hard photon & meson production workshop

European Centre for Theoretical studies
Trento, Italy
10th-15th October

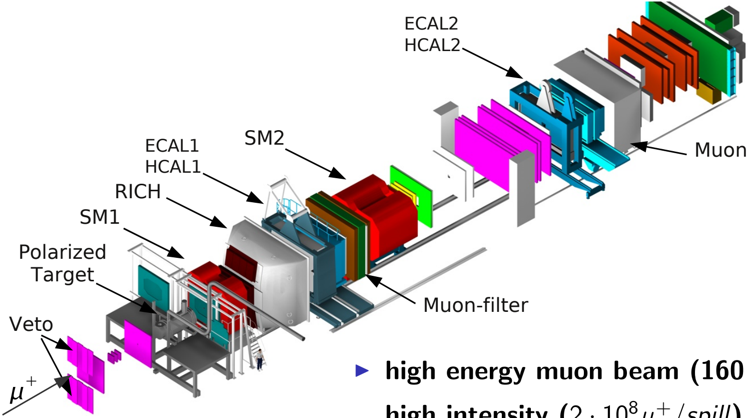
Studies of TMDs at COMPASS

Heiner Wollny
CEA-Saclay Irfu/SPhN
on behalf of COMPASS

Outline:

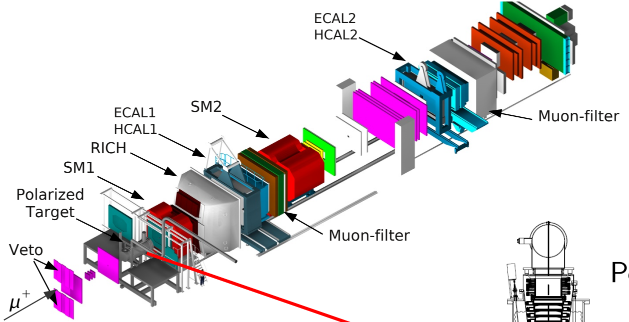
- Transversity: single hadrons, hadron pairs, Λ baryons
- TMDs: measured with transversely, longitudinally and unpolarized nucleons

COMPASS Detector (muon setup)



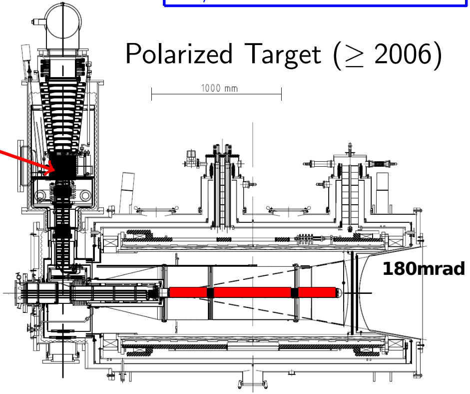
- **high energy muon beam (160 GeV)**
  high intensity $(2 \cdot 10^8 \mu^+/spill)$
  naturally polarized $(\sim 80\,\%)$
- **two stages spectrometer:**
  $\rightsquigarrow$ **large angular acceptance** $(0 \leq \theta_{lab} \leq 180\,\mathrm{mrad})$
  $\rightsquigarrow$ **broad kinematical range in** x **and** Q^2

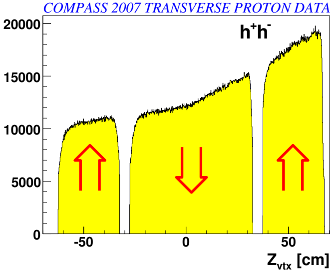
COMPASS Polarized Target



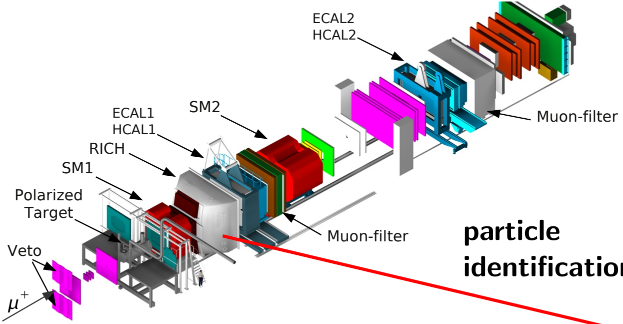
^{6}LiD or NH_3
50/90 % polarization
40/16 % dilution factor

Polarized Target ($\geq$ 2006)

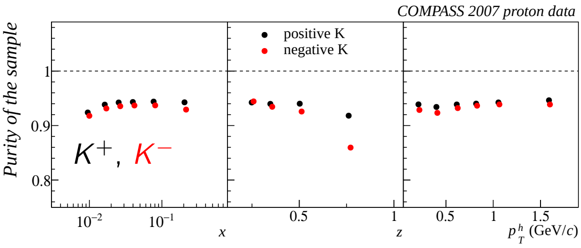


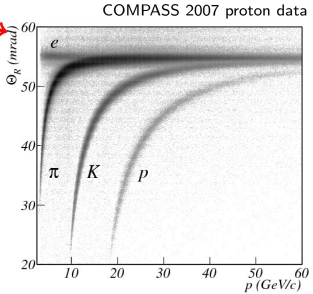


COMPASS RICH



particle identification



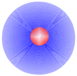


purity of $\pi^{\pm}$ sample $> 99\,\%$

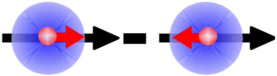
Nucleon in Leading Order

In leading order three parton distributions are needed to describe the structure of the nucleon:

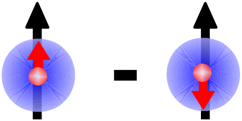
$\mathbf{q}(x)$



$\Delta\mathbf{q}(x)$



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



quark distribution
in unpolarized DIS
$\ell\, N \to \ell' X$

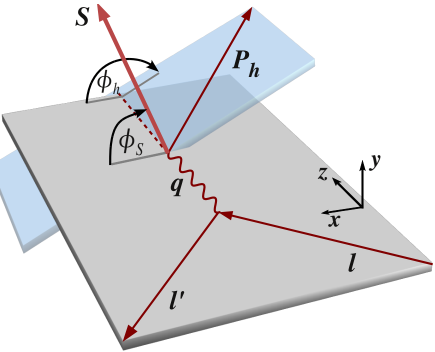
helicity distribution
in polarized DIS
$\vec{\ell}\, \vec{N} \to \ell' X$

transversity distribution
in polarized SIDIS

1. $\ell\, N^{\uparrow} \to \ell' h X$ Collins FF
2. $\ell\, N^{\uparrow} \to \ell' hh X$ Interference FF
3. $\ell\, N^{\uparrow} \to \ell' \Lambda^{\uparrow} X$ FF of $q^{\uparrow} \to \Lambda^{\uparrow}$

Measuring transversity with Collins-FF $\Delta_T^0 D_q^h$:

fragmentation of a transversely polarized quark into an unpolarized hadron



$\rightsquigarrow$ azimuthal asymmetry:

$$\boxed{N_h \;\propto\; 1 \pm A \cdot \sin \phi_{Coll}}$$

$$\phi_{Coll} = \phi_h + \phi_S - \pi$$

ϕ_h: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin of initial quark

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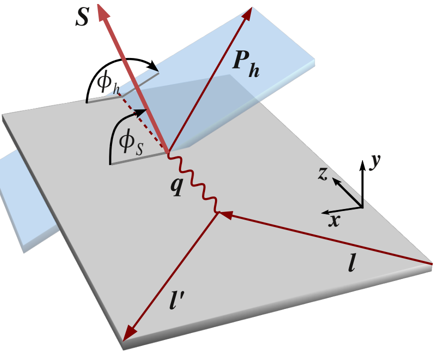

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ϕ_h: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin of initial quark

$$A_{Coll} = \frac{A}{f\ P_T D_{nn}} \propto \sum_q e_q^2 \cdot\ \Delta_T q \otimes \Delta_T^0 D_q^h$$

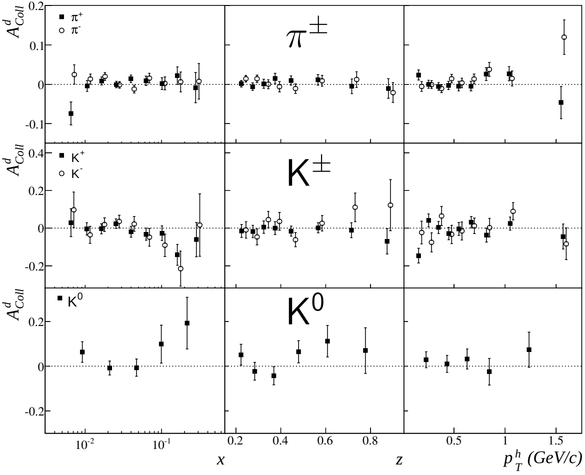
f = target dilution

P_T = target polarization

$D_{nn} = \frac{1-y}{1-y+\frac{y^2}{2}}$ = transverse spin transfer

Collins Asymmetries: ^{6}LiD (2003-2004)

PLB 673 (2009) 127-135



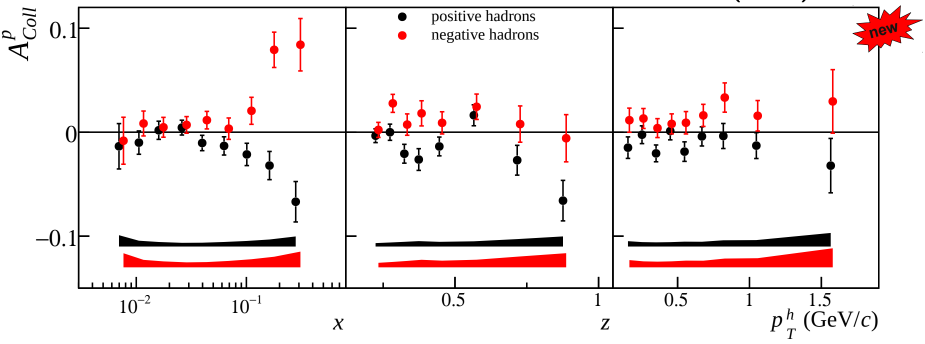
all asymmetries are small, compatible with zero

systematical error: $\sigma_{sys} \leq 0.3\,\sigma_{stat}$

Collins Asymmetries: NH$_3$ (2007)

DIS 2010

PLB 692 (2010), 240

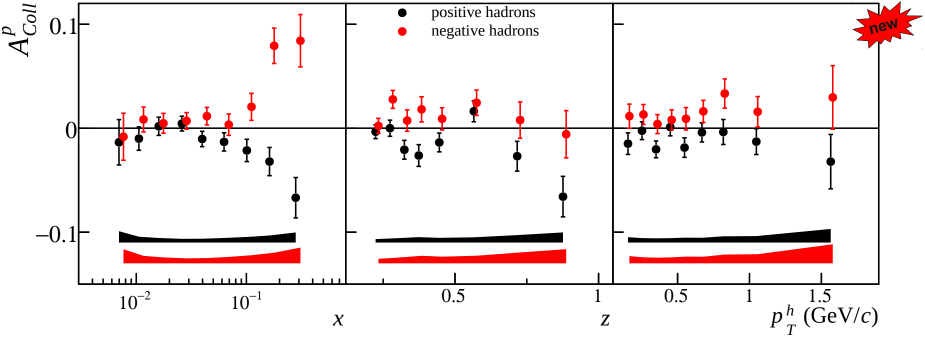


- Large asymmetries for proton $\sim 10\,\%$

Collins Asymmetries: NH_3 (2007)

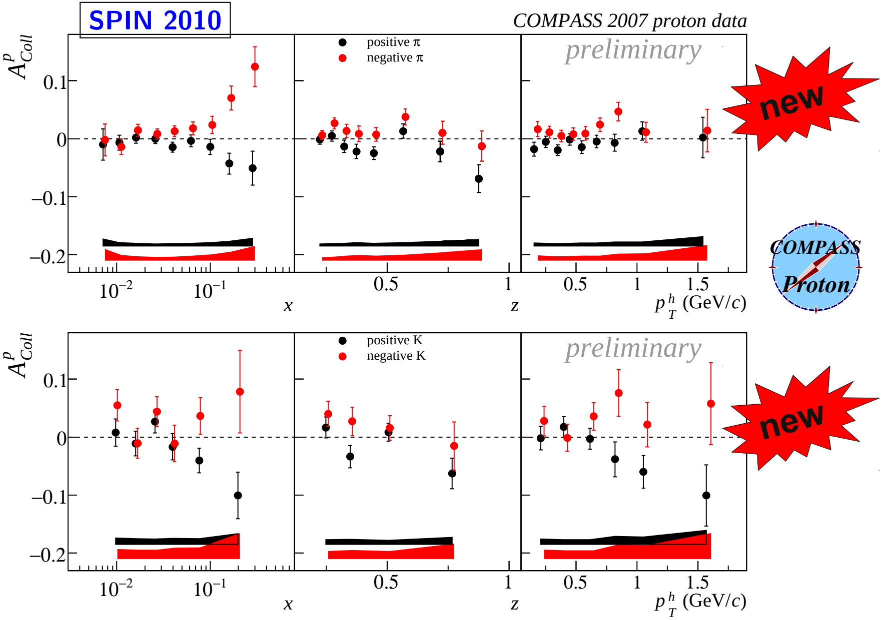
DIS 2010

PLB 692 (2010), 240

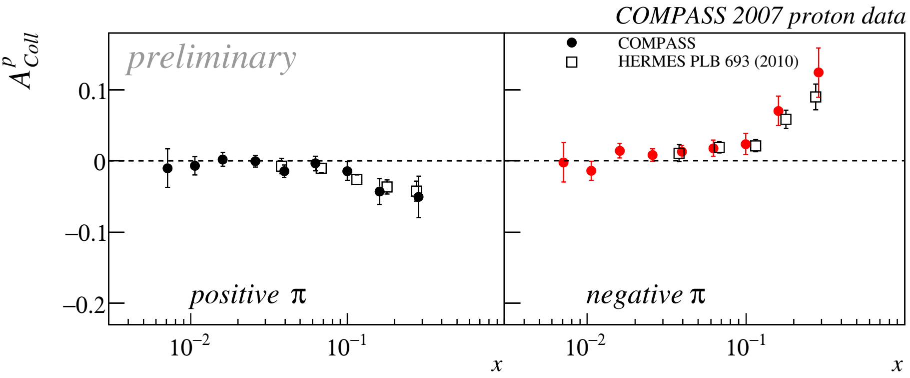


- Large asymmetries for proton $\sim 10\,\%$
- Small asymmetries for deuteron
  $\rightsquigarrow$ cancellation of $\Delta_T\,\mathrm{u}$ and $\Delta_T\,\mathrm{d}$

Collins Asymmetries for $\pi^{\pm}$ and $K^{\pm}$: NH_3 (2007)

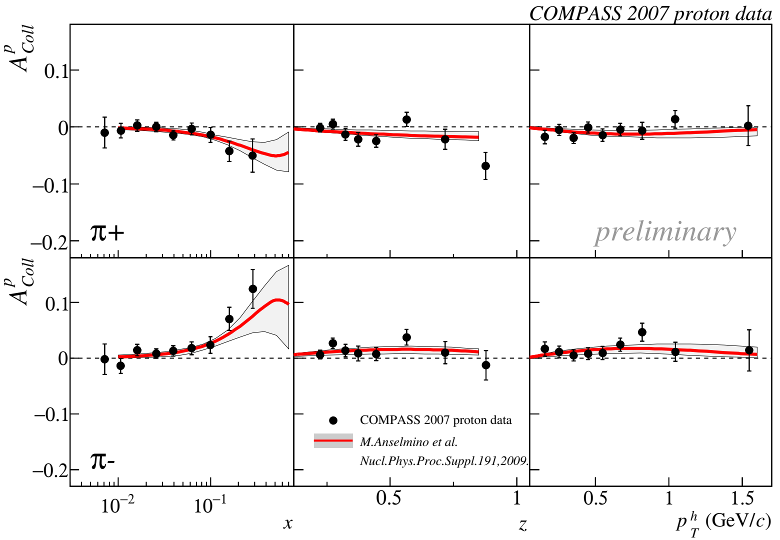


Collins Asymmetries for $\pi^{\pm}$: NH_3 (2007)



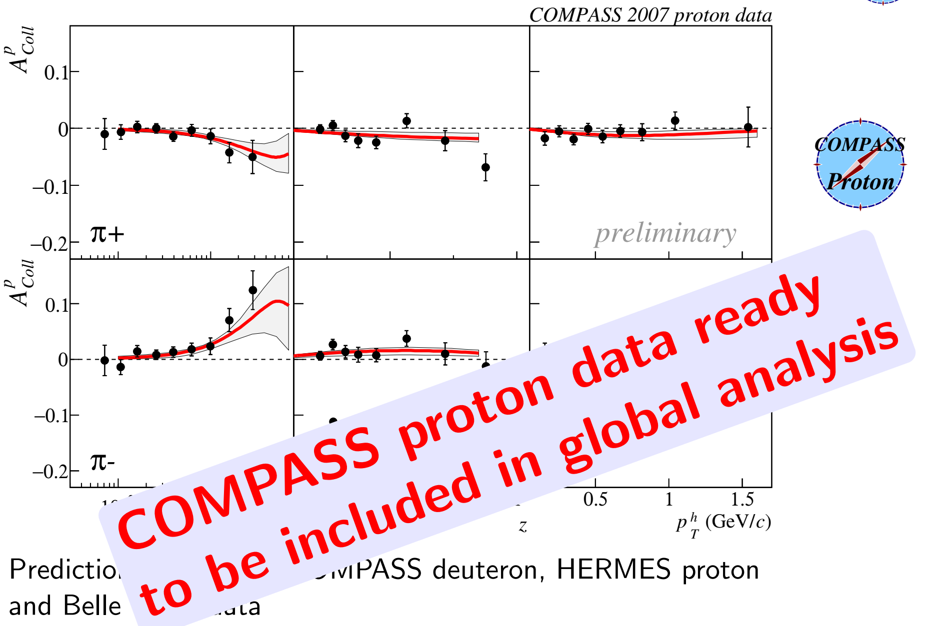
- Good agreement in overlap region (HERMES results are not D_{nn} corrected)

Collins Asymmetries for $\pi^{\pm}$: NH_3 (2007)



Predictions from fit to COMPASS deuteron, HERMES proton and Belle e^+e^- data

Collins Asymmetries for $\pi^{\pm}$: NH_3 (2007)

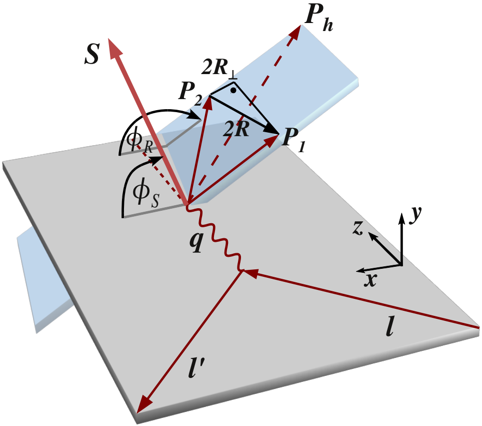


Predictio[...]MPASS deuteron, HERMES proton and Belle [...]ata

Measuring transversity with polarized Dihadron-Interference-FF $H_1^{\sphericalangle}$:

fragmentation of transversely polarized quark into two unpolarized hadrons and rest X

$\rightsquigarrow$ azimuthal asymmetry:



$$\boxed{N_{h^+h^-} \propto 1 \pm A \cdot \sin\phi_{RS} \cdot \sin\theta}$$

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

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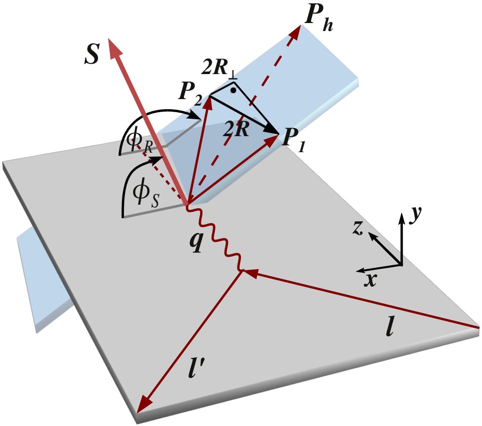

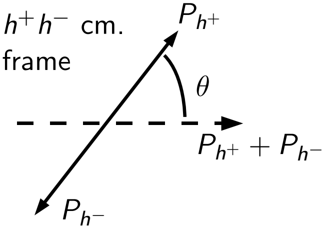

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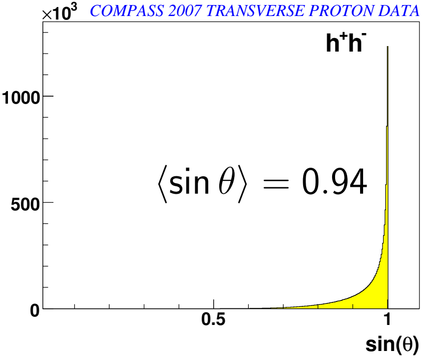

$\langle \sin\theta \rangle = 0.94$

For this analysis:
$\sin\theta$ can be neglected

Measuring transversity with polarized Dihadron-Interference-FF $H_1^{\sphericalangle}$:

fragmentation of transversely polarized quark into two unpolarized hadrons and rest X

$\rightsquigarrow$ azimuthal asymmetry:

$$\boxed{N_{h^+h^-} \propto 1 \pm A \cdot \sin\phi_{RS}}$$

$$\phi_{RS} = \phi_R + \phi_S - \pi$$

$$A_{RS} = \frac{A}{f\ P_T D_{nn}} \propto \sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\sphericalangle}$$

f = target dilution

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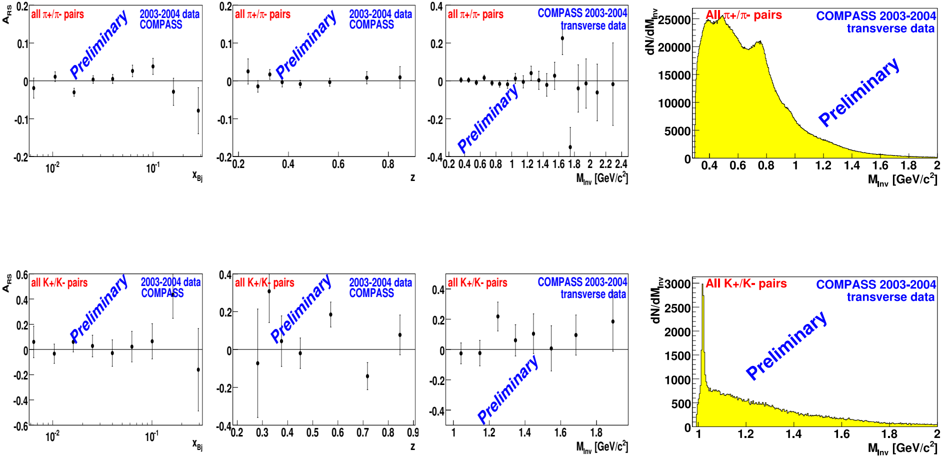
$D_{nn} = \frac{1-y}{1-y+\frac{y^2}{2}}$ = transverse spin transfer

Dihadron Asymmetries: ^{6}LiD (2003-2004)



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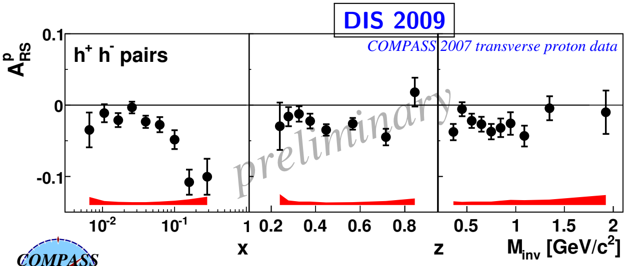
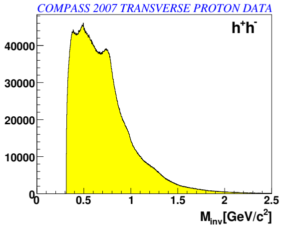
Dihadron Asymmetries: NH_3 (2007)





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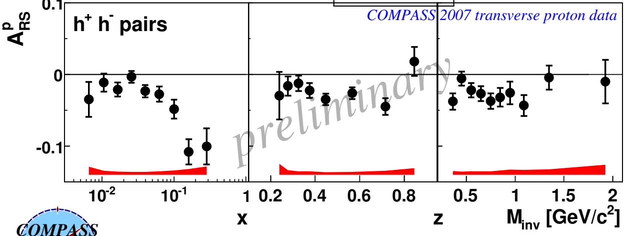
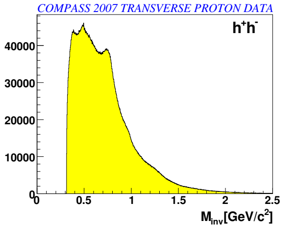
Dihadron Asymmetries: NH_3 (2007)

DIS 2009





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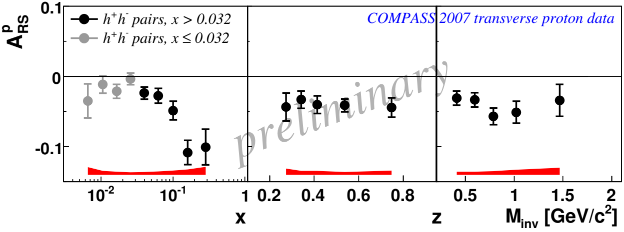
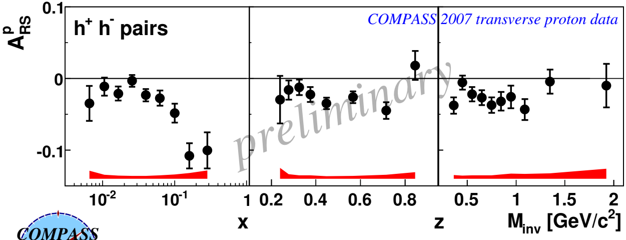
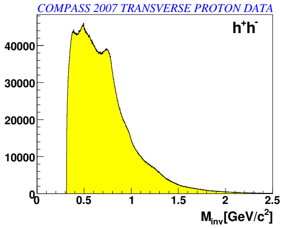


Dihadron Asymmetries: NH$_3$ (2007)





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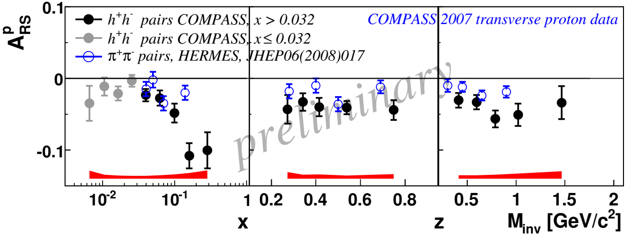
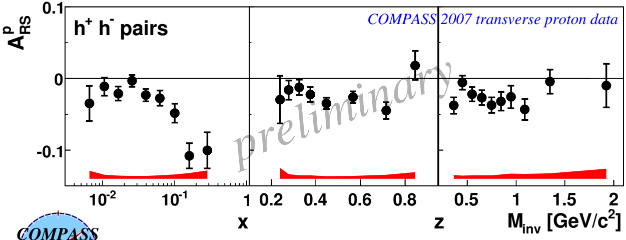
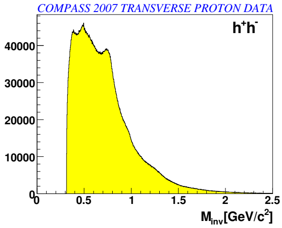


COMPASS measurement covers much larger range in x





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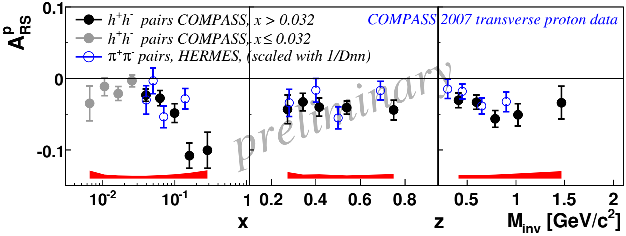
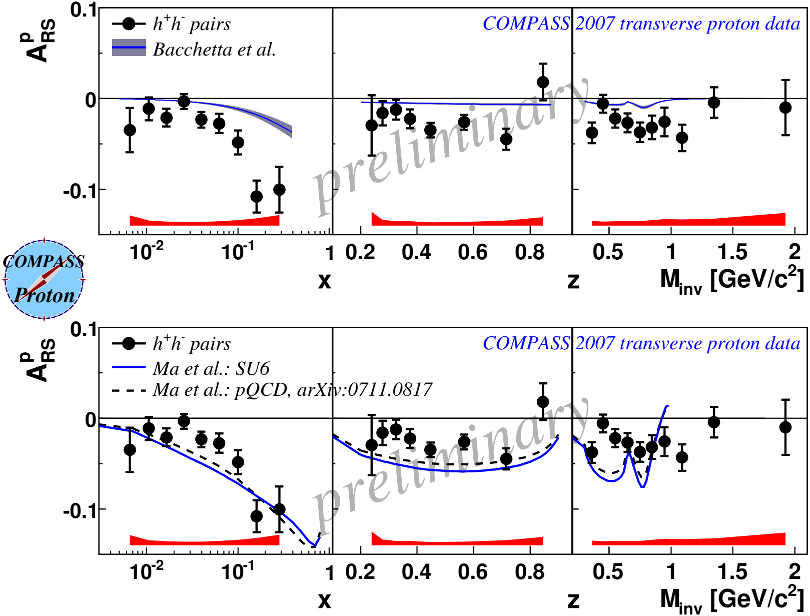


HERMES values scaled with $1/D_{nn}$

COMPASS measurement covers much larger range in x

Dihadron Asymmetry: NH_3 (2007)



Measuring transversity with polarized Λ-FF $\Delta_T D_q^{\Lambda}$:

transversely polarized quark transfers its spin to Λ-Baryon

Λ-Polarization: $P_{\Lambda} \propto f\, P_T D_{nn} \sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T D_q^{\Lambda}$

measured via parity violating decay

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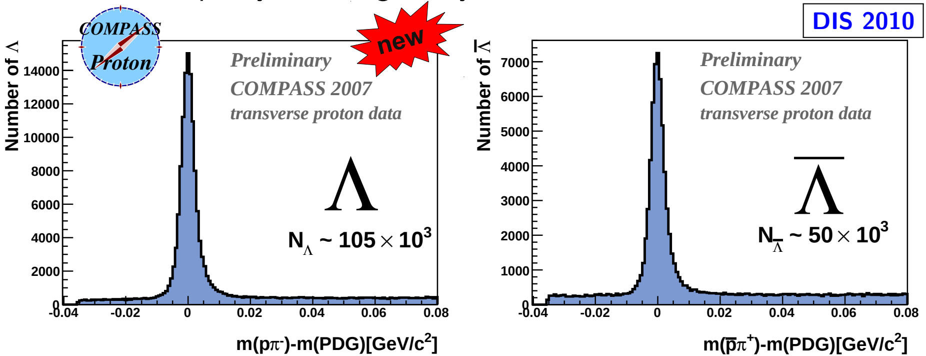
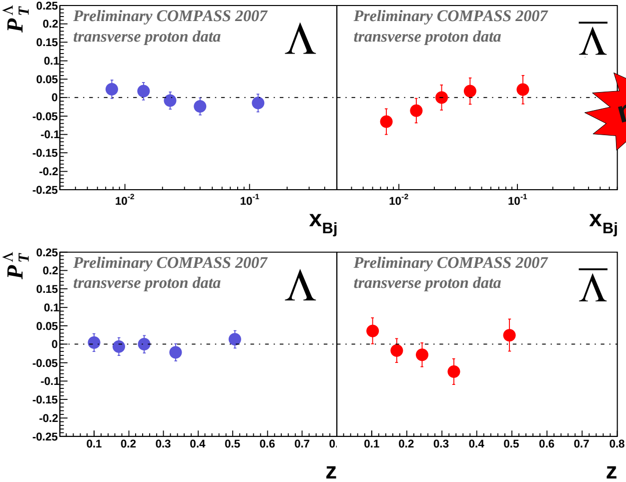
DIS 2010



Transverse Λ-Polarization: NH_3 (2007)

DIS 2010



new

systematical error: $\sigma_{sys} \leq 0.74\,\sigma_{stat}$

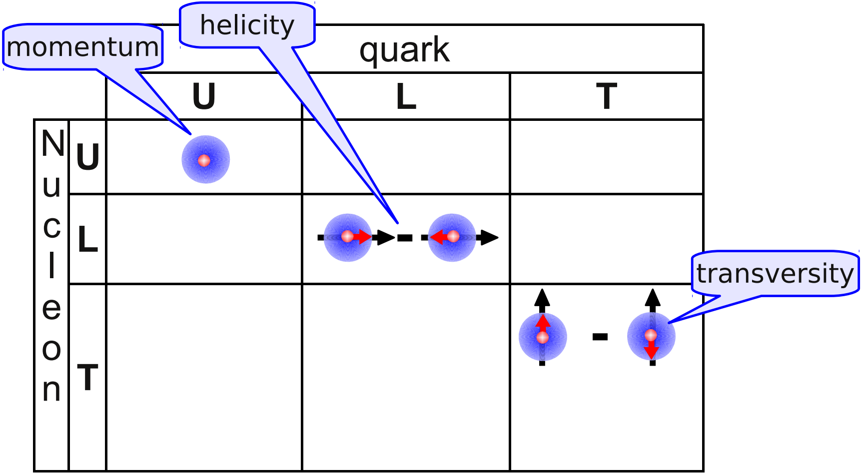
P_T^Λ, $P_T^{\bar{\Lambda}}$ small, compatible with zero $\rightsquigarrow$ small analyzing power of $\Delta_T D_q^\Lambda$

P_T^Λ, $P_T^{\bar{\Lambda}}$ for deuteron also compatible with zero

TMDs

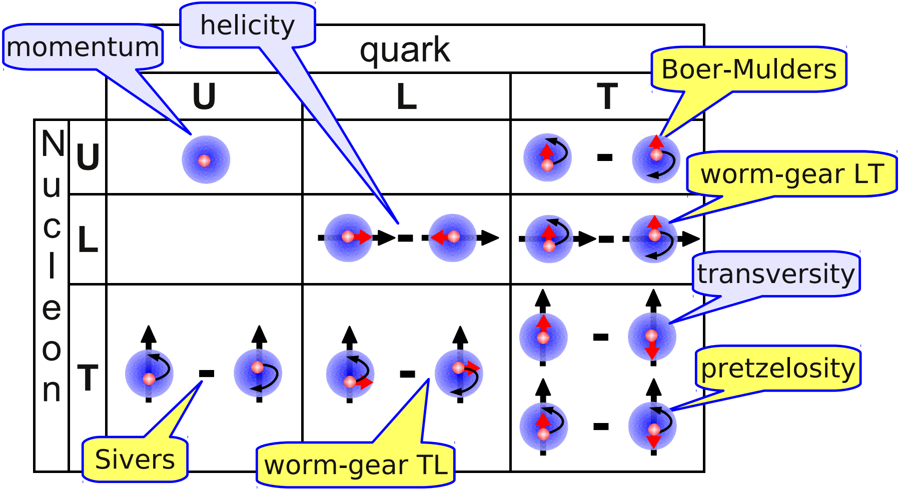
TMDs

Three parton distribution functions when integrating over $k_\perp$



TMDs

Eight parton distribution functions when taking into account $k_\perp$



General Expression of polarized SIDIS Cross-Section

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

unpolarized target

longitudinally polarized target

transversely polarized target

A.Bacchetta et al

JHEP 0702:093,2007

E-print number: hep-ph/0611265

COMPASS

twist-2

twist-3

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

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\ \ldots$$

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

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

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

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

$$\left.+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\boxed{F_{LT}^{\cos(2\phi_h-\phi_S)}}\right]\Bigg\},$$

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COMPASS

twist-2

twist-3

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

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

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

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

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

Collins ✓

A.Bacchetta et al

JHEP 0702:093,2007

E-print number: hep-ph/0611265

COMPASS

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

$$
\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ \ldots
$$

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

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

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

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

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

twist-2

twist-3

Sivers

Collins ✓

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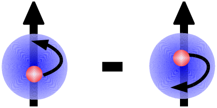
Sivers Asymmetry

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} \propto \Delta_0^T q \otimes D_q^h$$

Sivers PDF $\Delta_0^T q$: 

correlation between intrinsic transverse momentum
of the quarks and the transverse polarization of the nucleon

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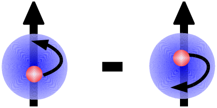
Sivers PDF $\Delta_0^T q$: 

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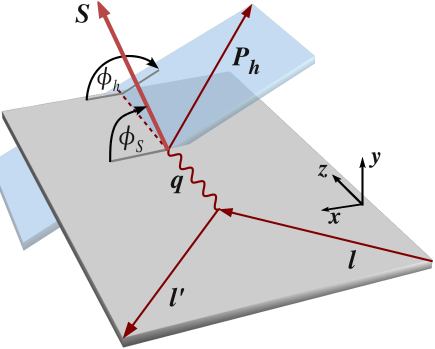

$\rightsquigarrow$ azimuthal asymmetry:

$$\boxed{N_h \propto 1 \pm A \cdot \sin(\phi_h - \phi_S)}$$

ϕ_h: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin of initial quark

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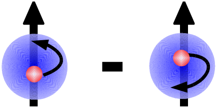
Sivers PDF $\Delta_0^T q$: 

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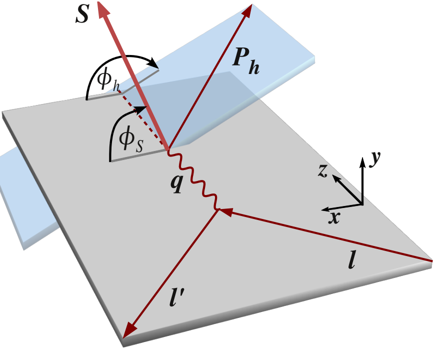


$\rightsquigarrow$ azimuthal asymmetry:

$$\boxed{N_h \propto 1 \pm A \cdot \sin(\phi_h - \phi_S)}$$

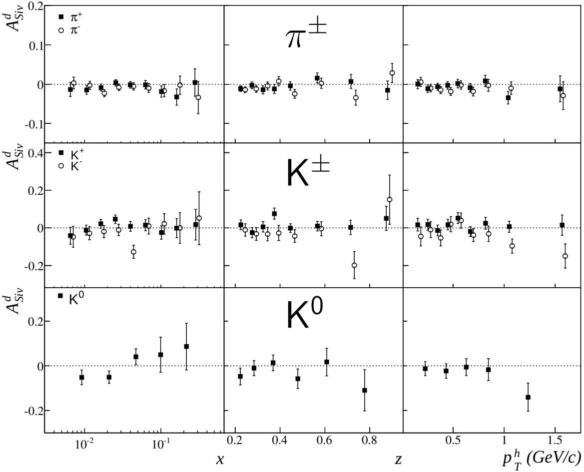
ϕ_h: azimuthal angle of hadron

ϕ_S: azimuthal angle of spin of initial quark

$$\boxed{A_{Siv} = \frac{A}{f\ P_T} \propto \sum_q e_q^2 \cdot \Delta_0^T q \otimes D_q^h}$$

Sivers Asymmetries: ^{6}LiD (2003-2004)

PLB 673 (2009) 127-135



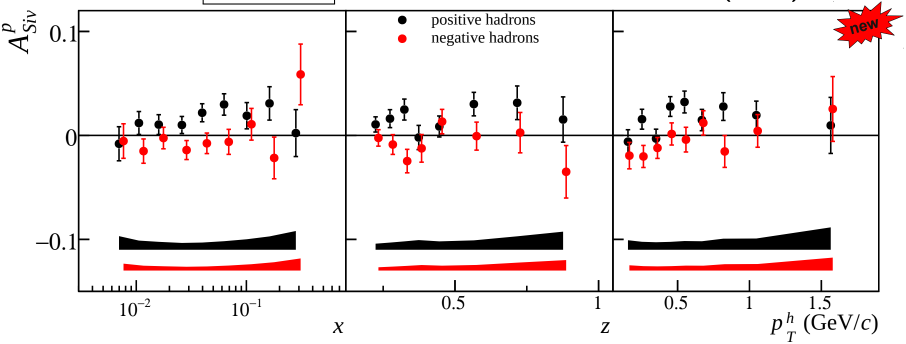
all asymmetries are small, compatible with zero

systematical error: $\sigma_{sys} \leq 0.3\,\sigma_{stat}$

Sivers Asymmetries: NH_3 (2007)

DIS 2010

PLB 692 (2010), 240

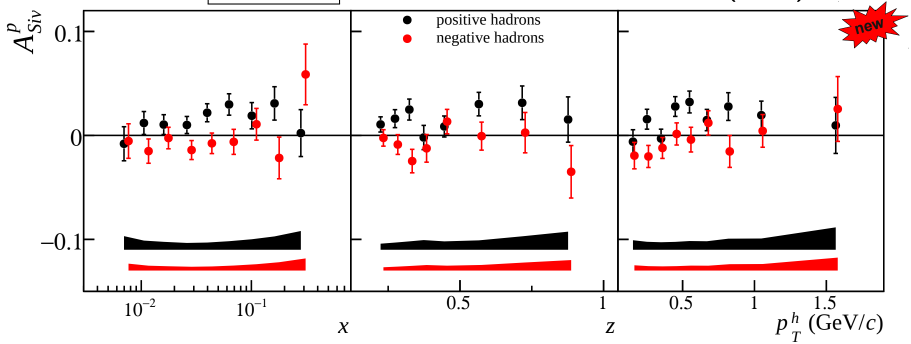


for h^+ additional absolute systematical uncertainty of ± 0.01

- positive asymmetry for h^+
- asymmetry for h^- small, compatible with zero

Sivers Asymmetries: NH_3 (2007)

DIS 2010 **PLB 692 (2010), 240**

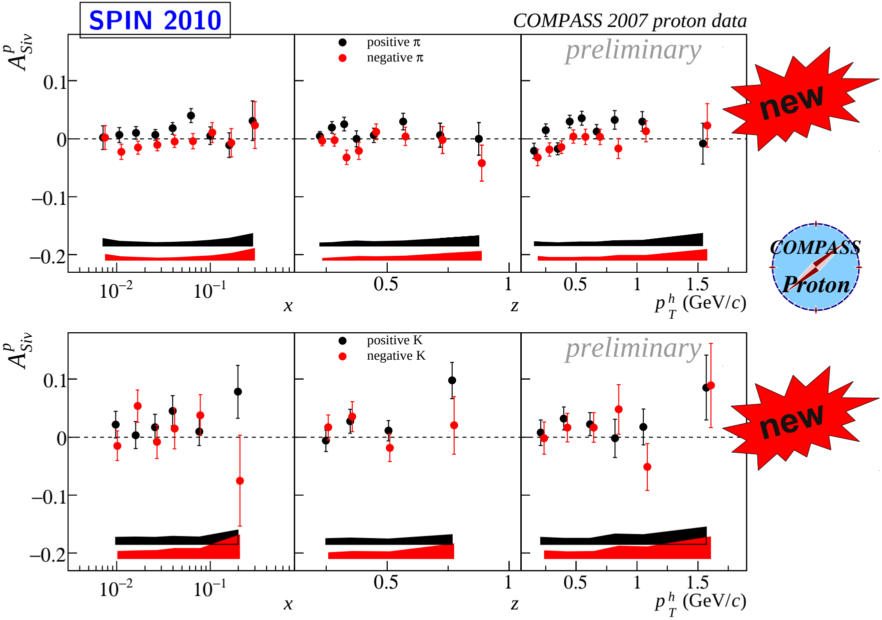


for h^+ additional absolute systematical uncertainty of ± 0.01

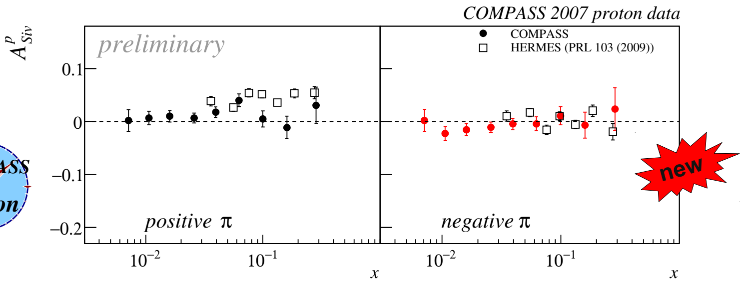
- positive asymmetry for h^+
- asymmetry for h^- small, compatible with zero
- Small asymmetries for deuteron
  $\rightsquigarrow$ opposite sign of Δ_0^T u and Δ_0^T d

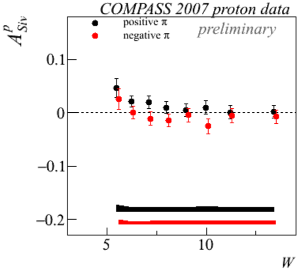
Sivers Asymmetries for $\pi^{\pm}$ and K$^{\pm}$: NH_3 (2007)

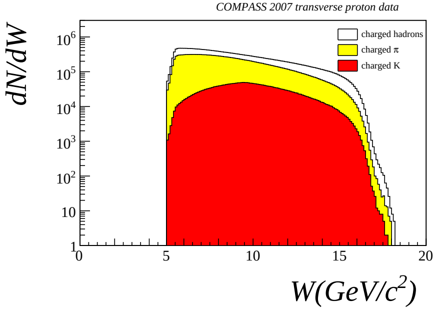
SPIN 2010



Sivers Asymmetries: NH_3 (2007)







possible W dependence

twist-2

twist-3

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

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ \dots$$

Sivers ✓

Collins ✓

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

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

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

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

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

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COMPASS

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

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twist-2

twist-3

Sivers ✓

Collins ✓

pretzelosity

worm-gear

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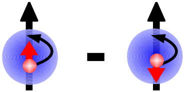
Pretzelosity

$F_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp,q} \otimes \Delta_T^0 D_q^h$, Pretzelosity PDF $h_{1T}^{\perp,q}$: 

correlation of parton transv. momentum and transv. polarization in a transversely polarized nucleon

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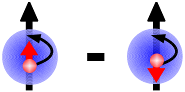
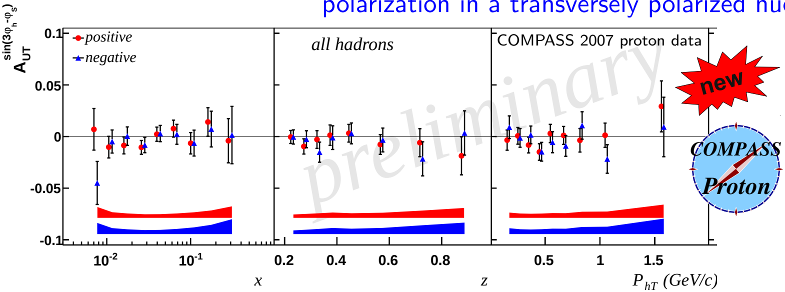


correlation of parton transv. momentum and transv. polarization in a transversely polarized nucleon



Pretzelosity: NH_3 (2007) & ^{6}LiD (2002-2004)

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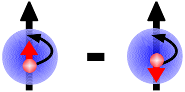
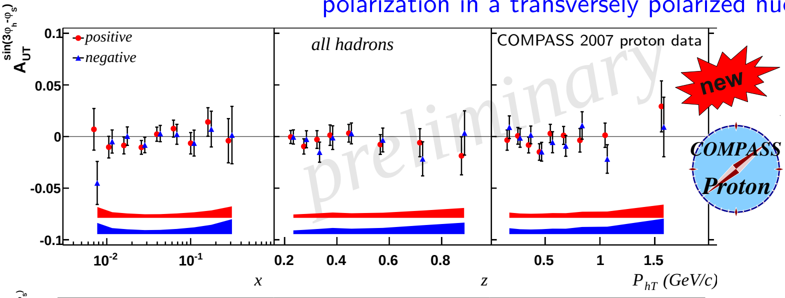
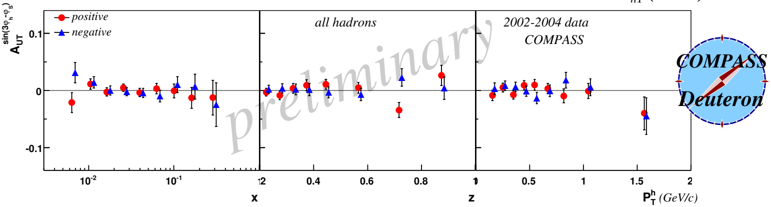


correlation of parton transv. momentum and transv. polarization in a transversely polarized nucleon

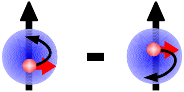




Worm-gear (TL)

$F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T}^q \otimes D_q^h,$

worm-gear PDF g_{1T}^q:



correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon

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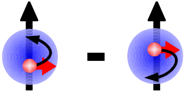
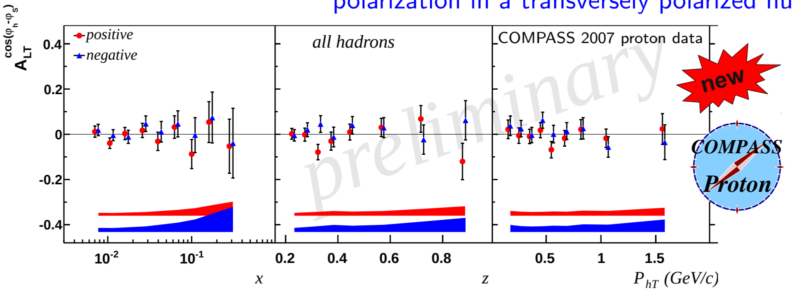


correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon



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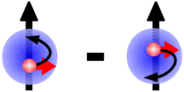
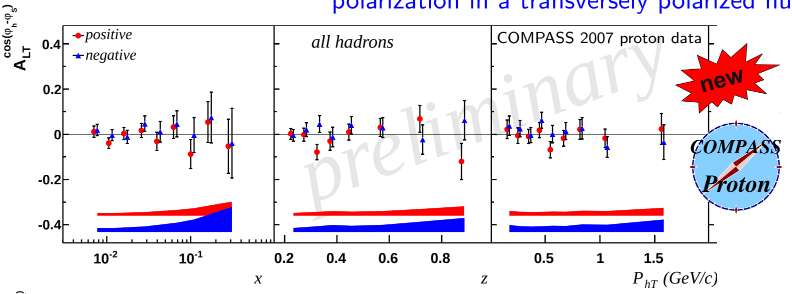
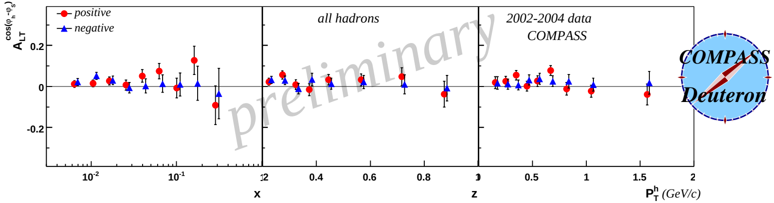
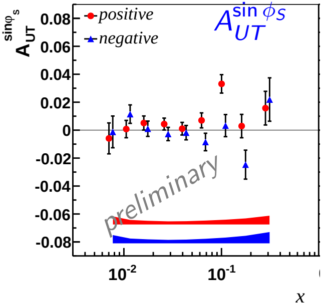


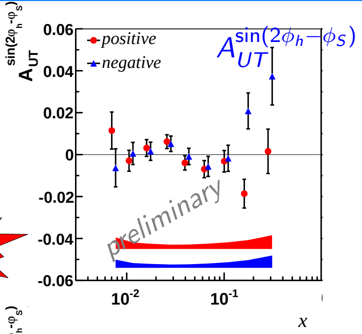
correlation of parton transv. momentum and long. polarization in a transversely polarized nucleon

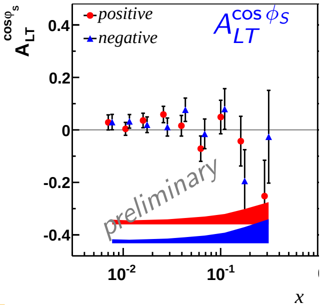


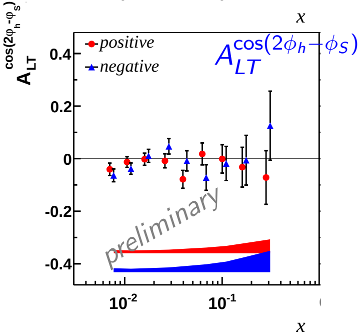


Twist-3 Structure Functions: NH_3 (2007)









SIDIS Cross-Section: unpolarized target

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

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

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

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- $F_{UU}^{\cos\phi}$ and $F_{UU}^{\cos 2\phi}$: Cahn Effect + Boer-Mulders $\cancel{(+\text{ pQCD})}$
- $F_{LU}^{\sin\phi_h}$: beam asymmetry (beam polarization: $P_{\mu^+} \approx -80\,\%$)

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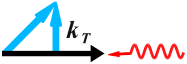
Cahn Effect 

kinematical effect due to transv. momentum of partons in the nucleon

- $F_{UU}^{\cos\phi}$ and $F_{UU}^{\cos 2\phi}$: Cahn Effect + Boer-Mulders ~~(+ pQCD)~~
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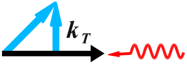
Cahn Effect


kinematical effect due to transv. momentum of partons in the nucleon

Boer-Mulders $h_1^\perp$:

correlation of parton transv. momentum and transv. polarization in an unpolarized nucleon

- $F_{UU}^{\cos\phi}$ and $F_{UU}^{\cos 2\phi}$: Cahn Effect + Boer-Mulders ~~(+ pQCD)~~
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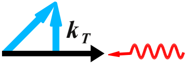
Cahn Effect 

kinematical effect due to transv. momentum of partons in the nucleon

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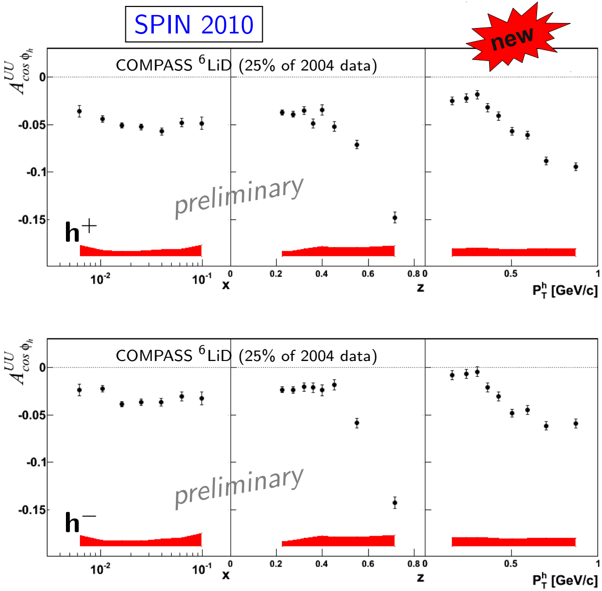
- $F_{LU}^{\sin\phi_h}$: beam asymmetry (beam polarization: $P_{\mu^+} \approx -80\,\%$)
- Target polarization canceled by event weighting
- Detector acceptance corrected by MC simulation

SPIN 2010

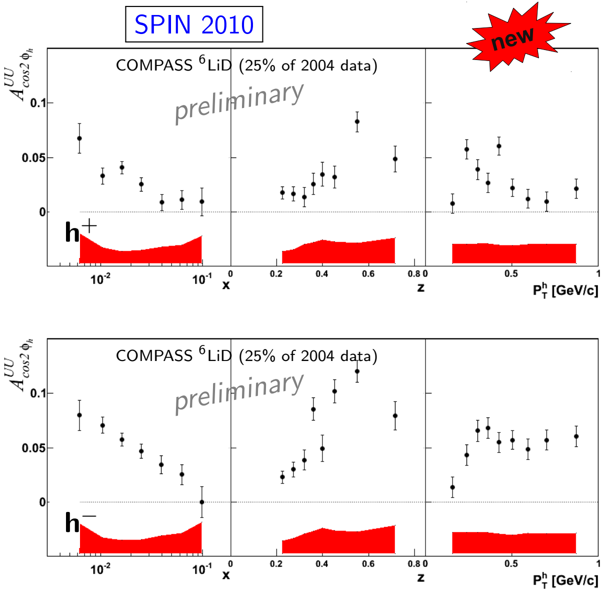


$A^{UU}_{\cos\phi}$: Mainly Cahn effect

- Large negative asymmetries
- Charge dependent

Unpolarized Asymmetries: ^{6}LiD (2004 part)

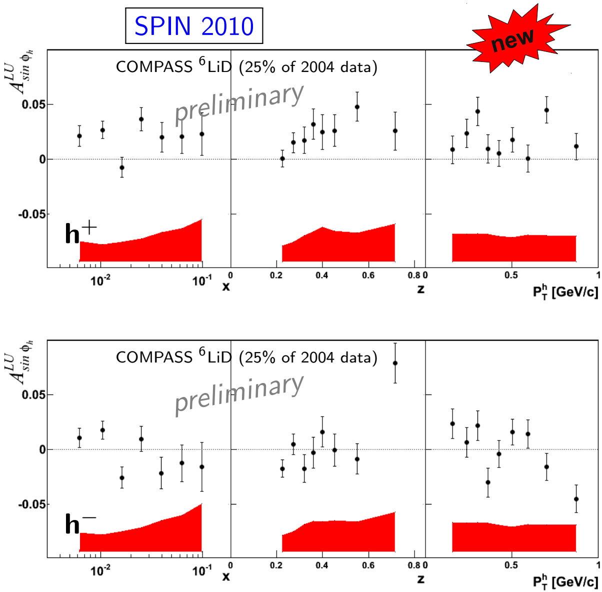
SPIN 2010



$A^{UU}_{\cos 2\phi}$: Boer-Mulders TMD

$+\text{Cahn} \propto \left(\frac{k_\perp}{Q}\right)^2$

- Large positive asymmetries
- Charge dependent



$A^{LU}_{\sin\phi}$: twist-3 effect due to beam polarization

- h^+ positive asymmetry
- h^- small asymmetry, compatible with zero

Summary

Many new results from COMPASS:

- Collins asymmetries for $\pi^\pm$ and $K^\pm$ for deuteron and proton target
  $\rightsquigarrow$ New proton results ready to be used in a global analysis
- Dihadron asymmetries for deuteron and proton target
  $\rightsquigarrow$ Ultimate cross-check for Transversity extraction
- Sivers asymmetries for $\pi^\pm$ and $K^\pm$ for deuteron and proton target
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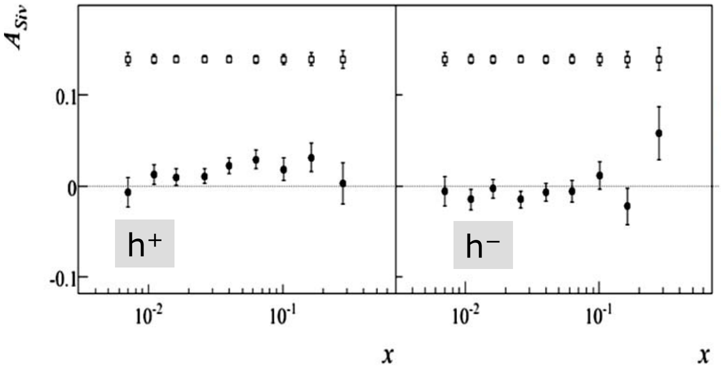
COMPASS is a major player in nucleon spin physics

One full year with transverse data taking has nearly finished



2010 run (proj)

COMPASS 2007

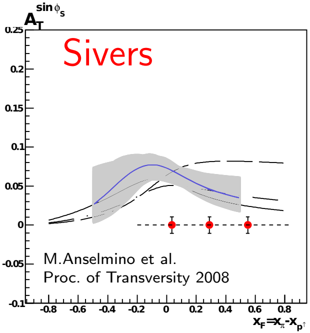
PLB 692 (2010) 240

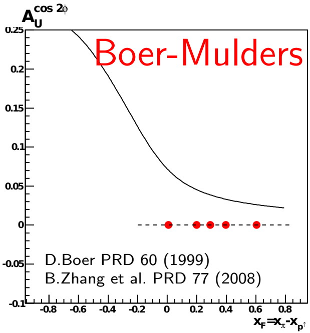
COMPASS-II proposal approved by SPSC

...proposal for two years GPD and two years DY...

$$\pi P^{\uparrow} \rightarrow \mu\bar{\mu}X$$

Predictions and expected statistical errors ($2\ \mathrm{GeV}/c^2 < M_{\mu\mu} < 2.5\ \mathrm{GeV}/c^2$)





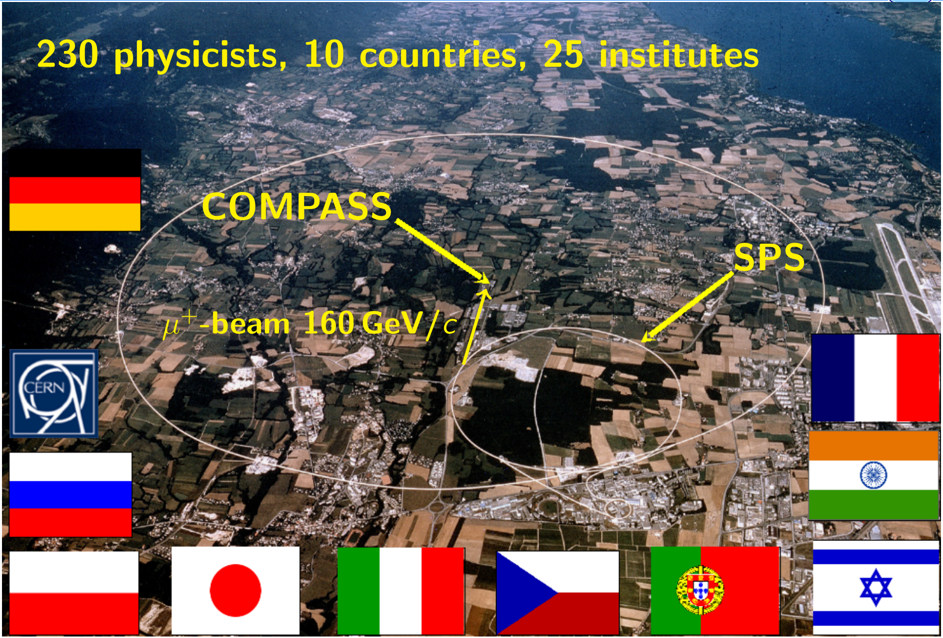
End

Thank You

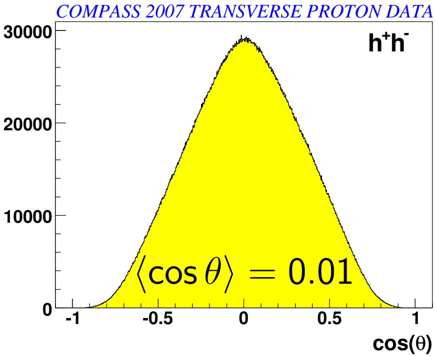
email: heiner.wollny@cern.ch

Back Up

COMPASS Experiment



Measuring transversity with polarized Dihadron-Interference-FF $H_1^{\sphericalangle}$:



$\rightsquigarrow$ azimuthal asymmetry:

$$N_{h^+h^-} \;\propto\; 1 \pm A \cdot \sin\phi_{RS} \cdot \sin\theta$$

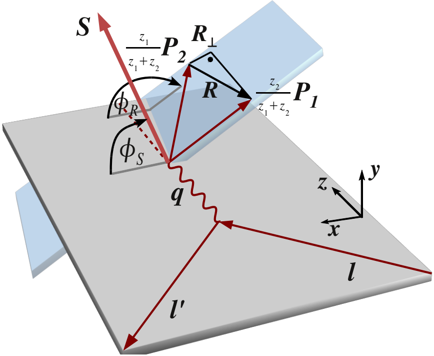
$$\phi_{RS} = \phi_R + \phi_S - \pi$$

$$A_{RS} = \frac{A}{f\ P_T D_{nn}} \propto \sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\sphericalangle}$$

$$H_1^{\sphericalangle} = H_1^{\sphericalangle,sp} + \cos\theta\, H_1^{\sphericalangle,pp}$$

$\rightsquigarrow$ only sensitive to $H_1^{\sphericalangle,sp}$

Definition of R_T and ϕ_R

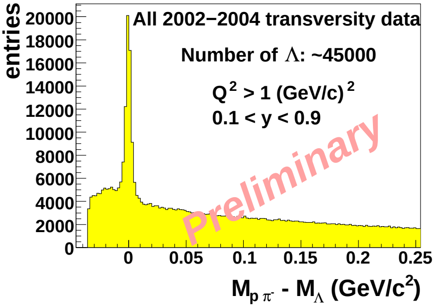


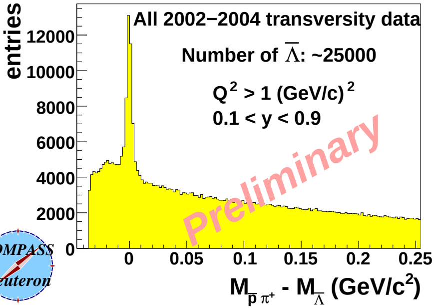
$$\mathbf{R_T} = \frac{z_2\mathbf{P_{1T}} - z_1\mathbf{P_{2T}}}{z_1+z_2}$$

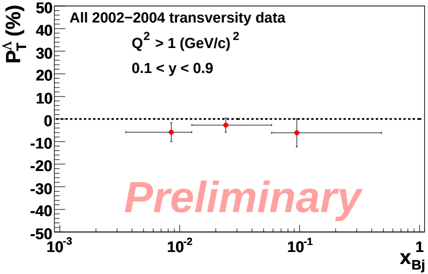
$$\cos\phi_R = \frac{\vec{q}\times\vec{\ell}}{|\vec{q}\times\vec{\ell}|} \cdot \frac{\vec{q}\times\vec{R}_T}{|\vec{q}\times\vec{R}_T|},$$

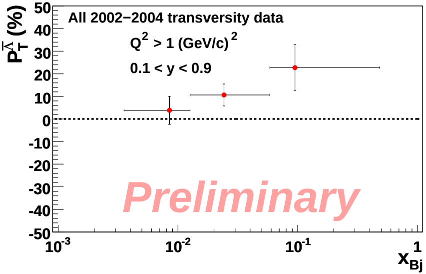
$$\sin\phi_R = \frac{(\vec{\ell}\times\vec{R}_T)\cdot\hat{q}}{|\hat{q}\times\vec{\ell}||\hat{q}\times\vec{R}_T|}$$

Transverse Λ-Polarization: ^{6}LiD (2002-2004)



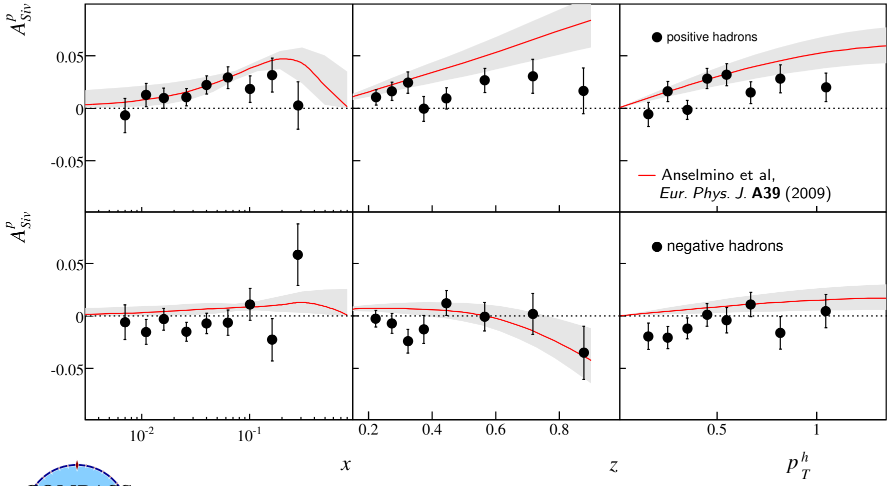






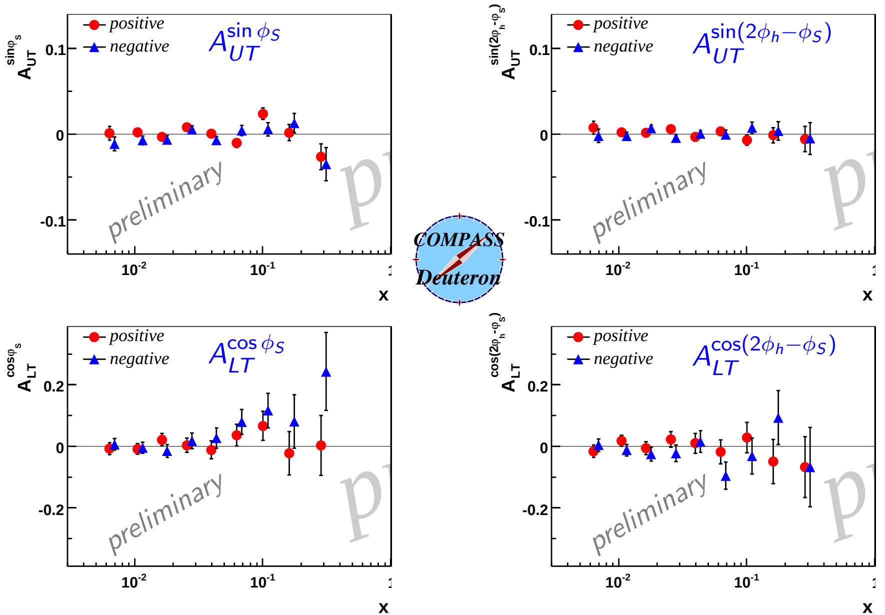
systematical errors are smaller than the statistical ones

Sivers Asymmetries: NH_3 (2007)



Predictions from fit to COMPASS deuteron and HERMES proton SIDIS data

Twist-3 Structure Functions: ^{6}LiD (2002-2004)



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{\ \cdots$$
$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\ \sin\phi_h\,\boxed{F_{UL}^{\sin\phi_h}}+\varepsilon\sin(2\phi_h)\,\boxed{F_{UL}^{\sin 2\phi_h}}\right]$$
$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,\boxed{F_{LL}}+\sqrt{2\,\varepsilon(1-\varepsilon)}\ \cos\phi_h\,\boxed{F_{LL}^{\cos\phi_h}}\right]$$

`A.Bacchetta et al`

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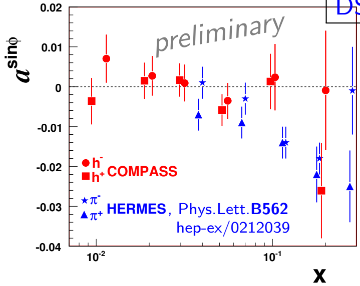
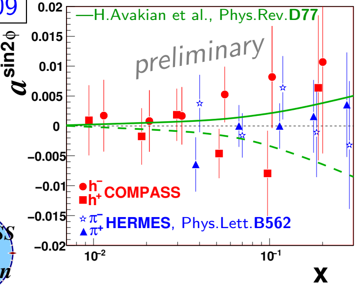
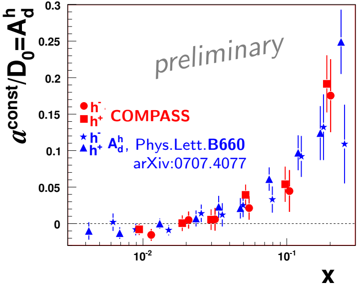
- $F_{LL} \propto \Delta q \otimes D_q^h$
- $F_{UL}^{\sin\phi_h}$, $F_{UL}^{\sin 2\phi_h}$, $F_{LL}^{\cos\phi_h}$: twist-3, complex parton picture

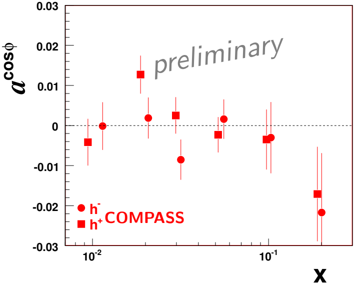
Longitudinally Polarized Target: ^{6}LiD (2002-2004)

DSPIN 2009









Publication is on the way

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