Measurements of spin-azimuthal asymmetries in SIDIS and extraction of underlying 3D PDFs

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INT Program INT-18-3

Probing Nucleons and Nuclei in High Energy Collisions

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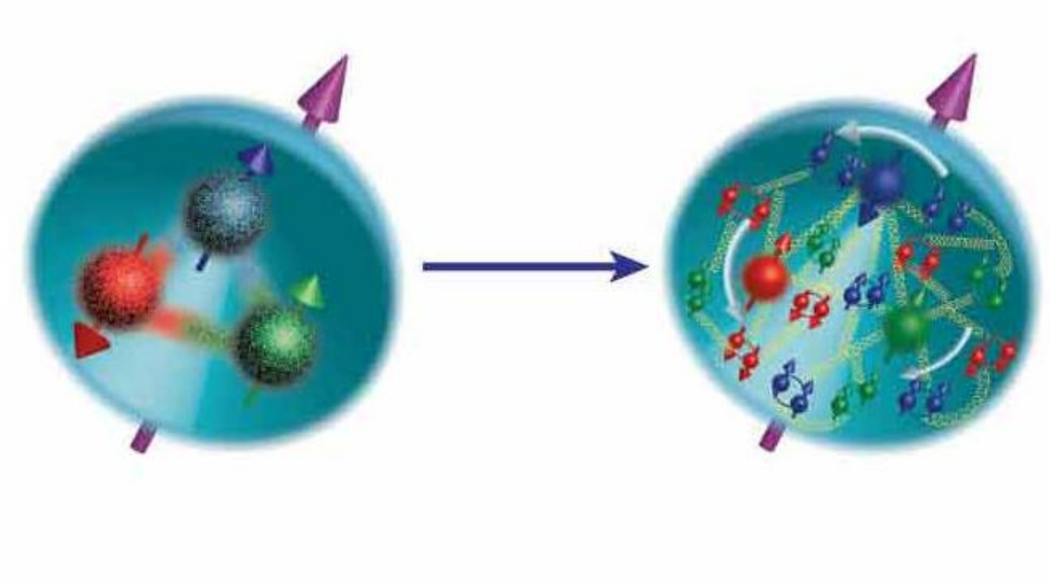


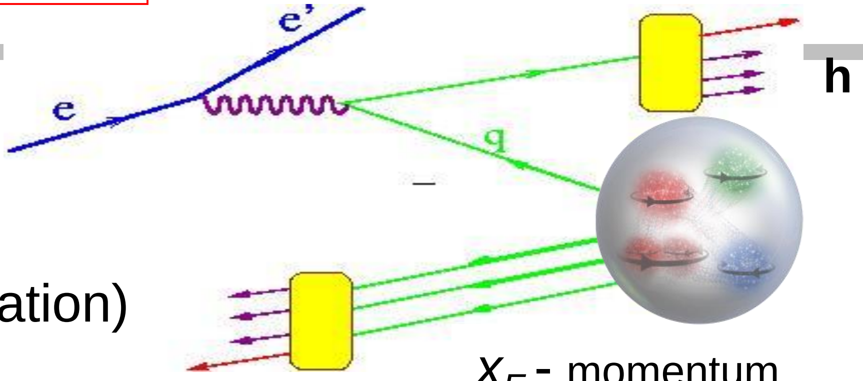
Outline

Introduction
SSA and azimuthal distributions
Non perturbative sea and k_T-distributions
Studies of TMD evolution from JLab12 to EIC
Complementarity of SIDIS experiments
    First look at CLAS12 data
Experimental factors affecting extraction of SFs
    Efficiency and acceptance
    Correlated di-hadrons contributions
    Radiative Corrections
    Nuclear modifications of partonic distributions
Understanding of systematics of measurements and the role of MC
Extraction and Validation Framework for 3D PD example for DIS
Conclusions

Single hadron production in hard scattering

$x_F>0$ (current fragmentation)

$x_F<0$ (target fragmentation)



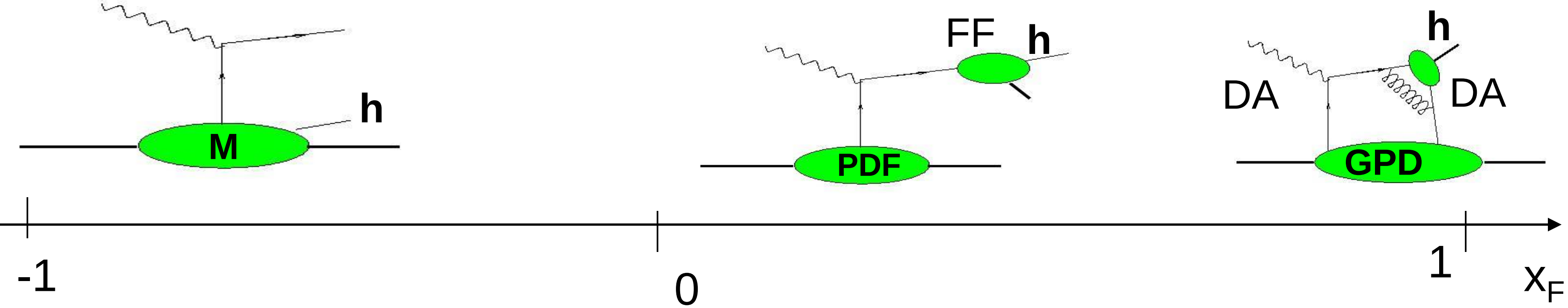
x_F - momentum in the CM frame

Target fragmentation

Current fragmentation

semi-inclusive

exclusive



Fracture Functions

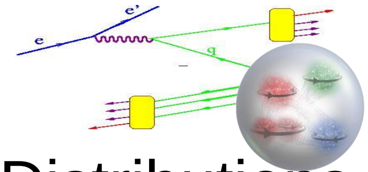
k_T-dependent PDFs

Generalized PDFs

Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

3D structure of the nucleon

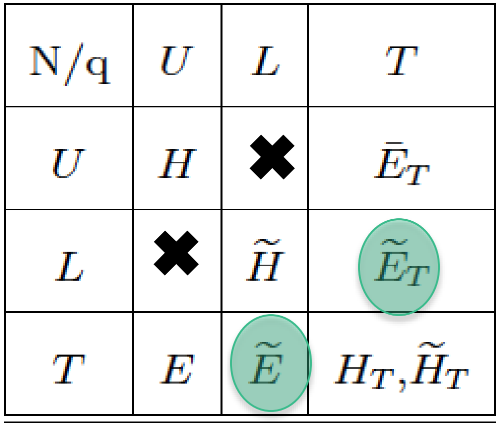
Non-perturbative distributions in hard scattering



TMDs

	U	L	T
U	f_1	✖	$h_1^\perp$
L	✖	g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

GPDs

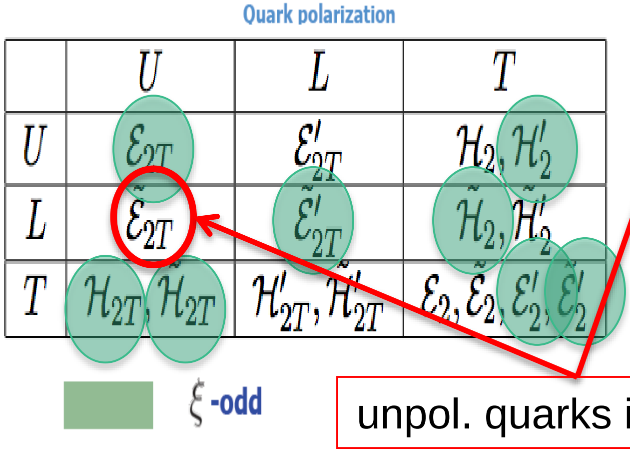


N/q	U	L	T
U	H	✖	$\bar{E}_T$
L	✖	$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

Wigner Distributions

	U	L	T
U	F_{11}	G_{11}	H_{11}, H_{12}
L	F_{14}	G_{14}	H_{17}, H_{18}
T	$\bar{F}_{12}, \bar{F}_{13}$	$\bar{G}_{12}, \bar{G}_{13}$	$\bar{H}_{13}, H_{14}$ $\bar{H}_{15}, \bar{H}_{16}$

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



Quark polarization

	U	L	T
U	$\mathcal{E}_{2T}$	$\mathcal{E}'_{2T}$	$\mathcal{H}_2, \mathcal{H}'_2$
L	$\tilde{\mathcal{E}}_{2T}$	$\tilde{\mathcal{E}}'_{2T}$	$\tilde{\mathcal{H}}_2, \tilde{\mathcal{H}}'_2$
T	$\mathcal{H}_{2T}, \tilde{\mathcal{H}}_{2T}$	$\mathcal{H}'_{2T}, \tilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2, \tilde{\mathcal{E}}_2, \mathcal{E}'_2, \tilde{\mathcal{E}}'_2$

🟩 ξ-odd

Fracture Functions

	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

unpol. quarks in long. pol. nucleon related to OAM!

SIDIS x-section

SIDIS $\ell(l) + N(P,S) \to \ell(l) + h(P_h) + X$

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

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

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

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

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

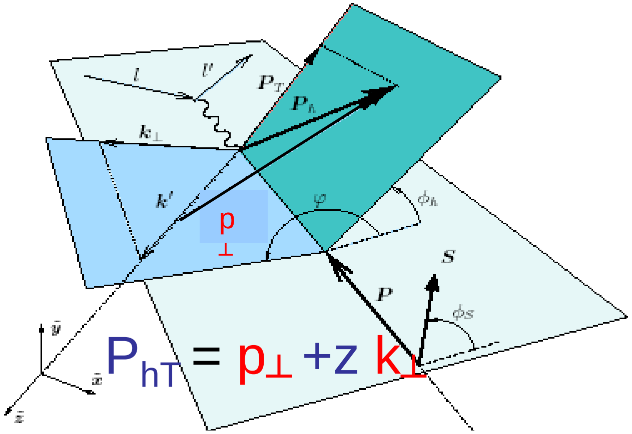
$$+\,|S_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

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

$$+\,|S_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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



$P_{hT} = p_\perp + z\,k_\perp$

$$F_{UU,T} = x\sum_q e_q^2 \int d^2\mathbf{p}_\perp d^2\mathbf{k}_\perp \delta^{(2)}(zk_\perp + p_\perp - P_{hT})\,f^q(x,k_\perp)\,D^{q\to h}(z,p_\perp)$$

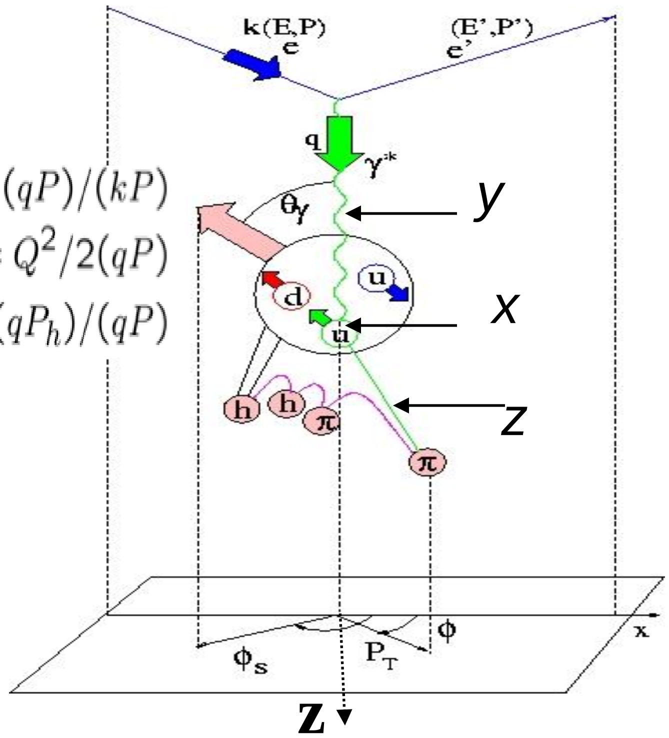
or

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

$$+\,Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M/Q)\,.$$

or any representation of structure functions!!!

SIDIS kinematical plane and observables

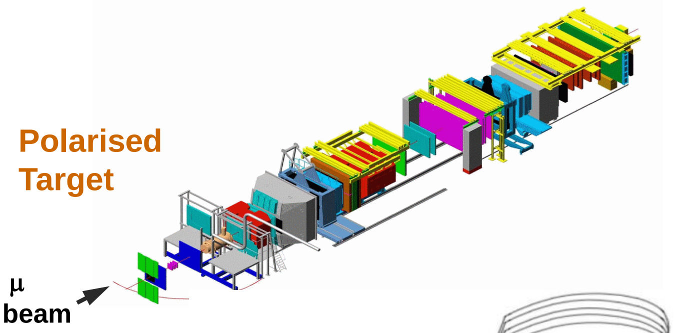


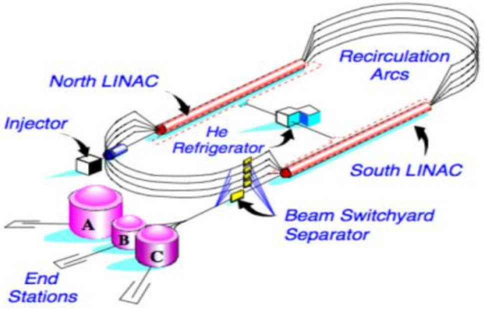
$y = (qP)/(kP)$

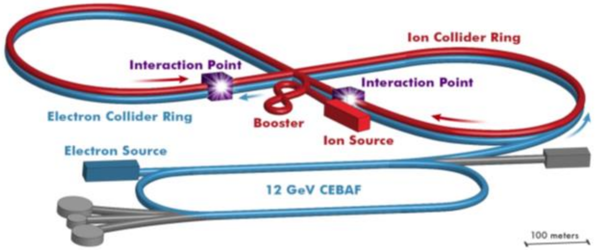
$x = Q^2/2(qP)$

$z = (qP_h)/(qP)$

Polarised Target







$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$

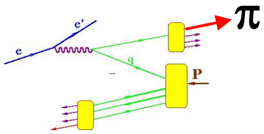
$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

beam polarization

target polarization

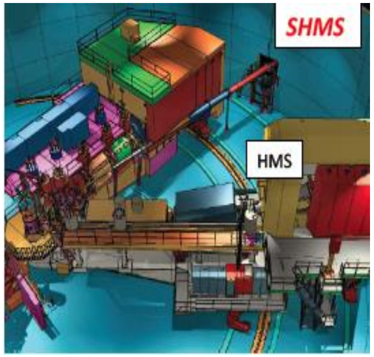
corrections for the region of large kT~Q

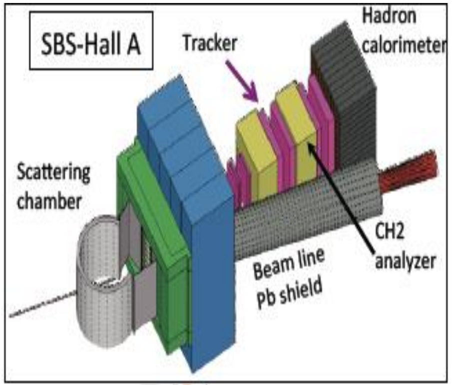


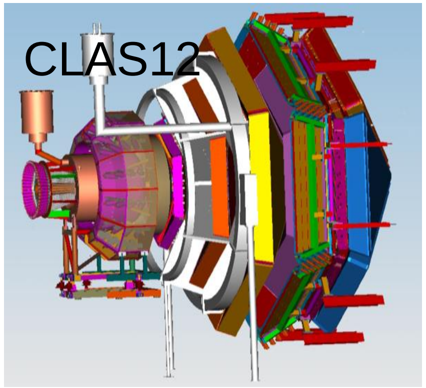
SIDIS at JLab12

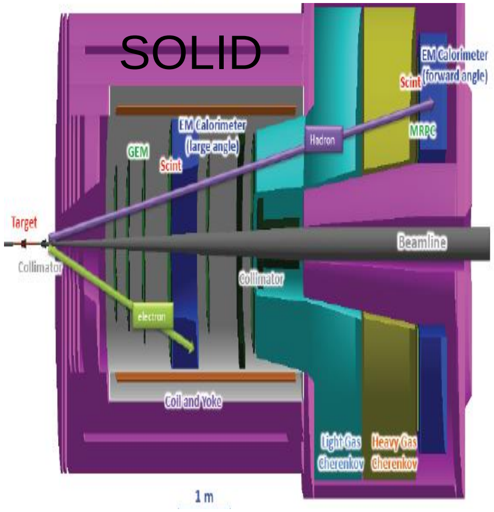
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

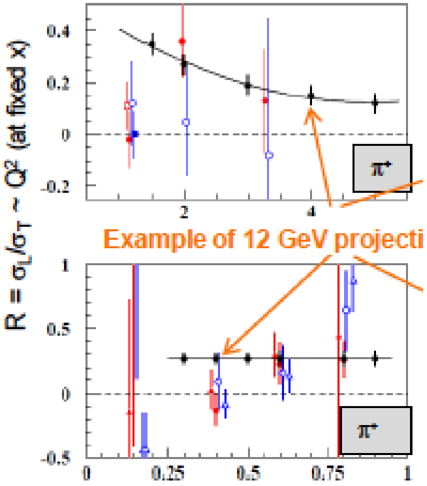
Complementary measurements with different targets

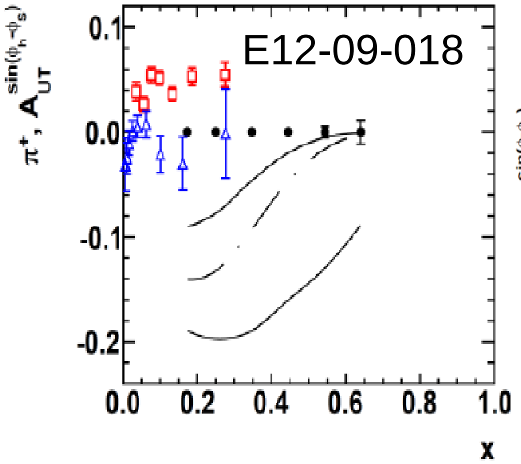


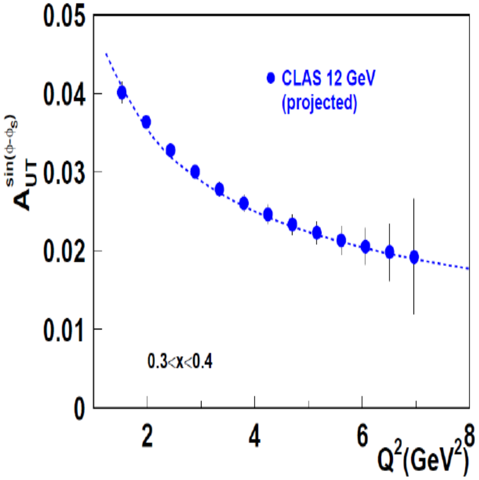


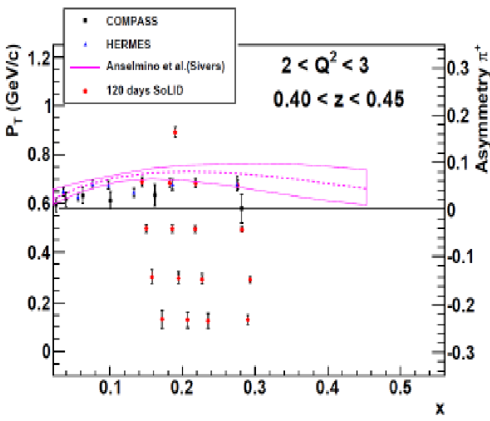












Combination of high resolution measurements from spectrometers combined with large acceptance data from CLAS12 and SOLID would allow to pin down all TMDs in the valence region

JLEIC energy reach and luminosity

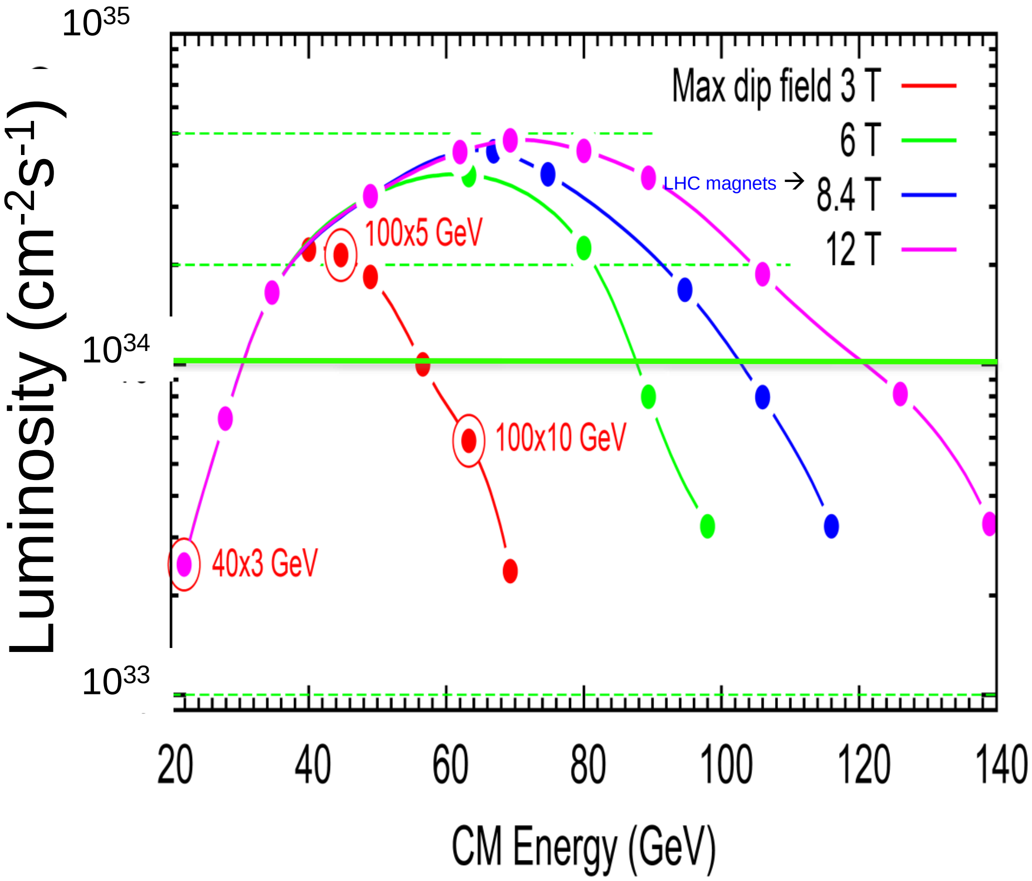
energy range:

E_e: **3 to 12 GeV**

E_p: **40 to 100 GeV**

$\sqrt{s}$: **20 to 65 GeV**

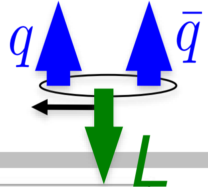
(upper limit depends on magnet tech. choice)

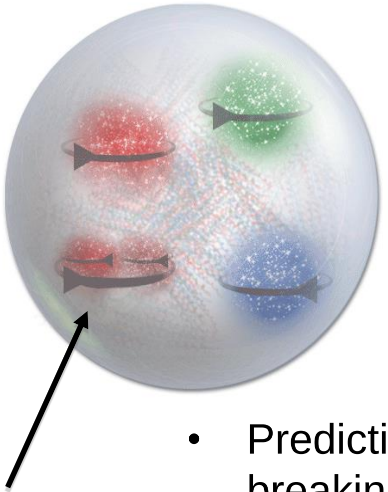


- **Electron complex**
  - CEBAF
  - Electron collider ring
- **Ion complex**
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring

Main focus→ proton?

Non-perturbative distributions

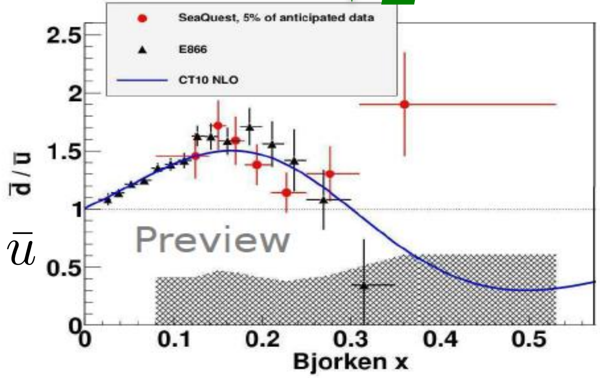




“Pion tornado”?

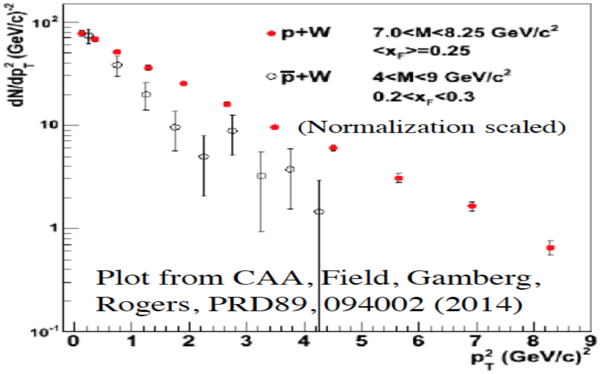
Non-perturbative sea in nucleon is a key to understand the nucleon structure

-- Large flavor asymmetry as evidence $\bar{d} > \bar{u}$ provides a hint for region where non-perturbative effects will be significant

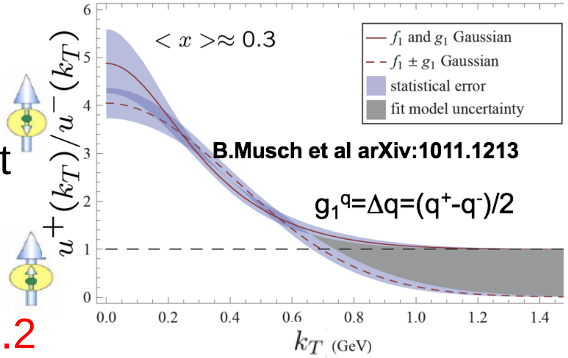


- Predictions from dynamical model of chiral symmetry breaking [Schweitzer, Strikman, Weiss JHEP 1301 (2013) 163]

  -- k_T (sea) >> k_T (valence)
  -- short-range correlations between partons (small-size q-qbar pairs)
  -- directly observable in P_T-dependence of hadrons in SIDIS



Plot from CAA, Field, Gamberg, Rogers, PRD89, 094002 (2014)



B.Musch et al arXiv:1011.1213

$g_1^q = \Delta q = (q^+ - q^-)/2$

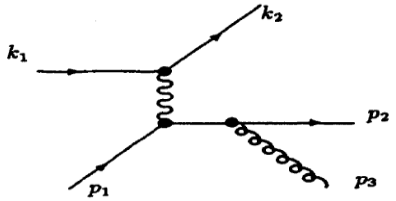
- spin and momentum of struck quarks are correlated with remnant
- correlations of spins of q-q-bar with valence quark spin and transverse momentum will lead to observable effects
- Non-perturbative sea most relevant for x>0.01, more for 0.1<x<0.2

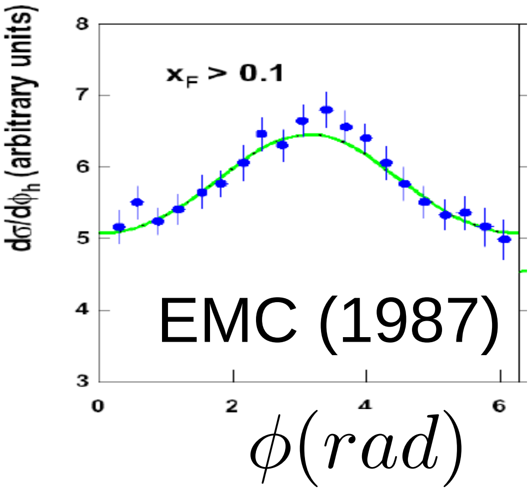
Azimuthal asymmetries in SIDIS

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

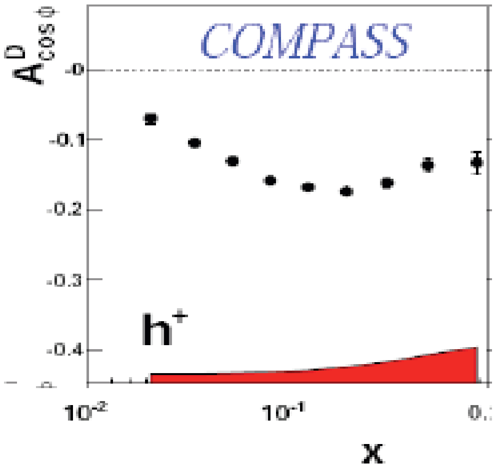
Non-perturbative vs perturbative

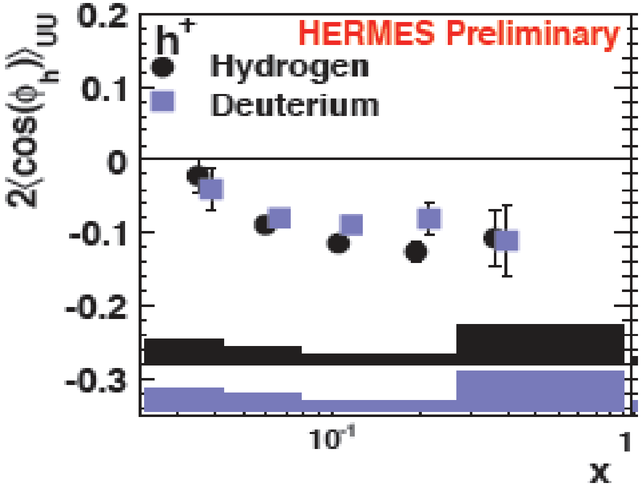
Cahn 1978 Georgi & Politzer, Mendez 1978



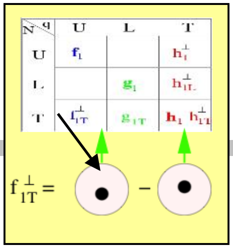


EMC (1987)





Large cosϕ modulations observed by EMC were reproduced in electroproduction of hadrons in SIDIS with unpolarized targets at COMPASS and HERMES

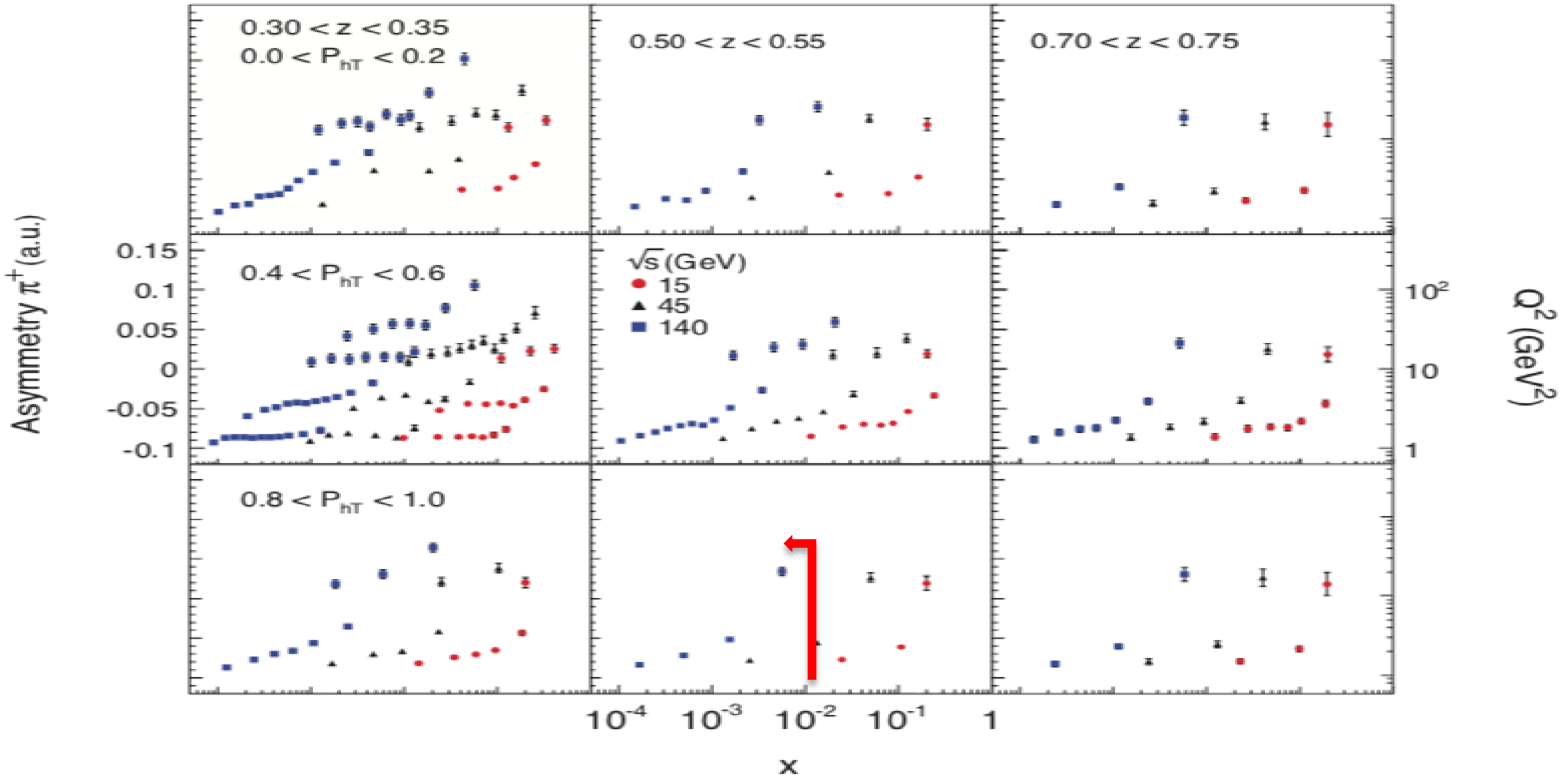


Sivers effect: π+ from EIC

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

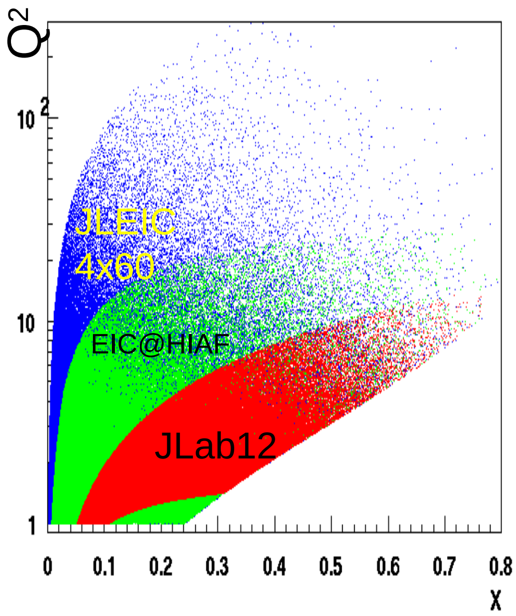
√s = 140 GeV, √s = 45 GeV and √s = 15 GeV EIC configurations, respectively.
Event counts correspond to an integrated luminosity of 10 fb−1

arXiv: 1212.1701

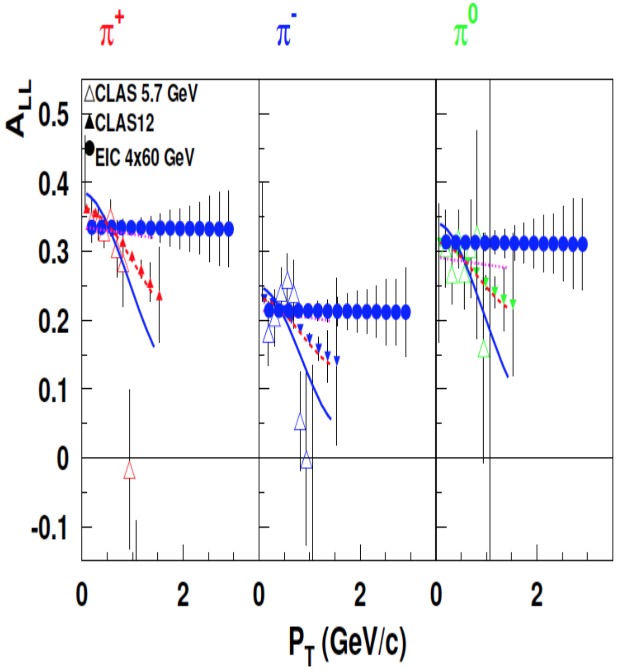


- Large acceptance and energy range of EIC makes it ideal place to study the contributions of sea quarks to Sivers asymmetry
- Crucial to understand evolution and transverse momentum dependence of Sivers
- Lower energies provide wider x-range for region where non-perturbative effects are significant, and overlap with JLab12

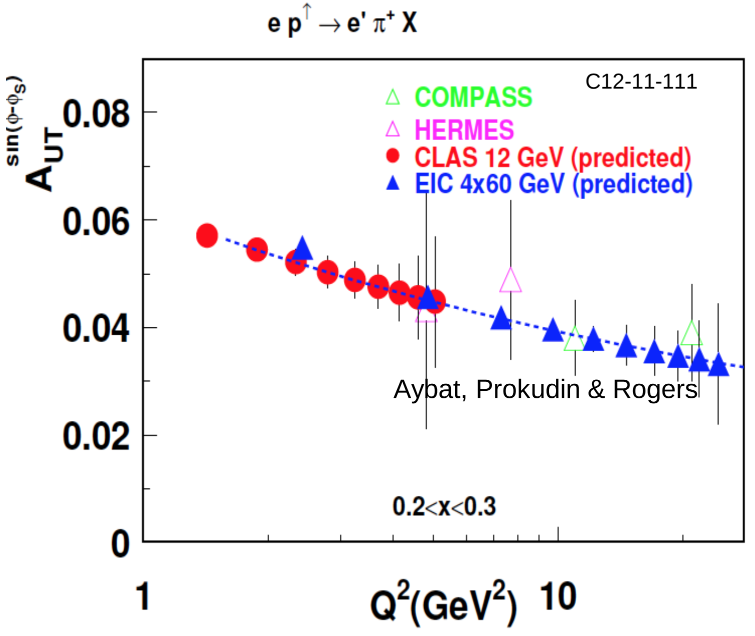
Evolution and k_T-dependence of TMDs



CLAS12/EIC kinematical coverage



k_T-dependence of $g_1(x, k_T)$



Q^2-dependence of Sivers, $f_1^\perp(x, k_T)$

- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range (most critical for TMD studies)
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

Experiment-Theory interaction

Theorist come up with some description of the x-section, based on some set of structure functions

Experimentalists measure certain quantities (multiplicity, asymmetry, x-section

Observables in form of a table bin# <average kin> | observable | <err>stat | <err>syst

Define procedure to extract parameters defining the involved SFs

Extract those parameters, based on input from experiment.
Normally theory is not dictating the output form (excl. weighted asymmetries)

What will be the most efficient format for the data (and metadata)?

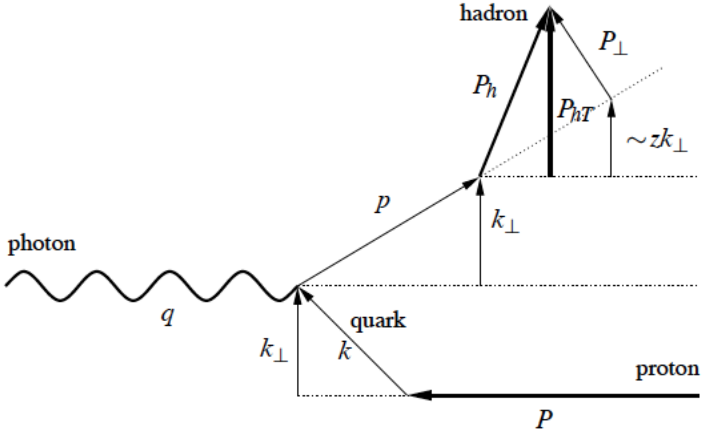
- Data required for certain analysis may require event by even info
- How to store and preserve the data (for unbinned analysis)
- Alternative to store full events (all tracks) event level analysis (ELA)?
  - Should provide easy access for theory

A set of Structure Functions needed for x-section

From simple

$$F_{UU,T} = x \sum_a e_a^2 f_1^a(x)\, D_1^{a\to h}(z)\, \frac{1}{\pi\langle P_{h\perp}^2\rangle}\, e^{-P_{h\perp}^2/\langle P_{h\perp}^2\rangle}$$

$$\langle P_{h\perp}^2\rangle^2 = z^2\langle k_{q,\perp}^2\rangle + \langle p_{q\to h\perp}^2\rangle\,.$$



to more and more sophysticated

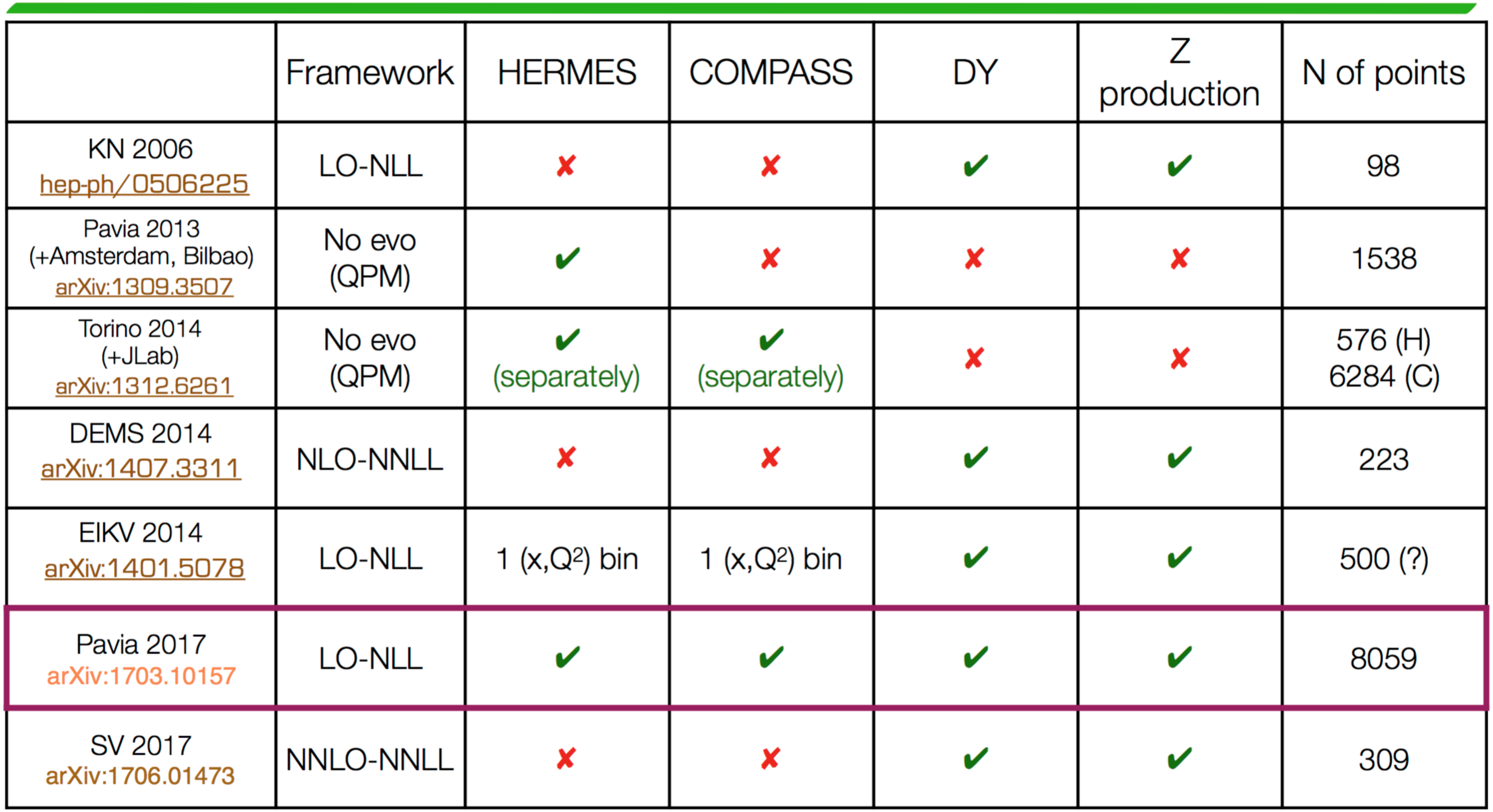
$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d\boldsymbol{k}_\perp\, d\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp)$$
$$+\, Y_{UU,T}(Q^2,P_{hT}^2)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

Urgent things we need (Signori INT-2018):

- SIDIS: distinction of different fragmentation mechanism
- a faithful Monte Carlo implementation of TMD sensitive processes

Extracting TMDs

INT-2018, A. Signori



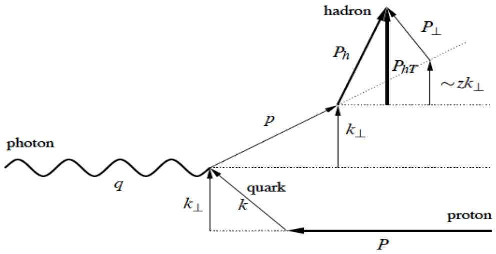
	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

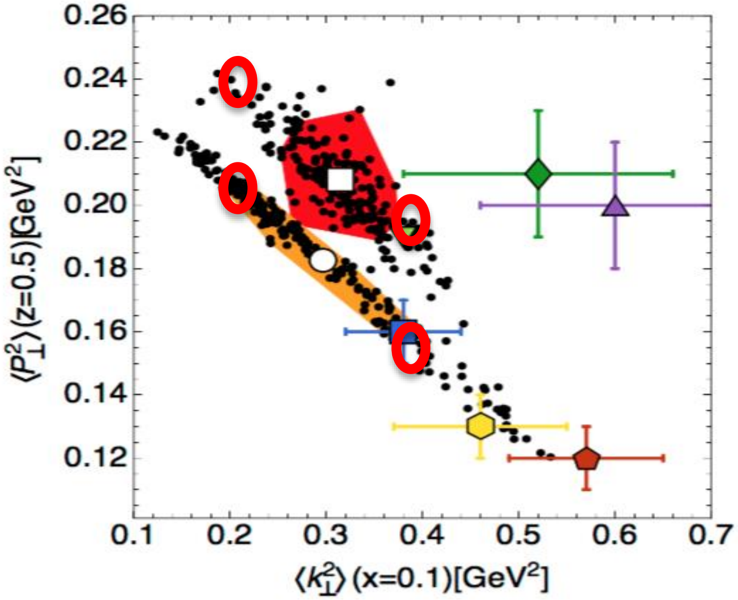
No systematics from unaccounted processes and contributions

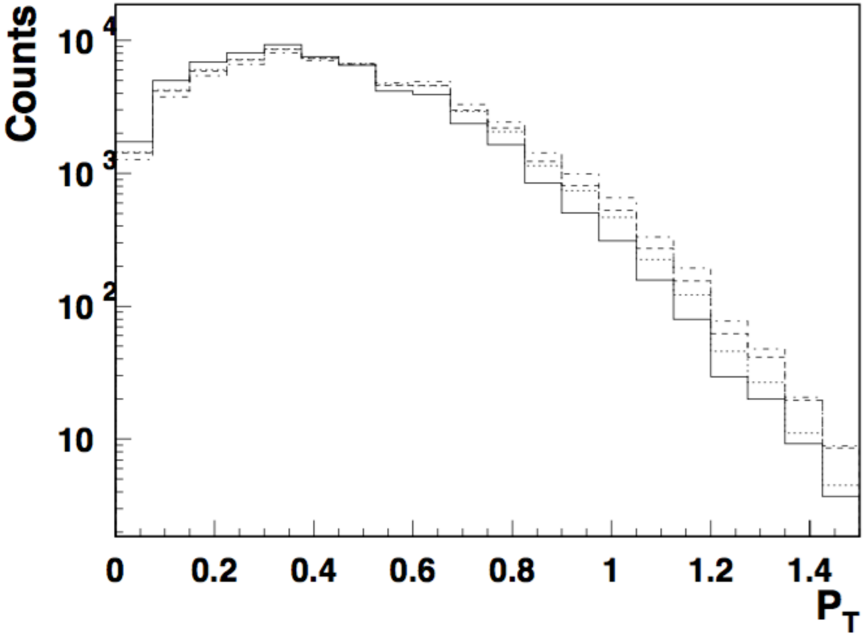
Extracting the average transverse momenta

Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§]

$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2) \int dk_\perp \, dP_\perp \, f_1^a(x,k_\perp^2;\mu^2) \, D_1^{a\to h}(z,P_\perp^2;\mu^2) \, \delta(zk_\perp - P_{hT} + P_\perp) + Y_{UU,T}(Q^2,P_{hT}^2) + \mathcal{O}(M/Q) .$$







$$m_N^h(x,z,\boldsymbol{P}_{hT}^2) = \frac{\pi}{\sum_a e_a^2 f_1^a(x)} \times \sum_a e_a^2 \, f_1^a(x) \, D_1^{a\to h}(z) \, \frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}$$

- Extraction very sensitive to input (replicas)
- Most sensitive to parameters is the large P_T region
- Multiplicity alone may not be enough to separate $\langle k_T\rangle$ from average $\langle p_T\rangle$

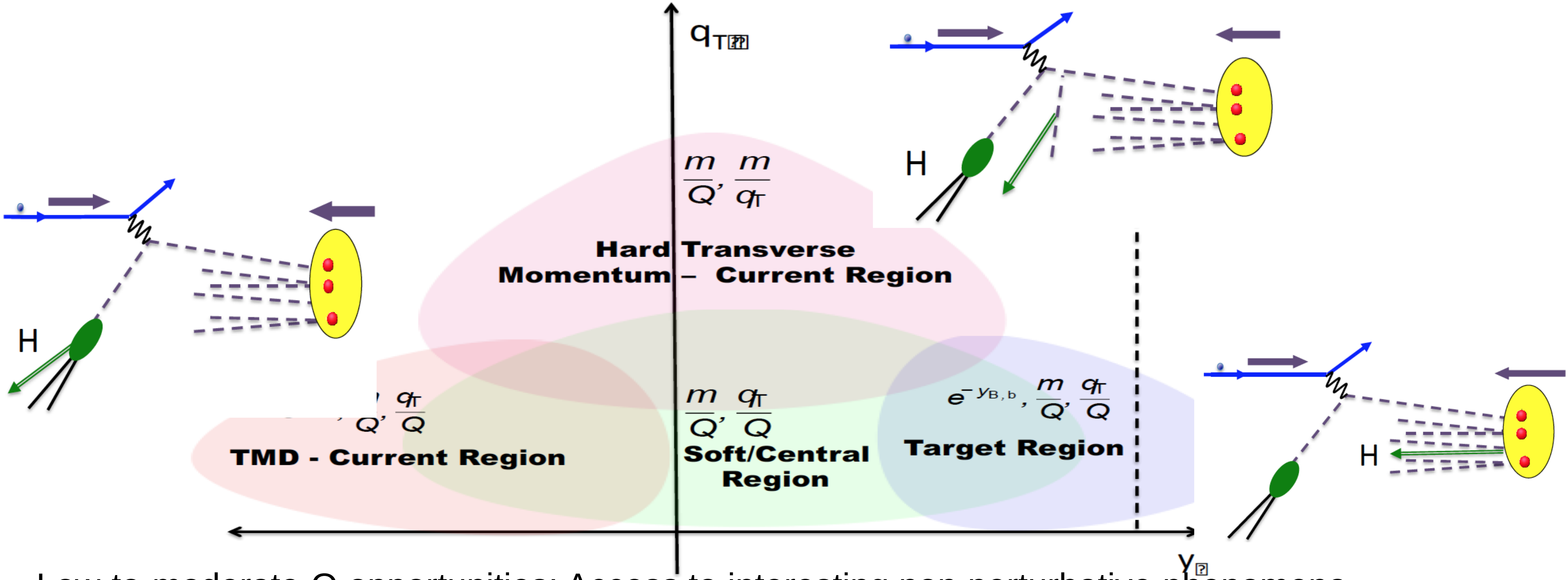
Sea is not divided to perturbative and non-perturbative

T. Rogers (INT-2018)

Other factors

Challenges at moderate scales

- Non-zero hadron masses
- Constituents have non-zero virtuality, mass, etc.
- The separation between regions gets squeezed.



Low-to-moderate Q opportunities: Access to interesting non-perturbative phenomena

Mass effects need to be accounted for

Systematic diagnostic tools needed

Estimating systematics

Steps for Extraction and Validation procedure (need realistic SIDIS MC)

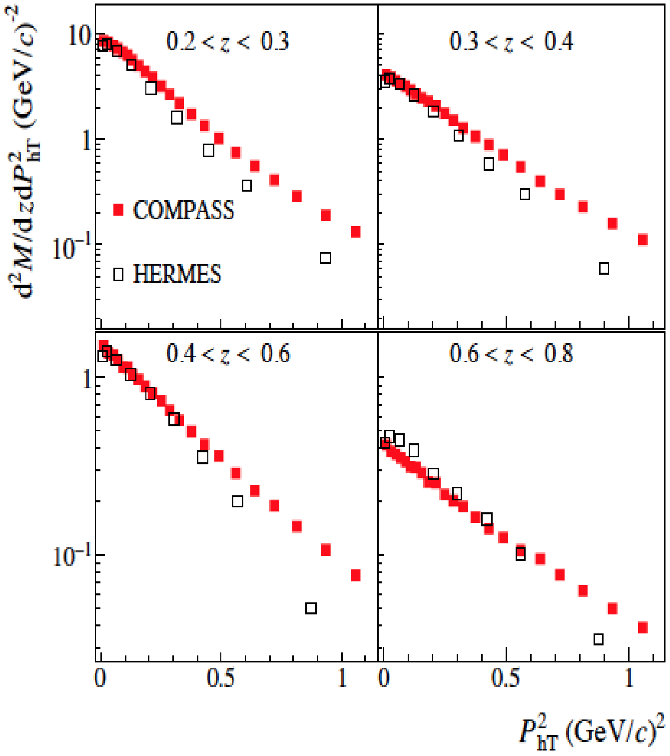
1) make sure we can recover the underlying 3D PDFs (TMD/GPD…) PDF from generated for a given beam energy sample
2) make sure we can recover the underlying 3D PDFs (TMD/GPD…) from reconstructed for a given detector configuration sample

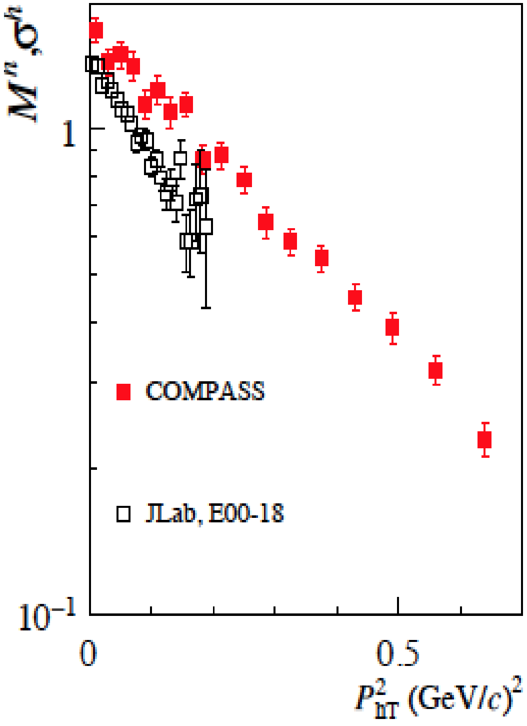
1) add radiative effects
2) add other SFs to see the effect of Cahn on extraction of the F_UU,T and check the extraction of cos and cos2 moments
3) add/eliminate evolution effects with HT effects and see if we can indeed separate them
4) add F_UU,L part and see the effect of disregarding it in the extraction.

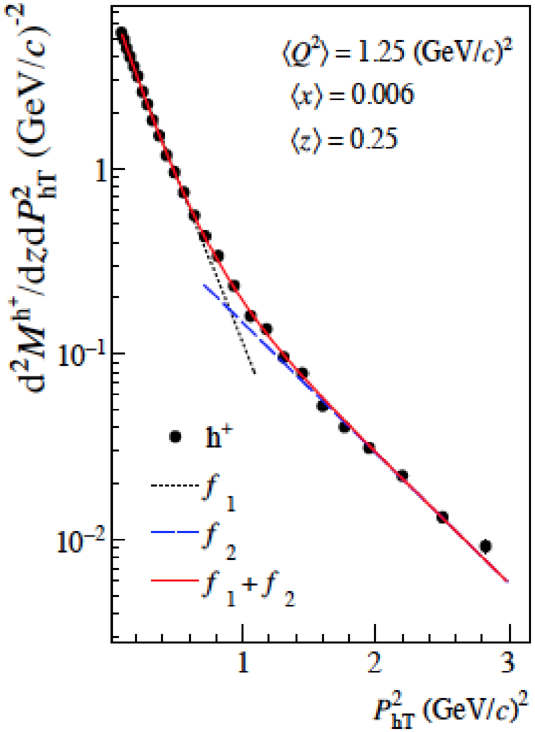
.... big list of systematic checks....

Multiplicities of hadrons in SIDIS

COMPASS:1709.07374



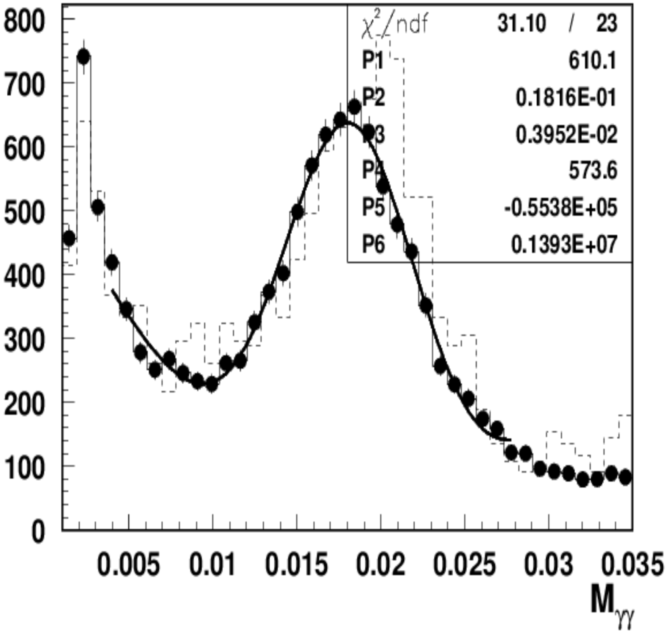




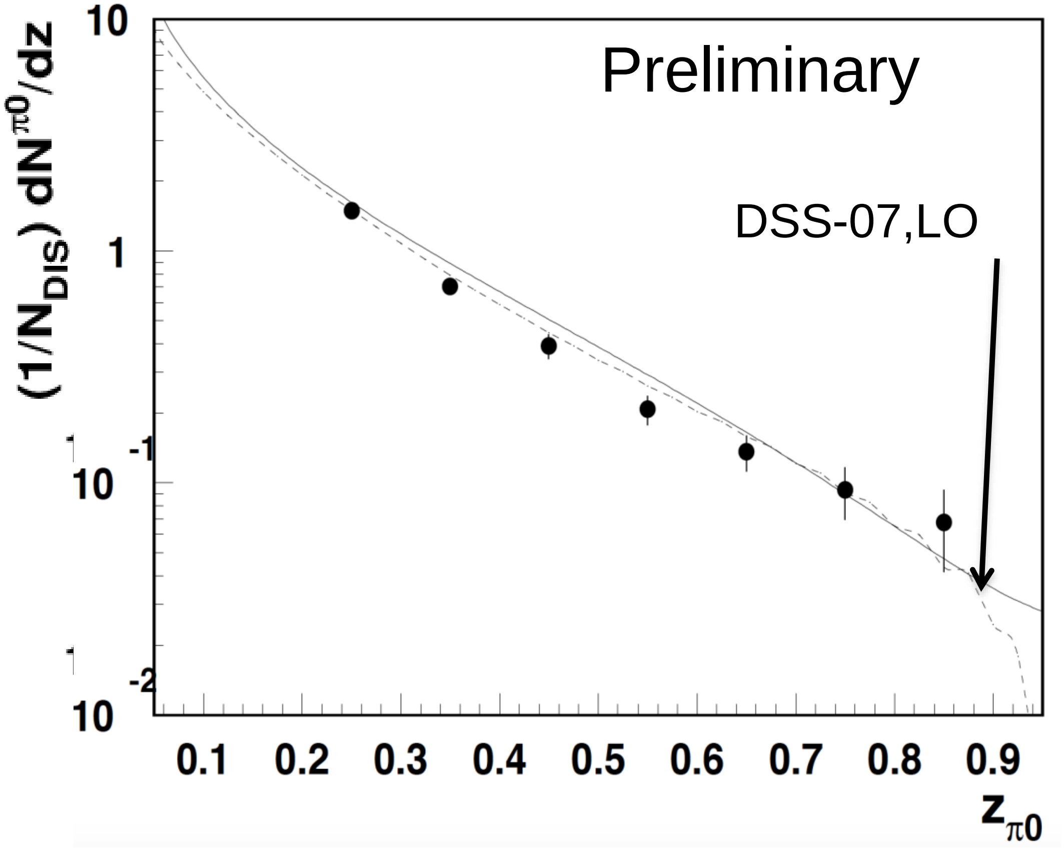
- Lower the beam energy, less phase space for high P_T
- P_T-weighting may be hard to control

- What is the origin of the tail?
- Is there a problem with the perturbative part (Sato) or with high P_T-part of TMD?

clas12: e’ □^{0}X multiplicity



1% of CLAS12 spring run



Efficiency fairly constant at z>0.25

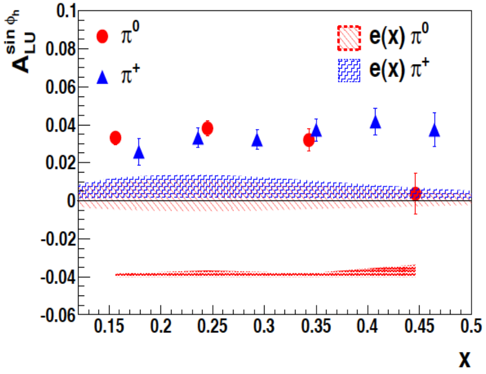
- Ratio e’□^{0}X/ e'X follows z-dependence of the fragmentation function
- Multiplicity consistent with HERMES,clas6,LO FFs
- Improve the fiducial cuts and estimate systematics due to various cuts

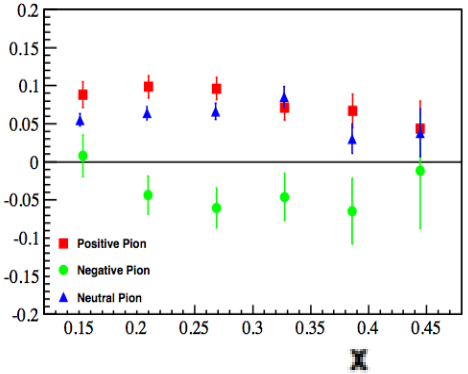
Quark-gluon correlations: flavor dependence

Higher Twist PDFs

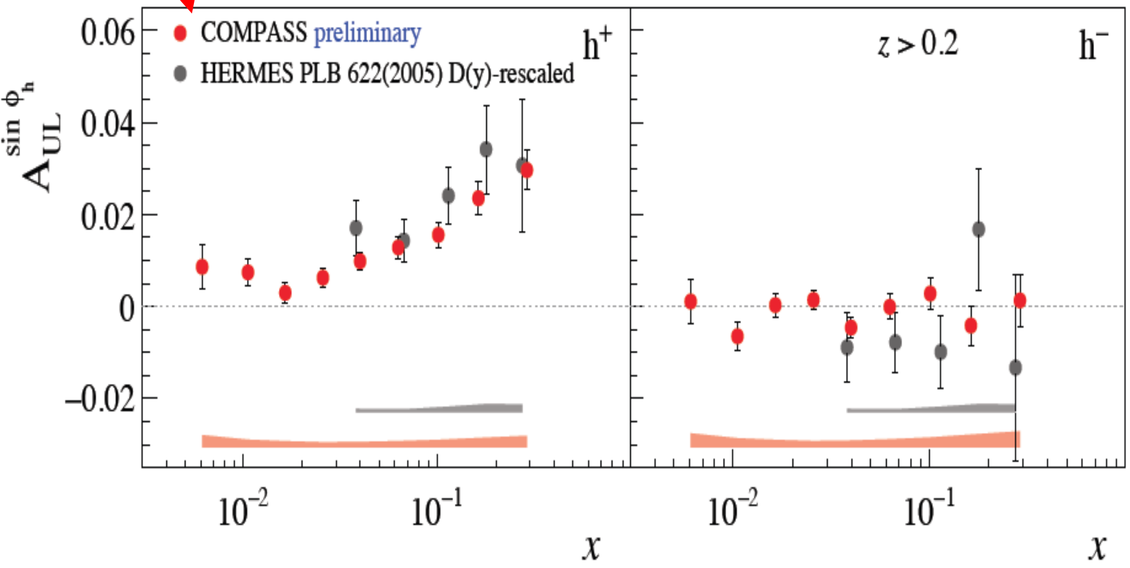
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, e
L	$f_L^\perp$	$g_L^\perp$	h_L, e_L
T	$f_T, f_T^\perp$	$g_T, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

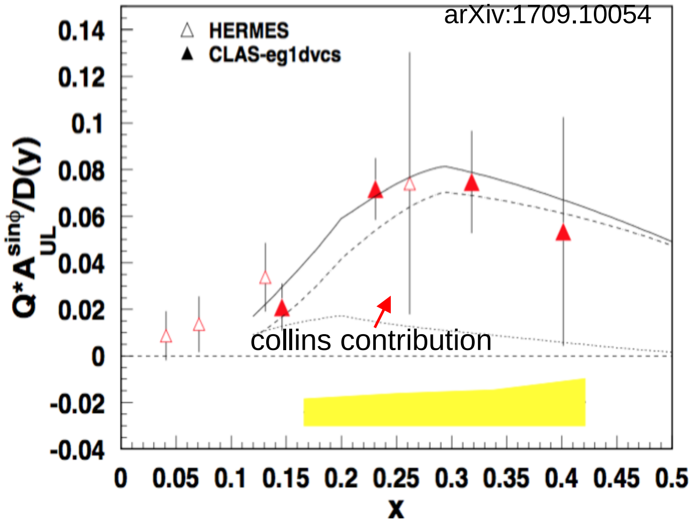
1) roughly equal $\pi^+\pi^0$ SSA
2) π^- SSA much smaller, consistent with 0 or<0





CLAS/HERMES





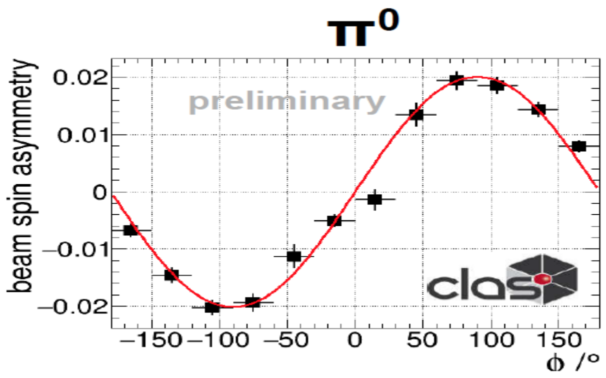
arXiv:1709.10054

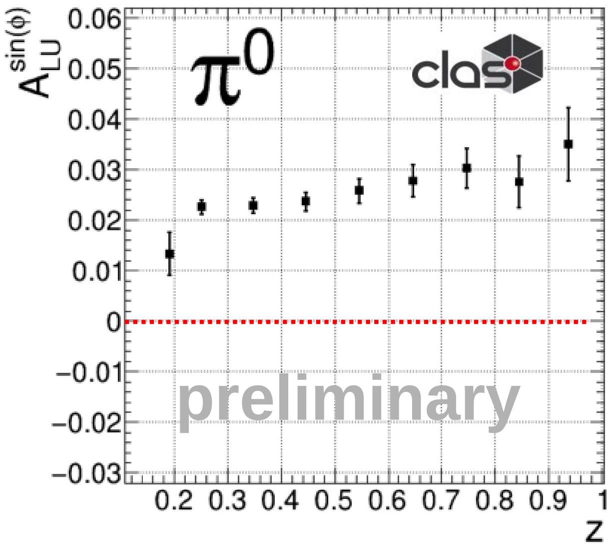
collins contribution

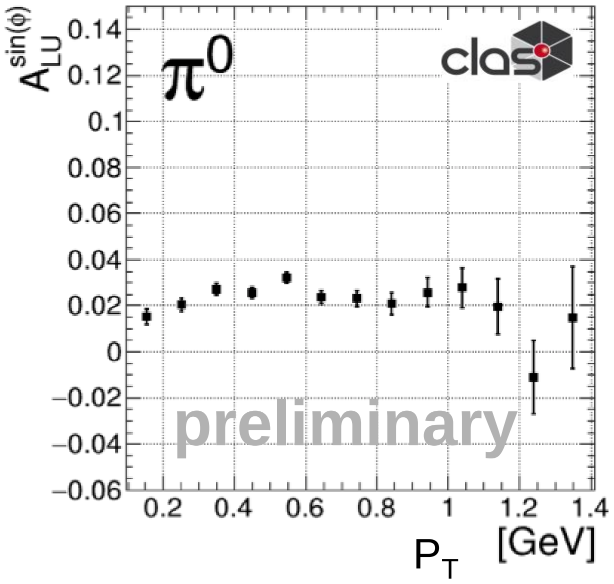
- Significant longitudinal beam and target SSA measured at HERMES, JLab and COMPASS may be related to higher twist distribution functions
- $\sin\phi$ modulations for $\pi^+\pi^0$ consistent with dominance of Sivers mechanism
- Subleading asymmetries comparable with leading ones (1/Q terms should be accounted)

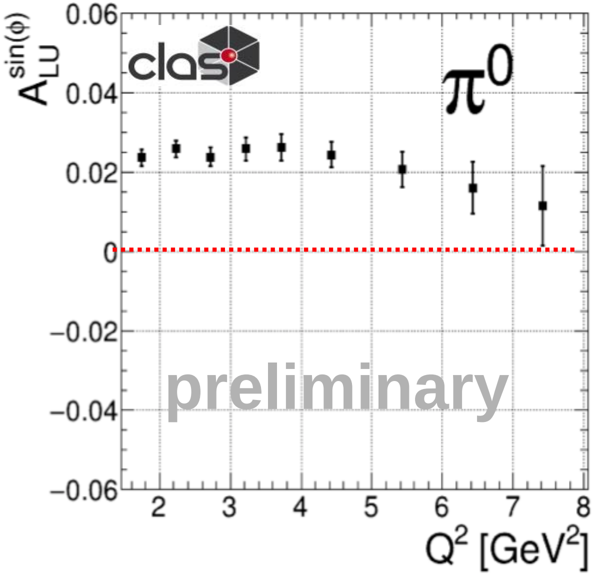
First look at CLAS12 data

$$BSA_i = \frac{1}{P_e}\cdot\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$









With only 2% of expected unpolarized target data, clas12 already provides a superior measurement

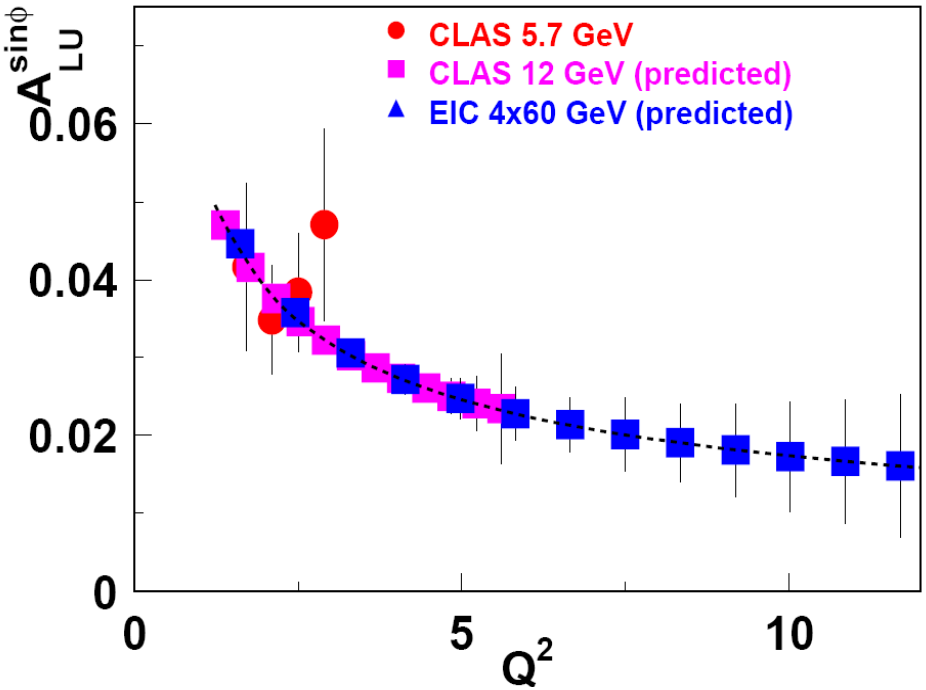
Will require fine multidimensional binning to study Q^2-dependence

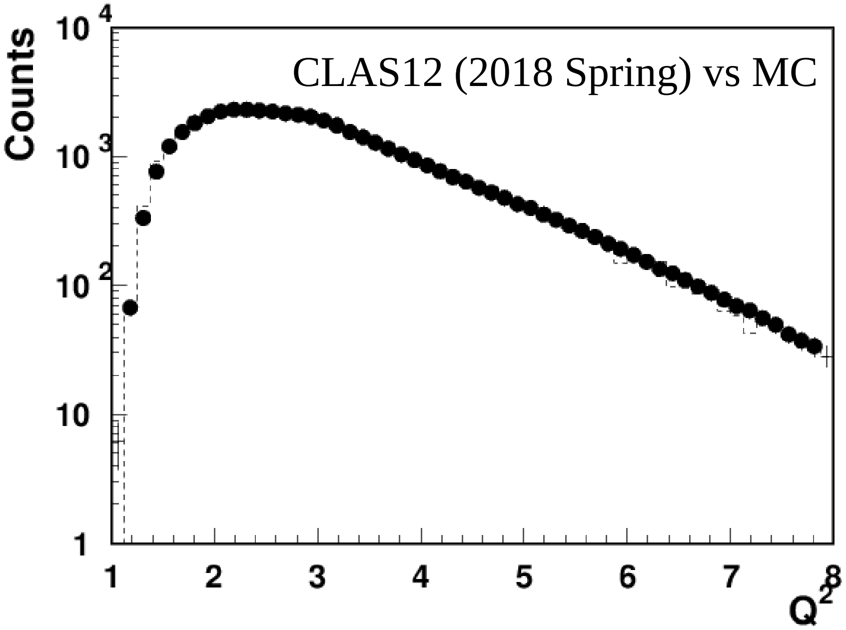
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, e
L	$f_L^\perp$	$g_L^\perp$	h_L, e_L
T	$f_T, f_T^\perp$	$g_T, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

From JLab12 to EIC

$$A_{LU} \propto g^\perp(x) D_1(z)$$

JLab@12GeV (25/50/75)
→0.1<x_B<0.7 : valence quarks
EIC √s = 140, 50, 15 GeV
→10^{-4}<x_B<0.3: gluons and quarks, higher P_T and Q^2.


$\vec{e}\, p \to e' \pi^+ X$



- •Understanding of quark-gluon correlations is crucial for precision studies of the structure of the nucleon.
- •At medium energies all experiments measure very significant HT contributions
- •Large HT effects may indicate the breakdown of the theory
- •Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

Correlations of spin, longitudinal and transverse degrees

- How k_T distributions of partons depending on spin and flavor modify in medium?

- How studies of proton transverse structure will improve our understanding of medium effects?

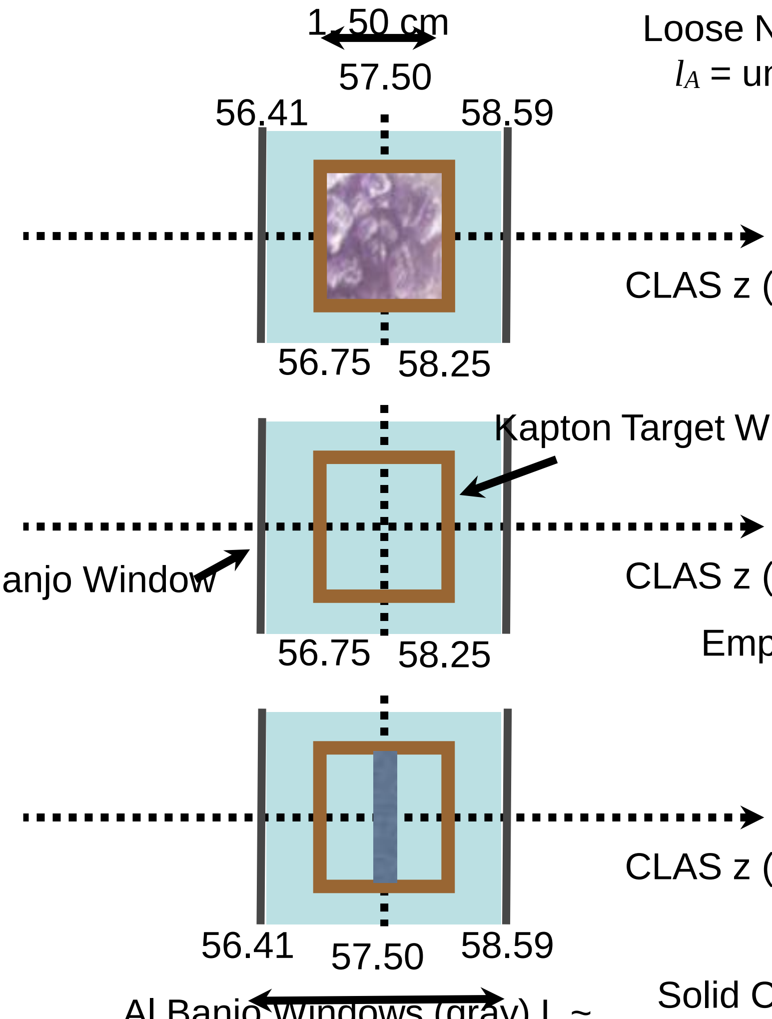
- How studies of medium modifications will improve our understanding of the proton structure?

Tools:

- Polarized and unpolarized SIDIS resolve flavor and spin effects
- Polarized SIDIS will help to resolve the spin-orbital effects in medium

Joint analysis of polarized and unpolarized target data is crucial for studies of orbital effects in general and medium modification in particular

Target Schematic



Kapton cup windows (brown) L_{cup} = 1.50 cm

57.50

56.41 58.59

Loose NH_3 beads (purple)
l_A = unknown, packing fraction

CLAS z (cm)

56.75 58.25

Kapton Target Window

Al Banjo Window

CLAS z (cm)

56.75 58.25

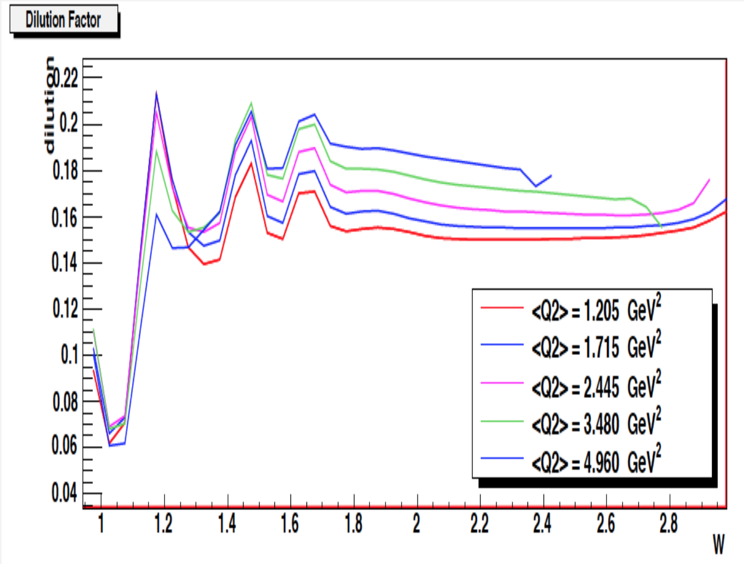
Empty target cup

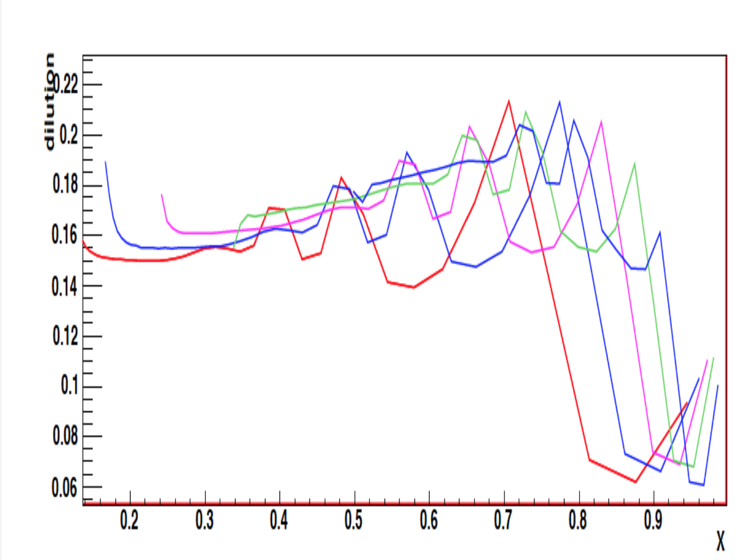
CLAS z (cm)

56.41 57.50 58.59

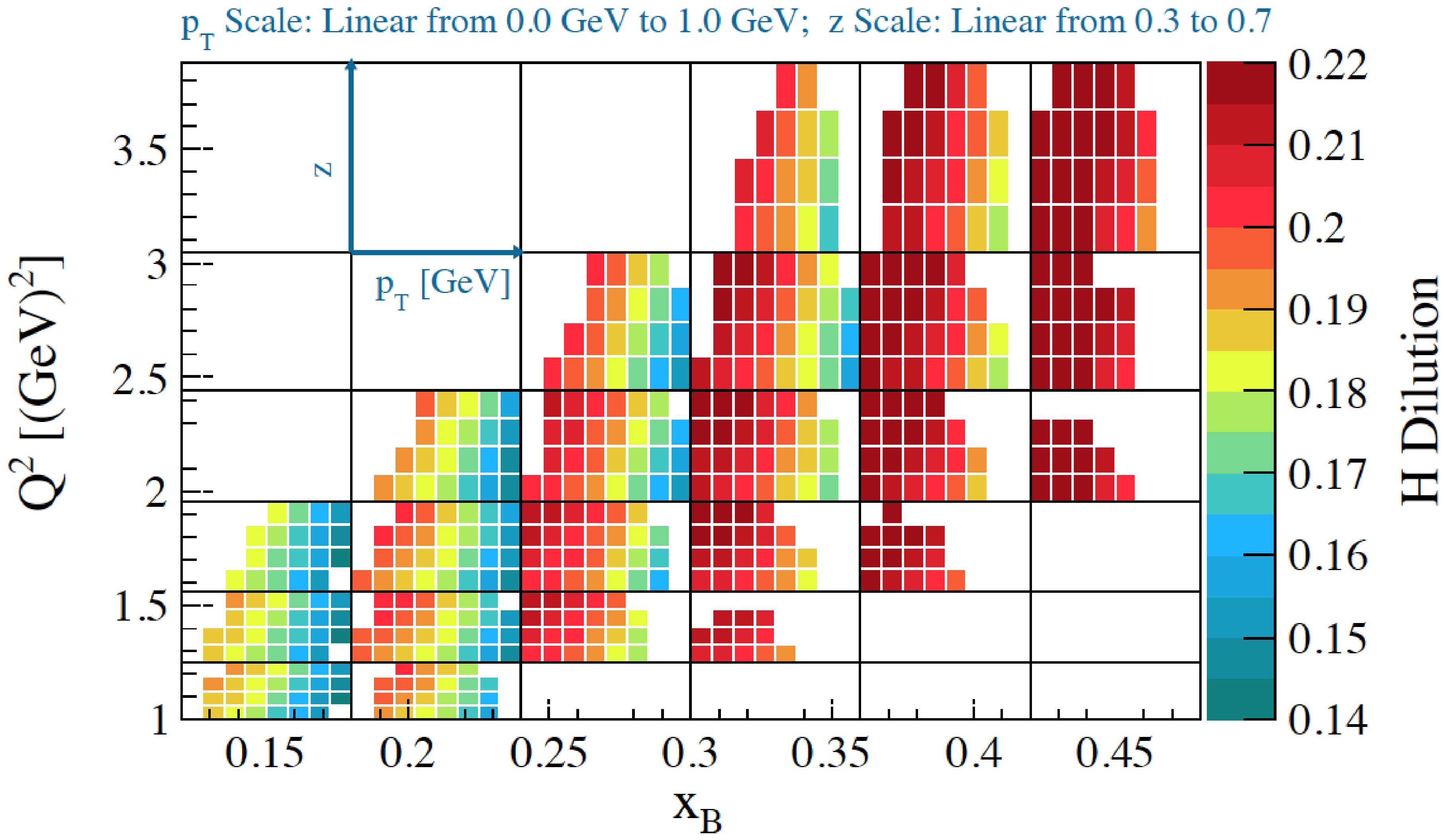
Al Banjo Windows (gray) L ~ 2.18 cm
Helium filled (gray shading)

Solid Carbon target
l_c = 0.40 cm





SIDIS dilution factor



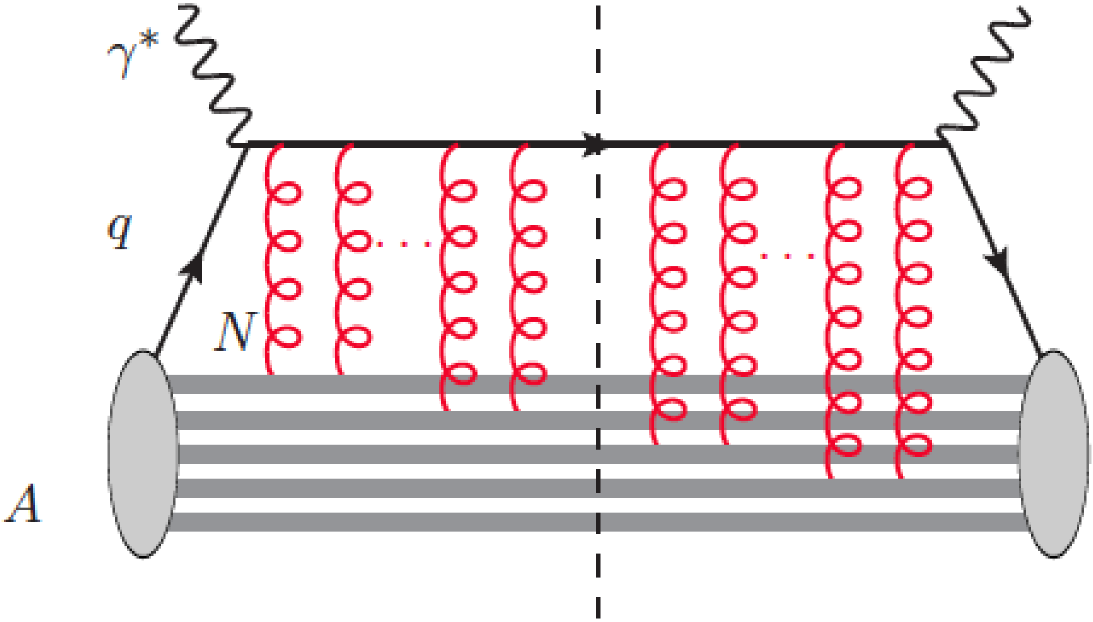
k_T in medium and FSI

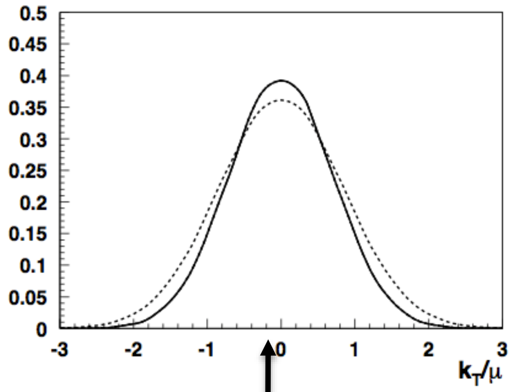
Tang,Wang & Zhou
Phys.Rev.D77:125010,2008

$$f_q^N(x,\vec{k}_T)$$

$$f_q^A(x,\vec{k}_T) = \frac{A}{\pi\Delta_{2F}}\int d^2 l_T e^{-(\vec{k}_T-\vec{l}_T)^2/\Delta_{2F}} f_q^N(x,\vec{l}_T)$$

total transverse momentum broadening squared





k_T-distributions wider in nuclei?

the intrinsic transverse momentum of partons arises naturally from multiple soft gluon interaction inside the nucleon or nucleus.

$$F_{UU}^{\cos\phi} \propto f^{\perp q} D_1^q$$

Modification of Cahn effect

$$< cos\phi >_{eN} \propto \frac{|\vec{k}_T| x f_N^{\perp q}(x, k_T)}{f_N^q(x, k_T)}$$

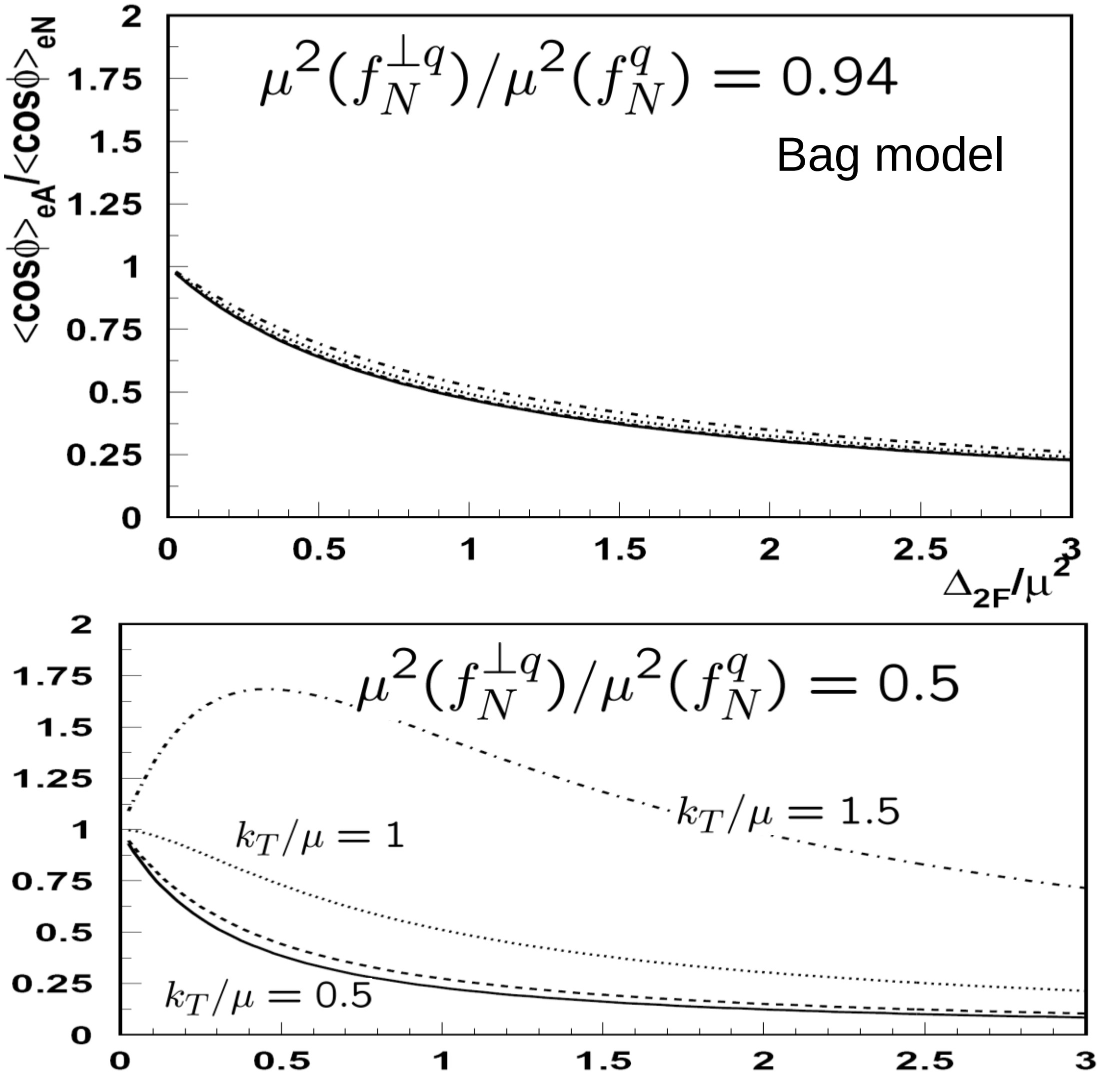
$$f_N^q(x, k_T) = \frac{1}{\pi\mu_0^2} f_N^q(x) e^{-k_T^2/\mu_0^2}$$

Modifies in medium

$$\mu_0^2 \rightarrow \mu_0^2 + \Delta_{2F}$$

$$\frac{< \cos\phi >_{eA}}{< \cos\phi >_{eN}} = \frac{\mu_0^2}{\mu_0^2 + \Delta_{2F}}$$

Gao, Liang & Wang **arXiv:1001.3146**



Medium modification of the azimuthal asymmetry is a very sensitive probe of the twist-2 and twist-3 TMD quark distributions

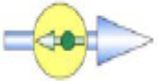
Medium modification and spin observables

I. Cloet

- In medium quarks are more relativistic
- lower components of quark wavefunctions enhanced
- quark lower components have larger angular momentum
- quark spin ➔ orbital angular momentum in medium

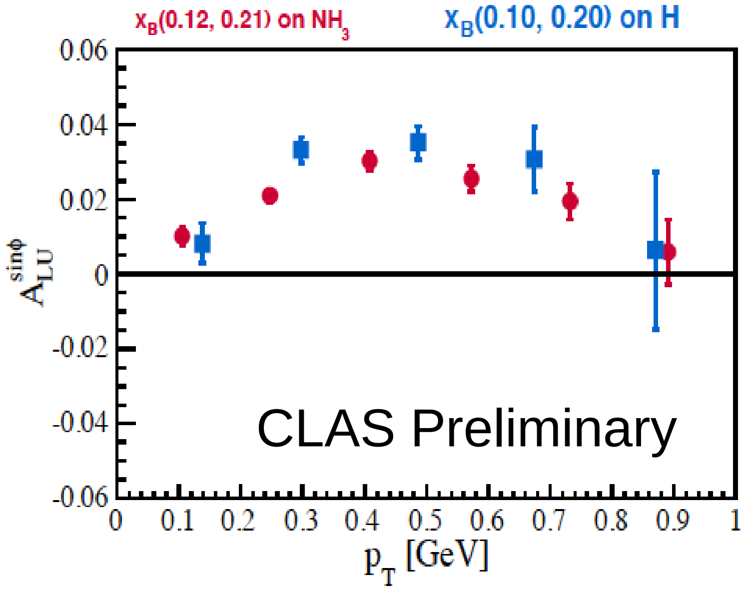
- observables sensitive to orbital motion will have strongest medium modifications

H.A.,Brodsky,Yuan & Deur

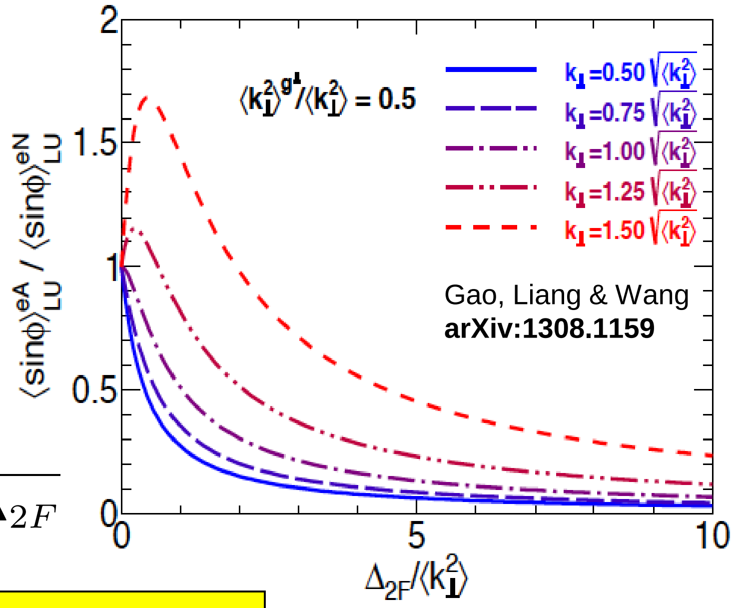


$$q^{-}_{L=1} \sim (1-x)^5 log^2(1-x)$$

- q- most sensitive to orbital motion
- medium modifies the orbital motion



$$\frac{A^{\sin\phi}_{LU,eA}}{A^{\sin\phi}_{LU,eN}} \approx \frac{\mu^2}{\mu^2 + \Delta_{2F}}$$

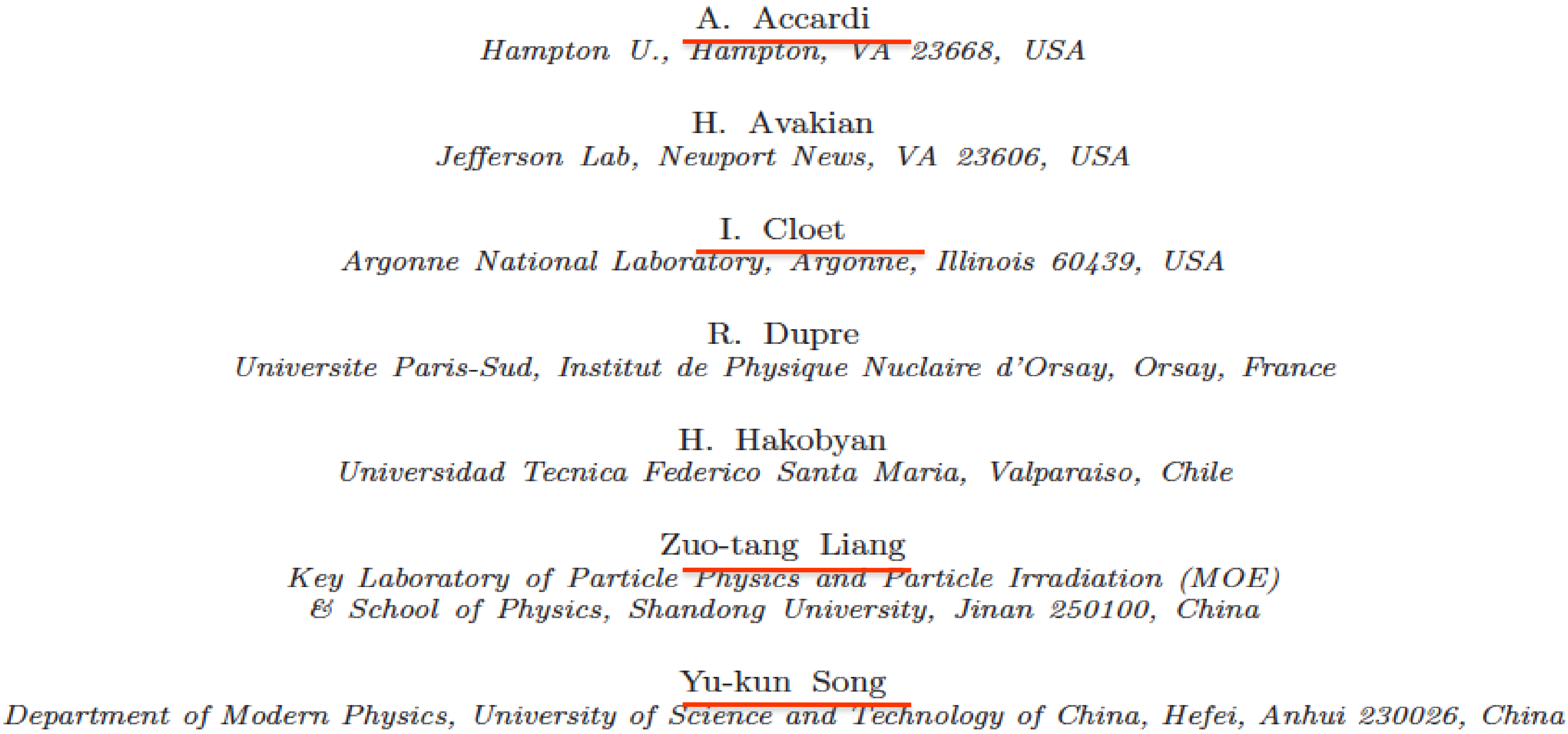


Gao, Liang & Wang
arXiv:1308.1159

spin and azimuthal asymmetries provide important information on partonic distributions in bound nucleons.

Medium modification of hadronic distributions in SIDIS

PAC42 LoI (2014)



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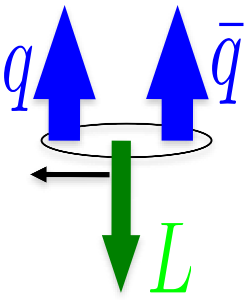
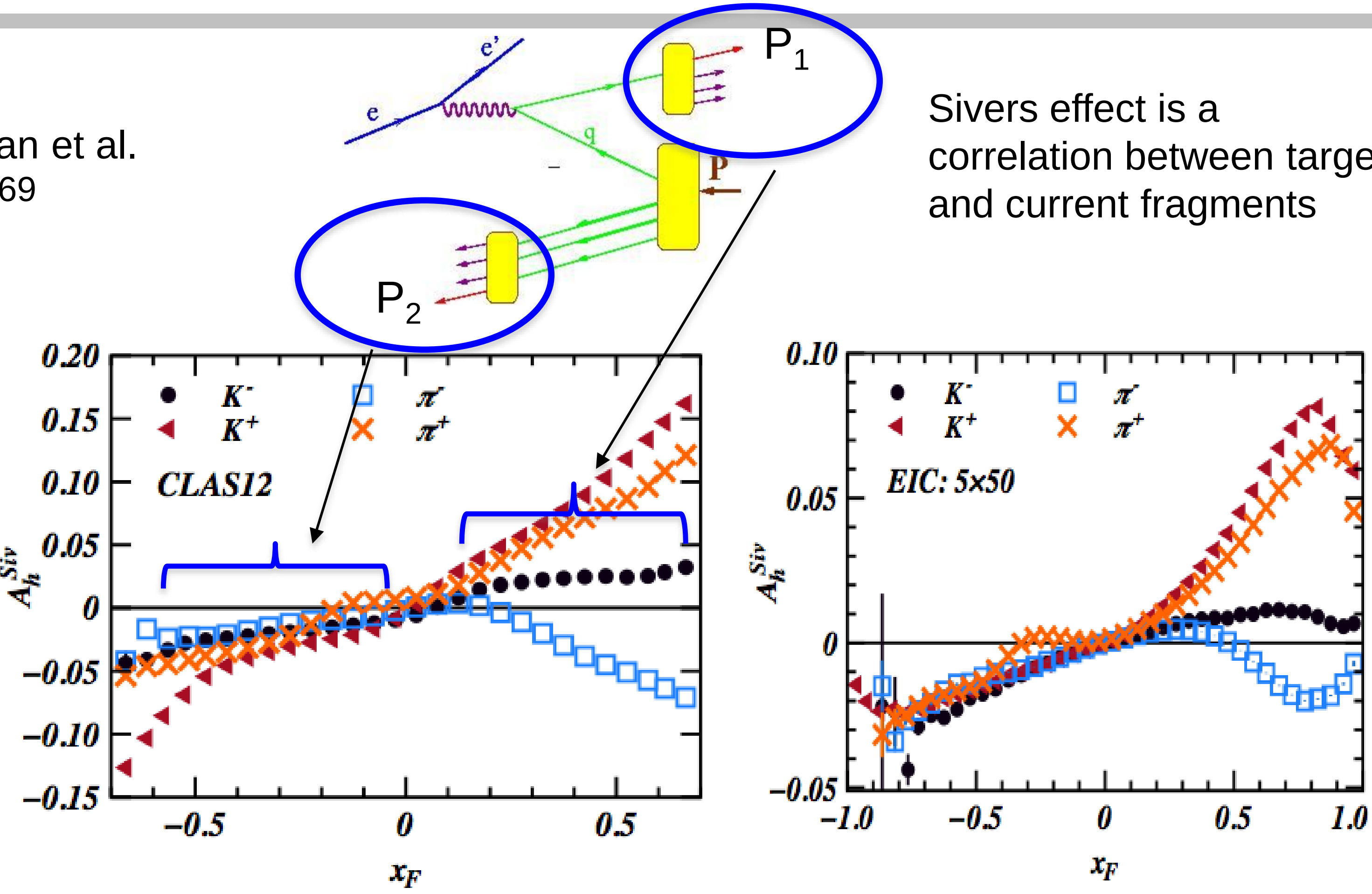
Sivers effect in Target fragmentation

H. Matevosyan et al.
arXiv:1502.02669

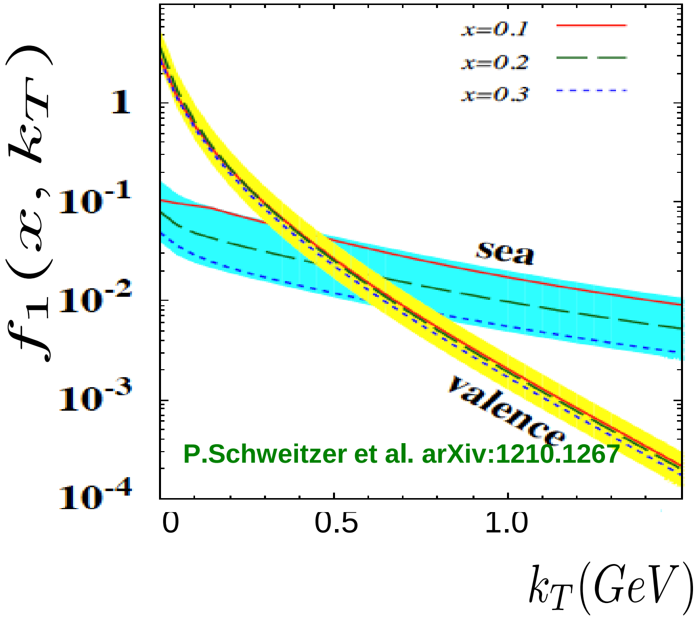




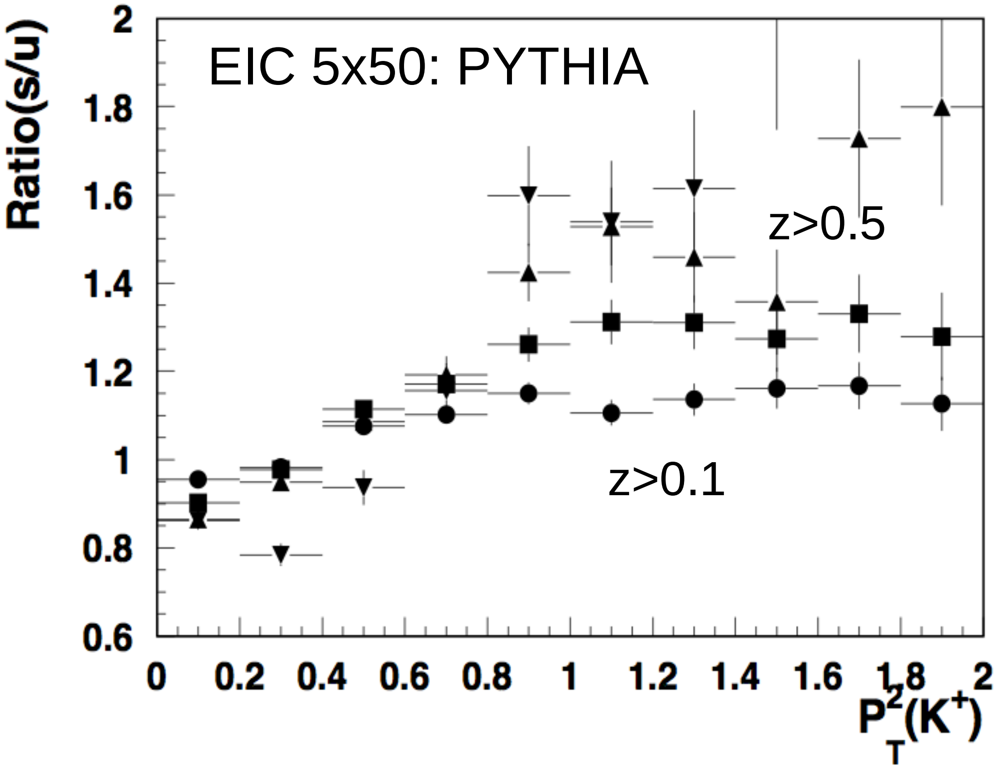
Sivers effect is a correlation between target and current fragments

Wide coverage of CLAS12 and EIC will allow studies of kinematic dependences of the Sivers effect, both in current and target fragmentation regions

P_T-distributions of Kaons from s and u quarks



P.Schweitzer et al. arXiv:1210.1267



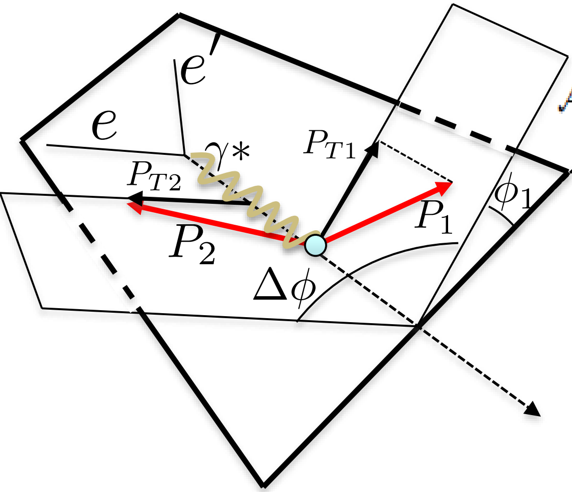
Increase the $\langle k_T \rangle$ in PYTHIA
(no orbital effects accounted)

- At relatively large x (x>0.01), where non perturbative sea start to dominate significant fraction of Kaons may come from s-quarks
- Additional control possible by detection of target fragments

B2B hadron production in SIDIS: First measurements

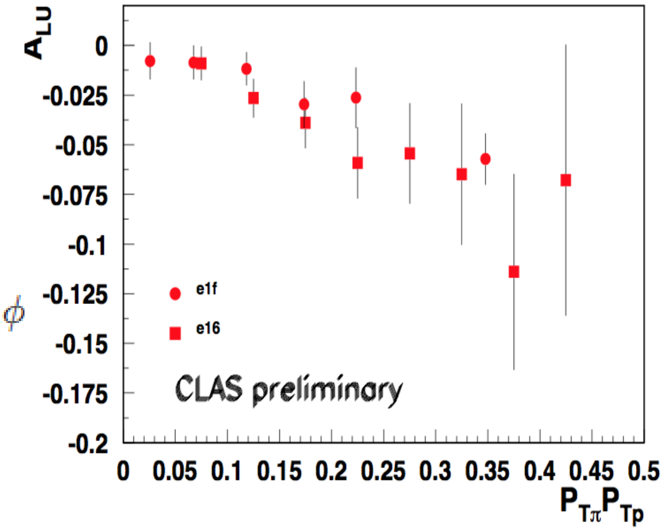
M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

$$ep \longrightarrow e'p\pi^+X$$

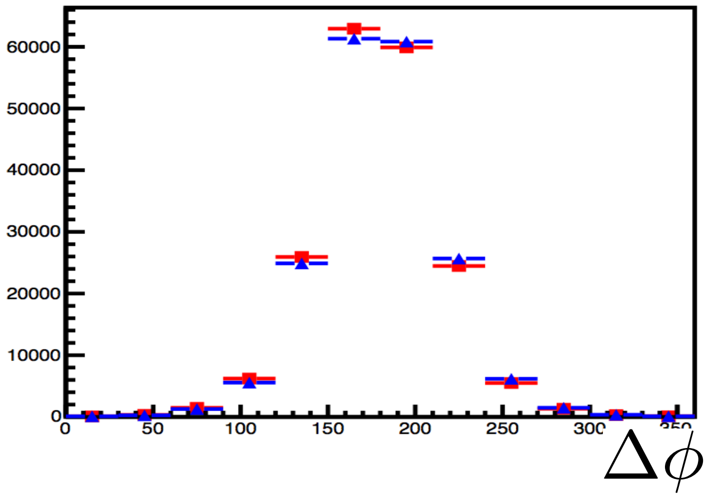


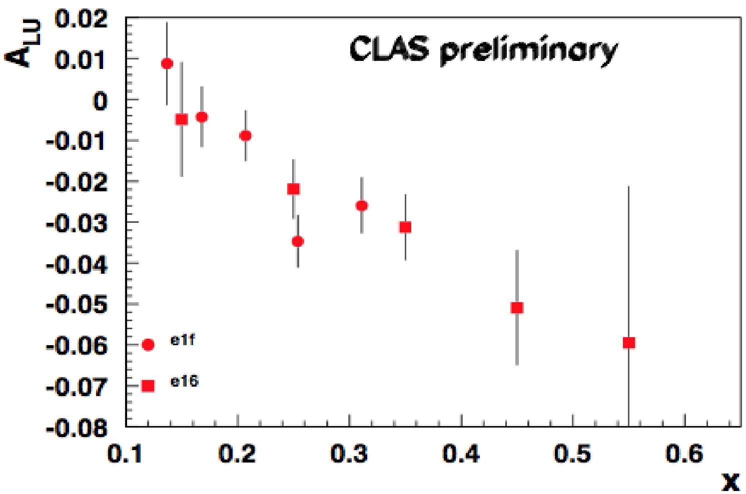
$$\mathcal{A}_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{C}[w_5 M_L^{\perp,h} D_1]}{\mathcal{C}[M D_1]}\sin\Delta\phi$$



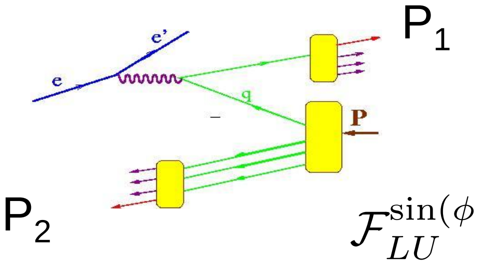
CLAS PRELIMINARY





Single spin symmetries observed by CLAS at 6 GeV increase at large x and P_T

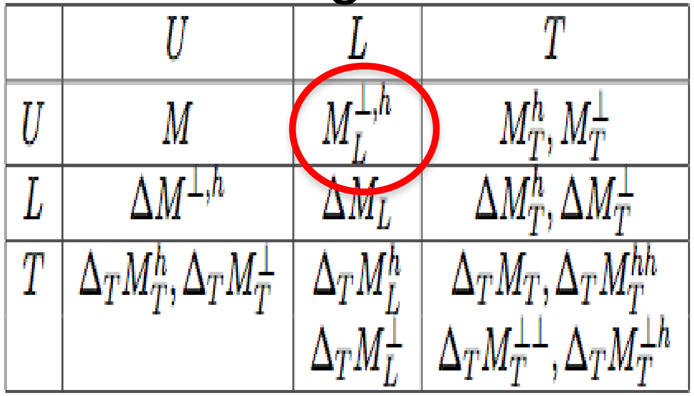
Back-to-back hadron (b2b) production in SIDIS



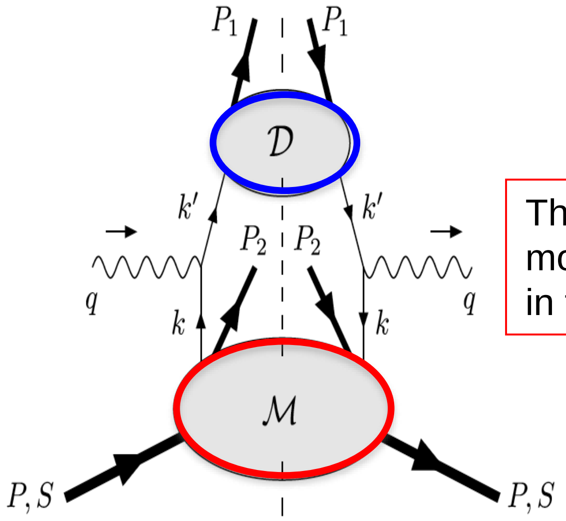
M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\vec{P}_{1\perp}\vec{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 M_L^{\perp h} D_1]$$

Leading Twist



	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$



The beam–spin asymmetry appears, at leading twist and low transverse momenta, in the deep inelastic inclusive lepto-production of two hadrons, one in the target fragmentation region and one in the current fragmentation region.

probability to produce the hadron h when a quark q is struck in a proton target

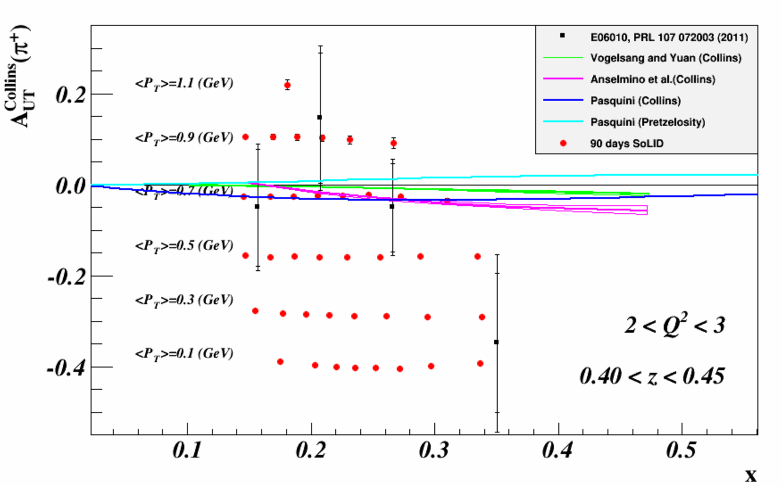
Back-to-back hadron production in SIDIS would allow:

- study SSAs not accessible in SIDIS at leading twist
- measure fracture functions
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- study entanglement in correlations in target vs current
- access quark short-range correlations and χSB (Schweitzer et al)
- ...

Transversity from SoLID

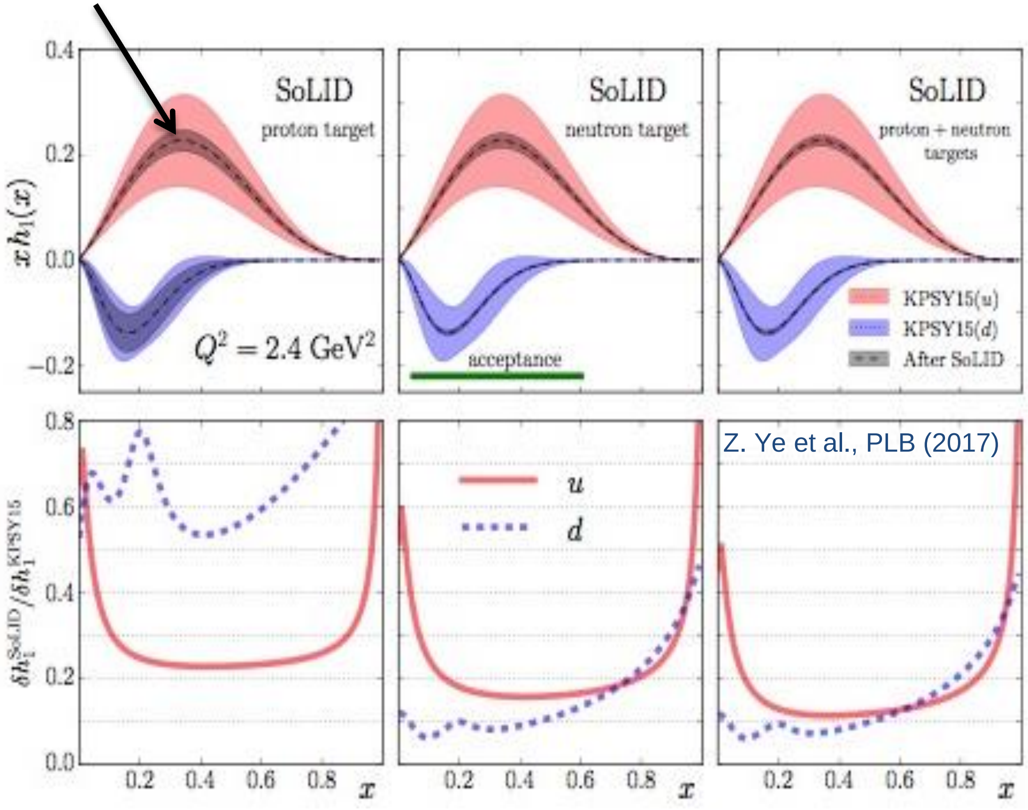
- Collins Asymmetries ~ Transversity (x) Collins Function
- SoLID with trans polarized n & p → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

Significant improvement, but need to quantify the systematics from modeling (underlying assumptions)



Z. Ye et al., PLB (2017)

Nucleon structure & TMDs at leading twist

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

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

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

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

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

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

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

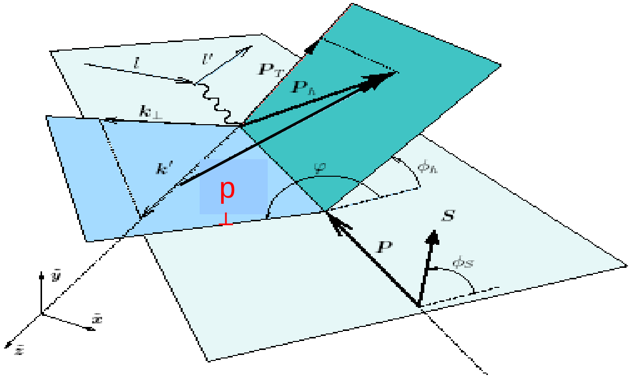
$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2}$$

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

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

Extraction of leading twist TMDs limited to formalism accounting for only leading twists will require some mechanisms for controlling the systematics (measure and simulate background effects).

Reproduce SIDIS output with MC



SIDIS MC in 7D (10D)

$$\frac{d\sigma_{\lambda\Lambda}^{eN\rightarrow e'hX}}{dx\,dQ^2\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_l\,d\phi_s}=\sum_{l=1}^{L} SF_l$$

step-1 $x_i, Q_i^2 z_i P_{hT}^{i2} \phi_h^i \phi_l^i \phi_s^i$

step-2 (for a given E$_{\text{beam}}$,λ,Λ) P_i^{el}, P_i^h

step-3 (detected for a given Detector configuration)

$$x_j, Q_j^2 z_j P_{hT,j}^2 \phi_h^j \phi_l^j \phi_s^j$$

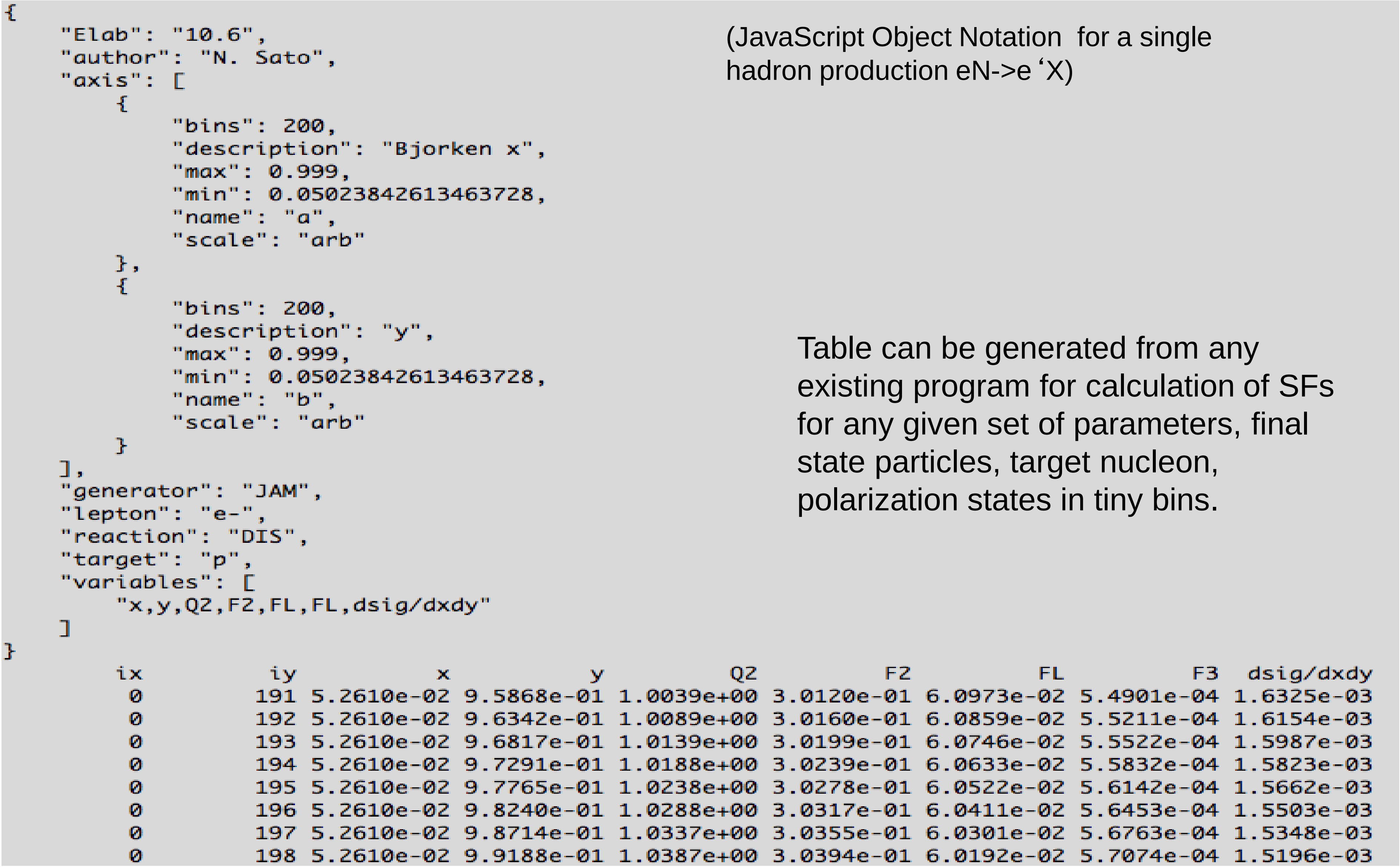
Theory

Provide a set of SF$_l$

For a given model/theory based on underlying non-perturbative input calculate SF$_l$

Output counts for a given energy and detector setup

Standard input for SFs



(JavaScript Object Notation for a single hadron production eN->e‘X)

```
{
    "Elab": "10.6",
    "author": "N. Sato",
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        {
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            "description": "Bjorken x",
            "max": 0.999,
            "min": 0.05023842613463728,
            "name": "a",
            "scale": "arb"
        },
        {
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            "description": "y",
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            "name": "b",
            "scale": "arb"
        }
    ],
    "generator": "JAM",
    "lepton": "e-",
    "reaction": "DIS",
    "target": "p",
    "variables": [
        "x,y,Q2,F2,FL,FL,dsig/dxdy"
    ]
}
```

```
        ix         iy          x          y         Q2         F2         FL         F3  dsig/dxdy
         0        191 5.2610e-02 9.5868e-01 1.0039e+00 3.0120e-01 6.0973e-02 5.4901e-04 1.6325e-03
         0        192 5.2610e-02 9.6342e-01 1.0089e+00 3.0160e-01 6.0859e-02 5.5211e-04 1.6154e-03
         0        193 5.2610e-02 9.6817e-01 1.0139e+00 3.0199e-01 6.0746e-02 5.5522e-04 1.5987e-03
         0        194 5.2610e-02 9.7291e-01 1.0188e+00 3.0239e-01 6.0633e-02 5.5832e-04 1.5823e-03
         0        195 5.2610e-02 9.7765e-01 1.0238e+00 3.0278e-01 6.0522e-02 5.6142e-04 1.5662e-03
         0        196 5.2610e-02 9.8240e-01 1.0288e+00 3.0317e-01 6.0411e-02 5.6453e-04 1.5503e-03
         0        197 5.2610e-02 9.8714e-01 1.0337e+00 3.0355e-01 6.0301e-02 5.6763e-04 1.5348e-03
         0        198 5.2610e-02 9.9188e-01 1.0387e+00 3.0394e-01 6.0192e-02 5.7074e-04 1.5196e-03
```

Table can be generated from any existing program for calculation of SFs for any given set of parameters, final state particles, target nucleon, polarization states in tiny bins.

Radiative DIS

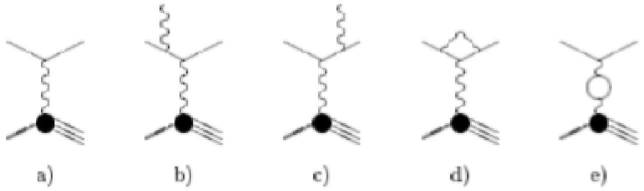
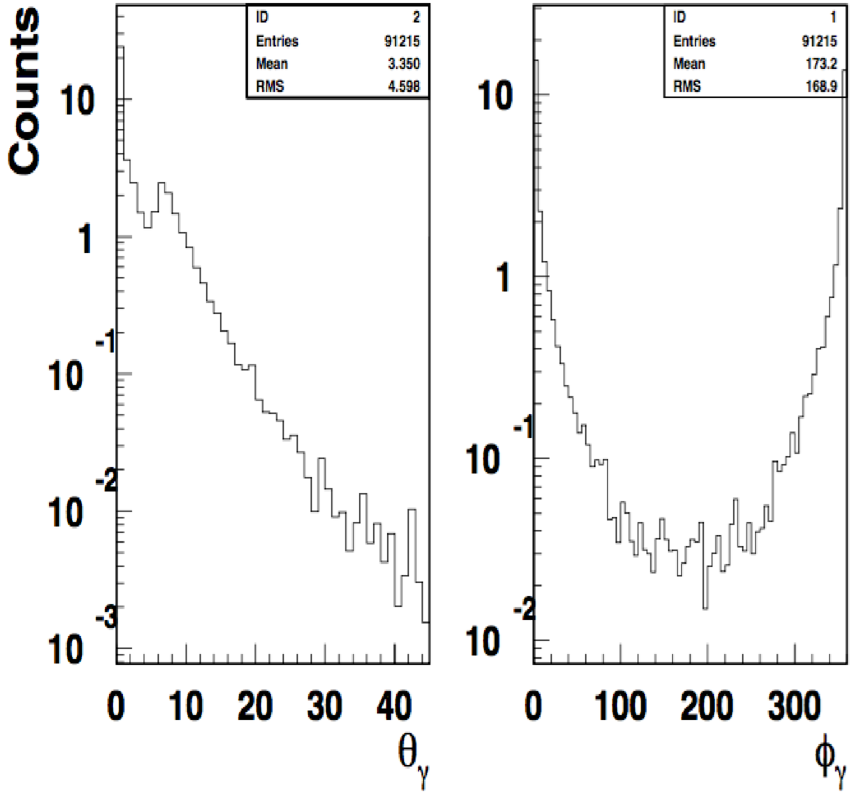
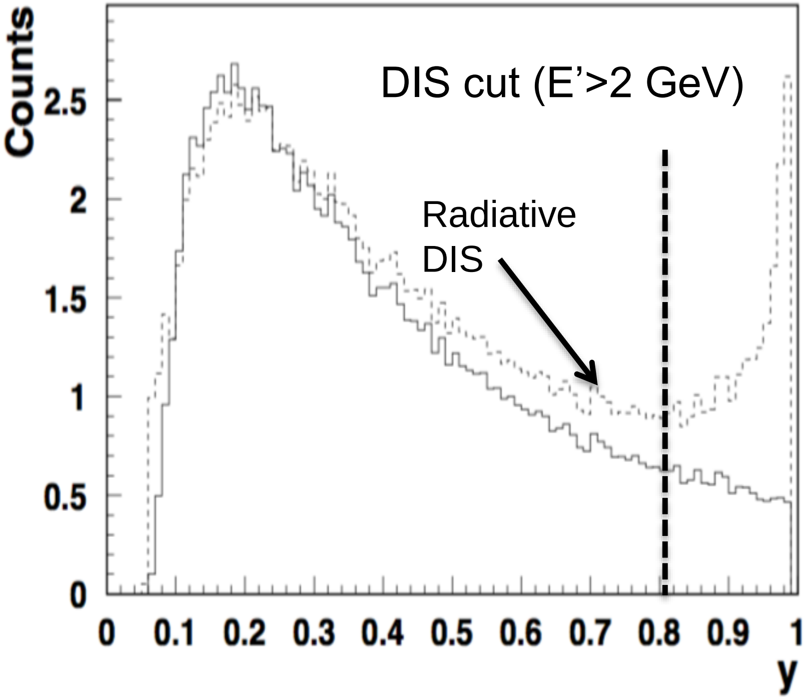


Figure 1: Feynman diagrams contributing to the Born and the radiative correction cross sections in lepton-nucleus scattering.

Akushevich et al. http://www.jlab.org/RC/radgen/

For EVA tests a DIS generator developed which works with x-sections, SFs, grids, has radiative effects.





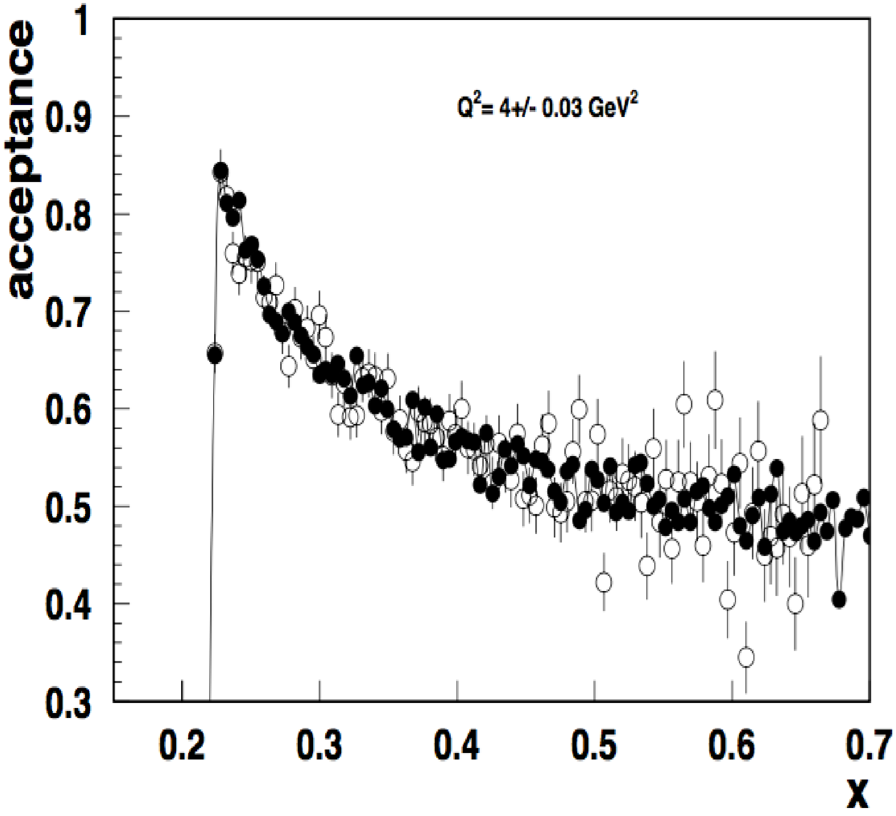
DIS cut (E’>2 GeV)

Radiative DIS

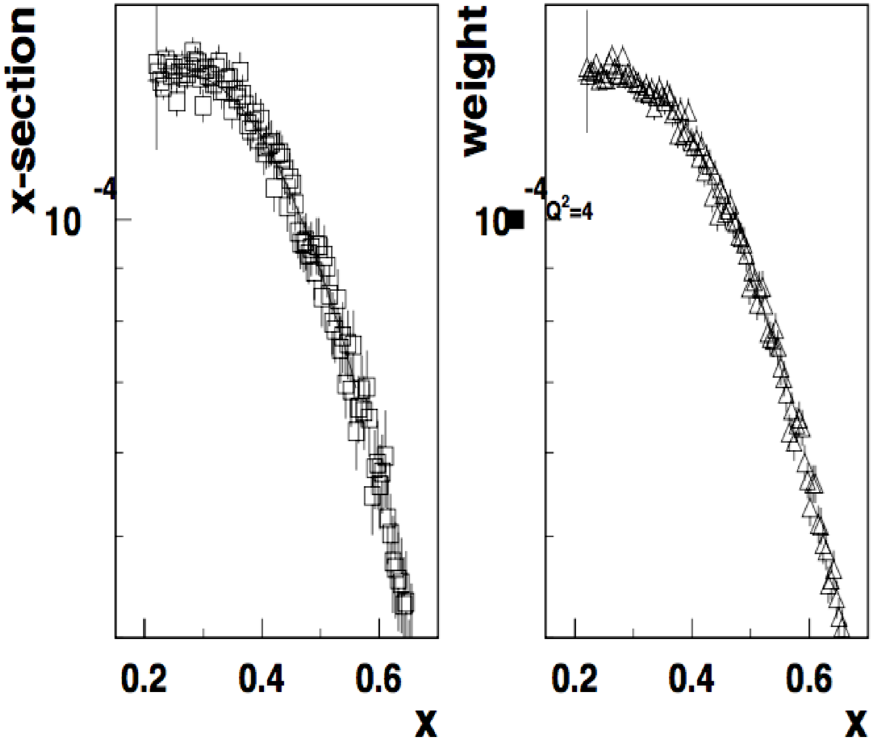
Recovering generated input from reconstructed set

Step-II

40Mil generated events (200x200 bins)

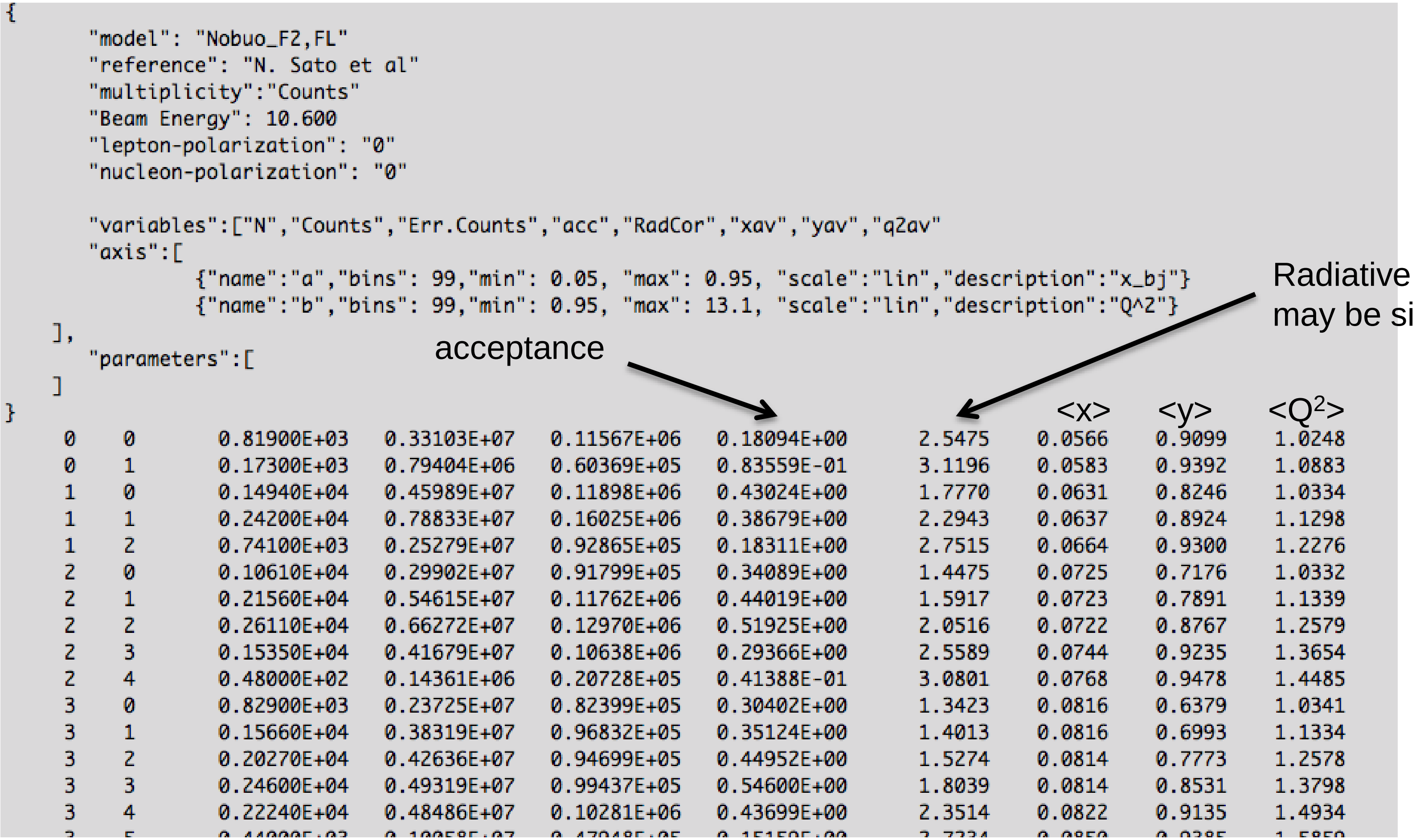


line N. Sato



- Acceptance can be defined using the weighted generator set
- Both MCs after reconstruction recover the generated input in most of the kinematics.)

Extraction of DIS x-section and acceptance



Radiative corrections may be significant

acceptance

<x> <y> <Q^2>

```
{
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        "reference": "N. Sato et al"
        "multiplicity":"Counts"
        "Beam Energy": 10.600
        "lepton-polarization": "0"
        "nucleon-polarization": "0"

        "variables":["N","Counts","Err.Counts","acc","RadCor","xav","yav","q2av"
        "axis":[
                  {"name":"a","bins": 99,"min": 0.05, "max": 0.95, "scale":"lin","description":"x_bj"}
                  {"name":"b","bins": 99,"min": 0.95, "max": 13.1, "scale":"lin","description":"Q^2"}
    ],
        "parameters":[
    ]
}
     0    0       0.81900E+03   0.33103E+07   0.11567E+06   0.18094E+00       2.5475   0.0566   0.9099   1.0248
     0    1       0.17300E+03   0.79404E+06   0.60369E+05   0.83559E-01       3.1196   0.0583   0.9392   1.0883
     1    0       0.14940E+04   0.45989E+07   0.11898E+06   0.43024E+00       1.7770   0.0631   0.8246   1.0334
     1    1       0.24200E+04   0.78833E+07   0.16025E+06   0.38679E+00       2.2943   0.0637   0.8924   1.1298
     1    2       0.74100E+03   0.25279E+07   0.92865E+05   0.18311E+00       2.7515   0.0664   0.9300   1.2276
     2    0       0.10610E+04   0.29902E+07   0.91799E+05   0.34089E+00       1.4475   0.0725   0.7176   1.0332
     2    1       0.21560E+04   0.54615E+07   0.11762E+06   0.44019E+00       1.5917   0.0723   0.7891   1.1339
     2    2       0.26110E+04   0.66272E+07   0.12970E+06   0.51925E+00       2.0516   0.0722   0.8767   1.2579
     2    3       0.15350E+04   0.41679E+07   0.10638E+06   0.29366E+00       2.5589   0.0744   0.9235   1.3654
     2    4       0.48000E+02   0.14361E+06   0.20728E+05   0.41388E-01       3.0801   0.0768   0.9478   1.4485
     3    0       0.82900E+03   0.23725E+07   0.82399E+05   0.30402E+00       1.3423   0.0816   0.6379   1.0341
     3    1       0.15660E+04   0.38319E+07   0.96832E+05   0.35124E+00       1.4013   0.0816   0.6993   1.1334
     3    2       0.20270E+04   0.42636E+07   0.94699E+05   0.44952E+00       1.5274   0.0814   0.7773   1.2578
     3    3       0.24600E+04   0.49319E+07   0.99437E+05   0.54600E+00       1.8039   0.0814   0.8531   1.3798
     3    4       0.22240E+04   0.48486E+07   0.10281E+06   0.43699E+00       2.3514   0.0822   0.9135   1.4934
```

- DIS output can be generated using input F_1,F_2 or F_2,F_L or directly x-sections
- Tables can be used by theorists for extraction of underlying SFs

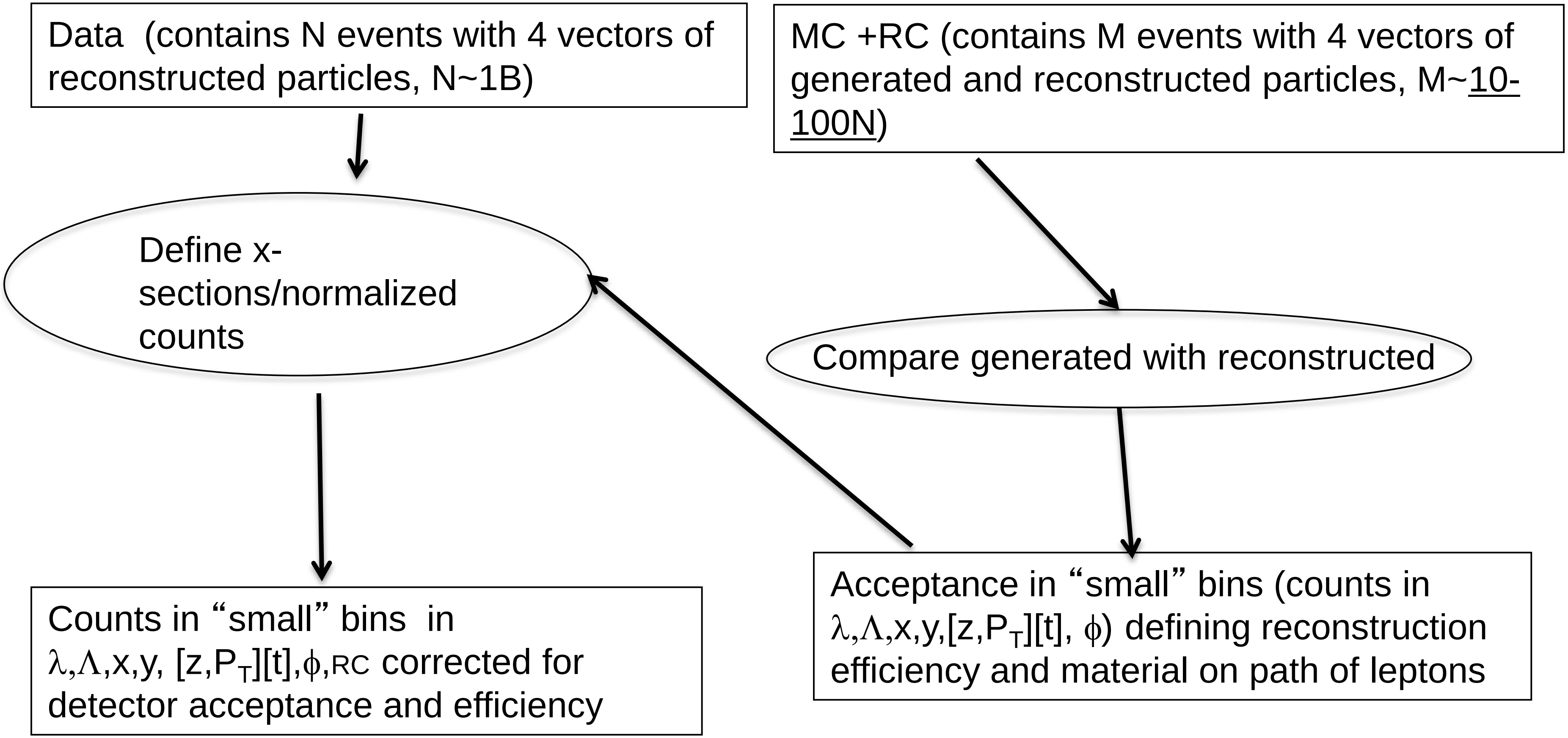
Summary

- Understanding the dynamics of partons in general, and non perturbative sea, in particular, will be crucial for understanding of strong interactions and nucleon should be the main focus
- Development of the framework for extraction of medium modified TMDs will be crucial for precision measurements of polarized TMDs
- Extraction of fragmentation functions should be performed independently to understand systematics due to fragmentation
- Extraction procedures should have a mechanism for estimation of systematics due to different unaccounted contributions (target fragmentation, phase space limitations, higher twists, exclusive hadron and di-hadron,…), could only be done with realistic, flexible MC with radiative effects

- Large acceptance of the EIC combined with clear separation of target and current fragmentation regions provide a unique possibility to study the nucleon structure including the target fragmentation region and correlations of target and current fragmentation regions
- Overlap in kinematics with JLab12 will be critical for interpretation of JLab12 data, as well as COMPASS and DY

Support slides

Analysis of azimuthal moments in SIDIS/HEP



Data (contains N events with 4 vectors of reconstructed particles, N~1B)

MC +RC (contains M events with 4 vectors of generated and reconstructed particles, M~10-100N)

Define x-sections/normalized counts

Compare generated with reconstructed

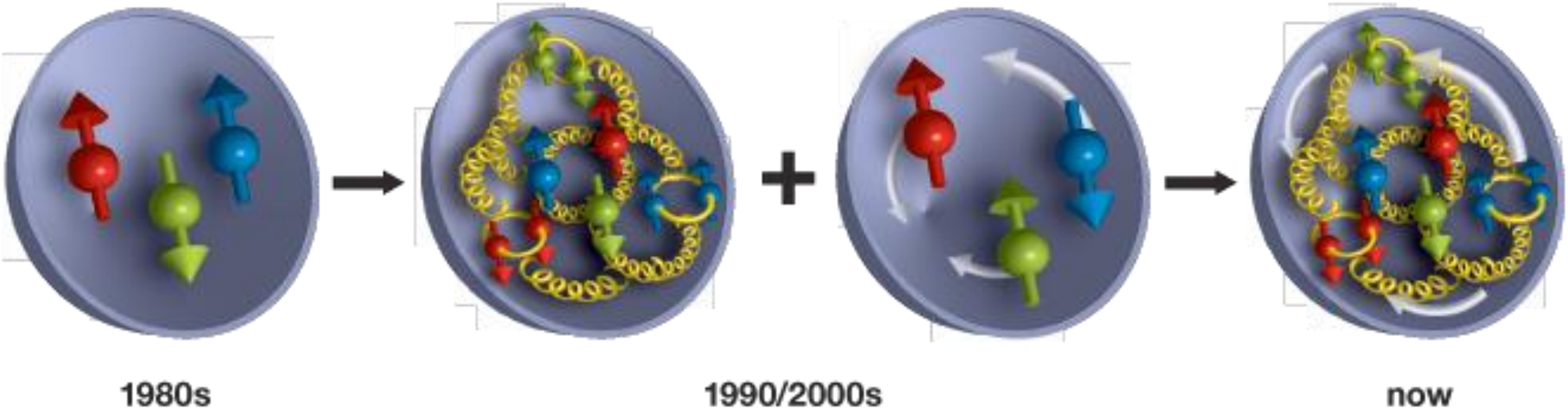
Counts in “small” bins in λ,Λ,x,y, [z,P_T][t],ϕ,RC corrected for detector acceptance and efficiency

Acceptance in “small” bins (counts in λ,Λ,x,y,[z,P_T][t], ϕ) defining reconstruction efficiency and material on path of leptons

- Counts in a given bin corrected by rec.efficiency and radiative effects
- Size of the bins dictated by the statistics allowing fits for extraction of azimuthal moments

Studies of 3D Structure of Nucleon

http://www.int.washington.edu/PROGRAMS/14-55w/



The ultimate goal:
a precise mapping of the 3D nucleon structure and a detailed flavor decomposition of 3D parton distribution functions

Organizers: Elke Aschenauer, Harut Avakian, Barbara Pasquini, Peter Schweitzer

Event generators for SIDIS studies

Main classes of event generators:

a)Full event generators where sets of outgoing particles are produced in the interactions between two incoming particles and a complete event is generated

Applications: attempt to reproduce the raw data
understand background conditions
estimating rates of certain types of events
planning and optimizing detector performances,…

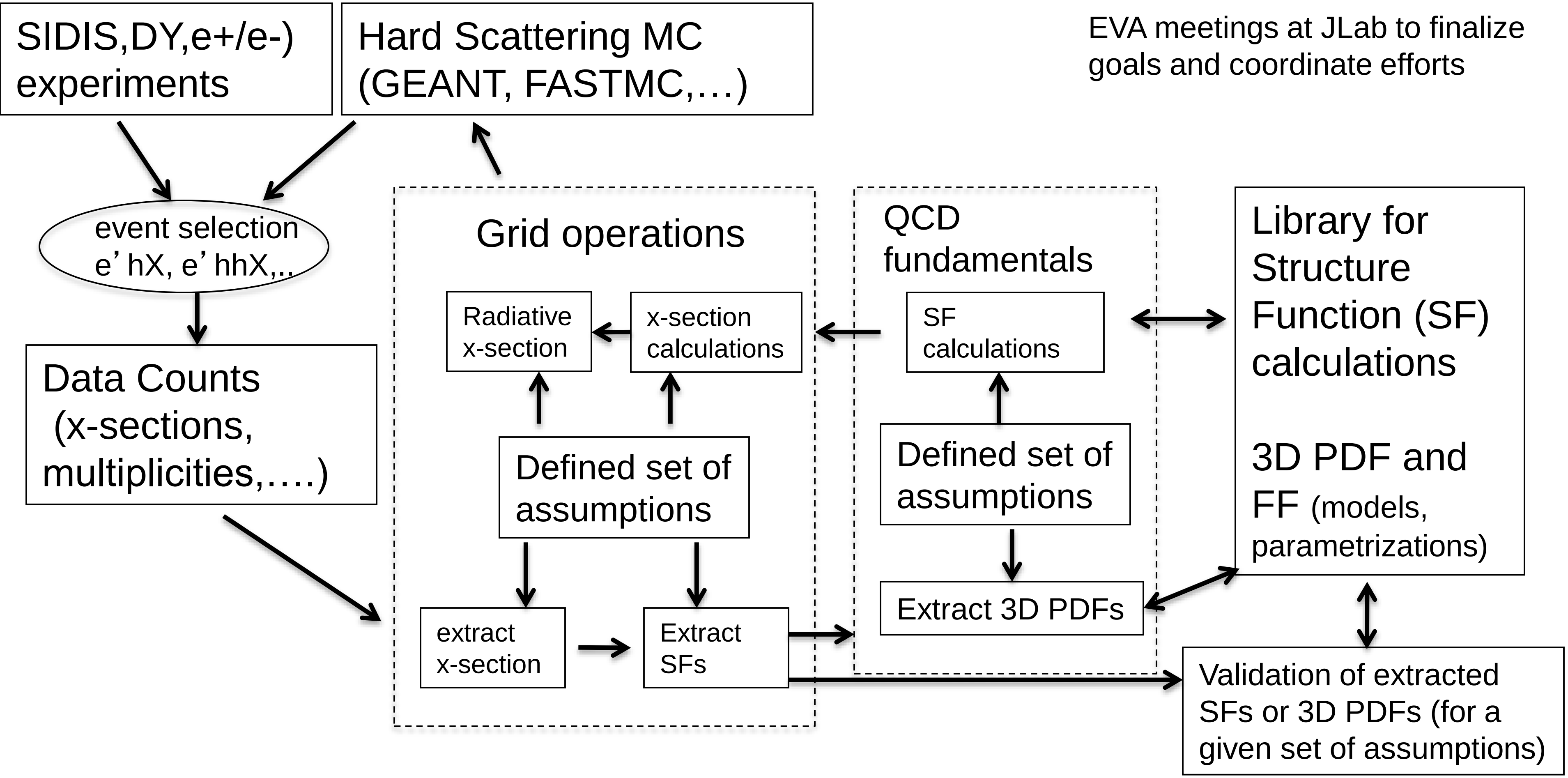
b) Specific event generators (single hadron, di-hadron,…) , where only the final state particles of interest are generated

Applications: providing fast tests of analysis procedures with relatively simple
integration of different input models.
developing analysis frameworks.
1) Providing events with cross section
2) Phase space with realistic x-sections provided as weight factors

+unfolding measured data for acceptance and detector resolution effects

3D PDF Extraction and VAlidation (EVA) framework

EVA meetings at JLab to finalize goals and coordinate efforts



SIDIS,DY,e+/e-) experiments

Hard Scattering MC (GEANT, FASTMC,…)

event selection e’ hX, e’ hhX,..

Data Counts (x-sections, multiplicities,….)

Grid operations

Radiative x-section

x-section calculations

Defined set of assumptions

extract x-section

Extract SFs

QCD fundamentals

SF calculations

Defined set of assumptions

Extract 3D PDFs

Library for Structure Function (SF) calculations

3D PDF and FF (models, parametrizations)

Validation of extracted SFs or 3D PDFs (for a given set of assumptions)

Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

Simple example

- Generate SIDIS events with latest and greatest SFs with evolution for a given beam energy:

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

- Put particles in GEANT MC for a specific detector (CLAS12/SOLID/…)
- Extract observables of interest (SSA, multiplicity, x-sections,..)

Use a given extraction framework with additional assumptions (gauss, with and without evolution,…) extract underlying SFs and 3D PDFs and see what you get

$$F_{UU,T} = x \sum_a e_a^2 f_1^a(x)\, D_1^{a\to h}(z)\, \frac{1}{\pi\langle P_{h\perp}^2\rangle}\, e^{-P_{h\perp}^2/\langle P_{h\perp}^2\rangle}$$

$$\langle P_{h\perp}^2\rangle^2 = z^2\langle k_{q,\perp}^2\rangle + \langle p_{q\to h\perp}^2\rangle\,.$$

What we need?

A topical collaboration to develop a dedicated MC with ability to implement self consistent spin-orbit correlations for studies of the 3D structure

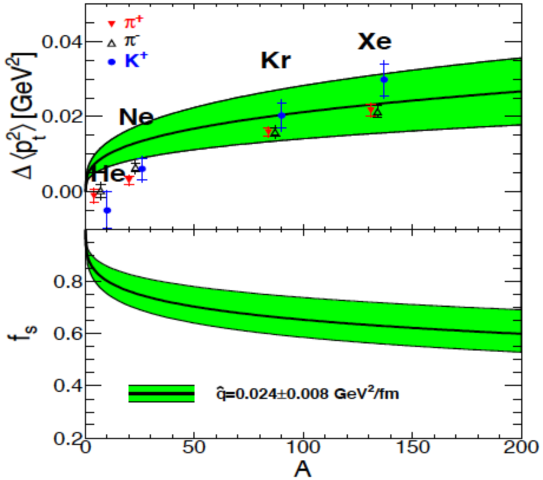
MC should have ability to include effects from target fragmentation, medium, radiative corrections, higher twists,….

Change the attitude to programing from “any capable physicist can do that” to “hire real professionals” that can develop user friendly flexible frameworks(2 in JLab)

Approximations on TMDs in medium

assume “maximal two gluon approximation” in accounting all higher-twist nuclear multiple parton correlations.

$$\Delta\langle p_{hT}^2\rangle_L^A \approx \Delta\langle p_{hT}^2\rangle^A \approx z_h^2\Delta_{2F}$$



A and J_A are the atomic number and spin

$$f_1^{q/A}(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}}\int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} f_1^{q/p}(x,\ell_\perp)$$

$$g_{1L}^{q/A}(x,k_\perp) \approx \frac{2J_A}{\pi\Delta_{2F}}\int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} g_{1L}^{q/p}(x,\ell_\perp)$$

Δ_{2F} represents the total transverse momentum broadening squared

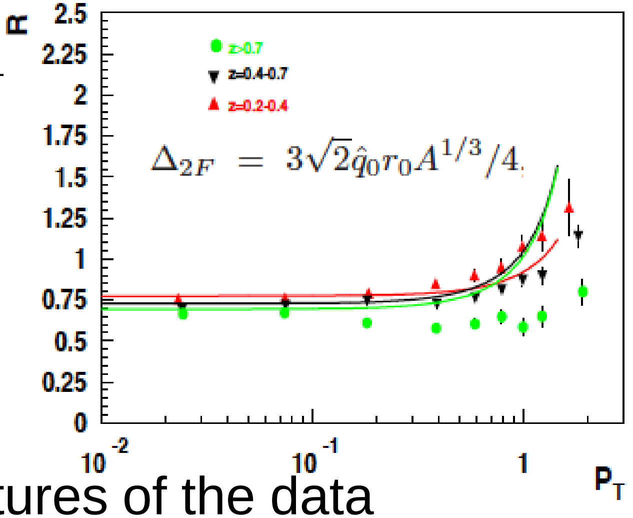
$$\alpha = \langle k_\perp^2\rangle + \Delta_{2F} \text{ and } \alpha^L = \langle k_\perp^2\rangle_L + \Delta_{2F}$$

$$\langle p_\perp^2\rangle + z_h^2\alpha \searrow$$

$$F_{UU}^A = \sum_q e_q^2 f_1^{q/A}(x_B)\, D_{h/q}(z_h)\frac{e^{-P_T^2/\langle P_T^2\rangle^A}}{\pi\langle P_T^2\rangle^A}$$

$$F_{LL}^A = \sum_q e_q^2 g_{1L}^{q/A}(x_B)\, D_{h/q}(z_h)\frac{e^{-P_T^2/\langle P_T^2\rangle_L^A}}{\pi\langle P_T^2\rangle_L^A}$$

$$R = \frac{F_{UU}^A}{F_{UU}^N}$$



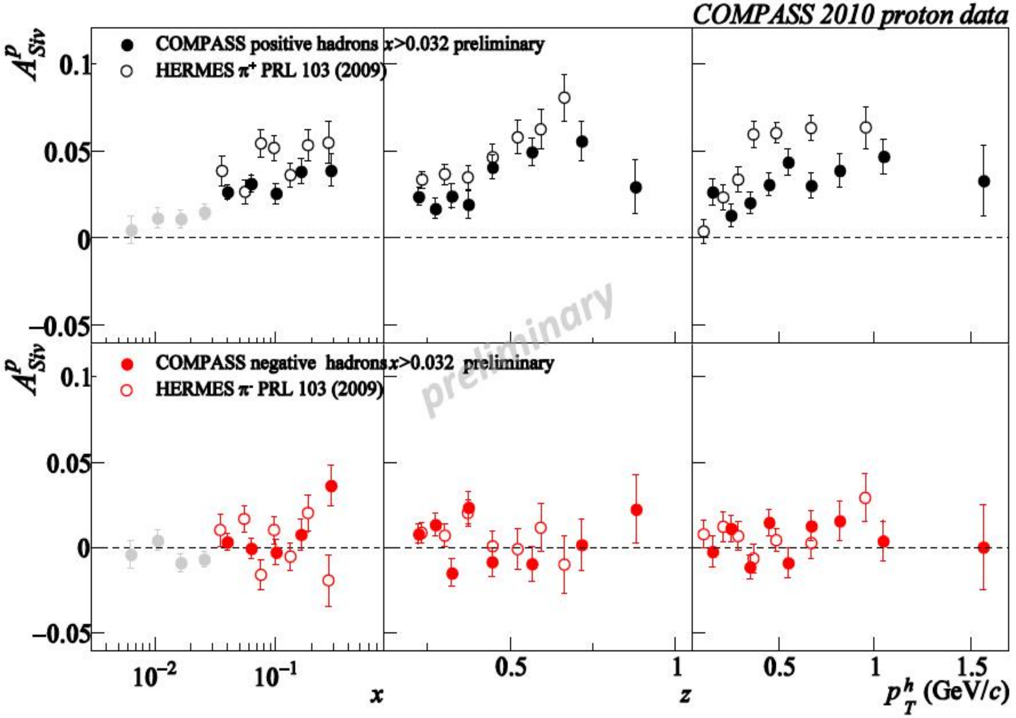
$$\Delta_{2F} = 3\sqrt{2}\hat{q}_0 r_0 A^{1/3}/4.$$

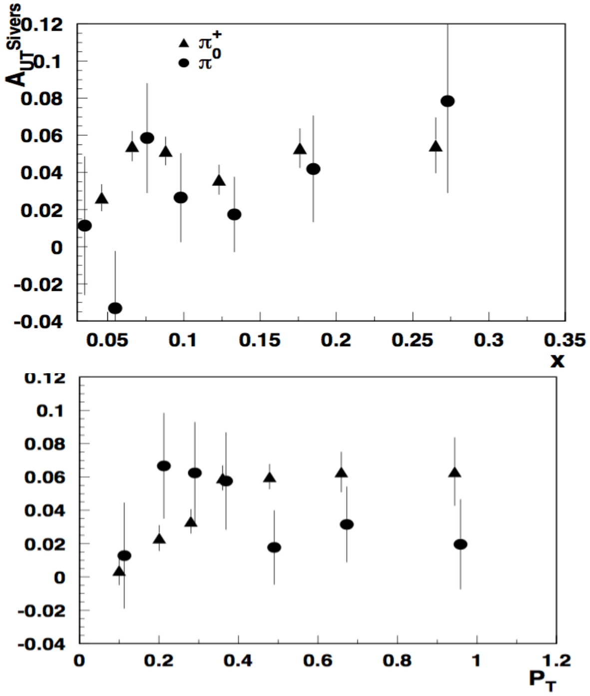
simple estimation can reproduce the main features of the data

Sivers asymmetry: pions

$$A_{UT}^{Siv} = A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{f_{1T}^{\perp u}(x,k_T)\otimes_W D_1^{u\to h}(z,p_T)}{f_1^u(x,k_T)\otimes D_1^{u\to h}(z,p_T)}$$

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





- π+/0, also K+ → Significant Sivers SSA increasing with x
- K- and π- consistent with 0 (contributions from different flavors cancel?).

Independent, high precision measurement in a wide Q^2 range is crucial

White paper

1212.1701.pdf

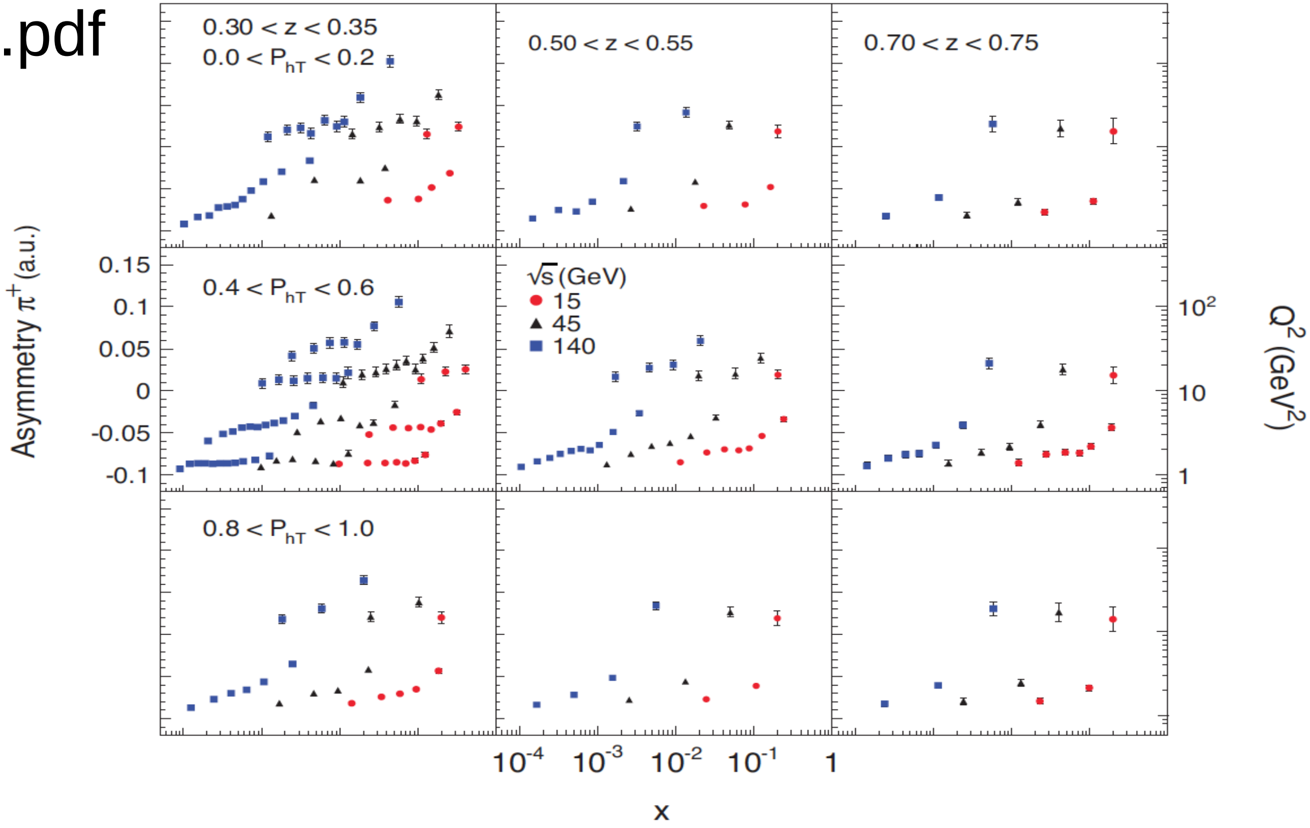
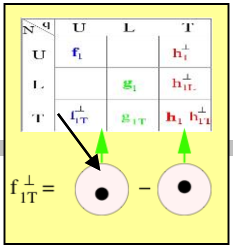


Figure 2.15: Four-dimensional representation of the projected accuracy for π^+ production in semi-inclusive DIS off the proton. Each panel corresponds to a specific z bin with increasing value from left to right and a specific P_{hT} bin with increasing value from top to bottom, with values given in the figure. The position of each point is according to its Q^2 and x value, within the range $0.05 < y < 0.9$. The projected event rate, represented by the error bar, is scaled to the (arbitrarily chosen) asymmetry value at the right axis. Blue squares, black triangles and red dots represent the $\sqrt{s} = 140$ GeV, $\sqrt{s} = 45$ GeV and $\sqrt{s} = 15$ GeV EIC configurations, respectively. Event counts correspond to an integrated luminosity of 10 fb^{-1} for each of the three configurations.

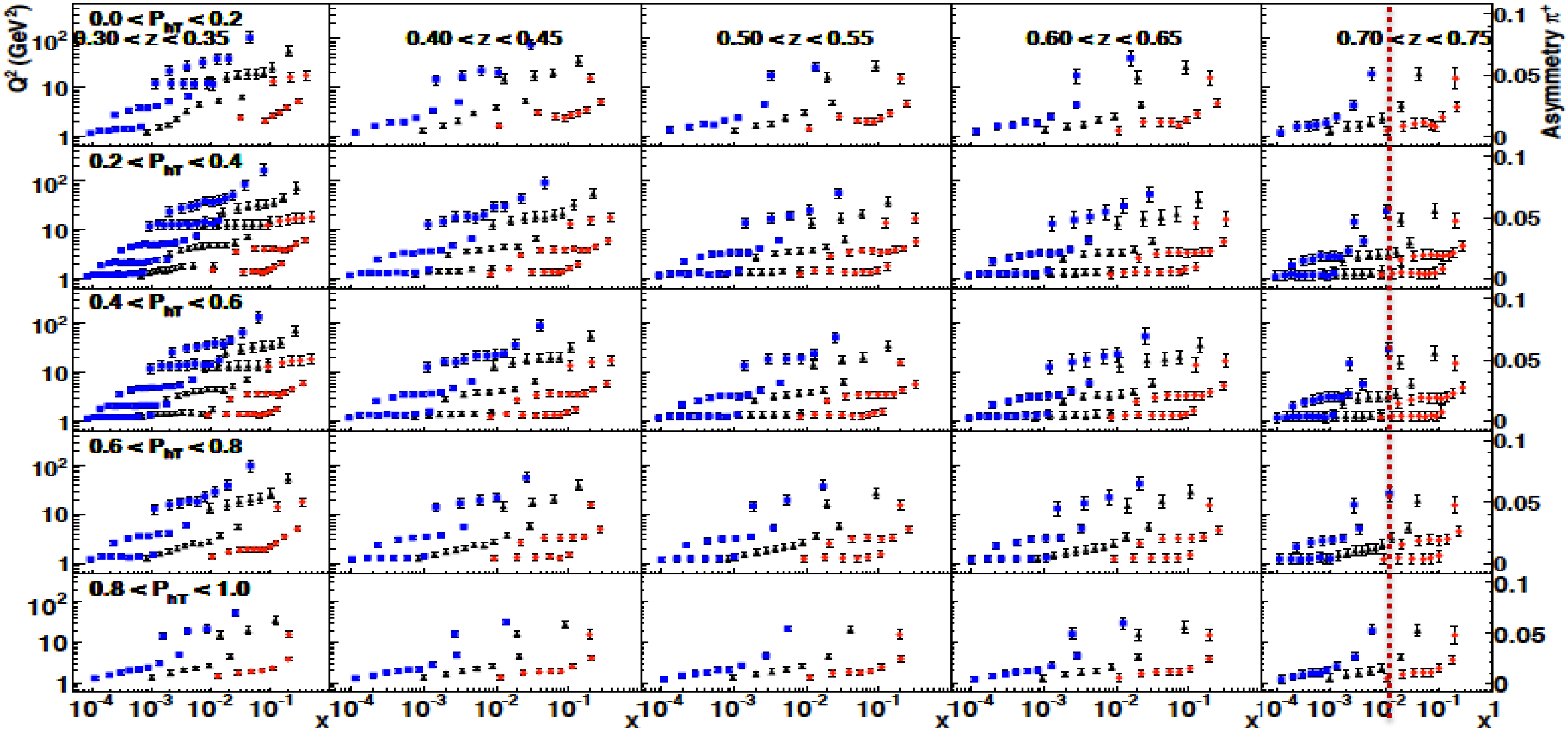


Sivers effect: π+ from EIC

$$A_{UT}^{\sin(\phi-\phi_S)} = \frac{\sum_q e_q^2 f_{1T}^{\perp q} D_1^q}{\sum_q e_q^2 f_1^q D_1^q}$$

√s = 140 GeV, √s = 50 GeV and √s = 15 GeV EIC configurations, respectively.
Event counts correspond to an integrated luminosity of 30 fb−1

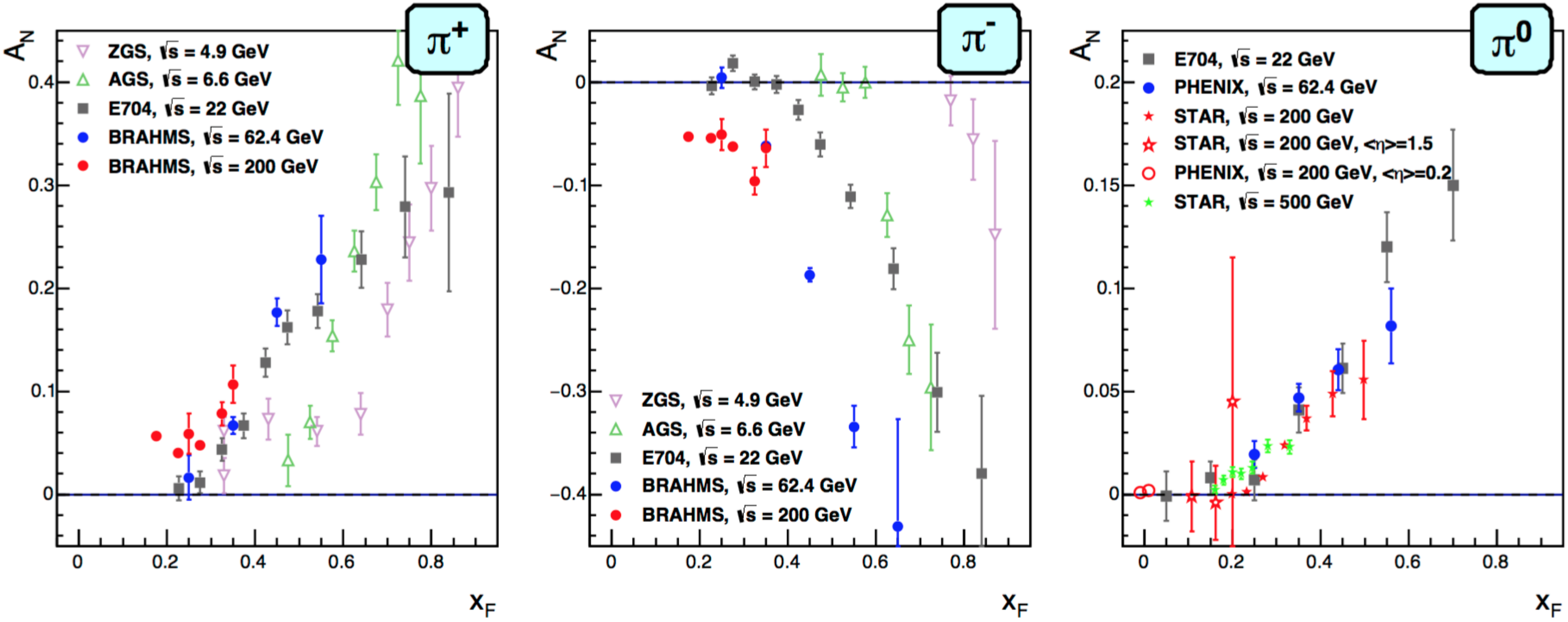
arXiv:1108.1713



- •Large acceptance and energy range of EIC makes it ideal place to study the contributions of sea quarks to Sivers asymmetry
- •Lower energies provide wider x-range for region where non-perturbative effects are significant, and overlap with JLab12

pi0s

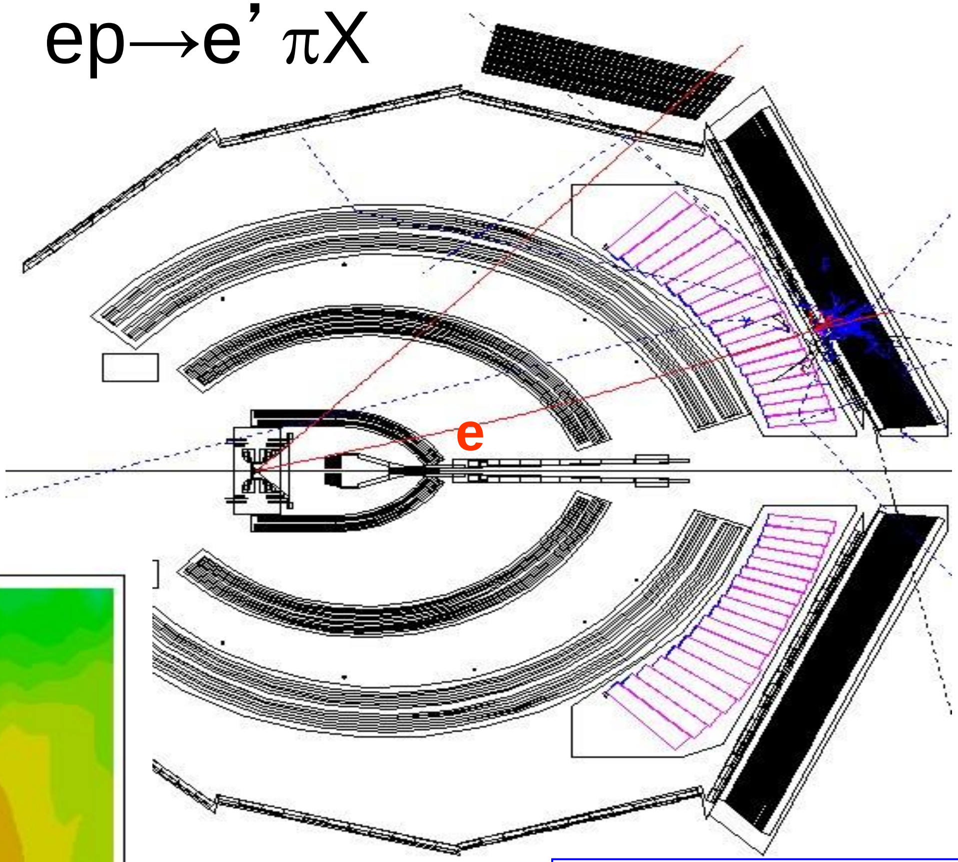
https://arxiv.org/pdf/1512.05379.pdf

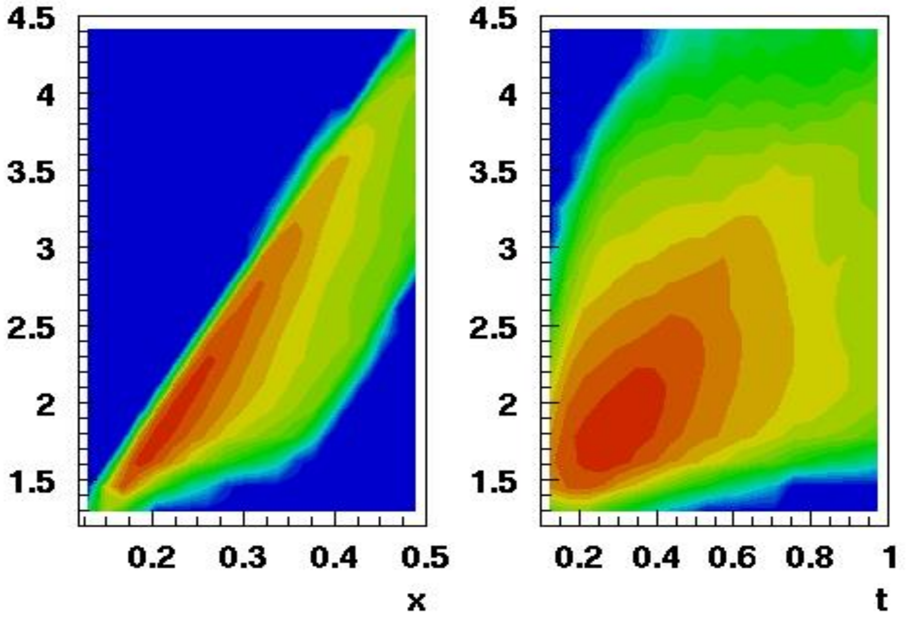


CLAS configuration with longitudinally pol. target

Longitudinally polarized target

$ep \rightarrow e' \pi X$

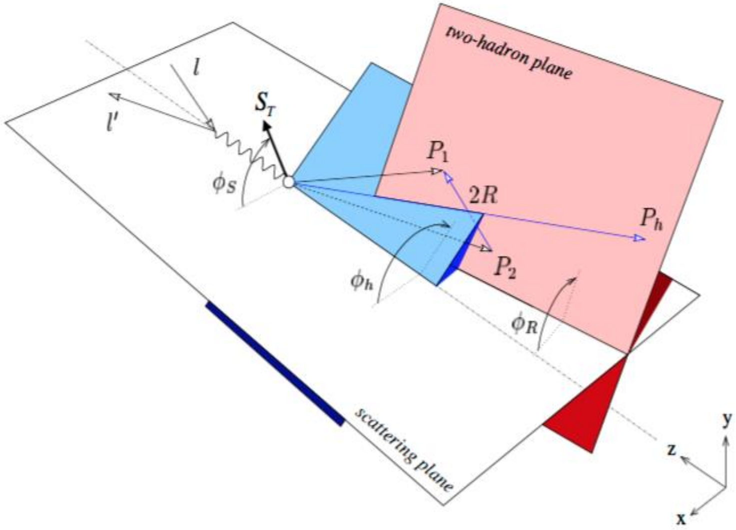




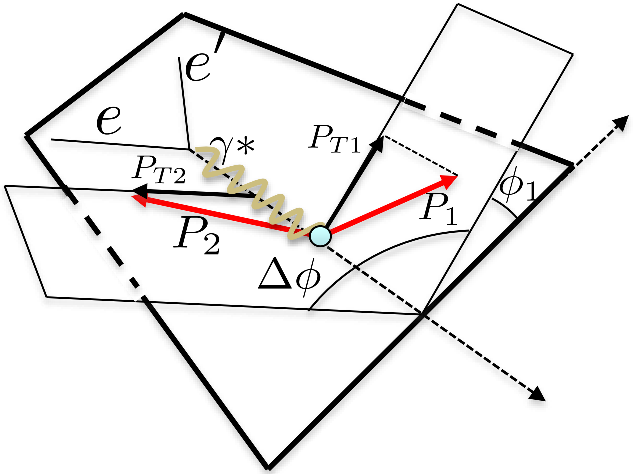
- **Polarizations:**
  - **Beam: ~70%**
  - **NH3 proton ~70%**
- **Target position -55cm**
- **Torus +/-2250**
- **Beam energy ~5.7 GeV**

Correlated hadron production in hard scattering

2 hadrons in current fragmentation



hadrons in current & target fragmentation



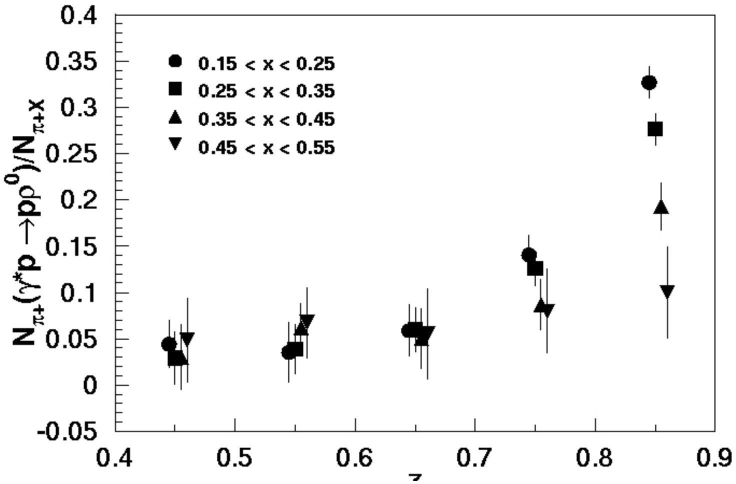
With ϕ_S, ϕ_1, ϕ_2, ϕ_R, ϕ_h several observables have been identified to study correlations

$\phi_R - \phi_S$, ϕ_R -accessing transversity and quark-gluon correlations *Radici & Bacchetta*
$\phi_R - \phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*
$\phi_1 - \phi_2$ -accessing correlations in current and target regions *Anselmino, Barone, Kotzinian*

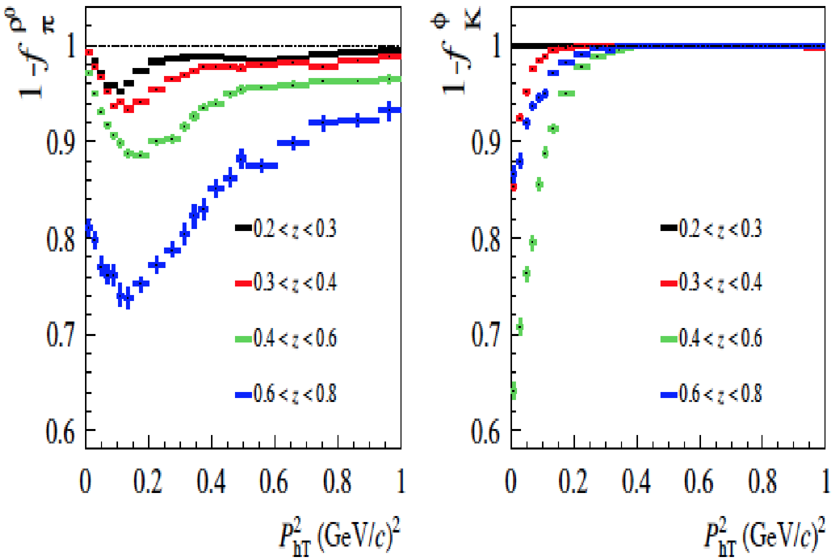
Some dihadron proposals approved by Jlab PAC with high ratings, more to come

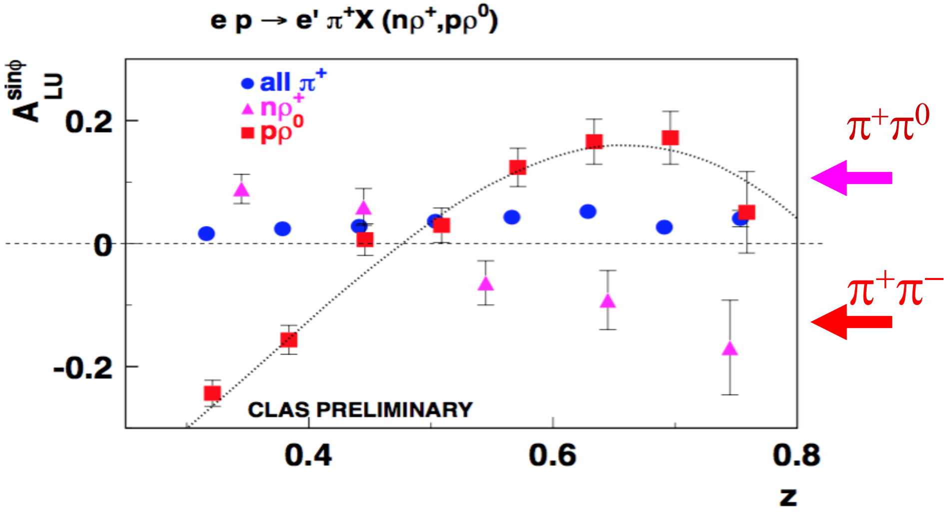
The role of vector mesons and dihadrons in SIDIS

1) Should we worry about pions/kaons coming from vector meson decays?
2) What about ρ+ and ρ-
3) What do we know about relevant observables for pions specifically coming from vector meson decays
4) What about SIDIS rhos (can we measure?)
5) What is radiative correction due to rho?
6) Vector meson as resonance in dihadron production?



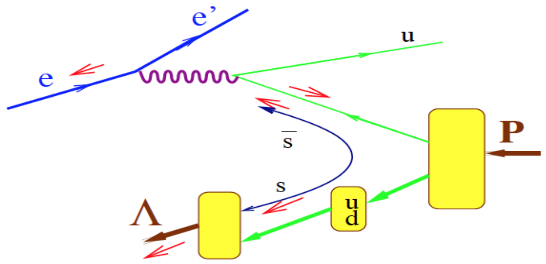
COMPASS:1709.07374

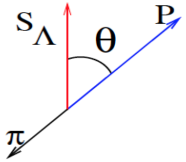




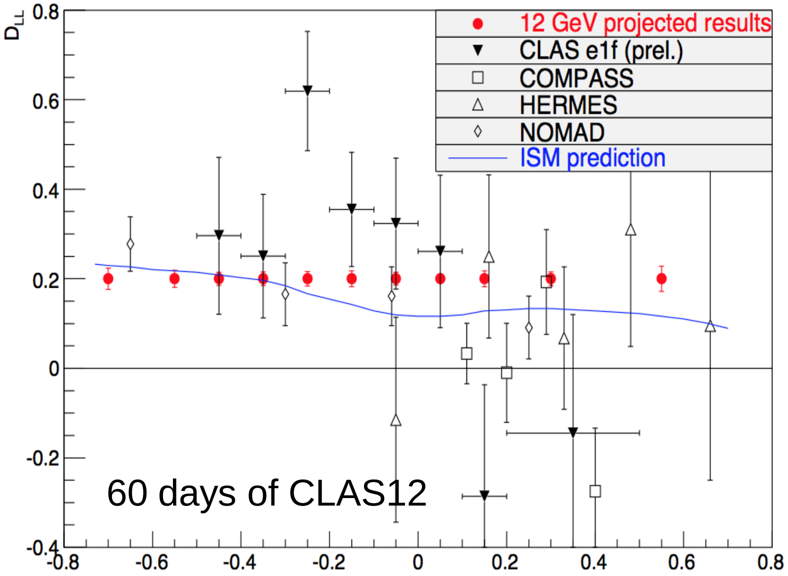
Fraction of dihadrons should be significantly higher at EIC!

Target fragmentation region: Λ production





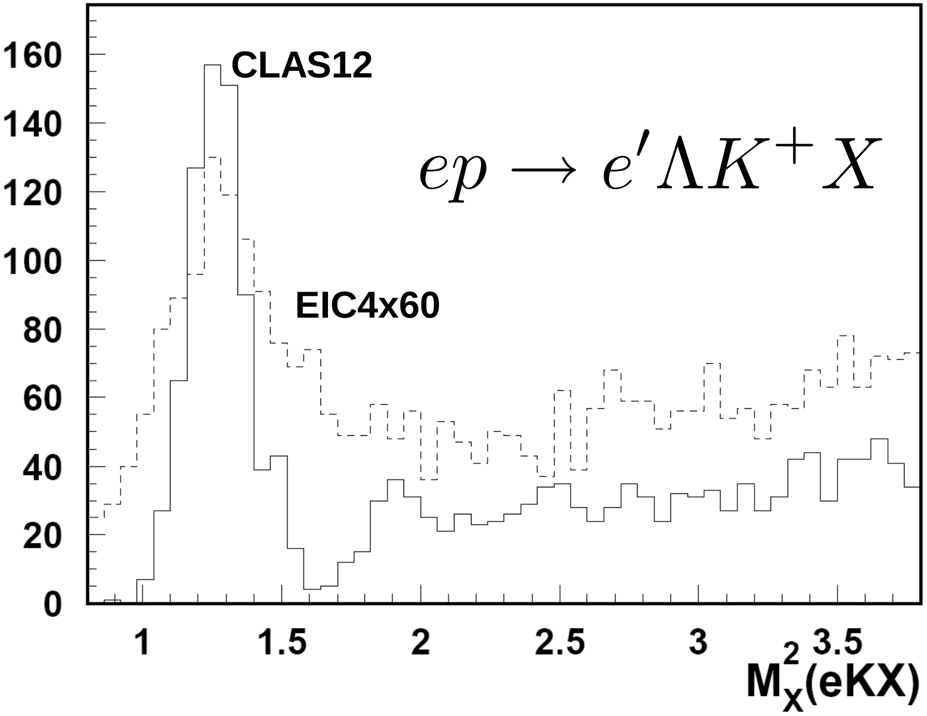
polarization transfer coefficient



60 days of CLAS12

$$A_{LUL}^{TFR} = hS_{\|}\frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

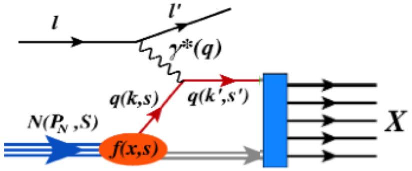
$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$



- Large acceptance of CLAS12 and EIC provide a unique possibility to study the nucleon structure in target fragmentation region
- First measurements already performed using the CLAS data at 6 GeV.

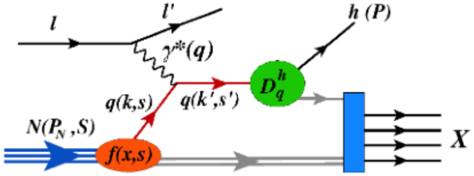
QCD: from testing to understanding

0h DIS

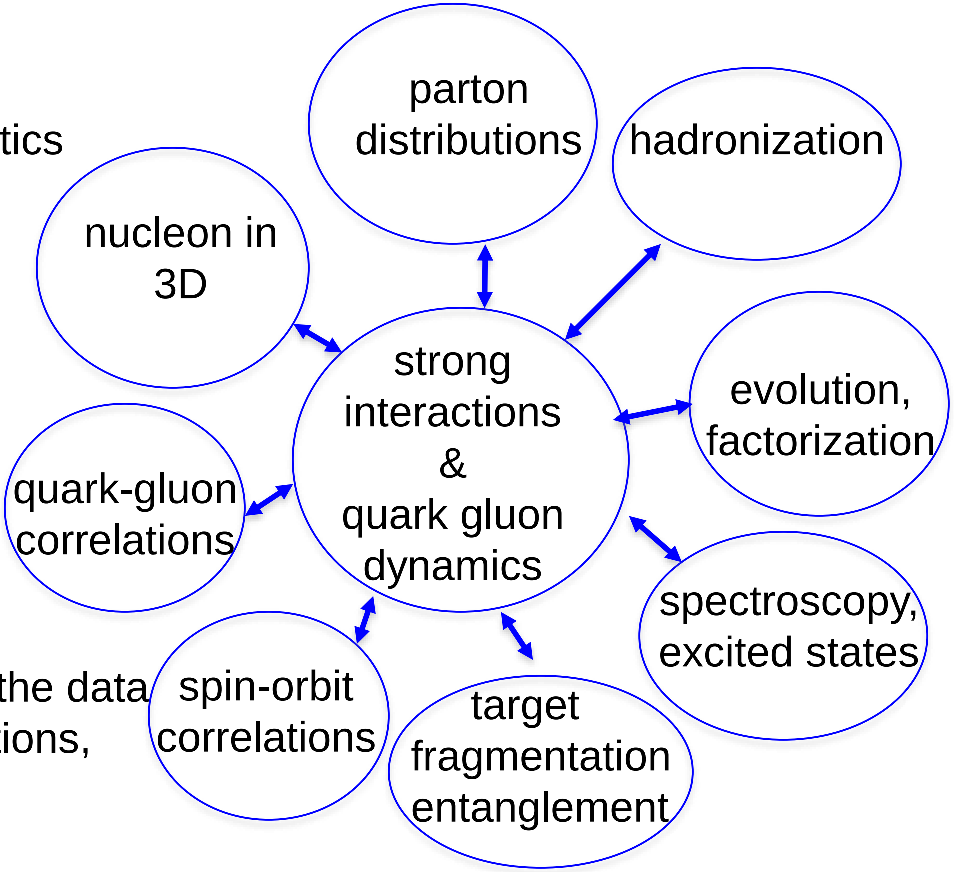


Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, current fragmentation, IMF)

1h SIDIS/DVMP



Understanding stage:
non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)



strong interactions & quark gluon dynamics

parton distributions

hadronization

nucleon in 3D

evolution, factorization

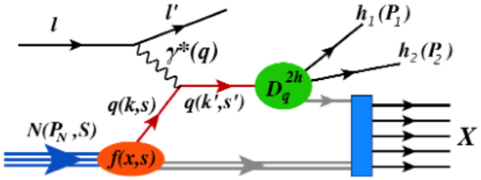
quark-gluon correlations

spectroscopy, excited states

spin-orbit correlations

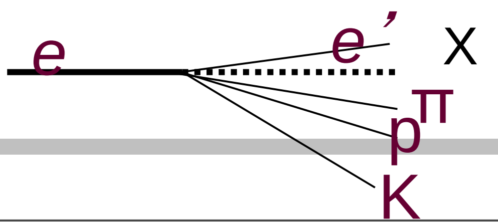
target fragmentation entanglement

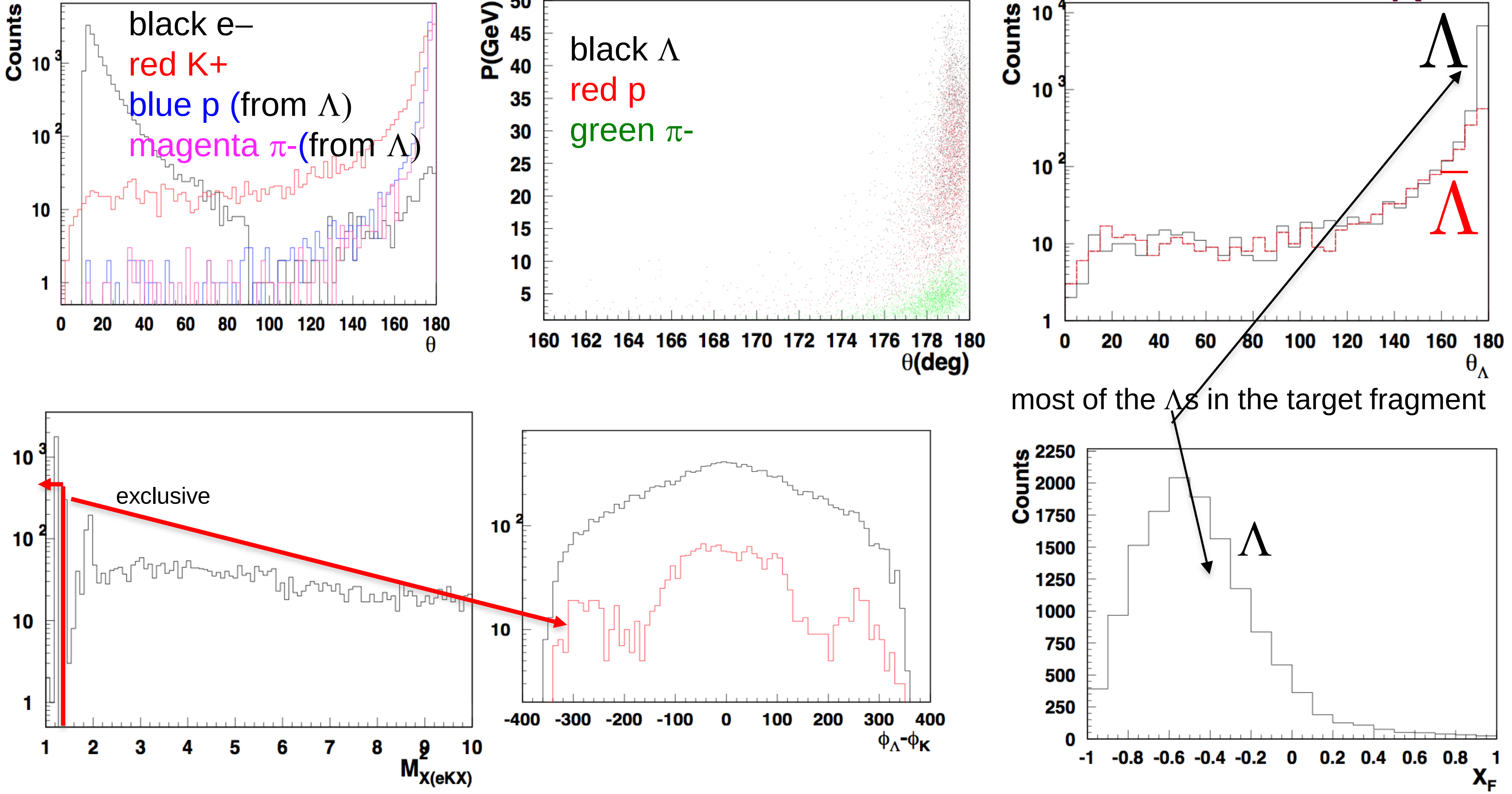
2h SIDIS/DVMP



production in SIDIS provides access to correlations inaccessible in simple SIDIS (BEC,dihadron fragmentation , correlations of target and current regions, entanglement....)

Lambda production in EIC (5x50 GeV)

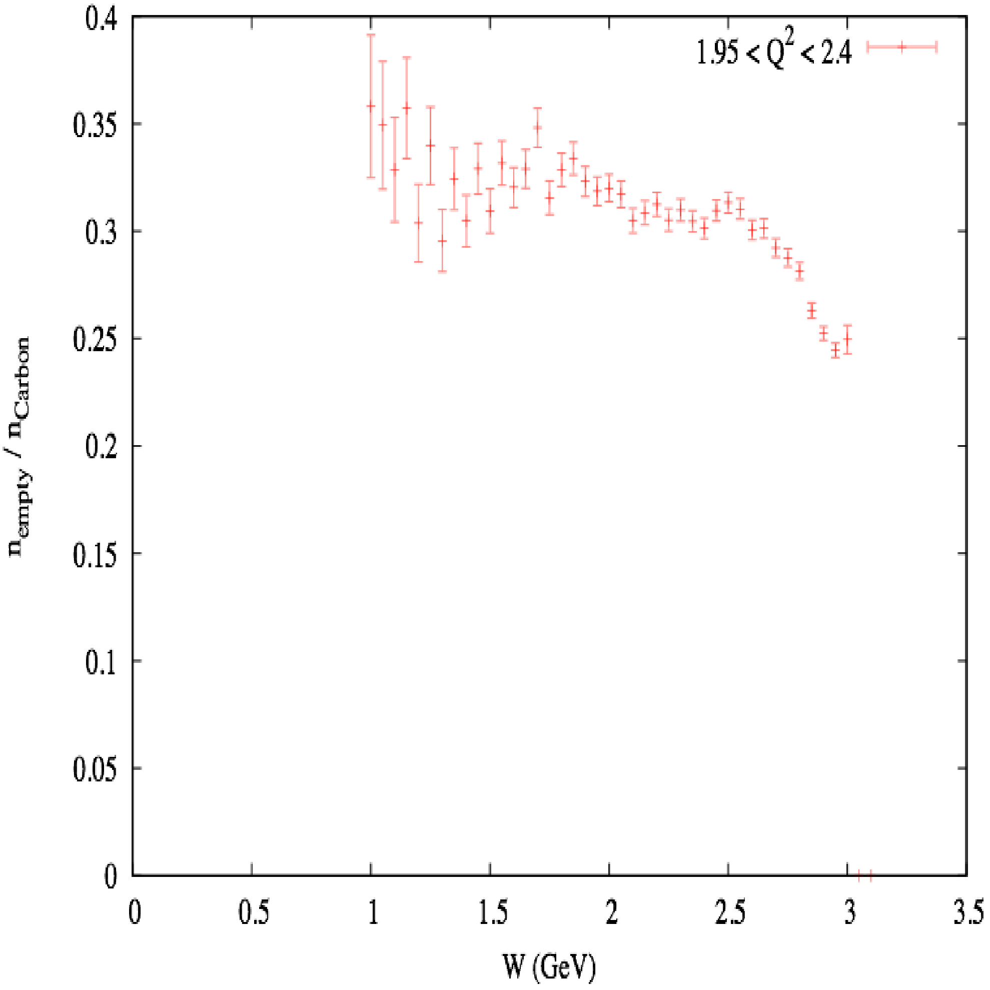


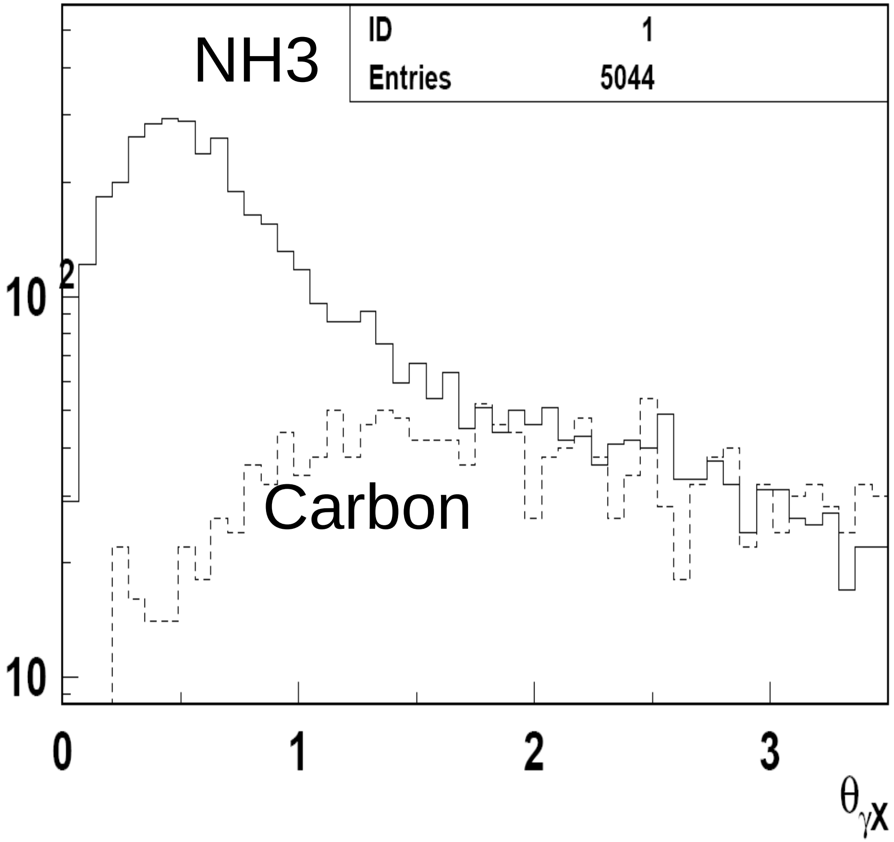


most of the Λs in the target fragment

At forward angles Lambdas are mainly from target fragments

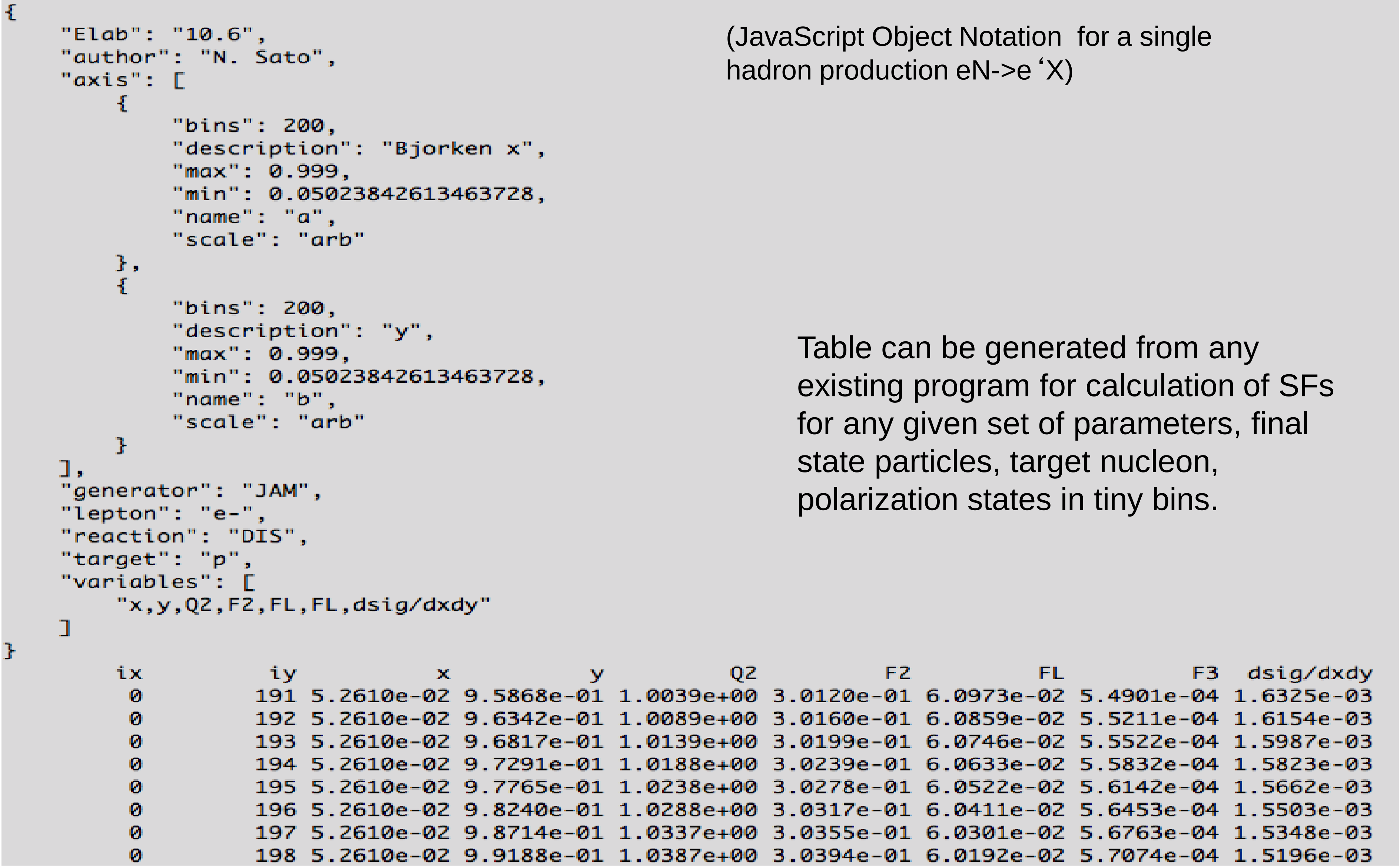
eg1dvcs: dilution factor studies





Dilution for $\theta\gamma_X$<1 degree f=0.87 for DVCS

Standard input for SFs



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    "reaction": "DIS",
    "target": "p",
    "variables": [
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    ]
}
```

(JavaScript Object Notation for a single hadron production eN->e‘X)

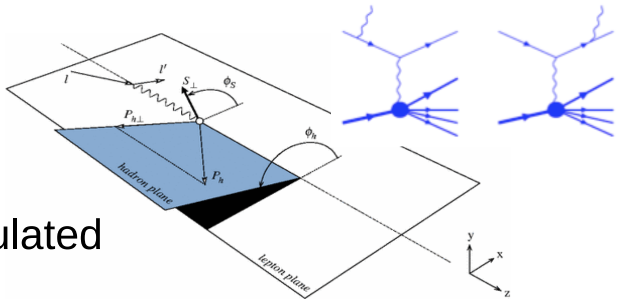
Table can be generated from any existing program for calculation of SFs for any given set of parameters, final state particles, target nucleon, polarization states in tiny bins.

```
        ix          iy          x          y          Q2          F2          FL          F3   dsig/dxdy
         0         191 5.2610e-02 9.5868e-01 1.0039e+00 3.0120e-01 6.0973e-02 5.4901e-04 1.6325e-03
         0         192 5.2610e-02 9.6342e-01 1.0089e+00 3.0160e-01 6.0859e-02 5.5211e-04 1.6154e-03
         0         193 5.2610e-02 9.6817e-01 1.0139e+00 3.0199e-01 6.0746e-02 5.5522e-04 1.5987e-03
         0         194 5.2610e-02 9.7291e-01 1.0188e+00 3.0239e-01 6.0633e-02 5.5832e-04 1.5823e-03
         0         195 5.2610e-02 9.7765e-01 1.0238e+00 3.0278e-01 6.0522e-02 5.6142e-04 1.5662e-03
         0         196 5.2610e-02 9.8240e-01 1.0288e+00 3.0317e-01 6.0411e-02 5.6453e-04 1.5503e-03
         0         197 5.2610e-02 9.8714e-01 1.0337e+00 3.0355e-01 6.0301e-02 5.6763e-04 1.5348e-03
         0         198 5.2610e-02 9.9188e-01 1.0387e+00 3.0394e-01 6.0192e-02 5.7074e-04 1.5196e-03
```

Additional complications: Experiment can’t measure just 1 SF

I. Akushevich et al (LDRD-2018)

$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S + ...$$



Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \rightarrow \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Due to radiative corrections, ϕ-dependence of x-section will get more contributions

- Some moments will modify
- New moments may appear, which were suppressed before in the x-section

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

Correction to normalization

$$\sigma_0(1 + \alpha\cos\phi_h)R_0(1 + r\cos\phi_h) \rightarrow \sigma_0 R_0(1 + \alpha r/2)$$

Correction to SSA

$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \rightarrow \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h - \phi_S) + sr/2S_T\sin(\phi_h + \phi_S))$$

Correction to DSA

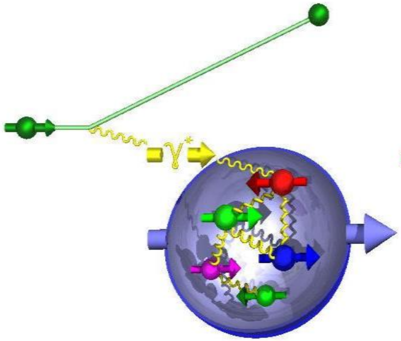
$$\sigma_0(1 + g\lambda\Lambda + f\lambda\Lambda\cos\phi_h)R_0(1 + r\cos\phi_h) \rightarrow \sigma_0 R_0(1 + (g + fr/2)\lambda\Lambda)$$

Simultaneous extraction of all moments is important also because of correlations!

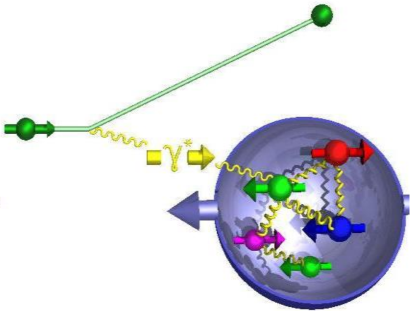
Polarized PDFs

$$g_1^u(x) = u^+(x) - u^-(x)$$

N/q	U	L
U	$\mathbf{f_1}$	
L		$\mathbf{g_1}$

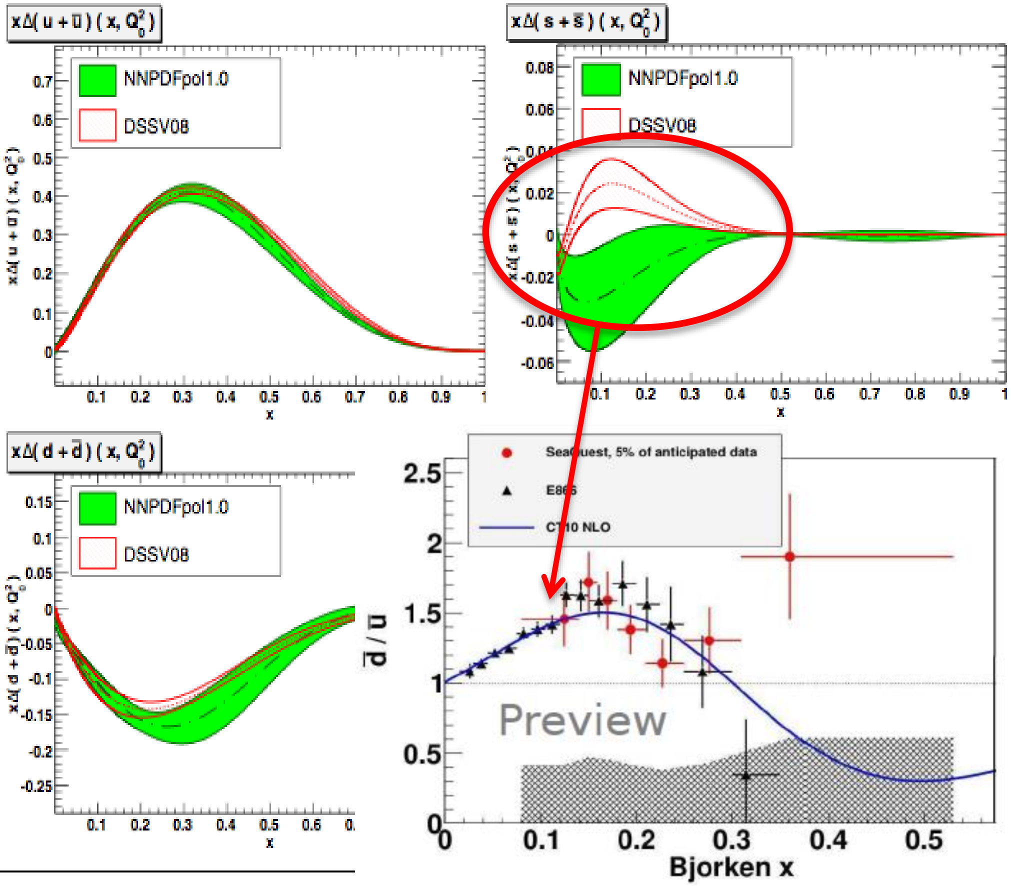


Parallel electron & quark spins



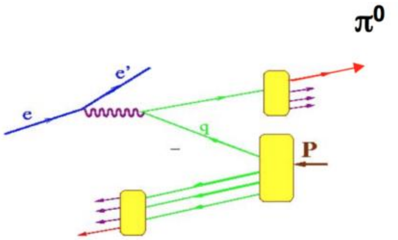
Anti-parallel electron & quark spins

Ball et al arXiv:1303.7236



- errors due to parameterizations and model dependence may be compatible with statistical and systematic errors from experiments
- may be some tension between DIS and SIDIS.

π0 SIDIS: advantages-I



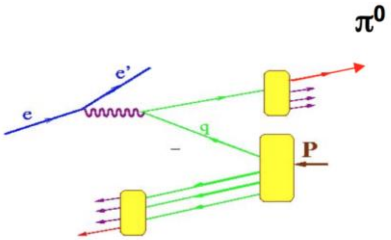
1) suppression of higher-twist contributions at large hadron energy fraction (particularly important at JLab energies where small z events are contaminated by target fragmentation)

2) the absence of ρ0 production which complicates the interpretation of the charged single-pion data

3) the fragmentation functions for u and d quarks to π0 are the same in first approximation

4) suppression of spin-dependent fragmentation for π0 s, due to the roughly equal magnitude and opposite sign of the Collins fragmentation functions for up and down

$\pi0$ SIDIS: advantages-II



5) longitudinal photon contribution, is suppressed in exclusive neutral pions production with respect to the transverse photon contribution, which is higher twist, suggesting that longitudinal photon contribution to SIDIS $\pi0$ will also be suppressed.

6) at large x , where the sea contribution is negligible, $\pi0$ multiplicities and double spin asymmetries will provide direct info on the fragmentation function of u and d -quarks to p$\pi0$.

7) $\pi0$ data has better uniformity and smaller variations of averages of $\mathbf{P}_T$ with **x** due to correlations between longitudinal and transverse momentum of quarks and hadrons

8) Particle ID (invariant mass of 2 photons) very different from charged pions

Multiplicities in SIDIS

For simple Gaussian distributions in k_T and p_T

$$m_N^h(x,z,\boldsymbol{P}_{hT}^2) = \frac{\pi}{\sum_a e_a^2\, f_1^a(x)}$$

$$\times \sum_a e_a^2\, f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}$$

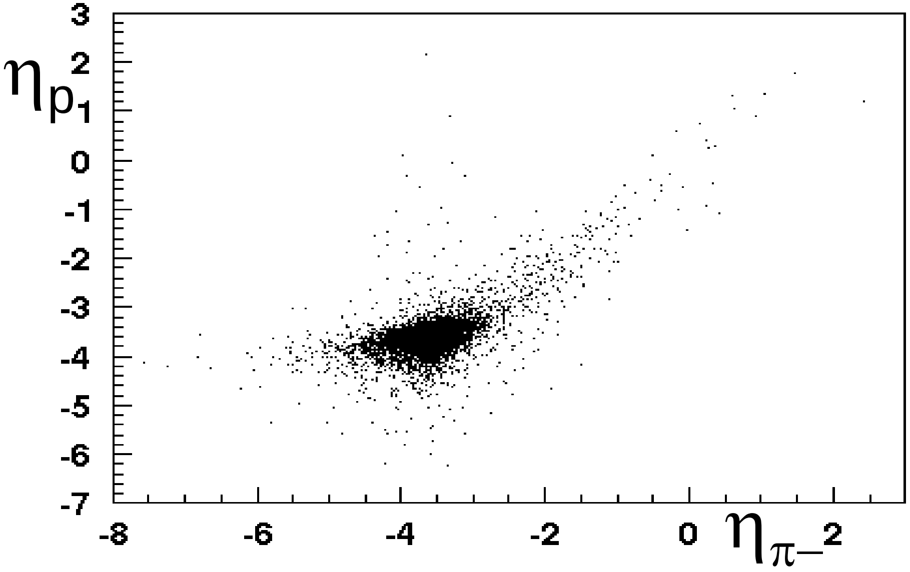
For p0 at large x, when sea contribution can be neglected the ratio e’□^{0}X/ e'X should follow z-dependence of the fragmentation function (after integration over P_T)

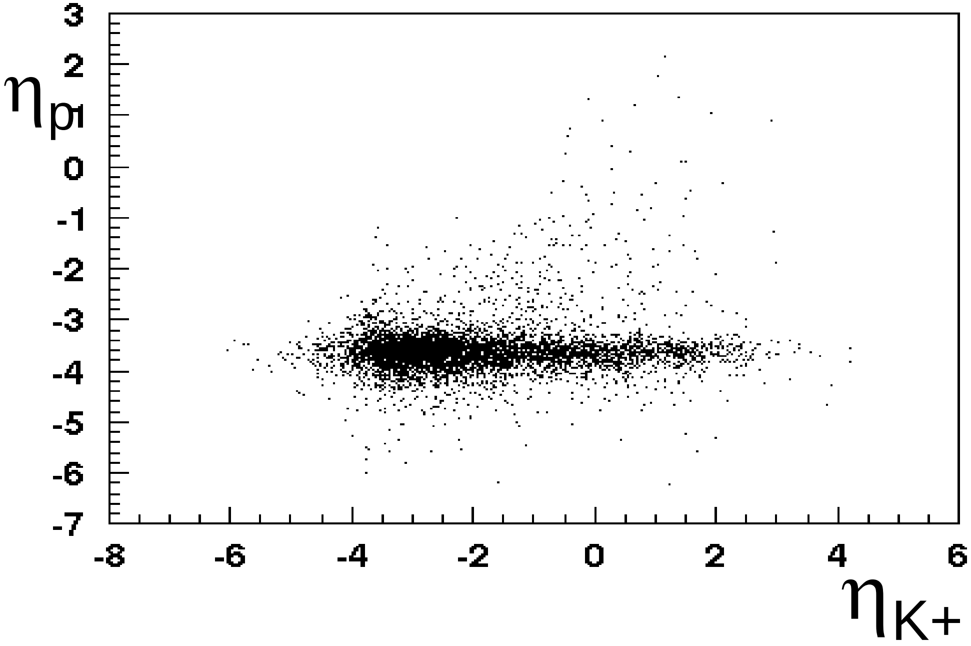
$$\sigma_p^{eX} \propto 4u + d + \ldots$$

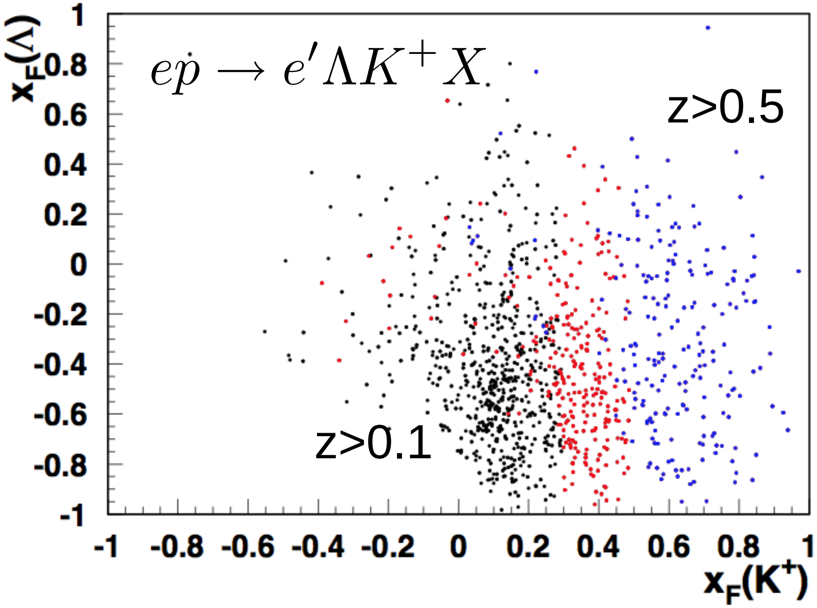
$$\sigma_p^{\pi^0} \propto 4uD^{u\to\pi^0} + dD^{d\to\pi^0} + \ldots$$

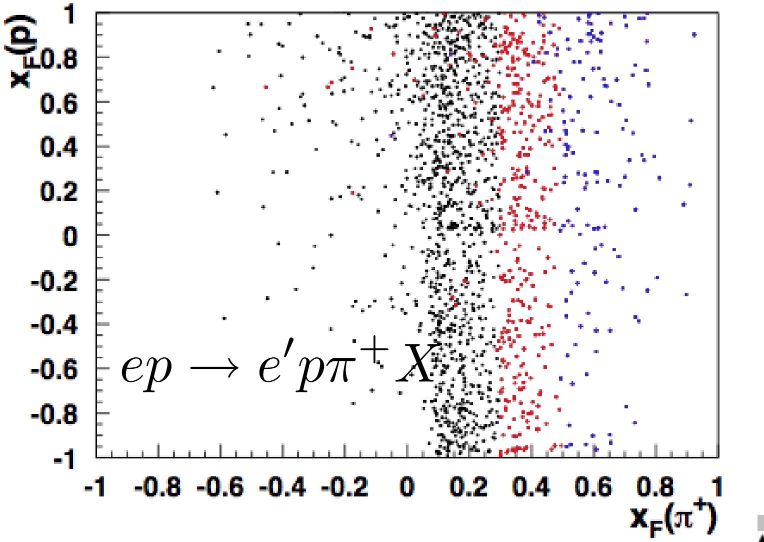
$$D^{u\to\pi^0} \approx D^{d\to\pi^0}$$

EIC 5x50 GeV: Kinematic distributions of Lambdas and Kaons



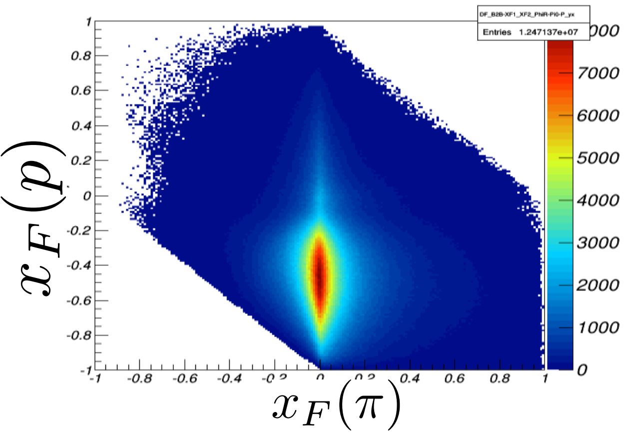


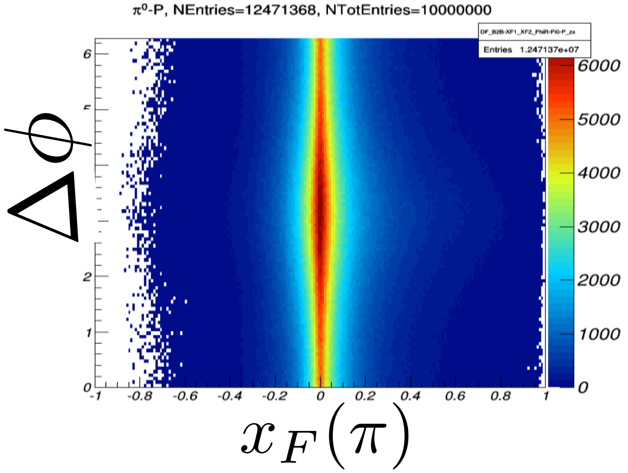


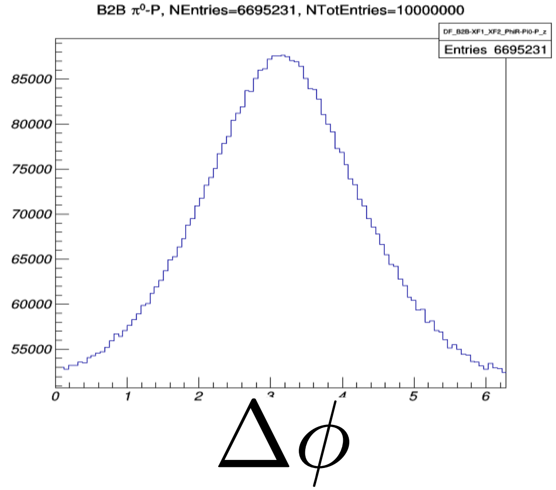


b2b distributions: EIC 5x50 (proton-pion)

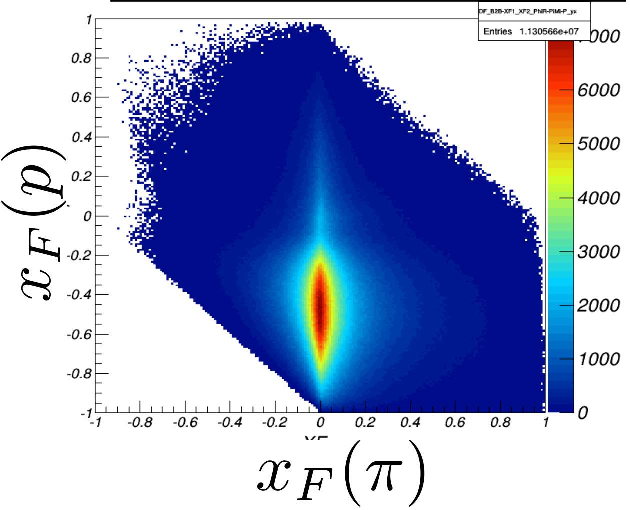
$$\boxed{ep \rightarrow e'p\pi^0 X}$$

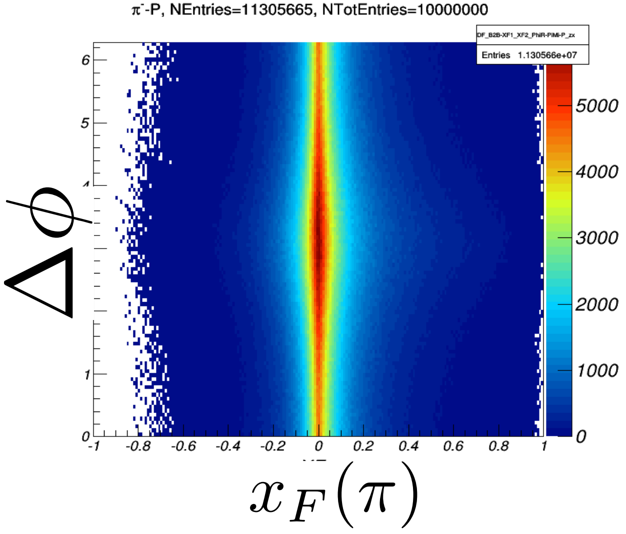


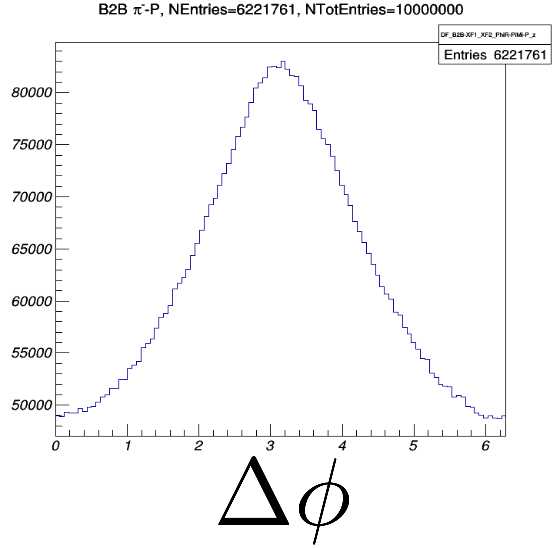




$$\boxed{ep \rightarrow e'p\pi^+ X}$$

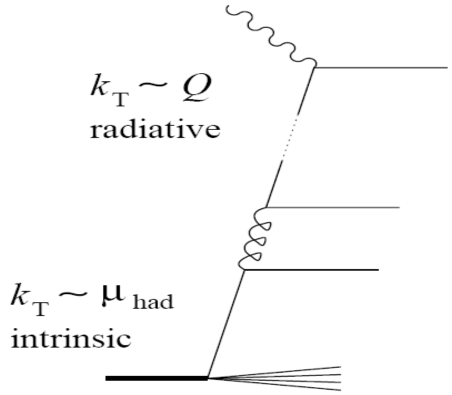




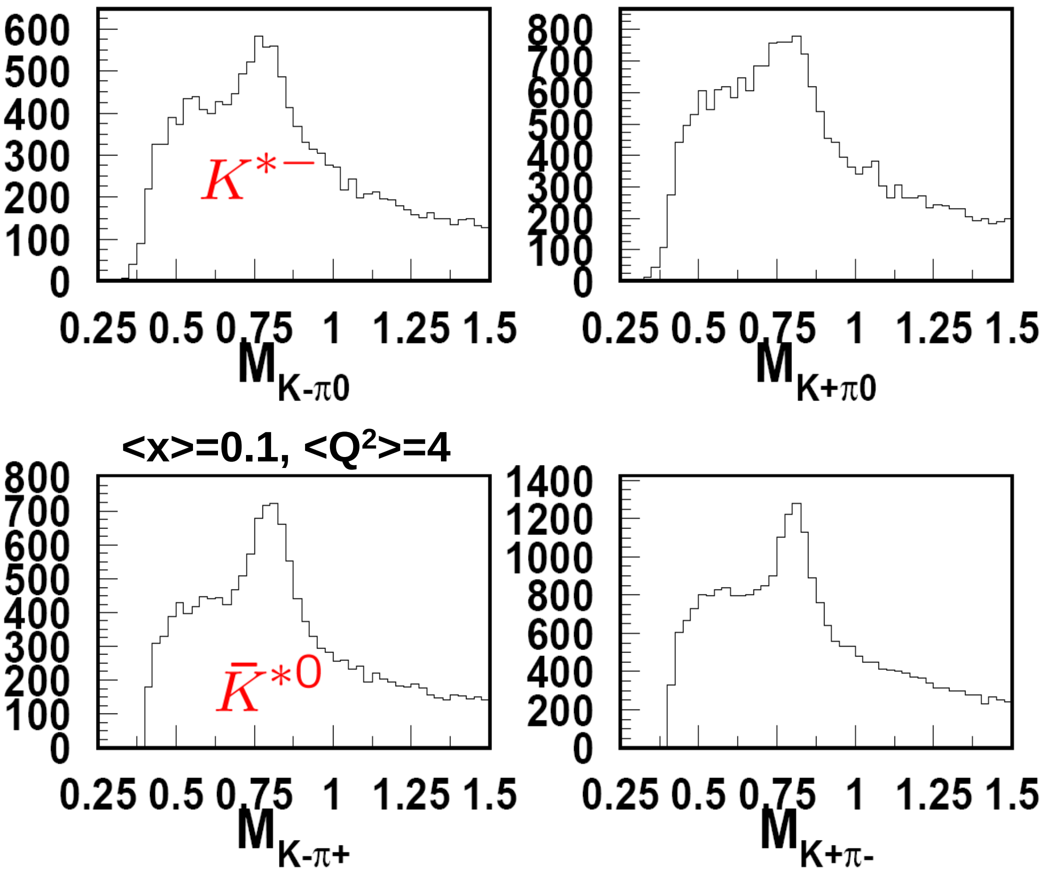


Intrinsic k_T: SIDIS observables

Schweitzer, Strikman, Weiss; in progress



EIC 4x60 (Lumi 10^{33},$cm^{-2}sec^{-1}$, ~1 hour)



- Aim: Observe intrinsic k_T of sea quarks due to QCD vacuum fluctuations
- Challenge: Separate intrinsic k_T from perturbatively generated k_T (DGLAP evolution)
- Idea: Isolate non-singlet sea through SIDIS cross section differences, e.g.

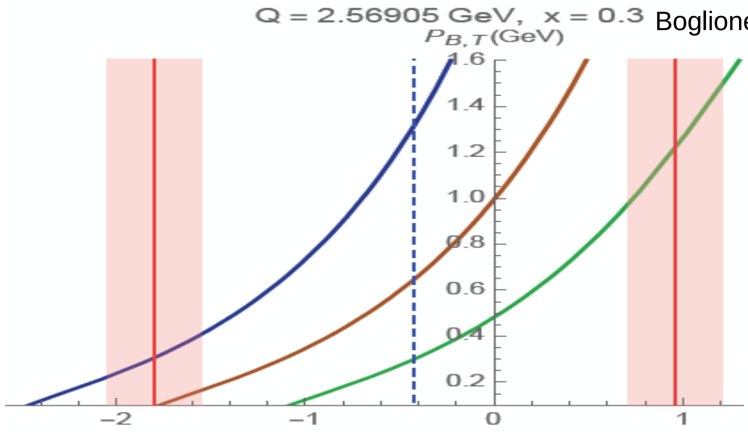
$$\overset{s\bar{u}}{d\sigma(K^{*-})} - \overset{s\bar{d}}{d\sigma(\bar{K}^{*0})} \sim (\bar{u} - \bar{d}) * FF$$

$$d\sigma(\rho^{+}) - d\sigma(\rho^{-}) \sim (u_{val} - d_{val}) * FF$$

σ(p) = 0.05 + 0.06*p [GeV] %

K*s can be studied with EIC

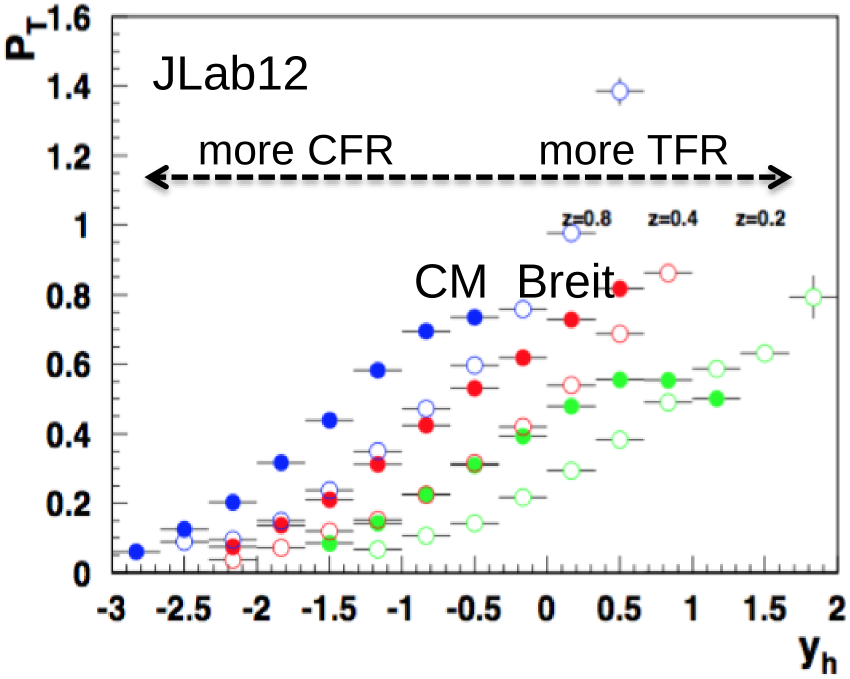
Additional complications: Experiment covers ranges described by different SFs



Boglione et al, Phys.Lett. B766 (2017) 245-253

$$y_h \equiv \frac{1}{2}\log(P_h^+/P_h^-)$$

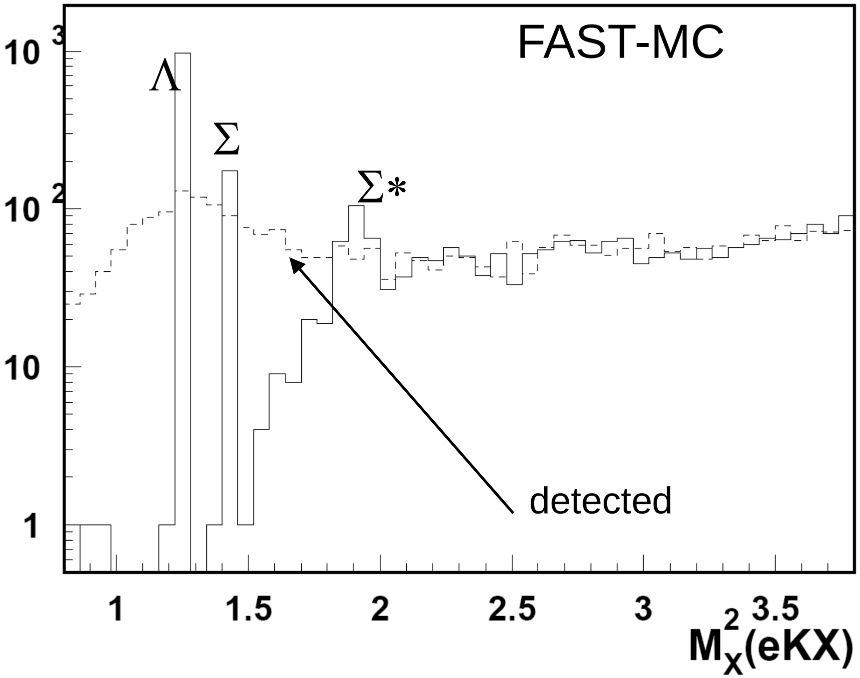
Kinematics covers regions with different fractions from target and current fragmentation

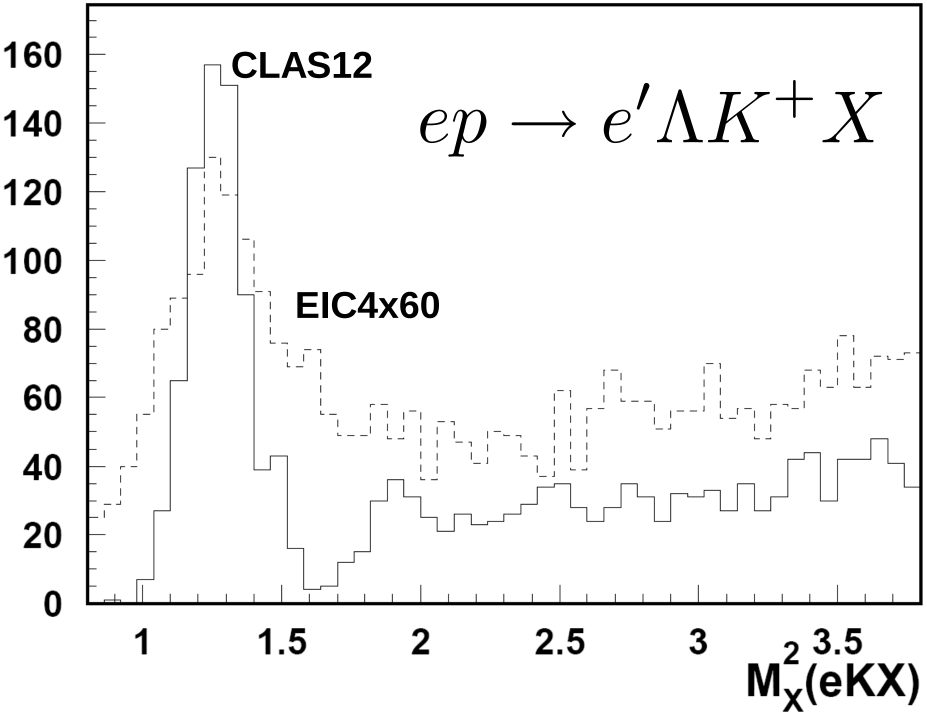


Understanding of the scale of ignored contributions (M/Q^2, P_T/Q^2, Target/Current correlations,…) will define the limits on precision for other involved contributions (ex. evolution).

Multidimensional bins ($\underline{x,y,z,P_T,\phi}$) are crucial for separation of different contributions

Kaon production in SIDIS

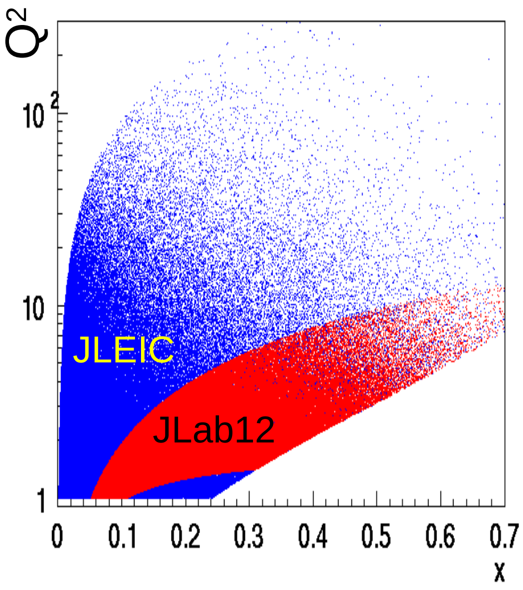




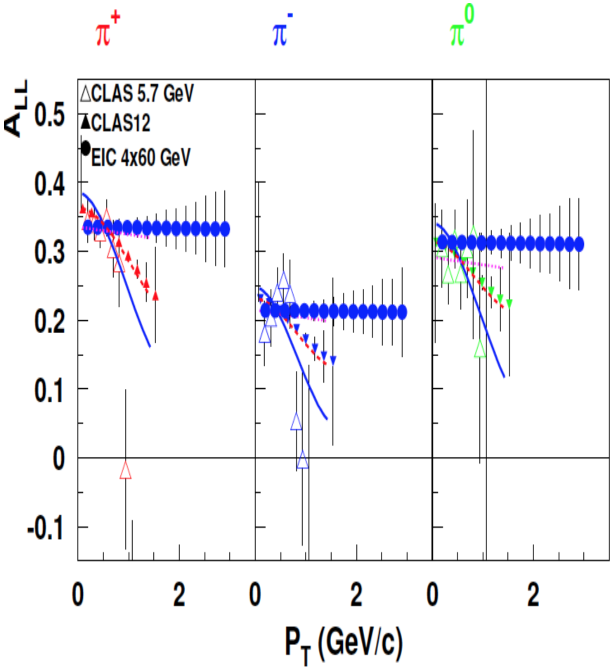
$\sigma(p) = 0.05 + 0.06*p$ [GeV] %

Identification using the missing mass may be possible

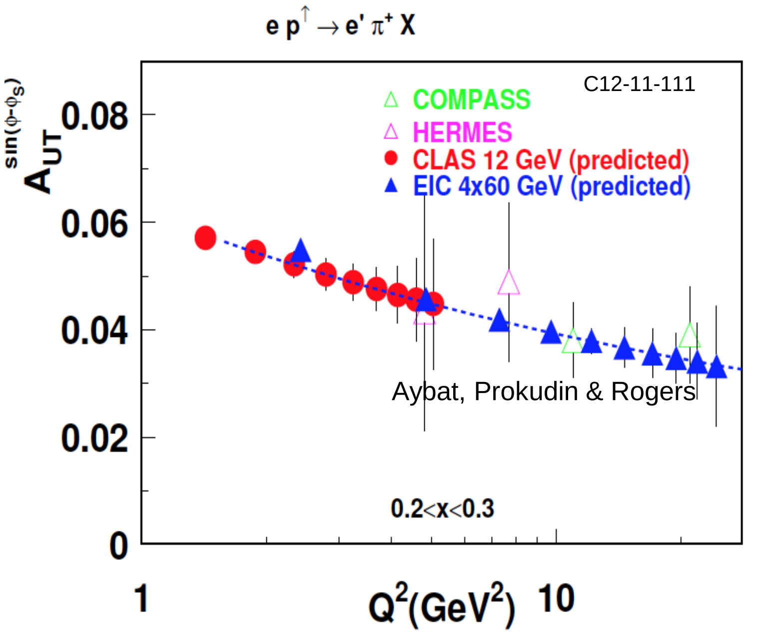
CLAS12: Evolution and k_T-dependence of TMDs



CLAS12 kinematical coverage



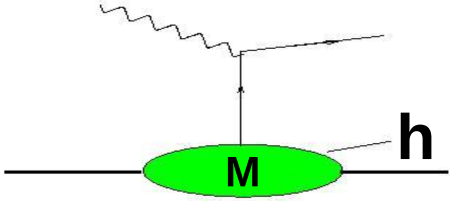
k_T-dependence of $g_1(x,k_T)$

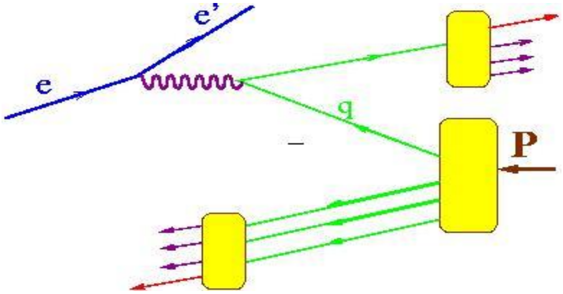


Q^2-dependence of Sivers, $f_1^{\perp}(x,k_T)$

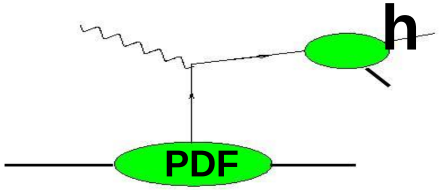
- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

Target Fragmentation



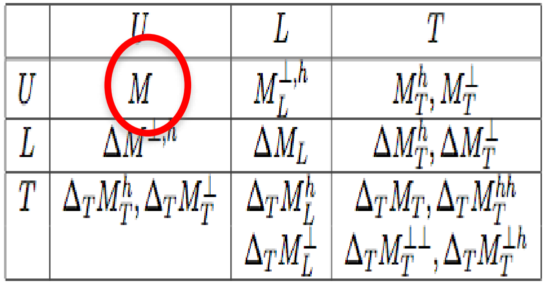


$x_F>0$ (current fragmentation)



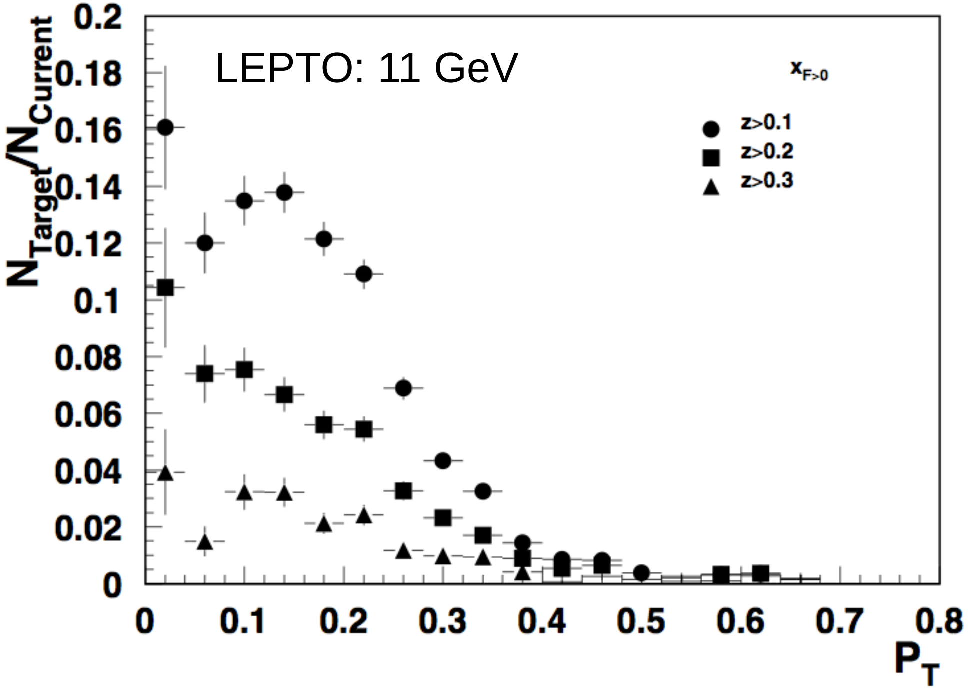
$x_F<0$ (target fragmentation)

Fracture Functions: probabilities to produce the hadron h when a quark q is struck in a proton target

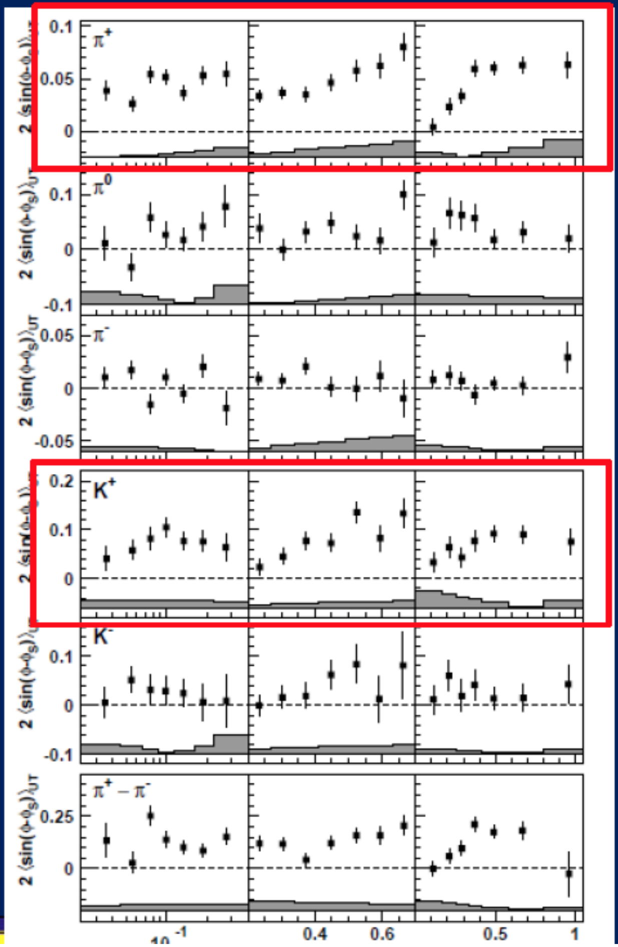


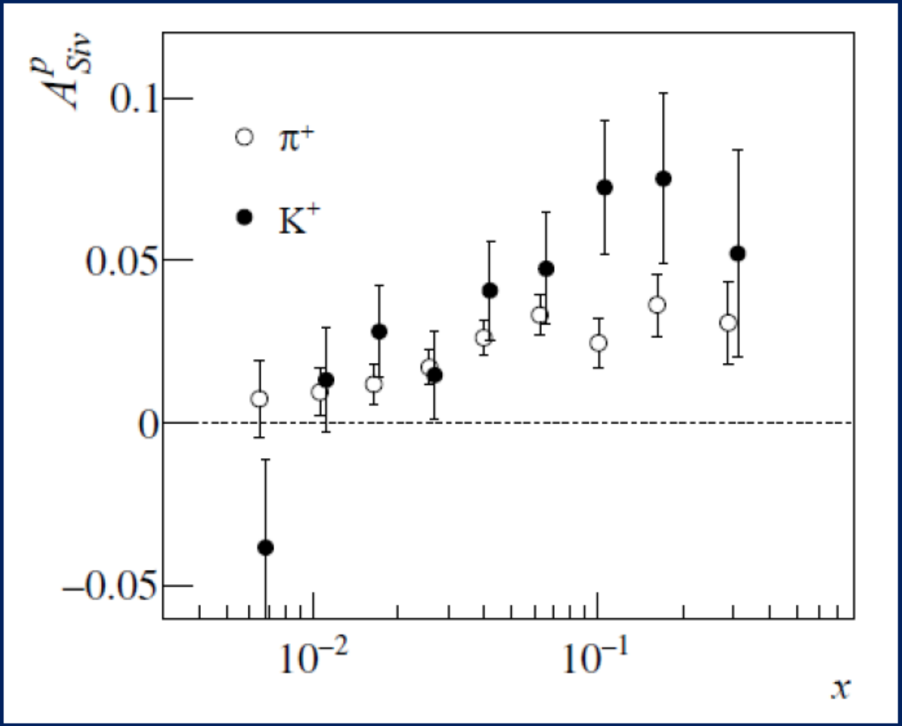
	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

- Hadrons produced in target fragmentation may be correlated with hadrons in the current fragmentation and their studies will be important for precision studies in current fragmentation.



Sivers TMD PDF for sea quarks **not** small?
SIDIS asymmetries larger for K^+ than π^+



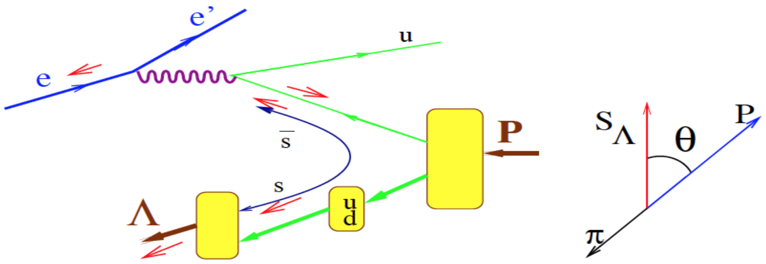


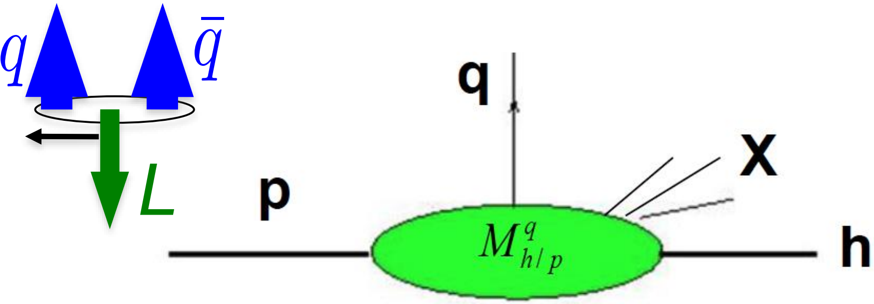
COMPASS, PLB744, 250 (2015)

HERMES, PRL103, 152002 (2009)
Note scale difference for π^+ vs. K^+!

Is it related to non-perturbative sea?

Target fragmentation region: Λ production





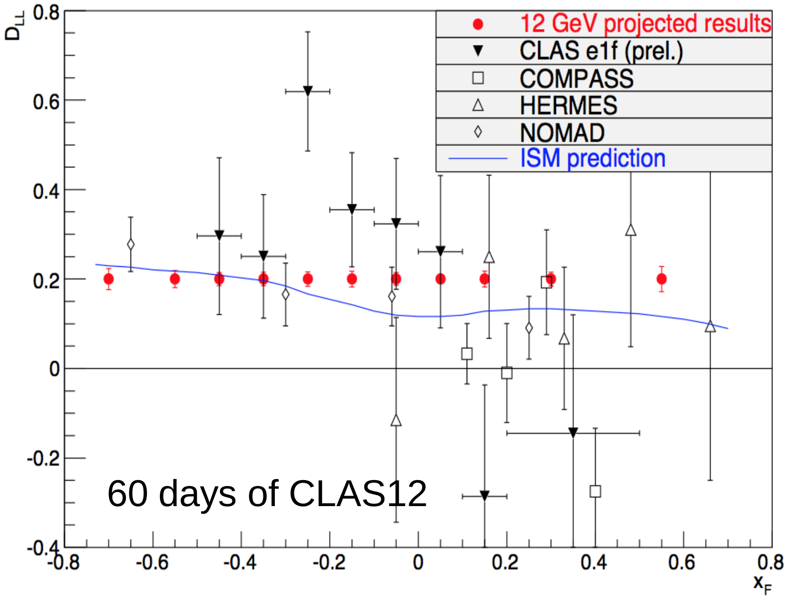
probability to produce the hadron h when a quark q is struck in a proton target

Measurements of fracture functions opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular

$$A_{LUL}^{TFR} = hS_{\parallel}\frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

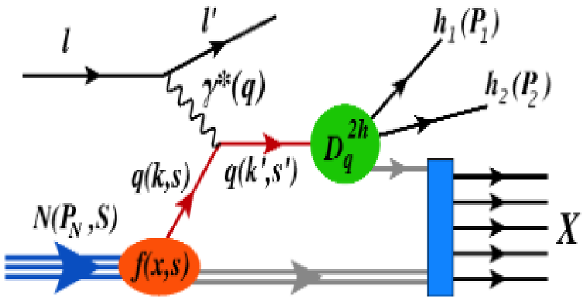
$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$

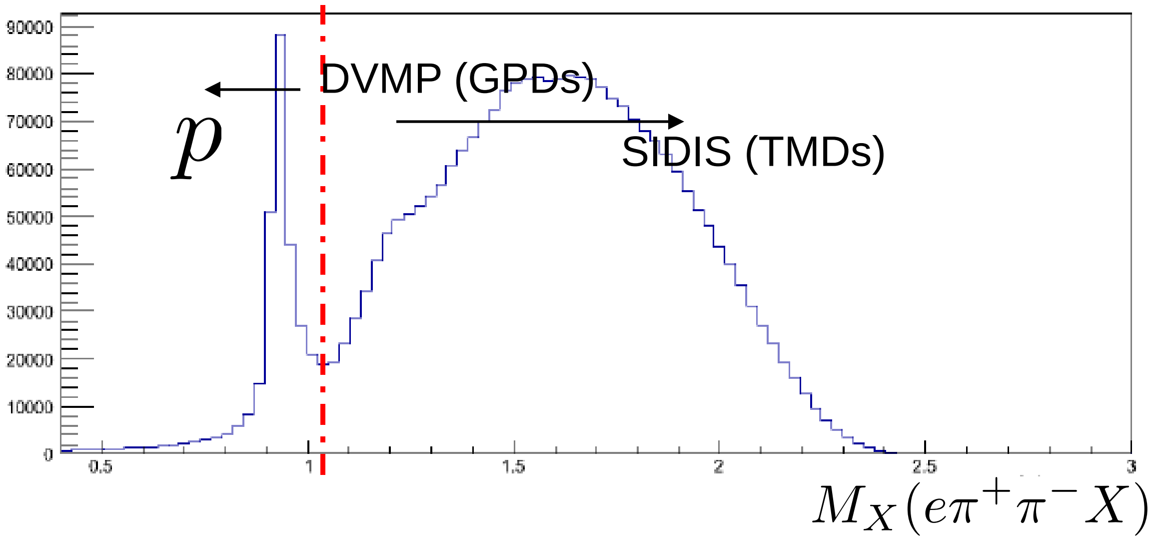
polarization transfer coefficient



- Large acceptance of CLAS12 and EIC provide a unique possibility to study the nucleon structure in target fragmentation region
- First measurements already performed using the CLAS data at 6 GeV.

Dihadron asymmetries from CLAS





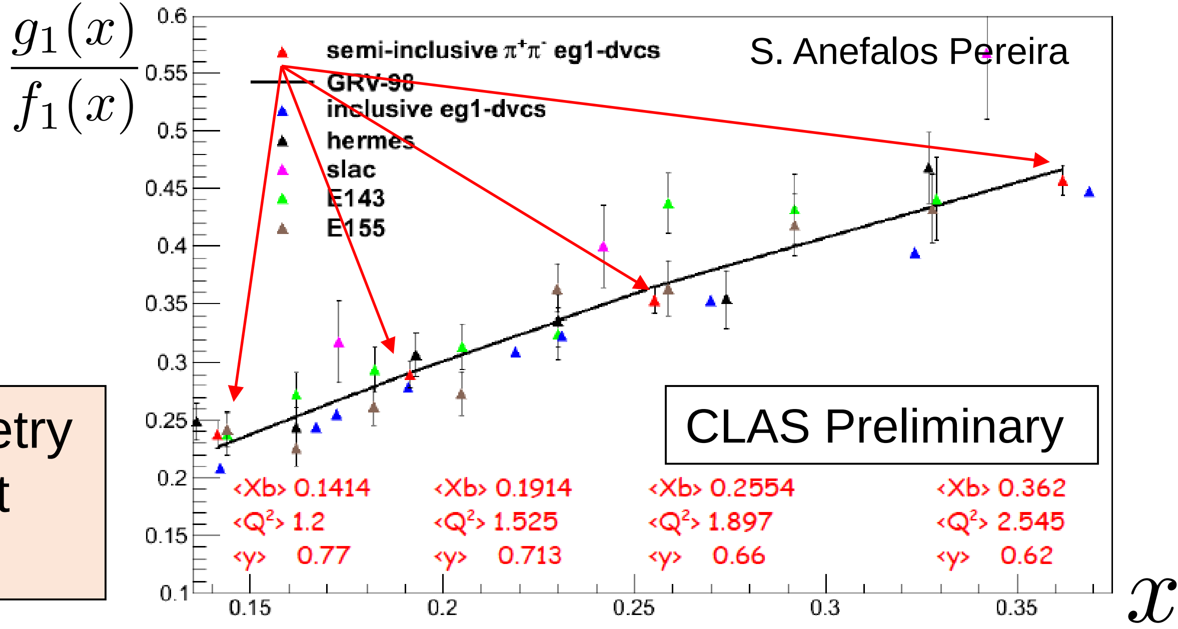
$$\frac{F_{LL}}{F_{UU}} \sim \frac{g_1(x)}{f_1(x)}$$

$$F_{UU,T} = x f_1^q(x)\, D_1^q(z, \cos\theta, M_h)$$

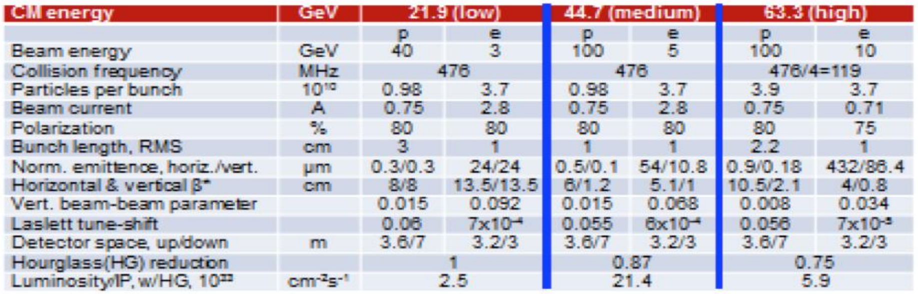
$$F_{LL} = x g_1^q(x)\, D_1^q(z, \cos\theta, M_h)$$

$$D_1^{u\to\pi+\pi-} \approx D_1^{d\to\pi+\pi-}$$

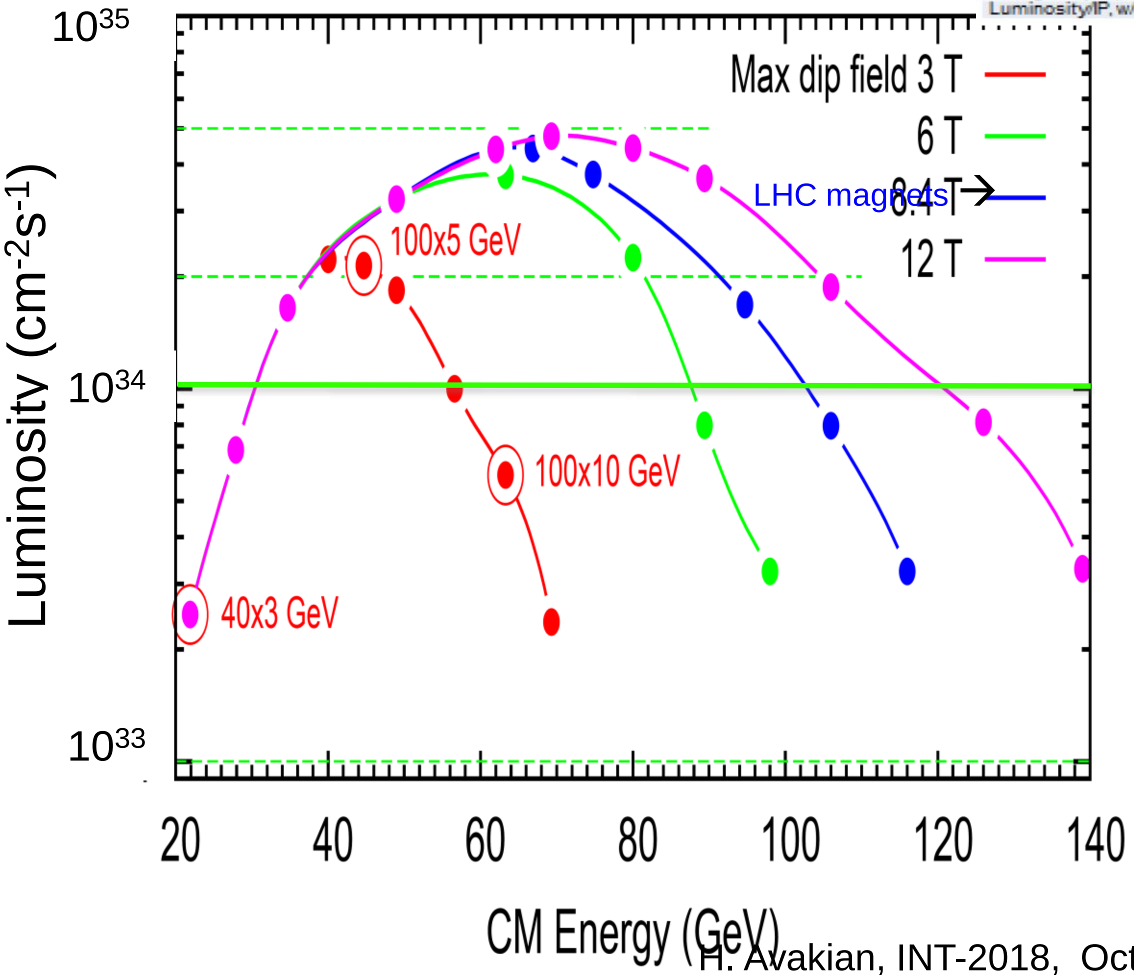
Dihadron double spin asymmetry measured at 6 GeV consistent with DIS



JLEIC energy reach and luminosity



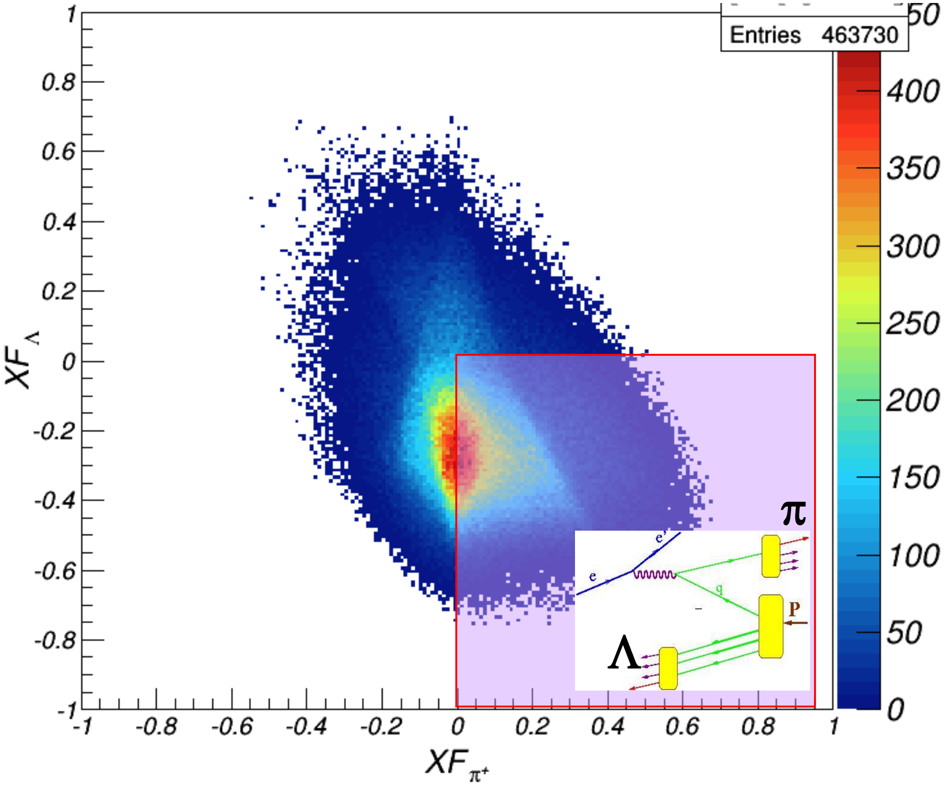
CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476/4=119	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	3.9	3.7
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	3	1	1	1	2.2	1
Norm. emittence, horiz./vert.	μm	0.3/0.3	24/24	0.5/0.1	54/10.8	0.9/0.18	432/86.4
Horizontal & vertical β^*	cm	8/8	13.5/13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam parameter		0.015	0.092	0.015	0.068	0.008	0.034
Laslett tune-shift		0.06	7×10^{-4}	0.055	6×10^{-4}	0.056	7×10^{-5}
Detector space, up/down	m	3.6/7	3.2/3	3.6/7	3.2/3	3.6/7	3.2/3
Hourglass(HG) reduction		1		0.87		0.75	
Luminosity/IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	2.5		21.4		5.9	



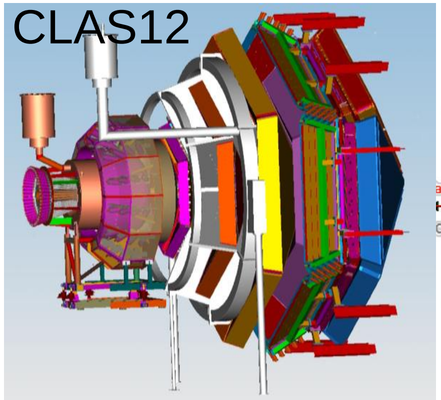
Dihadron production at JLAB12

Use the clasDIS (LUND based) generator + FASTMC to study hh pairs

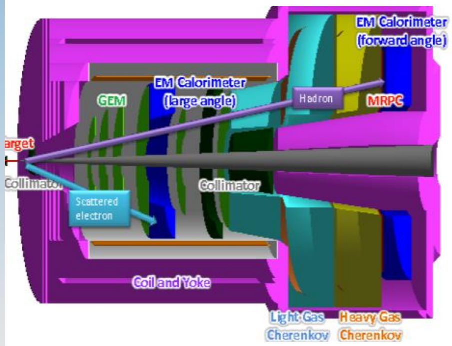
x_F - momentum in the CM frame

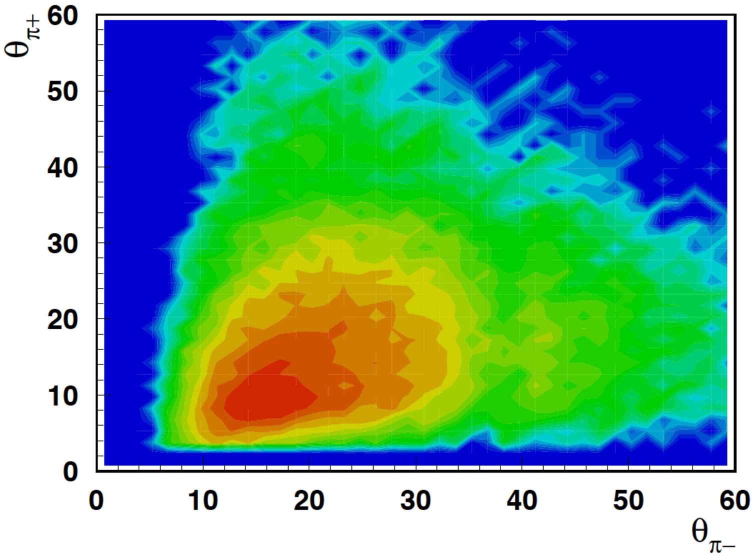


CLAS12



SoLID



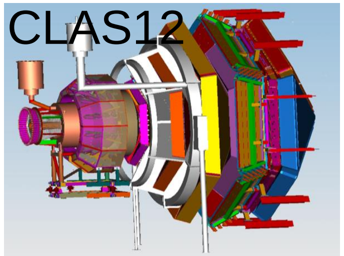


Dihadron sample defined by SIDIS cuts + $x_F>0$ (CFR) and $x_F<0$ (TFR) for both hadrons

Wide angular coverage is important

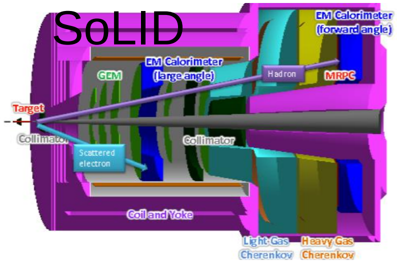
Accessing transversity in dihadron production at JLab

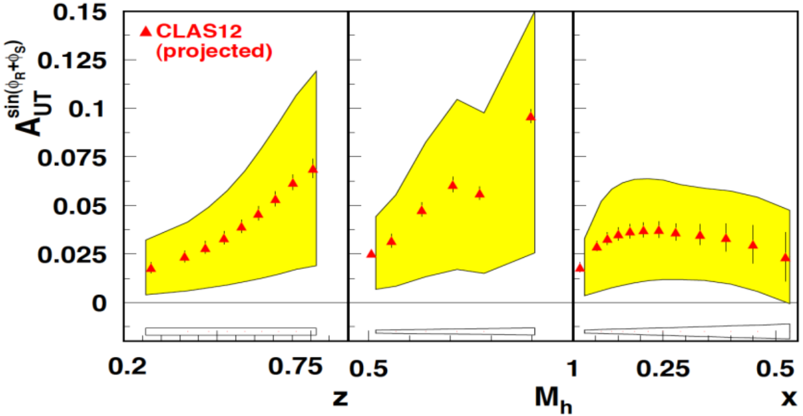
Measurements with polarized protons

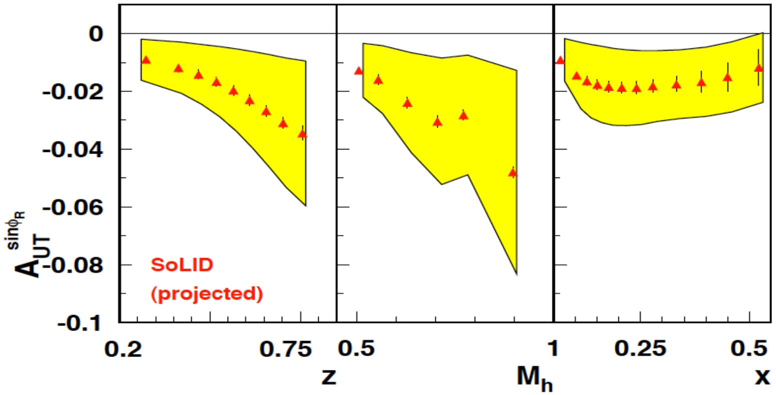


$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$

Measurements with polarized neutrons

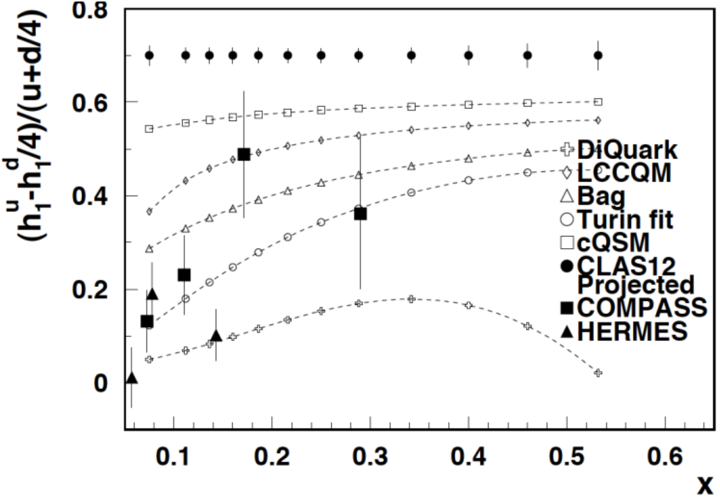






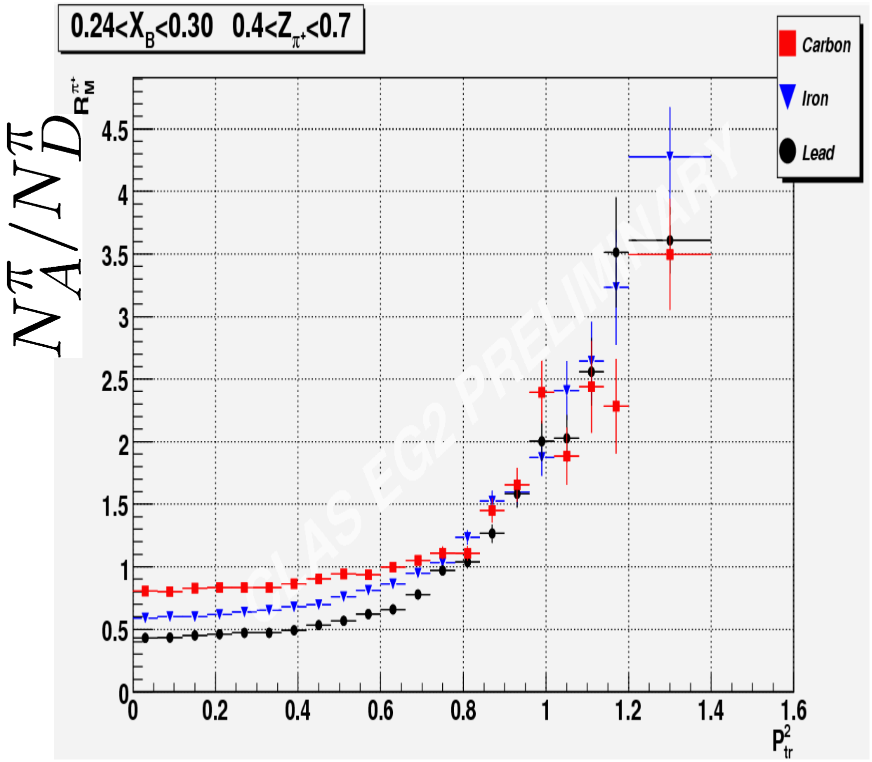
Bacchetta, Radici

$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$



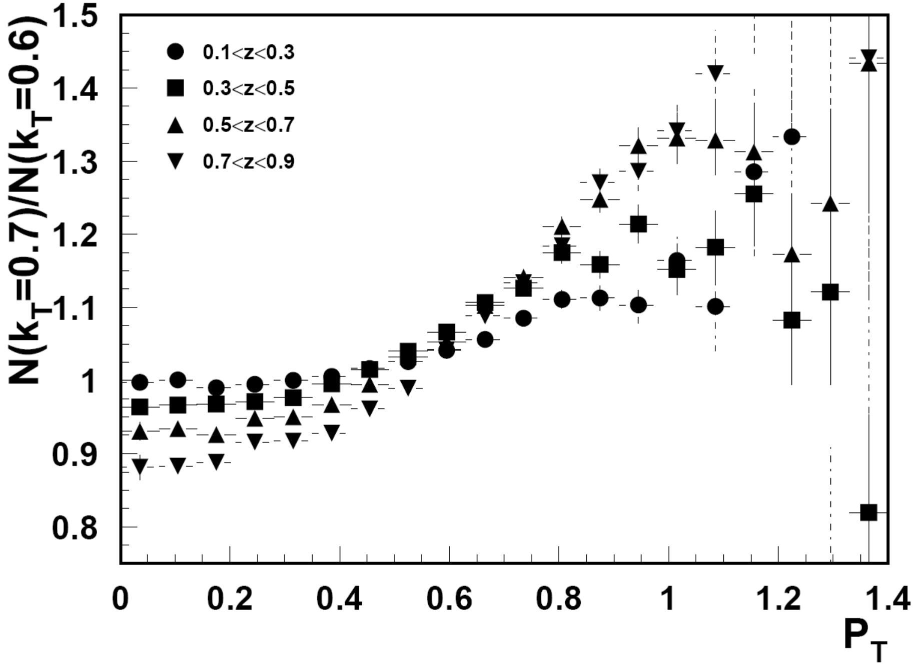
$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\,\left(4h_1^d(x) - h_1^u(x)\right)}{D_1^u(z,M_{\pi\pi})\,\left(4f_1^d(x) + f_1^u(x)\right)}$$

Quark distributions at large k_T



bigger effect at large z

$P_T = p_\perp + z\, k_T$



Higher probability to find a hadron at large P_T in nuclei

k_T-distributions may be wider in nuclei?

BGMP: extraction of k_T-dependent PDFs

Need: project x-section onto Fourier mods in b_T-space to avoid convolution

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$\int_0^\infty d|P_{h\perp}|\,|P_{h\perp}|\,J_0(|P_{h\perp}||b_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|P_{h\perp}|d|P_{h\perp}|}\right]$$

$$\Downarrow$$

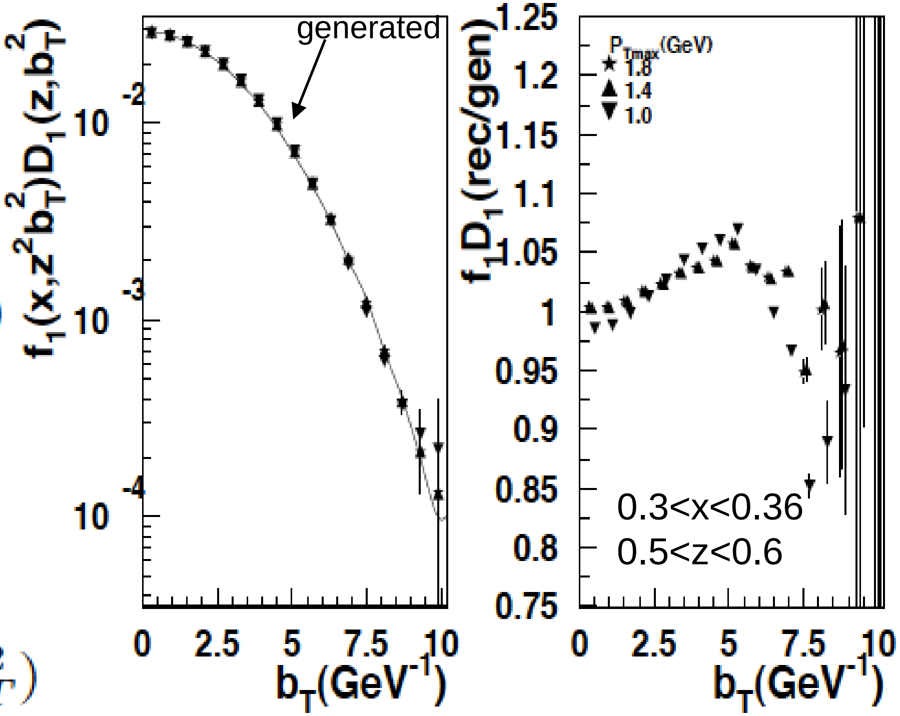
$$S_\pi^{unp\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta_i/A(x_i,y_i)$$

acceptance

$$A(x,y)=\frac{\alpha^2}{x_B y Q^2}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

$$\Downarrow$$

$$\tilde f_1^q(x,z^2b_T^2)\,\tilde D_1^{q\to\pi}(z,b_T^2)$$



Bessel weighting

$$\int_0^{2\pi} d\phi_h \sin\phi_h \int_0^\infty d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}|\frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|}\left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|}\right]$$

$$\sum_a e_a^2\tilde e^a(x,z^2b_T^2)\tilde H_1^{\perp(1)a}(z,b_T^2)+\ldots$$

- provides a model independent way to study kinematical dependences of TMD requires wide range in hadron P_T

k_T and FSI

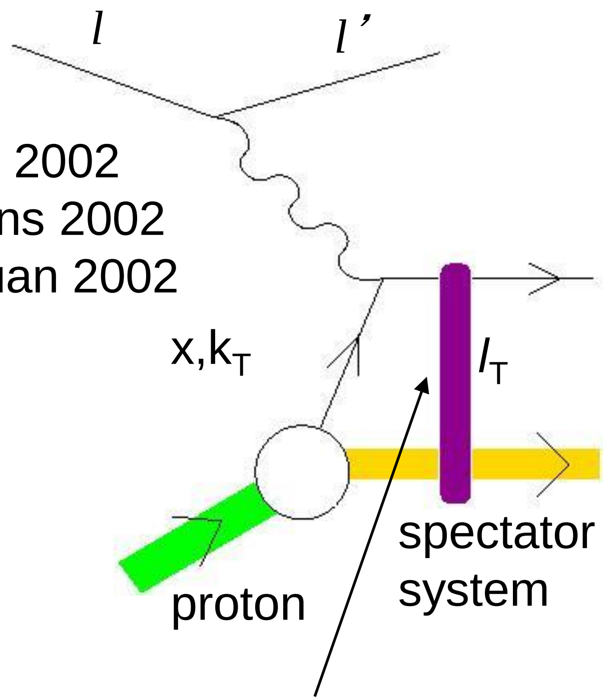
Tang,Wang & Zhou
Phys.Rev.D77:125010,2008

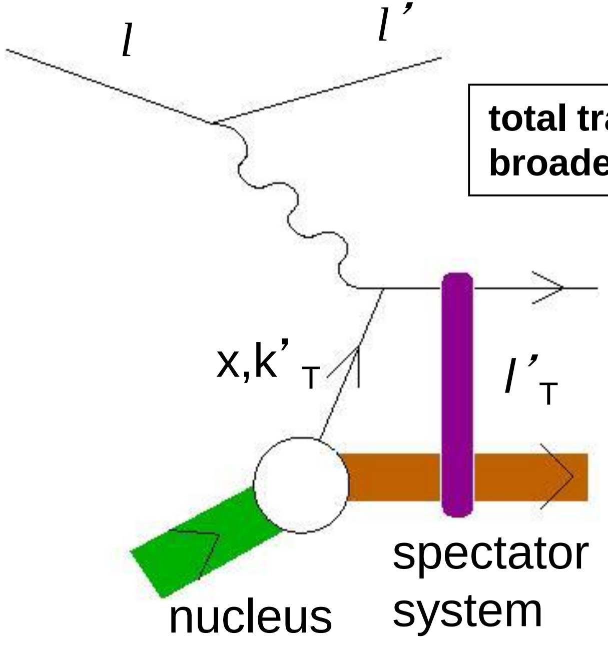
$$f_q^N(x,\vec{k}_T)$$

$$f_q^A(x,\vec{k}_T)=\frac{A}{\pi\Delta_{2F}}\int d^2 l_T e^{-(\vec{k}_T-\vec{l}_T)^2/\Delta_{2F}} f_q^N(x,\vec{l}_T)$$

total transverse momentum broadening squared

BHS 2002
Collins 2002
Ji,Yuan 2002



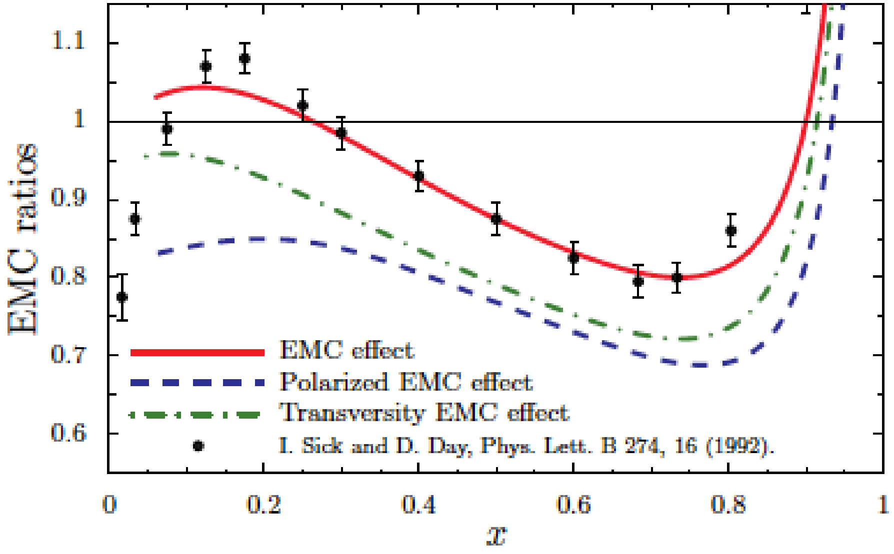


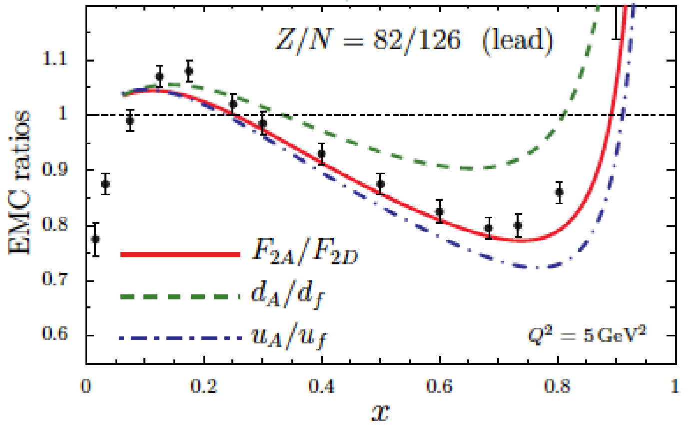
the intrinsic transverse momentum of partons arises naturally from multiple soft gluon interaction inside the nucleon or nucleus.

- The difference is coming from final state interactions (different remnant)

Medium modified spin observables (NJL model)

2014


Cloët, Bentz & Thomas, Phys. Rev. Lett. **95**, 052302 (2005)


Cloët, Bentz & Thomas, Phys. Rev. Lett. **109**, 182301 (2012)

EMC effect essentially a consequence of binding at the quark level

- Nuclear TMDs being computed in quark model of Cloët, Bentz & Thomas
  - already provides a natural explanation of the EMC effect
  - already predicts large polarized, transversity & flavor dependent EMC effects
- In model quarks feel the presence of the nuclear environment: *as a consequence bound nucleons are modified by the nuclear medium*
- Modification of the bound nucleon wave function by the nuclear medium is a *natural consequence* of quark level approaches to nuclear structure
- Nuclear TMDs: scalar field & fermi motion $\Longrightarrow \langle k_T^2\rangle^{\text{nuclear}} > \langle k_T^2\rangle^{\text{nucleon}}$

Modification of beam and target DSAs & SSAs

Gao, Liang & Wang **arXiv:1308.1159**

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

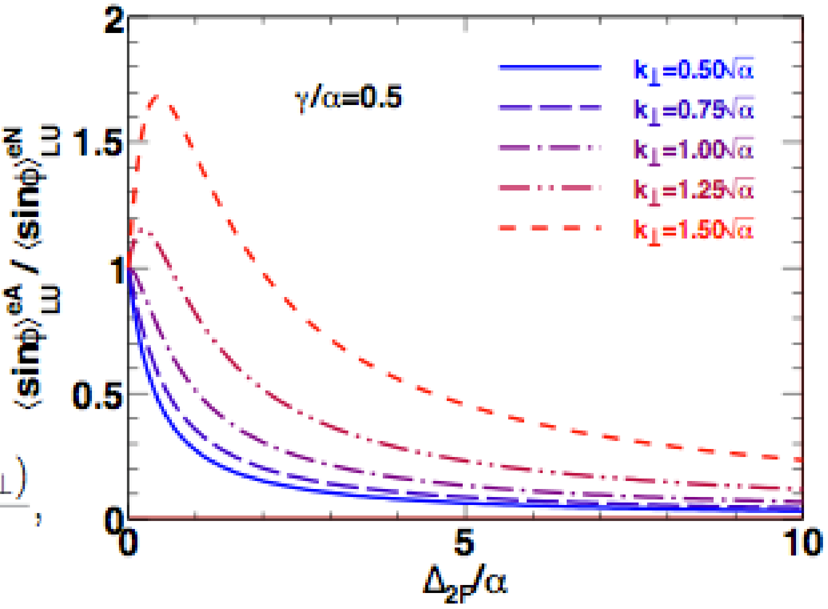
$$\frac{\langle\sin\phi\rangle^{eA}_{LU}}{\langle\sin\phi\rangle^{eN}_{LU}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}.$$

$$|\vec{k}_\perp|^2 g^{\perp A}(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}}\int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}}(\vec{k}_\perp\cdot\vec{\ell}_\perp)\, g^{\perp N}(x,\ell_\perp)$$

$$\langle\sin\phi\rangle_{LU} = \lambda_l\frac{|\vec{k}_\perp|}{Q}\frac{D(y)}{A(y)}\frac{x_B g^\perp(x_B,k_\perp)}{f_1(x_B,k_\perp)},$$

$$\langle\sin\phi\rangle_{UL} = \lambda\frac{|\vec{k}_\perp|}{Q}\frac{B(y)}{A(y)}\frac{x_B f_L^\perp(x_B,k_\perp)}{f_1(x_B,k_\perp)}.$$

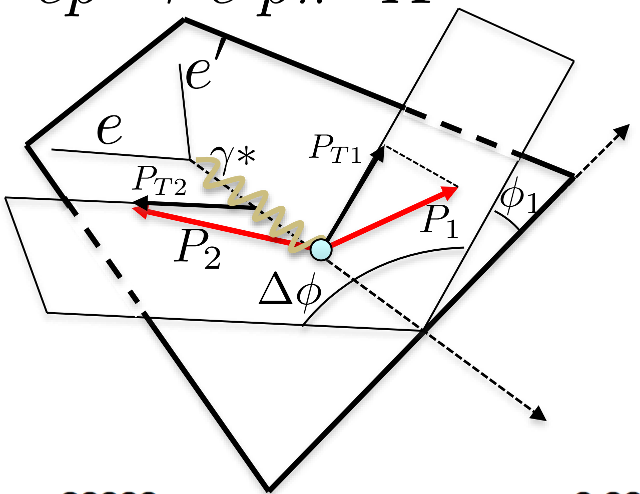
$$\langle\cos\phi\rangle_{LL} = -\frac{|\vec{k}_\perp|}{Q}\frac{B(y)x_B f^\perp(x_B,k_\perp)+\lambda_l\lambda D(y)x_B g_L^\perp(x_B,k_\perp)}{A(y)f_1(x_B,k_\perp)+\lambda_l\lambda C(y)g_{1L}(x_B,k_\perp)},$$

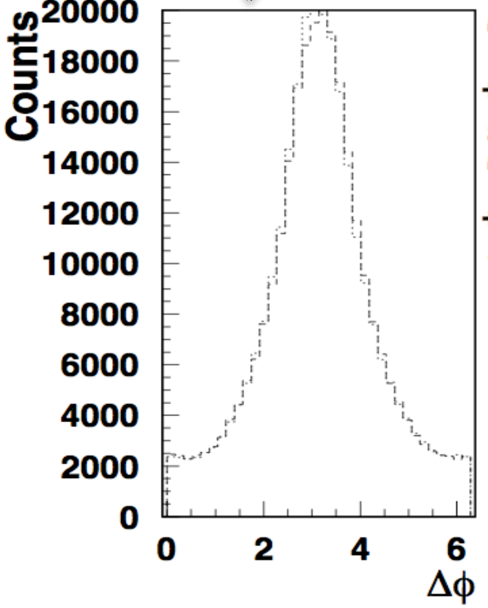


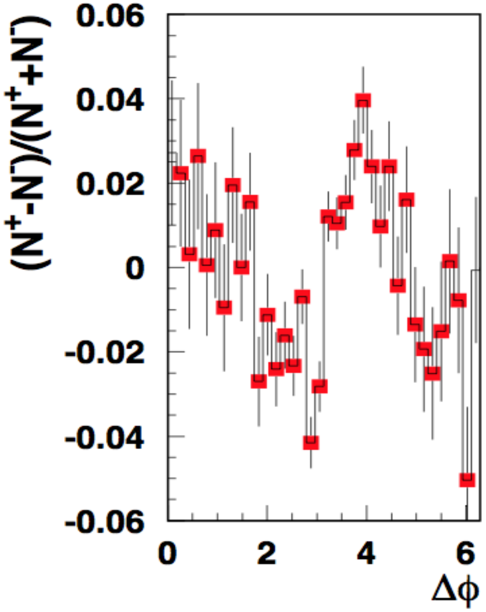
Medium modification of the azimuthal asymmetry is a very sensitive probe of the twist-2 and twist-3 TMD quark distributions

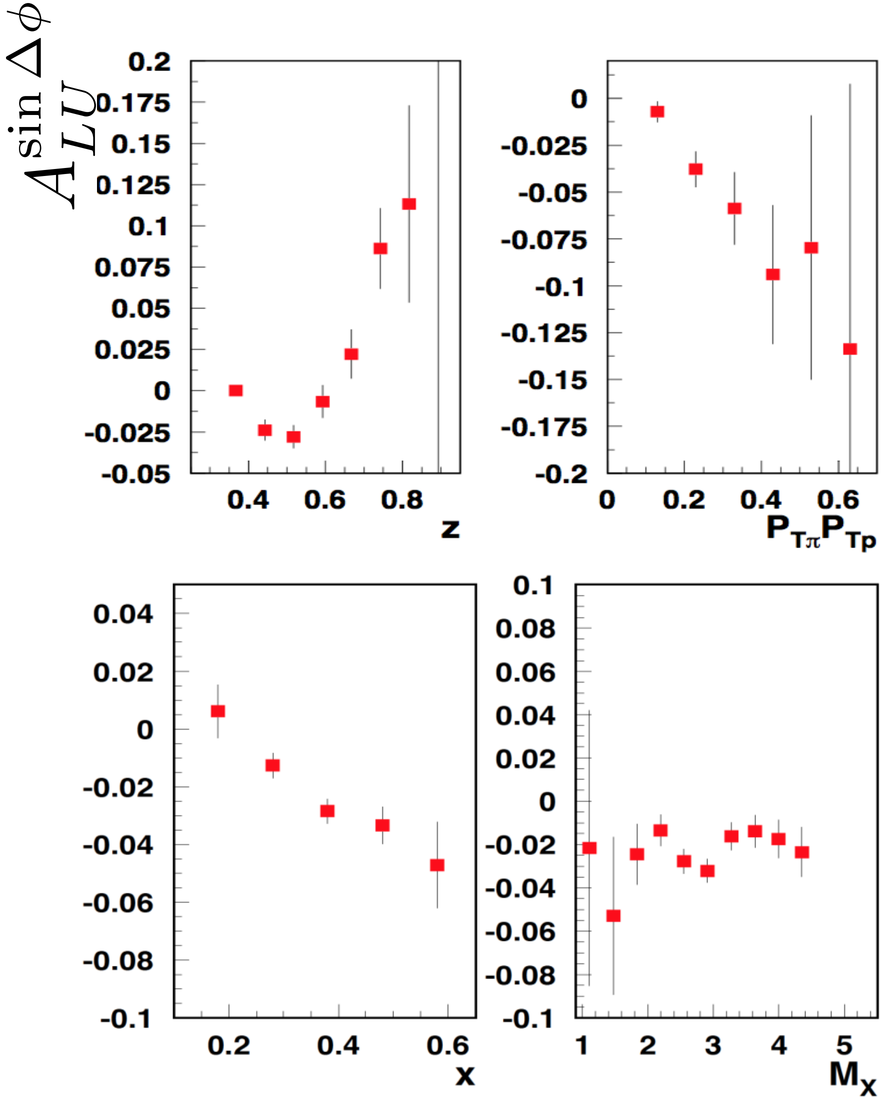
b2b SSAs

$ep \rightarrow e'p\pi^+X$

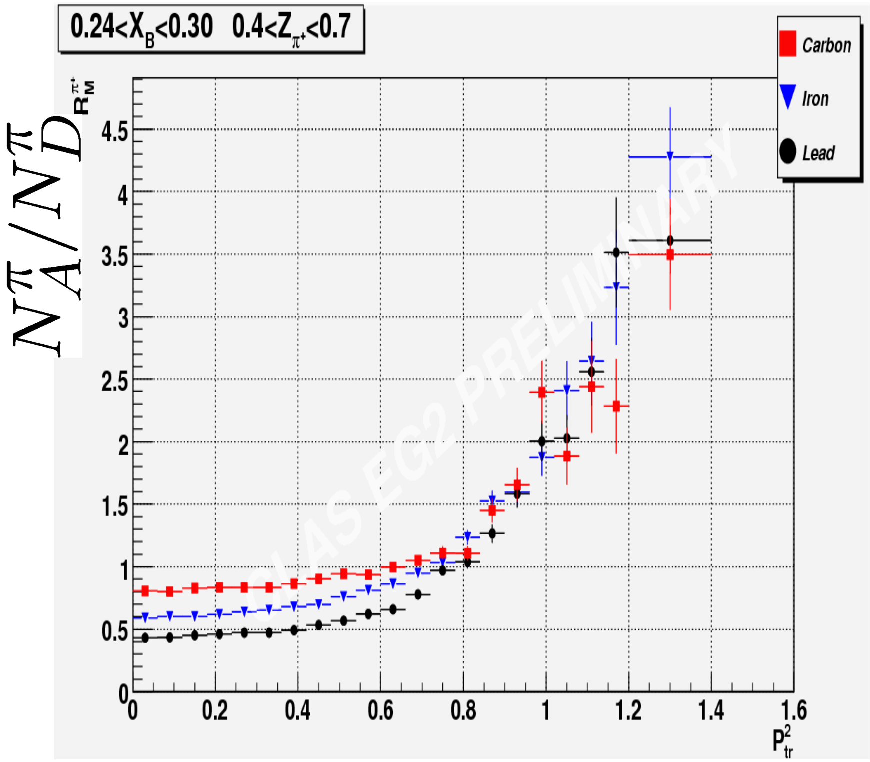






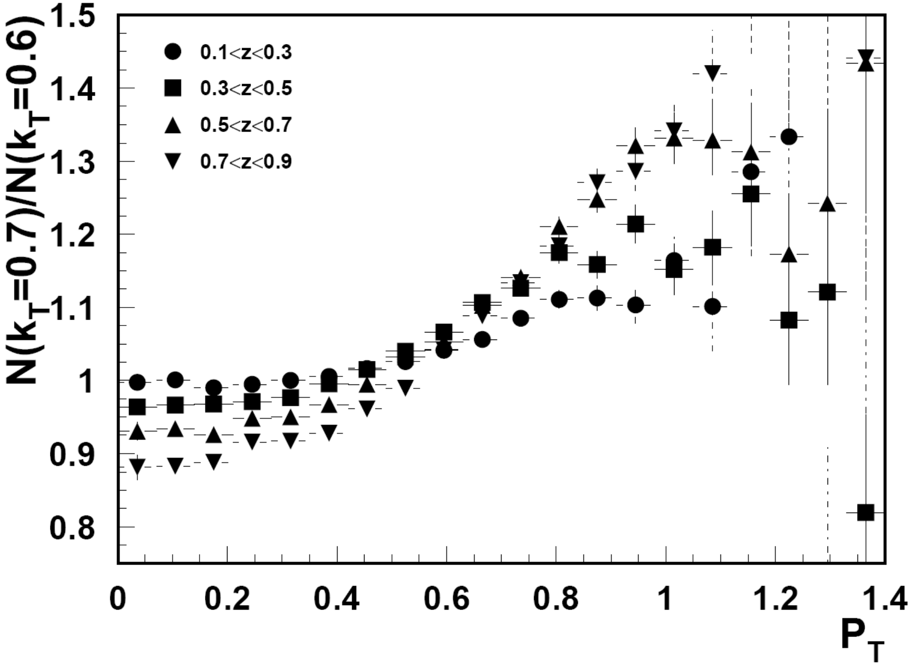


Quark distributions at large k_T



bigger effect at large z

$P_T = p_\perp + z\, k_T$



Higher probability to find a hadron at large P_T in nuclei

k_T-distributions may be wider in nuclei?

Jet limit: Higher Twist azimuthal asymmetries

$$F_{LU}^{\sin\phi} \propto g^{\perp q} D_1^q$$

$$F_{UU}^{\cos\phi} \propto f^{\perp q} D_1^q$$

Twist-2

N/q	U	L	T
U	$\mathbf{f}_1$		$h_1^\perp$

Twist-3

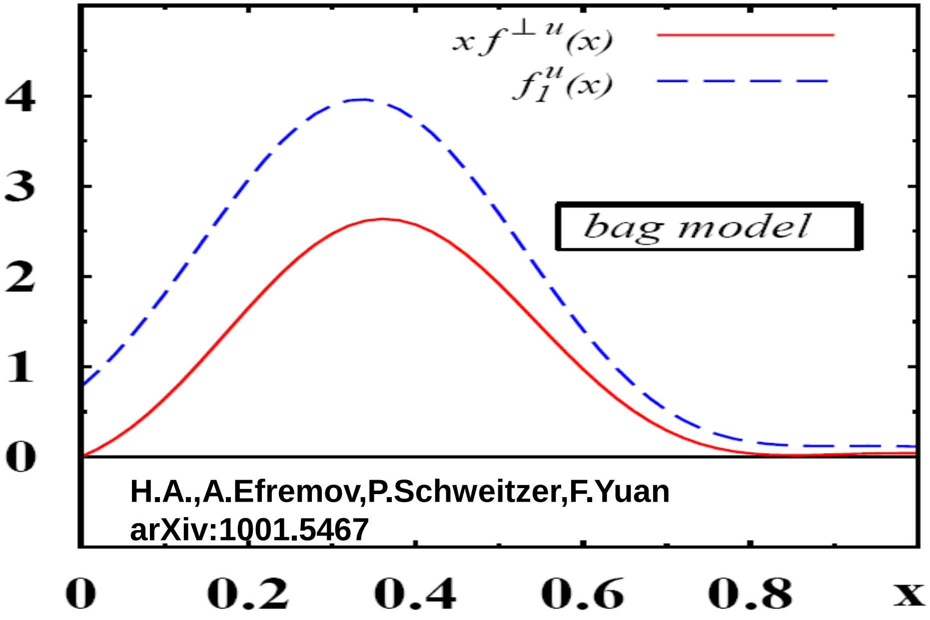
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, e

T-odd

$$xf^{\perp q} = x\tilde{f}^{\perp q} + f_1^q$$

“interaction dependent”

No leading twist, provide access to quark-gluon correlations



H.A.,A.Efremov,P.Schweitzer,F.Yuan arXiv:1001.5467

Modification of Cahn effect

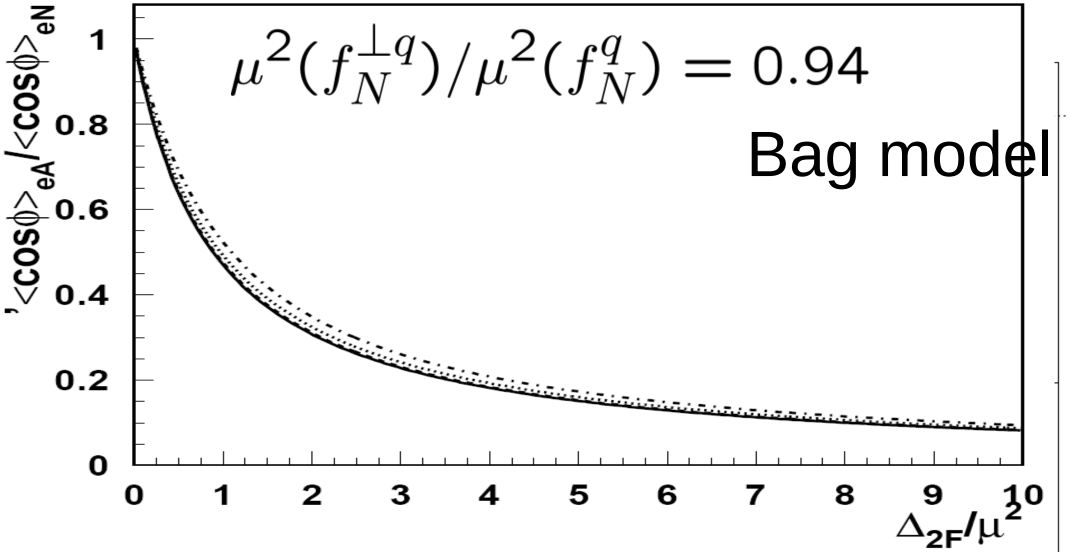
$$< cos\phi >_{eN} \propto \frac{|\vec{k}_T| x f_N^{\perp q}(x,k_T)}{f_N^q(x,k_T)}$$

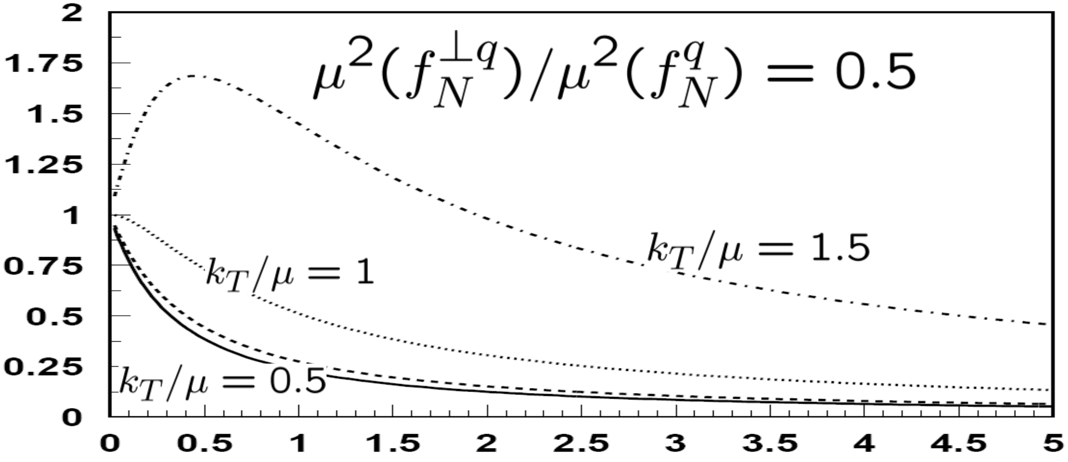
$$f_N^q(x,k_T) = \frac{1}{\pi\mu_0^2} f_N^q(x) e^{-k_T^2/\mu_0^2}$$

$$\Big\downarrow$$

$$\frac{< \cos\phi >_{eA}}{< \cos\phi >_{eN}} = \frac{\mu_0^2}{\mu_0^2 + \Delta_{2F}}$$

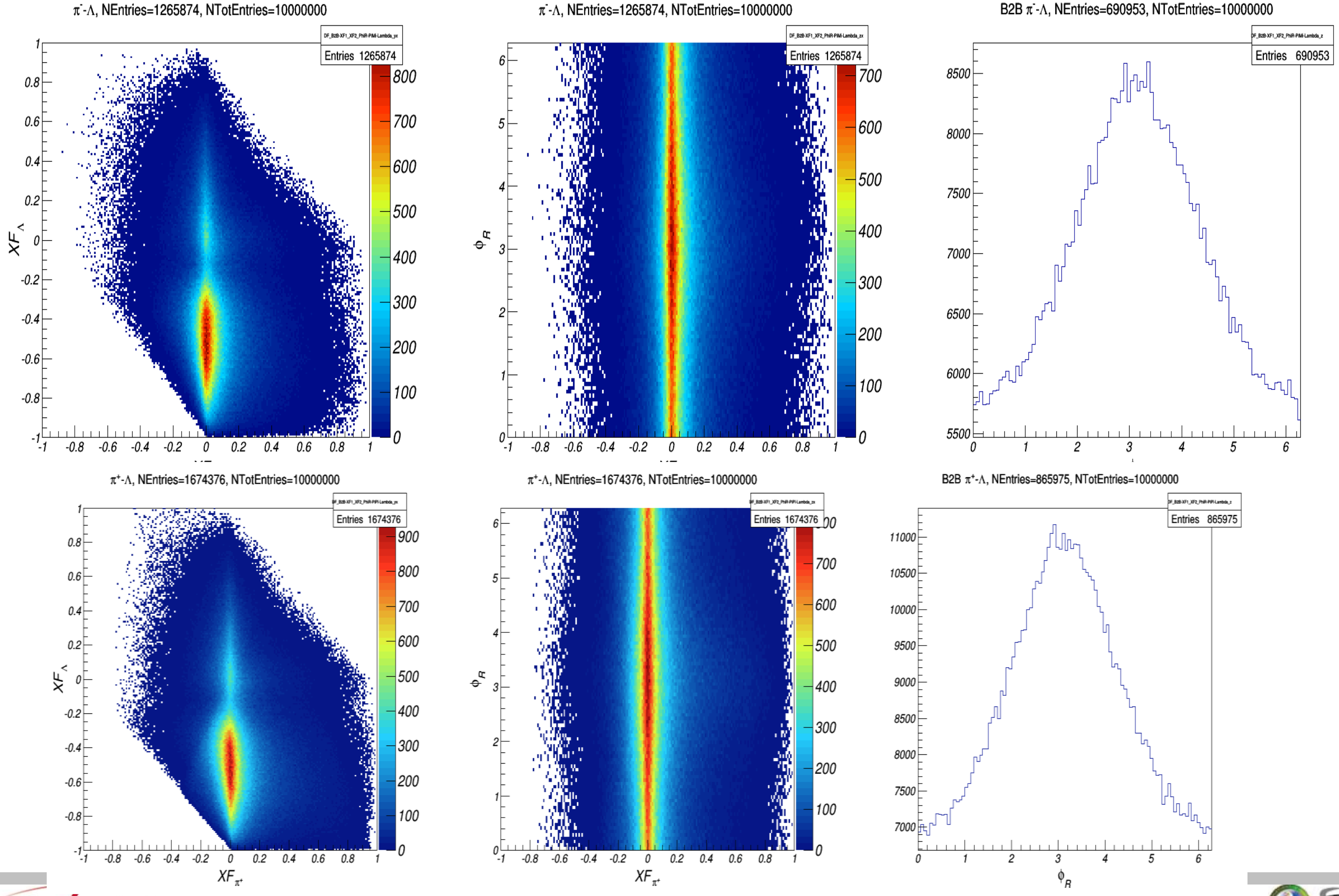
Gao, Liang & Wang **arXiv:1001.3146**



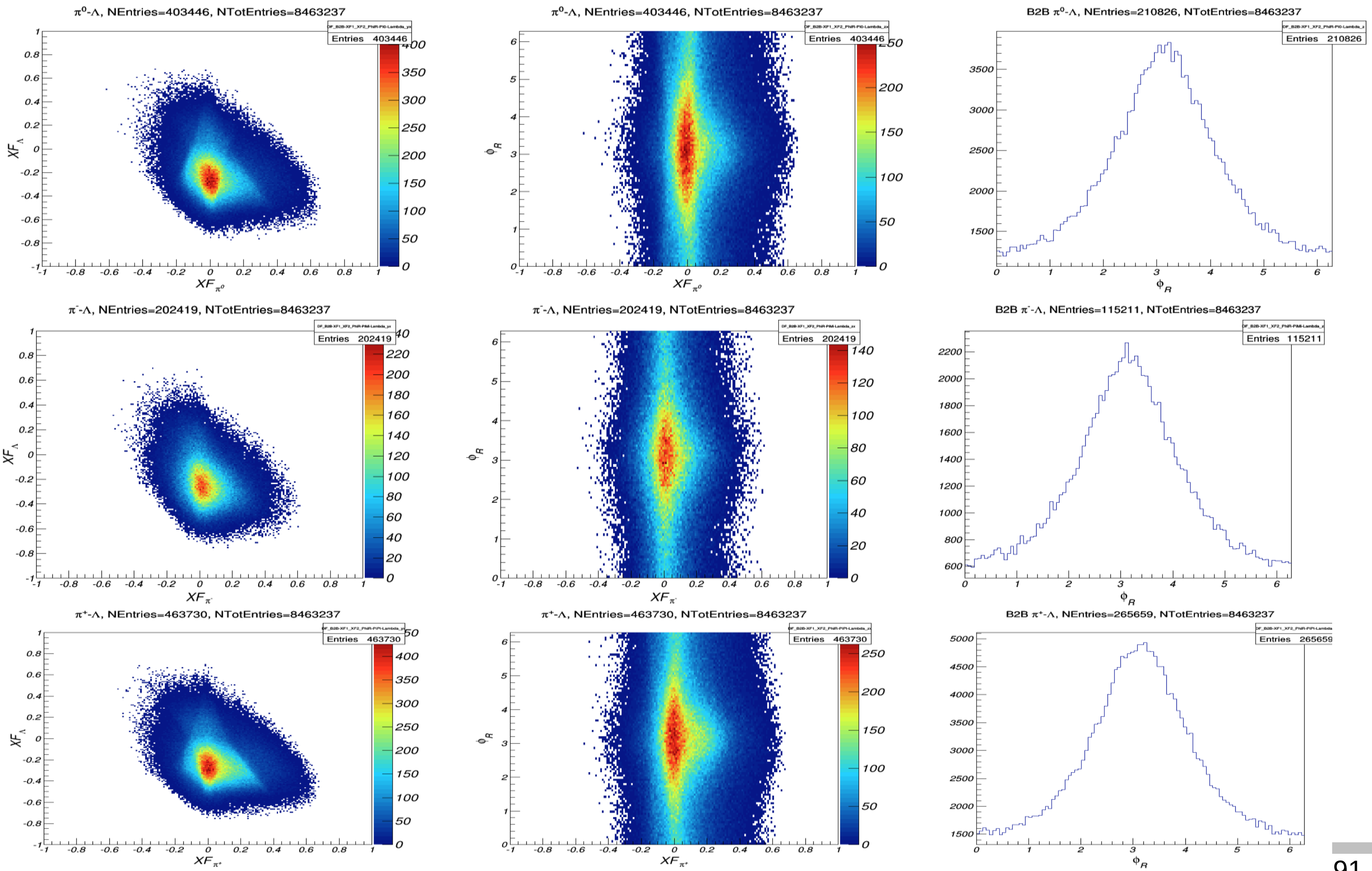


- Nuclear modification of Cahn may provide info on k_T broadening and proton TMDs

b2b distributions: EIC 5x50 (Lambda-pi)



b2b distributions: CLAS12(Lambda-pion)



One TMD PDF: Solution to Evolution

Ex: Cutoff Prescription:

$$\mathbf{b}_*(\mathbf{b}_\mathrm{T}) \equiv \frac{\mathbf{b}_\mathrm{T}}{\sqrt{1 + b_T^2/b_\mathrm{max}^2}}$$

$$\mu_b \equiv C_1/|\mathbf{b}_*(b_T)|$$

$$\tilde{F}_{f/P}(x, \mathbf{b}_\mathrm{T}; Q, Q^2) =$$

Collinear PDFs

$$\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x}, \mu_b) \times$$

$$\times \exp\left\{ \ln\frac{Q}{\mu_b}\tilde{K}(b_*; \mu_b) + \int_{\mu_b}^{Q} \frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu'); 1) - \ln\frac{Q}{\mu'}\gamma_K(g(\mu'))\right]\right\} \times$$

$$\times \exp\left\{ \underline{-g_{f/P}(x, b_T; b_\mathrm{max})} \underline{- g_K(b_T; b_\mathrm{max})} \ln\frac{Q}{Q_0} \right\}$$

Nonperturbative parts large b