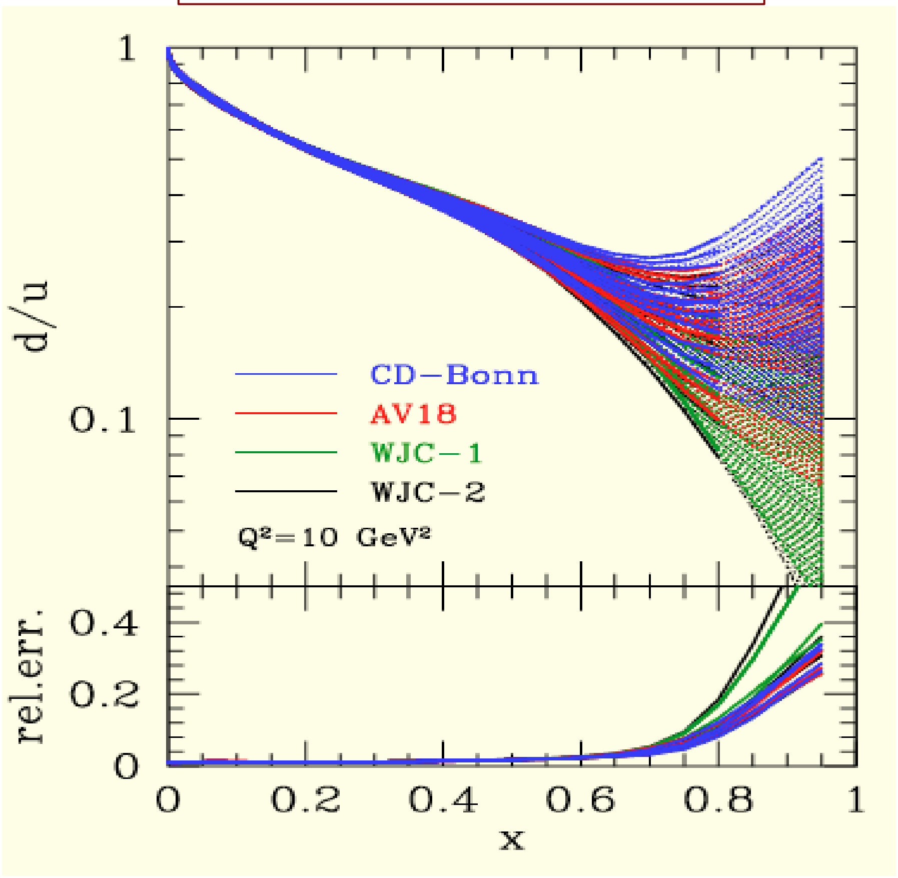
Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (GlueX and heavy baryon and meson spectroscopy)		2		2	**4**
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	3	1	**11**
The longitudinal momentum structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	6		**10**
The 3D quark structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	14	4		**23**
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	4	2	6		**12**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1		1	**5**
TOTAL	**18**	**23**	**19**	**4**	**64**

PAC fully and conditionally approved experiments: 64
More than 7 years of parallel running experiments.

DIS structure functions and $d_v(x)/u_v(x)$



From F_2^n/F_2^p measurements



d(x)/u(x) poorly constrained at x > 0.5

$$\approx \frac{4\, F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$$

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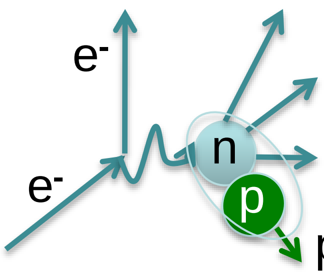
Neutron structure and quark distributions

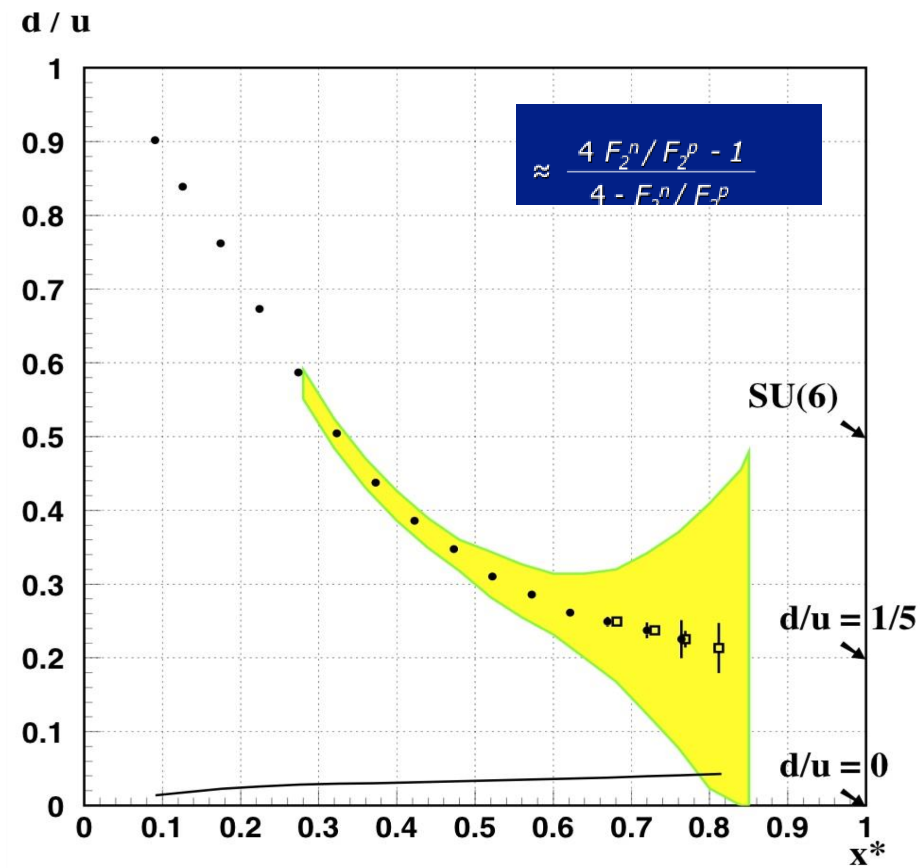
1) Measure F_2^n/F_2^p by tagging almost unbound neutrons using detection of low momentum protons in a radial TPC. 2) Other experiment will measure $^3H/^3He$.

E12-10-102

$e^- D \rightarrow e^- p_s X$



5 Tesla mag. field

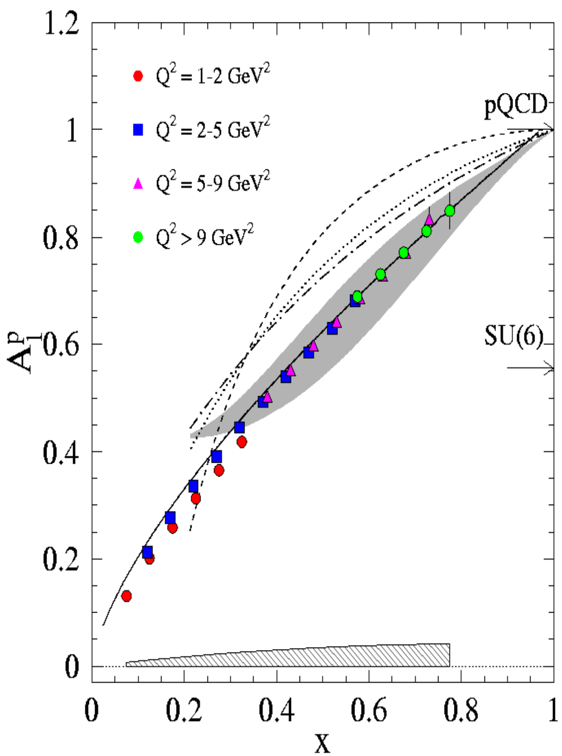


First model-independent measurement of F_2^n/F_2^p

Polarized PDFs on $\vec{p}/\vec{d}$ at 12GeV

Precise information on $A_1(x, Q^2)$ with flavor tag can reduce uncertainties in parton helicity distributions. The Q^2 dependence and QCD evolution can provide model-independent $\Delta G(x)$.

$$g_1(x,Q^2)_{\rm pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2 [(\Delta q + \Delta\bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f}],$$



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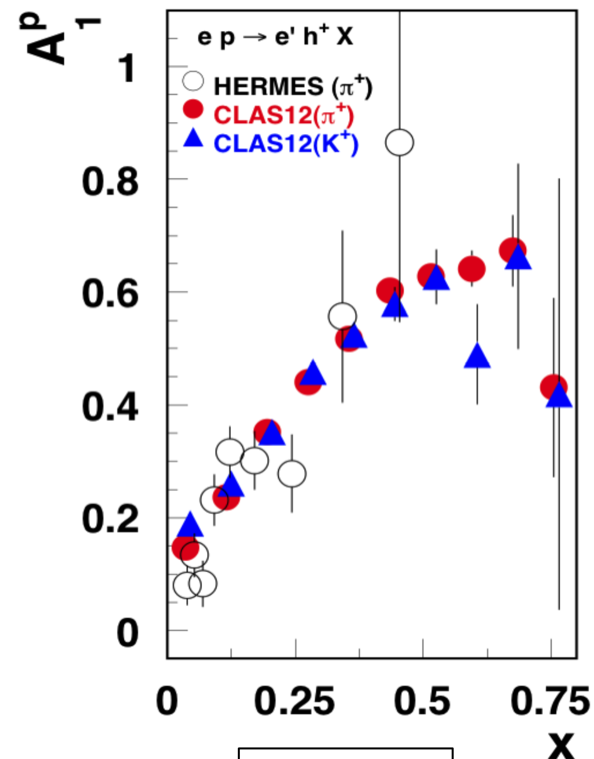
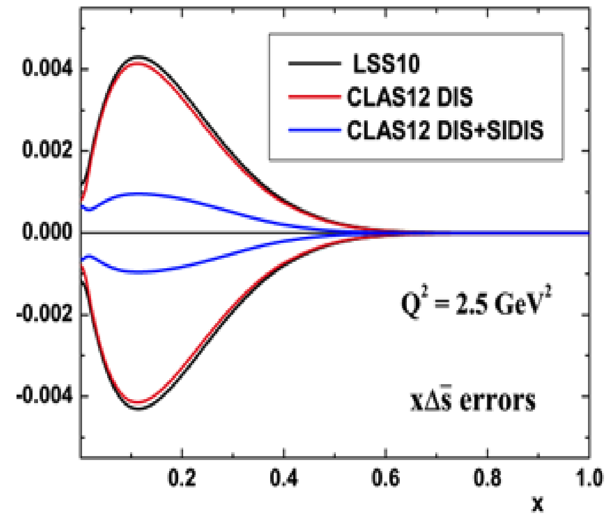
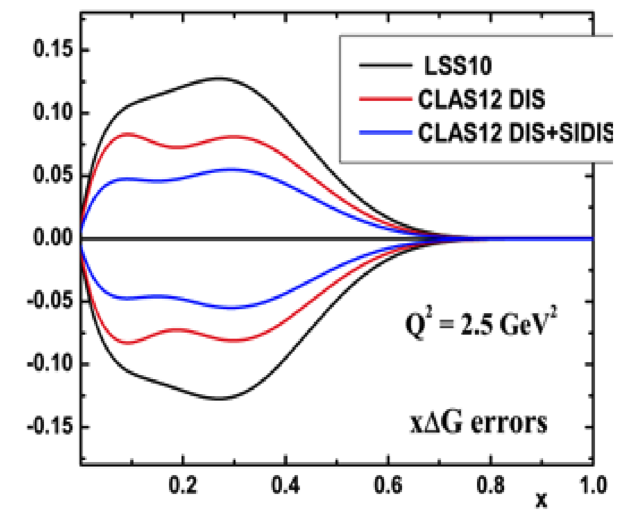


E12-09-007

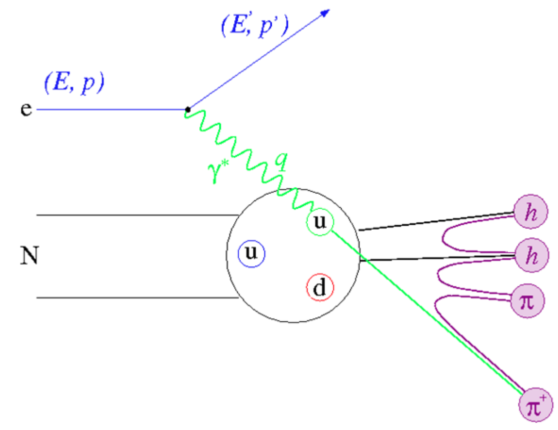
Improved PDFs from NLO analyses





Flavor-tagged polarized PDFs

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



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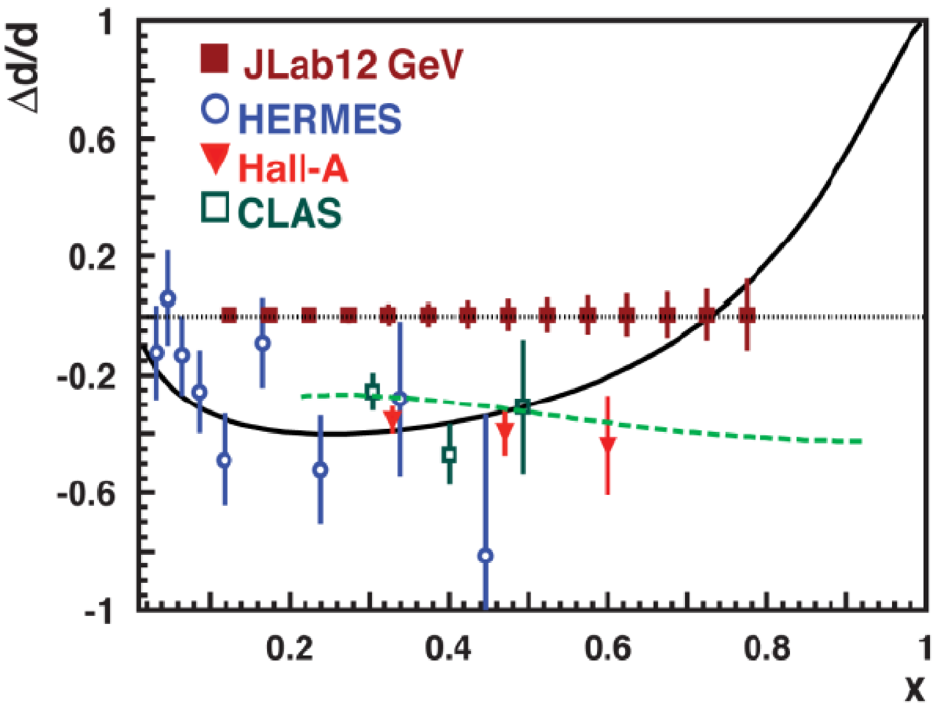
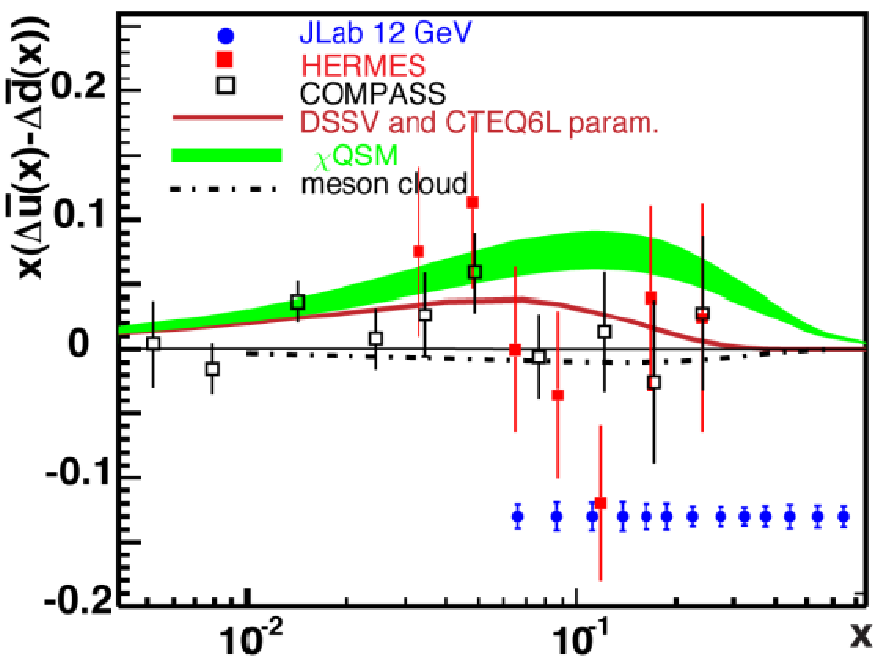




Generalized Parton Distributions

(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 transverse ***momentum*** space

Generalized Parton Distributions (GPD) H, $\tilde{H}$, E, $\tilde{E}$

3D nucleon imaging in transverse coordinate and longitudinal momentum space

Polarized DVCS directly probes GPDs

Nucleon polarization	Sensitivity to GPD
UP	H, $\tilde{H}$, E
LP	$\tilde{H}$, H, E
TP	E, H

Structural content of GPD E & H

Nucleon matrix element of the Energy-Momentum Tensor of q flavored quarks:

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

$M_2(t)$: Mass density in the nucleon

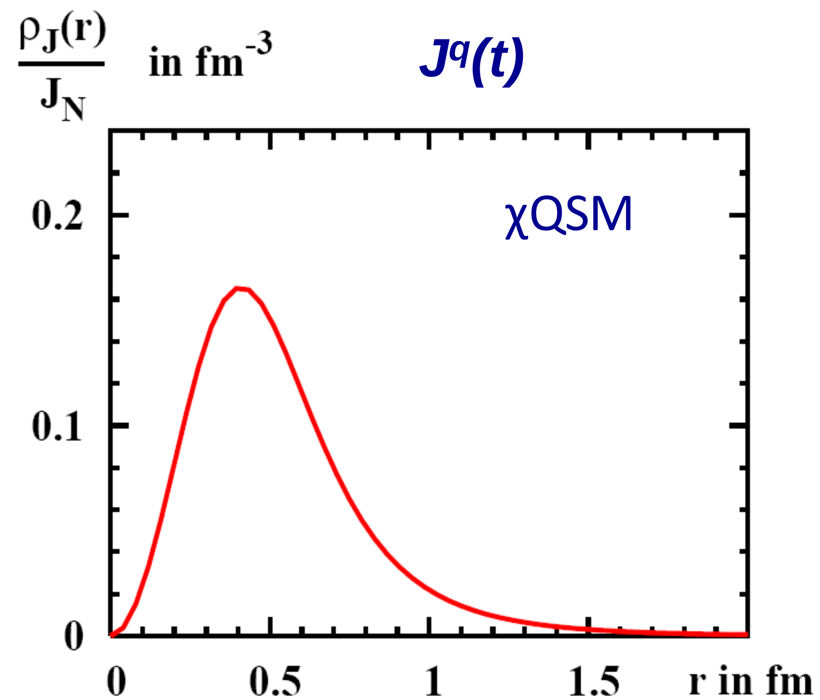
$J(t)$: Angular momentum density

$d_1(t)$: Pressure and shear forces

$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

$$M_2^q(t) + \frac{4}{5}d_1(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x H^q(x,\xi,t)$$

related to "D-term"



To determine $J(t)$, measurements of the x and t dependence of GPDs are needed.
To separate $M_2(t)$ and $d_1(t)$ measurements at small and large $\xi(x_B)$ are needed.

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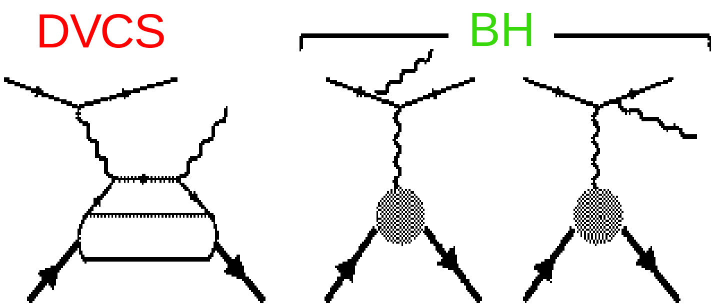
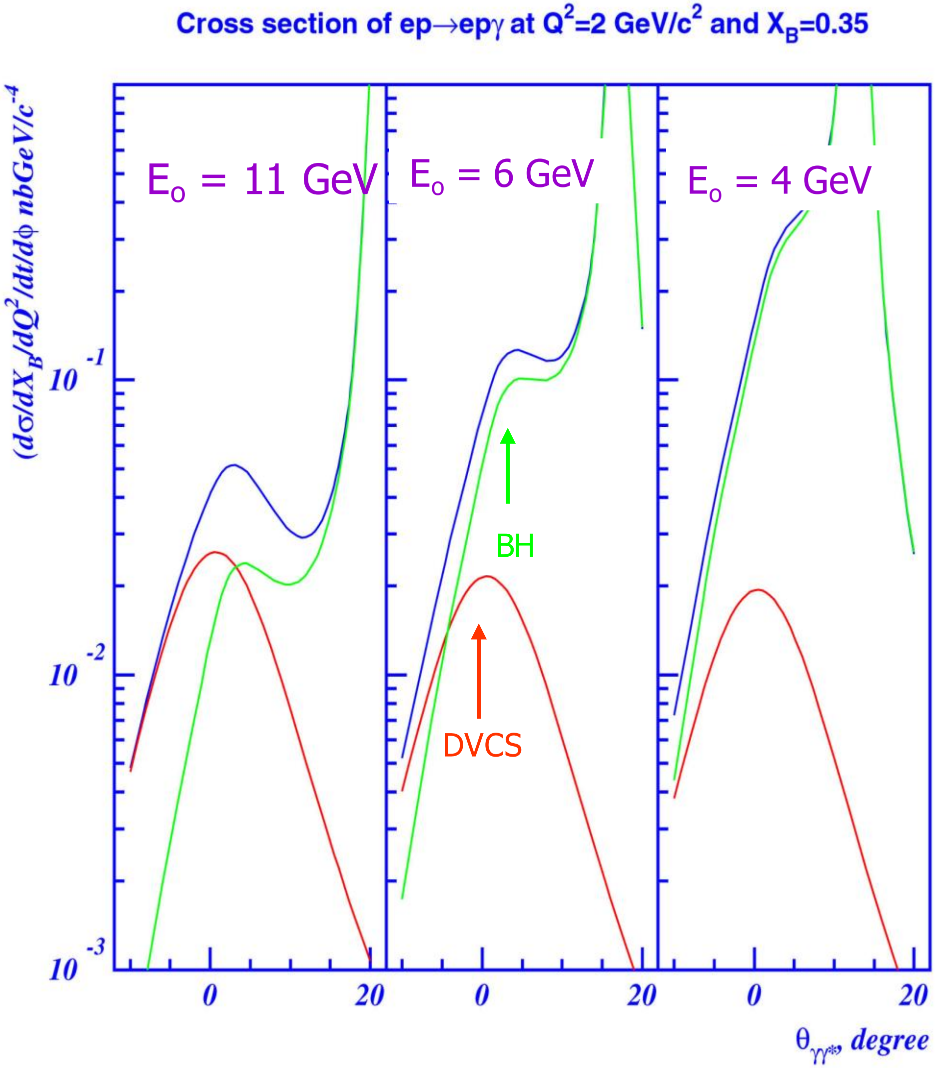
DVCS and Bethe-Heitler Process

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



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

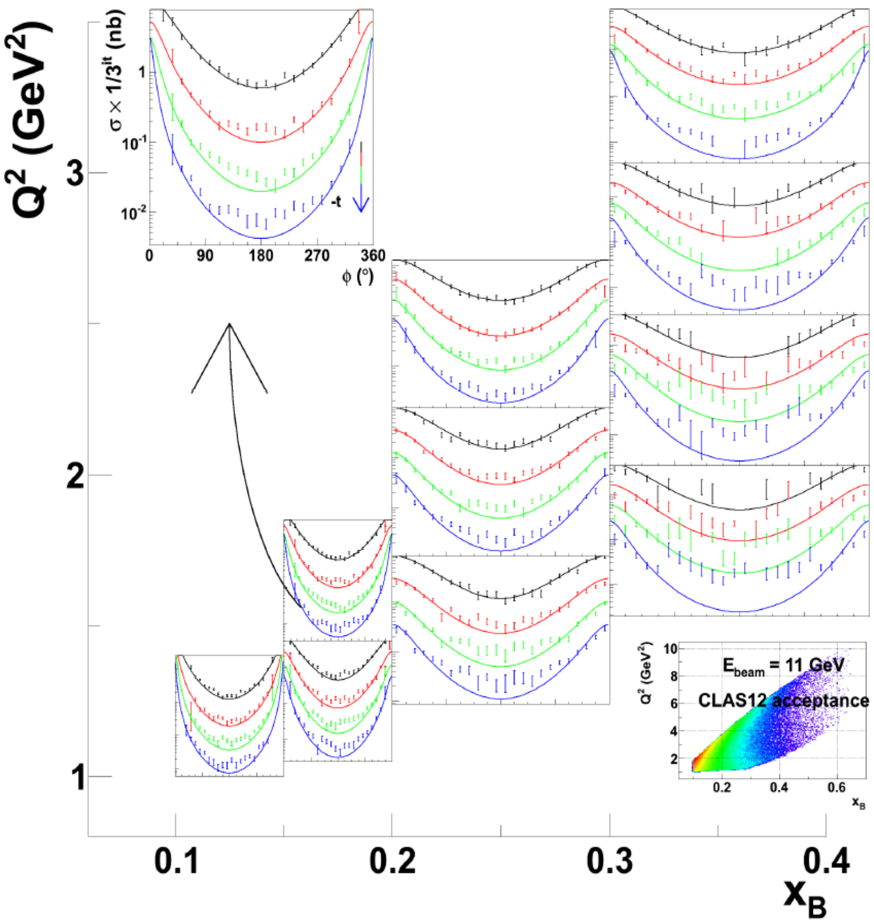
BH-DVCS interference generates beam and target polarization asymmetries that encode the nucleon structure content.



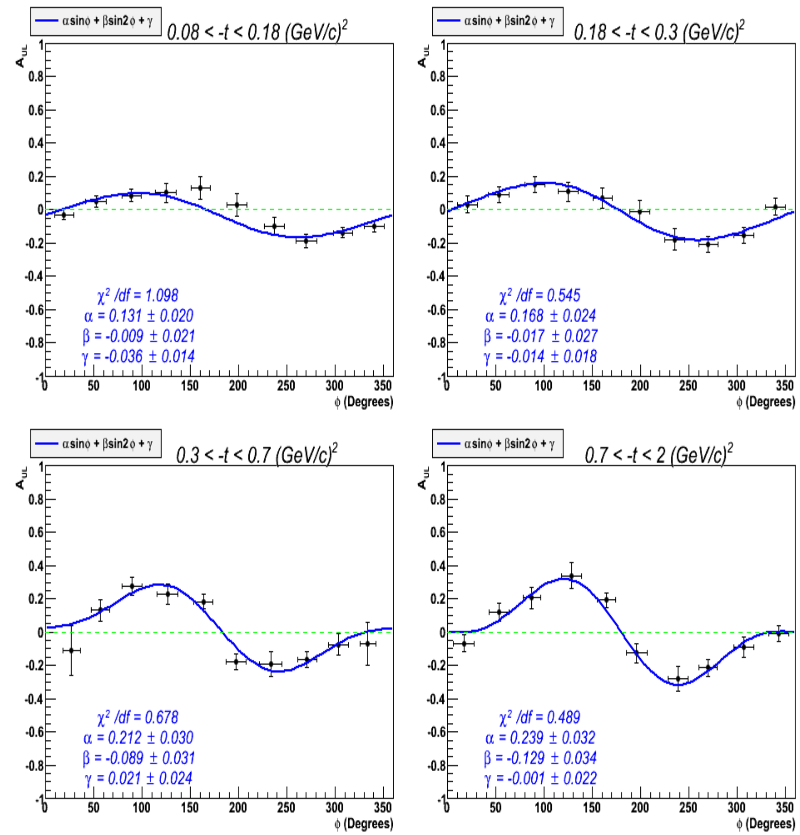
CLAS DVCS/BH cross sections

Large kinematical range in Q^2, x_B, t

Differential cross section (preliminary)



Target Asymmetry A_{UL} (preliminary)

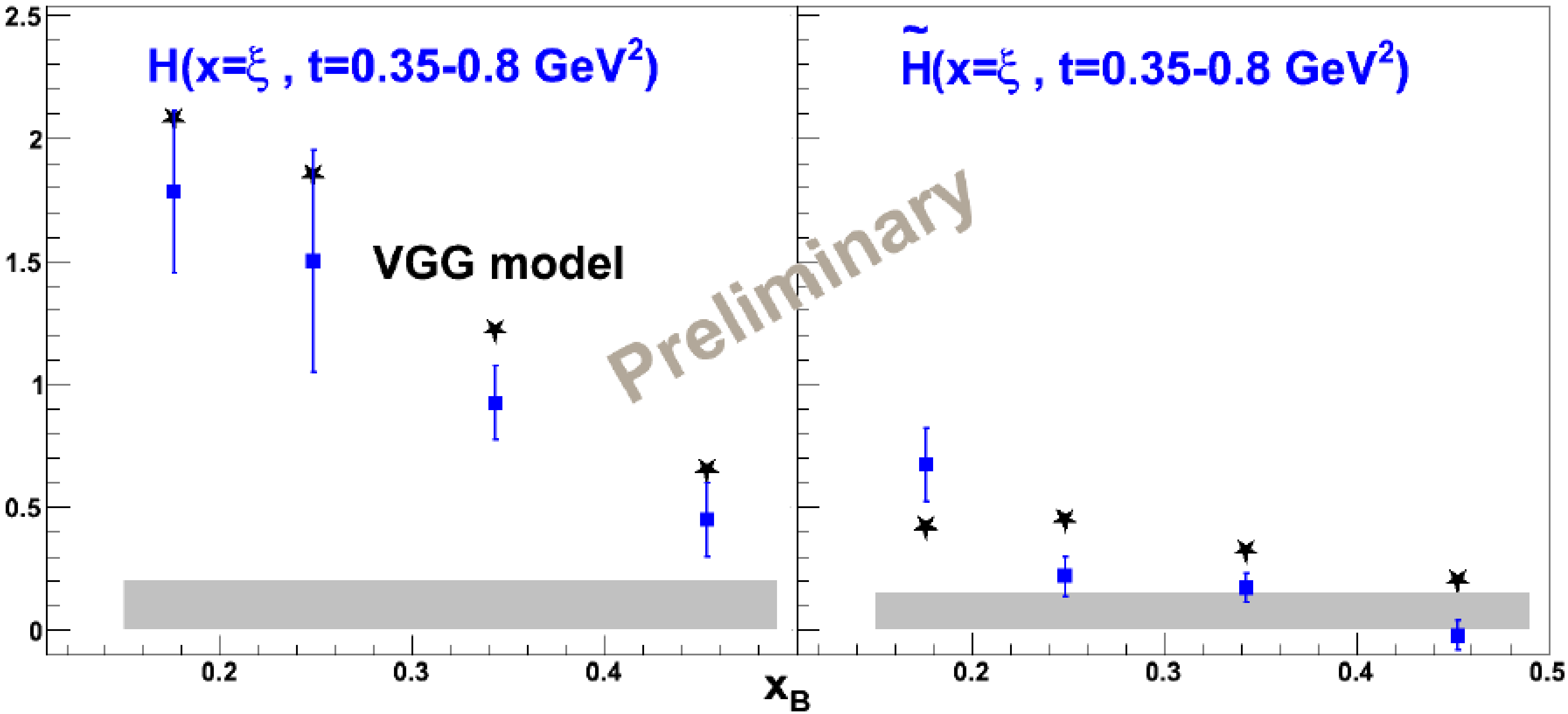


φ(deg)

Extracting CFF/GPDs from DVCS

Extraction in leading twist with:

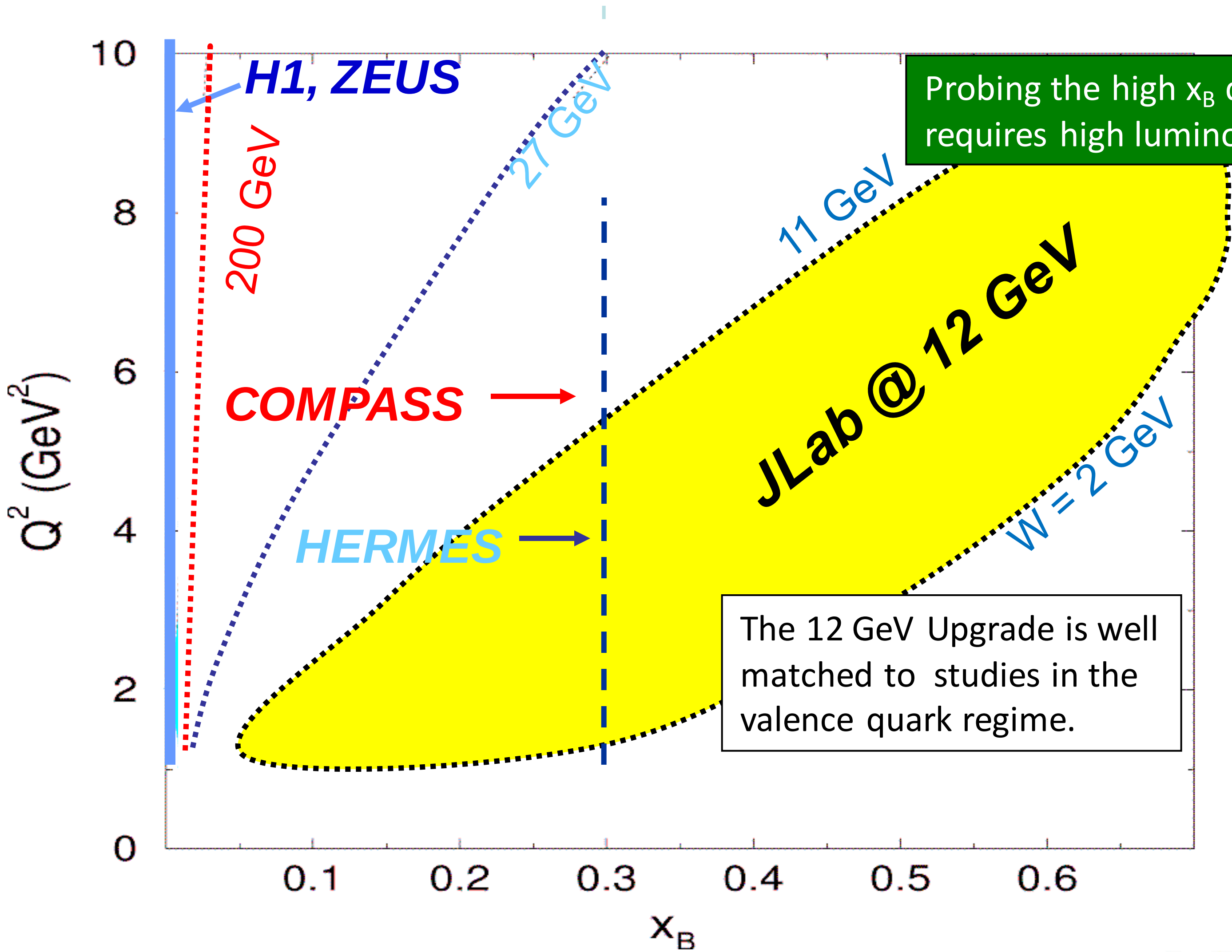
- **Preliminary results from CLAS on A_{UL}, A_{LL}**
- **Cross sections σ**



GPD dependencies versus x_B mirror their respective ordinary PDFs

$\tilde{H}$ and $H \leftrightarrow \Delta q(x)$ and $q(x)$

Kinematic coverage of DVCS @ 12GeV



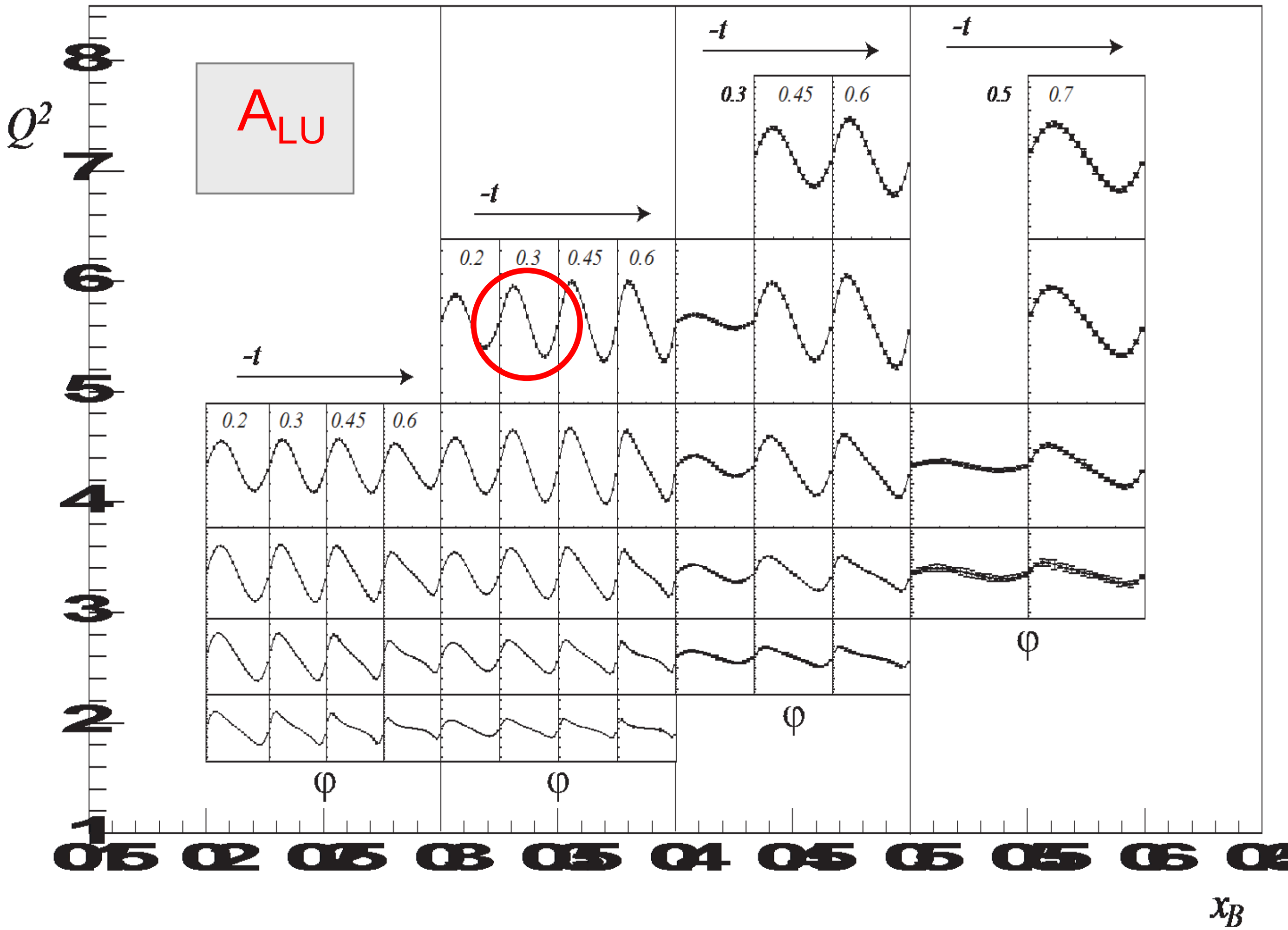
Probing the high x_B domain requires high luminosity

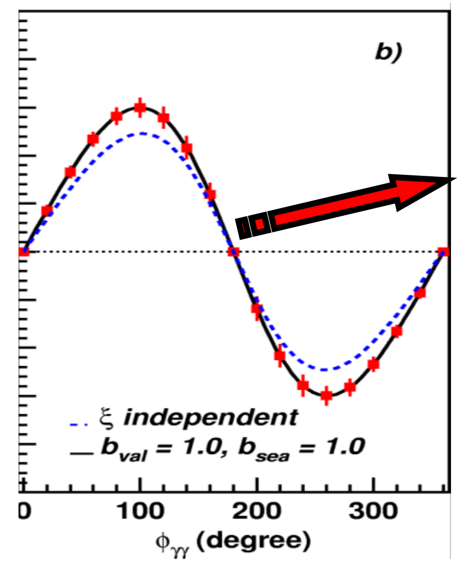
The 12 GeV Upgrade is well matched to studies in the valence quark regime.

A_{LU} projections for JLab@12GeV

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

$\vec{e}p$ --> epγ





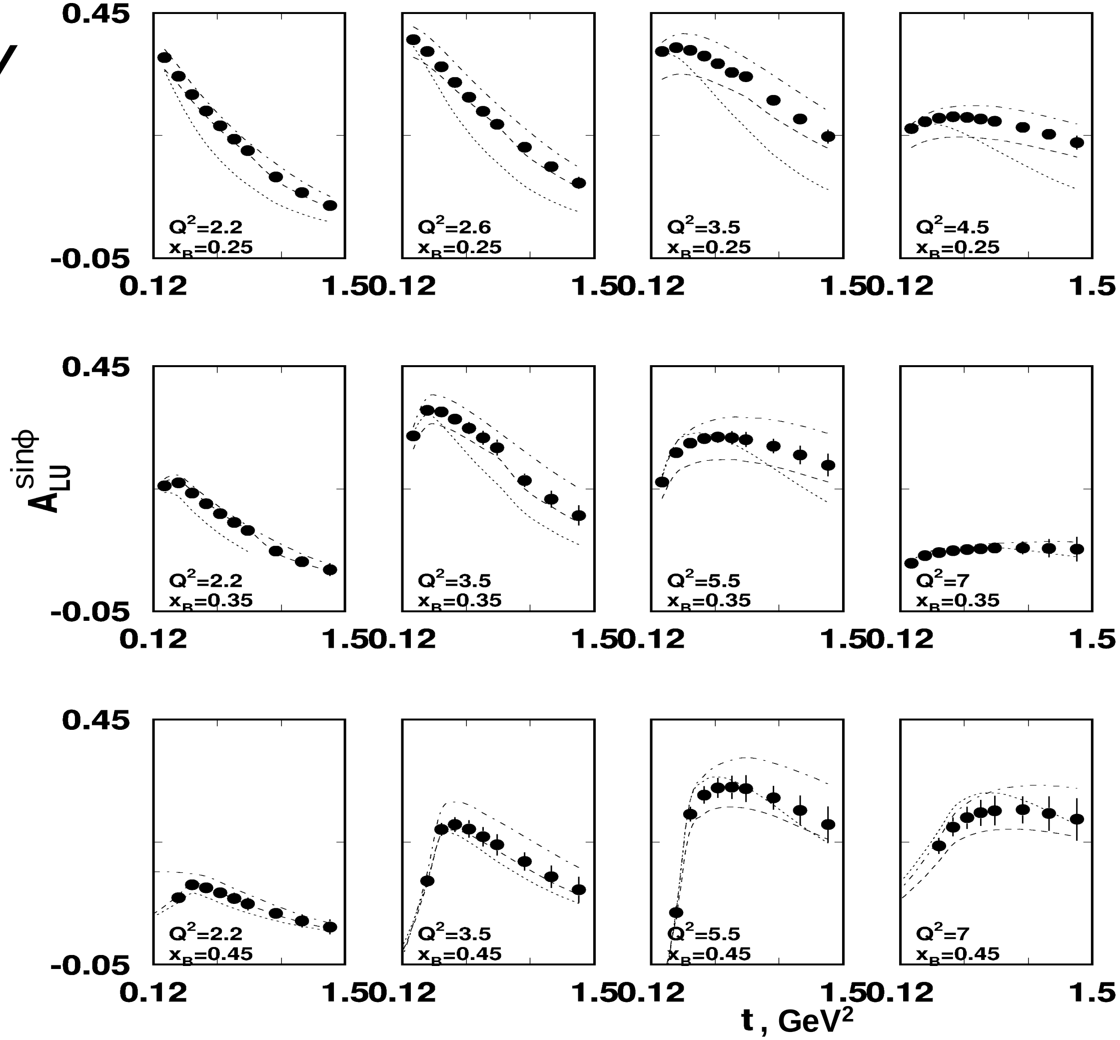
E12-06-114
E12-06-119

A_{LU} projections for protons

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

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

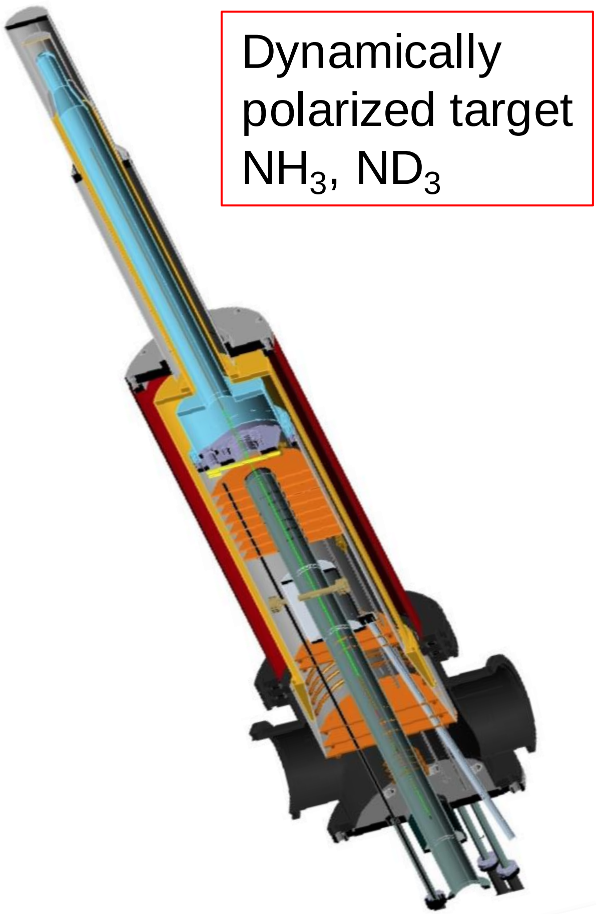
E_e=11GeV



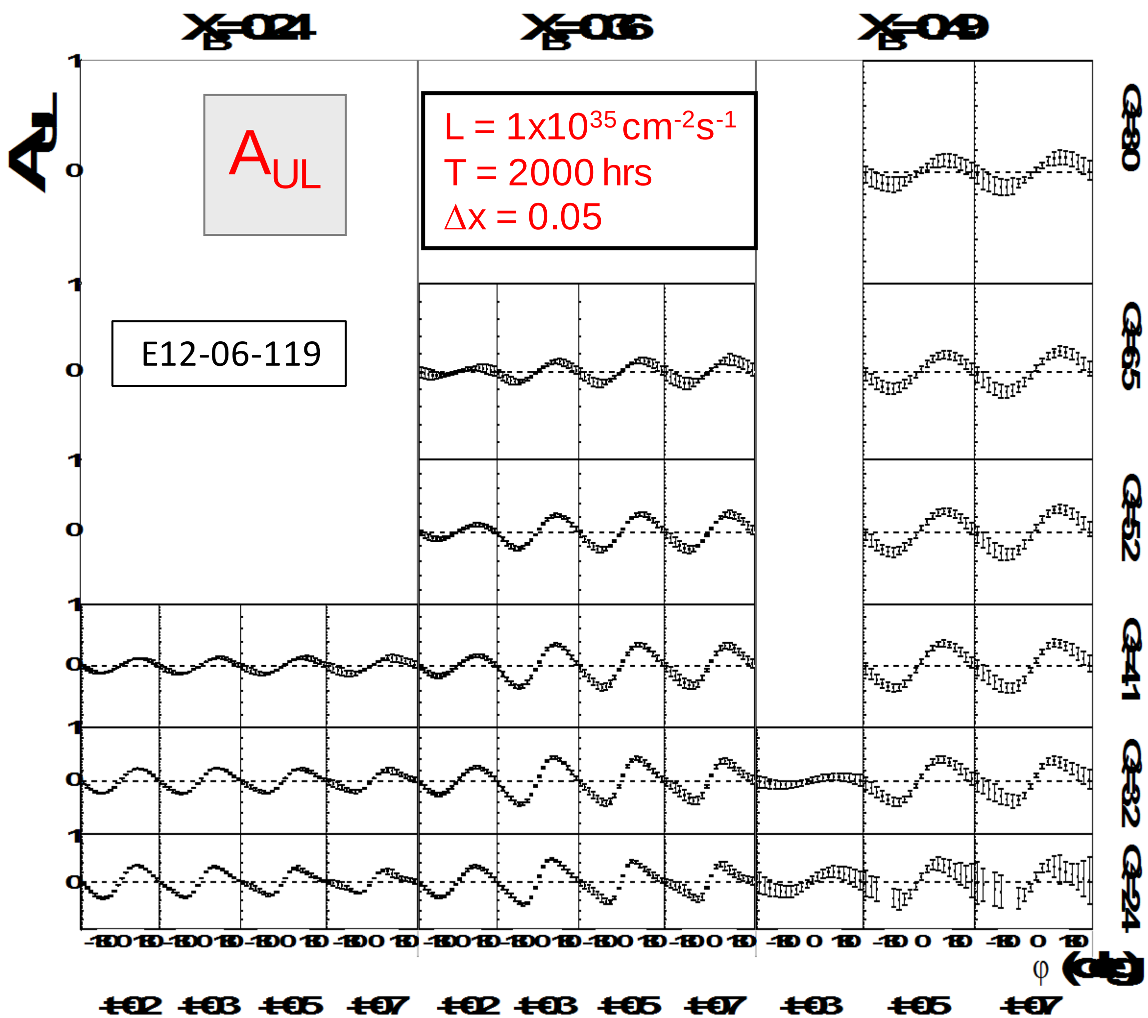
A_{UL} projections for protons

$e\,\vec{p} \rightarrow e p \gamma$

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



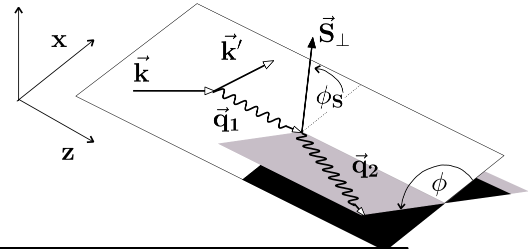
Dynamically polarized target NH_3, ND_3

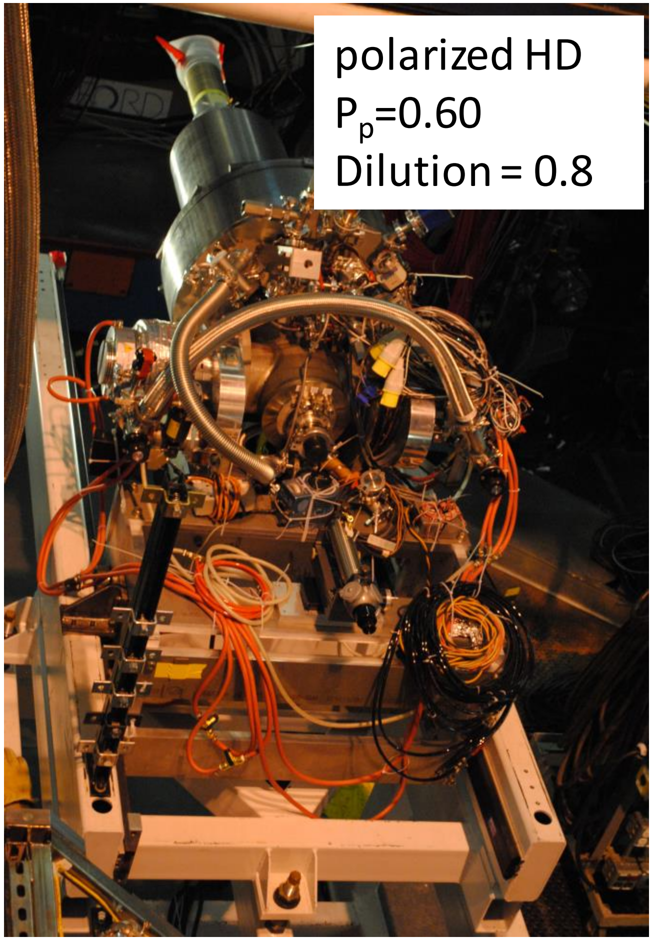


A_{UT} projections for 12GeV

$ep^{\uparrow} \rightarrow ep\gamma$

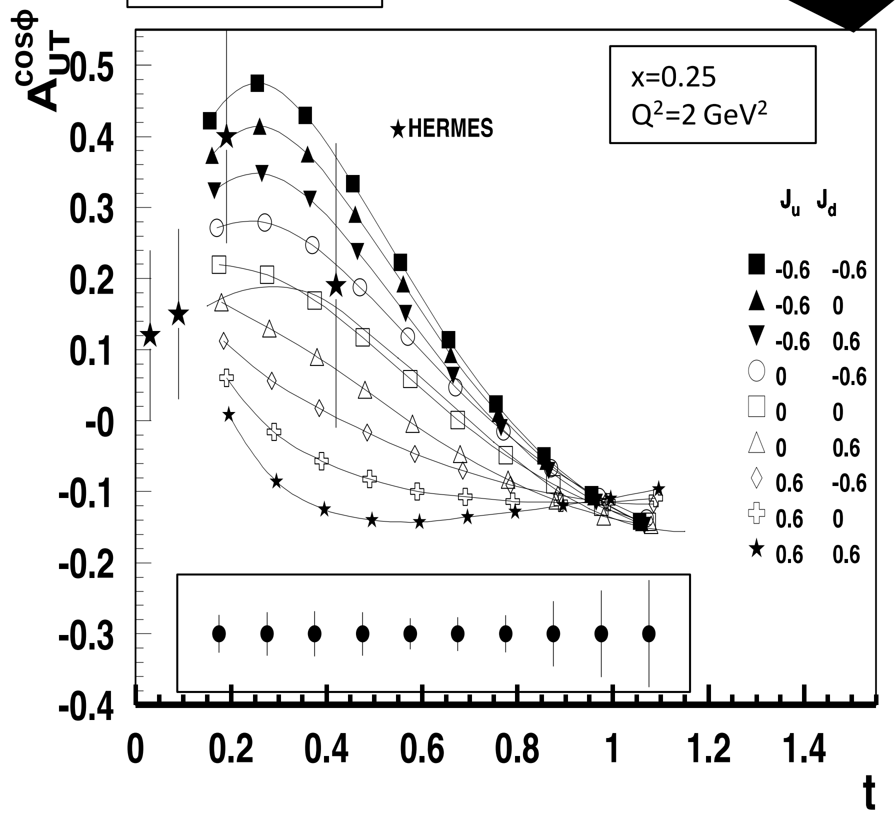
$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s-\phi)\{k(F_2\mathit{H} - F_1\mathit{E})\}d\phi$





polarized HD
P_p=0.60
Dilution = 0.8

C12-12-010

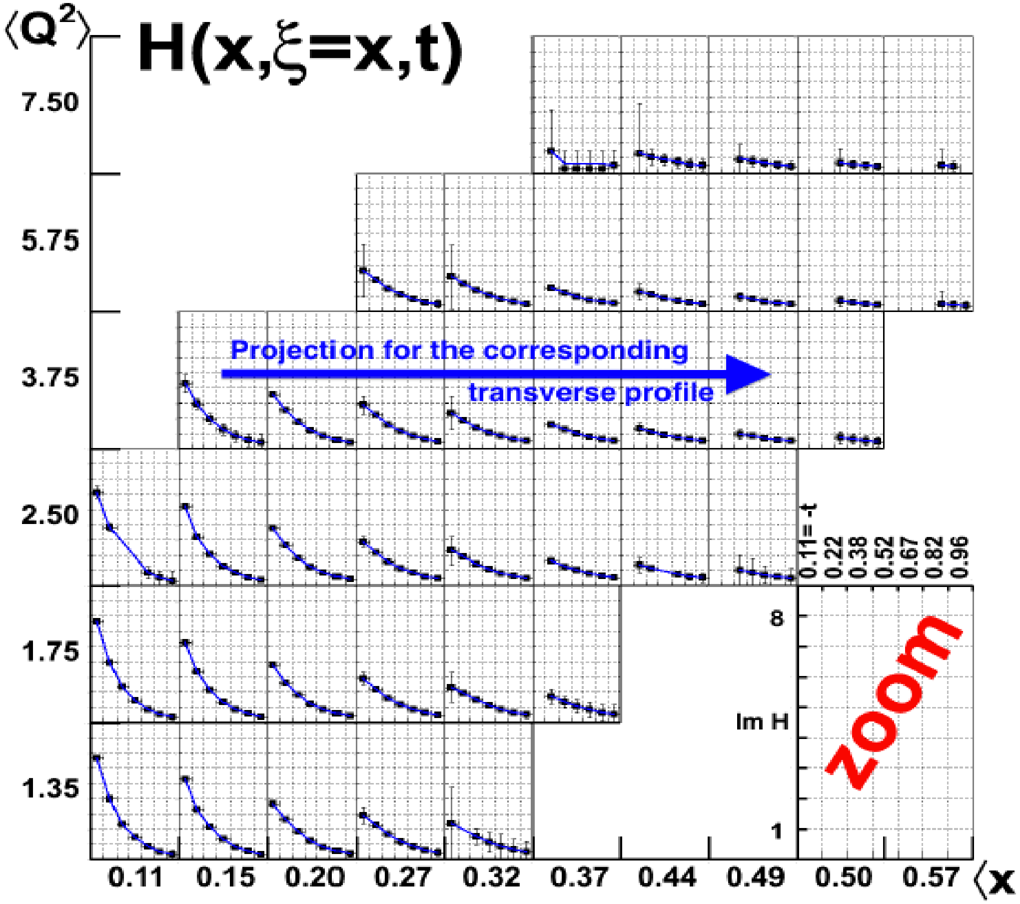


A_{UT} and A_{LT} are sensitive to the u and d-quark helicity content of the proton spin

GPD H from projected CLAS12 data

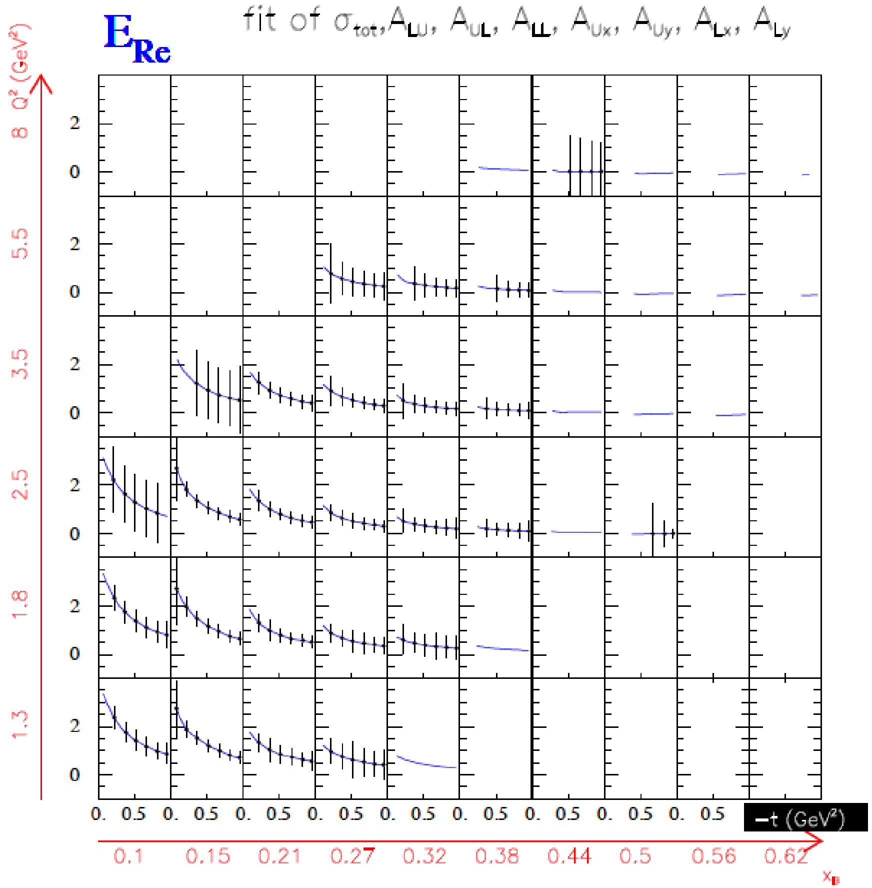
Review article: M. Guidal, H. Moutarde, M. Vanderhaeghen, Rept.Prog.Phys. 76 (2013) 066202

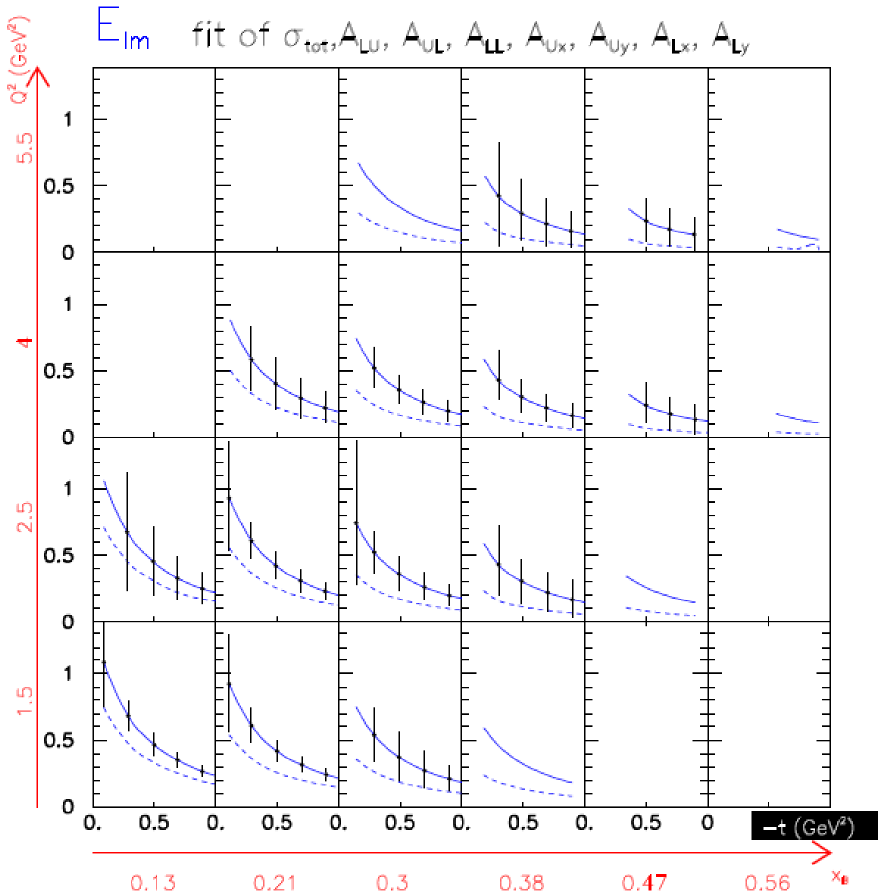
LO fit to all observables: σ, A_{LU}, A_{UL}, A_{LL}, A_{Ux}, A_{Uy}, A_{Lx}, A_{Ly}



For corrections see talk by H. Moutarde

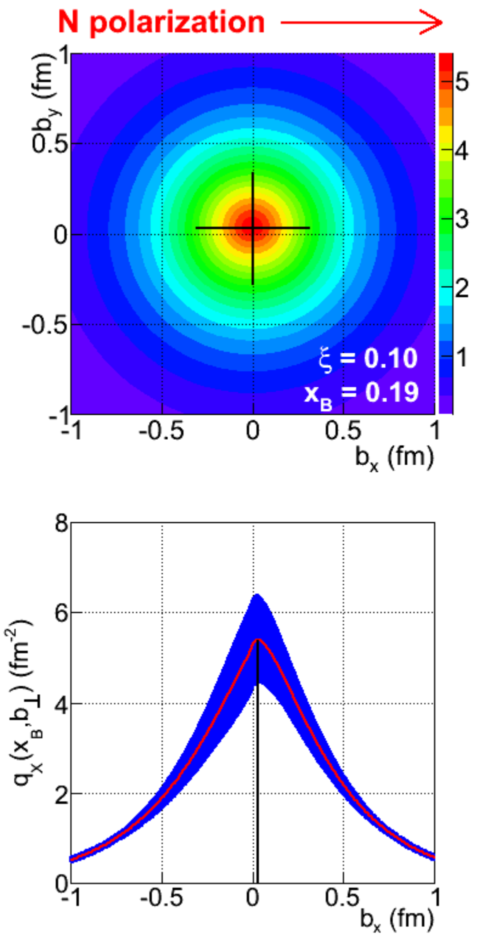
CFF E from projected CLAS12 data



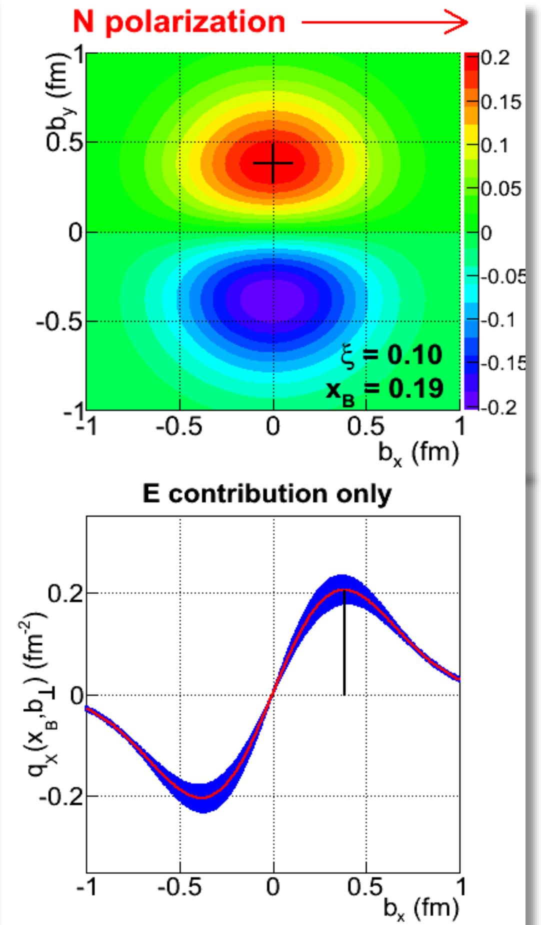


Projected quark densities in impact parameter

$$\rho_X(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} \left[H(x,0,t) - \frac{E(x,0,t)}{2M} \frac{\partial}{\partial b_y} \right] e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$



Contribution of *H+E*



Contribution of *E*

- Fourier transform of GPDs to access quark densities in impact parameter space.
- GPD ***E*** probes the u- and d-quark separation in impact parameter space. Transversely polarized proton shows flavor dipole.

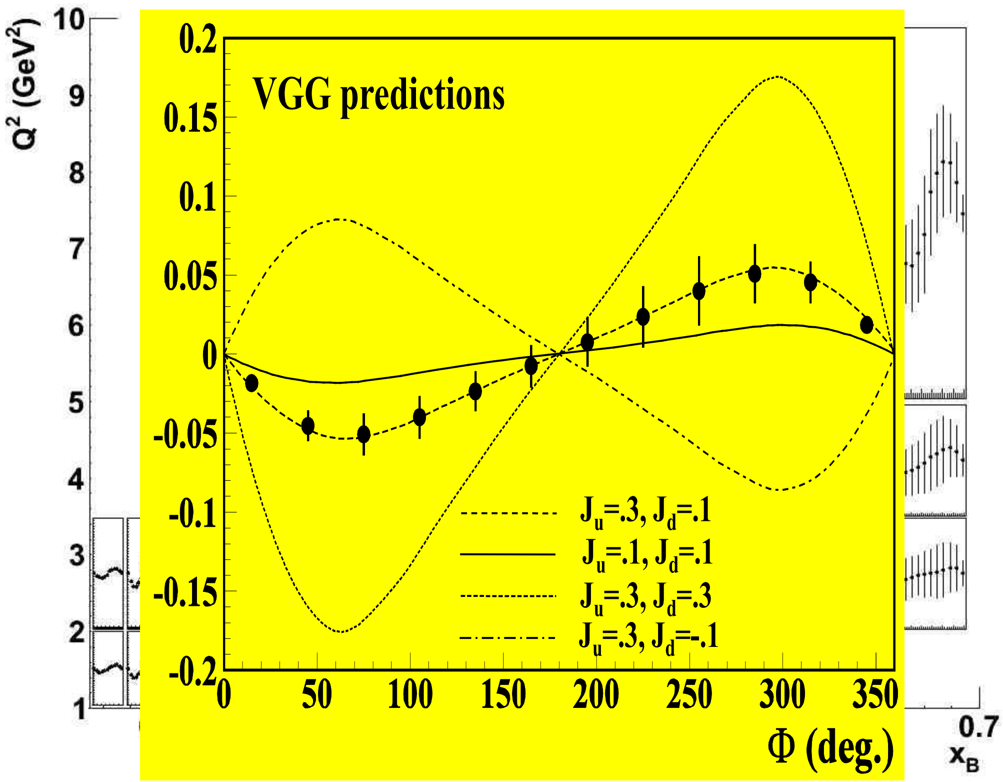
Beam asymmetries A_{LU} for neutrons

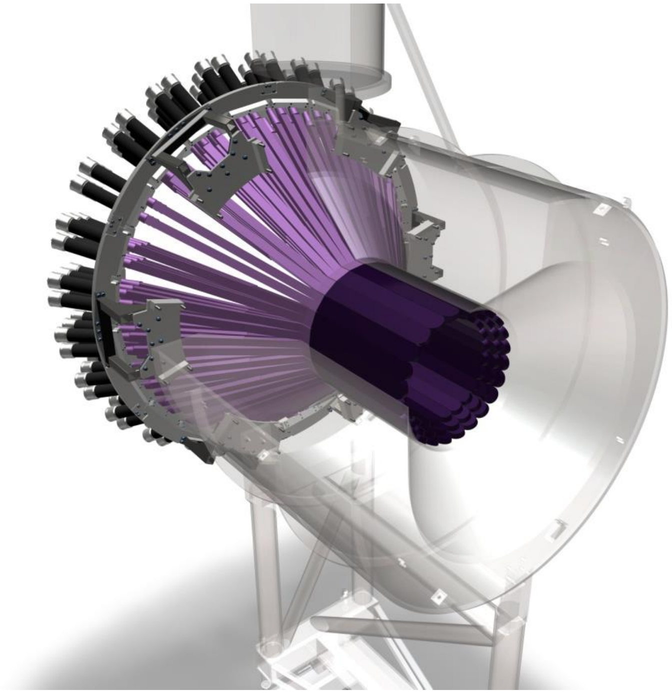
E12-11-003

Total of 588 bins in t, Q^2, x_B, ϕ

$t=-0.35GeV^2$
$Q^2=2.75GeV^2$
$x_B=0.225$

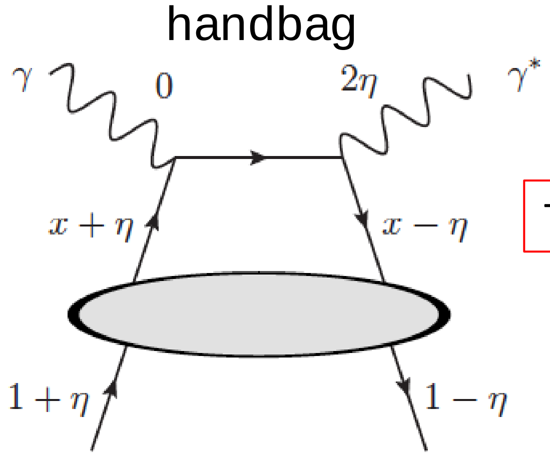
Central Neutron Detector





A_{LU} is highly sensitive to d-quark helicity contribution to nucleon spin.

Time-like Compton Scattering (TCS)



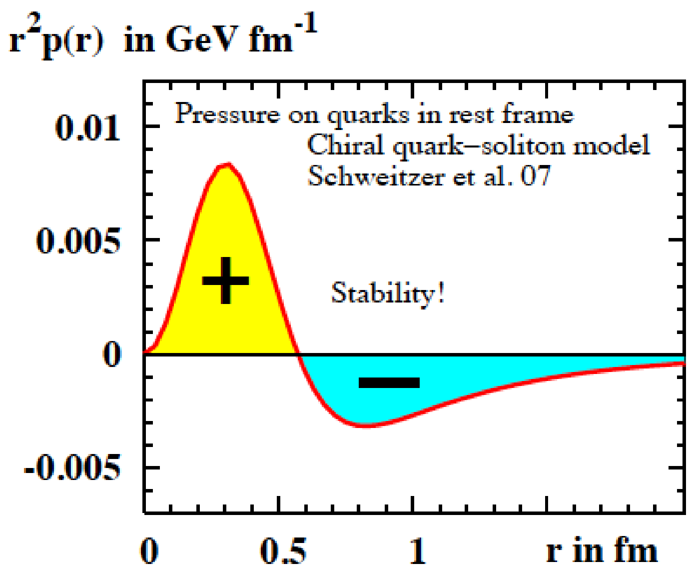
TCS-BH Int.

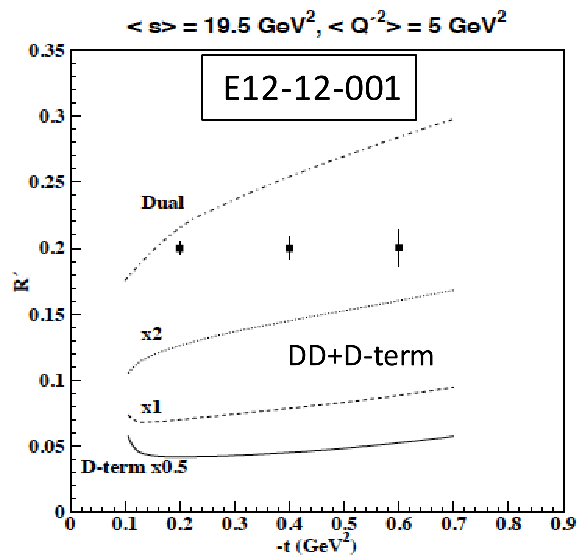
$$\frac{d\sigma_{\mathrm{INT}}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{\mathrm{em}}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L} \times \Big[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\Re e\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\Re e\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\Re e\tilde{M}^{+-} + \mathcal{O}\Big(\frac{1}{Q'}\Big)\Big],$$

$$\tau = \frac{Q'^2}{2(p\cdot q)} = \frac{Q'^2}{s-M^2},$$

In handbag dominance only one term survives

$$\tilde{M}^{--} = \frac{2\sqrt{t_0-t}}{M}\,\frac{1-\eta}{1+\eta}\Big[F_1\mathcal{H}_1 - \eta(F_1+F_2)\tilde{\mathcal{H}}_1 - \frac{t}{4M^2}F_2\mathcal{E}_1\Big]$$





Cosine moment of the weighted cross section integrated over θ.

Highly sensitive to D-term, i.e. pressure on quarks in rest frame.

Also measure threshold behavior of J/ψ production, E12-12-006.

Transverse Momentum Structure of Nucleon – 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

Transverse Momentum-dependent Distributions (TMD)

3D imaging of the nucleon in momentum space

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 $h_{1T}^\perp$

JLab has planned a complete SIDIS program with π/K to access quark TMDs

SIDIS and Transverse Momentum Distribution

SIDIS cross section in leading twist:

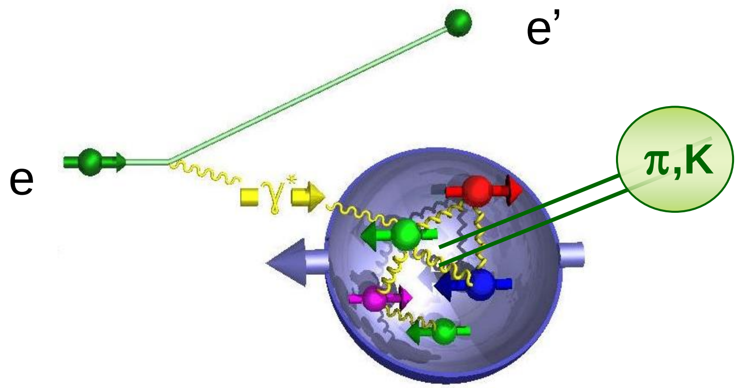
$$\frac{d\sigma}{dx\,dy\,dz\,d\varphi_S\,d\varphi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2(1-\varepsilon)}$$

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

$$+ S_L\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL} + |S_T|\Big[\sin(\varphi_h-\varphi_S)\,F_{UT,T}^{\sin(\varphi_h-\varphi_S)}$$

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

$$+ |S_T|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\varphi_h-\varphi_S)\,F_{LT}^{\cos(\varphi_h-\varphi_S)}\Big]\Big\},$$



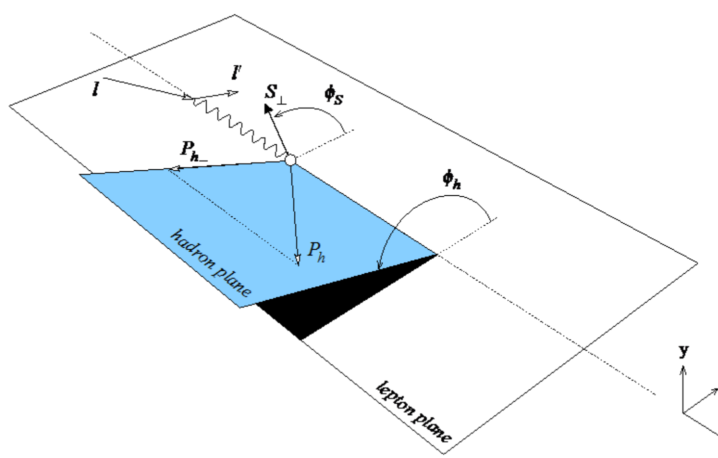
The 8 structure functions factorize into TMD parton distributions, fragmentation functions, and hard parts:

$$F_{UU} \propto f_1(x,k_\perp)\,D_1(z_h,p_\perp)\,H_{UU}(Q^2)$$

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

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

Integrals over transverse momentum of initial and scattered parton



A full program to access 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

E12-11-108: π^+, π^-

SOLID

H_2 | NH_3

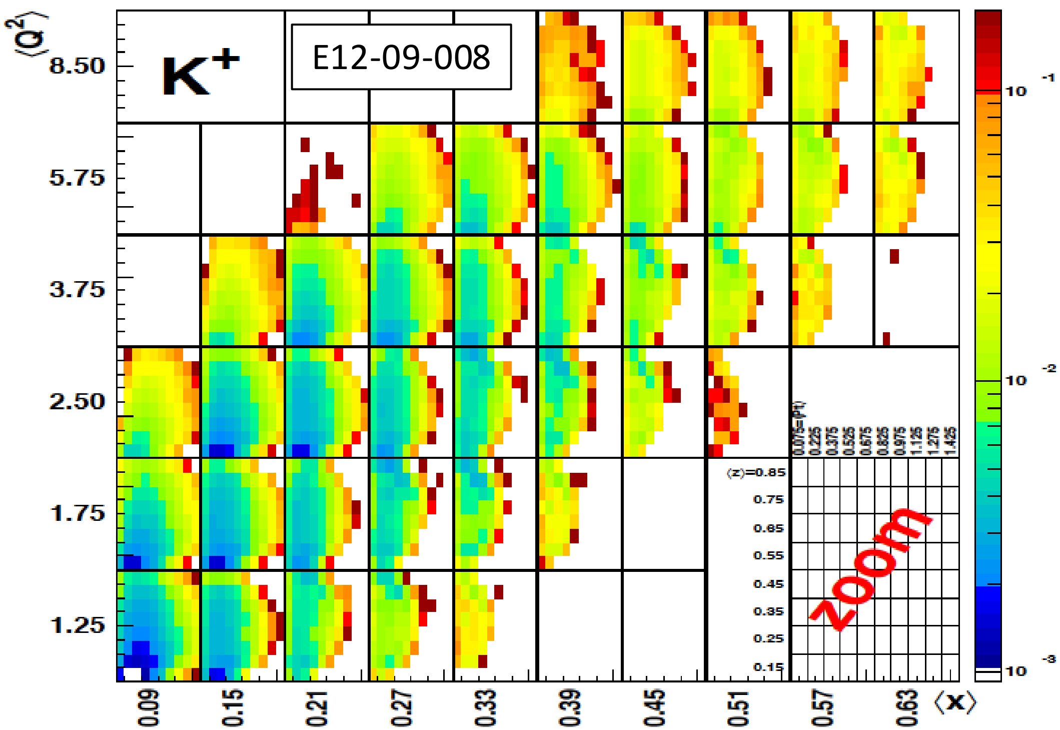
The TMD program will map the 4D phase space in Q^2, x, z, P_T

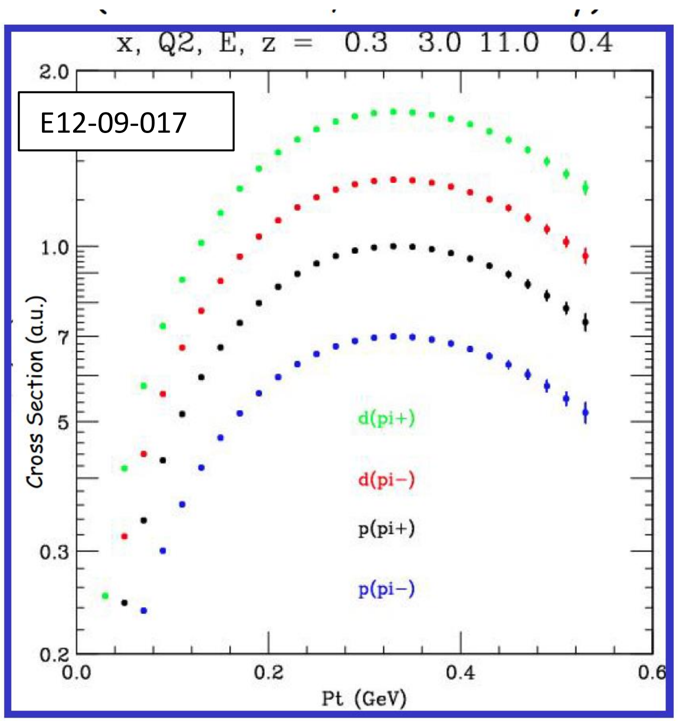
SIDIS π/K on unpolarized protons/deuterons

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

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





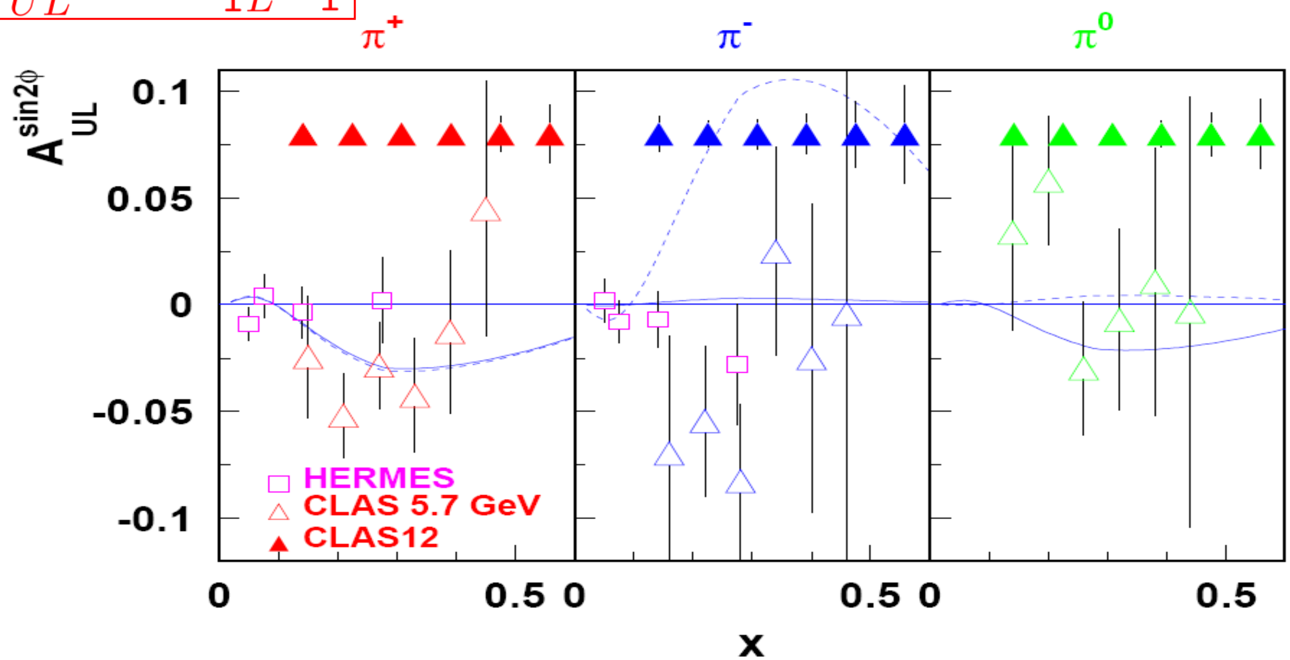
CLAS12 A_{UL} on longitudinally polarized target

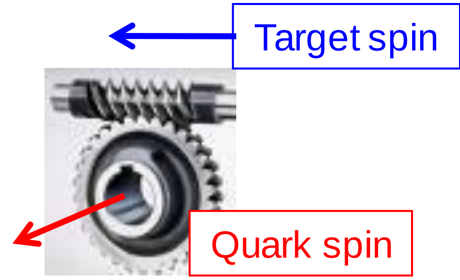
N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

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

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

E12-07-107
E12-09-009



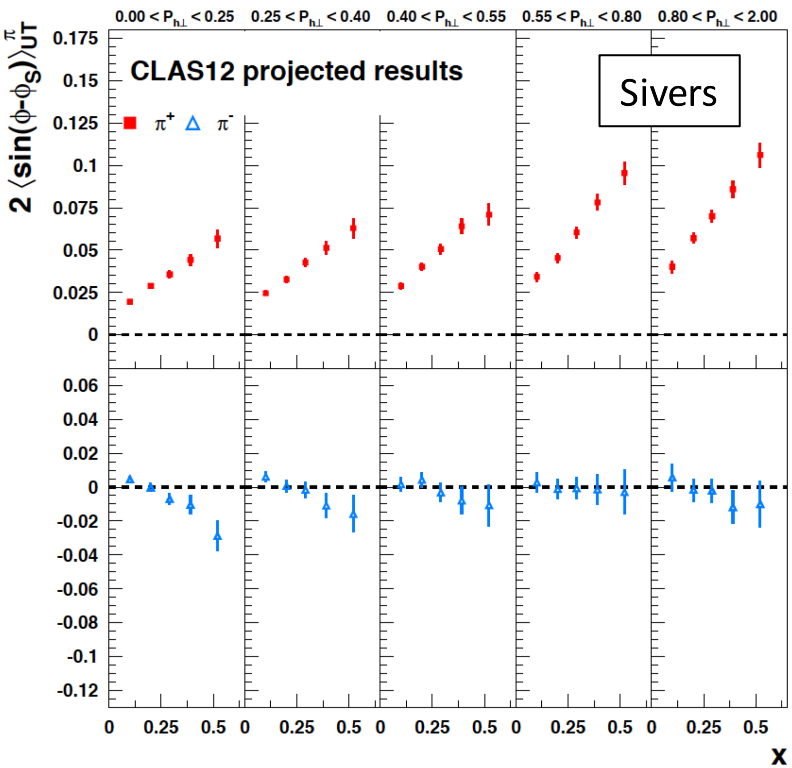


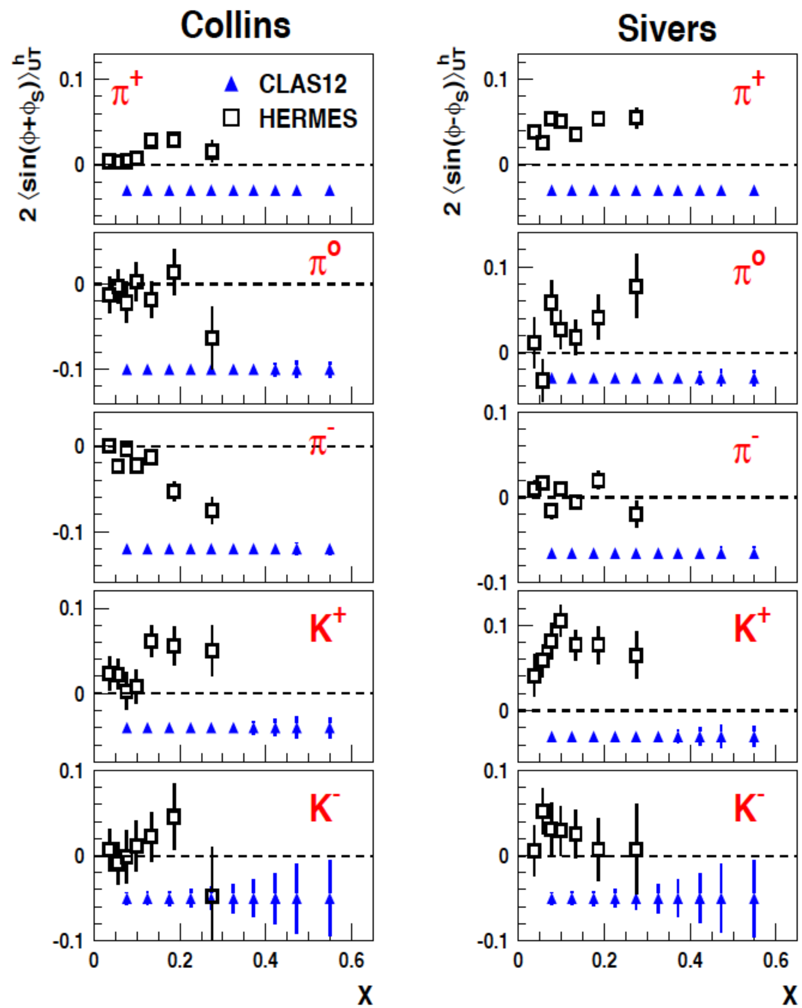
- Only leading twist azimuthal moment for longitudinally polarized target. The $\sin 2\phi$ moment is sensitive to spin-orbit correlations.

A_{UT} on transverse polarized proton

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 $h_{1T}^\perp$

E12-11-108
C12-11-111





High statistics allows for x-$P_\perp$ binning

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

JLab TMD ^{3}He Program @ 12 GeV

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

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

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

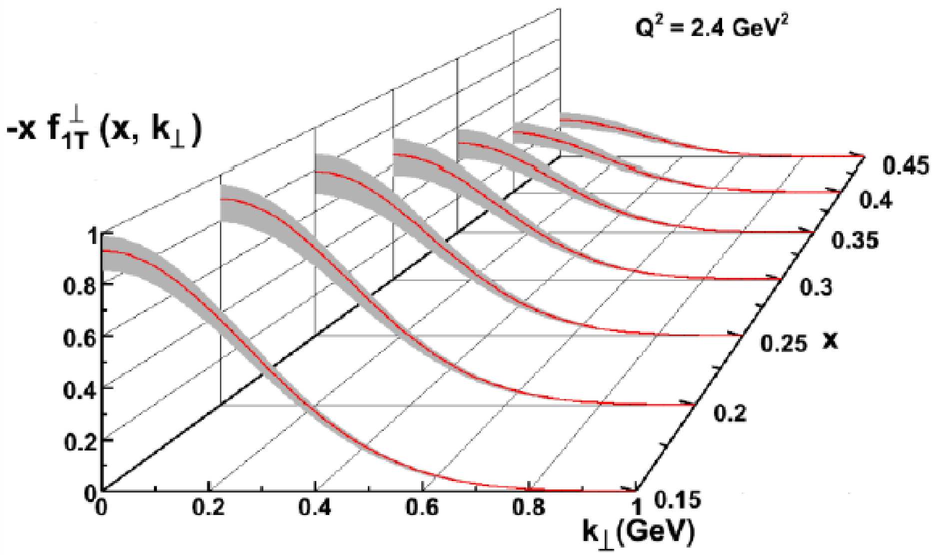
E12-07-007: π^+, π^- — Solid

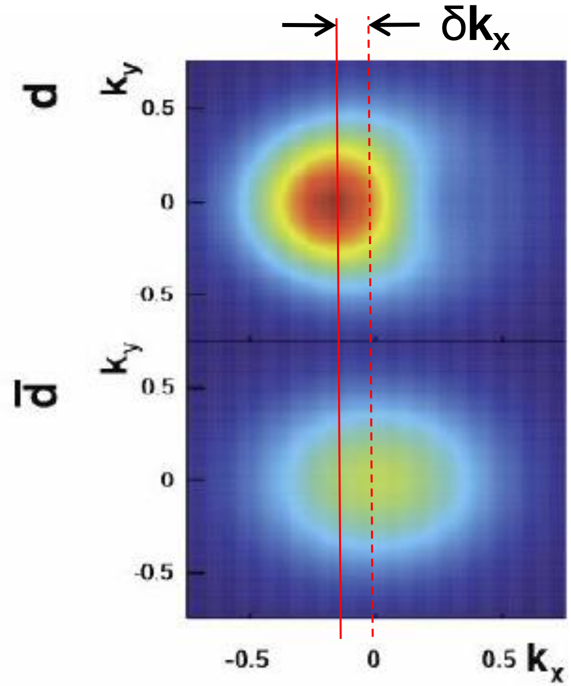
E10-006: π^+,π^-
E12-09-018: π^+,π^-, K^+,K^- — Solid, SBS

^{3}He

Momentum Tomography with TMDs

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.

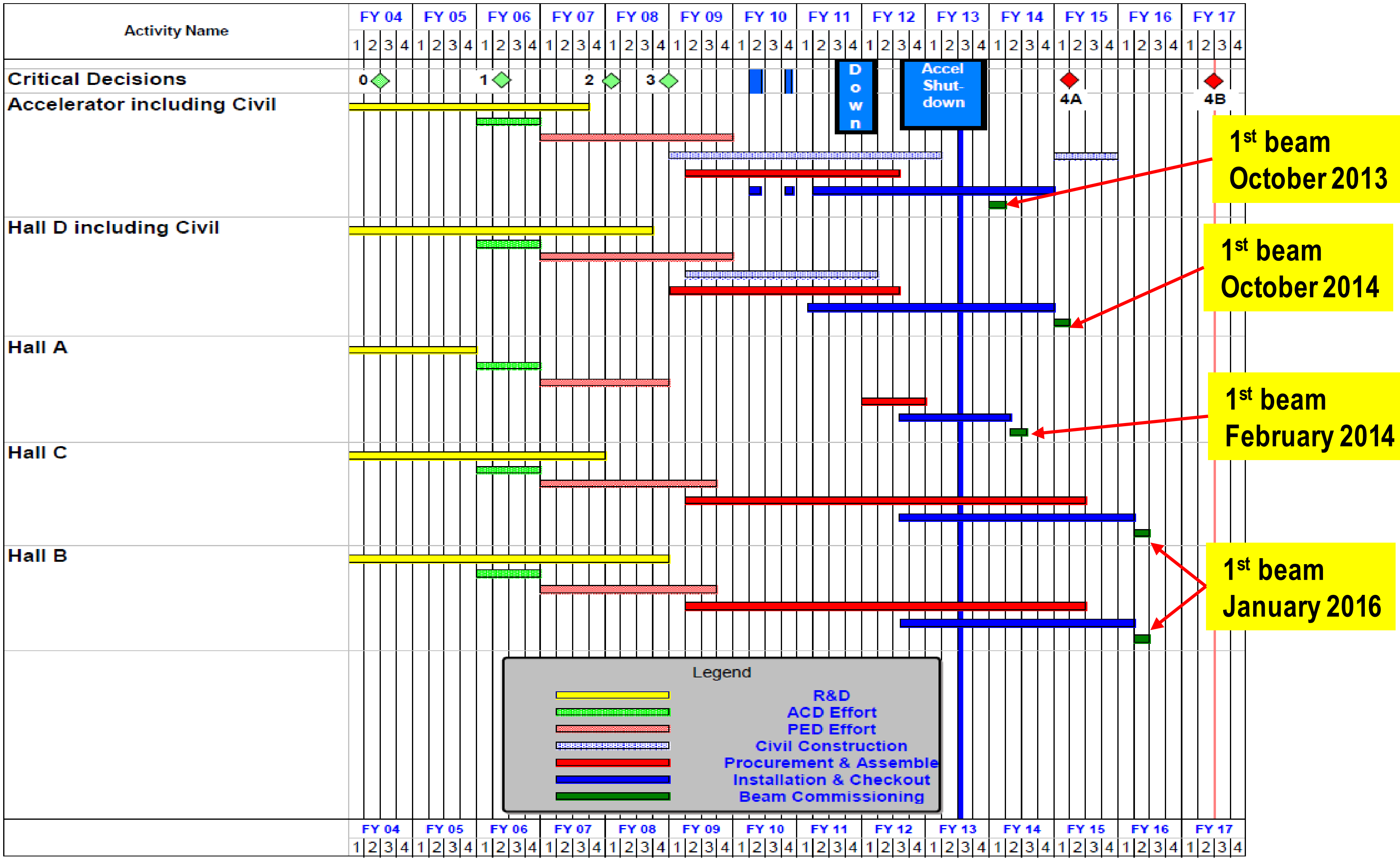




d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. A non-zero $\delta\mathbf{k_x}$ value requires a non-zero orbital angular momentum.

δk_x

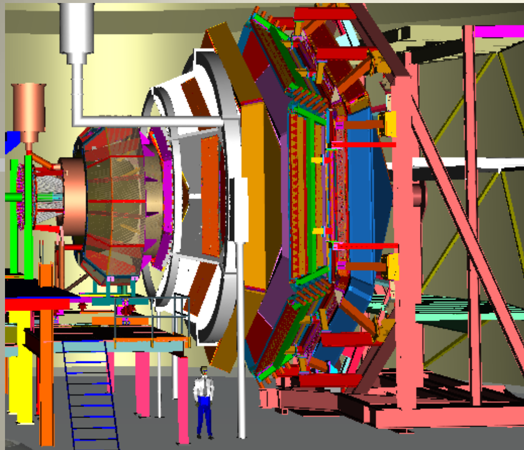
12 GeV UPGRADE REBASELINE SCHEDULE



Summary

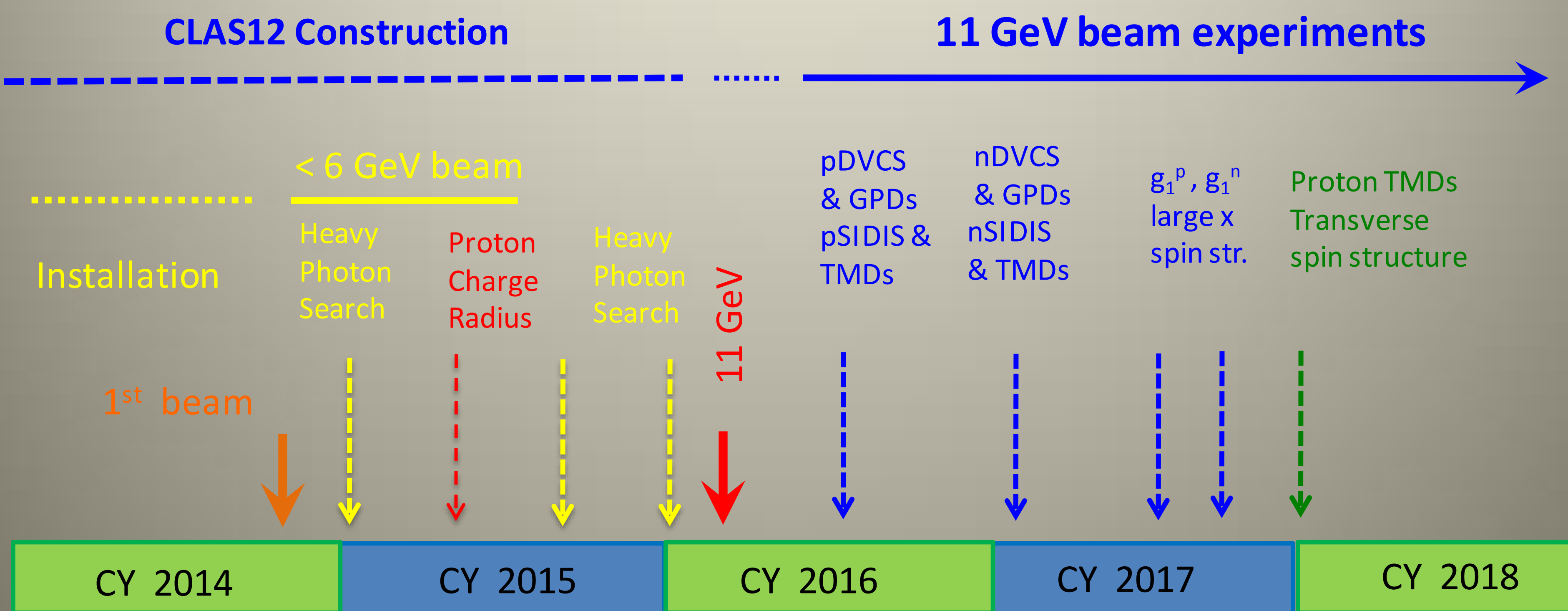
- JLab 12 GeV upgrade has a broad science program covering many facets of hadron physics.
- Extending knowledge of PDFs to high x in measurements of (un)polarized structure functions using tagging. Addresses part of the nucleon "spin-puzzle" and extend knowledge of quark density distribution at high x.
- Precision studies of DVCS in polarization measurements give access to GPDs and enable quark spatial imaging. They relate to the quark spin, mass and force distributions in the nucleon (confinement?).
- Precise measurements of SIDIS improve access to TMDs and quark momentum tomography, and relate to the quark orbital angular momentum.
- Many topics not discussed, hadron spectroscopy, high precision parity experiments, nucleon e.m. form factors, dark matter searches, QCD and nuclei, ….

Additional slides



Preliminary Plans for First Years of Beam in Hall B

- **Highly rated experiments in first 3 years of running**
- **PCR, HPS, pDVCS, nDVCS, pSIDIS, g_1^p/g_1^n**
- **High discovery potential during first year**

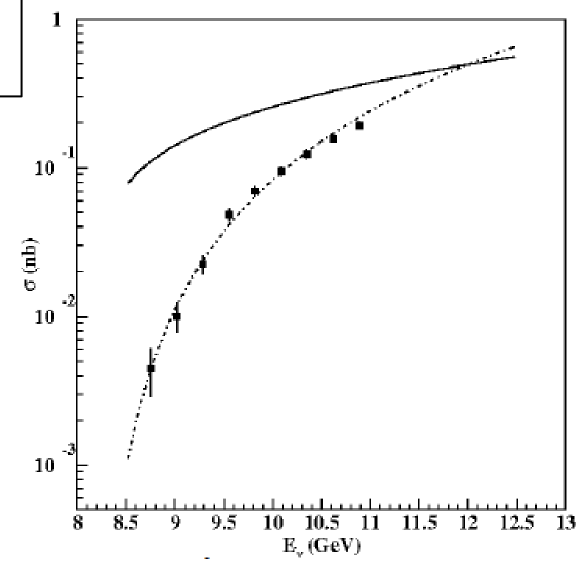


Exclusive J/ψ production near threshold

$c\bar{c}$ produced in small-size configurations

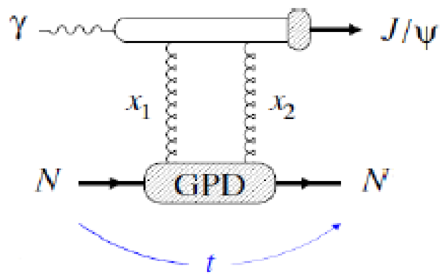
- probes small distances ~ $1/M_{J/\psi}$

E12-12-001
E12-12-006



J/ψ production at high W

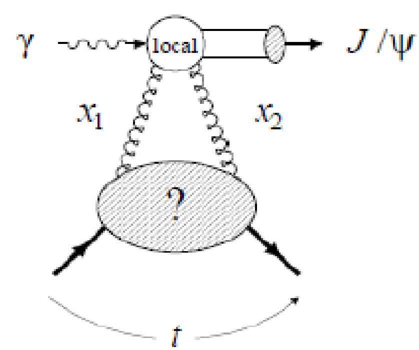
Access to gluon GPDs at small x.



J/ψ production near threshold

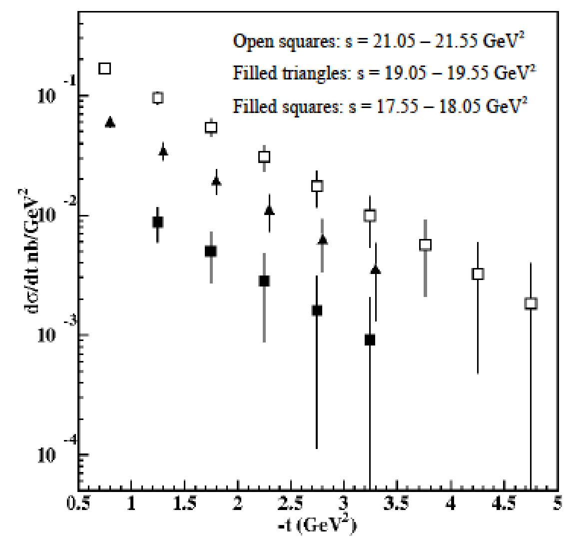
Large t_{min} implies large skewness x_1-x_2

More natural interpretation in terms of a gluonic form factor sensitive to non-perturbative gluon field.



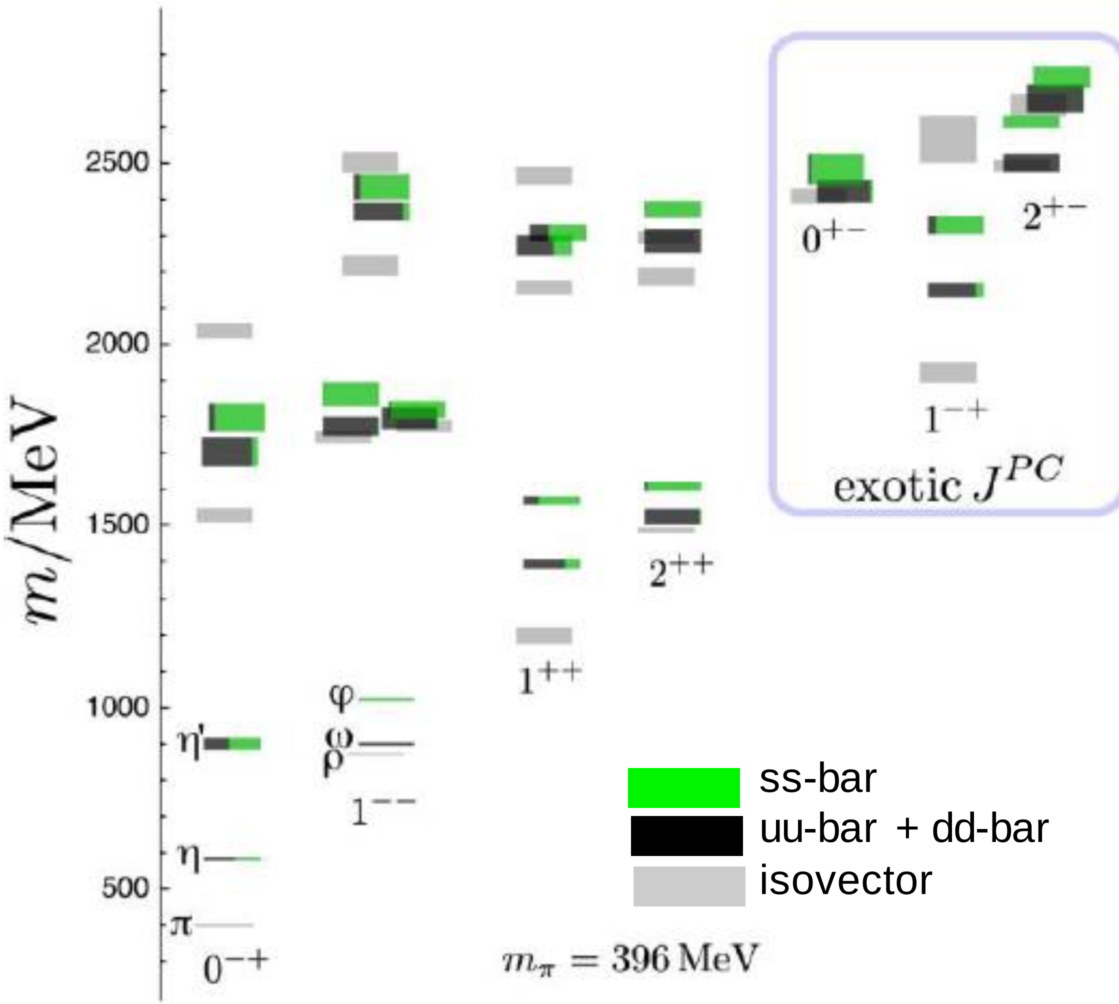
$$A(\gamma + p \to J/\psi + p) \propto F_{2g}(t)$$

gluonic form factor

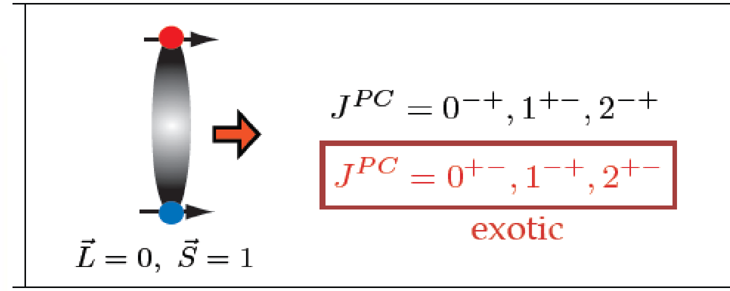


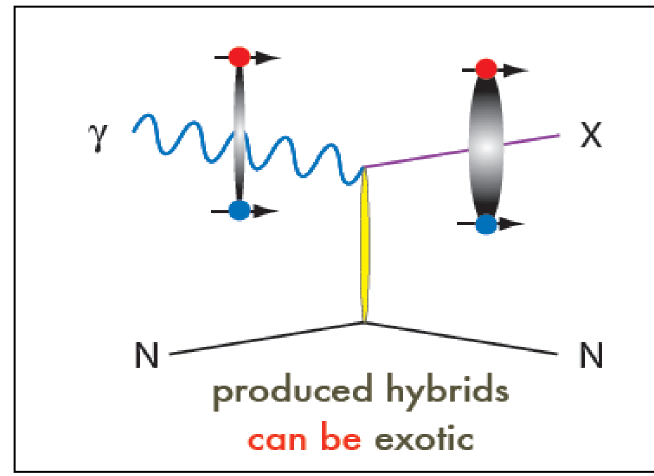
Gluonic d.o.f. in meson excitations

Isoscalar mesons from LQCD



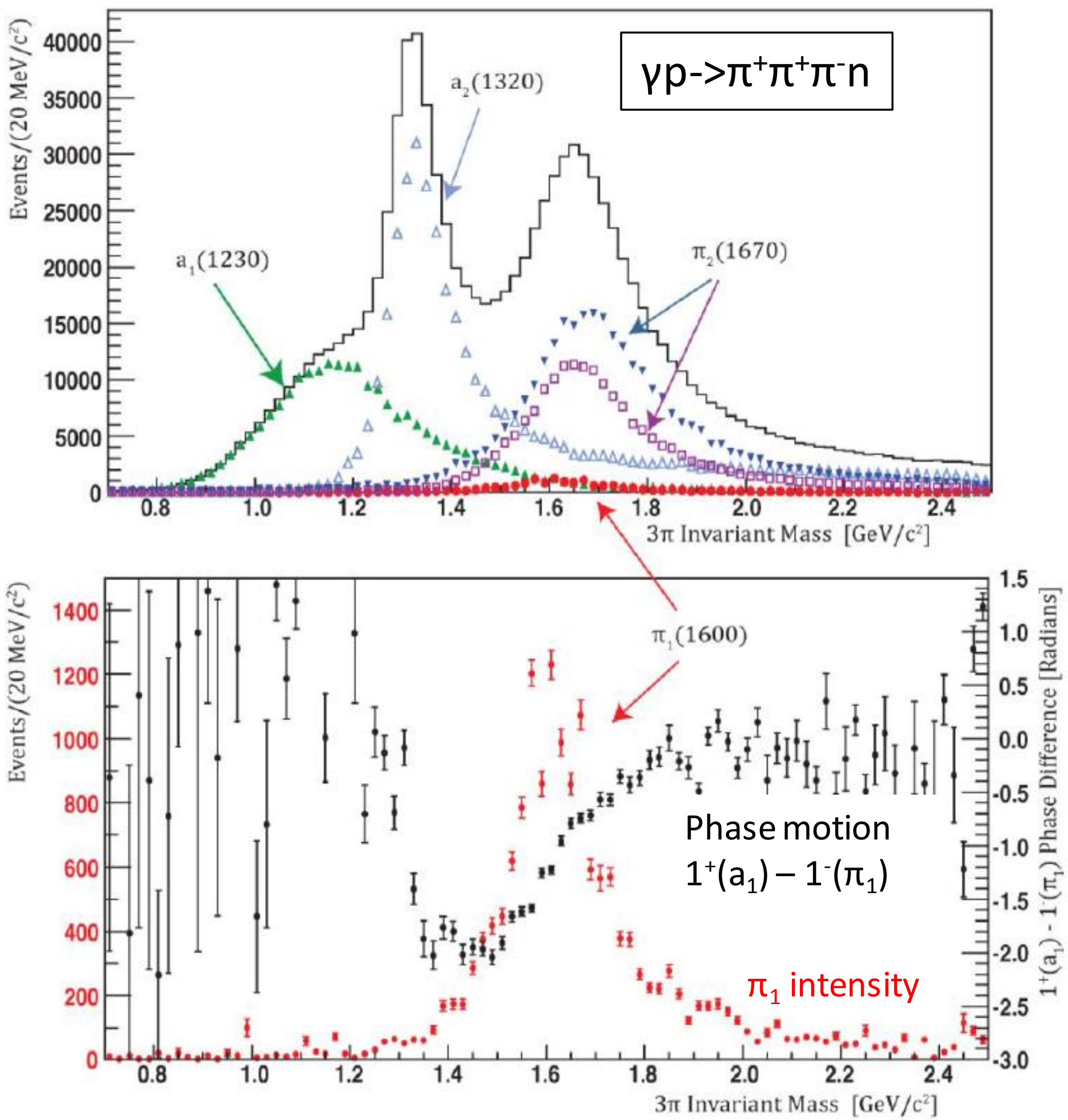
J. Dudek et al., arXiv:1208:124





Real photons may be a good probe of exotic mesons.
Large program is in preparation with the GlueX experiment.

Extracting an exotic J^{PC} signal in GlueX



E12-06-102

Amplitude analysis of MC generated data shows that a very small exotic $\pi_1(1600)$ signal can be isolated from the much larger signals of ordinary mesons.

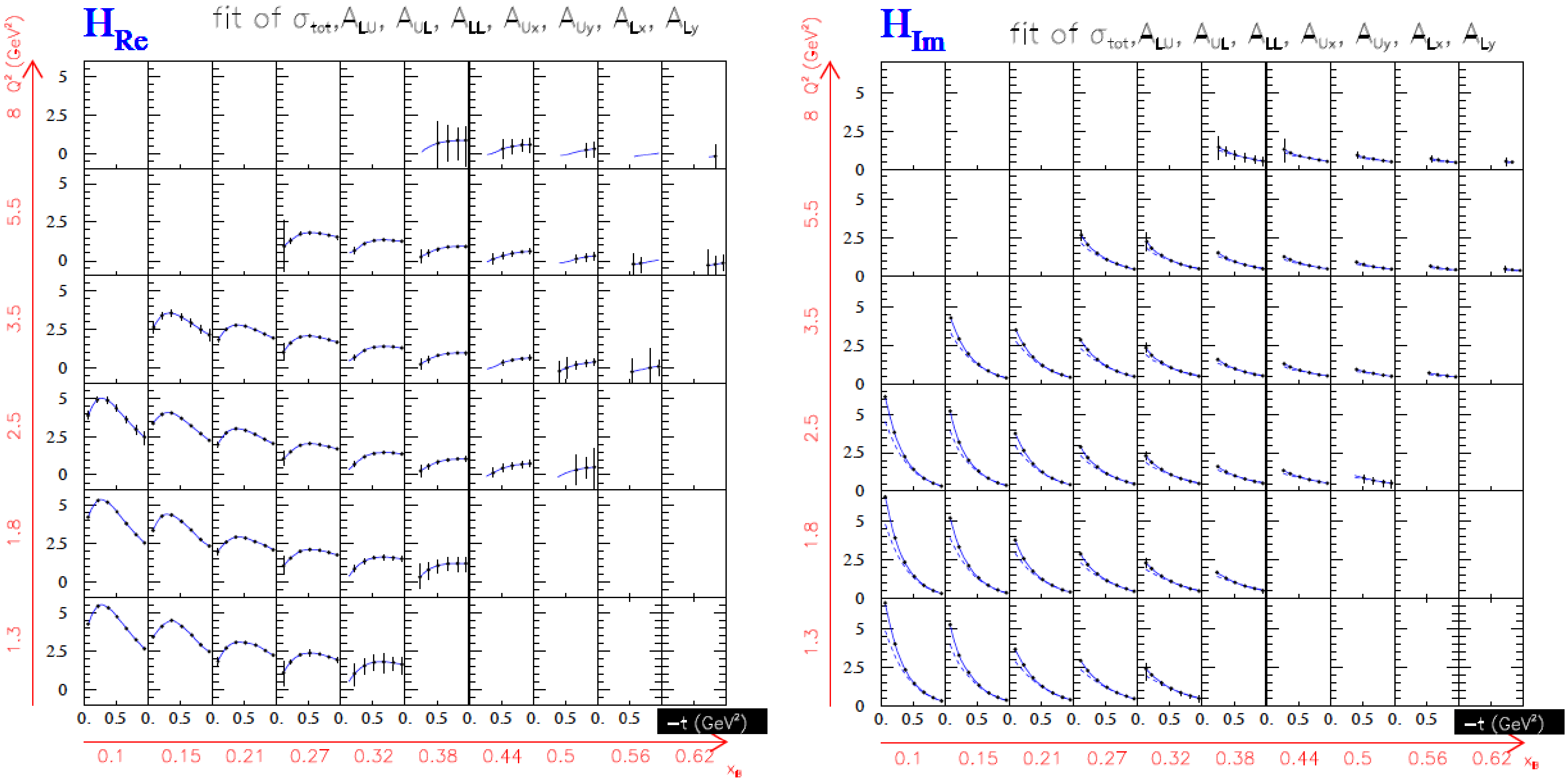
CLAS results set upper limit of 13.5nb for $\pi_1(1600)$ production in this channel, less than 2% of $a_2(1320)$.
M. Nozar, PRL 102 (2009) 102002.

A complementary program is in preparation with CLAS12 with quasi-real photons.

E12-11-005

CFF H from projected CLAS12 data

M. Guidal, H. Moutarde, M. Vanderhaeghen, Rept.Prog.Phys. 76 (2013) 066202



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