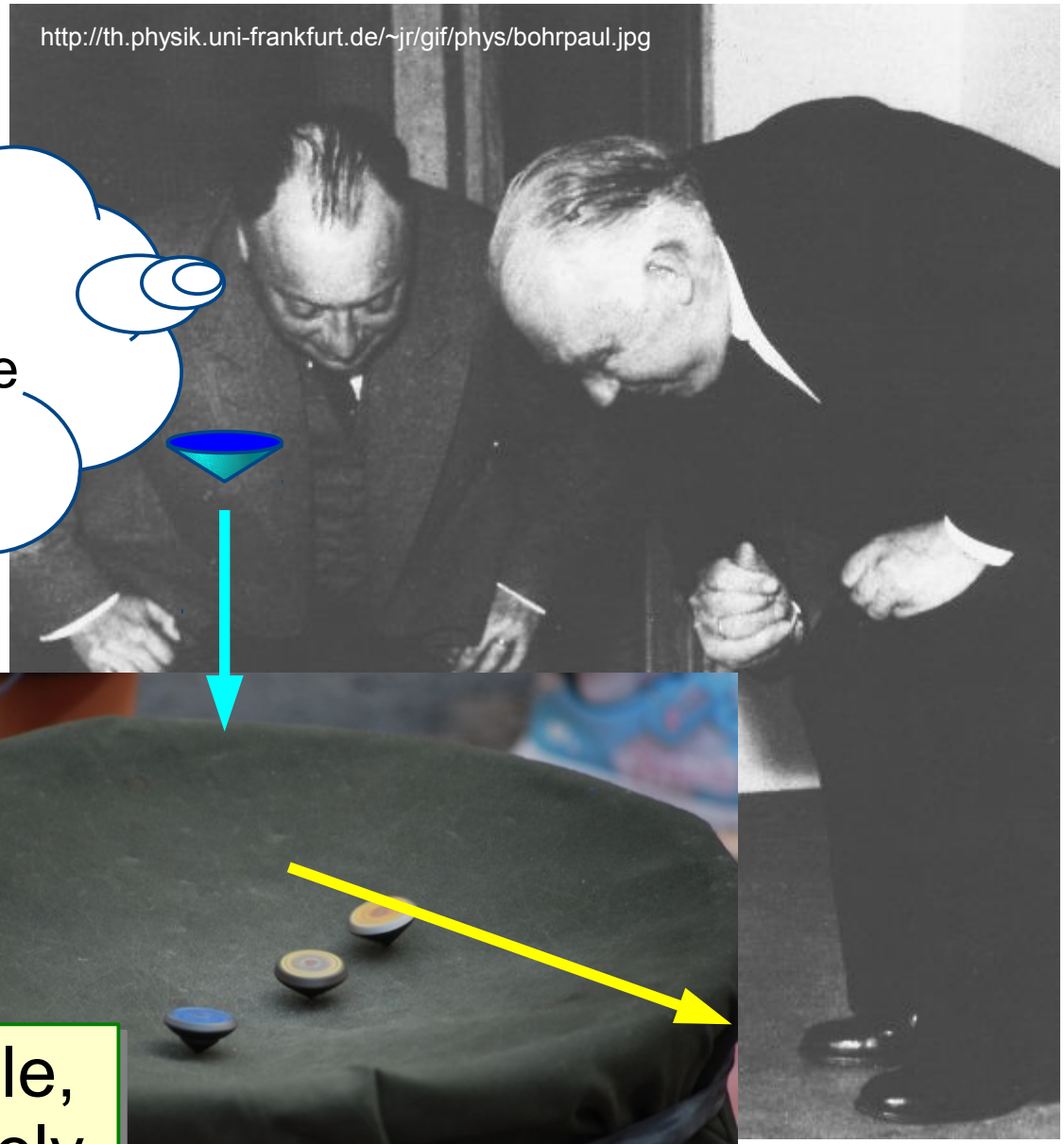
3. Transverse Momentum Dependent PDF in DIS

YAMAGATA UNIVERSITY



Let's kick from side

Instead of turning the table, try to polarized transversely.

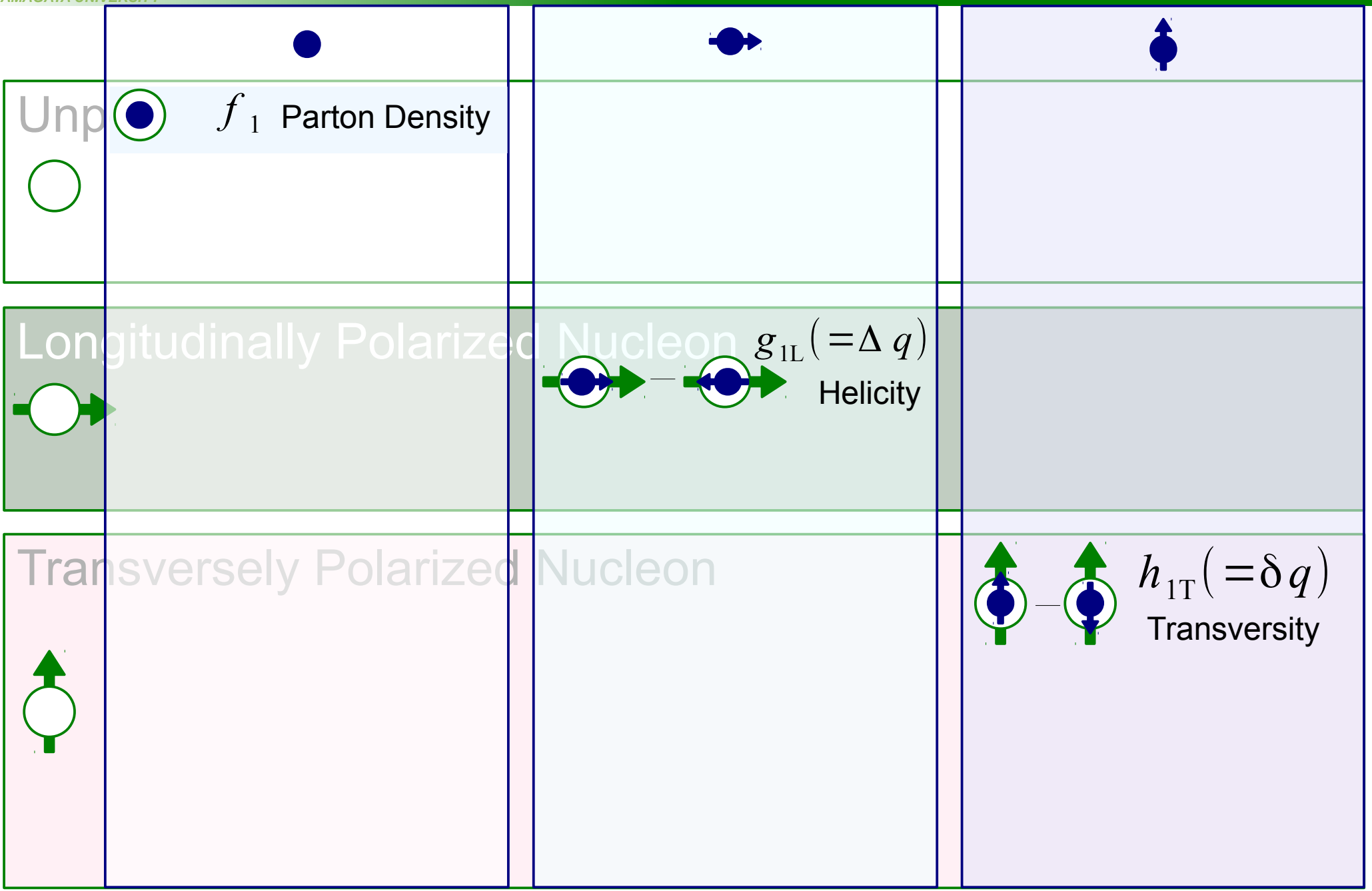
3. Transverse Momentum Dependent PDF in DIS

YAMAGATA UNIVERSITY

- PDF with transverse spin
  - Helicity and Transversity
- TMDs in SIDIS
- Experimental highlights from HERMES & COMPASS
- COMPASS II

Parton distribution functions

YAMAGATA UNIVERSITY



Helicity and Transversity

YAMAGATA UNIVERSITY

Transversity base

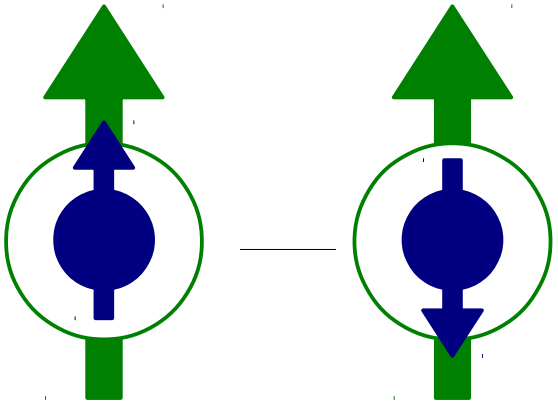
$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left[|+\rangle + \mathrm{i}|-\rangle\right]$$

$$|\downarrow\rangle = \frac{1}{\sqrt{2}}\left[|+\rangle - \mathrm{i}|-\rangle\right]$$

Helicity base

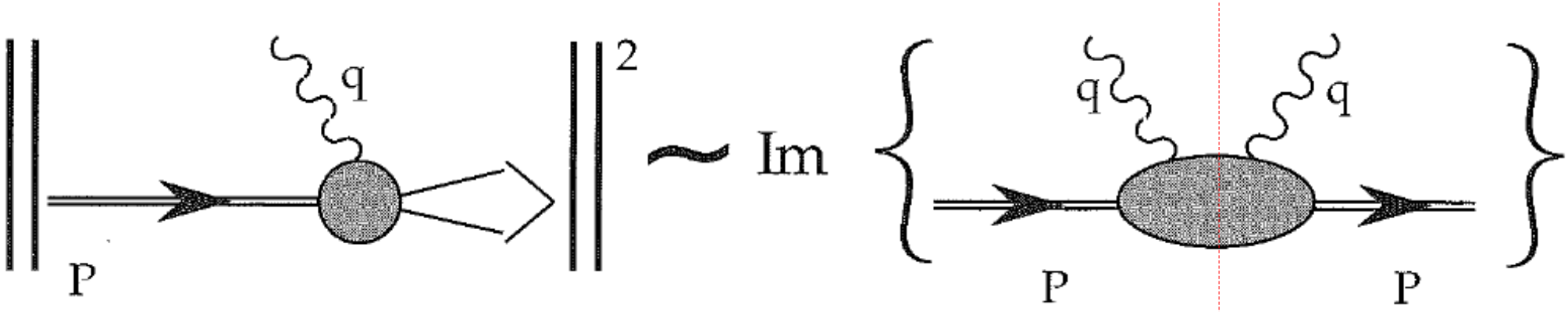
Transversity

$h_{1\mathrm{T}}(=\delta q)$

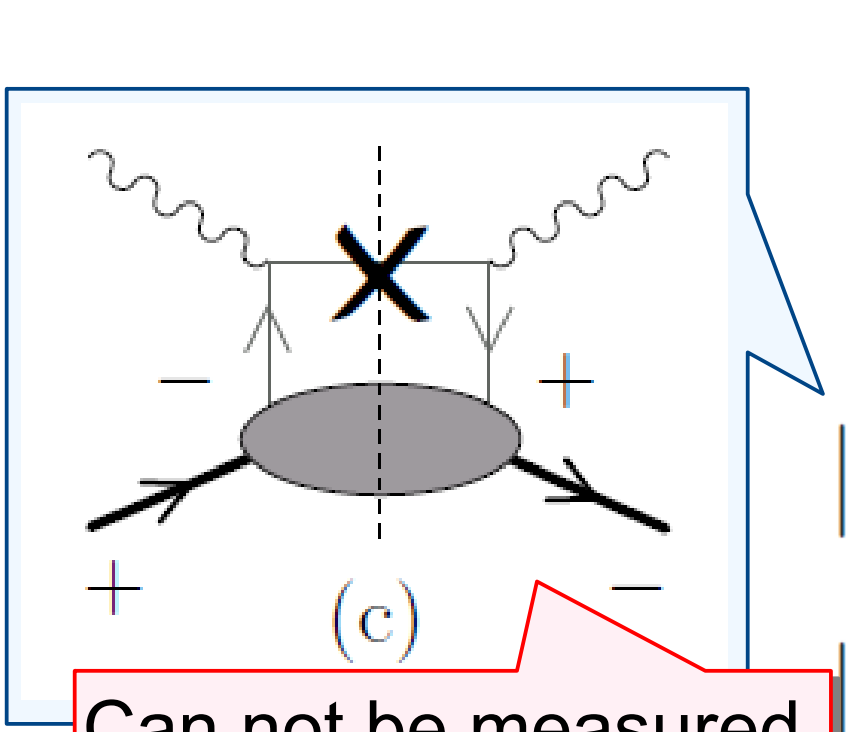


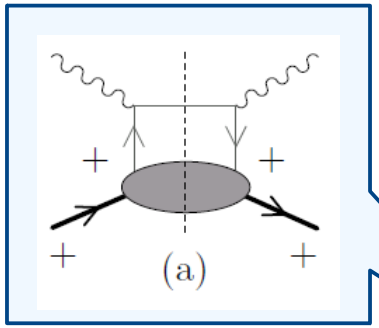
Chiral Odd

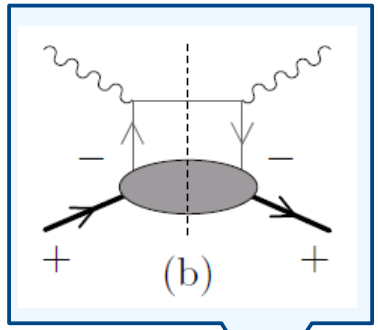
DIS cross section & virtual Compton amplitude



The spin structure of the proton, S. D. Bass







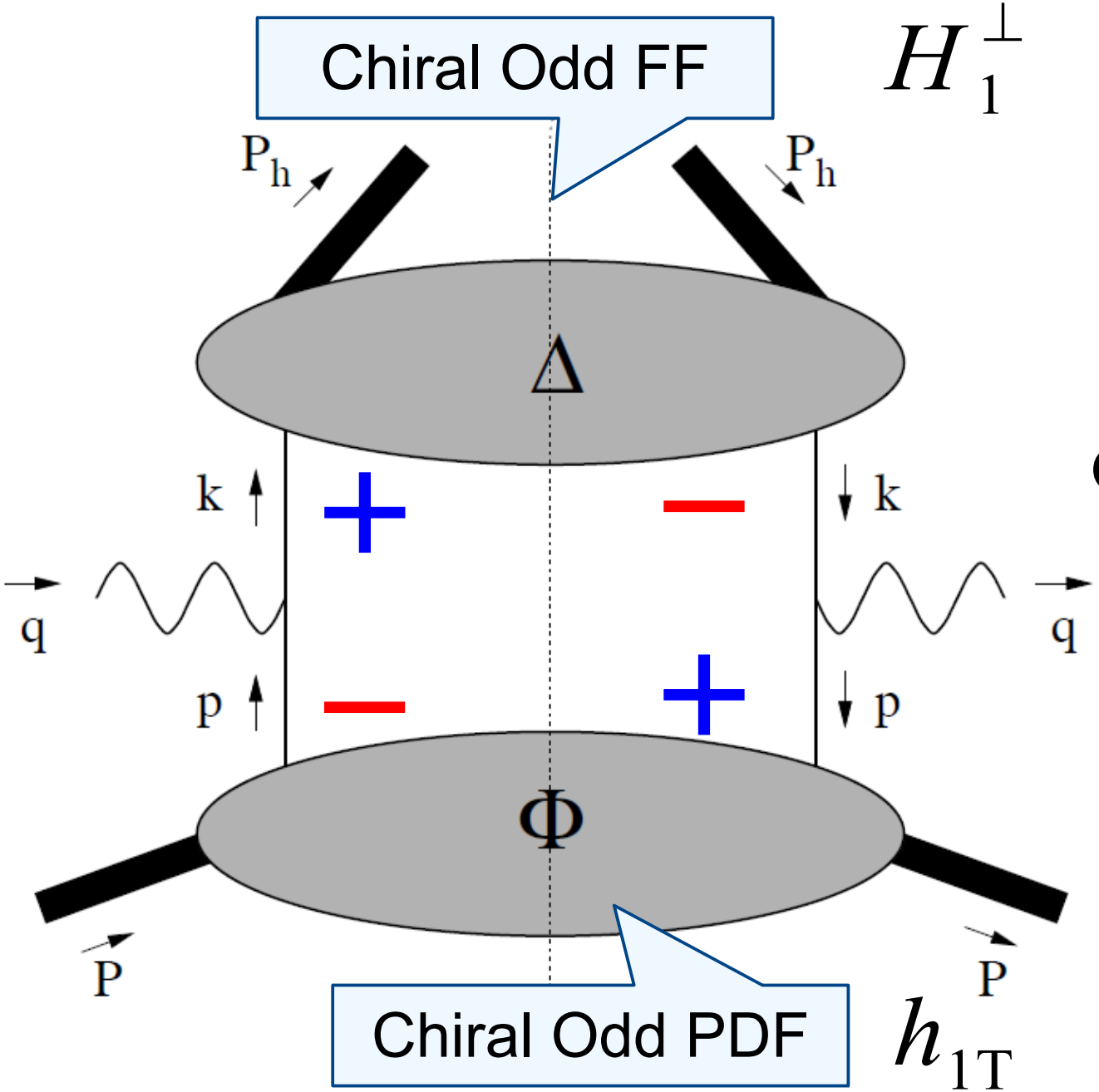
$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left[|+\rangle + i|-\rangle\right]$$

$$|\downarrow\rangle = \frac{1}{\sqrt{2}}\left[|+\rangle - i|-\rangle\right]$$

Can not be measured in DIS

Transversity in SIDIS

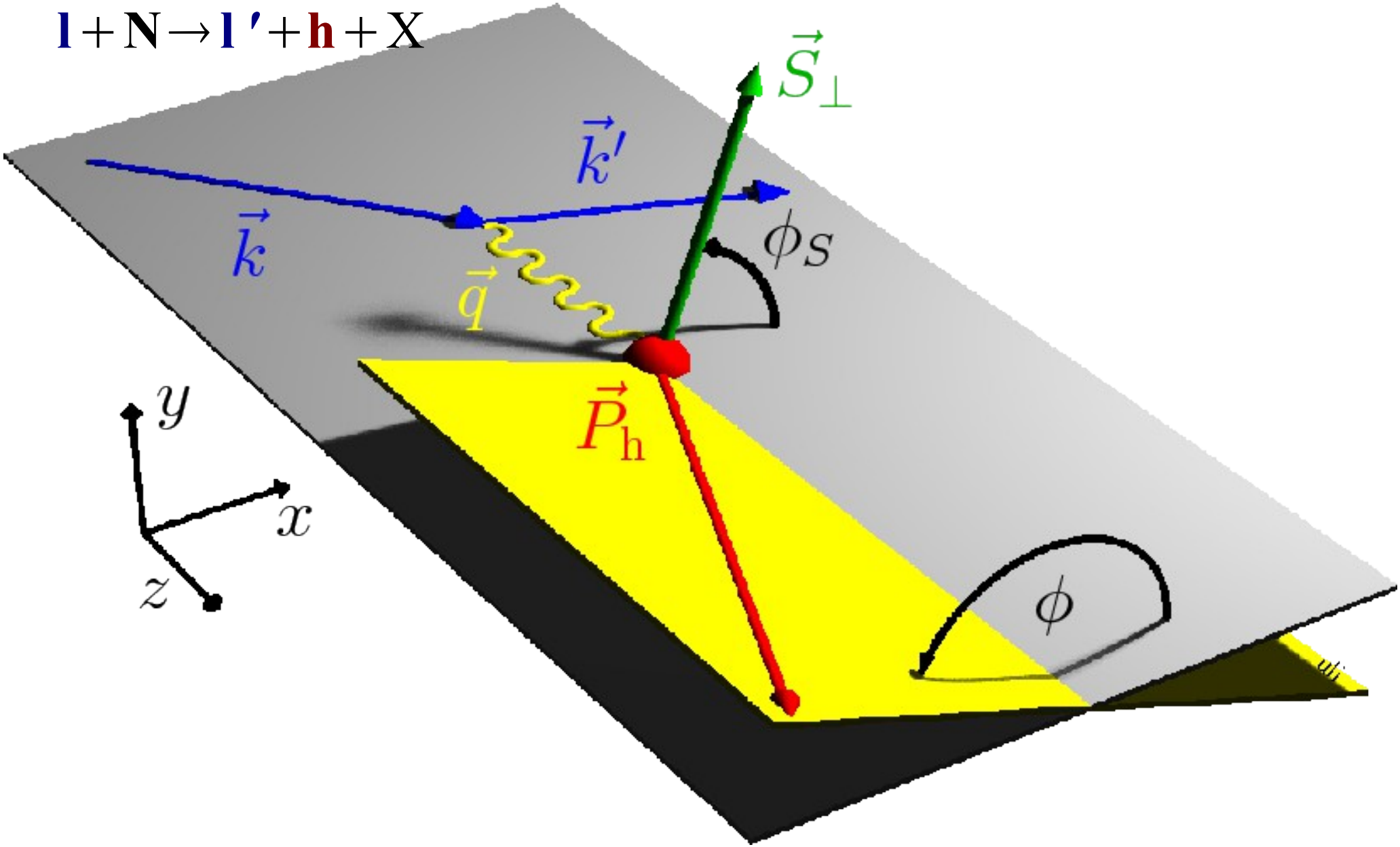
YAMAGATA UNIVERSITY



$$\sigma \sim h_{1T} \otimes H_1^\perp$$

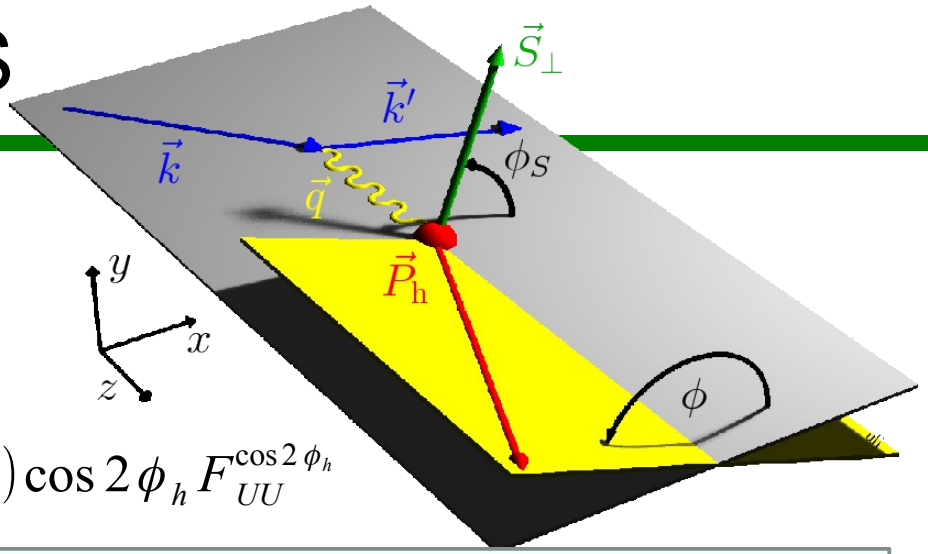
Azimuthal angles in SIDIS

YAMAGATA UNIVERSITY



Azimuthal angles in SIDIS

YAMAGATA UNIVERSITY



$$e + N \rightarrow e' + h + X$$

$$d\sigma \propto$$

$$\frac{1+(1-y)^2}{2} F_{UU} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

$$+ S_L\left[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\sin\phi_h F_{UL}^{\sin\phi_h}\right]$$

$$+ S_L P_z^l\left[\frac{1-(1-y)^2}{2} F_{LL} + y\sqrt{1-y}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

$$+ S_T\left[\frac{1+(1-y)^2}{2}\sin(\phi_h-\phi_S) F_{UT}^{\sin(\phi_h-\phi_S)}\right.$$
$$+(1-y)\left(\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}\right)$$
$$\left.+(2-y)\sqrt{1-y}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\right)\right]$$

$$+ S_T P_z^l\left[\frac{1-(1-y)^2}{2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + y\sqrt{1-y}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\right)\right]$$

Leading-twist

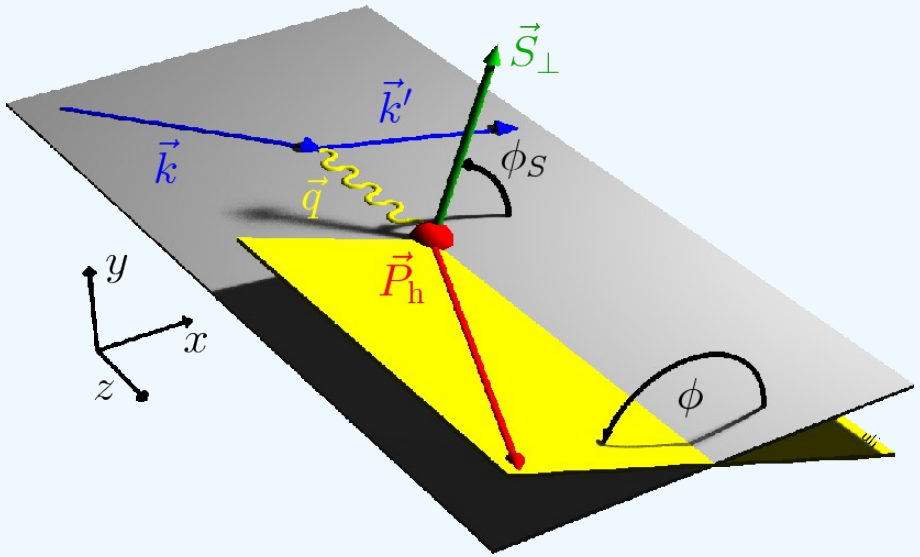
Transverse Momentum Dep

With pol. beam

Unp

Lon

Transversely Polarized Nucleon



$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

$h_{1L}^\perp$ Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

$f_{1T}^\perp$ Sivers

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

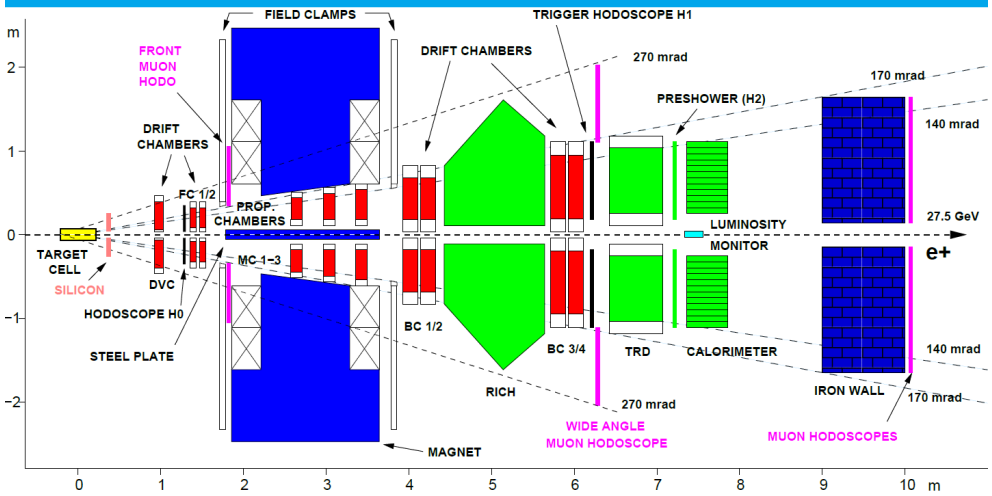
$h_{1T}^\perp$ Pretzelosity

$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

Polarized DIS experiment

YAMAGATA UNIVERSITY

The HERMES spectrometer



Internal gas targets:
- Longitudinally polarized *H, D*
- Transversely polarized *H*
- Unpolarized *H, D, ^{4}He, N, Ne, Kr, Xe*

Forward magnetic spectrometer
- Momentum resolution *1-2%*
- Particle identification: *RICH, TRD, H2, calorimeter*

hermes

S. Yaschenko, Overview of recent HERMES results 4

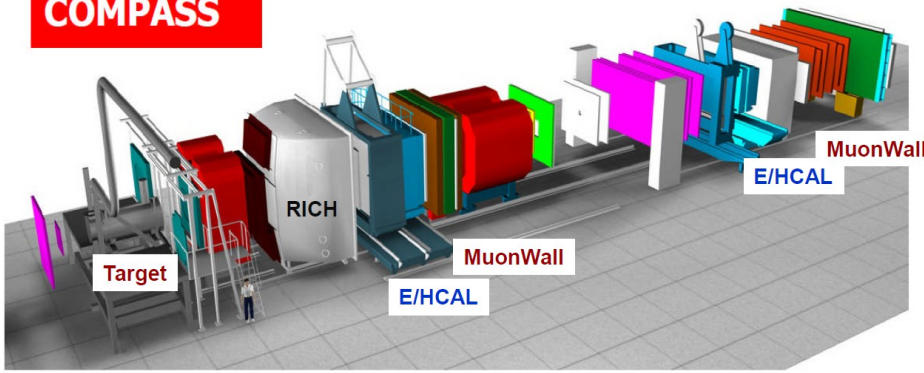
DESY

COMPASS

COMPASS spin

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)



variety of tracking detectors to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

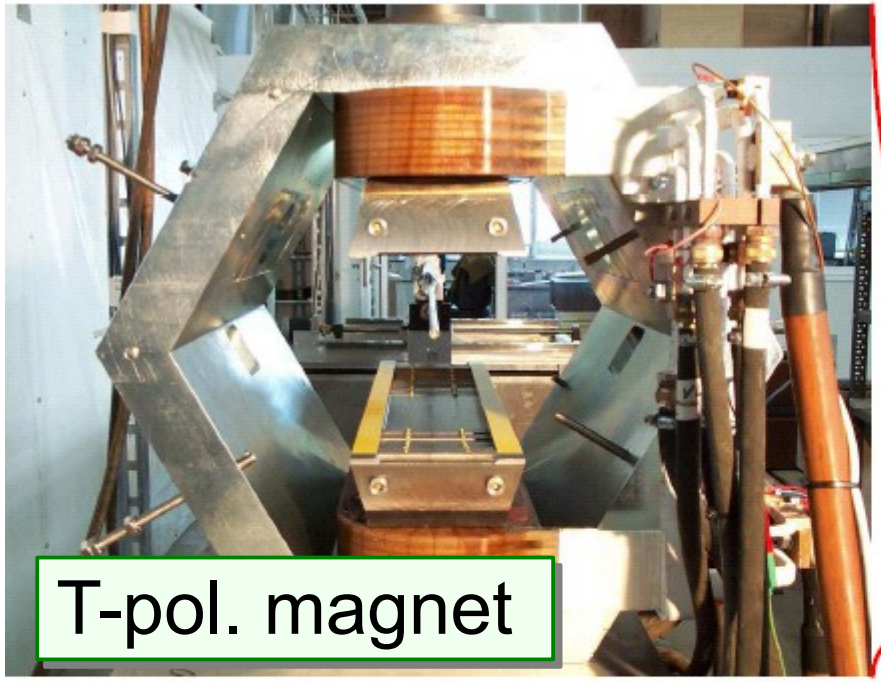
SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*

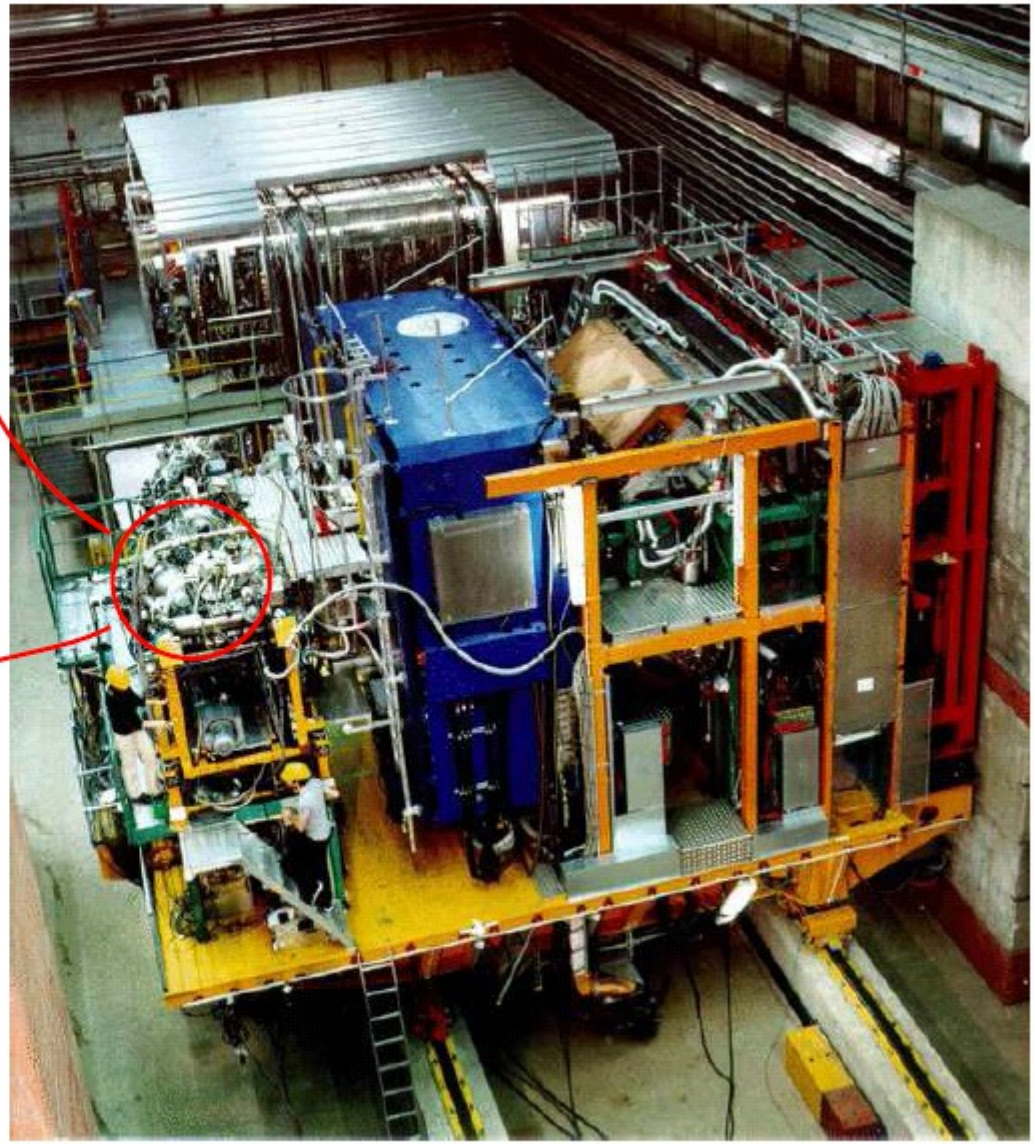
Beam	26.7 GeV pol. electron/positron	
Target	1996-1997	Long. H
	1998-2000	Long. D
	2002-2005	Trans. H
	2006-2007	unpol. H

Beam	160 GeV pol. muon	
Target	2002 - 2006	Long. + Trans. ^{6}LiD.
	2007	Long. + Trans. NH_3
	2010	Trans. NH_3
	2011	Long. NH_3

HERMES pol. target system

YAMAGATA UNIVERSITY



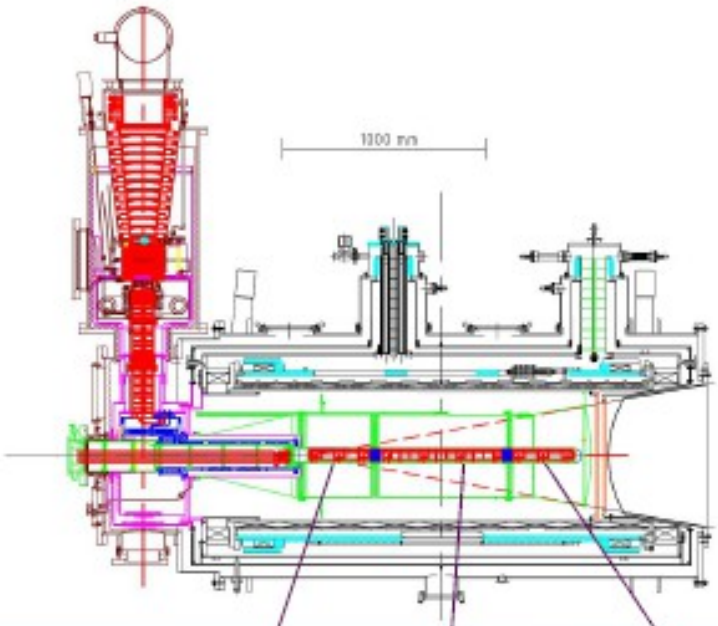


- atomic beam source
- ⇒ pure gas target, no dilution
- transversely pol. hydrogen

  polarization $\sim 75\%$
- 90s flipping time ⇒ small systematics

COMPASS pol. target system

YAMAGATA UNIVERSITY

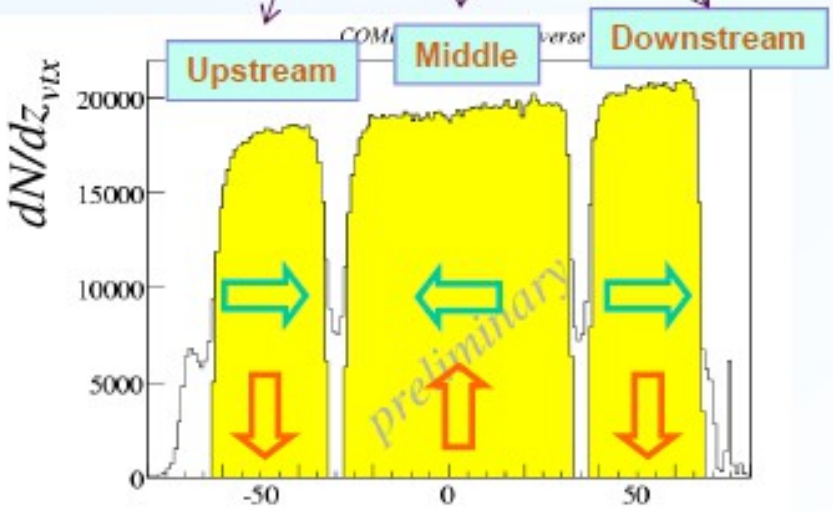


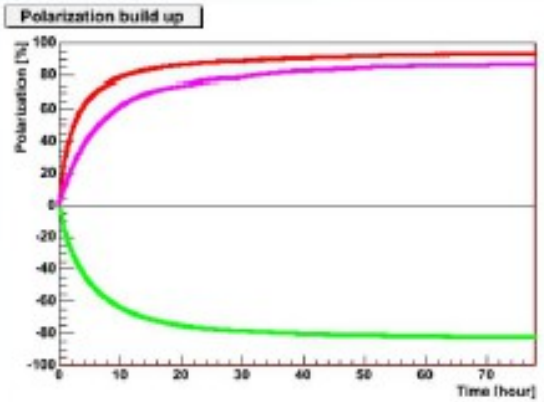
Solid polarized target operated
in ***Dynamic Nuclear Polarization*** technique
with a dilution refrigerator

PT magnet:
→+180~-180 mrad geometrical acceptance

To match larger acceptance:
→3 target cells: reduction of false asymmetries

Target:
→NH_3 for proton , ^{6}LiD for deuteron
→ longitudinal & transverse mode available
→very long relaxation time (~ 4000 h)
→magnetic field rotation without polarization loss
→ Polarization of NH_3 -92%, +88%, -83%





Publications from

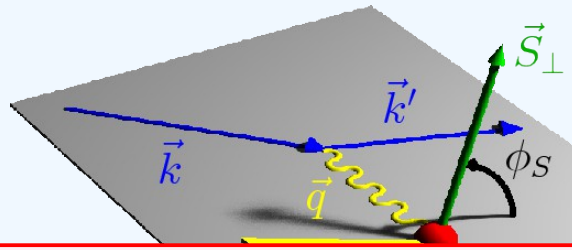
YAMAGATA UNIVERSITY

Boer-Mulders	$\langle \cos 2\phi \rangle_{UU}$	(p) h, π, K (d) h, π, K PRD87(2013)012010	
Mulders-Kotzinian	$\langle \sin 2\phi \rangle_{UL}$	(d) π, K PLB562(2003)182	(d) h EPJC70(2010)39
Sivers	$\langle \sin(\phi-\phi_S) \rangle_{UT}$	(p) π, K PRL103(2009)152002	(p) h PLB717(2012)383 (d) pi, K PLB673(2009)127
Transversity	$\langle \sin(\phi+\phi_S) \rangle_{UT}$	(p) π, K PLB693(2010)11	(p) h PLB717(2012)376 (d) pi, K PLB673(2009)127
	$\langle \sin(3\phi-\phi_S) \rangle_{UT}$		
	$\langle \cos(\phi-\phi_S) \rangle_{LT}$		

Sivers & Transversity

YAMAGATA UNIVERSITY

Unp



With Transversely polarized target

$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

$h_{1L}^\perp$ Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

Transversely Polarized Nucleon

$f_{1T}^\perp$ Sivers

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

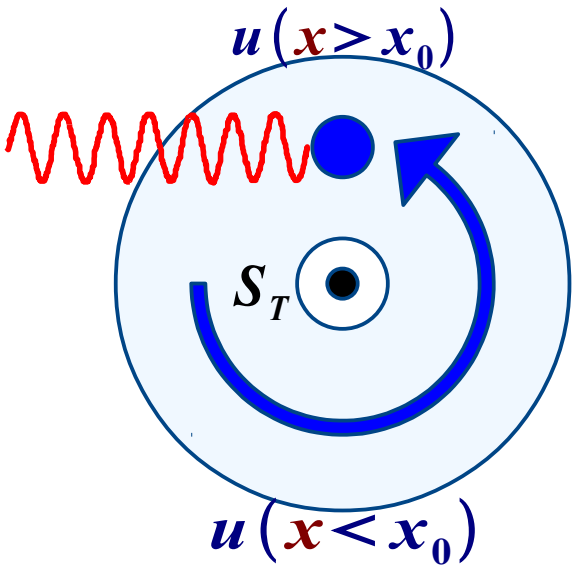
$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

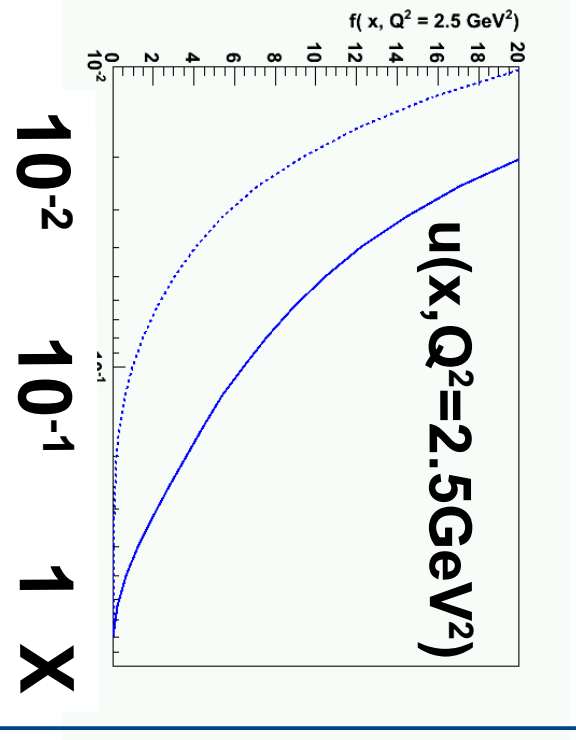
$h_{1T}^\perp$ Pretzelosity

$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

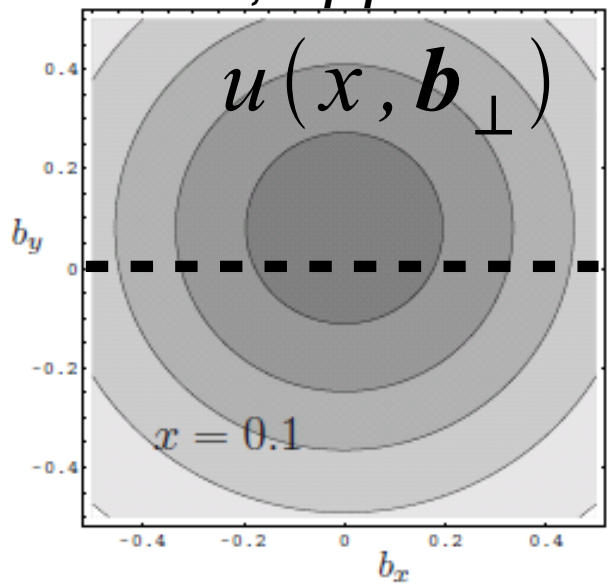
Sivers asymmetry

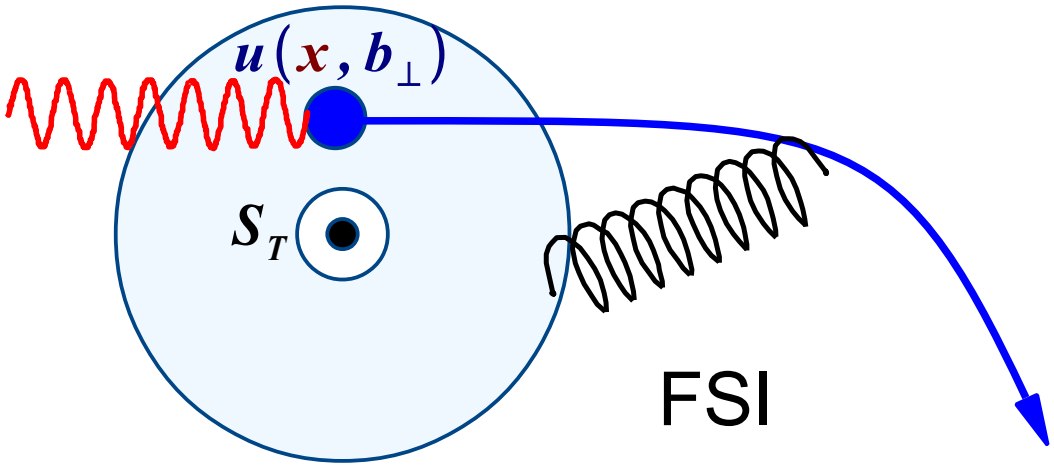
YAMAGATA UNIVERSITY



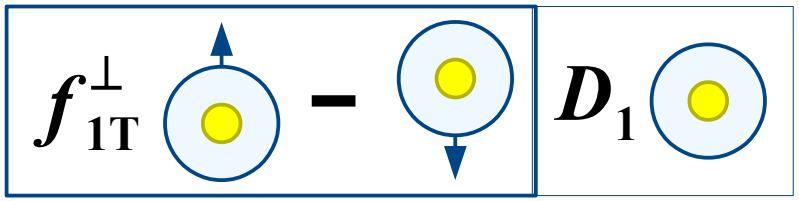


M. Burkardt, hep-ph/0309269





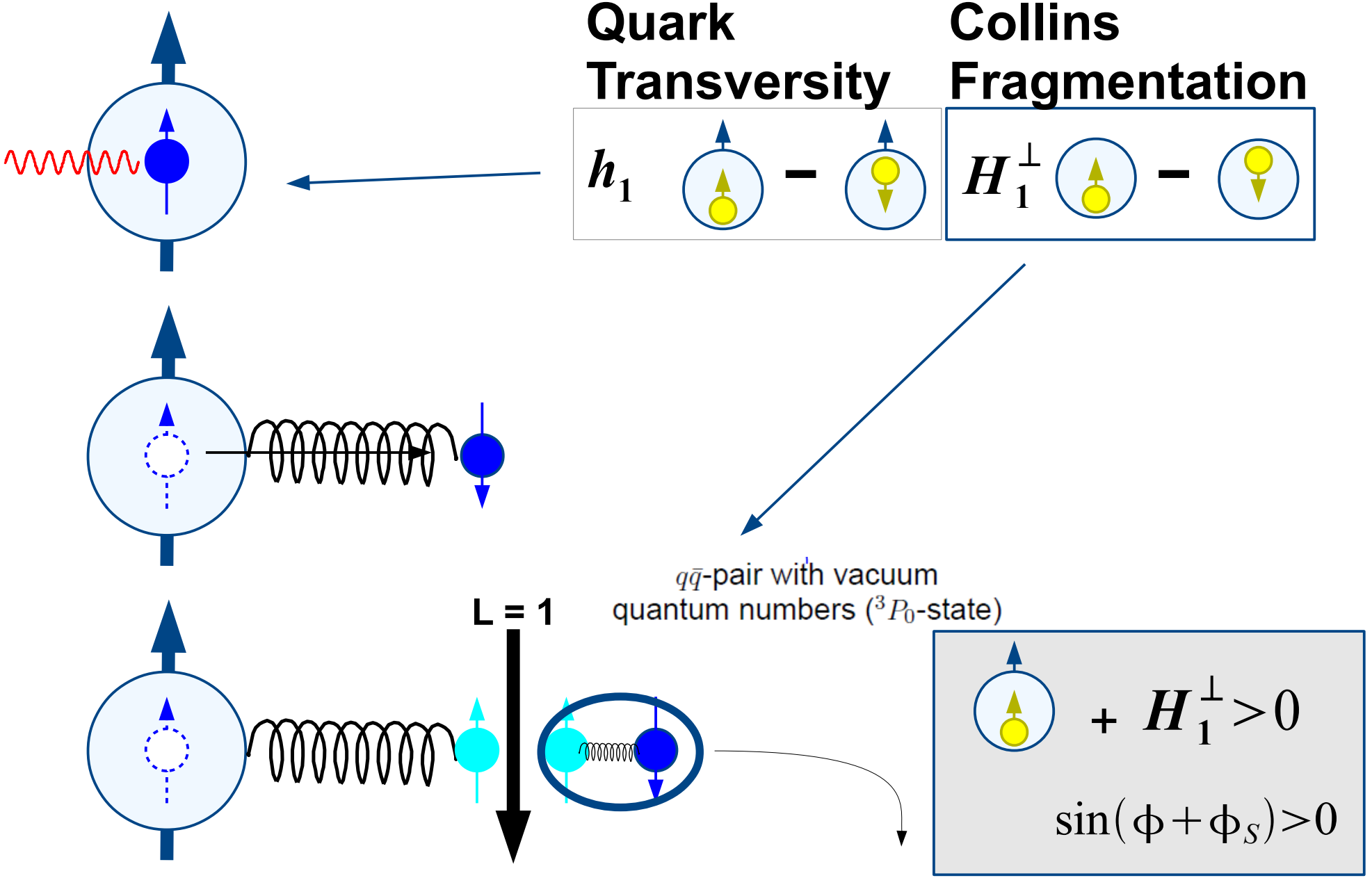
Sivers Fragmentation



$$\sin(\phi-\phi_S)>0$$

Transversity: Collins asymmetry

YAMAGATA UNIVERSITY

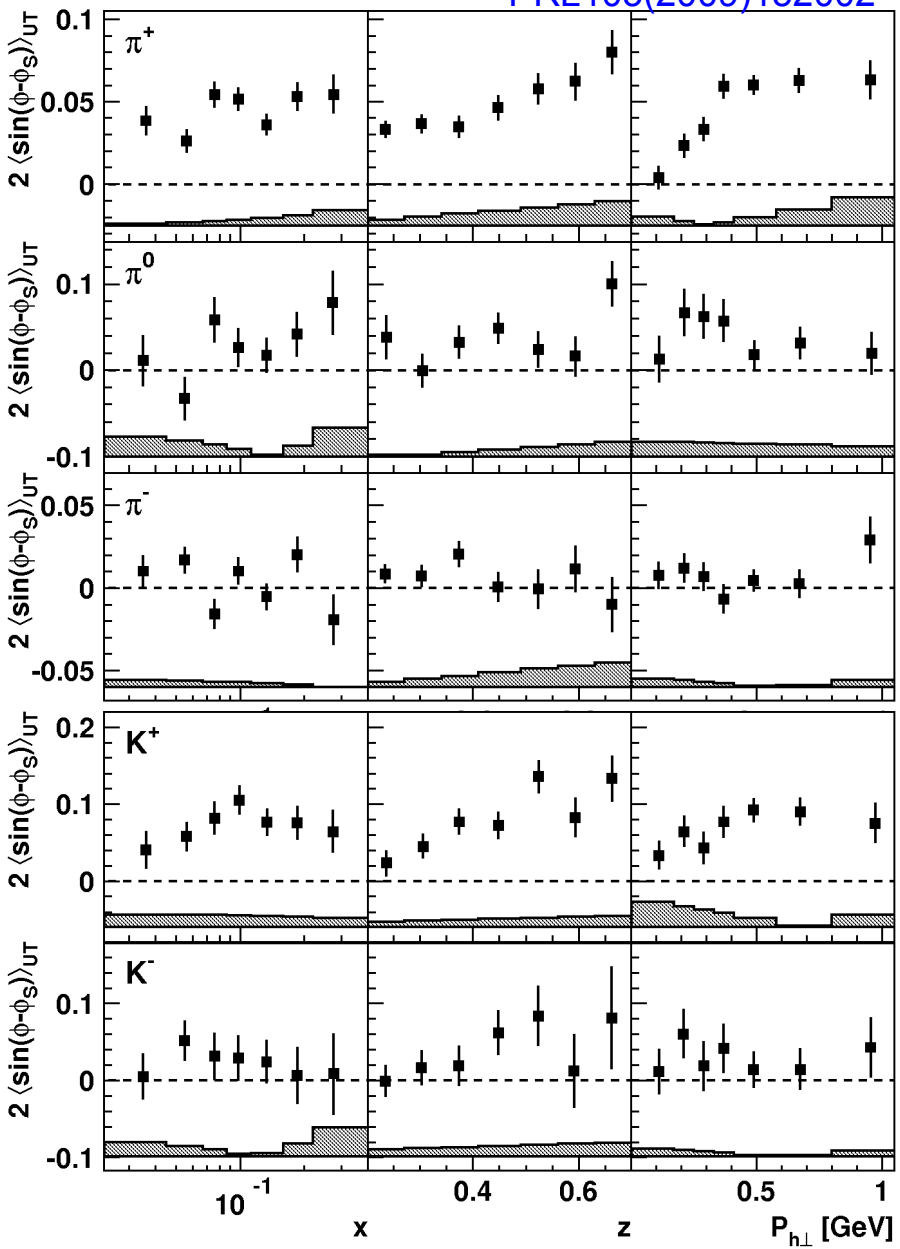


Sivers and Transversity

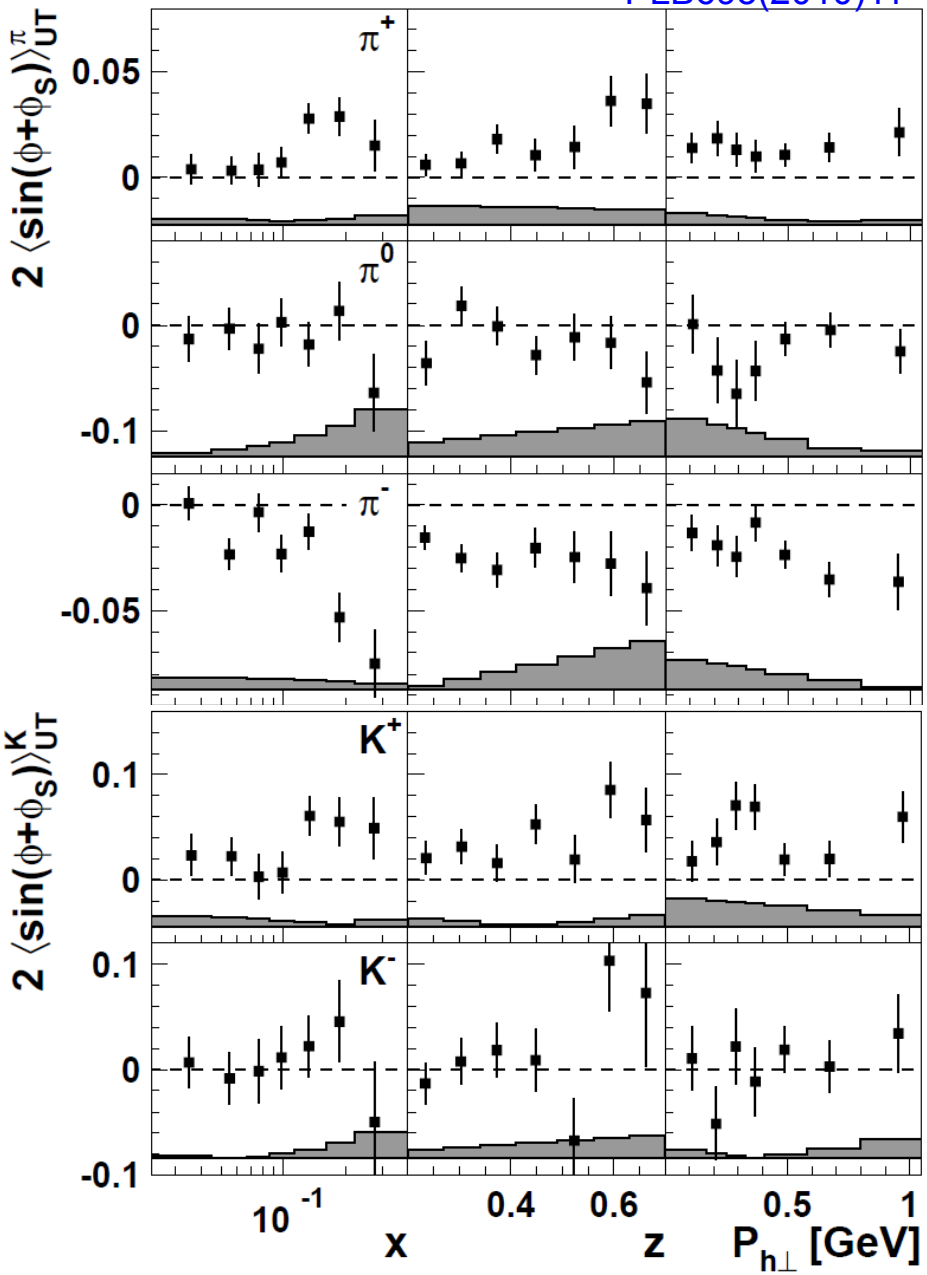
YAMAGATA UNIVERSITY

hermes

$f_{1T}^{\perp} \otimes D_1 \sim \sin(\phi - \phi_S)$ PRL103(2009)152002



$h_{1T} \otimes H_1^{\perp} \sim \sin(\phi + \phi_S)$ PLB693(2010)11

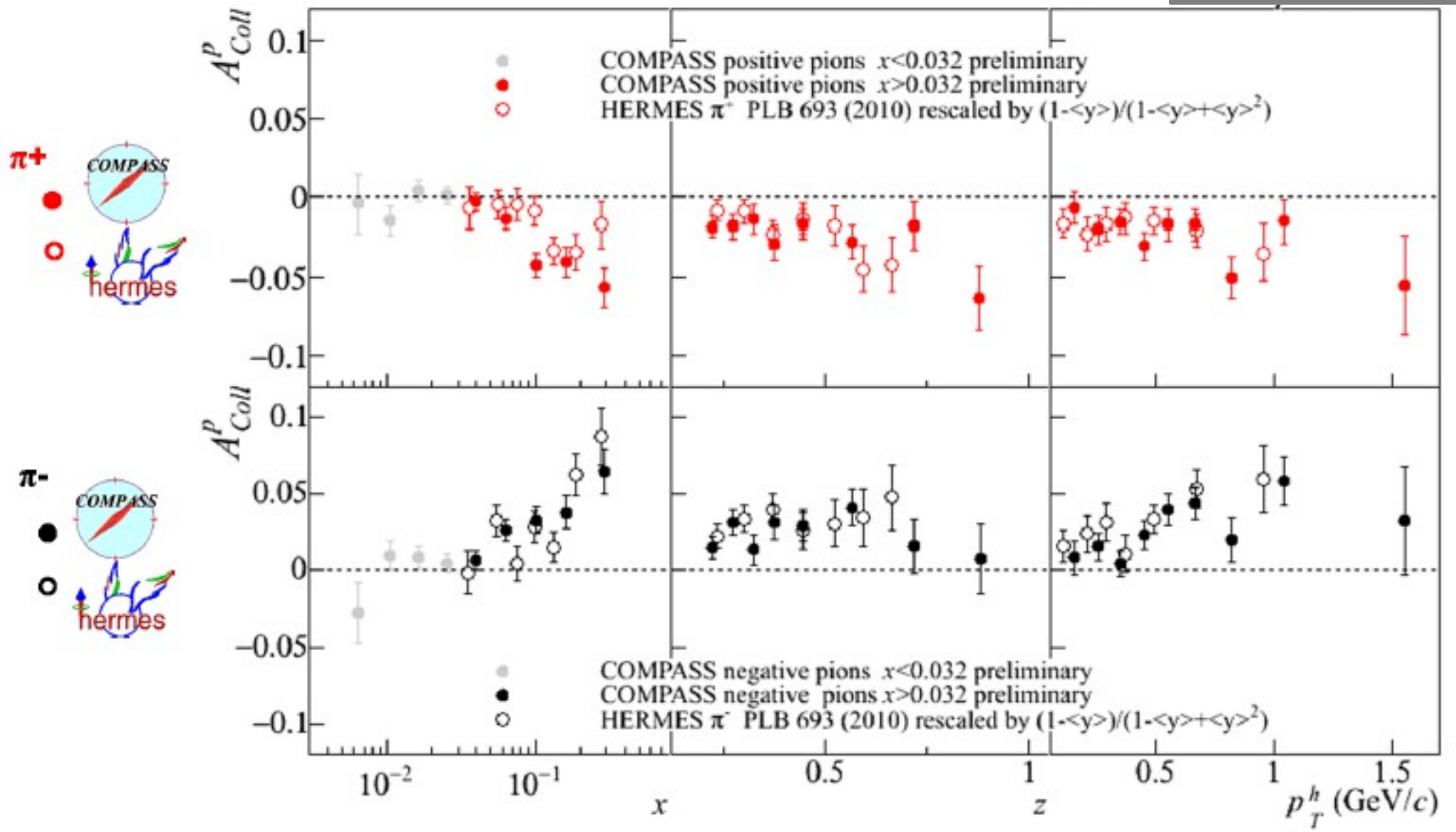


Transversity

$$h_{1T} \otimes H_1^{\perp} \sim \sin\left(\phi + \phi_S\right)$$

YAMAGATA UNIVERSITY

A. Martin, DIS2013



Extraction of Transversity

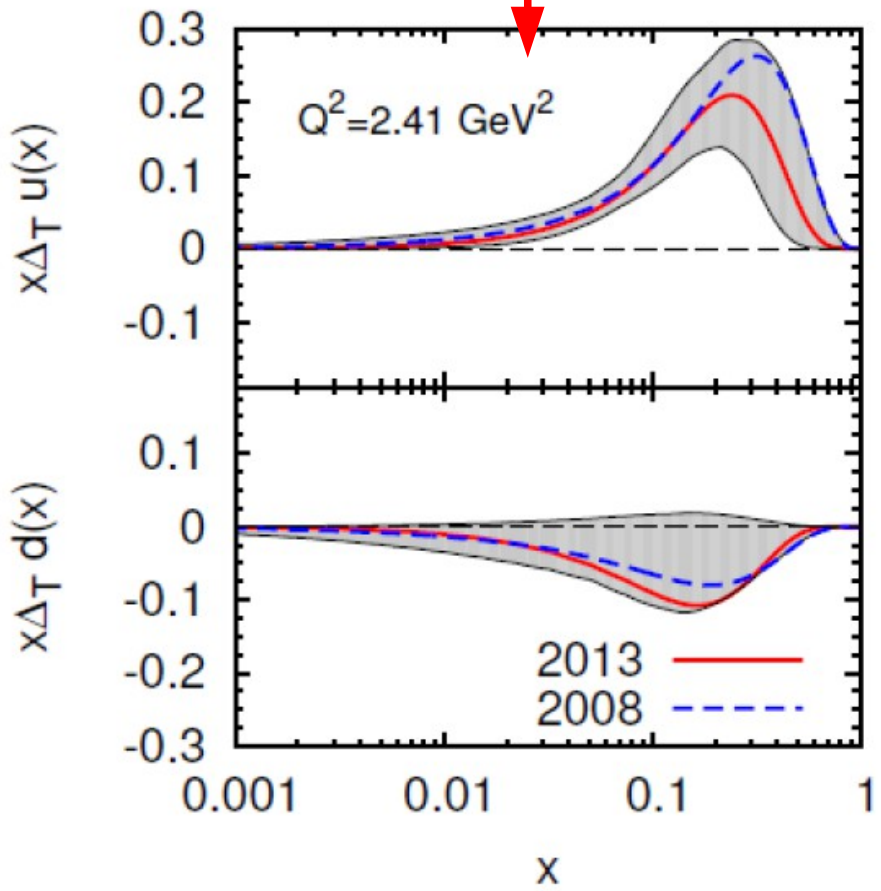
YAMAGATA UNIVERSITY

M. Anselmino et al., arXiv:1303.3822

HERMES, COMPASS

$$A_{UT}^{\sin(\phi+\phi_S)} \sim h_{1T} \otimes H_1^{\perp}$$

Belle

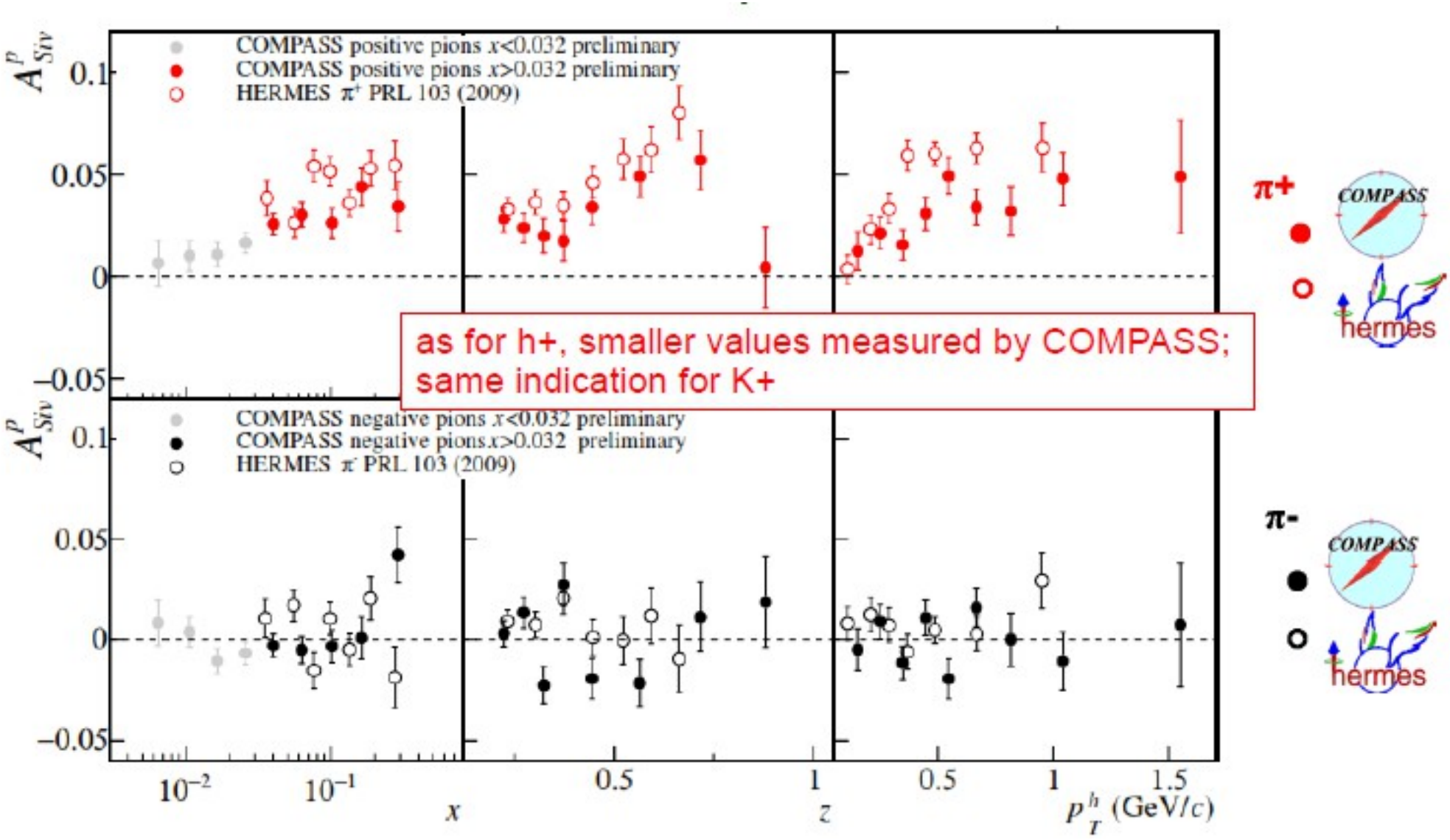


Sivers

YAMAGATA UNIVERSITY

$$f_{1T}^{\perp} \otimes D_1 \sim \sin(\phi - \phi_S)$$

A. Martin, DIS2013

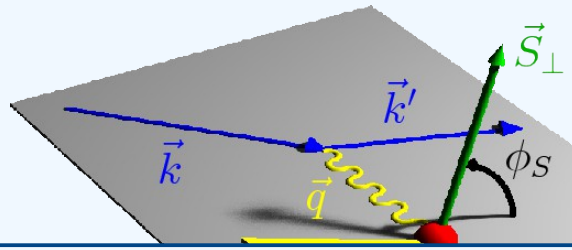


Worm-gear

YAMAGATA UNIVERSITY

With pol. beam

Unp



With Transversely polarized target

$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

$h_{1L}^\perp$ Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

Transversely Polarized Nucleon

$f_{1T}^\perp$ Sivers

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

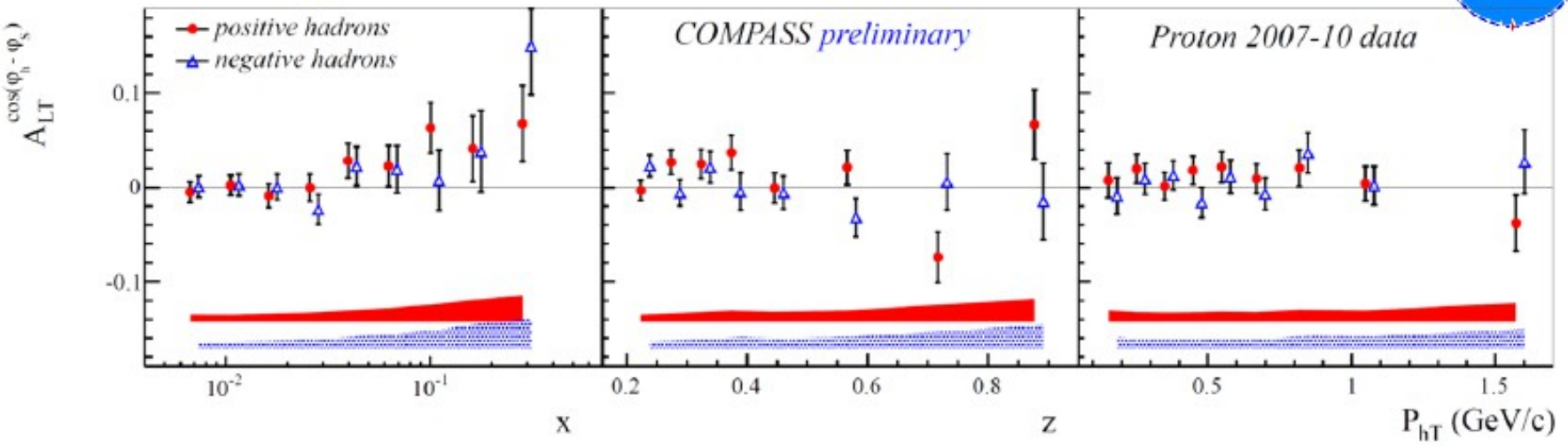
$h_{1T}^\perp$ Pretzelosity

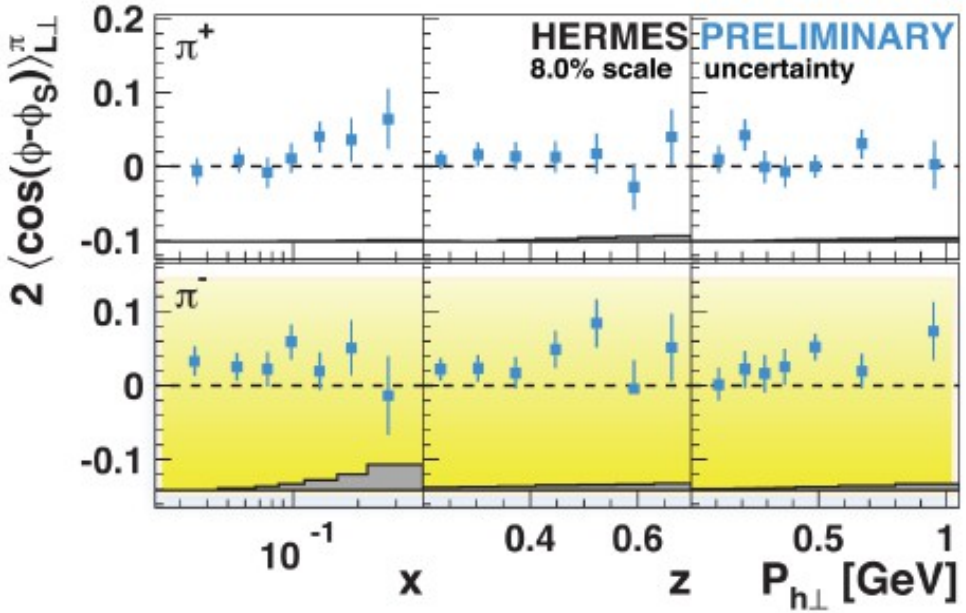
$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

Worm-gear

$$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$$

Results for $A_{LT}^{\cos(\varphi_h - \varphi_S)}$ COMPASS - HERMES



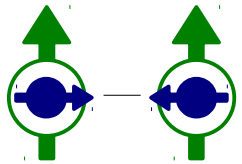


Similar trend for $A_{LT}^{\cos(\varphi_h - \varphi_S)}$ asymmetry is present in HERMES preliminary results.

B. Parsamyan, DIS2013

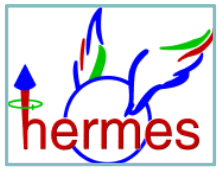
Worm-gear

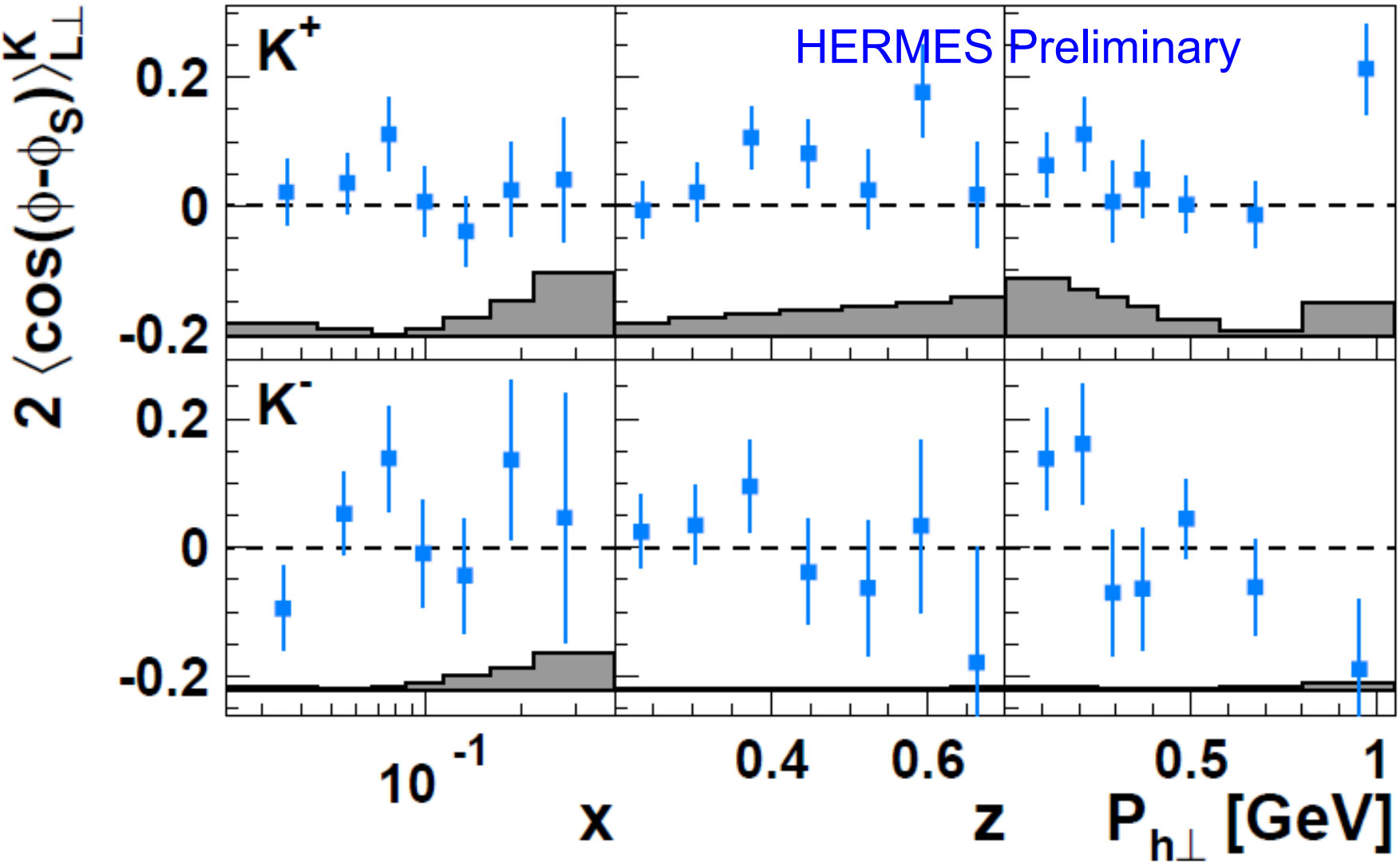
$$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$$



g_{1T}

Worm-gear

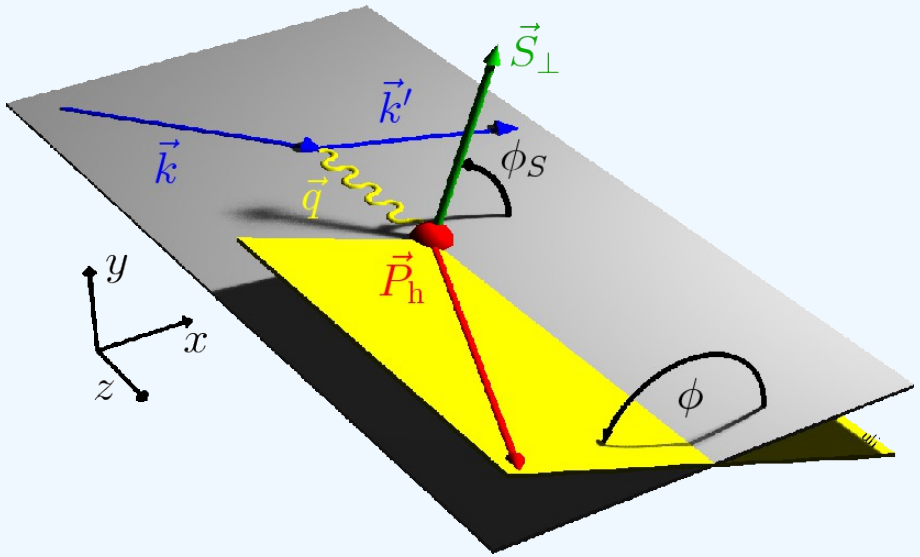




Mulders-Kotzinian

$h_{1L}^{\perp} \otimes H_1^{\perp} \sim \sin 2\phi$

YAMAGATA UNIVERSITY



Unp

$h_1^{\perp}$ Boer-Mulders

$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$

Lon

$h_{1L}^{\perp}$ Mulders-Kotzinian

$h_{1L}^{\perp} \otimes H_1^{\perp} \sim \sin 2\phi$

Trans ly Polarized Nucleon

$f_{1T}^{\perp}$ Sivers

g_{1T}

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^{\perp} \sim \sin(\phi+\phi_S)$

$h_{1T}^{\perp}$ Pretzelosity

$f_{1T}^{\perp} \otimes D_1 \sim \sin(\phi-\phi_S)$

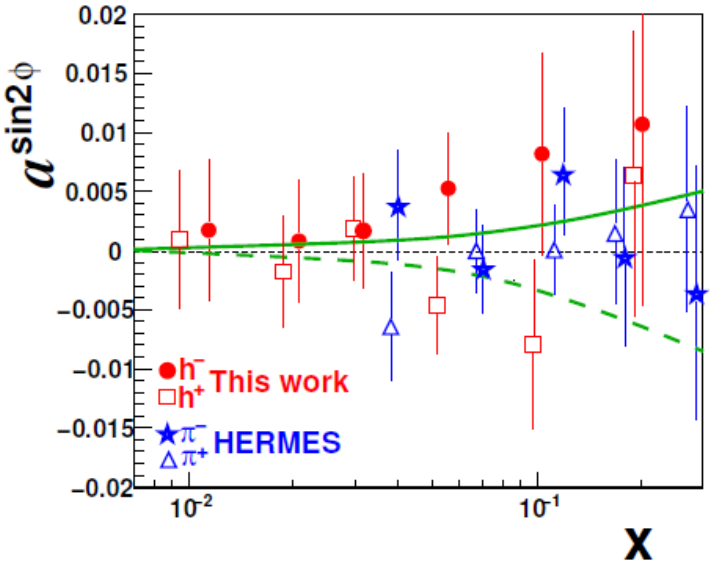
$g_{1T} \otimes D_1 \sim \cos(\phi-\phi_S)$

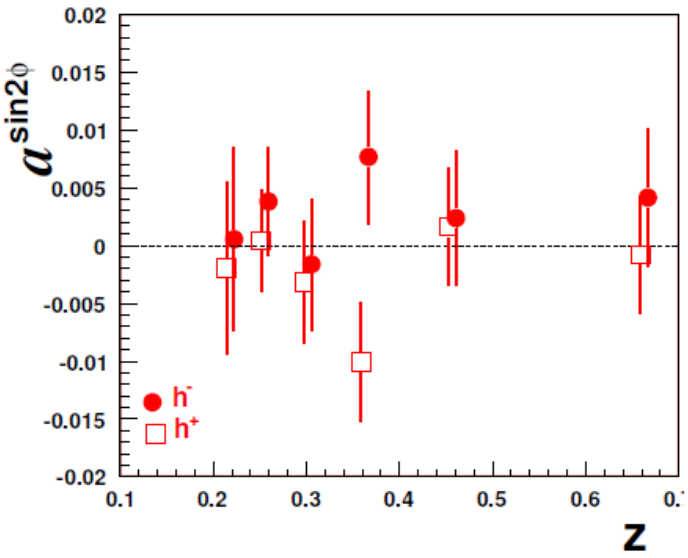
$h_{1T}^{\perp} \otimes H_1^{\perp} \sim \sin(3\phi-\phi_S)$

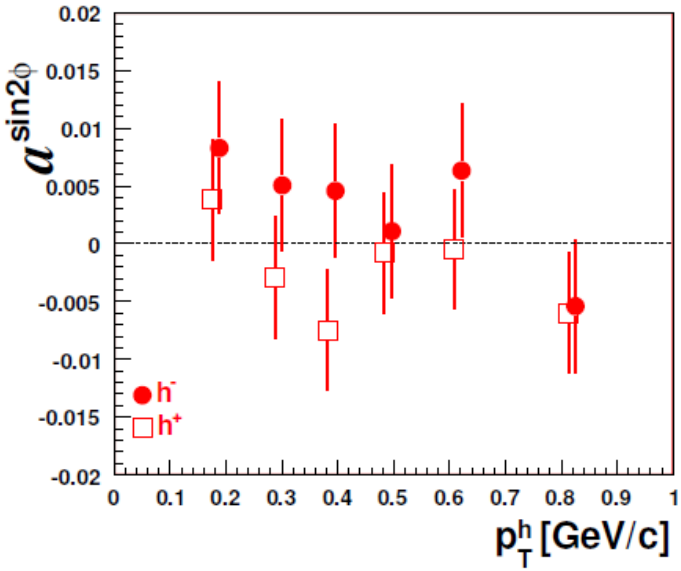
With longitudinal polarized target

Mulders-Kotzinian

$$h_{1L}^{\perp} \otimes H_1^{\perp} \sim \sin 2\phi$$







EPJC70(2010)39

PLB562(2003)182

Boer-Mulders

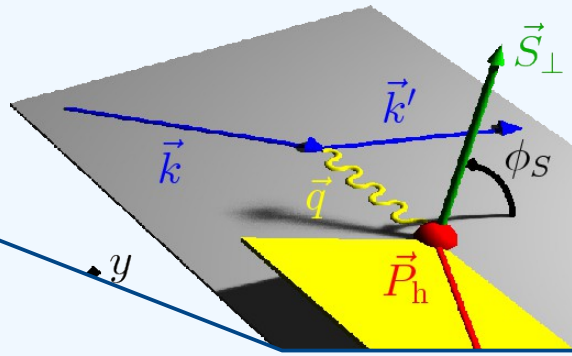
$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$

YAMAGATA UNIVERSITY

Unp

Lon

Transversely Polarized Nucleon



Unpolarized target

$h_1^{\perp}$ Boer-Mulders

$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$

$h_{1L}^{\perp}$ Mulders-Kotzinian

$h_{1L}^{\perp} \otimes H_1^{\perp} \sim \sin 2\phi$

$f_{1T}^{\perp}$ Sivers

$f_{1T}^{\perp} \otimes D_1 \sim \sin(\phi - \phi_S)$

g_{1T} Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

$h_{1T}(=\delta q)$ Transversity

$h_{1T} \otimes H_1^{\perp} \sim \sin(\phi + \phi_S)$

$h_{1T}^{\perp}$ Pretzelosity

$h_{1T}^{\perp} \otimes H_1^{\perp} \sim \sin(3\phi - \phi_S)$

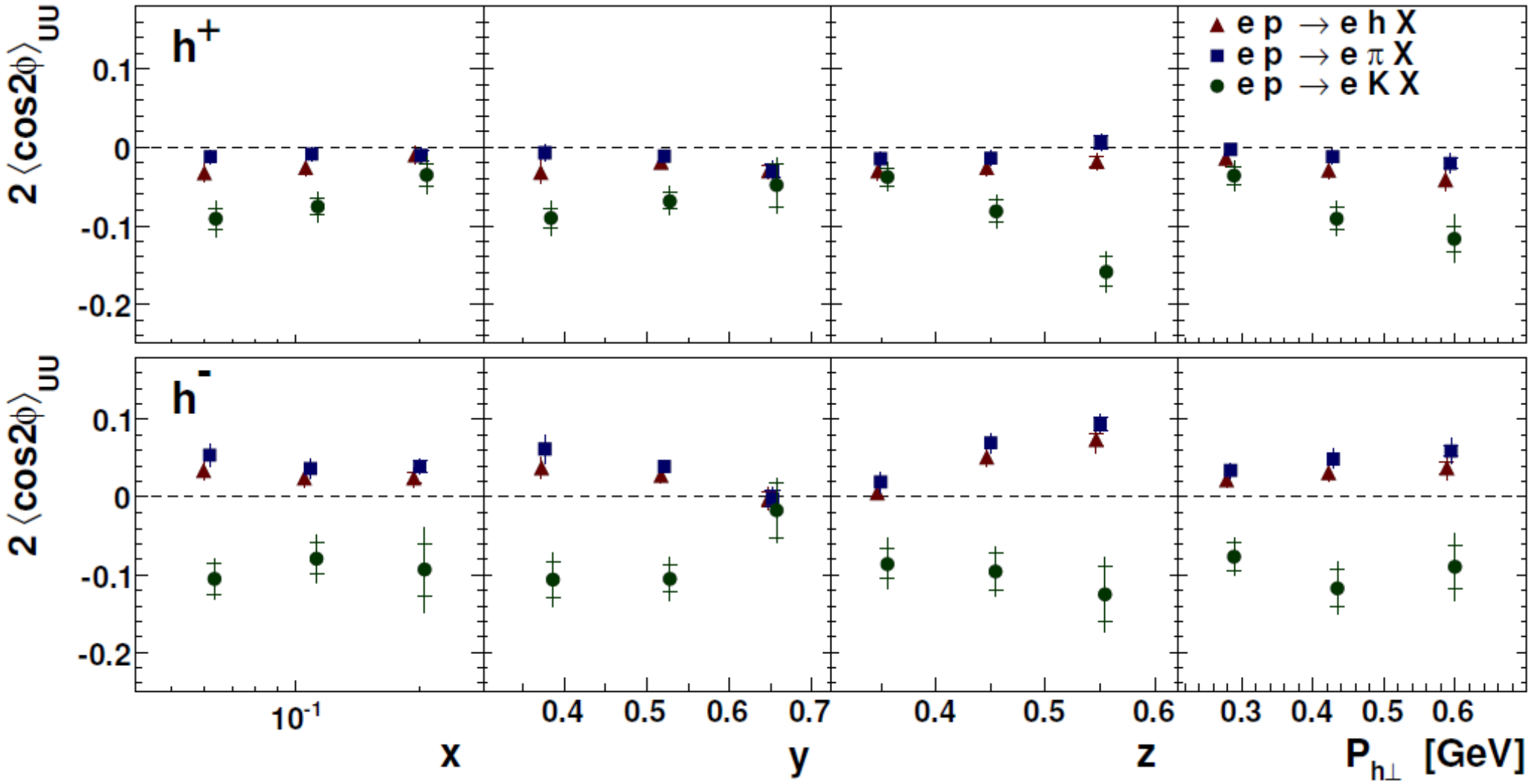
Boer-Mulders

$$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$$

YAMAGATA UNIVERSITY

Proton target

PRD87(2013)012010

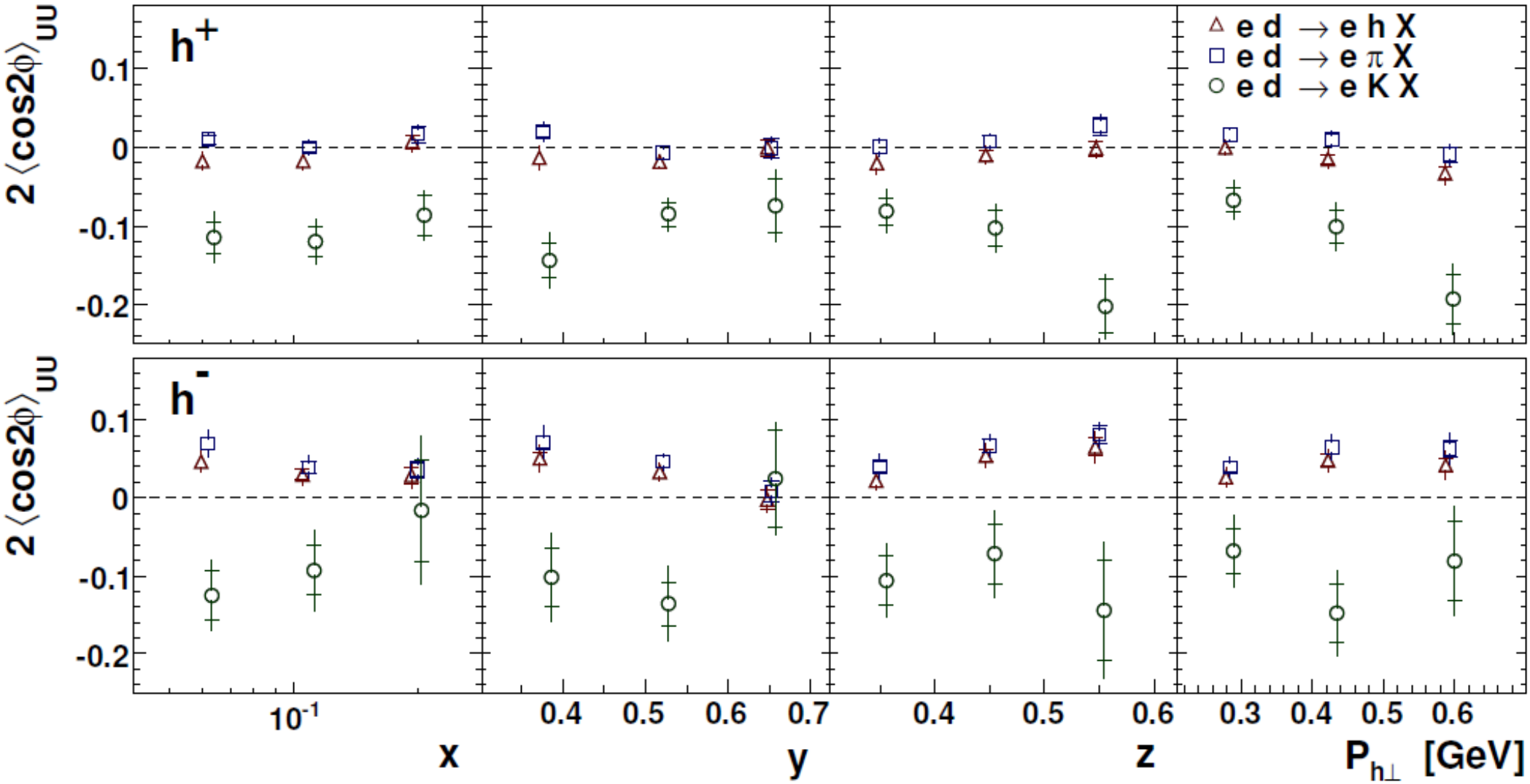


Boer-Mulders

$$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$$

Deuteron target

PRD87(2013)012010



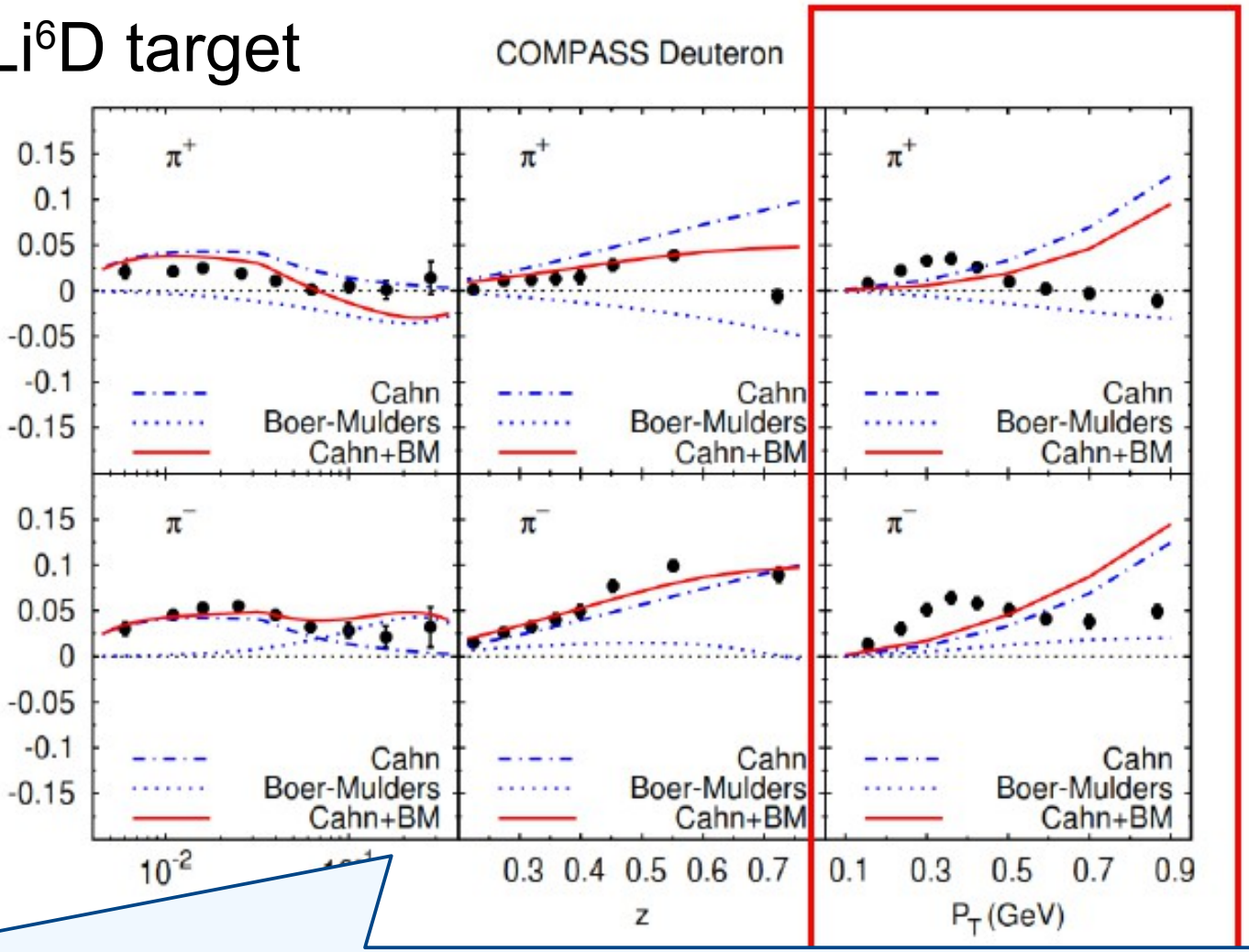
Boer-Mulders

$$h_1^{\perp} \otimes H_1^{\perp} \sim \cos 2\phi$$

YAMAGATA UNIVERSITY

$A_{\cos 2\phi_h}^{UU}$

Li^{6}D target



Preliminary results on multi-D analysis
New data from COMPASS-II GPD (2012&2015)
with **Liq. H target**

Beyond twist-2 TMDs

SIDIS x-section

COMPASS

A.Kotzinian, Nucl. Phys. B441, 234 (1995). Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

$$\frac{d\sigma}{dxdydzdP_{hT}^2 d\varphi_h d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

$$1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+$$

$$S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+$$

$$S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+$$

S_T [

$$\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+$$

$$\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+$$

$$\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+$$

$$\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+$$

$$\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)$$

] +

$S_T\lambda$ [

$$\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+$$

$$\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+$$

$$\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)$$

]

Sivers & Collins

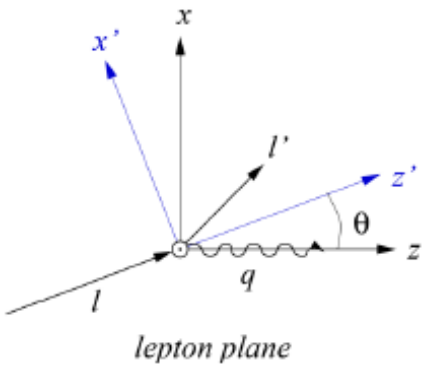
Pretzelosity

Worm-gear

Higher twists

SSA

DSA



lepton plane

Twist-2

Twist-3

24 April 2013 Bakur Parsamyan 8

New programs (COMPASS II)

approved by CERN Research Board in 2010

- Polarized Drell-Yan measurement — 2014
  TMD PDFs — *π^- beam with polarized proton target*
- GPD measurement — *$\mu^+ \mu^-$ beam with liquid hydrogen target*
  Transverse imaging — 2015 - 2016
- Pion and Kaon polarizability — *π^-, K^- (μ^-) beam with nucleus target*
  Chiral perturbation theory

With a upgraded COMPASS spectrometer

Single pol. Drell-Yan and TMDs

YAMAGATA UNIVERSITY

The LO expansion of the single polarized Drell-Yan cross section is

$$\frac{d\sigma}{d^4 q d\Omega} = \frac{\alpha^2}{Fq^2}\hat{\sigma}_U \left\{ \left(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\right) + \left|\vec{S}_T\right| \left[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \right) \right] \right\}$$

- $A_U^{\cos 2\phi} : (BM)_\pi \otimes (BM)_P$
- $A_T^{\sin\phi_S} : (f_1)_\pi \otimes (Sivers)_P$
- $A_T^{\sin(2\phi+\phi_S)} : (BM)_\pi \otimes (\mathrm{Pr}etz.)_P$
- $A_T^{\sin(2\phi-\phi_S)} : (BM)_\pi \otimes (Trans.)_P$

A : azimuthal asymmetries :: convolution of

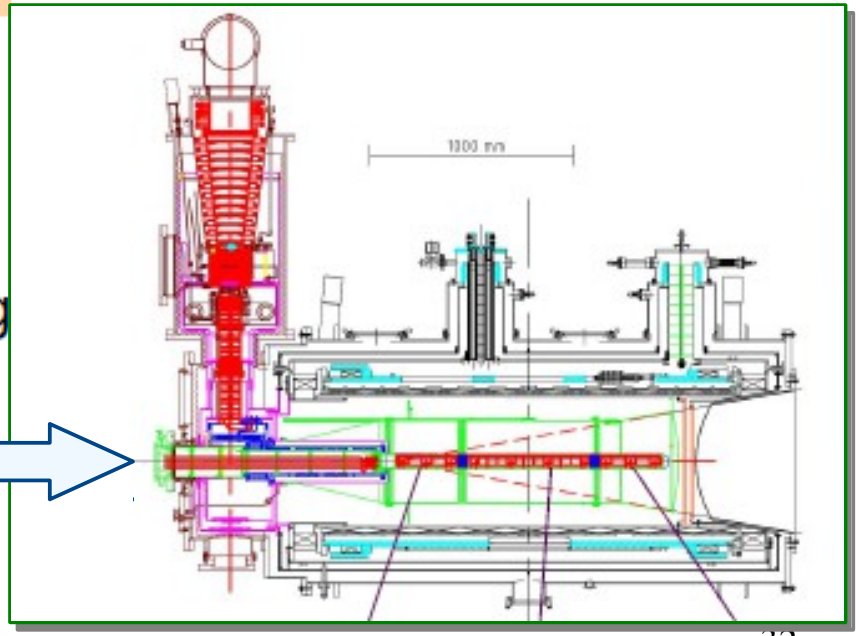
D : depolarization factor

S : target spin component

$\hat{\sigma}_U$: part of the cross-section surviving integ

F : $4\sqrt{(P_a \cdot P_b)^2 - M_a^2 M_b^2}$

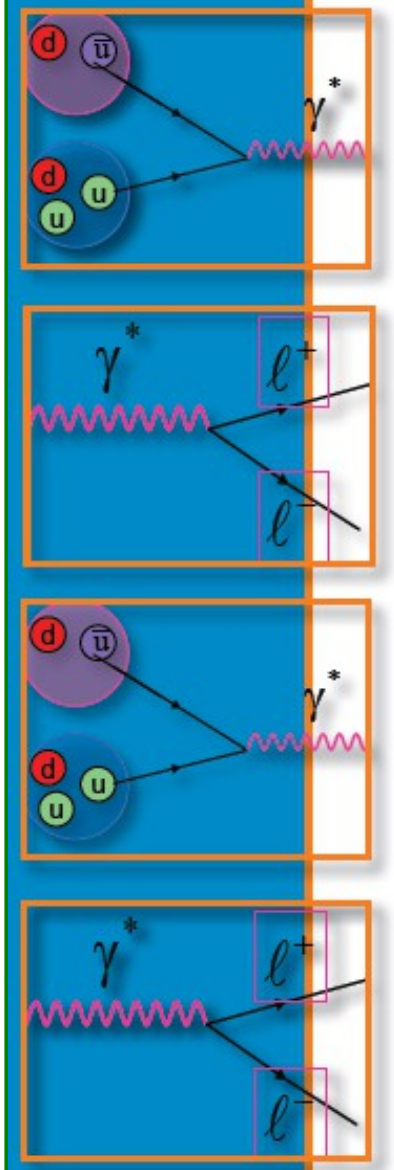
π



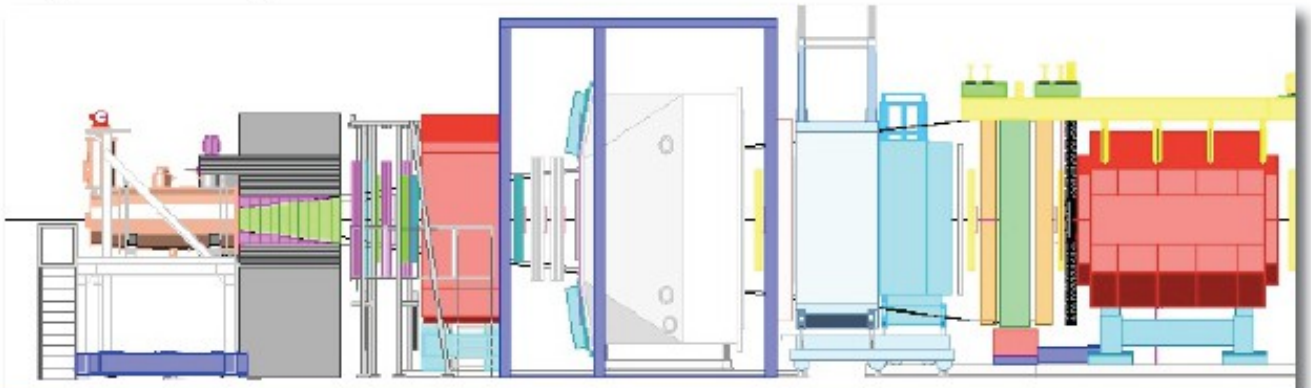
COMPASS II : Drell-Yan setup

M. Chiosso, DIS2013

Drell-Yan @ COMPASS-II



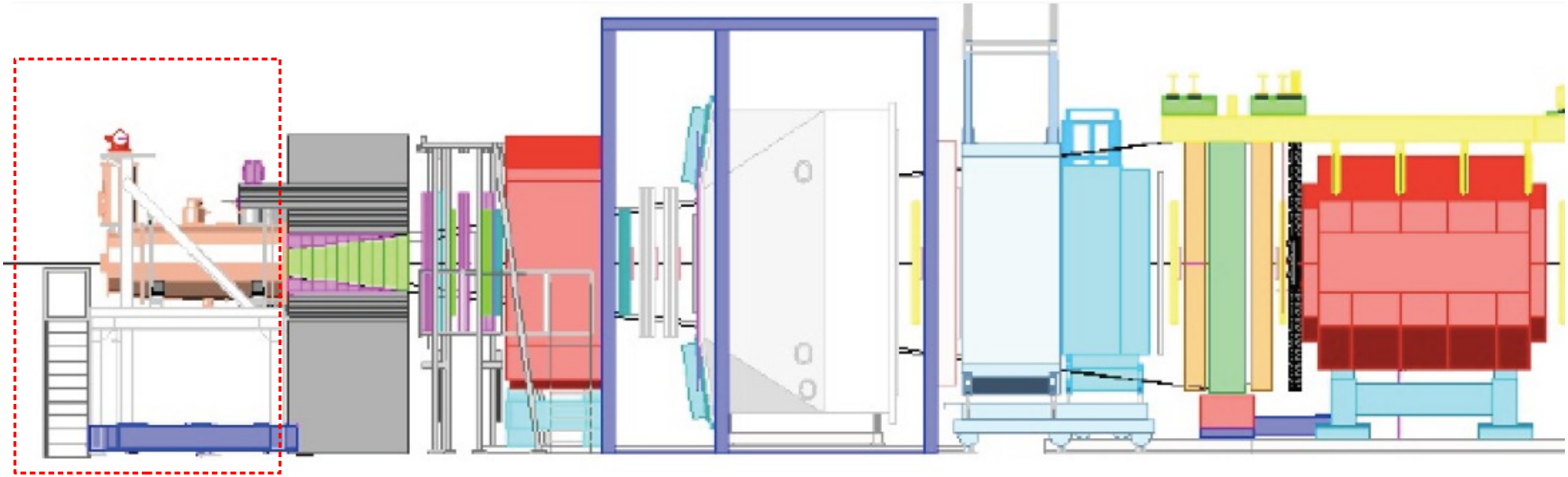
- Large angular acceptance spectrometer
- π^- beam at 190 GeV/c with the intensity up to 1×10^8 particles/second
- Large acceptance COMPASS Superconducting Solenoid Magnet
- Transversely polarized NH_3 target working in frozen spin mode with long relaxation time
- Hadron absorber downstream of the target
- A detection system designed to stand relatively high particle fluxes
- A Data Acquisition System (DAQ) that can handle large amounts of data at large trigger rates
- Trigger based on hodoscope signals coincidence, homothetic and pointing to the target



15

COMPASS II : Drell-Yan setup

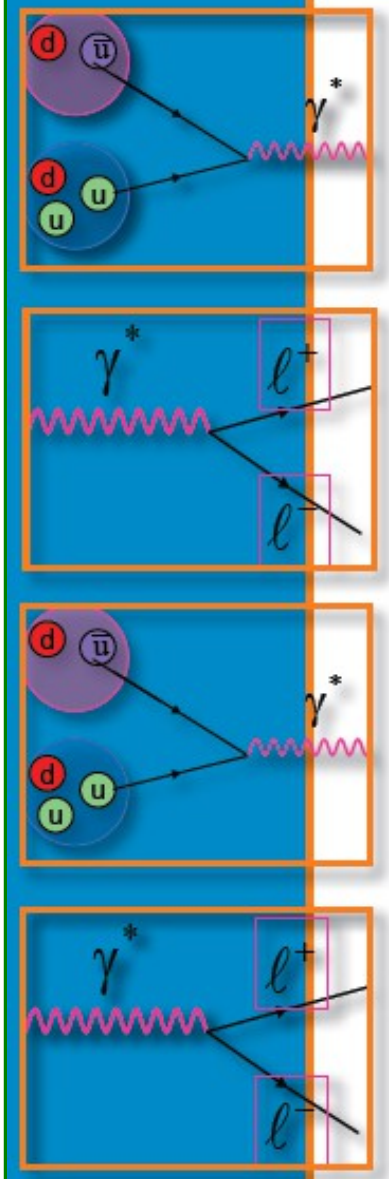
YAMAGATA UNIVERSITY



- Entire target system will be moved to upstream
- Modify pol. target cell to have enough space between “↑” and “↓” cells.
- Install hadron absorber into the empty space
- Install “vertex” detector

COMPASS II : Drell-Yan setup

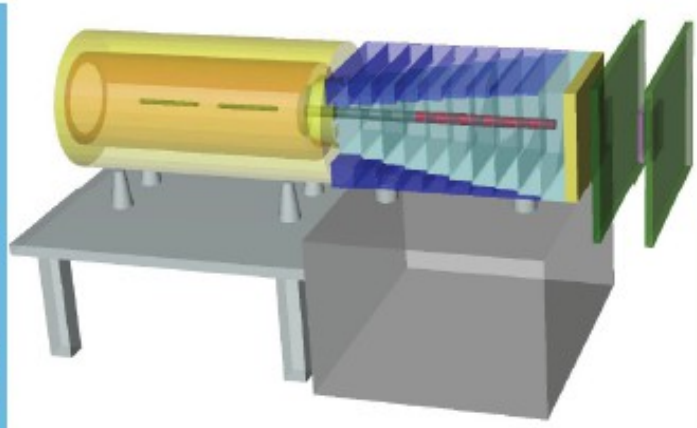
DY setup: new hardware developments

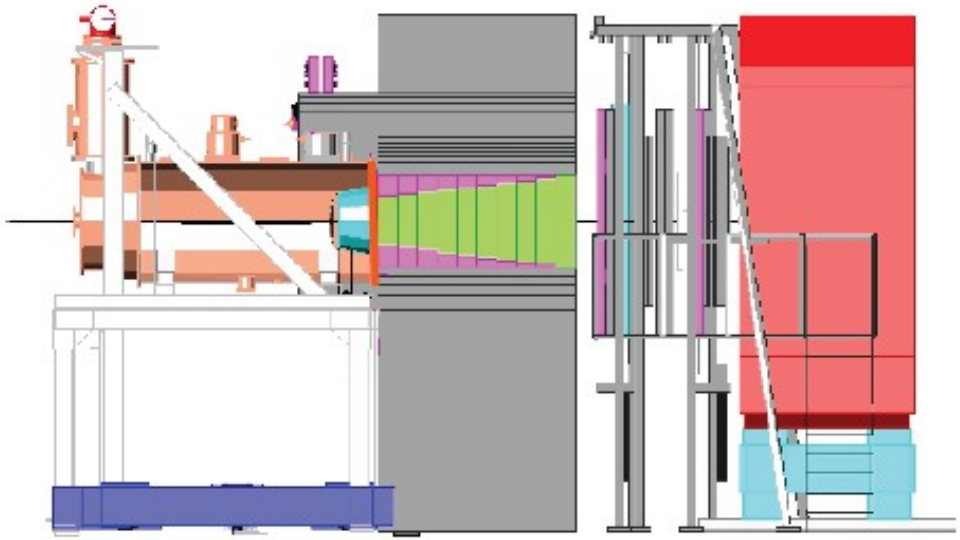


Two target cells (NH3) inside the dipole (55 cm length, 4 cm diameter, spaced by 20 cm)

An absorber 236 cm long, downstream the target

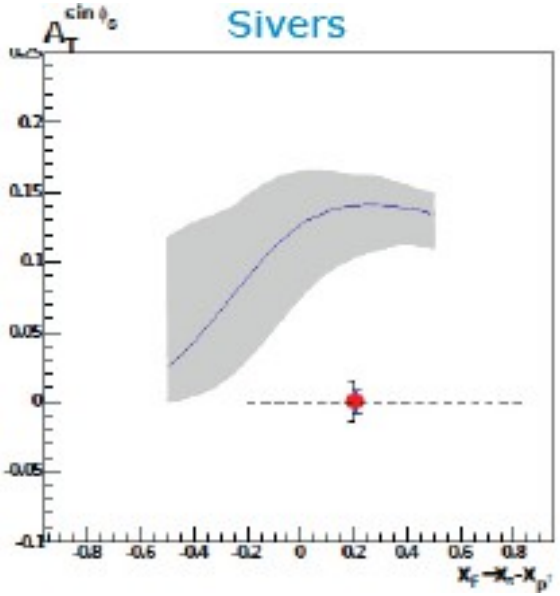
Possibility to place a scintillator fibers detector between target and absorber to improve vertex resolution

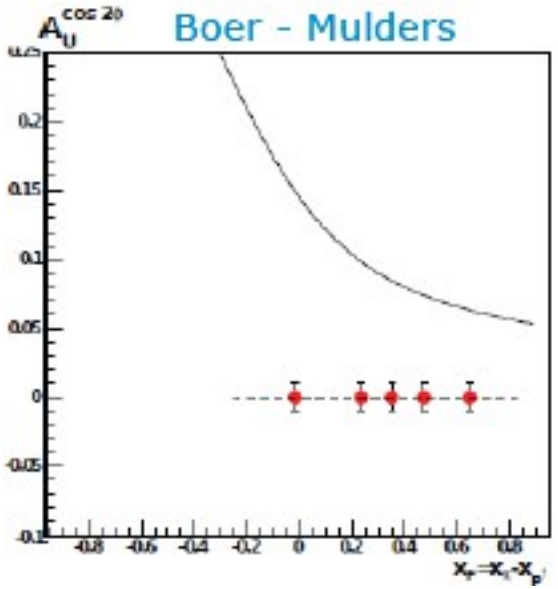


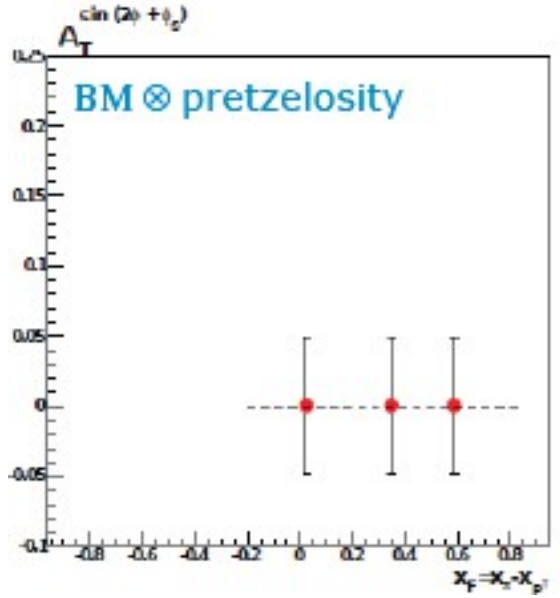


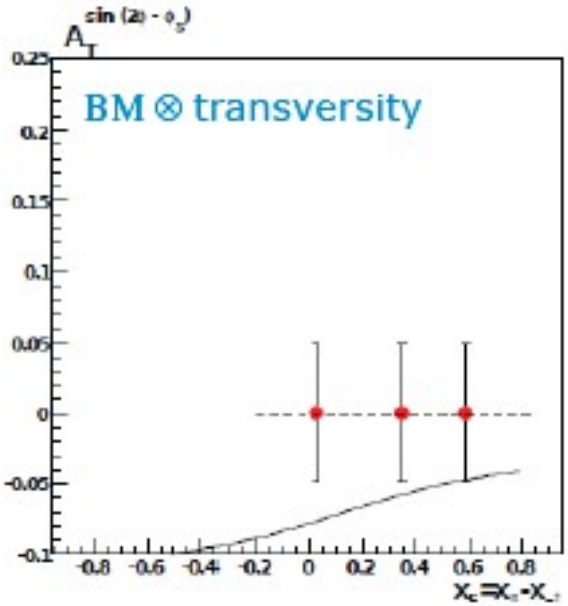
COMPASS II: Drell-Yan Goal

YAMAGATA UNIVERSITY









2 years of data taking
DY 4.-9. GeV/c²

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS}$$

$$h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}$$