Experimental results on TMDs and future perspectives

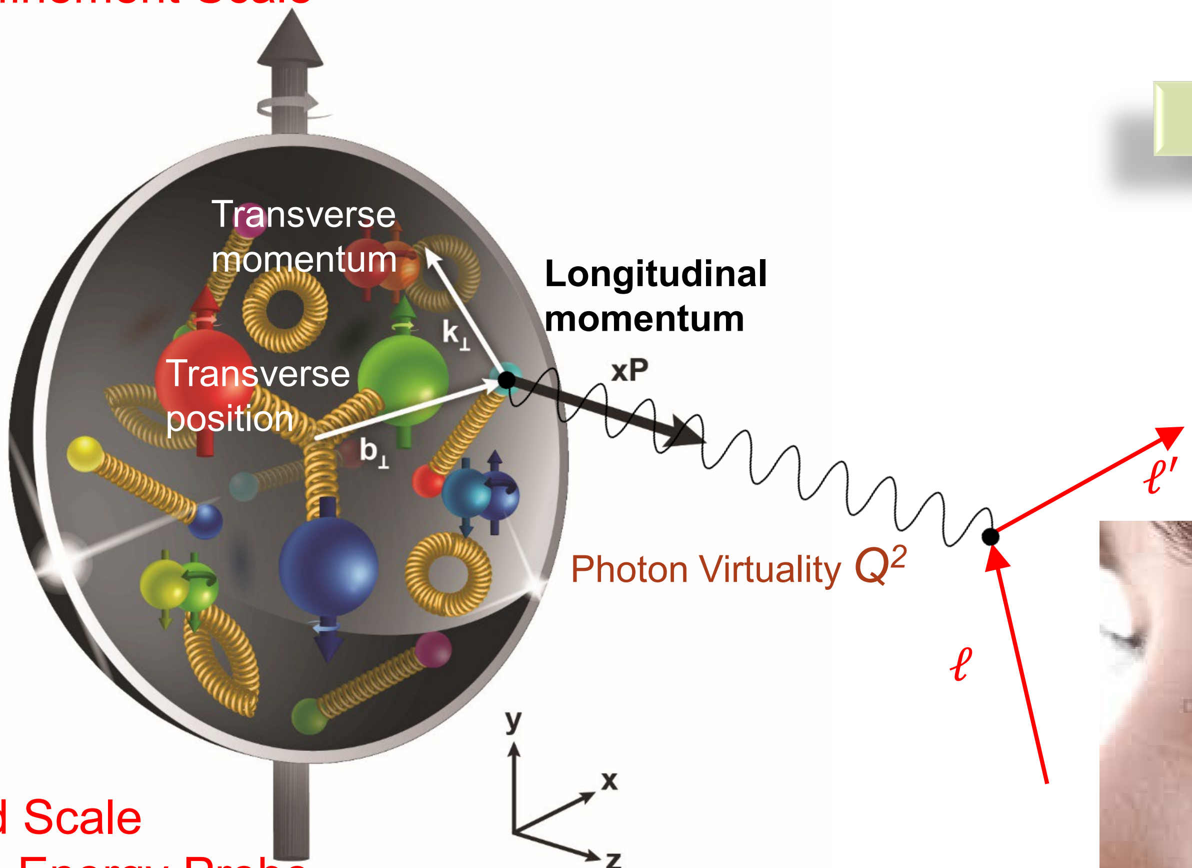
Andrea Bressan
University of Trieste and INFN

INFN

XXIX Cracow EPIPHANY Conference
16–19 January 2023, Henryk Niewodniczański Institute, Cracow, Poland

Transverse structure of the Nucleon

Confinement Scale

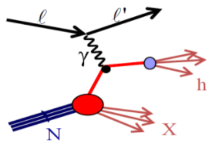


$$W_p^q\left(x, \vec{k}_\perp, \vec{b}_T\right)$$

Hard Scale
High Energy Probe

Accessing TMD PDFs and FFs

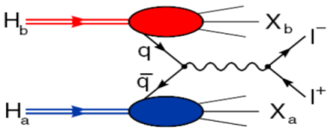
- TMD factorization works in the domain where there are two observed momenta in the process, such as SIDIS, DY, e^+e^-. $Q \gg q_T$: Q is large to ensure the use of pQCD, q_T is much smaller such that it is sensitive to parton's transverse momentum
- SIDIS off (un)polarized p, d, n targets



HERMES
COMPASS
JLab12
future: ***EIC***

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

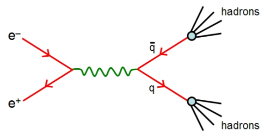
- (un)polarised Drell-Yan



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

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

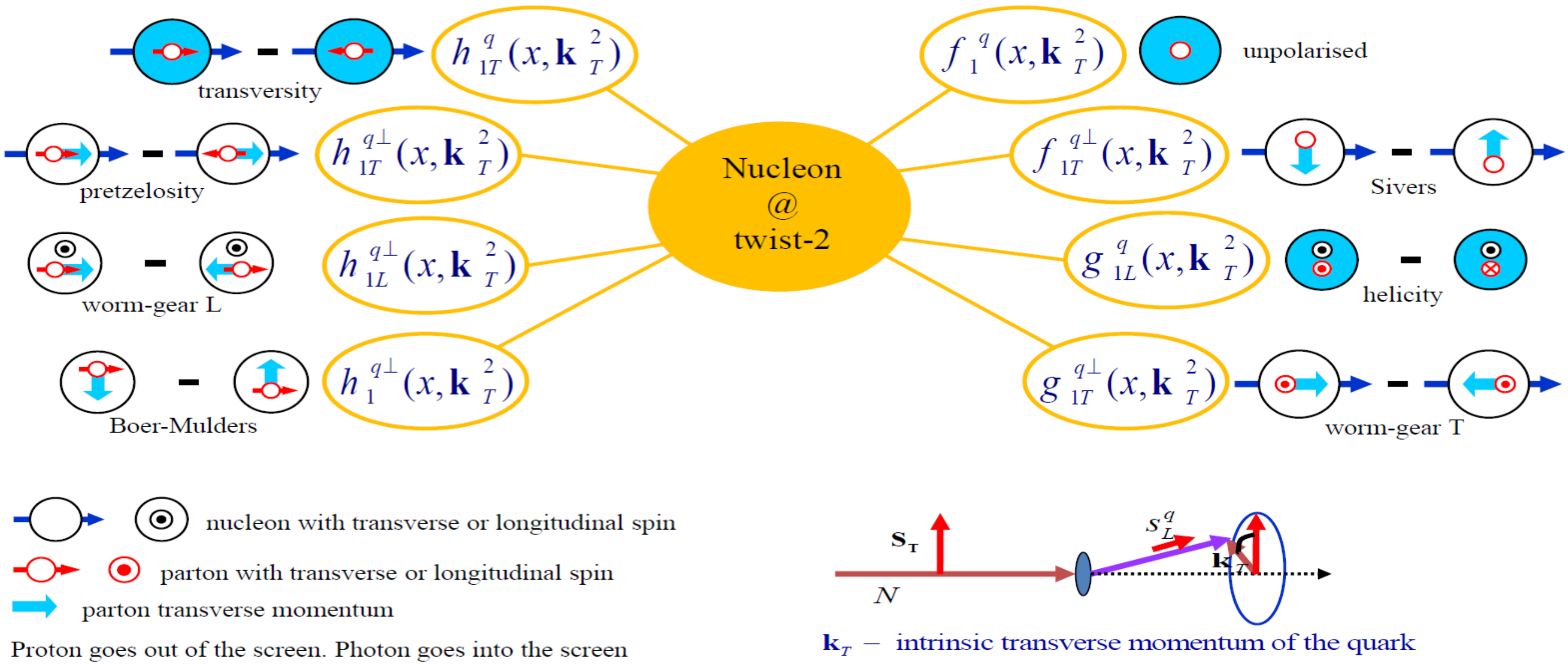
- $e^+e^- \to h_1 h_2$



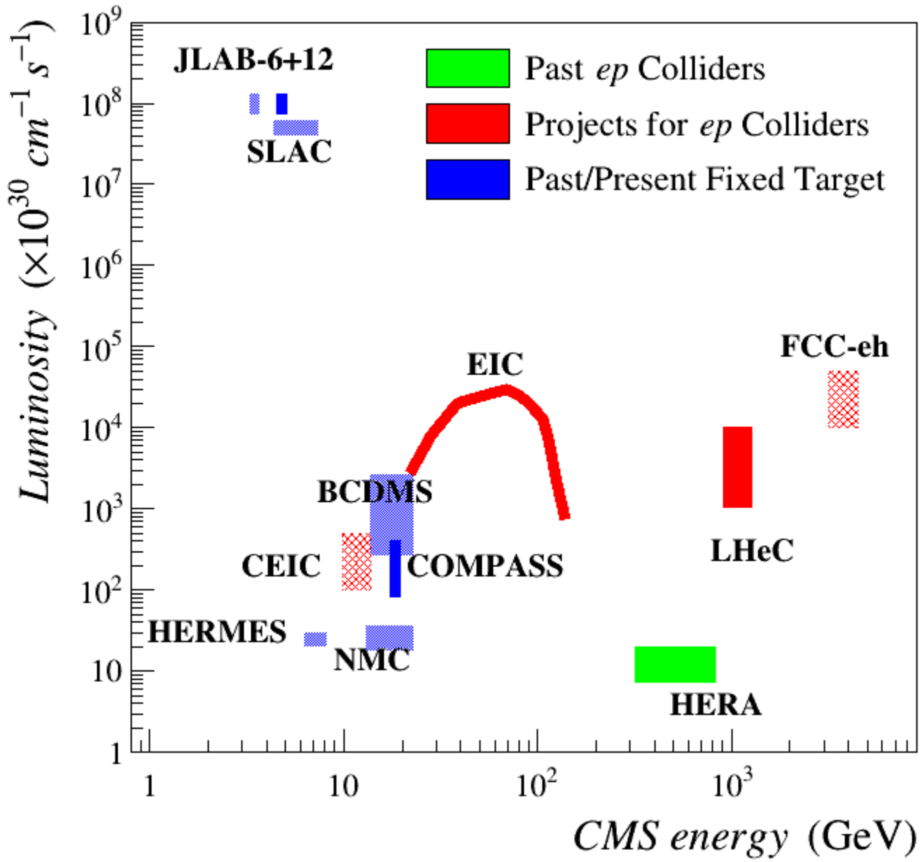
BaBar
Belle
Bes III

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

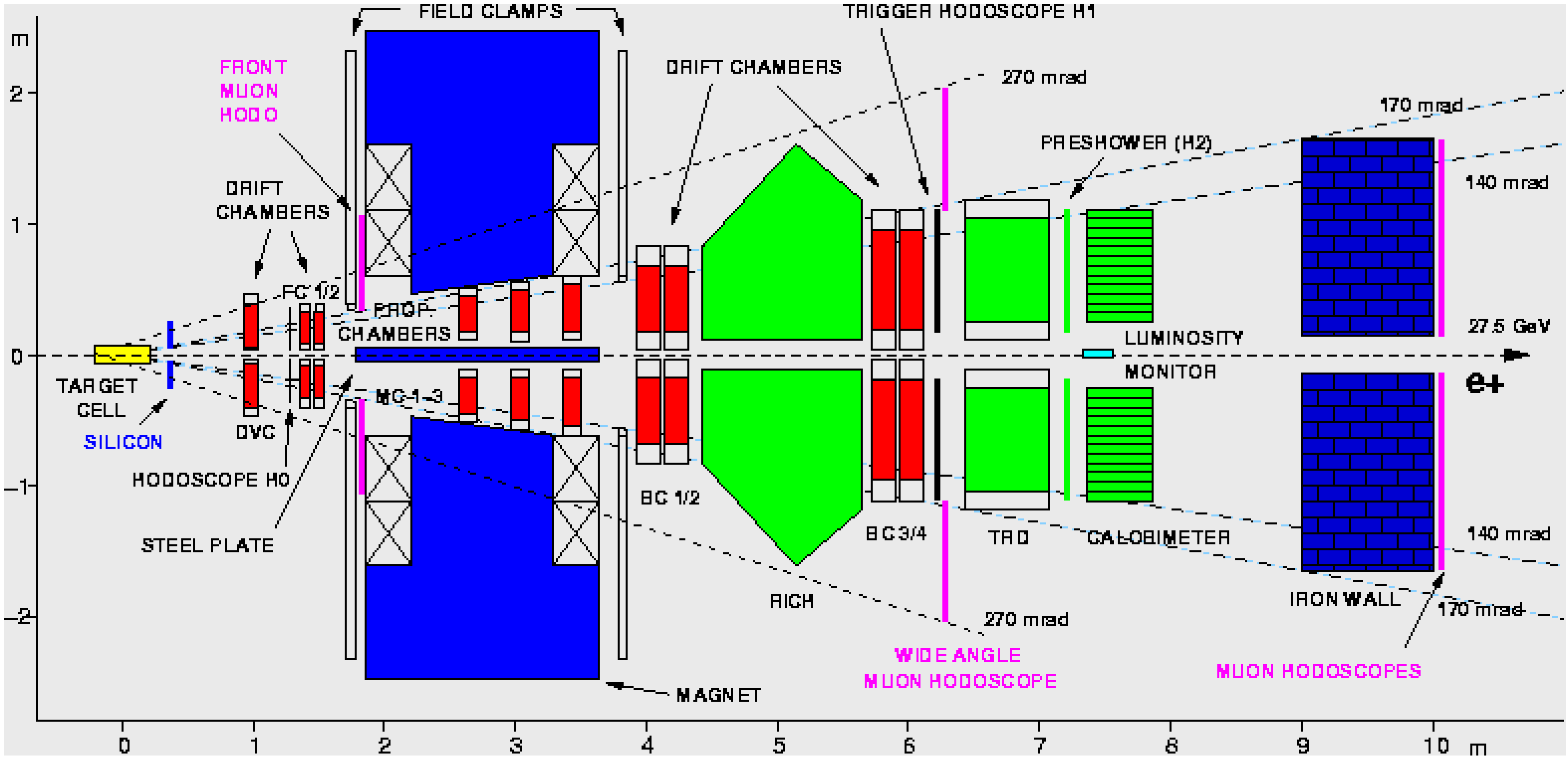
TMD Distribution Functions



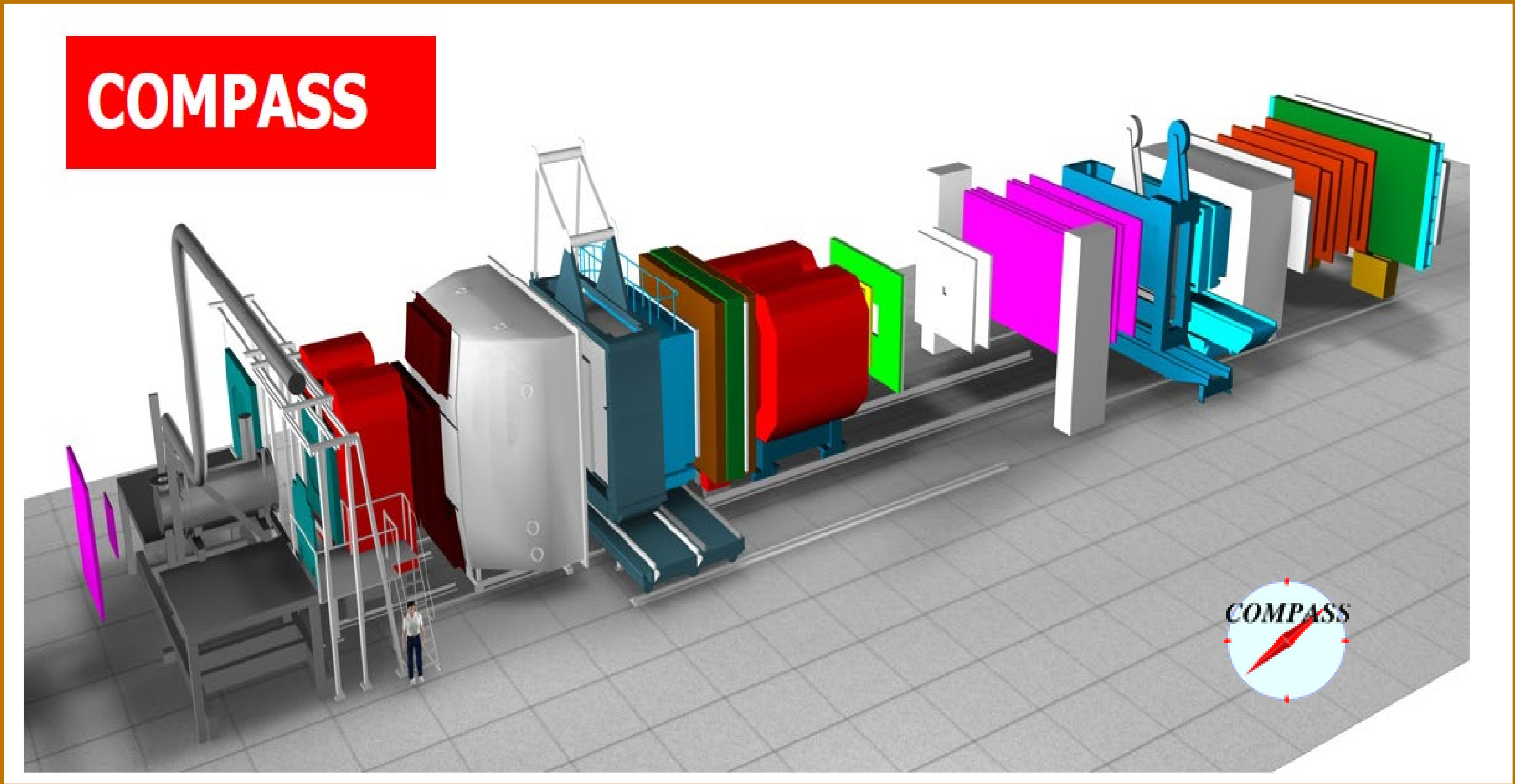
DIS around the world



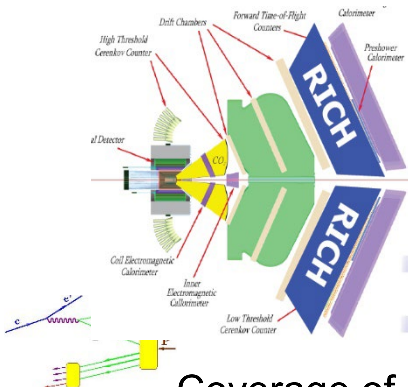
SIDIS @ HERMES



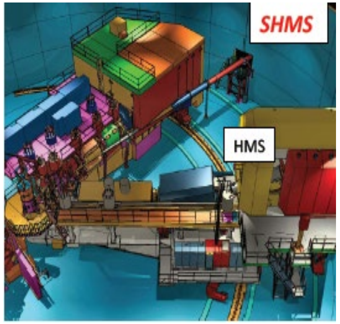
SIDIS @ COMPASS



SIDIS at JLab12



Coverage of large Q^2 and large P_T



CLAS12

Proton

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-, K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+,K^-,K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Quark spin polarization (columns) / Nucleon polarization (rows)

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C | Hall A

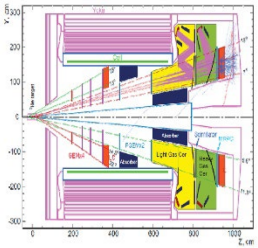
E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

C12-11-108: π^+,π^-

Solid

H_2 NH_3



CLAS12

D_2

E09-008: π^+,π^-,π^0 K^+, K^-, K^0

E07-107: π^+,π^-,π^0
E09-009: K^+,K^-,K^0

D_2, ND_3

Quark spin polarization (columns) / Nucleon polarization (rows)

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS SHMS

D_2

Precision measurements of all SFs in a wide range

^3He

C12-20-002
$\pi^+,\pi^-.\pi^0,K+$

Quark spin polarization (columns) / Nucleon polarization (rows)

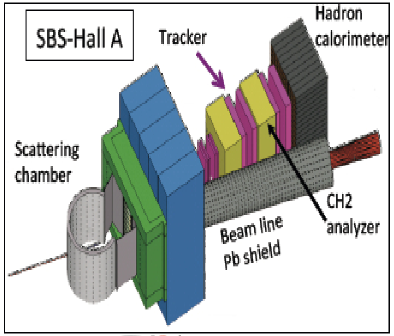
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall A

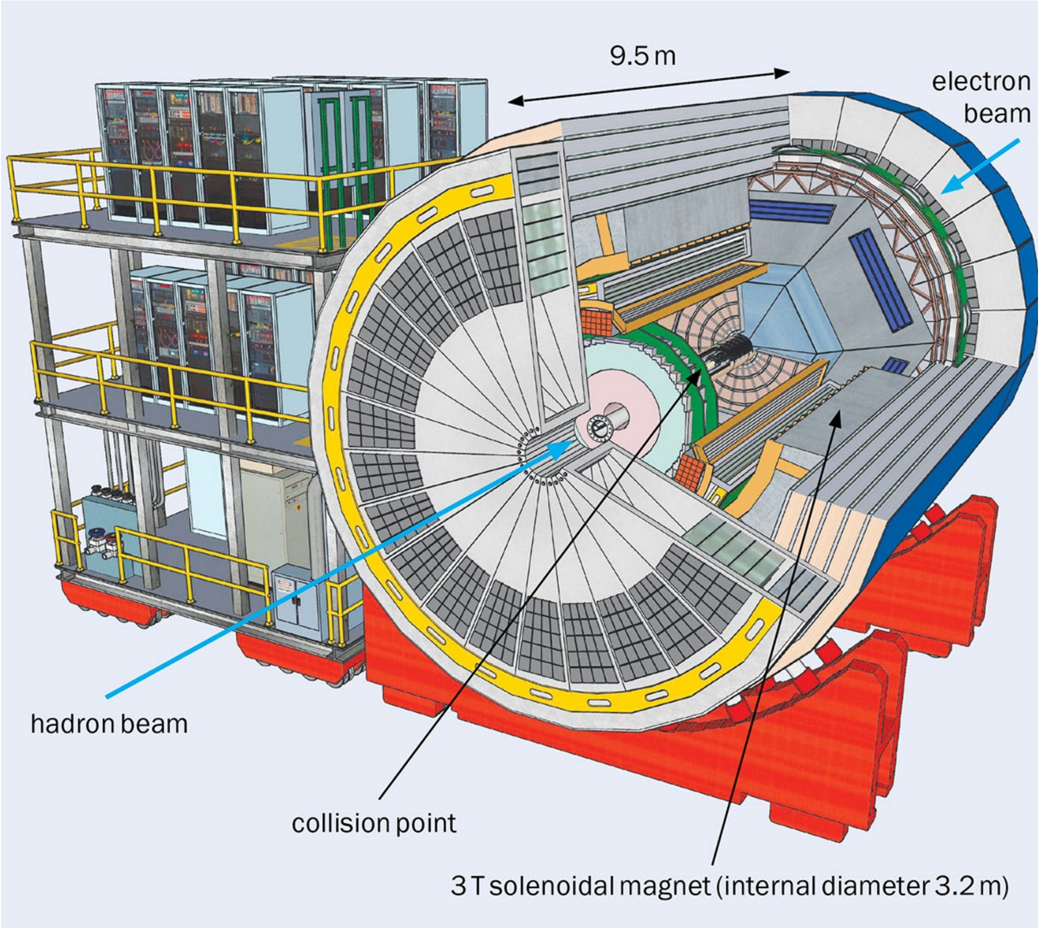
E12-07-007: π^+, π^- — Solid

E10-006: π^+,π^- — Solid
E12-09-018: π^+,π^-, K^+,K^- — SBS

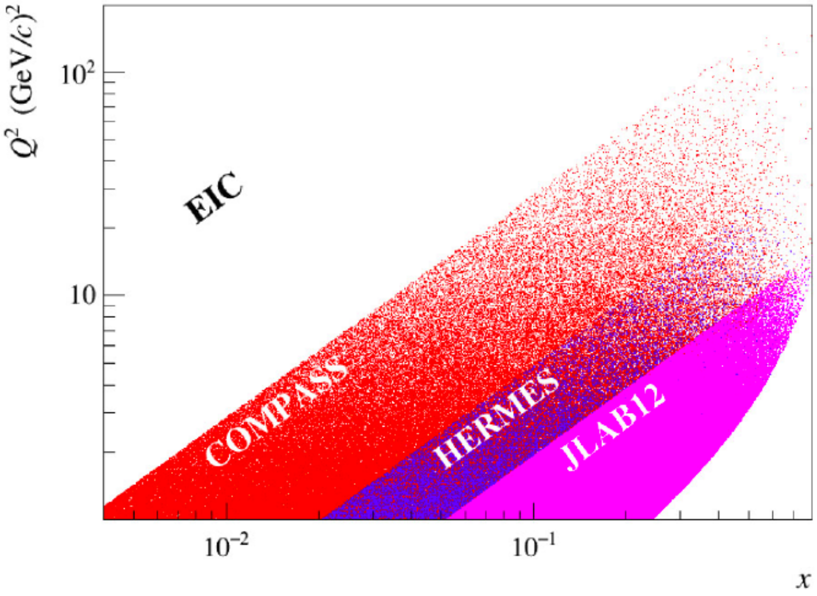
^3He

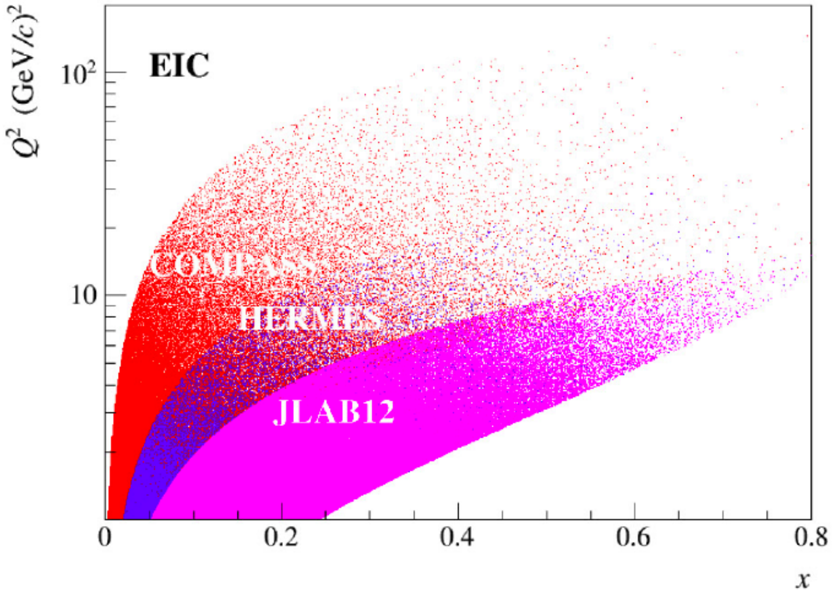


Future SIDIS @ EIC



Kinematic coverage



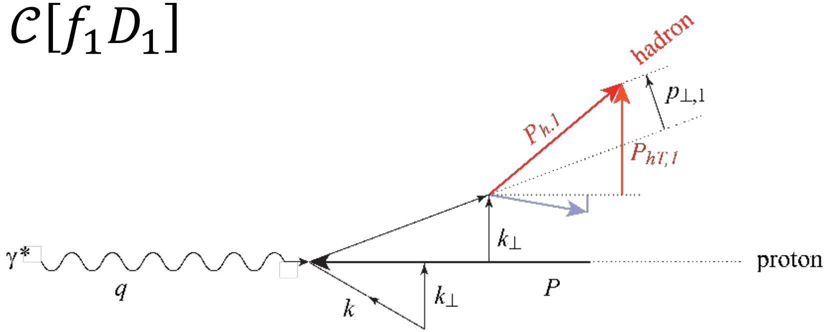


CAROSELLO

UNPOLARIZED

Unpolarized SIDIS

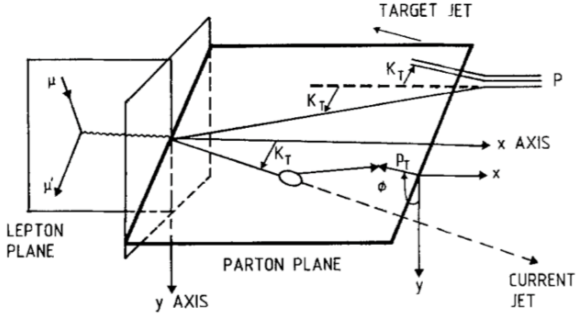
- The cross section is proportional to $\mathcal{C}[f_1 D_1]$
  - $f_1(x, k_\perp, Q^2)$
  - $D_1(z, p_\perp, Q^2)$



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

- Difficult measurements where one has to correct for the apparatus acceptance

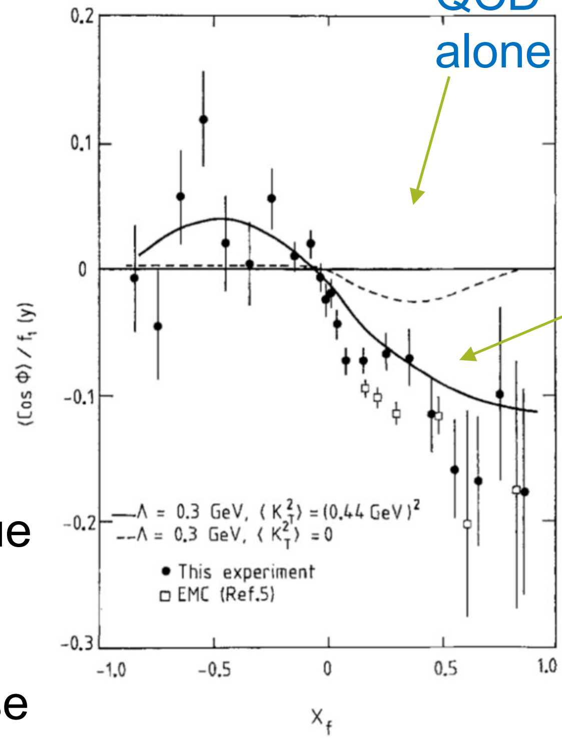
Intrinsic transverse motion; an old story



- Cross section for SIDIS process expected to be

$$d\sigma \sim \sigma_0[1 + A\cos\phi_h + B\cos 2\phi_h]$$

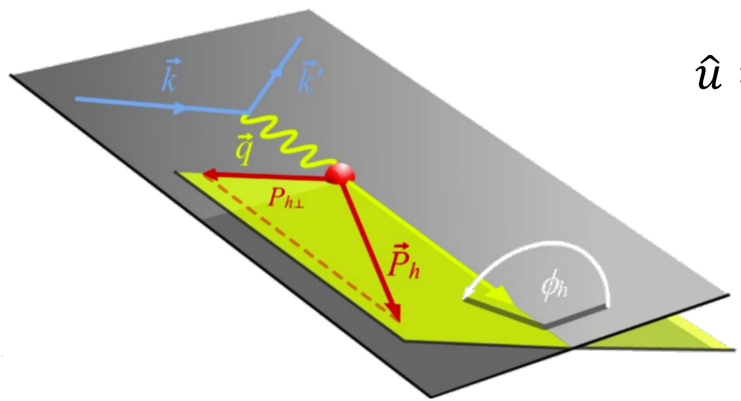
- Georgi and Politzer [1978]: azimuthal modulations of hadrons around the jet axis due to gluon radiation. Effect regarded as a clean QCD test [*Phys.Rev.Lett.* 40 (1978) 3].
- R.N. Cahn [1978]: same modulations can arise due to the quark intrinsic motion ($k_\perp$) [*Phys.Lett.B* 78 (1978) 269]



EMC experiment [1987]
Fit: Konig-Kroll model [1982]+Lund

Unpolarised Azimuthal Modulation

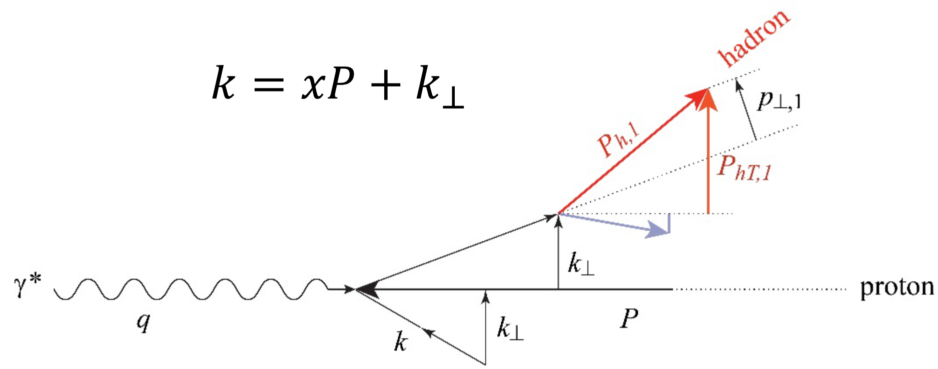
The cross-section is $d\sigma^{\ell p\to\ell' hX} = \sum_q f_q(x,Q^2) \otimes d\sigma^{\ell q\to\ell' q} \otimes D_q^h(z,Q^2)$ with the partonic process is given by $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2$



$$\hat{s} \coloneqq (\ell + k)^2 \sim 2\ell \cdot k \xrightarrow{k_\perp = 0} sx$$

$$\hat{u} \coloneqq (\ell' - k)^2 \sim -2\ell' \cdot k \xrightarrow{k_\perp = 0} -sx(1-y)$$

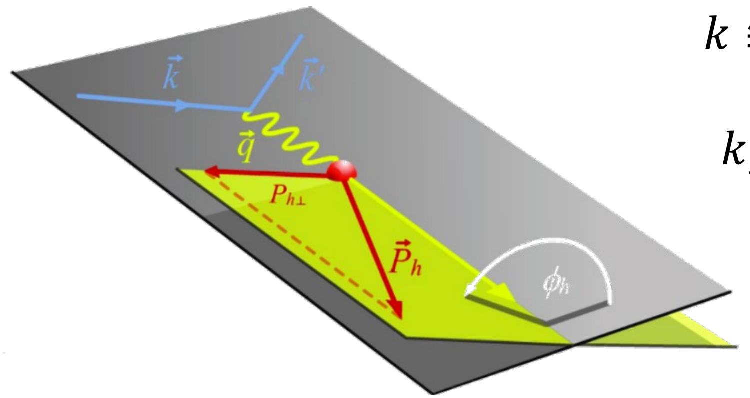
$$k = xP + k_\perp$$



In collinear PM $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2 \propto [1 + (1-y)^2]$, i.e. no ϕ_h dependence.

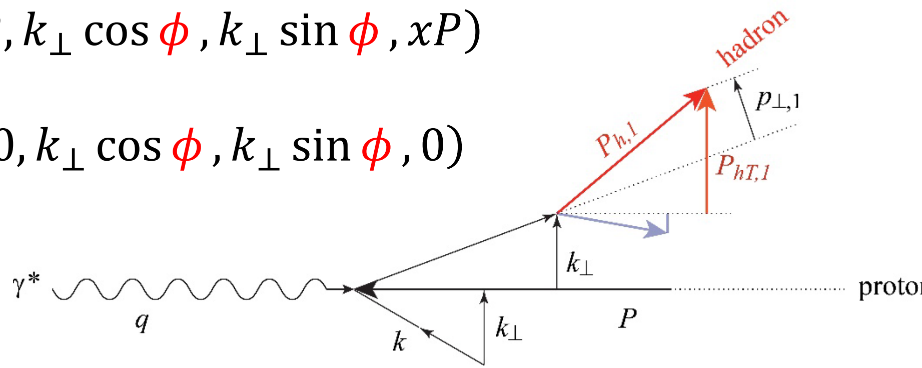
Unpolarised Azimuthal Modulation

When $k_\perp$ is taken into account:



$$k \cong (xP, k_\perp \cos\phi, k_\perp \sin\phi, xP)$$

$$k_\perp \cong (0, k_\perp \cos\phi, k_\perp \sin\phi, 0)$$



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

and

$$d\sigma^{\ell q \to \ell' q} \propto \hat{s}^2 + \hat{u}^2 \propto \left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi\right]^2 + (1-y)^2\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi\right]^2,$$

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

Cahn: Phys.Lett.B 78 (1978) 269

These effects can be estimated by adopting a model for the transverse momentum distribution of partons in a hadron and for the transverse momentum given to hadrons in the quark decay. Suppose that both these distributions are gaussian:

$$f(x, p_\perp) \propto e^{-ap_\perp^2}, \qquad D(z, p_\perp) \propto e^{-bp_\perp^2}, \qquad (16a, b)$$

where f represents the quark distribution and D the fragmentation function. Let the z-direction be defined as in fig. 1. Then the longitudinal momentum of the struck parton is xP and that of the observed hadron is zxP. If the transverse momentum of the struck parton is $\boldsymbol{p}_{1\perp}$ and that of the observed hadron is $\boldsymbol{p}_\perp$, then the momentum of the observed hadron transverse to the parton direction is (for $zxP \gg |\boldsymbol{p}_{1\perp}|, |\boldsymbol{p}_\perp|$) just $\boldsymbol{p}_\perp - z\boldsymbol{p}_{1\perp}$.

Semi Inclusive unpolarised DIS Cross Section

The account of the transverse motion of the quark result in the following general form of the unpolarised semi-inclusive deep inelastic cross-section

$$\frac{d^5\sigma}{dxdydzdP_{hT}^2 d\phi_h} = \frac{\alpha^2}{xyQ^2}\left[(1-y)+\frac{y^2}{2}\right]F_2(x,Q^2)\times$$

$$M_{UU}^h\left\{1+\frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}A_{UU}^{\cos\phi_h}\cos\phi_h+\frac{2(1-y)}{1+(1-y)^2}A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right\}$$

Where we have introduced the amplitude of the azimuthal asymmetries as

$$A_{UU}^{\cos X\phi_h}\left(x,z,P_{hT}^2;Q^2\right)=\frac{F_{UU}^{\cos X\phi_h}\left(x,z,P_{hT}^2;Q^2\right)}{F_{UU}^h(x,z,P_{hT}^2;Q^2)}$$

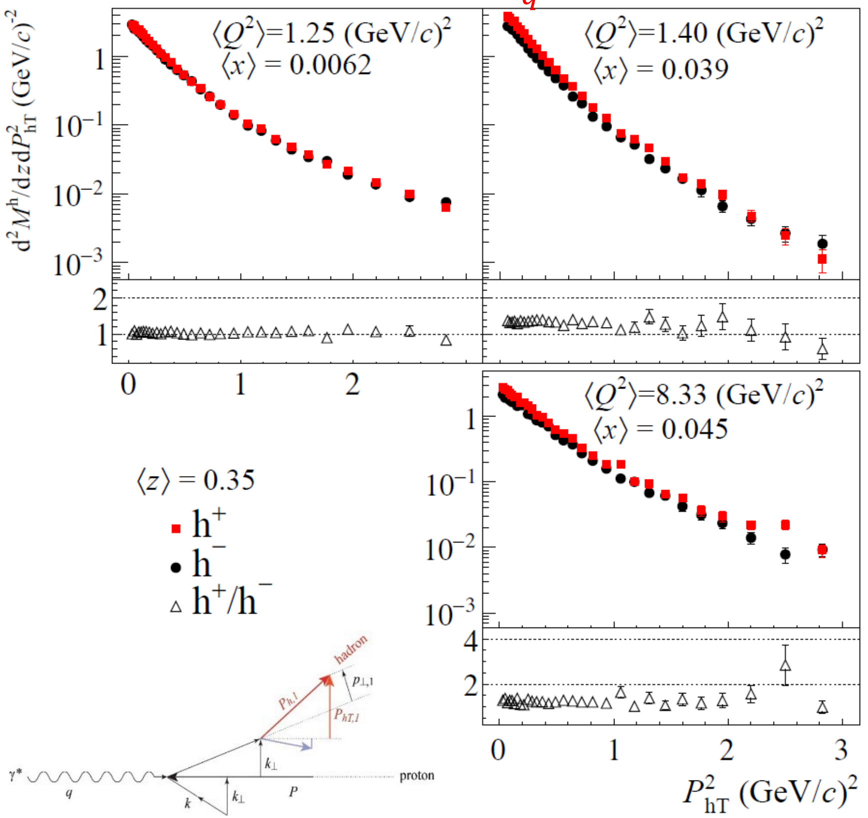
An the angular independent ratio

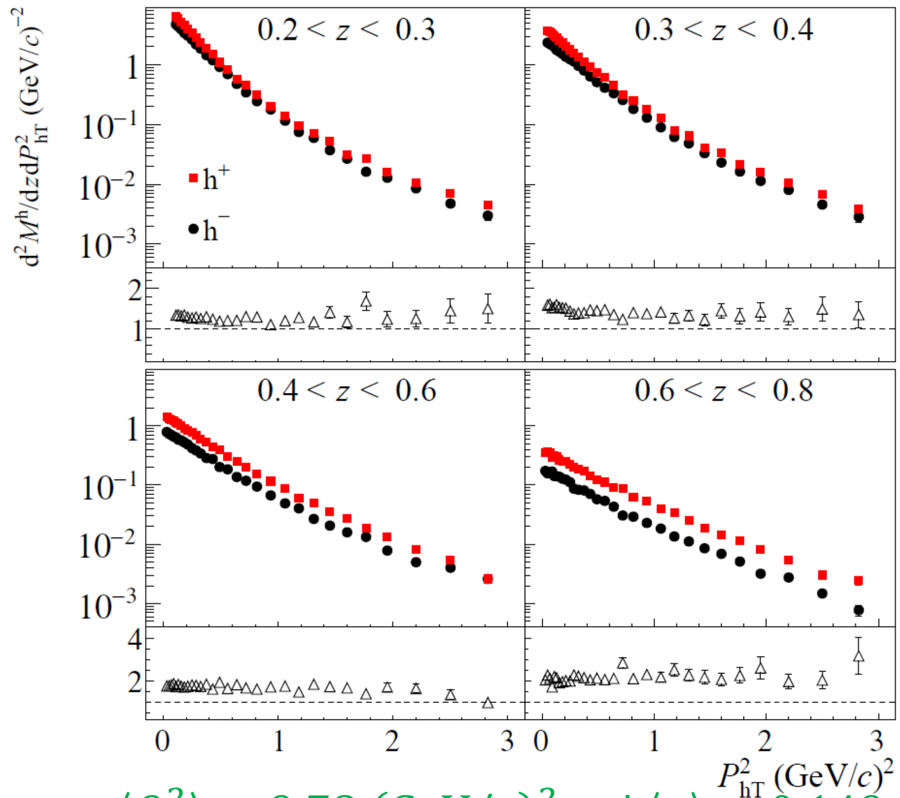
$$M_{UU}^h\left(x,z,P_{hT}^2;Q^2\right)=\frac{F_{UU}^h\left(x,z,P_{hT}^2;Q^2\right)}{F_2(x,Q^2)}$$

Experimentally these are more difficult measurements than spin asymmetries, since we have to correct for the apparatus acceptance

Positive vs Negative charged hadrons (^{6}LiD)

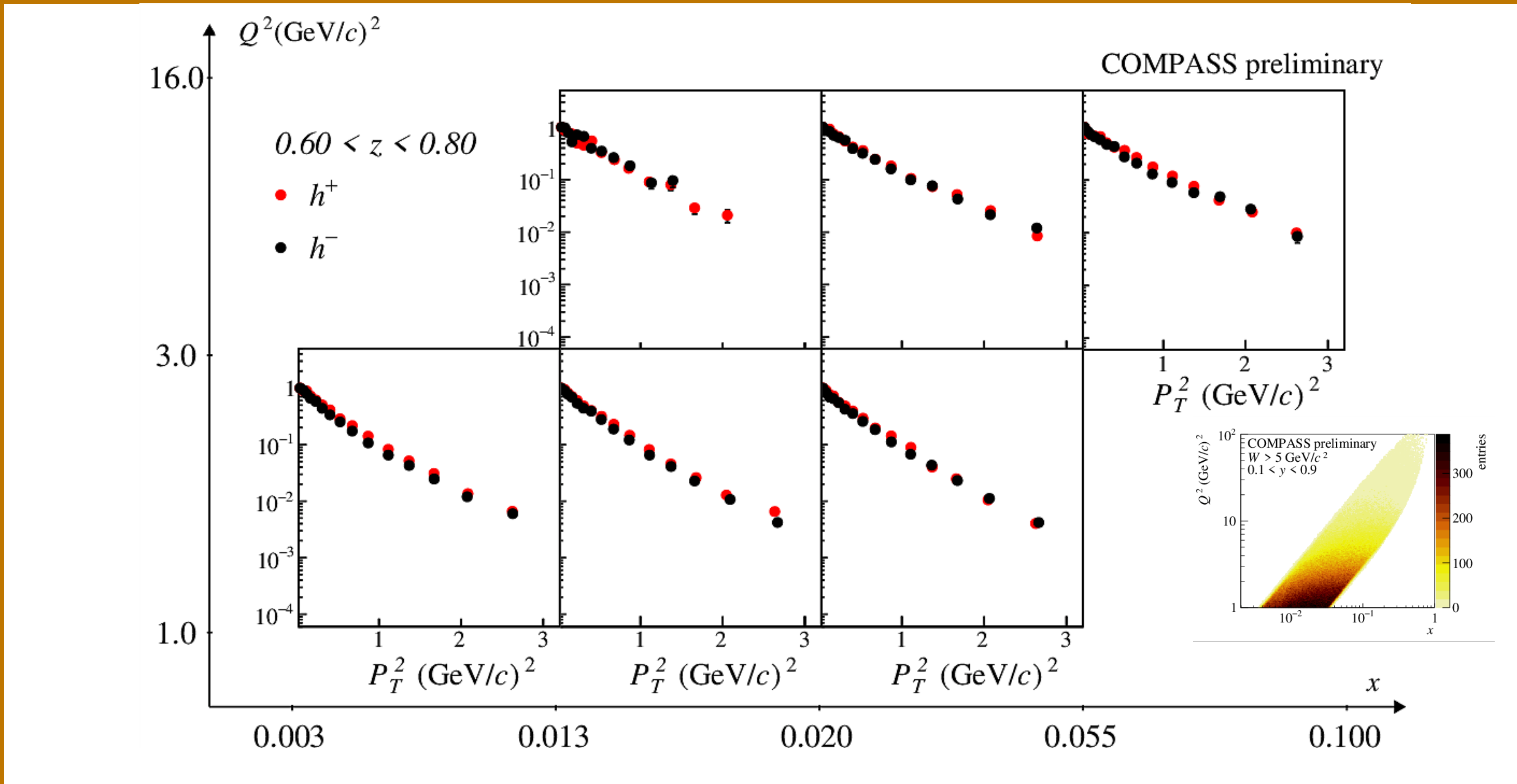
$$F_{UU}^{h}\left(x,z,P_{hT}^{2};\ Q^{2}\right)=x\sum_{q}e_{q}^{2}\int d^{2}\vec{k}_{\perp}d^{2}\vec{p}_{\perp}\delta\left(\vec{p}_{\perp}+z\vec{k}_{\perp}-\vec{P}_{hT}\right)\ f_{1}^{q}(x,k_{\perp}^{2};Q^{2})D_{1}^{q\to h}(z,p_{\perp}^{2};Q^{2})$$



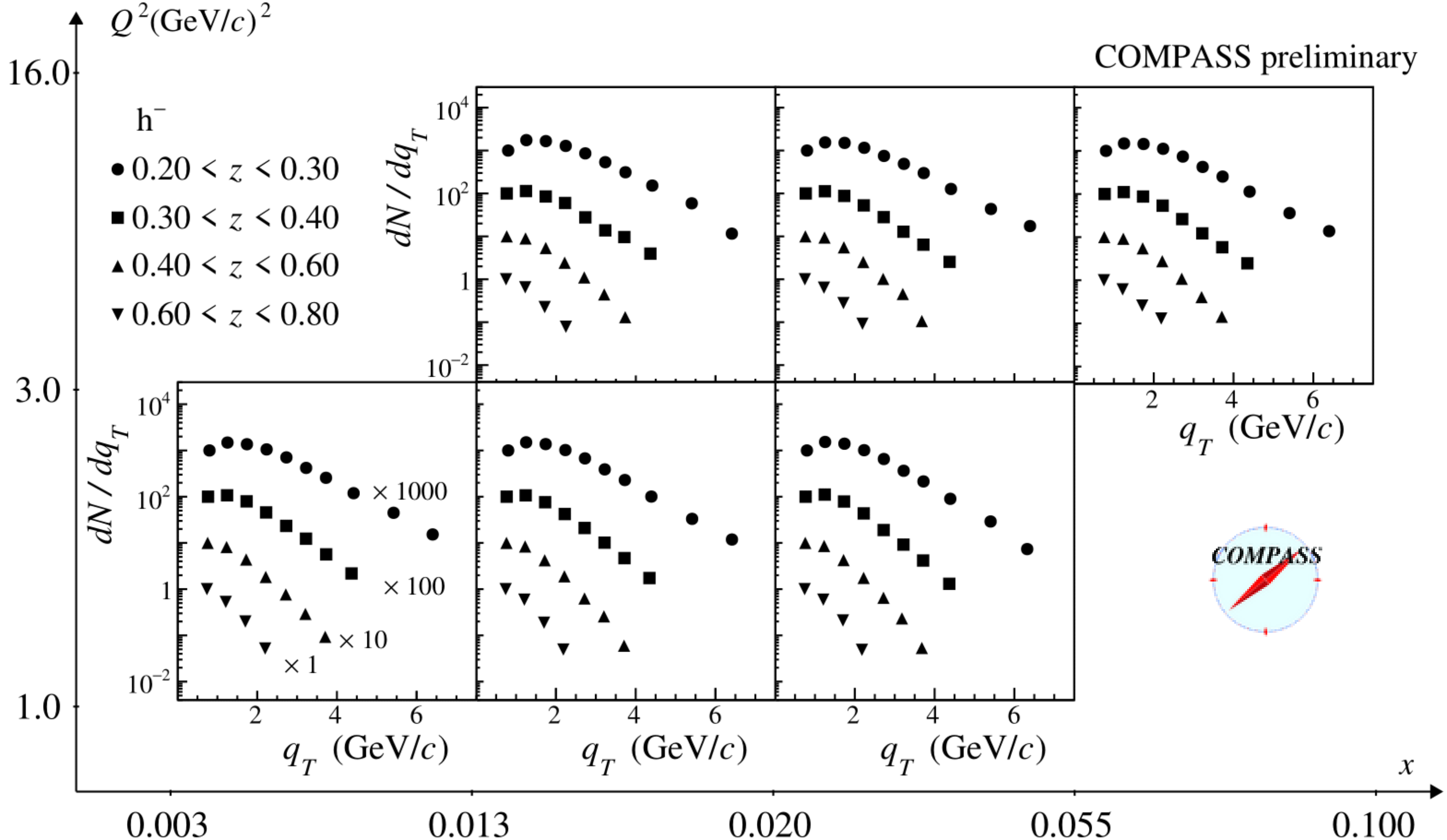


$\langle Q^2\rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x\rangle = 0.149$

Positive vs Negative charged hadrons (LH_2)



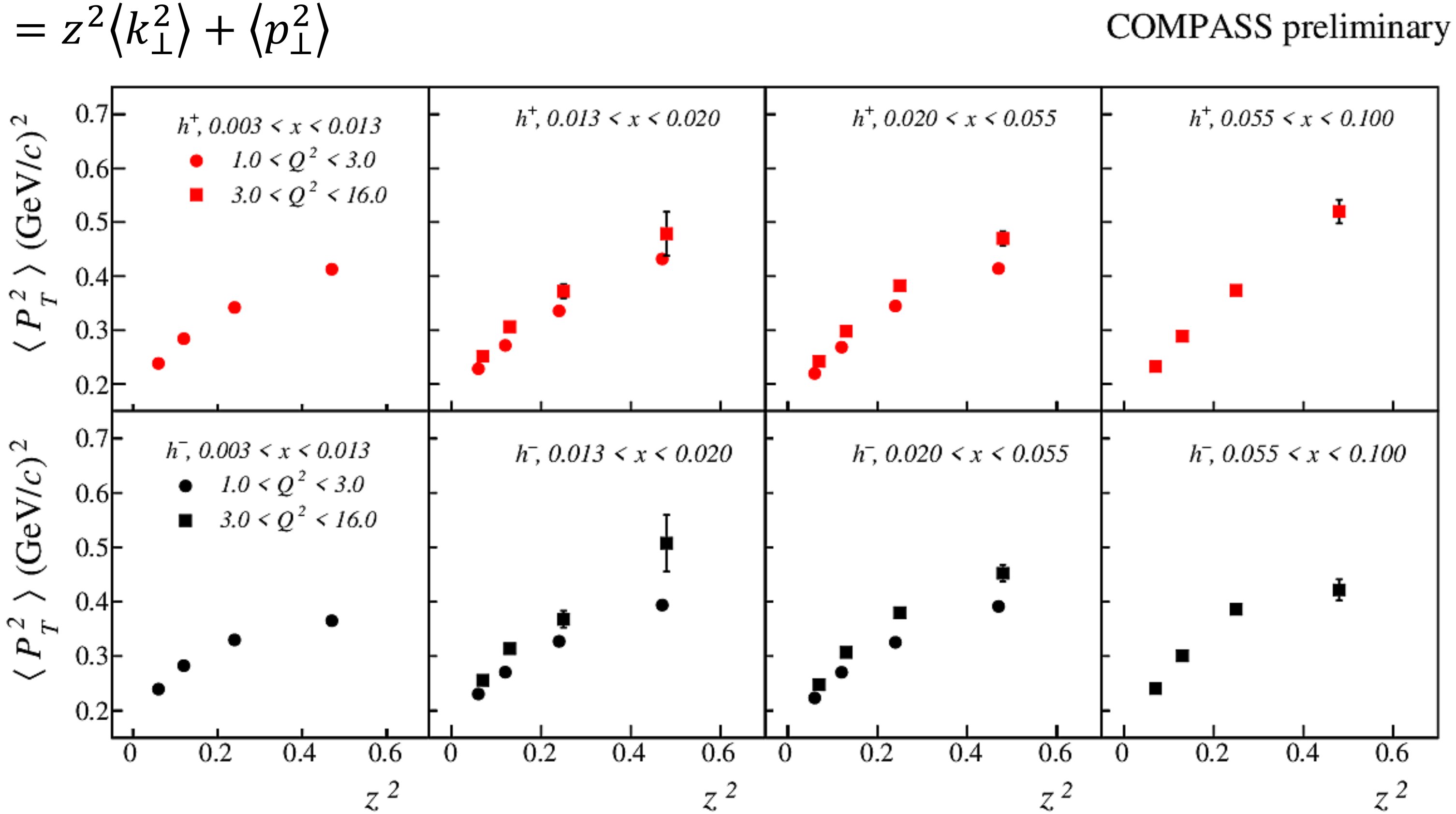
Unpolarized q_T distributions



Slope dependence

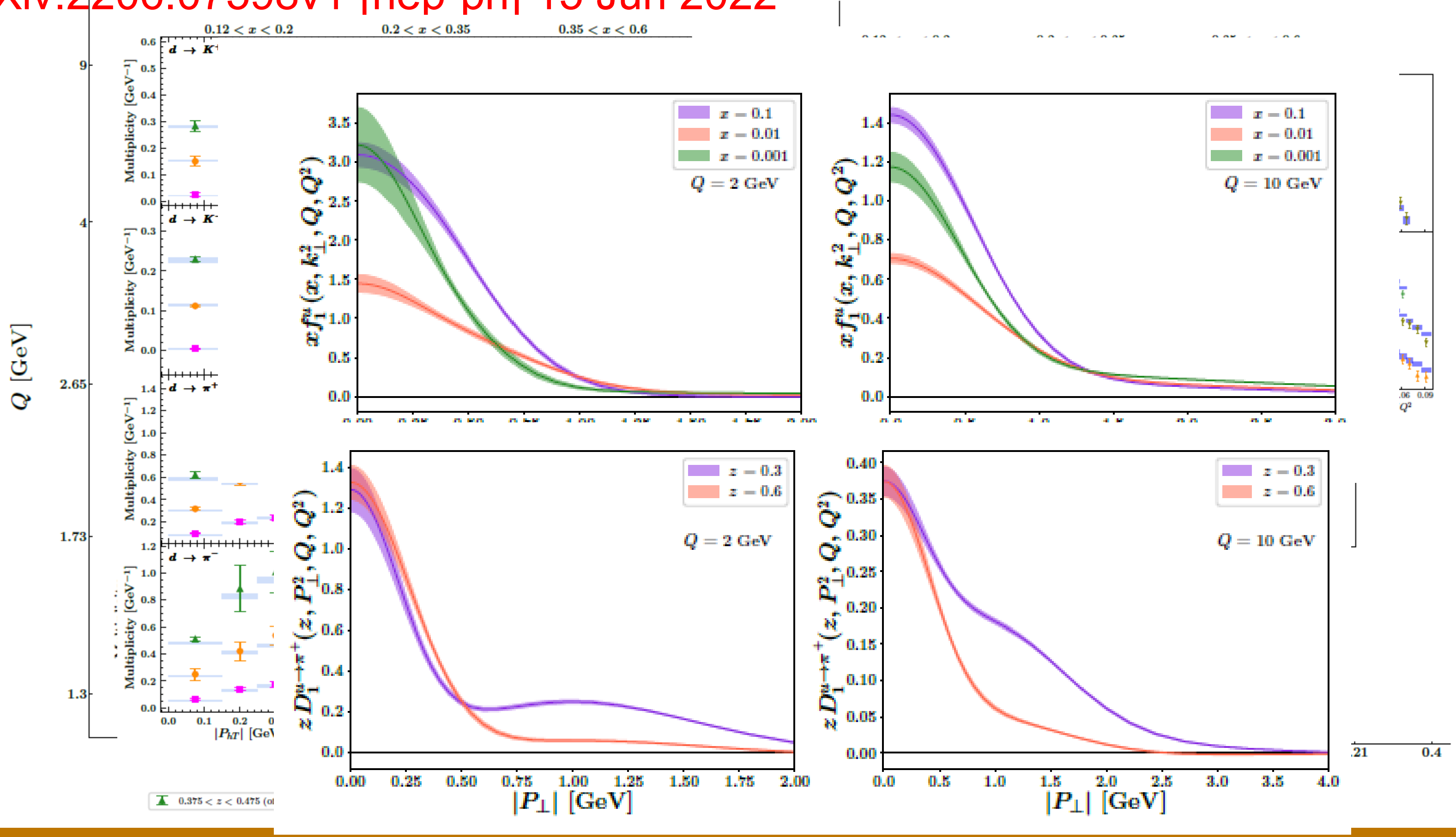
A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to

$\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



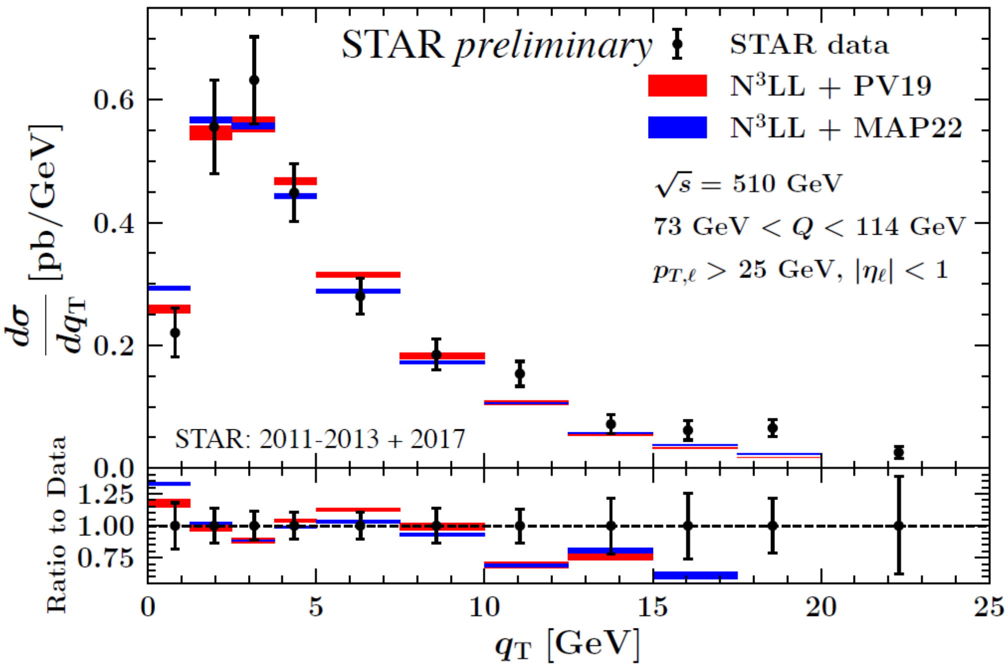
Phenomenological fits

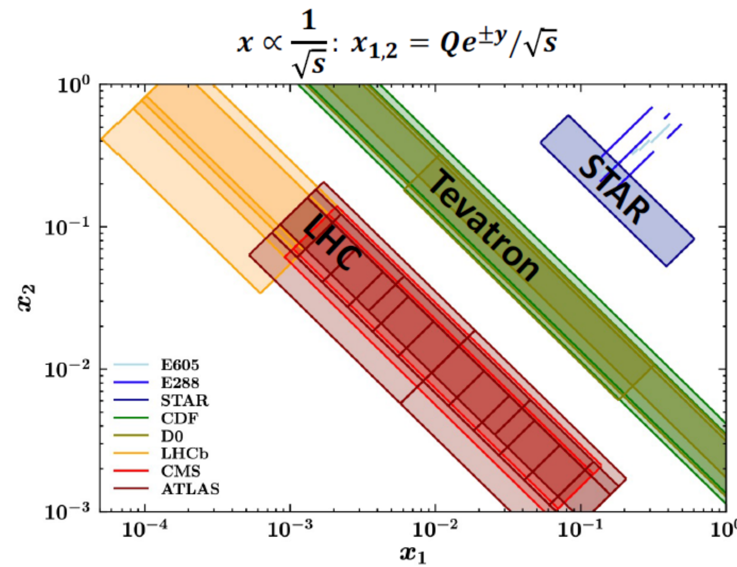
arXiv:2206.07598v1 [hep-ph] 15 Jun 2022



Z^0 cross-section at STAR

- Unpolarized TMDs are also accessed at pp collision





A. Bacchetta et al., JHEP 07(2020) 117

Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

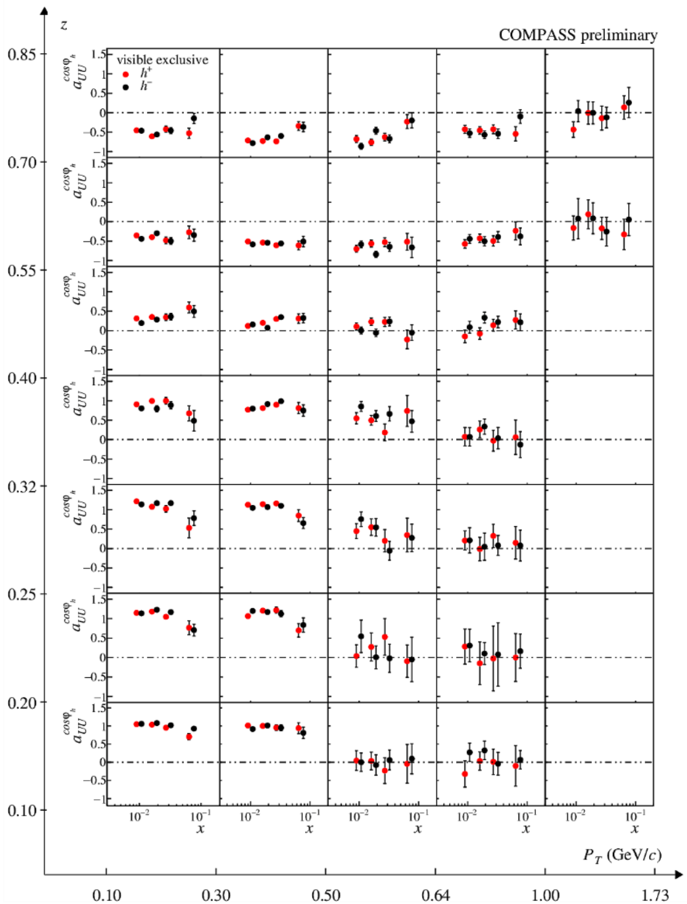
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z\left(\hat{h}\cdot\vec{k}_\perp\right)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

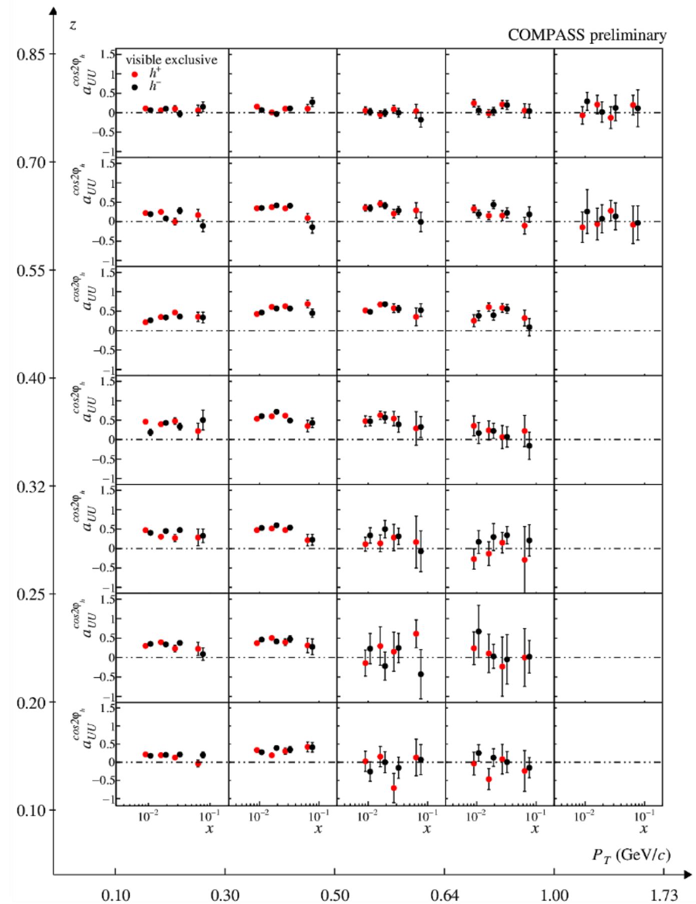
$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{p}_\perp\right) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Cahn $\cos\phi_h$ and Boer-Mulders $\cos 2\phi_h$ Asyms

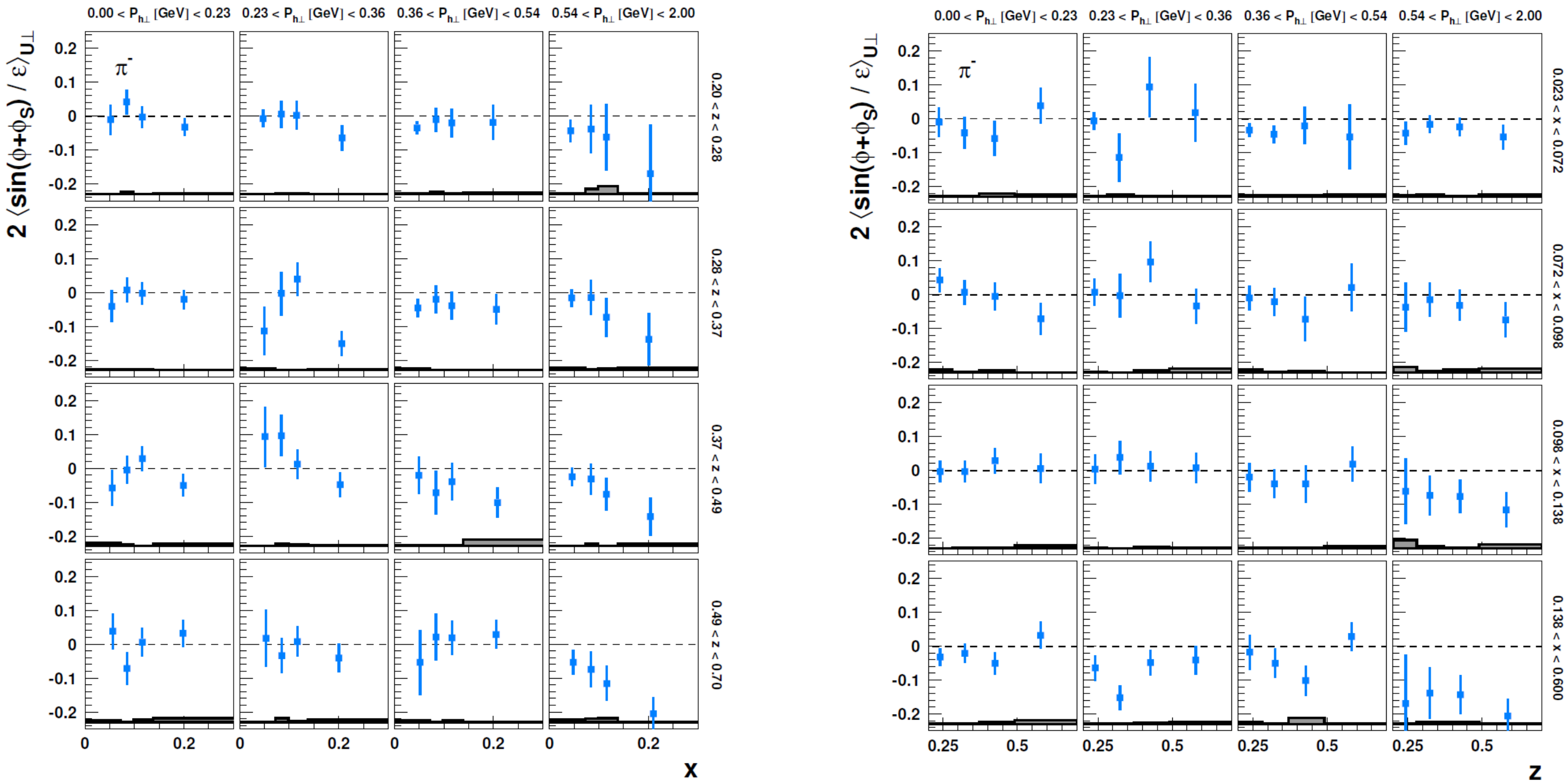




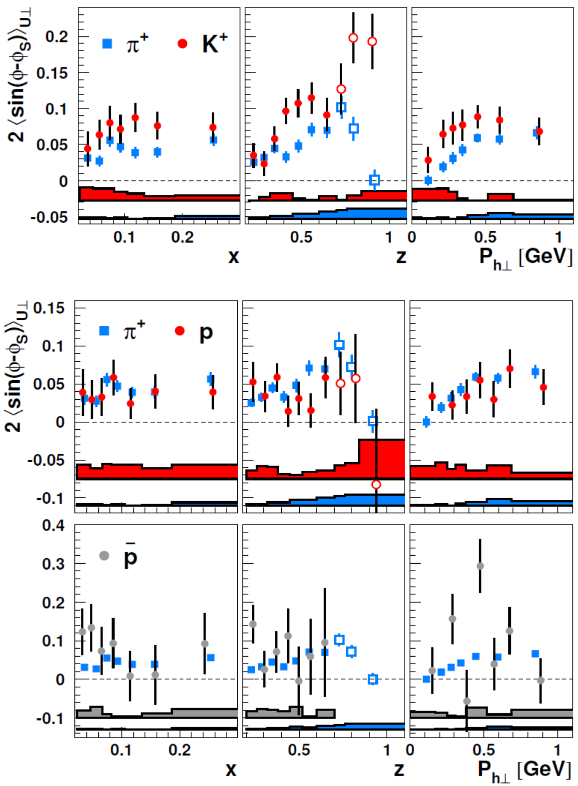
Carosello

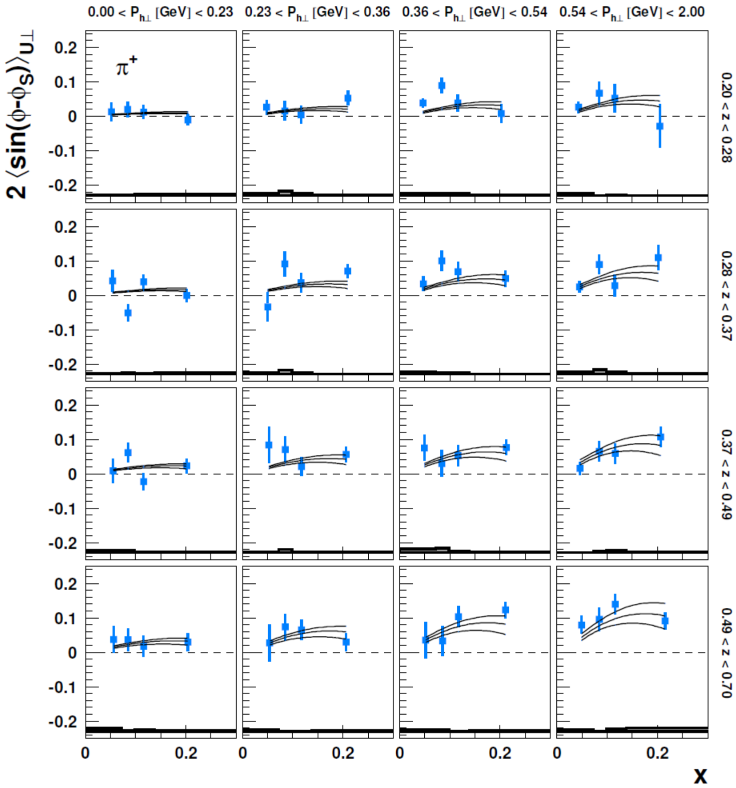
Single Spin Asymmetries

HERMES 3D ssa - COLLINS



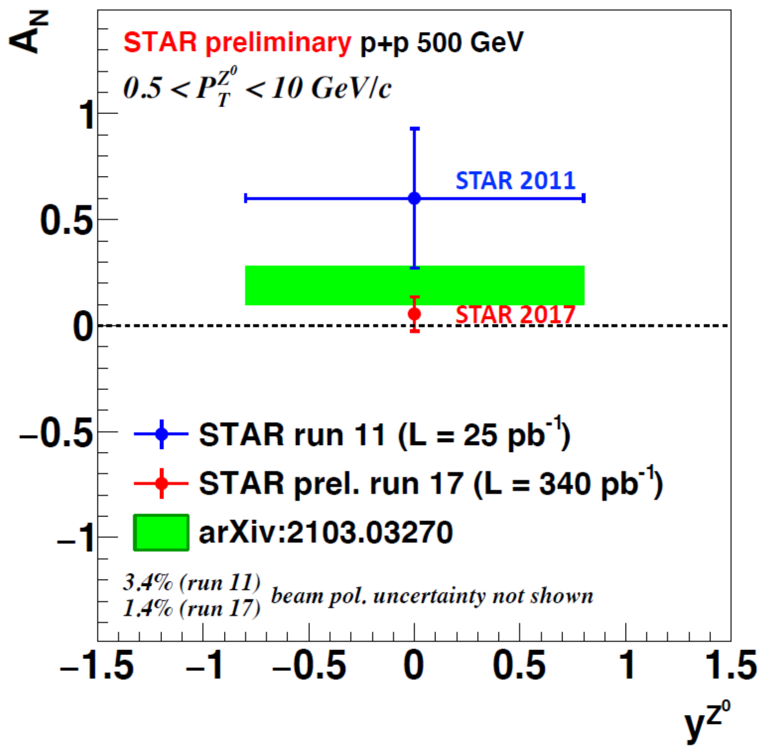
HERMES 3D ssa - SIVERS

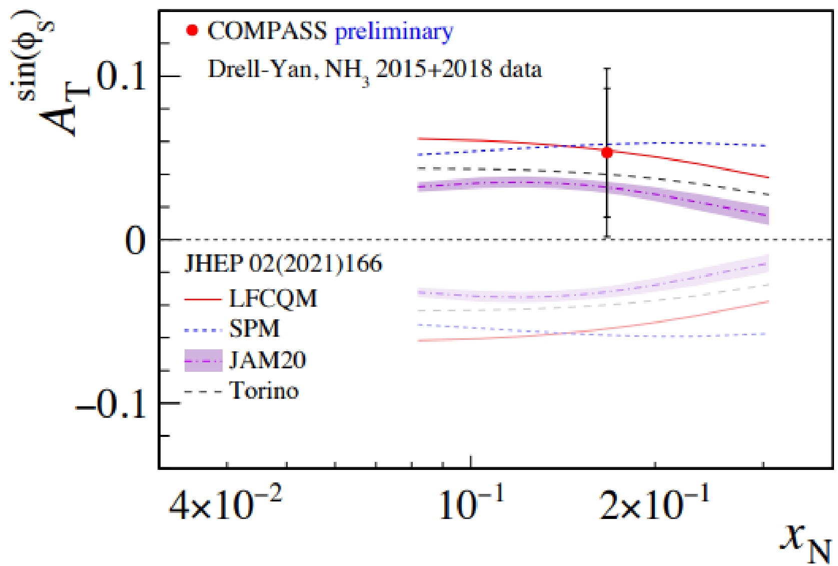




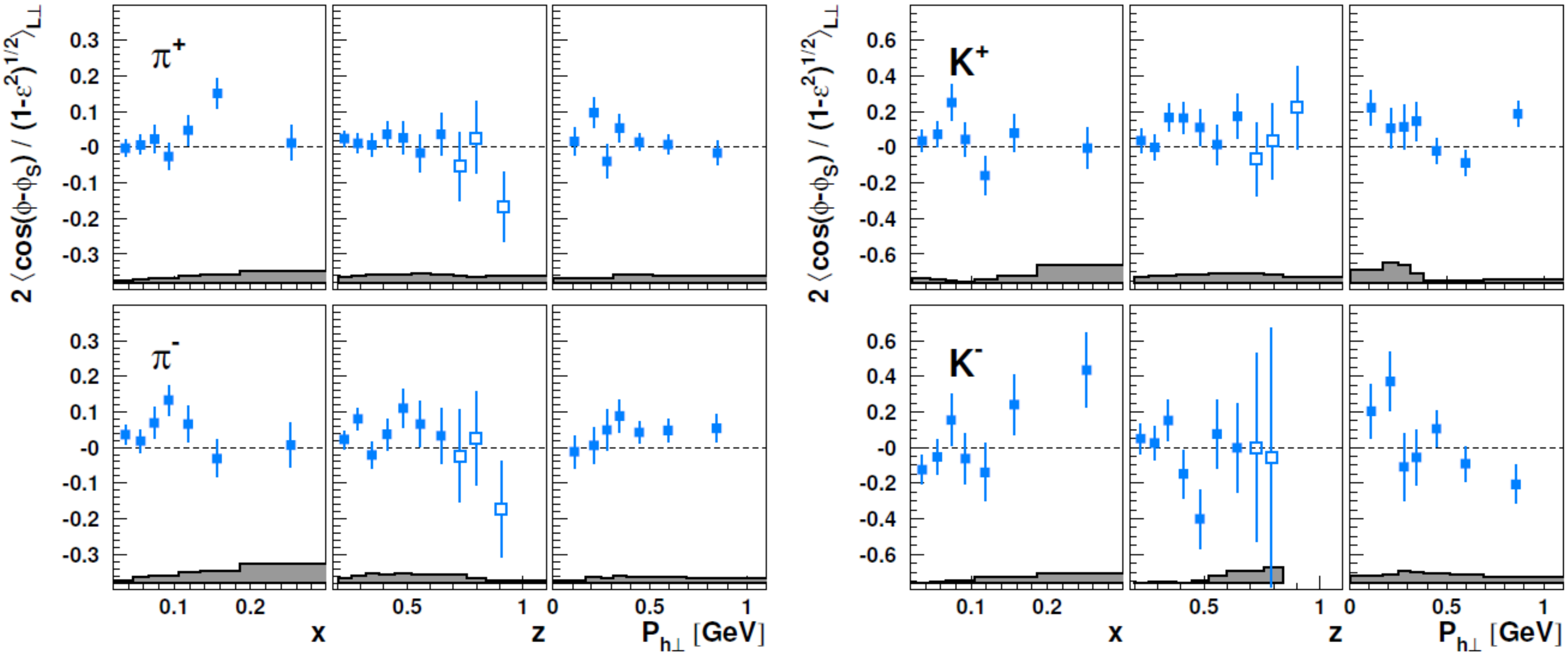
Sivers change of sign – no conclusive status

Measured TSSA of Z^0





HERMES 3D ssa – WORM GEAR (II)



CAROSELLO

FUTURE MEASUREMENTS/RESULTS

Already on tape

- COMPASS @ CERN:
  - 2016-17 DVCS and SIDIS on $\mathrm{LH_2}$
  - 2022 on transversely polarized $^{6}\mathrm{LiD}$
- Jlab 12 – proton/deuteron unpolarised

Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal	10.6 GeV

Almost on tape

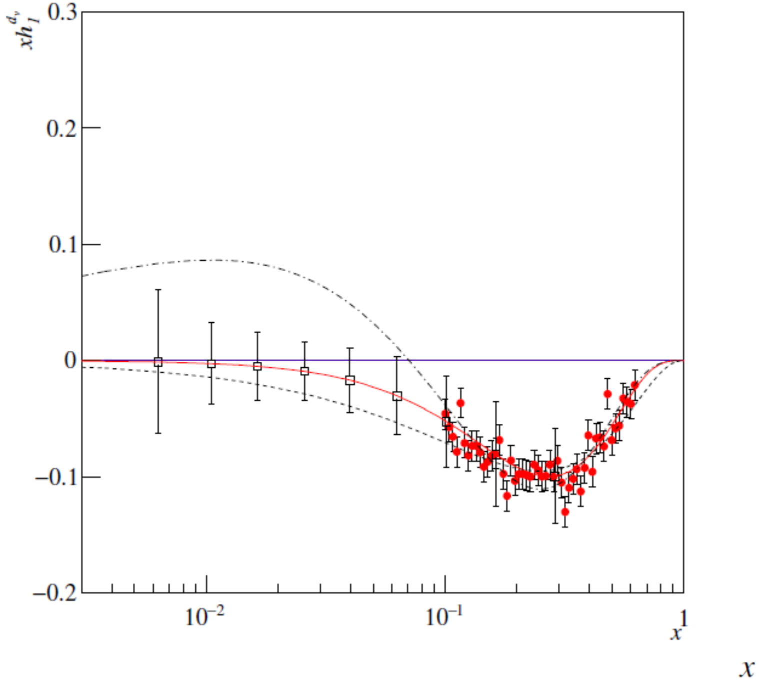
- Jlab 12 – polarized
  - CLAS12

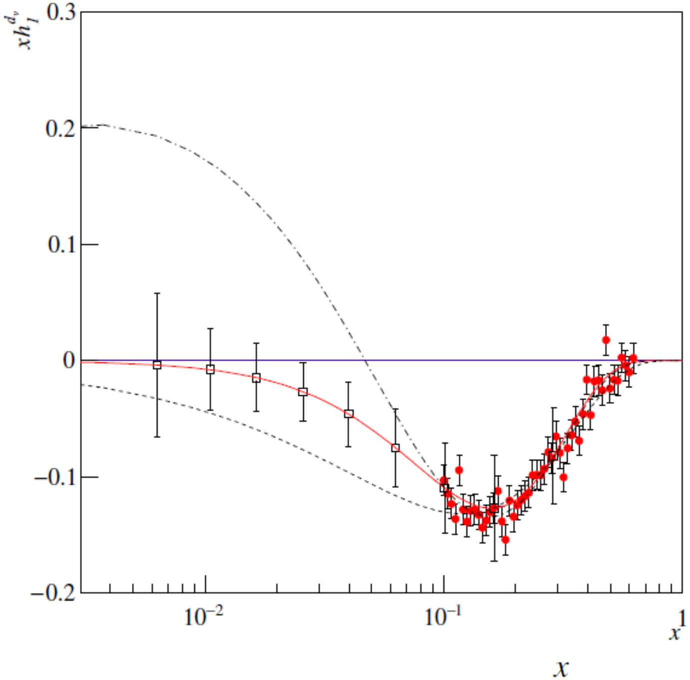
Year	Period	Run	Target	Polarization	Beam
> 2022		RGH	HDice, NH_3-ND_3	Transverse	10.6 GeV
> 2022			^3He	Longitudinal	10.6 GeV
> 2022		RGG	^7LiD, ^6LiH	Longiudinal	10.6 GeV

  - Hall A - E12-09-018 Neutron transverse SSAs

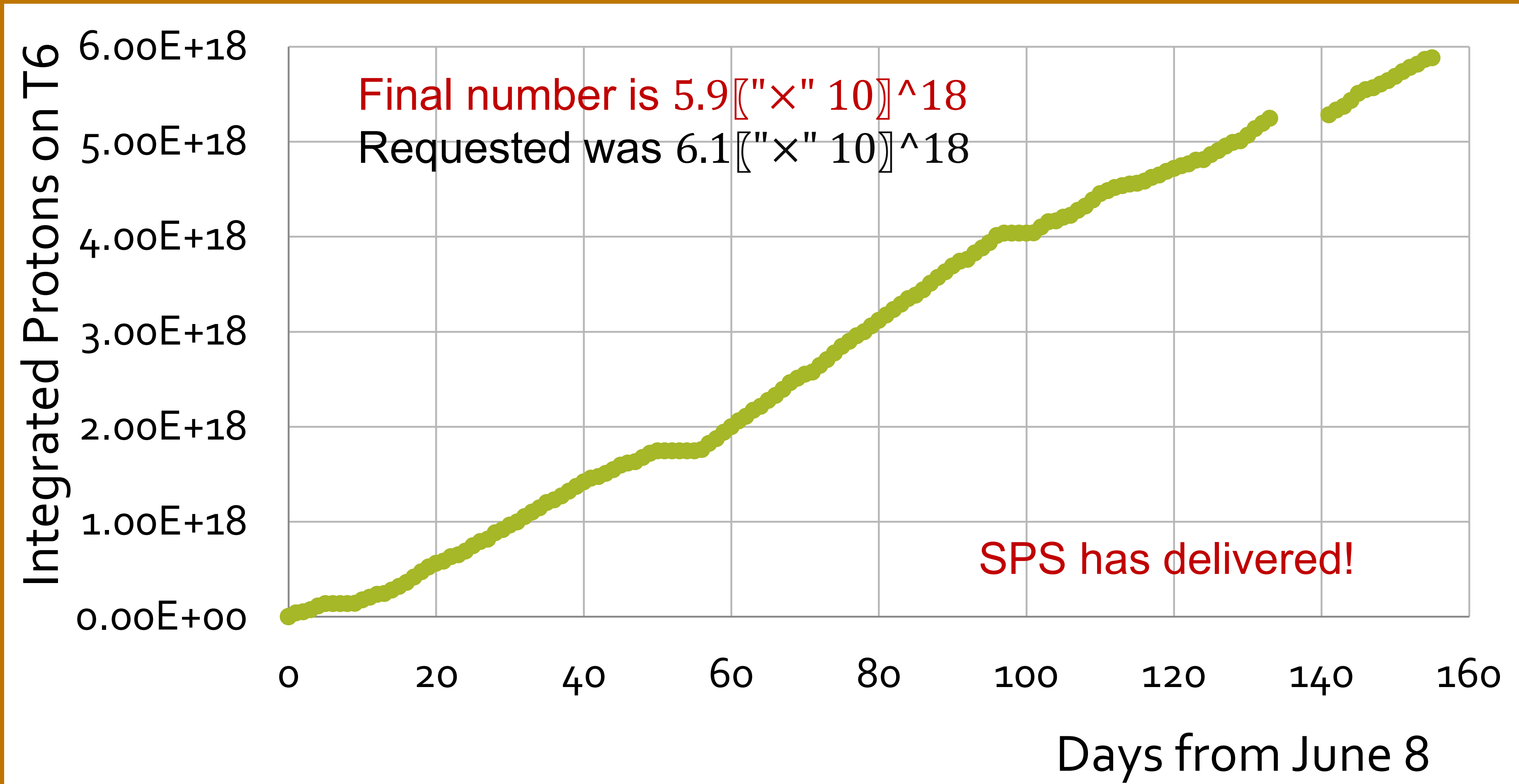
COMPASS deuteron data in 2022

- Expected gain in precision on u- and d-quark transversity



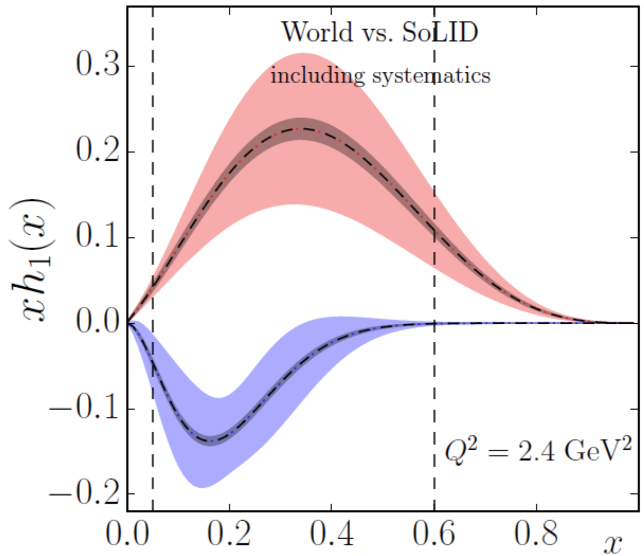


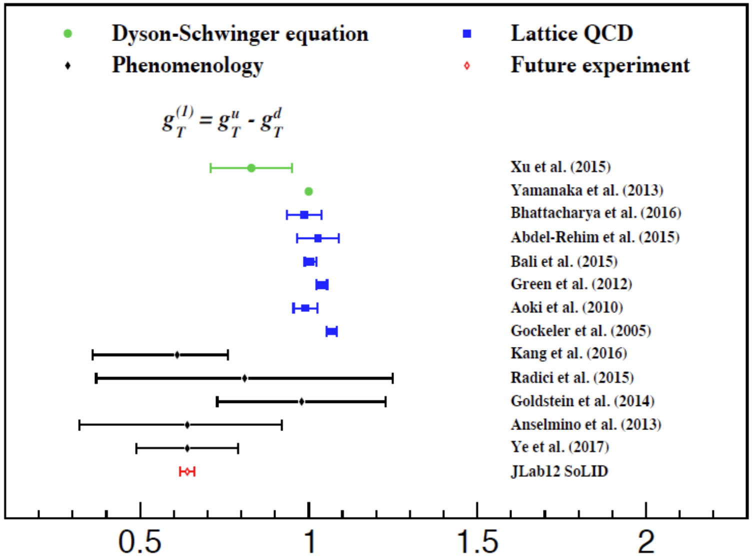
COMPASS 2022 RUN – integrated stat



JLAB12 More in the feauture

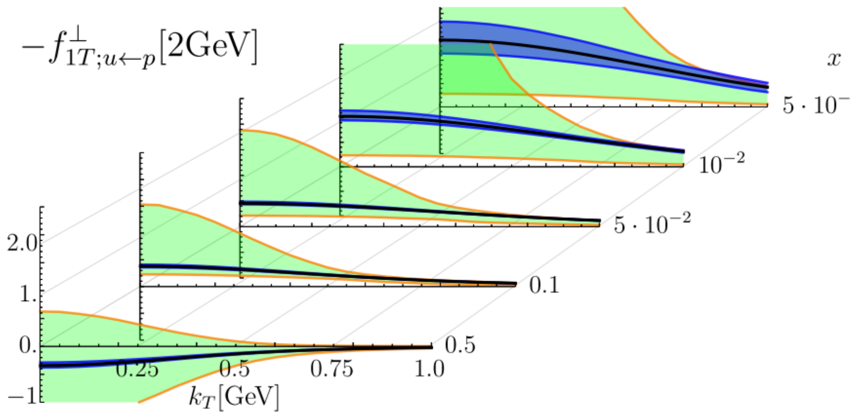
- CLAS12 and SOLID

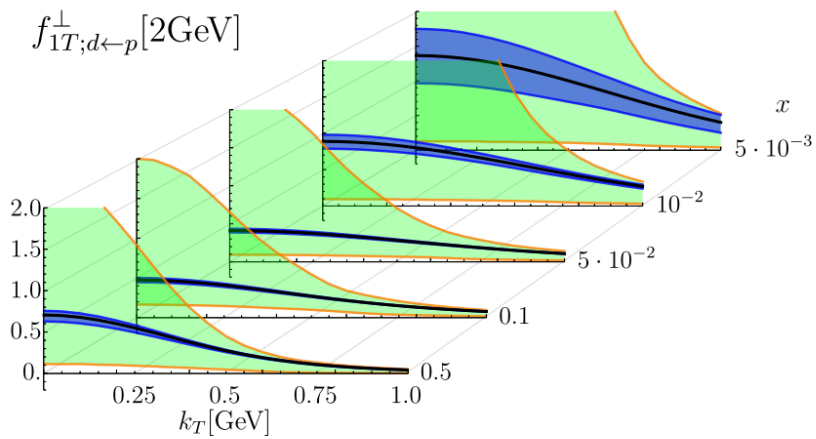


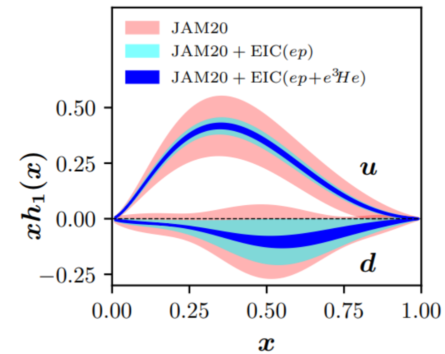


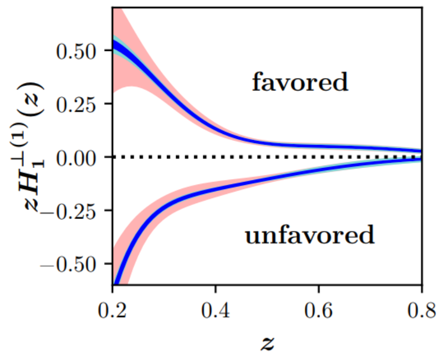
TMDs at the EIC

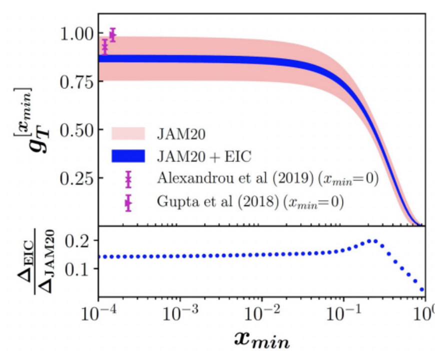
Glimps of the projected precision

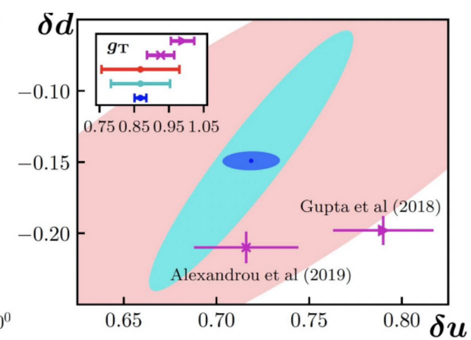








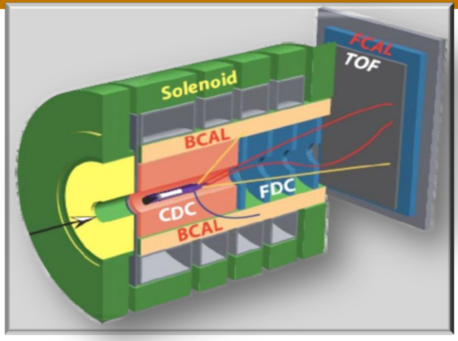


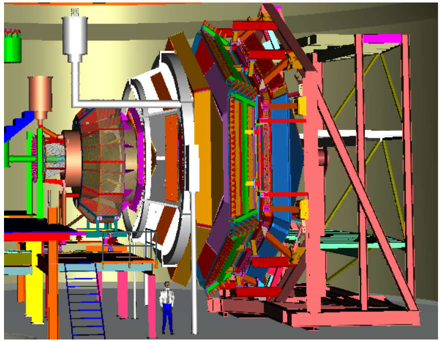



Thank you

12 GeV Upgrade Physics Instrumentation

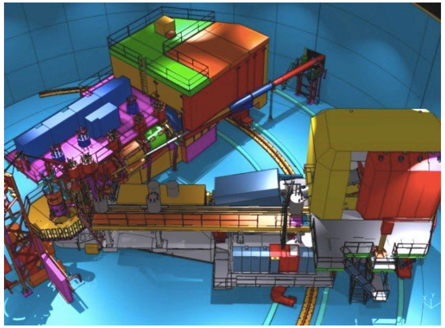
GLUEx (Hall D): exploring origin of confinement by studying hybrid mesons

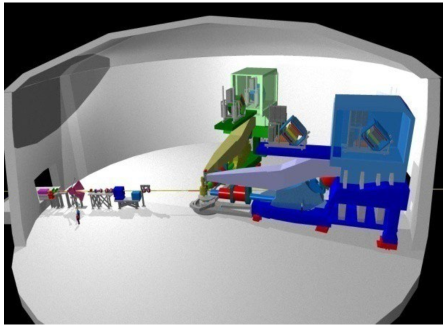




CLAS12 (Hall B): understanding nucleon structure via generalized parton distributions

SHMS (Hall C): precision determination of valence quark properties in nucleons and nuclei





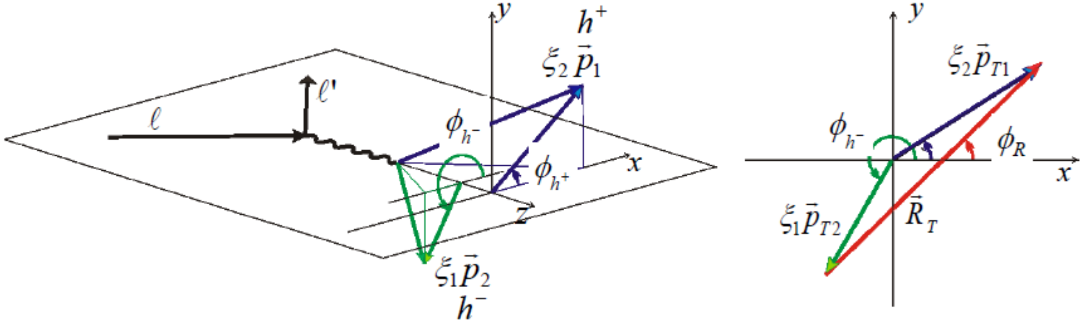
Hall A: nucleon form factors

& future new experiments like Moller & SOLID

The asymmetries

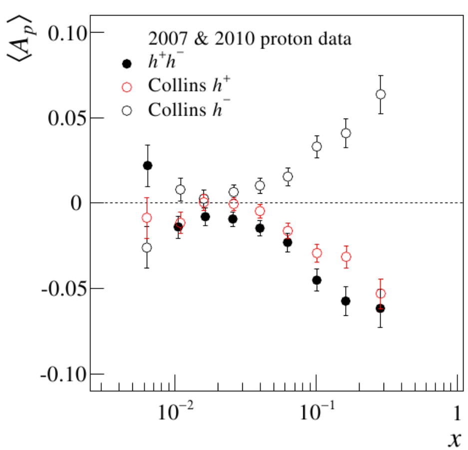
- The asymmetries are:
- $$A_{U(L),T}^{w(\phi_h,\phi_S)}(x,z,p_T;Q^2) = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$
- When we measure on 1D
- $$A_{U(L),T}^{w(\phi_h,\phi_S)}(x) = \frac{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T F_{U(L),T}^{w(\phi_h,\phi_S)}}{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T \left(F_{UU,T}+\varepsilon F_{UU,L}\right)}$$

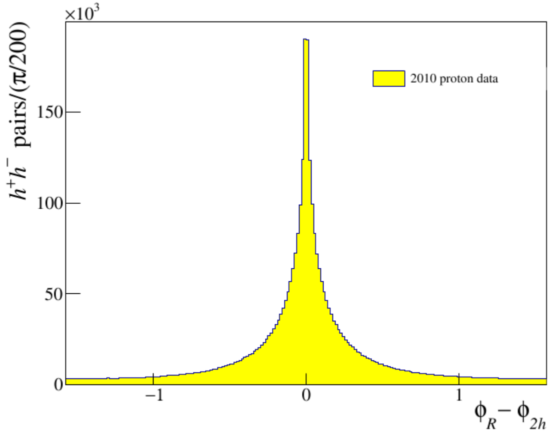
Hadron correlations

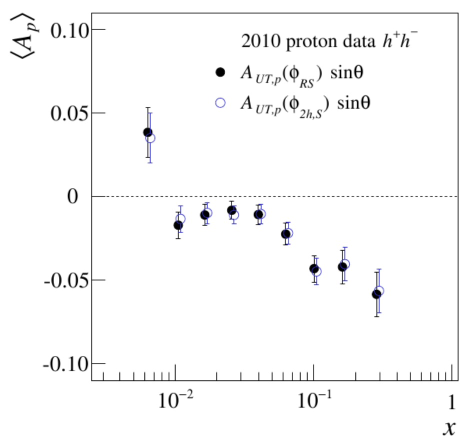


Interplay between Collins and IFF asymmetries

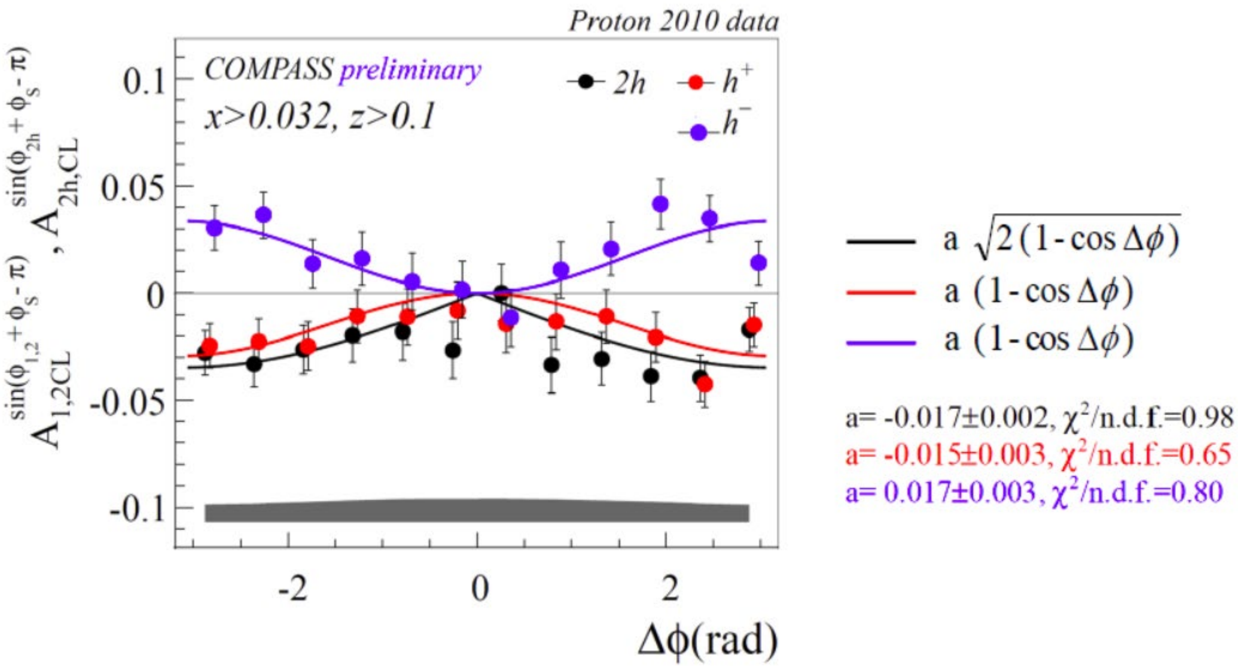
common hadron sample for Collins and 2h analysis







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 $4/\pi$

Hints for a common origin of 1h and 2h mechanisms

From Collins asymmetries to transversity

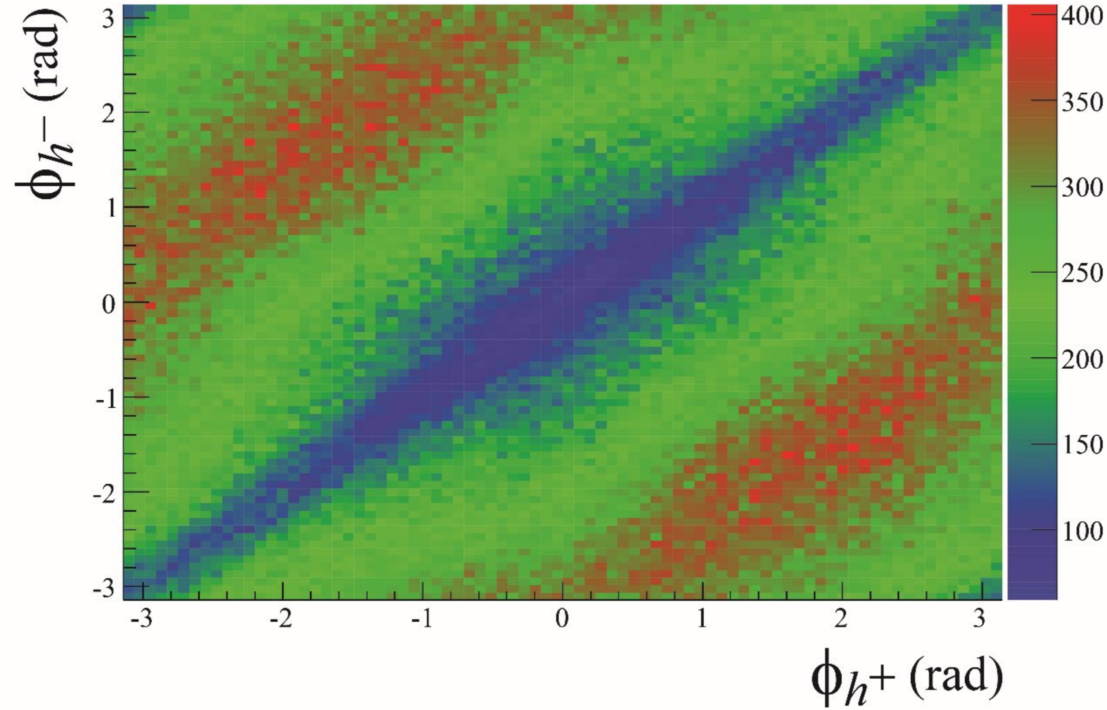
- Following Physical Review D 91, 014034 (2015), in the valence region

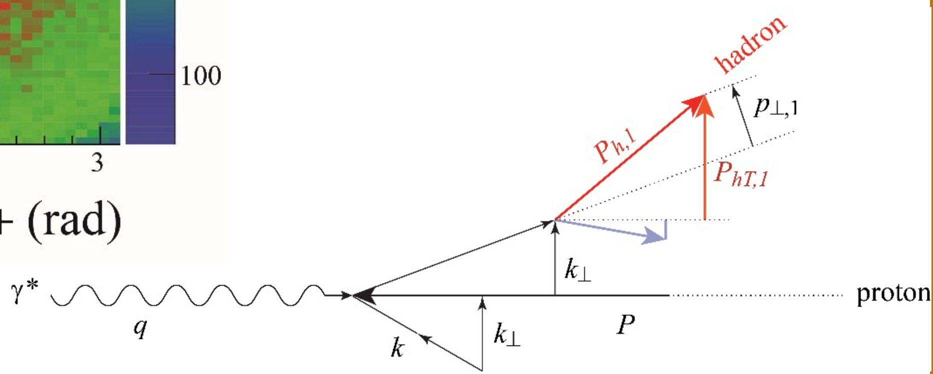
$$x h_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(x f_p^+ A_p^+ - x f_p^- A_p^-\right) + \frac{1}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right)\right]$$

$$x h_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(x f_d^+ A_d^+ - x f_d^- A_d^-\right) - \left(x f_p^+ A_p^+ - x f_p^- A_p^-\right)\right]$$

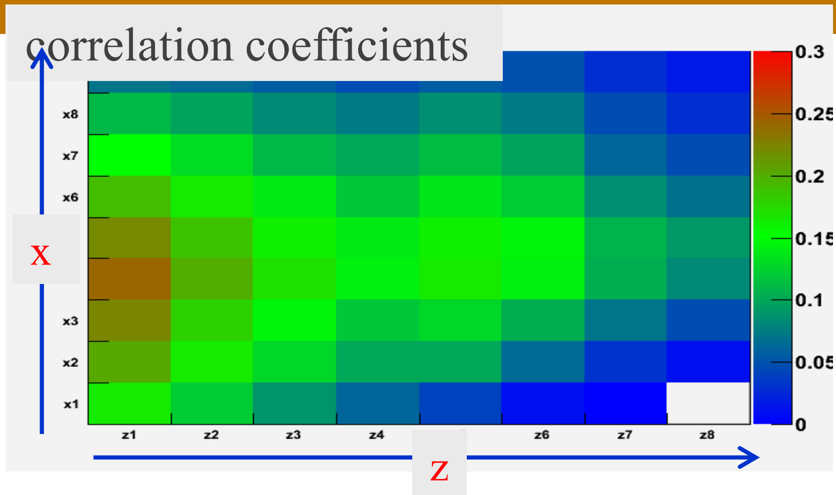
With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

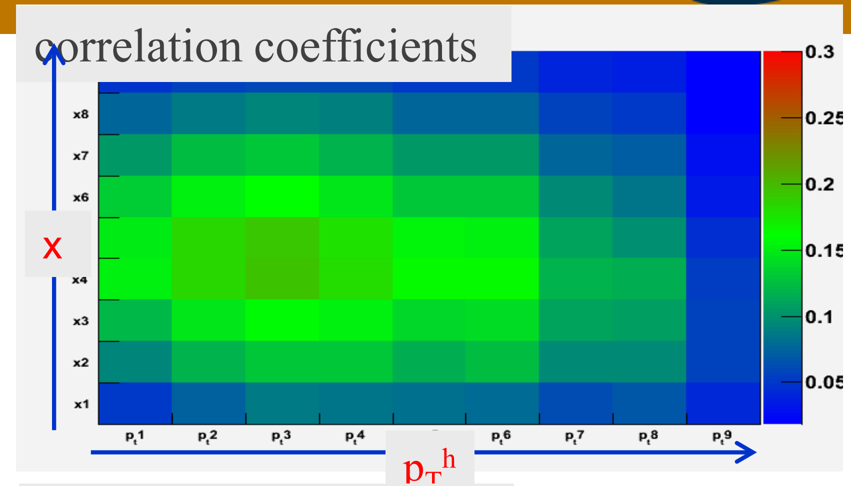
Is correlation having an impact?

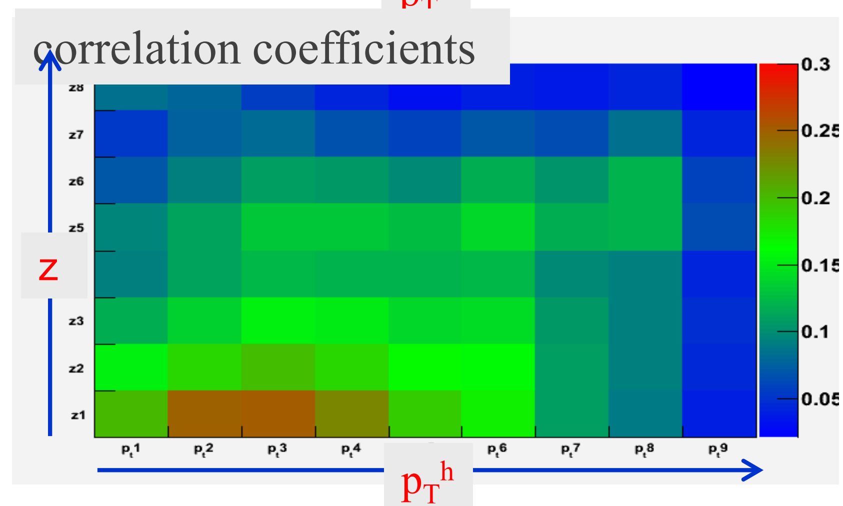




Statistical correlations







charged pions

also available for

charged hadrons

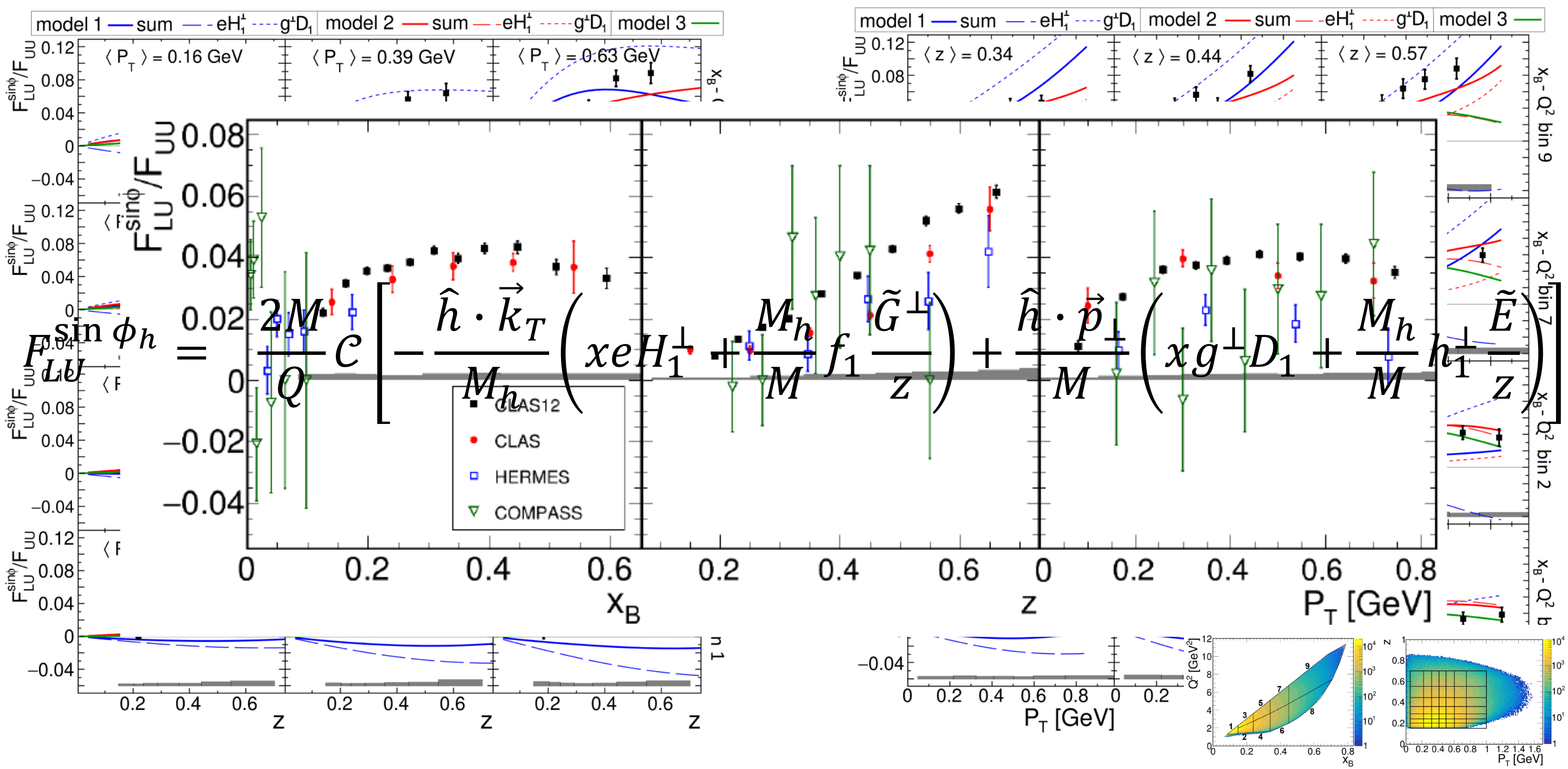
charged kaons

have to be taken into account

Carosello

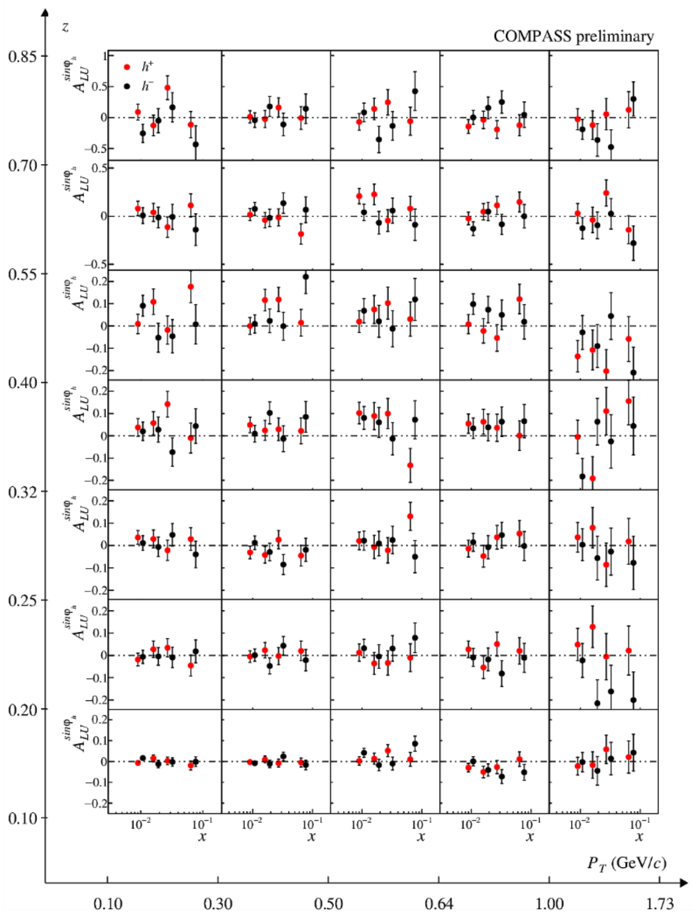
Higher twists

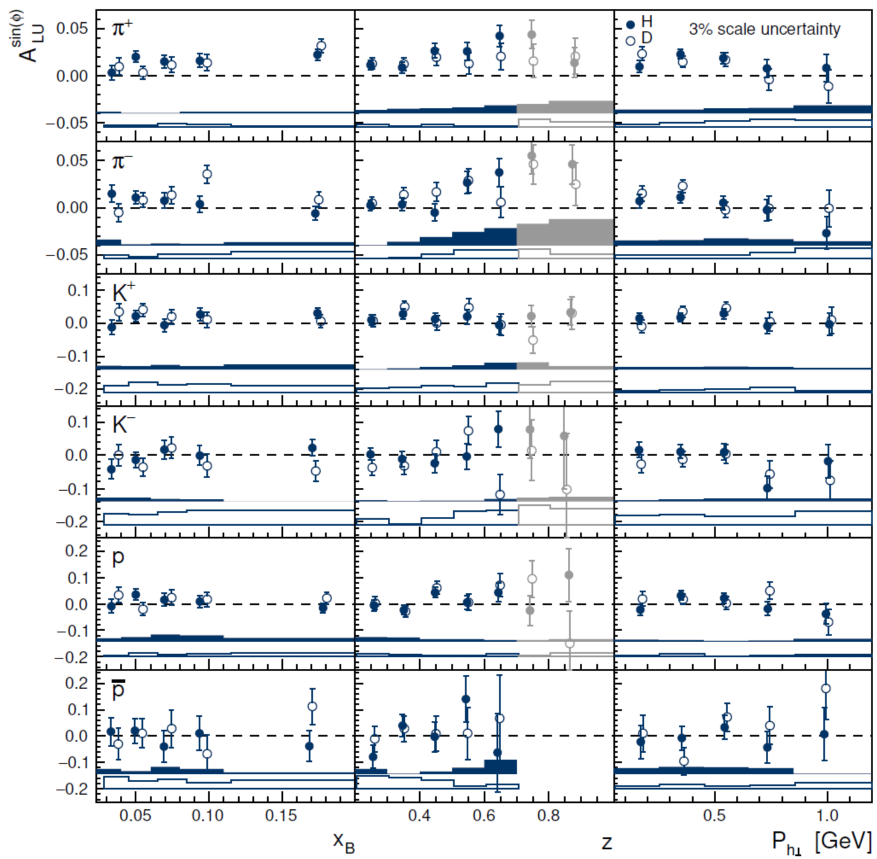
Beam Spin Asymmetry Measurements



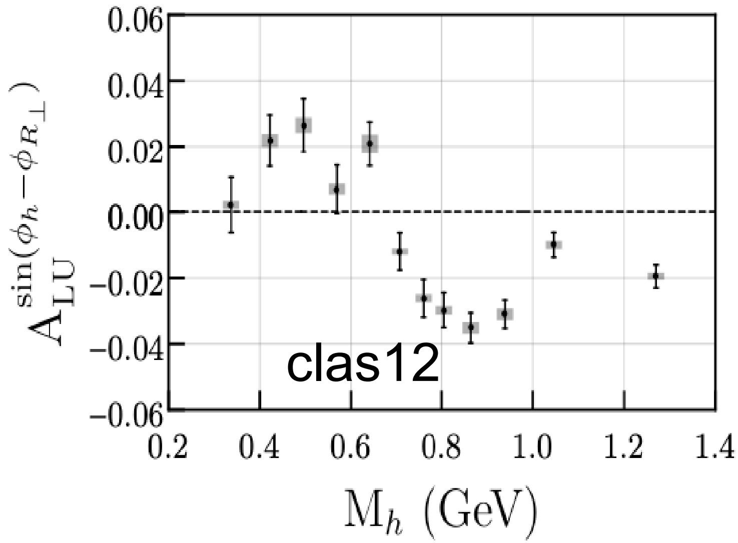
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot\vec{p}_{\perp}}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

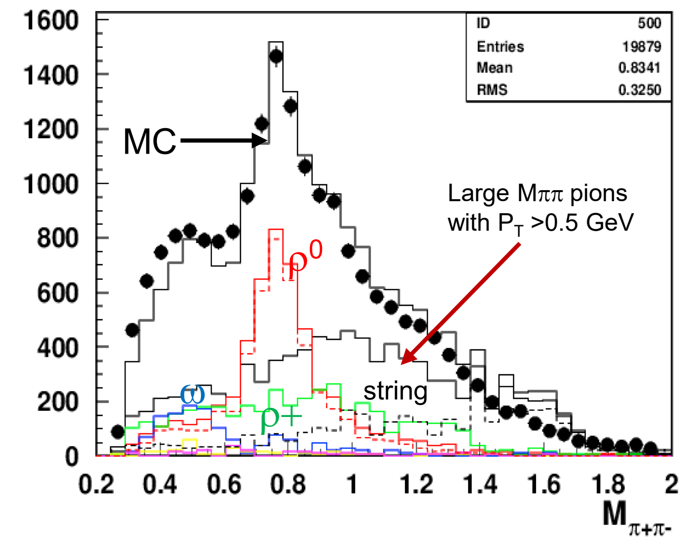
Beam Spin Asymmetry Measurements





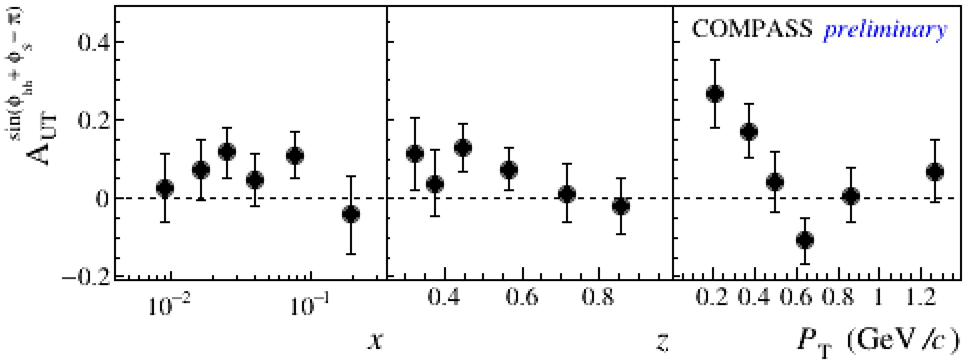
2 hadron correlations in CFR $ep \to e'\pi^+\pi^-X$





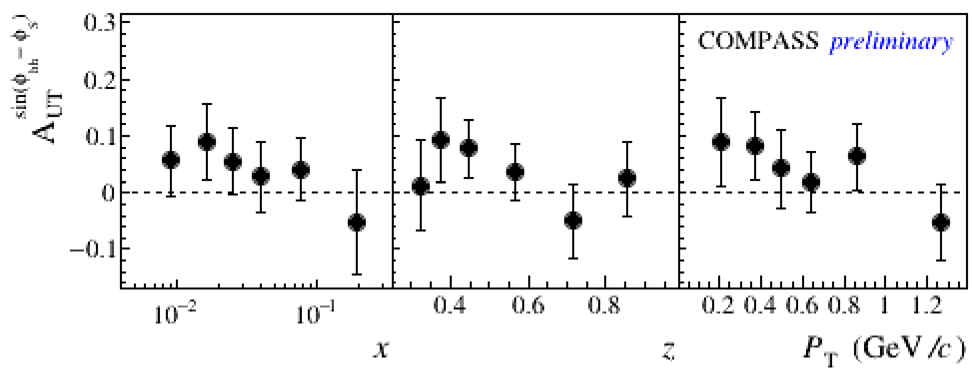
- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)
- Direct pions dominate only at relatively high P_T, (P_T >0.6-0.7 GeV)

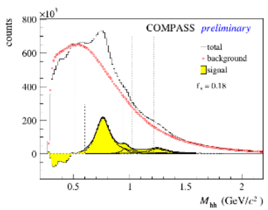
Collins/Sivers for ρ^0



- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T

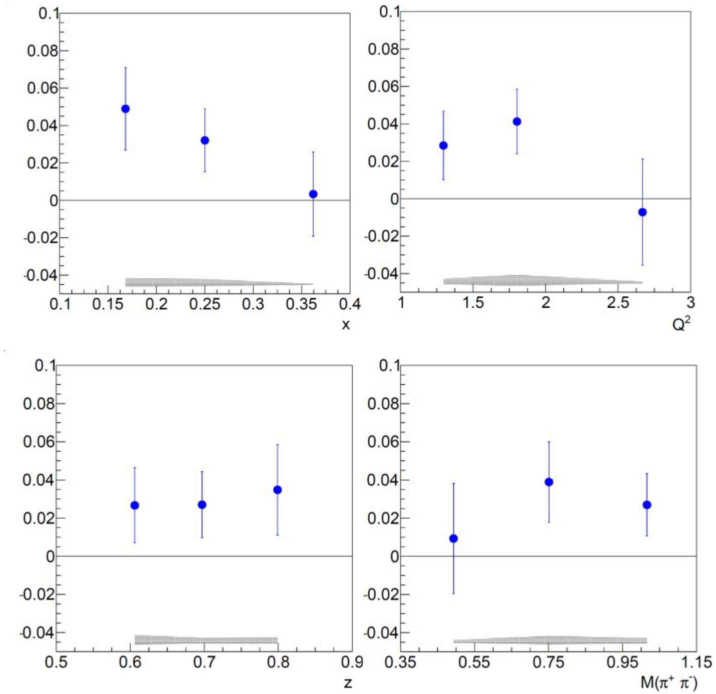
- indication for a positive asymmetry
- similar to π^0 as expected from the models





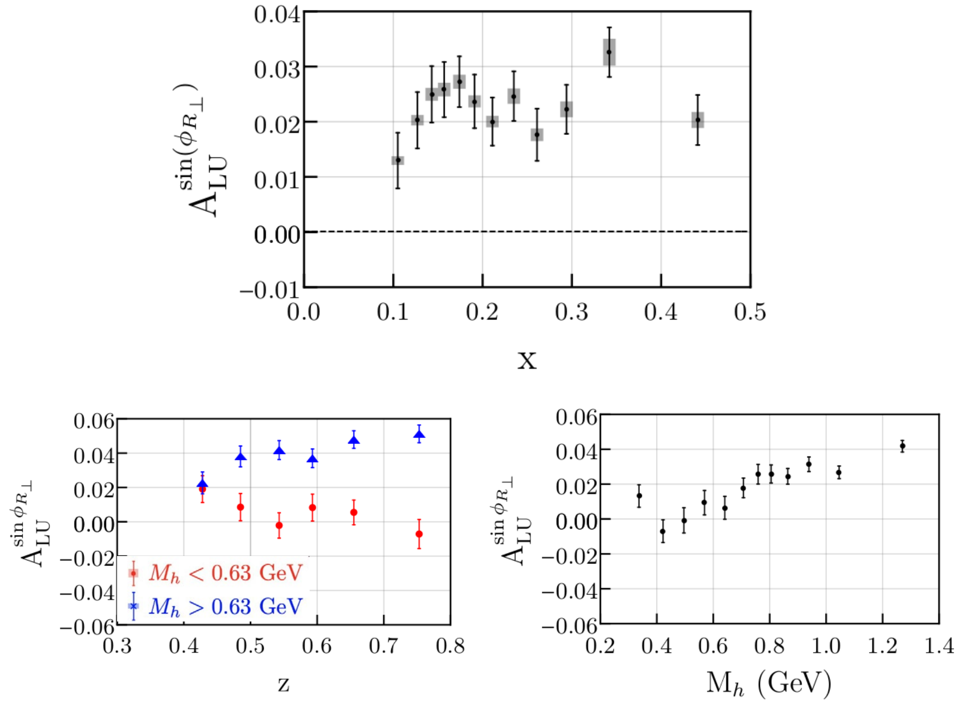
Beam Spin Asymmetry Measurements

Updated CLAS6 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$



Phys.Rev.Lett. 126 (2021) 6, 062002

CLAS12 $\pi^+\pi^-$ $A_{LU}^{\sin\phi_R}$



Phys.Rev.Lett. 126 (2021) 152501

$$d\sigma_{LU} \propto W\lambda_e \sin\phi_{R_\perp}\left[xeH_1^{\measuredangle} + \frac{1}{z}f_1\tilde{G}\right]$$