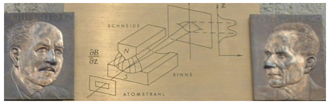
TMD Experiments

Fulvio Tessarotto

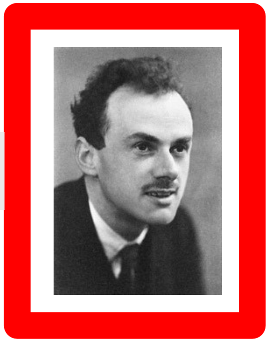
(INFN Trieste)

TMD physics roots

1913 atomic nucleus
1919 proton
1922 Stern-Gerlach
1925 spin 100 years!
1933 proton anomalous magnetic moment

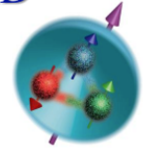


$$(i\not\partial - m)\,\psi = 0$$



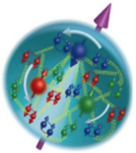
→ Nucleon spin structure: TMD

- 1964 Quark model



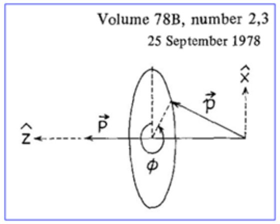
- 1969 Parton model

- 1973 asymptotic freedom and QCD

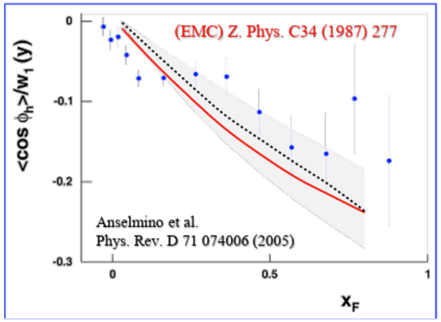


- 1976 large transverse single spin asymmetry in forward $\pi^{\pm}$ production ~50 years

- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries



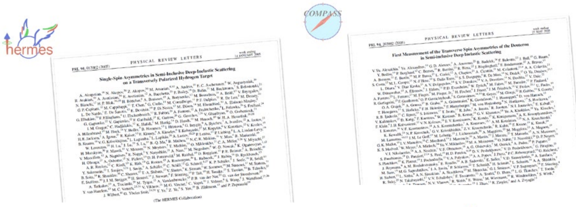
Volume 78B, number 2,3
25 September 1978



(EMC) Z. Phys. C34 (1987) 277

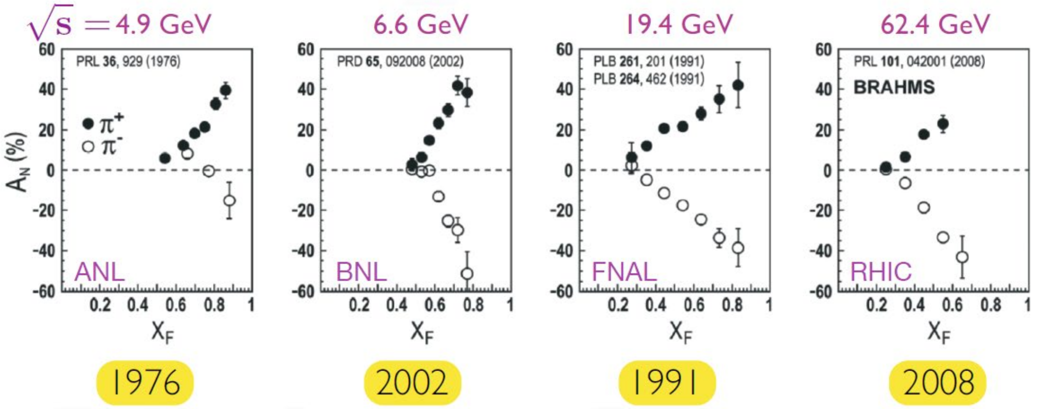
Anselmino et al.
Phys. Rev. D 71 074006 (2005)

(SLAC) Phys. Rev. Lett. 31, 786 (1973)
(EMC) Phys. Lett. B 130 (1983) 118,
(EMC) Z. Phys. C34 (1987) 277
(EMC) Z. Phys. C52, 361 (1991).
(E665) Phys. Rev. D48 (1993) 5057
(ZEUS) Eur. Phys. J. C11, 251 (1999)
(ZEUS) Phys. Lett. B 481, 199 (2000)
(H1) Phys. Lett. B654, 148 (2007)



- 2005 first published evidence of non-zero Collins and Sivers effects (HERMES-COMPASS) 20 years!

Transverse spin asymmetries: a long-standing puzzle



1978: Kane, Pumplin & Repko: transverse-spin asymmetries suppressed in pQCD

1990: Sivers proposes transverse spin-momentum correlation for quark distributions

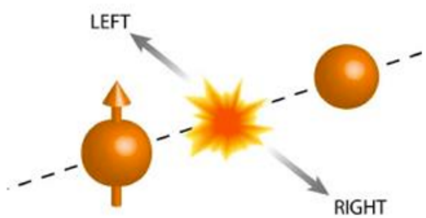
1993: Collins dislikes (& disproves) idea, introduces similar correlation in fragmentation

1996: Mulders&Tangerman: compendium of azimuthal asymmetries

1998: Boer&Mulders: naive T-odd observables -> Boer-Mulders distribution

2002: Brodsky, Hwang & Schmidt: resurrection of Sivers idea

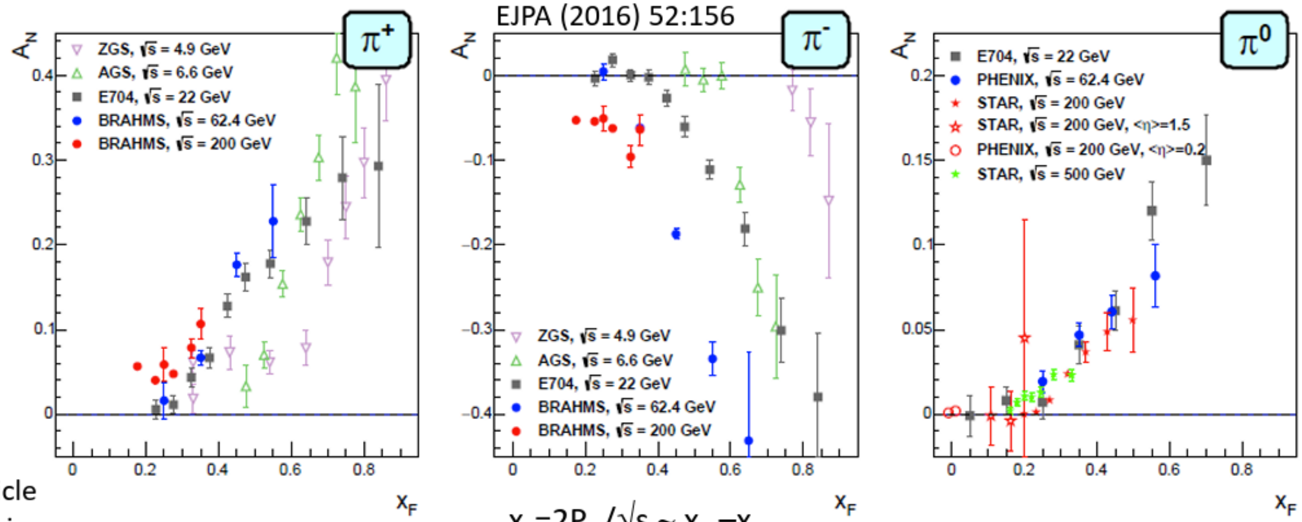
$p^{\uparrow} p \rightarrow h X$ (pioneer role)



$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Azimuthal angular dependence of particle production relative to the transverse spin direction of the polarized proton in the proton-proton collision

EJPA (2016) 52:156



$x_F = 2P_L/\sqrt{s} \sim x_1 - x_2$

large TTSA in the forward direction (large x_F)

In p+p collisions up to 500 GeV over 40 years

mostly independent of energy

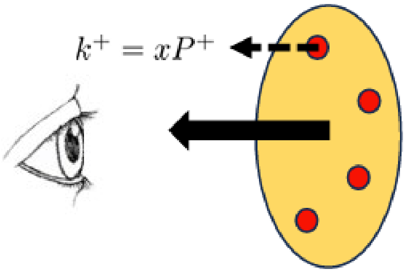
Cannot be explained in the leading-twist collinear picture

TMD distributions

“Quest for understanding hadrons and the origin of their mass and spin”

➔ mapping of quarks and gluons with their dynamics and multiple degrees of freedom

1D



Parton Distribution Functions

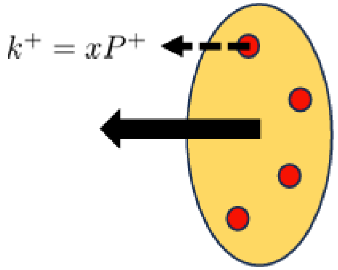
PDFs (x)

TMD distributions

“Quest for understanding hadrons and the origin of their mass and spin”

➔ mapping of quarks and gluons with their dynamics and multiple degrees of freedom

1D

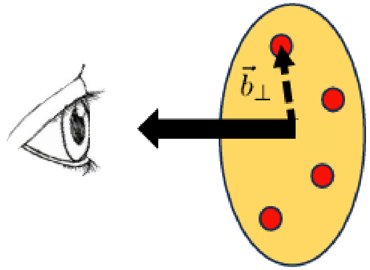


2D

Form Factors

PDFs (x)

FFs (Δ)



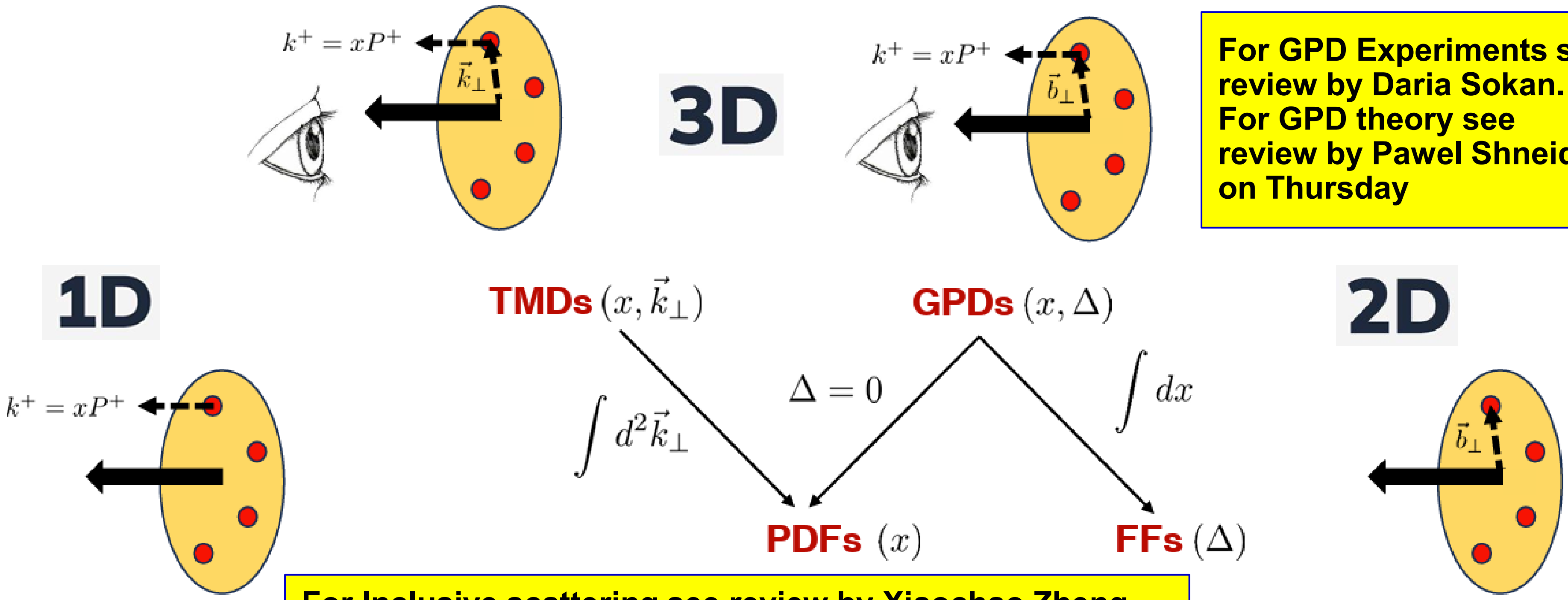
TMD distributions

“Quest for understanding hadrons and the origin of their mass and spin”

➔ mapping of quarks and gluons with their dynamics and multiple degrees of freedom

Transverse Momentum-dependent Distributions

Generalized Parton Distributions



**For GPD Experiments see review by Daria Sokan.
For GPD theory see review by Pawel Shneider on Thursday**

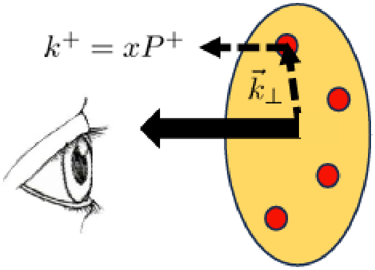
For Inclusive scattering see review by Xiaochao Zheng

TMD distributions

“Quest for understanding hadrons and the origin of their mass and spin”

➔ mapping of quarks and gluons with their dynamics and multiple degrees of freedom

Transverse Momentum-dependent Distributions



3D

TMDs $(x, \vec{k}_\perp)$

TMD Theory: great progress!

COLLINS-SOPER EQUATIONS

Differential equations
diagonal in flavor space

$$\frac{d\ln \tilde F(x,b_T,\mu,\zeta)}{d\ln\mu} = \gamma_F(\mu)$$

- Anomalous dimension of TMD, can be expanded in perturbative series
  Known up to 4 loops
  R.N. Lee, A. von Manteuffel, R.M. Schabinger, A.V. Smirnov, V.A. Smirnov and M. Steinhauser, Phys. Rev. Lett. 128 (2022) 212002

$$\frac{\partial\ln \tilde F(x,b_T,\mu,\zeta)}{\partial\ln\sqrt{\zeta}} = \tilde K(b_T,\mu)$$

- Collins-Soper kernel, can be expanded in perturbative series at small b_T
  Known up to 4 loops
  C. Duhr, B. Mistlberger and G. Vita, Phys. Rev. Lett. 129 (2022) 162001
  I. Moult, H.X. Zhu and Y.J. Zhu, JHEP 08 (2022) 280

$$\frac{d\tilde K(b_T,\mu)}{d\ln\mu} = -\gamma_K(\mu)$$

- Cusp anomalous dimension, can be expanded in perturbative series
  Known up to 5 loops
  F. Herzog, S. Moch, B. Ruijl, T. Ueda, J.A.M. Vermaseren, A. Vogt, Phys. Lett. B 790 (2019)

ζ = Collins-Soper parameter

Collins-Soper kernel $\tilde K$ is specific for TMDs

DGLAP EQUATIONS

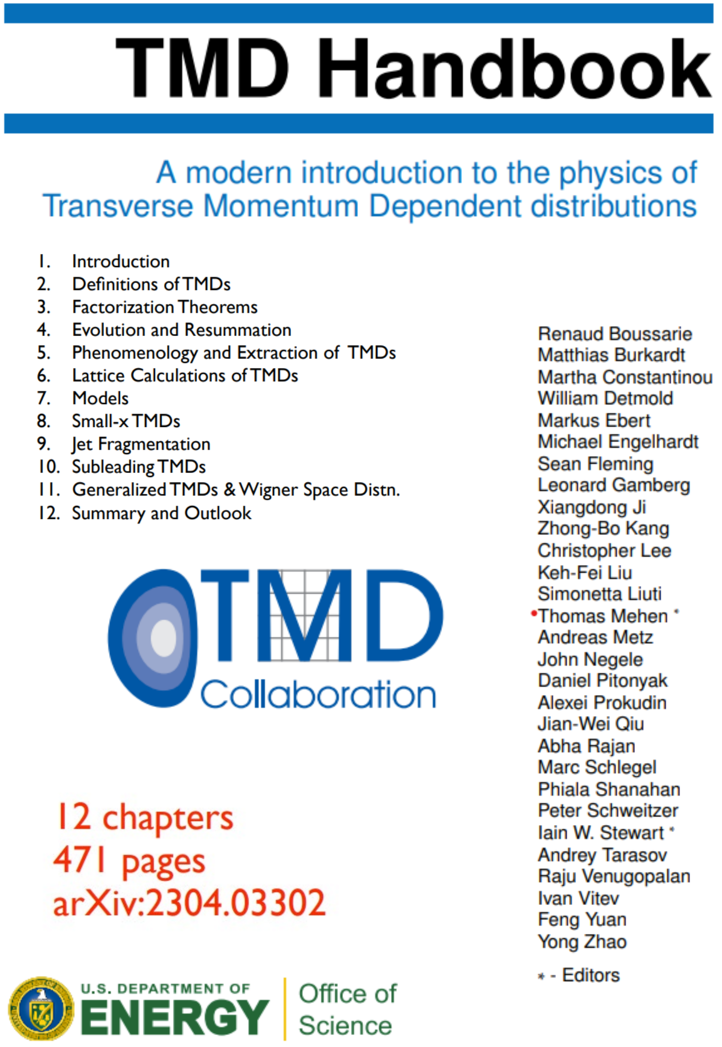
Integro-differential equations
non diagonal in flavor space

$$\mu^2\frac{d}{d\mu^2} f_q(x,\mu) = \sum_{f'=q,\bar q,g}\int_x^1 \frac{dy}{y} P_{q\to f'}(y) f_{f'}\left(\frac{x}{y},\mu\right)$$

μ = UV renormalization scale

See TMD theory review by Kazuhiro Watanabe on Thursday

For lattice calculations of TMD see review by Wei Wang later today



TMD Handbook

A modern introduction to the physics of
Transverse Momentum Dependent distributions

1. Introduction
2. Definitions of TMDs
3. Factorization Theorems
4. Evolution and Resummation
5. Phenomenology and Extraction of TMDs
6. Lattice Calculations of TMDs
7. Models
8. Small-x TMDs
9. Jet Fragmentation
10. Subleading TMDs
11. Generalized TMDs & Wigner Space Distn.
12. Summary and Outlook

Renaud Boussarie
Matthias Burkardt
Martha Constantinou
William Detmold
Markus Ebert
Michael Engelhardt
Sean Fleming
Leonard Gamberg
Xiangdong Ji
Zhong-Bo Kang
Christopher Lee
Keh-Fei Liu
Simonetta Liuti
*Thomas Mehen *
Andreas Metz
John Negele
Daniel Pitonyak
Alexei Prokudin
Jian-Wei Qiu
Abha Rajan
Marc Schlegel
Phiala Shanahan
Peter Schweitzer
Iain W. Stewart *
Andrey Tarasov
Raju Venugopalan
Ivan Vitev
Feng Yuan
Yong Zhao

* - Editors

TMD Collaboration

12 chapters
471 pages
arXiv:2304.03302

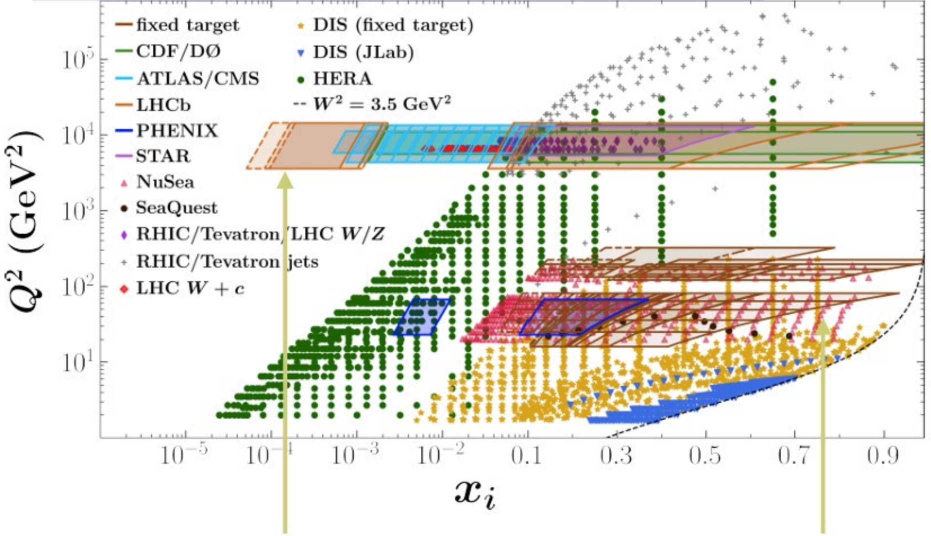
U.S. DEPARTMENT OF ENERGY | Office of Science

progress still ongoing

New phenomenological approaches

Combined extraction of pdfs and TMDs

TMD GROUP
(A. Prokudin at QCD-N IWHSS)

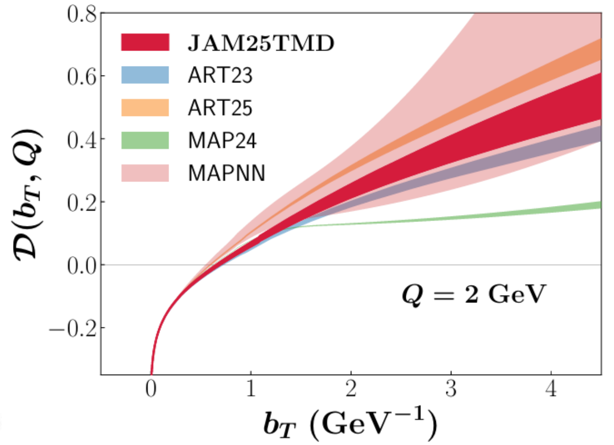


Precise data at small and intermediate x

Data at large-x

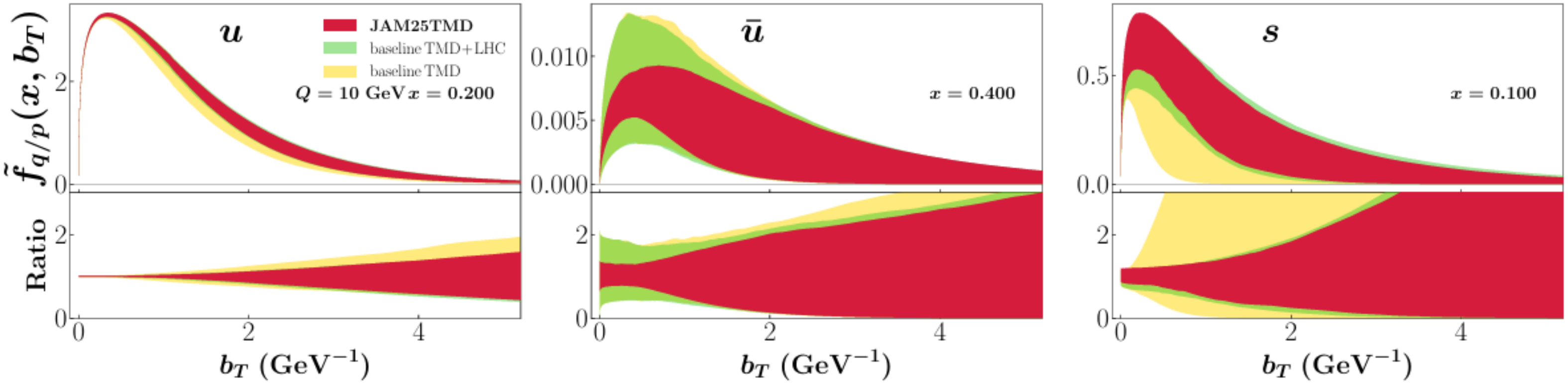
PRELIMINARY RESULTS

P. C. Barry et al in prepration



Collins Soper kernel compares well to existing extractions.

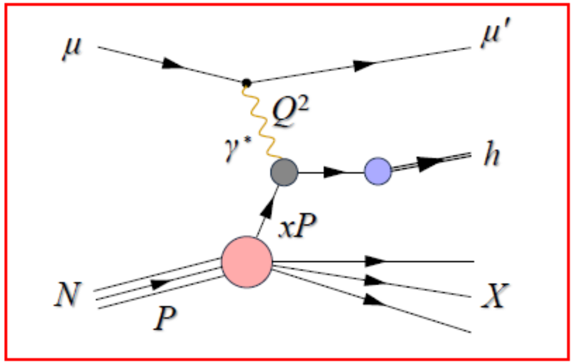
ART24: V. Moos, I. Scimemi, A. Vladimirov, P. Zurita JHEP 05 (2024) 036
ART25: V. Moos, I. Scimemi, A. Vladimirov, P. Zurita e-Print: 2503.11201
MAP24: MAP Collaboration, A. Bacchetta, JHEP 08 (2024) 232
MAPNN: MAP Collaboration, A. Bacchetta, Phys.Rev.Lett. 135 (2025) 2, 021904



List of main TMD contributing experiments

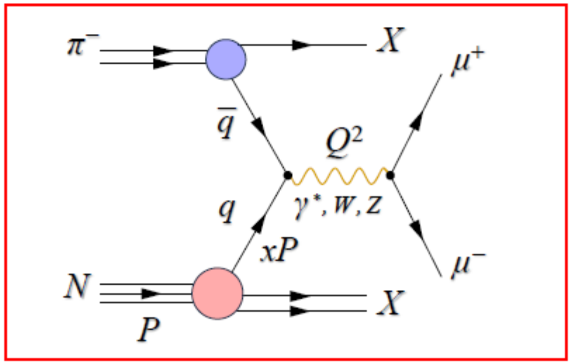
For fragmentation functions see review by Anselm Vossen after the coffee break

Semi-inclusive DIS



hermes DESY COMPASS CERN Jefferson Lab clas SoLID

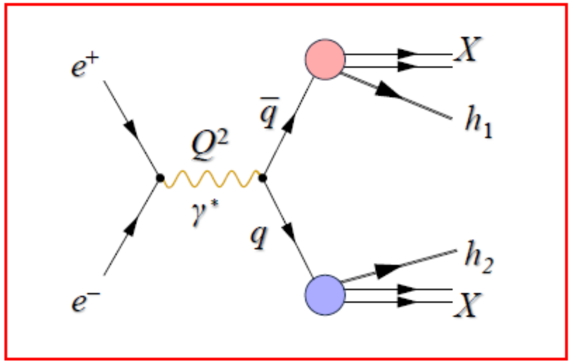
Drell-Yan process



COMPASS CERN STAR SPIN QUEST Fermilab LHC spin AMBER Apparatus for Meson and Baryon Experimental Research

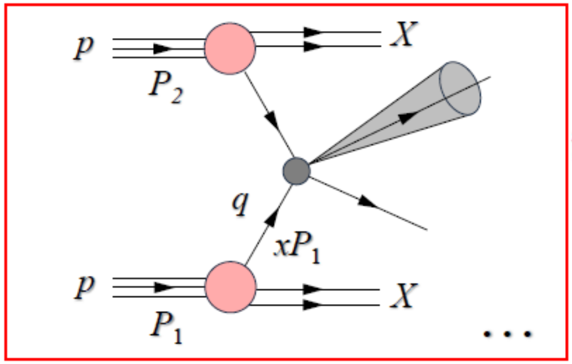
ePIC Jefferson Lab @ 22 GeV

Electron-positron annihilation



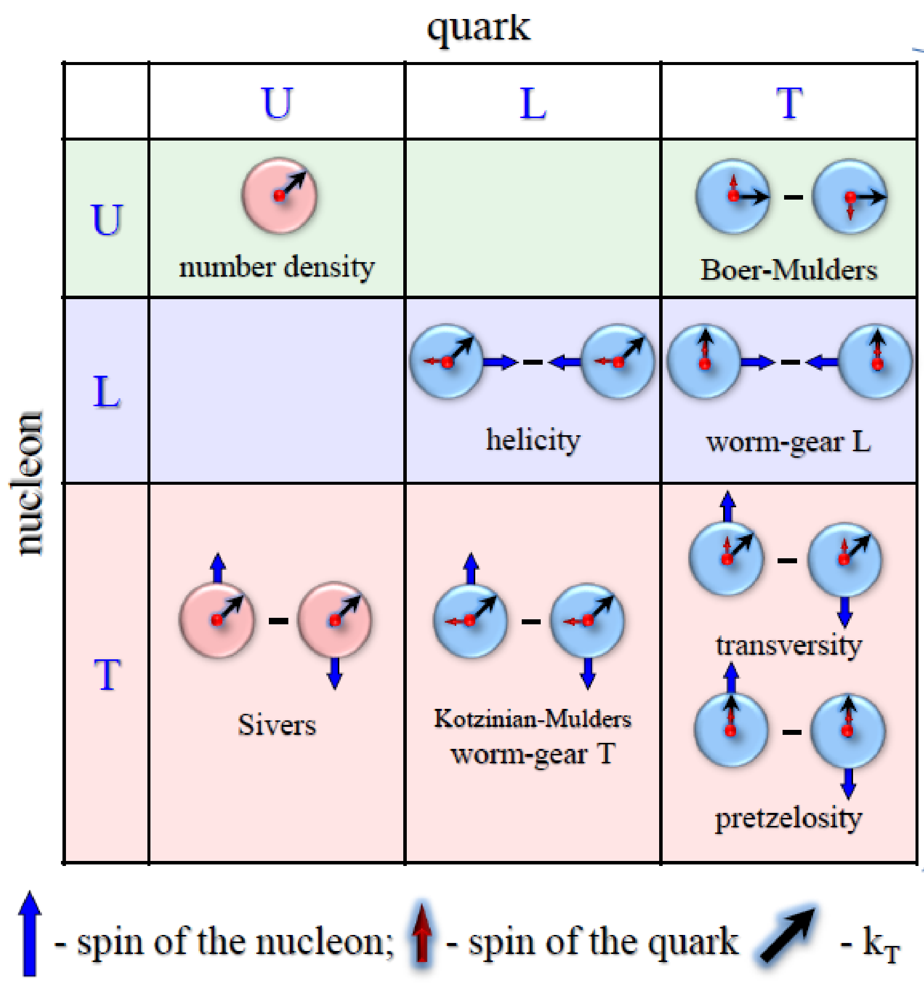
Belle KEK BABAR SLAC BESIII

pp, pA-scattering, jet production, etc.



Brookhaven National Laboratory STAR PHENIX sPHENIX NICA

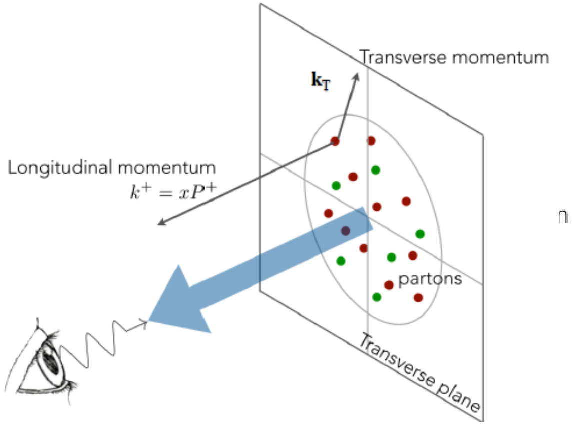
TMDs at twist-2



quark

nucleon

	U	L	T
U	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		chiral-odd $h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x, \boldsymbol{k}_T^2)$ Helicity	chiral-odd $h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	chiral-odd $h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity



SIDIS cross-section at twist-2

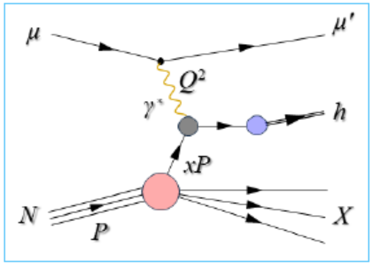
$$\frac{d\sigma^{LO}}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left\{\begin{aligned}
&1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
&+S_L\,\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}A_{LL} \\
&+S_T\left[\begin{aligned}&A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\ &+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\ &+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\end{aligned}\right] \\
&+S_T\lambda\left[\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right]
\end{aligned}\right\}$$

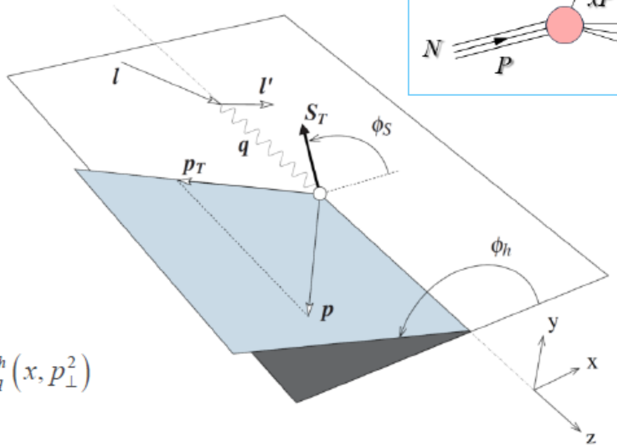
quark

nucleon

	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	$h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	$h_1^q(x,\boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity



$A_{UU}^{\cos 2\phi_h} \propto \underline{h_1^{\perp q}} \otimes \underline{H_{1q}^{\perp h}}$	Boer-Mulders (T-odd)
$A_{UT}^{\sin(\phi_h-\phi_s)} \propto \underline{f_{1T}^{\perp q}} \otimes D_{1q}^h$	Sivers (T-odd)
$A_{UT}^{\sin(\phi_h+\phi_s)} \propto \underline{h_1^q} \otimes \underline{H_{1q}^{\perp h}}$	Transversity
$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto \underline{h_{1T}^{\perp q}} \otimes \underline{H_{1q}^{\perp h}}$	Pretzelosity



$$\otimes \equiv \mathbb{C}[wfD] = x\sum_q e_q^2\int d^2\boldsymbol{k}_T d^2\boldsymbol{p}_\perp \delta^{(2)}\left(z\boldsymbol{k}_T+\boldsymbol{p}_\perp-\boldsymbol{P}_h\right)w\left(\boldsymbol{k}_T,\boldsymbol{p}_\perp\right)f^q\left(x,k_T^2\right)D_q^h\left(x,p_\perp^2\right)$$

Unpolarised SIDIS multiplicities

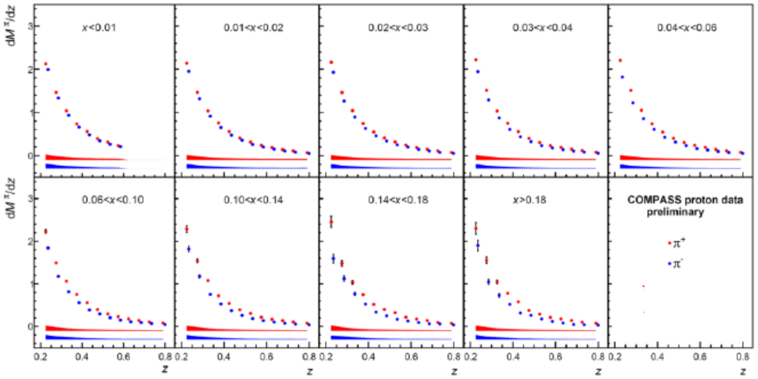
Hadron multiplicities; h±, $\pi^\pm$ and $K^\pm$ (2016 data)

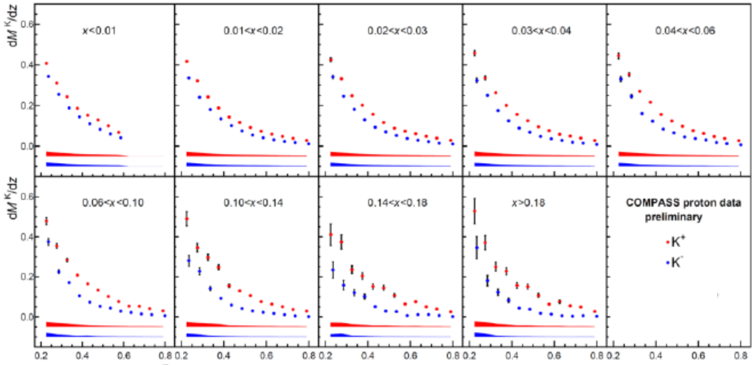
$f_1^q(x, \boldsymbol{k}_T^2)$
number density

collinear

A set of complex corrections:

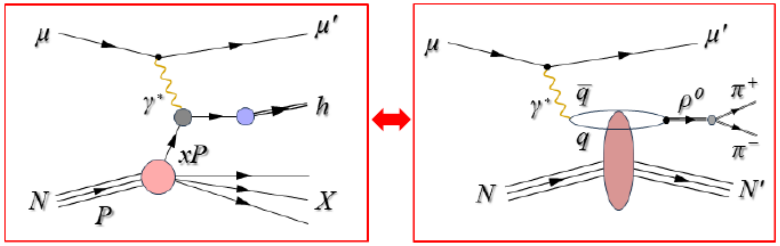
- Acceptance, rad. corrections, PID, diffractive VMs, etc.





New radiative corrections (DJANGOH)

[PRD 112 (2025) 012002](PRD 112 (2025) 012002)



Diffractive VM production

- In DIS γ* interacts with a single quark
- DVMP - γ* fluctuates into a VM
  - VM then interacts diffractively with the nucleon through multiple gluon exchange
- DVMP correction: two MC samples are used

SIDIS

- LEPTO 6.5 MC (diffractive contributions off)

Diffractive ρ^0 and ϕ mesons

- HEPGEN generator

Diffractive events enhance at low x and Q^2

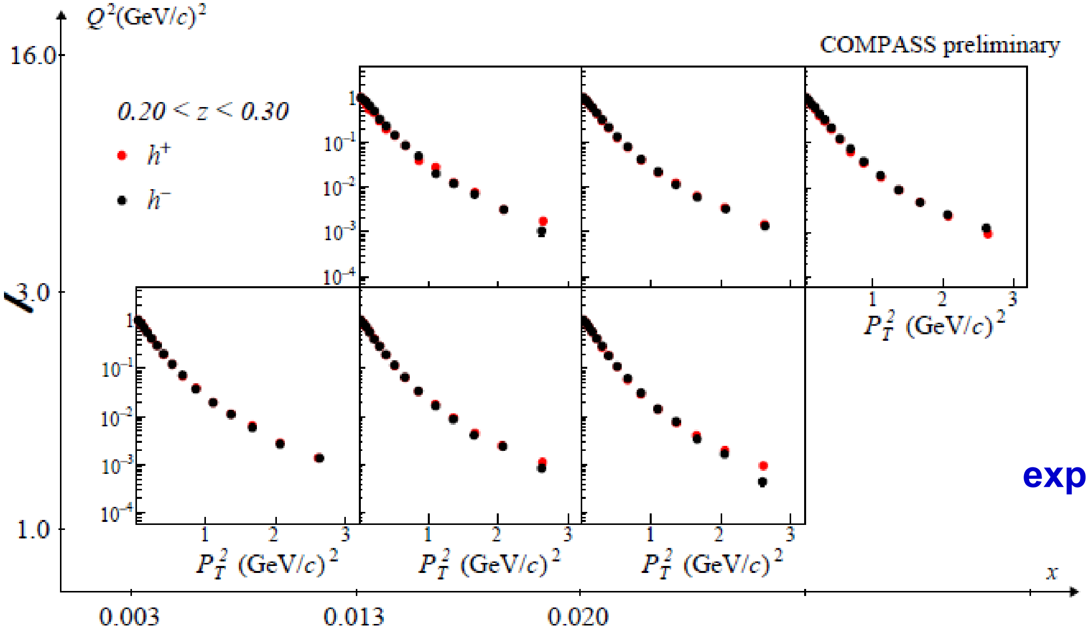
- Pions from ρ^0 decay (at high z)

For pions maximum correction can reach even 50%

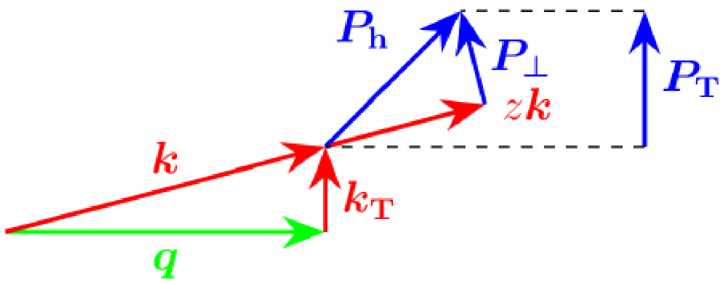
- Kaons from ϕ decay ($0.4 < z < 0.6$)

For kaons maximum correction ~24%
for ($z \approx 0.6$ and $Q^2 \approx 1$ (GeV/c)^2.

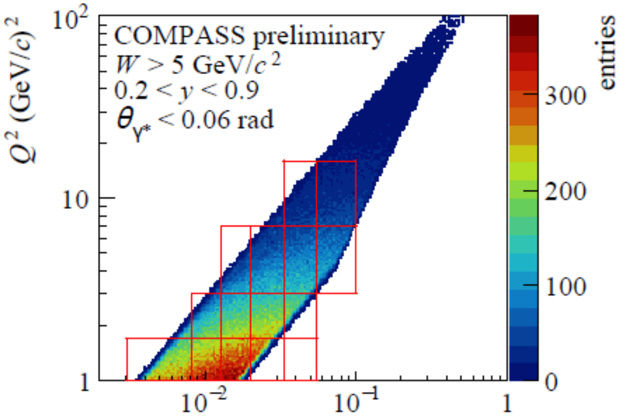
P_T^2 distributions

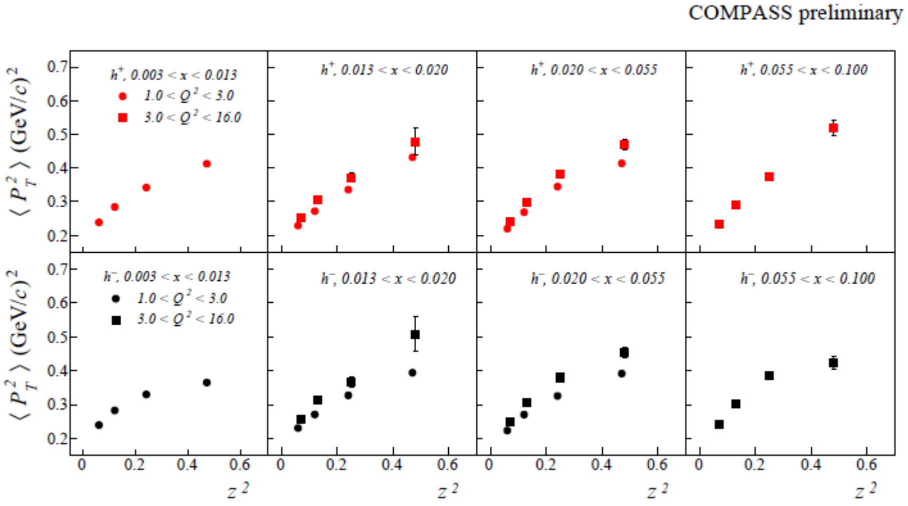


Intrinsic + fragmentation



expected: $\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle P_\perp^2 \rangle$.

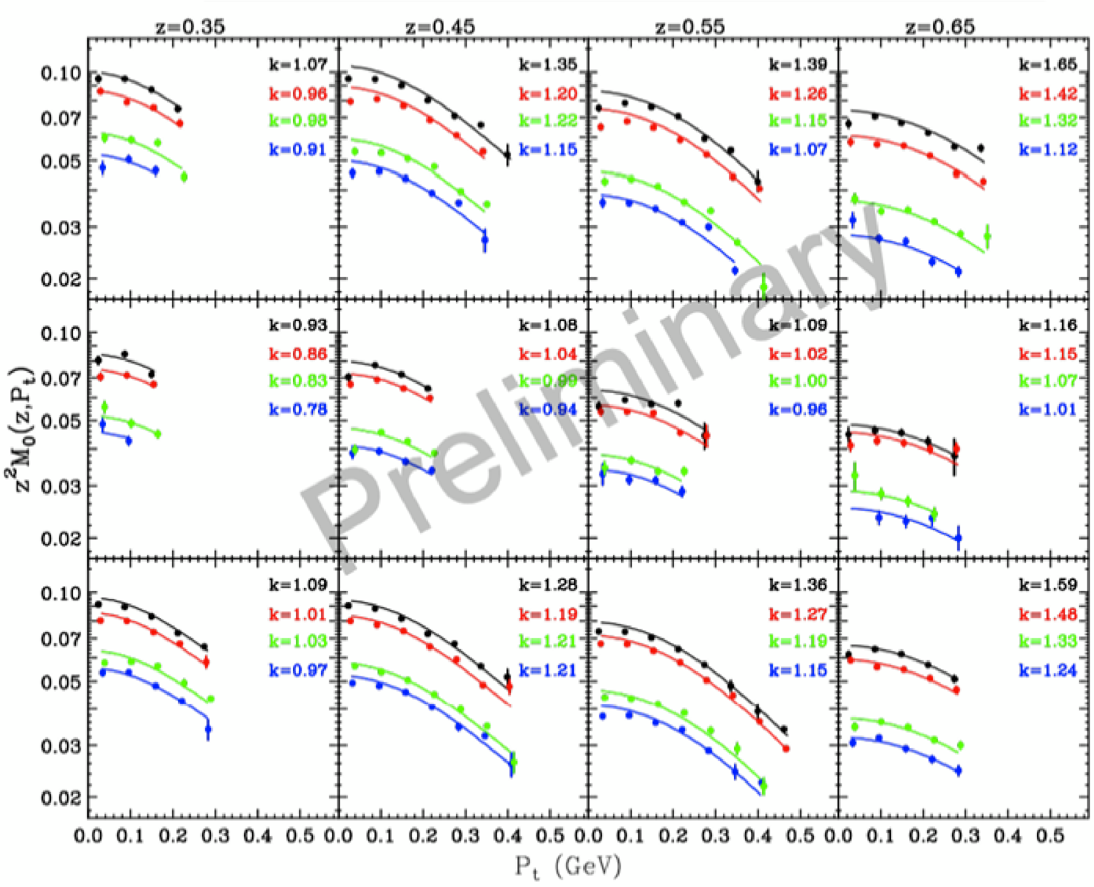




deviation from $\langle P_T^2 \rangle = z^2 \langle k_T^2 \rangle + \langle P_\perp^2 \rangle$

TMDs from JLAB Halls C

Solid: Curves
from MAP
scaled by factor
k:
Bacchetta et al,
JHEP 10 (2022)



- ● π^+ from p
- ● π^+ from d
- ● π^- from d
- ● π^- from p

III x=0.45, Q^2=4.5 GeV^2

II x=0.3, Q^2=4.1 GeV^2

I x=0.31, Q^2=3 GeV^2

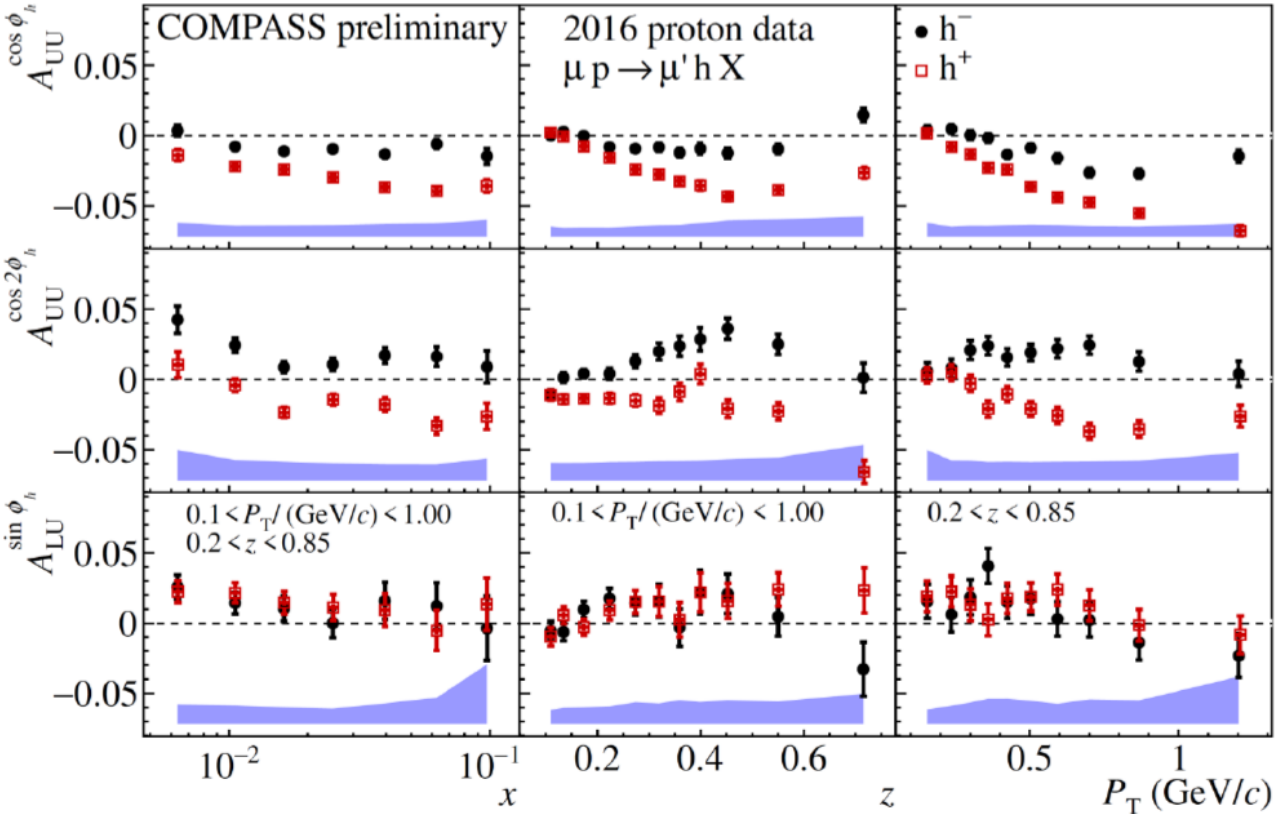
Averaged over ϕ^*

Unpolarised SIDIS modulations

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h+\ldots\right)$$

Target spin independent part of the cross-section: three asymmetries



Cahn effect
Different for h+, h$^-$
Non-trivial Q^2 dependence

Boer-Mulders effect
Collins-like behavior
(h$^+$h$^-$ - mirror symmetry)

Beam-spin asymmetry
higher-twist effect
non-zero, positive trend

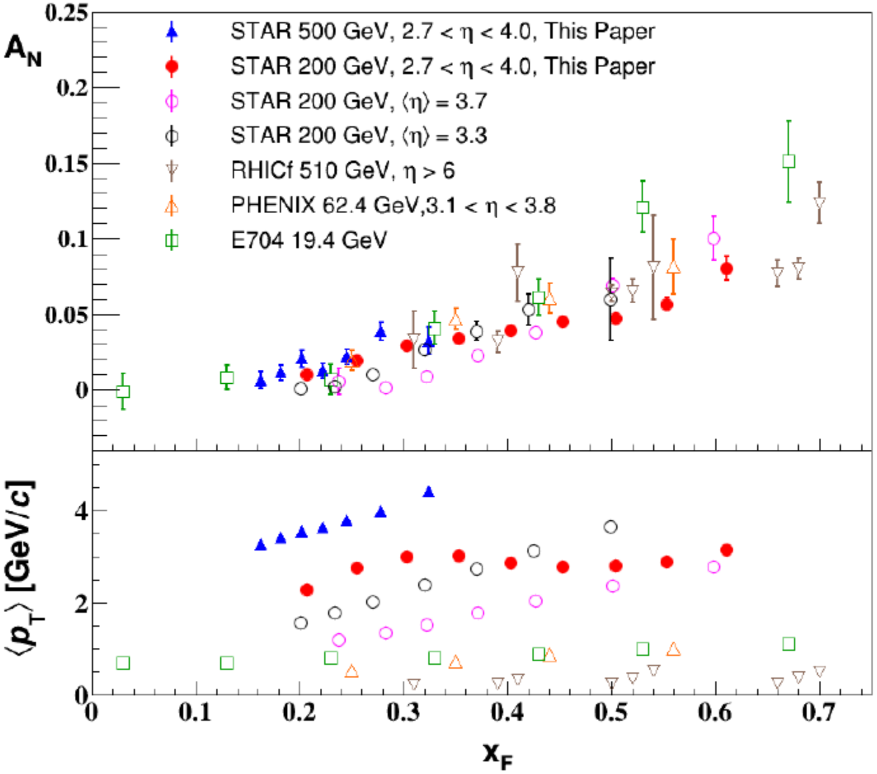
A_N in proton-proton collision

$$A_N \equiv \frac{d\Delta\sigma(S_T)}{d\sigma},$$

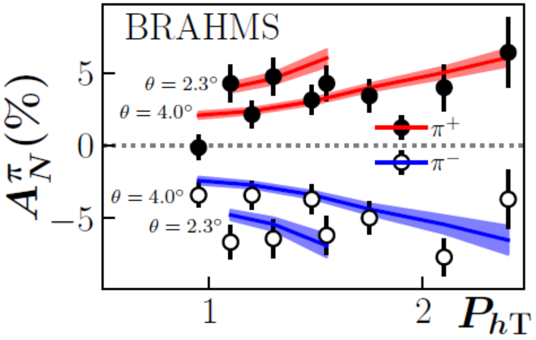
where $d\Delta\sigma(S_T) \equiv \frac{1}{2}[d\sigma(S_T) - d\sigma(-S_T)]$ and $d\sigma \equiv \frac{1}{2}[d\sigma(S_T) + d\sigma(-S_T)]$

$$\begin{aligned} d\Delta\sigma(S_T) = {} & \mathcal{H}_A \otimes f_{a(3)} \otimes f_{b(2)} \otimes D_{h/c(2)} \\ & + \mathcal{H}_B \otimes f_{a(2)} \otimes f_{b(3)} \otimes D_{h/c(2)} \\ & + \mathcal{H}_h \otimes f_{a(2)} \otimes f_{b(2)} \otimes D_{h/c(3)}\,, \end{aligned}$$

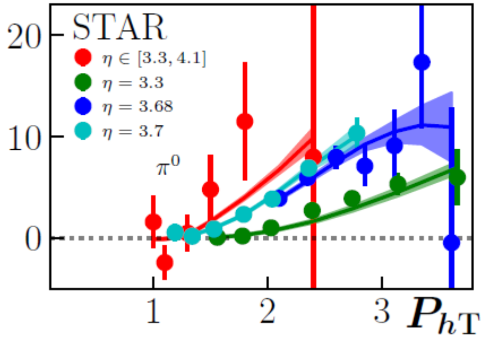
π° production



PRD 103 (2021) 092009



***AIP Conf. Proc.* 915 (2007) 533**

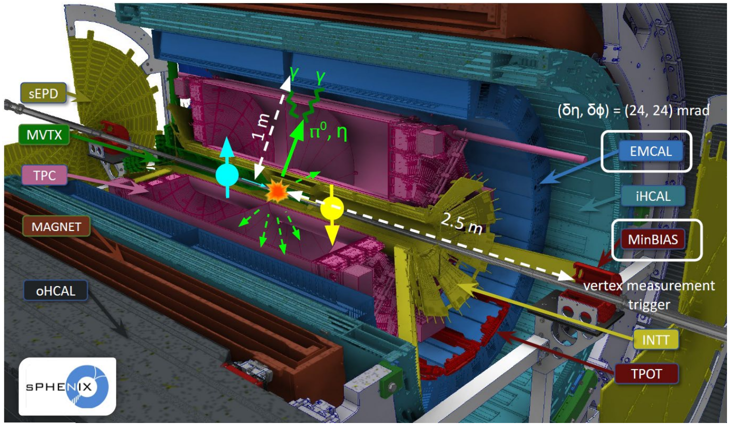


PRD 86 (2012) 051101

curves: PRD 102 (2020) 054002

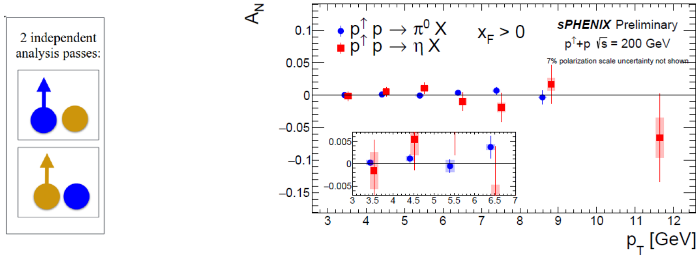
First sPHENIX SSA extractions (π°, η)

- At Brookhaven National Lab (Upton, New York)
- 3.8 km circumference
- Cu, Au, Ru, $\cdots$, $p^\uparrow$
- 111 polarized bunches per beam
- Polarized proton-proton collisions for Run-2024 at $\sqrt{s} = 200 GeV$
- Average polarization: $P \sim 50\%$ (2024)
- New detector sPHENIX
  - Installed in 2022
  - Commissioned in 2023/24
  - **First Physics Run in 2024**



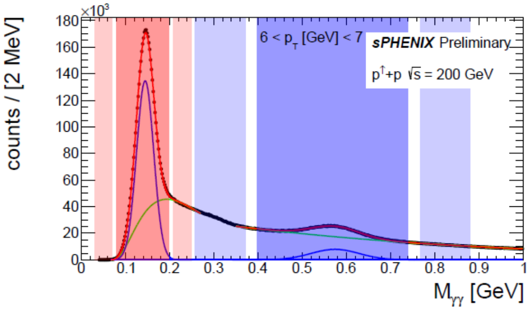
sPHENIX: $0 < \eta$ (pseudo-rapidity) < 2

$0 < x_{\mathrm{Feynman}} < 0.15$



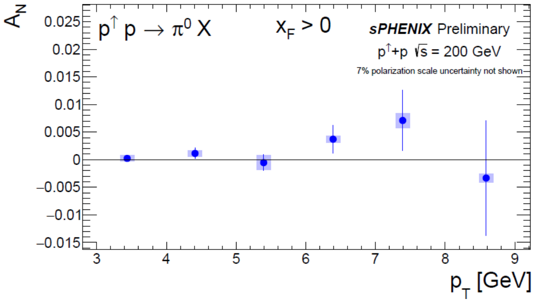
(Beam-averaged)

- p_{T}-dependent asymmetry mostly consistent with zero
- Some p_{T} bins expected to be added later:
  - π^0: $[1,\ 2]\,\mathrm{GeV}$, $[2,\ 3]\,\mathrm{GeV}$
  - η: $[2,\ 3]\,\mathrm{GeV}$

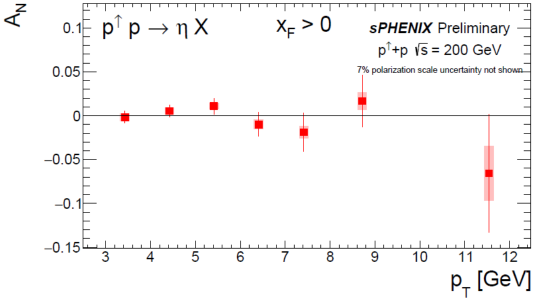


$$A_N = \frac{A_N^{\mathrm{total}} - r\,A_N^{\mathrm{bk}}}{1 - r}$$

π^0 Asymmetry



η Asymmetry



Preliminary sPHENIX results

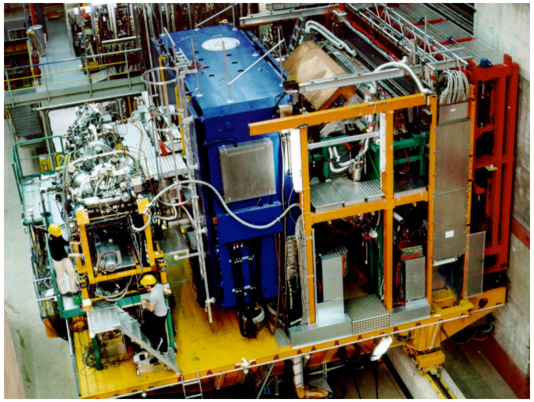
- First extraction of TSSAs using the sPHENIX detector and the RHIC Run-2024 $p^\uparrow p$ data at $\sqrt{s} = 200$ GeV and $\eta > 0$
- The forward π^0 and η meson TSSAs are consistent with zero
- TSSAs are compatible with former PHENIX TSSAs at mid-rapidity within uncertainties

Future prospects

- Extend the measurement to smaller p_{T} domain
  - π^0: $[3, 10]\,\mathrm{GeV} \rightarrow [1, 10]\,\mathrm{GeV}$
  - η: $[3, 20]\,\mathrm{GeV} \rightarrow [2, 20]\,\mathrm{GeV}$
- x_F-dependent asymmetries ($-0.15 < x_F < 0.15$)
- η-dependent asymmetries (forward and backward)

Comparison of RHIC results at different average pseudo-rapidities,
sPHENIX covers previously unmeasured range
$\Rightarrow$ will contribute to further understand transverse single-spin asymmetries in polarized hadron collisions

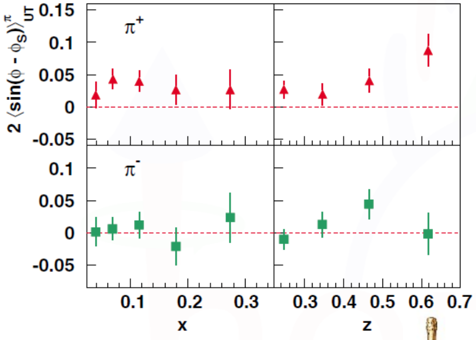
Sivers TMD

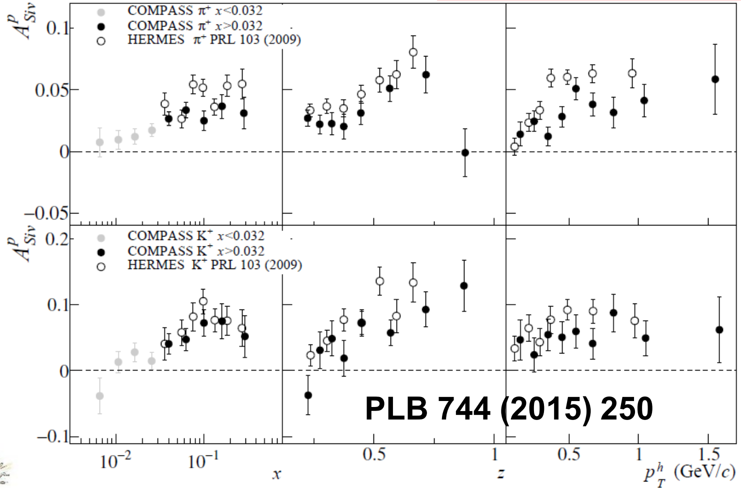


The Sivers function $f_{1T}^{\perp}$ encodes the correlation between the partonic intrinsic motion and the transverse spin of the nucleon, and it generates a dipole deformation in momentum space and could not exist without the contribution of orbital angular momentum of partons to the spin of the nucleon. It arises from interaction of the initial or final state quark with the remnant of the nucleon and thus, many of its features reveal the gauge link structure that reflects the kinematics of the underlining process Above all, the difference between initial and final state gauge link contours leads to the opposite signs for Sivers functions in SIDIS and DY kinematics

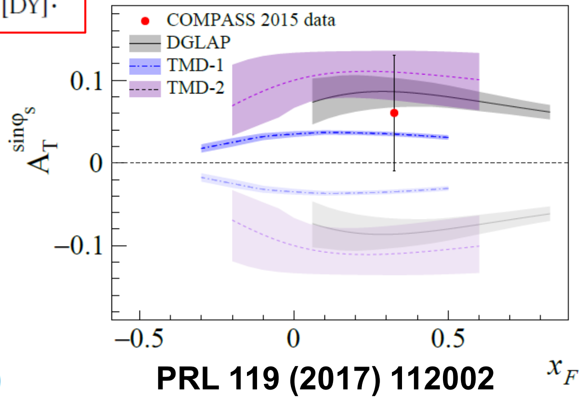
$$\boxed{f_{1T}^{\perp}(x,k_T)_{[\mathrm{SIDIS}]} = -f_{1T}^{\perp}(x,k_T)_{[\mathrm{DY}]}.}$$

[Phys. Rev. Lett. 94 (2005) 012002]

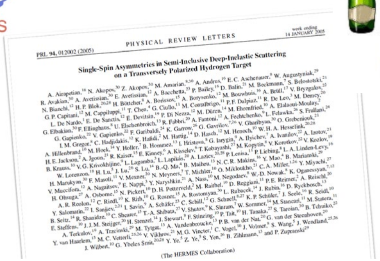




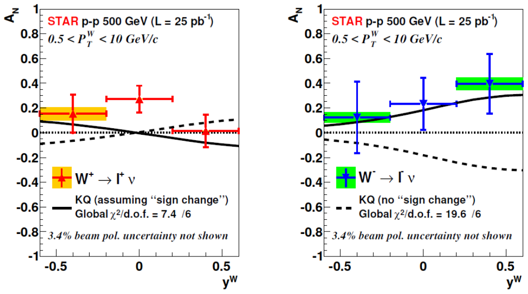
PLB 744 (2015) 250



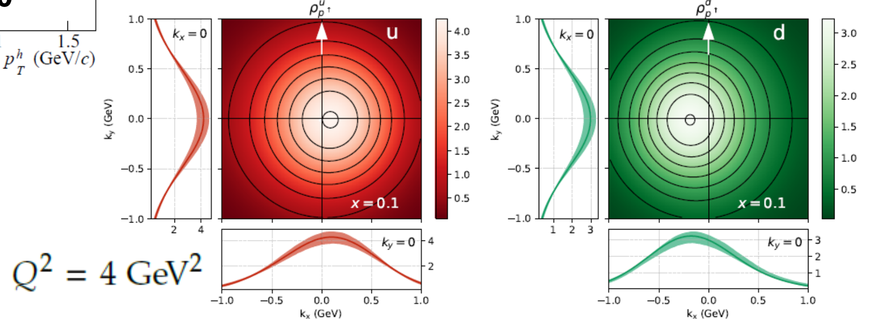
PRL 119 (2017) 112002



PRL 94 (2005) 012002

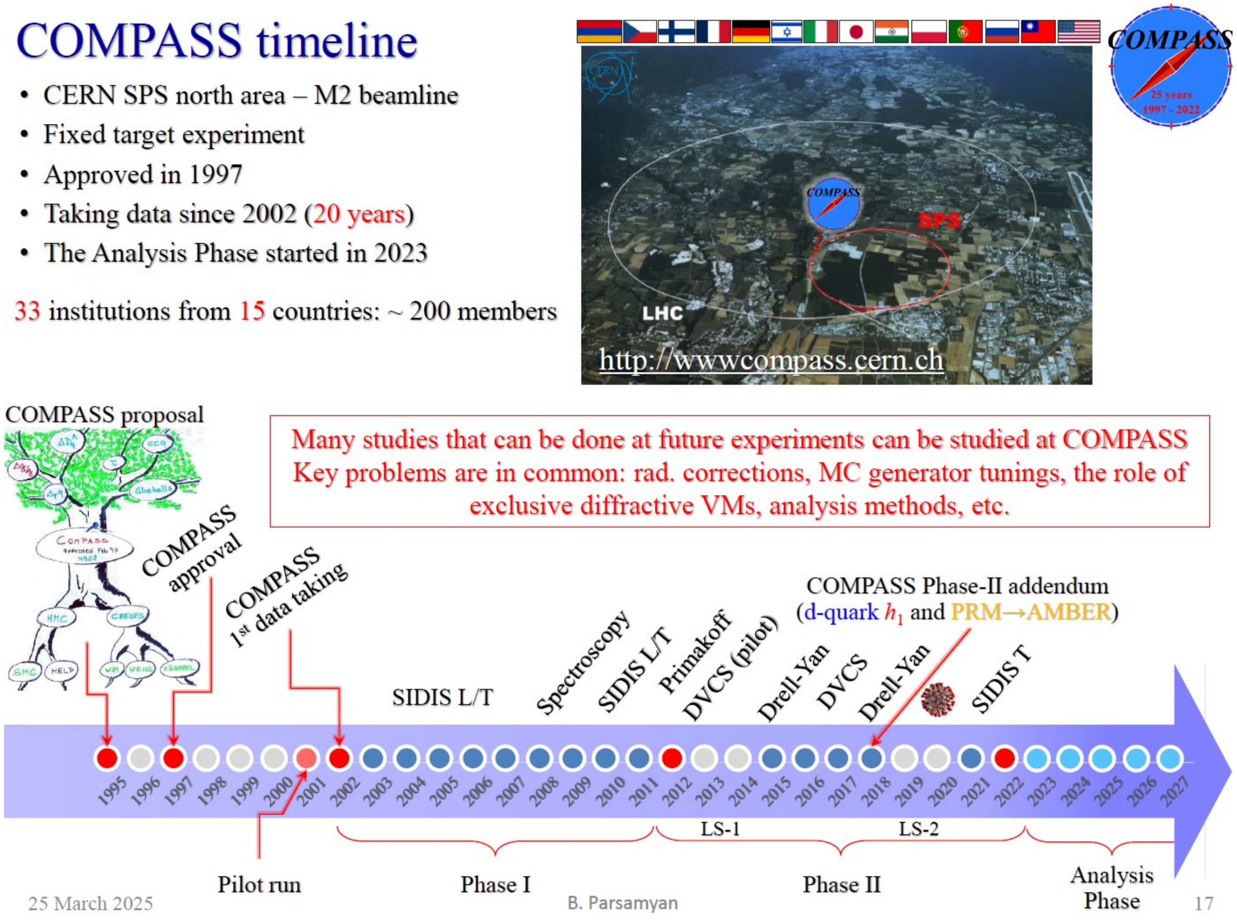


PRL 116 (2016) 132301



A. Bacchetta et al. PLB 827 (2022) 136961

COMPASS data taking: 20 years



COMPASS timeline

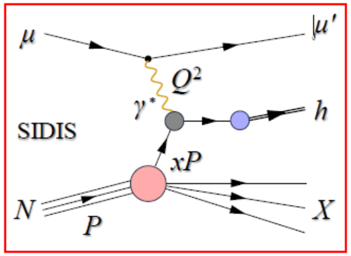
- CERN SPS north area – M2 beamline
- Fixed target experiment
- Approved in 1997
- Taking data since 2002 (20 years)
- The Analysis Phase started in 2023

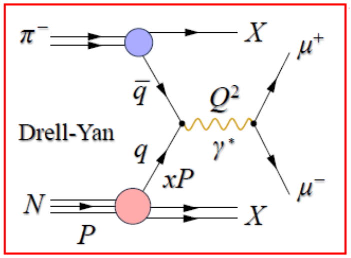
33 institutions from 15 countries: ~ 200 members

http://wwwcompass.cern.ch

Many studies that can be done at future experiments can be studied at COMPASS
Key problems are in common: rad. corrections, MC generator tunings, the role of exclusive diffractive VMs, analysis methods, etc.

25 March 2025 B. Parsamyan 17





Nucleon structure

- Hard scattering of $\mu^\pm$ and π^- off (un)polarized P/D targets
- Inclusive and Semi-Inclusive DIS
- Drell-Yan and J/ψ production
- Study of nucleon spin structure
    - Longitudinal and Transverse
- Collinear and TMD pictures
- Parton distribution functions and fragmentation functions

COMPASS data taking campaigns

Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH_3)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
		2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
		2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

COMPASS

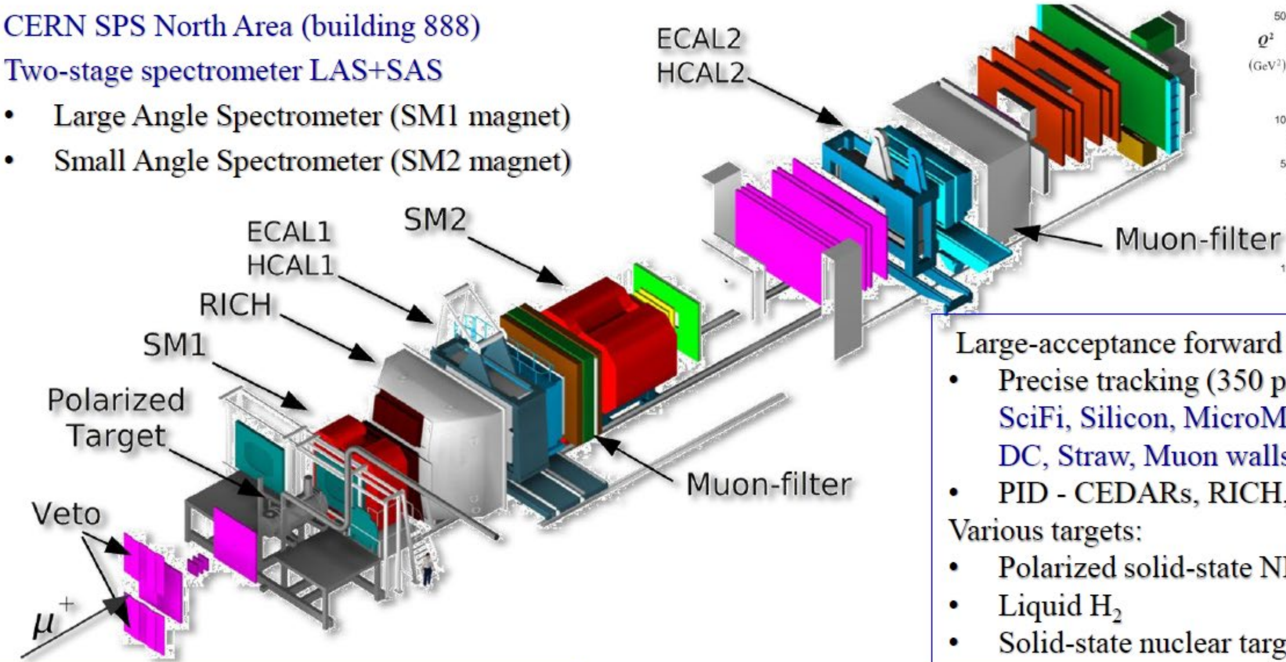
COMPASS experimental setup

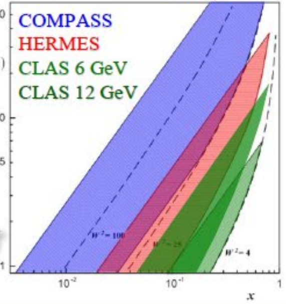
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





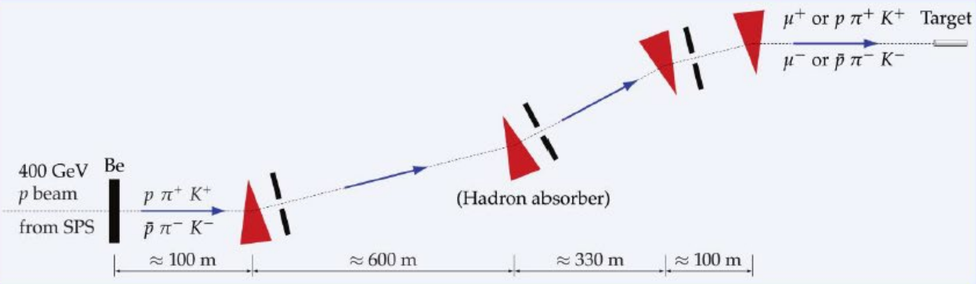
Large-acceptance forward spectrometer

- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
- PID - CEDARs, RICH, calorimeters, MWs

Various targets:

- Polarized solid-state NH_3 or ^{6}LiD
- Liquid H_2
- Solid-state nuclear targets (e.g. Ni, W, Pb)

- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized



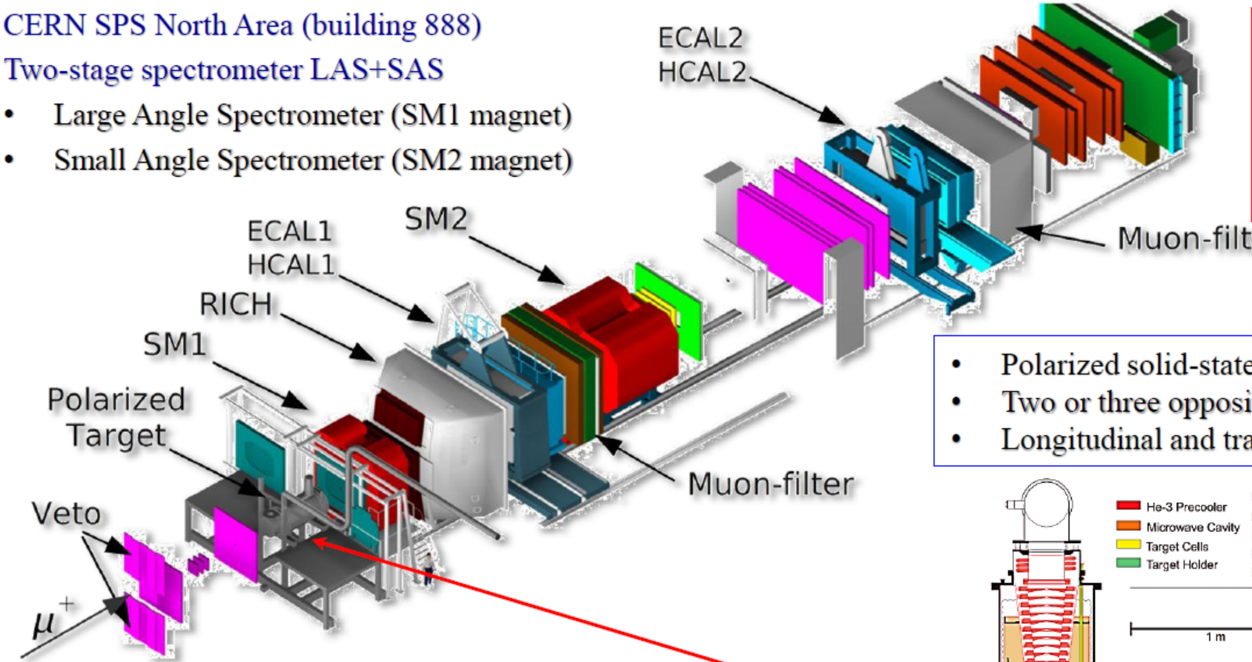
COMPASS experimental setup: Phase II (SIDIS program)

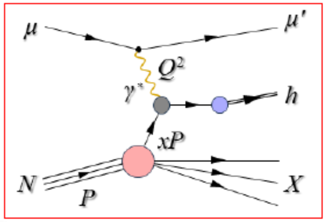
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

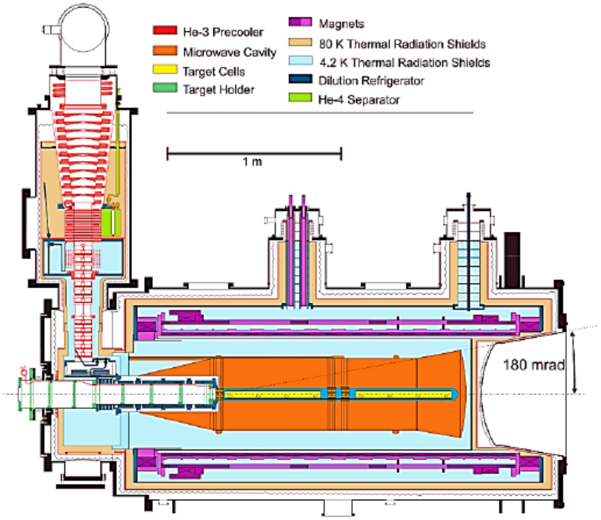
Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





- Polarized solid-state NH$_3$ or ^{6}LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization



- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h$^-$ beam: 97% π^-, 2% K^-, 1% p
  - h$^+$ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

COMPASS

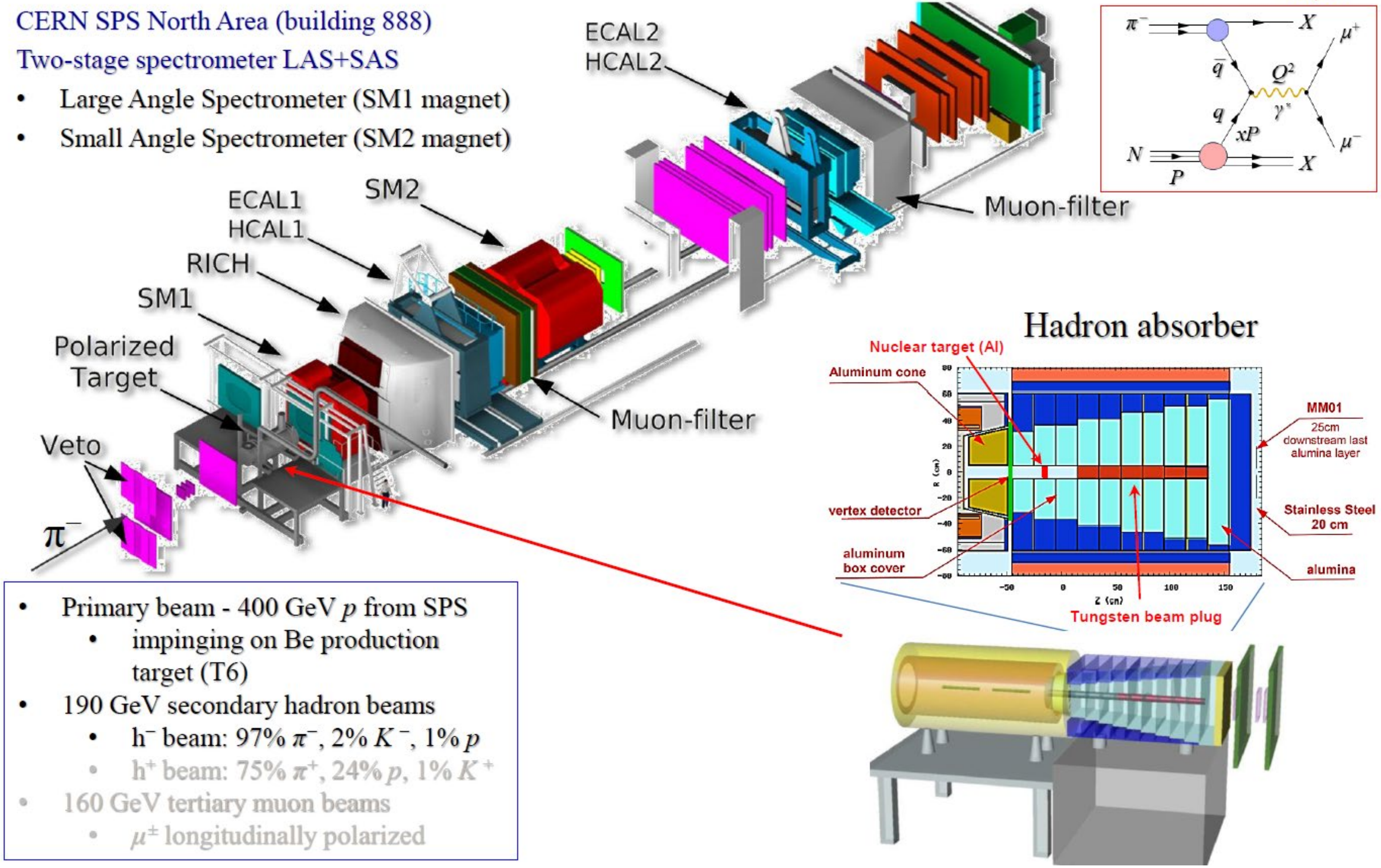
COMPASS experimental setup: Phase II (DY program)

COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

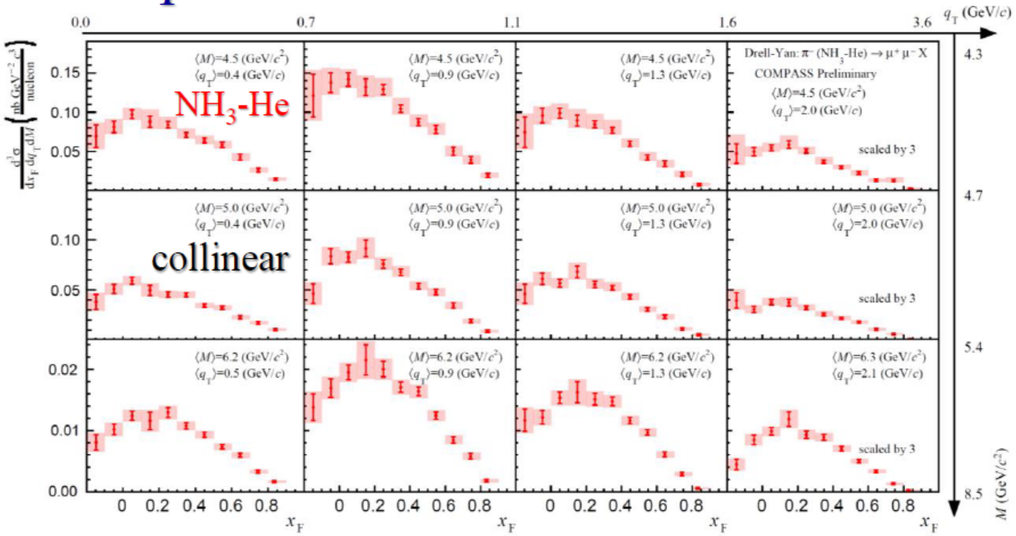
- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)

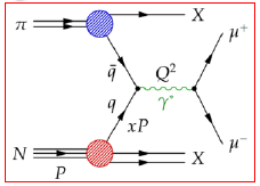


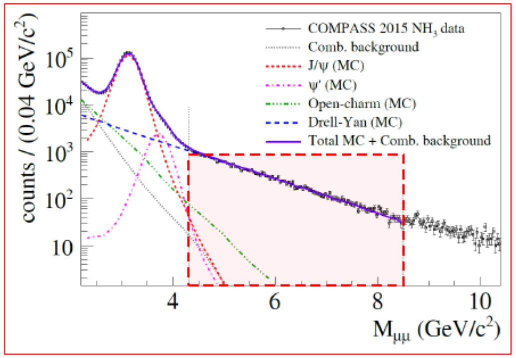
- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h⁻ beam: 97% π^-, 2% K^-, 1% p
  - h⁺ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

Unpolarized Drell-Yan

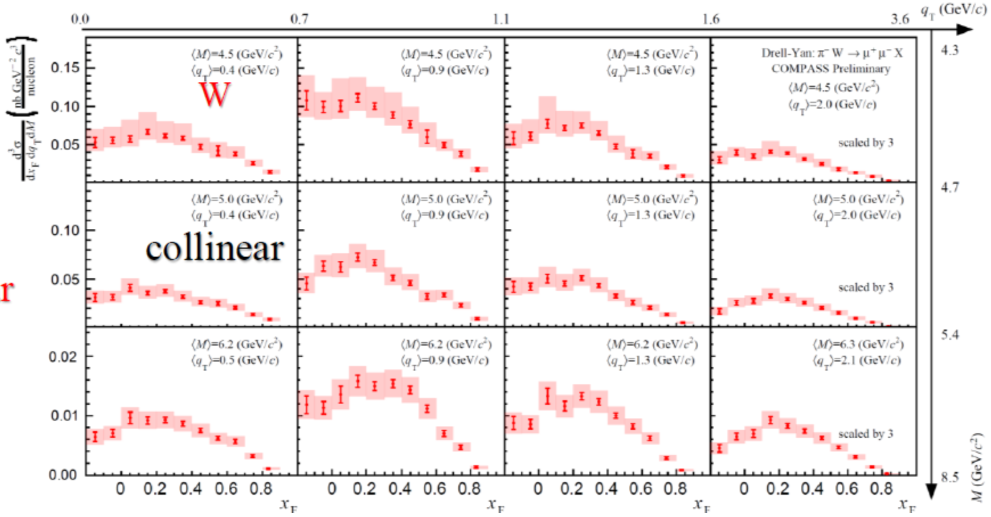
3D unpolarized Drell-Yan cross section on NH_3 and W





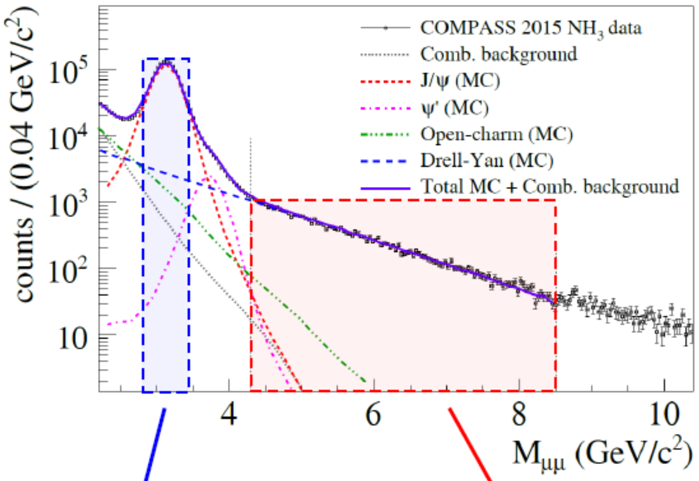


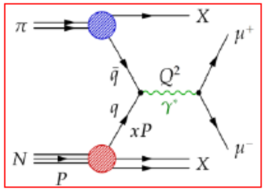
- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF



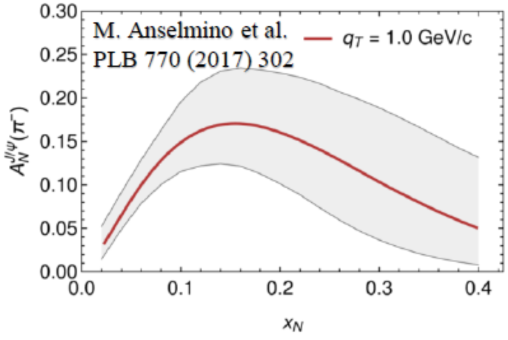
Drell-Yan cross-section

Single-polarized Drell-Yan cross-section at twist-2 (LO)

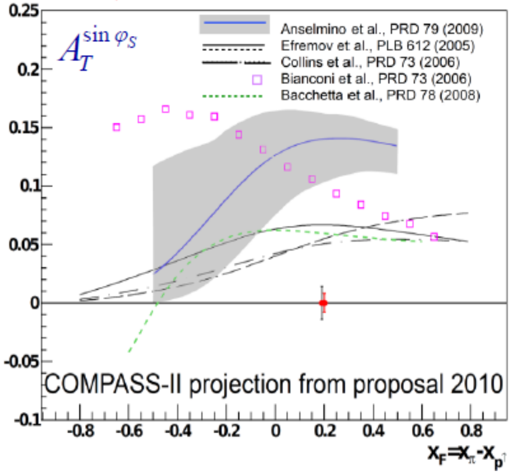




$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin\left(2\varphi_{CS}+\varphi_S\right) \end{array} \right) \end{array} \right] \end{array} \right\}$$



expected to be large



COMPASS-II projection from proposal 2010

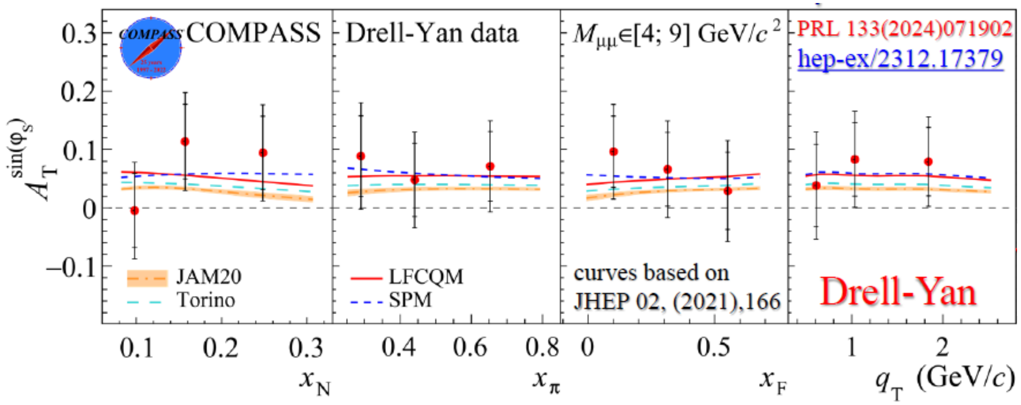
$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes \underline{f_{1T,p}^{\perp q}}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{q}}$	Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1T,p}^{\perp q}}$	Pretzelosity

SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

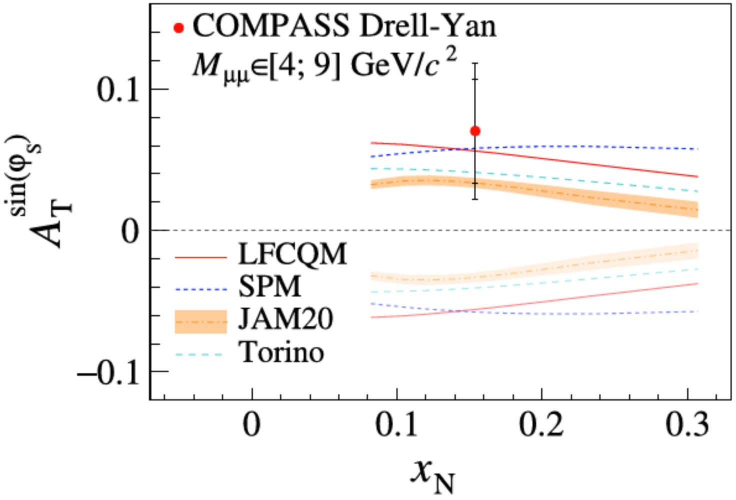
Sivers: DY and SIDIS

Sivers DY TSA

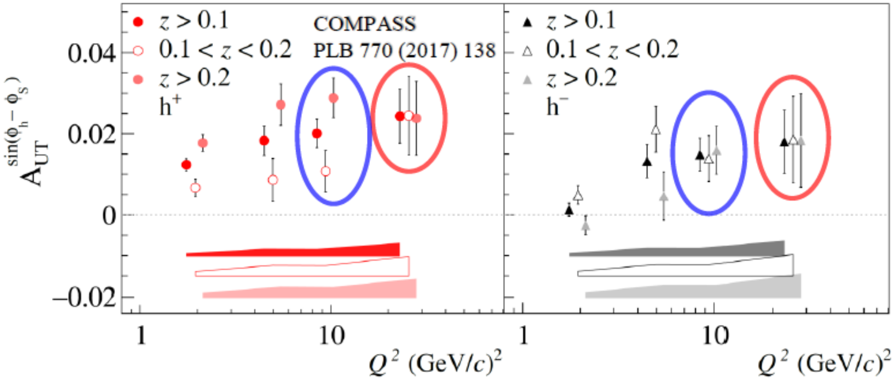
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$



PRL 133 (2024) 071902



in the same kinematic range



Sivers SIDIS TSA

$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$

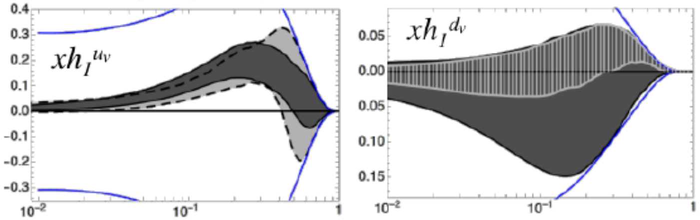
consistent with sign change

Transversity and Collins effect

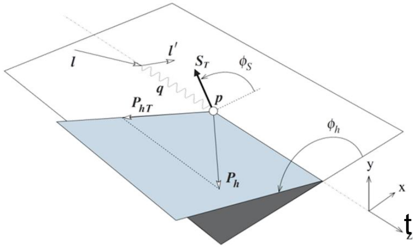
Transversity (h_1) measures the probability to find a quark in an eigenstate of transversely projected Pauli-Lubanski spin in a transversely polarized nucleon.
Transversity PDF concept: Ralston and Soper, 1979.
h_1 with f_1 and g_1 → leading power collinear description of the structure of a spin ½ hadron.
h_1 chiral odd → another chiral odd function needed for a chiral even observable.
Collins FF: correlation between transverse spin of fragmenting quark and transverse momentum of produced final hadron. It is chiral odd.
Collins FF: cos(2φ) modulation in e+e- cross-section → Collins FF and h_1 measurable.

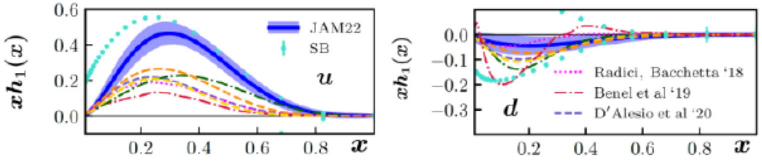
The Collins asymmetry in SIDIS is $A_{UT}^{\sin(\phi_h+\phi_S)}$ and given by the expression

$$A_{UT}^{\sin(\phi_h+\phi_S)} \equiv \frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU,T}} = M_h \frac{\mathcal{B}[\tilde{h}_1^{(0)}\,\tilde{H}_1^{\perp(1)}]}{\mathcal{B}[\tilde{f}_1^{(0)}\,\tilde{D}_1^{(0)}]}\,.$$



[M. Radici, A. Bacchetta, Phys. Rev. Lett. 120 (2018)]



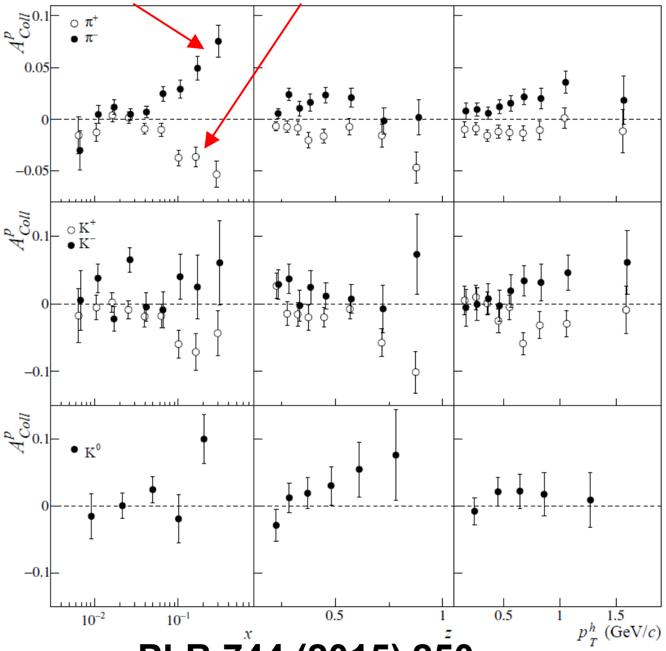


[JAM, Phys. Rev. D 106 (2022)]

$$H^{\perp}_{1\pi^+/u} = H^{\perp}_{1\pi^+/\bar{d}} = H^{\perp}_{1\pi^-/\bar{u}} = H^{\perp}_{1\pi^-/d} \equiv H^{\perp}_{1fav}$$

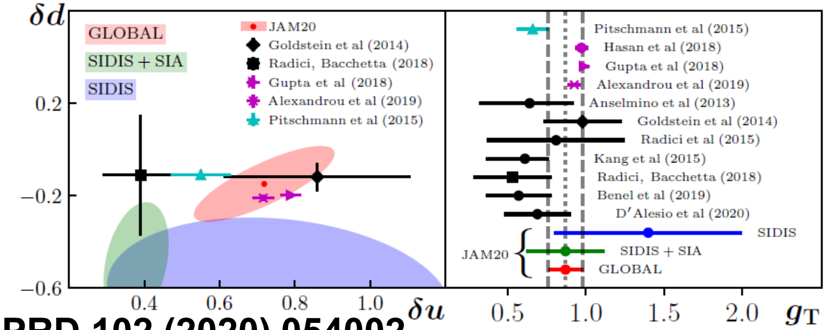
$$H^{\perp}_{1\pi^+/\bar{u}} = H^{\perp}_{1\pi^+/d} = H^{\perp}_{1\pi^-/u} = H^{\perp}_{1\pi^-/\bar{d}} \equiv H^{\perp}_{1unf}$$

favored and unfavored Collins are both large



PLB 744 (2015) 250

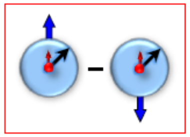
tensor charges: $g_T^u = \int_0^1 dx\,(h_1^u(x) - h_1^{\bar{u}}(x))\,,\qquad g_T^d = \int_0^1 dx\,(h_1^d(x) - h_1^{\bar{d}}(x))$



PRD 102 (2020) 054002

Collins effect in 2022 COMPASS data

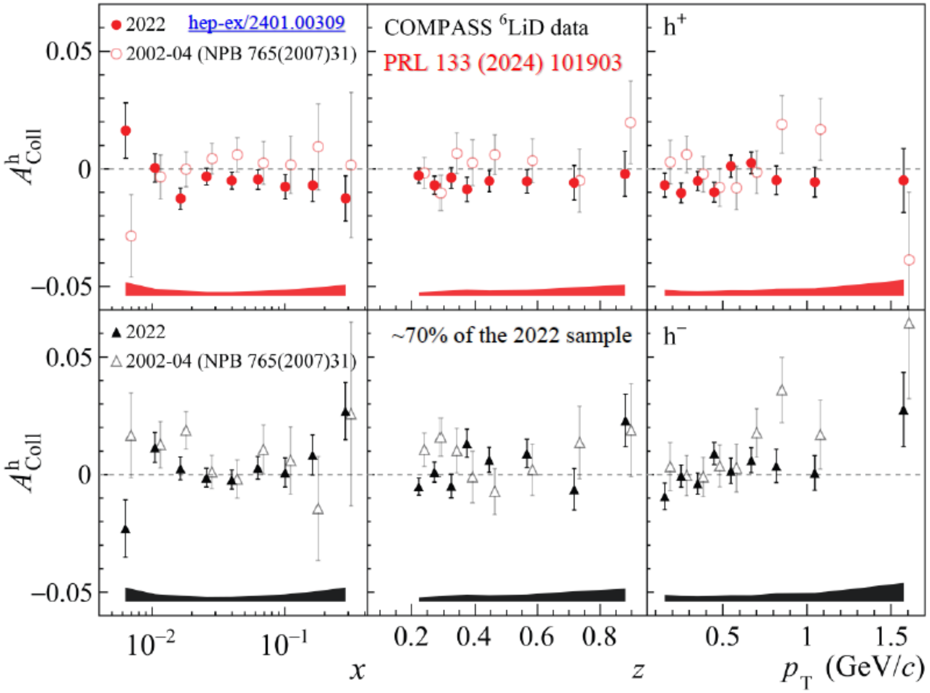
SIDIS TSAs: Collins effect and Transversity

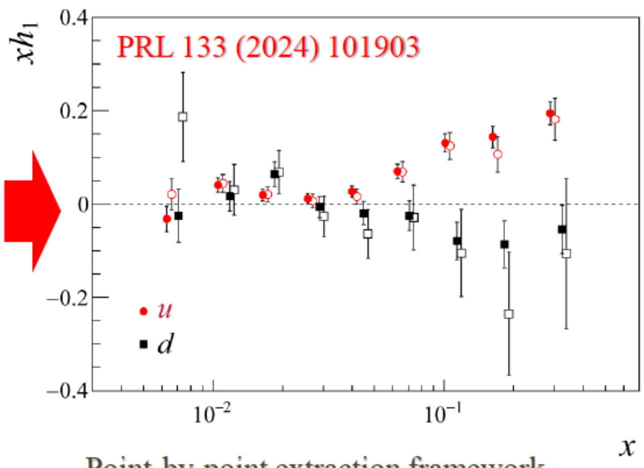


$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\ldots\right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results HERMES/COMPASS
  (Q^2 is different by a factor of ~2-3)
- New deuteron data crucial to constrain *d*-quark transversity





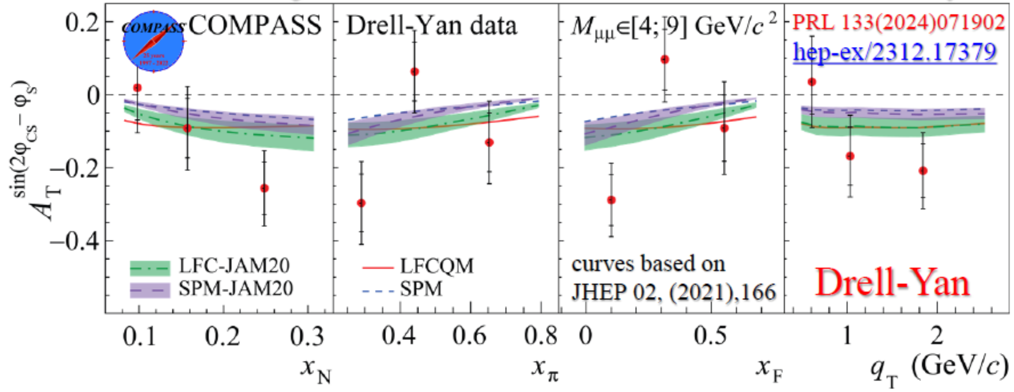
Point-by-point extraction framework
A. Martin et al. PRD **91**, 014034 (2015)
A. Martin et al. PRD **95**, 094024 (2017)

COMPASS 2022 run – highly successful data-taking!

- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

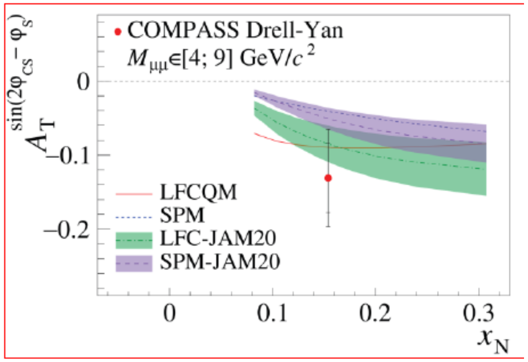
COMPASS Drell-Yan: transversity

Transversity TSA: Drell-Yan and J/ψ

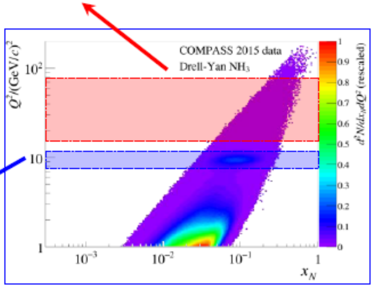


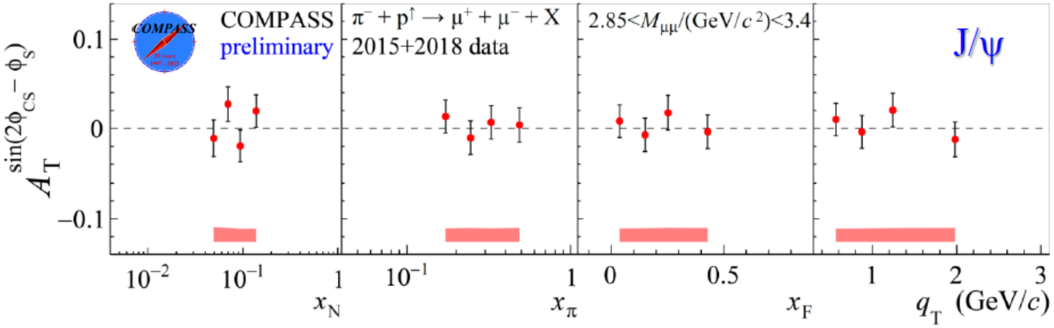
Transversity DY TSA

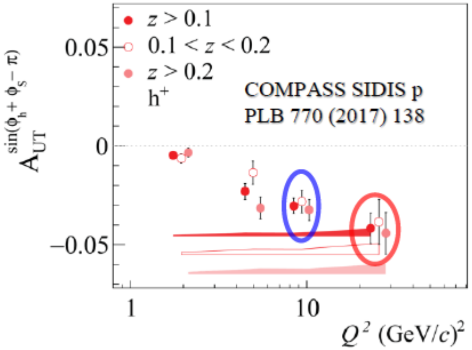
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$$



- The Drell-Yan Transversity asymmetry is negative (~2 s.d.)



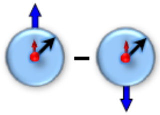




- J/ψ Sivers asymmetry is compatible with zero (within ~ 1%)
- Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS
- J/ψ Transversity TSA is also compatible with zero
- Hint that J/ψ production might go via gg fusion in COMPASS?
- Access to small gluon TMDs?

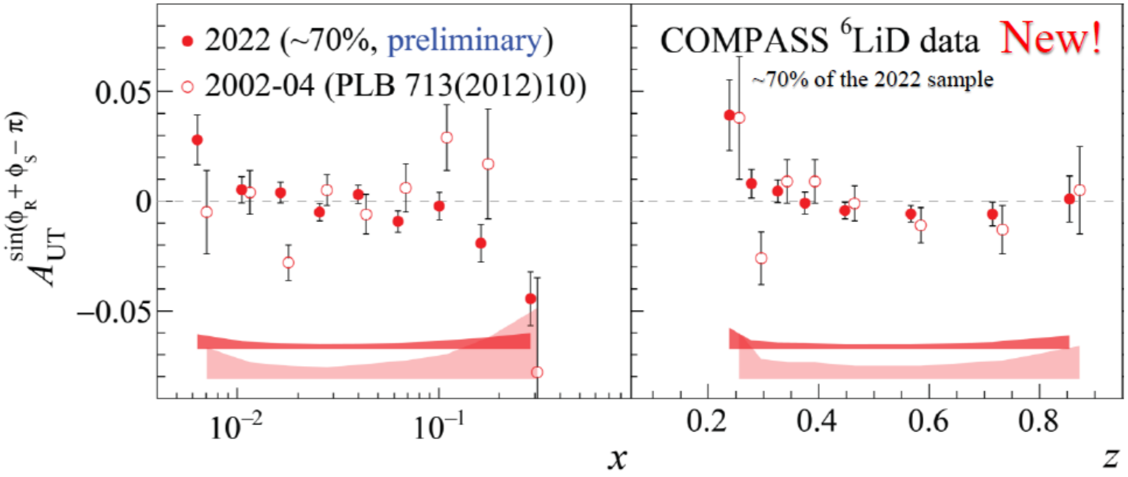
SIDIS dihadron

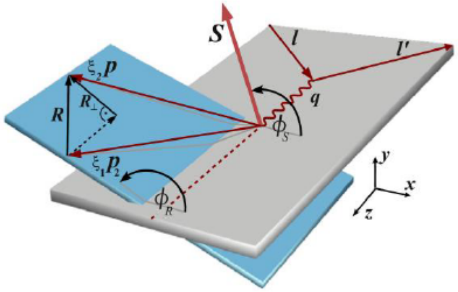
Dihadron Collins effect and Transversity



$$\frac{d^7\sigma}{d\cos\theta\, d M_{hh}\, d\phi_R\, dz\, dx\, dy\, d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\Bigg((1-y+\frac{y^2}{2})\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z, M_{hh}^2, \cos\theta) + S_\perp(1-y)\sum_q e_q^2 \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{hh}}\sin\theta\;\; \sin\phi_{RS}\;\, h_1^q(x)\;\, H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos\theta)\Bigg)$$

$$A_{UT}^{\sin\phi_{RS}} = \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{hh}}\frac{\sum_q e_q^2\, h_1^q(x)\; H_{1,q}^{\triangleleft}(z, M_{hh}^2, \cos\theta)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z, M_{hh}^2, \cos\theta)}$$





COMPASS 2022 run – highly successful data-taking!

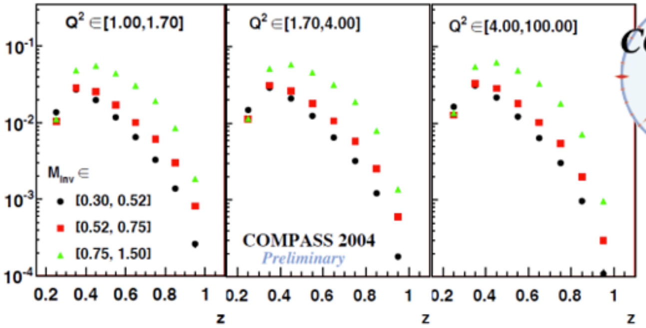
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades
- New results – dihadron Collins-like asymmetries
- Access to collinear transversity PDF; Non-zero trend at large *x*
- Precision comparable with proton results

COMPASS dihadron panorama

Multiplicities:

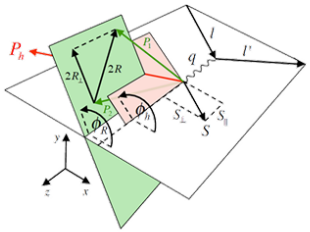
preliminary results from 2004 **deuteron** data: bins of Q^2, M_{hh}, z
[SPIN2012, Phys.Part.Nucl. 45 (2014) 138]

$Q^2 > 1\ GeV^2$
$0.1 < y < 0.9$
$0.003 < x < 0.7$
$W > 5\ GeV/c$
$z_i > 0.1$
$x_{F,i} > 0.1$
$E_{miss} > 3\ GeV/c^2$
$R_T > 0.07\ GeV/c$



multiplicities measurement with **proton** target data (LH_2, 2016): ongoing - *results soon*

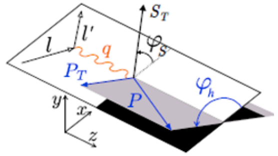
Modulations:



$$P_{hT} = P_{1T} + P_{2T}, \quad \phi_h$$

$$R_T = \frac{z_2 P_{1T} - z_1 P_{2T}}{z_1 + z_2}, \quad \phi_R$$

$$z = z_1 + z_2, \quad M_{hh}$$



$P_T,\ \phi_h$ $\qquad$ P_T, z

Unpolarised:

at twist-2

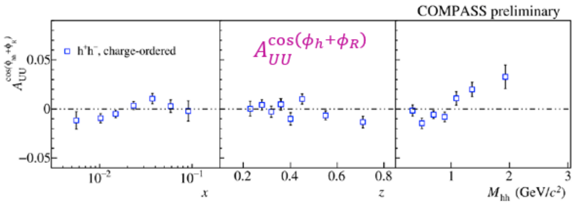
$$\frac{d\sigma(lH \to l' h_1 h_2 X)_{OO}}{d\Omega\, dx\, dz_h\, d\xi\, d^2\vec{P}_{h\perp} d^2\vec{R}_\perp} \propto \Big\{ A(y)\mathcal{F}[f_1 D_1] - |\vec{R}_\perp| B(y) \underline{\cos(\phi_h + \phi_R)} \mathcal{F}\Big[\vec{\hat{h}} \cdot \vec{p}_T \frac{\boxed{h_1^\perp H_1^\measuredangle}}{M(M_1+M_2)}\Big]$$

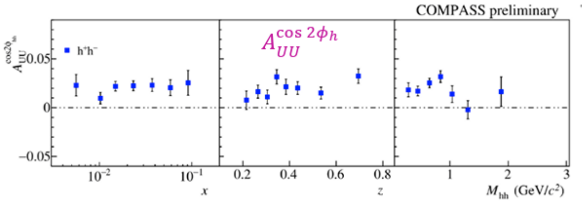
$$- B(y)\underline{\cos(2\phi_h)}\mathcal{F}\Big[(2\vec{\hat{h}} \cdot \vec{p}_T \vec{\hat{h}} \cdot \vec{k}_T - \vec{p}_T \cdot \vec{k}_T) \frac{\boxed{h_1^\perp H_1^\perp}}{M(M_1+M_2)}\Big]\Big\},$$

$$\frac{d\sigma(lH \to l' h_1 h_2 X)_{LO}}{d\Omega\, dx\, dz_h\, d\xi\, d^2\vec{P}_{h\perp} d^2\vec{R}_\perp} \propto \Big\{ \cdots - \lambda_e |\vec{R}_\perp| C(y) \sin(\phi_h - \phi_R) \mathcal{F}\Big[\vec{\hat{h}} \cdot \vec{k}_T \frac{f_1 G_1^\perp}{2M_1 M_2}\Big]\Big\}$$

measured at COMPASS with proton target (2016 data)

unpolarised targets





different from zero:
can they be used to access the Boer-Mulders function?

Longitudinal:

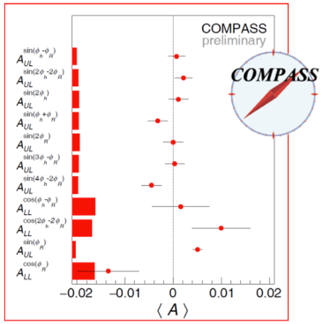
dihadron longitudinal spin asymmetries

longitudinally polarised targets

$$d\sigma = d\sigma_{UU} + \lambda d\sigma_{LU} + S_L(d\sigma_{UL} + \lambda d\sigma_{LL}) + S_L(d\sigma_{UT} + \lambda d\sigma_{LT})$$

$d\sigma_{UL} \propto \sin(\phi_h - \phi_R) A_{UL}^{\sin(\phi_h-\phi_R)}$ □ $g_{1L} \otimes G_{1,UT}^\perp$
$+\sin(2\phi_h - 2\phi_R) A_{UL}^{\sin(2\phi_h-2\phi_R)}$ □ $g_{1L} \otimes G_{1,TT}^\perp$
$+\varepsilon\{\sin(2\phi_h) A_{UL}^{\sin(2\phi_h)}$ □ $h_{1L}^\perp \otimes H_{1,UU}^\perp$
$+\sin(\phi_h + \phi_R) A_{UL}^{\sin(\phi_h+\phi_R)}$ □ $h_{1L}^\perp \otimes H_{1,UT}^\measuredangle$
$+\sin(2\phi_R) A_{UL}^{\sin(2\phi_R)}$ □ $h_{1L}^\perp \otimes H_{1,TT}^\measuredangle$
$+\sin(3\phi_h - \phi_R) A_{UL}^{\sin(3\phi_h-\phi_R)}$ □ $h_{1L}^\perp \otimes H_{1,UT}^\perp$
$+\sin(4\phi_h - 2\phi_R) A_{UL}^{\sin(4\phi_h-2\phi_R)}\}$ □ $h_{1L}^\perp \otimes H_{1,TT}^\perp$
$d\sigma_{LL} \propto \sqrt{1-\varepsilon^2}\{A_{LL}^1$ □ $g_{1L} \otimes D_{1,UT}$
$+\cos(\phi_h - \phi_R) A_{LL}^{\cos(\phi_h-\phi_R)}$ □ $g_{1L} \otimes D_{1,TT}$
$+\cos(2\phi_h - 2\phi_R) A_{LL}^{\cos(2\phi_h-2\phi_R)}\}$ □ $g_{1L} \otimes D_{1,UU}$

twist-2



twist-3

$d\sigma_{UL} \propto \sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_R) A_{UL}^{\sin(\phi_R)}$ □ $Q^{-1}[h_L \cdot H_{1,UT}^\measuredangle + g_1 \cdot \tilde{G}_{UT}^\measuredangle]$
$+\varepsilon \sin(2\phi_R) A_{UL}^{\sin(2\phi_R)}$
$d\sigma_{LL} \propto \sqrt{1-\varepsilon^2} A_{LL}^1$
$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_R) A_{LL}^{\cos(\phi_R)}$ □ $Q^{-1}[e_L \cdot H_{1,UT}^\measuredangle + g_1 \cdot \tilde{D}_{UT}^\measuredangle]$

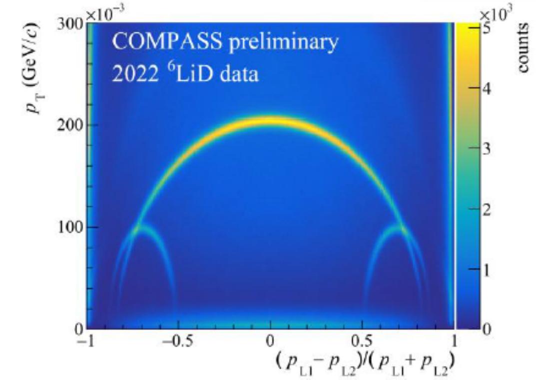
Bacchetta & Radici: Phys. Rev. D69 094002
Bacchetta & Radici & Gliske: Phys. Rev. D90 114027

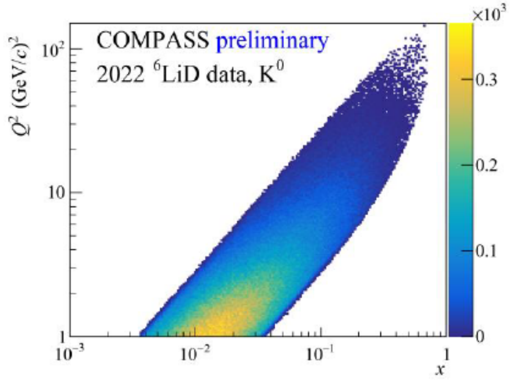
Collins effect for K°

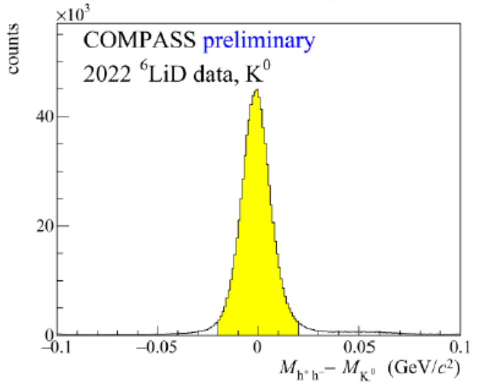
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

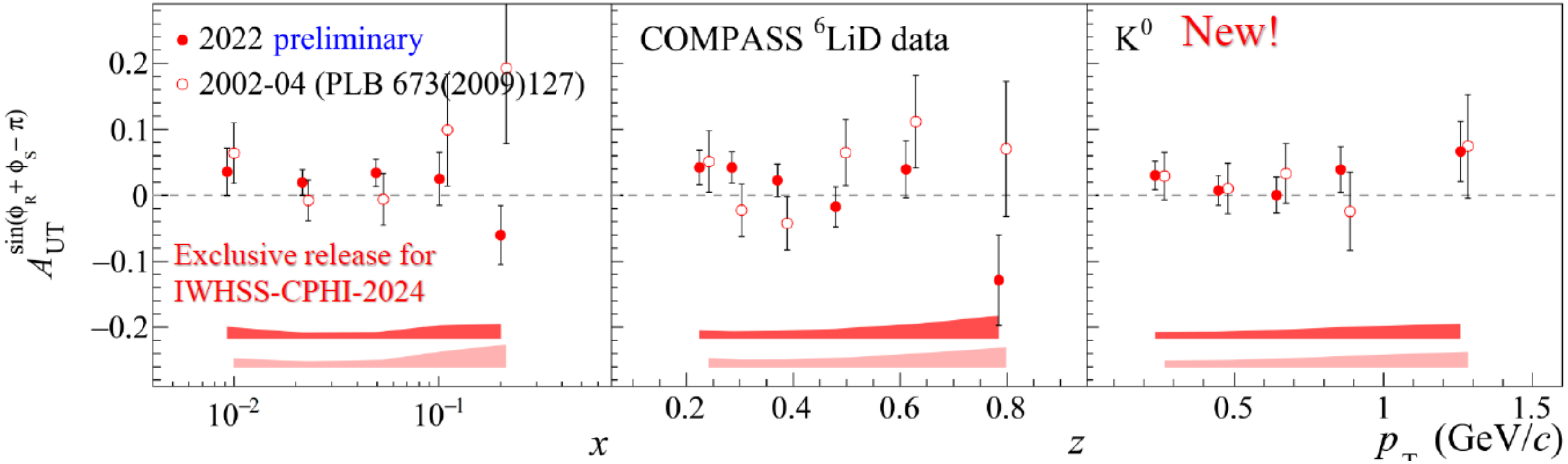
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{h}\cdot p_T}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

Measured on P/D in SIDIS and in dihadron SIDIS
Compatible results HERMES/COMPASS
(Q^2 is different by a factor of ~2-3)
New deuteron data crucial to constrain *d*-quark transversity









New!

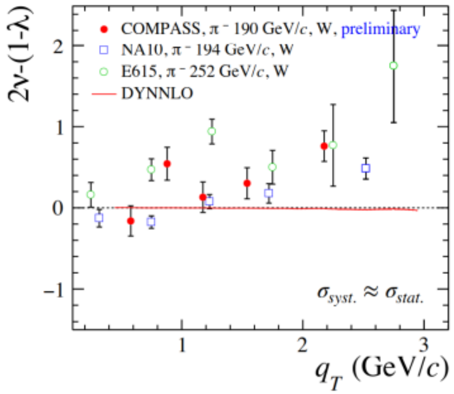
Exclusive release for IWHSS-CPHI-2024

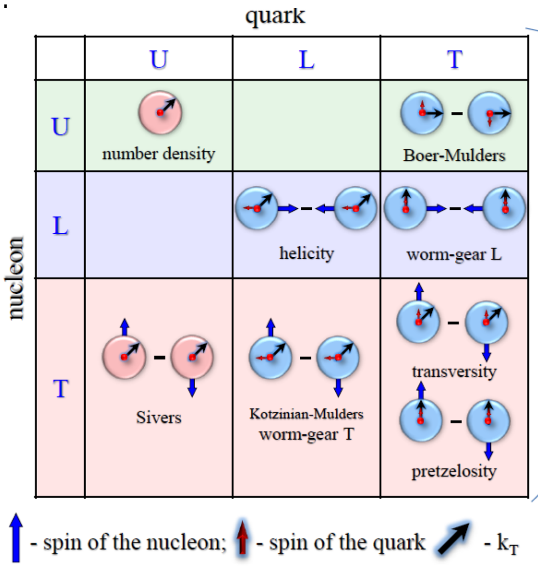
Boer-Mulders, worm-gear, Kotzinian-Mulders, Pretzelosity

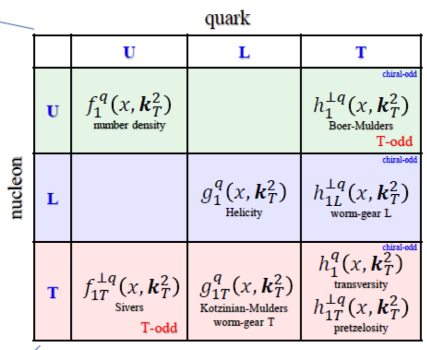
Boer-Mulders: distribution of unpolarized quarks in transversely polarize target (counterpart of Sivers). It is both T-odd and chiral odd.

$$\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi}\frac{1}{\lambda+3}\left[1+\lambda\cos^2\theta_{CS}+\mu\sin(2\theta_{CS})\cos\varphi_{CS}+\frac{\nu}{2}\sin^2\theta_{CS}\cos(2\varphi_{CS})\right]$$

DY unpolarized cross-section: Lam-Tung relation violation → Boer Mulders effect?







quark

nucleon	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ number density		chiral-odd $h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ Boer-Mulders T-odd
L		$g_1^q(x,\boldsymbol{k}_T^2)$ Helicity	chiral-odd $h_{1L}^{\perp q}(x,\boldsymbol{k}_T^2)$ worm-gear L
T	$f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ Sivers T-odd	$g_{1T}^q(x,\boldsymbol{k}_T^2)$ Kotzinian-Mulders worm-gear T	chiral-odd $h_1^q(x,\boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)$ pretzelosity

Pretzelosity: transversely polarized quarks in transversely polarized nucleon. It is related to orbital angular momentum

Transversely-polarised target part at leading twist: $\hat{\boldsymbol{h}} = \boldsymbol{P}_\mathrm{T}/P_\mathrm{T}$

$$F_{\mathrm{UT,T}}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp}{M} f_{1\mathrm{T}}^\perp D_1\right] \qquad \text{(Sivers effect)}$$

$$F_{\mathrm{UT,L}}^{\sin(\phi_h-\phi_S)} = 0$$

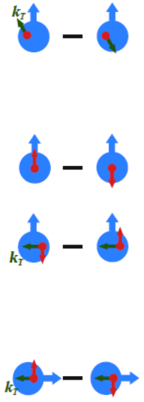
$$F_{\mathrm{UT}}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathrm{T}}{M_h} h_1 H_1^\perp\right] \qquad \text{(Collins effect} \rightarrow \text{transversity)}$$

$$F_{\mathrm{UT}}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)(\boldsymbol{P}_\perp\cdot\boldsymbol{k}_\mathrm{T})+P_\perp^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathrm{T})-4(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)^2)(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_\mathrm{T})}{2M^2M_h} h_{1\mathrm{T}}^\perp H_1^\perp\right]$$

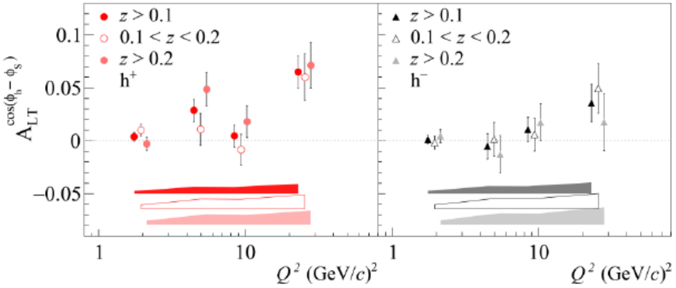
(→ pretzelosity)

$$F_{\mathrm{LT}}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp}{M} g_{1\mathrm{T}} D_1\right] \qquad \text{(Kotzinian–Mulders effect)}$$

$F_{\mathrm{LT}}^{\cos(\phi_S)}$, $F_{\mathrm{LT}}^{\cos(2\phi_h-\phi_S)}$… purely sub-leading twist $(1/Q)$



Kotzinian–Mulders asymmetry:



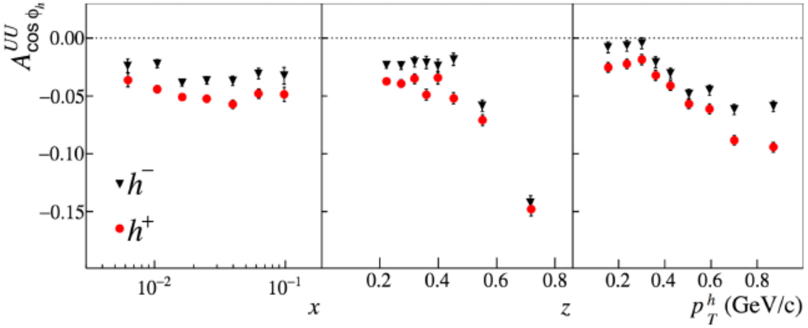
Asymmetry on $p^\uparrow$

[Compass, Phys. Lett. B 770 (2017) 138]

Subleading TMDs

$$\begin{aligned}\frac{d^6\sigma_{\text{subleading}}}{dx\,dy\,dz_h\,d\phi_S\,d\phi_h\,dP_{hT}^2} = \frac{\alpha_{em}^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right)\Big\{&p_1 F_{UU,L} + \cos(\phi_h)\,p_3\,F_{UU}^{\cos(\phi_h)}\\ &+ \lambda\sin(\phi_h)\,p_4\,F_{LU}^{\sin(\phi_h)} + S_L\sin(\phi_h)\,p_3\,F_{UL}^{\sin(\phi_h)} + \lambda\,S_L\cos(\phi_h)\,p_4\,F_{LL}^{\cos(\phi_h)}\\ &+ S_T\sin(2\phi_h-\phi_S)\,p_3\,F_{UT}^{\sin(2\phi_h-\phi_S)} + S_T\sin(\phi_S)\,p_3\,F_{UT}^{\sin(\phi_S)}\\ &+ S_T\sin(\phi_h-\phi_S)\,p_1\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\\ &+ \lambda\,S_T\cos(\phi_S)\,p_4\,F_{LT}^{\cos(\phi_S)} + \lambda\,S_T\cos(2\phi_h-\phi_S)\,p_4\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big\},\end{aligned}$$

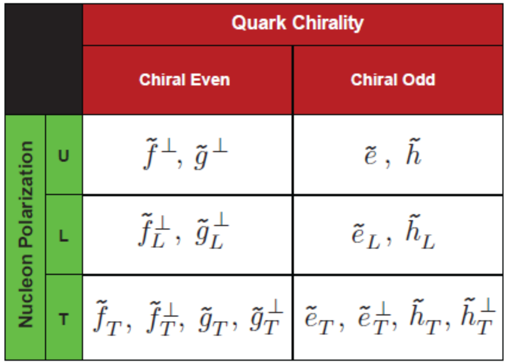
NPB 886 (2014) 1046



COMPASS data, for a ^{6}LiD target, of the Cahn asymmetry $A^{UU}_{\cos\phi_h}|_{\text{fig.}} \propto F_{UU}^{\cos\phi_h}/F_{UU}$

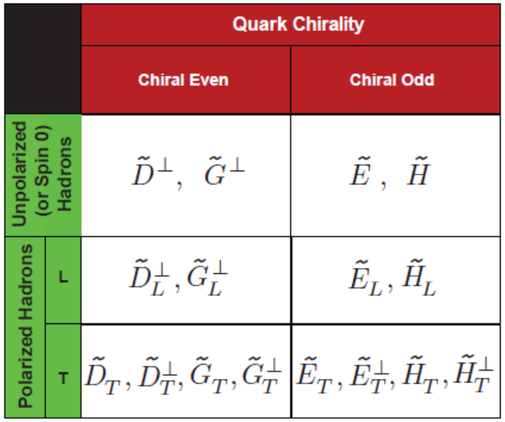
Suppressed by factor Λ/Q

Subleading Quark-Gluon-Quark TMDPDFs



Nucleon Polarization		Quark Chirality	
		Chiral Even	Chiral Odd
	U	$\tilde f^\perp$, $\tilde g^\perp$	$\tilde e$, $\tilde h$
	L	$\tilde f_L^\perp$, $\tilde g_L^\perp$	$\tilde e_L$, $\tilde h_L$
	T	$\tilde f_T$, $\tilde f_T^\perp$, $\tilde g_T$, $\tilde g_T^\perp$	$\tilde e_T$, $\tilde e_T^\perp$, $\tilde h_T$, $\tilde h_T^\perp$

Subleading Quark-Gluon-Quark TMDFFs



		Quark Chirality	
		Chiral Even	Chiral Odd
Unpolarized (or Spin 0) Hadrons		$\tilde D^\perp$, $\tilde G^\perp$	$\tilde E$, $\tilde H$
Polarized Hadrons	L	$\tilde D_L^\perp$, $\tilde G_L^\perp$	$\tilde E_L$, $\tilde H_L$
	T	$\tilde D_T$, $\tilde D_T^\perp$, $\tilde G_T$, $\tilde G_T^\perp$	$\tilde E_T$, $\tilde E_T^\perp$, $\tilde H_T$, $\tilde H_T^\perp$

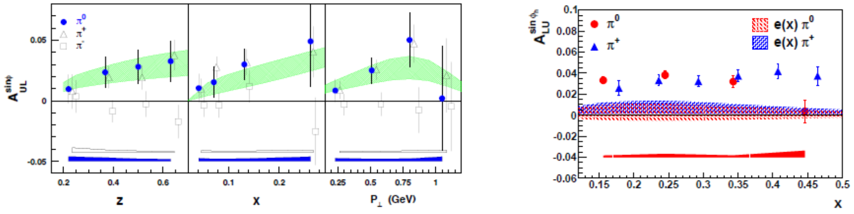
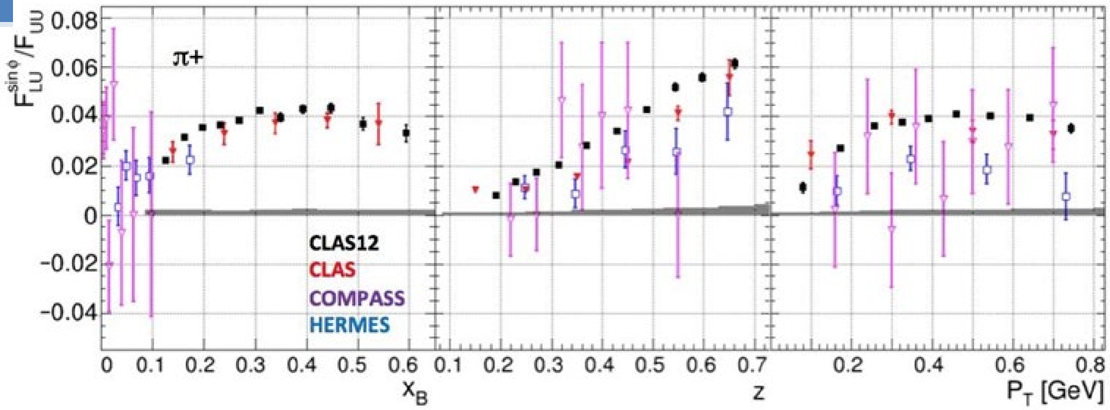


Figure 10.5: **Left:** HERMES data for the longitudinal target-spin asymmetry $A_{UL}^{\sin\phi_h} \propto F_{UL}^{\sin\phi_h}/F_{UU}$ for pion production [1286]. Error bars include the statistical uncertainties only. The filled (blue) and open (white) bands at the bottom of the panels represent the systematic uncertainties for neutral and charged pions, respectively. The shaded (green) areas show a range of predictions of a model calculation [1291, 1292] applied to the case of π^0 production. **Right:** CLAS data for the beam-spin asymmetry $A_{LU}^{\sin\phi_h} \propto F_{LU}^{\sin\phi_h}/F_{UU}$ for π^0 and π^+ as a function of x at an average $P_{hT} = 0.38\,\text{GeV}$ and for $0.4 < z < 0.7$ [1293]. The error bars correspond to statistical uncertainties, and the red error band at the bottom of the plot corresponds to systematic uncertainties. The red and blue hatched bands show model calculations involving only the term proportional to $e \otimes H_1^\perp$ in Eq. (10.27) for π^0 and π^+, respectively.

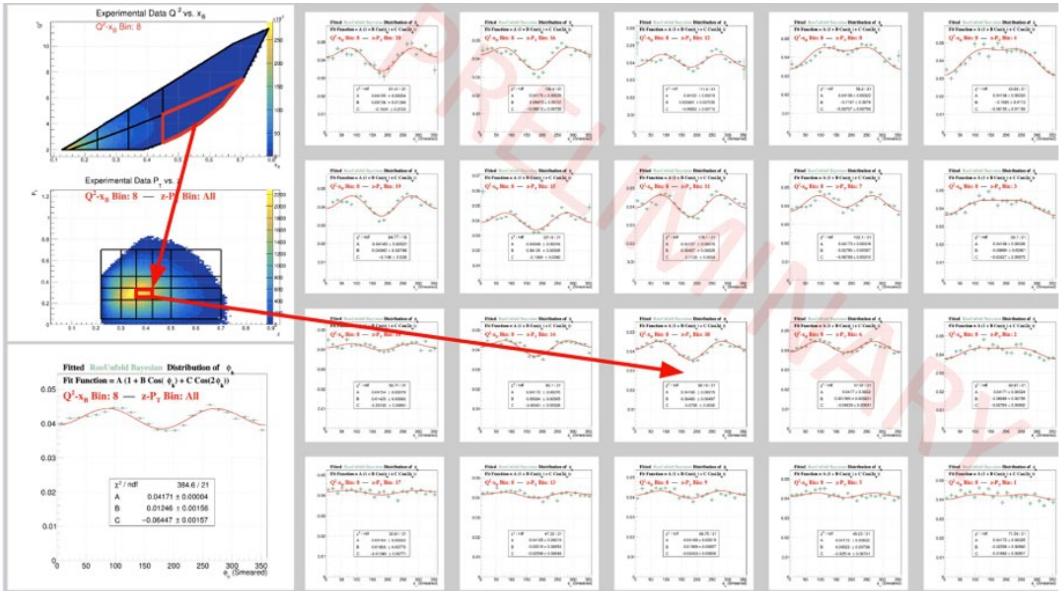
TMD handbook figure

CLAS12

Beam Spin Asymmetry @ CLAS12



Azimuthal Modulations @ CLAS12

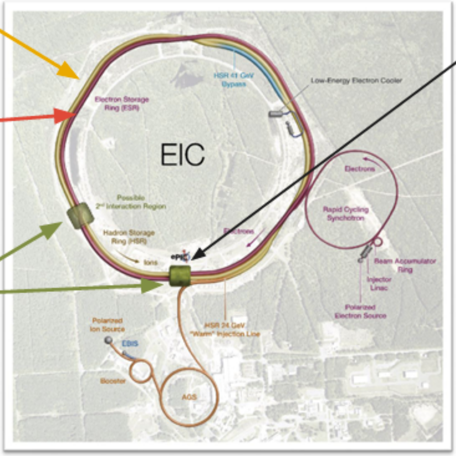


ePIC

Hadron Storage Ring (RHIC Rings)
41, 100-275 GeV

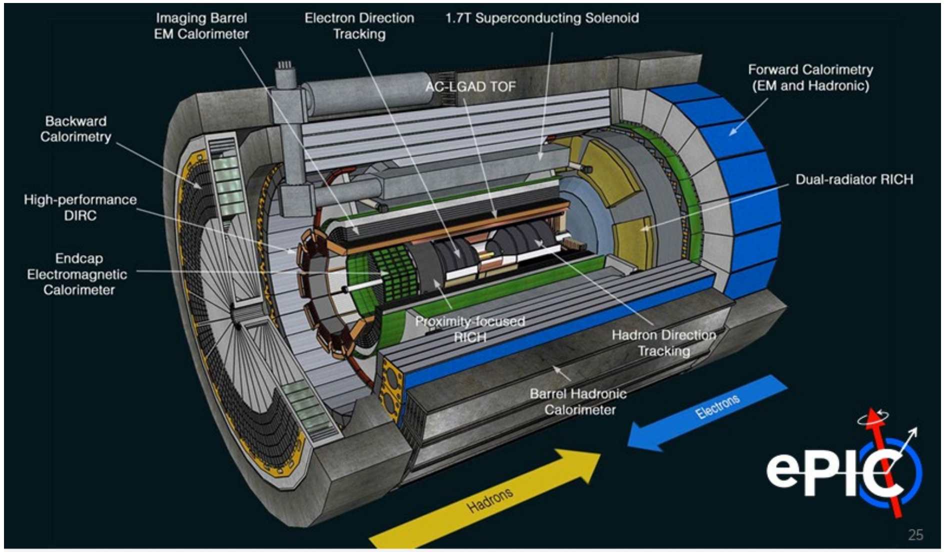
Electron Storage Ring **5–18 GeV**
- Polarized electron source
- Electron pre-injector (750 MeV Linac)
- Rapid Cycling Synchrotron design to avoid depolarizing resonances (750 MeV - top energy)

Interaction Region(s)
- **High Luminosity Target:** L= 10^{33}–10^{34} $cm^{-2}sec^{-1}$ 10 – 100 fb^{-1}/year
- **Highly Polarized Beams:** 70%
- 25 mrad (IP1) crossing angle with crab cavities
- Bunch Crossing ~ 10.2 ns/98.5 MHz

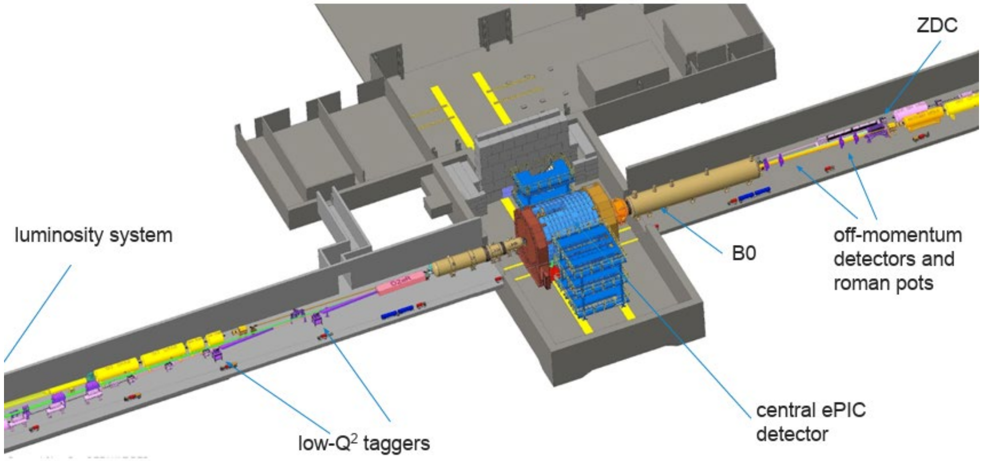


Detector located at 6 o'clock of the EIC Ring

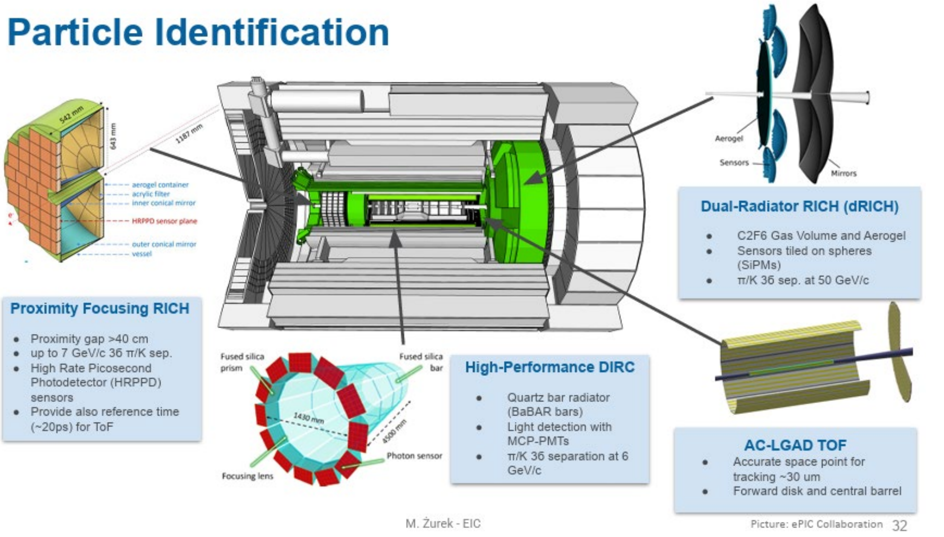
The **ePIC Collaboration** formed in July 2022 is dedicating to the realization of the project detector
- 178 Institutions, 26 countries, 4 world's region
- > 901 collaborators



ePIC is more than 80 m long…



Particle Identification



Proximity Focusing RICH
- Proximity gap >40 cm
- up to 7 GeV/c 3б π/K sep.
- High Rate Picosecond Photodetector (HRPPD) sensors
- Provide also reference time (~20ps) for ToF

High-Performance DIRC
- Quartz bar radiator (BaBAR bars)
- Light detection with MCP-PMTs
- π/K 3б separation at 6 GeV/c

Dual-Radiator RICH (dRICH)
- C2F6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3б sep. at 50 GeV/c

AC-LGAD TOF
- Accurate space point for tracking ~30 um
- Forward disk and central barrel

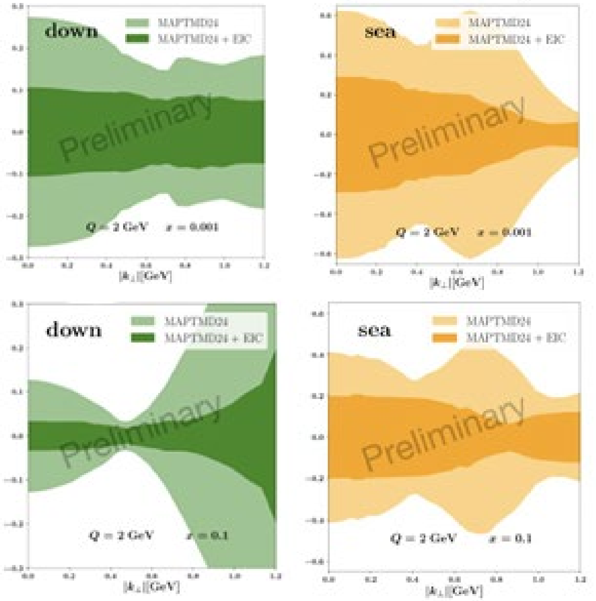
M. Żurek - EIC

Picture: ePIC Collaboration 32

EIC impact

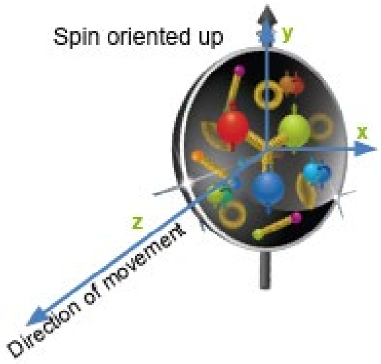
Glimpse at the unpolarized f1 TMD: TMD PDFs obtained using MAP24 global TMD fit, only π+ production

L. Rossi, EICUG Meeting 2025

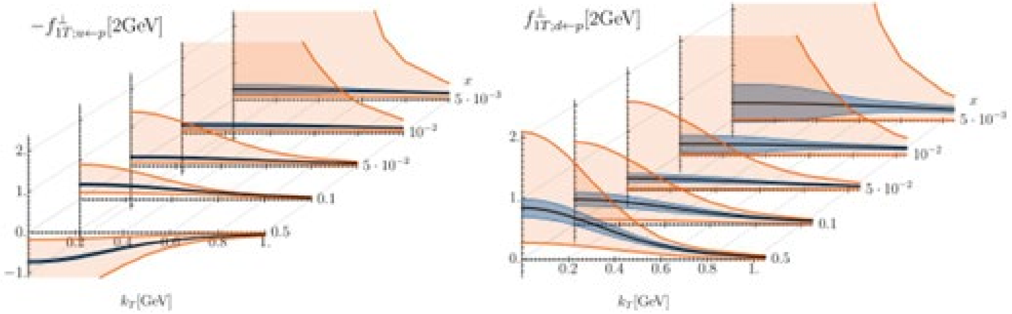


Impact on u and d quark Sivers distributions:

- Sivers function: correlates the proton's transverse spin with an unpolarized parton's transverse momentum
- Accessible in single spin asymmetries A_{UT}



R. Seidl, et al., Nucl.Instrum.Meth.A 1049 (2023) 168017

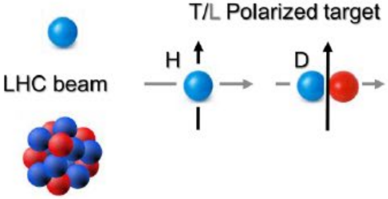


LHCspin

LHCspin experiment

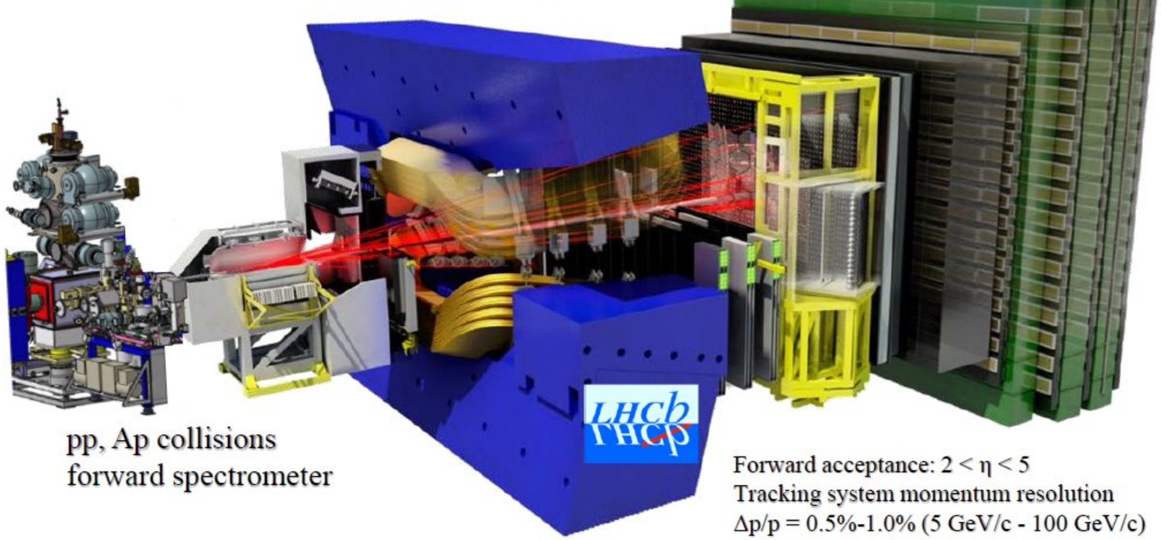
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

0.45 - 7 TeV



2.76 TeV

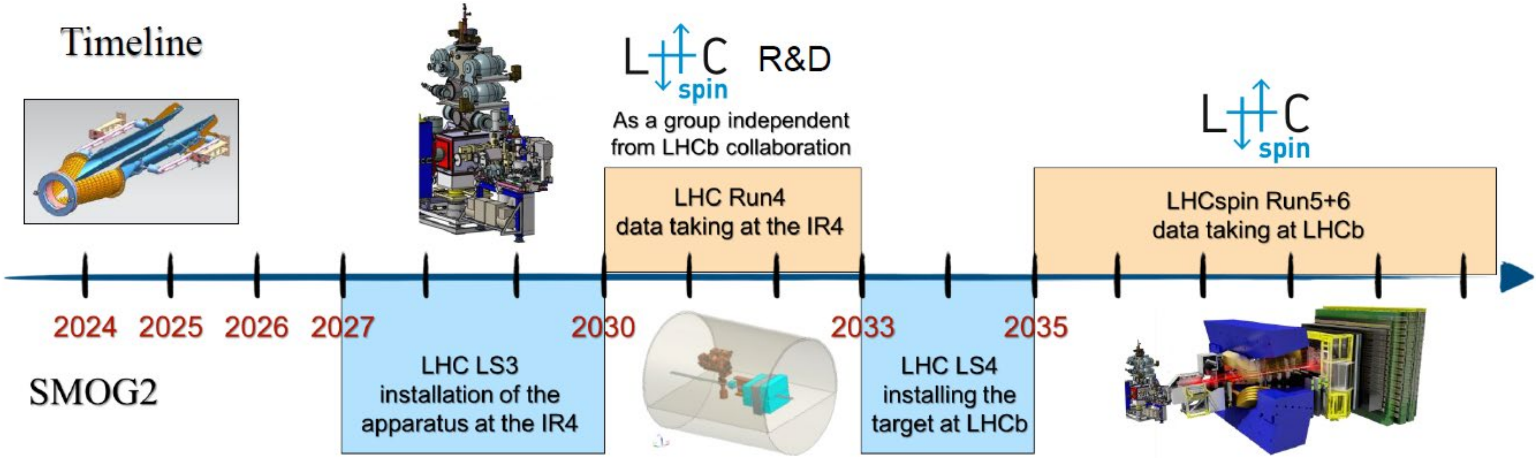
pp: $\sqrt{s} \simeq 29 - 115$ GeV
Ap: $\sqrt{s} \simeq 72$ GeV



pp, Ap collisions
forward spectrometer

Forward acceptance: $2 < \eta < 5$
Tracking system momentum resolution
$\Delta p/p = 0.5\%\text{-}1.0\%$ (5 GeV/c - 100 GeV/c)

Timeline



As a group independent from LHCb collaboration

LHC Run4
data taking at the IR4

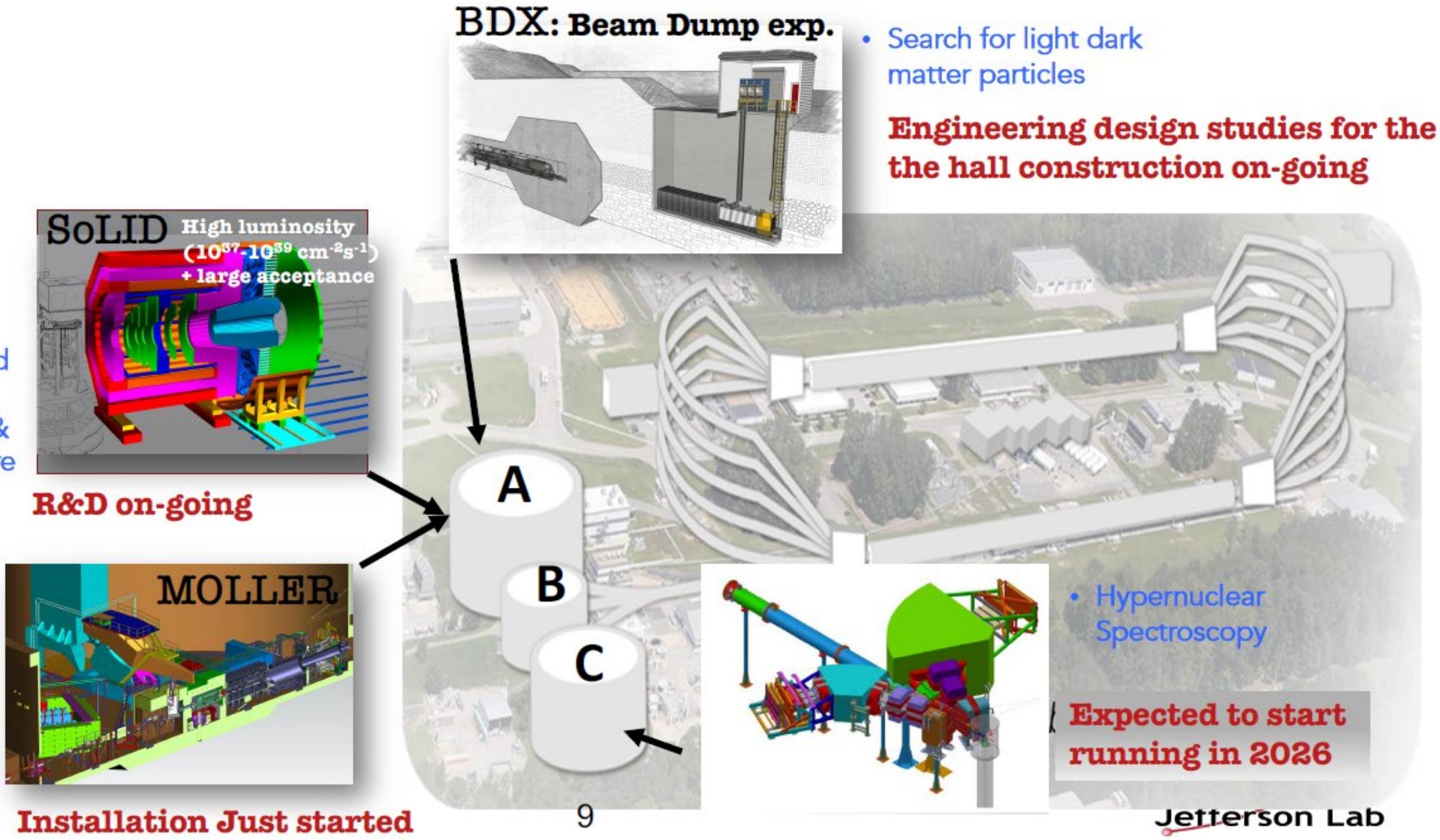
LHCspin Run5+6
data taking at LHCb

SMOG2

LHC LS3
installation of the apparatus at the IR4

LHC LS4
installing the target at LHCb

JLAB program



BDX: Beam Dump exp.

- Search for light dark matter particles

Engineering design studies for the the hall construction on-going

- Precision nucleon 3D imaging
- Origin of the proton mass and gluonic force
- BSM searches & nucleon structure

R&D on-going

- Ultra-precise measurement of the weak charge of the electron

Installation Just started

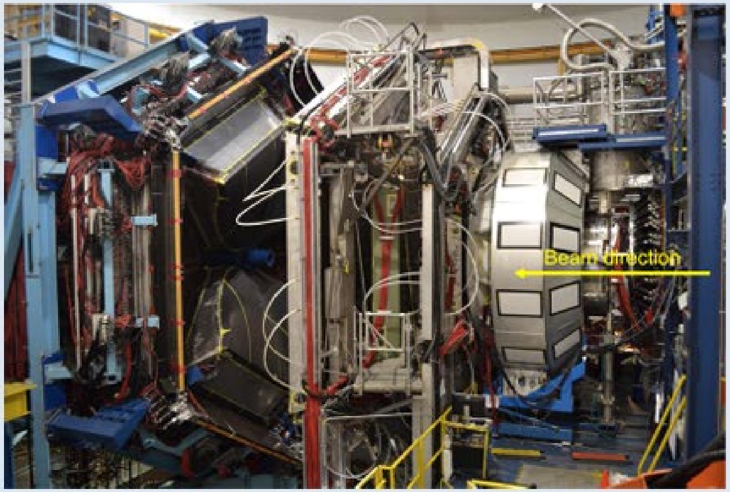
- Hypernuclear Spectroscopy

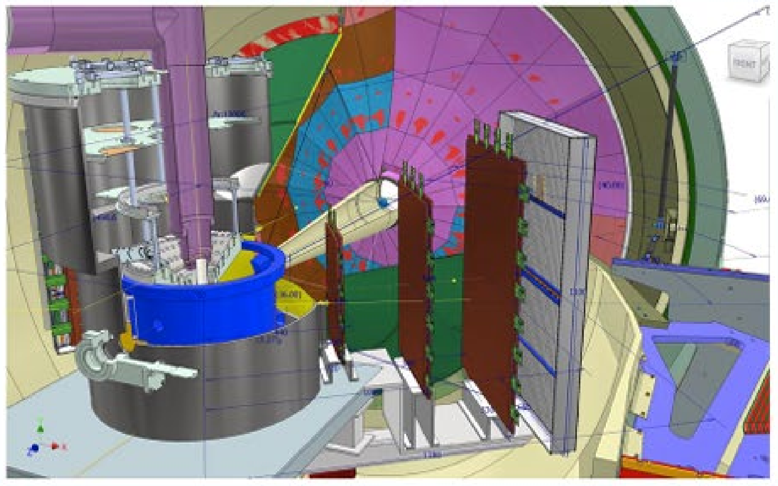
Expected to start running in 2026

CLAS12

RGH implements the target configuration which is most sensitive to the 3D nucleon structure study and capitalizes on CLAS12 with a complete set of target polarizations

100 (physics) + 25 (ancillary) PAC days approved to achieve unprecedent precision in the valence region





RGH aim: The SIDIS and exclusive measurements will significantly improve our understanding of tensor charge, spin-orbit correlations, and quark angular momentum, complementing past and ongoing CLAS12 studies.

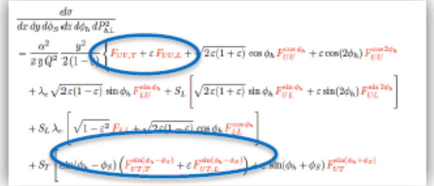
JLAB 22 GeV

JLab: IDEAL PLACE TO CARRY OUT IMAGING STUDIES in the non-perturbative region

High Luminosity + High Polarized beam and target + High Resolutions State-of-the-art detectors + Versatile experimental setup + Multiparticles FS detection

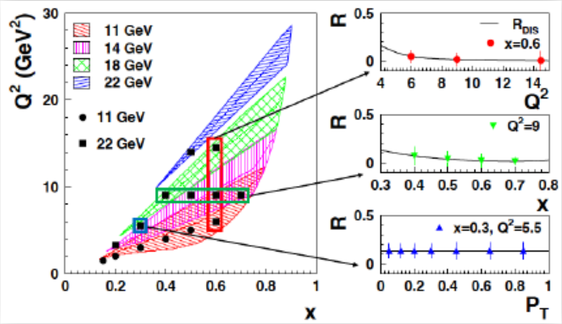
Several advancements @ 22 GeV, including:

1. **Multidimensional** studies of the evolution of 3D observables **with Q^2**
2. Unique opportunity to **measure γ^*_L & γ^*_T** contributions to observables **at higher Q^2**

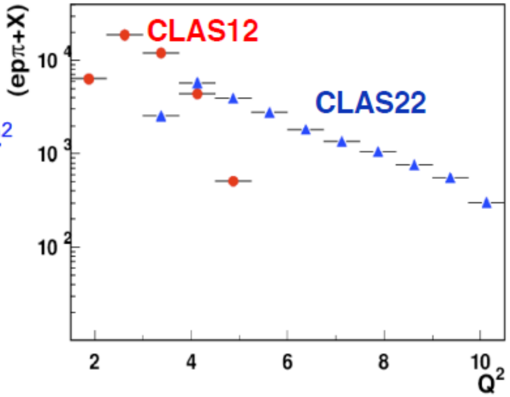


$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\lambda_e\Big[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)}$$

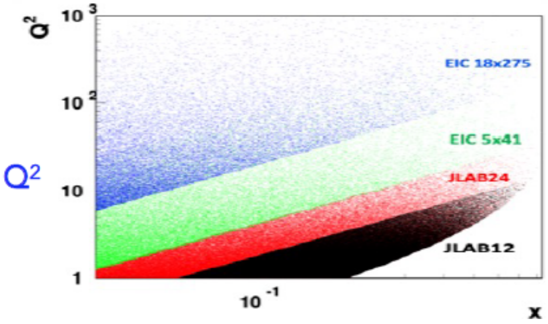
Neglecting γ_L* biases TMD extractions and factorization studies, limiting the accuracy of spin-dependent QCD insights



$$R = \frac{\sigma_L}{\sigma_T}$$



3. A unique opportunity to evaluate the **contribution of various processes at higher Q^2**



All critical aspects for a deeper and better understanding of our current measurements and future measurements at EIC!

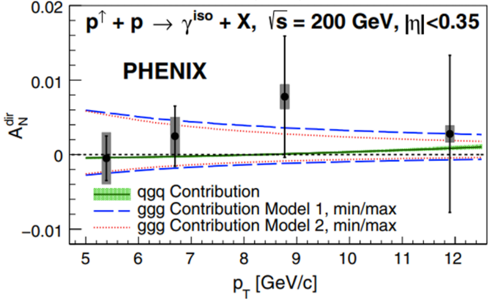
13

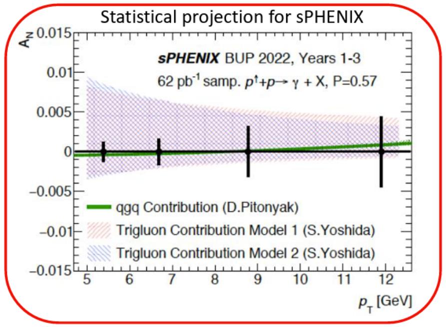
sPHENIX program

Direct photon or jet TSSAs in $p^{\uparrow} p \to \gamma X$ and $p^{\uparrow} p \to$ jet X

Clean processes: No fragmentation so only Sivers mechanism in the initial state

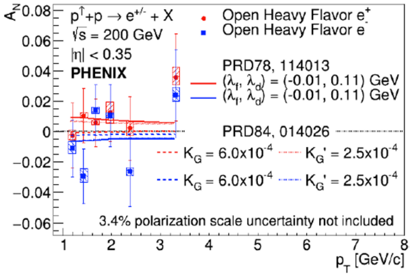
PRL 127 (2021) 162001

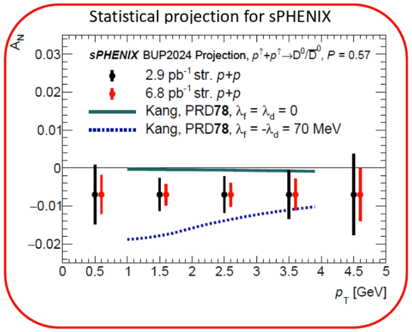



Statistical projection for sPHENIX

Heavy flavor production at √s=200 GeV is dominated by gluon-gluon fusion
So TSSAs will highlight the tri-gluon collerator

PRD 107 (2023) 5, 052012




Statistical projection for sPHENIX

Parametrisations of the 3-gluon correlator in 2 models

Kang, Qiu, Vogelsang, Yuan, PRD78 $T_G^{(f)}(x,x) = \lambda_f G(x), \quad T_G^{(d)}(x,x) = \lambda_d G(x)$

17

Hadron in jet TSSAs in $p^{\uparrow} p \to$ jet h X

2 scales: jet transverse momentum $\mathbf{p_T}$
+ hadron transv. momentum within the jet $\boldsymbol{k}_{\perp H}$

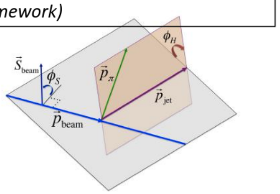
Rich information in the azimuthal distribution

Collins azimuthal asymmetry

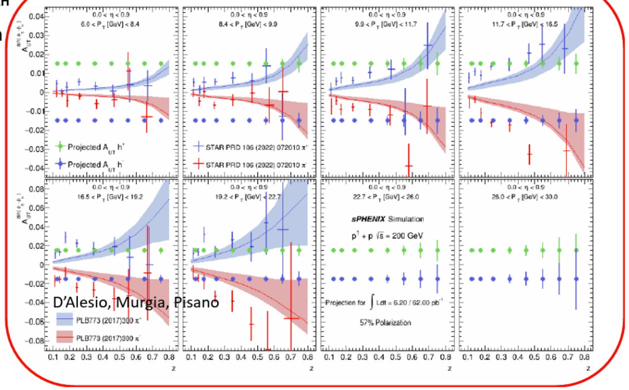
$$A_N^{\sin(\phi_S - \phi_\pi^H)}$$
$$\propto h_1^q(x_a, \boldsymbol{k}_{\perp a}^2) \otimes f_1(x_b, \boldsymbol{k}_{\perp b}^2) \otimes \Delta\hat{\sigma} \otimes H_1^{\perp q}(z, \boldsymbol{k}_{\perp \pi}^2)$$

Transversity PDF ⊗ f_1 ⊗ $\Delta\hat{\sigma}$ ⊗ Collins FF

(in TMD framework)



The RHIC Cold QCD Plan for 2024 to 2028
Completing the RHIC Science Mission



Di-hadron TSSAs in $p^{\uparrow} p \to h^+ h^- X$

Quark transversity can also be accessed by di-hadron fragmentation

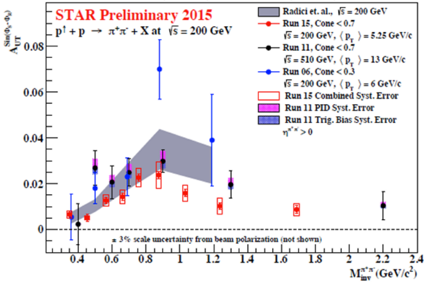
$$A_{UT} \propto f_1^a(x_a) h_1^b(x_b) \times \frac{d\Delta\sigma_{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat{t}} H_1^{\sphericalangle c}(z_h, M_h)$$

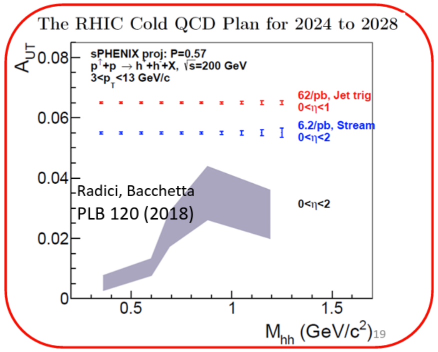
f_1 x Transversity PDF x $\Delta\hat{\sigma}$ x IFF (dihadron Interference FF)

(in Collinear framework)

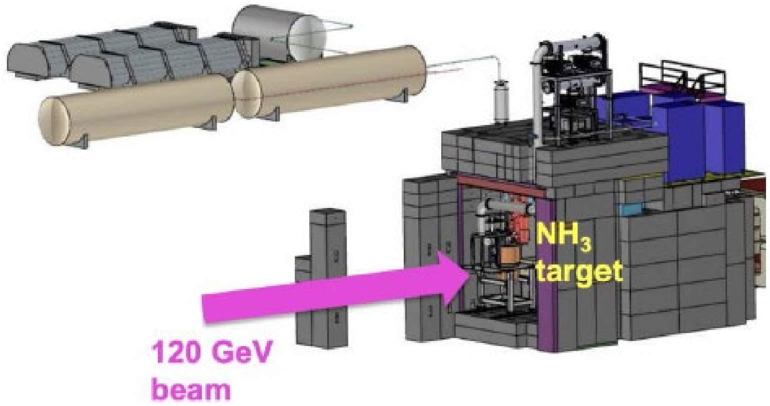
Significant constraints on the u and d-quark transversities
Importance for the nucleon tensor charge determination

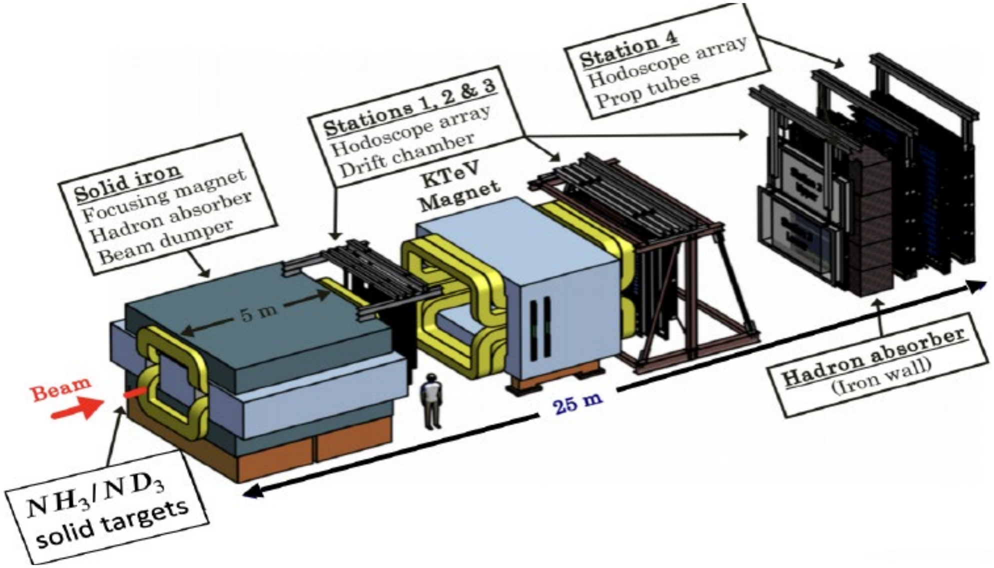
PRL 115 (2015), PLB 780 (2018)




The RHIC Cold QCD Plan for 2024 to 2028

SpinQuest



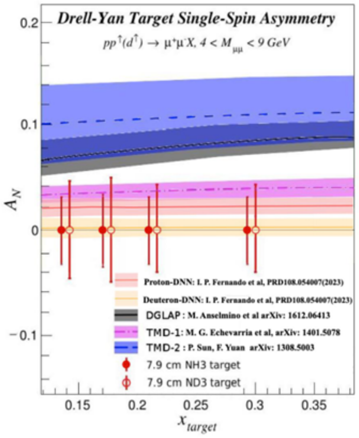


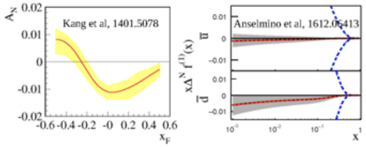
- Experiment will run for two full years to collect a sufficient Drell–Yan data sample.

- Projected uncertainties:
    - Statistical uncertainties: 3 – 5%.
    - Efficiency and Acceptance: 3%

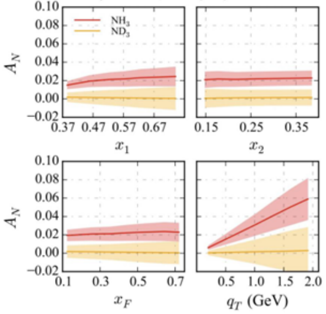
Systematic: minimized via careful target material characterization, polarization monitoring, and beam-target alignment.

If $A_N \neq 0$: "Smoking Gun" evidence for $L_{\bar{u},\bar{d}} \neq 0$





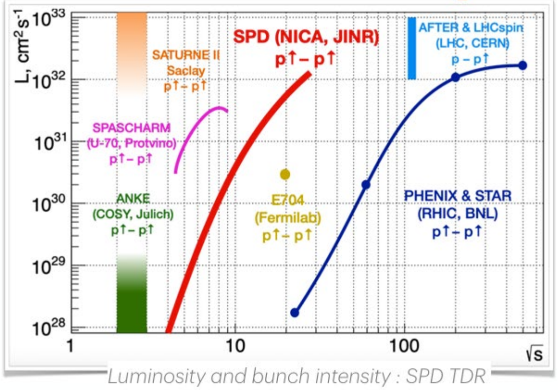
I. P. Fernando and D. Keller
Phys. Rev. D 108, 054007 (2023)



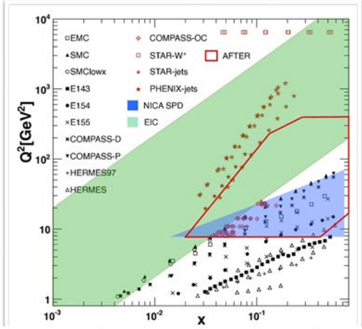
SpinQuest
Commisioning + first data
Plans a run in 2026

NICA

SPD in World landscape of polarised physics



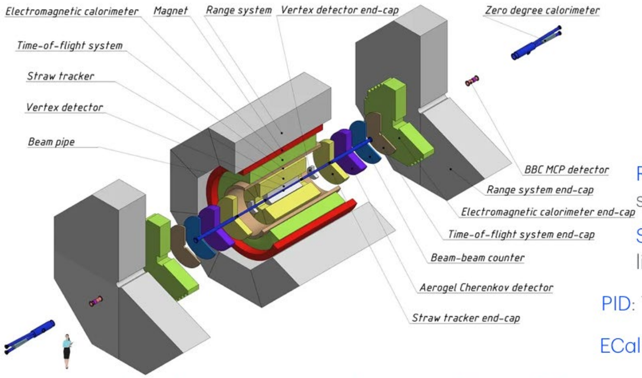
Luminosity and bunch intensity : SPD TDR



Kinematical coverage for major probes at the SPD: charmed mesons, high-p_T photons, charmonia

At NICA, there will be a unique opportunity to utilize polarized deuteron beams!

Spin Physics Detector setup



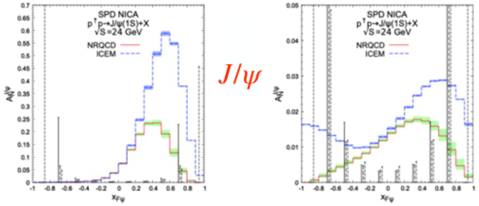
Range system: muon/hadron separation

Silicon vertex detector: for short lived particle decays

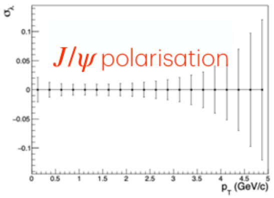
PID: TOF + FARICH + STRAW (dE/dx)

ECal: for prompt photons

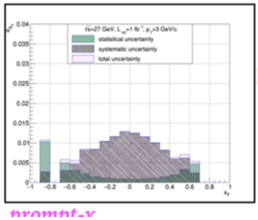
SPD Technical Design Report: V.Abazov et al.(SPD Collaboration), Natural Sci.Rev. 1 (2024) 1.



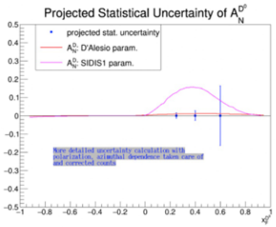
Different inputs for gluon Sivers function



$A_N^{J/\psi}$ predictions for SPD kinematics (and projected uncertainties for one year of recorded data) [Phys. Rev. D 104, 016008]



Prompt γ



D^0

1 year = 10^7 s,

$\sqrt{s} = 27$ GeV

Conclusions

- TMD physics made enormous progress in 20 years

- New insight in the dynamic hadron structure

- Brilliant future for ongoing experiments and new facilities