Exclusive Hadron Observables

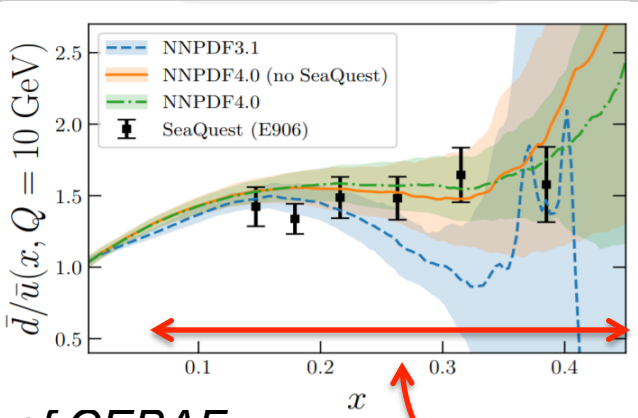
Harut Avakian (JLab)

RGH meeting, Nov 13, 2026

- Exclusive hadron production from longitudinal and transverse photons
- Updating experimental extraction procedures
- Updating the analysis framework
  - •from structure functions→helicity structure functions→helicity amplitudes
  - •from bin-based analysis to event-based analysis
- Critical role of MC simulations(precise exclusive MC most critical for SIDIS and vice versa)
- Summary

Understanding the QCD: from observables to QCD dynamics

Moving from testing QCD to understanding it
→ Detailed studies of non-perturbative QCD dynamics in 3D space through measurements of multiplicities, and spin-azimuthal modulations



JLAB uniqueness:

- *Superior luminosity and high polarization of leptons of CEBAF*
- *High resolutions of detectors*
- *Ability for multidimensional and multiparticle detection for all possible target polarizations in the kinematics where non-perturbative effects are significant*
- *Ability to measure exclusive processes and properly separating contributions from longitudinal photons*
- *Dominant fraction of hard scattering data available at $Q^2<10\ GeV^2$*

All the above makes JLab unique in disentangling the genuine intrinsic transverse structure of hadrons encoded in 3D partonic distributions with **controlled systematics in the kinematics dominated by valence quarks**

- **What upgrades in analysis and hardware needed to achieve goals?**
- **Based on new frameworks evaluate the full set of data needed**

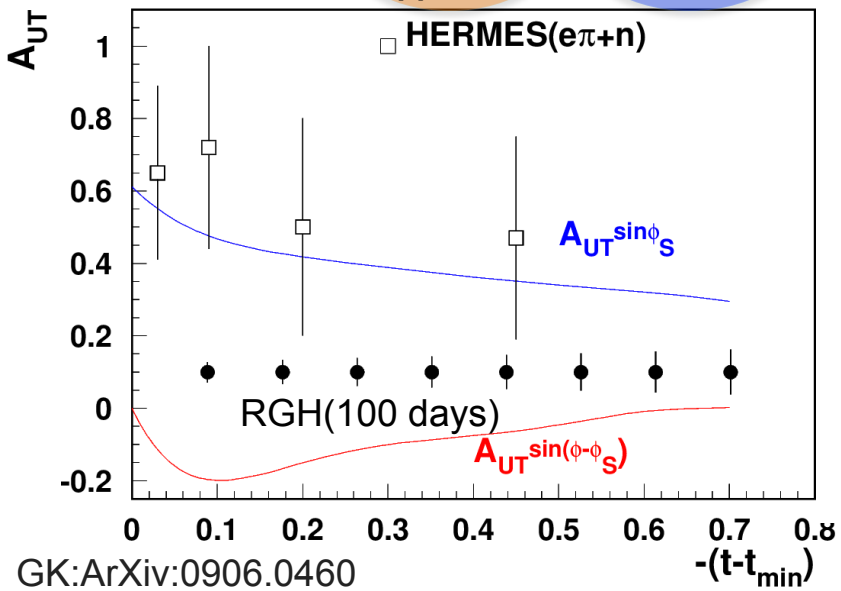
CLAS12 A_{UT}: exclusive hadrons with RGH

Significant transverse asymmetries predicted for exclusive π+

$$A_{UT}^{\sin\phi_s}\,\sigma_0 \simeq \sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\left[\mathcal{M}_{0+,++}\,\frac{\bar{E}_T}{\mathcal{M}_{0-,0+}}\,\frac{\widetilde{E}}{\mathcal{M}_{0-,0+}} - \mathcal{M}^{*}_{0-,++}\,\frac{H_T}{\mathcal{M}_{0+,0+}}\,\frac{\widetilde{H}}{\mathcal{M}_{0+,0+}}\right]$$

$$F_i^u - F_i^d$$

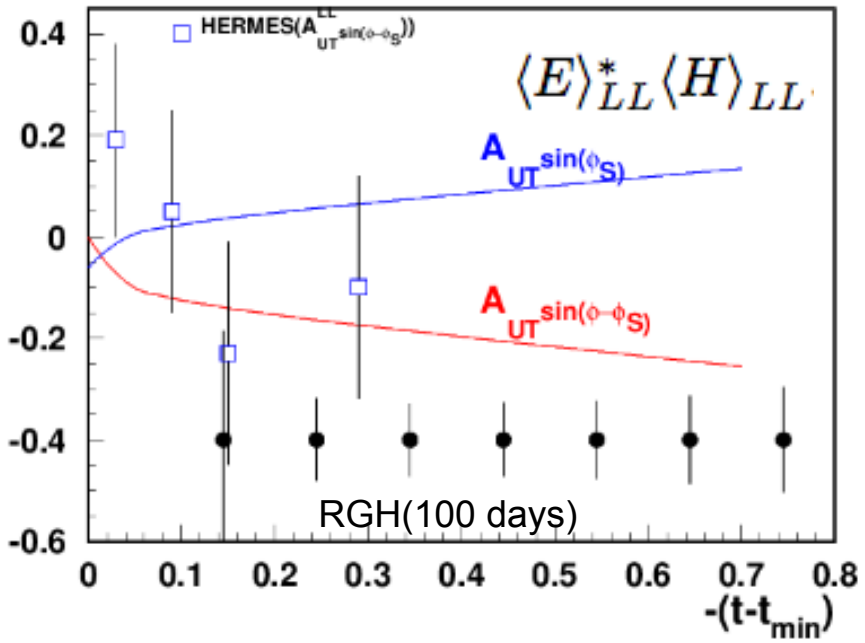
suppressed enhanced



GK:ArXiv:0906.0460

GK:ArXiv:1310.1472

exclusive (ep→e'pρ^0)



Sivers SSA (GPD-E) for exclusive rho predictions from Goloskokov&Kroll

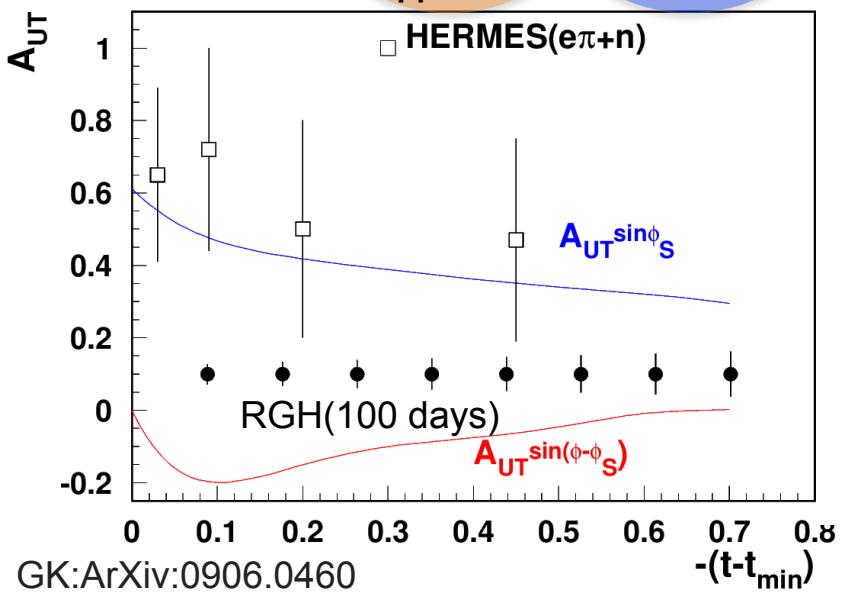
- Exclusive processes help in understanding of longitudinal photon contributions
- CLAS12, best positioned for measurements of exclusive processes, requiring combination of high statistics, good resolution and multiple observables
- A_{UT} for pions, large, and can be used for target polarization (in addition to A_{LT}^{el})

CLAS12 A_{UT}: exclusive hadrons with RGH

Significant transverse asymmetries predicted for exclusive π+

$$A_{UT}^{\sin\phi_s}\,\sigma_0 \simeq \sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\left[\mathcal{M}_{0+,++}\,\frac{\bar{E}_T}{F_i^u - F_i^d}\,\mathcal{M}_{0-,0+} - \mathcal{M}^*_{0-,++}\,\frac{H_T}{F_i^u - F_i^d}\,\mathcal{M}_{0+,0+}\right]$$

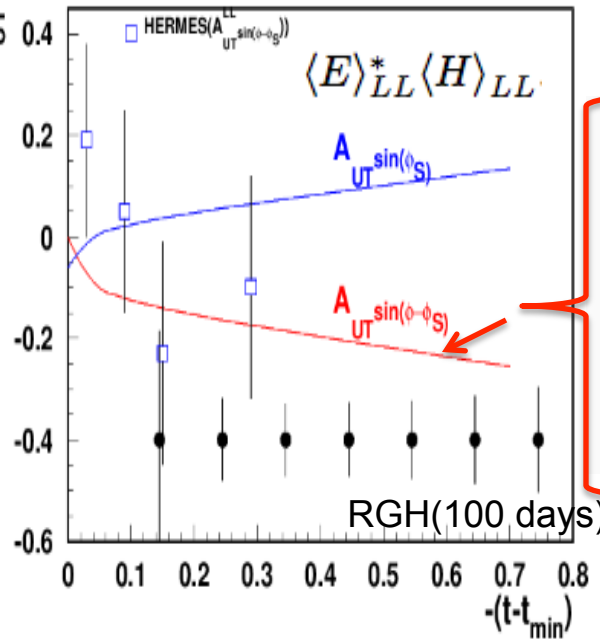
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GK:ArXiv:0906.0460

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exclusive ($ep \to e'p\rho^0$)

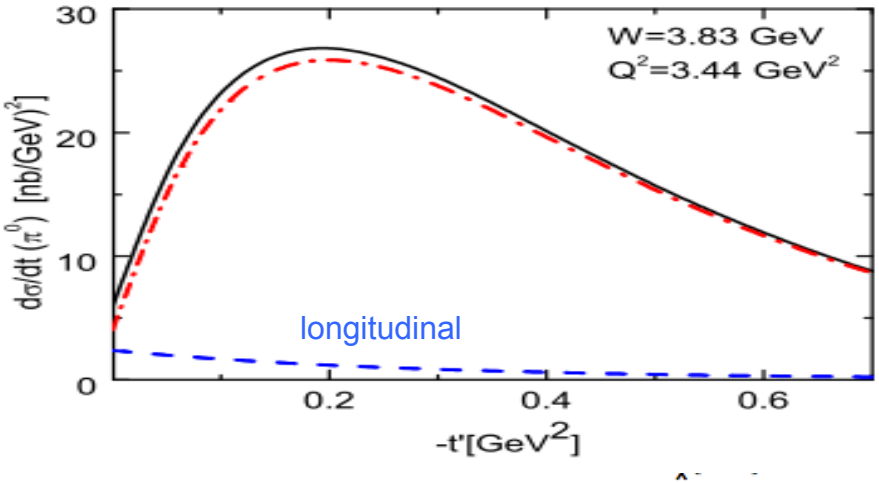


$$N_{TT} = \sigma_{UT}^{TT,\sin(\phi-\phi_S)}$$
$$N_{TL} = \sigma_{UT}^{TL,\sin(\phi-\phi_S)}$$
$$N_{LT} = \sigma_{UT}^{LT,\sin(\phi-\phi_S)}$$
$$N_{LL} = \sigma_{UT}^{LL,\sin(\phi-\phi_S)}$$

Sivers SSA (GPD-E) for exclusive rho predictions from Goloskokov&Kroll

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CLAS12 A_{UT}:exclusive π^0

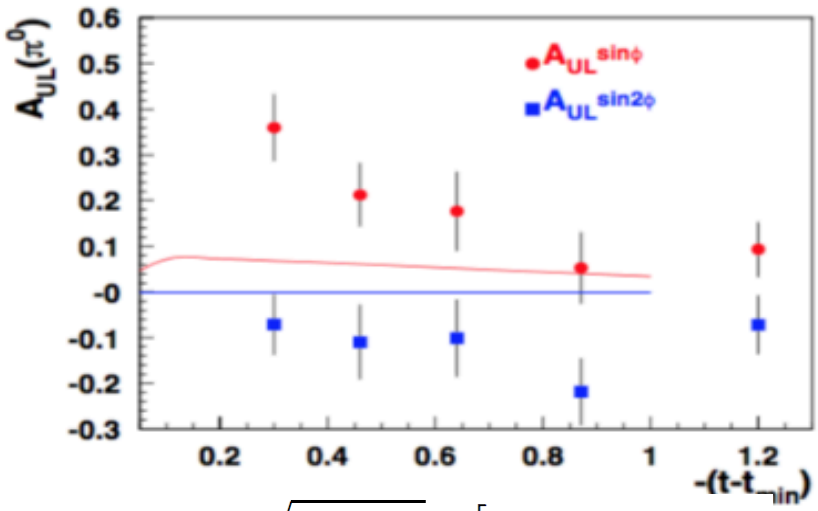


GK:ArXiv:1106.4897

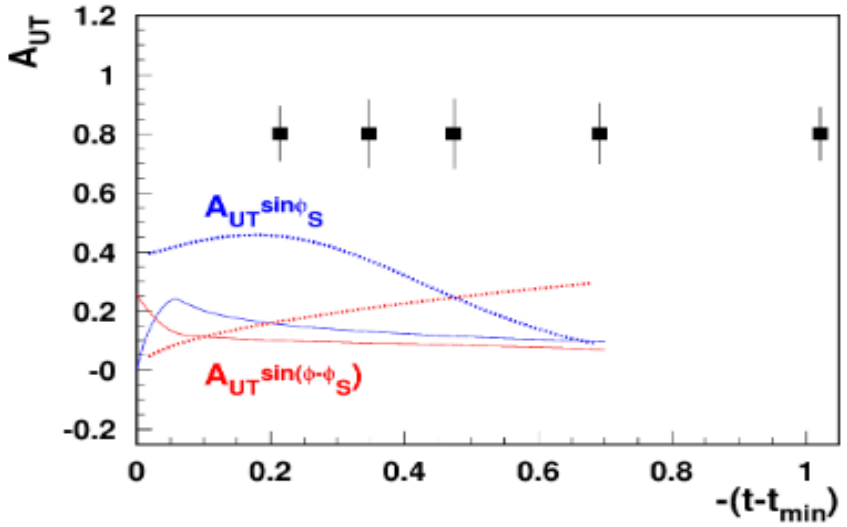
Significant transverse asymmetries predicted for exclusive π0 $(e_u F_i^u - e_d F_i^d)/\sqrt{2}$

$$A_{UT}^{\sin\phi_s}\sigma_0 \simeq \sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\left[\mathcal{M}^*_{0+,++}\,\mathcal{M}_{0-,0+}\,\bar{E}_T\,\tilde{E}_1 - \mathcal{M}^*_{0-,++}\,\mathcal{M}_{0+,0+}\,H_T\,\tilde{H}\right]$$

enhanced suppressed



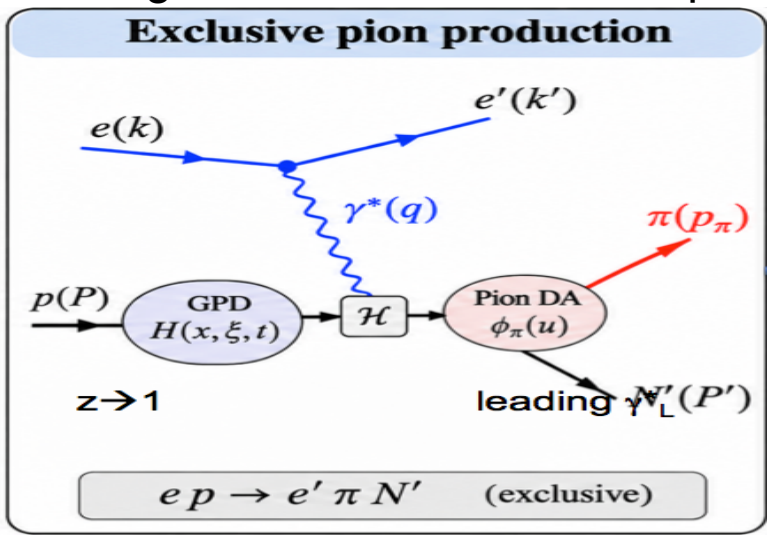
$$A_{UL}\sigma_0 \simeq -\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\left[2\mathcal{M}^*_{0+,++}\,\mathcal{M}_{0+,0+} + \mathcal{M}^*_{0-,++}\,\mathcal{M}_{0-,0+}\right].$$



Sort out large E~ (needed to explain HERMES A_{UL})

Azimuthal moments in Exclusive: Higher Twists

Twist-3 contributions can be comparable to, or even dominate over, leading-twist contributions at experimentally accessible Q^2



Leading Twist DAs

Hadron	$q\bar{q}_L$	$q\bar{q}_T$
π	$\phi_{2;\pi}$	—
V_L	$\phi_\parallel$	—
V_T	—	$\phi_\perp$

Leading Twist GPDs

quark polarization

	q_U	q_L	q_T
N_U	H	—	$\overline{E}_T$
N_L	—	$\widetilde{H}$	$\widetilde{E}_T$
N_T	E	$\widetilde{E}$	H_T, $\widetilde{H}_T$

GK: transverse photons and chiral-odd transversity GPDs

$$\frac{d\sigma_T}{dt} \simeq \frac{1}{2\kappa}\left(|\mathcal{M}_{0-,++}|^2 + 2|\mathcal{M}_{0+,++}|^2\right)$$

$$\mathcal{M}_{0-,++} \sim \frac{\mu_\pi}{Q} H_T \otimes \phi_{3;\pi}$$

$$\mathcal{M}_{0+,++} \sim \frac{\mu_\pi}{Q}\frac{\sqrt{-t'}}{4M} \overline{E}_T \otimes \phi_{3;\pi}$$

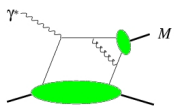
π^0, p, γ^*_T

Higher twist GPDs coupled to leading twist Distribution amplitudes

N \ q	U	L	T
U	$\mathcal{E}_{2T}$	$\mathcal{E}'_{2T}$	$\mathcal{H}_2, \mathcal{H}'_2$
L	$\widetilde{\mathcal{E}}_{2T}$	$\widetilde{\mathcal{E}}'_{2T}$	$\widetilde{\mathcal{H}}_2, \widetilde{\mathcal{H}}'_2$
T	$\mathcal{H}_{2T}, \widetilde{\mathcal{H}}_{2T}$	$\mathcal{H}'_{2T}, \widetilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2, \widetilde{\mathcal{E}}_2, \mathcal{E}'_2, \widetilde{\mathcal{E}}'_2$

Higher twist DAs coupled to leading twist GPDs

Hadron	Longitudinal $q\bar{q}$ (chiral-even)	Transverse $q\bar{q}$ (chiral-odd)
π	—	$\phi^p_{3;\pi}$, $\phi^\sigma_{3;\pi}$
V_L	—	$h^{(t,s)}_\parallel$
V_T	$g^{(v,a)}_\perp$	—



The factorization based framework with HT GPDs is not yet available
Ex. non-flip HT GPD

Modifying experimental extraction

- Develop a framework for exclusive processes based on helicity amplitudes (currently in development for ρ, $\pi 0$ $\pi+$) **and use it in realistic projections for future measurements (RGA,RGK,RGB,RGC,RGN,…)**

- Move from cross sections and multiplicities to spin dependent multiplicities/ cross sections and helicity amplitudes

- Move from bin-based analysis to event-based analysis, combining several data sets

- Separating L/T photon contributions critical for interpretation both for SIDIS and Hard Exclusive
- Develop a realistic MCs for exclusive processes based on helicity amplitudes and extraction frameworks based on helicity amplitudes(currently available for ρ, $\pi 0$ $\pi+$)
- Validation of the output of complex extraction frameworks using realistic MC becomes high priority

Modifying the phenomenology

Use the same formalism for Master Formula for eN → e′hX , for direct extraction of helicity structure functions (HSFs) from data, both for SIDIS and exclusive limit. In exclusive case express cross sections directly in terms of helicity amplitudes, both in extraction framework and MC for validation of results.

Develop a realistic MC using the helicity amplitudes with physics motivated kinematical dependences with subsequent calculations of Helicity Structure Functions, SDMEs and regular SFs
→Realistic SIDIS MC needed for proper evaluation of exclusive backgrounds
→Realistic exclusive MC (VMs, in particular) needed for evaluation of SIDIS backgrounds

Add proper description of exclusive rhos and pions in the polarized PYTHIA, with the latest fragmentation functions from Belle to evaluate the σ_T in the exclusive limit, compare with BKM

Run the full generation, reconstruction, and amplitude extraction chain for different beam energies at JLab and COMPASS, check the L/T ratio extraction with direct Rosenbluth separation, combining JLab and COMPASS data

Push for development of the factorization based description of exclusive processes including the higher twist GPDs and contributions from semi-exclusive processes

One-photon exchange cross sections for eh→e'hX

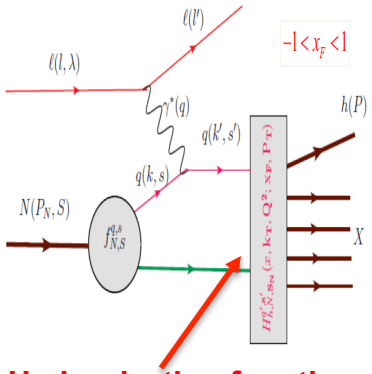
$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP_{h\perp}^2 d\phi_h} = \frac{K(x,y)}{Q^4}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi}\right\}$$

$M_X^2 - M_p^2 > 0$

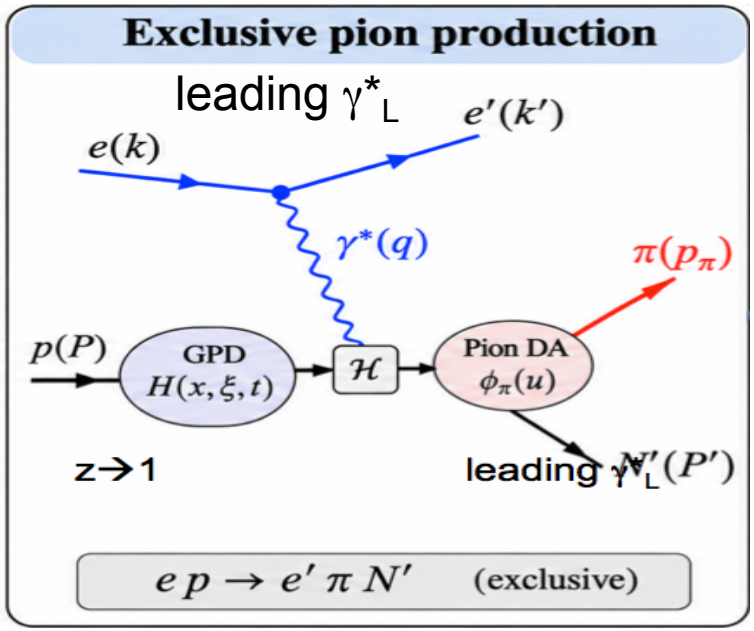
$t = (P-q)^2$

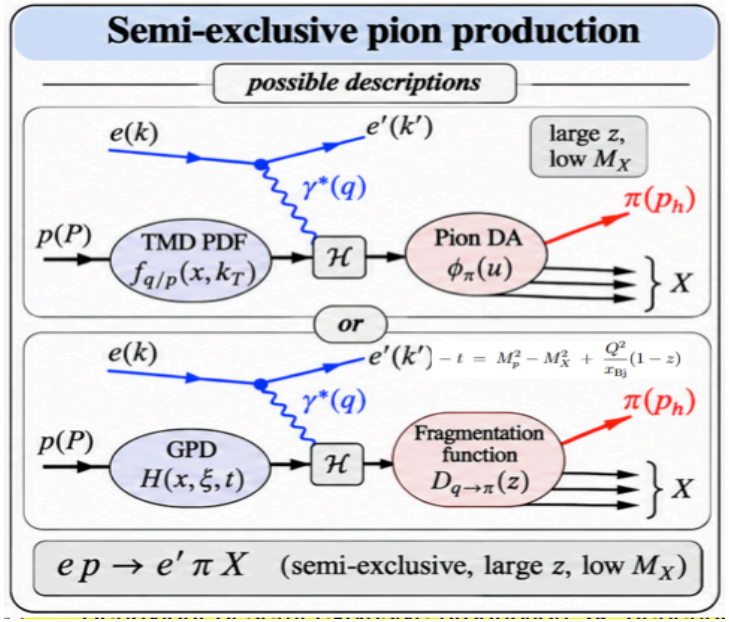
The only difference with exclusive production is the

probability to produce π+



Hadronization function describes the probability to produce a hadron (π,K,…) for a given leftover configuration with spin and flavor content





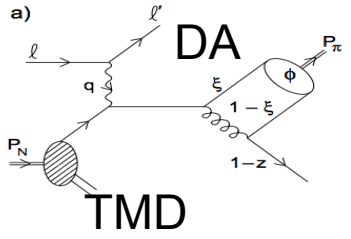
$$-t = M_p^2 - M_X^2 + \frac{Q^2}{x_{\rm Bj}}(1-z)$$

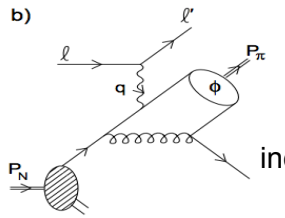
leading γ^*_T z→1 leading γ^*_L

- Full event generators such (ex. PYTHIA based on string fragmentation) are for years describing semi-inclusive production of hadrons in the full energy range, extending to account polarization in exclusive limit will be important both for SIDIS and exclusive !!!)
- Semi-exclusive limit defines "in-coherent" production in exclusive limit
- Behaviour of semi-exclusive production, Q^2-dependence of γ^*_T and γ^*_T contributions practically unknown!!!

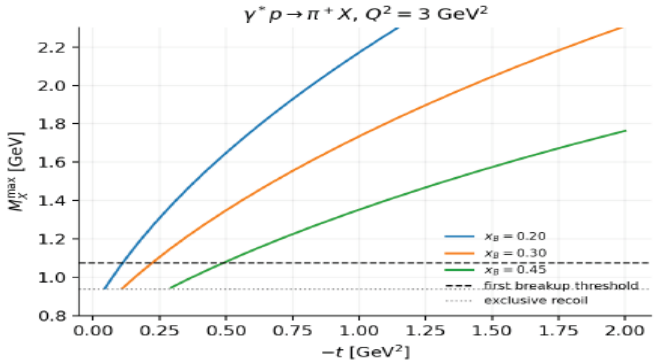
SIDIS cross sections in the z→1 limit

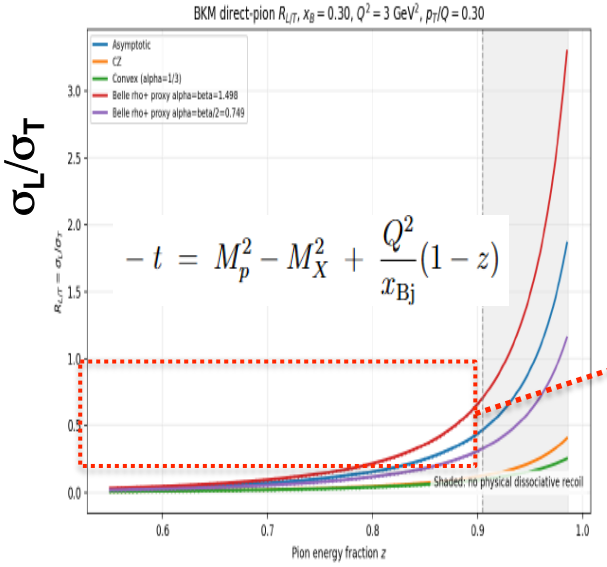
Brandenburg Muller, Khoze (BMK) arXiv: 9410327 semi-exclusive processes (z→1) provide corrections to SIDIS and HEP



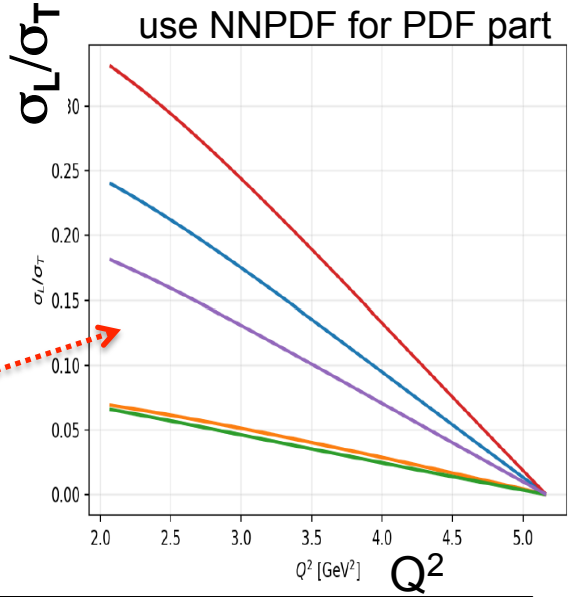


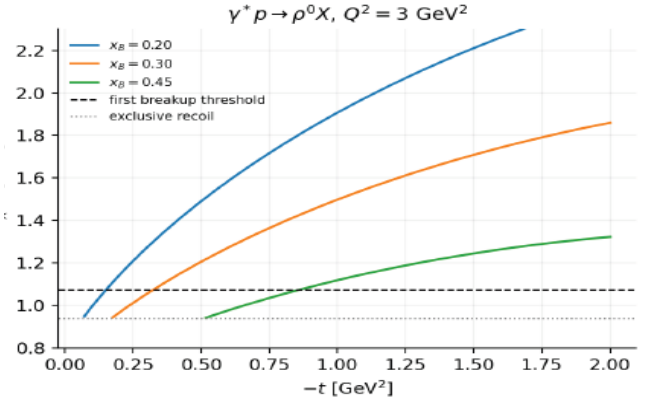
incoherent "exclusive"

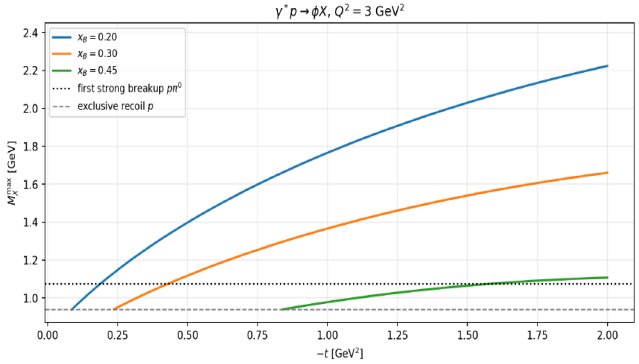




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Possible contribution from γ^*_T may be increasing with Q^2 and decreasing with t !!!

Transverse & Longitudinal photons

Structure function	γ^* helicity	prefactor	low-P_{hT} twist	low-P_{hT} PDF	high-P_{hT} twist	high-P_{hT} order	high-P_{hT} power	JLab	EIC
$F_{UU,T}$	TT	1	2	f_1	2	α_s	$1/P_{hT}^2$	+	+
$F_{UU,L}$	LL	ϵ	4		2	α_s	$1/Q^2$	+	=
$F_{UU}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	h, $f^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	=
$F_{UU}^{\cos 2\phi_h}$	TT	ϵ	2	$h_1^\perp$	2	α_s	$1/Q^2$ [*]	+	+
$F_{LU}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	e, $g^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	−
$F_{UL}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	h_L, $f_L^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	=
$F_{UL}^{\sin 2\phi_h}$	TT	ϵ	2	$h_{1L}^\perp$	2	α_s^2	$1/Q^2$ [*]	+	=
F_{LL}	TT	$\sqrt{1-\epsilon^2}$		g_1	2	α_s	$1/P_{hT}^2$	+	=
$F_{LL}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	e_L, $g_L^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	−
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	TT	1	2	$f_{1T}^\perp$	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	LL	ϵ	4		3	α_s	$1/(Q^2P_{hT})$	+	−
$F_{UT}^{\sin(\phi_h+\phi_S)}$	TT	ϵ	2	h_1	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT}^{\sin(3\phi_h-\phi_S)}$	TT	ϵ	2	$h_{1T}^\perp$	3	α_s	$1/(Q^2P_{hT})$ [*]	=	−
$F_{UT}^{\sin\phi_S}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	f_T, h_T, $h_T^\perp$+ tw. 2	3	α_s	$1/(QP_{hT}^2)$	+	=
$F_{UT}^{\sin(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T^\perp$, h_T, $h_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(\phi_h-\phi_S)}$	TT	$\sqrt{1-\epsilon^2}$	2	g_{1T}	3	α_s	$1/P_{hT}^3$	+	=
$F_{LT}^{\cos\phi_S}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	g_T, e_T, $e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T^\perp$, e_T, $e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−

Need a similar table for exclusive Helicity Structure Functions!!!

Bacchetta-0611265

$$-t = M_p^2 - M_X^2 + \frac{Q^2}{x_{\rm Bj}}(1-z)$$

$$P_T^2(t) \simeq -(1-x_B)t = (1-x_B)|t|$$

Important features to notice

- No L in Double Spin 0 moment
- Some critical observables (cross sections, $\sin(\phi-\phi_S)$ containl contributions from TT/LL and can't be separated easily
- Several TT terms, may provide info on T-amplitudes
- P_{hT} and k_T critical for understanding of transverse x-sections

SIDIS/HEP formalisms: from SF→HSH(Helicity SFs)

Longitudinal beam and target (Bacchetta et al: 0611256)

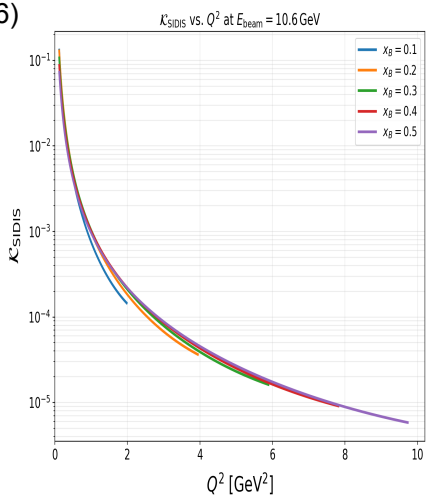
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_h^2} = \mathcal{K}_{\rm SIDIS}$$

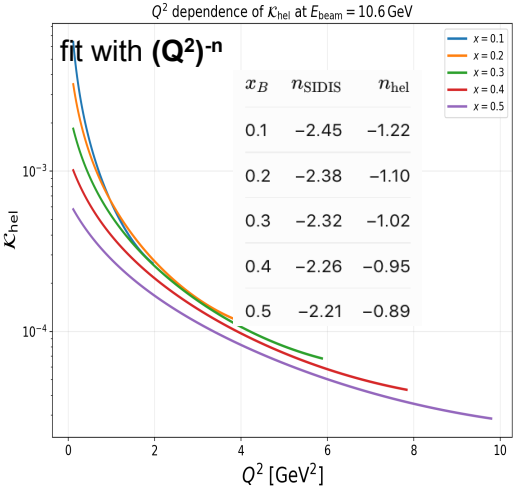
$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h}$$

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

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

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





note: kinematic factors not exactly $1/Q^4$ and $1/Q^2$

Shortcut version

$$\frac{{\rm d}\sigma_{\rm SIDIS}}{{\rm d}x\,{\rm d}y\,{\rm d}\psi\,{\rm d}z\,{\rm d}\phi_h\,{\rm d}P_{h\perp}^2} = \mathcal{K}_{\rm hel}\sum_{XY}\mathcal{W}_{XY}[\mathscr{F}[H]].$$

$$T_{\mu\lambda}^{\nu\sigma}(W,Q^2,t), \quad \mu,\nu\in\{-1,0,+1\}, \quad \lambda,\sigma\in\{-\tfrac{1}{2},+\tfrac{1}{2}\}$$

HSFs→ linear combinations of SFs

Exclusive→ $\gamma^*(\mu)+p(\lambda)\to V(\nu)+p'(\sigma)$.

$$\frac{{\rm d}\sigma^{\rm excl}}{{\rm d}x\,{\rm d}y\,{\rm d}\psi\,{\rm d}t\,{\rm d}\phi_h} = \mathcal{K}_{\rm hel}\sum_{XY}\mathcal{W}_{XY}[\mathscr{F}]$$

$$\mathcal{K}_{\rm hel} \equiv \frac{\alpha y(1-x)}{8\pi^3 x(1-\epsilon)}$$

sum over final states

$$\mathscr{F}_{UU,T} = \tfrac{1}{2}(\mathcal{H}_{++}^{++}+\mathcal{H}_{++}^{--}) = \frac{\mathcal{C}}{2}\sum_{\nu=-1}^{1}\sum_{\sigma=\pm\frac{1}{2}}\left(|T_{++}^{\nu\sigma}|^2+|T_{+-}^{\nu\sigma}|^2\right)$$

γ^*_T γ^*_T p

$$\mathscr{F}_{UU,L} = \mathcal{H}_{00}^{++} = \mathcal{C}\sum_{\nu=-1}\sum_{\sigma=\pm\frac{1}{2}}|T_{0+}^{\nu\sigma}|^2,$$

- Interconnection of observables more relevant in exclusive limit, where they connect directly to helicity amplitudes
- In deeper dive into partonic structure more correlations will show up

HEP: from HSF→Helicity amplitudes

$$\gamma^*(\mu) + p(\lambda) \to V(\nu) + p'(\sigma). \quad \rightarrow \quad \boxed{T^{\nu\sigma}_{\mu\lambda}(W, Q^2, t)}, \quad \mu, \nu \in \{-1, 0, +1\}, \quad \lambda, \sigma \in \{-\tfrac{1}{2}, +\tfrac{1}{2}\}$$

$$\frac{\mathrm{d}\sigma^{\mathrm{excl}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}t\,\mathrm{d}\phi_h} = \mathcal{K}_{\mathrm{hel}} \sum_{XY} \mathcal{W}_{XY}[\mathscr{F}]$$

$$\mathscr{F}_{UU,T} = \tfrac{1}{2}(\mathcal{H}^{++}_{++} + \mathcal{H}^{--}_{++}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{++}|^2 + |T^{\nu\sigma}_{+-}|^2\right)$$

$$\mathscr{F}_{UU,L} = \mathcal{H}^{++}_{00} = \mathcal{C} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} |T^{\nu\sigma}_{0+}|^2,$$

Sivers type contributions for Transverse Target

$$\mathscr{F}^{\sin(\phi_h-\phi_S)}_{UT,T} = -\,\mathrm{Im}\,\mathcal{H}^{+-}_{++} = -\mathcal{C}\,\mathrm{Im} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{+-} (T^{\nu\sigma}_{++})^*,$$

$$\epsilon\, \mathscr{F}^{\sin(\phi_h-\phi_S)}_{UT,L} = -\,\mathrm{Im}\,\mathcal{H}^{+-}_{00} = -\mathcal{C}\,\mathrm{Im} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{0+})^*,$$

$$\sqrt{2\epsilon(1+\epsilon)}\, \mathscr{F}^{\sin\phi_S}_{UT} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}\,\mathcal{H}^{+-}_{+0} = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{++})^*$$

$$\mathscr{F}^{\cos\phi_h}_{UU} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathcal{H}^{++}_{+0} + \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Re} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} [T^{\nu\sigma}_{0+} (T^{\nu\sigma}_{++})^* + T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{+-})^*]$$

$$\mathscr{F}^{\cos\phi_h}_{LL} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathcal{H}^{++}_{+0} - \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Re} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} [T^{\nu\sigma}_{0+} (T^{\nu\sigma}_{++})^* - T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{+-})^*]$$

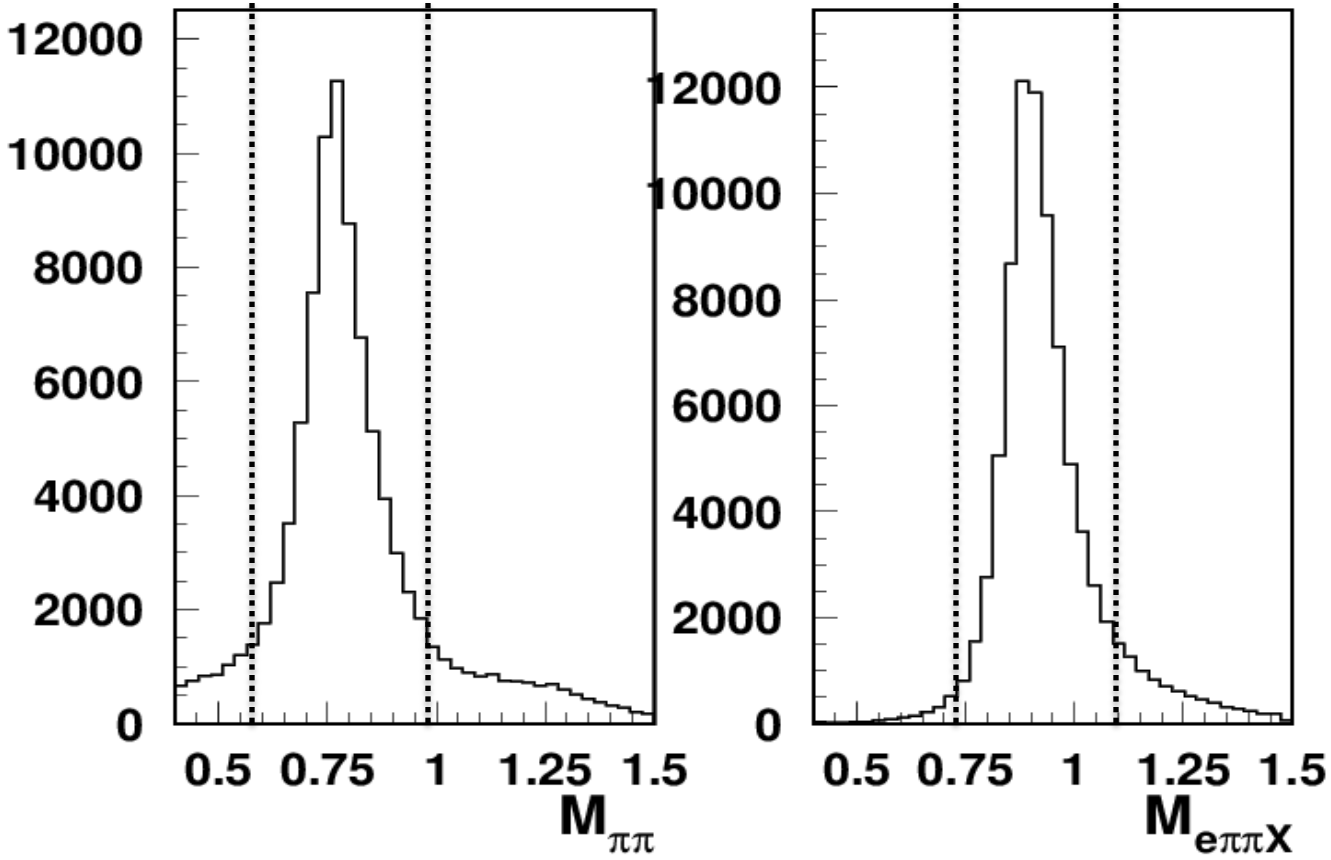
$$\sqrt{2\epsilon(1-\epsilon)}\, \mathscr{F}^{\sin\phi_h}_{LU} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+0} + \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} [T^{\nu\sigma}_{0+} (T^{\nu\sigma}_{++})^* + T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{+-})^*]$$

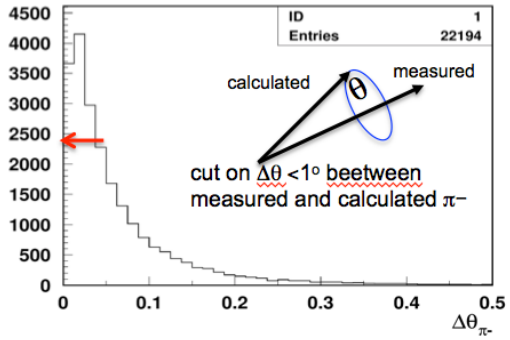
$$\mathscr{F}^{\sin\phi_h}_{UL} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+0} - \mathcal{H}^{--}_{+0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} [T^{\nu\sigma}_{0+} (T^{\nu\sigma}_{++})^* - T^{\nu\sigma}_{0-} (T^{\nu\sigma}_{+-})^*]$$

- Interconnection of observables more relevant in exclusive limit, where they connect directly to same helicity amplitudes
- Observables with transverse target provide independent access to proton helicity flip amplitudes

Backgrounds: CLAS12 RGA 10.6 GeV

Background to exclusive rho mainly includes other exclusive 2 pion samples and not exclusive rhos (<10%, to be finalized with proper account of BW tails)
Detection of all 4 final state particles allows introduction of strict cuts (Q^2>1,W>2)

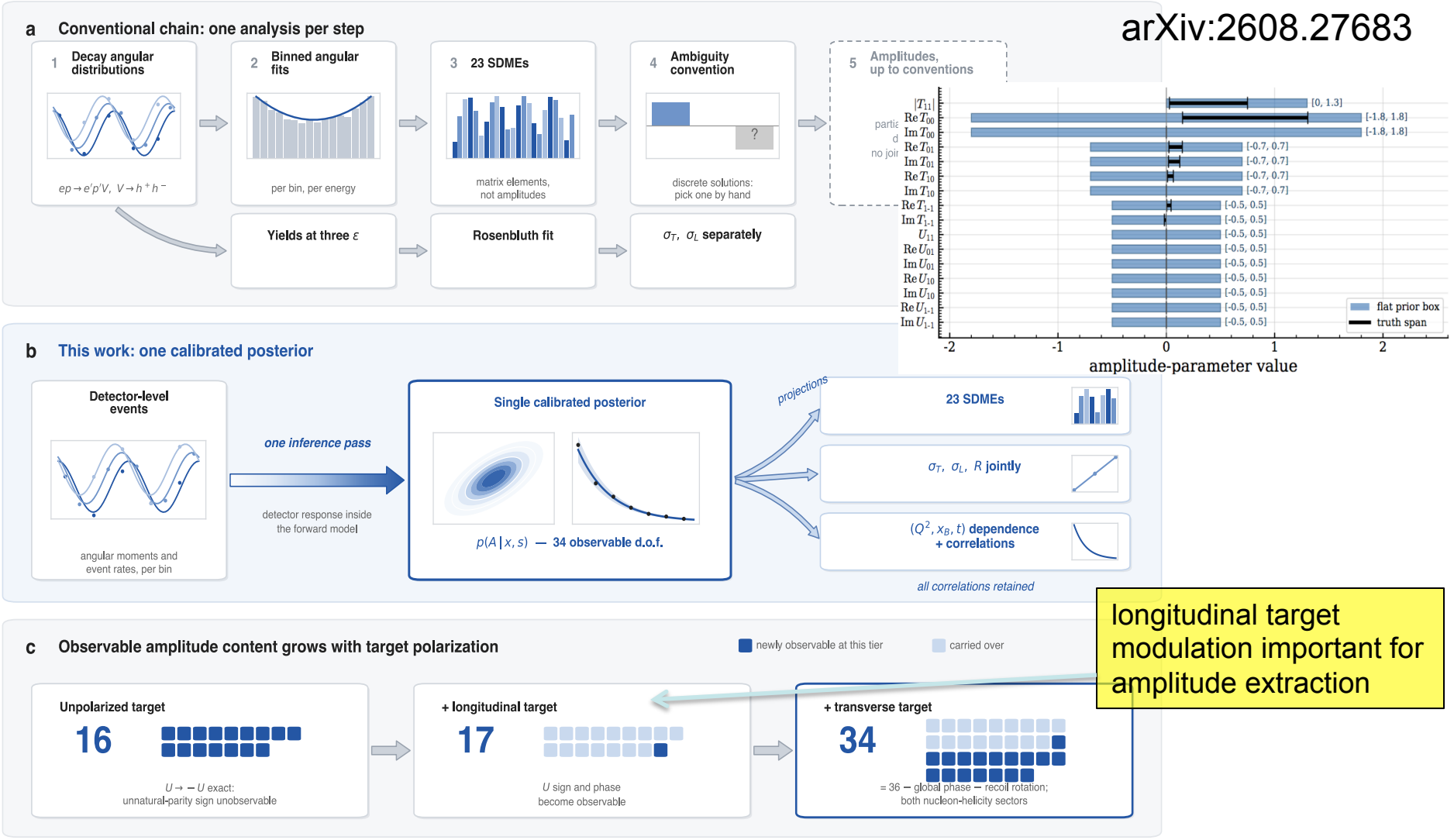




Contributions from other 2pi exclusive states could be evaluated using dedicated MC

Direct Bayesian Inference of Helicity Amplitudes from Detector-Level Data

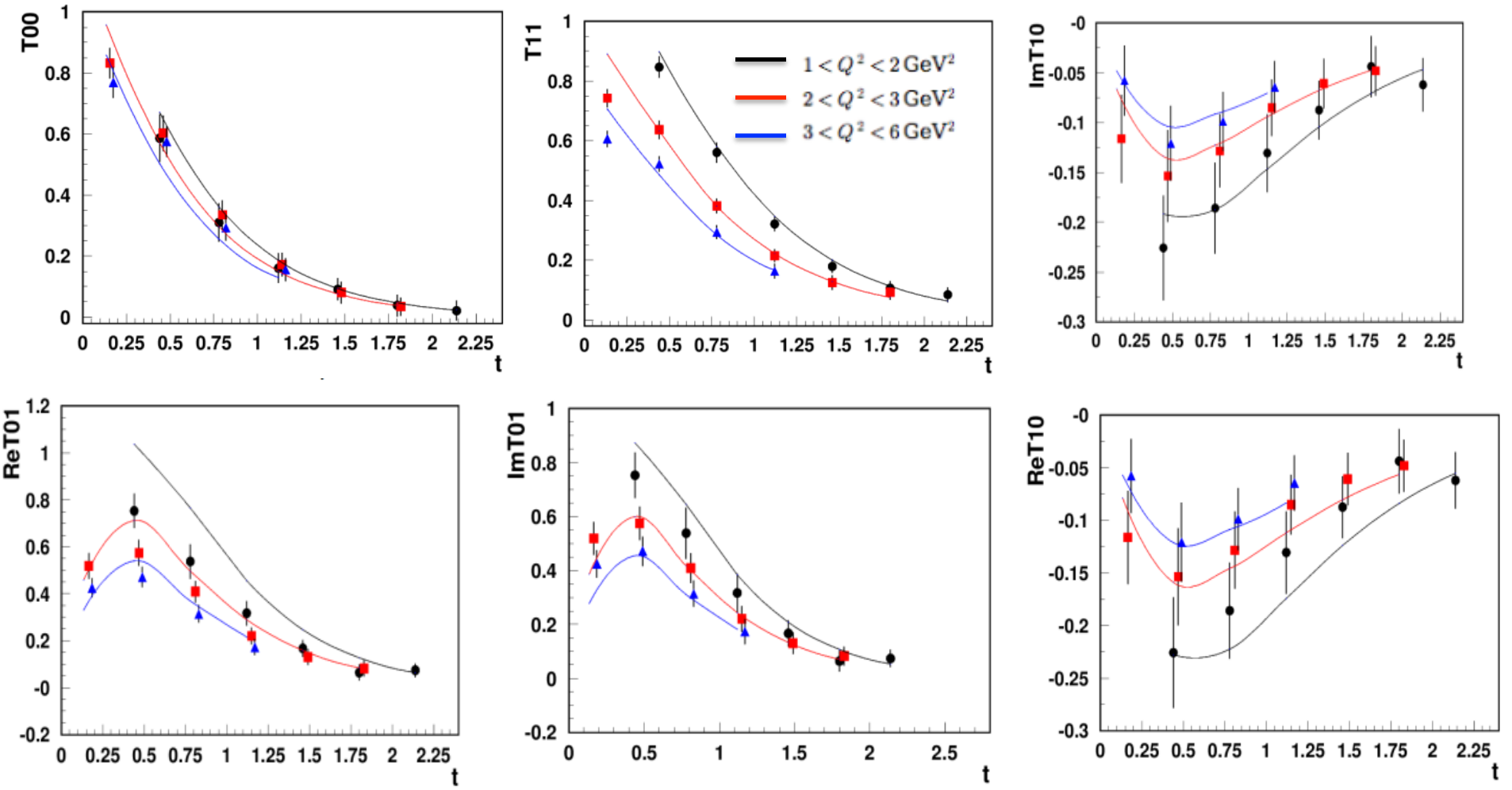
arXiv:2608.27683



longitudinal target modulation important for amplitude extraction

set of amplitudes (A) set of conditions with min/max of amplitudes (s)

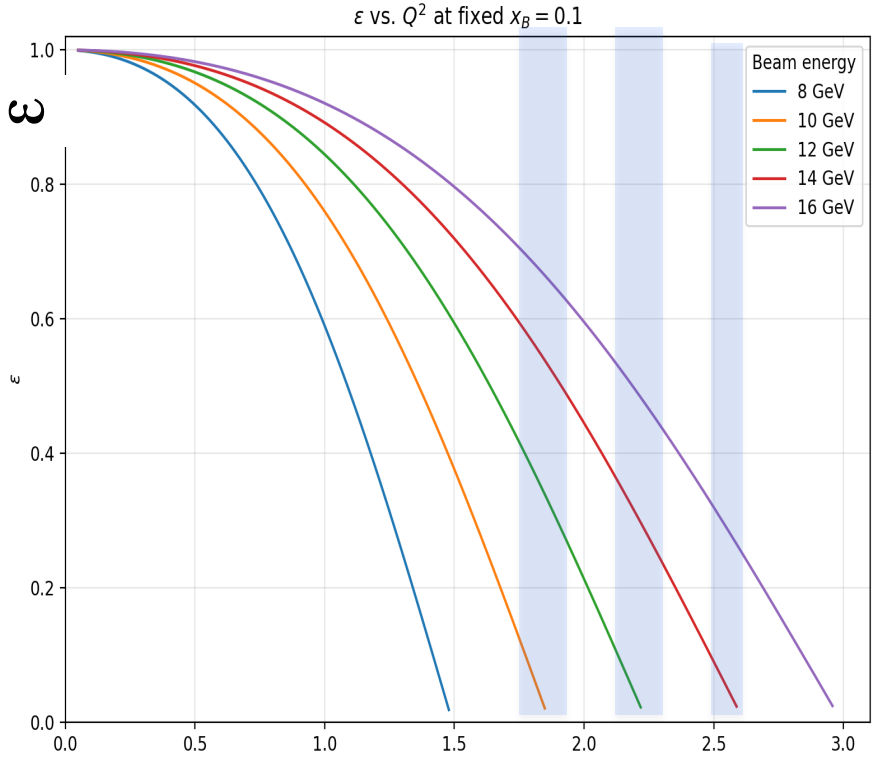
Validating the Direct Bayesian Inference framework

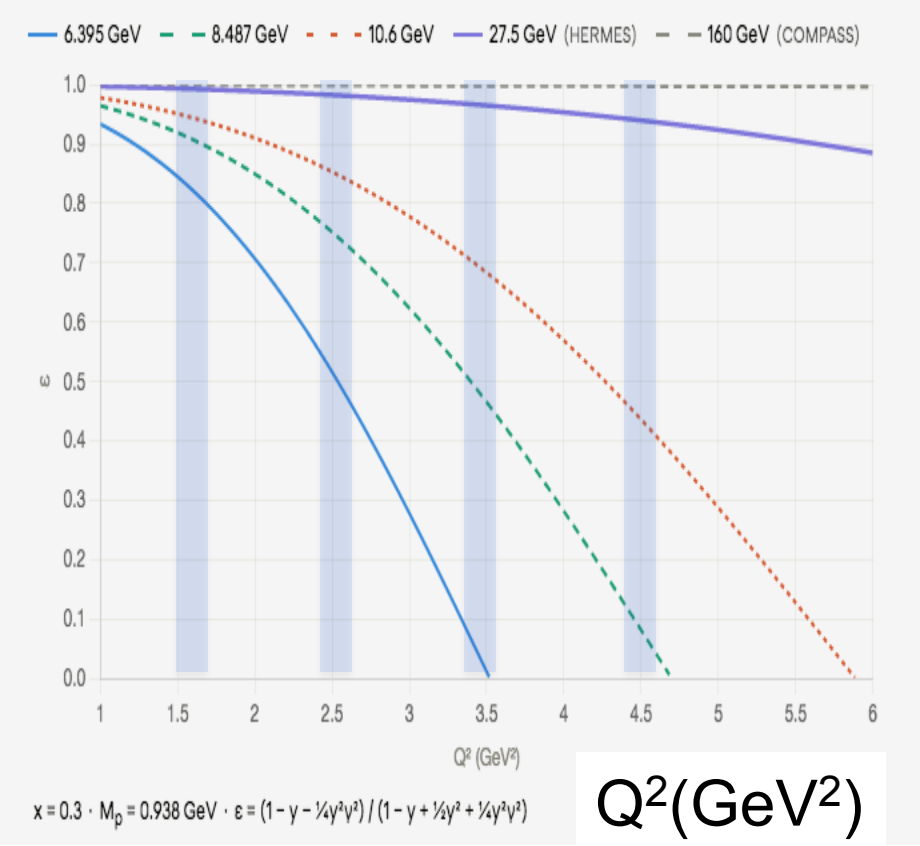


the framework is able to recover the amplitude (curves→generated) , most importantly with controlled systematics!!!

ε-dependence for electroproduction experiments

CLAS12 already collected data on proton for 6.4,6.5,7.5.8.5.10.2,10.6 GeV





Combining SDME measurements (may need “event base” analysis) at CLAS12 and HERMES/COMPASS will be important for model independent separation of longitudinal part

Helicity Amplitudes: π+/-0

$$\frac{d\sigma_T}{dt} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} + \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2}\sum_{\sigma=\pm\frac{1}{2}}\left(|T^{0\sigma}_{+1,+}|^2 + |T^{0\sigma}_{+1,-}|^2\right),$$

$$\frac{d\sigma_L}{dt} = \mathcal{H}^{++}_{0,0} = \mathcal{C}\sum_{\sigma=\pm\frac{1}{2}}|T^{0\sigma}_{0,+}|^2,$$

$$\frac{d\sigma_{LT}}{dt} = -\frac{1}{\sqrt{2}}\,\mathrm{Re}(\mathcal{H}^{++}_{+1,0} + \mathcal{H}^{--}_{+1,0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Re}\sum_{\sigma=\pm\frac{1}{2}}\left[T^{0\sigma}_{0,+}(T^{0\sigma}_{+1,+})^* + T^{0\sigma}_{0,-}(T^{0\sigma}_{+1,-})^*\right],$$

$$\frac{d\sigma_{TT}}{dt} = -\,\mathrm{Re}\,\mathcal{H}^{++}_{+1,-1} = -\mathcal{C}\,\mathrm{Re}\sum_{\sigma=\pm\frac{1}{2}}T^{0\sigma}_{-1,+}(T^{0\sigma}_{+1,+})^*.$$

p_{recoil}

γ^*_T p

γ^*_L

from parity invariance

$$T^{0,-\sigma}_{-\mu,-\lambda} = (-1)^{\lambda-\mu-\sigma}T^{0,\sigma}_{\mu,\lambda}$$

$$T^{0,\mp}_{-\mu,\mp} = (-1)^{-\mu}T^{0,\pm}_{\mu,\pm}$$

with nucleon helicity conservation, 3

$$T^{0,+}_{+1,+}, T^{0,+}_{0,+}, T^{0,+}_{-1,+}$$

2.2 Polarized beam, unpolarized target: LU (one)

$$\frac{d\sigma_{LT'}}{dt} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+1,0} + \mathcal{H}^{--}_{+1,0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im}\sum_{\sigma=\pm\frac{1}{2}}\left[T^{0\sigma}_{0,+}(T^{0\sigma}_{+1,+})^* + T^{0\sigma}_{0,-}(T^{0\sigma}_{+1,-})^*\right].$$

2.3 Unpolarized beam, longitudinal target: UL (two)

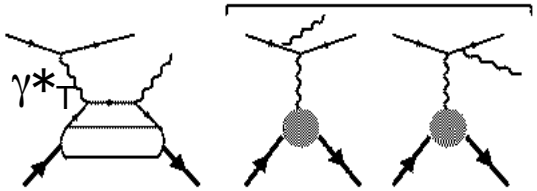
$$\frac{d\sigma^{\sin\phi_h}_{UL}}{dt} = -\frac{1}{\sqrt{2}}\,\mathrm{Im}(\mathcal{H}^{++}_{+1,0} - \mathcal{H}^{--}_{+1,0}) = -\frac{\mathcal{C}}{\sqrt{2}}\,\mathrm{Im}\sum_{\sigma=\pm\frac{1}{2}}\left[T^{0\sigma}_{0,+}(T^{0\sigma}_{+1,+})^* - T^{0\sigma}_{0,-}(T^{0\sigma}_{+1,-})^*\right],$$

$$\frac{d\sigma^{\sin 2\phi_h}_{UL}}{dt} = -\,\mathrm{Im}\,\mathcal{H}^{++}_{+1,-1} = -\mathcal{C}\,\mathrm{Im}\sum_{\sigma=\pm\frac{1}{2}}T^{0\sigma}_{-1,+}(T^{0\sigma}_{+1,+})^*.$$

- Cross sections of exclusive processes extracted in terms of helicity SFs (amplitudes for exclusive processes) would allow usage of correlations between observables
- Longitudinally polarized target adds only 1 additional amplitude and several connected observables.

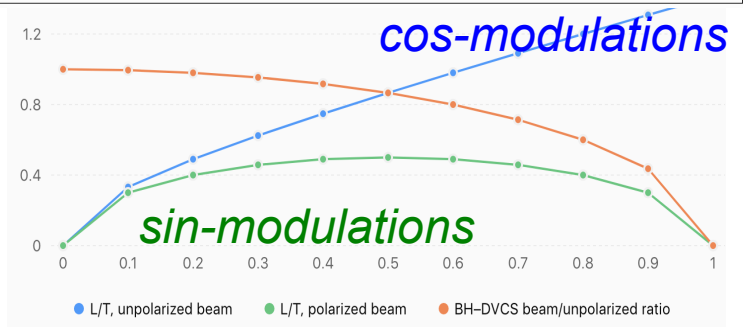
Helicity amplitudes: DVCS





$\sin\phi$ in pure DVCS squared $\longleftrightarrow$ twist-2 $\times$ twist-3,

$\sin\phi$ in BH–DVCS $\longleftrightarrow$ BH $\times$ twist-2 DVCS.



$$U_{0+} = \frac{1}{2\mathcal{D}} \sum_{\nu=\pm1} \sum_{\sigma,\lambda} T^{\nu\sigma}_{0\lambda} \left(T^{\nu\sigma}_{+1,\lambda}\right)^*$$

DVCS L/T : $\mathrm{Im}(T_L T_T^*)$,

BH $-$ DVCS : $\mathrm{Im}(T_{\mathrm{BH}} T_T^*)$

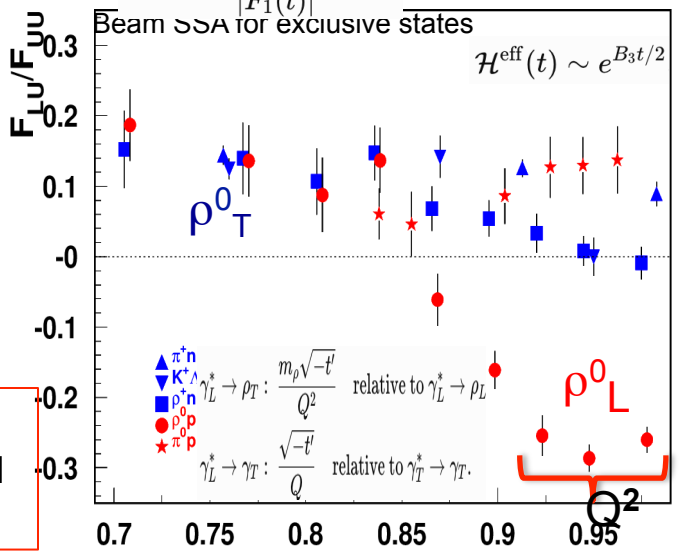
$$W^{\mathrm{DVCS}}_{LU} = -2\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\,U_{0+}\sin\phi$$

$$s^{\mathcal{I}}_{1,\mathrm{unp}} = 16K(\epsilon)P_\ell \frac{\sqrt{1-\epsilon^2}}{1+\sqrt{1-\epsilon^2}}\,\mathrm{Im}\,\mathcal{C}^{\mathcal{I}}_{\mathrm{unp}}$$

Observable	Pure DVCS: L/T interference	BH–DVCS interference: leading harmonic
UU	$\cos\phi\ \mathrm{Re}(T_0 T_+^*)$	$\cos\phi\ \mathrm{Re}\,\mathcal{C}^{\mathcal{I}}_{UU}$
LU	$\sin\phi\ \mathrm{Im}(T_0 T_+^*)$	$\sin\phi\ \mathrm{Im}\,\mathcal{C}^{\mathcal{I}}_{UU}$
UL	$\sin\phi\ \mathrm{Im}(T_0 T_+^*)$, helicity difference	$\sin\phi\ \mathrm{Im}\,\mathcal{C}^{\mathcal{I}}_{LP}$
LL	$\cos\phi\ \mathrm{Re}(T_0 T_+^*)$, helicity difference	$\cos\phi\ \mathrm{Re}\,\mathcal{C}^{\mathcal{I}}_{LP}$
UT	$\sin(\phi-\phi_S)\cos\phi$ and $\cos(\phi-\phi_S)\sin\phi$	Transverse-target spin harmonics involving ϕ, ϕ_S
LT	$\sin(\phi-\phi_S)\sin\phi$ and $\cos(\phi-\phi_S)\cos\phi$	Corresponding beam–transverse-target spin harmonics

$$R_{LT/\mathcal{I}} = \frac{x_B y(-t)|\mathcal{P}_1\mathcal{P}_2|}{Q^2(2-x_B)(2-y)} \left|\frac{\mathrm{Im}\,\mathcal{C}^{\mathrm{DVCS}}_{\mathrm{unp}}(\mathcal{F}^{\mathrm{eff}},\mathcal{F}^*)}{\mathrm{Im}\,\mathcal{C}^{\mathcal{I}}_{\mathrm{unp}}(\mathcal{F})}\right|$$

$$R(t) \sim \frac{|t|\,|\mathcal{P}_1\mathcal{P}_2|}{|F_1(t)|} e^{B_3 t/2}$$



-For all exclusive final states dominated by u-quarks Beam SSA~10-15%
-DVCS L/T vs BH-DVCS interference contributions have different ε t, and Q^2-dependences and can be separated in precision measurements

Combining run groups: using process files

YAML-header

```
# format_version: 1.0
# experiment: CLAS12
# beam_energy: 10.55
# columns:
#   - {name: run, unit: "1", description: "run number"}
#   - {name: event, unit: "1", description: "event number"}
#   - {name: hel-lep, unit: "1", description: "lepton helicity"}
#   - {name: hel-lpro, unit: "1", description: "proton helicity"}
#   - {name: el_e, unit: "GeV", description: "e- energy"}
#   - {name: el_t, unit: "rad", description: "e- polar angle"}
#   - {name: el_f, unit: "rad", description: "e- azimuthal angle"}
#   - {name: el_z, unit: "cm", description: "e- z-vertex"}
#   - {name: pp_e, unit: "GeV", description: "pi+ energy"}
#   - {name: pp_t, unit: "rad", description: "pi+ polar angle"}
#   - {name: pp_f, unit: "rad", description: "pi+ azimuthal angle"}
#   - {name: pp_z, unit: "cm", description:  "pi+ z-vertex"}
#   - {name: pm_e, unit: "GeV", description:  "pi- energy"}
#   - {name: pm_t, unit: "rad", description: "pi- polar angle"}
#   - {name: pm_f, unit: "rad", description: "pi- azimuthal angle"}
#   - {name: pm_z, unit: "cm", description: "pi- z-vertex"}
#   - {name: pr_e, unit: "GeV", description: "proton energy"}
#   - {name: pr_t, unit: "rad", description: "proton polar angle"}
#   - {name: pr_f, unit: "rad", description: "proton azimuthal angle"}
#   - {name: pr_z, unit: "cm", description: "proton z-vertex"}
#   - {name: pimang, unit: "rad", description: "cone angle for pi-"}
#   - {name: phi, unit: "rad", description: "phi-trento"}
#   - {name: cost, unit: "rad", description: "original supplied angular field, not a cosine; definition unverified"}
#   - {name: varphi, unit: "rad", description: "varphi"}
#   - {name: W_calc, unit: "GeV", description: "invariant mass W from initial proton and scattered-electron four-momentum"}
#   - {name: Phi_Diehl, unit: "rad", description: "Trento lepton-to-dipion production-plane angle"}
#   - {name: varphi_Diehl, unit: "rad", description: "pi+ azimuth in dipion rest frame, z=-recoil p and x=target transverse"}
#   - {name: theta_Diehl, unit: "rad", description: "pi+ polar angle in dipion rest frame relative to -recoil p; range [0,pi]"}
#
# reaction: "e p -> e_prime p_prime pi_plus pi_minus"
# beam_axis: "+z laboratory"
# target: "stationary proton"
# reconstructed_meson: "pi+ + pi-"
# angle_convention: "Diehl arXiv:0704.1565v2 section 2, Figures 1-2"
# angle_range: "Phi_Diehl and varphi_Diehl in [0,2pi); theta_Diehl in [0,pi]"
# beam_energy_source: "command-line --beam-energy (default 10.55 GeV); never sum of final-state energies"
# note: "Existing phi,cost,varphi preserved; they are not assumed identical to reconstructed Diehl angles"
# DATA:
   16982     38786  1  1   6.648   0.176   5.198  -1.315   0.523   0.821   2.582  -3.471   3.199   0.268   2.197  -0.990   1.162   0.424   0.436
   16982     73600 -1  1   7.427   0.185   3.280  -3.516   1.305   0.375   5.631  -5.594   1.387   0.576   0.534  -4.071   1.267   0.389   0.236
   16982     83938 -1  1   6.380   0.192   0.339  -4.162   2.307   0.174   2.667  -8.435   1.579   0.339   4.197  -3.765   1.186   0.821   3.401
   16982    137255  1  1   5.542   0.184   2.303  -2.222   1.815   0.368   6.045  -3.155   2.113   0.574   5.256  -2.297   1.977   0.404   2.541
   16982    411965 -1  1   7.005   0.167   4.148  -3.275   0.901   0.368   2.284  -3.608   2.262   0.350   0.376  -2.745   1.192   0.669   1.315
   16982    418143 -1  1   6.949   0.144   4.262  -3.848   0.972   0.304   0.139  -5.947   2.245   0.531   1.149  -3.910   1.264   0.421   3.720
   16982    450572 -1  1   6.475   0.200   5.505  -2.524   2.476   0.324   2.610  -4.489   1.235   0.575   1.909  -3.483   1.190   0.220   4.634
   16982    519869 -1  1   1.552   0.533   2.580  -2.695   0.695   0.378   5.450  -5.615   7.618   0.144   5.231  -2.053   1.436   0.617   1.525
   16982    548562 -1  1   2.683   0.343   2.340  -2.808   2.048   0.297   6.230  -4.213   5.397   0.142   5.438  -1.925   1.082   1.188   3.448
   16982    650277 -1  1   6.508   0.207   1.975  -4.215   0.626   0.794   4.805  -4.207   2.892   0.334   5.576  -3.929   1.162   0.495   3.640
   16982    669259 -1  1   4.228   0.331   2.555  -0.085   1.850   0.292   6.111  -1.547   4.177   0.207   5.384   0.115   1.172   0.260   0.189
   16982    743767 -1  1   3.916   0.258   3.094  -0.461   3.875   0.170   0.561  -5.025   2.473   0.347   6.089  -1.742   1.170   0.631   3.649
   16982    852771  1  1   6.079   0.214   2.144  -0.269   1.283   0.597   5.065  -1.968   2.535   0.334   5.105  -0.784   1.317   0.430   1.360
```

Files directly readable by AI, without any further explanation of content

Will need for signal, background, MC including, generated and reconstructed, where available.

SUMMARY

- RGH experiment provides critical input for extraction of a complete set of underlying amplitudes describing exclusive processes, in combination with RGC&RGN

- Combine RGK/RGA/RGC for separating L/T photon contributions both for SIDIS(large z) and Hard Exclusive processes

- Moving from bin-based analysis to event-based analysis will be important for amplitude extraction from all targets, using process files for all relevant processes, including unpolarized and polarized hydrogen and deuteron

- Iteratively update the MC, using the complex extraction framework allowing realistic evaluation of required sizes of needed data sets, including 10.6 RGH and in addition lower/higher energy polarized RGC/RGN

- Push theory for development of the framework to include higher twist effects in Hard Exclusive processes, HT GPDs, in particular (validation in Q^2-dependences of all relevant observables will be critical)

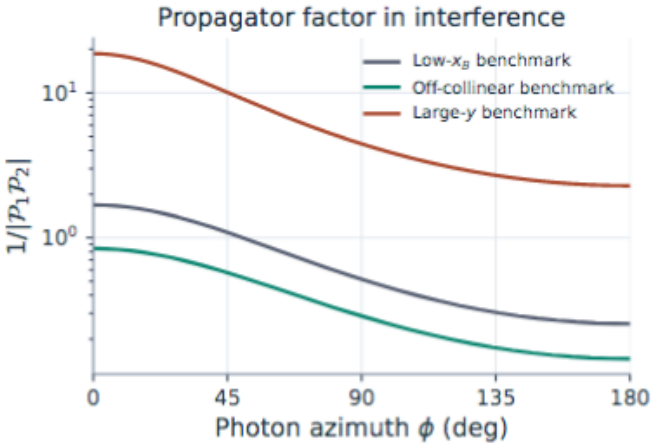
- support slides

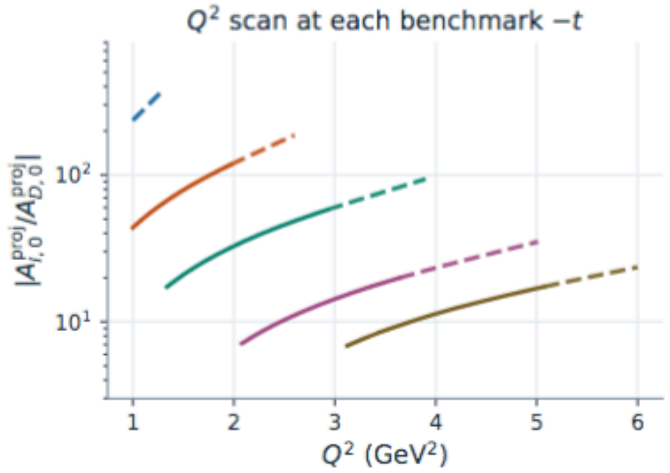
Transverse target:DVCS vs DVCS+BH

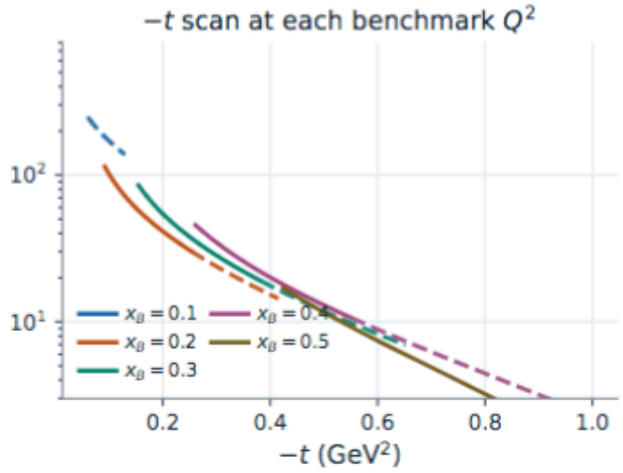
$$d\sigma(e_\ell, s) = U(\phi) + e_\ell U_I(\phi) + s\, S_\perp\, [N_D(\phi,\delta) + e_\ell N_I(\phi,\delta)], \qquad U = d\sigma_{\mathrm{BH},UU} + d\sigma_{\mathrm{DVCS},UU}$$

$$\delta = \phi - \phi_S.$$

Contribution	Harmonic	HERMES ampl
Charge-even, squared DVCS	$\sin\delta$	$-7.3 \pm 2.4 \pm 0.$
Charge-odd, DVCS–BH	$\sin\delta$	$+3.5 \pm 2.4 \pm 2.$
Charge-odd, DVCS–BH	$\sin\delta\cos\phi$	$-16.4 \pm 3.9 \pm 2$
Charge-odd, DVCS–BH	$\cos\delta\sin\phi$	$+0.5 \pm 4.0 \pm 1.$

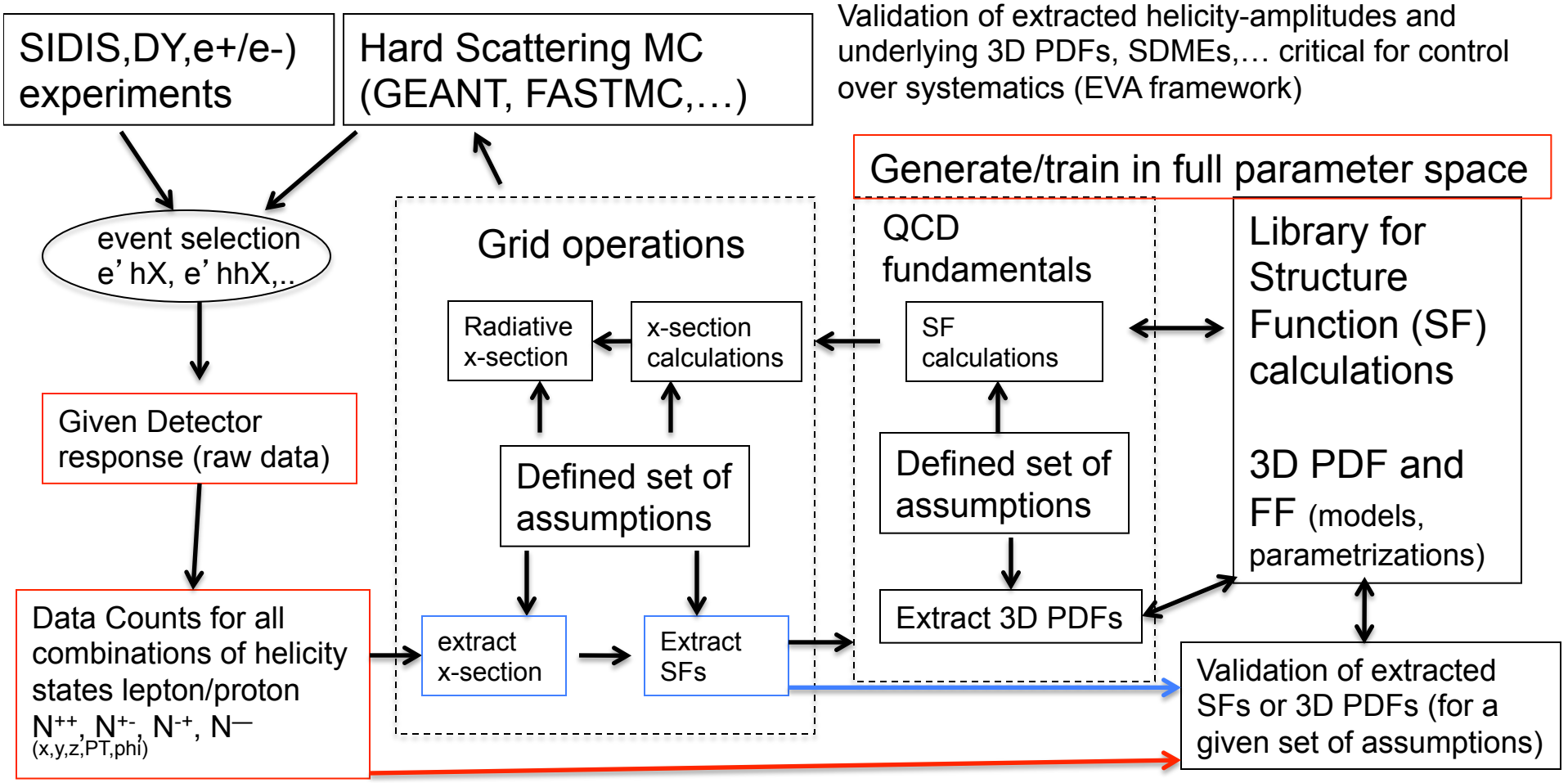






Interference over pure DVCS decreases at large t

3D PDF Extraction and VAlidation frameworks



Direct extraction of a given parameter sets from all steps using AI tools for the extraction of 3D PDFs from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing (can be iterative)

“process” files

Ex. of process files for 3 beam (6.5,7.5,10.6) energies prepared both for MC and data

A data file ex. for exclusive pi+ from RGK 8.477 GeV sample

run#	ev#	λe	λp	P_{e^-}	θ_{e^-}	ϕ_{e^-}	Z_e	P_{π^+}	θ_{π^+}	ϕ_{π^+}	Z_{π^+}
56470	612	-1	0	7.852	0.119	3.270	-4.549	2.578	0.240	6.280	-1.655
56470	677	1	0	5.299	0.159	3.556	-2.241	5.173	0.223	0.045	-2.850
56470	918	1	0	8.107	0.104	2.296	-5.031	1.377	0.903	5.487	-4.998

.....

A data file with 900K rho0s from RGA 10.6 GeV MC sample

generated momenta of all 4 final particles

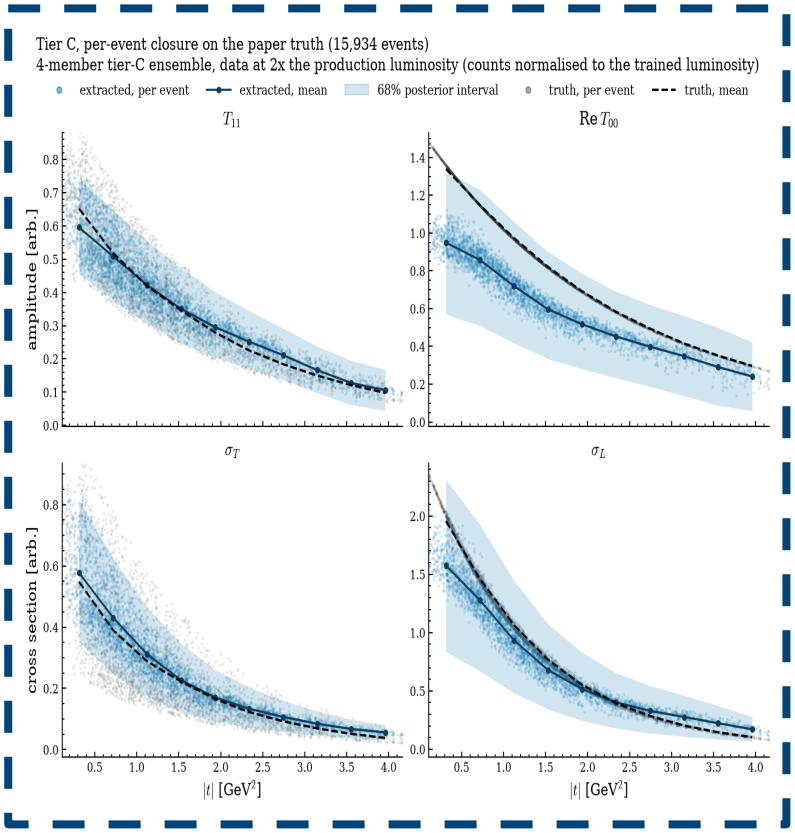
only written if reconstructed

10040	123	-1	7.476	0.149	3.108	2.655	0.408	5.955	0.173	1.318	6.003	1.254	0.404	1.502										
10040	124	1	7.355	0.104	1.301	1.567	0.532	4.987	1.446	0.048	6.048	1.170	0.771	3.049										
10040	125	1	5.785	0.128	6.227	1.207	0.326	2.578	3.437	0.171	4.464	1.109	0.954	2.155	5.775	0.128	6.218	1.203	0.336	2.580	3.424	0.171	4.466	1.092	0.949	2.151
10040	126	1	8.890	0.103	2.534	1.126	0.482	5.807	0.295	0.884	3.546	1.227	0.706	5.877										
10040	127	1	6.103	0.136	5.827	0.897	0.273	2.349	2.773	0.435	3.689	1.765	0.652	1.085										
10040	128	1	5.412	0.150	3.165	0.435	0.666	0.153	4.712	0.137	0.066	0.979	0.386	3.777										
10040	129	-1	7.030	0.152	1.961	0.470	0.558	0.549	2.308	0.087	6.135	1.731	0.835	4.717										
10040	130	1	7.831	0.177	4.352	1.958	0.263	1.222	0.189	1.556	1.101	1.560	0.636	1.222										
10040	131	-1	4.258	0.162	4.530	1.582	0.391	0.915	4.560	0.098	1.046	1.138	0.892	3.527	4.249	0.161	4.539	1.582	0.393	0.911	4.550	0.098	1.048	1.127	0.864	3.526
10040	132	1	8.817	0.116	4.965	0.670	0.481	3.221	0.395	1.211	0.892	1.657	0.593	1.795										
10040	133	1	4.508	0.187	5.317	4.007	0.134	2.511	1.953	0.138	0.217	1.070	1.013	2.341										
10040	134	-1	8.243	0.109	0.846	0.684	0.184	2.379	1.547	0.608	3.973	1.064	0.276	5.410										
10040	135	1	7.579	0.107	1.815	0.462	0.640	3.245	2.448	0.239	5.088	1.049	0.772	5.556										
10040	136	1	7.811	0.120	3.879	1.152	0.239	2.510	1.413	0.530	0.849	1.162	0.709	6.139										
10040	137	1	3.890	0.250	0.042	4.672	0.134	3.237	1.766	0.165	0.514	1.210	0.914	3.347										
10040	138	-1	3.975	0.209	5.463	5.108	0.210	2.299	1.083	0.452	2.995	1.372	0.722	5.881										
10040	139	1	6.601	0.147	2.629	0.751	0.750	5.989	2.966	0.286	5.718	1.220	0.491	2.808										
10040	140	-1	5.430	0.135	0.173	0.832	0.483	4.146	4.220	0.136	3.445	1.056	0.866	1.485	5.436	0.135	0.173	0.829	0.491	4.121	4.174	0.134	3.479	1.051	0.848	1.479
10040	141	1	9.111	0.091	4.138	0.832	0.970	1.103	0.233	0.837	3.764	1.363	0.319	0.591										
10040	142	1	5.305	0.196	2.851	0.325	0.068	2.061	4.901	0.204	6.167	1.006	0.578	4.773										
10040	143	-1	7.588	0.173	2.488	0.516	0.900	6.020	2.051	0.494	5.403	1.384	0.069	0.913										
10040	144	-1	8.469	0.109	0.749	1.443	0.776	3.773	0.256	0.628	1.197	1.369	0.178	5.260										
10040	145	1	8.395	0.123	5.768	0.995	0.226	1.630	1.015	0.772	2.748	1.133	0.386	3.062										
10040	146	1	5.269	0.201	1.466	0.432	0.317	0.599	4.833	0.214	4.604	1.004	0.412	3.900										

Extraction of amplitudes event-by-event

- **Feasibility published:** amplitudes from detector-level data with calibrated uncertainties
- **New:** first event-by-event closure; calibration targets identified
- **Plan:** phased, validated on conventional observables, with a decision point at month 12
- **Deliverable:** a validated, reusable extraction on CLAS12 φ and ρ^0 data, ready for high-luminosity JLab and the EIC
- **Request:** LDRD over FY27 and FY28, one postdoc to develop framework for event-by-event analysis

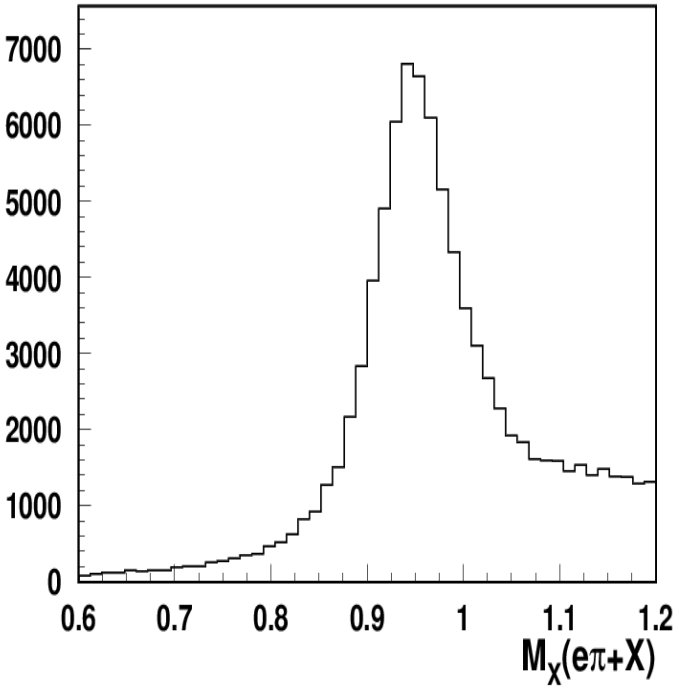
First event-by-event closure



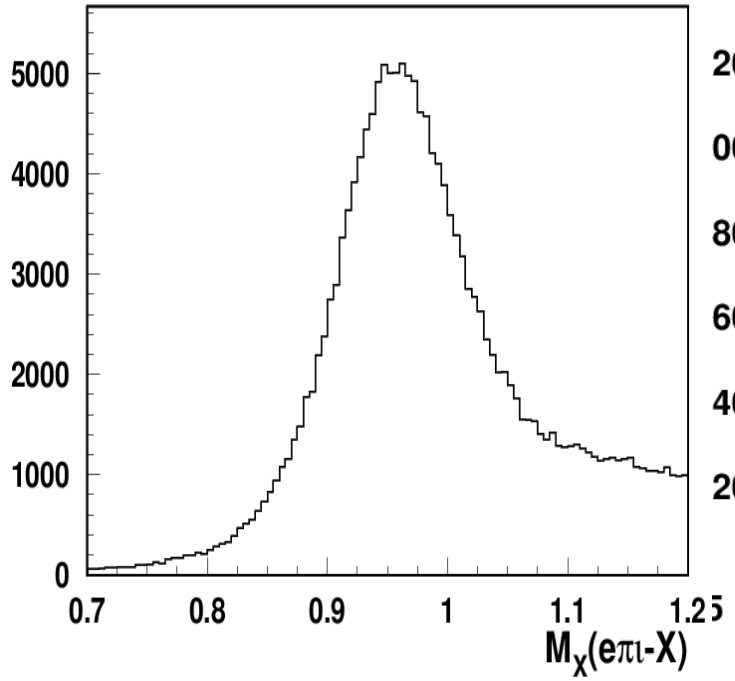
Development of event-based analysis will allow combination of different data sets including Hall A/C and COMPASS

Handling backgrounds

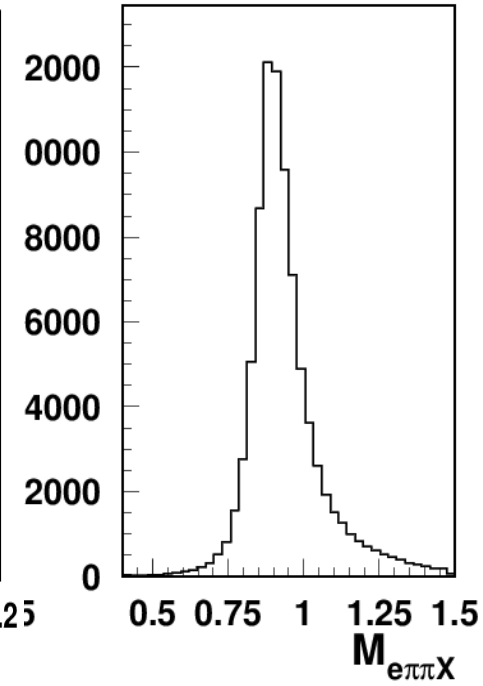
ep->e'π+X(neutron not detected)



en->e'π-X(proton detected)



ep->e' $\pi^+\pi^-$X(+protor



More particles detected less backgrounds, but there is always something left, and quantification of impact should be included in the framework

From HSFs to Helicity Amplitudes

$T^{\nu\sigma}_{\mu\lambda}$ helicity amplitudes describing $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$ depend on x,Q^2,t

helicities

$$\mu, \nu \in \{-1, 0, +1\}, \quad \lambda, \sigma \in \{-\tfrac{1}{2}, +\tfrac{1}{2}\}.$$

$$F_{UU,T} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} + \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 + |T^{\nu\sigma}_{+1,-}|^2\right)$$

$$F_{UU,L} = \mathcal{H}^{++}_{0,0} = \mathcal{C} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} |T^{\nu\sigma}_{0,+}|^2$$

$$F_{LL} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 - |T^{\nu\sigma}_{+1,-}|^2\right)$$

↓ pion limit v=0

$$\frac{d\sigma_{LL}}{dt} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{0\sigma}_{+1,+}|^2 - |T^{0\sigma}_{+1,-}|^2\right)$$

amplitude	photon	nucleon	Δ	forward factor K
$M_{0+,0+}$	L	non-flip	0	1
$M_{0-,0+}$	L	flip	−1	$\sqrt{-t'}/2M_p$
$M_{0+,++}$	T(+1)	non-flip	+1	$\sqrt{-t'}/2M_p$
$M_{0-,++}$	T(+1)	flip	0	1
$M_{0+,-+}$	T(−1)	non-flip	−1	$\sqrt{-t'}/2M_p$
$M_{0-,-+}$	T(−1)	flip	−2	$-t'/4M_p^2$

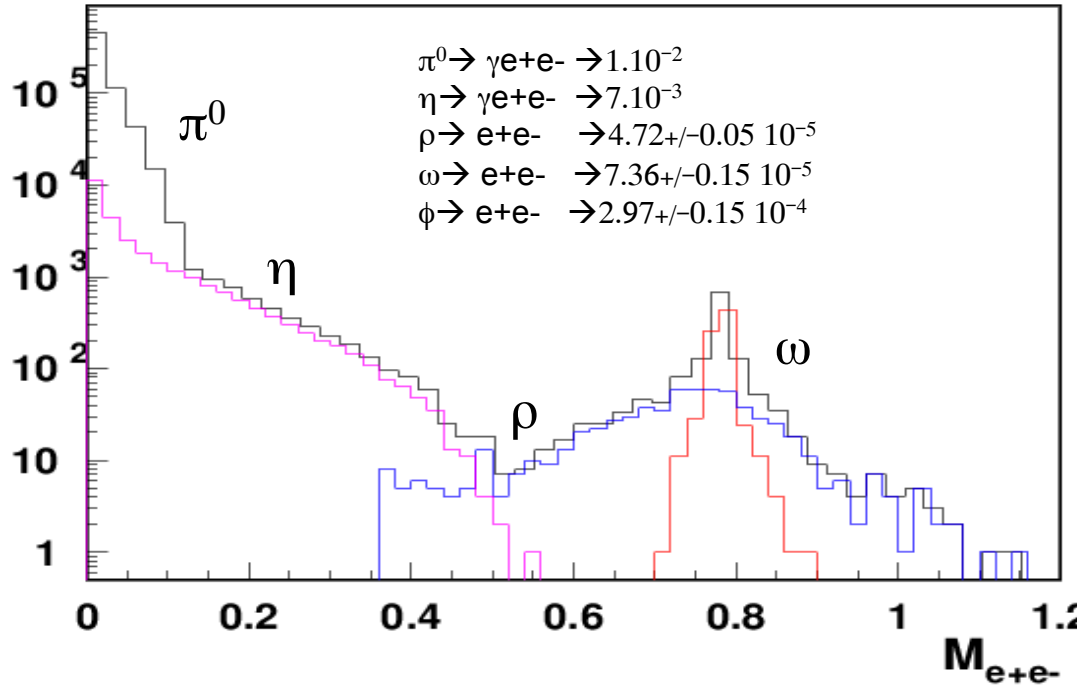
six independent amplitudes

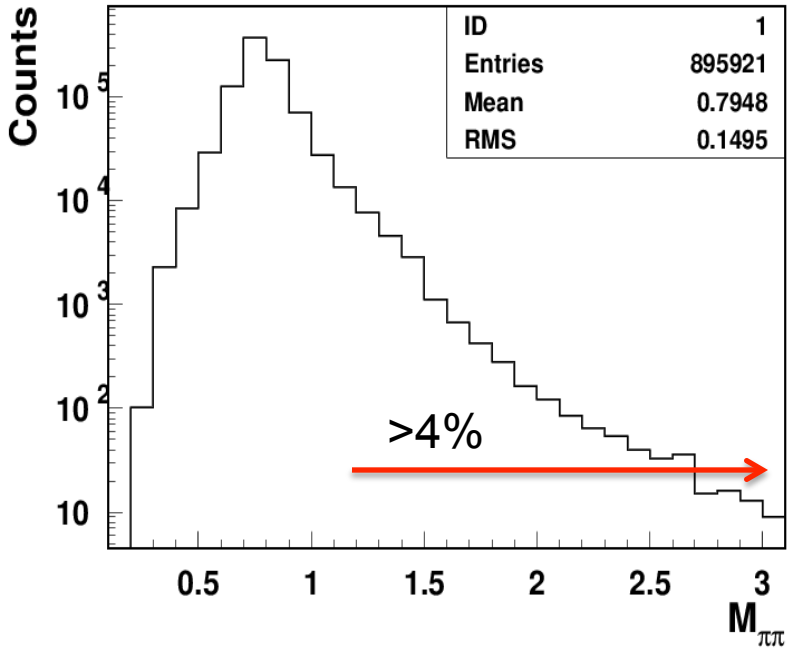
Cross sections of exclusive processes extracted in terms of helicity SFs provide direct/complementary access to underlying amplitudes

Using e+e- to estimate vector mesons

The invariant mass of dihadrons is contaminated by other vector mesons, with shape not changing significantly with hadronization fraction to spin-1 vs spin-0 mesons

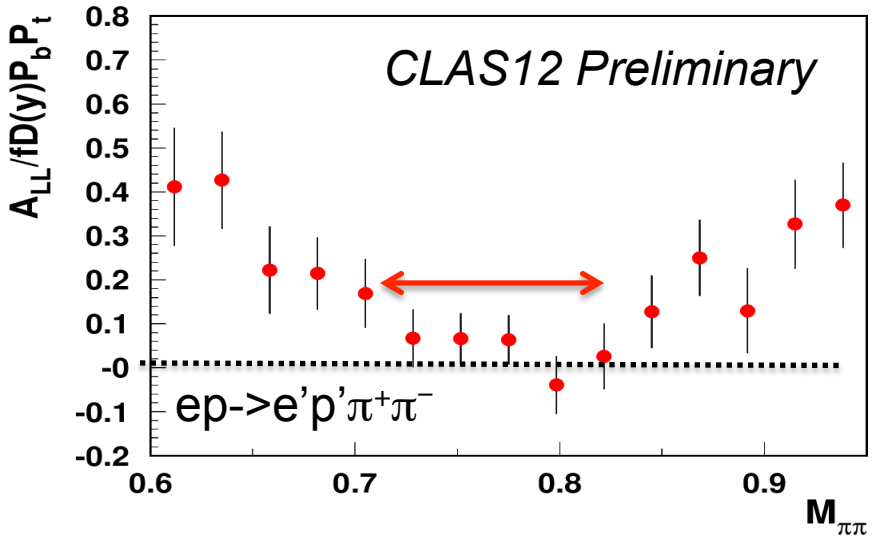
decays of π and η are kinematically separeated from ω and ρ^0





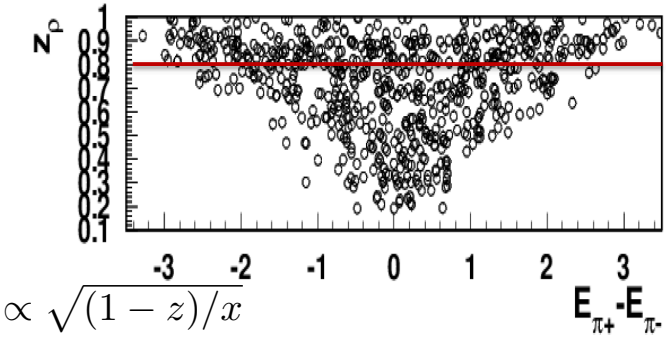
VMS are visible in lepton pair production even for Q2>1.
Significant fraction of VM leptonic decays ep→e'e+e-X may affect DY and TCS studies.

Studies of ρ^0 impact with longitudinally polarized NH_3 target

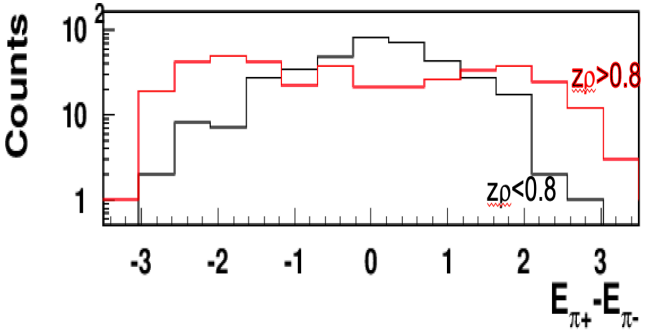


Need clear separation of hydrogen from NH_3
and "diffractive" exclusive ρ0s from exclusive $\pi+\pi-$

Polarization of rho



$$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$$

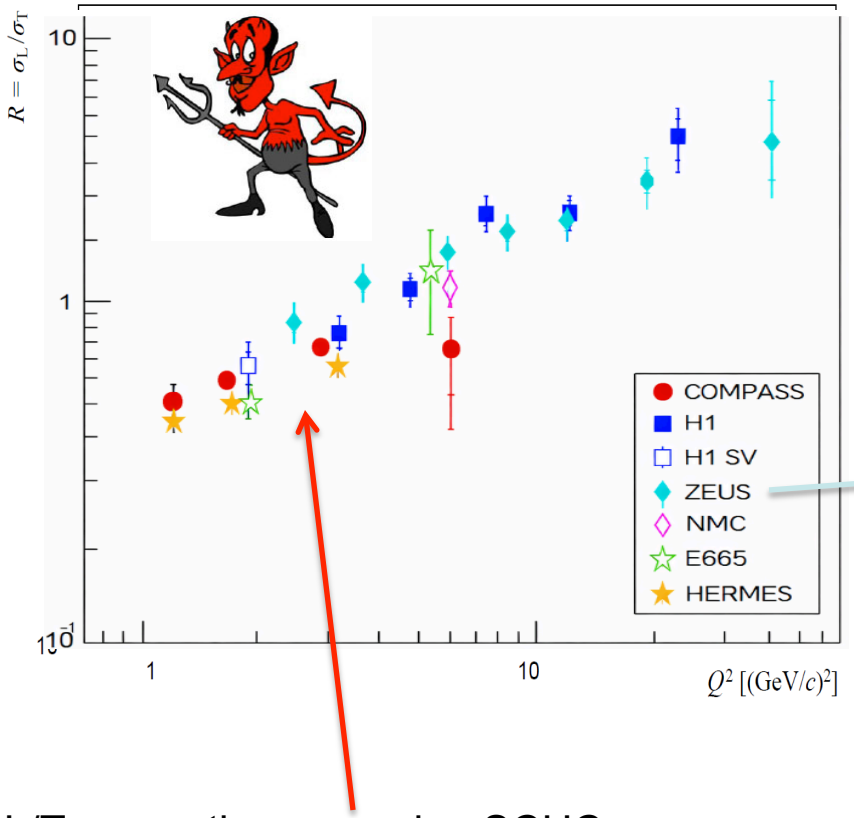


- DSA is P-even, SSA is P-odd
- longitudinal photon cross section is P-odd

→ contribution appears only in the SSA, a P-odd observable, and does not appear in DSA(→significant dilution in DSA)

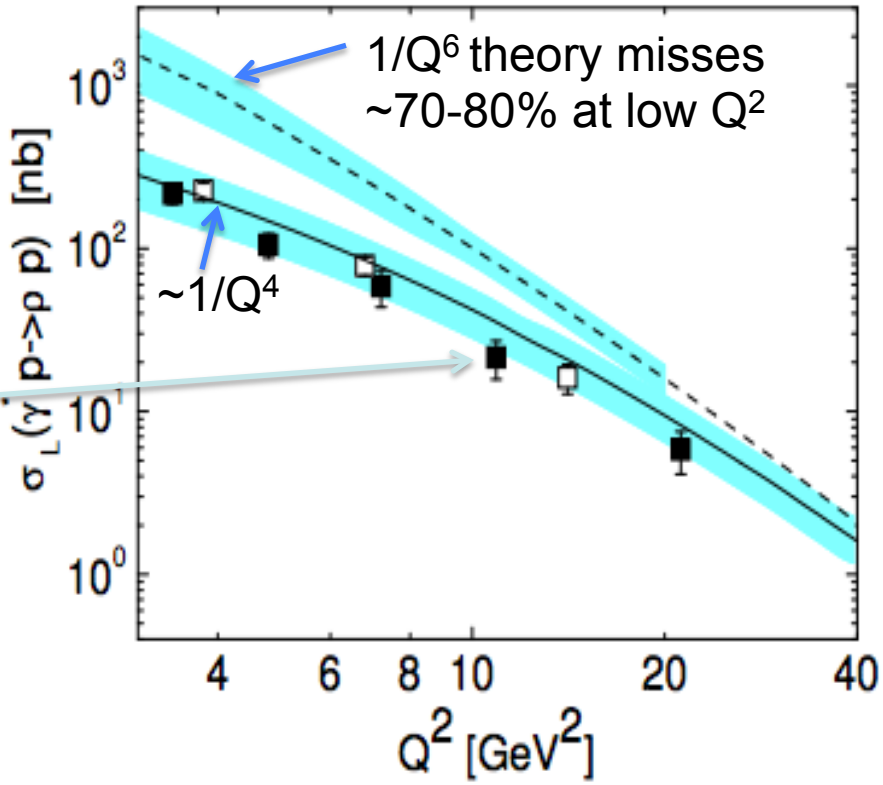
At large z (small t) the shapes of distributions (getting asymmetric) clearly indicate dominance of longitudinal rho

Separating Longitudinal photon contributions



L/T separation assuming SCHC (helicity conservation)

"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge." D.J. Boorstin

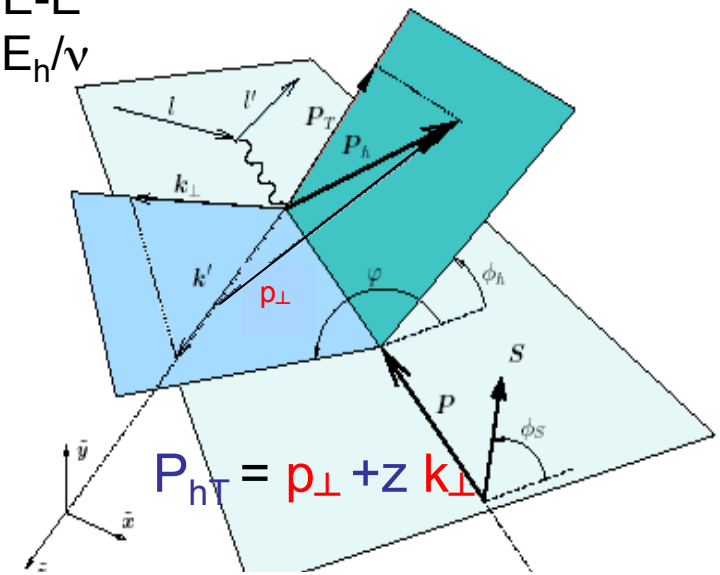


The ZEUS measurements, followed by others, indicated that the longitudinal photon contributions (diffractive rho) drop as ~1/Q^4 → dramatically underestimate low Q^2 ρ^0s

To be checked both, extraction of σ_L cross-section and evaluation of σ_L/σ_T

DIS kinematical coverage and observables

ν=E-E'
$z=E_h/\nu$



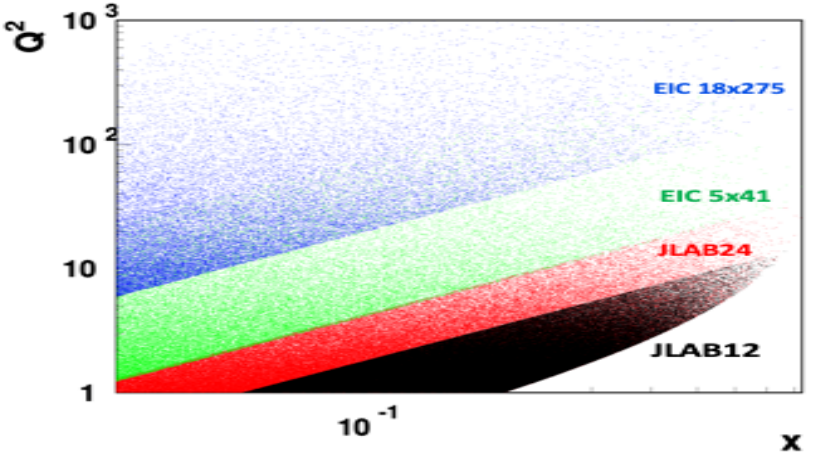


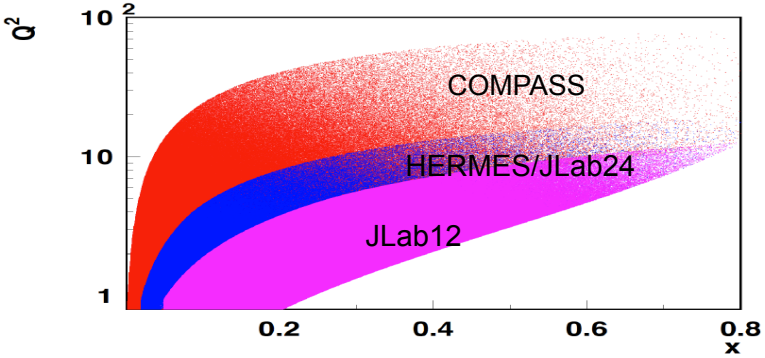


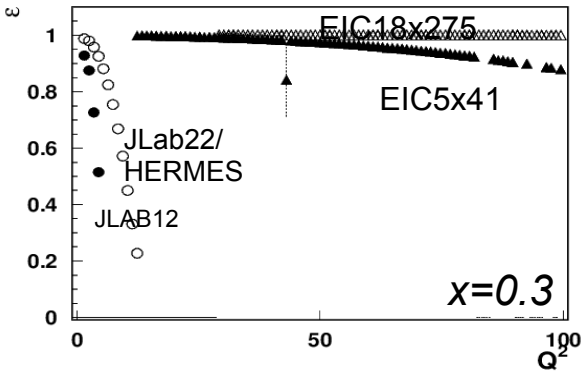




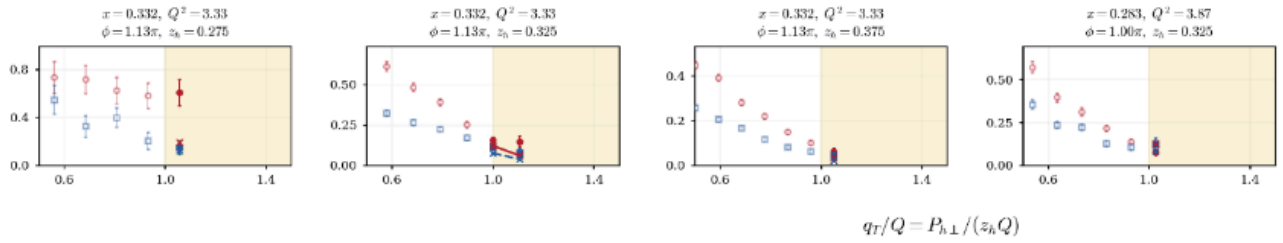
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$



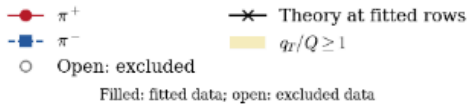




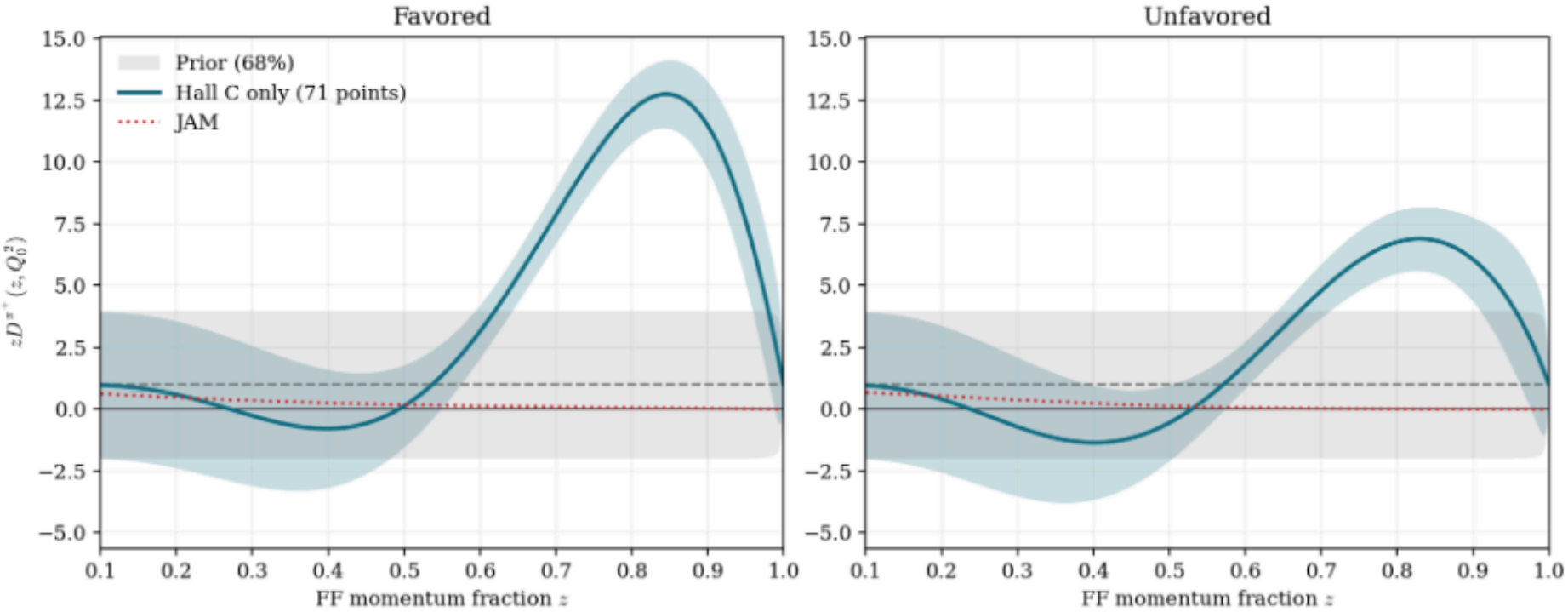
Pion multiplicities



N. Sato (High Lumi Workshop)

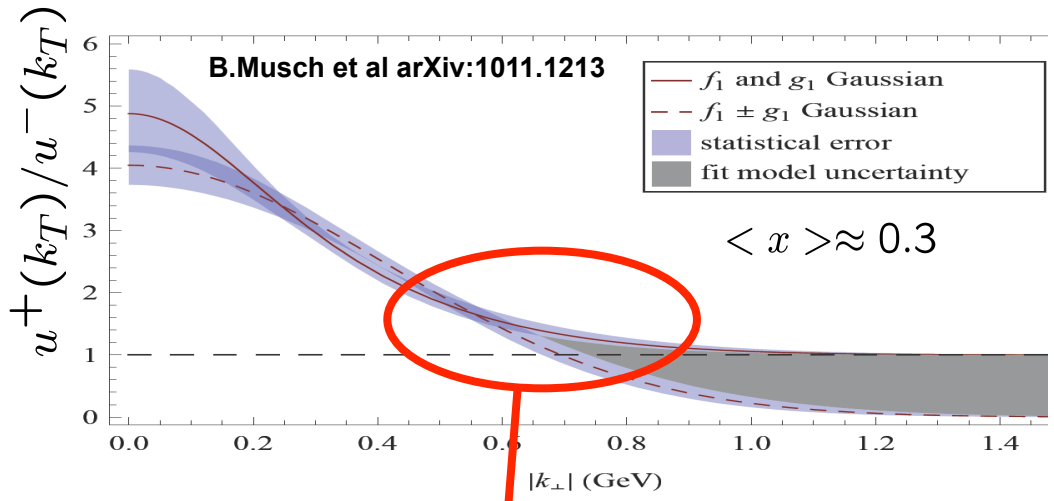


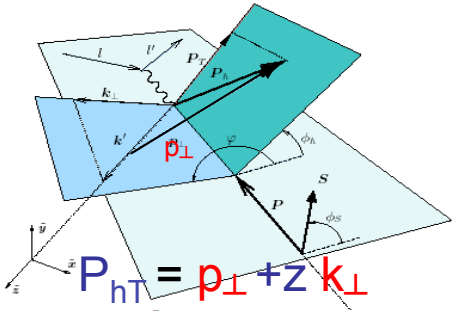
PRELIMINARY

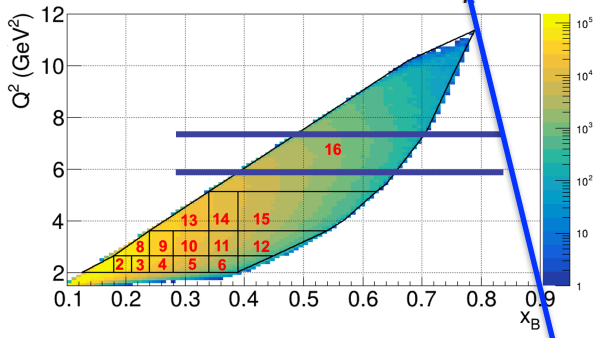


To fit Hall-C data on precision multiplicities→ modification needed for FFs
Arbitrary cuts in z and M_X should be studied in details, also for evaluating the systematics

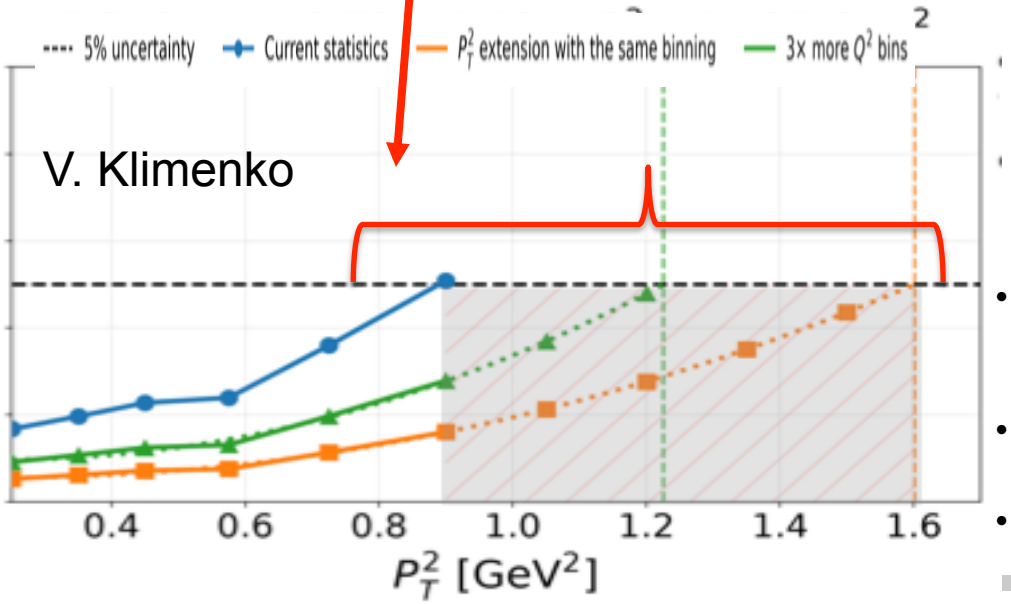
SIDIS: Extending the phase space in P_T,Q^2







$0.5 < z < 0.6$

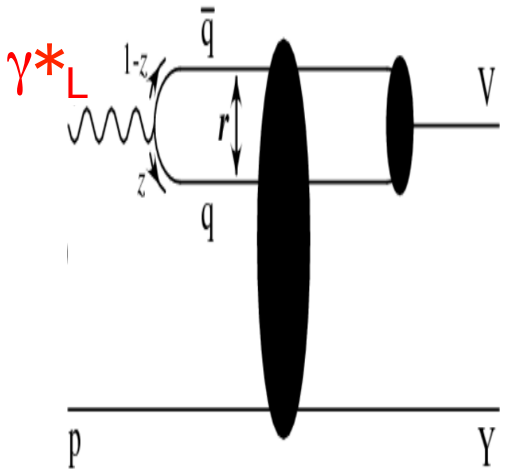


- Increase of the phase space should be accounted for most critical range P_T>0.7 GeV from 1 bin to 5 (x5)
- Large z important, but requires understanding of HT effects
- Higher Q^2 critical for measurements of HT

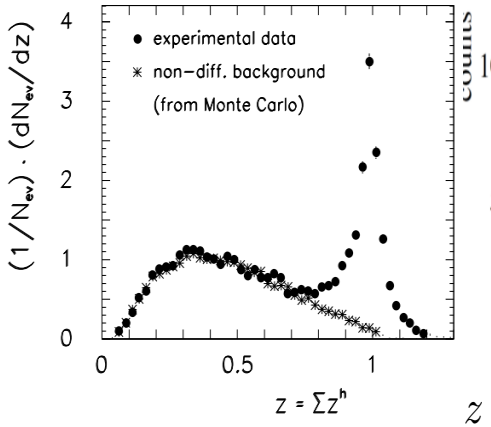
Exclusive VMs (ρ^0, ω,ϕ, J/Ψ,…)

$$\gamma^*(\mu) + p(\lambda) \rightarrow \rho(\nu) + p(\sigma)$$

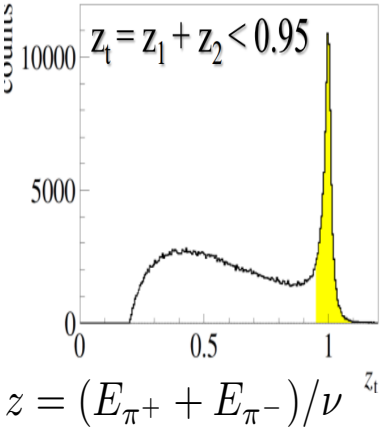
$\mu, \nu, \lambda, \sigma$ → helicities



E665 Eμ = 470 GeV

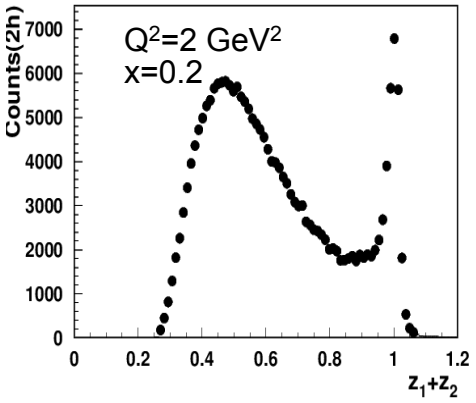


COMPASS Eμ = 160 GeV



$z = (E_{\pi^+} + E_{\pi^-})/\nu$

CLAS12 E=10.6 GeB



Estimated ~20% contributions from rho to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS

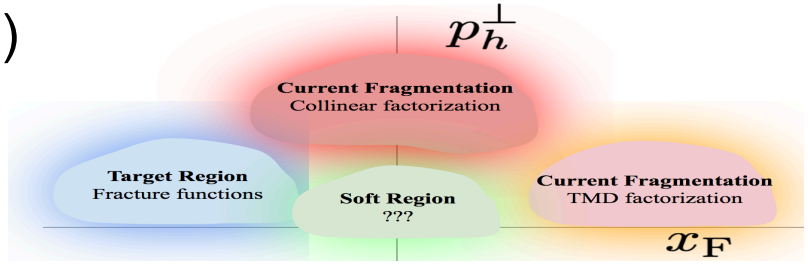
→most longitudinally polarized ρ^0

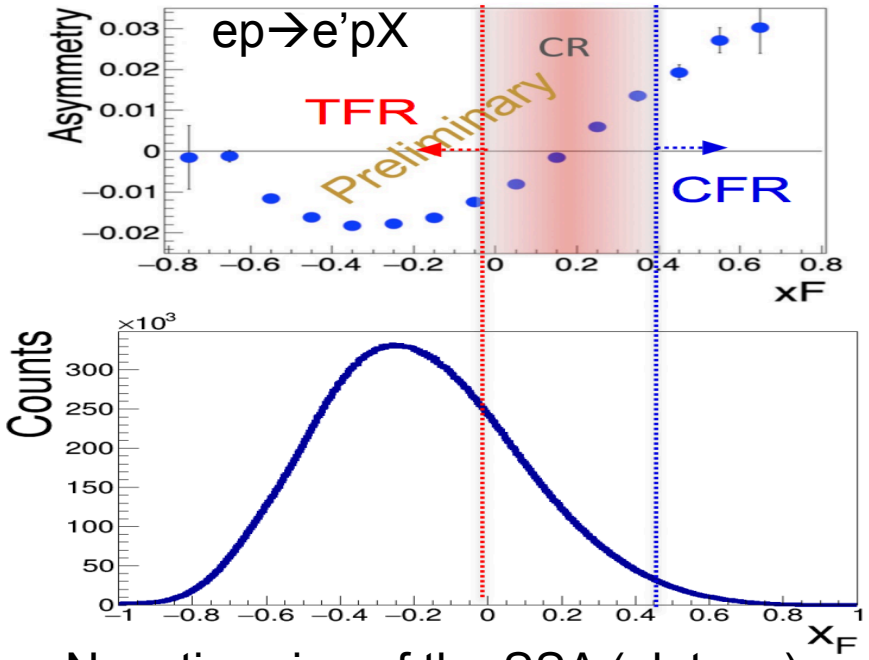
For GPD based interpretation need experimental separation of contributions

Studies of exclusive processes require high resolution and multidimensional measurements !!!
No indication of “Different rho at JLab”?

Measuring target fragmentation at JLab

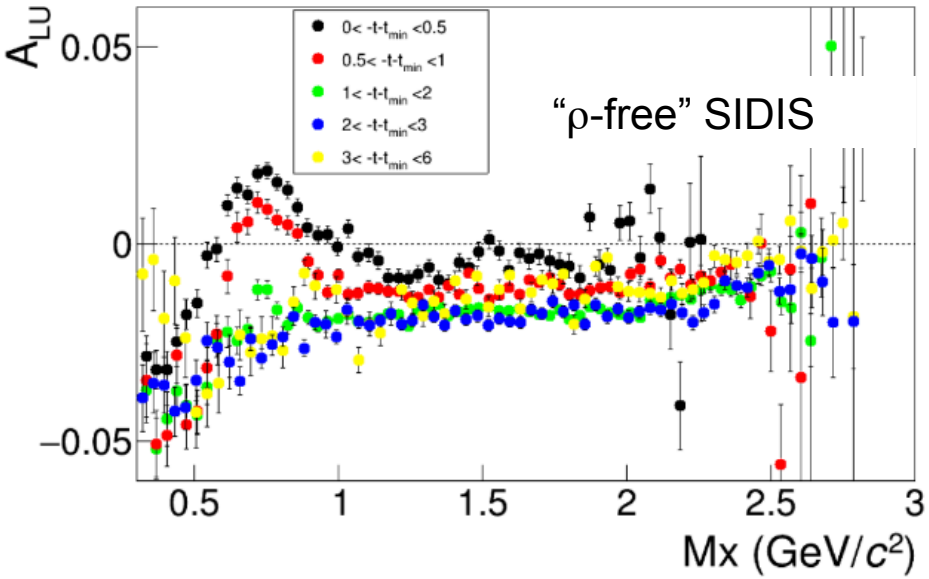
Separating Target Fragmentation Region TFR from Current fragmentation region (CFR)





Negative sign of the SSA (plateau) defines the TFR dominance

F. Benmokhtar & Duquesne U.



Major difference only for protons at small t!

With beams in polarized SIDIS typically always polarized, beam SSA can serve as a tool to separate

1) kinematical regions (CFR/TFR)
2) dynamical contributions
3) cut on M_X eliminate exclusive VMs

Theory-Experiment Dialogue: How to proceed

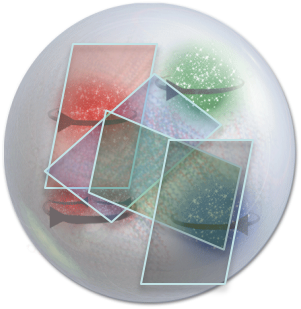
1. Keeping the formalism the same, including the input data where it works well, and try to get a better description using more sophisticated TMD models for TMD PDFs, and TMD FFs, search kinematics where theory is applicable (typically very large Q^2)



2. Try to extend the theory adding contributions assumed irrelevant in existing phenomenology, including also accounting of NLO terms. Most importantly extend the kinematics, where the factorized picture can work ($q_T/Q<1$). Significant progress reported at QCD evolution workshop.



3. Try to extend the theory coverage by measuring certain processes in the input data set that are not accounted for in the phenomenology most importantly the longitudinal photon contributions

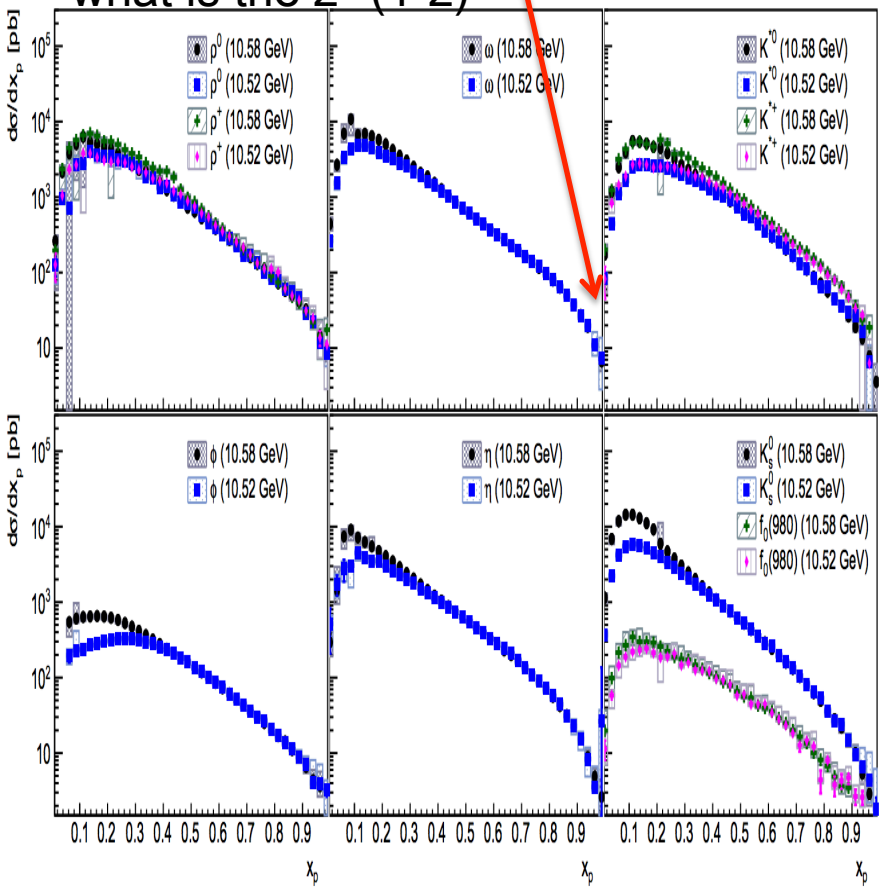


Measurements of Q^2-dependence of observables is key for validation (Combine JLab & COMPASS)!!!

cross sections in the z→1 limit from e+e-

what is the z^{α} $(1-z)^{\beta}$

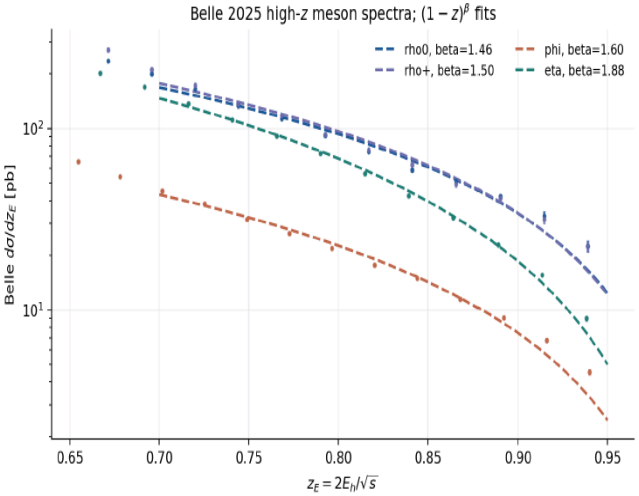
2411.12216



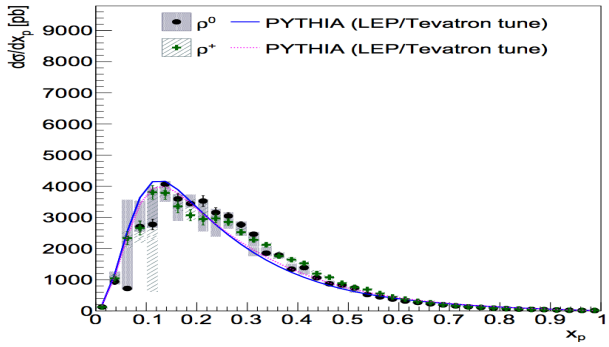
Belle: production cross sections as a function of x_p

Meson	Energy [GeV]	beta
rho0	10.58	1.455
rho+	10.58	1.498
omega	10.58	1.485
phi	10.58	1.599
K*0	10.58	1.707
K*+	10.58	1.590
eta	10.58	1.884
pi+ + pi-	10.52	~1.9*
K+ + K-	10.52	~2.1*

SI-fits of Belle data



incoherent "exclusive"



slightly more rho+!

Possible contribution from γ^*_T

Semi-exclusive contributions more suppressed for scalar mesons

γ^*_T contribution from $\rho 0$ $\rho +$ comparable?

From SFs to HSFs

$$\frac{d\sigma_{SIDIS}}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \mathcal{K}_{SIDIS}\sum_{XY}\mathcal{W}_{XY}[F] = \mathcal{K}_{EXC}\sum_{XY}\mathcal{W}_{XY}[H],, \qquad XY = UU, LU, UL, LL, UT, LT,$$

$$\mathcal{K}_{SIDIS} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-)}\left(1+\frac{\gamma^2}{2x}\right), \mathcal{K}_{EXC} = \frac{\alpha y(1-x)}{8\pi^3 x(1-\epsilon)}.$$

proton

photon–proton interference densities H_{mn}^{ij}

photon

$$F_{mn}^{ij}(x,Q^2,z,P_{h\perp}^2) = \frac{Q^2(1-x)}{4\pi^3\alpha}\left(1+\frac{\gamma^2}{2x}\right)^{-1} H_{mn}^{ij}(x,Q^2,z,P_{h\perp}^2).$$

$$\frac{d\sigma^{excl}}{dx\,dy\,d\psi\,dt\,d\phi_h} = \mathcal{K}_{EXC}\sum_{XY}\mathcal{W}_{XY}[\mathcal{H}],, \qquad XY = UU, LU, UL, LL, UT, LT,$$

$$\begin{aligned}\mathcal{W}_{UU} = {} & \tfrac{1}{2}\left(H_{+1,+1}^{++} + H_{+1,+1}^{--}\right) + \epsilon H_{0,0}^{++} \\ & - \sqrt{\epsilon(1+\epsilon)}\cos\phi_h\ \mathrm{Re}\left(H_{+1,0}^{++} + H_{+1,0}^{--}\right) \\ & - \epsilon\cos(2\phi_h)\ \mathrm{Re}\,H_{+1,-1}^{++}.\end{aligned}$$

where in the expressions for $\mathcal{W}_{XY}$ $H_{mn}^{ij}(z,P_{h\perp}^2)\big|_{p'}$ are replaced by $\mathcal{H}_{mn}^{ij}(W,Q^2,t)$, defined as

$$\mathcal{W}_{LL} = S_\parallel\lambda_e\left[\frac{\sqrt{1-\epsilon^2}}{2}\left(H_{+1,+1}^{++} - H_{+1,+1}^{--}\right) - \sqrt{\epsilon(1-\epsilon)}\cos\phi_h\ \mathrm{Re}\left(H_{+1,0}^{++} - H_{+1,0}^{--}\right)\right].$$

$$H_{mn}^{ij}(z,P_{h\perp}^2)\big|_{p'} = \frac{Q^2}{\mathcal{I}}\mathcal{H}_{mn}^{ij}(t_z)\,\delta\left[P_{h\perp}^2 - P_{h\perp,excl}^2(t_z)\right], \quad t_z = \frac{Q^2}{\mathcal{I}}(z-1),$$

Important to connect processes and write them in terms of HSFs, explicitly containing correlations between unpolarized and polarized measurements

From HSFs to Helicity Amplitudes

$T^{\nu\sigma}_{\mu\lambda}$ helicity amplitudes describing $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$ depend on x,Q^2,t

helicities

$$\mu, \nu \in \{-1, 0, +1\}, \quad \lambda, \sigma \in \{-\tfrac{1}{2}, +\tfrac{1}{2}\}.$$

$$F_{UU,T} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} + \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 + |T^{\nu\sigma}_{+1,-}|^2\right)$$

$$F_{UU,L} = \mathcal{H}^{++}_{0,0} = \mathcal{C} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} |T^{\nu\sigma}_{0,+}|^2$$

$$F_{LL} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\nu=-1}^{1} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{\nu\sigma}_{+1,+}|^2 - |T^{\nu\sigma}_{+1,-}|^2\right)$$

↓ pion limit v=0

$$\frac{d\sigma_{LL}}{dt} = \tfrac{1}{2}(\mathcal{H}^{++}_{+1,+1} - \mathcal{H}^{--}_{+1,+1}) = \frac{\mathcal{C}}{2} \sum_{\sigma=\pm\frac{1}{2}} \left(|T^{0\sigma}_{+1,+}|^2 - |T^{0\sigma}_{+1,-}|^2\right)$$

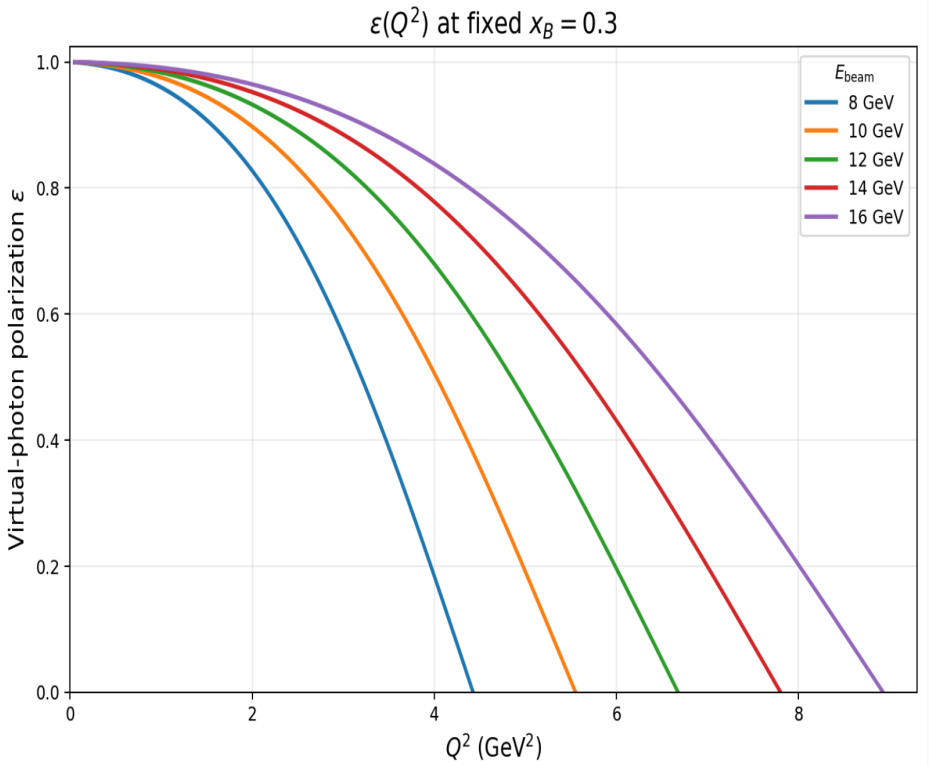
amplitude	photon	nucleon	Δ	forward factor K
$M_{0+,0+}$	L	non-flip	0	1
$M_{0-,0+}$	L	flip	−1	$\sqrt{-t'}/2M_p$
$M_{0+,++}$	T(+1)	non-flip	+1	$\sqrt{-t'}/2M_p$
$M_{0-,++}$	T(+1)	flip	0	1
$M_{0+,-+}$	T(−1)	non-flip	−1	$\sqrt{-t'}/2M_p$
$M_{0-,-+}$	T(−1)	flip	−2	$-t'/4M_p^2$

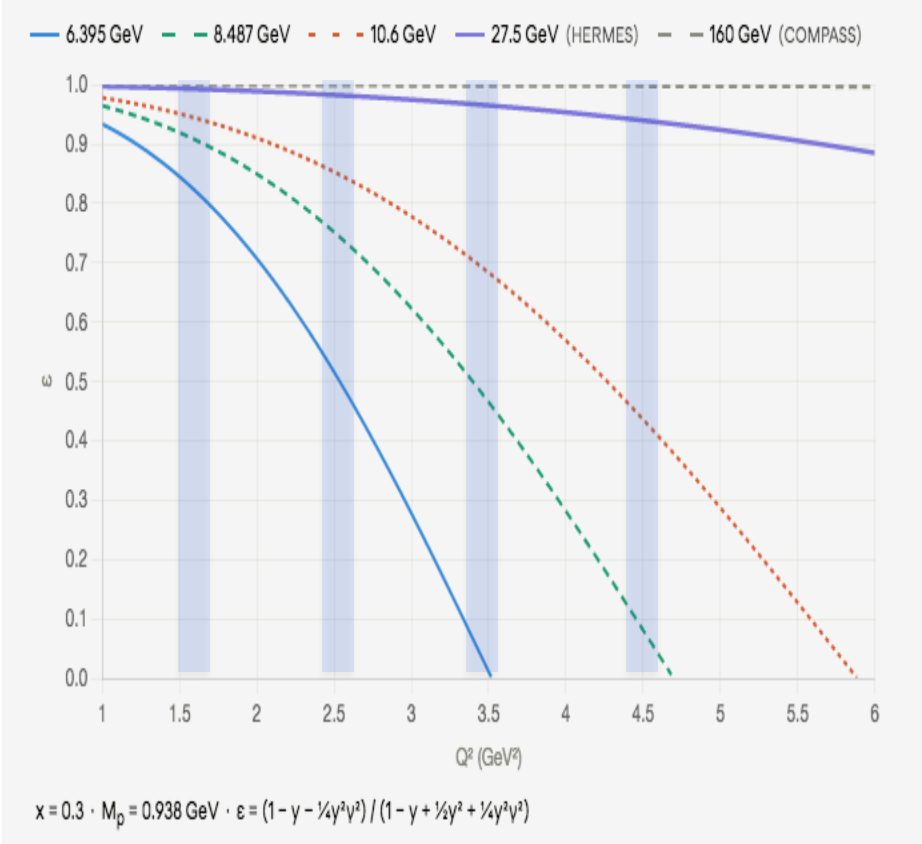
six independent amplitudes

Cross sections of exclusive processes extracted in terms of helicity SFs provide direct/complementary access to underlying amplitudes

ε-dependence for electroproduction experiments

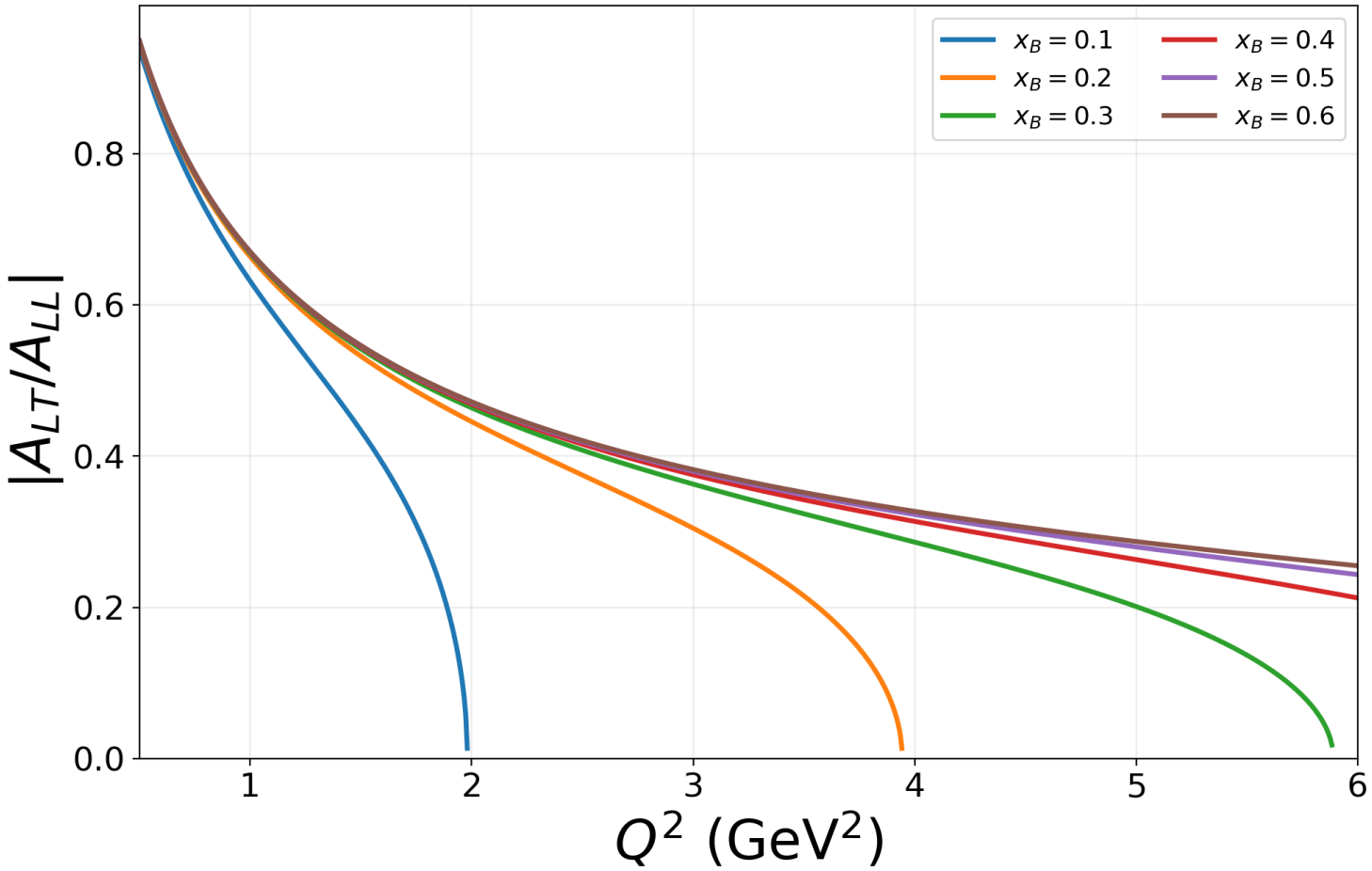
CLAS12 already collected data on proton for 6.4,6.5,7.5.8.5.10.2,10.6 GeV





Combining SDME measurements (may need “event base” analysis) at CLAS12 and HERMES/COMPASS will be important for model independent separation of longitudinal part

Monitoring the polarization



The double spin asymmetry for elastics at lower Q2 is comparable to L-Pol target