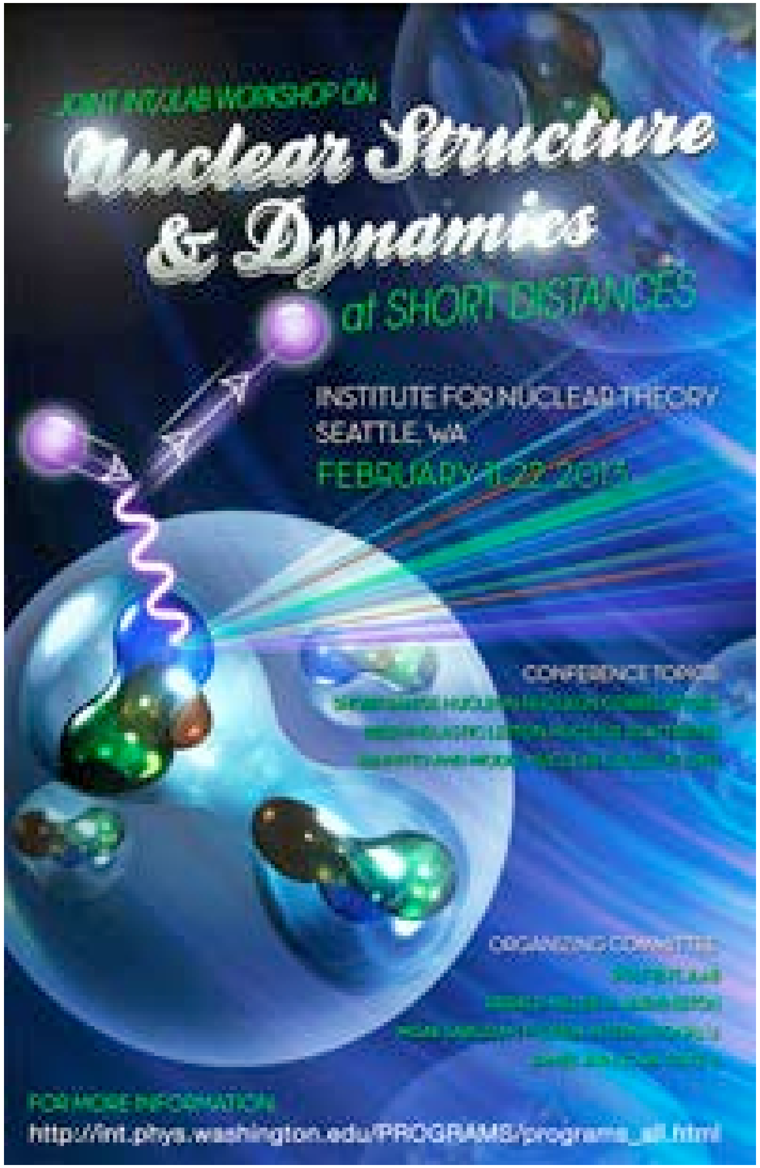
Medium Modification of Azimuthal Asymmetries in SIDIS



Harut Avakian (JLab)

INT Workshop INT-13-52W

Nuclear Structure and Dynamics at Short Distances

February 11 -22, 2013

Outline

Transverse structure of the nucleon and partonic correlations in terms of partonic degrees of freedom of QCD

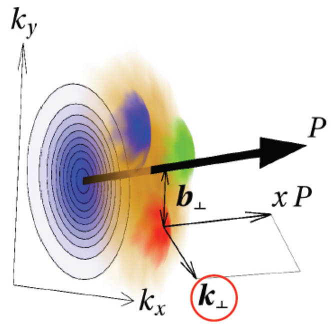
- Introduction
- Hard scattering processes and correlations between transverse and longitudinal degrees of freedom
- k_T-effects with unpolarized and polarized SIDIS
- Medium modification effects
- Studies of 3D PDFs at Jlab , JLab12 & beyond
- Summary

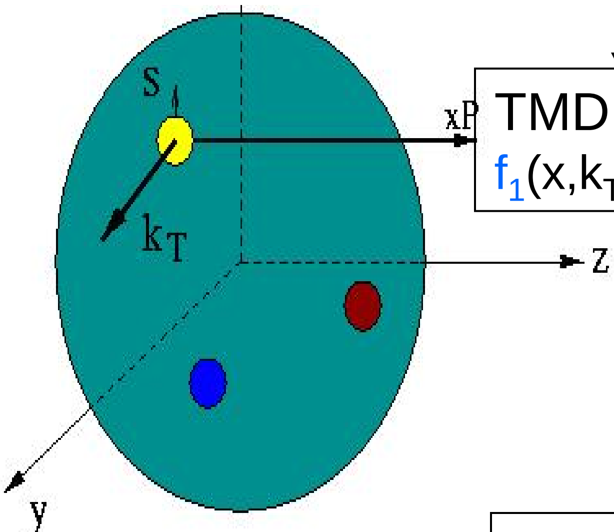
Structure of the Nucleon

$W_p^u(k,r_T)$ "Mother" Wigner distributions

d^2r_T d^2k_T

GPDs/IPDs

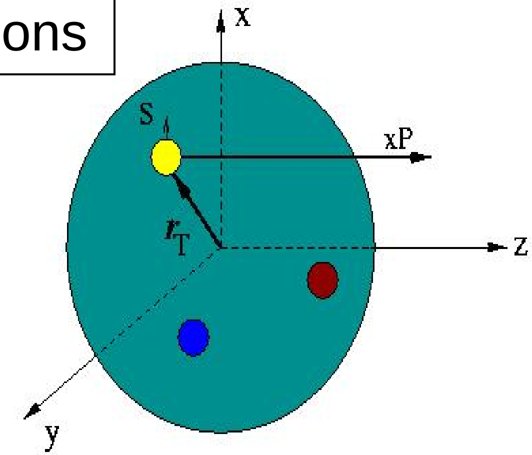




TMD PDFs
$f_1(x,k_T)$, $g_1(x,k_T)$, ..

d^2k_T

PDFs $f_1^u(x)$, $g_1^u(x)$,..



quark polarization

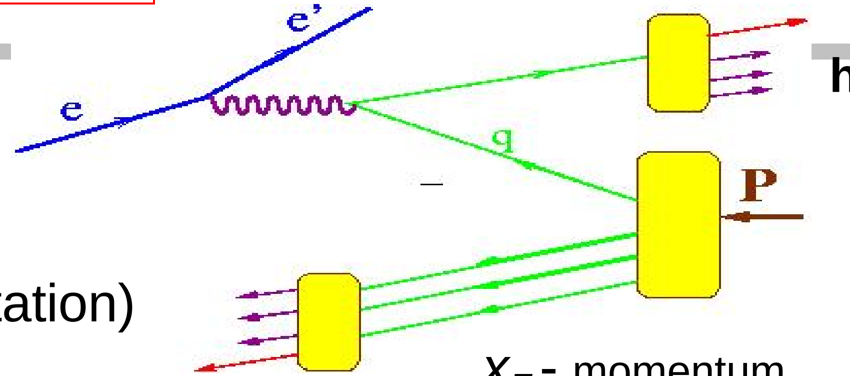
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Proton polarization

- Gauge invariant definition (Belitsky,Ji,Yuan 2003)
- Universality of k_T-dependent PDFs (Collins,Metz 2003)
- Factorization for small k_T (Ji,Ma,Yuan 2005)
- Evolution of TMDs, (Collins,Aybat,Rogers 2011)

Single hadron production in hard scattering

$x_F>0$ (current fragmentation)



$x_F<0$ (target fragmentation)

x_F - momentum in the CM frame

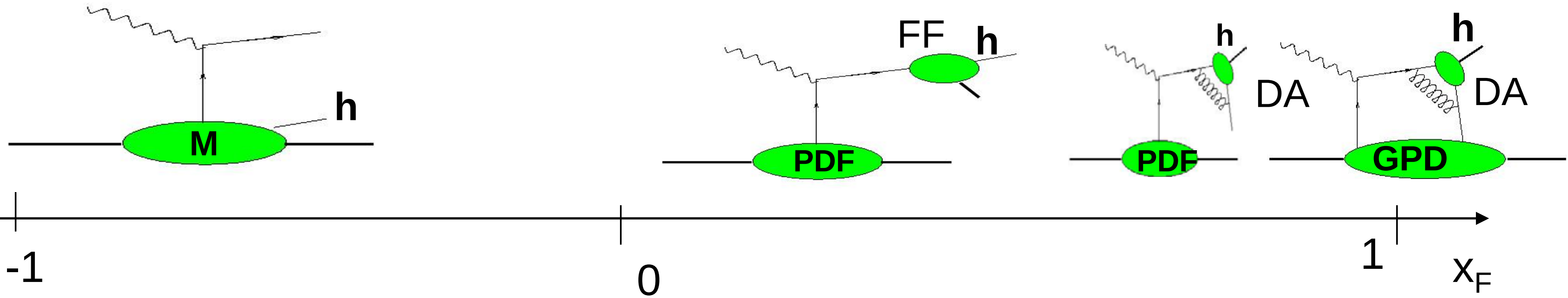
Target fragmentation

Current fragmentation

semi-inclusive

semi-exclusive

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

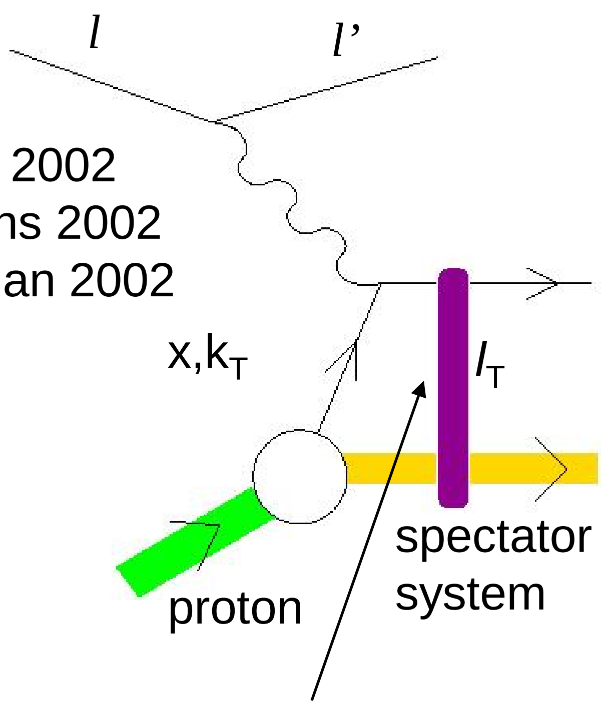
k_T and FSI

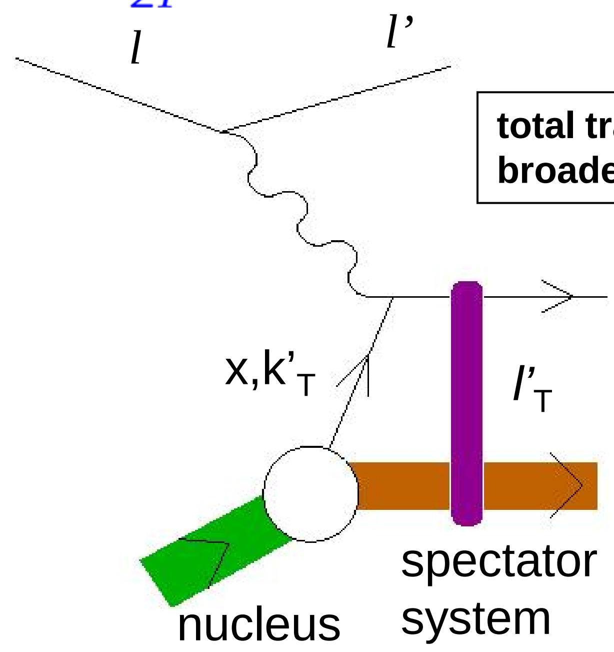
Tang,Wang & Zhou
Phys.Rev.D77:125010,2008

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

total transverse momentum broadening squared

BHS 2002
Collins 2002
Ji,Yuan 2002

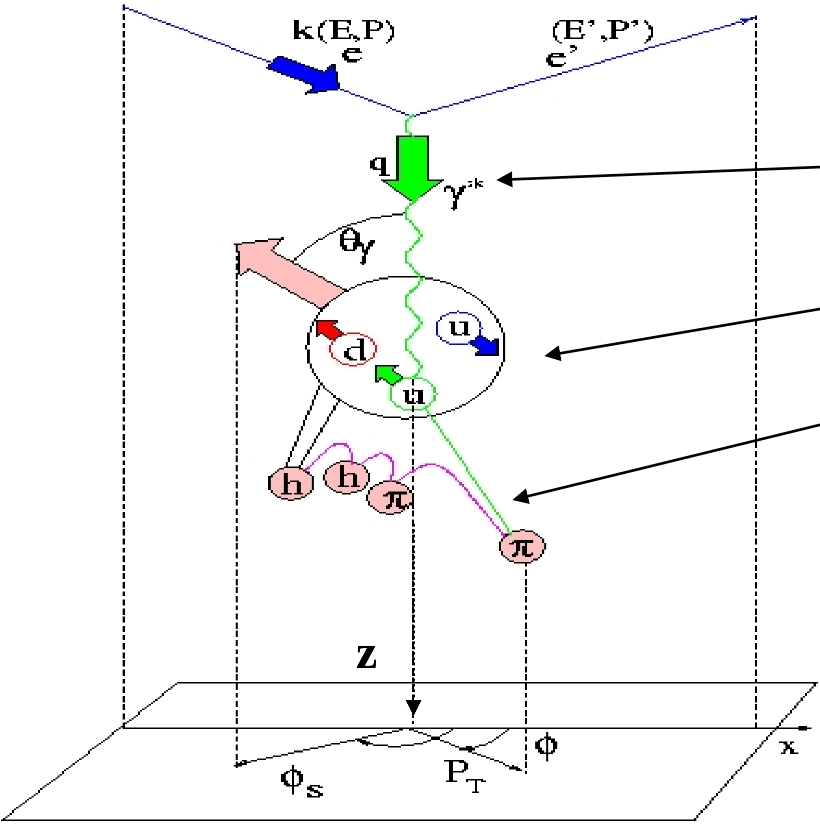




the intrinsic transverse momentum of partons arises naturally from multiple soft gluon interaction inside the nucleon or nucleus.

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

Polarized Semi-Inclusive DIS



$$\nu = E - E'$$
$$Q^2 = (k - k')^2$$
$$y = \nu / E$$
$$x = Q^2 / 2M\nu$$
$$z = E_h / \nu$$

$$d\sigma^h \propto \sum q_f(x) \otimes \mathbf{d}\sigma_f(y) \otimes D_f^{q \to h}(z)$$

Hadron-Parton transition: by distribution function $f_1^u(x)$ probability to find a **u**-quark with a momentum fraction ***x***

Parton-Hadron transition: by fragmentation function $D_u^{q \to \pi}(z)$ probability for a **u**-quark to produce a $\pi^+(\pi^-)$ with momentum fraction ***z***

Target polarization **Beam polarization**

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

$$A_{UL}^{\sin 2\phi} = \frac{\sigma_{UL}}{\sigma_{UU}}$$

sin2ϕ moment of the cross section for unpolarized beam and long. polarized target

Azimuthal moments in SIDIS

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

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, $h_T^\perp$, $e_T^\perp$

$D_1^{q\rightarrow h}$ | $H_1^{\perp q\rightarrow h}$

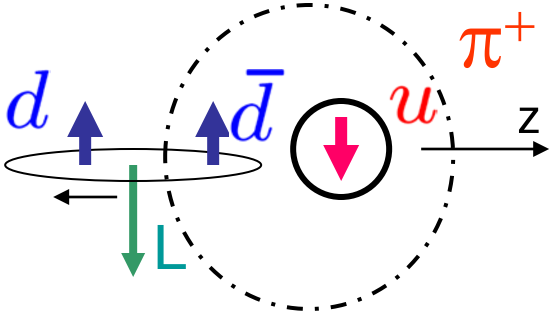
Experiment for a given target polarization measures all moments simultaneously

Azimuthal dependence in hard scattering

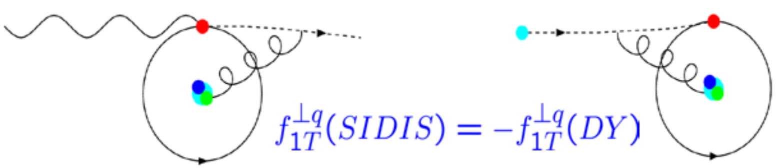
Collins mechanism/ asymmetries generated in the hadronization process of transversely polarized quarks

$$D(z,P_T)=D_1(z,P_T)+H_1 4\,(z,P_T)\ \sin(\phi_C)$$

- **L/R SSA generated in fragmentation**
- **Unfavored SSA with opposite sign**
- **No effect in target fragmentation**



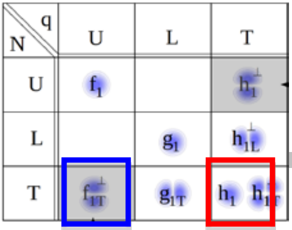
Sivers mechanism/ asymmetries in the distribution due to final state interactions!



SIDIS

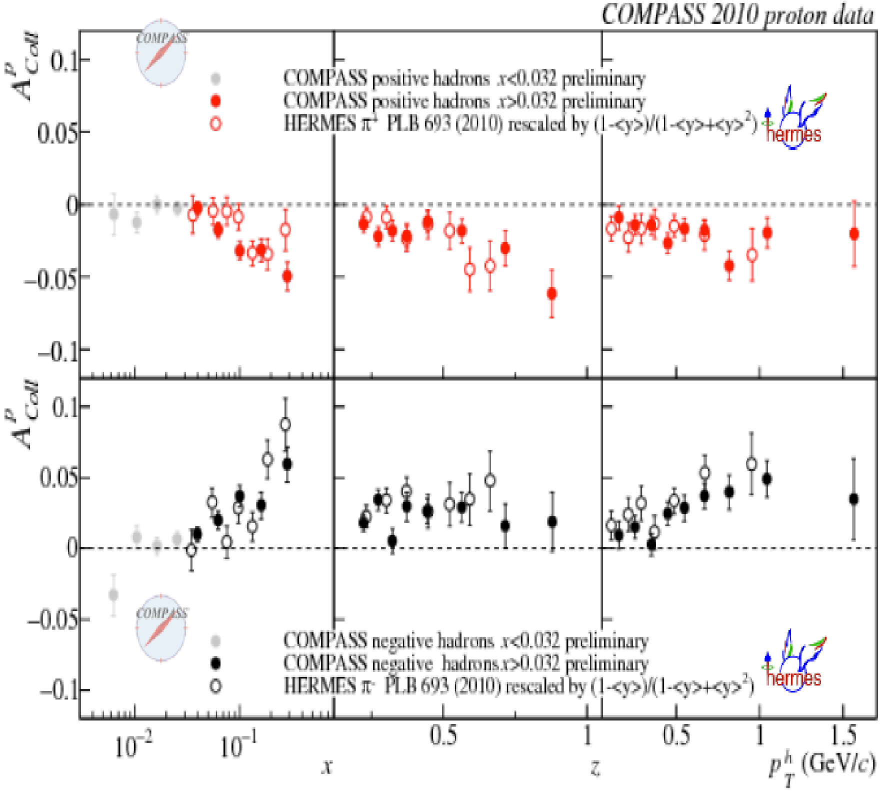
Drell-Yan

- **L/R SSA generated in distribution**
- **Hadrons from struck quark have the same sign SSA**
- **Opposite effect in target fragmentation**

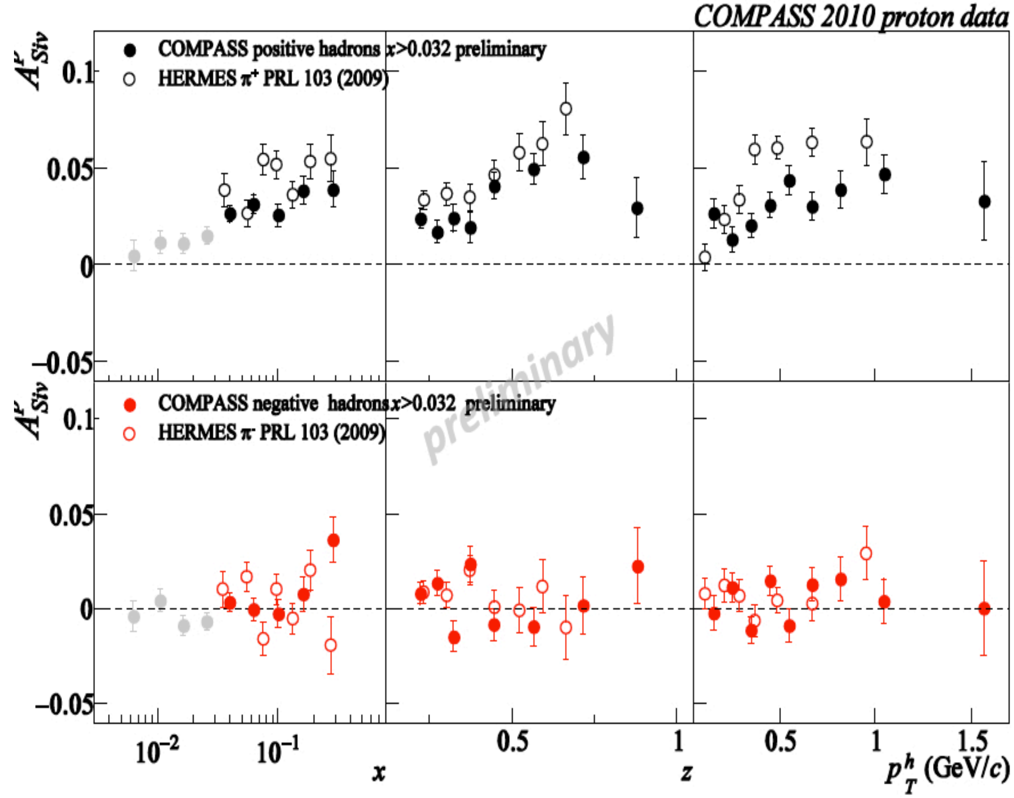


TMD Distributions: Transverse target

$h_1 H_1^{\perp}$



$f_{1T}^{\perp} D_1$



- Large Collins effect with opposite sign for π– (suppressed for π0)
- Large Sivers effect for π+/0 with small effect for π–
- Data suggests Q^2 evolution of Sivers function may be significant

Correlations of spin, longitudinal and transverse degrees

- What are the k_T distributions of partons?
- Do they depend on spin and flavor of partons?
- Do they modify in medium, and how ?
- 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?

Possible new tools:

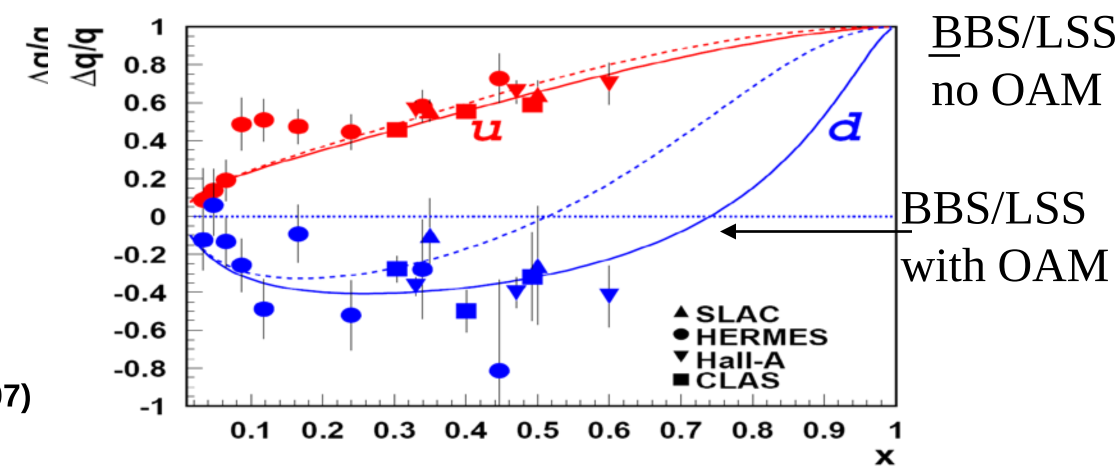
- Polarized DIS resolve the spin effects in medium
- Polarized and unpolarized SIDIS resolve flavor and spin effects

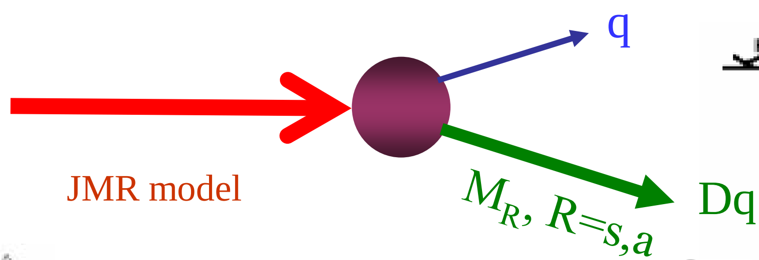
Quark longitudinal polarization

$$u^+(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

$$u^-(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

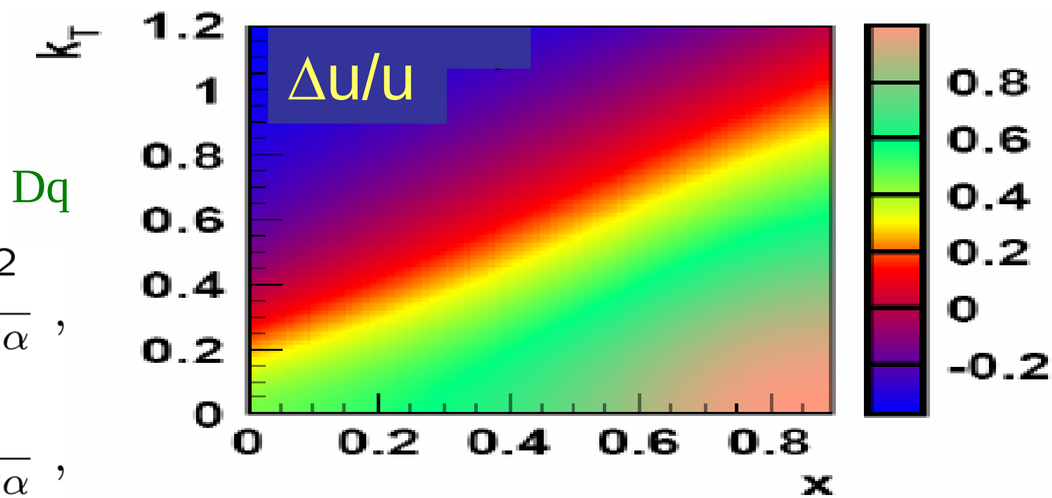
Effect of the orbital motion on the q- may be significant (H.A.,S.Brodsky, A.Deur,F.Yuan 2007)





$$u^+(x,\mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

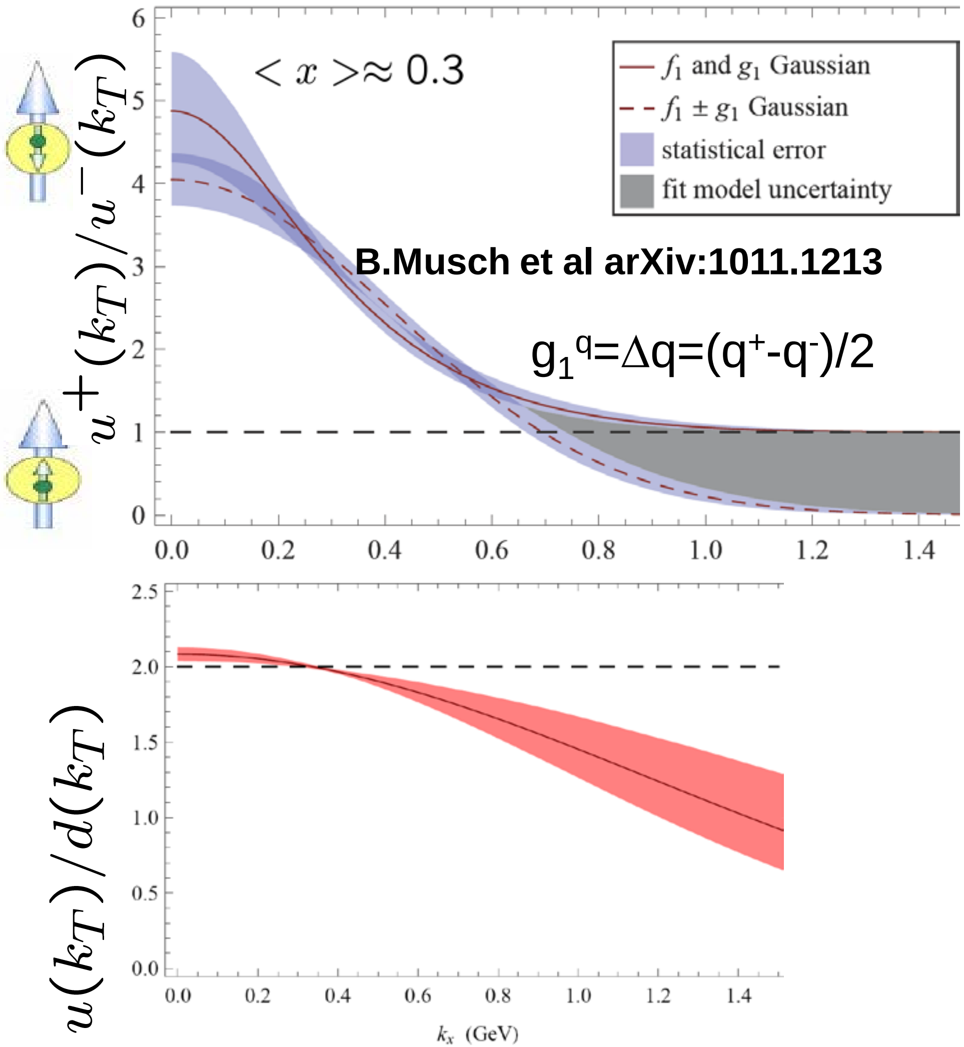
$$u^-(x,\mathbf{k}_T^2) \propto \frac{\mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$



(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian

For given x the sign of the polarization asymmetry may change at large k_T!!!

Quark distributions at large k_T: lattice

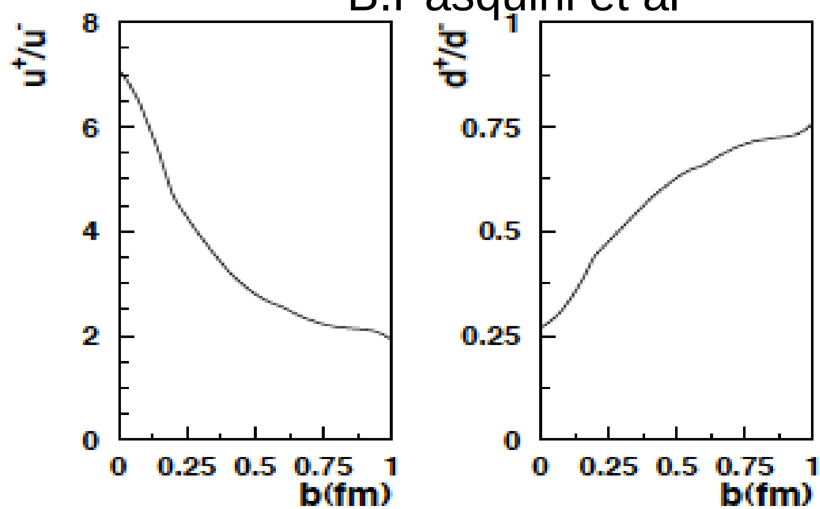


$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

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

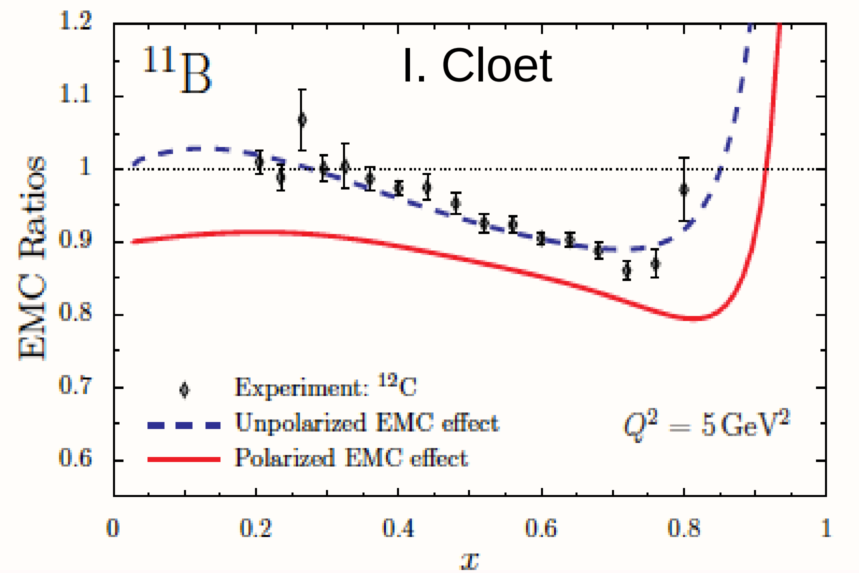
Higher probability to find a quark anti-aligned with proton spin at large k_T and b_T

B.Pasquini et al



k_T-distributions of TMDs may depend on flavor and spin

Medium modified spin observables (NJL model)



Proton spin states	Δu	Δd	Σ	g_A
p	0.97	-0.30	0.67	1.267
^{7}Li	0.91	-0.29	0.62	1.19
^{11}B	0.88	-0.28	0.60	1.16
^{15}N	0.87	-0.28	0.59	1.15
^{27}Al	0.87	-0.28	0.59	1.15
Nuclear Matter	0.79	-0.26	0.53	1.05

EMC effect essentially a consequence of binding at the quark level

- Angular momentum of nucleon: $J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$
  - in medium $M^* < M$ and therefore quarks are more relativistic
  - lower components of quark wavefunctions are enhanced
  - quark lower components usually have larger angular momentum
  - $\Delta q(x)$ very sensitive to lower components
- Conclusion: quark spin → orbital angular momentum in-medium

Polarized EMC effect using the CLAS12 detector

Individual Letter of Intent Report

Letter of Intent: LOI-10-005

Title: The EMC Effect in Spin Structure Functions

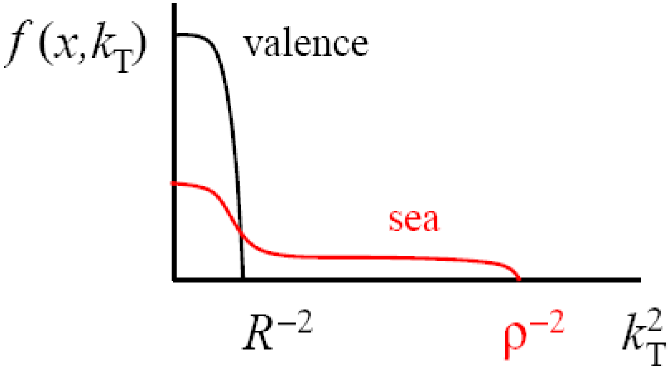
Spokespersons: W. Brooks

Motivation:
The proposed measurements are inclusive spin-dependent asymmetry measurements using a longitudinally polarized ^{7}LiH target in the DIS kinematics with a Q^2 ranging from 2 to 9 $(GeV/c)^2$ and x ranging from 0.1 to 0.7. The goal of the proposed experiment is to determine the spin structure function ratio of $g_1(Li)/g_1(p)$ in order to investigate whether there is a spin EMC effect.

Issues:

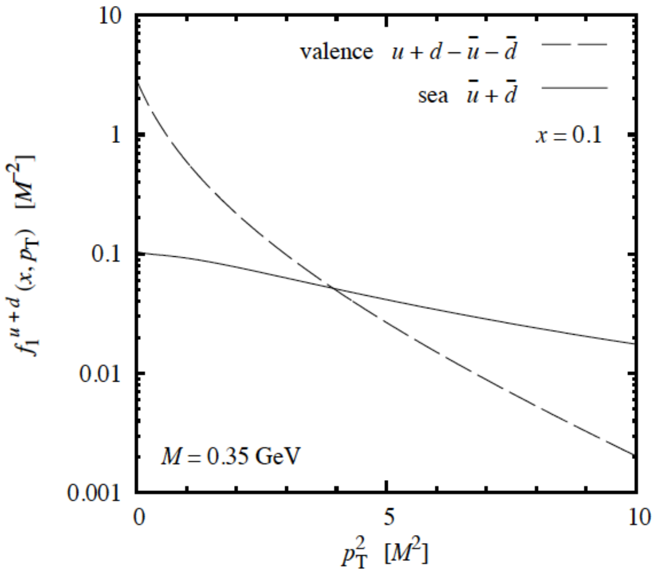
- How to remove the neutron contribution in 7Li to the spin-dependent asymmetry in order to extract g1p(Li).
- Effect of Final State Interactions on effective proton polarization in 7Li, uncertainty in the nuclear spin structure

Intrinsic k_T: Valence vs. sea quarks



- Valence and sea quarks have different intrinsic k_T distributions

valence	$k_T \sim R^{-1}$	nucleon size
sea	$k_T \sim \rho^{-1}$	vacuum fluctuations



$\rightarrow$ Effect of QCD vacuum structure

- Average transverse momentum of sea determined by size of vacuum fluctuations: $\langle k_T^2 \rangle \sim \rho^{-2}$ Power-like tail $f^{\bar{q}}(x, p_T) \sim C(x)/p_T^2$ up to cutoff scale ρ^{-2}
- **chiral quark soliton model:** based on QCD vacuum from instanton

$$< k_T^2 >_{sea} \approx 3 < k_T^2 >_{val}$$

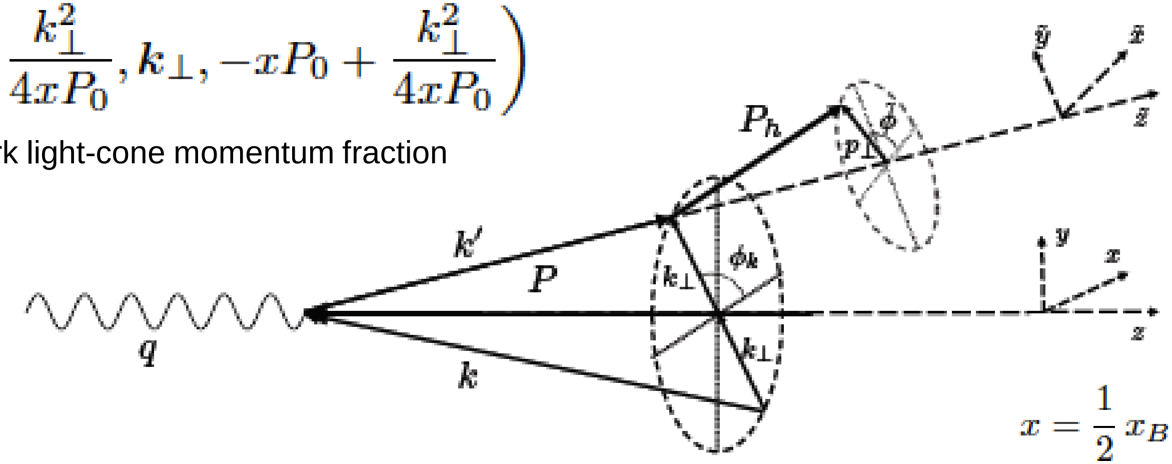
Schweitzer, Strikman, Weiss; arXiv:1210.1267

Monte-Carlo simulation of SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,d\mathbf{p}_\perp^2\,d\mathbf{k}_\perp^2} = K\left[\sum_q J\left\{f_q(x,k_\perp)D_{q,h}(z,p_\perp) + \lambda\sqrt{1-\epsilon}\,g_q(x,k_\perp)D_{q,h}(z,p_\perp)\right\}\right]$$

$$k = \left(xP_0 + \frac{k_\perp^2}{4xP_0}, k_\perp, -xP_0 + \frac{k_\perp^2}{4xP_0}\right)$$

Quark light-cone momentum fraction



$$x = \frac{1}{2}x_B\left(1+\sqrt{1+\frac{4k_\perp^2}{Q^2}}\right)$$

$$f_1(x,k_\perp) = f_1(x)\frac{e^{-\frac{k_\perp^2}{<k_\perp^2>x(1-x)}}}{<k_\perp^2>x(1-x)} \qquad D_1(z,p_\perp) = D_1(z)\frac{e^{-\frac{p_\perp^2}{<p_\perp^2>z(1-z)}}}{<p_\perp^2>z(1-z)}$$

MC differential in quark transverse momenta is required to understand details of correlations

Kinematic correlations at finite Q^2

From energy/momentum conservation

$$xP_0 + \frac{k_\perp^2}{4xP_0} \le P_0 \;\Rightarrow\; k_\perp^2 \le 4x(1-x)P_0^2$$

energy of the parton have to be less than the energy of the parent hadron

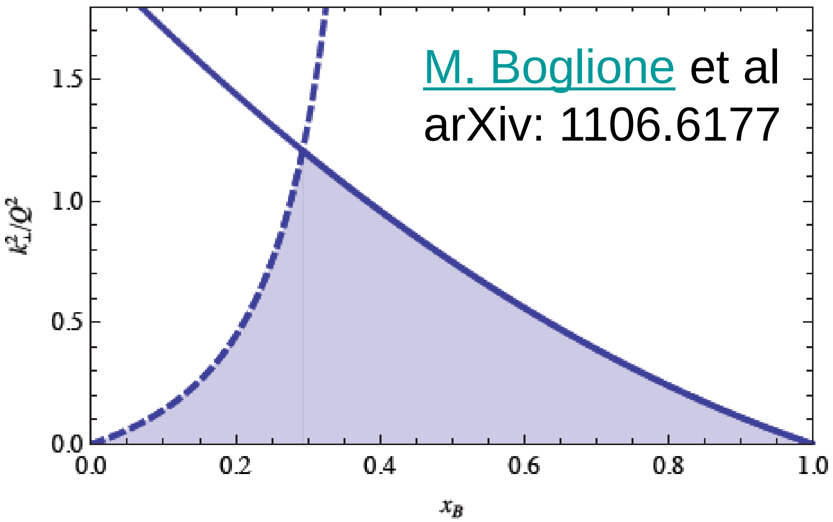
$$\Rightarrow\; k_\perp^2 \le (2-x_B)(1-x_B)Q^2$$

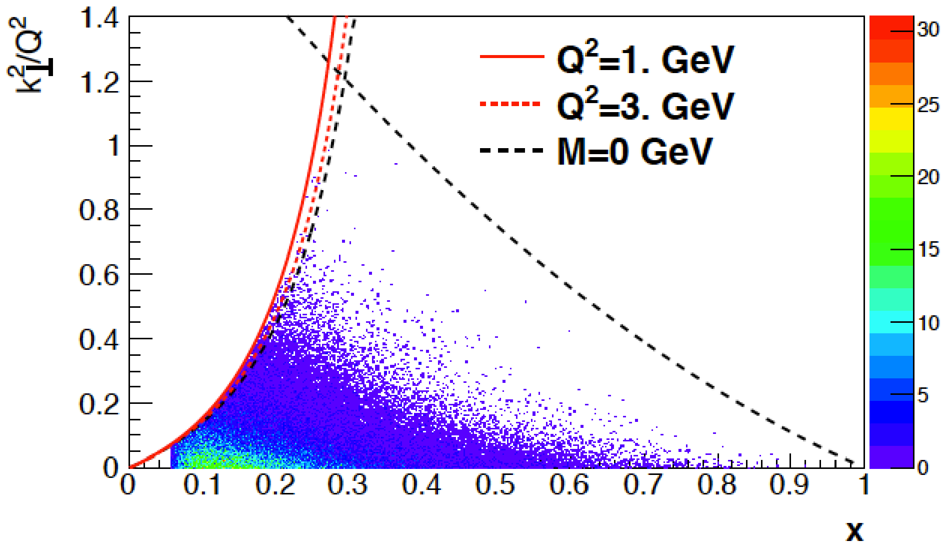
$$f_q(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$

Requiring the parton to move in the forward direction

$$(P\cdot k) > 0 \;\Rightarrow\; k_\perp^2 \le 4x^2P_0^2$$

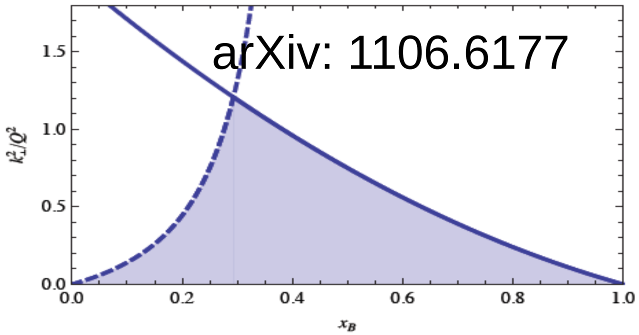
$$k_\perp^2 \le \frac{x_B(1-x_B)}{(1-2x_B)^2}Q^2$$



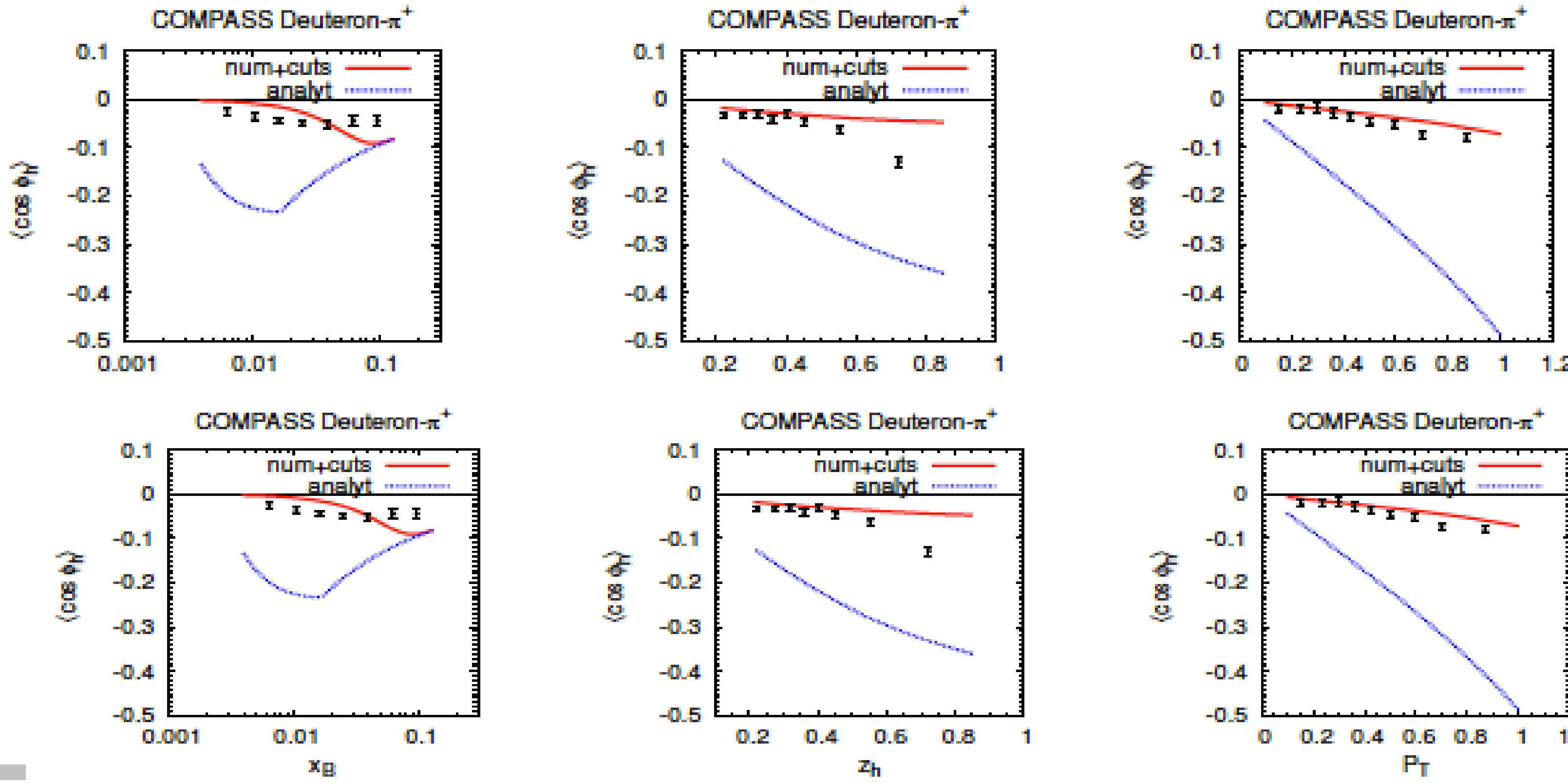


x and k_T are not independent at low Q^2 even in factorized Gaussian approach!

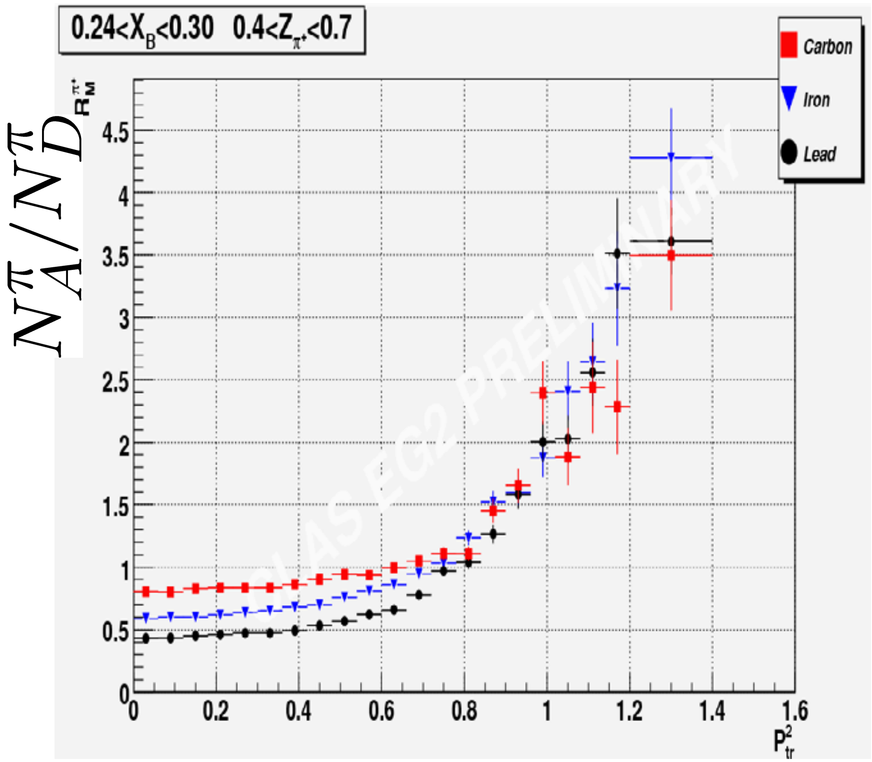
Kinematic correlations at finite Q^2



x and k_T are not independent at low Q^2 even in factorized Gaussian approach!

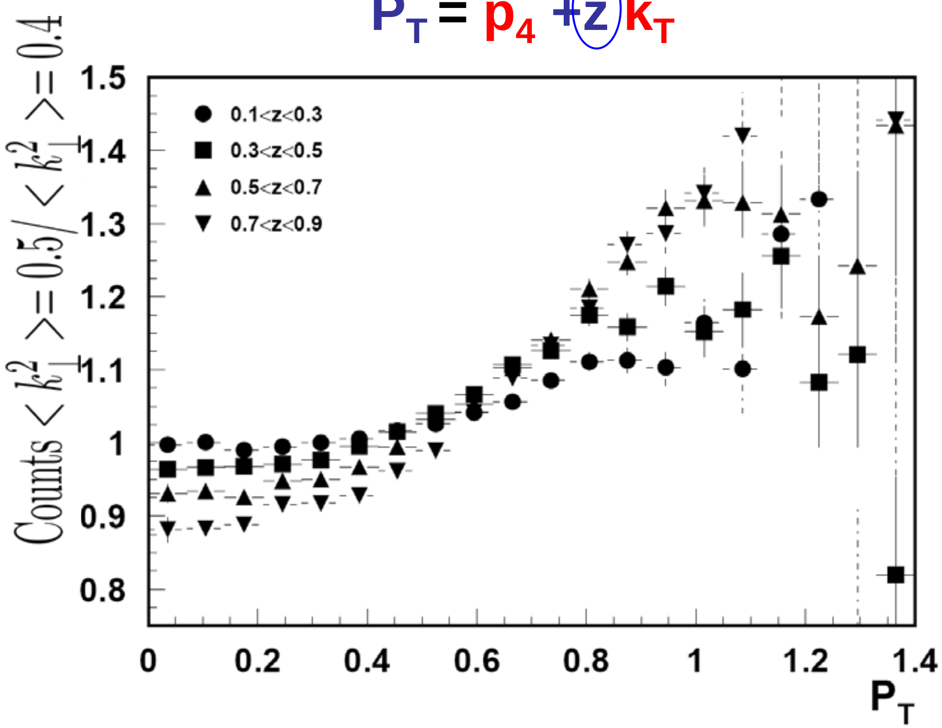


Quark distributions at large k_T



bigger effect at large z

$P_T = p_4 + z k_T$



Higher probability to find a hadron at large P_T in nuclei

k_T-distributions may be wider in nuclei?

Understanding of modification of k_T widths in nuclei is important also for nucleon TMDs

Azimuthal distributions in SIDIS

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

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

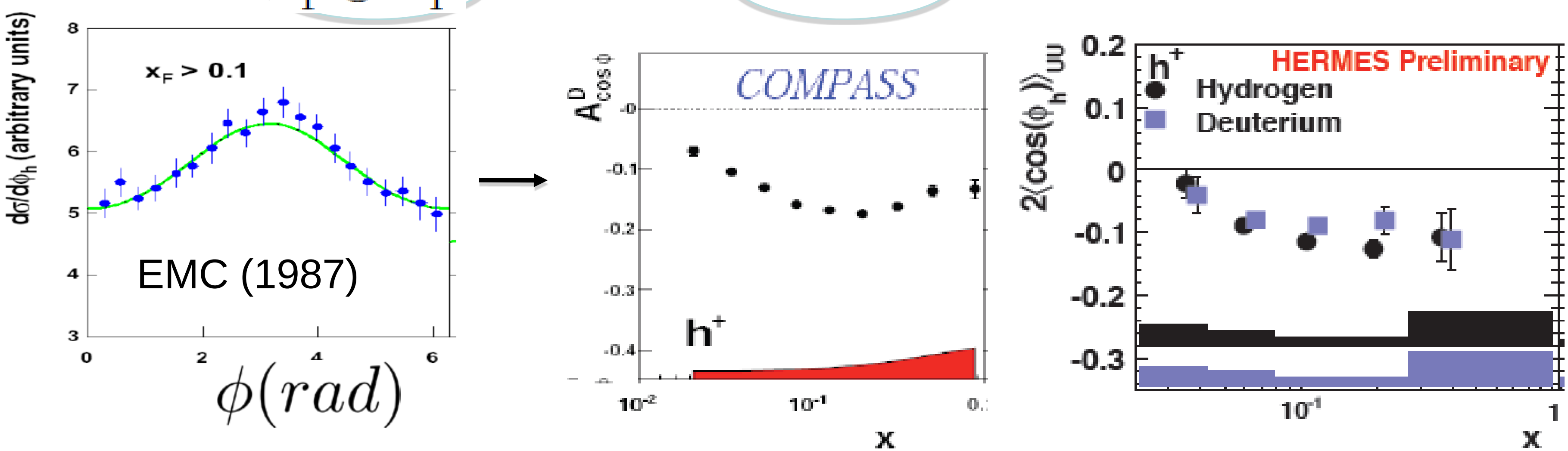
$f_1 \otimes D_1$

h.t.

h.t.

$h_1^\perp \otimes H_1^\perp$

h.t.



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

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

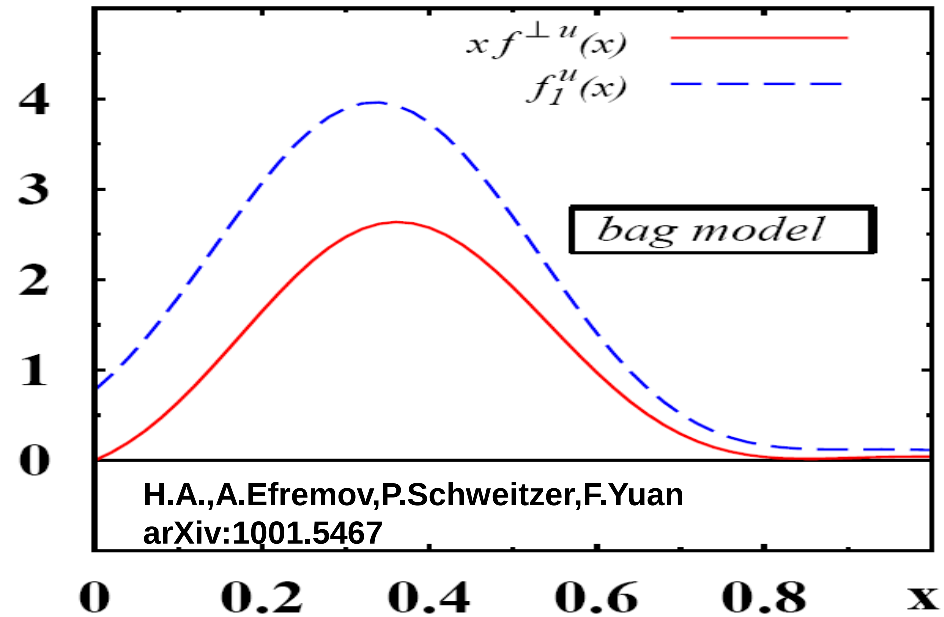
N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^{\perp}$

Twist-3

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

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

"interaction dependent" ➔ 0 if one neglects the soft gluon interaction



No leading twist ➔ provides access to quark-gluon correlations

First data available from lattice!

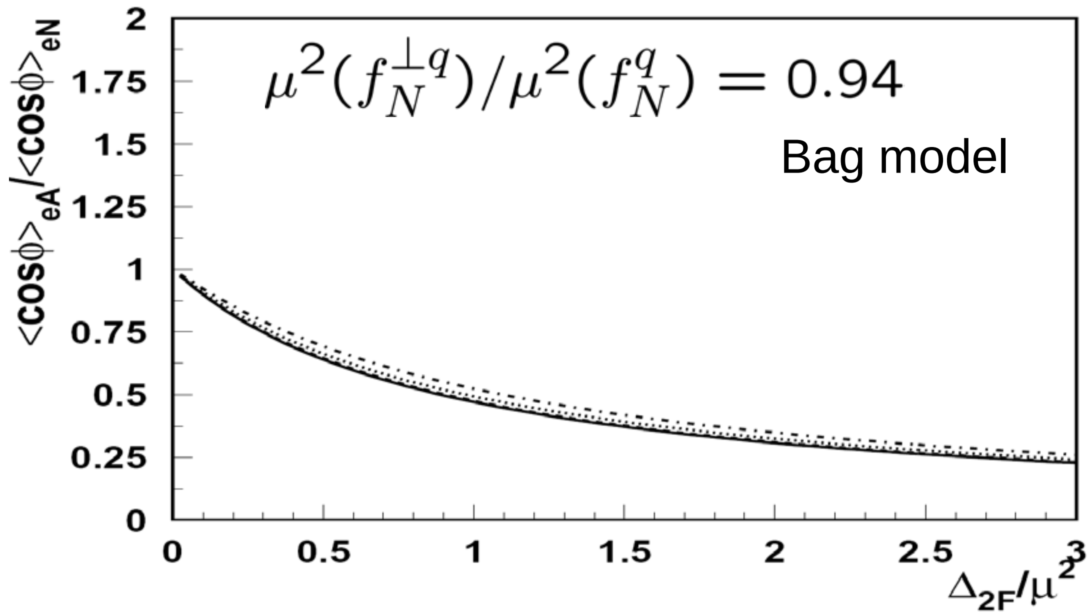
$F_{UU}^{\cos\phi} \propto f^{\perp q} D_1^q$ Modification of Cahn effect

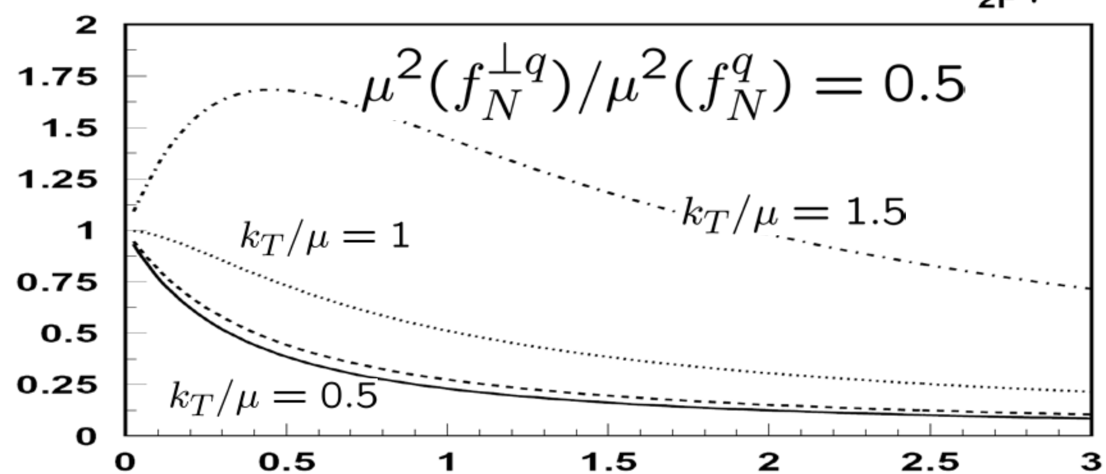
$$< \cos\phi >_{eN} \propto \frac{|\vec{k}_T| x f_N^{\perp q}(x, k_T)}{f_N^q(x, k_T)}$$

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

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

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





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 of cos2ϕ moment in SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,d^2\vec{P}_h} = \frac{4\pi\alpha^2 s}{Q^4}[x(1-y+y^2/2)F_{UU}$$

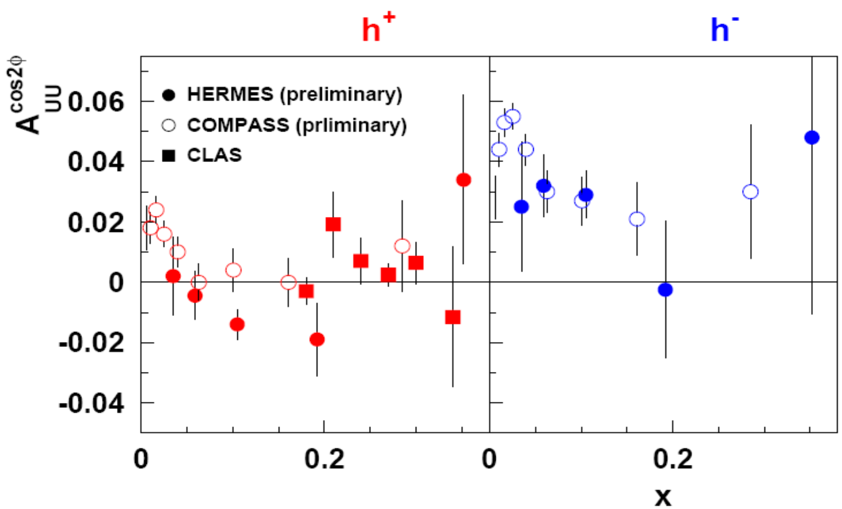
$$-x(1-y)\cos(2\phi)F_{UU}^{\cos 2\phi}]$$

TMD PDFs

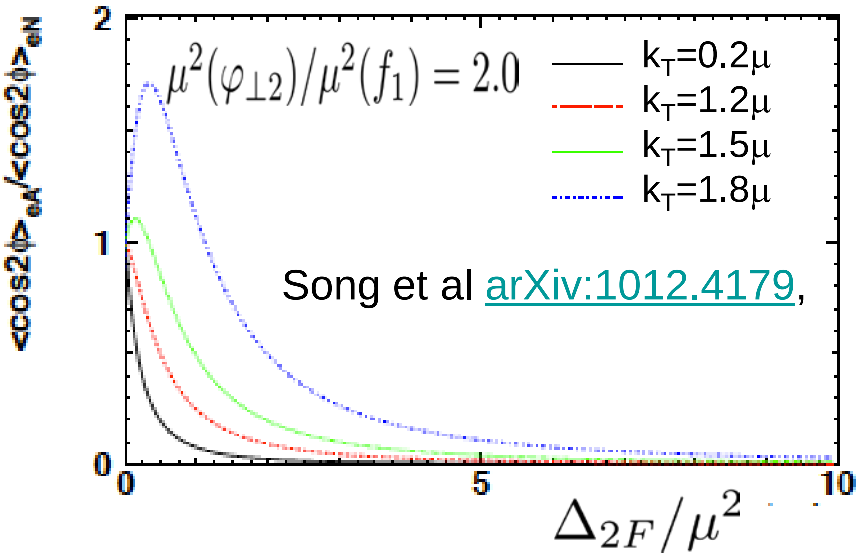
$f_1 D_1$

at leading twist $\longrightarrow h_1^\perp H_1^\perp$

Boer-Mulders contribution probes the polarized fragmentation function (suppressed for π^0!)



at twist 4 (Cahn effect)

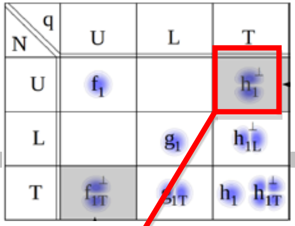


Song et al arXiv:1012.4179,

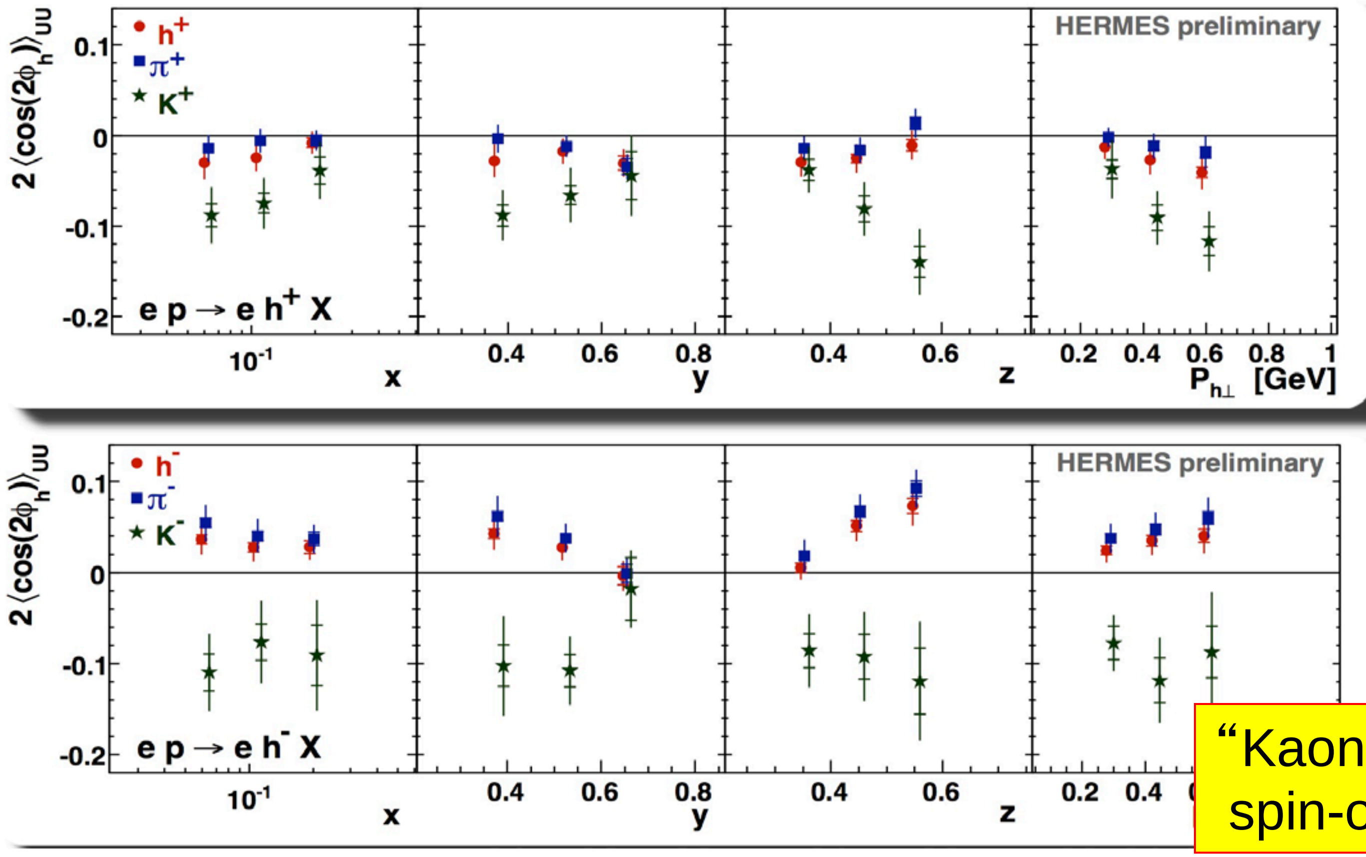
- **Measurements of cos2ϕ from different experiments consistent**

calculations of the azimuthal asymmetries are valid in the small transverse momentum region where NLO pQCD corrections are not dominant.

Kaon <cos2ϕ> @ HERMES



$h_1^{\perp} H_1^{\perp}$



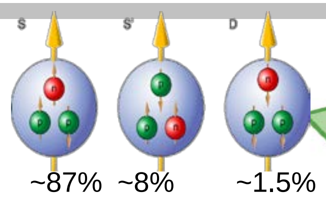
$K^-\{s\bar{u}\}$ $K^+\{u\bar{s}\}$

$H_1^{\perp,u\to K^-} \overset{?}{\approx} H_1^{\perp,u\to K^+}$

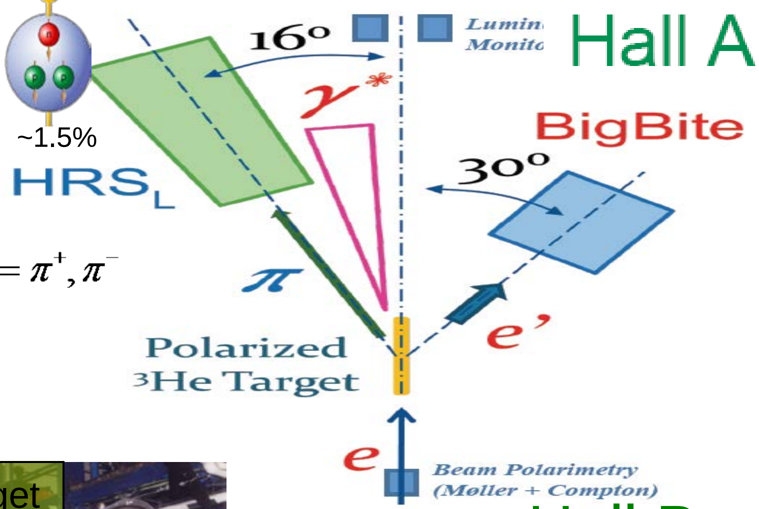
"Kaon puzzle" in spin-orbit correlations

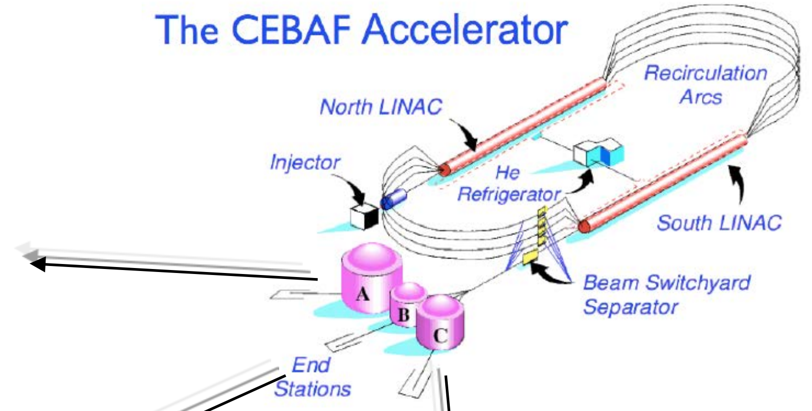
- $K^+\{u\bar{s}\}$ $\pi^+\{u\bar{d}\}$ $\xrightarrow[u-dominance]{?}$ $\frac{H_1^{\perp,u\to K^+}}{D_1^{u\to K^+}} > \frac{H_1^{\perp,u\to \pi^+}}{D_1^{u\to \pi^+}}$
- Relative sign H_1^4 fav / H_1^4 unfav for π and K inconsistent

JLab Experimental Halls

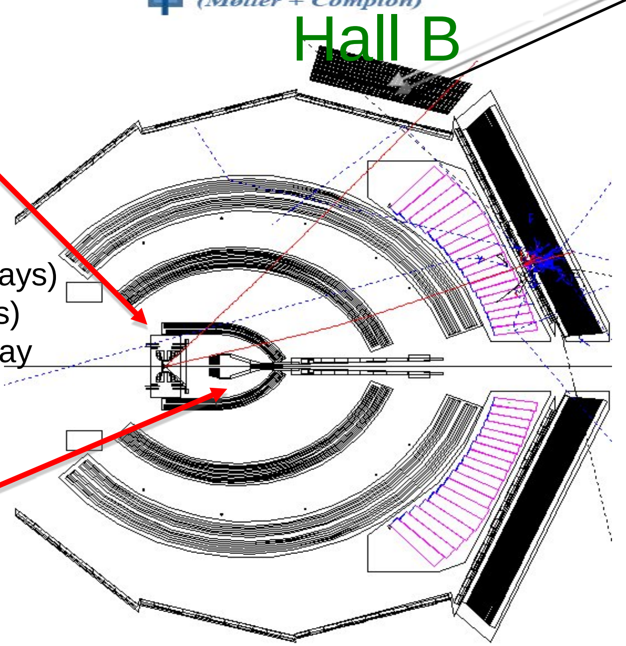


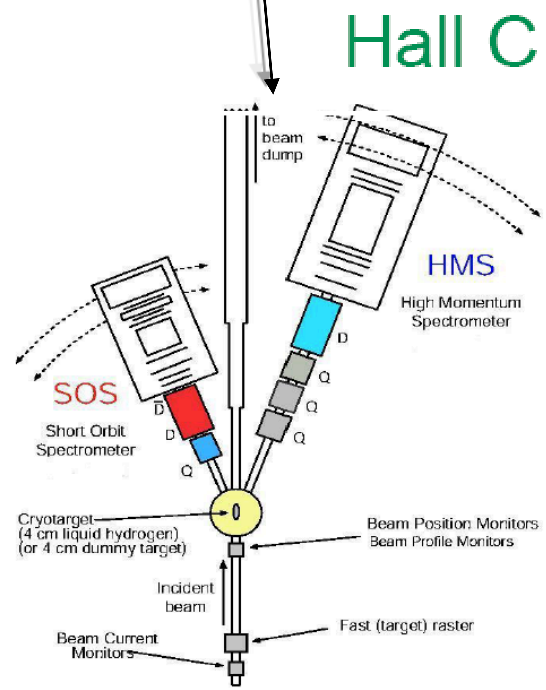
$^{3}\mathrm{He}^{\uparrow}(e, e'h), \; h = \pi^{+}, \pi^{-}$





Polarized NH3/ND3 (no IC, ~5 days)
Unpolarized H (with IC ~ 60 days)
Polarized NH3/ND3 with IC 60 day
10% of data on carbon





P_T-dependence studies at Hall-C

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 $h_{1T}^{\perp}$

$$P_t = p_t + zk_t$$

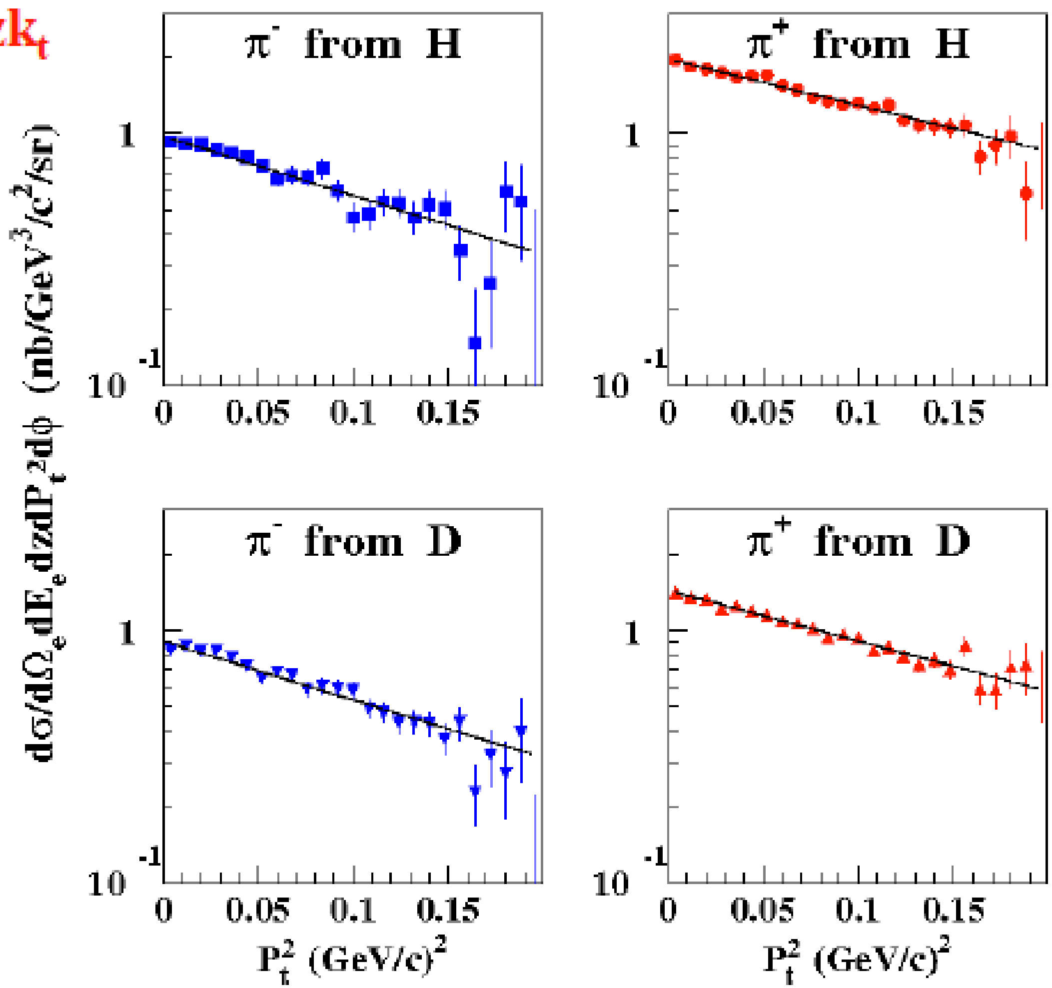
$$\sigma_{SIDIS} \sim \sigma_{DIS}\,(dN/dz)\; b\, \exp(-bP_t^2)$$

$b_H^- = 5.44 \pm 0.36$

$b_D^- = 5.35 \pm 0.26$

$b_H^+ = 4.24 \pm 0.17$

$b_D^+ = 4.64 \pm 0.17$



H. Mkrtchyan(DIS2011)

Experiment E00-108

Beam energy 5.5 GeV

4 cm LH2 and LD2 targets

Data (assuming only valence quarks and only two fragmentation functions contribute) indicate that k_T-width of u-quarks and d-quarks may be different

Longitudinally Polarized Beam SSA

$$A_{LU}(\phi) = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-}$$

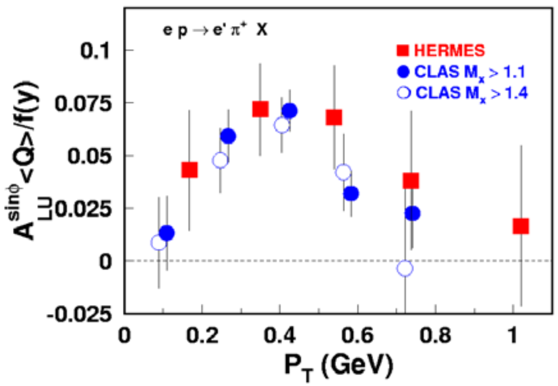
HT function related to force on the quark. Burkardt (2008),Qiu(2011)

N/q	U	L	T
U			e

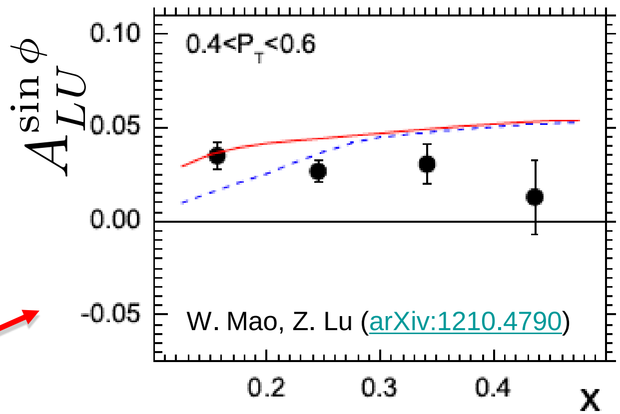
$A_{LU}^{Collins} \sim eH_1^{\perp}$

Efremov et al (2003)

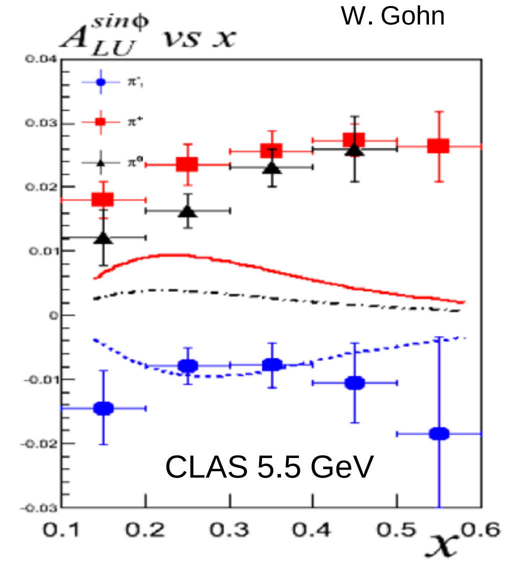
A_{LU} CLAS @4.3 GeV (2003)



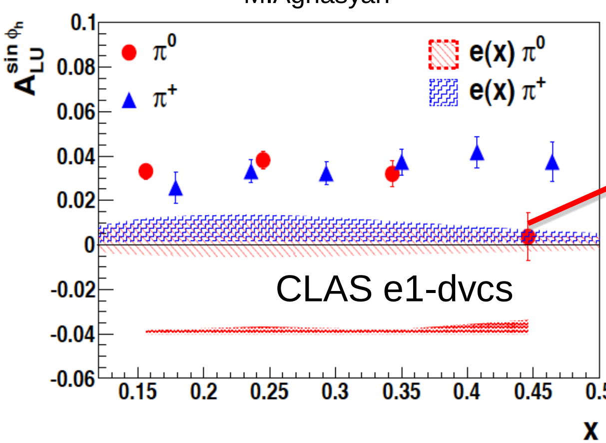
$g^{\perp} D_1$



W. Gohn



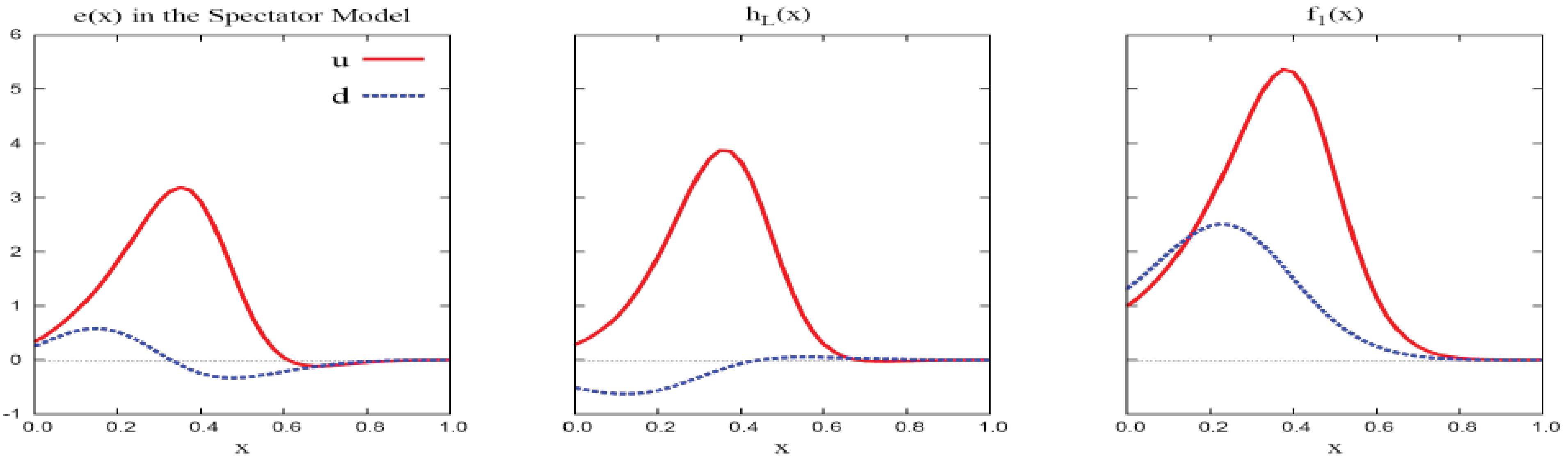
M.Aghasyan

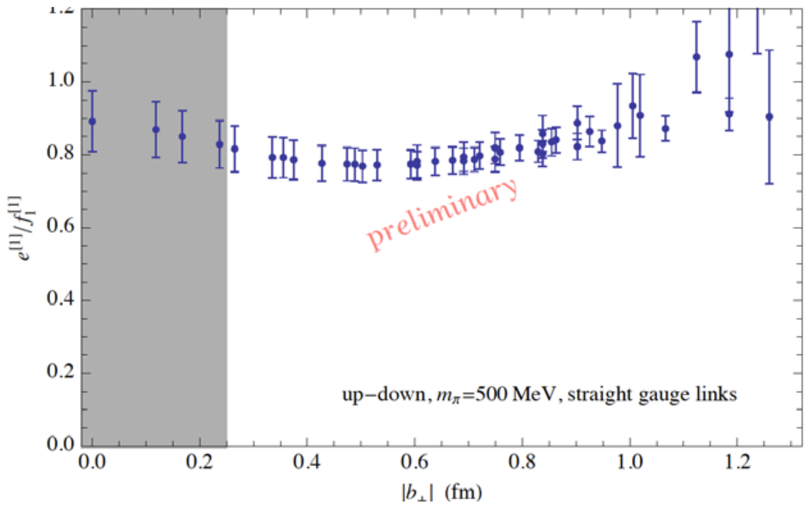


Collins type contribution may be dominant for π-

Sivers type contribution may be dominant for π^0

Model predictions: unpolarized target





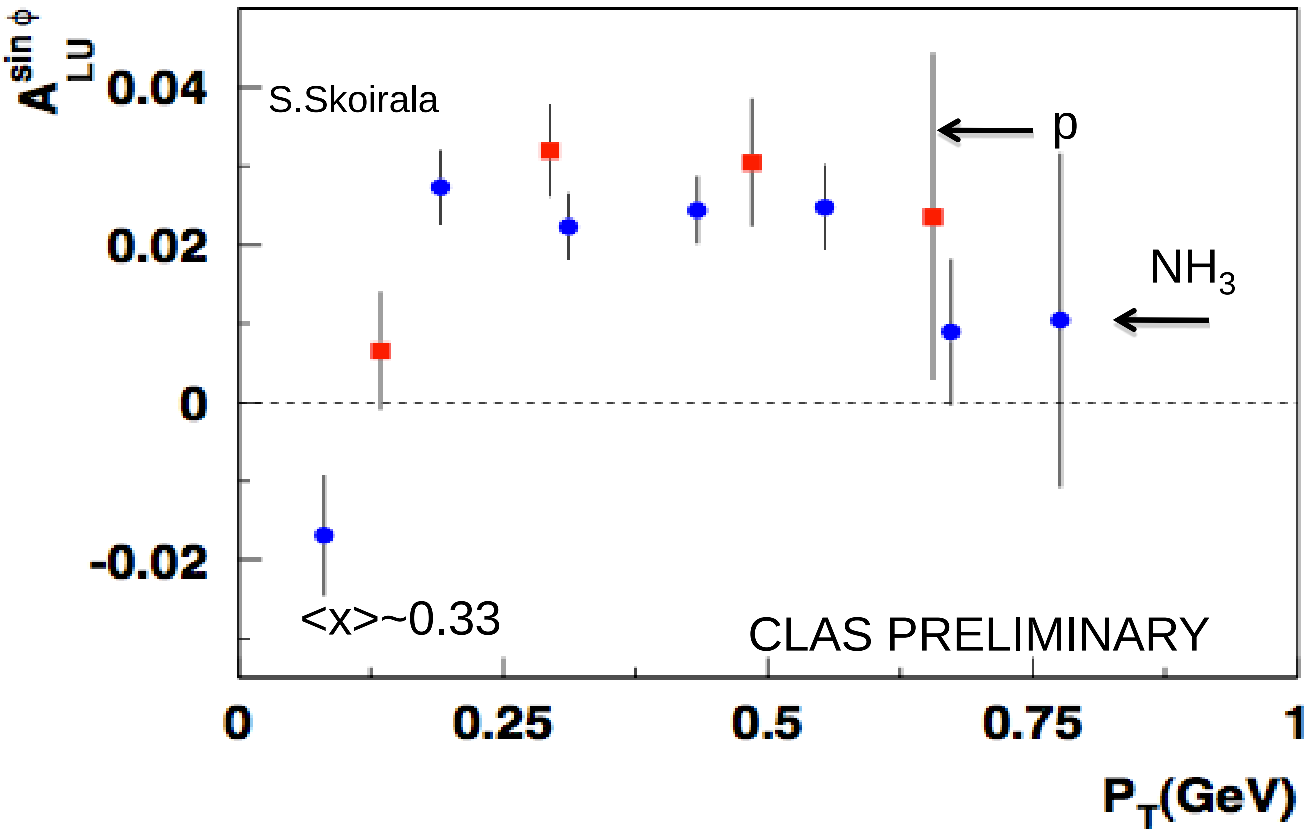
Lattice provides important cross check with data and models for all HT TMDs (Musch et al, arXiv:1011.1213)

$$f_1^{[1]}(\boldsymbol{k}_\perp^2) \equiv \int_{-1}^{1} dx \; f_1(x, \boldsymbol{k}_\perp^2)$$

$$\frac{e^{[1]}}{f_1^{[1]}} = \frac{\tilde{A}_1}{\tilde{A}_2}$$

- Models agree on a large beam SSA for ππ pair production
- Lattice results for u-d can be directly compared to models and data.

Beam Single Spin Asymmetries from nuclear target



Significant beam SSA observed in SIDIS with nuclear targets at Jlab (CLAS)

Interpretations will require extractions for different targets (C,D2,ND3,..) and theory describing medium modification of PDFs

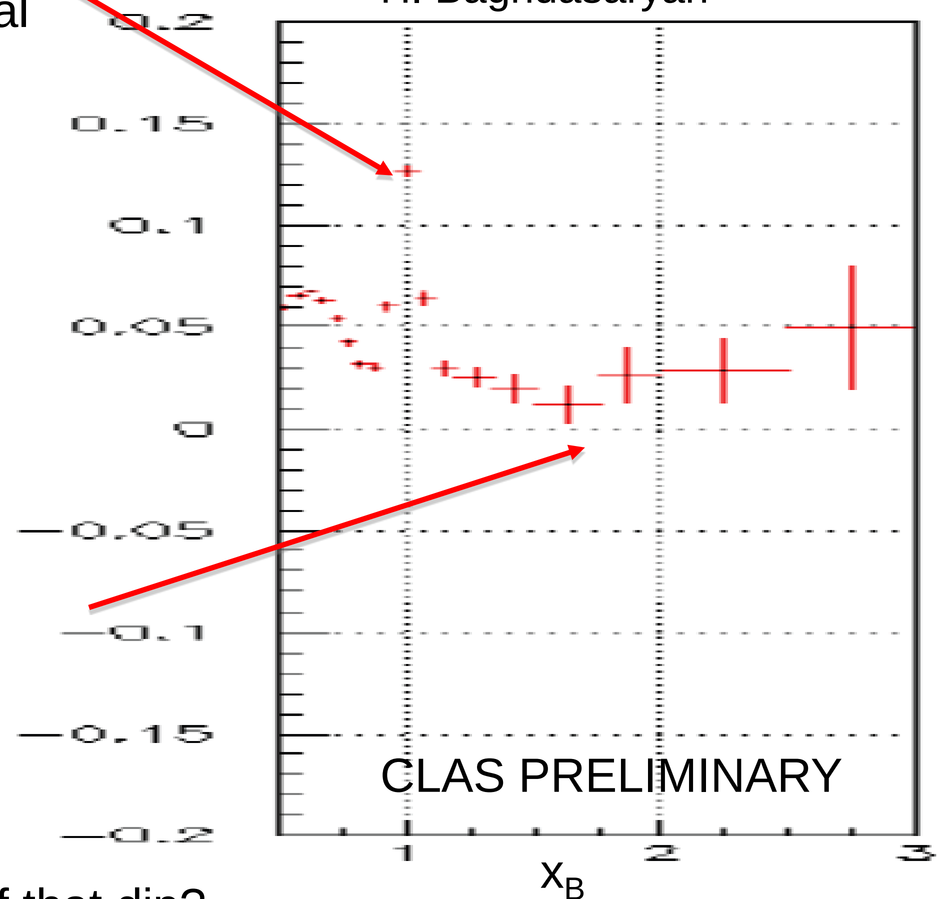
CLAS@6 GeV: double spin asymmetry on NH_3 in DIS

Expectations

- If we are scattering on object with mass=M_N

1. The double spin asymmetry should be equal to the asymmetry at x_B=1 quasi-elastic asymmetry
2. The double spin asymmetry behaves according to state the nucleon is (example Deuteron can have contribution from D-wave)

H. Baghdasaryan



Scattering at x_B>1 means

- Scattering on the object with mass>M_N
- Scattering on the nucleon with momentum(where momentum of nucleon in antiparallel to q vector)

What is the nature of that dip?

Measurements of SS azimuthal asymmetries in SIDIS

$$\frac{d\sigma}{dxdyd\phi_S d\phi_h dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}sin\phi_h F_{UL}^{sin\phi_h} + \epsilon sin(2\phi_h)F_{UL}^{sin(2\phi_h)}\right]$$

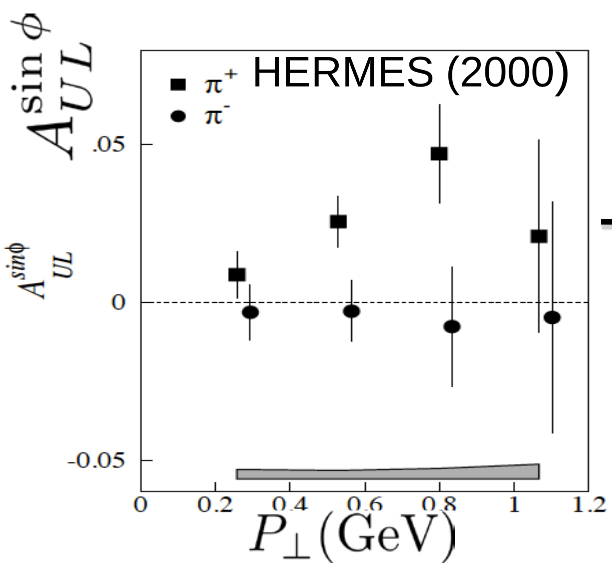
$$+S_L\lambda_e\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}cos(\phi_h)F_{LL}^{cos(\phi_h)}\right]$$

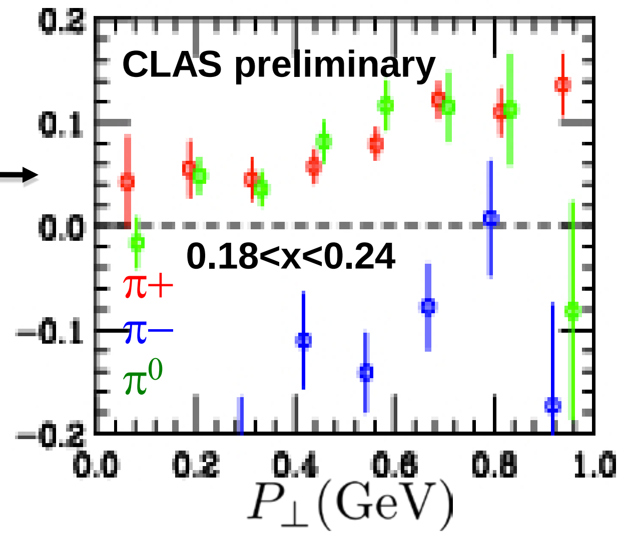
h.t. ($F_{UL}^{sin\phi_h}$)

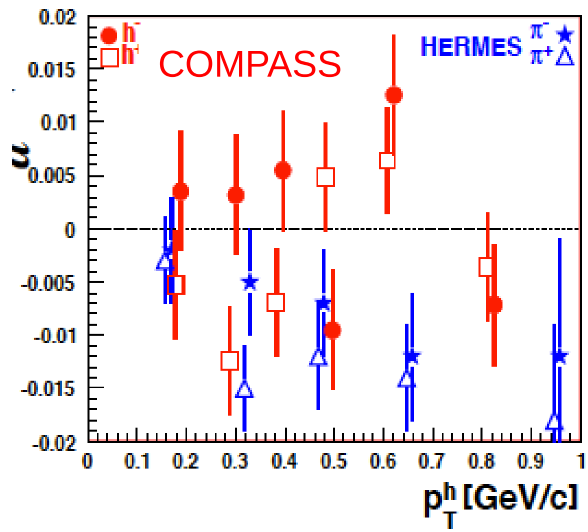
$h_{1L}^{\perp} \otimes H_1^{\perp}$ ($F_{UL}^{sin(2\phi_h)}$)

$g_{1L} \otimes D_1$ (F_{LL})

h.t. ($F_{LL}^{cos(\phi_h)}$)







Large sinϕ modulations have been observed in electroproduction of hadrons in SIDIS with longitudinally polarized targets

A_1 – P_T dependence

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 $h_{1T}^\perp$

$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$

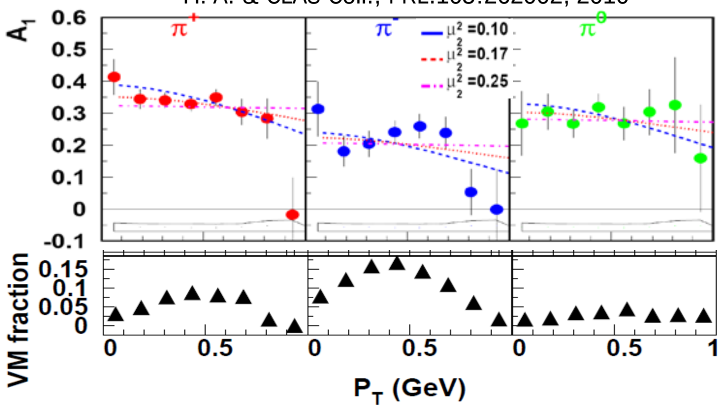
M. Anselmino et al PRD74:074015, 2006

μ_0^2=0.25GeV^2

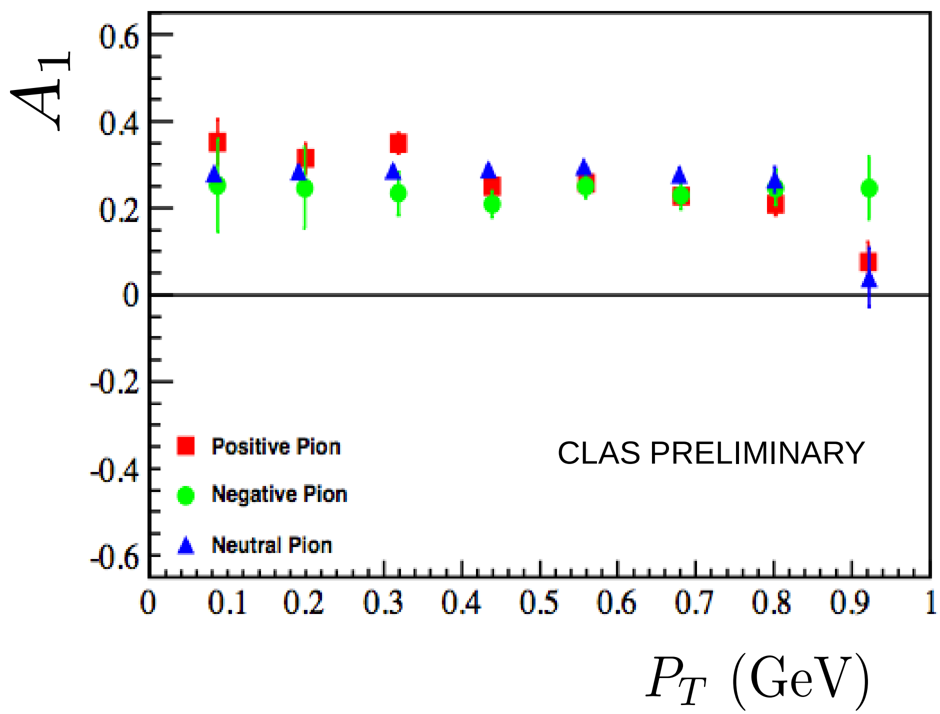
μ_D^2=0.2GeV^2

0.4<z<0.7

H. A. & CLAS Coll., PRL.105:262002, 2010



S. Skoirala



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

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

$$< P_T^2(z) >= z^2\mu_{0/2}^2 + \mu_D^2$$

The new data is consistent with old measurements, now available in several bins in x

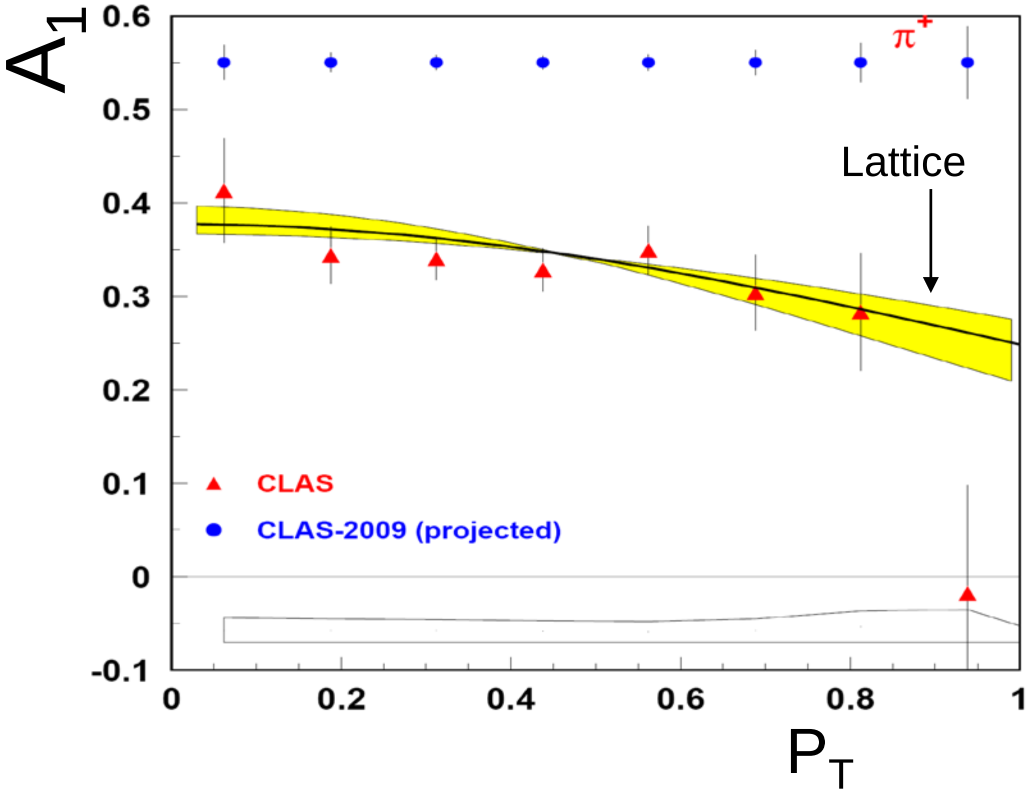
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

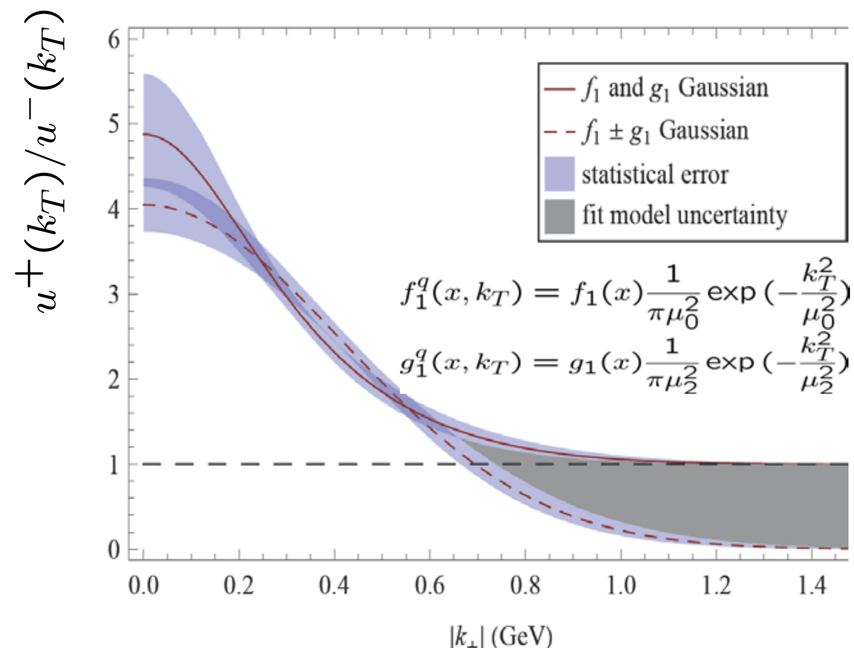
A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$A_1(x,z,P_T) = A_1(x,z)\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)$$





B.Musch et al arXiv:1011.1213

$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

Lattice calculations consistent with CLAS data indicating different widths of g_1 and f_1

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

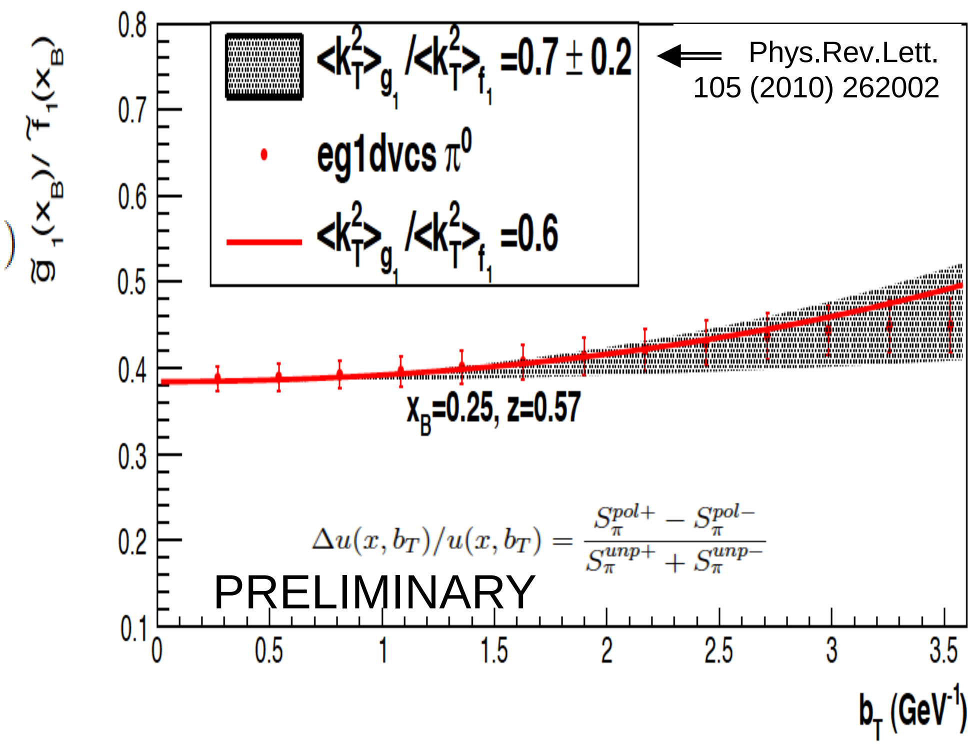
$$\int_0^\infty d|\boldsymbol{P}_{h\perp}|\;|\boldsymbol{P}_{h\perp}|\,J_0(|\boldsymbol{P}_{h\perp}||b_T|)\left[\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz_h\,d\phi_h\,|\boldsymbol{P}_{h\perp}|d|\boldsymbol{P}_{h\perp}|}\right]$$

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

acceptance

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

$$\tilde{f}_1^q(x,z^2b_T^2)\tilde{D}_1^{q\to\pi}(z,b_T^2)$$



- the formalism in **b_T-space** avoids convolutions
$\rightarrow$easier to perform a model independent analysis of TMDs
- Widths extracted from eg1dvcs π^0s consistent with published CLAS data

The Multi-Hall SIDIS Program at 12 GeV

M. Aghasyan, K. Allada, H. Avakian, F. Benmokhtar, E. Cisbani, J-P. Chen, M. Contalbrigo, D. Dutta, R. Ent, D. Gaskell, H. Gao, K. Griffioen, K. Hafidi, J. Huang, X. Jiang, K. Joo, N. Kalantarians, Z-E. Meziani, M. Mirazita, H. Mkrtchyan, L.L. Pappalardo, A. Prokudin, A. Puckett, P. Rossi, X. Qian, Y. Qiang, B. Wojtsekhowski

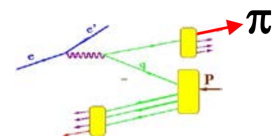
for the Jlab SIDIS working group

The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

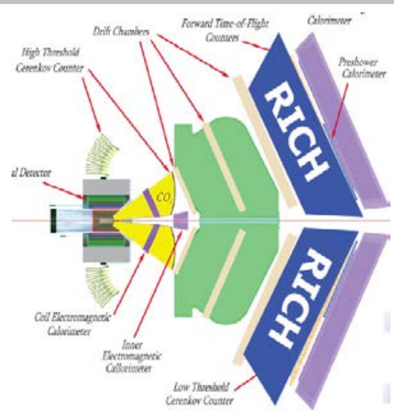
Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

Measurements with pions and kaons in the final state will also provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low Q^2 range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.



SIDIS at JLab12



CLAS12

Proton

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-, K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+,K^-,K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Quark spin polarization

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

Hall C | Hall A

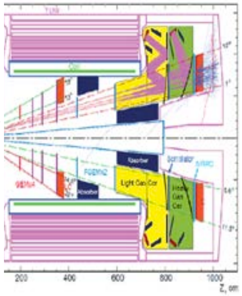
E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

C12-11-108: π^+,π^-

Solid

H_2 | NH_3

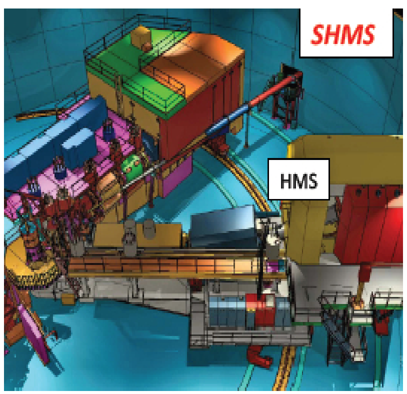


CLAS12

E09-008: π^+,π^-,π^0 K^+, K^-,K^0

E07-107: π^+,π^-,π^0
E09-009: K^+,K^-,K^0

D_2, ND_3



D_2

Quark spin polarization

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

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

Nuclear EMC
E12-10-008

D_2

Nuclear C,Fe
E12-06-106
E12-06-117

LOI-10-05 (7Li)

^3He

Quark spin polarization

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

Hall A

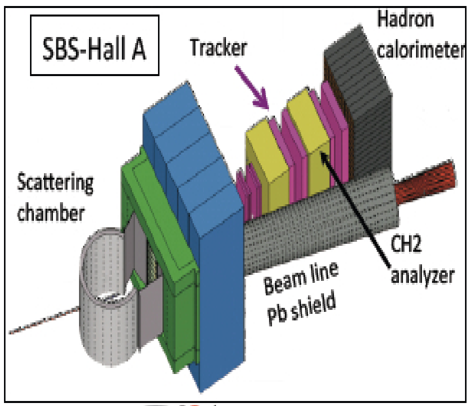
E12-07-007: π^+,π^-

Solid

E10-006: π^+,π^-
E12-09-018: π^+,π^-, K^+,K^-

Solid
SBS

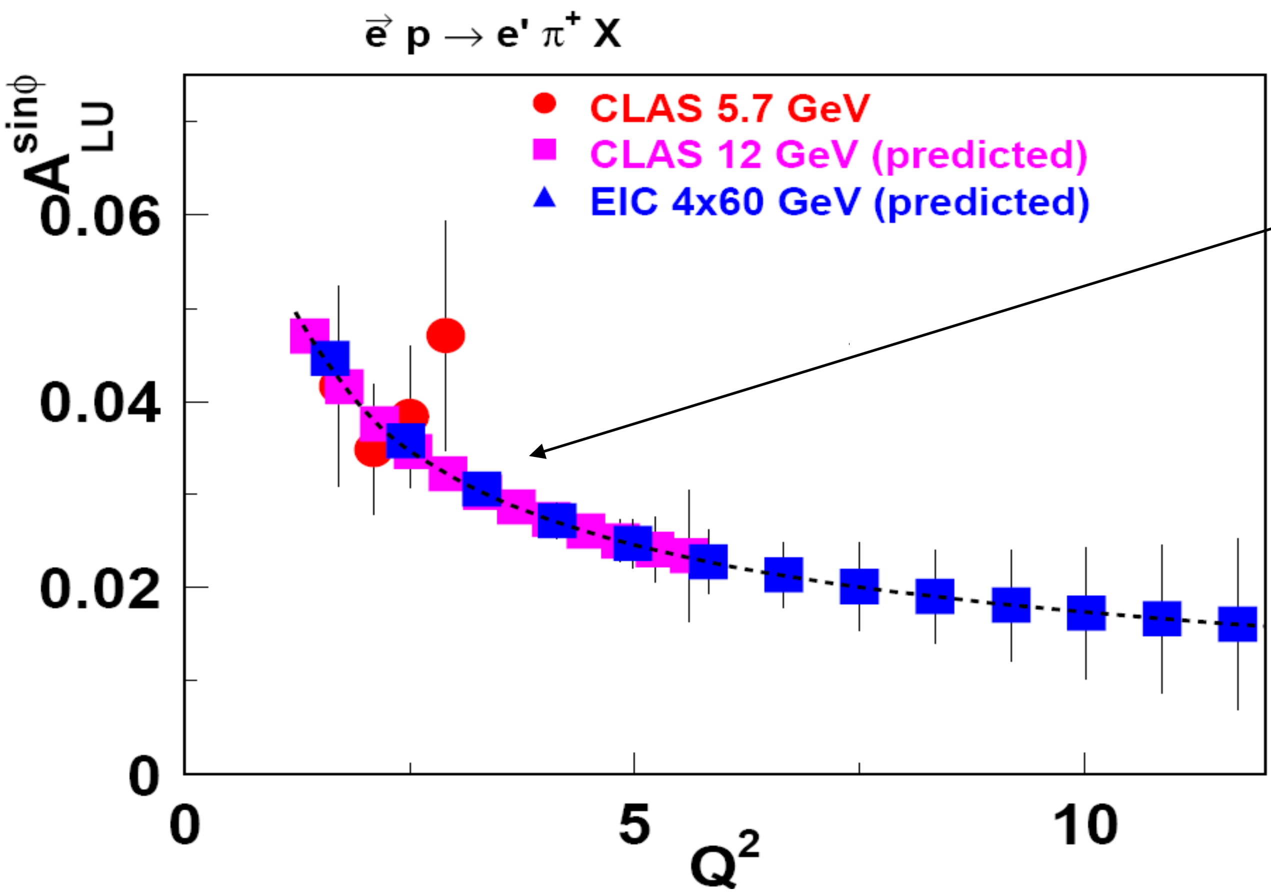
^3He



Q^2-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)}$ ~$F_{LU(UL)}$~ 1/Q (Twist-3)

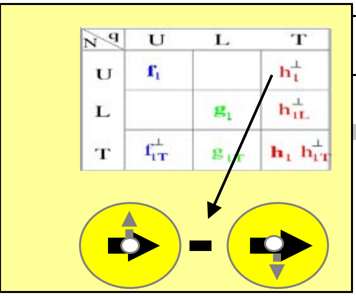
$A_{LU} \propto g^{\perp}(x) D_1(z)$



1/Q behavior expected (fixed x bin)

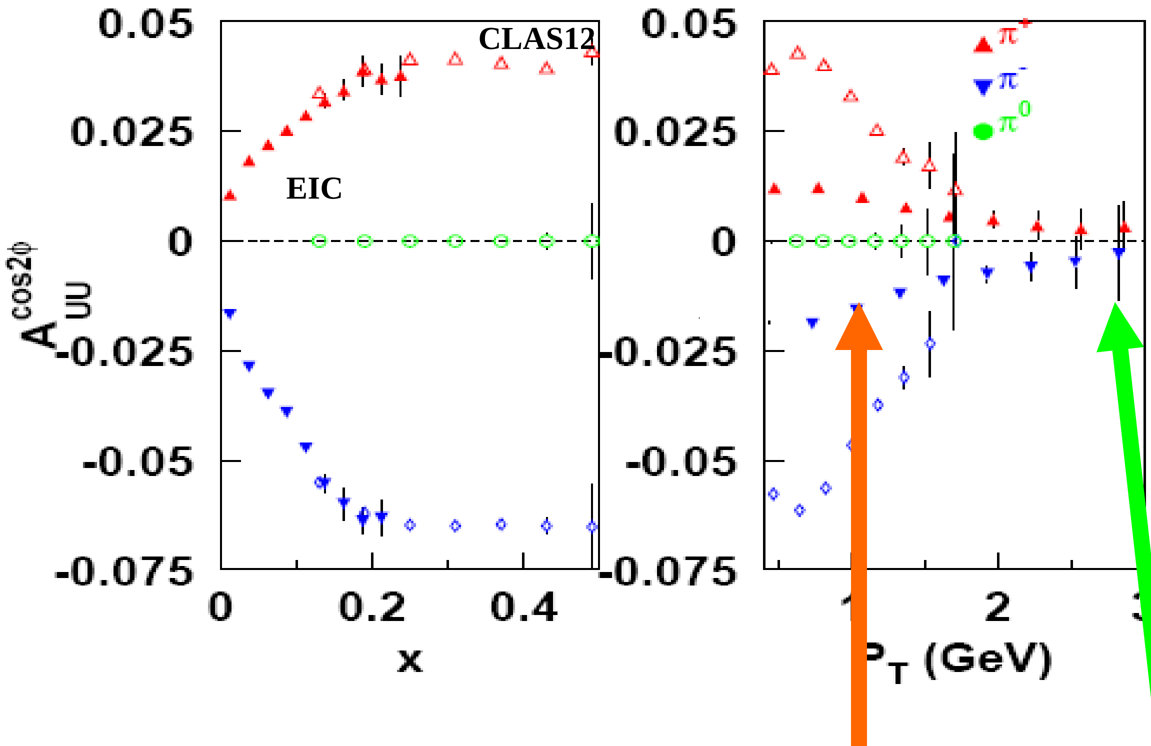
Study for Q^2 dependence of beam SSA allows to check the higher twist nature and access quark-gluon correlations.

Boer-Mulders Asymmetry with CLAS12 & EIC



5-7 GeV e → ← p 50-150 GeV

Transversely polarized quarks in the unpolarized nucleon



$\sin(\phi_C) = \cos(2\phi_h)$

$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$

$$\langle \cos 2\phi \rangle |_{P_{h\perp} \gg \Lambda_{QCD}} \propto \frac{1}{P_{h\perp}^2}$$

Nonperturbative TMD **Perturbative region**

CLAS12 and ELIC studies of transition from non-perturbative to perturbative regime will provide complementary info on spin-orbit correlations and test unified theory

Summary

•Sizable higher twist asymmetries measured both in SIDIS and exclusive production indicate the quark-gluon correlations may be significant at moderate Q^2

•Understanding of medium modifications of PDF is important for studies of proton structure

•Studies of 3D PDFs indicate that transverse distributions of partons depend on spin and flavor (model independent flavor decomposition tools are required to extract the in multidimensional space)

•Correlations of spin and transverse momentum of partons are crucial in understanding of the nucleon structure in terms of partonic degrees of freedom of QCD

Welcome to the exciting world of 3D parton distributions!!!

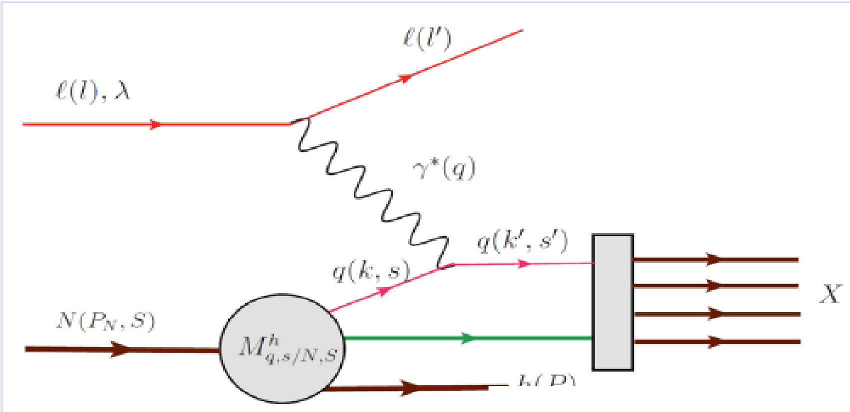
Support slides….

SIDIS in target fragmentation region

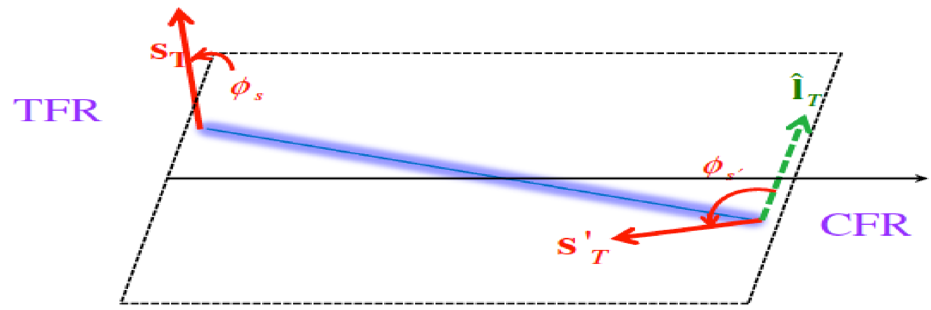
Aram Kotzinian

- TFR (based on M.Anselmino, V.Barone and AK, **arXiv:1102.4214;** PLB 699 (2011) 108)

SIDIS: TFR



Hadronization in SIDIS



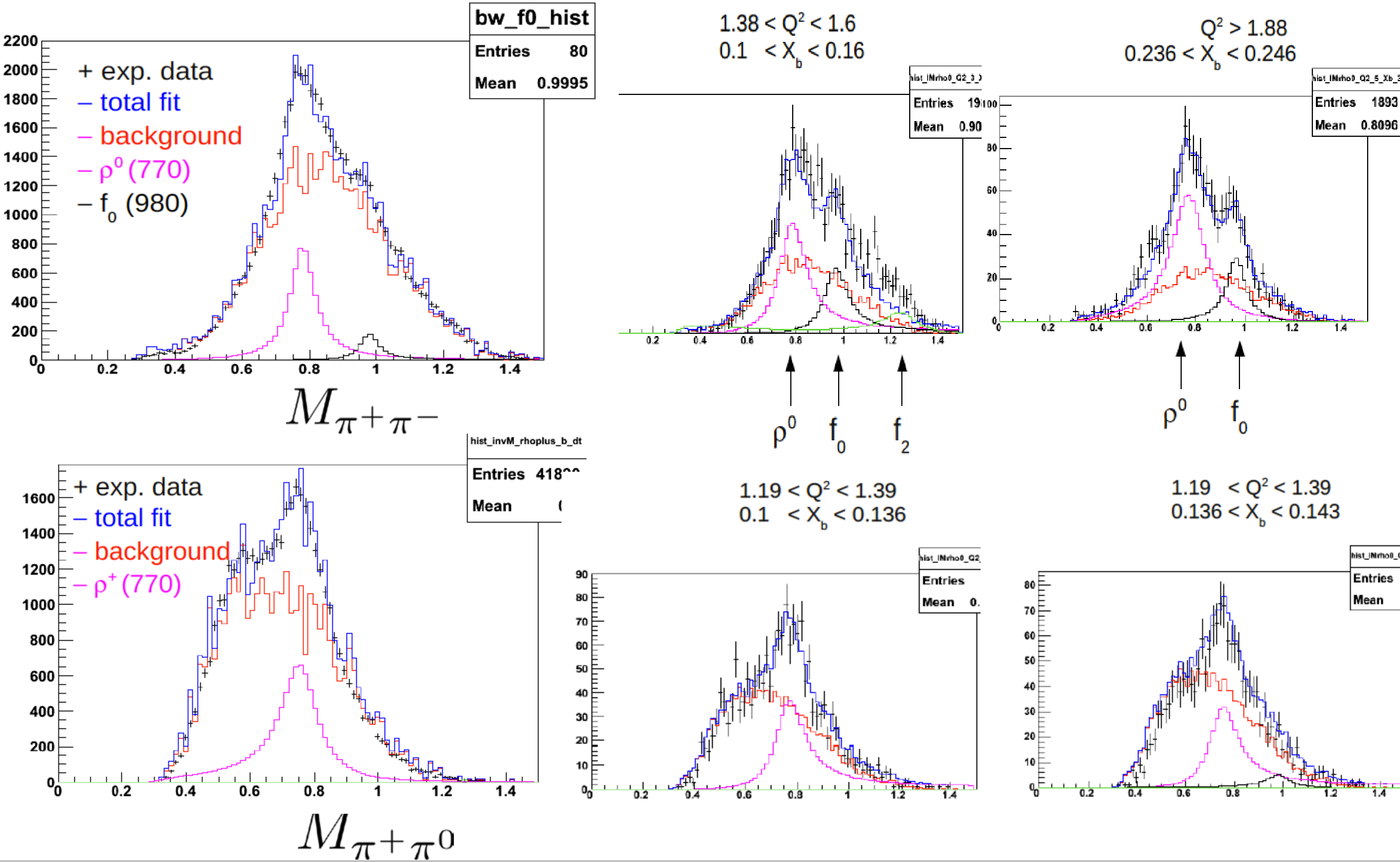
LO cross-section in TFR

$$\frac{d\sigma^{\ell(l,\lambda)+N(P_N,S)\to\ell(l')+h(P)+X}(x_F<0)}{dx\,dQ^2\,d\phi_S\,d\zeta\,d^2P_T} = \frac{\alpha^2 x}{yQ^4}\left(1+(1-y)^2\right)\sum_q e_q^2 \times$$

$$\times\left[\begin{array}{l} M\left(x,\zeta,P_T^2\right) - S_T\dfrac{P_T}{m_h}M_T^h\left(x,\zeta,P_T^2\right)\sin(\phi_h-\phi_S) + \\ \lambda D_{ll}(y)\left(S_L \Delta M_L\left(x,\zeta,P_T^2\right) + S_T\dfrac{P_T}{m_h}\Delta M_T^h\left(x,\zeta,P_T^2\right)\cos(\phi_h-\phi_S)\right) \end{array}\right]$$

- The ideal place to test the fracture functions factorization and measure these new functions are JLab12 and EIC facilities with full coverage of phase space

Dihadron simulations with LUND-MC @6 GeV



Forces and binding effects in the partonic medium

$$xe = x\tilde{e} + \frac{m}{M} f_1$$

Interaction dependent parts

$$xh_L = x\tilde{h}_L + \frac{p_T^2}{M^2} h_{1L}^{\perp} + \frac{m}{M} g_{1L}$$

"Wandzura-Wilczek approximation" is equivalent to setting functions with a tilde to zero.

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

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

Quark polarized in the x-direction with k_T in the y-direction

Interpreting HT (quark-gluon-quark correlations) as force on the quarks (Burkardt hep-ph:0810.3589)

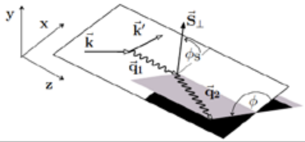
$$F^y(0) = \frac{M^2}{2} e_2$$

Boer-Mulders Force on the active quark right after scattering (t=0)

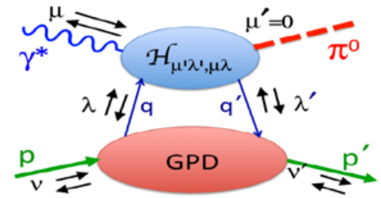
$$\int_0^1 dx\, x(e^q - e^{\bar{q}})(x) = \frac{m_q}{M_N}$$

current quark masses

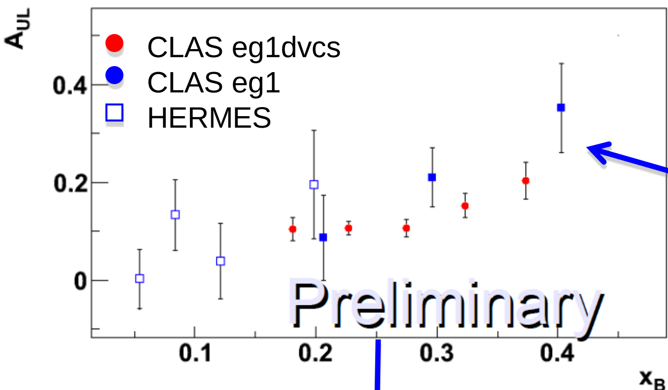
pion-nucleon sigma-term



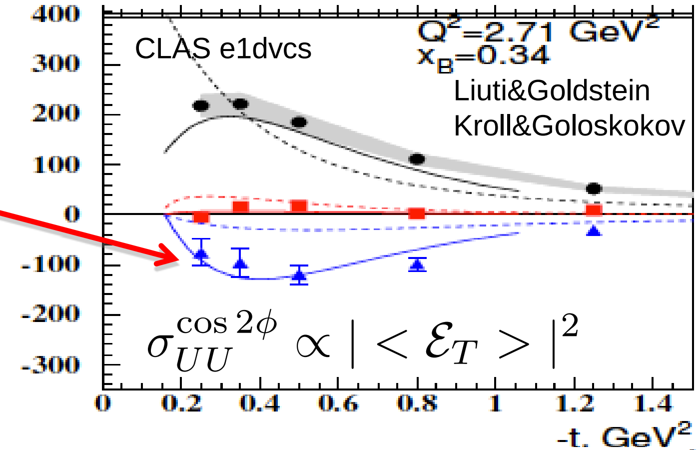
3D structure: GPDs

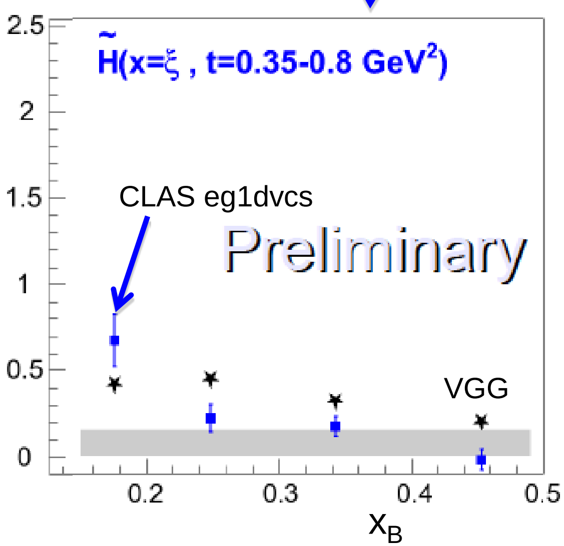


$$\sigma_{UL}^{sin\phi} \sim F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\mathcal{H}$$

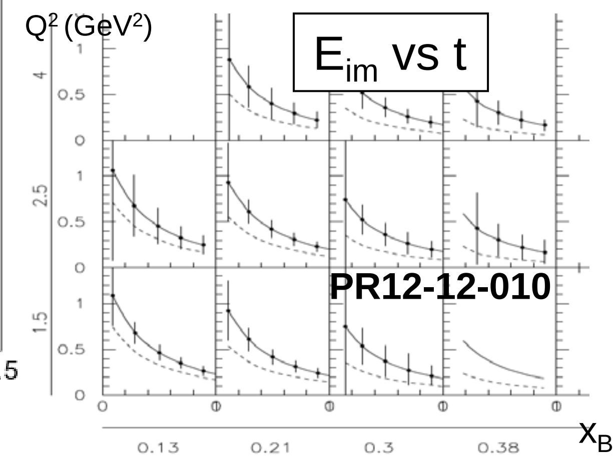


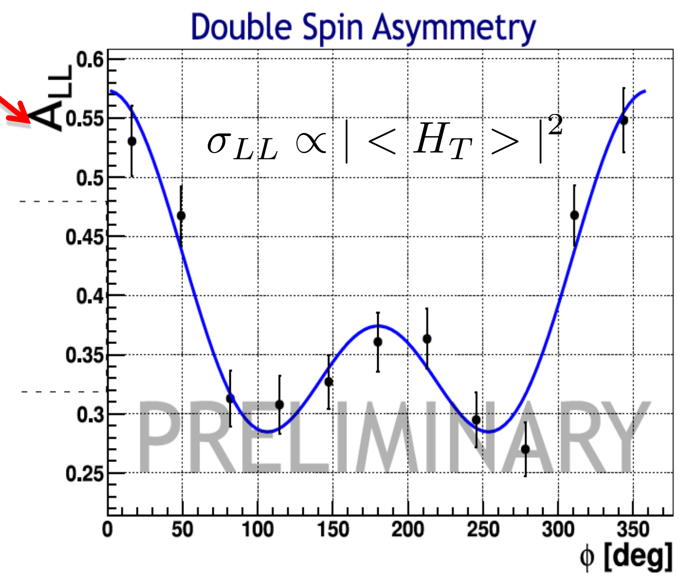
	ep→e′pγ		ep→e′pπ⁰
	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T,\widetilde{H}_T$





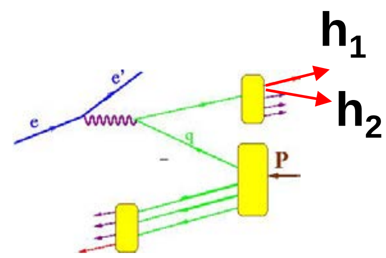
$$\sigma_{UT}^{\cos\phi} \sim \frac{1-x}{2-x}\frac{t}{M^2}F_2\mathcal{H} + \frac{t}{4M^2}(2-x)F_1\mathcal{E}$$





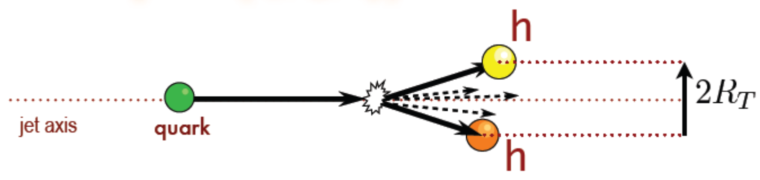
Spin-azimuthal asymmetries in hard exclusive photon (DVCS) and hadron (DVMP) production give access to underlying GPDs

Hadronization in current and target regions

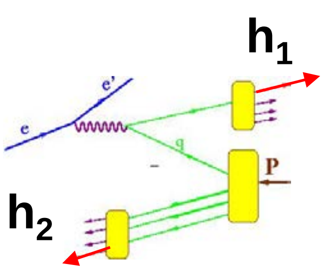


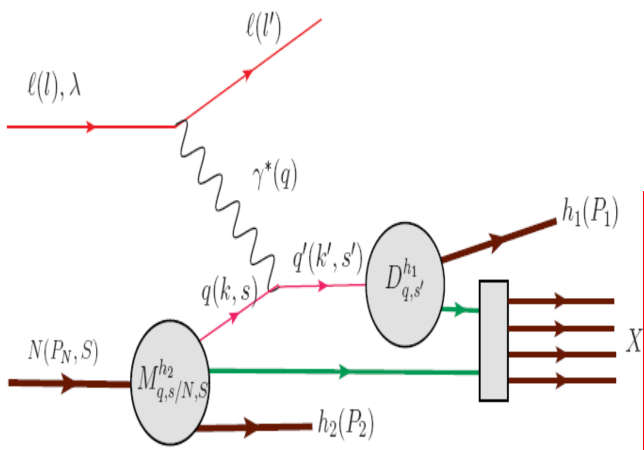
✦ DiFF

$D_1^{q\to h_1 h_2}(z_1, z_2, R_T^2)$



Collinear factorization





Anselmino/Barone/Kotzinian
arXiv:1107.2292 (2011)

Fracture Function:
conditional probabilities to find a quark with certain polarization and longitudinal momentum fraction xB and transverse momentum k_T inside a nucleon fragmenting into a hadron carrying a fraction z of the nucleon longitudinal momentum and a transverse momentum P_T

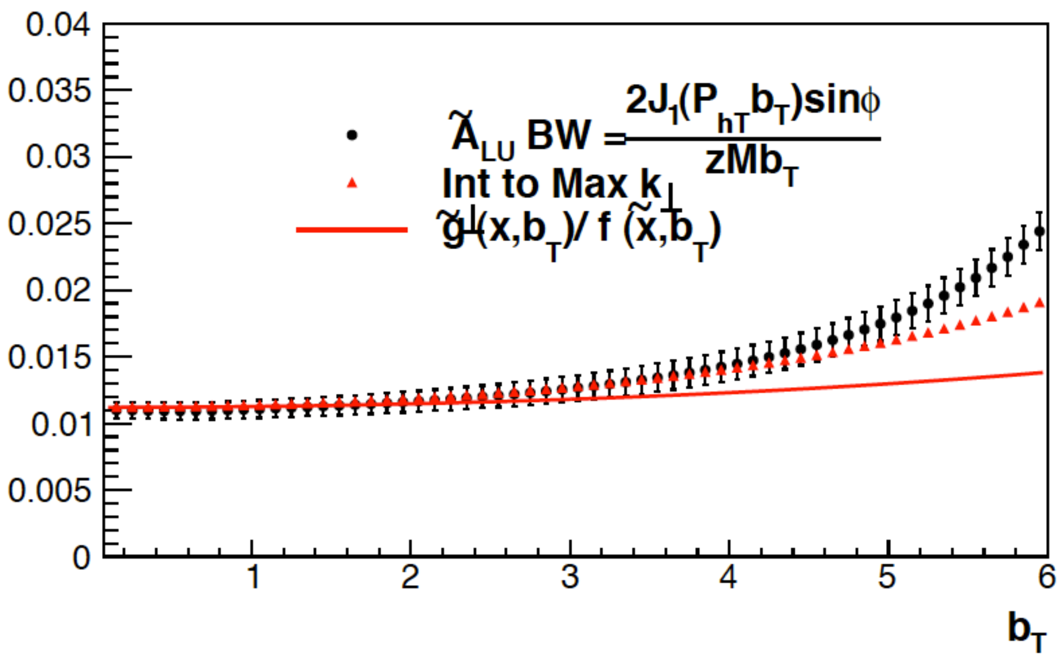
$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\Delta\hat{g}_1^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)\,.$$

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

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



- With different Bessel weights BGMP provides a model independent way to extract k_T-dependences for all TMDs
- requires wide range in hadron P_T