Study of the hadron structure using the polarised Drell-Yan process at COMPASS

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on behalf of the COMPASS collaboration

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COMPASS

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

CERN/FIS-NUC/0017/2015

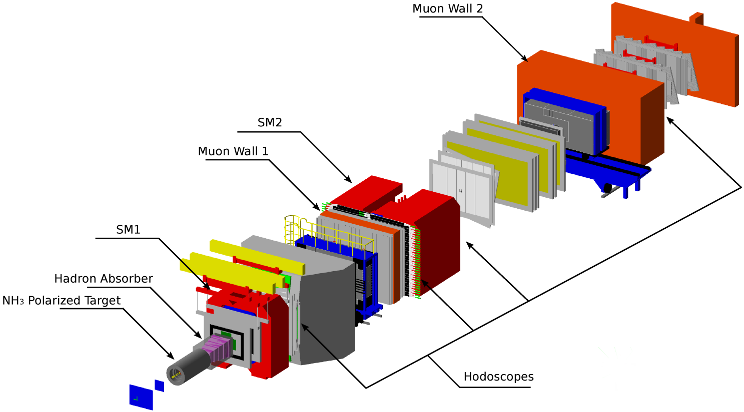
LIP

COMPASS experiment at CERN

COmmon Muon Proton Apparatus for Structure and Spectroscopy

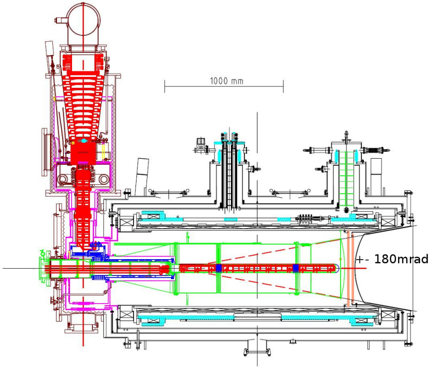
- Fixed target experiment at the end of M2 SPS beam line
- Around 240 collaborators from 13 countries and 22 institutes
- Data taking since 2002

COMPASS general purpose spectrometer



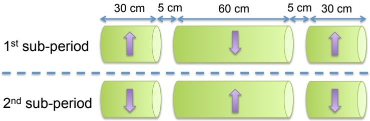
- Two stages spectrometer, wide angular acceptance, ±180 mrad
- About 350 detector planes
- Particles identification: Calorimeters, RICH and μ Filters
- Muon and hadron beams
- Polarised target (longitudinally and transversely polarised NH_3 and ^{6}LiD)

Polarised Target

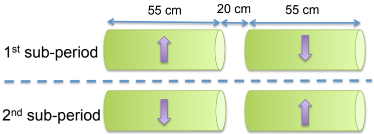


In transverse mode polarisation reversal every 2 weeks

Three target cells - SIDIS case



Two target cells - DY case



- NH_3 polarised target
- Polarisation ~ 80%
- dilution factor ~ 15% in SIDIS, ~ 22% in DY

Nucleon spin decomposition

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

Presently the contribution from the quarks to the proton spin is
$\Delta\Sigma\left(Q^2 = 3(\mathrm{GeV}/c^2)^2\right) = 0.30 \pm 0.01(stat) \pm 0.02(evol)$

The gluon's contribution seems small but with large uncertainties, more data is needed in a different phase space to constrain it

How to address the orbital angular momentum?

From 1D to 3D ⇒ **How are the charges distributed inside the nucleon?**

The 3D nucleon mapping in the momentum space is described by the Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDFs)

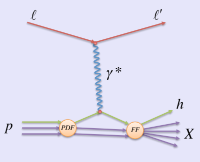
Nucleon Structure - TMD PDFs

The nucleon structure at leading twist QCD, taking into account the quarks intrinsic transverse momentum, k_T, is described by 8 TMD PDFs for each quark flavour

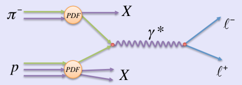
Quark \ Nucleon	unpolarised	longitudinally polarised	transversely polarised
unpolarised	f_1 unpolarised PDF		$f_{1T}^{\perp}$ (k_T) Sivers
longitudinally polarised		g_1 helicity	$g_{1T}^{\perp}$ worm-gear T
transversely polarised	$h_1^{\perp}$ Boer-Mulders	$h_{1L}^{\perp}$ worm-gear L	h_1 transversity; $h_{1T}^{\perp}$ pretzelosity

- Contributions of f_1, g_1 and h_1 survive the integration over k_T
- The other 5 distributions describe correlations between the quark's k_T, its spin and the nucleon's spin
- Most of these TMD PDFs can be accessed in COMPASS from

SIDIS and DY

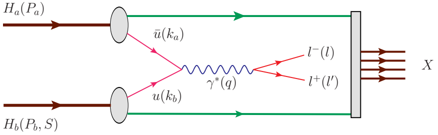


SIDIS: PDF ⊗ FF



DY: PDF ⊗ PDF

Single polarised DY



- $s = (P_a + P_b)^2$
- $x_{a(b)} = q^2/(2P_{a(b)} \cdot q)$
- $x_F = x_a - x_b$
- $Q^2 = q^2 = {M_{\mu\mu}}^2 = s x_a x_b$
- $q_T = k_{T\,a} + k_{T\,b}$

DY is an excellent tool to access TMD PDFs at COMPASS:

- No fragmentation functions involved, but the convolutions of 2 PDFs.
- All the TMD PDFs are expected to be sizeable in the valence quark region - dominant region when π^- is used as beam
- QCD TMD approach valid for Q ($M_{\mu\mu} > 4$ GeV/c^2) $\gg \langle p_T \rangle \sim 1$ GeV/c

Very low cross-section ☹

↓

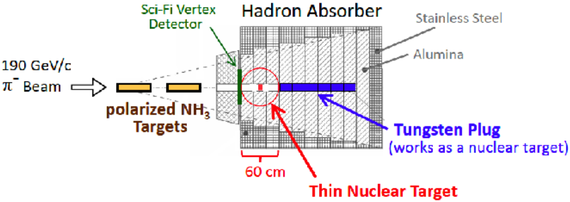
High intensity beam

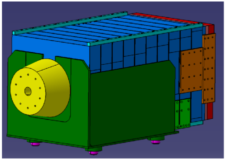
↓

Closed spectrometer adding a hadron absorber

Polarised DY programme

- π^- beam at 190 GeV/c
- two polarised NH_3 target cells

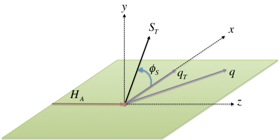


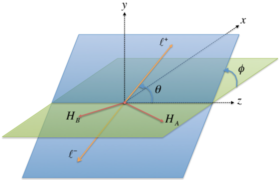


- Hadron absorber downstream of polarised target
  - Stops hadrons and non interacting beam ☺
  - Degrades resolutions ☹
- thin lithium foil in the dowstream part of the absorber to stop the slow neutrons produced in the absorber and reduce the radiation level in the first detectors
- Al and W targets → unpolarised DY studies → **See Takahiro Sawada's talk**

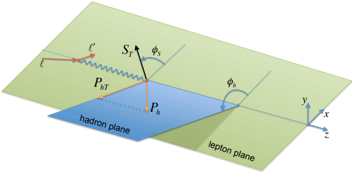
DY and SIDIS cross sections in terms of leading twist asymmetries

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



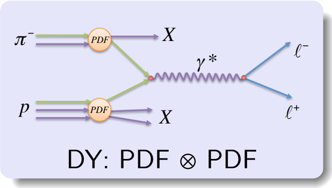


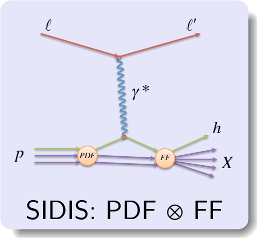
$$d\sigma^{SIDIS} \propto 1+\varepsilon\cos(2\phi_h)A_{UU}^{\cos(2\phi_h)}+S_T\Big[\sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_S)}+\varepsilon\sin(\phi_h+\phi_S)A_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+\varepsilon\sin(3\phi_h-\phi_S)A_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$



Leading twist asymmetries in DY and SIDIS - TMD PDFs

The **same nucleon PDFs** can be accessed through the two processes





DY		SIDIS
$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$
$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	transversity	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$	pretzelosity	$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$

Sivers function

Theoretical prediction of the Sivers sign change

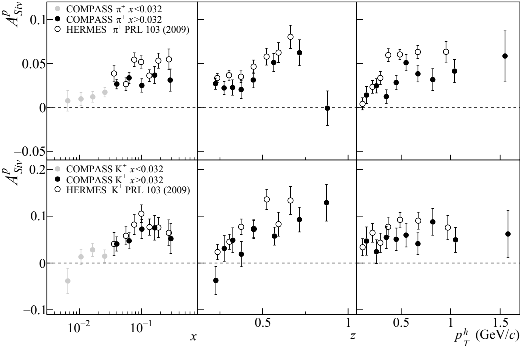
$$f_{1T}^{\perp}(x, k_T)|_{DY} = -f_{1T}^{\perp}(x, k_T)|_{SIDIS}$$

Crucial test of the QCD TMD approach

COMPASS SIDIS proton data from 2007 and 2010

Comparison between COMPASS and HERMES results

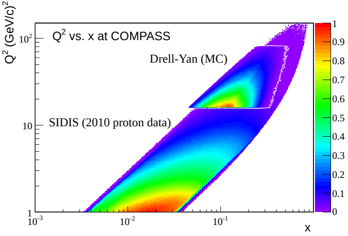
↪ Difference points to a possible Q^2 evolution effect



(COMPASS *PLB 744 (2015) 250*)

DY and SIDIS phase-space overlap at large Q^2

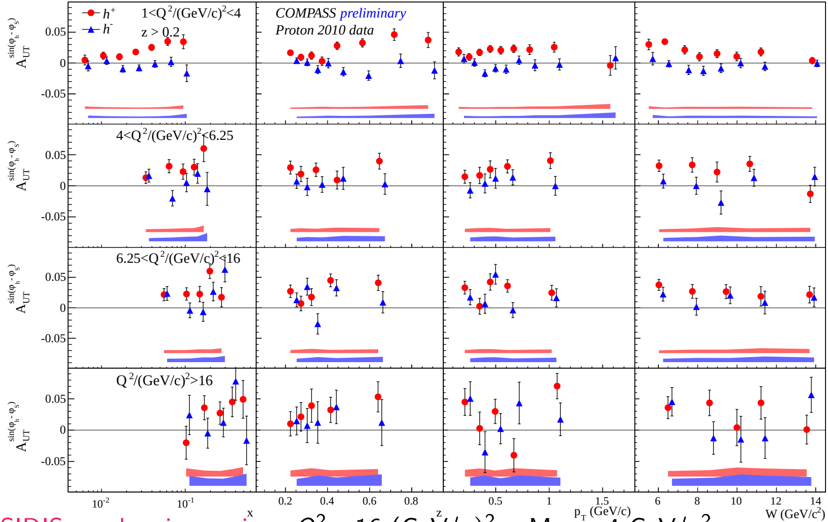
Avoid evolution effects



SIDIS Data MultiDimensional Analysis – Sivers asymmetry

2D analysis: 4 Q^2 ranges, each divided in bins of x, z, p_{Th}, W

Contribution for evolution studies



DY/SIDIS overlapping region: $Q^2 > 16\ (\mathrm{GeV}/c)^2 \equiv M_{\mu\mu} > 4\ \mathrm{GeV}/c^2$

Polarised DY data-taking at COMPASS

2009	2014	2015
π^- beam at 190 GeV/c		
2 C_2H_4 cells unpolarised	2 NH_3 cells unpolarised	2 NH_3 cells transversely polarised
$I_{beam} \sim 1.6 \times 10^7 \pi/s$	$I_{beam} \sim 6 \times 10^7 \pi/s$	$I_{beam} \sim 8.1 \times 10^7 \pi/s$
3 days data taking	17 days of stable data taking	4 months of stable data taking

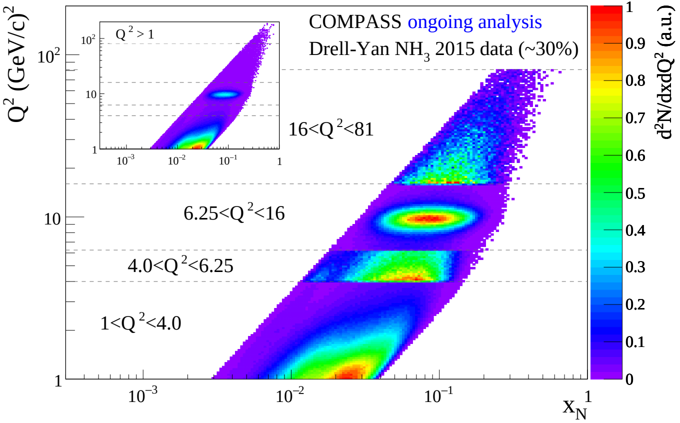
↓ Feasibility of the experiment

↓ First unpolarised high mass DY data

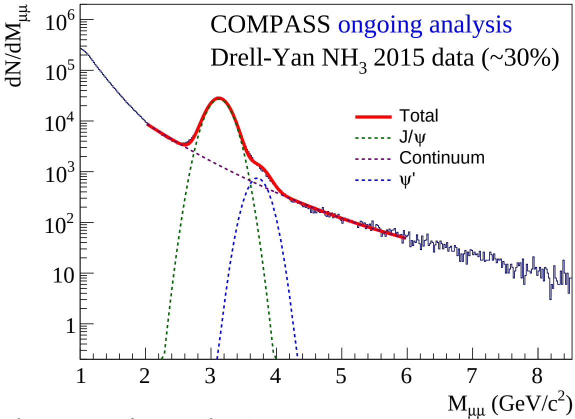
↓ First polarised DY data

Drell-Yan measurement - 2015 run

- Test production of 3/9 of the data collected in 2015
- Four mass ranges:
  - $1 < M_{\mu\mu} < 2$ GeV/c^2
  - $2 < M_{\mu\mu} < 2.5$ GeV/c^2
  - $2.5 < M_{\mu\mu} < 4$ GeV/c^2 $\rightarrow$ J/ψ region
  - $4 < M_{\mu\mu} < 9$ GeV/c^2 $\rightarrow$ High mass range



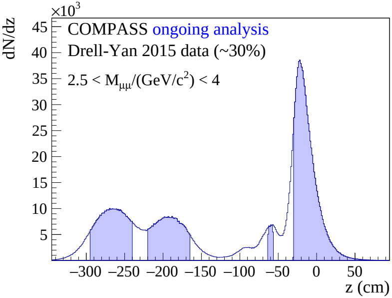
Dimuon mass distribution



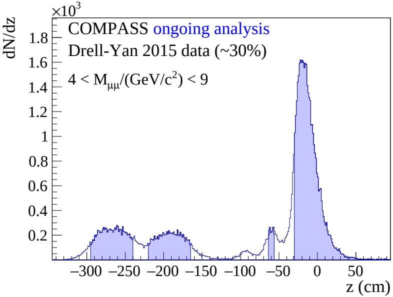
- Continuum has several contributions:
  - DY
  - Open Charm ($D\bar{D}$ decays into correlated muons)
  - Combinatorial Background (π and K decays into uncorrelated muons)
- small contamination for $M_{\mu\mu} > 4$ GeV/c^2 (mainly from ψ')

J/ψ and High mass regions

J/ψ region



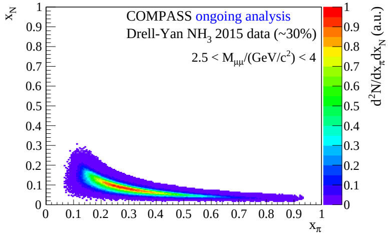
High mass region

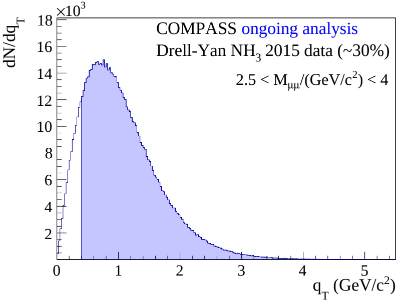


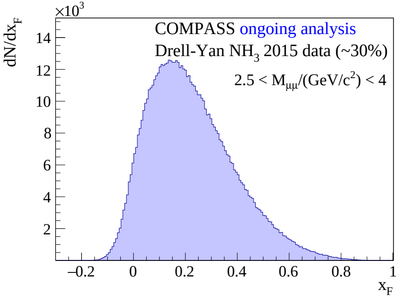
- All the targets are well separated (2 NH_3 cells, Al and W)
- For the asymmetry studies only the events from the NH_3 target cells are used $\sim 30\%$ of statistics from all targets
- The optimization of selection criteria is still under study

J/ψ region

- Much larger statistics wrt the high mass region, ~ 700k pairs but with several contributions
- Valence quarks region

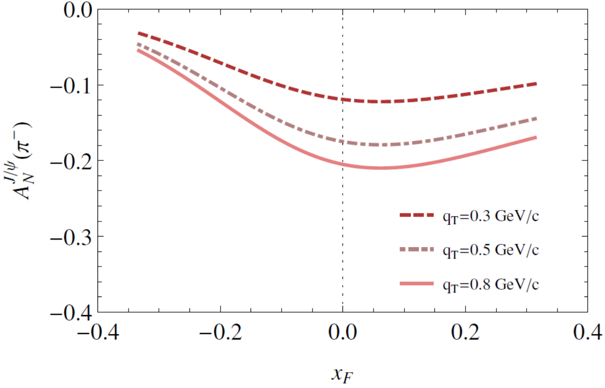






Sivers asymmetry prediction for J/ψ

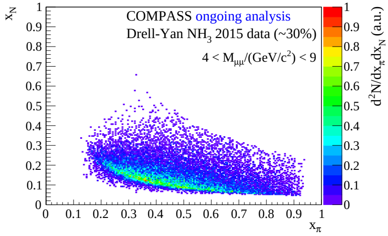
Recent publication from Anselmino *et al*, arXiv:1607.00275v1 (4 July)

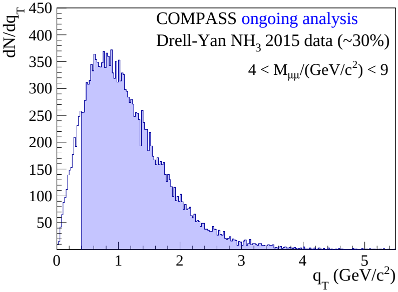


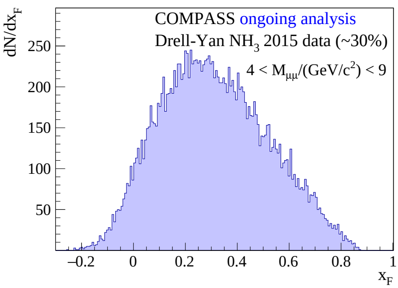
Significant Sivers asymmetry in COMPASS kinematic coverage
$\langle x_F \rangle \sim 0.2$ and $\langle q_T \rangle \sim 1.0$ GeV/c

High mass region: $4 < M_{\mu\mu} < 9$ GeV/c^2

- Valence quarks region
- $\langle q_T \rangle \sim 1$ GeV/c
- $\langle x_F \rangle \sim 0.3$

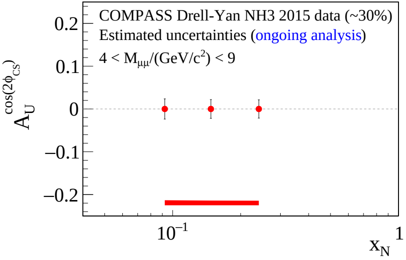




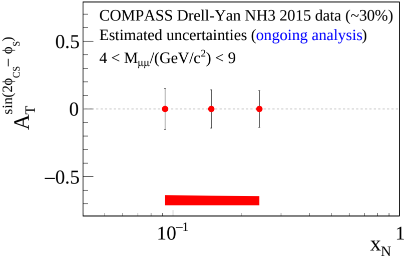


Asymmetries uncertainties in high mass range

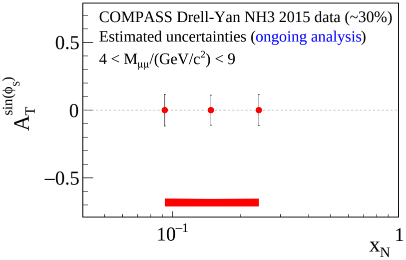
$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$ (Boer-Mulders)



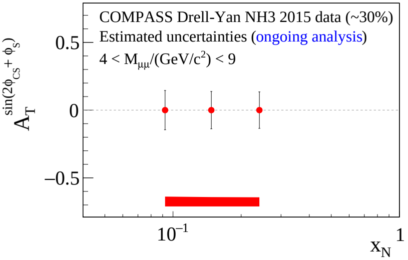
$A_{UT}^{\sin(2\phi-\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$(transversity)



$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$ (Sivers)



$A_{UT}^{\sin(2\phi+\phi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$(pretzelosity)



Future polarised DY programmes

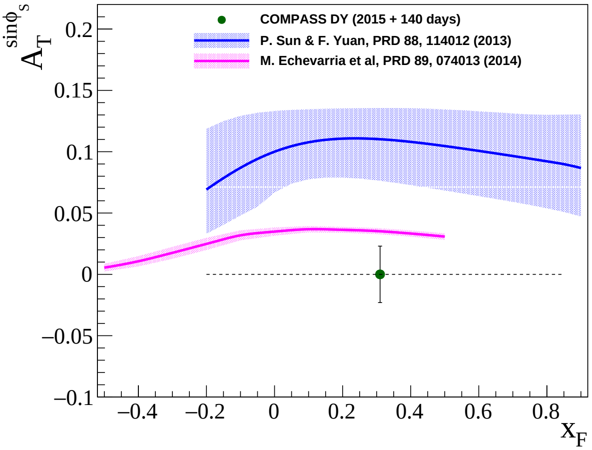
Worldwide plans to study TMD PDFs via the polarised DY process

Facility	type	timeline
COMPASS	fixed target, $\pi^- p^\uparrow$	2015 + 2018
Fermilab (SeaQuest)	fixed target, $p^\uparrow p$	$>$ 2016
RHIC (STAR*, PHENIX)	collider, $p^\uparrow p$	$>$ 2016
J-PARC	fixed target, $p^\uparrow p$	$>$ 2018
FAIR (Panda)	collider, $\bar{p}^\uparrow p^\uparrow$	$>$ 2018
JINR (NICA)	collider, $p^\uparrow p^\uparrow$	$>$ 2018

*STAR results on TSA in $p^\uparrow + p \to W^\pm/Z^0$ (PRL 116, 132301(2016)) corresponds to a very high $Q^2 \sim 80^2$ (91^2) $(\text{GeV}/c^2)^2$ and favour theoretical models that include a change of sign for the Sivers function, if TMD evolution effects are small.

Projected Sivers asymmetry uncertainty

2015 data + 2018 assuming 140 days



- $\sim 2.3\%$ statistical uncertainty
- Estimated systematic smaller than statistical

Final remarks

- The first ever polarised DY measurement using π^- beam and proton polarised target was done by COMPASS in 2015.
  $\hookrightarrow$ These data are being analysed.
- Unique opportunity to extract the TMD PDFs from both SIDIS and DY in the same experiment.
- DY results will be fundamental to test the Sivers sign change prediction.
- The possibility to have a second year of polarised DY data taking in 2018 is about to be approved.

First COMPASS DY polarised data results on the asymmetries will be ready soon ☺