Polarized Drell-Yan Measurements at COMPASS

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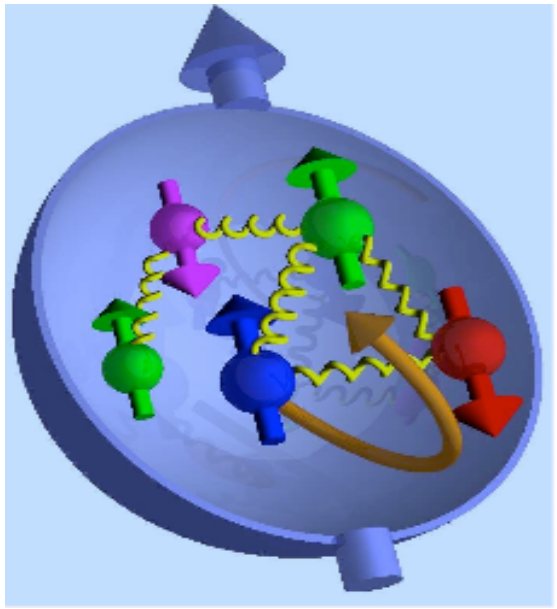
Outline

- Nucleon spin structure
- SIDIS & Drell-Yan processes
- COMPASS experiment at CERN
- COMPASS SIDIS results
- Preliminary results from DY run 2015
- Expected accuracy for Sivers in DY
- Conclusion

Nucleon spin structure



- Proton spin $\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+ L_{q,g}$
- Naive parton model expects ΔΣ=1
- EMC(1988) ΔΣ compatible with zero
- Precision data today ΔΣ~0.3
- Recently ΔG non-zero, positive at x_g range accessed

  (RHIC, COMPASS) $\Delta G=0.2^{+0.06}_{-0.07}$

de Florian et al.Phys.Rev.Lett. 113 (2014) no.1, 012001

- $L_{q,g}$ still unexplored, accessible e.g. via Generalized PDFs

  (DVCS & DVMP & SIDIS at COMPASS, JLAB)

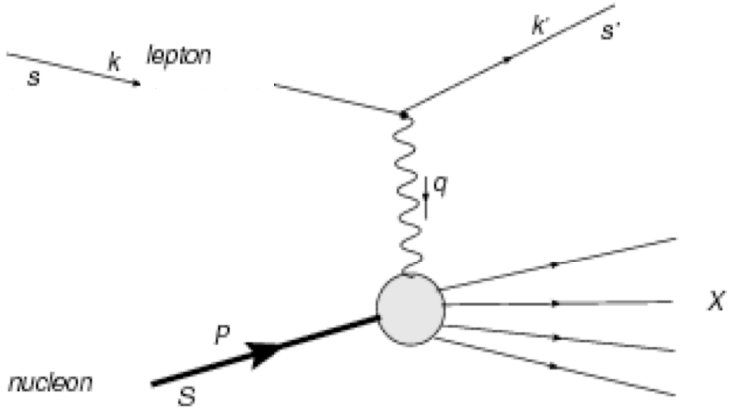
Nucleon spin structure

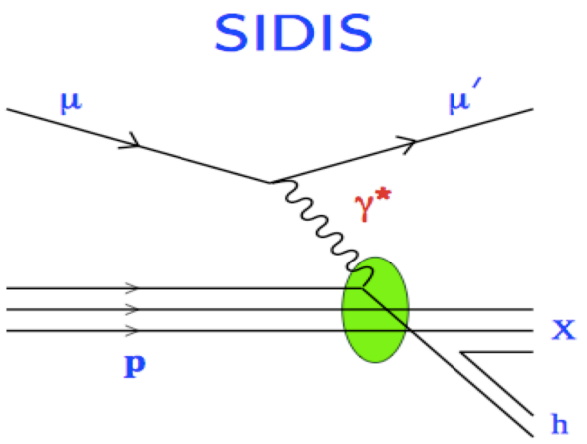
At leading-twist (LO), neglecting parton transverse momentum(collinear aproximation):

- 3 funtions $\mathbf{f_1}$(number density), $\mathbf{g_1}$(helicity), $\mathbf{h_1}$(transversity)
- f_1, g_1 well measured in (inclusive) Deep Inelastic Scattering

  (EMC, NMC, Hermes, HERA, COMPASS, CLASS)
- h_1 is chiral-odd and cannot be measured in inclusive DIS (Semi-inclusive reaction needed)

h_1 extraction requires knowledge of Collins fragmentation function





$lepton + p \rightarrow lepton' + X$

$lepton + p \rightarrow lepton' + h + X$

Twist-2 TMD PDFs

Nucleon / Quark	U	L	T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **Number density**		$f_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Sivers**
L		$g_1^q(x,\boldsymbol{k}_T^2)$ **Helicity**	$g_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Kotzinian-Mulders or Worm-gear T**
T	$h_1^{q\perp}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders**	$h_{1L}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Worm-gear L**	$h_1^q(x,\boldsymbol{k}_T^2)$ **Transversity** $h_{1T}^{q\perp}(x,\boldsymbol{k}_T^2)$ **Pretzelosity**

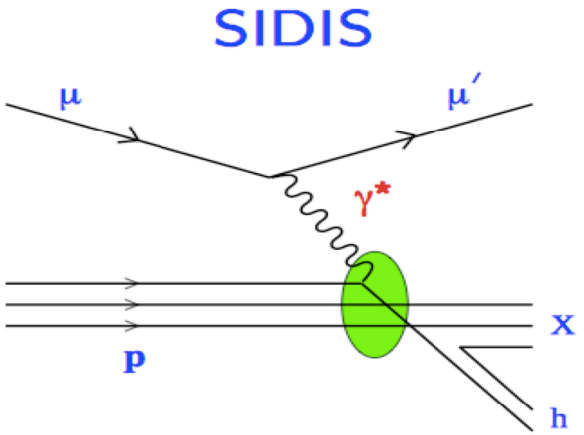
+ two FFs: $D_{1q}^h(z,P_\perp^2)$ and $H_{1q}^{\perp h}(z,P_\perp^2)$

Beyond collinear approximation if we consider partons transverse momentum k_T (LO QCD parton model with TMD-factorization):

- The nucleon spin-structure can be parametrized by 8 twist-2 TMD PDFs
- They can be accessed by measuring azimuthal asymmetries in DY or SIDIS processes

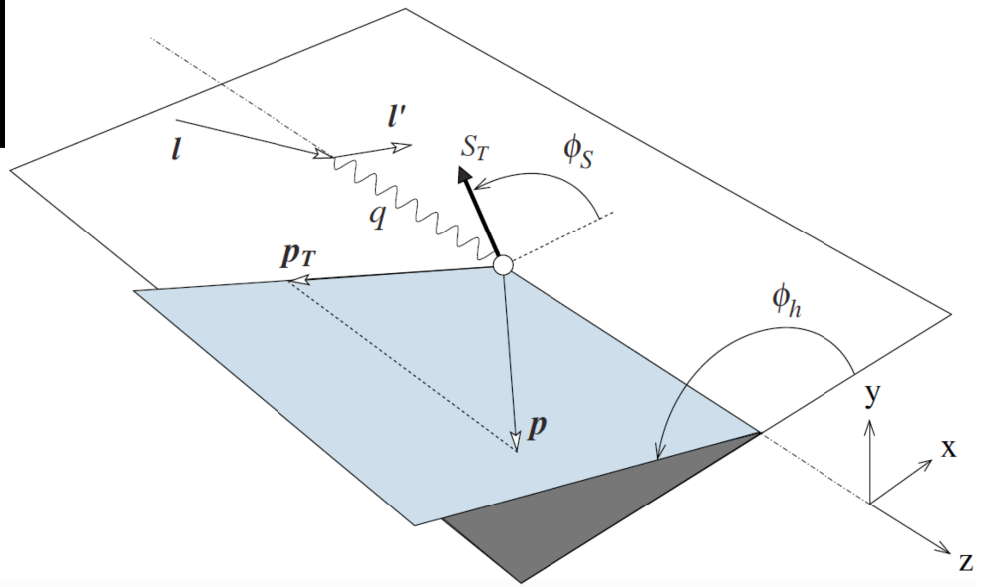
- Complementarity
- Posibility to test the TMD approach

Polarized SIDIS cross-section



SIDIS involves both Fragmentation Functions and TMD PDFs

[redacted]



$$\frac{d\sigma^{LO}_{SIDIS}}{dxdydzdp_T^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]$$

$$\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{\ 1+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\right.$$

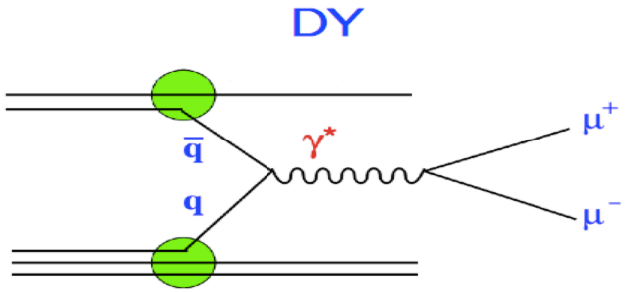
$$+\ \mathrm{S_T}\left[\begin{array}{l}\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\ +\ \sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\ +\ \sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\end{array}\right]$$

$$\left.+\ \mathrm{S_T}\lambda\left[\cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\right)\right]\ \right\}$$

For transversely polarized nucleons

[redacted]

Drell-Yan process



- Cross-section involves no FFs, only TMD PDFs (pion/nucleon)
- Dilepton final state
- Gives possibility to study pion or kaon structure

$$hadron1 + hadron2 \rightarrow \mu + \mu + X$$

At COMPASS: $\pi^- + p \rightarrow \mu + \mu + X$

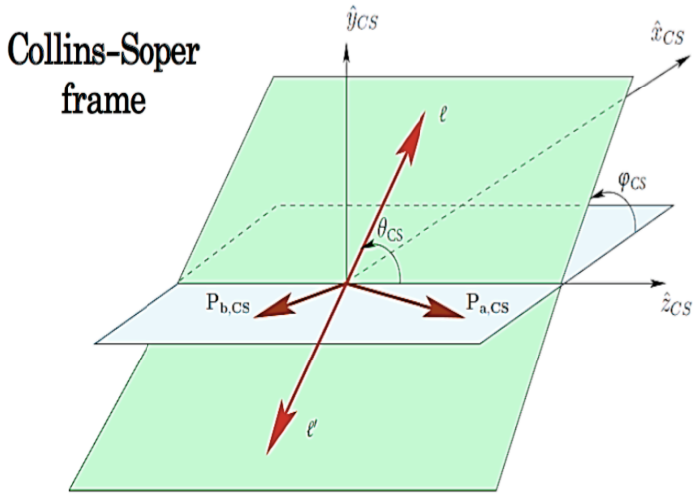
$$s = (P_1 + P_2)^2$$

$$x_{1,2} = q^2 / (2q \cdot P_{1,2})$$

$$x_F = x_1 - x_2$$

$$Q^2 = q^2 = M^2_{\mu\mu} = s x_1 x_2$$

Unpolarized cross-section: $$\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\varphi_{CS} + \frac{\nu}{2} \sin^2\theta \cos 2\varphi_{CS}\right)$$



Lam-Tung relation

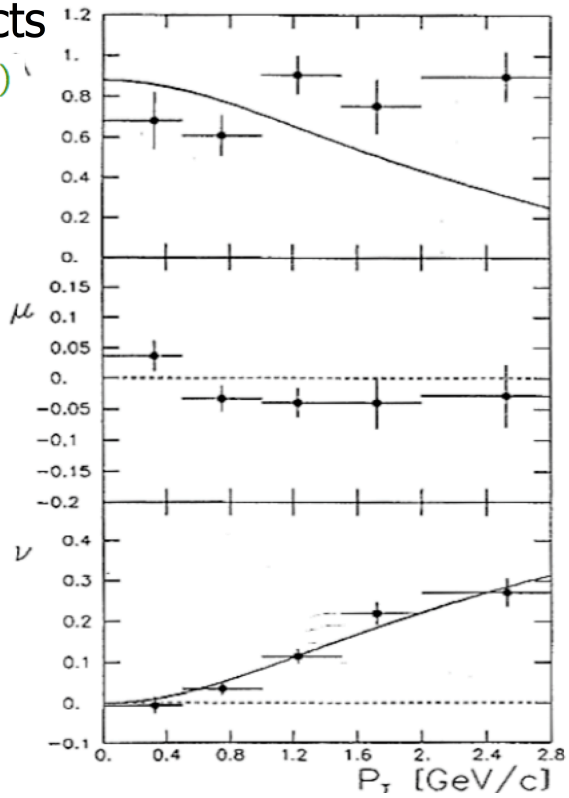
Lam-Tung relation(LO, collinear QCD)

$$1-\lambda-2\nu=0$$

- First measured in pion induced DY in 1980' (NA10 &E615)
- Large modulation of the cos2φ (ν parameter), up to 30%
- Violation of the Lam-Tung relation
- L-T violation not seen in proton induced DY at E866,
- nor at p-bar induced Drell-Yan in CDF
- Recent ATLAS and CMS Drell-Yan and Z production results show strong L-T violation
- Recently – violation could be explained by QCD radiative effects

J-C.Peng, W-C. Chang, R.E. McClellan, O. Teryaev, Phys.Lett.B **758**, 384 (2016)
M. Lambertsen and W. Vogelsang, Phys.Rev. D **93**, 114013 (2016)

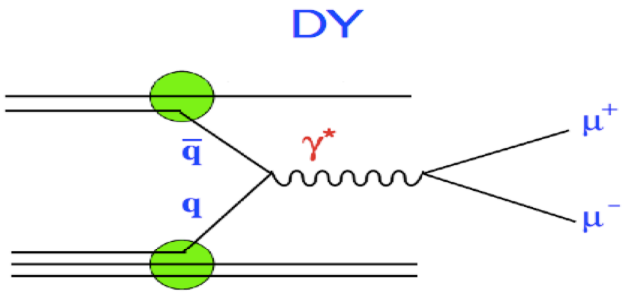
Study of Lam-Tung relation violation is one of the goals of COMPASS DY program (proton, Al, W targets)



NA10 (π^- W 194 GeV) Z.Phys.C 31, 513 (1986)

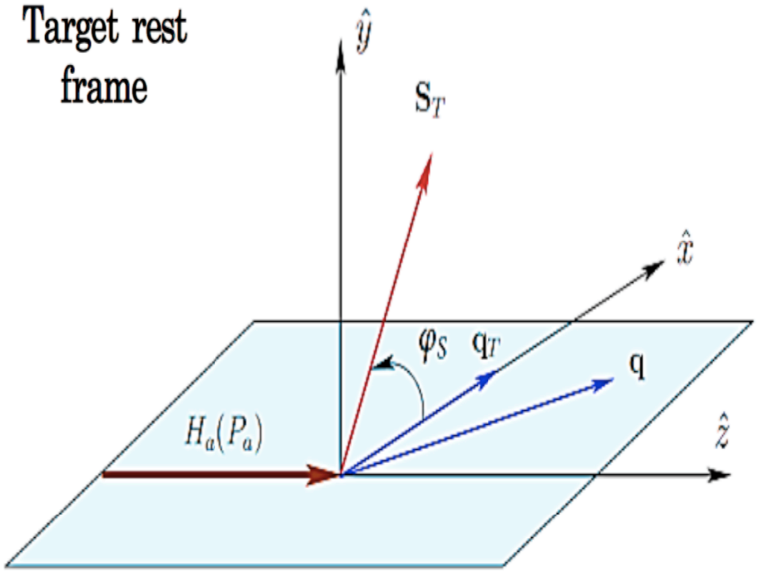
Single Polarized Drell-Yan cross-section at twist-2

$$\frac{d\sigma^{LO}}{d\Omega} = \frac{\alpha_{em}^2}{Fq^2} F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + D_{[\sin^2\theta_{CS}]} \left(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \right) \right] \right\}$$



$$D^{LO}_{[f(\theta)]} = \frac{f(\theta)}{1+\cos^2\theta}$$

D-factors



$A_U^{\cos 2\phi}$: Boer-Mulders $h_1^\perp(\pi) \otimes$ Boer-Mulders $h_1^\perp(p)$

$A_T^{\sin \phi_S}$: unpolarised PDF $f_1(\pi) \otimes$ Sivers $f_{1T}^\perp(p)$

$A_T^{\sin(2\phi+\phi_S)}$: Boer-Mulders $h_1^\perp(\pi) \otimes$ pretzelosity $h_{1T}^\perp(p)$

$A_T^{\sin(2\phi-\phi_S)}$: Boer-Mulders $h_1^\perp(\pi) \otimes$ transversity $h_1(p)$

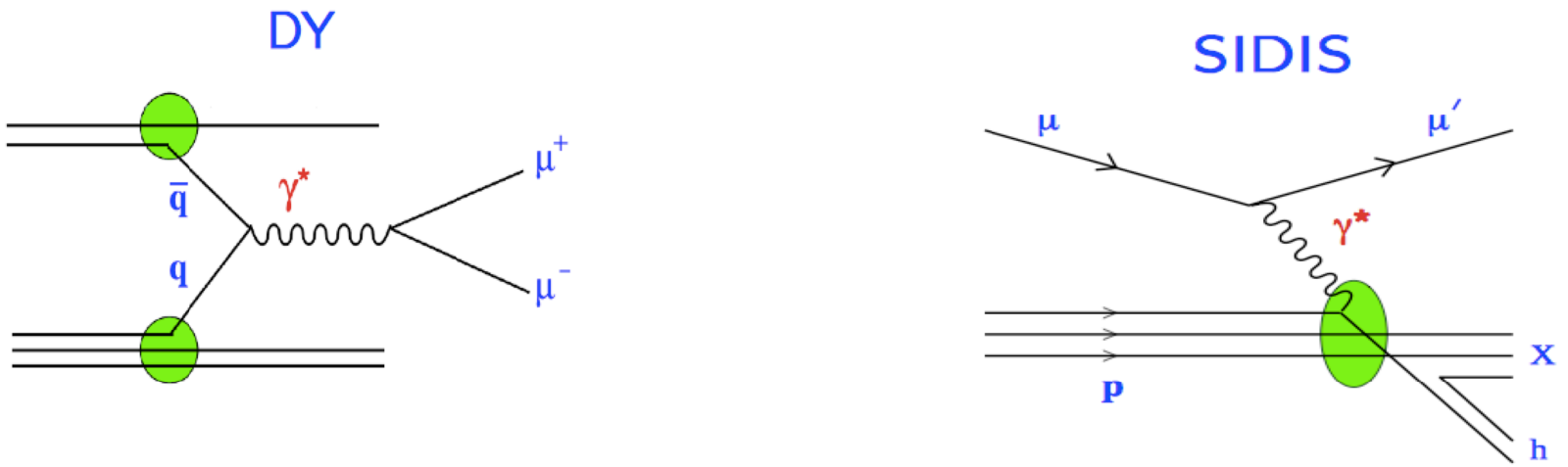
DY vs SIDIS

Fundamental QCD prediction:

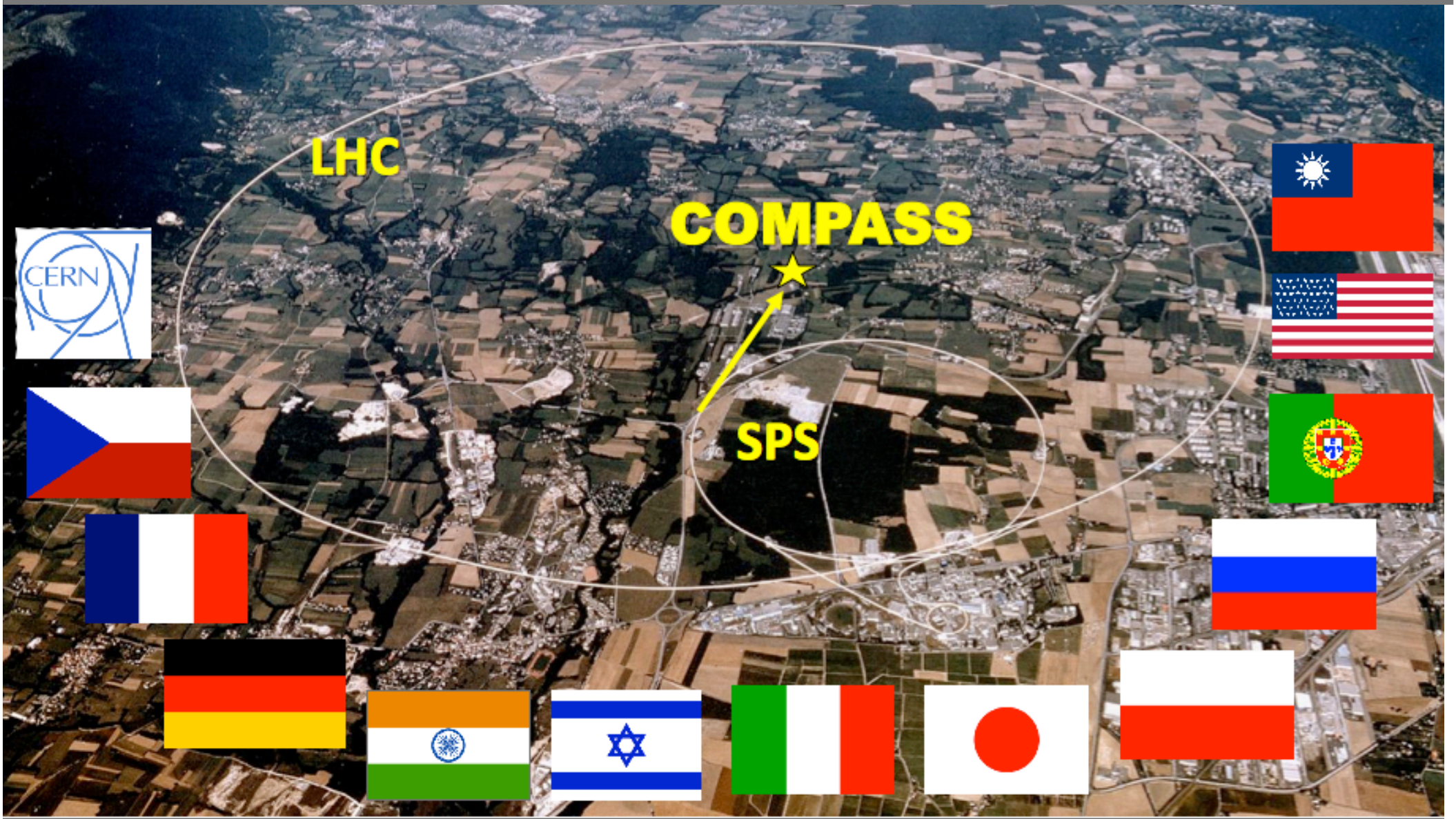
Due to their time-reversal odd nature Boer-Mulders and Sivers functions are expected to change sign when measured in SIDIS and Drell-Yan

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

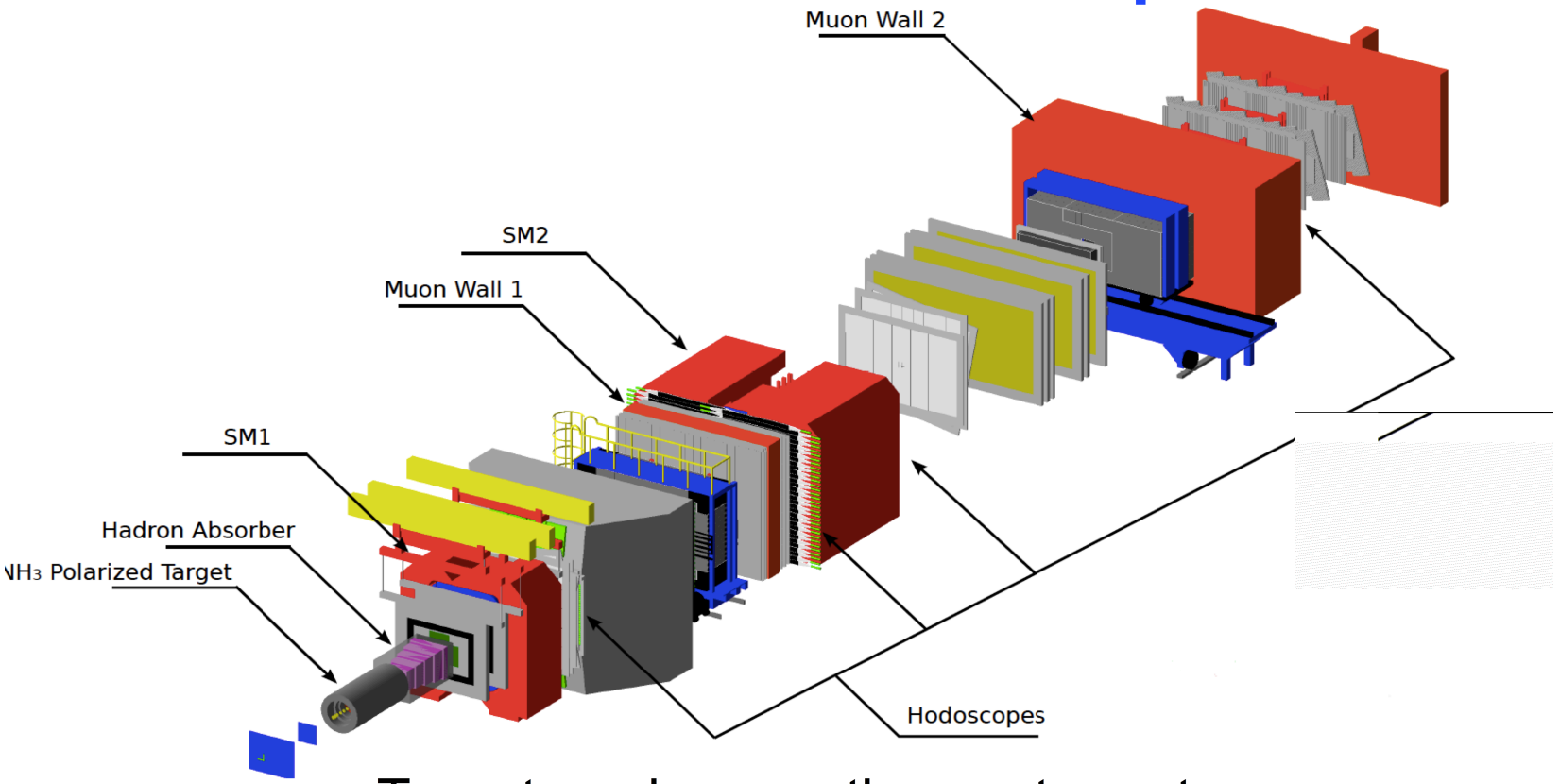
$$h_1^{\perp}(x, k_T)|_{DY} = -h_1^{\perp}(x, k_T)|_{SIDIS}$$



COMPASS: Versatile facility to study QCD with hadron (pions, kaon, antiprotons) and muon beams for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP, ...



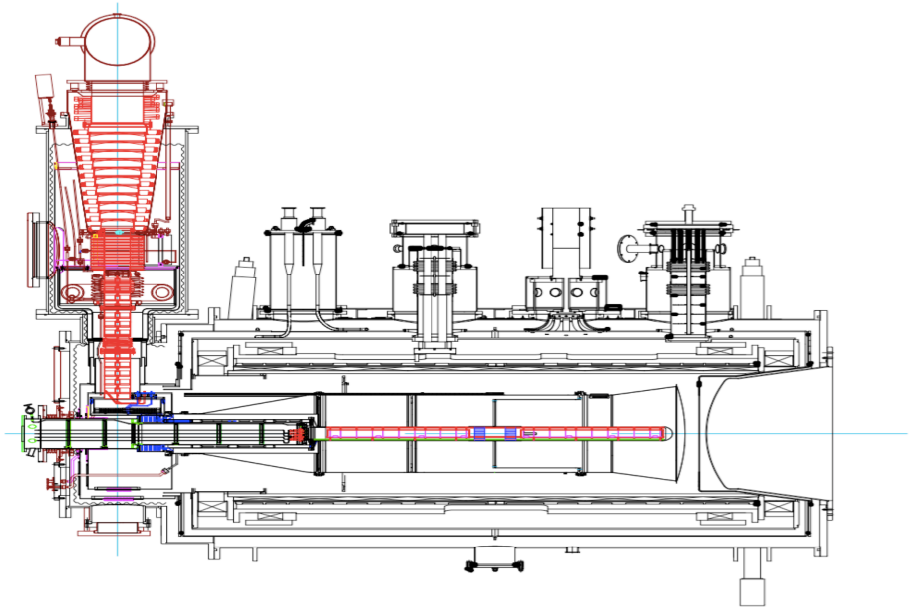
COMPASS experiment

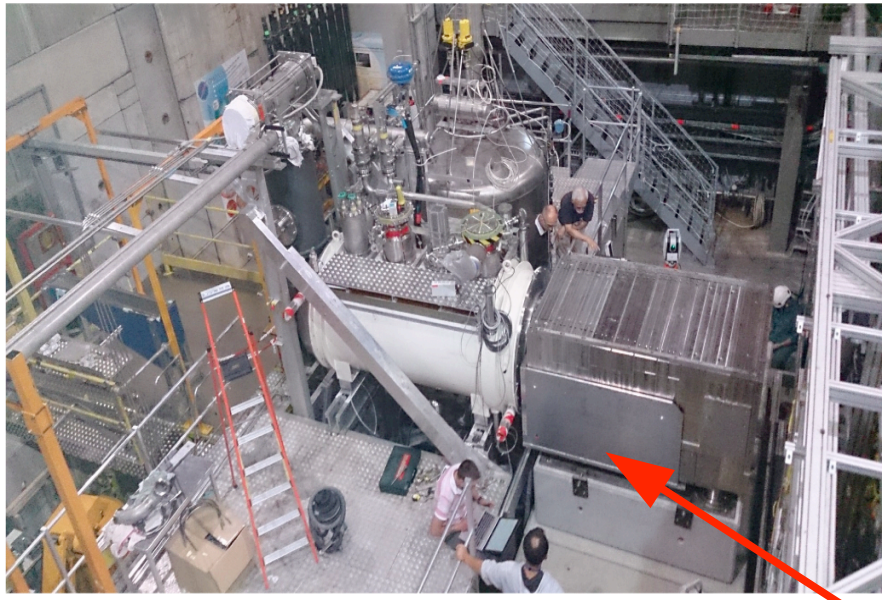


- Two staged magnetic spectrometer
- Calorimeters in both stages
- PID in first stage
- Lepton & hadron beams, polarized NH_3 , ^6LiD targets or various unpolarized nuclear targets(Al, Pb, C, W,..)
- ~300 tracking planes
- Hadron absorber for DY running
- Hadron beam ~97 % pion,~ 2 % kaons, ~1 % antiprotons

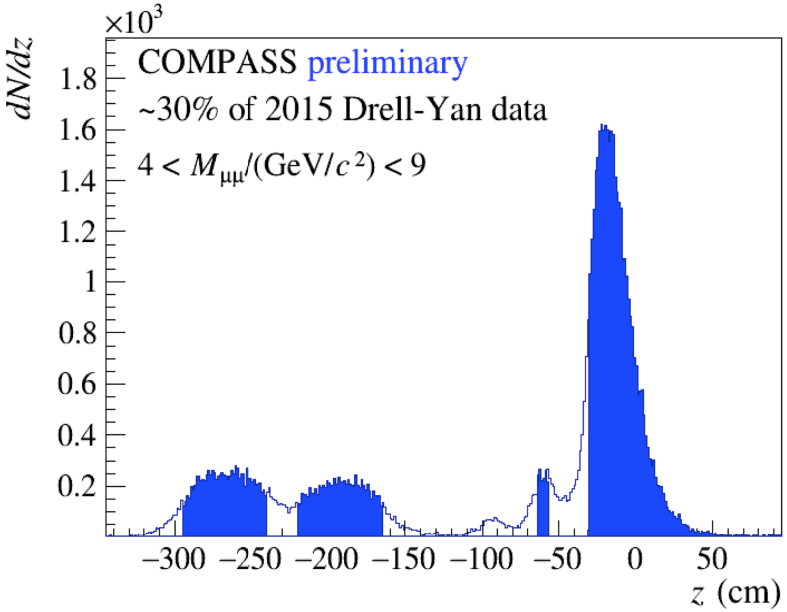
Polarized target

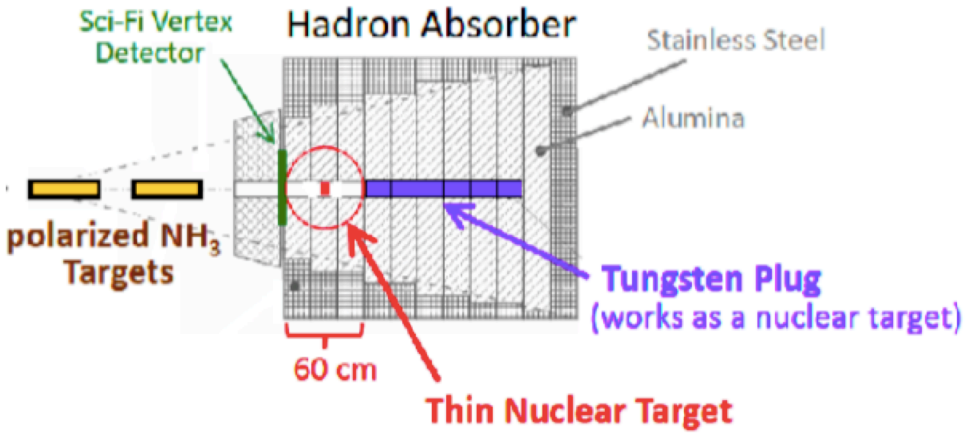
- 1,5 l of material (=solid ammonia)
- Dilution refrigerator for frozen spin mode, T~60 mK
- SC magnet 2 in 1 - 2.5 T solenoid for polarizing the material
  0,6 T dipole to keep the transverse polarization
- Two cell design with 10 NMR coil for polarization measurement
- Heating by hadron beam leads to relaxation time ~1000 h
- Typical P=80 %





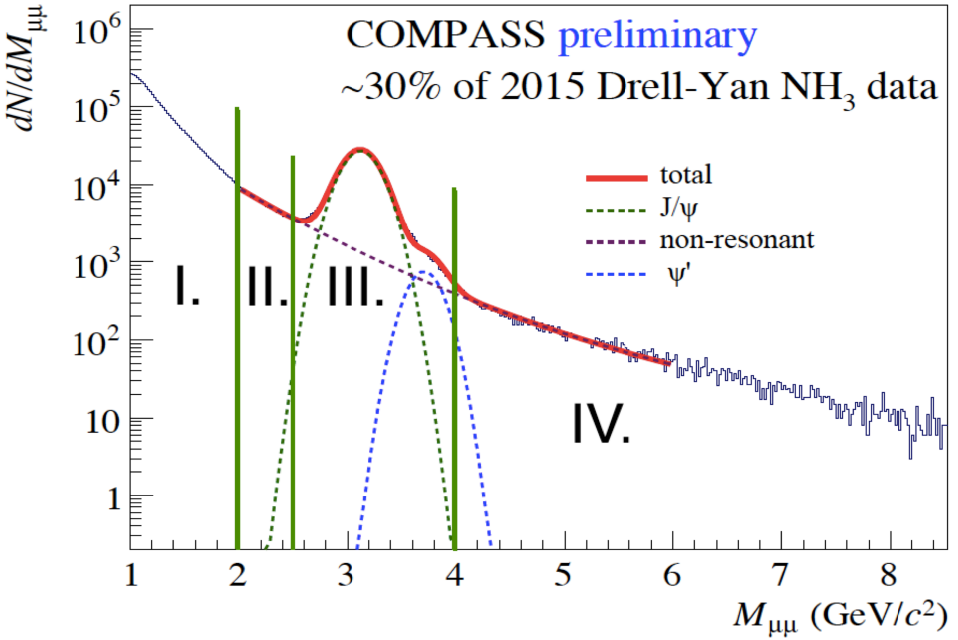
- Hadron absorber with beam plug made of tungsten
- Aditional Al target inside

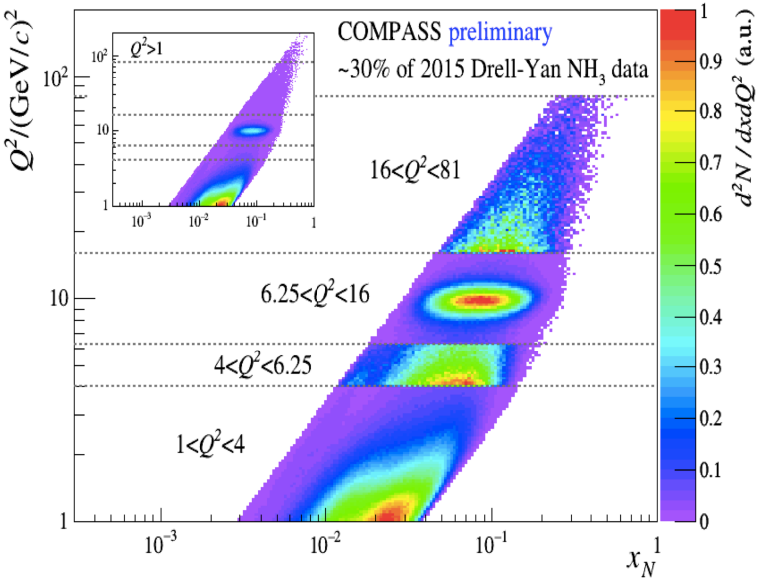




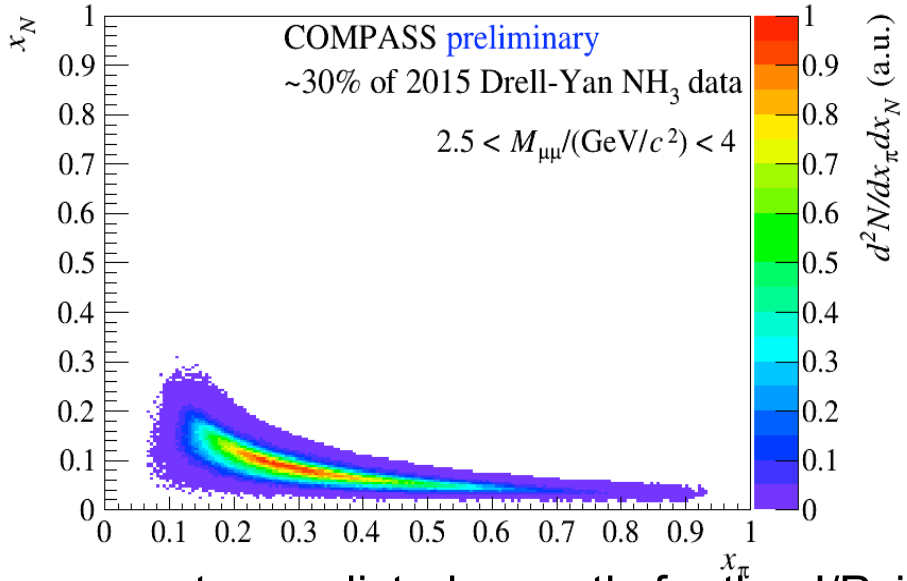
COMPASS DY mass-ranges

- I. Low mass 1-2 GeV/c^2
  high DY cross-section + high combinatorial background
- II. Intermediate mass 2-2.5 GeV/c^2
  Large contamination from open-charm and combinatorial background
- III. J/Psi range 2.5-4 GeV/c^2
  J/Psi dominates
  difficult to disentagle DY
- IV.High mass 4-9 GeV/c^2
  almost bgr free, low cross-section, valence quark region

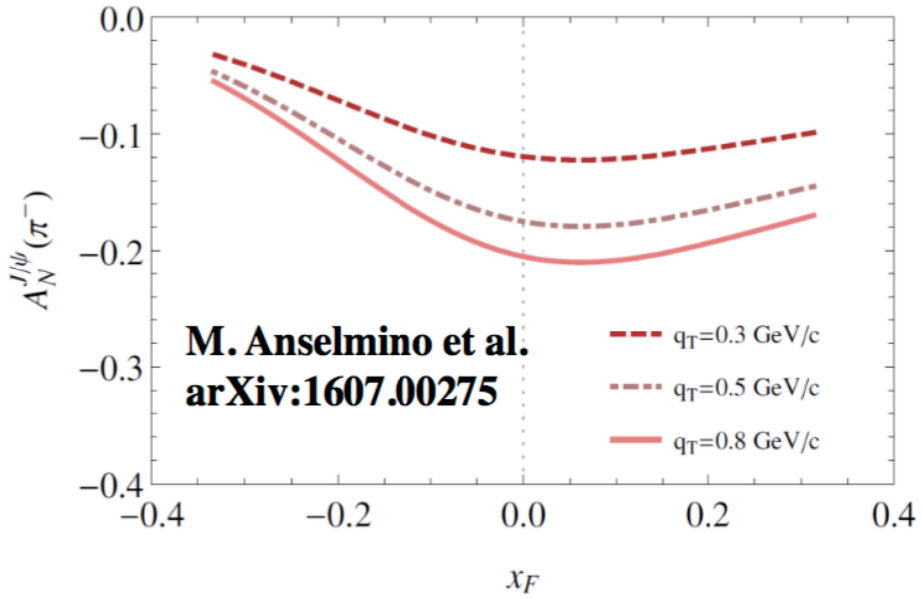




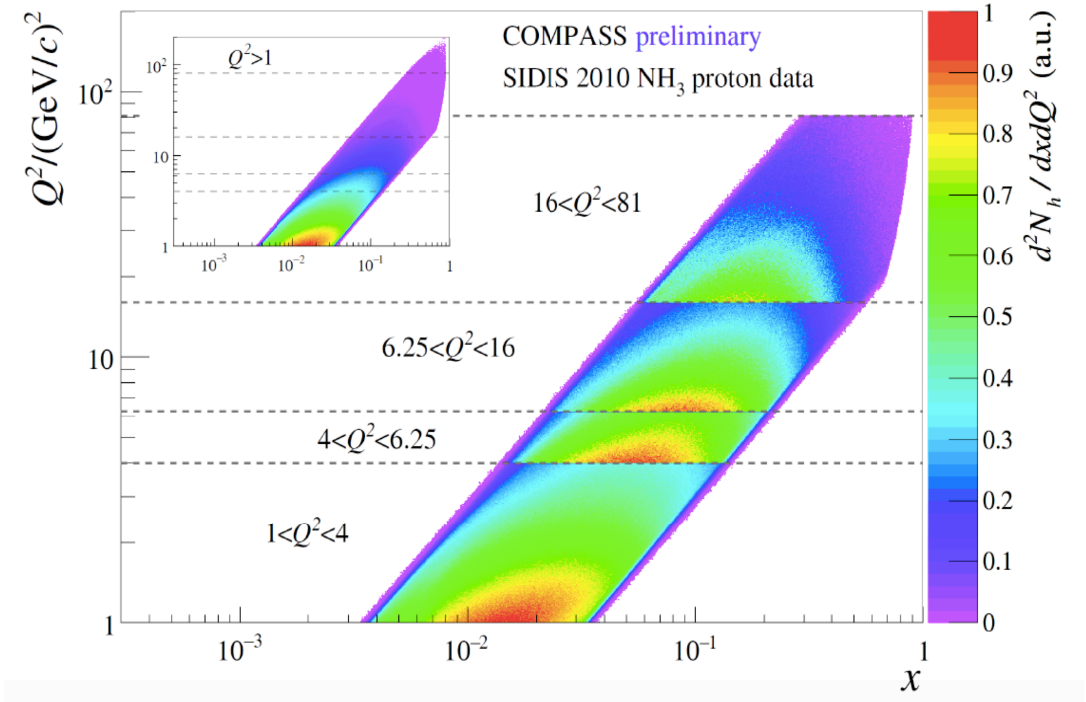
J/Psi mass-range

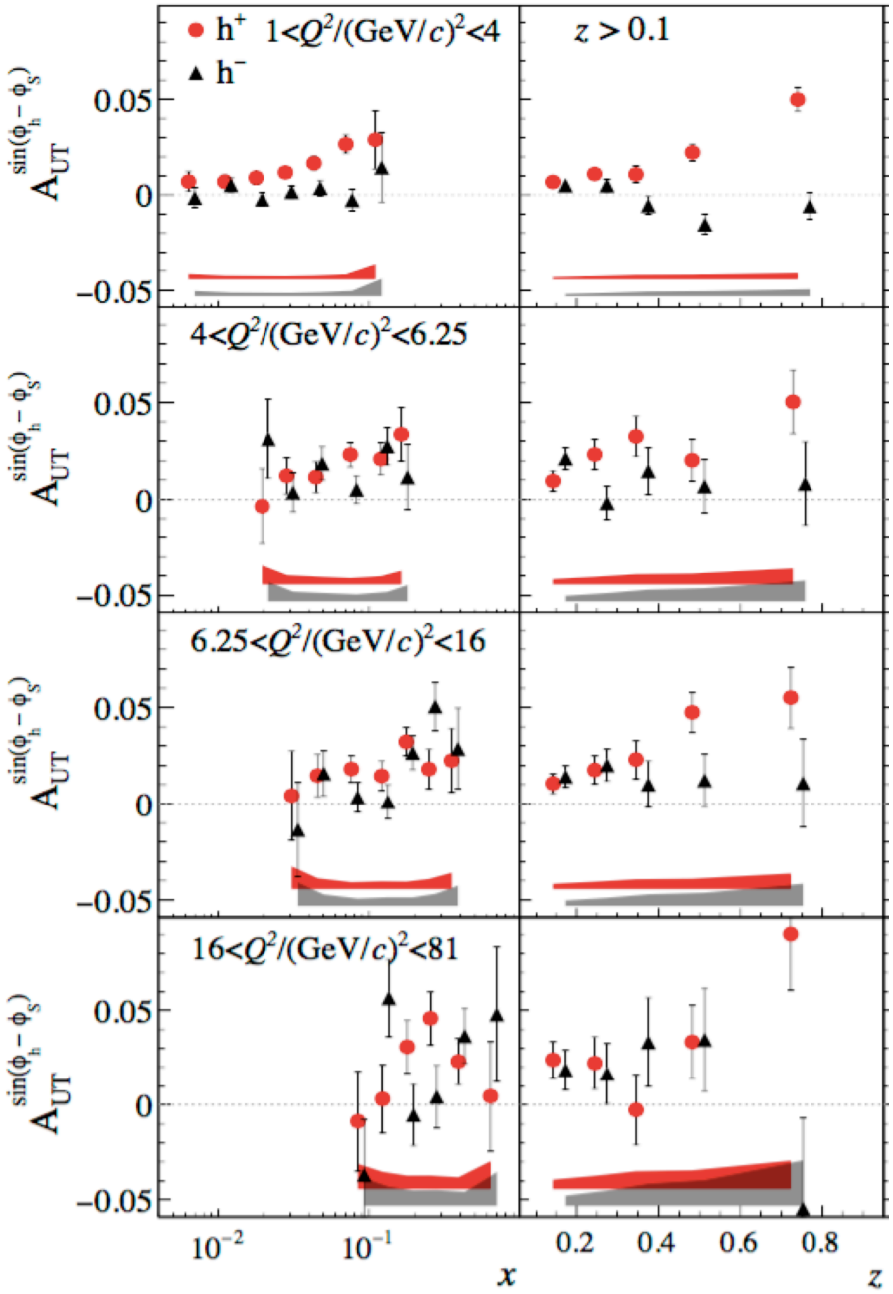


Large asymmetry predicted recently for the J/Psi by Anselmino et al.



SIDIS Sivers in DY mass-ranges





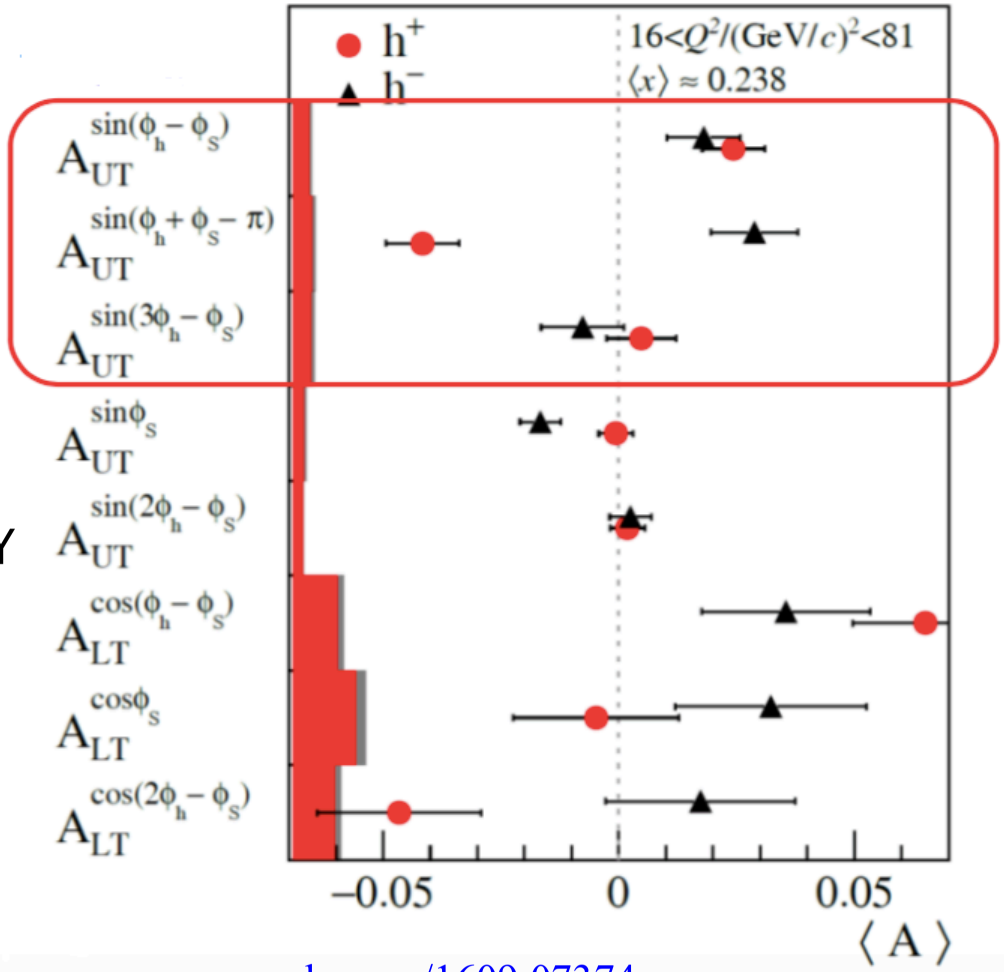
Sivers asymmetry extracted from 2010 SIDIS data in all 4 Q^2 ranges of DY

Clear Sivers asymmetry seen in all mass ranges, including the one corresponding to high mass DY

hep-ex/1609.07374

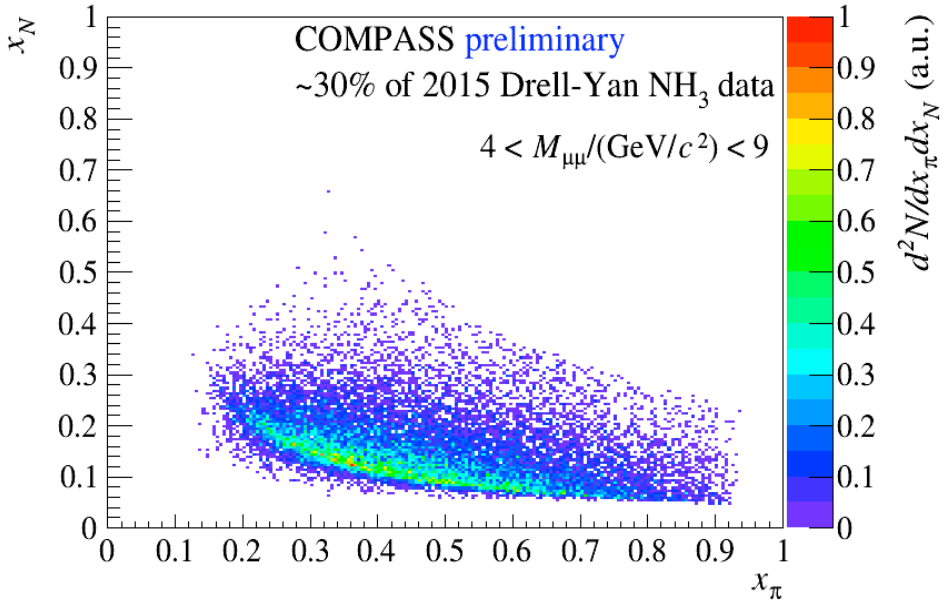
SIDIS Sivers in DY mass-ranges

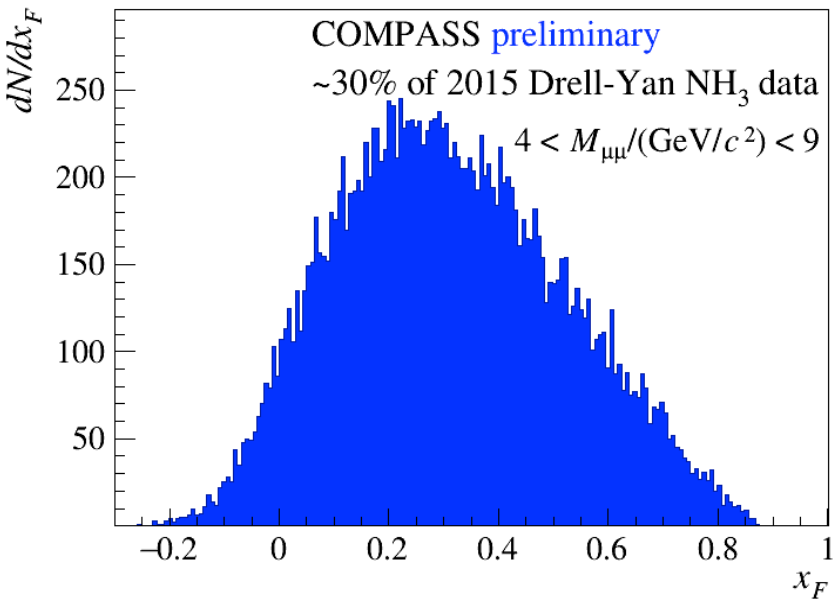
Clear Sivers asymmetry seen in all mass ranges, including the one corresponding to high mass DY

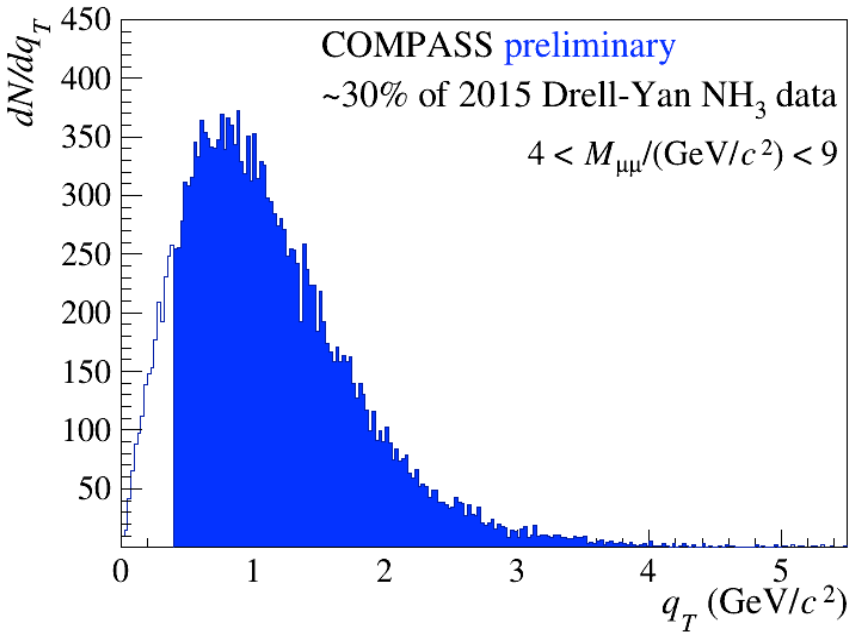


hep-ex/1609.07374

2015 kinematics distributions

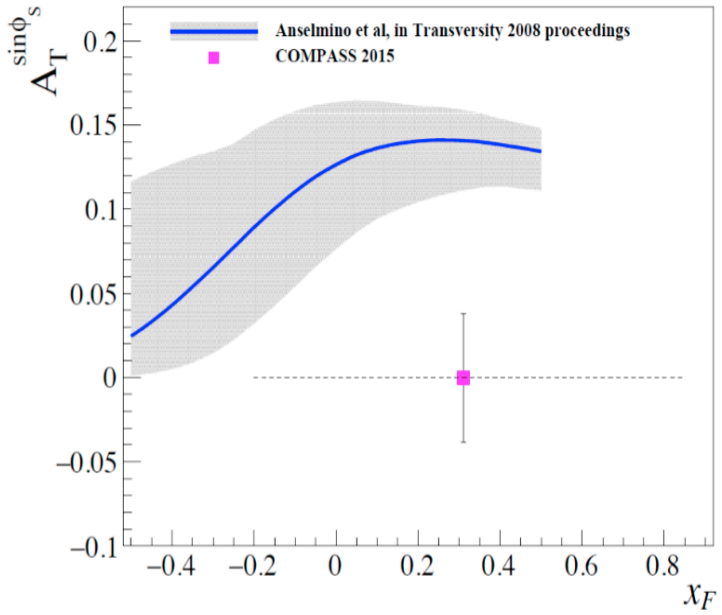




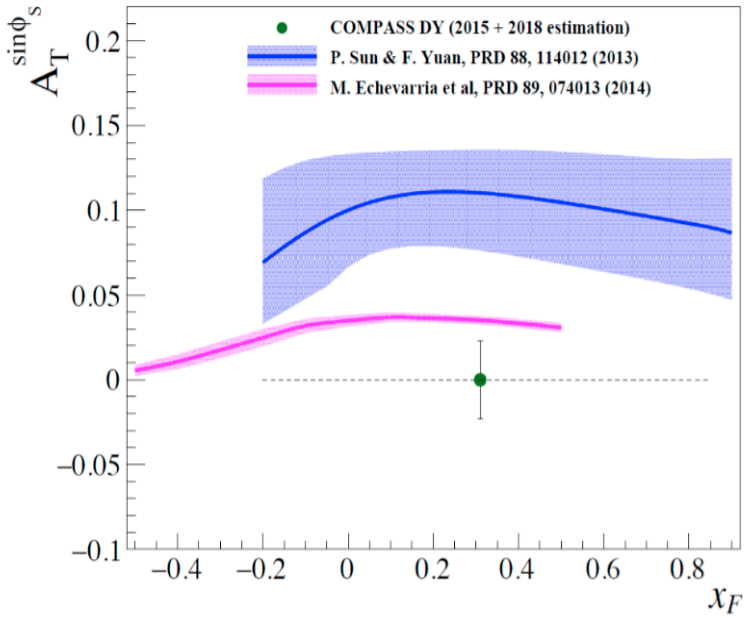


Expected accuracy for Sivers in DY

- Theoretical predictions for the asymmetry vary very much



- Statistical accuracy expected for the full 2015 data sample



- Expectation with additional year of data

P.Sun et al., PRD 88, 114002 (2013)
M. Echevarria et al., PRD 89, 674015 (2014)

Theory curve from Anselmino et al. using only DGLAP evolution

M. Anselmino et al., in Proceedings of Transversity 2008:
World Scientific, ed. by G. Ciullo et al., April 2009, ISBN:978-981-4277-77-8, p. 138.

Conclusion

- COMPASS performed the first ever polarized DY measurement
- Good prospects for determing the Sivers sign change
- Good prospects for study of unpolarized DY
- Data analysis ongoing
- More data possibly in 2018

Thank you for your attention!

Spares

Recent STAR measurement

Recently STAR measured the left-right asymmetry of dilepton production in p-p collisions with one of the beams polarized

Mass region of Z-boson

Data favors a Sivers TMD with sign-change between DY and SIDIS.

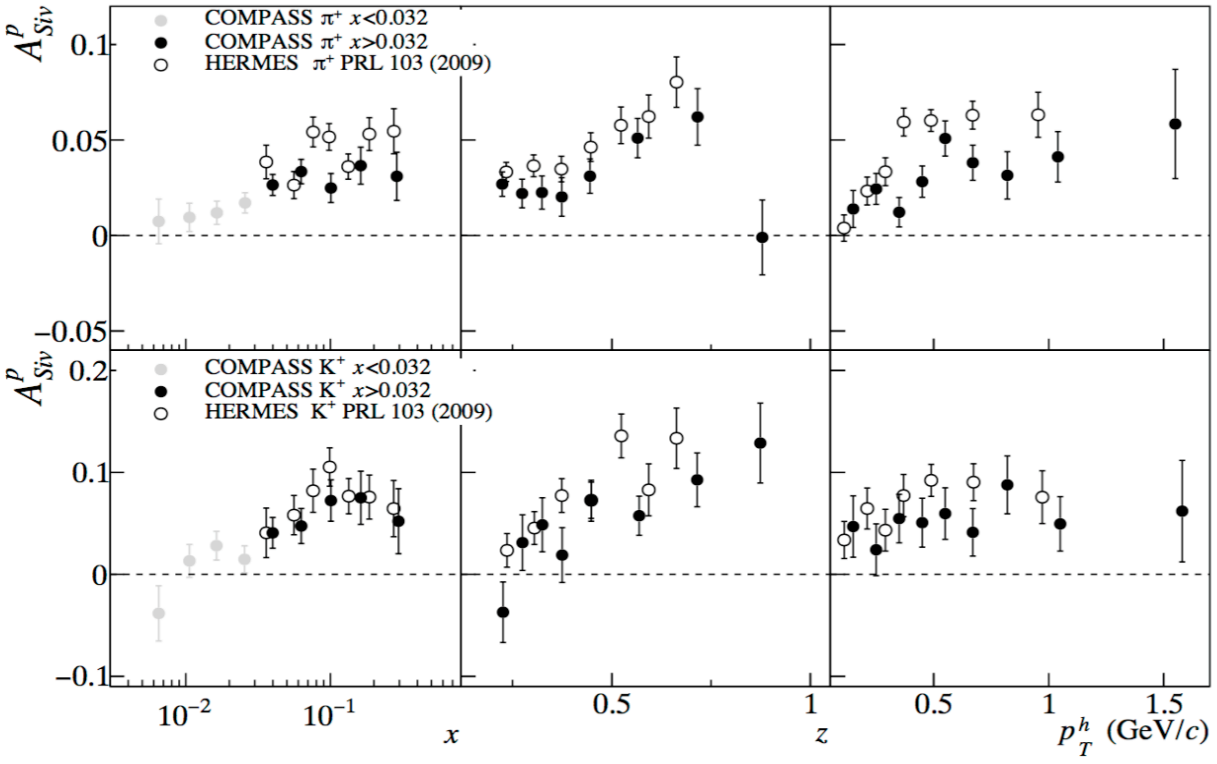
But they performed the measurement of Sivers in very different energy regime from SIDIS measurements, effects of evolution likely to be non- negligible.

The advantage of COMPASS is to acess the Sivers asymmetry in a comparable x-Q^2 phase space , with similar target and spectrometer, both in SIDIS and DY, thus minimizing possible Q^2 evolution effects

Hardware modifications for DY data taking

- Hadron absorber+beam plug
- SciFi Vertex detector downstream the target
- Dimuon trigger based on hodoscopes
- New PMM stations
- New large-area DC chamber
- “Proton-free” target cells
- New DAQ system
- Target magnet refurbishment

COMPASS SIDIS results



- Clear effect seen for both pions & kaons
- Smaller than HERMES
- Q^2 2-3x higher than HERMES->TMD evolution??