Studies of Spin-Orbit Correlations

H. Avakian (JLab)

Correlations in Partonic and Hadronic Interactions 2020 (CPHI-2020)

- **Understanding azimuthal distributions of hadrons**
- **Introducing studies of SSA**
- **Kotzinian-Mulders Asymmetries**
- **Target fragmentation and Fracture Functions**
- **Correlations of target and current fragmentation**
- **Summary**

ELSEVIER

Nuclear Physics B 441 (1995) 234–256

NUCLEAR
PHYSICS B

New quark distributions and semi-inclusive electroproduction on polarized nucleons

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SIDIS described in the LGHF

laboratory gamma-lepton frame (later known as Trento convention)

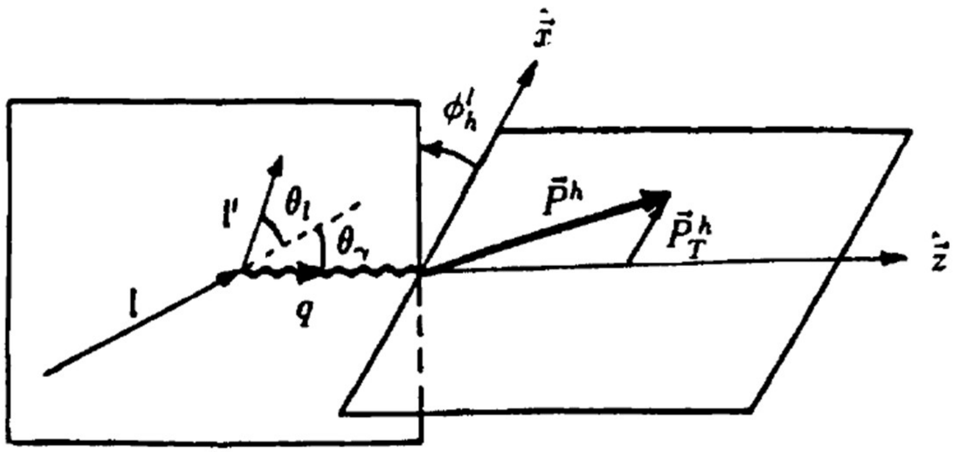

Fig. 2. Lepton and produced hadron momenta in the LGHF.

$$C^{(S)}_{h_{1L}^{\perp}} = -2(1-y)\sin 2\phi_l^h \frac{P_T^{h\,2}}{m_D m_F} \sum_q e_q^2 \alpha^{(S)}_{h_{1L}^{\perp}} (1 - \alpha^{(S)}_{h_{1L}^{\perp}}) A^{(S)}_{h_{1L}^{\perp}}. \quad (54)$$

As is clear from (54), one can separate the contributions of $C^{(0)}_{g_{1L}}$ and $C^{(S)}_{h_{1L}^{\perp}}$ by measuring the target longitudinal-spin asymmetry for different values of ϕ_l^h, P_T^h and y. If the experiment shows that $C^{(S)}_{h_{1L}^{\perp}} \neq 0$, then one can conclude that both the twist-two DF, $h_{1L}^{\perp}$, and FF, $F^{(S)}$, are nonzero. Thus, in principle, it is possible to investigate the Collins effect (a spin dependent FF) with a longitudinally polarized beam and target by analyzing existing SMC semi-inclusive data in different bins of ϕ_l^h, as was done without

Single-Spin Asymmetries in electroproduction

HERMES note 96.059

π^0 Electro-production in Deep Inelastic Scattering

H.R.Avakian, P.Di Nezza, V.Gyurjyan, K.Oganessyan

INFN - Laboratori Nazionali di Frascati

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Dec 1996

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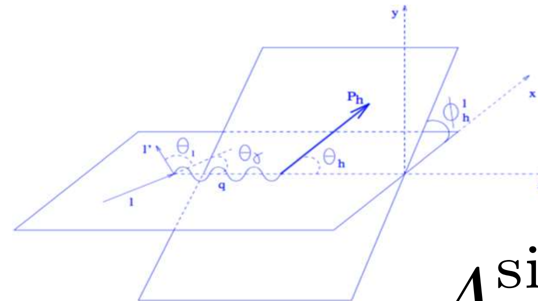
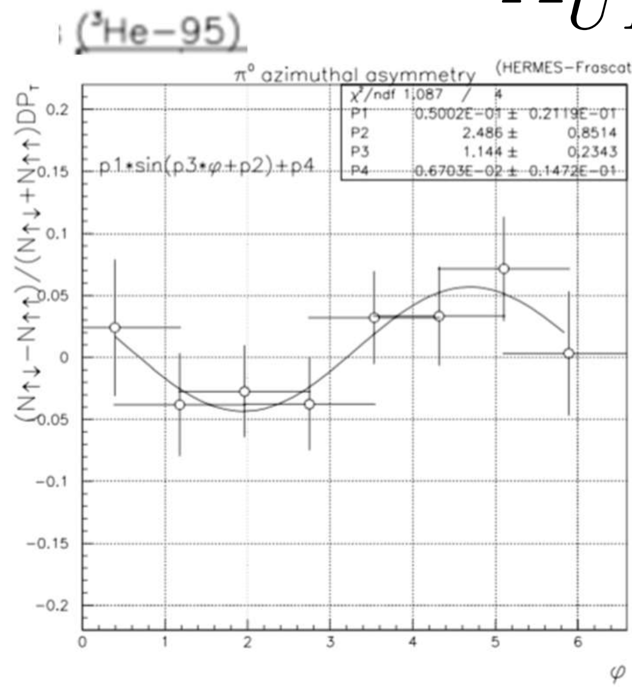
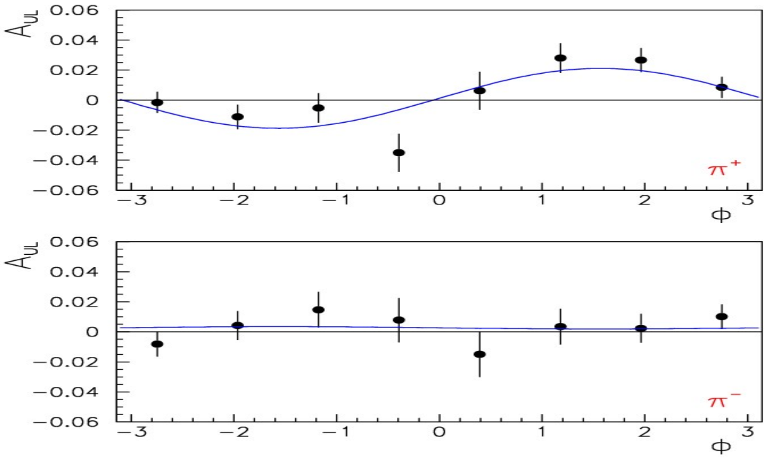


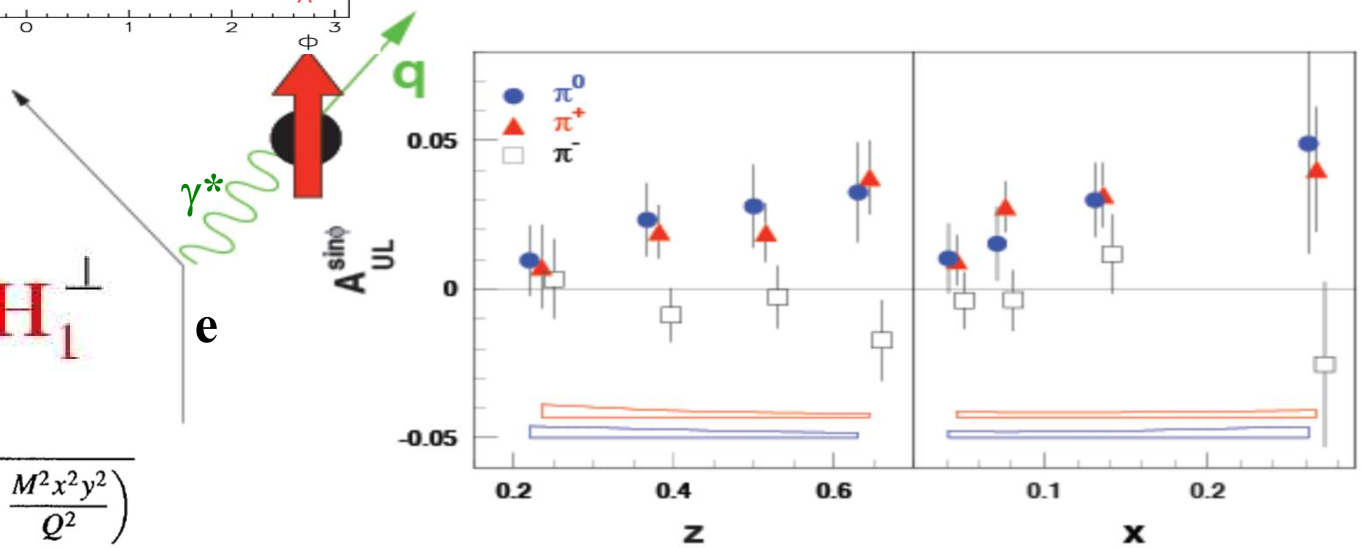
$$A_{UL}^{\sin\phi}$$



HERMES effect



Transverse with respect to γ*



Collins

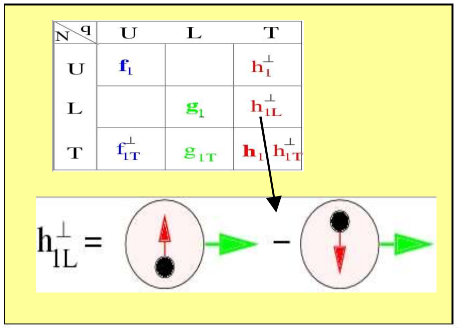
$$A_{UT} \sim (1-y)\, h_1 H_1^{\perp}$$

$$\sin\theta_\gamma = \sqrt{\frac{4M^2x^2}{Q^2+4M^2x^2}\left(1-y-\frac{M^2x^2y^2}{Q^2}\right)}$$

First measurement of significant SSA in electroproduction

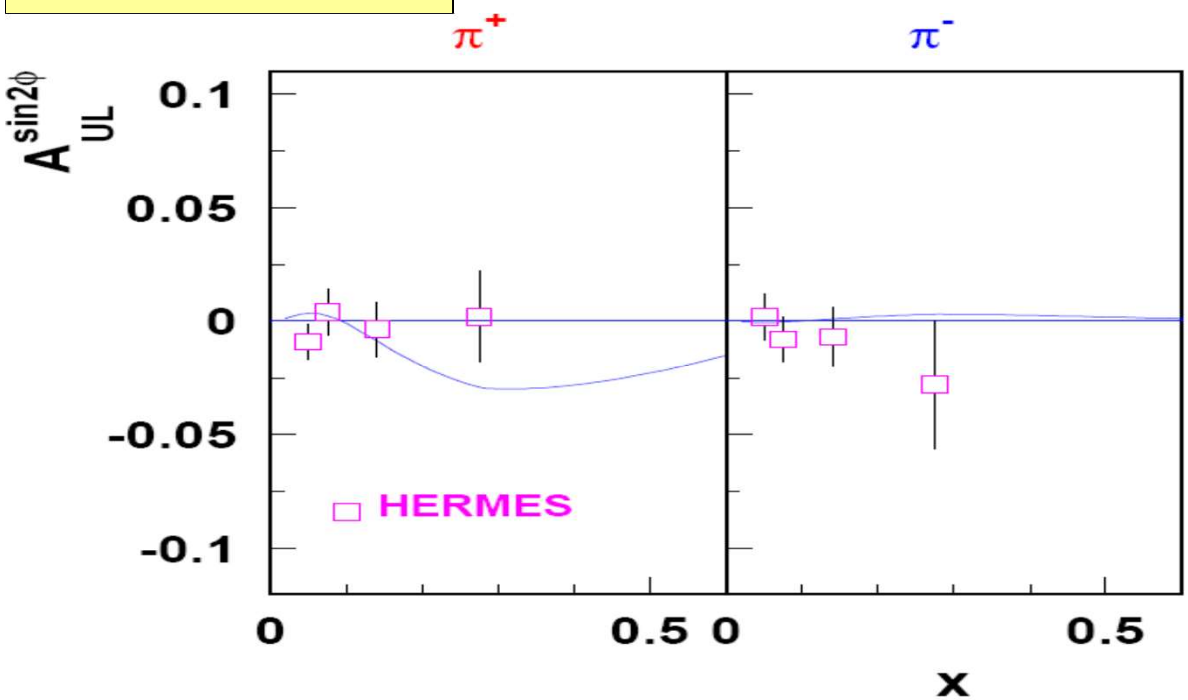
Collins fragmentation: Longitudinally polarized target

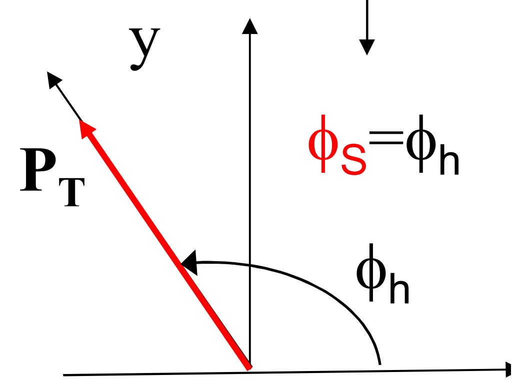
Kotzinian-Mulders Asymmetry (1996)



$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$

$(s_T k_T)(pS_L) \leftrightarrow h_{1L}^{\perp}$



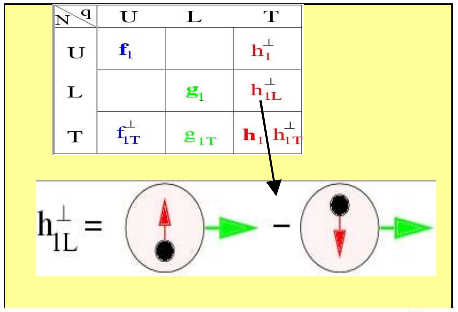


$\sin(\phi_h + \phi_S) = \sin(2\phi_h)$

curves, χQSM from Efremov et al

- **Study transversely polarized quarks in the longitudinally polarized proton**
- **Provides independent information on the Collins function.**

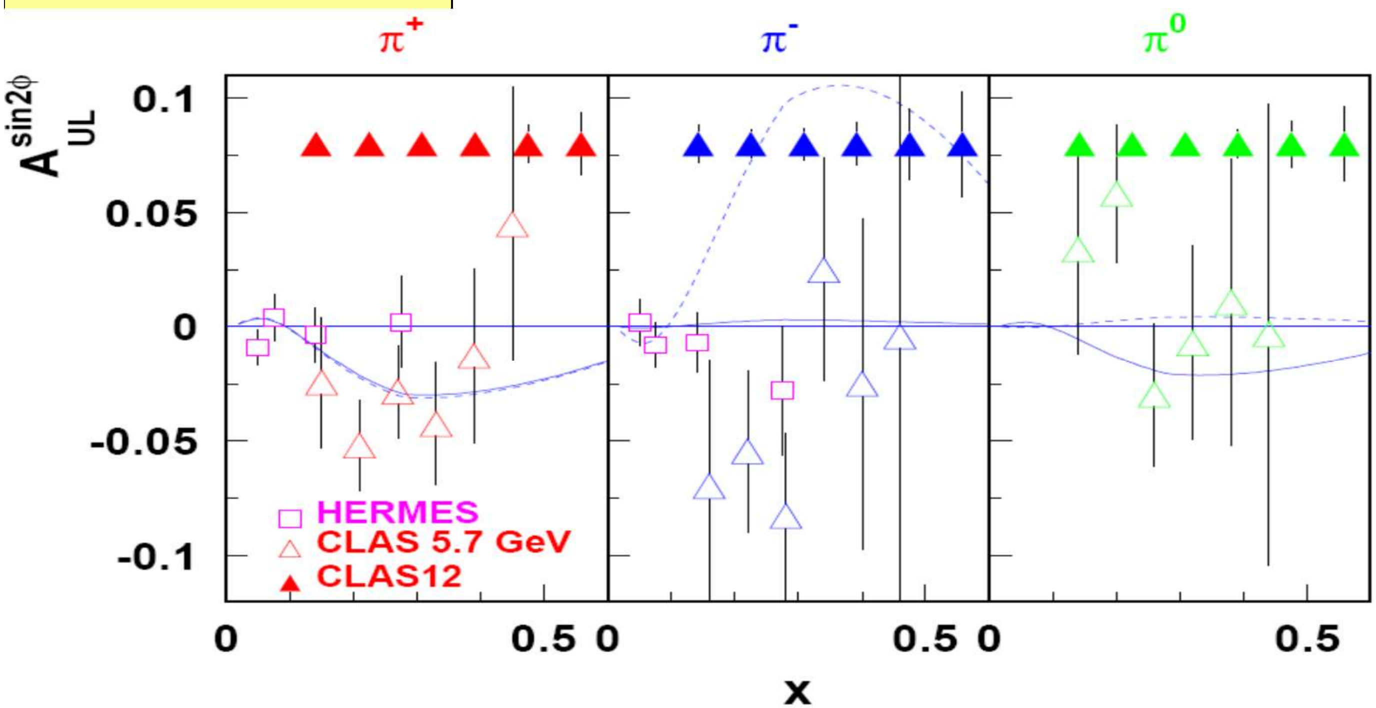
Collins fragmentation: Longitudinally polarized target



Kotzinian-Mulders Asymmetry

Transversely polarized quarks in the long. polarized nucleon

$$\sigma_{UL}^{KM} \sim \; h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$



curves, χQSM from Efremov et al

$$H_1^{\perp u \to \pi^+} \approx -H_1^{\perp u \to \pi^-}$$

- KM sin2ϕ moment, sensitive to spin-orbit correlations: the only leading twist azimuthal moment for longitudinally polarized target
- More info will be available from SIDIS (COMPASS,EIC) and DY (RHIC,GSI)

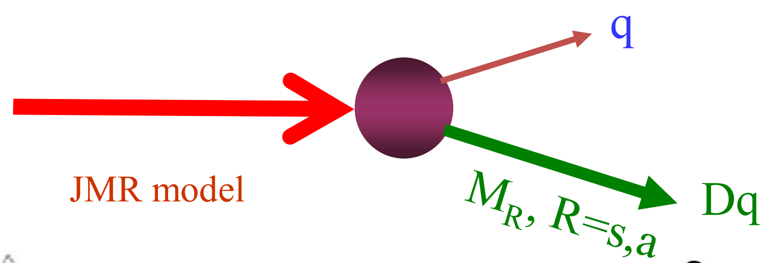
Quark distributions at large k_T: models

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

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

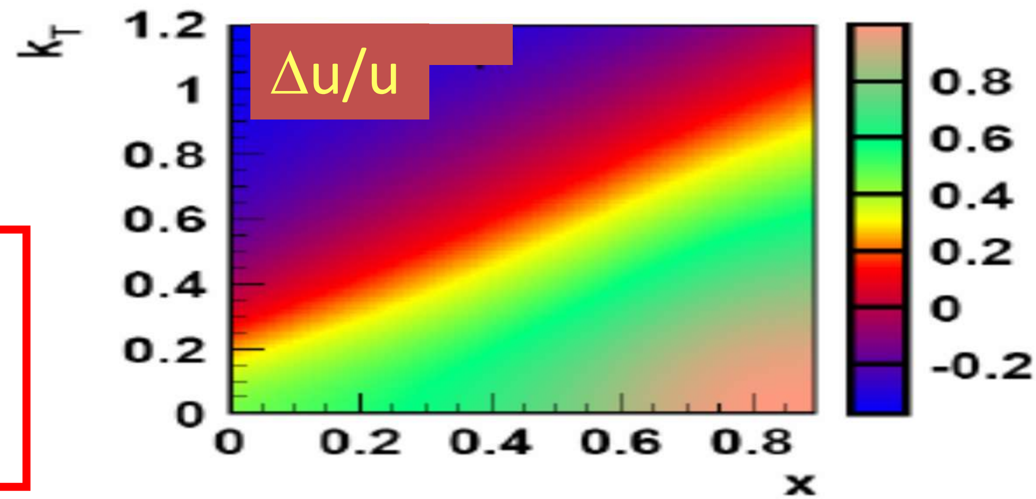
Effect of the orbital motion on the q- may be most significant

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



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

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

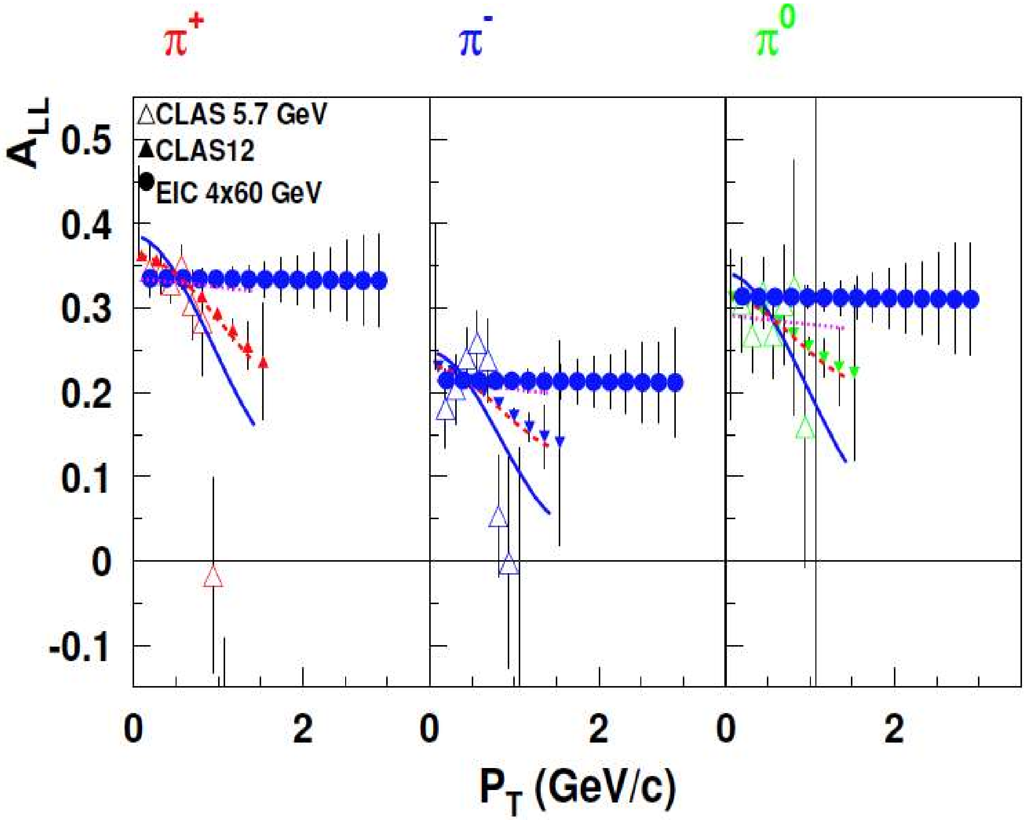


(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian

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



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

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

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

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

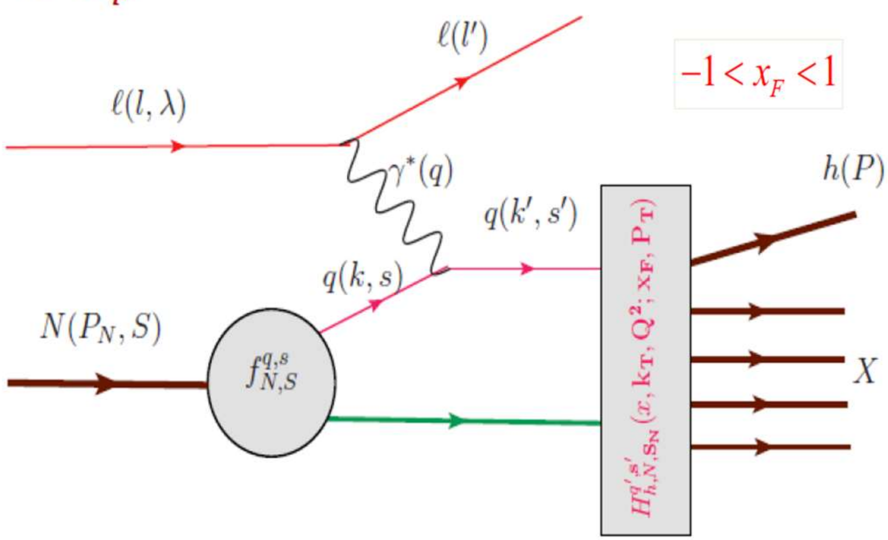
π+ A_{LL} can be explained in terms of broader k_T distributions for f_1 compared to g_1
π- A_{LL} may require non-Gaussian P_T-dependence for different helicities and flavors

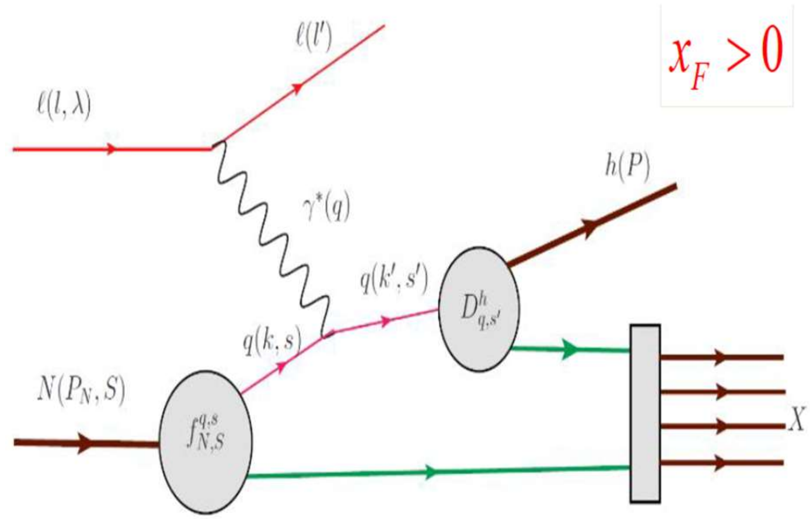
Hadronization and factorization

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

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

$Q^2 \gg M_p^2$





Hadronization Function
→ conditional probability to produce hadron $\boldsymbol{h}$

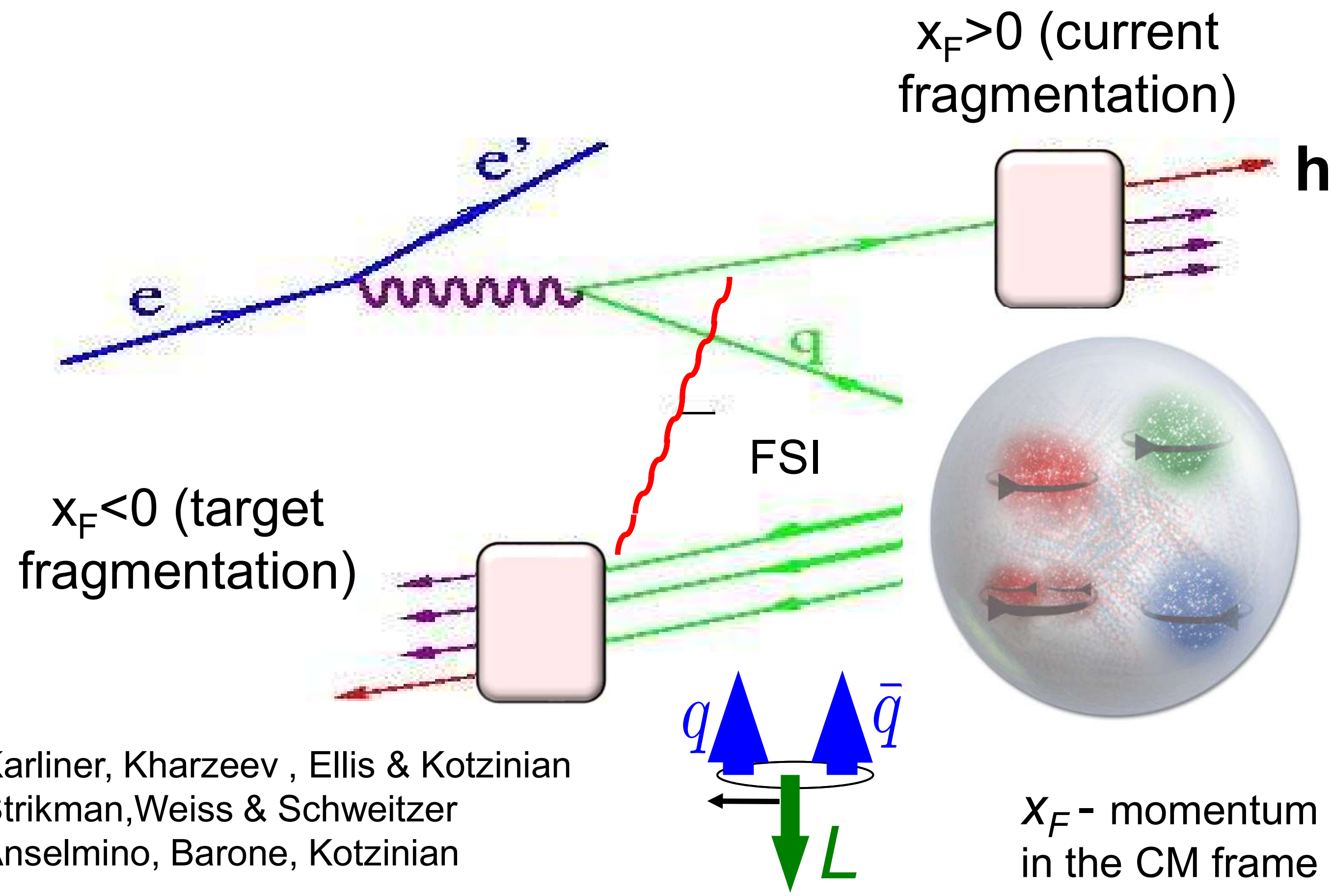
$$H^{q'}_{h/N}\left(x,\mathbf{k}_T,Q^2;x_F,\mathbf{P}^h_T;\mathbf{s}'_q,\mathbf{S}_N\right)$$

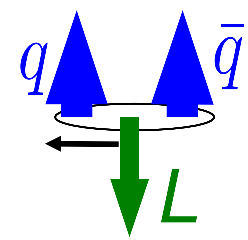
Quark Fragmentation Functions
(*universal and independent*)

$$D^h_{q,s'}\left(z,\mathbf{p}_T,Q^2\right)$$

Where this works?

Hadron production in hard scattering





X. Artru & Z. Belghobsi

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

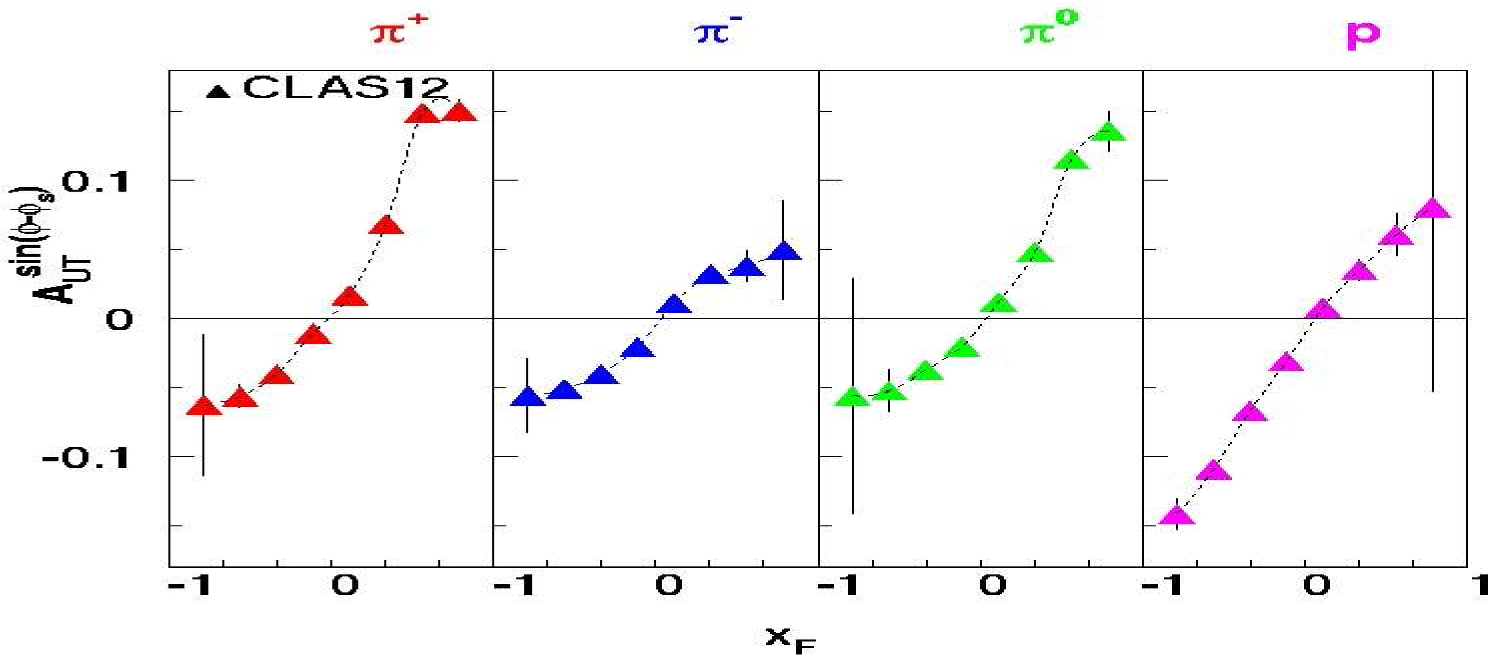
x_F - momentum in the CM frame

2-hadron correlations in CFR studied in EMC(1986) and COMPASS, Jlab, EIC

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

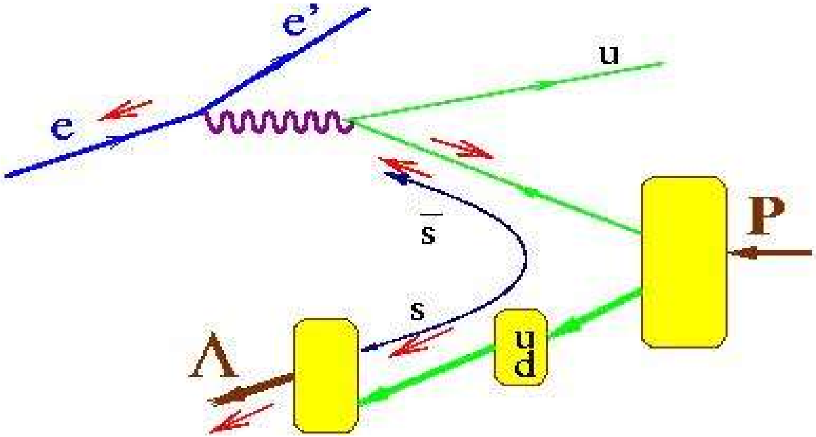
Sivers effect in the target fragmentation

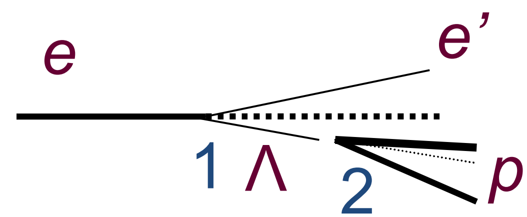
A.Kotzinian



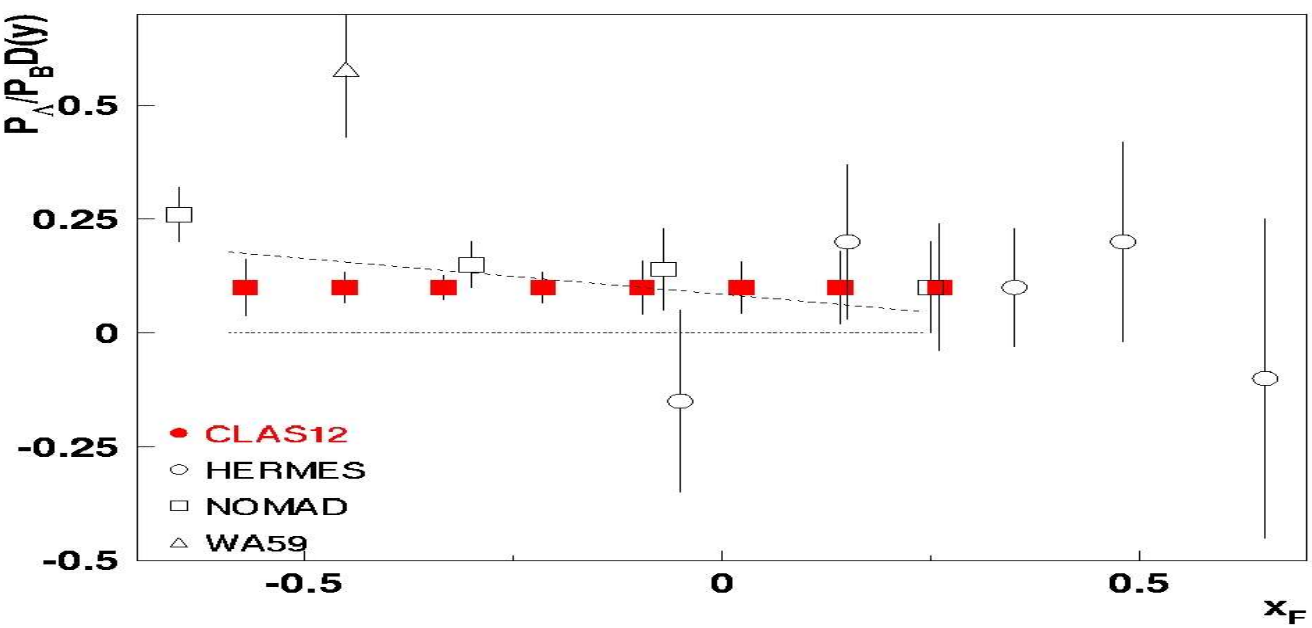
High statistics of CLAS12 will allow studies of kinematic dependences of the Sivers effect in target fragmentation region

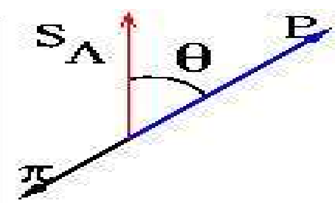
Λ polarization in the target fragmentation





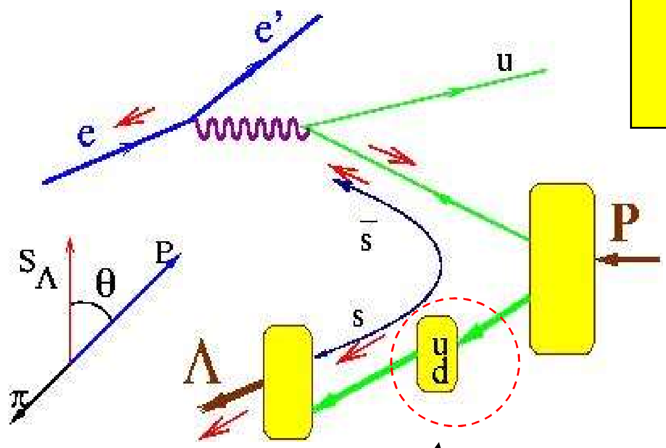
Λ – unique tool for polarization study due to self-analyzing parity violating decay





Wide kinematic coverage of CLAS12 allows studies of hadronization in the target fragmentation region

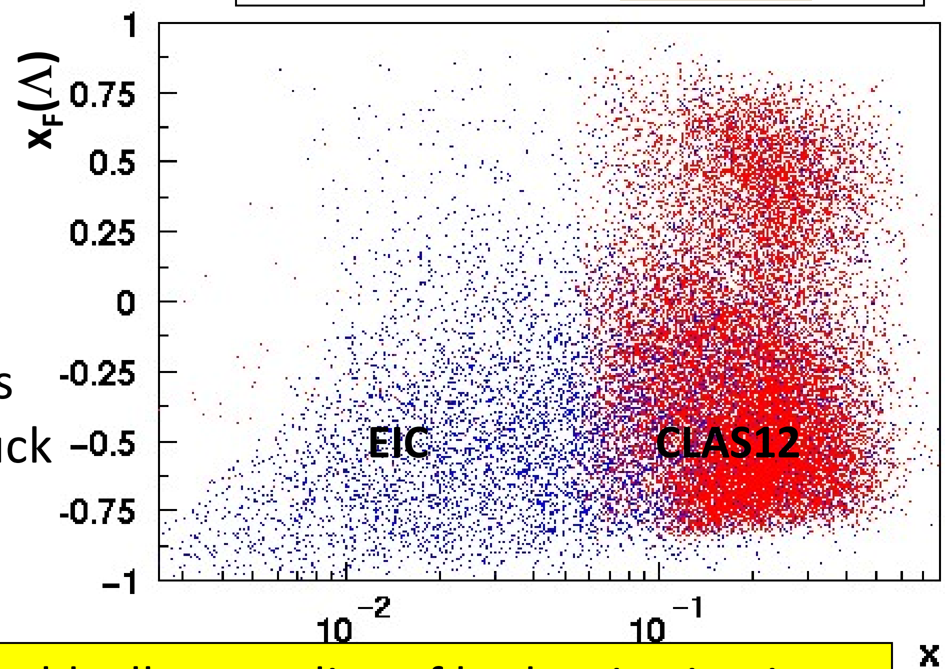
Λ production in the target fragmentation



Λ polarization in TFR provides information on contribution of strange sea to proton spin

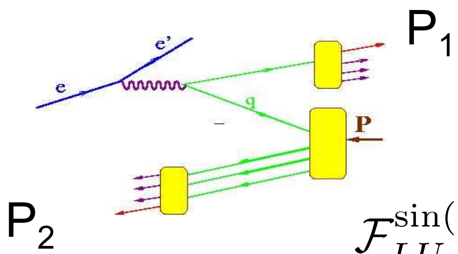
(ud)-diquark is a spin and isospin singlet s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$

Study polarized diquark fracture functions sensitive to the correlations between struck quark transverse momentum and the diquark spin.



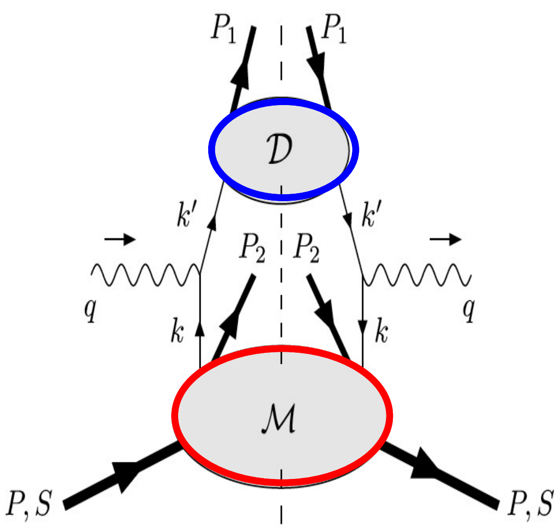
Wide kinematical coverage of EIC would allow studies of hadronization in the target fragmentation region (fracture functions)

Target fragmentation in SIDIS



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

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



Leading Twist

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

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

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

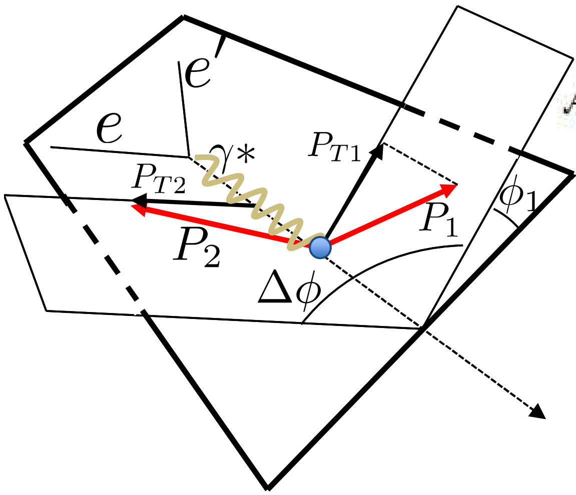
Understanding of Target Fragmentation Region (TFR) is important for interpretation of the Current FR

- Need a consistent theoretical description for TFR
- Measure/model fracture functions

B2B hadron production in SIDIS: First measurements

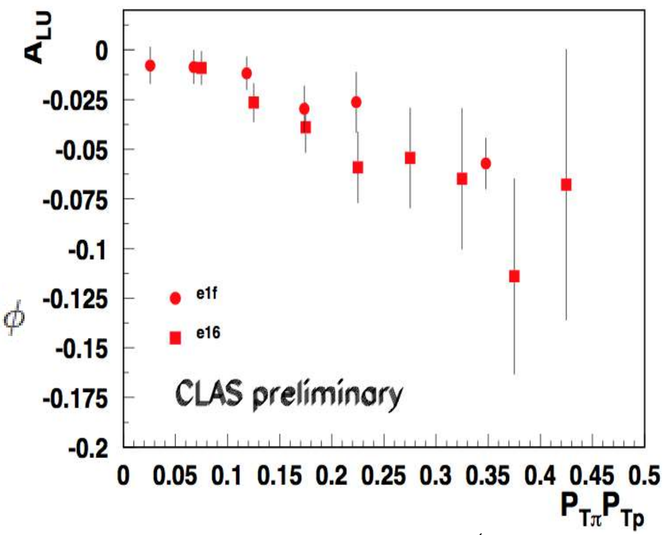
M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

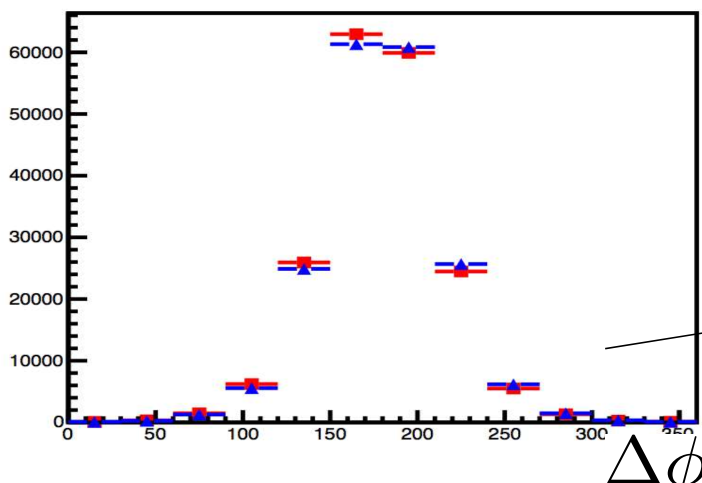
$$ep \to e' p \pi^+ X$$

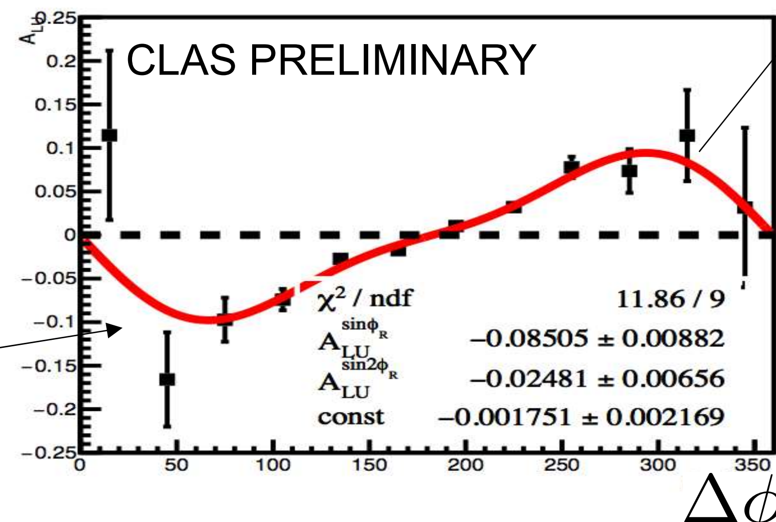


$$A_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

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







Significant asymmetries observed by CLAS at 6 GeV

SUMMARY

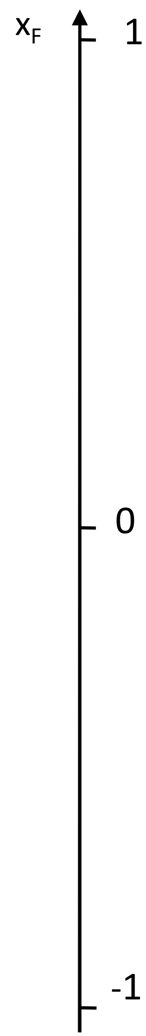
Correlations play a crucial role in non perturbative dynamics

Close communication of theorists and experimentalists was critical in extraction and interpretation of all kind of spin-azimuthal asymmetries

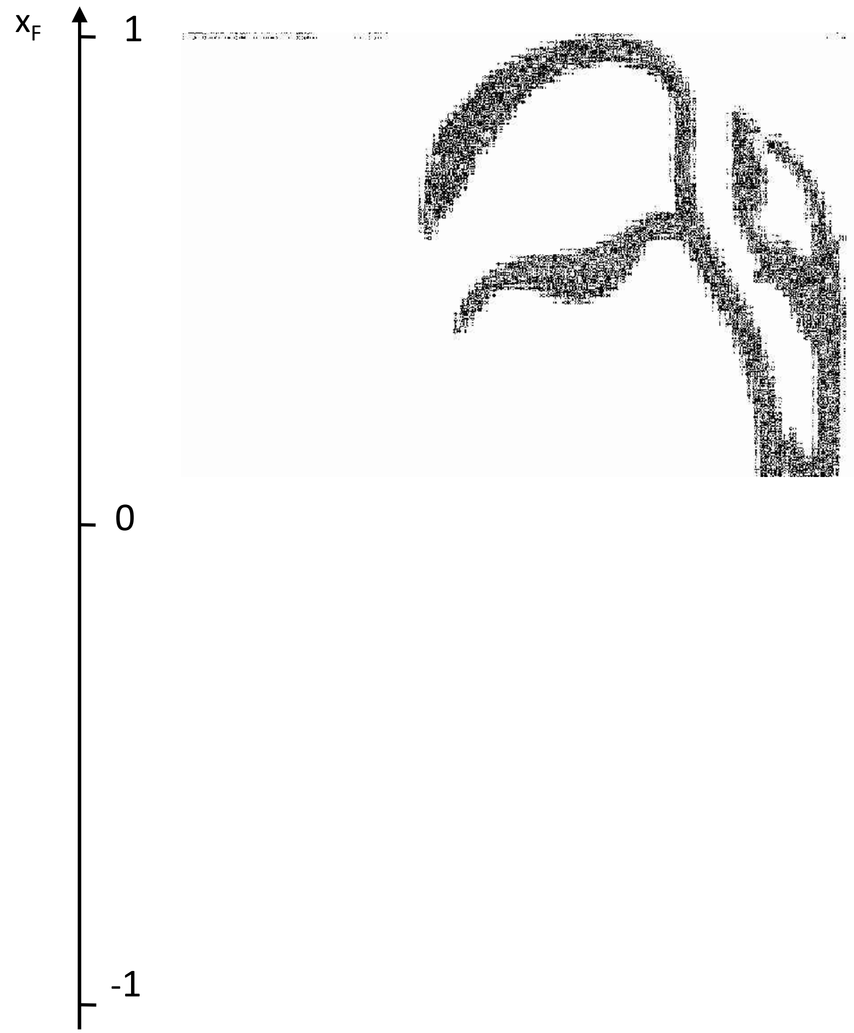
Target fragmentation can be an important (so far undervalued) domain for understanding of the partonic interactions and correlations

A proper visualization of the nucleon structure will require understanding of target fragmentation

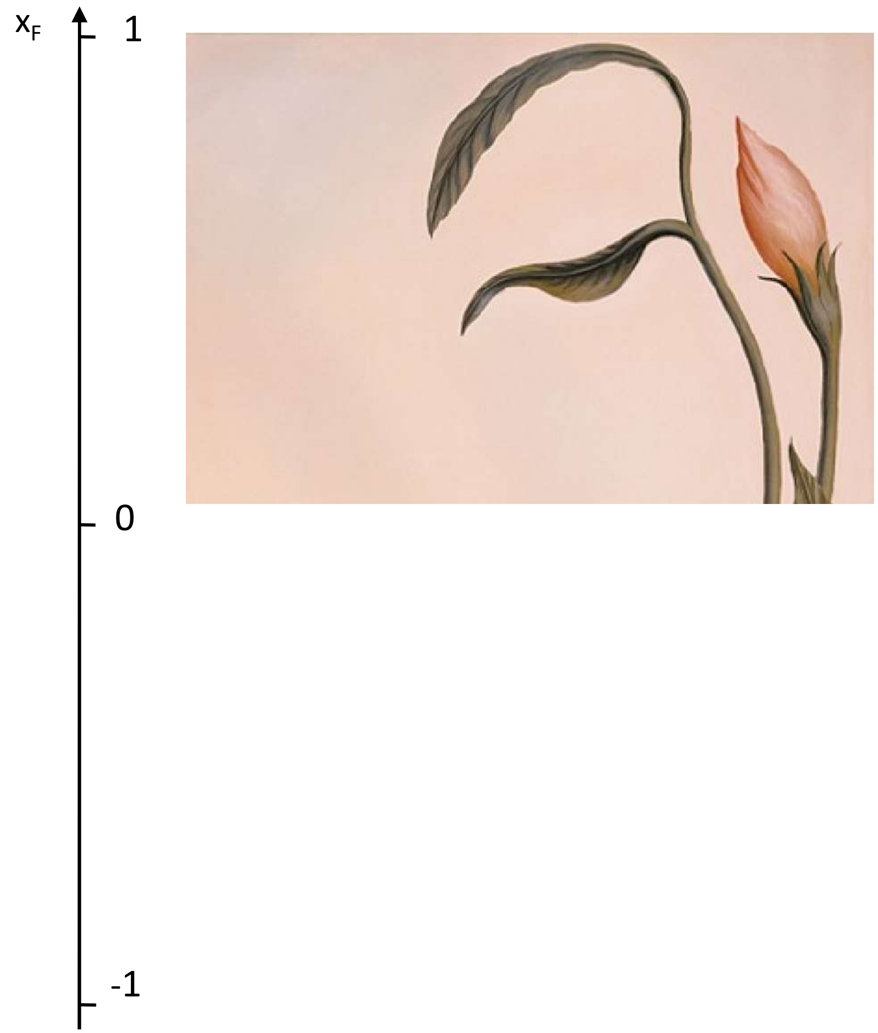
CFR



Larger phase space
higher W, z, x
different asymmetries

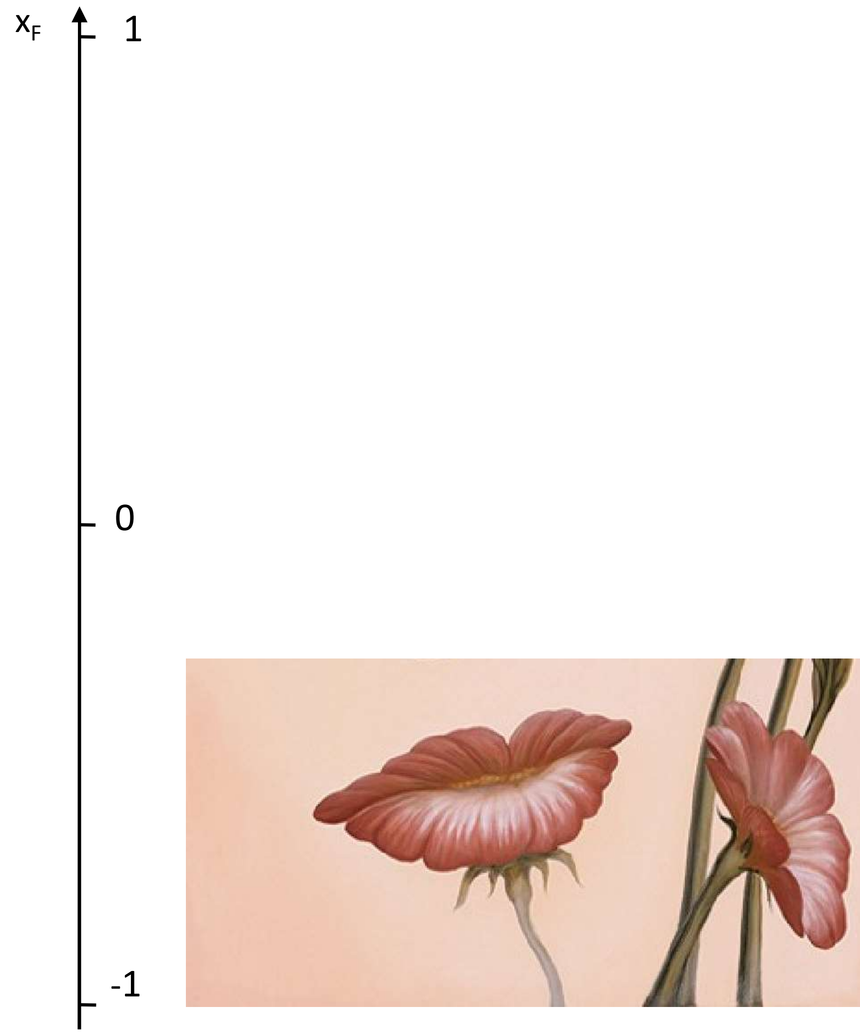


Better resolution,
higher statistics



Saclay, 18-Nov-16

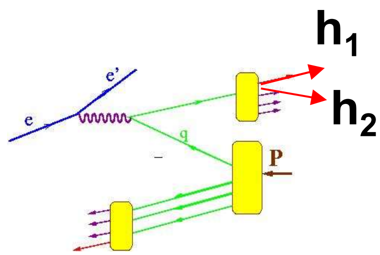
TFR with good
resolution etc

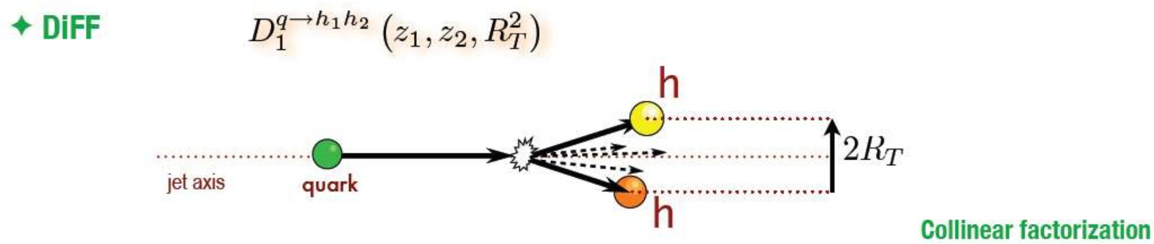


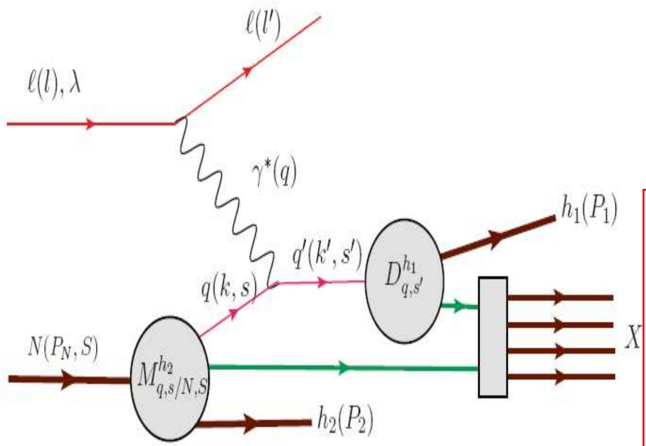
Full picture can be
surprising and beautiful

Support slides

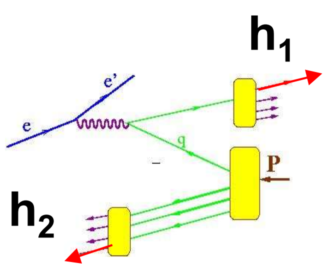
Hadronization in current and target regions





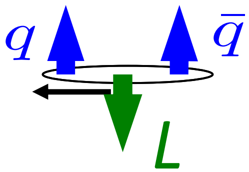


Anselmino/Barone/Kotzinian
arXiv:1107.2292 (2011)

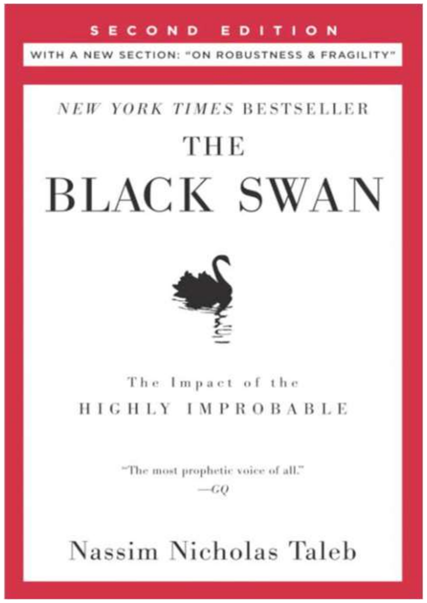


$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_2 m_N} F_{k1}^{\Delta\hat{g}_1^{\perp h}\cdot D_1} \sin(\phi_1 - \phi_2)\,.$$

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



SSAs: Black Swans of Nucleon Structure



1. **rarity**: it is an outlier, as it lies outside the realm of regular expectations, because *nothing in the past can convincingly point to its possibility*.
2. **it carries an extreme impact**.
3. **retrospective** (not prospective) **predictability**: in spite of its outlier status, human nature makes us concoct explanations for its occurrence *after the fact, making it explainable and predictable.*

One single observation can invalidate a general statement derived from millennia of confirmatory sightings of millions of white swans. All you need is one single (ugly) black bird.

Three stages for new phenomena

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