



Transverse Spin Effects and TMDs in Semi-Inclusive DIS

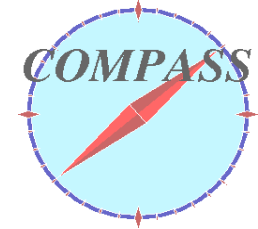
from the COMPASS Experiment
at CERN



Rainer Joosten
University of Bonn



COMPASS



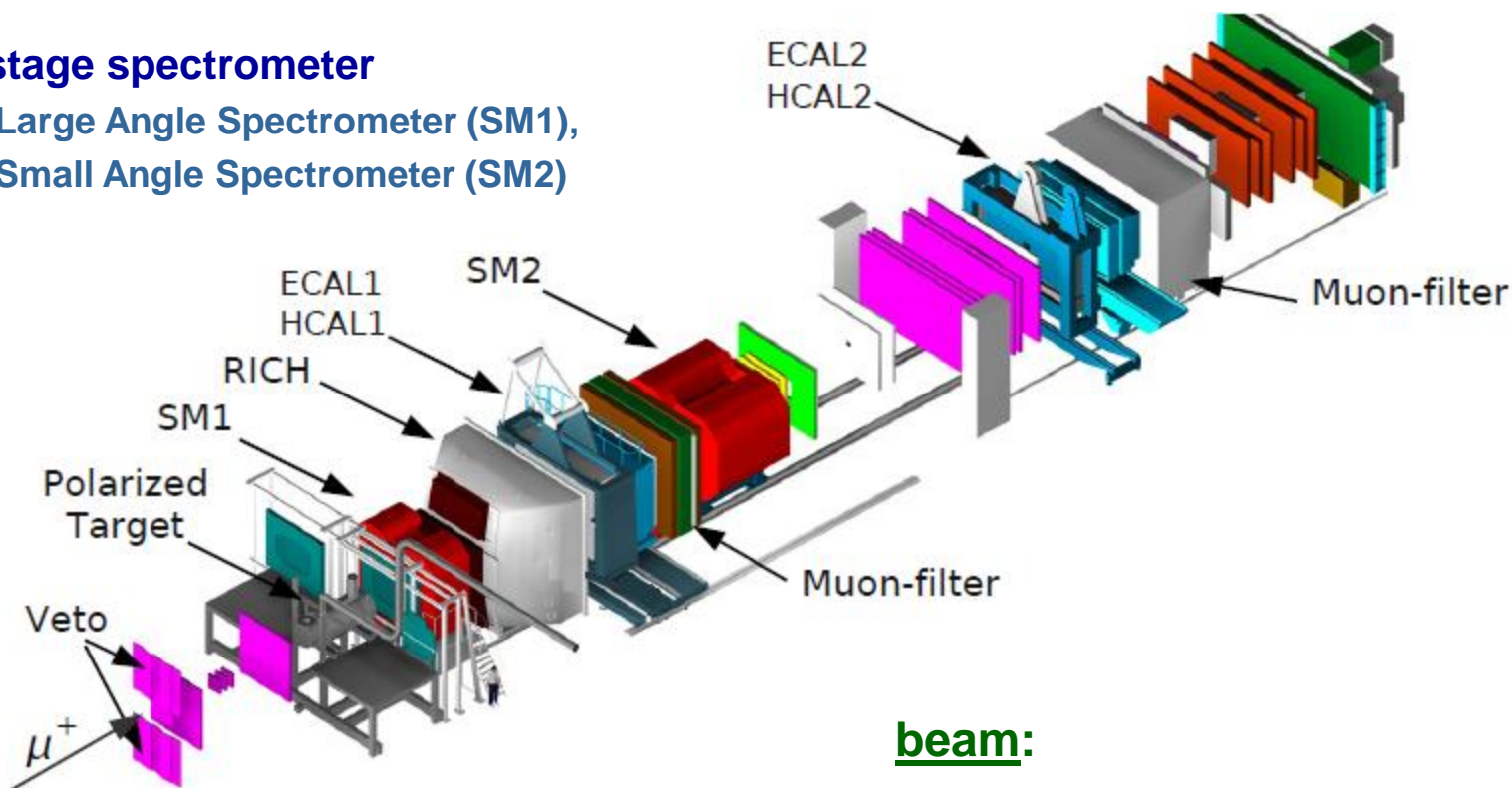
- high energy beam
- large angular acceptance
- broad kinematical range

$$0.003 < x < 0.7$$

$$10^{-3} < Q^2 < 10^2 \text{ (GeV/c)}^2$$

two stage spectrometer

Large Angle Spectrometer (SM1),
Small Angle Spectrometer (SM2)



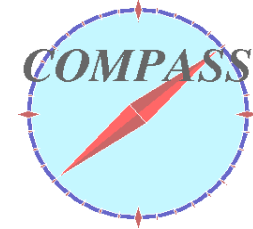
beam:

160 GeV/c

longitudinal polarisation -76%

intensity $2 \cdot 10^8 \mu^+/\text{spill}$ (4.8s/16.2s)

COMPASS



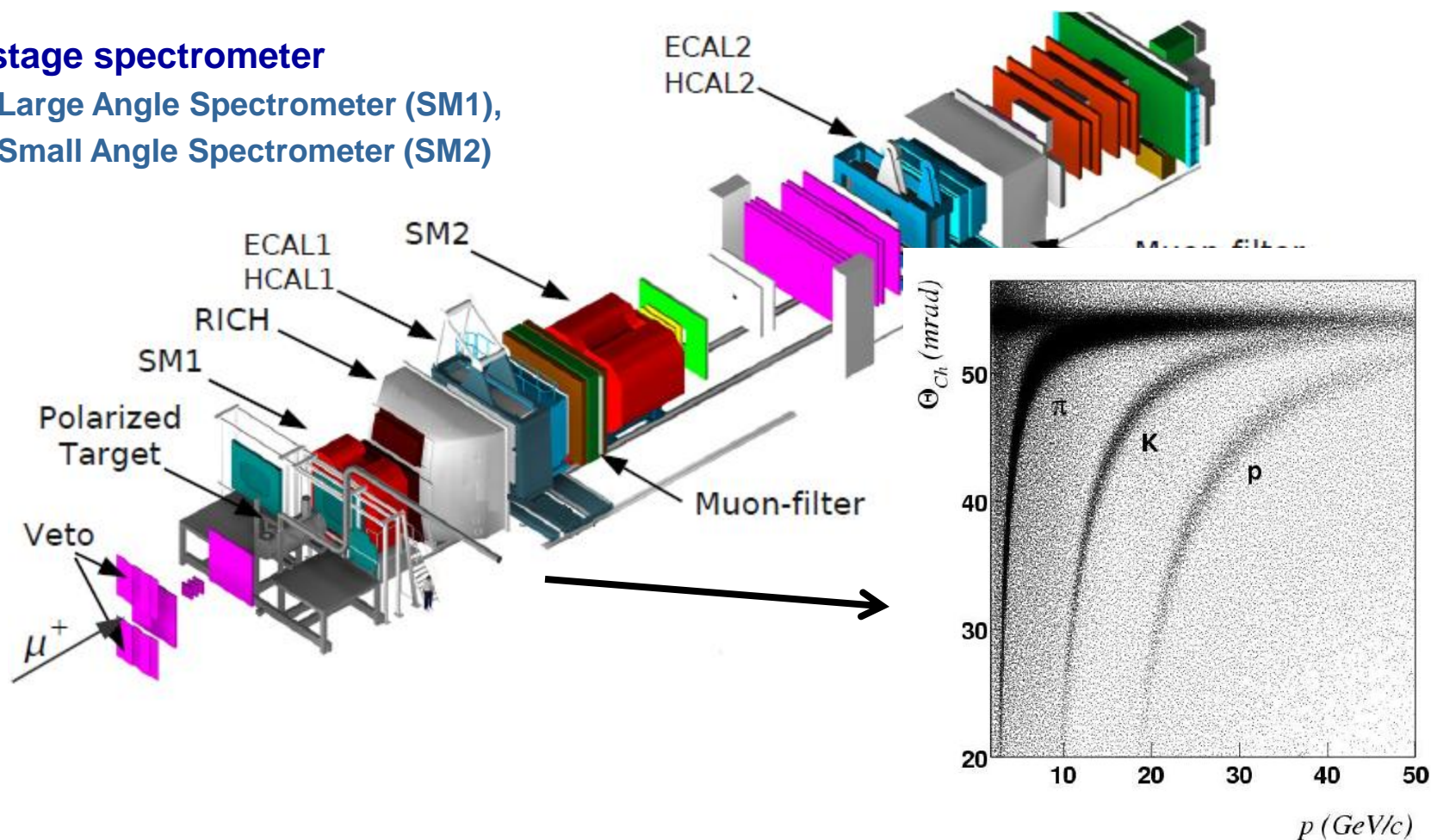
- high energy beam
- large angular acceptance
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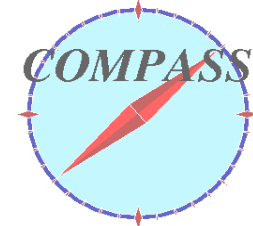
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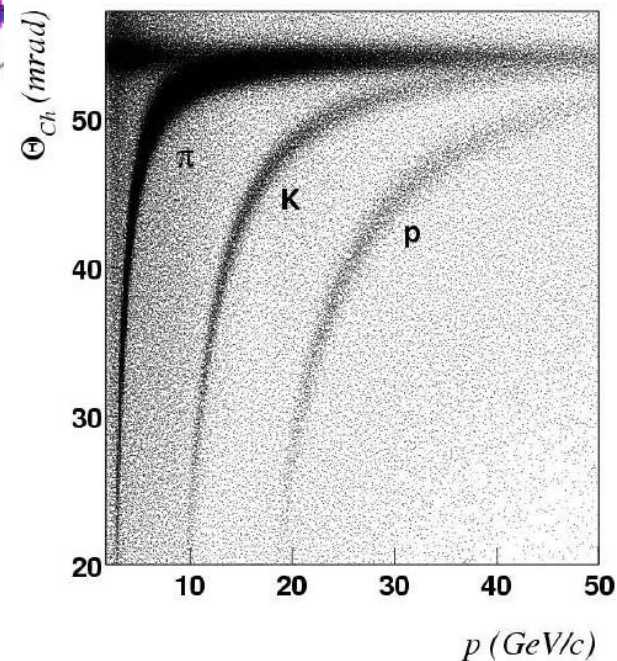
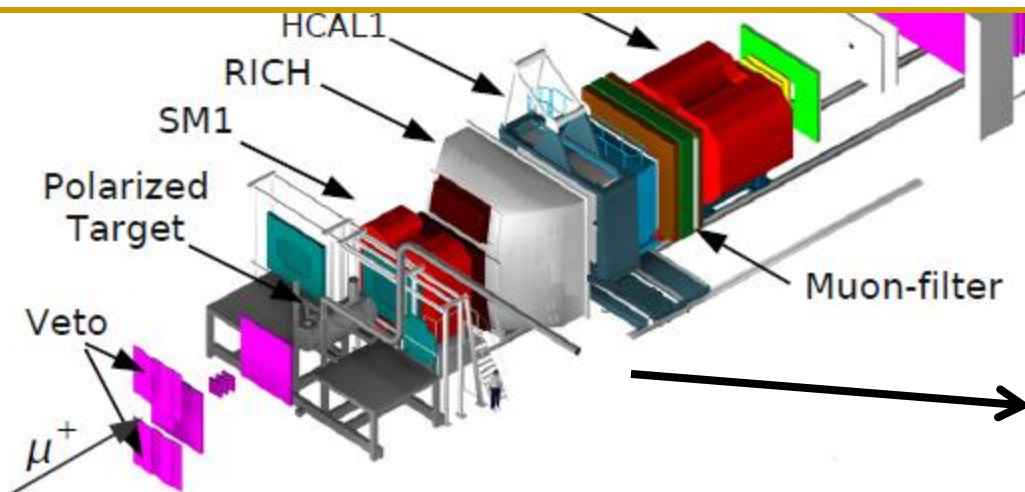
Polarized Target:

2002-2004: ${}^6\text{LiD}$ ($P_T \approx 50\%$, $f = 0.38$)

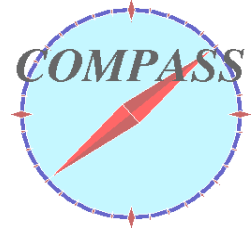
2007: NH_3 ($P_T \approx 90\%$, $f = 0.14$)

solid state targets

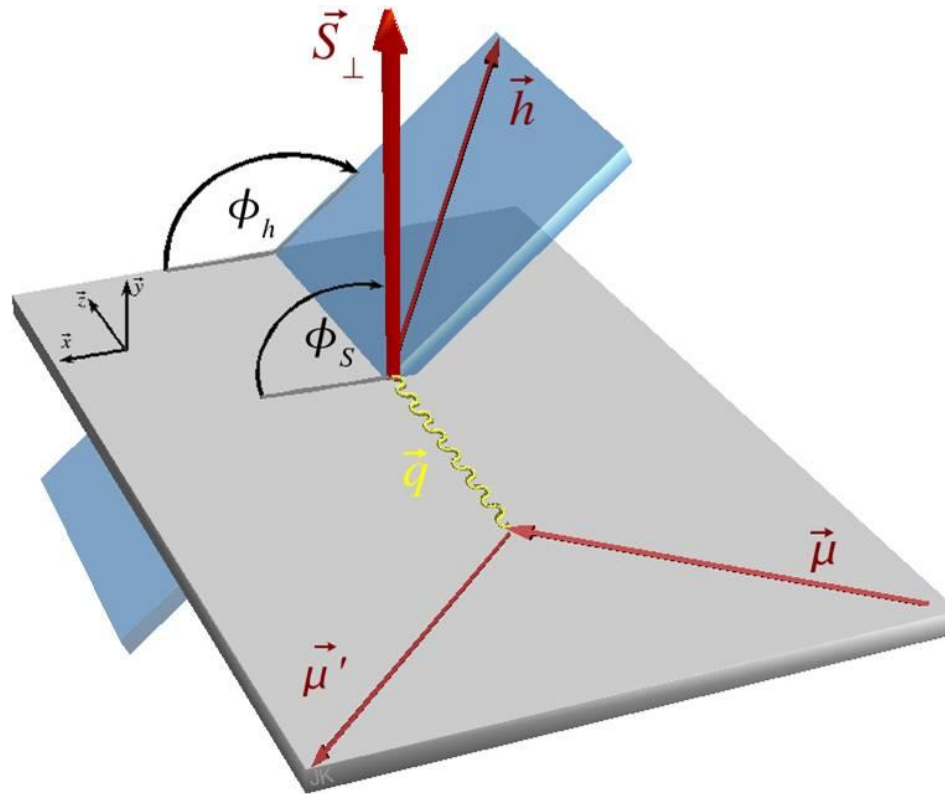
Polarization reversal: once a week



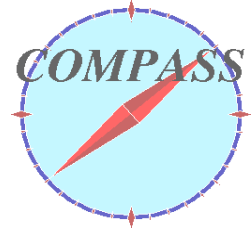
Perspective of the talk



SIDIS reactions in one photon exchange

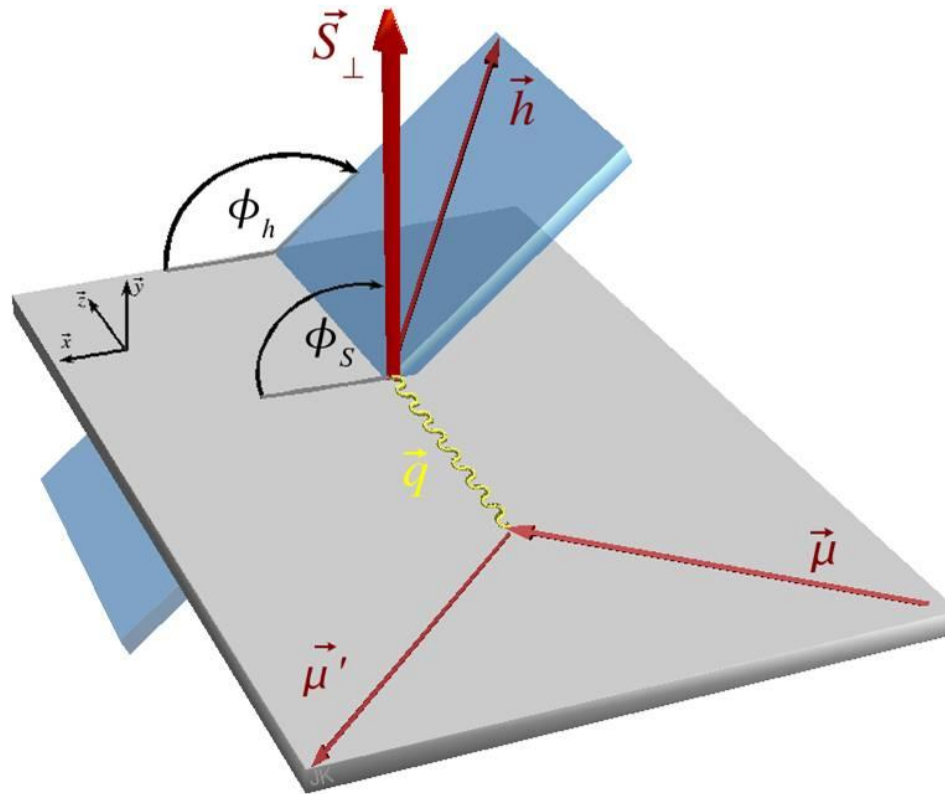


Perspective of the talk

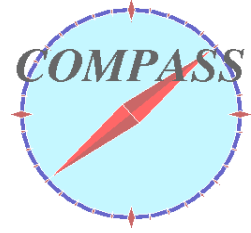


SIDIS reactions in one photon exchange

$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

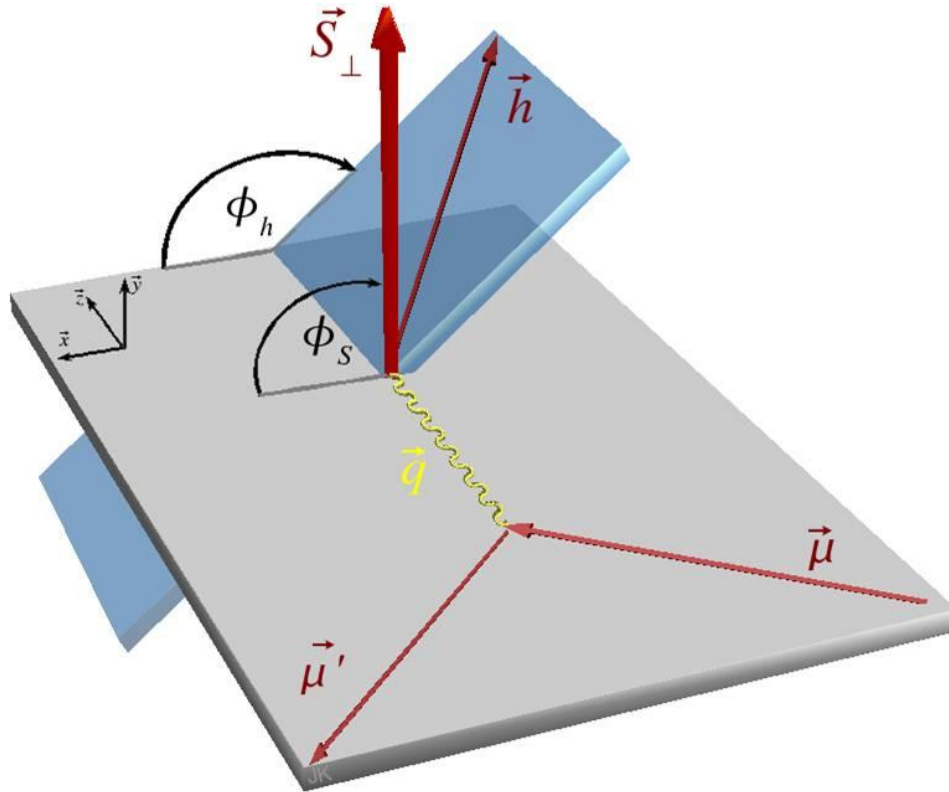


Perspective of the talk



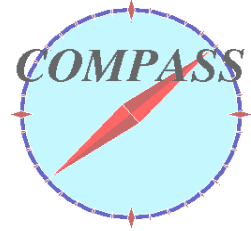
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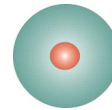


With different targets (p, d, n) and identification of the final hadron:
flavour separation

The collinear case

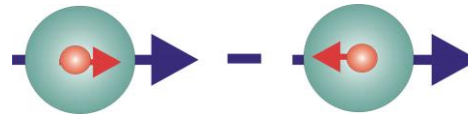
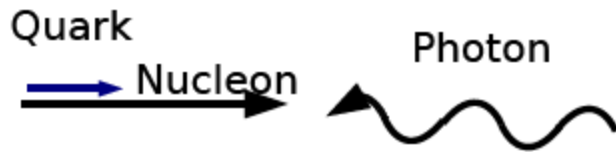


In the collinear QPM



$$f_1(x) = q^+(x) + q^-(x)$$

$f_1(x)$



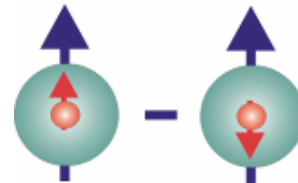
$$g_1(x) = q^+(x) - q^-(x)$$

$g_1(x)$

or integrated over k_T

Helicity

three quark distribution functions contribute in leading order



$$h_1(x) = q_T^\uparrow(x) - q_T^\downarrow(x)$$

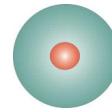
$h_1(x)$

Transversity

The collinear case

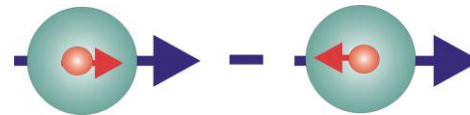
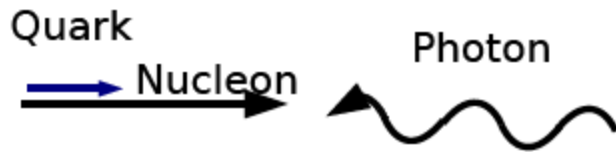


In the collinear QPM



$$f_1(x) = q^+(x) + q^-(x)$$

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or integrated over k_T

three quark distribution functions contribute in leading order

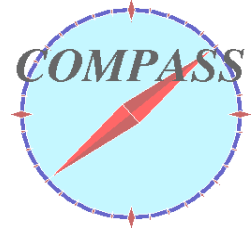


$$h_1(x) = q_T^\uparrow(x) - q_T^\downarrow(x)$$

$h_1(x)$

Helicity

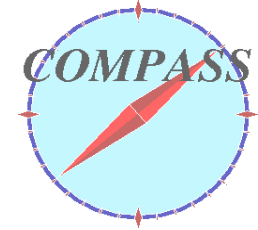
Transversity



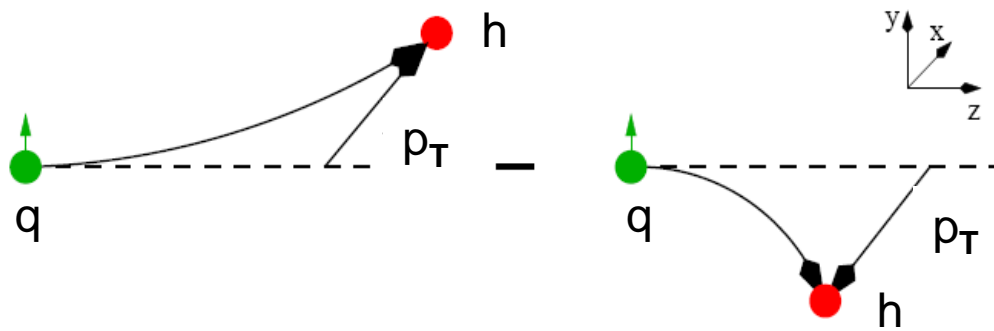
3 approaches in SIDIS:

- **Azimuthal asymmetries in one hadron production**
(Collins effect)
- **Azimuthal asymmetries in hadron pair production**
(Interference fragmentation functions)
- **Transverse hyperon (Λ) polarization**

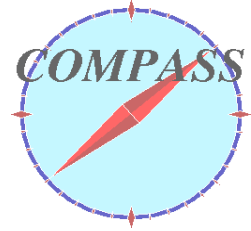
Collins-Effect



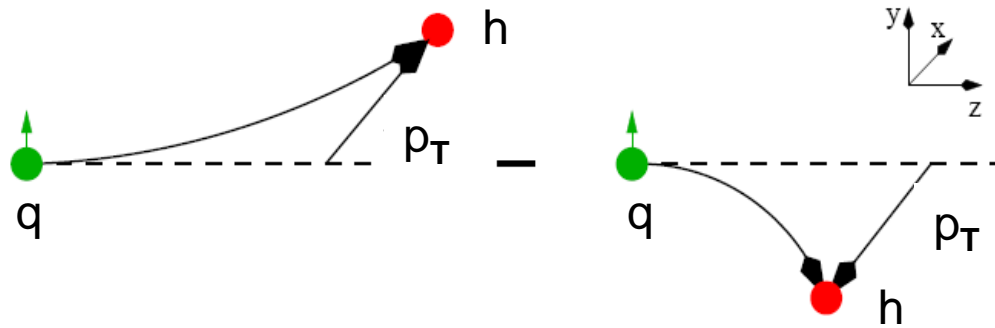
The Collins FF $H_1^{\perp q}(z, p_T)$ correlates the
transverse spin of the fragmenting quark and the
transverse momentum p_T of produced hadron h



Collins-Effect



The Collins FF $H_1^{\perp q}(z, p_T)$ correlates the
transverse spin of the fragmenting quark and the
transverse momentum p_T of produced hadron h



Measured asymmetry:

$$F_{UT}^{\sin(\phi_h + \phi_s)} \propto h_1 \otimes H_1^{\perp}$$

$$A_{\text{Coll}} \propto \frac{\sum_q e_q^2 h_1^q(x) \otimes H_1^{\perp q}(z, p_T)}{\sum_q e_q^2 f^q(x) \cdot D_q^h(z)}$$

Deuteron Results: Collins Effect

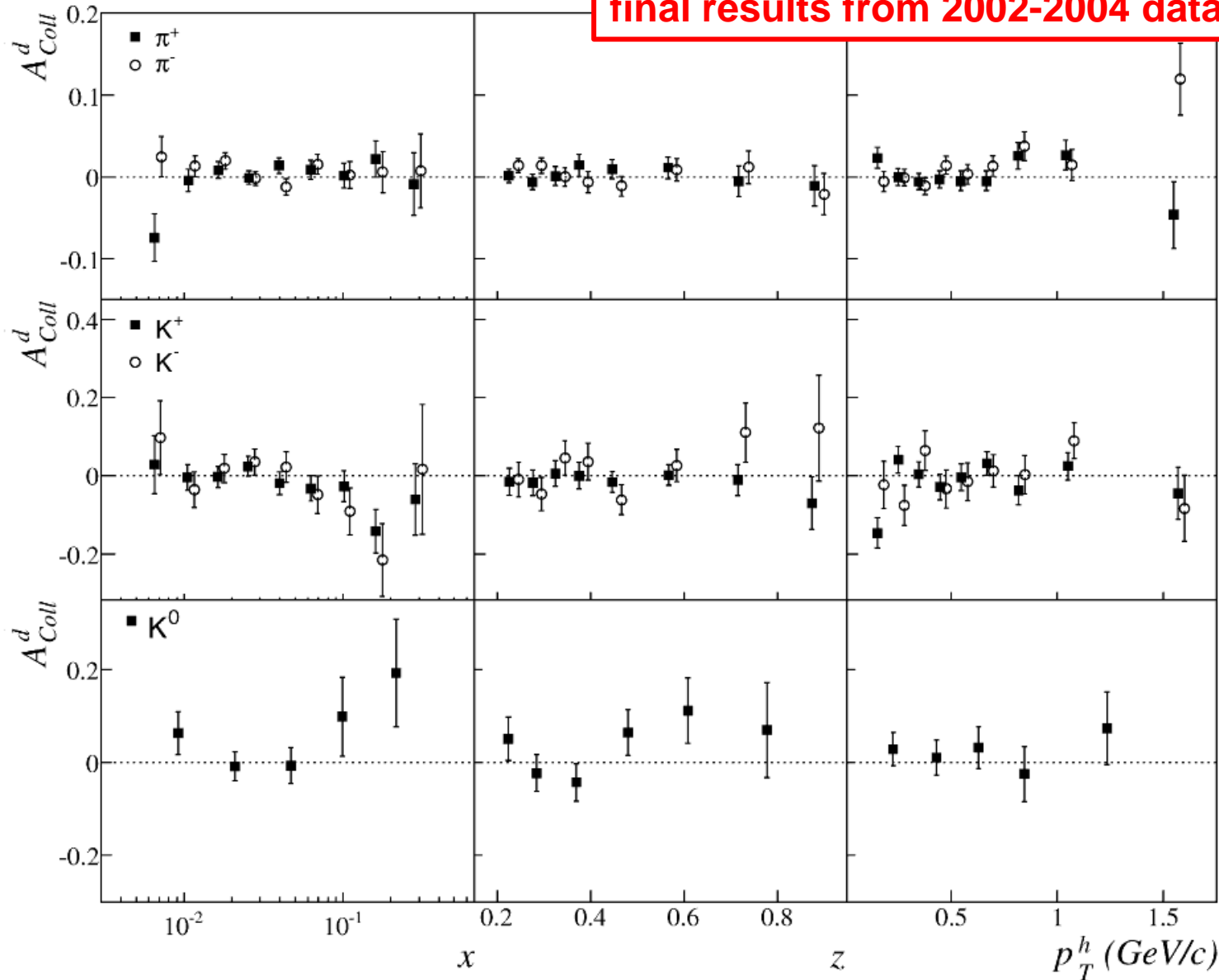


final results from 2002-2004 data

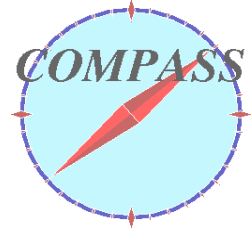
*Physics Letters
B 673 (2009)
127–135*

Deuteron
target

2002-2004

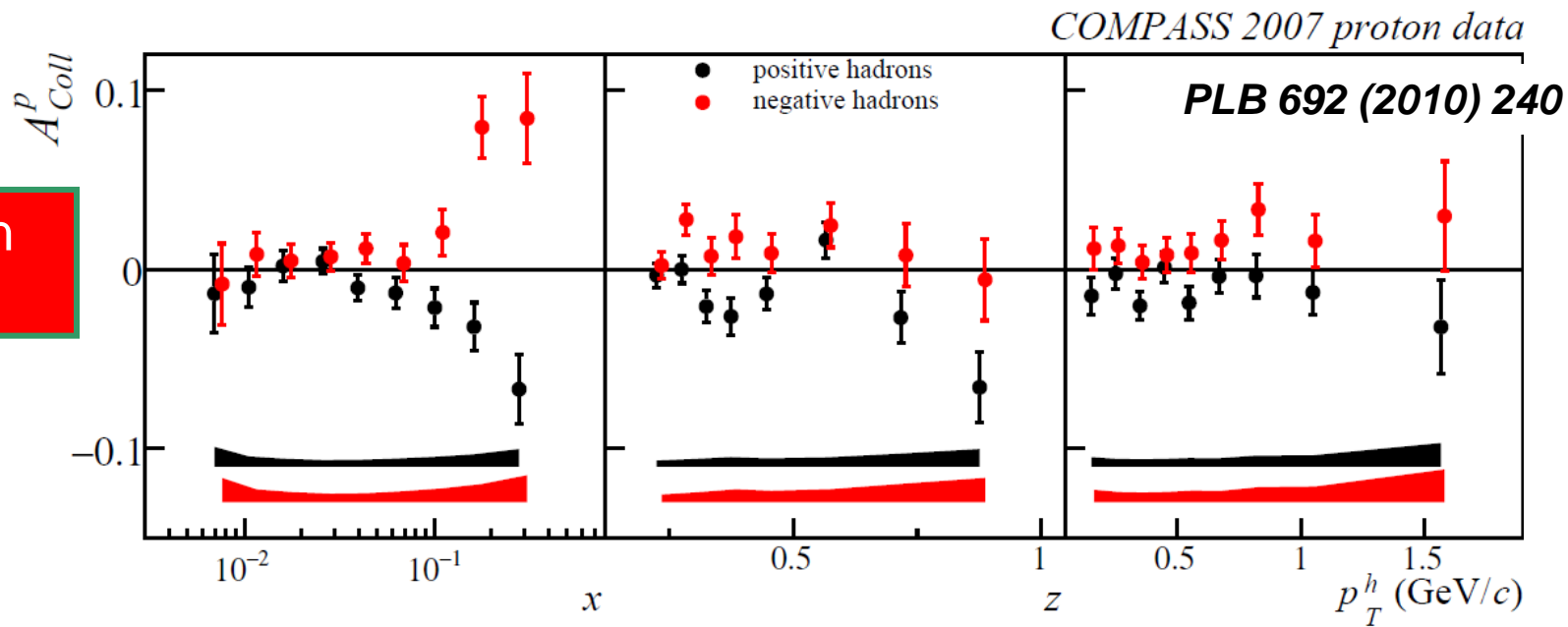


Collins asymmetry



Full 2007 statistics

Proton target



Collins asymmetry

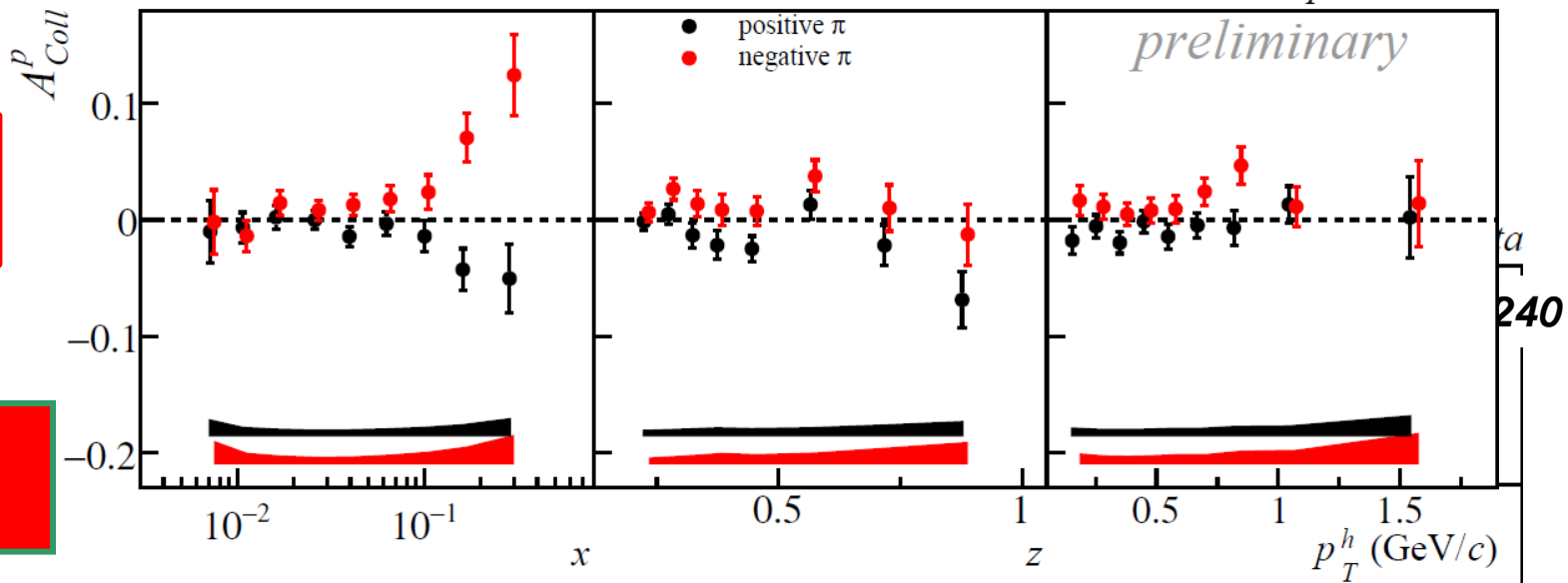


Full 2007 statistics

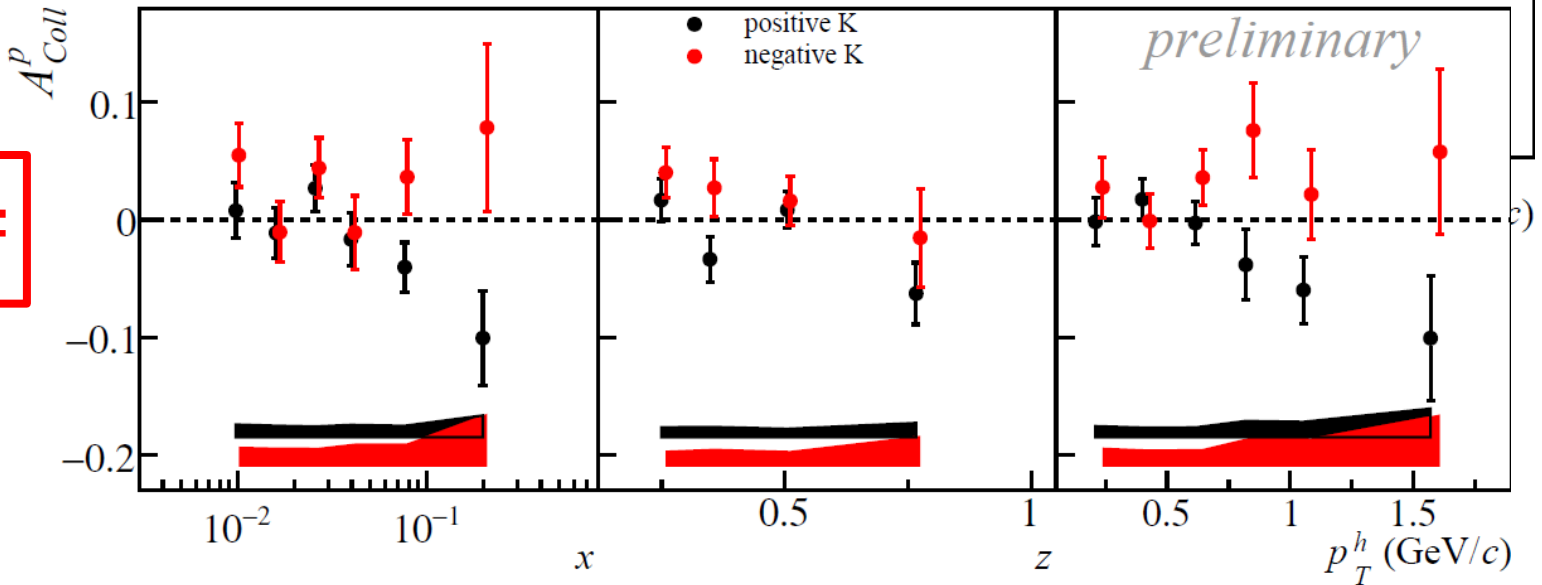
COMPASS 2007 proton data

π^\pm

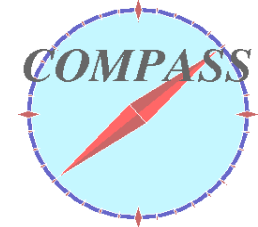
Proton target



K^\pm



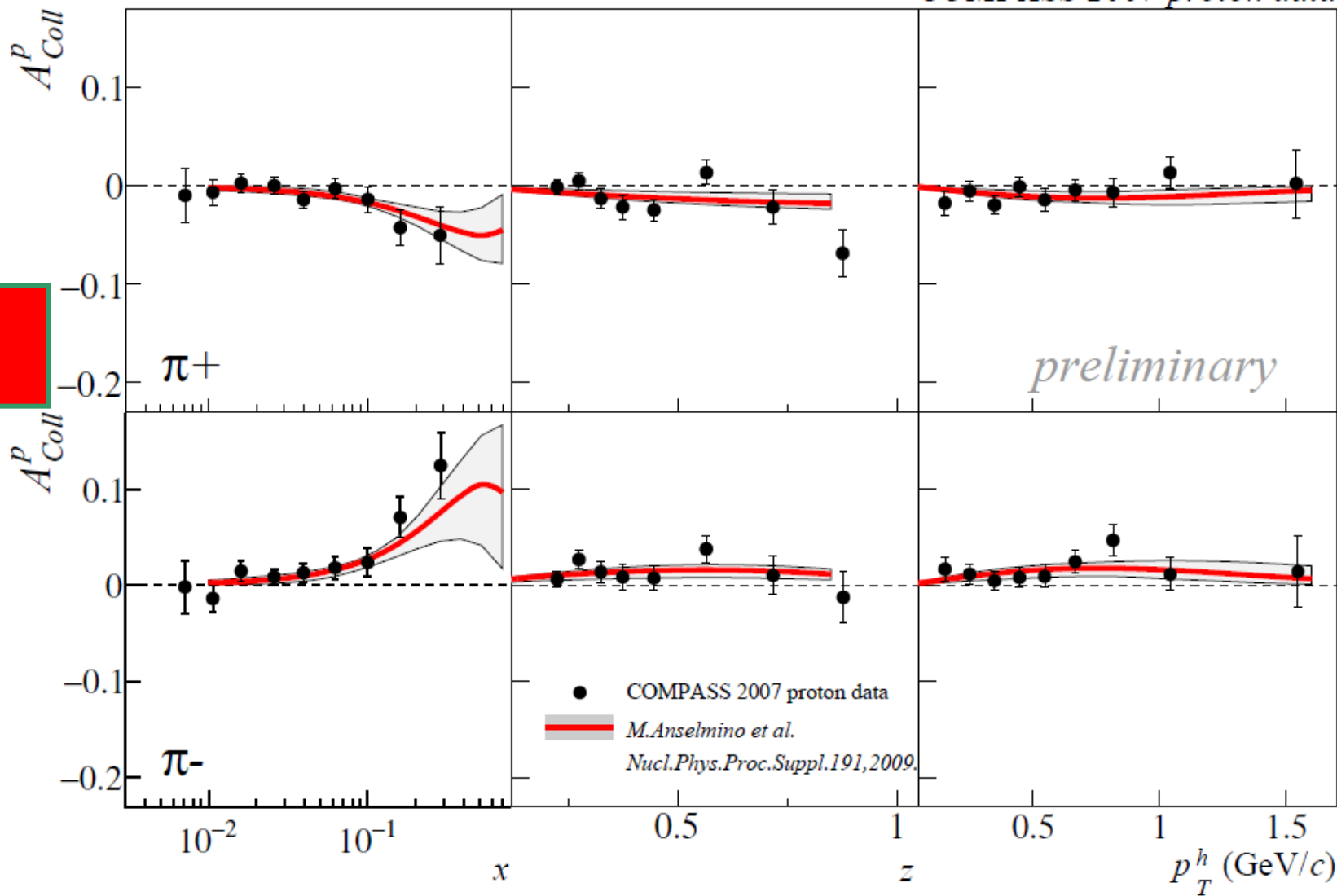
Collins asymmetry



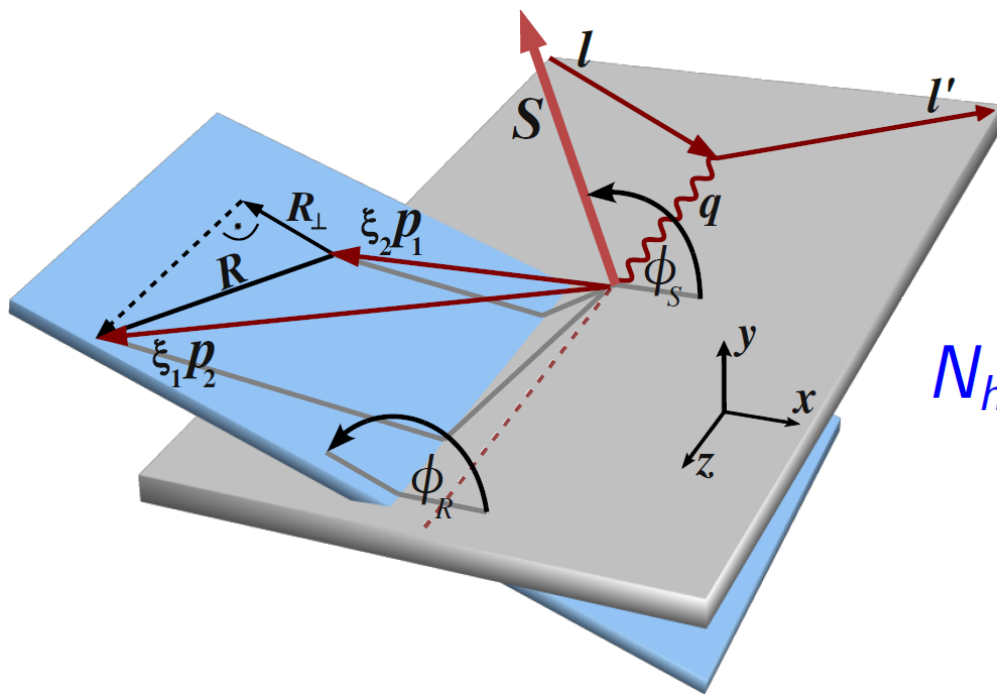
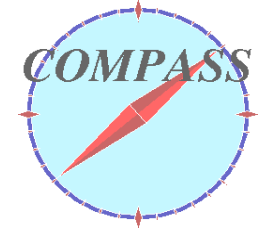
Full 2007 statistics

COMPASS 2007 proton data

Proton target

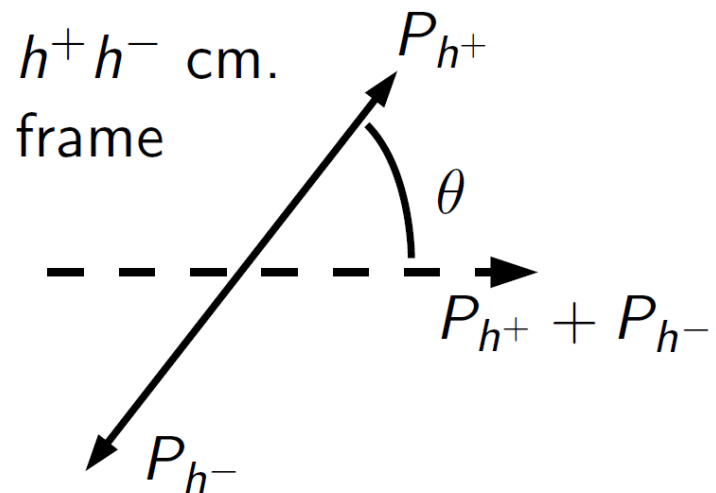


Transversity in 2-Hadron Production

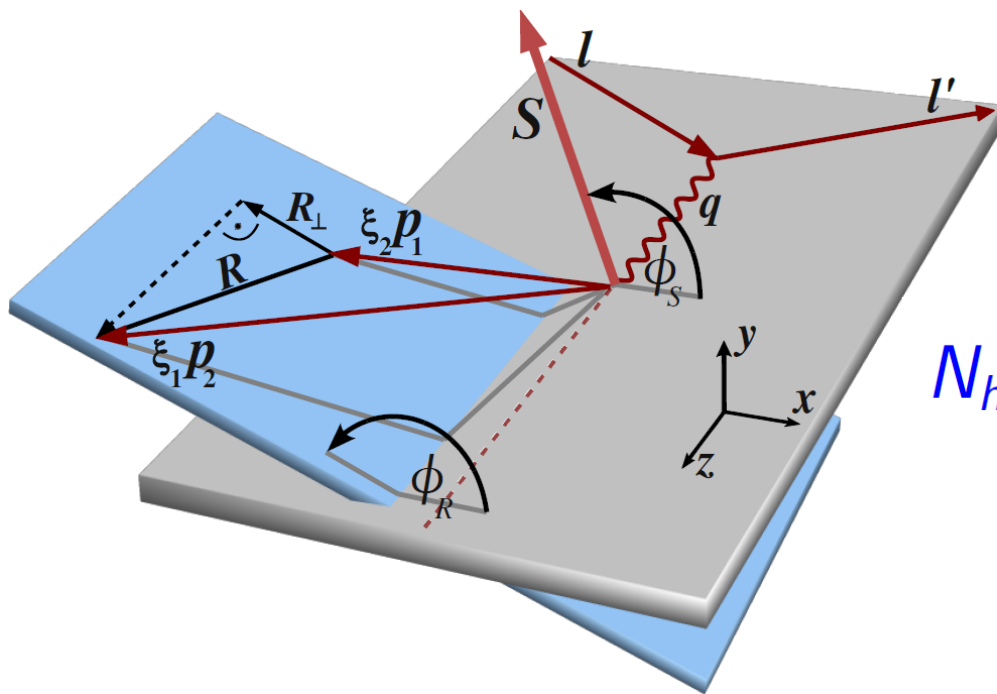
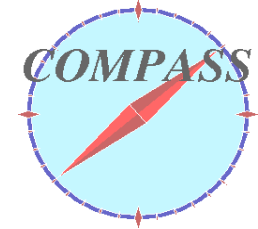


$$N_{h^+h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$$

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

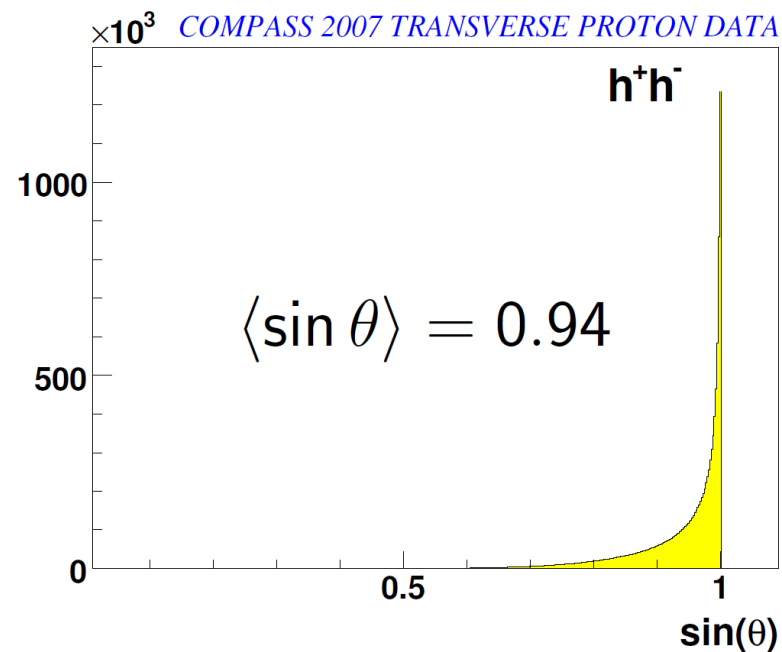


Transversity in 2-Hadron Production

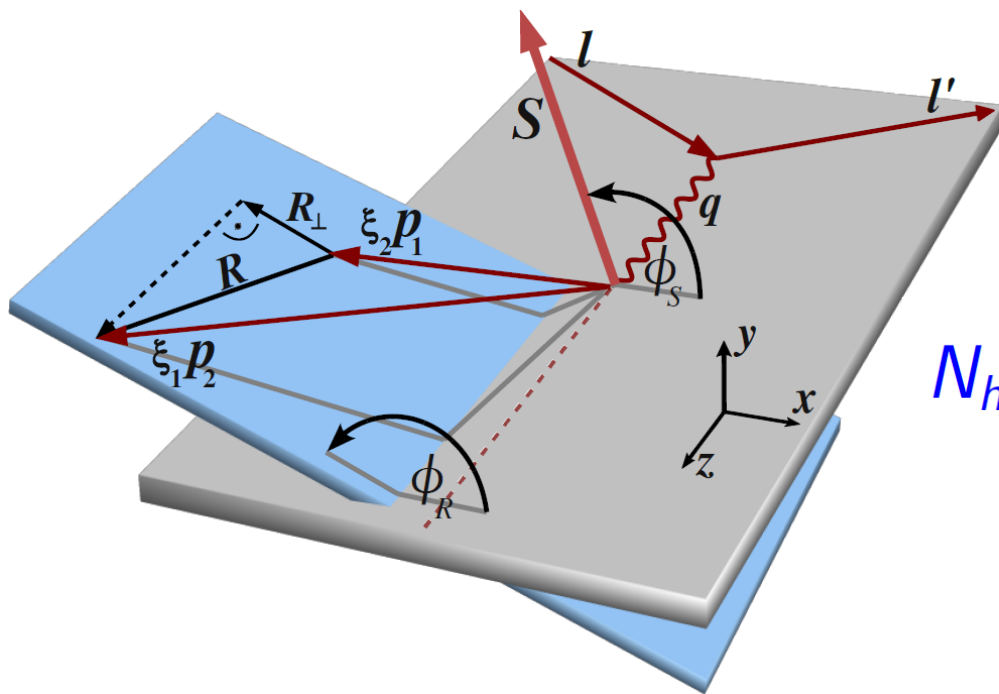


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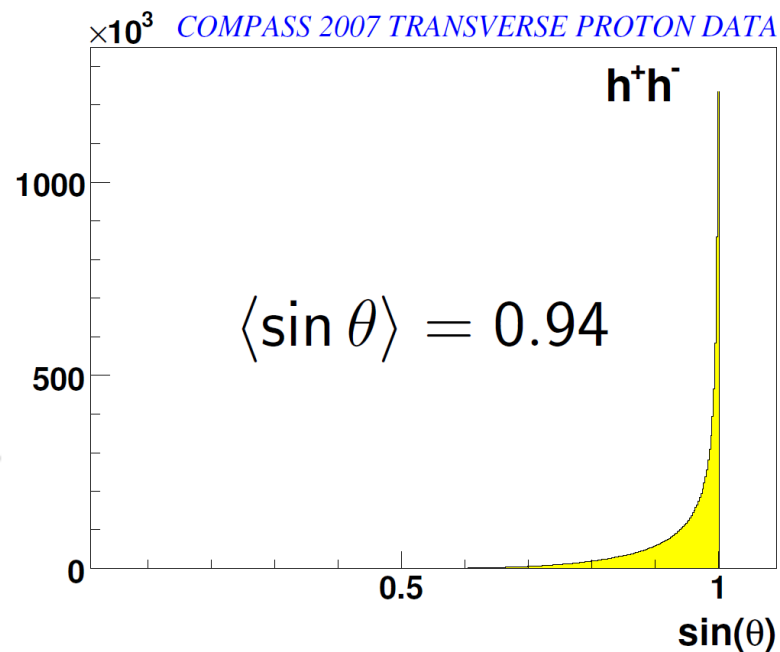
Transversity in 2-Hadron Production



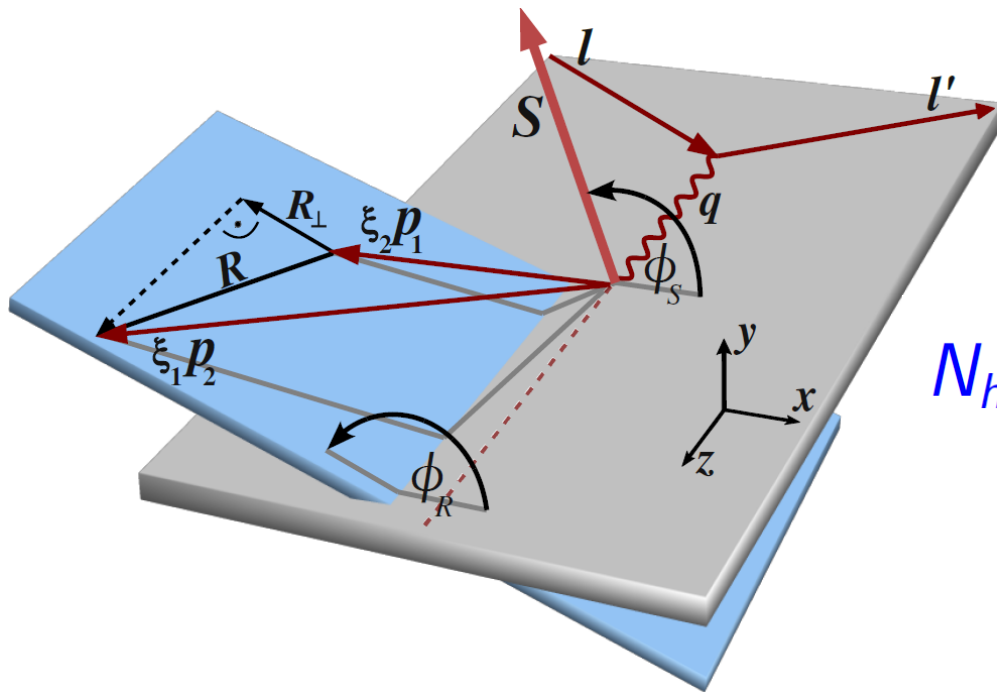
$$N_{h^+h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$$

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

$$A_{RS} = \frac{\sum_q e_q^2 \cdot h_1(x) \cdot H_1^{\leftarrow}(z, M_{h^+h^-}^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_1(z, M_{h^+h^-}^2)}$$



Transversity in 2-Hadron Production

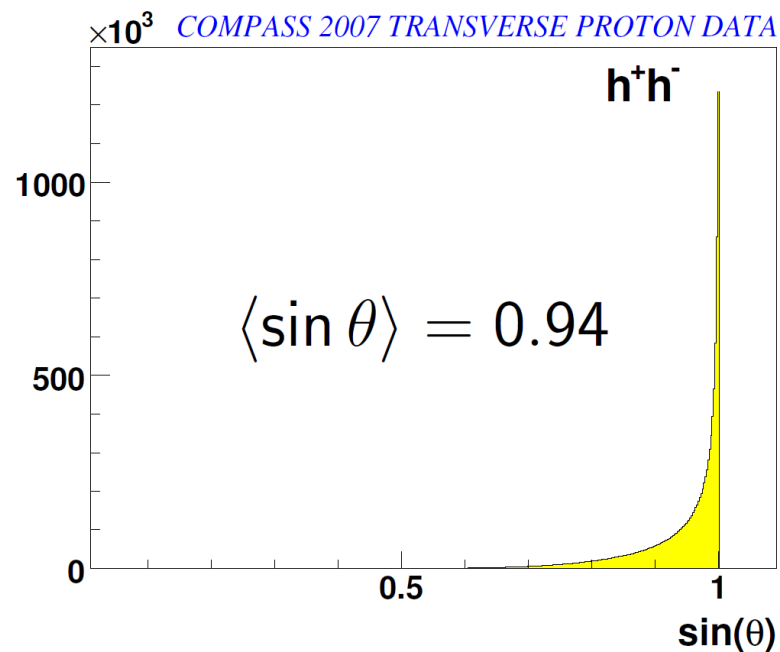


$$N_{h^+h^-} \propto 1 \pm A \cdot \sin \phi_{RS} \cdot \sin \theta$$

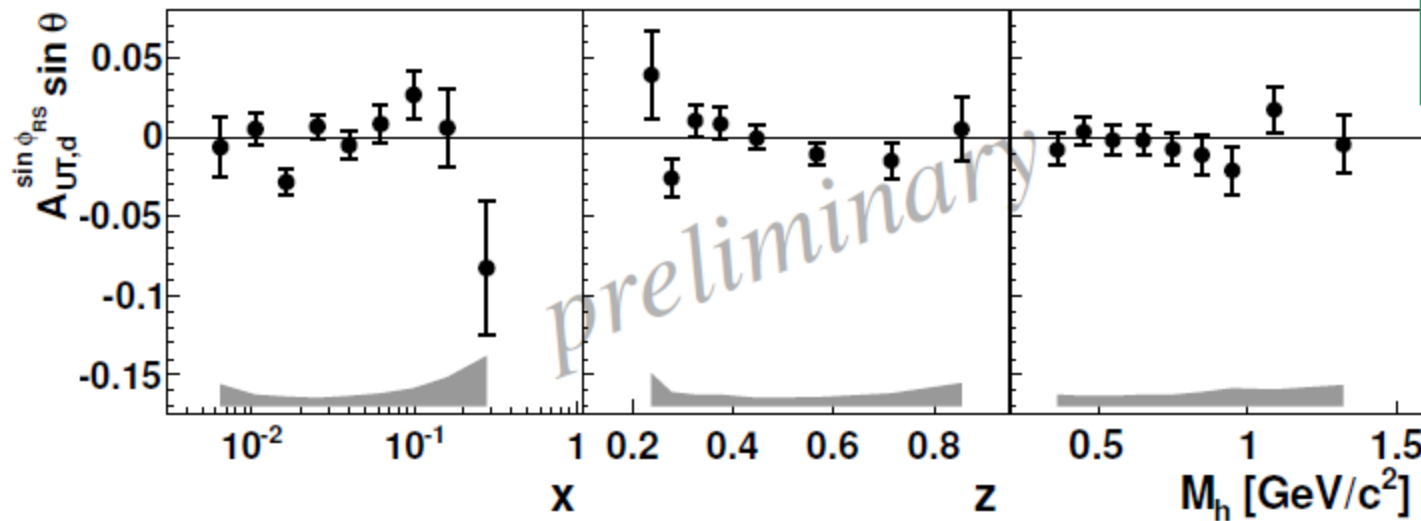
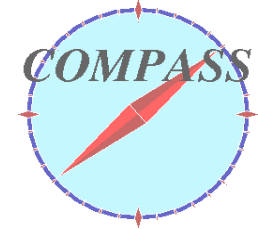
$$\phi_{RS} = \phi_R + \phi_S - \pi$$

$$h_1 \cdot H_1^{\triangleleft}$$

**Independent access
to transversity !**

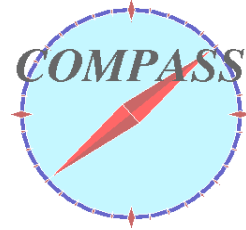


Transversity in 2-Hadron Production



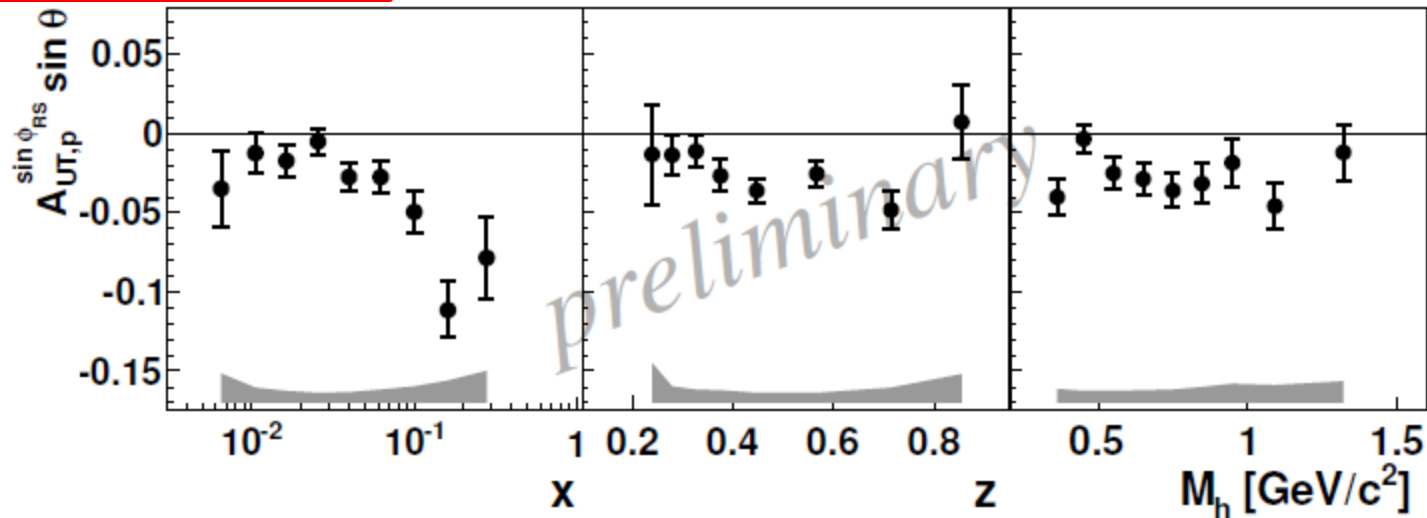
Deuteron target

Transversity in 2-Hadron Production

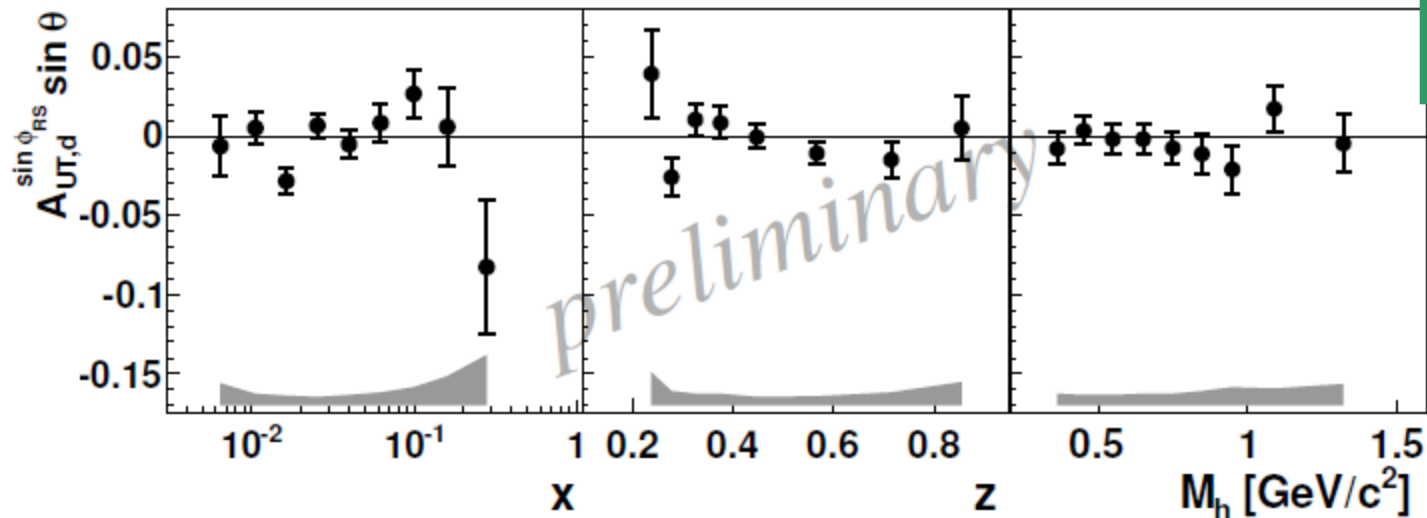


Full 2007 statistics

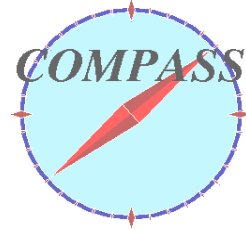
Proton target



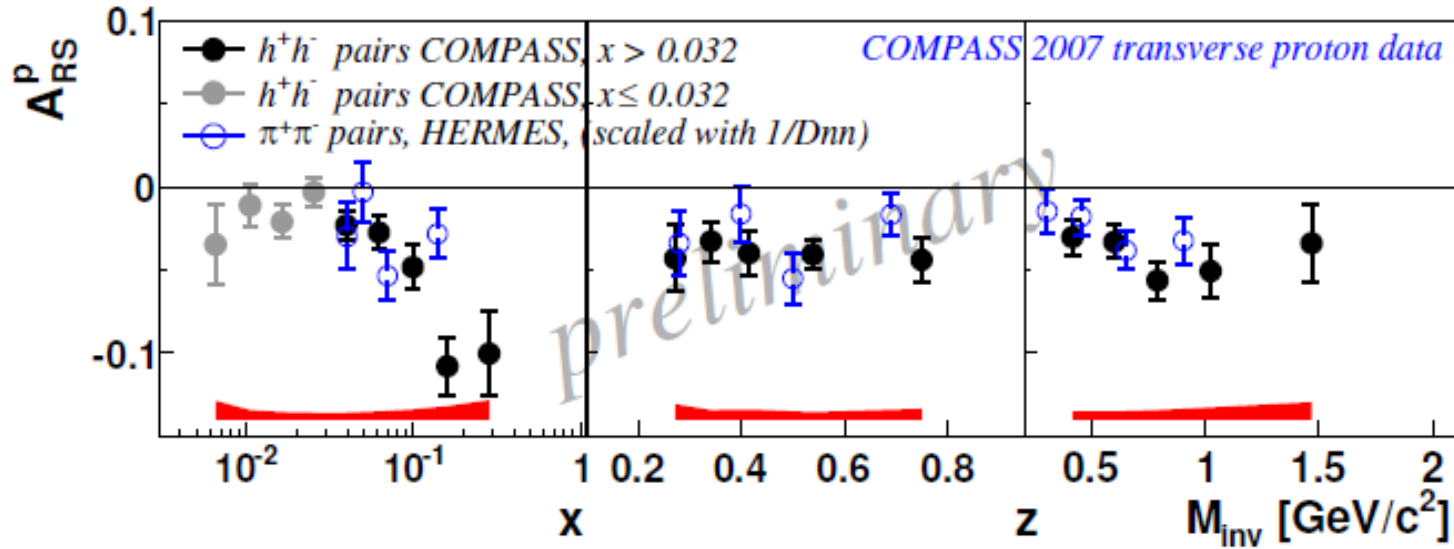
Deuteron target



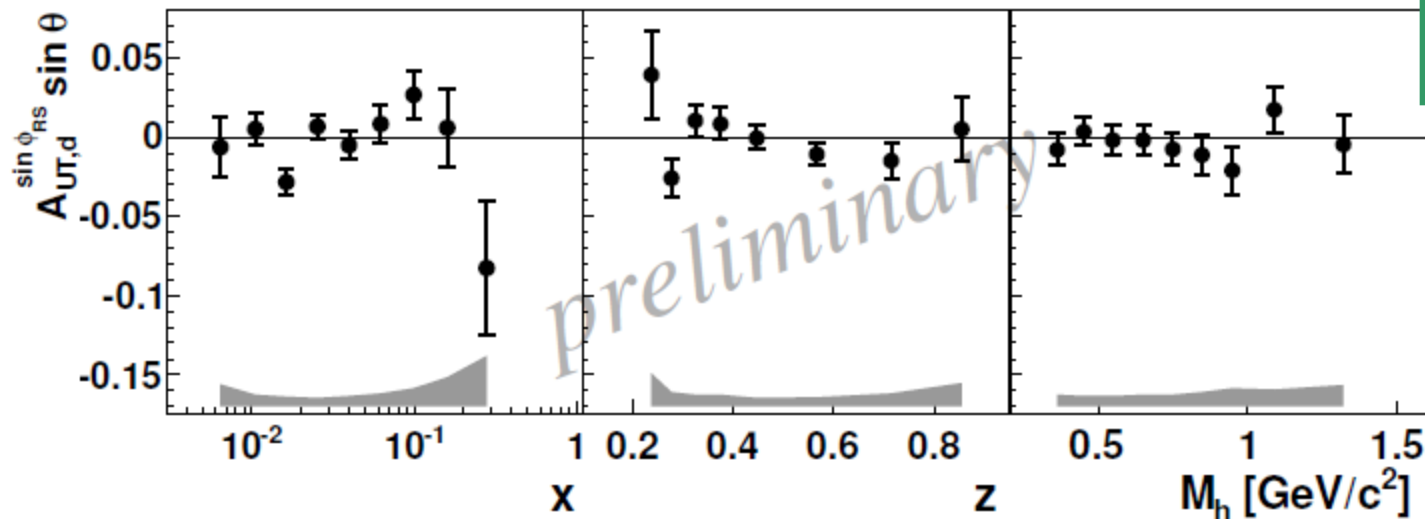
Transversity in 2-Hadron Production



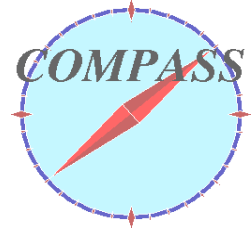
Proton target



Deuteron target



Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

intrinsic quark motion



Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Distribution Functions (x, k_T^2)			
N / q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}^\perp	h_{1T}, h_{1T}^\perp

Fragmentation Functions $(z, P_{h\perp}^2)$	
q/h	U
U	D_1
T	H_1^\perp

Transversity

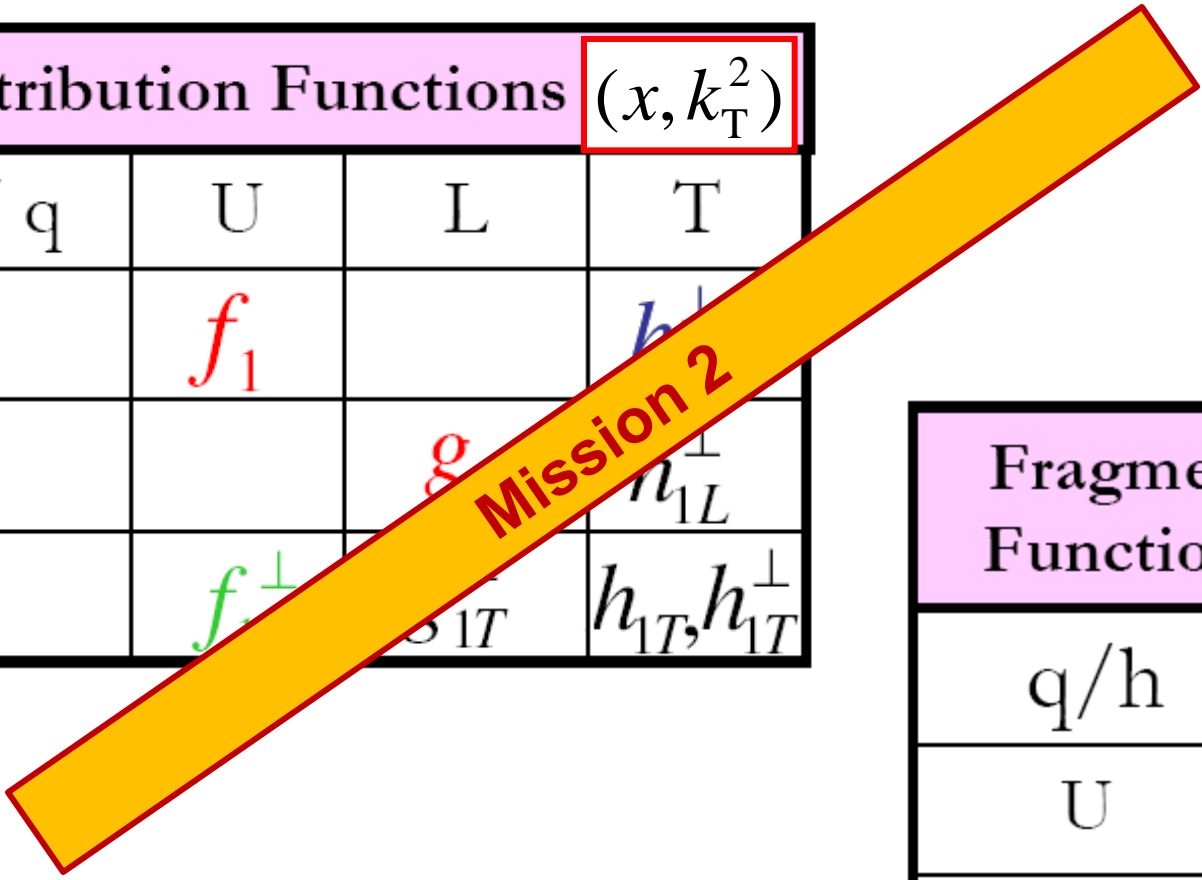
$$h_1 \otimes H_1^\perp$$

Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Distribution Functions (x, k_T^2)			
N / q	U	L	T
U	f_1		h_1^\perp
L		g	n_{1L}^\perp
T	f_{1T}^\perp	s_{1T}	h_{1T}, h_{1T}^\perp



Fragmentation Functions $(z, P_{h\perp}^2)$	
q/h	U
U	D_1
T	H_1^\perp

Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Distribution Functions (x, k_T^2)			
N / q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}^\perp	h_{1T}, h_{1T}^\perp

Sivers

$$f_{1T}^\perp \otimes D_1$$

Fragmentation Functions $(z, P_{h\perp}^2)$	
q/h	U
U	D_1
T	H_1^\perp

Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Distribution Functions (x, k_T^2)			
N / q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}^\perp	$h_{1T}^\perp, h_{1T}^\perp$

“pretzelosity”

$$h_{1T}^\perp \otimes H_1^\perp$$

Fragmentation Functions $(z, P_{h\perp}^2)$	
q/h	U
U	D_1
T	H_1^\perp

Introducing transverse momentum k_T



$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

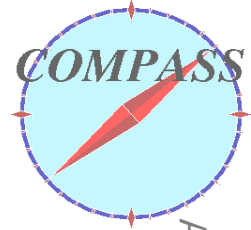
Distribution Functions (x, k_T^2)			
N / q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}^\perp	h_{1T}, h_{1T}^\perp

“worm-gear”

$$g_{1T} \otimes D_1$$

Fragmentation Functions $(z, P_{h\perp}^2)$	
q/h	U
U	D_1
T	H_1^\perp

Cross section for transverse target spin



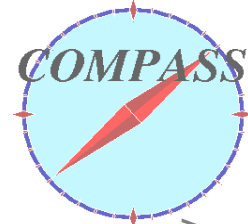
Mission 2

(4 LO)

NLO

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

Cross section for transverse target spin



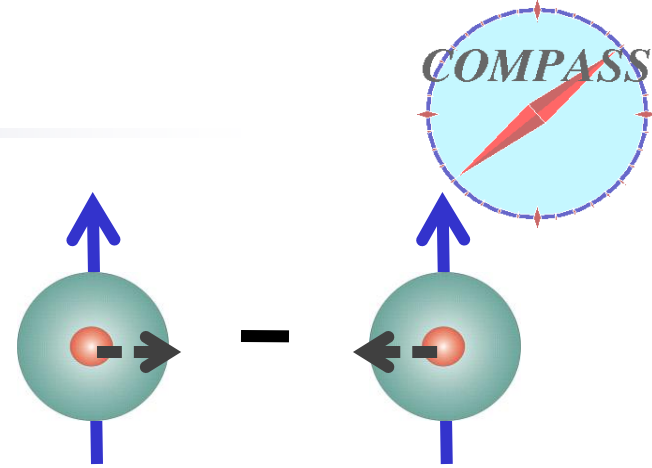
(4 LO)

NLO

$$\begin{aligned}
 \frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = & \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ \dots \dots \right. \\
 & \boxed{f_{1T}^{\perp q} \otimes D_{1q}^h} \\
 & \quad \text{Sivers} \\
 & + |\mathbf{S}_{\perp}| \left[\sin(\phi_h - \phi_S) \left(\underbrace{F_{UT,T}^{\sin(\phi_h - \phi_S)}}_{\text{transversity}} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \right. \\
 & \quad + \varepsilon \sin(\phi_h + \phi_S) \underbrace{F_{UT}^{\sin(\phi_h + \phi_S)}}_{\text{pretzelosity}} + \varepsilon \sin(3\phi_h - \phi_S) \underbrace{F_{UT}^{\sin(3\phi_h - \phi_S)}}_{\text{pretzelosity}} \\
 & \quad + \left. \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \right. \\
 & + |\mathbf{S}_{\perp}| \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) \underbrace{F_{LT}^{\cos(\phi_h - \phi_S)}}_{\text{worm-gear}} + \left. \left[\sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \right. \right. \right. \\
 & \quad \left. \left. + \left. \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\} \\
 & \quad \boxed{g_{1T}^q \otimes D_{1q}^h} \\
 & \quad \text{worm-gear}
 \end{aligned}$$

Sivers Effect

Distribution of unpolarized quarks with transverse momentum k_T in a transversely polarized nucleon



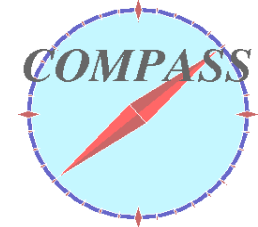
$$A_{UT}^{\sin(\phi_h - \phi_S)} \propto f_{1T}^\perp(x) \otimes D_1(z)$$

The Sivers asymmetry:

$$A_{\text{Siv}} \propto \frac{\sum_q e_q^2 f_{1T}^q(x, k_T) \otimes D_q^h(z)}{\sum_q e_q^2 f(x) \cdot D_q^h(z)}$$

Sivers asymmetries

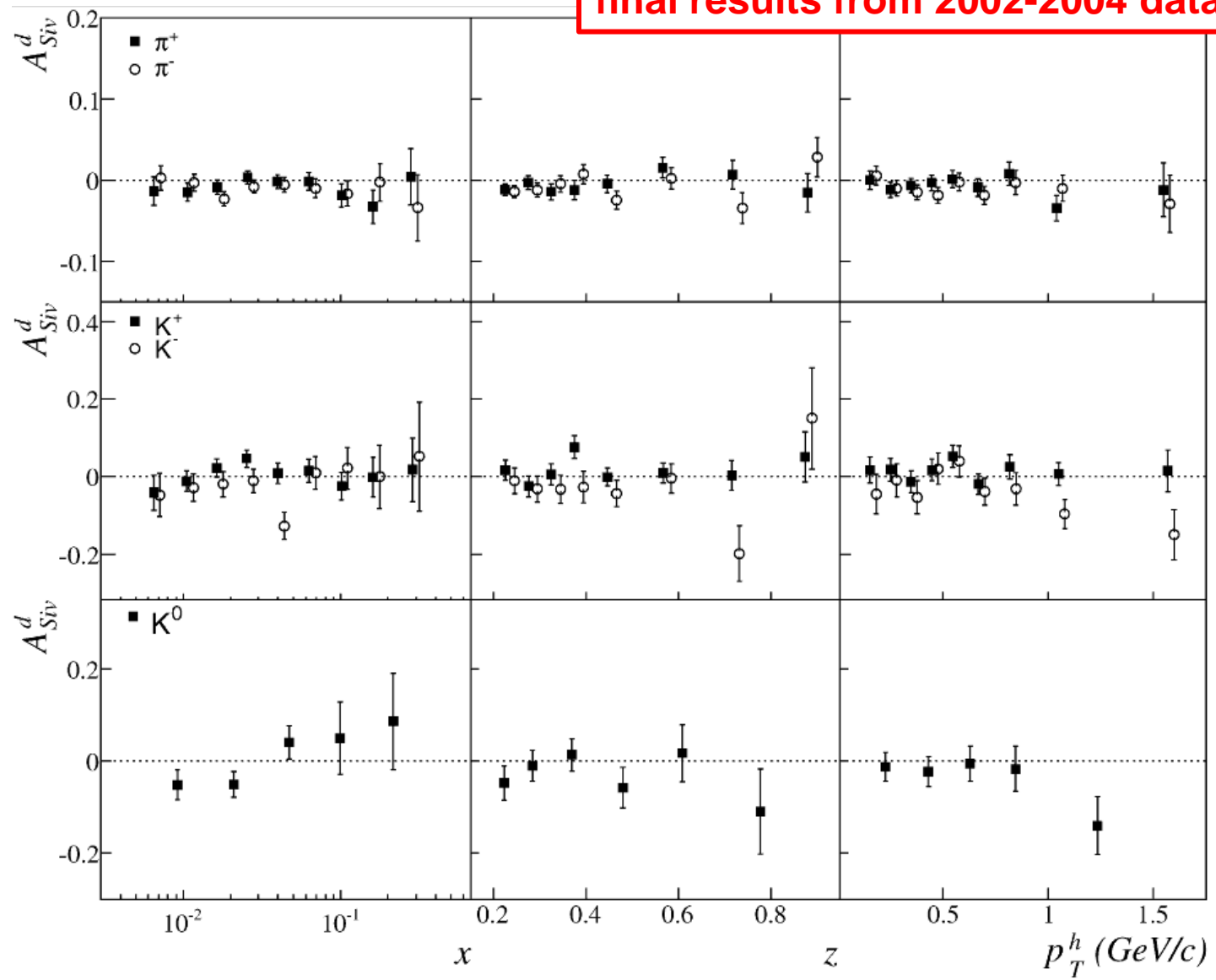
$$f_{1T}^\perp(x) \otimes D_1(z)$$



final results from 2002-2004 data

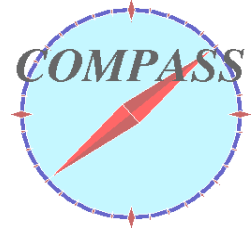
Deuteron Target

PLB 673 (2009) 127

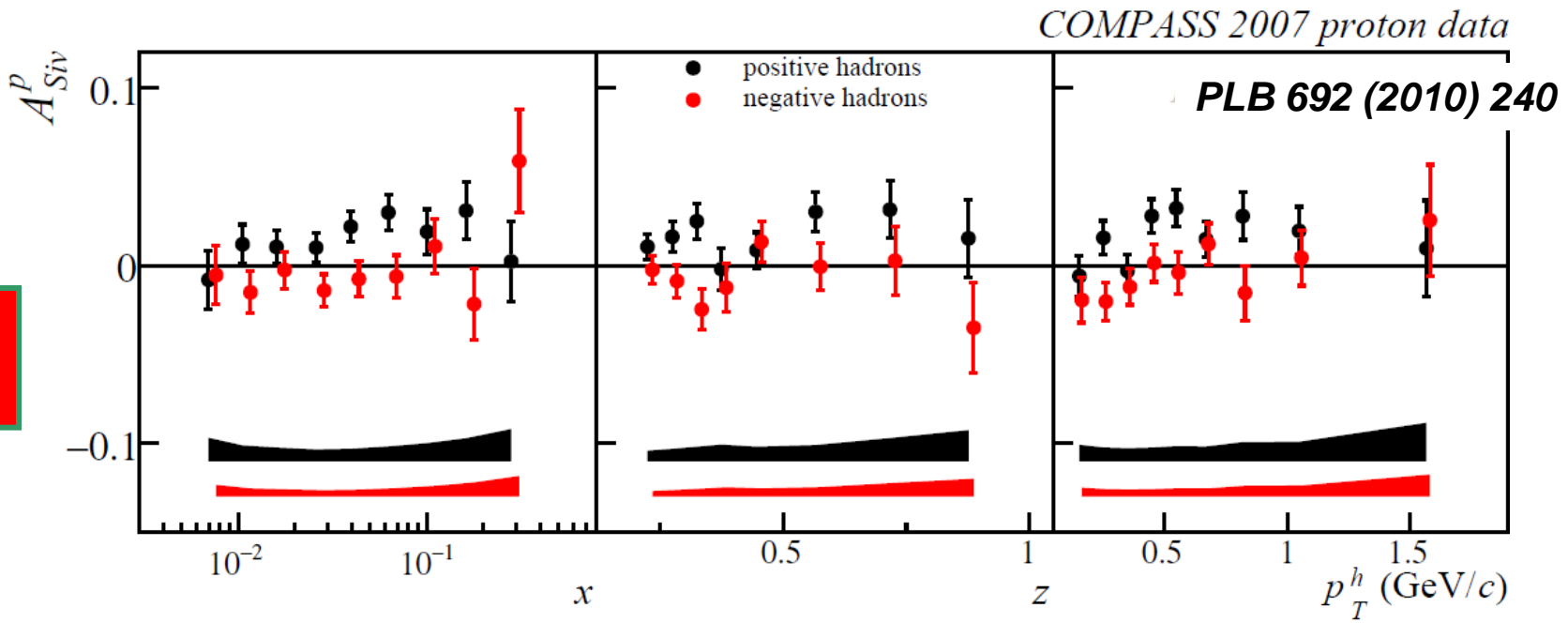


Sivers asymmetries

$$f_{1T}^\perp(x) \otimes D_1(z)$$



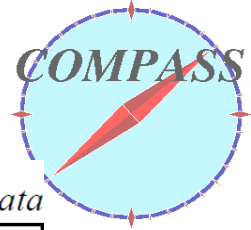
Full 2007 statistics



Proton target

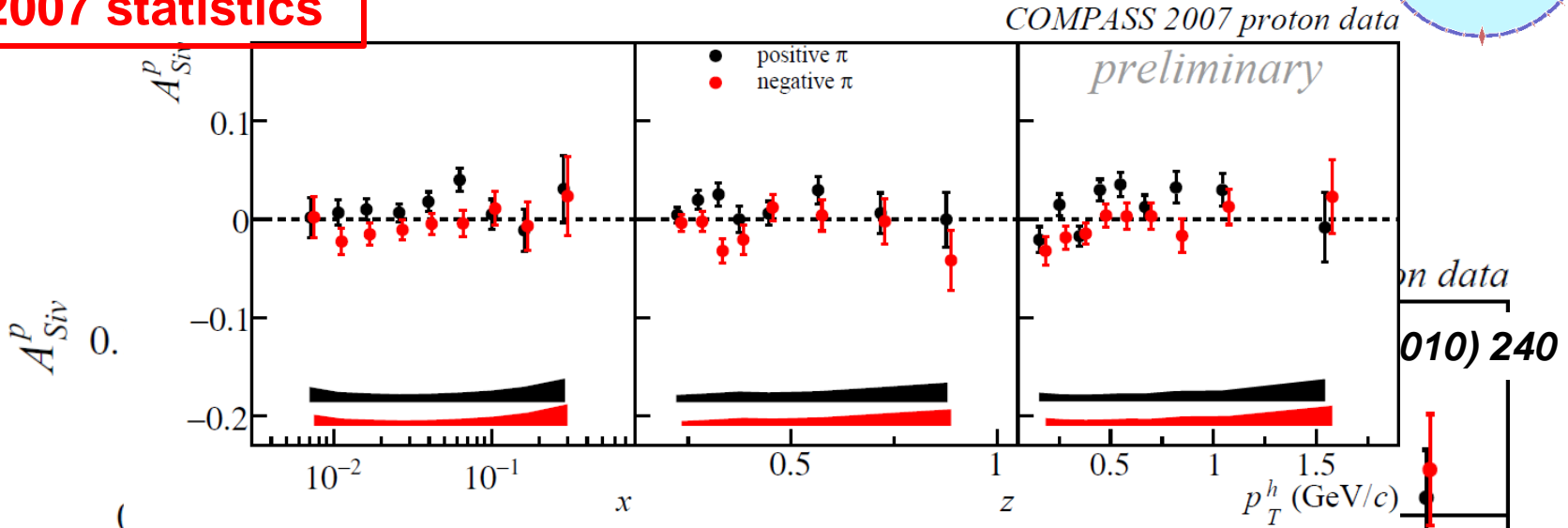
Sivers asymmetries

$$f_{1T}^\perp(x) \otimes D_1(z)$$



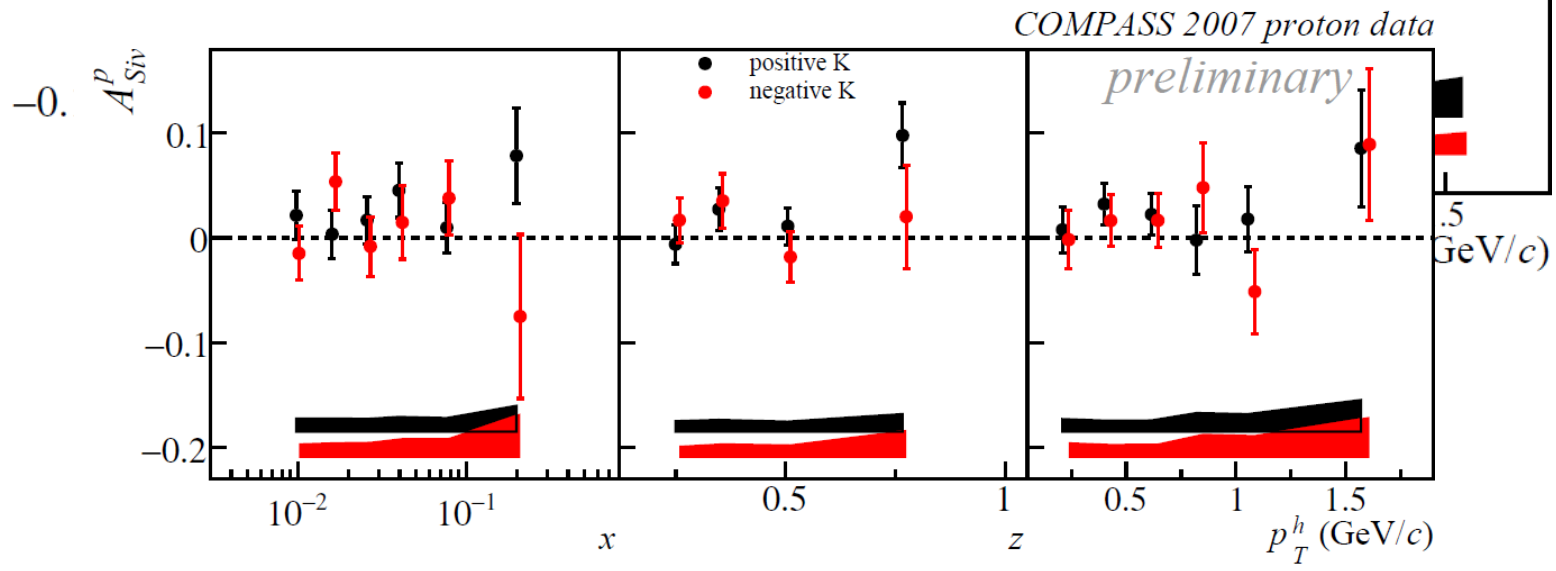
Full 2007 statistics

π^\pm



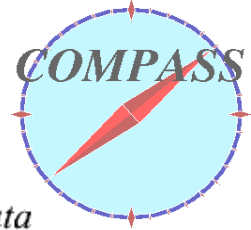
Proton target

K^\pm

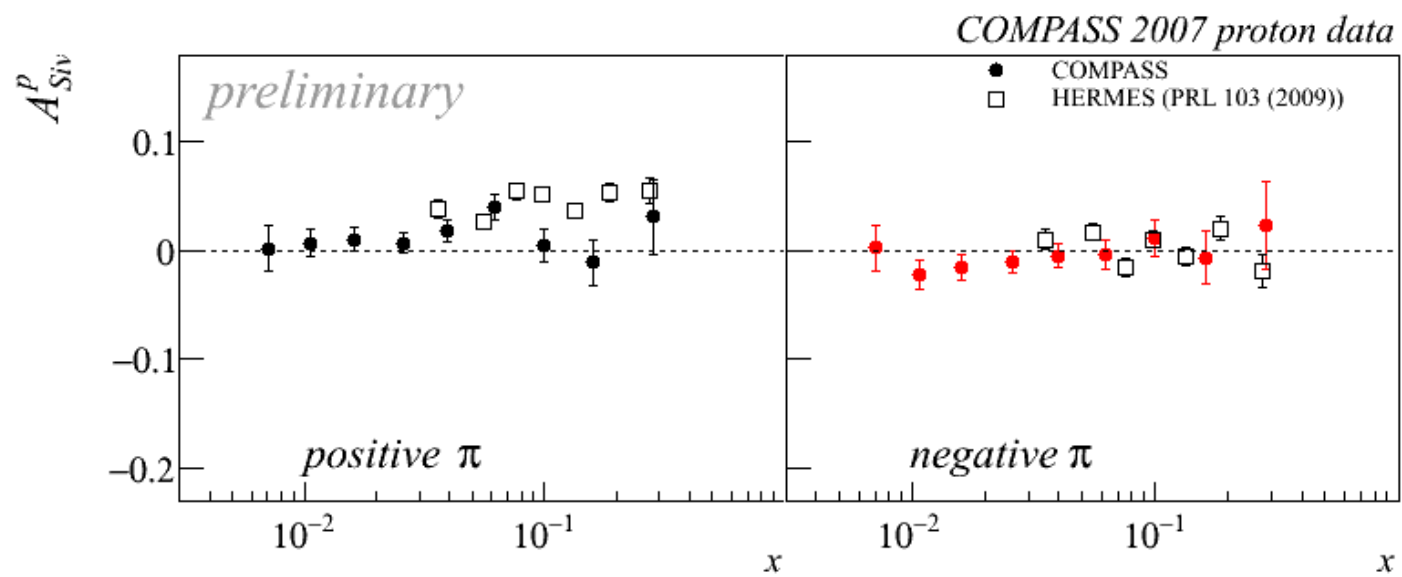


Sivers asymmetries

$$f_{1T}^\perp(x) \otimes D_1(z)$$

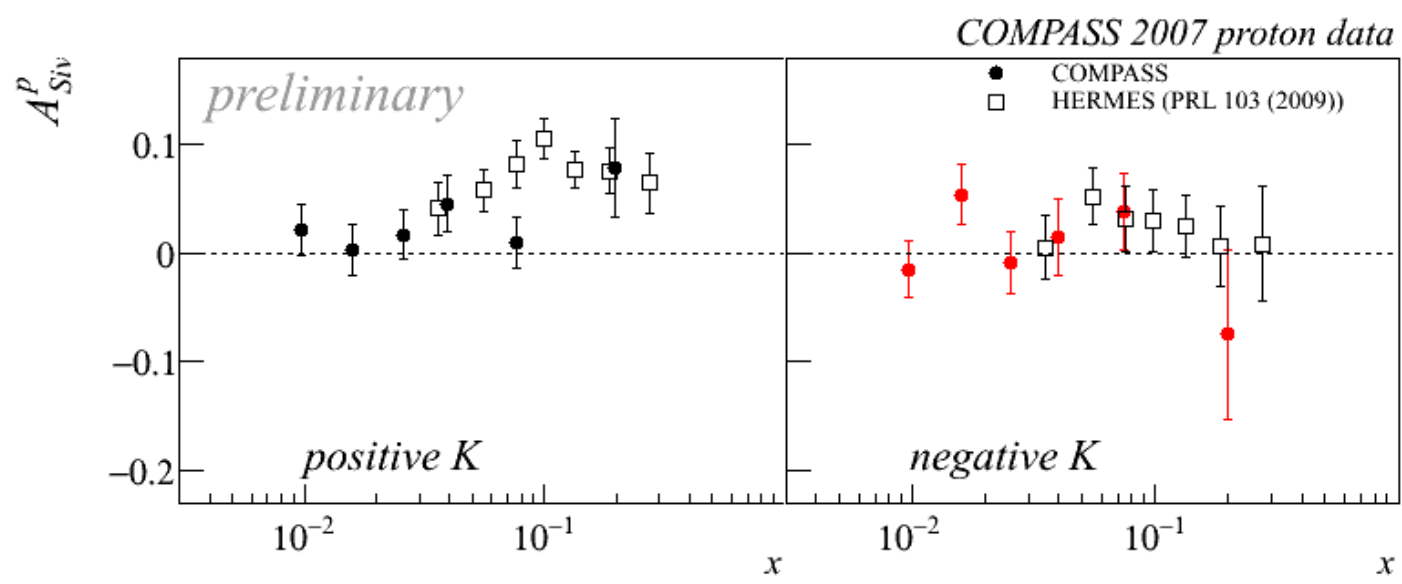


π^\pm



Proton target

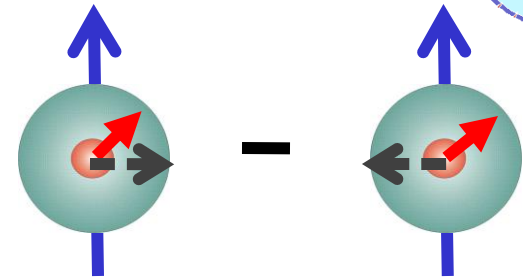
K^\pm



Target transverse spin results – (LO)

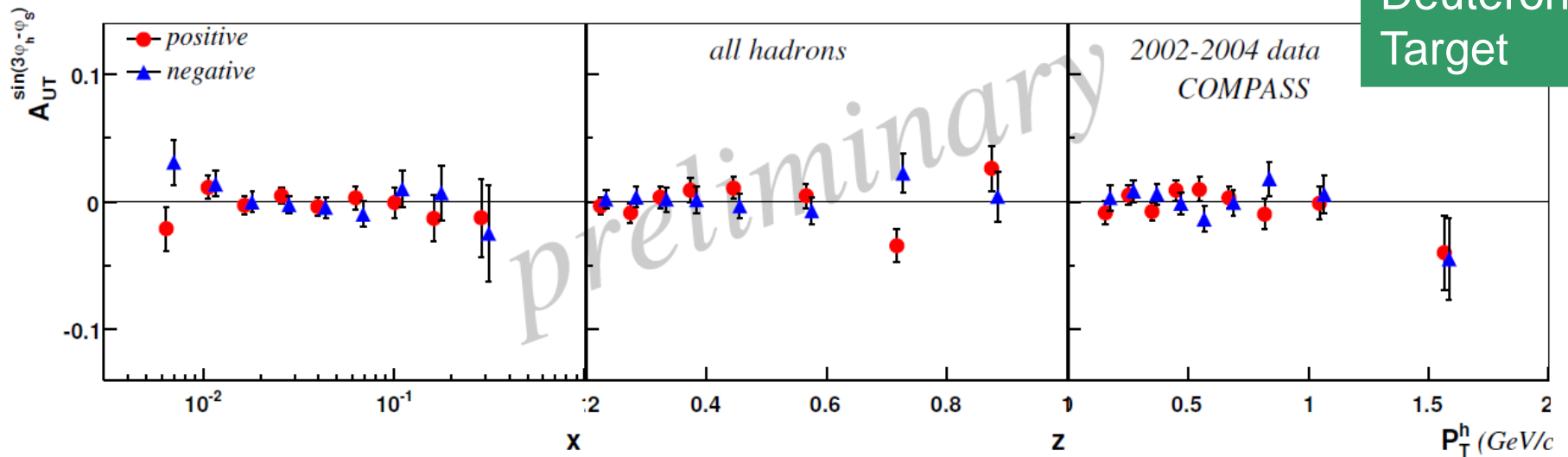


Correlation of the parton transverse momentum and transverse polarization in a transversely polarized nucleon



“Pretzelosity”

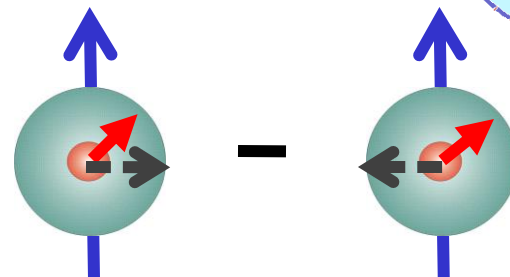
$$A_{UT}^{\sin(3\varphi_h - \varphi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$



Target transverse spin results – (LO)



Correlation of the parton transverse momentum and transverse polarization in a transversely polarized nucleon

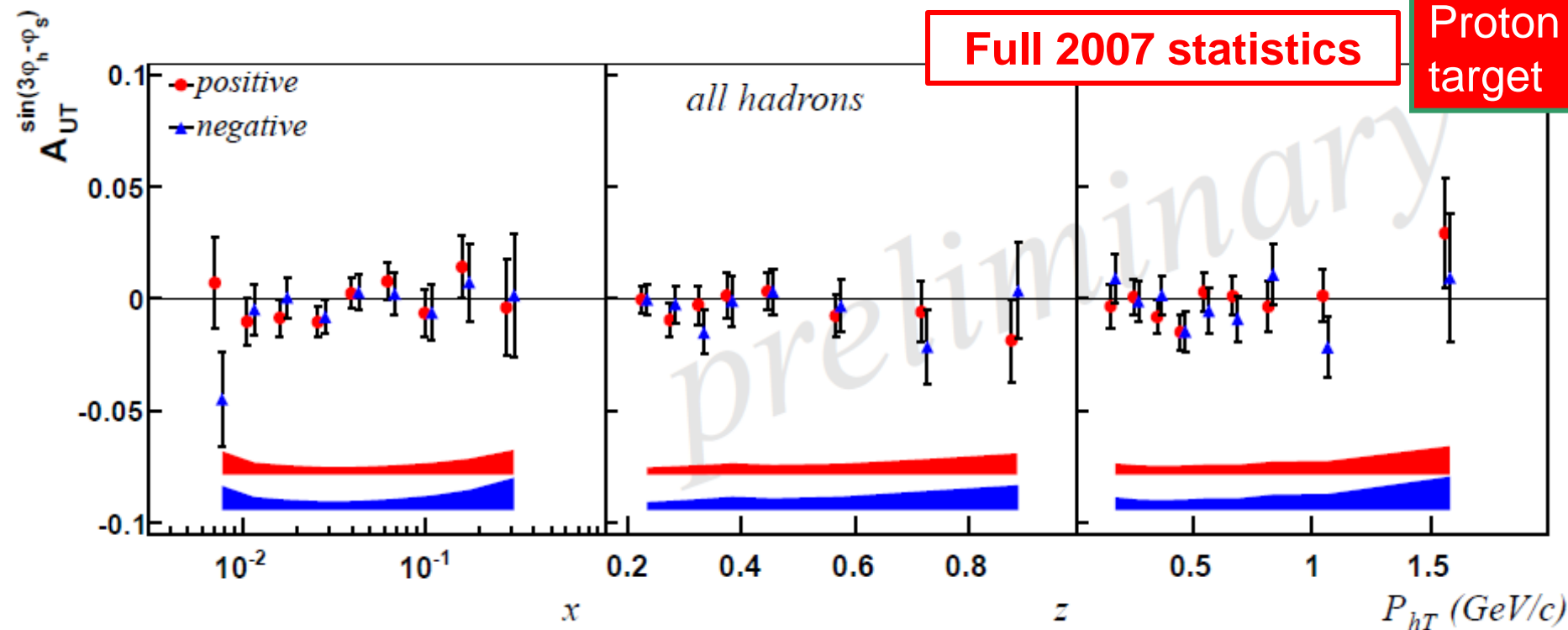


“Pretzelosity”

$$A_{UT}^{\sin(3\varphi_h - \varphi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

Full 2007 statistics

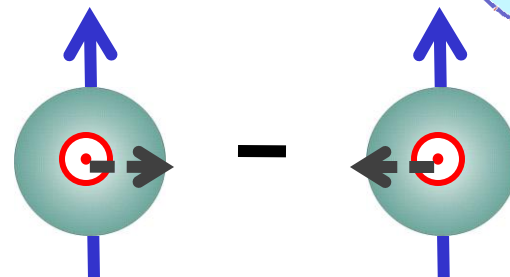
Proton target



Target transverse spin results – (LO)



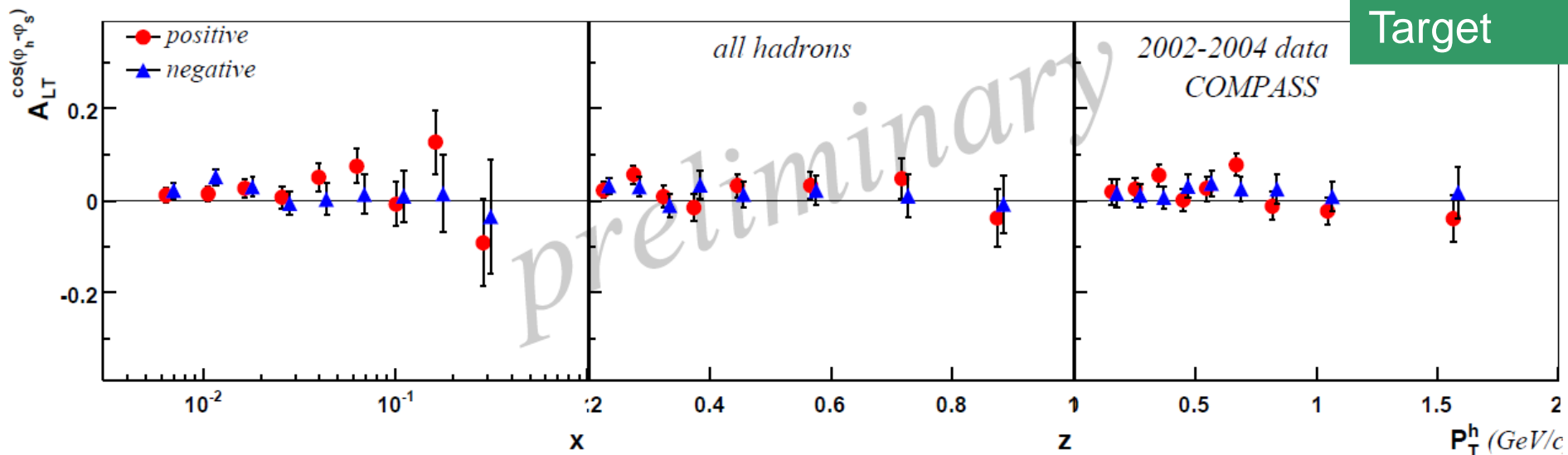
Correlation of the parton transverse momentum and longitudinal polarization in a transversely polarized nucleon



“worm-gear”

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

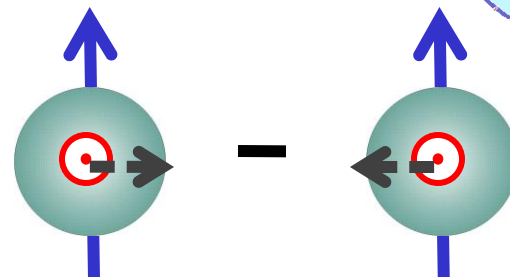
Deuteron Target



Target transverse spin results – (LO)



Correlation of the parton transverse momentum and longitudinal polarization in a transversely polarized nucleon

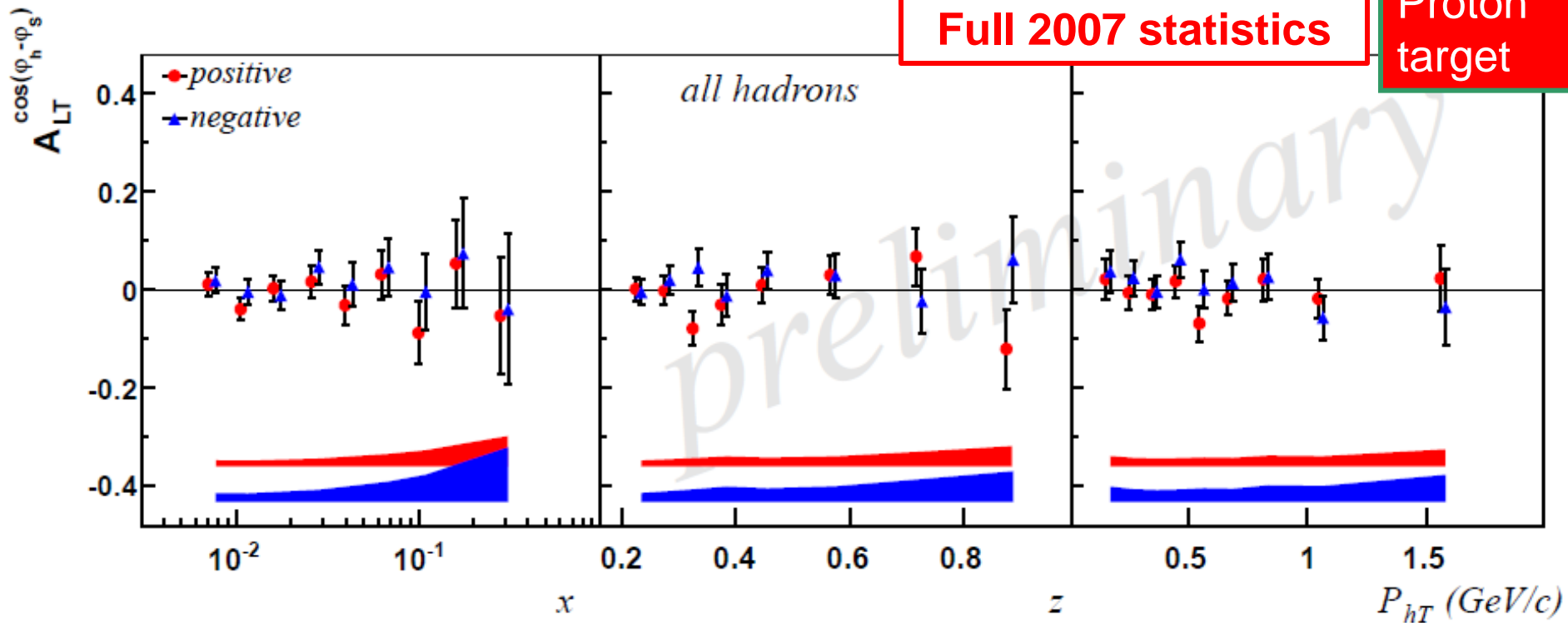


“worm-gear”

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

Full 2007 statistics

Proton target

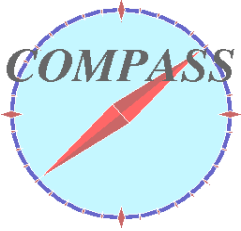




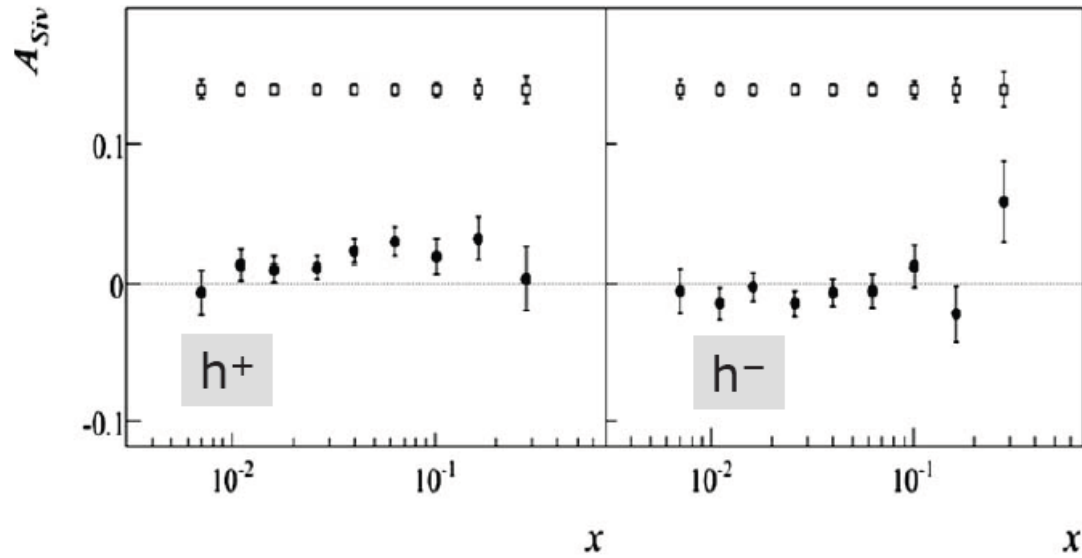
Many recent results from COMPASS:

- Transversity
 - **Collins asymmetries** for π^\pm and K^\pm for proton and deuteron targets
 - should be included in the global fit
 - **Dihadron asymmetries** for proton and deuteron targets
 - independent access to transversity
- **Sivers asymmetries** for π^\pm and K^\pm for proton and deuteron targets
 - should be included in the global fit
- Large **azimuthal asymmetries** of charged hadrons for **unpolarized** deuteron target
 - indication of non-vanishing Boer Mulders function

Outlook

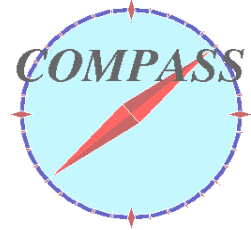


Short term:

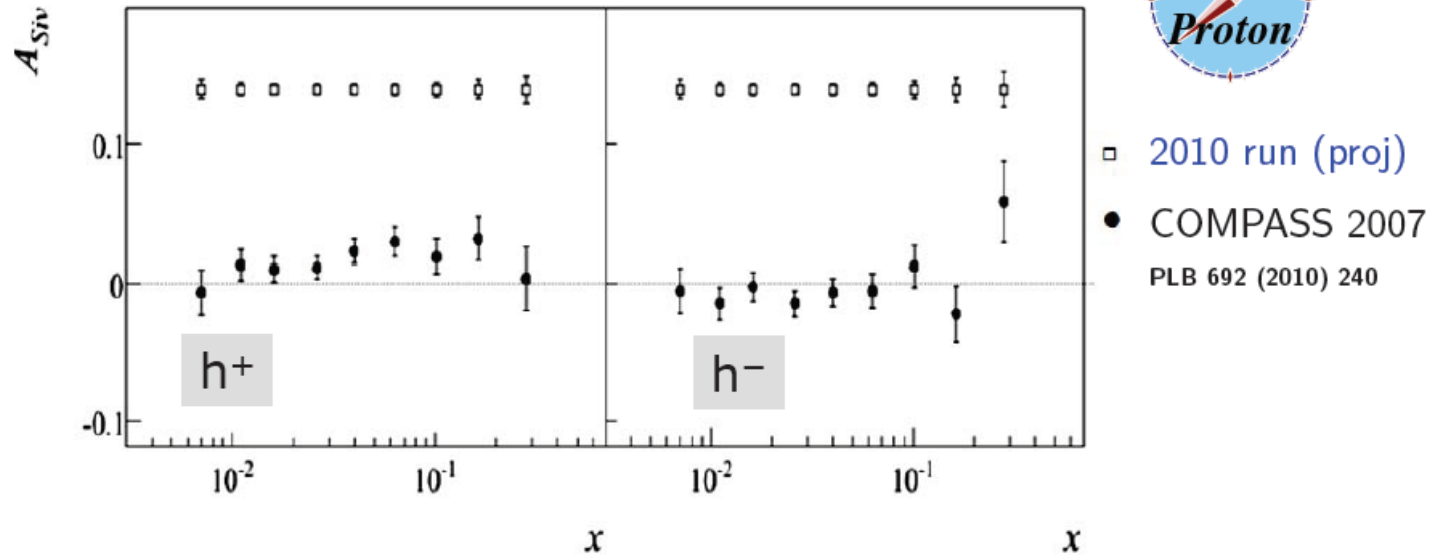


- 2010 run (proj)
 - COMPASS 2007
- PLB 692 (2010) 240

Outlook



Short term:

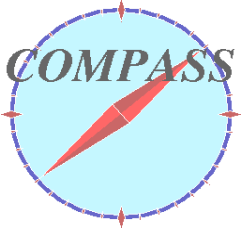


Medium and long term:

COMPASS II proposal accepted

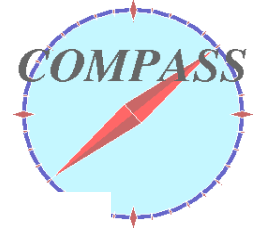
- Two years of DVCS measurements to attack GPDs
- Two years of Drell-Yan measurements

$$\pi P^\uparrow \rightarrow \mu^+ \mu^- X$$



Backup slides

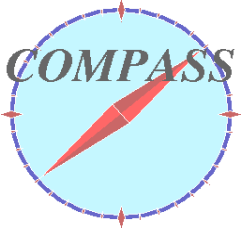
Unpolarized Target Cross-Section



$$\frac{d\sigma}{dx dy d\psi dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\ \left. + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin\phi_h} \right.$$

Cahn effect, Boer-Mulders DF and ~~pQCD~~

Measured using target-spin averaged samples



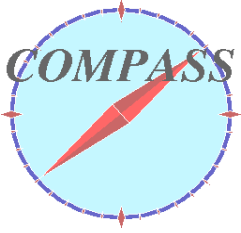
Cahn effect:

$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Leading order QED, $k_T \neq 0$

$$\frac{d\sigma}{d\phi_h} \propto \mathbf{1} - 4 \frac{\langle k_t^2 \rangle z P_t}{Q \langle P_t^2 \rangle} \mathbf{D}_{\cos\phi_h}(\mathbf{y}) \cos\phi_h + \dots$$

$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \quad \text{access to} \quad \langle k_T^2 \rangle$$



Cahn effect:

$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

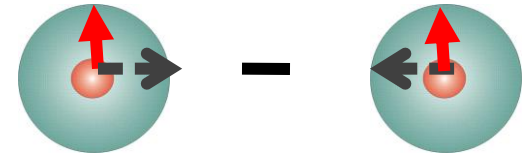
Leading order QED, $k_T \neq 0$

$$\frac{d\sigma}{d\phi_h} \propto \mathbf{1} - 4 \frac{\langle k_T^2 \rangle_z P_t}{Q \langle P_t^2 \rangle} \mathbf{D}_{\cos\phi_h}(\mathbf{y}) \cos\phi_h + \dots$$

$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \quad \text{access to} \quad \langle k_T^2 \rangle$$

Boer Mulders effect:

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



$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \propto h_1^\perp \otimes H_1^\perp$$



Cahn effect:

Flavour independent

$$d\sigma^{l+N \rightarrow l'+h+X} \propto DF \otimes d\sigma^{l+q \rightarrow l'+q'} \otimes FF$$

Leading order QED, $k_T \neq 0$

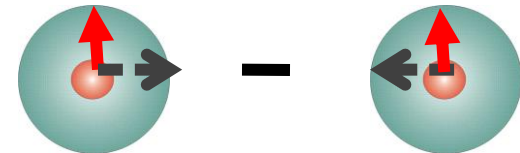
$$\frac{d\sigma}{d\phi_h} \propto \mathbf{1} - 4 \frac{\langle k_t^2 \rangle z P_t}{Q \langle P_t^2 \rangle} D_{\cos\phi_h}(\mathbf{y}) \cos\phi_h + \dots$$

$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \quad \text{access to} \quad \langle k_T^2 \rangle$$

Boer Mulders effect:

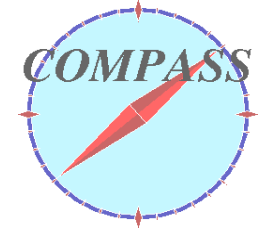
Flavour dependent

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



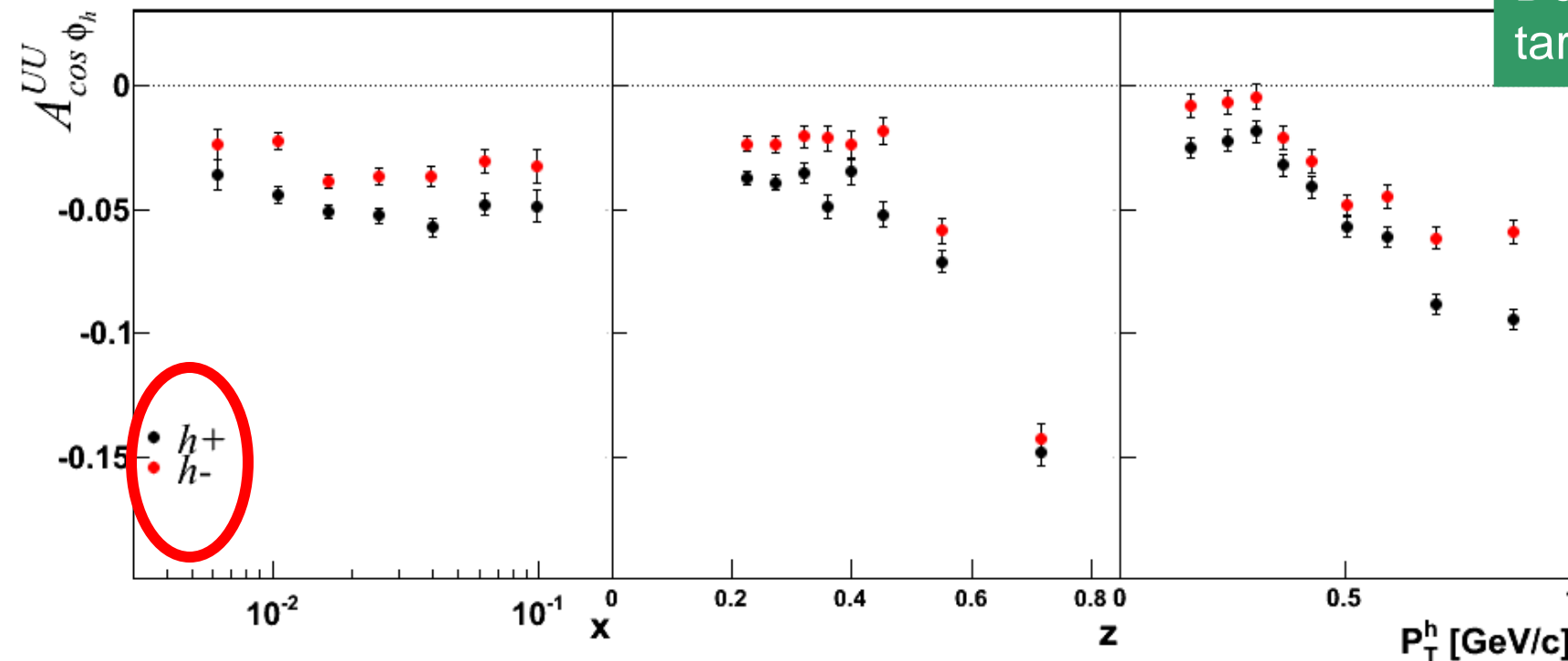
$$F_{UU}^{\cos\phi}, F_{UU}^{\cos 2\phi} \propto h_1^\perp \otimes H_1^\perp$$

Unpolarised Azimuthal Asymmetries



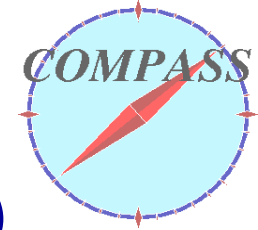
$\cos\phi$ modulation (Cahn + Boer-Mulders)

Deuteron target



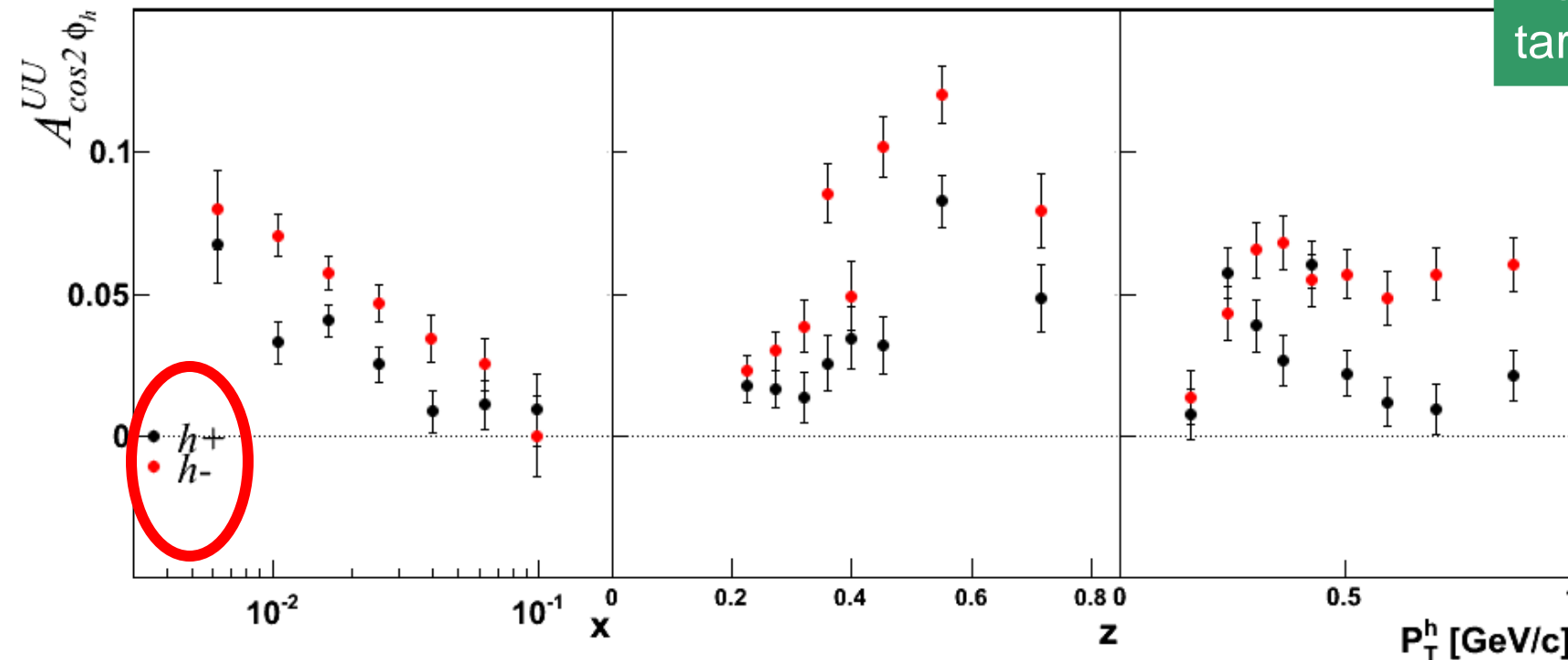
- Large negative asymmetries
- Charge dependent

Unpolarised Azimuthal Asymmetries



$\cos 2\phi$ modulation (Cahn + Boer-Mulders)

Deuteron target



- Large positive asymmetries
- Strongly charge dependent

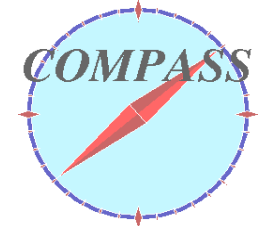
Transversity from Λ Production



$$lp^\uparrow \rightarrow l'\Lambda^\uparrow X$$

$$P_\Lambda(x, z) = f P_T D_{NN}(y) \frac{\sum_q e_q^2 h_1^q(x) \Delta_T D_q^\Lambda(z)}{\sum_q e_q^2 f_1^q(x) D_q^\Lambda(z)}$$

Transversity from Λ Production



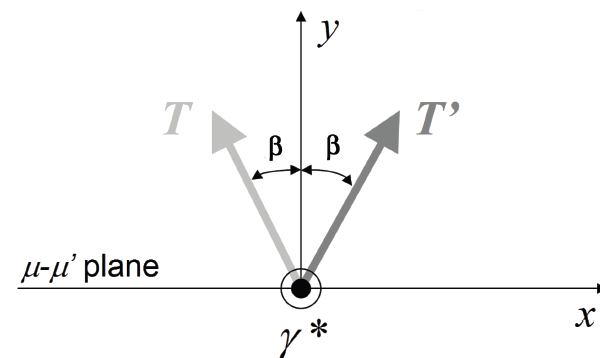
$$lp^\uparrow \rightarrow l'\Lambda^\uparrow X$$

$$P_\Lambda(x, z) = f P_T D_{NN}(y) \frac{\sum_q e_q^2 h_1^q(x) \Delta_T D_q^\Lambda(z)}{\sum_q e_q^2 f_1^q(x) D_q^\Lambda(z)}$$

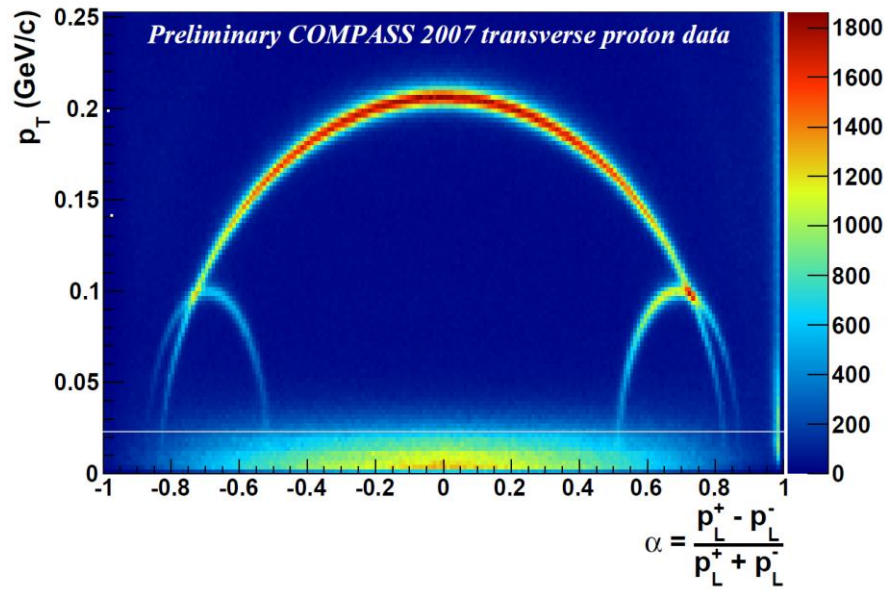
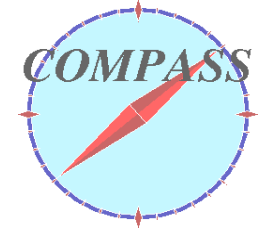
$$\Lambda \rightarrow p \pi \quad BR \approx 64\%$$

$$W(\Theta_{T'}) \propto 1 + \alpha P_T^\Lambda \cos \Theta_{T'}$$

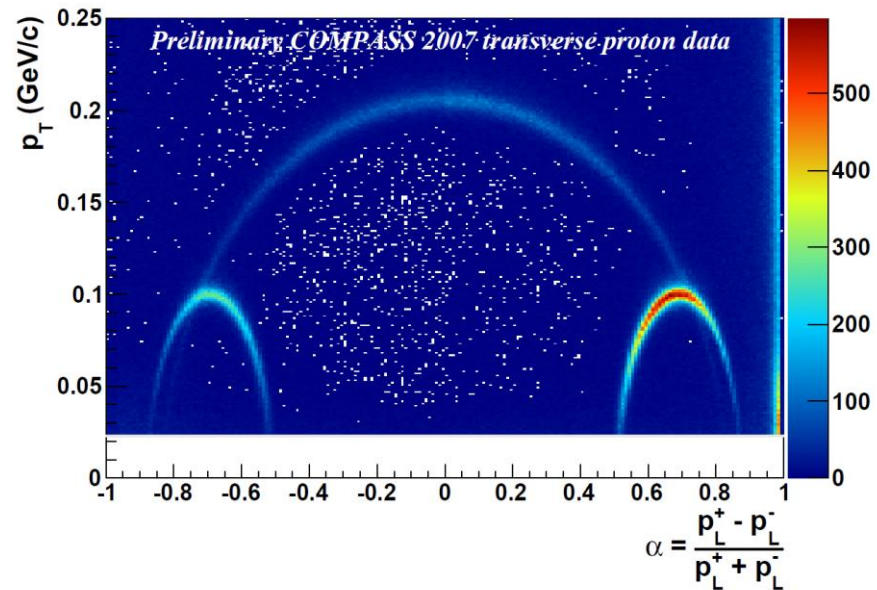
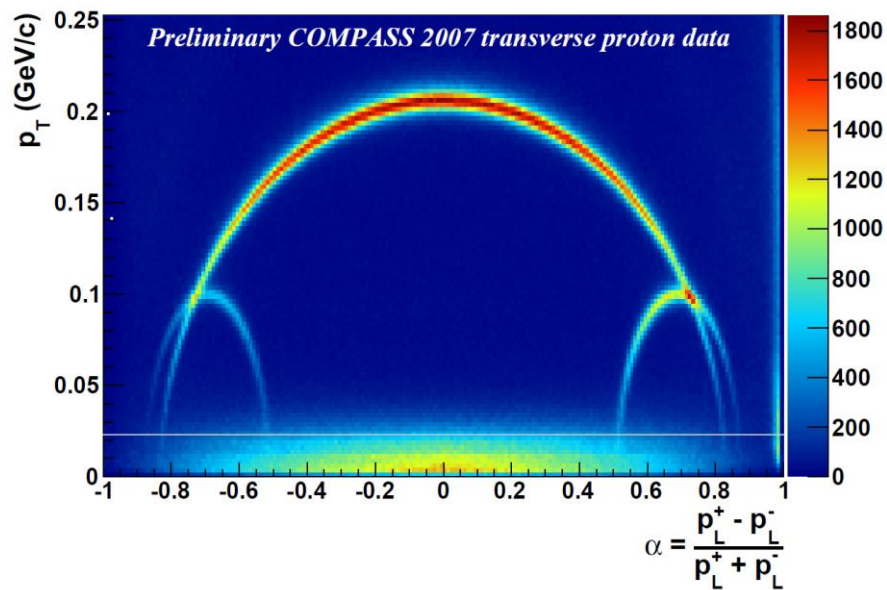
$$\alpha = \pm 0.642 \pm 0.013$$



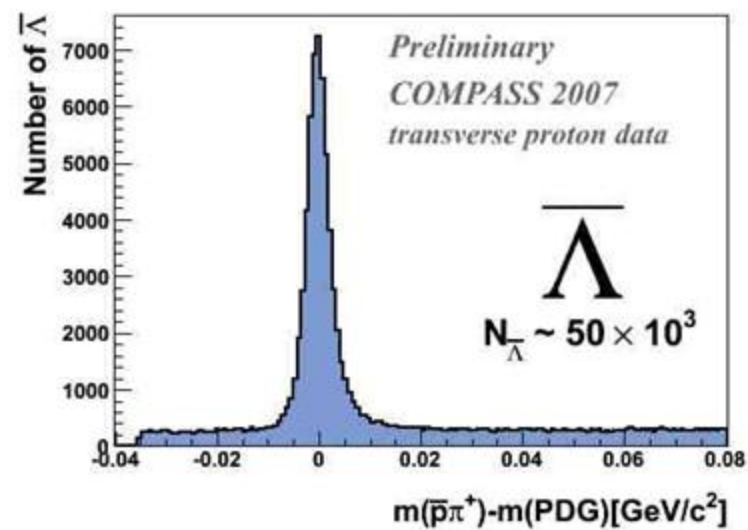
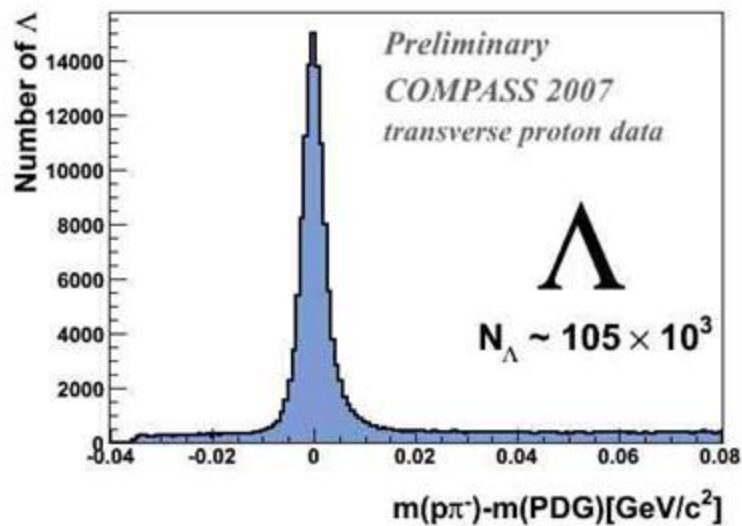
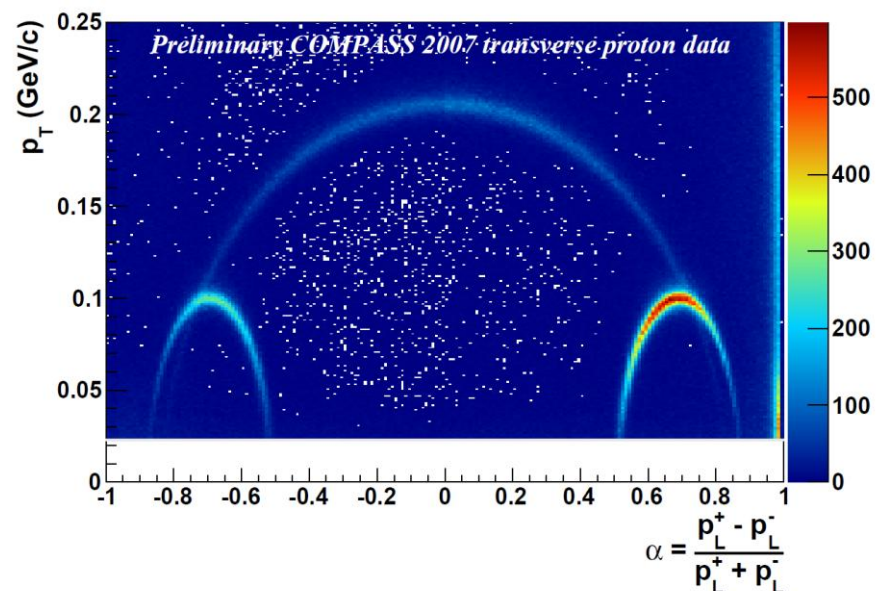
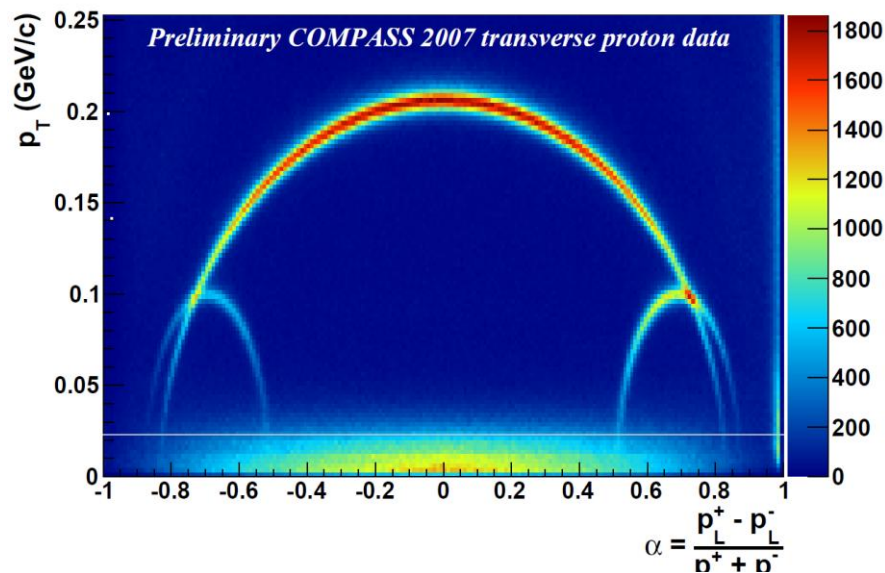
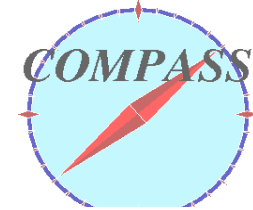
Transversity from Δ Production



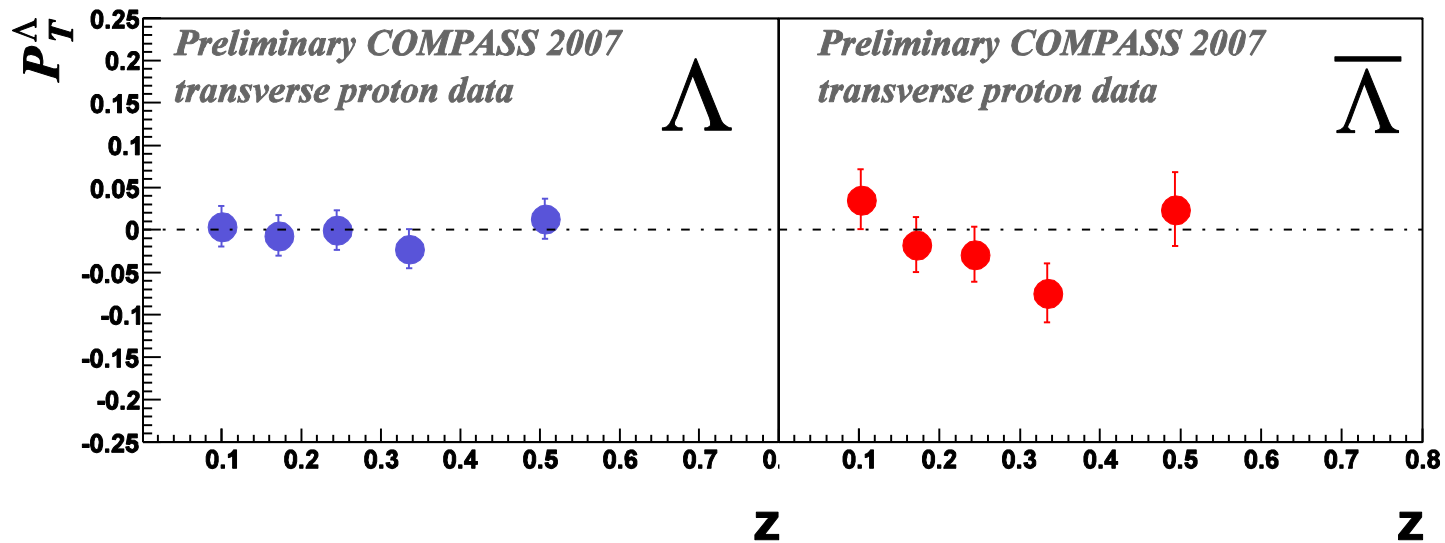
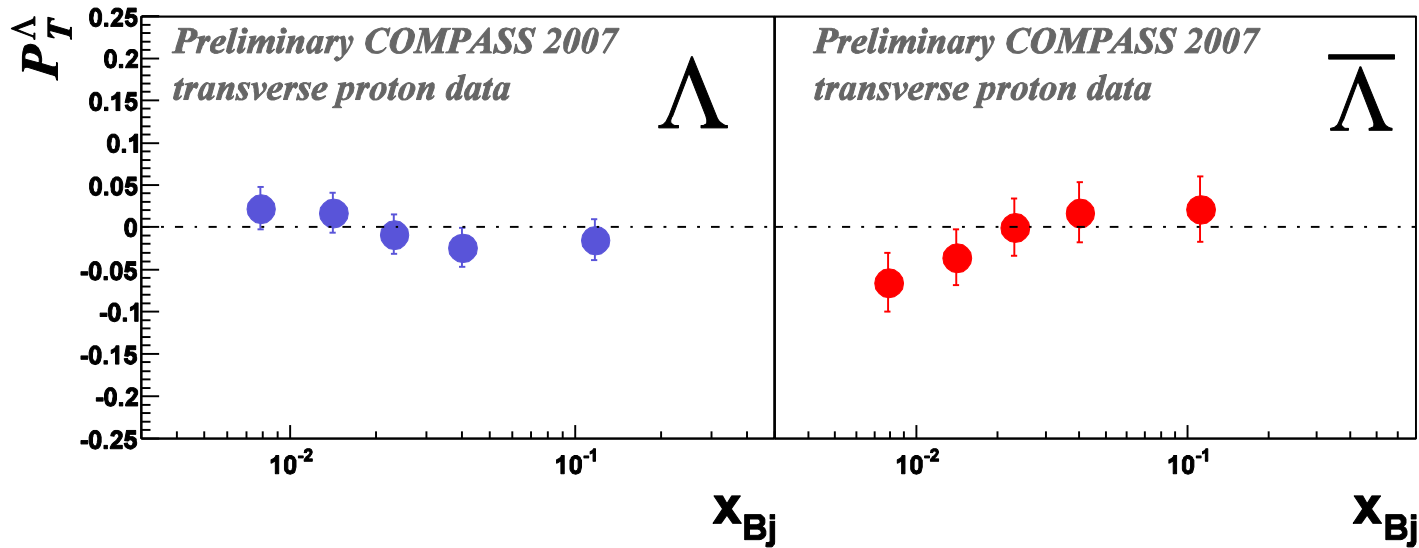
Transversity from Δ Production



Transversity from Λ Production



Lambda Selection and Polarization



Target transverse spin results – (NLO)

