High-Luminosity Workshop Highlights: TMDs

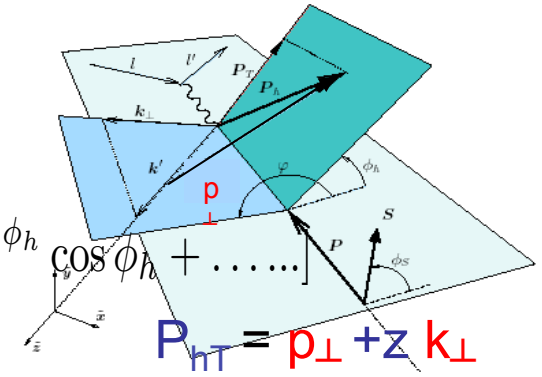
Harut Avakian (JLab)

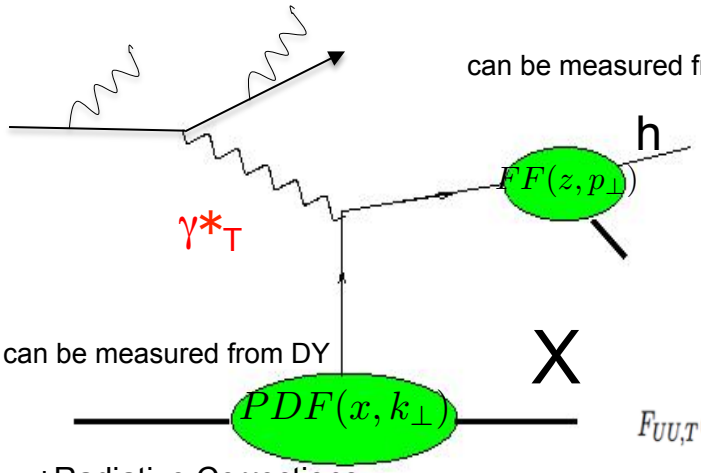
CLAS12 Collaboration Meeting, Nov 19, 2026

- Access to TMDs in SIDIS
  - •Understanding physics backgrounds (longitudinal photons)
  - •Contamination, correlations → understanding systematics
- Upgrading luminosity and reconstruction tools
- Updating the analysis framework
  - •from structure functions→helicity structure functions
  - •from bin-based analysis to event-based analysis
- Conclusions and Summary

SIDIS: from observables to TMDs

$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP_{h\perp}^2 d\phi_h} = \frac{\pi\alpha^2 y}{x_B y Q^2(1-\epsilon)}\left[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \ldots\ldots\right]$$





Probability to produce 1 or 2 hadrons in single photon exchange

$$eN \to e'hX$$

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

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

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = x\sum_q \mathcal{H}_{UU,T}^q(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) + Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

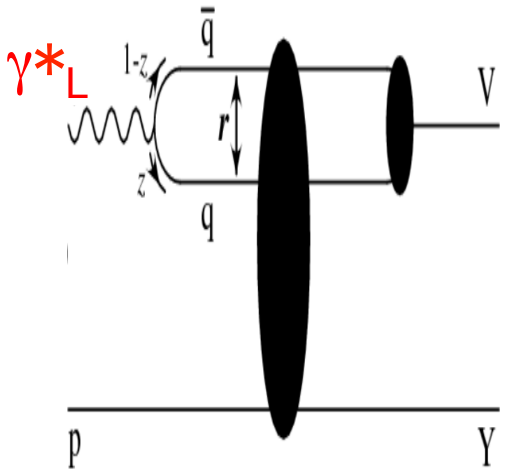
hard part

- Factorization proven for transverse photons, providing access to TMD distribution and fragmentation functions
- Separation of longitudinal and transverse photon contributions in SIDIS, and **development of new experimental extraction framework, identified as the main focus for near term**

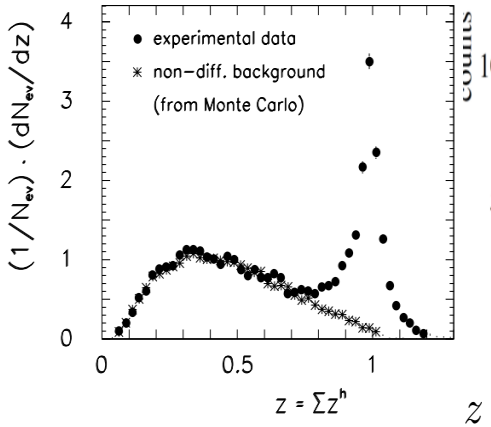
Exclusive VMs (ρ^0, ω,ϕ, J/Ψ,…)

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

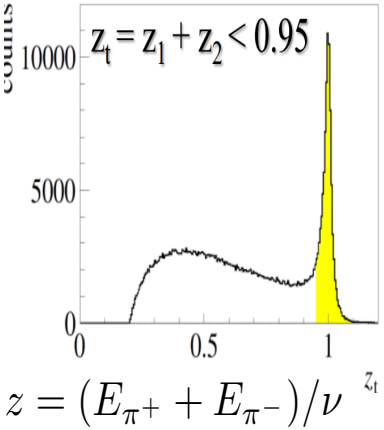
$\mu, \nu, \lambda, \sigma$ → helicities



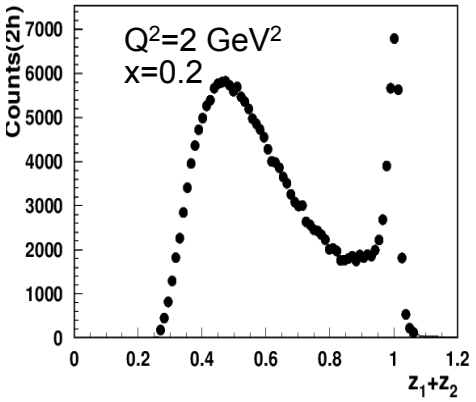
E665 Eμ = 470 GeV



COMPASS Eμ = 160 GeV



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 their fraction will only increase at higher energies
→No indication of "Different rho at JLab"?

For GPD based interpretation need experimental separation of contributions

Studies of exclusive processes require high resolution and multidimensional measurements !!!

Highlights from presentations

1) Leonard Gamberg on relevance of L/T separation (predicted R ~25-30%)
2) Dave Gaskell on Hall-C L/T measurements (measured R ~25%)
3) Fatiha on the role of Target Fragmentation and “rho-free” SIDIS
4) Nobuo on attempts to describe the JLab data (modification of FF in large z-limit)
5) Valerii Klimenko on CLAS12 unpolarized studies
6) Anselm Vossen on CLAS12 polarized SIDIS

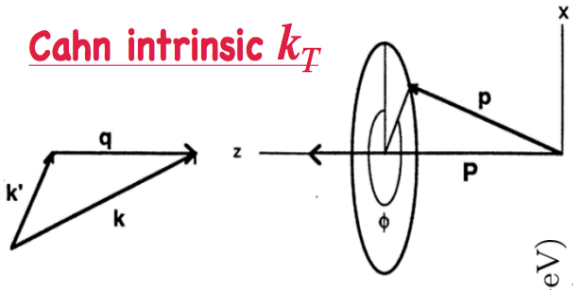
7) Akushevich on RC to azimuthal modulations, and introduction of cross contributions (cross contribution to measured moments due to RC)
8) Ralf Seidl on latest fragmentation function (large z exclusive limit measured, and can be used in comparison with semi-exclusive limit)
9) Bakur Parsamyan on COMPASS (studies of impact of VMs on SIDIS)
10) Vlad Khachatryan on SIDIS with Solid lite
11) Andrew Puckett on SIDIS at Hall-A
12) Albi Kerbizi on Polarizing Pythia hadronization (introduction of polarization effects critical for studies of polarization effects in MC)

SIDIS phenomenology

L. Gamberg(JLab Hi Lumi workshop)

Factorization & Matching collinear to TMD unpolarized/angle independent Collins Soper Sterman NPB 1985

Cahn intrinsic k_T



- **"TMD" region**

$$(p_T \sim k_T) \sim q_T \ll Q$$

- Low TMD factorization

$M \sim q_T \ll Q$

$F_{UU,T} \sim \mathbb{C}\left[f_1 D_1\right]$ Leading power

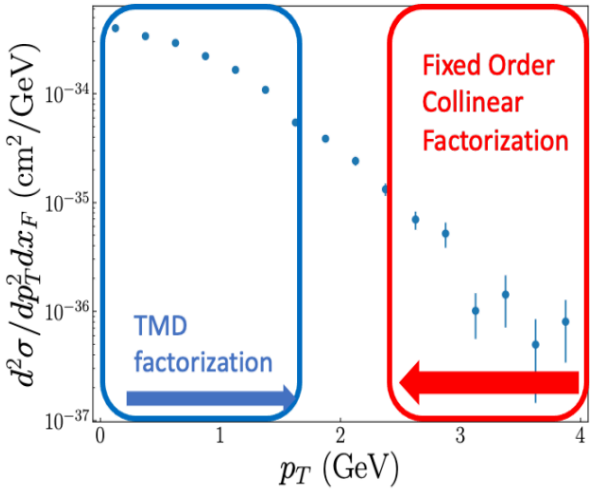
$F_{UU,L} \sim \frac{M^2}{Q^2}\mathbb{C}\left[\frac{p_T^2}{M^2} f_1 D_1\right]$ Sub-sub leading

- High collinear factorization

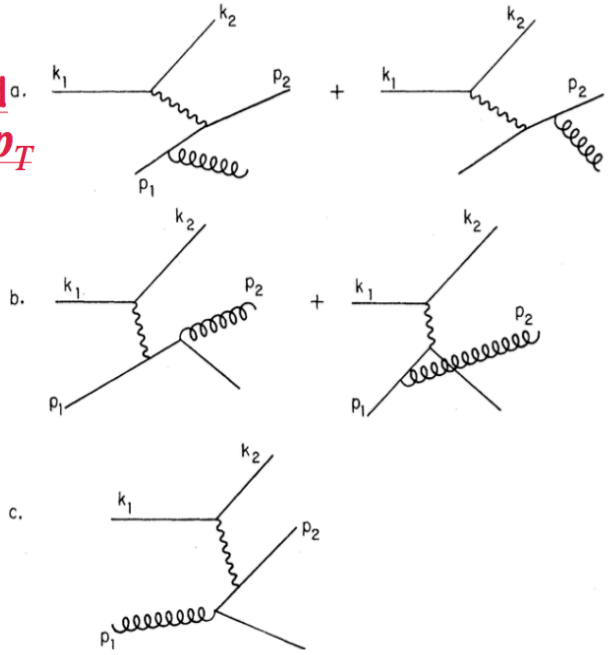
$M \ll q_T \sim Q$

$F_{UU,T} = \alpha_s \mathbb{F}\left[f_1 D_1\right]$ Leading power

$F_{UU,L} = \alpha_s \mathbb{F}\left[f_1 D_1\right]$ Leading power



Georgi & Politzer hard gluon bremsstrahlung p_T



- **"Collinear" region**

$$\Lambda_{qcd} \ll q_T \sim Q$$

Comprehensive study of matching the hi & low $q_T = P_{h\perp}/z$ in the AY (overlap) region in SIDIS attention given to azimuthal and polarization dependence Bacchetta, Boer, Diehl, Mulders JHEP (2008)

SIDIS phenomenology

L. Gamberg(JLab Hi Lumi workshop)

Pheno impacts/opportunities

R_{SIDIS} predictions at Compass kinematics

→ full error budget

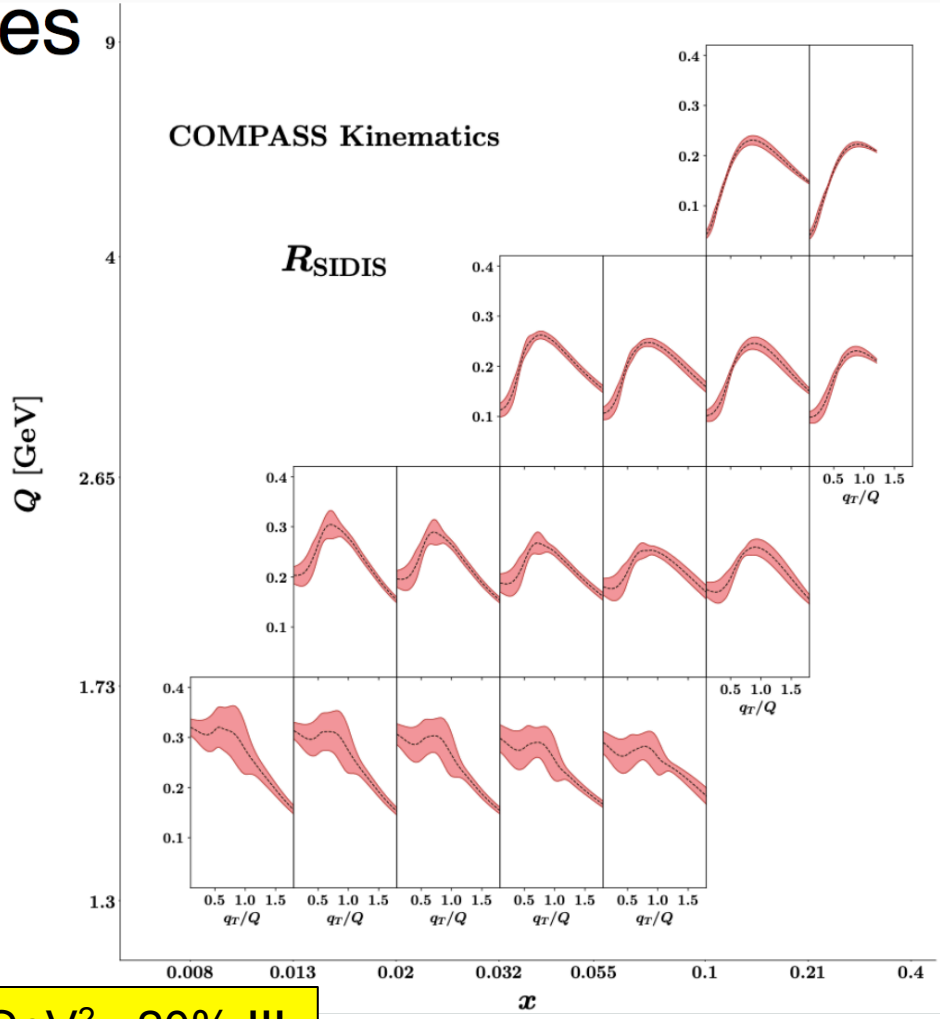
→ trends with increasing Q

(1) Magnitude of $R_{\mathrm{SIDIS}}(q_T \to 0)$ decreases

(2) $R_{\mathrm{SIDIS}}(q_T \to 0) \sim (q_T/Q)^2$

(3) Uncertainty decreases

How do theory & experimental uncertainties compare?



Note: Longitinal fraction event at Q^2 ~100 GeV^2 ~20% !!!

D. Gaskell

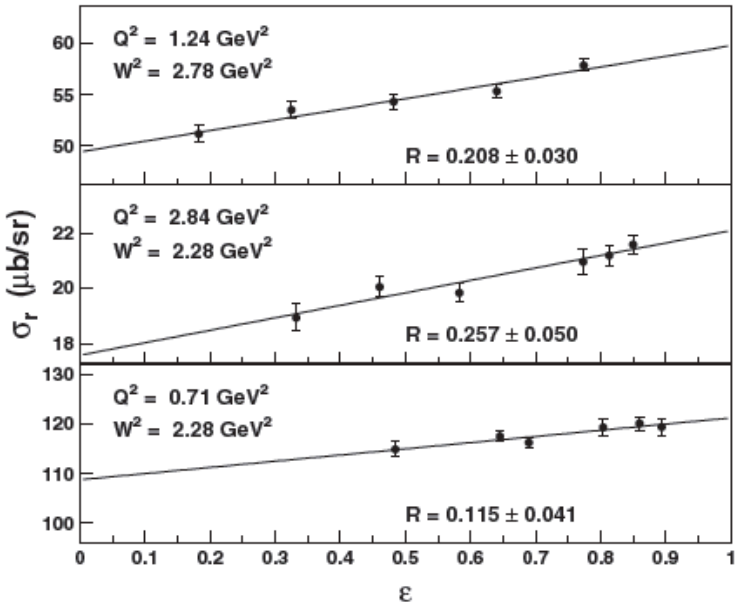
(Inclusive) Rosenbluth (L-T) Separations

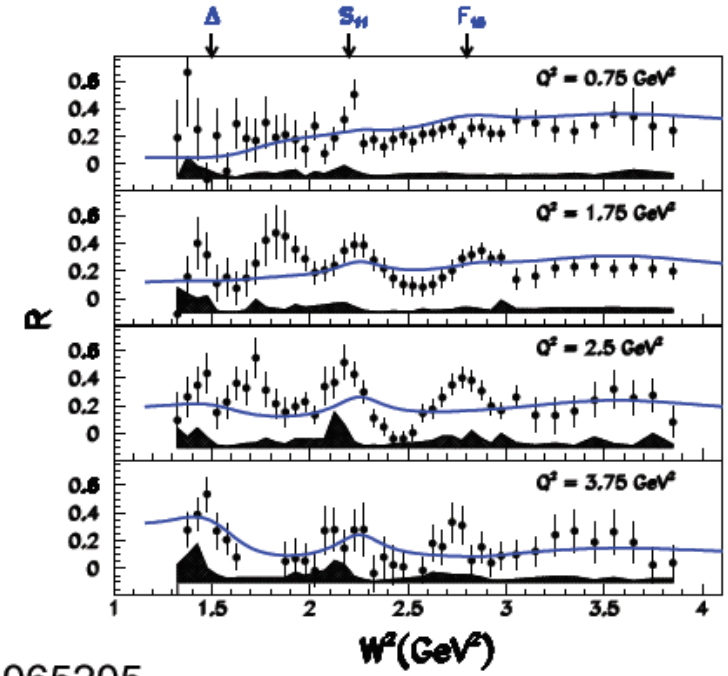
ive measurements:

$$\frac{d\sigma}{d\Omega dE} = \Gamma\left[\sigma_T(\nu, Q^2) + \epsilon\sigma_L(\nu, Q^2)\right]$$

by making measurements at different beam energies while
g x and Q^2 fixed)

$$\epsilon = \left[1 + 2\left(1 + \frac{Q^2}{4M^2x^2}\right)\tan^2\frac{\theta}{2}\right]^{-}$$



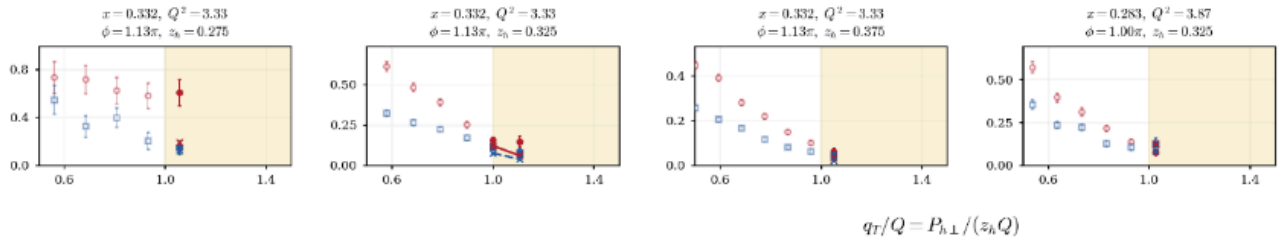


on Lab

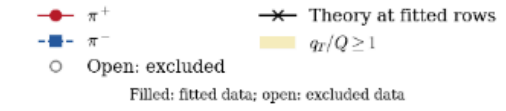
- *Phys.Rev.C* 105 (2022) 6, 065205

In pion SIDIS the R is expected to be bigger

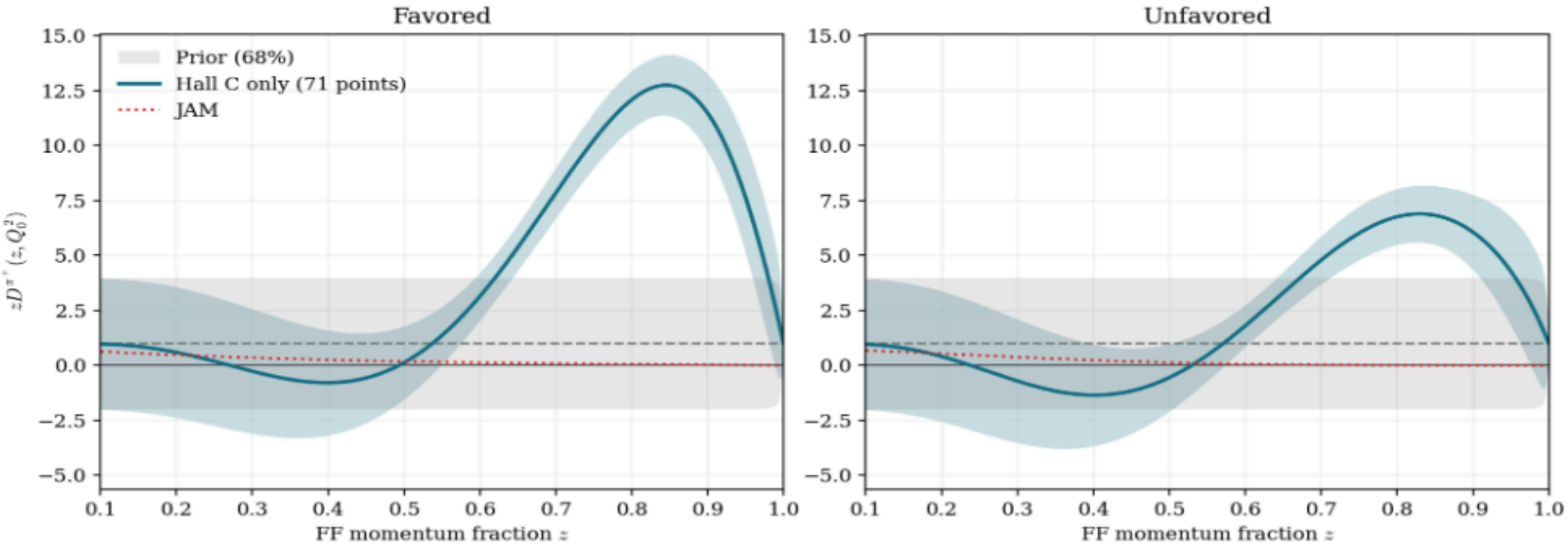
Pion multiplicities



N. Sato (High Lumi Workshop)



PRELIMINARY



- To fit Hall-C data on precision multiplicities→ modification needed for FFs
- Cuts in z and M_X should be studied in details, also for evaluating the systematics (ex z<0.7)

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

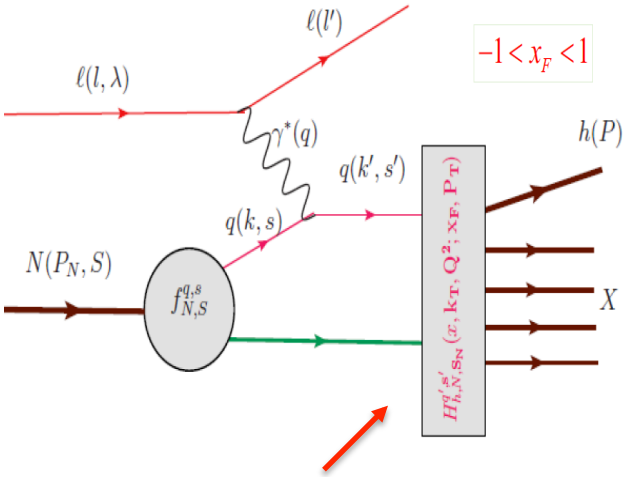
$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP_{h\perp}^2 d\phi_h} = \frac{K(x,y)}{Q^4}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi}\right\}$$

$M_X^2 - M_p^2 > 0$

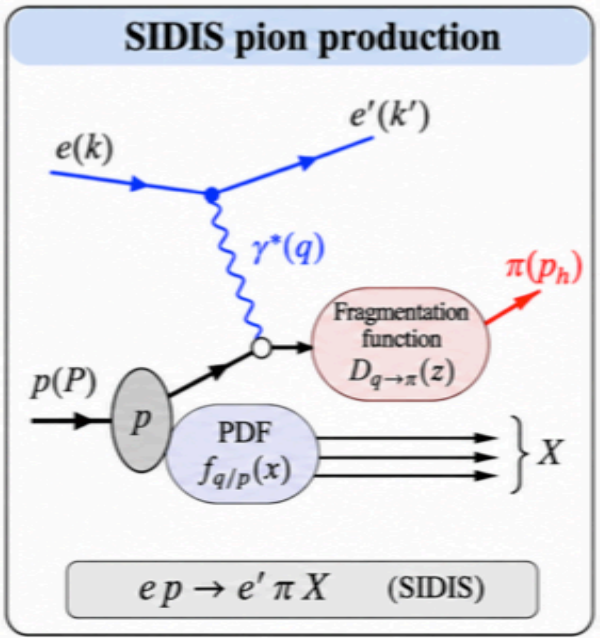
$-t = M_p^2 - M_X^2 + \frac{Q^2}{x_{Bj}}(1-z)$

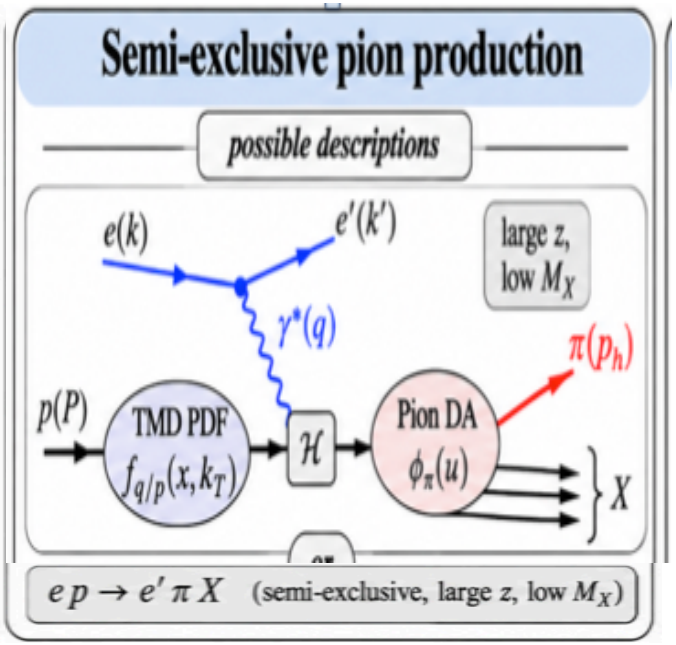
The only difference with exclusive production is the

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



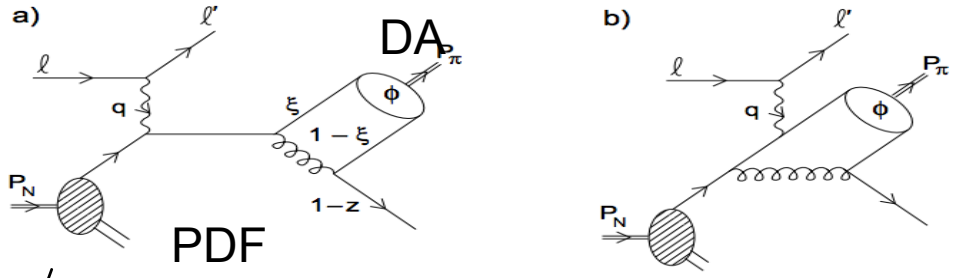


leading γ^*_T z→1 leading γ^*_L

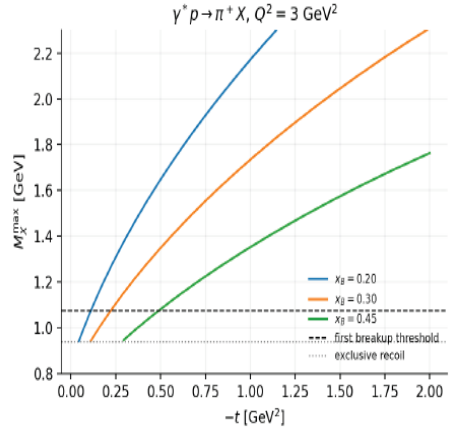
- Full event generators such (ex. PYTHIA now accounting polarization degrees of freedom) describe semi-inclusive production of hadrons in the full energy range of experiments and also exclusive limit!!!)
- Semi-exclusive limit defines "in-coherent" production in exclusive limit
- Behaviour of semi-exclusive production, Q^2-dependence of γ^*_T and γ^*_T contributions practically unknown!!!

SIDIS cross sections in the z→1 limit

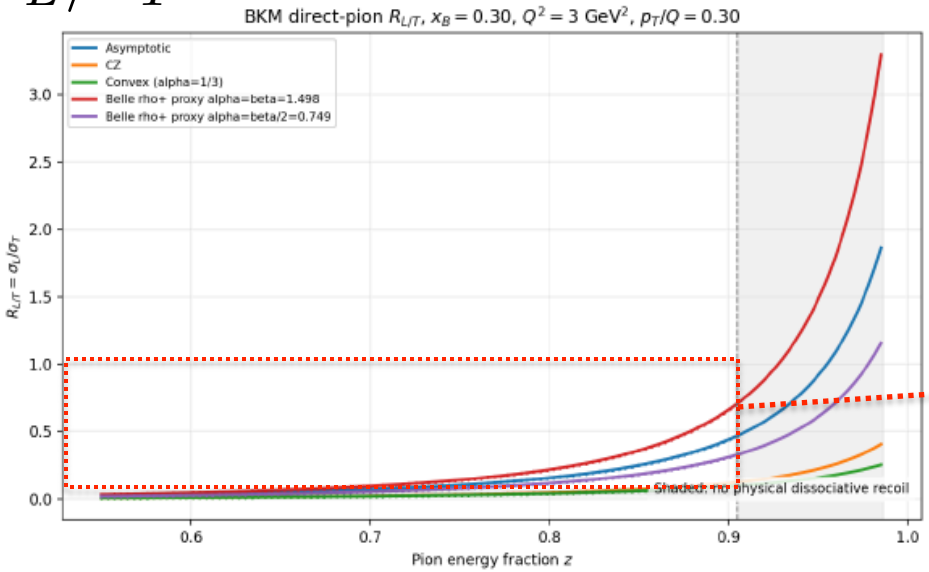
Brandenburg Muller, Khoze (BMK) arXiv: 9410327 semi-exclusive processes (z→1) provide corrections to SIDIS and HEP



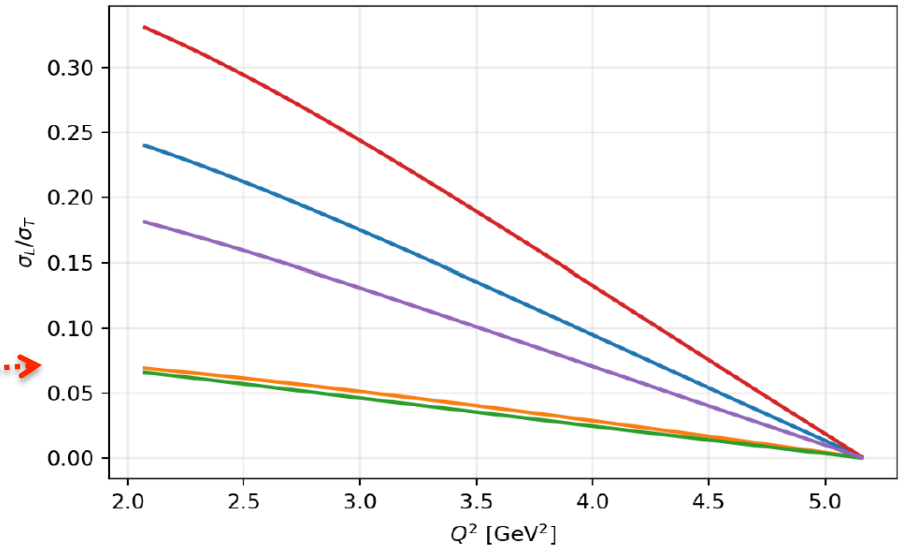
incoherent
"exclusive"



σ_L/σ_T



σ_L/σ_T use NNPDF for PDF part



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

Transverse & Longitudinal photons

Structure function	γ^* helicity	prefactor	low-P_{hT} twist	low-P_{hT} PDF	high-P_{hT} calculation twist	order	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	$\sqrt{1-\epsilon^2}$	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	$1/(QP_{hT}^2)$	=	–

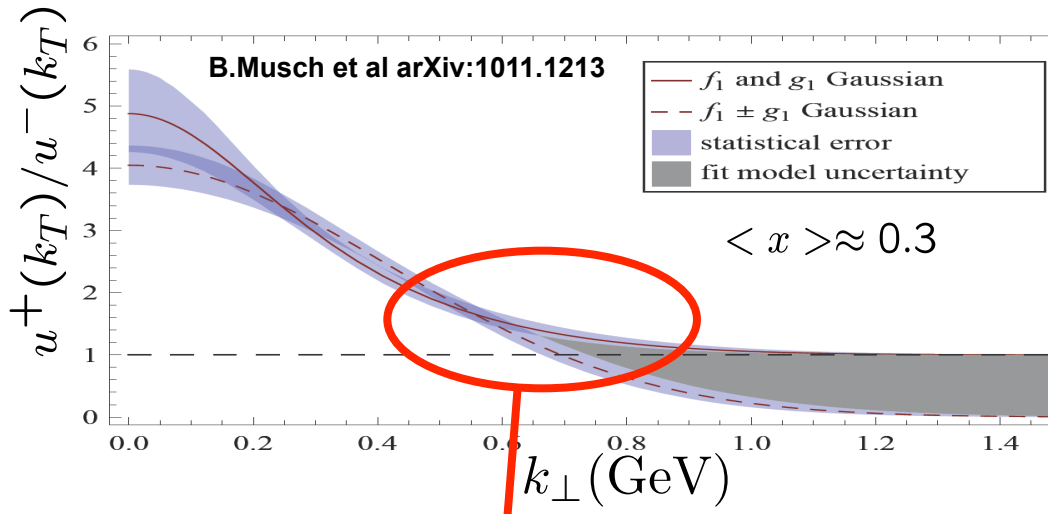
Need a similar table for exclusive Helicity Structure Functions!!!

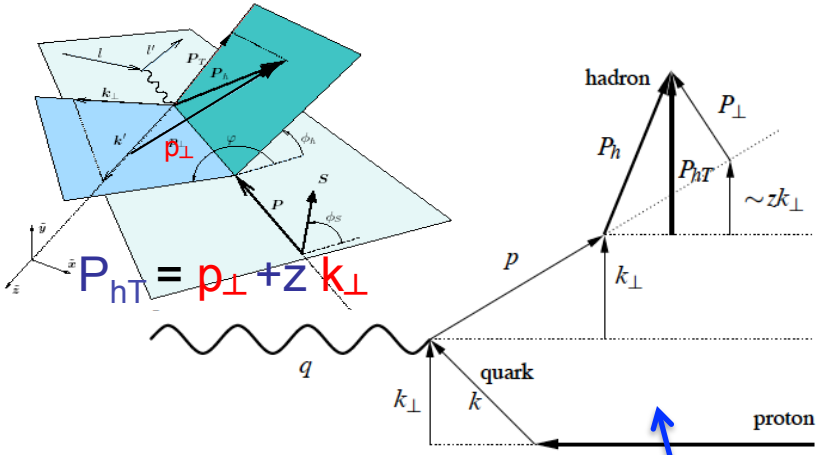
Bacchetta-0611265

Important features to notice

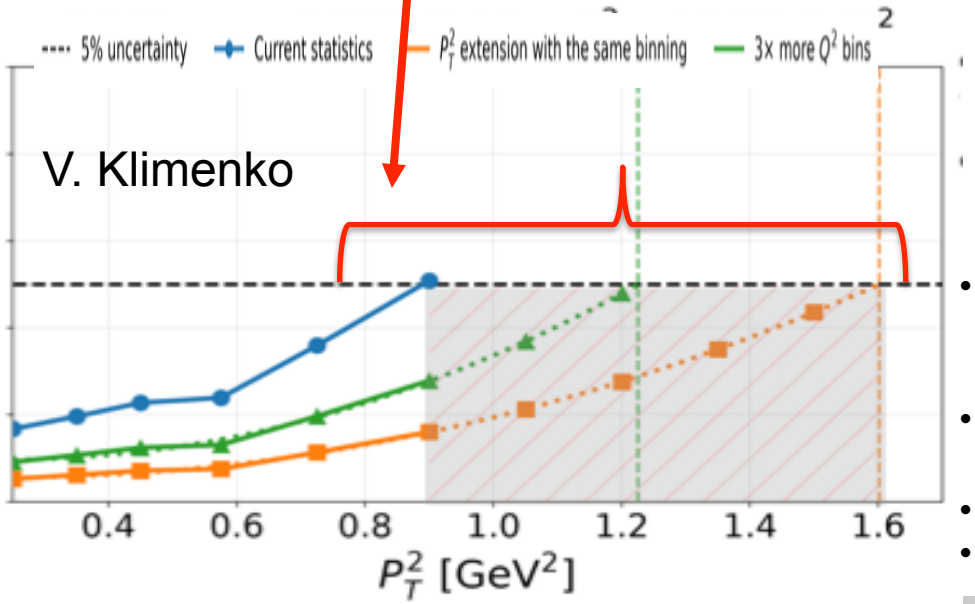
- Some critical observables (cross sections, $\sin(\phi-\phi_S)$ containl contributions from TT/LL and can't be separated easily
- No L in Double Spin 0 moment
- Important to quantify cross contributions of different modulations due to RC and acceptance
- HT contributions large and can serve important role in understanding the dynamics

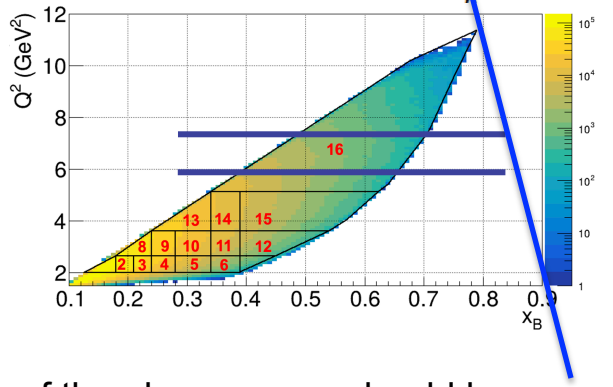
SIDIS: Extending the phase space in P_T,Q^2





$0.5 < z < 0.6$

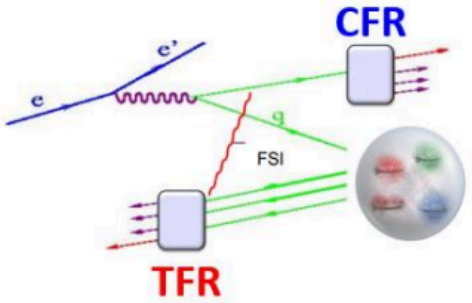


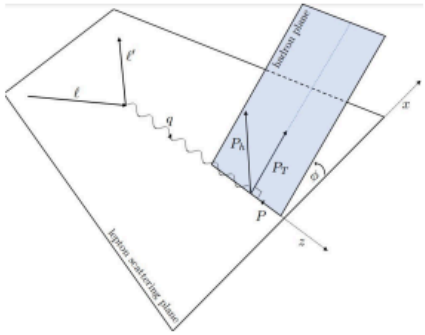


- Increase of the phase space should be accounted for most critical range P_T>0.7 GeV from 1 bin to 5 (x5)
- Large z important, but requires understanding of HT(quark-gluon correlation) effects
- Higher Q^2 critical for measurements of HT
- Higher P_T has less contributions from L-photon

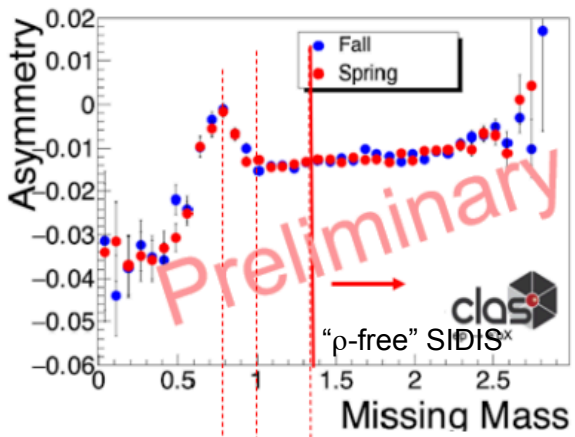
Selection of Target Fragmentation Region events: epX

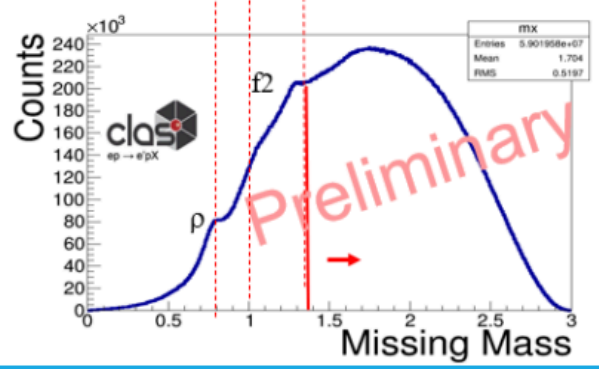
F. Benmokhtar (Duquesne U.)

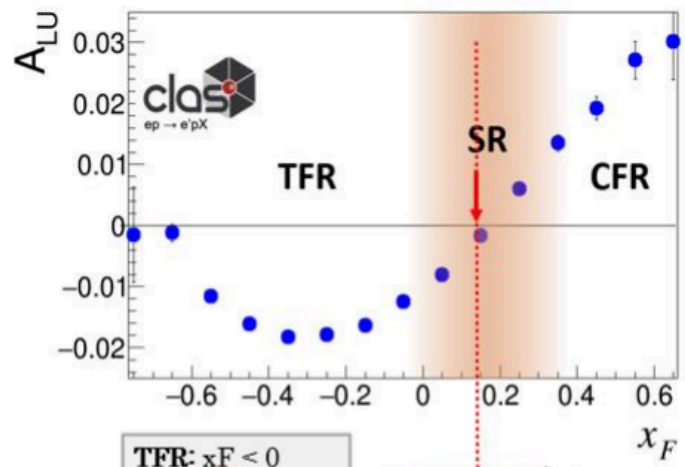


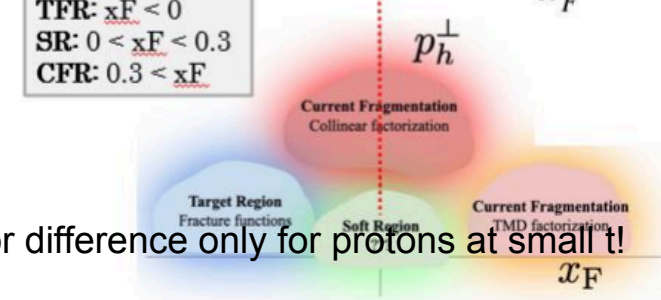


$$A(\phi)_{LU} = \frac{1}{p}\left(\frac{N^+ - N^-}{N^+ + N^-}\right)$$









Major difference only for protons at small t!

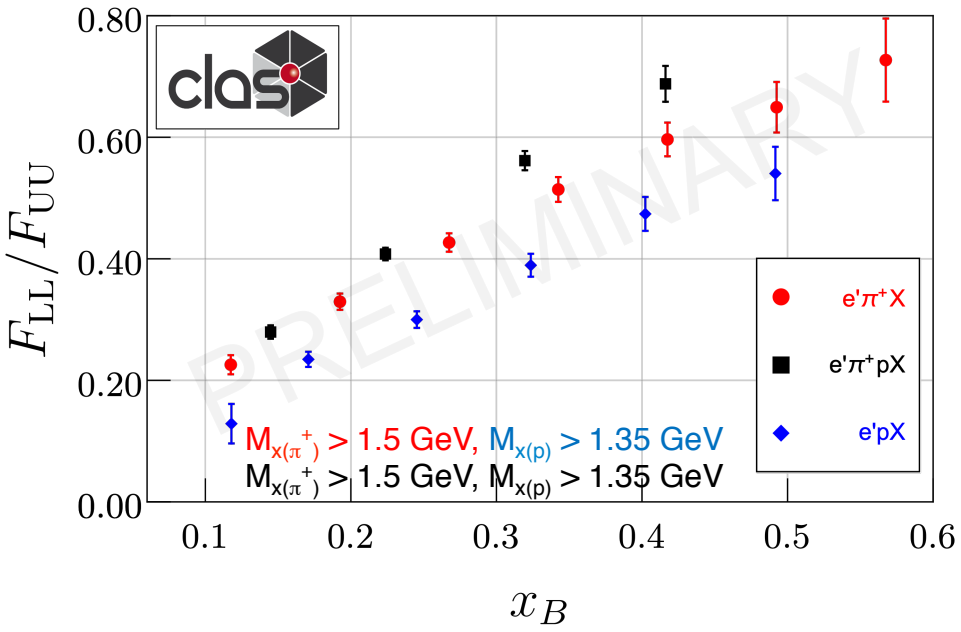
F. BENMOKHTAR, CLAS12 VINCENT ROCKSMOOT, NA, NOV 2025 18

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

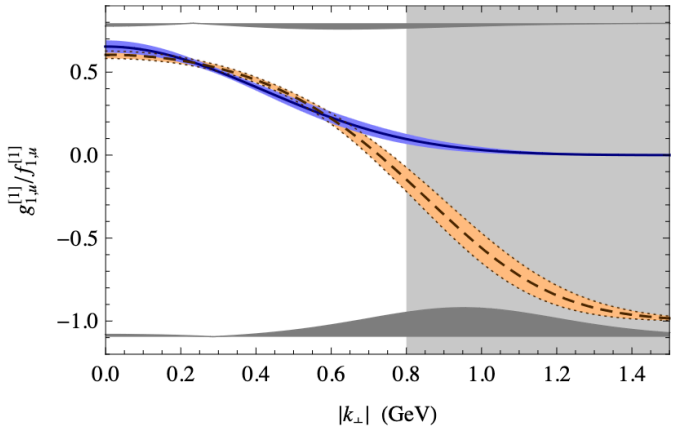
Longitudinal DSAs for single hadrons

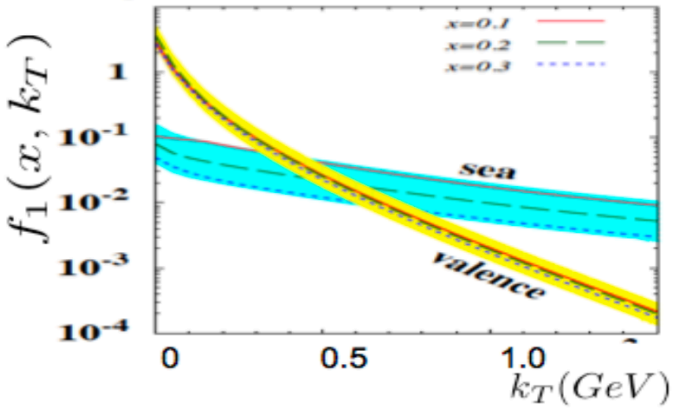
A. Vossen

- Explore p_T dependence of $A_{LL} \propto f_1(x, k_T)/g_1(x, k_T)$
- Sensitive to spin dynamics
- Relativistic dynamics (Melosh rotation)



B. Musch et al (arxiv 1011.1213)





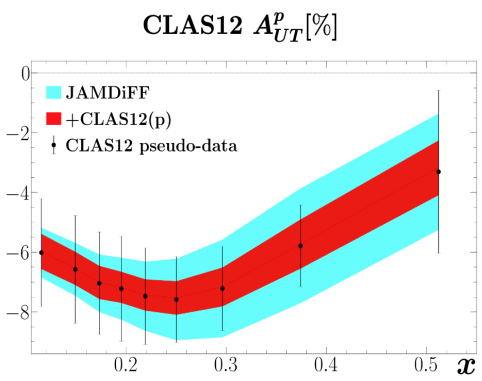
Double spin asymmetries likely get significant dilution from exclusive VM production dominated by longitudinal photons

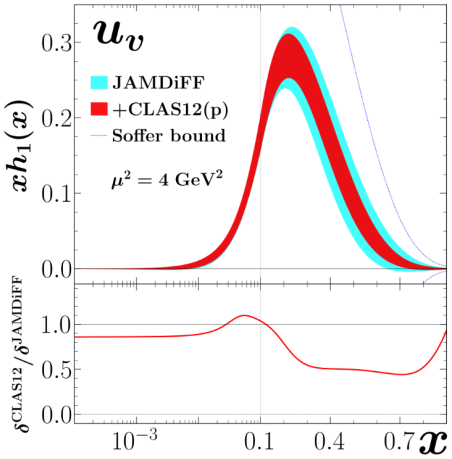
P.Schweitzer et al. arXiv:1210.1267

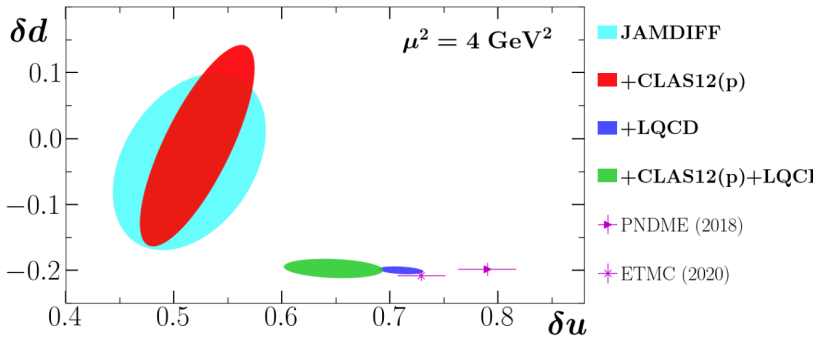
$e\ p \rightarrow e\ \pi+\pi-X$

A. Vossen

- **Run Group H:** 1st transversely polarized target experiment at CLAS12
- Recently approved with rating **A** by the Program Advisory Committee (PAC) – awaiting beam-time
- Recent projections from the JAM group show **RG-H** will be *competitive* with lattice efforts to constrain the tensor charge [8]





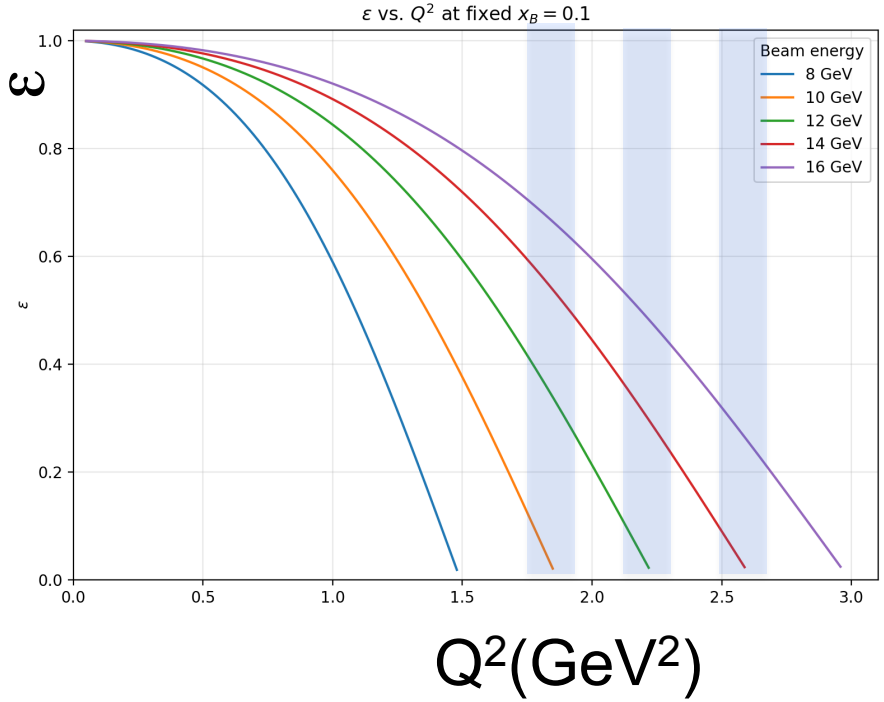


Sawaya et al (*Phys.Rev.D* 114 (2026) 7, 074009)

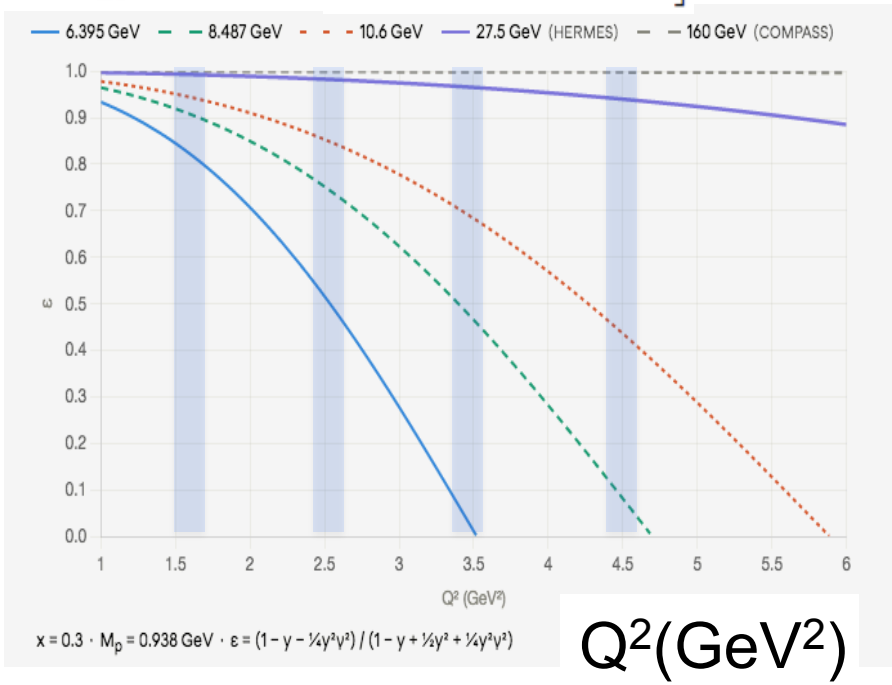
ε-dependence for electroproduction experiments

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

$$\frac{d^4\sigma}{dx_B\,dQ^2\,dt\,d\phi} = \frac{\Gamma_H}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos(2\phi) + P_\ell\sqrt{2\epsilon(1-\epsilon)}\frac{d\sigma_{LT'}}{dt}\sin\phi\right]$$



$Q^2(GeV^2)$



$Q^2(GeV^2)$

Combining measurements (will benefit from "event base" framework) at different energies of JLab and HERMES/COMPASS will be important for model independent separation of dynamical contributions in a wide Q^2 range with controlled systematics

Wider range in Q^2 (making bridge with COMPASS/EIC) will benefit from energy upgrade

Experimental studies of 3D QCD in SI era

Increasing the luminosity and/or energy, will provide access to higher Q^2 and P_T, and open new opportunities for separation of different dynamical contributions in the most critical kinematics

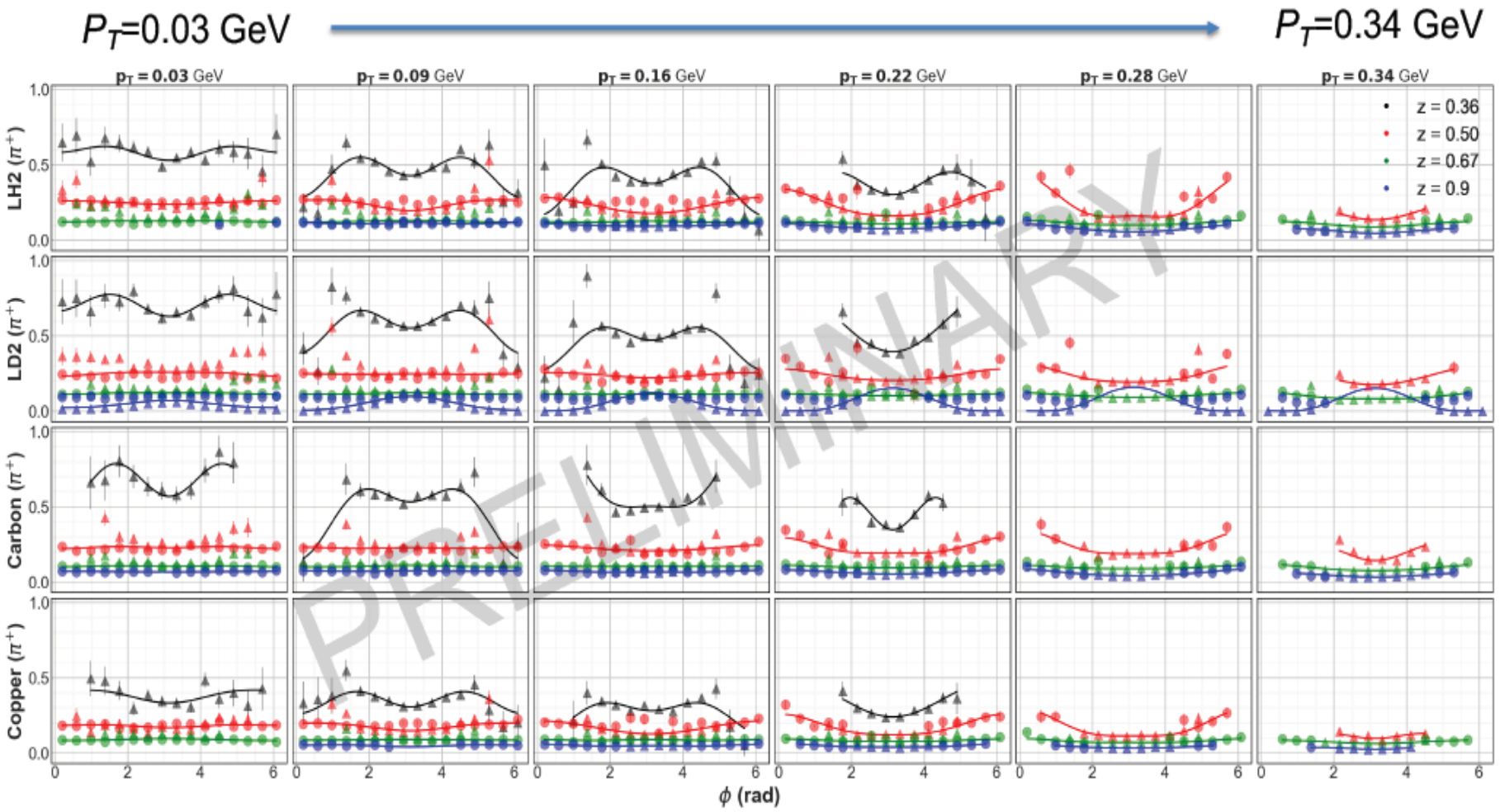
- Separation of dynamical contributions, including L/T photon contributions critical for interpretation both for SIDIS and Hard Exclusive
- Combination of measurements of spin-dependent cross sections and multiplicities (unpolarized, longitudinally and transversely polarized targets)
- Moving from bin-based analysis to event-based analysis increases sensitivity, and helps with combination of data sets from different experiments and facilities

- Validation of the output of AI-based complex extraction frameworks is critical, making development of realistic SIDIS MC (polarized PYTHIA) and exclusive MCs for exclusive processes based on helicity amplitudes(currently available for ρ, $\pi 0$ $\pi+$) high priority

- support slides

Preliminary R-SIDIS Multiplicities

D. Gaskell



Julio Gil Gutierrez, UTK

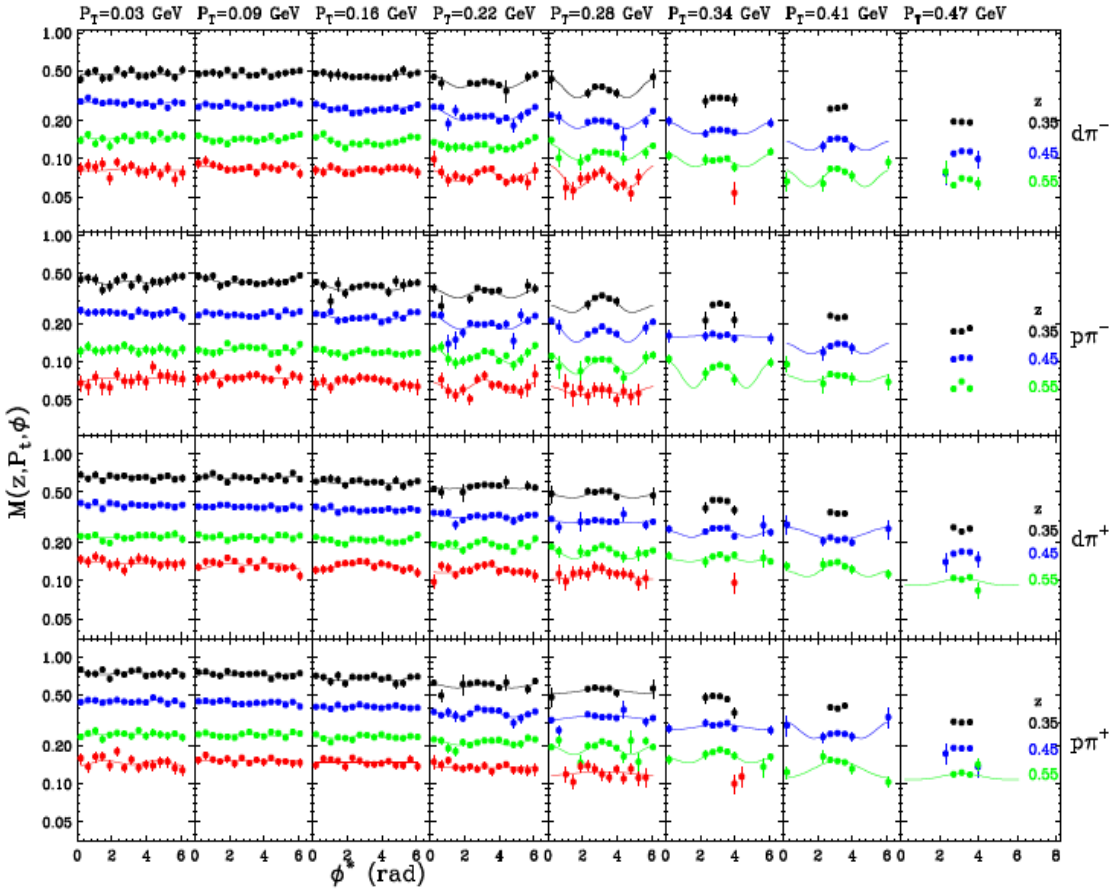
Hall C Results: P_T and ϕ Dependent Multiplicities

P_T and ϕ dependence extracted for several kinematics

I) x=0.31, Q^2=3 GeV^2
II) x=0.30, Q^2=4.1 GeV^2
III) x=0.45, Q^2=4.5 GeV^2

Multiplicity can be extracted by fit to the following form:

$$M(z, P_t, \phi) = M_0 \left[1 + A\cos\phi + B\cos 2\phi\right]$$



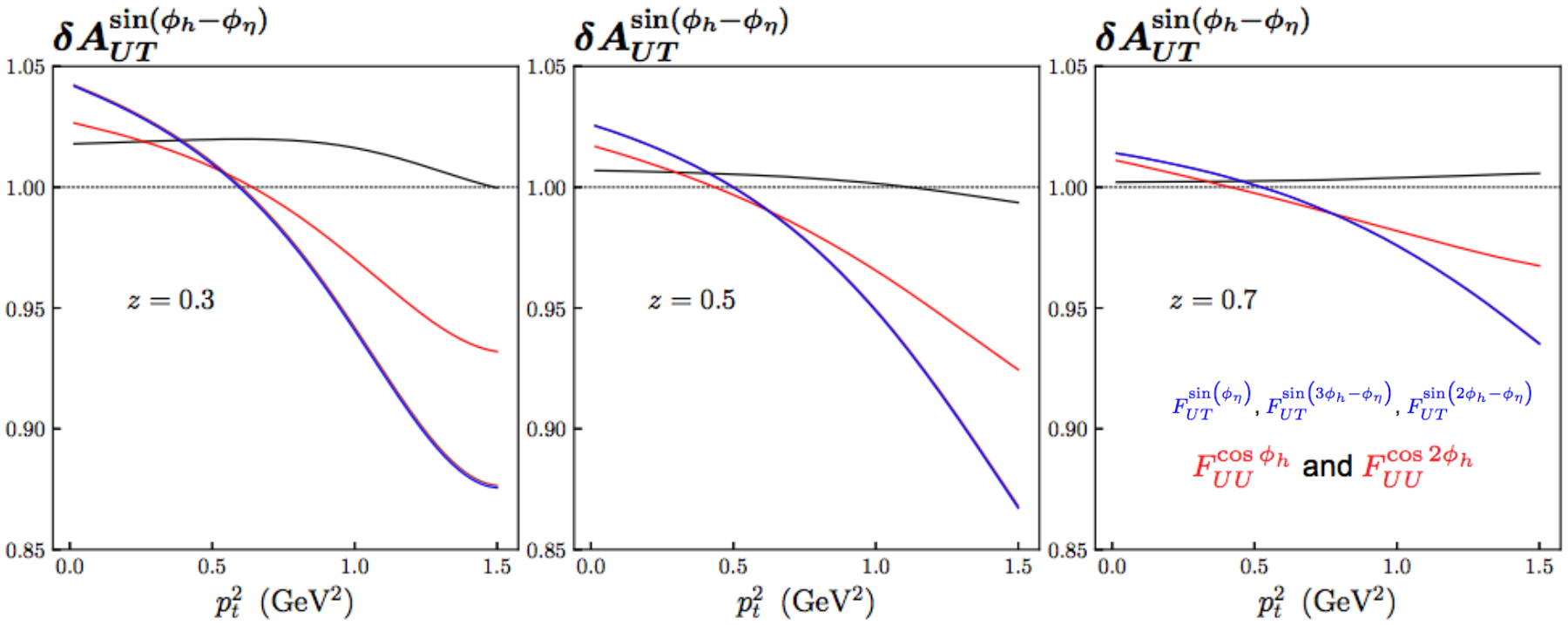
x=0.31, Q^2=3 GeV^2

PT-SIDIS: *Phys.Rev.C* 113 (2026) 3, 035205

Sivers asymmetries for JLab

$E_{beam} = 11$ GeV, $Q^2 = 3$ GeV^2, $x = 0.2$

I. Akushevich



$$\delta A_{UT}^{\sin(\phi_h-\phi_\eta)} = 1 + \frac{A_{UT,\,RC}^{\sin(\phi_h-\phi_\eta)}}{A_{UT,\,B}^{\sin(\phi_h-\phi_\eta)}}$$

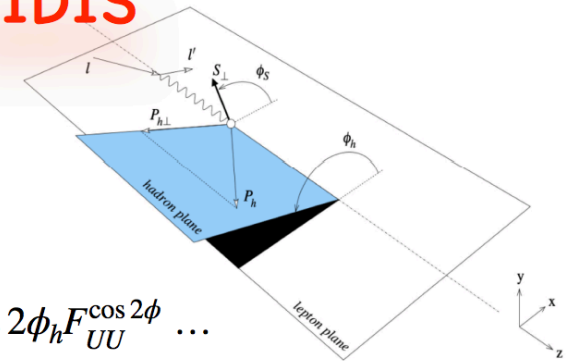
cross contributions from other moments may be significant!!!

SIDIS phenomenology

L. Gamberg(JLab Hi Lumi workshop)

21st century interpretation: from DIS to SIDIS

$$R = \frac{\sigma_L}{\sigma_T} \longrightarrow \frac{F_{UU,L}}{F_{UU,T}}$$



$$\frac{d\sigma}{dx dy dz d\phi_h dP_{h\perp}} = \frac{\alpha^2}{xQ^2}\frac{y}{2(1-\varepsilon)}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi} + \varepsilon\cos 2\phi_h F_{UU}^{\cos 2\phi} \ldots\right.$$

- Does ∃ TMD observable for $F_{UU,L}$?
- Tree level TMD factorization Mulders et al. NPB 1996 Bacchetta et al. JHEP 2007

$$F_{UU,T} = \mathbb{C}\left[f_1 D_1\right], \qquad F_{UU,L} = \mathbb{C}\left[\,.\,?\,.\,\right]$$

$$\mathcal{C}\left[wfD\right] = \sum_a x e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T + \boldsymbol{q}_T\right) w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2)$$

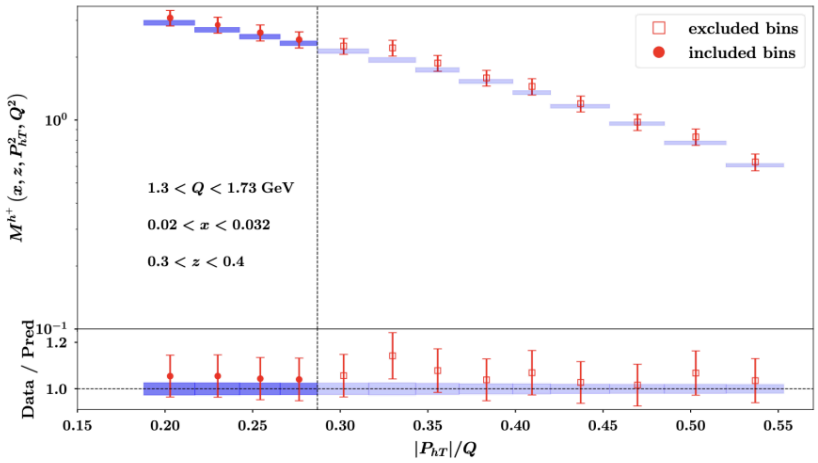
SIDIS phenomenology

L. Gamberg(JLab Hi Lumi workshop)

Multiplicity: SIDIS cross section normalized to DIS

$$M^h(Q^2,x,z,P_{h\perp}) \equiv \frac{dxdQ^2}{d^2\sigma^{\rm DIS}(Q^2,x)}\frac{d^4\sigma^h(Q^2,x,z,P_{h\perp})}{dxdQ^2dzdP_{h\perp}}$$

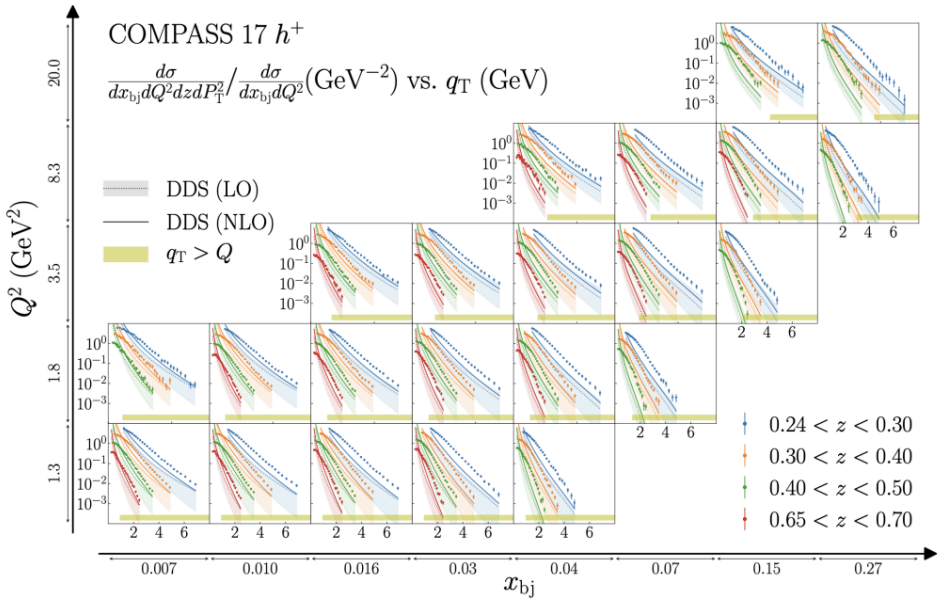
MAP Bacchetta et. al., arXiv:2206.07598v2 [hep-ph] (2022)



W term describe "large" P_{hT} data surprisingly well beyond "TMD region"? MAPTMD22

Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution	FF evolution
NLL	0	1	2	LO	LO
N^2LL	1	2	3	NLO	NLO
N^3LL^-	2	3	4	NNLO	NLO
N^3LL	2	3	4	NNLO	NNLO

Gonzalez-Hernandez et. al., arXiv:1808.04396v2 [hep-ph] (2018)



FO theory does not describe "large" q_T data so well

Take away: Interplay of large & small P_{hT}

SIDIS phenomenology

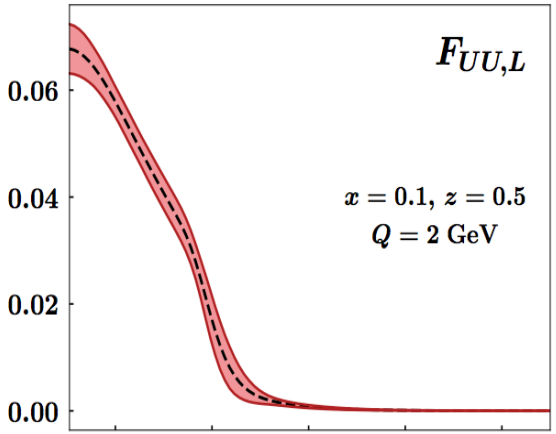
L. Gamberg(JLab Hi Lumi workshop)

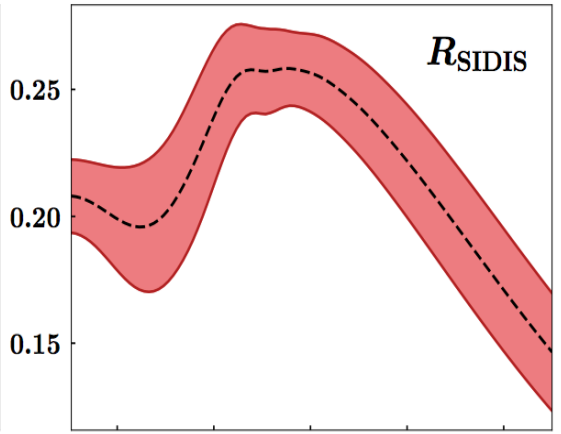
Transverse momentum dependence

$$R_{SIDIS} = \frac{F_{UU,L}}{F_{UU,T}}$$

→ weight for TMD contribution

$$v(p_T) = \frac{4p_T^2}{1 + 4p_T^2/Q^2} \to \frac{4p_T^2}{Q^2} \text{ when } p_T \sim 0$$





$$F_{UU,L} = w(q_T)\, F_{UU,L}^{[M\sim q_T \ll Q]} + \left(1 - w(q_T)\right) F_{UU,L}^{[M \ll q_T \sim Q]}$$

$$F_{UU,L}^{[M\sim q_T \ll Q]} = \frac{M^2}{Q^2}\mathbb{C}\left[w(p_T) f_1 D_1\right], \qquad F_{UU,L}^{[M \ll q_T \sim Q]} = \textit{Fixed order}$$

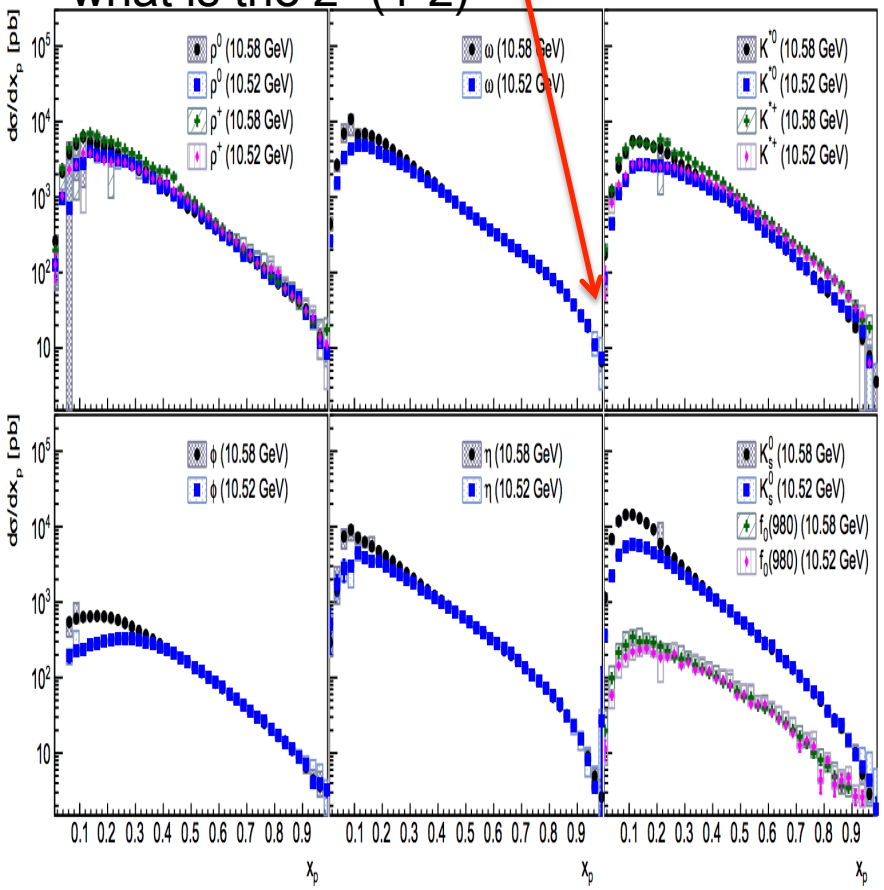
$$q_T = P_T/z$$

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

R. Seidl

what is the z^{α} $(1-z)^{\beta}$

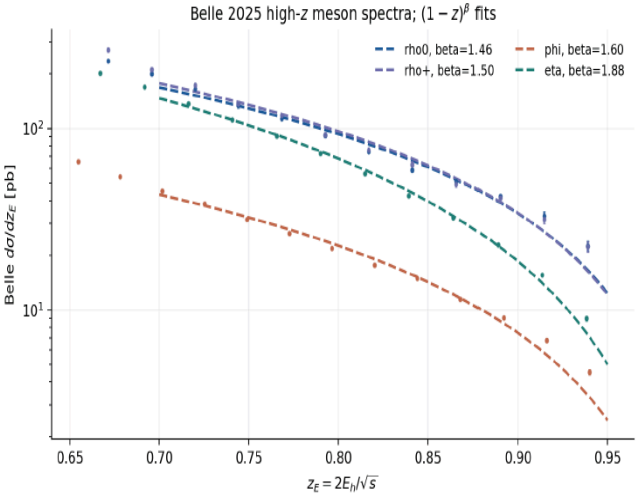
2411.12216



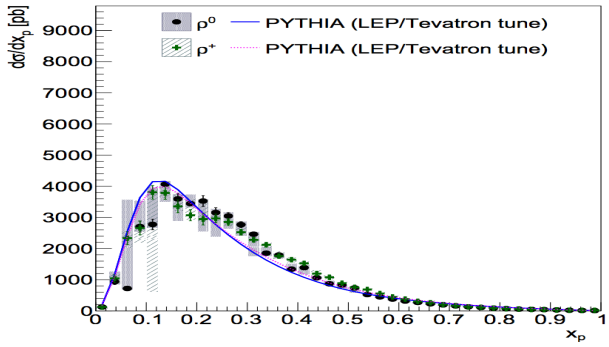
Belle: production cross sections as a function of x_p

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"



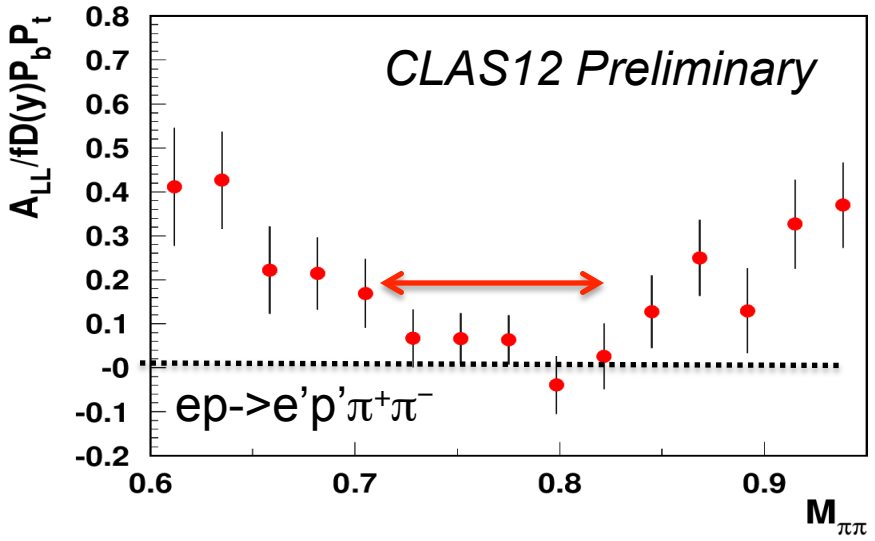
slightly more rho+!

Possible contribution from γ^*_T

Semi-exclusive contributions more suppressed for scalar mesons

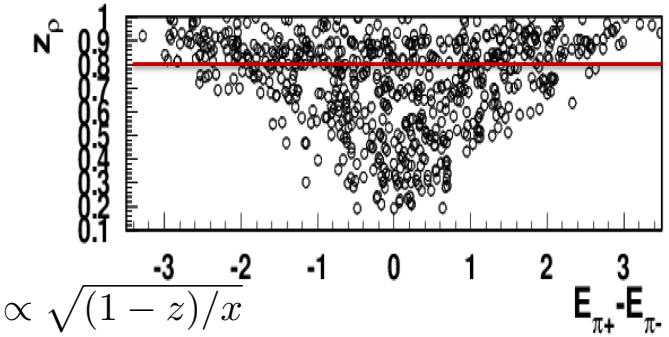
γ^*_T contribution from $\rho 0$ $\rho +$ comparable?

Studies of ρ^0 impact with longitudinally polarized NH_3 target

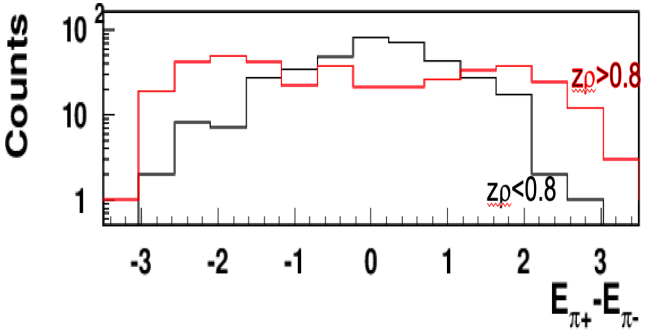


Need clear separation of hydrogen from NH_3
and "diffractive" exclusive ρ0s from exclusive $\pi+\pi-$

Polarization of rho



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



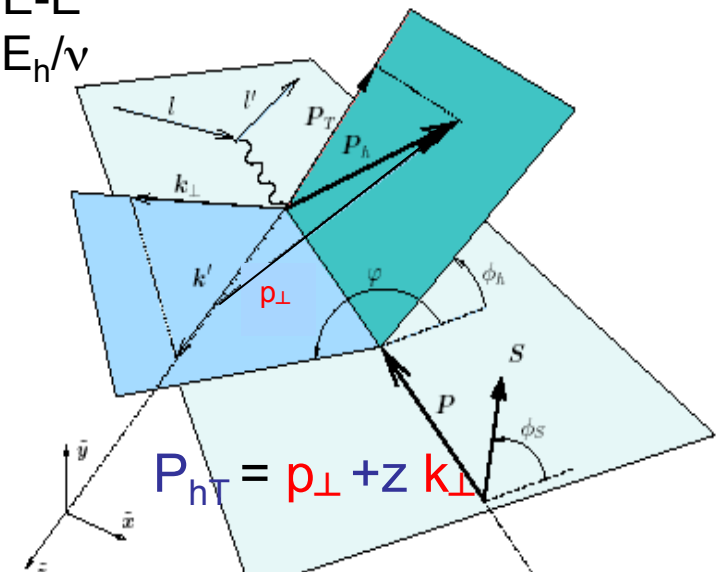
- DSA is P-even, SSA is P-odd
- longitudinal photon cross section is P-odd

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

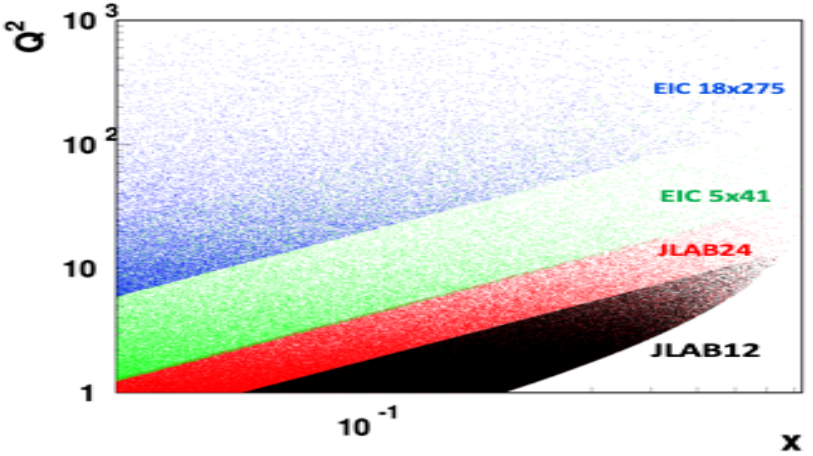
At large z (small t) the shapes of distributions (getting asymmetric) clearly indicate dominance of longitudinal rho

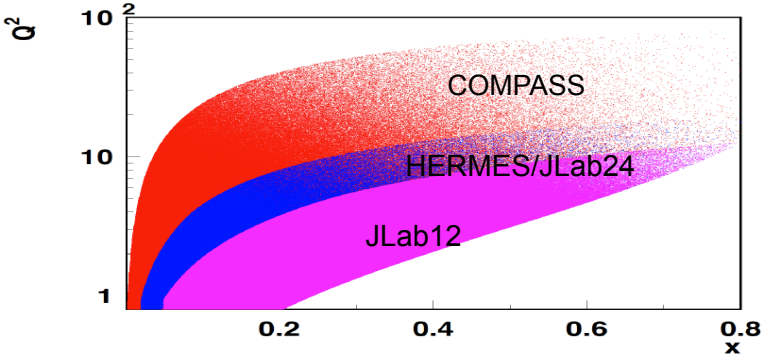
DIS kinematical coverage and observables

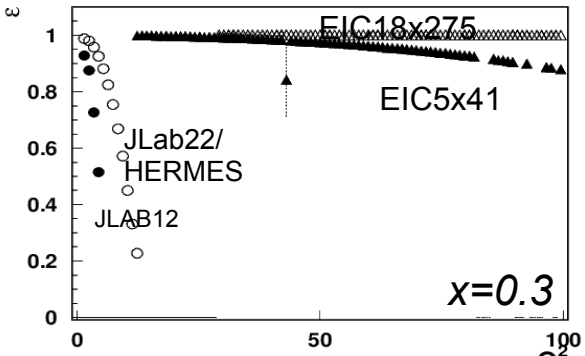
ν=E-E'
z=E_h/ν



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



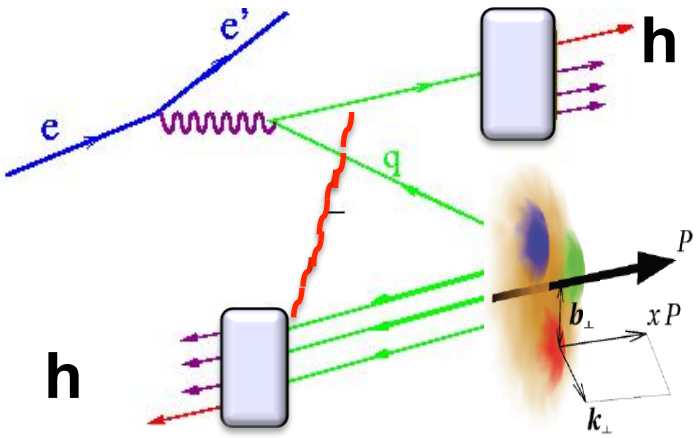




3D PDFs: Hadron production in electroproduction

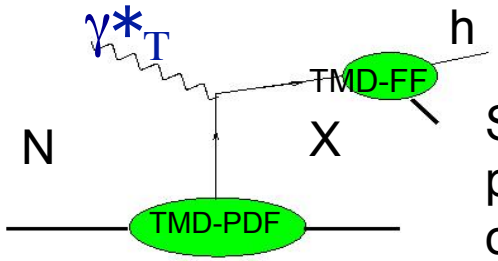
$x_F>0$

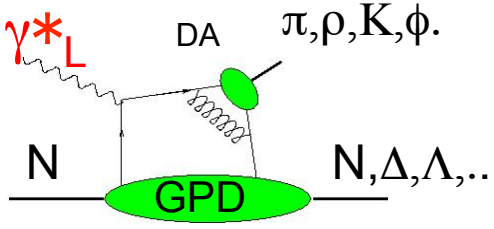
Current Fragmentation Region (CFR)

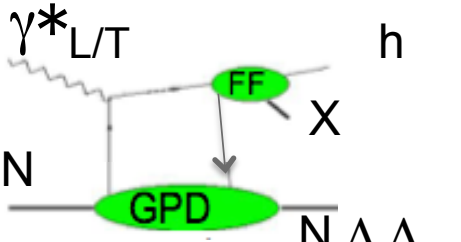


Target Fragmentation Region (TFR)

$x_F<0$







Semi-exclusive production (Guo-Yuan)

Study

x,Q^2,z,P_T,ϕ,ϕ_S ~$1/Q^4$

SIDIS→Flavor and polarization dependence of transverse momentum distributions

$x,Q^2,t,\phi,\phi_S+\phi,\theta$ ~$1/Q^6$

Exclusive→Flavor and polarization dependence of transverse space distributions

Back2Back→correlations and entanglement of CFR and TFR, controlling CFR, allowing access to GPDs and GTMDs

- Different non-perturbative objects may be involved with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

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

Use the latest fragmentation functions from Belle to evaluate the σT in exclusive limit from PYTHIA, compare with σTotal for different final state exclusive mesons

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

SIDIS formalism: from SF→HSH(Helicity SFs)

Longitudinal beam and target (Bacchetta et al: 0611256)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

Shortcut version

$$\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}z\,\mathrm{d}\phi_h\,\mathrm{d}P_{h\perp}^2} = \mathcal{K}_{\mathrm{SIDIS}}\sum_{XY}\mathcal{W}_{XY}[F],\qquad XY = UU, LU, UL, LL, UT, LT$$

$$\mathcal{K}_{\mathrm{SIDIS}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\mathcal{W}_{UU}[R] = R_{UU,T}+\epsilon R_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\,R_{UU}^{\cos\phi_h}+\epsilon\cos 2\phi_h\,R_{UU}^{\cos 2\phi_h}$$
$$\mathcal{W}_{LU}[R] = \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\,R_{LU}^{\sin\phi_h},$$
$$\mathcal{W}_{UL}[R] = S_\parallel\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h\,R_{UL}^{\sin\phi_h}+\epsilon\sin 2\phi_h\,R_{UL}^{\sin 2\phi_h}\right],$$
$$\mathcal{W}_{LL}[R] = \lambda_e S_\parallel\left[\sqrt{1-\epsilon^2}\,R_{LL}+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_h\,R_{LL}^{\cos\phi_h}\right],$$

- 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

$$\mathcal{K}_{\mathrm{SIDIS}}K_A = \frac{\alpha y(1-x)}{8\pi^3 x(1-\epsilon)} \equiv \mathcal{K}_{\mathrm{hel}}.$$

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

$$K_A = \frac{Q^2(1-x)}{4\pi^3\alpha}\left(1+\frac{\gamma^2}{2x}\right)^{-1}$$

HSFs→ linear combinations of SFs

$$\boxed{F_{XY}^w = K_A\,\mathscr{F}_{XY}^w[H],}$$

p

$$F_{UU,T} = \frac{K_A}{2}(H_{++}^{++}+H_{++}^{--}),\qquad F_{UU,L} = K_A H_{00}^{++}$$

γ^*_T γ^*_L

$$F_{LL} = K_A\tfrac{1}{2}(H_{++}^{++}-H_{++}^{--})$$

$$F_{LU}^{\sin\phi_h} = -K_A\frac{1}{\sqrt{2}}\,\mathrm{Im}(H_{+0}^{++}+H_{+0}^{--})$$

$$F_{UL}^{\sin\phi_h} = -K_A\frac{1}{\sqrt{2}}\,\mathrm{Im}(H_{+0}^{++}-H_{+0}^{--})$$

the same for cos, but real parts

From HSFs to Helicity Amplitudes (π+)

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

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

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

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

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)

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

2.3 Unpolarized beam, longitudinal target: UL (two)

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

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

- 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.

Azimuthal moments in SIDIS: Higher Twists

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

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{H}}{z}\right)\right]$$

Higher Twists→ quark gluon interactions

Higher twist in distribution coupled to leading twist in fragmentation

Higher twist in fragmentation coupled to leading twist in fragmentation

Leading Twist

quark polarization

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

hadron polarization

quark polarization: q/h	U	L	T
U	D_1		$D_{1T}^\perp$
L		G_{1L}	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	H_1 $H_{1T}^\perp$

Higher Twist PDFs

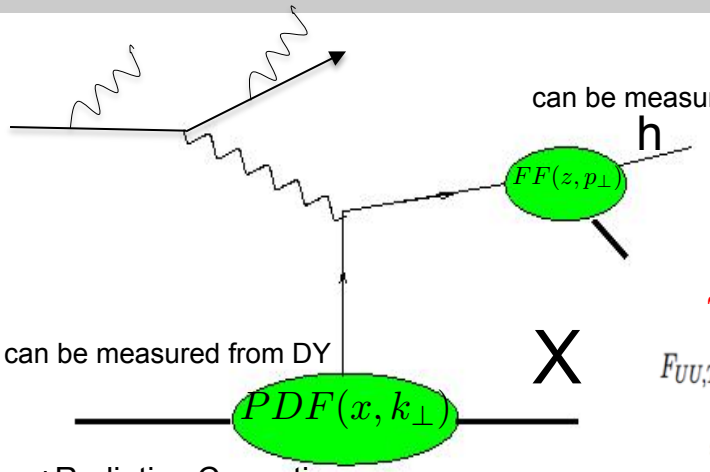
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, e
L	$f_L^\perp$	$g_L^\perp$	h_L, e_L
T	f_T, $f_T^\perp$	g_T, $g_T^\perp$	h_T, e_T, $h_T^\perp$, $e_T^\perp$

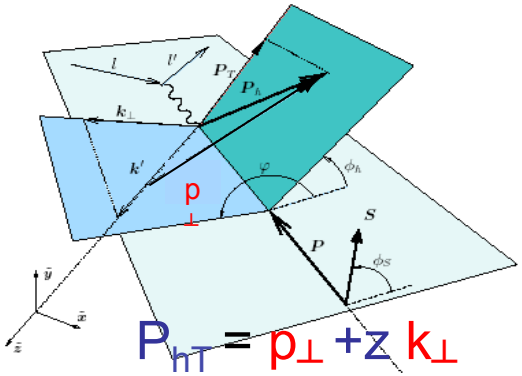
Higher Twist FFs

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	D_T, $D_T^\perp$
L	$G^\perp$	$G_L^\perp$	G_T, $G_T^\perp$
T	H, E	H_L, E_L	H_T, E_T, $H_T^\perp$, $E_T^\perp$

Dynamics is encoded in interactions and it is important to have proper frameworks for their analysis

Exclusive backgrounds in SIDIS





Probability to produce 1 or 2 hadrons in single photon exchange

$$\frac{d\sigma}{dx\, dy\, d\phi_S\, dz\, d\phi_h\, dP_{h\perp}^2} \qquad eN \to e'hX$$

γ^*_T

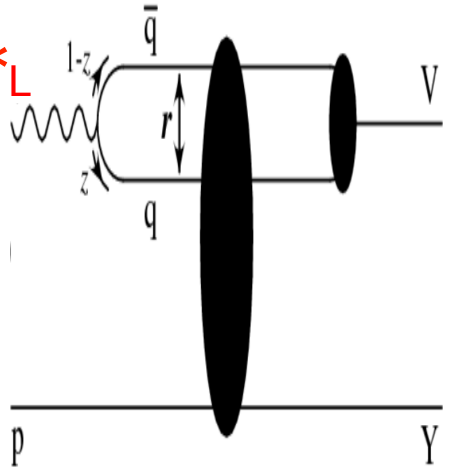
$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2) \int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) + Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

hard part

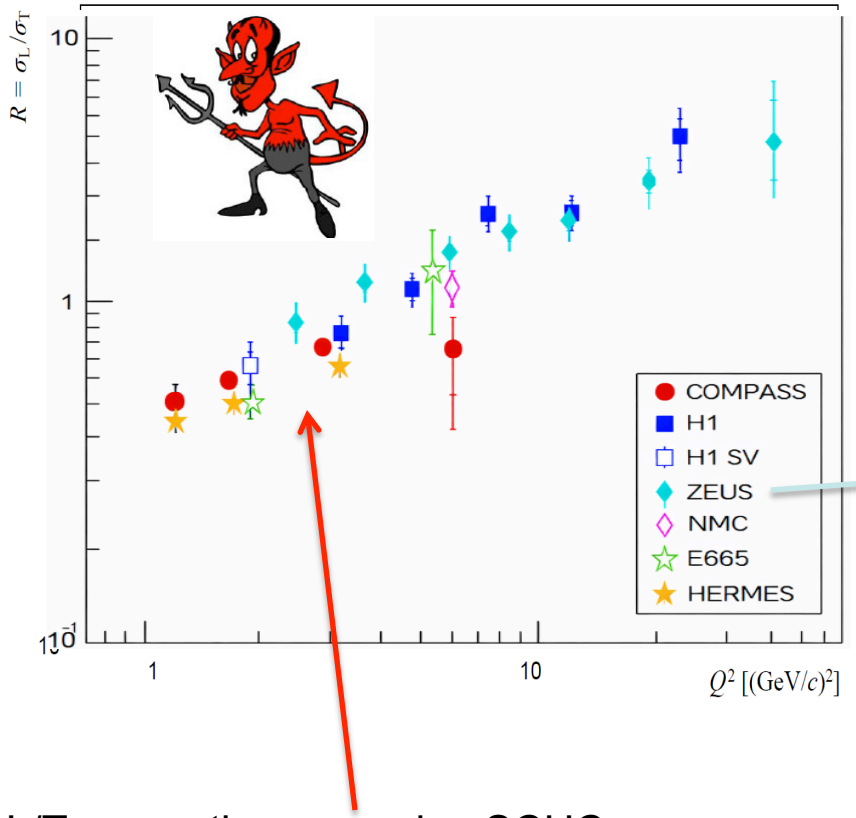
γ^*_L



Data has it all!!! Dealing with unaccounted terms:

- Experiment measures mix of processes, and is important to separate them
- Dominant contributions from L-photons, likely exclusive rho0
- Only Q2-dependence could validate claims about different dynamical contributions

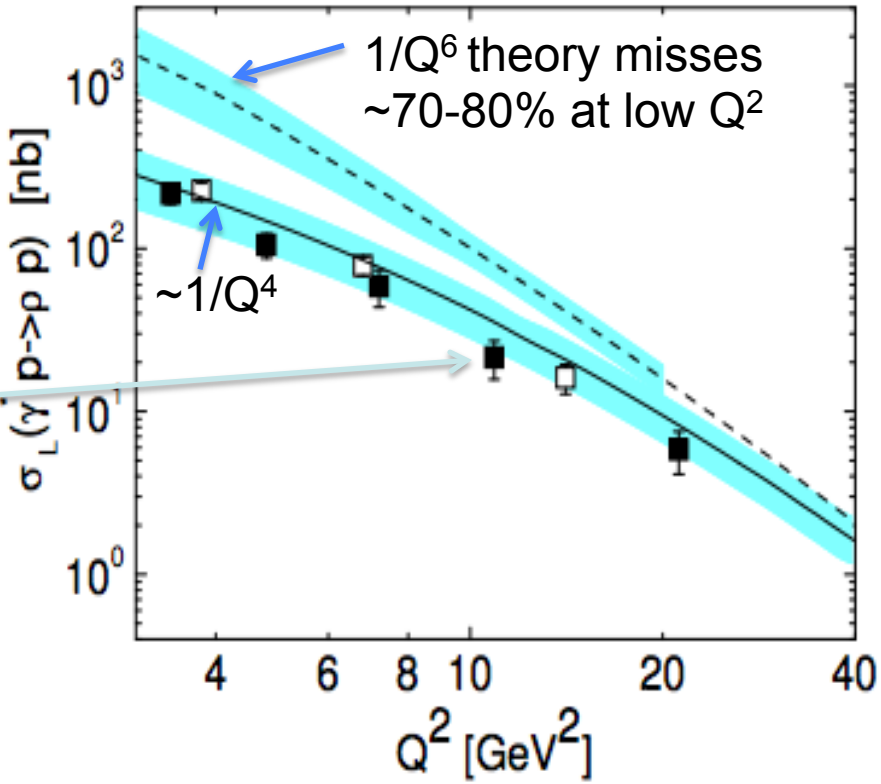
Separating Longitudinal photon contributions



L/T separation assuming SCHC (helicity conservation)

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

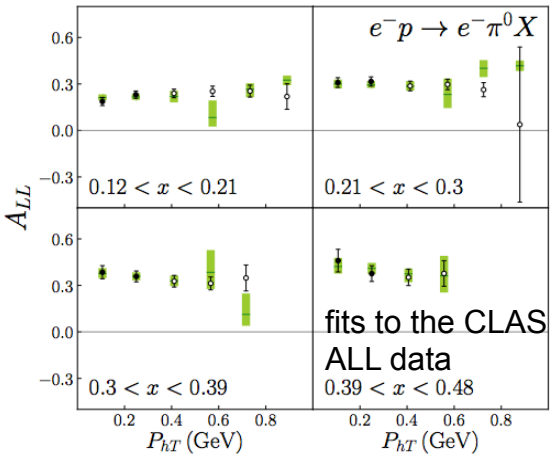
D.J. Boorstin

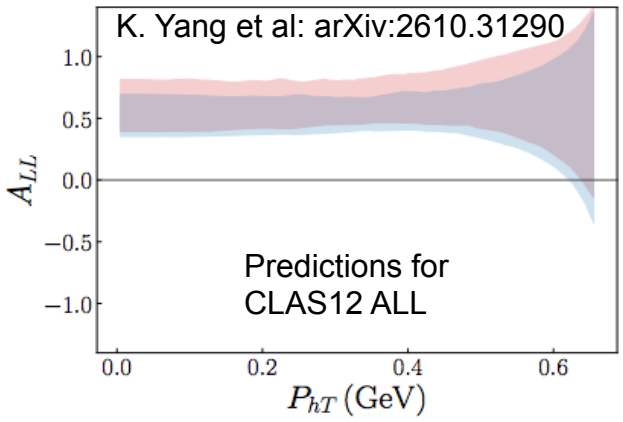


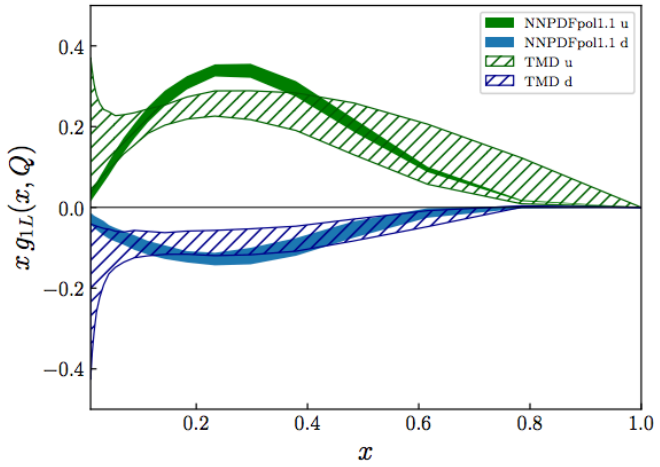
The ZEUS measurements, followed by others, indicated that the longitudinal photon contributions (diffractive rho) drop as ~1/Q^4 → dramatically underestimate low Q^2 ρ^0s

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

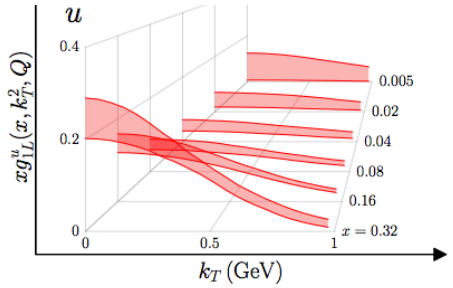
SIDIS: Extracting the helicity TMD

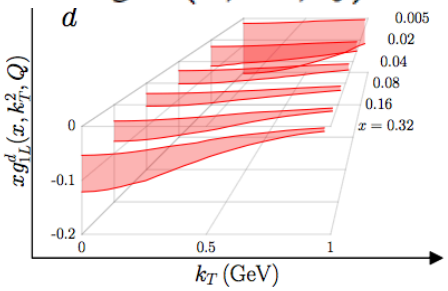


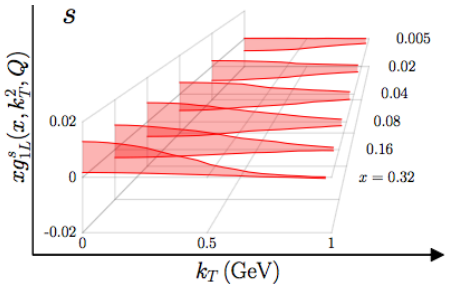


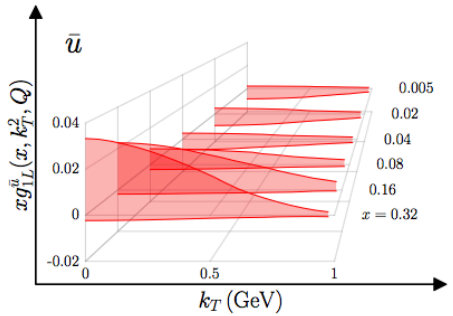


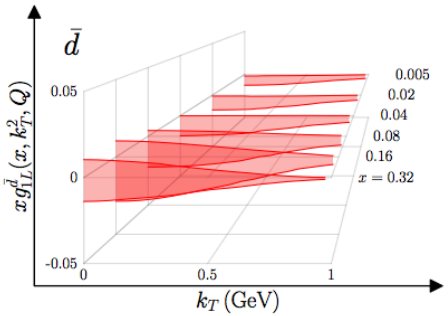
extracted helicity distributions $xg_{1L}(x, k_T, Q)$ at $Q = 2\,\mathrm{GeV}$

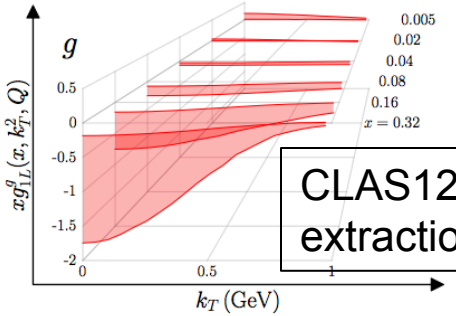








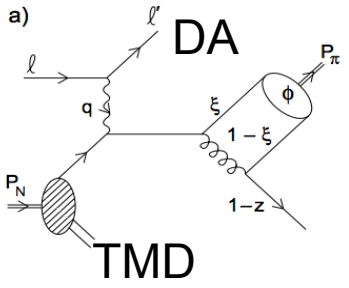


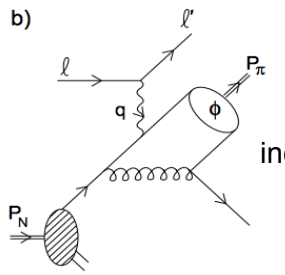


CLAS12 data critical for extraction of g1 TMD!!!

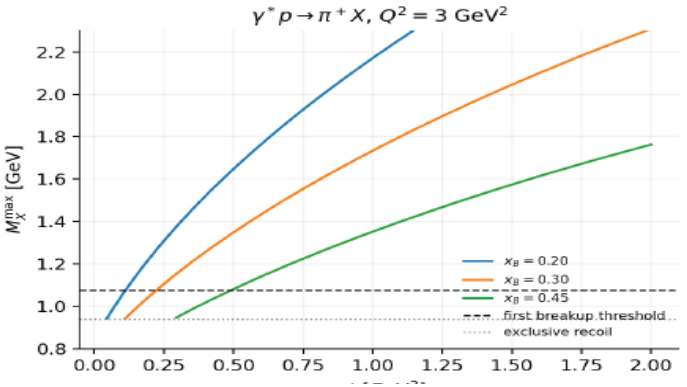
SIDIS cross sections in the z→1 limit

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

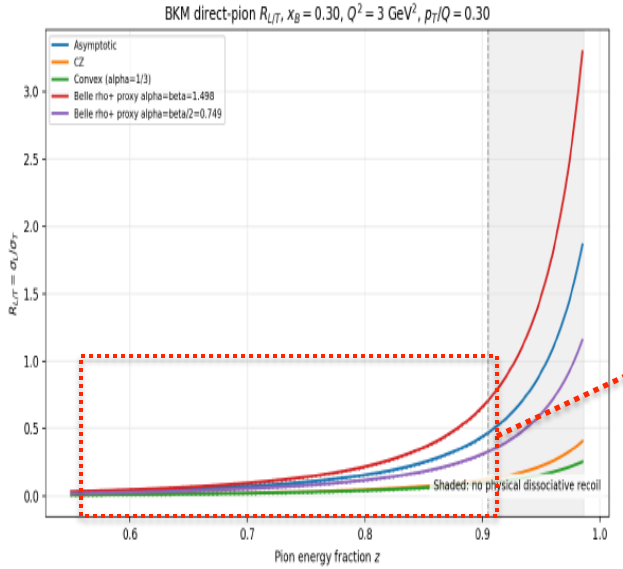


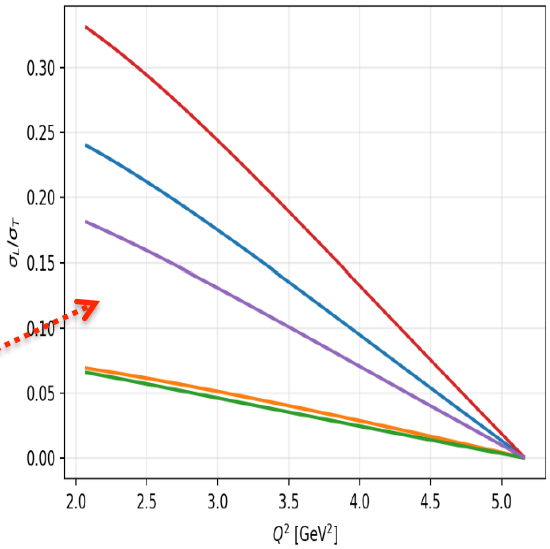


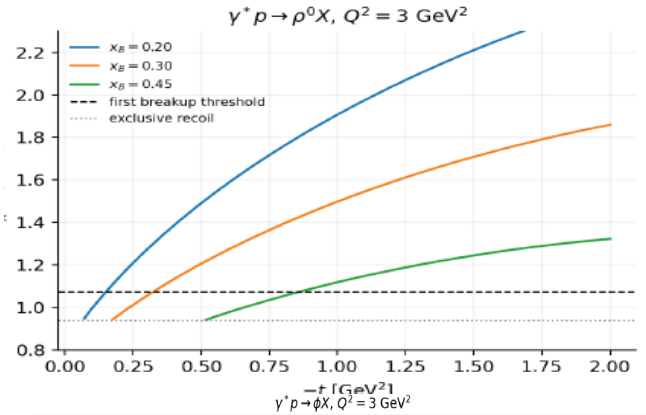
incoherent "exclusive"

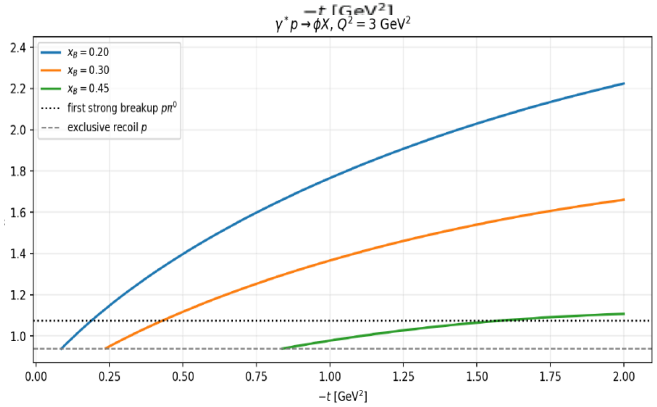


use NNPDF for PDF part





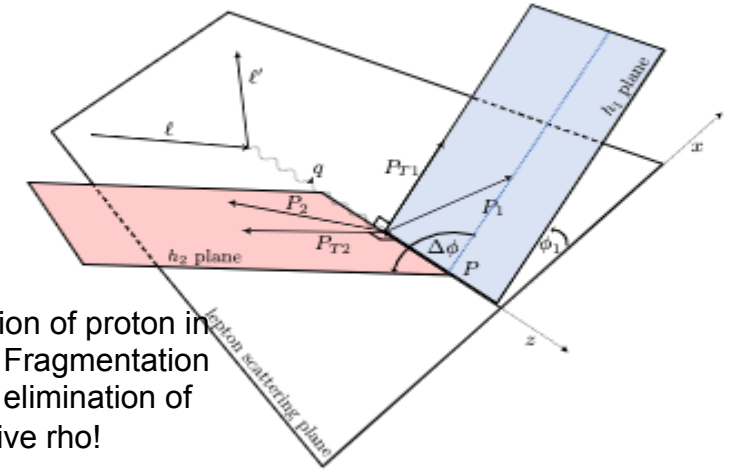




Possible contribution from γ^*_T may be increasing with t and Q^2 !!!

Accessing polarized quarks in Back-2-Back SIDIS

ep→e'pπX (short range quark correlations)

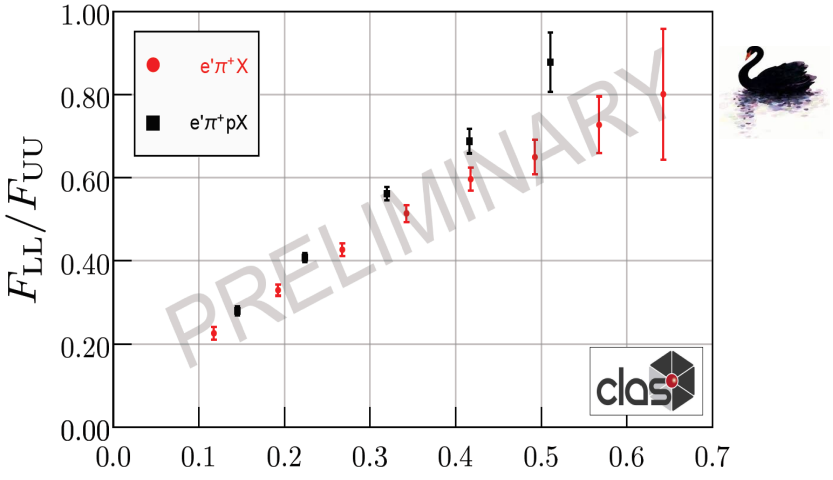


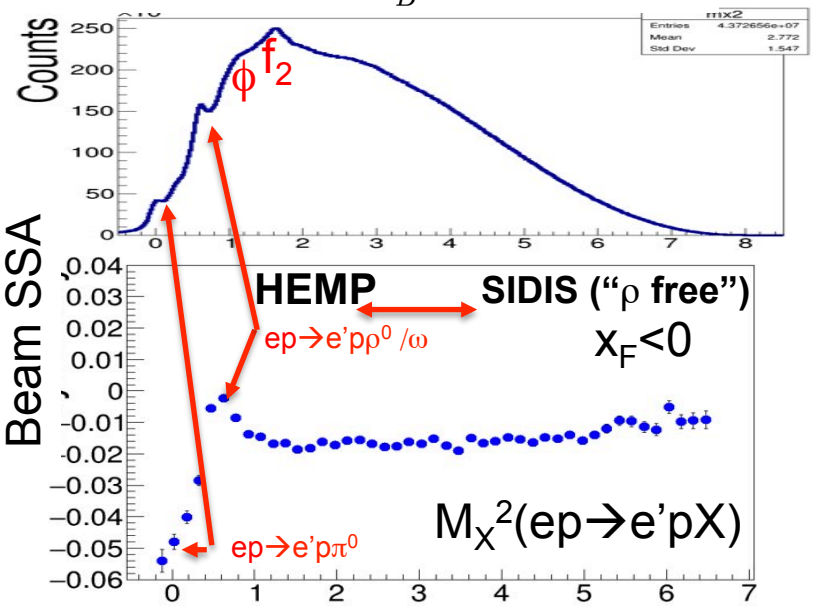
Detection of proton in Target Fragmentation allows elimination of exclusive rho!

Possible theory formalisms:

- **Formalism based on fracture functions (Anselmino, Barone, Kotzinian (back-to-back, b2b, hadron production, DSIDIS)**
- **Semi-exclusive processes, involving GPDs/GTMDs on proton side (TFR) and FFs on pion side (CFR) Yuan and Guo**

- Measurements of A_{LL} for ρ^0 indicate very small values, and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.5 GeV (excluding exclusive ρ^0)
- Higher A_{LL} will change the phenomenology used last 40 years in DIS and SIDIS studies!!!





Preserving process files with YAML

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# 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"}
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#    - {name: pm_f, unit: "rad", description: "pi- azimuthal angle"}
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#    - {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

- Move from cross sections and multiplicities to spin dependent multiplicities/ cross sections, for semi-inclusive and exclusive processes
- Prepare process files for all relevant Semi-Inclusive processes and exclusive processes, including unpolarized and polarized hydrogen and deuteron targets
- Combine RGK/RGA/RGC for separating L/T photon contributions both for SIDIS and Hard Exclusive (backgrounds)
- Move from bin-based analysis to event-based analysis
- Validation of the output of complex extraction frameworks using realistic MC becomes high priority
- Push theory for development of the framework to include higher twist effects both in SIDIS and Hard Exclusive processes

Theory-Experiment Dialogue: How to proceed

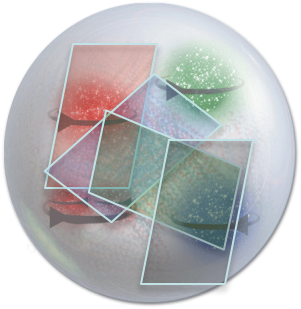
1. Keeping the formalism the same, including the input data where it works well, and try to get a better description using more sophisticated TMD models for TMD PDFs, and TMD FFs, search kinematics where theory is applicable (typically very large Q^2)



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)!!!

“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

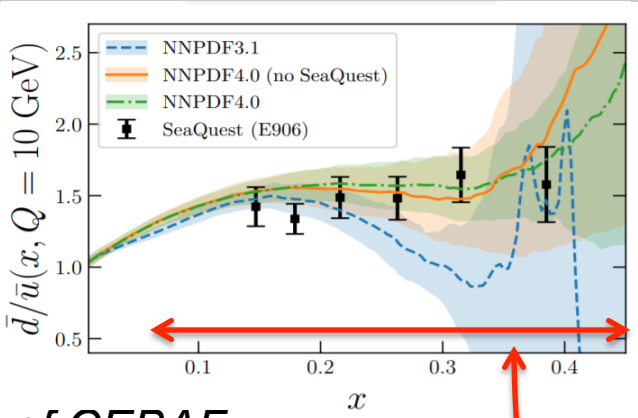
generated momenta of all 4 final particles

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										

Non-perturbative QCD in SI era: 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* $Q^2 < 10\ \mathrm{GeV}^2$

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**

Questions to address

- Semi-Exclusive production (Berger-Brodsky higher twist) provide a bridge between SIDIS and Hard Exclusive processes, are a major challenge for theory, and can shed light on problems in phenomenology of either one

•Experimental extraction helicty SFs (SIDIS) and helicity amplitudes (exclusive) should should aim at separation of contributions from L/T γ*s

•Detailed MC could help to understand better different contributions in the x-section of single or double pion production in exclusive limit?

•How we deal with "real" data with finite beam energies and limited phase space?

•What we learn comparing pseudoscalars (pions and kaons) and VMs(rho and phi) ?

•What we gain with combined analysis of unpolarized and long. pol. data

From SFs to HSFs

$$\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\psi\,\mathrm{d}z\,\mathrm{d}\phi_h\,\mathrm{d}P_{h\perp}^2} = \mathcal{K}_{\mathrm{SIDIS}} \sum_{XY} \mathcal{W}_{XY}[F] = \mathcal{K}_{\mathrm{EXC}} \sum_{XY} \mathcal{W}_{XY}[H],, \qquad XY = UU, LU, UL, LL, UT, LT,$$

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

proton

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

photon

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

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

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

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

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

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

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

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

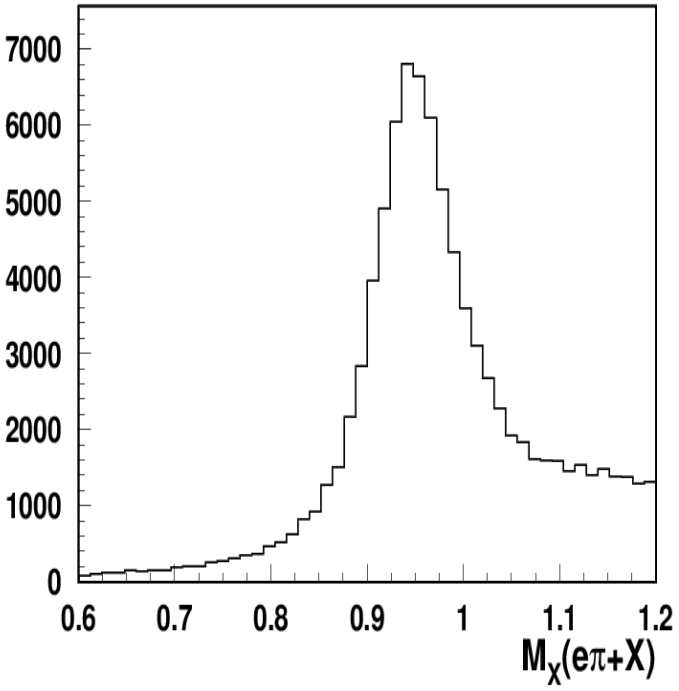
amplitude	photon	nucleon	Δ	forward factor K
$M_{0+,0+}$	L	non-flip	0	1
$M_{0-,0+}$	L	flip	−1	$\sqrt{-t'}/2M_p$
$M_{0+,++}$	T(+1)	non-flip	+1	$\sqrt{-t'}/2M_p$
$M_{0-,++}$	T(+1)	flip	0	1
$M_{0+,-+}$	T(−1)	non-flip	−1	$\sqrt{-t'}/2M_p$
$M_{0-,-+}$	T(−1)	flip	−2	$-t'/4M_p^2$

six independent amplitudes

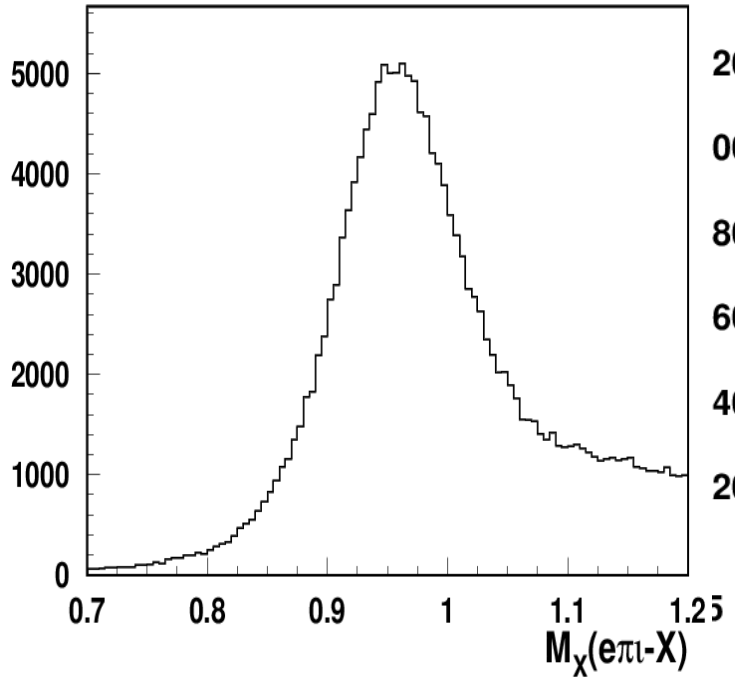
Cross sections of exclusive processes extracted in terms of helicity SFs provide direct/complementary access to underlying amplitudes

Handling backgrounds

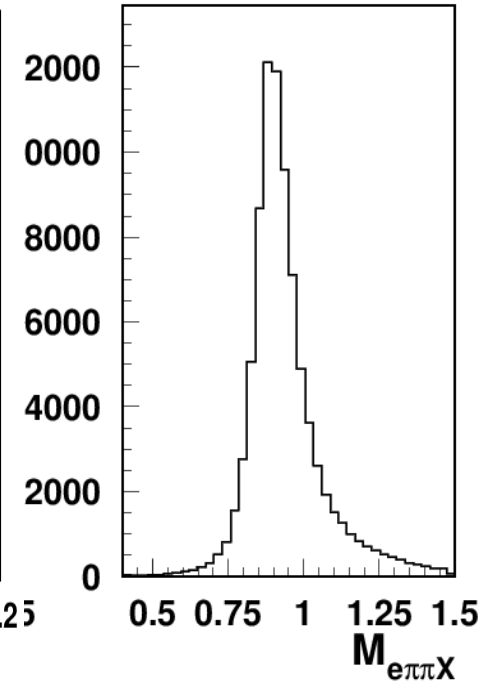
ep->e'π+X(neutron not detected)



en->e'π-X(proton detected)



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

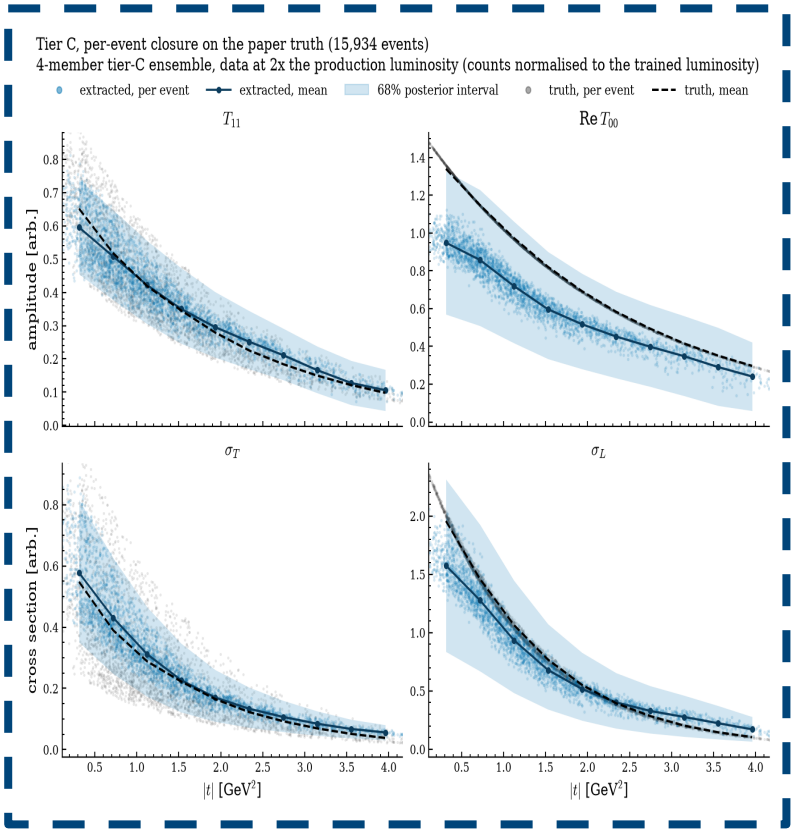


More particles detected less backgrounds, but there is always something left, and quantification of impact should be included in the framework

Extraction of amplitudes event-by-event

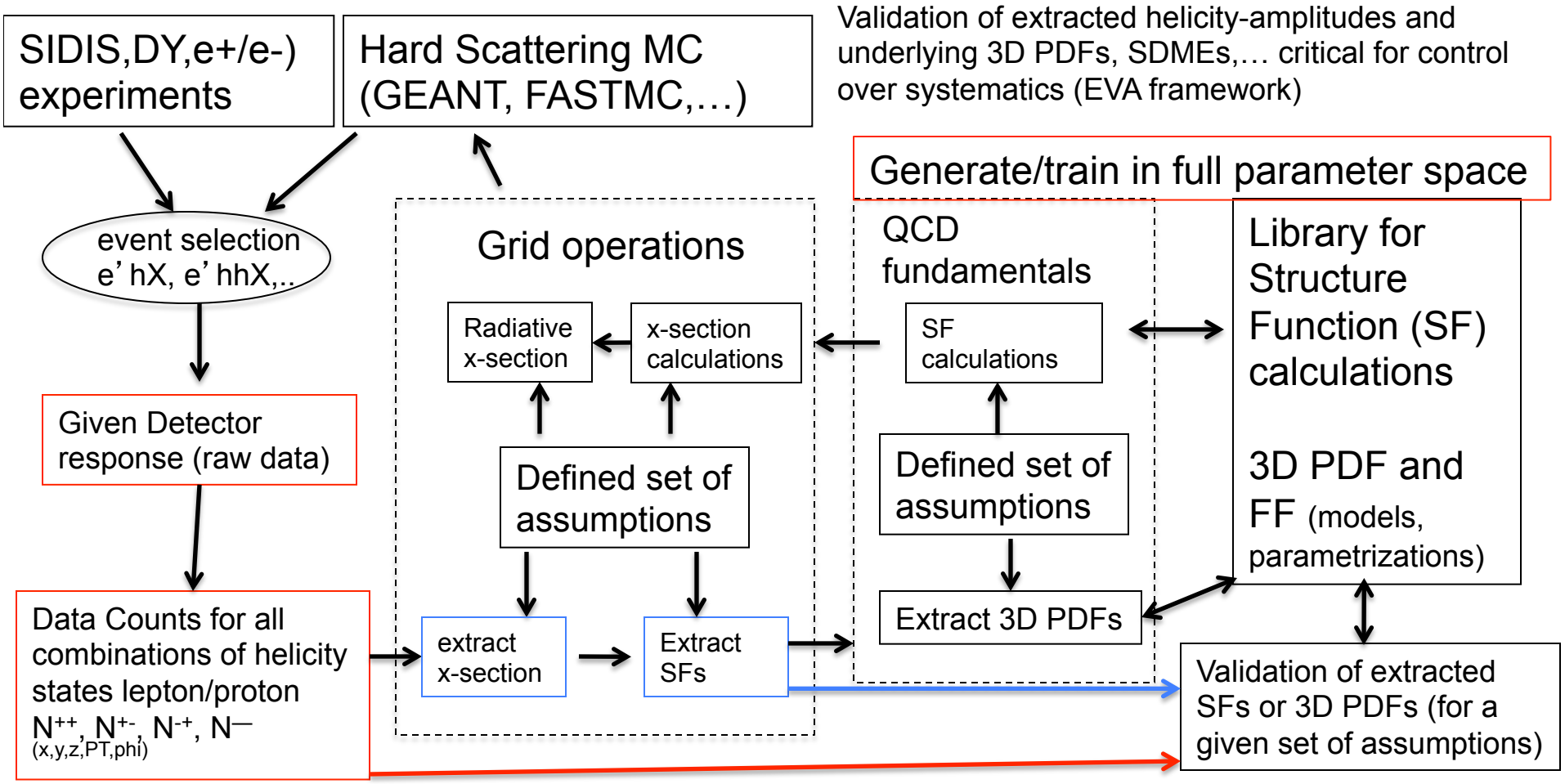
- **Feasibility published:** amplitudes from detector-level data with calibrated uncertainties
- **New:** first event-by-event closure; calibration targets identified
- **Plan:** phased, validated on conventional observables, with a decision point at month 12
- **Deliverable:** a validated, reusable 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

3D PDF Extraction and VAlidation frameworks

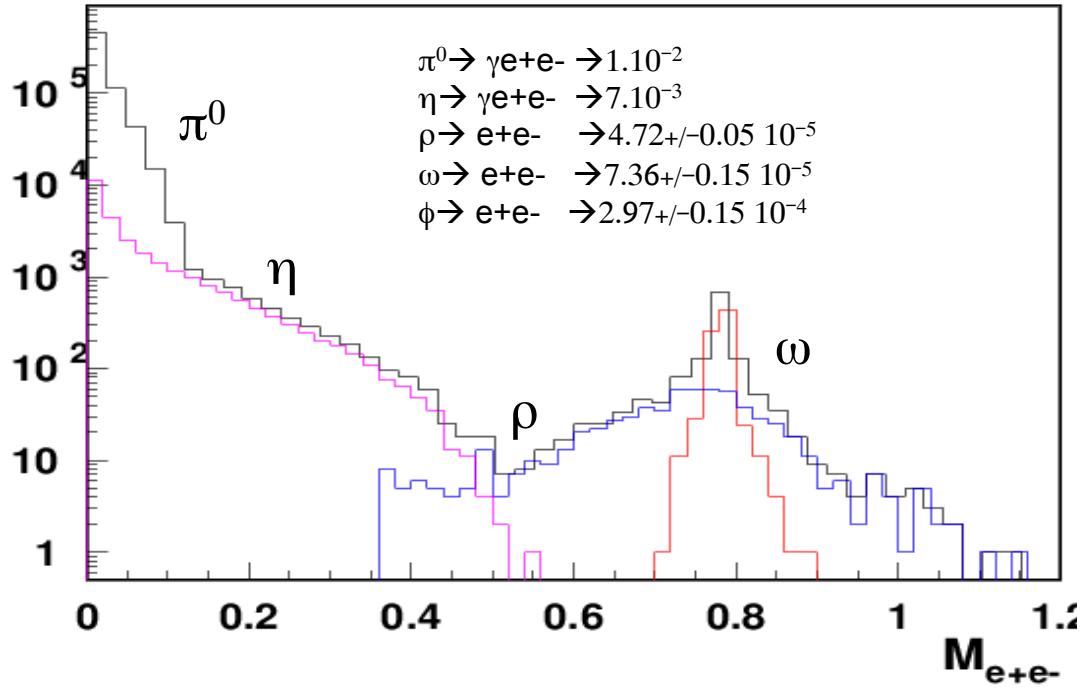


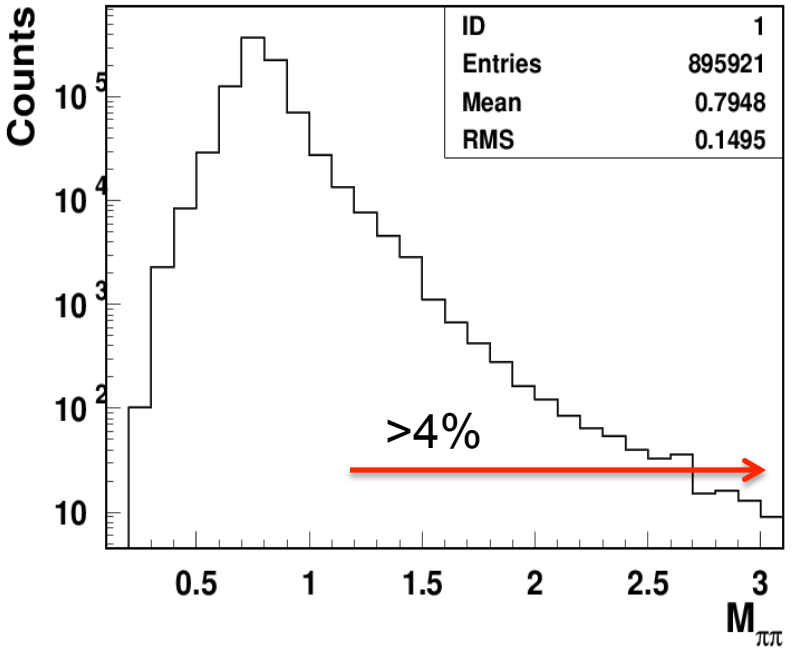
Direct extraction of a given parameter sets from all steps using AI tools for the extraction of 3D PDFs from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing (can be iterative)

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

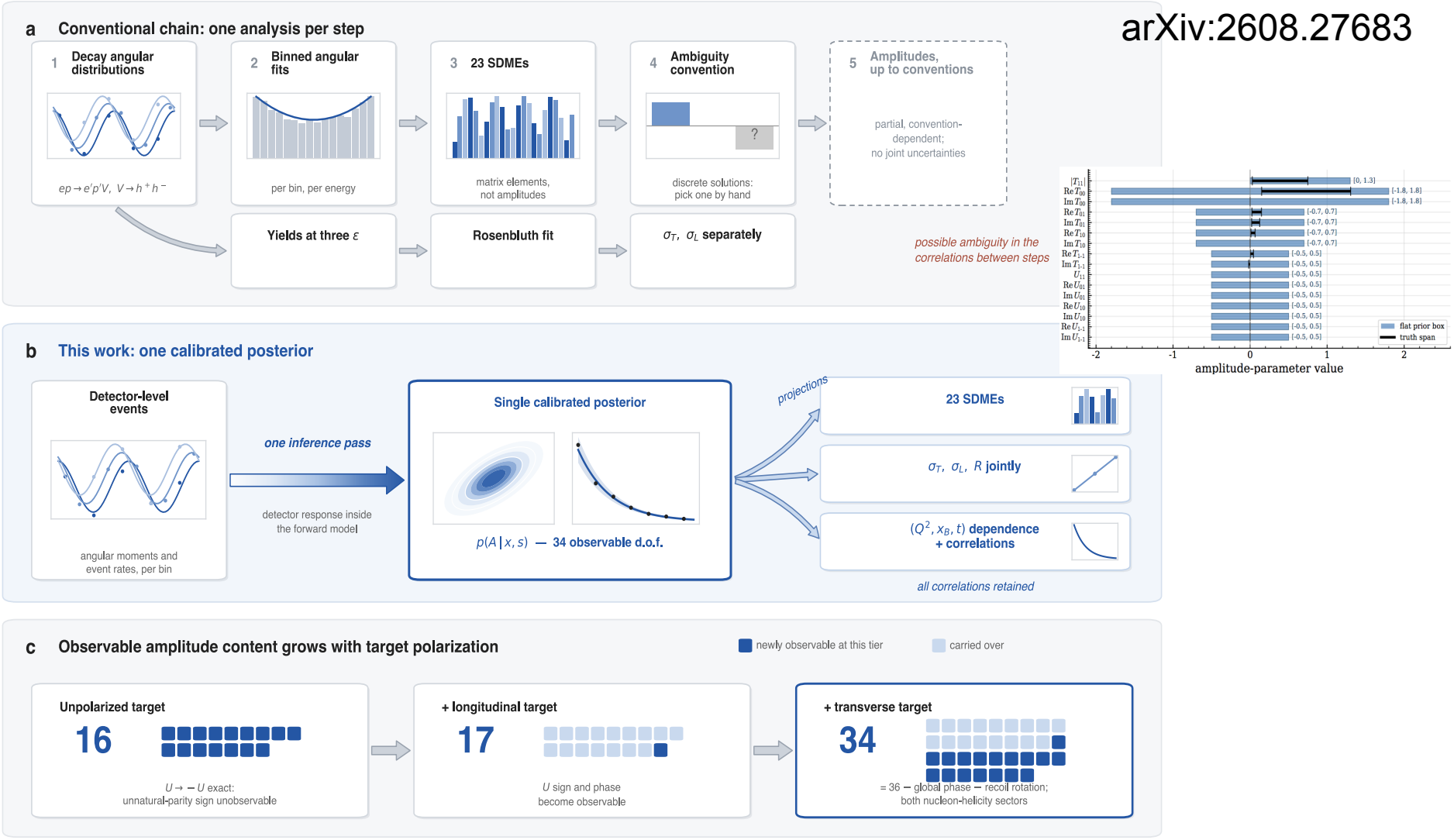




VMS are visible in lepton pair production even for Q2>1.
Significant fraction of VM leptonic decays ep→e'e+e-X may affect DY and TCS studies.

Direct Bayesian Inference of Helicity Amplitudes from Detector-Level Data

arXiv:2608.27683



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