TMD experiments from COMPASS SIDIS

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on behalf of COMPASS Collaboration

Hadron China 2017, 24-28, 2017, Nanjing

OUTLINE

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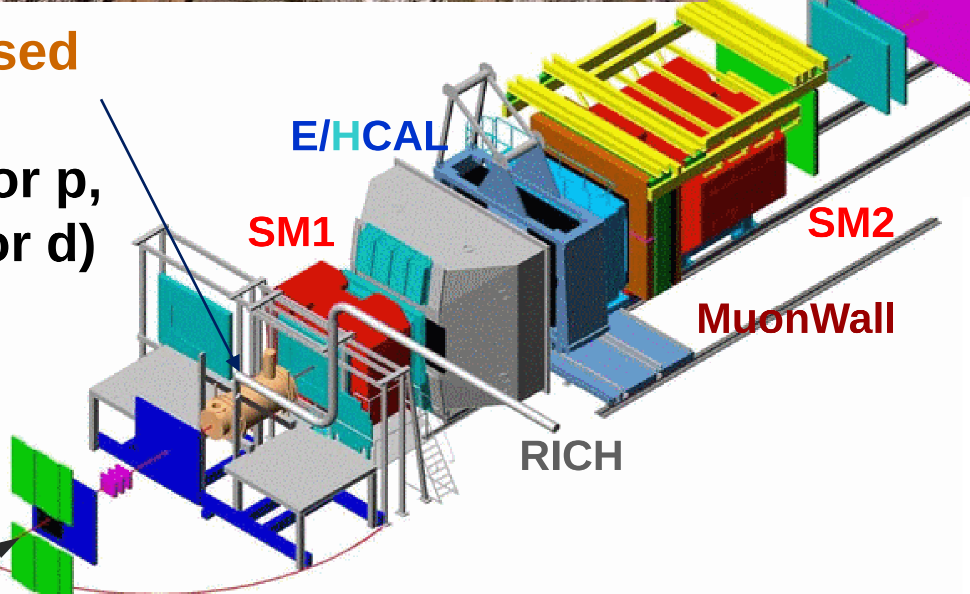
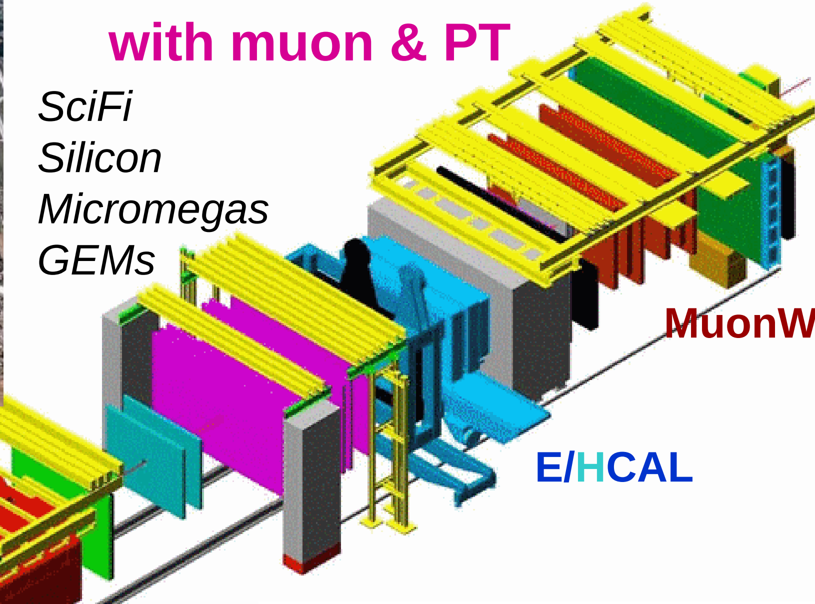
  - *Nucleon PDFs*
- ***Collins asymmetry***
  - *Collins Asymmetry for single-hadron production*
  - *Di-hadron Asymmetry*
- ***Sivers asymmetry***
  - *Sivers Asymmetry for single-hadron production*
  - *Weighted Sivers asymmetry*
- ***Gluon Sivers asymmetry***
- ***Conclusion***

COMPASS at CERN

DIS & SI-DIS setup
with muon & PT

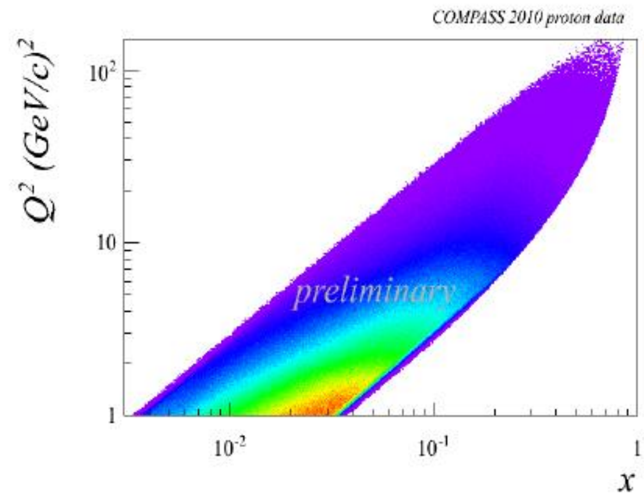



Polarised Target
(NH_3 for p, ^{6}LiD for d)

Pol. μ beam fom SPS

160-200 GeV, pol. = 80%

two stage spectrometer
tracking, calorimetry, PID

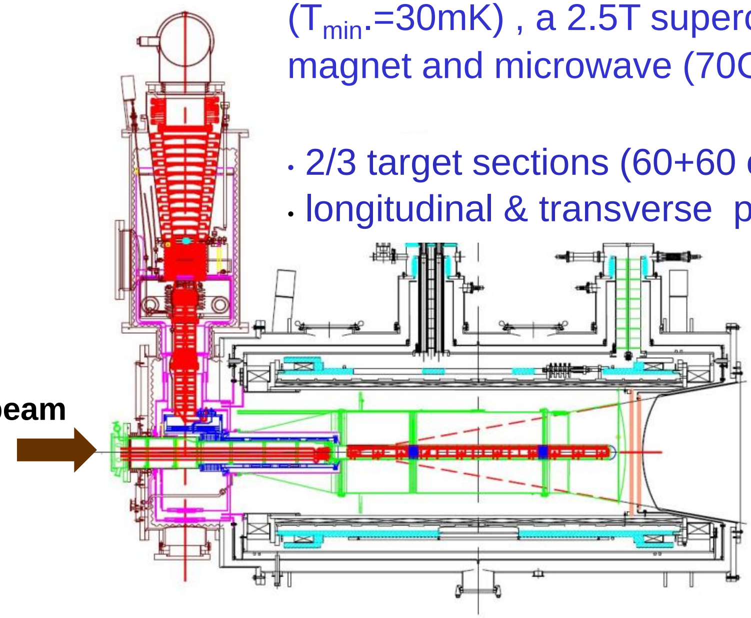


The Polarized Target System

DNP technique with a dilution refrigerator (T_{min}.=30mK) , a 2.5T superconducting magnet and microwave (70GHz) system

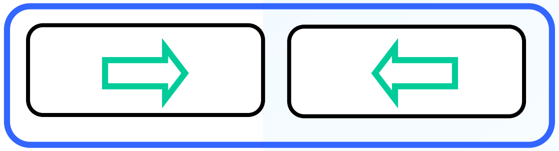
- 2/3 target sections (60+60 cm/30+60+30 cm)
- longitudinal & transverse pol. modes

beam

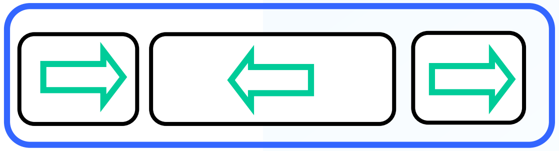


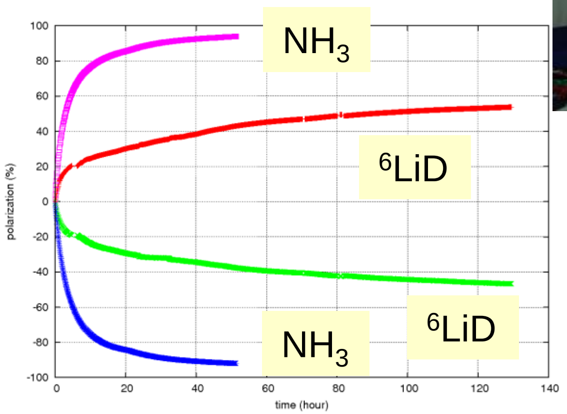
The world biggest PT

2002 - 2004



2006 - 2011





→ Polarization of proton(NH_3) ~90%

→Polarization of deuteron(^{6}LiD) ~50%

- ^{6}Li (~ α+d) also polarized

→ dilution factor f=50%

The Polarized Target System

DNP technique with a dilution refrigerator ($T_{min.}$=30mK) , a 2.5T superconducting magnet and microwave (70GHz) system

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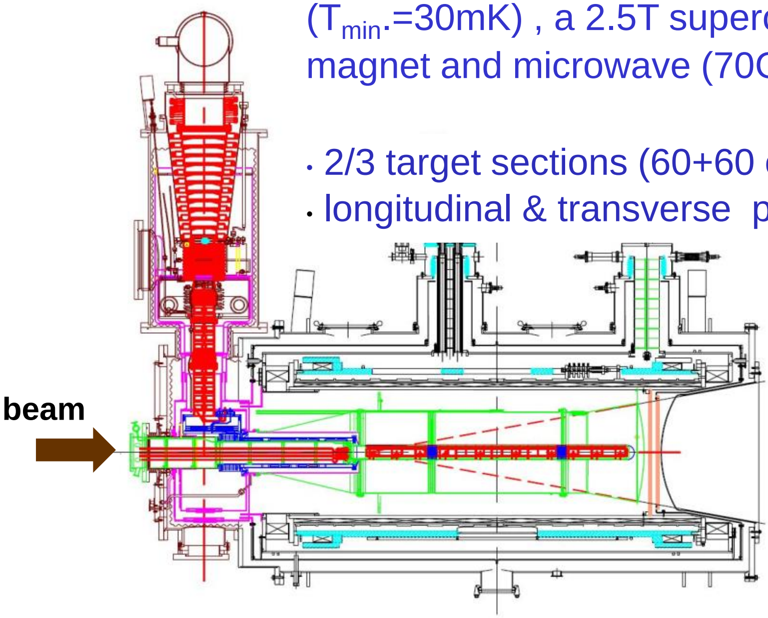

The world biggest PT

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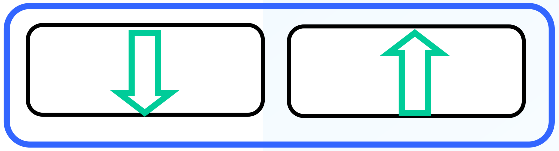

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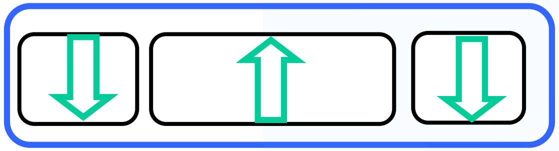

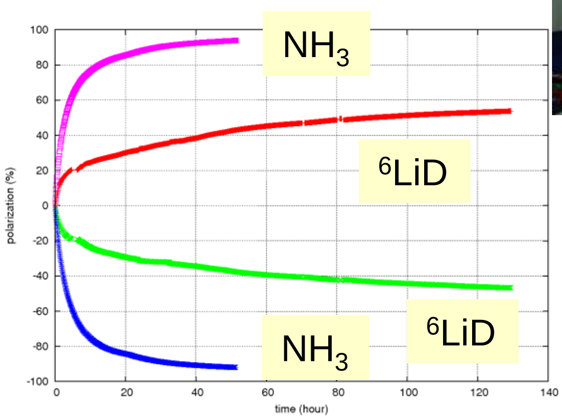

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Nucleon PDFs

At LO, taking account of transverse momentum(k_T) of the quarks

Quark \ Nucleon	unpol.	long. pol.	trans. pol.
unpol.	$q(=f_1)$ **number density** Nucleon Parton		$f_{1T}^{\perp}$ **Sivers** **T-odd** k_T
long. pol.		$\Delta q(=g_{1L})$ **helicity**	g_{1T} **worm-gear-1** k_T
trans. pol.	$h_1^{\perp}$ **Boer-Mulders** k_T **T-odd**	$h_{1L}^{\perp}$ **worm-gear-2** k_T	$\Delta_T q(=h_1)$ **transversity** $h_{1T}^{\perp}$ **pretzelosity** k_T

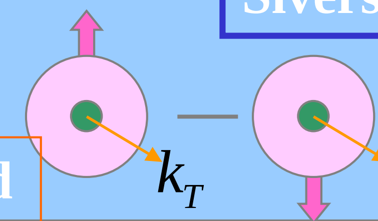
Sivers & BM-functions

Nucleon

unpol. | long. pol. | trans. pol.

Quark: unpol. | long. pol. | trans. pol.

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



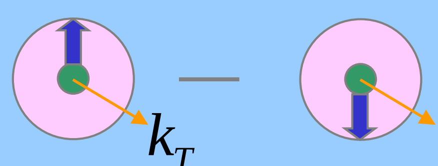
T-odd

Sivers- and BM-functions are relateted to quark OAM and expected to be process dependent

J. Collins, Phys. Lett. B **536**, 43 (2002).

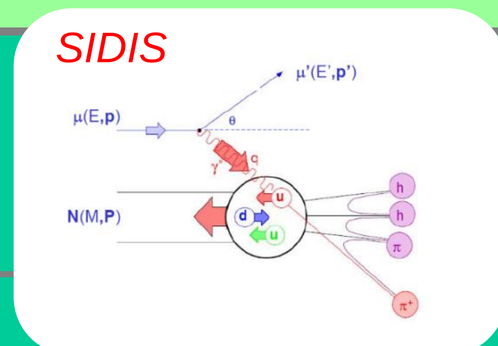
$$f_{1T}^{\perp q}(x,k_{\perp}^2)_{SIDIS} = -f_{1T}^{\perp q}(x,k_{\perp}^2)_{DY}$$

$h_1^{\perp}$ **Boer-Mulders**

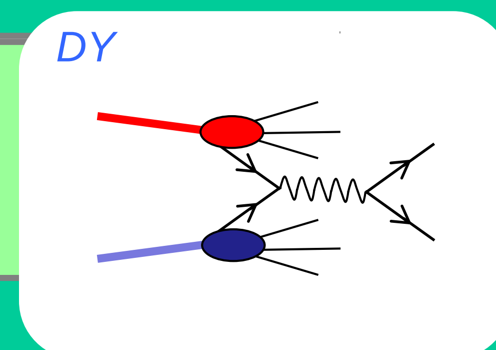


T-odd

SIDIS



DY



$$h_1^{\perp}(x,k_{\perp}^2)_{SIDIS} = -h_1^{\perp}(x,k_{\perp}^2)_{DY}$$

SIDIS x-section for single hadron production

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

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

$$\left\{\begin{array}{l}
1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\varphi_h}+\cos(2\varphi_h)\times\varepsilon A_{UU}^{\cos(2\varphi_h)}+\\
\lambda\sin\varphi_h\times\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\varphi_h}+\\
S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h A_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)A_{UL}^{\sin(2\phi_h)}\right]+\\
S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h A_{LL}^{\cos\phi_h}\right]+\\
S_T\left[\begin{array}{l}
\sin\varphi_S\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+\\
\sin(\varphi_h-\varphi_S)\times\left(A_{UT}^{\sin(\varphi_h-\varphi_S)}\right)+\\
\sin(\varphi_h+\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}\right)+\\
\sin(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}\right)+\\
\sin(3\varphi_h-\varphi_S)\times\left(\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)
\end{array}\right]+\\
S_T\lambda\left[\begin{array}{l}
\cos\varphi_S\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}\right)+\\
\cos(\varphi_h-\varphi_S)\times\left(\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\varphi_h-\varphi_S)}\right)+\\
\cos(2\varphi_h-\varphi_S)\times\left(\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\varphi_h-\varphi_S)}\right)
\end{array}\right]
\end{array}\right\}$$

Transverse Target Spin Asymmetries

Sivers

$$\sin\phi_S A_{UT}^{\sin\phi_S}$$
$$\phi_S\equiv\varphi_h-\varphi_s$$

Collins

$$\sin\phi_C A_{UT}^{\sin\phi_C}$$
$$\phi_C\equiv\varphi_h-\varphi_{s'}=\varphi_h+\varphi_s-\pi$$

$$A_{U(L),T}^{w(\varphi_h,\varphi_s)}=\frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

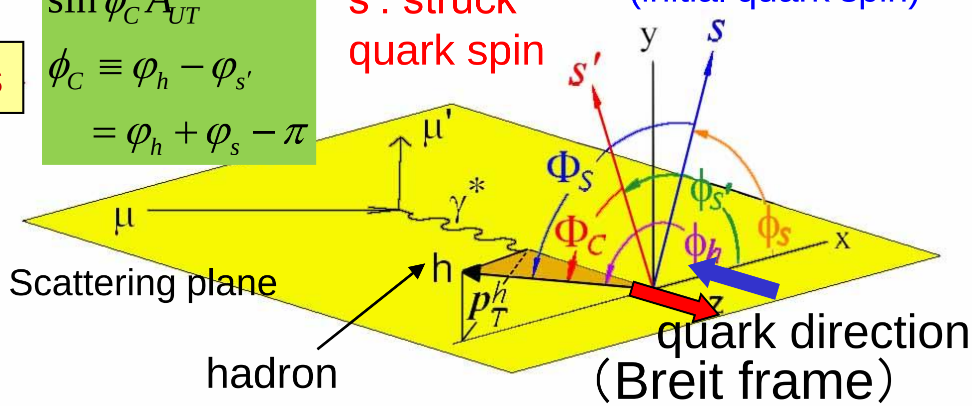
S: nucleon covariant spin vector

λ:lepton helicity

$$\varepsilon=\frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\quad \gamma=\frac{2Mx}{Q}$$

s: nucleon spin
(initial quark spin)

s': struck quark spin



15 asymmetries:

2-"UU",1-"LU",2-"UL", 2-"LL",5-"UT", 3-"LT"

All measured in COMPASS for p & d

Collins & Sivers asymmetries

Transversity

Collins F.F. (polarized quark fragmentation)

$$A_{Coll} \approx \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\perp q}}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

can be used for quark polarimeter

Collins mechanism

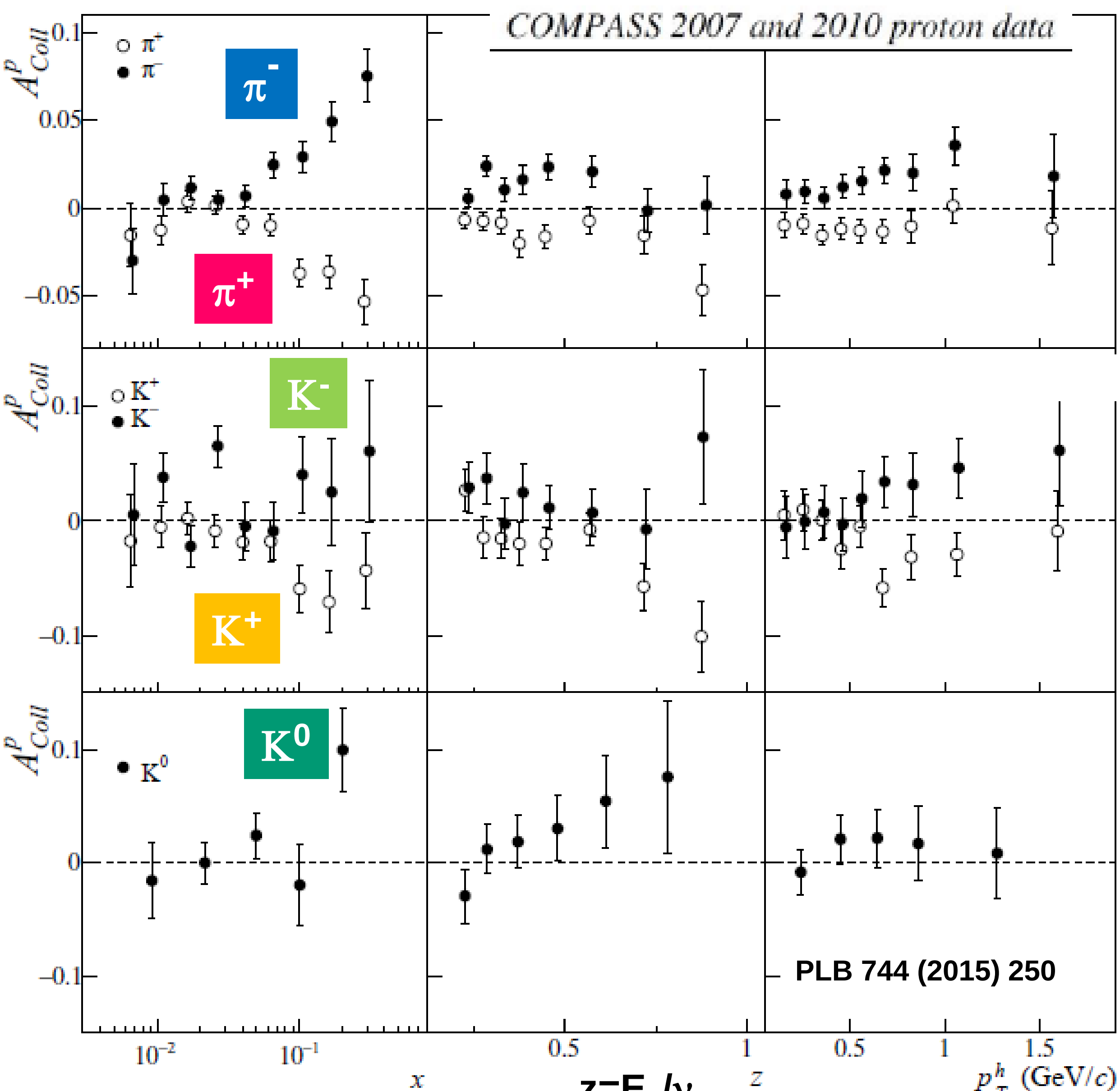
unpol. F.F.

Sivers PDF

$$A_{Siv} \approx \frac{\sum_q e_q^2 \cdot f_{1T,q}^{\perp} \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Sivers effect

Collins Asymmetry on Proton



z=E$_h$/ν

Event Selection

Q^2>1 (GeV/c)^2

W>5 GeV/c^2

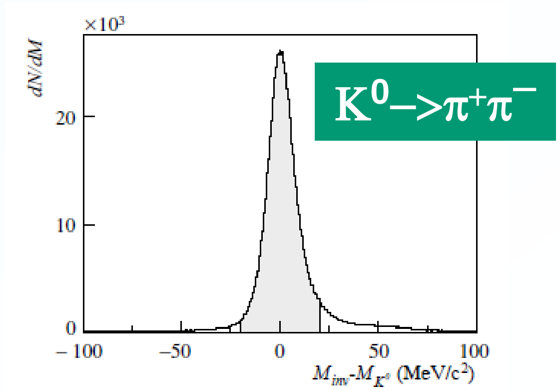
0.05 < y < 0.9

z > 0.1

$|P^h_T|$ > 0.07 GeV/c

Clearly non-zero in valence region, negative for π^+, positive for π^-

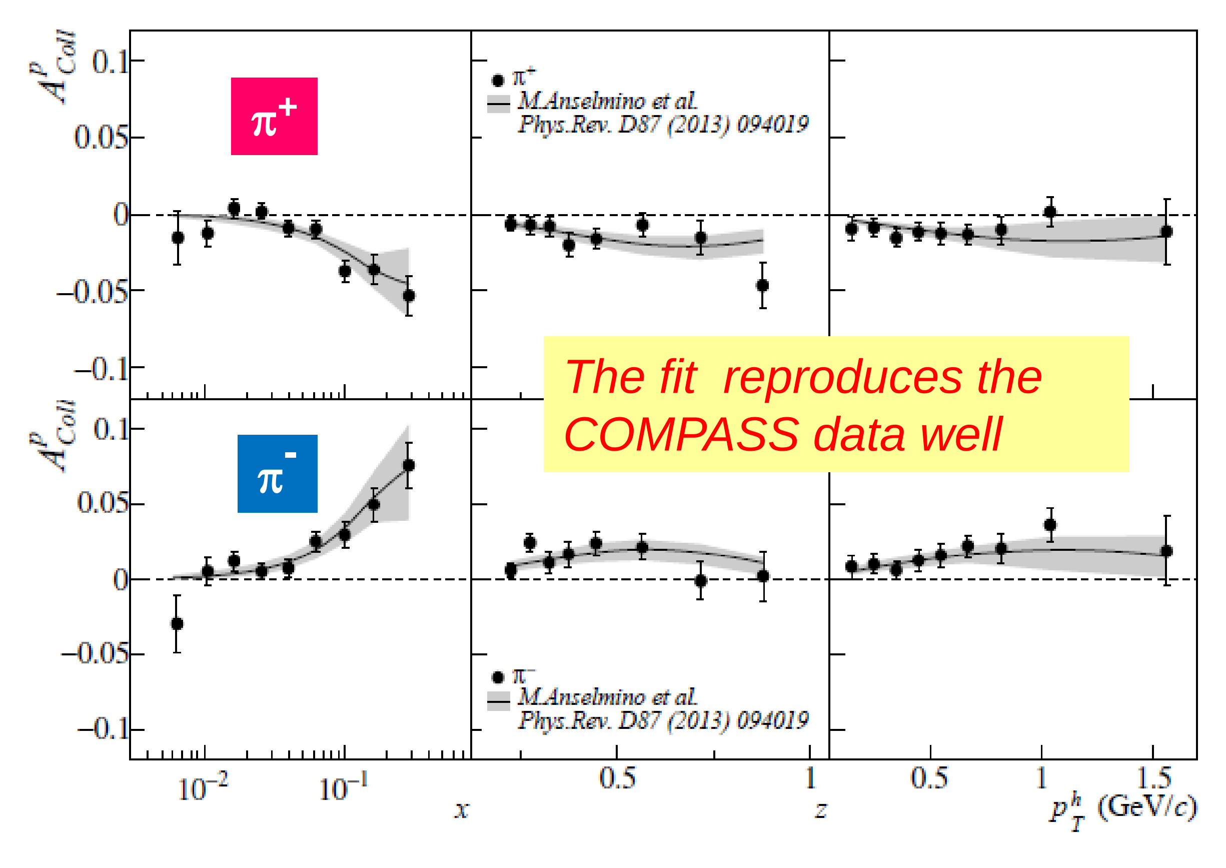
Similar trend for K, negative for K^+, positive for K^-



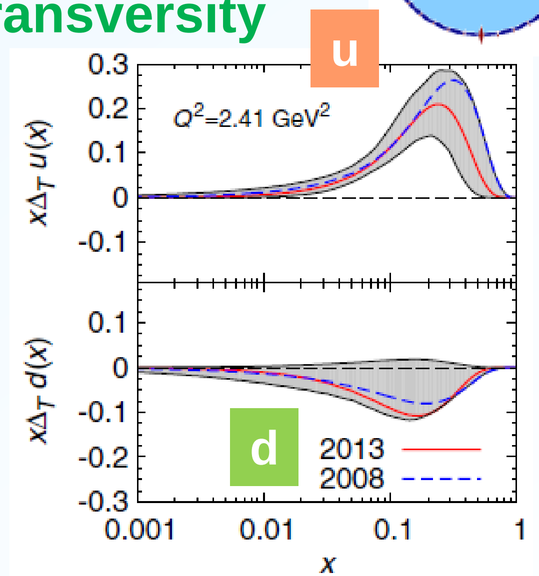
Deuteron target asymmetries compatible with zero (COMPASS PLB673 (2009) 127)

Collins Asymmetry compared with a Fit

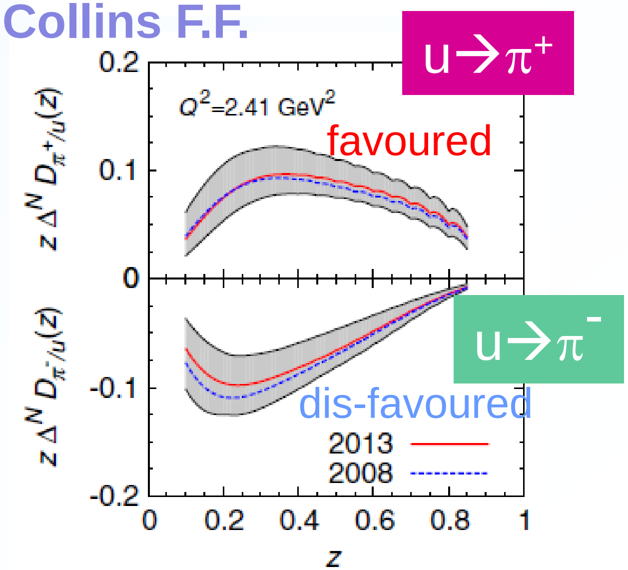
COMPASS 2007 and 2010 proton data



Transversity



Collins F.F.



global fit by Anselmino group with HERMES, COMPASS, Belle data [PRD87(2013) 094019]

Di-hadron Asymmetry & Transversity

$$lN^{\uparrow} \rightarrow l'h^+h^-X$$

Transversity PDF

"Di-hadron FF"

$$A_{UT}^{\sin\phi_{RS}} \approx \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot H_q^{\angle}}{\sum_q e_q^2 \cdot f_{q\,T}^{\,q} q \cdot D_q^{2h}}$$

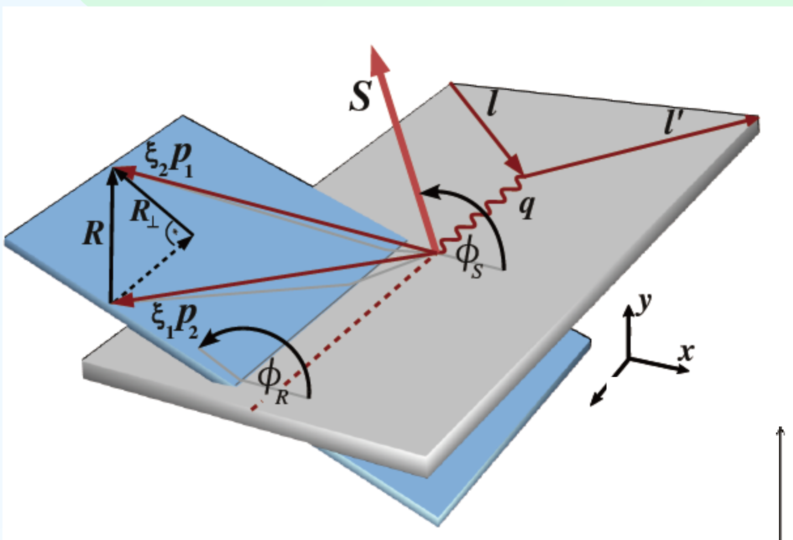
Modulation according to

$$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$$

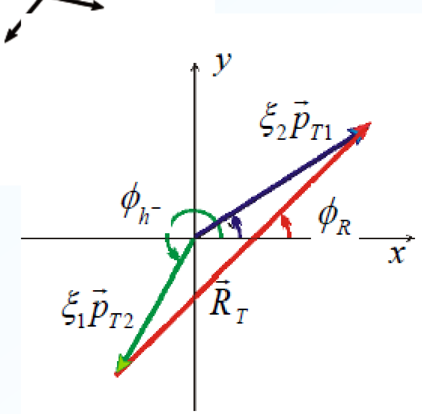
ϕ_R: azimuthal angle of **R** (Relative hadron momentum vector)

$$\boldsymbol{R} = \frac{z_2 \boldsymbol{p}_1 - z_1 \boldsymbol{p}_2}{z_1 + z_2} =: \xi_2 \boldsymbol{p}_1 - \xi_1 \boldsymbol{p}_2$$

$$\phi_R = \frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}}{|(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}|}\arccos\left(\frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot(\boldsymbol{q}\times\boldsymbol{R})}{|\boldsymbol{q}\times\boldsymbol{l}||\boldsymbol{q}\times\boldsymbol{R}|}\right)$$



the γ^*-nucleon system



$\phi_{S'}$: azimuthal angle of struck quark spin

ϕ_S: azimuthal angle of initial quark spin

$$N_{h^+h^-}(x, y, z, M^2_{h^+h^-}, \cos\theta, \phi_{RS}) \propto \sigma_{UU}\left(1 + f(x,y) P_T D_{nn}(y) A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS}\right),$$

Di-hadron Asymmetry on Proton

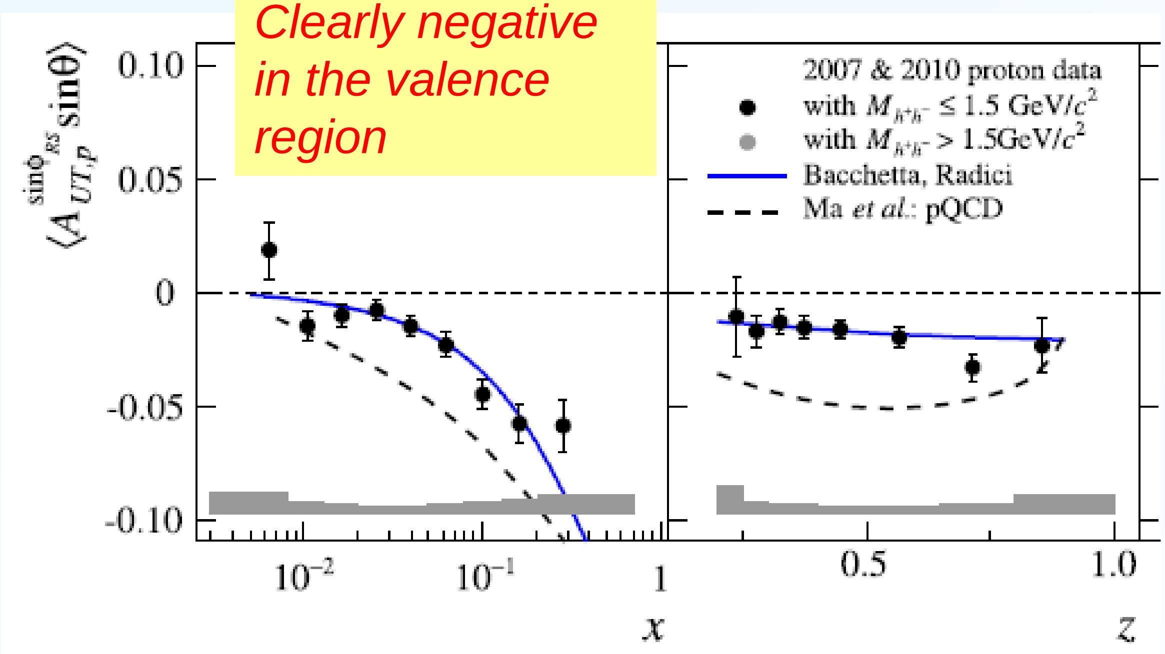
COMPASS 2007/2010 proton

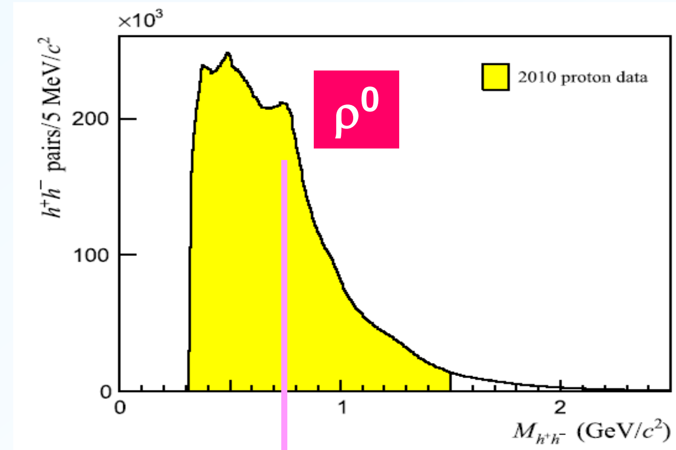
Event Selection

$Q^2>1$ (GeV/c)^2
$W>5$ GeV/c^2
$0.1 < y < 0.9$
$z > 0.1$
$|R_T| > 0.07$ GeV/c

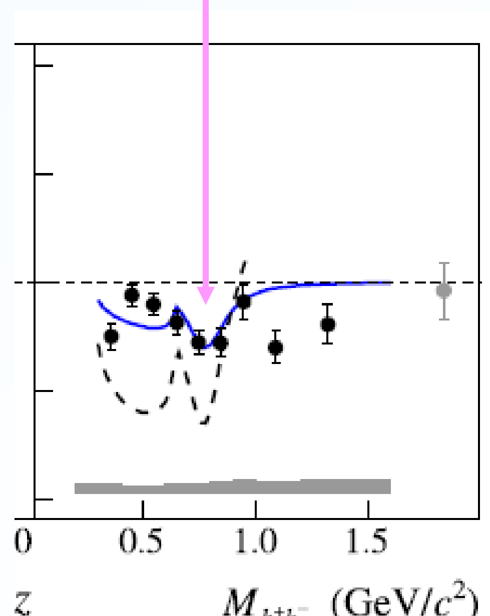
Npair=3.5×10^7
after the cuts

Clearly negative in the valence region





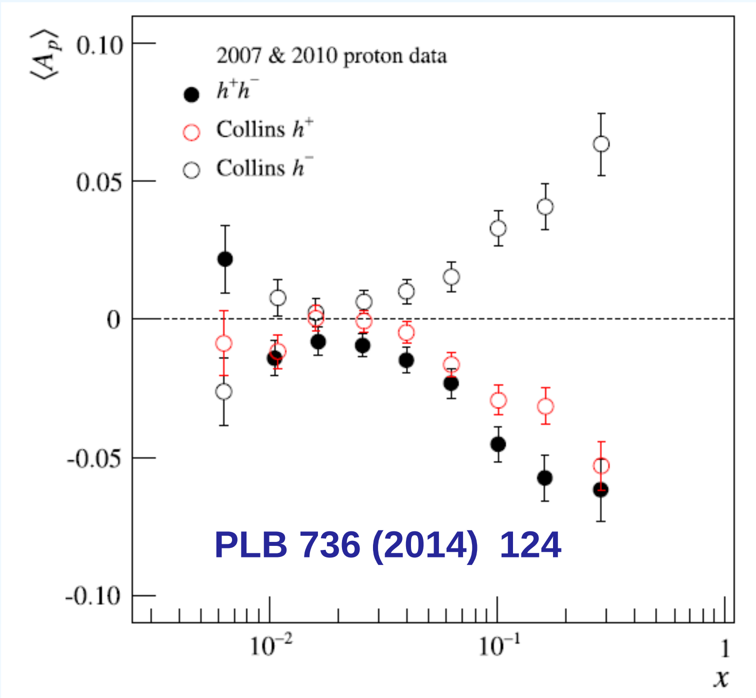
pion mass is assumed



Phys. Lett. B736 (2014) 124

Deuteron data also published
PLB 713 (2012) 10
The asymmetry is compatible with zero !

Interplay; Di-hadron & Collins Asymmetries



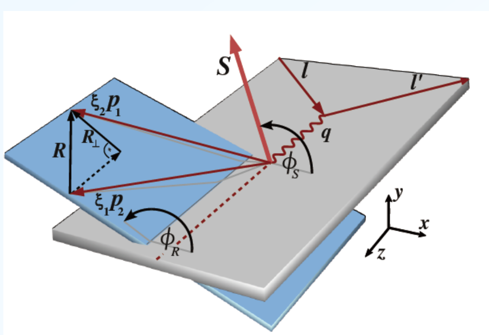
[1] Mirror symmetry between Collins h^+ and h^-

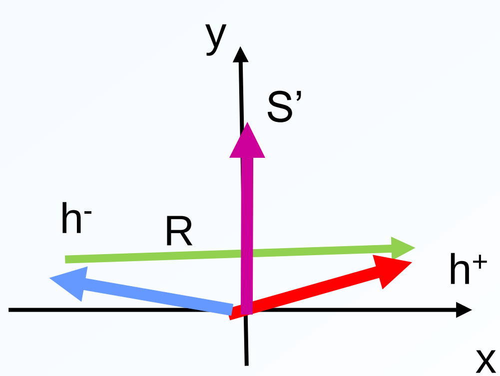
[2] Di-hadron asymmetry similar to the Collins h^+

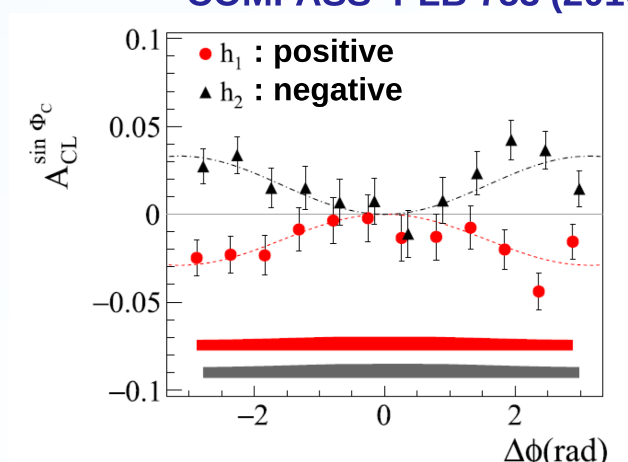
➔ Hint of common physical origin between Di-hadron FF and Collins mechanism

Further study on the Collins asymmetries for the di-hadron events gave indication that they are driven by the common origin

COMPASS PLB 753 (2016) 406

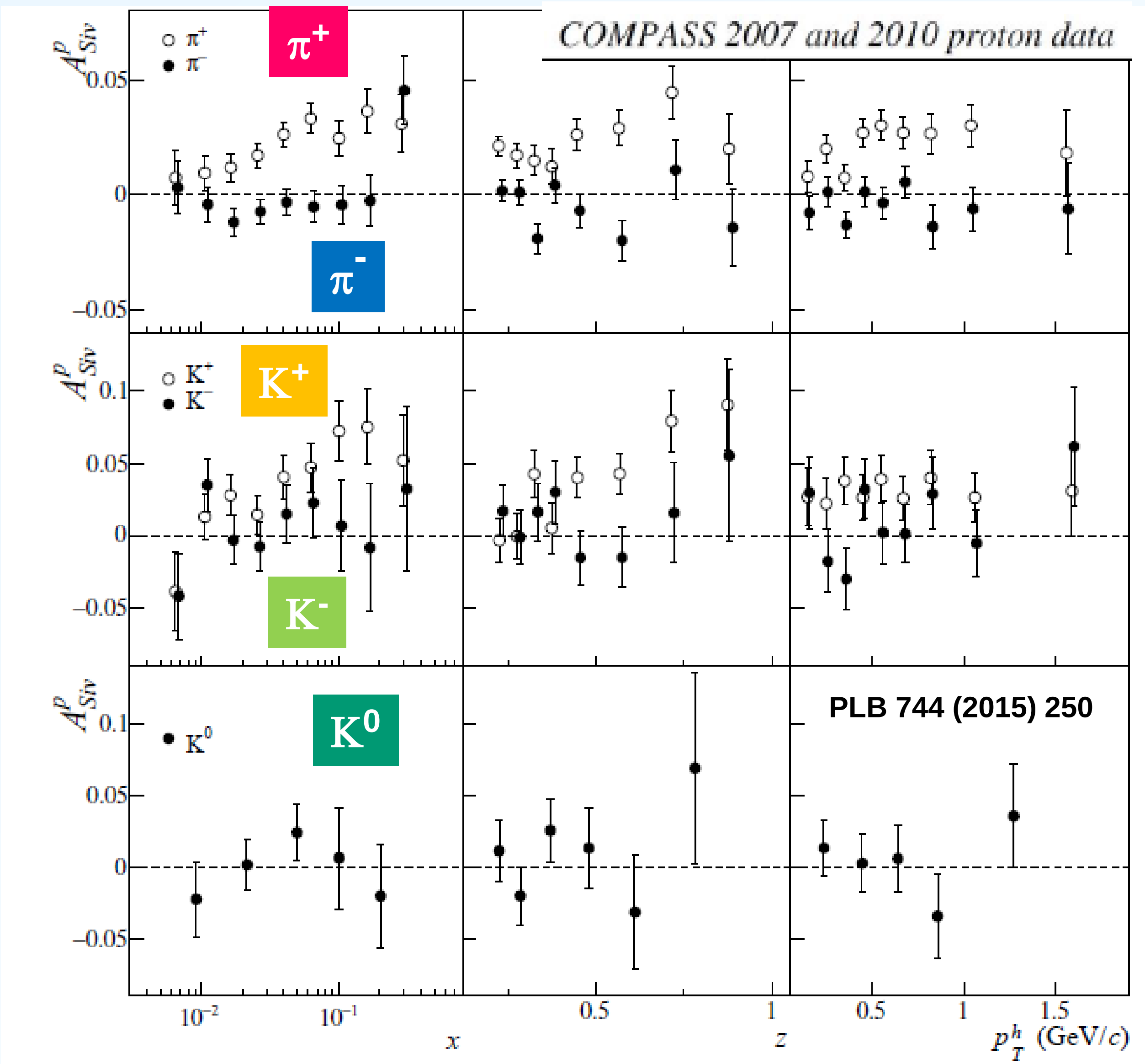






$\Delta\phi = \phi_1 - \phi_2$

Sivers Asymmetry on Proton

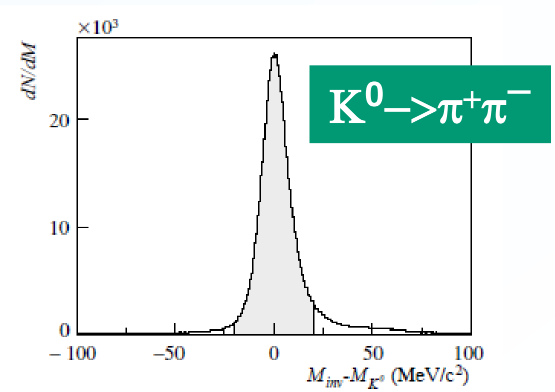


Event Selection

$Q^2 > 1$ (GeV/c)^2
W>5 GeV/c^2
$0.05 < y < 0.9$
$z > 0.1$
$|P^h_T| > 0.07$ GeV/c

Significantly large signal for π^+ and K^+

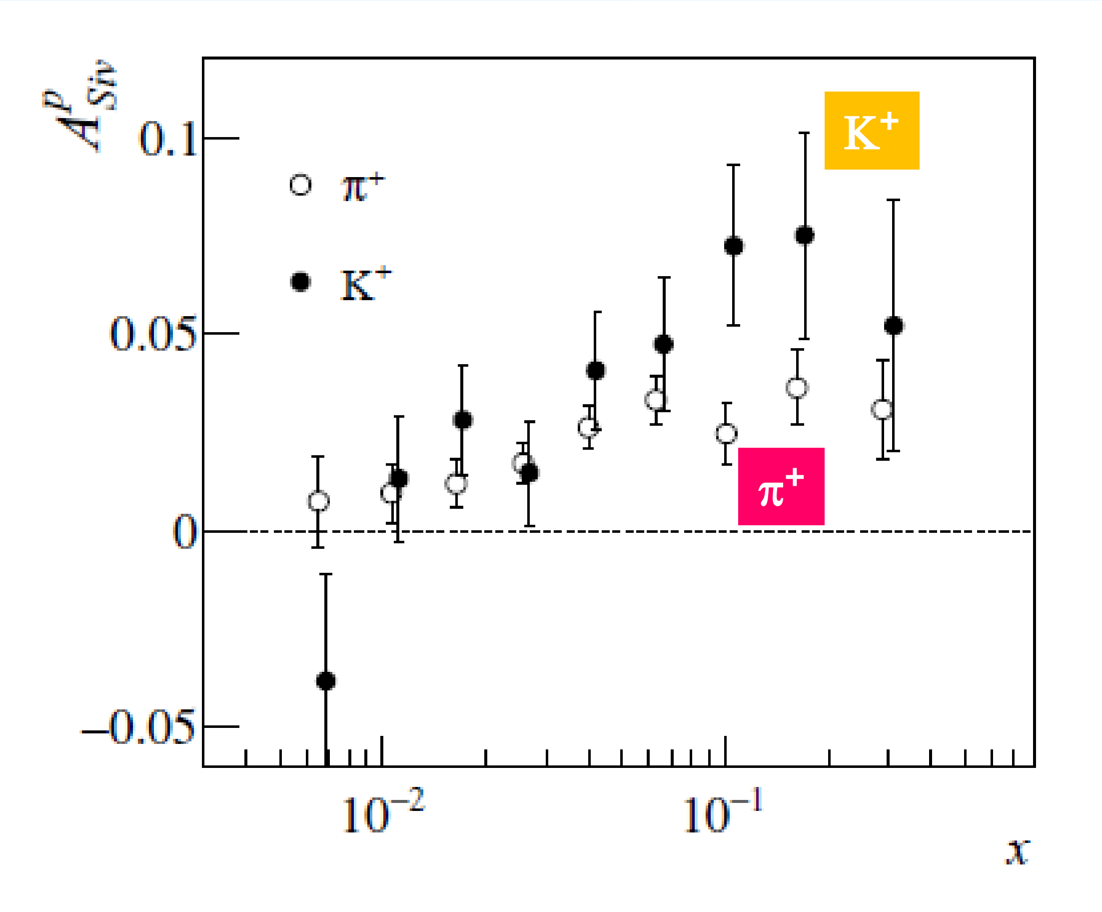
Compatible with zero for π^-, K^- and K^0



Deuteron target asymmetries compatible with zero (COMPASS PLB673 (2009) 127)

Sivers Asymmetry on Proton; π^+ & K^+

COMPASS 2007 and 2010 proton data

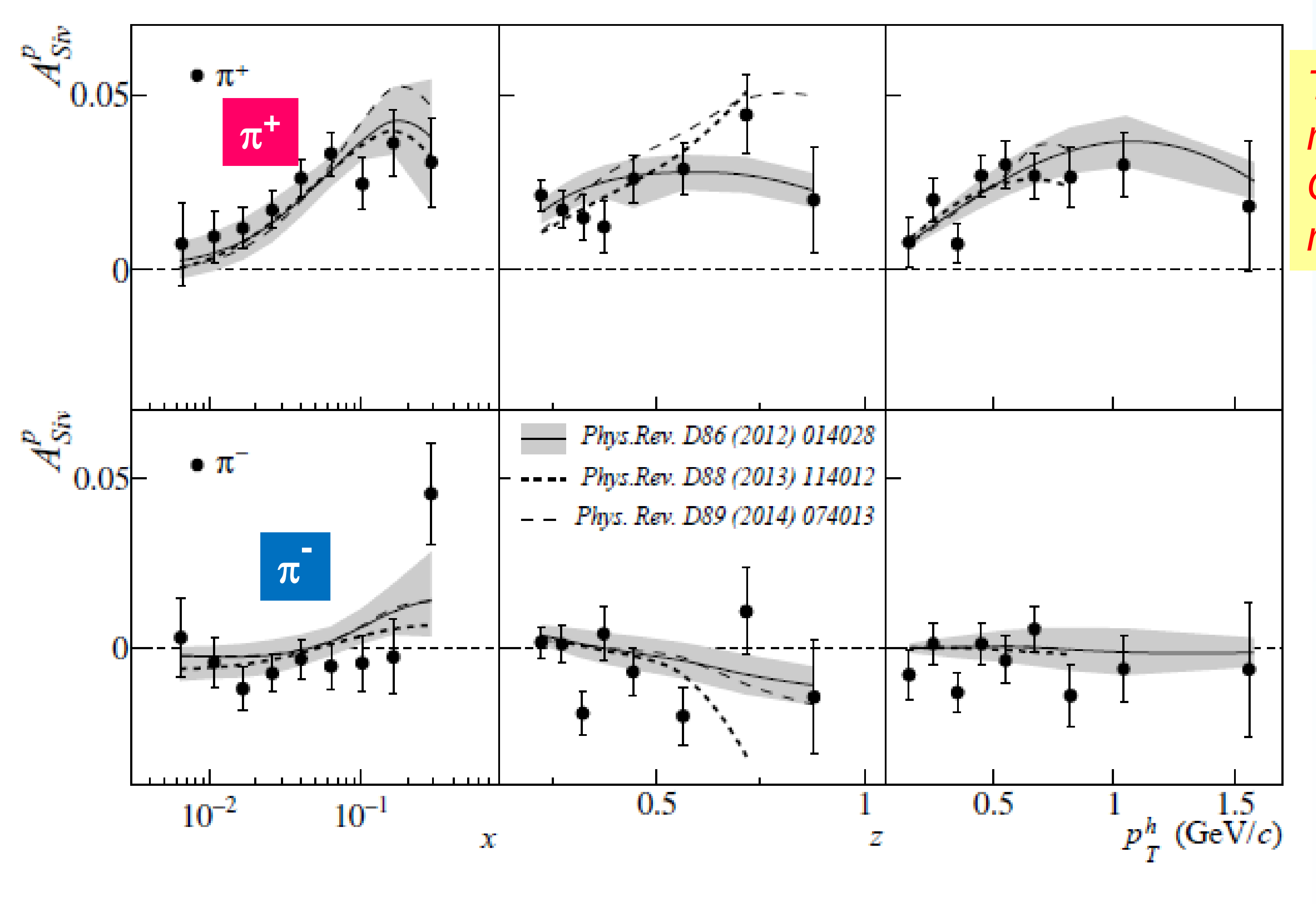


K^+ signal is even larger than that of π^+

➔ possible contribution from sea quarks

Sivers Asymmetry compared with Global Fits

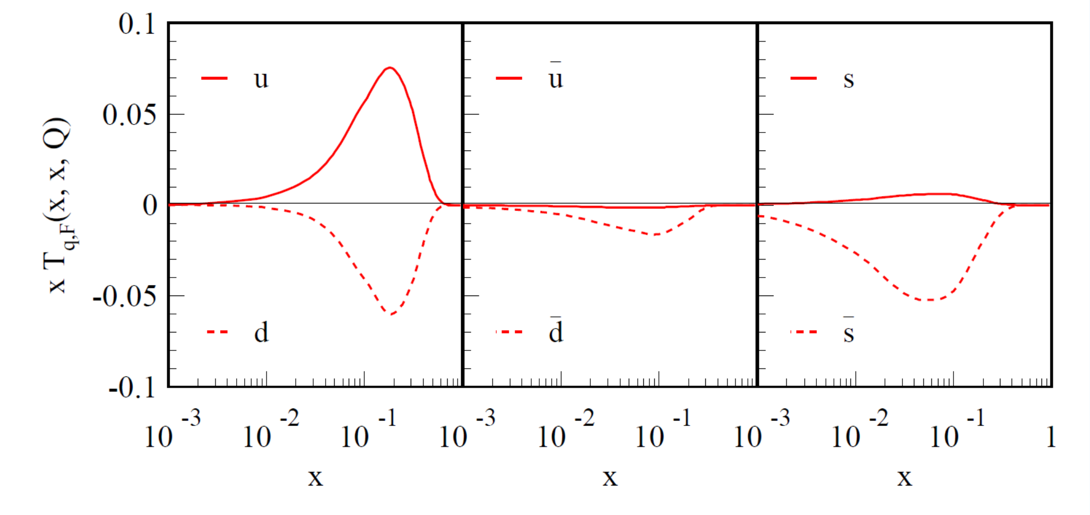
COMPASS 2007 and 2010 proton data



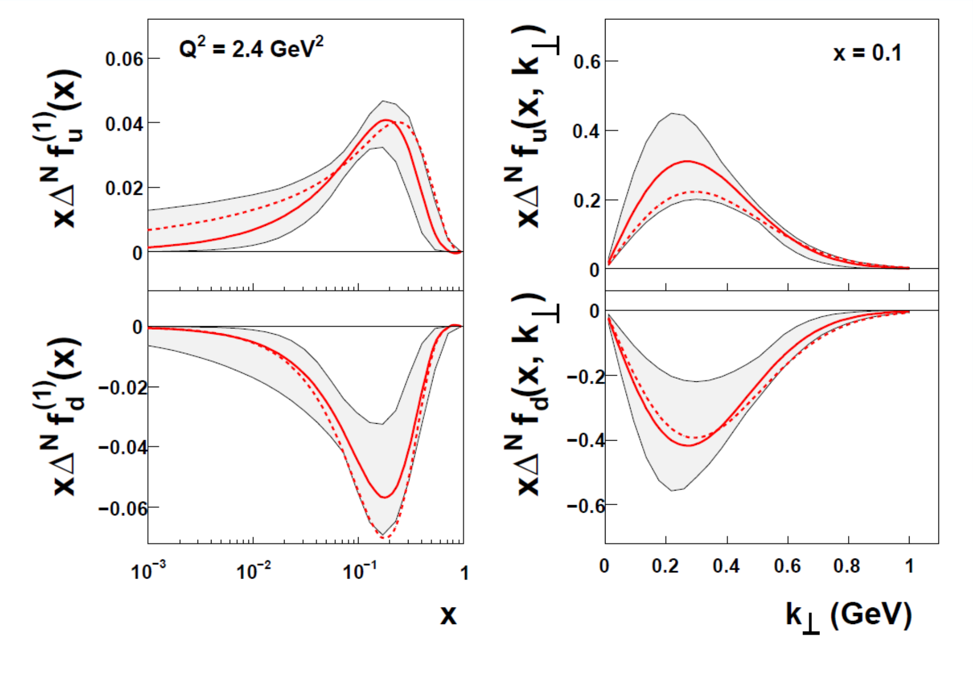
The fits reproduce the COMPASS data reasonabley well.

COMPASS results for unidentified hadrons on proton is included in the global fits

Extracted Sivers function by global fits



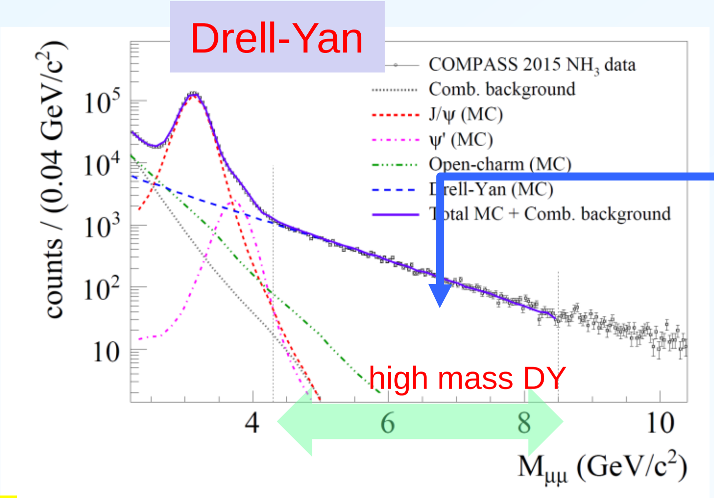
G.Miguel et al., Phys. Rev. D 89, 074013 (2014)

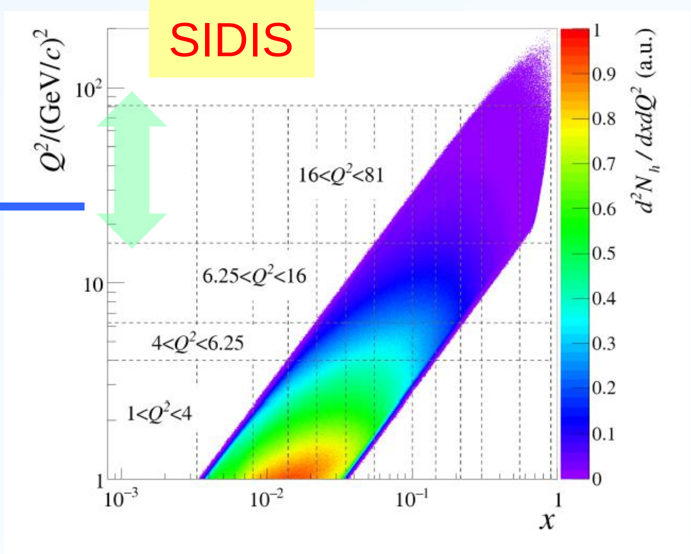


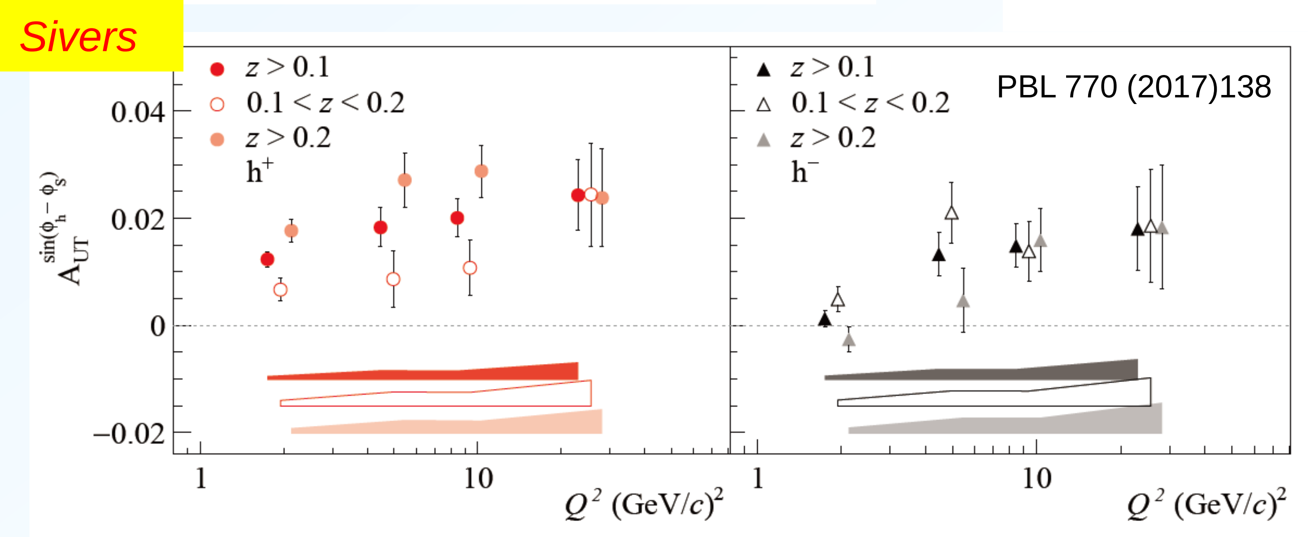
Anselmino et al., Eur.Phys.J.A39:89-100,2009

Q^2 dependence of Sivers Asymmetries

COMPASS has measured the TSA in different Q^2 ranges in SIDIS





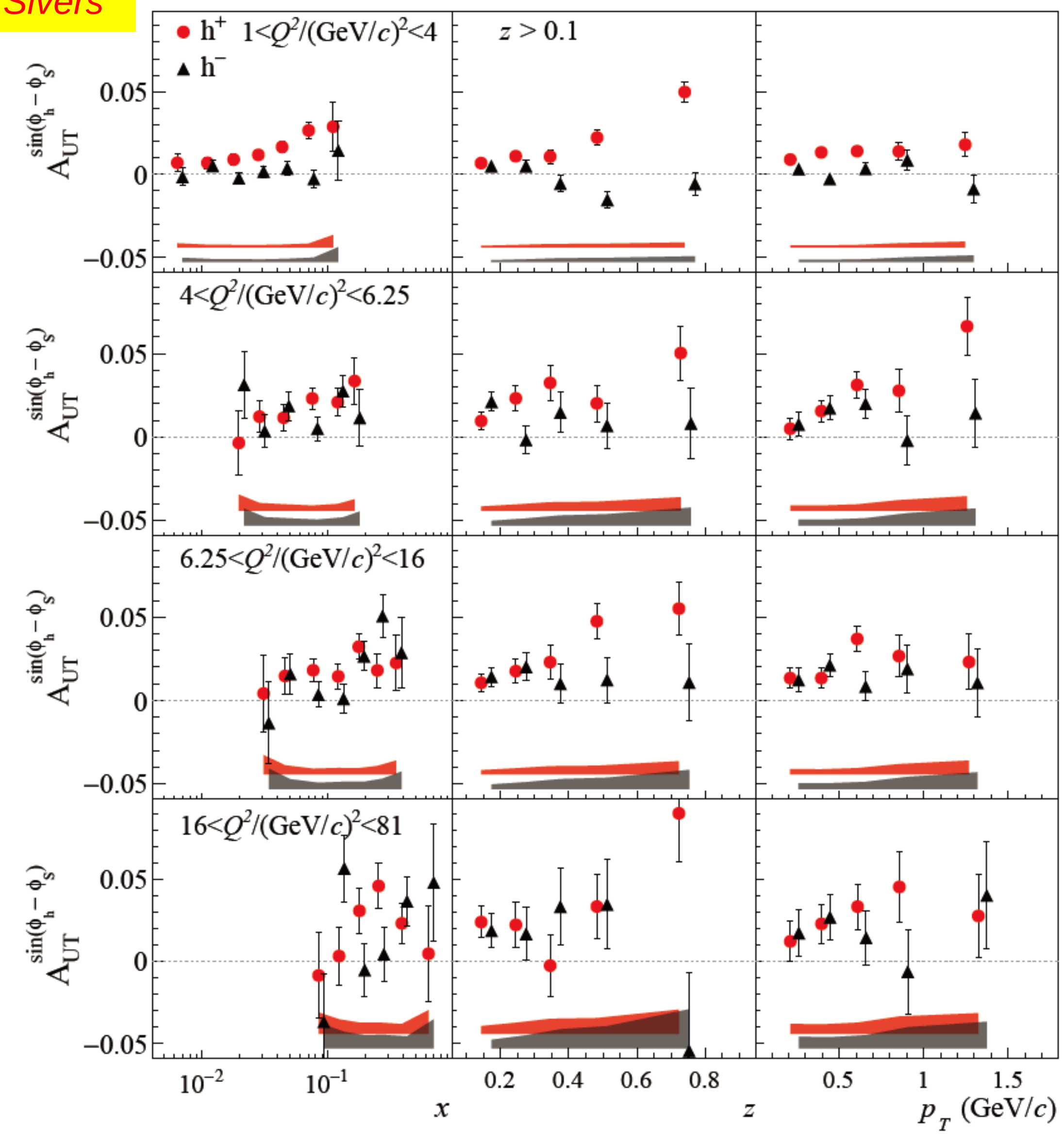


h^+ : The data are positive in all the Q^2-ranges.

h^- : The lowest Q^2 data are compatible with 0 and data become significantly positive in the other ranges.

Multi Dimensional Sivers Asymmetries

Sivers



PBL 770 (2017)138

h^+ : A>0 in whole Q^2, increasing as x, z & Pt.

h^- : less and not prominent

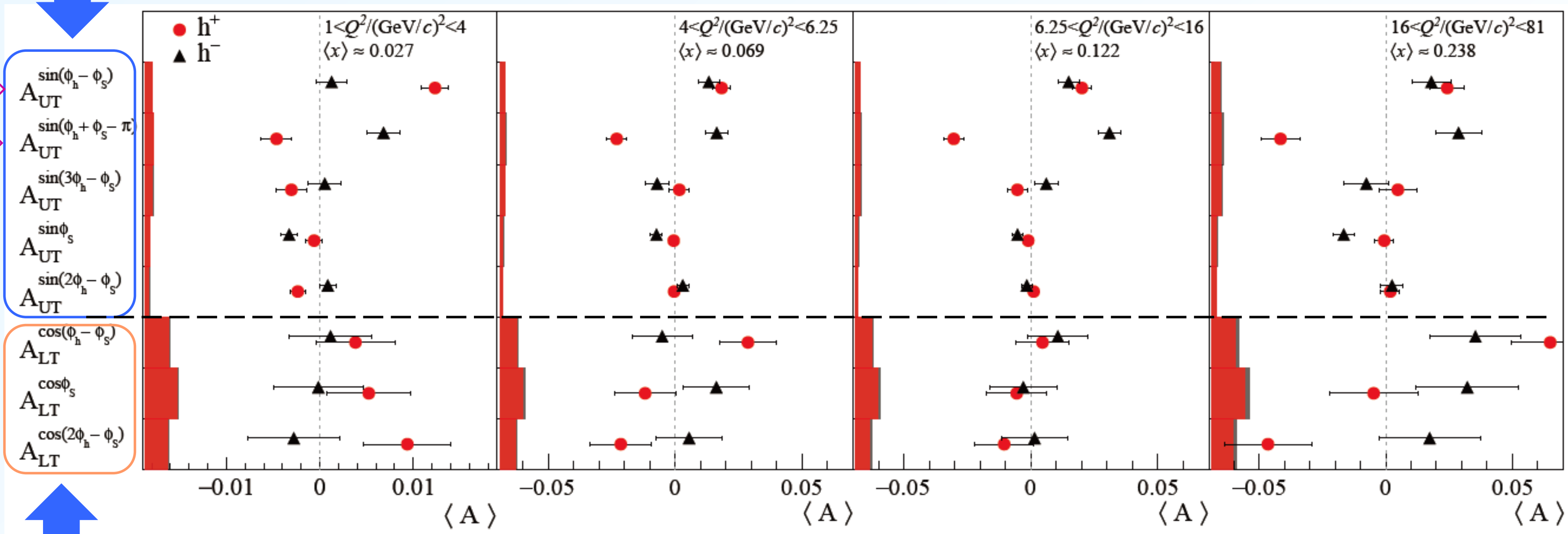
Other TSAs in different Q^2 ranges

transverse target spin Asymmetries

PLB 770 (2017) 138

Sivers

Collins



beam spin & target spin Asymmetries

P_T^h Weighted Sivers Asymmetry

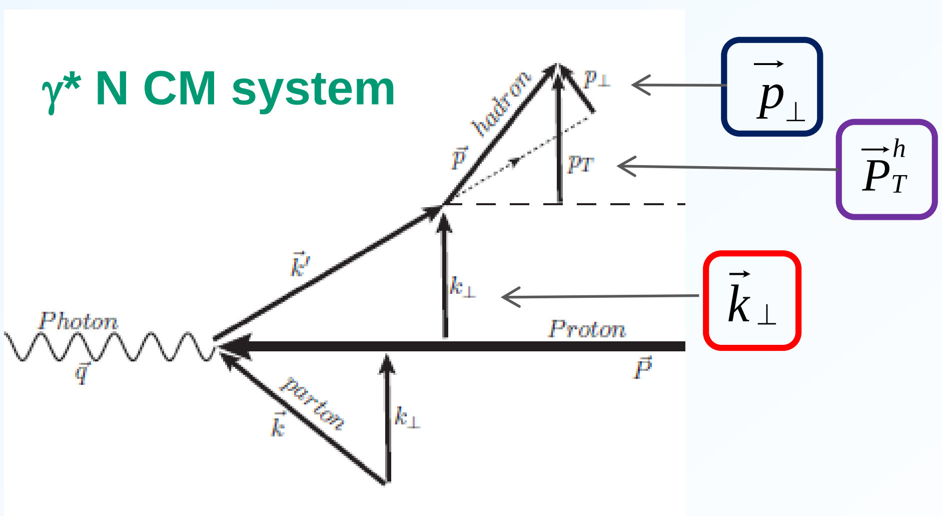
"standard" Sivers Asymmetry: $$N_h^{\pm}(\varphi_{Siv.}) = N_h^0\left[1 \pm S_T A_{Siv.} \sin\varphi_{Siv.}\right]$$

$$\varphi_{Siv.} \equiv \varphi_h - \varphi_S$$

LO QCD parton model
$$A_{Siv.} \propto \frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp} \otimes D_{1,q}^h}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x) \cdot D_{1,q}^h(z)}$$

$\otimes$: convolution over transverse momenta

$$f_{1T,q}^{\perp} \otimes D_{1,q}^h = \int d^2\vec{P}_T^h \int d^2\vec{k}_T \int d\vec{p}_{\perp} \delta^2(z\vec{k}_T + \vec{p}_{\perp} - \vec{P}_T^h) \frac{\vec{k}_T \cdot \vec{P}_T^h}{M P_T^h} f_{1T}^{\perp} D_1$$
$$\vec{P}_T^h \approx \vec{p}_{\perp} + z\vec{k}_T$$



usually solved
using Gaussian model for PDF and FFs

$$f_{1T}^{\perp}(x, k_T^2, Q^2) = f_{1T}^{\perp}(x, Q^2) \frac{1}{\pi \langle k_T^2 \rangle_S} e^{-k_T^2/\langle k_T^2 \rangle_S}$$

$$D_1(z, p_{\perp}^2, Q^2) = D_1(z, Q^2) \frac{1}{\pi \langle p_{\perp}^2 \rangle} e^{-p_{\perp}^2/\langle p_{\perp}^2 \rangle}$$

simple product

$$A_{Siv.} = a_G \frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp(1)} \cdot D_{1,q}^h}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x) \cdot D_{1,q}^h(z)} \qquad a_G = \frac{\sqrt{\pi} M}{\sqrt{\langle k_T^2 \rangle_S + \langle p_{\perp}^2 \rangle / z^2}}$$

Model dependent !

P_T^h Weighted Sivers Asymmetry

"P_T^h weighted " Sivers Asymmetry:

proposed by

A. Kotzinian and P. J. Mulders, PLB 406 (1997) 373
D. Boer and P. J. Mulders, PRD 57 (1998) 5780
J. C. Collins et al. PRD 73 (2006) 014021

If you weight with $w = P_T^h / Mz$

$$N_h^{\pm,W}(\varphi_{Siv.}) = N_h^{0,W}\left[1 \pm S_T A_{Siv.}^W \sin\varphi_{Siv.}\right]$$

convolution → simple product of Sivers(first moment) and FF

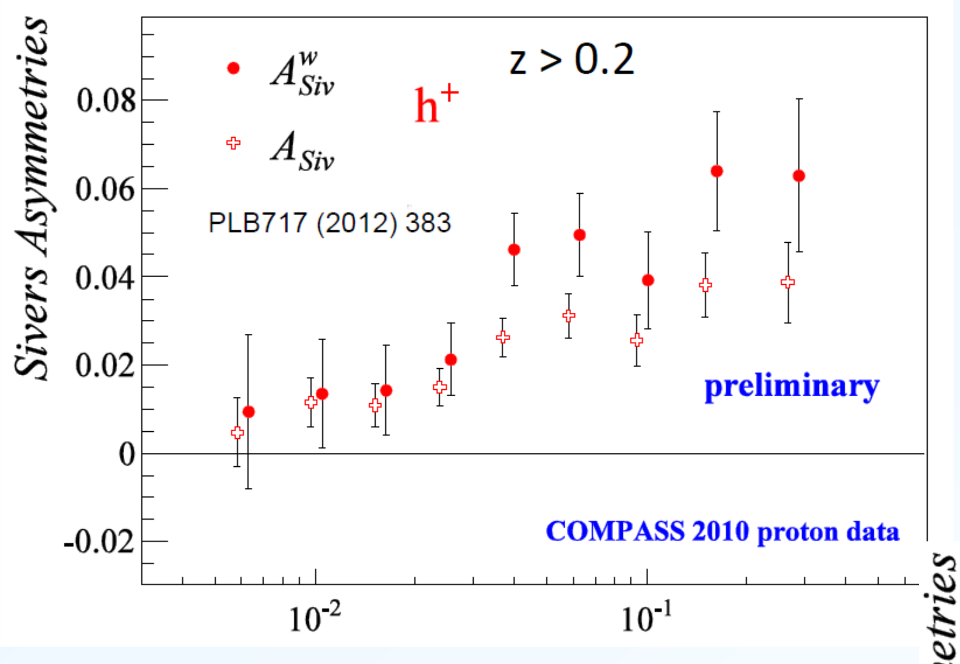
$$A_{Siv.}^w = 2A_{Siv.}^{(1)} = 2\frac{\sum_{quarks} e_q^2 f_{1T,q}^{\perp(1)}(x) \cdot D_{1,q}^h(z)}{\sum_{quarks} e_q^2 f_{1,q}(x) \cdot D_{1,q}^h(z)}$$

first moment of Sivers PDF

$$f_{1T}^{\perp(1)}(x) = \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2)$$

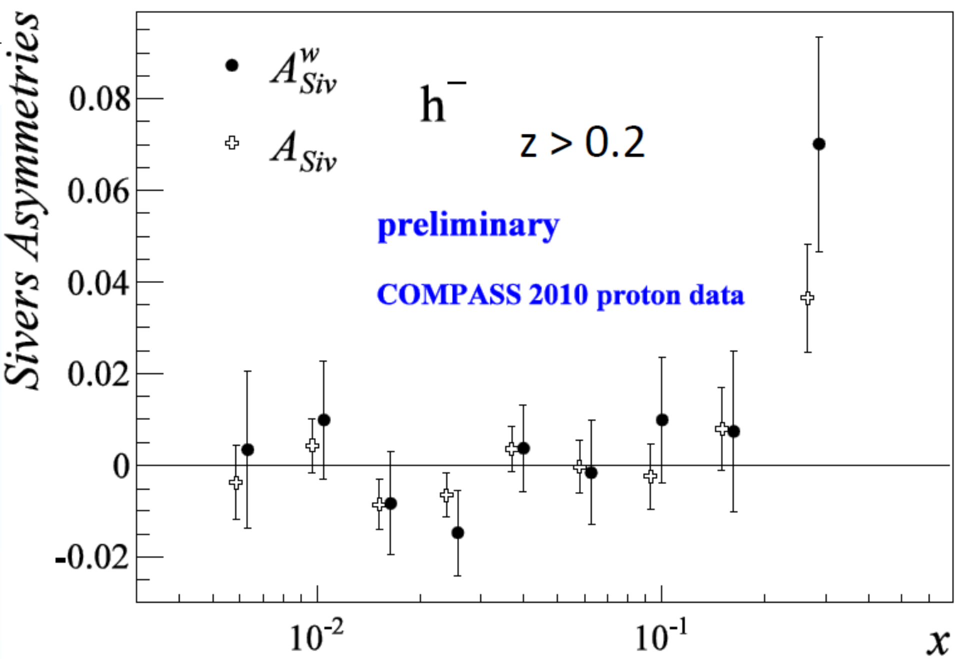
model independent way (no assumption on the shape of PDFs and FFs)

P_T^h Weighted Sivers Asymmetry



$$A^w_{Siv.} = 2A^{(1)}_{Siv.} = 2\frac{\sum_{quarks} e_q^2 f_{1T,q}^{\perp(1)}(x)\cdot D_{1,q}^h(z)}{\sum_{quarks} e_q^2 f_{1,q}(x)\cdot D_{1,q}^h(z)}$$

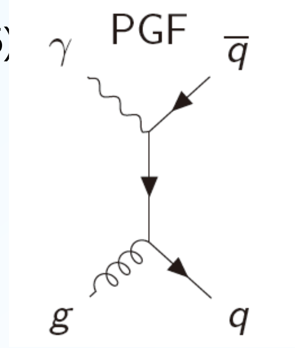
$$A_{Siv.} = a_G \frac{\sum_{quarks} e_q^2 \cdot f_{1T,q}^{\perp(1)} \cdot D_{1,q}^h}{\sum_{quarks} e_q^2 \cdot f_{1,q}(x)\cdot D_{1,q}^h(z)}$$



Gluon Sivers Asymmetry

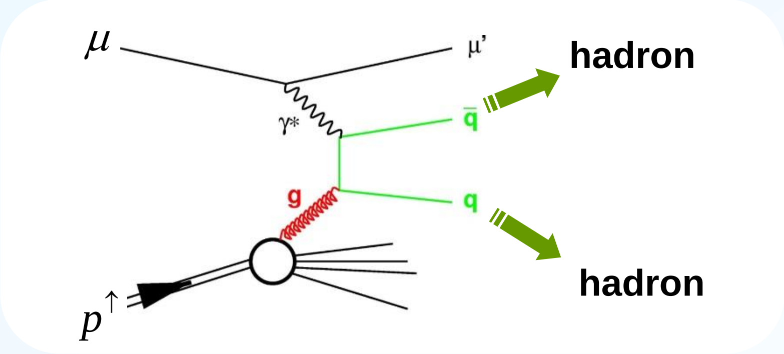
Sivers effect for also gluons? Gluon OAM ?

Recent review → D. Boer et al., Adv. High Energy Phys., 2015, 371396 (2015)



It can be studied with the asymmetry for photon-gluon-fusion

To enhance the PGF, 2-hadrons with high Pt are detected.



The azimuthal angle of the hadron pair, ϕ_{2h} , is strongly correlated with the gluon azimuthal angle ϕ_g

Data sample : 2010 proton target, 2003,4 deuteron target

Event selection :

$$Q^2 > 1\,(GeV/c)^2,\ W > 5GeV/c^2,\ 0.9 > \mathrm{y} > 0.1,$$

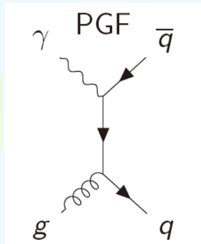
$$P_{T1} > 0.7GeV/c,\ P_{T2} > 0.4GeV/c,\ \mathrm{z}_1, \mathrm{z}_2 > 0.1,\ \mathrm{z}_1 + \mathrm{z}_2 < 0.9$$

Without charge constraint for the hadron pair

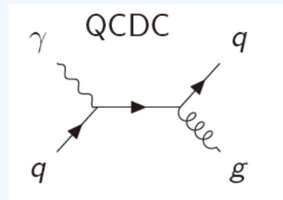
Gluon Sivers Asymmetry

However, one has to take account of the background processes;

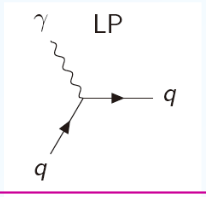
signal



+



BG



The asymmetry can be decomposed as:

MC

$$fP_T A_{2h}^{Siv.} \sin\phi_{Siv.} = fP_T \left(R_{PGF} A_{PGF}^{Siv.} + R_{QCDC} A_{QCDC}^{Siv.} + R_{LP} A_{LP}^{Siv.}\right) \sin\phi_{Siv.}$$

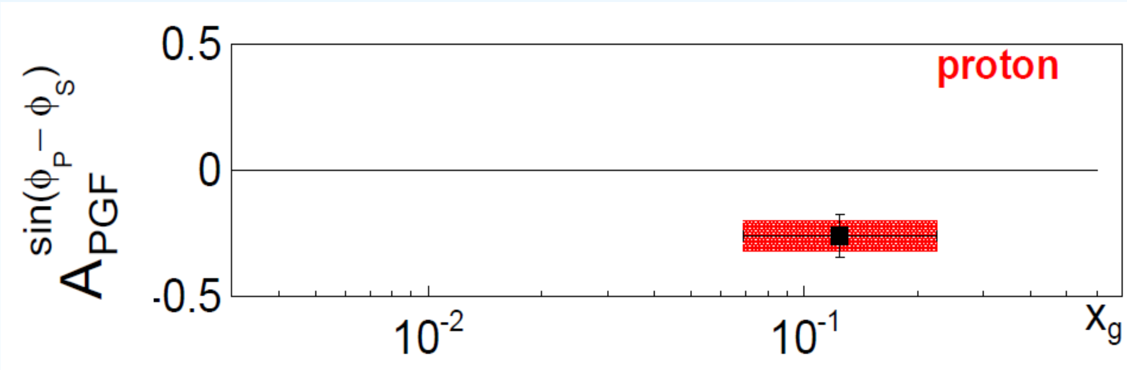
With a help of MC simulation, the process fractions(*Ri*) are evaluated.

The MC simulation :

- Generator LEPTO + GEANT + Reconstruction program
- PDF: MSTW2008
- Parton shower: on
- FLUKA for secondary interactions
- Special generator tuning for high-Pt events

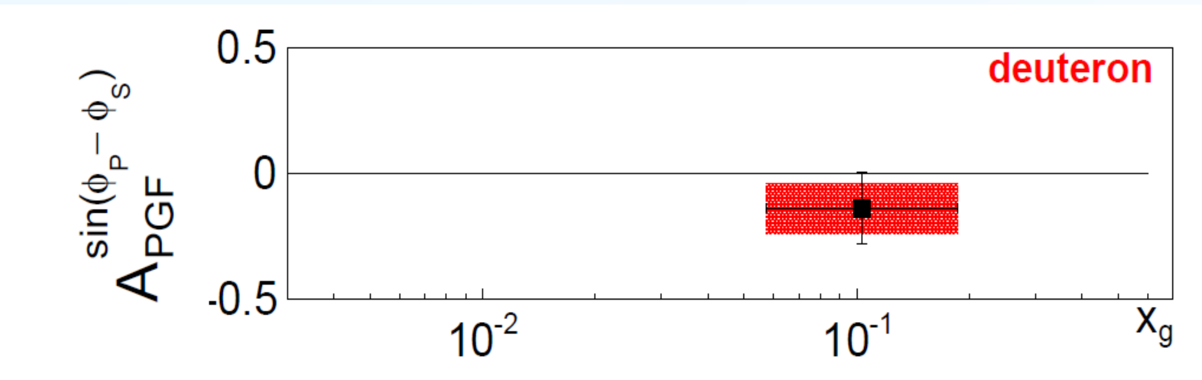
Fitting the data with Neural Network trained by the MC, each asymmetry is determined.

Gluon Sivers Asymmetry : Results



$$A_{PGF}^{Siv.p} = -0.26 \pm 0.09(stat.) \pm 0.06(sys.)$$

$$\langle x_g \rangle = 0.15$$



$$A_{PGF}^{Siv.d} = -0.14 \pm 0.15(stat.) \pm 0.10(sys.)$$

$$\langle x_g \rangle = 0.15$$

proton & deuteron combined

$$A_{PGF}^{Siv.} = -0.23 \pm 0.08(stat.) \pm 0.05(sys.)$$

Two standard deviation from zero → Gluon Sivers effect ?

Conclusions

- SIDIS gave and is giving fundamental contribution to the study of the transverse spin structure of the nucleon.

- COMPASS has provided TSA data for proton and deuteron.

- The Collins asymmetries and Sivers Asymmetries were found to be different from zero for proton although they are consistent with zero for deuteron.

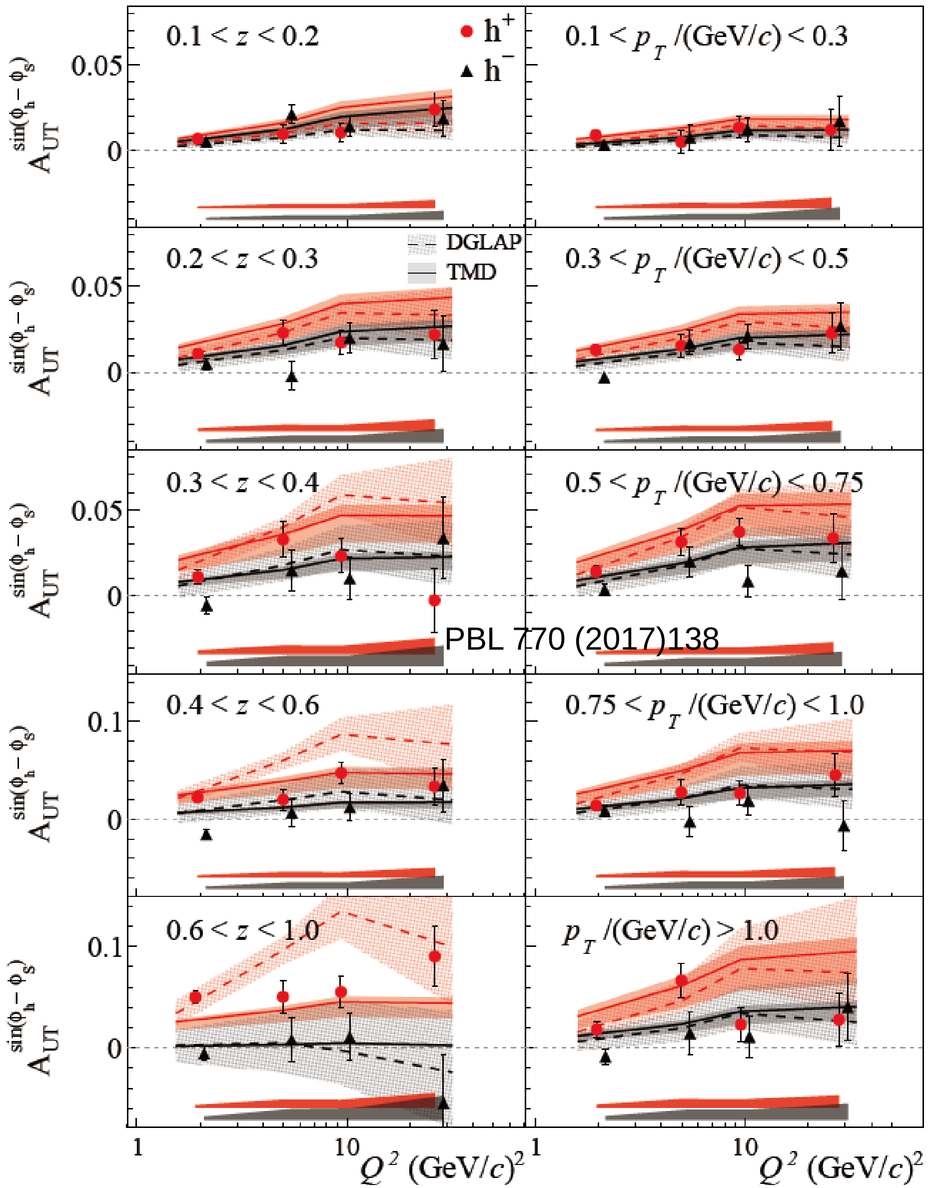
- There is an interplay between the single hadron Collins asymmetries and di-hadron asymmetries suggesting common origin in production mechanism.

- The Sivers asymmetries were obtained in different Q^2 ranges. One of the ranges corresponds to the di-muon mass range where the Drell-Yan measurement of COMPASS was performed.

- The Sivers asymmetry for PGF was found to be negative with two standard deviation from zero suggesting the possible gluon Sivers effect.

Spares

Comparison with calculations



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In good agreement with the calculations in low-z & low Pt ranges.

Calculations are based on fits of one-dimensional data (PRD72(2005)094007 [Erratum:PRD 72 099903(2005)], EPJ A39 (2009)89)

However, in high-z & high-Pt ranges, clear discrepancies are seen.

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Expected property for the Sivers PDF

Sivers function is process dependent.

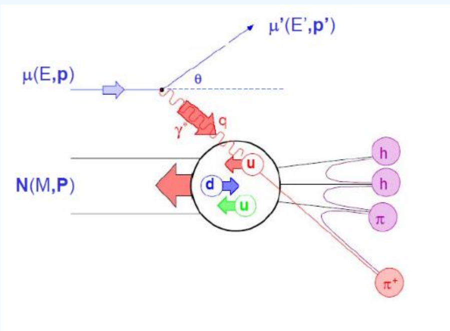
J. Collins, Phys. Lett. B **536**, 43 (2002).

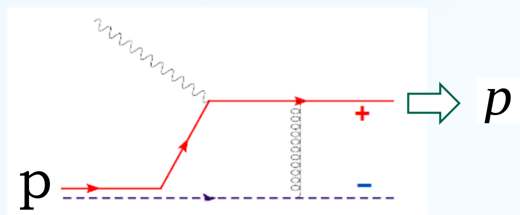
$$f_{1T}^{\perp q}(x,k_\perp^2)_{SIDIS} = -f_{1T}^{\perp q}(x,k_\perp^2)_{DY}$$

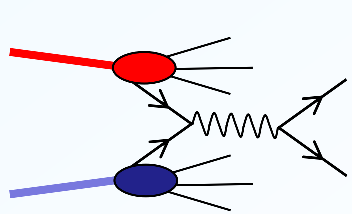
sign change !

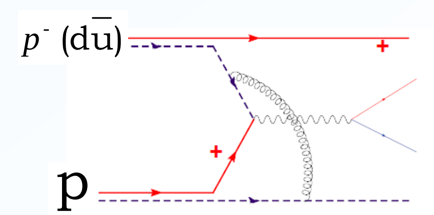
SIDIS : with final state interaction (FSI)

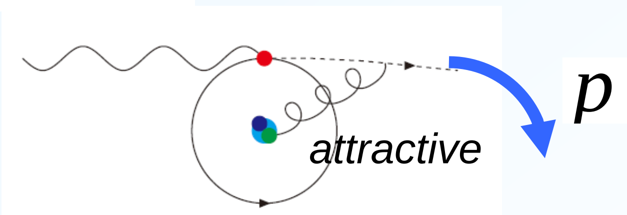
Drell-Yan: with initial state interaction (ISI)

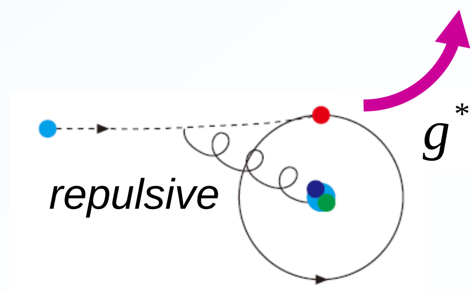










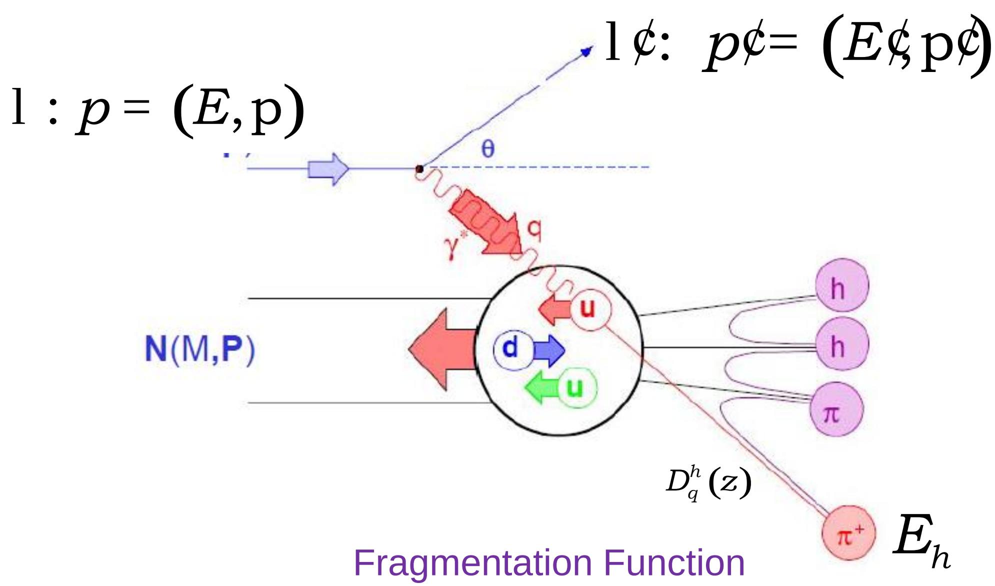


ejected (red) quark is attracted by the anti-red spectators

before annihilating with the red active quark, the approaching anti-quark(anti-red) is repelled by the anti-red spectators

This is to be checked in the common kinematical region in COMPASS experimentally.

SIDIS Kinematics



Fragmentation Function

$$Q^2 = -(p - p')^2$$

$$\nu = E - E'$$

$$x \overset{Lab.}{=} Q^2 / 2M\nu$$

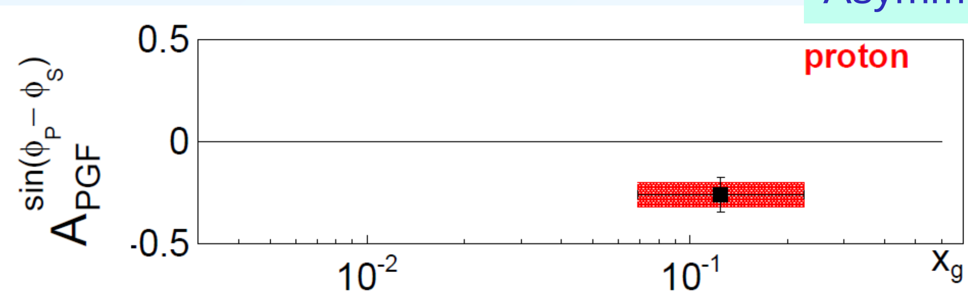
$$y = \nu / E$$

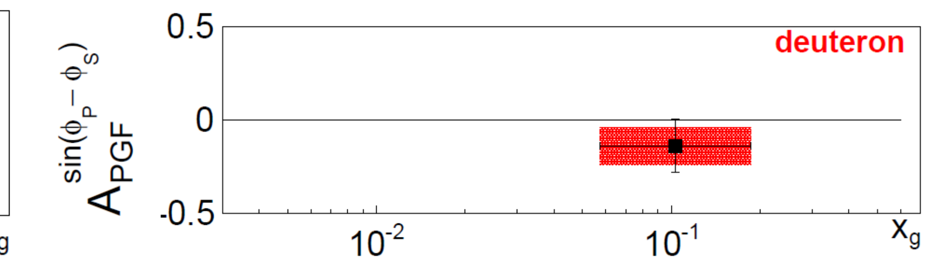
$$z = E_h / \nu$$

Energy fraction of the hadron

Gluon Sivers Asymmetry : Results

Asymmetries for PGF





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$$\langle x_g \rangle = 0.15$$

$$A_{PGF}^{Siv.d} = -0.14 \pm 0.15(stast.) \pm 0.10(sys.)$$

$$\langle x_g \rangle = 0.15$$

$$A_{PGF}^{Siv.} = -0.23 \pm 0.08(stast.) \pm 0.05(sys.)$$

Asymmetries for BG