Selected Results and Future Perspectives for TMD Observables at CERN with COMPASS

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

Transverse Momentum Dependent PDFs

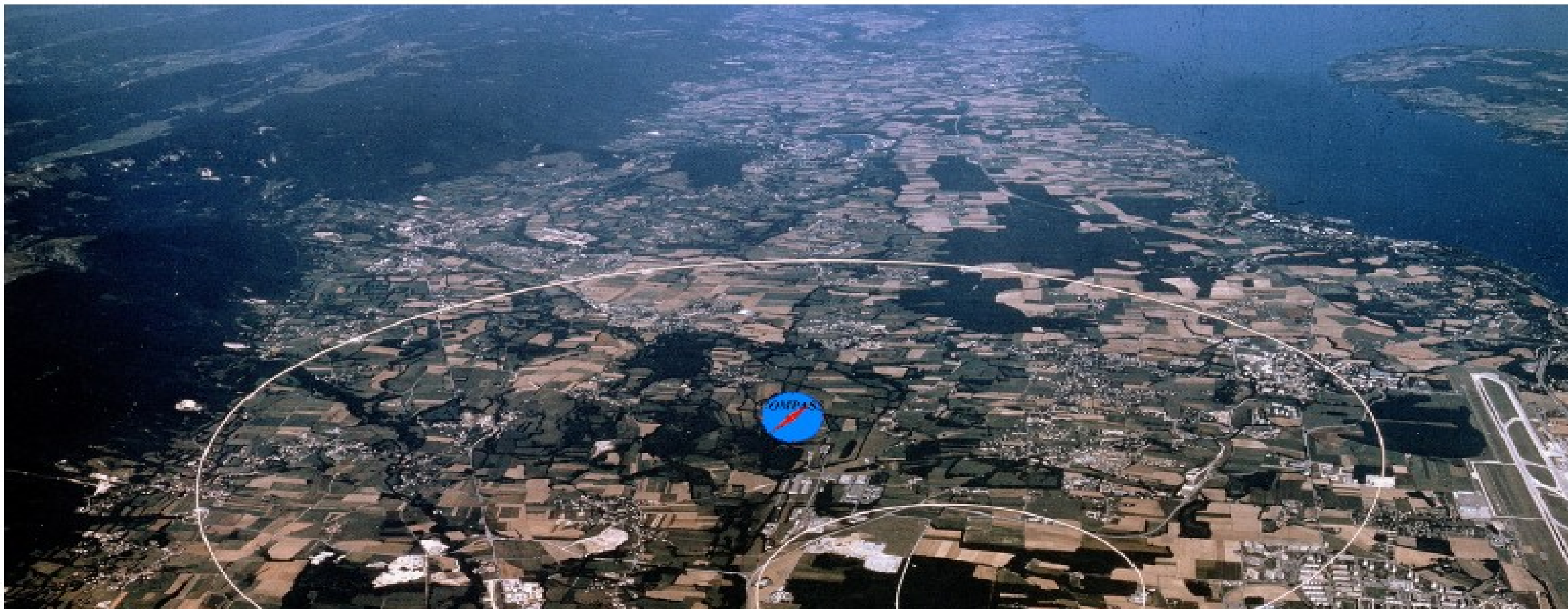
Single Spin Asymmetries in SIDIS from COMPASS
Constraining Boer Mulders-, Sivers- and Transversity-distributions

Drell-Yan at COMPASS

- Set-up
- Data taking in 2014 and 2015
- Plans for 2016-2018
- First Steps towards the future: COMPASS 2020

COMPASS at the CERN SPS

COmmon Muon Proton Apparatus for Structure and Spectroscopy



Broad physics program between COMPASS I and II

Studies of nucleon spin structure with longitudinally and transversely polarized ^{6}LiD and NH_3 targets in DIS, SIDIS and Drell-Yan processes.

SIDIS and exclusive reactions with lq hydrogen targets.

Hadron Spectroscopy and Primakov Reactions with hadron beams and unpolarized targets.

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

Saclay

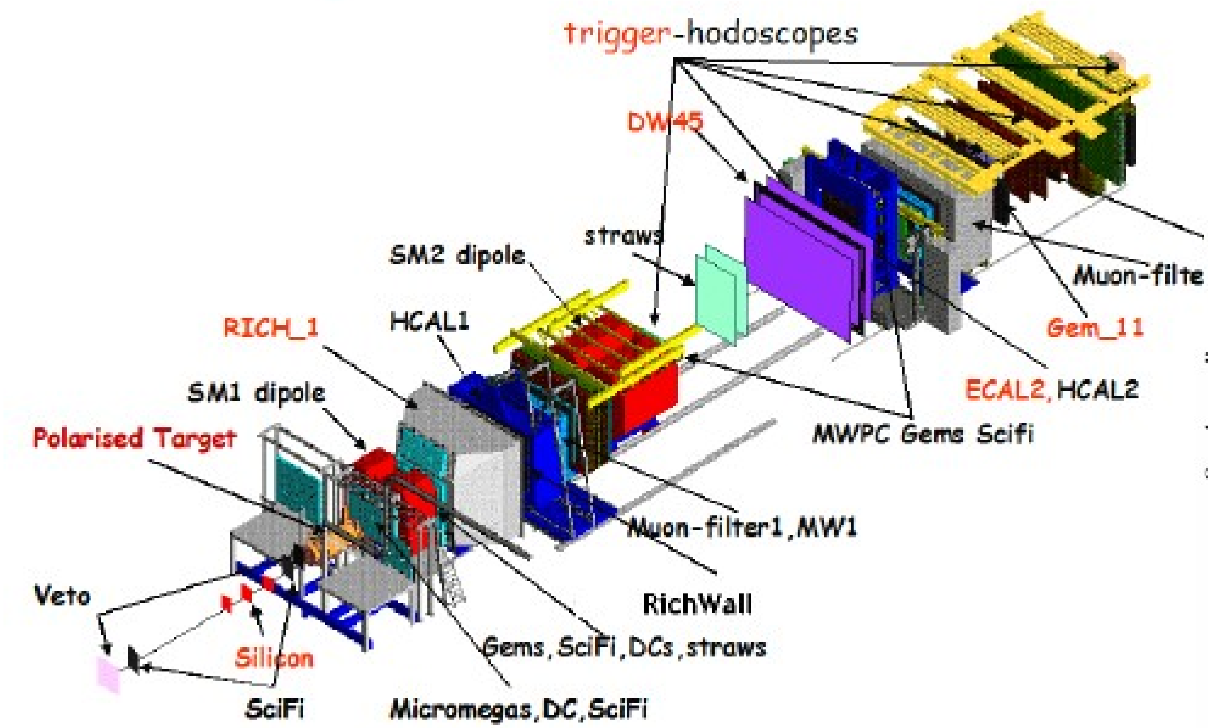
Torino (University,INFN),
Trieste (University,INFN)

~250 physicists from 24 institutions in 13 countries

COMPASS – Important Instrumentation Features

Two staged large acceptance spectrometers with high rate capability:

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

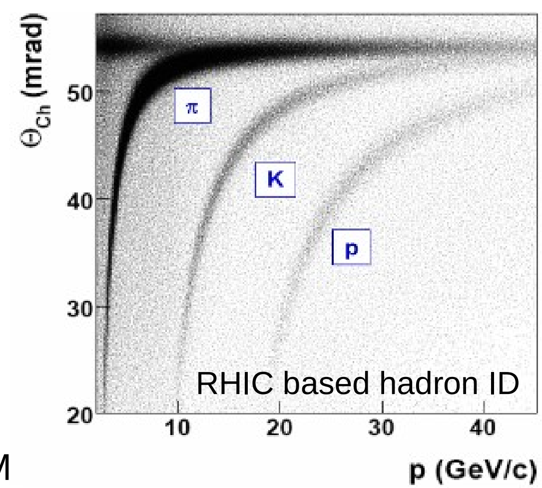


1.Muon, electron or hadron secondary beams with the momentum range 20-250 GeV and intensities up to 10^8 particles per second.

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

3.Powerful tracking system – 350 planes.

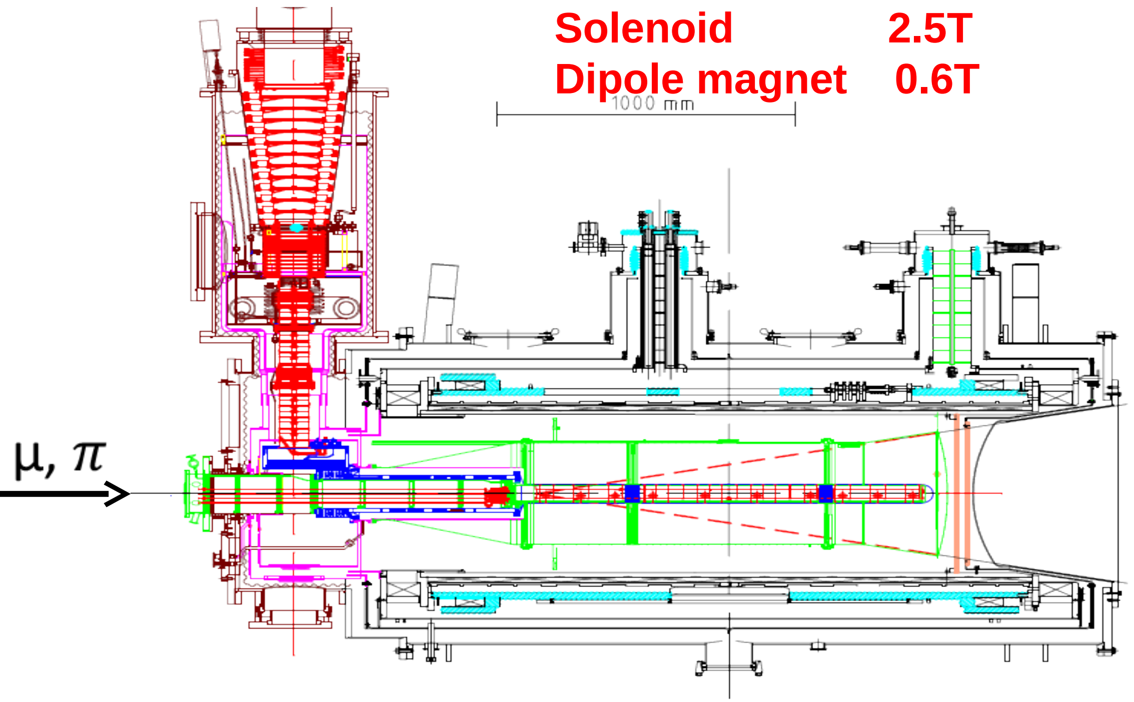
4. Versatile PID – RICH Muon Walls, Calorimeters.



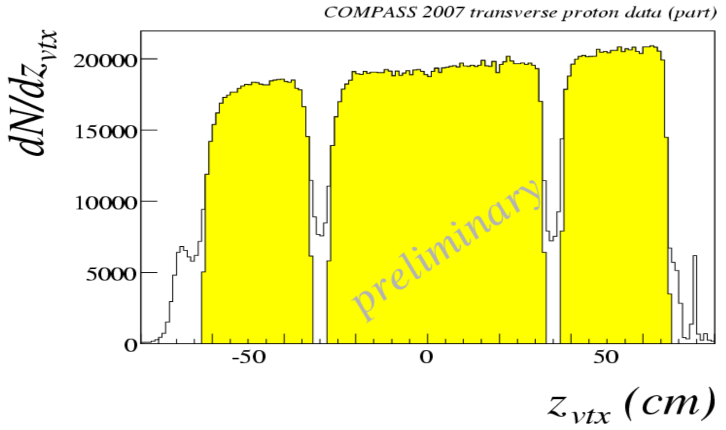
COMPASS – Important Instrumentation Features

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

Solenoid 2.5T
Dipole magnet 0.6T



Vertex distribution for SIDIS

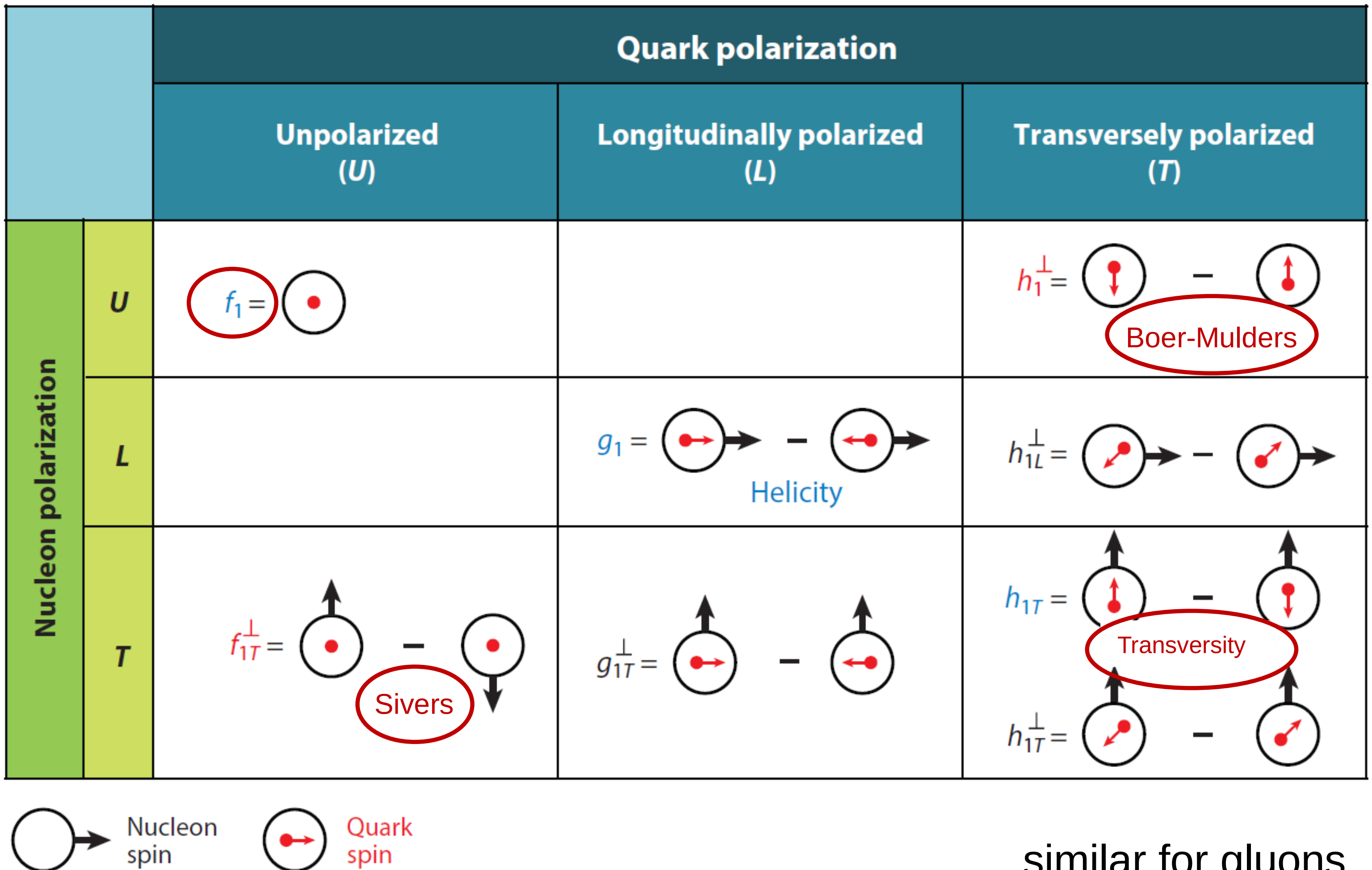


Opposite polarization in different target segments reversed frequently

	d (^6LiD)	p (NH_3)
Polarization	50%	90%
Dilution factor	40%	16%

Transverse Momentum Dependent Quark Distribution Functions at Leading Twist

from Acardi et al. arXiv:1212.1701

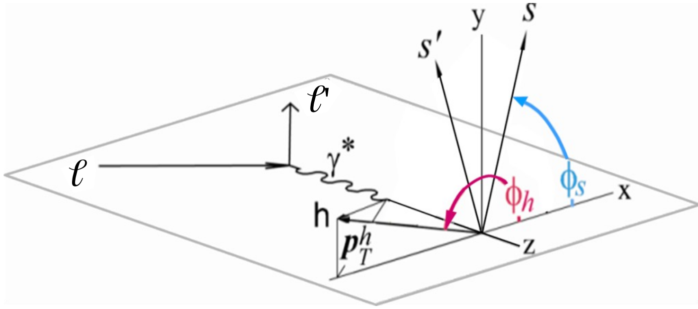


similar for gluons

TMD Modulations in the SIDIS and Drell-Yan Cross Sections

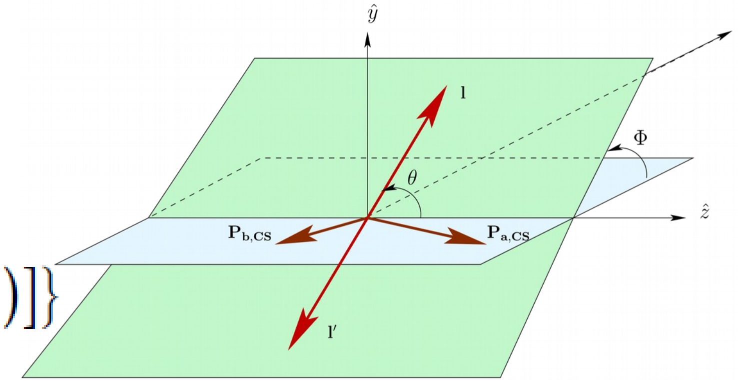
SIDIS:

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



DY:

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



Modulation Amplitudes vs TMDs

SIDIS:

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

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

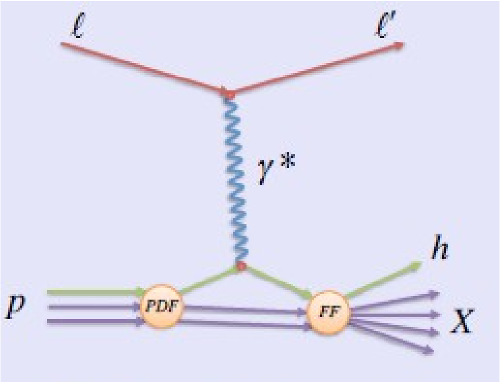
$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^{q} \otimes H_{1q}^{\perp h}$$

DY:

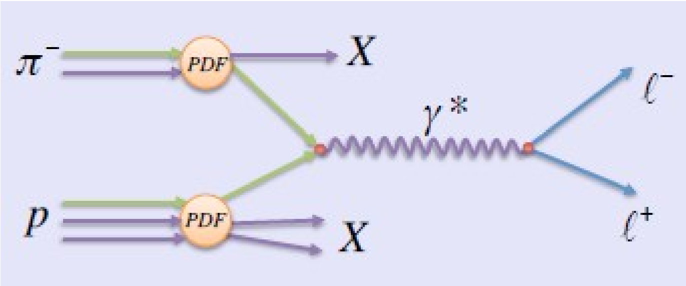
$$A_{UU}^{\cos(2\phi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$ Boer-Mulders

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

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



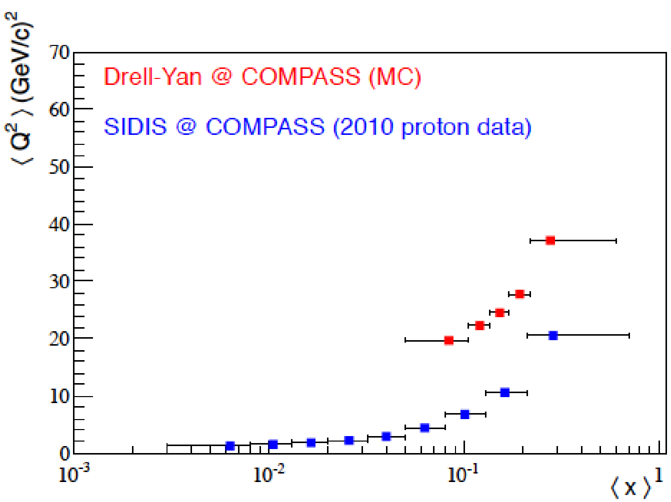
SIDIS: PDF ⊗ FF

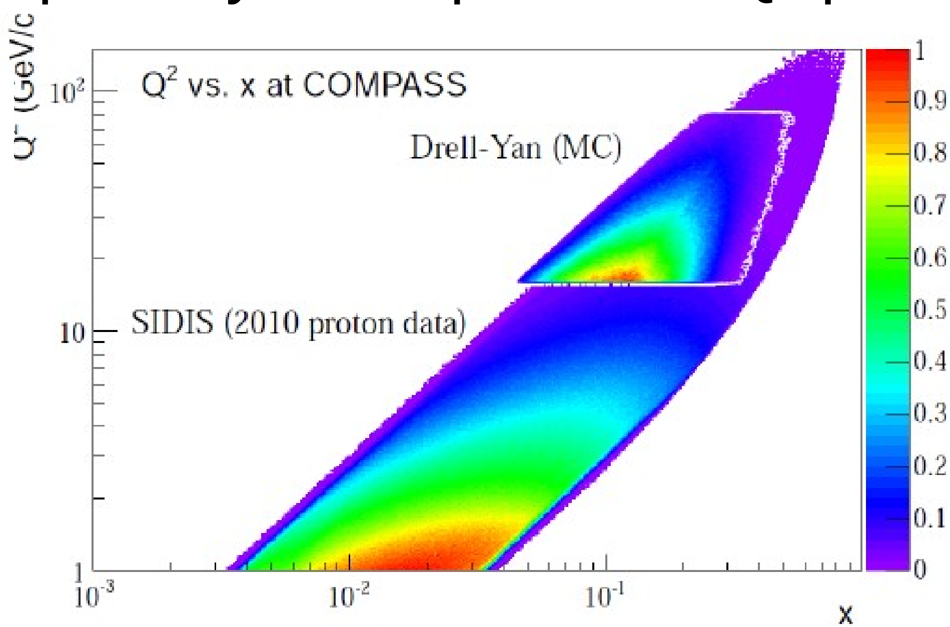


DY: PDF ⊗ PDF

Kinematic Coverage: SIDIS vs Drell-Yan

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

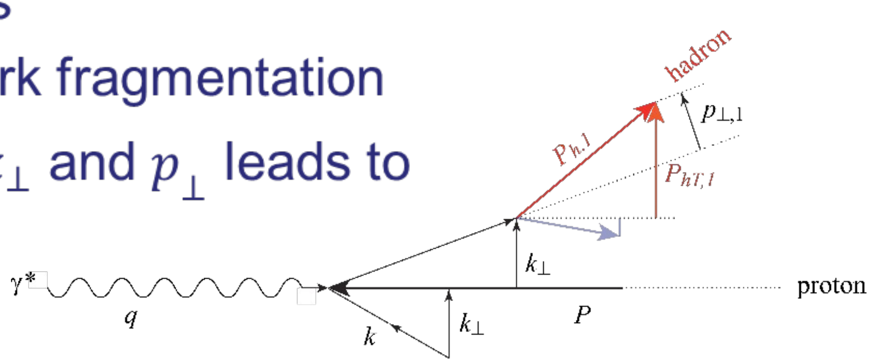




In the region of overlap in x, the average Q^2 in Drell-Yan is about two times larger compared to SIDIS

Transverse Momentum Dependence in the Unpolarized Cross Section

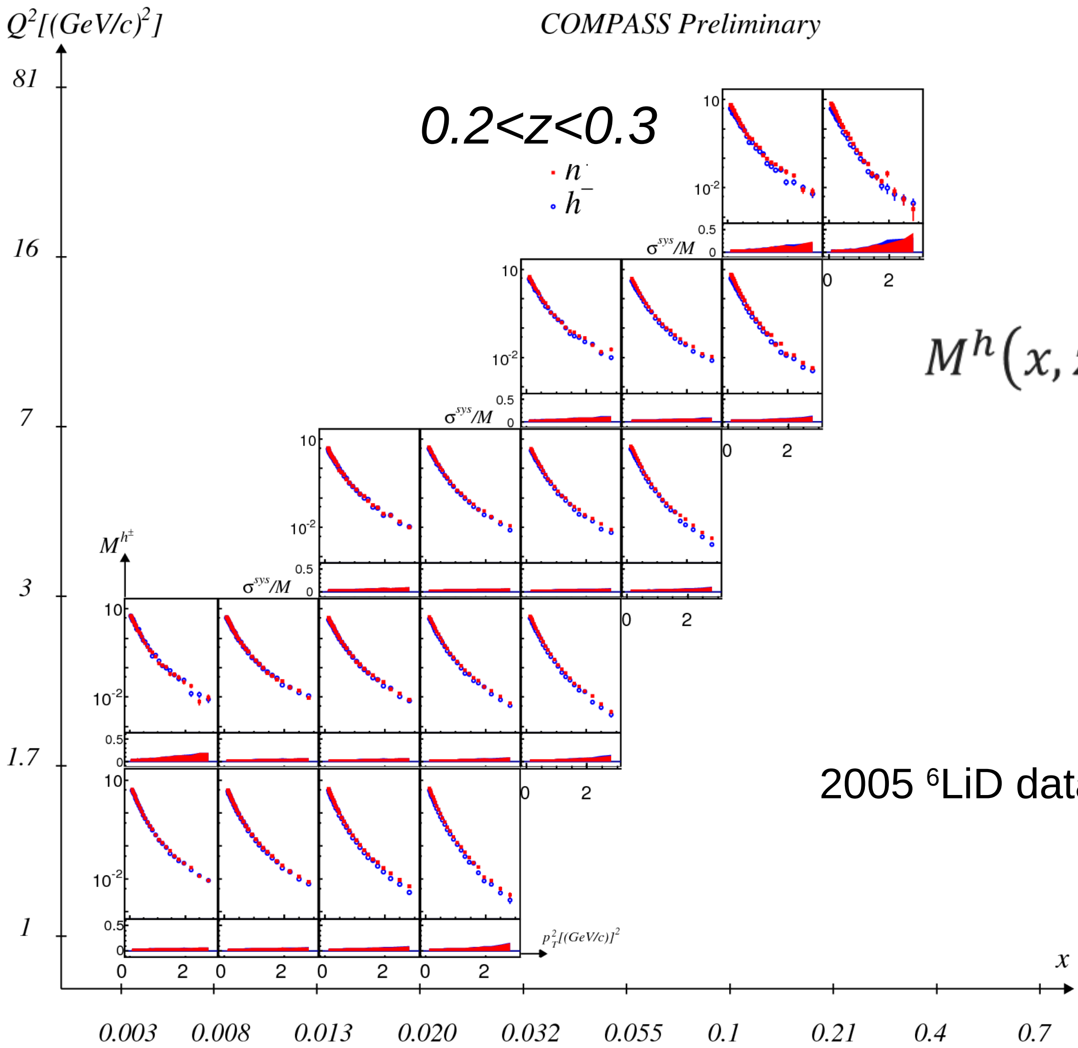
- The cross-section dependence on transverse hadron momentum, P_{hT}, results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



- The azimuthal modulations in the unpolarized cross-sections originate from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

Challenge: requires correction for apparatus acceptance!

Hadron Multiplicities vs x,Q^2, z and p_{hT}



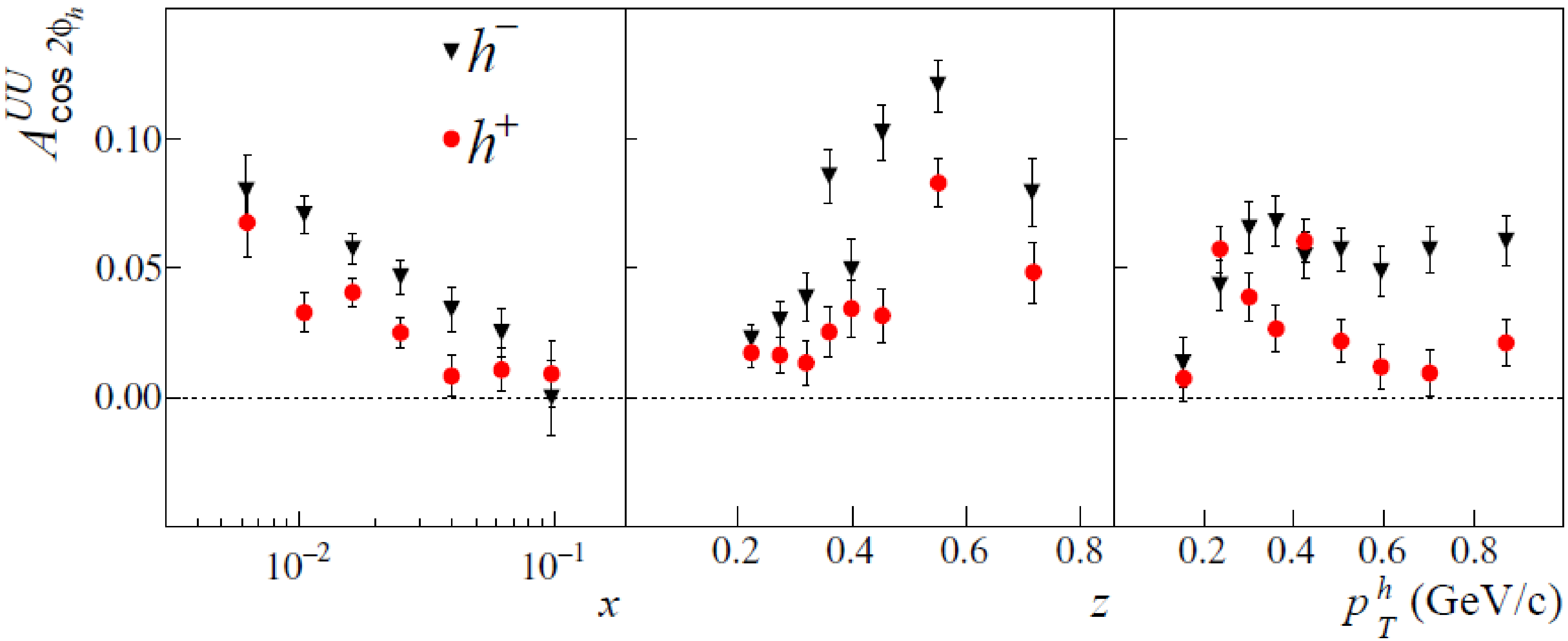
$$M^h(x, z, P_{hT}^2; Q^2) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2}$$

2005 ^{6}LiD data, COMPASS preliminary at Spin 2014

Boer-Mulders and Cahn: $A^{UU}_{\cos 2\phi_h}$

COMPASS, Nucl. Phys. B886 (2014)1046

2004 ^{6}LiD target data

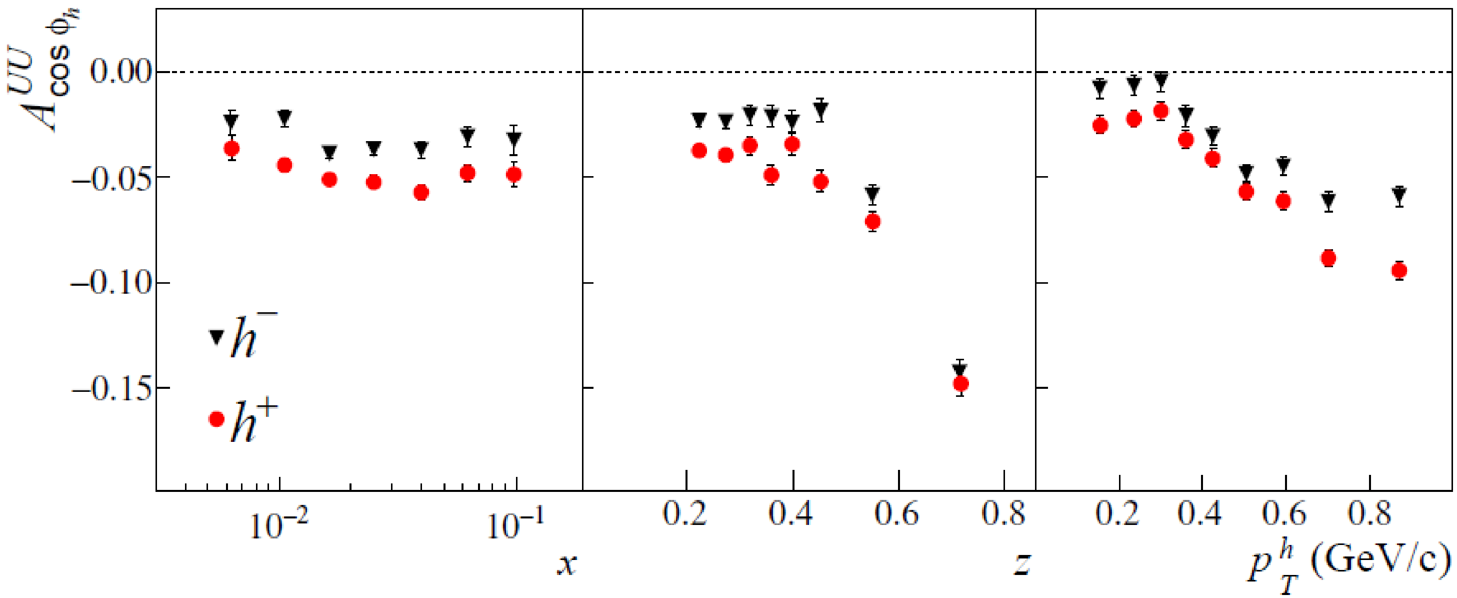


$$\frac{d\sigma}{p_T^h\, dp_T^h\, dx\, dy\, dz\, d\phi_h} = \sigma_0 \Big(1 + \epsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \\ + \epsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h + \lambda \epsilon_3 A^{LU}_{\sin\phi_h} \sin\phi_h \Big)$$

Boer-Mulders and Cahn: $A^{UU}_{\cos\phi_h}$

COMPASS, Nucl. Phys. B886 (2014)1046

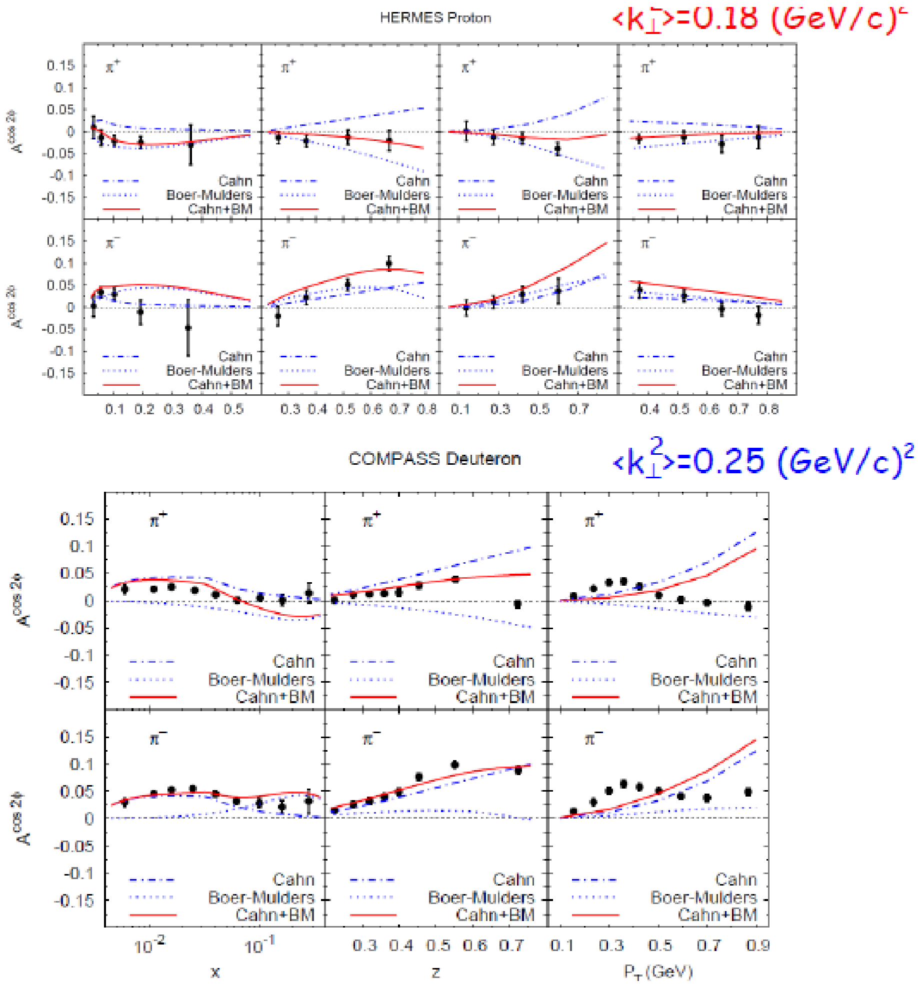
2004 ^{6}LiD target data



$$\frac{d\sigma}{p_T^h\, dp_T^h\, dx\, dy\, dz\, d\phi_h} = \sigma_0 \Big(1 + \epsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \\ + \epsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h + \lambda \epsilon_3 A^{LU}_{\sin\phi_h} \sin\phi_h\Big)$$

Towards a Global Analyis of $A^{UU}_{\cos 2\phi_h}$, A^{UU} in SIDIS and $A^{UU}_{\cos 2\phi_{CS}}$ in Drell-Yan

V. Barone, S. Melis and A. Prokudin Phys. Rev. D81, 114026 (2010)



- ✔Cahn effect (Twist-4) comparable to BM effect
- ✔Same sign of Cahn contribution for positive and negative pion
- ✔Different average transverse momenta are preferred
- ✔BM contribution opposite in sign for positive and negative pions

Data at different Q^2 (and from Drell-Yan) will help to isolate BM contributions

Extraction of Transversity Distributions and Determination of the Tensor Charge

SIDIS

~ $\delta q(x)$ x $CFF(z)$

~ $\delta q(x)$ x $IFF(z)$

COMPASS

e^+e^-

~ $CFF(z_1)$ x $CFF(z_2)$

~ $IFF(z_1)$ x $IFF(z_2)$

$pp \rightarrow$ jets

~ $G(x_1)x\delta q(x_2)$ x $CFF(z)$

$pp \rightarrow h^+ + h^- + X$

~ $G(x_1)x\delta q(x_2)$ x $IFF(z)$

$\pi p \rightarrow l^+ + l^- + X$ Drell-Yar

~ $h_1^\perp(x_1)$ x $\delta q(x_2)$

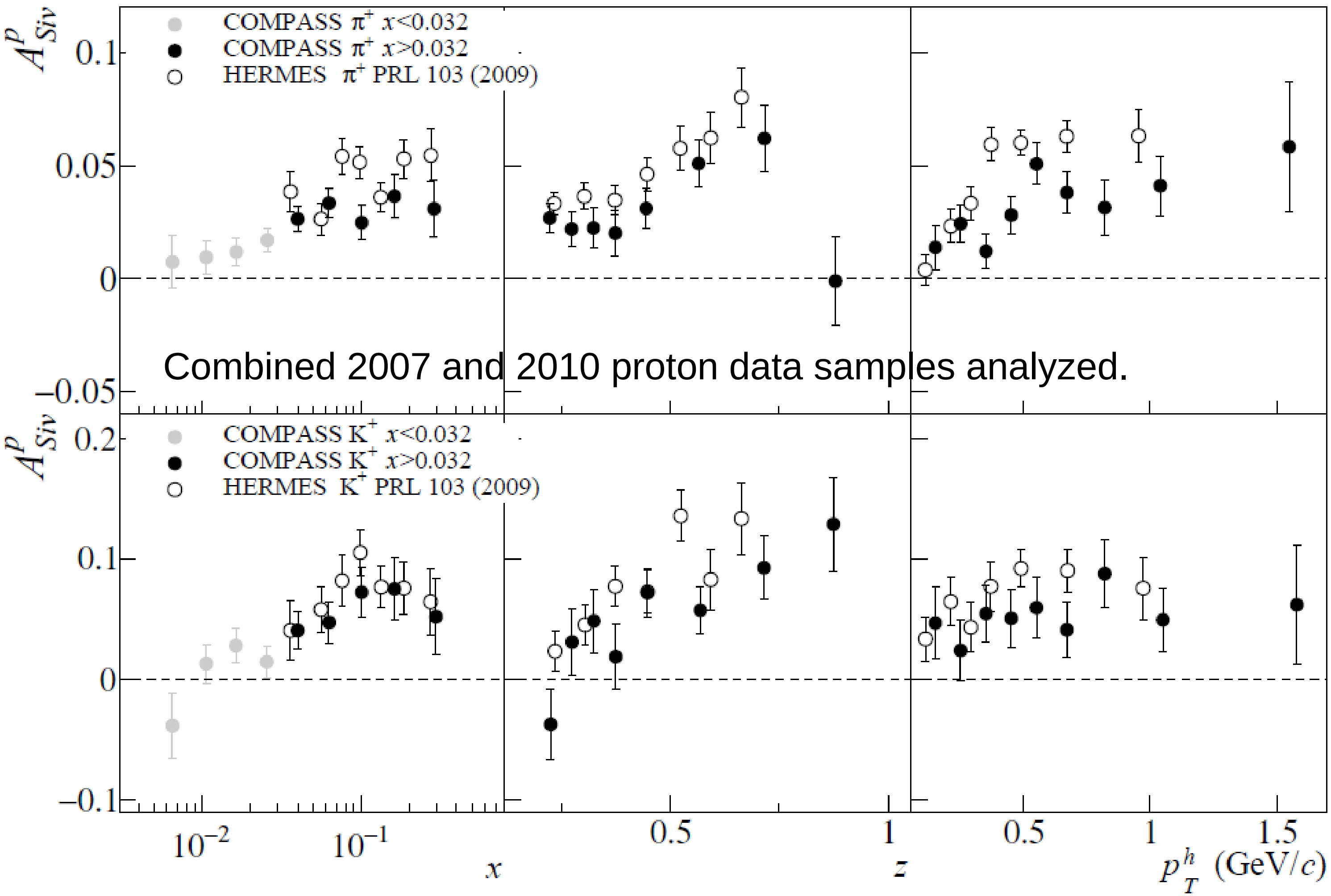
Theory

Transversity, $\delta q(x)$
Tensor Charge

Lattice QCD: Tensor Charge =
$\Sigma_{q=u,d}\int_0^1 \delta q(x)dx$

Collins Asymmetries for Pions on Proton Targets

COMPASS Phys.Lett. B744:250(2015)



Combined 2007 and 2010 proton data samples analyzed.

Transversity & Tensor Charge Extracted with TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Experiment	hadron	Target	dependence	# ndata	χ^2	$\chi^2/ndata$
COMPASS [97]	π^+	LiD	x	9	11.16	1.24
COMPASS [97]	π^-	LiD	x	9	9.08	1.01
COMPASS [97]	π^+	LiD	z	8	3.26	0.41
COMPASS [97]	π^-	LiD	z	8	7.29	0.91
COMPASS [97]	π^+	LiD	$P_{h\perp}$	6	4.19	0.70
COMPASS [97]	π^-	LiD	$P_{h\perp}$	6	4.50	0.75
COMPASS [96]	π^+	NH_3	x	9	21.46	2.38
COMPASS [96]	π^-	NH_3	x	9	6.23	0.69
COMPASS [96]	π^+	NH_3	z	8	7.80	0.98
COMPASS [96]	π^-	NH_3	z	8	10.29	1.29
COMPASS [96]	π^+	NH_3	$P_{h\perp}$	6	3.82	0.64
COMPASS [96]	π^-	NH_3	$P_{h\perp}$	6	3.85	0.64
HERMES [95]	π^+	H	x	7	5.37	0.77
HERMES [95]	π^-	H	x	7	12.61	1.80
HERMES [95]	π^+	H	z	7	3.04	0.43
HERMES [95]	π^-	H	z	7	3.23	0.46
HERMES [95]	π^+	H	$P_{h\perp}$	6	1.60	0.27
HERMES [95]	π^-	H	$P_{h\perp}$	6	4.82	0.80
JLAB [9]	π^+	^{3}He	x	4	3.90	0.98
JLAB [9]	π^-	^{3}He	x	4	3.11	0.78
				140	130.65	0.93

Experiment	Observable	dependence	# ndata	χ^2	$\chi^2/ndata$
BELLE [12]	A_0^{UL}	z	16	13.02	0.81
BELLE [12]	A_0^{UC}	z	16	11.54	0.72
$BABAR$[98]	A_0^{UL}	z	36	34.61	0.96
$BABAR$[98]	A_0^{UC}	z	36	15.17	0.42
$BABAR$[98]	A_0^{UL}	$P_{h\perp}$	9	9.09	1.01
$BABAR$[98]	A_0^{UC}	$P_{h\perp}$	9	4.33	0.48
			122	87.76	0.72

Data sets from SIDIS (HERMES, JLab, COMPASS) and e^+e^- (Belle, BaBar)

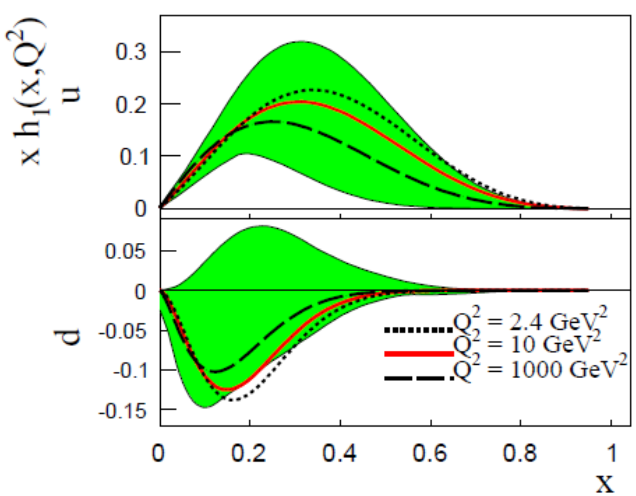
Fit describes data sets well!

Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

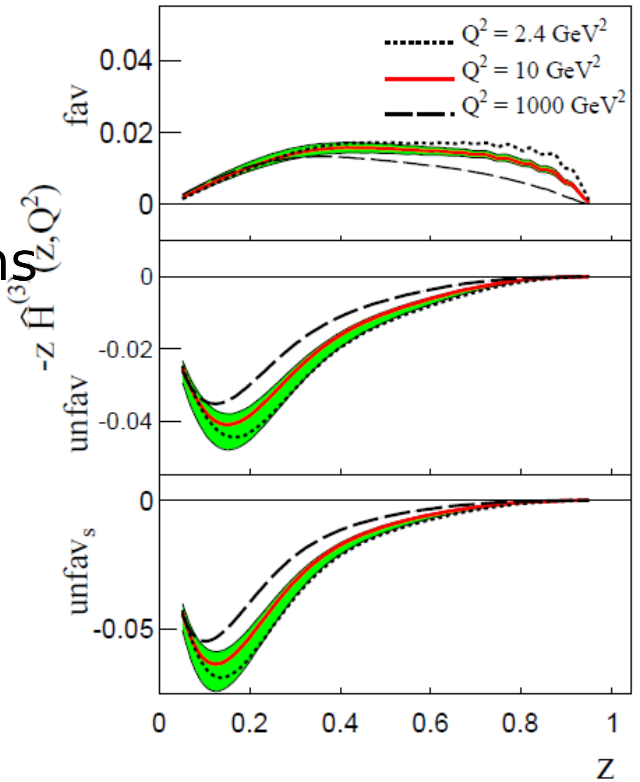
Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

Results given at
Q^2=2.4, 10 and 1000 GeV^2

up and down
transversity distributions



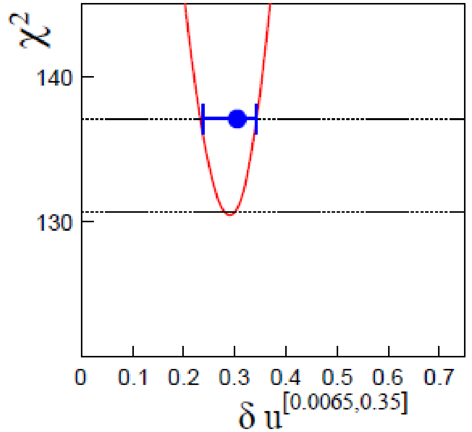
Favored and unfavored
Collins FF

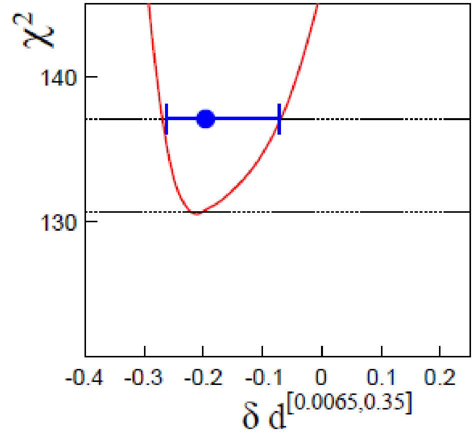


Transversity and the Tensor Charge Extracted Using TMD Evolution and Recent Data Sets

Z.-B. Kang., A. Prokudin, P. Sun, F. Yuan - Phys.Rev. D93 (2016) 1, 014009

up and down contributions to tensor charge





Integrals in data region

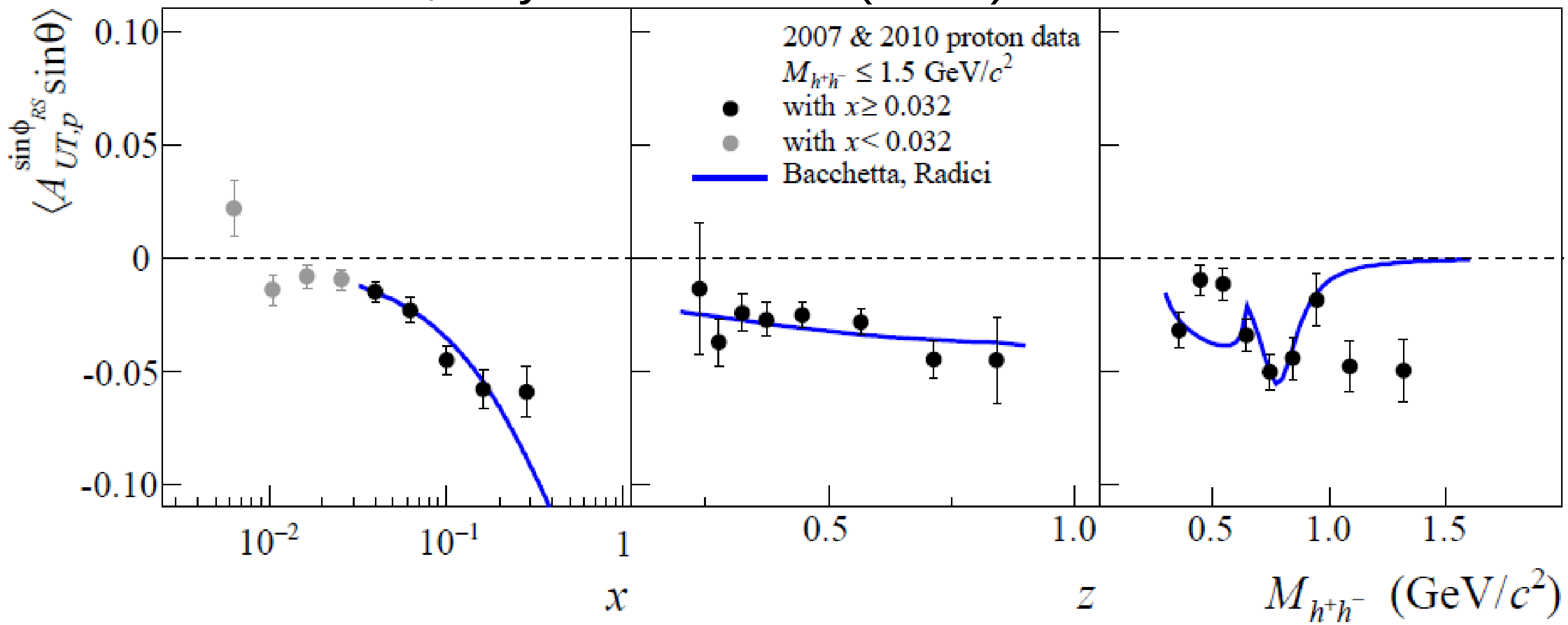
$$\delta u^{[0.0065,0.35]} = +0.30^{+0.04}_{-0.07}$$
$$\delta d^{[0.0065,0.35]} = -0.20^{+0.12}_{-0.07}$$

Integrals in [0,1]

$$\delta u^{[0,1]} = +0.39^{+0.07}_{-0.11}$$
$$\delta d^{[0,1]} = -0.22^{+0.14}_{-0.08}$$

2 Hadron IFF Asymmetries

COMPASS, Phys. Lett. B736 (2014)124

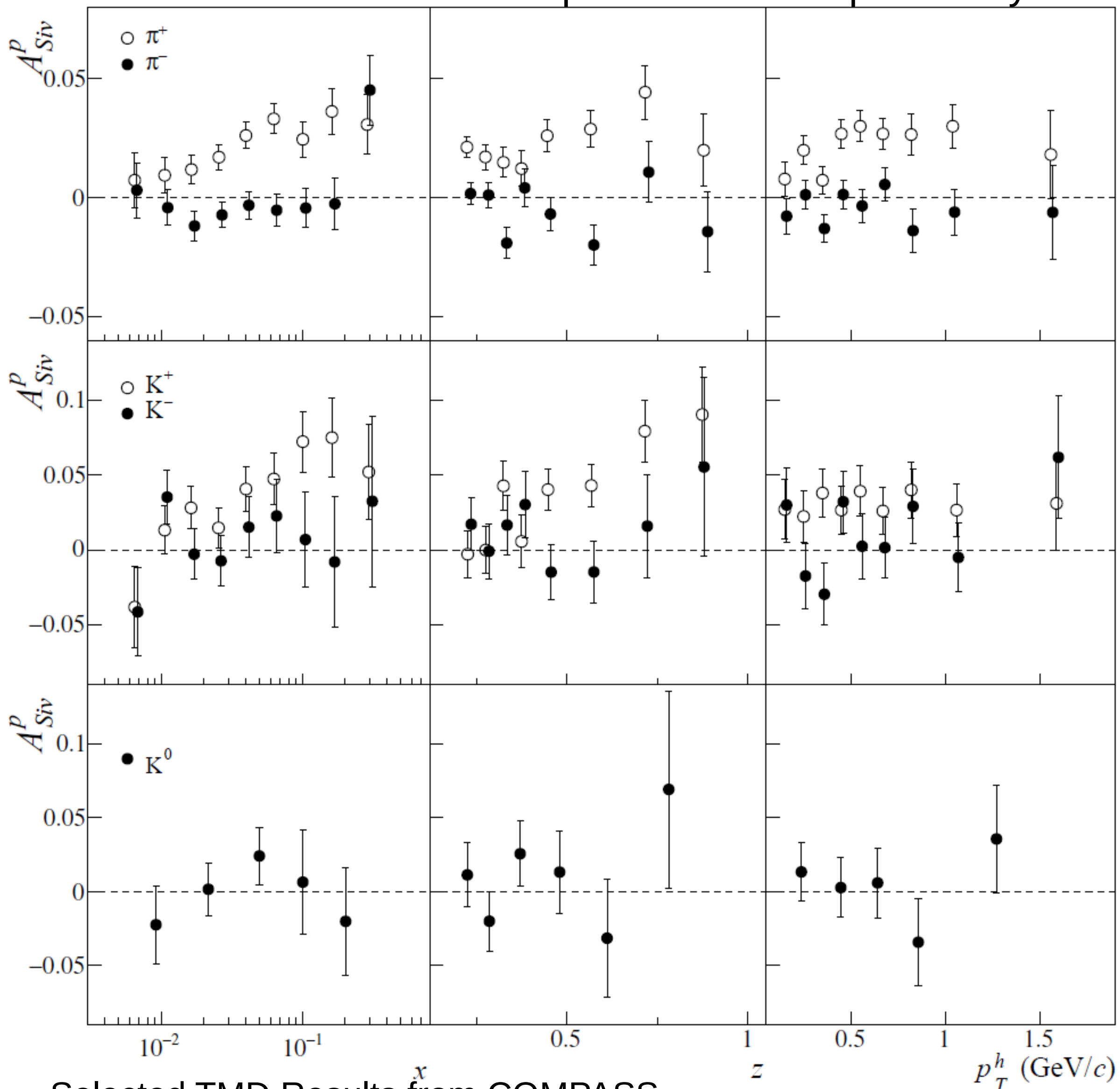


Combined 2007 and 2010 proton data samples analyzed.
Good agreement to prediction based on fit to Collins data.

Sivers Asymmetries for π,K and K⁰

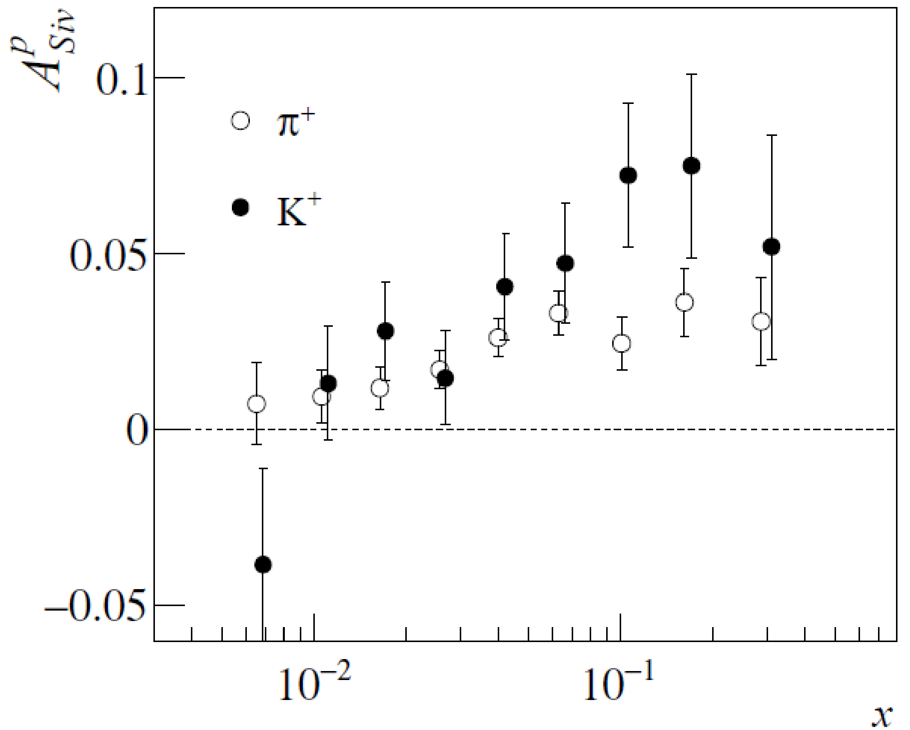
Combined 2007 and 2010 proton data samples analyzed.

COMPASS Phys.Lett. B744:250(2015)



Sivers Asymmetries for π^+ vs K^+

COMPASS Phys.Lett. B744:250(2015)

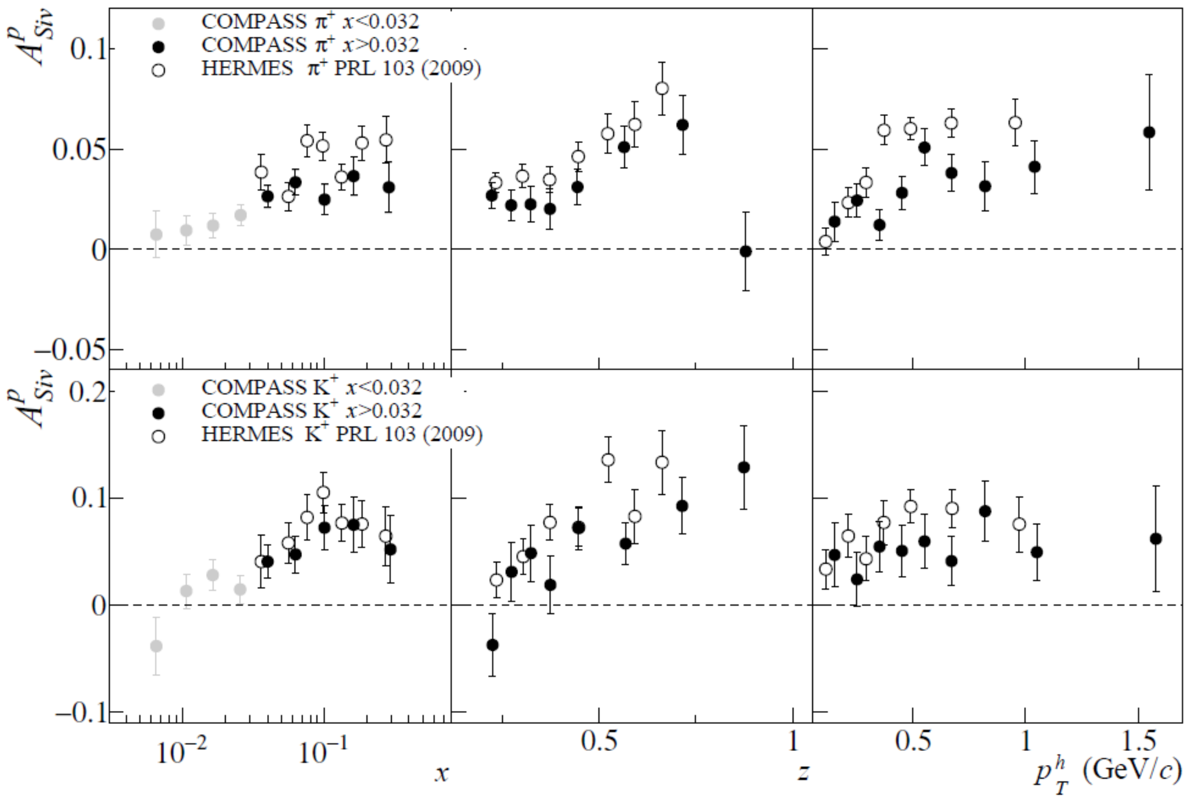


Kaon asymmetries slightly larger Compared to pion? Evidence for sea contribution?

Combined 2007 and 2010 proton data samples analyzed.

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

COMPASS Phys.Lett. B744:250(2015)



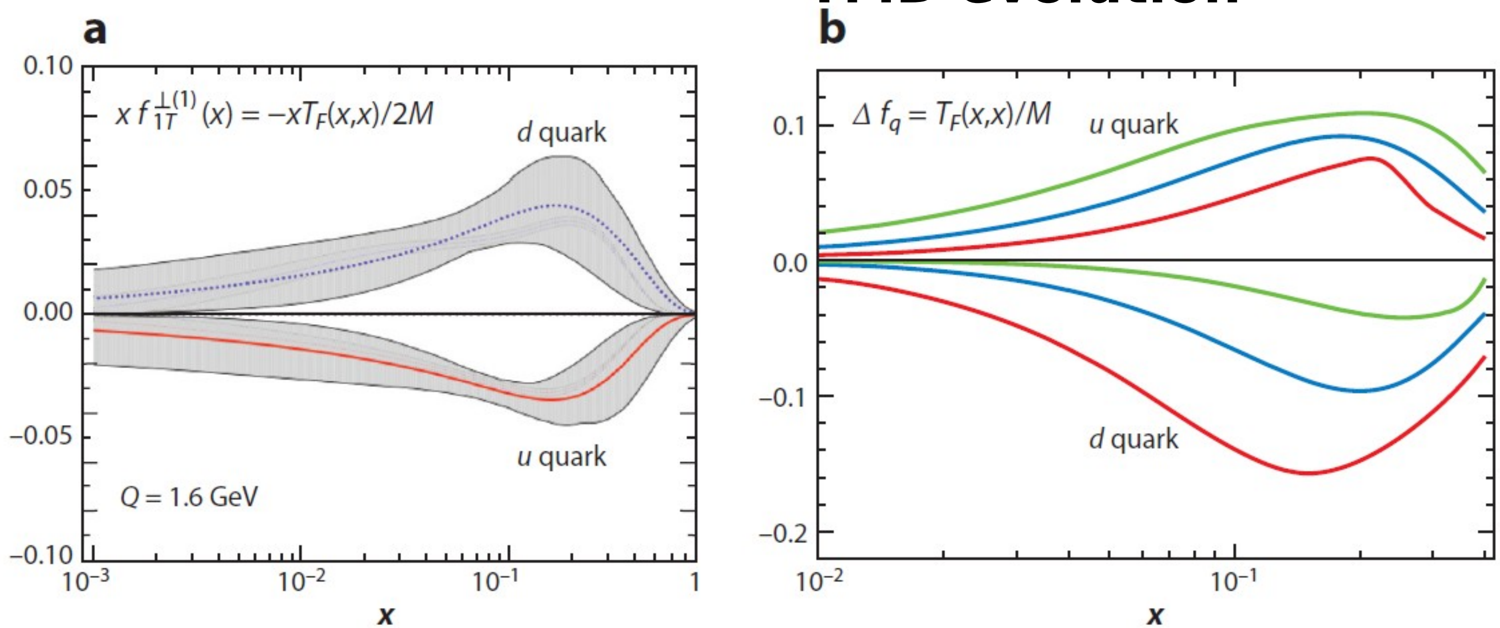
Combined 2007 and 2010 COMPASS proton data samples analyzed.

Sivers – Global Analysis of HERMES & COMPASS Data

Anselmino M, et al. arXiv:1107.4446 [hep-ph] (2011) Sun P, Yuan F. *Phys. Rev. D* 88:114012 (2013)

Leading order analysis

Full QCD analysis including TMD evolution

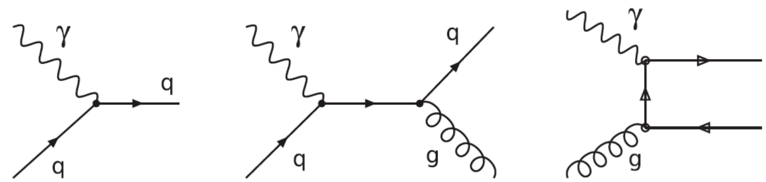


Still significant errors, no data for x>0.35 ➔ J-Lab 12

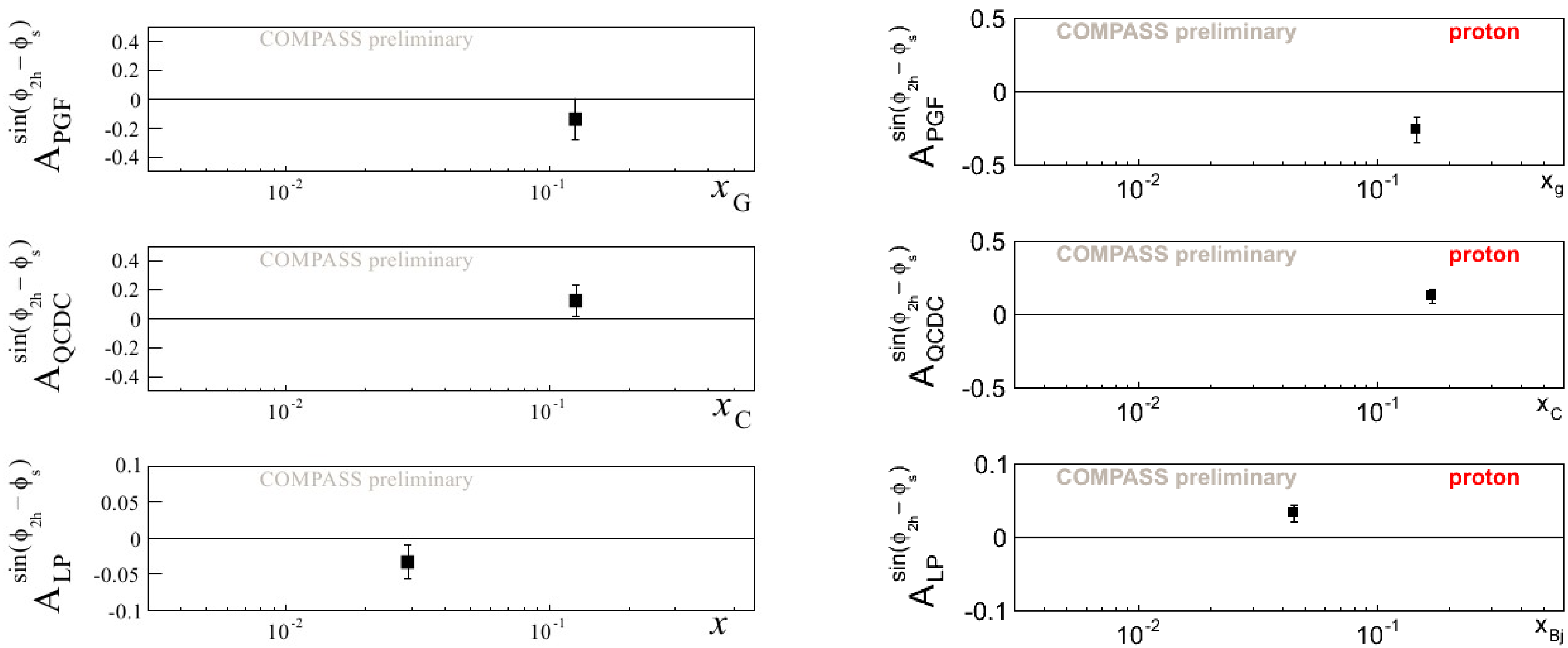
Sign Change ➔ COMPASS Drell-Yan (NSAC Milestone .

Sivers Asymmetries on ^{6}LiD and NH_3 for Gluons

Krzysztof Kurek and Adam Szabelski **Szabelski**
for the COMPASS collaboration



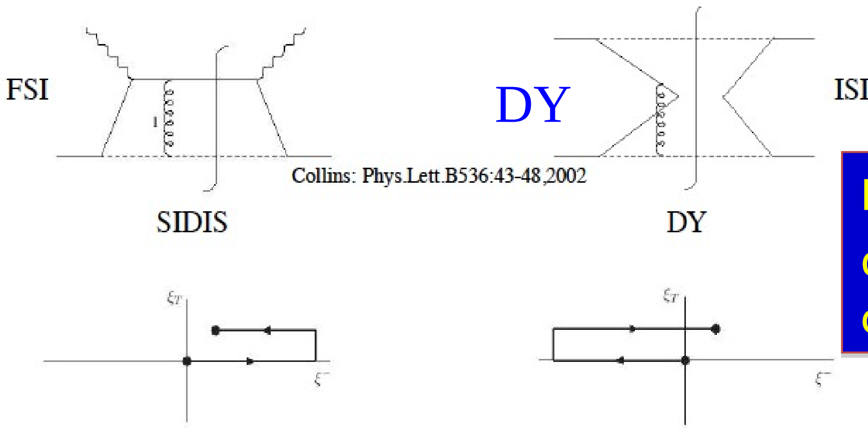
XVI Workshop on High Energy Spin Physics (D-SPIN2015) IOP Publishing Journal of Physics: Conference Series 678 (2016) 012055



$$A_{Siv} = R_{PGF} A_{Siv}^{PGF} + R_{QCDC} A_{Siv}^{QCDC} + R_{LP} A_{Siv}^{LP}$$

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

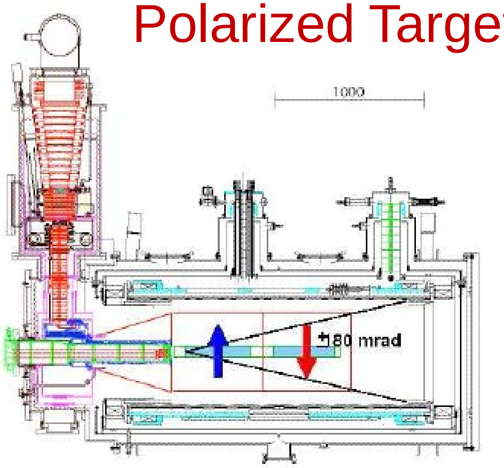
Need to confirm sign reversal in polarized Drell-Yan!

NSAC performance Milestone HP13 for 2015

TEST “modified” universality of TMD pdfs!

Instrumentation Updates for Drell-Yan Physics

Polarized Target

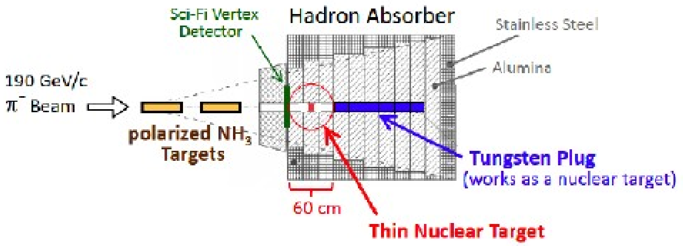


- Two cells of NH_3
- Polarisation ~ 80%
- Dilution factor ~ 22%

Hadron beam

190 GeV/c π beam (small contamination of K and $\bar{p}$)

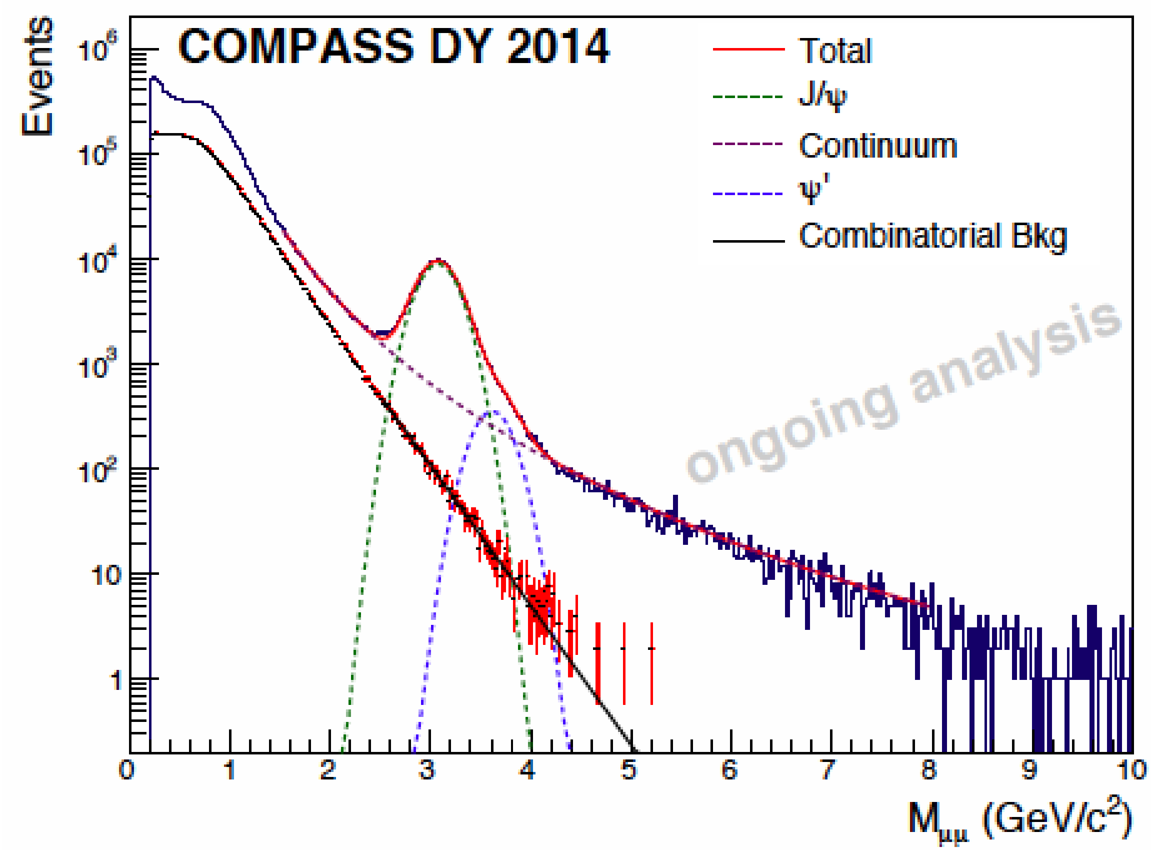
Hadron Absorber



- Due to small cross-section, measurement requires high luminosity
- Hadron absorber downstream of target
  - Stops hadrons and non interacting beam
  - Degrade resolutions, two target cells, vertex detector
- Nuclear targets: Al and W ⇒ unpolarised DY studies

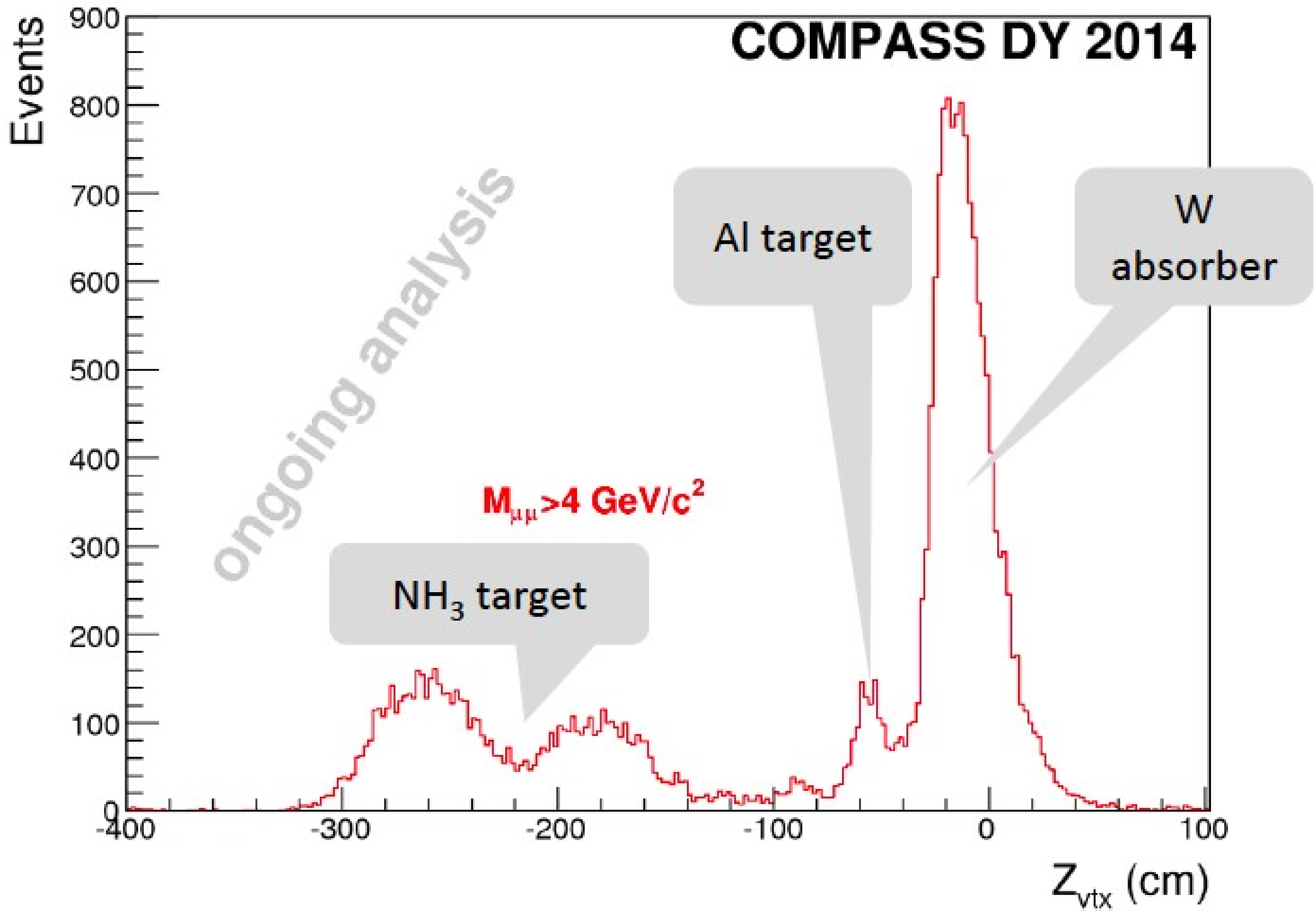
2014 Drell-Yan Pilot Run: Di-Muon Mass Spectrum

- Short Pilot Run in 2014 (~2 weeks of stable data taking)
- No polarization
- Beam intensity up to 8x10[7] /s
- No vertex detector

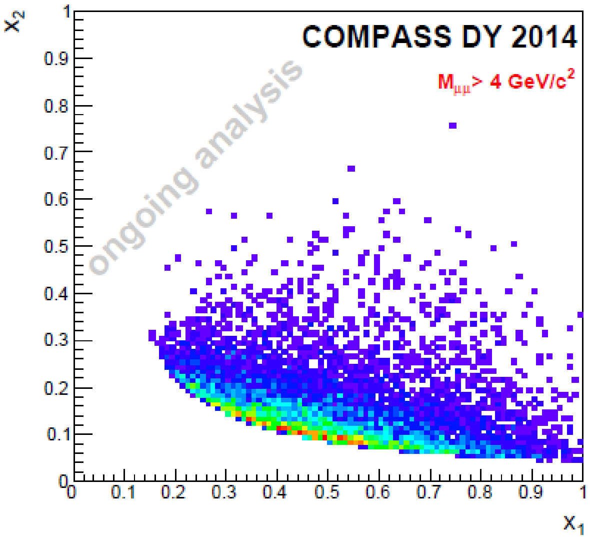


2014 Drell-Yan Pilot Run: Vertex Distribution

Z- coordinates vertex distribution, $M_{\mu\mu}$ > 4 GeV



2014 Drell-Yan Pilot Run: Resulting Analyses



Valence quarks region coverage

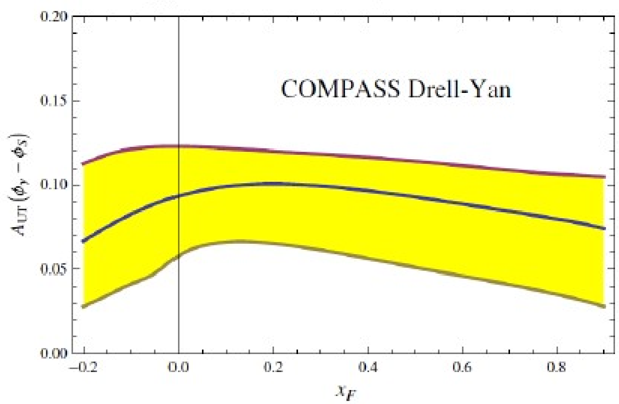
(1) Study of nuclear effects based on Al and W-targets will improve precision of existing information on EMC effect.

(2) Improve precision on testing the Lam Tung sum rule

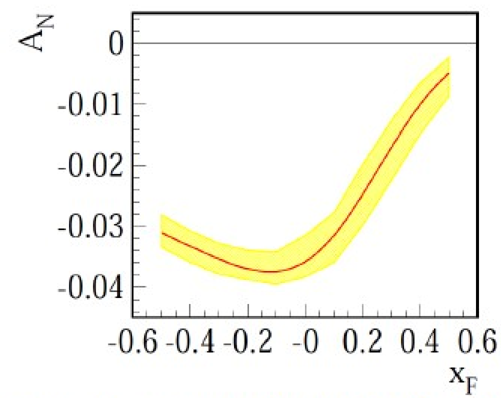
First Polarized Drell-Yan Run - 2015

- NH_3 **polarised** target (plus Al and W targets)
- $\boldsymbol{I_{beam}} \sim \mathbf{10^8 \pi/s}$ - very high intensity
- Four months of stable data taking are being analysed
  $\hookrightarrow$ **One period already produced**
- $M_{\mu\mu} > 4$ GeV$/c^2$ ~ **80000 $\mu^+\mu^-$ pairs** expected from polarised target
- $\delta A_{UT}^{\sin(\phi_S)} \sim 2.8\% \Rightarrow$ Models predict $A_{UT}^{\sin(\phi_S)}$ from 5% to 10%

Sivers asym: $A_{UT}^{\sin(\phi_S)} = A_{UT}(\phi_\gamma - \phi_S) = -A_N$, the same pion PDF is used (PRD 45 (1992) 2349)



P. Sun and F. Yuan, PRD 88 (2013) 114012,
$x_F = x_\pi - x_p$, $p_T < 2$ GeV$/c$



Echevarria *et al*, PRD 89 (2014) 074013,
$x_F = x_p - x_\pi$, $p_T < 1$ GeV$/c$

COMPASS Run Plan and Planning for Future Physics and Upgrades

1. 2016-2017 – Two years of exclusive physics with muon beams on liquid hydrogen targets
2. 2018 – Drell-Yan with transversely polarized target NH_3

2016 – use series of workshops to formulate physics program for 2020 and beyond:

(1) COMPASS Workshop: Beyond 2020,
March 21-22, 2016 at CERN
Initial survey of ideas for SIDIS, exclusive physics, hadron spectroscopy and Drell-Yan.
(2) COMPASS Internal Study Groups.
(3) Physics Beyond Colliders, September 6-7, 2016, CERN.

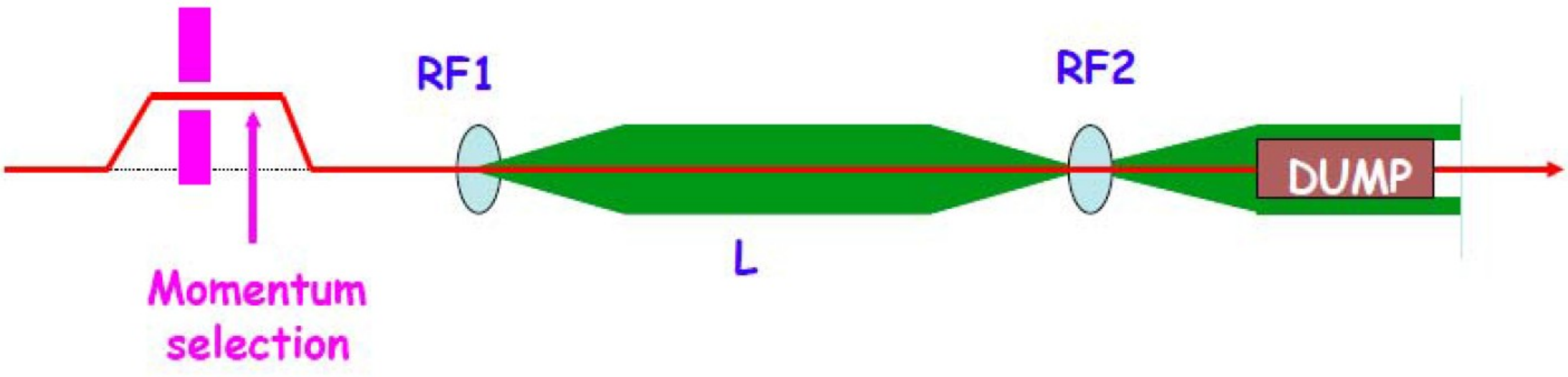
Physics at the SPS M2-Beamline – Beyond 2020

	physics item	key aspects of the measurement
Hadron	spectroscopy	280 GeV beam, higher intensity, π, K and $\bar{p}$ separation
GPD	E	transversely polarized proton target
SIDIS	h_1^d with same accuracy as h_1^u $f_1^\perp$ evolution	transversely polarized deuteron target 100 GeV and transversely polarized proton target
DY	universality of TMD PDFs flavor separation test of the Lam-Tung relation EMC effect in DY	higher statistics with transversely polarized proton target transversely polarized deuteron target hydrogen target different nuclear targets

First ideas were formulated for a document submitted to the European Strategy Preparatory Group in 2012. This document will be updated with ideas and result of the present workshops and study groups .

.

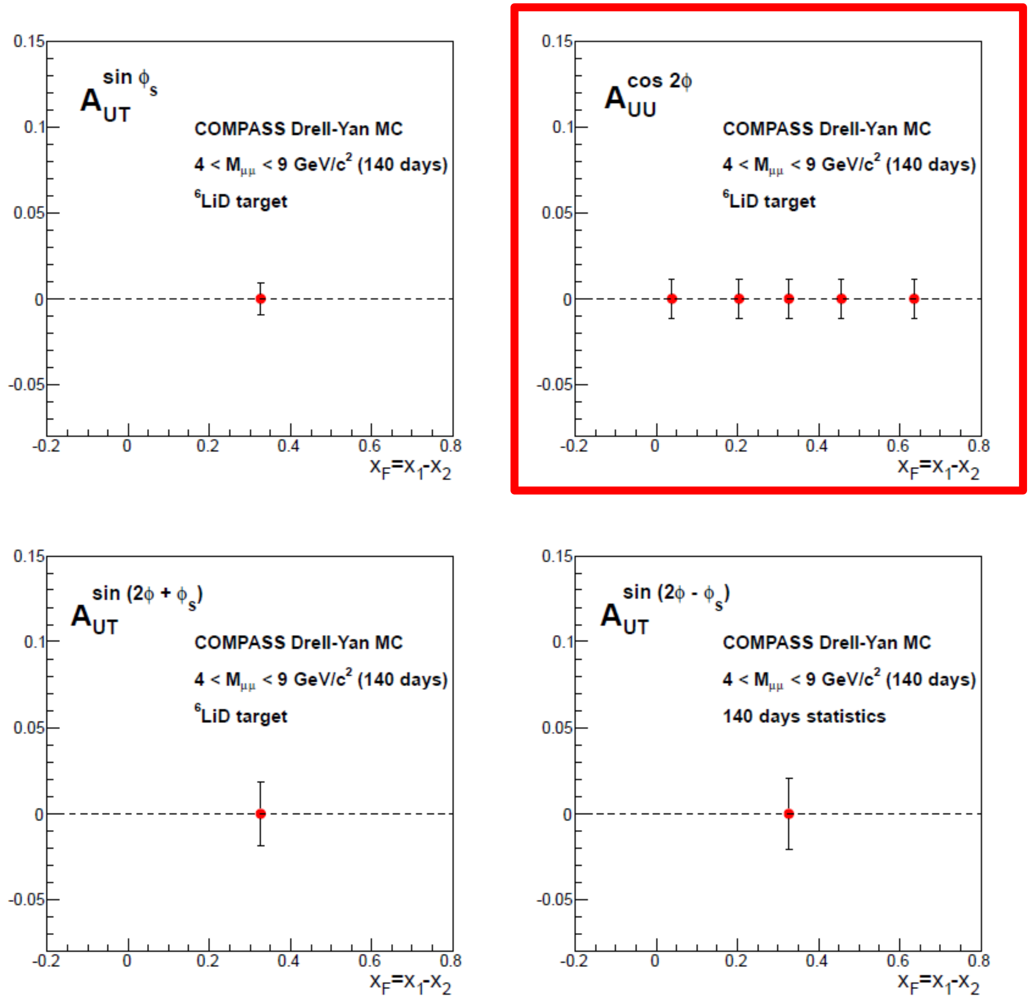
A Speculative Example: Physics with RF Separated Pion, Kaon and Anti-Proton Beams?



Particle type	From CKM beam	Antiproton beam
Beam momentum (GeV/c)	60	100
Momentum spread (%)	±1	±2
Angular emittance H,V (mrad)	±3.5, ±2.5	±3.5, ±2.5
Solid angle (μsterad)	10-12π	10-12π
% wanted particles lost on dump	37	20

Kaon and Anti-Protons Flux possibly reaching 10^7p./s

Pion and Kaon Structure from Drell-Yan Using a Hydrogen Target



beam BMF

$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

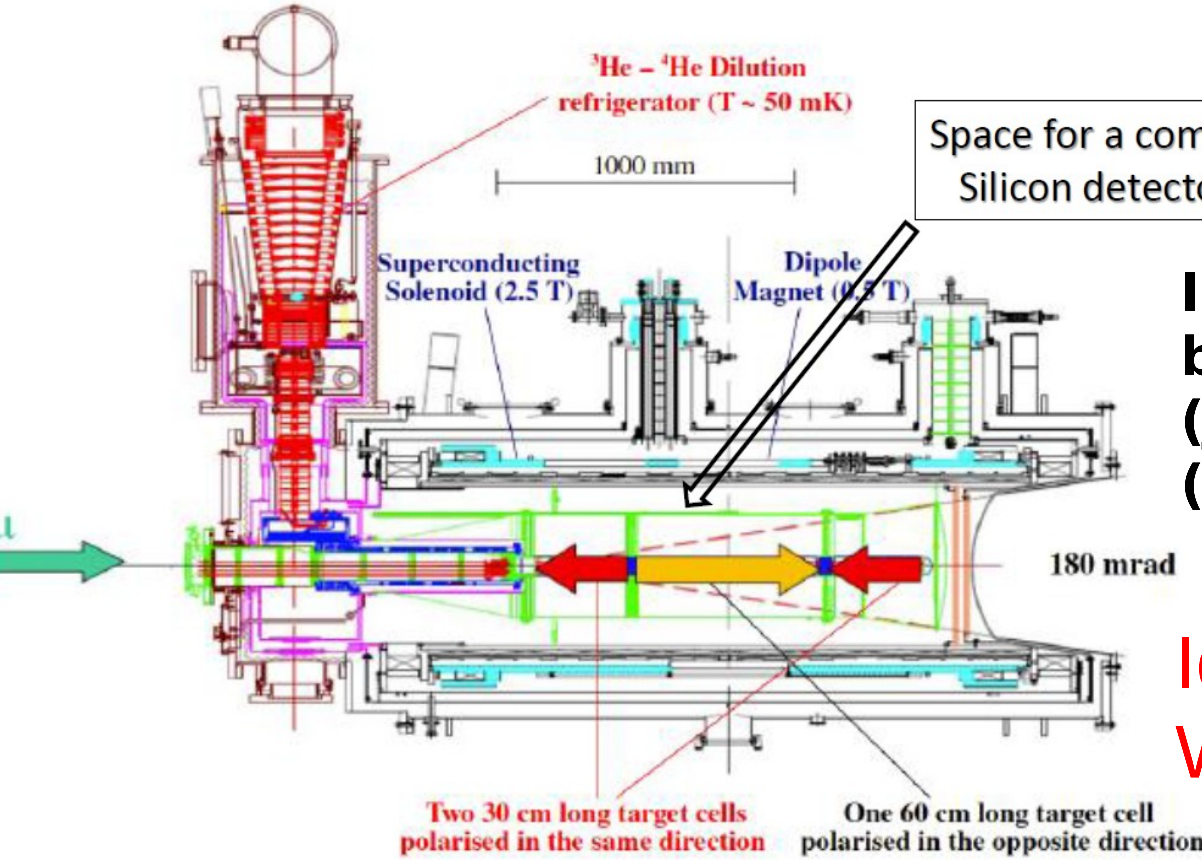
target BMF

Use anti—proton beam and CPT to get p-BMF,

Use pion and kaon beams to study meson structure! Unpol Or first comparison of Meson Baryon BMF and first compari of BMF for different mass mes

Consider Possible Addition of a Recoil Detector to the Polarized Target for Exclusive Physics

Space for a compact Silicon detector



Initial ideas and first wor
by Dubna (I. Savin), Mun
(J. Friedrich) and at CERN
(F. Gautheron and A. Ma

Ideas and Suggestion
Will be Welcome!

Summary:

COMPASS continues massive data taking for Drell-Yan and exclusive physics through 2018. Analyses of SIDIS, exclusive processes, Drell-Yan Data and hadron spectroscopy is in full swing.

For the next 10 years

- before any collider is available,
- and complementary to Jlab 12 GeV

COMPASS@CERN aims to continue as a major player in QCD physics using its unique high energy

- hadron- and muon beams.

Looking even further…a polarized lepton-nucleon collider appears to be a mandatory tool for achieving further progress!