The 3D structure of hadrons at Jefferson Lab

Carlos Muñoz Camacho

IPN-Orsay, CNRS/IN2P3 (France)

COMPASS beyond 2020
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Outline

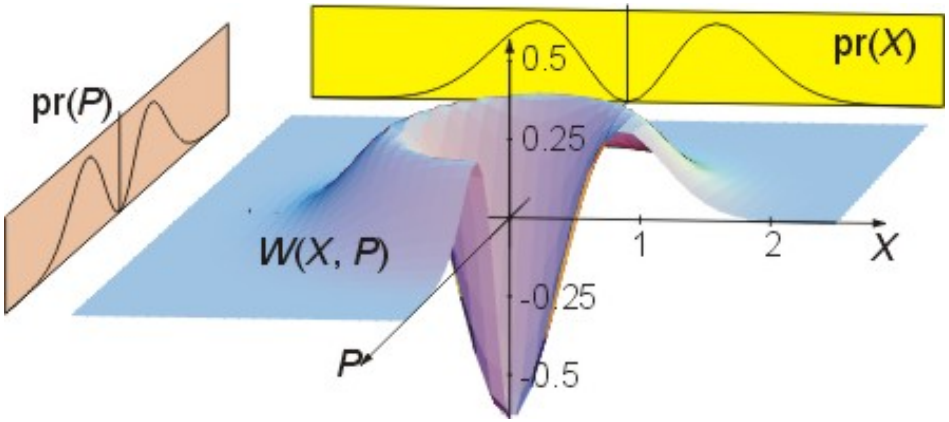
1. Experimental introduction to TMDs and GPDs
   (how they appear in exclusive and semi-inclusive experiments)

2. Jefferson Lab overview:
   - (Very!) short summary of 6 GeV achivements
   - Complementary of TMD/GPD programs in Hall A, B and C
   - Selected future measurements at 12 GeV

3. Summary and conclusion

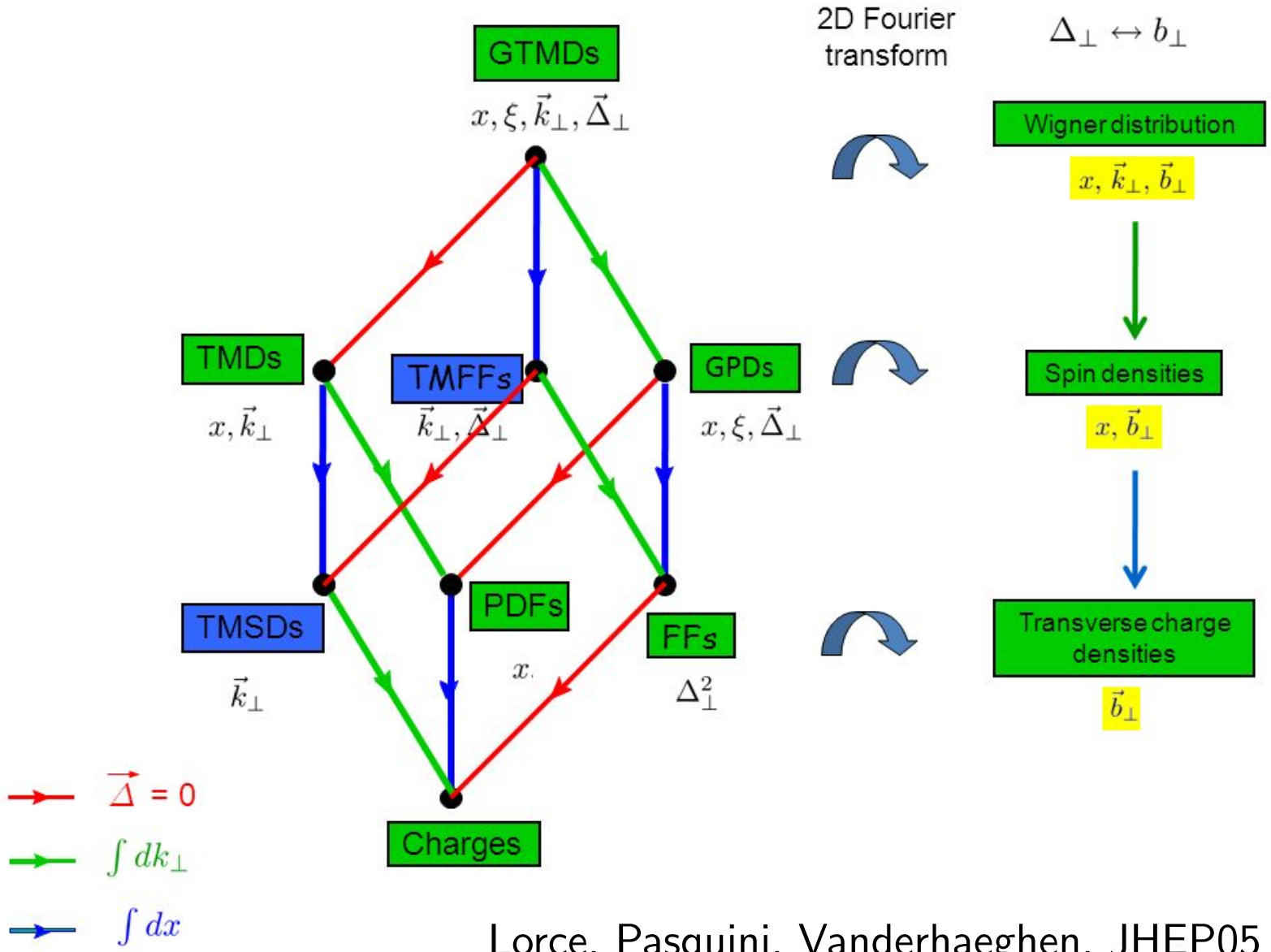
Unified view of nucleon structure

Wigner distribution (1933): $W(p,r) = \int d^3z e^{i\mathbf{p}z} \psi^*(\mathbf{r}+z/2)\psi(\mathbf{r}-z/2)$



- In quatum physics: $\Delta p \Delta r \gtrsim \hbar/2$ ("quasi-probability")
- In QCD: no known observable can access such a general function

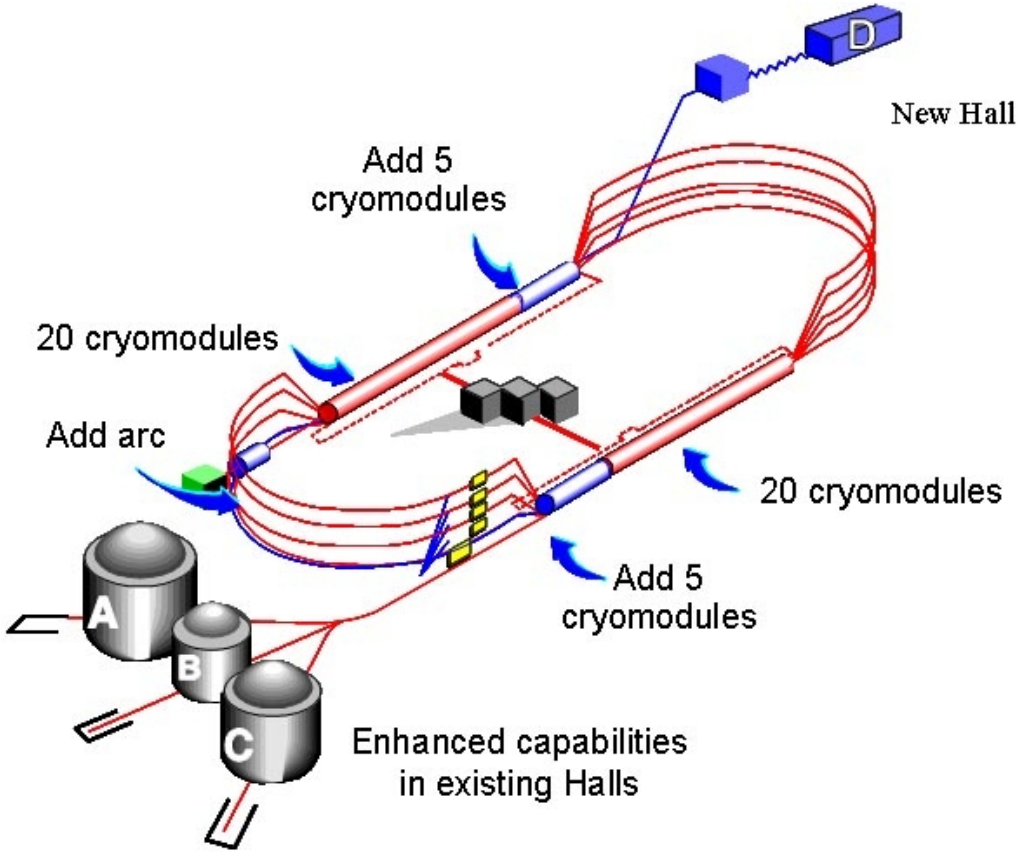
From Wigner distribution to observables



Lorce, Pasquini, Vanderhaeghen, JHEP05 (2011)

Jefferson Lab: upgraded to 12 GeV

- 6-12 GeV longitudinally polarized (>85%) continuous electron beam
- High intensity (>100 μA): luminosities $> 10^{38}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$
- 3 experimental Halls (A, B, C) w/ fixed target and dedicated detectors



Operations expected to start in Fall 2016, for 10–15 years...

Advantages & complementarities of Halls A/B/C for exclusive and semi-inclusive measurements

Hall A

- Polarized neutron measurements ($\mathcal{L} > 10^{37}$ Hz/cm^2)
- Large acceptance, open geometry spectrometers (SoLID)

Hall B

- Very large acceptance ($\mathcal{L} \sim 10^{35}$ Hz/cm^2)
- Many-dimensional phase space

Hall C

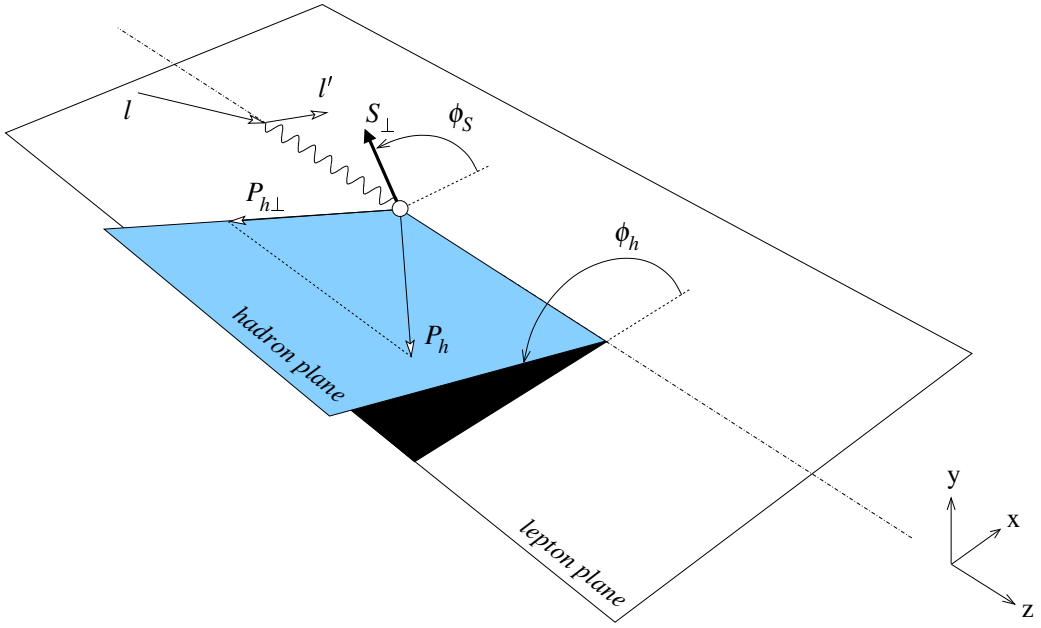
- L/T separations
- High luminosity ($\mathcal{L} > 10^{38}$ Hz/cm^2)
- Precision measurements with small acceptance spectrometers

Partial overlap

Excellent for cross-checks and understanding systematic effets

Semi-inclusive DIS cross section

$$\ell(l) + p(P) \to \ell(l') + h(P_h) + X,$$



- Virtual photon: $q = l - l'$, $Q^2 = -q^2$
- Lepton fractional energy loss: $y = P \cdot q / P \cdot l$
- Fraction of energy transfer carried by the struck quark: $z = P \cdot P_h / P \cdot q$

Semi-inclusive DIS cross section

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad+|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$

Bacchetta et al., JHEP 02, 093 (2007)

Accessing TMDs through experiment

For example, the unpolarized SIDIS cross section:

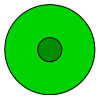
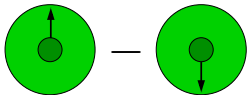
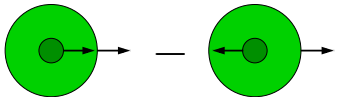
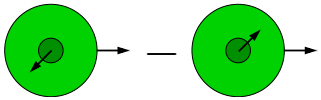
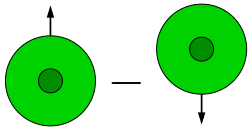
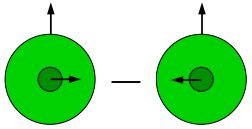
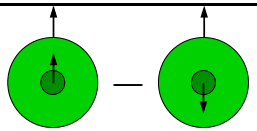
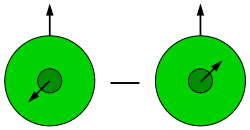
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\times$$
$$\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}\right\},$$

$$\mathbf{F_{UU,T}} = x\sum_f e_f^2 \int d^2\boldsymbol{p}_T d^2\boldsymbol{k}_T \delta^{(2)}(z\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}) f_1^f(x,p_T^2) D^f(z,k_T^2)\,,$$

$f_1^f(x,p_T^2)$ = Unpolarized TMD

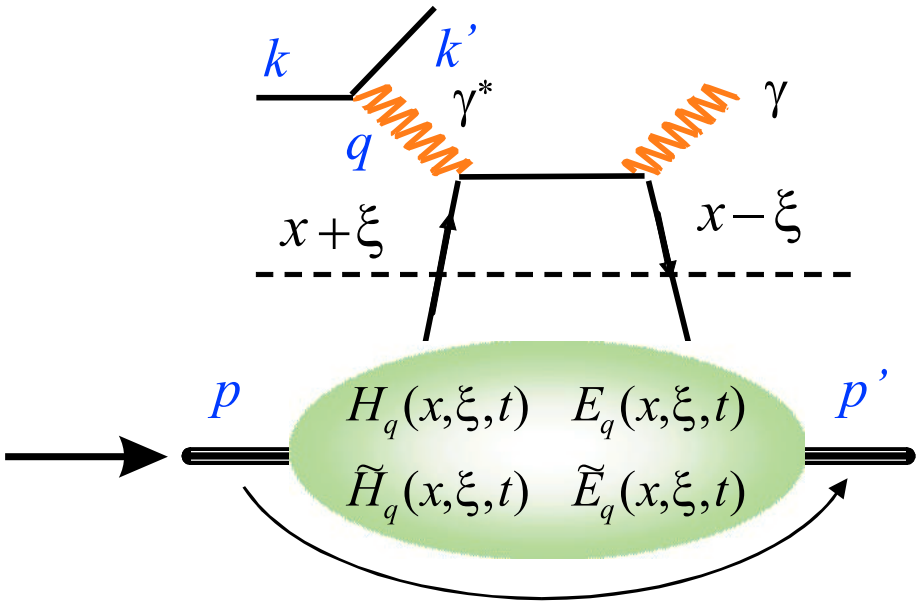
$D^f(z,k_T^2)$ = Unpolarized fragmentation function

Twist-2 TMDs for spin 1/2 hadrons

		Quark polarization		
		U	L	T
Nucleon polarization	U	f_1  Unpolarized		$h_1^\perp$  Boer-Mulder
	L		g_{1L}  Helicity	$h_{1L}^\perp$  Worm-gear
	T	$f_{1T}^\perp$  Sivers	g_{1T}  Worm-gear	h_{1T}  Transversity $h_{1T}^\perp$  Pretzelosity

Probabilistic interpretation of twist-2 TMDs

Deeply Virtual Compton Scattering (DVCS): $\gamma^* \, p \to \gamma \, p$



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

Handbag diagram

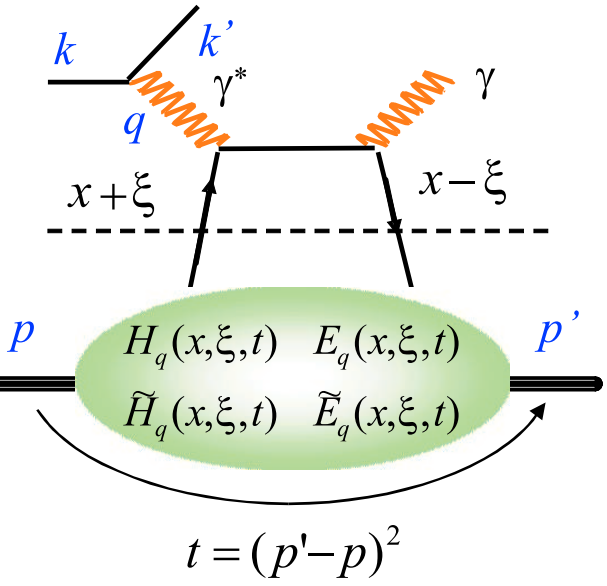
High Q^2
Perturbative QCD

Non-perturbative
GPDs

Bjorken limit:

$$Q^2 = \left.\begin{array}{rcl} -q^2 & \to & \infty \\ \nu & \to & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

Generalized Parton Distributions



- Correlate between different partonic states
- Correlate momentum and position of partons
- Access to new fundamental properties of the nucleon

Contribution of the **angular momentum of quarks** to proton spin:

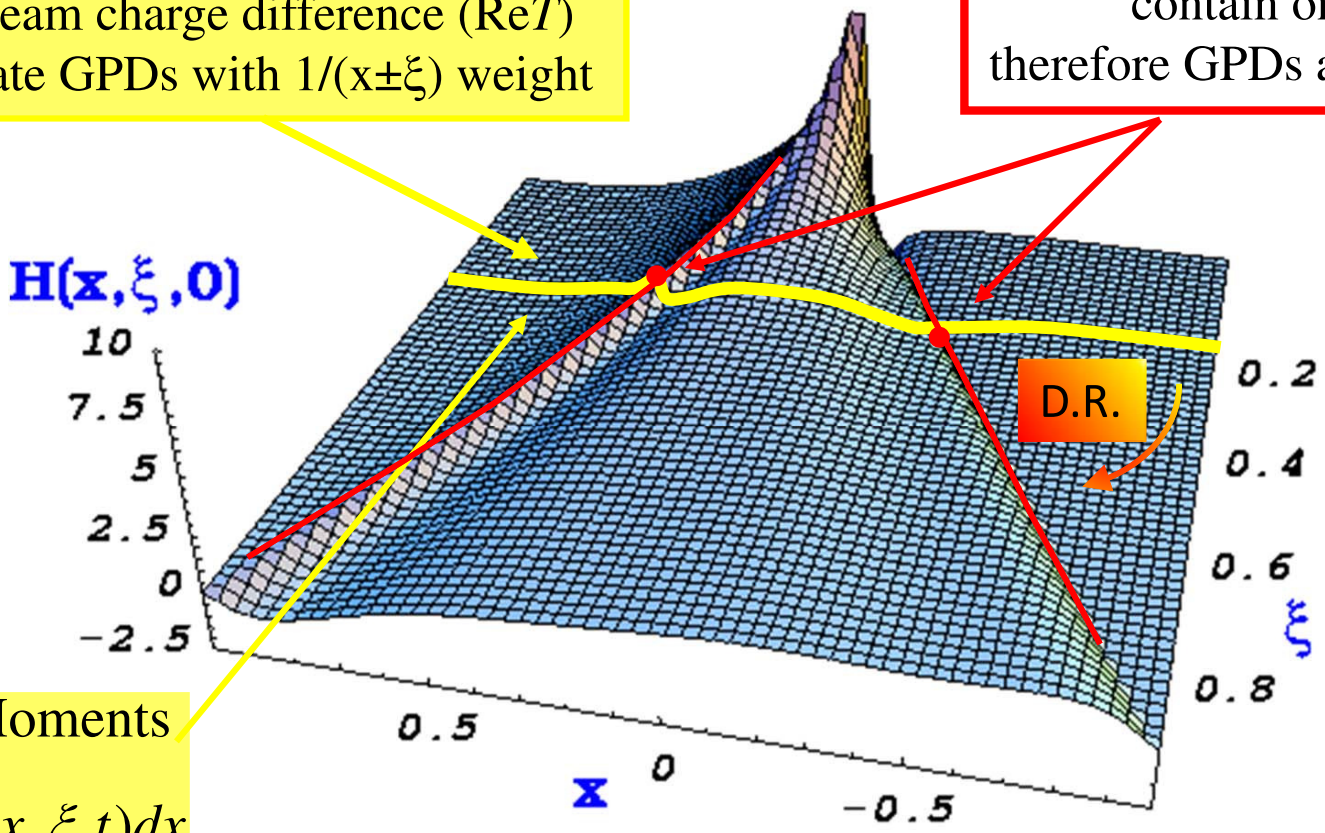
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

DVCS cleanest process to access GPDs

GPD experimentally: Compton Form Factors (CFFs)

Cross-section (σ) measurement and beam charge difference (Re*T*) integrate GPDs with 1/(x±ξ) weight

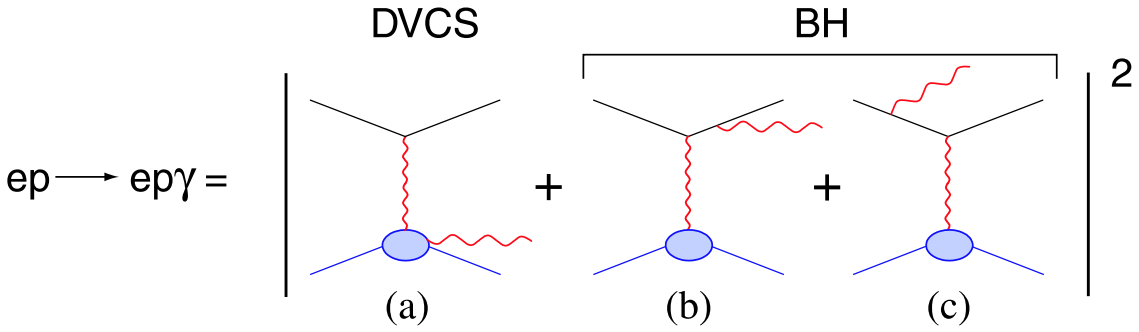
Beam or target spin Δσ contain only Im*T*, therefore GPDs at $x = \xi$ and $-\xi$



Lattice Moments

$$= \int x^n H(x,\xi,t)dx$$

DVCS experimentally: interference with Bethe-Heitler (BH)



At leading twist:

$$d^5\overrightarrow{\sigma} - d^5\overleftarrow{\sigma} = \Im m\,(T^{BH}\cdot T^{DVCS})$$

$$d^5\overrightarrow{\sigma} + d^5\overleftarrow{\sigma} = |BH|^2 + \Re e\,(T^{BH}\cdot T^{DVCS}) + |DVCS|^2$$

$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi\, H(x=\xi,\xi,t)}_{\text{Access in helicity-dependent cross-section}} + \ldots$$

Accessing different GDPs

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (ITSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B kF_2\tilde{\mathcal{E}}\ldots\}d\phi$$

Polarized beam, longitudinal target (BITSA)

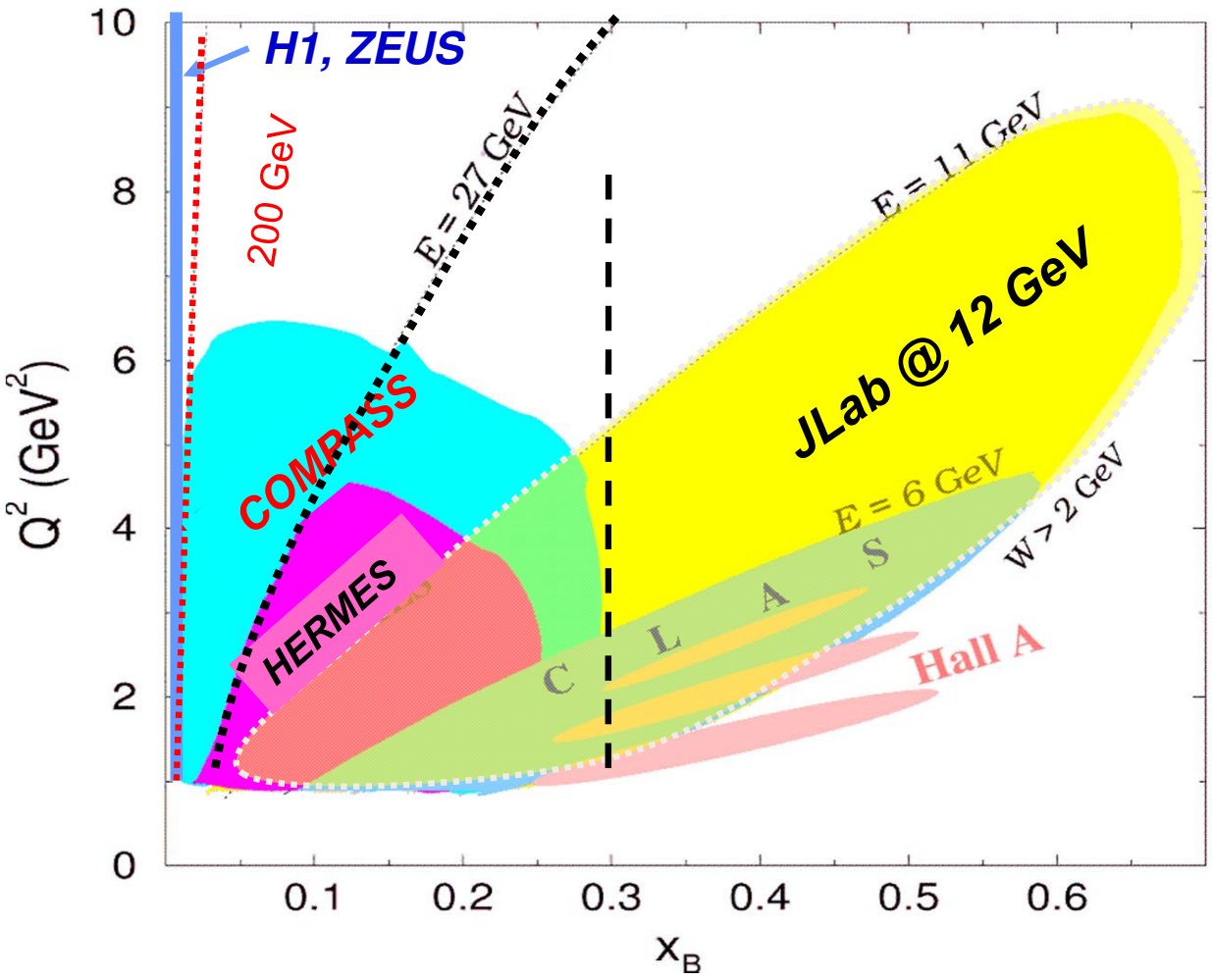
$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\ldots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$$

Kinematic coverage

Kinematic complementarity between different facilities:



Summary of JLab results at 6 GeV

- Different measurements of SIDIS asymmetries in polarized p and n
- Initial tests of SIDIS reaction mechanism, compatible with LO approaches

- First indications of validity of GPD formalism at moderate Q^2
- DVCS primarily studied in detail (DVMP need higher Q^2)
- DVCS deviates significantly from Bethe-Heitler
  ($\rightarrow$ cross section measurements needed, not only asymmetries)

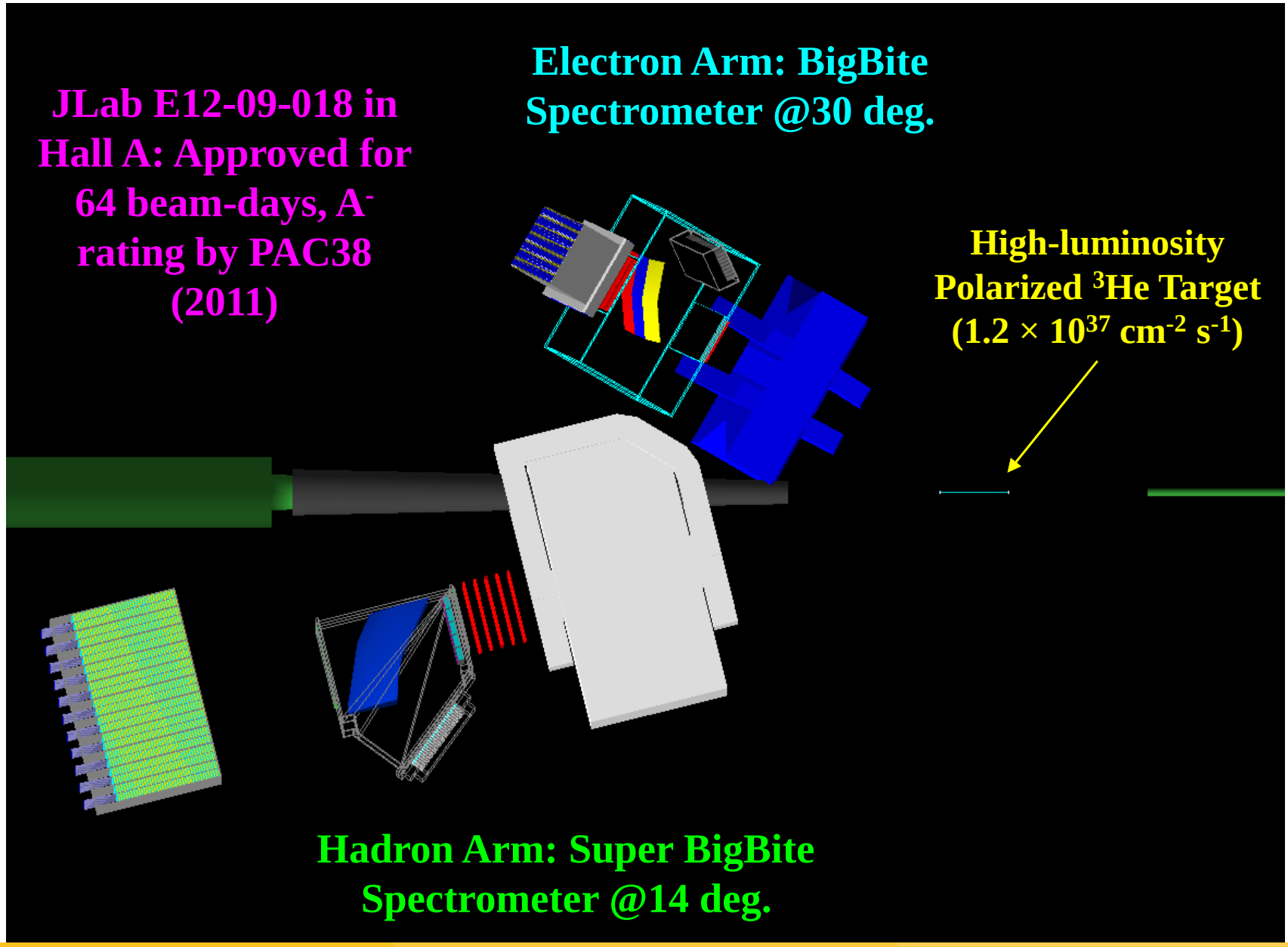
- Higher twist corrections likely necessary to fully describe the data
- Extremely accurate data to constrain models and global fits

Overview and selected highlights of SIDIS with JLab12

The JLab12 TMD/GPD program:

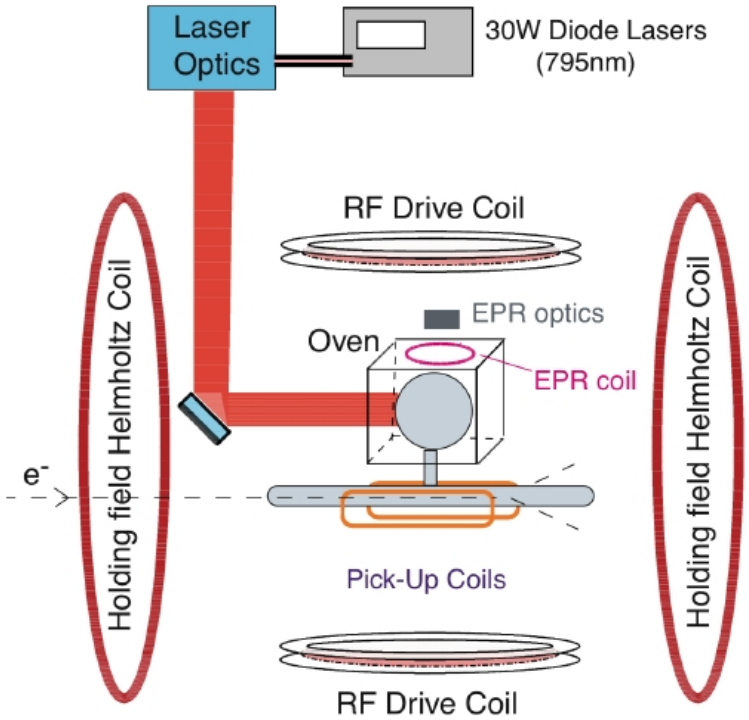
- High luminosity
- Large acceptance
- High-performance polarized targets
- Proton/Neutron for flavor separation
- Valence quark region
- Different Halls complementarity

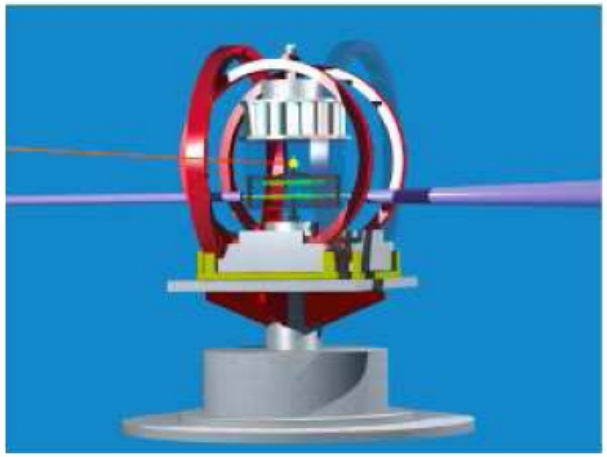
Hall A: neutron transversity with BigBite + Super Bigbite



Polarized ^3He target

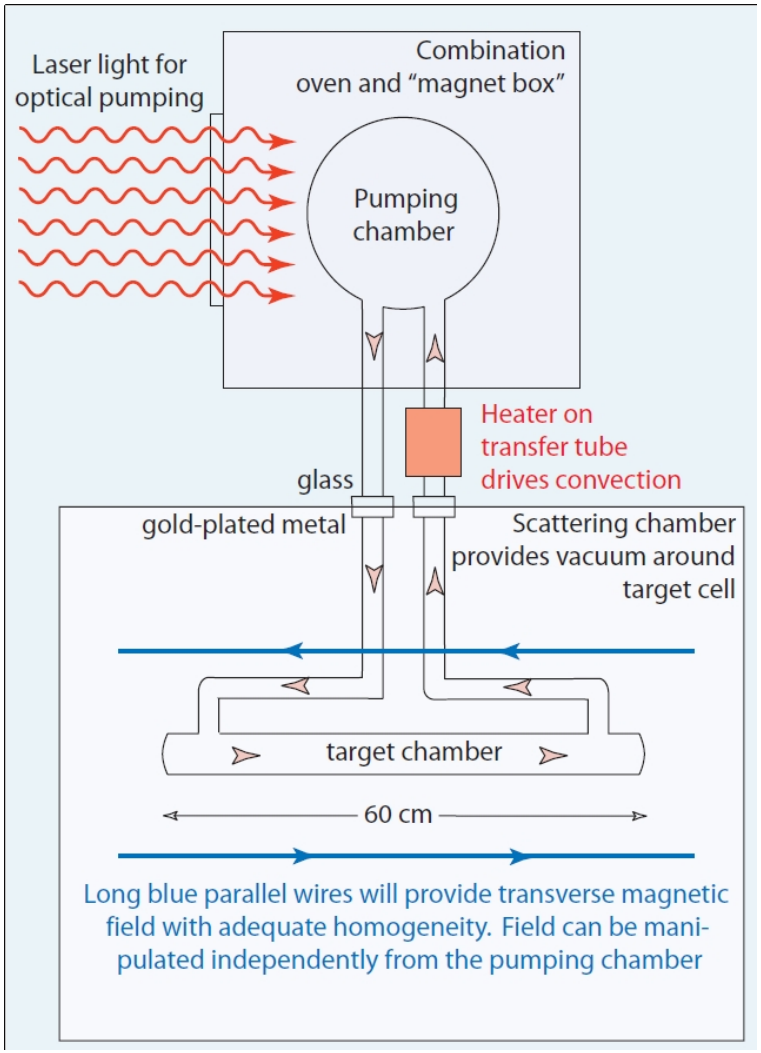
- n lum. of $10^{36}/\text{cm}^2/\text{s}$ (14 atm$\times$40 cm)
- "Background" luminosity:
  - p in ^3He + entrance/exit windows
  - $10^{37}/\text{cm}^2$ total luminosity
- Polarization: 50%
  - Nuclear physics dilution factor 0.86 (d-state)
  - -2.8% p polarization
  - Long. & Trans.



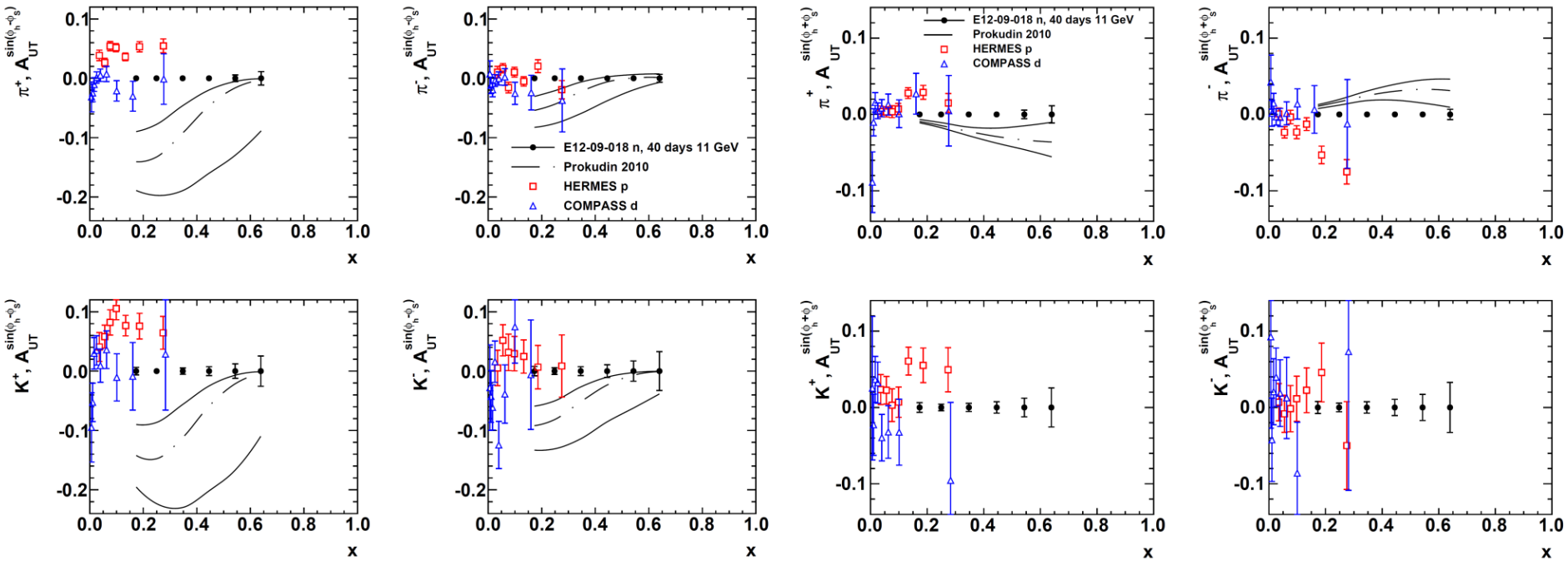


^{3}He target upgrade

- Separate polarization and tgt volumes
  - Increase throughput by factor 10–100
  - Cool and/or compress ^{3}He in target area by a factor of 10 (10K at 10 atm$\times$20 cm)
  - Rapid cycling of ^{3}He through target
    - Reduce depolarization effect of tgt density, beam current, tgt walls
    - Replace thick glass with thin metallic walls
- Neutron luminosity of $10^{37}/\text{cm}^2/\text{s}$
  - Proton luminosity $2 \cdot 10^{37}/\text{cm}^2/\text{s}$
  - Endcaps $\leq 10^{37}/\text{cm}^2/\text{s}$
- Target polarization: $0.5 \cdot (0.86n - 0.028p)$



Hall A: Collins and Sivers SSAs



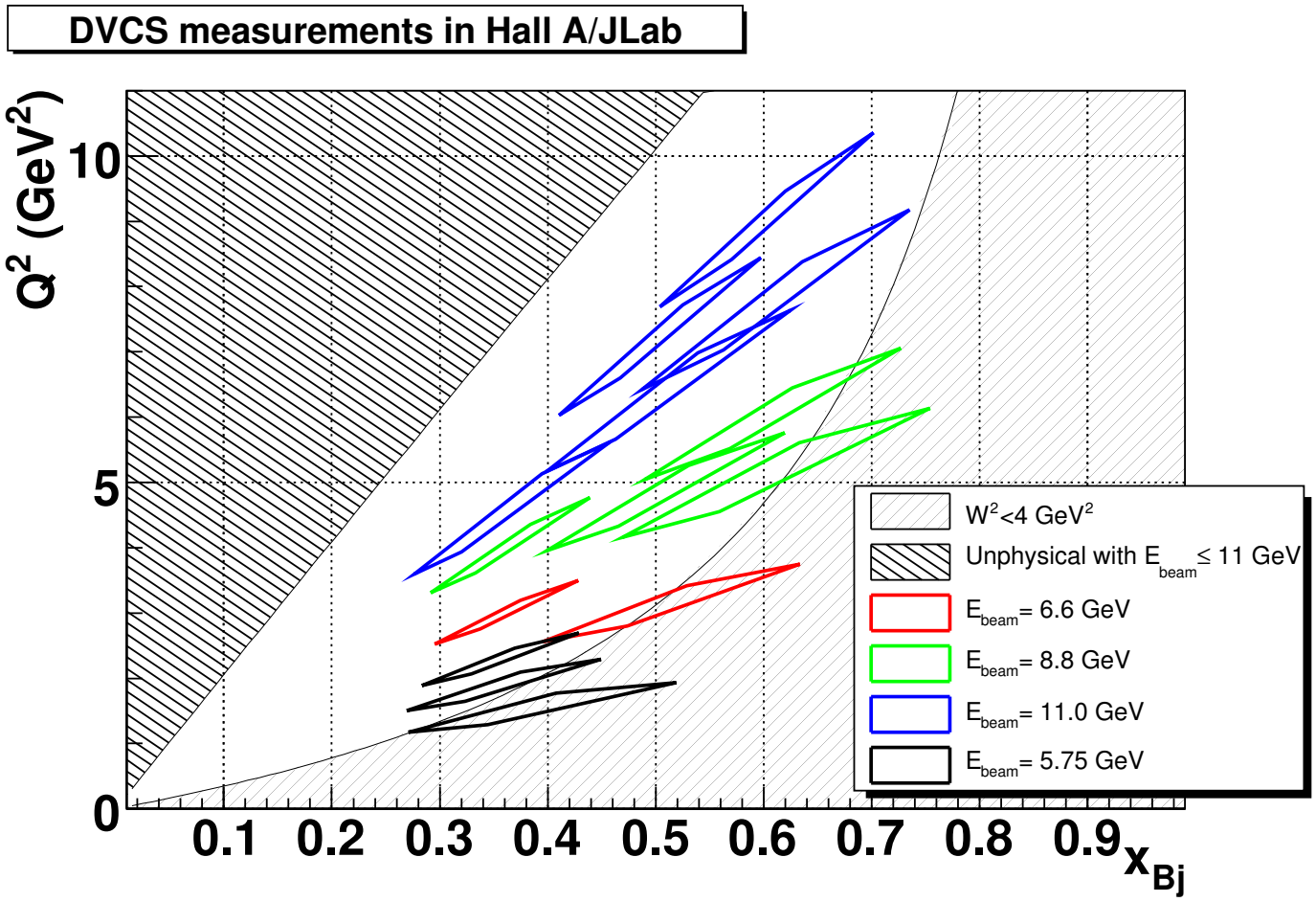
Projected A_{UT}^{Sivers} *vs.* x Projected A_{UT}^{Collins} *vs.* x

- E12-09-018: statistical FOM for the neutron ~ 100 better than HERMES proton data and ~ 1000 better than E06-010 neutron data
- K and π^0 data will help flavor separation and understanding the reaction mechanism

E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)

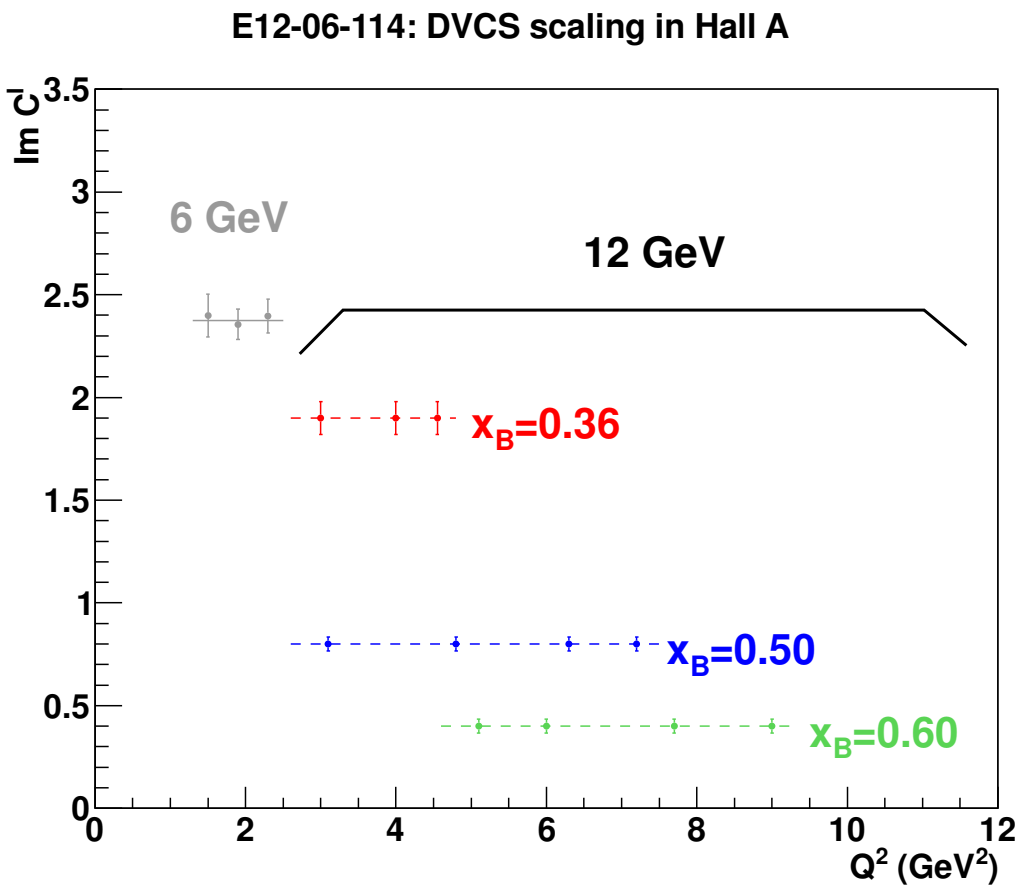


88 days

250k events/setting

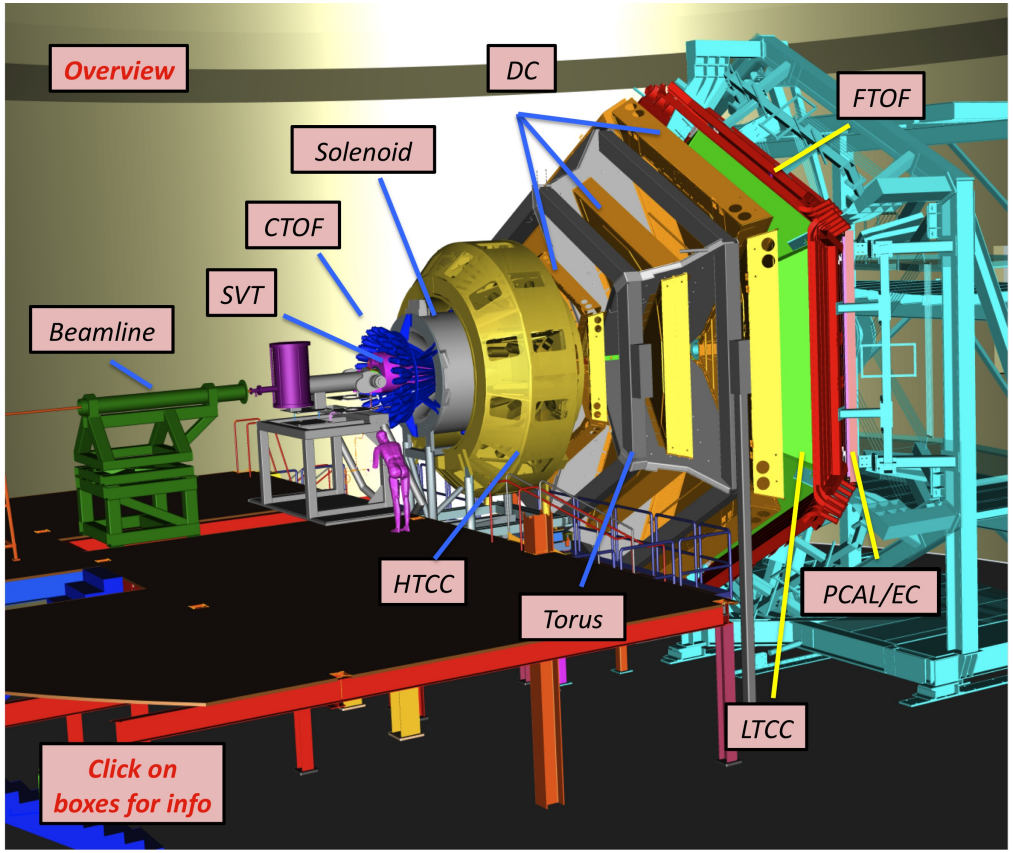
1 year of operations in JLab/Hall A

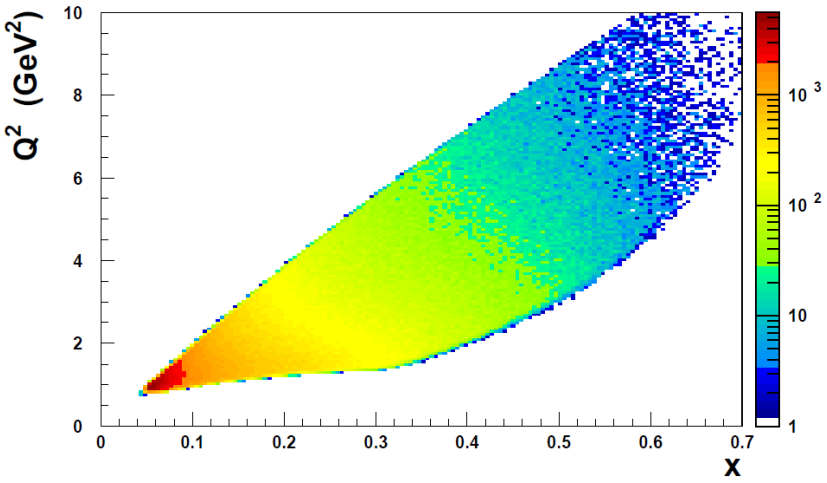
High precision Q^2 dependence of GPD-related terms



- Very high precision Q^2 dependence of each azimuthal term
- Check of applicability of QCD factorization at accessible values of Q^2
- High twist contributions will be quantified

CLAS12





Q^2 and x_B kinematic coverage of CLAS12

+ Non-based equipement for better tracking and PID:

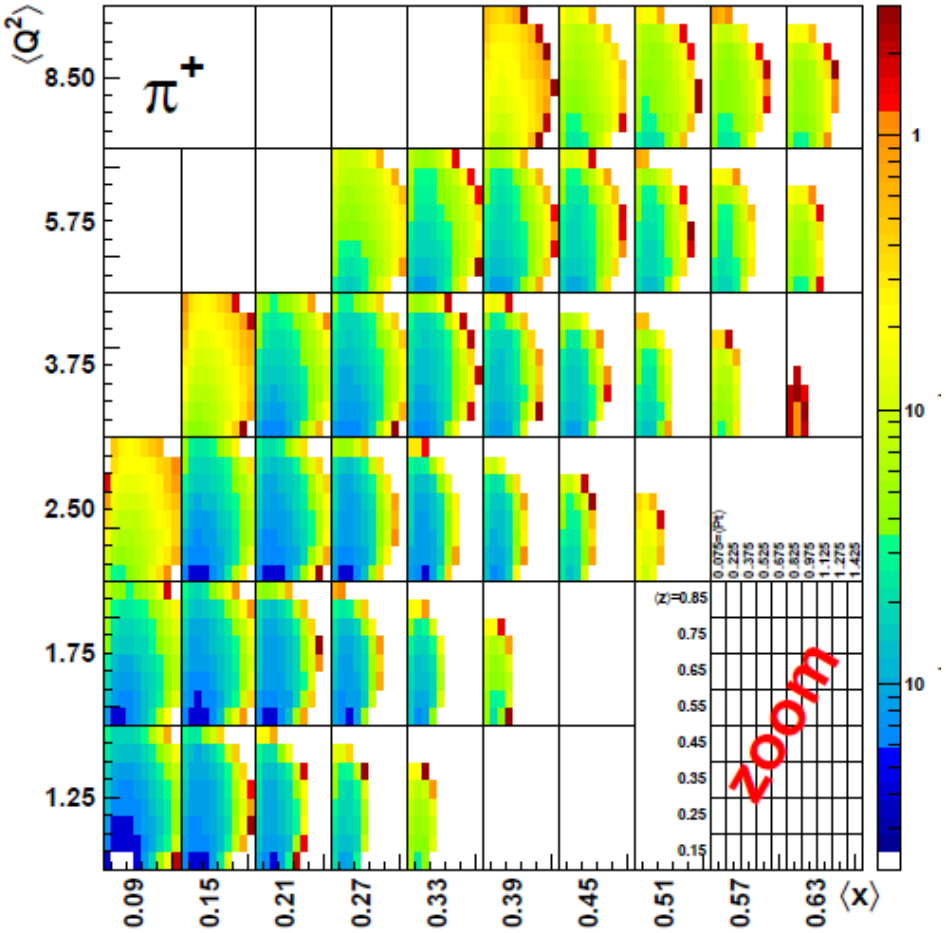
- RICH
- MicroMegas tracker
- Central Neutron Detector
- Forward Tagger

- Large acceptance ($\sim 2\pi$), general purpose detector, $\mathcal{L} \sim 10^{35}$ Hz/cm^2
- Multi-dimensional survey of exclusive and semi-inclusive reactions

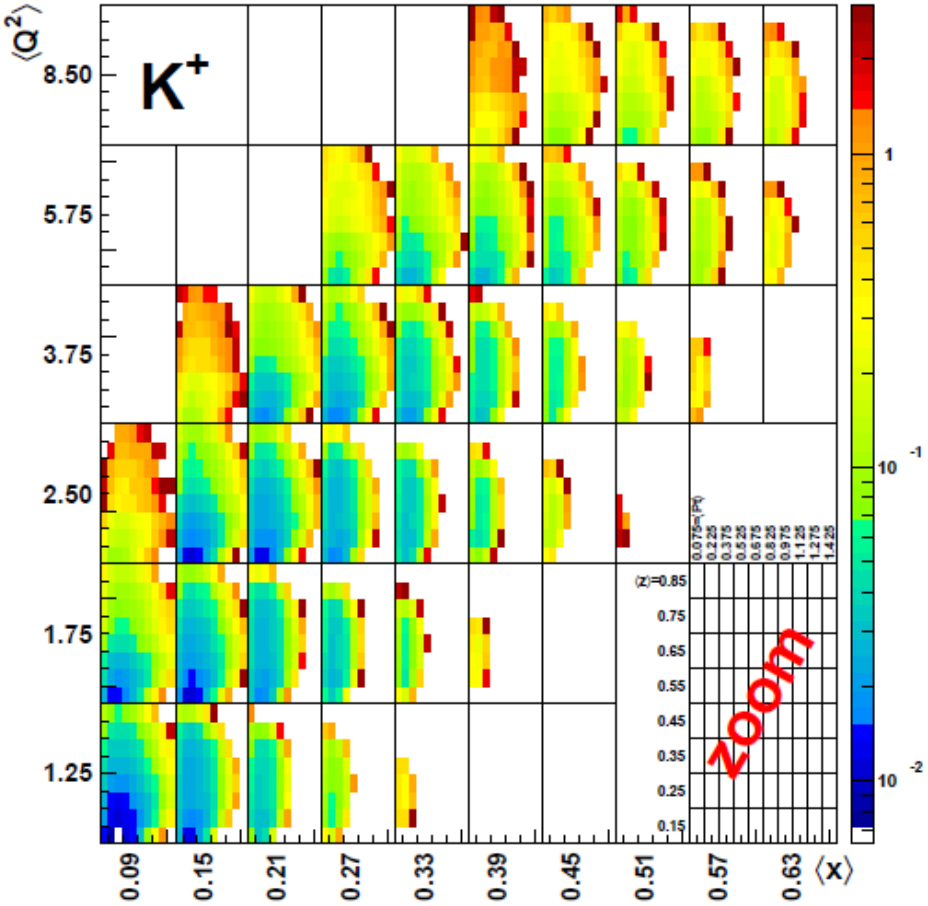
CLAS12 approved TMD & GPD programs

1. Run group A (139 days): unpolarized LH_2 target
   - SIDIS unpolarized cross sections and A_{LU}
   - DVCS and DVMP cross sections and BSA on the proton
2. Run group B (90 days): unpolarized LD_2 target
   - SIDIS unpolarized cross sections and A_{LU}
   - DVCS and DVMP BSA on the neutron
3. Run group C (170 days): longitudinally polarized proton (NH_3) and deuteron (ND_3) targets
   - A_{LL} and A_{UL} for SIDIS
   - A_{LL} and A_{UL} for DVCS and DVMP

CLAS12 multi-dimensional precision in SIDIS



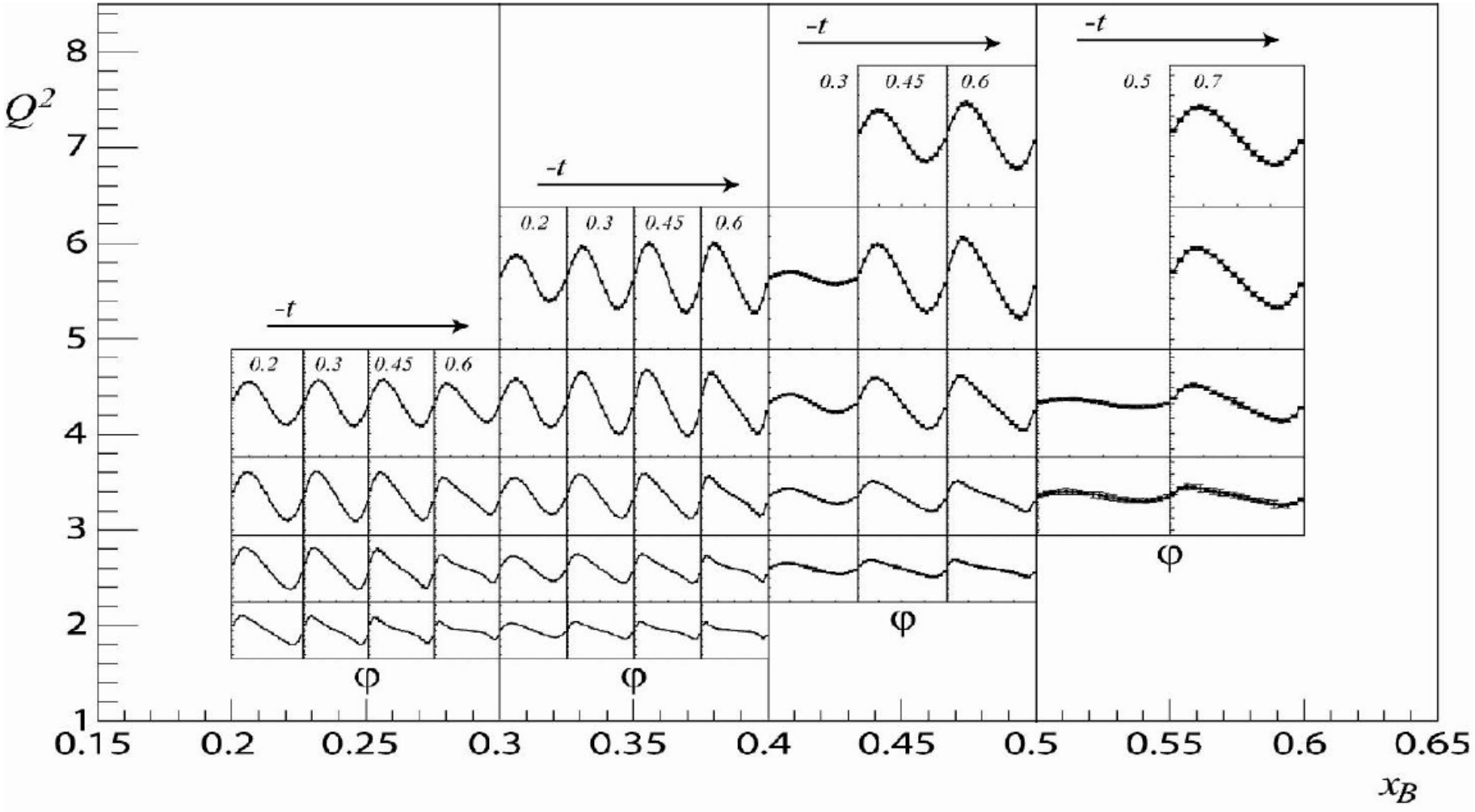
4D analysis for π^+



4D analysis for K^+

E12-06-119: DVCS on the proton with CLAS12

High statistical precision in multi-dimesional BSAs



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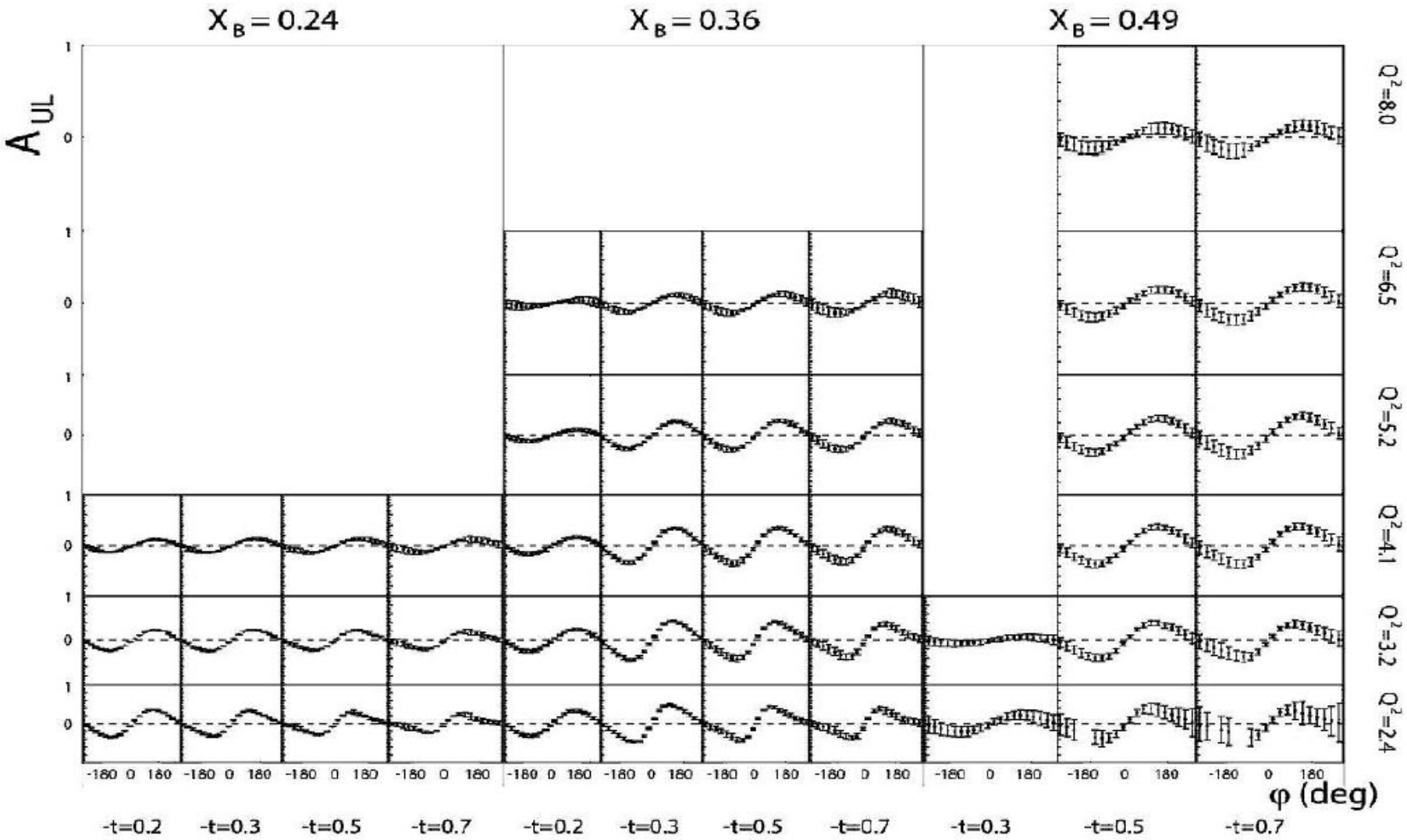


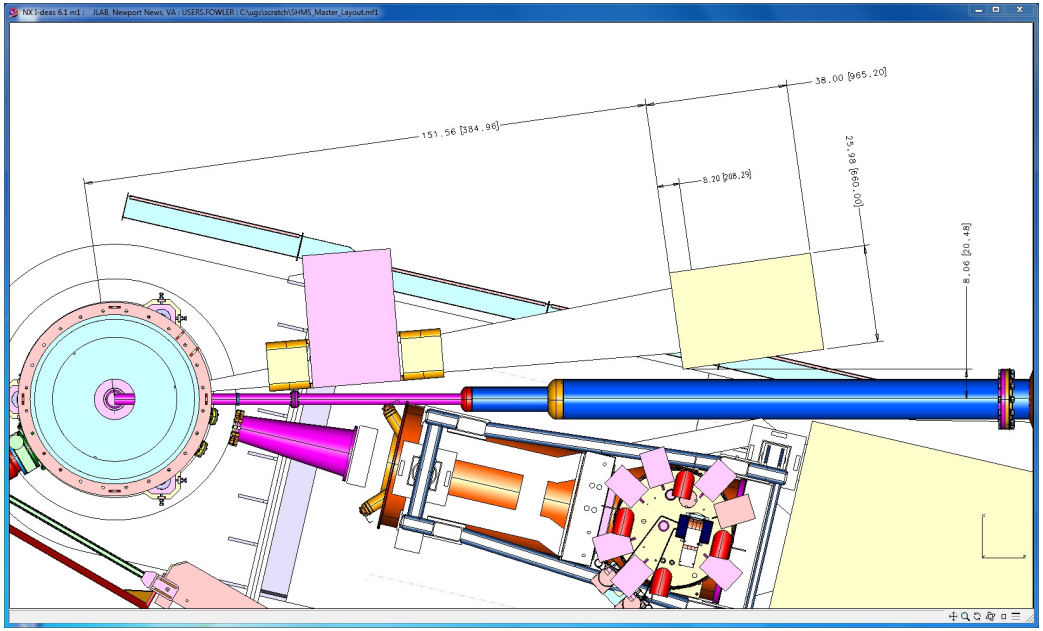
Hall C: high precision L/T separations

- High Momemetum Spectrometer ($p < 7.3GeV$): scattered electron
- $PbWO_4$ calorimeter: γ/π^0 detection
- Sweeping magnet

DVCS experiment E12-13-010:

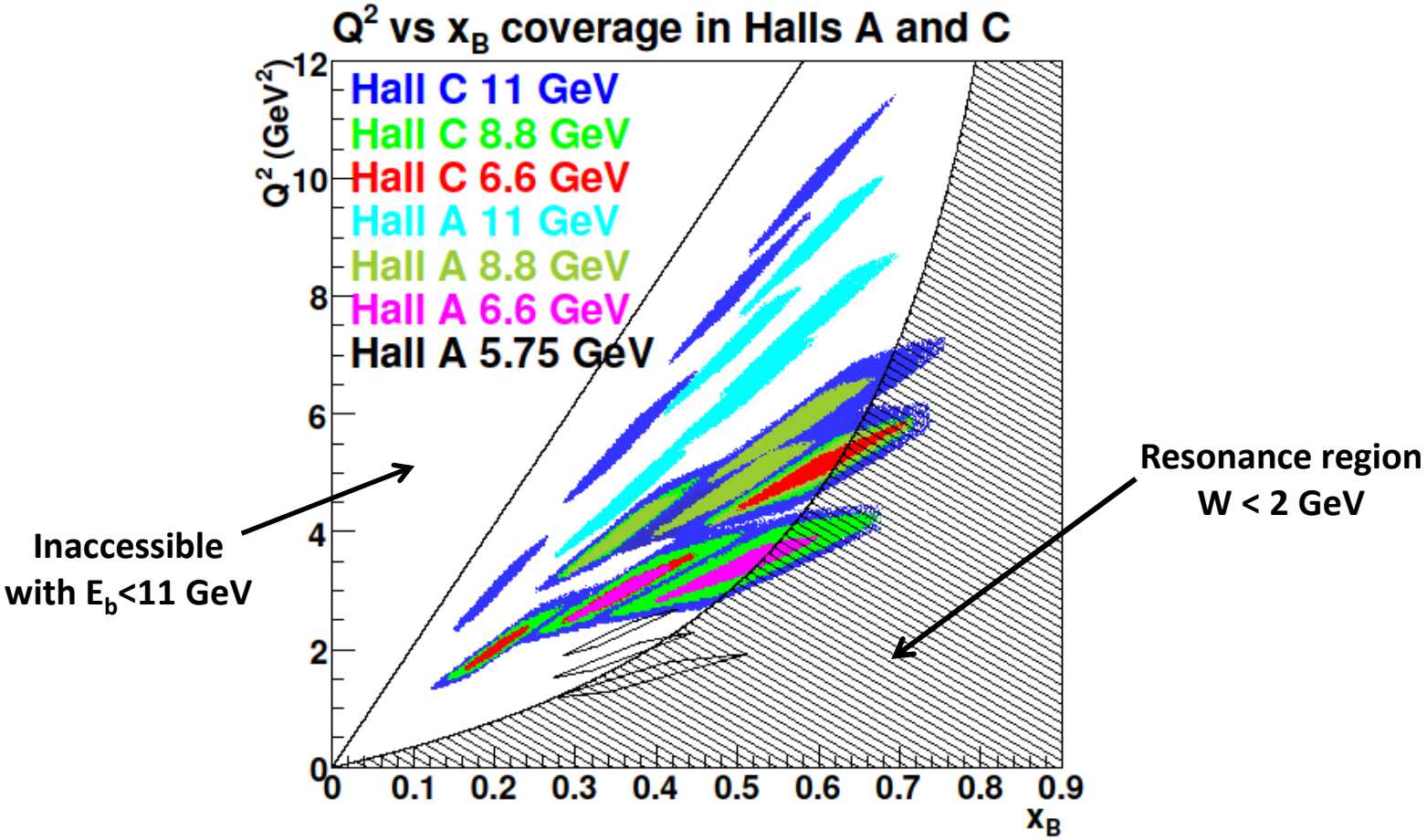
$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3$$

$$|\mathcal{T}^{DVCS}|^2 \propto 1/y^2 = (k/\nu)^2$$



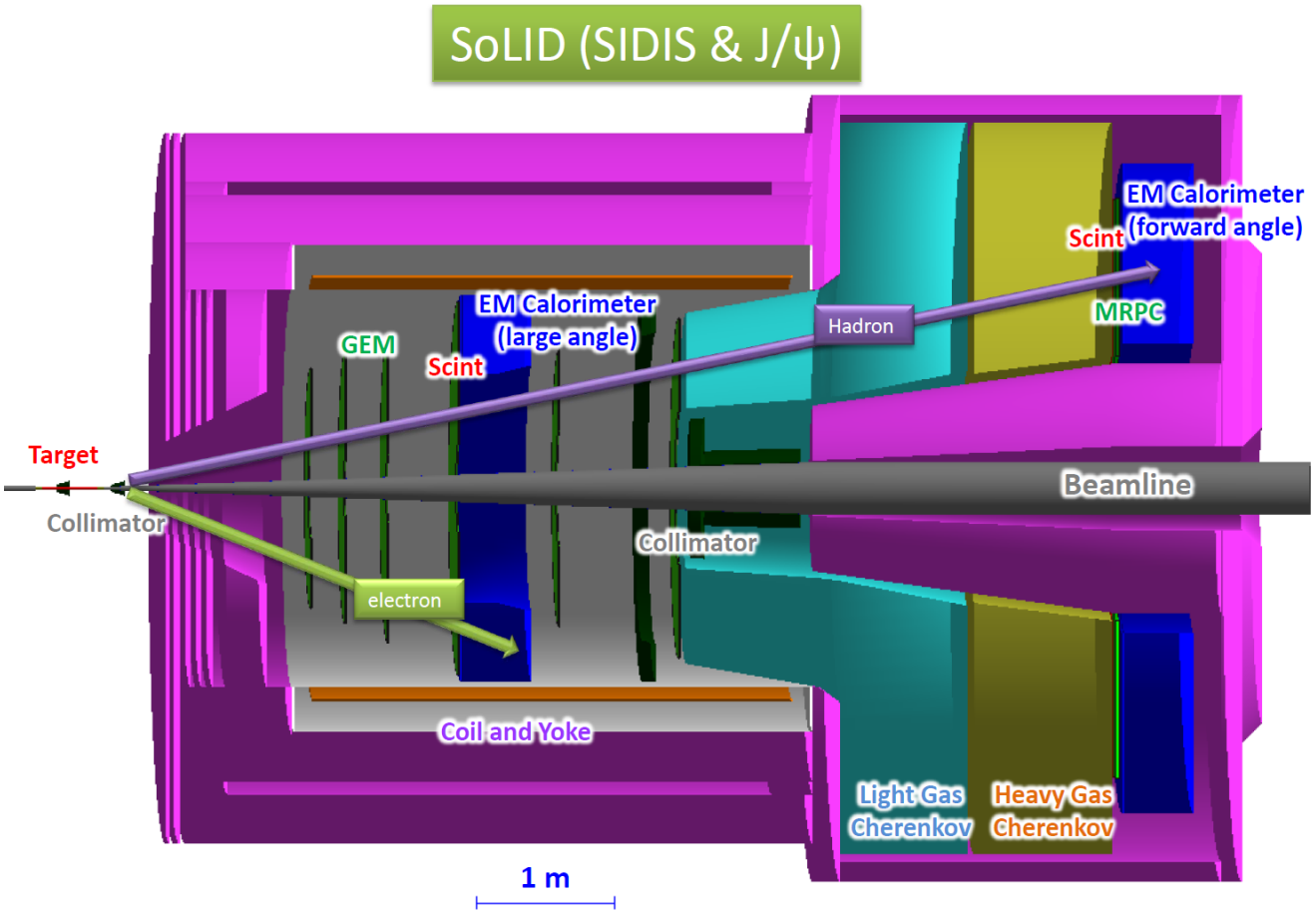
$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

E12-12-010: DVCS beam energy separation in Hall C



Recently approved by JLab PAC: to be run in ∼2019–2020

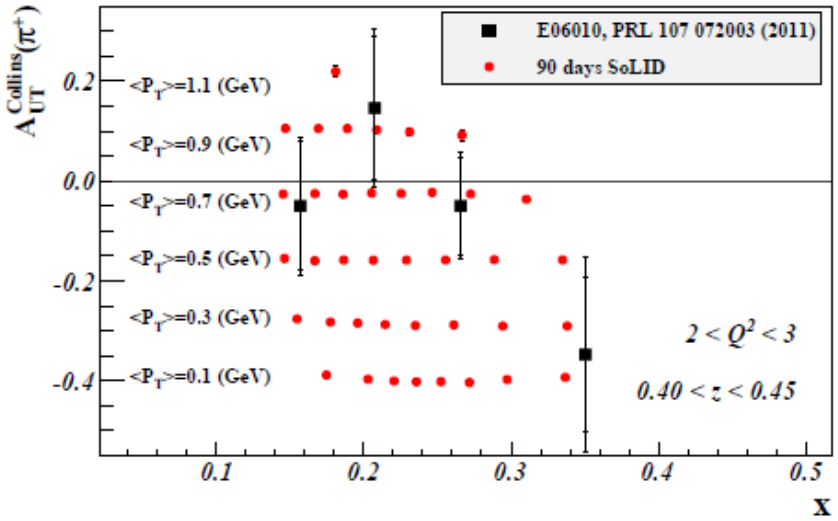
SoLID: Solenoidal Large Intensity Device

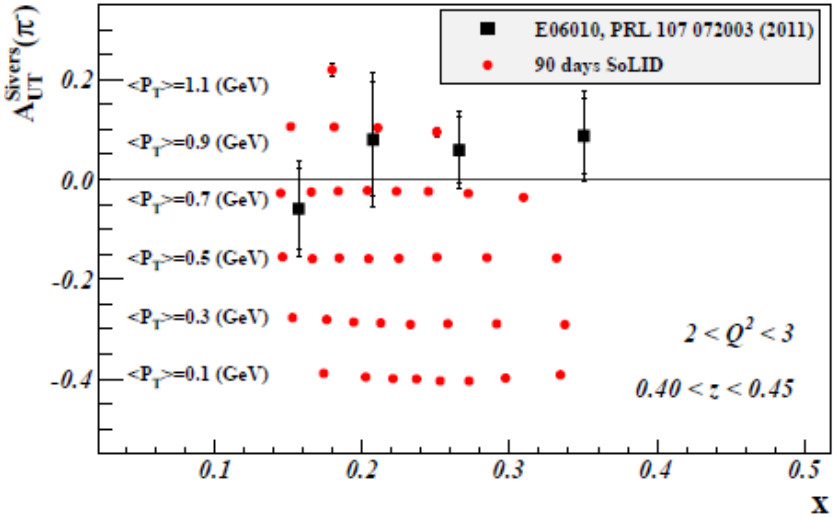


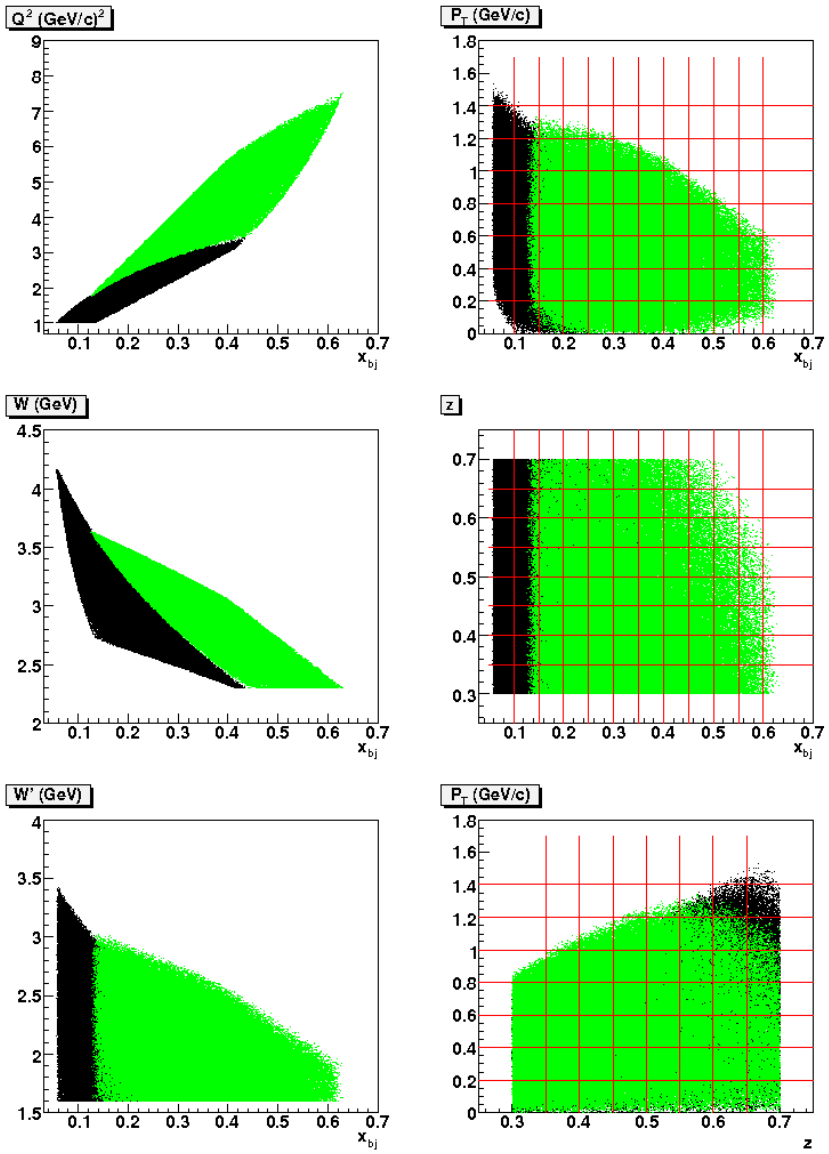
"Ultimate" precision 4D mapping of SIDIS pol. target A_{UT}, A_{LT}, A_{UL}, A_{LL}

Would combine large acceptance from Hall B with high luminosity of Hall A

SOLID A_{UT} projections on the neutron (from ^{3}He)







Forward + central detector coverage

Summary

- JLab at 6 GeV has already made significant contributions to the TMD and GPD programs
- The upcoming 12 GeV upgrade will enable a comprehensive multi-dimensional mapping of TMDs and GPDs in the valence region.
- Multi-hall attack will provide statistical precision and systematic control
- JLab 12 GeV commissioning underway, first physics beam expected as soon as Fall 2016.