Experimental overview of TMD PDFs from SIDIS and Drell-Yan data

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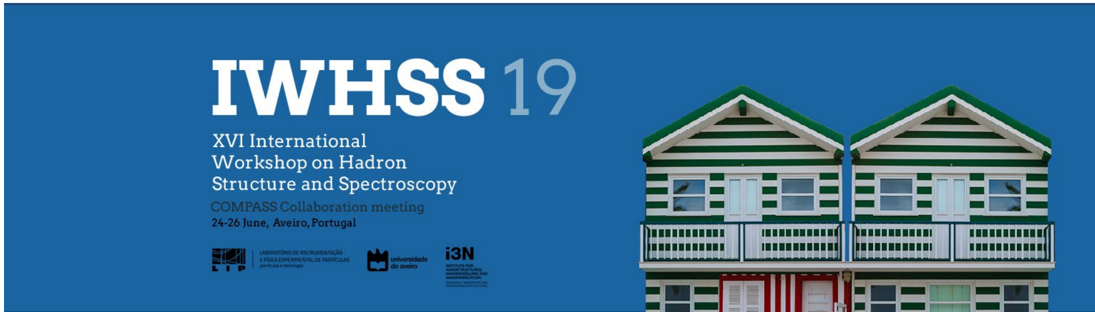
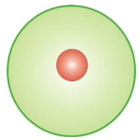
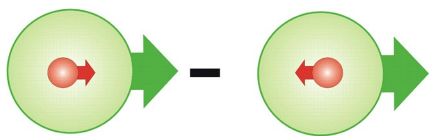
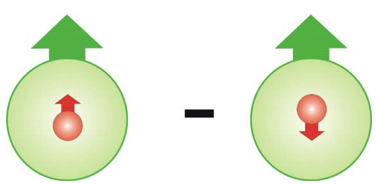


The Nucleon Structure

the three collinear PDFs

$f_1(x)$  number $q(x)$

$g_1(x)$  helicity $\Delta q(x)$

$h_1(x)$  **transversity** $\Delta_T q(x)$

- a chirally-odd distribution, hence not observable in DIS
- theoretically well known
- first experimental evidence in 2005

The Nucleon Structure

taking into account the quark **intrinsic transverse momentum** k_T,
at leading order 8 Transverse Momentum Dependent PDFs are needed for a full description of the nucleon structure

all allowed correlations between nucleon spin, parton spin, parton transverse momentum

quark polarisation \ **nucleon** polarisation	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity* $h_{1T}^{\perp}$	$\Delta_T q$

most of the information came from SIDIS

The Nucleon Structure

taking into account the quark **intrinsic transverse momentum** k_T,
at leading order 8 Transverse Momentum Dependent PDFs are needed for a full description of the nucleon structure

all allowed correlations between nucleon spin, parton spin, parton transverse momentum

transverse spin components only

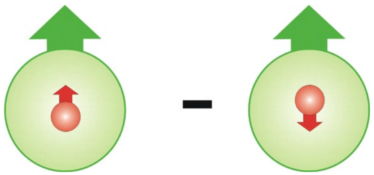
quark polarisation \ nucleon polarisation	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ *Sivers*	$\Delta_0^T q$
L		g_1 *helicity* Δq	g_{1T}	
T	$h_1^{\perp}$ *Boer Mulders*	$h_{1L}^{\perp}$	h_1 *transversity*; $h_{1T}^{\perp}$	$\Delta_T q$

The most famous new PDFs

h_1 transversity function

transversely polarized quarks in a transversely polarized nucleon

correlation between the transverse spins

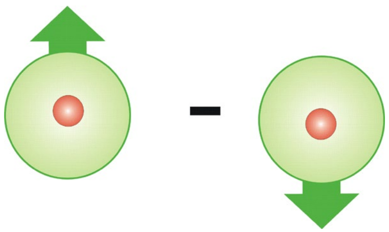


chiral-odd
survives to integration over transverse momenta
tensor charge

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

unpolarized quarks in a transversely polarized nucleon

correlation between the parton transverse momentum and the nucleon spin

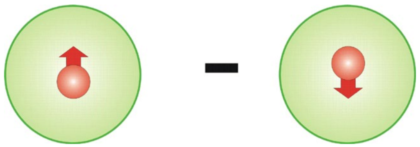


T-odd

$h_1^{\perp}$ Boer-Mulders function:

transversely polarized quarks in an unpolarized nucleon

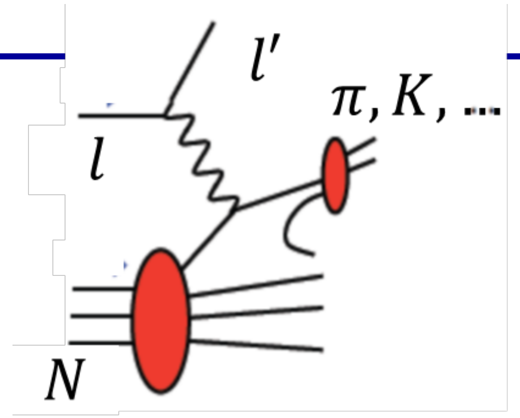
correlation between the transverse momentum and the transverse spin of the partons



T-odd

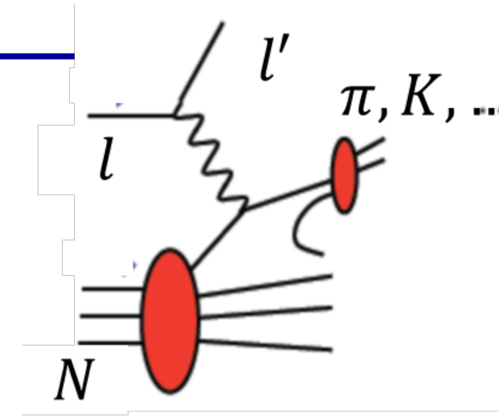
measurable in SIDIS

Semi-Inclusive Deep Inelastic Scattering



$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

Semi-Inclusive Deep Inelastic Scattering



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

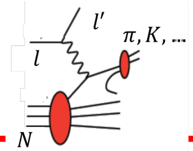
Annotations:

- $F_{UU}^{\cos 2\phi_h}$ → $h_1^\perp \otimes H_1^\perp$
- $F_{UL}^{\sin 2\phi_h}$ → $h_{1L}^\perp \otimes H_1^\perp$
- $F_{UT,T}^{\sin(\phi_h-\phi_S)}$ → $f_{1T}^\perp \otimes D_1$
- $F_{UT}^{\sin(\phi_h+\phi_S)}$ → $h_1 \otimes H_1^\perp$
- $F_{UT}^{\sin(3\phi_h-\phi_S)}$ → $h_{1T}^\perp \otimes H_1^\perp$
- $F_{LT}^{\cos(\phi_h-\phi_S)}$ → $g_{1T} \otimes D_1$

14 independent azimuthal modulations

amplitudes of the modulations
→ TMD PDFs

Semi-Inclusive Deep Inelastic Scattering

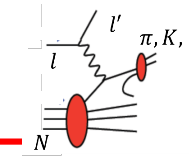


MAJOR RESULT:

in the past 15 years 2 of these new PDF's have been measured and shown to be different from zero

by COMPASS and HERMES

Semi-Inclusive Deep Inelastic Scattering



MAJOR RESULT:
in the past 15 years 2 of these new PDF's have been measured and shown to be different from zero

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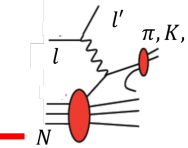
the transversity PDF Collins asymmetry $\sim \boldsymbol{h_1} \otimes H_1^{\perp}$
amplitude of the sine modulation in $\phi_h + \phi_s - \pi$

the Sivers PDF Sivers asymmetry $\sim \boldsymbol{f_{1T}^{\perp}} \otimes D_1$
amplitude of the sine modulation in $\phi_h - \phi_s$

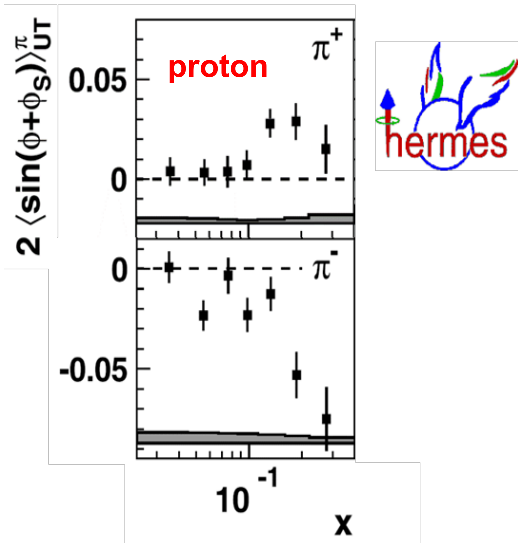
A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON

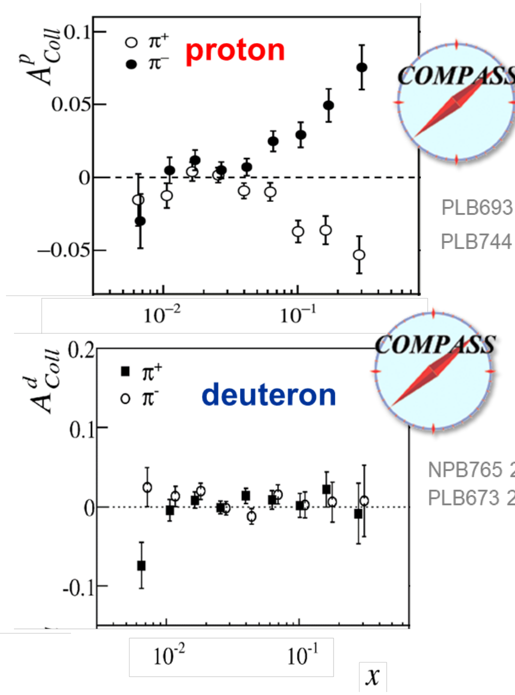
Collins asymmetry $\sim h_1 \otimes H_1^\perp$



since 2005 evidence for non-zero Collins asymmetry on proton

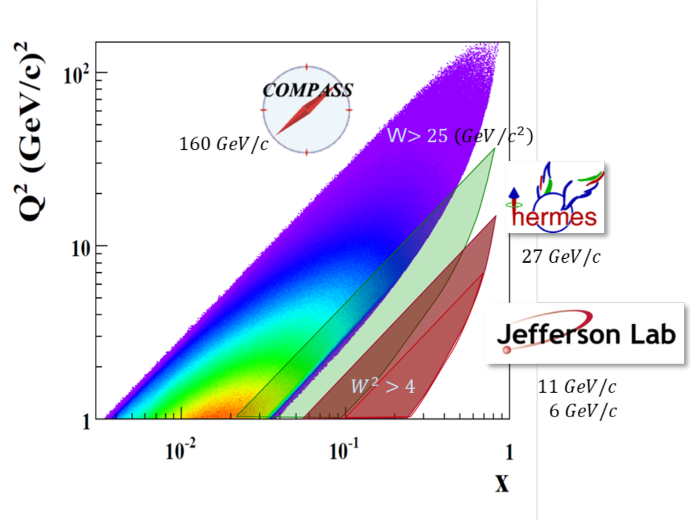
PLB693 2010 final results



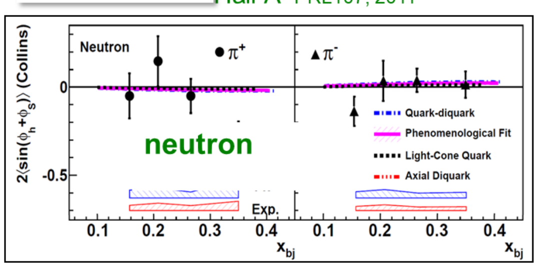


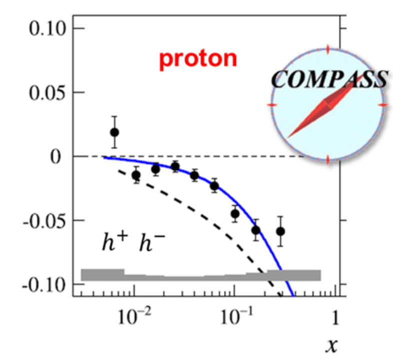
PLB693 2010
PLB744 2015

NPB765 2007
PLB673 2009

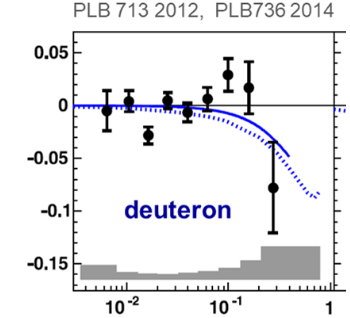


Jefferson Lab Hall A PRL107, 2011

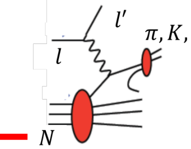




PLB 713 2012, PLB736 2014



Collins asymmetry $\sim h_1 \otimes H_1^\perp$



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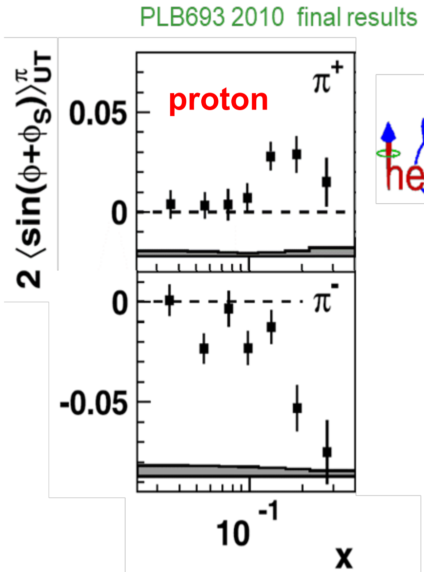
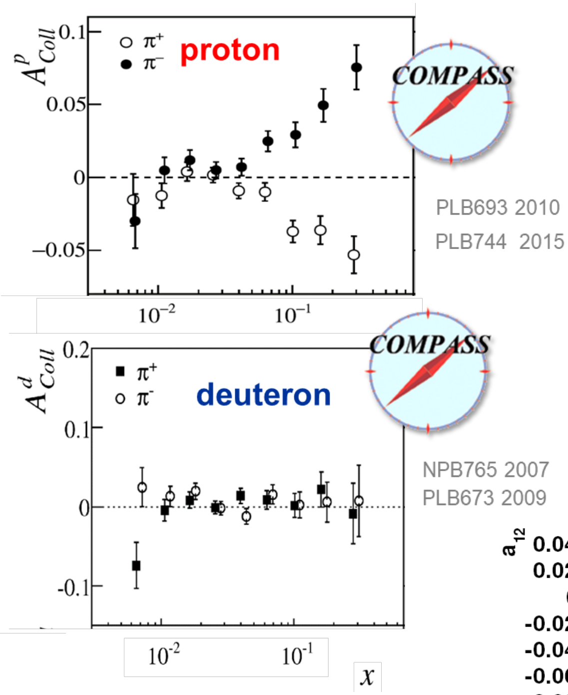
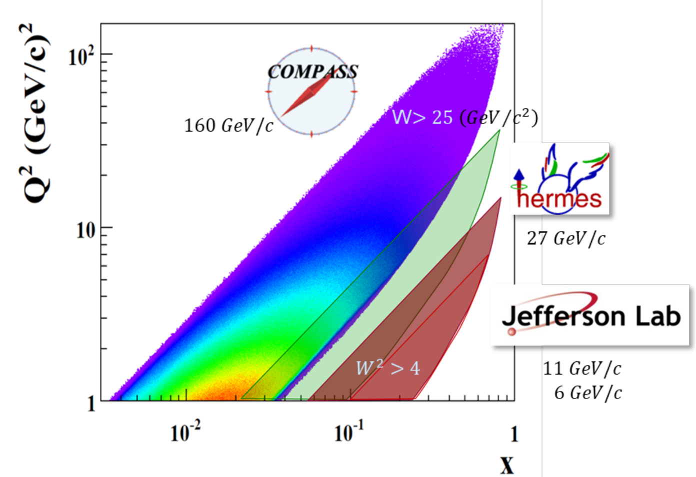
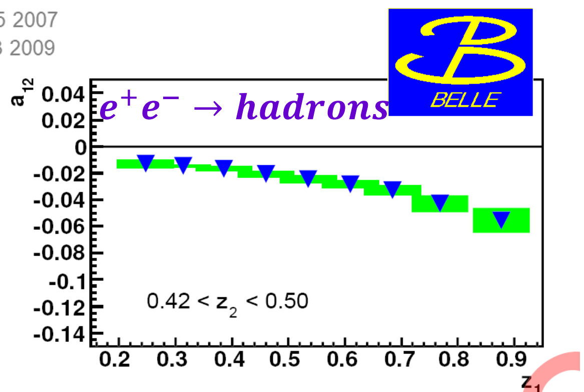
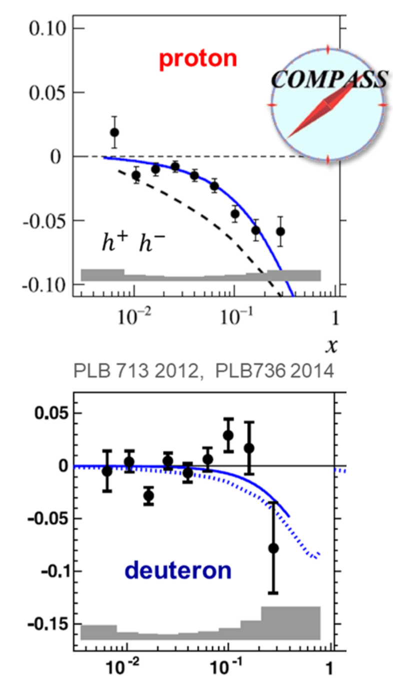
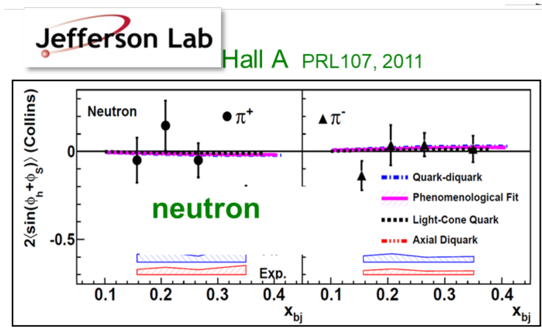


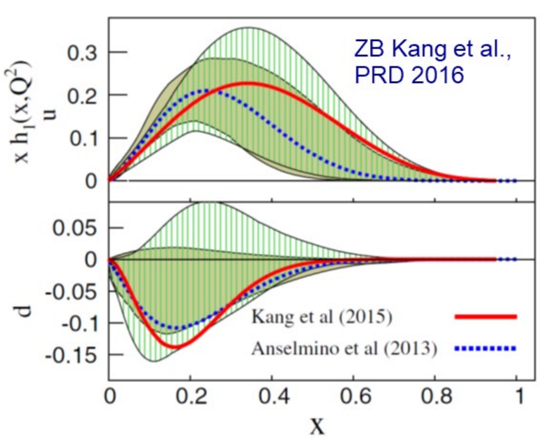








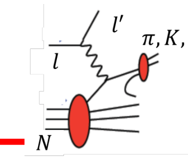




accessing transversity in SIDIS

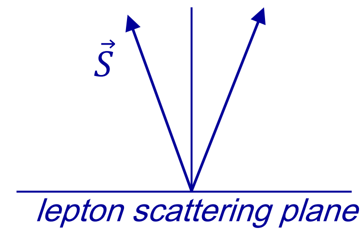
recent experimental developments

Λ / $\bar{\Lambda}$ polarisation



transversity induced Lambda polarisation

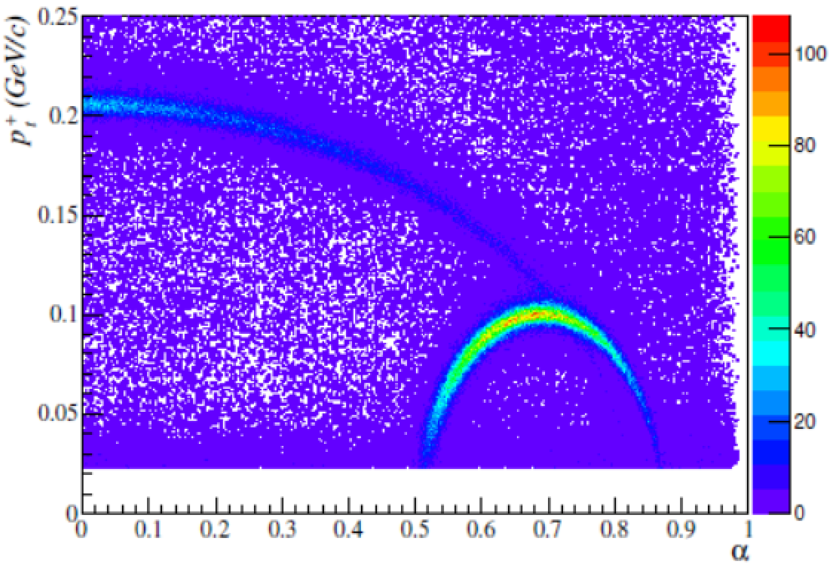
measured using the "reflected" direction of the nucleon spin i.e. the transverse polarisation of the struck quark if transversity is different from zero

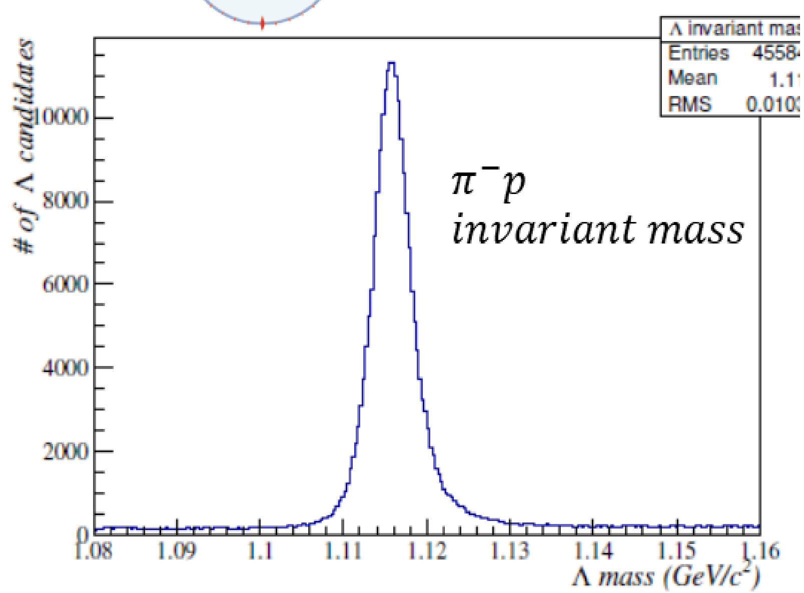


completely unknown

$$P_\Lambda = \frac{\sum_q e_q^2\, h_1^q\, H_1^{\Lambda/q}}{\sum_q e_q^2\, f_1^q\, D_1^{\Lambda/q}}$$

COMPASS 2010 proton data
preliminary

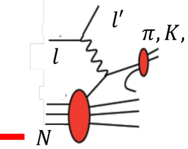




$Q^2 > 1\ (\mathrm{GeV/c})^2$

~300k Λ
~150k $\bar{\Lambda}$

Λ / $\bar{\Lambda}$ polarisation



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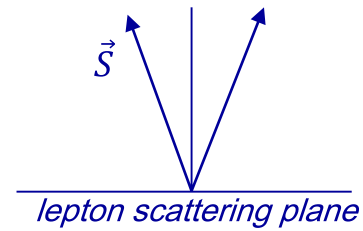
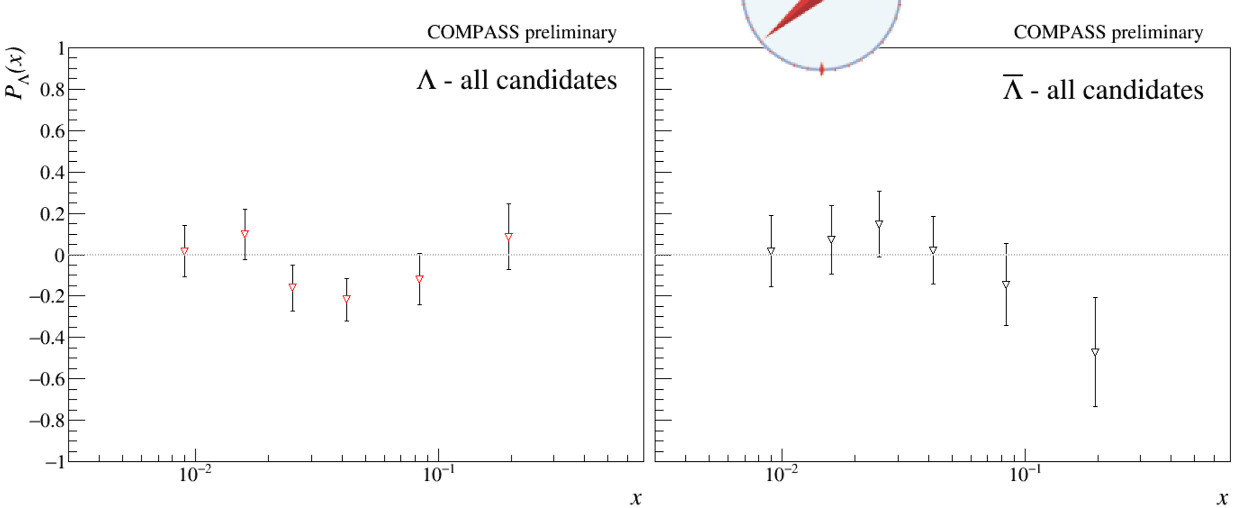


$$P_\Lambda = \frac{\sum_q e_q^2 \, h_1^q \, H_1^{\Lambda/q}}{\sum_q e_q^2 \, f_1^q \, D_1^{\Lambda/q}}$$

completely unknown

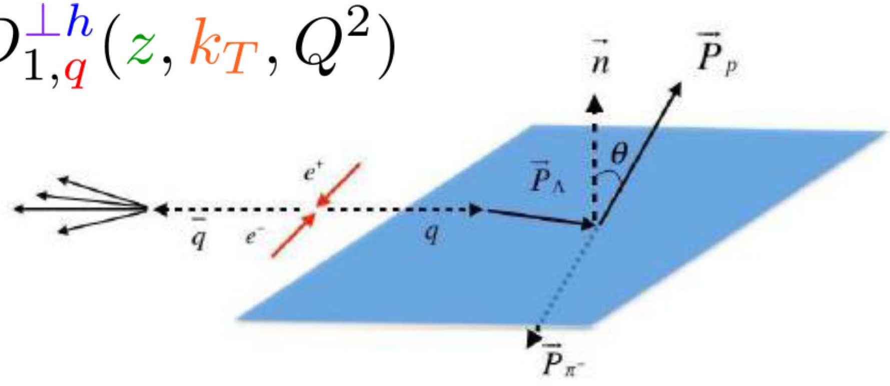


statistically limited
still the only existing measurement

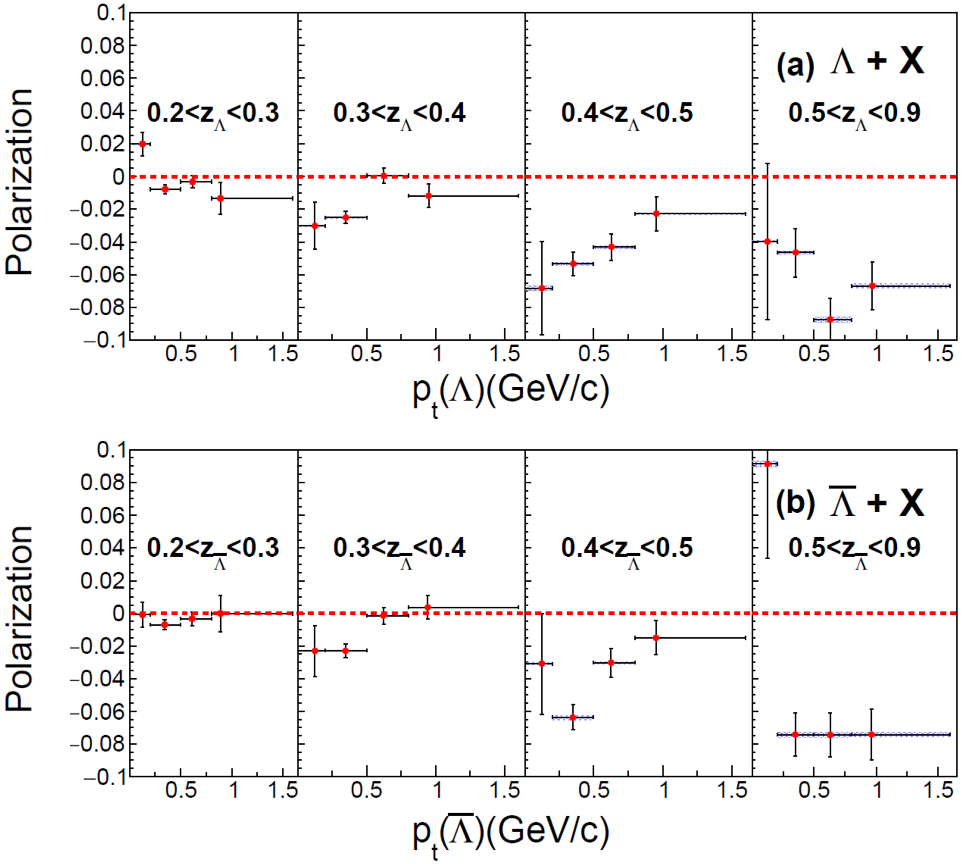
with different assumptions,this measurement can give information either on h_1^s or on $H_1^{\Lambda/q}/D_1^{\Lambda/q}$

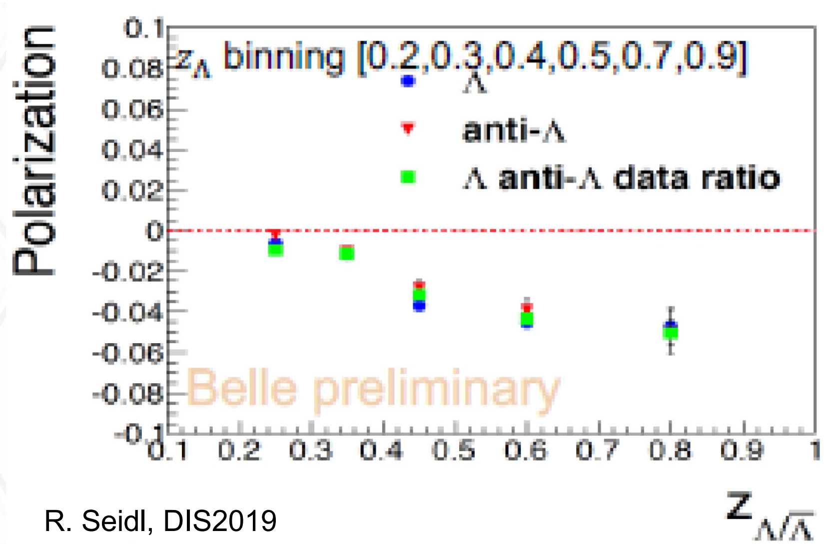
Λ / $\bar{\Lambda}$ polarisation in e^+e^-

$$D_{1,q}^{\perp h}(z, k_T, Q^2)$$



PRL122 2019

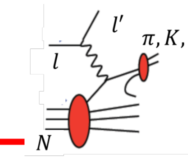




R. Seidl, DIS2019

Collins difference asymmetries

Collins difference asymmetries



namely
the asymmetries in the difference of opposite charge hadrons distributions

- **they have been proposed a long time ago**

  L.L. Frankfurt et al., PLB 230 141 (1989) 141
  E. Christova and E. Leader, NPB 607 (2001) 369
  A.N. Sissakian, O.Yu. Shevchenko and O.N. Ivanov, PRD 73, (2006) 094026 ….

- they are in the COMPASS Proposal (1996), for SIDIS off longitudinally and transversely polarised protons and deuterons

- they have been measured in SIDIS off longitudinally polarised deuterons

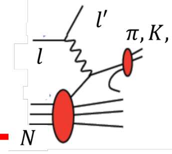
  M. Alekseev et al [COMAPSS Coll] PLB 660 (2008) 458, HERMES

- they were never measured in SIDIS off transversely polarised nucleons

first extraction from the COMPASS measurement of the
Collins asymmetries for h^+ and h^+
in SIDIS off transversely polarised protons and deuterons

V. Barone et al., PRD99 (2019)

Collins difference asymmetries



cross-sections for hadrons (pions) of opposite charge ($\pm$)
transversely polarised nucleons

$$\sigma_t^{\pm}(\Phi_C) = \sigma_{0,t}^{\pm} + f\, P_T\, D_{NN}\ \sigma_{C,t}^{\pm} \sin\Phi_C + \cdots \qquad t = p, d$$

- **Collins asymmetries** $A_{C,t}^{\pm} = \dfrac{\sigma_{C,t}^{\pm}}{\sigma_{0,t}^{\pm}}$

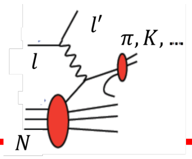
- **difference asymmetries**
  (two slightly different definitions)
  $A_{D,t} = \dfrac{\sigma_{C,t}^{+} - \sigma_{C,t}^{-}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}$ $\qquad A'_{D,t} = \dfrac{\sigma_{C,t}^{+} - \sigma_{C,t}^{-}}{\sigma_{0,t}^{+} - \sigma_{0,t}^{-}}$

if the acceptances for h^+ and h^+ are the same, they can be obtained from the measured Collins asymmetries:

$$A_{D,t} = \frac{\sigma_{0,t}^{+}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}\ A_{C,t}^{+} - \frac{\sigma_{0,t}^{-}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}\ A_{C,t}^{-} \qquad \sigma_{0,t}^{\pm} \sim\ N_t^{\pm} \sim 1/\mathrm{var}(A_{C,t}^{\pm})$$

$$= \frac{\mathrm{var}(A_{C,t}^{-})}{\mathrm{var}(A_{C,t}^{+}) + \mathrm{var}(A_{C,t}^{+})} A_{C,t}^{+} - \frac{\mathrm{var}(A_{C,t}^{+})}{\mathrm{var}(A_{C,t}^{+}) + \mathrm{var}(A_{C,t}^{+})} A_{C,t}^{-}$$

Collins difference asymmetries



in terms of PDFs

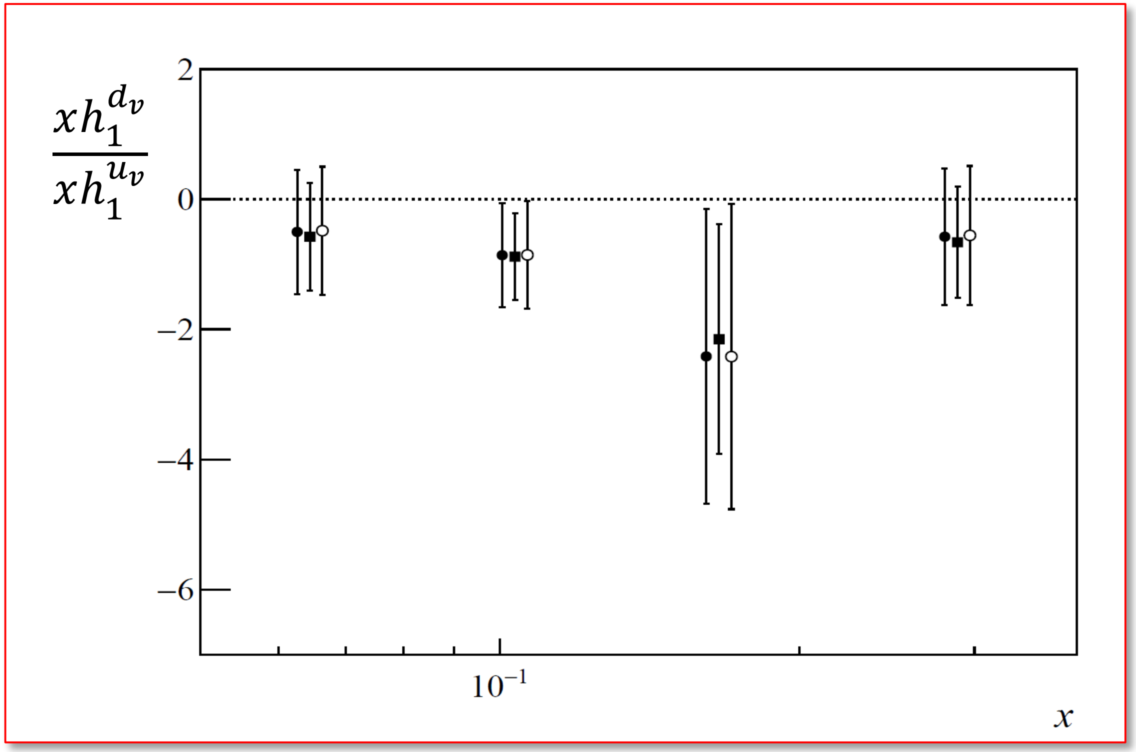
$$\frac{A_{D,d}}{A_{D,p}} = 3\,\frac{\sigma^+_{0,p} + \sigma^-_{0,p}}{\sigma^+_{0,d} + \sigma^-_{0,d}}\,\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}} \qquad \frac{A'_{D,d}}{A'_{D,p}} = \frac{4f_1^{u_v} - f_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}\,\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}}$$

from standard PDFs and FFs parametrisations

→ they allow to extract $xh_1^{d_v}/xh_1^{d_v}$ without knowing H_1

- ● from A_D
- ■ from A'_D
- ○ from $xh_1^{d_v}$ and $xh_1^{u_v}$

A. Martin, F.B., V. Barone
PRD91 2015



Collins difference asymmetries

in terms of PDFs

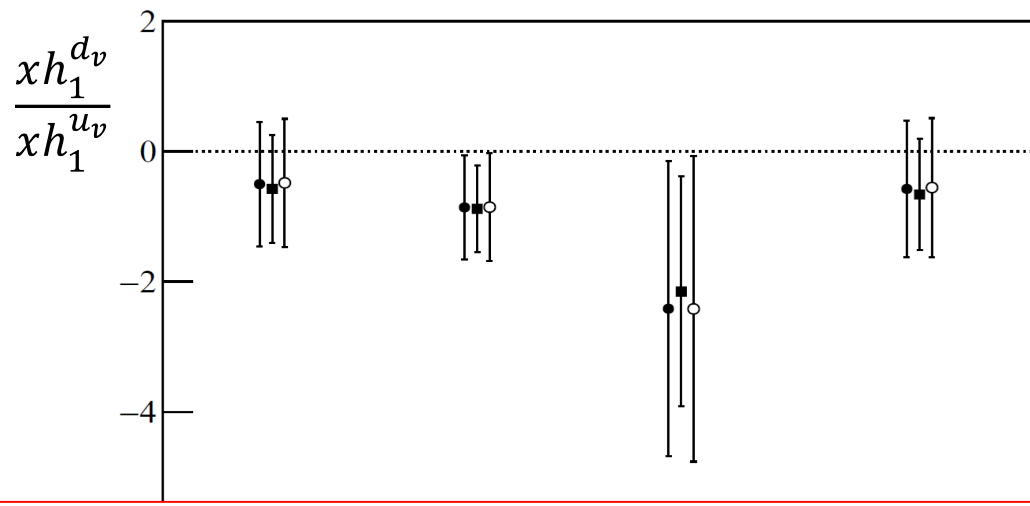
$$\frac{A_{D,d}}{A_{D,p}} = 3\,\frac{\sigma^+_{0,p}+\sigma^-_{0,p}}{\sigma^+_{0,d}+\sigma^-_{0,d}}\;\frac{h_1^{u_v}+h_1^{d_v}}{4h_1^{u_v}-h_1^{d_v}} \qquad \frac{A'_{D,d}}{A'_{D,p}} = \frac{4f_1^{u_v}-f_1^{d_v}}{f_1^{u_v}+f_1^{d_v}}\;\frac{h_1^{u_v}+h_1^{d_v}}{4h_1^{u_v}-h_1^{d_v}}$$

from standard PDFs and FFs parametrisations

→ they allow to extract $xh_1^{d_v}/xh_1^{u_v}$ without knowing H_1

- ● from A_D
- ■ from A'_D
- ○ from $xh_1^{d_v}$ and $xh_1^{u_v}$

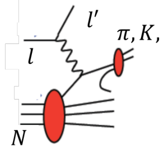
A. Martin, F.B., V. Barone
PRD91 2015



ratios $h_1^{d_v}/\,h_1^{u_v}$ essentially identical with ratios obtained from standard transversity extractions using SIDIS and e^+e^- data

nice cross-check: everything is consistent

Longitudinal double-spin asymmetries of $e^{\pm}$ on p and d



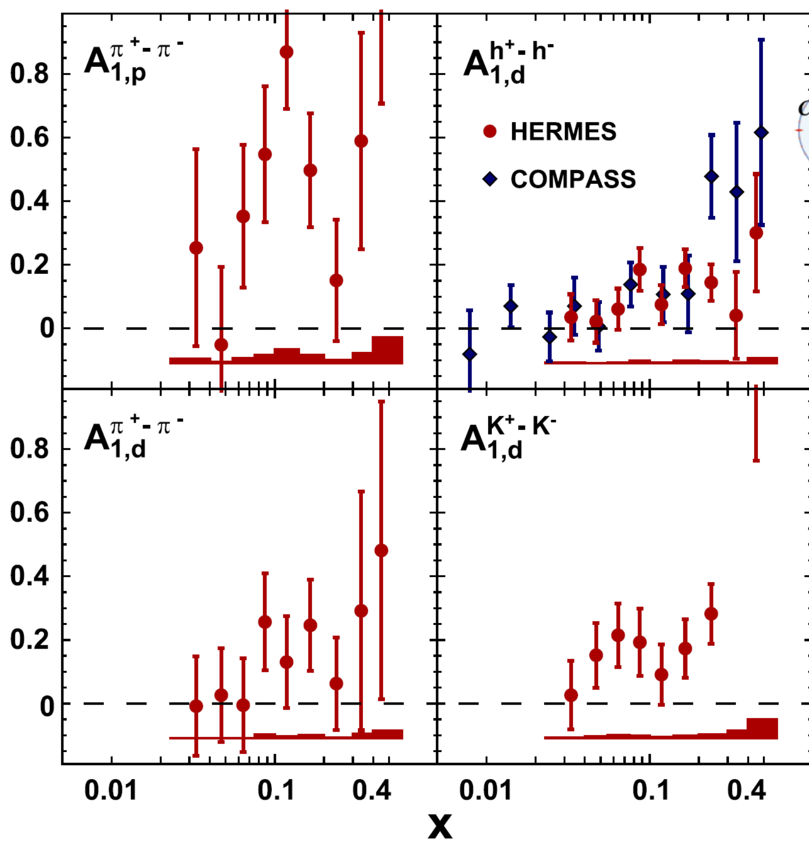
$$A_1^{h^+-h^-}(x) \equiv \frac{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) - (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})}{(\sigma_{1/2}^{h^+} - \sigma_{1/2}^{h^-}) + (\sigma_{3/2}^{h^+} - \sigma_{3/2}^{h^-})}$$

in terms of PDFs

$$A_{1,d}^{h^+-h^-} \stackrel{\mathrm{LO\,LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}$$

$$A_{1,p}^{h^+-h^-} \stackrel{\mathrm{LO\,LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

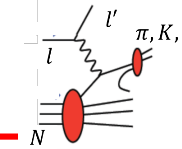
hermes PRD99 2019



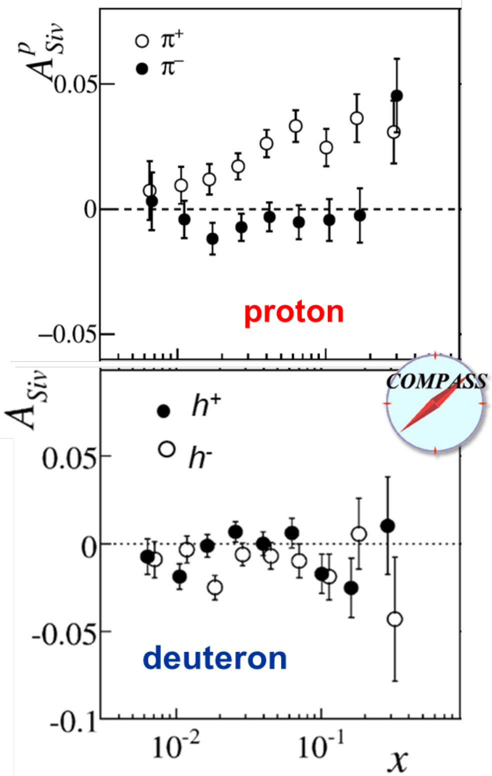
COMPASS PLB660 2008

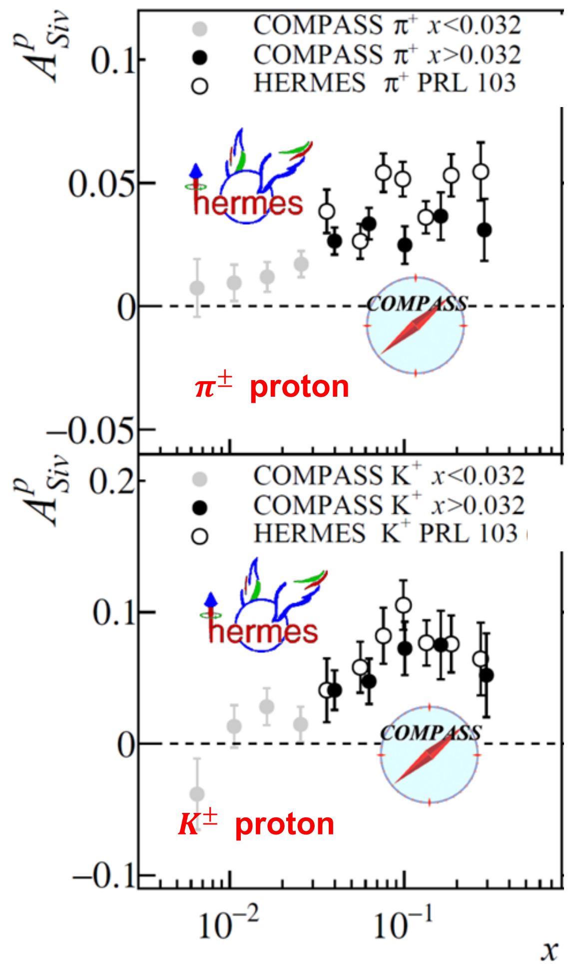
the Sivers function

Sivers asymmetry $\sim f_{1T}^{\perp} \otimes D_1$



as in the Collins case, since 2005 evidence for non-zero asymmetry on proton





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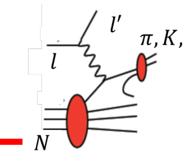

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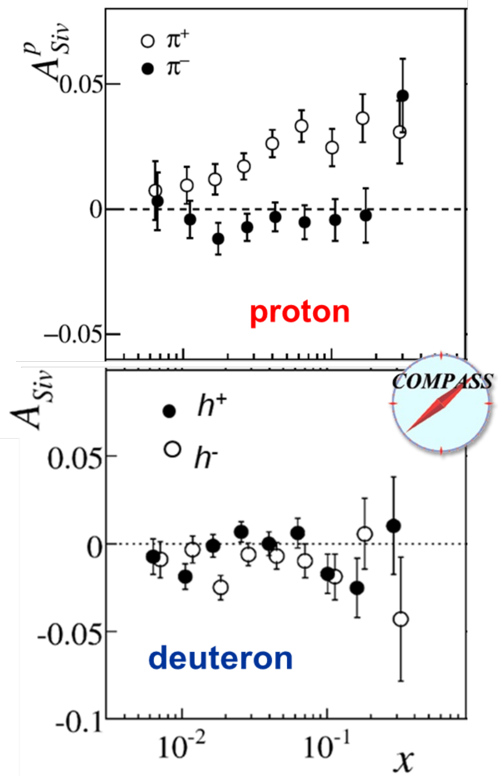
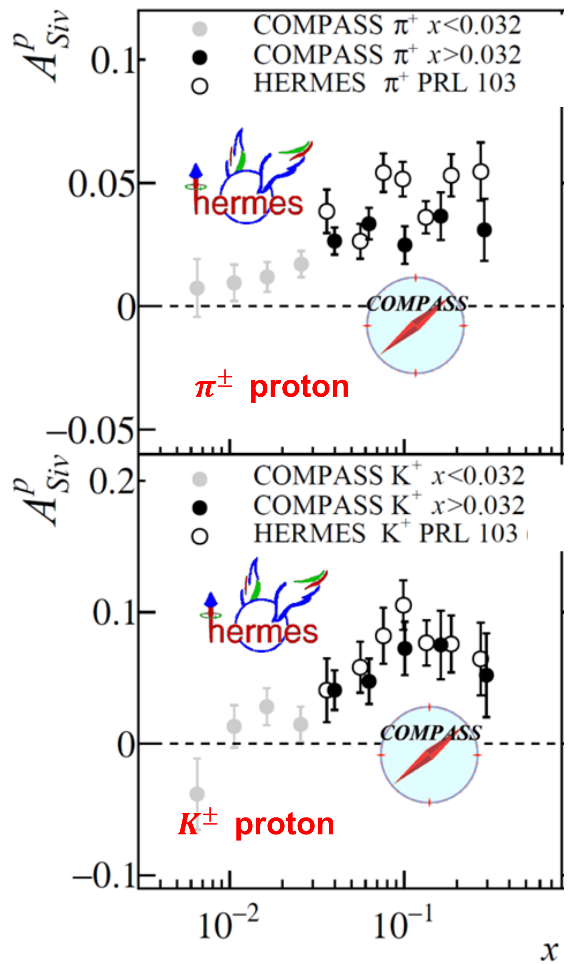
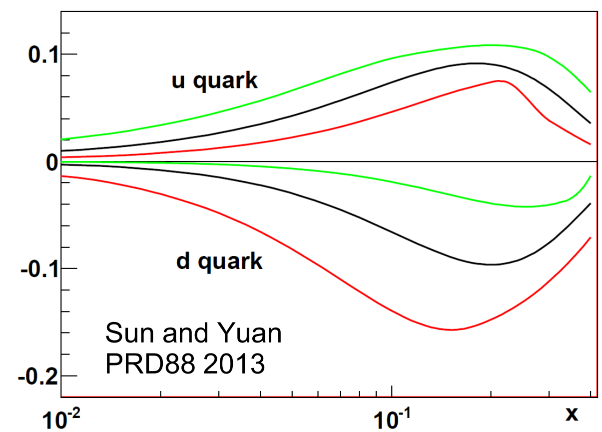
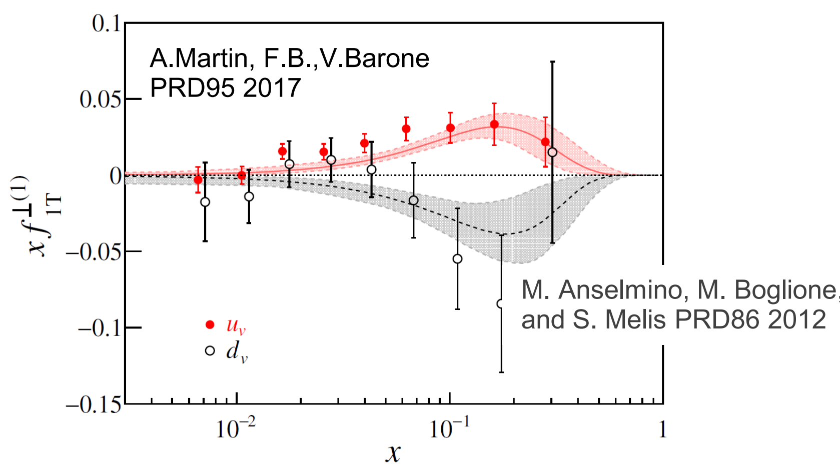
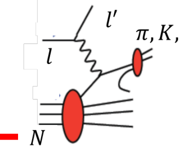


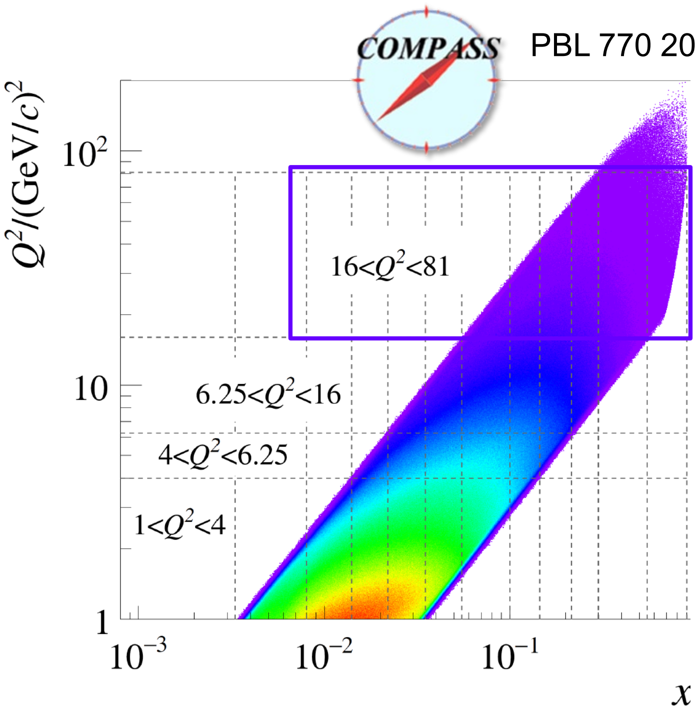






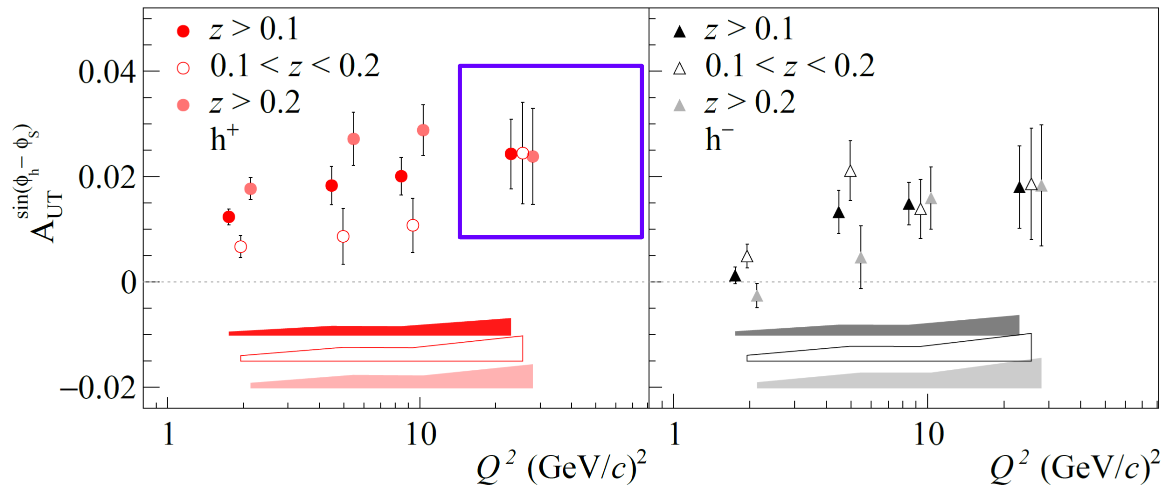
Sivers asymmetry recent results



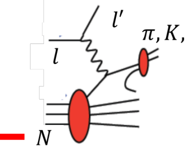


PBL 770 2017, multiD analysis **proton**

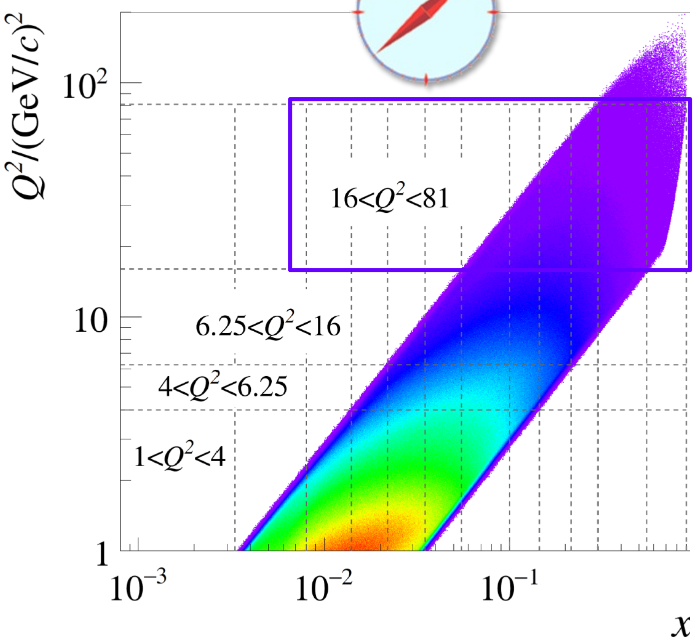
~ same x, Q^2 range as in the COMPASS Drell-Yan measurement



Sivers asymmetry   recent results



PBL 770 2017, multiD analysis **proton**



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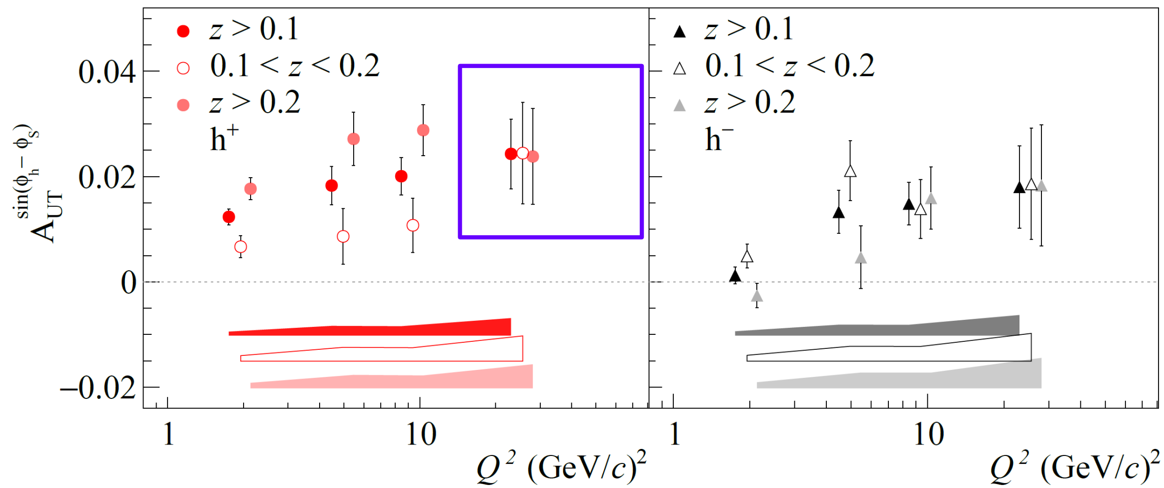
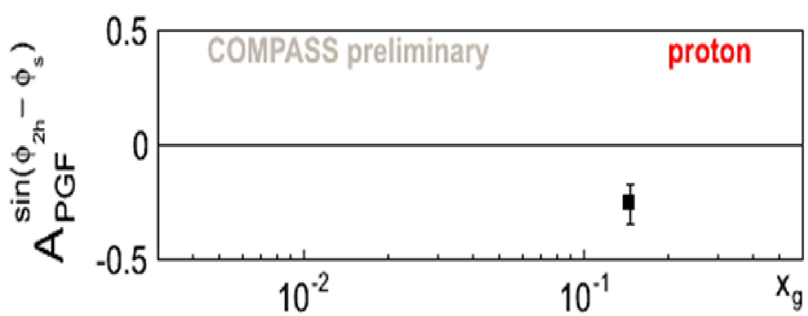
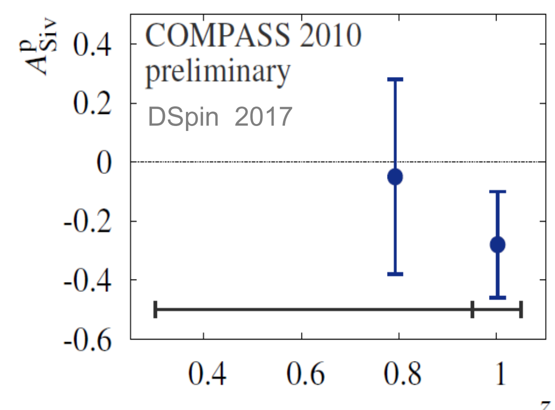


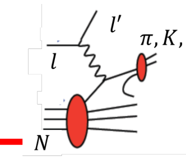
gluon Sivers related TSAs: high P_T hadron pairs J/Ψ production

PLB772 2017



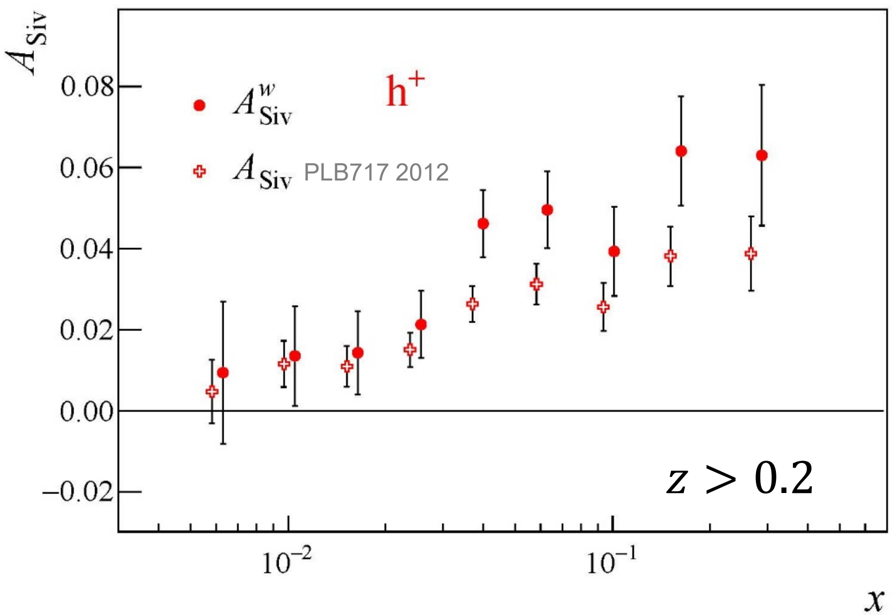


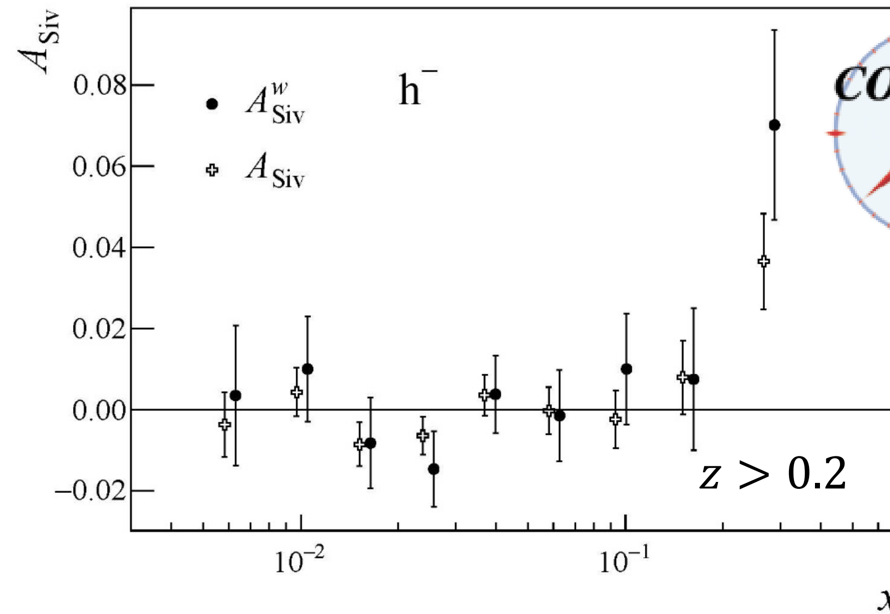
the P_T/zM weighted Sivers asymmetry



more results in NPB 940 (2019) 34

$$A^w_{Siv}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\widetilde{D}_1^q}{\sum_q e_q^2 x f_1^q(x)\widetilde{D}_1^q} \qquad \widetilde{D}_1^q = \int_{z_{min}}^{z_{max}} dz D_1^q(z)$$





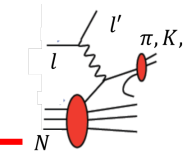
the trends of the weighted and unweighted asymmetries are similar both for positive and negative hadrons

positive hadrons: asymmetry clearly different from zero, in particular at large x

assuming u-dominance, $A^{w,+}_{Siv}(x) \simeq 2\, f_{1T}^{\perp(1)u}(x)/f_1^u(x)$

→ first direct measurement of $f_{1T}^{\perp(1)u}(x)$

the P_T/zM weighted Sivers asymmetry



extraction of $f_{1T}^{\perp(1)}(x)$

neglecting the sea-quark Sivers distributions, it is

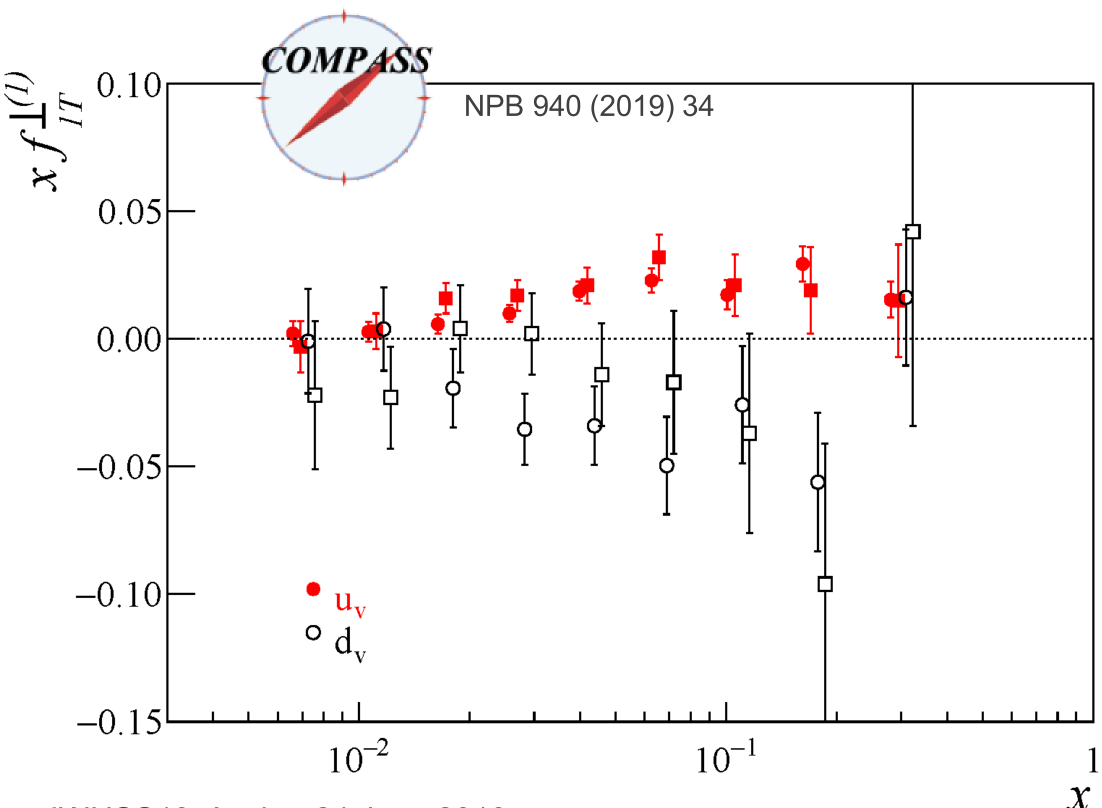
$$x f_{1T}^{\perp(1)u_v} = \frac{1}{8}\frac{\delta^+ A_{Siv}^{w,+}\widetilde{D}_1^{d,-} - \delta^- A_{Siv}^{w,-}\widetilde{D}_1^{d,+}}{\widetilde{D}_1^{u,+}\widetilde{D}_1^{d,-} - \widetilde{D}_1^{d,+}\widetilde{D}_1^{u,-}}$$

$$x f_{1T}^{\perp(1)d_v} = \frac{1}{2}\frac{\delta^- A_{Siv}^{w,-}\widetilde{D}_1^{u,+} - \delta^+ A_{Siv}^{w,+}\widetilde{D}_1^{u,-}}{\widetilde{D}_1^{u,+}\widetilde{D}_1^{d,-} - \widetilde{D}_1^{d,+}\widetilde{D}_1^{u,-}}$$

$$\widetilde{D}_1^{q,\pm} = \int_{z_{min}}^{z_{max}} dz D_1^{q,\pm}(z)$$

$$\delta^{\pm} = 9\,\Sigma_q e_q^2 x f_1^q \widetilde{D}_1^q$$

$f_1^q, \widetilde{D}_1^{q,\pm}$ from parametrisations (CTEQ5D and DSS)

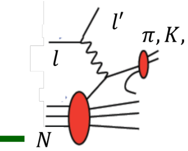


- ■ previous point-by-point extraction
  A.Martin, F.B., V.Barone, PRD95, 2017
  using pion Sivers asymmetries from the COMPASS p and d data,
  no assumptions on the Sivers sea quarks, Gaussian ansatz
- ❑ slightly different trend for $f_{1T}^{\perp(1)d_v}$, uncertainties on average larger by a factor ~1.5

the differences are mainly due to the use of the p data only and to the assumption on the sea-quarks

other non-zero signals in SIDIS

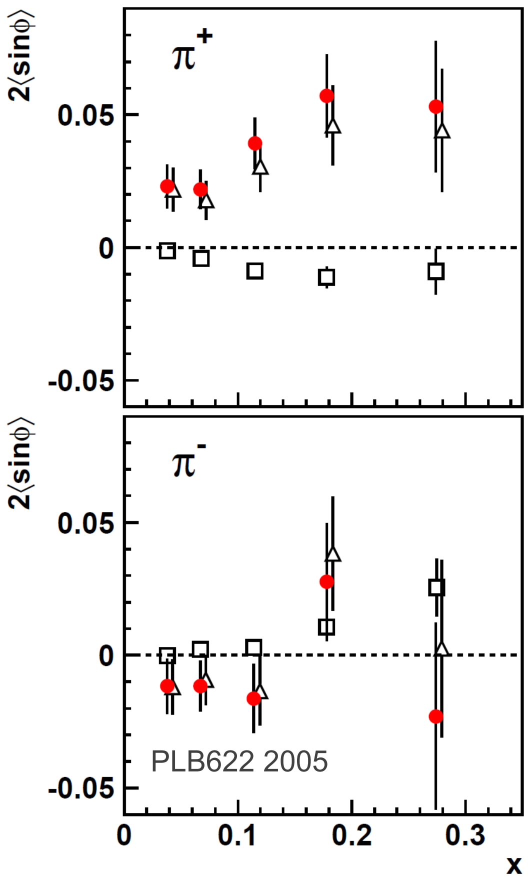
SIDIS off longitudinally polarised p



$$A_{UL}^{\sin\phi_h} = F_{UL}^{\sin\phi_h} / F_{UU}$$

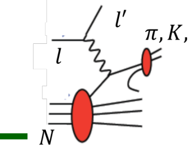
$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(x h_L^q H_{1q}^{\perp h} + \frac{M_h}{M}\, g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(x f_L^{\perp q} D_{1q}^h - \frac{M_h}{M}\, h_{1L}^{\perp q} \frac{\tilde{H}_q^h}{z}\right)\right\}$$

Q-suppressed,
different "twist" contributions



factor $\sqrt{2\,\epsilon(1+\epsilon)}$

SIDIS off longitudinally polarised p



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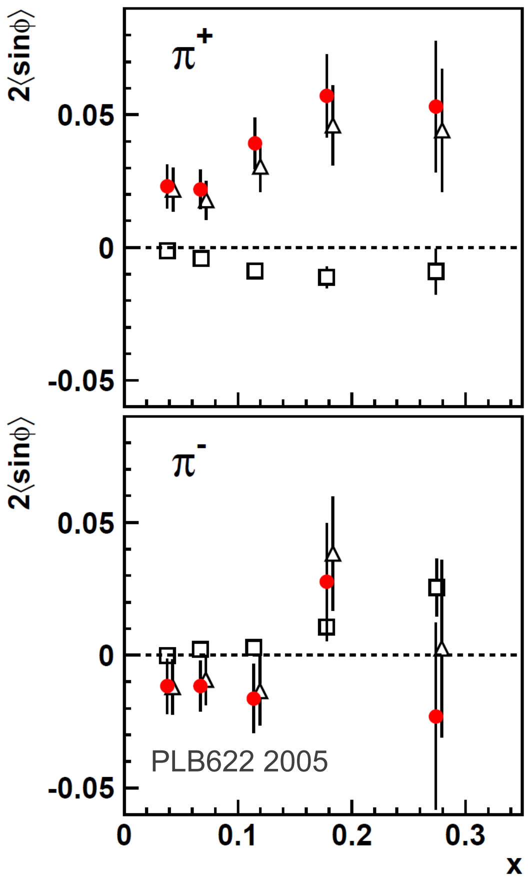
Q-suppressed,
different "twist" contributions

hermes



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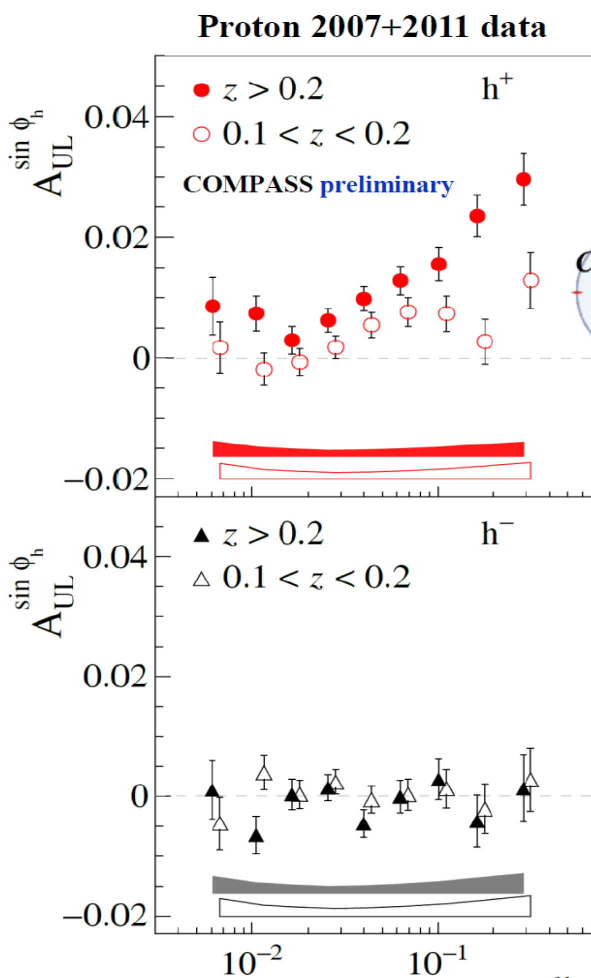


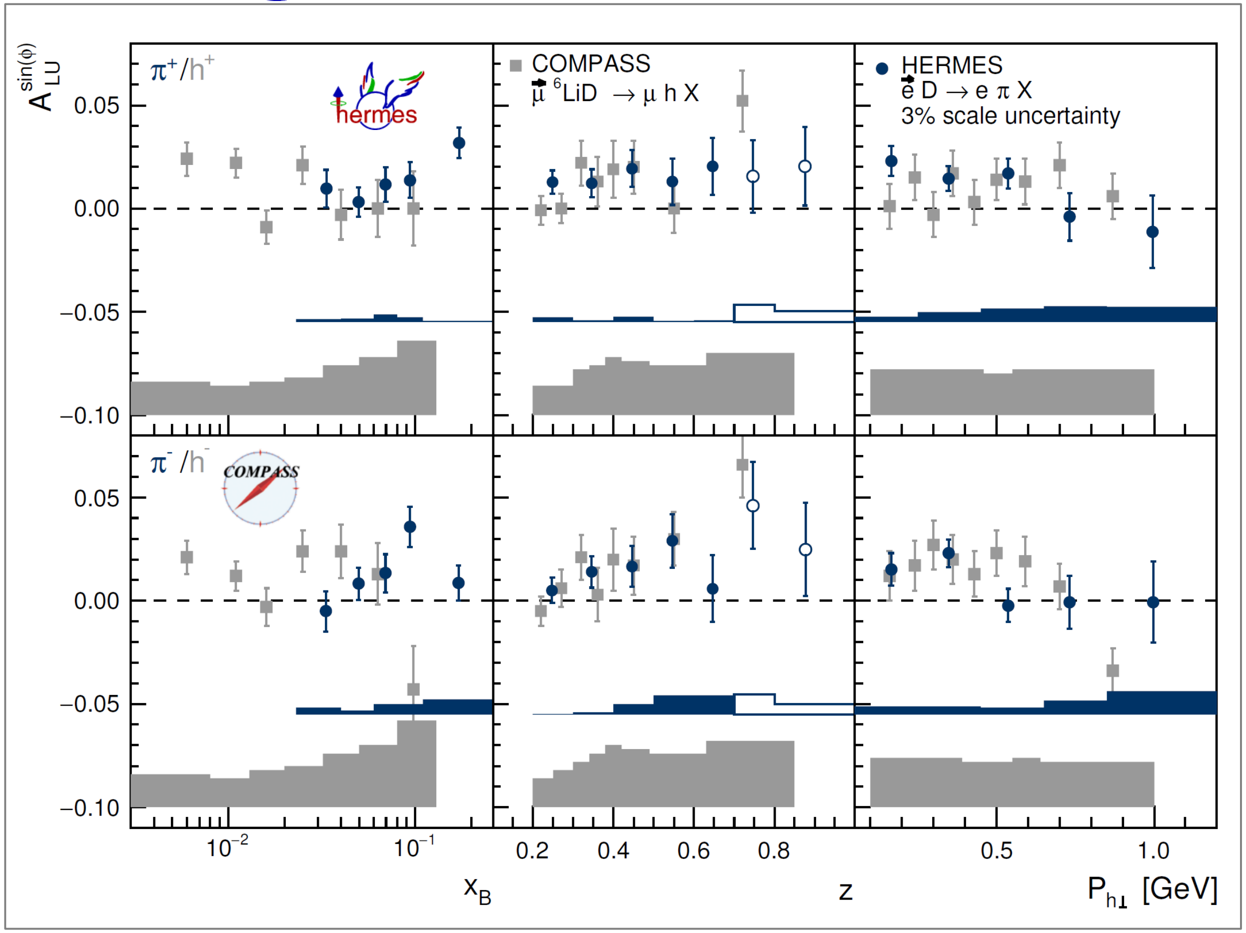
Beam helicity asymmetries

$$A_{LU}^{\sin\phi_h} = F_{LU}^{\sin\phi_h} / F_{UU}$$

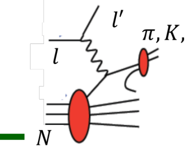
$$F_{LU}^{\sin(\phi)}(x, Q^2, z, P_{h\perp}) = \frac{2M}{Q} C\left[-\frac{\hat{h}\cdot\vec{k}_T}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{h}\cdot\vec{p}_T}{M}\left(xg^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp} \frac{\tilde{E}}{z}\right)\right]$$

Q-suppressed,
different "twist" contributions

hermes arXiv:1903.08544 2019 $\pi^{\pm}, K^{\pm}, p, \bar{p}$ on p and d



Beam helicity asymmetries



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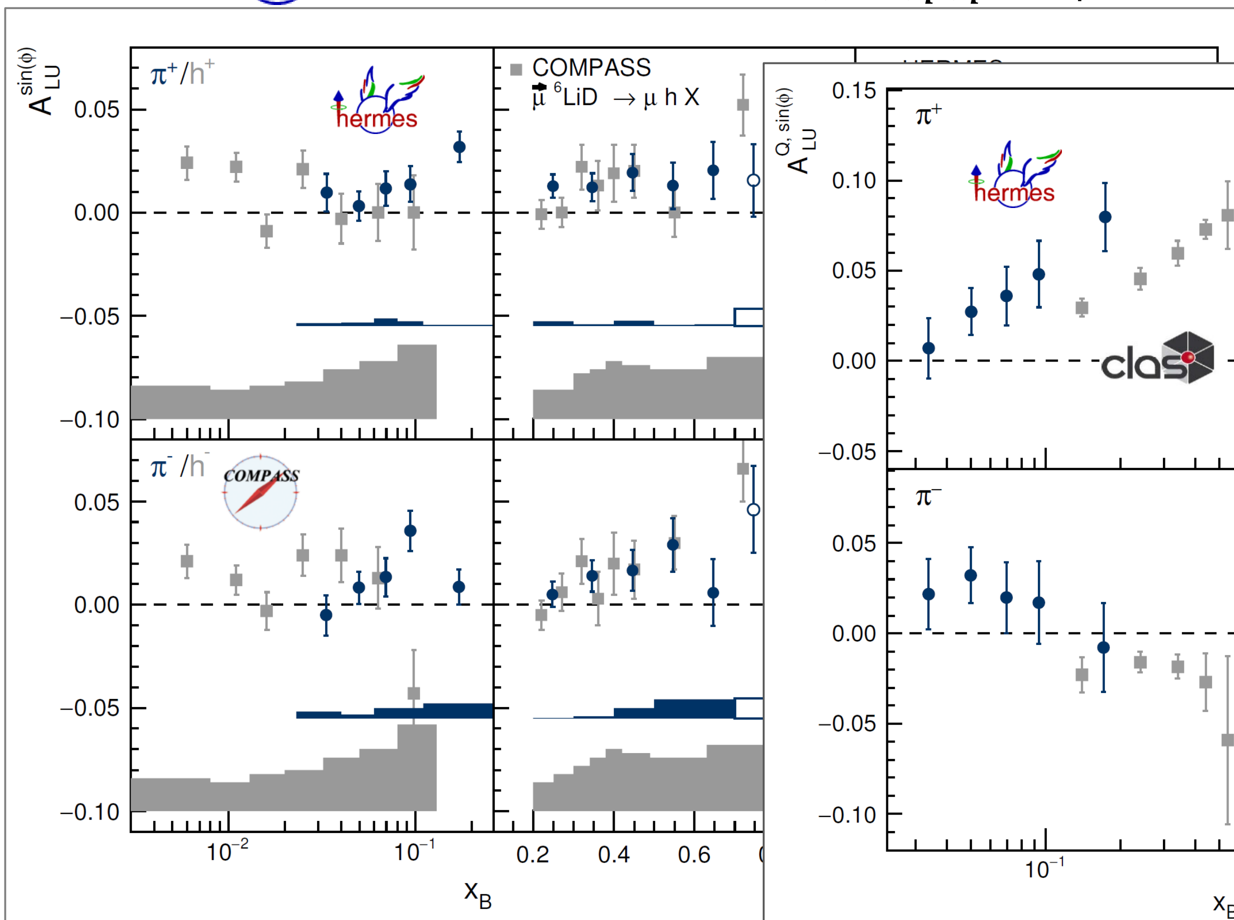
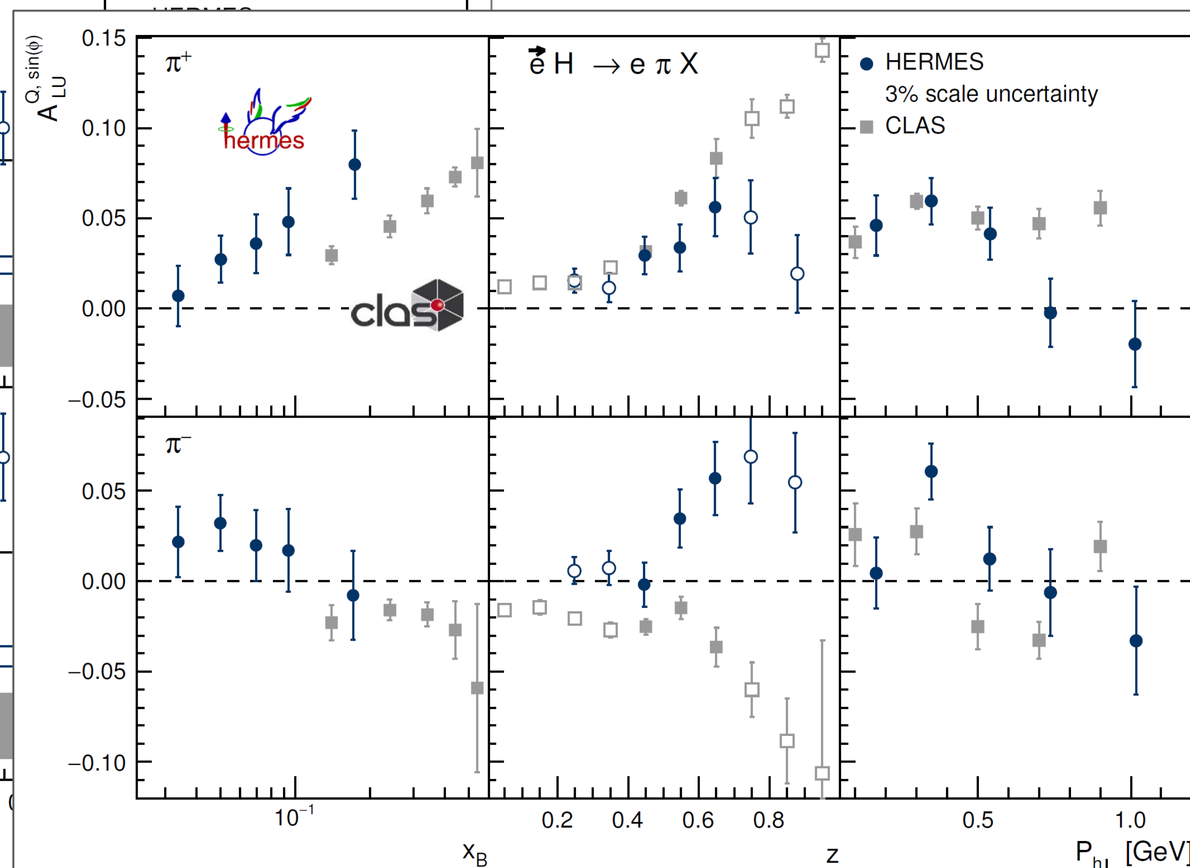
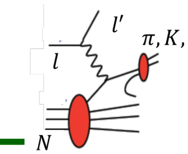
hermes arXiv:1903.08544 2019 $\pi^{\pm}, K^{\pm}, p, \bar{p}$ on p and d

Q-suppressed,
different "twist" contributions





Beam helicity asymmetries



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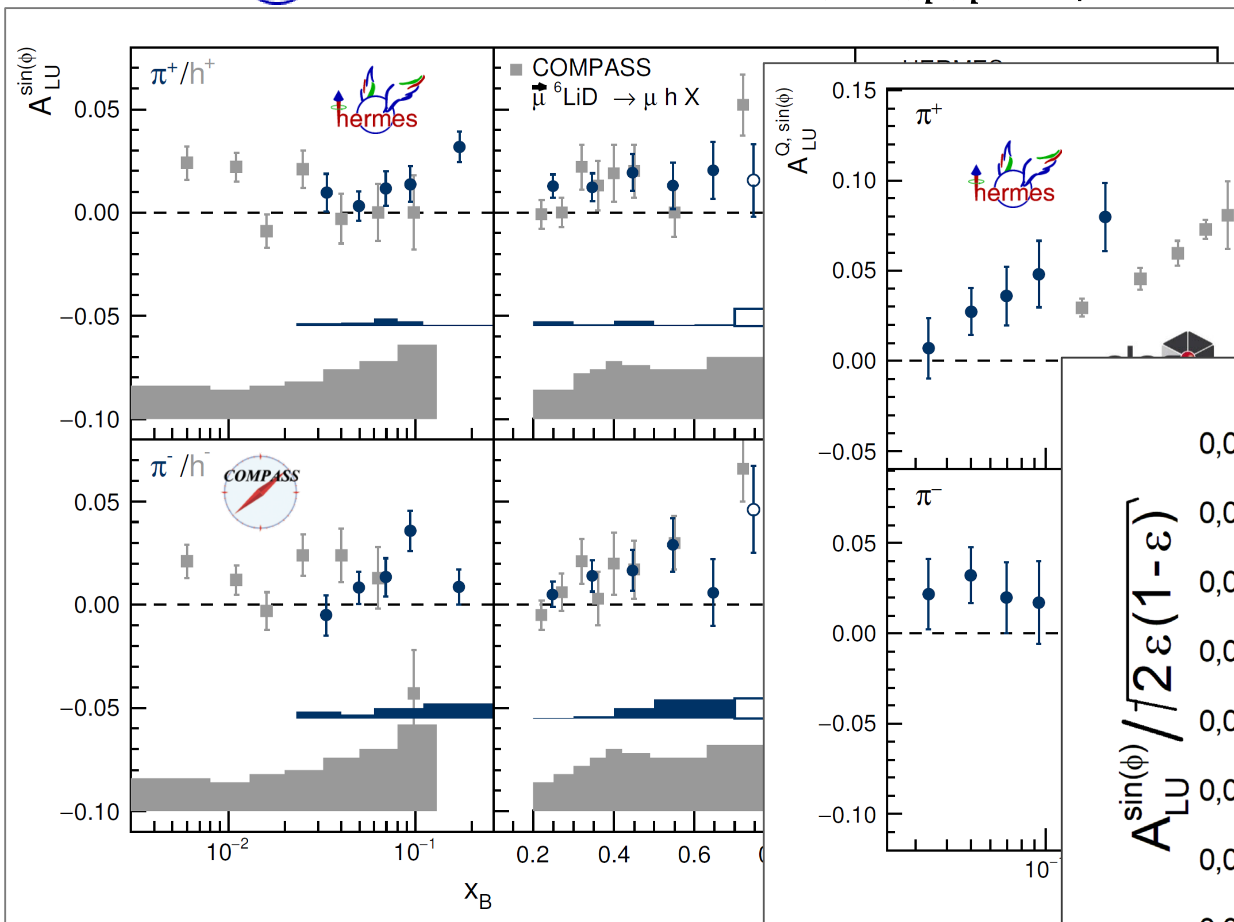
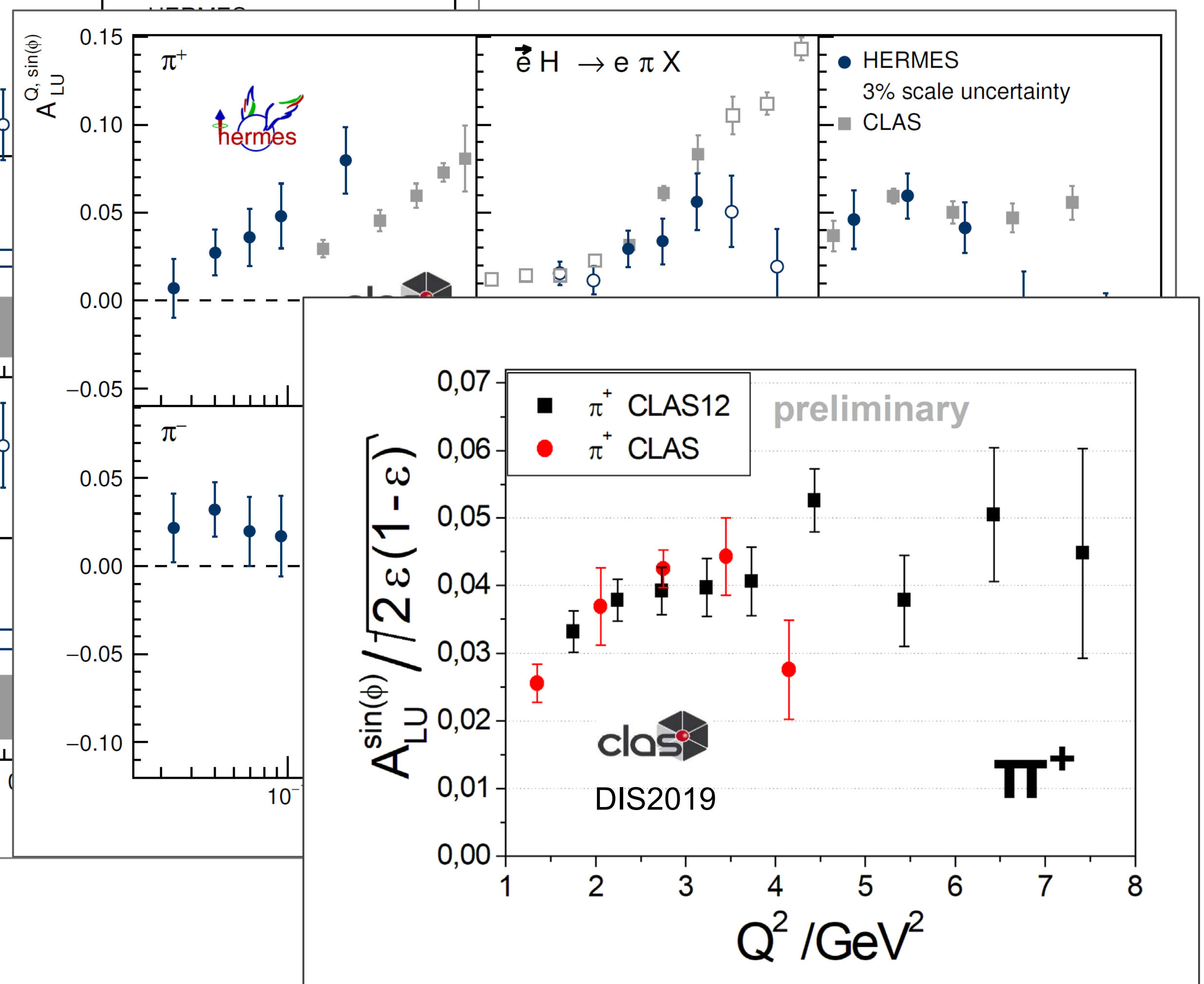
arXiv:1903.08544 2019 $\pi^\pm, K^\pm, p, \bar{p}$ on p and d

Q-suppressed,
different "twist" contributions

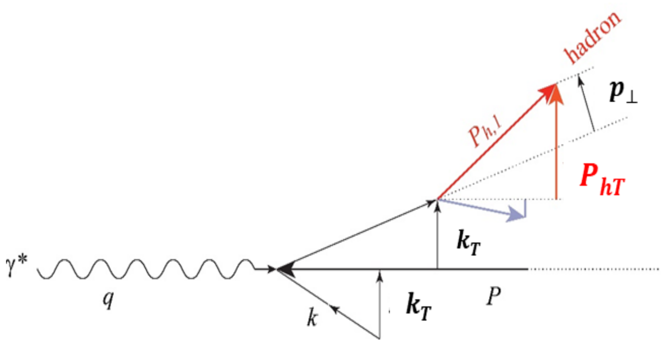




unpolarised SIDIS

unpolarised SIDIS

Relevance for TMDs:



- the cross-section dependence on P_{hT} comes from:
  - intrinsic k_T of the quarks
  - $p_\perp$ generated in the quark fragmentation

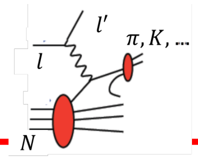
$$\langle {P_{hT}}^2 \rangle = \langle {p_\perp}^2 \rangle + z^2 \langle {k_T}^2 \rangle$$

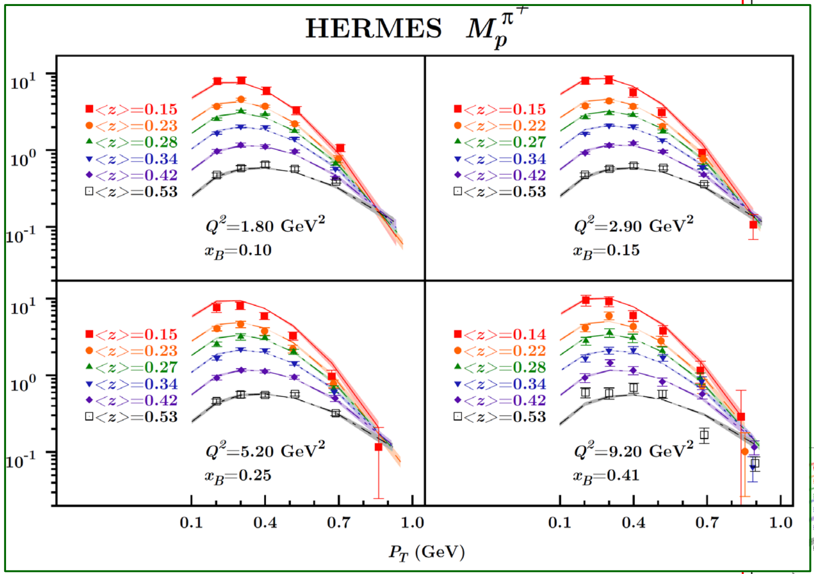
- the azimuthal modulations in the unpolarized cross-sections comes from:
  - intrinsic k_T of the quarks
  - Boer-Mulders PDF

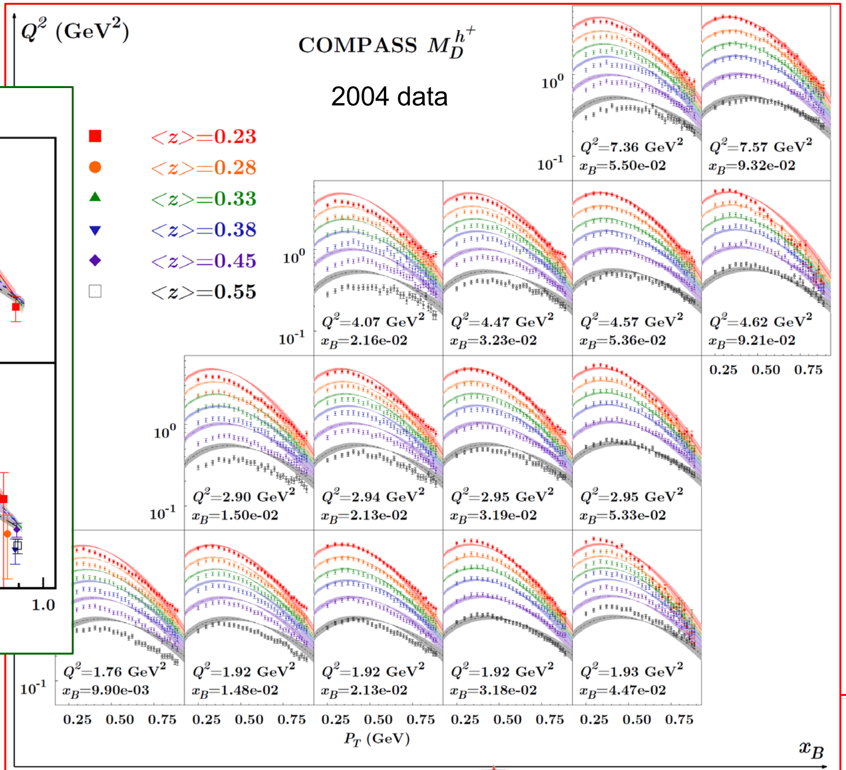
combined analysis should allow to disentangle the different effects

measured on p and/or d at Jlab, HERMES, COMPASS

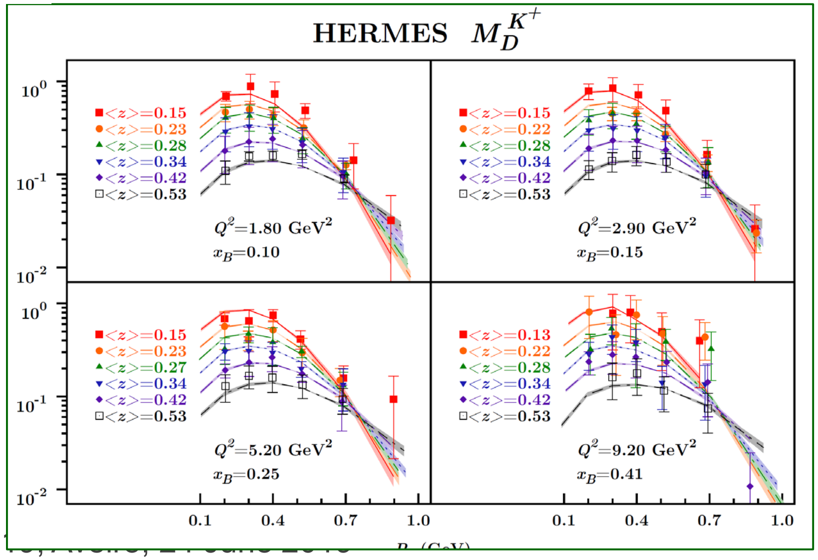
unpolarised SIDIS – P_{Th} distributions

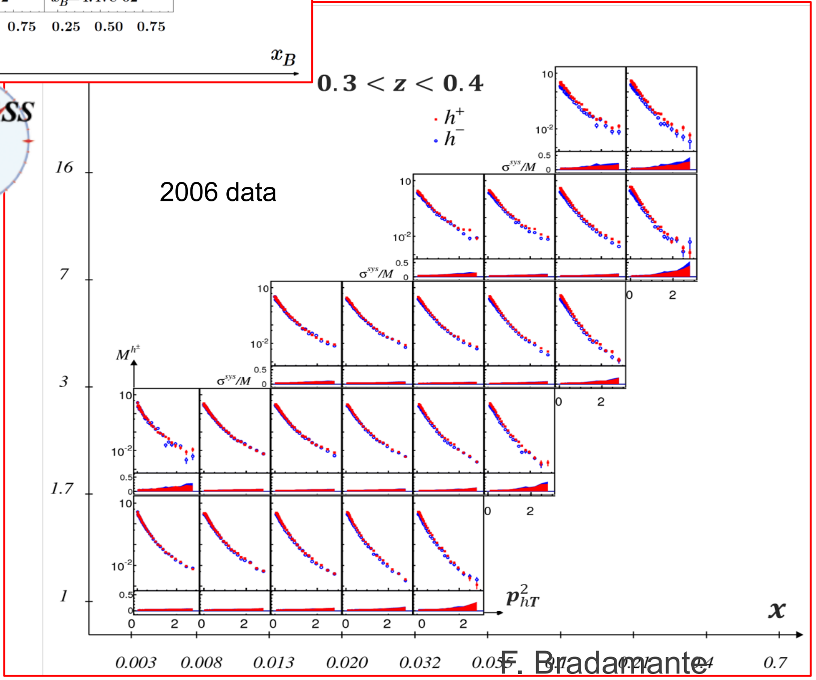






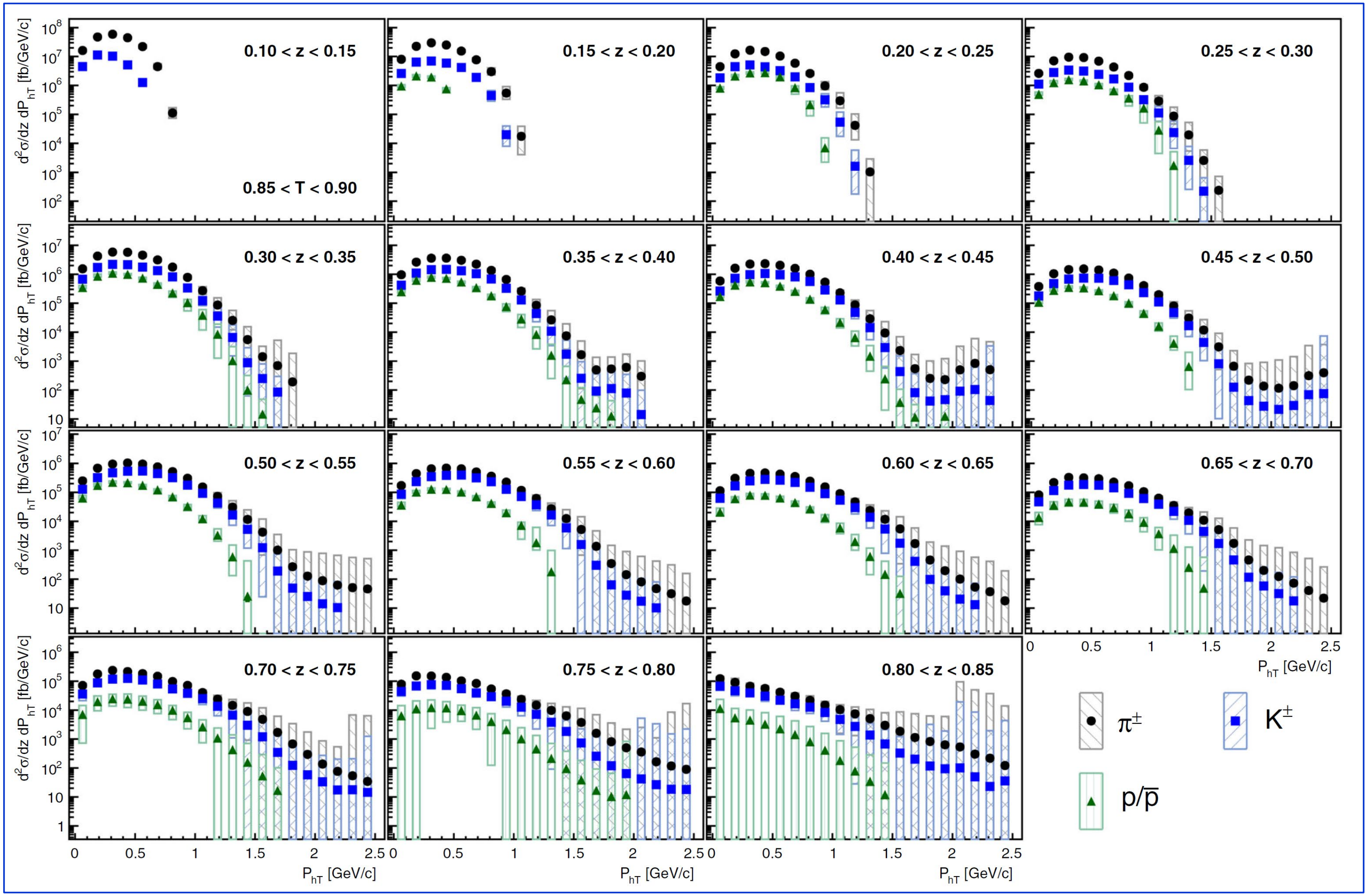
a lot of phenomenological work ...
also including Drell-Yan data





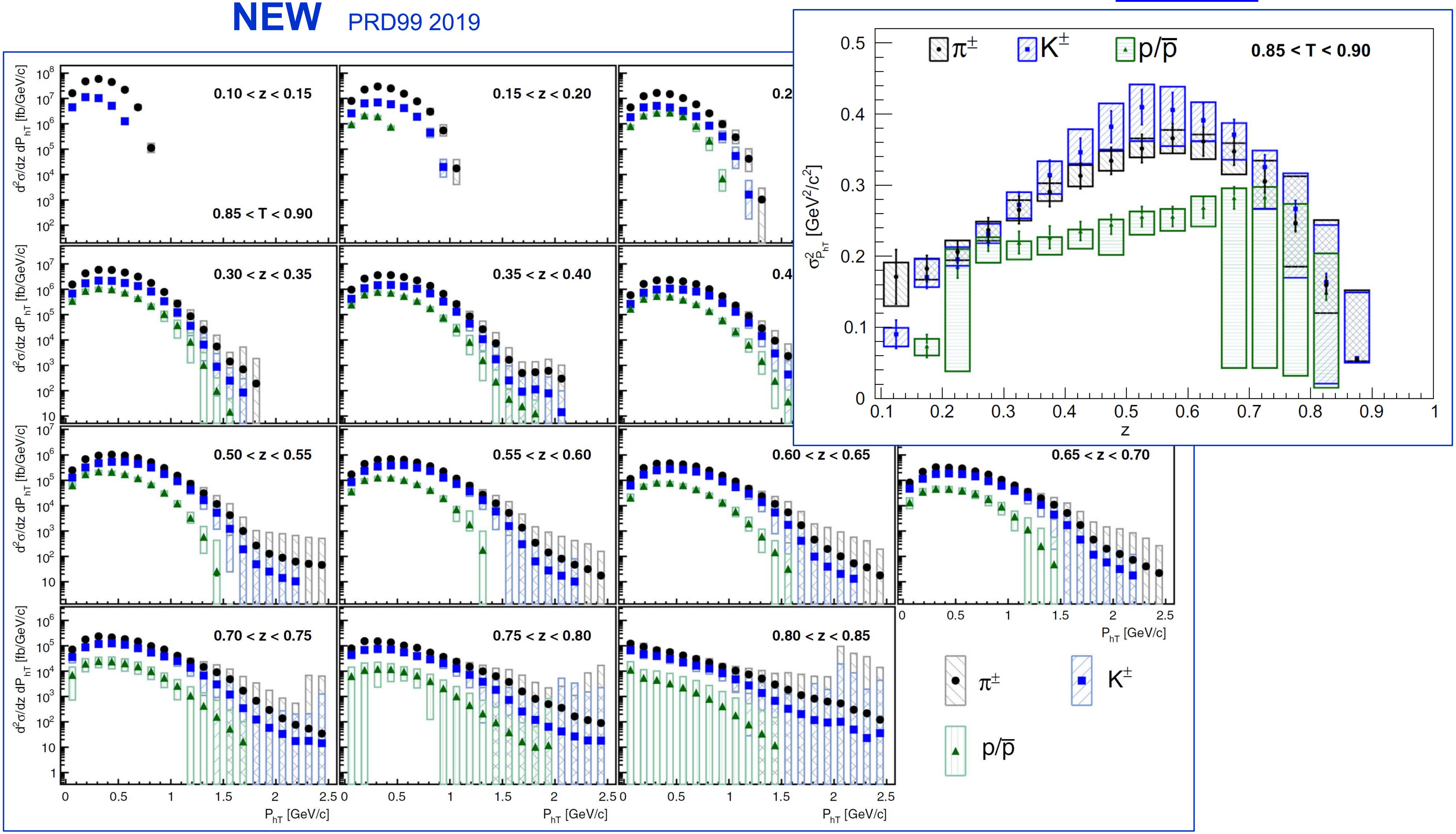
e^+e^- – P_{Th} distributions

NEW PRD99 2019



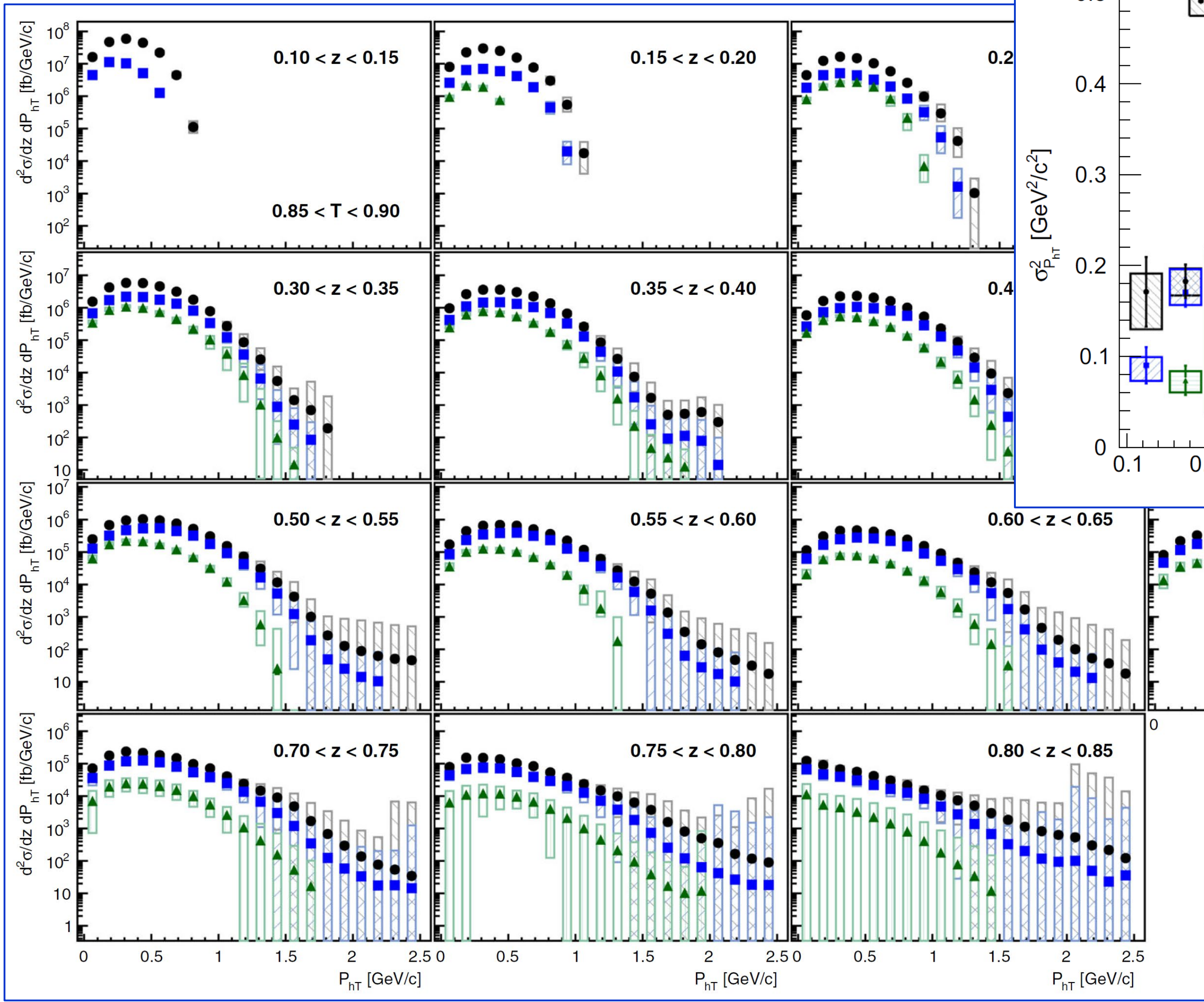
e^+e^- – P_{Th} distributions

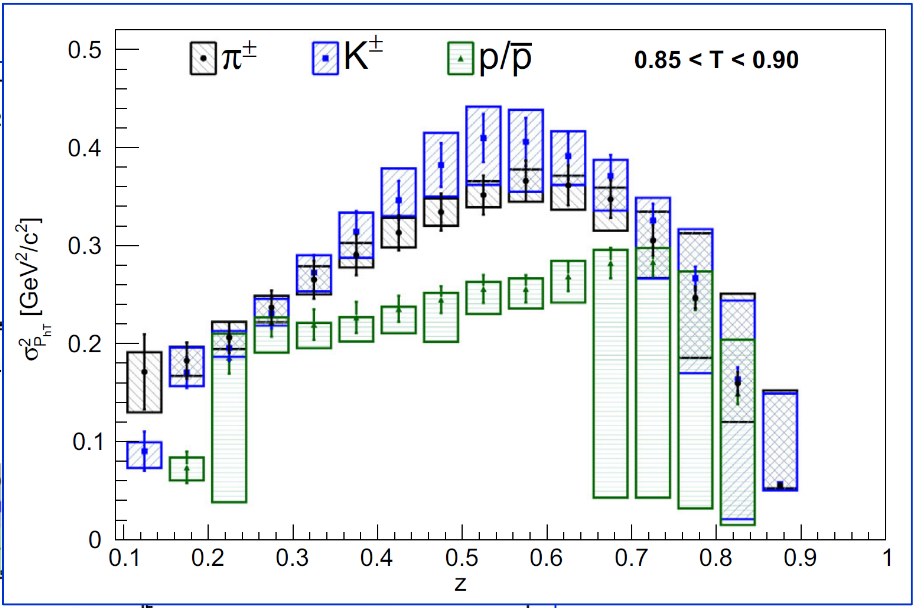
NEW PRD99 2019

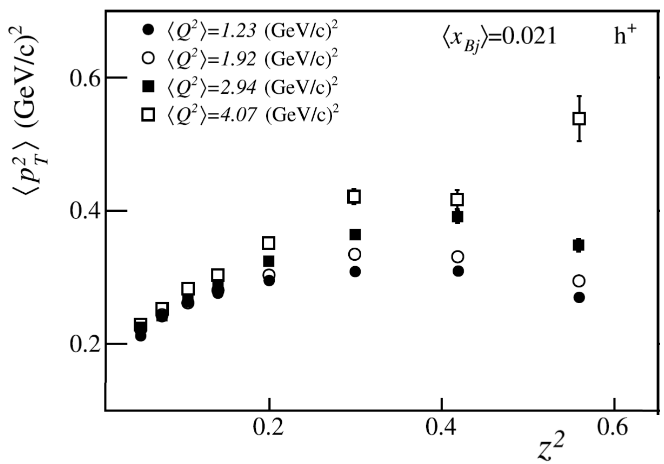


e^+e^- — P_{Th} distributions

NEW PRD99 2019

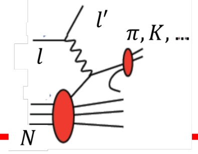




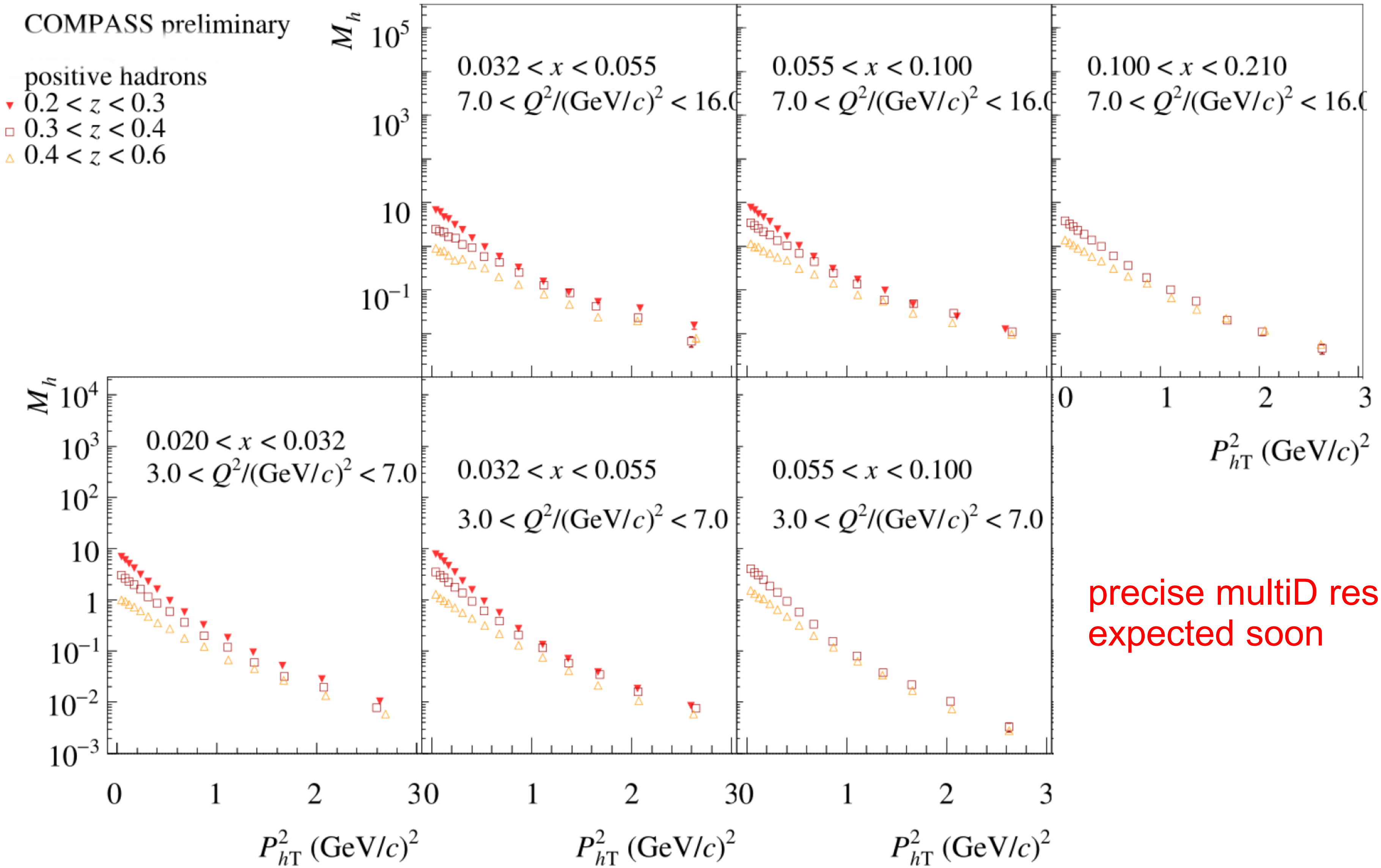


COMPASS EPJC73 2013

unpolarised SIDIS – P_{Th} distributions



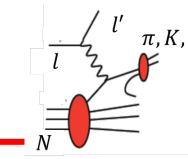
new: preliminary results from COMPASS
proton data 2016-2017

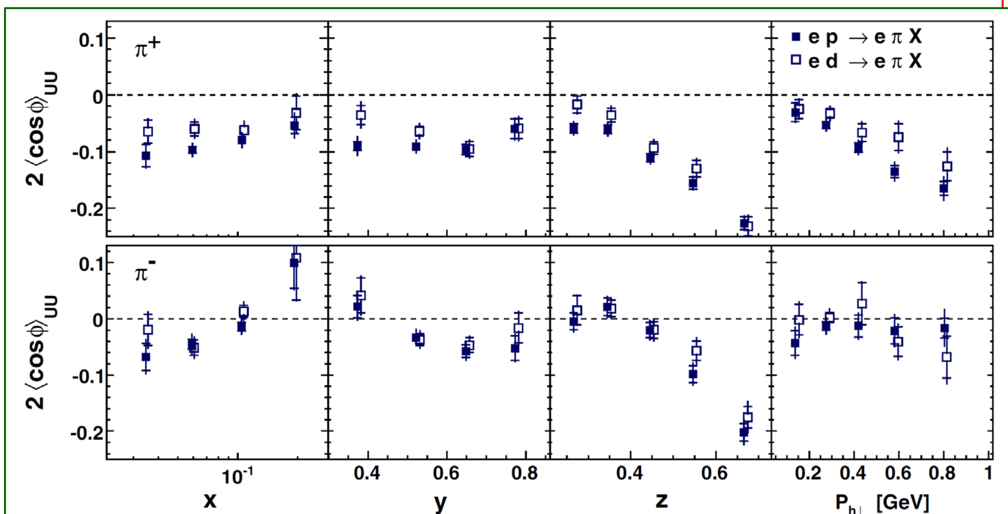


precise multiD results
expected soon

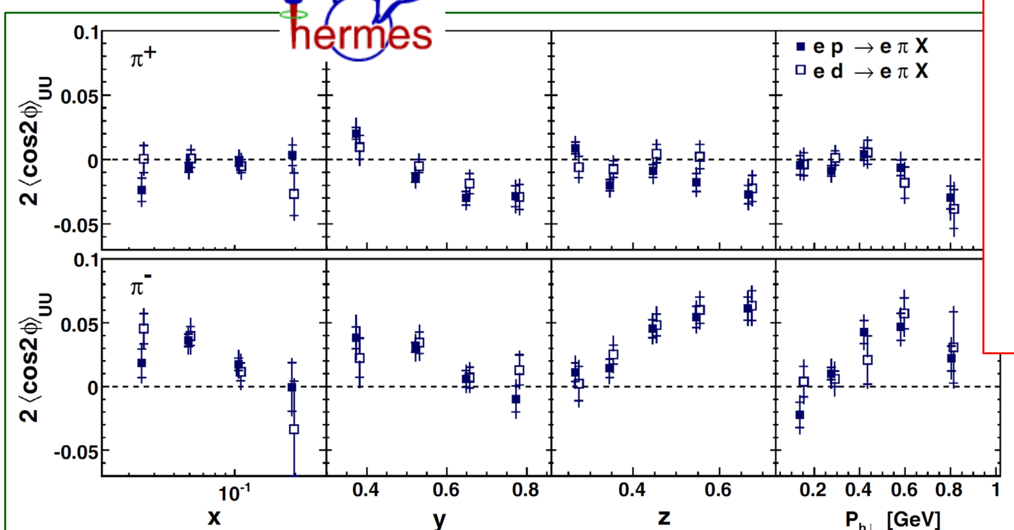
unpolarised SIDIS – azimuthal asymmetries

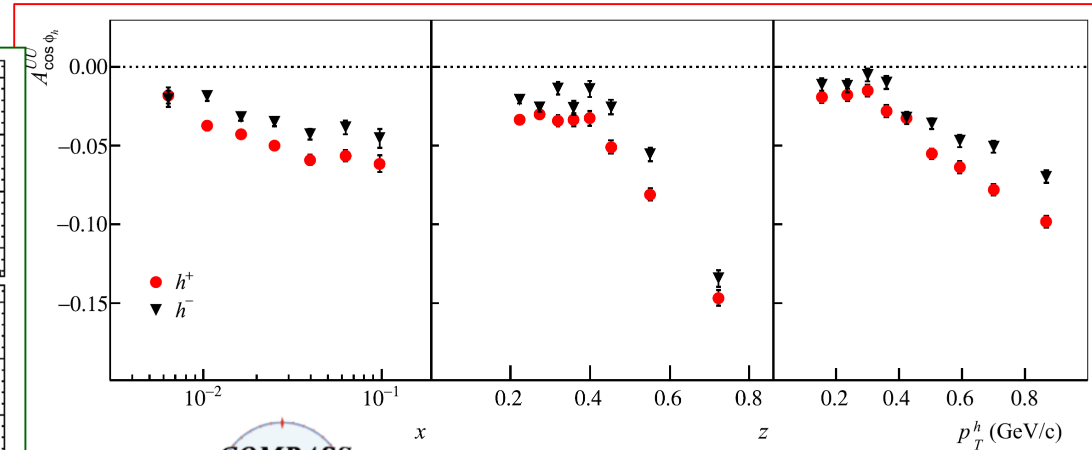
unpolarised SIDIS – azimuthal asymmetries



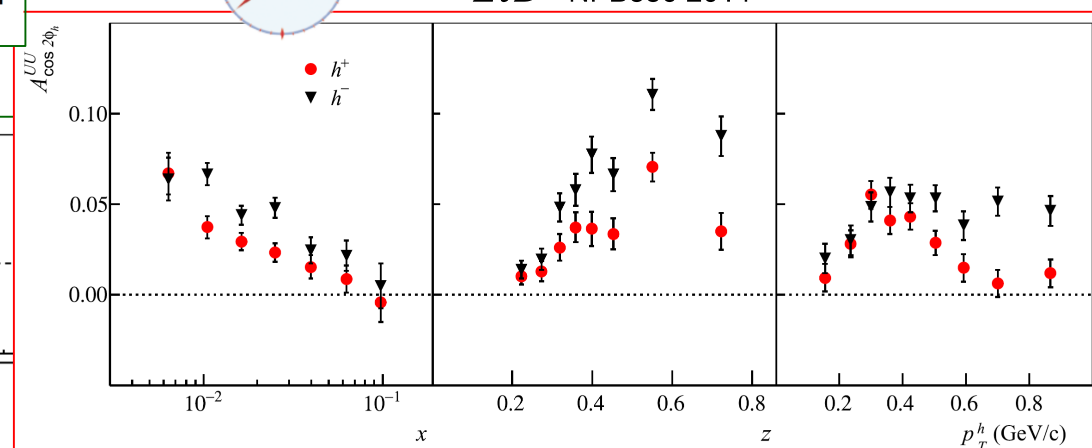


PRD87 2013



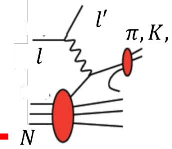


^6LiD NPB886 2014



not easy to see Boer-Mulders

unpolarised SIDIS – azimuthal asymmetries



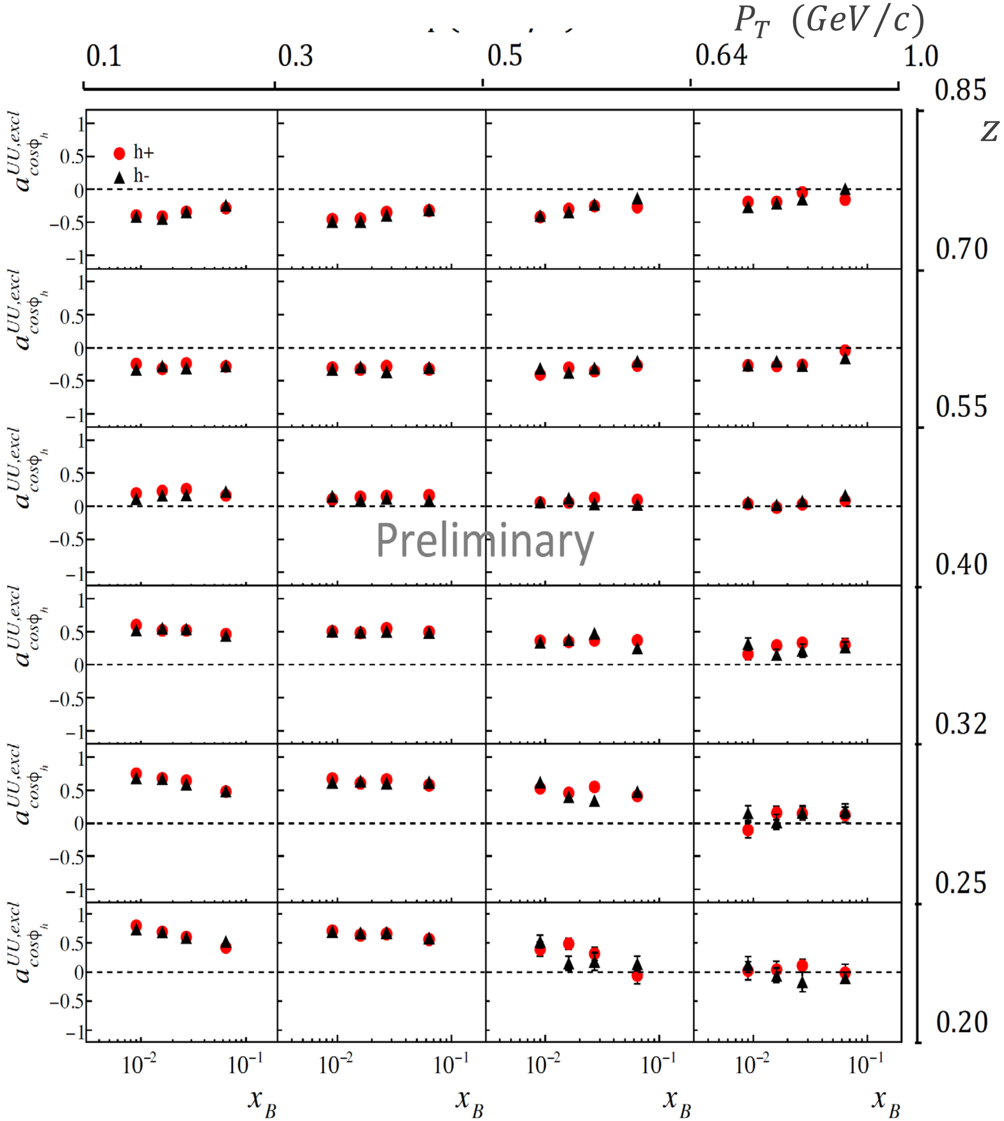
new: contribution from exclusive (vector meson) events

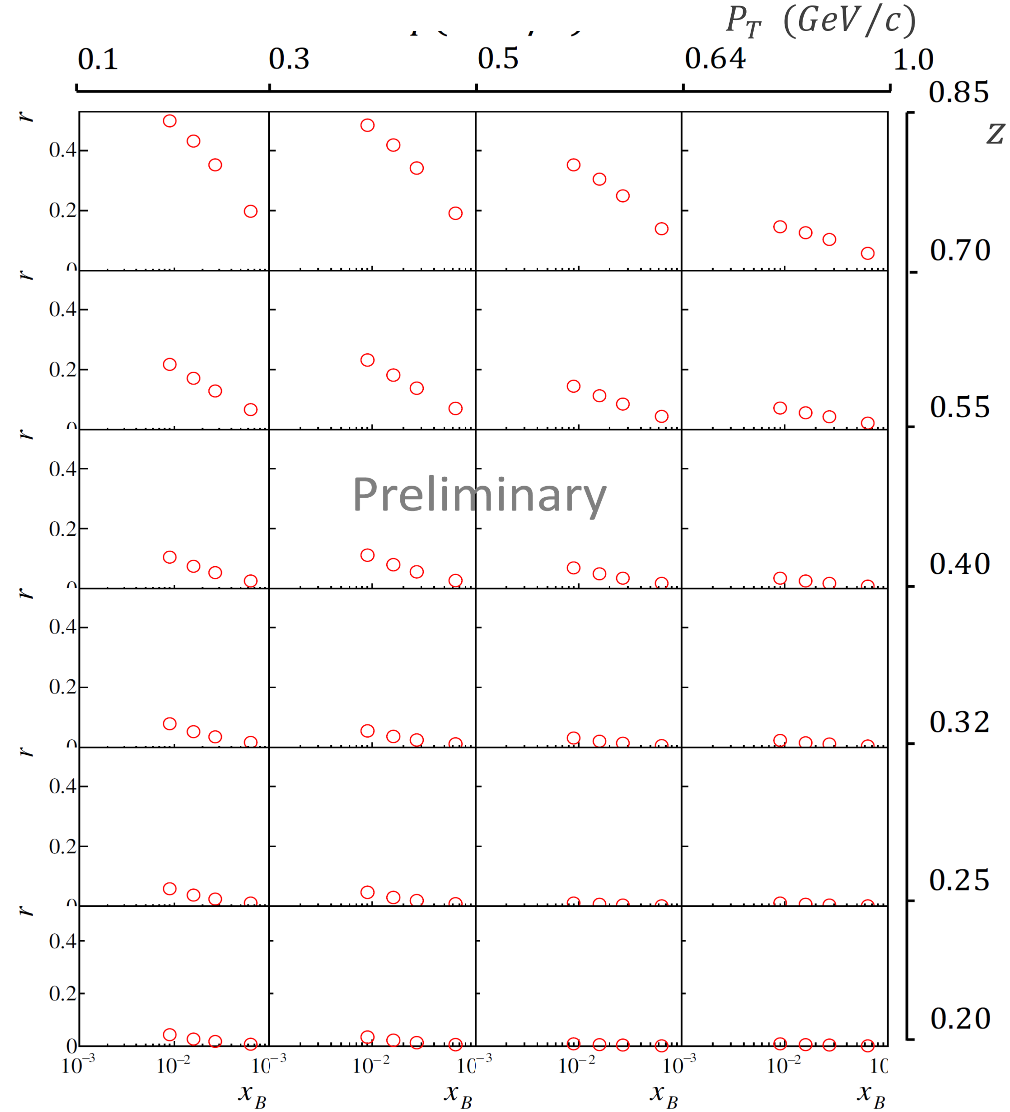
COMPASS ^{6}LiD SPIN2018

amplitudes of the $\cos\phi$ modulation
for exclusive hadron pairs (from data)

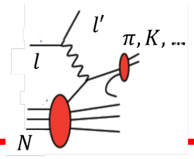
$$r = \frac{N_h^{excl}}{N_h^{excl} + N_h^{SIDIS}}$$

from HEPGEN (ρ^0) and Lepto

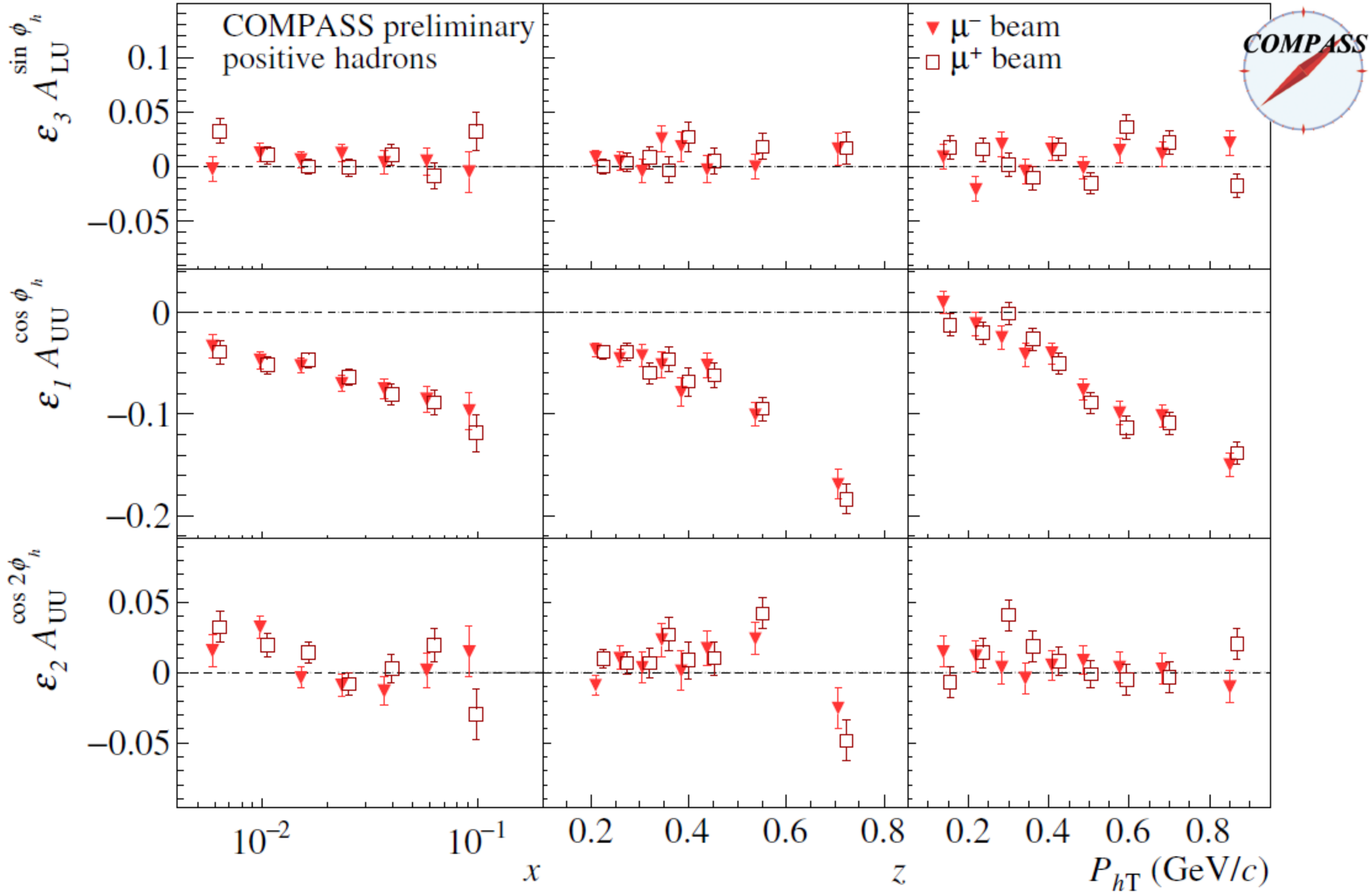




unpolarised SIDIS – azimuthal asymmetries

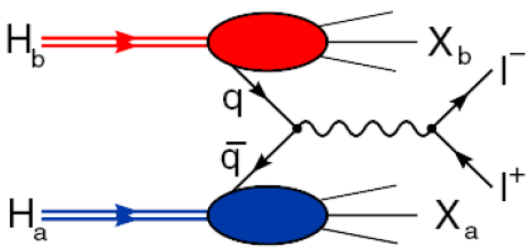


new: preliminary results from COMPASS 2016-2017 proton data



also, precise multiD results from JLab12 experiments expected soon

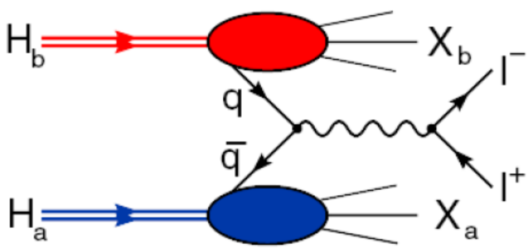
DRELL-YAN PROCESS



COMPLEMENTARY APPROACH TO SIDIS

DRELL-YAN PROCESS

COMPLEMENTARY APPROACH TO SIDIS

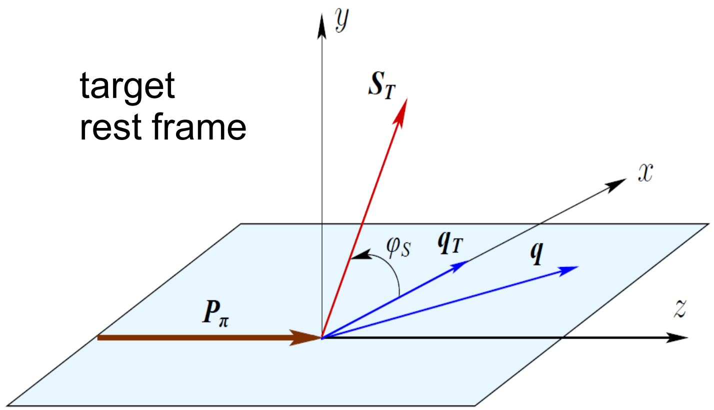


COMPASS is measuring for the first time
the Drell-Yan process $\pi^- p \rightarrow \mu^+ \mu^- X$
on a transversely polarized proton target → **Sivers**, …

new results for $\bar{d}/\bar{u}$ from SeaQuest

SpinQuest in perspective (end 2019?) @ FNAL for
sea-quark transversity
and **Sivers PDFs**

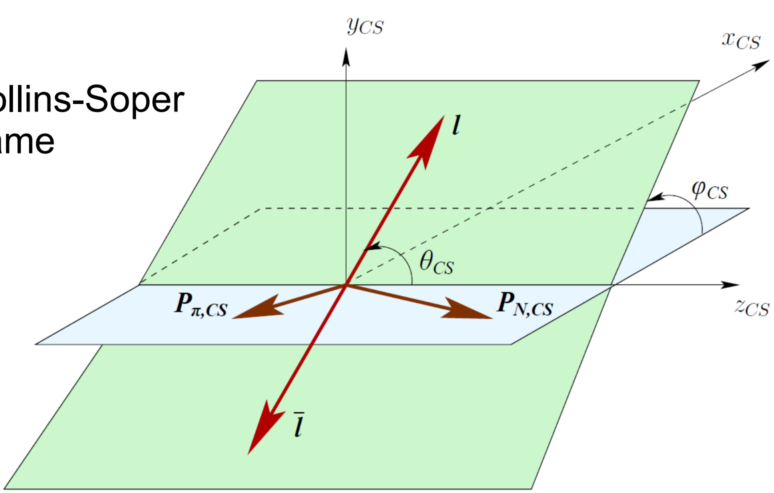
Drell-Yan cross-section



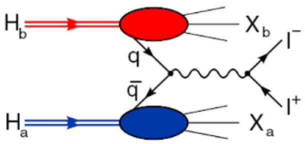
general expression

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + \cos^2\theta_{CS} A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$
$$+ S_T \Big[\Big(A_T^{\sin\varphi_S} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S$$
$$+ \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big)$$
$$+ \sin^2\theta_{CS} \Big(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}$$

$$\lambda = A_U^1, \mu = A_U^{\cos\varphi_{CS}}, \nu = 2\, A_U^{\cos 2\varphi_{CS}}$$



Drell-Yan cross-section



general expression $\pi^- p \rightarrow l^+ l^- X$

$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \Big\{ 1 + \cos^2\theta_{CS}\, A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}$$

$$+ S_T \Big[\Big(A_T^{\sin\varphi_S} + \cos^2\theta_{CS}\, \tilde{A}_T^{\sin\varphi_S} \Big) \sin\varphi_S$$

$$+ \sin 2\theta_{CS} \Big(A_T^{\sin(\varphi_{CS}+\varphi_S)} \sin(\varphi_{CS}+\varphi_S) + A_T^{\sin(\varphi_{CS}-\varphi_S)} \sin(\varphi_{CS}-\varphi_S) \Big)$$

$$+ \sin^2\theta_{CS} \Big(A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) + A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \Big) \Big] + \cdots \Big\}$$

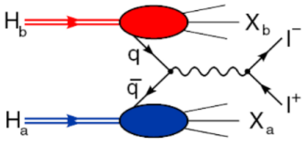
$A_U^{\cos 2\varphi_{CS}}$ → $\boldsymbol{h_1^\perp \otimes h_1^\perp}$ — **Boer-Mulders** of the π, **Boer-Mulders** of the p

$A_T^{\sin\varphi_S}$ → $\boldsymbol{f_1 \otimes f_{1T}^\perp}$ — of the π, **Sivers** of the p

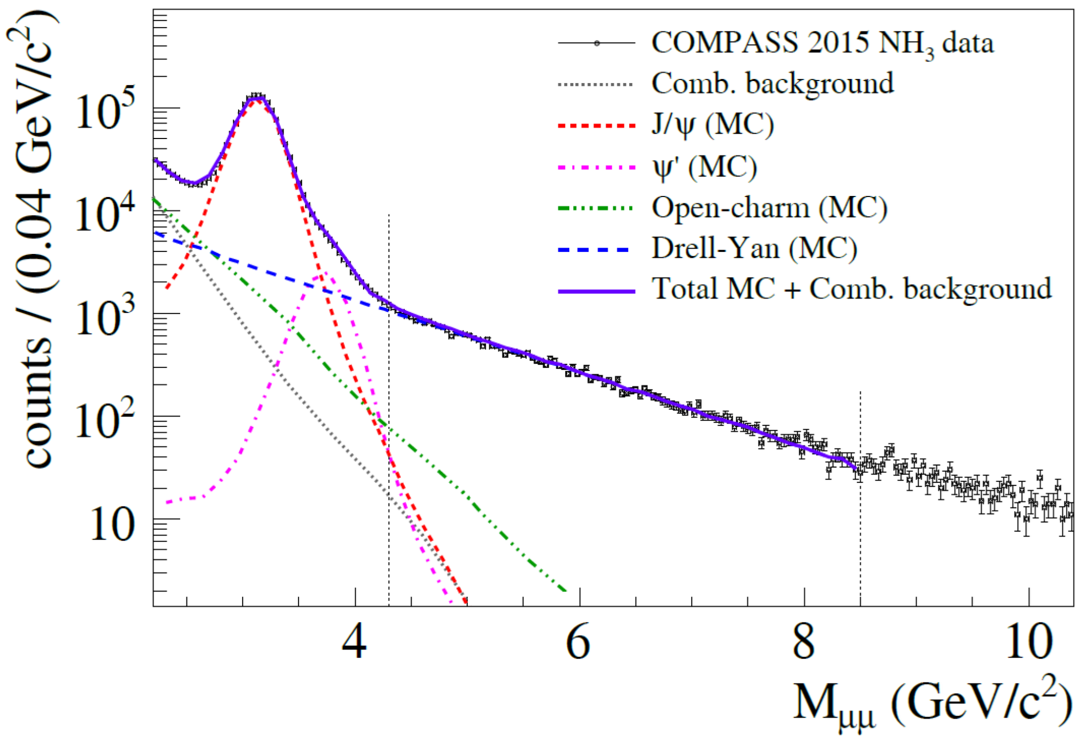
$A_T^{\sin(2\varphi_{CS}+\varphi_S)}$ → $\boldsymbol{h_1^\perp \otimes h_{1T}^\perp}$ — **Boer-Mulders** of the π, **pretzelosity** of the p

$A_T^{\sin(2\varphi_{CS}-\varphi_S)}$ → $\boldsymbol{h_1^\perp \otimes h_1}$ — **Boer-Mulders** of the π, **transversity** of the p

Drell-Yan at COMPASS

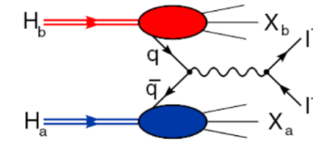


190 GeV π^- beam, transversely polarised proton (NH3) target

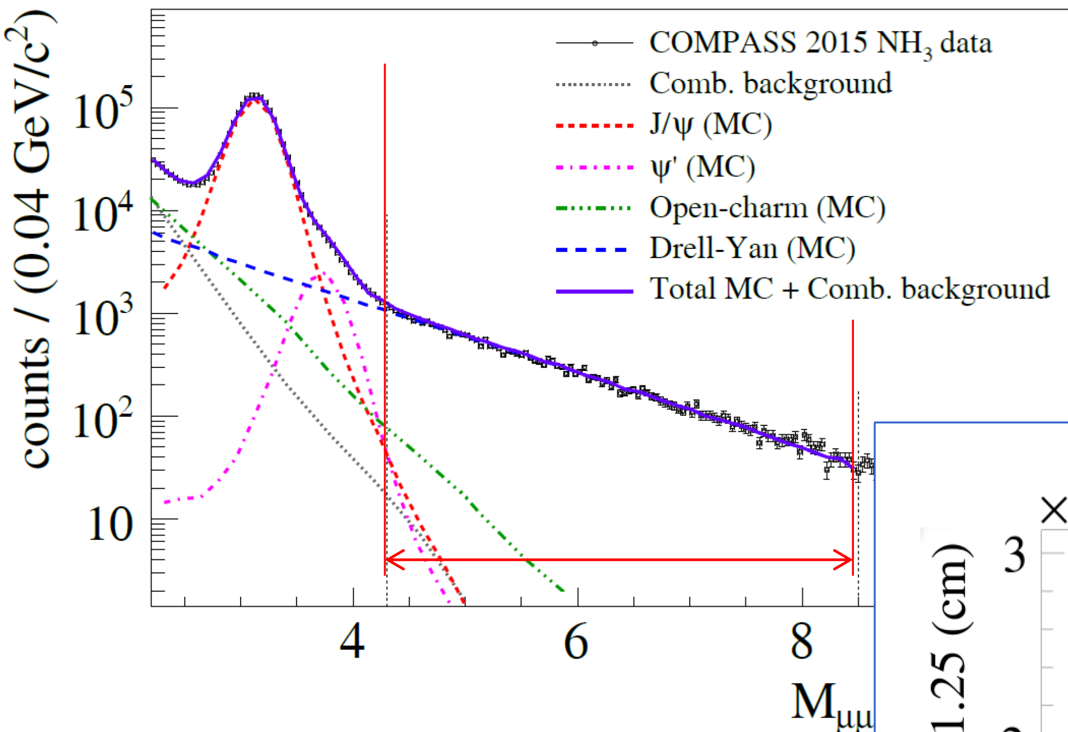


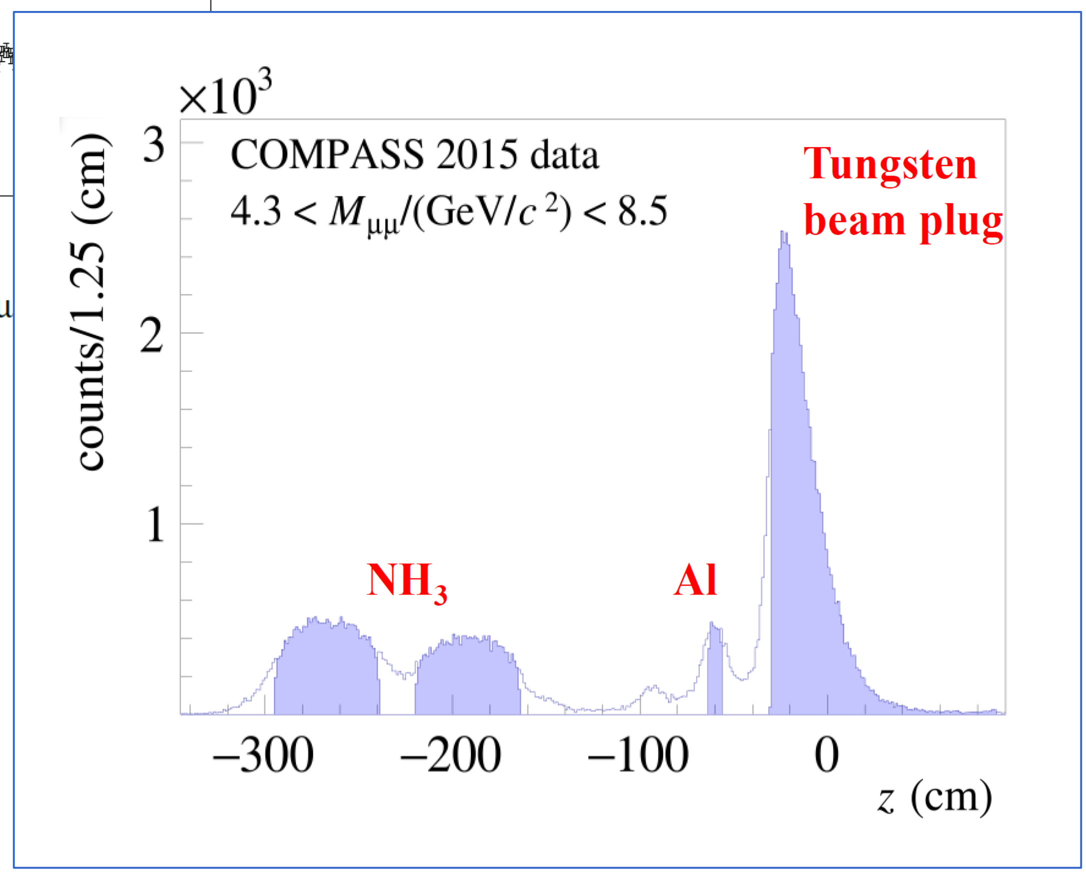
DIS2019

Drell-Yan at COMPASS



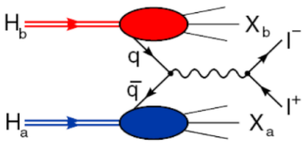
190 GeV π^- beam, transversely polarised proton (NH3) target





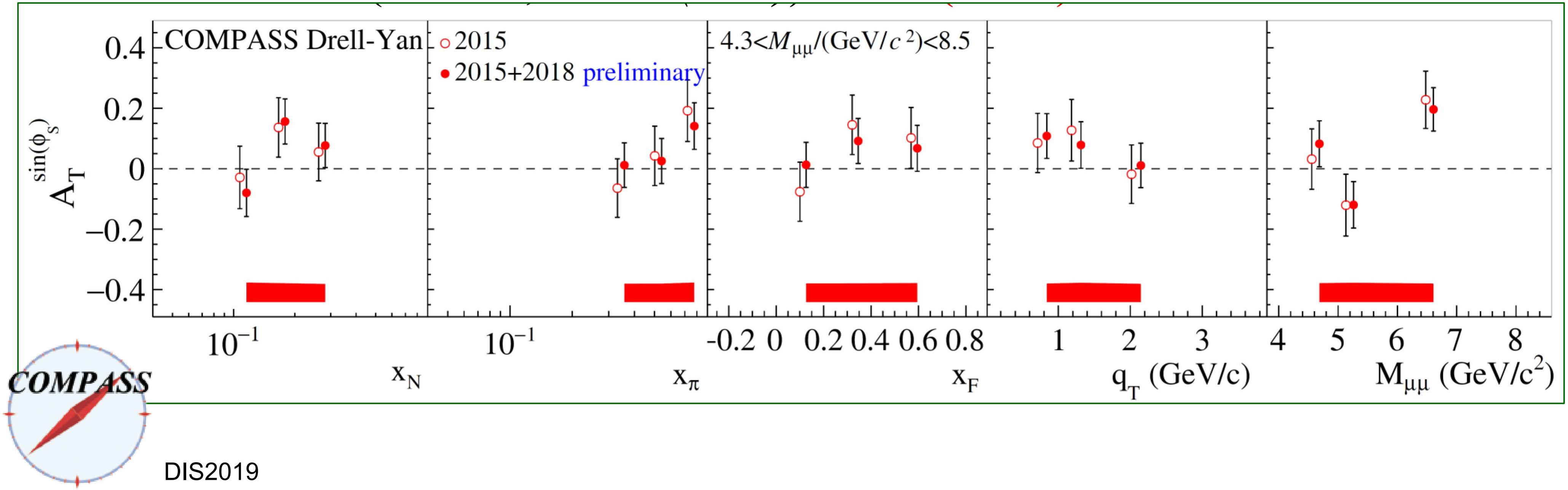
DIS2019

Drell-Yan at COMPASS



190 GeV π^- beam, transversely polarised proton (NH3) target

Sivers asymmetry



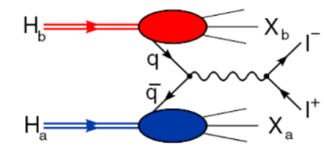
DIS2019

COMPASS Drell-Yan $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$

○ 2015 PRL119 (2017)

● 2015+2018 (~50%) preliminary

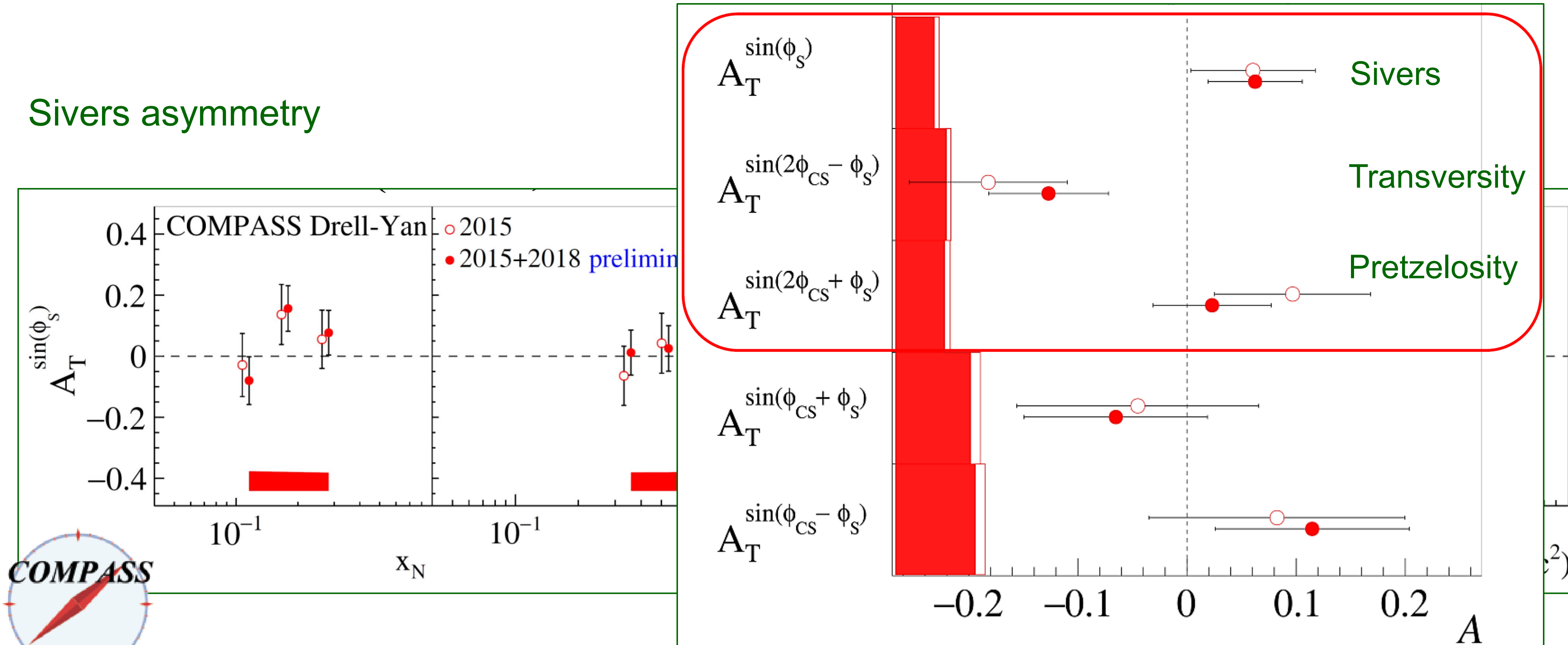
Drell-Yan at COMPASS



190 GeV π^- beam, transversely polarised proton (NH3) target

Sivers asymmetry

Transverse Spin asymmetries



COMPASS

DIS2019

COMPASS Drell-Yan $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$

○ 2015 PRL119 (2017)

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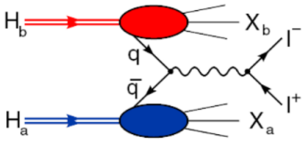
Drell-Yan at COMPASS



190 GeV π^- beam, transversely polarised proton (NH3) target

q_T/M weighted asymmetries

$$A_T^{\sin\varphi_S \frac{q_T}{M_p}}(x_\pi, x_N) \approx -2\frac{f_{1T}^{\perp(1)\,u}(x_N)}{f_{1,p}^u(x_N)}$$

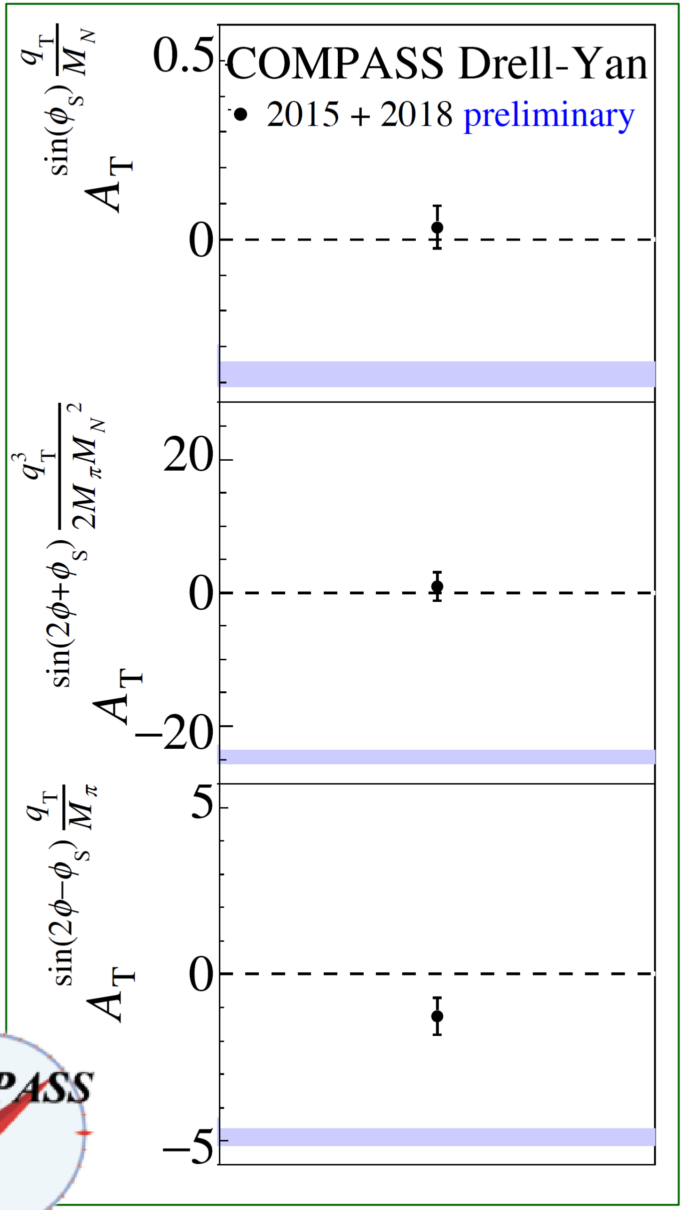
Sivers

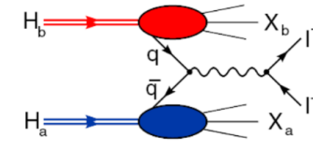
$$A_T^{\sin(2\varphi+\varphi_S)\frac{q_T^3}{2M_p M_\pi}}(x_\pi, x_N) \approx -2\frac{h_{1,\pi}^{\perp(1)\,\bar{u}}(x_\pi)\, h_{1T,p}^{\perp(2)\,u}(x_N)}{f_1^{\bar{u}}(x_\pi)\, f_{1,p}^u(x_N)}$$

Pretzelosity

$$A_T^{\sin(2\varphi-\varphi_S)\frac{q_T}{M_\pi}}(x_\pi, x_N) \approx -2\frac{h_{1,\pi}^{\perp(1)\,\bar{u}}(x_\pi)\, h_{1,p}^u(x_N)}{f_1^{\bar{u}}(x_\pi)\, f_{1,p}^u(x_N)}$$

Transversity





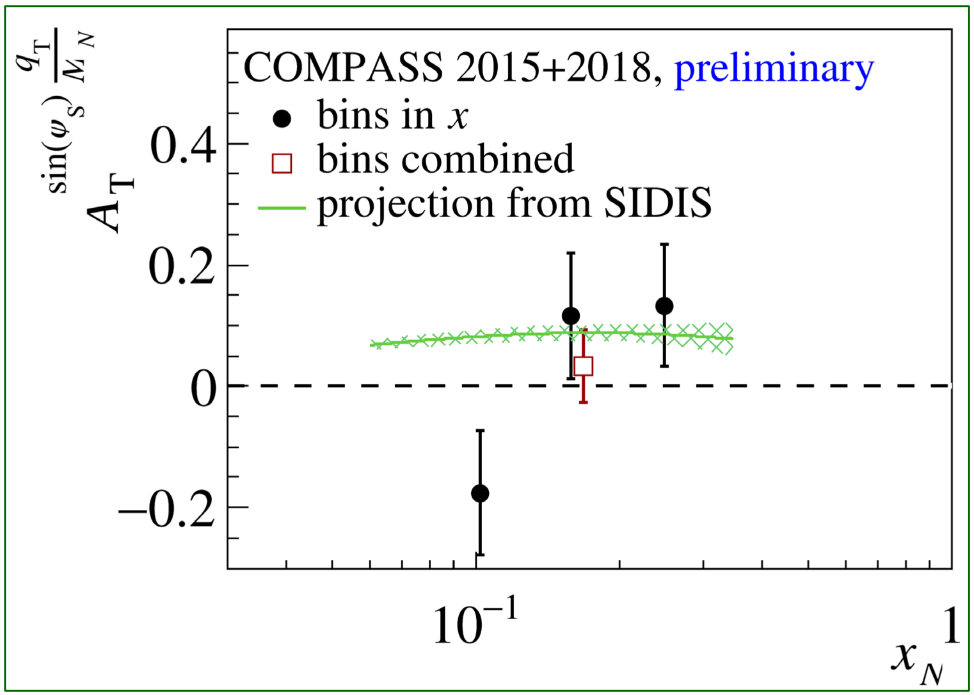
Drell-Yan at COMPASS

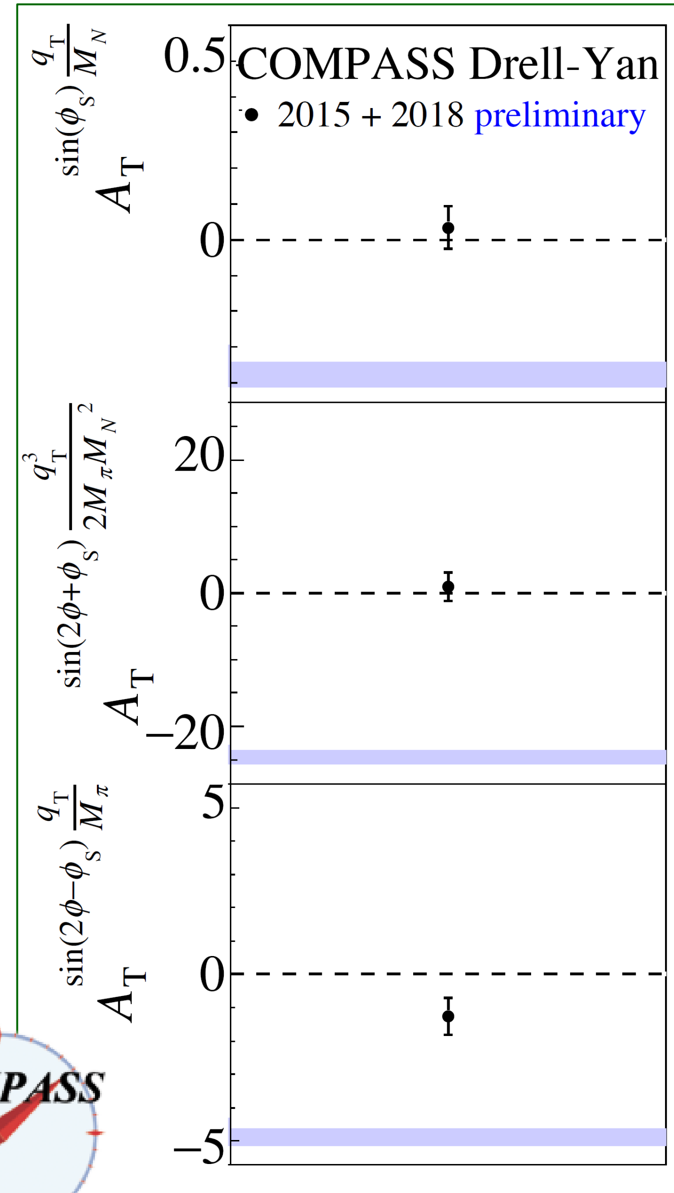
190 GeV π^- beam, transversely polarised proton (NH3) target

q_T-weighted asymmetries

$$A_T^{\sin\varphi_S \frac{q_T}{M_p}}(x_\pi, x_N) \approx -2\frac{f_{1T}^{\perp(1)u}(x_N)}{f_{1,p}^{u}(x_N)}$$

Sivers



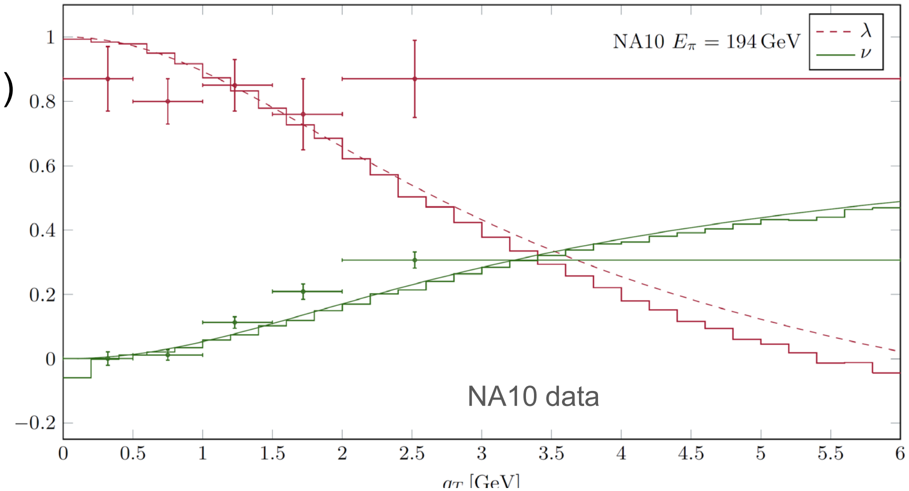


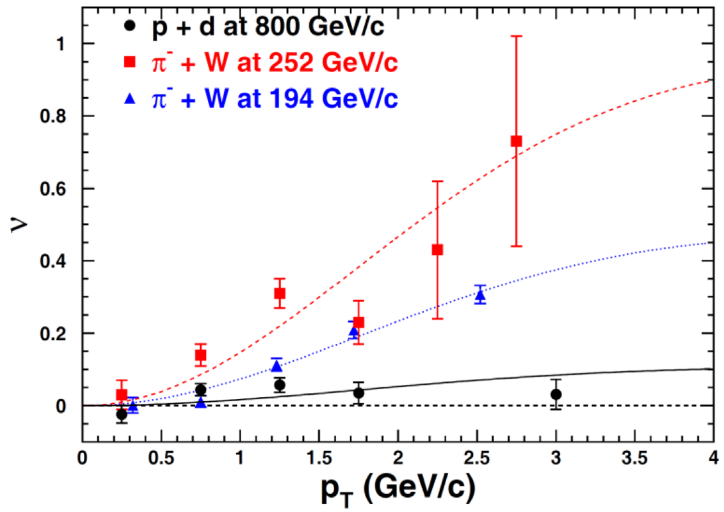
unpolarised Drell-Yan

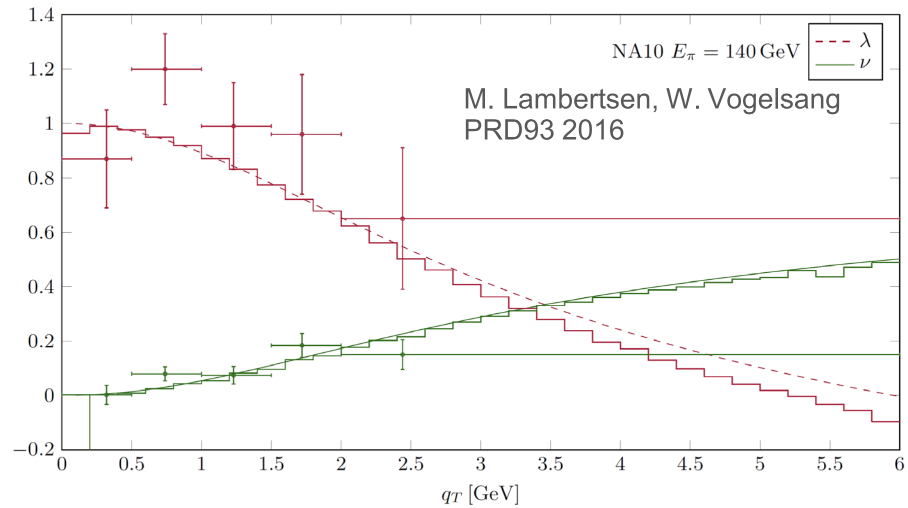
$$\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\sigma}_U \left\{1 + \cos^2\theta_{CS}\, A_U^1 + \sin 2\theta_{CS}\, A_U^{\cos\varphi_{CS}} \cos\varphi_{CS} + \sin^2\theta_{CS}\, A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS}\right\}$$

λ μ $\nu/2$

- "naive" Drell–Yan model
  collinear ($k_T = 0$) LO pQCD
  $\boldsymbol{\lambda = 1, \mu = \nu = 0}$
- intrinsic transverse momentum + QCD effects
  $\boldsymbol{\lambda \neq 1, \mu \neq 0, \nu \neq 0}, with\ \boldsymbol{1 - \lambda = 2\nu}$ (Lam-Tung relation)
- experimentally
  $\lambda \neq 1, \mu \neq 0, \nu \neq 0$



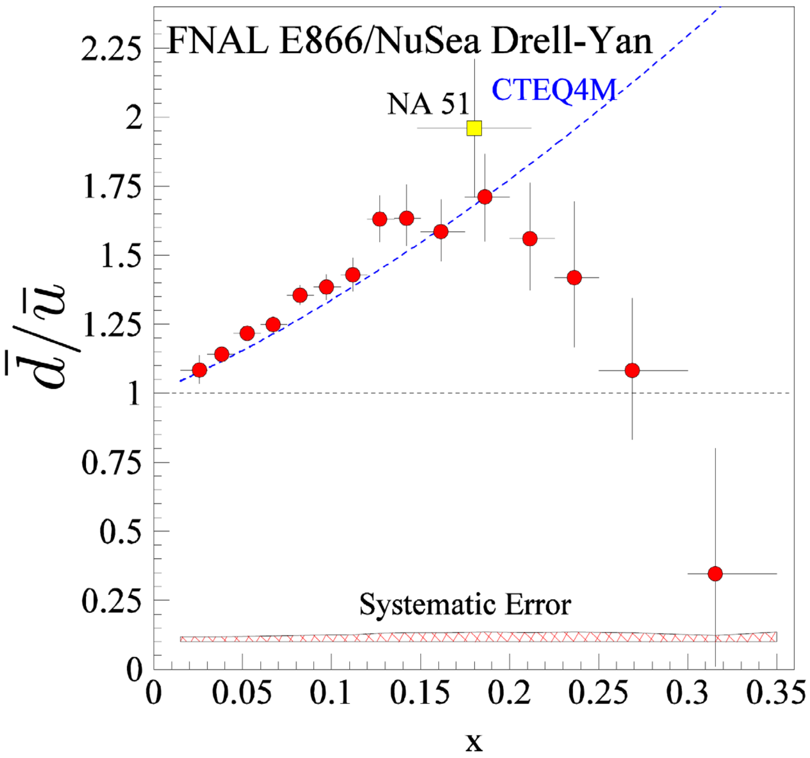




unpolarised Drell-Yan

flavor asymmetry of nucleon sea

- $$\frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2}\left(1+\frac{\bar{d}(x)}{\bar{u}(x)}\right)$$
  $x_F >> 0$
- Significant deviation of $\bar{d}/\bar{u}$ from 1
- Asymmetry has a strong dependence on *x*
- Can *x* dependence be explained?



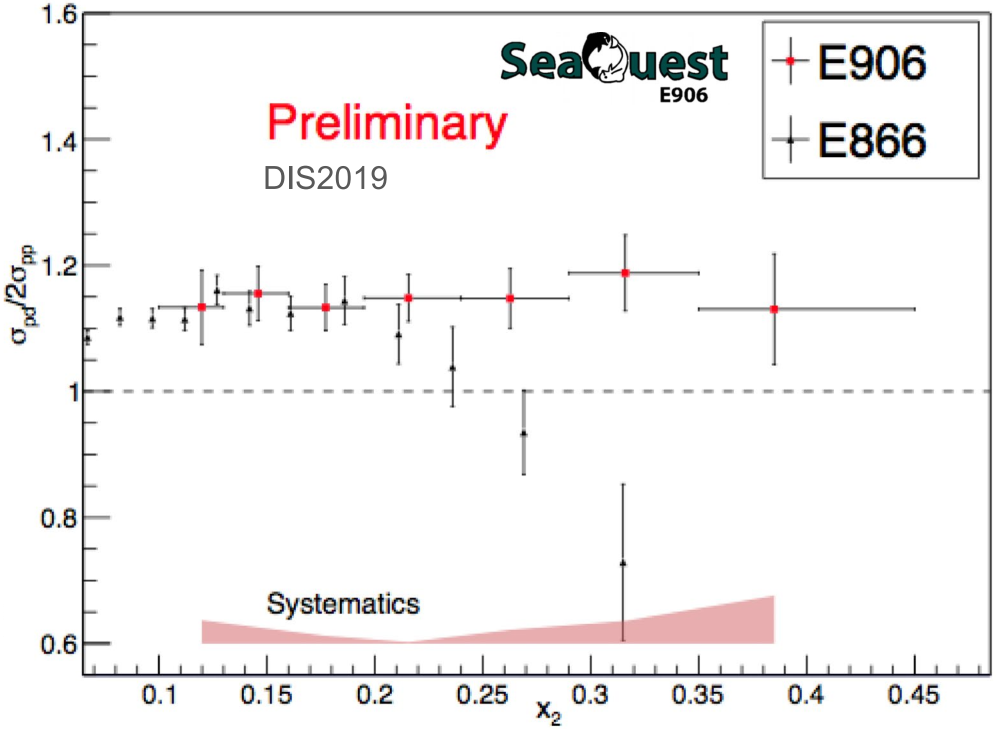
800 GeV protons

unpolarised Drell-Yan

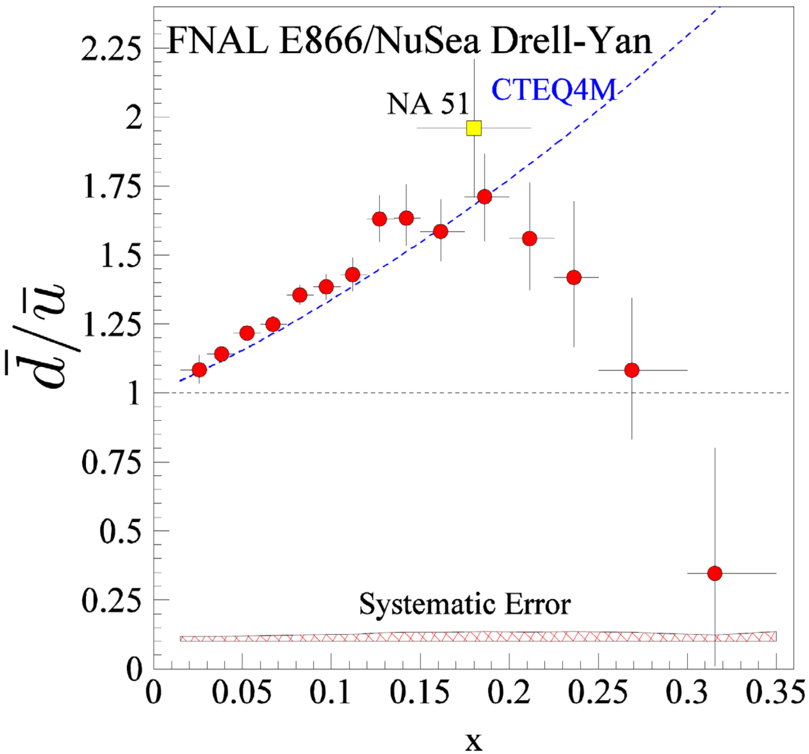
flavor asymmetry of nucleon sea

- $$\frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right)$$

$x_F >> 0$



120 GeV



800 GeV protons

TMD PDFs from SIDIS and Drell-Yan

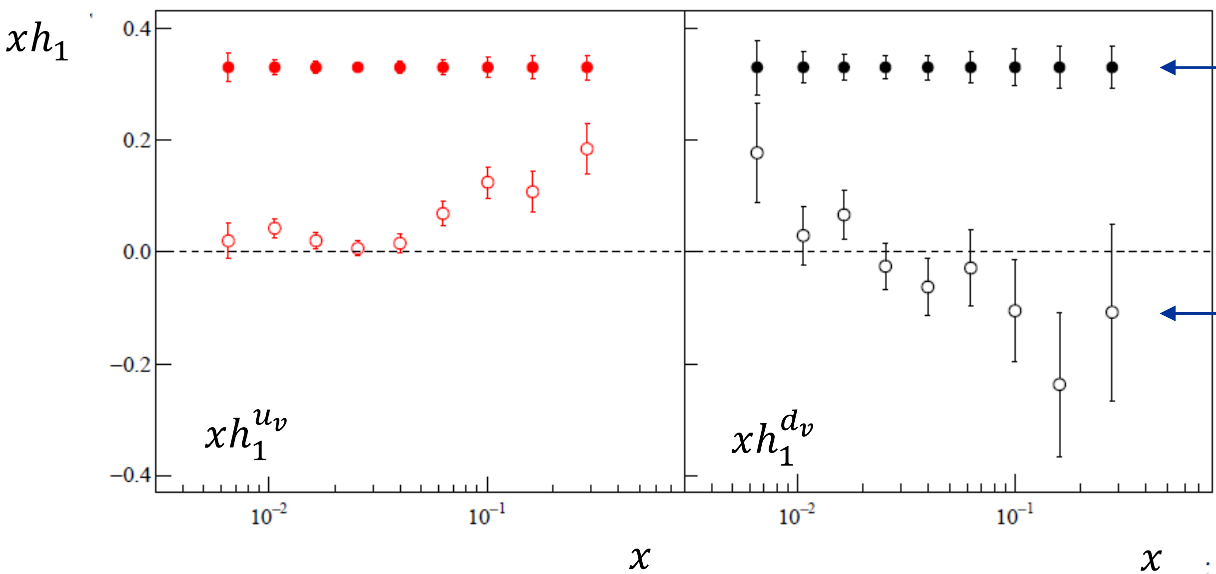
future

TMD PDFs from SIDIS and Drell-Yan

future

SIDIS

- COMPASS: transversely polarised deuteron 2021



projected
gain in precision:
up to 2 for the u-quark
2 to 4 for the d-quark

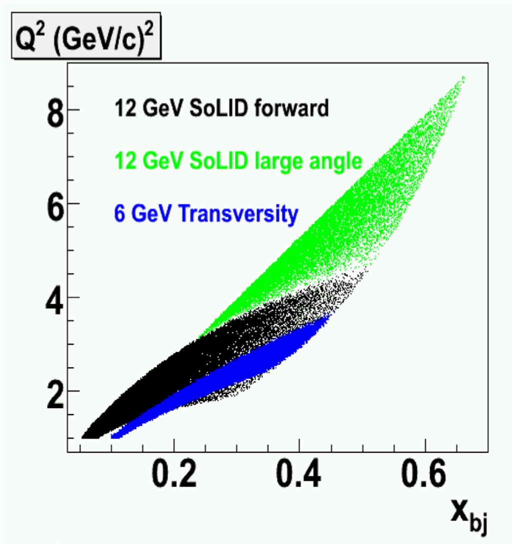
present

TMD PDFs from SIDIS and Drell-Yan

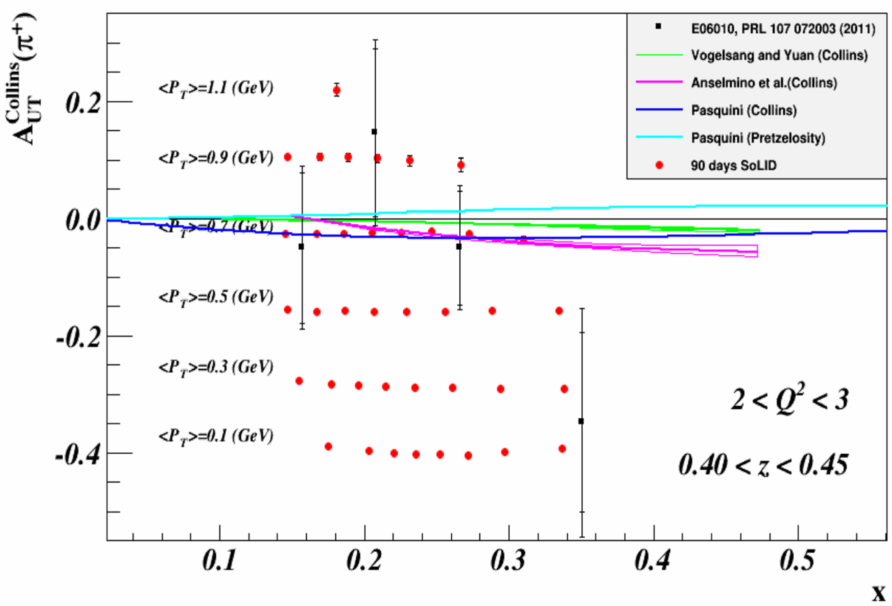
future

SIDIS

- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?



One example on Collins asymmetry



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

TMD PDFs from SIDIS and Drell-Yan

future

SIDIS

- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...

TMD PDFs from SIDIS and Drell-Yan

future

SIDIS

- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...

Drell-Yan

- SpinQuest ~2019?
- COMPASS++/AMBER ~2024?
- LHC
- ...

TMD PDFs from SIDIS and Drell-Yan

future

SIDIS

- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...

Drell-Yan

- SpinQuest ~2019?
- COMPASS++/AMBER ~2024?
- LHC
- ...

and soon many new results from already collected data

SIDIS and Drell-Yan cross-sections, SeaQuest, ...