Transverse Spin at JLab

Contalbrigo Marco - INFN Ferrara

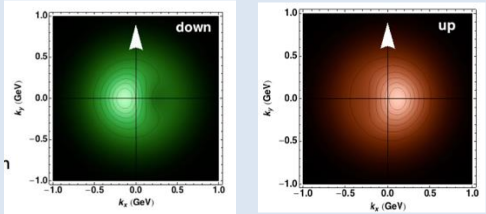
SPIN 2025, 22th-27th September 2025

3D Nucleon Structure by DIS

TMD (x, k_T) quark polarisation

nucleon polarisation

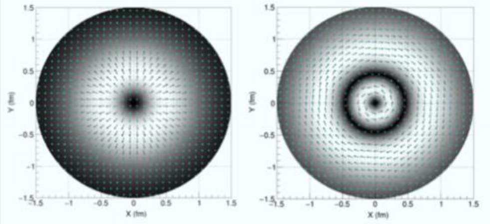
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	$h_1, h_{1T}^{\perp}$



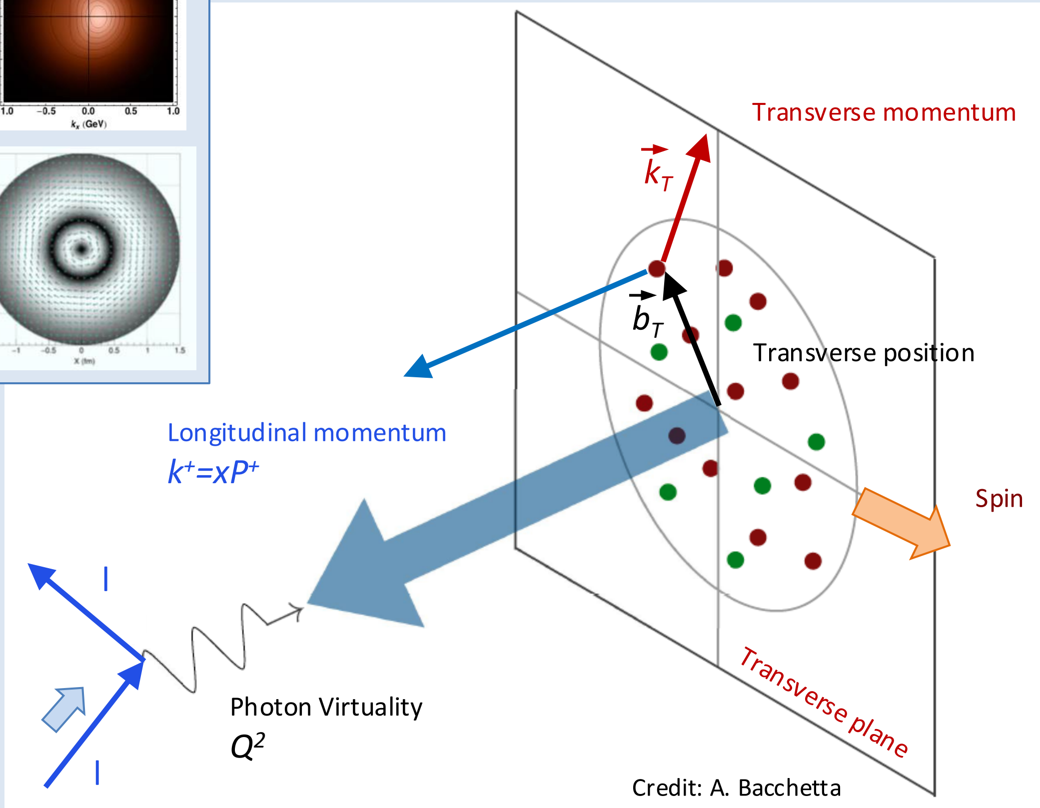
GPD (x, b_T) quark polarisation

nucleon polarisation

N/q	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T, \tilde{H}_T$



Confinement Scale



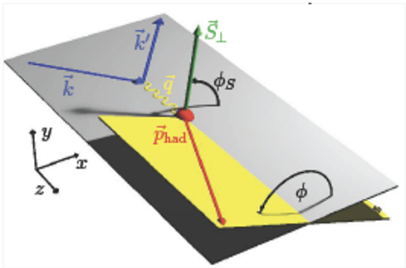
High Energy Probe
Hard Scale

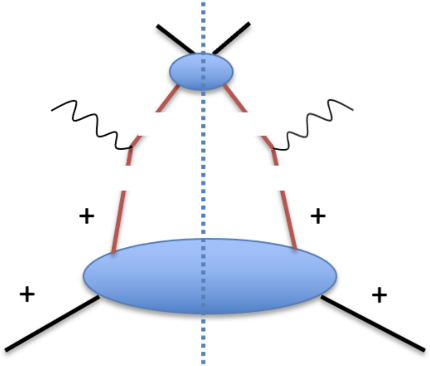
Semi-Inclusive DIS and TMDs

$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_h\,d\phi\,d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_T\left[\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$





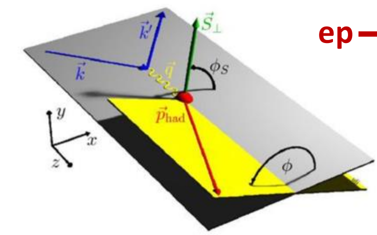
Quark fragmentation

TMD Factorization holds for p_T<<Q

Quark parton distribution

Wide kinematic coverage is needed to resolve the convolution

$$F_{UU} = f \otimes D = x\sum_q e_q^2 \int d^2p_T\, d^2k_T \;\; \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_T - \mathbf{p}_T)\; w(\mathbf{k}_T,\mathbf{p}_T)\; f^q(x,k_T^2)\; D^q(z,p_T^2)$$

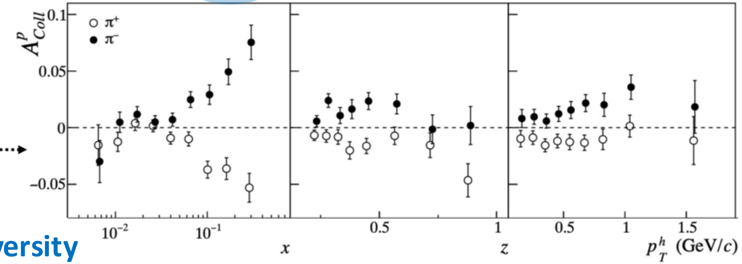


ep → e'hX, e'hhX

$$\frac{d\sigma_{UT}}{dx\,dQ^2\,dz\,dP_{h\perp}\,d\phi\,d\phi_S} \propto \left[F_{UU} + \epsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\sin(2\phi)F_{LU}^{\sin(2\phi)}\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL}\right]$$
$$+ S_T\left[\sin(\phi-\phi_S)\,F_{UT}^{\sin(\phi-\phi_S)} + \epsilon\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)}\right]$$
$$+ \lambda_e S_T\left[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q^2}\right)$$

$$\sigma_{UT}^{Collins} \propto S_T\,\sin(\phi+\phi_S)\,C[h_1(x,k_T) \times H_1^\perp(z,p_T)]$$

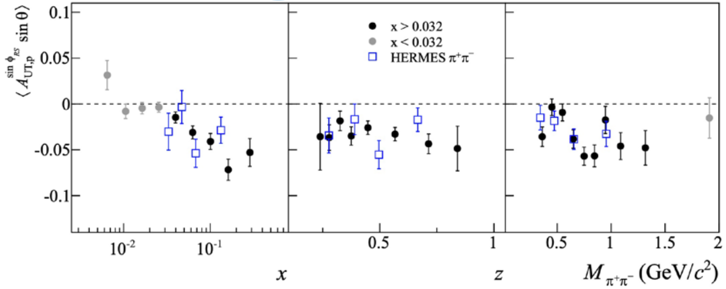
C. Adolph, PLB 744 (2015) 250



Transversity

$$\sigma_{UT}^{IFF} \propto S_T\,\sin(\phi_{R\perp}+\phi_S)\sin(\theta)\;h_1(x)H_1^{\sphericalangle}(z,M_{hh})$$

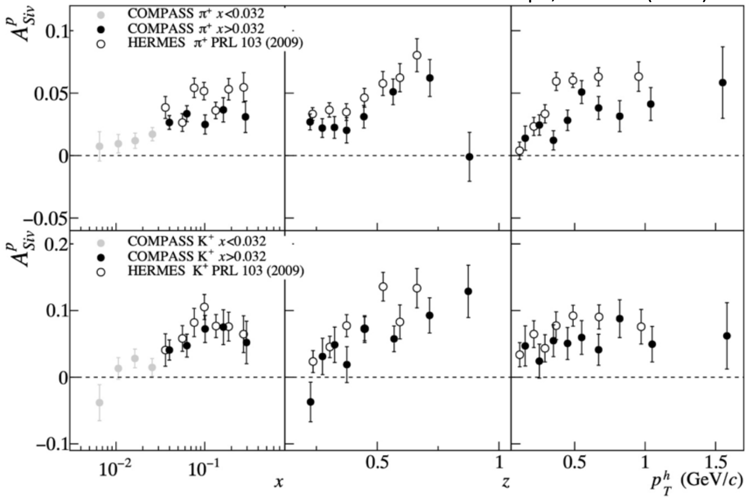
G.D. Alexeev, PLB 845 (2023) 138155

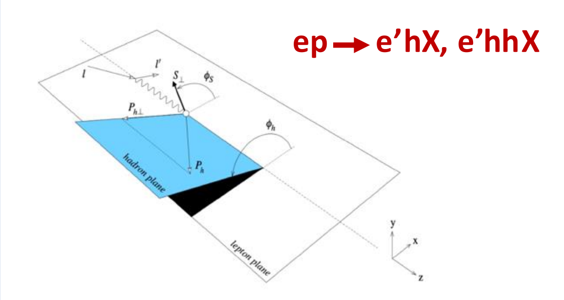


Sivers

$$\sigma_{UT}^{Sivers} \propto S_T\,\sin(\phi-\phi_S)\,C[f_{1T}^\perp(x,k_T) \times D_1(z,p_T)]$$

C. Adolph, PLB 744 (2015) 250

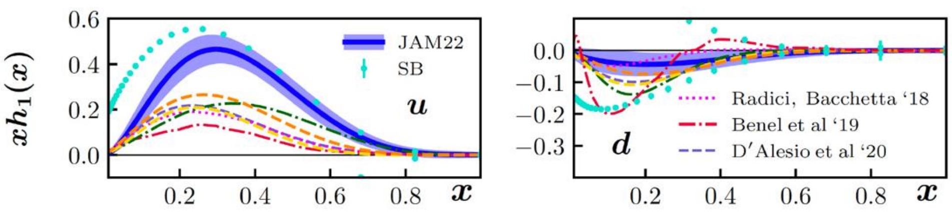




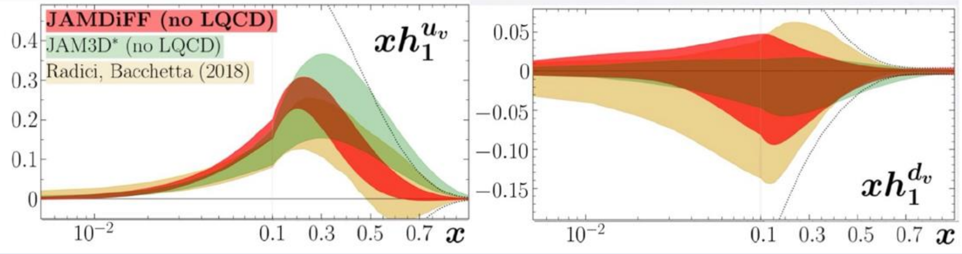
Large sensitivity expected in the valence region
Lack of data above x = 0.3 and no fully differential (4D) analysis available so far

CLAS12 can be the first experiment to achieve a 4D analysis in the valence region

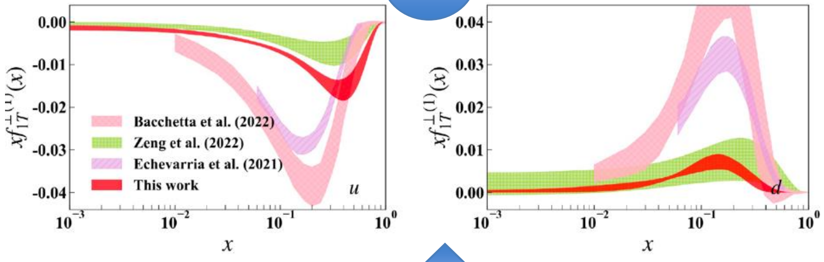
Transversity from single hadron SIDIS



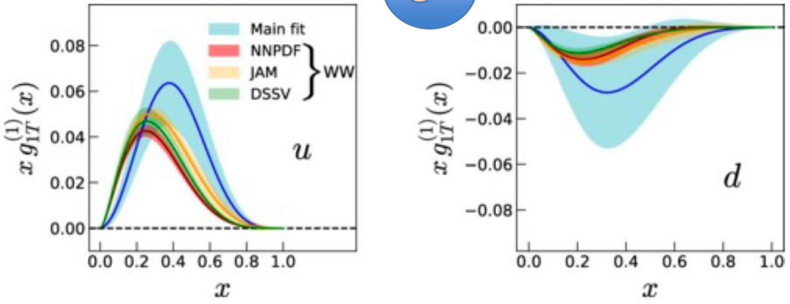
Transversity from di-hadron SIDIS



Sivers

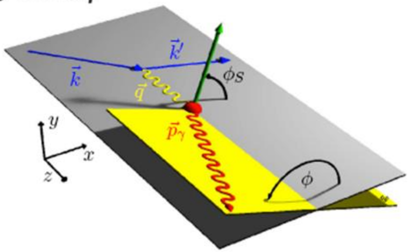


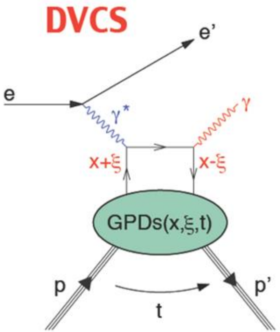
Kotzinian-Mulders

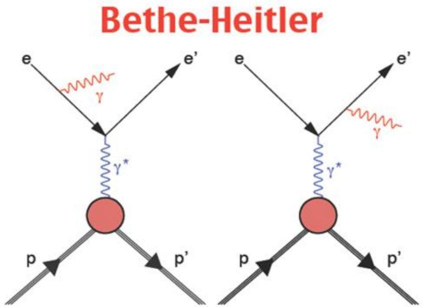


$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} \propto \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

ep → e' p' γ





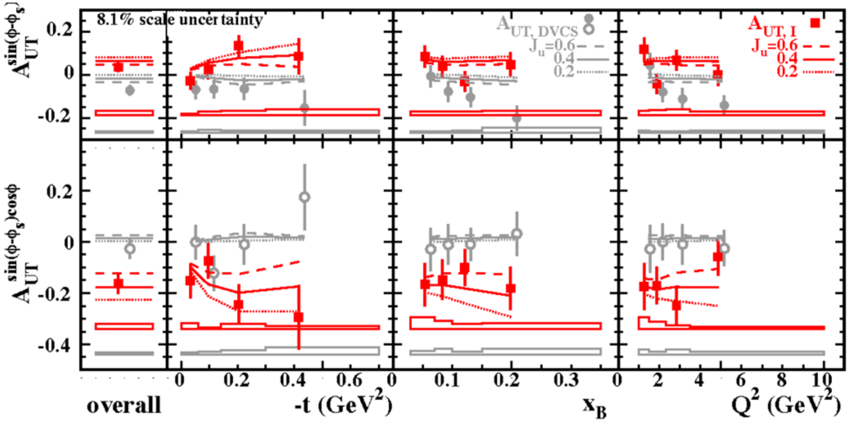


Rare access to Im$\mathcal{E}$ CFF with no kinematic suppression

$$d\sigma^{\mathrm{I}}_{UT} = \frac{-K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left\{\sum_{n=0}^{3} c^{\mathrm{I}}_{n,\mathrm{TP}-}\sin(\phi-\phi_S)\cos(n\phi) + \sum_{n=1}^{3} s^{\mathrm{I}}_{n,\mathrm{TP}+}\cos(\phi-\phi_S)\sin(n\phi)\right\}$$

$$c^{\mathrm{I}}_{1,\mathrm{TP}-} \propto -\frac{M}{Q}\Im\mathrm{m}\left\{\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right] + x_B\xi\left[F_1(\mathcal{H}+\mathcal{E}) - (F_1+F_2)(\tilde{\mathcal{H}} + \frac{t}{4M^2}\tilde{\mathcal{E}})\right]\right\}$$

A. Airapetian, PLB 74 (2011) 15



GPD E is essential to pin down the quark dynamics (OAM)
It is poorly known expecially for the u-quark flavor

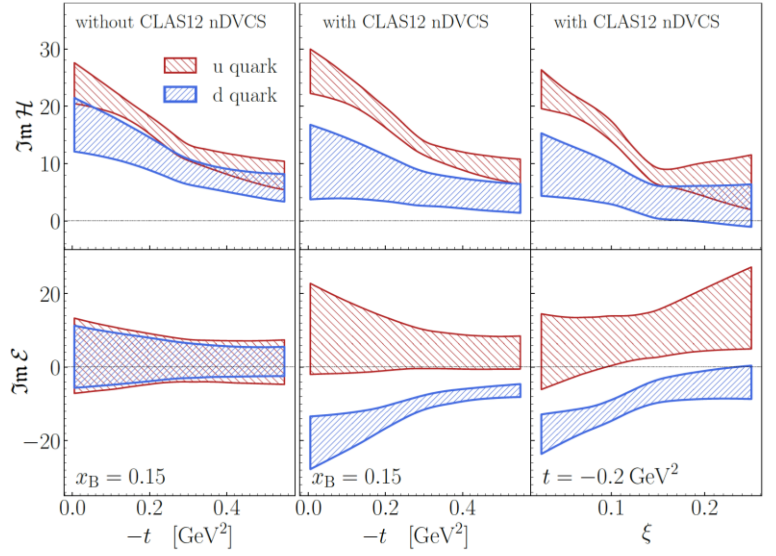
$$\sum_q \int_{-1}^{+1} dx\, x[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = 2\, J_q$$

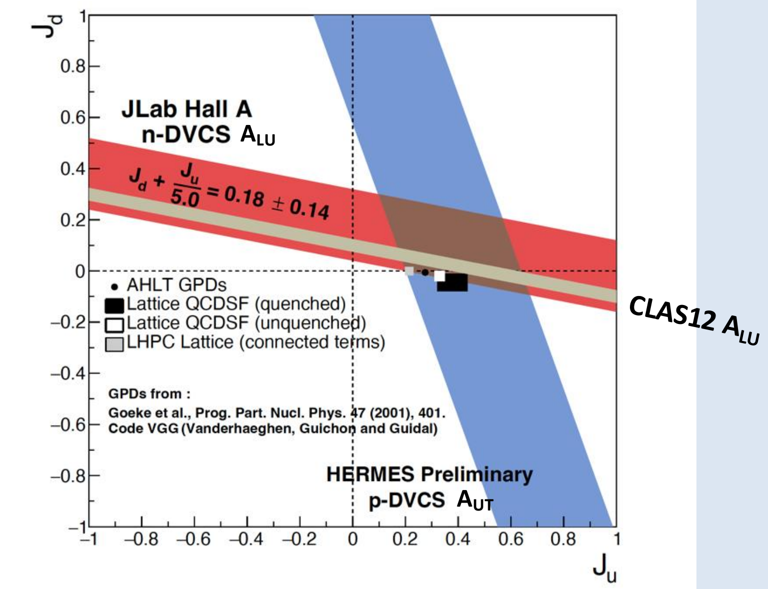
CLAS12 can be the first experiment in exploiting both
A_{LU} measurement on neutron with
A_{UT} measurement on proton

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

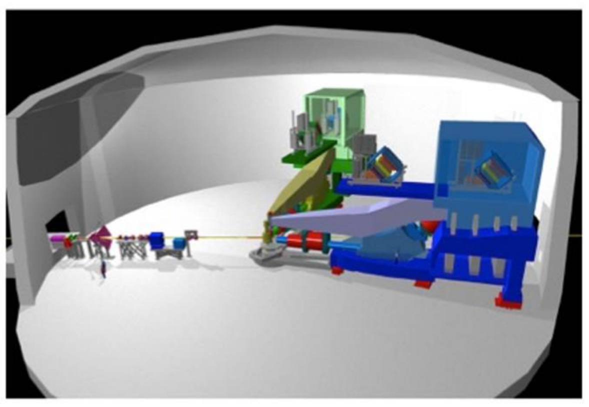
$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \dots\}$$

CLAS12 RGB measurement of A_{LU} on neutron, Phys.Rev.Lett. 133 (2024) 21, 211903





SBS: Spectrometer Pair



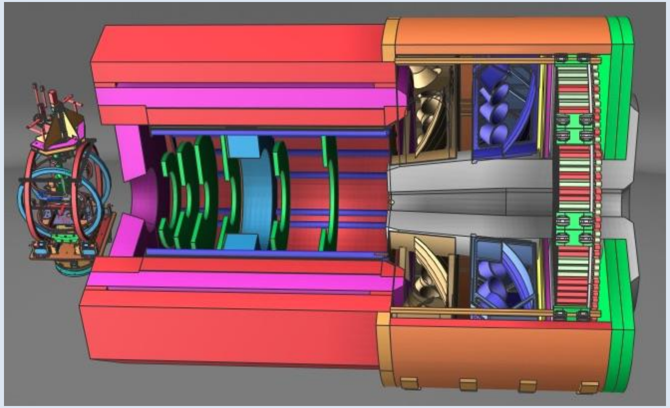
Hall-A:

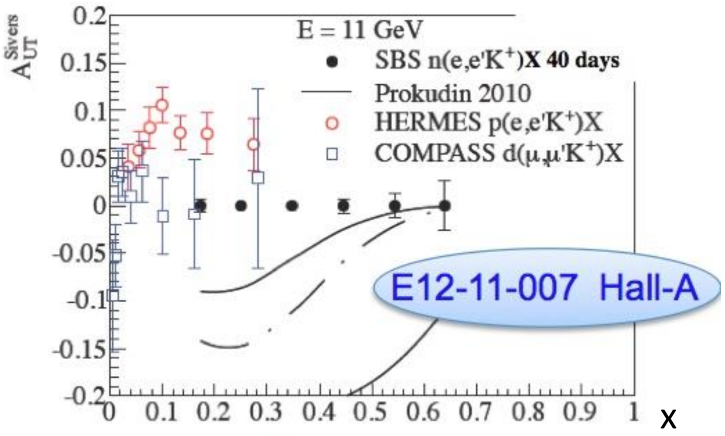
High-luminosity
$10^{38}\ cm^{-2}s^{-1}$

^{3}He targets

Wide coverage

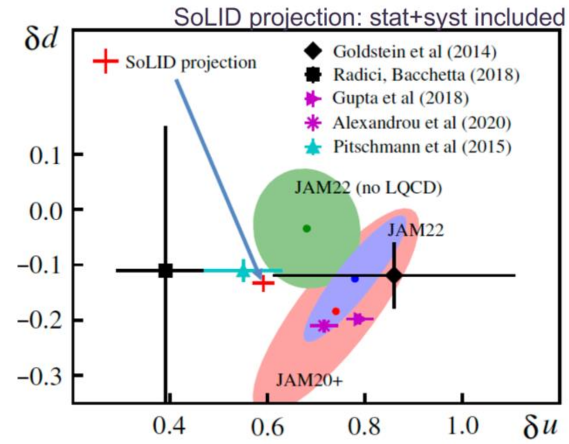
SOLID: Large Acceptance Detector





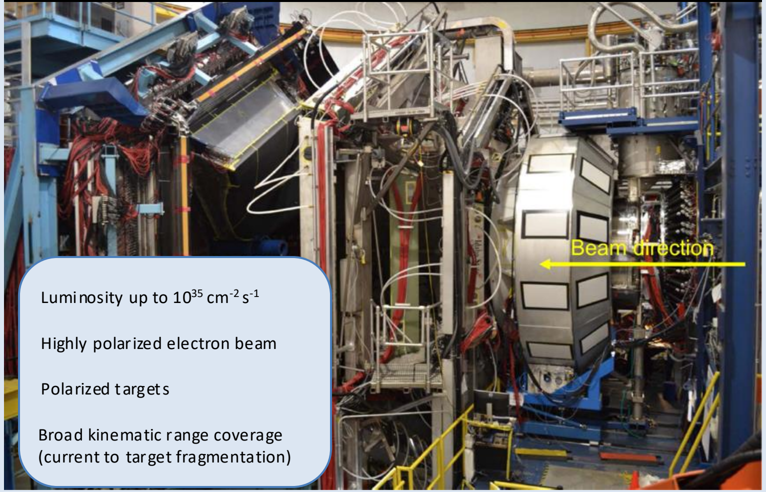
H. Gao

Z. Ye



CLAS12

Large acceptance spectrometer. Operational since 02/18



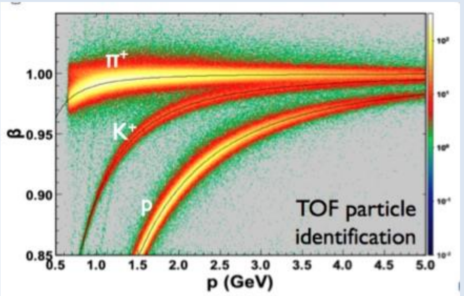
Luminosity up to 10^{35} cm^{-2} s^{-1}

Highly polarized electron beam

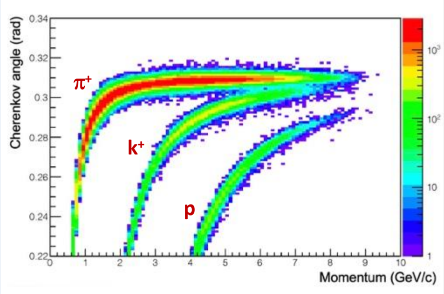
Polarized targets

Broad kinematic range coverage (current to target fragmentation)

Time of flight



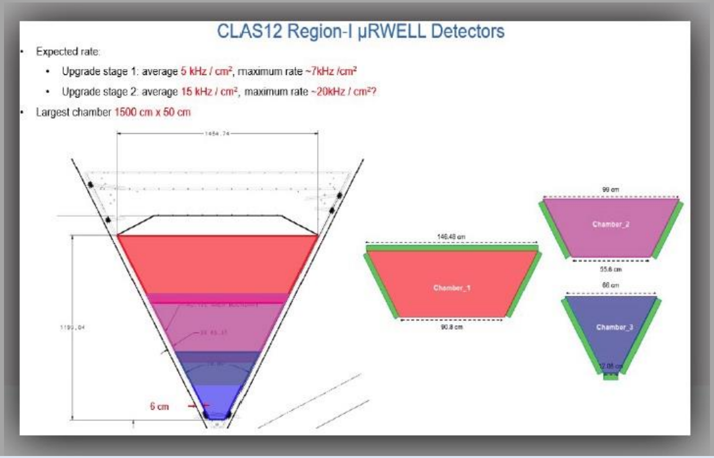
Ring-imaging Cherenkov



Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal	10.6 GeV
~ 2029		RGH	NH_3-ND_3	Transverse	10.6 GeV
> 2029			^3He	Longitudinal	10.6 GeV
> 2029		RGG	^7LiD, ^6LiH	Longiudinal	10.6 GeV

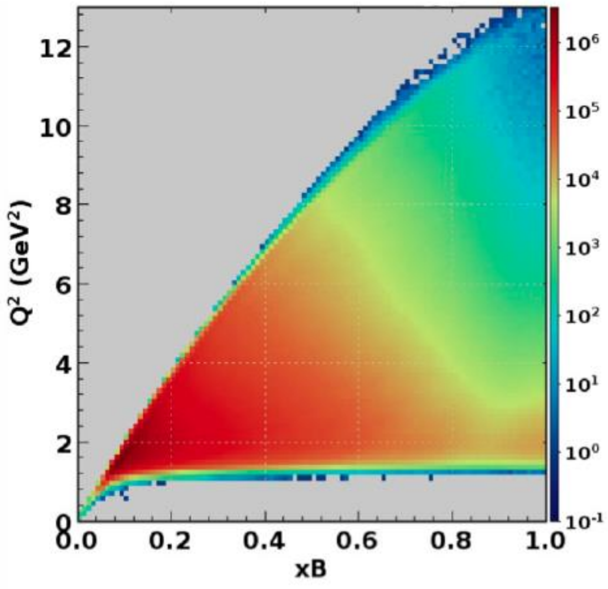
Luminosity upgrade Stage-1: $2x10^{35}$ $cm^{-2}s^{-1}$ 3 years

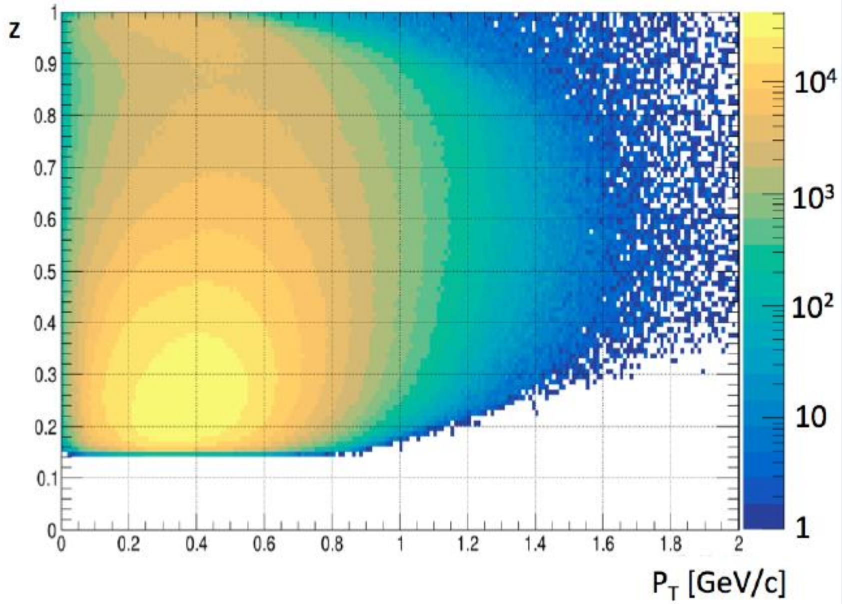
Stage-2: > 10^{37} $cm^{-2}s^{-1}$ 7-10 years



Features: wide phase space cover, excellent PID and statistics optimized for a multi-D analysis

- disentangle kinematical correlations
- verify expected dependences (e.g. in Q^2) and isolate peculiar regimes (e.g. in z)
- study transition regions (e.g. in P_T)



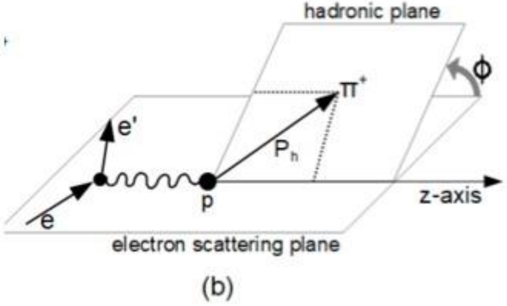


CLAS12 proton data (RGA)

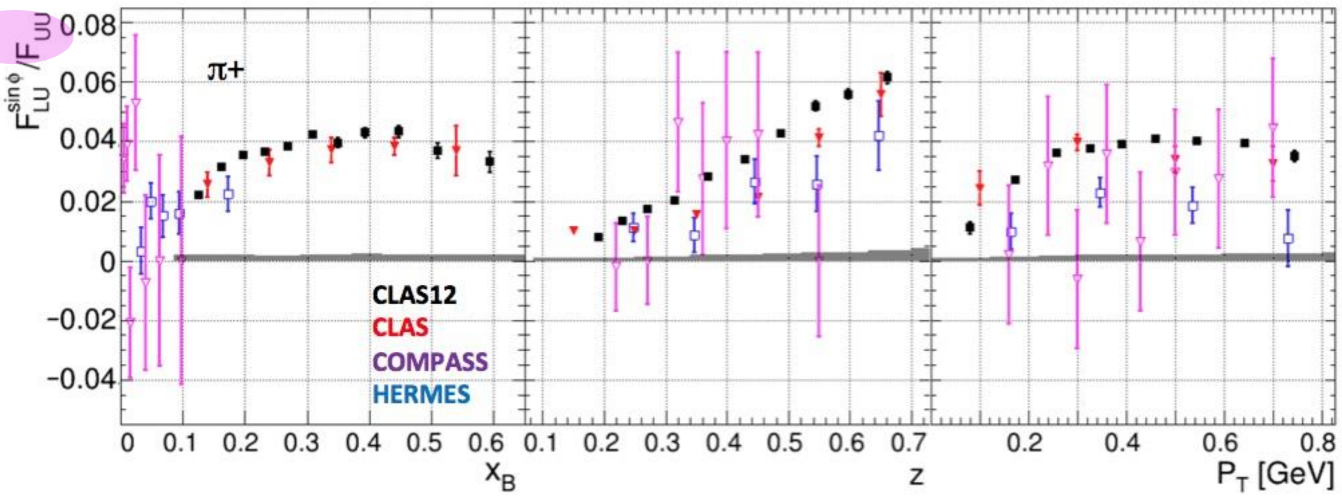
S. Diehl et al., e-Print: 2101.03544

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x_B e H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot P_T}{M}\left(x_B g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

86.9±2.6 %

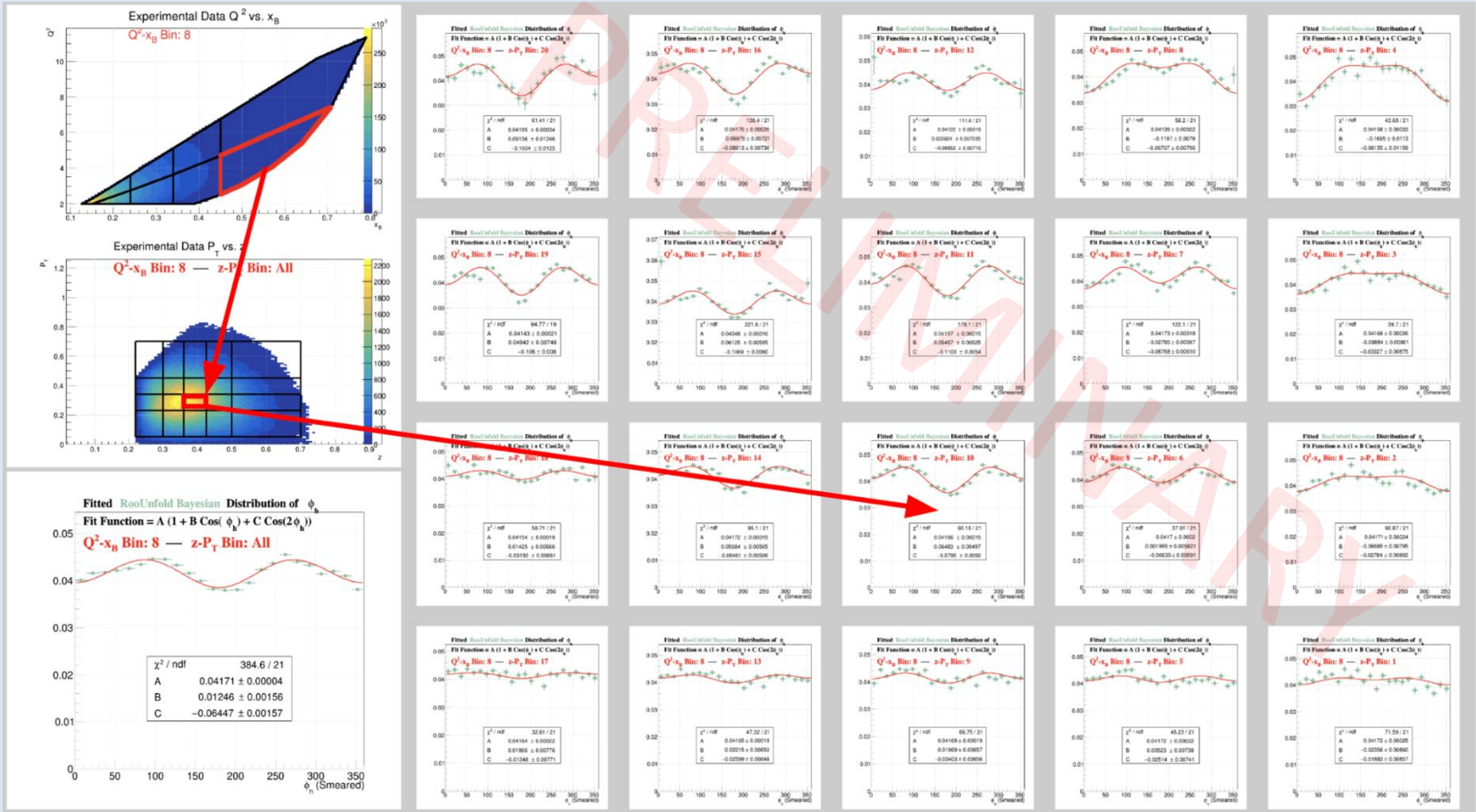


$$A_{LU} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

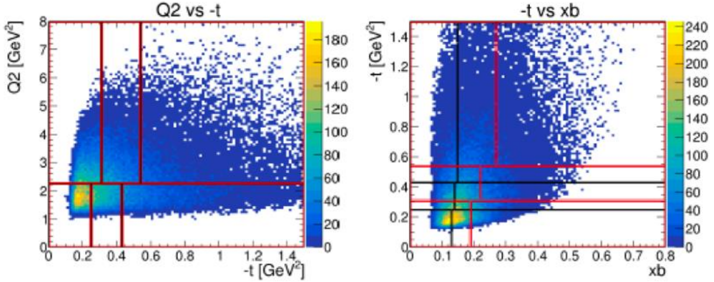


Acceptance being unfolded with a multidimensional kinematic binning and improving MC

$$\frac{d\sigma_{UT}}{dx dQ^2 dz dP_{h\perp} d\phi d\phi_S} \propto \left[F_{UU} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \dots\right]$$



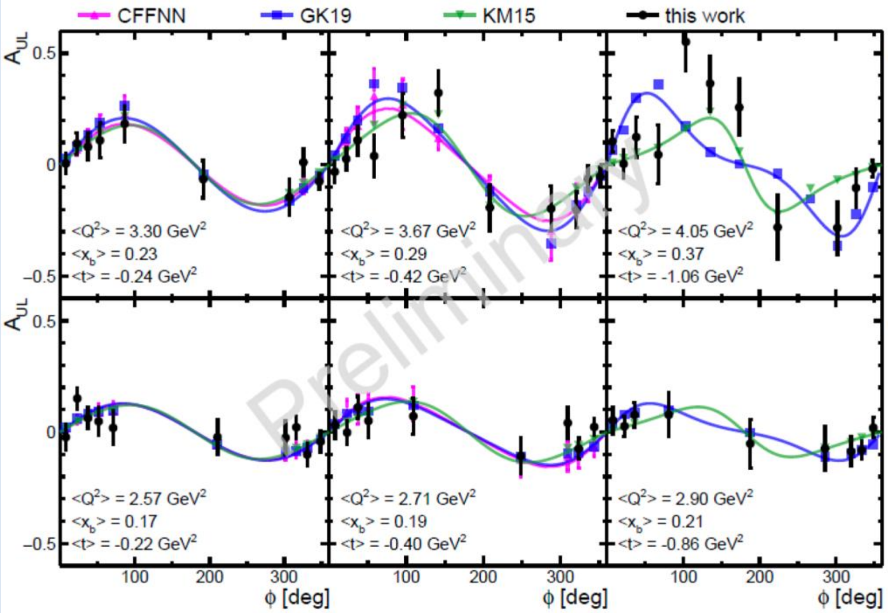
pDVCS on Longitudinally Polarized NH_3 Target @ CLAS12

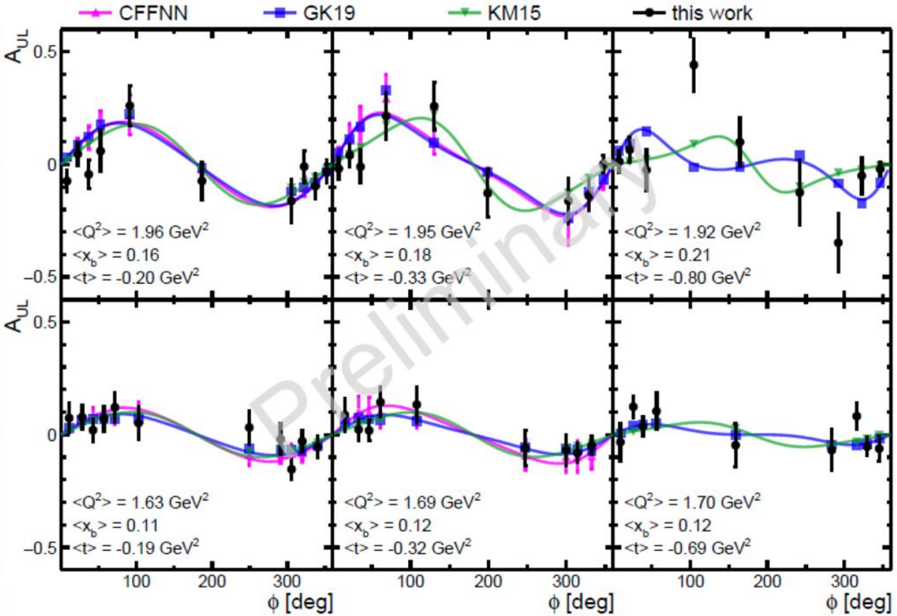


$\vec{e}\vec{p} \to ep\gamma$

~30% of the collected data

$$\Delta\sigma_{UL} \sim \sin\phi\ \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2\, \tilde{\mathcal{E}} + \dots\}$$





Run Group H @ CLAS12

RGH approved with NH_3 target by PAC 53 - 2025

Experiment	Contact	Title	Rating	PAC days
C12-11-111	M. Contalbrigo	Transverse spin effect in SIDIS at 11 GeV with a transversely polarized target using CLAS12	A	100 + 25
C12-12-009	H. Avakian	Measurement of transversity with di-hadron production in SIDIS with a transversely polarized target	A	100 + 25
C12-12-010	L. Elauadrhiri	Deeply Virtual Compton scattering at 11 GeV with transversely polarized target using the CLAS12 detector	A	100 + 25
C12-11-111A	H. Avakian	Measurements of Single Spin Asymmetries in exclusive production of hadrons with RGH transversely polarized target		100 + 25

Access to unique observables in

- SIDIS hadron
- SIDIS Di-hadron
- DVCS
- DVMP

Gather unprecedented information on

Transversity	GPD E
Tensor charge	quark OAM
Sivers, $h_{1T}^{\perp}$, $g_{1T}^{\perp}$, $H_1^{\perp}$	……..

RGH Target & Magnet

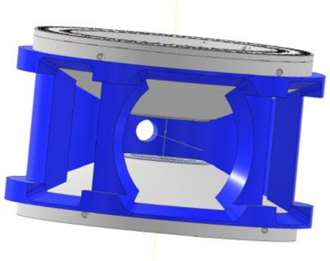
HD-ice: ruled out after beam tests at UITF

NH_3: Viable solution to prioritize physics (2-3 yr)

Consolidated dynamically polarized technology

Designed based on already successful realizations

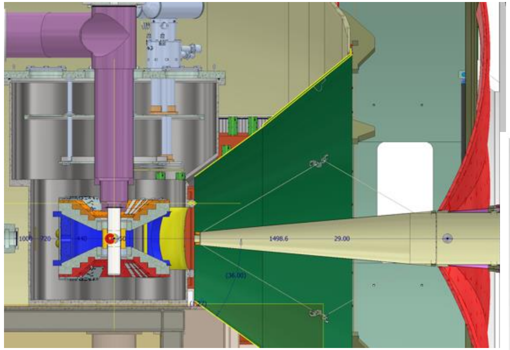
- Hall-A G2p-Gep target (replica optimized for HTCC)
- Hall-C E12-15-005 magnet (replica optimized for recoil detection)



5T dipole acceptance:

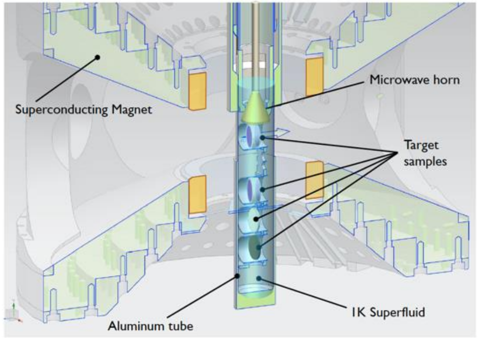
$\pm$ 25° vertical

$\pm$ 70° horizontal

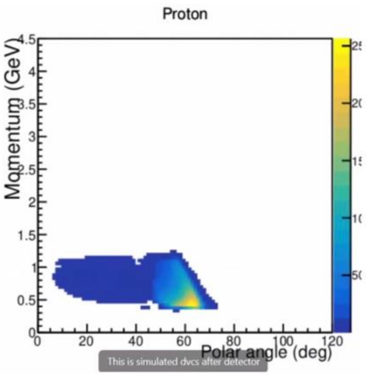


Target cryostat in front of CLAS12

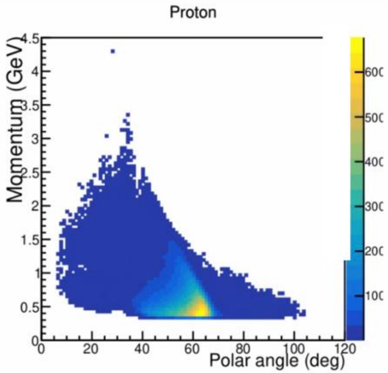
Target ladder details



RGH (MC)



RGA (data)

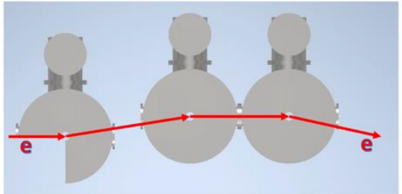


RGH Beam Line

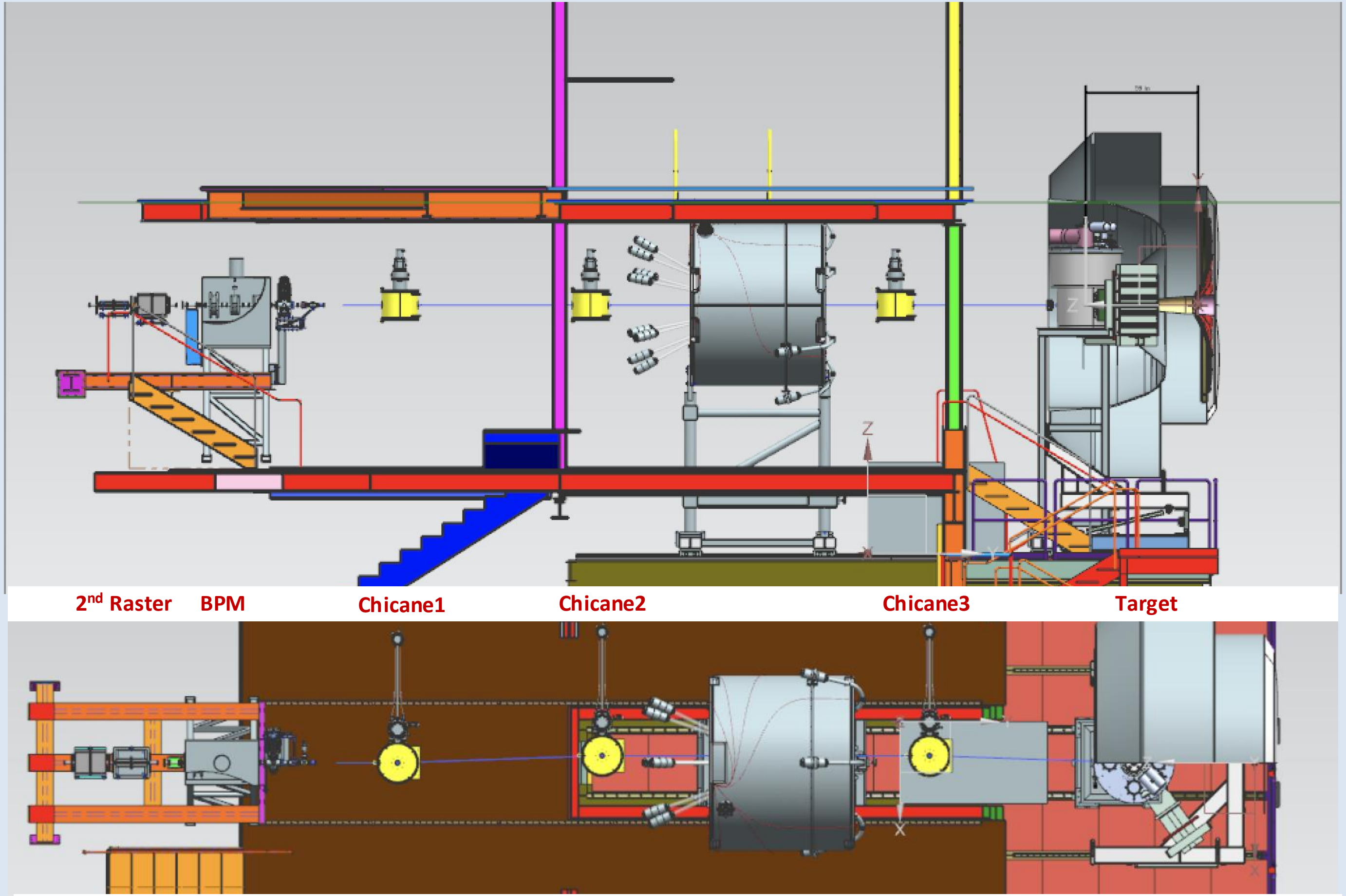
Based on

existing 0.7 cm raster

commercial 7.5T magnets



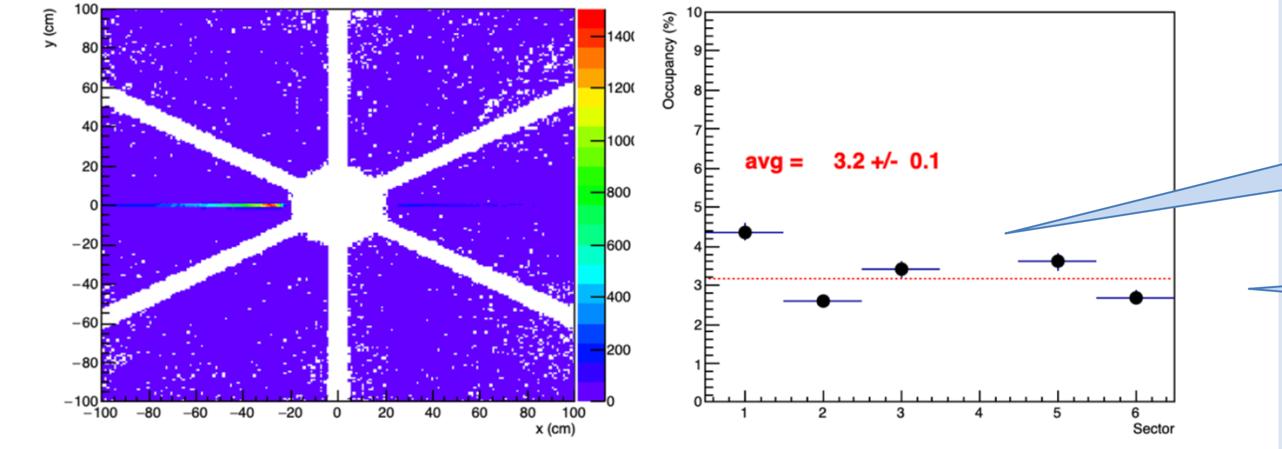
- ✓ space
- ✓ synchrotron radiation
- ✓ beam rastering



Beam pipe + 1 cm lead in the proper locations suppress synchrotron radiation to a negligible level

Geant Simulation: DC Occupancy

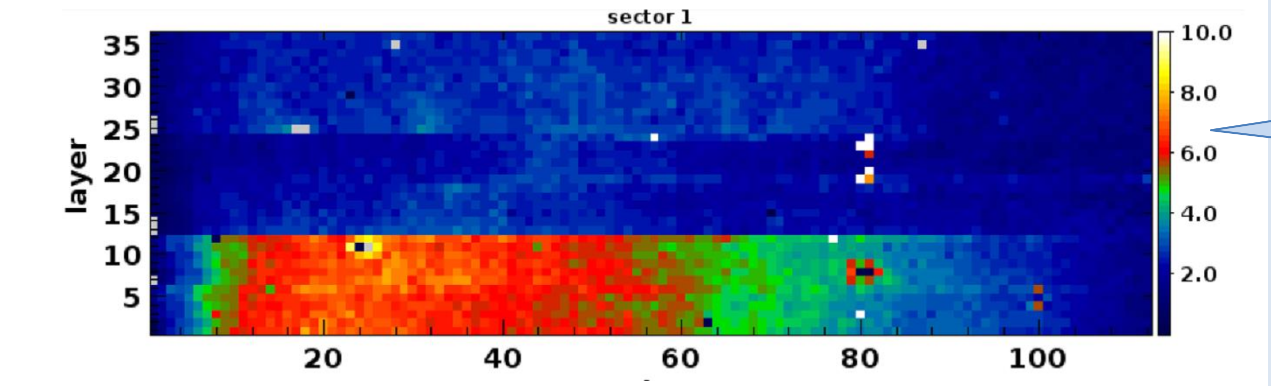
CLAS12 GEANT simulation framework



RGH MC (NH_3)

Assume to switch OFF DC in sector 4 and move RICH in sector 3

x2 with CLAS12 gate



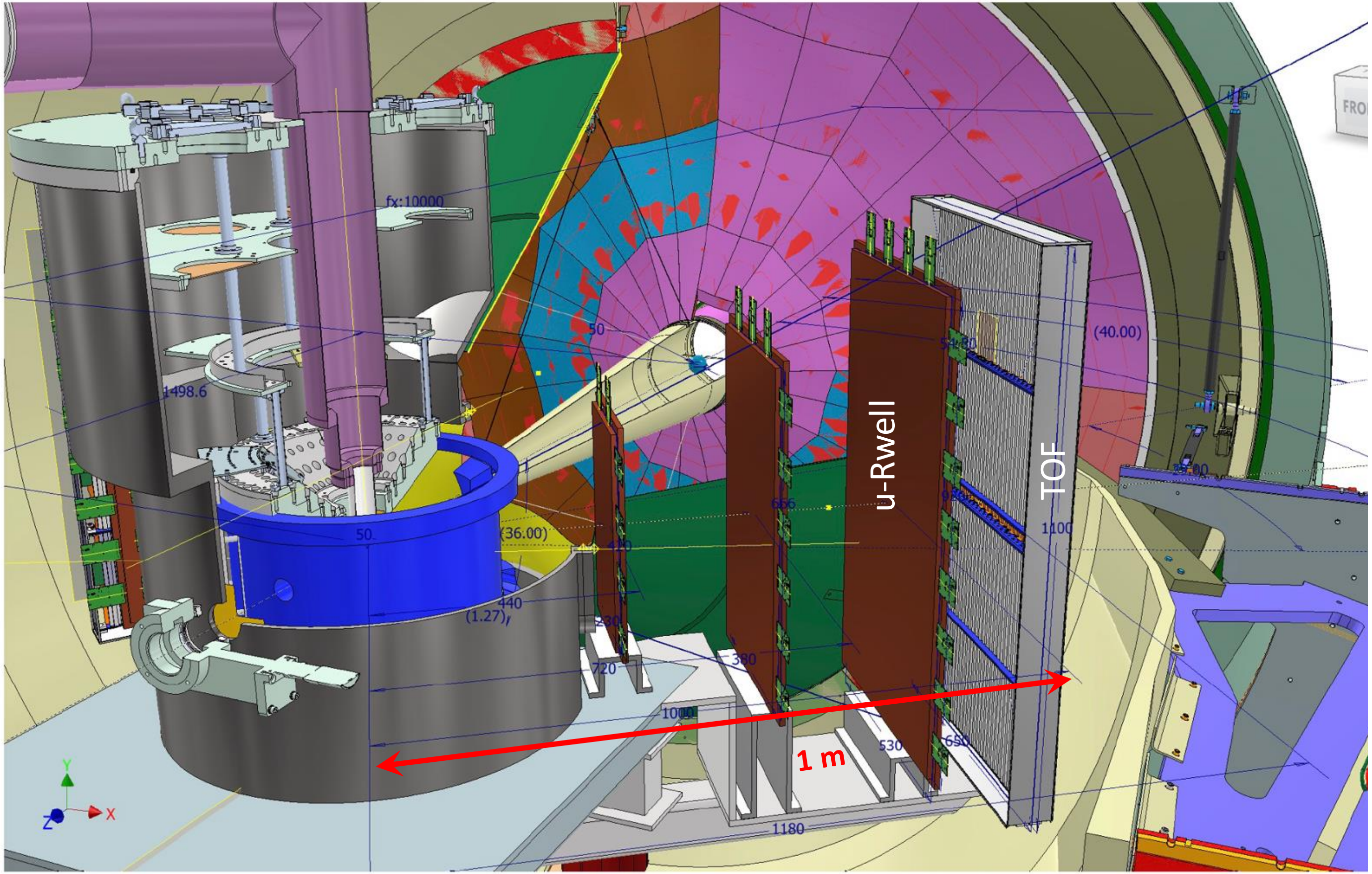
RGC DATA (NH_3)

Present performance*

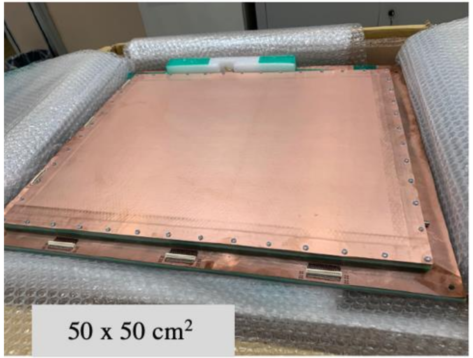
Typical DC occupancy measured at CLAS12

*No high-lumi

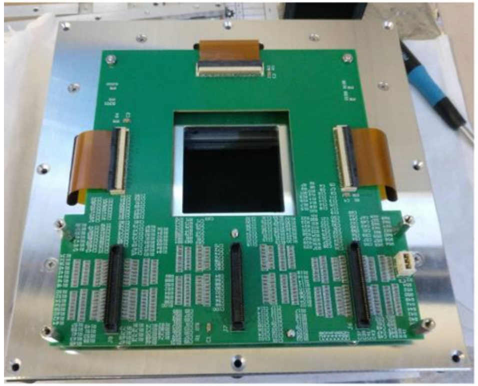
New recoil detector to cover the optimized target magnet acceptance. R&D expected to be completed in 2026.



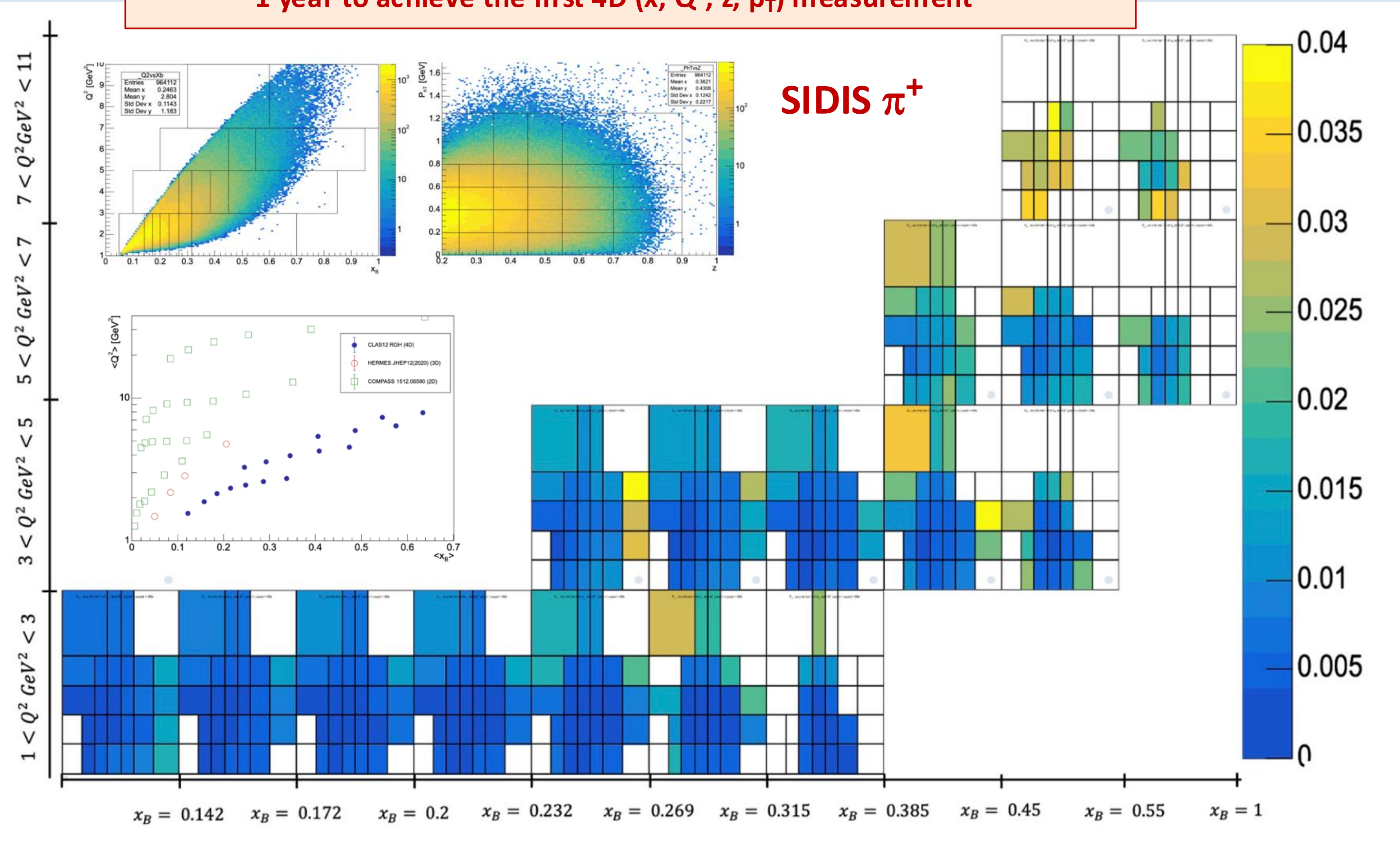
μ-Rwell tracking



Scintillator + SiPM TOF



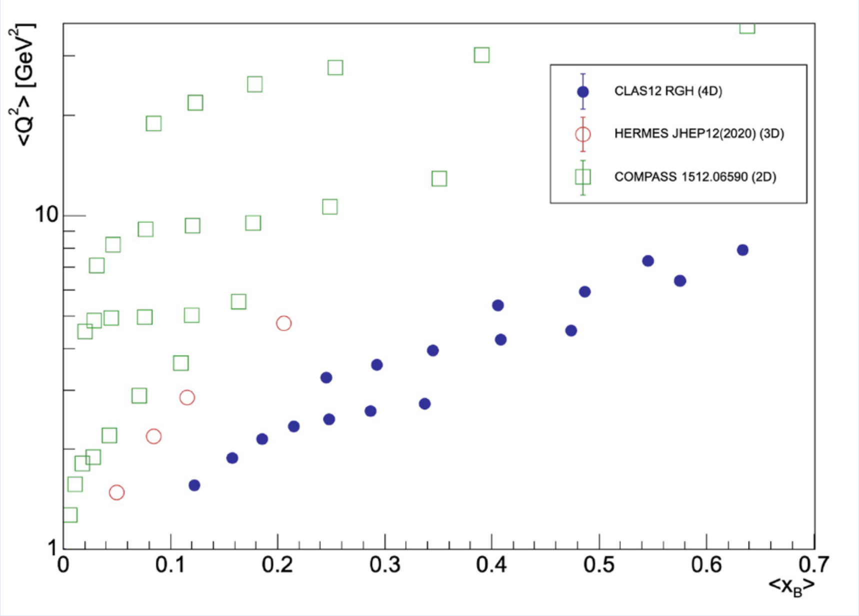
~ 1 year to achieve the first 4D (x, Q^2, z, p_T) measurement



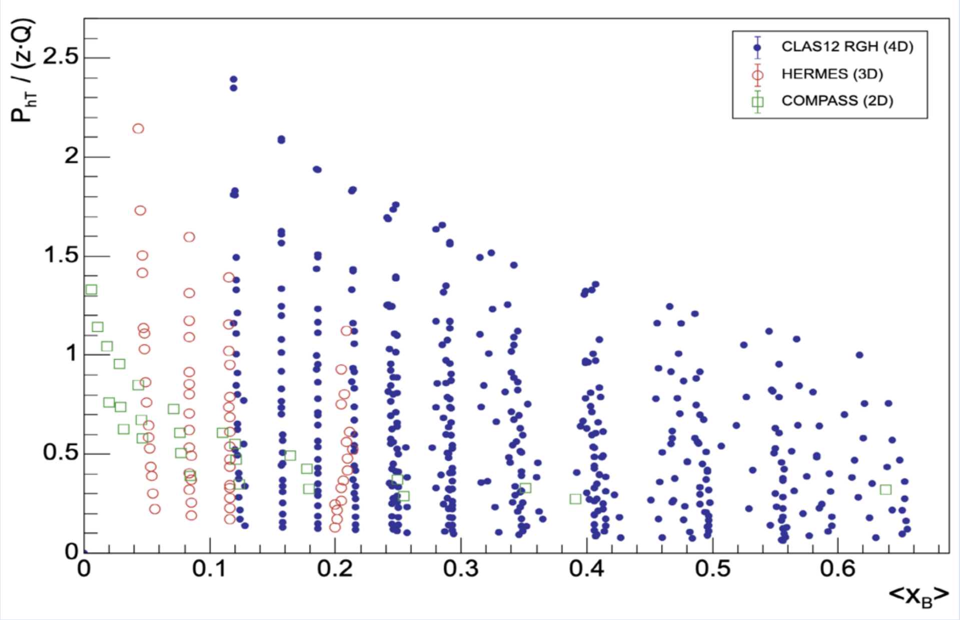
TMD Regime

~ 1 year to achieve a broad kinematic coverage in an unexplored valence regime

Fully differential analysis over Q^2
in between HERMES and COMPASS



Wide span over conventional parameters
used to single-out QCD (TMD) regimes



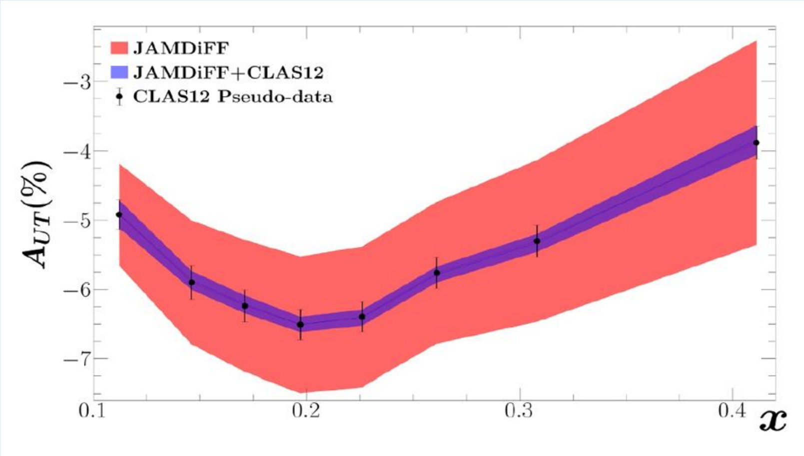
Impact Study: Tensor Charge from SIDIS

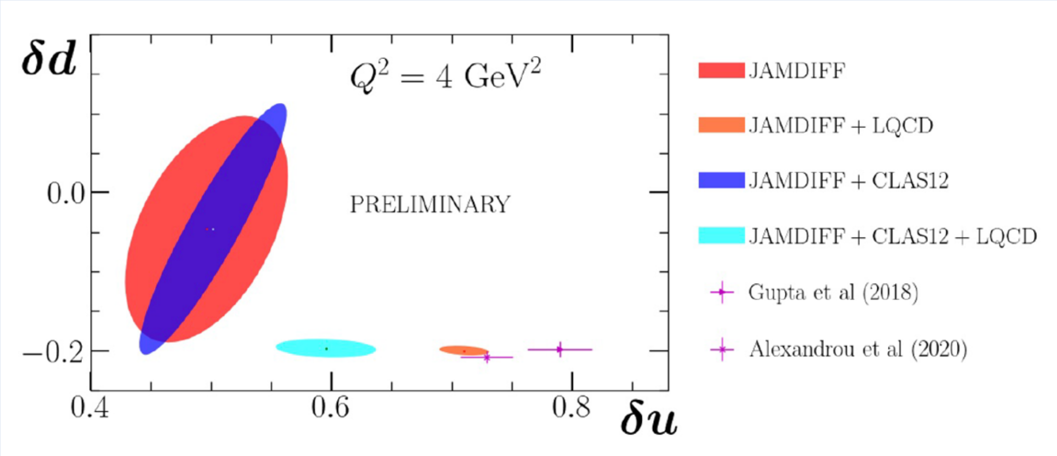
Fundamental quantity related to BSM physics: EDM and tensor coupling

$$\delta u = \int_0^1 dx\,(h_1^u(x) - h_1^{\bar{u}}(x)), \quad \delta d = \int_0^1 dx\,(h_1^d(x) - h_1^{\bar{d}}(x))$$

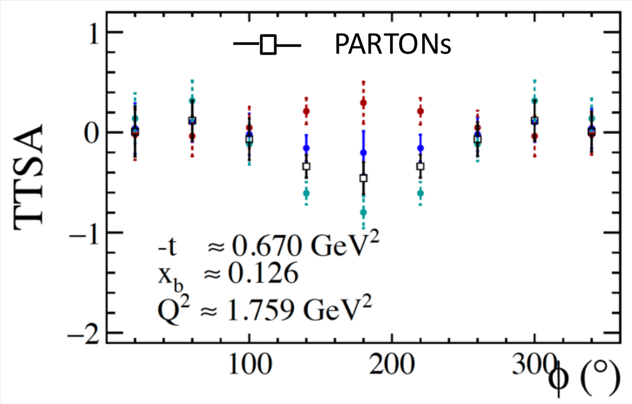
Projections with and without CLAS12 di-hadron pseudo-data (with lattice inputs)

~ 1 year to be competitive in precision to lattice for δu



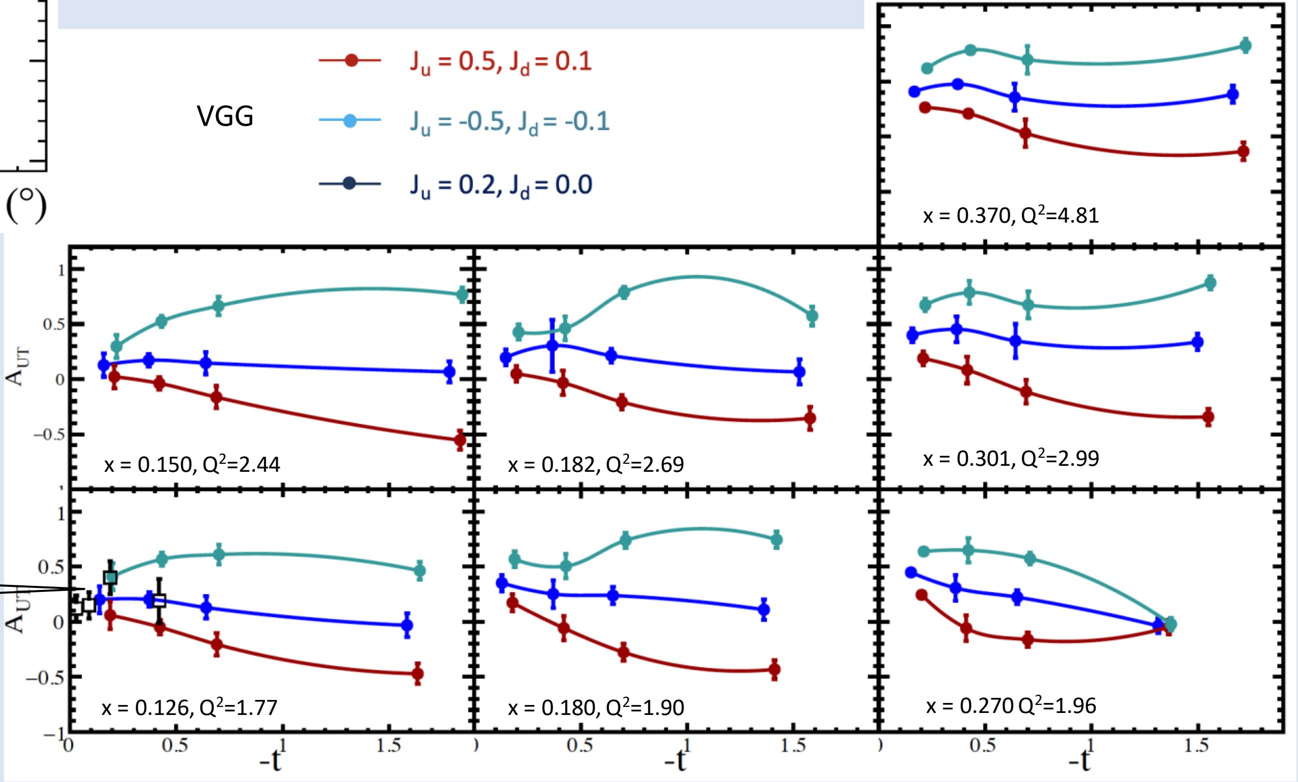


Impact Study: OAM from DVCS



~ 1 year to get unprecedented access to elusive quark angular momenta

Supersede the only other A_{UT} measurement
Pair with A_{LU} measurement done by RGB on neutron

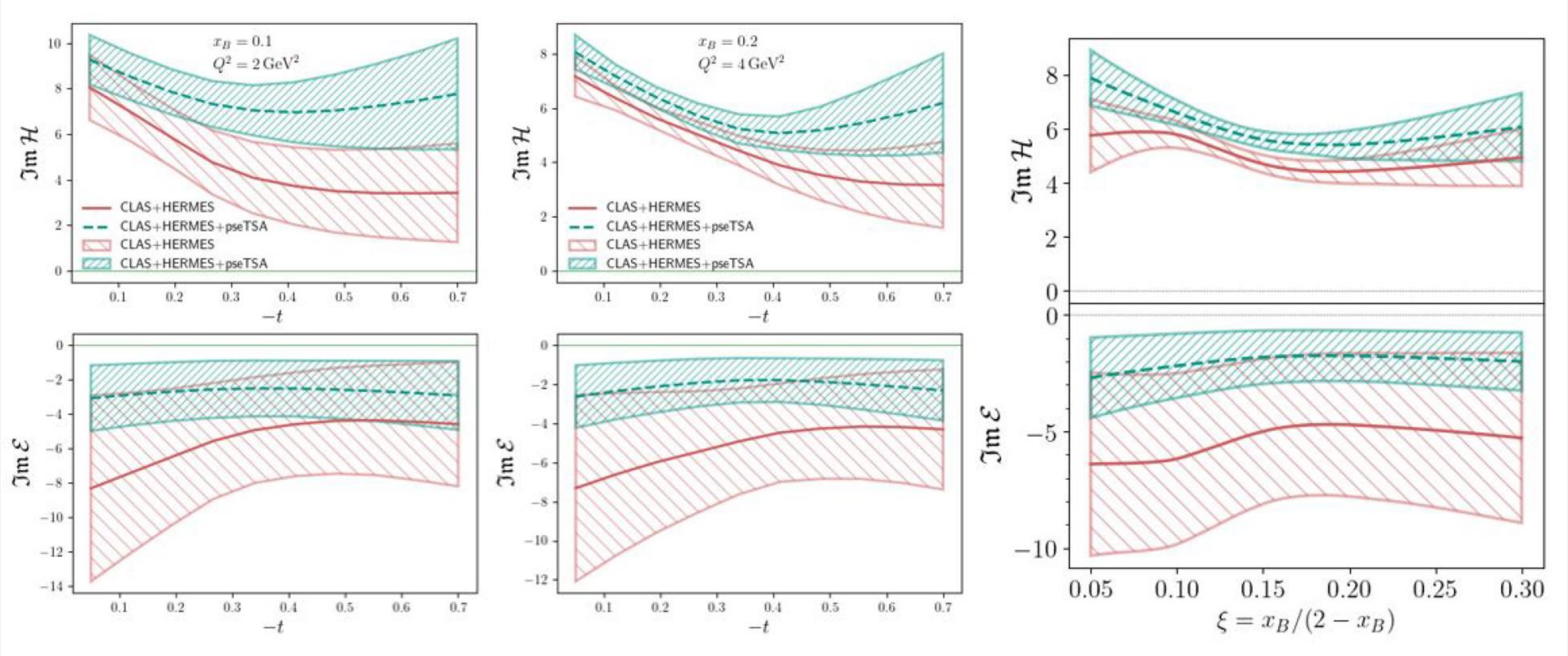


Superior discrimination power between various OAM model hypotheses

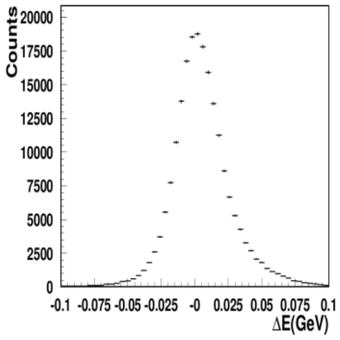
HERMES

Analysis of Melany Higuera Angulo using GEPARD framework (JLab LDRD project) and relevant data + RGH pseudo-data

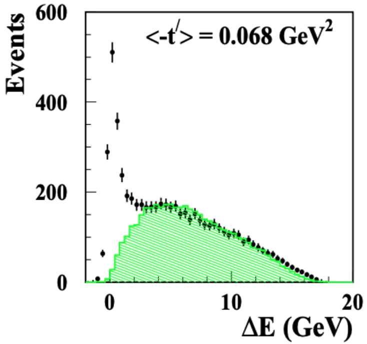
~ 1 year to reduce by 2/3 the uncertainty on Im $\mathcal{E}$



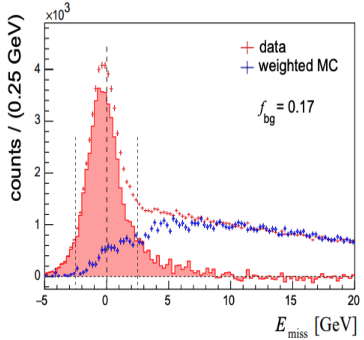
CLAS12
(width <0.1 GeV)



HERMES
(width ~0.6 GeV)

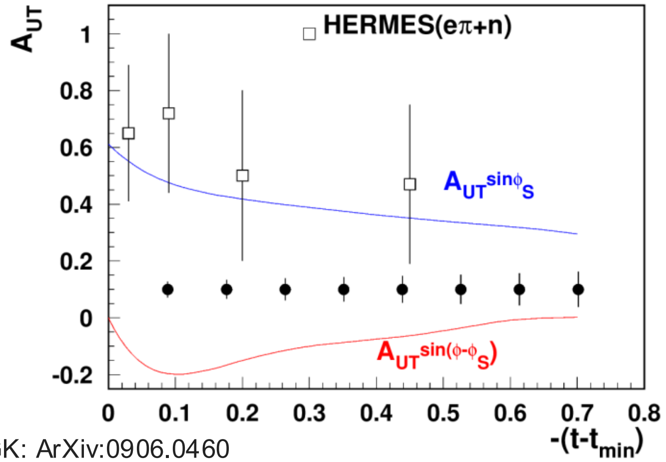


COMPASS
(width ~2 GeV)



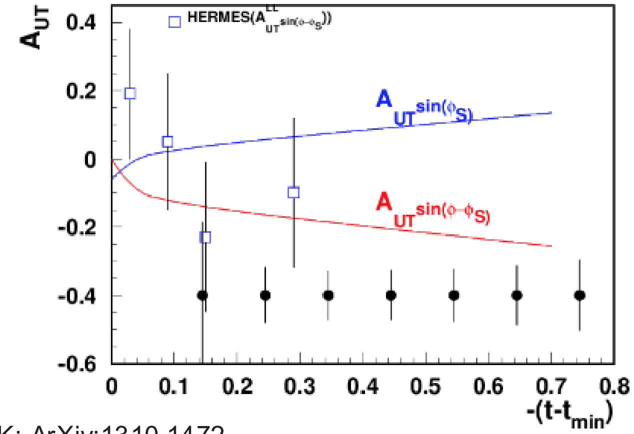
Exclusive processes help in understanding of elusive GPDs and longitudinal photon contributions in SSA
CLAS12 investigation benefits from high statistics, good resolution and multiple observables

Exclusive π+



GK: ArXiv:0906.0460

Exclusive ρ

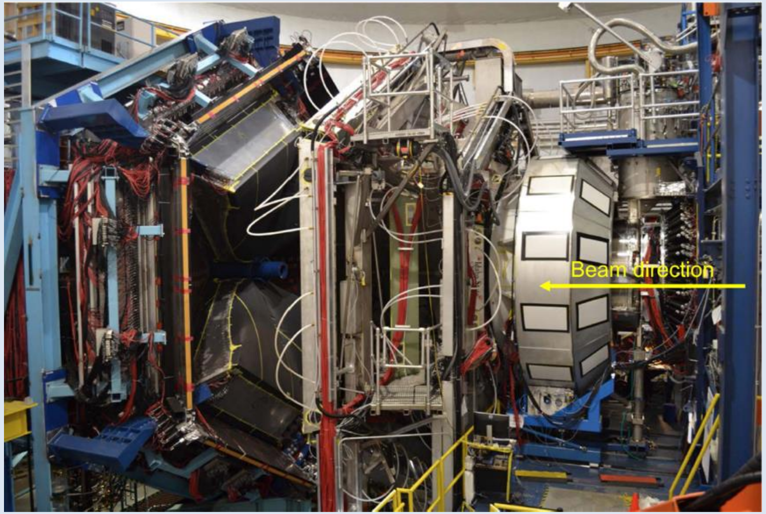


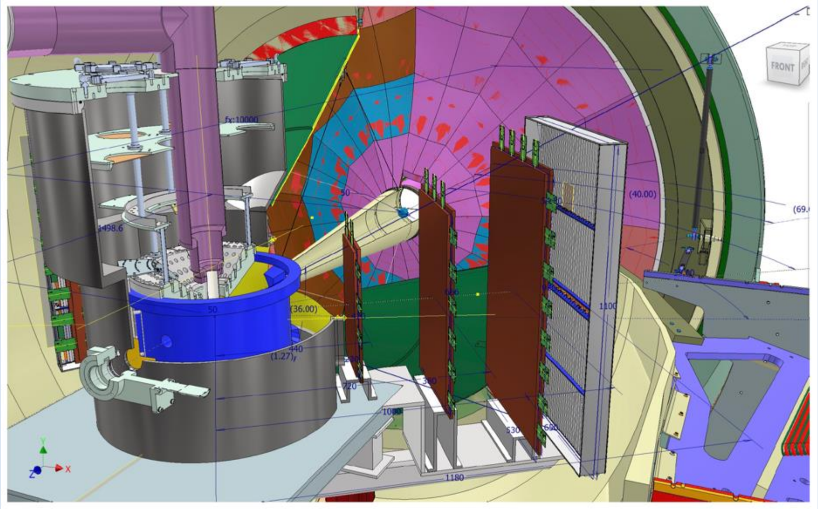
GK: ArXiv:1310.1472

Conclusions

RGH implements the target configuration which is most sensitive to the 3D nucleon structure study and capitalizes on CLAS12 with a complete set of target polarizations

100 (physics) + 25 (ancillary) PAC days approved to achieve unprecedent precision in the valence region





RGH aim: The SIDIS and exclusive measurements will significantly improve our understanding of tensor charge, spin-orbit correlations, and quark angular momentum, complementing past and ongoing CLAS12 studies.