

Transverse-momentum dependent effects in semi-inclusive DIS at COMPASS

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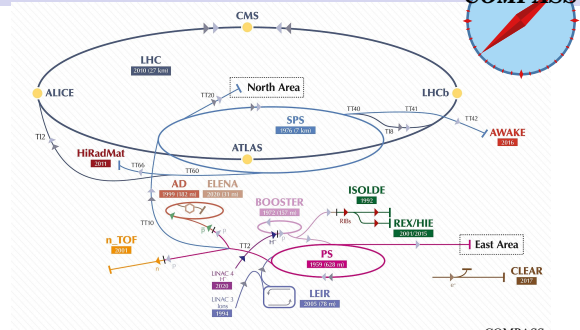
CZ+SK HEP Workshop 2026
Academy of Science, Prague



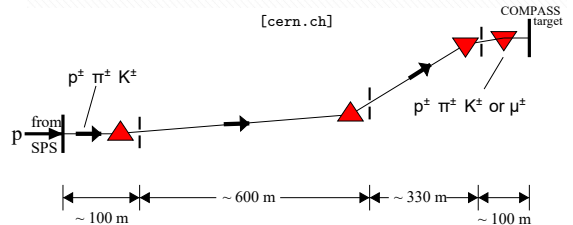
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OF MATHEMATICS
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Charles University

COMPASS experiment at CERN

- Experiment at CERN SPS North Area at the M2 beamline

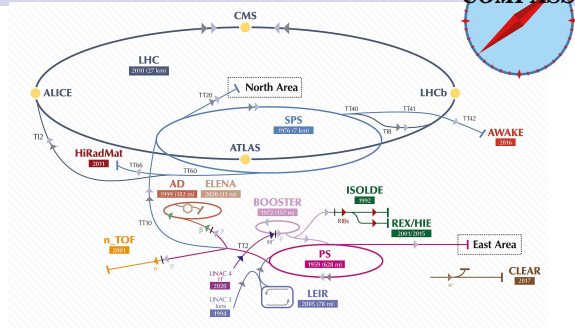


[cern.ch]

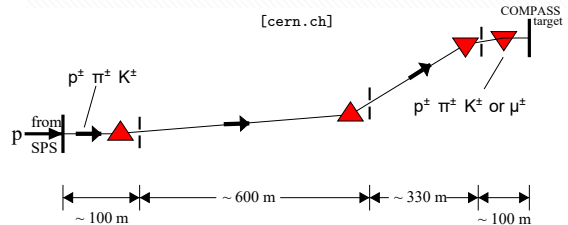


COMPASS experiment at CERN

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- Data taking 2002–2022
- Wide physics program:
 - (3D) Structure of the nucleon
 - Hadron spectroscopy
 - Primakoff reactions

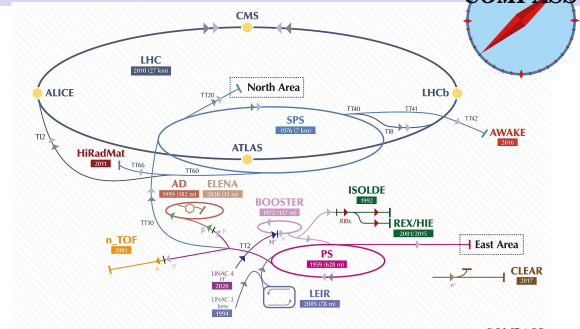


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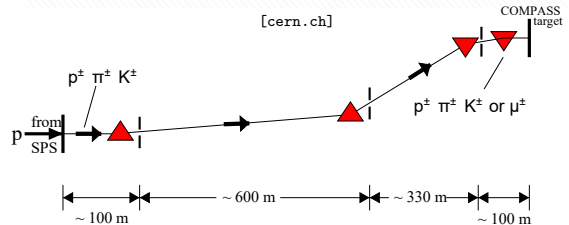


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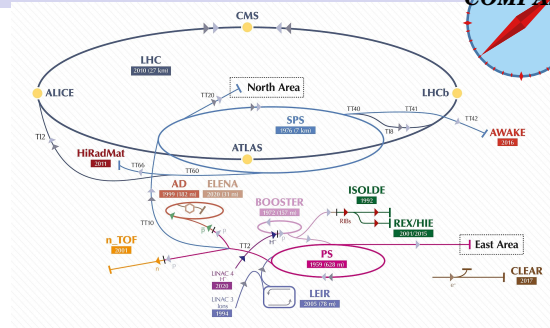
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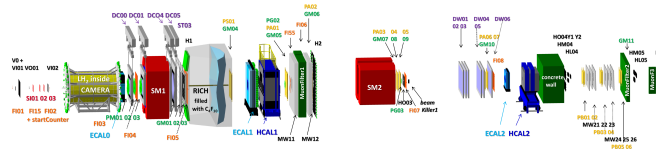
COMPASS experiment at CERN



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 - (3D) Structure of the nucleon
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- Possibility to select:
 - **polarised muon beams**
 - **hadron beams**
- Interchangeable target:
 - Polarised targets (^6LiD , NH_3)
 - Unpolarised targets (liquid H)
 - Other nuclear targets (Al, W)
- Successor: AMBER experiment
 - $\bar{p}$ x-section, p radius, Drell-Yan



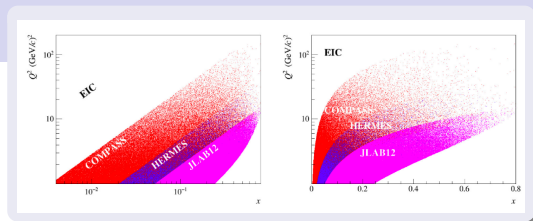
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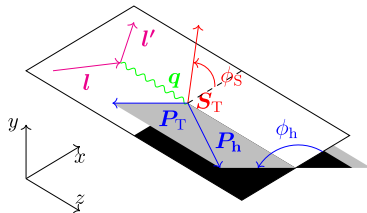
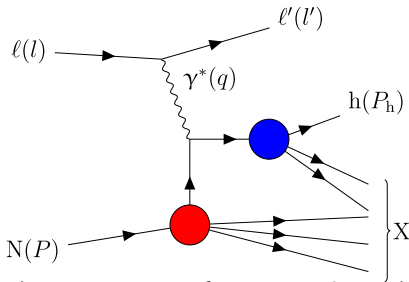
2016/17 setup with unpolarised liquid hydrogen target

Semi-inclusive DIS

$$\ell(l) + N(P) \rightarrow \ell'(l') + h(P_h) + X$$



- Hadron P_T originates from **quark k_T** and **fragmentation** $\rightarrow$ TMDs:
TMD-PDFs $f^q(x, k_T, Q^2)$ and TMD-FFs $D^{q \rightarrow h}(z, P_\perp, Q^2)$
- P_T and **azimuthal angle ϕ_h** are defined in γ^* -nucleon system (GNS):



$$x \equiv \frac{Q^2}{2P \cdot q}$$

$$Q^2 \equiv -(l - l')^2$$

$$y \equiv \frac{q \cdot P}{k \cdot P}$$

$$W^2 \equiv (q + P)^2$$

$$z \equiv \frac{P \cdot P_h}{P \cdot q}$$

Semi-inclusive DIS: x-section

$$\frac{d\sigma}{dx dy dz d\phi_S d\phi_h dP_T^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) (F_{UU,T} + \varepsilon F_{UU,L}) \quad \phi_h, \phi_S \text{ integrated}$$

$$\left\{ \begin{aligned} &1 + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{UU}^{\cos \phi_h} + \varepsilon \cos 2\phi_h A_{UU}^{\cos 2\phi_h} \\ &+ \lambda \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h A_{LU}^{\sin \phi_h} \end{aligned} \right.$$

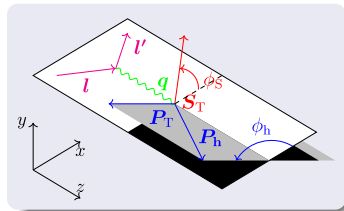
unpolarised

$$\begin{aligned} &S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h A_{UL}^{\sin \phi_h} + \varepsilon \sin 2\phi_h A_{UL}^{\sin 2\phi_h} \right] \\ &+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{LL}^{\cos \phi_h} \right] \end{aligned}$$

longitudinal

$$\begin{aligned} &S_T \left[\sin(\phi_h - \phi_S) \left(A_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon A_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\ &\quad + \varepsilon \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} \\ &\quad \left. + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S A_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) A_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\ &S_T \lambda \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) A_{LT}^{\cos(\phi_h - \phi_S)} \right. \\ &\quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S A_{LT}^{\cos \phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) A_{LT}^{\cos(2\phi_h - \phi_S)} \right] \Big\} \end{aligned}$$

transverse

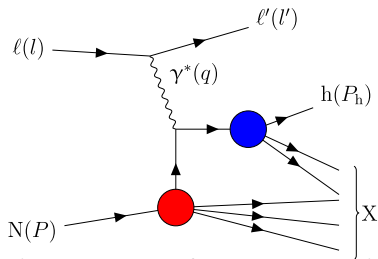


Interpreting SIDIS through factorisation

- In TMD factorisation region $\frac{P_T}{z} \ll Q$

$$A_{XY}^{f(\phi_h)} \propto F_{XY}^{f(\phi_h)} = \mathcal{C}[w \textcolor{red}{f} \textcolor{blue}{D}] = x \sum_q e_q^2 \int d^2 k_T d^2 P_\perp \delta^{(2)}(z k_T + P_\perp - P_T) w(k_T, P_\perp) \textcolor{red}{f}^q(x, k_T, Q^2) D^{q \rightarrow h}(z, P_\perp, Q^2)$$

- Leading order **TMD-PDFs** $\longrightarrow$



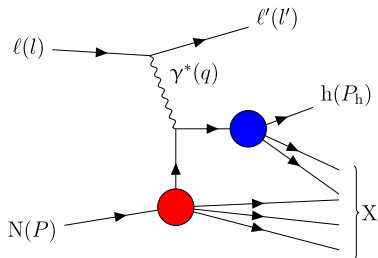
Parton polarisation	Parent hadron polarization		
	Unpolarised	Longitudinal	Transverse
	 $f_1^q(x, k_T^2)$ (unpolarised)		 $f_{1T}^{\perp q}(x, k_T^2)$ (Sivers)
		 $g_1^q(x, k_T^2)$ (helicity)	 $g_{1T}^q(x, k_T^2)$ (Kotzinian–Mulders)
	 $h_1^{\perp q}(x, k_T^2)$ (Boer–Mulders)	 $h_{1L}^{\perp q}(x, k_T^2)$ (worm-gear)	 $h_1^q(x, k_T^2) / h_{1T}^{\perp q}(x, k_T^2)$ (transversity)/(pretzelosity)

Interpreting SIDIS through factorisation

- In TMD factorisation region $\frac{P_T}{z} \ll Q$

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- Leading order $\text{TMD-FFs} \rightarrow$

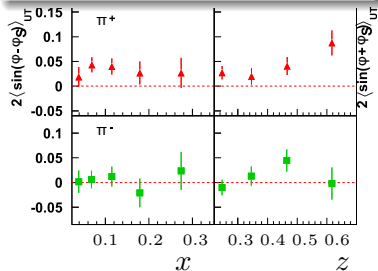


	Hadron polarisation		
	Unpolarised	Longitudinal	Transverse
Parent quark polarisation	U $D_1^{q \rightarrow h}(z, P_\perp)$ (unpolarised)	–	$D_{1T}^{\perp q \rightarrow h}(z, P_\perp)$ (polarising)
	L –	$G_{1L}^{q \rightarrow h}(z, P_\perp)$ (helicity)	$G_{1T}^{q \rightarrow h}(z, P_\perp)$
	T $H_1^{\perp q \rightarrow h}(z, P_\perp)$ (Collins)	$H_{1L}^{\perp}(z, P_\perp)$	$H_{1T}^{q \rightarrow h}(z, P_\perp)$ $H_{1T}^{\perp q \rightarrow h}(z, P_\perp)$

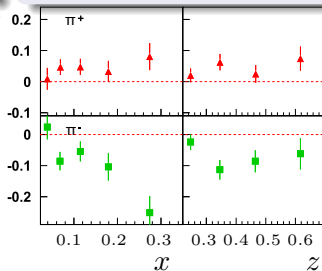
First results of COMPASS and HERMES TSAs

- Collins $A_{UT}^{\sin(\phi_h+\phi_S)} \propto \mathcal{C}[w_{\text{Coll}} h_1 H_1^\perp]$ $\rightarrow$ First inputs for measurement of h_1
- Sivers $A_{UT}^{\sin(\phi_h-\phi_S)} \propto \mathcal{C}[w_{\text{Siv}} f_{1T}^\perp D_1]$ $\rightarrow$ Non-zero Sivers effect

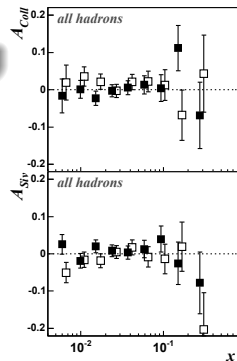
HERMES results on proton $\downarrow$



COMPASS results on deuteron $\rightarrow$



[HERMES PRL94(2005)012002]



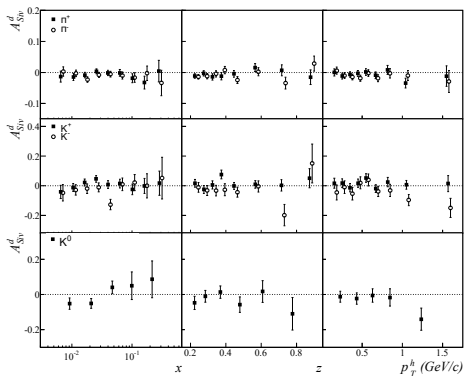
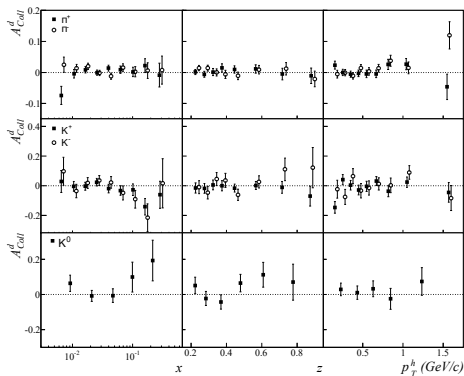
[COMPASS PRL94(2005)202002]

First results of COMPASS and HERMES TSAs

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- Sivers $A_{UT}^{\sin(\phi_h-\phi_S)} \propto \mathcal{C}[w_{\text{Siv}} \textcolor{red}{f}_{1T}^\perp D_1]$

→ First inputs for measurement of $\textcolor{red}{h}_1$

→ With PID and full 2002–2004 in 2009



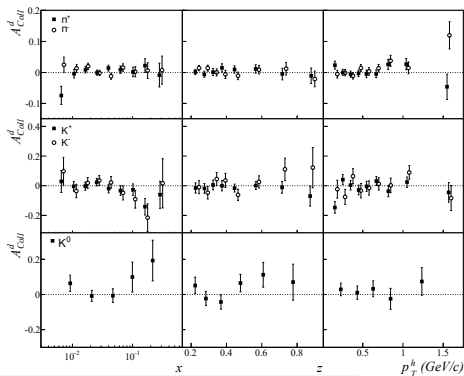
[COMPASS PLB673(2009)127–135]

First results of COMPASS and HERMES TSAs

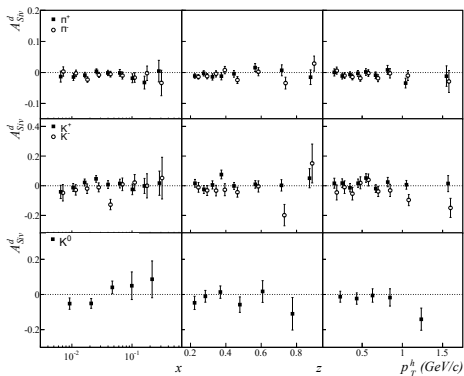
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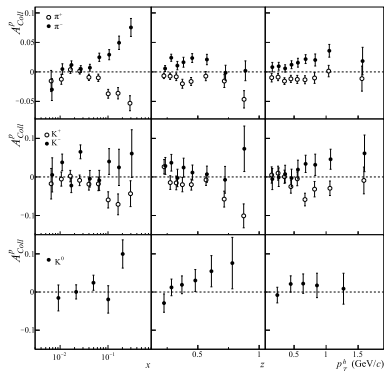
d results zero within σ_{stat}



[COMPASS PLB673(2009)127–135]

SIDIS off transversely polarised proton from 2010

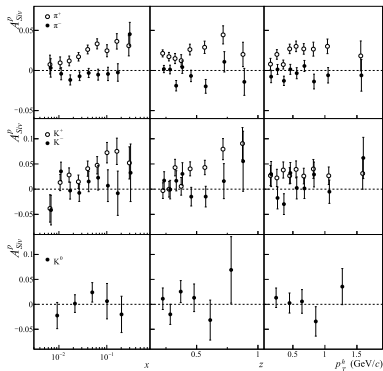
- Collins $A_{UT}^{\sin(\phi_h+\phi_S)} \propto \mathcal{C}[w_{\text{Coll}} h_1^\perp H_1^\perp]$
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- First COMPASS results on proton

[COMPASS Phys. Lett. B 717 (2012) 376, 383]

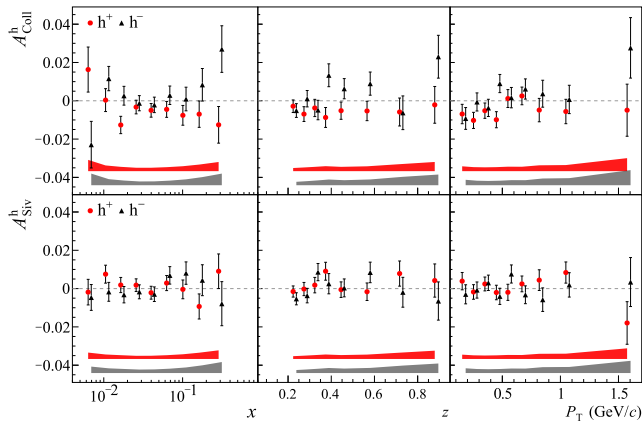
→ Collins and Sivers confirmed to be non-0



[COMPASS PLB717(2012)376]

SIDIS off transversely polarised deuteron from 2022 data

- Collins $A_{UT}^{\sin(\phi_h+\phi_S)} \propto \mathcal{C}[w_{\text{Coll}} \textcolor{red}{h}_1 \textcolor{blue}{H}_1^\perp]$
- Sivers $A_{UT}^{\sin(\phi_h-\phi_S)} \propto \mathcal{C}[w_{\text{Siv}} \textcolor{red}{f}_{1T}^\perp \textcolor{blue}{D}_1]$
- 2022 run improved precision of the first 2002–2004 measurement

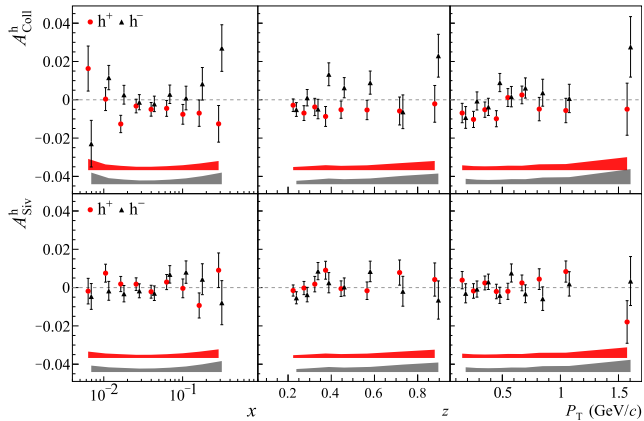


[COMPASS PRL133(2024)10]

SIDIS off transversely polarised deuteron from 2022 data

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→ very small effect due to the cancellation of contributions from u and d quarks



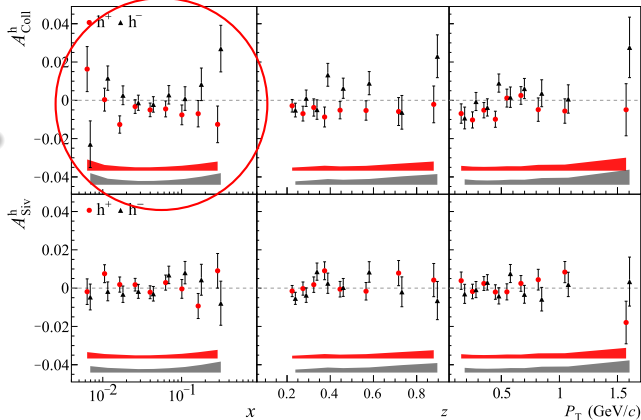
[COMPASS PRL133(2024)10]

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mirror effect

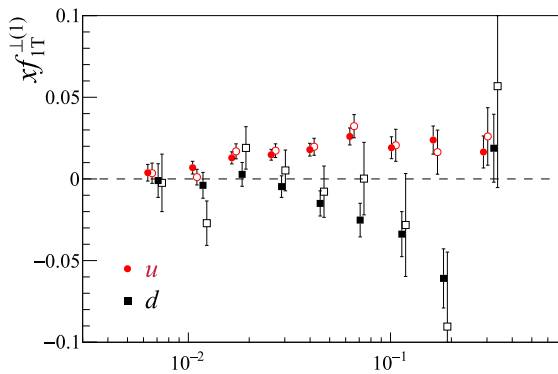
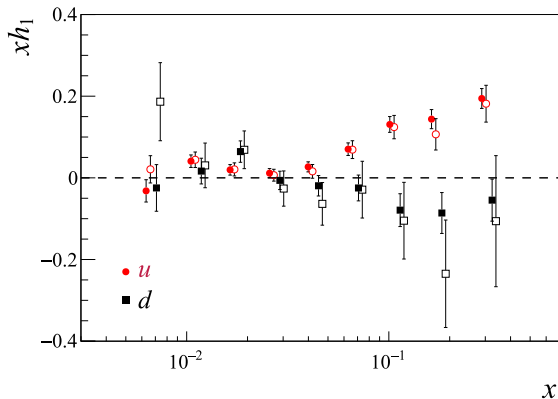


[COMPASS PRL133(2024)10]

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- Sivers $A_{UT}^{\sin(\phi_h-\phi_S)} \propto \mathcal{C}[w_{\text{Siv}} f_{1T}^\perp D_1]$

- important to constrain d quark TMDs
- big impact on transversity h_1



[COMPASS PRL133(2024)10]

SIDIS off transversely polarised proton vs. deuteron: other TSAs

- Preliminary results for other (higher twist) TSAs presented on DIS 2026:

- Kotzinian-Mulders

$$A_{LT}^{\cos(\phi_h - \phi_S)} \propto \mathcal{C}[w_{K-M} g_{1T}^q D_1]$$

- Pretzelosity

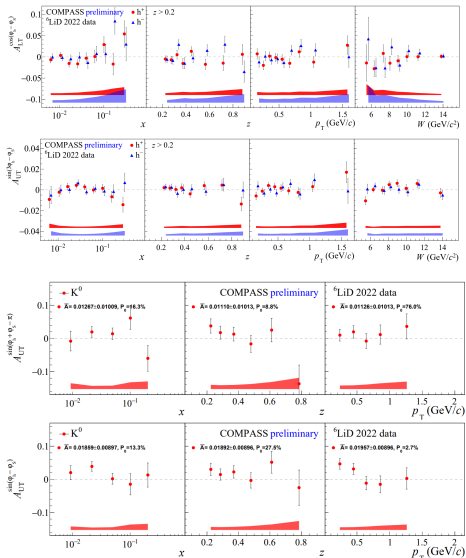
$$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto \mathcal{C}[w_{Pz} h_{1T}^\perp H_1^\perp]$$

- Preliminary K^0 transverse spin asymmetries:

- Collins $A_{UT}^{\sin(\phi_h + \phi_S)} \propto \mathcal{C}[w_{\text{Coll}} h_1 H_1^\perp]$

- Sivers $A_{UT}^{\sin(\phi_h - \phi_S)} \propto \mathcal{C}[w_{\text{Siv}} f_{1T}^\perp D_1]$

- Ongoing work on $\pi^\pm$ and $K^\pm$ PID using RICH detector



Semi-inclusive DIS: x-section

$$\frac{d\sigma}{dx dy dz d\phi_S d\phi_h dP_T^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) (F_{UU,T} + \varepsilon F_{UU,L}) \quad \phi_h, \phi_S \text{ integrated}$$

$$\left\{ 1 + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{UU}^{\cos \phi_h} + \varepsilon \cos 2\phi_h A_{UU}^{\cos 2\phi_h} + \lambda \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h A_{LU}^{\sin \phi_h} \right.$$

unpolarised

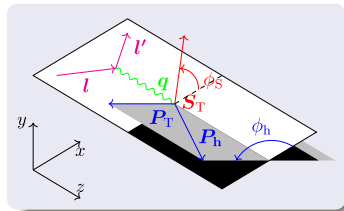
$$\left. S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h A_{UL}^{\sin \phi_h} + \varepsilon \sin 2\phi_h A_{UL}^{\sin 2\phi_h} \right] + S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{LL}^{\cos \phi_h} \right] \right.$$

longitudinal

$$\left. S_T \left[\sin(\phi_h - \phi_S) \left(A_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon A_{UT,L}^{\sin(\phi_h - \phi_S)} \right) + \varepsilon \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S A_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) A_{UT}^{\sin(2\phi_h - \phi_S)} \right] \right.$$

$$\left. S_T \lambda \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) A_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S A_{LT}^{\cos \phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) A_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\}$$

transverse

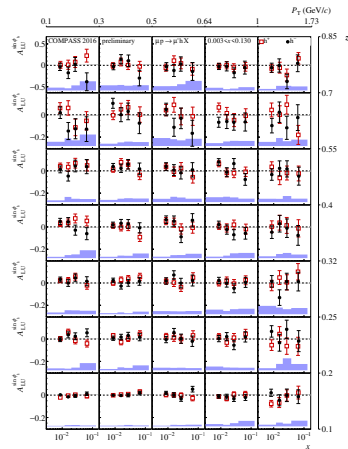
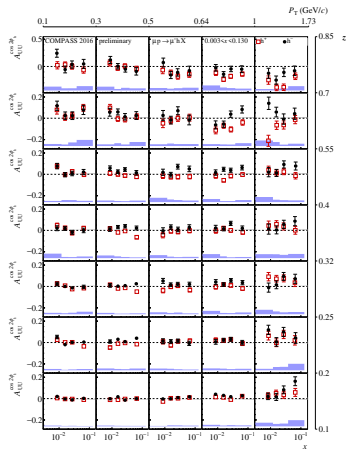
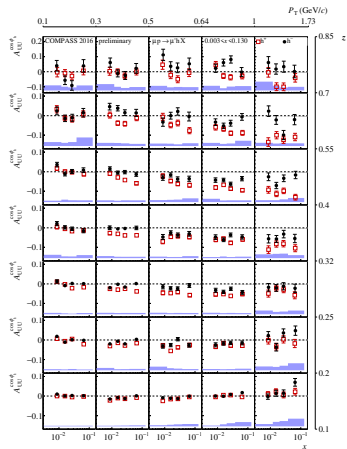


SIDIS off unpolarised proton from 2016 data (preliminary results)

$$A_{UU}^{\cos\phi_h} \propto \mathcal{C}[w_{\text{Cahn}} f_1 D_1]$$

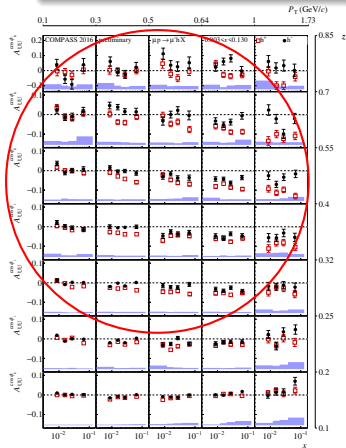
$$A_{UU}^{\cos 2\phi_h} \propto \mathcal{C}[w_{\text{BM}} h_1^\perp H_1^\perp]$$

$$A_{LU}^{\sin\phi_h} \propto \mathcal{C}[\dots]$$



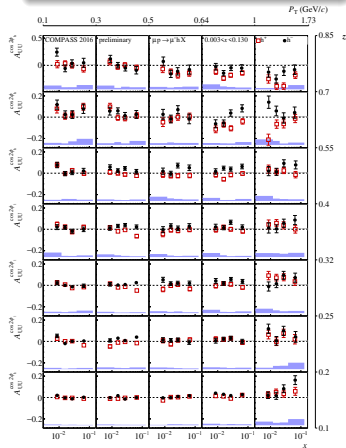
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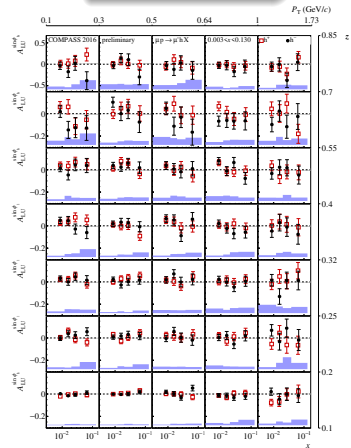


Cahn effect

$$A_{UU}^{\cos 2\phi_h} \propto \mathcal{C}[w_{\text{BM}} h_1^\perp H_1^\perp]$$

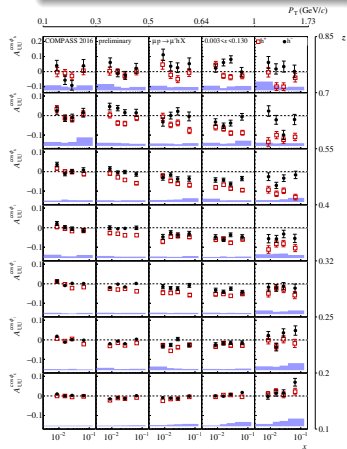


$$A_{LU}^{\sin\phi_h} \propto \mathcal{C}[\dots]$$



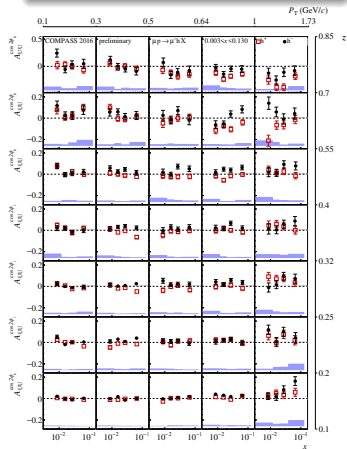
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$$A_{UU}^{\cos\phi_h} \propto \mathcal{C}[w_{\text{Cahn}} f_1 D_1]$$

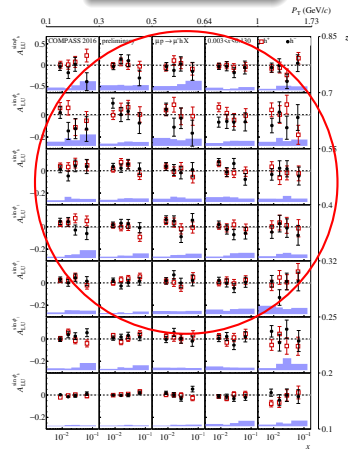


Cahn effect

$$A_{UU}^{\cos 2\phi_h} \propto \mathcal{C}[w_{\text{BM}} h_1^\perp H_1^\perp]$$



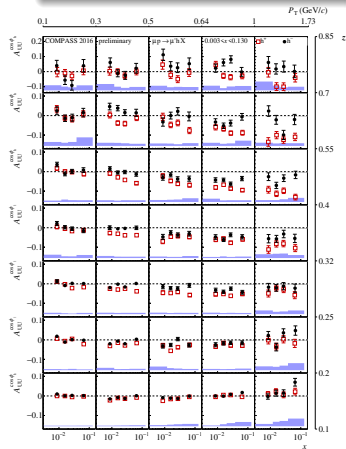
$$A_{LU}^{\sin\phi_h} \propto \mathcal{C}[\dots]$$



slightly positive

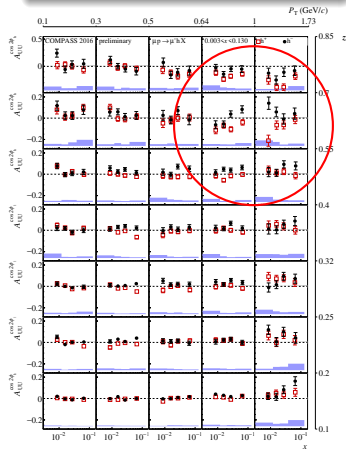
SIDIS off unpolarised proton from 2016 data (preliminary results)

$$A_{UU}^{\cos\phi_h} \propto \mathcal{C}[w_{\text{Cahn}} f_1 D_1]$$



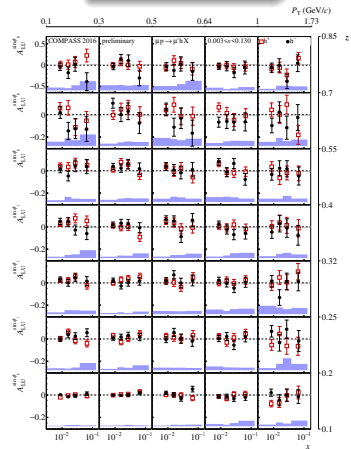
Cahn effect

$$A_{UU}^{\cos 2\phi_h} \propto \mathcal{C}[w_{\text{BM}} h_1^\perp H_1^\perp]$$



hints of mirror effect

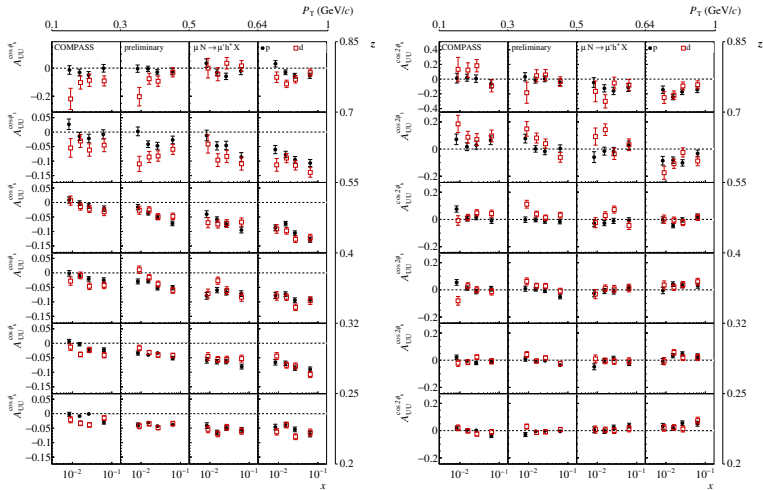
$$A_{LU}^{\sin\phi_h} \propto \mathcal{C}[\dots]$$



slightly positive

SIDIS off unpolarised proton vs. deuteron h^+

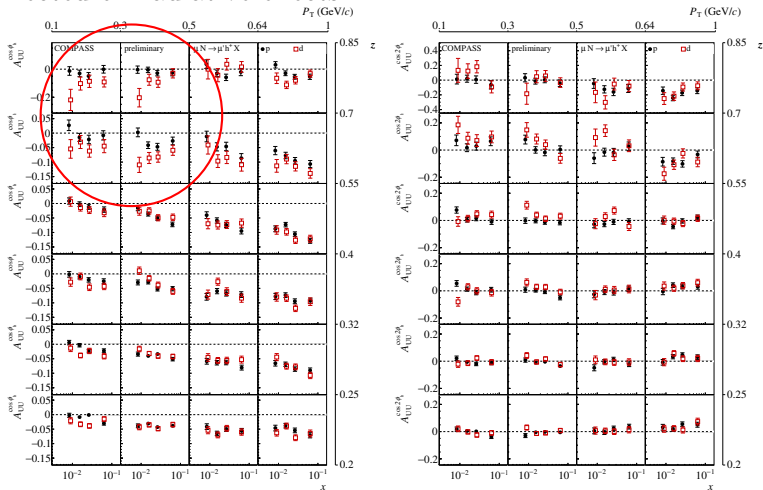
- Preliminary results on proton (2016) vs. on isoscalar target (2004) [NPB201407 019]



SIDIS off unpolarised proton vs. deuteron h^+

- Preliminary results on proton (2016) vs. on isoscalar target (2004) [NPB201407 019]
- Both not corrected on radiative effects

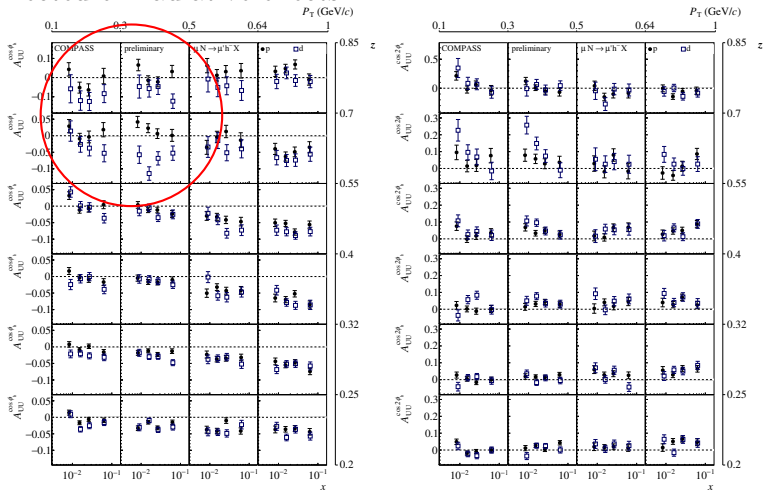
flavour
dependence?



SIDIS off unpolarised proton vs. deuteron h^-

- Preliminary results on proton (2016) vs. on isoscalar target (2004) [NPB201407 019]
- Both not corrected on radiative effects

flavour
dependence?



Semi-inclusive DIS: x-section

$$\frac{d\sigma}{dx dy dz d\phi_S d\phi_h dP_T^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) (F_{UU,T} + \varepsilon F_{UU,L}) \quad \phi_h, \phi_S \text{ integrated}$$

$$\left\{ \begin{aligned} &1 + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{UU}^{\cos \phi_h} + \varepsilon \cos 2\phi_h A_{UU}^{\cos 2\phi_h} \\ &+ \lambda \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h A_{LU}^{\sin \phi_h} \end{aligned} \right.$$

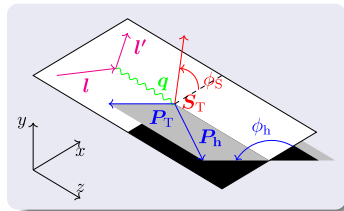
unpolarised

$$\begin{aligned} &S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h A_{UL}^{\sin \phi_h} + \varepsilon \sin 2\phi_h A_{UL}^{\sin 2\phi_h} \right] \\ &+ S_L \lambda \left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h A_{LL}^{\cos \phi_h} \right] \end{aligned}$$

longitudinal

$$\begin{aligned} &S_T \left[\sin(\phi_h - \phi_S) \left(A_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon A_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\ &\quad + \varepsilon \sin(\phi_h + \phi_S) A_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) A_{UT}^{\sin(3\phi_h - \phi_S)} \\ &\quad \left. + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S A_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) A_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\ &S_T \lambda \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) A_{LT}^{\cos(\phi_h - \phi_S)} \right. \\ &\quad \left. + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S A_{LT}^{\cos \phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) A_{LT}^{\cos(2\phi_h - \phi_S)} \right] \end{aligned}$$

transverse



Unpolarised SIDIS – P_T^2 -distributions and P_T^2 -multiplicities

- Unpolarised SIDIS x-section integrated over ϕ_h :

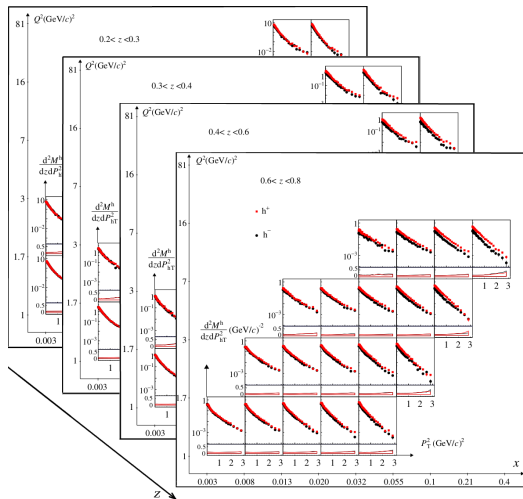
$$\frac{d\sigma}{dx dQ^2 dz dP_T^2} = \frac{2\pi^2\alpha^2}{xyQ^2} \frac{[1 + (1-y)^2]}{y^2} \underbrace{\mathcal{C}[\color{red}{f_1}(x, \color{red}{k_T}) D_1(z, P_\perp)]}_{F_{UU} \equiv F_{UU,T} + \varepsilon F_{UU,L}}$$

- Normalised to the DIS cross-section $\rightarrow$ multiplicities $\rightarrow$ much cleaner observable

$$M^{h^\pm}(x, Q^2, z, P_T^2) \equiv \frac{d\sigma^h}{dx dQ^2 dz dP_T^2} \bigg/ \frac{d\sigma^{\text{DIS}}}{dx dQ^2} = \frac{1}{\Delta P_T^2 \Delta z} \frac{N^{h^\pm}(x, Q^2, z, P_T^2)}{N^{\text{DIS}}(x, Q^2)}$$

$\rightarrow$ Measured by counting numbers of hadrons $N^{h^\pm}$ and number of DIS events N^{DIS}

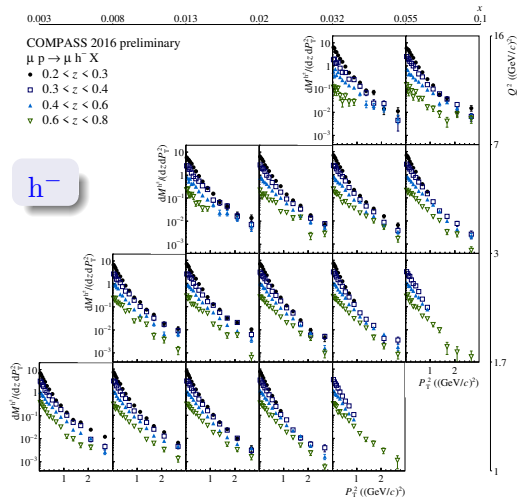
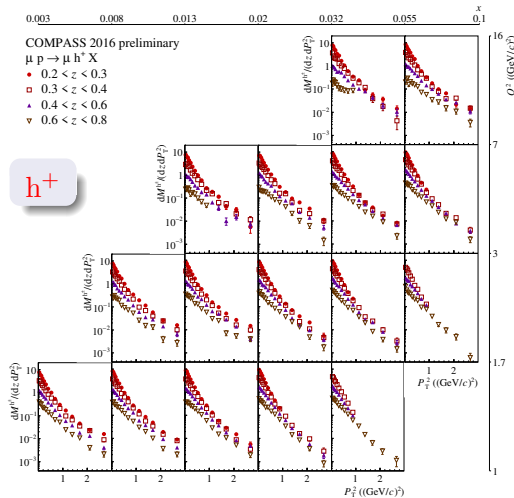
P_T^2 -multiplicities on deuteron from 2006 data



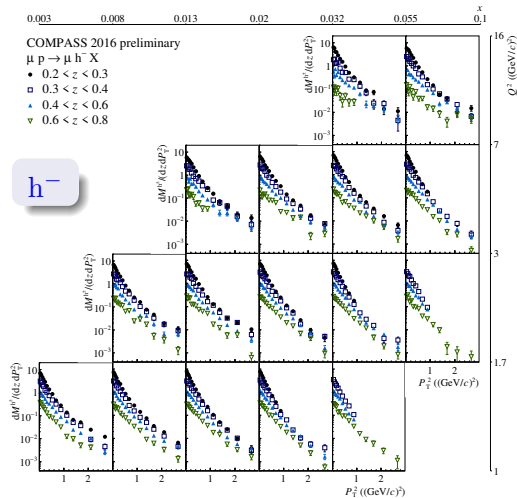
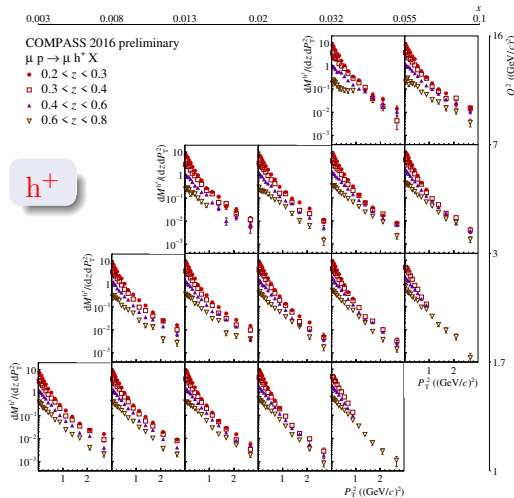
- As multiplicities published in 2018
- inclusive correction on radiative effects
- cross-section based correction on background from exclusive processes
- Ongoing work on refinement of the radiative correction and correction on background from exclusive processes

[COMPASS PRD97(2018)032006]

P_T^2 -multiplicities on proton from 2016 data (preliminary results)



P_T^2 -multiplicities on proton from 2016 data (preliminary results)



decreasing slope with $z \rightarrow$ compatible with results on deuteron

Summary and conclusions

- SIDIS is an important tool for probing the structure of nucleons (full 3D structure described by 8 **TMD-PDFs**)
- **TMD-PDFs** are obtained from global fits
- data from scattering experiments like COMPASS are inputs for such global fits:
 - **transverse spin asymmetries (TSAs):**
 - Unique measurement of Collins, Sivers effect on proton and deuteron
 - New preliminary results for higher twist TSAs and K^0 Collins and Sivers
 - Ongoing work on PID
 - **unpolarised azimuthal asymmetries:**
 - Access to Boer-Mulders effect
 - New preliminary multi-D results on proton from 2016 data
 - **P_T^2 -dependent multiplicities:**
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Summary and conclusions

- SIDIS is an important tool for probing the structure of nucleons (full 3D structure description)
- **TMD**
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 - t
- u
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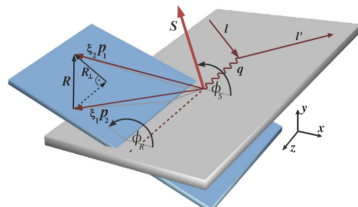
Thank you for your attention!

Backup

Dihadron SIDIS asymmetries

- Convolution over k_T integrated out of the cross-section
- Direct access to collinear transversity $h_1^q(x)$

$$\begin{aligned} \frac{d\sigma}{d\cos\theta dM_{hh} d\phi_R dz dx dy d\phi_S} &= \frac{\alpha^2}{2\pi Q^2 y} \left\{ \left(1 - y + \frac{y^2}{2}\right) \sum_q e_q^2 f_1^q(x) \underbrace{D_{1,q}(z, M_{hh}^2, \cos\theta)}_{\text{dihadron unpolarised FF}} \right. \\ &\quad \left. + S_T(1 - y) \sum_q e_q^2 \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{hh}} \sin\theta \sin\phi_{RS} \times h_1^q(x) \underbrace{H_{1,q}^\triangleleft(z, M_{hh}^2, \cos\theta)}_{\text{interference FF}} \right\}. \\ &= \sigma_0 \left[1 + S_T D_{NN} A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS} \right] \quad \phi_{RS} = \phi_R - \phi_S \end{aligned}$$

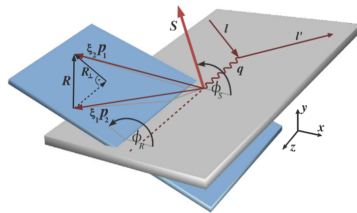
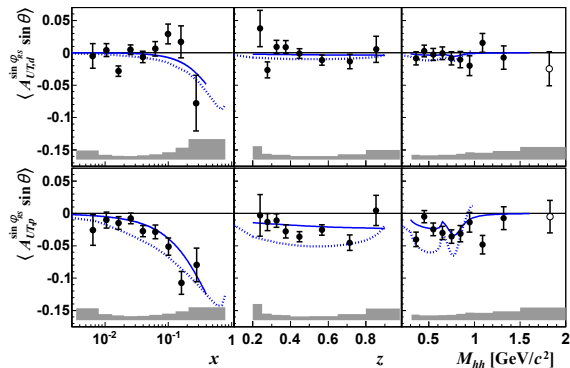


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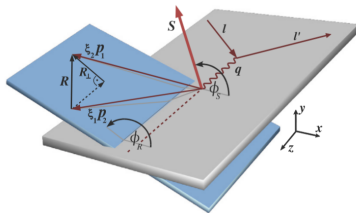
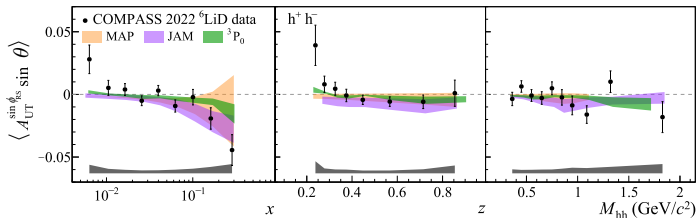
[COMPASS PLB713(2012)10]

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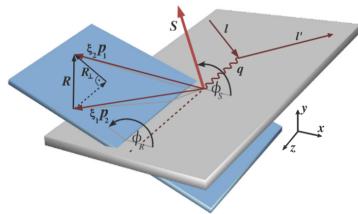
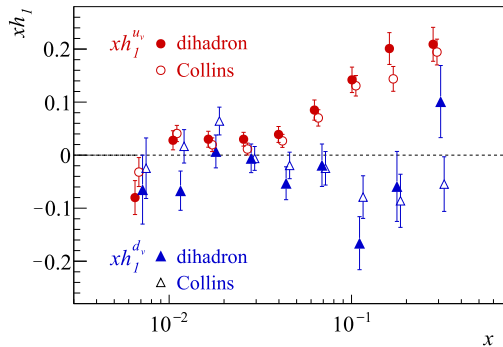
[COMPASS paper accepted to PRL]

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[COMPASS paper accepted to PRL]

Unpolarized SIDIS – structure functions

- Unpolarized SIDIS cross-section: [A. Bacchetta et al., JHEP0702(2007)]

$$\frac{d\sigma}{dx dy dz d\phi_h dP_T^2} = \frac{2\pi\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left[F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \varepsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda \sqrt{2\varepsilon(1+\varepsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h \right]$$

- P_T^2 distributions at twist 2: $F_{UU} = F_{UU,T} + \varepsilon F_{UU,L} \approx F_{UU,T}$

$$\frac{d\sigma}{dx dQ^2 dz dP_T^2} = \frac{2\pi^2\alpha^2}{xyQ^2} \frac{[1 + (1-y)^2]}{y^2} F_{UU}$$

- Structure functions $F_{XU}^{f(\phi_h)}(x, z, P_T^2, Q^2)$ interpretation $\rightarrow$ weighted convolutions:

$$\mathcal{C}[w f D] = x \sum_q e_q^2 \int d^2k_T d^2P_\perp \delta^{(2)}(zk_T + P_\perp - P_T) w(k_T, P_\perp) f^q(x, k_T, Q^2) D^{q \rightarrow h}(z, P_\perp, Q^2)$$

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$$\frac{d\sigma}{dx dQ^2 dz dP_T^2} = \frac{2\pi^2\alpha^2}{xyQ^2} \frac{[1 + (1-y)^2]}{y^2} F_{UU} \propto \sum_q \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle_q}\right)$$

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$$\mathcal{C}[w \textcolor{red}{f} \textcolor{blue}{D}] = x \sum_q e_q^2 \int d^2k_T d^2P_\perp \delta^{(2)}(zk_T + P_\perp - P_T) w(k_T, P_\perp) f^q(x, k_T, Q^2) D^{q \rightarrow h}(z, P_\perp, Q^2)$$

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- Leading twist description of unpolarized SIDIS:

TMD-PDFs $f^q(x, k_{\text{T}}, Q^2)$:

unpolarized $\textcolor{red}{f}_1$

Boer-Mulders $\textcolor{red}{h}_1^{\perp}$

TMD-FFs $D^{q \rightarrow h}(z, P_{\perp}, Q^2)$:

unpolarized $\textcolor{blue}{D}_1$

Collins $\textcolor{blue}{H}_1^{\perp}$

$$F_{\text{UU},\text{T}} = \mathcal{C}[\textcolor{red}{f}_1 \textcolor{blue}{D}_1] \quad F_{\text{UU},\text{L}} = 0 \quad F_{\text{LU}}^{\sin \phi_h} = 0 + \dots$$

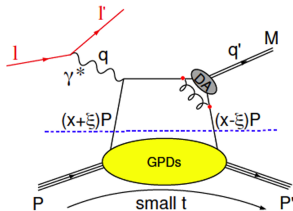
$$F_{\text{UU}}^{\cos 2\phi_h} = \mathcal{C} \left[\frac{2(\hat{\mathbf{h}} \cdot \mathbf{k}_{\text{T}})(\hat{\mathbf{h}} \cdot \mathbf{P}_{\perp}) - (\mathbf{k}_{\text{T}} \cdot \mathbf{P}_{\perp})}{zM M_h} \textcolor{red}{h}_1^{\perp} \textcolor{blue}{H}_1^{\perp} \right] \quad \leftarrow \quad \hat{\mathbf{h}} = \frac{\mathbf{P}_{\text{T}}}{|\mathbf{P}_{\text{T}}|}$$

- Up to order $\frac{1}{Q}$:

$$F_{\text{UU}}^{\cos \phi_h} = \frac{2M}{Q} \mathcal{C} \left[\underbrace{-\frac{(\hat{\mathbf{h}} \cdot \mathbf{k}_{\text{T}})}{M} \textcolor{red}{f}_1 \textcolor{blue}{D}_1}_{\text{Cahn effect}} + \underbrace{\frac{k_{\text{T}}^2 (\hat{\mathbf{h}} \cdot \mathbf{P}_{\perp})}{zM^2 M_h} \textcolor{red}{h}_1^{\perp} \textcolor{blue}{H}_1^{\perp}}_{\text{Boer-Mulders effect}} + \dots \right] \quad \leftarrow \quad \text{W.W. type approximation}$$

Background treatment

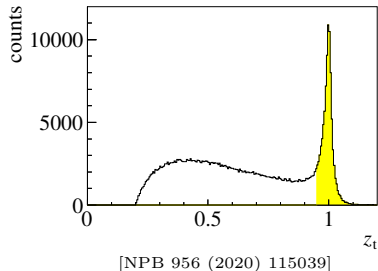
- Background process: HEMP
 - only non-negligible contributors: $\rho \rightarrow \pi^+\pi^-$ and $\phi \rightarrow K^+K^-$
 - Exclusive vector mesons (EVM) inherit polarization from γ^*
- large amplitudes of azimuthal modulations for decay products
- In case of hadrons from DVMs:



- **visible hadron pairs**
 - both hadrons reconstructed
 - rejected using '**DVM cut**':

$$z_t = z_{h+} + z_{h-} < 0.95$$

- **invisible hadrons**
 - 1 hadron reconstructed
 - subtracted from ϕ_h distributions using HEPGEN MC $\equiv$ **DVM subtraction**

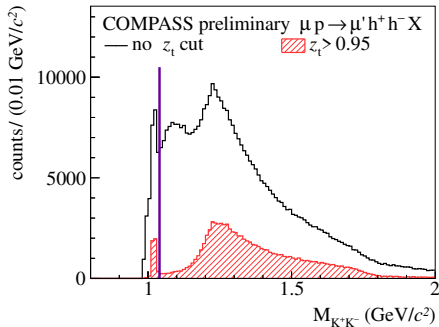
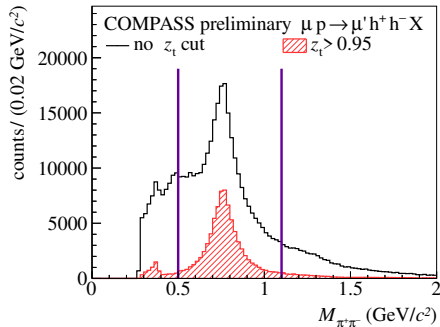


Visible hadron pairs: looking for hadrons from DVMs

- ρ and ϕ mesons are visible in invariant mass distributions of the **visible hadron pairs**:

$$\rho \rightarrow \pi^+ \pi^- : M_{K^+ K^-} \in [1.04, \infty] \text{ GeV}/c^2$$
$$\text{and } M_{\pi^+ \pi^-} \in [0.5, 1.1] \text{ GeV}/c^2$$

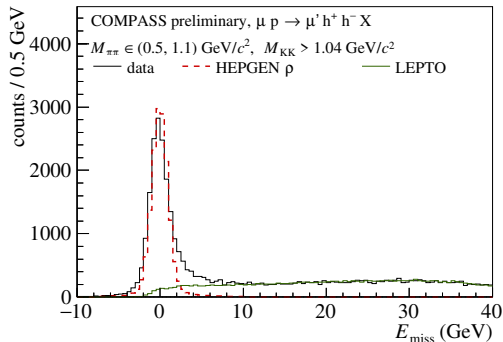
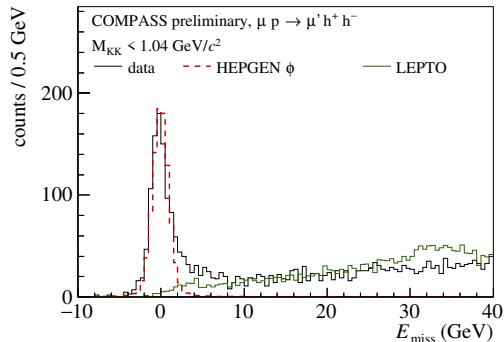
$$\phi \rightarrow K^+ K^- : M_{K^+ K^-} \in [0, 1.04] \text{ GeV}/c^2$$



Subtraction of invisible hadrons from DVM decays

- Normalization of HEPGEN ρ and HEPGEN ϕ is estimated using E_{miss} distributions of **visible hadron pairs**

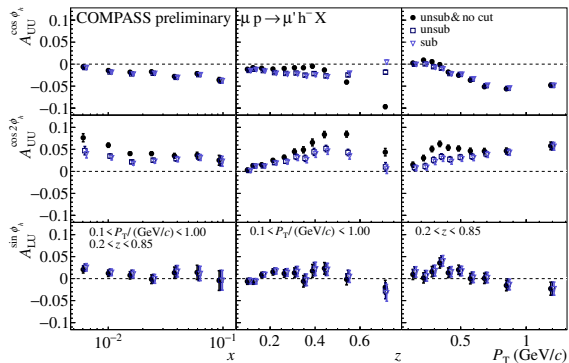
$$E_{\text{miss}} = \frac{M_X^2 - M_p^2}{2M_p} \quad M_X^2 = (p + q - P_{h^+} - P_{h^-})^2$$



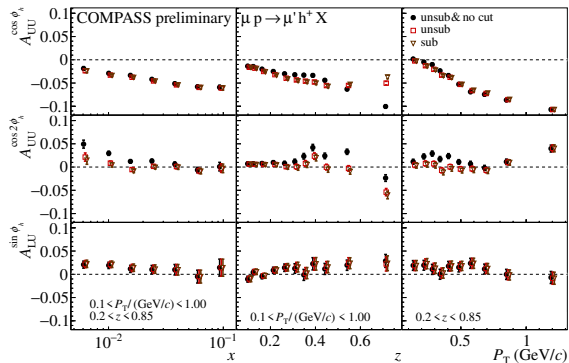
Effect of DVM cut and subtraction in 1D

- Background of hadrons from DVM decays has significant impact on the results
- High z , low x and low P_T regions are affected the most

negative hadrons

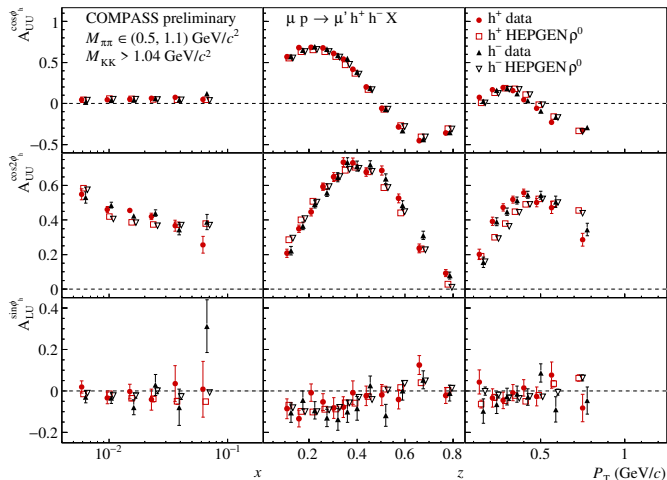


positive hadrons



Azimuthal asymmetries of visible hadron pairs in data and HEPGEN

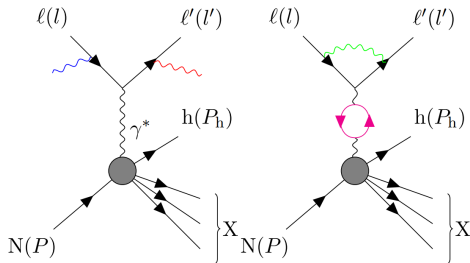
- HEPGEN nicely describes modulations in measured data thanks to SDMEs being plugged in [EPJC (2023) 83 924]



Radiative corrections

- Cross-section is defined at tree level $\rightarrow$ radiative corrections account for QED radiative effects (RE):

- $\rightarrow$ renormalisation of the vertices
- $\rightarrow$ radiation of photons along the μ , μ' and virtual photon
- $\rightarrow$ corresponding changes in x , Q^2 and orientation of GNS



- impact of RE in hadronic variables (such as ϕ_h) accessed only through simulations
- DJANGO: modified LEPTO generator with hadronization in JETSET and SOPHIA [K. Charchuła et al., DJANGO]

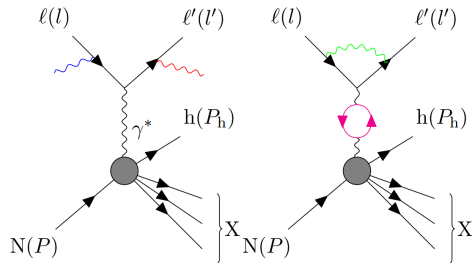
- applied by multiplying ϕ_h distributions bin-by-bin by fraction η

$$\eta(\phi_h) = \frac{N_h^{\text{RE-off}}(\phi_h)}{N_h^{\text{RE-on}}(\phi_h)}$$

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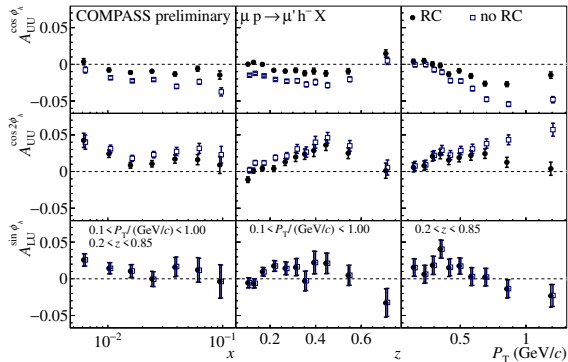
- applied by multiplying P_T^2 distributions bin-by-bin by fraction η

$$\eta(P_T^2) = \frac{N_h^{\text{RE-off}}(P_T^2)}{N_h^{\text{RE-on}}(P_T^2)}$$

Effect of RC on measured azimuthal asymmetries in 1D binning

- The effect on azimuthal asymmetries grows with P_T , x and goes down with z
- No effect is observed (nor expected) for $A_{LU}^{\sin \phi_h}$

h^-



h^+

