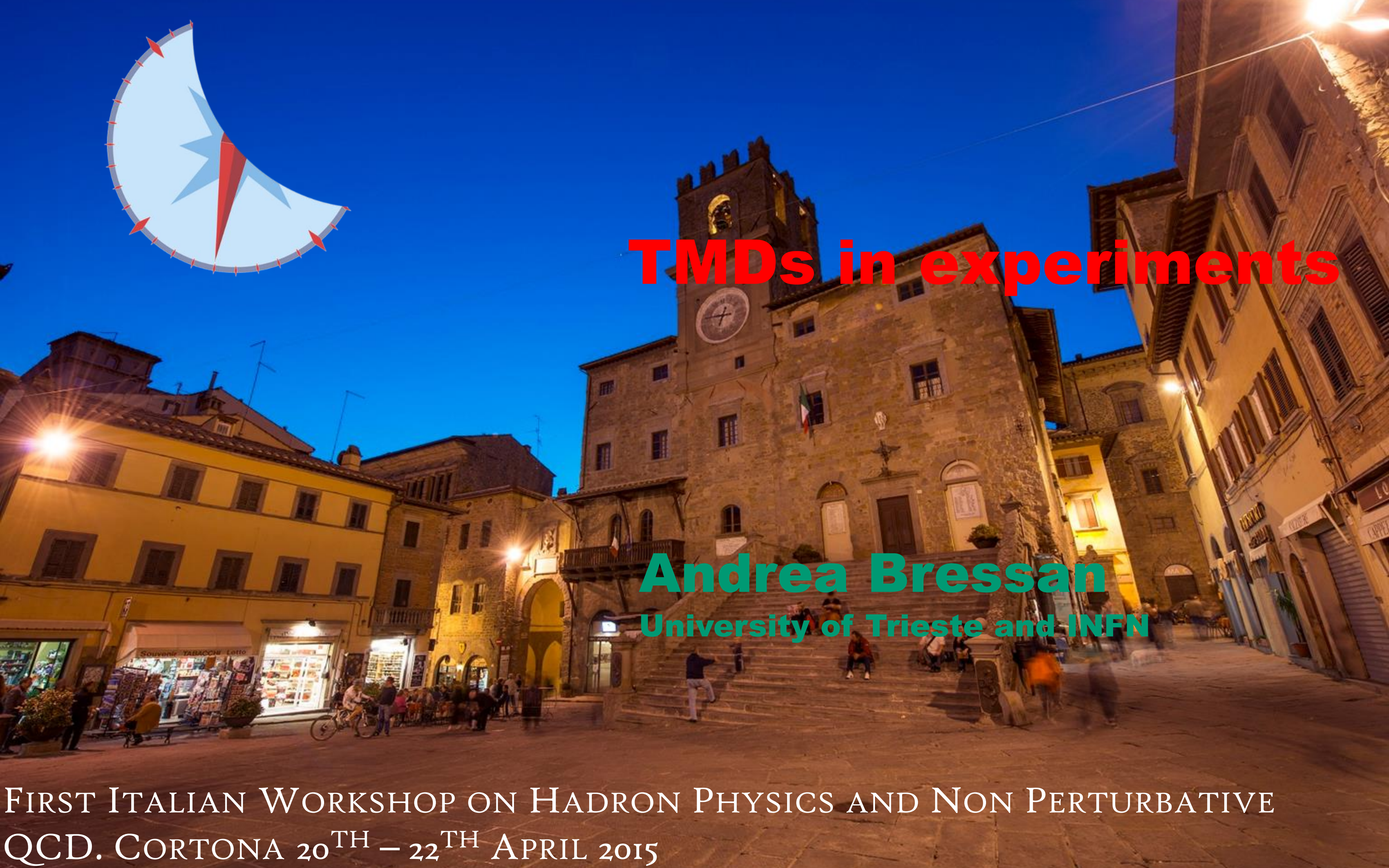

TMDs in experiments

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First Italian Workshop on Hadron Physics and Non Perturbative QCD. Cortona 20th – 22th April 2015

Boosting transverse Spin

Let's take a Dirac free plane wave particle of mass m and spin $\vec{S} = S_z\hat{z} = \frac{1}{2}\hat{z}$, and boost it by $\beta = p/E$ along $\hat{x}$

$$\vec{p} = 0 \qquad\qquad \vec{p} = p\hat{x}$$

$$\psi = \frac{1}{2}\begin{pmatrix}1\\0\\0\\0\end{pmatrix}e^{-imt} \xRightarrow{\text{boost by }\beta\hat{x}} \psi = N\begin{pmatrix}1\\0\\0\\\frac{p}{E+m}\end{pmatrix}e^{-i(px-Et)t}$$

And for Spin?

$$\frac{\psi^\dagger\Sigma\psi}{\psi^\dagger\psi} = \hat{z} \qquad \Sigma = \begin{pmatrix}\sigma & 0\\0 & \sigma\end{pmatrix} \qquad \frac{\psi^\dagger\Sigma\psi}{\psi^\dagger\psi} = \hat{z}\left(1-\left(\frac{p}{E+m}\right)^2\right)$$

$$\sigma = \begin{pmatrix}\hat{z} & \hat{x}-i\hat{y}\\ \hat{x}+i\hat{y} & -\hat{z}\end{pmatrix} \qquad \frac{\psi^\dagger\Sigma\psi}{\psi^\dagger\psi} = \frac{1}{\gamma^2}\hat{z}$$

Boosting orbital angular momenta

Simple orbit with L_z only ($p_z = 0, z = 0 \Longrightarrow L_x = L_y = 0$)

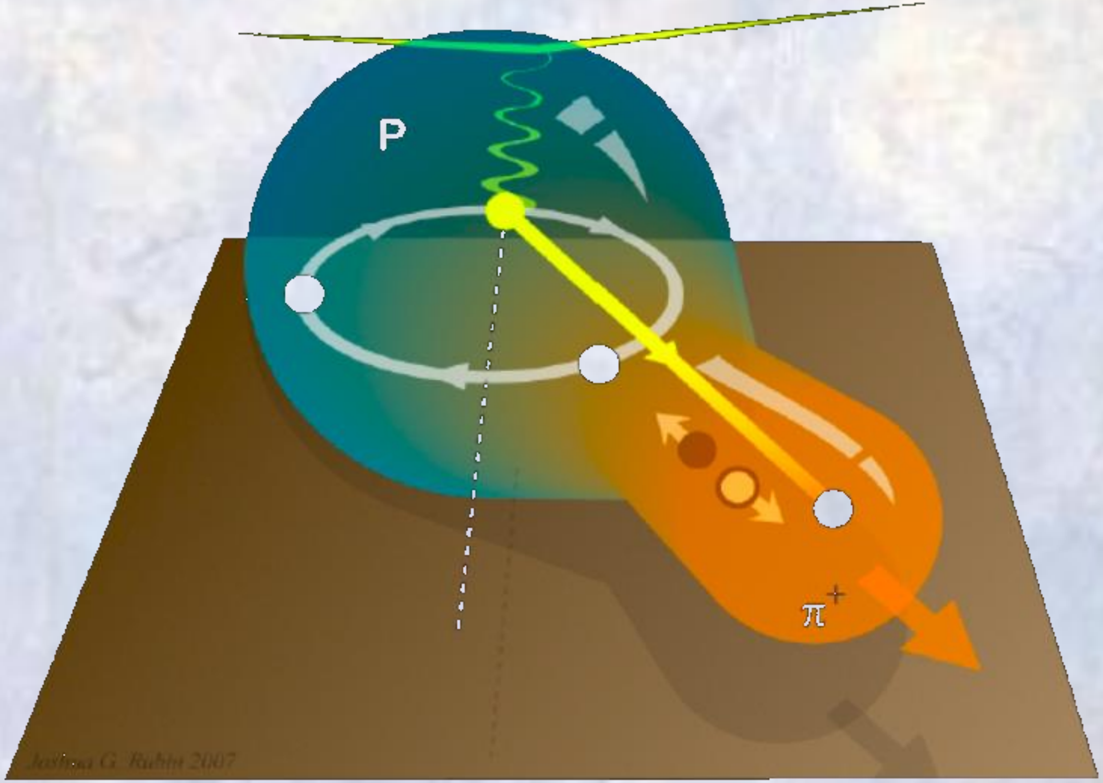
$$M^{\mu\nu} = x^\mu p^\nu - x^\nu p^\mu = \begin{pmatrix} 0 & tp_x - xE & tp_y - yE & 0 \\ \cdot & 0 & L_z & 0 \\ \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & 0 \end{pmatrix}$$

Boosting $\beta = p/E$ along $\hat{x}$

$$(M')^{ab} = \Lambda^a_\mu \Lambda^b_\nu M^{\mu\nu} = \begin{pmatrix} 0 & tp_x - xE & \gamma\left[\left(tp_y - yE\right) - \beta L_z\right] & 0 \\ \cdot & 0 & \gamma\left[L_z - \beta\left(tp_y - yE\right)\right] & 0 \\ \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & 0 \end{pmatrix}$$

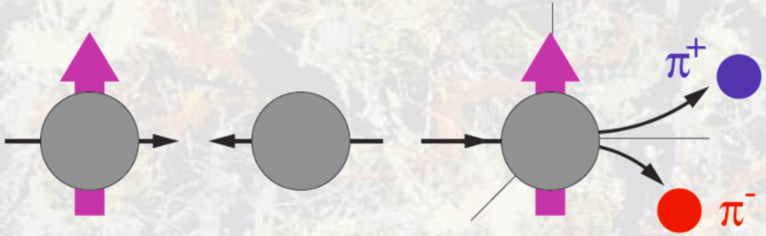
So $L'_z = \gamma L_z - \gamma\beta p_y(ct) + \gamma\beta y(E/c) \approx \gamma L_z - \vec{r}_{cm}(t) \times \vec{p}$

TMD and Single Spin Asymmetries

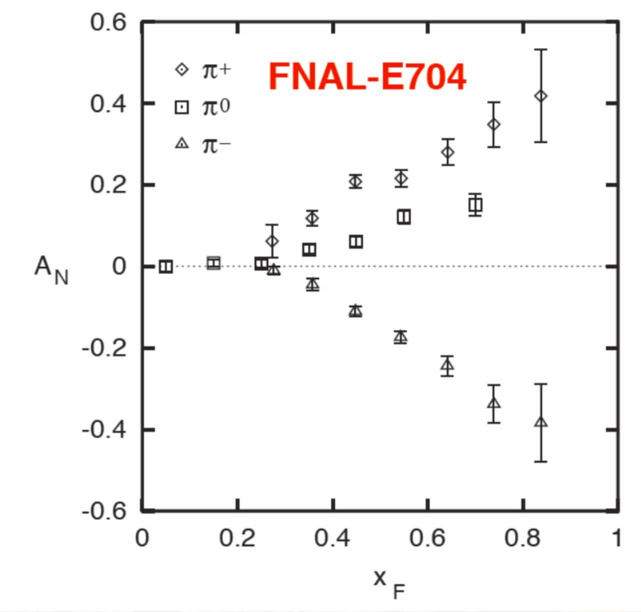


The (re)start: SSA in $p^{\uparrow}p \longrightarrow \pi X$

Huge ***SSA*** for ***forward*** meson production measured by E704 in 1991



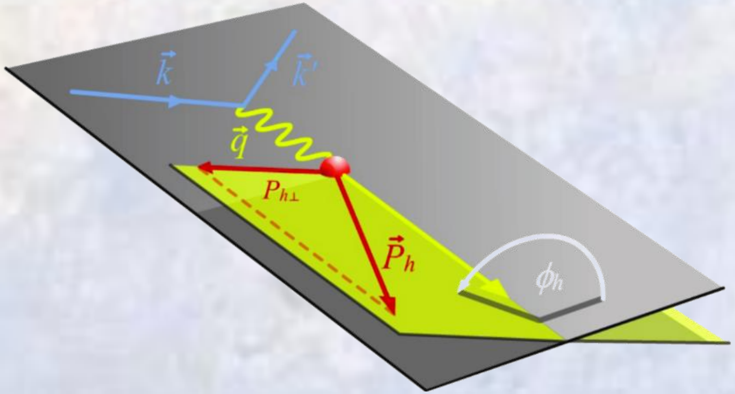
$$A_N = \frac{1}{p_{\text{Beam}}} \frac{N^{\pi}_{\text{left}} - N^{\pi}_{\text{right}}}{N^{\pi}_{\text{left}} + N^{\pi}_{\text{right}}}$$

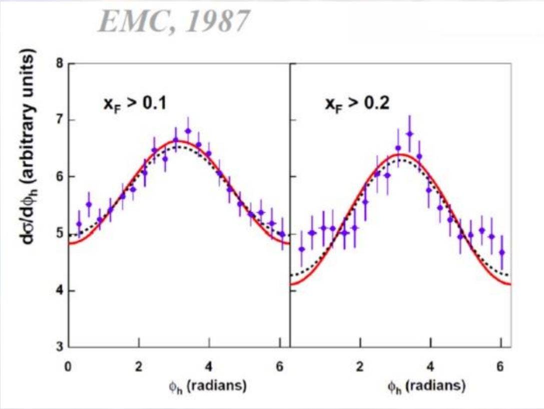


The observable is $\propto \vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$, odd under naïve time reversal (time reversal without interchange of initial and final states)

(Re)start: another TM effect

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





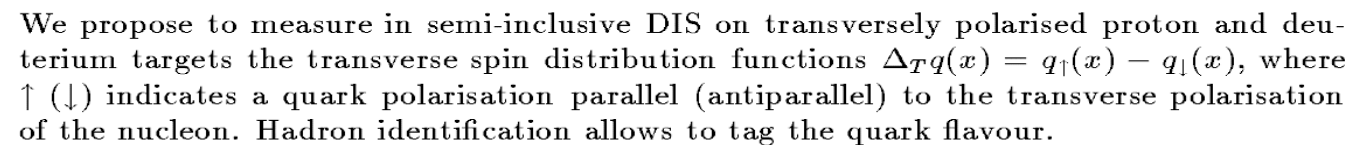
$d\sigma^{\ell p\to\ell' hX} = \sum_q f_q(x,Q^2)\otimes d\sigma^{\ell q\to\ell' q}\otimes D_q^h(z,Q^2)$ where, in collinear PM $d\sigma^{\ell q\to\ell' q} = \hat{s}^2+\hat{u}^2 = x[1+(1-y)^2]$, i.e. no ϕ_h dependence. Taking into account the parton transverse momentum in the kinematics leads to:

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

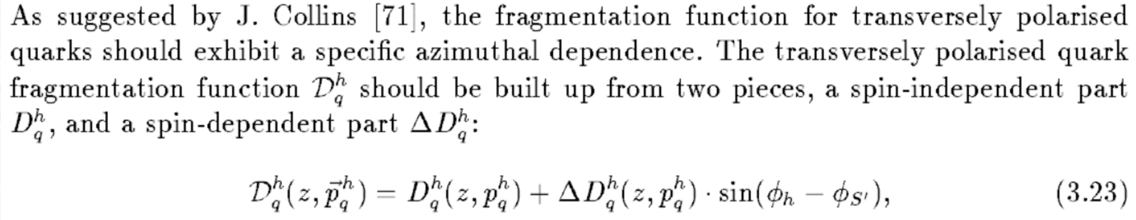
Resulting in the $\cos\phi_h$ and $\cos 2\phi_h$ modulations observed in the azimuthal distributions

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:

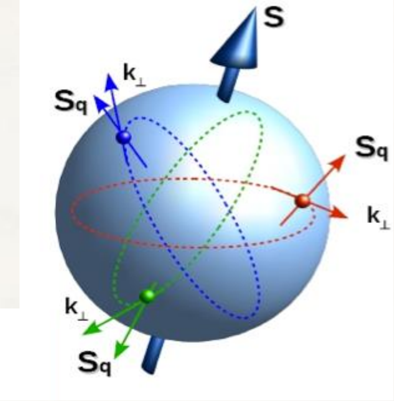
$$\mathcal{D}_q^h(z, \vec{p}_q^{\,h}) = D_q^h(z, p_q^h) + \Delta D_q^h(z, p_q^h) \cdot \sin(\phi_h - \phi_{S'}), \qquad (3.23)$$

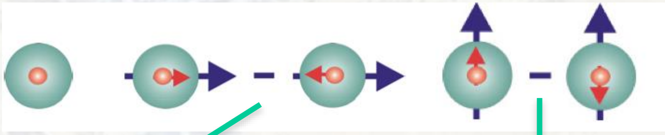
- The measurement of the Sivers PDF was added to the program soon after … the other TMD with the developments over the years
- Measurements started in 2002 by HERMES (p) and COMPASS (d)
- This field has grown considerably in the last years and comes one of high priority measurements for the JLab12 program

The spin of the proton

Three twist-2 quark DF's in collinear approximation ($\int dk_\perp$)

$$\Phi^{\mathrm{Tw-2}}_{\mathrm{Coll}}(x) = \frac{1}{2}\{q(x) + S_L\gamma_5 g_1(x) + S_T\gamma_5\gamma^1 h_1(x)\}n^+$$

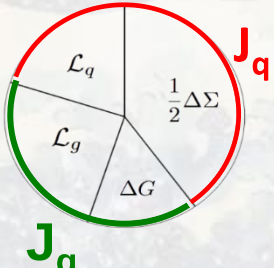




helicity

transversity

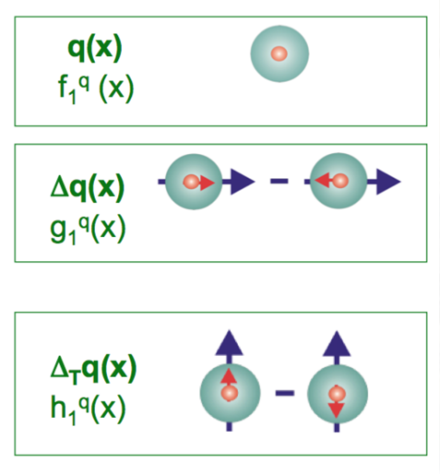
$$\frac{S_z^N}{\hbar} = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$



≈30% : Spin puzzle

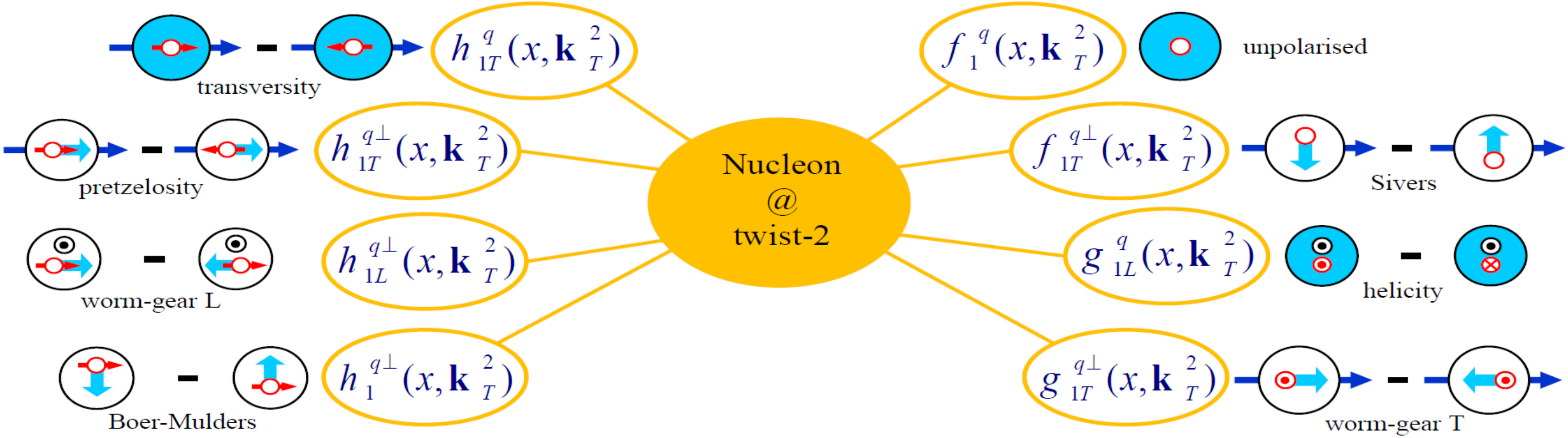
NR limit
[boost, rotat.]=0

➡ $h_1(x,Q^2) = g_1(x,Q^2)$



When $k_\perp$ is taken into account …

TMD Distribution Functions



Nucleon @ twist-2

$h_{1T}^{q}(x,\mathbf{k}_T^2)$ transversity

$h_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ pretzelosity

$h_{1L}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear L

$h_{1}^{q\perp}(x,\mathbf{k}_T^2)$ Boer-Mulders

$f_{1}^{q}(x,\mathbf{k}_T^2)$ unpolarised

$f_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ Sivers

$g_{1L}^{q}(x,\mathbf{k}_T^2)$ helicity

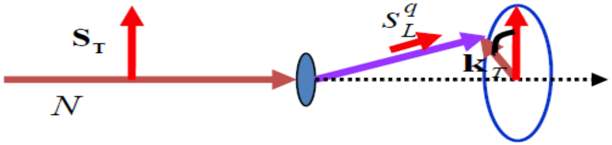
$g_{1T}^{q\perp}(x,\mathbf{k}_T^2)$ worm-gear T

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

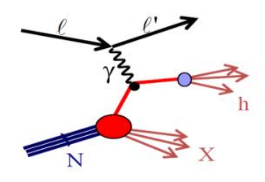
Proton goes out of the screen. Photon goes into the screen



$\mathbf{k}_T$ – intrinsic transverse momentum of the quark

Accessing TMD PDFs and FFs

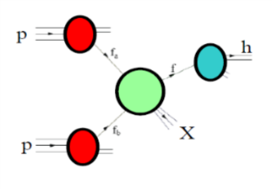
- SIDIS off polarized p, d, n targets



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

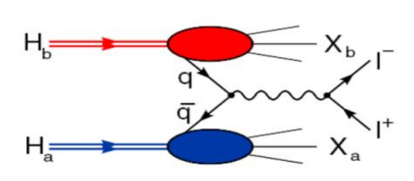
$$\sigma^{\ell p\to\ell' hX}\sim q(x)\otimes\hat{\sigma}^{\gamma q\to q}\otimes D_q^h(z)$$

- hard polarised pp scattering



RHIC

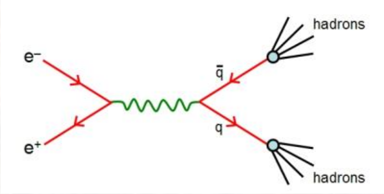
- polarised Drell-Yan



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

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

- $e^+e^-\to h_1h_2$

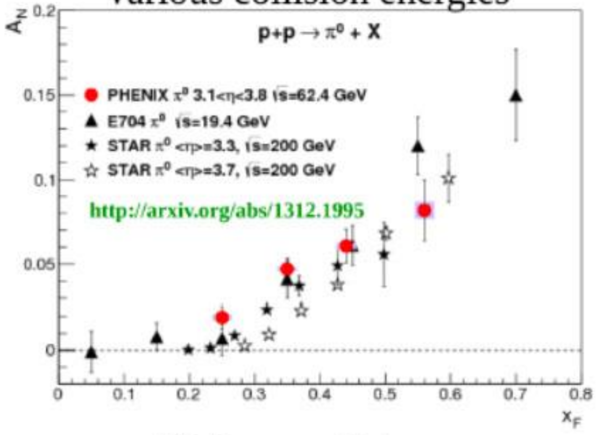


BaBar
Belle
Bes III

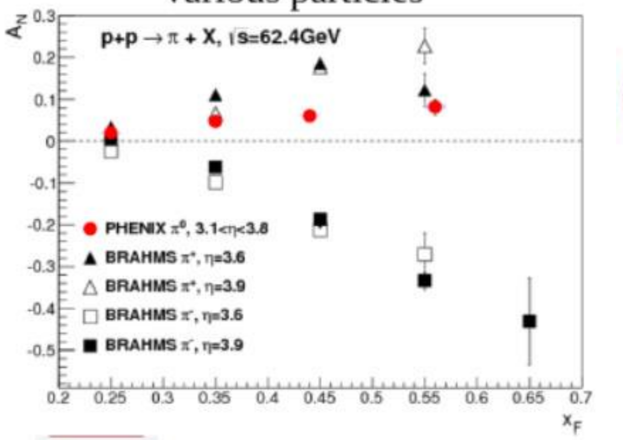
$$\sigma^{e^+e^-\to h_1h_2}\sim\hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s})\otimes D_q^{h_1}(z_1)\otimes D_q^{h_2}(z_2)$$

SSA in $p^{\uparrow}p \longrightarrow \pi X$

Various collision energies



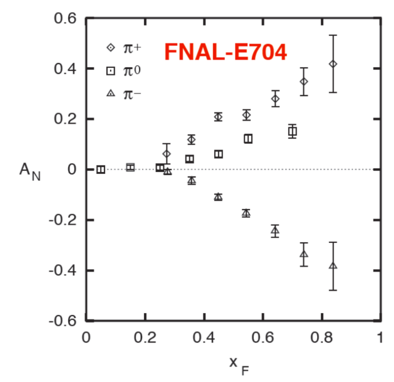
Various particles



STAR

PHENIX

BRAHMS

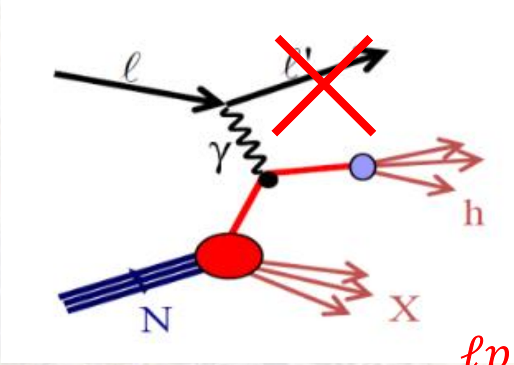


origin not yet clear

to understand it, measurement of A_N in

$\ell N^{\uparrow} \rightarrow \pi X$

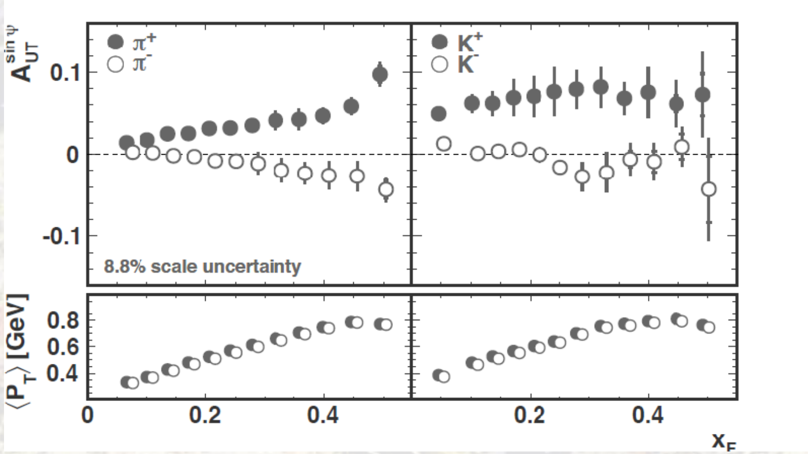
HERMES inclusive SSAs



$\ell p^{\uparrow} \longrightarrow hX$

Relevant kinematic:

- Feynman $x_F =$
- Transverse had
- Azimuthal hadr



π^+ nearly l

π^- similar t

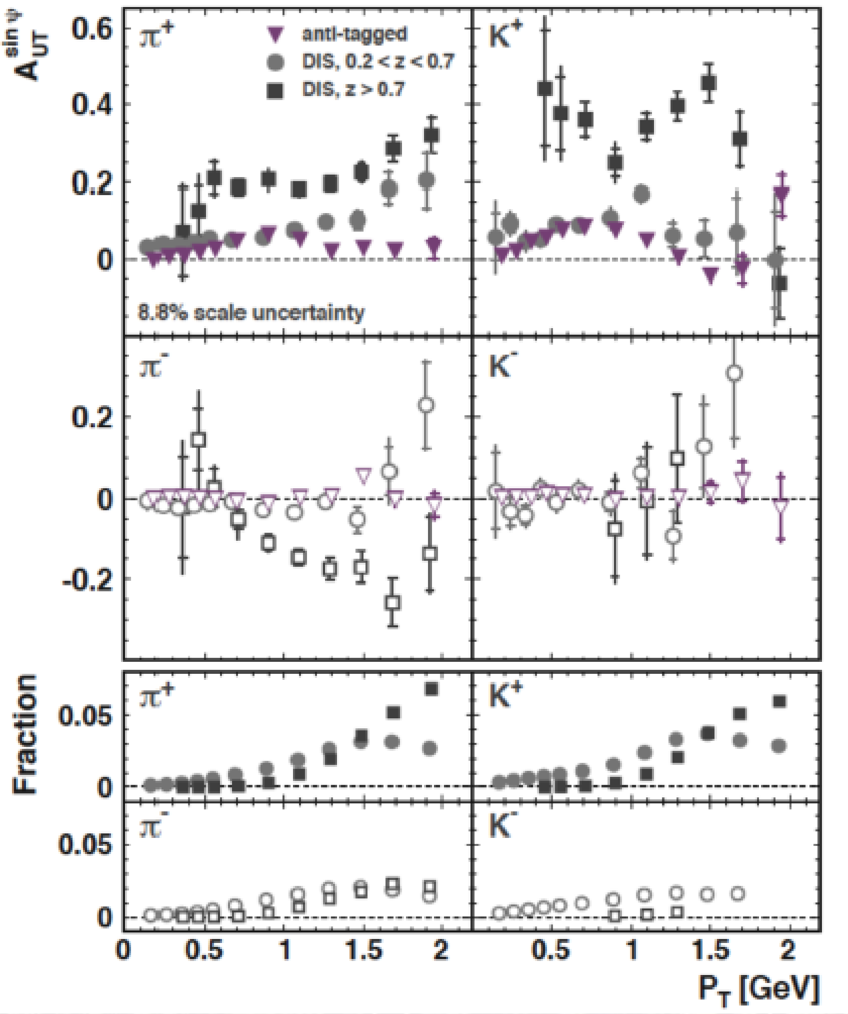
K^+ about c

$K^- \approx 0$

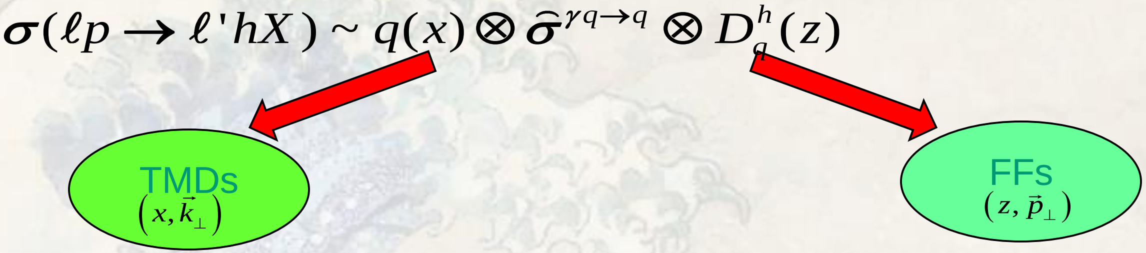
Different be

Asymmetri

for differen



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

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

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...)

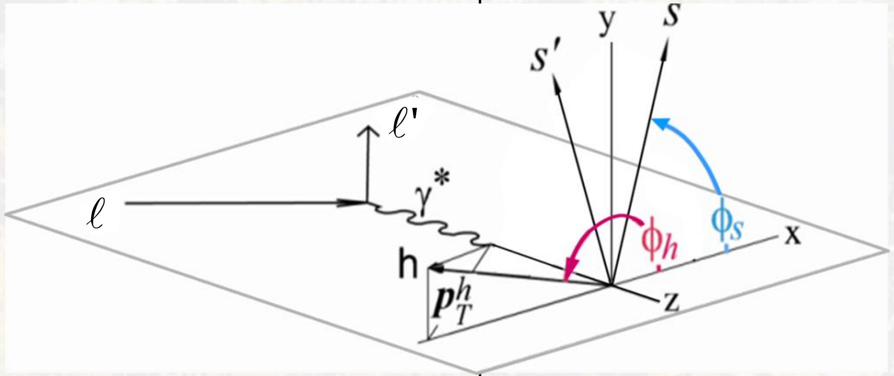
SIDIS 1h x-section

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

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

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

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



LO content

SIDIS

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

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

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

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

$$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h}$$

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

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

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

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

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

DY

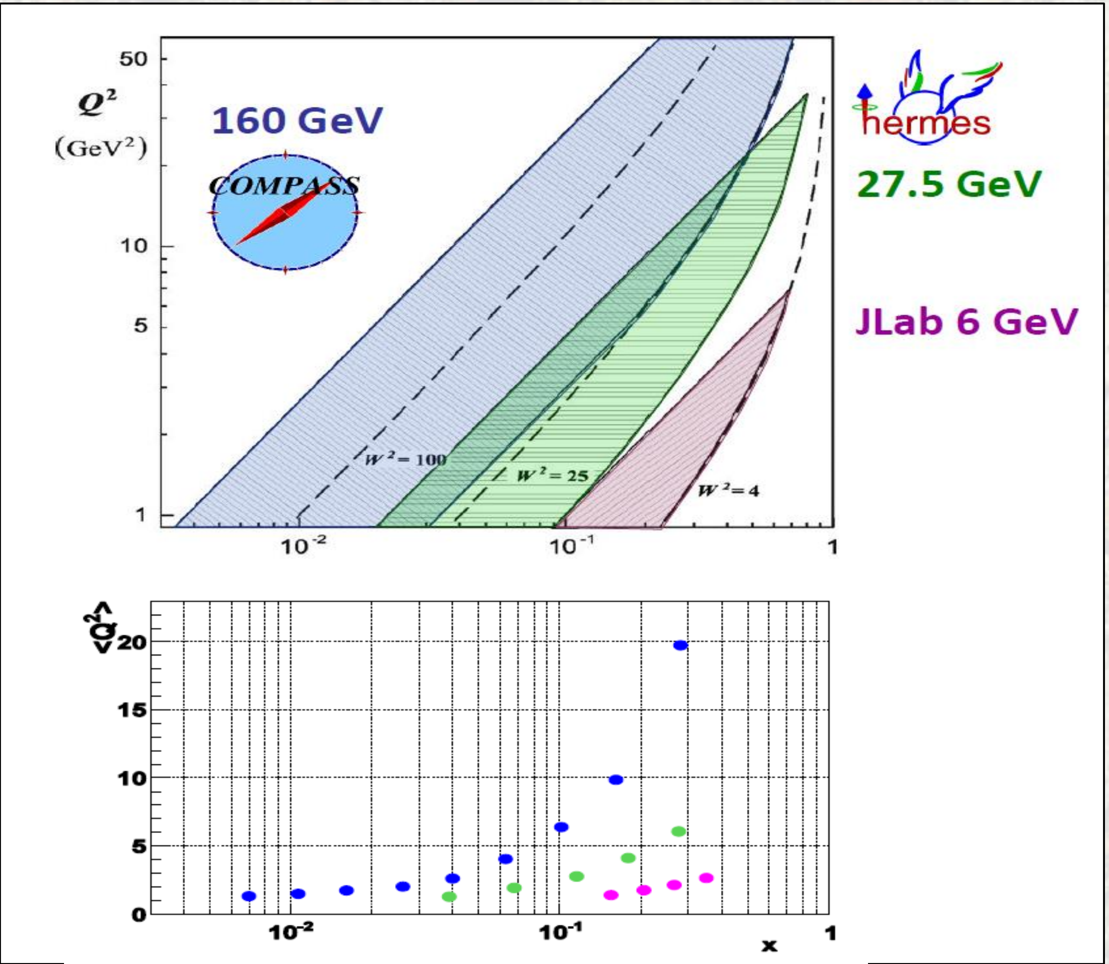
$$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$$

$$A_T^{\sin(2\varphi_{CS} - \varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_1^q$$

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

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

Phase space of different SIDIS - experiments



0.004 < x < 0.3, 25<W²<200GeV²

0.023 < x < 0.4, 10<W²< 50GeV²

0.14 < x < 0.5, 4<W²< 10GeV²

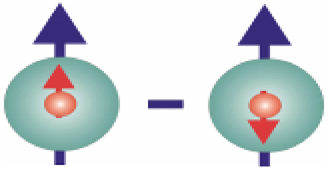
Transversity PDF

$h_1^q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

$\Delta_T q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



$q=u_v, d_v, q_{sea}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound……………… $2|h_1| \leq q + \Delta q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………. $\delta q \equiv \int dx \left[h_1^q(x) - h_1^{\bar{q}}(x) \right]$
- sum rule for transverse spin in PM… $\frac{1}{2} = \frac{1}{2}\sum h_1^q + L_q + L_g$ *Bakker, Leader, Trueman, PRD 70 (04)*
- it is related to GPD's
- is chiral-odd: decouples from inclusive DIS

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

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

$\ell N^{\uparrow} \rightarrow \ell'$ Λ X

"Collins" asymmetry

"Collins" Fragmentation Function

"two-hadron" asymmetry

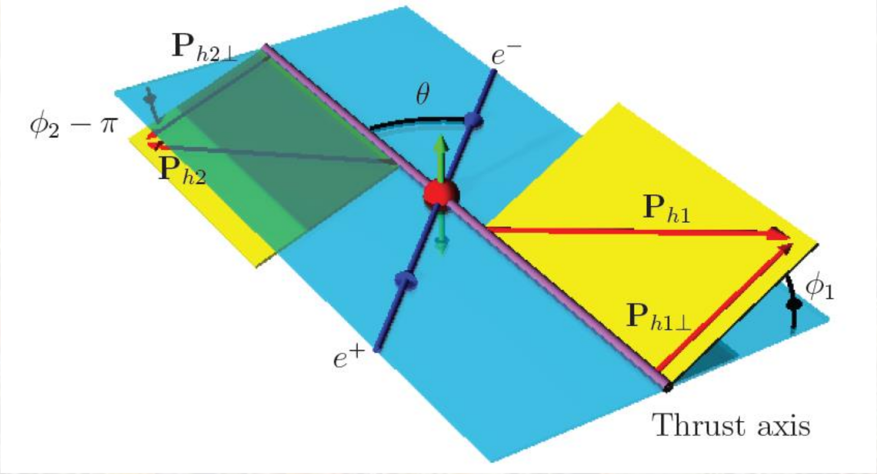
"Interference" Fragmentation Function

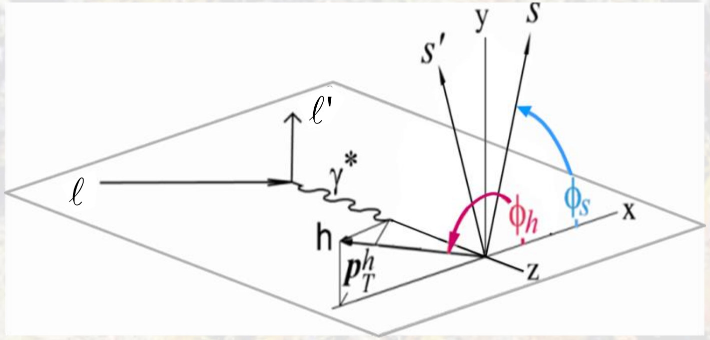
Λ polarisation

Fragmentation Function of q↑→Λ

Transversity from Collins SSA and Collins FF

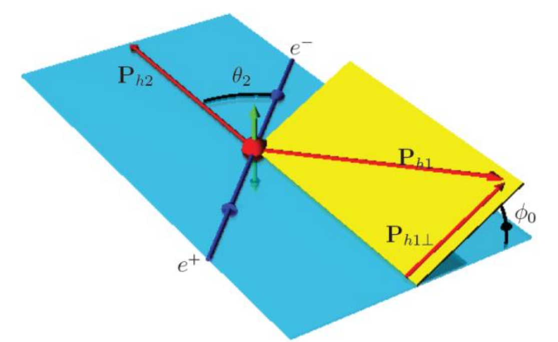
$$A_{UT}^{\sin(\phi_h+\phi_S-\pi),h} = \frac{\sum_q e_q^2\, h_1^q(k_\perp)\otimes H_1^{\perp q\to h}(p_\perp)}{\sum_q e_q^2\, f_1^q \otimes D_1^{q\to h}}$$



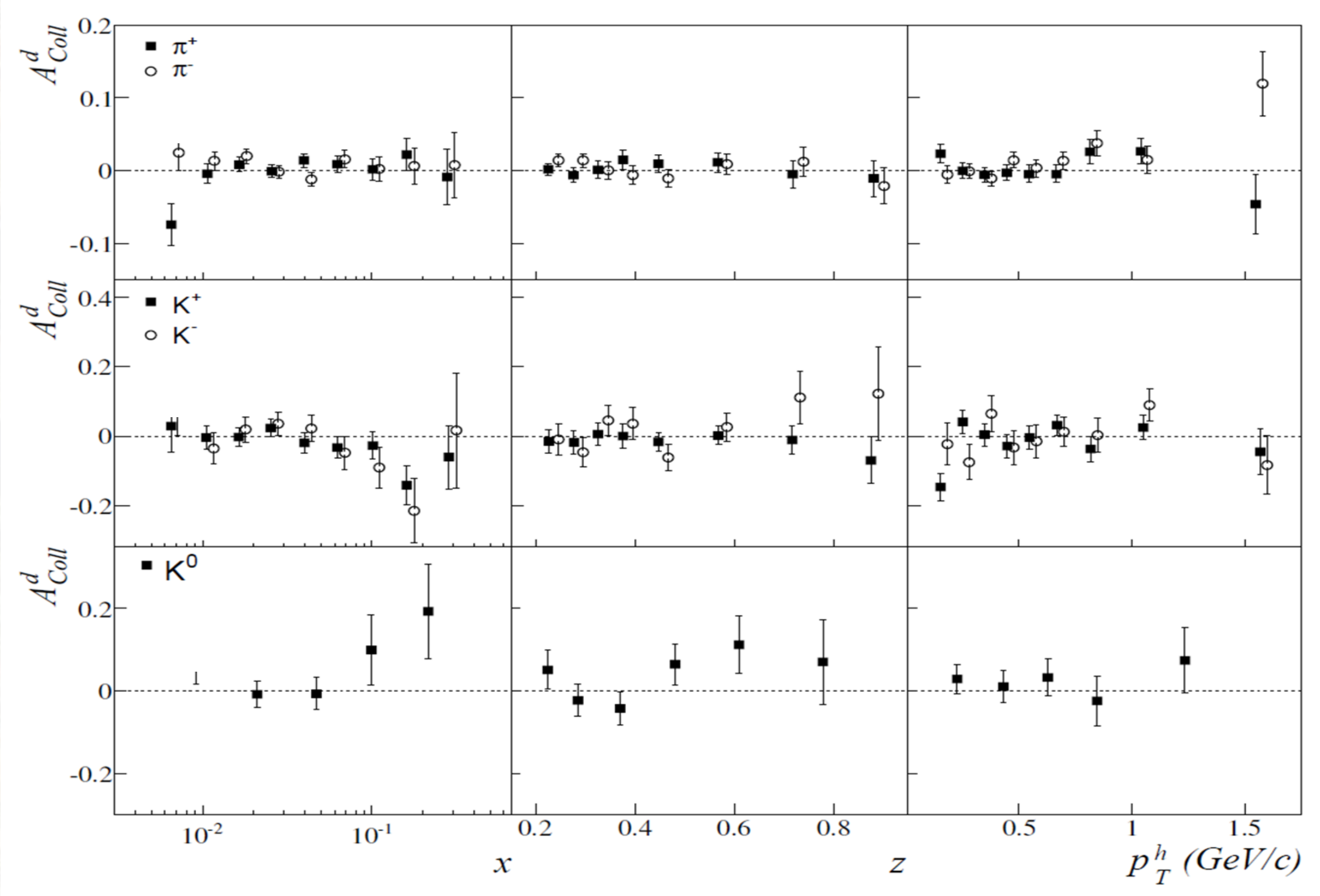


$$A_{12}^{h_1h_2} = \frac{\sin^2\theta}{1+\cos^2\theta}\,\frac{\sum_q e_q^2\, H_1^{\perp(1/2)q\to h_{1/2}}\, H_1^{\perp(1/2)\bar{q}\to h_{1/2}}}{\sum_q e_q^2\, D_1^{q\to h_{1/2}}\, D_1^{\bar{q}\to h_{1/2}}}$$

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 deuteron



Collins asymmetry on proton

x > 0.032 region

charged pions

COMPASS and HERMES results

π+

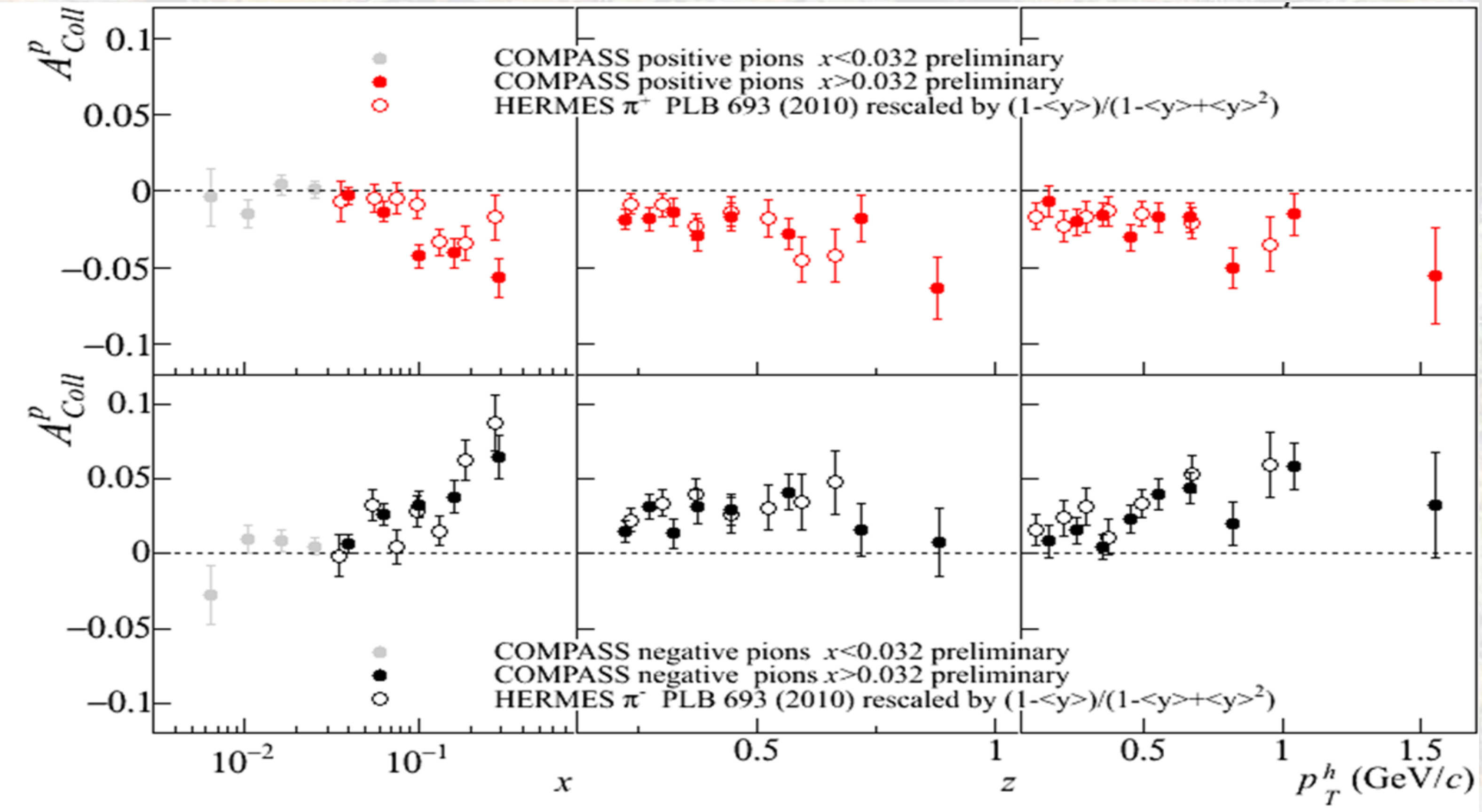
●

○

π-

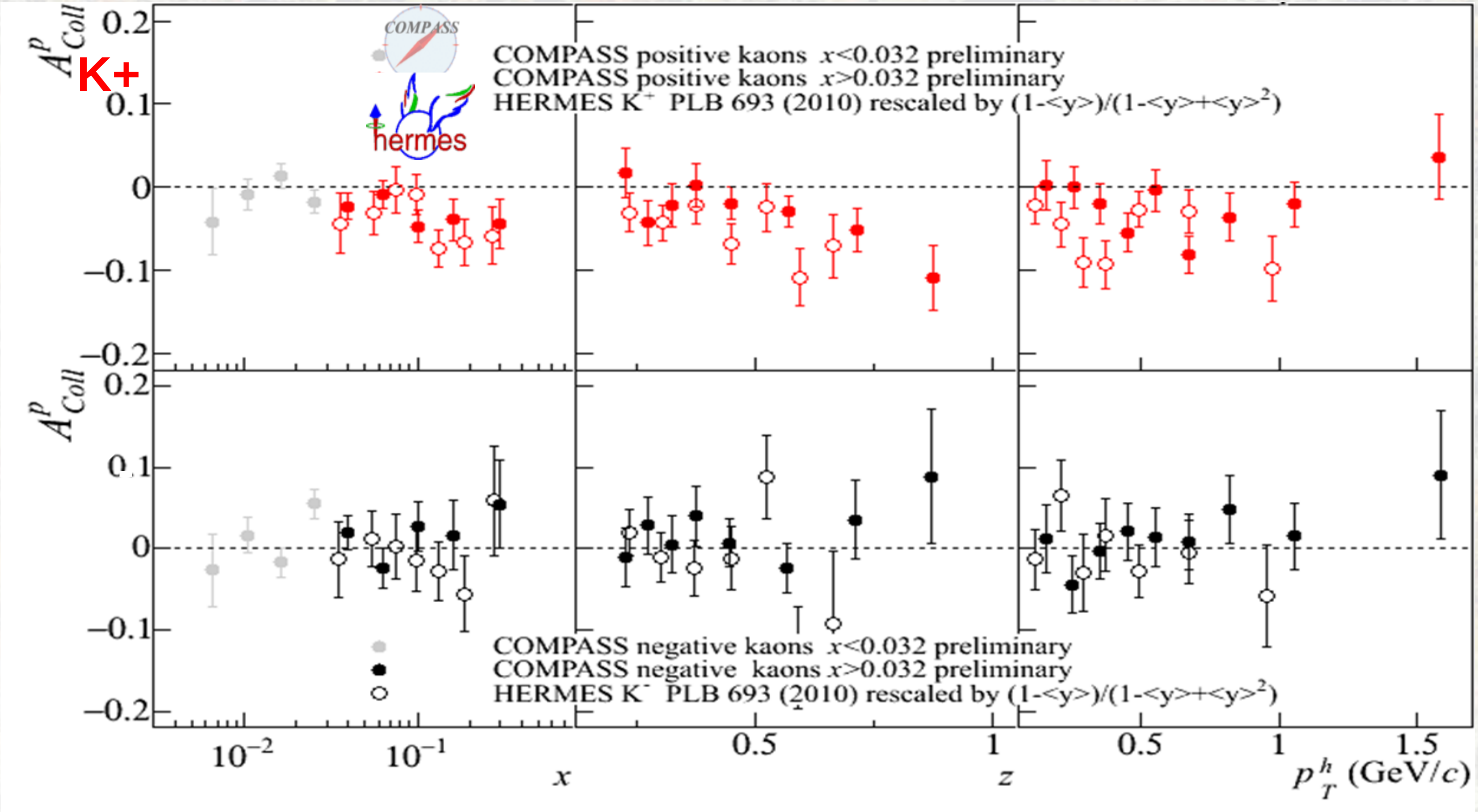
●

○



Collins asymmetry on proton x > 0.032 region

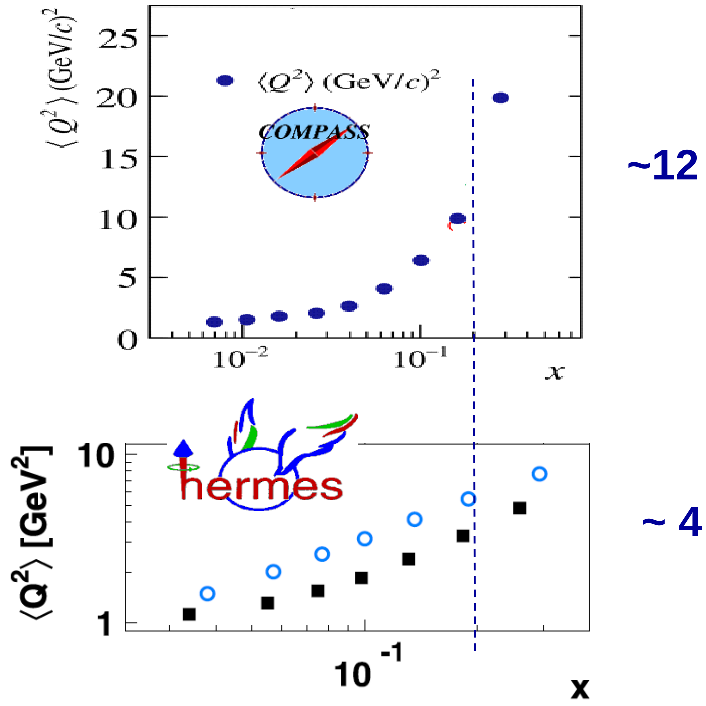
charged kaons **COMPASS and HERMES results**



Collins asymmetry on proton

x > 0.032 region

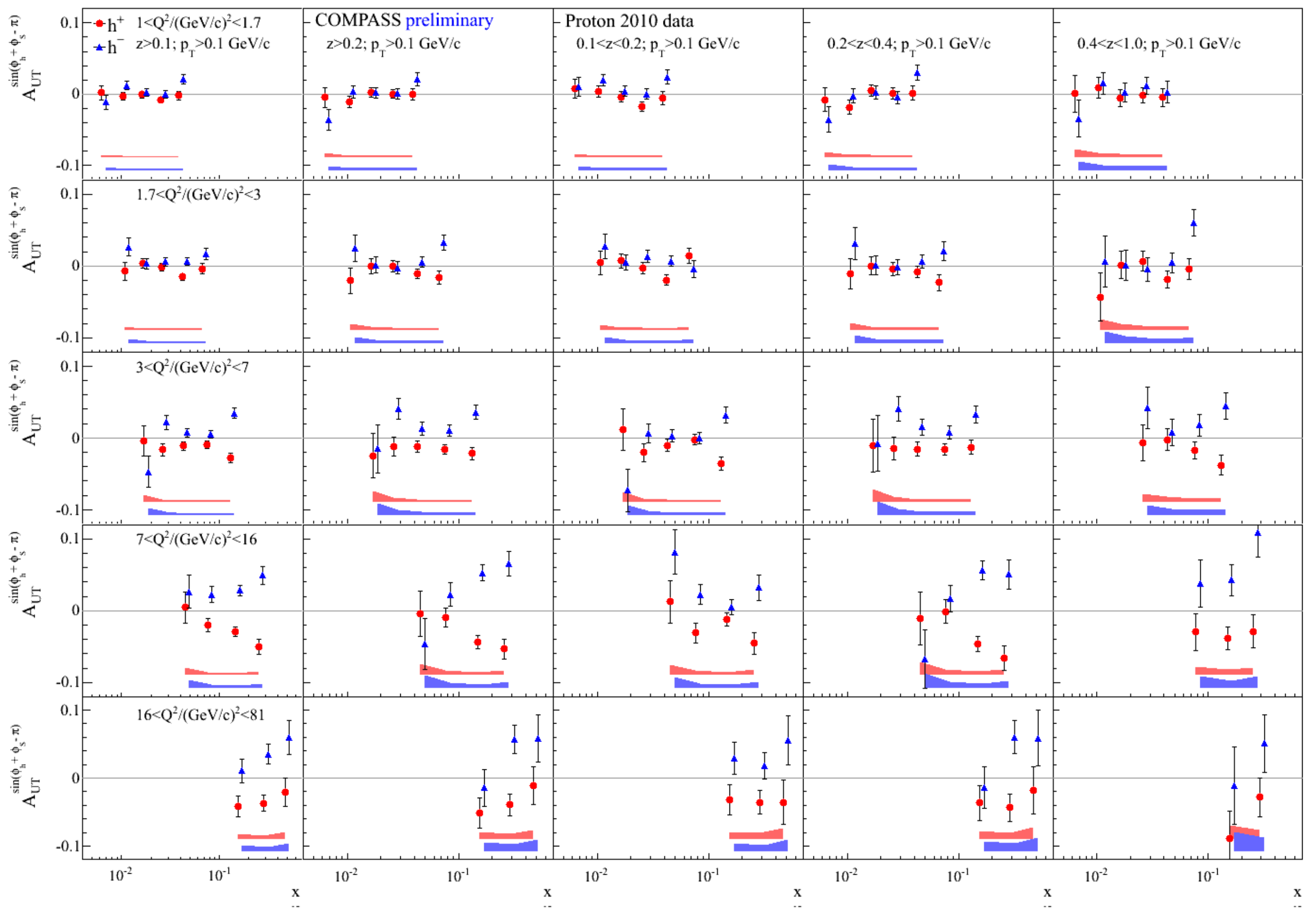
same strength:
a very important, not obvious result!

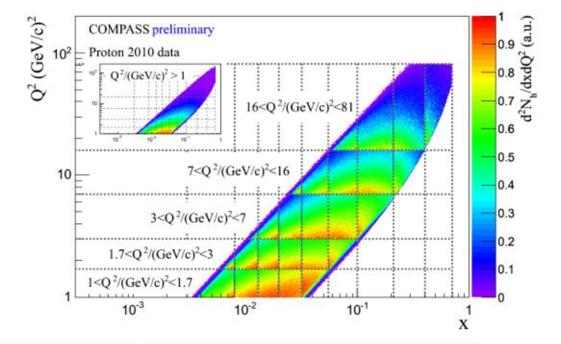


no strong Q^2 dependence

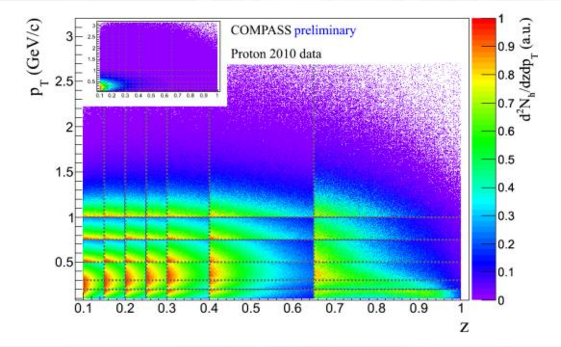
Collins asymmetry on proton. Multidimensional

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



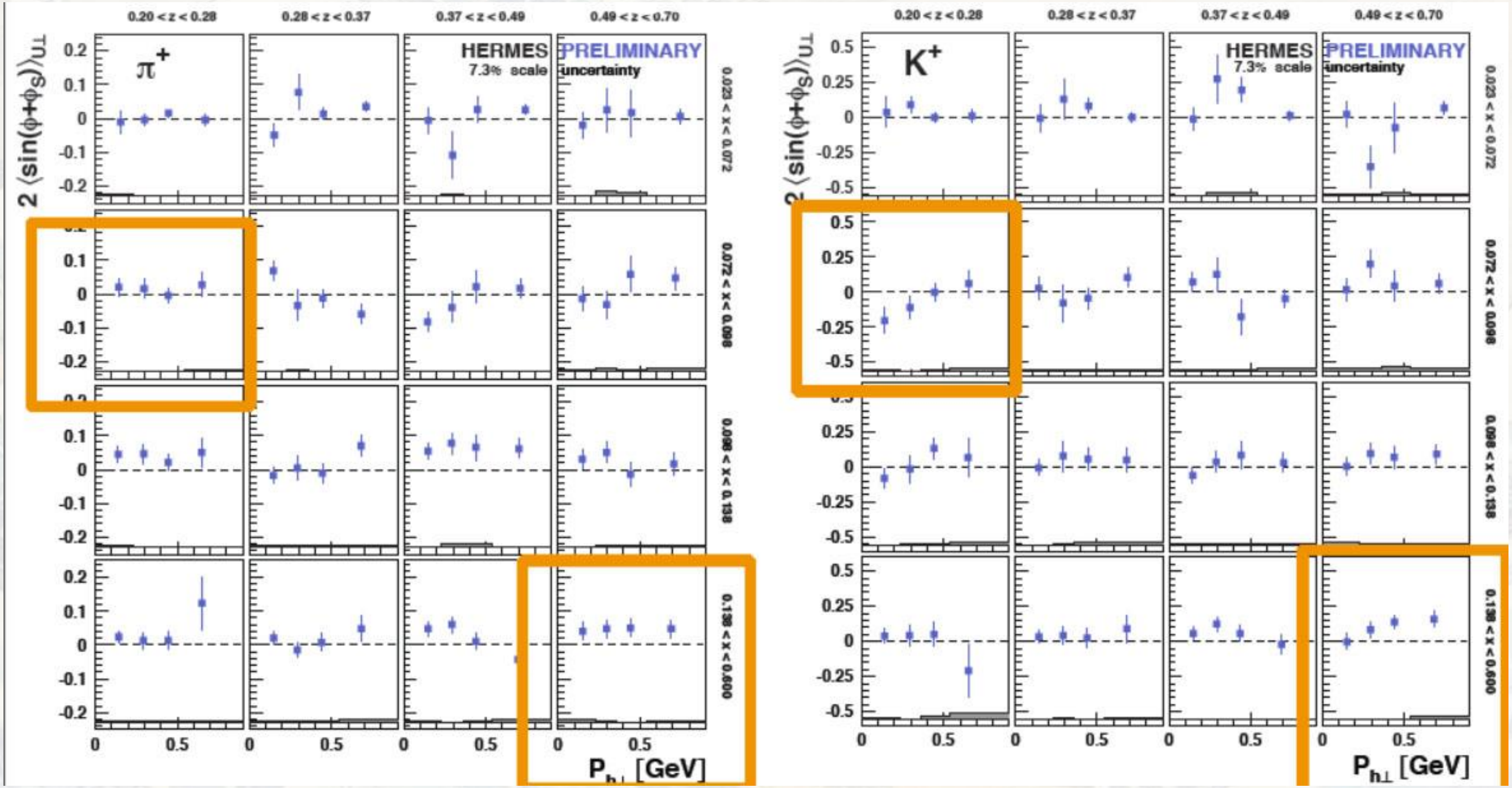


One dense plot out of many



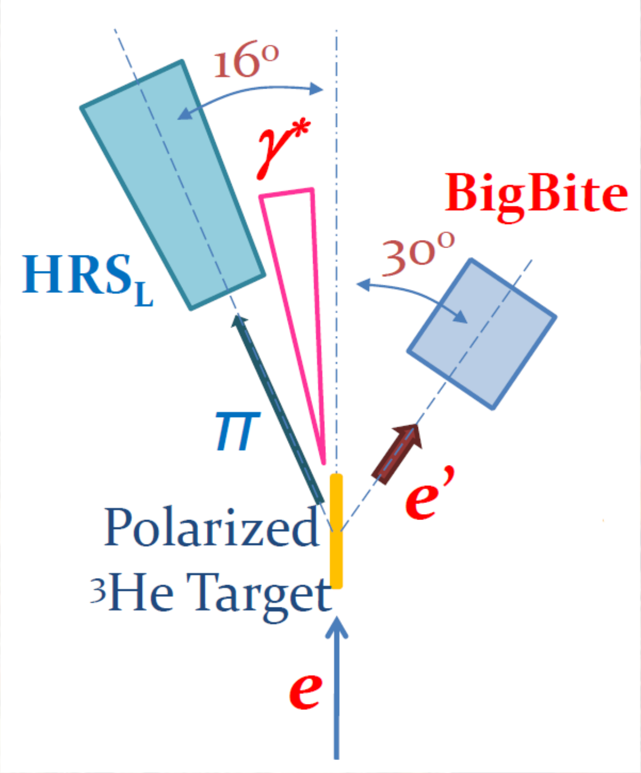
Collins asymmetry on proton. Multidimensional

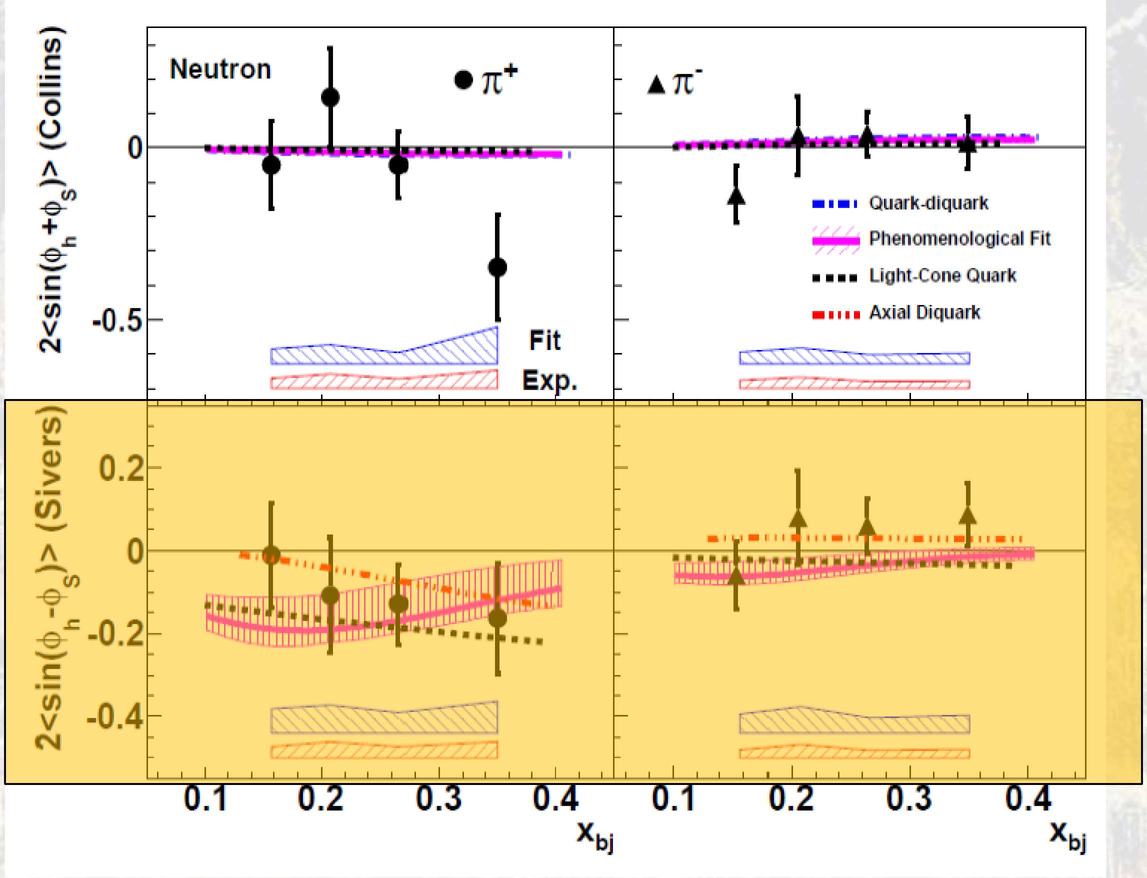
Extraction of TSAs within a Multi-D $(x{:}\,z{:}\,p_T)$ approach



Collins asymmetry on neutron

PRL 107 072003 (2011)





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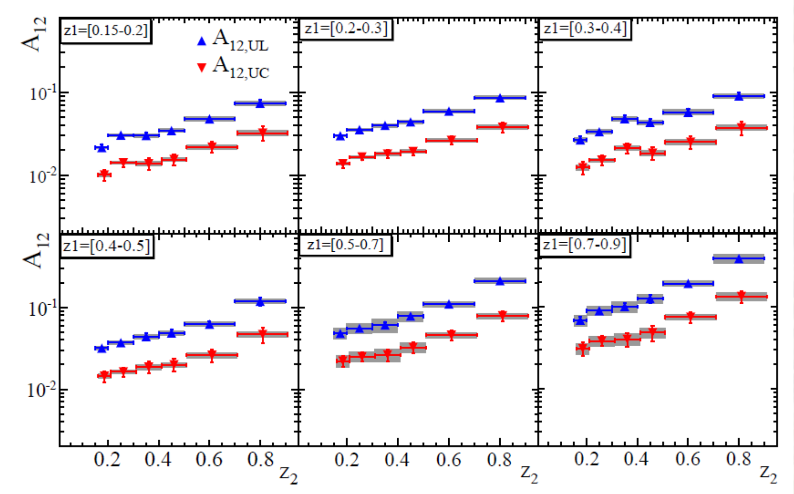
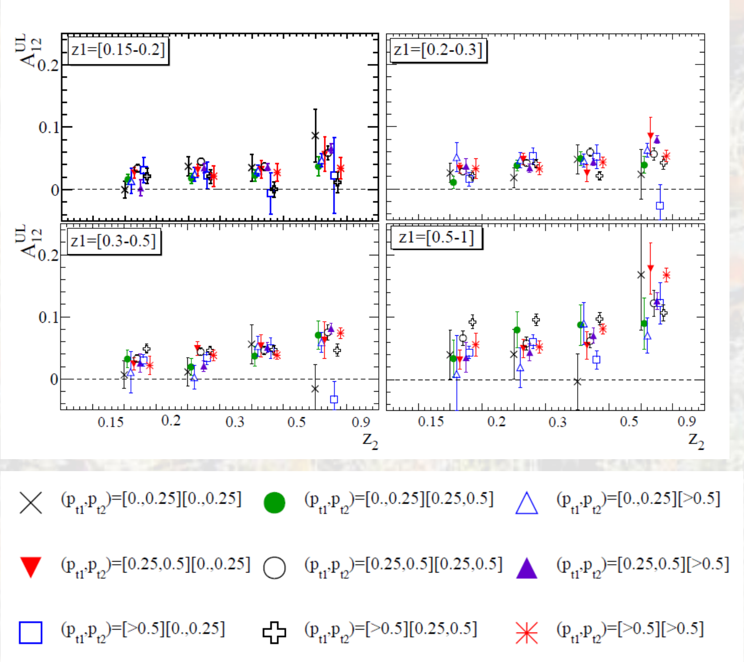
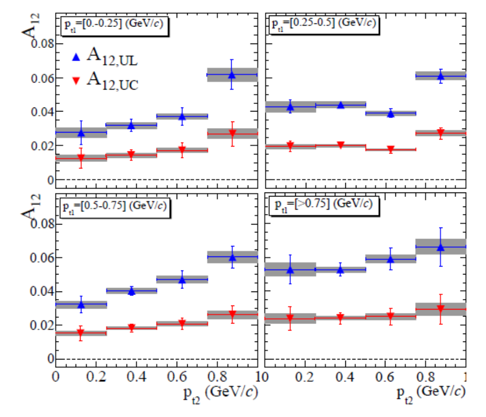
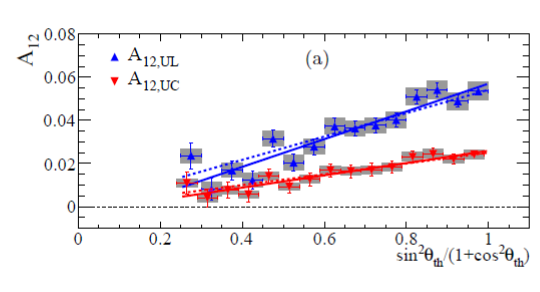
Collins asymmetry on e^+e^-







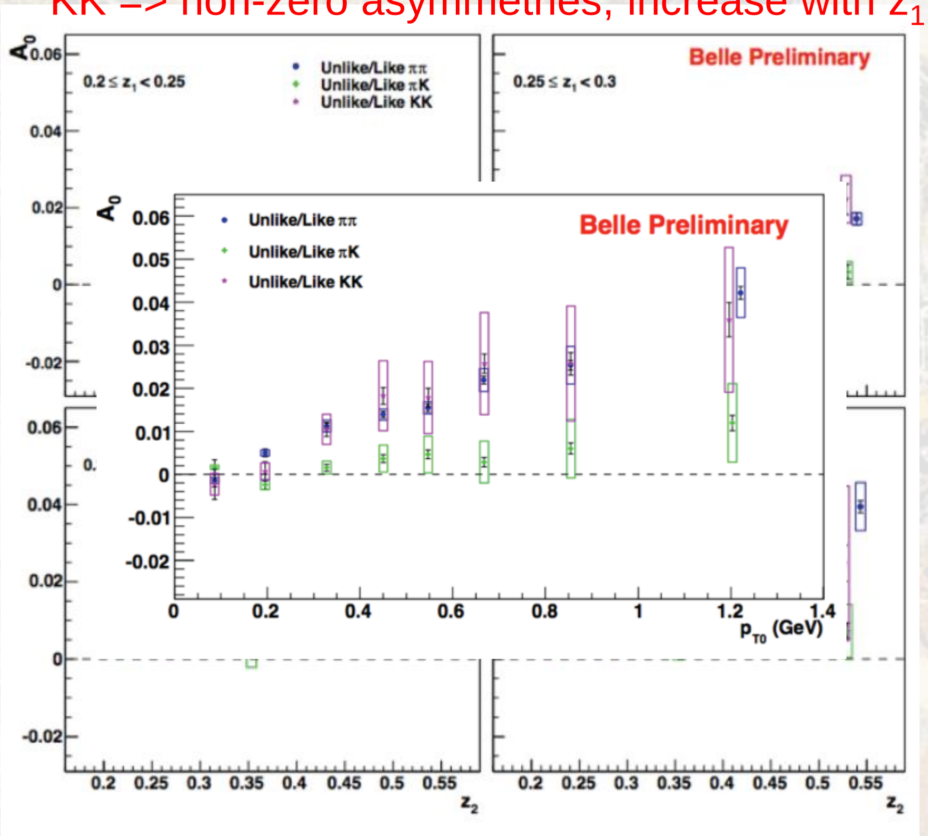


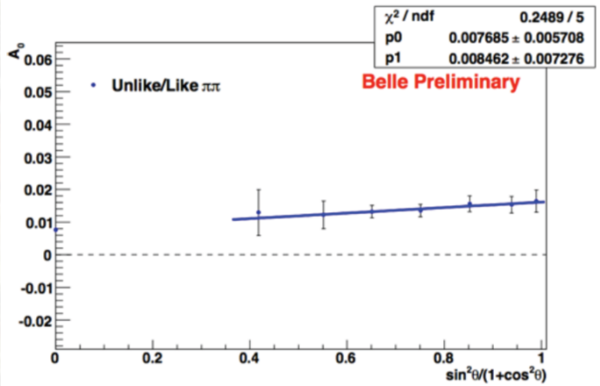
Collins asymmetry o

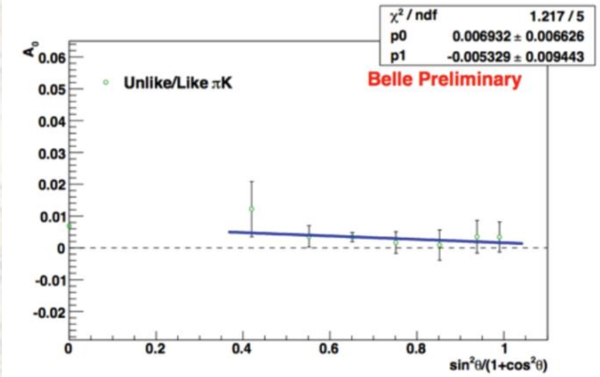
$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

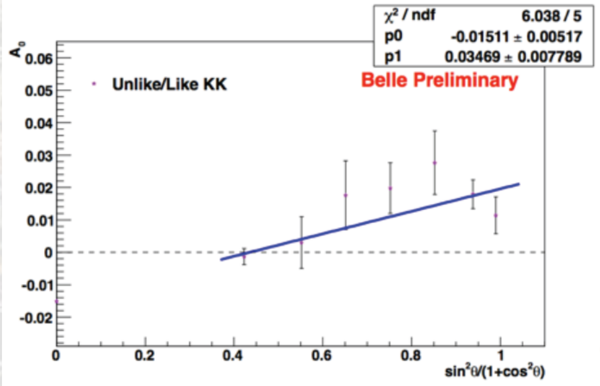
πK => asymmetries compatible, with zero

KK => non-zero asymmetries, increase with z_1,z_2



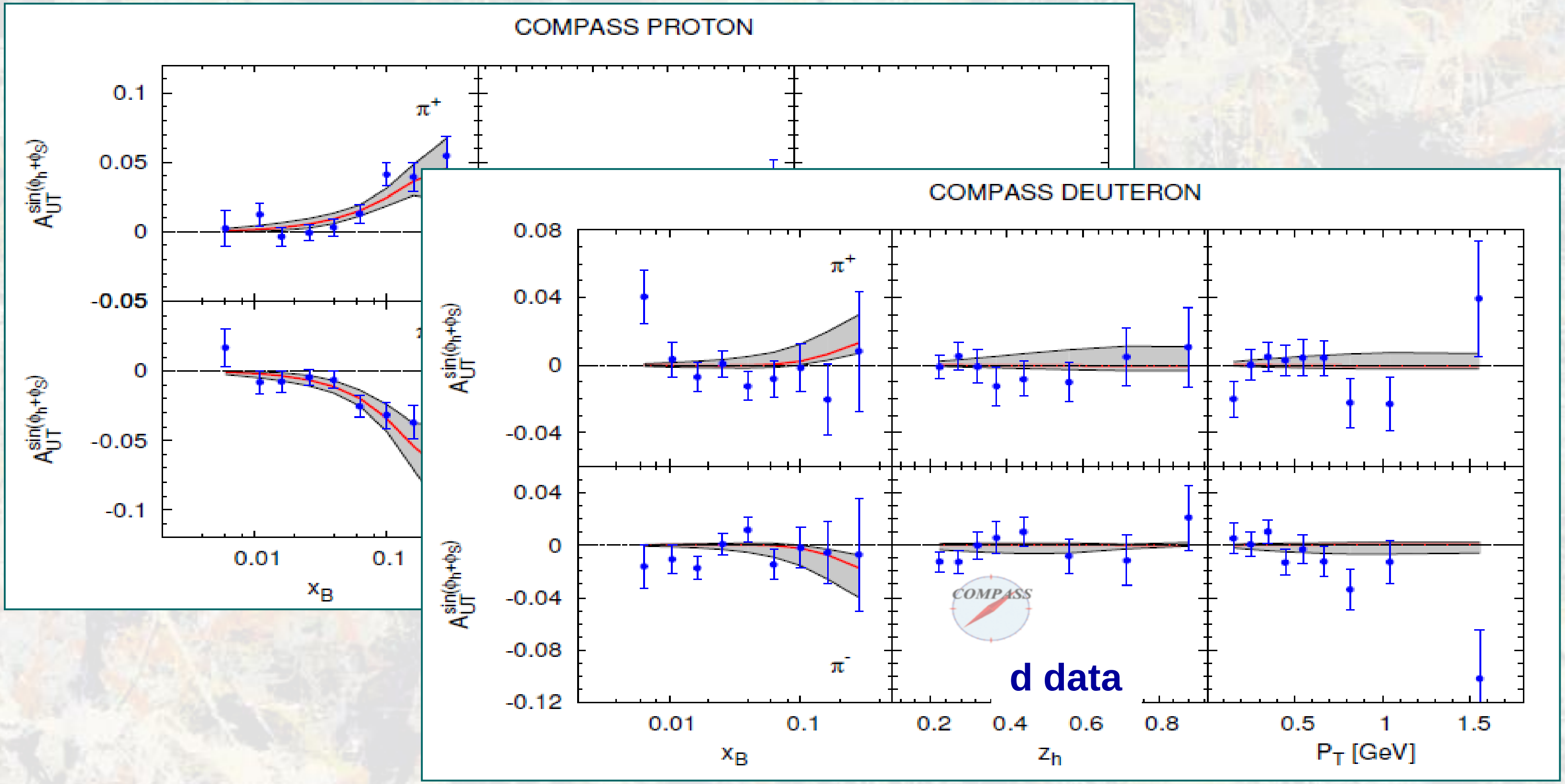






Collins asymmetry fits

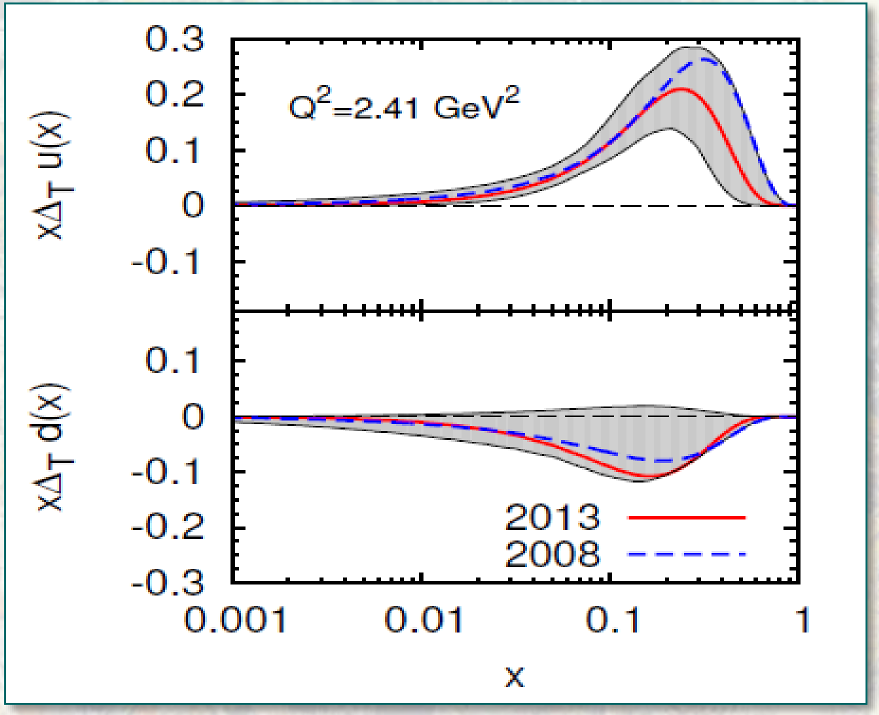
M. Anselmino et al., arXiv:1303.3822
fit to HERMES p, COMPASS p and d, Belle e^+e^- data

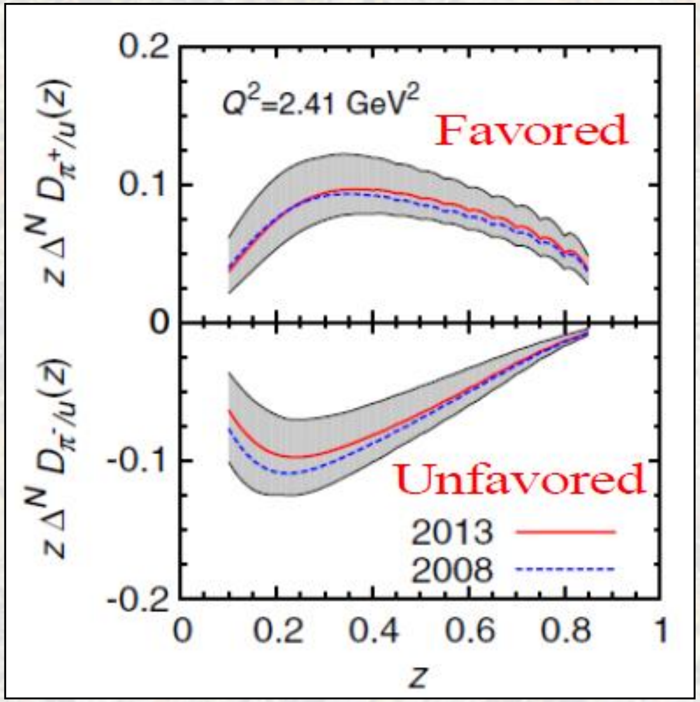


d data

Transversity from Collins

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

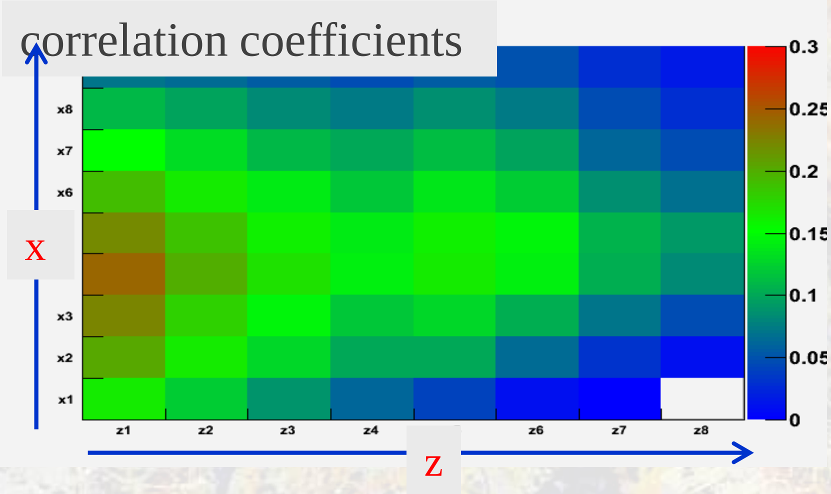


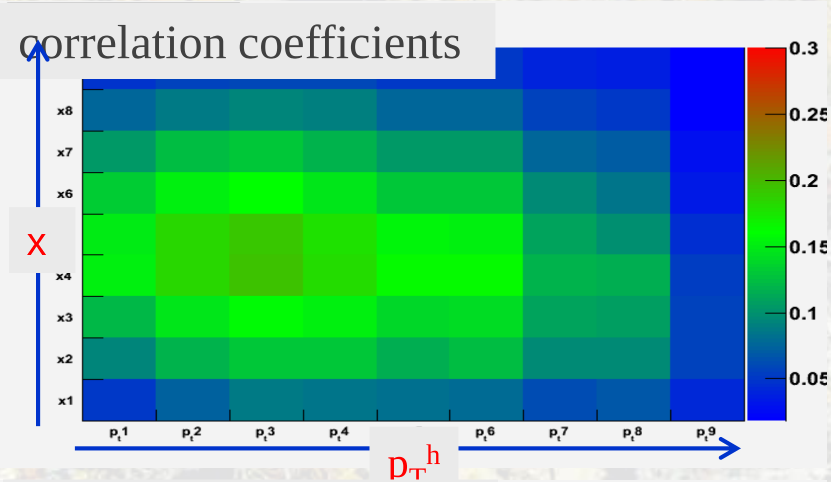


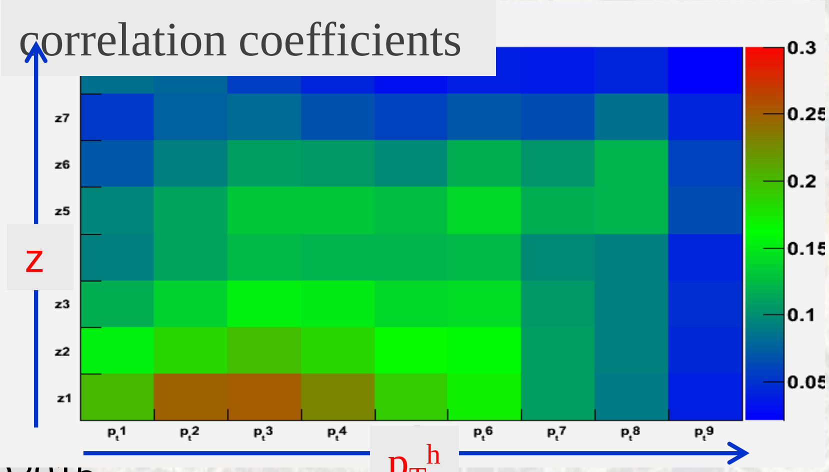
Anselmino et al. arXiv: 1303.3822

statistical correlations

Collins (Sivers, …) asymmetries measured vs x, z, p_T^h







charged pions

also available for

charged hadrons

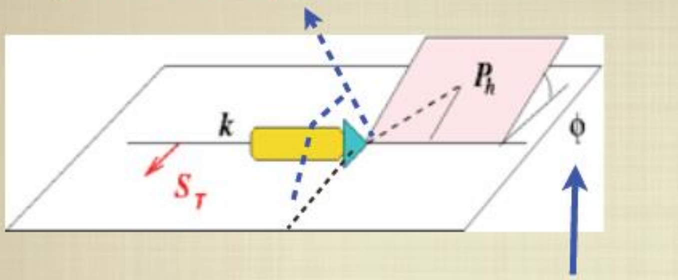
charged kaons

have to be taken into account

The other way to

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

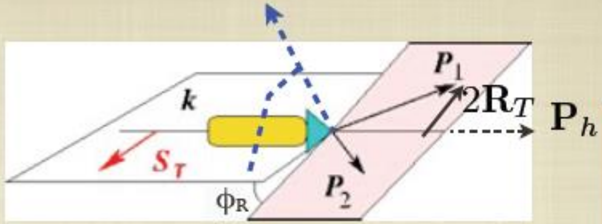
single-spin asymmetry → **convolution**

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

TMD factorization

The Di-hadron Fragm. Funct. mechanism

Collins, Heppelman, Ladinsky, NP B420 (94)



$P_{hT}=0$
collinear!

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

azimuthal orientation of hadron pair

=

spin analyzer of fragmenting quark

single-spin asymmetry → **product**

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

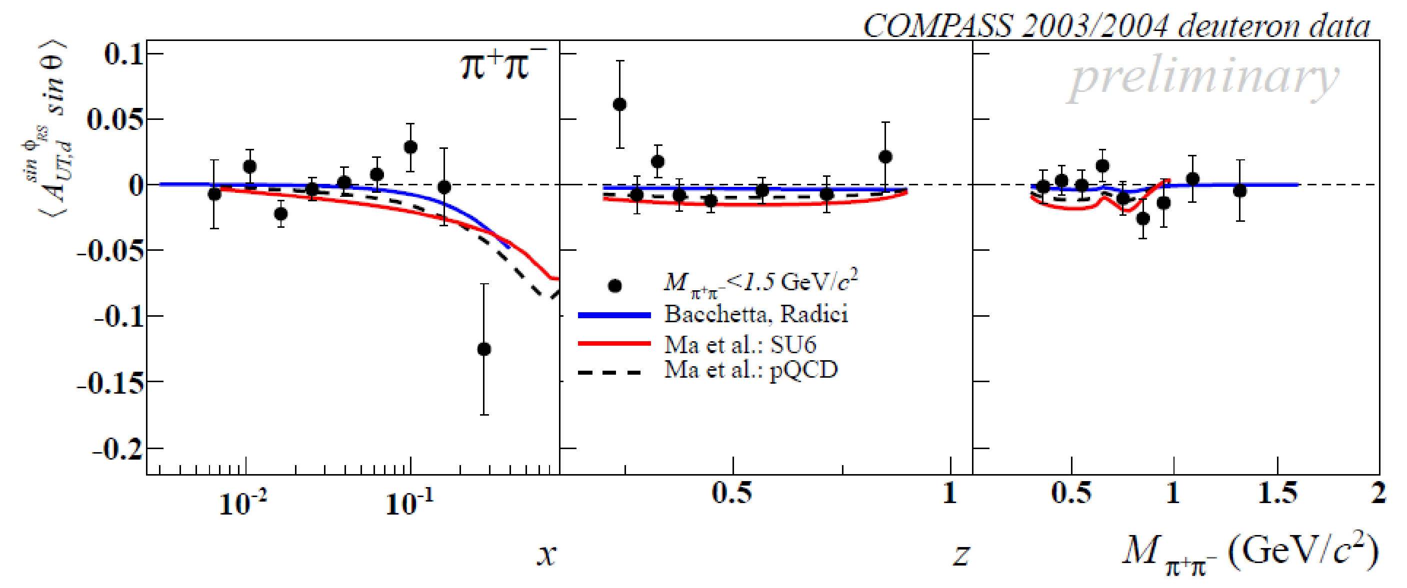
Radici, Jakob, Bianconi PR D65 (02); Bacchetta, Radici, PR D67 (03)

collinear factorization
evolution equations understood

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

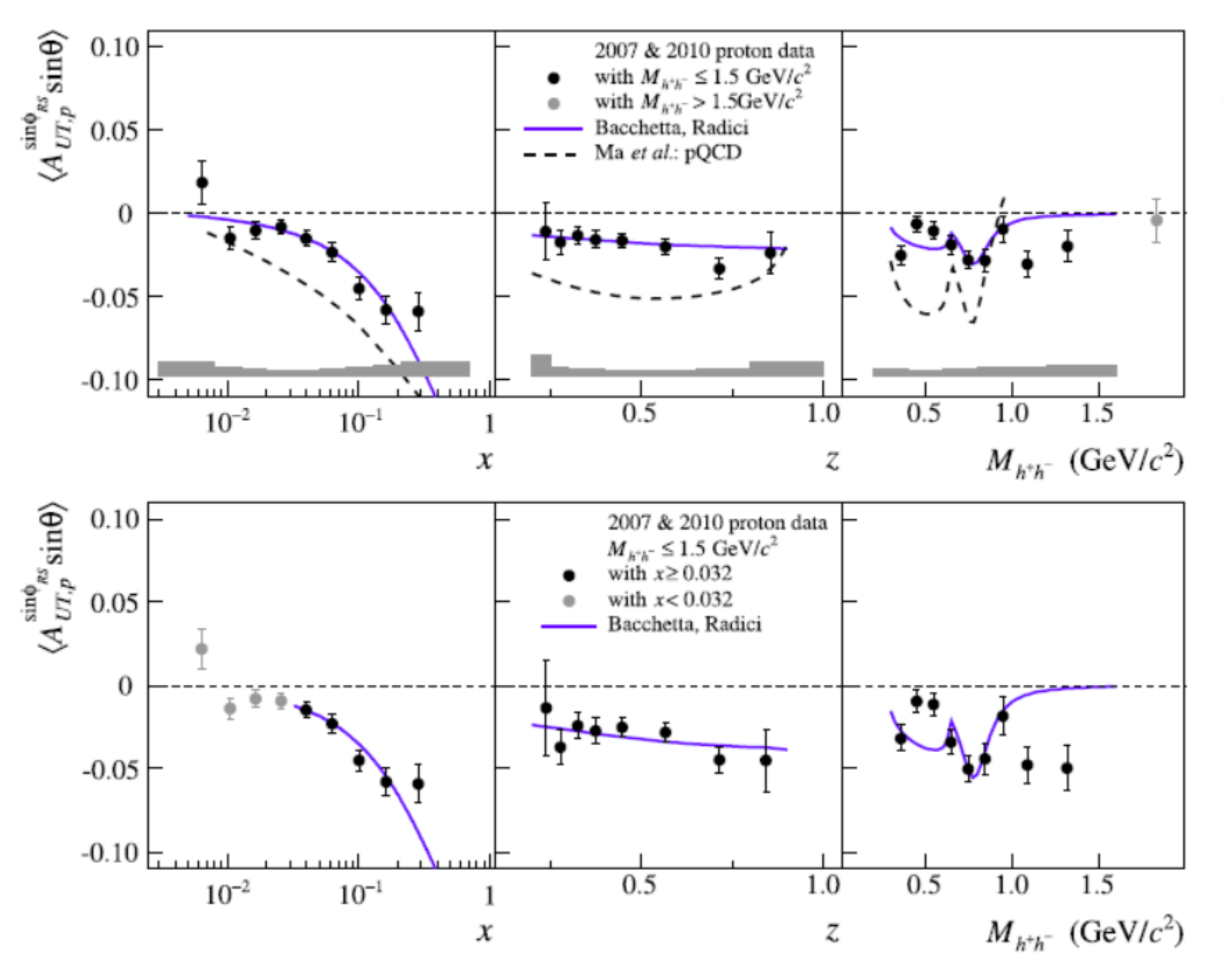
YTISREVSNART

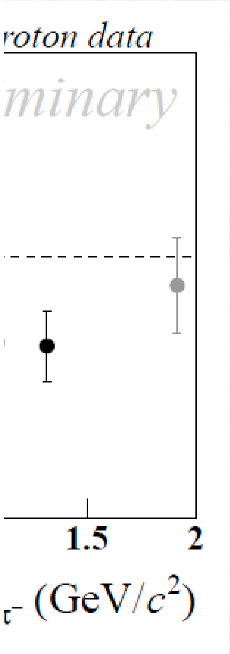
2h asymmetries on d



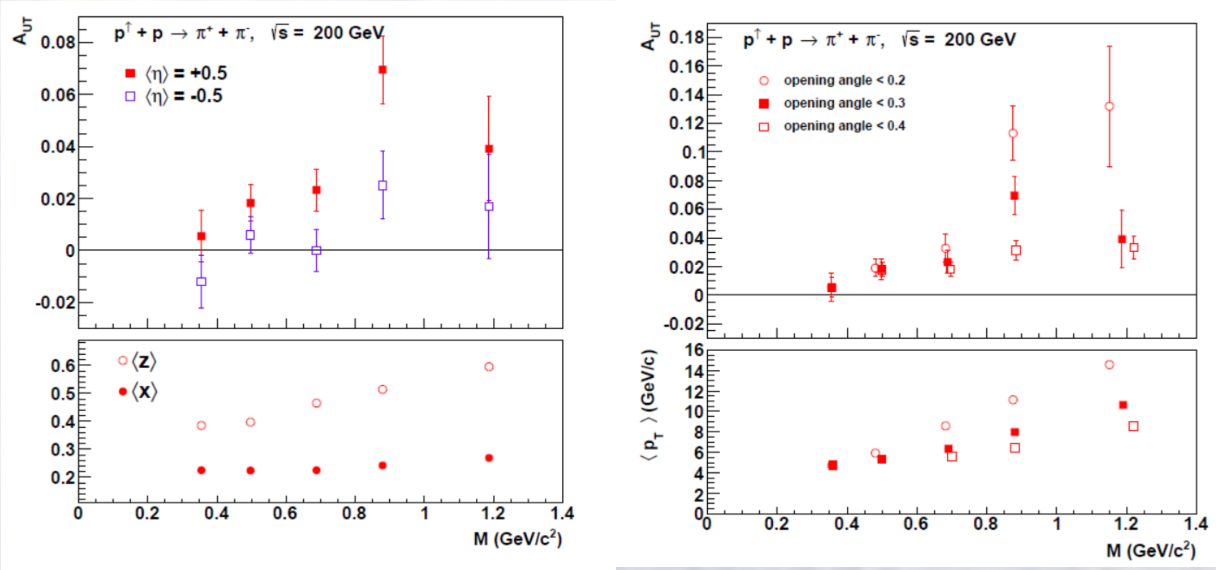
$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1 h_2}^{\measuredangle}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1 h_2}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}$$

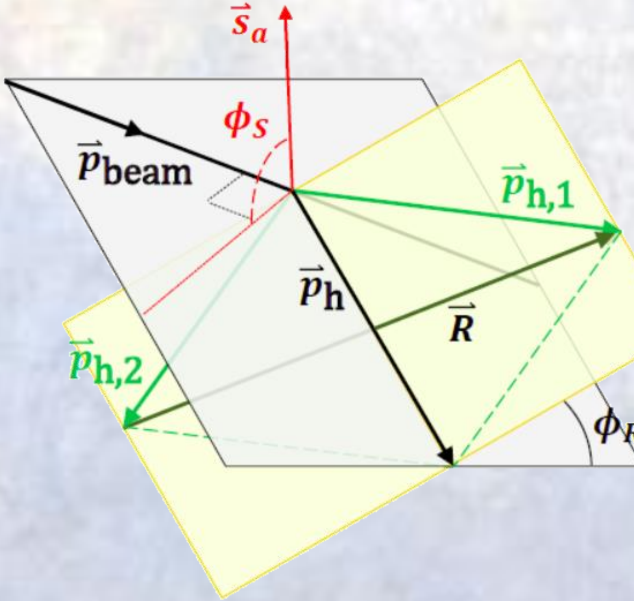
2h asymmetries on p





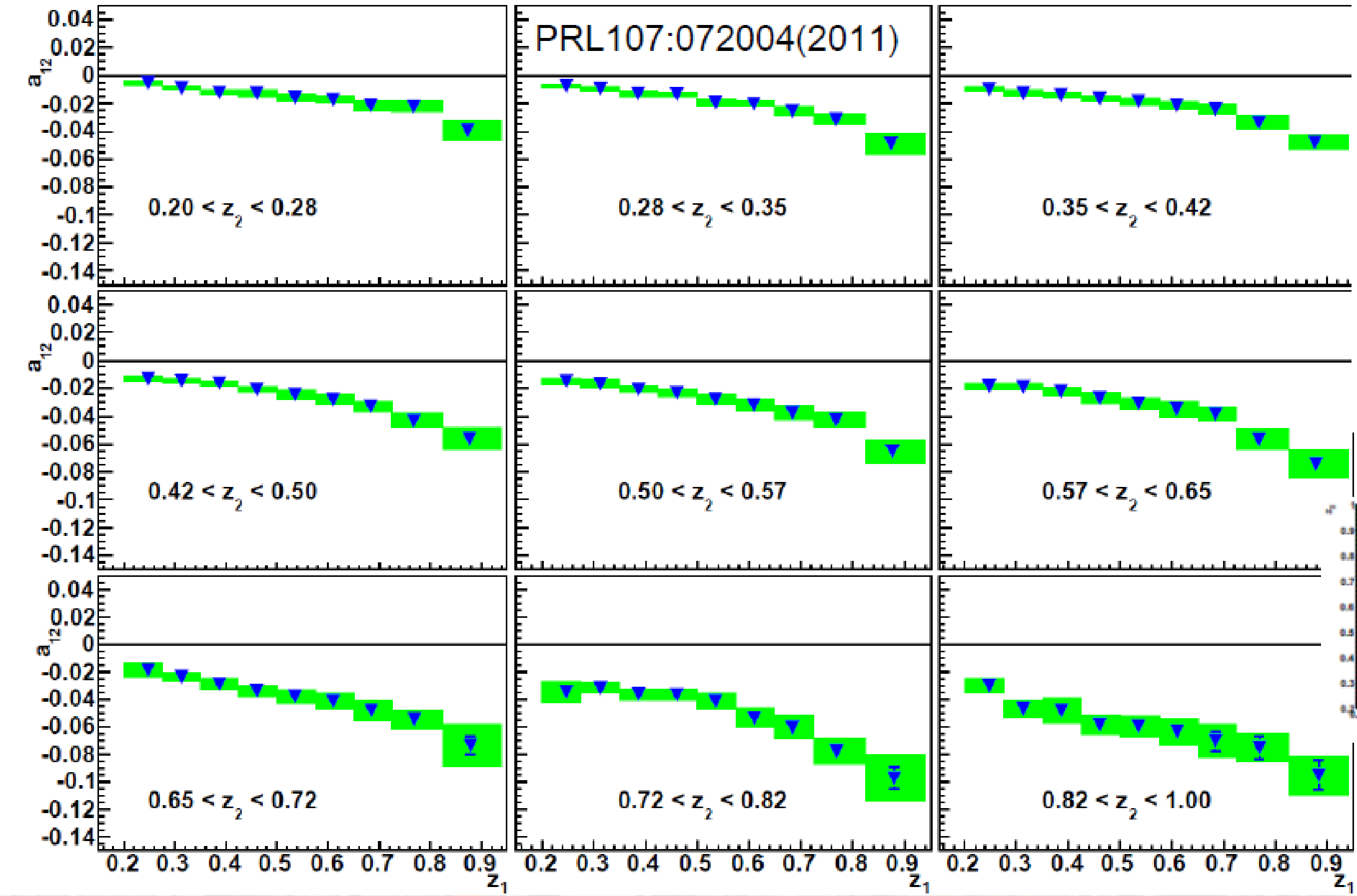
2h asymmetries in $p^{\uparrow}p \longrightarrow \pi\pi X$

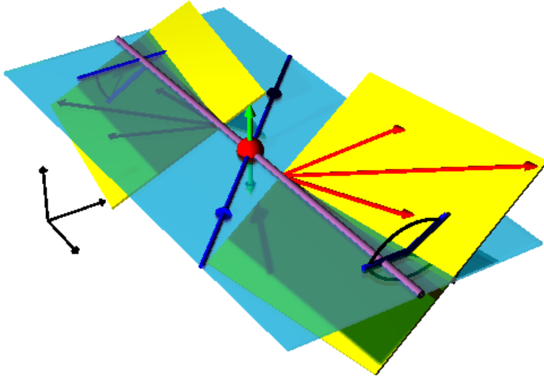


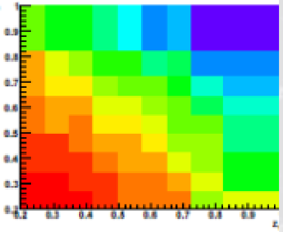


$$d\sigma_{UT} \propto \sin\phi_{RS}\, f_1 \otimes h_1 \otimes \hat{\sigma}^{qq\to qq} \otimes H_{1,q}^{\measuredangle}(z, M)$$

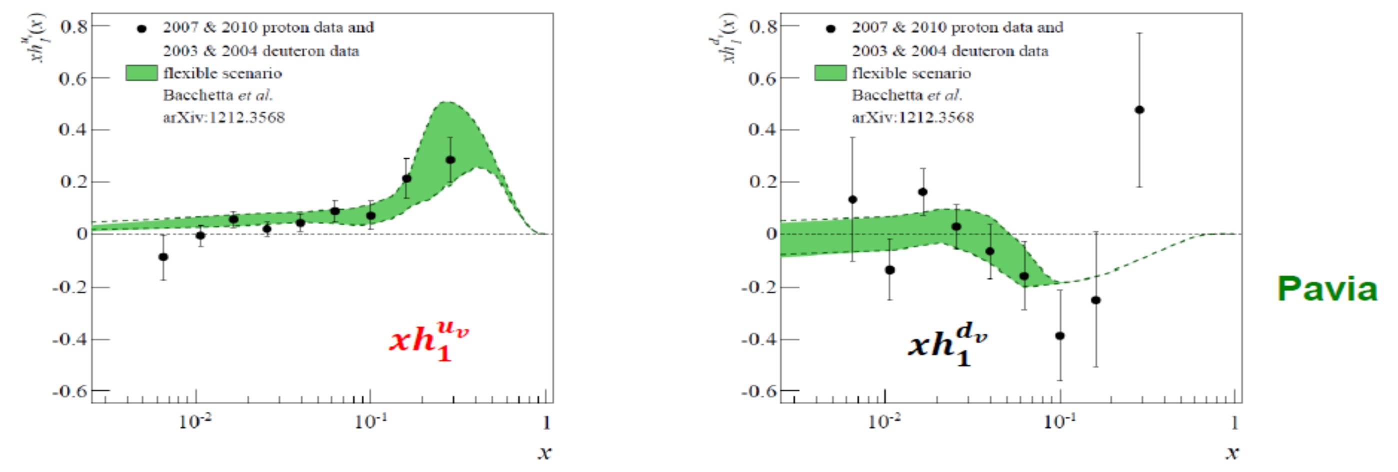
IFF asymmetry on e^+e^-


PRL107:072004(2011)



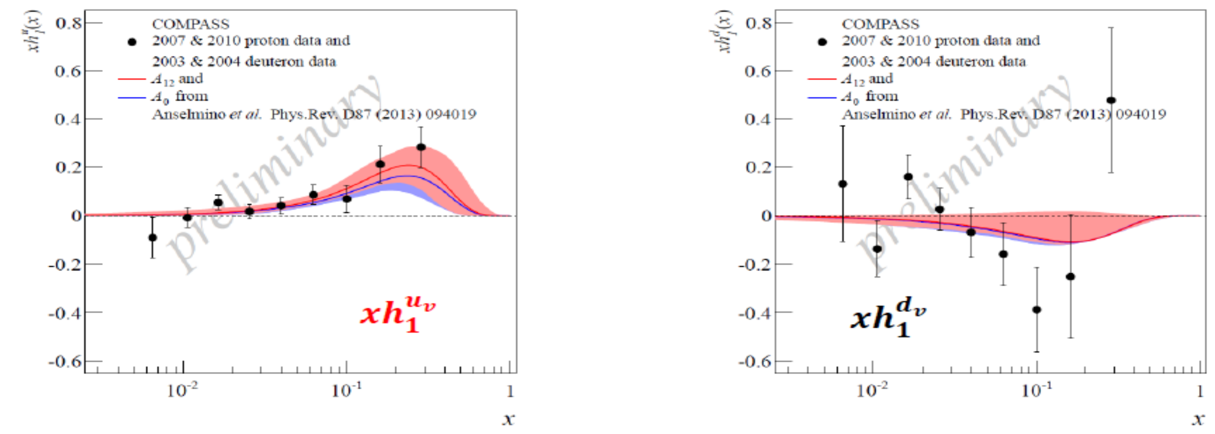


Transversity from 2h p and d results



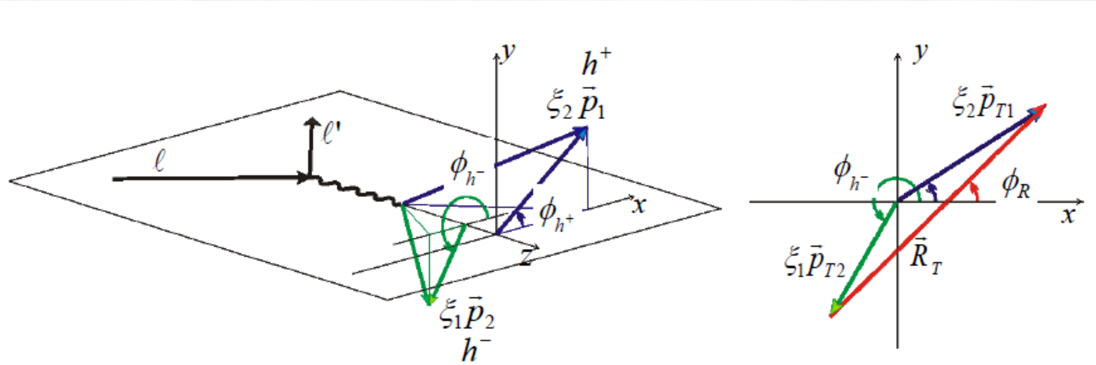
Pavia

Torino



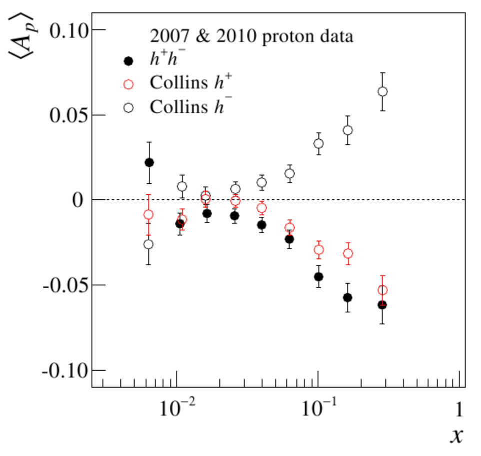
use the same coefficients evaluated by A. Bacchetta et al. from Belle data
[JHEP1303 (2013)119]

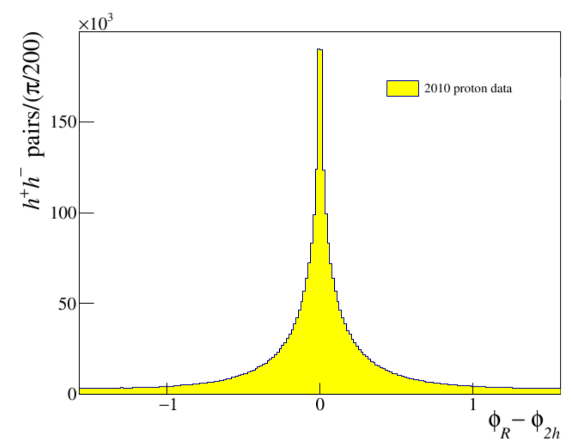
Hadron correlations

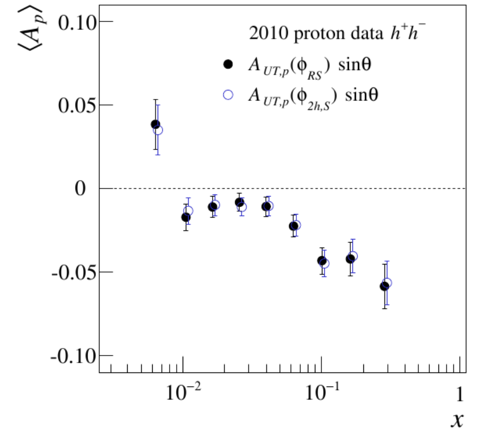


Interplay between Collins and IFF asymmetries

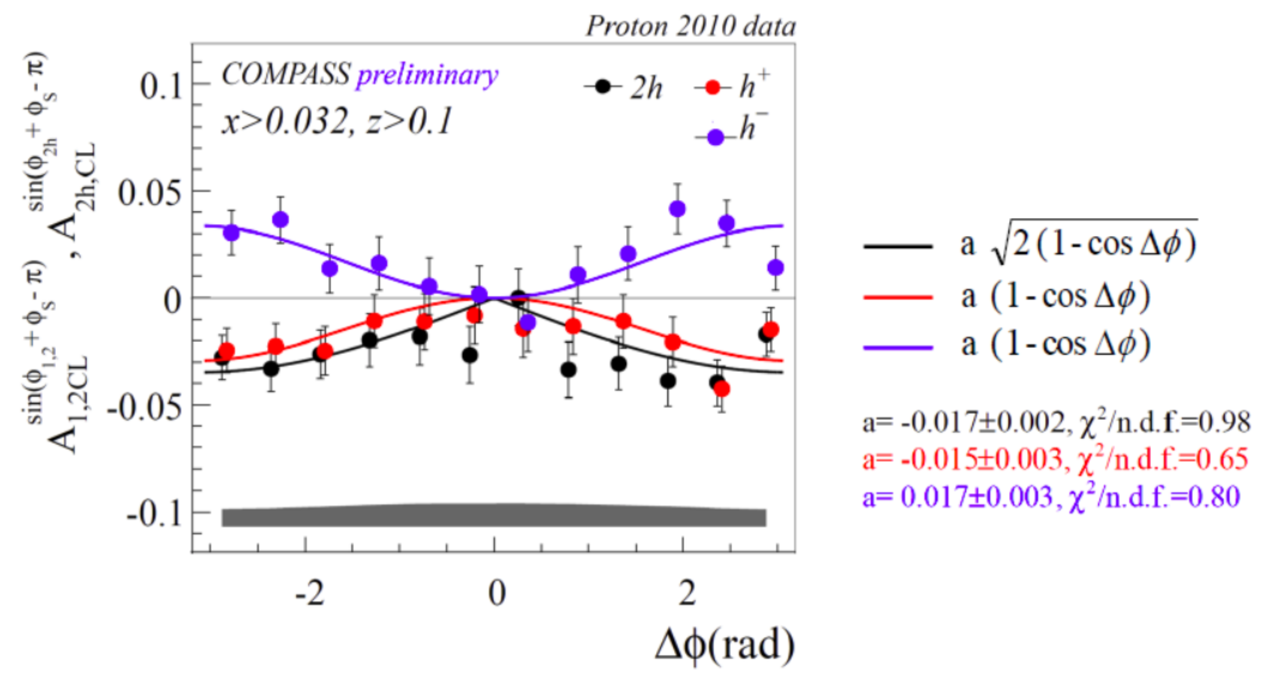
common hadron sample for Collins and 2h analysis







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:

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

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

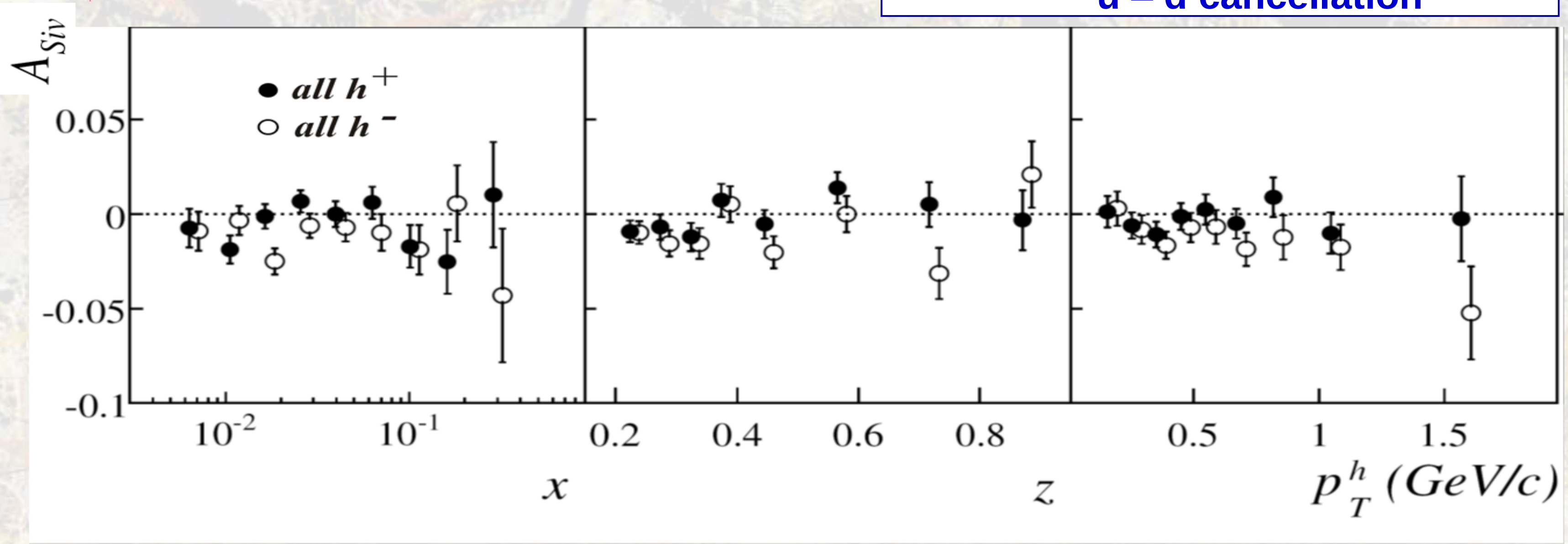
The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES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

PLB 673 (2009) 127

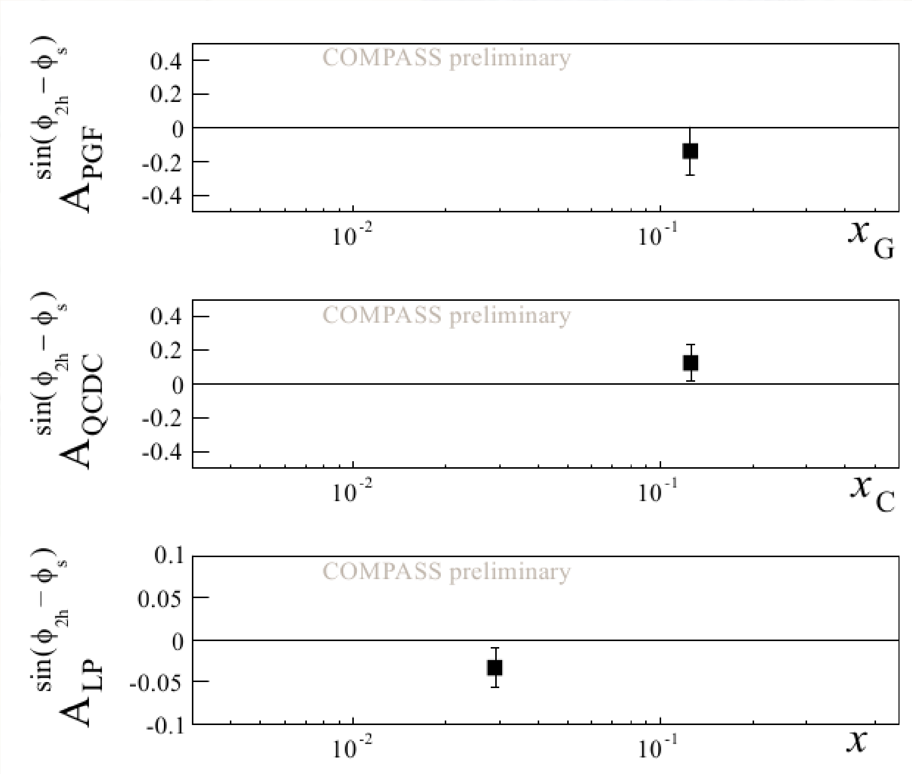
understood as

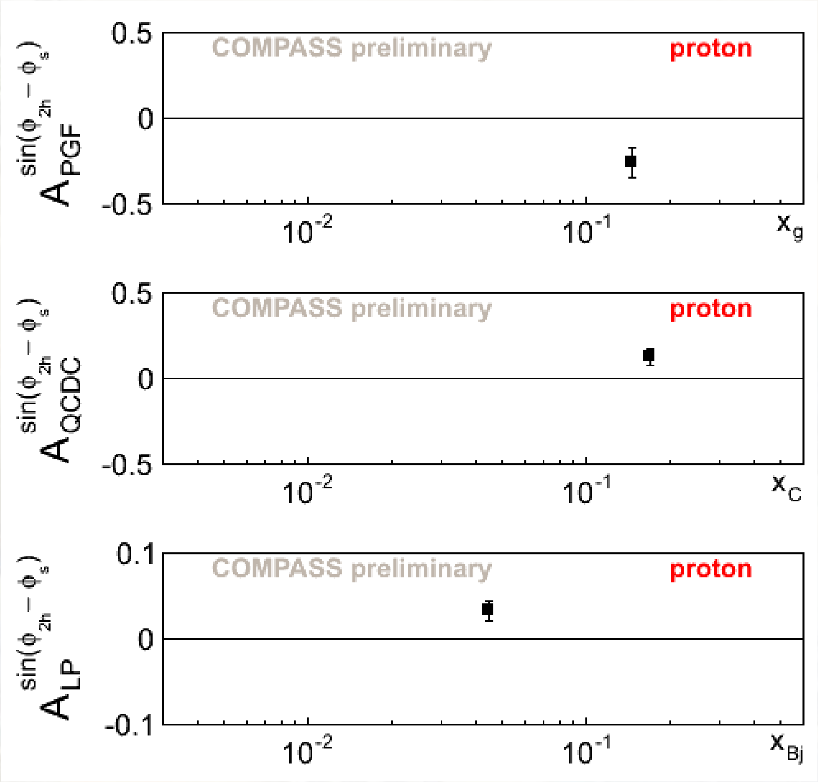
u – d cancellation



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

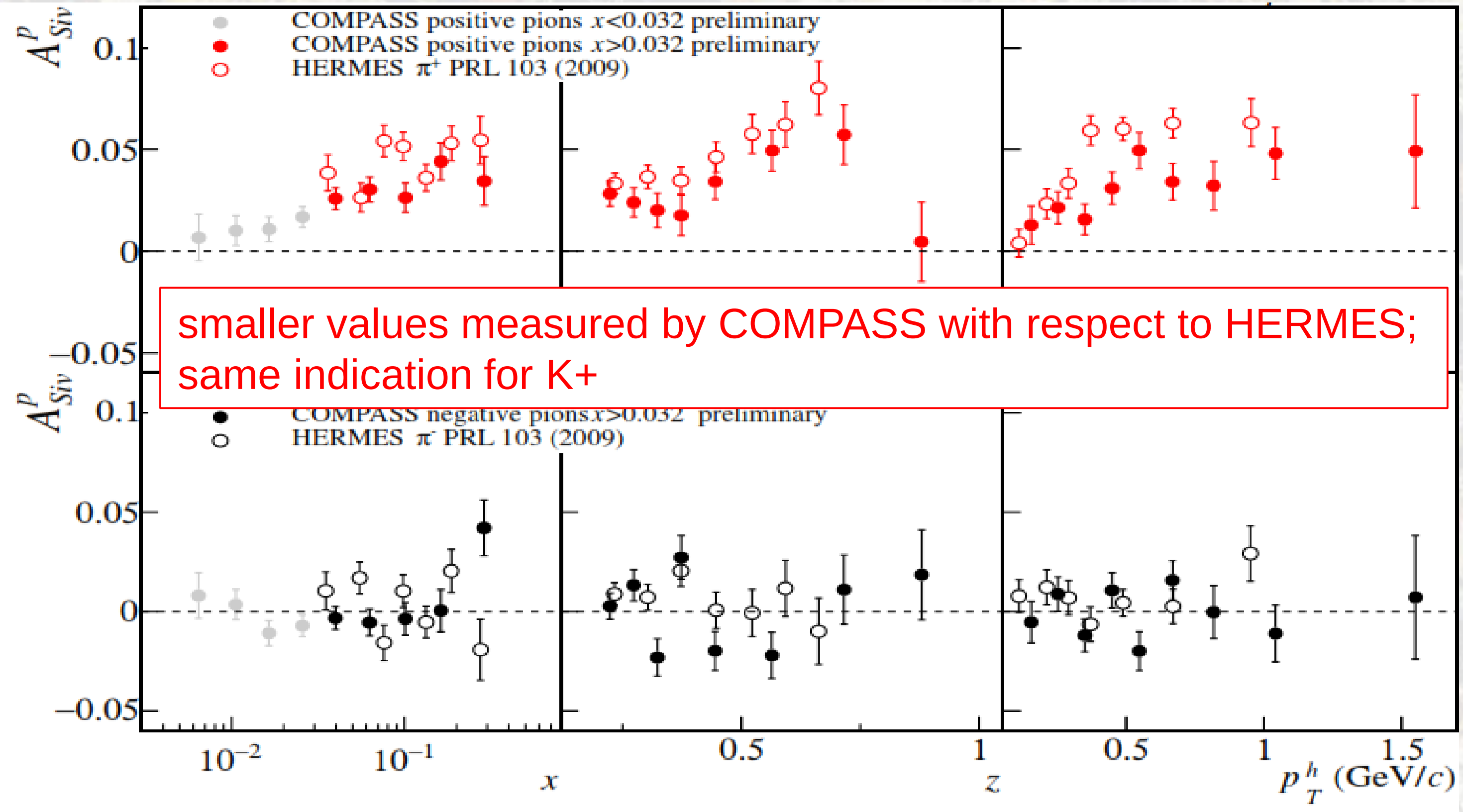
Sivers asymmetry on deuteron and proton for Gluons





Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS



smaller values measured by COMPASS with respect to HERMES;
same indication for K+

π^+

● COMPASS

○ hermes

π^-

● COMPASS

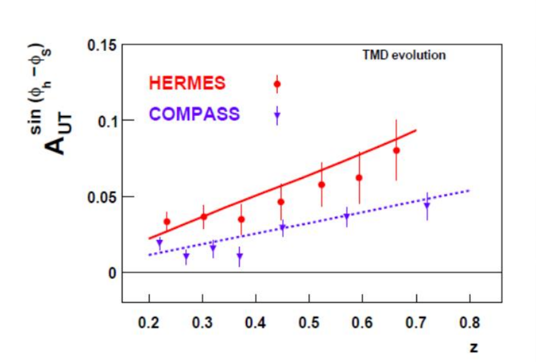
○ hermes

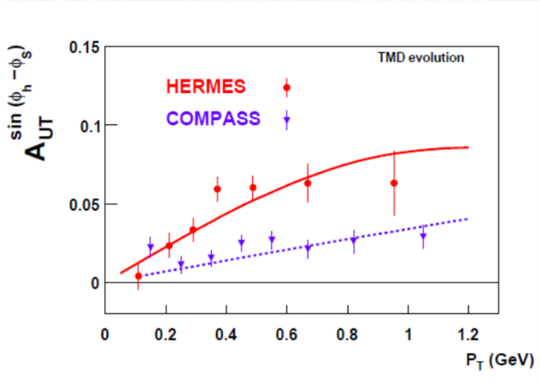
Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

comparison with

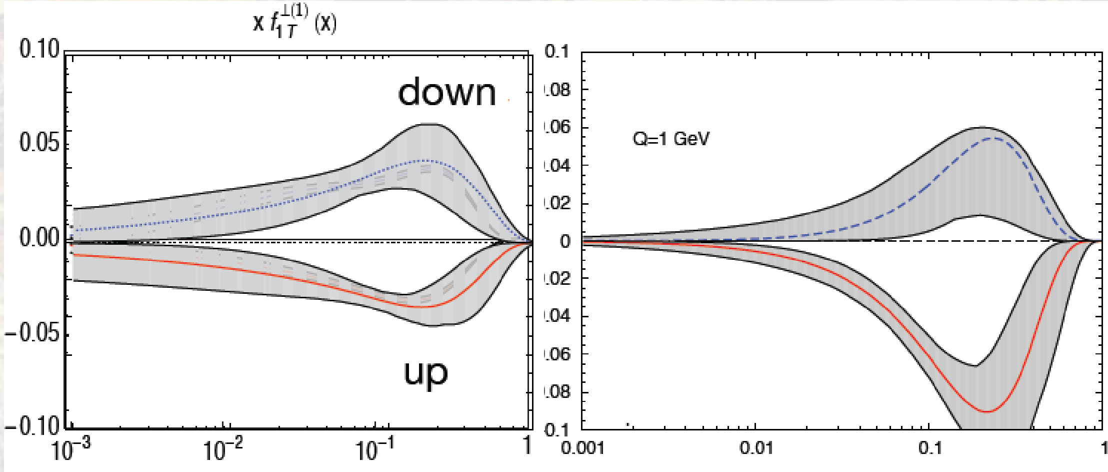
S. M. Aybat, A. Prokudin and T. C. Rogers calculations PRL 108 (2012) 242003





No TMD evolution

with TMD evolution



Chromodynamic lensing

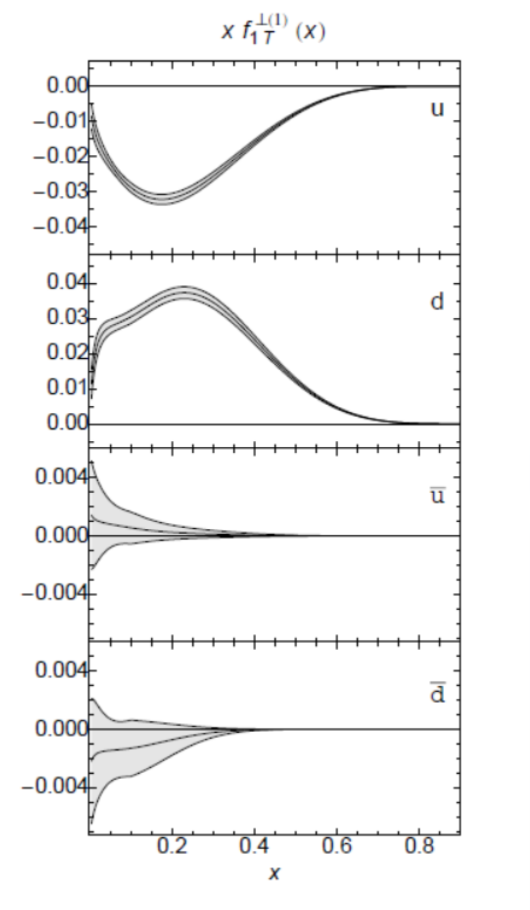
Use SIDIS Sivers asymmetry data to constrain shape
Use anomalous magnetic moments to constrain integral

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

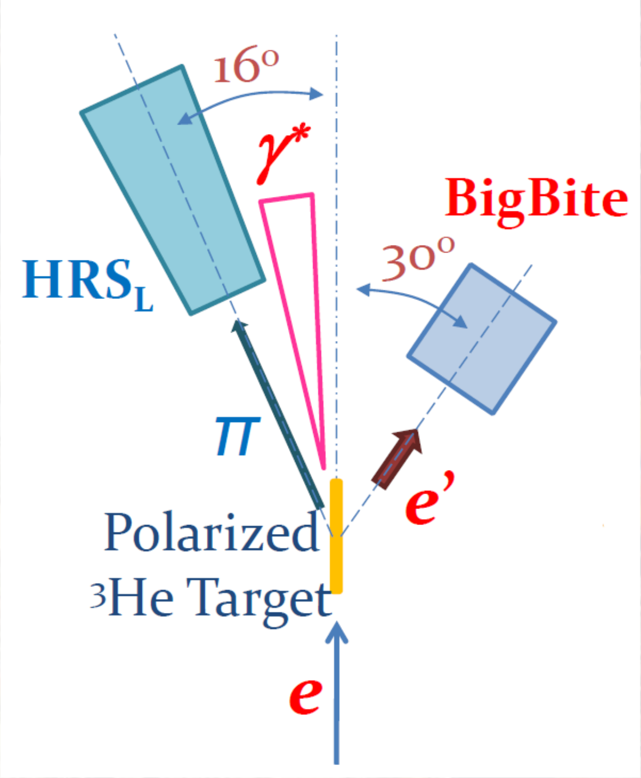
$L(x)$ – Lensing function (from Burkart)
E^q – GPD related to quark OAM

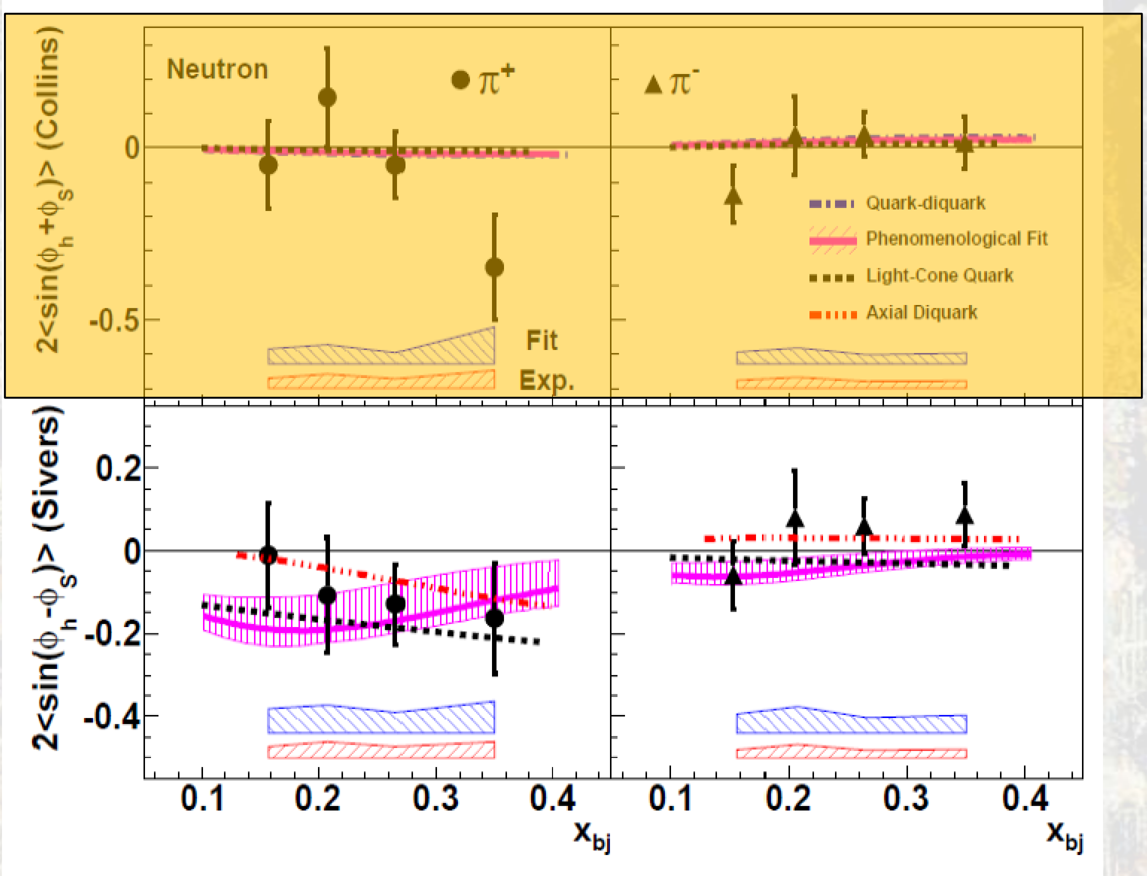
n-th moment of a TMD with respect to $k_\perp$

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



Sivers asymmetry on neutron





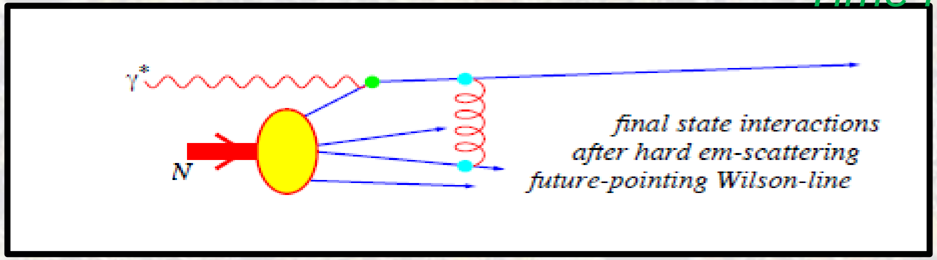
JLab Hall A

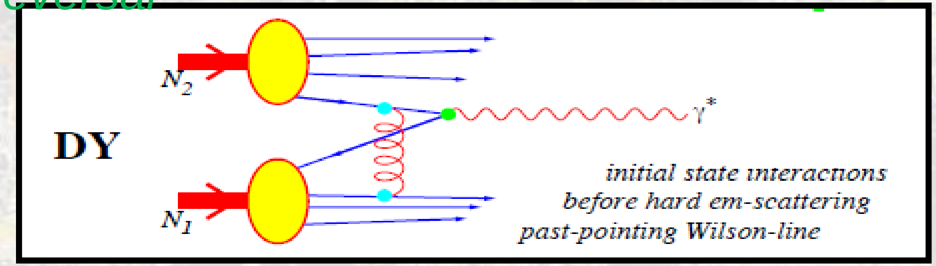
Test of universality

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

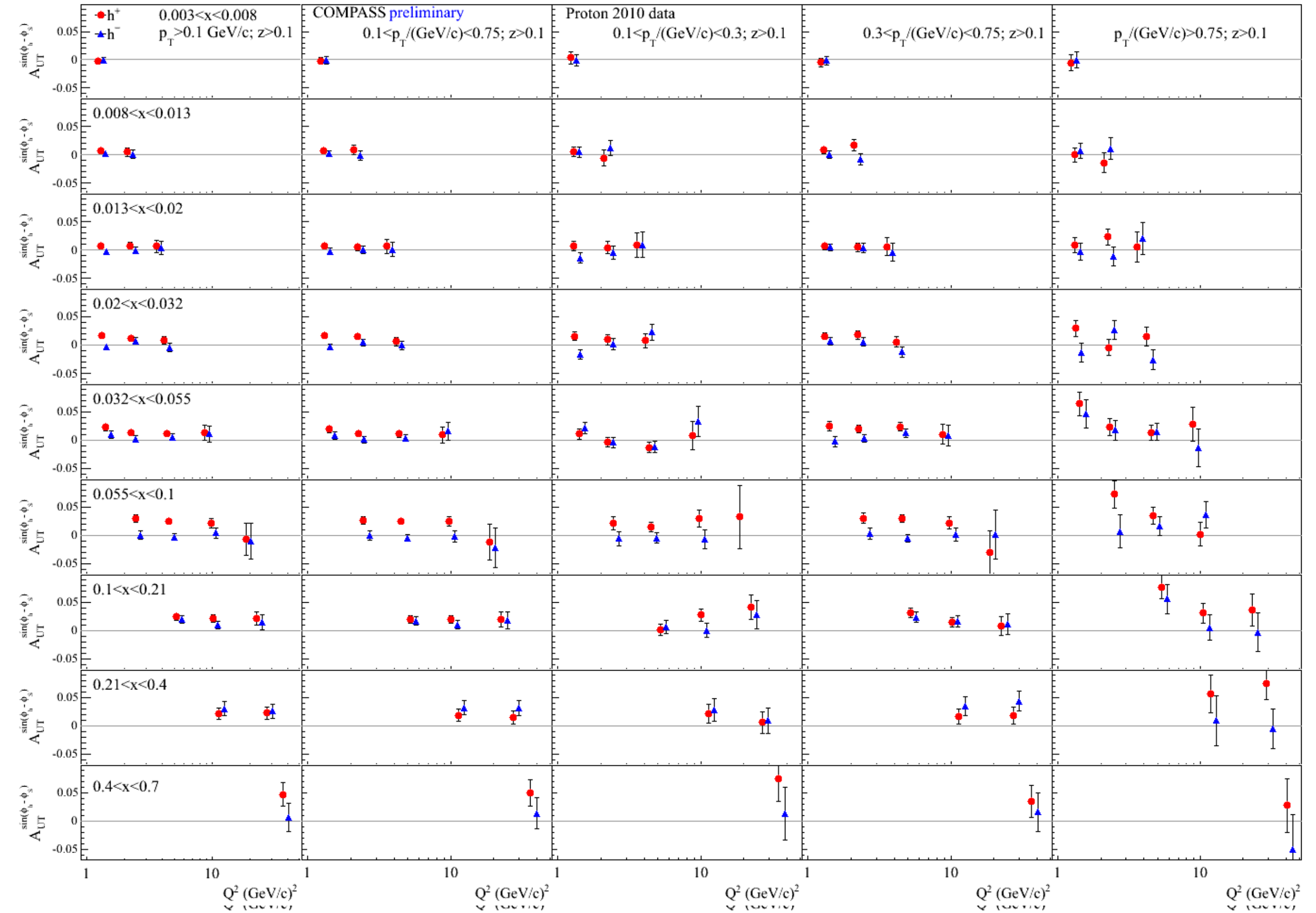
$$\boxed{h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)}$$

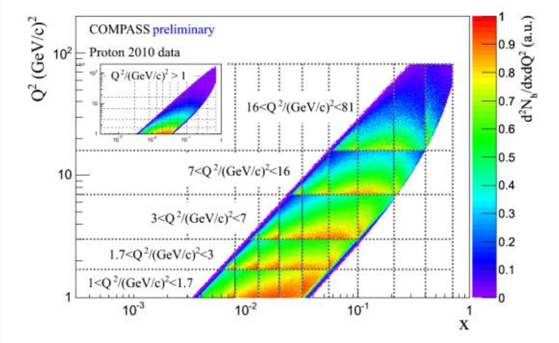
Sivers

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

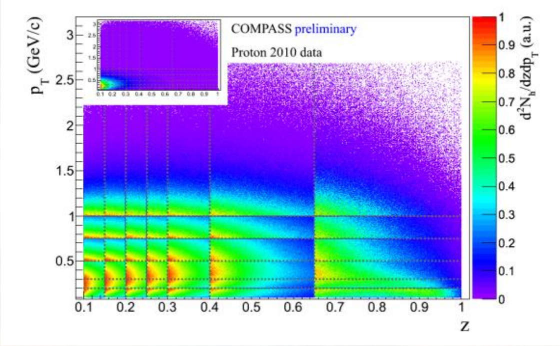
Sivers asymmetry on proton. Multidimensional

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

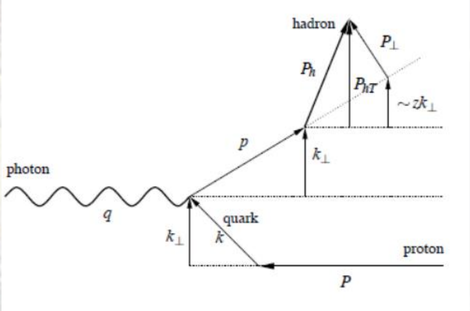




DY RUN STARTING!!!



Importance of unpolarized SIDIS for TMDs

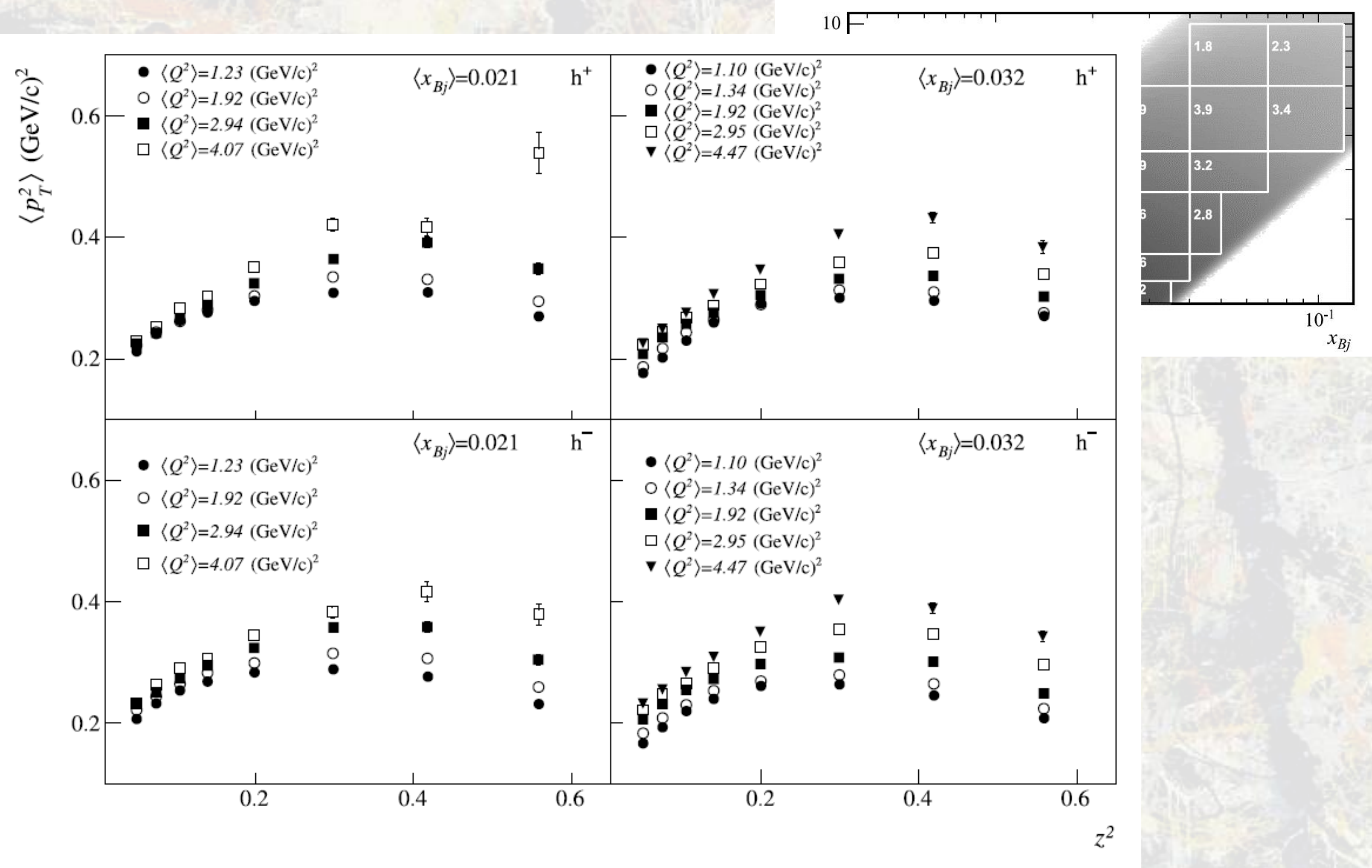


- The cross-section dependence from p_T^h results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle p_{T,h}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$

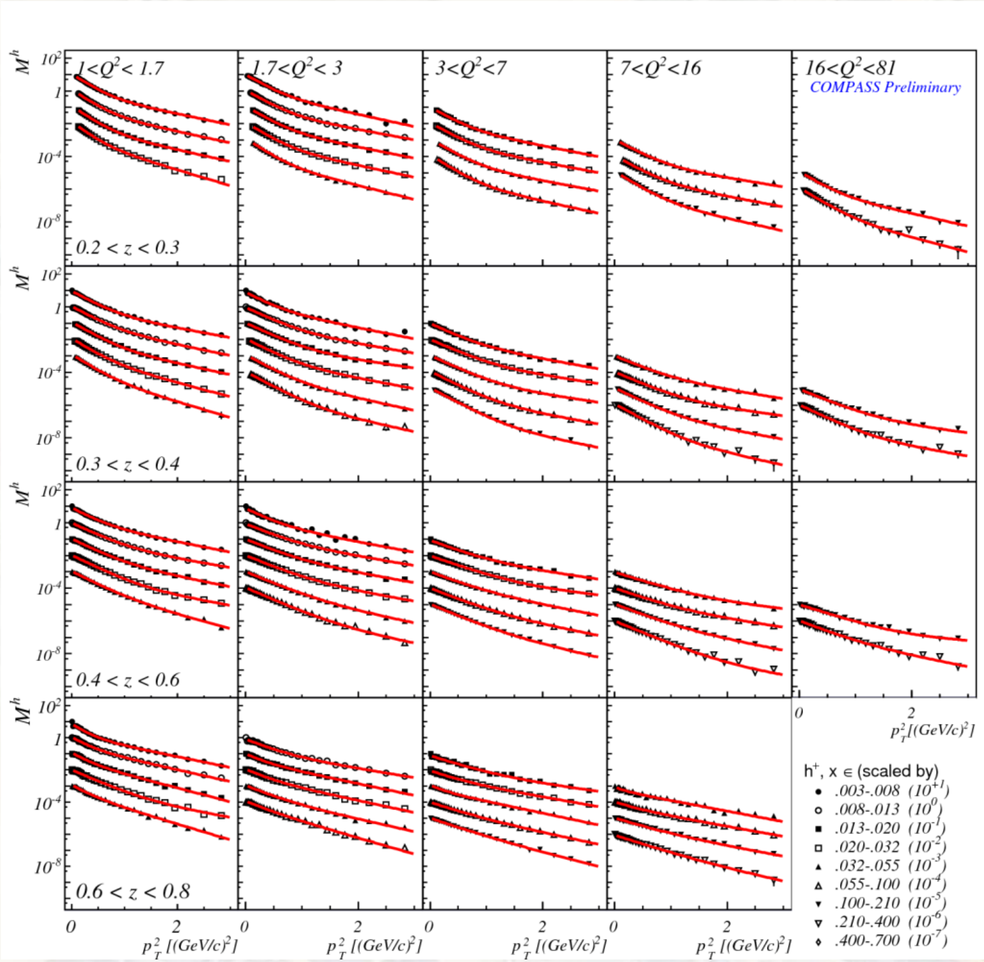
- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

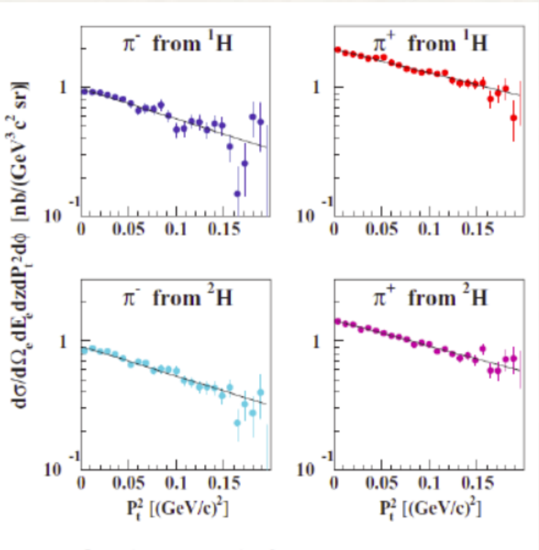
These are difficult measurements were one has to correct for the apparatus acceptance

X-section dep. from p_T^h

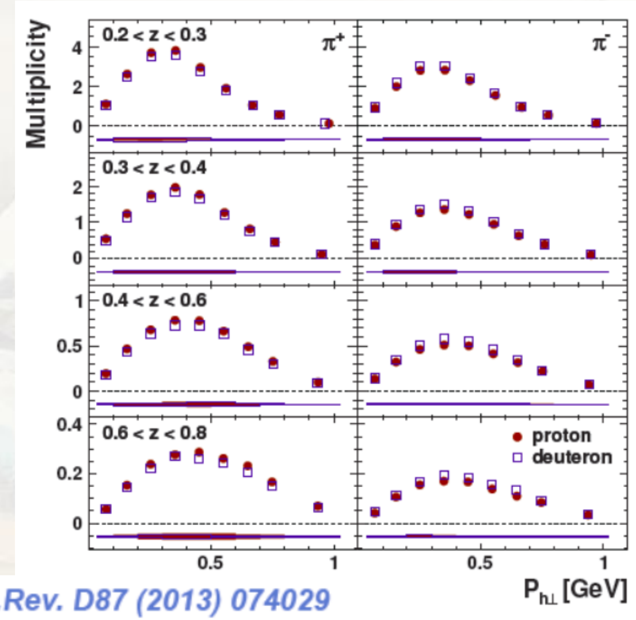


New results



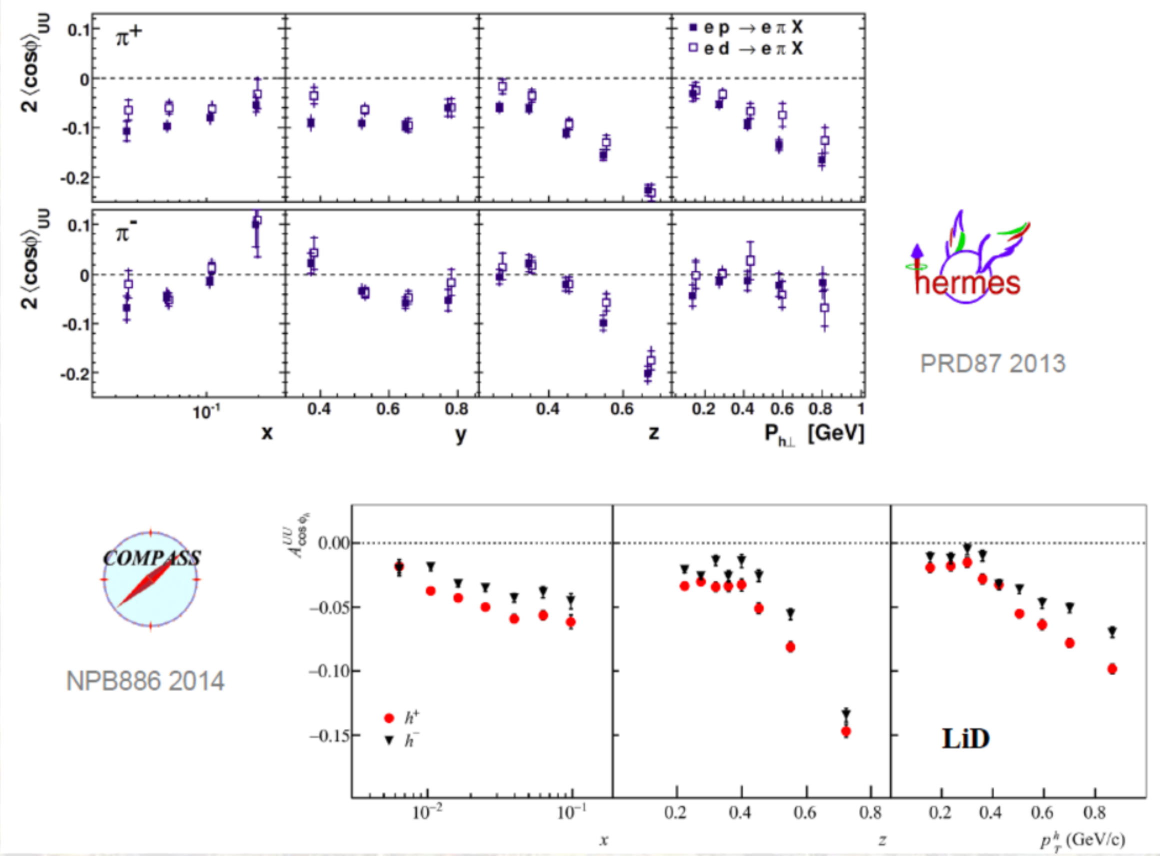


Asaturyan et al. PRC85 2012



Phys.Rev. D87 (2013) 074029

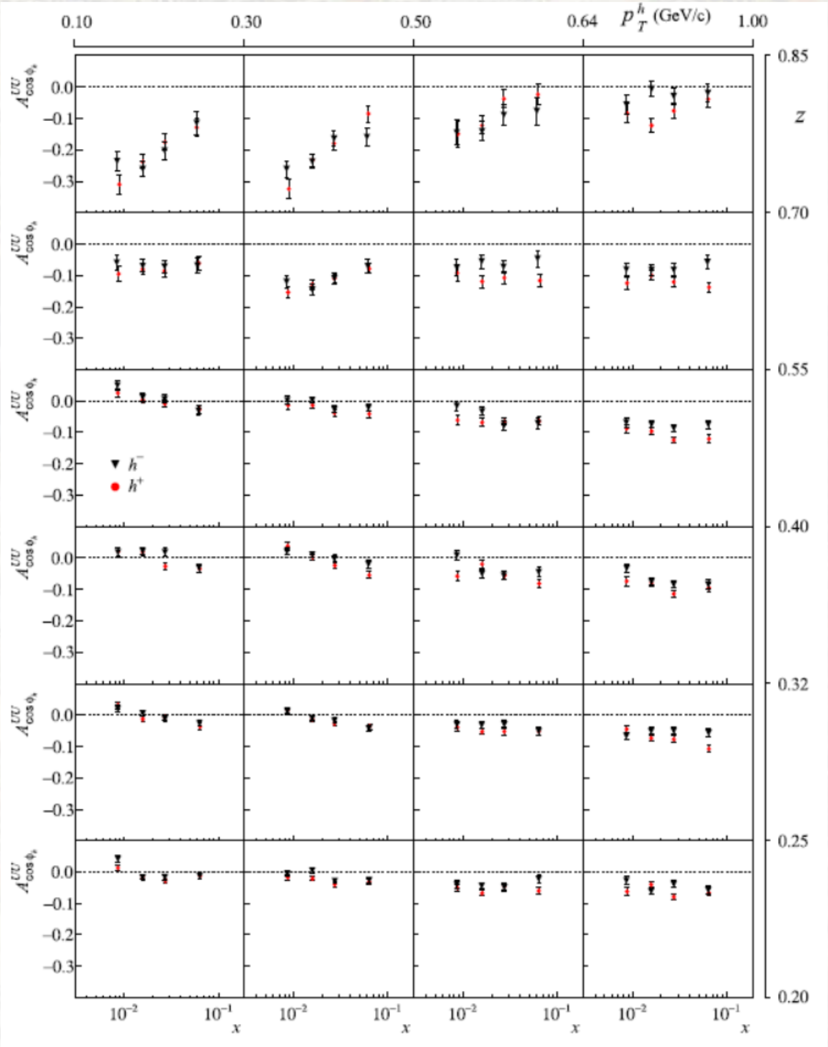
Boer-Mulders and Cahn effects, a reminder

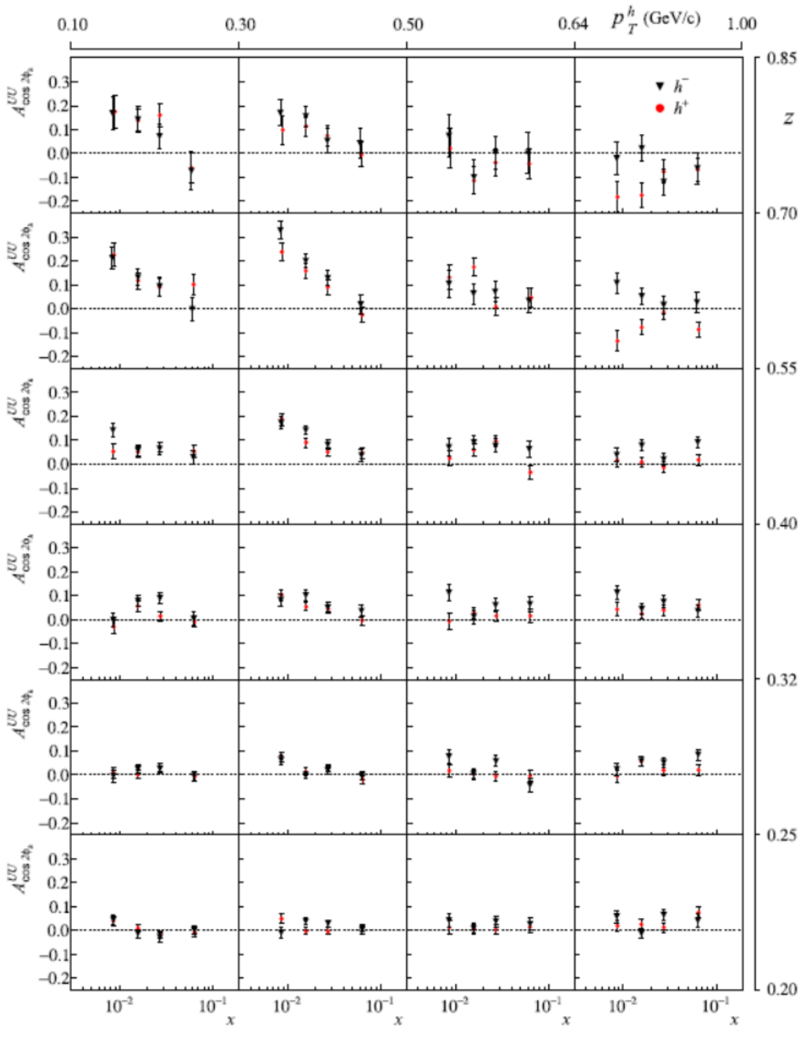


PRD87 2013

NPB886 2014

Boer-Mulders and Cahn effects





Conclusions (?)

- A lot of data on the shelf being used;
- New PP results from RHIC
- SIDIS results will continue to come in the future both from COMPASS and from JLAB12;
- In the near future COMPASS will provide first polarized DY

Whats NEXT?

Theory side, a suggestion

- The amount of data is rapidly increasing;
- The phenomenological analysis of Collins/Sivers/Unpolarised Asyms…is helping to get insight on the mechanisms
- We have strong groups of IT theorists leading the field
- Maybe (?) it is the right time for them to setup a Collaborations, aiming to a global analysis of all this data sets.

And for experiments …

Nucleon Structure Outlook

- This is a defining period for the future, which can be bright
- Next decade g [illegible] ortant input from HL-LHC, COMPASS, JLab-12 GeV
- LHeC (and FC [illegible] an envisioned 60-GeV ERL off the LHC (or its upgrade). They wi [illegible] **ate tools to study high-energy DIS**, and allow unprecedented m [illegible] of
  - parton distributions of glu [illegible] and nuclei, down to the region of the highest-density matter
  - precision Higgs characterization
  - resolving proton (and LQ) structure dow [illegible] 10^{-5} fm
- EIC science requires **polarization** & **luminosi** [illegible] **on capability**. EIC allows a **unique opportunity** to make a (textb [illegible] reakthrough in nucleon structure and QCD dynamics
  - explore and image the 3D (spin) structure of the nucleon

Rolf Ent: Workshop on the Long Term Strategy of INFN
CSN1
Elba, May 22 – May 24, 2014

Lepton scattering has proven its science value over the last 5 decades!
These projects deserve the strongest support – they can be on your horizon!

Electron Ion Colliders

Past

Possible Future

Europe

US

EIC

China

CEIC

Europe

	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	70-150	12-70 → 140	12 → 65	14
proton x_{min}	1 x 10^{-5}	5 x 10^{-7}	4 x 10^{-5}	5 x 10^{-5}	7 x10^{-3} →3x10^{-4}	5 x 10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} s^{-1}]	2 x 10^{31}	10^{33-34}	10^{33} → 10^{34}	10^{34-35}	10^{32-33} → 10^{35}	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2025	2025	Post-12 GeV	2019 → 2030	upgrade to FAIR

Followed by FCC-he?

Figure-8

Figure-8

Dormant

High-Energy Physics

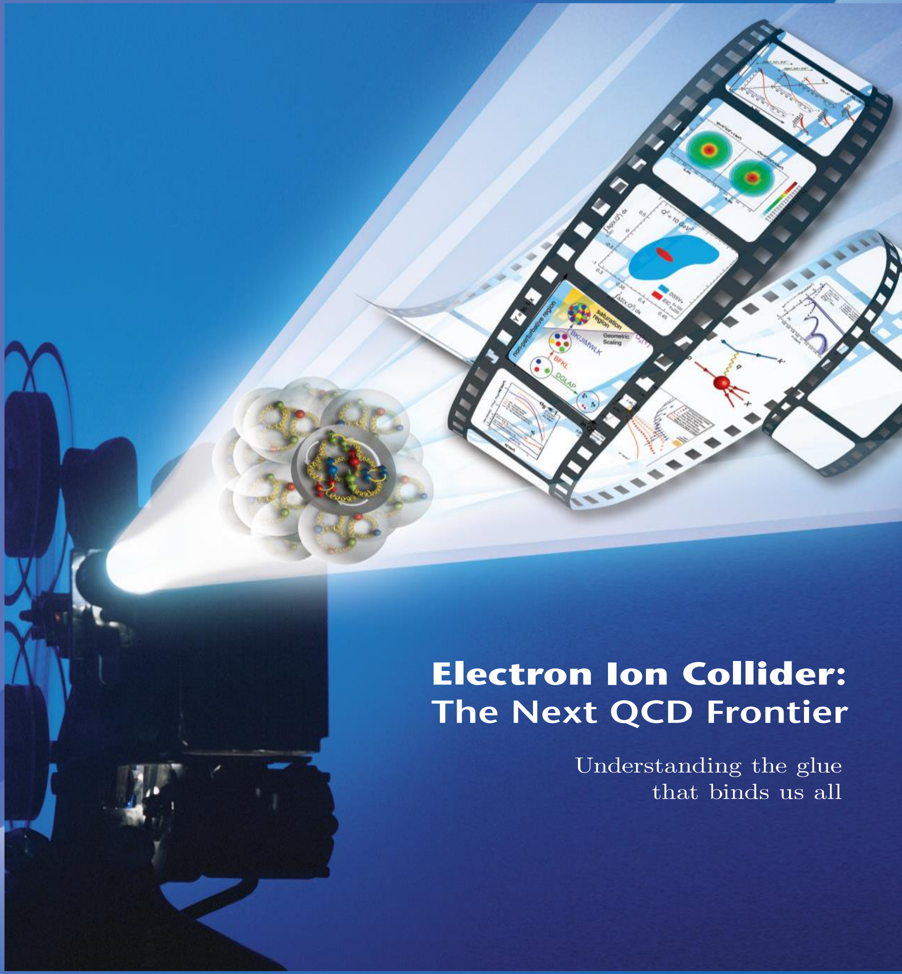
Hadron Physics

Note: x_{min} ~ x @ Q^2 = 1 GeV^2

All of us dream of

EIC:

the MACHINE to image quarks and gluons



Electron Ion Collider:
The Next QCD Frontier

Understanding the glue
that binds us all

Thank You

Other SSAs - Deuteron data

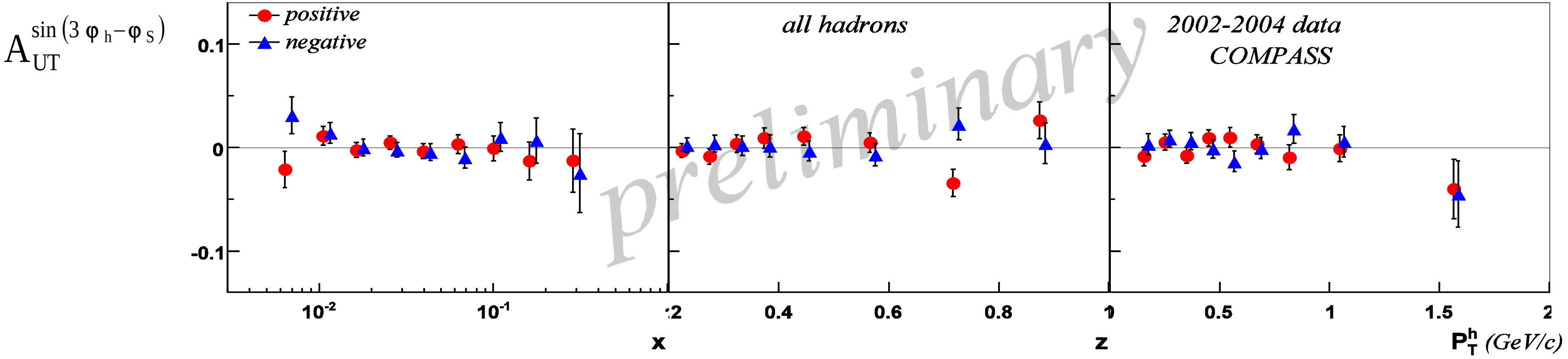
$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

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

two twist-2 asymmetries can be interpreted in QCD parton

“pretzelosity” ⊗ Collins FF

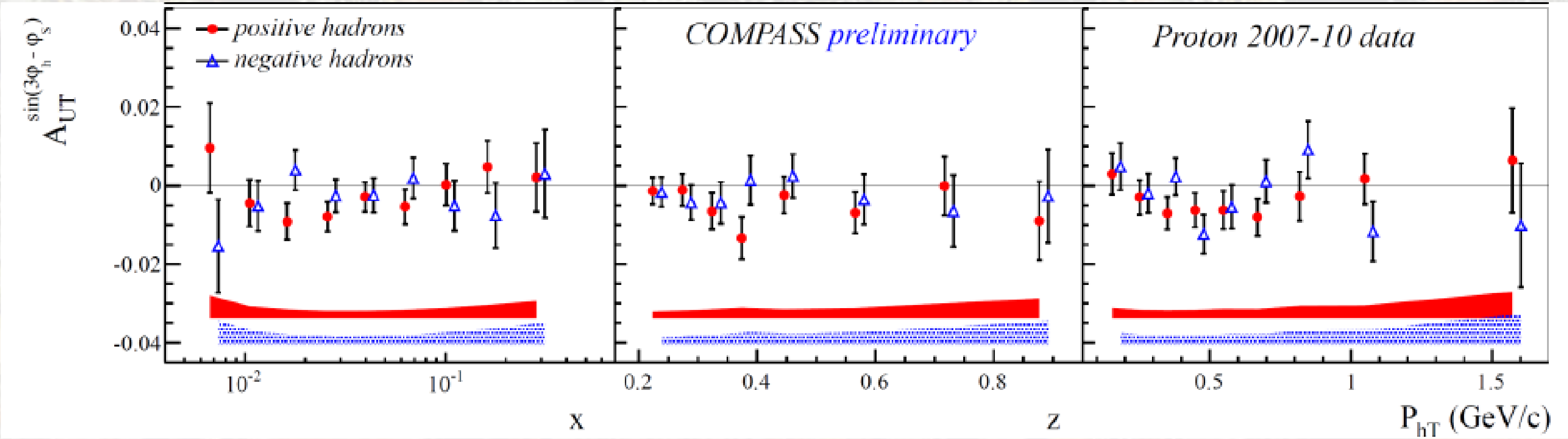
In some models $h_{1T}^{\perp} = g_1 - h_1$



on deuteron asymmetries compatible with zero: again cancellation between proton and neutron?

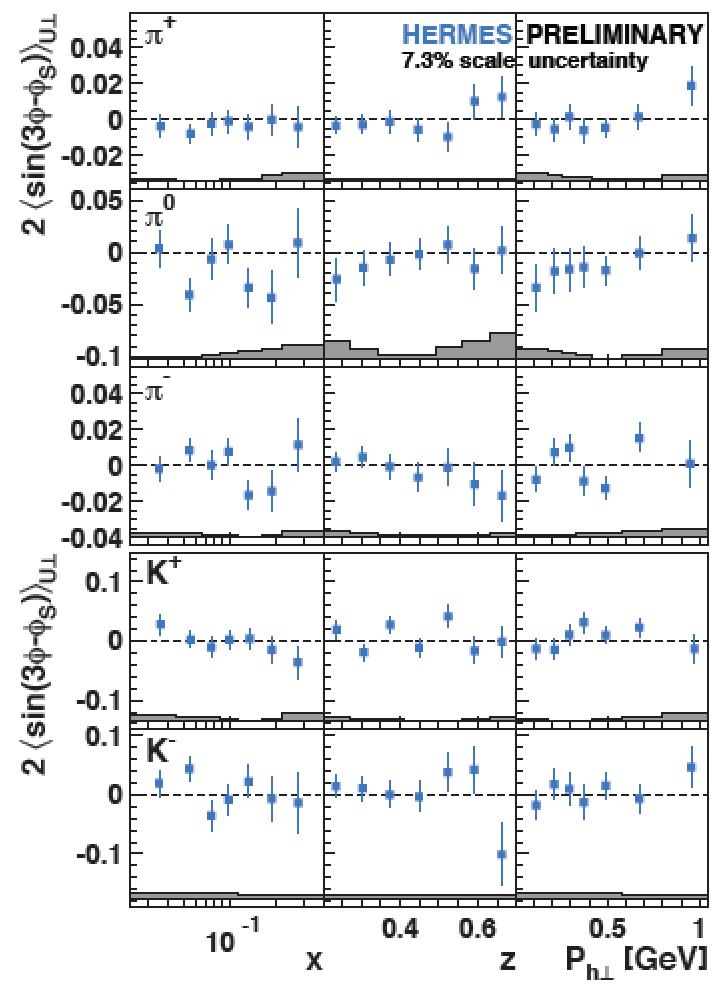
Other SSAs - proton data

“pretzelosity” ⊗ Collins FF



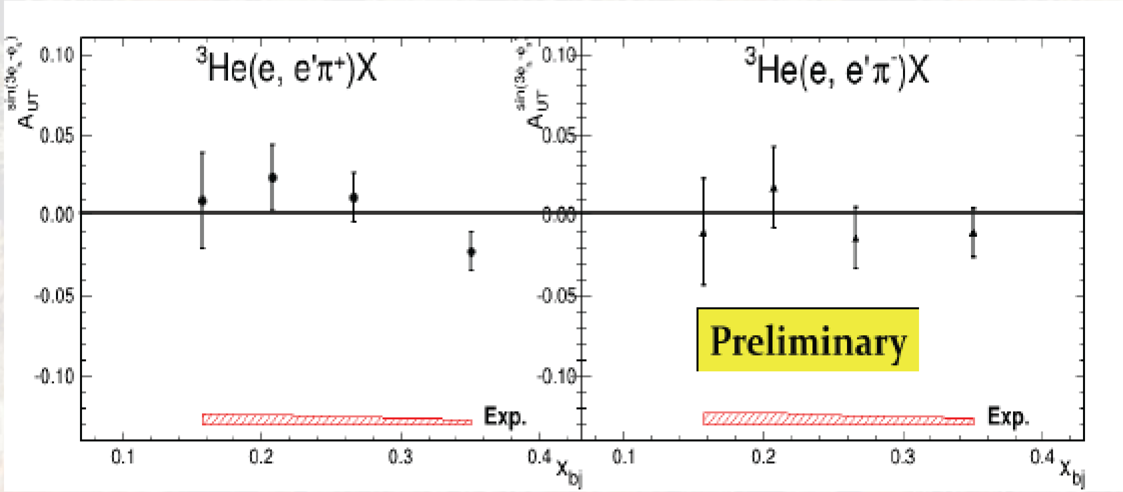
Other SSAs - proton data

“pretzelosity” ⊗ Collins FF



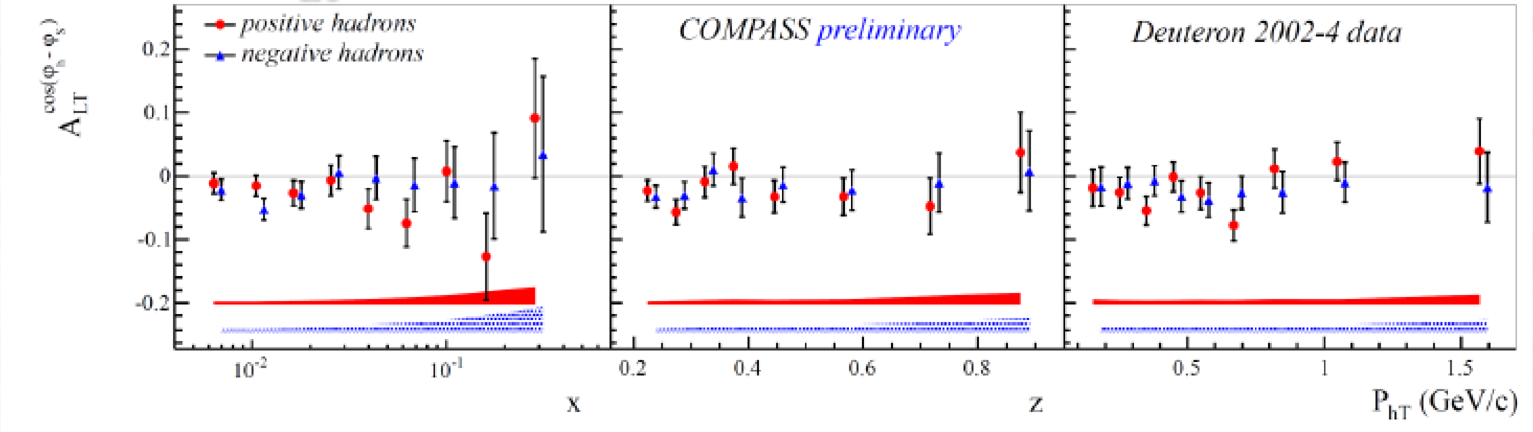
Other SSAs - neutron data

“pretzelosity” ⊗ Collins FF



Other Transverse Target spin asymmetries on d

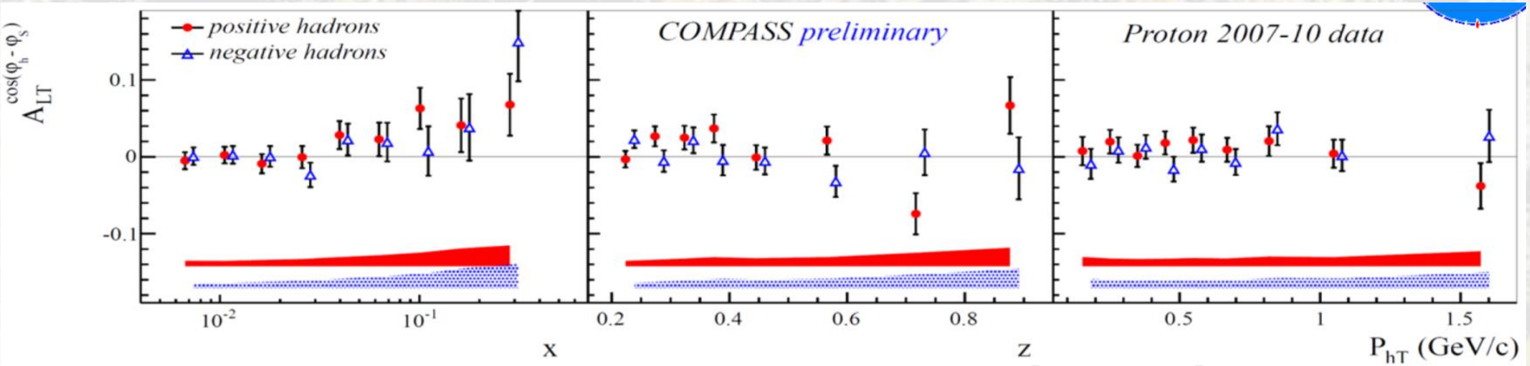
$A_{LT}^{\cos(\varphi_h-\varphi_s)}$



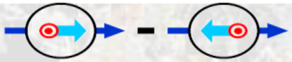
$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :

Other Transverse Target spin asymmetries on p

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

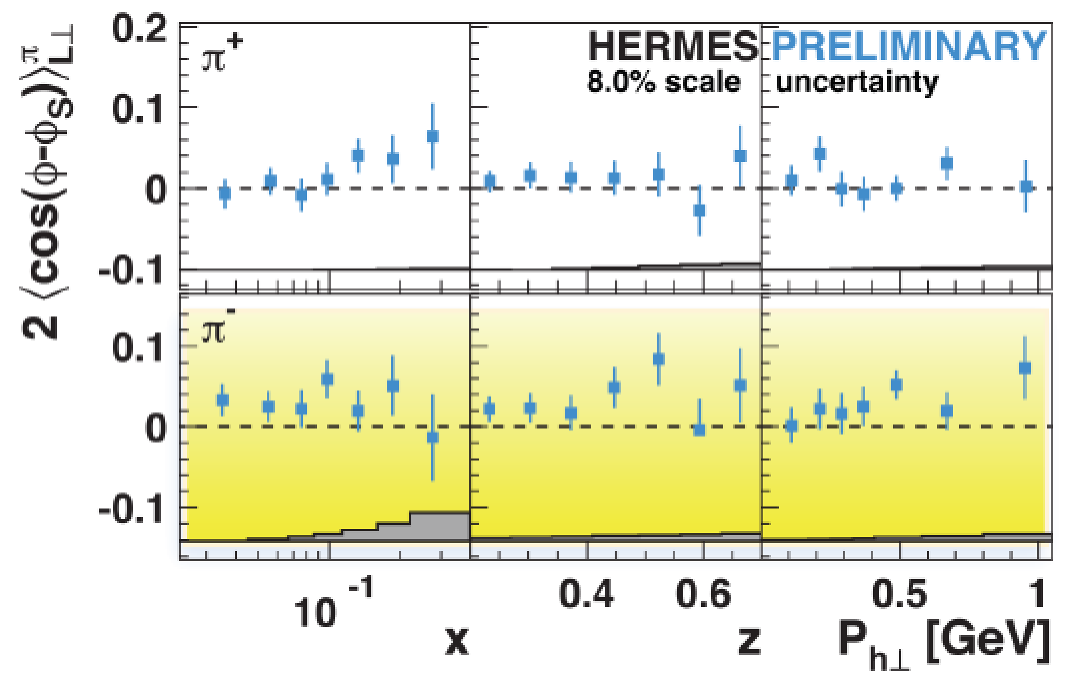


$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$, "Worm Gear" PDF g_{1T}^q :

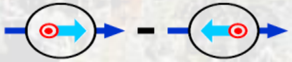


Other Transverse Target spin asymmetries on p

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

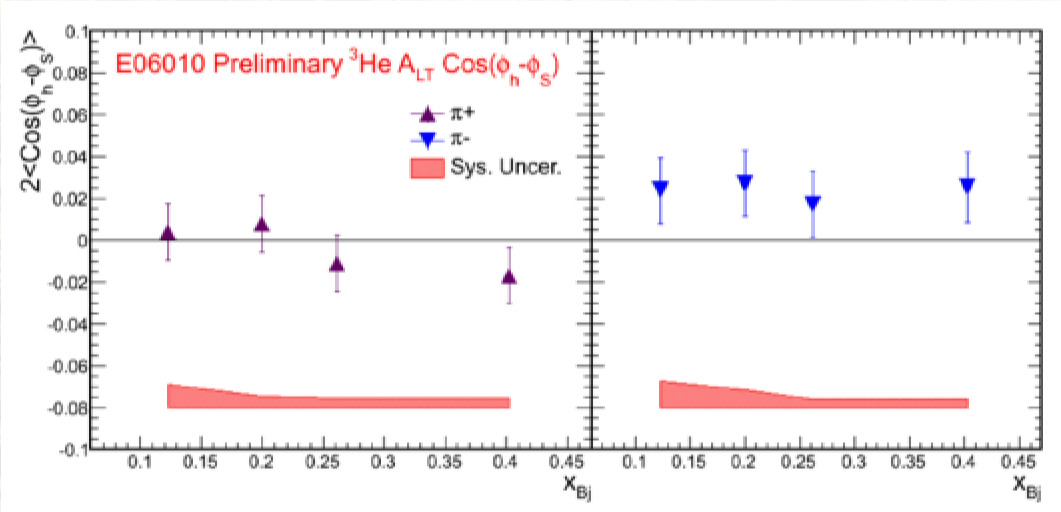


$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$, "Worm Gear" PDF g_{1T}^{q} :

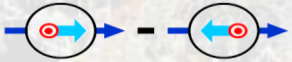


Other Transverse Target spin asymmetries on n

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



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



Collins Asymmetry on p - π, K id.

Correlation between outgoing hadron & quark transverse spin → h_1^u & h_1^d

π+

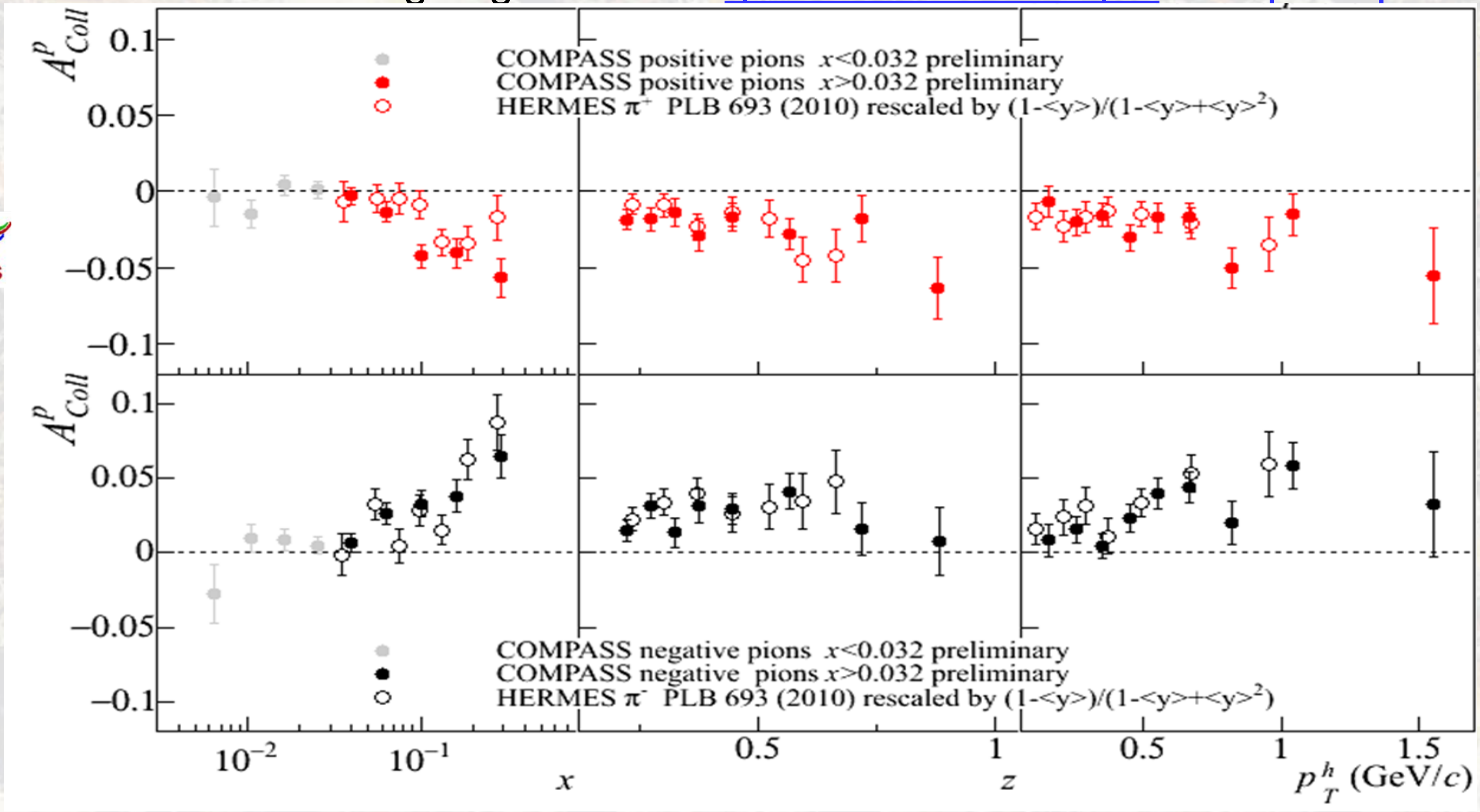
●

○

π-

●

○



- **Agreement HERMES/COMPASS → no Q^2 dependence seen**

Now also produced in bins of z and y

Importance of unpolarized SIDIS for TMDs

- The cross-section dependence from p_T^h results from:
    - intrinsic k_T of the quarks
    - $p_\perp$ generated in the quark fragmentation

- The azimuthal modulations in the unpolarized cross-sections comes from:
    - Intrinsic k_T of the quarks
    - The Boer-Mulders PDF

These are difficult measurements requiring to take into account apparatus acceptance

- COMPASS and HERMES have
    - results on ^6LiD $(\sim d)$ and d from
    - No measurements on p since on NH_3 $(\sim p)$ nuclear effects may be important

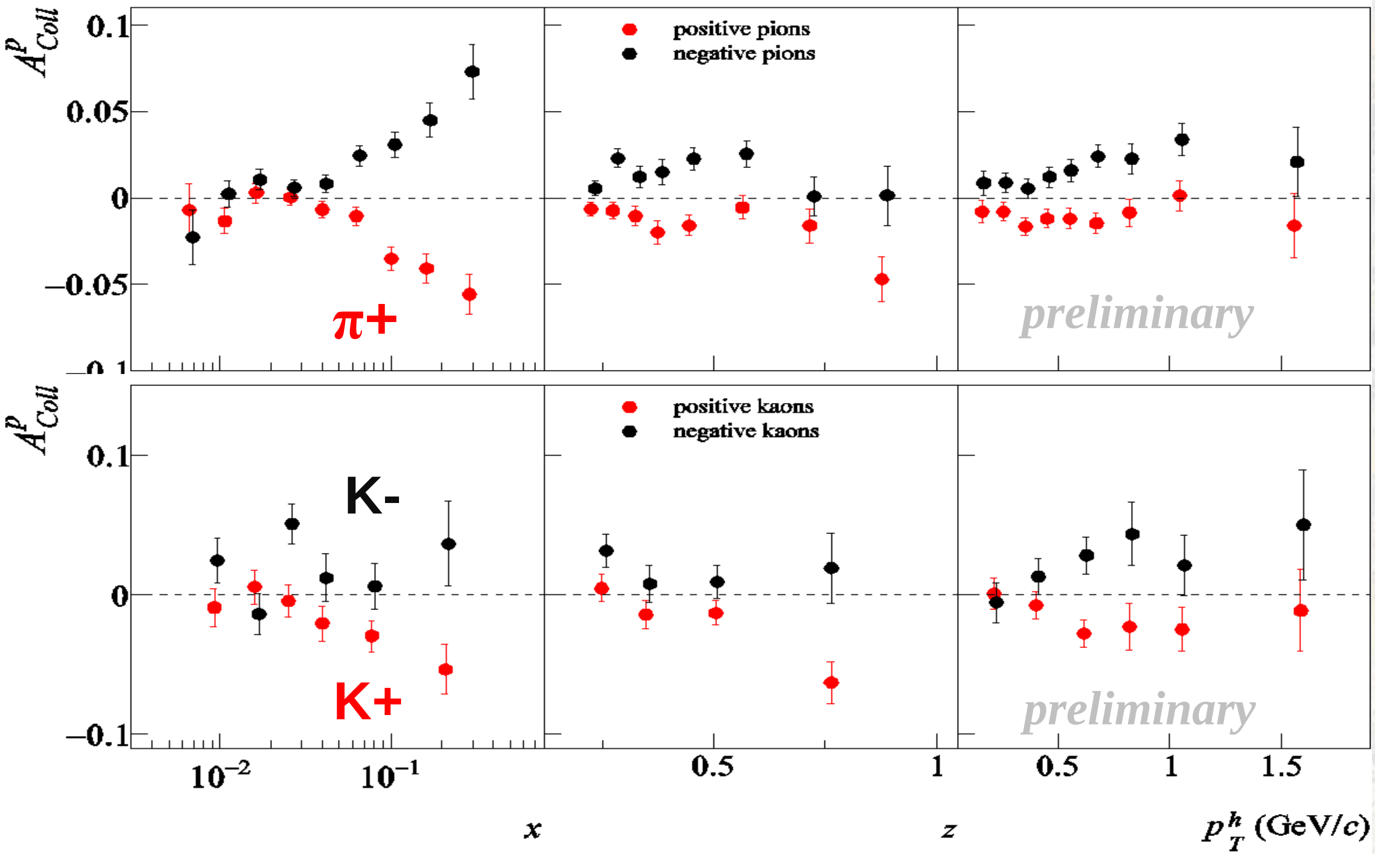
- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

Collins asymmetry on proton

charged pions and kaons

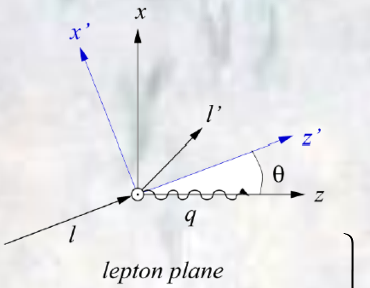
~ h+ / h-

compatible
with π+ / π-



combined 2007 – 2010 results

SIDIS 1h x-section



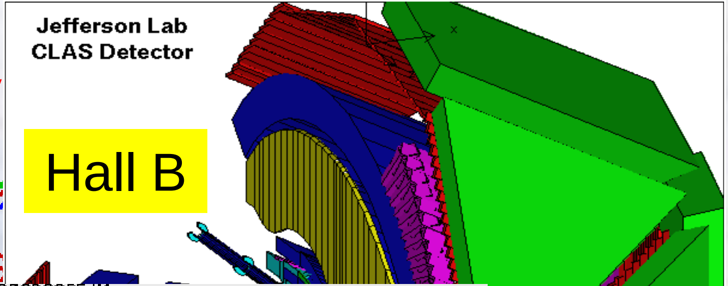
$$\frac{d\sigma}{dxdydzdP_{h\perp}^2\,d\varphi_h\,d\varphi_S}=\left[\frac{\cos\theta}{1-\sin^2\theta\sin^2\varphi_S}\right]\left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\times\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

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

Players on SIDIS play

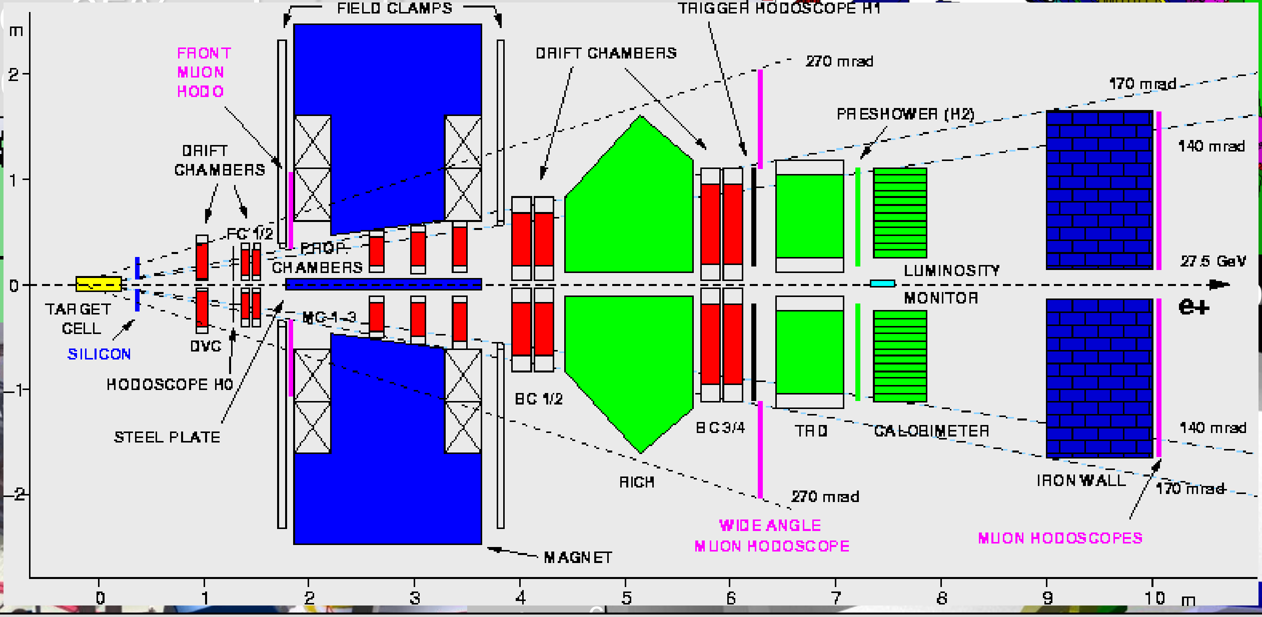
Jefferson Lab CLAS Detector

Hall B

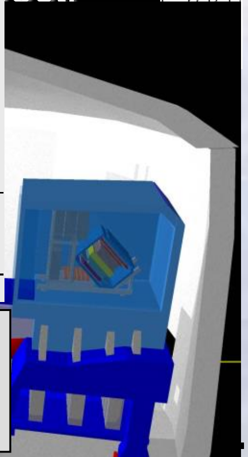


Beam: ≤6 GeV e

Target: polarize



ect.



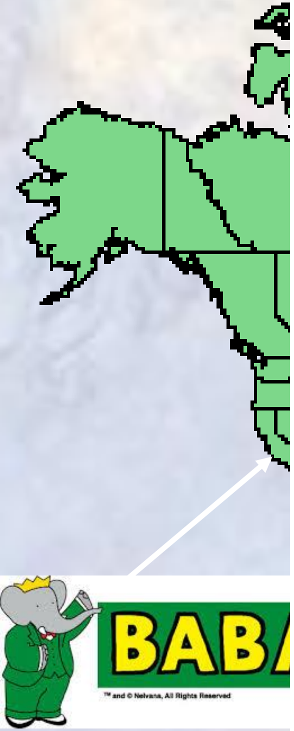
Beam: 27.5 GeV e±; <50>% polarization

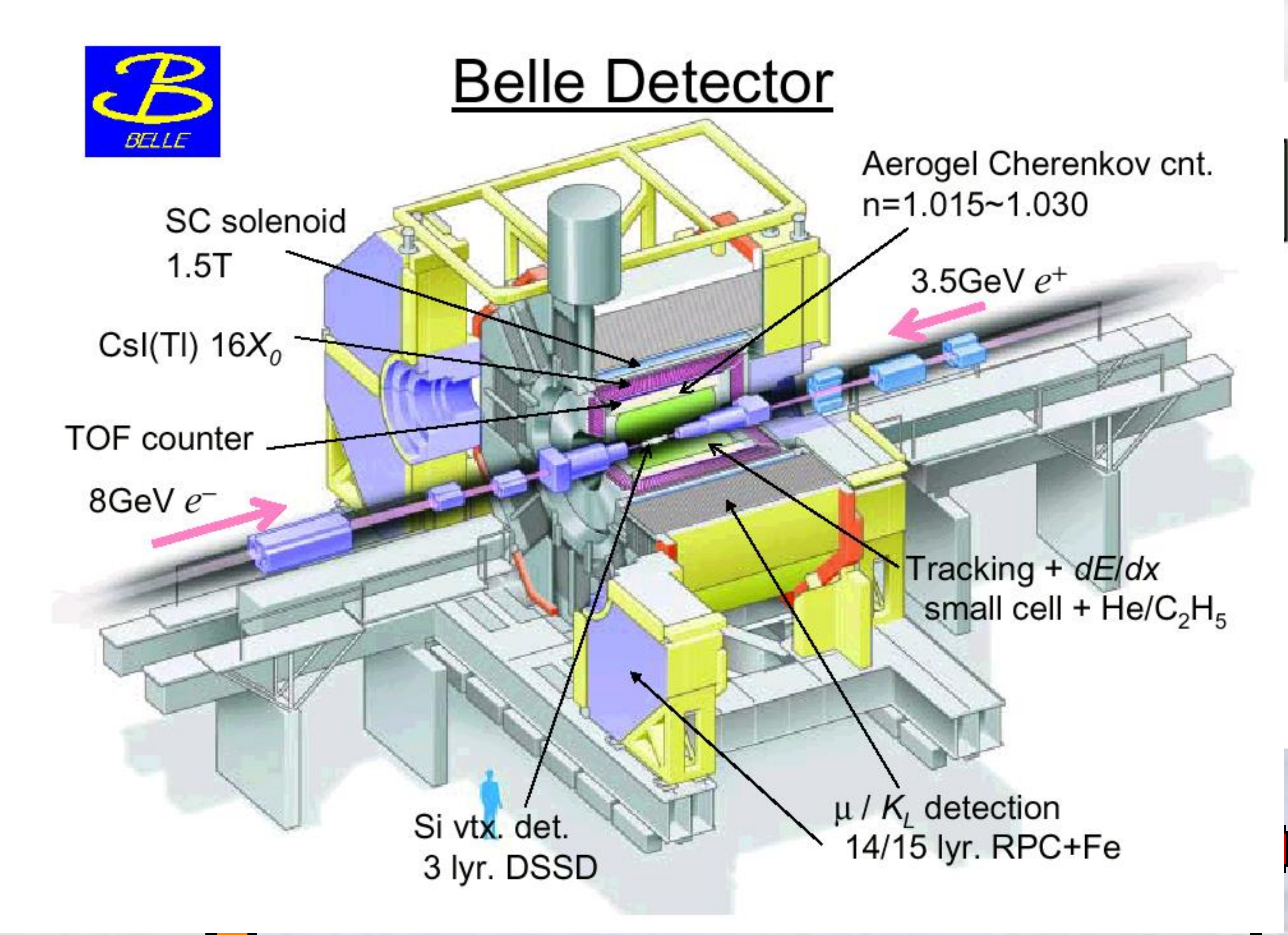
Target: polarized p gas targets; ⟨85%⟩ polarization

7 GeV spectrometer,
1.8 GeV spectrometer,
large installation experiments

Two high-resolution
4 GeV spectrometers

Players on FF playground





Spin, L and the free Dirac H

$$\boldsymbol{H} = \boldsymbol{\alpha} \cdot \vec{p} + \boldsymbol{\beta} m$$

$$\vec{L} = \mathbf{1}\, \vec{x} \times \vec{p}$$
$$= \mathbf{1}\, i\vec{x} \times \vec{\nabla}$$

$\Rightarrow$ L position dependent, doesn't commute with ∂_i in $\boldsymbol{H}$

$$\left[\boldsymbol{H}, \vec{L}\right] = -\boldsymbol{\alpha} \cdot \vec{\nabla}$$

$\vec{L}$ not conserved

$$\vec{\Sigma} = \begin{pmatrix} \vec{\sigma} & 0 \\ 0 & \vec{\sigma} \end{pmatrix}$$

$\Rightarrow$ Pauli matrices in $\vec{\Sigma}$ and $\boldsymbol{H}$ do not commute

$$\left[\boldsymbol{H}, \vec{\Sigma}\right] = \mathbf{2}\boldsymbol{\alpha} \cdot \vec{\nabla}$$

spin not conserved

$$\left[\boldsymbol{H}, \vec{L} + \frac{1}{2}\vec{\Sigma}\right] = \left[\boldsymbol{H}, \vec{J}\right] = 0$$ J conserved