Semi-Inclusive DIS at COMPASS

Athira Vijayakumar
HUGS Summer School 2023

OVERVIEW

- Motivation
- What are PDFs, TMD PDFs, TMD FFs?
- What is SIDIS? Why SIDIS?
- COMPASS - Muon Run 2022
- Future prospects in TMD Physics

MOTIVATION

Curious to know about the fundamentals of the universe?

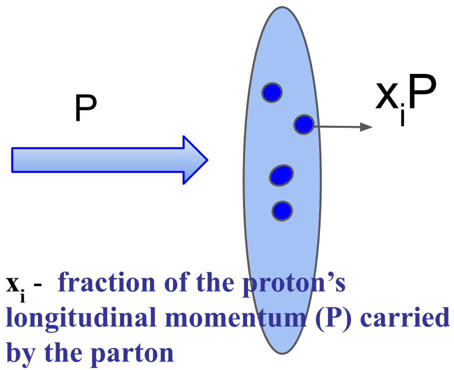
Look at the building blocks - protons and neutrons!

Understand how they are held together - the strong nuclear force!

Investigate what is inside them - complex internal structure!

Plenty of theoretical and experimental evidence for transverse motion of partons within nucleons → **Nucleon Tomography!**

PDFs, TMD-PDFs and TMD-FFs

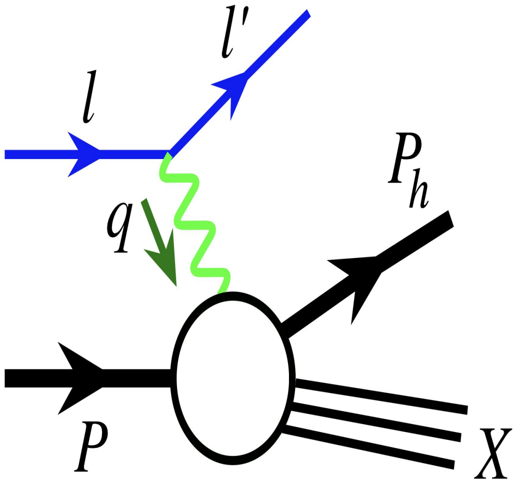


x_i - fraction of the proton's longitudinal momentum (P) carried by the parton

Parton **D**istribution **F**unctions describe the longitudinal momentum distributions of partons (quarks and gluons) inside the nucleon.

Transverse momentum extensions of longitudinal momentum–dependent parton distribution functions are called transverse momentum–dependent (**TMD**) **PDF**s.

Access TMD PDFs through Semi Inclusive Deep Inelastic Scattering (**SIDIS**).

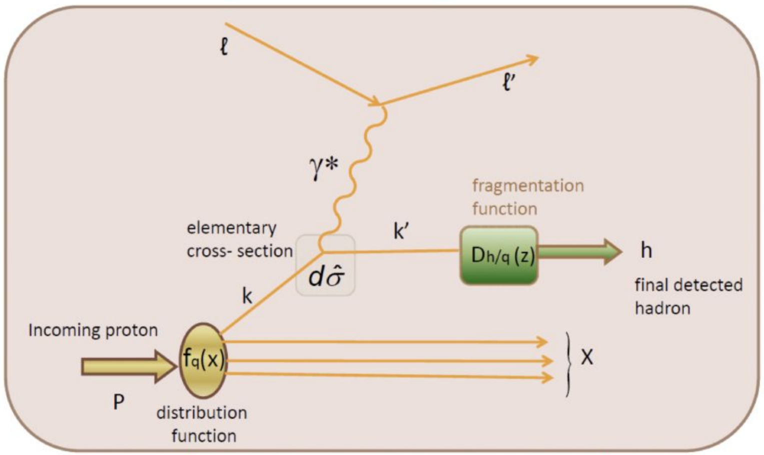


TMD-PDFs encode transverse momentum and transverse spin of the partons and their correlations (also with the nucleon spin) as a function of Bjorken x, Q^2 and the parton transverse momentum k_T.

PDFs, TMD-PDFs and TMD-FFs

At leading twist, a complete description of the nucleon structure is given by **eight independent TMD-PDFs**.

Analogously, **TMD-FFs** (Fragmentation Functions) encode the probability of a hadron to arise from a fragmenting parton with a certain fraction of the parton's longitudinal momentum and a small transverse momentum relative to the parton.



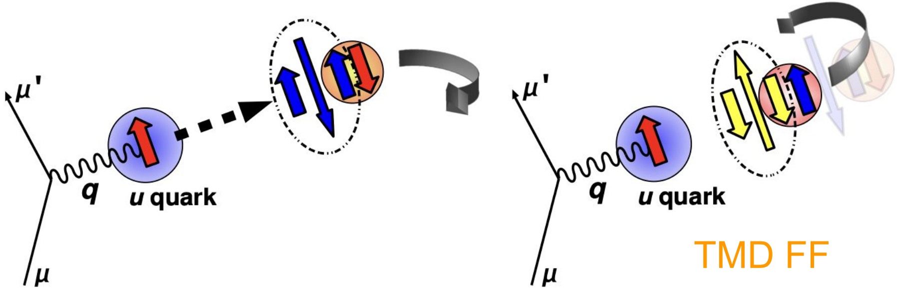
$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

In today's talk, we will discuss the Transversity and Sivers PDF and Collins FF

Collins and Sivers Effects

Collins function: unpolarized hadron from a transversely polarized quark

$$D_{q/h}(z,\vec{p}_\perp,\vec{s}_q) = D_{q/h}(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\,\vec{s}_q\cdot(\hat{k}\times\vec{p}_\perp)$$

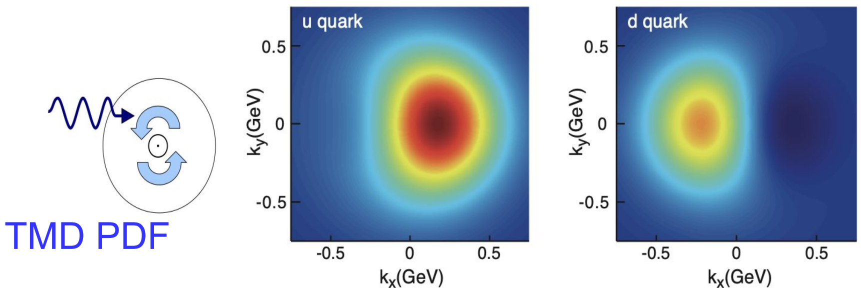


Sivers function: unpolarized quark distribution inside a transversely polarized nucleon

$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\,\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$

Spin independent　　Spin dependent

$x f_1(x, k_T, S_T)$



Eur. Phys. J. A (2016) 52: 154

COMPASS Muon Run 2022

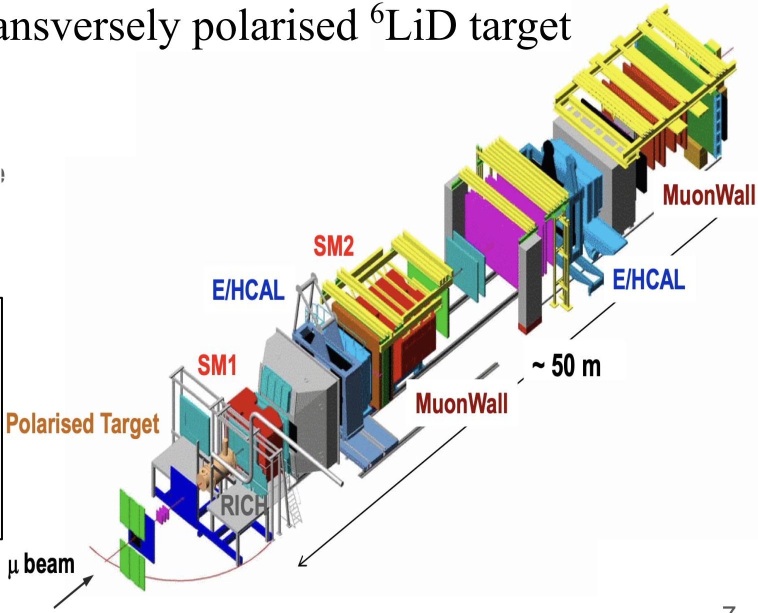
(COmmon Muon Proton Apparatus for Structure and Spectroscopy)

- 2022 muon beam at 160 GeV
- Variety of tracking detectors to cope with different particle flux with a good azimuthal and angular acceptance
- Calorimeters and Muon Identification

❖ Located at SPS at CERN in Geneva

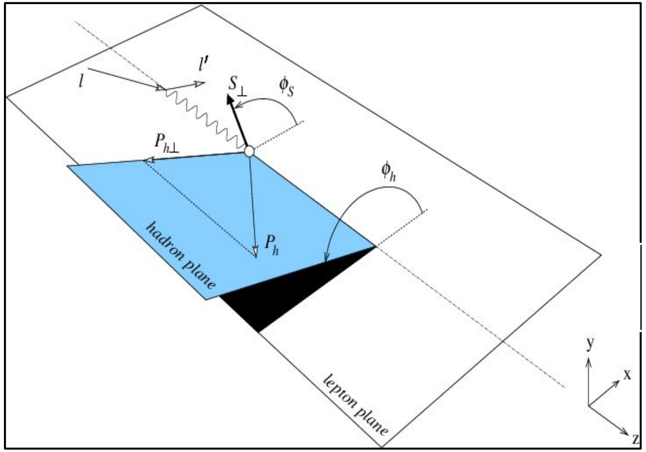
❖ Fixed target experiment, Consists of two spectrometers

❖ 2022 Run is aimed at SIDIS of muons off transversely polarised ^{6}LiD target



The 2022 data-taking campaign was the last run of the COMPASS experiment, and the last of the experiment's exploratory study of the nucleon structure.

What we measure at COMPASS

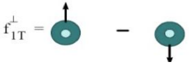


Experimental Observable:

$$A_{UT} = \frac{1}{fS_T}\frac{N^{\uparrow}(\phi_h) - N^{\downarrow}(\phi_h)}{N^{\uparrow}(\phi_h) + N^{\downarrow}(\phi_h)}$$

The differential cross-section of SIDIS can be expressed as;

$$d\sigma = d\sigma_{00} + \lambda_l d\sigma_{L0} + S_L(d\sigma_{0L} + \lambda_l d\sigma_{LL}) + S_T(d\sigma_{0T} + \lambda_l d\sigma_{LT}),$$



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

Sivers $\otimes$ D1

The scattering cross-section can be broken down as ~

$$harmonic(\phi_h, \phi_s).\,PDF \otimes FF$$

$$A_{UT} = \frac{d\sigma_{0T}}{d\sigma_{00}}$$

$$d\sigma_{0T} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)} \cdot \left\{ \sin(\phi_h - \phi_S) F_{UT}^{\sin(\phi_h - \phi_S)} + \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right.$$

$h_1 \otimes H_1^{\perp}$

transversity $\otimes$Collins

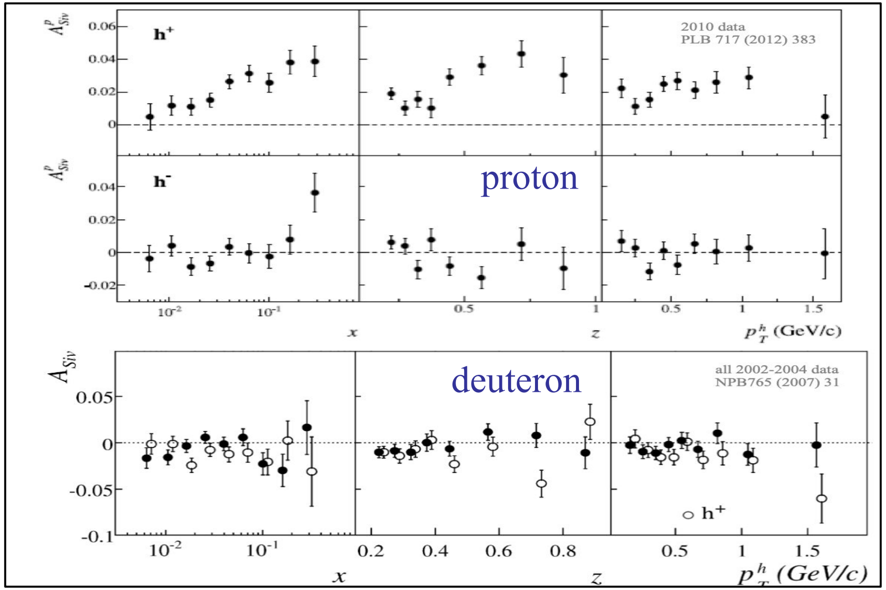
$h_{1T}^{\perp} \otimes H_1^{\perp}$

pretzelosity $\otimes$Collins

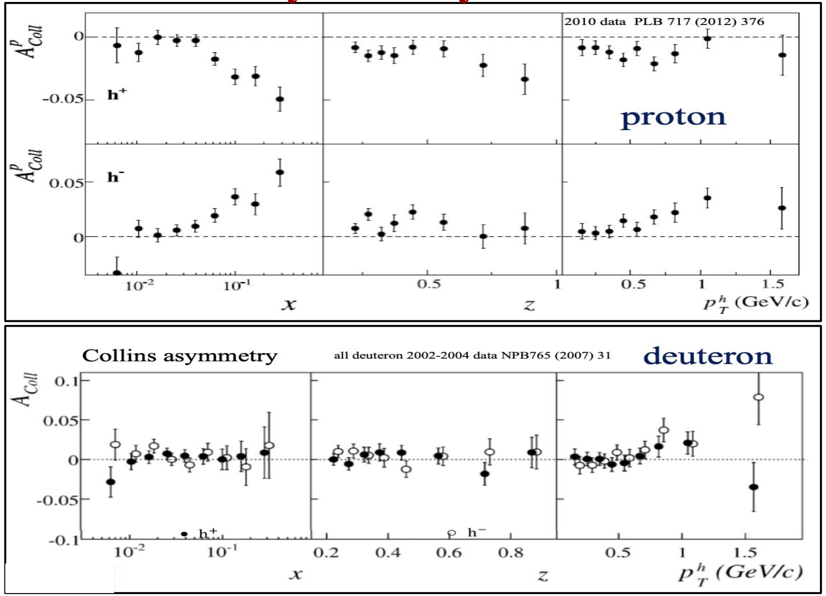
M. Anselmino *et al*., PRD 83, 114019 (2011)

Previous Results from COMPASS

Sivers asymmetry



Collins asymmetry



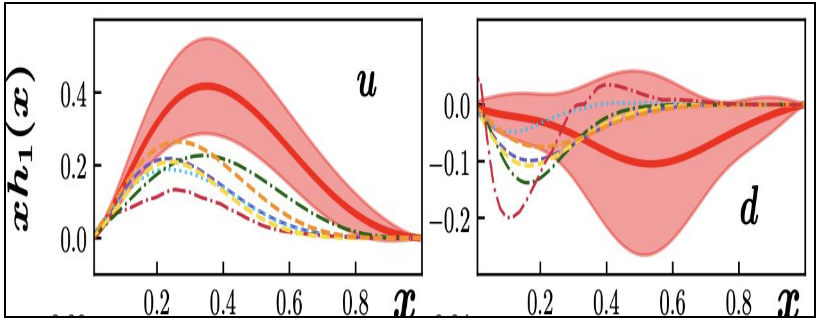
- Proton: Clearly positive for positive hadrons
    - Compatible with zero for negative hadrons(?)
- Deuteron: Compatible with zero but large uncertainties
    - Attributed to u/d - quark cancellation effects

- Proton: Clear signal in the valence region
    - Opposite signs for h+ and h-
- Deuteron: Compatible with zero
    - Maybe a signal at high Pt?
    - Indication of u and d quarks cancellation?

What more in 2022 Run

Reduce the uncertainties!

Phys. Rev. D 102, 054002 (2020)

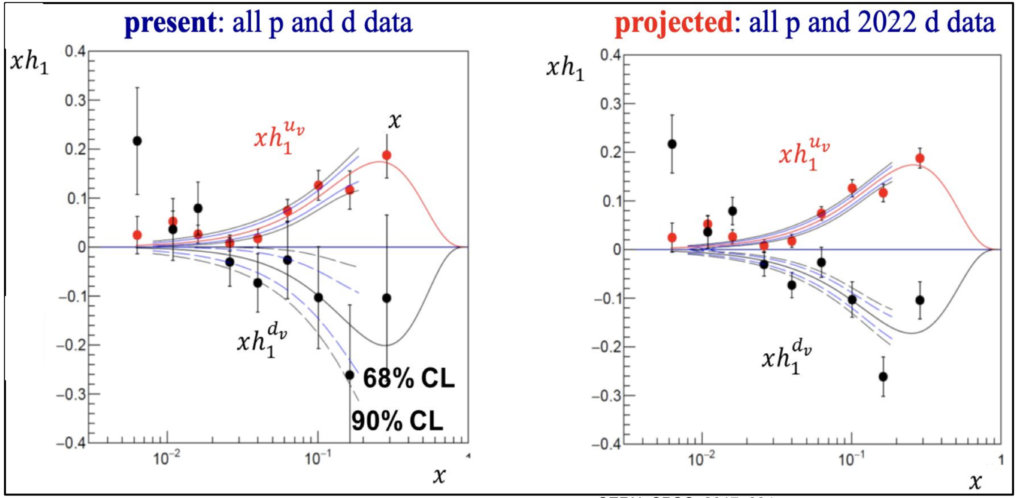


The 2022 run on transversely polarized deuteron target is expected to improve the d quark distributions significantly!

The analysis has begun.
Exciting results coming soon!!

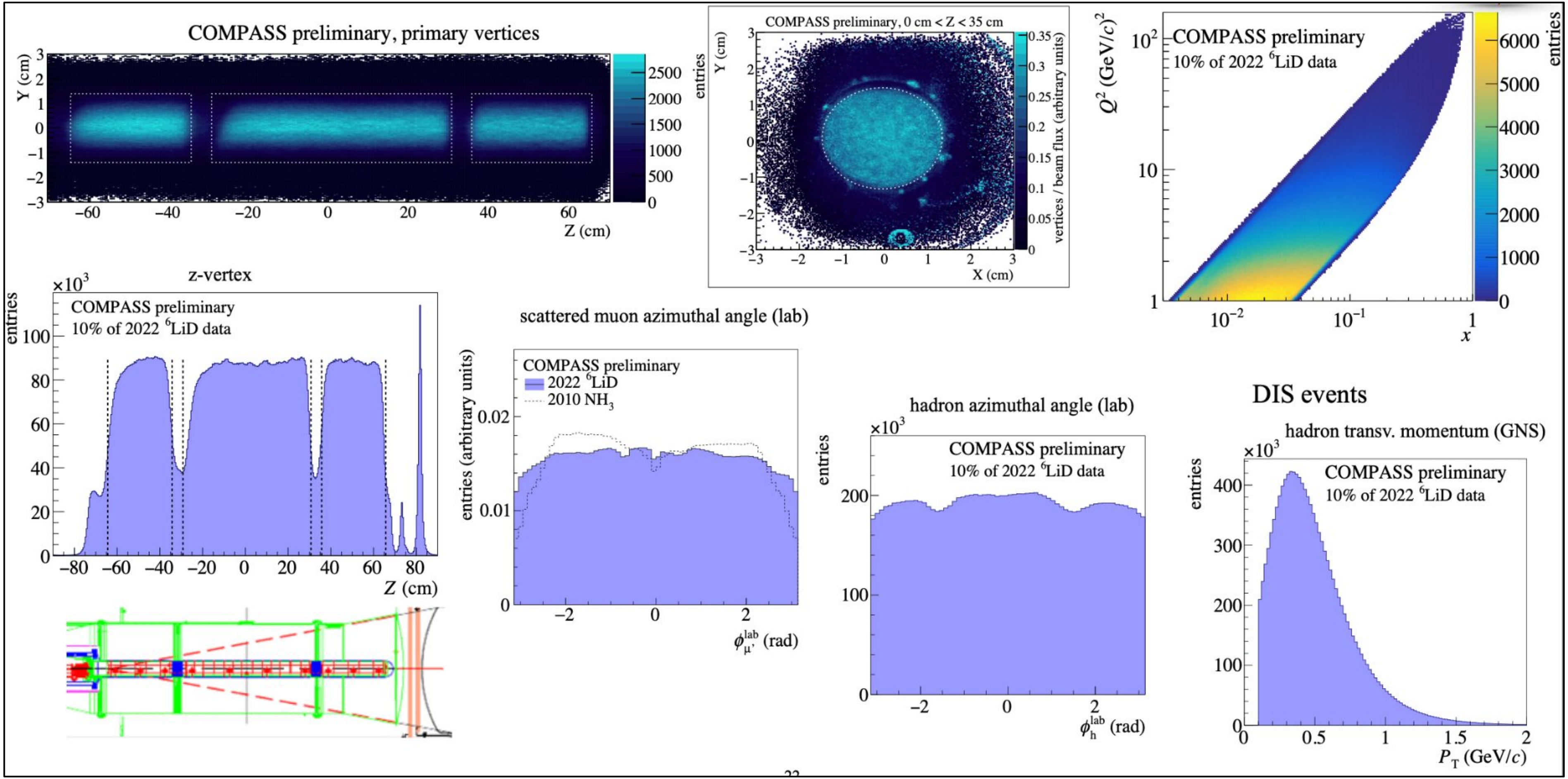
Impact on transversity TMD PDFs and tensor charge

$\Omega_x: 0.008 \div 0.210$	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d}(x)$	$g_T = \delta_u - \delta_d$
present	0.201 ± 0.032	-0.189 ± 0.108	0.390 ± 0.087
projected	0.201 ± 0.019	-0.189 ± 0.040	0.390 ± 0.044



CERN–SPSC–2017–034

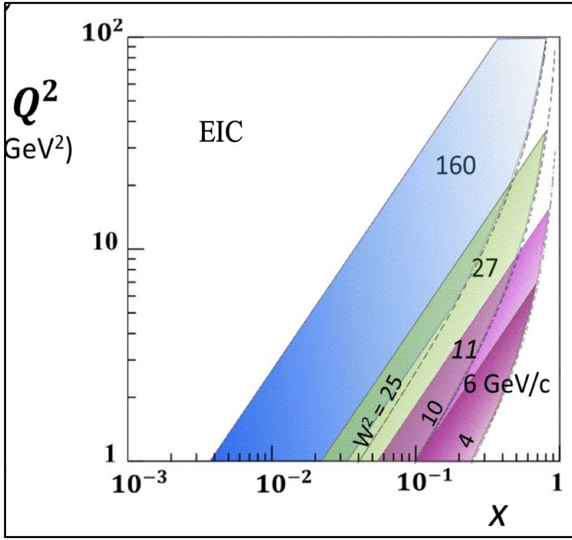
Initial look at 2022 data



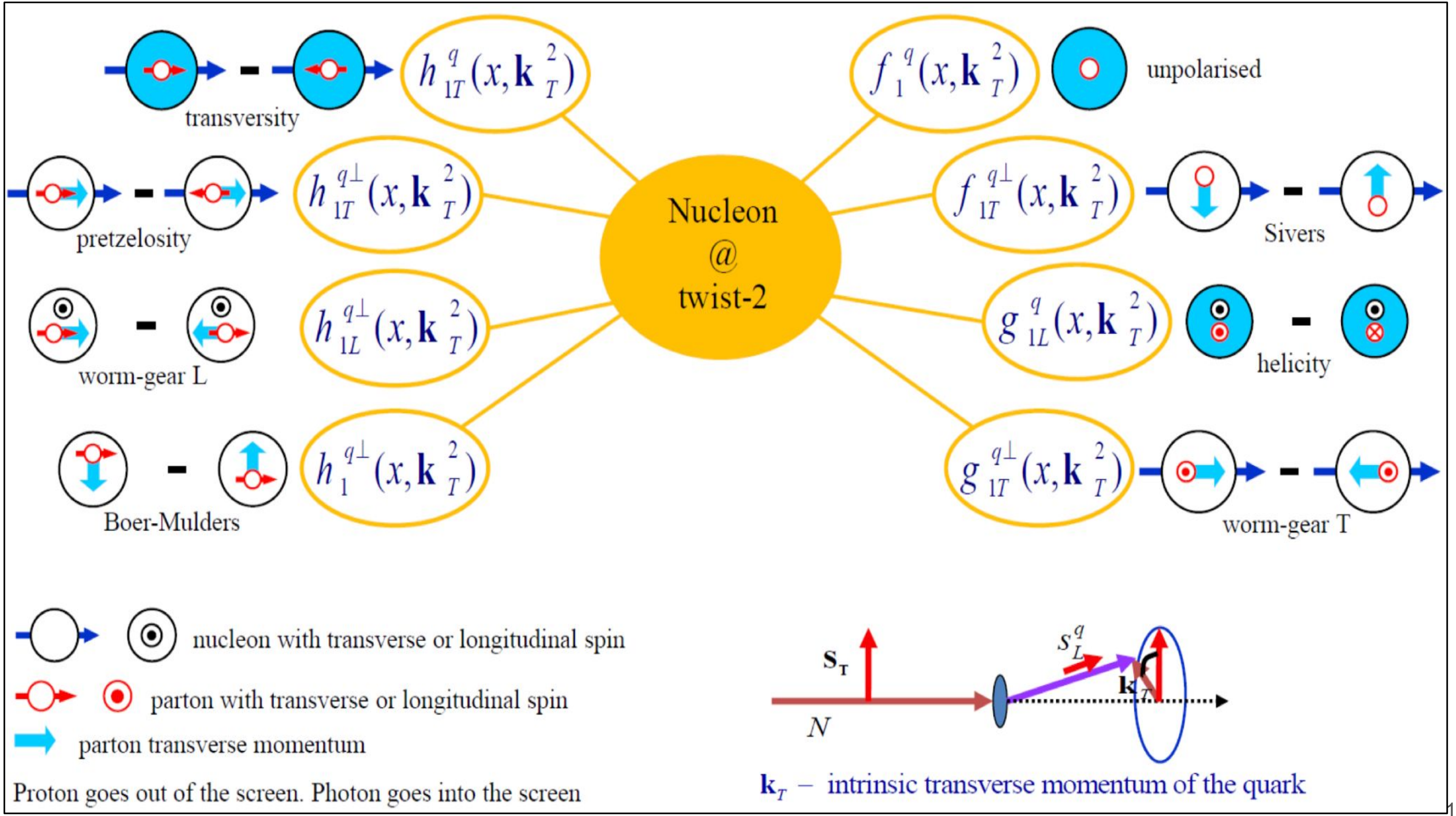
Future prospects

- Precise measurements are needed in particular at larger x.

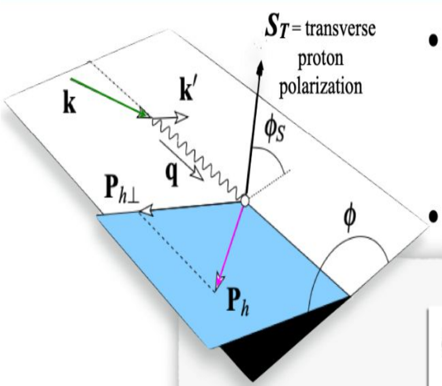
- The complementary measurements at Jlab 12 and 20+ will allow for a more precise measurement of the tensor charge and, in the farther future, the EIC.



Backup



transversity
$h_{1T}^{q}(x,\mathbf{k}_T^2)$
pretzelosity
$h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$
worm-gear L
$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$
Boer-Mulders
$h_{1}^{q\perp}(x,\mathbf{k}_T^2)$
Nucleon @ twist-2
$f_{1}^{q}(x,\mathbf{k}_T^2)$
unpolarised
$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$
Sivers
$g_{1L}^{q}(x,\mathbf{k}_T^2)$
helicity
$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$
worm-gear T
nucleon with transverse or longitudinal spin
parton with transverse or longitudinal spin
parton transverse momentum
Proton goes out of the screen. Photon goes into the screen
$\mathbf{S}_T$
N
s_L^q
$\mathbf{k}_T$
$\mathbf{k}_T$ – intrinsic transverse momentum of the quark



- Cross section can be broken down in independent harmonic modulations ("azimuthal asymmetry amplitudes") times a PDF convoluted with a fragmentation function
- Experimental observable is of the type

"~ harmonic(ϕ, ϕ_S) · PDF ⊗ FF"

$$A_{UT}(\phi) = \frac{1}{f S_T} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

$$\sigma(\phi, \phi_S) \equiv \frac{d^6\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{hT}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x}\right)$$

$$\Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\,\cos\phi\, F_{UU}^{\cos\phi} + \epsilon\,\cos(2\phi)\, F_{UU}^{\cos(2\phi)} + \lambda_e \left[\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi\, F_{LU}^{\sin\phi}\right] +$$

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

$$+ |S_T| \Big[\sin(\phi - \phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \epsilon\,\sin(\phi + \phi_S)\, F_{UT}^{\sin(\phi+\phi_S)} + \epsilon\,\sin(3\phi - \phi_S)\, F_{UT}^{\sin(3\phi-\phi_S)}$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)}\,\sin(2\phi - \phi_S)\, F_{UT}^{\sin(2\phi-\phi_S)}\Big]$$

$$+ |S_T| \lambda_e \left[\sqrt{1-\epsilon^2}\,\cos(\phi - \phi_S)\, F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\epsilon(1-\epsilon)}\,\cos(2\phi - \phi_S)\, F_{LT}^{\cos(2\phi-\phi_S)}\right]\Big\},$$

no proton polarization

longitudinal proton polarization

transverse proton polarization

Cahn-effect + BM ⊗ Collins

Worm-gear (Kotzinian-Mulders) ⊗ Collins

BM ⊗ Collins

Sivers ⊗ D1

Worm-gear ⊗ D1

Transversity ⊗ Collins

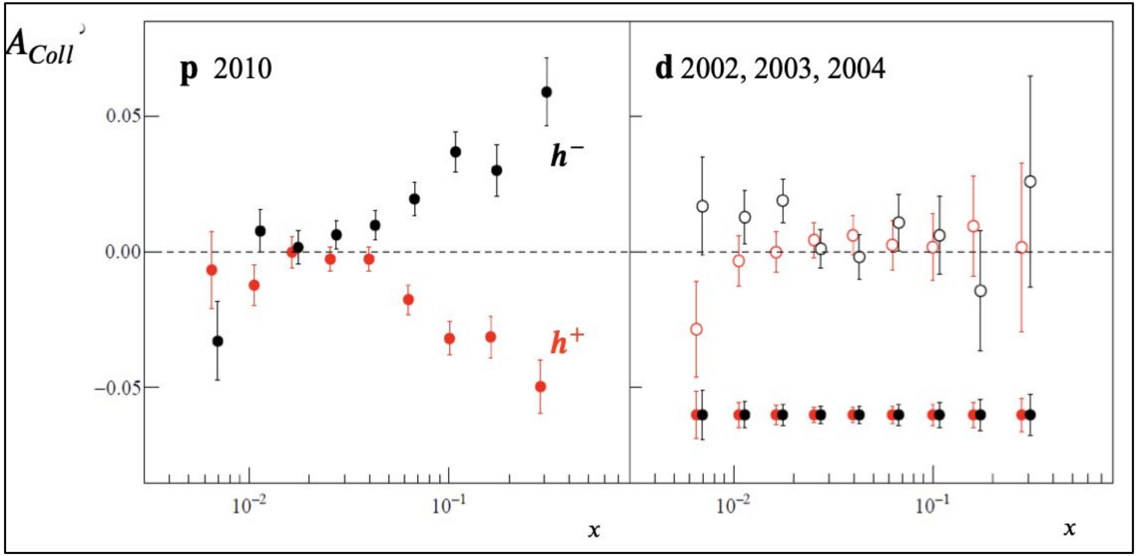
Pretzelosity ⊗ Collins

$F_{XY[Z]}$ = structure function. X=beam, Y= target polarization, [Z= virtual-photon polarization]. X, Y ∈ {U, L, T}. λ_e = helicity of the lepton beam. S_L and S_T = longitudinal and transverse target polarization. ϵ = ratio of longitudinal / transverse photon fluxes

[Bacchetta, Diehl, Klaus Goeke, Metz, Mulders, Schlegel, JHEP 02 (2007) 093]

The deuteron asymmetries will have statistical uncertainties (relative to proton 2010 data)

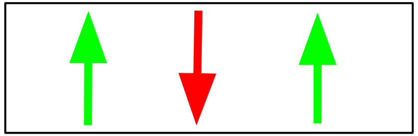
$\sigma_d \cong 0.6\, \sigma_p^{2010}$



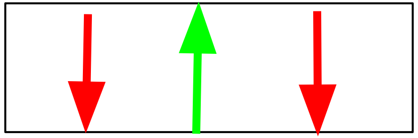
Data taking period in 2022

- Divided into two sub-periods(a week each)

Sub-period 1



Sub-period 2



2022-W01 Hide	294615 295153	06-02 23:33 06-22 08:55	+−+ −+−	Physics	t0, t1

- Sub-periods:
  1. 294902–295017, polarity: +−+, run list
     2022-06-07 17:42:33 – 2022-06-12 13:14:40
     Online P: +39.7%, −40.6%, +42.5%, measured 2022-06-07 12:09:44
  2. 295020–295153, polarity: −+−, run list
     2022-06-16 13:21:27 – 2022-06-22 08:55:11
     Online P: unknown