Polarised Drell-Yan results from COMPASS

XIV Hadron Physics: Florianópolis, 23 March 2018

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on behalf of the COMPASS collaboration

Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

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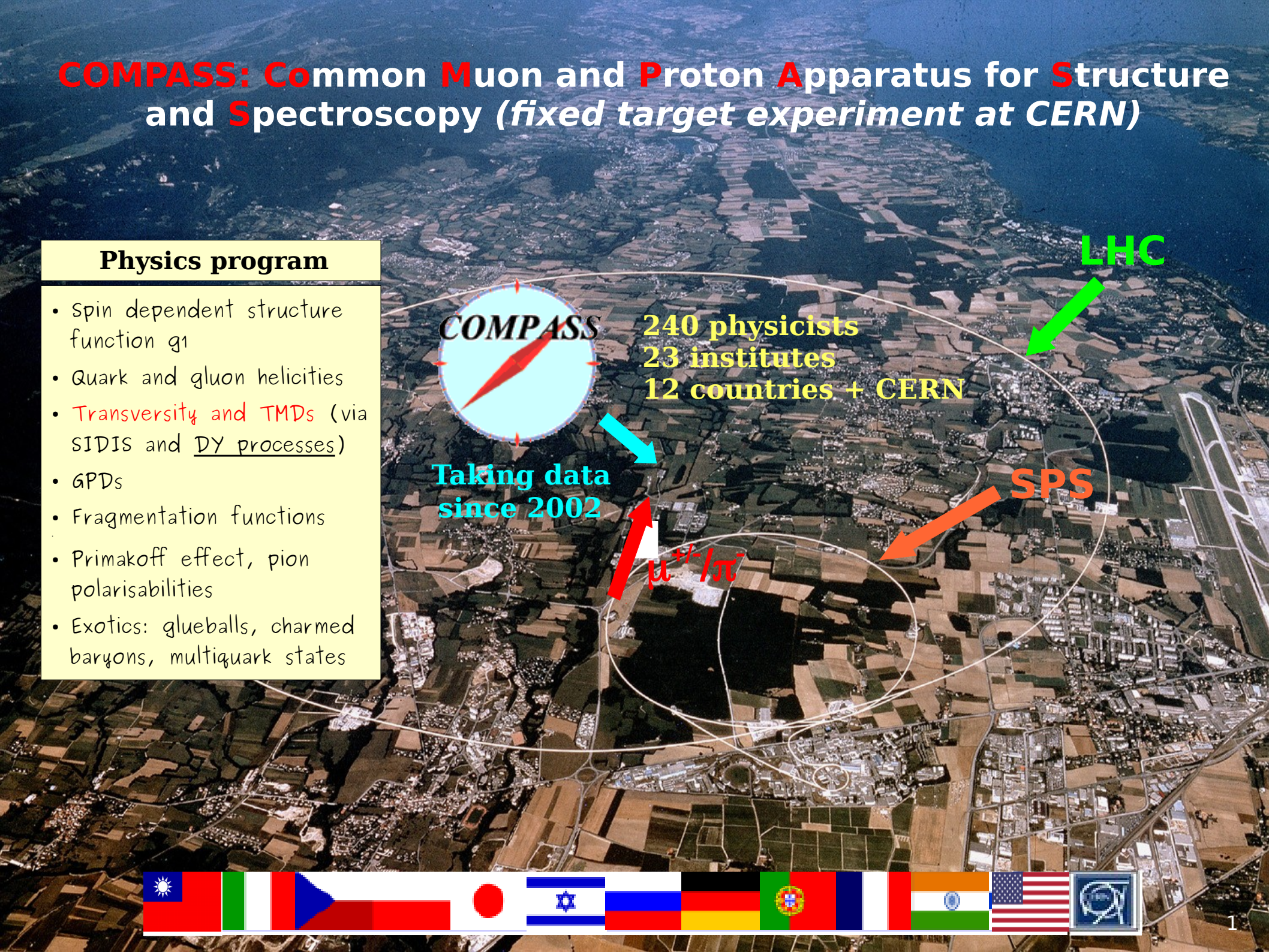
COMPASS: Common Muon and Proton Apparatus for Structure and Spectroscopy *(fixed target experiment at CERN)*

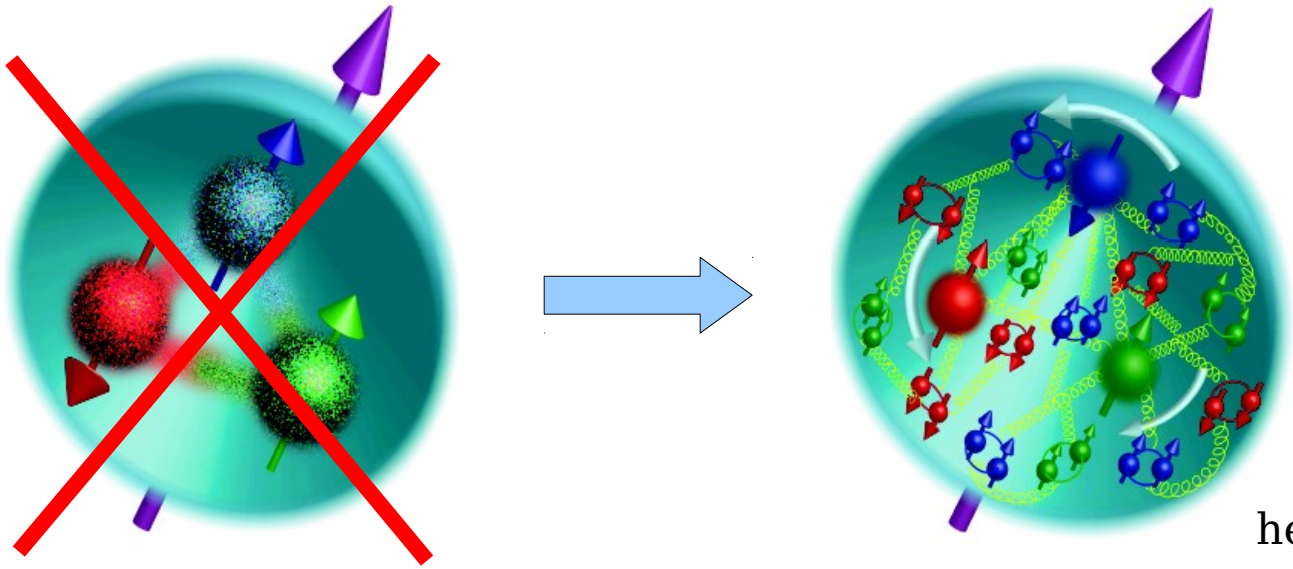
Physics program

- Spin dependent structure function g1
- Quark and gluon helicities
- Transversity and TMDs (via SIDIS and DY processes)
- GPDs
- Fragmentation functions
- Primakoff effect, pion polarisabilities
- Exotics: glueballs, charmed baryons, multiquark states



A picture of the QCD fundamental state: the proton

The base element of all matter is a complex QCD object:



quark and gluon helicities measured at COMPASS

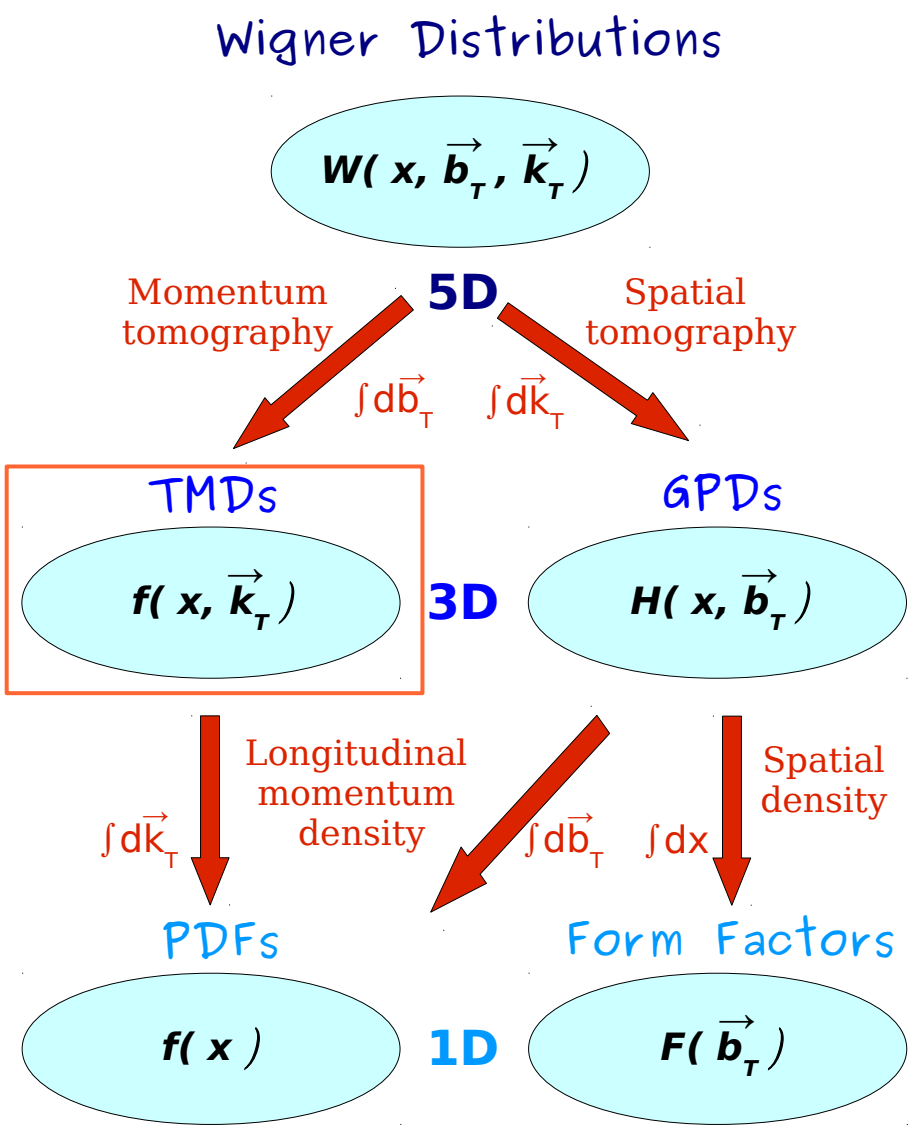
- Main questions addressed by COMPASS on the proton structure:

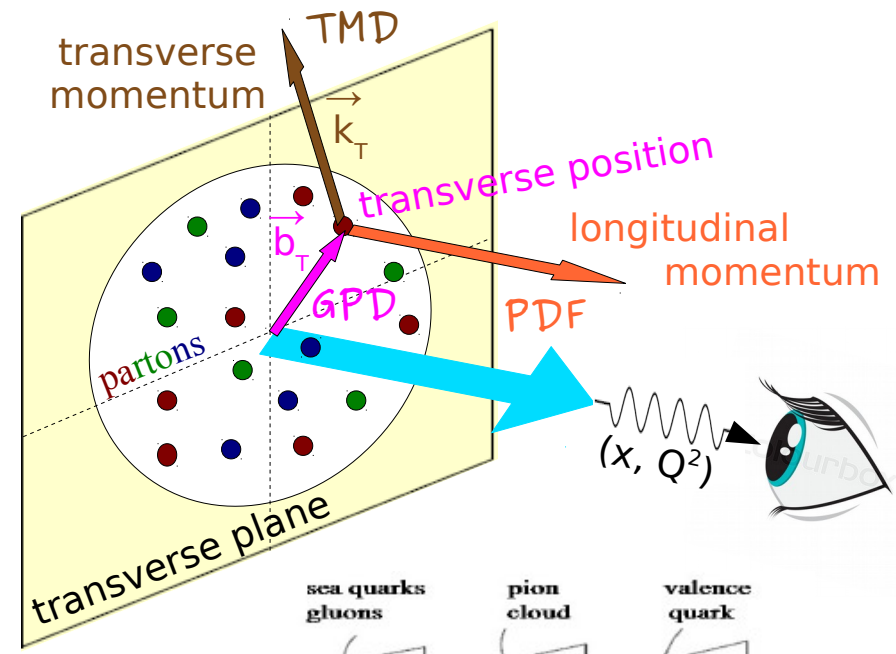
1) What is the nature of the proton spin?

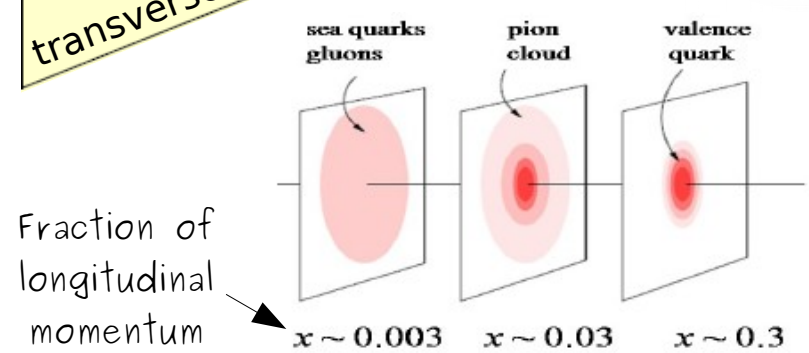
$$S_z^N = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^{q,g}$$

2) How are the confined partons (quarks and gluons) distributed in the position and in the momentum space?

General description of the proton structure







GPDs: Generalized Parton Distributions
TMDs: Transverse Momentum Dependent PDFs

Nucleon structure in the momentum space

3 PDFs (x) & **5 TMDs (x, $\vec{k}_T$)**:

Quark / Nucleon	Unpolarised	Longitudinal Polarisation	Transverse Polarisation
Unpolarised	f_1 *(Number density)*		$h_1^{\perp}$ *(Boer Mulders)*
Longitudinal Polarisation		g_1 *(Helicity)*	$h_{1L}^{\perp}$ *(Worm Gear)*
Transverse Polarisation	$f_{1T}^{\perp}$ *(Sivers)*	g_{1T} *(Worm Gear)*	h_1 *(Transversity)*; $h_{1T}^{\perp}$ *(Pretzelosity)*

Study $\Delta q(x, Q^2)$ and $\Delta g(x, Q^2)$

(Transversity)
Study $\Delta_T q(x, Q^2)$

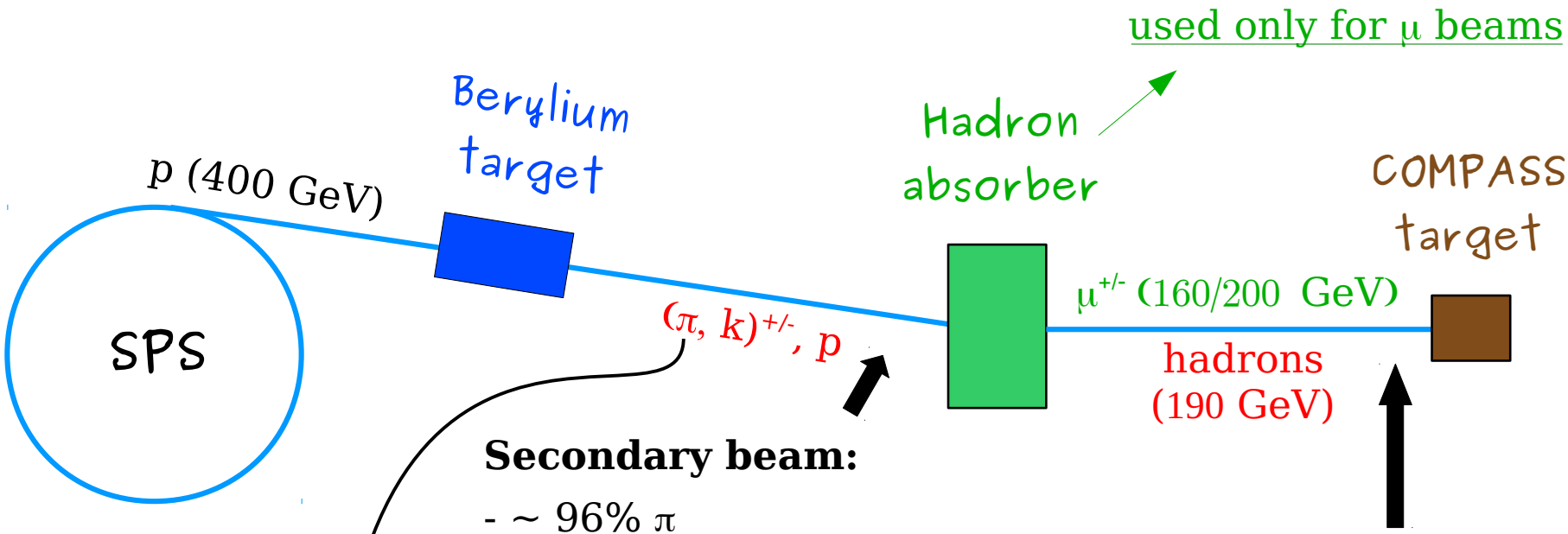
Surviving k_T integration

$$\Phi_{Coll}^{Tw-2}(x) = \frac{1}{2}\left[q(x) + S_L \gamma_5 \Delta q(x) + S_L \gamma_5 \gamma^1 \Delta_T q(x)\right]$$

Contains information about the Orbital Angular Momentum *(OAM)*

Investigated at COMPASS via measurement of spin asymmetries

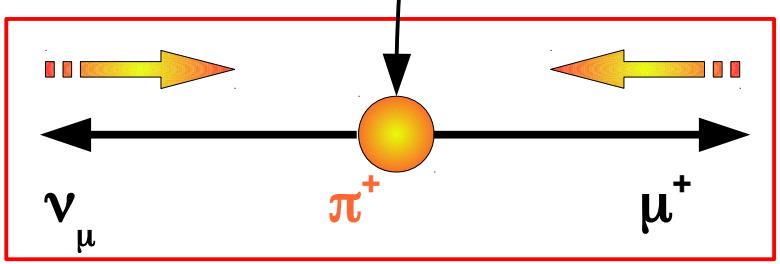
The M2 beamline at CERN



Secondary beam:

- ~ 96% π
- 600 m decay pipe

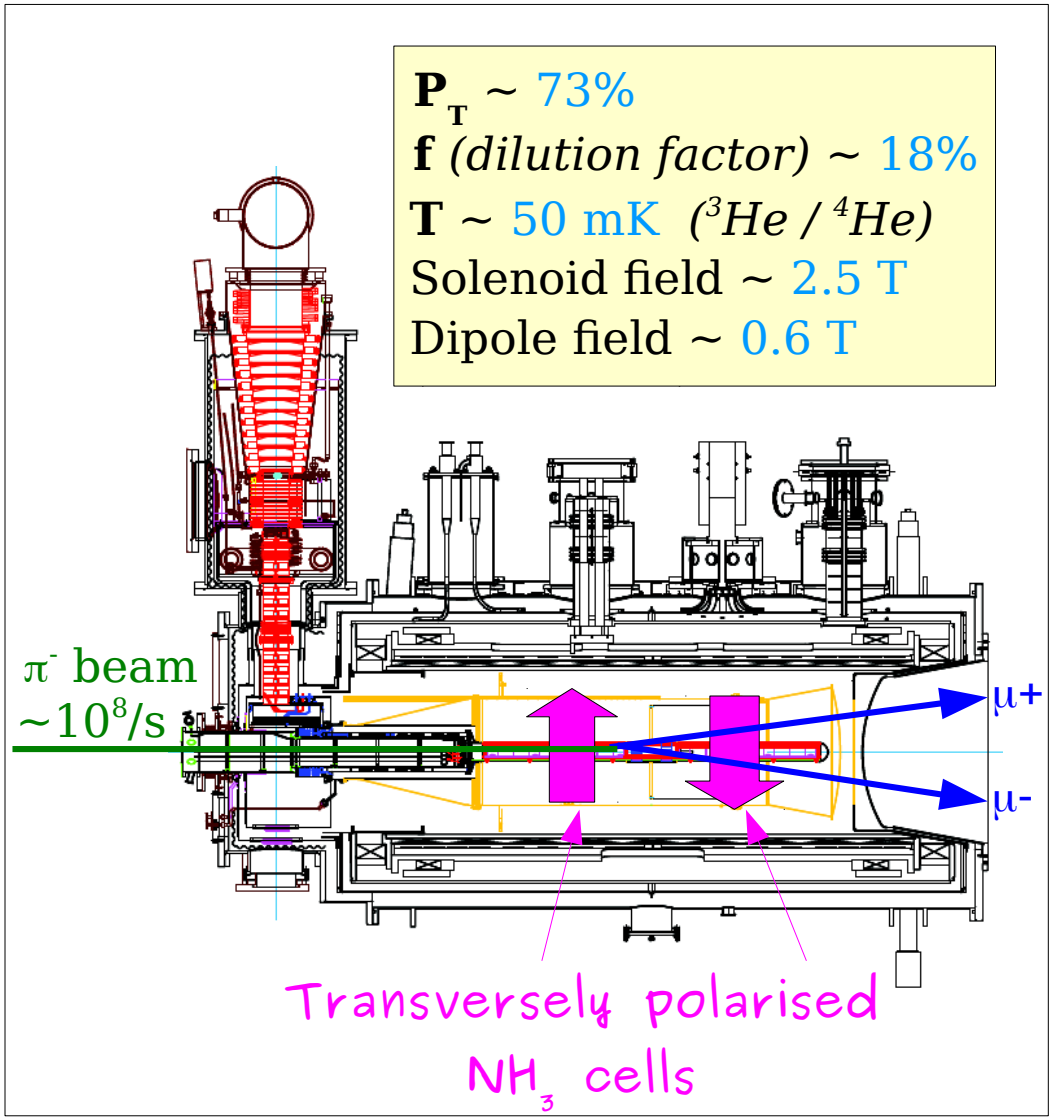
400 m for momentum and beam selection
(up to 10^8 particles/s)



Naturally polarised muon beam for SIDIS measurements: $P_\mu \sim 80\%$

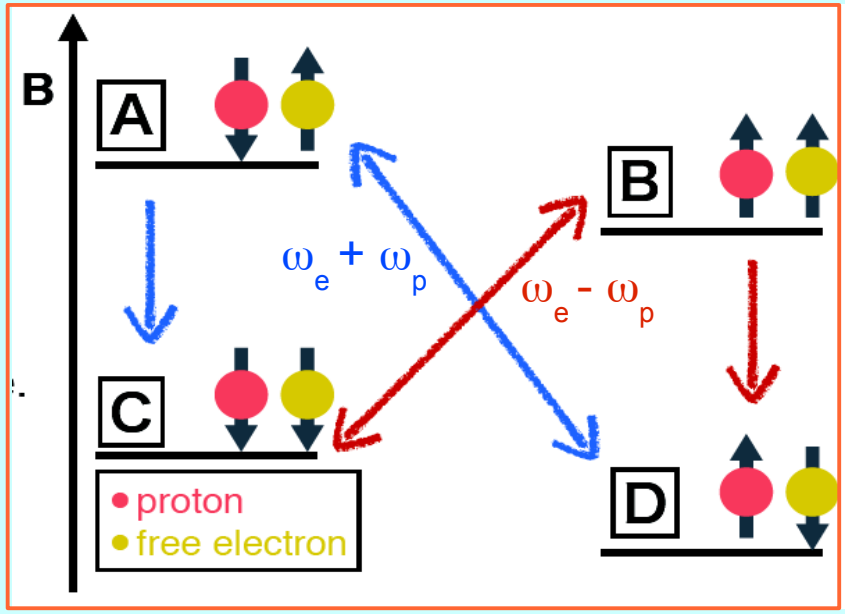
The polarised target of COMPASS

Drell-Yan setup in 2015

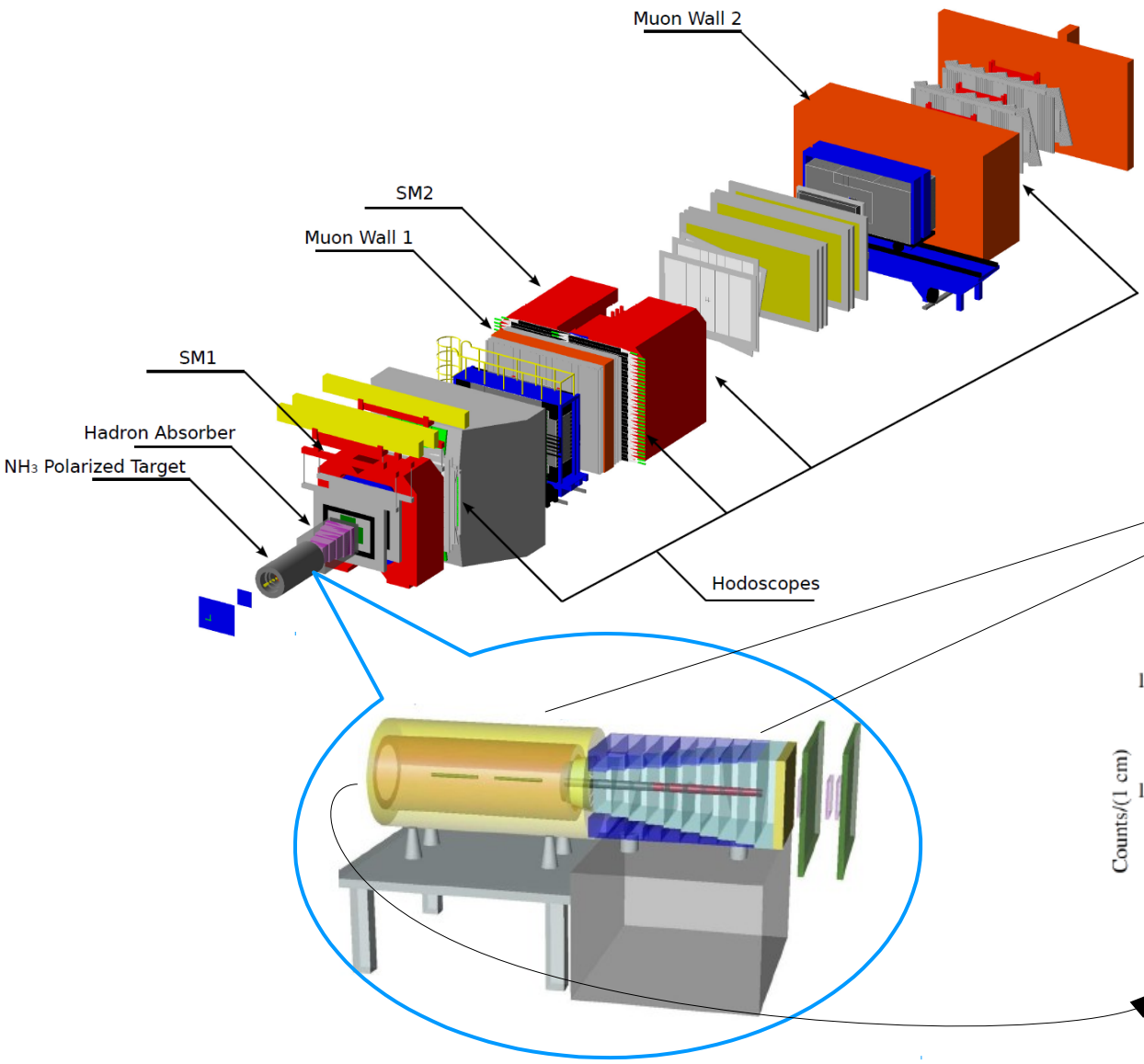


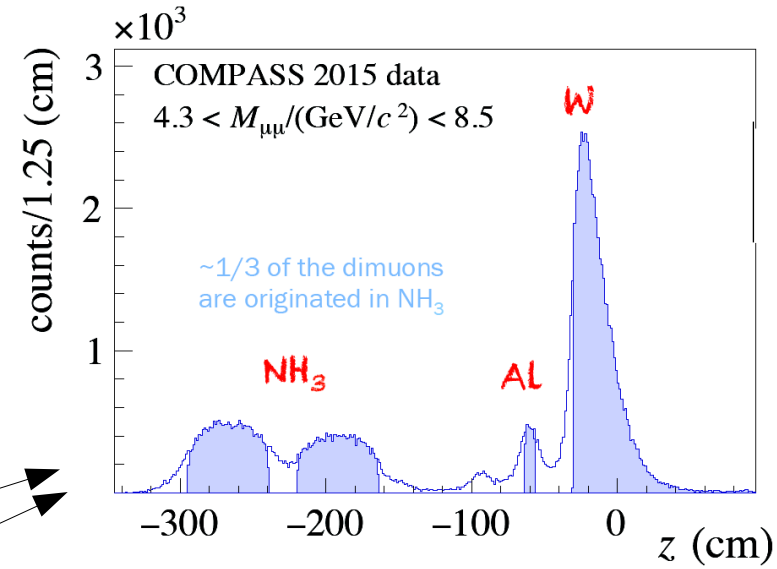
Dynamic Nuclear Polarisation:

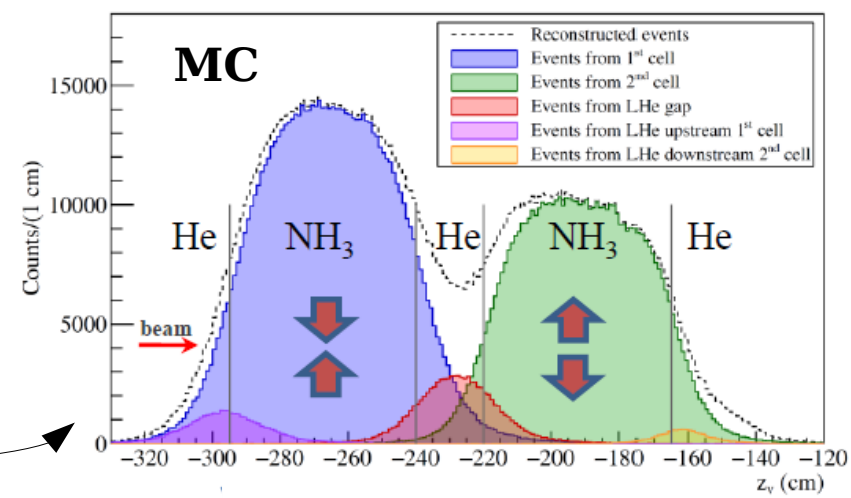
- The target is irradiated with a specific microwave frequency for a simultaneous spin flip of the electron–nucleon system
- The nucleon keeps its spin due to its long relaxation time



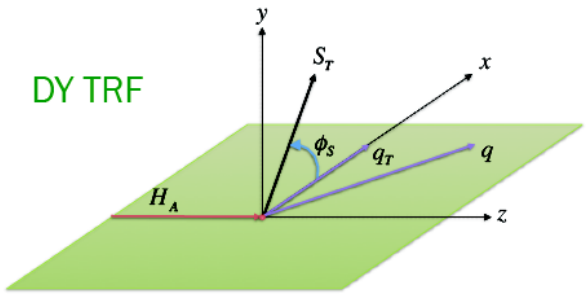
COMPASS spectrometer for the Drell-Yan setup: Double stage spectrometer for large angles *(SM1)* and small angles *(SM2)*

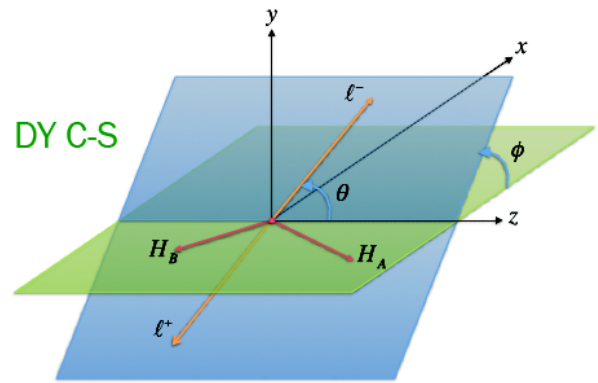


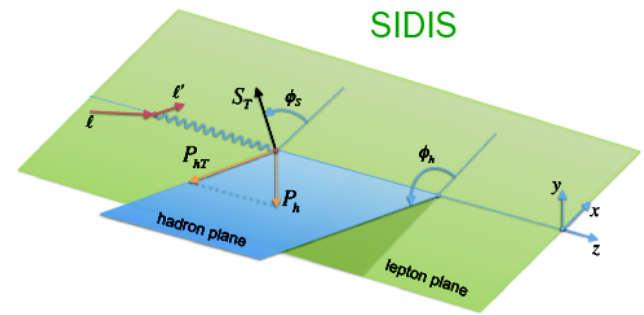




The Drell-Yan (DY) and SIDIS cross-sections using a transversely polarised target



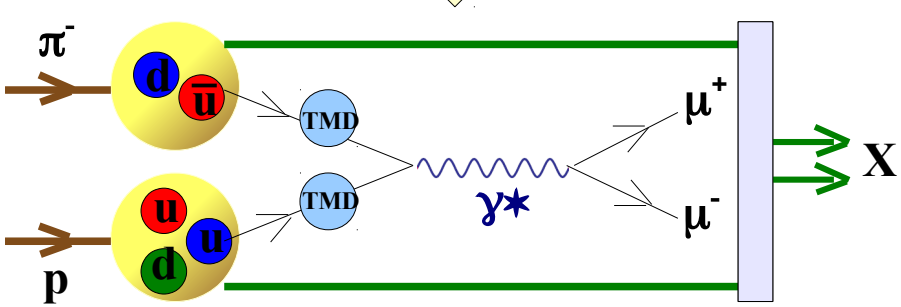


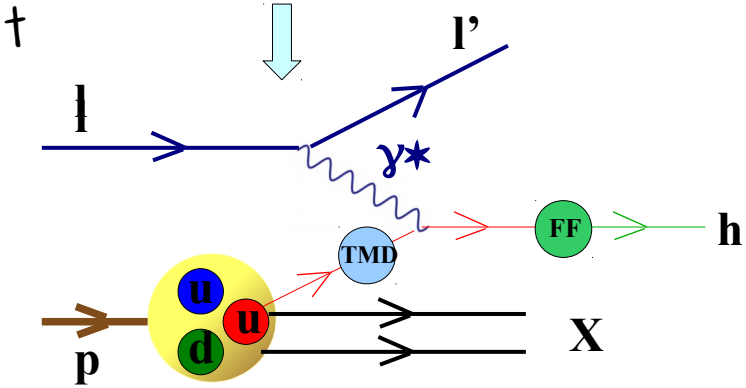


$$
\begin{aligned}
d\sigma^{DY} \propto \big(1 &+ \cos^2(\theta) + \sin^2(\theta) A_{UU}^{\cos(2\phi)} \cos(2\phi) \\
&+ S_T\big[\big(1 + \cos^2(\theta)\big) A_{UT}^{\sin(\phi_S)} \sin(\phi_S \\
&+ \sin^2(\theta)\big(A_{UT}^{\sin(2\phi - \phi_S)} \sin(2\phi - \phi_S)\big) \\
&+ A_{UT}^{\sin(2\phi + \phi_S)} \sin(2\phi + \phi_S)\big)\big]
\end{aligned}
$$

$$
\begin{aligned}
d\sigma^{SIDIS} \propto \big(1 &+ \epsilon \cos(2\phi_h) A_{UU}^{\cos(2\phi_h)} \\
&+ S_T\big[\sin(\phi_h - \phi_s) A_{UT}^{\sin(\phi_h - \phi_s)} \\
&+ \epsilon \sin(\phi_h + \phi_s) A_{UT}^{\sin(\phi_h + \phi_S)} \\
&+ \epsilon \sin(3\phi_h - \phi_s) A_{UT}^{\sin(3\phi_h - \phi_S)}
\end{aligned}
$$

Leading Twist





Interpretation of azimuthal spin asymmetries

Pion PDF/TMDs

Spin (in)dependent fragmentation functions → **(D)H**

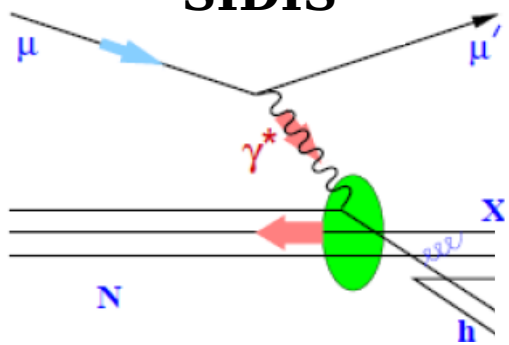
DY		SIDIS
$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer–Mulders	$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$
$A_{UT}^{\sin(2\phi - \phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	Transversity	$A_{UT}^{\sin(\phi_h + \phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi + \phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$	Pretzelosity	$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$

Proton TMDs

Universality of the TMDs

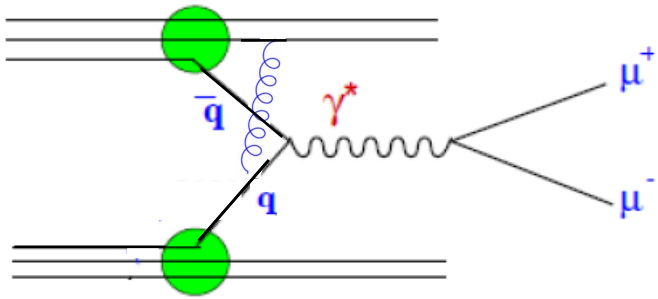
- The <u>resummation of soft gluons</u> in a k_T dependent PDF <u>is process dependent</u>:

SIDIS



Final state interactions

DY



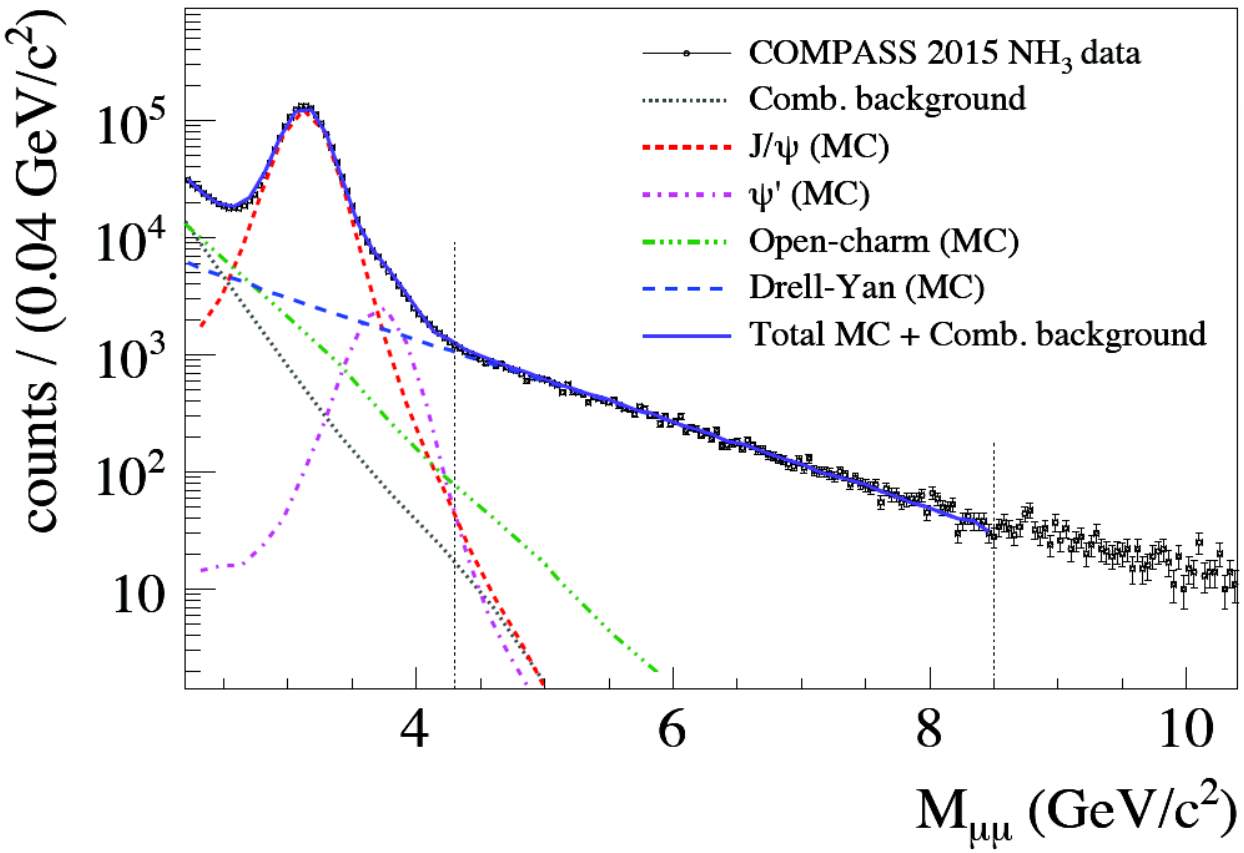
Initial state interactions

- The difference between the initial and final state interactions leads to T-Odd Sivers and Boer-Mulders TMDs. <u>The TMD factorization is only ensured if</u>:

$$f_{1T,p}^{\perp q}(DY) = -f_{1T,p}^{\perp q}(SIDIS) \qquad h_{1,p}^{\perp q}(DY) = -h_{1,p}^{\perp q}(SIDIS)$$

Crucial test of the TMD approach being performed by COMPASS!

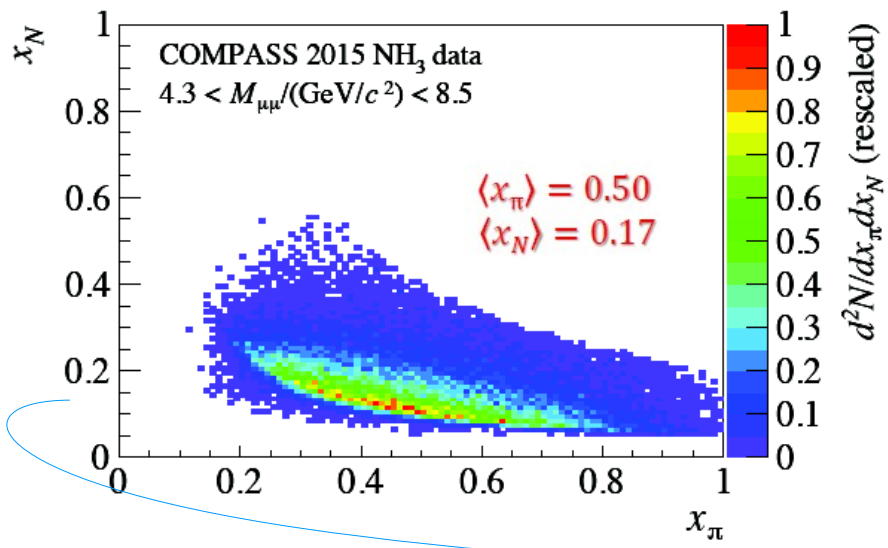
Dimuon mass spectrum from polarised DY

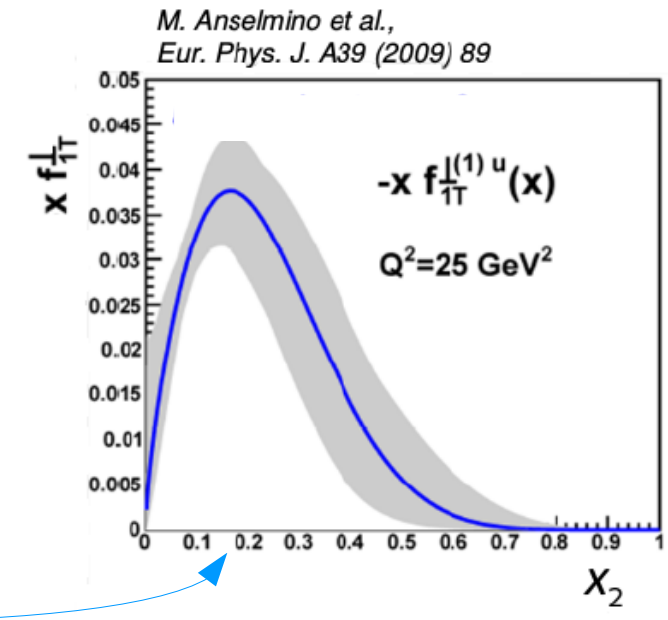


Good agreement between Data and Monte-Carlo

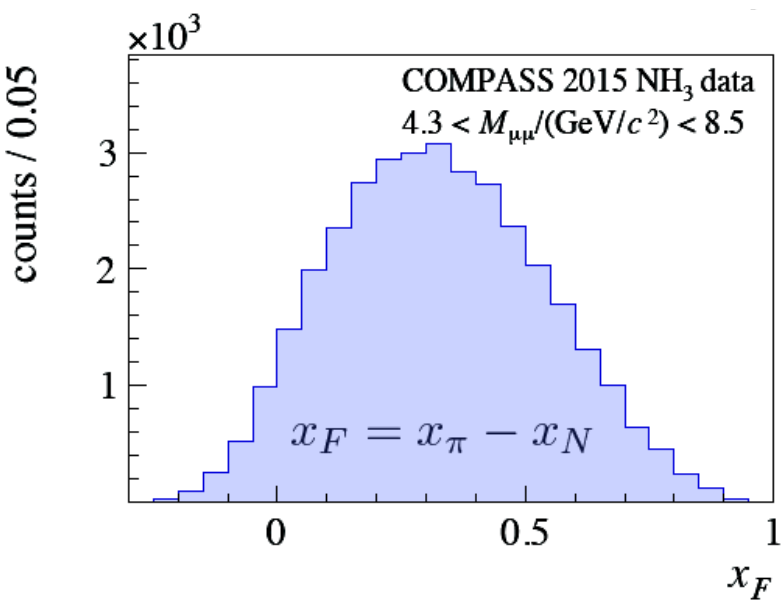
<u>35000 DY dimuons</u> are used for the extraction of the transverse spin asymmetries → $M_{\mu\mu} \in [4.3, 8.5]$ GeV/c² (contamination < 4%)

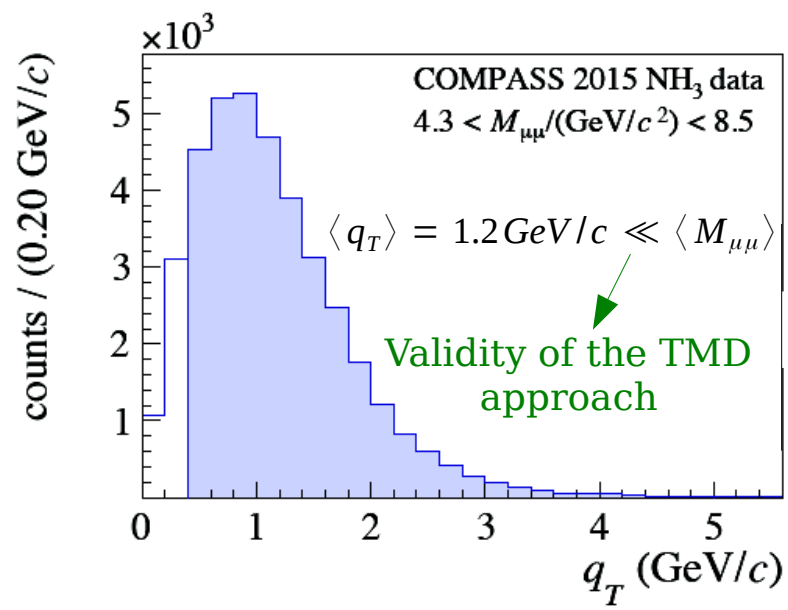
Kinematic distributions in the high mass range





Valence region where the Sivers TMD is predicted to be large!

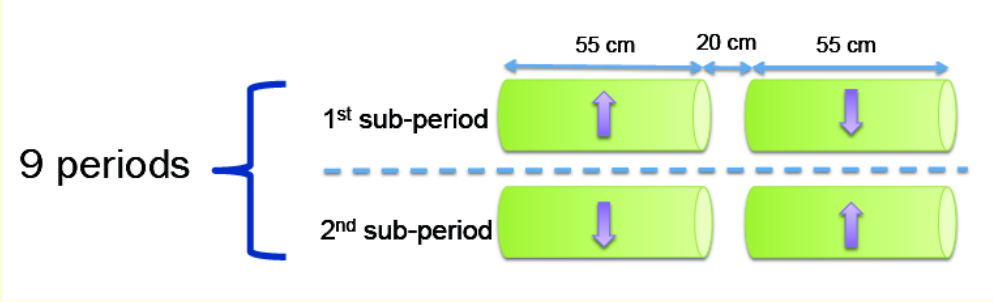




Extraction of the Twist-2 & Twist-3 Transverse Spin Asymmetries

- A total of 5 TSAs are extracted using an <u>unbinned maximum likelihood method:</u>

$$d\sigma^{DY} \propto 1 + D_{[\sin(2\theta)]} A_{UU}^{\cos(\phi)} \cos(\phi) + D_{[\sin^2(\theta)]} A_{UU}^{\cos(2\phi)} \cos(2\phi) + S_T [D_{[1+\cos^2(\theta)]} A_{UT}^{\sin(\phi_S)} \sin(\phi_S)$$
$$+ D_{[\sin^2(\theta)]} (A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S))$$
$$+ D_{[\sin(2\theta)]} (A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) + A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S))]$$



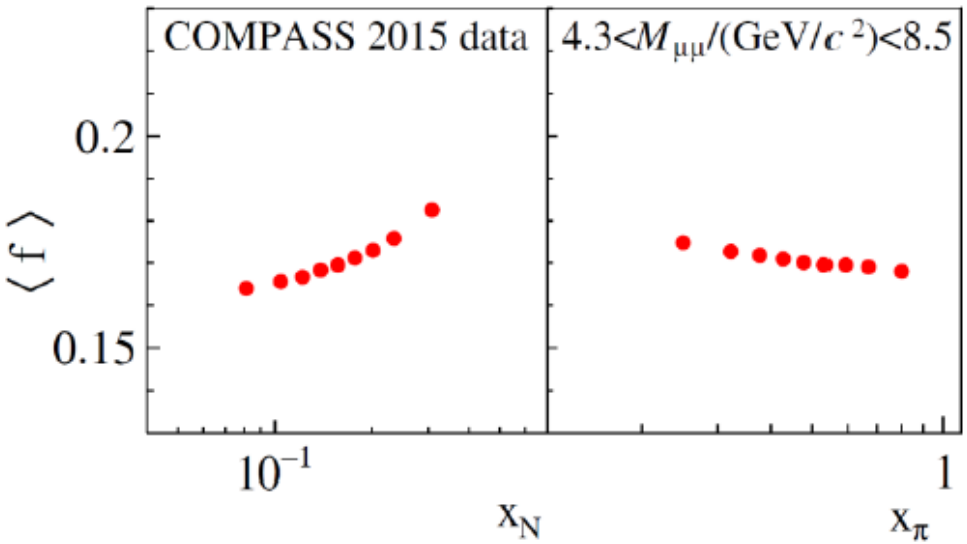
$$A^{raw} = P_T f D A^{phys}$$

The asymmetries are weighted with the dilution factor f and the depolarisation factors D

$$D_{[\sin(2\theta)]} = \frac{\sin(2\theta)}{1+\lambda\cos^2(\theta)} \quad D_{[1+\cos^2(\theta)]} = \frac{1+\cos^2(\theta)}{1+\lambda\cos^2(\theta)} \quad D_{[\sin^2(\theta)]} = \frac{\sin^2(\theta)}{1+\lambda\cos^2(\theta)} \quad f = \frac{n_H \sigma_{\pi^- H}^{DY}}{n_H \sigma_{\pi^- H}^{DY} + \Sigma_A n_A \sigma_{\pi^- A}^{DY}}$$

The dilution and depolarisation factors

Fraction of polarisable material

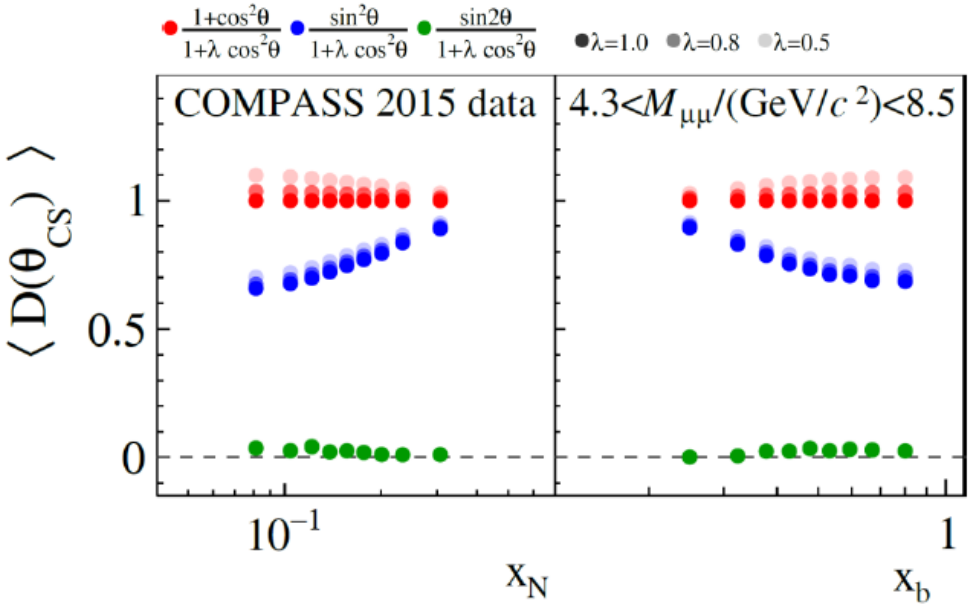


f ~ 0.18 with an <u>uncertainty of 8%</u>

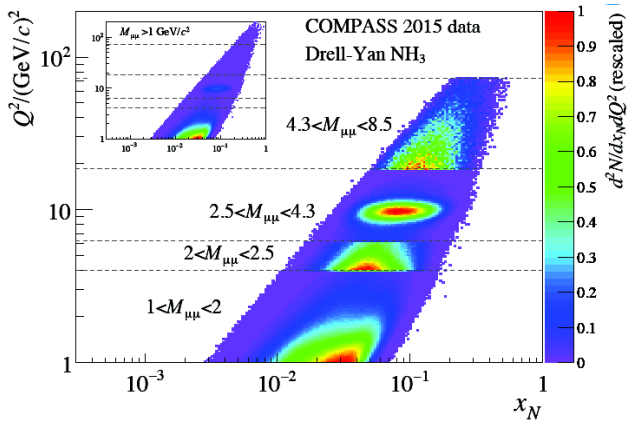
Takes into account the migration of events from one target cell to another

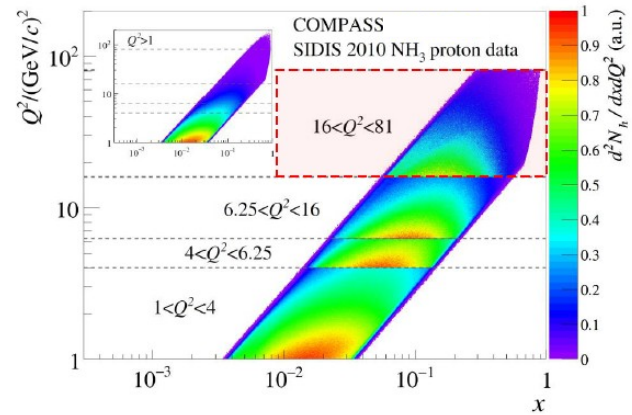
The depolarisation factors are evaluated for **λ = 1** (Drell–Yan model with $K_T = 0$)

Other scenarios with λ ≠ 1 lead to a <u>maximum uncertainty of 5%</u>



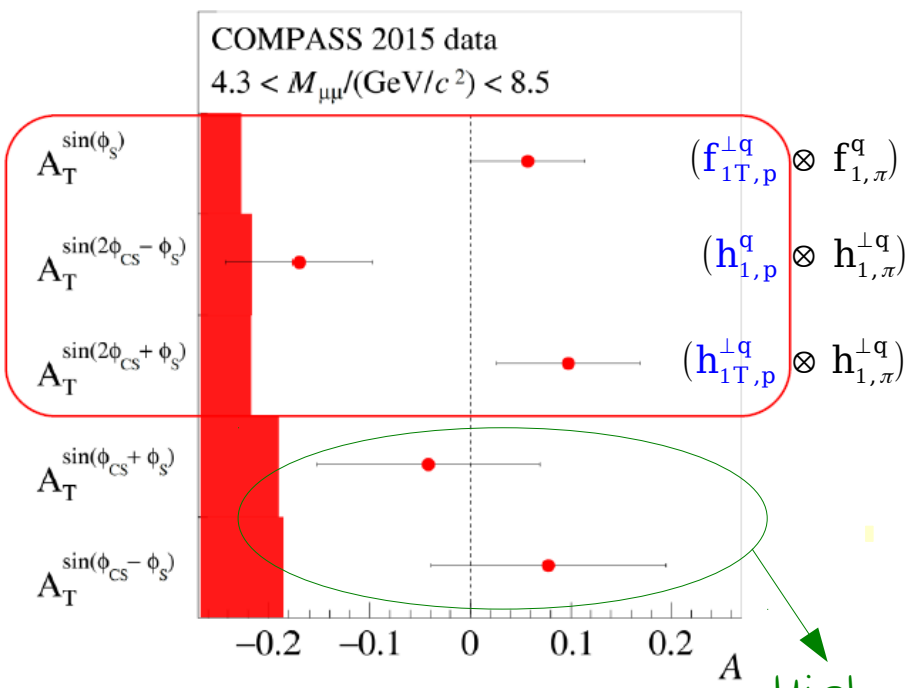
TSA results: DY & SIDIS measurements in the same kinematic region

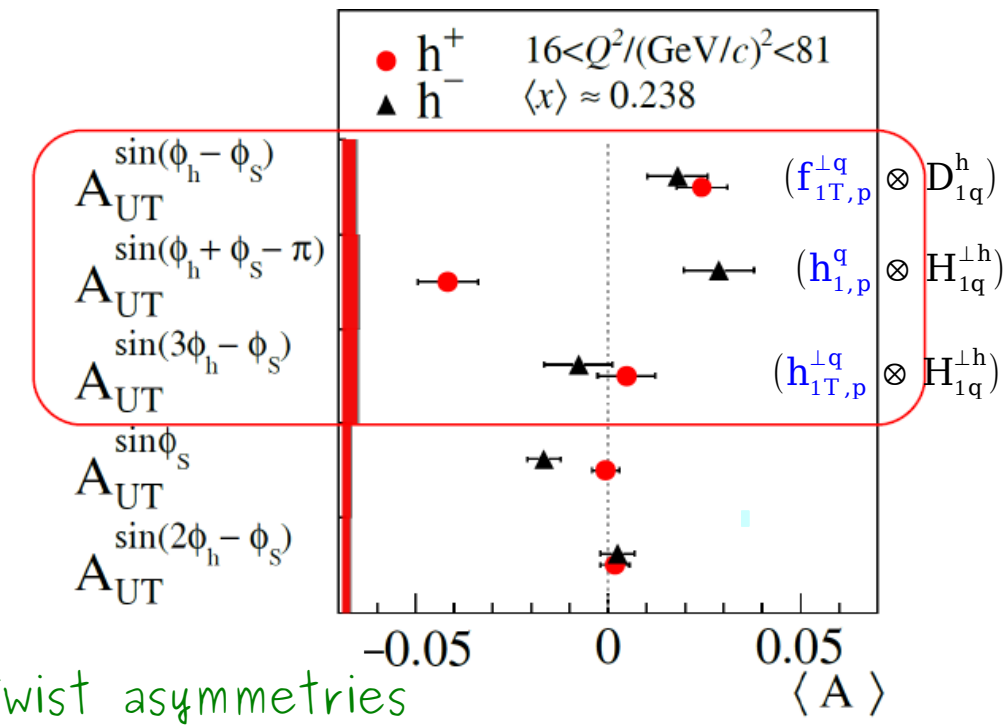




DY: *COMPASS PRL 119, 112002 (2017)*

SIDIS: *COMPASS PLB 770 (2017) 138*

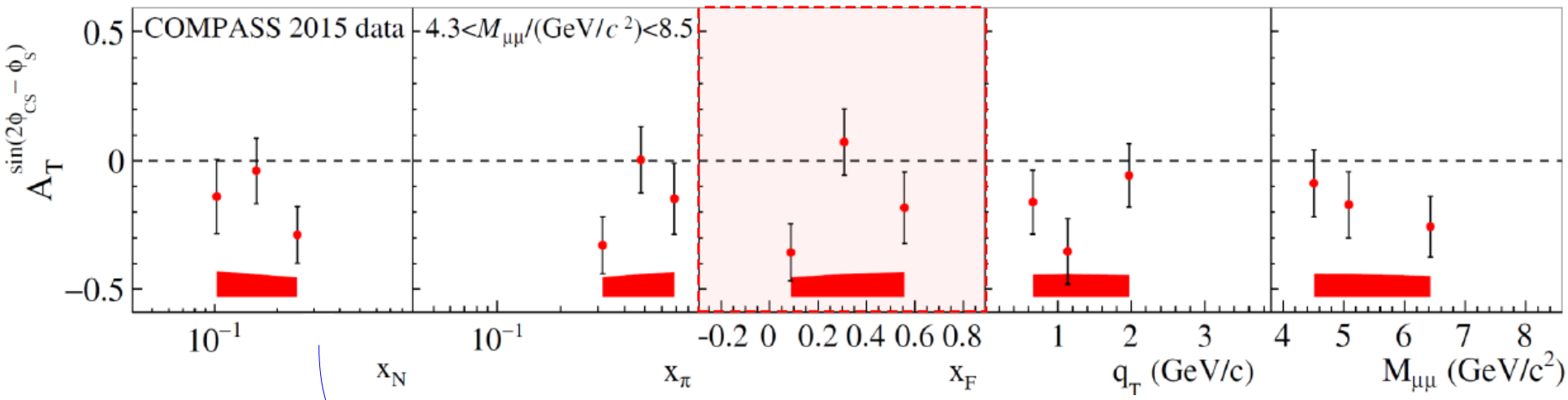




Higher-Twist asymmetries

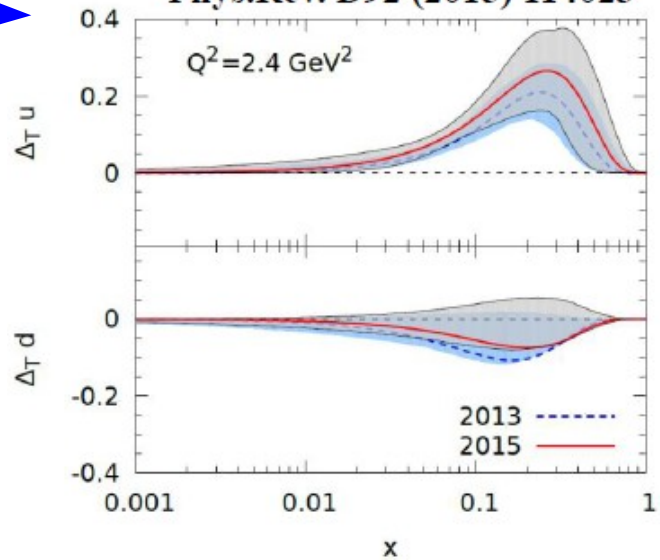
A closer look to the DY Transversity
(significant asymmetry in SIDIS)

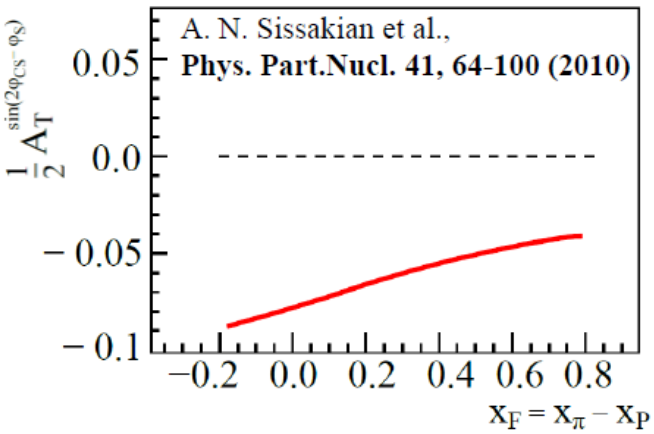
COMPASS PRL 119, 112002 (2017)



The DY data cover the region where the quarks transversity is expected to be significant

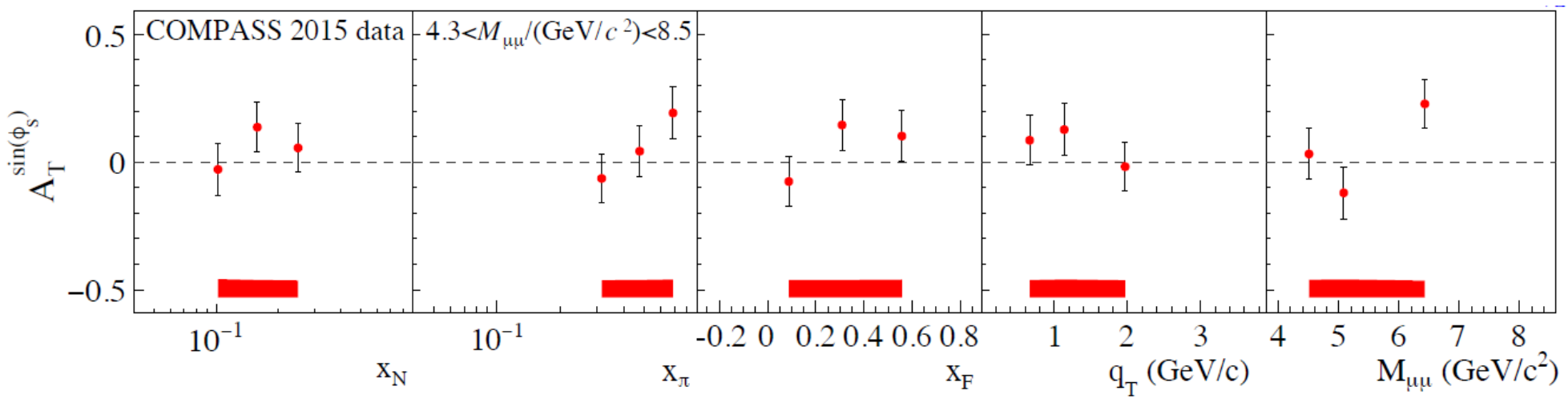
M. Anselmino et al.
Phys.Rev. D92 (2015) 114023



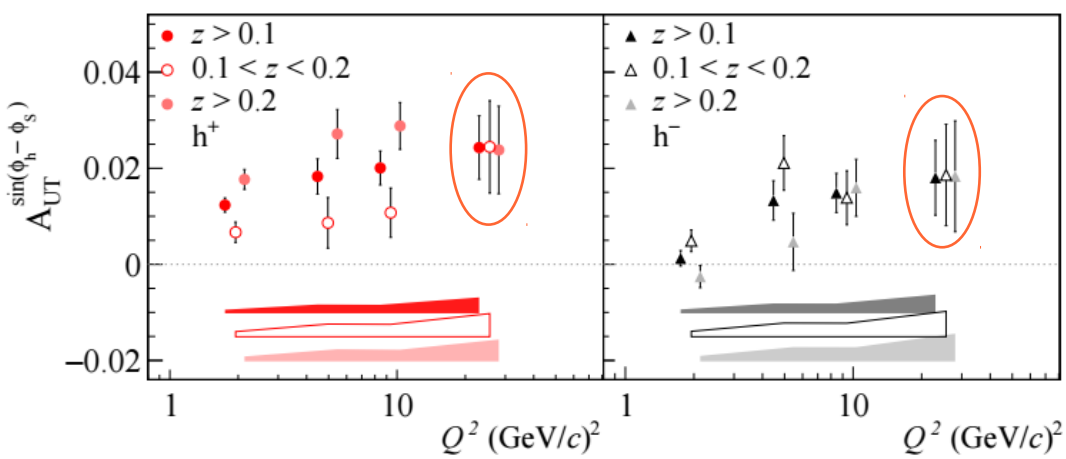


A closer look to the DY Sivers

DY - *COMPASS PRL 119, 112002 (2017)*



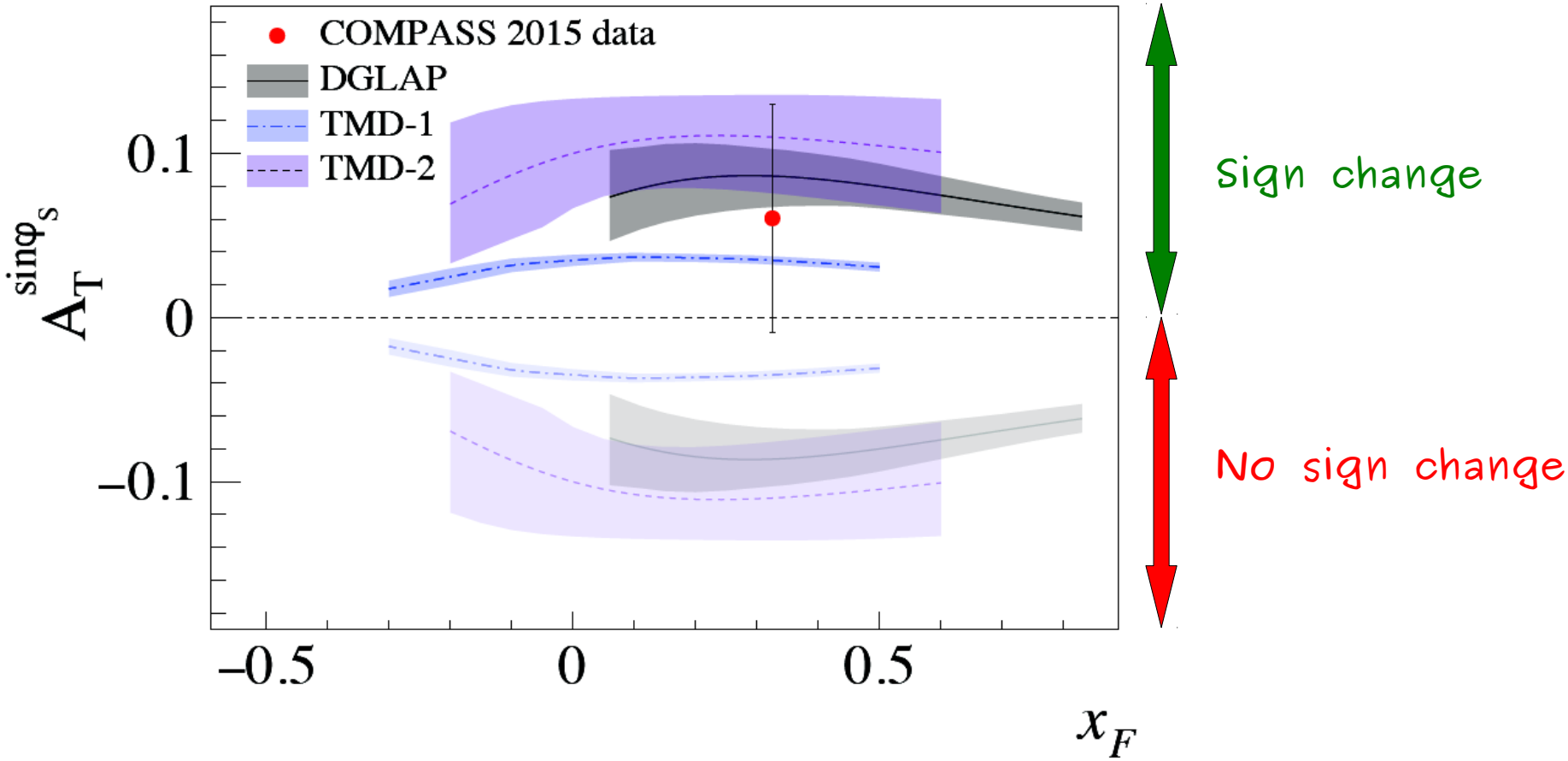
SIDIS - *COMPASS PLB 770 (2017) 138*



Significantly positive for both hadron charges at high Q^2
(encodes information about the orbital angular momentum of quarks)

What about the Sivers sign change?

Sivers asymmetry in Drell-Yan: Sign Change is favored



DGLAP (2016) M. Anselmino *et al.*, arXiv:1612.06413, fit to COMPASS, HERMES and JLab SIDIS data
TMD-1 (2014) M. Echevarria *et al.*, PRD 89 (2014) 074013, fit to COMPASS, HERMES and JLab SIDIS data, $0<p_T<1$ and $4<M<9$ GeV/c^2
TMD-2 (2013) P. Sun and F. Yuan, PRD 88 (2013) 114012, fit to COMPASS and HERMES data, $p_T<2$ GeV/c and $4<M<9$ GeV/c^2

Summary and Outlook

- In 2015 COMPASS performed the first ever polarised Drell-Yan measurement using a pion beam. **The main results are:**

  - The Pretzelosity asymmetry is compatible with zero *(positive with a significance of about 1σ)*. The two higher-twist asymmetries are also compatible with zero.

  - The Transversity asymmetry is negative with a significance of 2σ

  - The predicted sign change for the Sivers TMD when accessed via SIDIS or DY processes is consistent with the measured asymmetries → First world test to the universality of the T-Odd TMDs *(using the γ^* channel for the DY lepton pair production)*

- A second year of polarised DY data taking will take place in 2018 to improve the experimental uncertainties *(for the moment the DY Sivers asymmetry is only 1σ away from zero)*