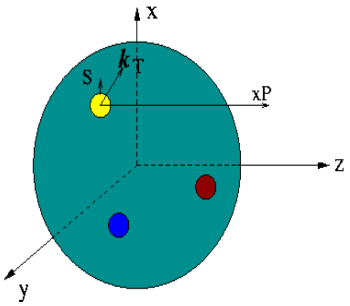
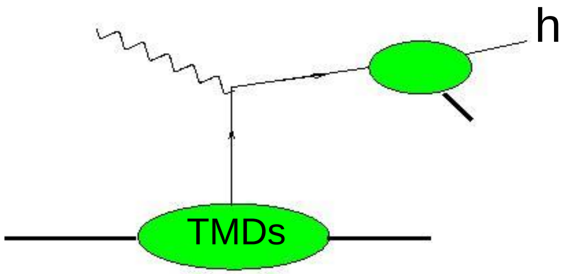
Disentangling different effects, from higher twist to target fragmentation

Harut Avakian (JLab)

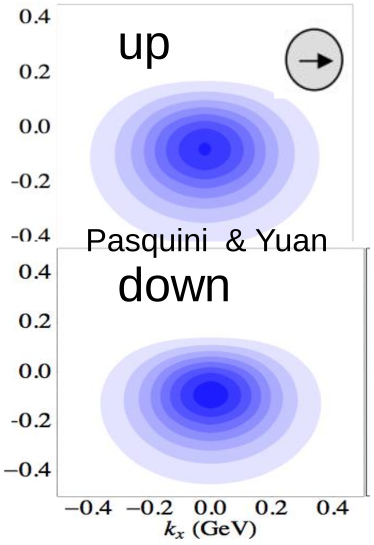
3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions



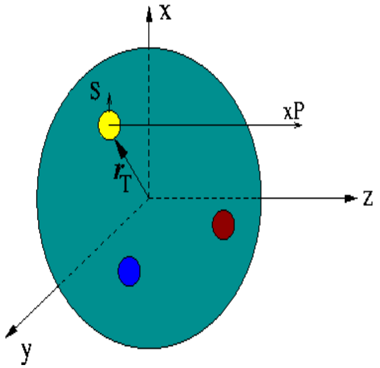


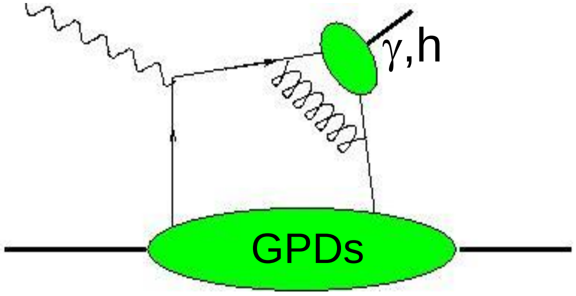
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$



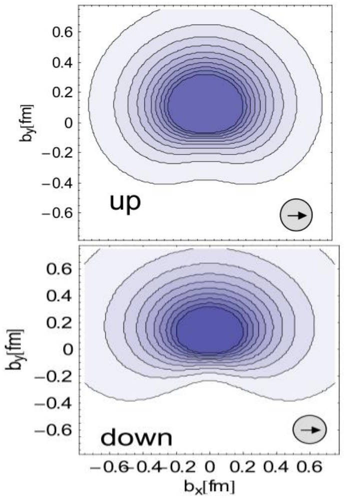
Pasquini & Yuan

Hard exclusive processes and spatial distributions of partons





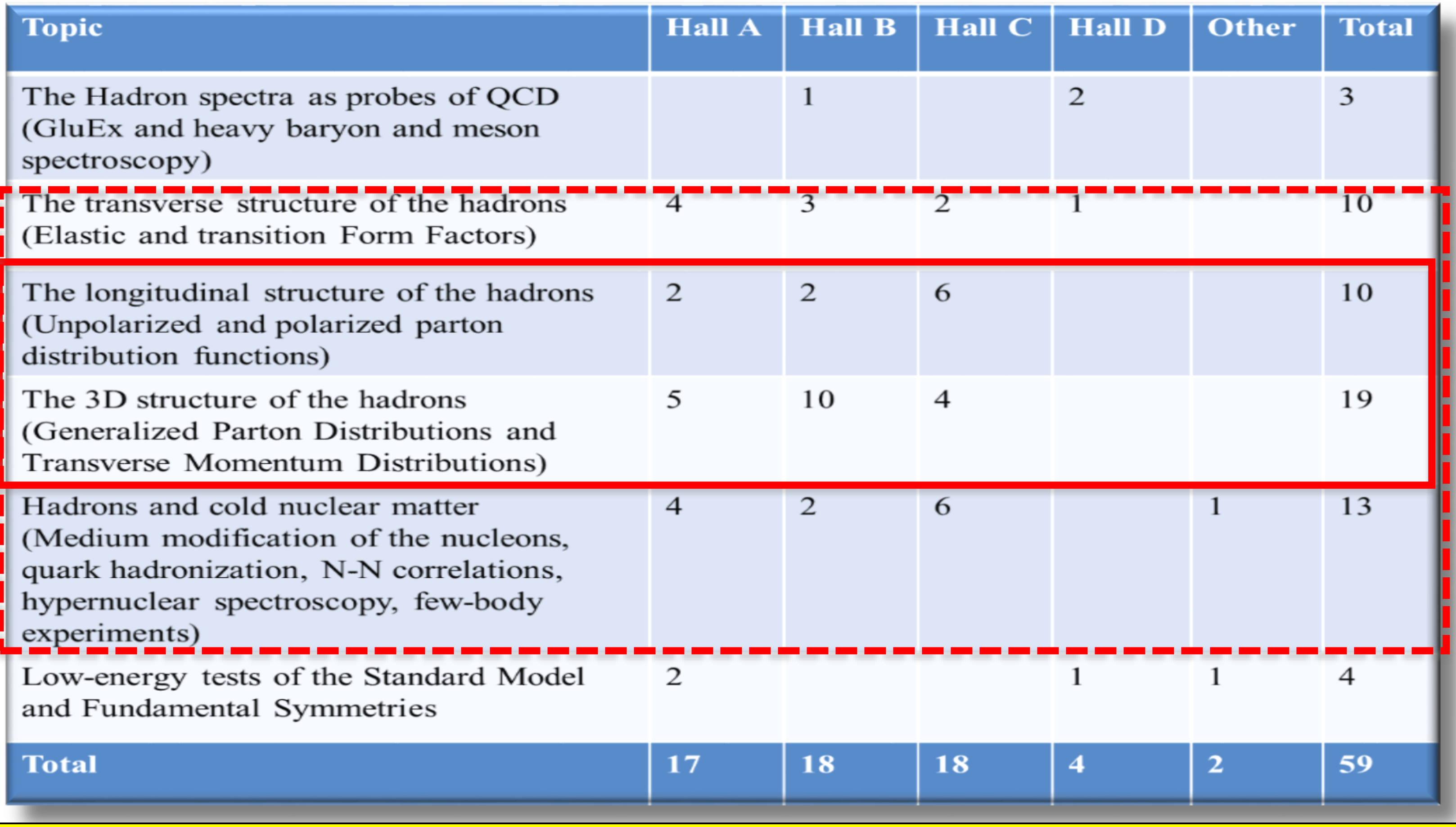
	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



(QCDSF)

The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations

12 GeV Approved Experiments by Physics Topics



Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy)		1		2		3
The transverse structure of the hadrons (Elastic and transition Form Factors)	4	3	2	1		10
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	2	6			10
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	10	4			19
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	4	2	6		1	13
Low-energy tests of the Standard Model and Fundamental Symmetries	2			1	1	4
Total	**17**	**18**	**18**	**4**	**2**	**59**

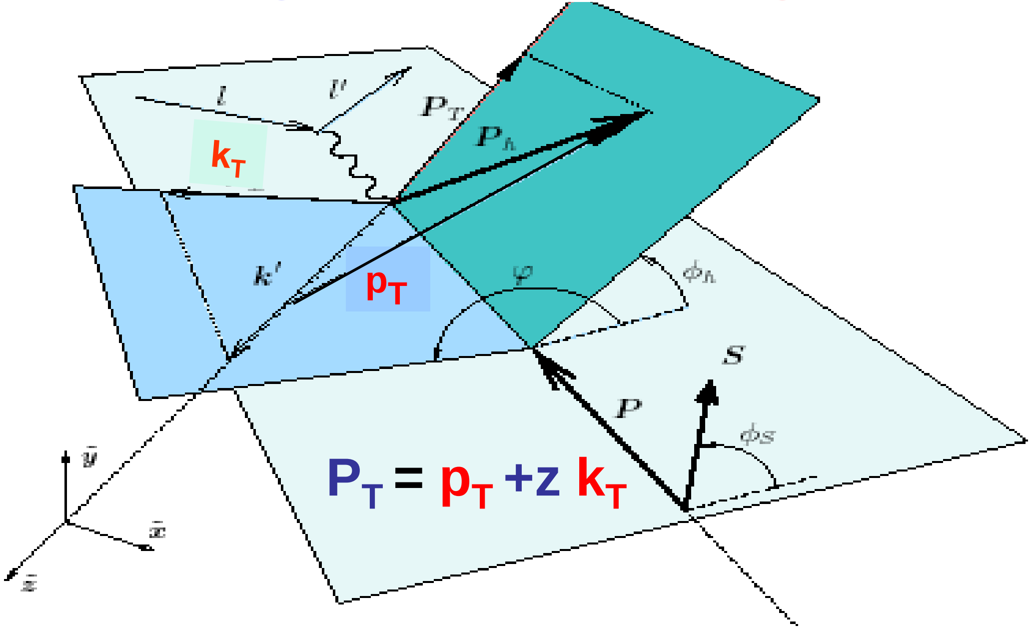
JLab 2015 Science & Technology review closeout bullets:

- develop an integrated picture of what measurements are necessary and will be conducted in determining the GPDs and TMDs
- develop milestones for extraction of GPDs and TMDs from experiment

SIDIS: partonic cross sections

$$\nu = (qP)/M$$
$$Q^2 = (k-k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

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



$P_T = p_T + z\, k_T$

Azimuthal moments in hadron production in SIDIS provide access to different structure functions and underlying transverse momentum dependent distribution and fragmentation functions.

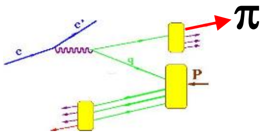
$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

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

beam polarization

target polarization

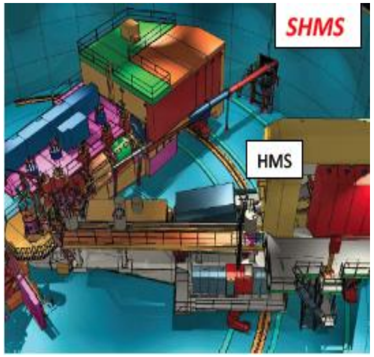
corrections for the region of large kT~Q

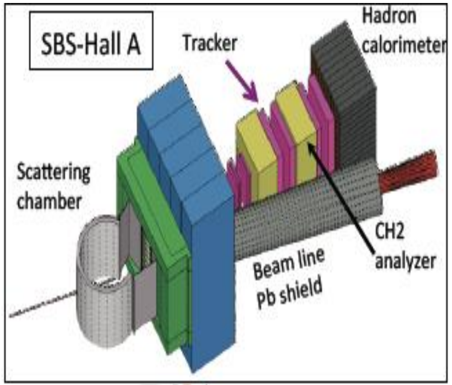


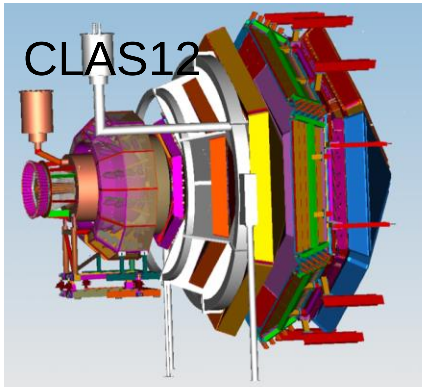
SIDIS at JLab12

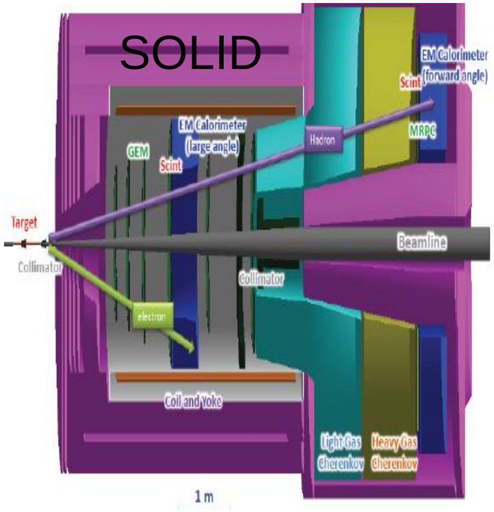
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

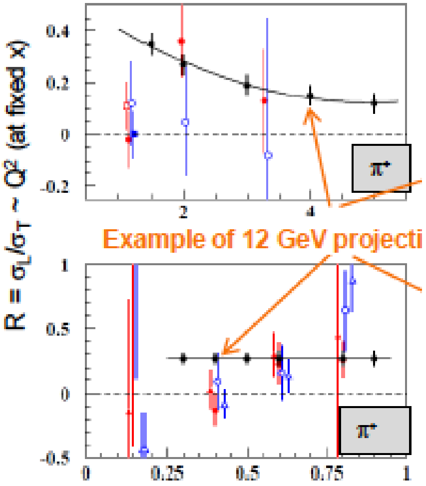
Complementary measurements with different targets

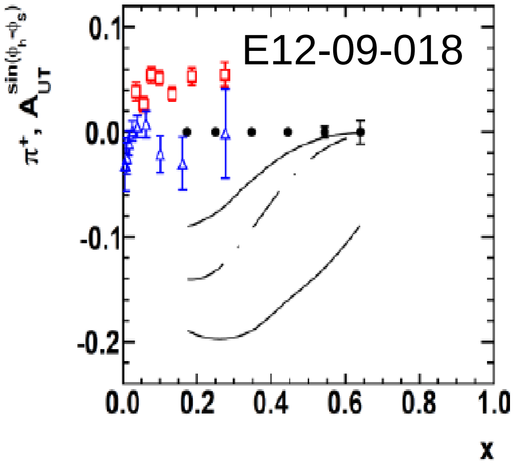


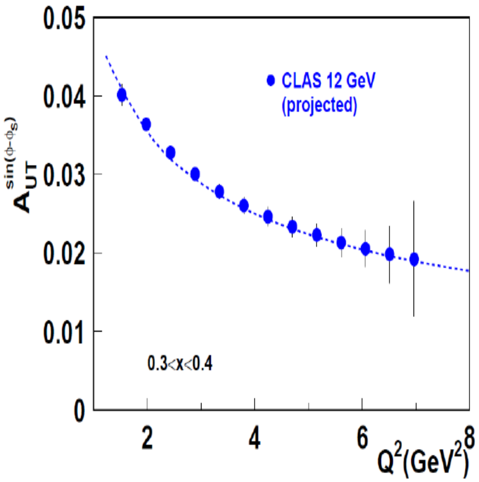


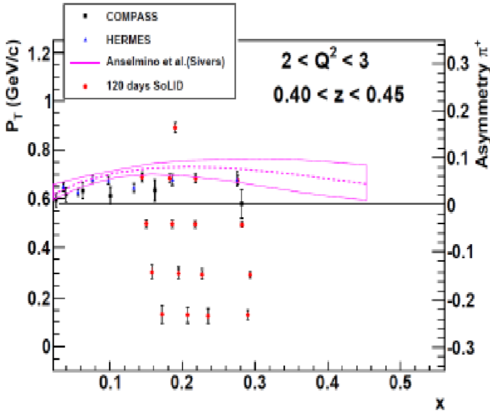






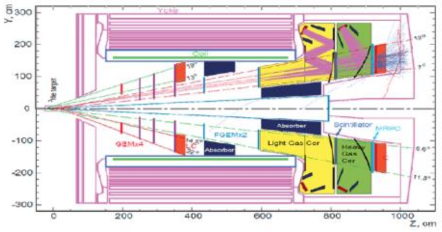






Combination of high resolution measurements from spectrometers combined with large acceptance data from CLAS12 and SOLID would allow to pin down all TMDs in the valence region

A_{UT} studies at JLab

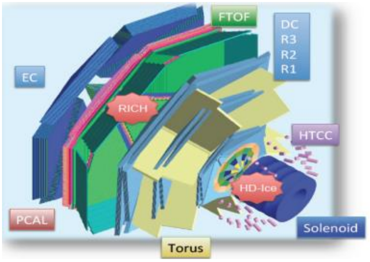


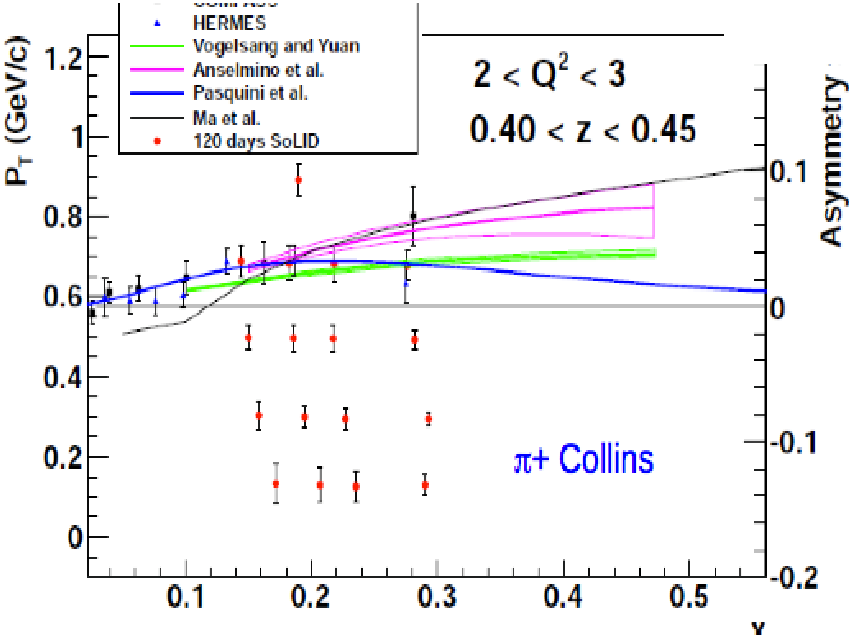
SOLID

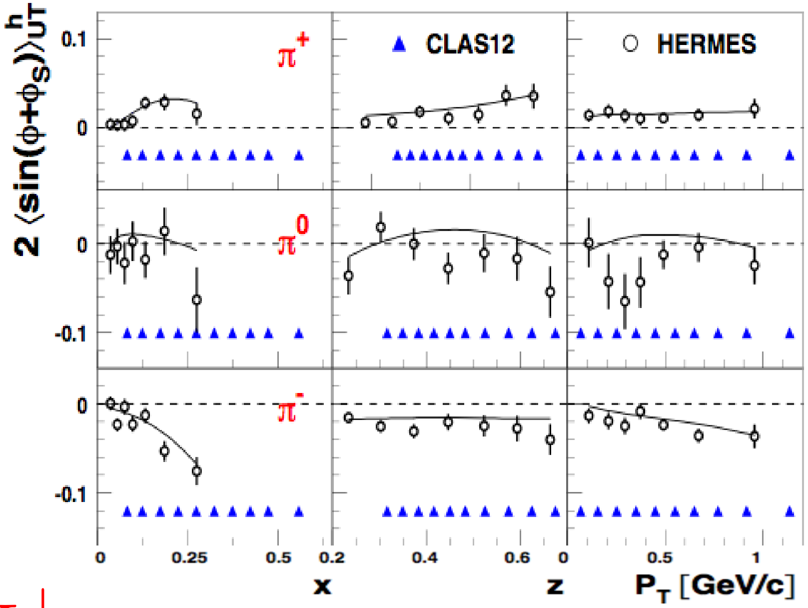
E12-11-108

CLAS12

C12-11-111



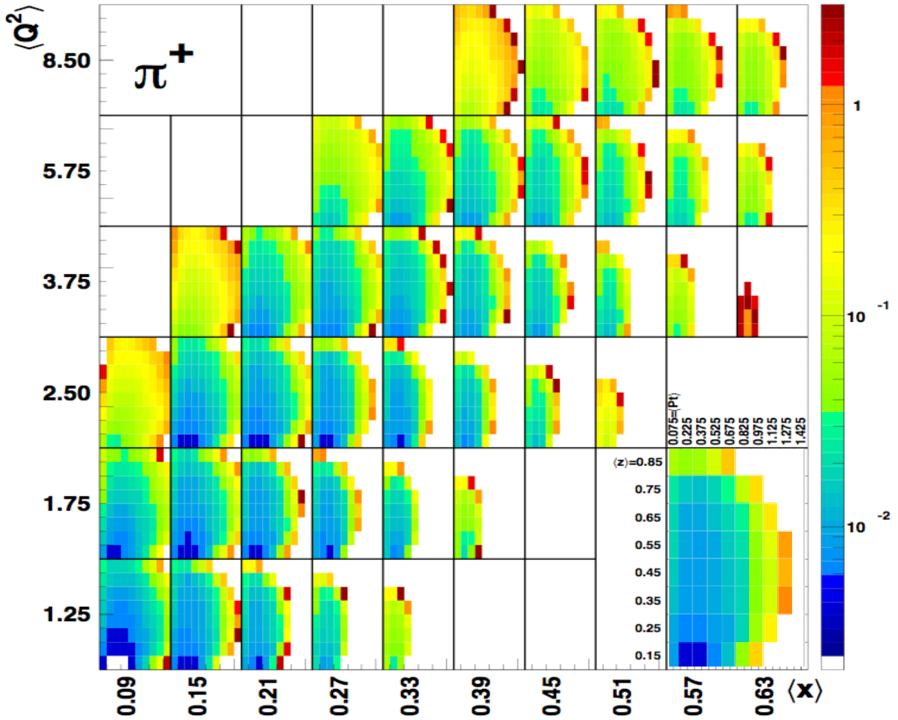


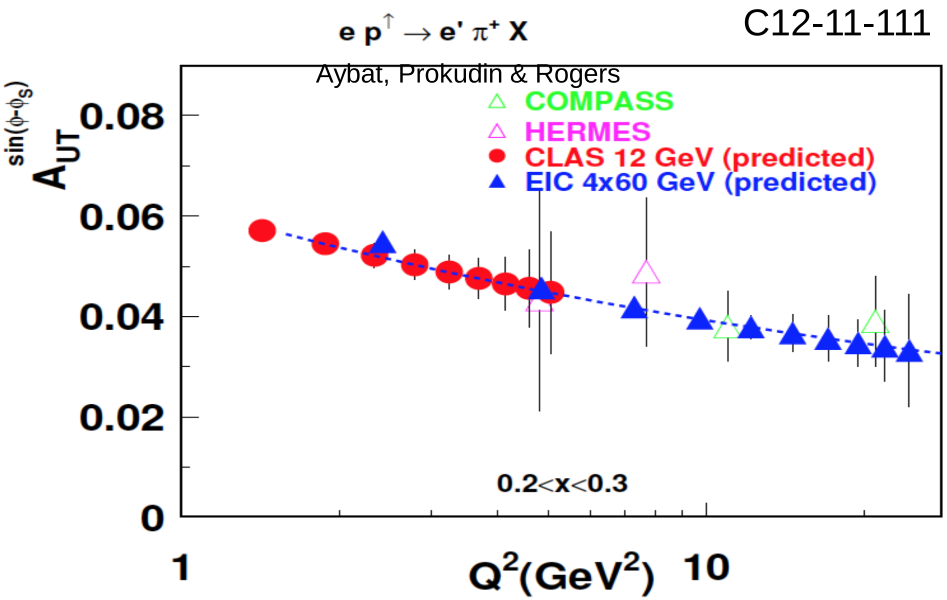


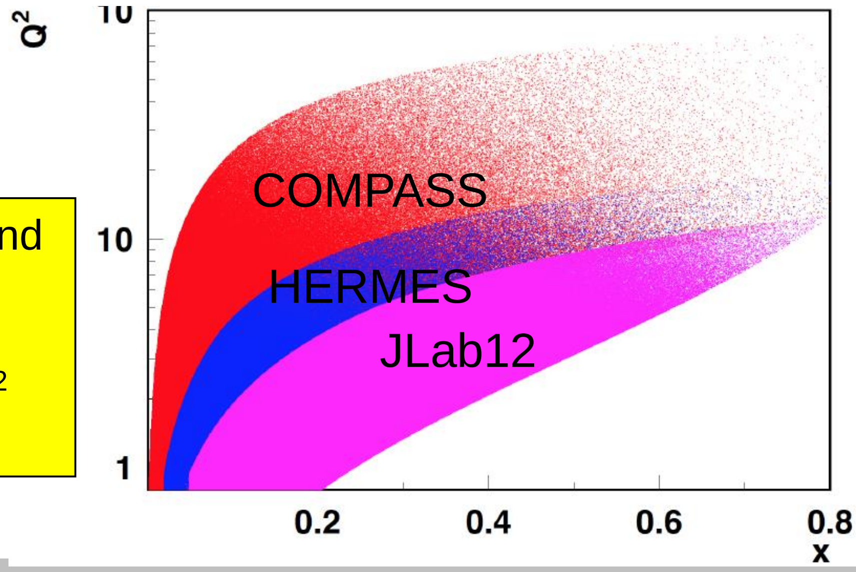
$$h_1 H_1^{\perp}$$

Precision 4-d mapping of Collins target SSA using SoLID and CLAS12

CLAS12 A_{UT} with transverse proton target







- 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 the non-trivial Q^2 evolution of Sivers asymmetry.

QCD fundamentals for TMD extraction

arXiv:1101.5057

TMD factorization: QCD at leading twist

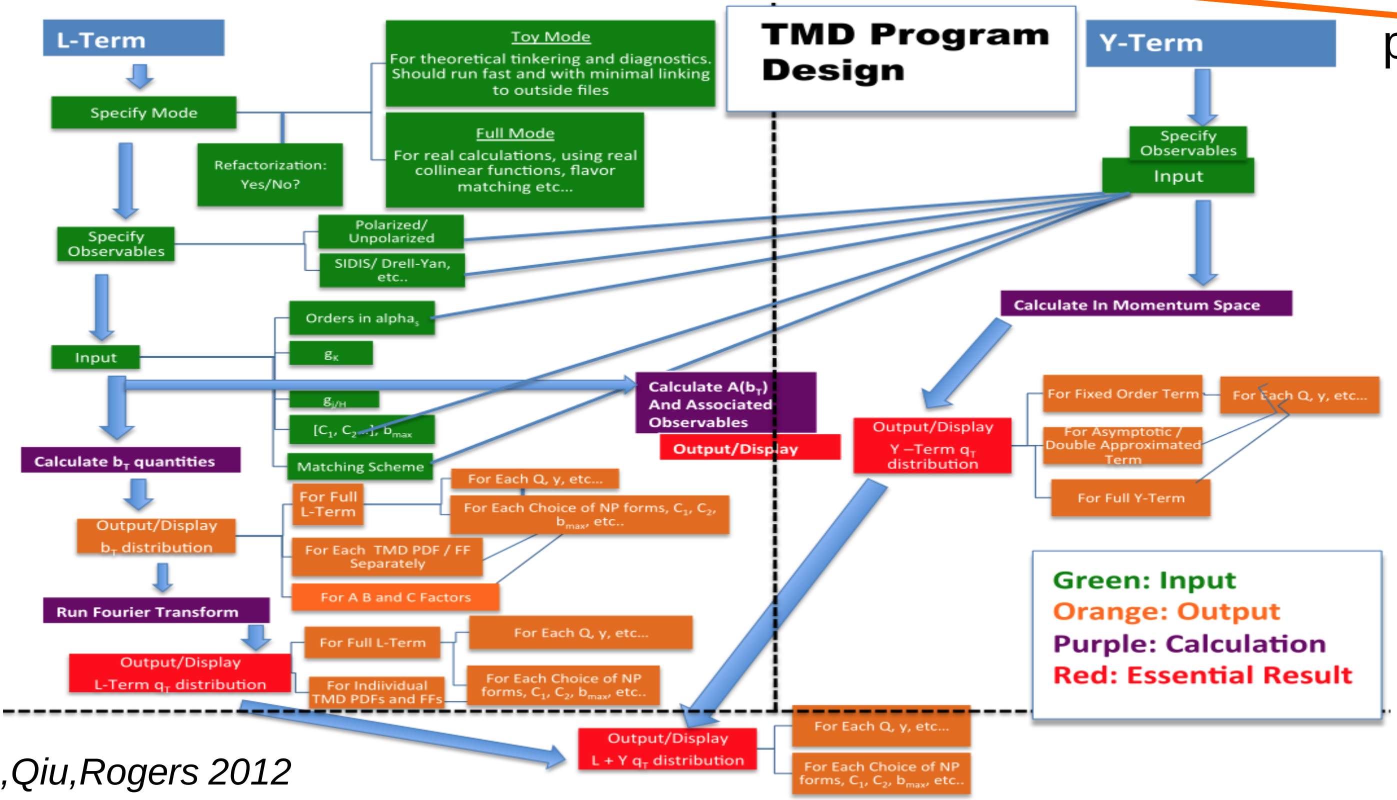
$$\tilde{F}_{f/P}(x, \mathbf{b}_T; \mu, \zeta_F) = \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x}, \mu_b)}^{\text{A}}$$

$$P_T \sim \Lambda_{QCD} \ll Q, \quad \Lambda_{QCD} \ll P_T \ll Q, \quad P_T \sim Q, \text{ and } P_T > Q.$$

$$\times \overbrace{\exp\left\{ \ln\frac{\sqrt{\zeta_F}}{\mu_b}\tilde{K}(b_*;\mu_b) + \int_{\mu_b}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu');1) - \ln\frac{\sqrt{\zeta_F}}{\mu'}\gamma_K(g(\mu'))\right]\right\}}^{\text{B}} \times \overbrace{\exp\left\{\boxed{g_{j/P}(x,b_T)} + g_K(b_T)\ln\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\}}^{\text{C}}$$

T.Rogers(JLab)

parameterize



TMD Program Design

L-Term

Specify Mode

Refactorization: Yes/No?

Toy Mode
For theoretical tinkering and diagnostics. Should run fast and with minimal linking to outside files

Full Mode
For real calculations, using real collinear functions, flavor matching etc...

Specify Observables

Polarized/ Unpolarized

SIDIS/ Drell-Yan, etc..

Input

Orders in alpha$_s$

g_K

$g_{j/H}$

$[C_1, C_2 \ldots], b_{max}$

Matching Scheme

Calculate A(b_T) And Associated Observables

Output/Display

Calculate b_T quantities

Output/Display b_T distribution

For Full L-Term

For Each Q, y, etc...

For Each Choice of NP forms, C_1, C_2, b_{max}, etc..

For Each TMD PDF / FF Separately

For A B and C Factors

Run Fourier Transform

Output/Display L-Term q_T distribution

For Full L-Term

For Each Q, y, etc...

For Indiividual TMD PDFs and FFs

For Each Choice of NP forms, C_1, C_2, b_{max}, etc..

Output/Display L + Y q_T distribution

For Each Q, y, etc...

For Each Choice of NP forms, C_1, C_2, b_{max}, etc..

Y-Term

Specify Observables

Input

Calculate In Momentum Space

Output/Display Y –Term q_T distribution

For Fixed Order Term

For Each Q, y, etc...

For Asymptotic / Double Approximated Term

For Full Y-Term

Green: Input
Orange: Output
Purple: Calculation
Red: Essential Result

Aybat,Collins,Qiu,Rogers 2012
Collins&Rogers 2015

Goals and requirements

The unambiguous interpretation of any SIDIS experiment (JLab in particular) in terms of leading twist transverse momentum distributions (TMDs) requires understanding of evolution properties and large k_T corrections(Y-term), control of various subleading $1/Q^2$ corrections, radiative corrections, knowledge of involved transverse momentum dependent fragmentation functions, understanding of hadronic backgrounds not originating from current quarks.

- Leading twist QCD fundamentals (Y-term, matching at large P_T..)
- higher twist effects
- TMD fragmentation functions
- target fragmentation correlations with current fragmentation

- Finite energies, finite phase space (target and hadron mass corrections,..)
- radiative corrections including the full list of structure functions

Understanding of relative scales, sizes and kinematic dependences of different contributions is crucial for estimate of extraction systematic errors (theory and experiment)

Analysis framework

- Differential input (SIDIS):

bin#	x	Q^2	y	W	M_X	ϕ	z	P_T	λ	Λ	N(counts)	RC
1 … N												

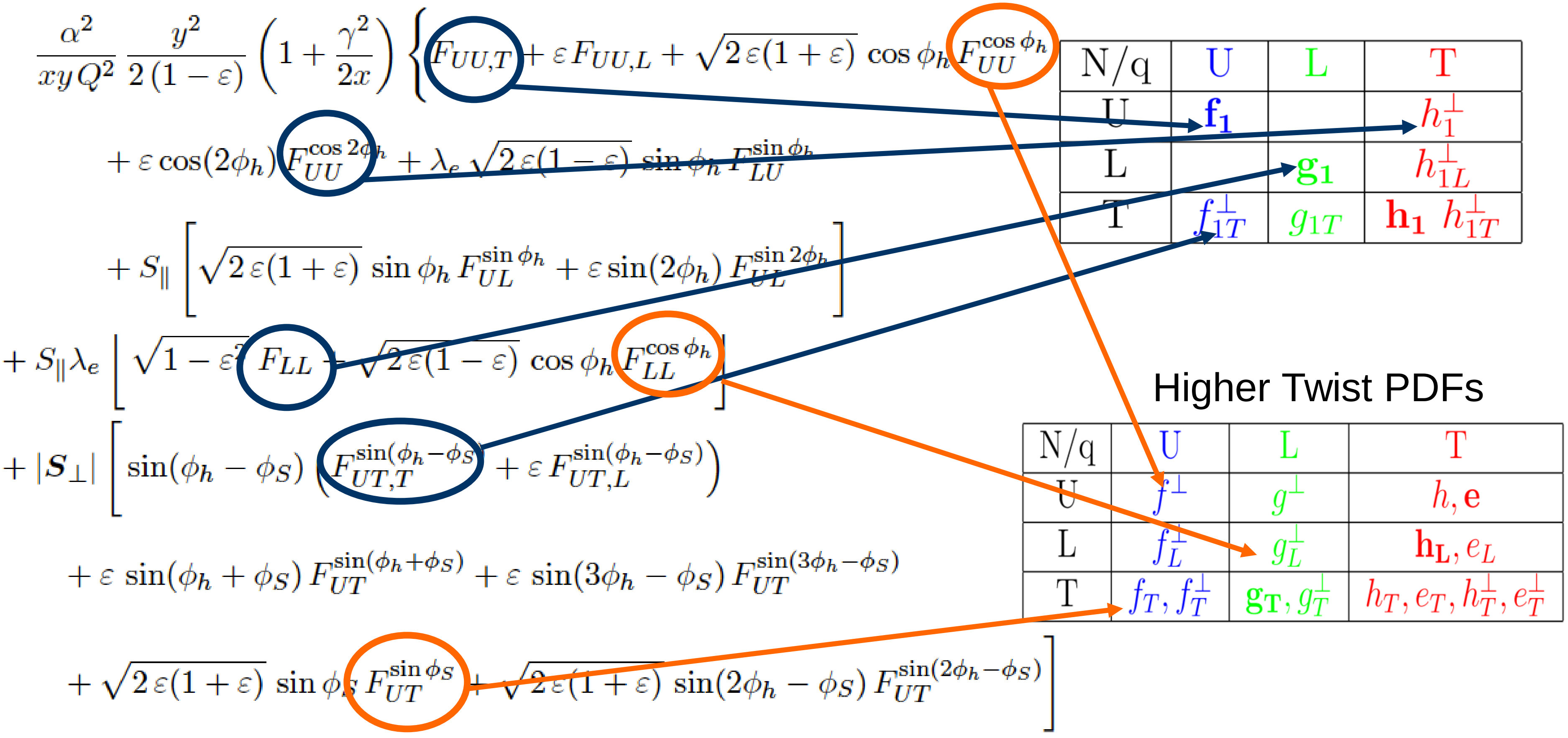
M. Aghasyan et al arXiv:1409.0487 (JHEP)

- Differential input (HEMP):

bin#	x	Q^2	y	W	M_X	ϕ	t		λ	Λ	N(counts)	RC
1 … N												

•Need a TMD/GPD extraction framework to define the needed precision of input data
•Framework for the multidimensional experimental observables should allow validation (extracting TMDs from input MC).
•Define all the data from other experiments which may be needed (data preservation)

Azimuthal moments in SIDIS



$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\quad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

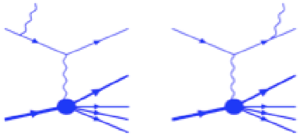
quark polarization

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

Higher Twist PDFs

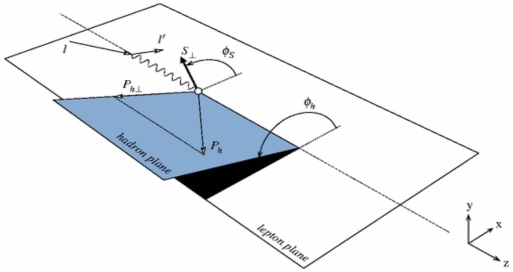
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

Experiment for a given target polarization measures all moments simultaneously



QED radiative corrections in SSA

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



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

$$\sigma_{XY}^{h}(x,z,P_T) \to \sigma_{XY}^{B,h}(x,z,P_T) \times R(x,z,P_T,\phi_h) + \sigma_{XY}^{R,h}(\dots).$$

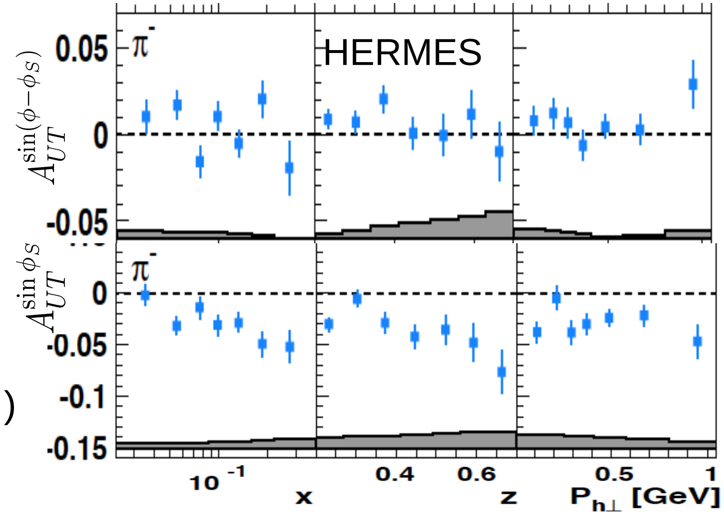
using a simple approximation

$$R(x,z,P_T,\phi) = f_{XY}(x,z,P_T) * (1 + a_{XY} * cos\phi + ...)$$

we can get correction factors to moments (ex. for RC for $\sigma_{UT}^{\cos\phi}$)

we can get new moments

In reality contributions will me more complicated



$$\sigma_{UU} -> \sigma_{UU} + 1/2\sigma_{UU}^{\cos\phi} f_{UU} a_{UU}$$

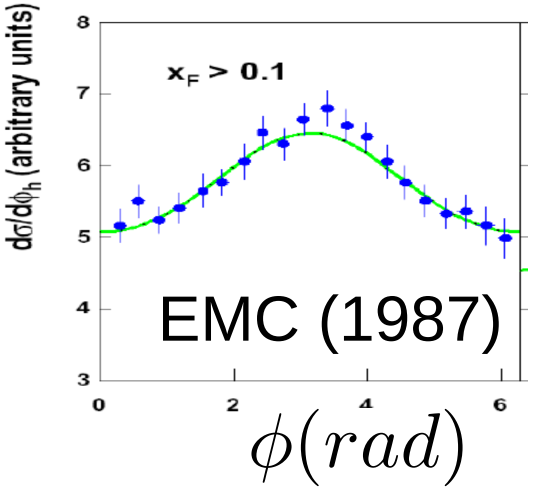
$$\sigma_{UT}^{\sin(\phi-\phi_S)} = 1/2\sigma_{UT}^{\sin\phi_S} f_{UT} a_{UT}$$

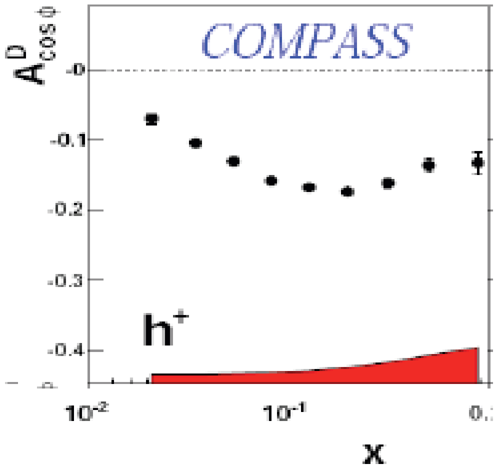
Due to radiative corrections, ϕ-dependence of x-section will get more contributions
- Some moments will modify
- New moments may appear, which were suppressed before in the x-section

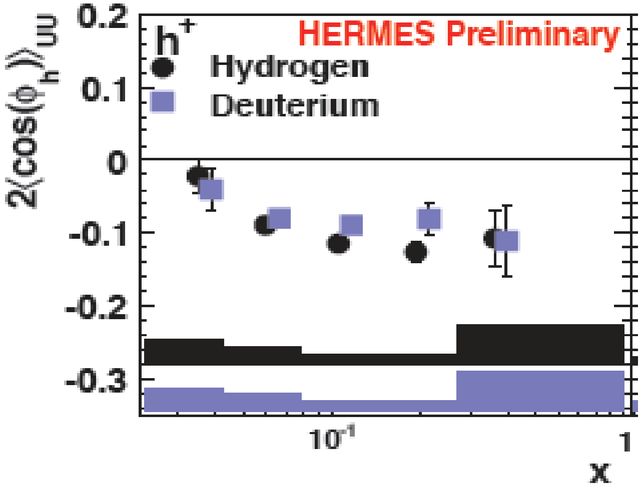
Higher twists in azimuthal distributions in SIDIS

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

HT







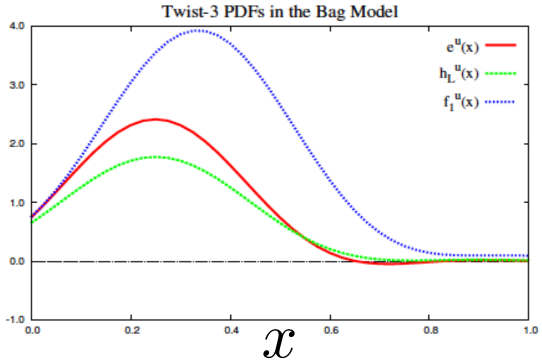
Large cosϕ modulations observed by EMC were reproduced in electroproduction of hadrons in SIDIS with unpolarized targets at COMPASS and HERMES

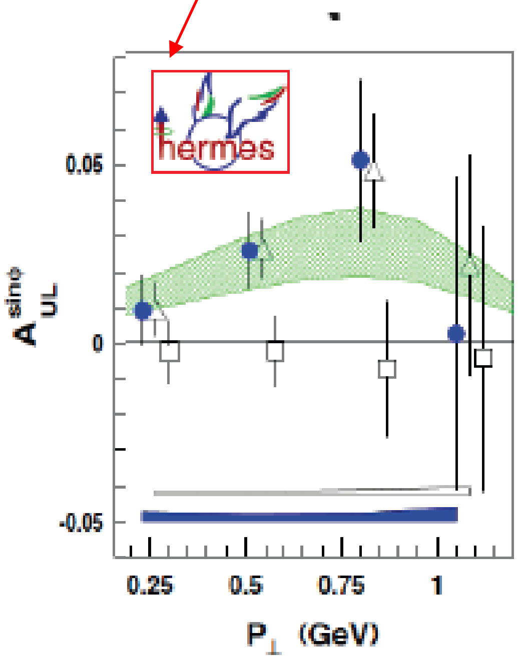
Quark-gluon correlations: Models vs Lattice

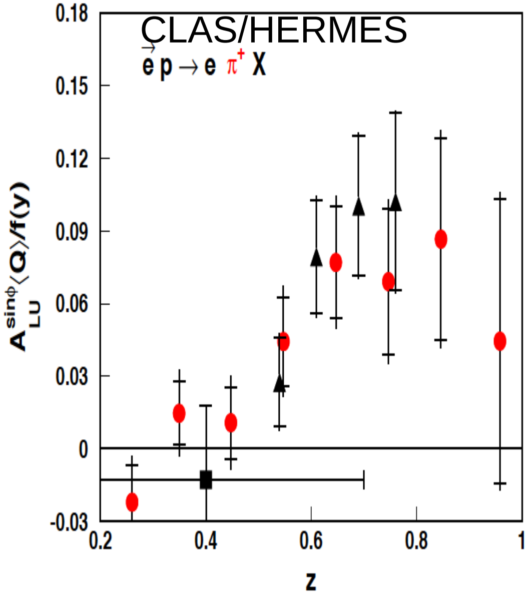
N/q	U	L	T
U			e
L			h_L
T		g_T	

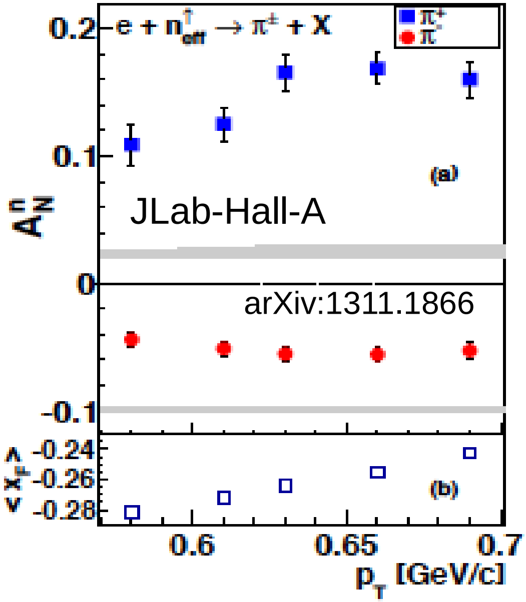
$$e_2 \equiv \int_0^1 dx x^2 \bar{e}(x)$$

Force on the active quark right after scattering (Burkardt)


Twist-3 PDFs in the Bag Model




CLAS/HERMES

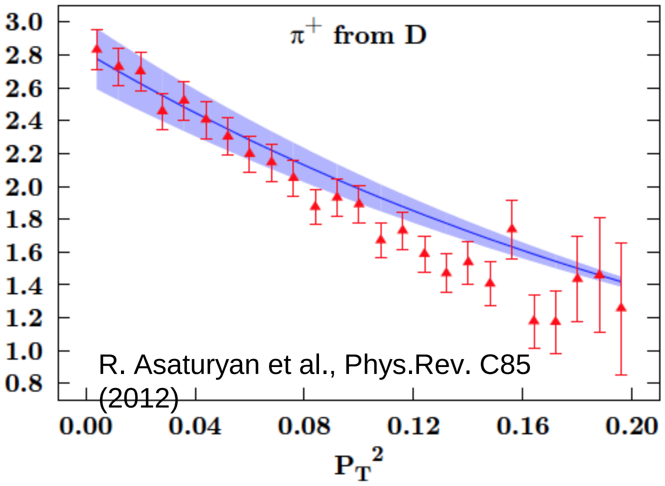

JLab-Hall-A

arXiv:1311.1866

- Significant longitudinal target SSA measured at JLab and HERMES may be related to HT and color forces
- Large transverse spin asymmetries observed in inclusive pion production (Hall-A, HERMES)
- Models and lattice agree on a large e/f1 -> large beam SSA

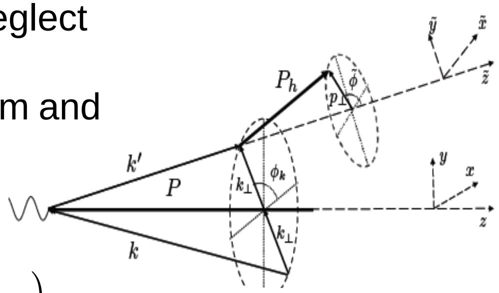
Finite phase space (including target, hadron mass) corrections

M. Anselmino et al., JHEP 1404 (2014)



R. Asaturyan et al., Phys.Rev. C85 (2012)

In real life (also MC) one can’t neglect nucleon mass, hadron mass and transverse momentum, momentum and baryon number conservation



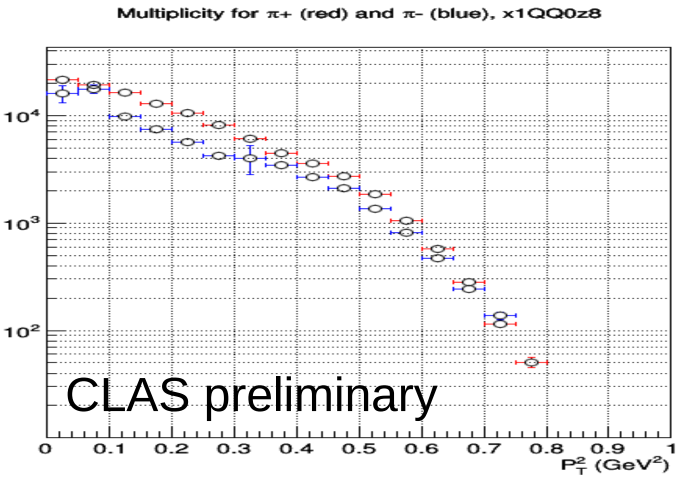
$$f^q(x,k_T,..) \otimes D^{q\to\pi^+}(z,p_T,..)$$

$$\downarrow$$

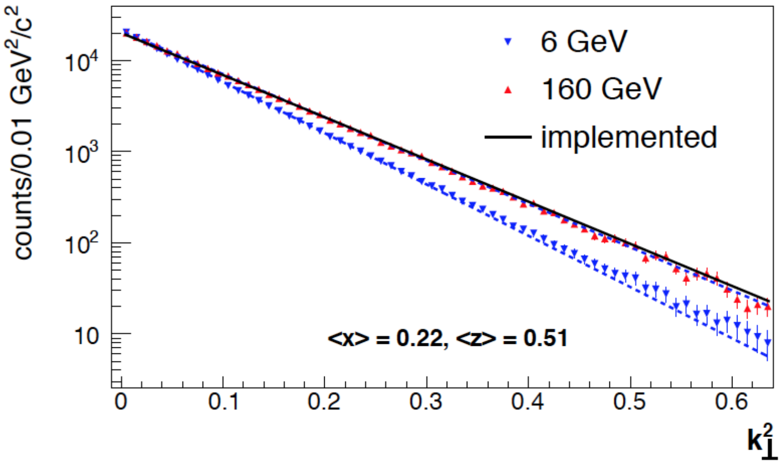
$$f^q(\xi,k_T,..) \otimes D^{q\to\pi^+}(\zeta,p_T,..)$$

$$\xi = \frac{2x_B}{1+\sqrt{1+4x_B^2M^2/Q^2}},$$

$$z_h = \frac{P_h\cdot p}{q\cdot p} = \frac{x_B}{\xi}\left(\zeta_h + \frac{\xi^2}{\zeta_h}\frac{M^2 m_{h\perp}^2}{Q^4}\right)$$



CLAS preliminary

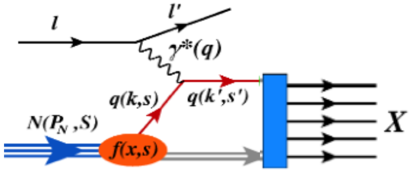


Phase space at low beam energies limits high P_T

MC: Aghasyan et al, JHEP 1503 (2015) 039

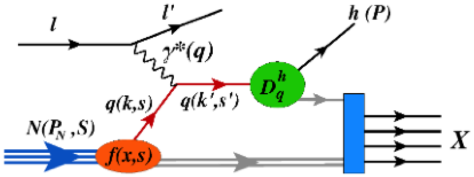
QCD: from testing to understanding

0h DIS



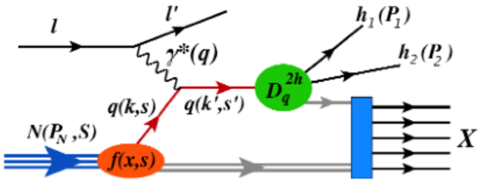
Testing stage:
pQCD predictions, observables in the kinematics where theory predictions are easier to get (higher energies, 1D picture, leading twist, current fragmentation, IMF)

1h SIDIS/DVMP

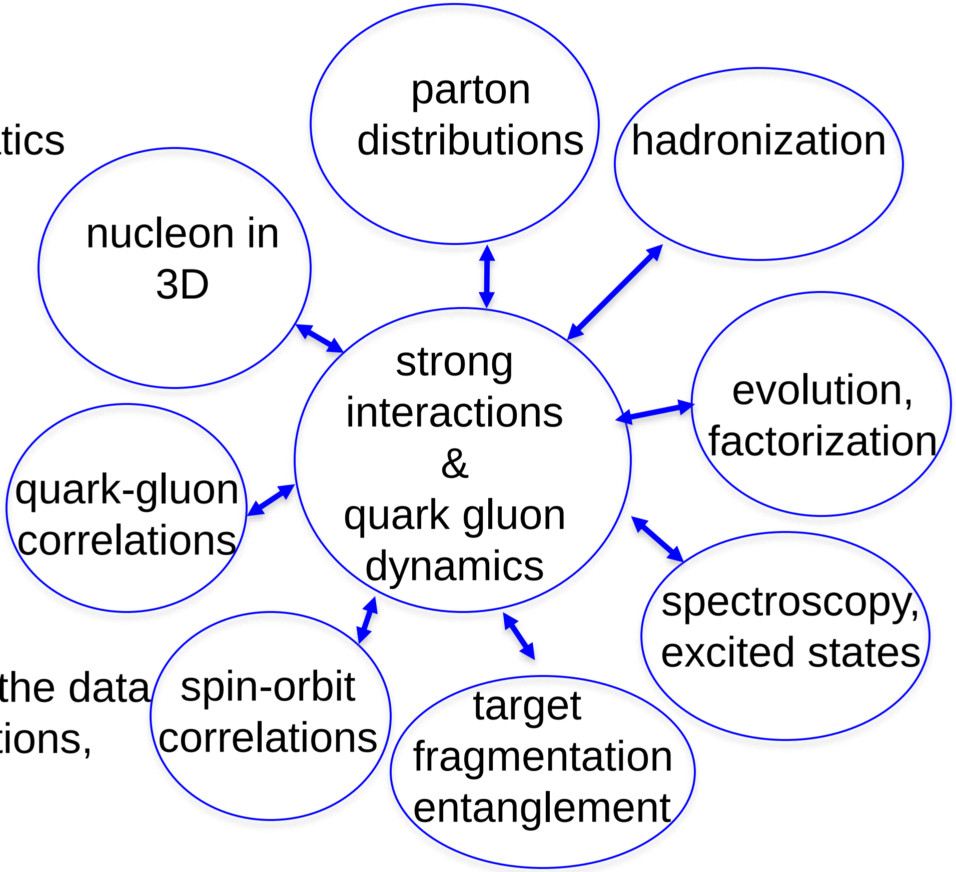


Understanding stage:
non-perturbative QCD, strong interactions, observables in the kinematics where most of the data is available (all energies, quark-gluon correlations, orbital motion)

2h SIDIS/DVMP



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



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

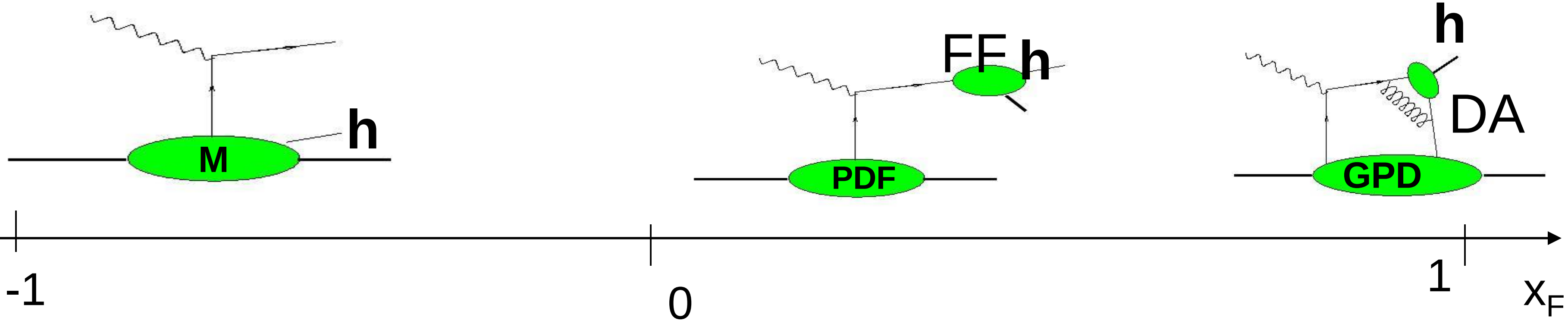
Leading Twist Generalized PDFs

Target fragmentation

Current fragmentation

semi-inclusive

exclusive



Fracture Functions

k_T-dependent PDFs

Generalized PDFs

	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	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

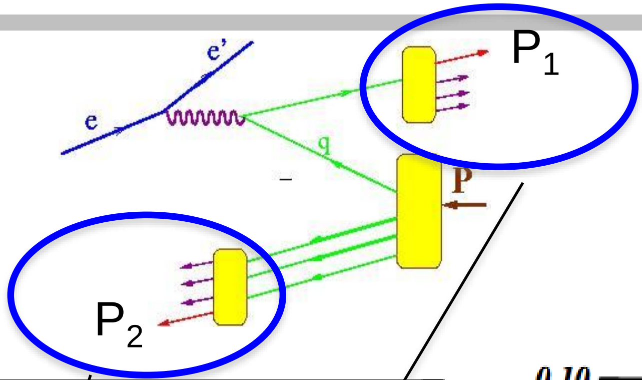
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

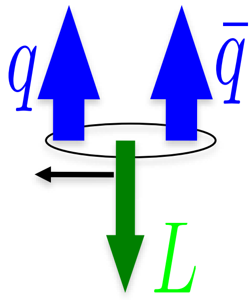
	U	L	T
U	$\mathcal{H}$		$\mathcal{E}_T$
L		$\widetilde{\mathcal{H}}$	$\widetilde{\mathcal{E}}_T$
T	$\mathcal{E}$	$\widetilde{\mathcal{E}}$	$\mathcal{H}_T, \widetilde{\mathcal{H}}_T$

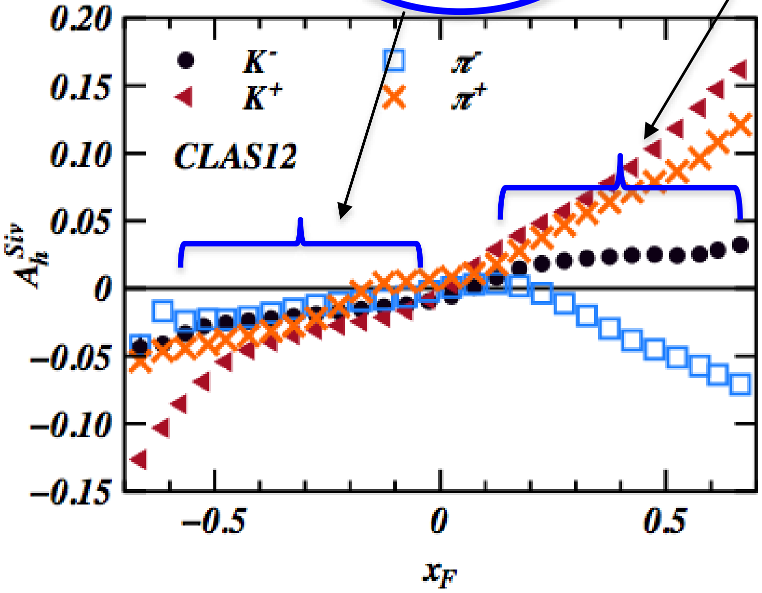
Large acceptance detectors would allow simultaneous measurements in full x_F-range, including target and current regions of SIDIS and exclusive processes.

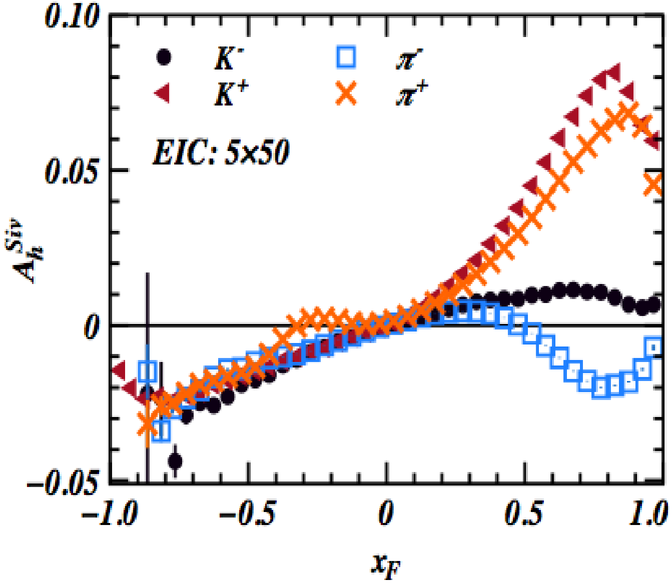
Sivers effect in the target fragmentation

H. Matevosyan et al.
arXiv:1502.02669







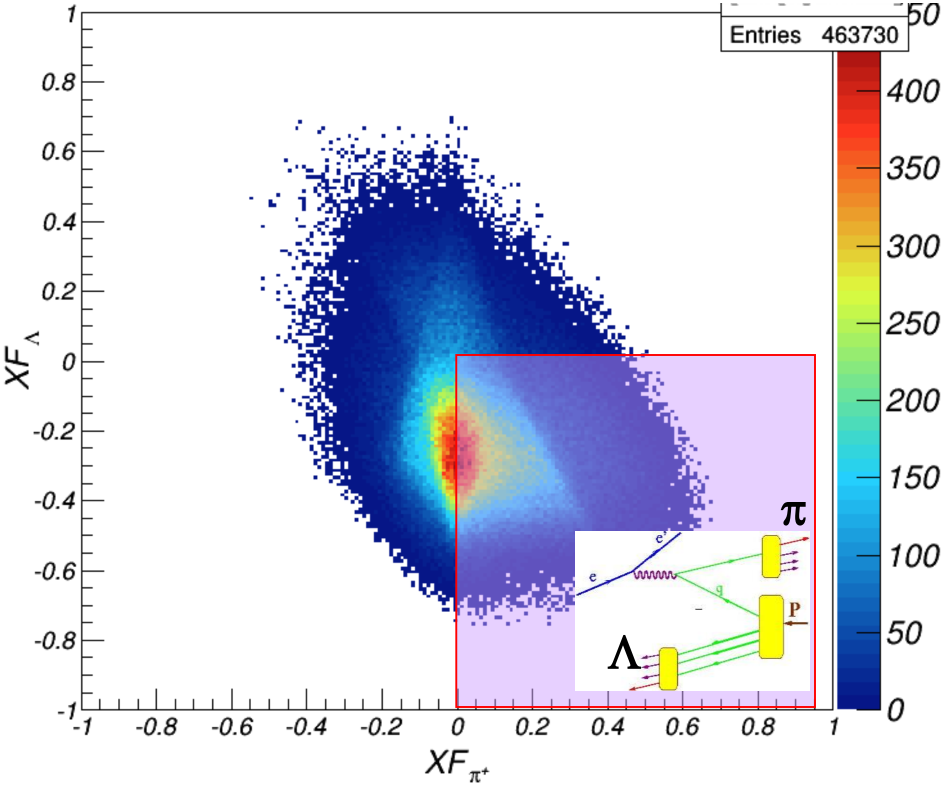


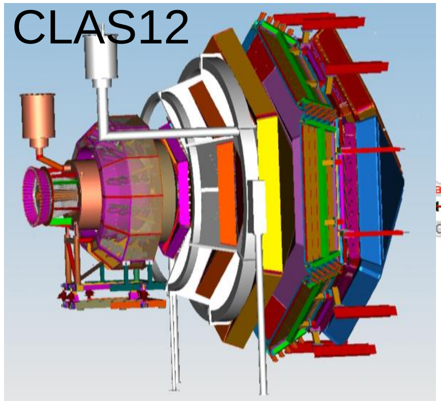
Wide coverage of CLAS12 and EIC will allow studies of kinematic dependences of the Sivers effect, both in current and target fragmentation regions

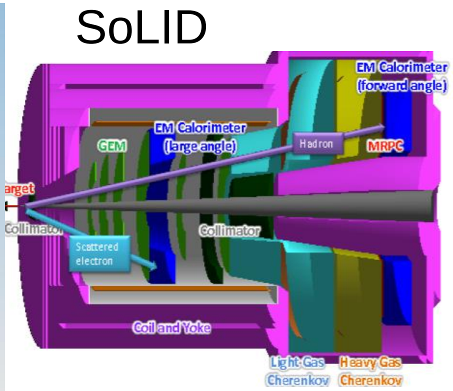
Dihadron production at JLAB12

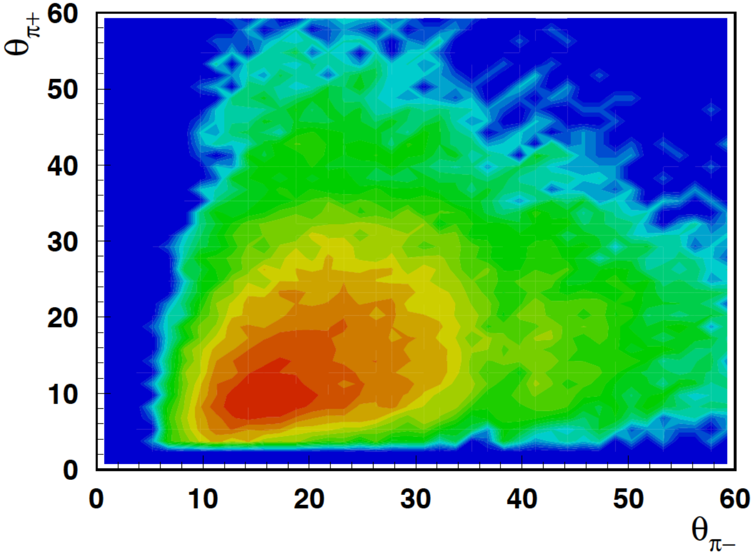
Use the clasDIS (LUND based) generator + FASTMC to study hh pairs

x_F - momentum in the CM frame





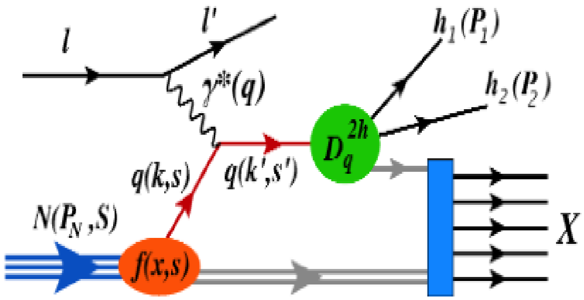


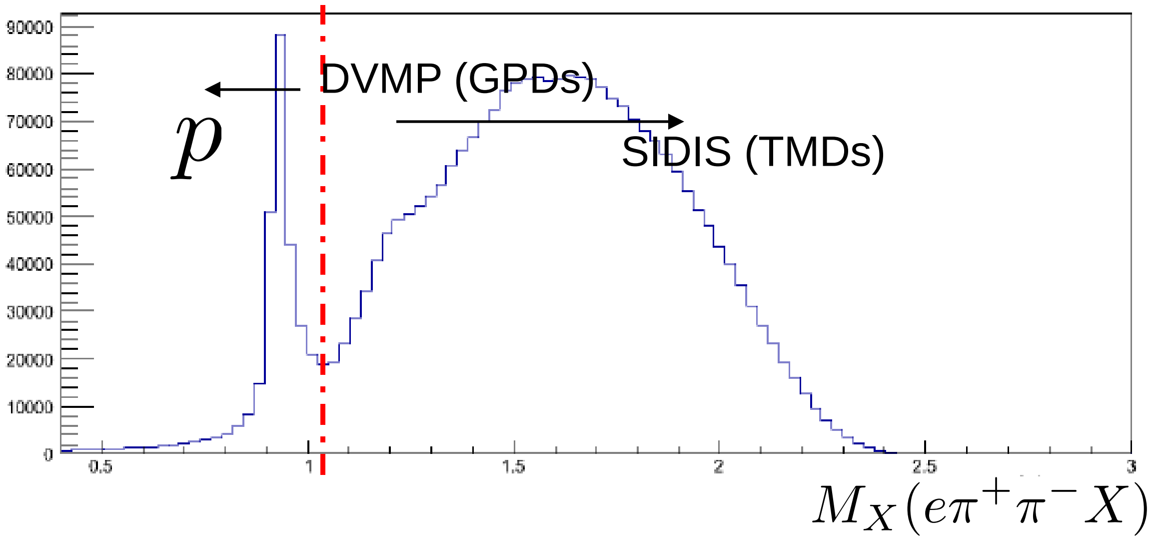


Dihadron sample defined by SIDIS cuts + $x_F>0$ (CFR) and $x_F<0$ (TFR) for both hadrons

Wide angular coverage is important

Dihadron asymmetries from CLAS





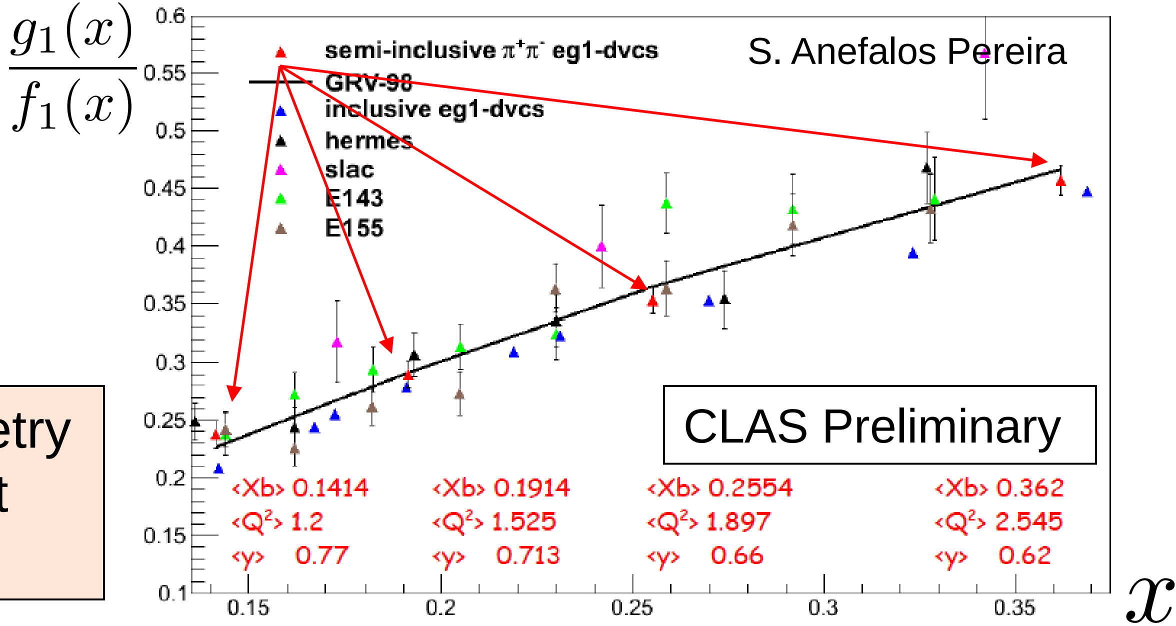
$$\frac{F_{LL}}{F_{UU}} \sim \frac{g_1(x)}{f_1(x)}$$

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

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

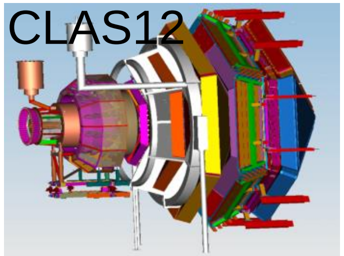
$$D_1^{u\to\pi+\pi-} \approx D_1^{d\to\pi+\pi-}$$

Dihadron double spin asymmetry measured at 6 GeV consistent with DIS



Accessing transversity in dihadron production at JLab

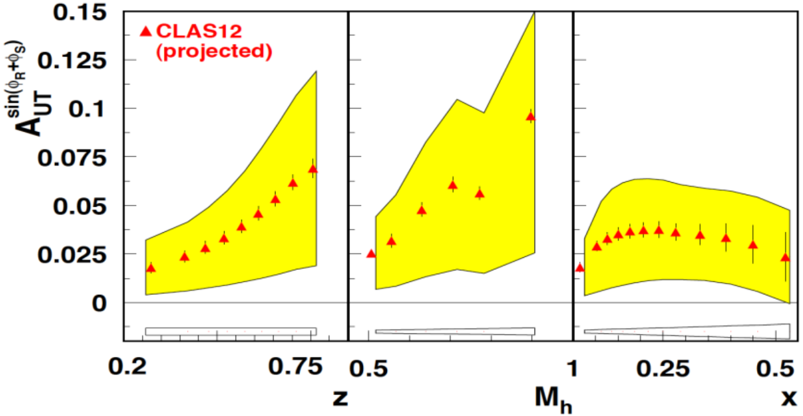
Measurements with polarized protons

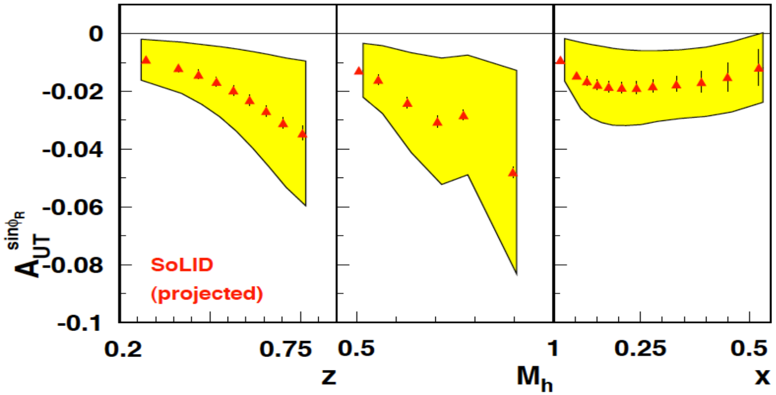

CLAS12

Measurements with polarized neutrons


SoLID

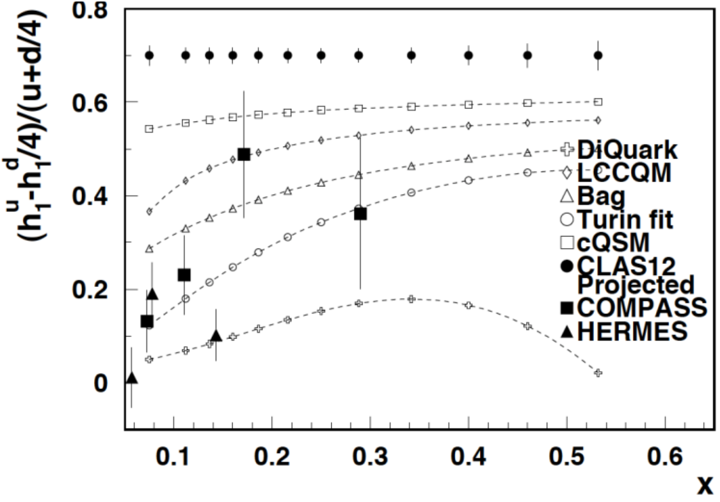
$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$





Bacchetta, Radici

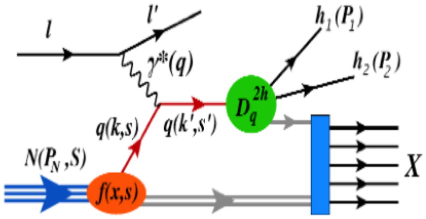
$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$



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

Accessing Sivers TMD in dihadron production at JLab

A. Kotzinian, H. H. Matevosyan, and A. W. Thomas,
Phys.Rev.Lett. 113, 062003 (2014), 1403.5562.



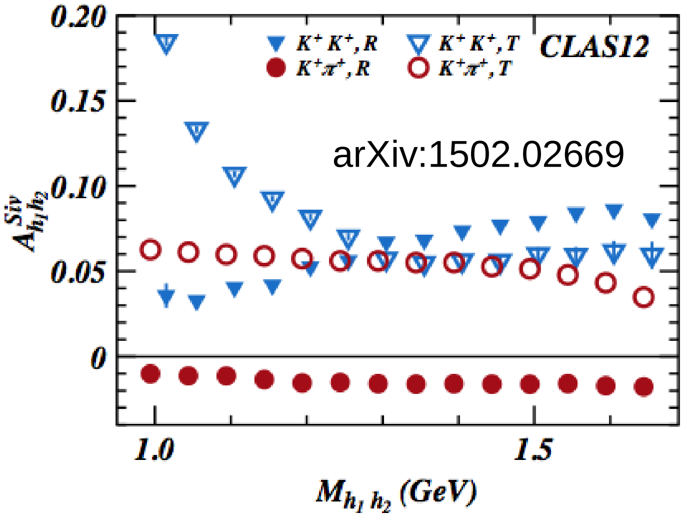
$$\frac{d\sigma^{h_1 h_2}}{dx\, dQ^2\, d\varphi_S\, dz_1\, dz_2\, d^2P_{1T}\, d^2P_{2T}} = C(x,Q^2)\,(\sigma_U + \sigma_S)$$

$$\sigma_2 \frac{P_{2T}}{M} \sin(\varphi_2 - \varphi_S) \qquad \sigma_1 \frac{P_{1T}}{M} \sin(\varphi_1 - \varphi_S)$$

where σ_S, σ_1 and σ_2 depend on $x, Q^2, z_1, z_2, P_{1T}, P_{2T}$ and $P_{1T} \cdot P_{2T}$ (or $\cos(\varphi_1 - \varphi_2)$).

$$\boldsymbol{P}_T = \boldsymbol{P}_\perp + z\boldsymbol{k}_T, \quad \boldsymbol{R}_T = \boldsymbol{R}_\perp + \frac{1}{2}(z_1 - z_2)\,\boldsymbol{k}_T$$

$\sigma_R \neq 0$ can be ensured, by choosing asymmetric cuts on the minimum values of **z**1 and **z**2.



arXiv:1502.02669

Proposal for PAC44

After integration over the azimuthal angle of total transverse momentum

$$P_T = P_{1T} + P_{2T}$$

The asymmetry as a function of transverse momentum

$$R = \frac{1}{2}(P_{1T} - P_{2T})$$

$$\frac{d\sigma^{h_1 h_2}}{P_T dP_T d^2 R} = C(x,Q^2)\left[\sigma_{U,} + S_T\left(\frac{P_T}{2M}\sigma_{T,1} + \frac{R}{M}\sigma_{R,0}\right)\sin(\varphi_R - \varphi_S)\right]$$

1st harmonic of the cos(ϕ_T-ϕ_R)

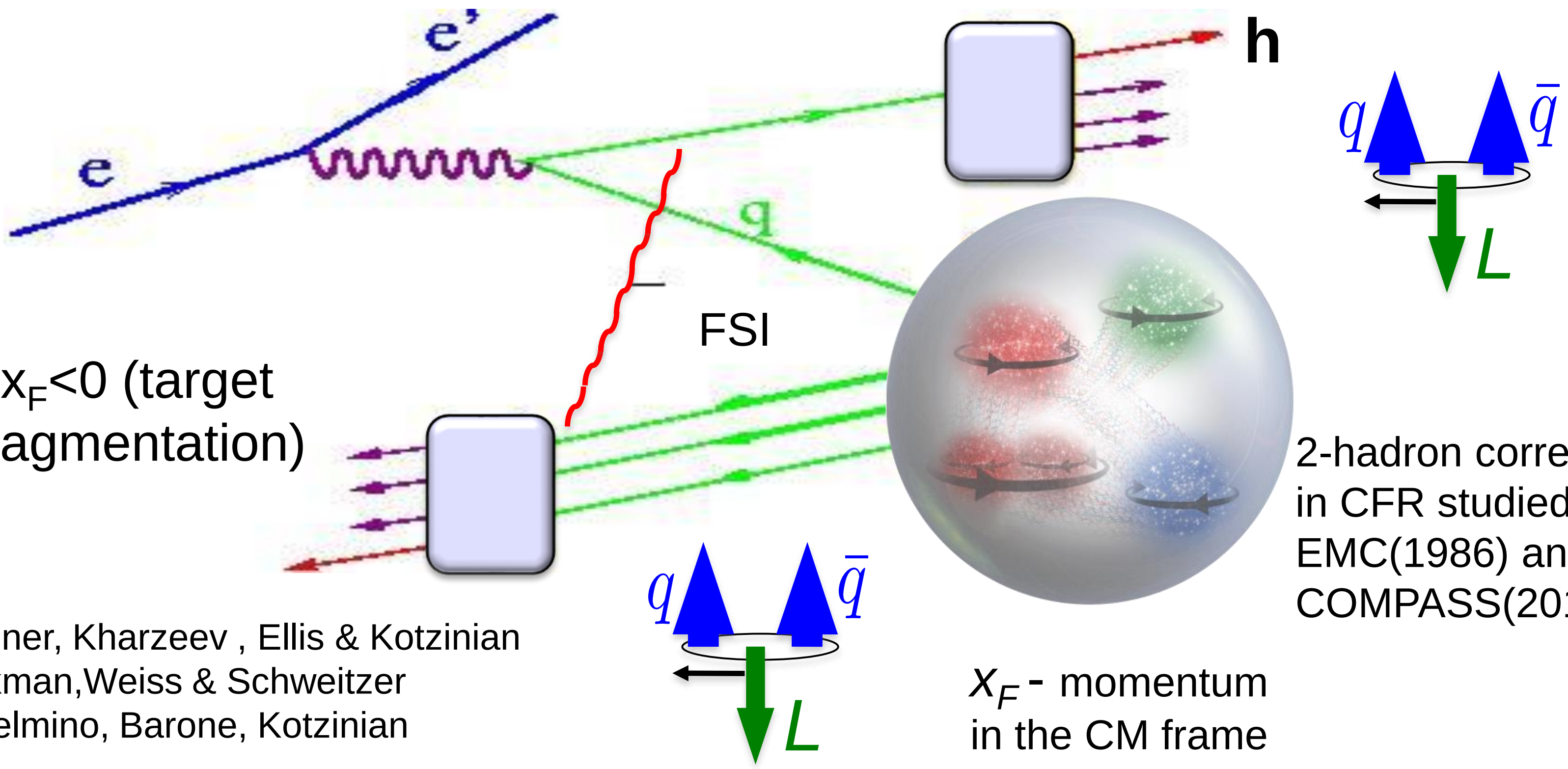
$$\sigma_T = \frac{1}{2}(\sigma_1 + \sigma_2),\ \sigma_R = \sigma_1 - \sigma_2.$$

- Measurements with polarized protons @ CLAS12
- Measurements with polarized neutrons @SOLID
- Measurements with EIC

Hadron production in hard scattering

$x_F>0$ (current fragmentation)

X. Artru & Z. Belghobsi



$x_F<0$ (target fragmentation)

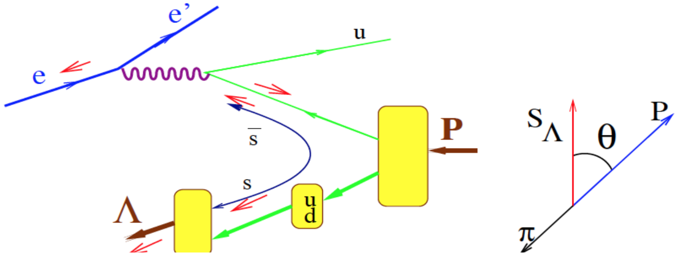
Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

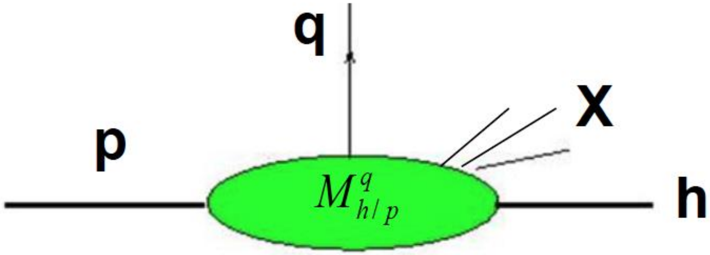
2-hadron correlations in CFR studied in EMC(1986) and COMPASS(2015)

x_F - momentum in the CM frame

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles

Target fragmentation region: Λ production





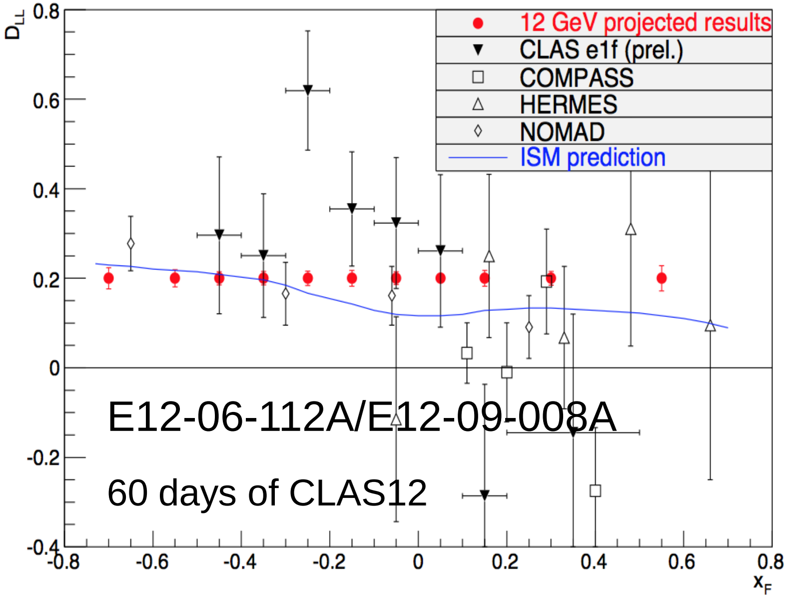
probability to produce the hadron h when a quark q is struck in a proton target

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

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

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

polarization transfer coefficient

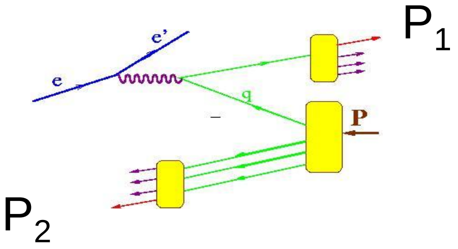


E12-06-112A/E12-09-008A

60 days of CLAS12

- 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.

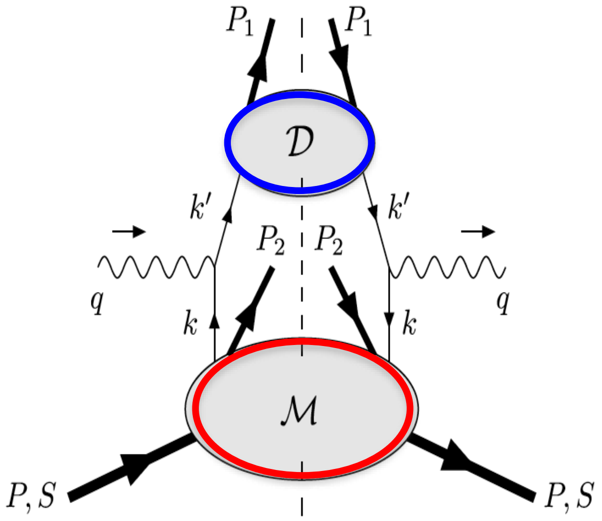
Back-to-back hadron (b2b) production in SIDIS



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

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

	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.

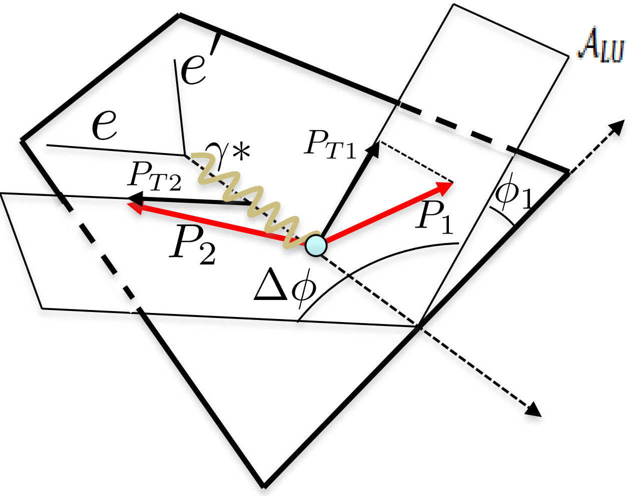
$$\mathcal{A}_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

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

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)
- ...

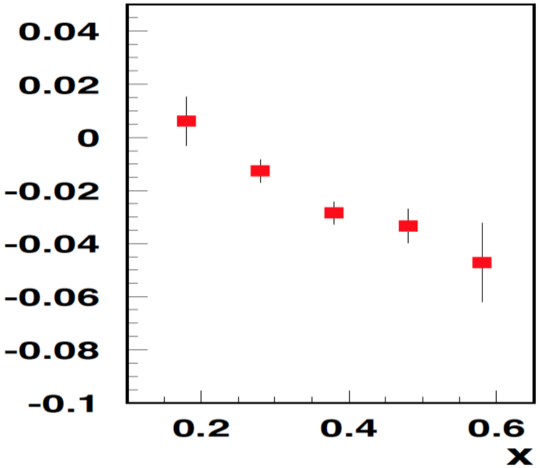
B2B hadron production in SIDIS: First measurements

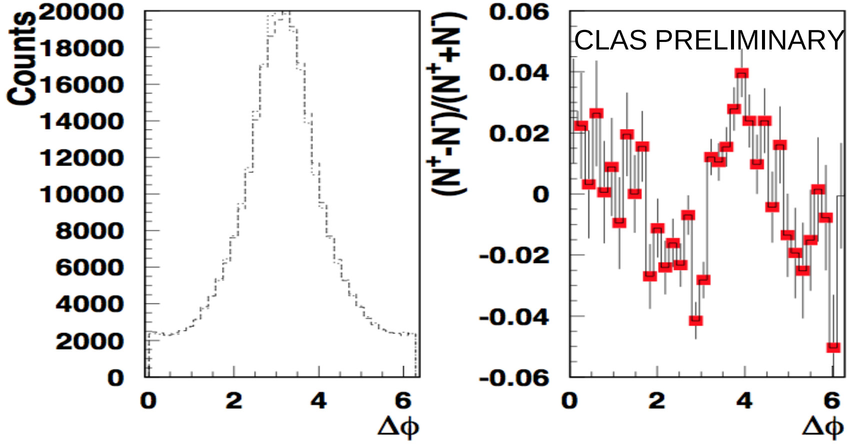
M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

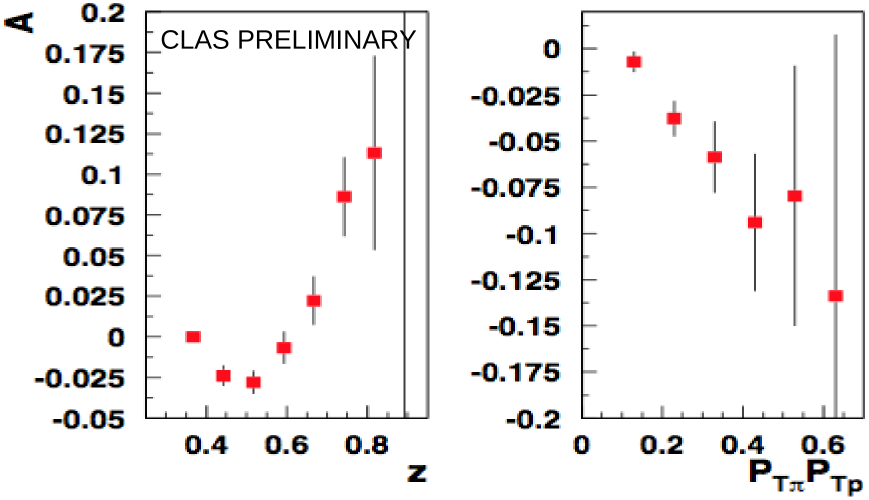


$$A_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\,\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\,\sin\Delta\phi$$

$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\,\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\,\frac{\mathcal{C}[w_5 M_L^{\perp,h} D_1]}{\mathcal{C}[MD_1]}\,\sin\Delta\phi$$

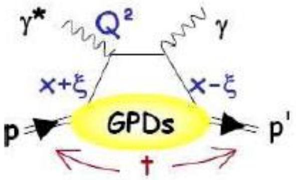






Significant asymmetries observed by CLAS at 6 GeV

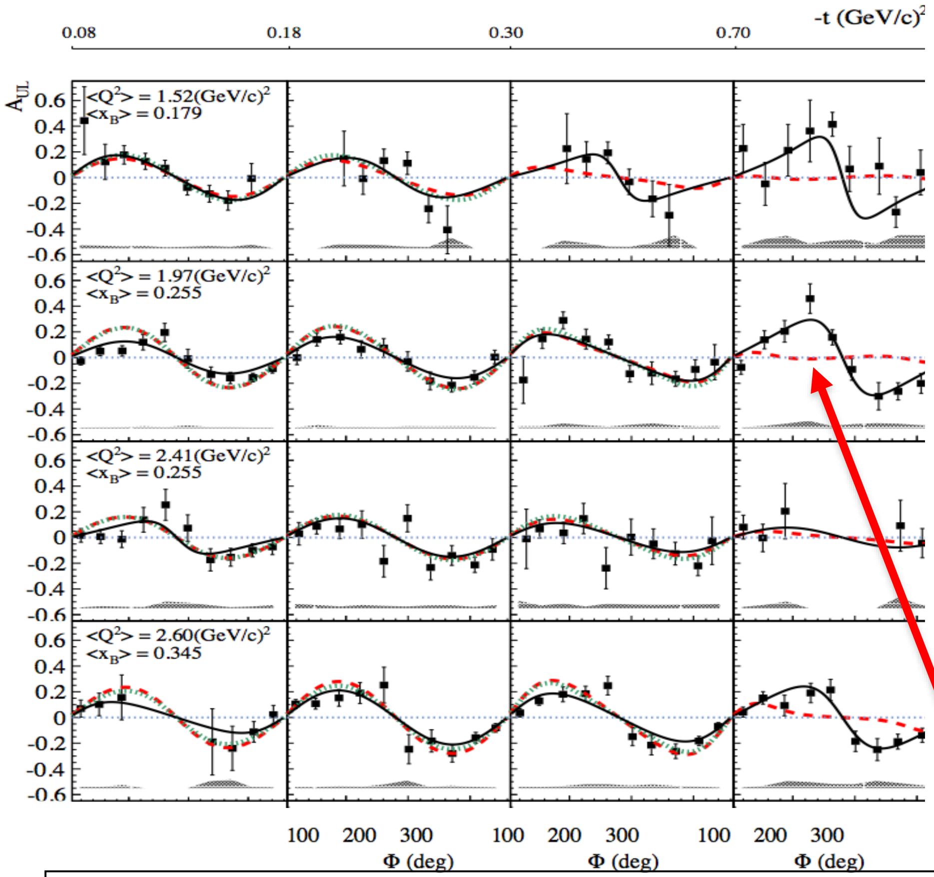
Polarized SSAs in DVCS



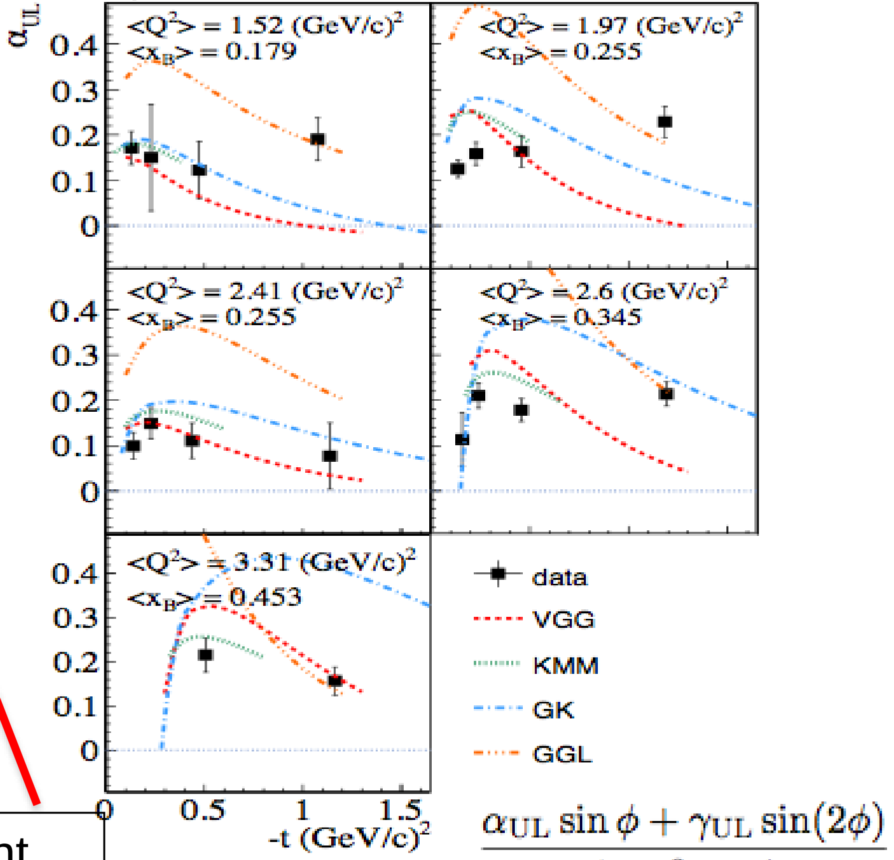
Unpolarized beam, longitudinal target (TSA) :

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

$\Rightarrow$ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$



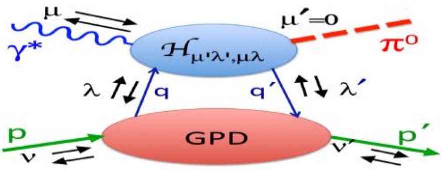
t-dependence of $\tilde{\text{H}}$ is hard to describe



$$\frac{\alpha_{UL}\sin\phi + \gamma_{UL}\sin(2\phi)}{1+\beta\cos\phi}$$

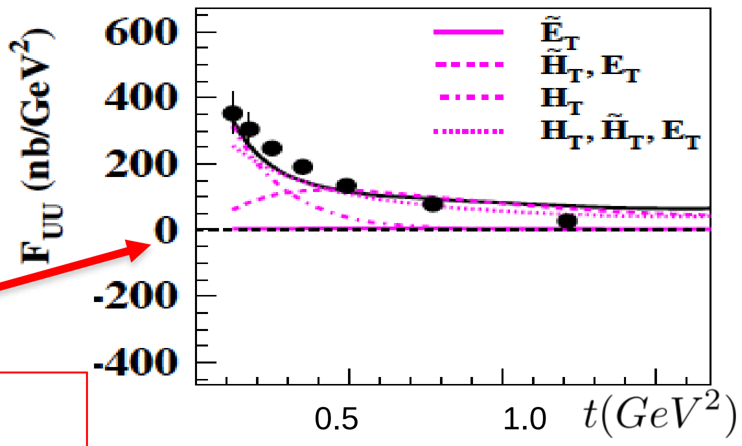
Higher twist contributions may be significant for polarization SSA in DVCS

SSAs in exclusive pseudoscalar meson production

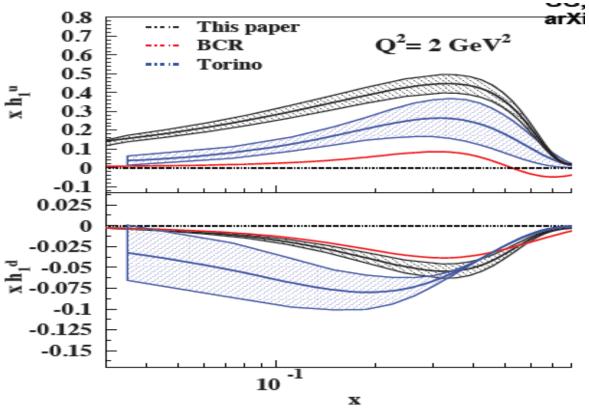


	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		H_T $\widetilde{H}_T$

transverse x-section dominates, providing access to chiral-odd GPDs



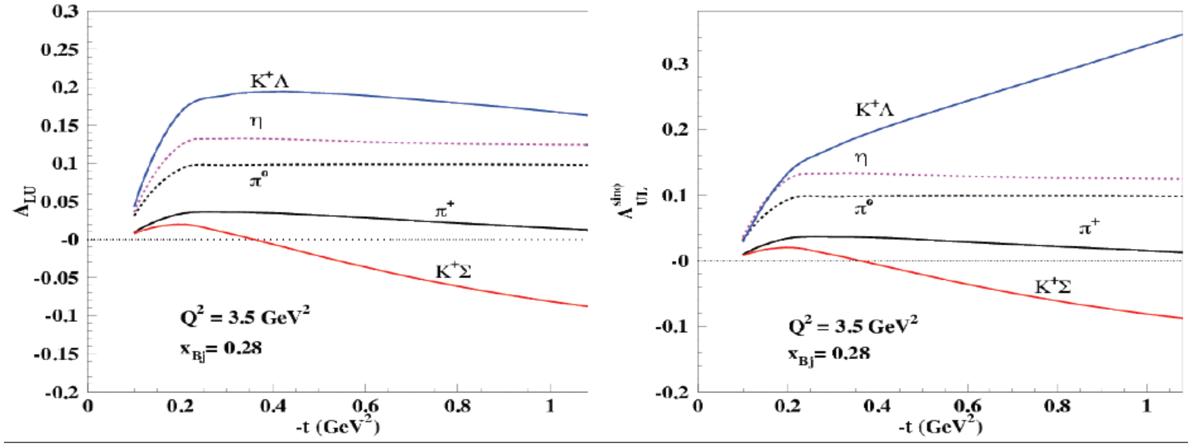
Goloskokov&Kroll



KΣ asymmetries are predicted to be large and with opposite sign to KΛ

Beam and target asymmetries in exclusive production of KΛ and KΣ are very sensitive to chiral-odd GPDs.

Goldstein, Hernandez, & Liuti



$$H_T^{\gamma^* p\to\pi^0 p} \sim [2H_T^u + H_T^d]$$

$$H_T^{\gamma^* p\to\eta p} \sim [2H_T^u - H_T^d]$$

$$H_T^{\gamma^* p\to K^+\Lambda} \sim [2H_T^u - H_T^d - H_T^s]$$

$$H_T^{\gamma^* p\to K^+\Sigma^0} \sim [H_T^d - H_T^s]$$

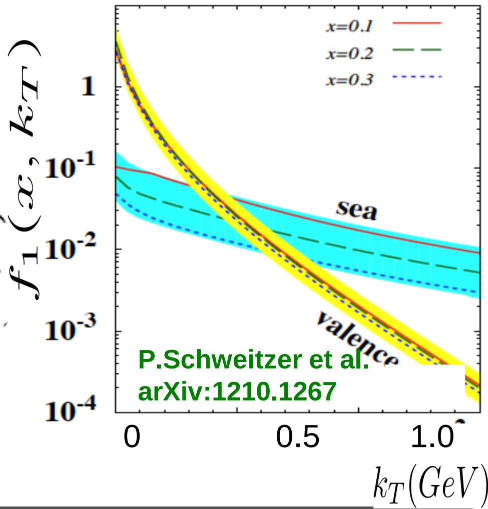
Proposal for PAC44

Exclusive production of KΛ and KΣ provide access to different combinations of chiral-odd GPDs

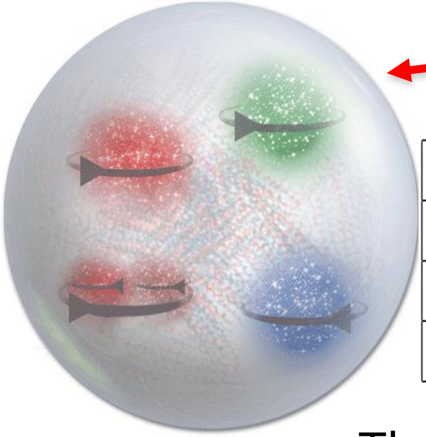
Nucleon Structure: What we are looking for?

$$\tilde{F}_{f/P}(x,\mathbf{b}_T;\mu,\zeta_F) = \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x},\mu_b)}^{\mathrm{A}}$$

$$\overbrace{\times \exp\left\{ \ln\frac{\sqrt{\zeta_F}}{\mu_b}\tilde{K}(b_*;\mu_b) + \int_{\mu_b}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu');1) - \ln\frac{\sqrt{\zeta_F}}{\mu'}\gamma_K(g(\mu'))\right]\right\}}^{\mathrm{B}} \times \overbrace{\exp\left\{ g_{j/P}(x,b_T) + g_K(b_T)\ln\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\}}^{\mathrm{C}}$$



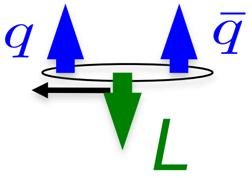
P.Schweitzer et al.
arXiv:1210.1267



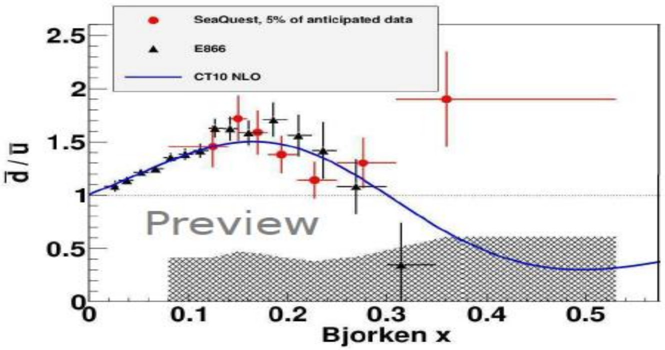
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

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

	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 quark-gluon dynamics manifests itself in a set of non-perturbative functions describing different spin-orbit correlations



What are the most relevant kinematics and sensitive observables to quark-gluon dynamics?

Summary

The main goal of the upgraded JLab 3D program is the study of spin and flavor dependence of transverse space and transverse momentum distributions of quarks.

- Understanding of target fragmentation and correlations between hadrons in target and current fragmentation regions is important for interpretation of semi-inclusive and exclusive production of hadrons.

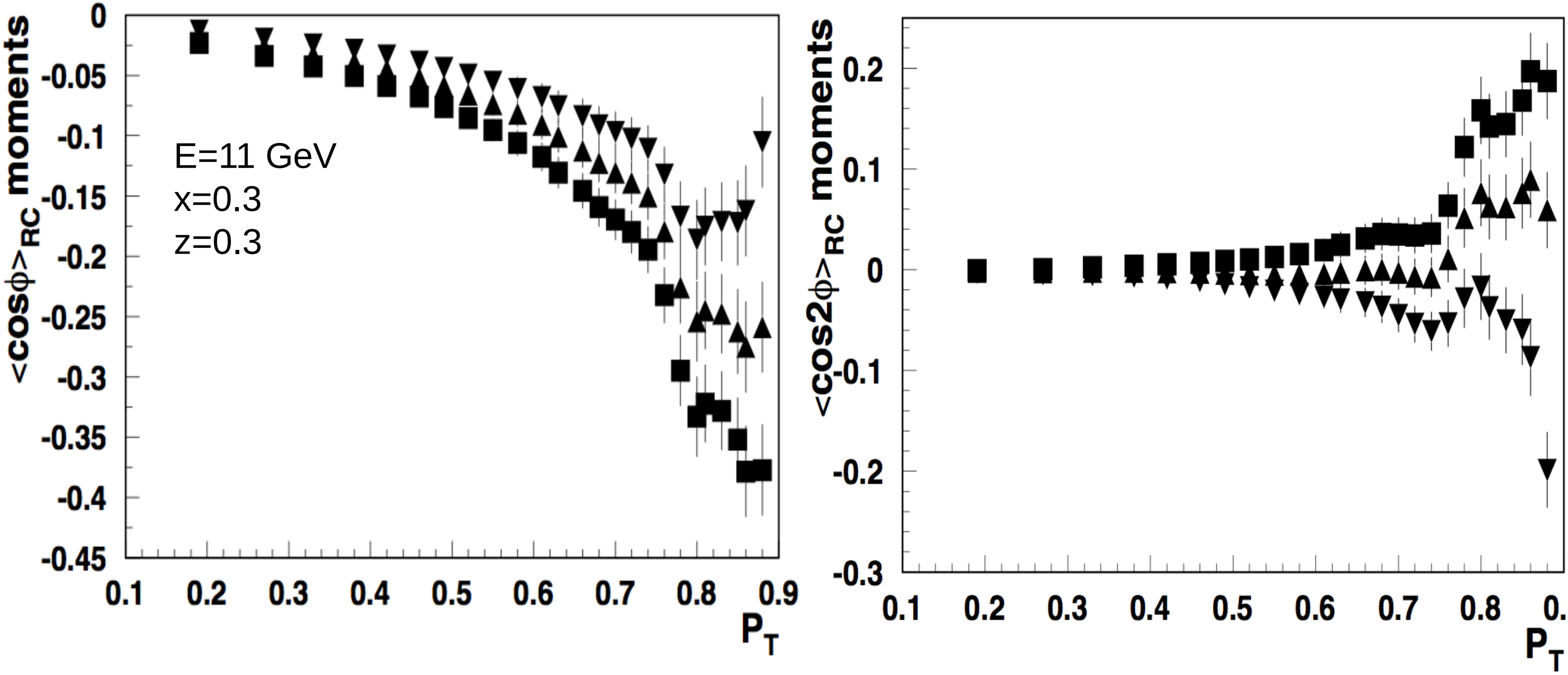
- Higher twists are indispensable part of SIDIS analysis and their understanding is crucial for interpretation of SIDIS leading twist observables

- Measurements with unpolarized, longitudinally and transversely polarized targets of hard exclusive and semi-inclusive processes combined with lattice studies will help to accomplish the program of studies of the 3D structure of the nucleon.

Need TMD/CFF extraction framework with controlled systematics.

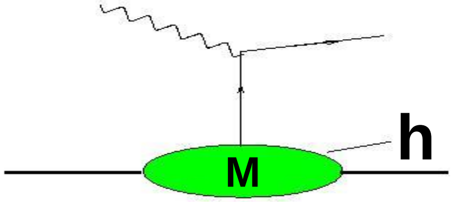
Support slides….

P_T -dependence of Radiative Corrections to F_{UU}

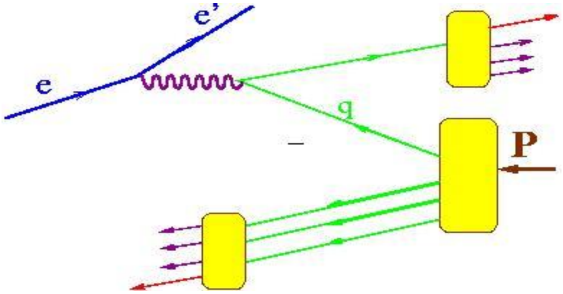


Azimuthal moments from radiative effects are large and very sensitive to input structure functions (3 different SFs plotted)

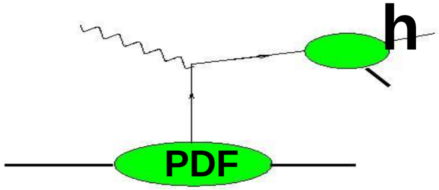
Target Fragmentation



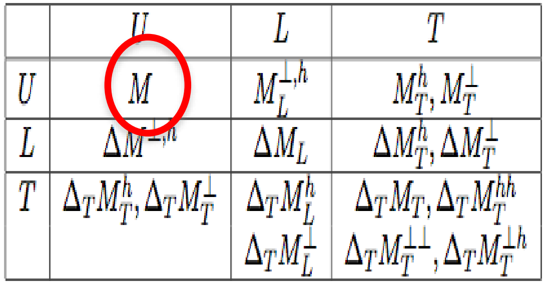
x_F<0 (target fragmentation)



x_F>0 (current fragmentation)

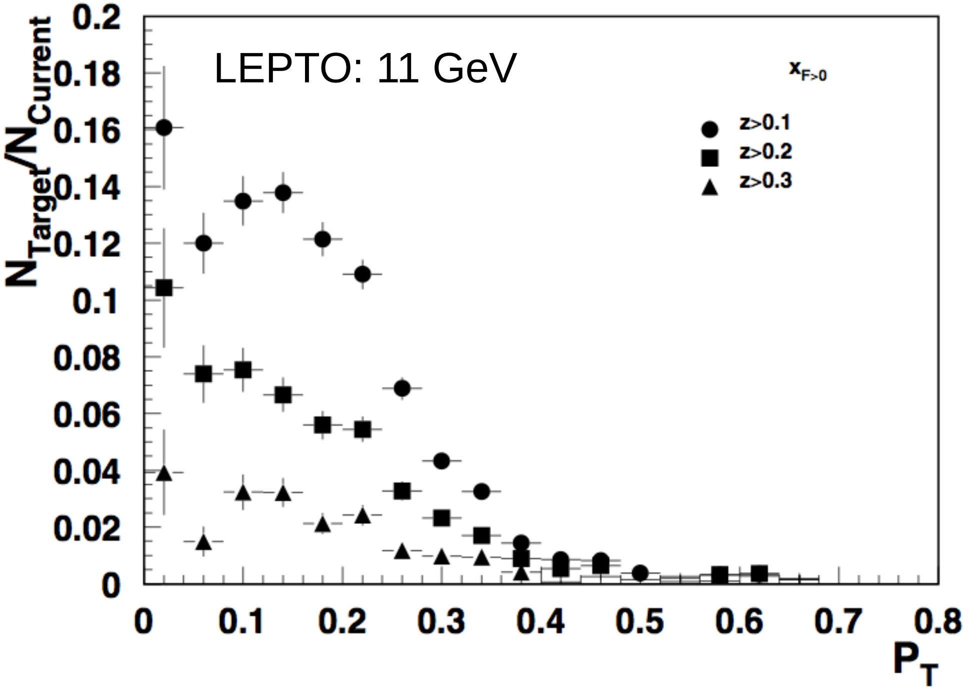


Fracture Functions: probabilities to produce the hadron h when a quark q is struck in a proton target



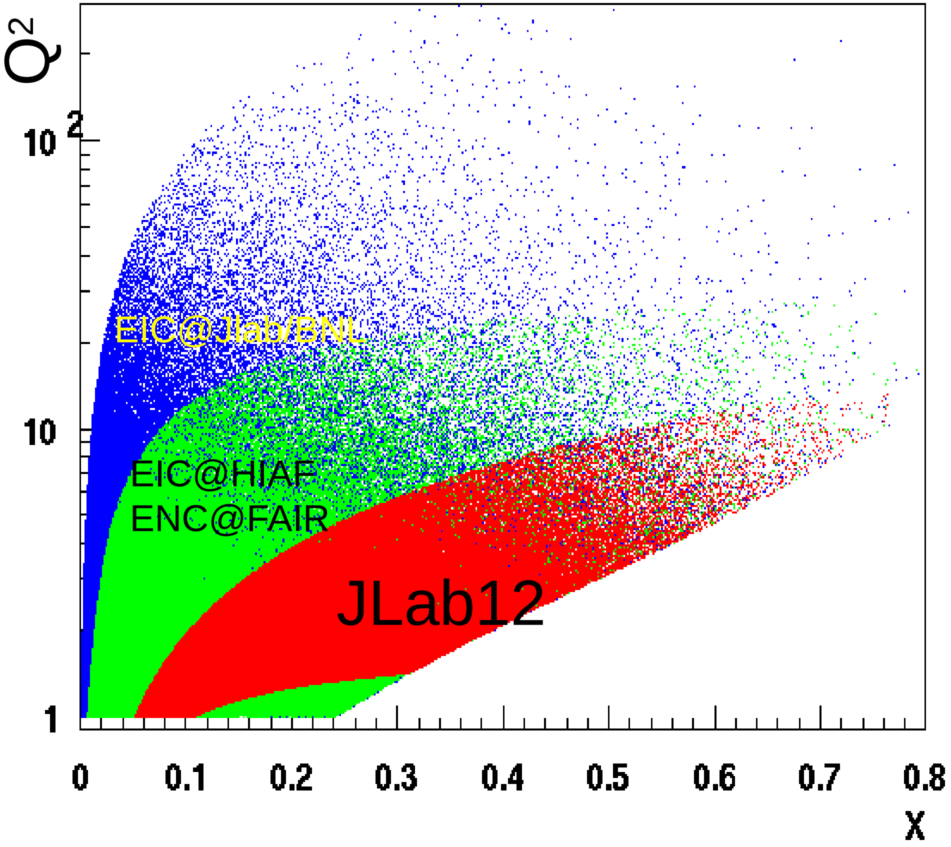
	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

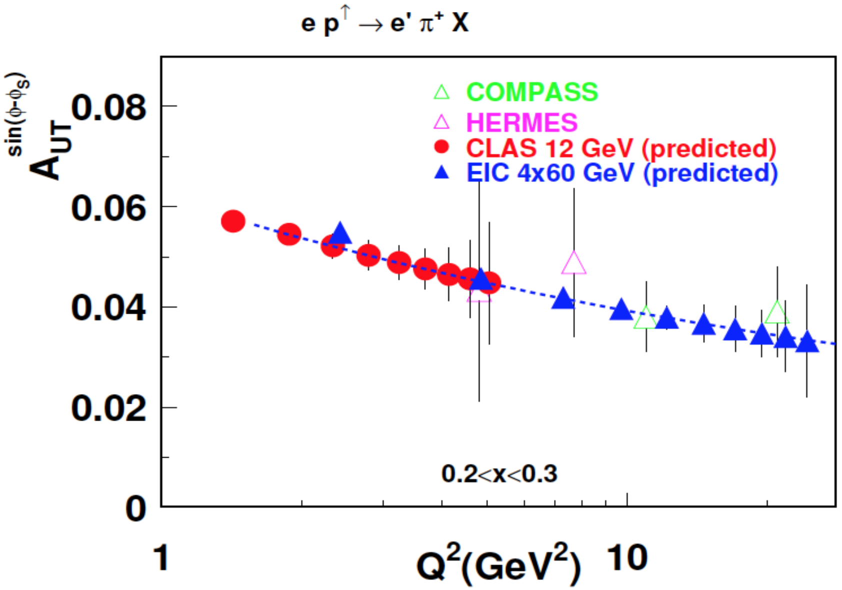
- Hadrons produced in target fragmentation may be correlated with hadrons in the current fragmentation and their studies will be important for precision studies in current fragmentation.



Evolution Studies: from JLab12 to EIC

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.

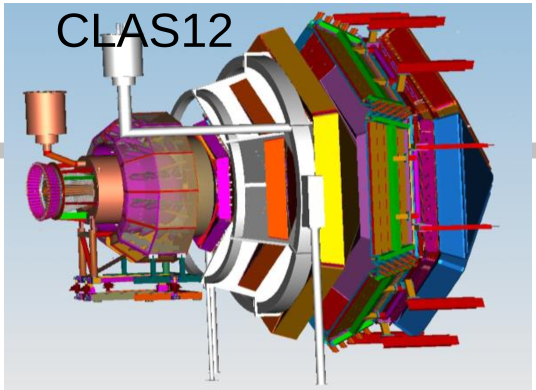




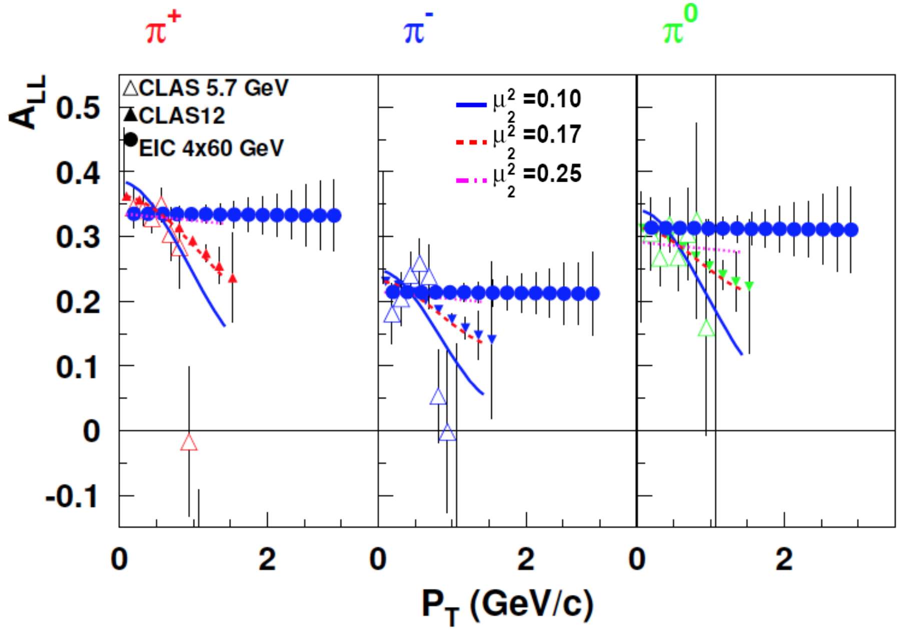
Aybat,Prokudin&Rogers hep:1112.4423
Sun & Yuan arXiv:1304.5037

- Q^2 – dependence of Sivers function is sensitive to the non-perturbative physics
- Wide range in Q^2 is crucial to study the evolution
- Study of large **x** domain requires high luminosity
- Overlap of EIC and JLab12 in the valence region will be crucial for the TMD program

A_1 P_T-dependence in SIDIS



$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \, e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$



M.Anselmino et al **hep-ph/0608048**

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\boxed{\mu_0^2}}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\boxed{\mu_2^2}}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$

J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- **A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

Flavor dependent TMD Fragmentation functions

https://www.phy.anl.gov/nsac-lrp/Whitepapers/StudyOfFragmentationFunctionsInElectronPositronAnnihilation.pdf

$$F_{UU} \propto \sum_q f_{1,q}(x,k_\perp) \otimes D_1^{q\to h}(z,p_\perp)$$

Even simple approximations require an additional set of parameters

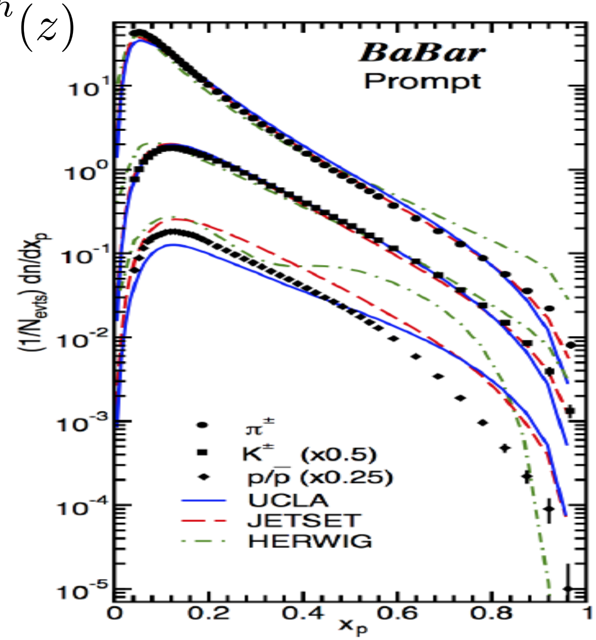
$$D_1^{q\to h,fav}(z,p_\perp) = D_1^{q\to h}(z) \times \frac{e^{-\frac{p_\perp^2}{\langle p_{\perp,fav}^2(z)\rangle}}}{\pi\langle p_{\perp,fav}^2(z)\rangle}$$

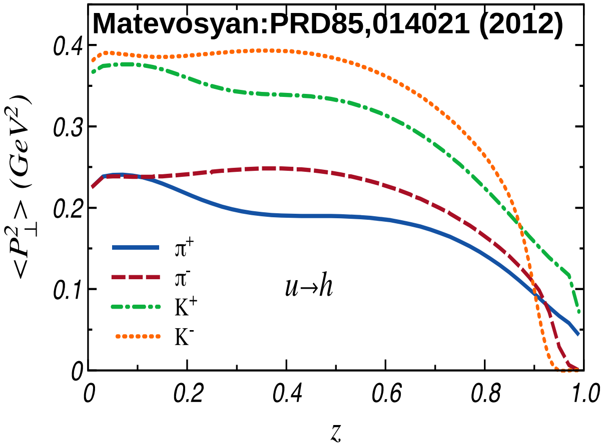
$$D_1^{q\to h,unf}(z,p_\perp) = D_1^{q\to h}(z) \times \frac{e^{-\frac{p_\perp^2}{\langle p_{\perp,unf}^2(z)\rangle}}}{\pi\langle p_{\perp,unf}^2(z)\rangle}$$

$$\langle p_{\perp,unf}^2(z)\rangle > \langle p_{\perp,fav}^2(z)\rangle$$

Measurements of flavor and spin dependence of transverse momentum dependent fragmentation functions will provide critical input to TMD extraction

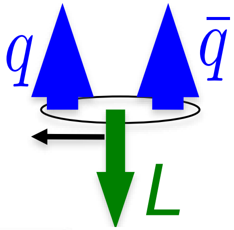
$D_1^{q\to h}(z)$



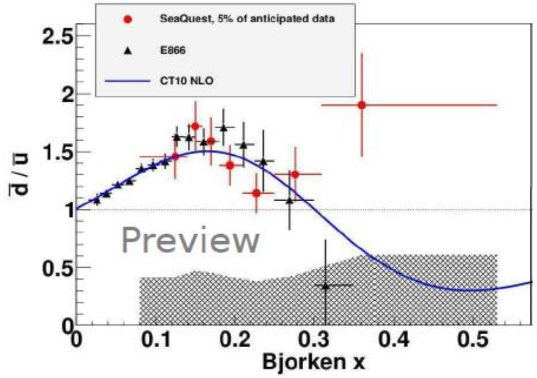


Features of partonic 3D non-perturbative distributions

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

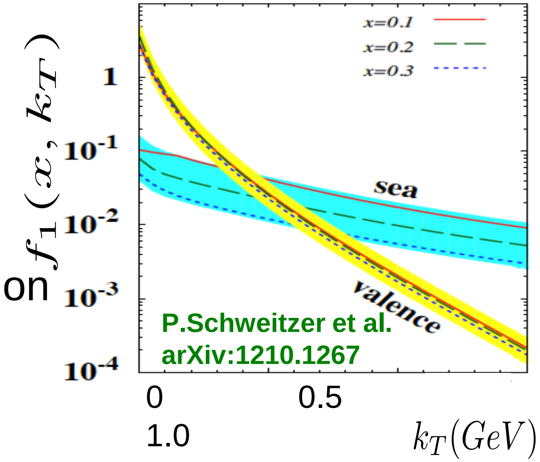


-- Large flavor asymmetry dbar > ubar as evidence



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

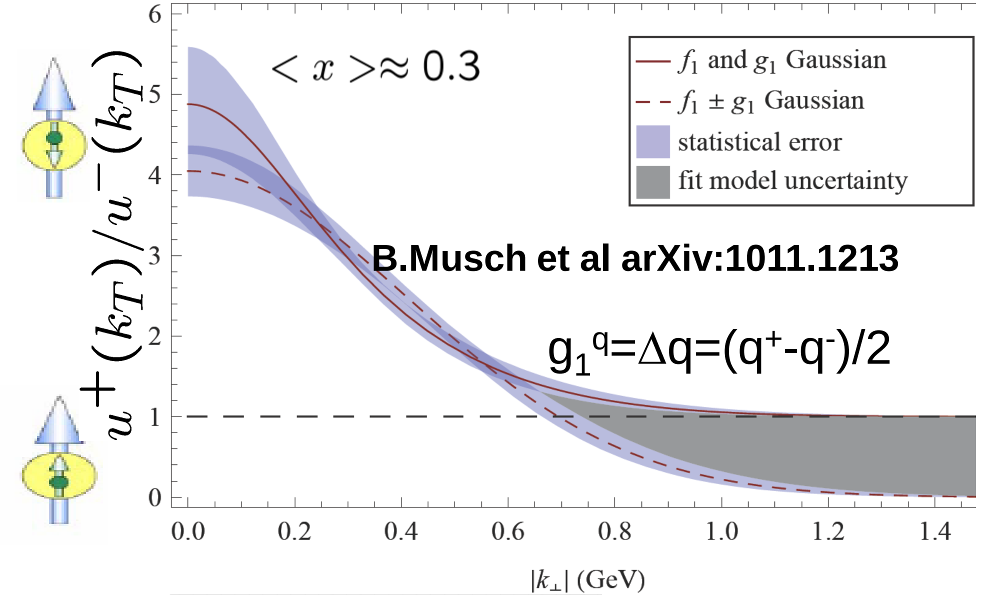
  -- k_T (sea) >> k_T (valence)
  -- short-range correlations between partons (small-size q-qbar pairs)
  -- directly observable in P_T-dependence of hadrons in SIDIS



P.Schweitzer et al.
arXiv:1210.1267

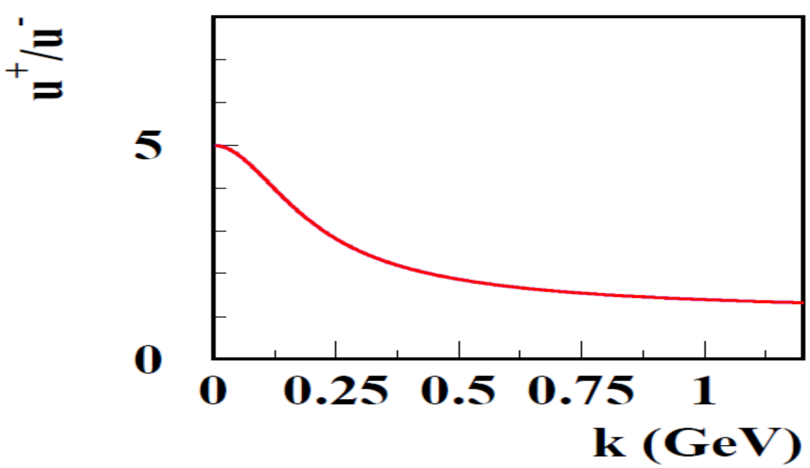
- spin and momentum of struck quarks are correlated with remnant
- large SSAs were observed at large P_T of hadrons, where the fraction of non-perturbative pairs may be very significant.
- correlations of spins of q-q-bar with valence quark spin and transverse momentum will lead to observable effects

Quark distributions at large k_T: lattice

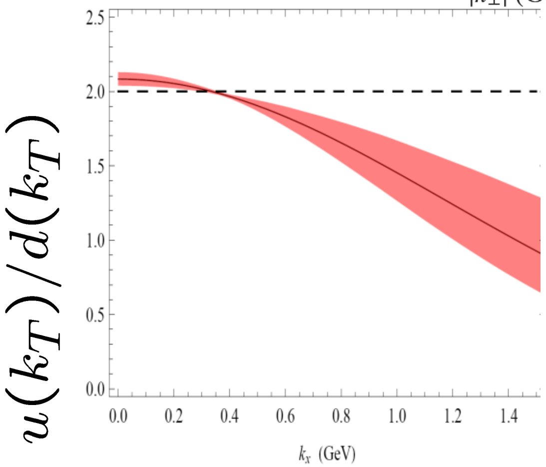


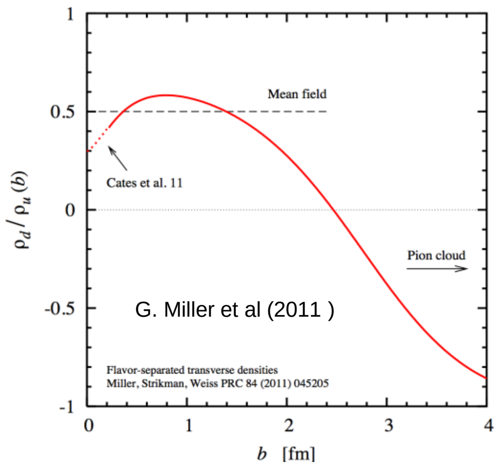
B.Musch et al arXiv:1011.1213

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



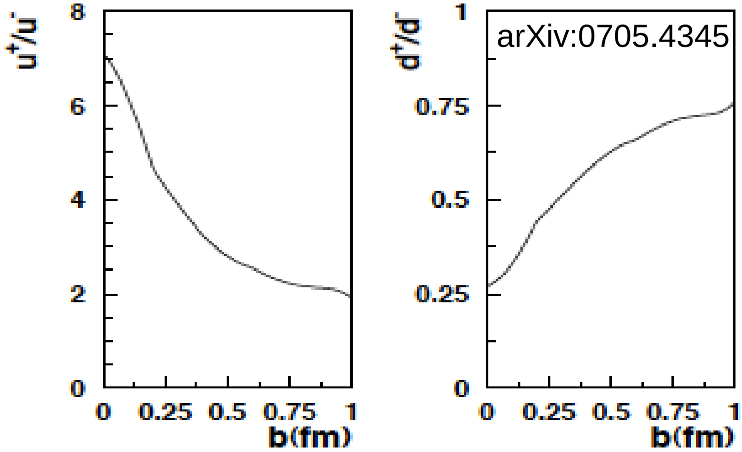
B.Pasquini et al





G. Miller et al (2011)

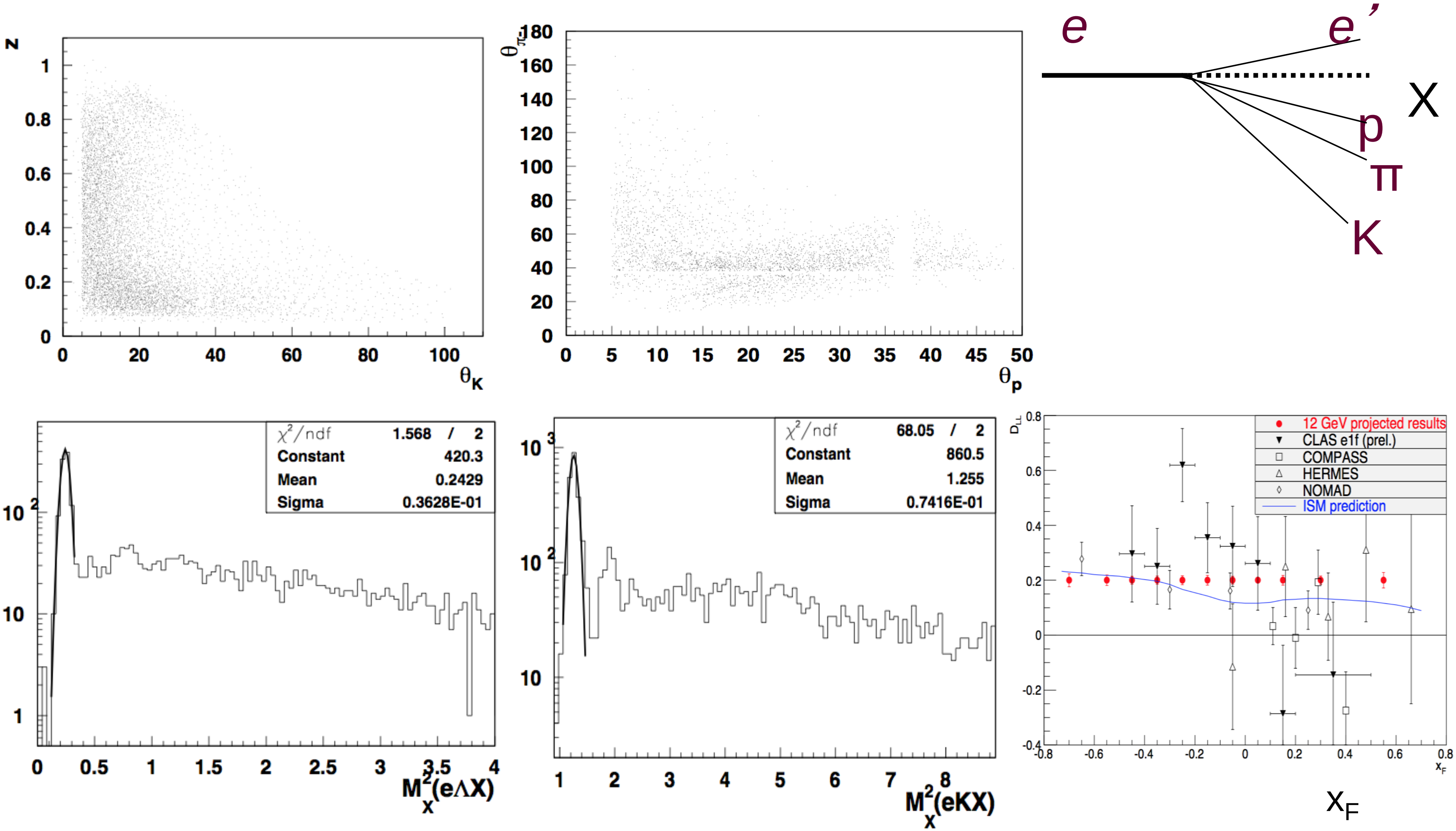
Flavor-separated transverse densities
Miller, Strikman, Weiss PRC 84 (2011) 045205



arXiv:0705.4345

Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

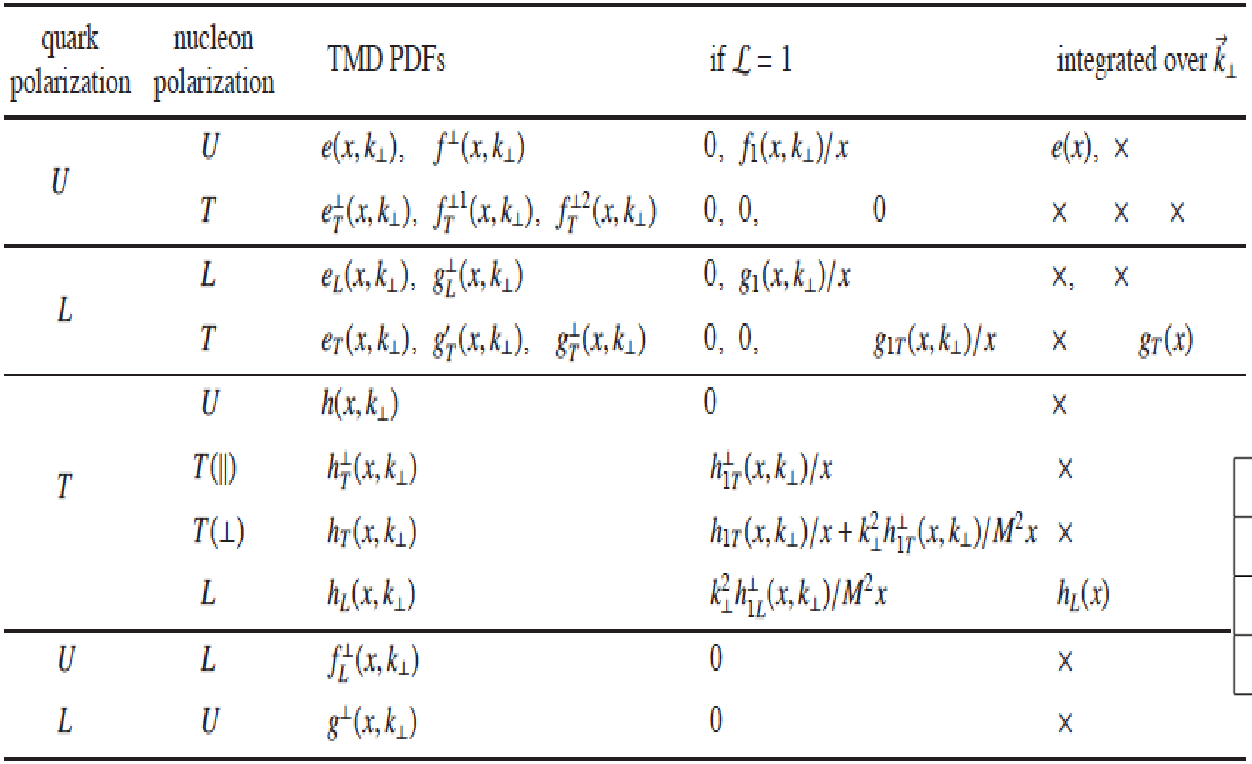
Controlling the flavor content with target-current correlations



- Large acceptance of CLAS12 (and EIC) provide a unique possibility to detect simultaneously hadrons in the forward and backward regions

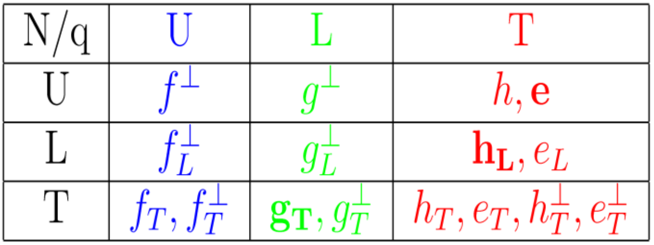
Higher Twists

http://arxiv.org/abs/arXiv:1506.07302



quark polarization	nucleon polarization	TMD PDFs	if $\mathcal{L}=1$	integrated over $\vec{k}_\perp$
U	U	$e(x,k_\perp)$, $f^\perp(x,k_\perp)$	0, $f_1(x,k_\perp)/x$	$e(x)$, ×
	T	$e_T^\perp(x,k_\perp)$, $f_T^{\perp 1}(x,k_\perp)$, $f_T^{\perp 2}(x,k_\perp)$	0, 0, 0	× × ×
L	L	$e_L(x,k_\perp)$, $g_L^\perp(x,k_\perp)$	0, $g_1(x,k_\perp)/x$	×, ×
	T	$e_T(x,k_\perp)$, $g_T'(x,k_\perp)$, $g_T^\perp(x,k_\perp)$	0, 0, $g_{1T}(x,k_\perp)/x$	× $g_T(x)$
T	U	$h(x,k_\perp)$	0	×
	$T(\parallel)$	$h_T^\perp(x,k_\perp)$	$h_{1T}^\perp(x,k_\perp)/x$	×
	$T(\perp)$	$h_T(x,k_\perp)$	$h_{1T}(x,k_\perp)/x + k_\perp^2 h_{1T}^\perp(x,k_\perp)/M^2 x$	×
	L	$h_L(x,k_\perp)$	$k_\perp^2 h_{1L}^\perp(x,k_\perp)/M^2 x$	$h_L(x)$
U	L	$f_L^\perp(x,k_\perp)$	0	×
L	U	$g^\perp(x,k_\perp)$	0	×

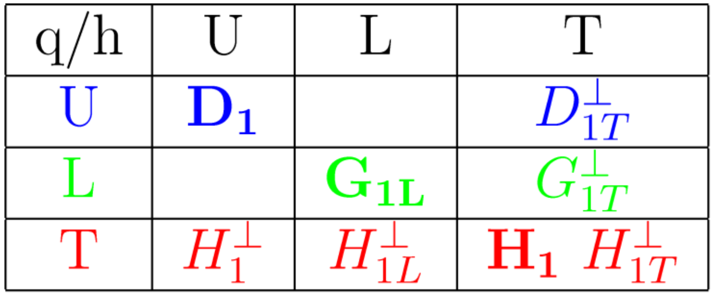
Higher Twist PDFs



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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

L = 1 , i.e. if we neglect the multiple gluon scattering and simply take a nucleon as an ideal gas system consisting of quarks and anti-quarks

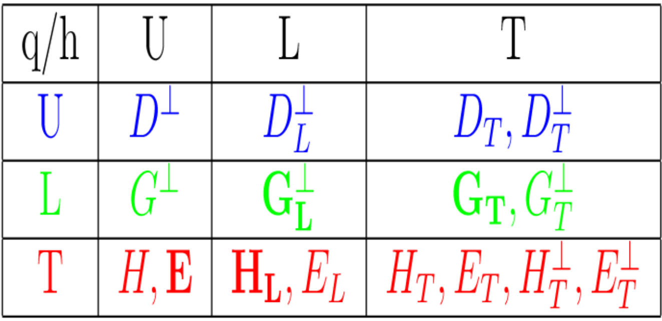
quark polarization	hadron polarization	TMD FFs	integrated over $\vec{k}_{F\perp}$	name
U	U	$D_1(z, k_{F\perp})$	$D_1(z)$	number density
	T	$D_{1T}^\perp(z, k_{F\perp})$	×	
L	L	$G_{1L}(z, k_{F\perp})$	$G_{1L}(z)$	spin transfer (longitudinal)
	T	$G_{1T}^\perp(z, k_{F\perp})$	×	
T	U	$H_1^\perp(z, k_{F\perp})$	×	Collins function
	$T(\parallel)$	$H_{1T}(z, k_{F\perp})$	$H_{1T}(z)$	spin transfer (transverse)
	$T(\perp)$	$H_{1T}^\perp(z, k_{F\perp})$		
	L	$H_{1L}^\perp(z, k_{F\perp})$	×	



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

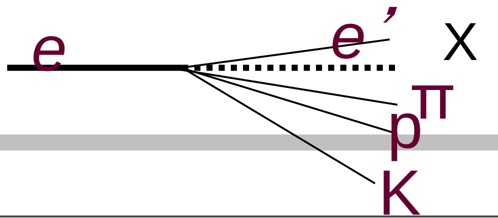
name
spin alignment

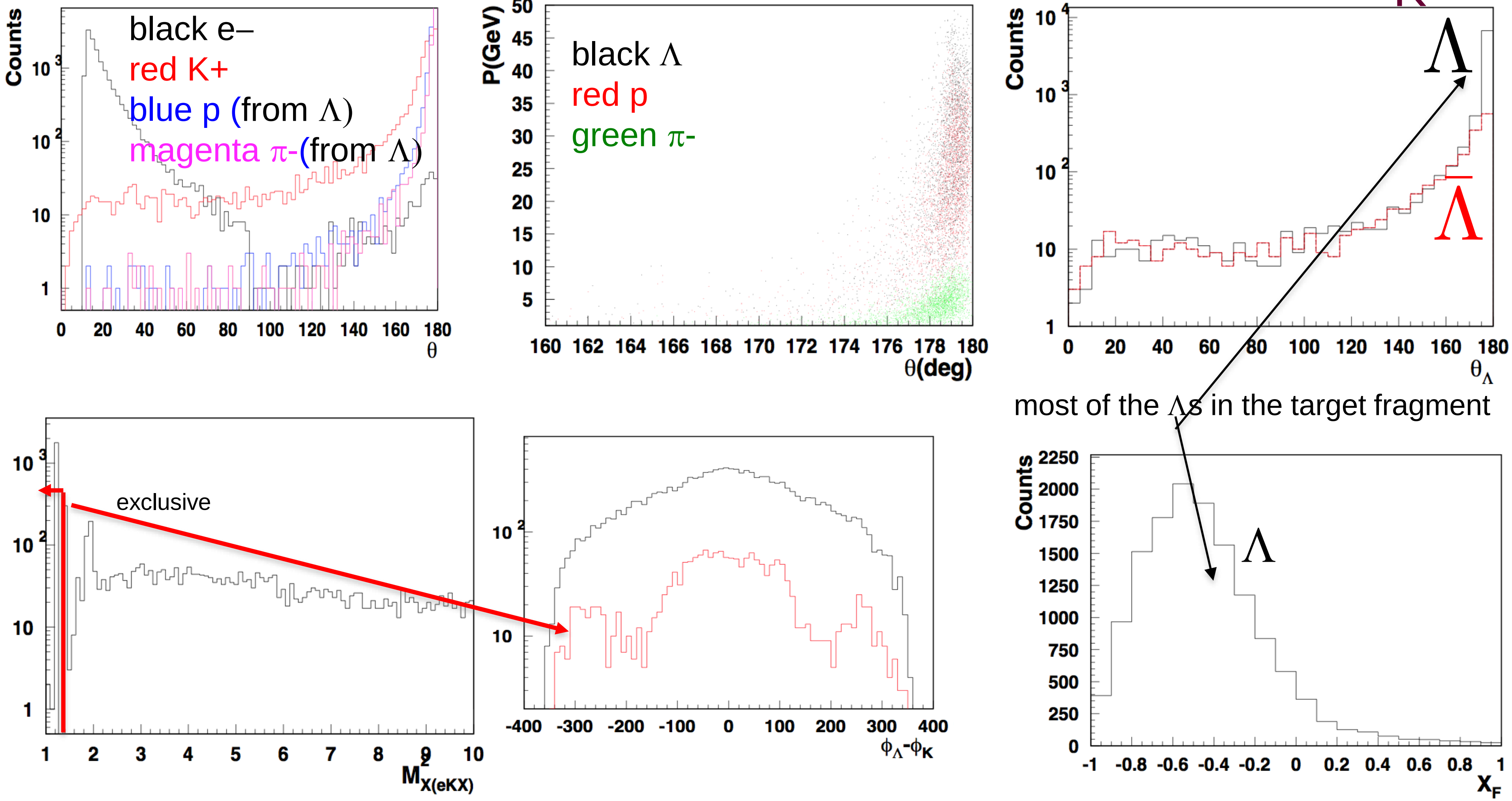
U	LT	$D_{1LT}^\perp(z, k_{F\perp})$	×
	TT	$D_{1TT}^\perp(z, k_{F\perp})$	×
L	LT	$G_{1LT}^\perp(z, k_{F\perp})$	×
	TT	$G_{1TT}^\perp(z, k_{F\perp})$	×
T	LL	$H_{1LL}^\perp(z, k_{F\perp})$	×
	LT	$H_{1LT}(z, k_{F\perp})$, $H_{1LT}^\perp(z, k_{F\perp})$	$H_{1LT}(z)$
	TT	$H_{1TT}^\perp(z, k_{F\perp})$, $H_{1TT}'^\perp(z, k_{F\perp})$	×



q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G}_L^\perp$	$\mathbf{G}_T, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H}_L, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

Lambda production in EIC (5x50 GeV)

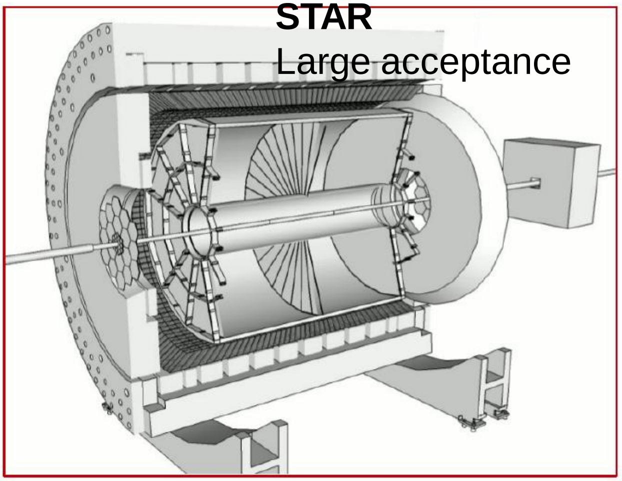




most of the Λs in the target fragment

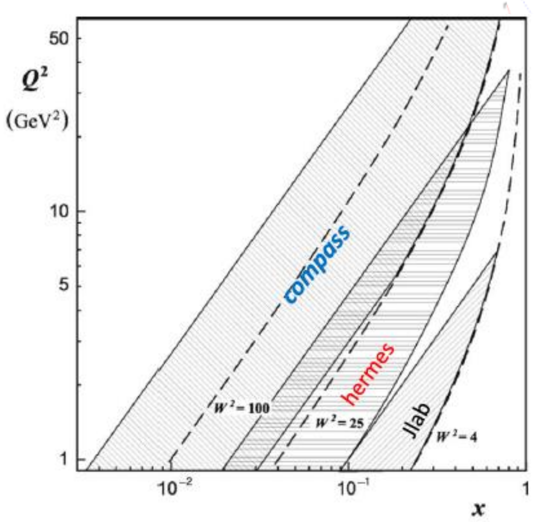
At forward angles Lambas are mainly from target fragments

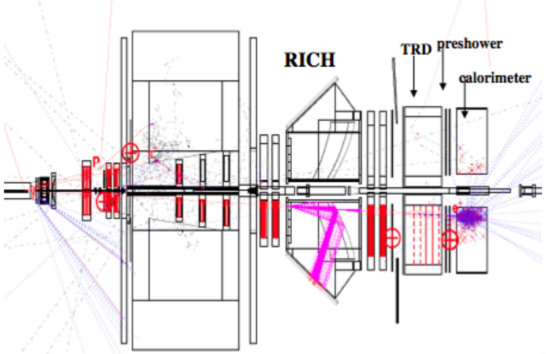
Our eyes into the 3D world

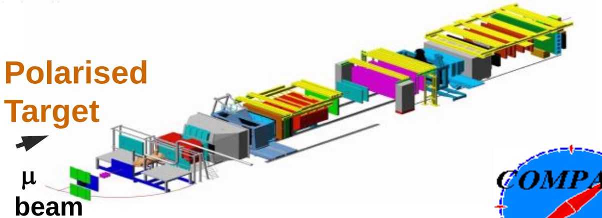


STAR

Large acceptance

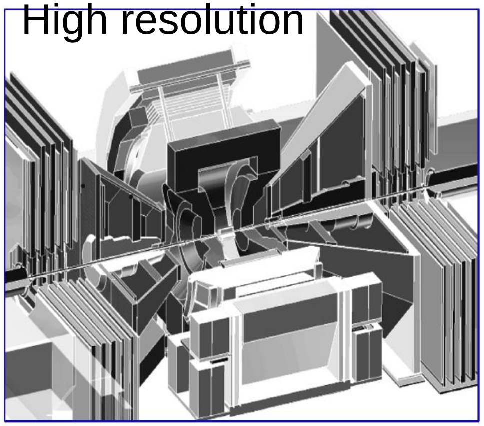






Polarised Target

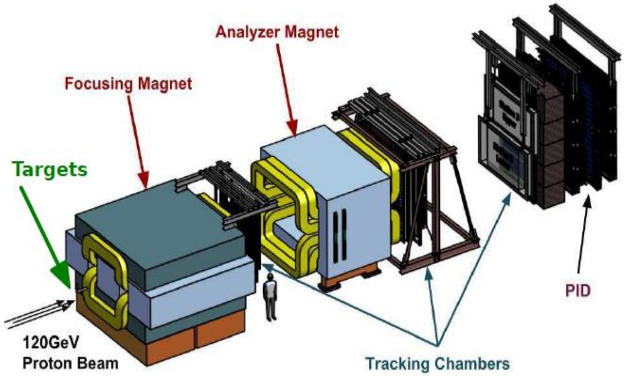
μ beam

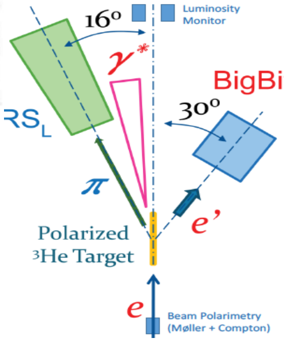


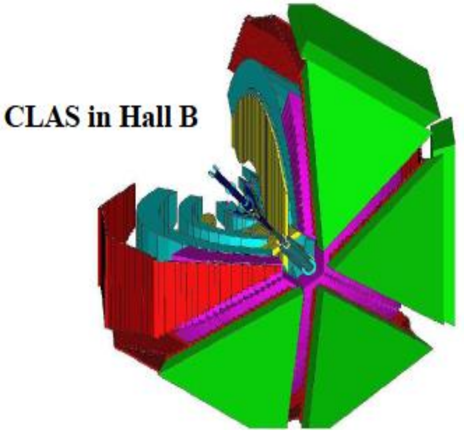
PHENIX

High resolution

SeaQuest



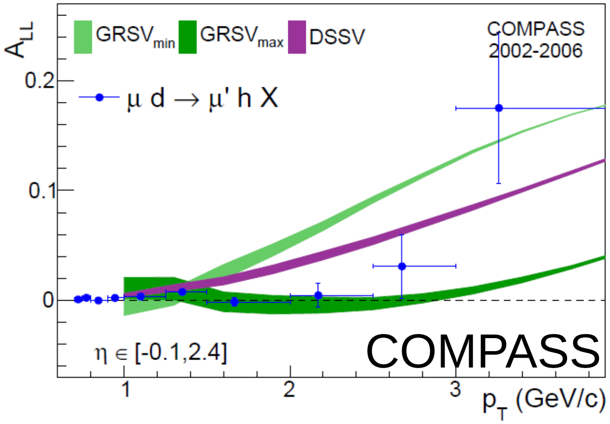




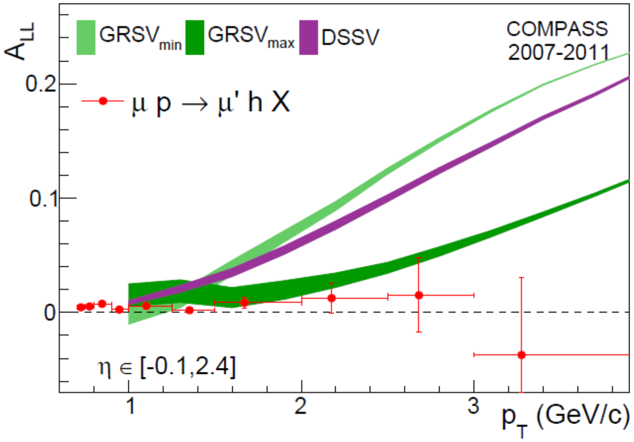
$$\sigma = \sigma_{UU} + P_t\sigma_{UL}\sin 2\phi + P_bP_t\sigma_{LT}\cos(\phi-\phi_S)\dots$$

Gluon polarization extraction from data and lattice

Photon-Gluon Fusion



- Large positive ΔG is favored

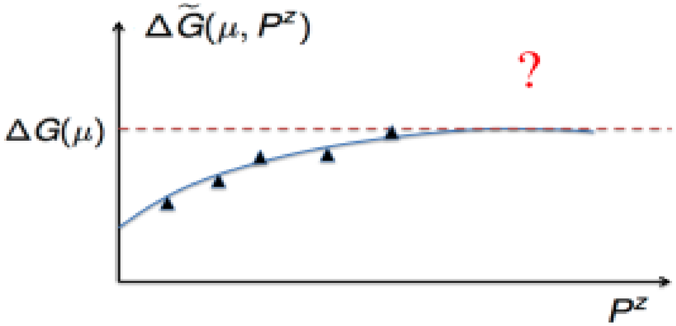


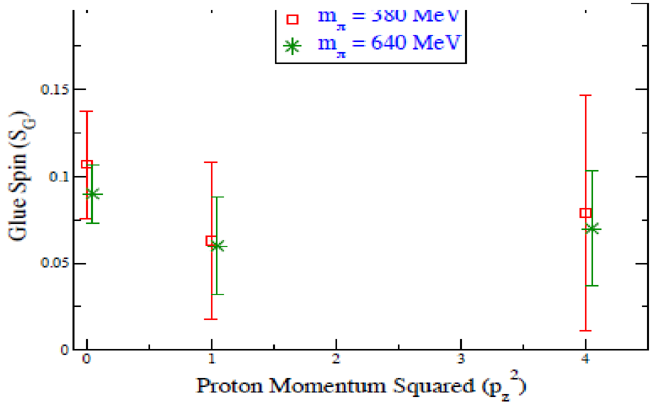
- Some discrepancy between theoretical model and experimental calculations.

Large Momentum Effective Field Theory (LaMET)

$$\tilde{O}(P/\Lambda) = Z(P/\Lambda, \mu/\Lambda) O(\mu) + \frac{c_2}{P^2} + \frac{c_4}{P^4} + \cdots$$

Quasi distribution
Matching coefficient
Partonic distribution





Extracting the moments with rad corrections

Moments mix in experimental azimuthal distributions

Simplest rad. correction $R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$

Correction to normalization

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

Correction to SSA

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

Correction to DSA

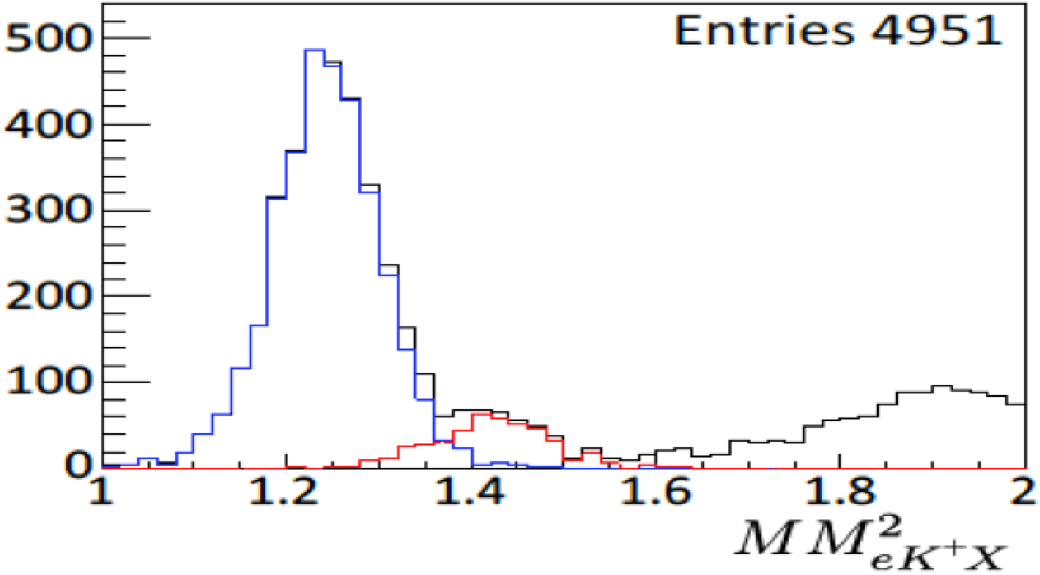
$$\sigma_0(1+g\lambda\Lambda+f\lambda\Lambda\cos\phi_h)R_0(1+r\cos\phi_h) \to \sigma_0 R_0(1+(g+fr/2)\lambda\Lambda)$$

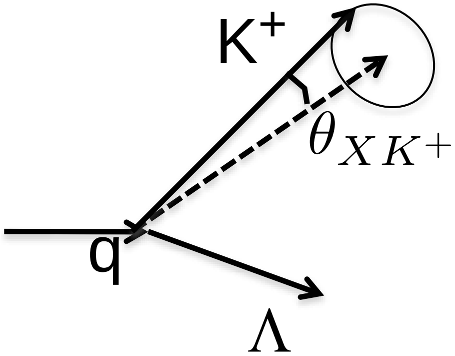
Generate fake DSA moments (cos)

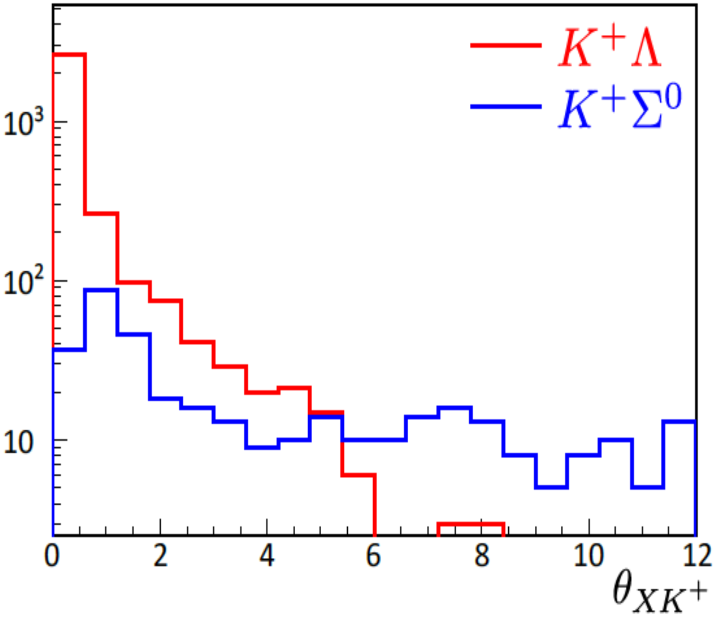
$$\sigma_0(1+g\lambda\Lambda)R_0(1+r\cos\phi_h) \to \sigma_0 R_0 gr\cos\phi_h$$

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

K+ Λ/Σ separation

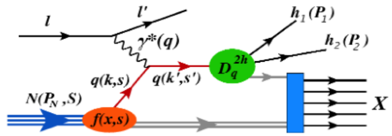




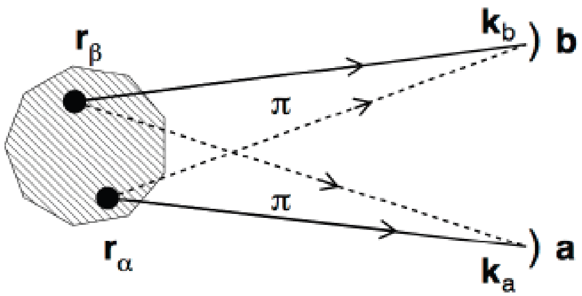


Detection of K+ p and π- would allow to separate of different final states (Λ,Σ,K*)

Bose-Einstein Correlations



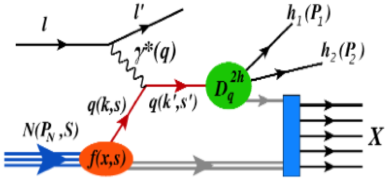
E. Kinney



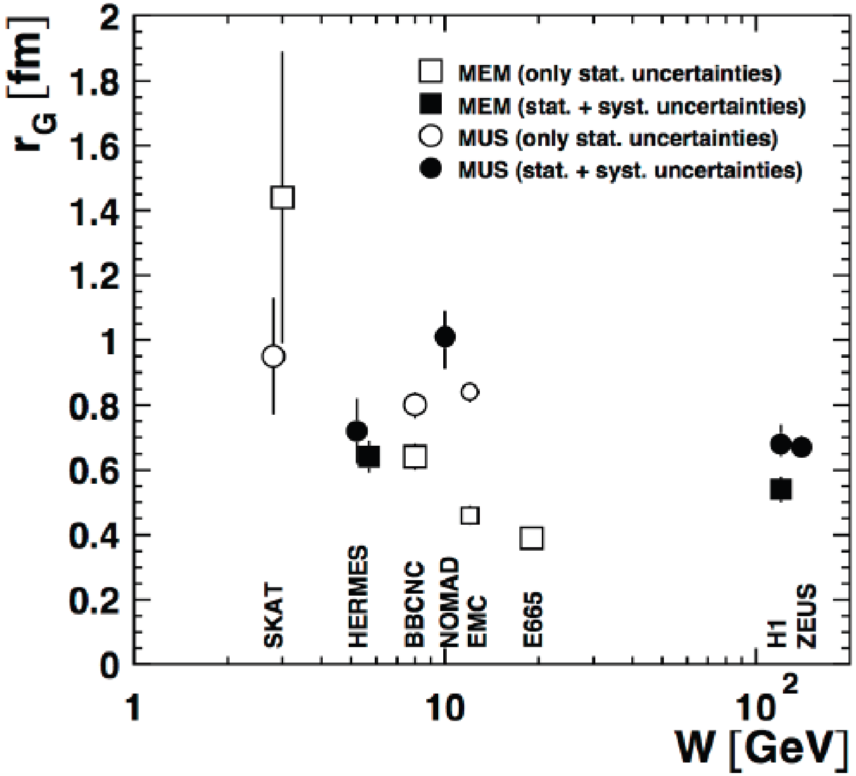
Two charged hadrons with momenta between 2 and 15 GeV required in addition to the scattered electron

double ratio is used, based on the experimental simulation:

1. RMEM(event mixing) = (like/mixed)exp / (like/mixed)MC
2. RMUS(unlike-sign pairs)= (like/unlike)MC



radius of the pion emission region

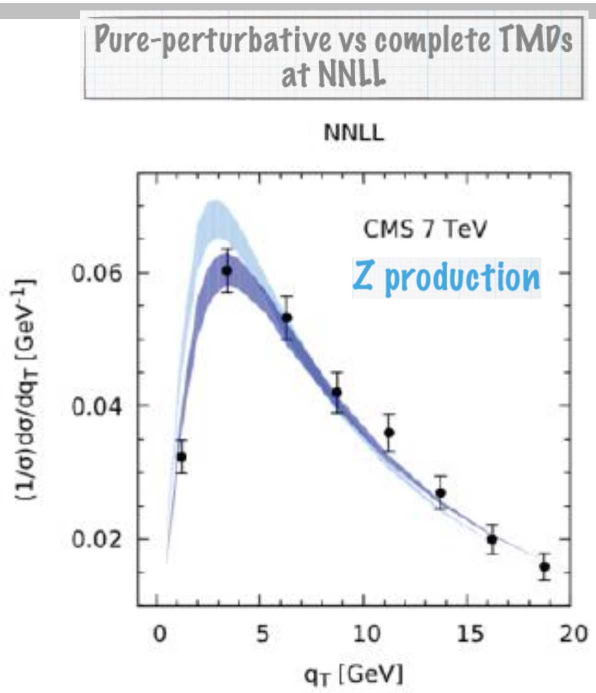


no significant dependence on the energy!

no significant dependence on medium

May provide unique information on spatial structure of fragmentation

TMD framework



Scimemi

$q_T^2 \gg \Lambda_{QCD}^2$ Pure perturbative regime

Example: Vector boson (Tevatron, LHC) and Higgs production at LHC (up to a certain precision, qT>5-10 GeV..),
Some DIS data from HERA

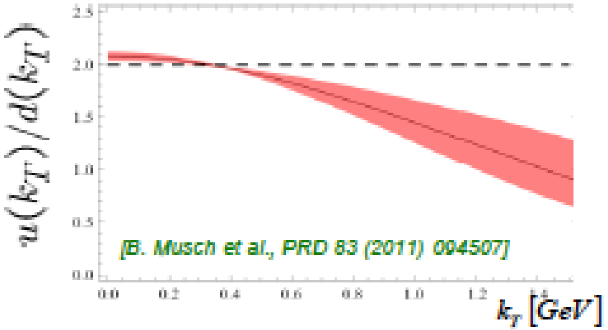
$q_T^2 \sim \Lambda_{QCD}^2$ TMD regime (in SIDIS ~q_T->k_T)

Example: DY Tevatron experiments (E288: Q=4-15GeV, q_T<2 GeV) no (usable) DIS data… waiting for EIC..

- Golden energy range for TMDs, Q>2-3 GeV, q_T<<Q. Large Q-range is needed to test the TMD framework (evolution) and LHC, e+e- colliders (Belle,BaBar,Bes) and EIC can provide inportant input

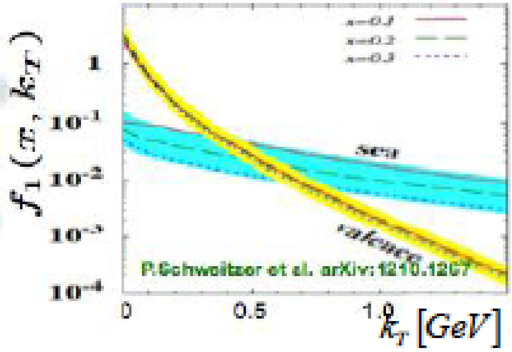
Studies of transverse momentum distributions

- ☐ Partonic interpretation of SIDIS typically assumes Gaussian, but data show that transverse momentum widths of quarks with **different flavor (and polarization)** can be different.



[B. Musch et al., PRD 83 (2011) 094507]

Higher probability to find more sea and d-quarks at large k_T

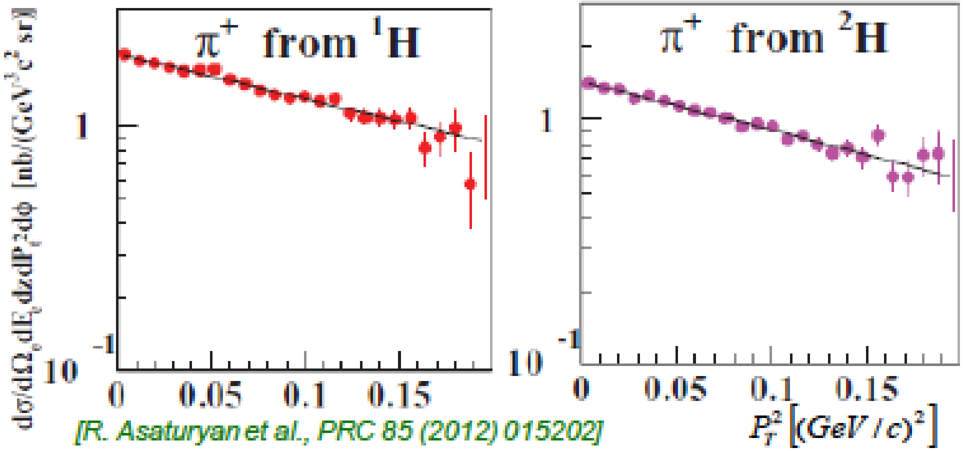


P.Schweitzer et al. arXiv:1210.1267

Measurements of hadronic multiplicities provide essential input for studies of k_T dependence of spin-independent distributions

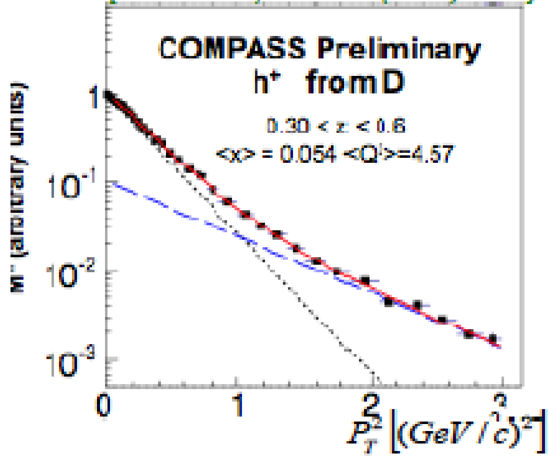
[HERMES, PRD 87 (2013) 074029]

[COMPASS, EPJC 73 (2013) 2531]



[R. Asaturyan et al., PRC 85 (2012) 015202]

$$P_T = p_T + z\,k_T + O(k_T^2/Q^2)$$

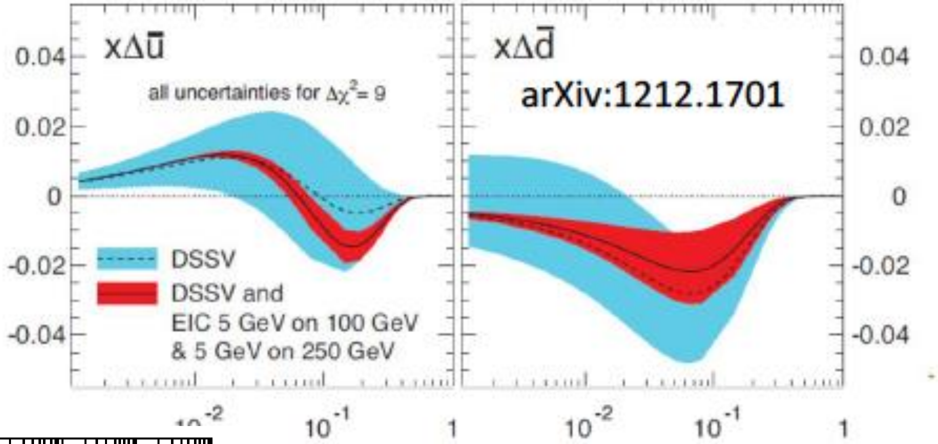


There are indications from both theory (lattice, χCQM) and experimental data of the k_T dependence of quark flavor distribution

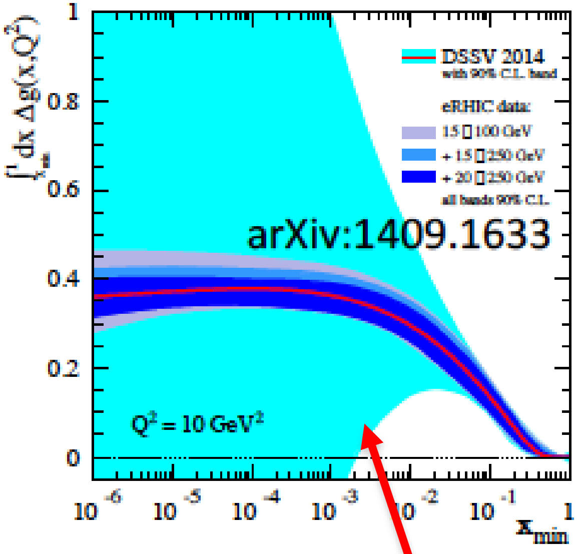
Future studies with EIC

eRHIC: Quark / Anti-Quark Constraints

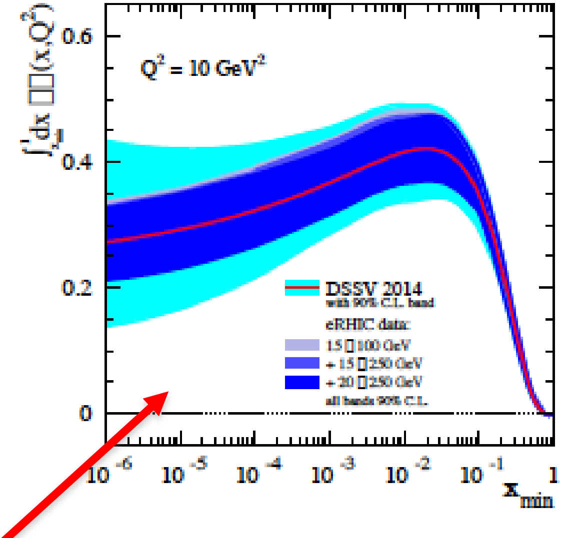
5 GeV electrons colliding with
100 and 250 GeV protons

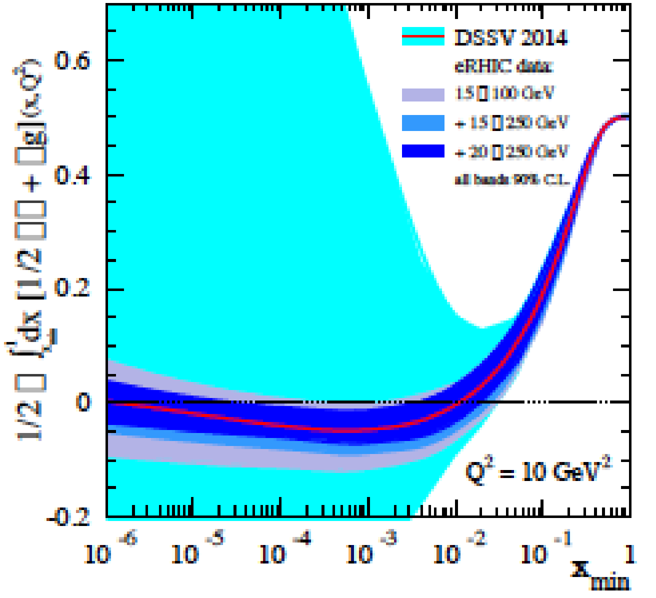


arXiv:1212.1701



arXiv:1409.1633



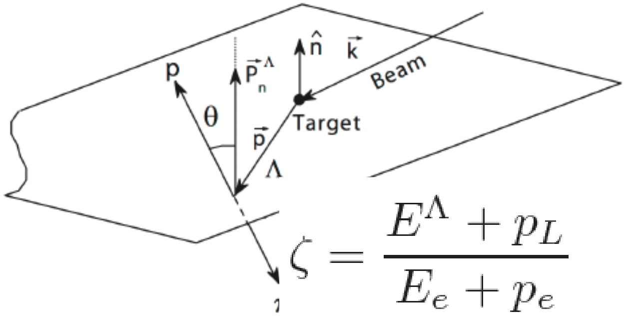


Constraints on gluon and quark contributions will provide independent check of orbital angular momentum component of proton spin

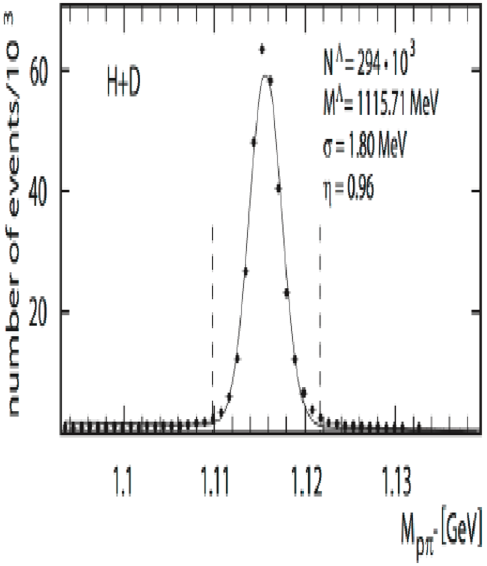
Transverse Lambda polarization in quasi-real photoproduction

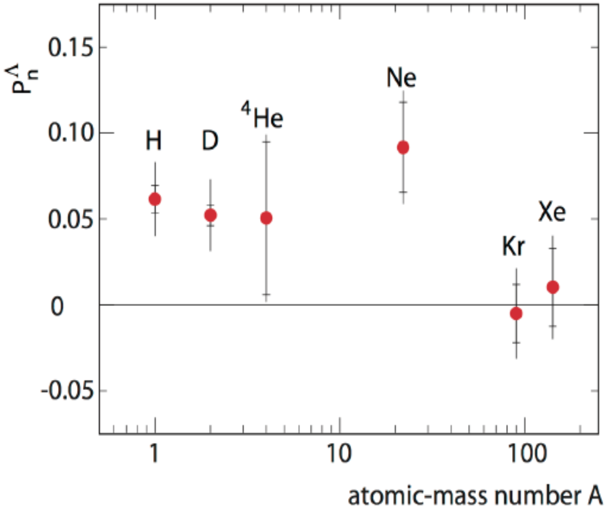
- Parity-violating weak decay allows polarization determination:

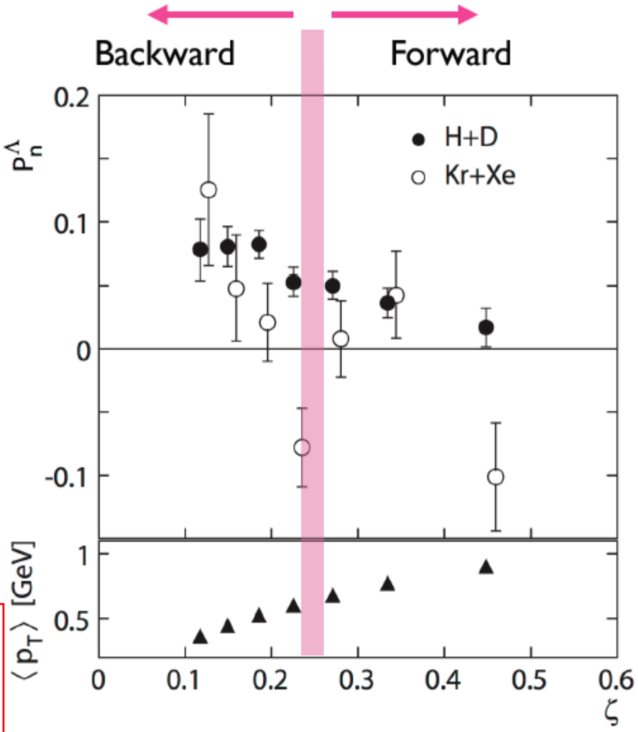
$$\frac{dN}{d\Omega} = \frac{dN_0}{d\Omega}(1 + \alpha P_n^\Lambda \cos\theta)$$



$$\zeta = \frac{E^\Lambda + p_L}{E_e + p_e}$$







Positive polarization in light nuclei
Polarization increases in target region

Measurements of Lambdas provide important information on spin-orbit correlations in target fragmentation region

π^0 new opportunities

High efficiency reconstruction of π^0 ρ+ ,η opens a new avenue in SIDIS and DVMP

SIDIS with neutral pions

1) Simple PID by π^0-mass (no kaon contamination)
2) SIDIS π^0 production is not contaminated by diffractive ρ
3) Less contaminated by resonance production
4) HT effects and exclusive π^0 suppressed
5) π^0 SSA less sensitive polarized fragmentation effects (Collins function suppressed)
6) Provides information complementary to $\pi^{+/-}$ information on PDFs

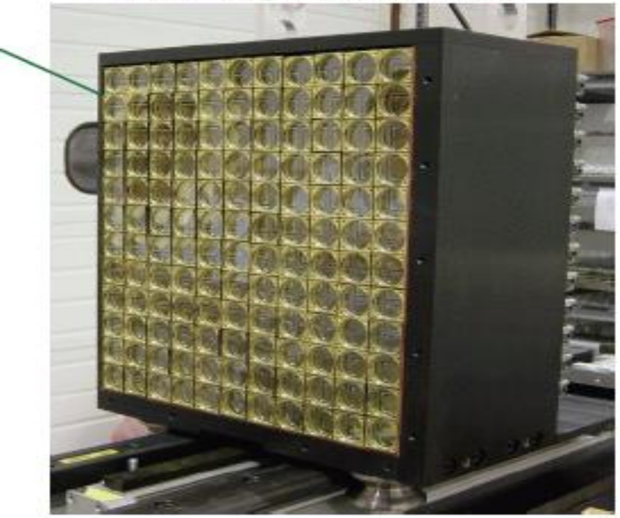
DVMP with neutral pions

1) π^0 production provides access to elusive transversity GPDs
2) Provides information complementary to $\pi^{+/-}$ information on GDFs

Detecting photons (γ, π^0,η,ρ+)

JLab Hall-A

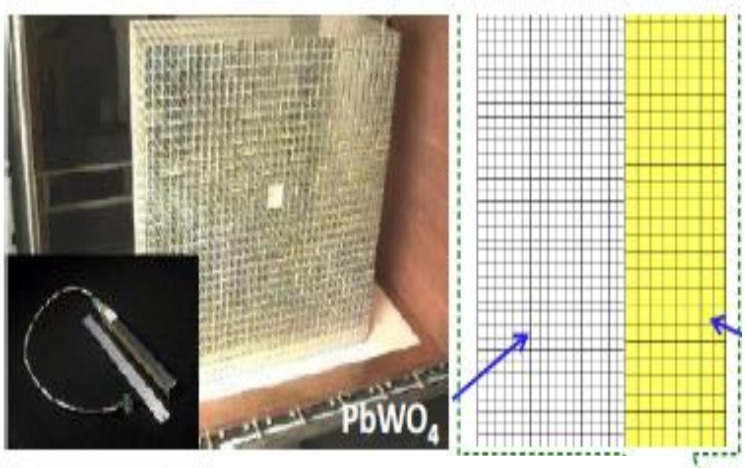
Electromagnetic Calorimeter



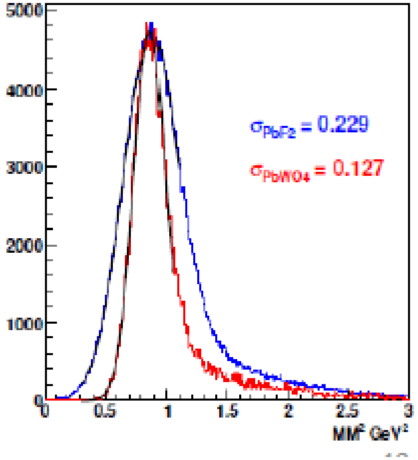
132 PbF_2 blocks
(208 in 2010)

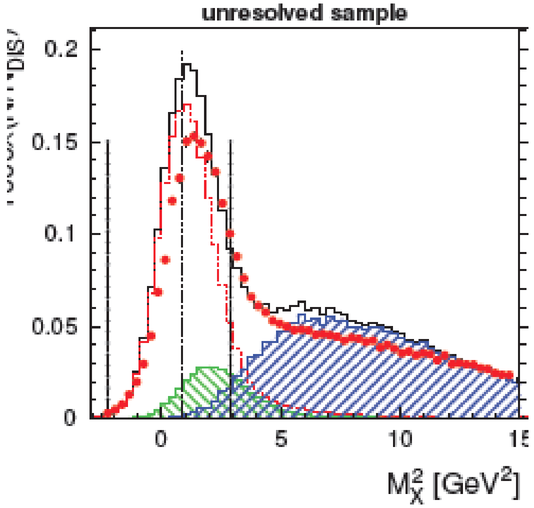
- ☐ E12-13-010 Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements (*approve*
- ☐ E12-13-007 Measurement of Semi-Inclusive π^0 production as Validation of Factorization (*approved* by P
- ☐ E12-14-003 Wide-Angle Compton Scattering at 8 &10 GeV Photon Energies (*approved* by PAC42)
- ☐ E12-14-005 Wide-Angle, Exclusive Photoproduction of π^0 (*approved* by PAC42)
- ☐ E12-14-006 Initial State Helicity Correlation in WACS (*approved* by PAC42)

Hall-C Neutral-Particle Spectrometer

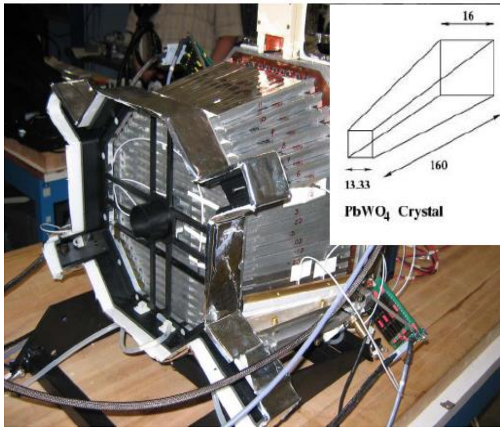


Simulated M_X^2 resolution





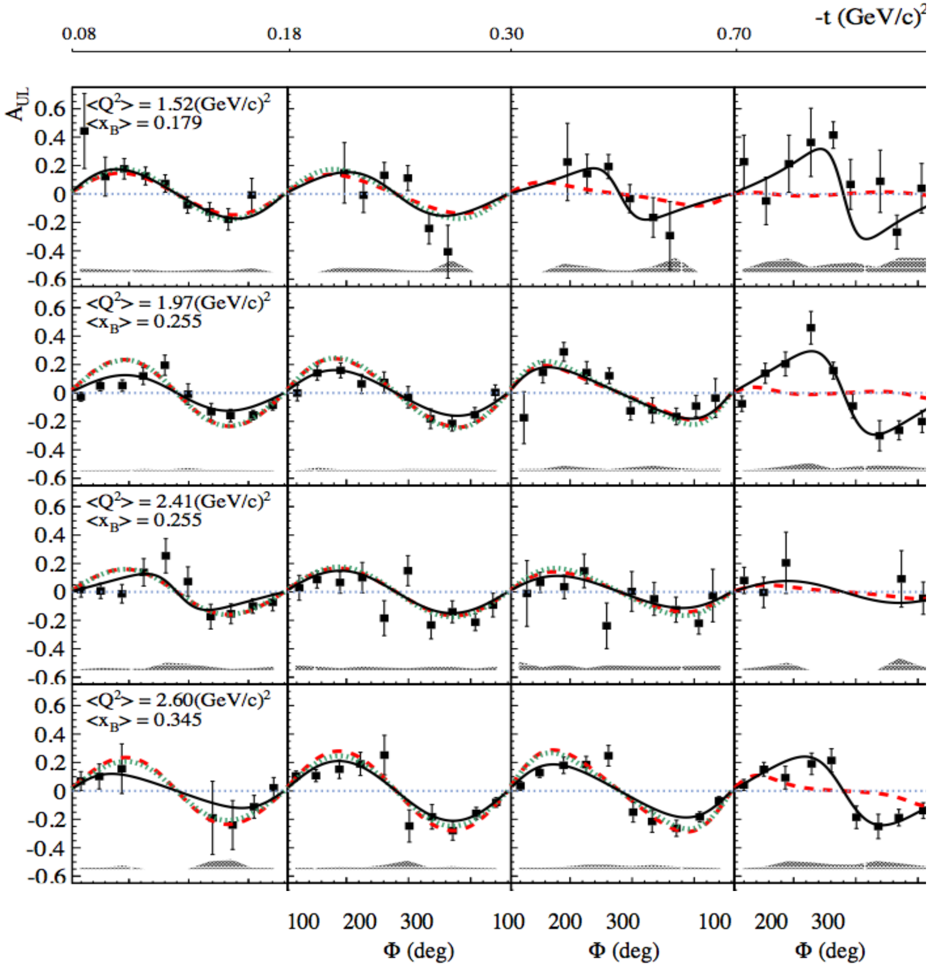
Hall-B Inner Calo

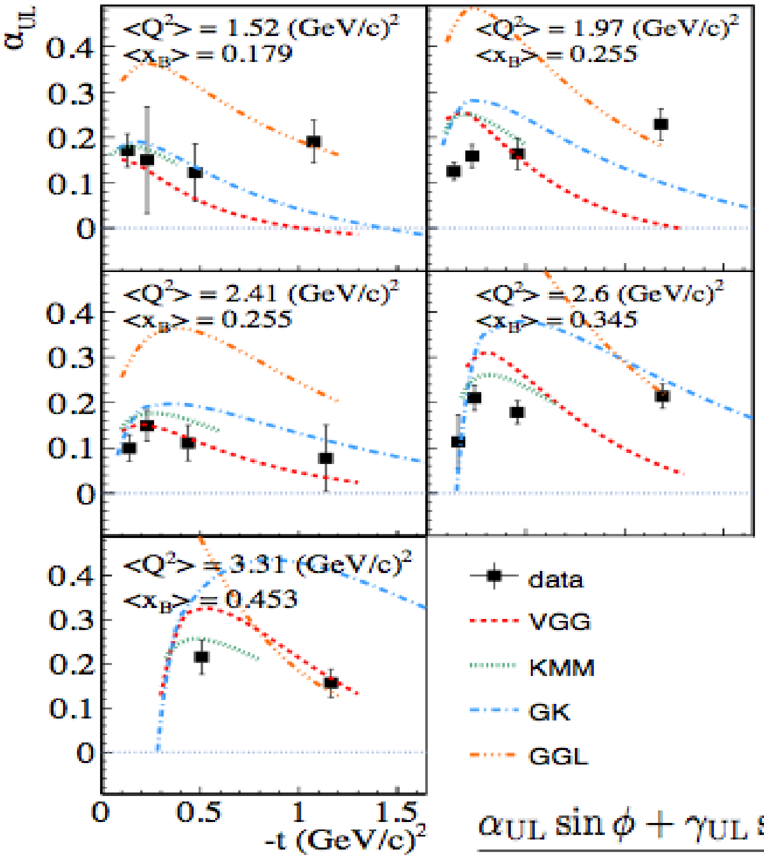


t-dependence of $\tilde{H}$

Unpolarized beam, longitudinal target (TSA) :

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





$$\frac{\alpha_{UL}\sin\phi+\gamma_{UL}\sin(2\phi)}{1+\beta\cos\phi}$$

Transverse momentum dependence of sea quark distributions

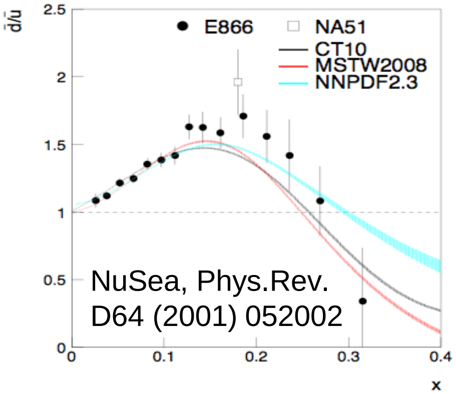
Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum distributions

$$f^a(x, k_T^2; Q^2)$$

TMD PDF for a given combination of parton and nucleon spins

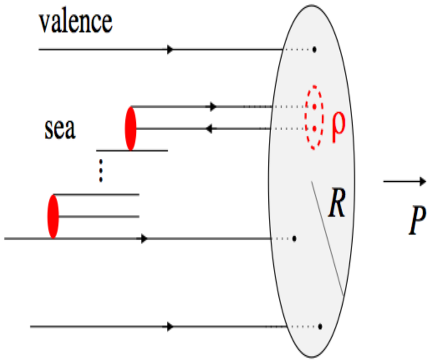
To apply the TMD formalism to data we need to understand the basic properties of the TMDs at a low scale, determined by non-perturbative QCD interactions

Nucleon could be regarded as a many-body system with short-range correlations induced by the chiral-symmetry breaking interactions.



NuSea, Phys.Rev. D64 (2001) 052002

Dynamical mechanisms producing intrinsic transverse momentum in the nucleon may be be very different for valence and sea quarks



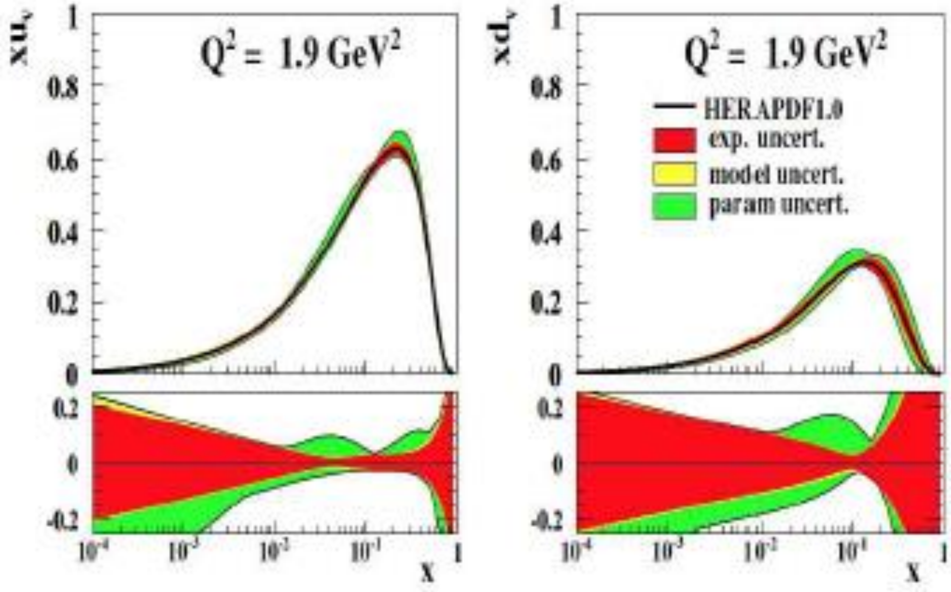
- k_T-distributions of valence quarks governed by the overall size of the nucleon of ~1fm (bag,light-front,..)
- sea k_T~vacuum fluctuations (0.3 fm), with significant contribution from short-range forces (ex. flavor structure of the sea)

- Short–range interactions $\rho \sim 0.3\,\mathrm{fm}$

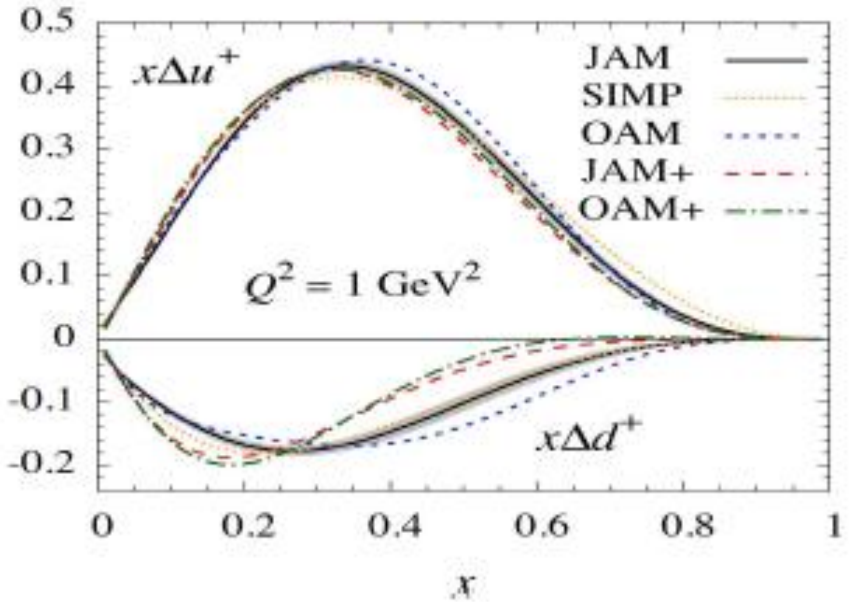
New dynamical scale $\rho \ll R$
Shuryak; Diakonov, Petrov 80's

Studies of 1D PDFs

F. Aaron et al., JHEP 1001 (2010)



P. Jimenez-Delgado et al (2014), 1403.3355.



- Strong model and parametrization dependence observed already for 1D PDFs
- Positivity requirement may change significantly the PDF (need self consistent fits of polarized and unpolarized target data!!!)

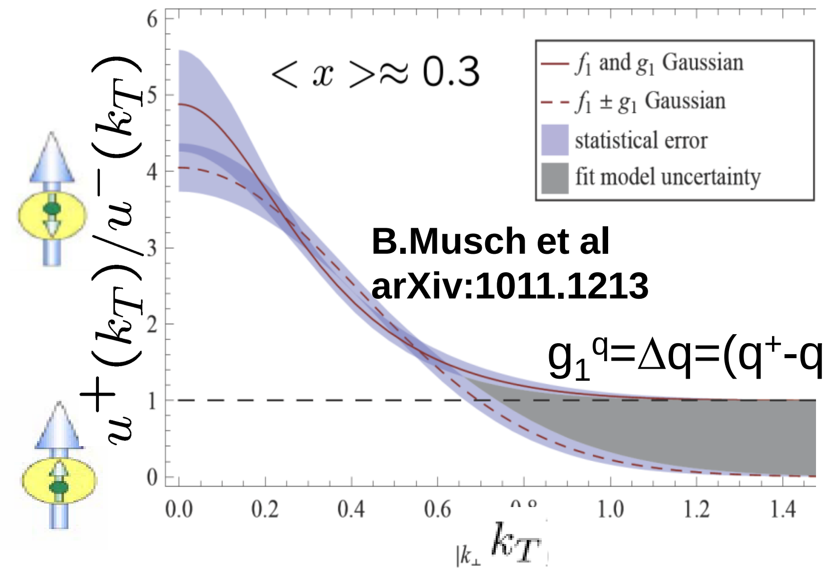
Three stages of SIDIS evolution at JLab

Any unexplained phenomenon passes through three stages before the reality of it is accepted.

- **During the first stage it is considered laughable.**
- **During the second stage, it is adamantly opposed.**
- **Finally, during the third stage, it is accepted as self-evident.**

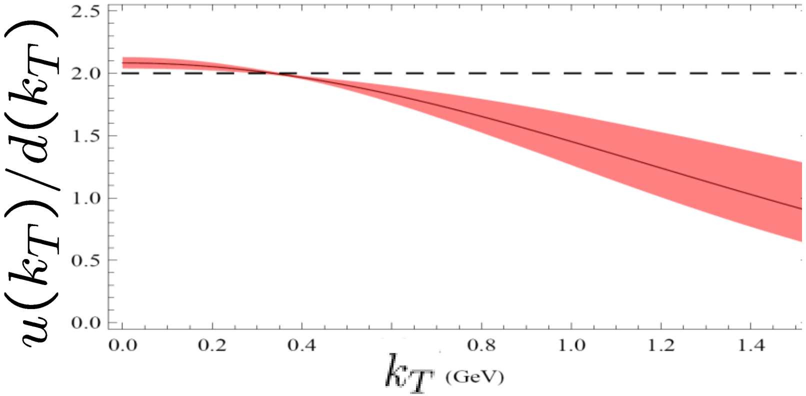
Arthur Schopenhauer

flavor and spin effects on k_T

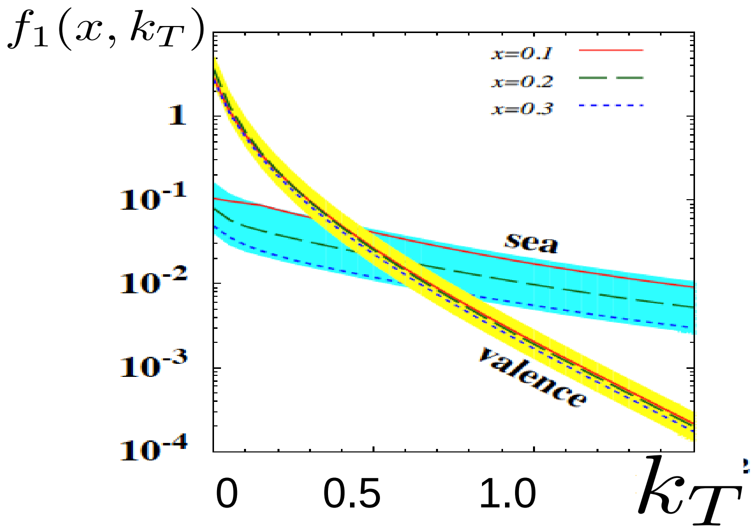


B.Musch et al arXiv:1011.1213

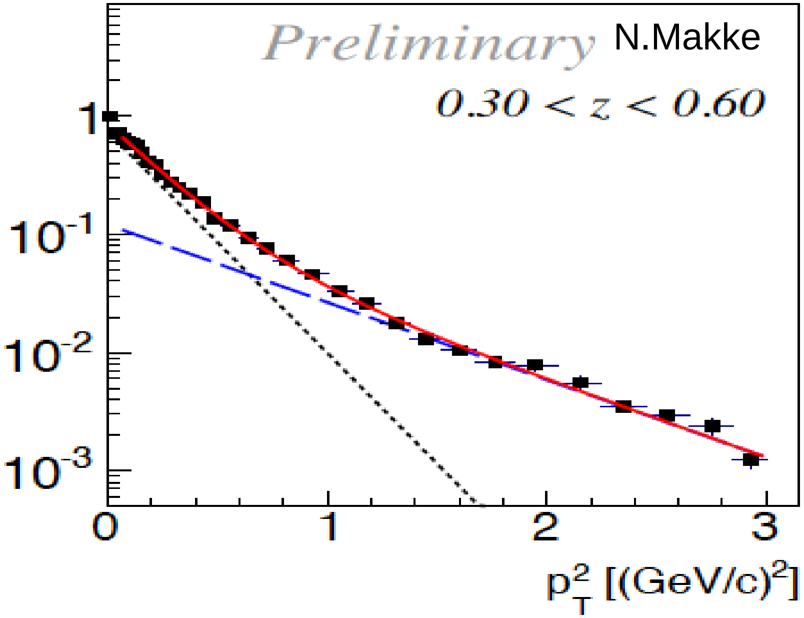
$g_1^q = \Delta q = (q^+ - q^-)/2$



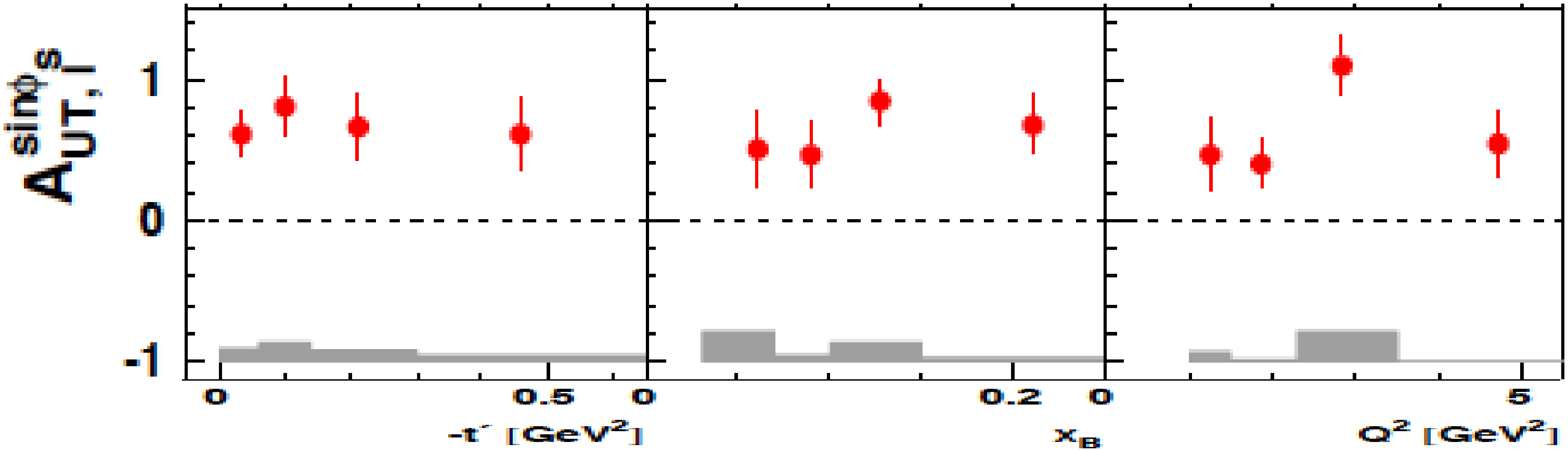
Higher probability to find a quark anti-aligned with proton spin, also more d-quarks at large k_T



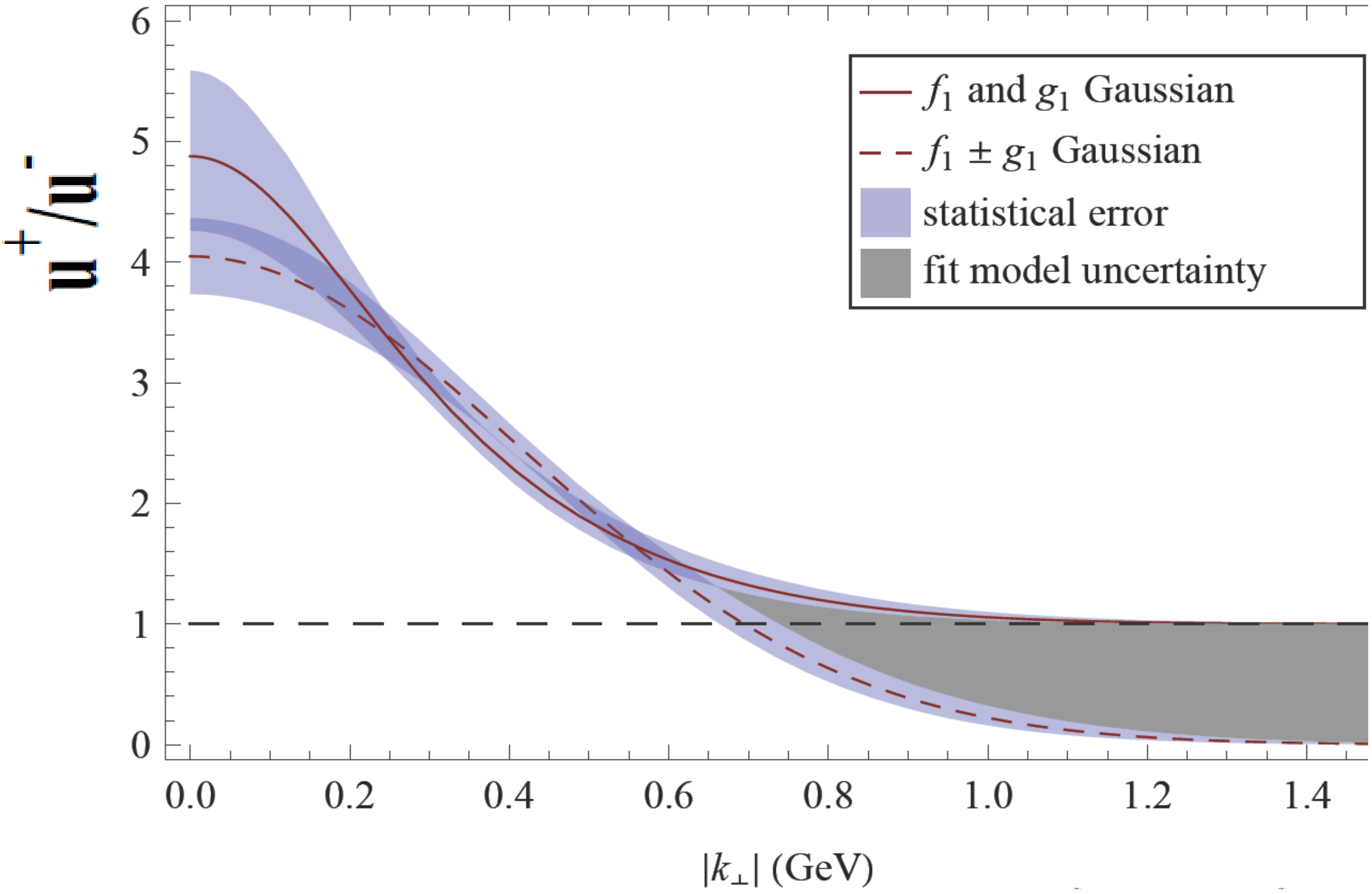
P. Schweitzer et al arXiv:1210.1267



HERMES AUT



Quark distributions at large k_T: lattice



arXiv:0705.4345

Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)