DiHadron Projections for RGH



Based on *Phys.Rev.D* 114 (2026) 7, 074009 (Yorgo Sawaya (Temple) et al)

Anselm Vossen

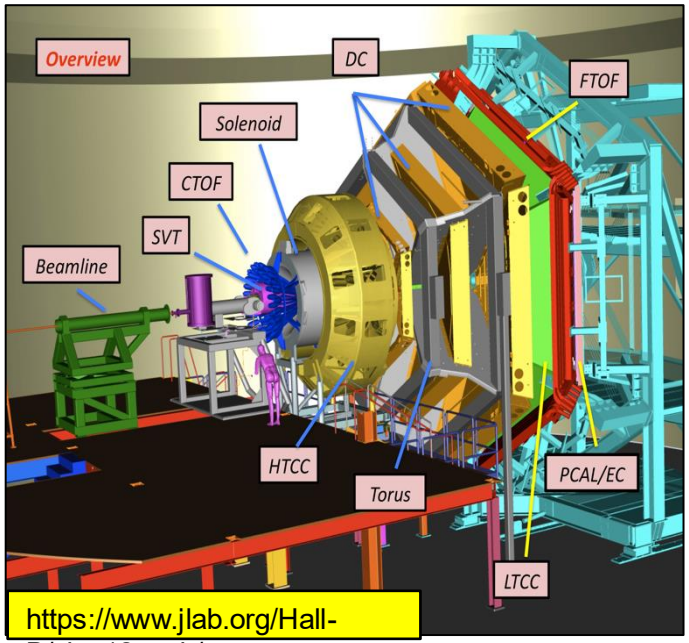
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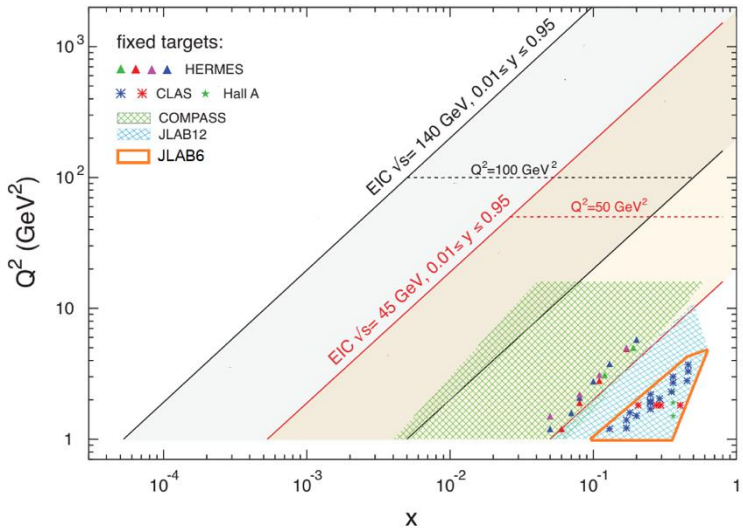
Duke UNIVERSITY

CLAS12 Spectrometer

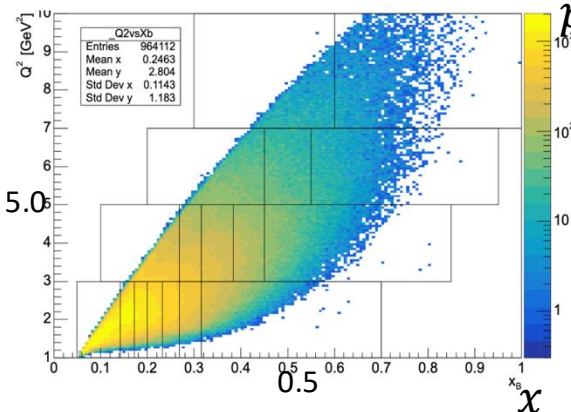
- CLAS12: high luminosity (10^{34}), wide acceptance, low Q^2 (higher twist measurements)
- Began data taking in Spring 2018 – many "run periods" now available: liquid H_2, D_2, polarized NH_3 and ND_3 etc.
- ~10.5 GeV electron beam, longitudinally polarized beam.



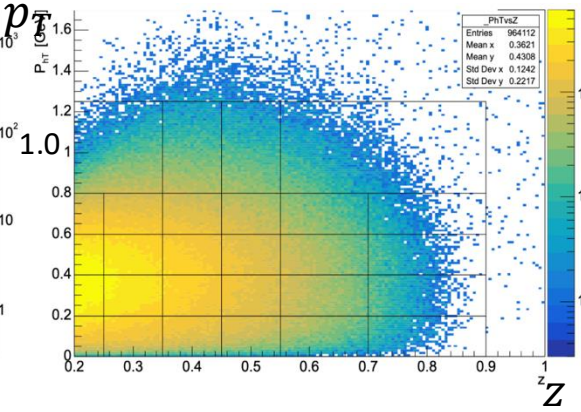
https://www.jlab.org/Hall-B/clas12-web/



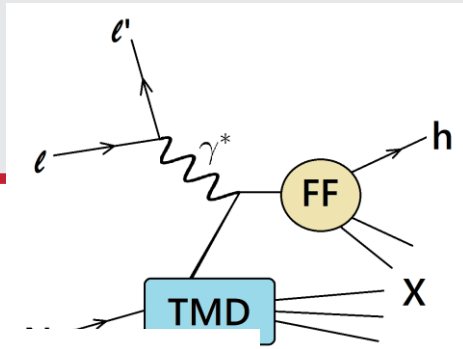
Q^2



p_T



SIDIS Observables at CLAS12



Run Group A (Unpolarized LH_2 target)
- ★ **unpolarized SIDIS cross section** off proton
- ★ A_{LU} **in Beam Spin Asymmetries**

Run Goup B (Unpolarized LD_2 target)
- ★ Complementary to RG-A
  → allow for ***u/d* quark flavor separation**

Run Group C (**longitudinally** polarized NH_3 and ND_3)
- ★ F_{UL} and F_{LL}

Run Group K (Unpolarized LH_2 target)
- ★ 6.5, 7.5, 8.4 GeV e- beam
- ★ $F_{UU,L}$, $F_{UU,T}$ Separation

Run Group H (**transversely** polarized NH_3)
- ★ F_{UT} structure function

➔ scheduled for FY 2029

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\Big]$$

$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

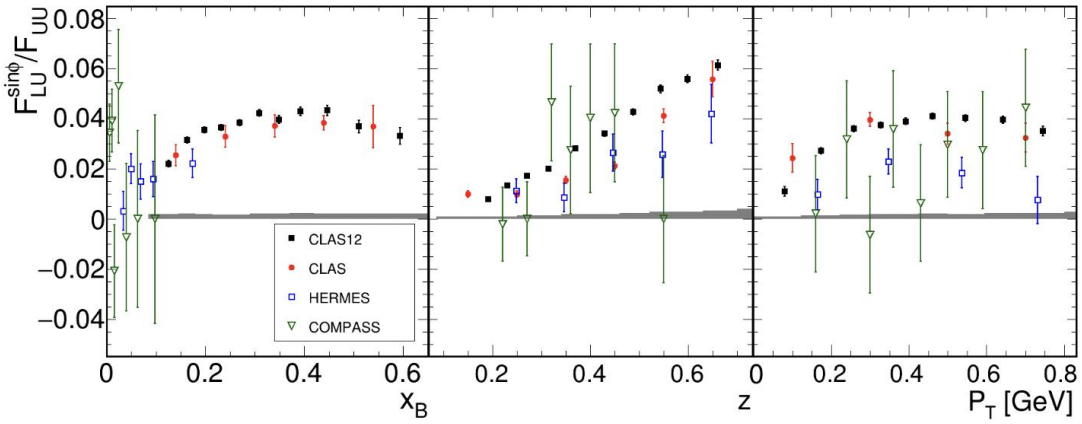
$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

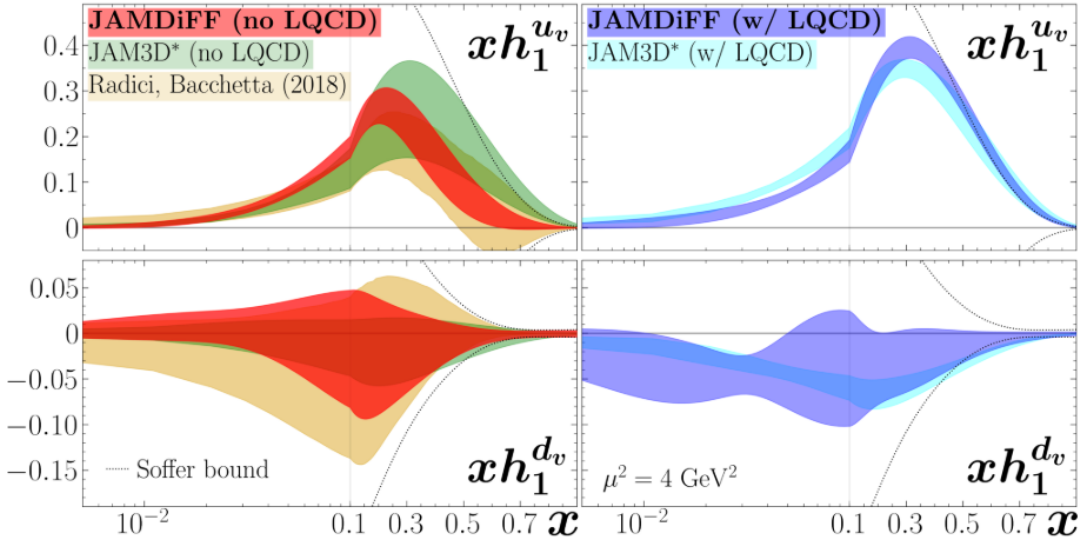
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

The CLAS12 physics program will have access to the full SIDIS cross section including all observables in a variety of flavors.

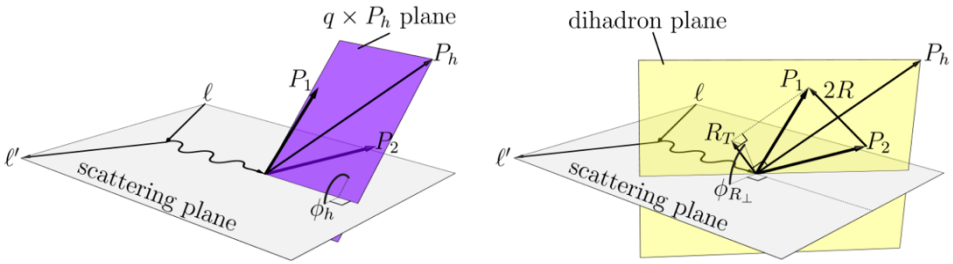
CLAS accesses phase space at high x

Phys.Rev.Lett. 128 (2022) 6, 062005



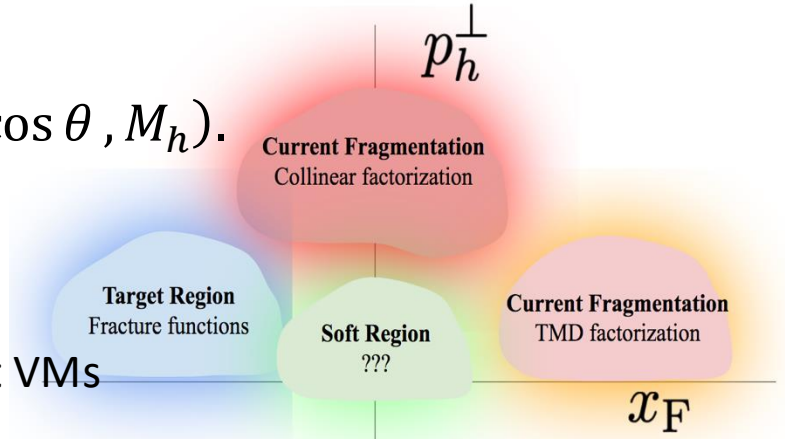


Here: Di-hadron Channel



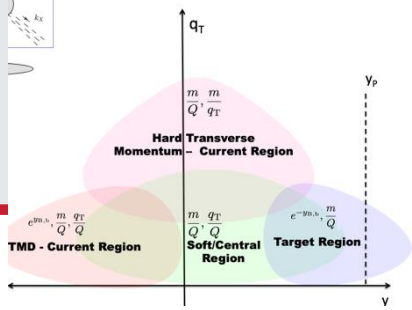
- Single Hadrons
- $F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_h}\ h_1^q(x,p_T^2)\,H_1^{\perp q}(z,k_T^2)\right],$
- $\mathcal{C}[w\,f\,D] = x\sum_q e_q^2 \int d^2p_T\,d^2k_T\ \delta^{(2)}\left(\vec{p}_T - \vec{k}_T - \frac{\vec{P}_{h\perp}}{z}\right) w\,f^q(x,p_T^2)\,D^q(z,k_T^2),$

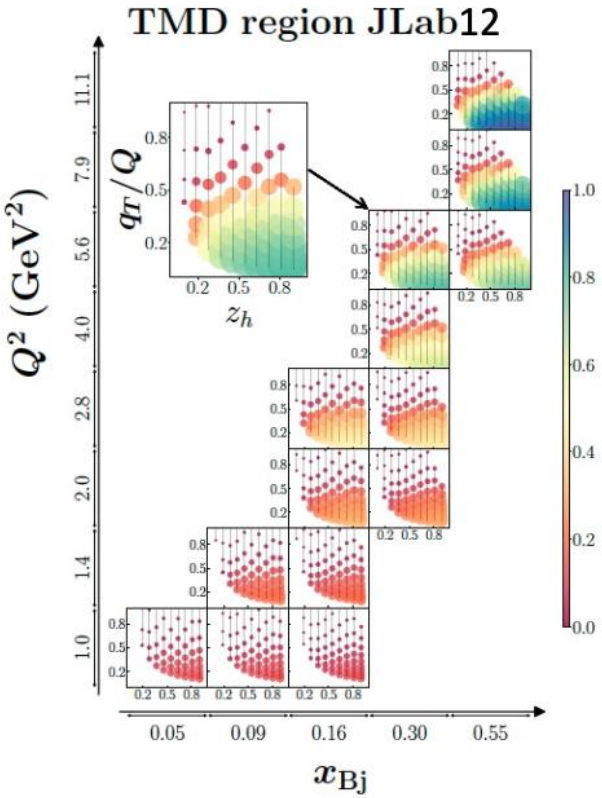
- Simpler Di-Hadrons:
- $F_{UT}^{\sin(\phi_R+\phi_S)} = x\sum_q e_q^2\ h_1^q(x)\ \frac{|\vec{R}|\ \sin\theta}{M_h}\ H_1^{\sphericalangle,q}(z,\cos\theta\,,M_h).$

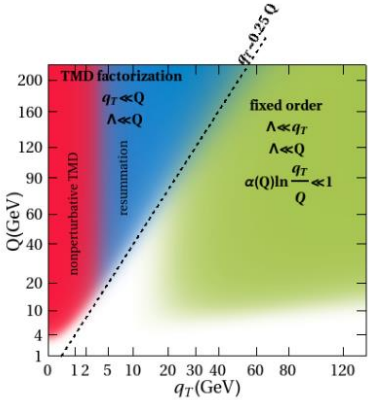


Advantages: Collinear Framework, more robust against VMs

Applicability of TMD Framework →Need $Q \gg p_T/z \gg \alpha_S$





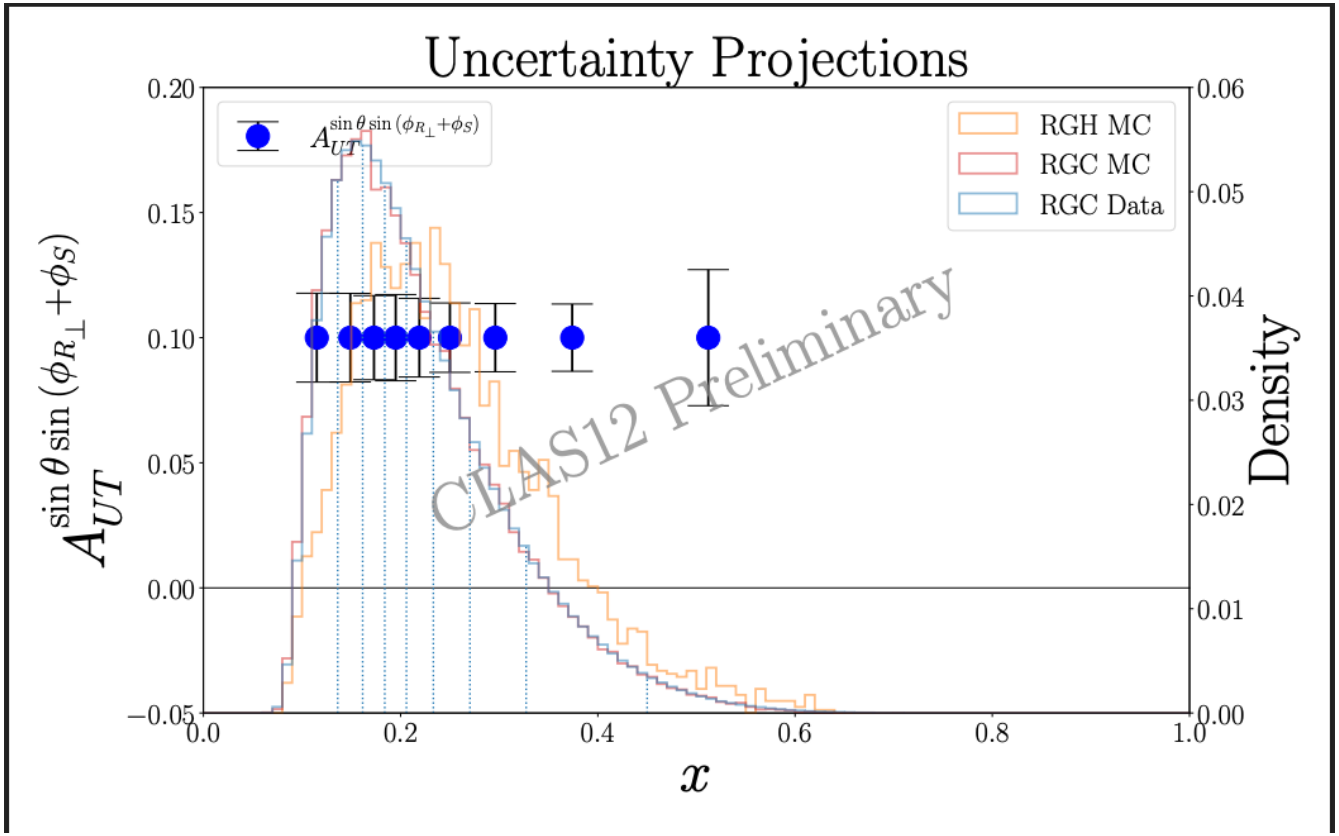


JHEP 04 (2022) 084

- Needs update…

Pseudodata

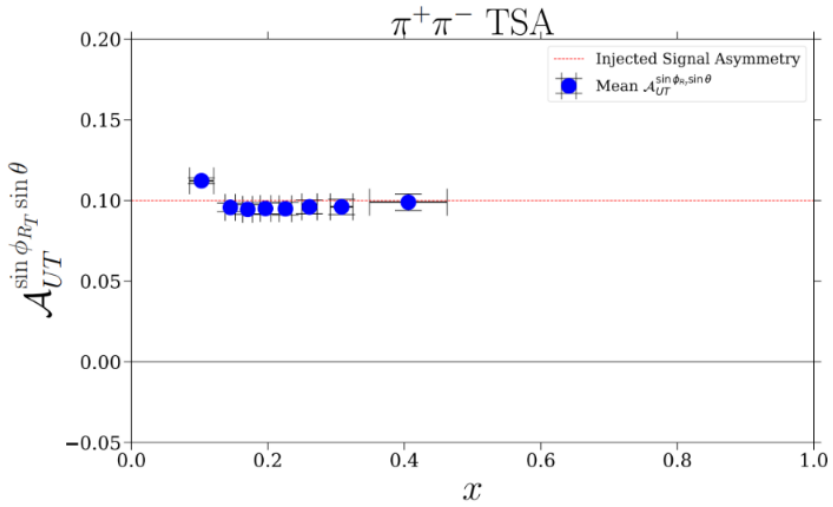
Work by Matthew McEneany

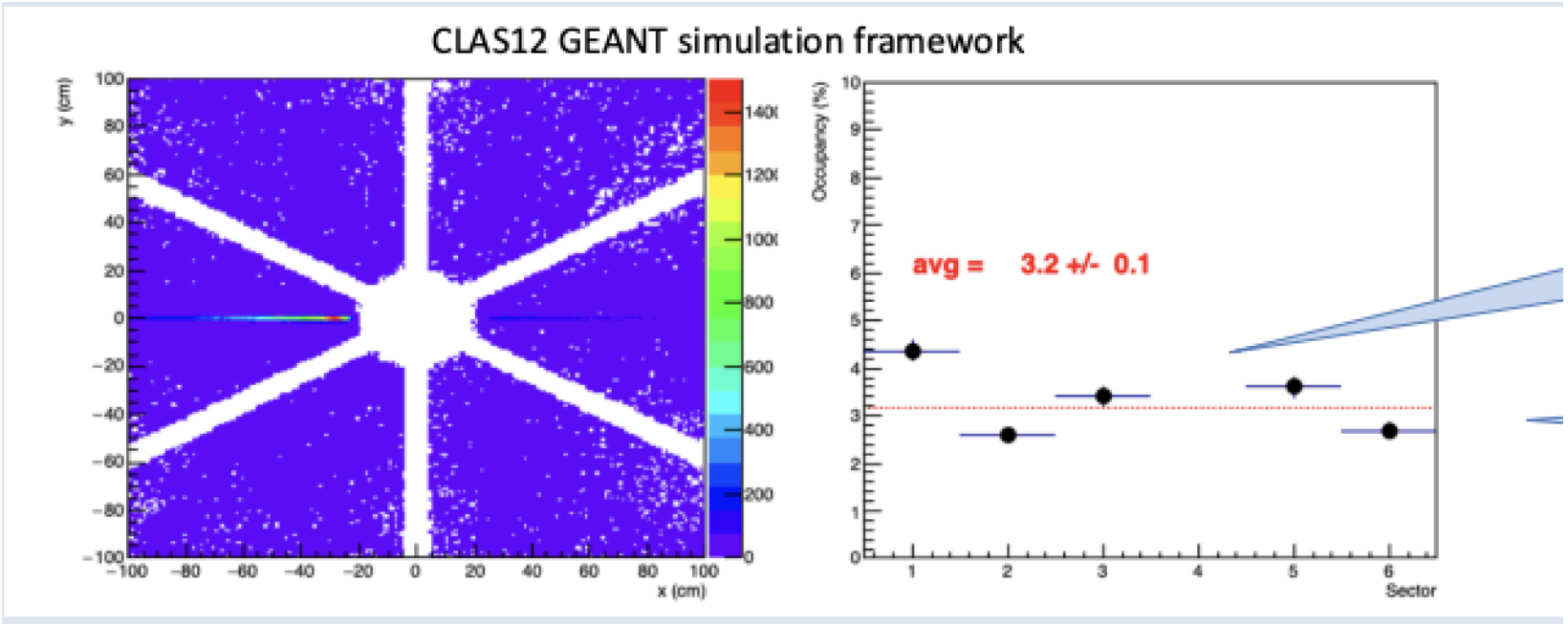


- Scaled up from RGC data using the ratio of RGC/RGH acceptance
- Scaled with assumed conservative luminosity of $\mathrm{L} = 5{\times}10^{33} cm^{-2} s^{-1}$ RGH
- Observation: Shift of data to higher x due to bending in the target field

Sector 4 Acceptance issue

- Sector 4 taken out
- Check that there are no acceptance effects





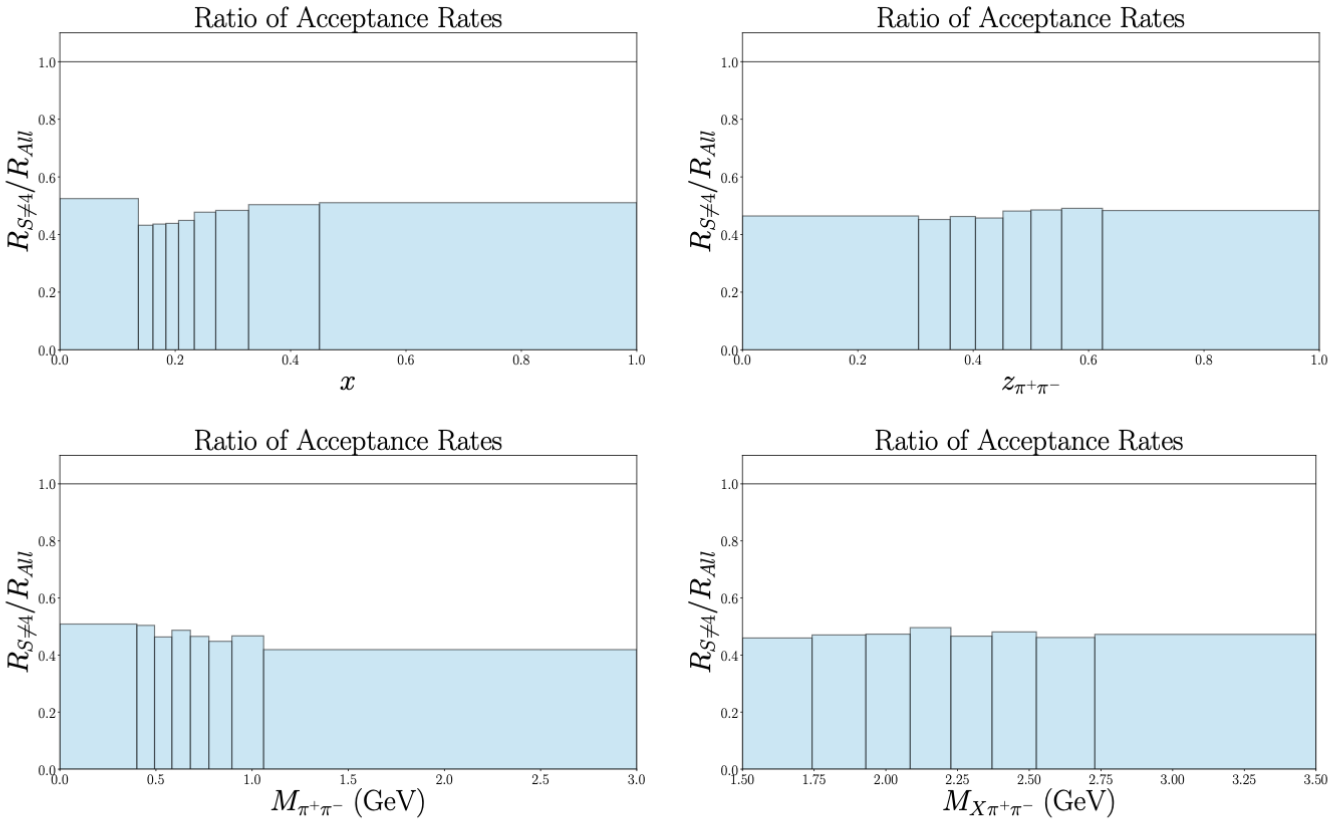


FIGURE 5.9: The ratio of final state acceptance rates with and without the sector 4 cut in the $\pi^+\pi^-$ channel of the RGH MC simulation for all the one-dimensional bin schemes.

- From Matthew's thesis

Systematics

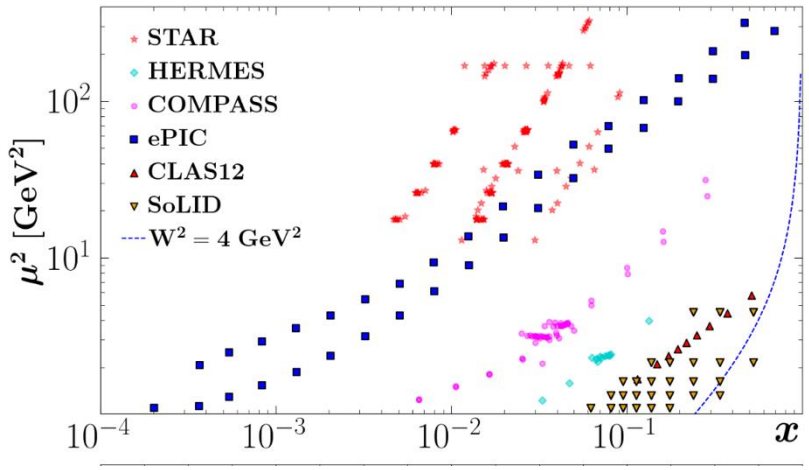
- Based on experience with CLAS12 analyses

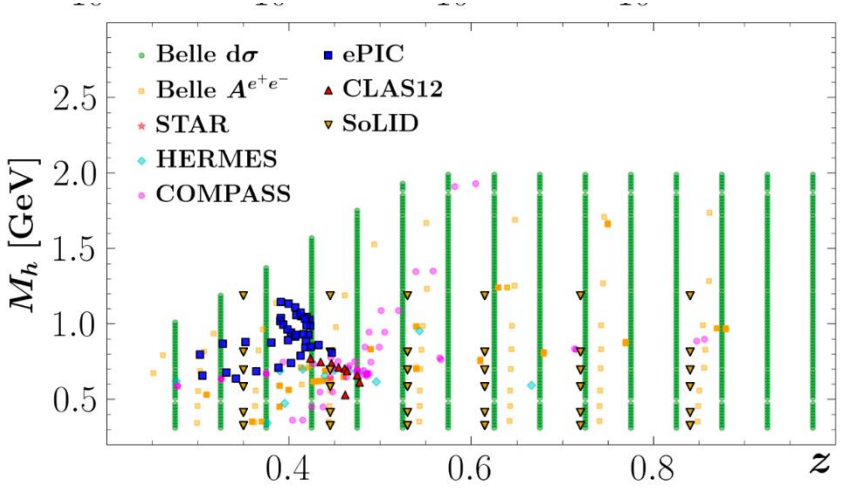
Target polarization	5%
Target dilution	2%
Baryonic contribution from target fragmentation	1–6%
Bin migration close to the ρ mass	1–10%

- For Projections used effective value of 5% point-to-point and 5% scale

Fit using JAMDiff Framework

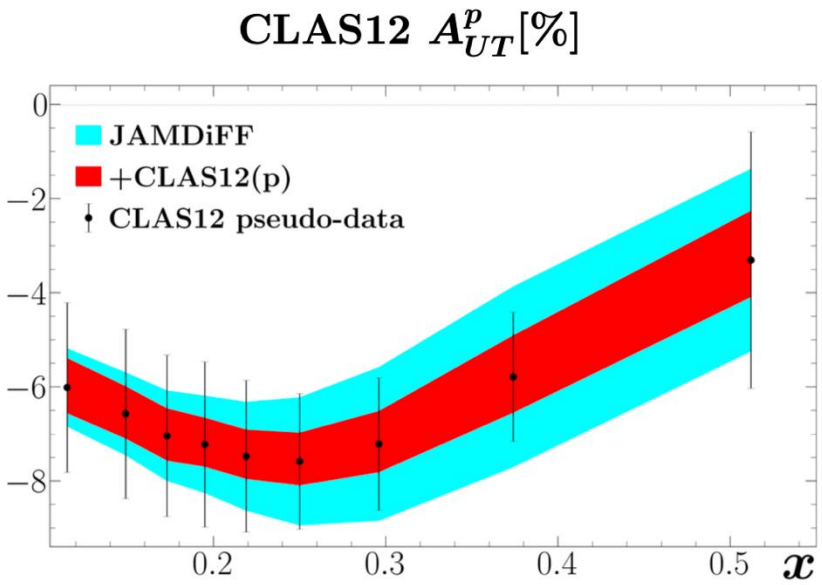
- JamDIFF contains world SIDIS (HERMES, COMPASS), pp (STAR) and e^+e^- (Belle) data
- Unpolarized PDF from JAM





Phys.Rev.D 114 (2026) 7, 074009

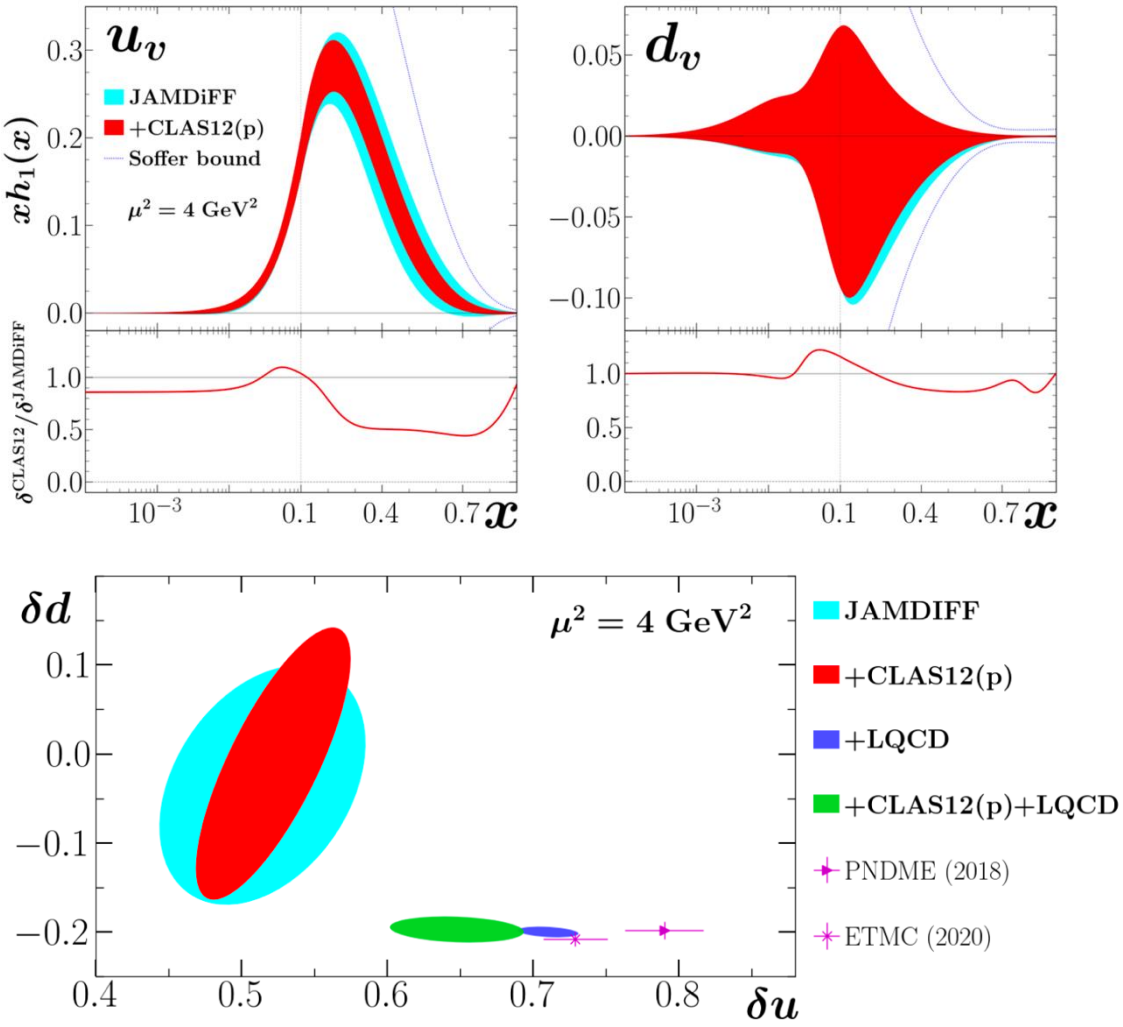
Impact of CLAS Data



- Significant Impact on transversity extraction

Phys.Rev.D 114 (2026) 7, 074009

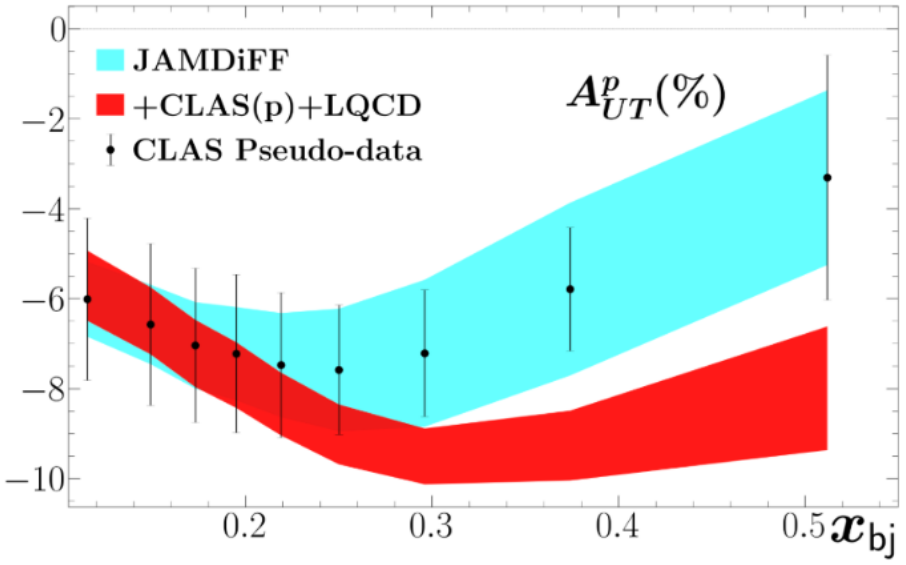
Impact on transversity and Tensor Charge

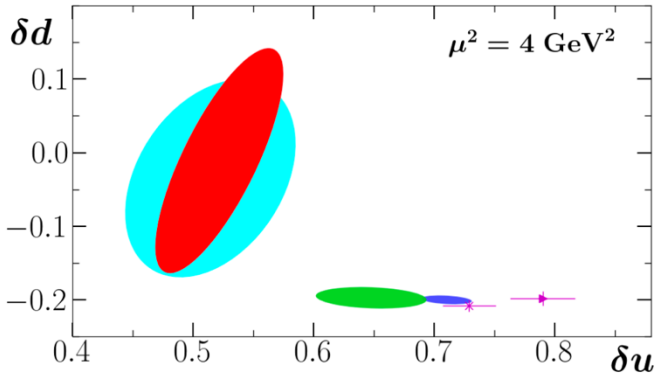


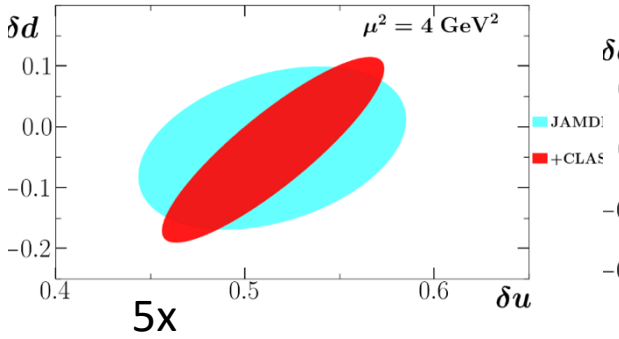
- Indication that CLAS12 data can differentiate between lattice and pheno results
- Including He3 target does not help (statistical impact too low)

Phys.Rev.D 114 (2026) 7, 074009

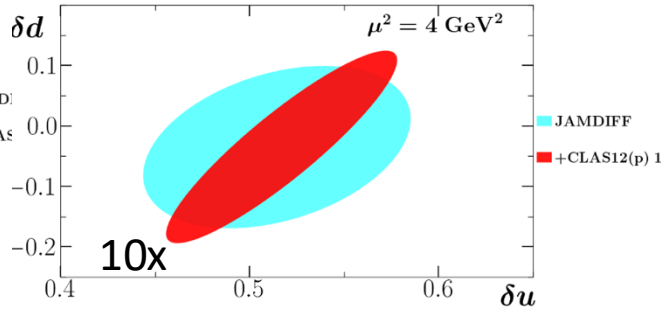
- Transversity w/ w/o lattice





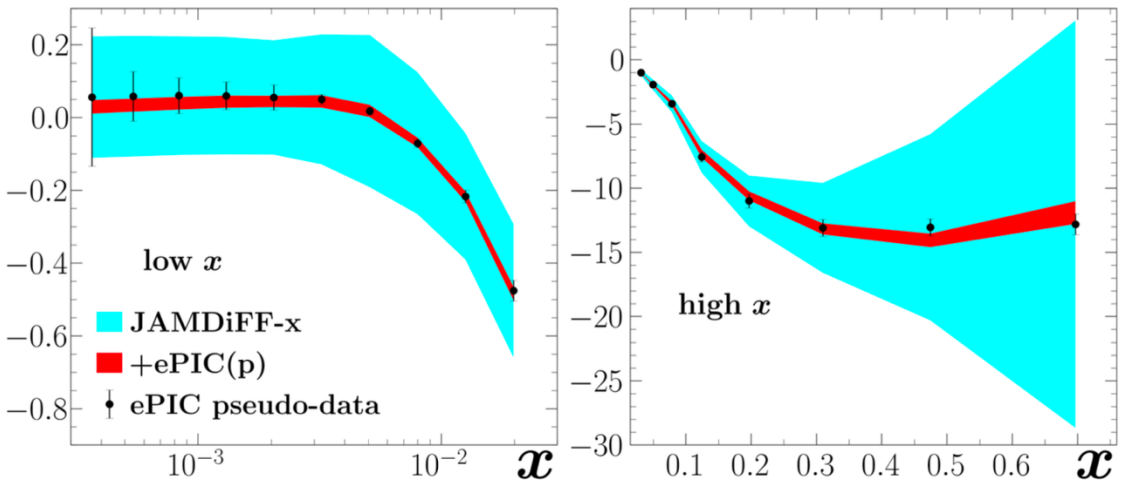


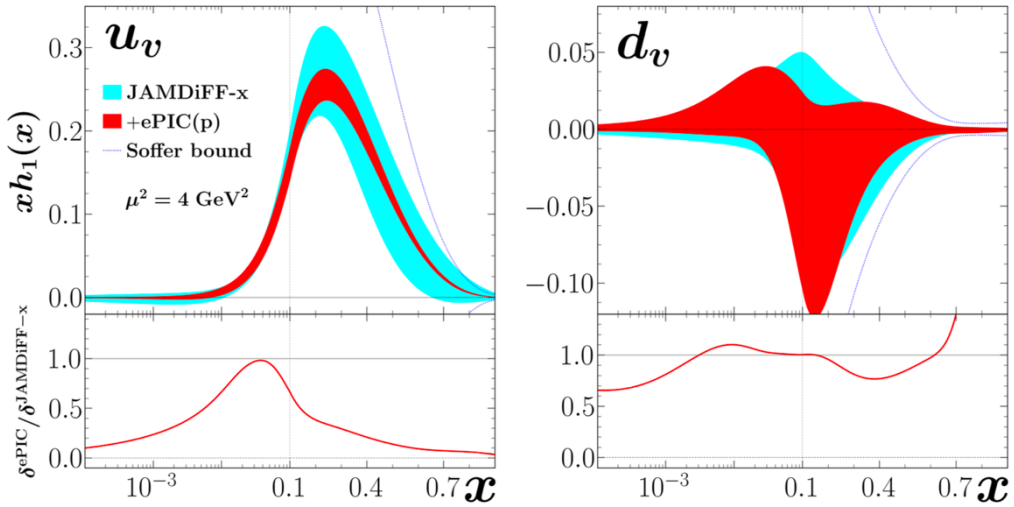
5x



10x

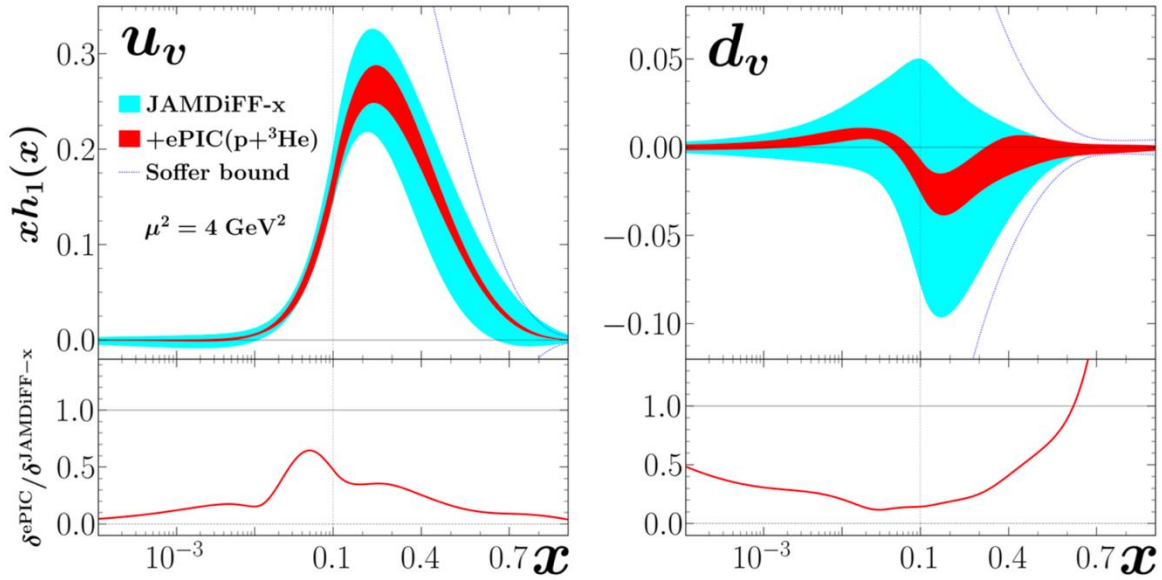
ePIC

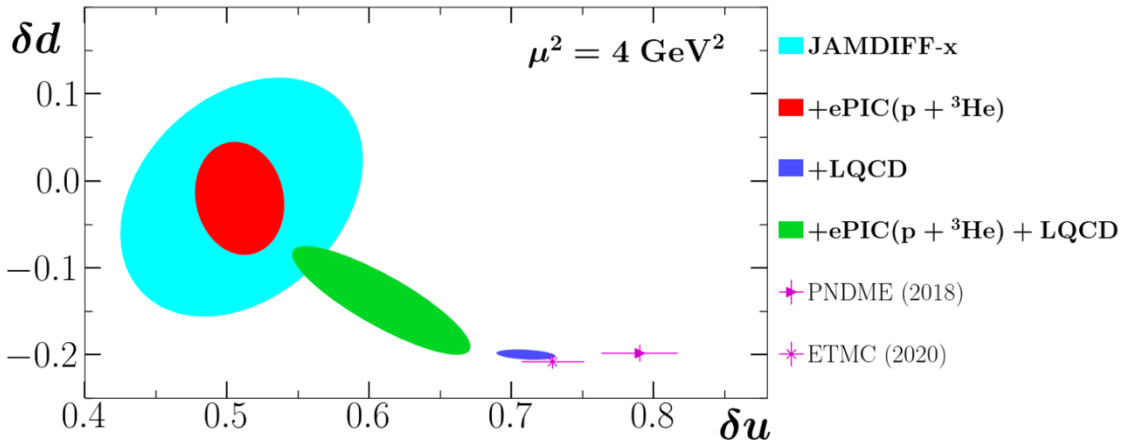




ePIC [?]	10 × 100	p	1D	18	10	2.3	5
	10 × 166	^{3}He	1D	19	8.65	2.3	5

ePIC + He3


u_v
JAMDiFF-x
+ePIC(p+^{3}He)
Soffer bound
$\mu^2 = 4$ GeV^2
$xh_1(x)$
$\delta^{\rm ePIC}/\delta^{\rm JAMDiFF-x}$
d_v
x


δd
δu
$\mu^2 = 4$ GeV^2
JAMDIFF-x
+ePIC(p + ^{3}He)
+LQCD
+ePIC(p + ^{3}He) + LQCD
PNDME (2018)
ETMC (2020)

Conclusion/Outlook

- CLAS12 data will have significant impact on extraction of transversity
- Given uncertain timeline of other experiments (SoLID, ePIC) results are urgently awaited by the theory community
- Additional single hadron channels will allow insight into TMD framework at Jlab energies
- Additional measurements VMs, Partial wave decomposition…

Backup

- $F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_h}\ h_1^q(x,p_T^2)\,H_1^{\perp q}(z,k_T^2)\right],$

- $\mathcal{C}[w\,f\,D] = x\sum_q e_q^2\ \int d^2\,p_T\,d^2k_T\ \delta^{(2)}\left(\vec{p}_T - \vec{k}_T - \frac{\vec{P}_{h\perp}}{z}\right) w\,f^q(x,p_T^2)\,D^q(z,k_T^2),$

- $F_{UT}^{\sin(\phi_R+\phi_S)} = x\sum_q e_q^2\ \ h_1^q(x)\ \frac{|\vec{R}|\ \sin\theta}{M_h}\ \ H_1^{\sphericalangle,q}(z,\cos\theta\,,M_h).$

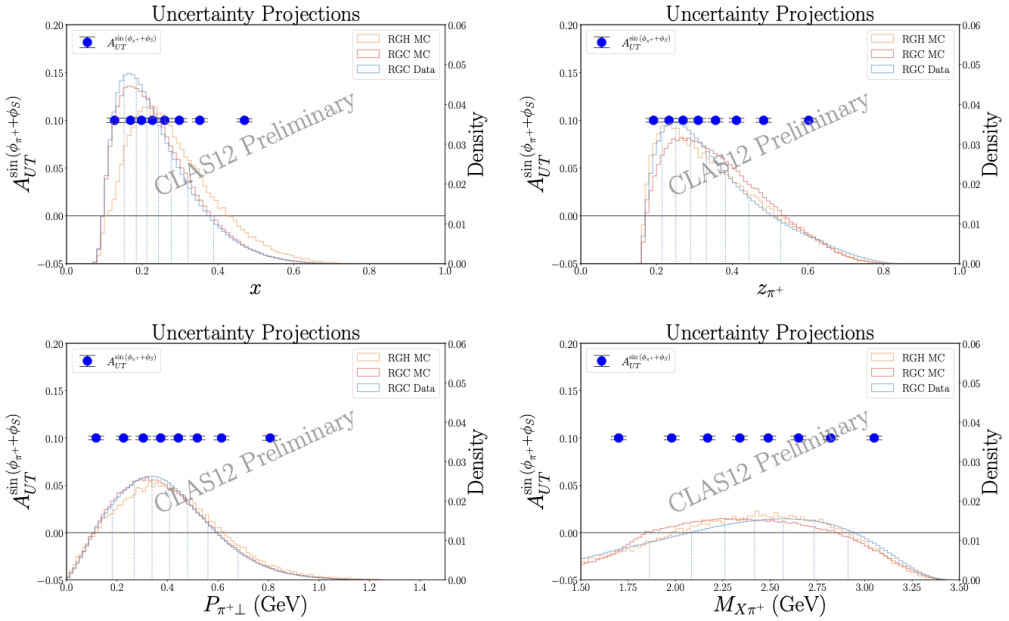


FIGURE 5.10: RGH asymmetry uncertainty projections binned in x, z_{π^+}, $P_{\pi^+\perp}$, and $M_{X\pi^+}$. Note that the y-axis values are held at 0.1 for easy comparison of the projected uncertainties across bins.

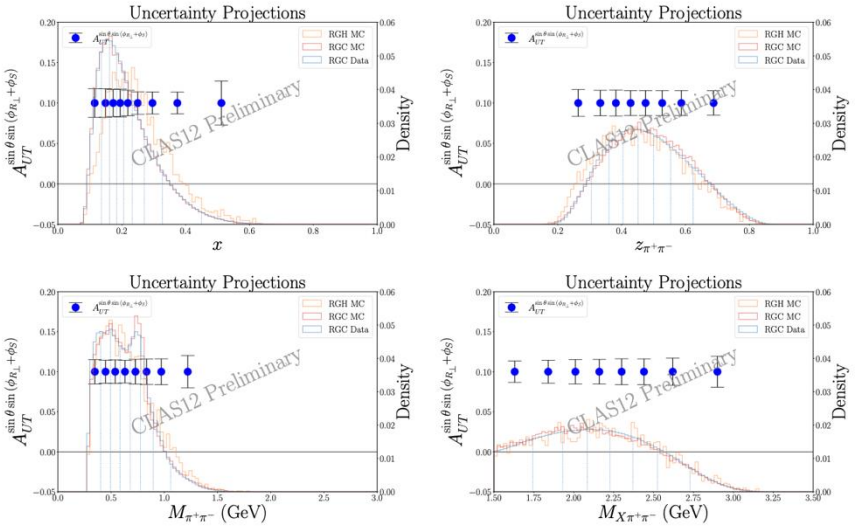
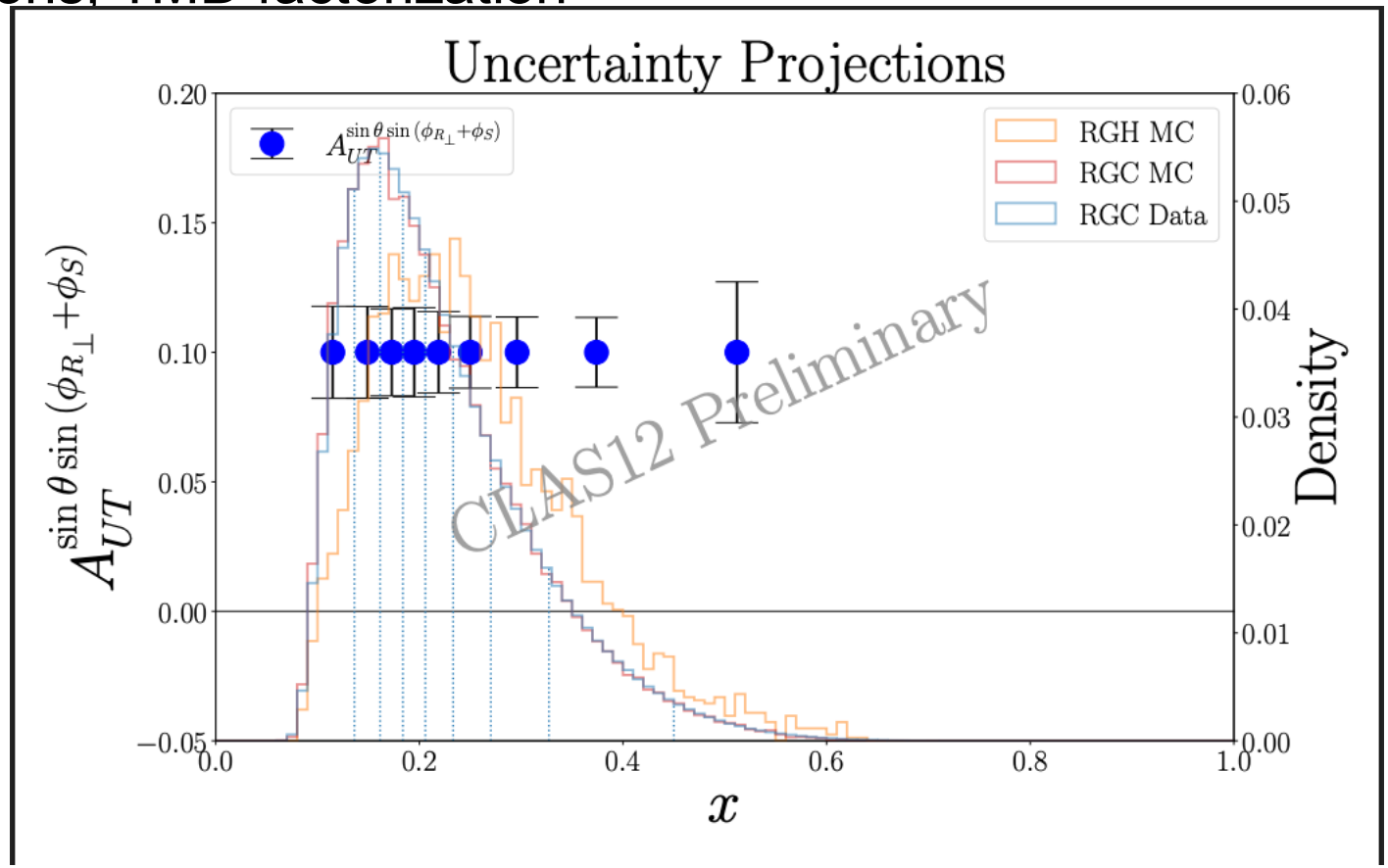


FIGURE 5.12: RGH asymmetry uncertainty projections binned in x, $z_{\pi^+\pi^-}$, $M_{\pi^+\pi^-}$, and $M_{X\pi^+\pi^-}$. Note that the y-axis values are held at 0.1 for easy comparison of the projected uncertainties across bins.

Why Di-hadrons

- Regions, TMD factorization



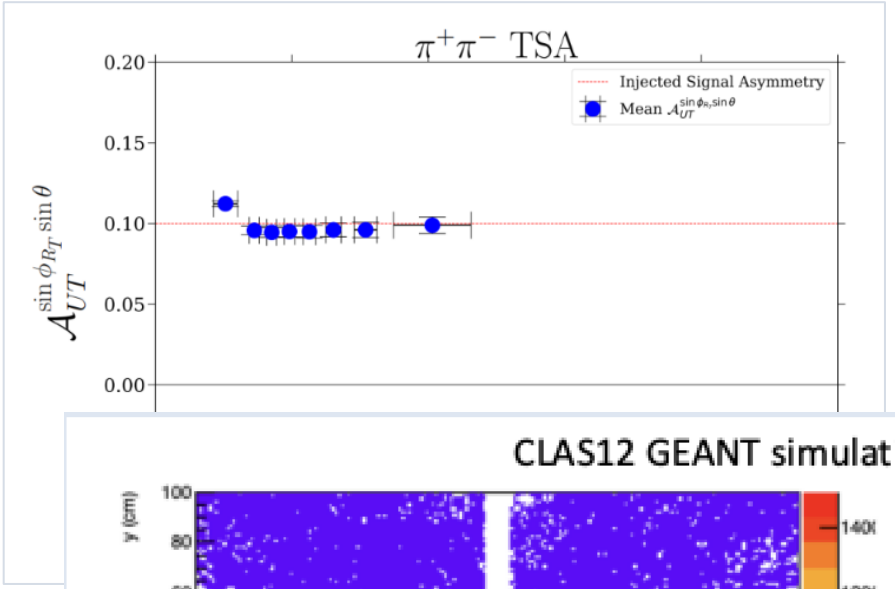
Physics → impact

Dataset	Uncorrelated (point-to-point)	Normalization (correlated)	
CLAS12 RGH ($\pi^+\pi^-$)	5%	5%	
ePIC	5%	2.3%	
SoLID	6.8% (“other”)	3%	

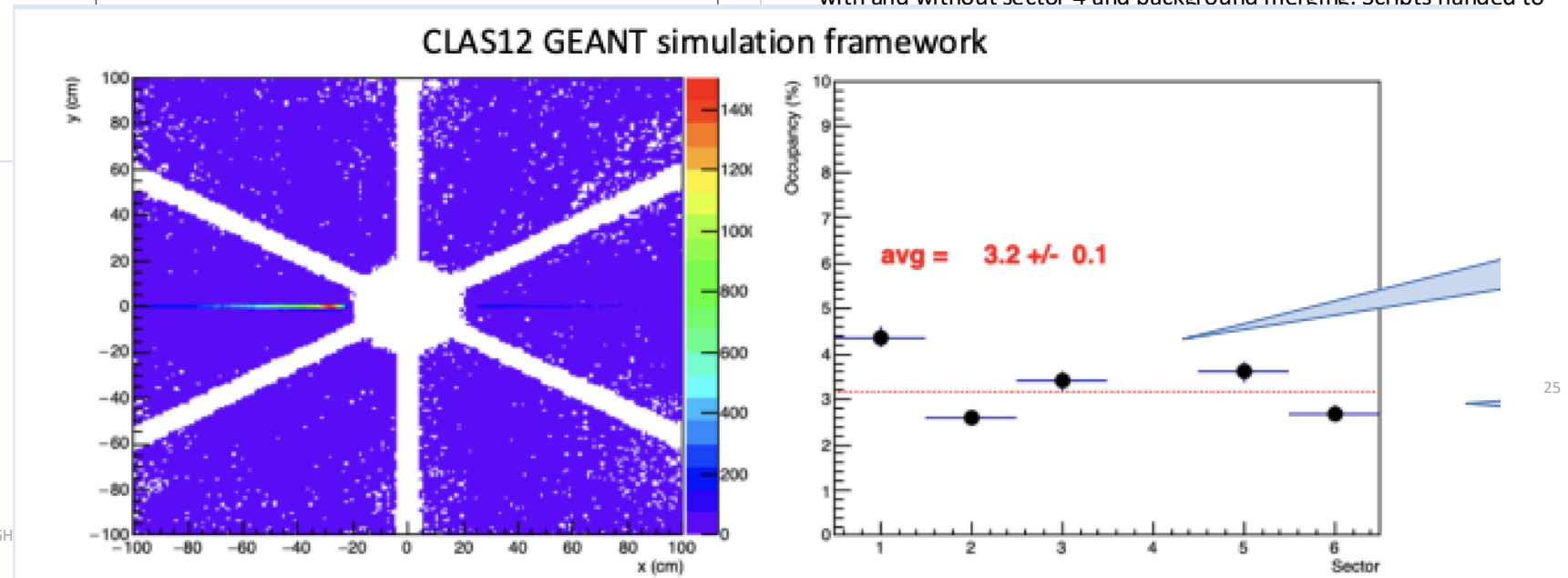
Target polarization	5%
Target dilution	2%
Baryonic contribution from target fragmentation	1–6%
Bin migration close to the ρ mass	1–10%

Comparison to Other Experiments

Sector-4 / acceptance systematics via injection (Feb 2025)



- **PAC request:** a systematic study of the RGH configuration (missing sector 4, reduced maximum angle)
- RGA fall 2018 inbending MC; constant A_inj = 0.1, extracted without sector 4; averaged over 16 random seeds
- CSV columns: bin, x (mean), y = A_extr − A_inj, xerr, yerr, ymin, ymax; binnings in x, z, M_h
- Result in x: extracted values ≈ 0.095–0.10 (slightly below 0.1); lowest-x bin ≈ 0.11
- **Next step (Marco, Apr 2025):** a larger MC to suppress fluctuations, with and without sector 4 and background merging. Scripts handed to



Simulation in brief

10^7

RGH MC events (1000 jobs × 10k), clasdis → gemc → recon-util

$3/17 \cdot 0.85$

NH_3 dilution and target polarization used for all RGH errors

0.015

Latest rough $\pi^+\pi^-$ δA_{UT} per bin (8 bins, no sector 4), Feb 2026

- **Approach:** RGH statistics are not taken from MC directly. RGC fall 2022 NH_3 data are rescaled bin by bin using RGH/RGC MC acceptance ratios and the luminosity × run-time ratio.
- **Errors grew over time:** the theory group used $\delta A_{UT} \approx 0.002$ (Jul 2024), then 0.006 (Nov 2024), then 0.015 (Apr 2025 onward). The changes come from fit-based rescaling, the actual RGC statistics, and the corrected RGH target length.
- **Validated:** Lorenzo Polizzi (Ferrara) reproduced the RGH π^+ x distribution with Matthew's MC files in March 2026.
- **No systematics in the projections:** Yorgo added 5% + 5% from the proposal (Matthew, May 2026).

Generation and reconstruction chain

Job chain (per file)

- **clasdis** (clas12-mcgen 3.13): SIDIS generator
- **gemc** 5.10 with the RGH GCard (an older GCard stopped working with gemc 5.9 in Jul 2024)
- **recon-util** coatjava 11.0.1 (own install; 11.0.4 should work)
- **hipo-utils -filter** to reduce output to DSTs
- One job per file: 36 h limit, 1 CPU, 2 GB per CPU; files capped at 10k events to avoid timeouts
- Disk (2024 sample): LUND 20 GB, gemc 47 GB, cooked 249 GB, DST 25 GB

clasdis settings (clasdis_submit.sh)

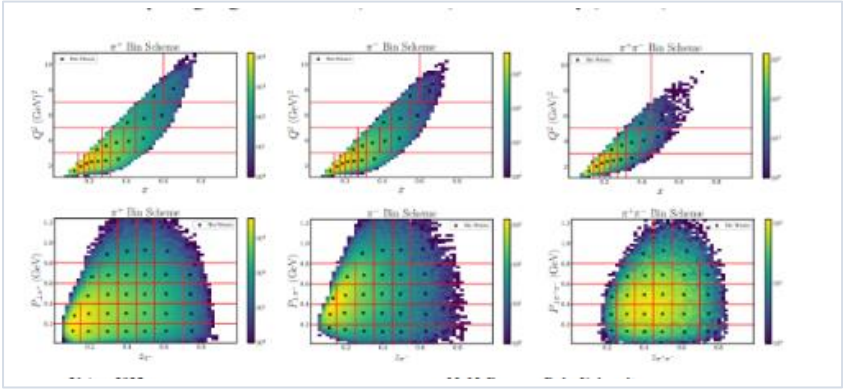
```
--targ proton  --beam 10.6
--zpos 0.0  --zwidth 2.84   # RGH target
--raster 0.02  --parj21 0.5  --nont
--nmax 10000  --trig 5000000 (per pol.)
--pol +1 and --pol -1  (500 jobs each)
```

- **Target fix (Mar 2026):** RGH target centered at z = 0 with zwidth = 2.84 cm. RGC-style zpos/zwidth were wrong for the RGH GCard, which explains Lorenzo's early mismatch.
- **Code:** github.com/mfmceneaney/rgh_simulation (instructions, Apr 2025) and rgh_projections (bin/duke_env.txt, jobs/rgh_simulation/mc_rgh)

RGC → RGH scaling (Apr 2025 slides)

Recipe

- R_RG,MC = N_rec / N_gen per bin, from RGH (clasdis) and RGC fall 2022 MC
- **N_RGH,i = N_RGC,i · (R_RGH,MC,i / R_RGC,MC,i) · (L_RGH / L_RGC)**
- L ratio = (100 d · 5×10^{33}) / (13.2 d · 4×10^{34}), using the RGC inbending NH_3 fall 2022 set (earlier: summer 2022)
- **σ_RGH,i = σ_RGC,i · (P_RGC / P_RGH) · √(N_RGC,i / N_RGH,i)**
- P_RGH = 0.85; the RGC errors already contain 1/P_RGC and dilution 1/(3/17)
- Injected A_UT = 0.1 for the projection plots



4D bin schemes: x–Q^2 (top) and z–P_T (bottom) for π^+, π^-, $\pi^+\pi^-$

- Generated 10^7 events, 79.08 mb total cross-section
- RGH angular acceptance: opening angle < 30° horizontal, < 25° vertical
- Single pion cuts: $Q^2 > 1$, $W > 2$, $y < 0.75$, $P_\pi \in [1.25, 5]$ GeV, $M_X > 1.5$
- $\pi^+\pi^-$ cuts: $Q^2 > 1$, $W > 2$, $y < 0.8$, $x_F > 0$, $M_X > 1.5$

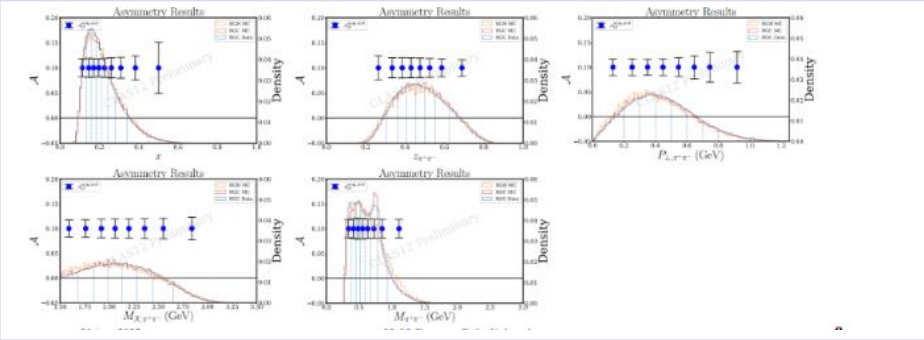
Asymmetry injection and extraction

Injection

Assign helicity h = +1 with P(h=1) = ½[1 + P_t · A(sin ϕ, D(y))], otherwise h = −1. A_UT = 0.1 injected with depolarization D(y) = (1−y)/(1−y+y²/2); modulation sin ϕ_π for π±, sin ϕ_RT sin θ for $\pi^+\pi^-$.

Extraction

Simultaneous unbinned maximum-likelihood fit, PDF = N[1 + h · P_t · A(sin ϕ, D(y))], with sin ϕ and D(y) as independent variables. The Jan 2026 update fits D(y) instead of bin-averaging it.



$\pi^+\pi^-$ 1D projections in x, z, P_T, M_X, M_h (Apr 2025)

- **Known issue:** the ϕ_S term was dropped in injection and in data extraction. Matthew noted in Apr 2025 that this is wrong for data, but it does not affect the statistics.
- **a0 vs a0_err:** a0 is a fitted RGC asymmetry, not the injected 0.1. Marco's check σ = (1/0.85)·1/√(N/32) suggested the a0_err values were too small.

Impact Studies

Other plans

- Sivers, Collins
- IFF flavor dependence
- Partial wave decomposition

EIC/SoLID

Comparison to the EIC