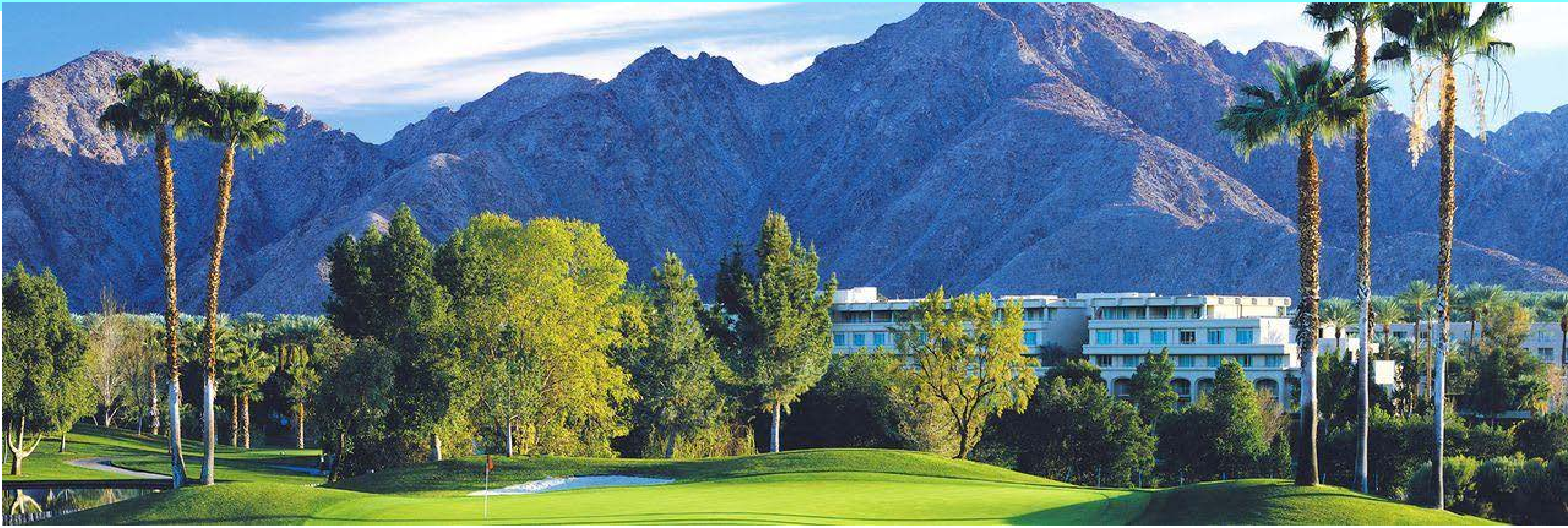
Drell-Yan Physics with Negative Pion Beam and Polarized Target at COMPASS

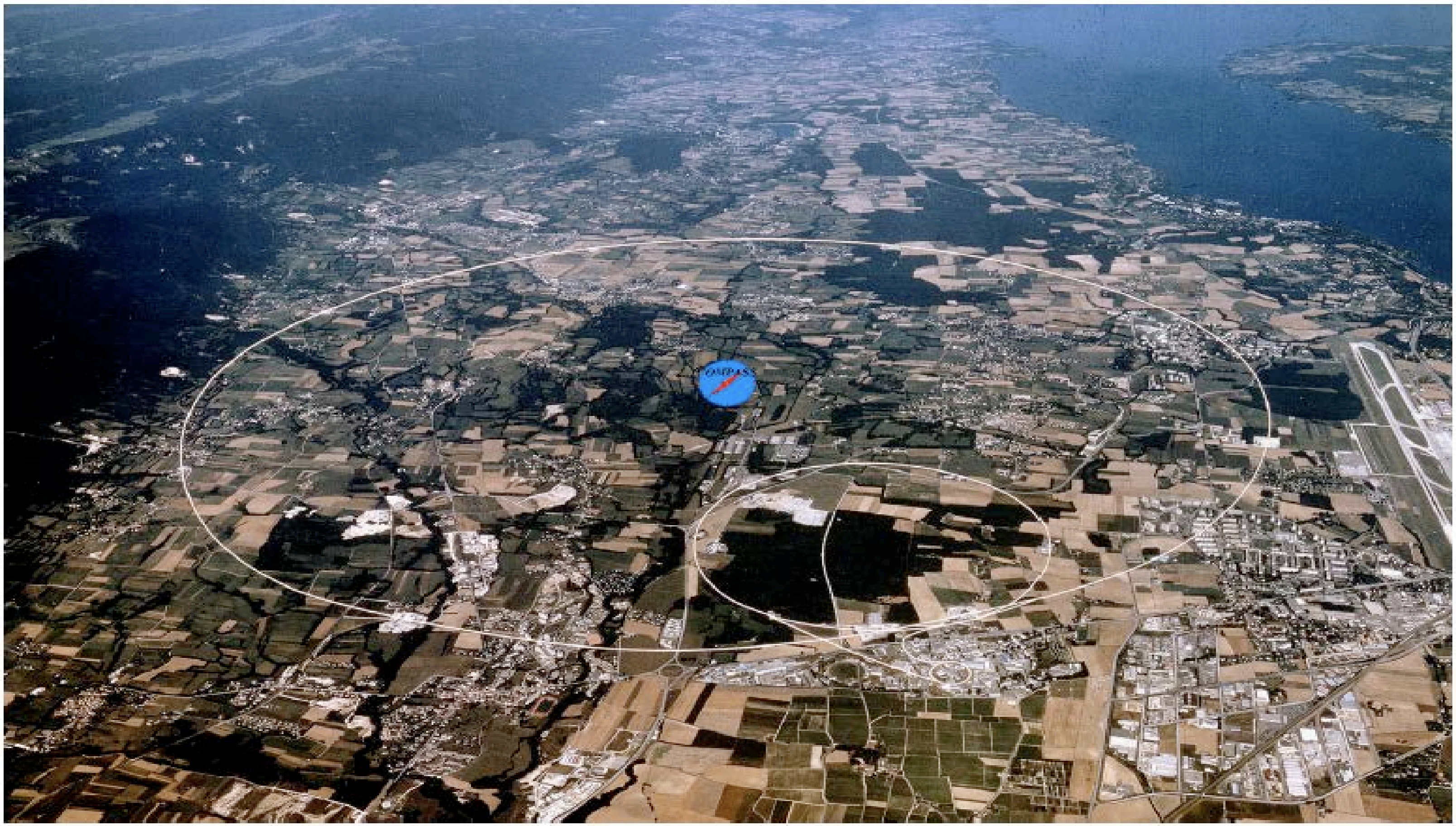


CIPANP, Palm Springs June 2, 2018

M. Grosse Perdekamp, University of Illinois

COMPASS at the CERN SPS

COmmon Muon Proton Apparatus for Structure and Spectroscopy



COMPASS Collaboration

Дубна (LPP and LNP), Москва (INR, LPI, State University), Протвино

Warsawa (NCBJ), Warsawa (TU) Warsawa (U)

Praha (CU/CTU)

Liberec (TU)

Brno (ISI-ASCR)

Calcutta (Matrivian)

Taipei (AS)

CERN

Yamagata

Lisboa/Aveiro

Tel Aviv

Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Mainz, TU München

UIUC

IRFU, CEA

Torino (University,INFN),

Trieste (University,INFN)

~250 physicists from 24 institutions in 13 countries

COMPASS: TMD Observables in SIDIS and Drell Yan

COMPASS at CERN: unique capability of measuring TMD observables with lepton beams (SIDIS) and hadron beams (Drell-Yan)

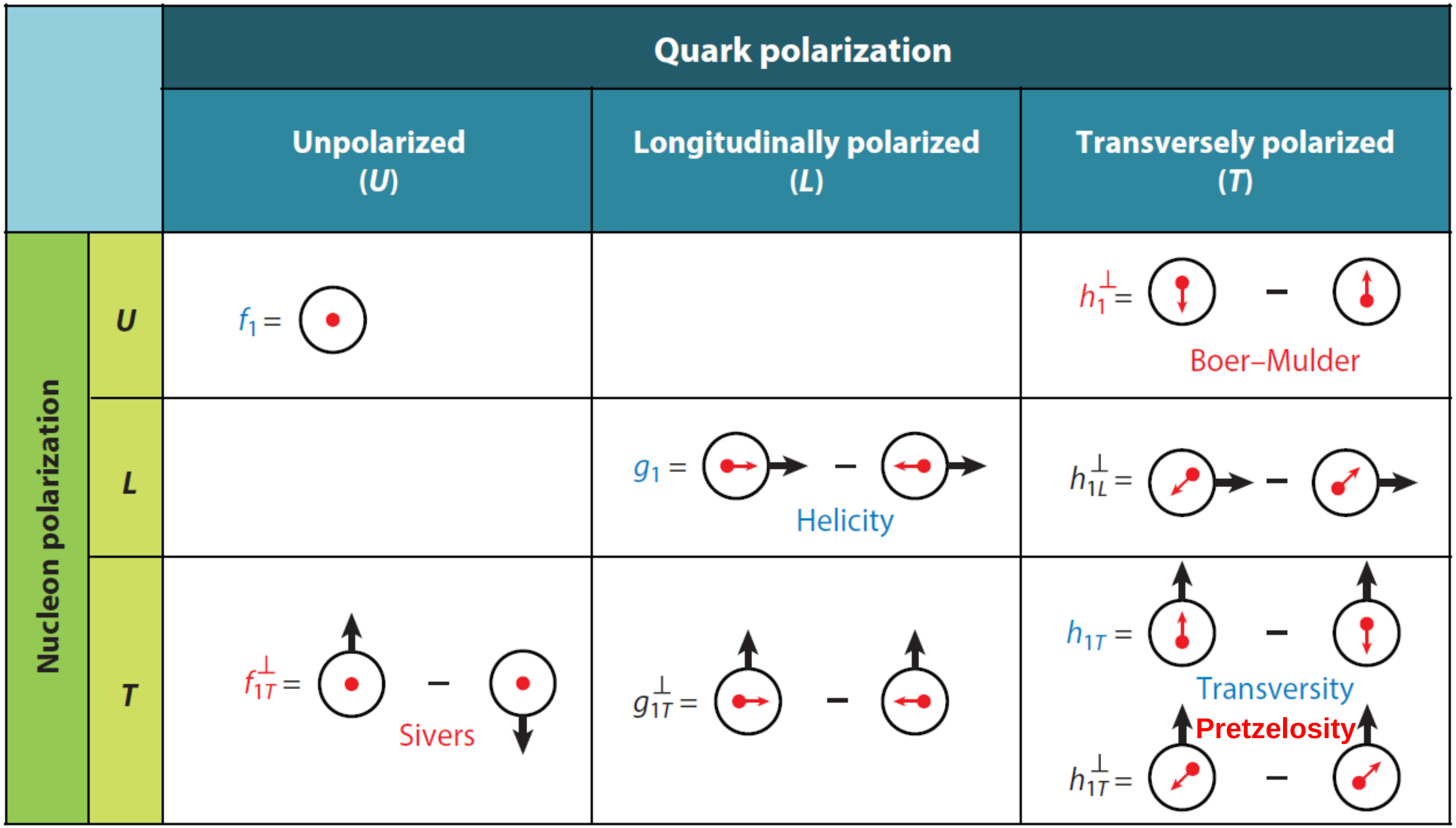
Transverse Momentum Dependent PDFs

Single Spin Asymmetries in SIDIS from COMPASS

Drell-Yan at COMPASS

- **Set-up**
- **Results from the Drell-Yan 2015 data**
- **Future with RF separated beams**

Helicity Flip Amplitudes at Leading Twist



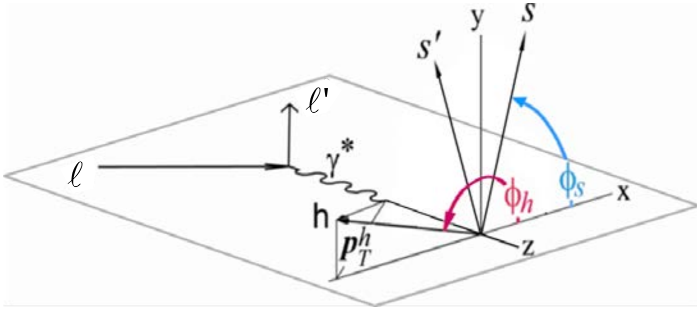
Transverse Momentum Dependent (TMD)

TMD independent

TMD Modulations in the SIDIS and Drell-Yan Cross Sections

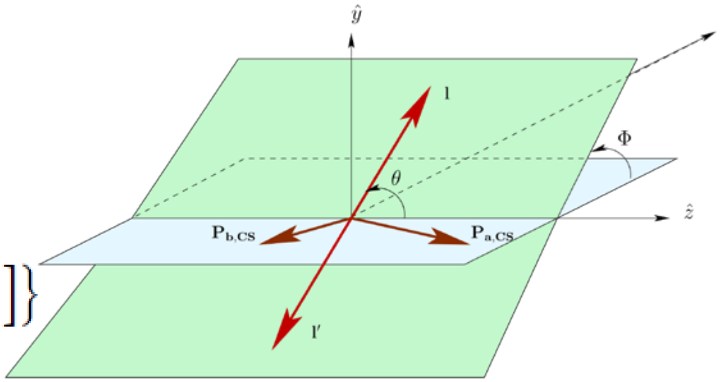
SIDIS @ LO

$$\frac{d\sigma}{dxdydzd\psi d\phi_h dP_{hT}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sigma_U \left\{1+\varepsilon\cos(2\phi_h)A_{UU}^{\cos(2\phi_h)}\right.$$
$$+S_T\left[\sin(\phi_h-\phi_S)A_{UT}^{\sin(\phi_h-\phi_S)}+\varepsilon\sin(\phi_h+\phi_S)A_{UT}^{\sin(\phi_h+\phi_S)}\right.$$
$$\left.+\varepsilon\sin(3\phi_h-\phi_S)A_{UT}^{\sin(3\phi_h-\phi_S)}\right]$$
$$\left.+S_T P_l\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)A_{LT}^{\cos(\phi_h-\phi_S)}\right]\right\}$$



DY @ LO

$$\frac{d\sigma}{d^4q d\Omega} = \frac{\alpha^2}{\Phi q^2}\hat{\sigma}_U\left\{\left(1+\cos^2(\theta)+\sin^2(\theta)A_{UU}^{\cos(2\phi)}\cos(2\phi)\right)\right.$$
$$+S_T\left[\left(1+\cos^2(\theta)\right)A_{UT}^{\sin(\phi_S)}\sin(\phi_S)\right.$$
$$\left.\left.+\sin^2(\theta)\left(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)+A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right)\right]\right\}$$



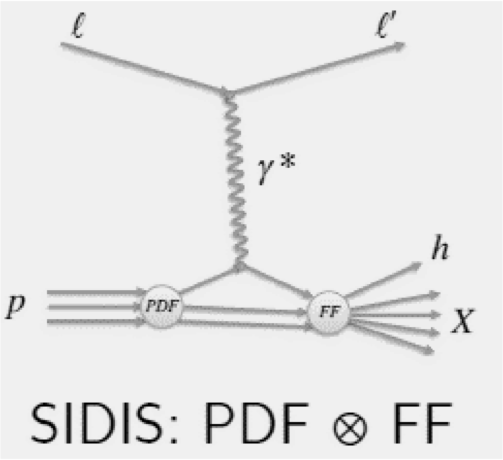
TMDs in SIDIS and Drell Yan Scattering

SIDIS @ LO

$$A_{UU}^{\cos(2\phi_h)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

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

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$$

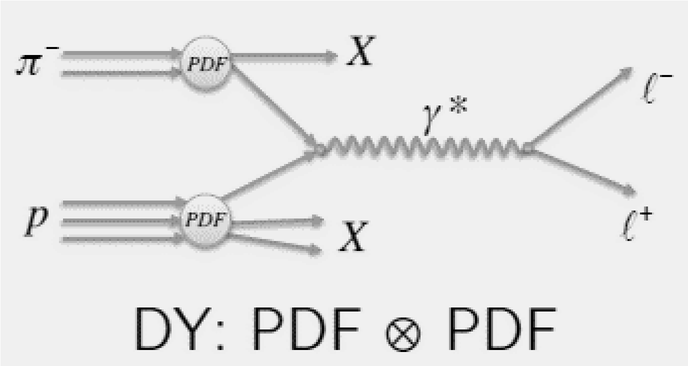


DY @ LO

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

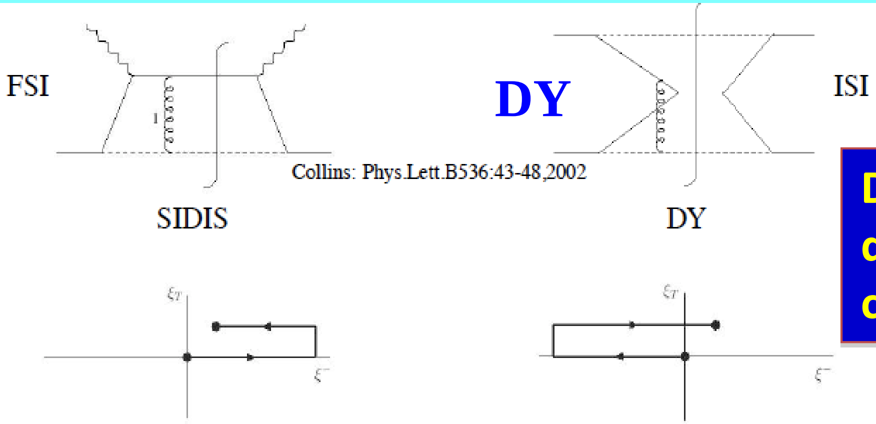
$$A_{UT}^{\sin(\phi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$ Sivers

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



Sign Change of Sivers- and Boer-Mulders Functions Between SIDIS and DY

SIDIS



Direction of the gauge-link integrals of k_T dep. pdfs is process-dependent and changes its sign between SIDIS and DY

Sivers $$f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -f_{1T}^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$$

Boer-Mulders $$h_1^{\perp}(x,\mathbf{k}_T)\Big|_{SIDIS} = -h_1^{\perp}(x,\mathbf{k}_T)\Big|_{DY}$$

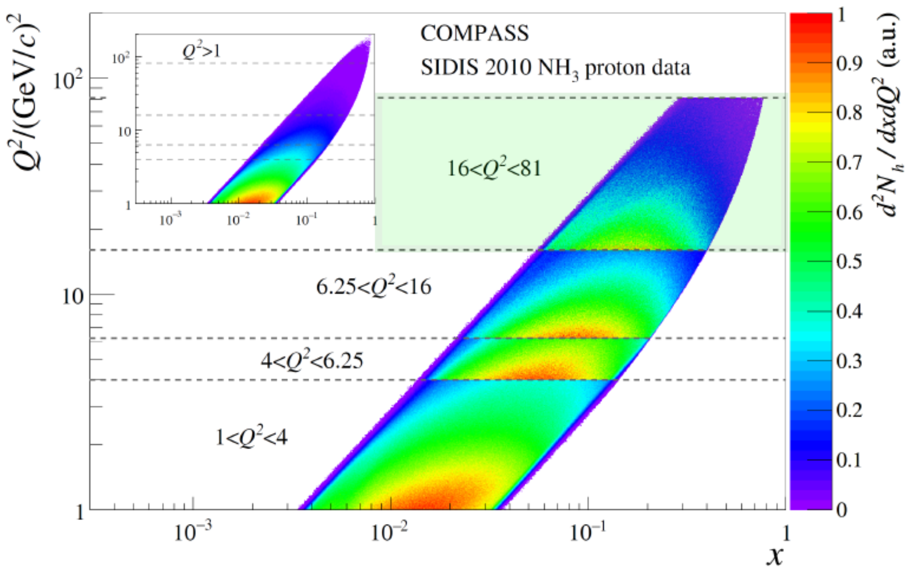
Need to confirm sign reversal in polarized Drell-Yan!

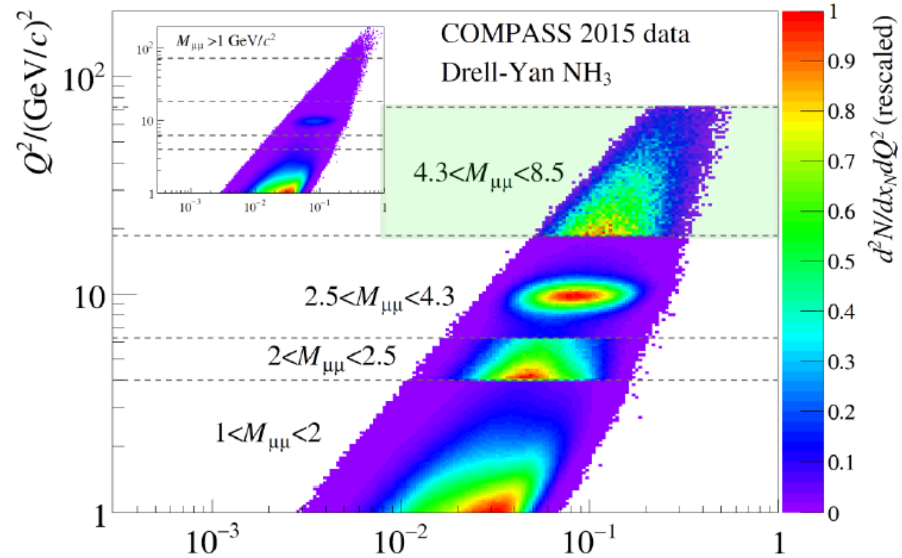
NSAC performance Milestone HP13

TEST "modified" universality of TMD pdfs!

COMPASS Kinematic SIDIS vs Drell-Yan

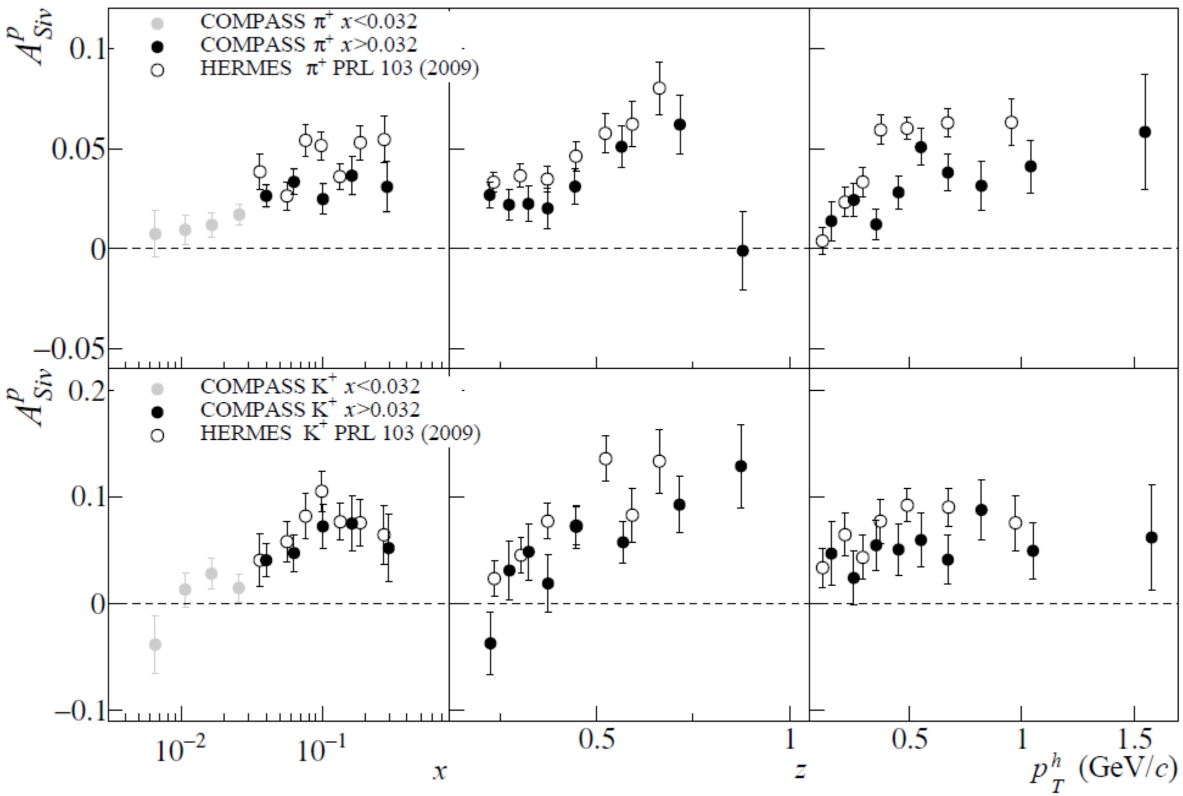
The phase space for Drell-Yan and SIDIS processes partially overlap in the x-Q^2 plane





COMPASS and HERMES Sivers Asymmetries in SIDIS for π^+ vs K^+

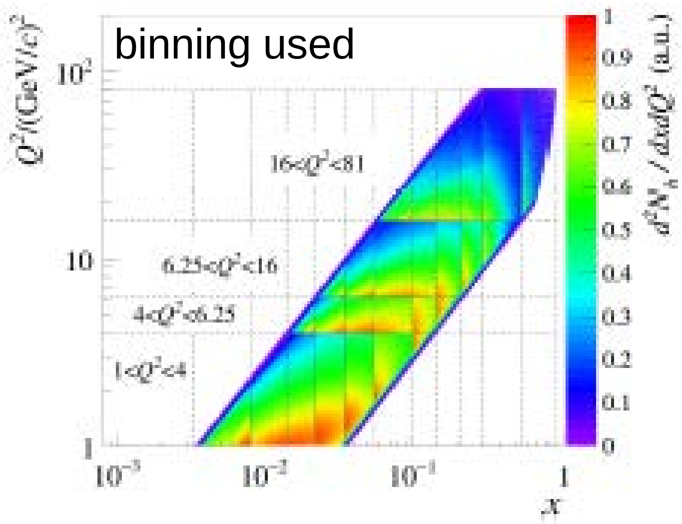
COMPASS Phys.Lett. B744:250(2015)

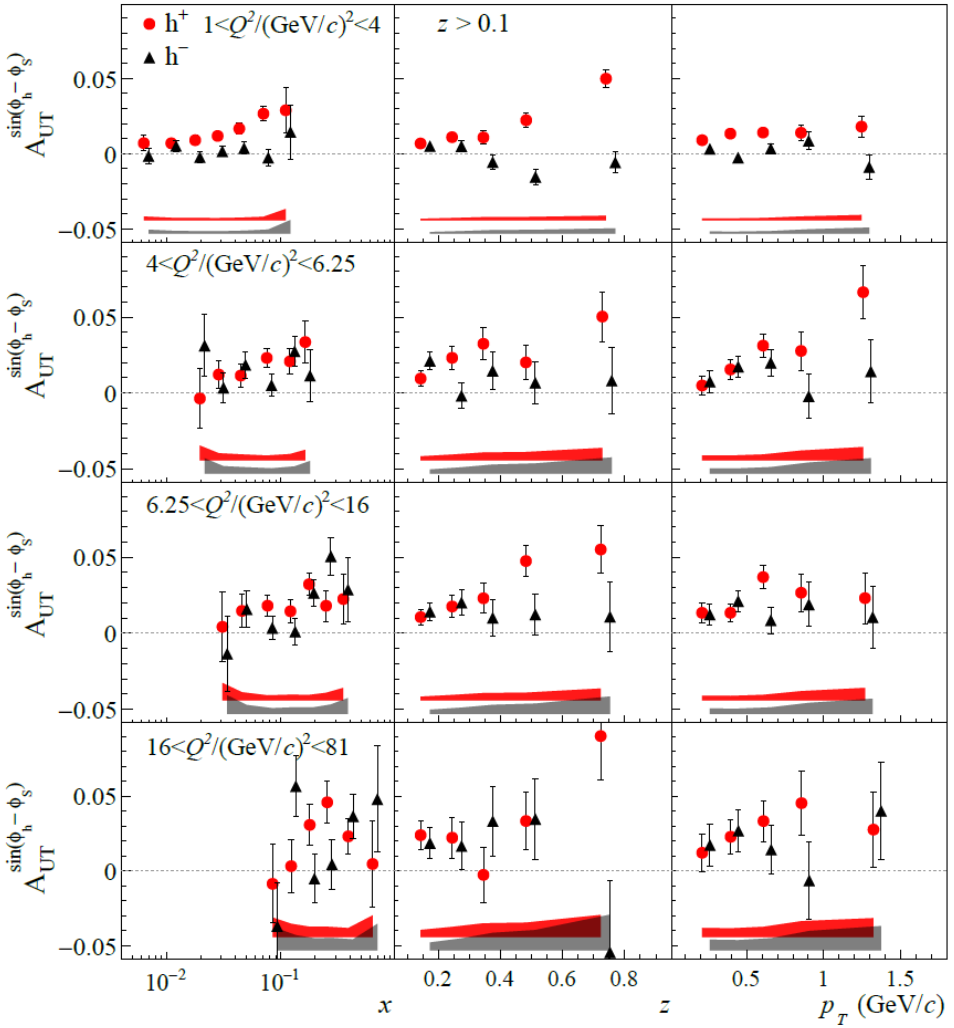


Combined 2007 and 2010 COMPASS proton data samples analyzed.

COMPASS SIDIS Sivers Asymmetries for Charged Hadrons in DY Q^2 Bins

COMPASS Phys.Lett. B770(2017)138

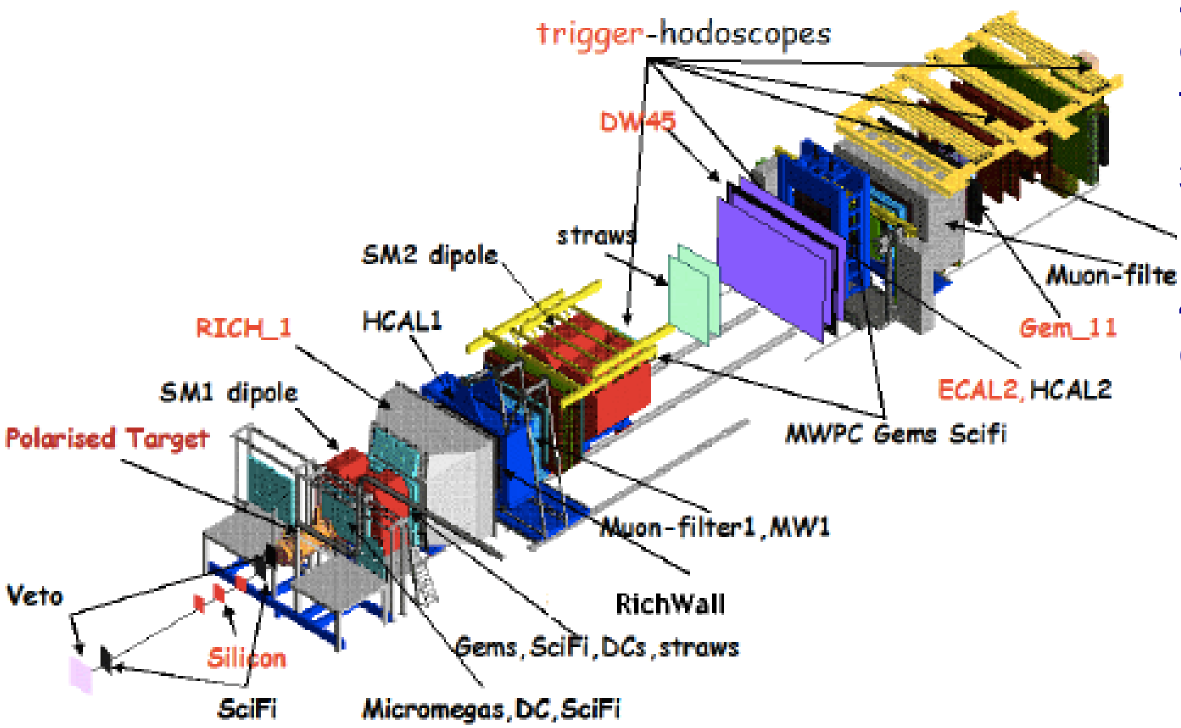




COMPASS – Instrumentation

Two stage large acceptance spectrometers with high rate capability:

- Large Angle Spectrometer (LAS)
- Small Angle Spectrometer (SAS)



1.Muon, electron or hadron secondary beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second.

2. Solid state polarized targets, NH_3 or ^6LiD, as well as liquid hydrogen target and nuclear targets.

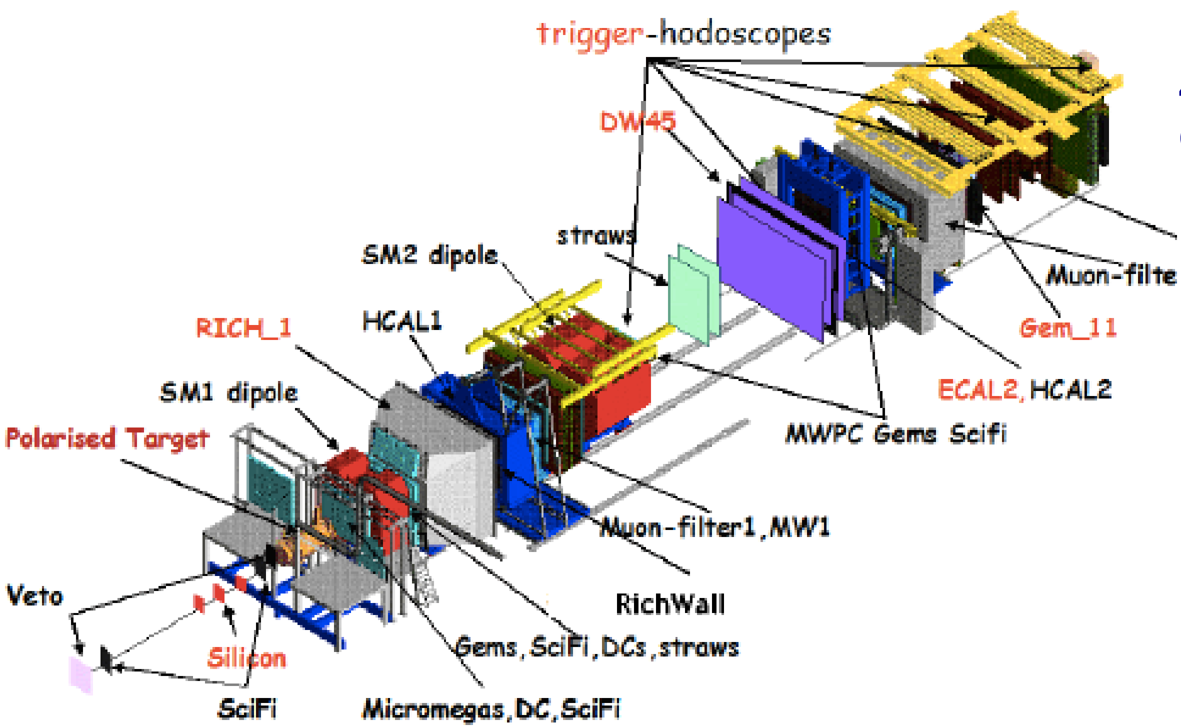
3.Powerful tracking system – 350 planes.

4. Versatile PID – RICH, Muon Walls, Calorimeters.

COMPASS – Instrumentation

Two stage large acceptance spectrometers with high rate capability:

1. Large Angle Spectrometer (LAS)
2. Small Angle Spectrometer (SAS)



…

2. Solid state polarized targets, NH_3 or ^6LiD, as well as liquid hydrogen target and nuclear targets.

3.Powerful tracking system – 350 planes.

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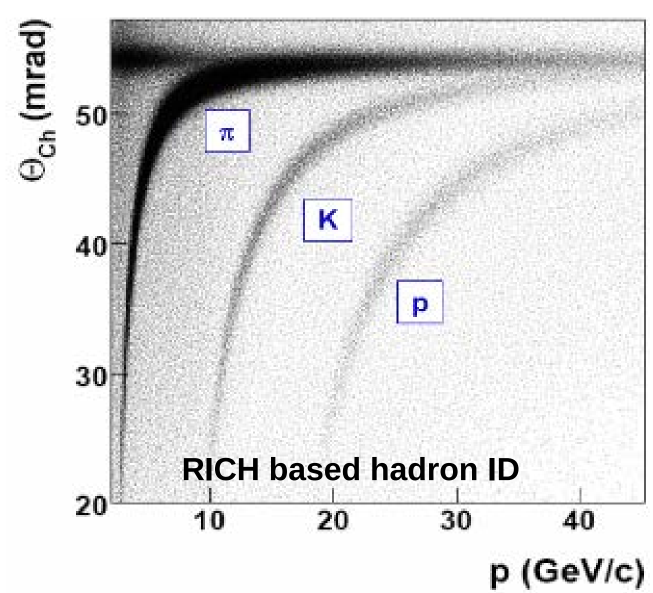
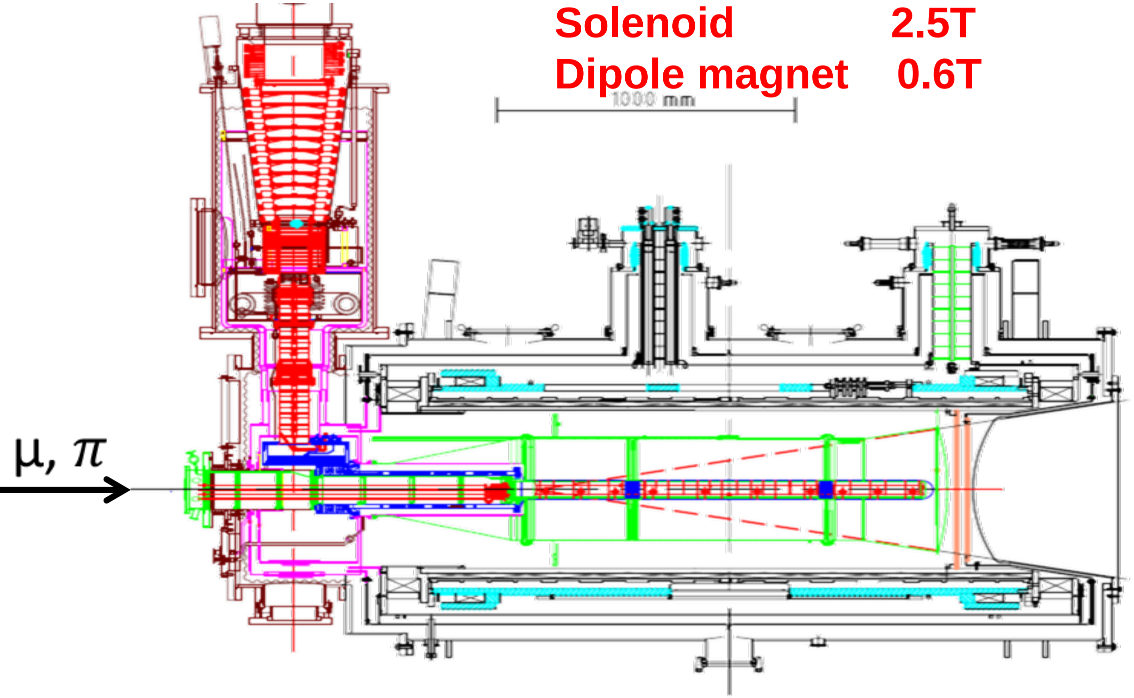
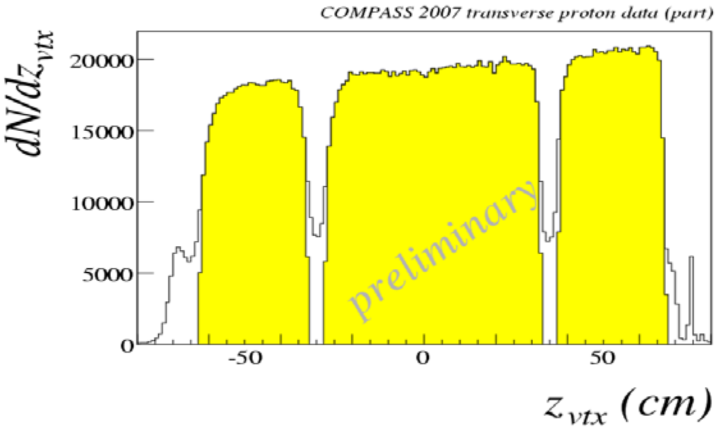


COMPASS – Solid Polarized Target

^{3}He – ^{4}He dilution refrigerator (T~50mK)



Vertex distribution for SIDIS



Opposite polarization in different target segments reversed frequently

	d (^{6}LiD)	p (NH_3)
Polarization	50%	80%
Dilution factor	38%	14%

COMPASS Raw Data, Monte Carlo Production and Data Analysis, on NCSA's Blue Waters (2017-2019)

Blue Waters @ NCSA for COMPASS data production

- June 2017: NSF grant (award #1713684) for PRAC (Petascale Computing Resource Allocations):
  - 9.4 million node hours
  - 2 years
  - >11% of all 2017 PRAC awards, worth about $7M

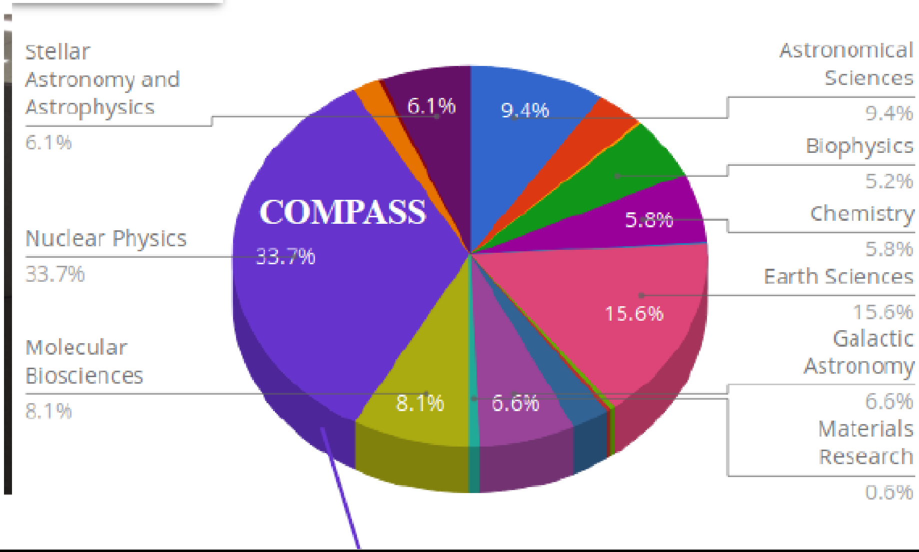
PRAC Proposal:

Mapping Proton Quark Structure Using Petabytes of COMPASS Data

9.4 millions node hours/year
1 node = 32 CPUs

- Proposal submitted with letters of support from 12 collaborating COMPASS institutions.

- Allows generation of large Monte-Carlo samples. Will significantly speed up COMPASS data analysis.



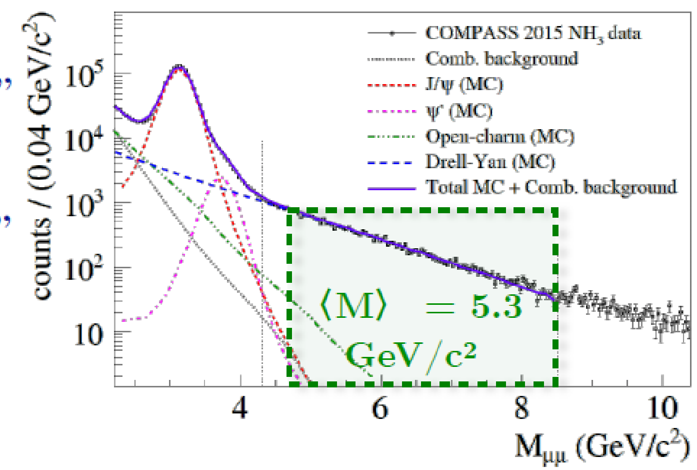
COMPASS Invariant Mass Bins in Drell-Yan

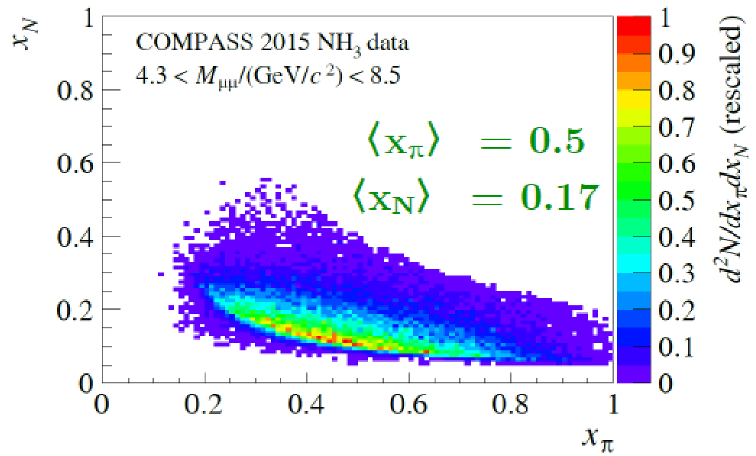
I. $1 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2$, "Low mass"
- Large background contamination

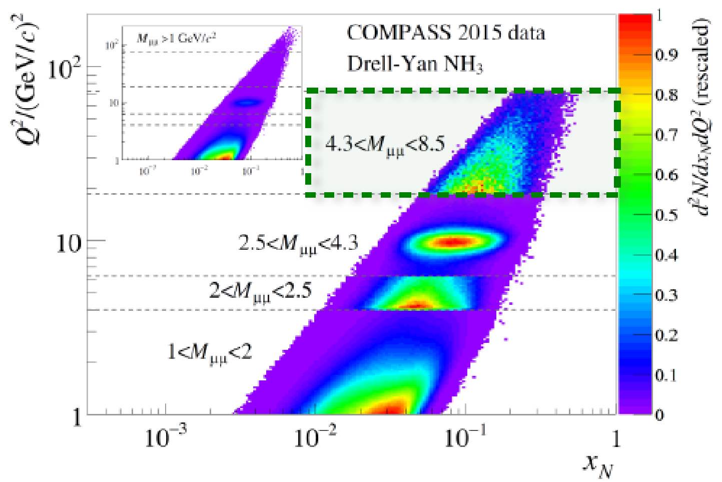
II. $2 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2.5$, "Intermediate mass"
- High DY cross section.
- Still low DY-signal/background ratio.

III. $2.5 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 4.3$, "Charmonia mass"
- Strong J/ψ signal → Studies of J/ψ physics.
- Good signal/background.

IV. $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$, "High mass"
- Beyond J/ψ and ψ' peak, background $< 4\%$.
- Valence quark region → Largest asymmetries!
- Low DY cross-section







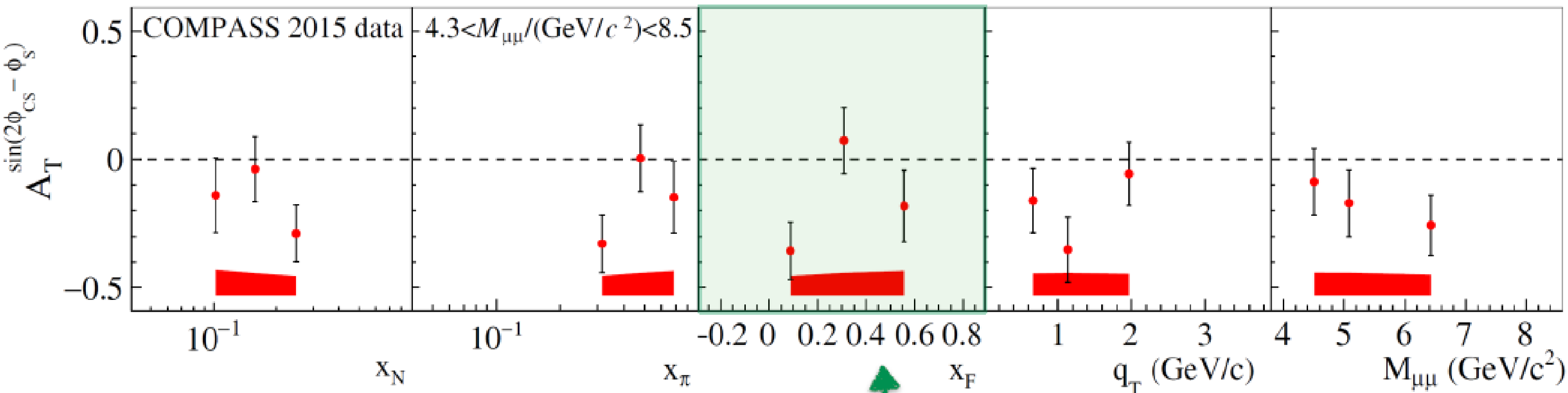
HM events are in the valence quark region

Drell-Yan TSAs : Transversity

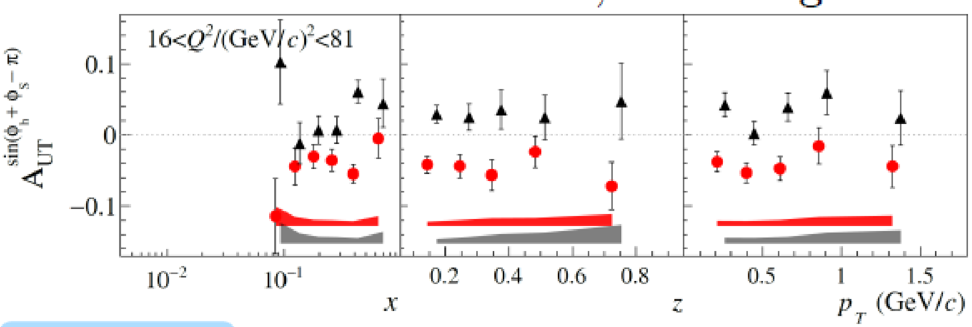
$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} + S_T \left[\sin\varphi_S A_T^{\sin\varphi_S} + D_{[\sin^2\theta]} \left(\sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)} + \sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)} \right) \right] \right.$$

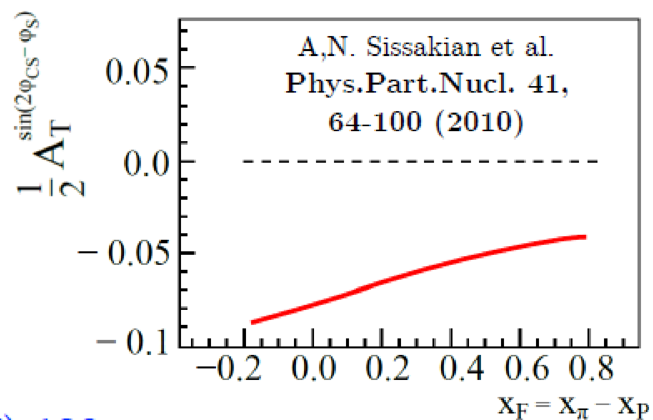
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$$

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



Collins TSA in SIDIS, HM range





$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^q \otimes H_{1q}^{\perp h}$$

COMPASS, **PLB 770 (2017) 138**

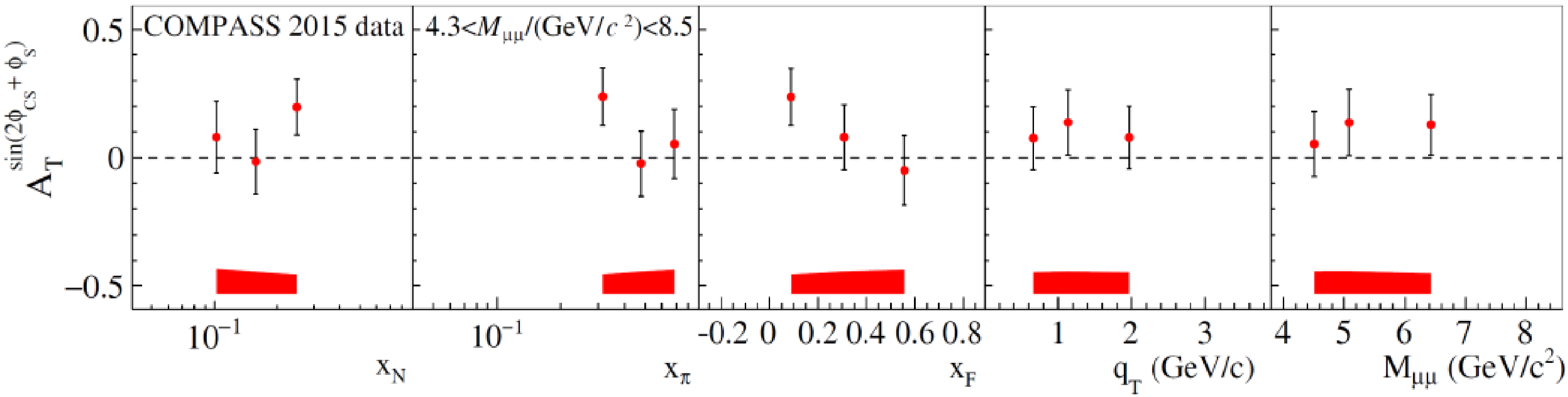
Drell-Yan TSAs : Pretzelosity

$$\frac{d\sigma^{LO}}{d\Omega d^4q} \propto \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta]}\cos(2\varphi_{CS})A_U^{\cos 2\varphi_{CS}} \\ + S_T \left[\begin{array}{l} \sin\varphi_S A_T^{\sin\varphi_S} \\ + D_{[\sin^2\theta]} \left(\begin{array}{l} \sin(2\varphi_{CS}+\varphi_S)A_T^{\sin(2\varphi_{CS}+\varphi_S)} \\ \sin(2\varphi_{CS}-\varphi_S)A_T^{\sin(2\varphi_{CS}-\varphi_S)} \end{array} \right) \end{array} \right. \end{array} \right.$$

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

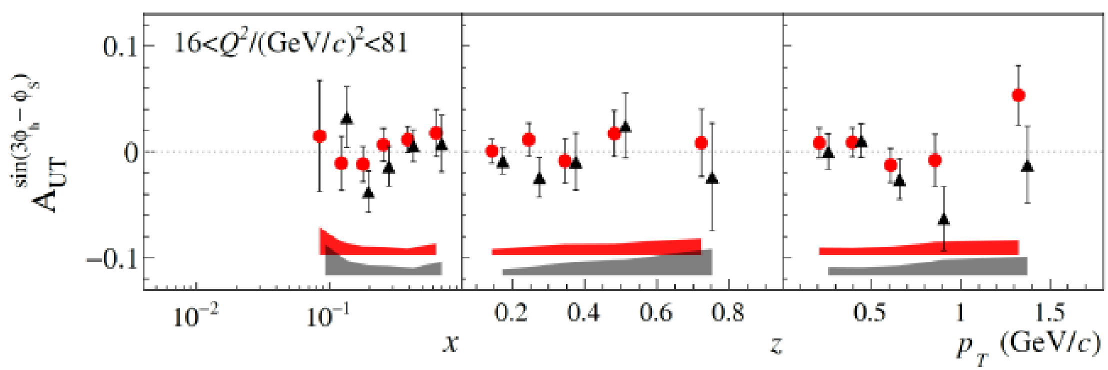
DY - HM range

COMPASS, PRL 119 112002 (2017)



Pretzelosity TSA in SIDIS, HM range

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$$



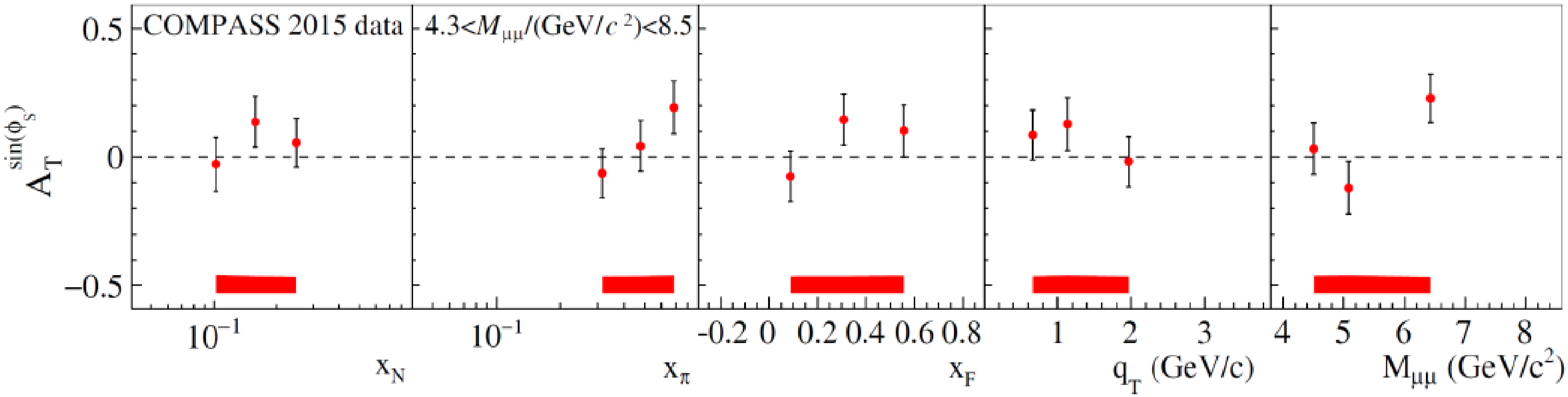
COMPASS, PLB 770 (2017) 138

Drell-Yan TSAs : Sivers

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

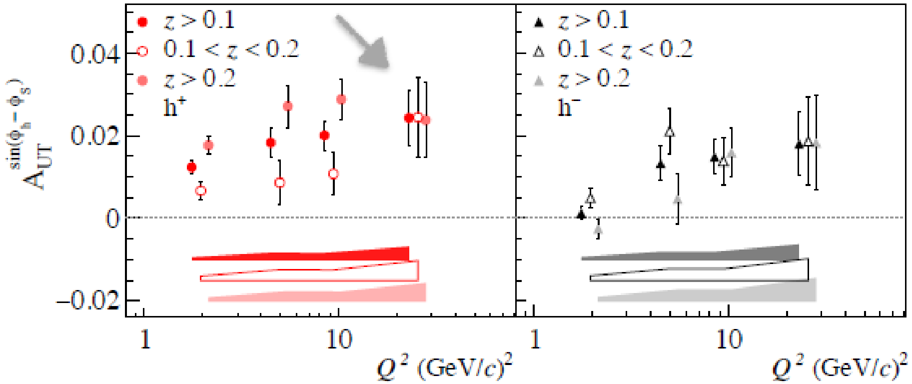
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$$

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



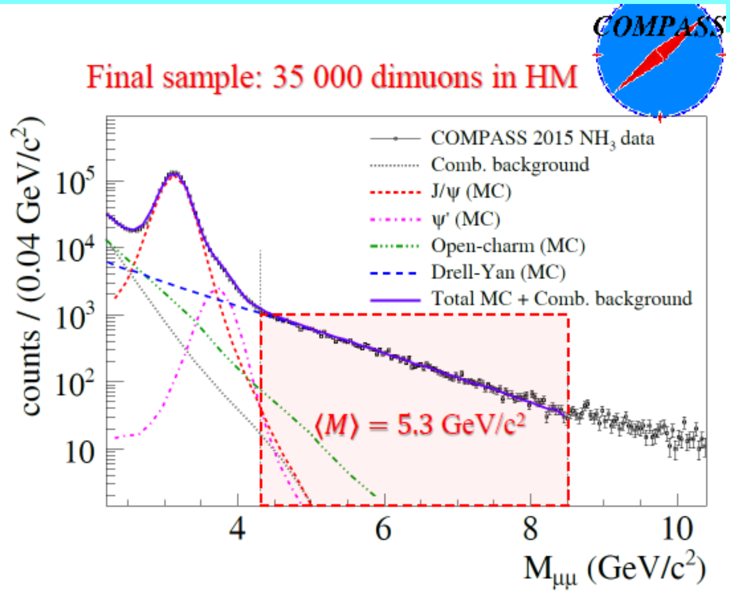
Sivers TSA in SIDIS, HM range

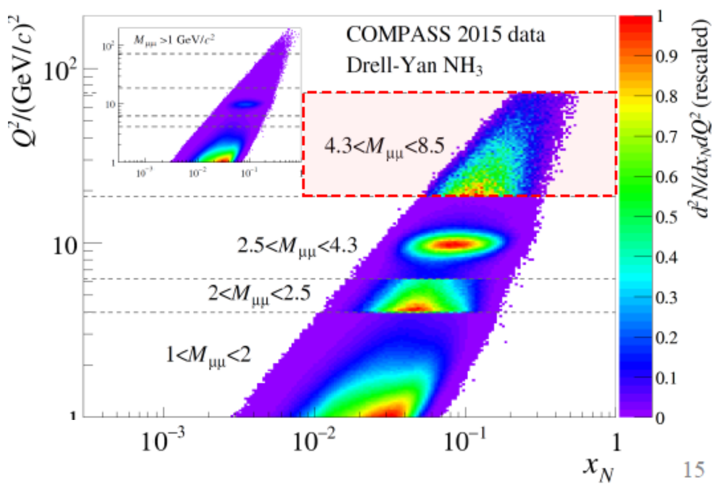
$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^h$$



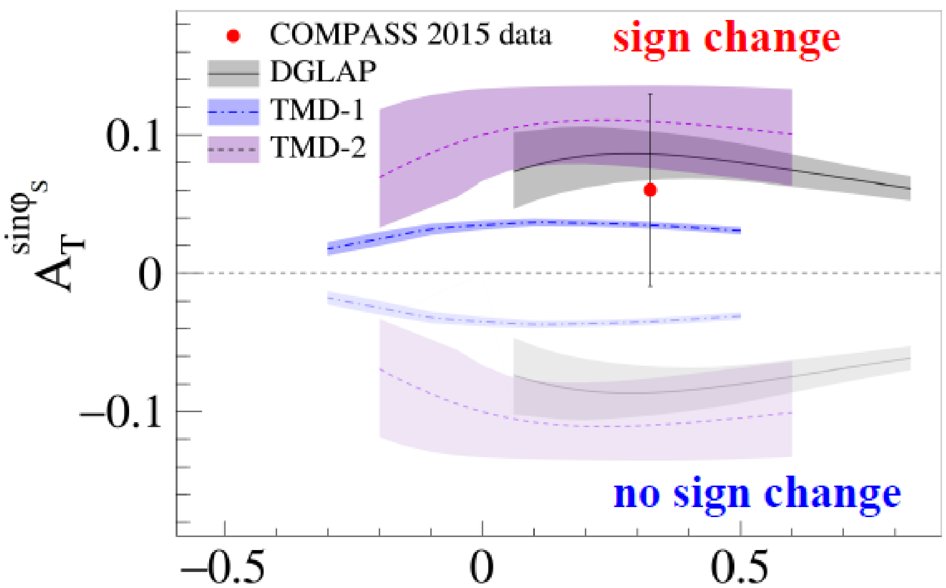
COMPASS, **PLB 770 (2017) 138**

Sivers Sign Change from SIDIS to Drell-Yan



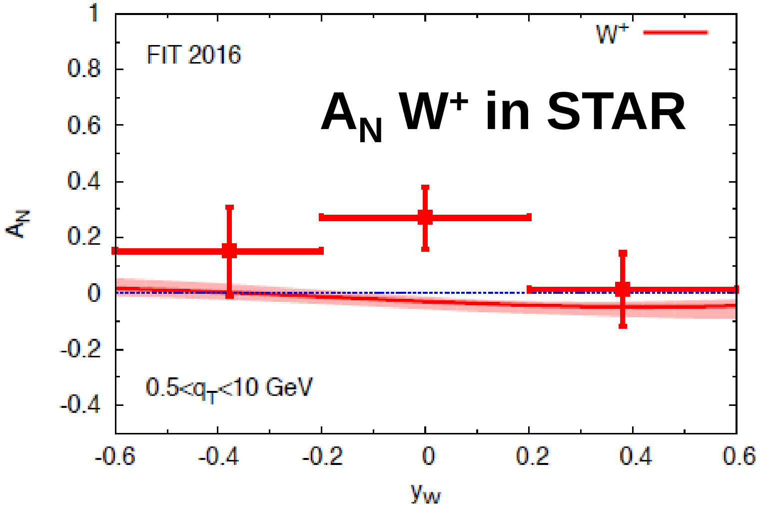


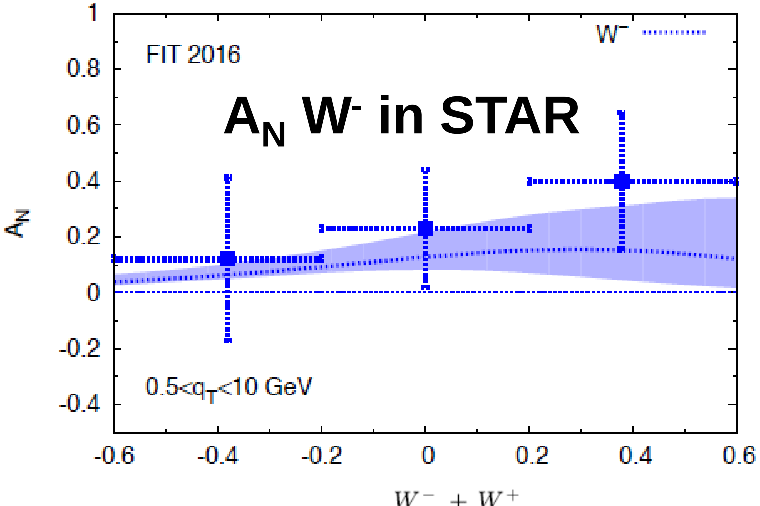
COMPASS
PRL 119, 112002 (2017)



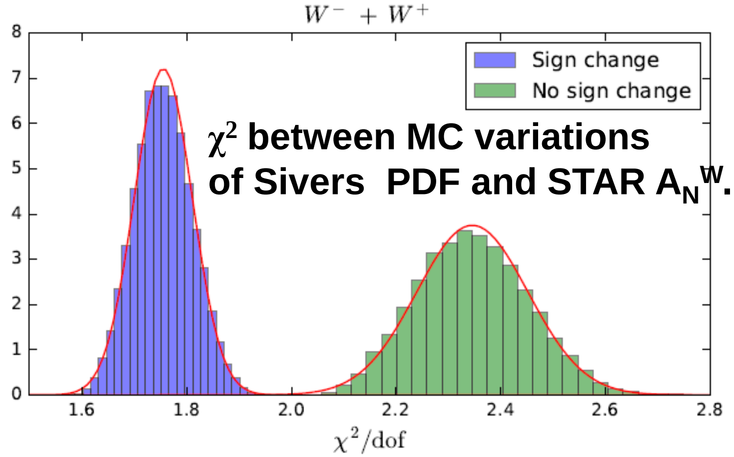
Sign Change in DY: A_N for W-Production in STAR

Comparison of A_N^W to Sivers from SIDIS by Anselmino, Boglione, D'Alesio, Murgia, JHEP 1704 (2017) 046



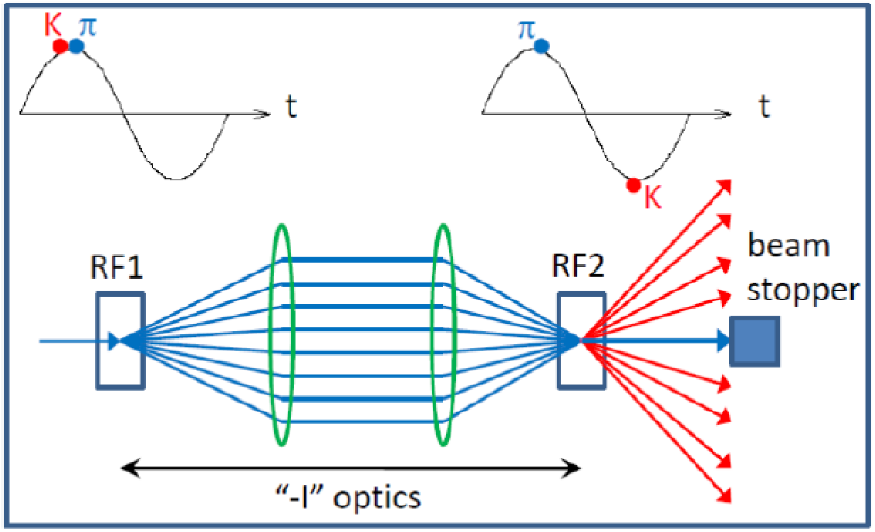


$A_N^{W+/-}$ slightly better compatible with sign change



Future: RF Separated Kaon and Anti-Proton Beams at CERN after LHC Luminosity Upgrades

- Deflection with 2 cavities
- Relative phase $= 0 \rightarrow$ dump
- Deflection of wanted particle given by $\Delta\phi \approx \frac{\pi f L}{c} \frac{m_w^2 - m_u^2}{p^2}$



To keep good separation, L should increase as $p^2 \rightarrow$ limits the beam momentum

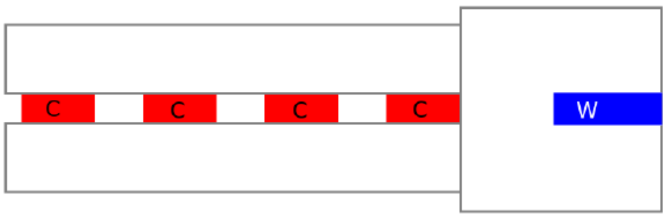
- Kaon With the current RP limits, for total beam flux of 7×10^7 particles/s:
  $I_{K-} \sim 2\times10^7/s$ at 100 GeV
  $I_{K+} \sim 2\times10^7/s$ at 100 GeV
- High intensity antiproton beam:
  $\sim 5 \times 10^7$ with current RP

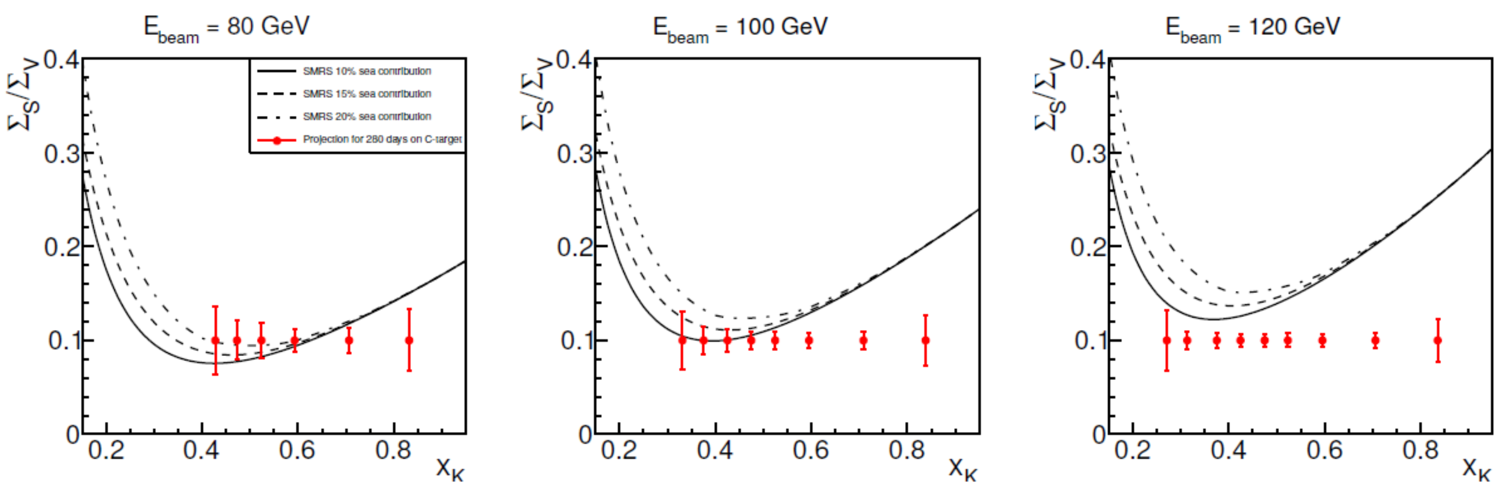
Discussion of RF upgrade from Vincent Andrieux, UIUC

Kaon Structure: Flavor Separation

- Dense & not too long for counting rate and acceptance considerations
- Isoscalar for sea-valence separation: J.T. Londergan *et al.*, PLB 380 (1996)
  - $\Sigma_S = \sigma_{DY}^{K^+D}$: Sensitive to valence and sea terms
  - $\Sigma_V = \sigma_{DY}^{K^-D} - \sigma_{DY}^{K^+D} = \frac{4}{9}\bar{u}_v^{K^-}(u_v^p + d_v^p)$: only valence sensitive
- Low A to minimize nuclear effect: Carbon target

First measurement of kaon sea!





Anti-Proton Beams for COMPASS

(1) measure Sivers asymmetries without uncertainty from pion pdf

(2) use transversity modulation, $\sin(2\phi_{CS}-\phi_S)$ for Boer Mulders measurement (less QCD radiative effects):

- ➔ extract transversity from SIDIS and e^+e^- measurements
- ➔ measure Drell Yan $A^{\sin(2\phi CS-\phi S)}$
- ➔ combine with SIDIS transversity to obtain proton Boer Mulders

Summary

Completed first measurement or Sivers TSA in Drell-Yan

➔ at current level in favor of sign change (2-sigma)

➔ current data taking from 5-2018 to 11-2018

➔ effort to extend Drell-Yan analysis to lower invariant mass using machine learning methods

RF upgrades: quark structure of the kaon
+ reduce uncertainties of Sivers measurement

- Kaon structure including valence sea separation
- Test of Lam Tung relation
- Model free TSA in DY with antiproton beam