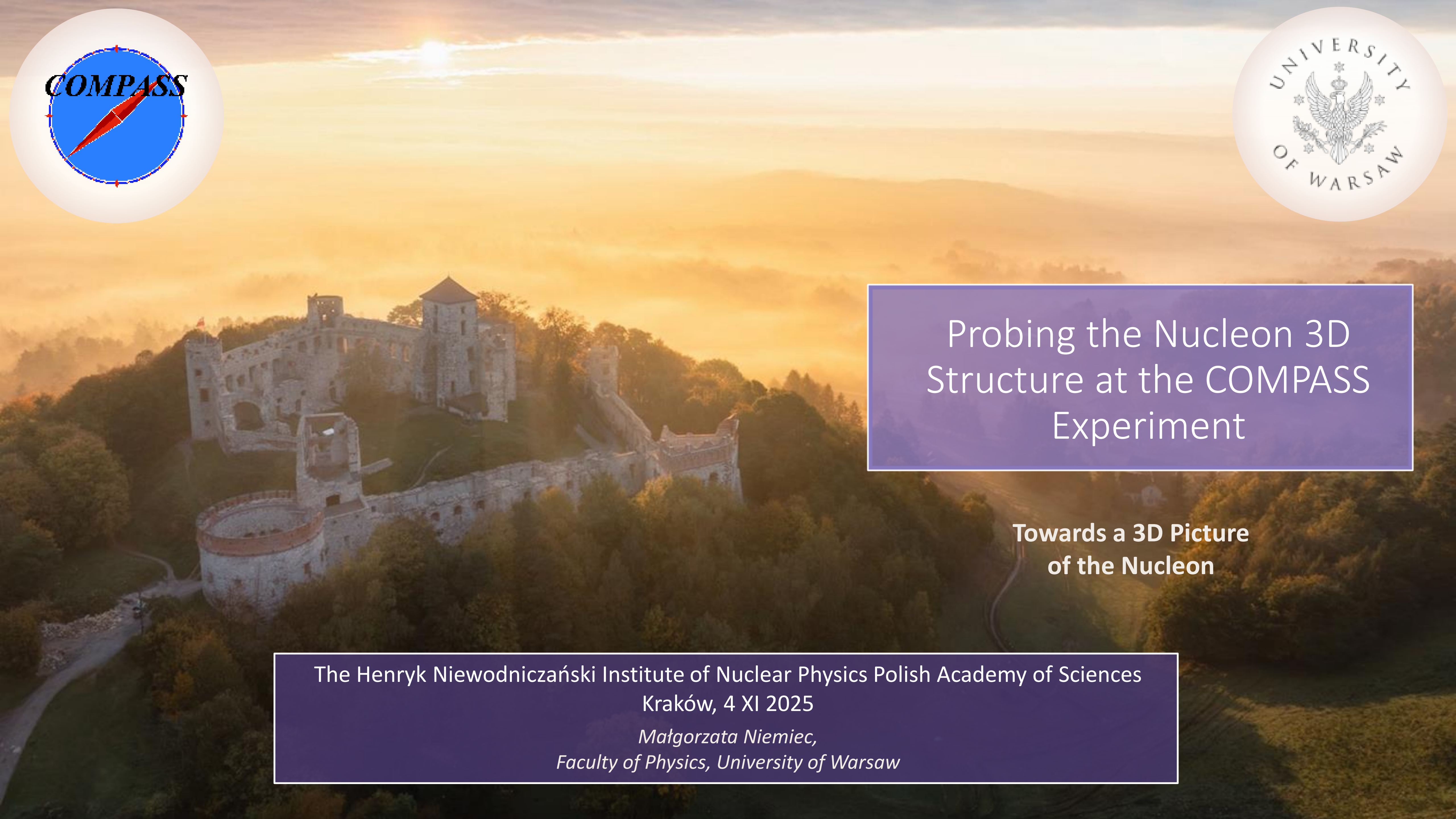


# Probing the Nucleon 3D Structure at the COMPASS Experiment

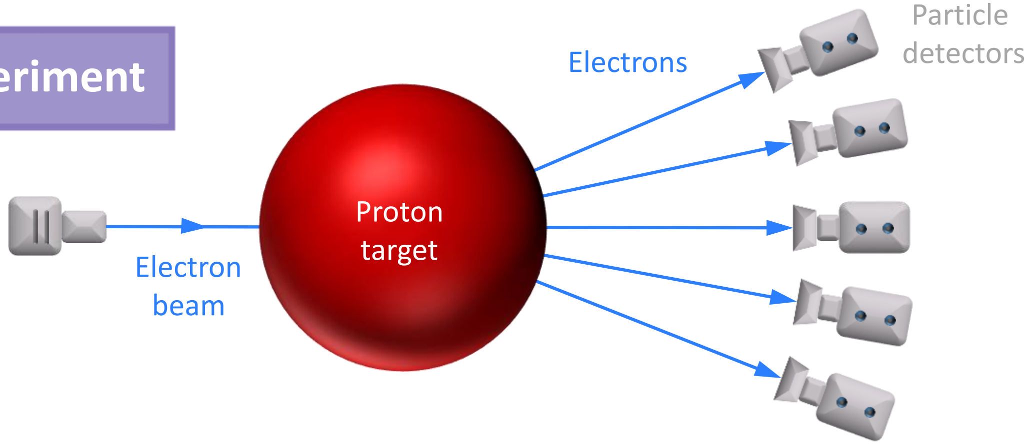
**Towards a 3D Picture of the Nucleon**

The Henryk Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences
Kraków, 4 XI 2025

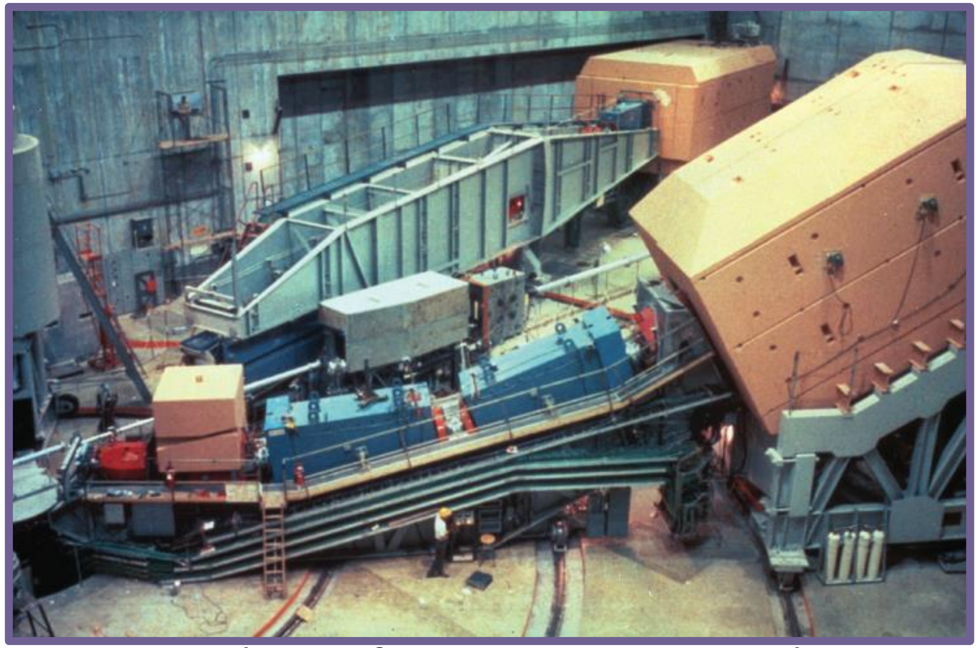
*Małgorzata Niemiec,*
*Faculty of Physics, University of Warsaw*

# Short Story of Spin Measurements

## Experiment

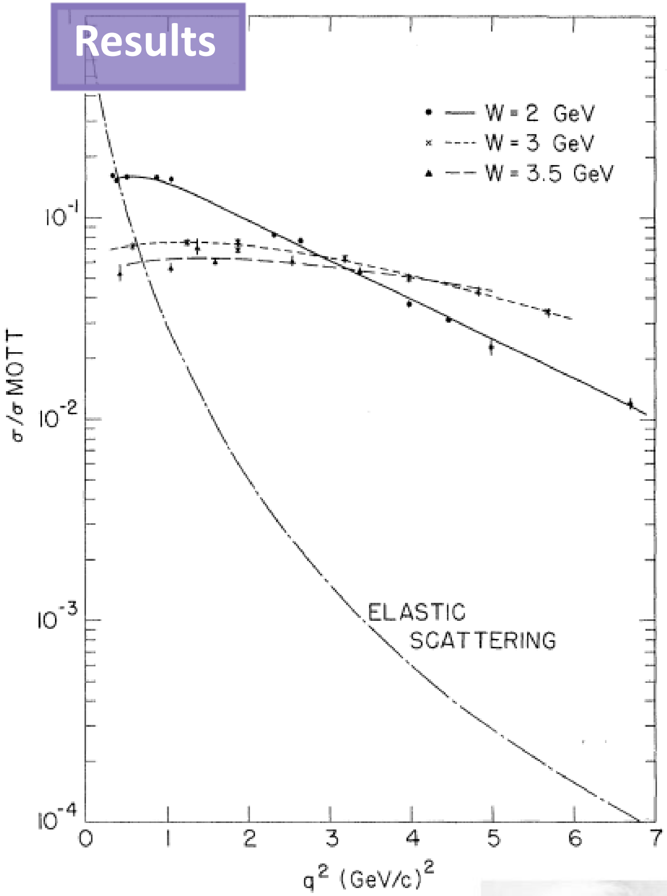



https://www.sciencephoto.com/media/1042/view/end-station-a-experimental-hall-slac



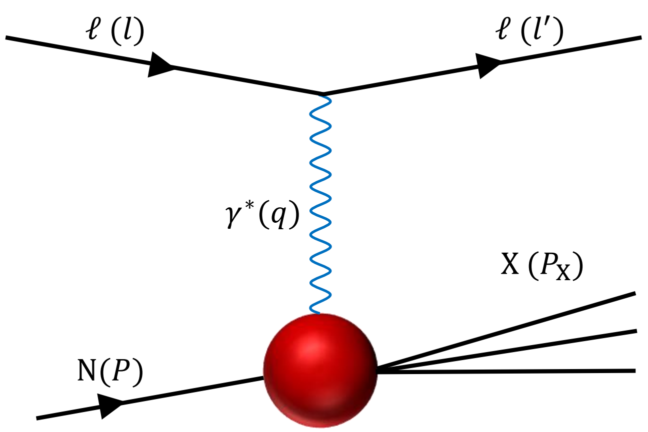
1968 photo of SLAC spectrometer that recorded electrons emerging from high-energy collisions with protons.

## Results



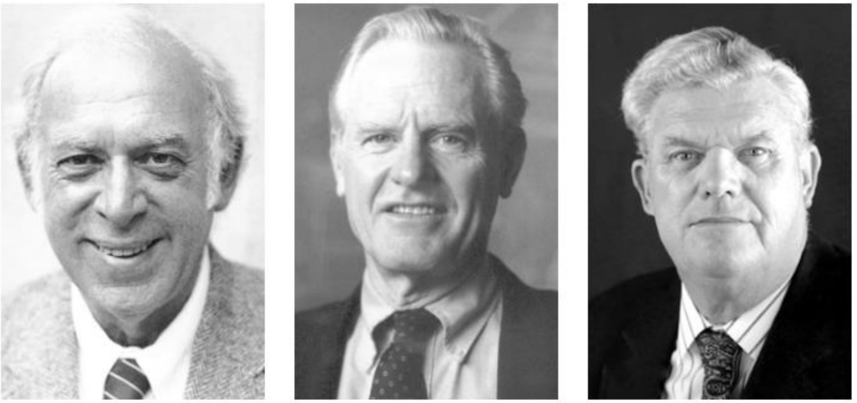

[M. Breidenbach et. al., Phys. Rev. Lett 23 (1969) 935]

## Interpretation



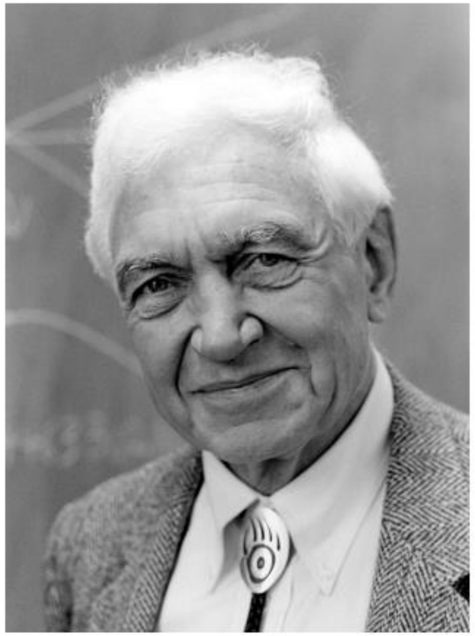

Scattering off **point-like constituents**: interpreted as **partons**

**Nobel Prize for J. I. Friedman, H. W. Hendall and R. E. Taylor in 1990**



https://www.nobelprize.org/prizes/physics/1990/summary/

# Short Story of Spin Measurements



http://biographicalmemoirs.org/pdfs/hughes-vernon.pdf

Vernon Hughes
father of spin measurements

- ❖ First measurement in SLAC, 1975, made by V. Hughes et al.
- ❖ Results with large uncertainties were agreed with expectations

Quark spin

Orbital angular momenta of quarks and gluons

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Gluon spin

Unexpected results of EMC (1987) starts the so-called "spin crisis"



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/89-73
8 June 1989

AN INVESTIGATION OF THE SPIN STRUCTURE OF THE PROTON IN DEEP INELASTIC SCATTERING OF POLARISED MUONS ON POLARISED PROTONS

*The European Muon Collaboration*

ABSTRACT

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured in the range $0.01 < x < 0.7$. The spin dependent structure function $g_1(x)$ for the proton has been determined and, combining the data with earlier SLAC measurements, its integral over $x$ found to be $0.126 \pm 0.010(stat.) \pm 0.015(syst.)$, in disagreement with the Ellis-Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of $g_1$ for the neutron. These integrals lead to the conclusion, in the naïve quark parton model, that the total quark spin constitutes a rather small fraction of the spin of the nucleon. Results are also presented on the asymmetries in inclusive hadron production which are consistent with the above picture.

https://www.bnl.gov/newsroom/news.php?a=114331

# Multi-dimensional Imaging of the Nucleon

$W(x, b_T\, k_T)$
Wigner distributions

$\int d^2 b_T$

$\int d^2 k_T$

$f(x, k_T)$
Transverse Momentum Dependent Parton Distributions Function
Semi-inclusive processes

$f(x, b_T)$
Impact Parameter Distributions

Fourier trf.
$b_T \leftrightarrow \Delta$

$H(x, 0, t)$
$t = -\Delta$

$\xi = 0$

$H(x, \xi, t)$
Generalised Parton Distributions
Exclusive processes

$\int d^2 k_T$

$\int d^2 b_T$

$\int dx$

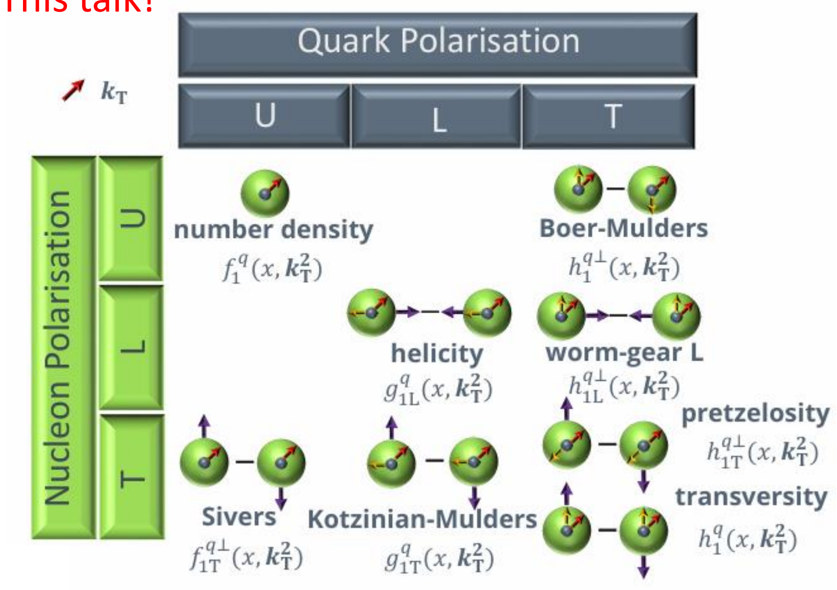
$\int dx\, x^{n-1}$

$F_1(\mathrm{t})$
Form Factors
Elastic scattering

$A_{n,0}(t) + 4\xi^2 A_{n,2}(t) + \ \ldots$
Generalised Form Factors
Lattice calculations

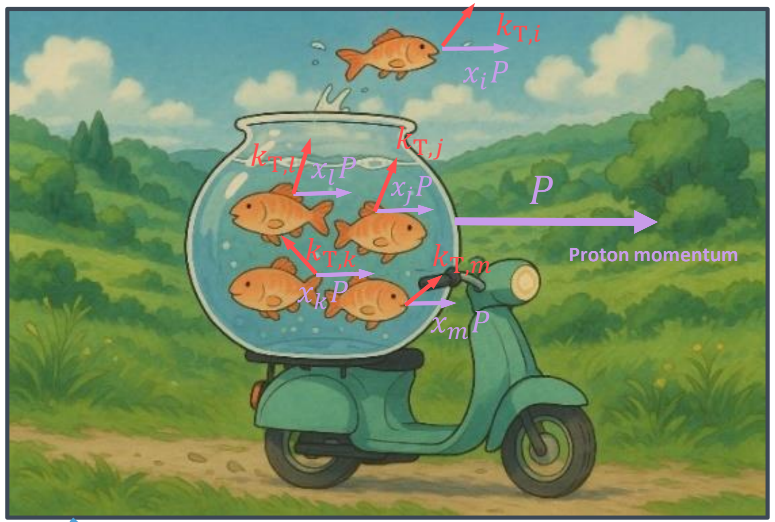
$f(x)$
Parton Densities
Inclusive and semi-inclusive processes

This talk!



# Nucleon Spin Structure

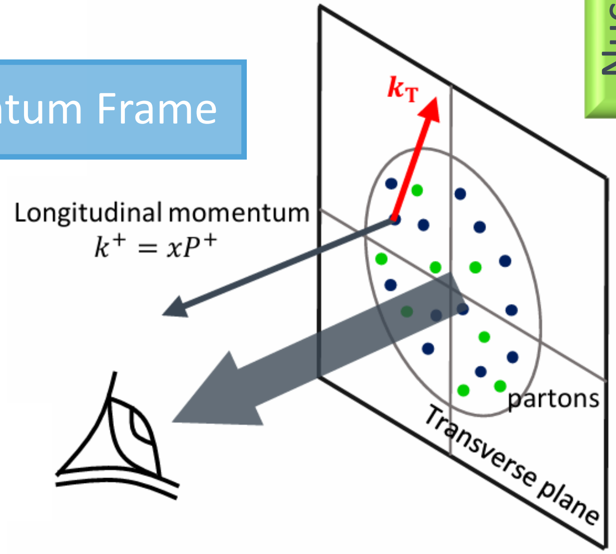
Fishes in Aquarium = Partons inside Proton

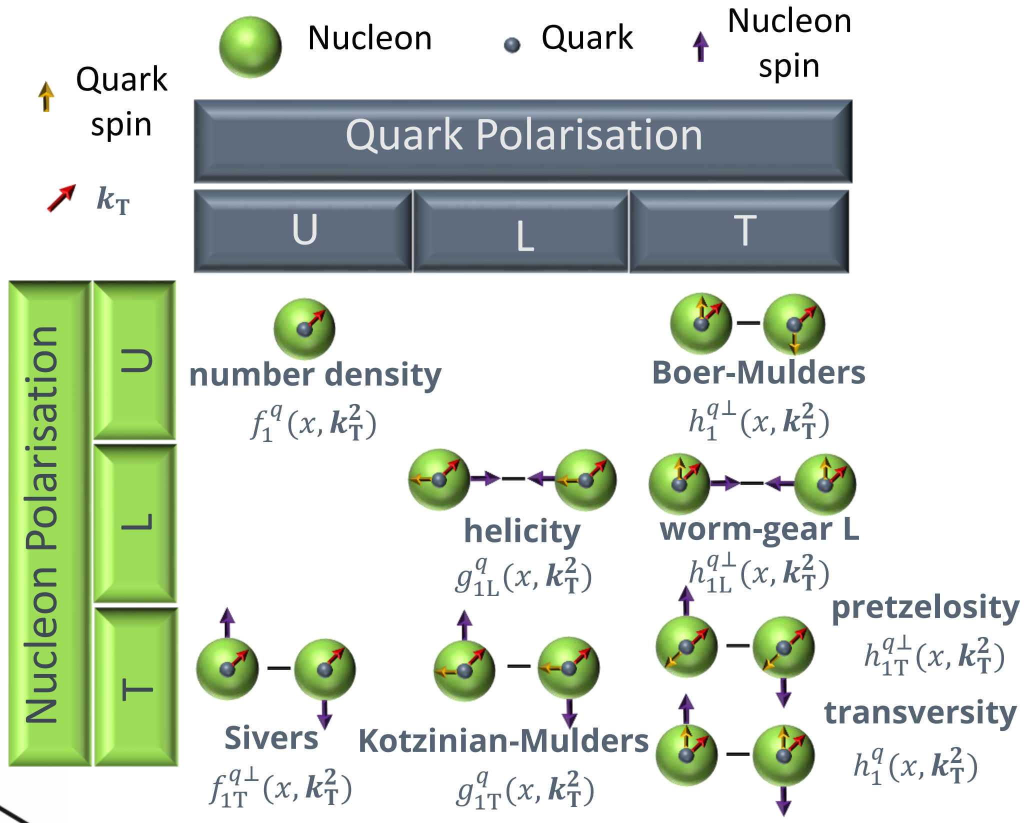



The Scooter = Infinite Momentum Frame

Twist-2
TMD PDFs

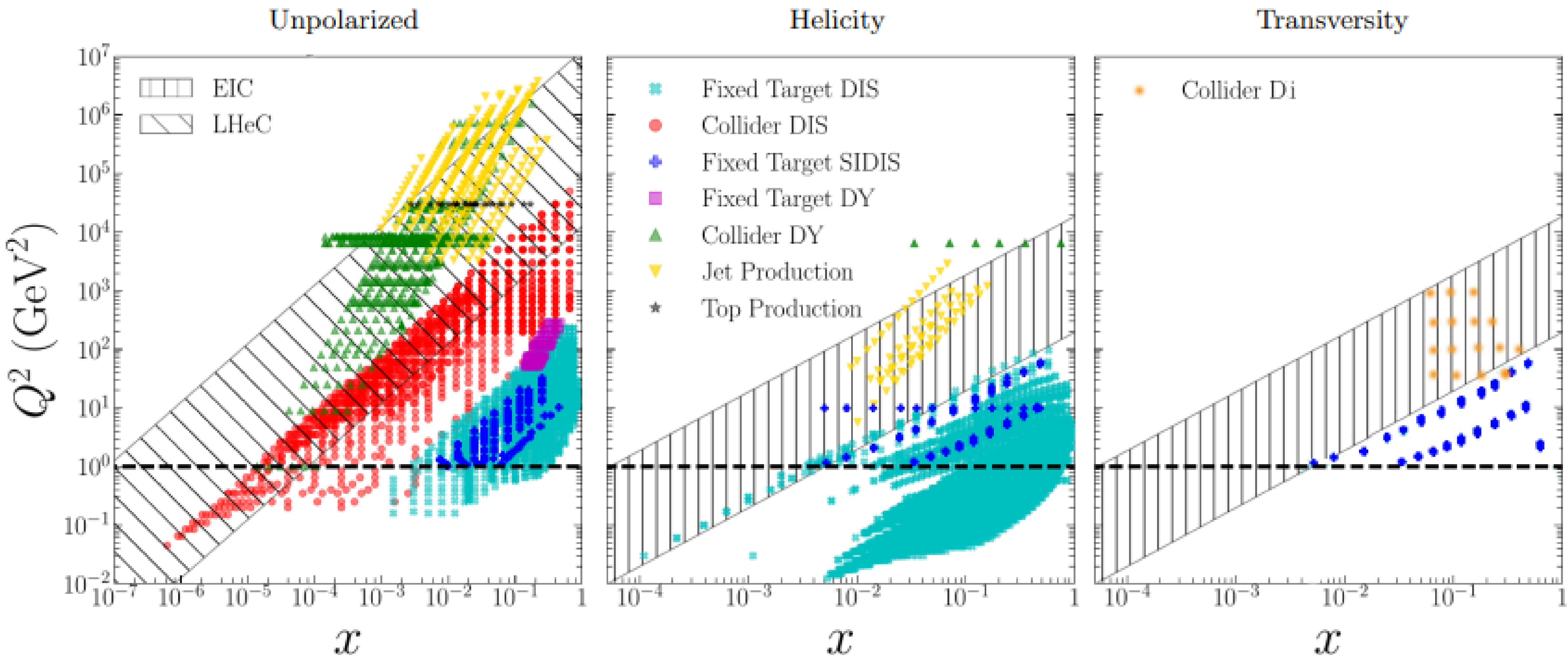
**8** leading-twist
**Transverse-Momentum**
**Dependent PDFs**
**(TMD PDFs)**




$$h_1^\perp(\mathrm{SIDIS}) = -h_1^\perp(\mathrm{DY})$$
$$f_{1\mathrm{T}}^\perp(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^\perp(\mathrm{DY})$$

# Map of Experimental Results

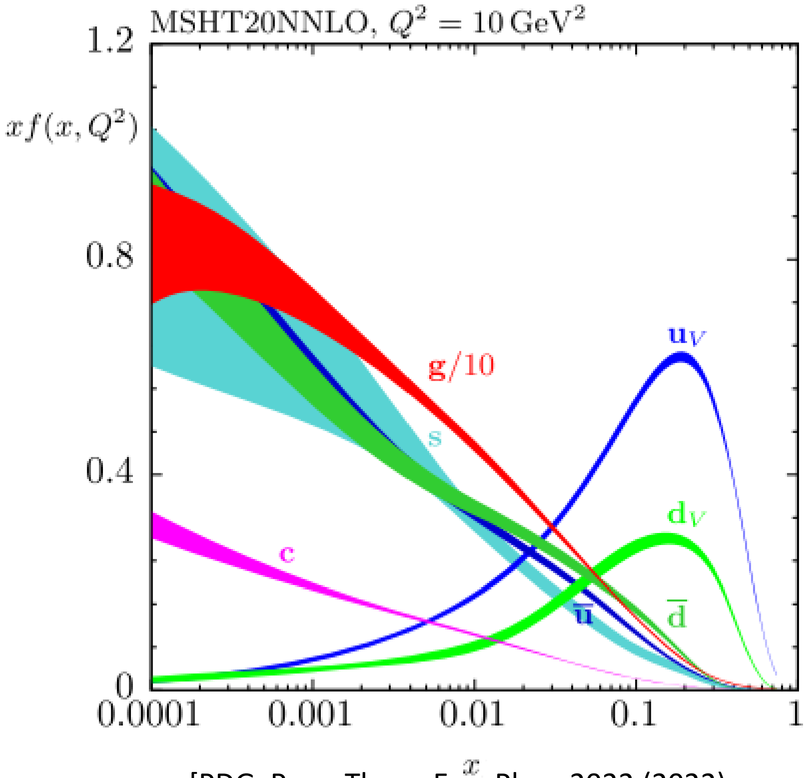



- Fraction of the nucleon's momentum carried by a quark $x$
- Photon virtuality $Q^2$

[Ethier & Nocera, Annu. Rev. Nucl. Part. Sci. 70 (2020) 43]

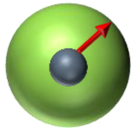
# Map of Experimental Results

## Number density




[PDG, Prog. Theor. Exp. Phys. 2022 (2022) 083C01; 2023 update]

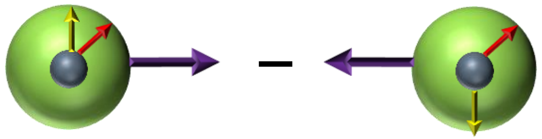
**Well-known**

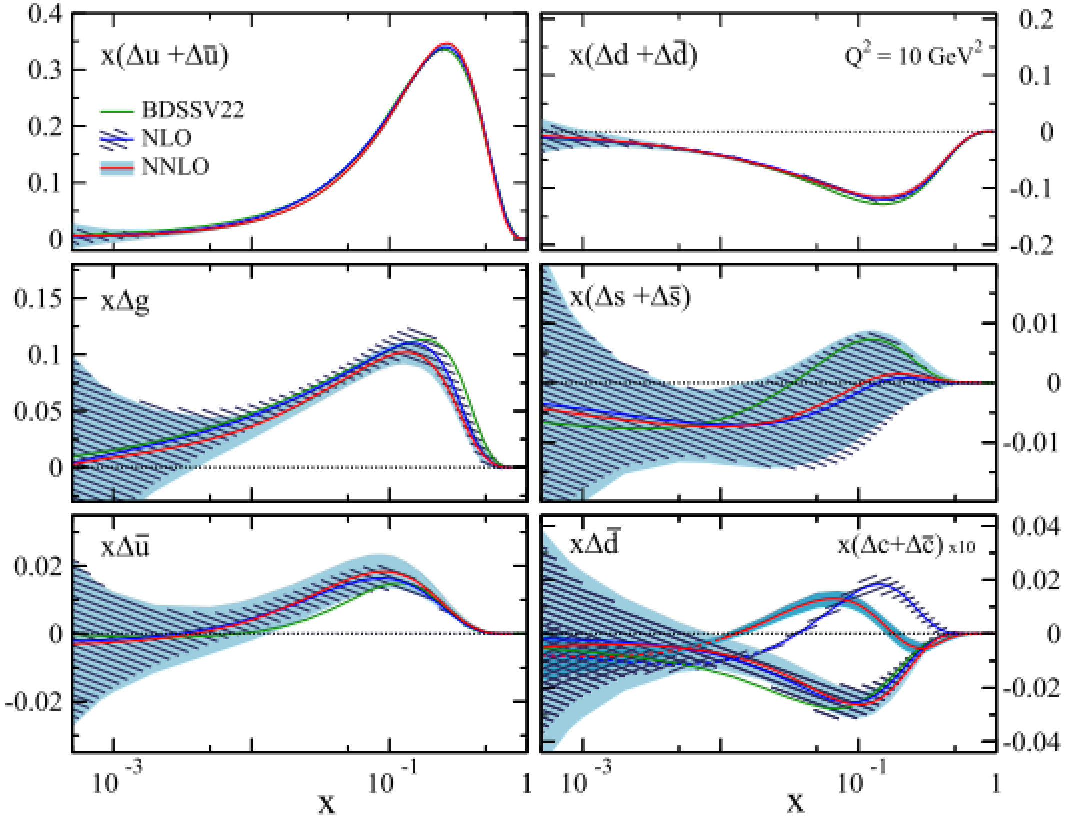


$f_1^q(x, \boldsymbol{k}_\mathrm{T}^2)$

## Helicity

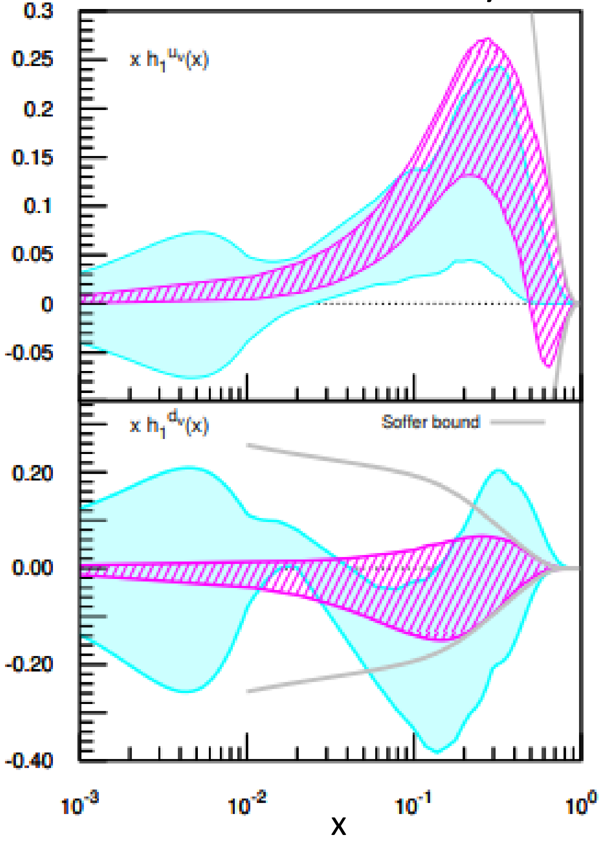
$g_{1\mathrm{L}}^q(x, \boldsymbol{k}_\mathrm{T}^2)$ **Less well-known**



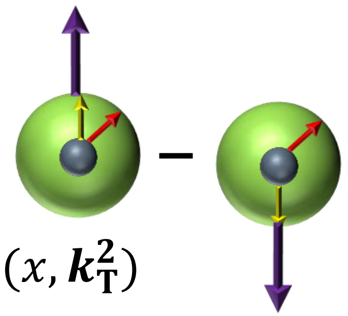



[Borsa *et al.*, Phys. Rev. Lett. 133 (2024) 151901]

## Transversity




[Bacchetta & Radici, PRL 120 (2018) 192001]
[Benel *et al.*, Eur. Phys. J. C 80 (2020) 465]

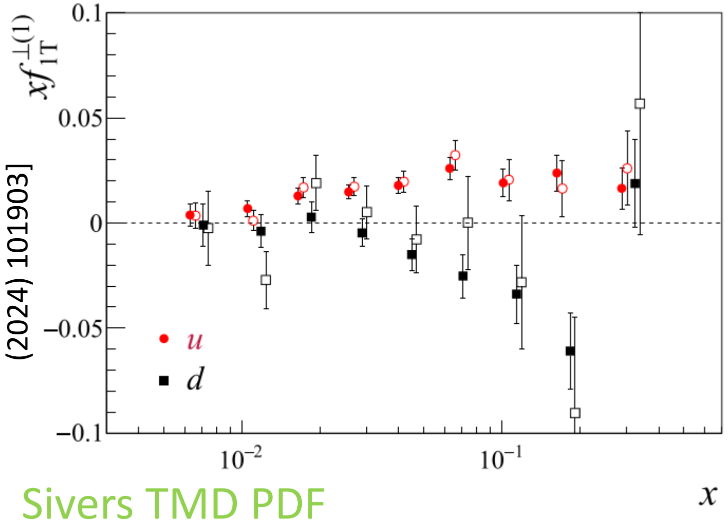


$h_1^q(x, \boldsymbol{k}_\mathrm{T}^2)$

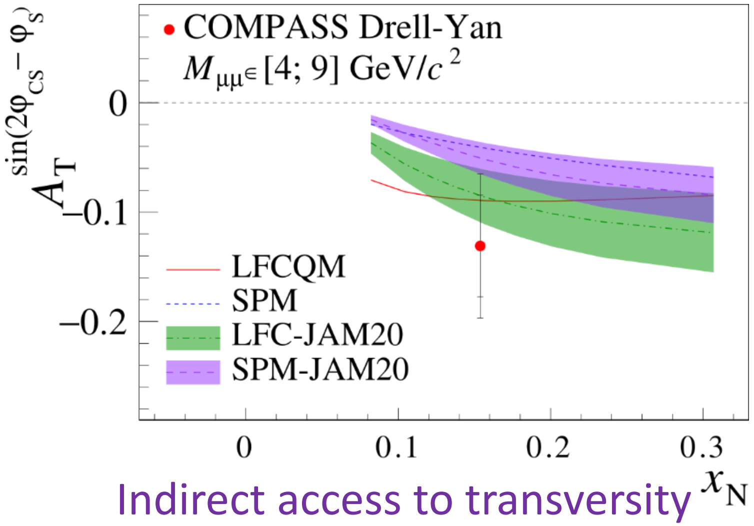
# Map of Experimental Results

## COMPASS

[COMPASS, Phys. Rev. Lett. 133 (2024) 101903]




Sivers TMD PDF




Indirect access to transversity

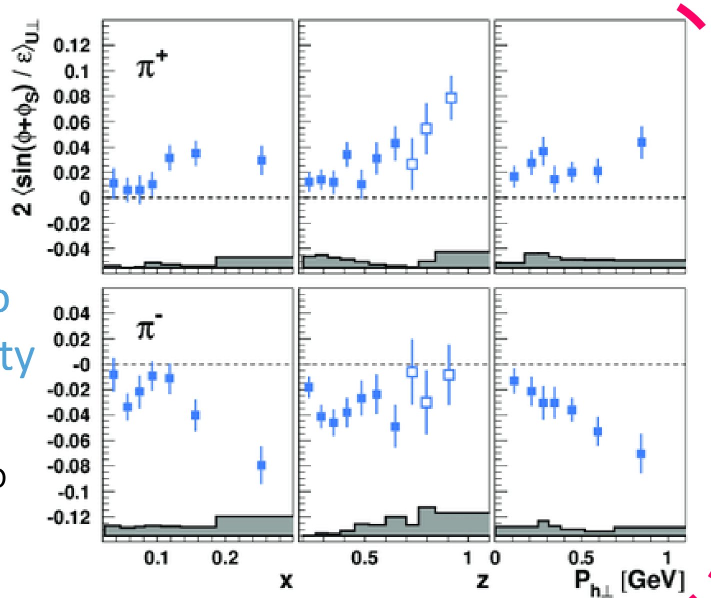
[COMPASS, Phys. Rev. Lett. 133 (2024) 071902]

Information on the remaining TMD PDFs is **even more limited**.

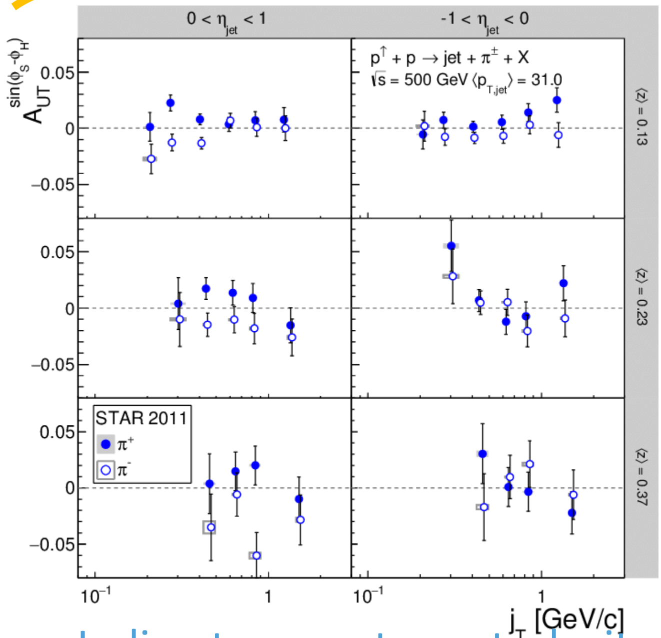
## HERMES

Indirect access to pretzelosity

[HERMES, Phys. Rev. D 102 (2020) 032007]

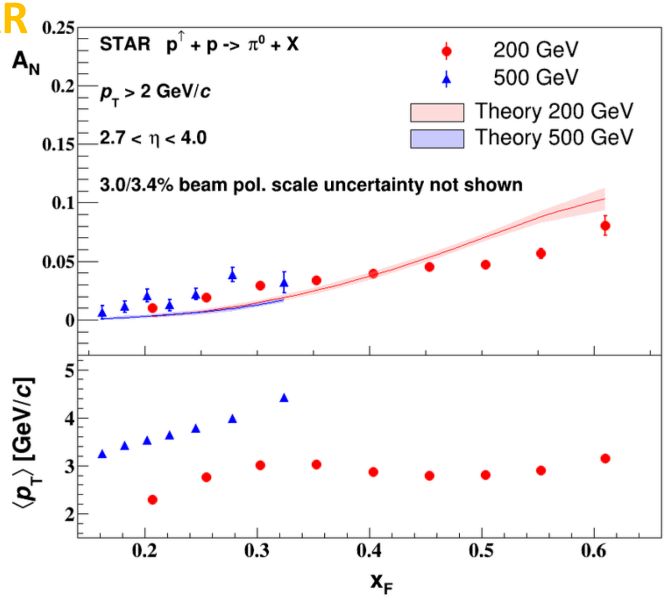



## STAR




Indirect access to pretzelosity

[STAR, Phys. Rev. D 97 (2018) 032004]

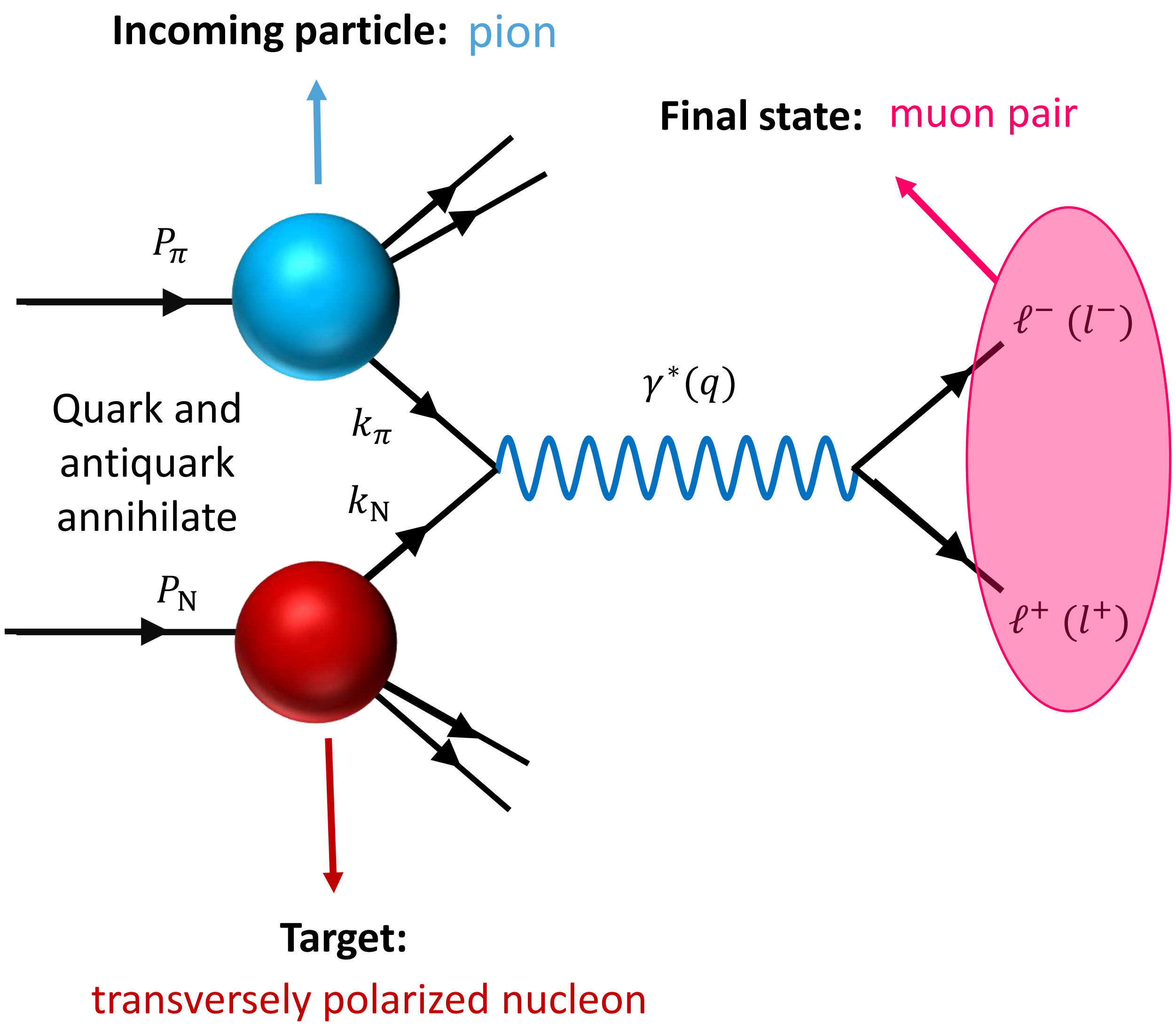



[STAR, Phys. Rev. D 103 (2021) 092009]

Indirect access to Boer-Mulders

# Drell-Yan process

Drell–Yan provide complementary access to **TMD PDFs** via **transverse–spin dependent azimuthal asymmetries (TSAs)**.

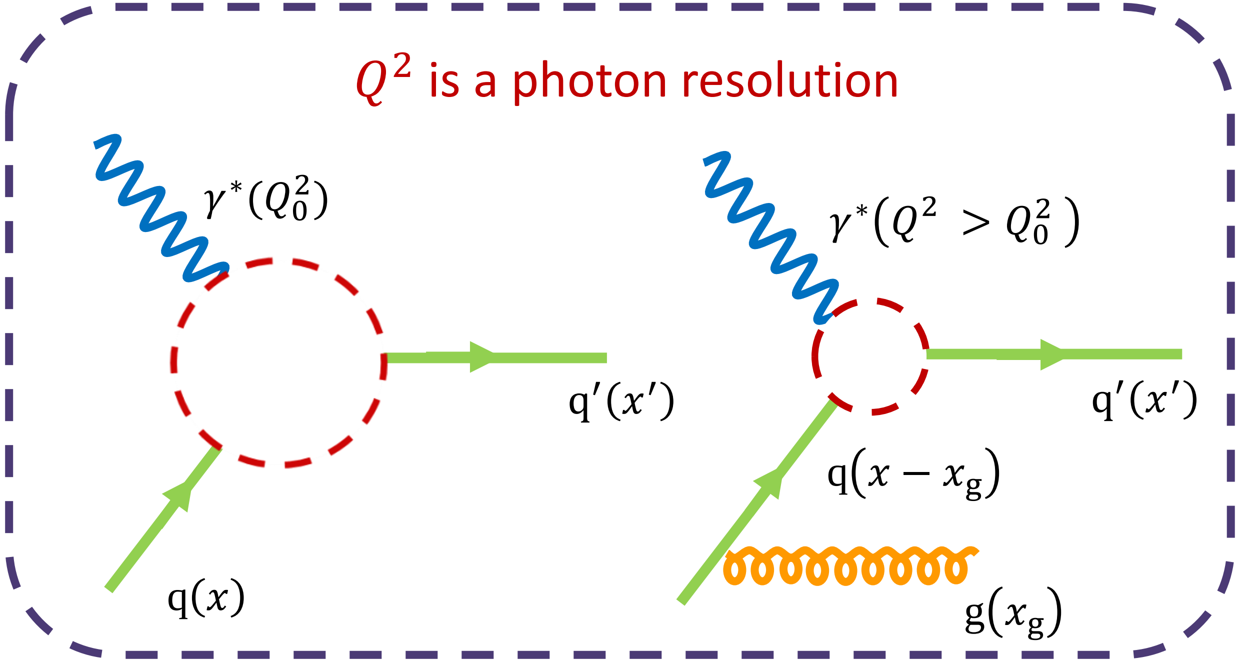



## Kinematic variables

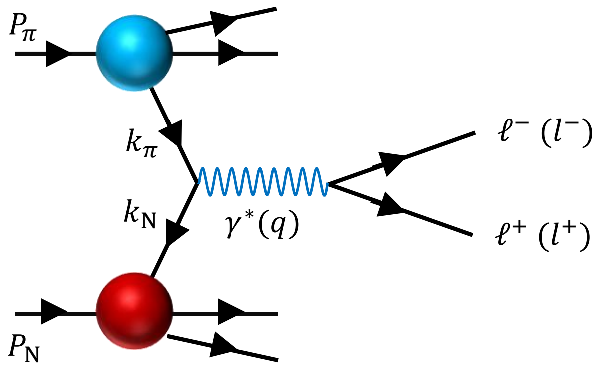
$x$ – Bjorken $x$

$q_T$ – transverse component (w.r.t target rest frame) of virtual photon momentum

$M_{\mu\mu} = \sqrt{Q^2}$ – virtuality of the photon, dimuon invariant mass

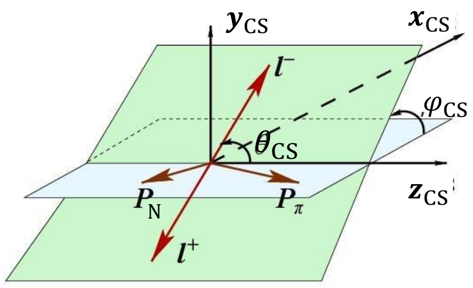


# Single-Polarised Drell-Yan

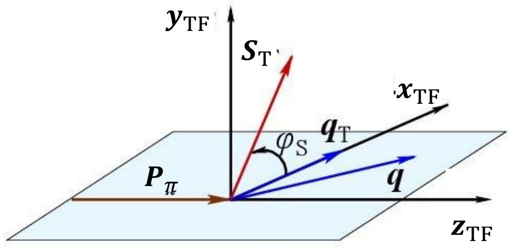



General expression of the cross-section of **pion-nucleon Drell-Yan** lepton-pair production on **a transversely polarised nucleon** can be written as follows:

$$\frac{d\sigma}{d^4q\,d\Omega} \propto \hat{\sigma}_U \left\{ \begin{array}{c} 1 + \cos^2\theta_{CS} A_U^1 + \sin 2\theta_{CS} \boxed{A_U^{\cos\varphi_{CS}}} \cos\varphi_{CS} + \sin^2\theta_{CS} A_U^{\cos(2\varphi_{CS})} \cos(2\varphi_{CS}) \\ +|S_T| \left[ \begin{array}{c} \left(A_T^{\sin\varphi_S} + \cos^2\theta_{CS} \tilde{A}_T^{\sin\varphi_S}\right) \sin\varphi_S \\ + \sin 2\theta_{CS} \left( \boxed{A_T^{\sin(\varphi_{CS}+\varphi_S)}} \sin(\varphi_{CS}+\varphi_S) + \boxed{A_T^{\sin(\varphi_{CS}-\varphi_S)}} \sin(\varphi_{CS}-\varphi_S) \right) \\ + \sin^2\theta_{CS} \left( A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \end{array} \right] \end{array} \right\}$$



Collin-Soper frame

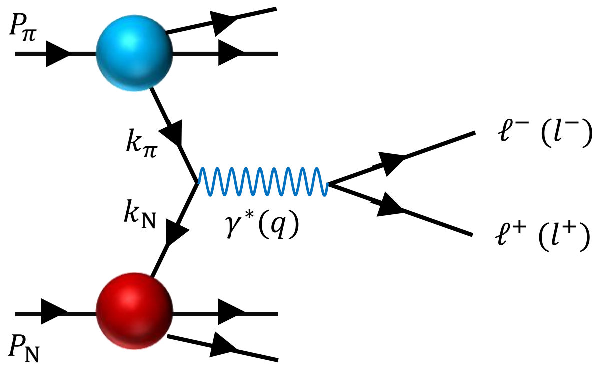


Target frame

$\boxed{\text{Purely 'higher-twist' objects}}$

But in LT QCD parton model the asymmetries are directly related to convolutions of LT TMD PDFs…

# Single-Polarised Drell-Yan

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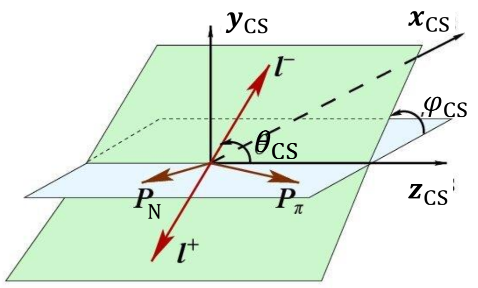
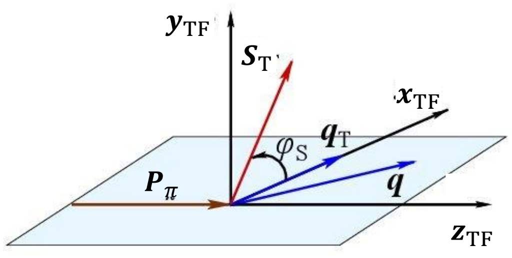



Collin-Soper frame

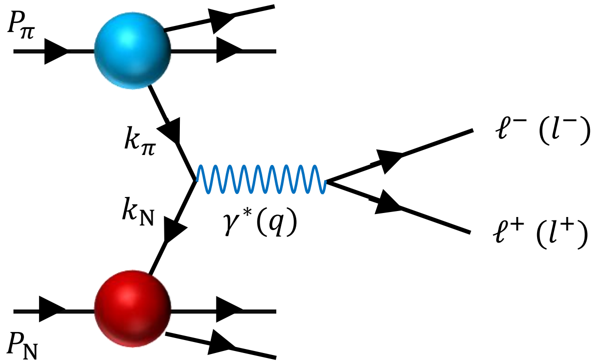



Target frame

Purely 'higher-twist' objects

**But at Leading Twist...**

# Single-Polarised Drell-Yan




Cross-section at LT for transversely polarised target:

$$\frac{\mathrm{d}\sigma^{\mathrm{LO}}}{\mathrm{d}^4q\,\mathrm{d}\Omega} \propto \hat{\sigma}_\mathrm{U}^{\mathrm{LO}} \left\{ \begin{array}{c} 1+\sin^2\theta_{\mathrm{CS}} \boxed{A_\mathrm{U}^{\cos(2\varphi_{\mathrm{CS}})}} \cos(2\varphi_{\mathrm{CS}}) \\ +|S_\mathrm{T}| \left[ \begin{array}{c} \boxed{A_\mathrm{T}^{\sin(\varphi_\mathrm{S})}} \sin(\varphi_\mathrm{S}) + \\ \sin^2\theta_{\mathrm{CS}} \left( \begin{array}{c} \boxed{A_\mathrm{T}^{\sin(2\varphi_{\mathrm{CS}}+\varphi_\mathrm{S})}} \sin(2\varphi_{\mathrm{CS}}+\varphi_\mathrm{S}) \\ + \\ \boxed{A_\mathrm{T}^{\sin(2\varphi_{\mathrm{CS}}-\varphi_\mathrm{S})}} \sin(2\varphi_{\mathrm{CS}}-\varphi_\mathrm{S}) \end{array} \right) \end{array} \right] \end{array} \right\}$$

At $q^2 \gg M_\mathrm{N}, M_\pi$ and $q_\mathrm{T} \ll q$, asymmetries given by convolutions of TMD PFDs!

**Boer-Mulders**

$$\boxed{A_\mathrm{U}^{\cos(2\varphi_{\mathrm{CS}})}} \propto h_{1,\pi}^{\mathrm{q}\perp} \otimes h_{1,\mathrm{N}}^{\mathrm{q}\perp}$$

**Sivers**

$$\boxed{A_\mathrm{T}^{\sin(\varphi_\mathrm{S})}} \propto f_{1,\pi}^{\mathrm{q}} \otimes f_{1\mathrm{T,N}}^{\mathrm{q}\perp}$$

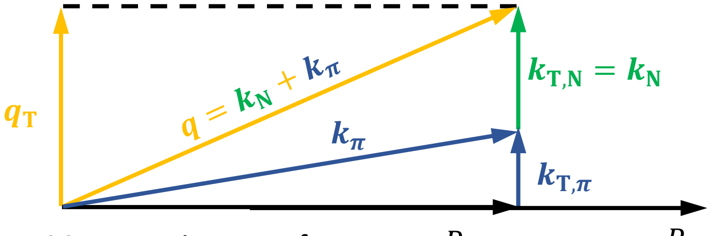
**Pretzelosity**

$$\boxed{A_\mathrm{T}^{\sin(2\varphi_{\mathrm{CS}}+\varphi_\mathrm{S})}} \propto h_{1,\pi}^{\mathrm{q}\perp} \otimes h_{1\mathrm{T,N}}^{\mathrm{q}\perp}$$

**Transversity**

$$\boxed{A_\mathrm{T}^{\sin(2\varphi_{\mathrm{CS}}-\varphi_\mathrm{S})}} \propto h_{1,\pi}^{\mathrm{q}\perp} \otimes h_{1,\mathrm{N}}^{\mathrm{q}}$$

Convolution runs over the intrinsic transverse momenta of the nucleon and the pion:




Momenta in target frame

$$\otimes \equiv \mathcal{C}\left[w(\boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}};\boldsymbol{k}_{\mathbf{T},\mathrm{N}};\boldsymbol{q}_{\boldsymbol{T}})\mathrm{f}_\pi \mathrm{f}_\mathrm{N}\right] = \frac{1}{\mathrm{N_c}}\sum_\mathrm{q} \left\{ \begin{array}{c} e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}}\mathrm{d}^2\boldsymbol{k}_{\mathbf{T},\boldsymbol{N}}\delta^{(2)}(\boldsymbol{q}_\mathbf{T} - \boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}} - \boldsymbol{k}_{\mathbf{T},\mathrm{N}}) \\ \times\, w(\boldsymbol{k}_{\mathbf{T},\boldsymbol{\pi}};\boldsymbol{k}_{\mathbf{T},\boldsymbol{N}};\boldsymbol{q}_\mathbf{T}) \left[ \begin{array}{c} f_\pi^{\bar{q}}(x_\pi, k_{\mathrm{T},\pi}^2) f_N^{q}(x_\mathrm{N}, k_{\mathrm{T,N}}^2) \\ + \\ f_\pi^{q}(x_\pi, k_{\mathrm{T},\pi}^2) f_N^{\bar{q}}(x_\mathrm{N}, k_{\mathrm{T,N}}^2) \end{array} \right] \end{array} \right\}$$

# From Convolution to Direct Access:
Extracting TMD PDFs

This complex integrals are hard to resolve.

**Boer-Mulders**

$\boxed{A_{U}^{\cos(2\varphi_{CS})}} \propto h_{1,\pi}^{q\perp} \otimes h_{1,N}^{q\perp}$

**Sivers**

$\boxed{A_{T}^{\sin(\varphi_{S})}} \propto f_{1,\pi}^{q} \otimes f_{1T,N}^{q\perp}$

**Pretzelosity**

$\boxed{A_{T}^{\sin(2\varphi_{CS}+\varphi_{S})}} \propto h_{1,\pi}^{q\perp} \otimes h_{1T,N}^{q\perp}$

**Transversity**

$\boxed{A_{T}^{\sin(2\varphi_{CS}-\varphi_{S})}} \propto h_{1,\pi}^{q\perp} \otimes h_{1,N}^{q}$

**Common Strategy**

Assume a specific functional form for the transverse momentum dependence (typically **Gaussian**).

**Alternative Approach**

Weighting with powers of the transverse momentum allows to avoid assumptions on $k_{\mathrm{T}}$.

**Asymmetry (TSA)**

$$A_{T}^{\sin(\varphi_{S})} \propto f_{1,\pi}^{q} \otimes f_{1T,N}^{q\perp}$$

$$A_{T}^{\sin(2\varphi+\varphi_{S})} \propto h_{1,\pi}^{q\perp} \otimes h_{1T,N}^{q\perp}$$

$$A_{T}^{\sin(2\varphi-\varphi_{S})} \propto h_{1,\pi}^{q\perp} \otimes h_{1,N}^{q}$$

$$A_{T}^{\sin\Phi W_{\Phi}} = \int \mathrm{d}^2 \boldsymbol{q}_{\mathrm{T}} W_{\Phi} A_{T}^{\sin\Phi},$$

where $W_{\Phi}$ is weight for $\Phi = \varphi_{S}, 2\varphi_{CS} \pm \varphi_{S}$.

The $n$-th moment of a TMD PDF of a pion or proton:

$$f^{(n)}(x) = \int \mathrm{d}^2 \boldsymbol{k}_{\mathrm{T}} \left(\frac{k_{\mathrm{T}}^2}{2M^2}\right)^n f(x, k_{\mathrm{T}}^2).$$

**Weighted Asymmetry (WTSA)**

$$A_{T}^{\sin(\varphi_{S})\frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,N}^{q\perp(1)}$$

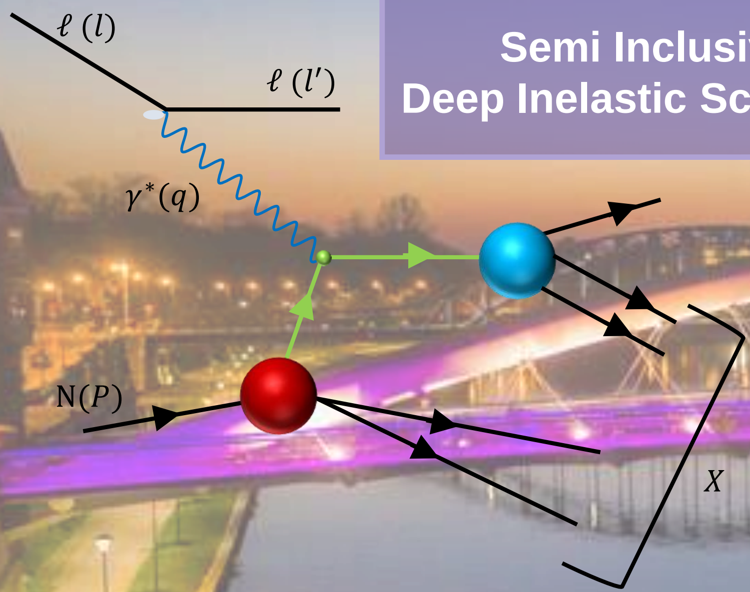
$$A_{T}^{\sin(2\varphi+\varphi_{S})\frac{q_T^3}{2M_N^2 M_\pi}} \propto h_{1,\pi}^{q\perp(1)} \times h_{1T,N}^{q\perp(2)}$$

$$A_{T}^{\sin(2\varphi-\varphi_{S})\frac{q_T}{M_\pi}} \propto h_{1,\pi}^{q\perp(1)} \times h_{1,N}^{q}$$

# COMPASS Bridge

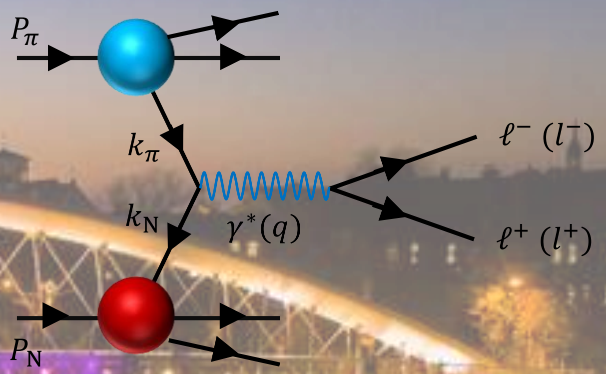
$A_{SIDIS} \propto PDF_N \otimes FF$

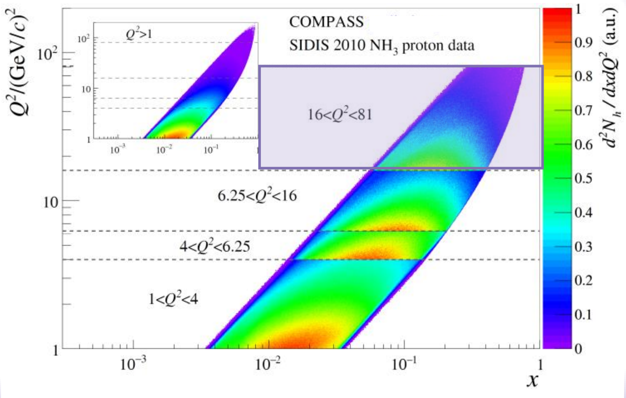
$A_{DY} \propto PDF_N \otimes PDF_{\pi^-}$



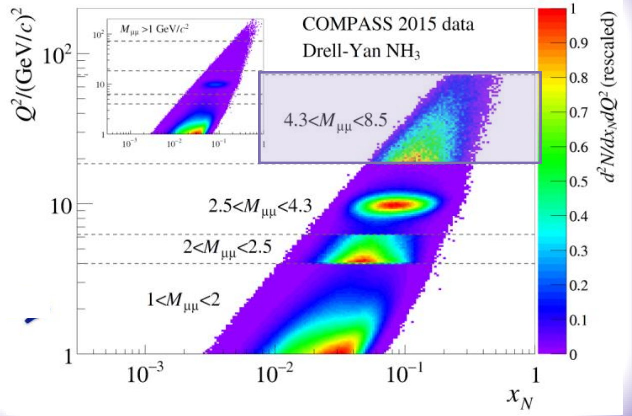

**Semi Inclusive Deep Inelastic Scattering**

**Drell-Yan process**




COMPASS achieves comparable $Q^2 - x$ kinematic coverage
Minimizing possible $Q^2$ evolution effects



# Example of TMD universality: Sivers function sign change

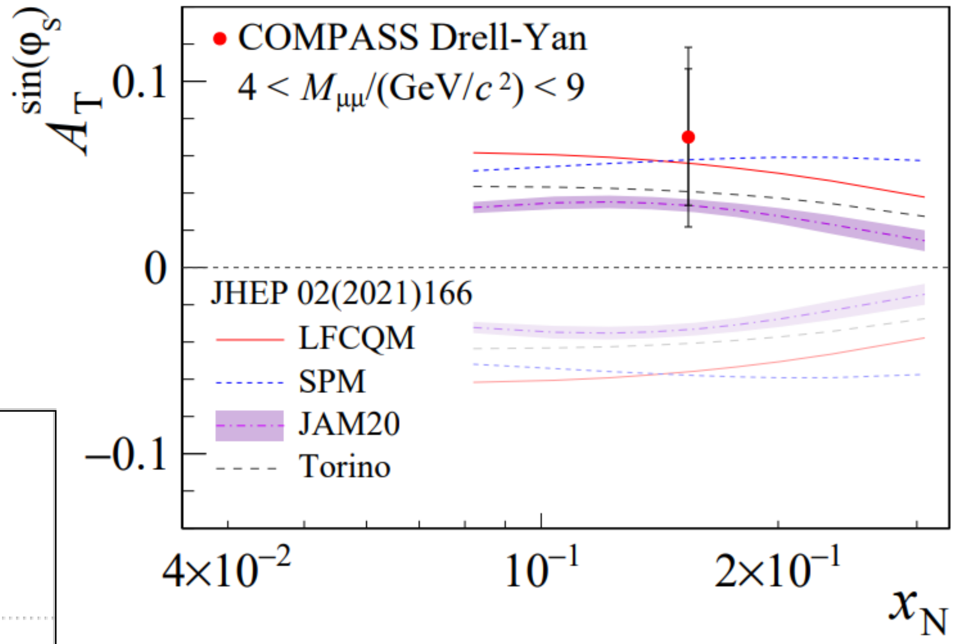
**The Sivers TMD PDF** describes how the distribution of unpolarized quarks inside a transversely polarized proton depends on the quark's transverse momentum.

**Prediction from QCD**

$$f_{1T}^{q\perp}(\text{SIDIS}) = -f_{1T}^{q\perp}(\text{DY})$$

**DY Sivers TSA**

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

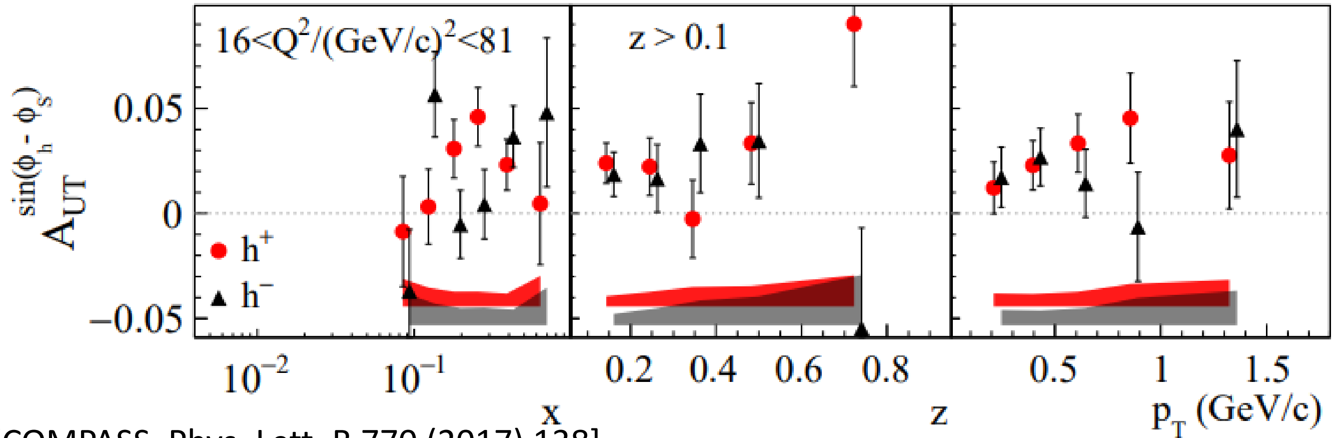



Sign Change

No Sign Change

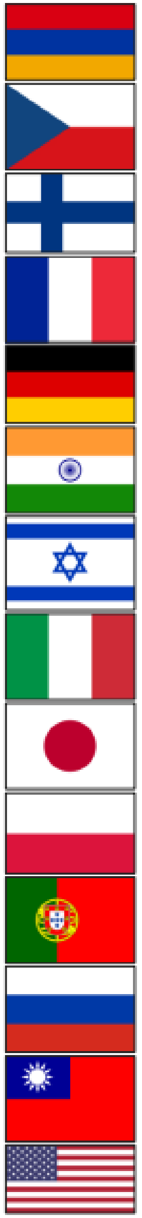
[COMPASS, Phys. Rev. Lett. 133 (2024) 071902]

**SIDIS Sivers TSA** $A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,N}^{q\perp} \otimes D_{1q}^{h}$




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

# COMPASS Experiment

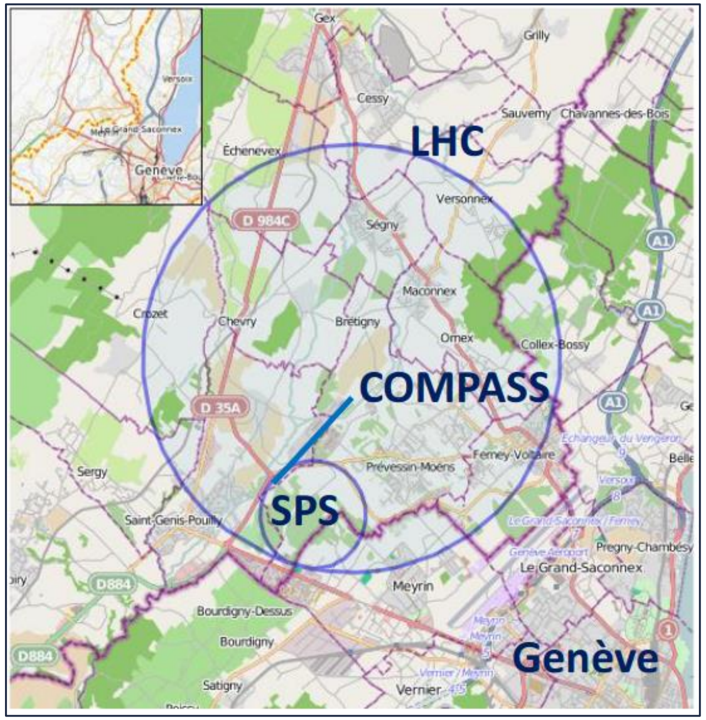


**Common Muon and Proton Apparatus for Structure and Spectroscopy**



- 24 institutions from 13 countries (~220 physicists)
- CERN SPS North Area
- Fixed target experiment

**Drell Yan data taking 2015 + 2018**

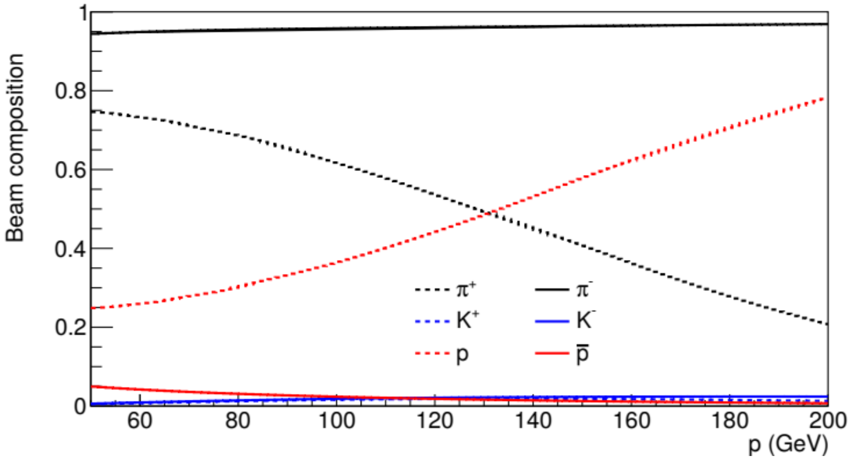




**Broad research programme in hadron structure and hadron spectroscopy**

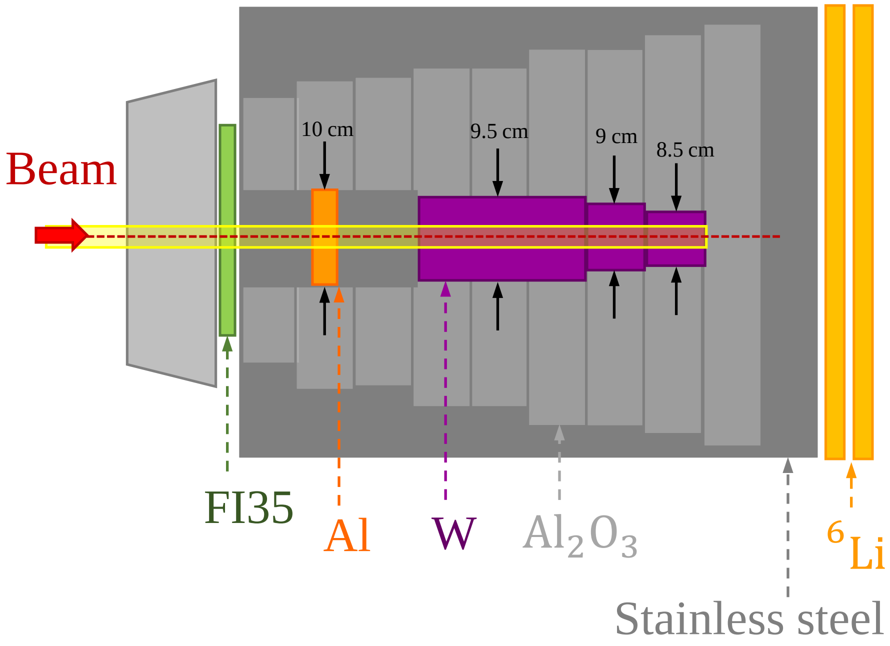
# COMPASS Spectrometer

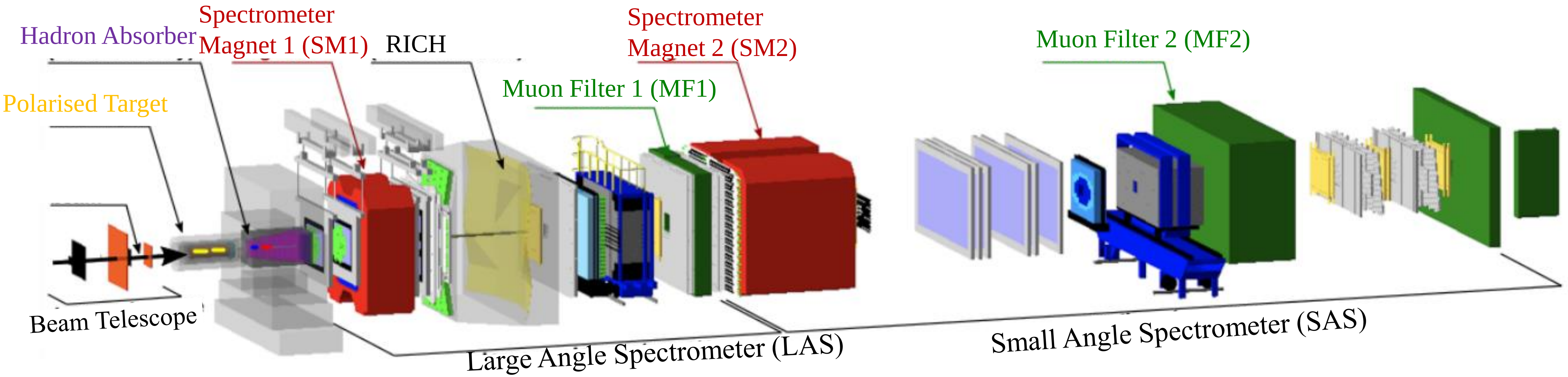
- High energy negative hadron beam: 190 GeV
- Beam composition: **97% $\pi^-$**, 2% $K^-$, 1% $p^-$



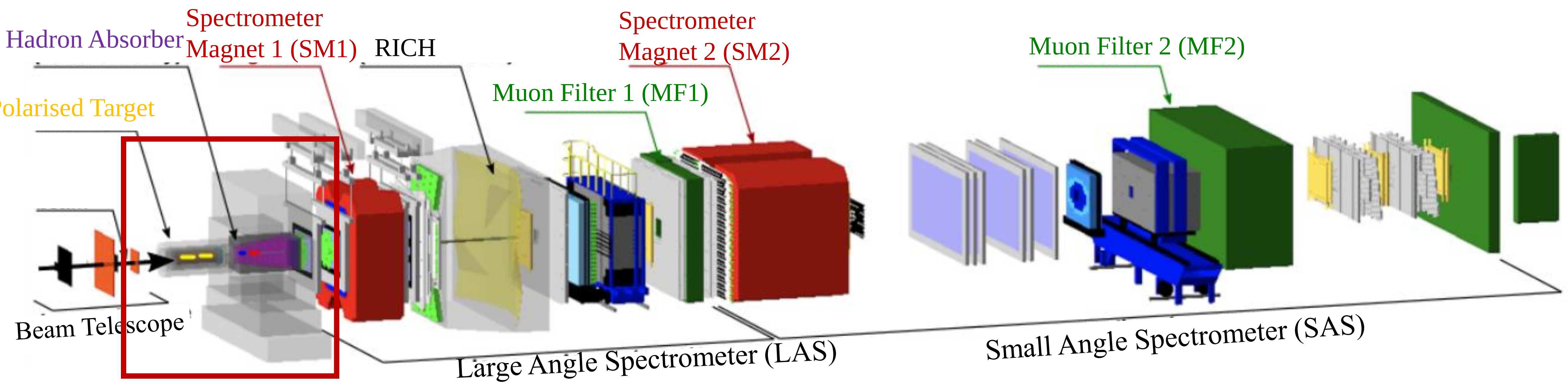

- **2 spectrometer** stages for a wide phase space coverage
- Muon identification system

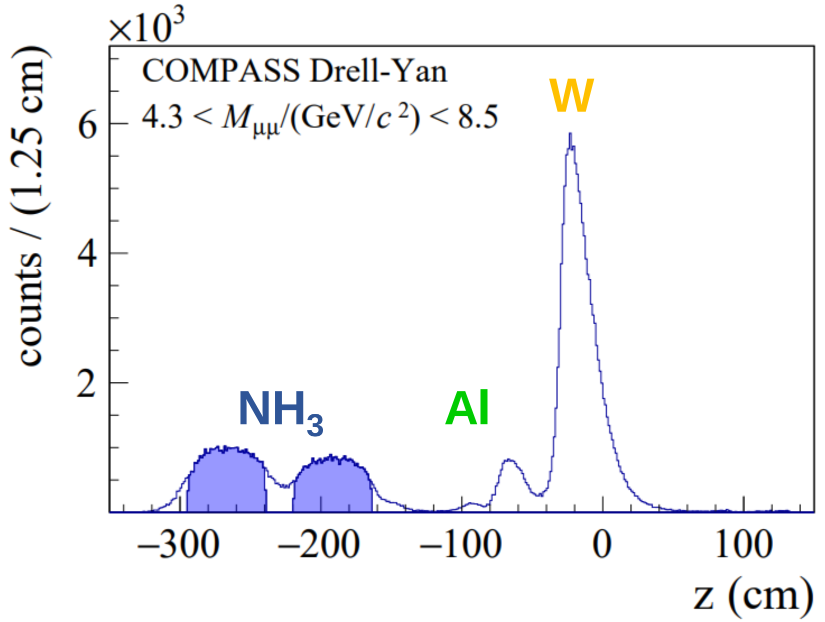
- Hadron absorber

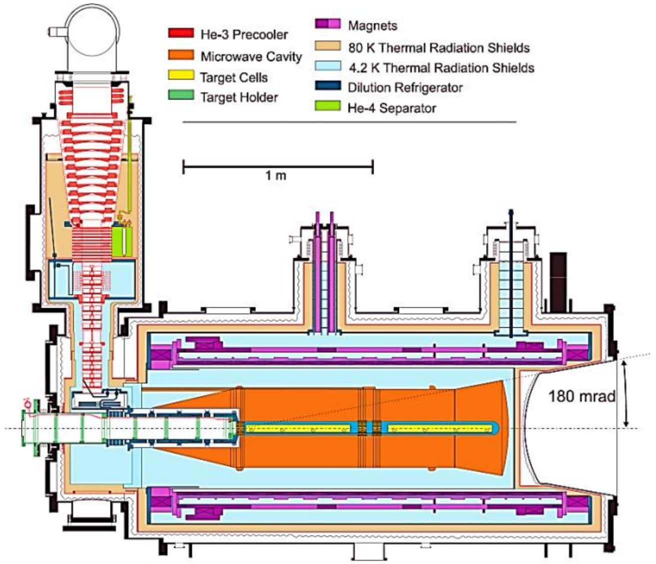


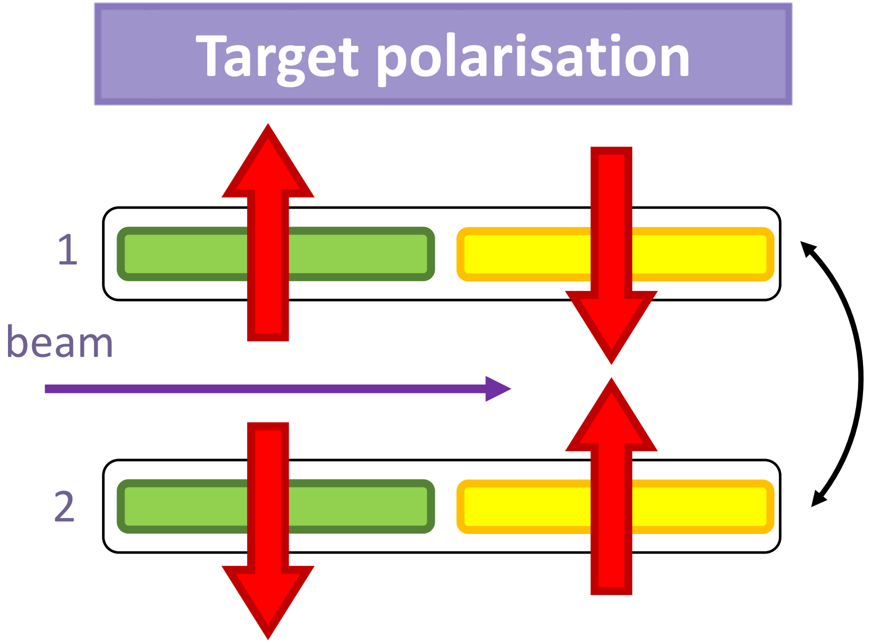



# Zoom on target region



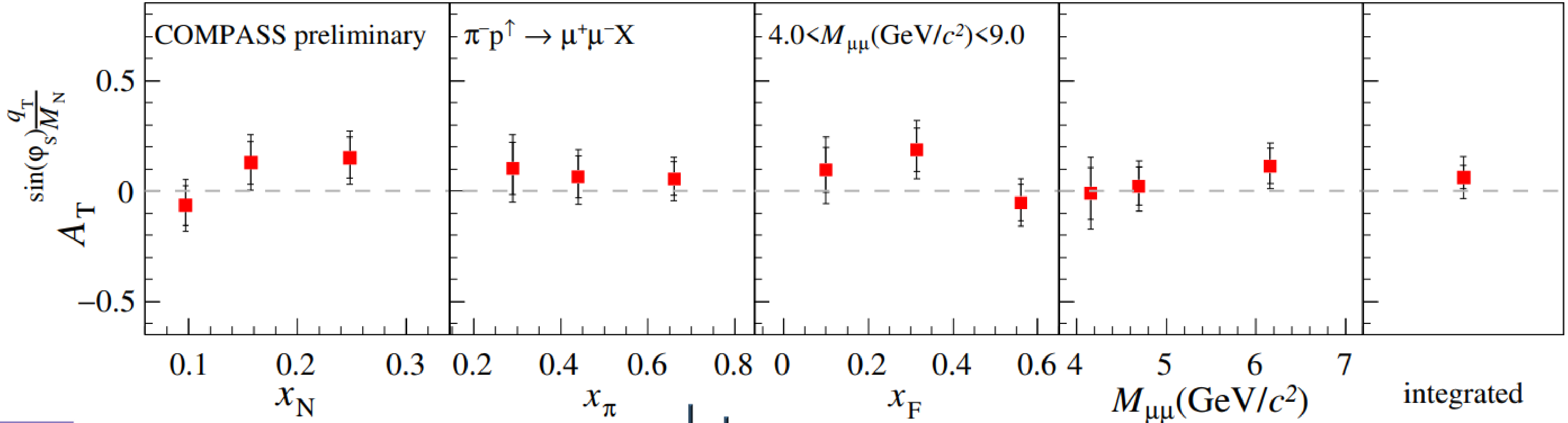




Target cells in 2015 + 2018 Drell–Yan

# **DY Sivers effect:** TSA and $q_T$-weighted TSA (WTSA)

$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^{q} \times f_{1T,N}^{q\perp(1)}$



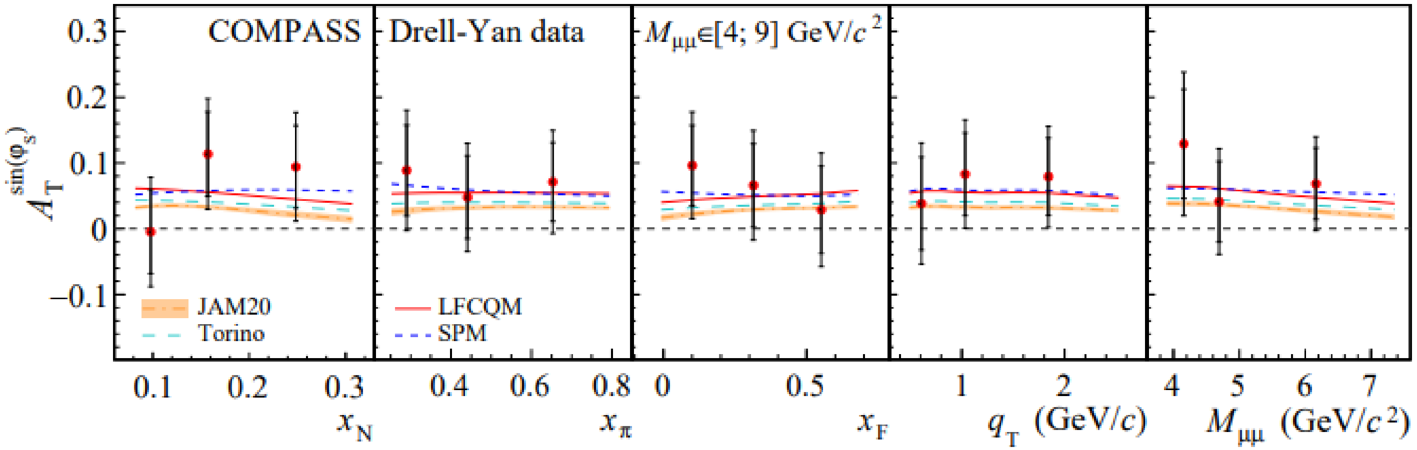

1σ positive **Sivers WTSA** compatible with **Sivers TSA**

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

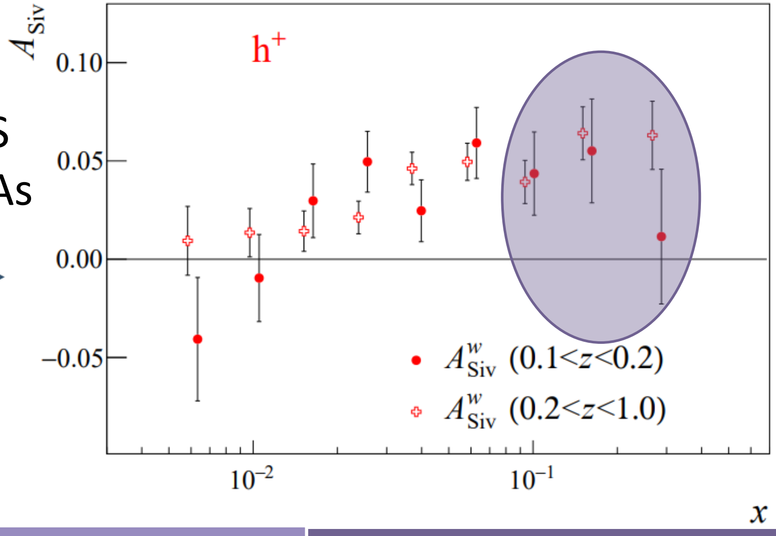
Drell-Yan TSAs

$A_{UT}^{\sin(\phi_h-\phi_S)\frac{P_T}{zM_N}} \propto f_{1T,N}^{q\perp(1)} \times D_{1q}^{h}$

SIDIS WTSAs



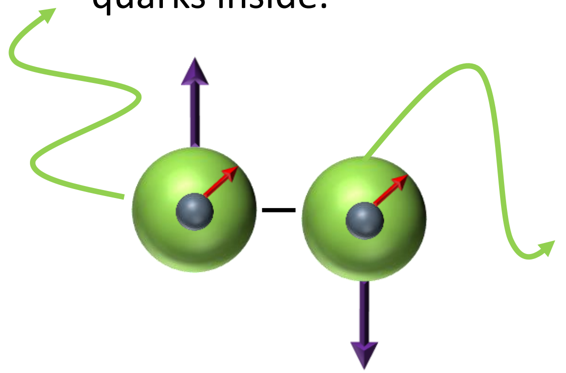

[COMPASS, Phys. Rev. Lett. 133 (2024) 071902]




COMPASS, Phys. Rev. Lett. 133 (2024) 071902

# Moving to TMD PDF Extraction: Understanding the Sivers Asymmetry

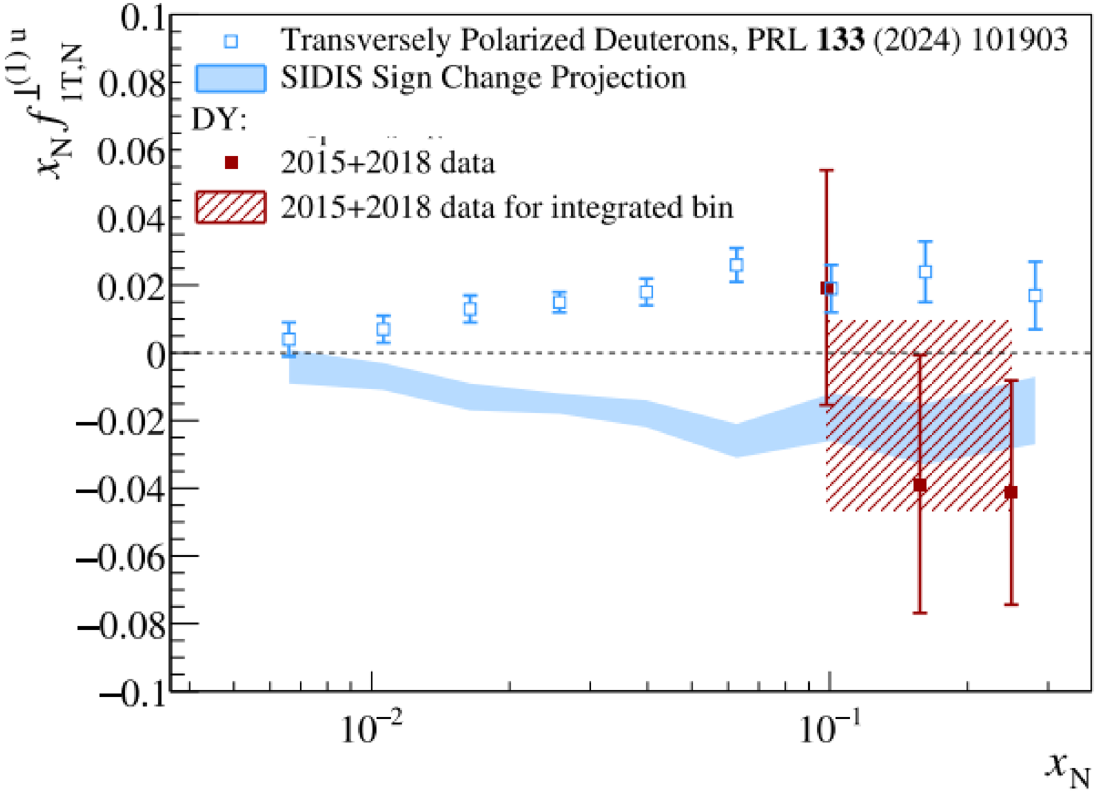
Measured asymmetries, especially those **weighted by transverse momentum $\boldsymbol{q_{\mathrm{T}}}$**, enable a direct and simplified connection to the underlying **TMD PDFs**




Nucleon spin-up/down inbalance hints at the **orbital contribution to proton spin.**

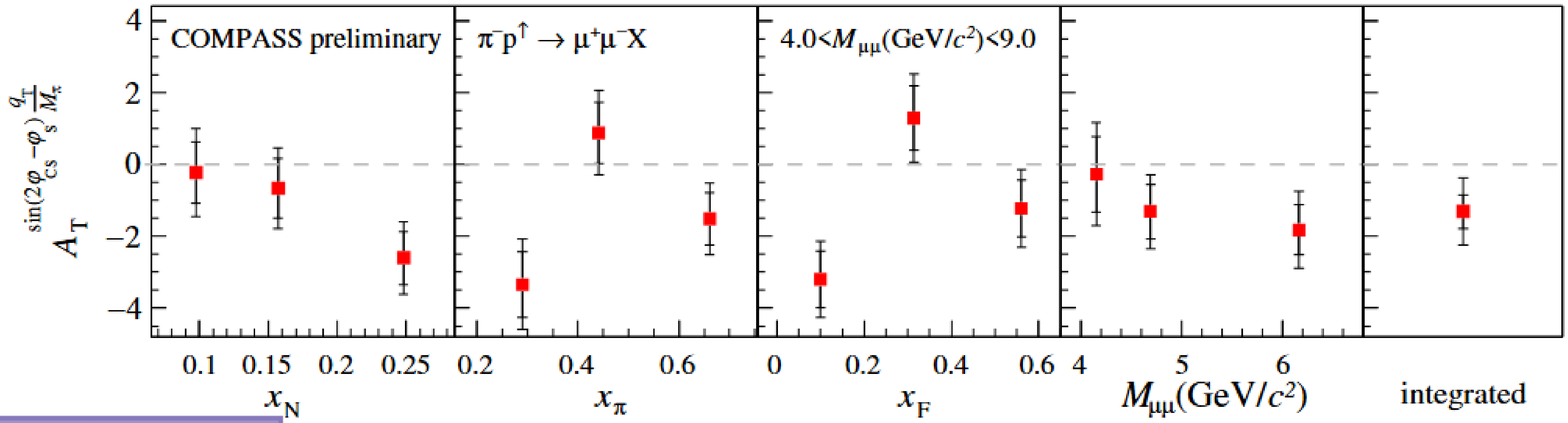
$$A_{\mathrm{T}}^{\sin\varphi_S \frac{q_{\mathrm{T}}}{M_{\mathrm{N}}}} = -2 \frac{\boxed{f_{1\mathrm{T,N}}^{\mathrm{q}\perp(1)}(x_N)}}{f_{1,,N}^{\mathrm{q}}(x_N)}$$

Number Density easy to find in database



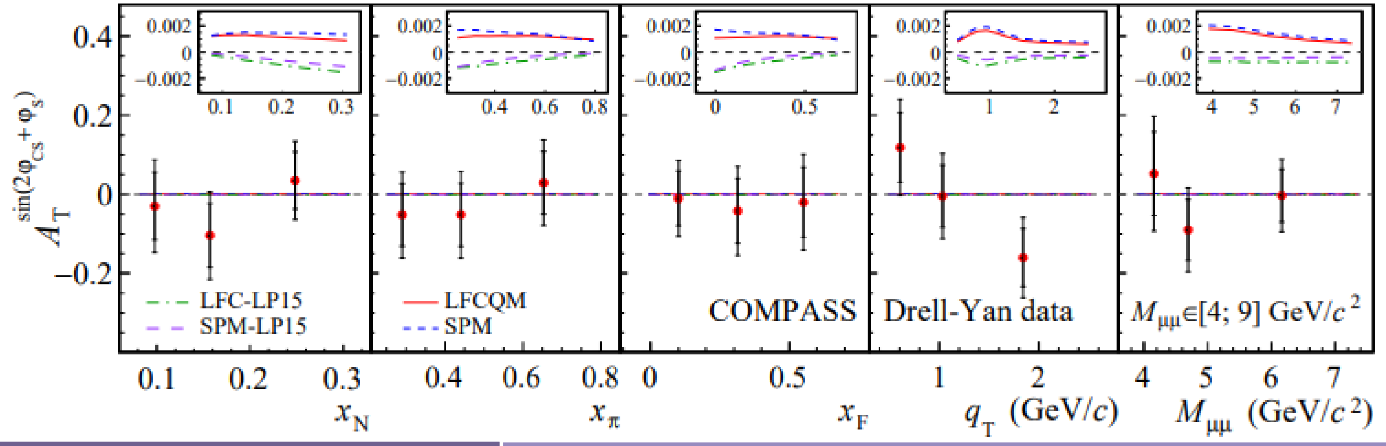
# DY Pretzelosity: TSA and $q_T$-weighted TSA (WTSA)

$A_T^{\sin(2\varphi+\varphi_S)\frac{q_T^3}{2M_N^2 M_\pi}} \propto h_{1,\pi}^{q\perp(1)} \times h_{1T,N}^{q\perp(2)}$




$A_T^{\sin(2\varphi+\varphi_S)} \propto h_{1,\pi}^{q\perp} \otimes h_{1T,N}^{q\perp}$

Drell-Yan TSAs



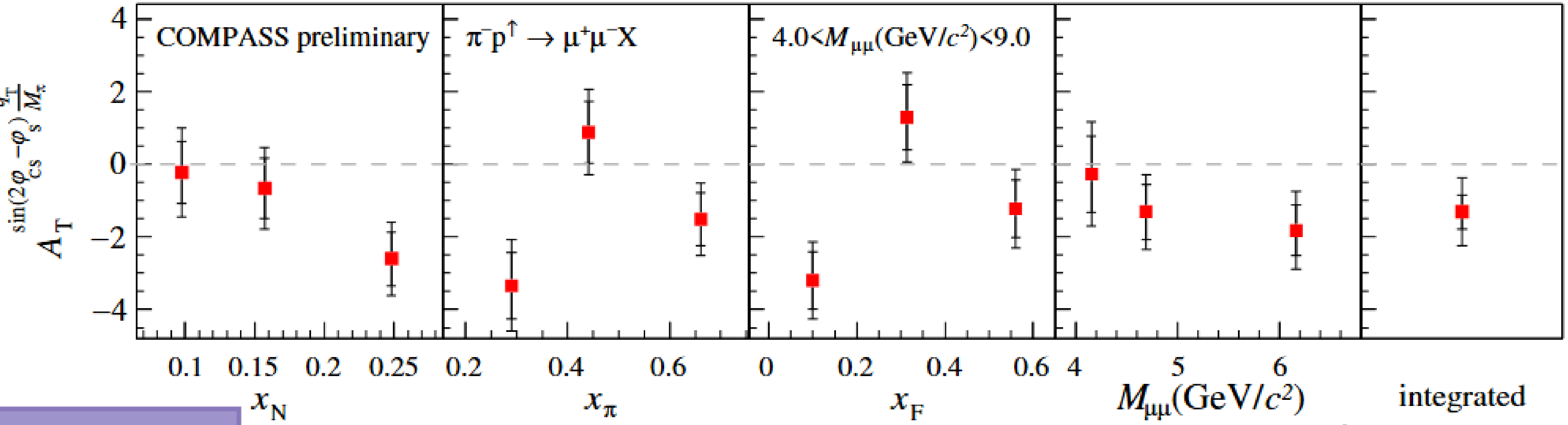

[COMPASS, Phys. Rev. Lett. 133 (2024) 071902]

**Pretzelosity** is expected to be zero

$2\sigma$ negative **Pretzelosity WTSA**

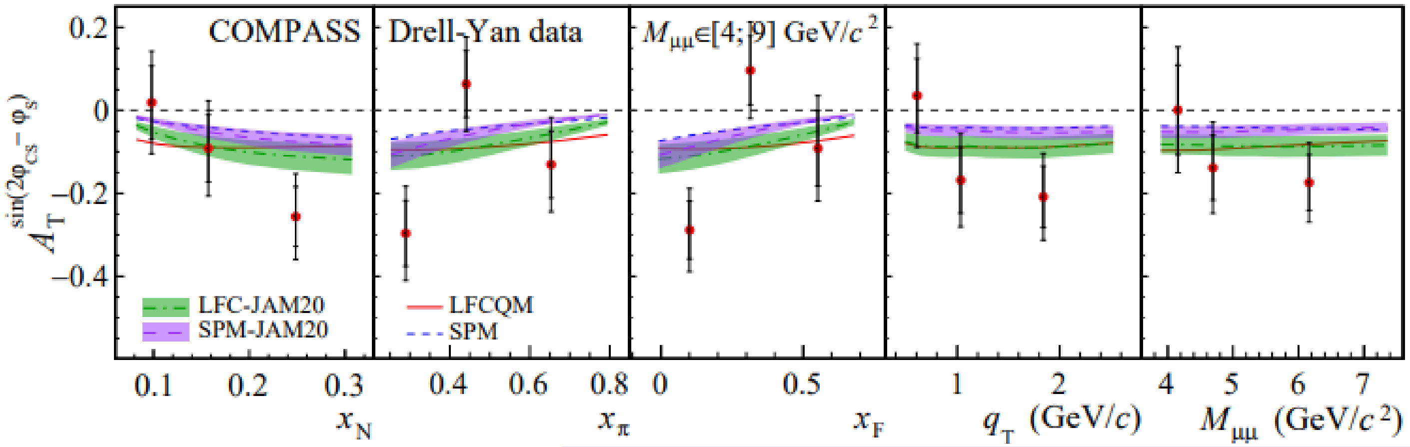
# **DY Transversity:** TSA and $q_T$-weighted TSA (WTSA)

$$A_T^{\sin(2\varphi_{CS}-\varphi_S)\frac{q_T}{2M_\pi}} \propto h_{1,\pi}^{\perp q(1)} \times h_{1,N}^{q}$$




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

Drell-Yan TSAs




[COMPASS, Phys. Rev. Lett. 133 (2024) 071902]

Results compatible with **Transversity TSA**

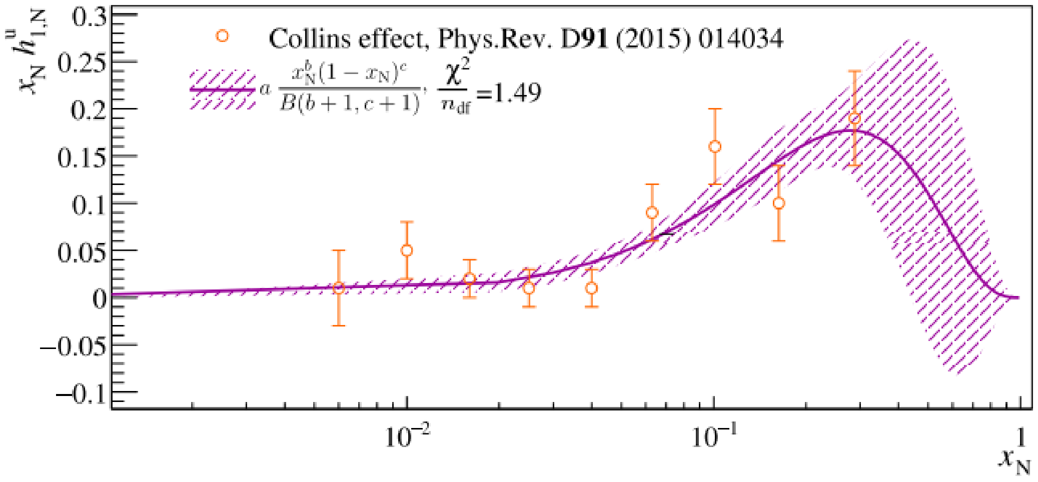
# **Transversity Asymmetries:** What can we extract from it?

That's what we're looking for:
**first moment of Boer-Mulders TMD PDFs of a pion**

$$A_{\mathrm{T}}^{\sin(2\varphi_{CS}-\varphi_S)\frac{q_T}{M_\pi}} = -2\,\frac{h_{1,\mathrm{N}}^{\mathrm{q}} \cdot h_{1,\pi}^{\mathrm{q}\perp(1)}}{f_{1,\mathrm{N}}^{\mathrm{q}} \cdot f_{1,\pi}^{\mathrm{q}}}$$

**Number Densities** of proton and pion easy to find in database

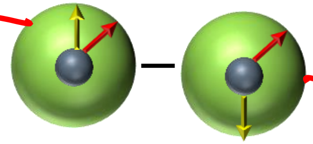
**Transversity of** TMD PDFs of proton

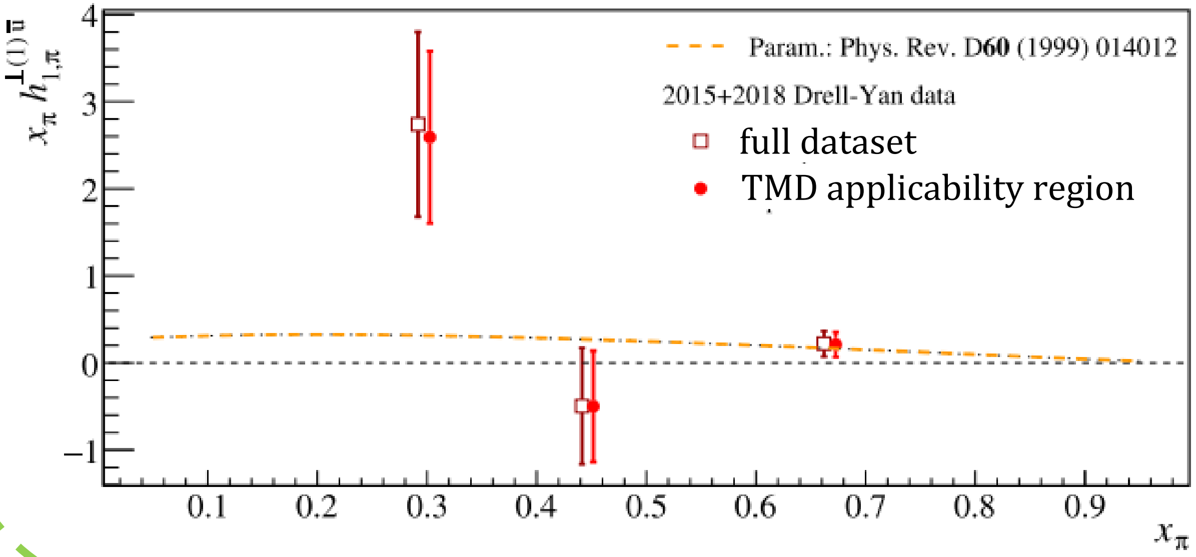



What is the net polarization of quarks inside an unpolarised proton?

Unpolarised nucleon with quark spin pointing up.

Unpolarised nucleon with quark spin pointing down.

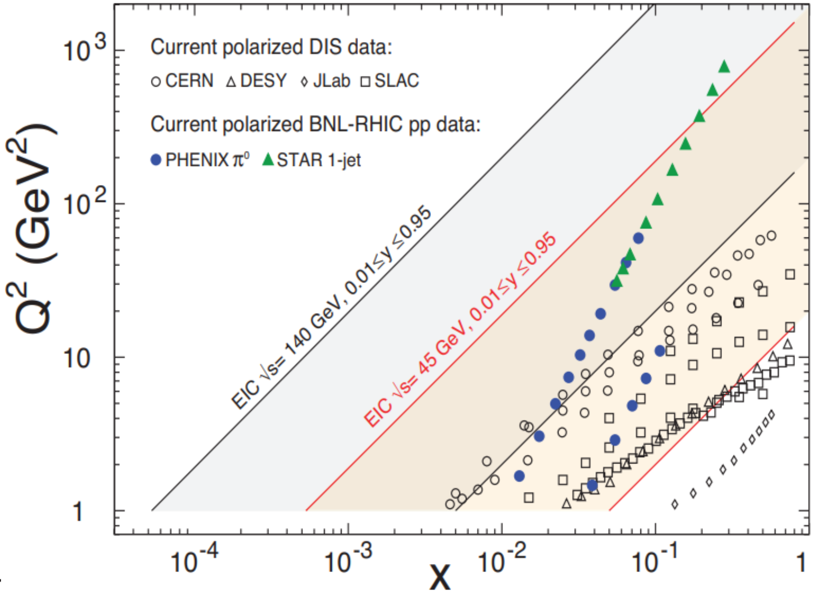


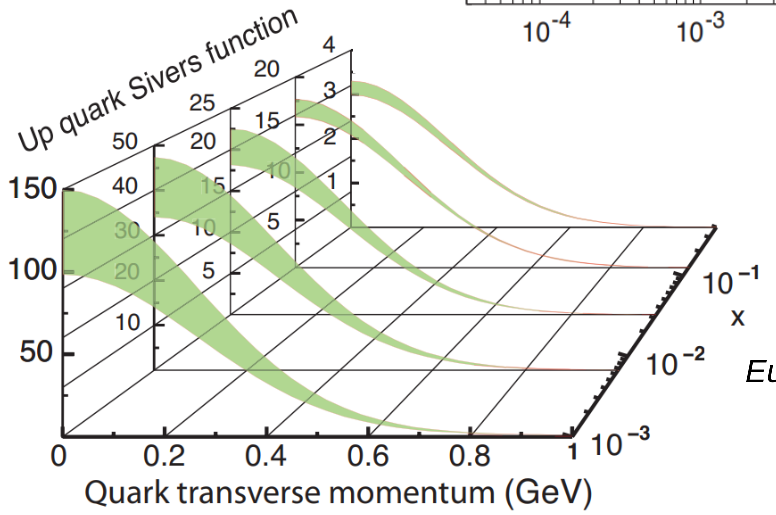


# Future of Hadron Physics

Huge efforts in the past&present … and future

EIC:
Electron Ion Collider



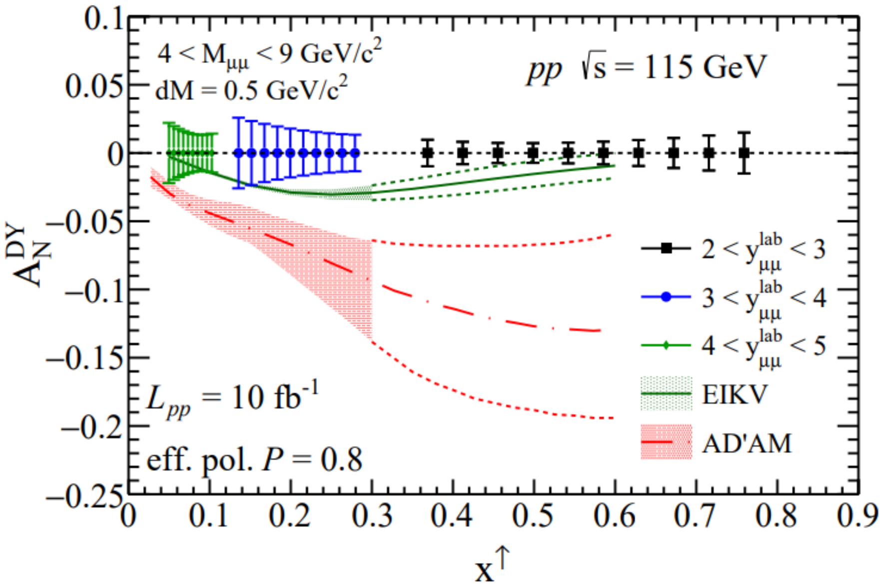




[EIC White Paper, *Eur.Phys.J.A* 52 (2016) 9, 268]

Asymmetry sensitive to the quark Sivers effect

LHCSpin

$$A_N \propto f_1^q \otimes f_{1T,N}^{q\perp}$$




[Hadjidakis *et al.* Phys. Rep. 911, 2021]

# Conclusions

- COMPASS **Drell–Yan program**, complemented by SIDIS results, provides the world's only direct test of TMD PDF universality — a unique window into the **3D nucleon structure!**

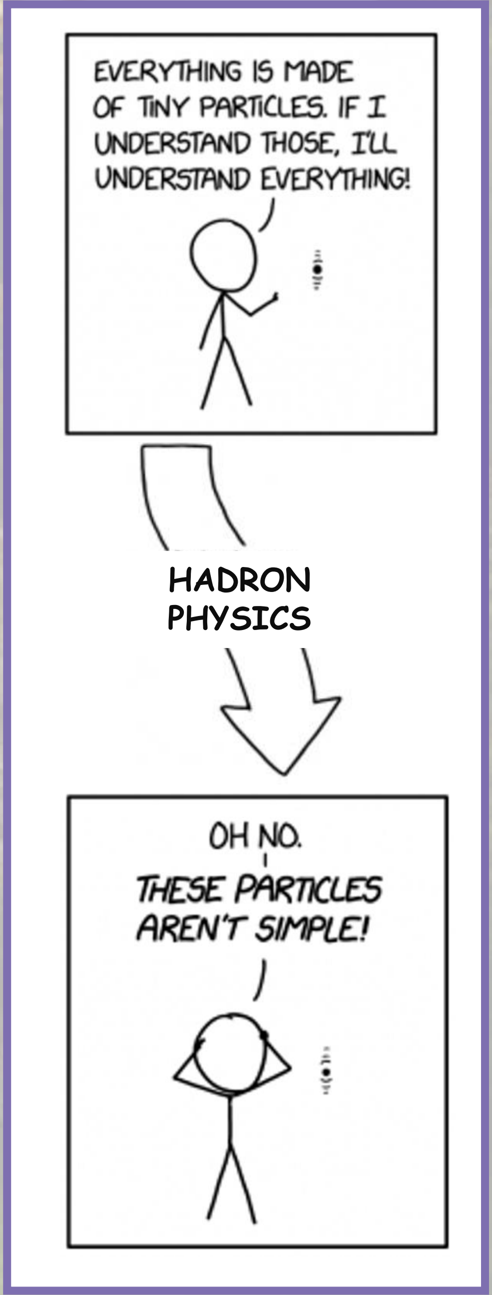
- **Drell–Yan transverse spin asymmetries**
  - $\sim 1\,\sigma$ **positive Sivers** $q_{\mathrm{T}}$-weighted asymmetries
  - $\sim 1\,\sigma$ **negative Pretzelosity**
  - $\sim 2\,\sigma$ **negative Transversity**

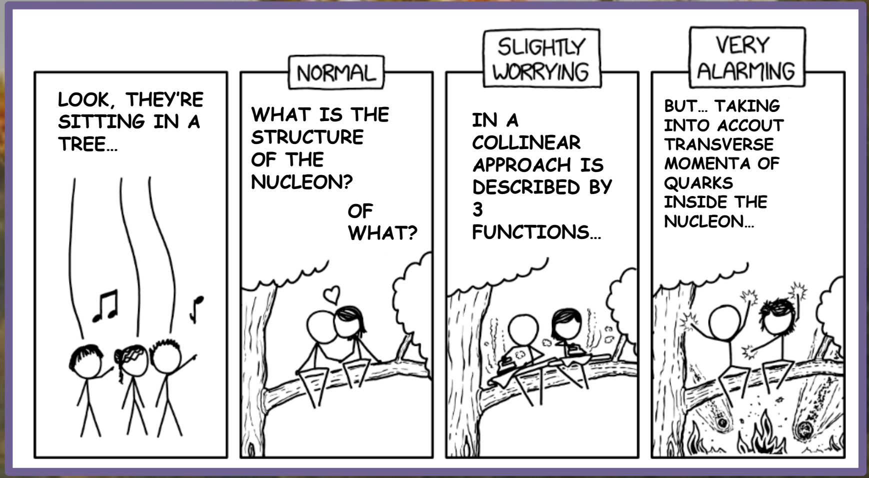
- **DY** Sivers asymmetry aligns with the expected **sign change** compared to **SIDIS**!

- Unweighted & weighted asymmetries → TMD PDFs extraction**, but weighted approach** gives a **direct probe** of TMD PDFs, including their **moments**

- Transversity asymmetries, and $h_{1,\mathrm{N}}$ enable the extraction of the Boer–Mulders TMD PDF.

- New experiment is on the horizon: **EIC and LHCSpin**



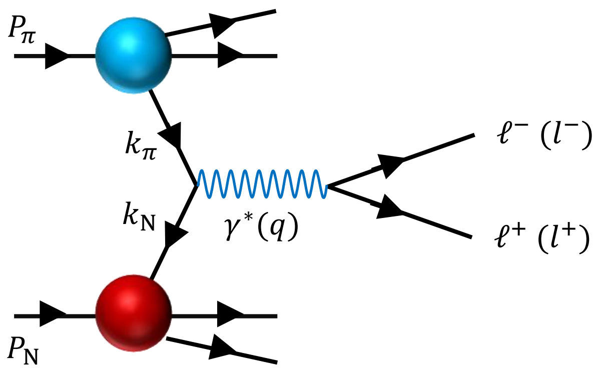

LOOK, THEY'RE SITTING IN A TREE...
NORMAL
WHAT IS THE STRUCTURE OF THE NUCLEON?
OF WHAT?
SLIGHTLY WORRYING
IN A COLLINEAR APPROACH IS DESCRIBED BY 3 FUNCTIONS...
VERY ALARMING
BUT... TAKING INTO ACCOUT TRANSVERSE MOMENTA OF QUARKS INSIDE THE NUCLEON...

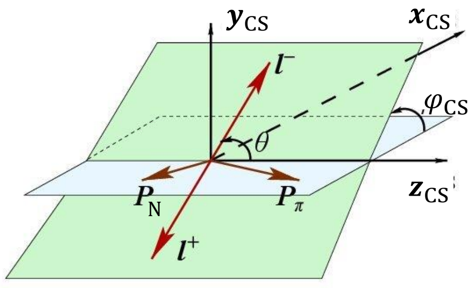
# Thank you!

# Single-Polarised Drell-Yan

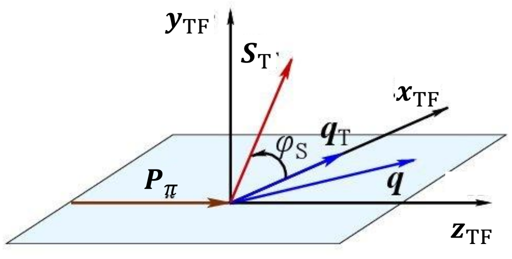
Cross-section, LO TMD approach for transversely polarised target:

$$\frac{d\sigma^{LO}}{d^4q\,d\Omega} \propto \hat{\sigma}_U^{LO}\left\{ 1+\sin^2\theta_{CS}\,A_U^{\cos(2\varphi_{CS})}\cos(2\varphi_{CS}) + |S_T|\left[ A_T^{\sin(\varphi_S)}\sin(\varphi_S) + \sin^2\theta_{CS}\left( A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S)\right)\right]\right\}$$




Collin-Soper frame




Target frame

**Boer-Mulders**

$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{q\perp} \otimes h_{1,N}^{q\perp}$

**Sivers**

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

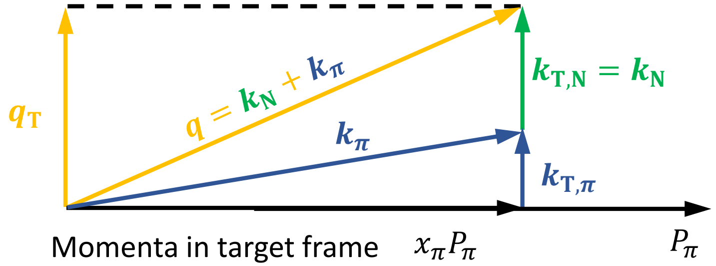
**Pretzelosity**

$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{q\perp} \otimes h_{1T,N}^{q\perp}$

**Transversity**

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

Convolution runs over the intrinsic transverse momenta of the nucleon and the pion:

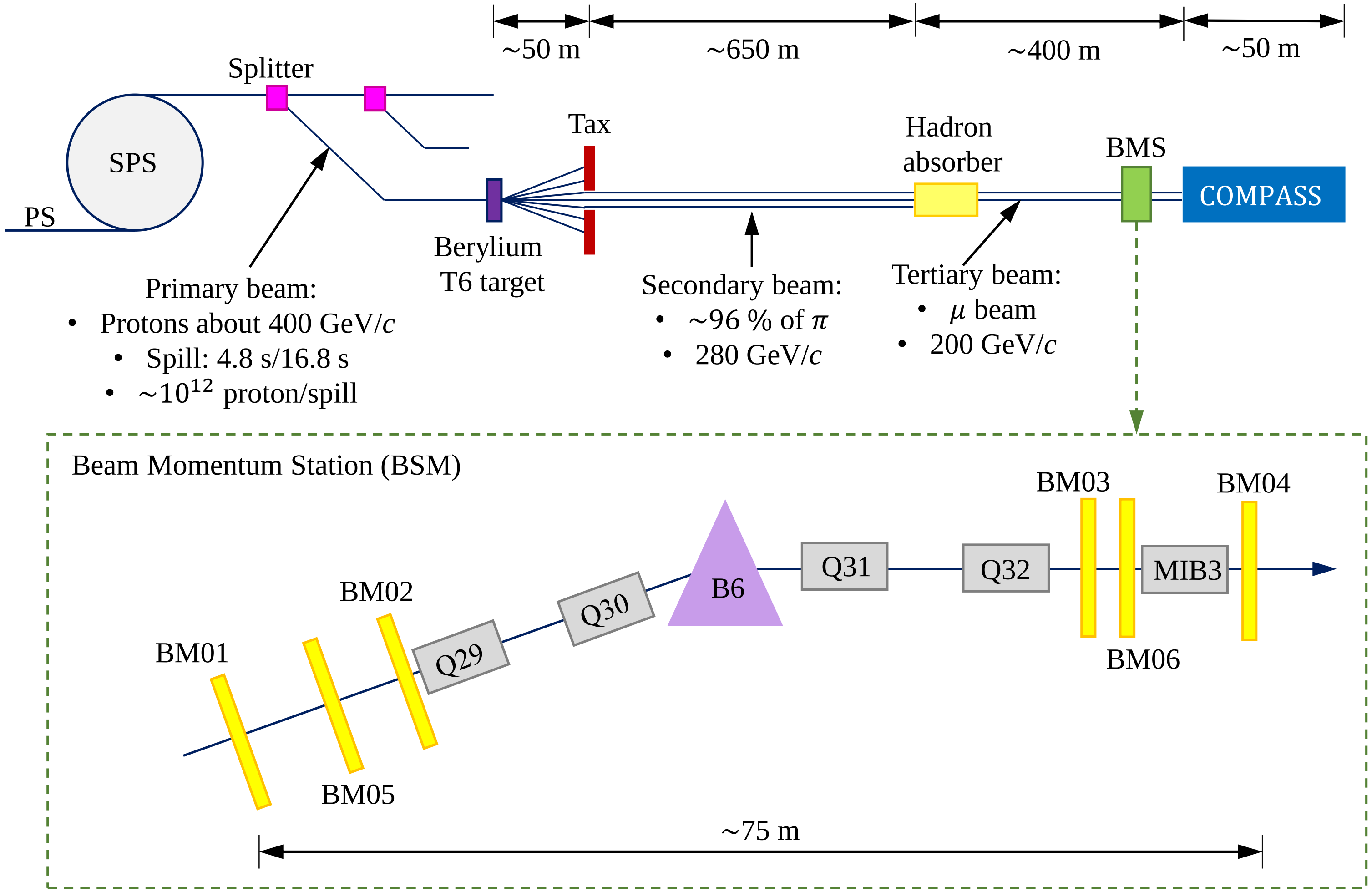


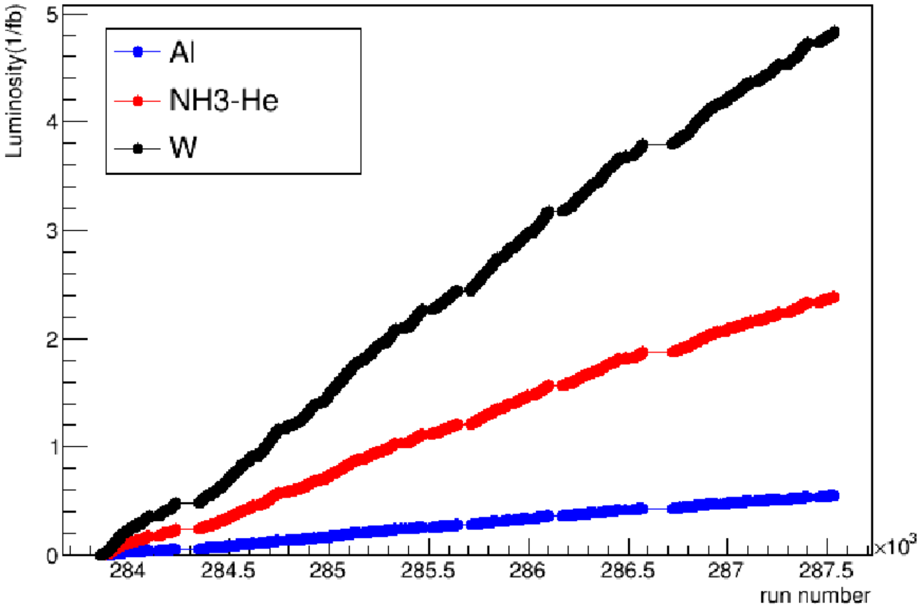

Momenta in target frame

$$\otimes = \mathcal{C}\left[w(\boldsymbol{k}_{T,\pi};\boldsymbol{k}_{T,N};\boldsymbol{q}_T)f_\pi f_N\right] = \frac{1}{N_c}\sum_q \left\{ e_q^2\int d^2\boldsymbol{k}_{T,\pi}d^2\boldsymbol{k}_{T,N}\,\delta^{(2)}(\boldsymbol{q}_T-\boldsymbol{k}_{T,\pi}-\boldsymbol{k}_{T,N}) \times w(\boldsymbol{k}_{T,\pi};\boldsymbol{k}_{T,N};\boldsymbol{q}_T)\left[ f_\pi^{\bar{q}}(x_\pi,k_{T,\pi}^2)f_N^{q}(x_N,k_{T,N}^2) + f_\pi^{q}(x_\pi,k_{T,\pi}^2)f_p^{\bar{q}}(x_p,k_{T,p}^2)\right]\right\}$$

# **Backup:** COMPASS beam for Drell-Yan

- High energy negative hadron beam: 190 GeV
- Beam composition: **97% $\pi^-$**, 2% $\mathrm{K}^-$, 1% $\mathrm{p}^-$




Integrated luminosity delivered to each target in 2018

- **Beam intensity:** 70 MHz average (30% duty cycle) → 55 MHz effective after time/target volume cuts
- Since no beam PID was available, the entire beam is treated as pions.
- Contamination included in systematics.

# **Backup:** Structure Functions in Terms of Single Polarised Drell-Yan

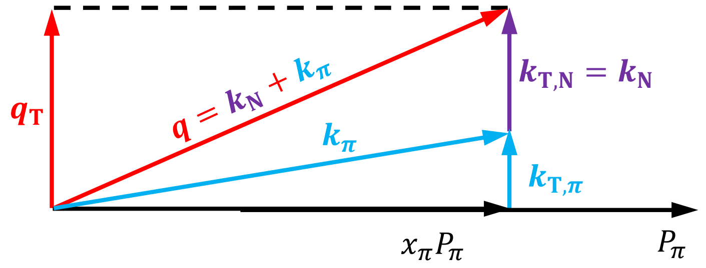
$$F_{\mathrm{T}}^{\sin(\varphi_S)} = \mathcal{C}\left[\frac{\boldsymbol{q_T k_{T,N}}}{q_T M_N} f_{1,\pi}\, f_{1T,p}^{\perp}\right]$$ Sivers for proton, number density for $\pi^-$

$$F_{\mathrm{T}}^{\sin(2\varphi_{CS}+\varphi_S)} = -\mathcal{C}\left[\frac{2(\boldsymbol{q_T k_{T,N}})[2(\boldsymbol{q_T k_{T,N}})(\boldsymbol{q_T k_{T,\pi}}) - q_T^2(\boldsymbol{k_{T,N} k_{T,\pi}})] - q_T^2 k_{T,N}^2(\boldsymbol{q_T k_{T,\pi}})}{2q_T^3 M_N^2 M_\pi} h_{1,\pi}^{\perp} h_{1T,N}^{\perp}\right]$$

Pretzelosity for nucleon, Boer–Mulders for $\pi^-$

$$F_{\mathrm{T}}^{\sin(2\varphi_{CS}-\varphi_S)} = -\mathcal{C}\left[\frac{\boldsymbol{q_T k_{T,\pi}}}{q_T M_\pi} h_{1,\pi}^{\perp} h_{1.N}\right]$$ Transversity for proton, Boer–Mulders for $\pi^-$

$$\mathcal{C}[w(\boldsymbol{k_{T,\pi}}; \boldsymbol{k_{T,N}}; \boldsymbol{q_T})\mathrm{f}_\pi \mathrm{f}_N] = \frac{1}{\mathrm{N_c}}\sum_q \left\{ \begin{array}{c} e_q^2 \int \mathrm{d}^2\boldsymbol{k_{T,\pi}} \mathrm{d}^2\boldsymbol{k_{T,N}} \delta^{(2)}(\boldsymbol{q_T} - \boldsymbol{k_{T,\pi}} - \boldsymbol{k_{T,N}}) \\ \times\, w(\boldsymbol{k_{T,\pi}}; \boldsymbol{k_{T,N}}; \boldsymbol{q_T}) \left[\begin{array}{c} f_\pi^{\bar{q}}(x_\pi, k_{T,\pi}^2) f_N^q(x_N, k_{T,N}^2) \\ + \\ f_\pi^q(x_\pi, k_{T,\pi}^2) f_p^{\bar{q}}(x_p, k_{T,p}^2) \end{array}\right] \end{array} \right\}$$



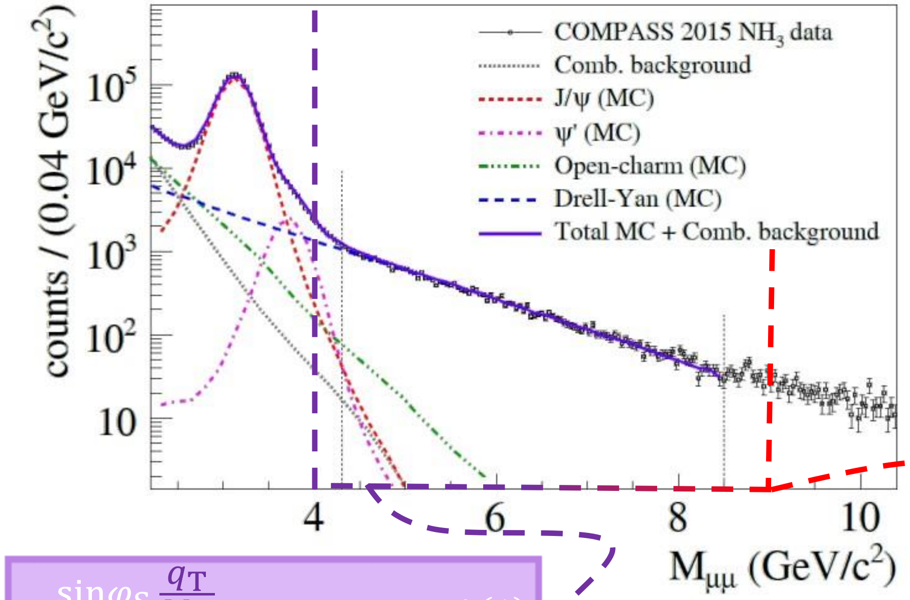
Momenta in target frame

- TMD PDFs can be accessed through measurement of target spin (in)dependent azimuthal asymmetries

$$A_{\mathrm{T}}^{\sin(\varphi_S)} = \frac{F_{\mathrm{T}}^{\sin(\varphi_S)}}{F_{\mathrm{U}}^1} \qquad A_{\mathrm{U}}^{\cos(\varphi_{CS})} = \frac{F_{\mathrm{U}}^{\cos(\varphi_{CS})}}{F_{\mathrm{U}}^1} \qquad A_{\mathrm{T}}^{\sin(2\varphi_{CS}+\varphi_S)} = \frac{F_{\mathrm{T}}^{\sin(2\varphi_{CS}+\varphi_S)}}{2F_{\mathrm{U}}^1} \qquad A_{\mathrm{T}}^{\sin(2\varphi_{CS}-\varphi_S)} = \frac{F_{\mathrm{T}}^{\sin(2\varphi_{CS}-\varphi_S)}}{2F_{\mathrm{U}}^1}$$

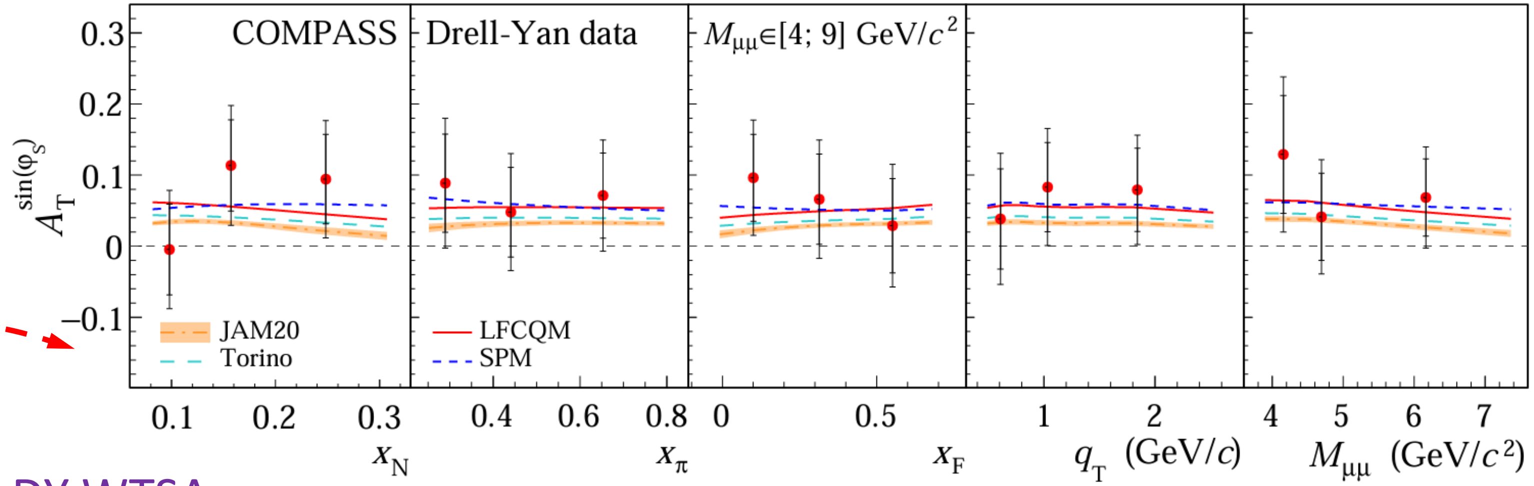
# **TSA Sivers effect:** Weighted and Unweighted Methods

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




DY TSA

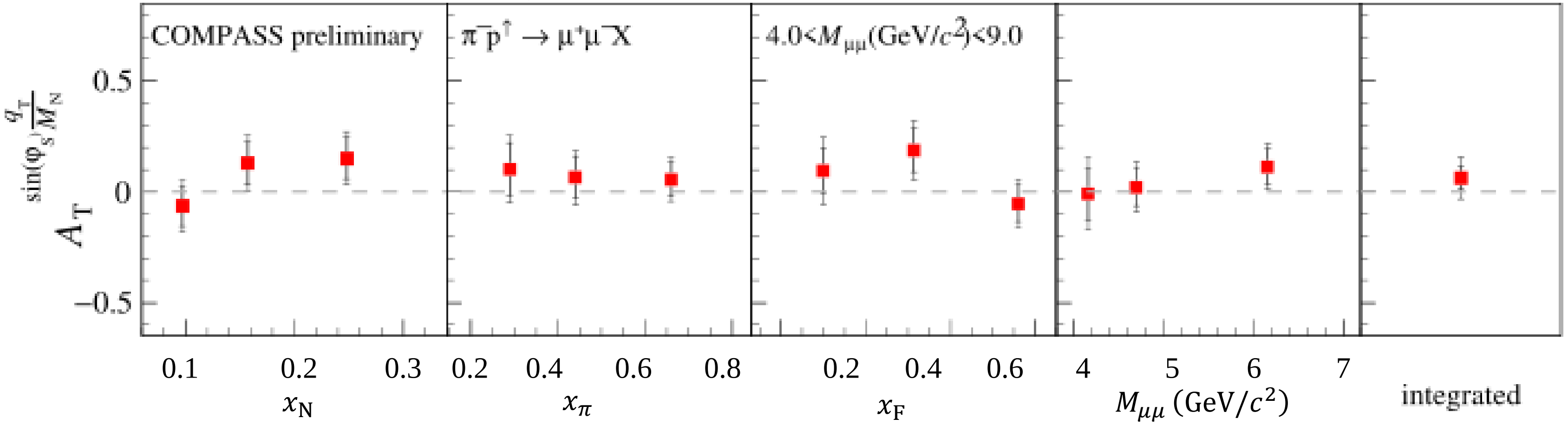
Sivers asymmetry tends to be 1.5 $\sigma$ positive. COMPASS, PRL 133 (2024) 071902




$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} \propto f_{1,\pi}^q \times f_{1T,N}^{q\perp(1)}$$

NEW! DY WTSA

Sivers effect is slightly positive, at about 1 $\sigma$.




Weighted Asymmetries WTSA:

$$A_T^{\sin\varphi_S \frac{q_T}{M_N}} = \int d^2\boldsymbol{q_T} \frac{q_T}{M_N} A_T^{\sin\varphi_S}.$$

- Removes the convolution
- Reduces model dependence
- Gives direct access to **moments** of TMD PDFs:

$$f^{(n)}(x) = \int d^2 k_T \left(\frac{k_T^2}{2M^2}\right)^n f(x, k_T^2)$$

$M$ - hadron mass