Future of 3D Imaging at Jefferson Lab
with Focus on CLAS12

XXVI International Workshop on Deep Inelastic Scattering and Related Subjects
Kobe, 16 – 20 April 2018

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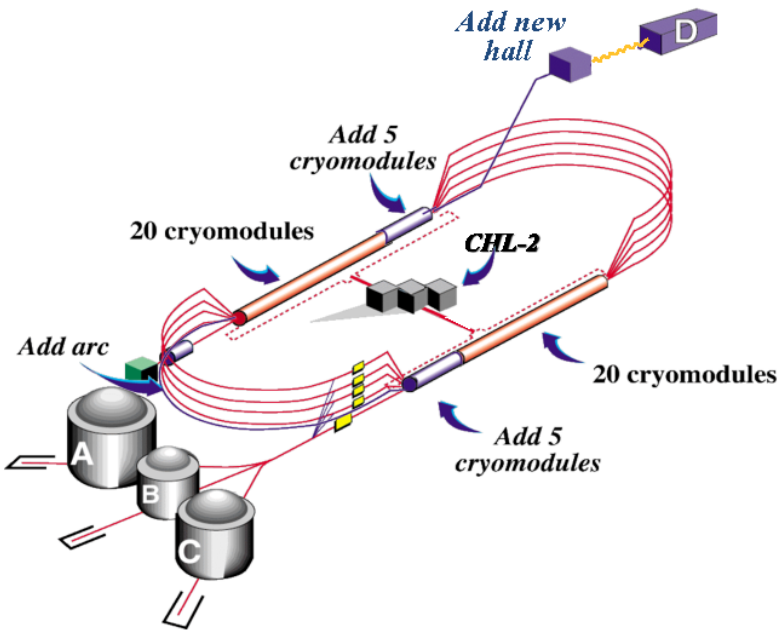
Stephen Bueltmann, Old Dominion University, Norfolk, VA, USA

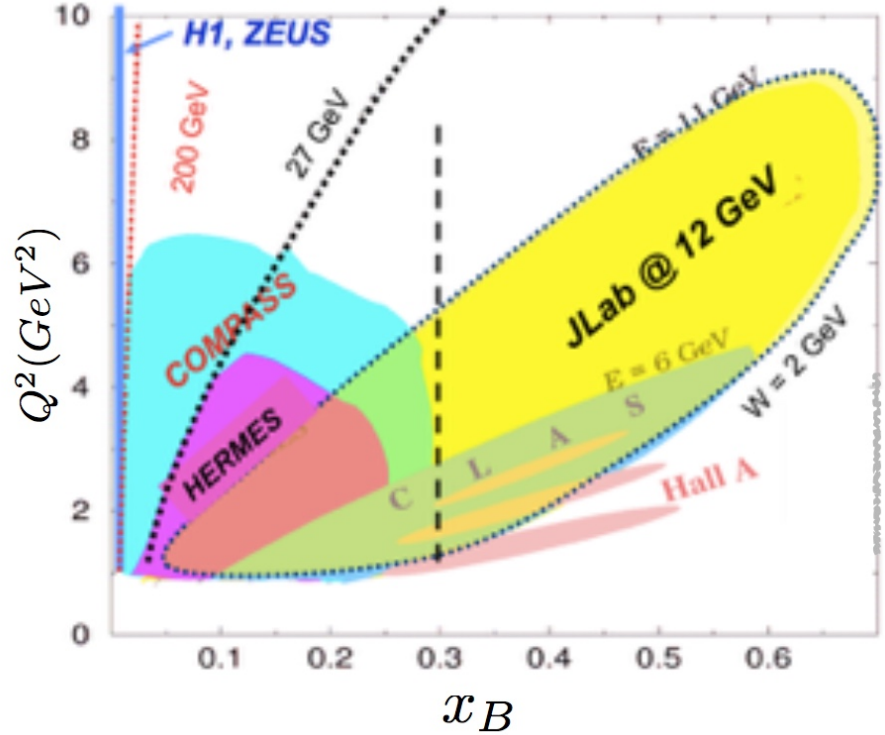
Jefferson Lab

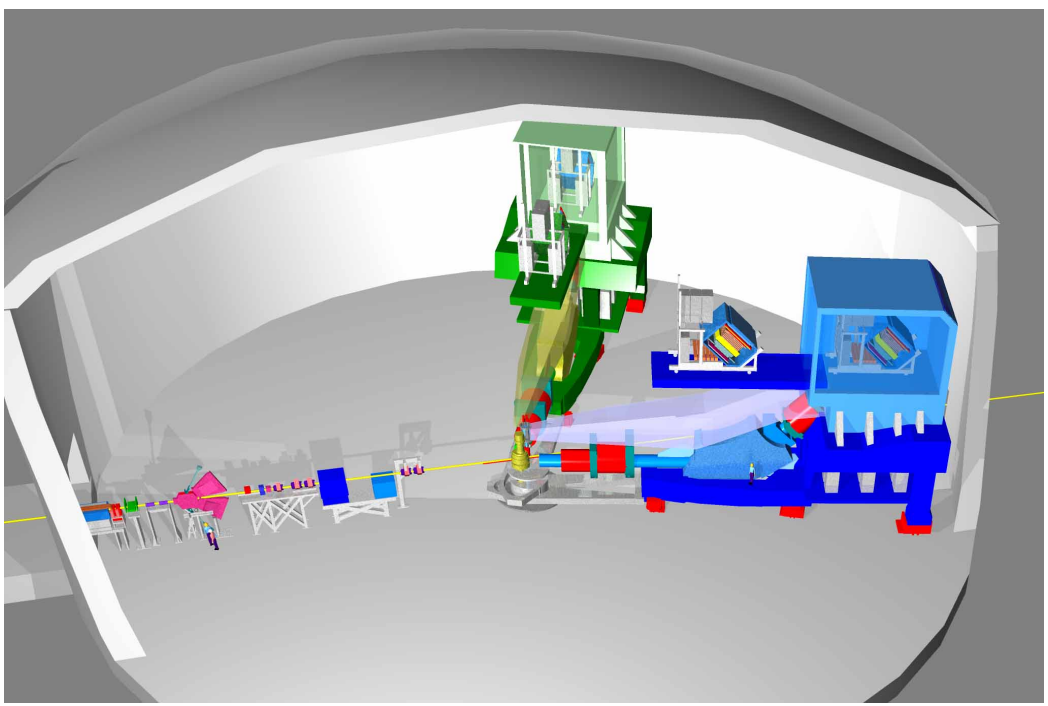
- Electron beam energy upgrade from 6 GeV to 11 GeV
- Energy spread < 10^{-4}
- Beam size at target < 400 μm ($\sigma \leq 200$ μm in Hall B)
- Beam polarization > 0.80
- Completed 2017

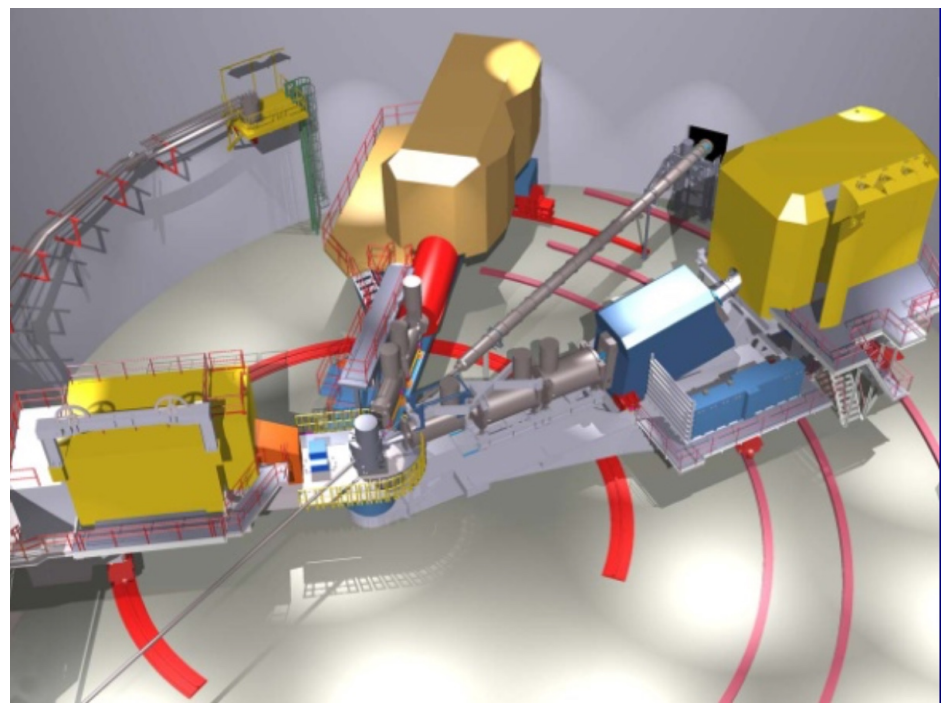


Jefferson Lab's Hall A and C

- Large moveable spectrometer
- Excellent momentum resolution < 10^{-4}
- High luminosity < 10^{38} cm^{-2} s^{-1}





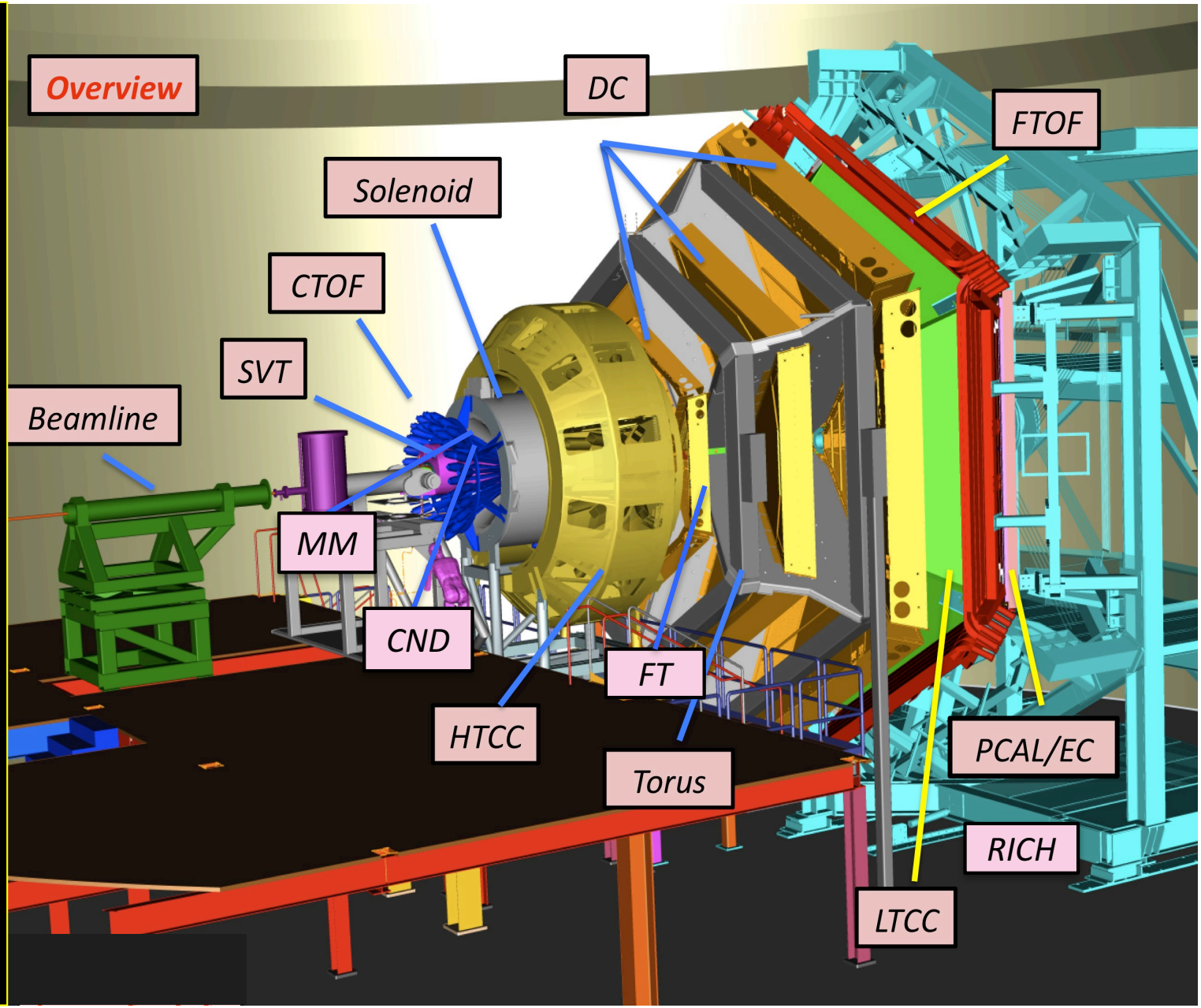


CLAS12 Detector in Hall B

Forward Detector
- Torus Magnet
- HT Cherenkov Counter
- Drift Chamber System
- LT Cherenkov Counter
- Forward ToF System
- Pre-Shower Calorimeter
- E.M. Calorimeter
- Forward Tagger
- RICH Detector

Central Detector
- Solenoid Magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Detector
- MicroMegas

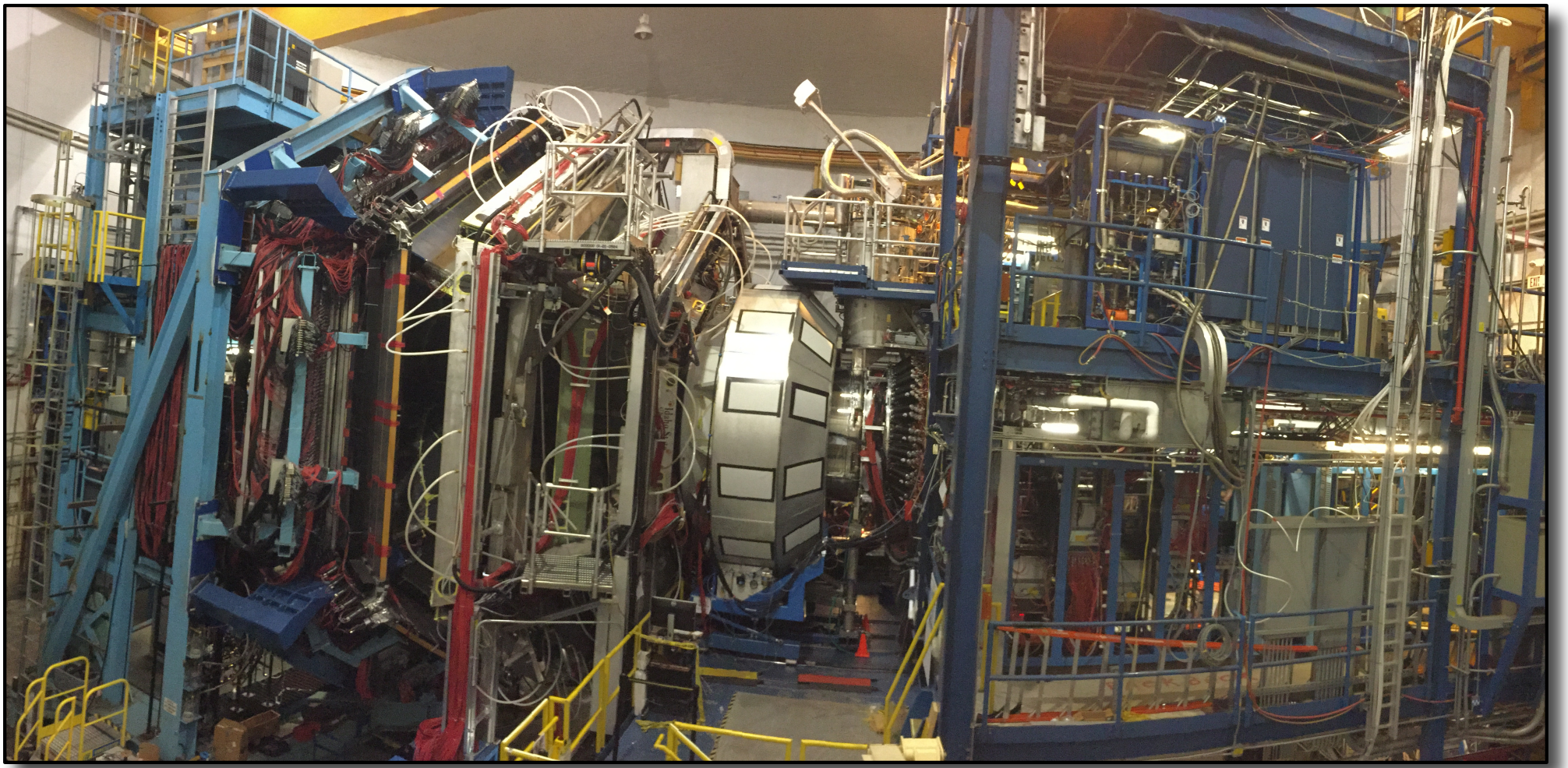
Beamline
- Photon Tagger Dump
- Shielding
- Targets
- Moller Polarimeter
- Faraday Cup



CLAS12 Detector

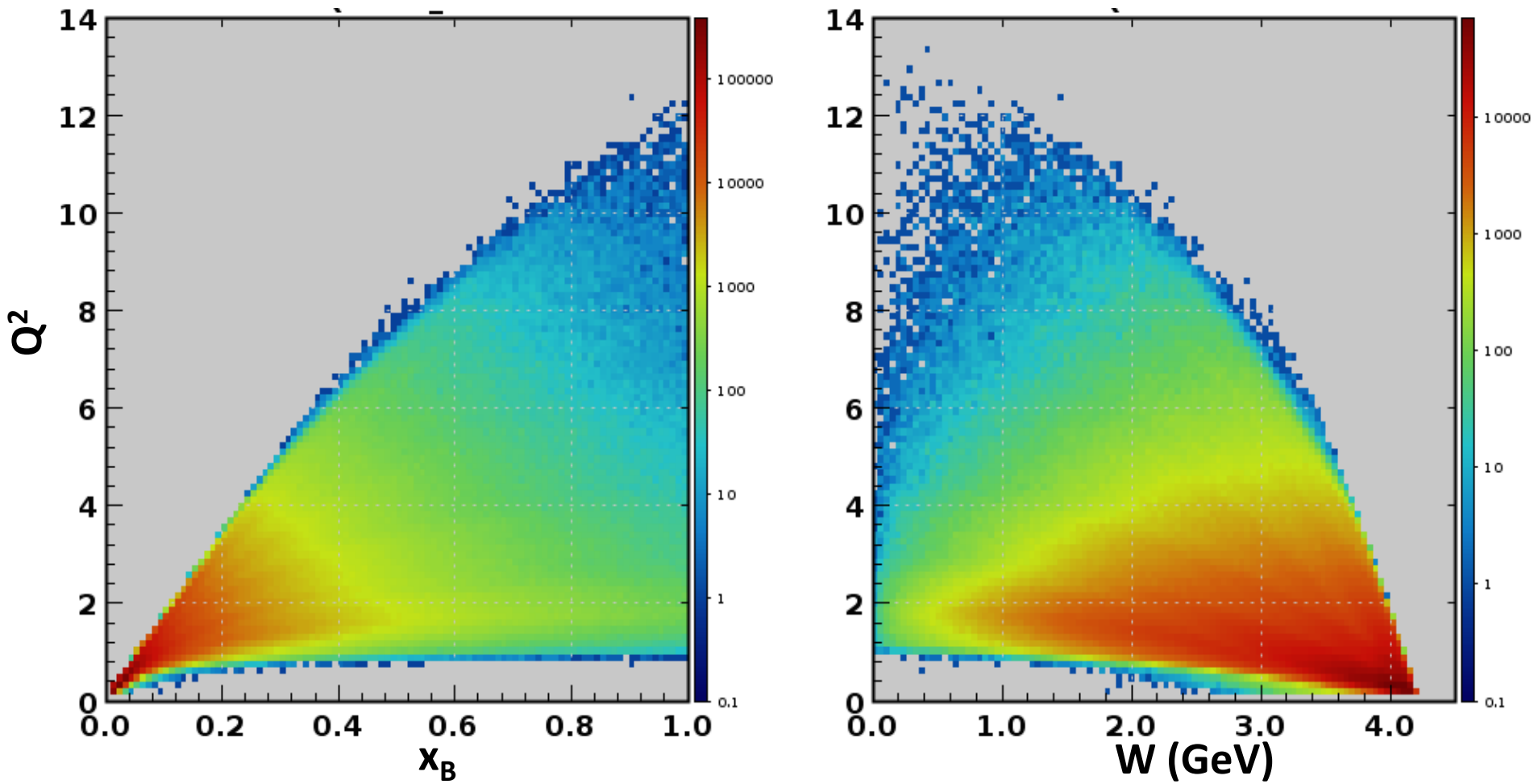
Engineering Run in December 2017

- Design luminosity < 10^{35} cm^{-2} s^{-1} (up to 800 nA current)
- 5 T solenoid magnet with $3 \cdot 10^{-4}$ homogeneity



CLAS12 Kinematic Reach

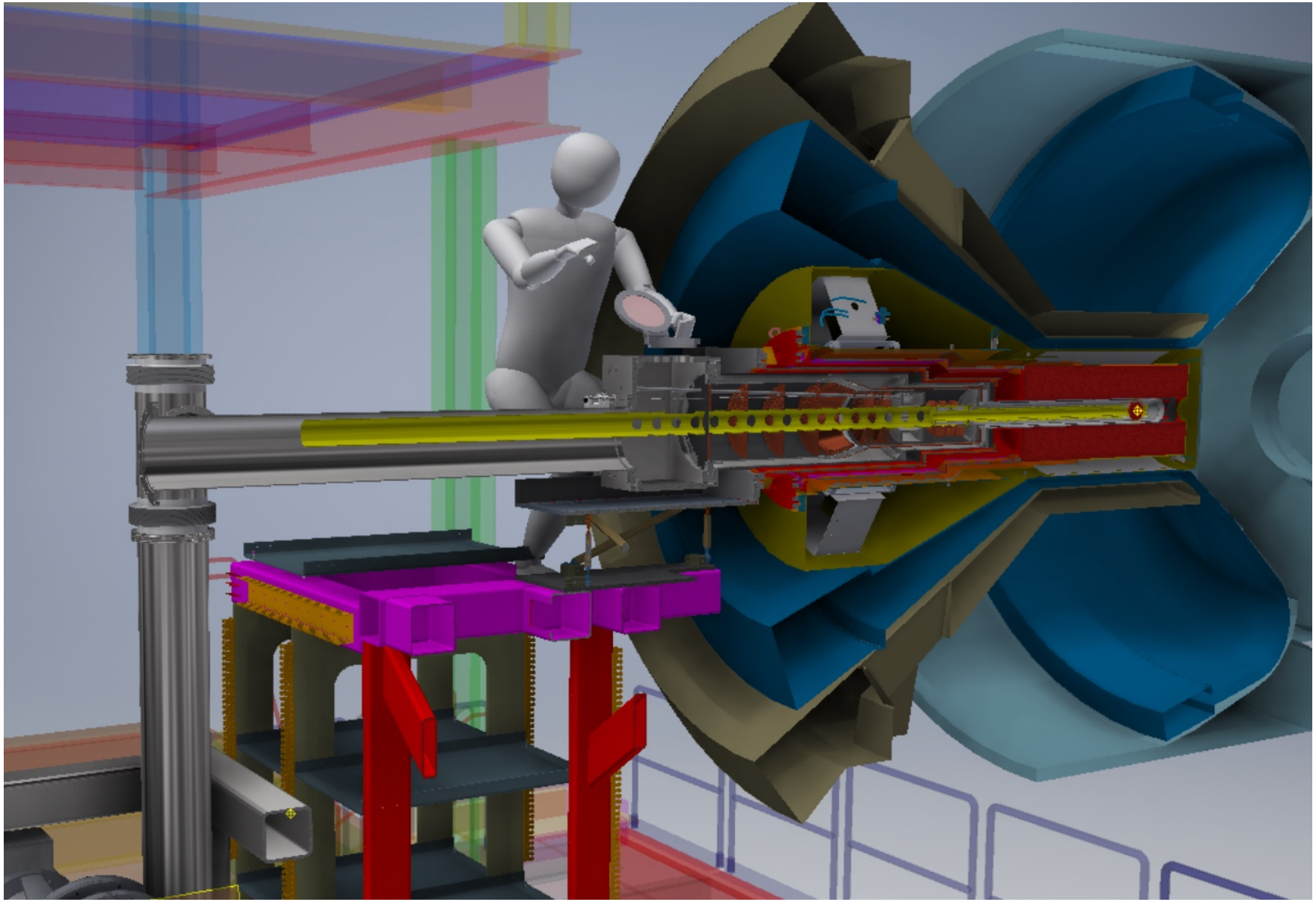
- Conditions
  - Electron beam energy 10.6 GeV
  - 3.6 T toroidal magnetic field (outbending electrons)



CLAS12 Targets

- Liquid hydrogen (2017/18)
  - Proton DVCS (beam spin asymmetries)
- Liquid deuterium (2019)
  - Neutron DVCS (beam spin asymmetries)
- High pressure deuterium gas (2019)
  - Neutron structure F_2^n
- Long. polarized solid NH_3 and ND_3 (2019/20)
  - Proton and neutron spin structure g_1^p and g_1^n
  - SIDIS
  - Proton and neutron DVCS target spin asymmetries
- Trans. polarized solid HD Ice (2021/22)

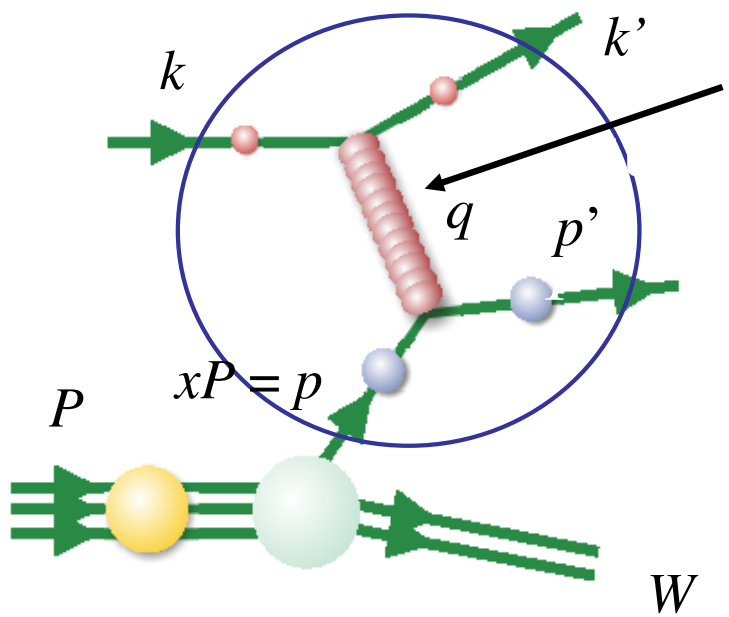
CLAS12 Solid Polarized Target



C. Keith, Jefferson Lab

Inclusive DIS and Structure Functions

- Lepton scattering off a nucleon



Virtual photon probes the structure

Kinematic variables:

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

$$W^2 = M^2 + 2M\nu - Q^2$$

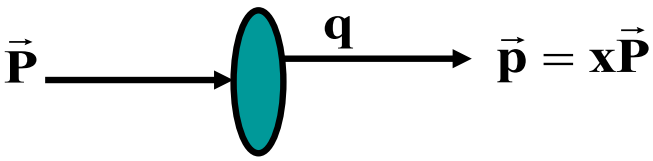
$$x = \frac{Q^2}{2M\nu}$$

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mxg_2(x,Q^2)\right]$$

The Nucleon Parton Model and TMDs

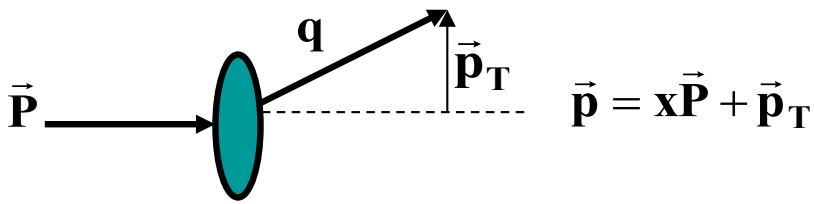
Collinear approximation



DIS distribution functions

$$f_1(x), g_1(x), h_1(x)$$

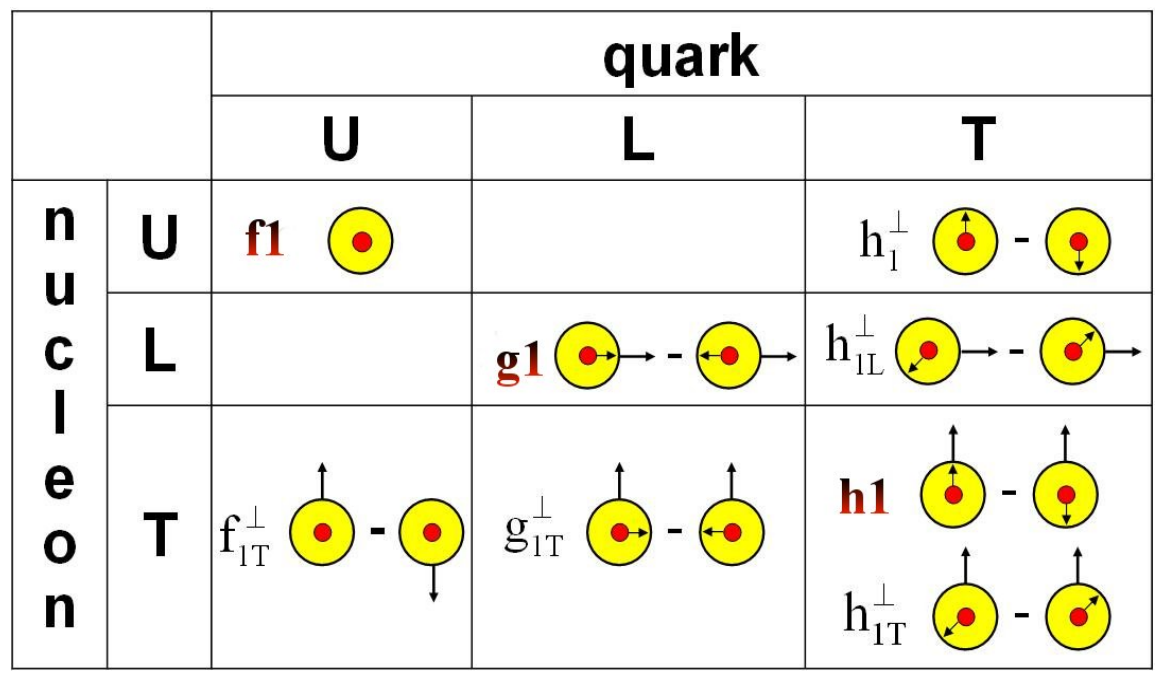
Parton transverse momentum



more complex dist. functions

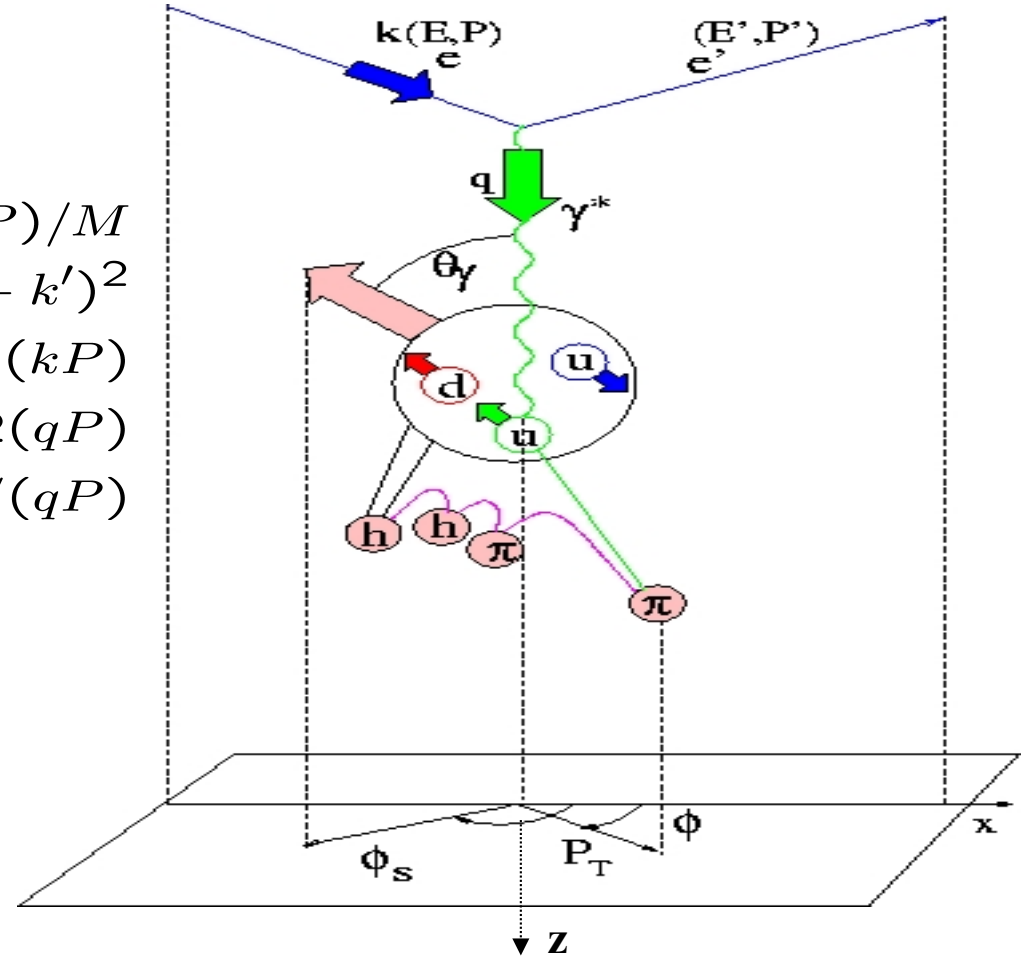
$$f_1(x, \vec{p}_T), g_1(x, \vec{p}_T), h_1(x, \vec{p}_T)$$

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons inside a nucleon with respect to x and the intrinsic transverse momentum p_T carried by the quarks



Semi-Inclusive DIS

$$\nu = (qP)/M$$
$$Q^2 = (k-k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$



Beam and target

- Unpolarized
- Longitudinally polarized
- Transversely polarized

Target polarization

Beam polarization

$$\sigma = \sigma_{UU} + P_t \sigma_{UL} \sin 2\phi + P_b P_t \sigma_{LT} \cos(\phi - \phi_S) \ldots$$

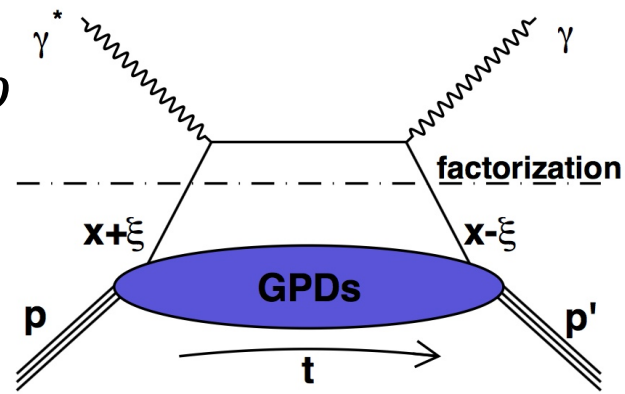
Azimuthal asymmetries arise due to correlations of spin and transverse momentum of quarks

Deeply-Virtual Compton Scattering
and Meson Production

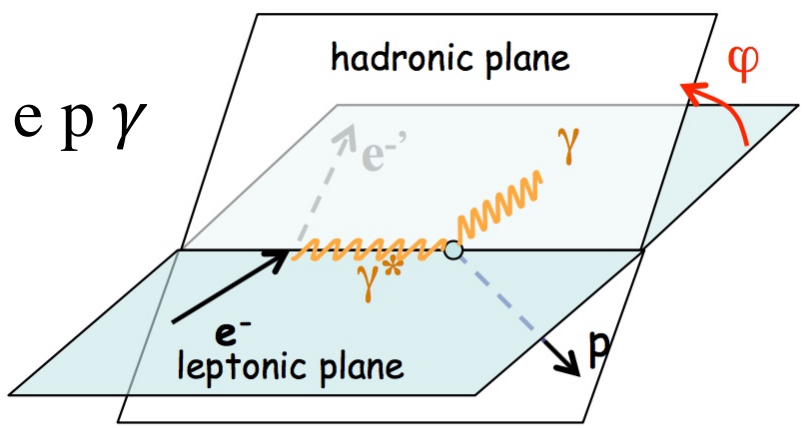
- DVCS gives access to Generalized Parton Distributions
  - Measure cross-section asymmetries

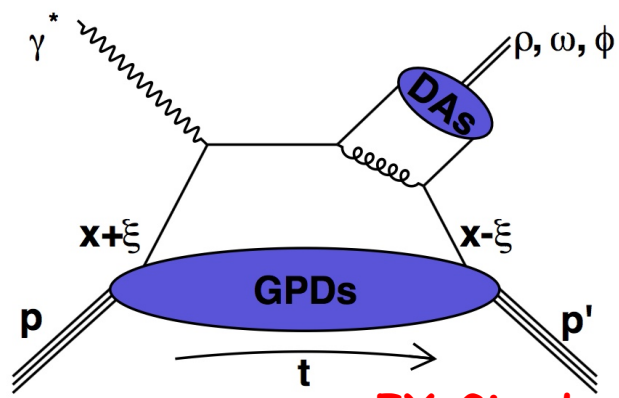
$$A_{UL} \propto \left(F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{1}{1+\xi} \mathcal{E} \right) + \ldots \right) \sin\varphi$$

$$A_{LU} \propto \left(F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right) \sin\varphi$$



e p → e p γ





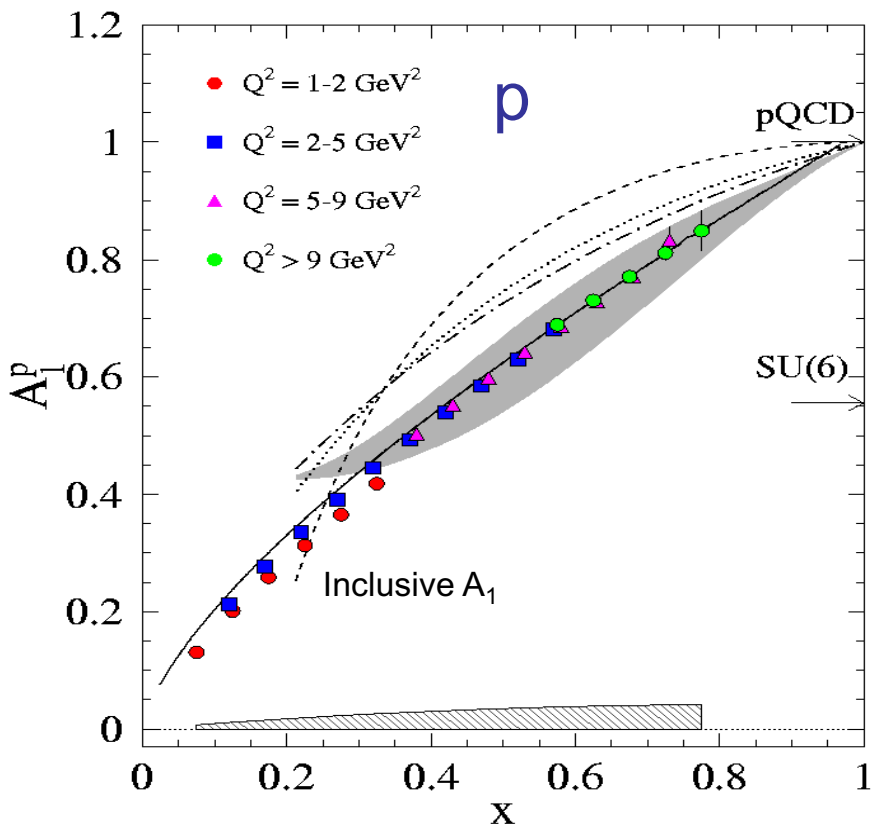
FX Girod

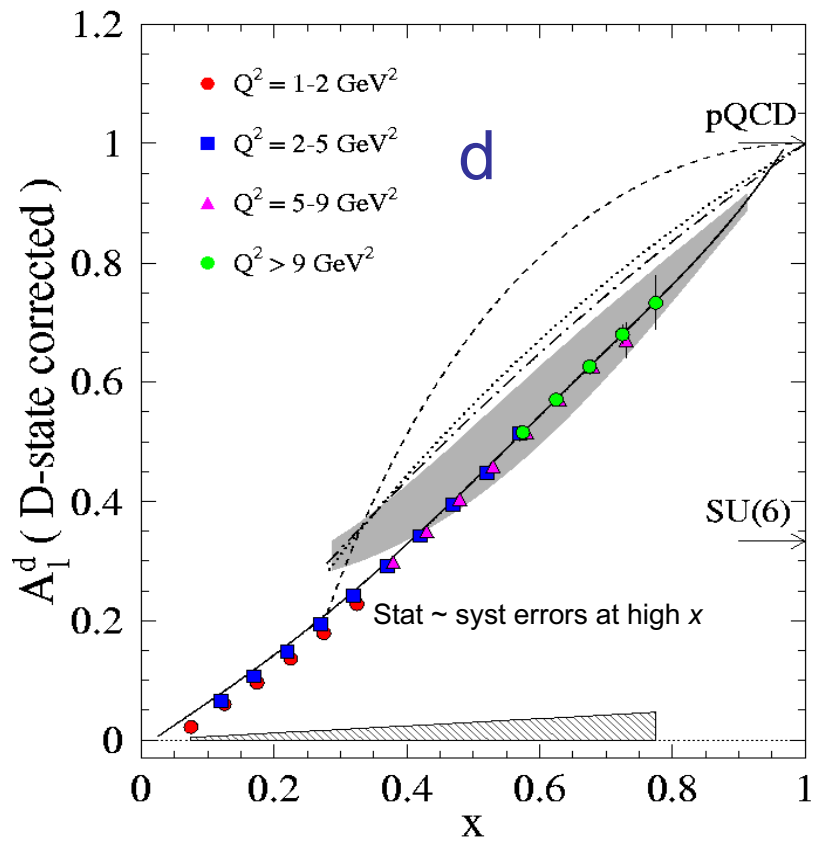
CLAS12 (SI)DIS Program

Experiment	Physics	Contact	Days	Energy / GeV	Target
E12-06-112	Proton's Quark Dynamics in SIDIS Pion Production	Avakian	60	11	lH_2
E12-09-007	Study of Partonic Distributions in SIDIS Kaon Production	Hafidi	30	11	lD_2
E12-09-008	Boer-Mulders Asymmetry in K SIDIS with H and D Targets	Contalbrigo	56	11	lD_2
E12-06-109	Longitudinal Spin Structure of the Nucleon	Kuhn	80	11	NH_3 ND_3
E12-09-007	Study of Partonic Distributions Using SIDIS K Production	Hafidi	80	11	NH_3 ND_3
E12-06-113	Free Neutron Structure at Large x	Bueltmann	42	11	D_2

Longitudinal Structure of the Nucleon
(eg12) E12-06-109

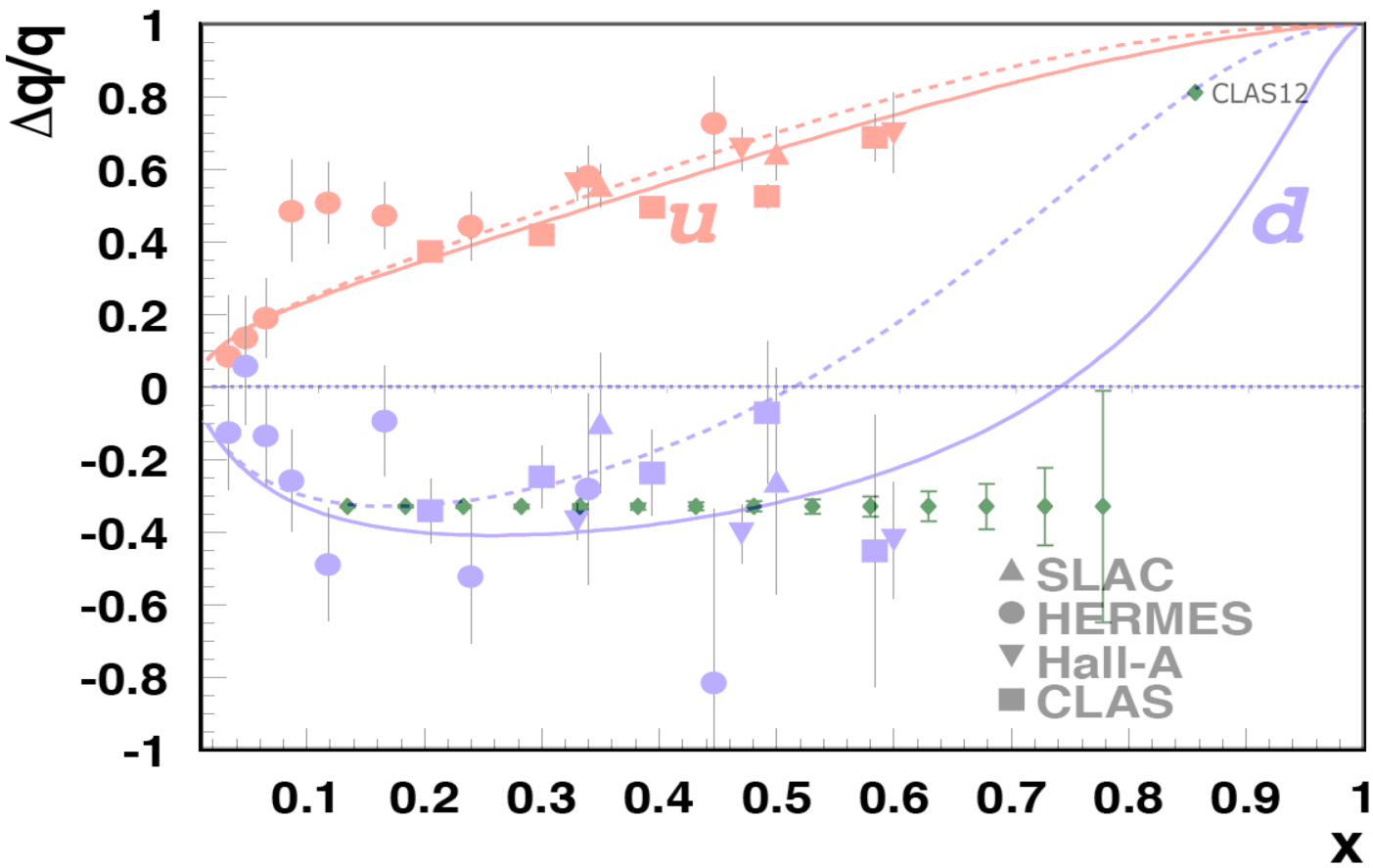
- Inclusive spin structure of proton and deuteron
- $\mathcal{L} = 2 \cdot 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $P_{\mathrm{beam}} > 0.8$, $P_{\mathrm{target\text{-}p}} = 0.8$, $P_{\mathrm{target\text{-}d}} = 0.4$





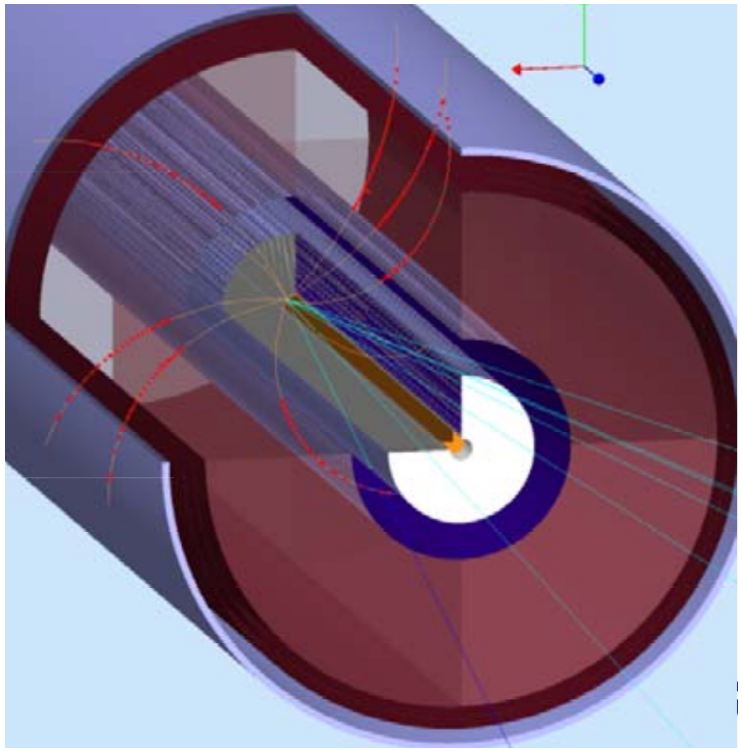
Longitudinal Structure of the Nucleon
(eg12) E12-06-109

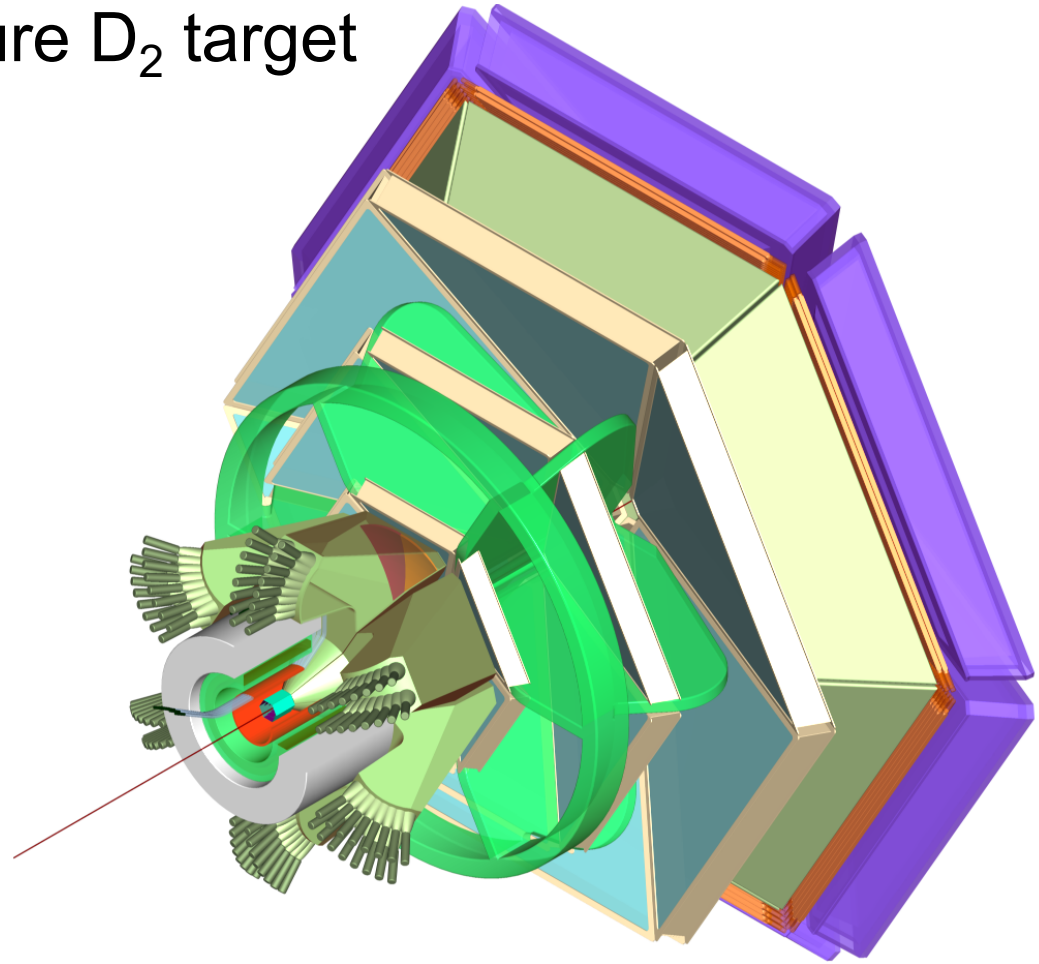
- Helicity structure of the nucleon in the valence region
  - quark polarization Δu/u, Δd/d as $x \to 1$



Structure of the Free Neutron
(Bonus12) E12-06-113

- Radial TPC to detect recoiling proton in d (e, e' p) X
- RTPC inside central detector solenoid
  - contains high pressure D_2 target

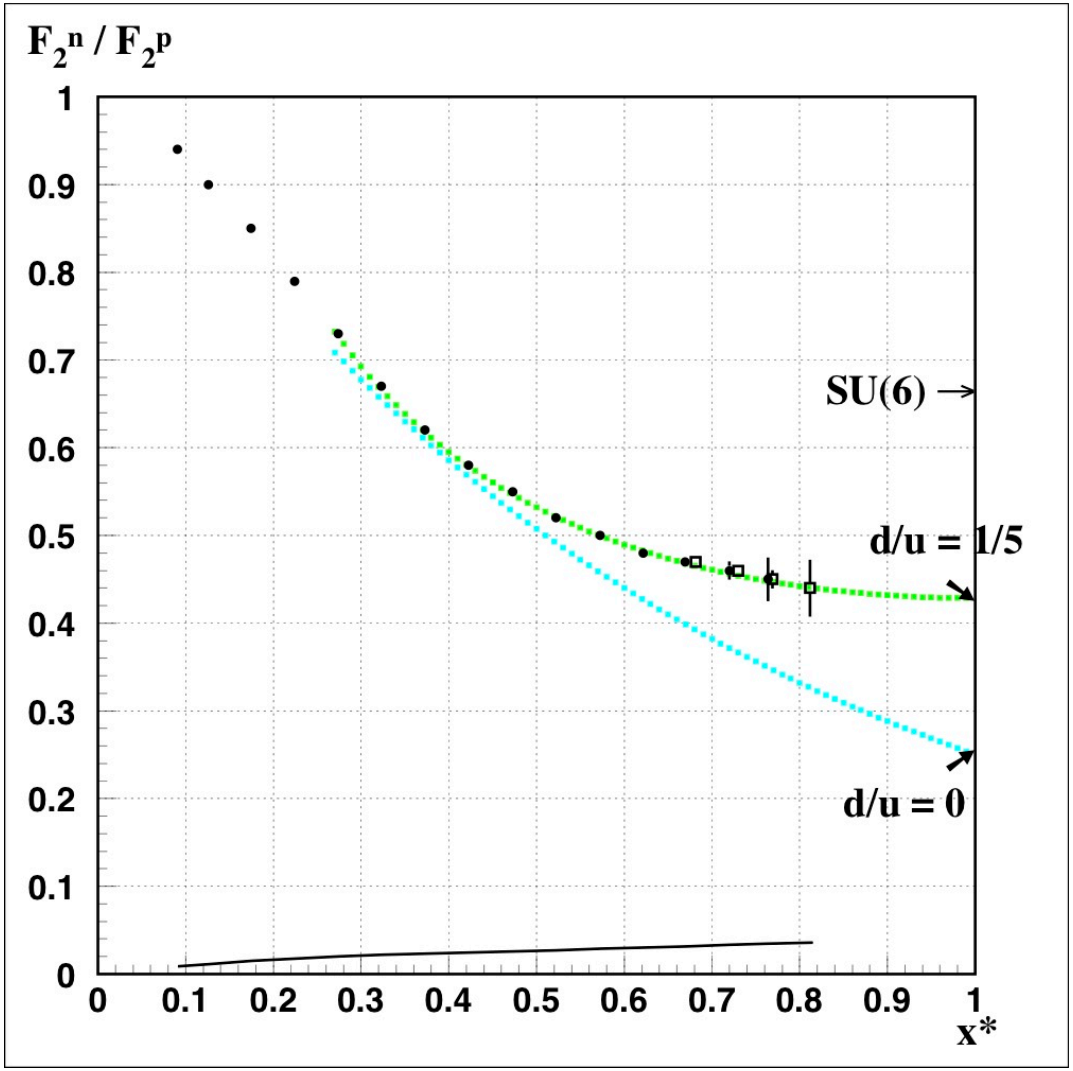




Structure of the Free Neutron
(Bonus12) E12-06-113

- Radial TPC to detect recoiling proton in d (e, e' p) X

- 35 days of data taking on D_2 and 5 days on H_2 with $\mathcal{L} = 2 \cdot 10^{34}$ cm^{-2} sec^{-1}
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $W^* > 2$ GeV
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $x^* = 0.80$ (bin centered $x^* = 0.76$)
- Relaxed cut of $W^* > 1.8$ GeV gives max. $x^* = 0.83$
- Overall scale error 5%
- Constrain d/u ratio

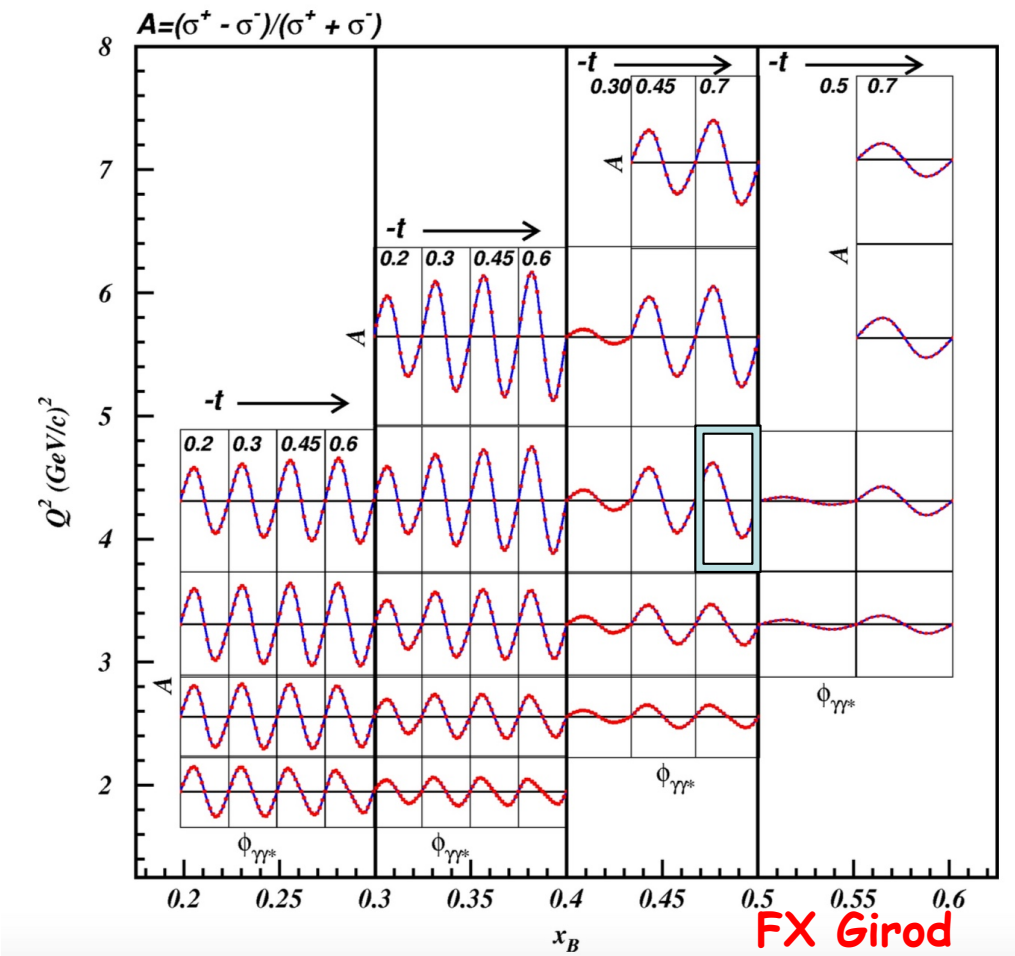


CLAS12 GPD Program

Experiment	Physics	Contact	Days	Energy / GeV	Target
E12-06-108	Hard Exclusive Electroproduction of π^0 and η	Kubarovski	80	11	lH_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	80	11	lH_2
E12-12-001	Timelike Compton Scattering & J/Ψ production in e^+e^-	Nadel-Turonski	120	11	lH_2
E12-12-007	Exclusive ϕ meson electroproduction	Girod	60	11	lH_2
E12-11-003	DVCS on Neutron Target	Niccolai	90	11	lD_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	120	11	NH_3
C12-12-010	DVCS with a transverse target	Elouadrhiri	110	11	HD-ice
E12-16-010	DVCS with CLAS12 at 6.6 GeV and 8.8 GeV	Elouadrhiri	50+50	6.6 & 8.8	lH_2
E12-17-012	Spectator-Tagged DVCS on Light Nuclei	Armstrong	45	11	D_2, ^4He

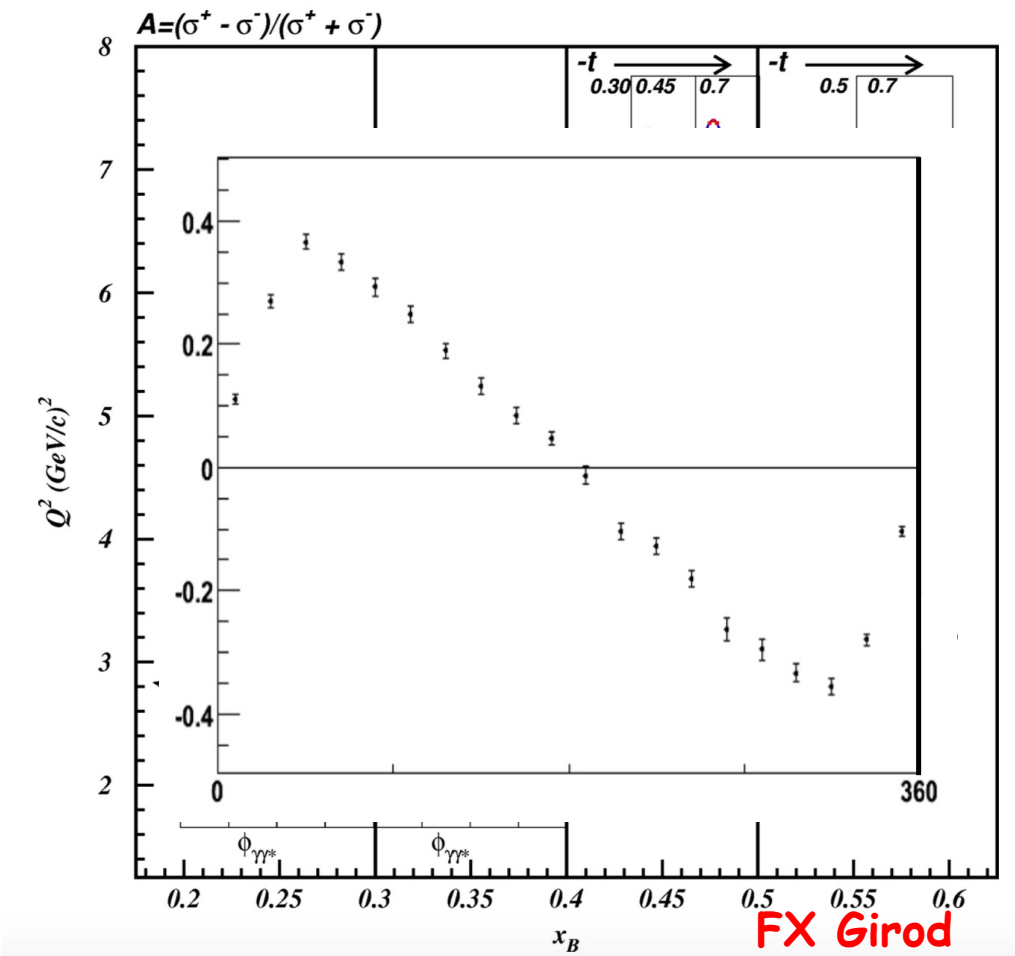
CLAS12 Beam Spin Asymmetries

- E12-06-119 taking presently data on hydrogen
- DVCS $$A_{\mathrm{LU}} \propto F_1 \mathcal{H} + \xi G_{\mathrm{M}} \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$
- $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $P_{\mathrm{beam}} > 0.8$
- Stat. uncertainties 1% (low Q^2) to 10% (high Q^2)



CLAS12 Beam Spin Asymmetries

- E12-06-119 taking presently data on hydrogen
- DVCS $$A_{\mathrm{LU}} \propto F_1 \mathcal{H} + \xi G_{\mathrm{M}} \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$
- $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $P_{\mathrm{beam}} > 0.8$
- Stat. uncertainties 1% (low Q^2) to 10% (high Q^2)

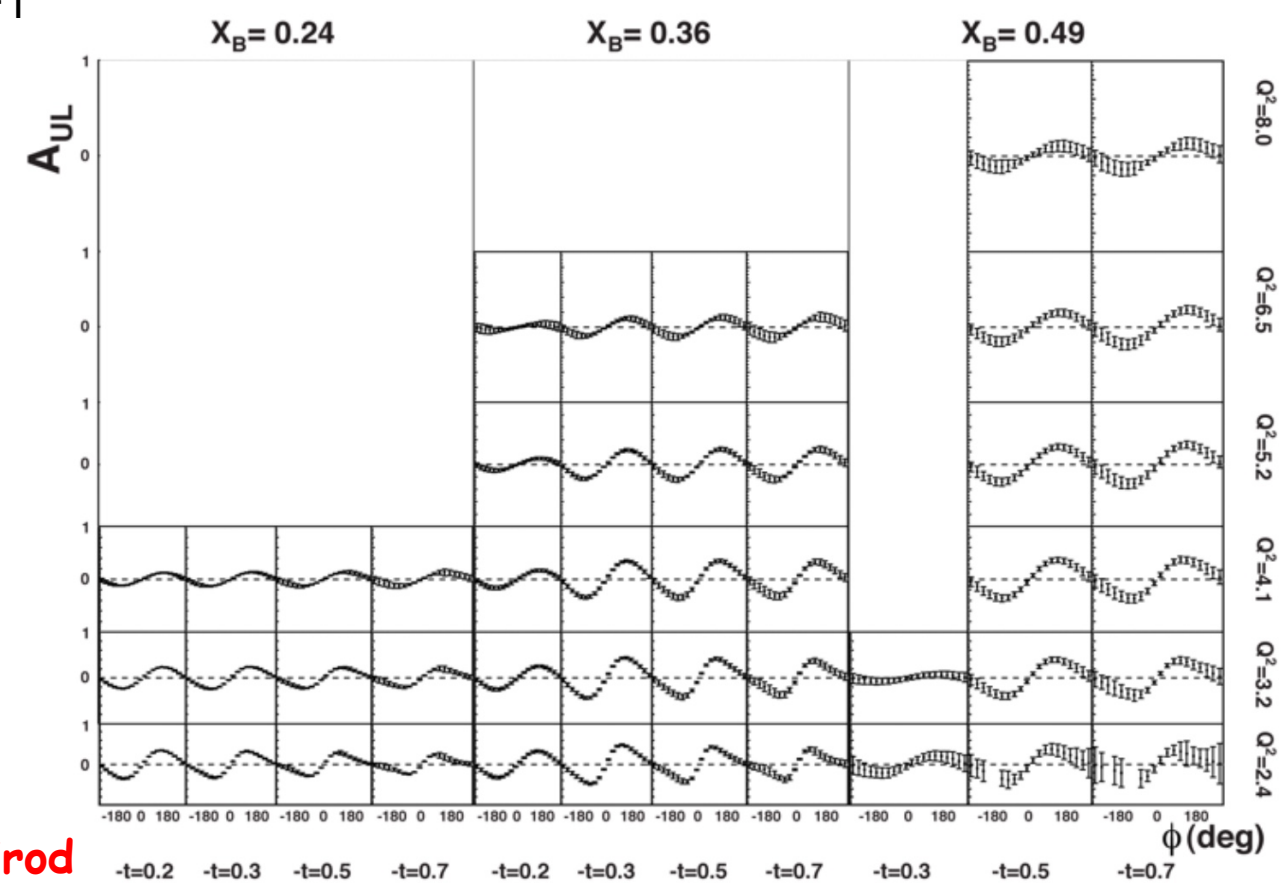


CLAS12 Target Spin Asymmetries

- E12-06-119 will take data on polarized NH_3
- DVCS

$$A_{\mathrm{UL}} \propto F_1 \tilde{\mathcal{H}} + \xi G_{\mathrm{M}} \left(\mathcal{H} + \frac{1}{1+\xi} \mathcal{E} \right) - \xi \frac{t}{4M^2} F_2 \tilde{\mathcal{E}}$$

- $\mathcal{L} = 2 \cdot 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- $P_{\mathrm{target}} = 0.8$
- Stat. uncertainties 2% (low Q^2) to 30% (high Q^2)



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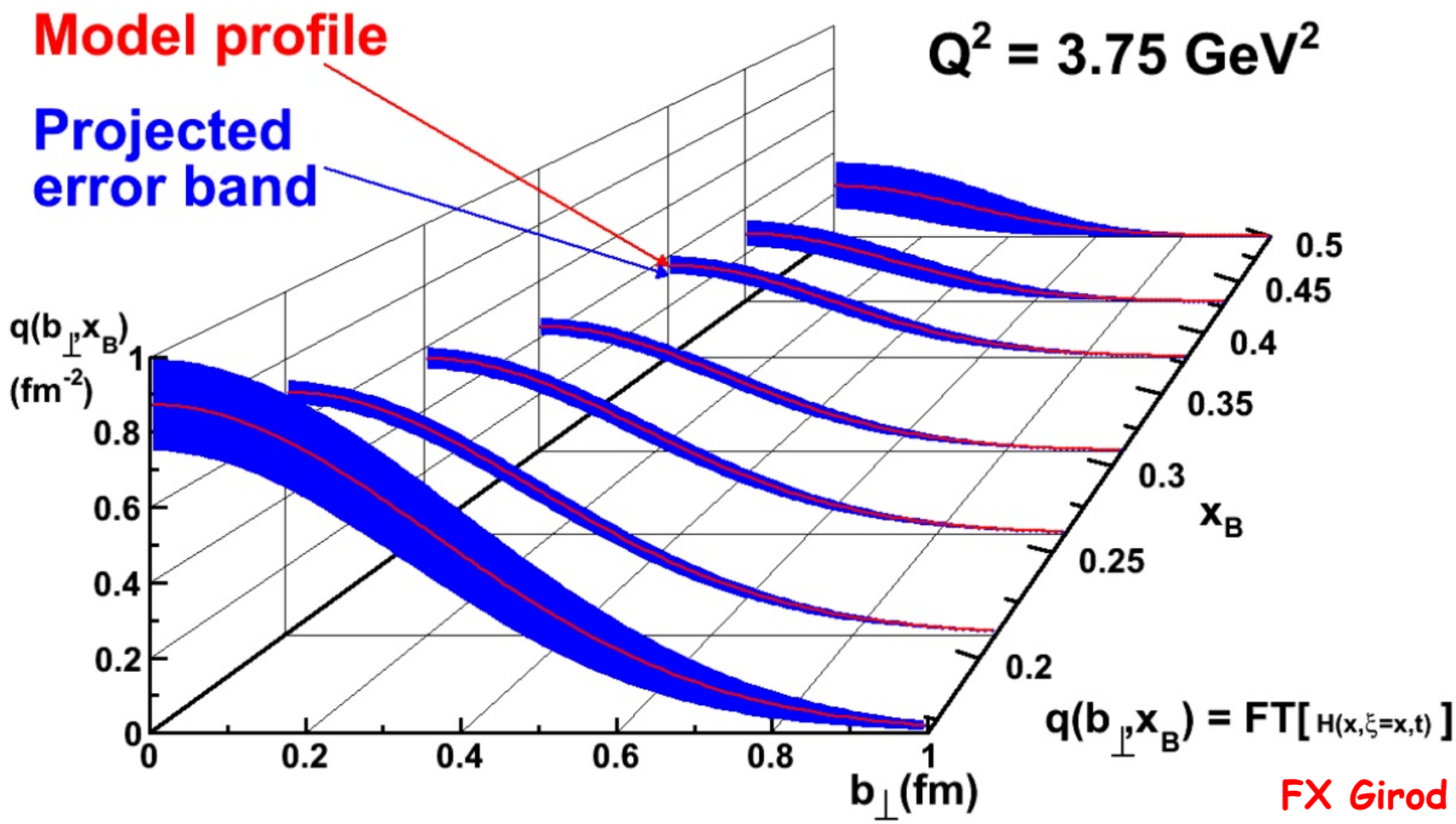
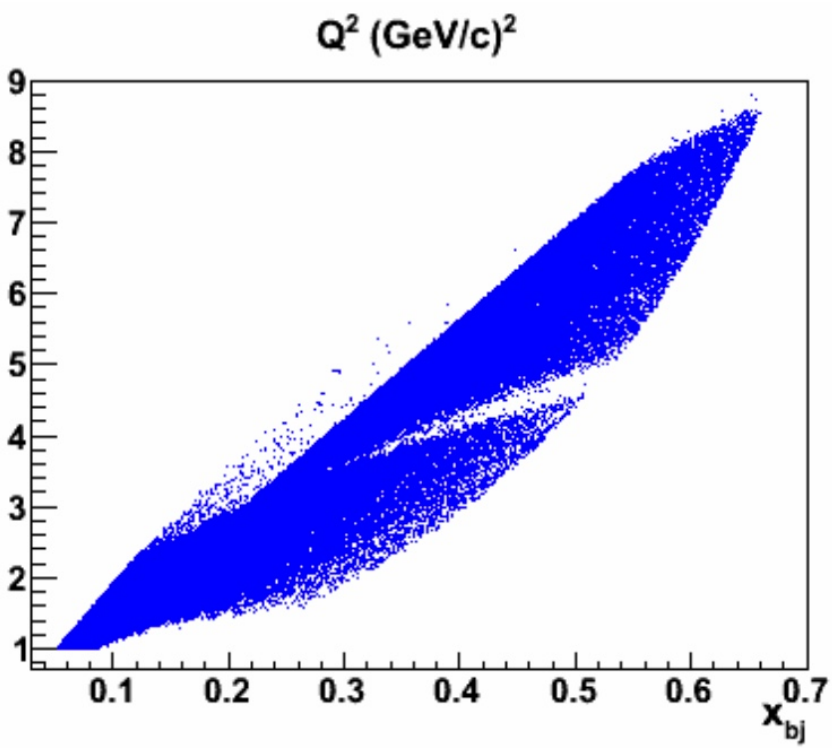
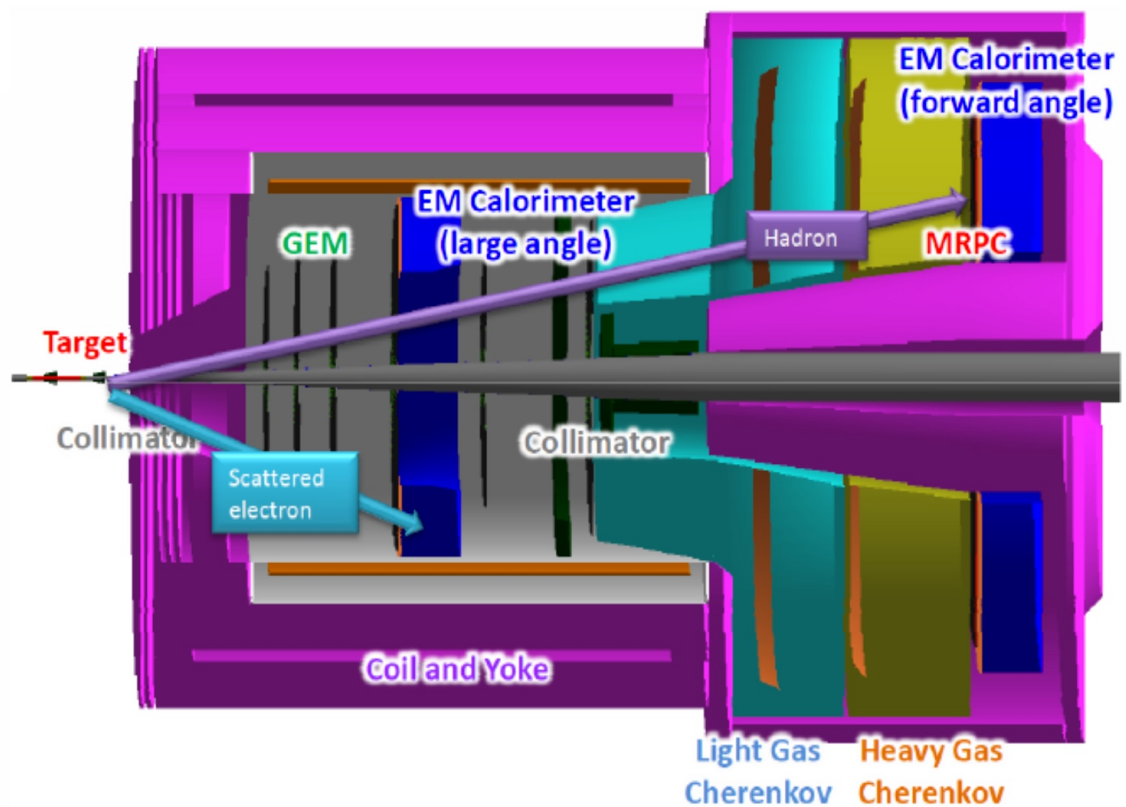
Projection of Nucleon Transverse Profile

- 

SoLID in Hall A

- Three SIDIS experiments to study TMDs
  - Measure double and single spin asymmetries on longitudinal and transversely polarized targets
- CLEO-II magnet, full azimuthal coverage
- $\mathcal{L} < 10^{39}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



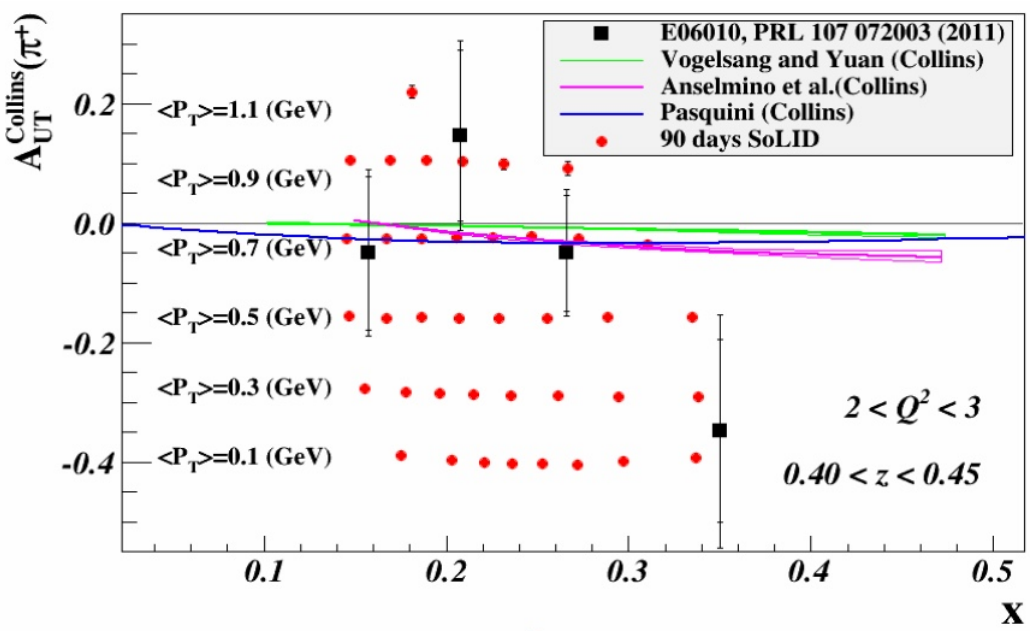


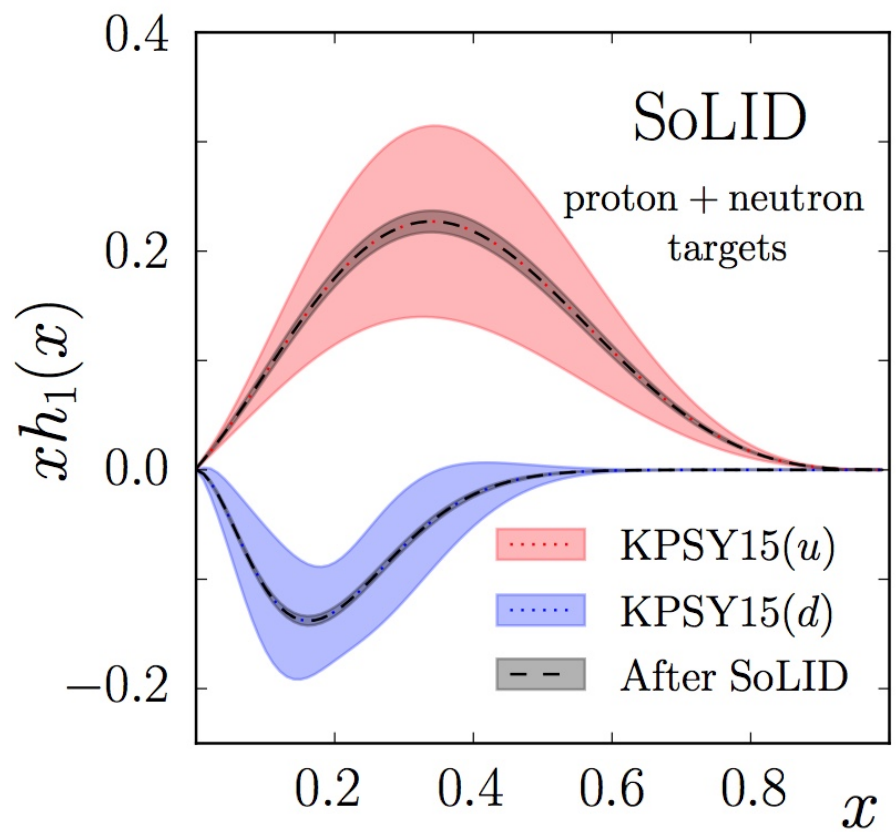
SoLID in Hall A

- Collins single-spin asymmetry in π production

$$A_{\mathrm{UT}} \propto h_1 \otimes H_1{}^{\perp} \ \sin(\phi + \phi_{\mathrm{S}})$$

  - Impact on global analysis of transversity function h_1





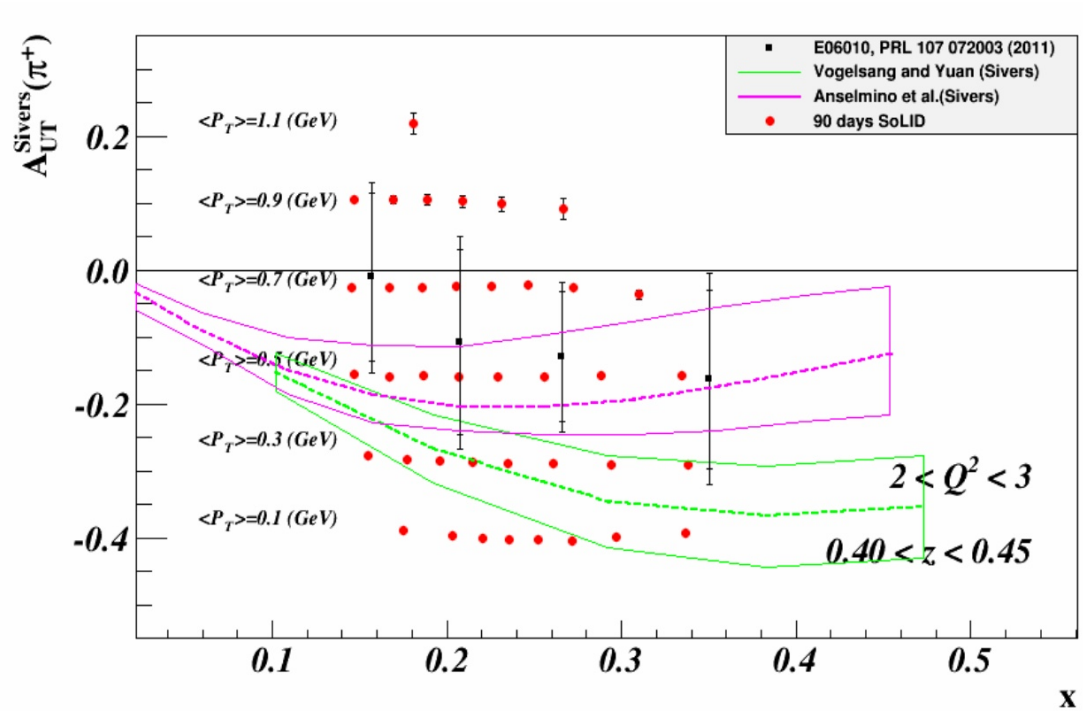
Z. Ye, N. Sato et al., Phys. Lett. B 767 (2017)

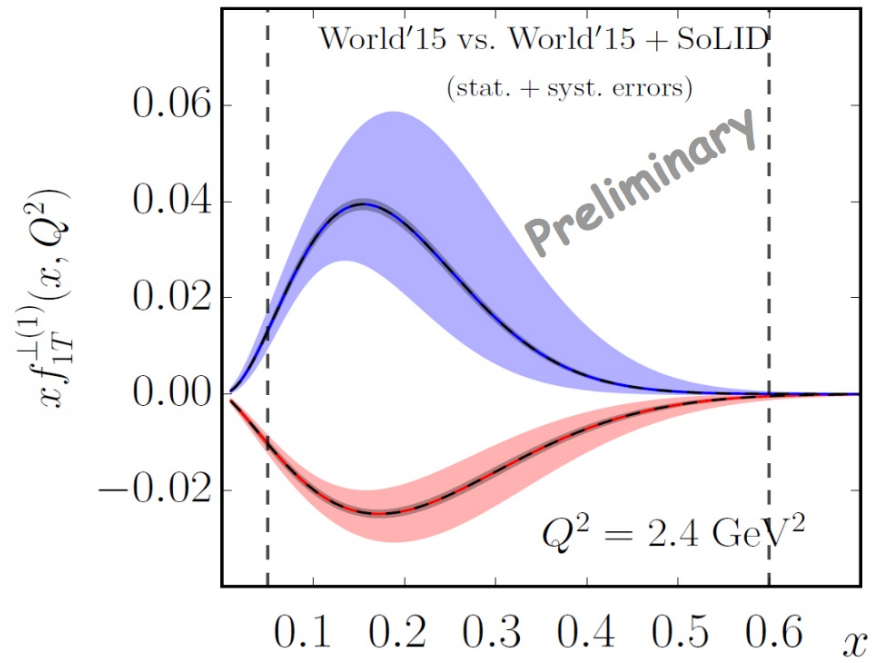
SoLID in Hall A

- Sivers function in single-spin asymmetry in π production

$$A_{\mathrm{UT}} \propto f_{1\mathrm{T}}{}^{\perp} \otimes D_1 \ \sin(\phi - \phi_{\mathrm{S}})$$

  - Impact on global analysis of Sivers function $f_{1\mathrm{T}}{}^{\perp}$





N. Sato, S. Liuti, A. Prokudin

Conclusions

- Jefferson Lab's upgrade to 11 GeV electron beam energy opens window to very large kinematic range
- Enables high-precision measurements of structure functions, TMDs and GPDs to map the 3D structure of the nucleon
- CLAS12 started data taking in 2017
- Experimental program presently covers 10 years of data taking