Fist measurement of transverse-spin-dependent azimuthal asymmetries in the Drell-Yan process

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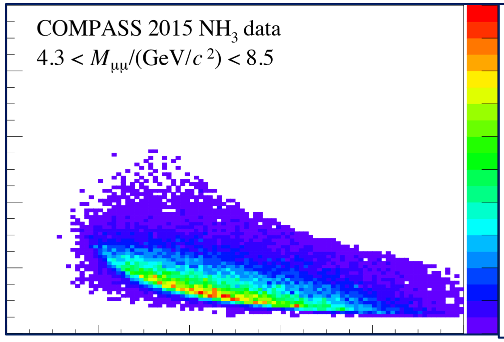
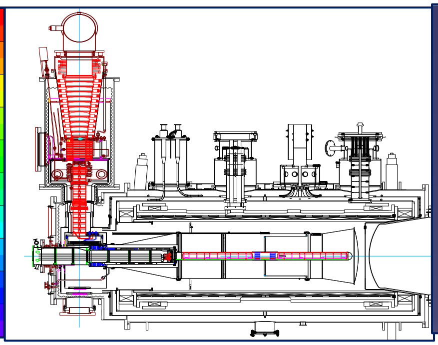
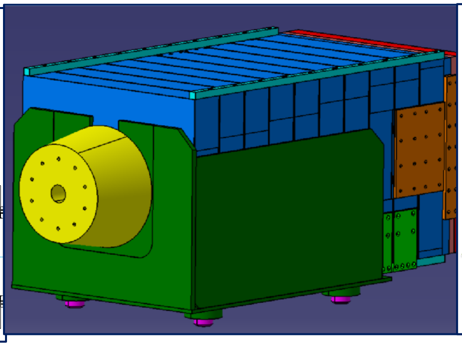
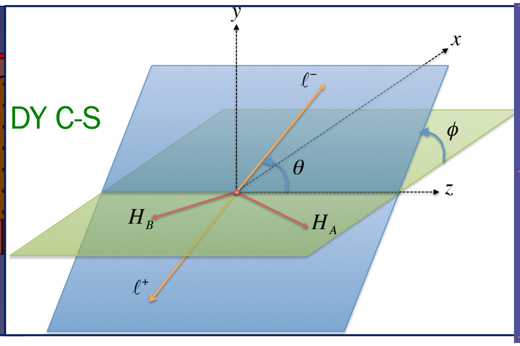
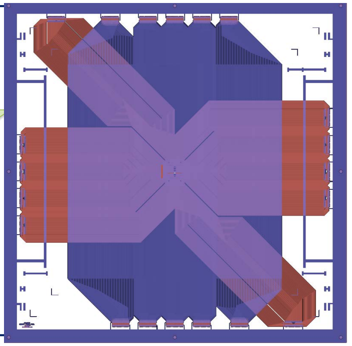
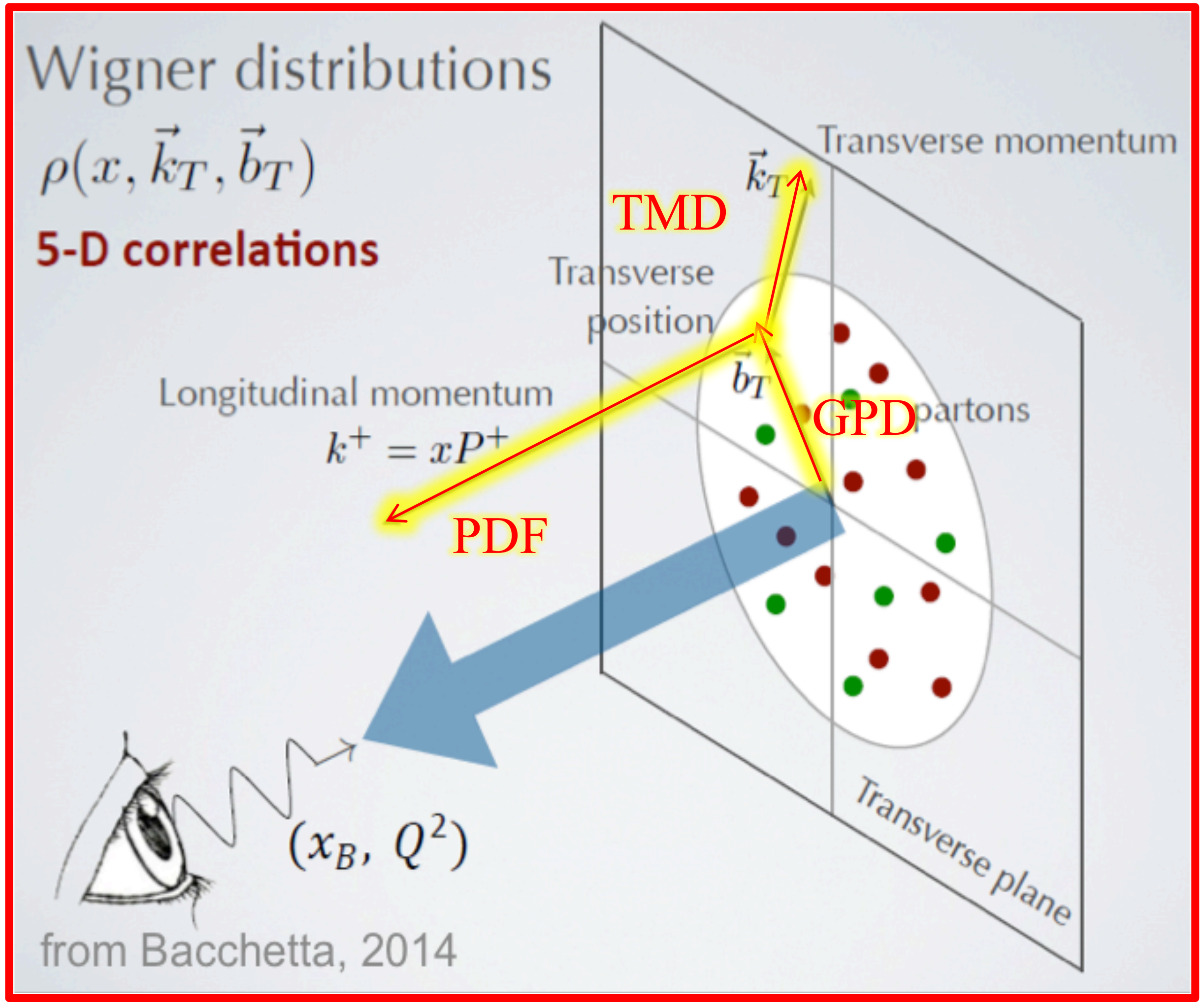




How are the quarks and gluons distributed inside the nucleon?

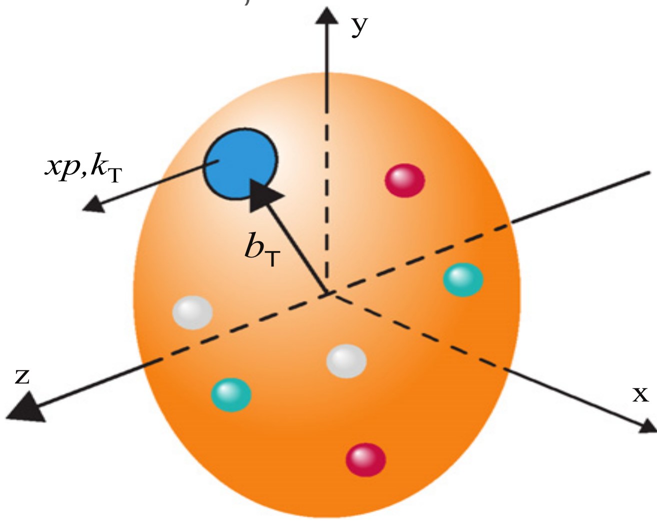
- Longitudinal structure
  - Longitudinal momentum, x_{Bj}
  - With DIS
- Transverse distributions
  - Transverse distance, b_T
  - With DVCS
  - Transverse momentum k_T
  - With SIDIS, Drell-Yan

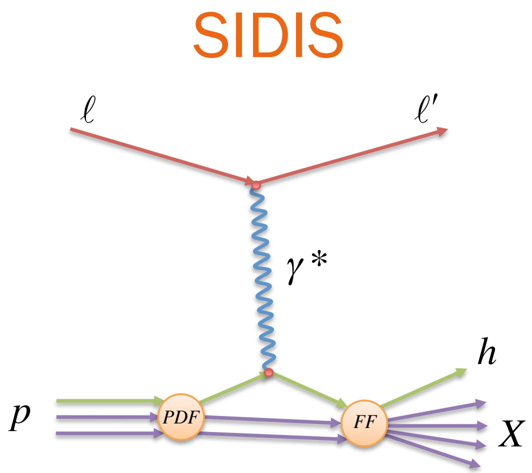


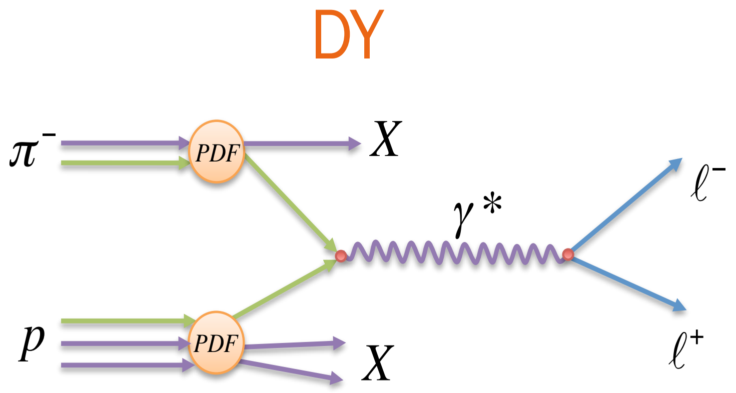
COMPASS experiment investigates the multidimensional structure of the nucleon

How to access TMD PDFs

- Goal of nucleon structure studies: distributions of partons inside the nucleon; understand their internal dynamics
  - Study PDF as a function of both x and $b_\perp$ (GPDs) or x and k_T (TMDs)







Assumption: the TMDs are universal (process-independent) ?

Collinear factorization (a pedestrian view)

- Factorization of short distance hard cross-section ⊗ the long-distance PDFs.
- Active partons are on shell and collinear:
  - $p_A, p_B << Q^2$;
  - $p_{TA}, p_{TB} << Q^2$
- Non-perturbative PDFs are universal

◆ Factorization theorems

Collins, Soper, Sterman, Adv. Ser. High En Phys. 5, 1988 + arXiv:hep-ph/0409313v1

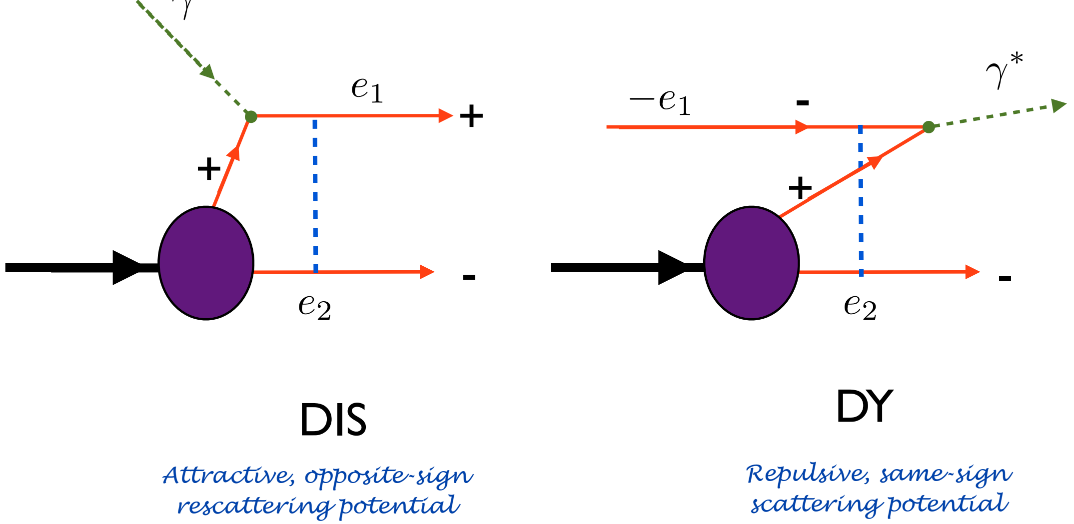
"The factorization formalism … is proved in the sense that all identified sources of leading power contributions are either factorizable or canceled in perturbative calculations to all orders in powers of α."

Peng and Qiu, PPNP 76 (2014) 43

TMD factorization (a pedestrian view)

- Collinearity no longer satisfied; transverse momentum to be taken into account
- The gauge links in TMDs are process-dependent (non universality)
- Gauge link are necessary to restore gauge invariance
- SIDIS vs DY: only a sign change --> modified universality for Sivers and Boer-Mulders

Brodsky et al., PRD 88, 014032 (2013)



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

Sivers TMD

Measurement of the sign-change: prove that the TMD factorization is correct

Transverse Momentum Dependent PDFs

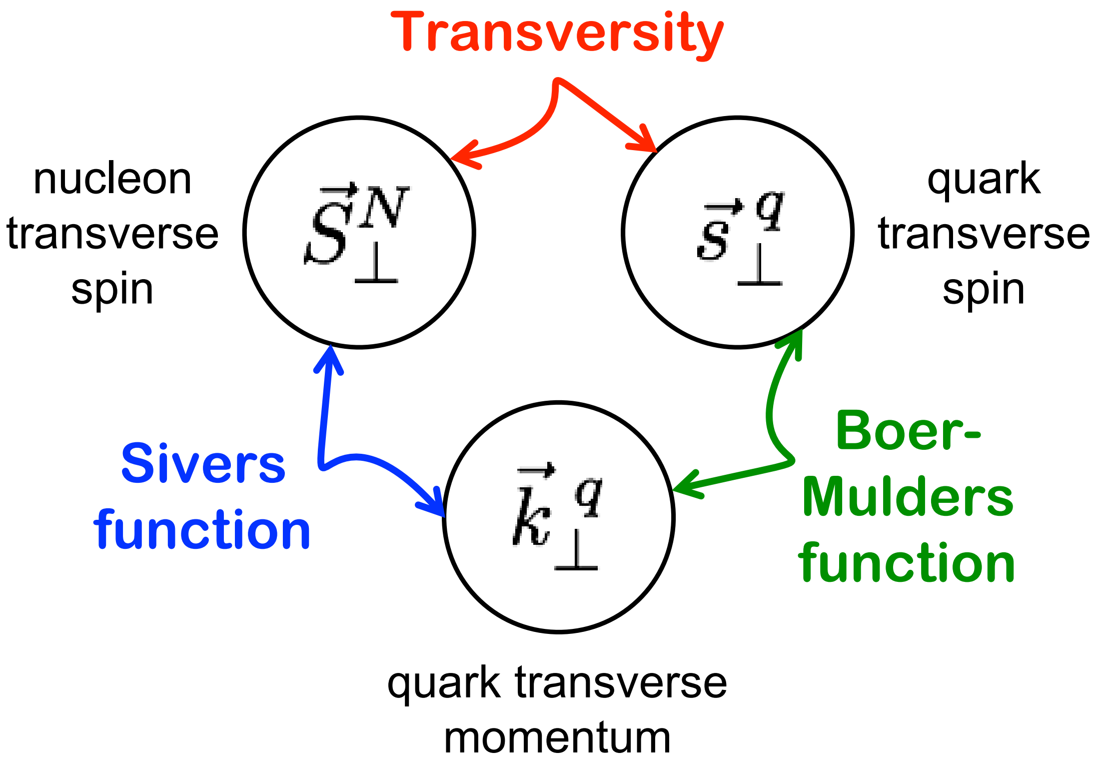
- 8 TMDs at leading twist

		nucleon polarization		
		U	**L**	**T**
quark polarization	**U**	f_1 *number density*		$f_{1T}^{\perp}$ *Sivers*
	L		g_1 *helicity*	g_{1T}
	T	$h_1^{\perp}$ *Boer-Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$

Sivers and BM TMDs are process-dependent (they have a “modified universality”)

TMDs and spin-momentum correlations

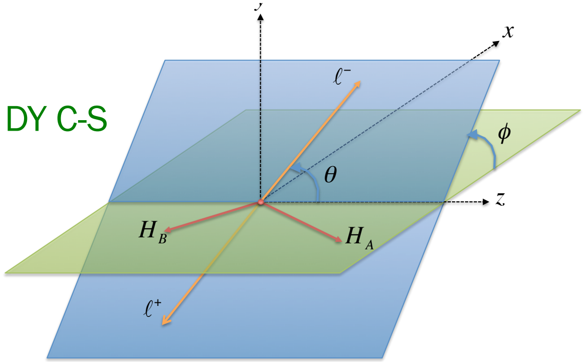
Correlations between transverse nucleon spin, quark spin and quark transverse momentum



Leading twist asymmetries in transversely polarized DY/SIDIS

Simultaneous measurement of all asymmetries

- Drell-Yan

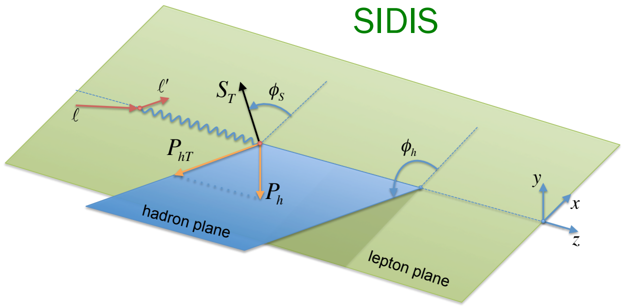


pion PDFs:

PDF: $h_{1,\pi}^{\perp q}$

BM: $f_{1,\pi}^{q}$

- SIDIS



Fragmentation functions:

Collins: $H_{1,q}^{\perp h}$

Unpol: $D_{1,q}^{h}$

unpolarized

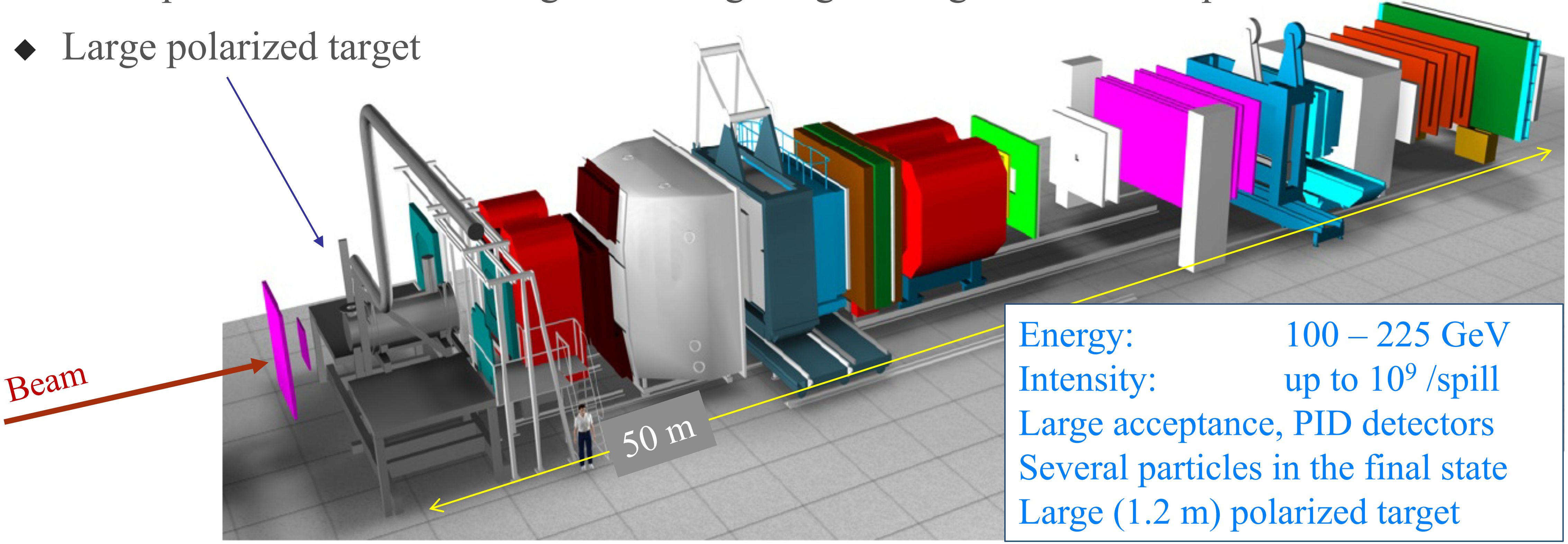
$A_{UU}^{\cos(2\phi)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$
$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes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

The four asymmetries are simultaneously extracted from either SIDIS or DY data

SIDIS measurement of the Sivers asymmetry

COMPASS : a large, fixed-target, versatile setup

- Beams: μ+ and μ−, π+ and π−, p, … − only place in the world!
- Built for detecting several particles in the final state
- Two spectrometers: Small-angle and Large-angle – large and flat acceptance
- Large polarized target

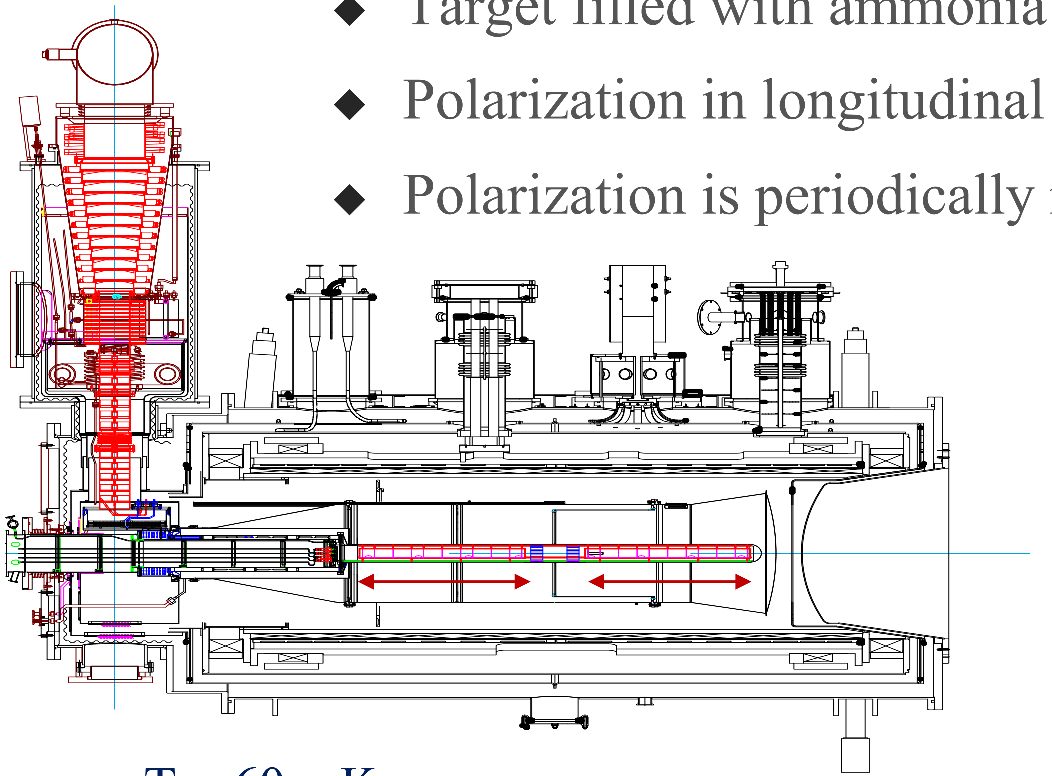


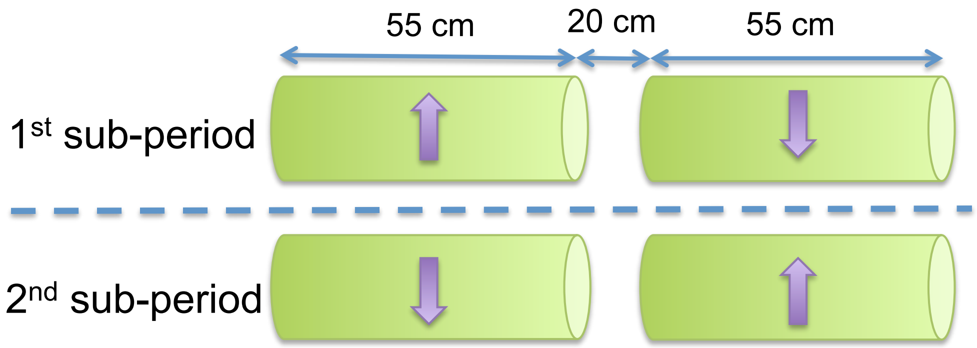
Energy: 100 – 225 GeV
Intensity: up to 10^9 /spill
Large acceptance, PID detectors
Several particles in the final state
Large (1.2 m) polarized target

Setup shown is used during SIDIS measurements

COMPASS polarized target

- Polarized target with two 55 cm long cells (for DY); three cells for SIDIS
- Superconducting magnets: solenoid + dipole
- Target filled with ammonia (NH_3) solid beads; also available: ^{6}LiD
- Polarization in longitudinal mode, data is taken in transverse mode
- Polarization is periodically reversed





T = 60 mK
B_s = 2.5 T, B_d = 0.6 T

Largest polarized target in the world
Coldest place at CERN

Semi-Inclusive DIS – Modulations and structure functions

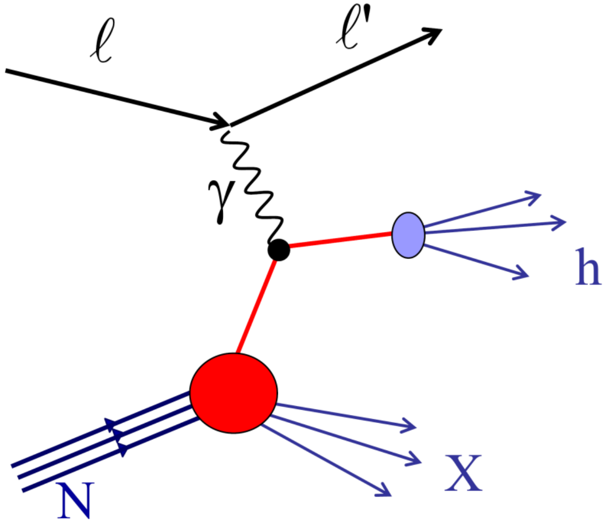
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =\ & \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\quad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

unpol target

$\rightarrow$ pol target

$\uparrow$ pol target

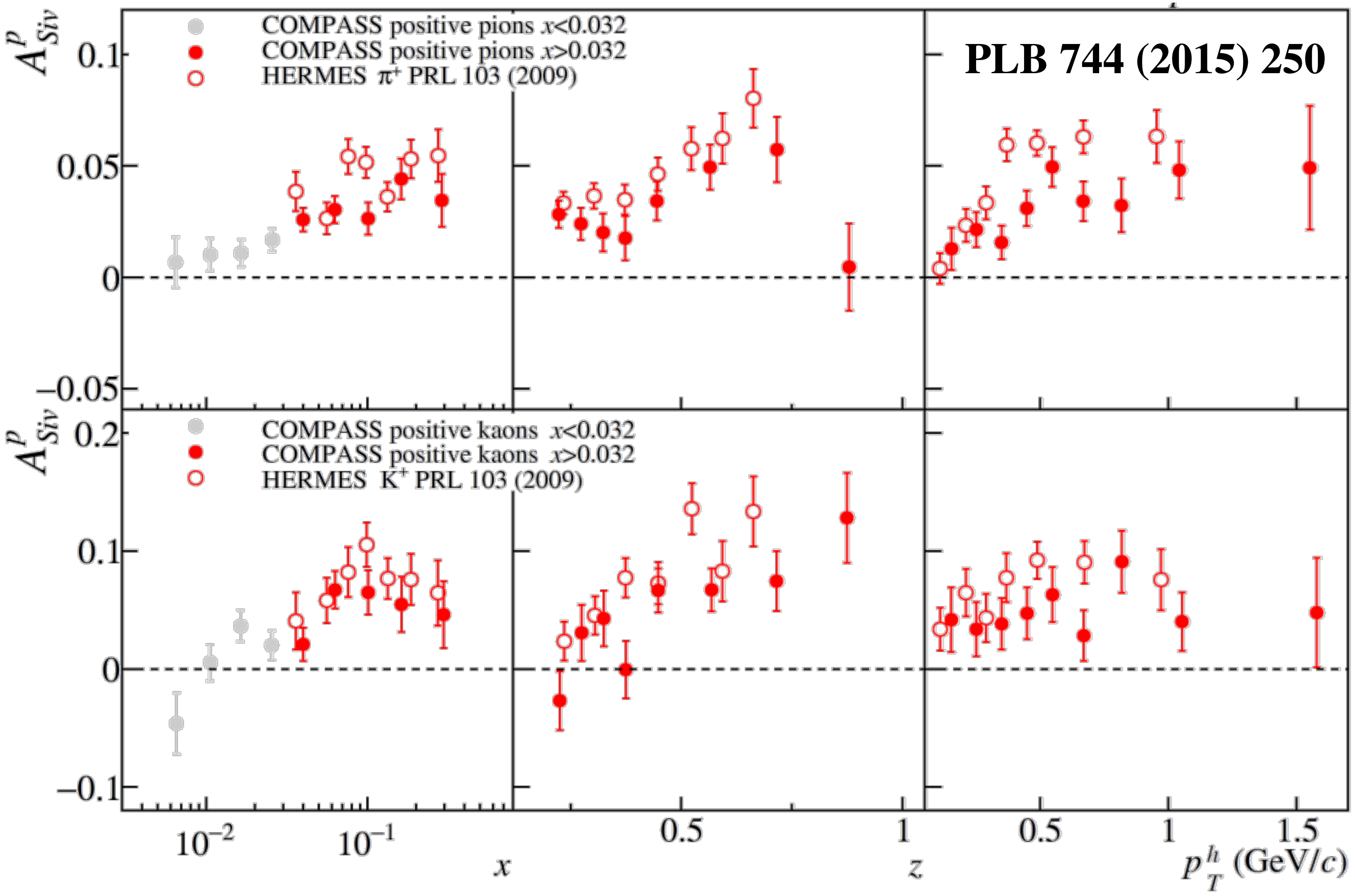
Sivers



$$A_{\mathrm{siv}} \approx \frac{\sum_q e_q^2\; f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2\; f_1^q \otimes D_{1q}^h}$$

SIDIS : measurement of all 14 structure functions.

SIDIS – Sivers Asymmetries on a proton target



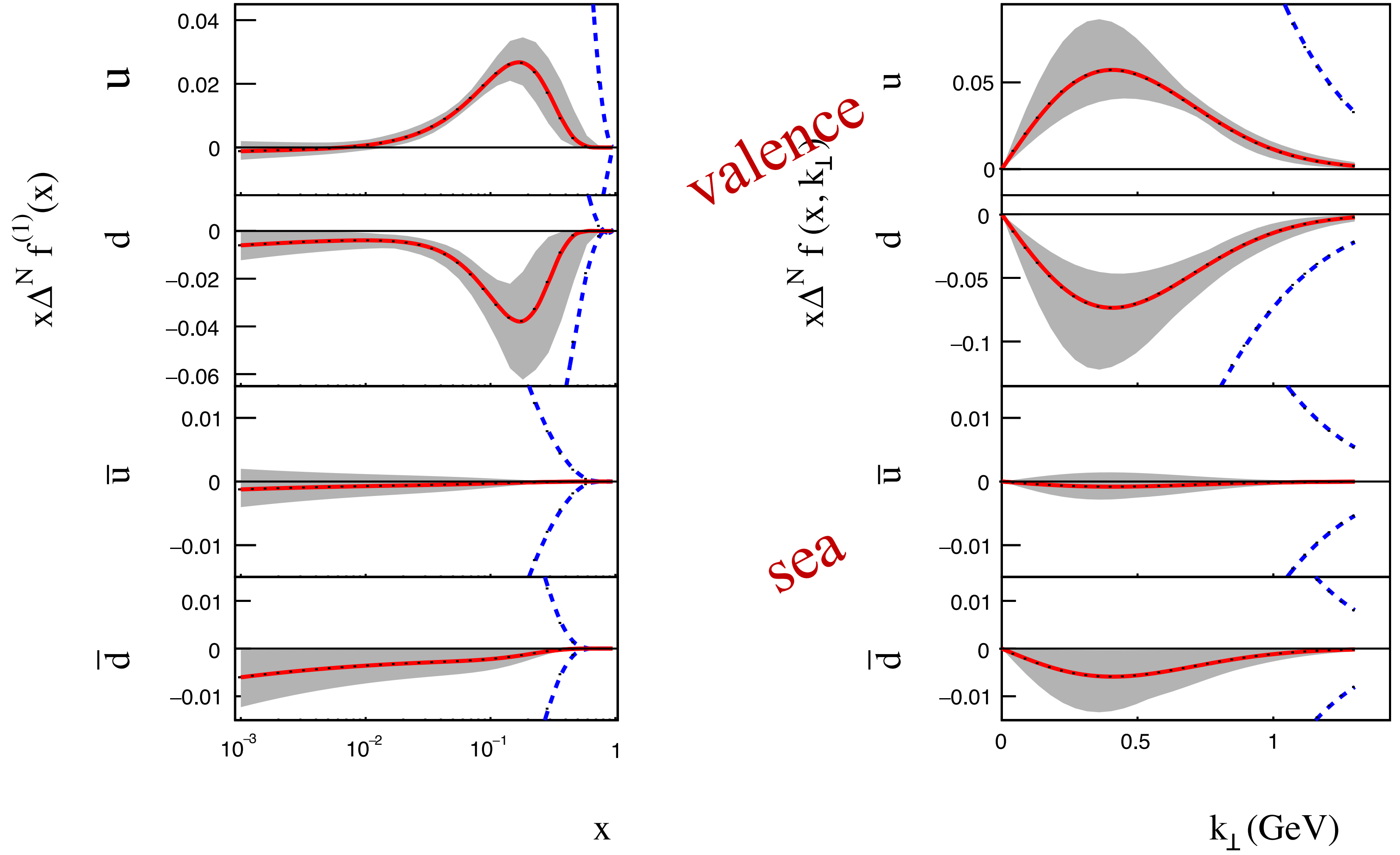
pions

kaons

Sivers asymmetries have been clearly observed

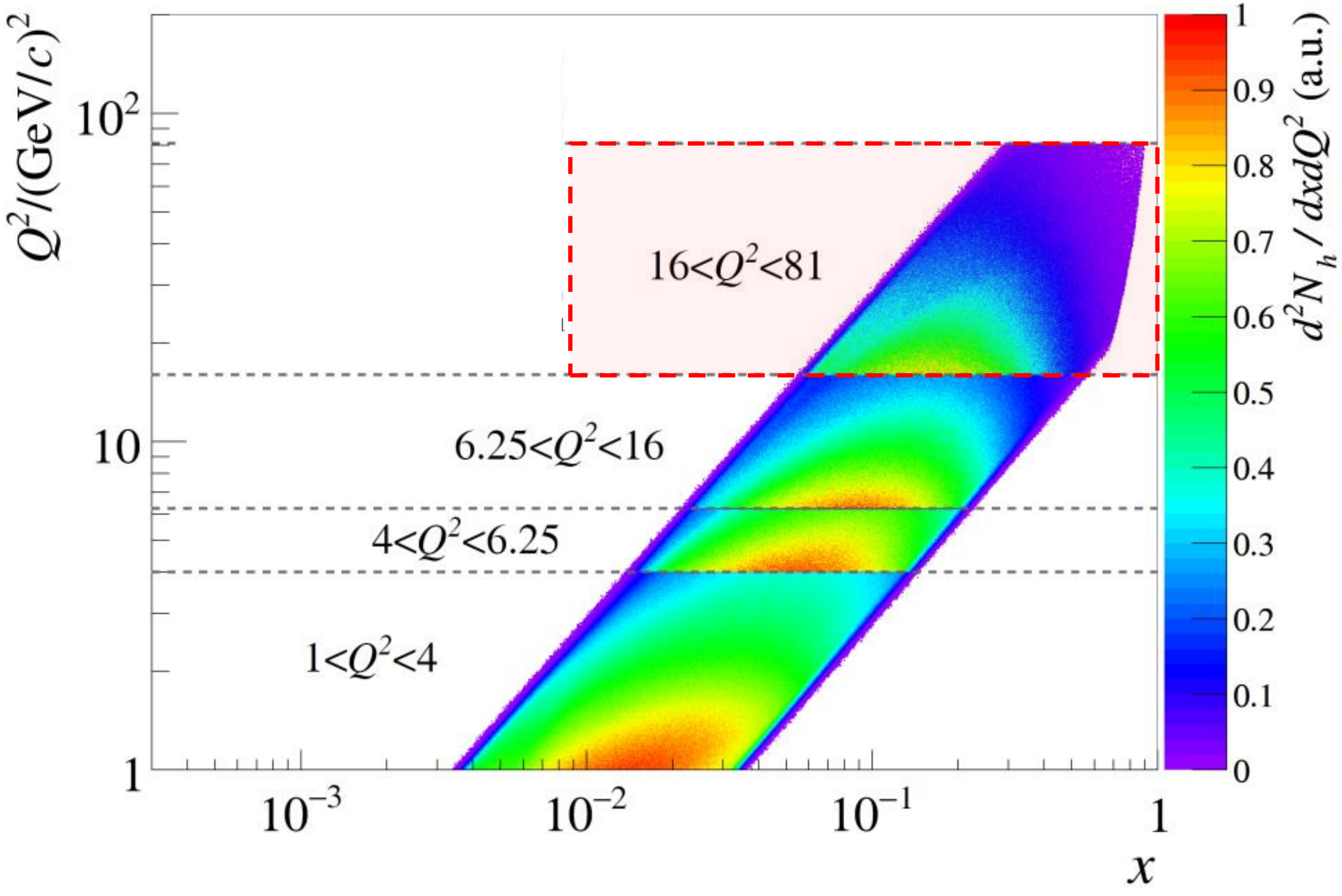
Sivers function – as extracted from the the data

Anselmino et al., JHEP1704 (2017) 046



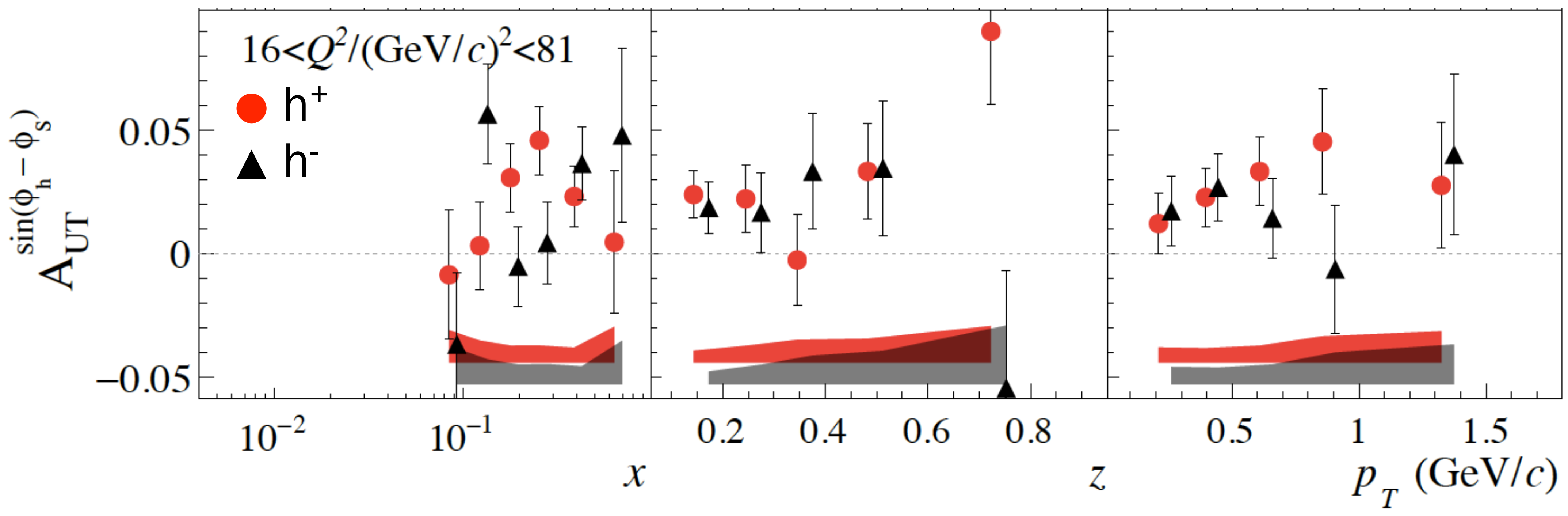
SIDIS Sivers TMD in the COMPASS Drell-Yan Q^2 range

COMPASS, Adolph et al., PL B770 (2017) 138



SIDIS asymmetry in the Drell-Yan mass range

COMPASS, Adolph et al., PL B770 (2017) 138



Sivers asymmetry is positive in the Drell-Yan Q^2 range

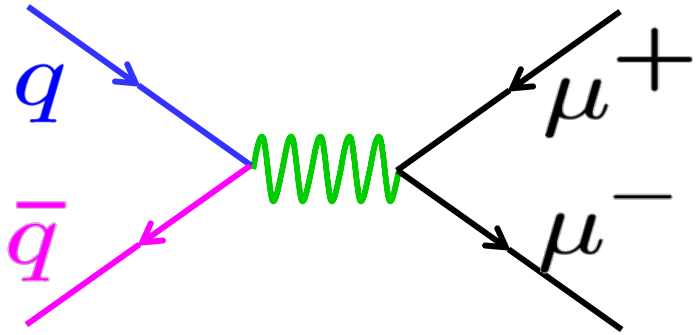
Drell-Yan measurement of the Sivers asymmetry

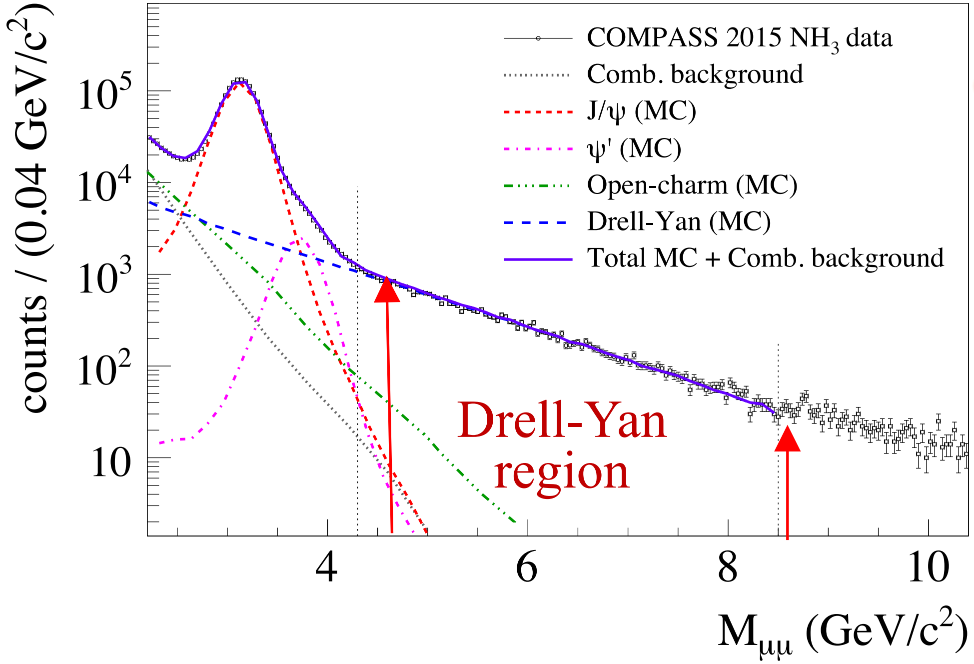
Drell-Yan cross section

- Convolution of two PDFs

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^4}\frac{x_1 x_2}{x_1 + x_2}\sum_a e_a^2\left[q_a(x_1)\bar{q}_a(x_2) + \bar{q}_a(x_1)q_a(x_2)\right]$$

$$Q^2 = M_{\mu\mu}^2$$





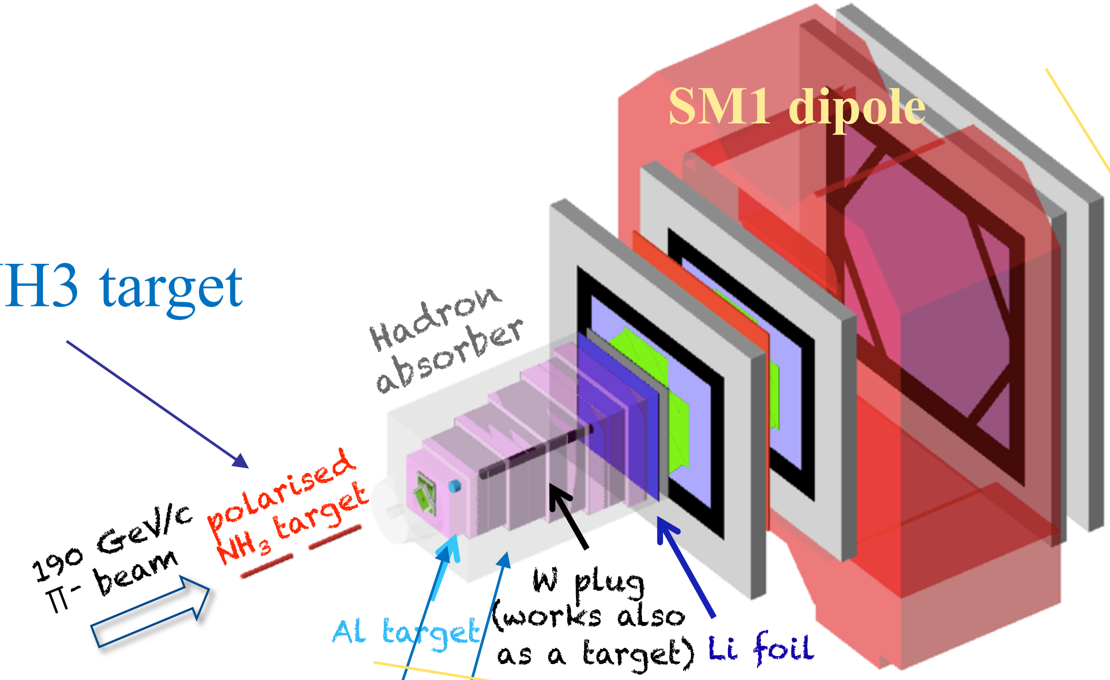
- At order (α_s^0) : a purely electromagnetic process
- NLO and NNLO corrections are well known

Drell-Yan is a well understood process

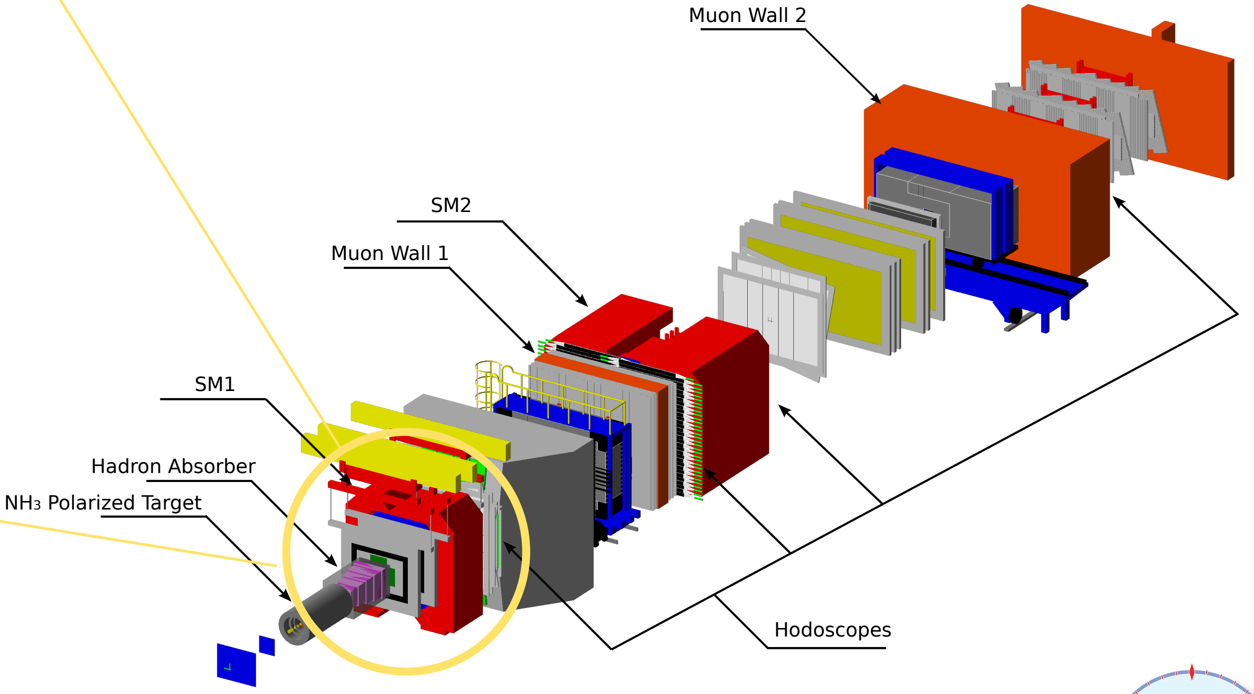
COMPASS – Drell-Yan setup

- Large hadron absorber, with a central Tungsten plug

NH3 target

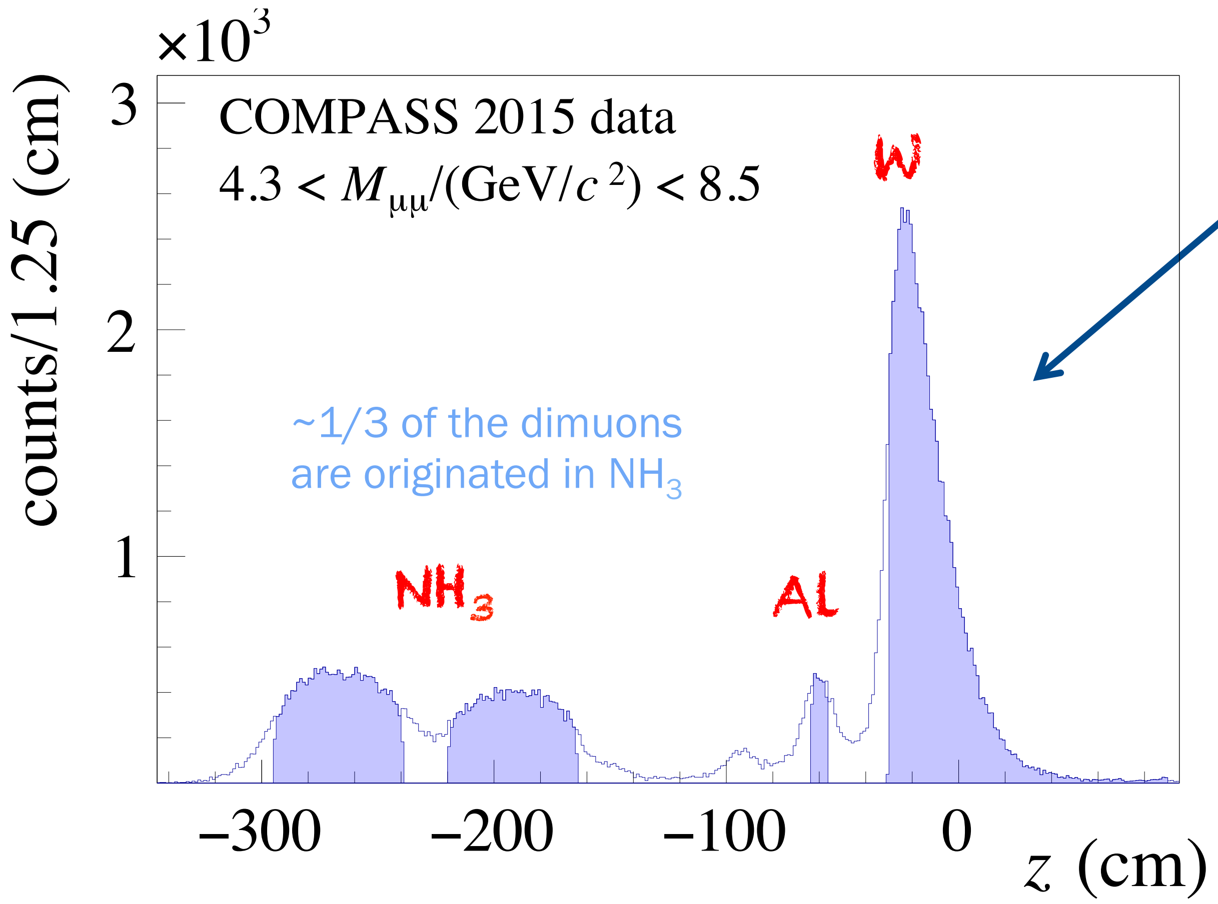


Al + W targets



Drell-Yan data taking: 2015 and 2018

Vertex distribution



W is 120 cm long but the majority of the beam interacts in its beginning

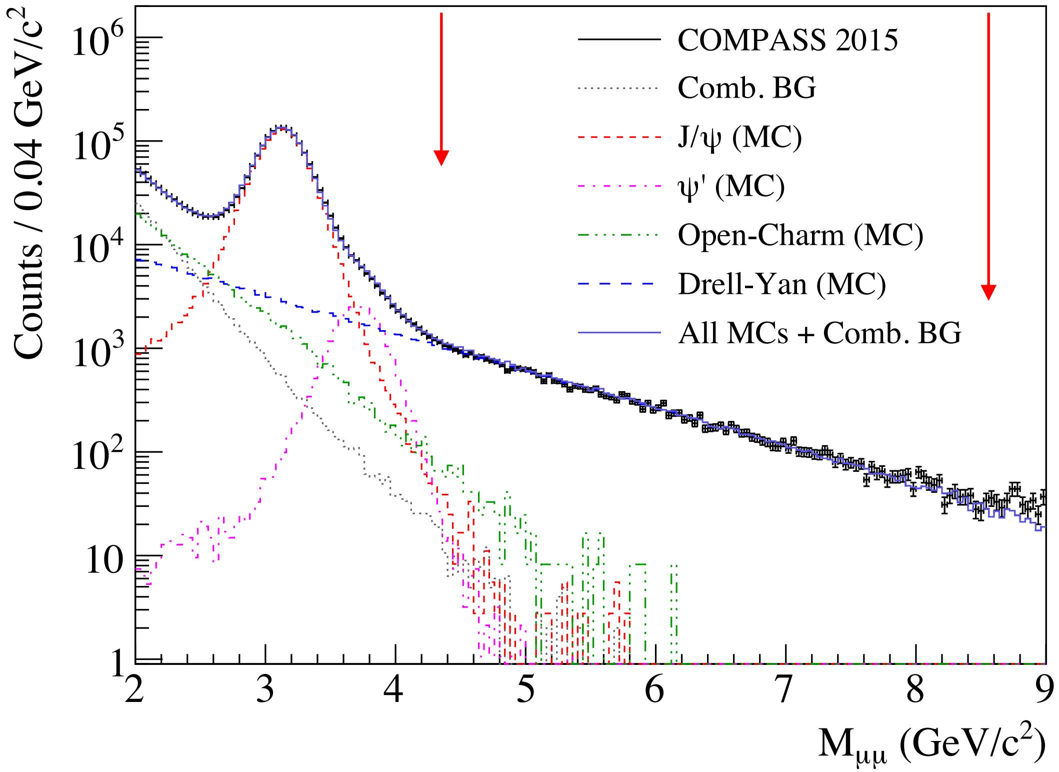
For TSAs analyses:
Only events from NH_3 cells are polarised

For unpolarised analyses:
Events from all 3 target types are useful

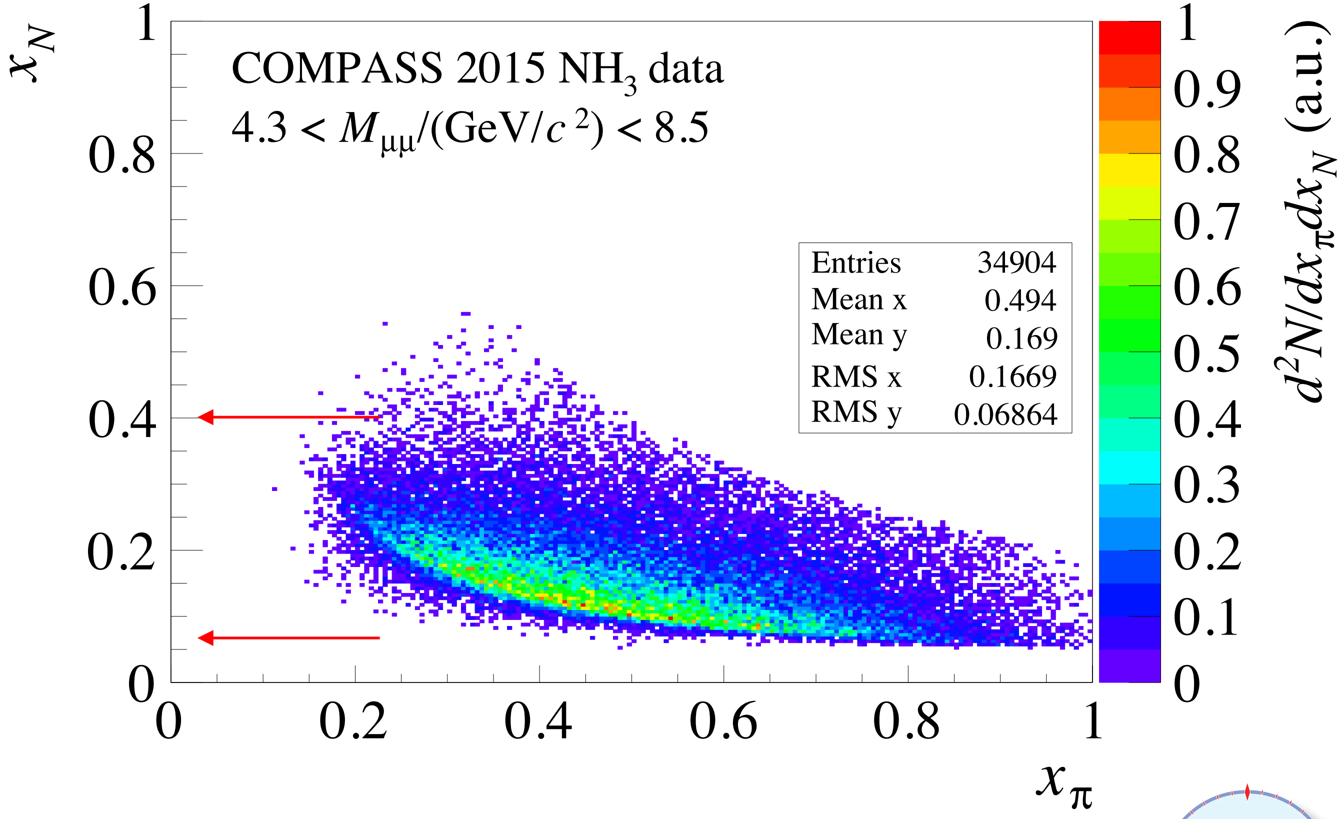
Di-muon sample – some results from 2015

- Drell-Yan data from 2015: 4.3 – 8.5 GeV/c^2

Mass spectrum



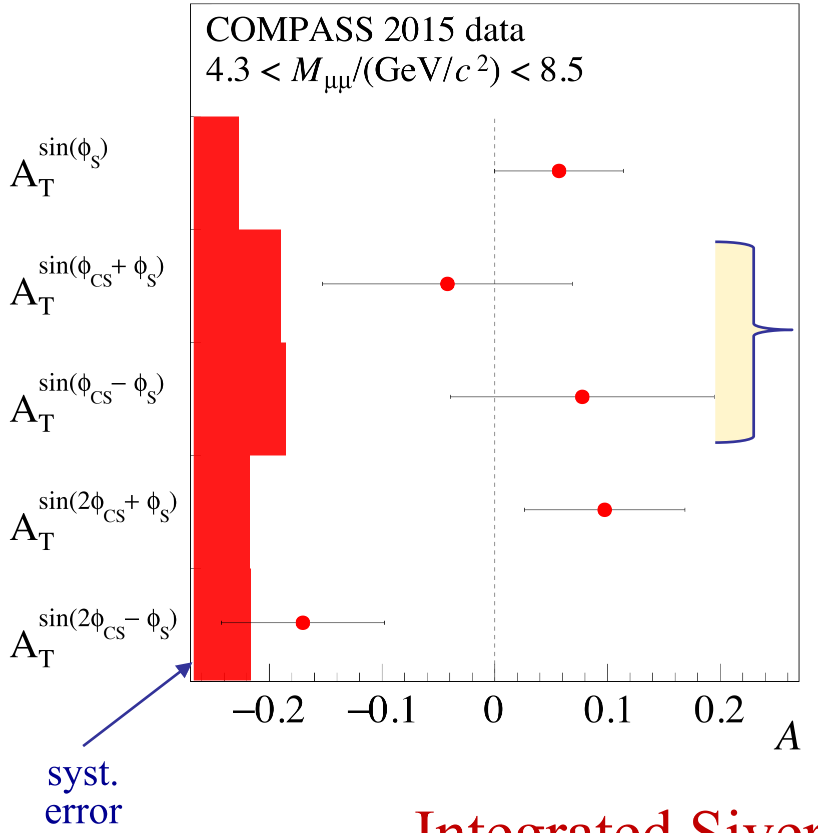
x_N vs x_π distribution



First Transverse Spin Asymmetries (TSA) results

Adolph et al. PRL 119, 112002 (2017).

- Averaged TSAs for 2015 data



Density PDF (π) ⊗ Sivers (p)

Higher twist asymmetries

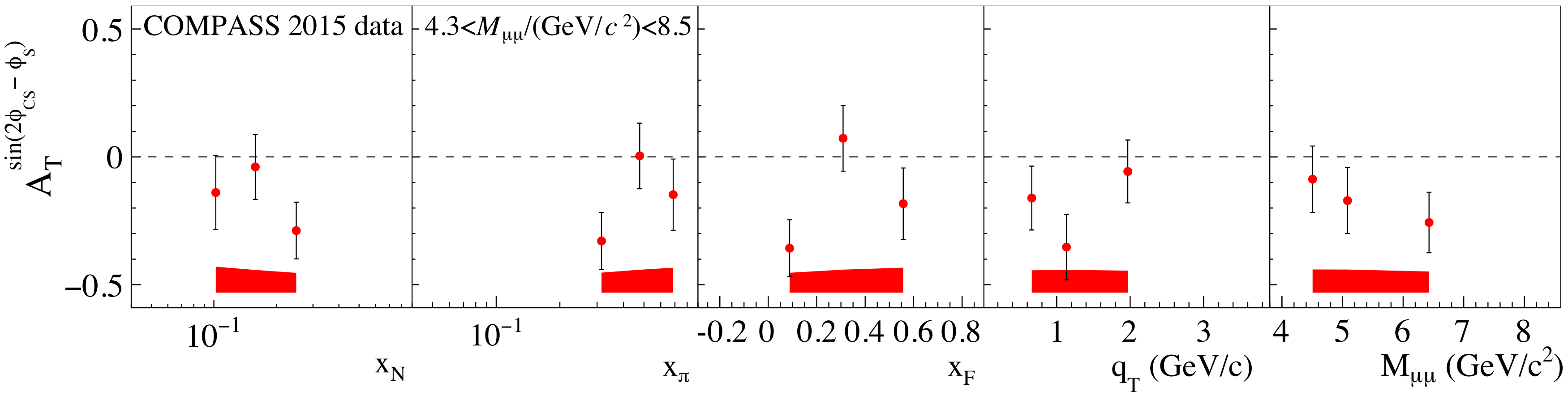
BM PDF (π) ⊗ Pretzelosity (p)

BM PDF (π) ⊗ Transversity (p)

Integrated Sivers asymmetry is positive (within one sigma)
Transversity is negative (two sigma), Pretzelosity positive (one sigma)

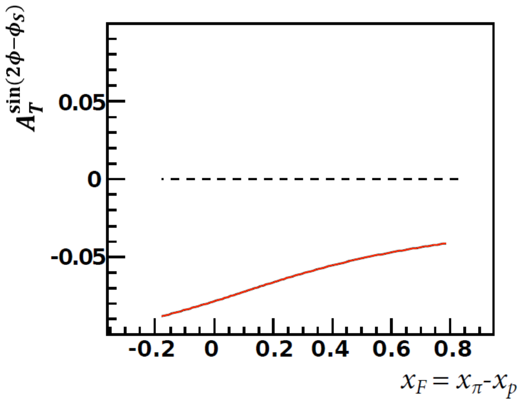
Drell-Yan : Transversity asymmetry

Adolph et al. PRL 119, 112002 (2017).



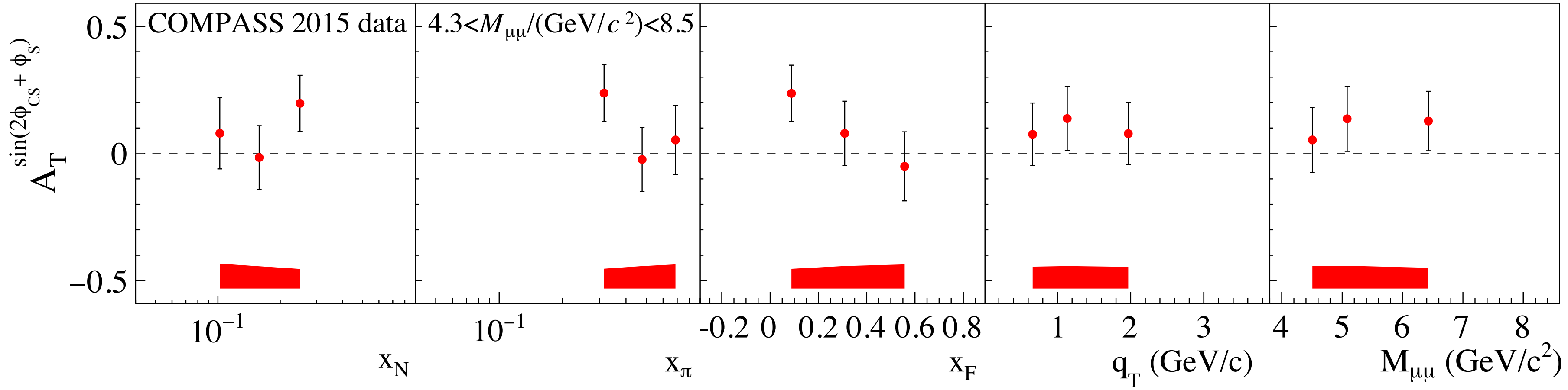
A. N. Sissakian et al.,
Phys. Part. Nucl. 41 (2010) 64

Compatible with our measurement

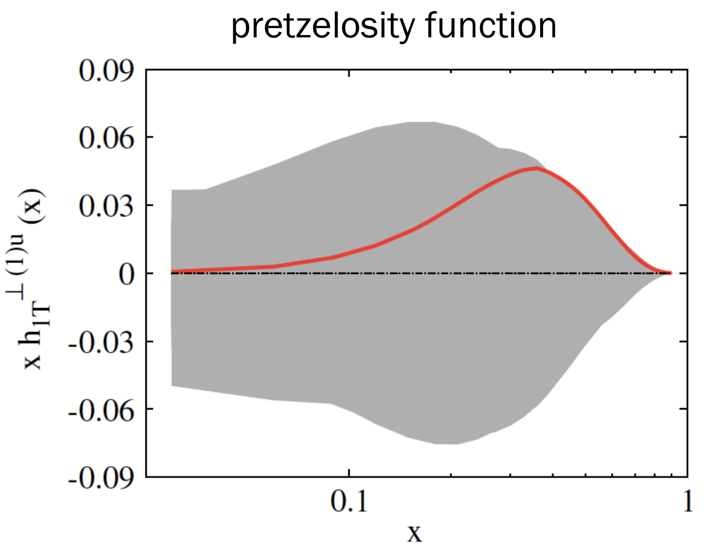


Drell-Yan : pretzelosity asymmetry

Adolph et al. PRL 119, 112002 (2017).



Asymmetry from SIDIS: Measurement compatible with zero within uncertainties

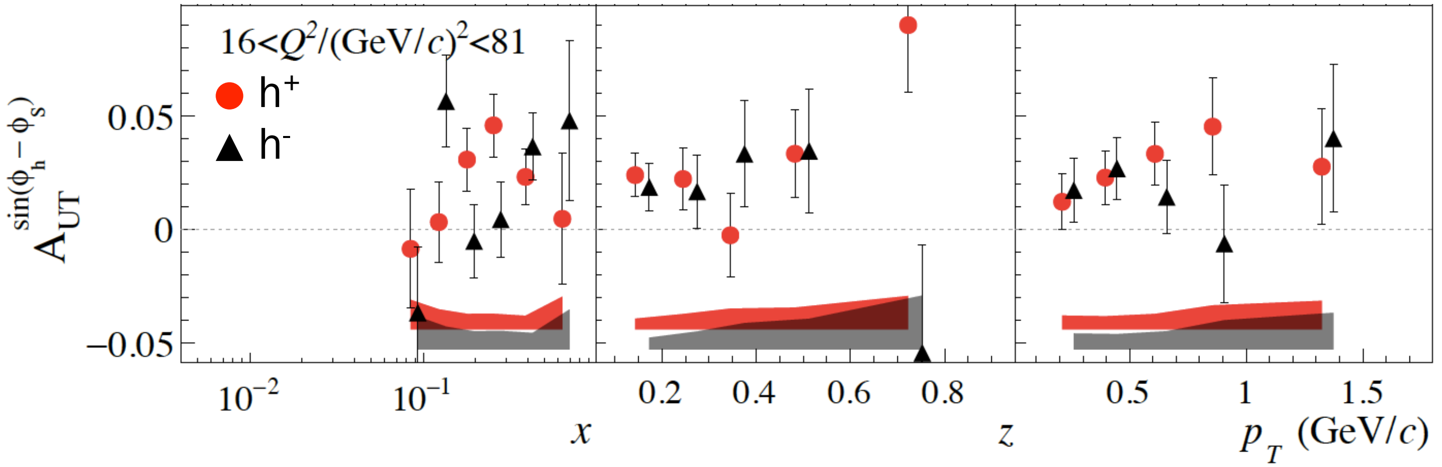


C. Lefky and A. Prokudin, PRD 91 (2015) 034010 **pretzelosity** function for **u quark** extracted from a fit to COMPASS, HERMES and JLab **SIDIS data**

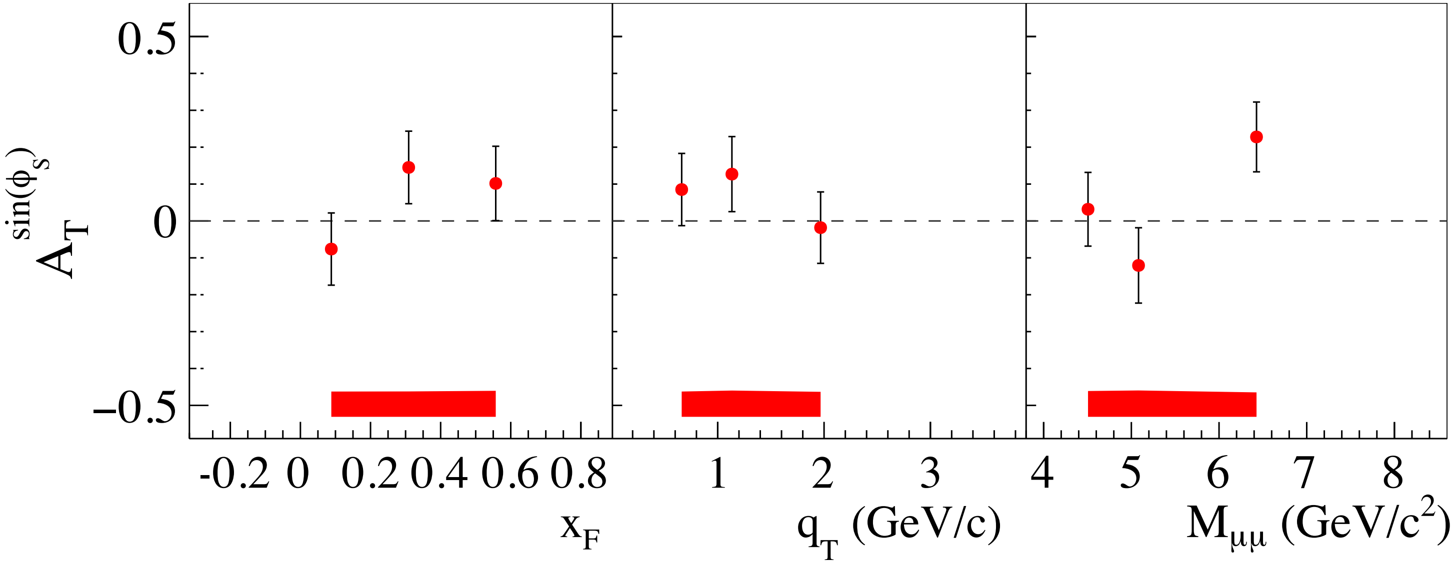
Transversity and pretzelosity TMDs have the same sign in SIDIS and DY

Sivers asymmetry : SIDIS vs Drell-Yan

SIDIS data Compass,
same Q^2 range as in DY

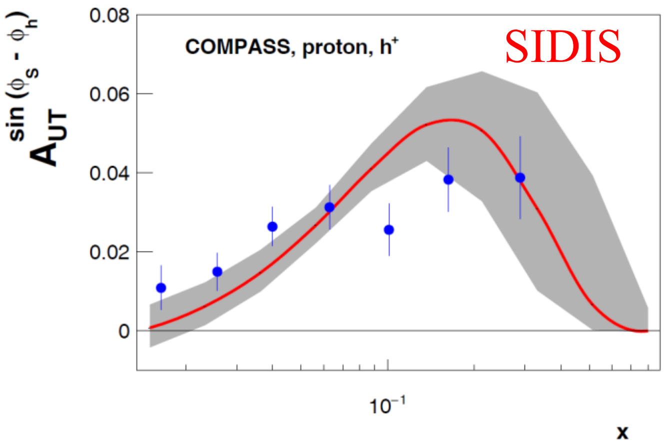


Drell-Yan data Compass
data range: 4.3 – 8.5 GeV

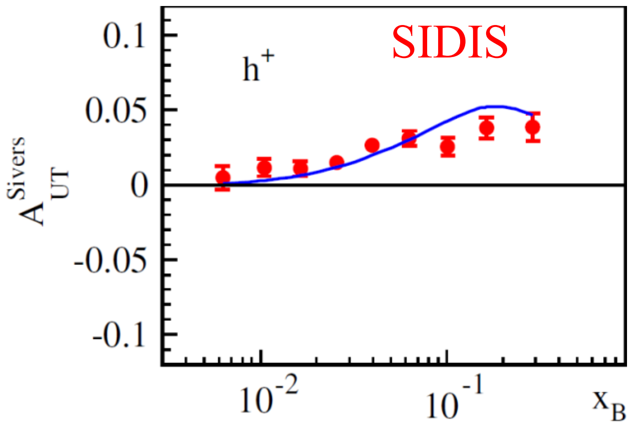


Sivers asymmetry in SIDIS : used to predict the Drell-Yan asymmetry

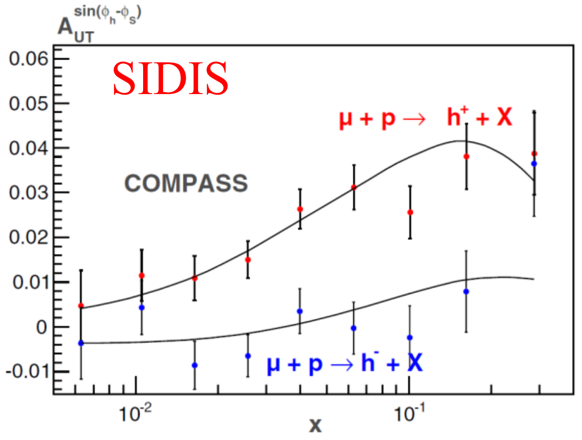
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



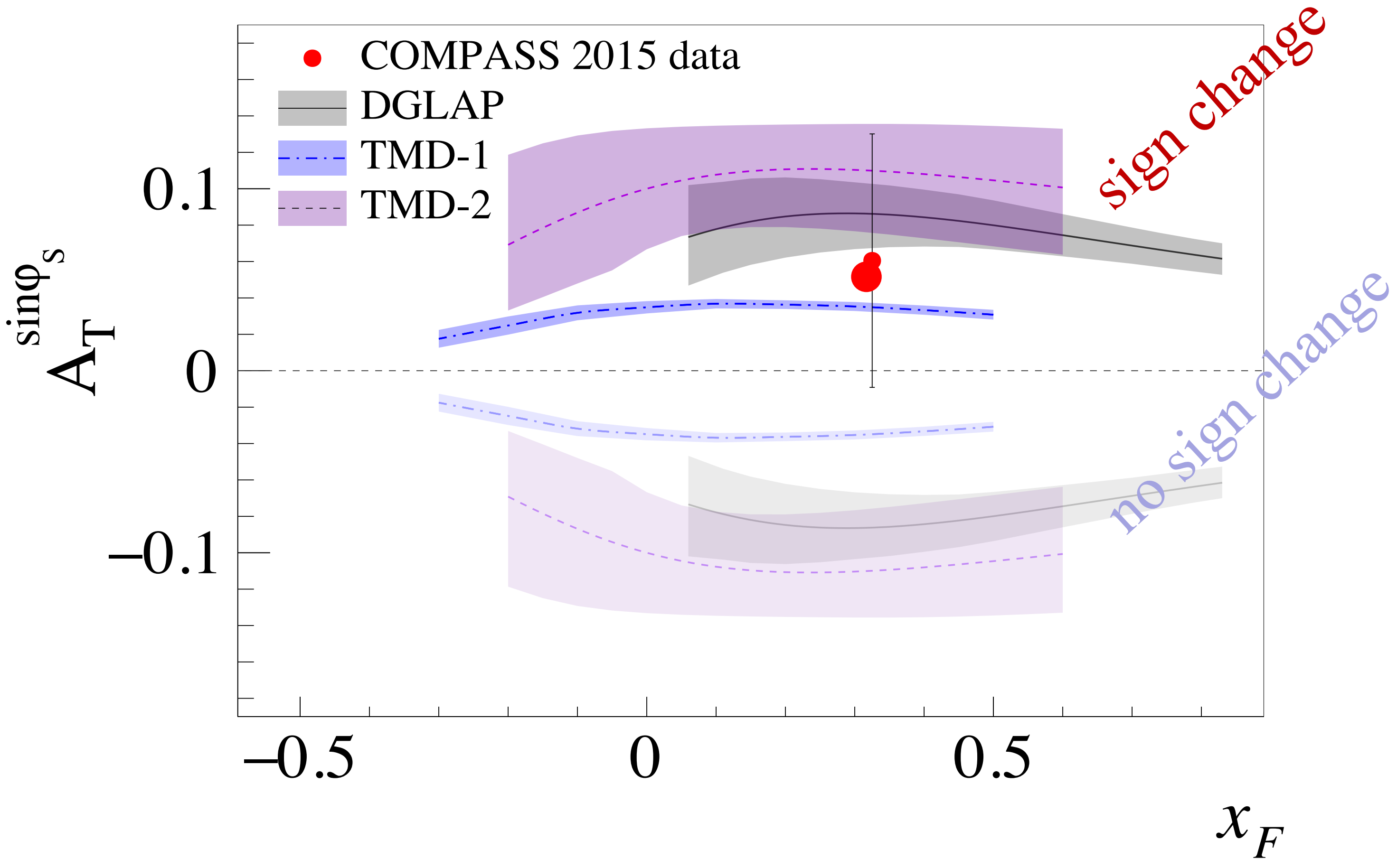
All theoretical calculation take into account the sign change

Final Drell-Yan Sivers asymmetry

unp. PDF Sivers

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

DGLAP: Anselmino et al. arXiv:1612.06413
TMD1: Echevarria et al. Phys Rev D89, 074013 (2014)
TMD2: Sun and Yuan, Phys Rev D88, 114012 (2013)



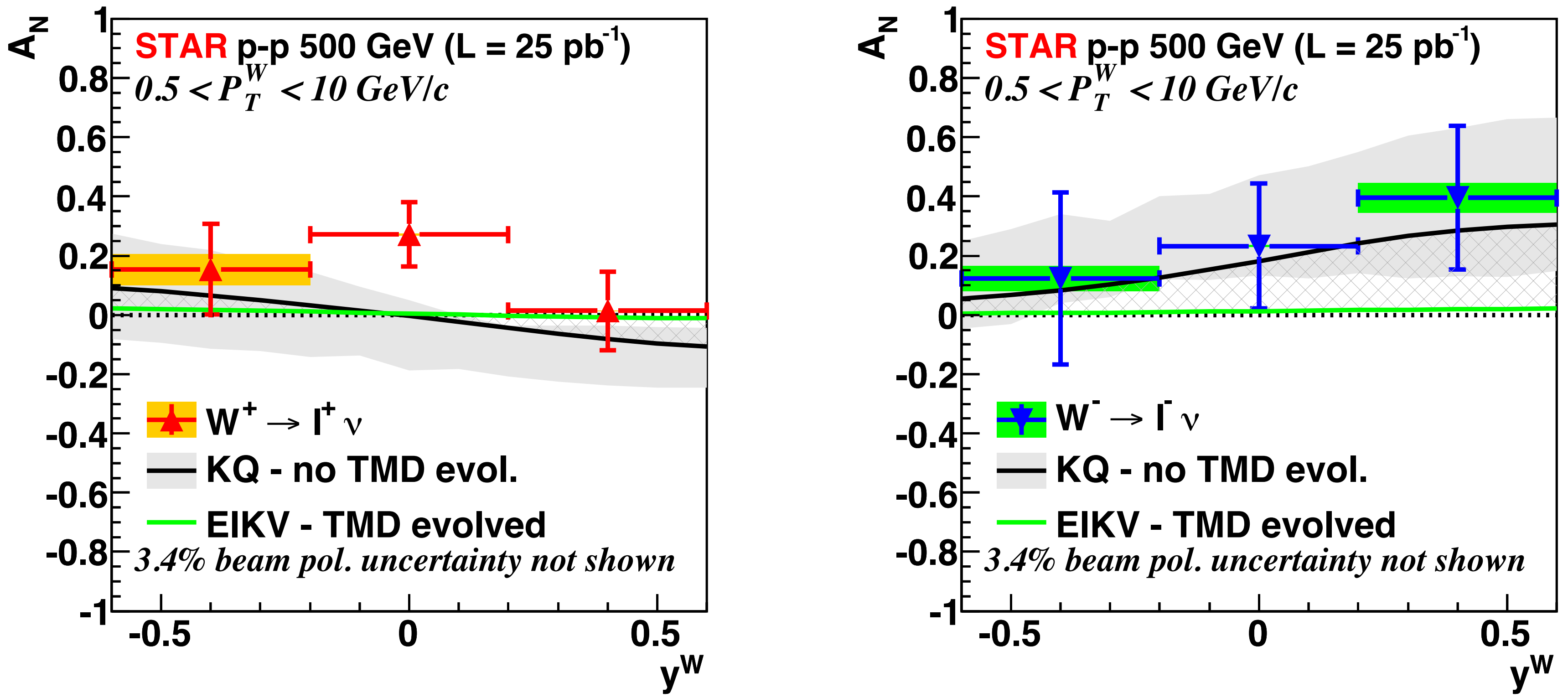
The measured Sivers asymmetry is consistent with the sign-change prediction

Summary

- The Sivers asymmetry measured in Drell-Yan in 2015 is found to be above zero (within 1 std dev.)
- The result is consistent with a sign change of the Sivers TMD
- The Transversity asymmetry is found to be below zero (within 2 std dev.)
- A number of additional results are expected to come soon (analysis ongoing):
  - unpolarized Drell-Yan cross sections and angular distributions for NH_3, Al, W
  - unpolarized J/psi production cross section and angular distributions
  - Polarized J/psi asymmetries

- One more year of Drell-Yan data taking in 2018 –
  should allow to triple our statistical accuracy

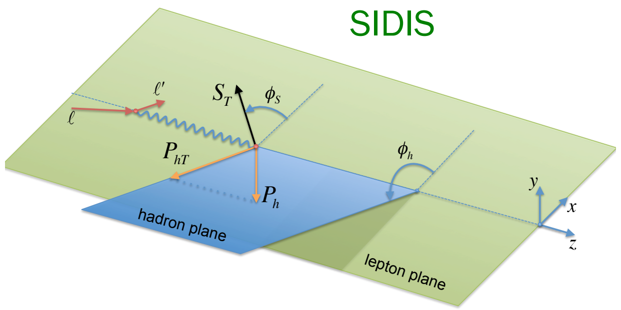
STAR results for W production – Sivers



Leading twist asymmetries in transversely polarized DY/SIDIS

- SIDIS

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



- Drell-Yan

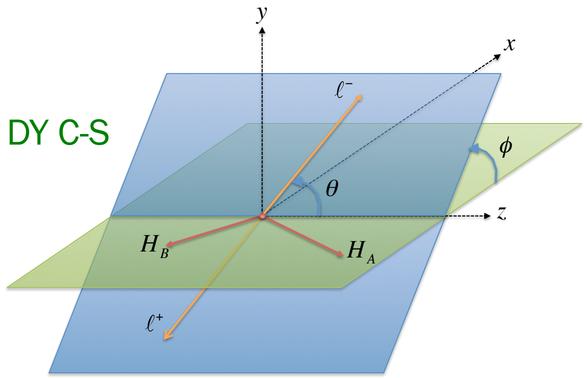
Boer-Mulders

Sivers

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

Transversity

Pretzelosity



- Collinear factorization in DY

$$\frac{d\sigma^{(\mathrm{LP})}_{A+B\to l\bar{l}+X}}{dQ^2 dy} = \sum_{ab}\int_0^1 dx_a \int_0^1 dx_b\, \phi_{a/A}(x_a,\mu)\,\phi_{b/B}(x_b,\mu)\,\frac{d\hat{\sigma}_{a+b\to l\bar{l}}(x_a,x_b,Q,\mu,\alpha_s)}{dQ^2 dy},$$

- TMD factorization in DY

$$\begin{aligned}\frac{d\sigma_{A+B\to l\bar{l}+X}(\vec{S}_a,\vec{S}_b)}{dQ^2 dy\, d^2\mathbf{q}_T} &= \sum_{a,b}\int dx_a\, dx_b\, d^2\mathbf{p}_{a\perp}\, d^2\mathbf{p}_{b\perp}\, \delta^2(\mathbf{q}_T - \mathbf{p}_{a\perp} - \mathbf{p}_{b\perp}) \\ &\times f^{\mathrm{DY}}_{a/A}(x_a,\mathbf{p}_{a\perp},\vec{S}_a,\mu)\, f^{\mathrm{DY}}_{b/B}(x_b,\mathbf{p}_{b\perp},\vec{S}_b,\mu)\,\frac{d\hat{\sigma}_{a+b\to l\bar{l}}(x_a,x_b,Q,y,\mu)}{dQ^2 dy} \\ &+ Y(q_T,Q,y) + \mathcal{O}\left((\Lambda_{\mathrm{QCD}}/Q)^{\alpha}\right),\end{aligned}$$