POETIC VI

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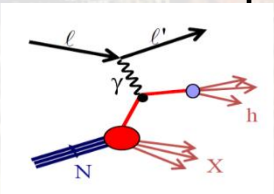
Measurements of transverse spin and transverse momentum effects at COMPASS

6TH INTERNATIONAL CONFERENCE ON PHYSICS OPPORTUNITIES AT AN EIC
POETIC VI, 7TH – 11TH OF SEPTEMBER 2015, PALAISEAU, PARIS, FRANCE

Accessing TMD PDFs and FFs

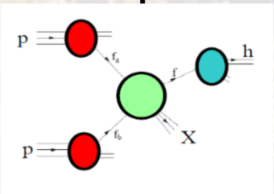
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab
future: ***eN colliders?***

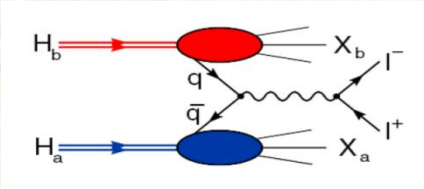
$$\sigma^{\ell p\to\ell' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z)$$

- hard polarised pp scattering



RHIC

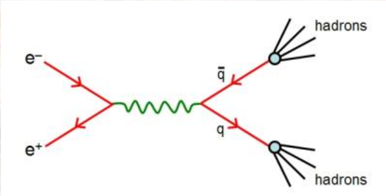
- polarised Drell-Yan



COMPASS
RHIC
FNAL
future: ***FAIR, JPark, NICA***

$$\sigma^{hp\to\mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$$

- $e^+e^- \to h_1 h_2$



BaBar
Belle
Bes III

$$\sigma^{e^+e^-\to h_1h_2} \sim \hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_q^{h_2}(z_2)$$

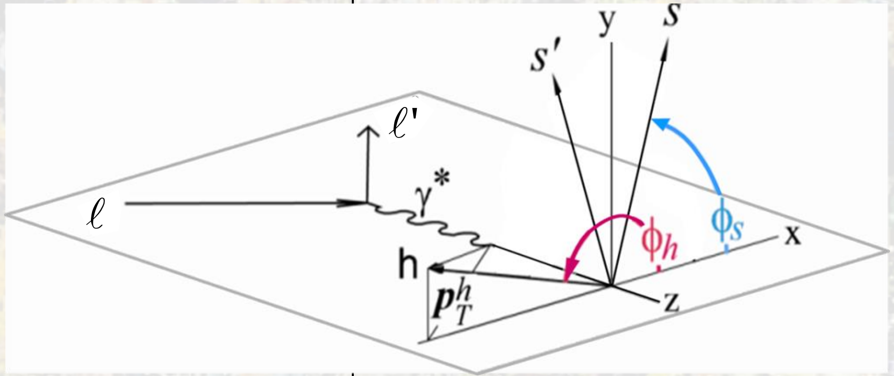
SIDIS 1h x-section

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

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

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

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



The polarized Drell-Yan process in π⁻ p

$$
\frac{d\sigma}{d^4q\,d\Omega} = \left[\frac{\alpha^2}{Fq^2} \left(F^1_{UU} + F^1_{UU} \right) \left(1 + A^1_{UU} \cos^2\theta \right) \right] \times
$$

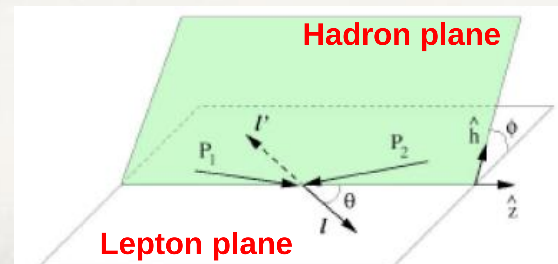
$$
\left\{ \begin{array}{l}
1 + \cos\varphi \times D_{[\sin 2\theta]} A^{\cos\varphi}_{UU} + \cos(2\varphi) \times D_{[\sin^2\theta]} A^{\cos(2\varphi_h)}_{UU} + \\
S_L \left[\sin\varphi \times D_{[\sin 2\theta]} A^{\sin\varphi}_{UL} + \sin(2\varphi) \times D_{[\sin^2\theta]} A^{\sin(2\varphi)}_{UL} \right] + \\
\mathbf{S}_T \left[\begin{array}{l}
\sin\varphi_S \times \left(D_{[1]} A^{\sin\varphi_S}_{UT} + D_{[\cos^2\theta]} \tilde{A}^{\sin\varphi_S}_{UT} \right) + \\
\sin(\varphi - \varphi_S) \times \left(D_{[\sin 2\theta]} A^{\sin(\varphi-\varphi_S)}_{UT} \right) + \\
\sin(\varphi + \varphi_S) \times \left(D_{[\sin 2\theta]} A^{\sin(\varphi+\varphi_S)}_{UT} \right) + \\
\sin(2\varphi - \varphi_S) \times \left(D_{[\sin^2\theta]} A^{\sin(2\varphi-\varphi_S)}_{UT} \right) + \\
\sin(2\varphi + \varphi_S) \times \left(D_{[\sin^2\theta]} A^{\sin(2\varphi_h+\varphi_S)}_{UU} \right)
\end{array} \right] +
\end{array} \right\}
$$

Collins-Soper frame (of virtual photon)

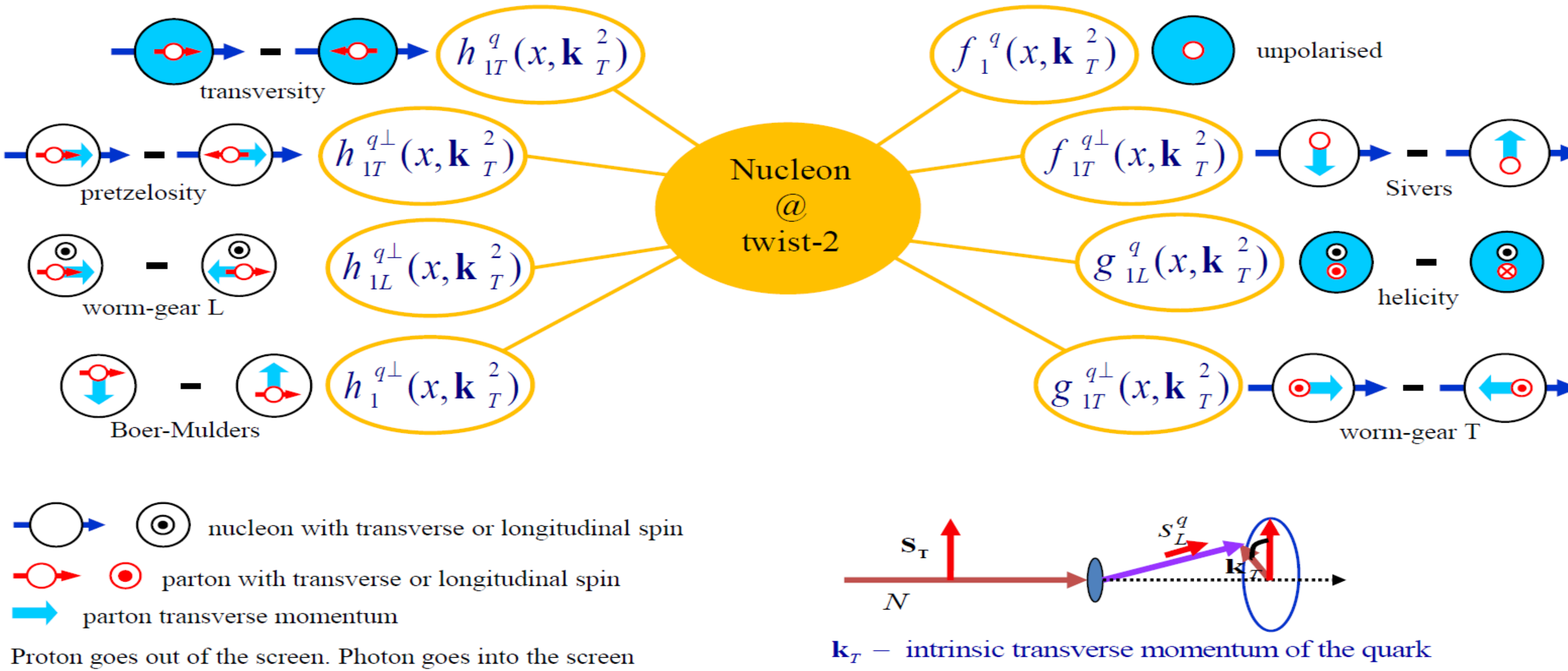
θ, φ lepton plane wrt hadron plane

target rest frame

φ_S target transverse spin vector /virtual photon



TMD Distribution Functions



LO content

SIDIS

$$A_{UU}^{\cos\phi_h} \propto \frac{1}{Q}\left(f_1^{q} \otimes D_{1q}^{h} - h_1^{\perp q} \otimes H_{1q}^{\perp h} + \cdots \right)$$

$$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + \frac{1}{Q}\left(f_1^{q} \otimes D_{1q}^{h} + \cdots \right)$$

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

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

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

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

$$A_{UT}^{\sin\phi_S} \propto \frac{1}{Q}\left(h_1^{q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \cdots \right)$$

$$A_{UT}^{\sin(2\phi_h-\phi_S)} \propto \frac{1}{Q}\left(h_1^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h} + \cdots \right)$$

$$A_{LT}^{\cos\phi_S} \propto \frac{1}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \cdots \right)$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto \frac{1}{Q}\left(g_{1T}^{q} \otimes D_{1q}^{h} + \cdots \right)$$

DY

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

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

$$A_{T}^{\sin\varphi_{CS}} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

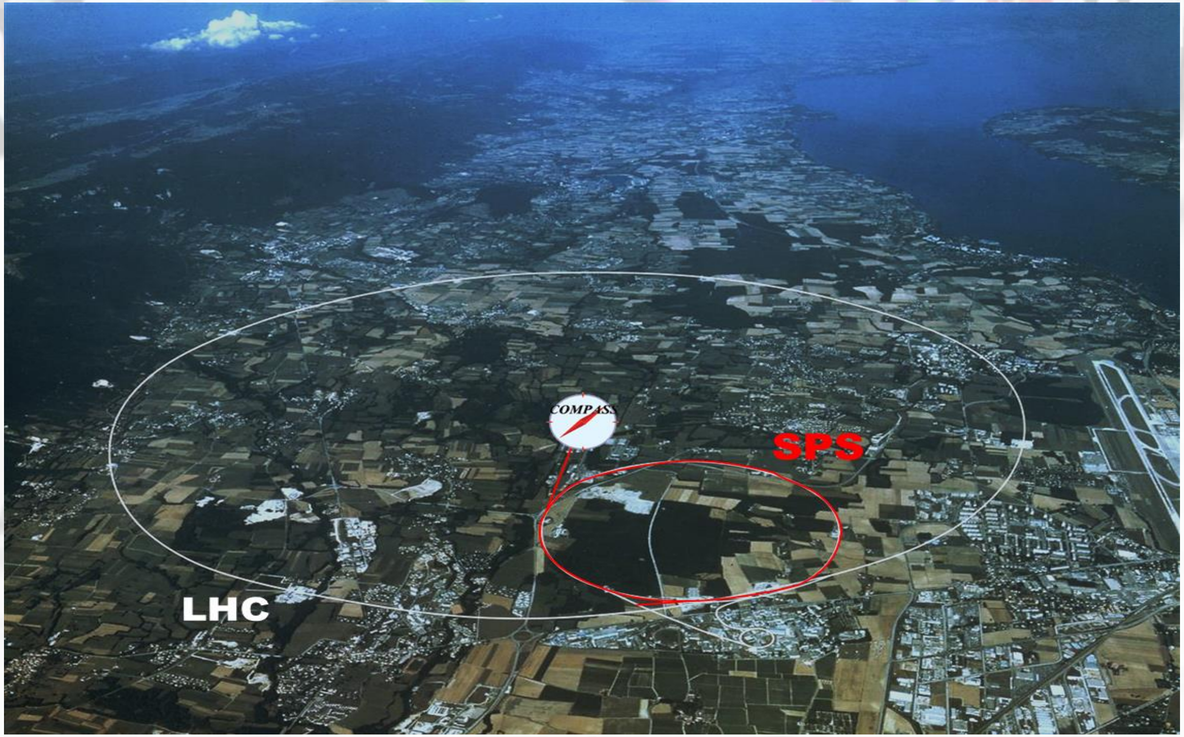
$$A_{T}^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$$

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

Collaboration
~ 250 physicists
from 24 Institutions
of 13 Countries

- **fixed target**
- **experiment**
- **at the CERN SPS**

data taking: since 2002



COMPASS Collaboration

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

CERN

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

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

Yamagata

USA (UIUC)

Praha (CU/CTU)

Liberec (TU)

Brno (ISI-ASCR)

Lisboa/Aveiro

Saclay

Calcutta (Matrivian)

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

Tel Aviv

Taipei (AS)

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

two stages spectrometer

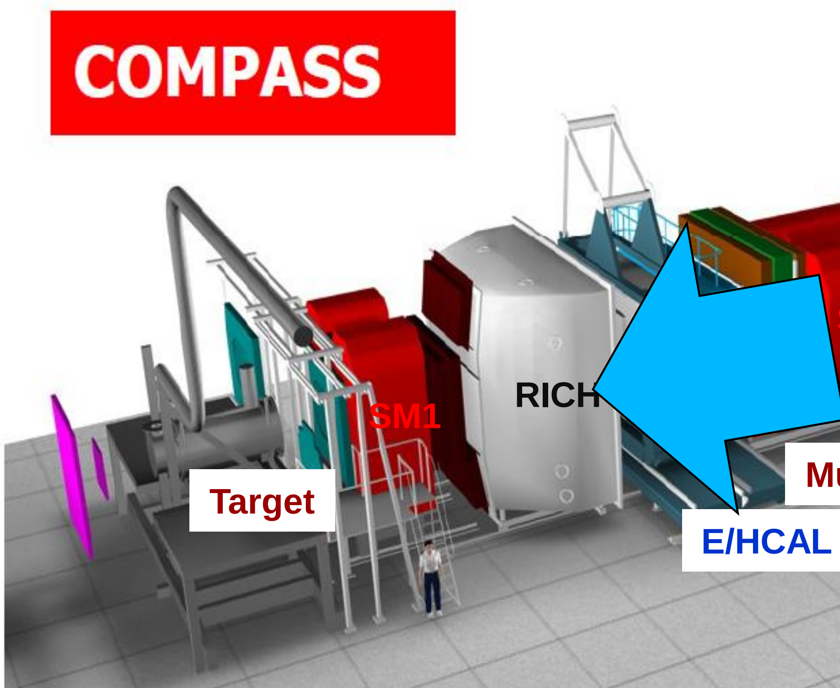
Large Angle Spectrometer (SM1)

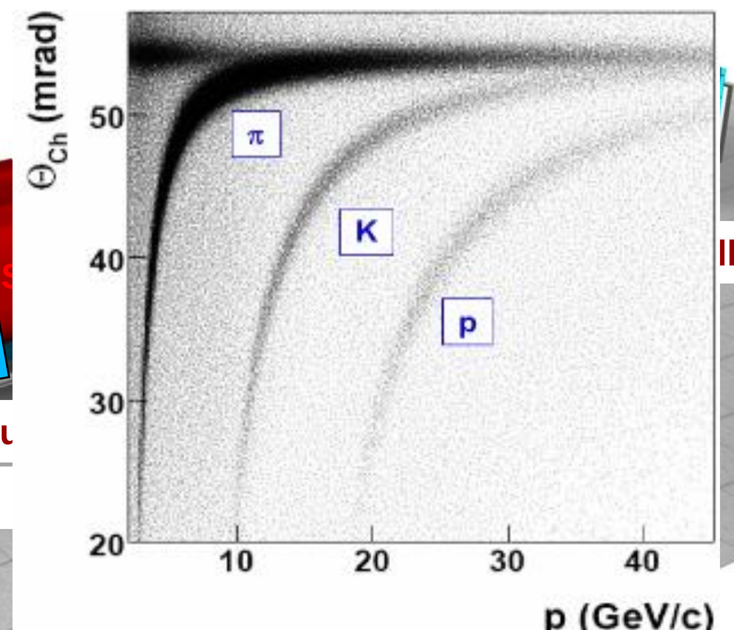
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

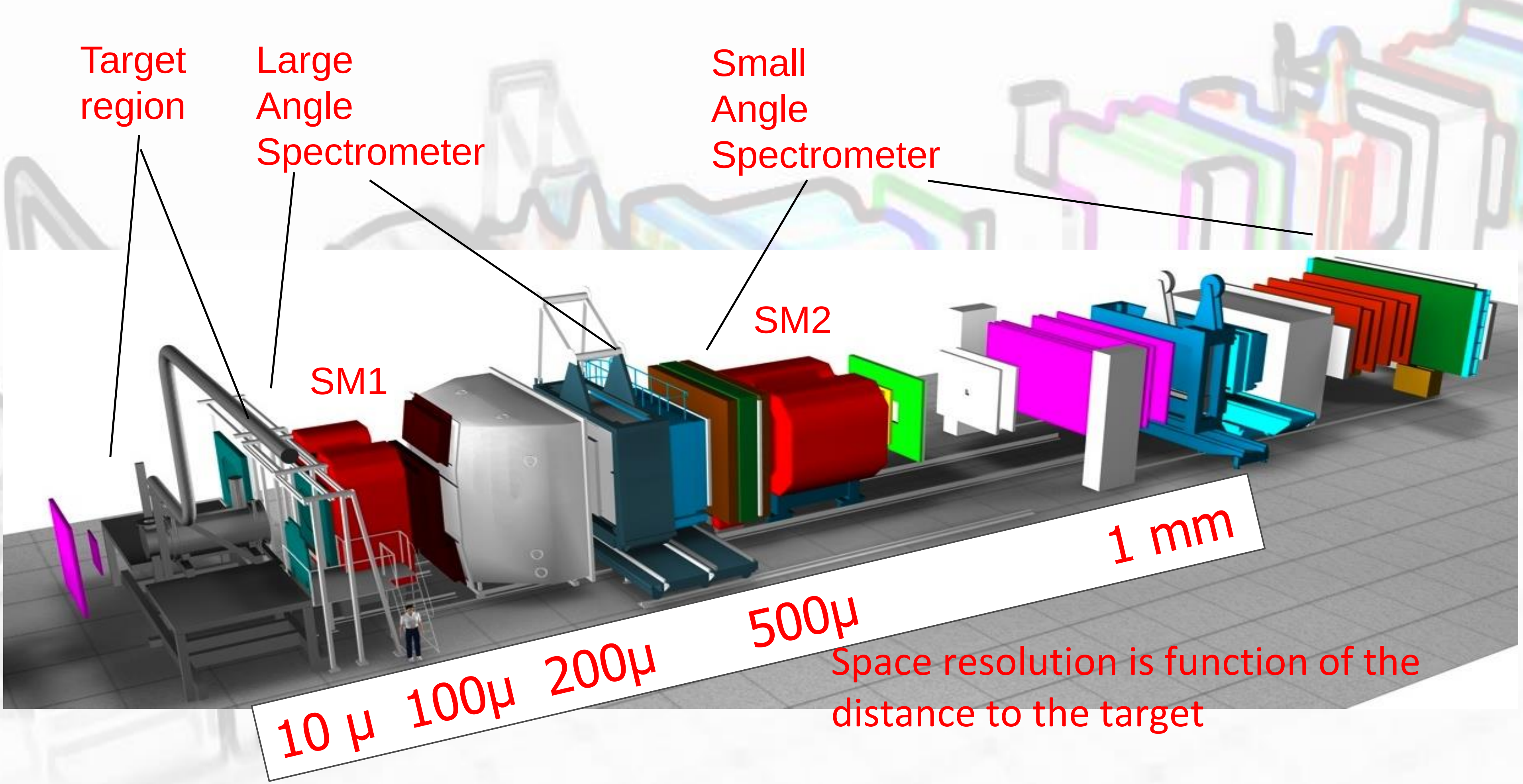
threshold: π ~2 GeV/c

K ~ 10 GeV/c





Space resolution

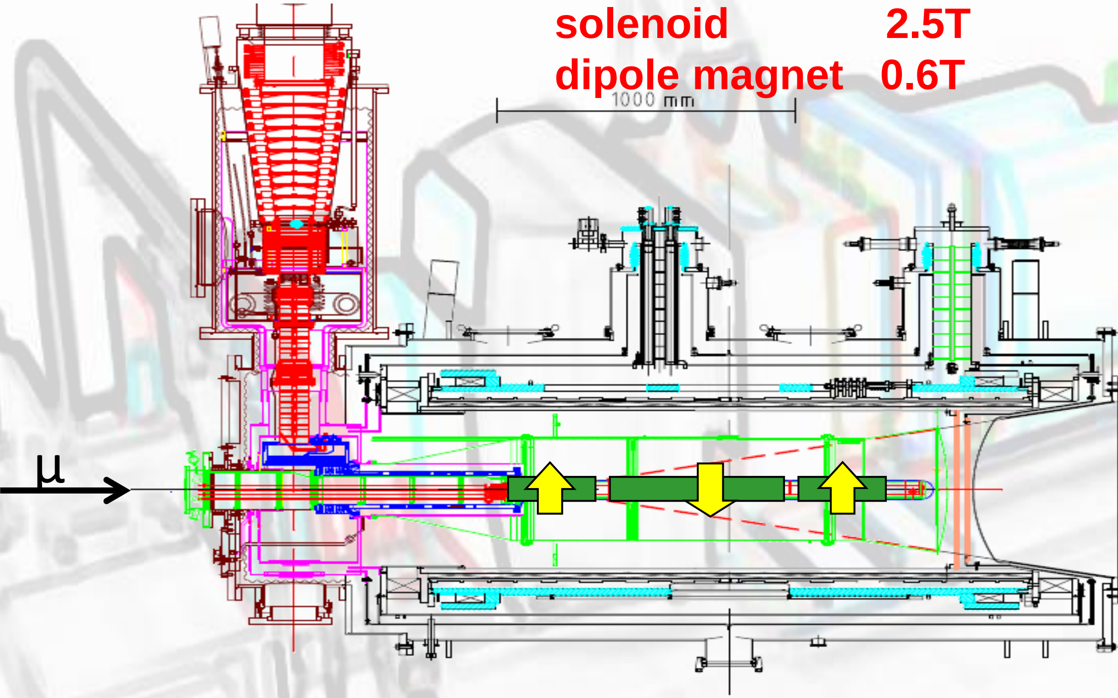


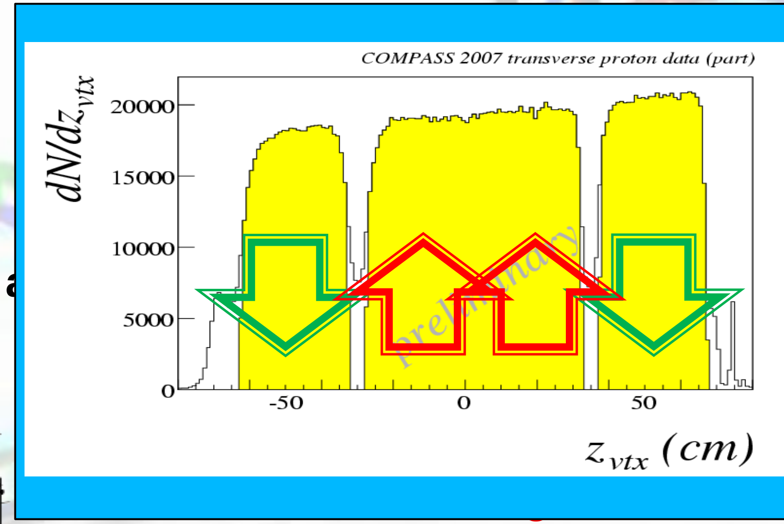
Space resolution is function of the distance to the target

the polarized target system (>2005)

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

solenoid 2.5T
dipole magnet 0.6T





opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

no evidence for relevant nuclear effects *(160 GeV)*

Few facts:

- Transverse Spin and Momentum effects were put under scrutiny by the COMPASS Proposal in 1996, starting with transversity via the Collins mechanism

We propose to measure in semi-inclusive DIS on transversely polarised proton and deuterium targets the transverse spin distribution functions $\Delta_T q(x) = q_{\uparrow}(x) - q_{\downarrow}(x)$, where $\uparrow$ ($\downarrow$) indicates a quark polarisation parallel (antiparallel) to the transverse polarisation of the nucleon. Hadron identification allows to tag the quark flavour.

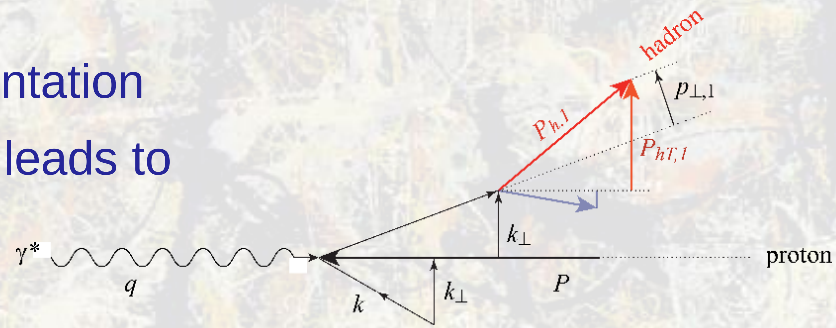
As suggested by J. Collins [71], the fragmentation function for transversely polarised quarks should exhibit a specific azimuthal dependence. The transversely polarised quark fragmentation function $\mathcal{D}_q^h$ should be built up from two pieces, a spin-independent part D_q^h, and a spin-dependent part ΔD_q^h:

$$\mathcal{D}_q^h(z, \vec{p}_q^{\,h}) = D_q^h(z, p_q^h) + \Delta D_q^h(z, p_q^h) \cdot \sin(\phi_h - \phi_{S'}), \qquad (3.23)$$

- The measurement of the Sivers PDF was added to the program soon after … the other TMD with the developments over the years
- Measurements started in 2002 by HERMES (p) and COMPASS (d)
- This field has grown considerably in the last years and comes one of high priority measurements for the JLab12 program

Unpolarized SIDIS

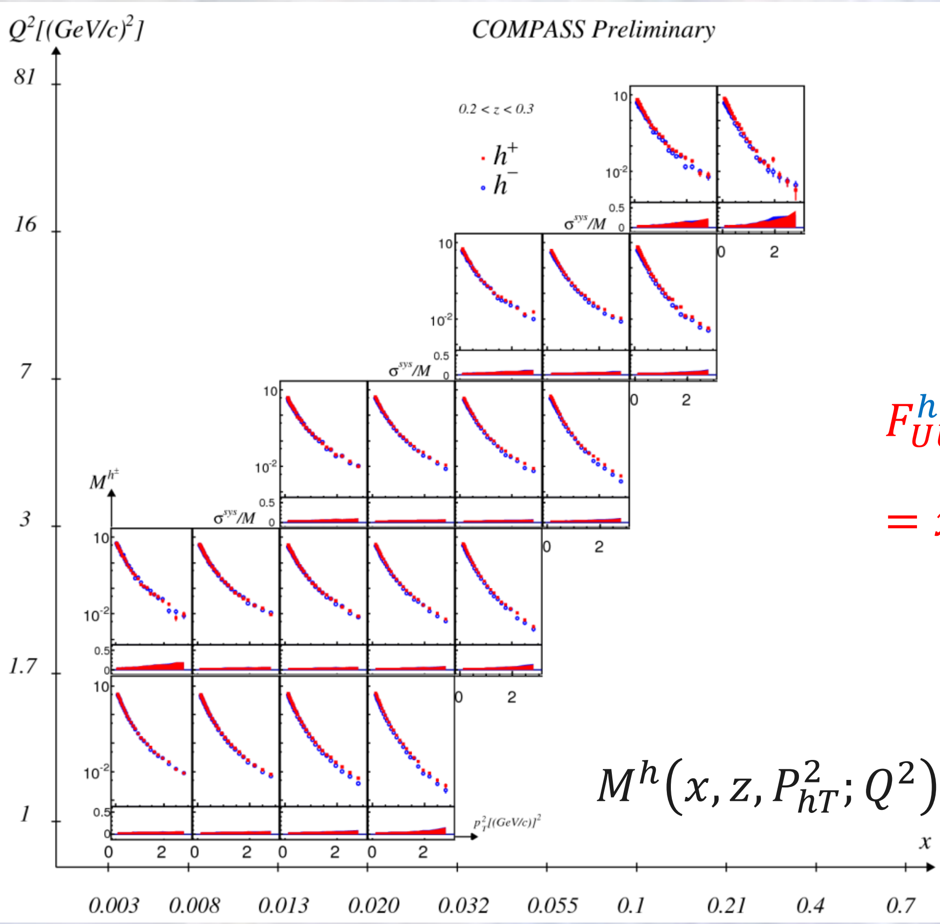
- The cross-section dependence from p_T^h results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle p_{T,h}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$

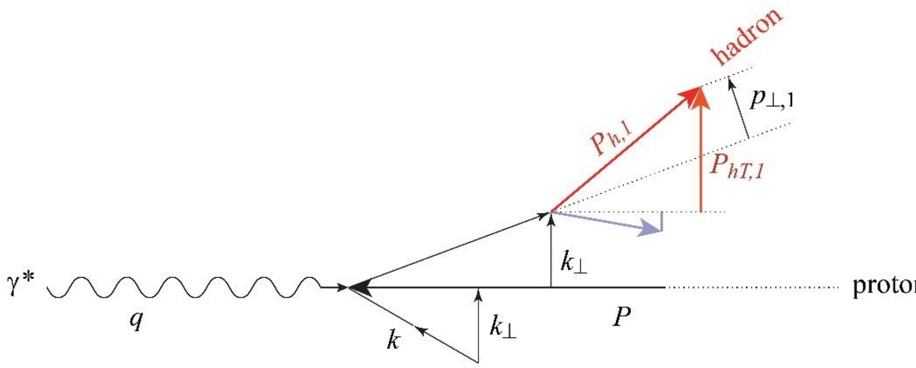


- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF
  - …

Difficult measurements were one has to correct for the apparatus acceptance

Unpolarized SIDIS

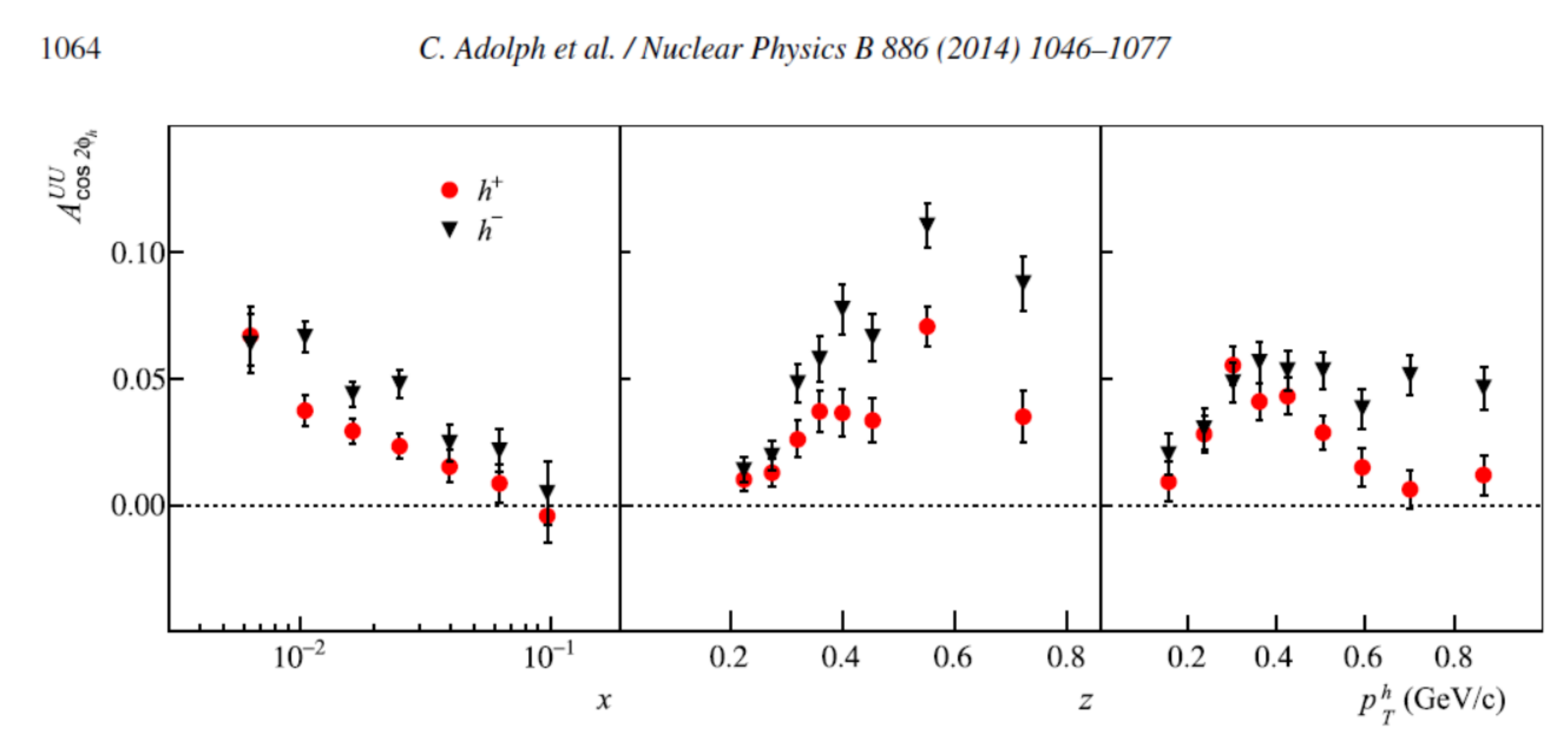




$$F_{UU}^h\left(x, z, P_{hT}^2;\ Q^2\right) = x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta\left(\vec{p}_\perp - z\vec{k}_\perp\right.$$

$$M^h\left(x, z, P_{hT}^2; Q^2\right) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2} \sim \frac{F_{UU}^h\left(x, z, P_{hT}^2;\ Q^2\right)}{F_{UU,T} + \varepsilon F_{UU,L}}$$

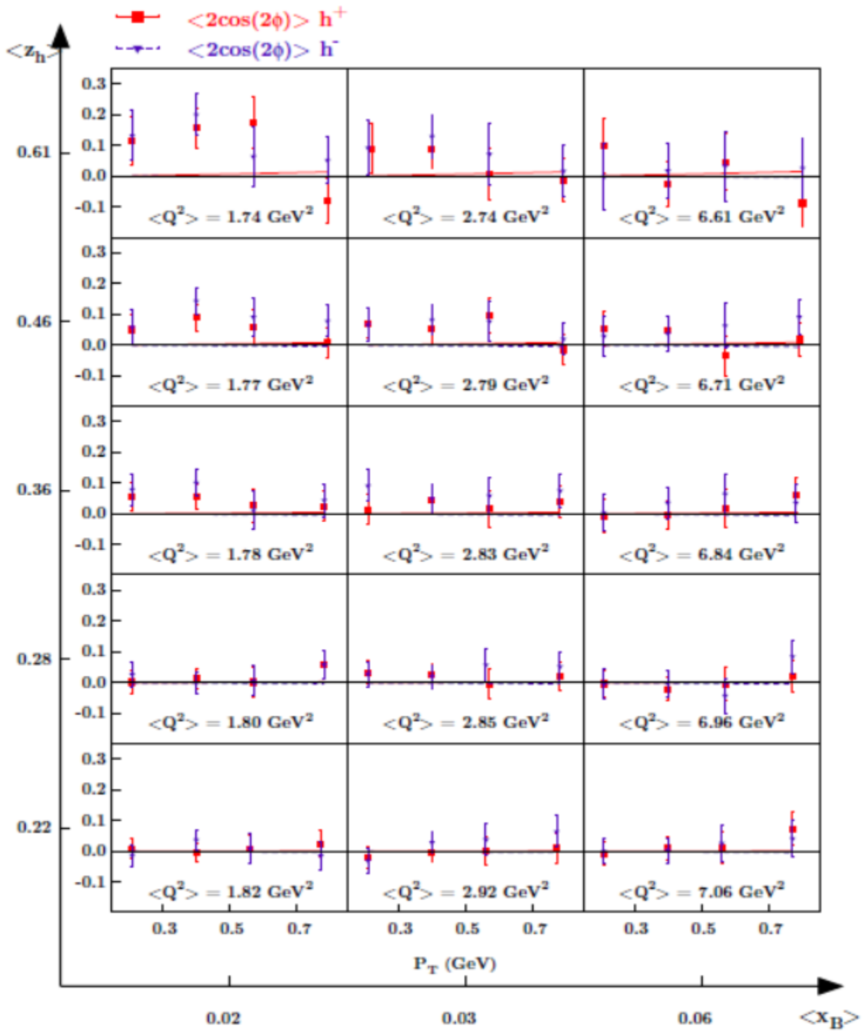
Boer-Mulders in $\cos 2\phi$

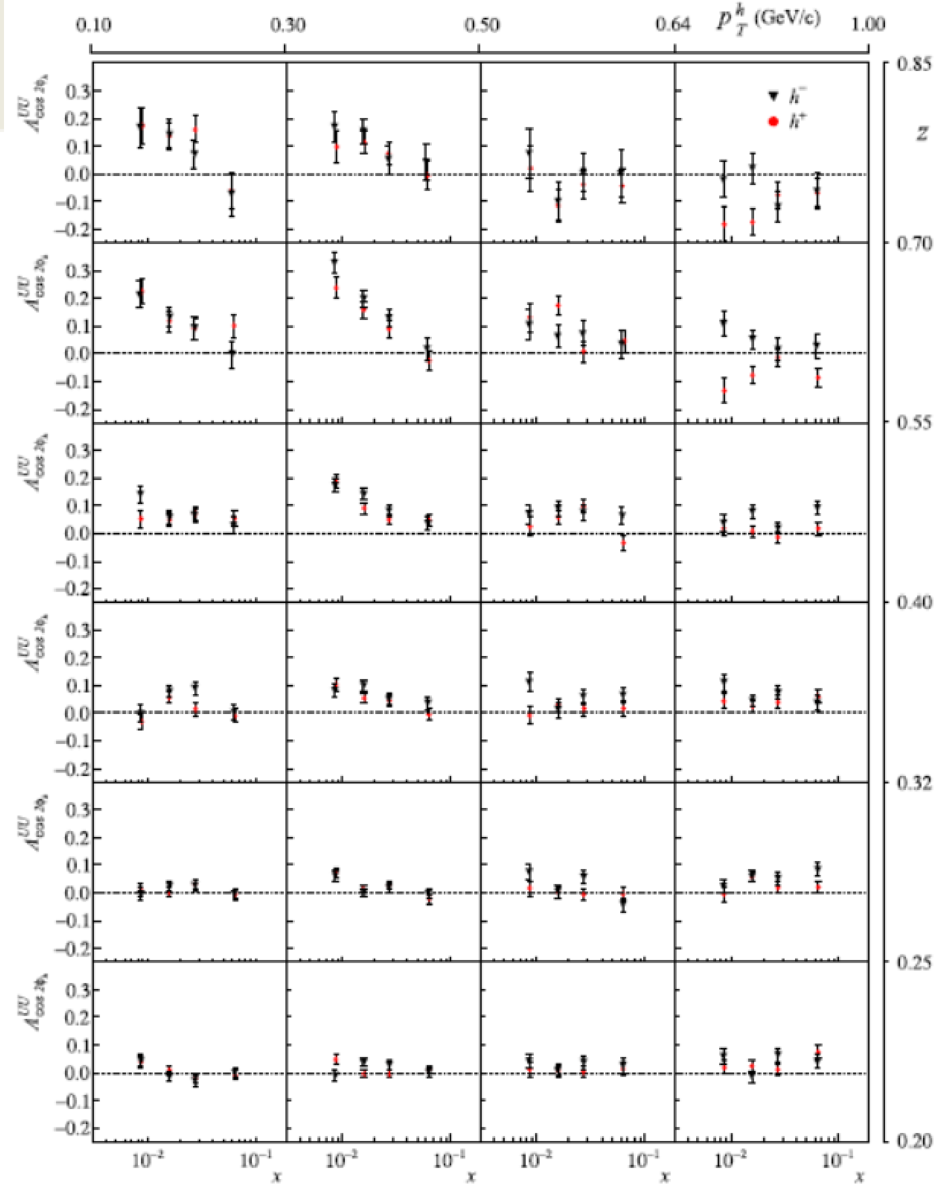


$$F_{UU}^{\cos 2\phi}(x, z, P_{hT}^2;\, Q^2)$$

$$= -x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{k}_\perp) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h} h_1^{\perp,q}(x, k_\perp^2; Q^2) H_1^{\perp,q\to h}(z, p_\perp^2; Q^2)$$

Boer-Mulders in $\cos 2\phi$





Transversity

is chiral-odd:

observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

can be measured in SIDIS on a transversely polarised target via "quark polarimetry"

$\ell N^{\uparrow} \rightarrow \ell' \, h \, X$

"Collins" asymmetry

"Collins" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \, h \, h \, X$

"two-hadron" asymmetry

"Interference" Fragmentation Function

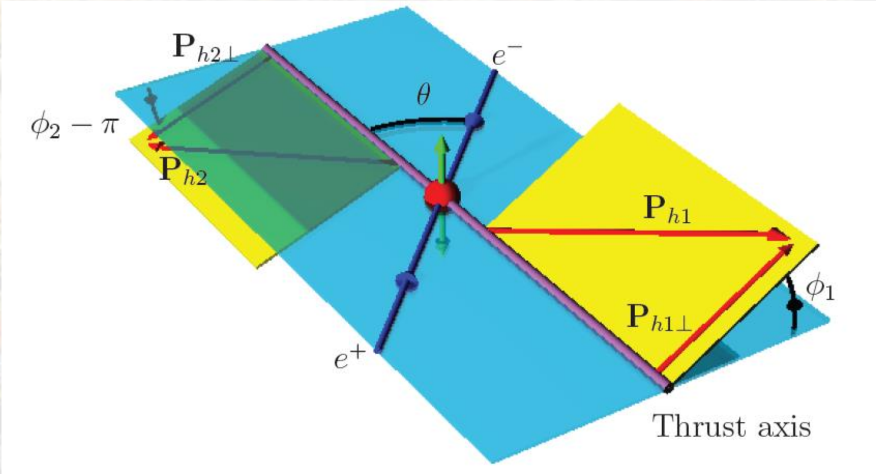
$\ell N^{\uparrow} \rightarrow \ell' \, \Lambda \, X$

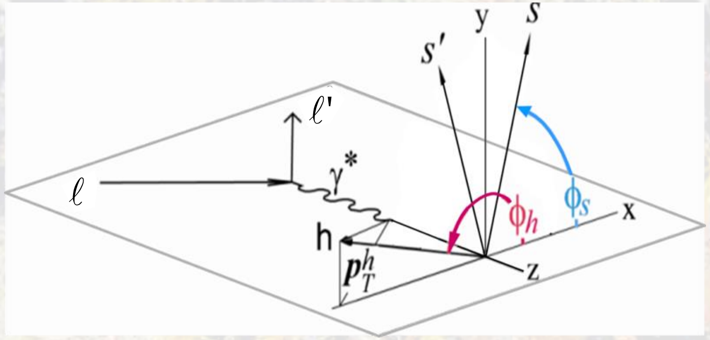
Λ polarisation

Fragmentation Function of $q\uparrow \rightarrow \Lambda$

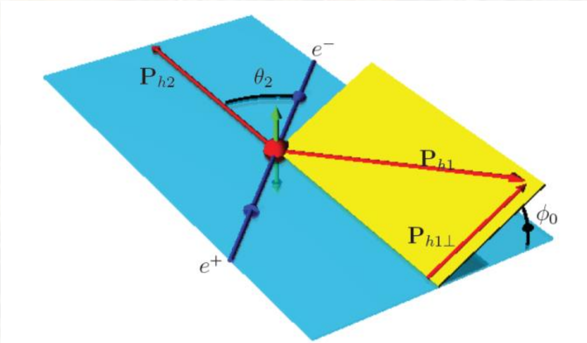
Transversity from Collins SSA and Collins FF

$$A_{UT}^{\sin(\phi_h+\phi_S-\pi),h} = \frac{\sum_q e_q^2\, h_1^q(k_\perp) \otimes H_1^{\perp q\to h}(p_\perp)}{\sum_q e_q^2\, f_1^q \otimes D_1^{q\to h}}$$





$$A_{12}^{h_1h_2} = \frac{\sin^2\theta}{1+\cos^2\theta} \frac{\sum_q e_q^2\, H_1^{\perp(1/2)q\to h_{1/2}} H_1^{\perp(1/2)\bar{q}\to h_{1/2}}}{\sum_q e_q^2\, D_1^{q\to h_{1/2}} D_1^{\bar{q}\to h_{1/2}}}$$



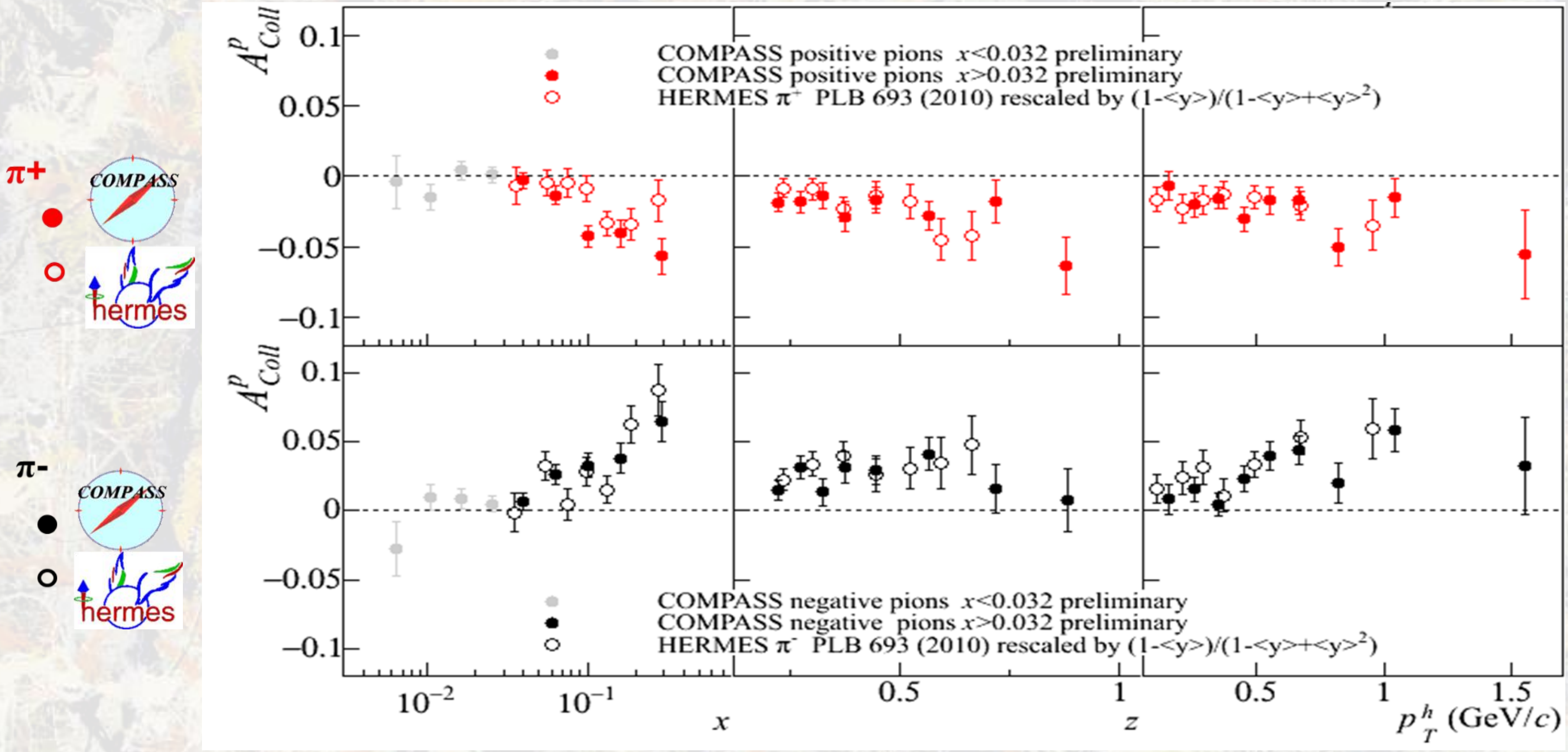
Collins effect:
a quark with an upward (downward) polarization, perpendicular to the motion, prefers to emit the leading meson to the left (right) side with respect to the quark direction

Collins asymmetry on proton

x > 0.032 region

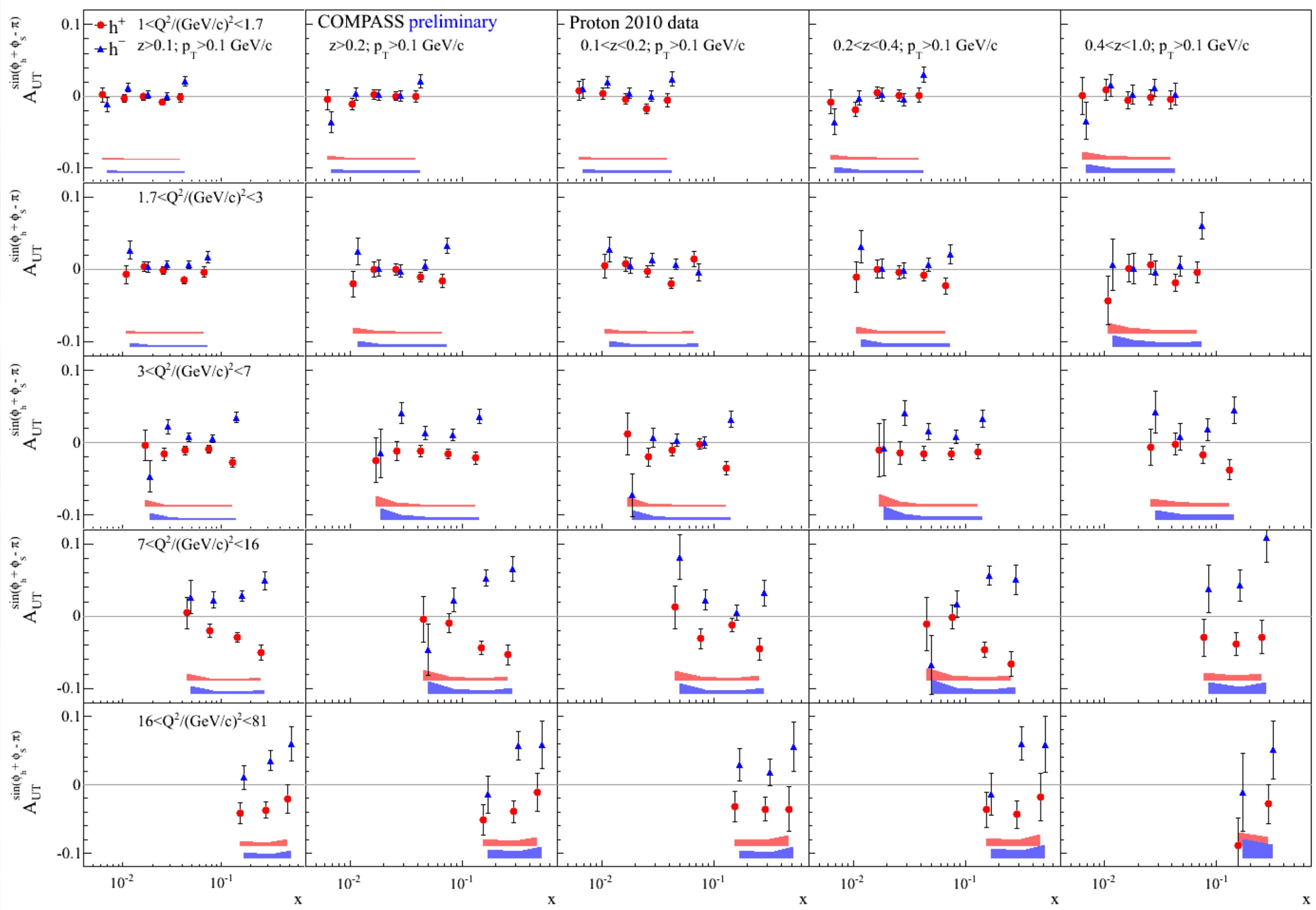
charged pions

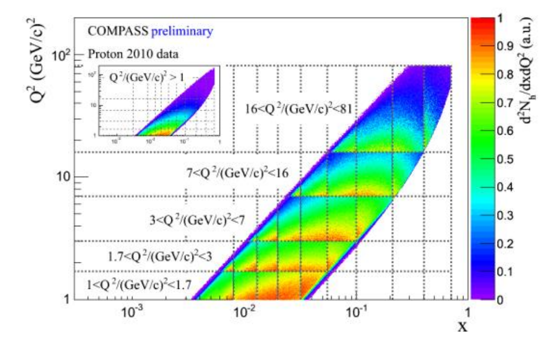
COMPASS and HERMES results



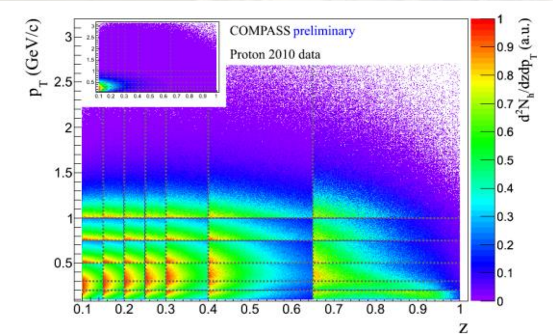
Collins asymmetry on proton. Multidimensional

First extraction of TSAs within a Multi-D $(x: Q^2: z: p_T)$ approach



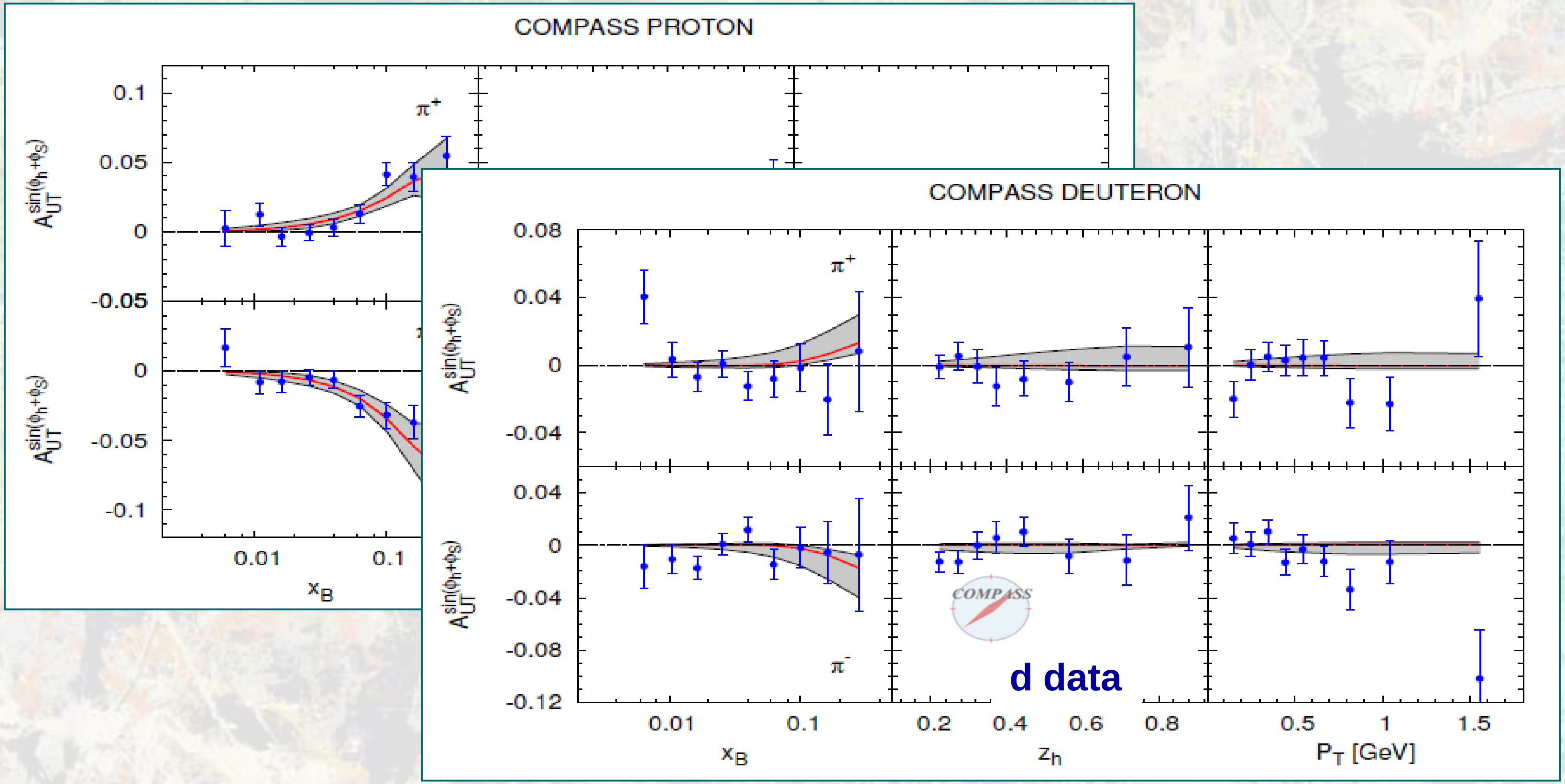


One dense plot out of many



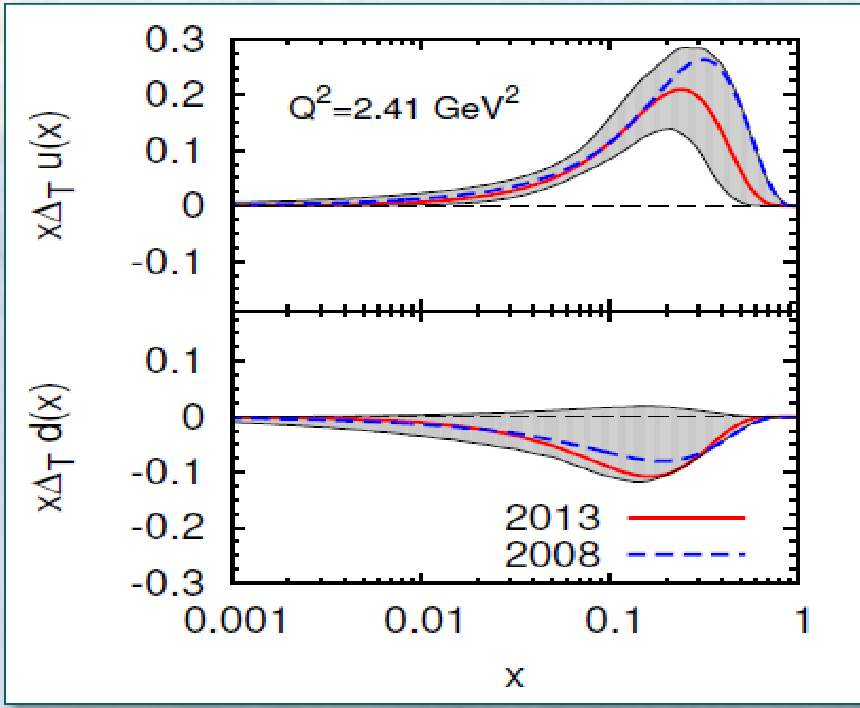
Collins asymmetry fits

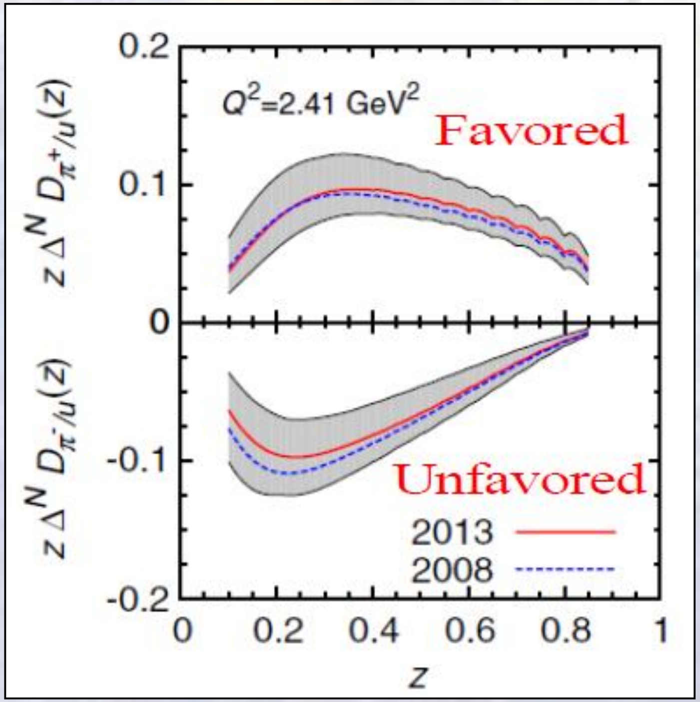
M. Anselmino et al., arXiv:1303.3822
fit to HERMES p, COMPASS p and d, Belle e^+e^- data



Transversity from Collins

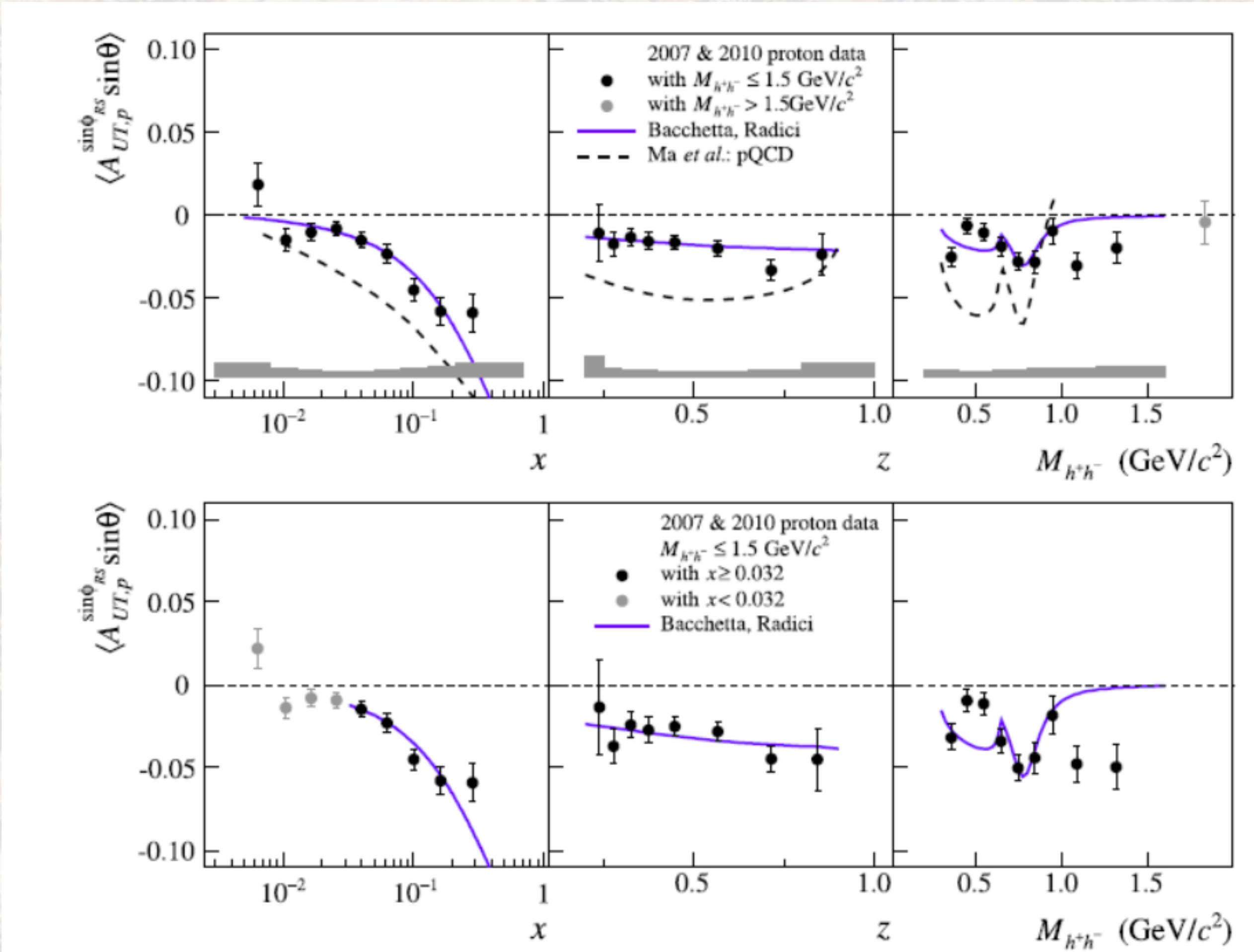
Combined analyses of **HERMES, COMPASS** and **BELLE fragm.fct.** data

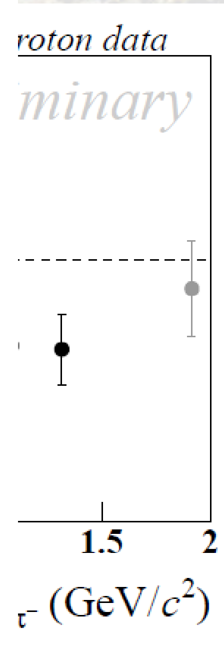




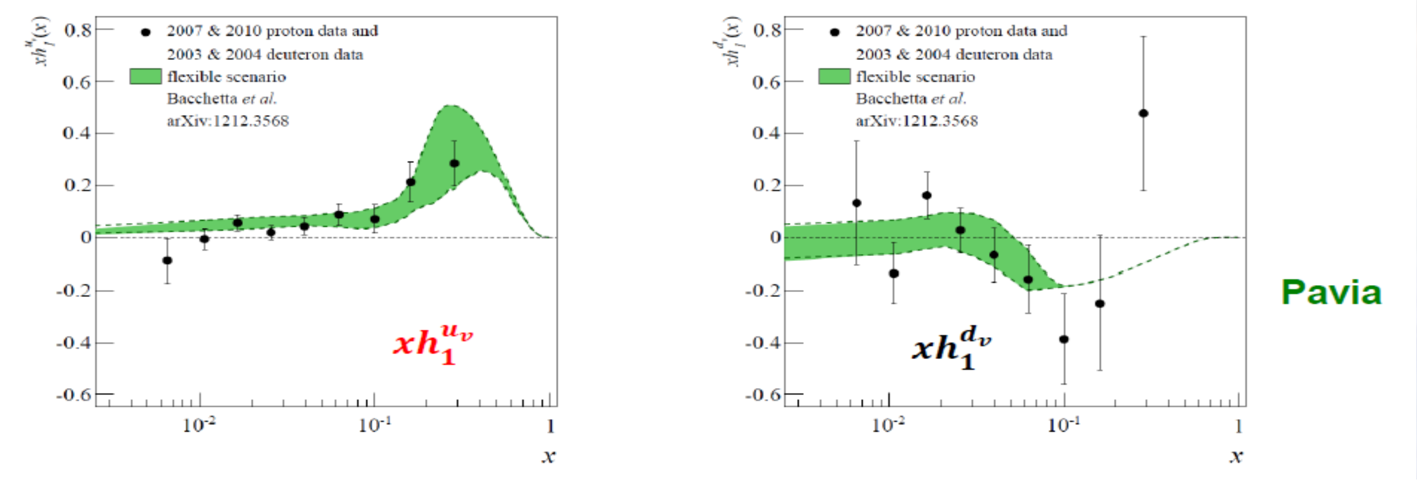
Anselmino et al. arXiv: 1303.3822

2h asymmetries on p

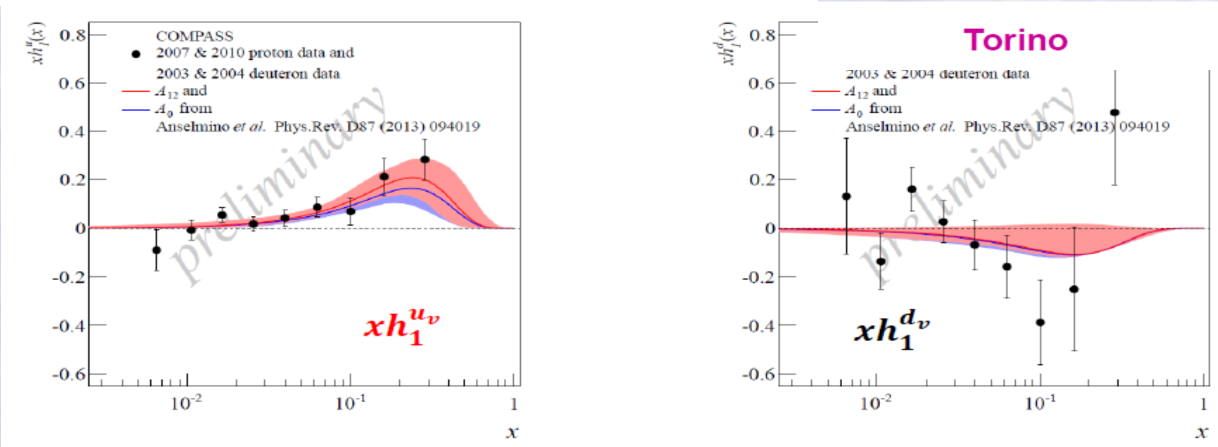




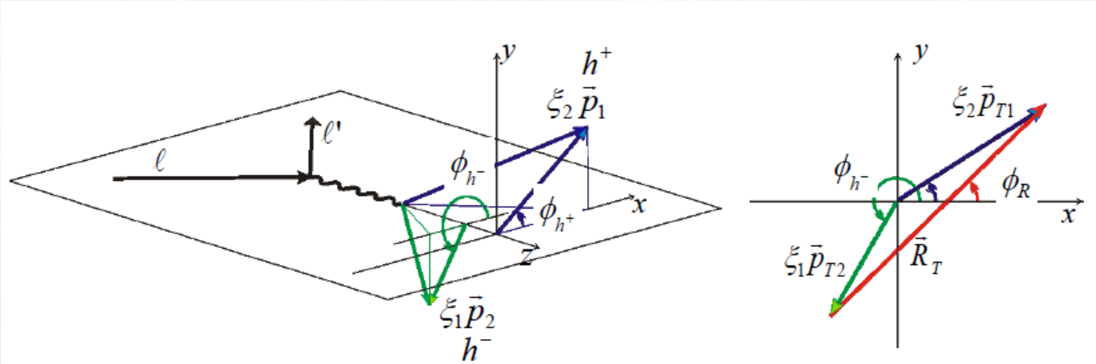
Transversity from 2h p and d results



use the same coefficients evaluated by A. Bacchetta et al. from Belle data [JHEP1303 (2013)119]

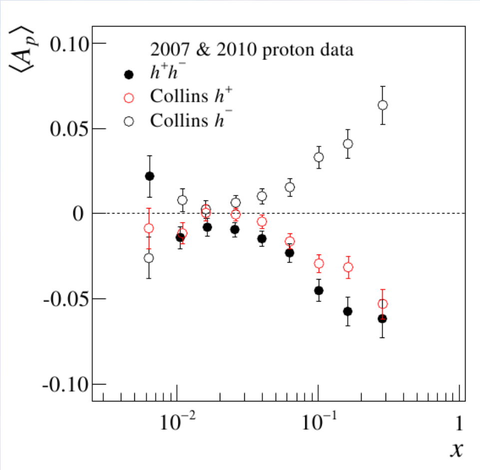


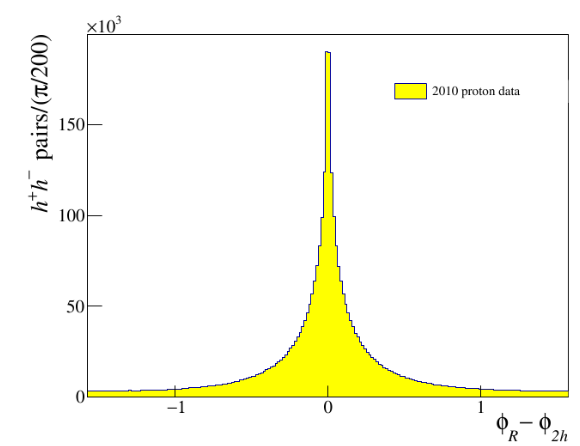
Hadron correlations

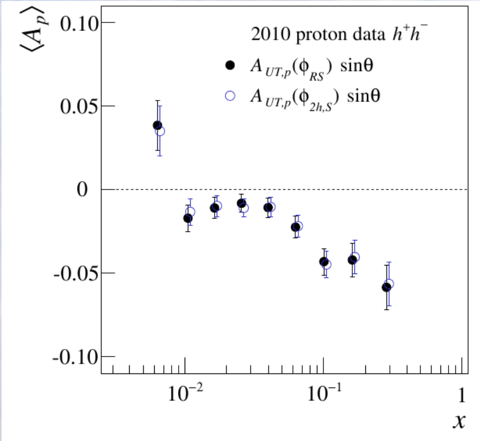


Interplay between Collins and IFF asymmetries

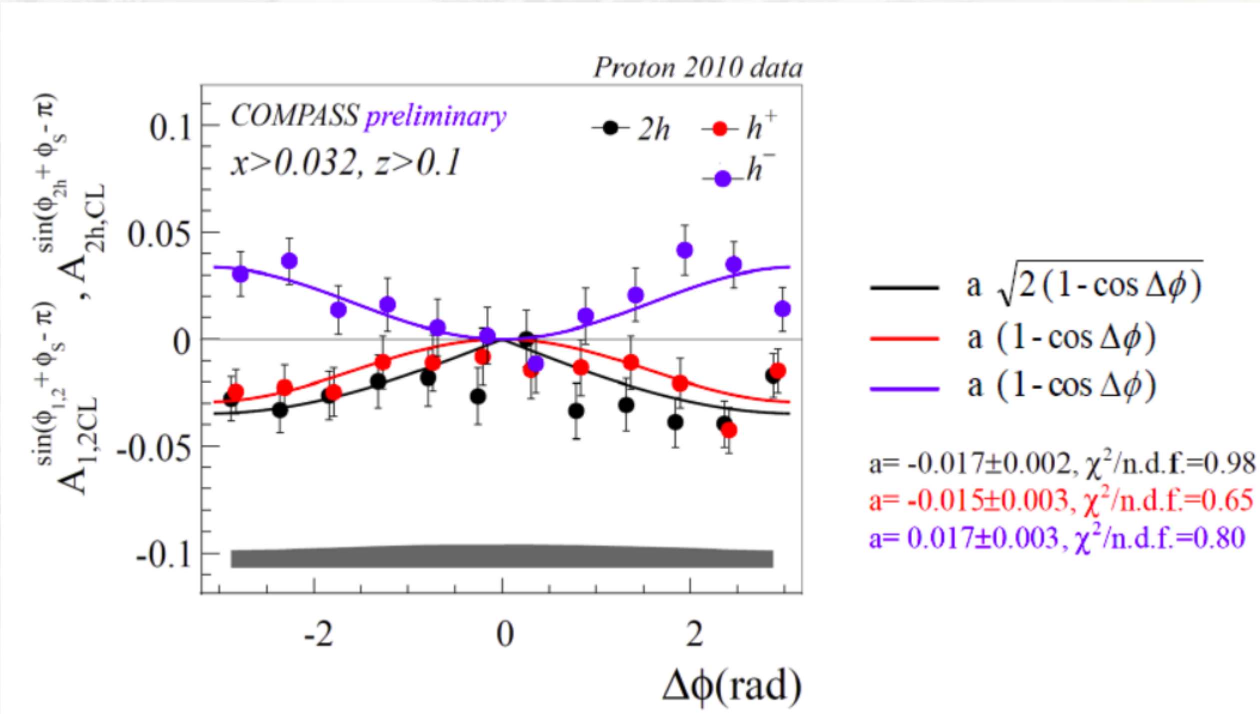
common hadron sample for Collins and 2h analysis







Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$



$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

$$= -\frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

ratio of the integrals compatible with $4/\pi$

Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

at LO:

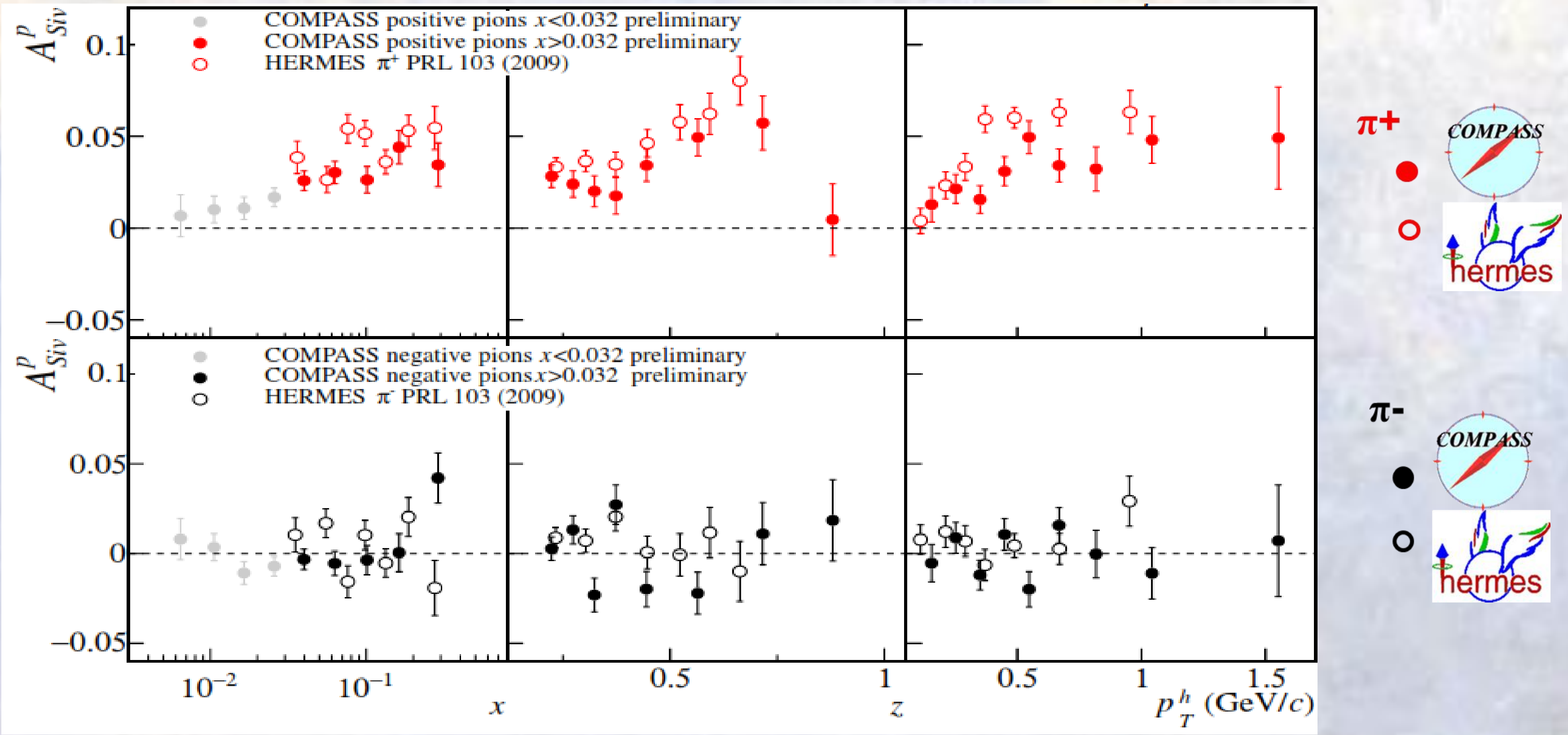
$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\boxed{\mu p^{\uparrow} \to \mu X h^{\pm}}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS

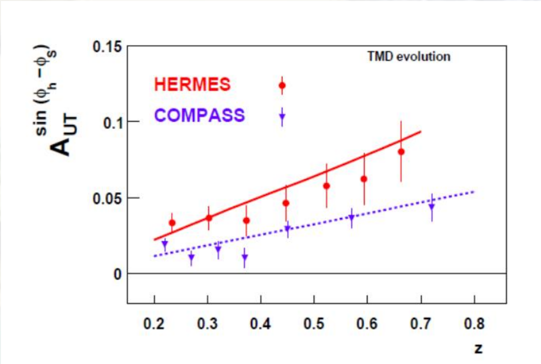


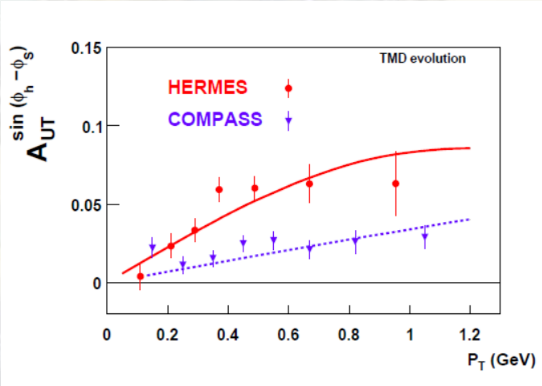
Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

comparison with

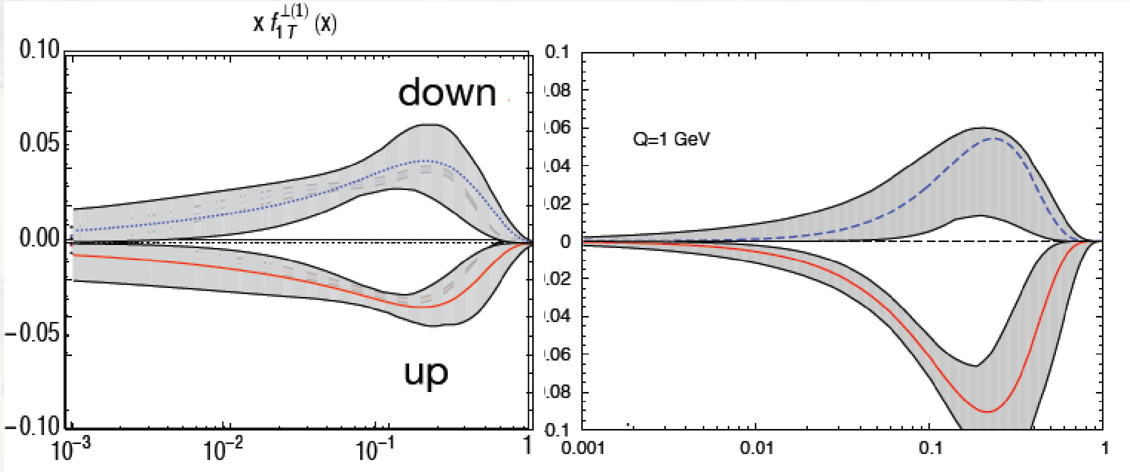
S. M. Aybat, A. Prokudin and T. C. Rogers calculations PRL 108 (2012) 242003





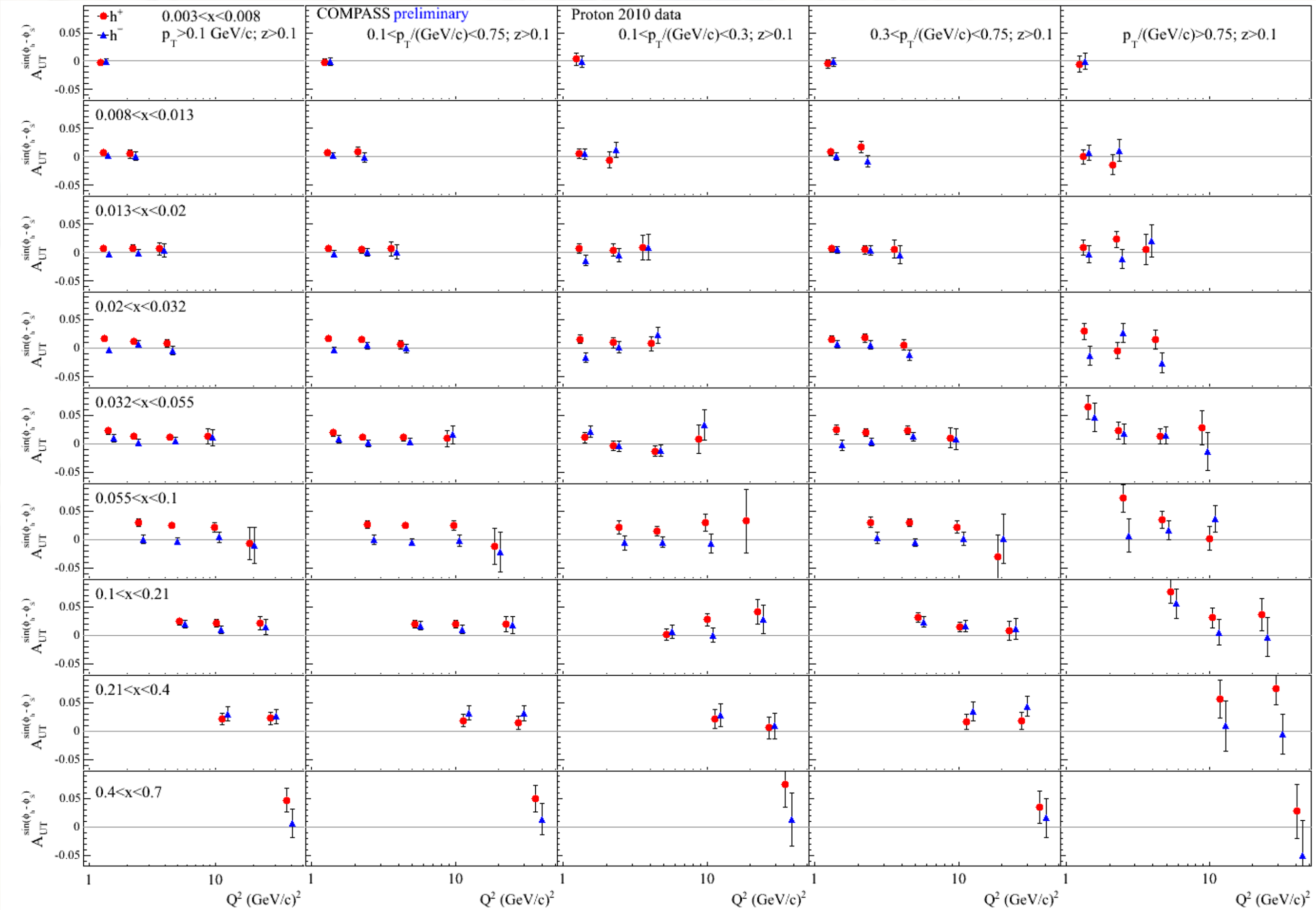
No TMD evolution

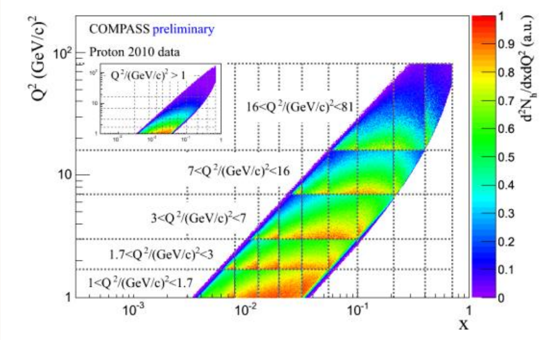
with TMD evolution

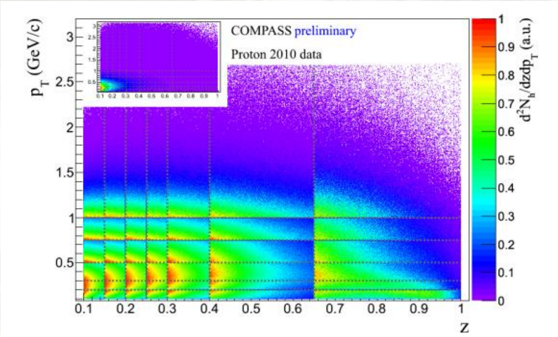


Sivers asymmetry on proton. Multidimensional

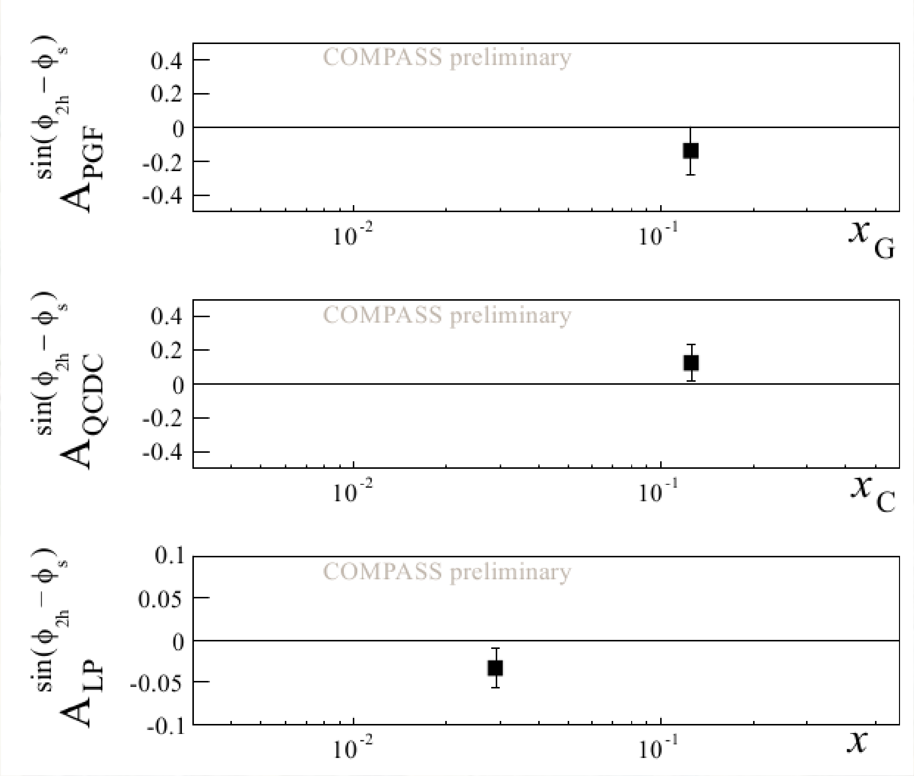
First ever extraction of TSAs within such a Multi-D $(x{:}\,Q^2{:}\,z{:}\,p_T)$ approach

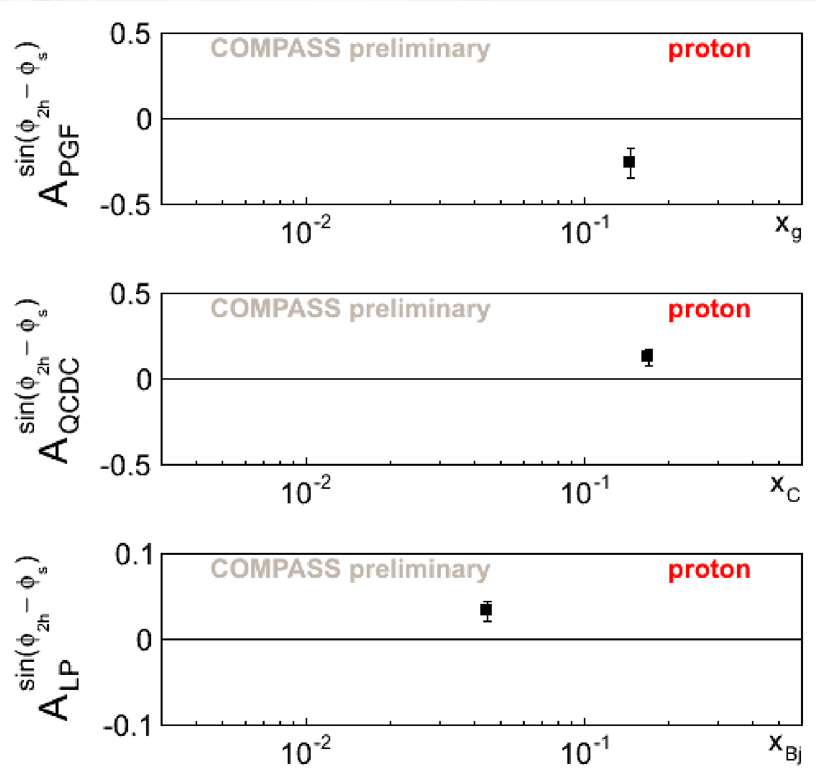






Sivers asymmetry on deuteron and proton for Gluons





NEAR FUTURE:

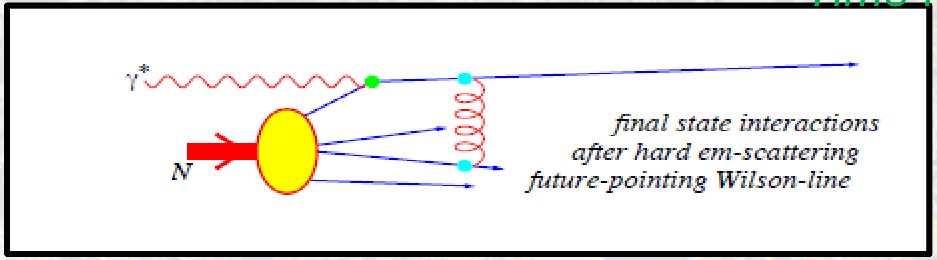
- polarized DY
- unpolarized SIDIS
- DVCS

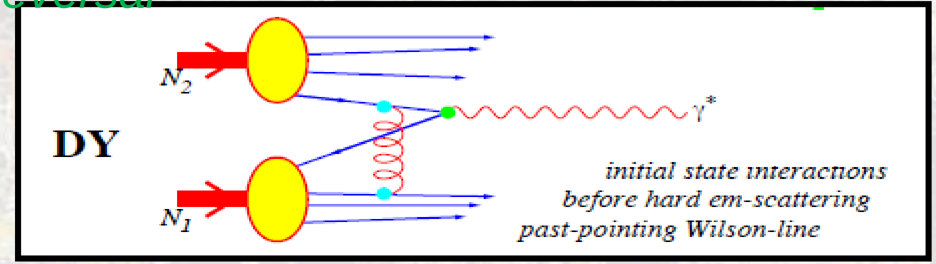
Test of universality

T-odd character of the Boer-Mulders and Sivers functions

In order not vanish by time-reversal invariance T-odd SSA require an interaction phase generated by a rescattering of the struck parton in the field of the hadron remnant

Time reversal





these functions are process dependent, they change sign to provide the gauge invariance

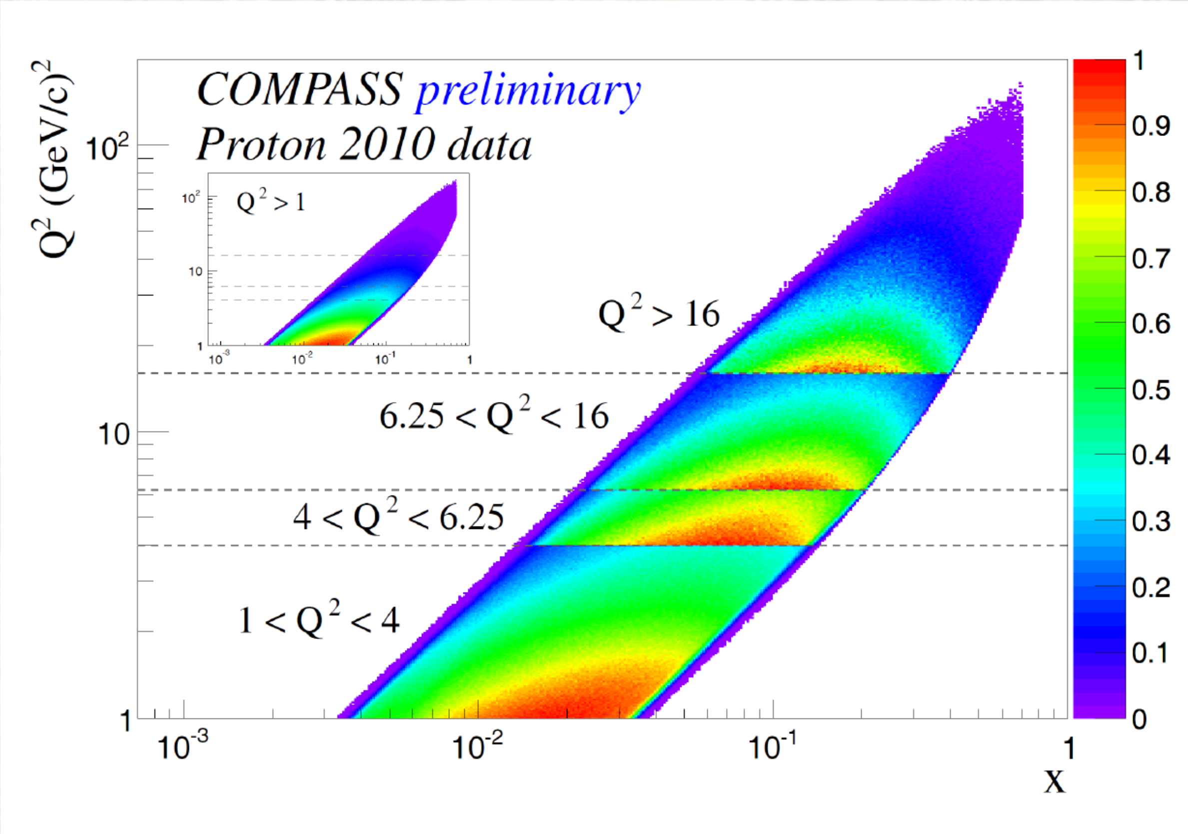
Boer-Mulders

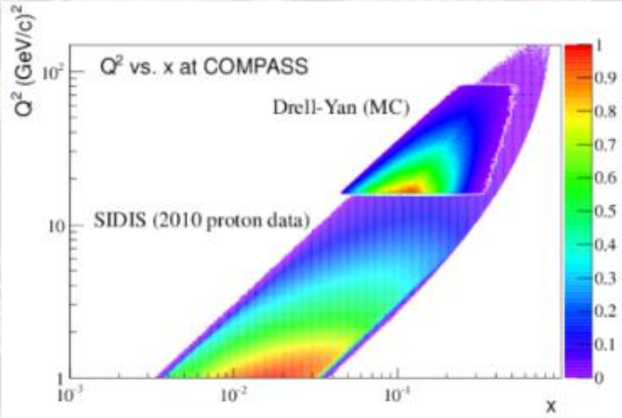
$$\boxed{h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)}$$

Sivers

$$\boxed{f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)}$$

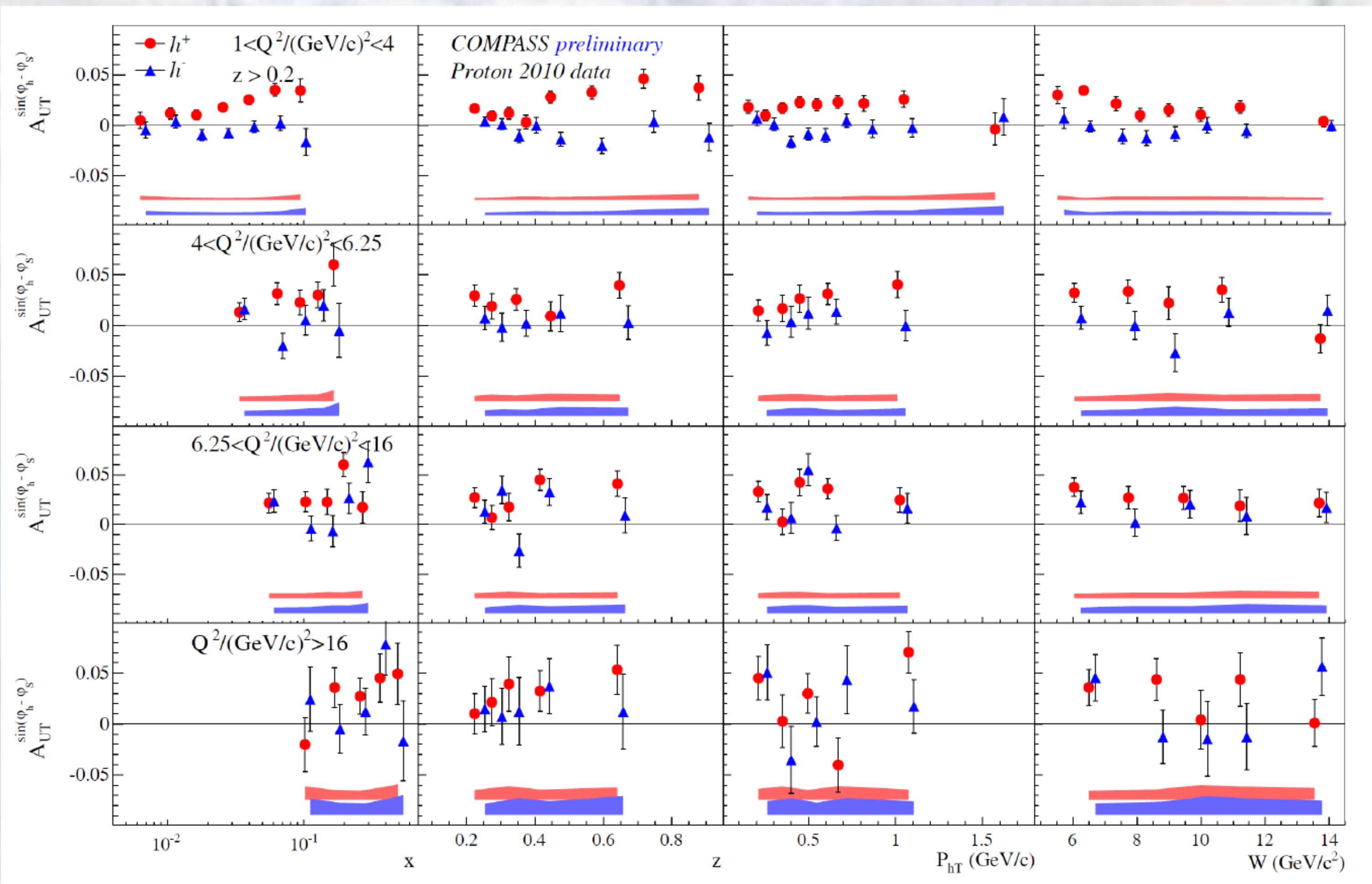
Q^2 vs x phase space at COMPASS



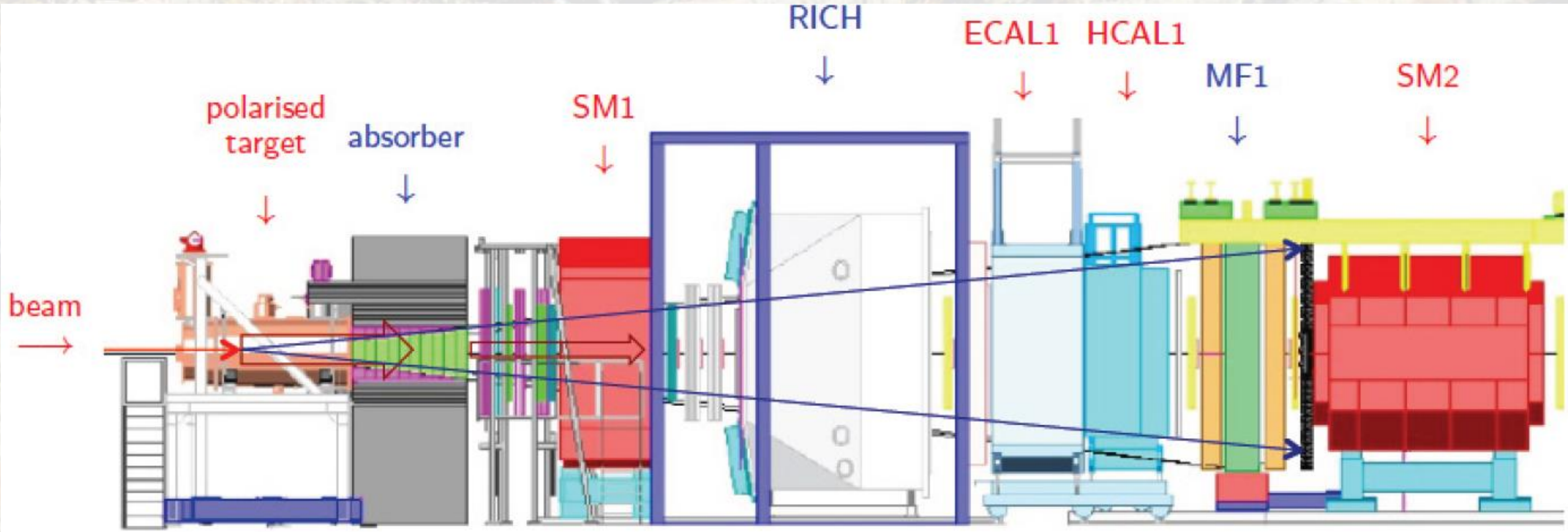


The phase spaces of the two processes overlap at COMPASS
➔ Consistent extraction of TMD DPFs in the same region

Sivers in DY range

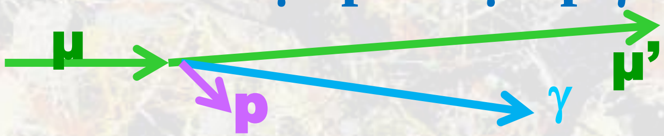


Hadron beam: Drell-Yan setup

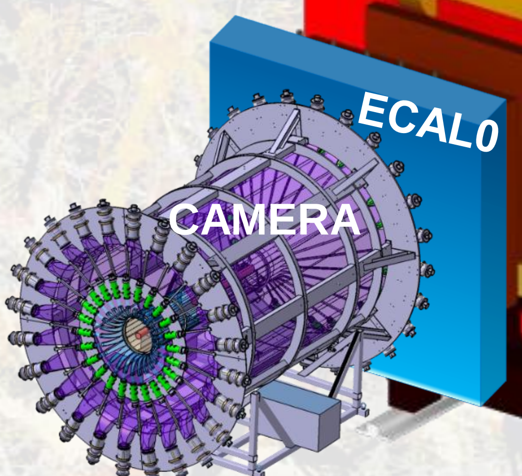


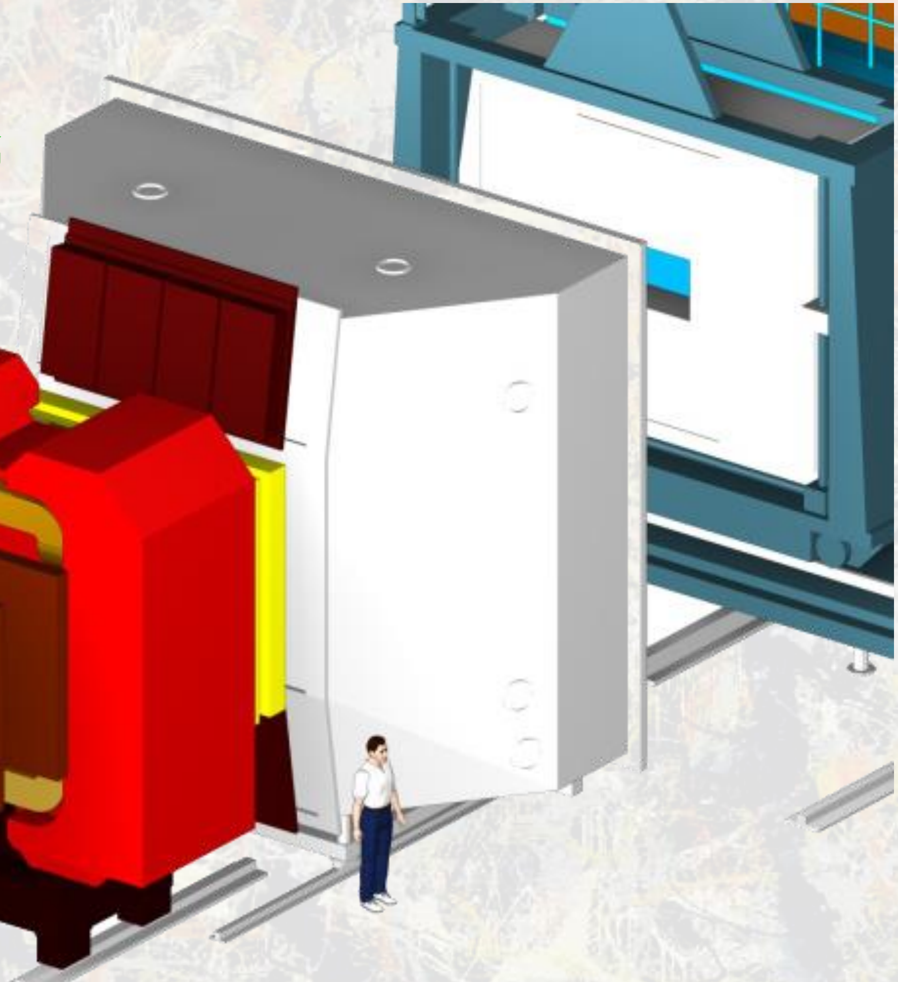
Upgrades of the COMPASS spectrometer

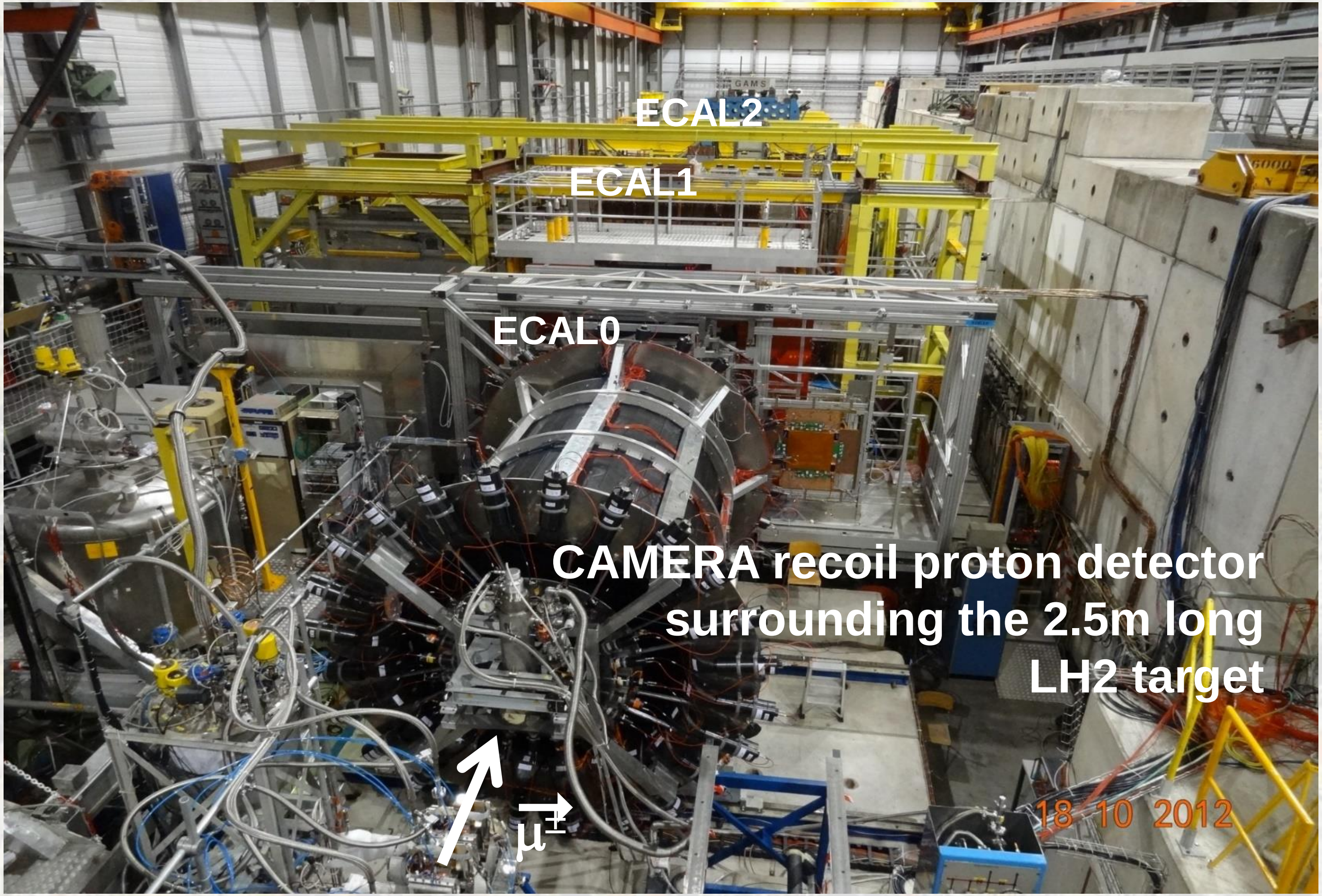
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$



New equipements:
- 2.5m LH2 target
- 4m ToF Barrel CAMERA
- ECAL0






ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\vec{\mu}^{\pm}$
18 10 2012

GPDs with Hard Exclusive γ and Meson Production

COMPASS-II 2016-17: **with LH_2 target + RPD (phase 1)** $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ **160 GeV**

- ✓ the t-slope of the DVCS and HEMP cross section
  → transverse distribution of partons
- ✓ the Beam Charge and Spin Sum and Difference
  → $\mathcal{R}e\, T^{DVCS}$ and $\mathfrak{I}m\, T^{DVCS}$ for the GPD H determination
- ✓ Vector Meson ρ^0, ρ^+, ω, Φ
- ✓ Pseudo-saclar π^0

(Using the 2007-10 data: transv. polarized NH_3 target without RPD)

Near COMPASS future is defined:

- 2014-2015: Transversely polarized DY
  - to check pseudo-universality ($[f_{1T}^{\perp}(x,Q^2)]_{DY} \approx -[f_{1T}^{\perp}(x,Q^2)]_{SIDIS}$)
- 2016-2017: Unpolarised DVCS/HVMP
  - (B slope and GPD H)
  - and unpolarised SIDIS on LH_2
  - $dn^h/(dN^\mu dz\, dp_T^2)$ i.e. p_T dependent multiplicities, and $h_{1T}^{\perp}$ Boer-Mulders TMD PDF
- 2018 to be discussed having in hand the performances in the previous years

More in the FUTURE:

	physics item	key aspects of the measurement
Hadron	glueballs	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

For the next 10 years

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

COMPASS@CERN can be a major player in QCD physics using its unique high energy both:

- **hadron beam and**
- **positive and negative muon beams**

Looking even further…a polarized lepton-nucleon collider well be a mandatory tool


Thank You

Results:

Year		
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ⁶LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	Full ⁶LiD statistics
2009	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full ⁶LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full 6LiD and NH_3statistics
2012	$A^h_{Siv,p}, A^h_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho-\phi_S)}_{UT,d}, A^{sin(\phi_\rho-\phi_S)}_{UT,p}$	Exclusive ρ^0 production− Full 6LiD and NH_3statistics
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d
2014	$A^{\sin\phi_h}_{UU,d}, A^{\cos\phi_h}_{UU,d}, A^{\cos 2\phi_h}_{UU,d}$ $A^{sin\phi_S}_{UT,p}, A^{cos\phi_S}_{LT,p}, A^{sin(2\phi_\rho-\phi_S)}_{UT,p} \ldots$ $A^g_{Siv,d}$	Unpol. azimuthal asymm.s Excl. ρ^0 production on NH_3 preliminary

Chromodynamic lensing

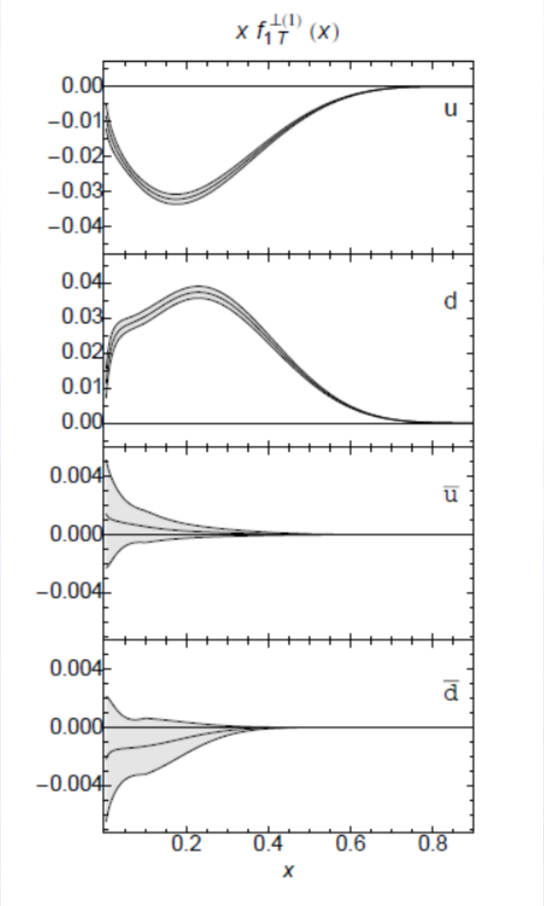
Use SIDIS Sivers asymmetry data to constrain shape

Use anomalous magnetic moments to constrain integral

$$f_{1T}^{\perp(0)q}(x, Q_L^2) = -L(x)E^q(x,0,0,Q_L^2)$$

$L(x)$ – Lensing function (from Burkart)

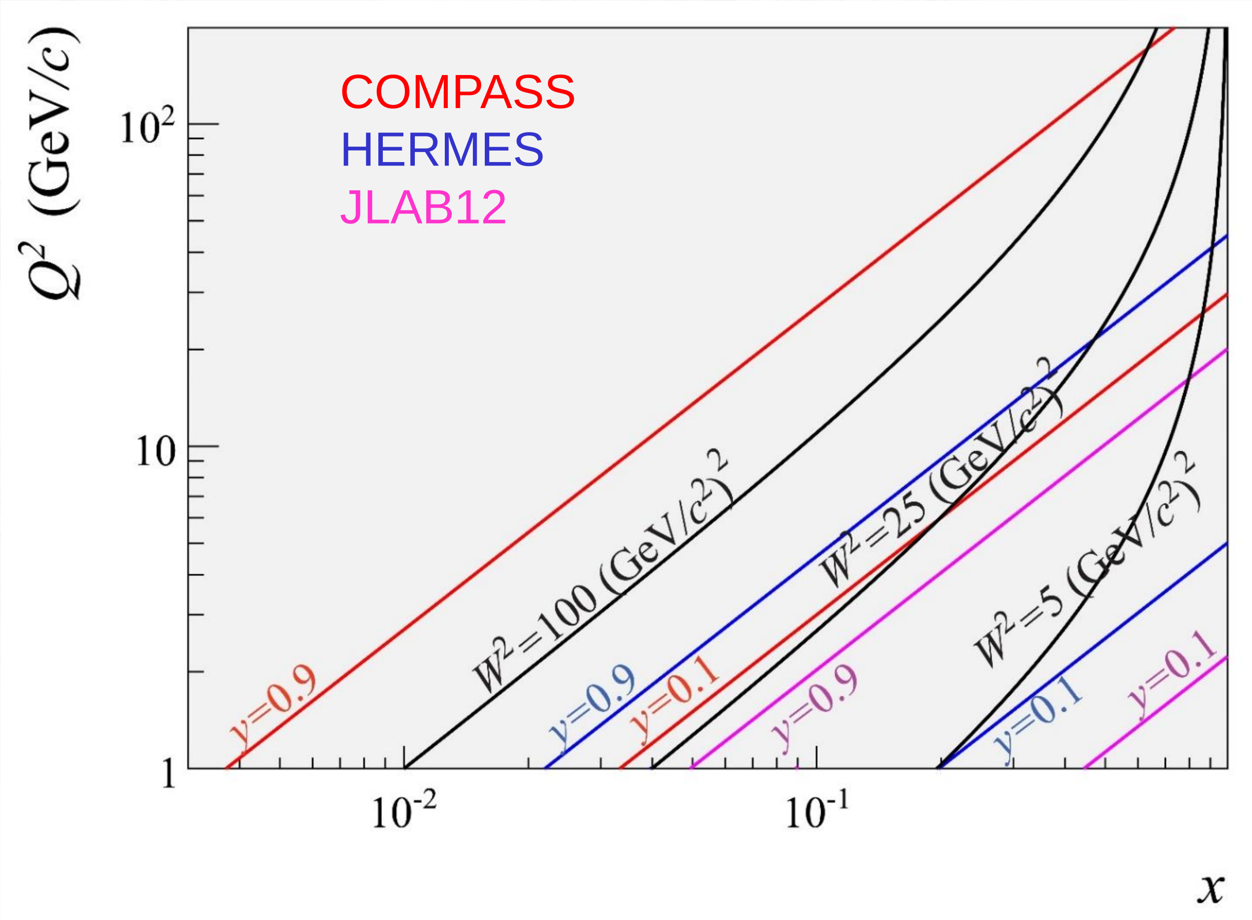
E^q – GPD related to quark OAM

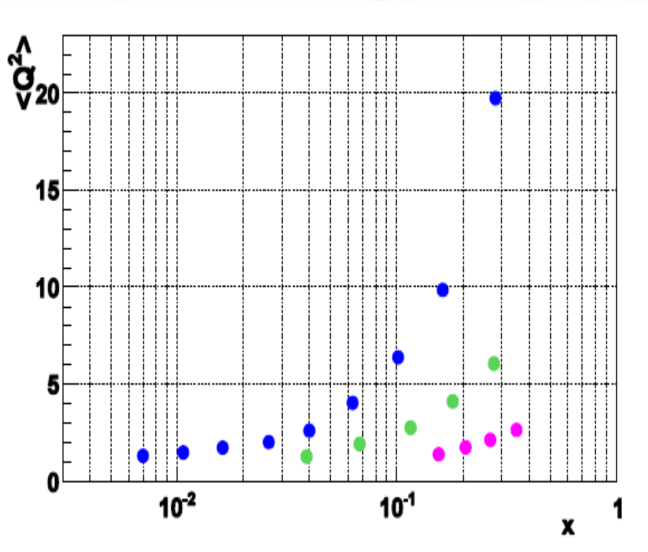


n-th moment of a TMD with respect to $k_\perp$

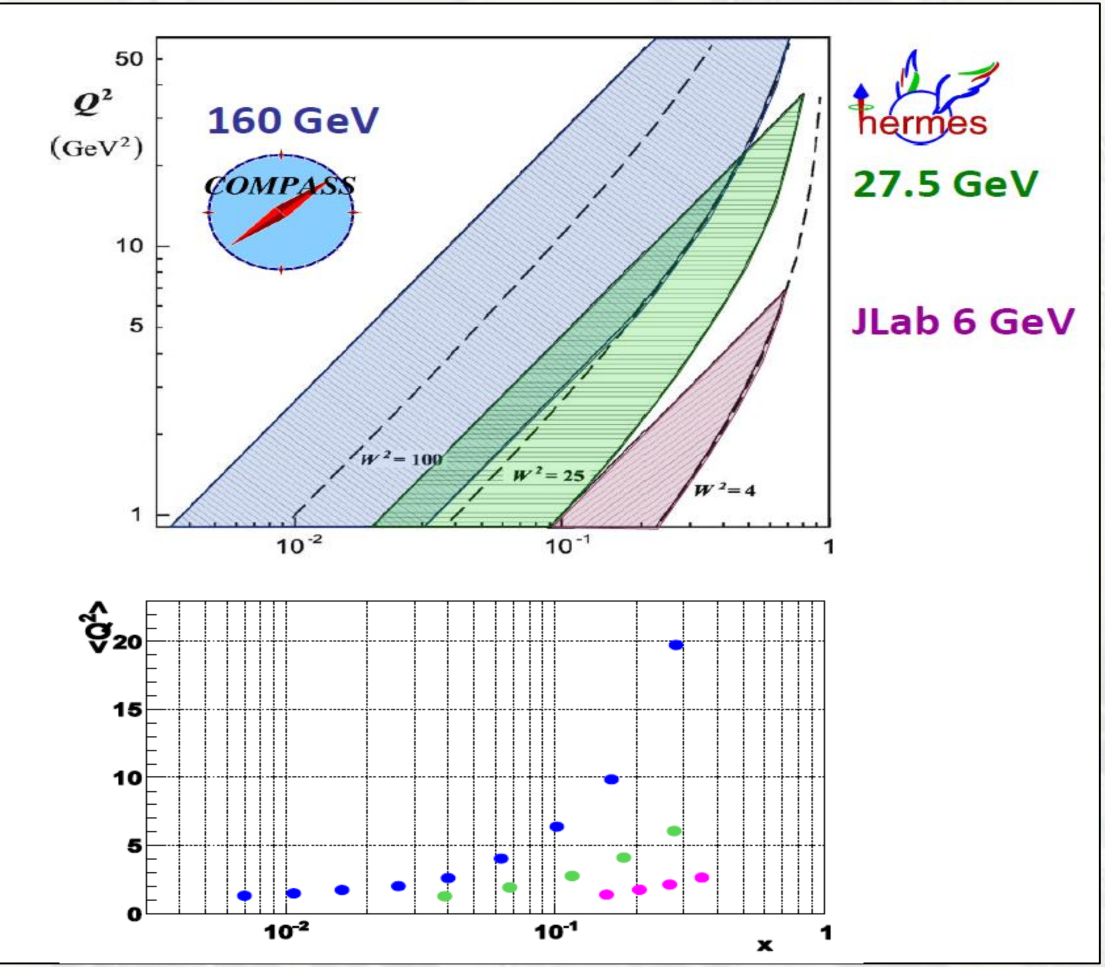
$$f_{1T}^{\perp(n)q}(x, Q^2) = \int d^2k_\perp \left(\frac{k_\perp^2}{2M^2}\right)^n f_{1T}^{\perp(0)q}(x, k_\perp^2, Q_L^2)$$

Kinematic coverage





Kinematic coverage



$0.004 < x < 0.3$, $25 < W^2 < 200\,\mathrm{GeV}^2$

$0.023 < x < 0.4$, $10 < W^2 < 50\,\mathrm{GeV}^2$

$0.14 < x < 0.5$, $4 < W^2 < 10\,\mathrm{GeV}^2$

Other SSAs - proton data

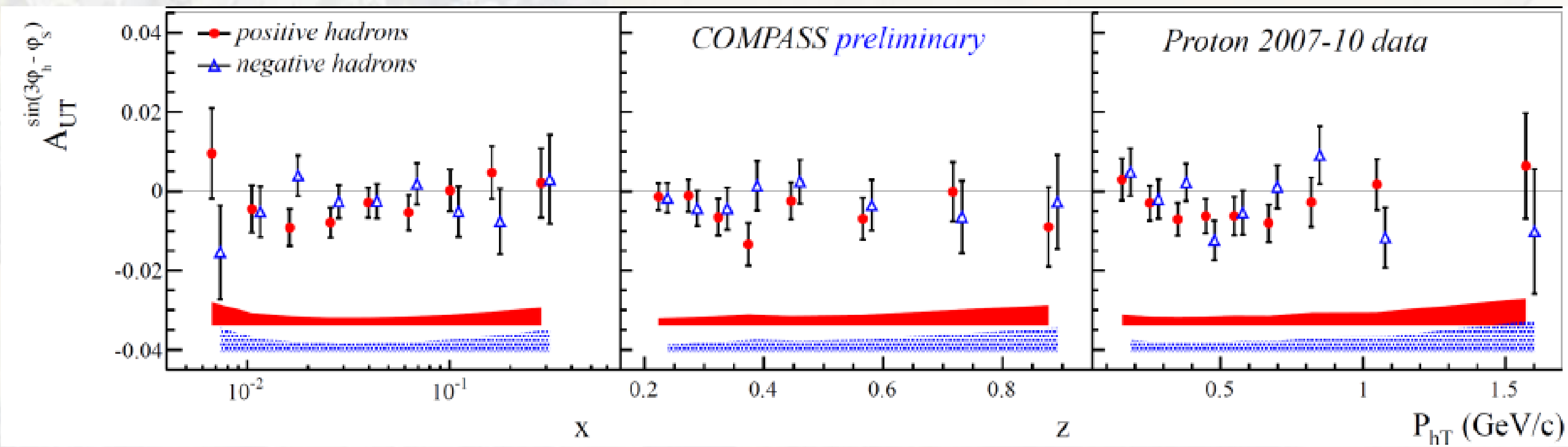
$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

two twist-2 asymmetries can be interpreted in QCD parton

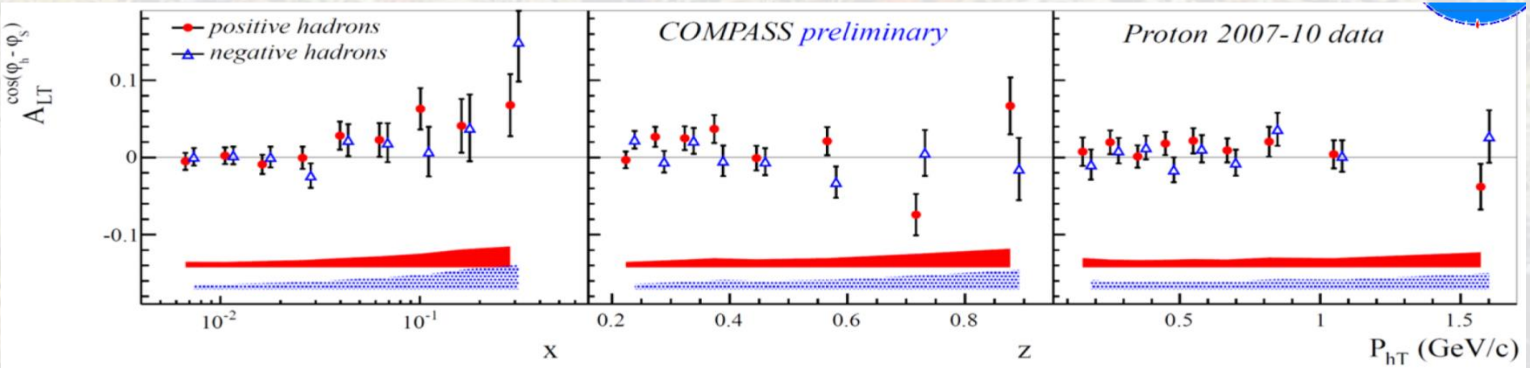
"pretzelosity" ⊗ Collins FF

In some models $h_{1T}^{\perp} = g_1 - h_1$

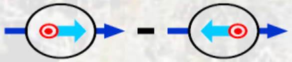


Other Transverse Target spin asymmetries on p

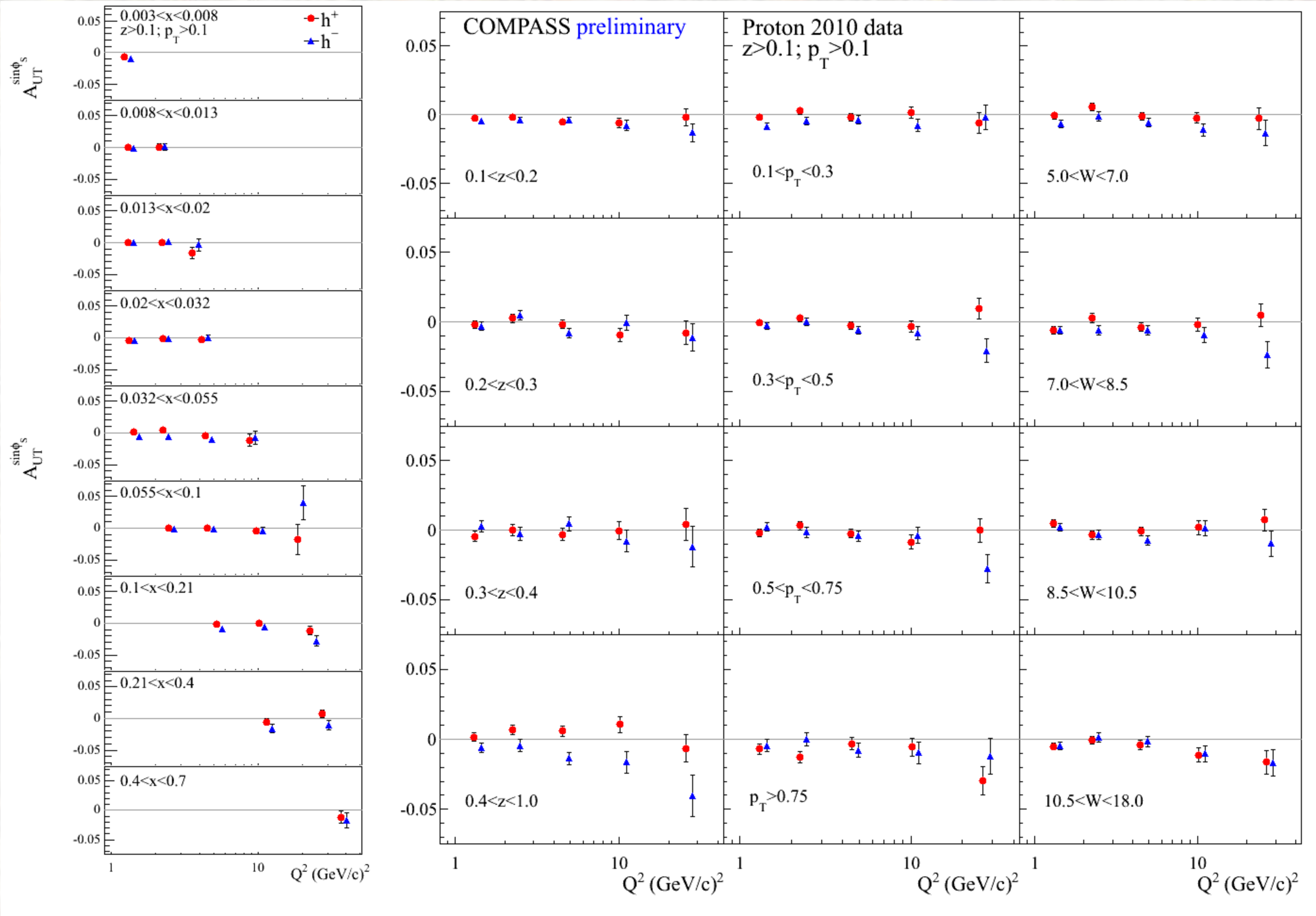
$A_{LT}^{\cos(\varphi_h - \varphi_s)}$



$A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :

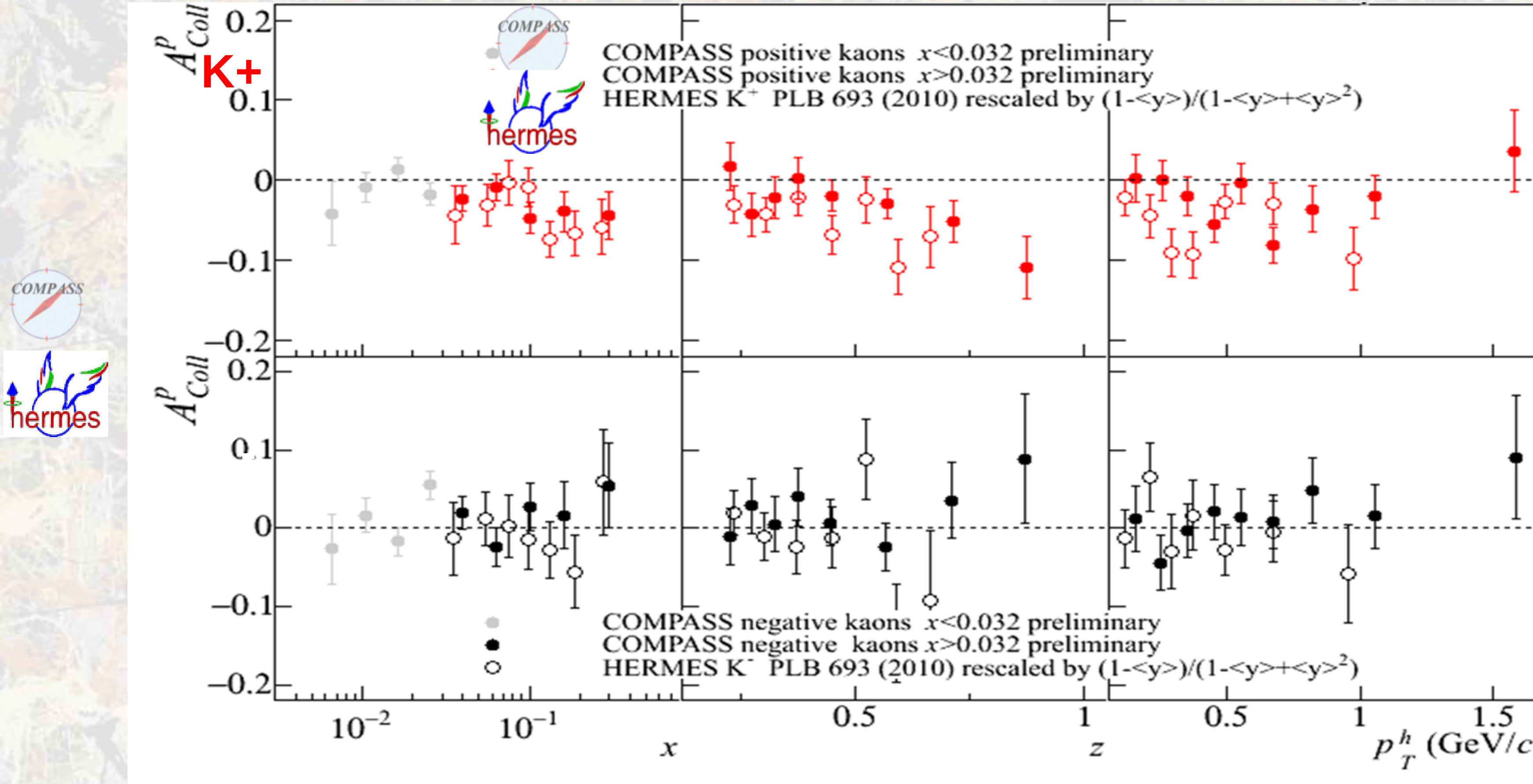


Other Transverse Target spin asymmetries on p

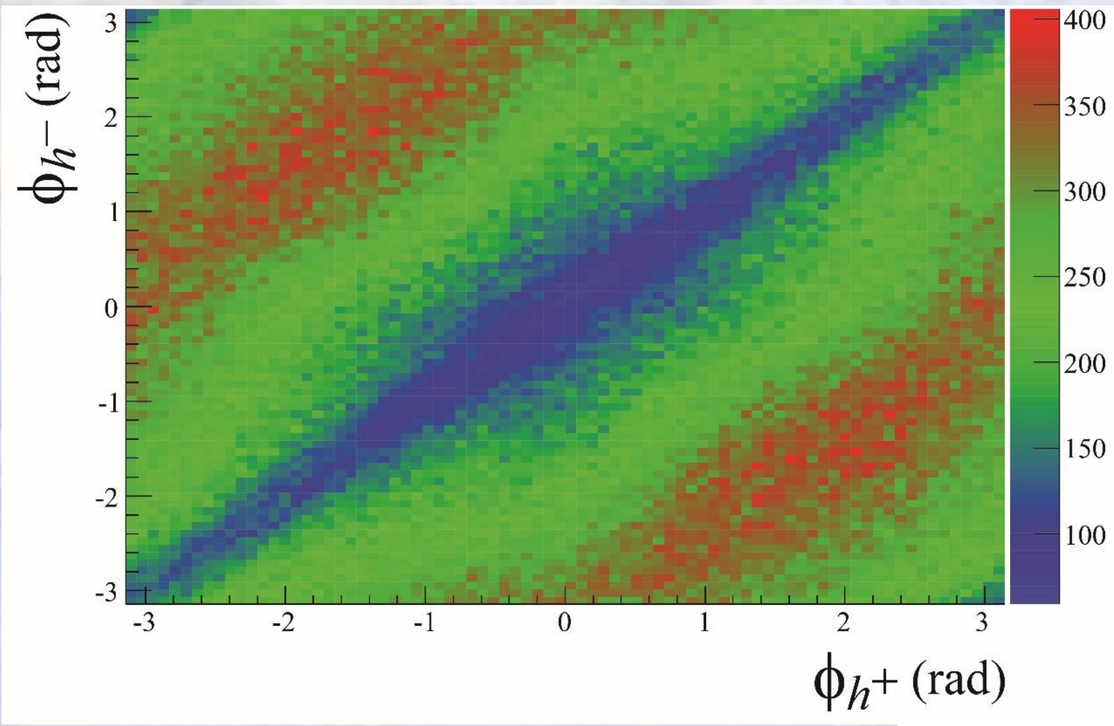


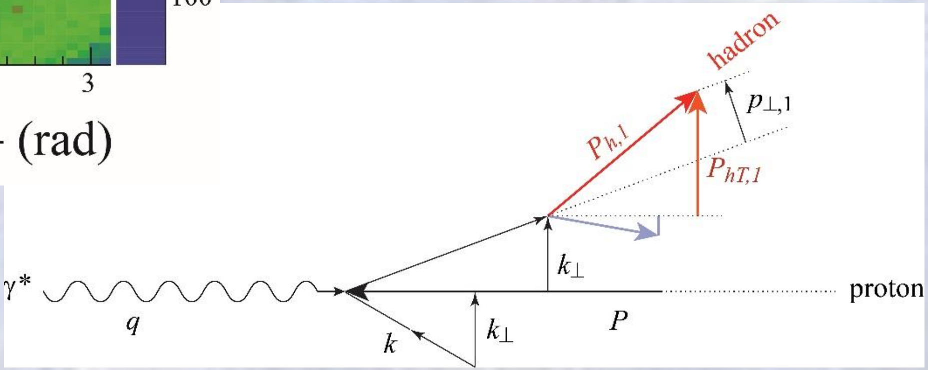
Collins asymmetry on proton x > 0.032 region

charged kaons **COMPASS and HERMES results**



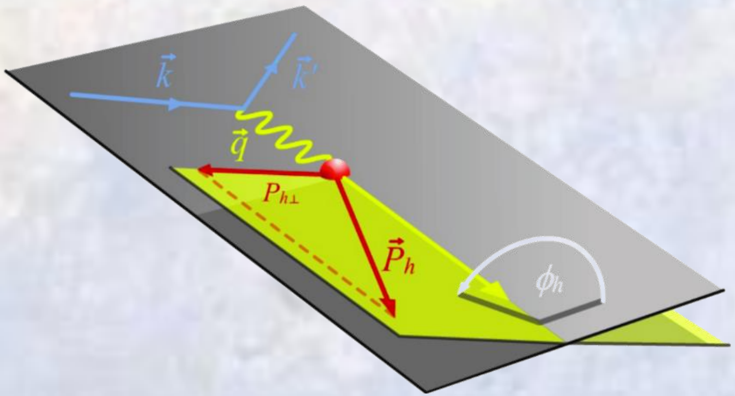
Is correlation having an impact?

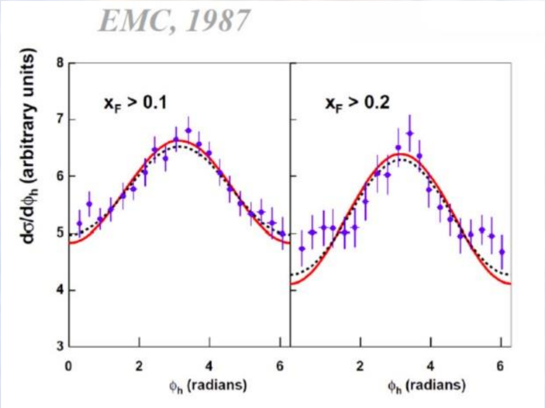




Unpolarised Azimuthal Modulation

Huge azimuthal ϕ modulation on unpolrised target measured by EMC in 1987





$d\sigma^{\ell p\to\ell' hX} = \sum_q f_q(x,Q^2)\otimes d\sigma^{\ell q\to\ell' q}\otimes D_q^h(z,Q^2)$ where, in collinear PM $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2 = x[1+(1-y)^2]$, i.e. no ϕ_h dependence. Taking into account the parton transverse momentum in the kinematics leads to:

$$\hat{s} = sx\left[1-\frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi_h\right]+\mathcal{O}\left(\frac{k_\perp^2}{Q}\right) \quad \hat{u} = sx(1-y)\left[1-\frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi_h\right]+\mathcal{O}\left(\frac{k_\perp^2}{Q}\right)$$

Resulting in the $\cos\phi_h$ and $\cos 2\phi_h$ modulations observed in the azimuthal distributions

SIDIS access to TMDs

$$\sigma(\ell p \to \ell' hX) \sim q(x) \otimes \hat{\sigma}^{\gamma q \to q} \otimes D_q^h(z)$$

TMDs $(x, \vec{k}_\perp)$

FFs $(z, \vec{p}_\perp)$

Nucleon polarization

Parton polarization	U	T	L
U	f_1	$f_{1T}^\perp$	
T	$h_1^\perp$	$h_1, h_{1T}^\perp$	$h_{1L}^\perp$
L		g_{1T}	g_{1L}

Hadron polarization

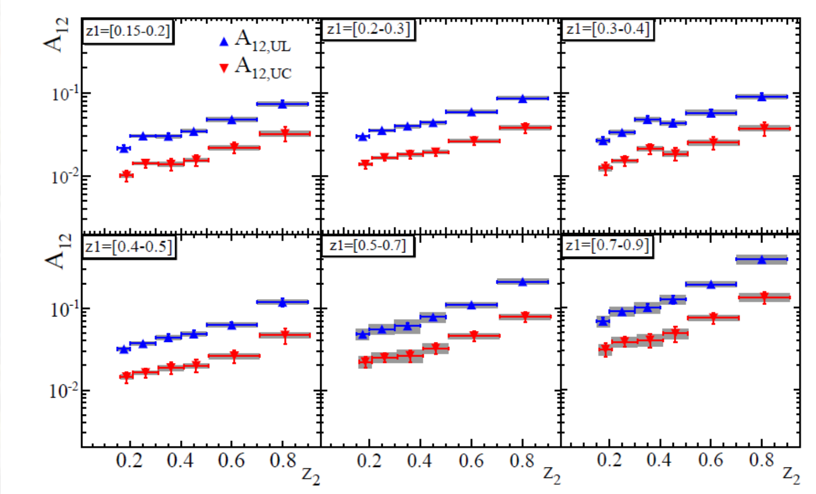
Parton polarization	U	T	L
U	D_1	$D_{1T}^\perp$	
T	$H_1^\perp$	H_1 , $H_{1T}^\perp$	$H_{1T}^\perp$
L		G_{1T}	G_{1L}

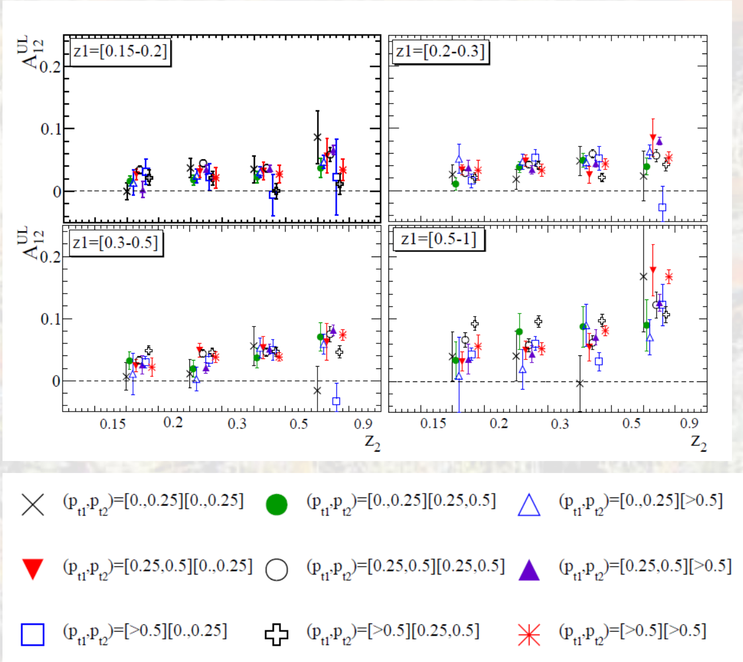
T odd

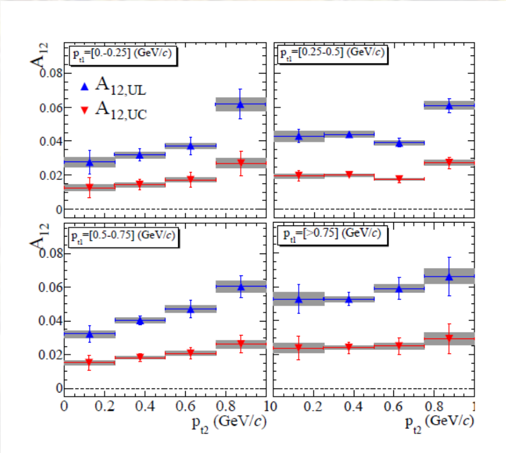
chiral odd

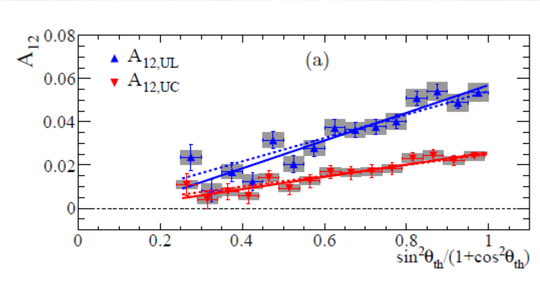
Factorisation (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

Collins asymmetry on e^+e^-



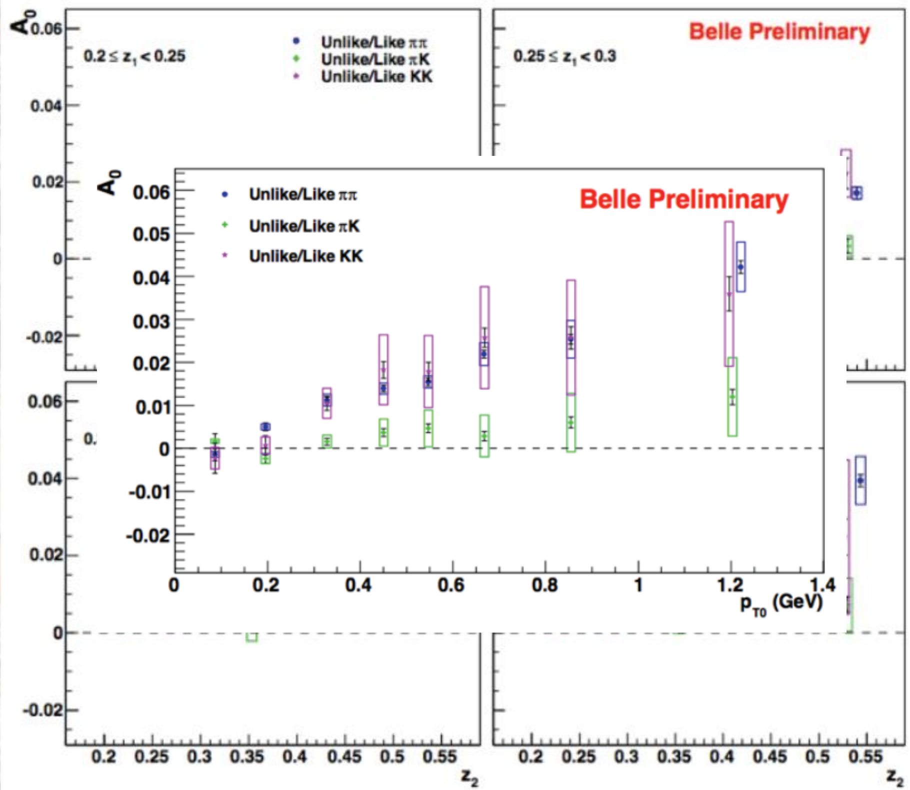


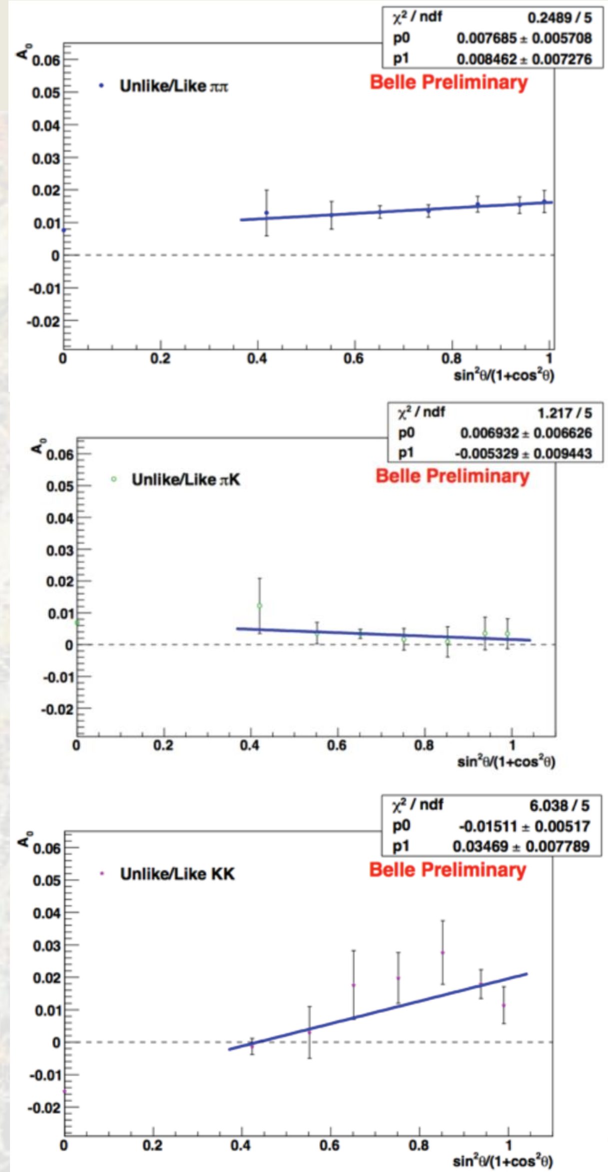




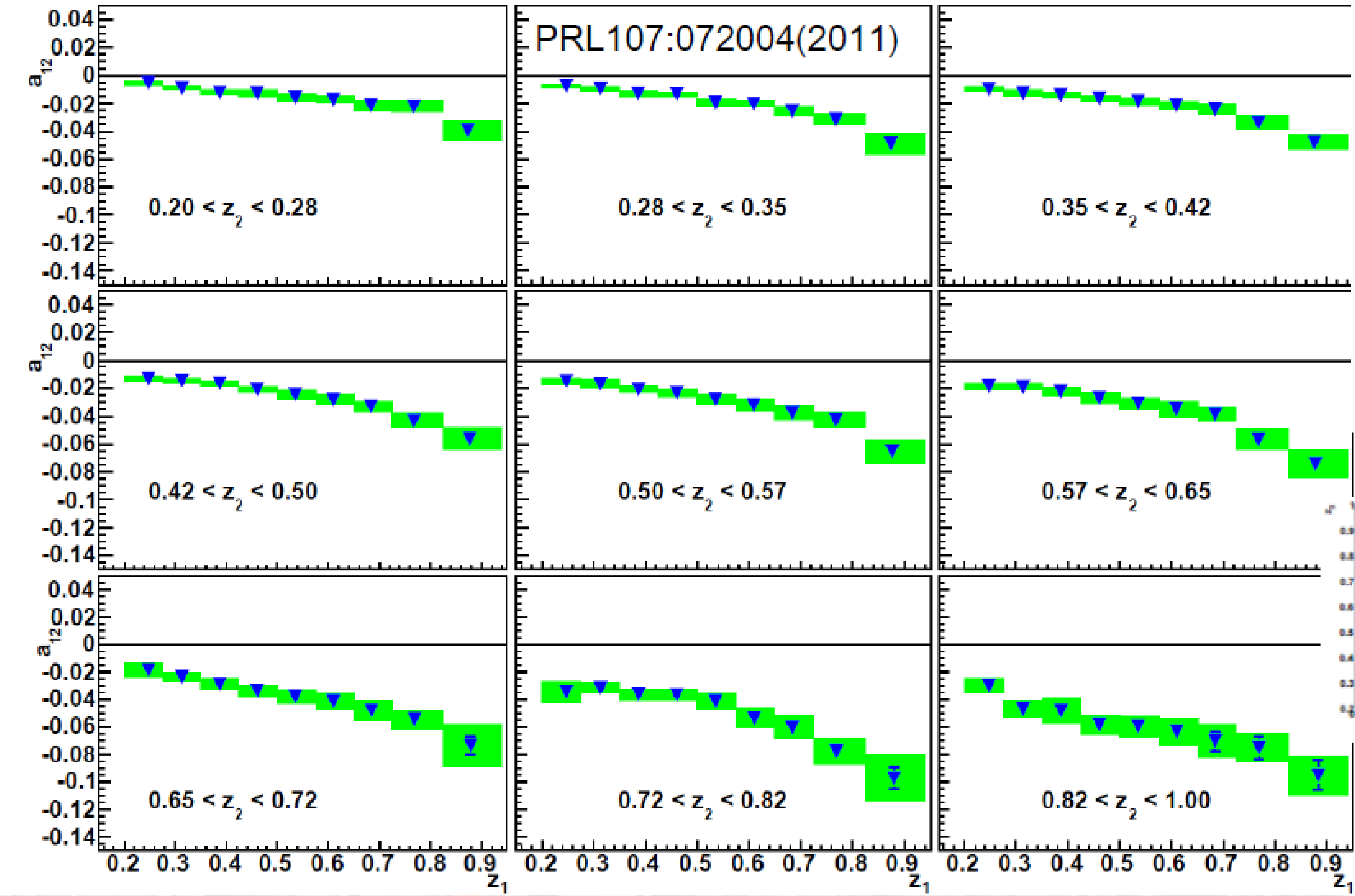
Collins asymmetry on e^+e^-

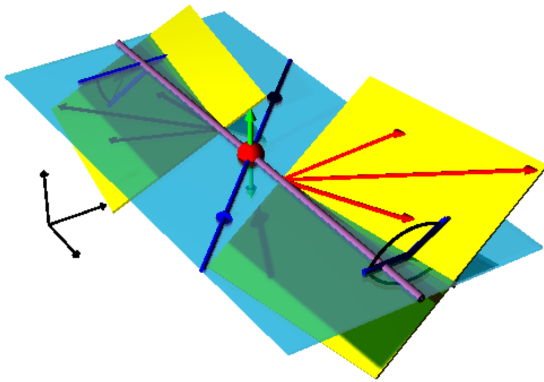
$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2
πK => asymmetries compatible, with zero
KK => non-zero asymmetries, increase with z_1,z_2

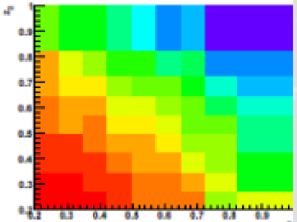




IFF asymmetry on e^+e^-

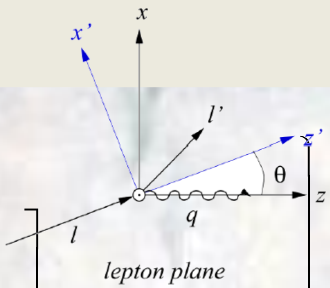




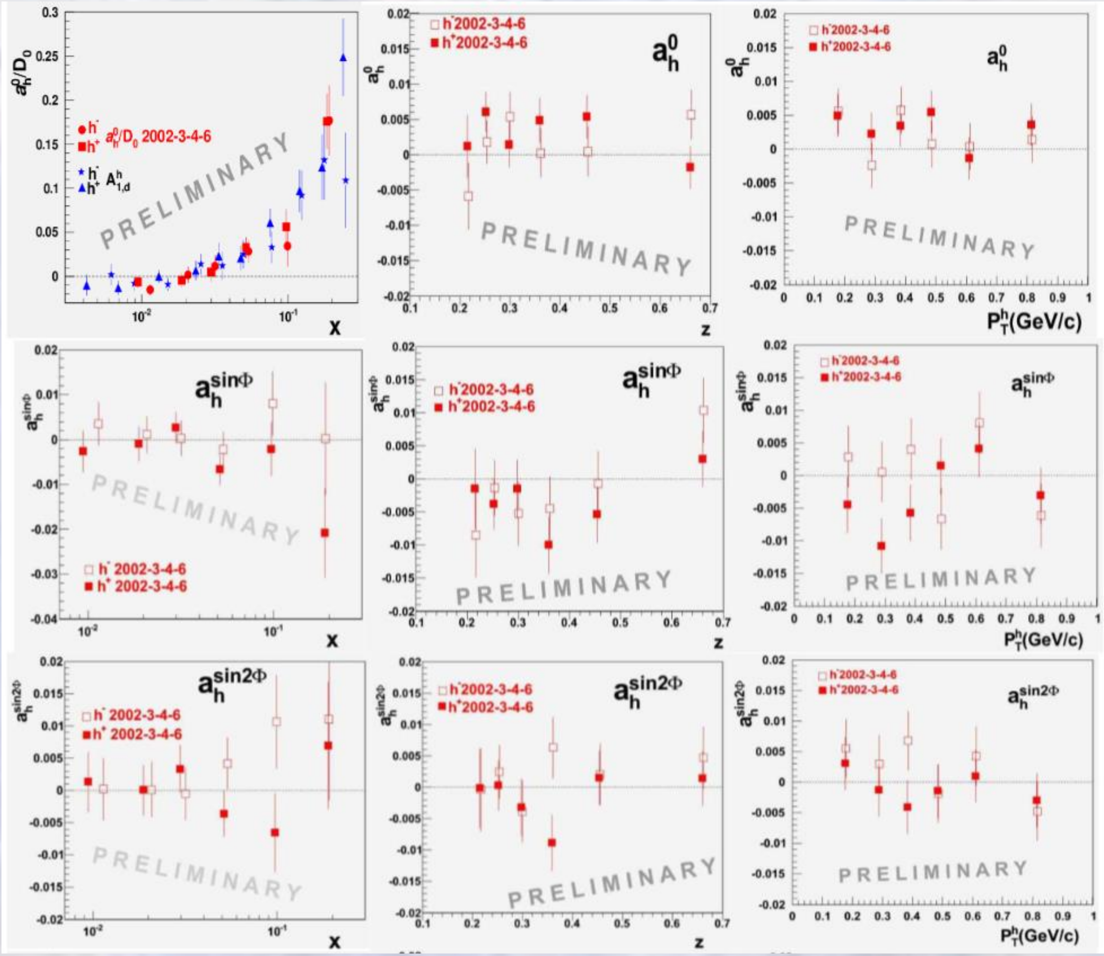


SIDIS 1h x-section

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\varphi_h\,d\varphi_S} = \left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\varphi_S}\right]\left[\frac{\alpha^2}{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 \\
&\Bigg\{ 1+\cos\varphi_h\times\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_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}+ \\
&\frac{\mathbf{P}_T}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\sin\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\varphi_S}\right)+ \\
&\quad\sin(\varphi_h-\varphi_S)\times\left(\cos\theta A_{UT}^{\sin(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad\sin(\varphi_h+\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(\varphi_h+\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad\sin(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+ \\
&\quad\sin(3\varphi_h-\varphi_S)\times\left(\cos\theta\varepsilon A_{UT}^{\sin(3\varphi_h-\varphi_S)}\right)+\sin(2\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\varepsilon A_{UL}^{\sin 2\varphi_h}\right)+\Bigg]+ \\
&\frac{\mathbf{P}_T\lambda}{\sqrt{1-\sin^2\theta\sin^2\varphi_S}}\Bigg[\cos\varphi_S\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\varphi_S}+\sin\theta\sqrt{(1-\varepsilon^2)}A_{LL}\right)+ \\
&\quad\cos(\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{\left(1-\varepsilon^2\right)}A_{UT}^{\cos(\varphi_h-\varphi_S)}+\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)+ \\
&\quad\cos(2\varphi_h-\varphi_S)\times\left(\cos\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{UT}^{\cos(2\varphi_h-\varphi_S)}\right)+\cos(\varphi_h+\varphi_S)\times\left(\frac{1}{2}\sin\theta\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\varphi_h}\right)\Bigg]\Bigg\}
\end{aligned}
$$



Longitudinal modulations



The asymmetries

- The asymmetries are:

$$A_{U(L),T}^{w(\phi_h,\phi_S)}(x,z,p_T;Q^2) = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

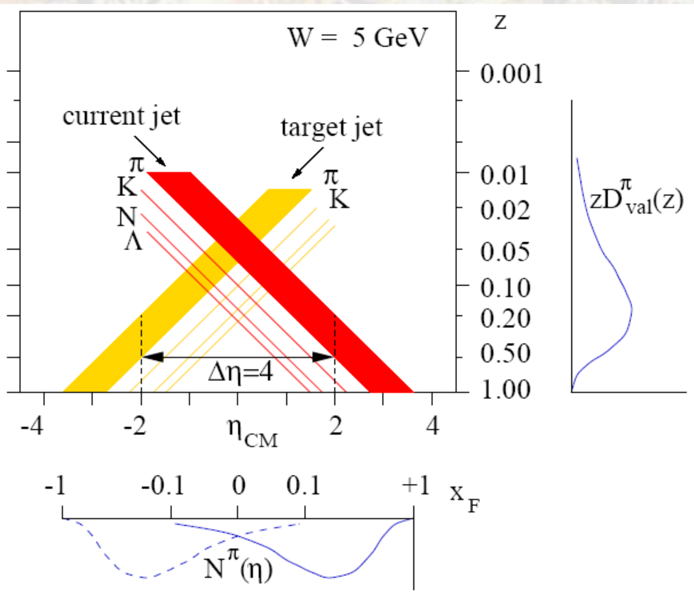
- When we measure on 1D

$$A_{U(L),T}^{w(\phi_h,\phi_S)}(x) = \frac{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T F_{U(L),T}^{w(\phi_h,\phi_S)}}{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T \left(F_{UU,T} + \varepsilon F_{UU,L}\right)}$$

Ed. Berger criterion (separation of CFR &TFR)

The typical hadronic correlation length in rapidity is

$$\Delta y_h \simeq 2$$



if the dynamics of quark fragmentation is to be studied independently of "contamination" from target fragmentation, it is necessary that $Y \gtrsim 4$, or, equivalently, that

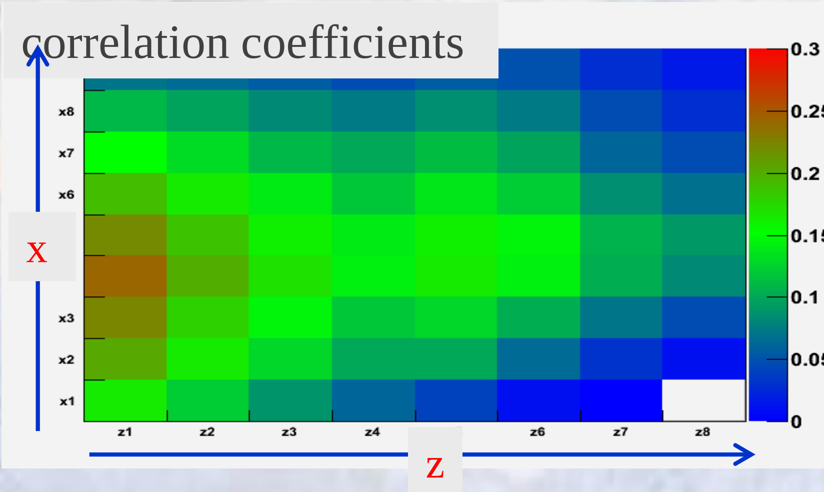
$$W_X = \left[\frac{Q^2(1-x)}{x}\right]^{1/2} \gtrsim 7.4\,\mathrm{GeV}. \qquad (17)$$

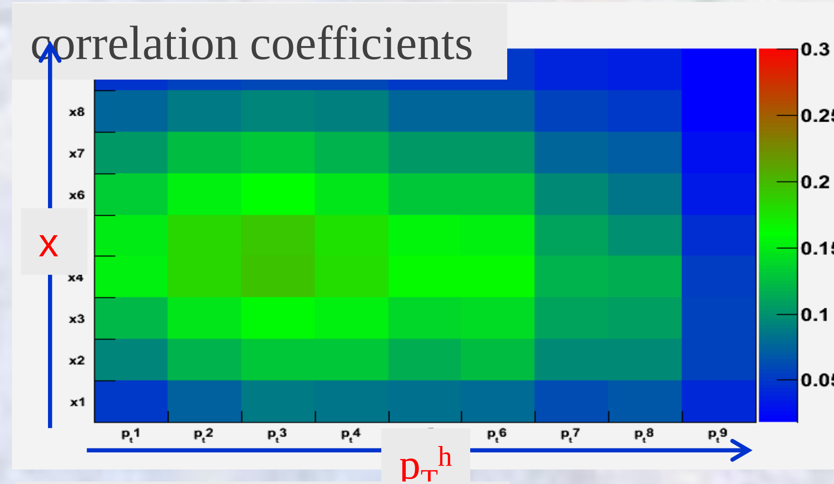
If the inequality Eq. (17) is satisfied, it should be possible to measure fragmentation functions $D(z, Q^2)$ over essentially the full range of z, $0 < z < 1$. Somewhat smaller values of W_X may be adequate if attention is restricted to the large z region. As Y is increased above 2, or

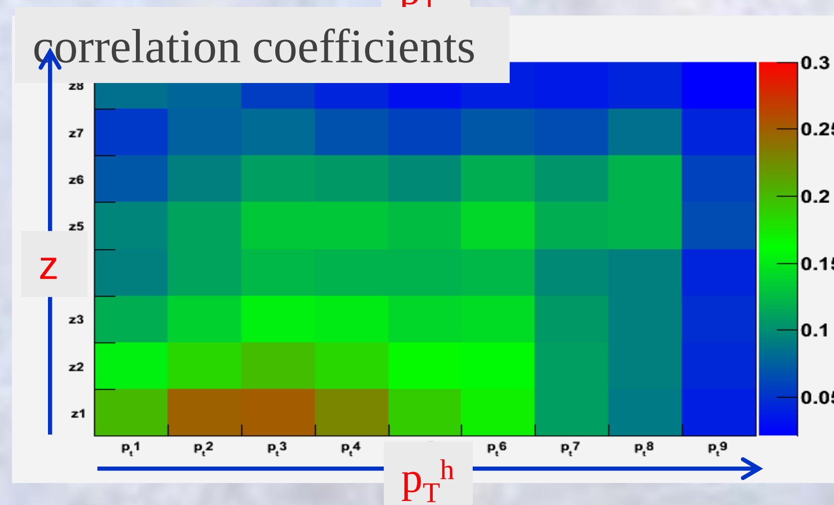
$$W_X \gtrsim 3\ \mathrm{GeV}, \qquad (18)$$

the quark and target fragmentation regions begin to separate. As long as $Y \gtrsim 2$, the hadrons with the largest values of z are most likely quark fragments. Data[14] from $e^+e^- \to hX$ show that a distinct function $D(z)$ may have developed for $z \gtrsim 0.5$ at $W = 3$ GeV. The region extends to $z \simeq 0.2$ for $W = 4.8$ GeV, and to $z \simeq 0.1$ for $W = 7.4$ GeV. For $z > 0.3$, fragmentation functions have been obtained from data[15] on $ep \to e'\pi^{\pm}X$ at $E = 11.5$ GeV, with $3 < W_X < 4$ GeV.

Statistical correlations







charged pions

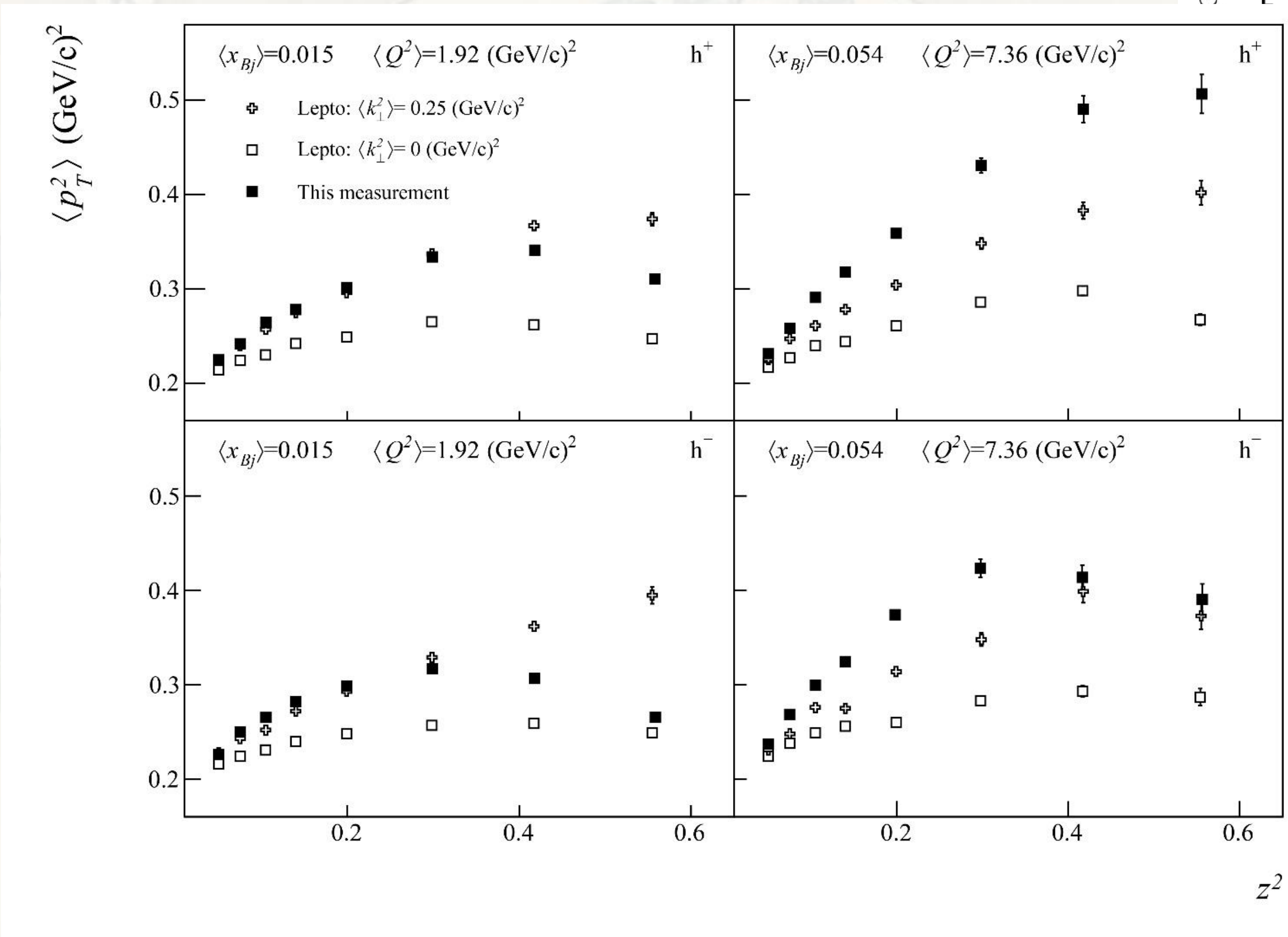
also available for

charged hadrons

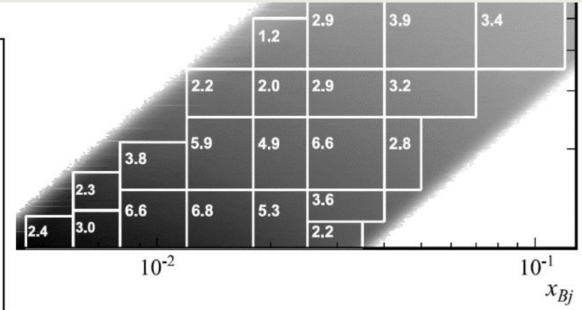
charged kaons

have to be taken into account

Mean values

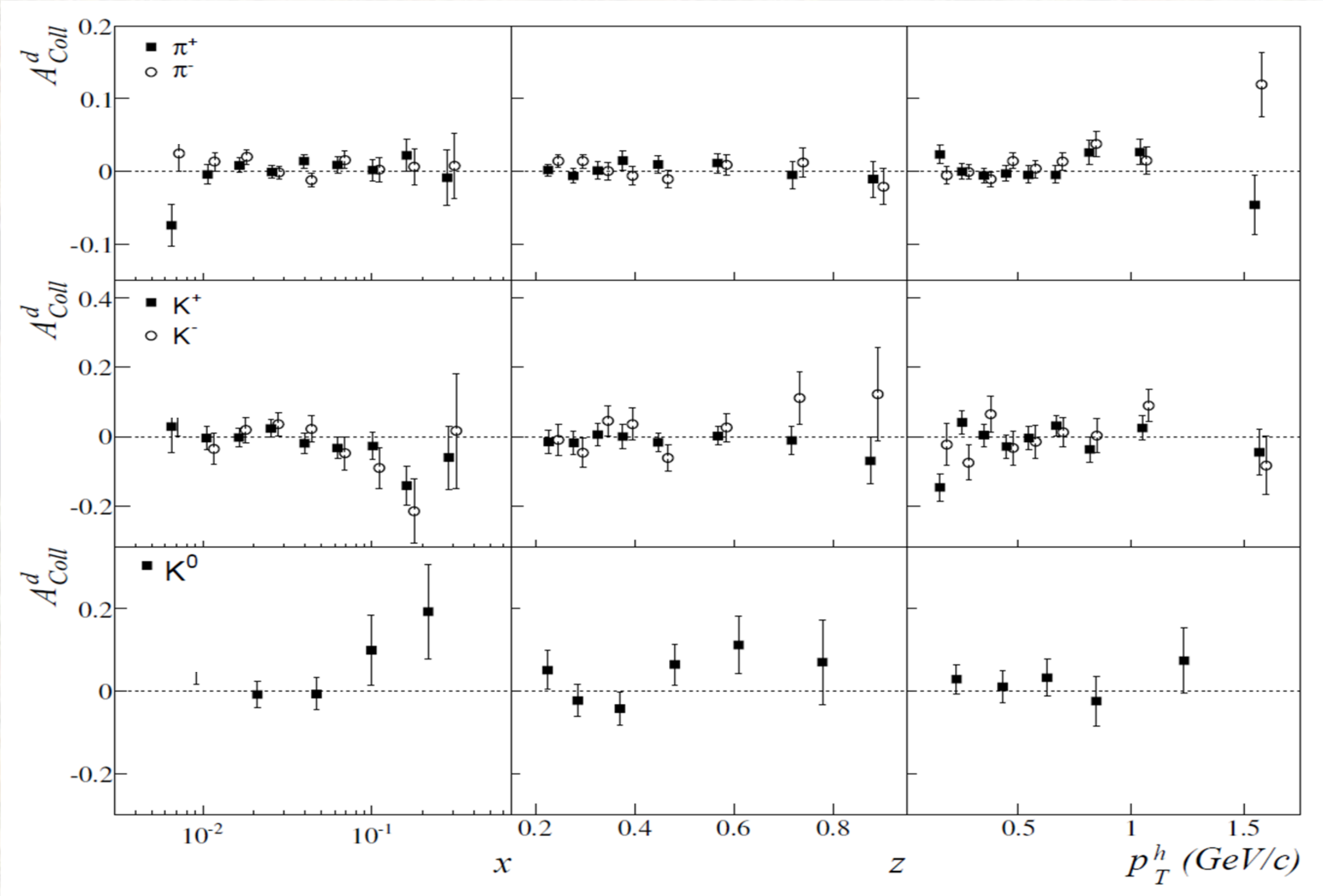


$\langle p_T^2 \rangle$ (GeV/c)^2
$\langle x_{Bj} \rangle$=0.015 $\langle Q^2 \rangle$=1.92 (GeV/c)^2 h$^+$
$\langle x_{Bj} \rangle$=0.054 $\langle Q^2 \rangle$=7.36 (GeV/c)^2 h$^+$
$\langle x_{Bj} \rangle$=0.015 $\langle Q^2 \rangle$=1.92 (GeV/c)^2 h$^-$
$\langle x_{Bj} \rangle$=0.054 $\langle Q^2 \rangle$=7.36 (GeV/c)^2 h$^-$
Lepto: $\langle k_\perp^2 \rangle$= 0.25 (GeV/c)^2
Lepto: $\langle k_\perp^2 \rangle$= 0 (GeV/c)^2
This measurement
0.2
0.3
0.4
0.5
0.2
0.4
0.6
z^2



2.9
3.9
3.4
1.2
2.2
2.0
2.9
3.2
5.9
4.9
6.6
2.8
3.8
2.3
6.6
6.8
5.3
3.6
2.4
3.0
2.2
10^{-2}
10^{-1}
x_{Bj}

Collins asymmetry on deuteron

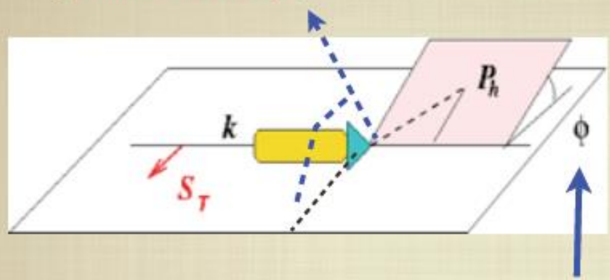


T h e o t h e r w a y t o

Y T I S R E V S N A R T

The Collins mechanism

J. Collins, NPB396 (93)



Collins angle

$$\mathbf{k} \times \mathbf{P}_h \cdot \mathbf{S}_T \propto \cos\left(\frac{\pi}{2} - \phi\right) = \sin\phi$$

transverse motion of hadron

=

spin analyzer of fragmenting quark

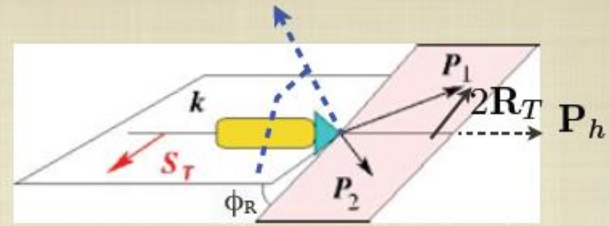
single-spin asymmetry → **convolution**

$$A_{UT}^{\sin(\phi)} \propto \left[h_1^q \otimes H_1^{\perp\, q\to h}\right]$$

TMD factorization

The Di-hadron Fragm. Funct. mechanism

Collins, Heppelman, Ladinsky, NP B420 (94)



$P_{hT}=0$
collinear!

$$\mathbf{P}_h \times \mathbf{R}_T \cdot \mathbf{S}'_T \propto \cos(\phi_{S'_T} - (\phi_{R_T} + \pi/2))$$
$$= \cos(\pi - \phi_S - (\phi_{R_T} + \pi/2))$$
$$= \sin(\phi_{R_T} + \phi_S)$$

azimuthal orientation of hadron pair

=

spin analyzer of fragmenting quark

single-spin asymmetry → **product**

$$A_{UT}^{\sin(\phi_R+\phi_S)} \propto h_1^q(x)\, H_1^{\sphericalangle\, q\to h_1 h_2}(z, R_T^2)$$

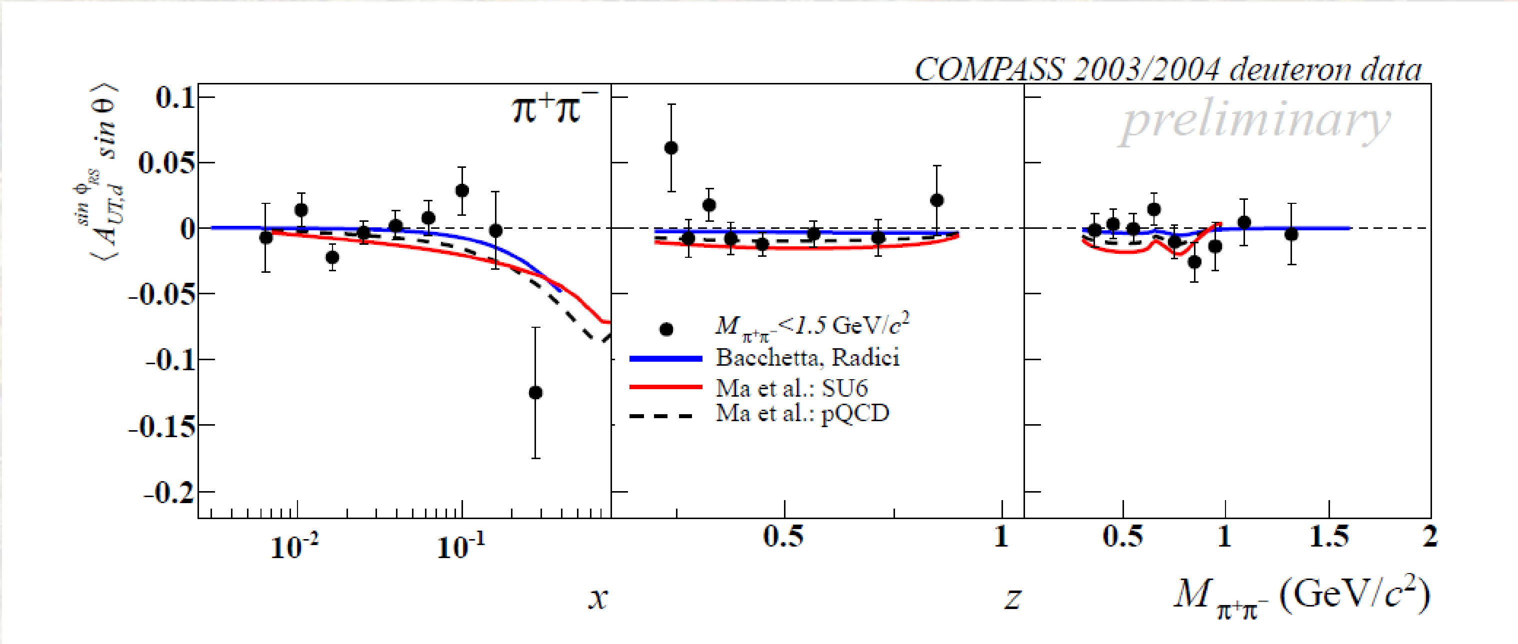
Radici, Jakob, Bianconi PR D65 (02); Bacchetta, Radici, PR D67 (03)

collinear factorization

evolution equations understood

Ceccopieri, Radici, Bacchetta, P.L. B650 (07)

2h asymmetries on d



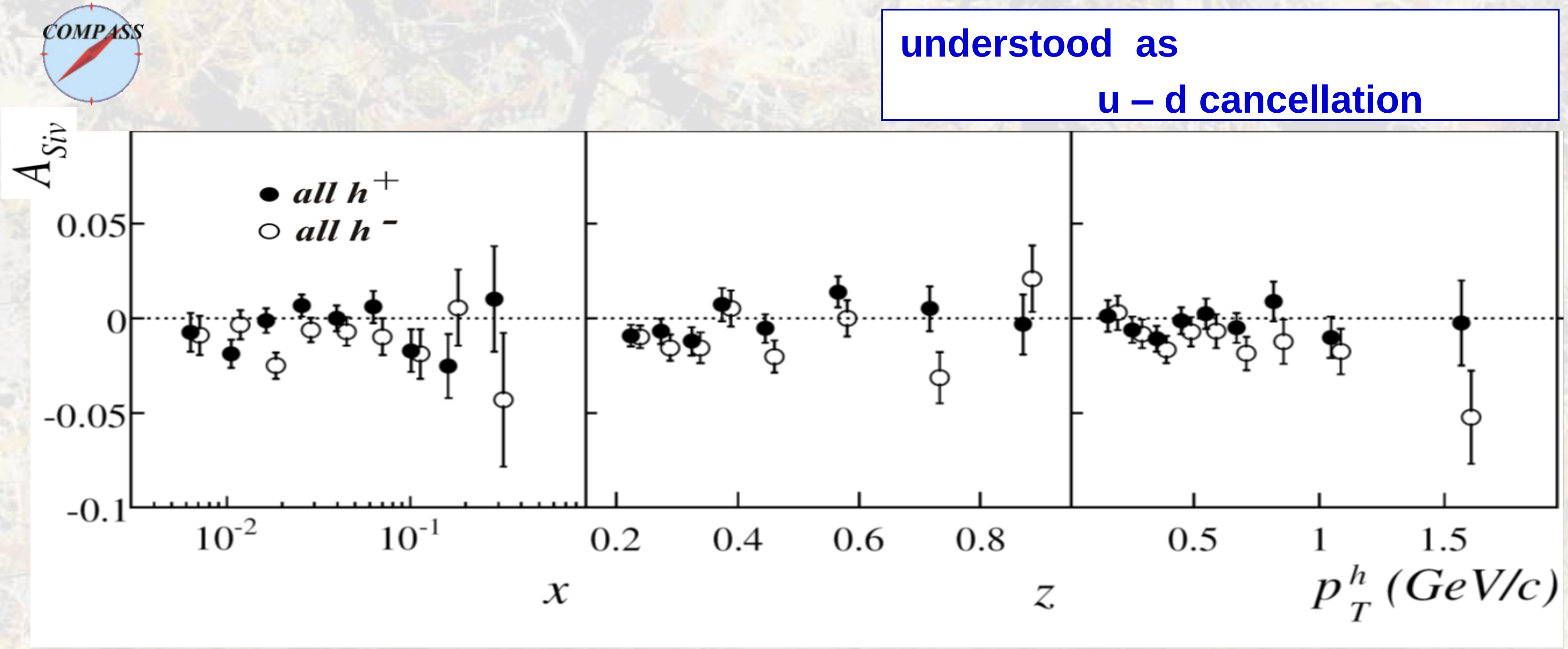
$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1h_2}^{\sphericalangle}\left(z, \mathcal{M}_{h_1h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1h_2}\left(z, \mathcal{M}_{h_1h_2}^2\right)}$$

Sivers asymmetry on deuteron

PLB 673 (2009) 127

understood as

u – d cancellation



$$f_{1T,u}^{\perp} \approx -f_{1T,d}^{\perp}$$