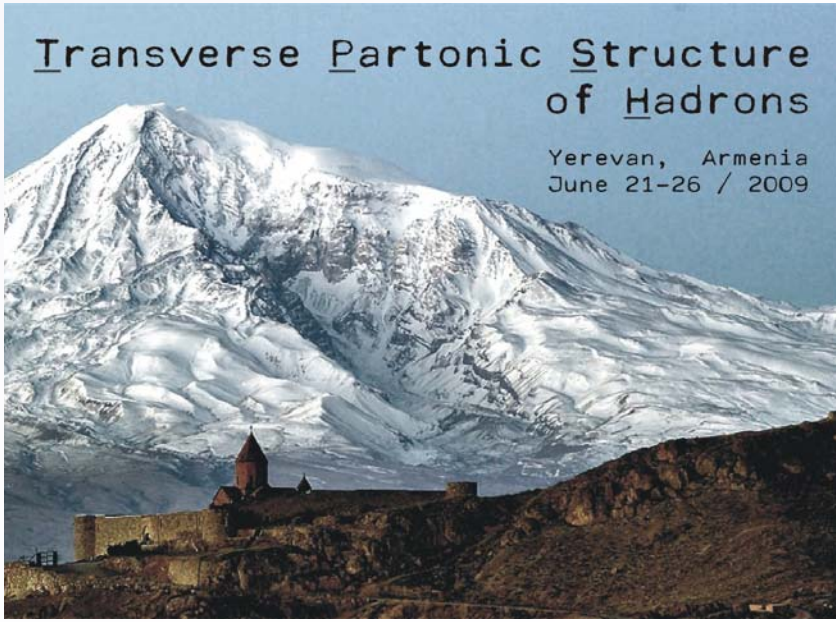
TRANSVERSITY MEASUREMENTS AT COMPASS

Franco Bradamante

Trieste University and INFN

on behalf of the COMPASS Collaboration



OUTLOOK

the COMPASS experiment

results on

- transversity : Collins asymmetries
  2 hadron asymmetries
  Λ polarization
- Sivers asymmetries
- other TMD asymmetries
- unpolarised azimuthal asymmetries
- exclusive ρ asymmetries

conclusions

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COMPASS

fixed target experiment
at the CERN SPS
broad physics programme

data taking since 2002:

muon beam	deuteron (^{6}LiD) polarised target	2002 2003 2004	L/T target polarisation 4:1
		2006	L target polarisation only
	proton (NH_3) polarised target	2007	L /T target polarisation 1:1
hadron beam	LH target	2008 2009	

muon beam: **160 GeV/c** longitudinal polarisation -80%
intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

COMPASS

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

two stages spectrometer

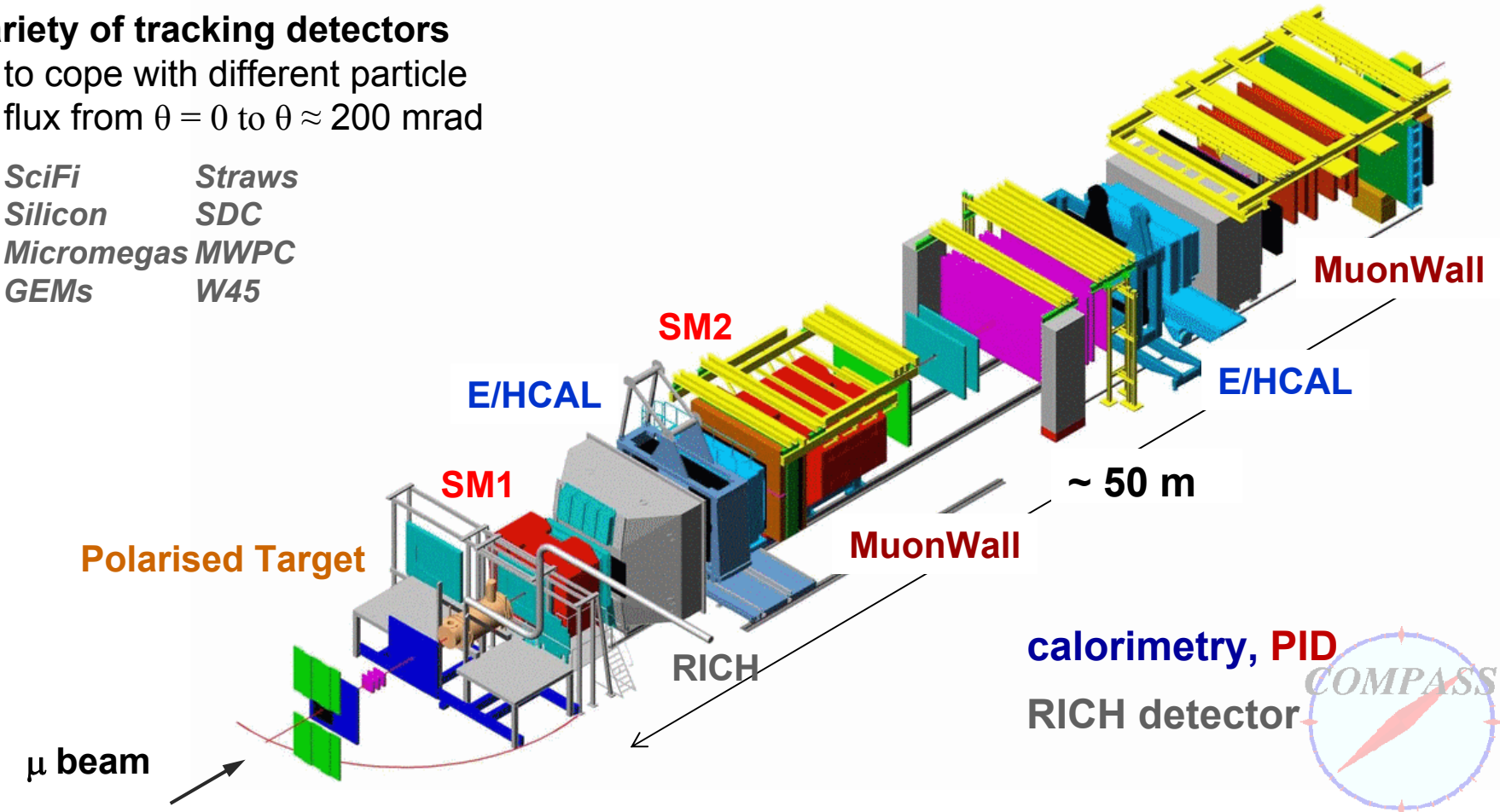
Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

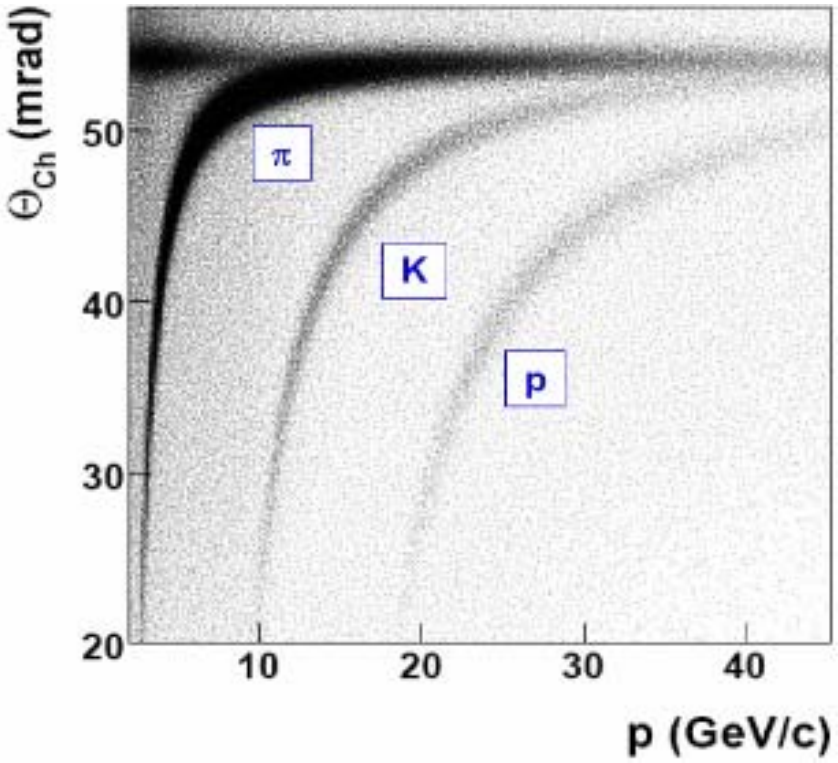
SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



calorimetry, PID

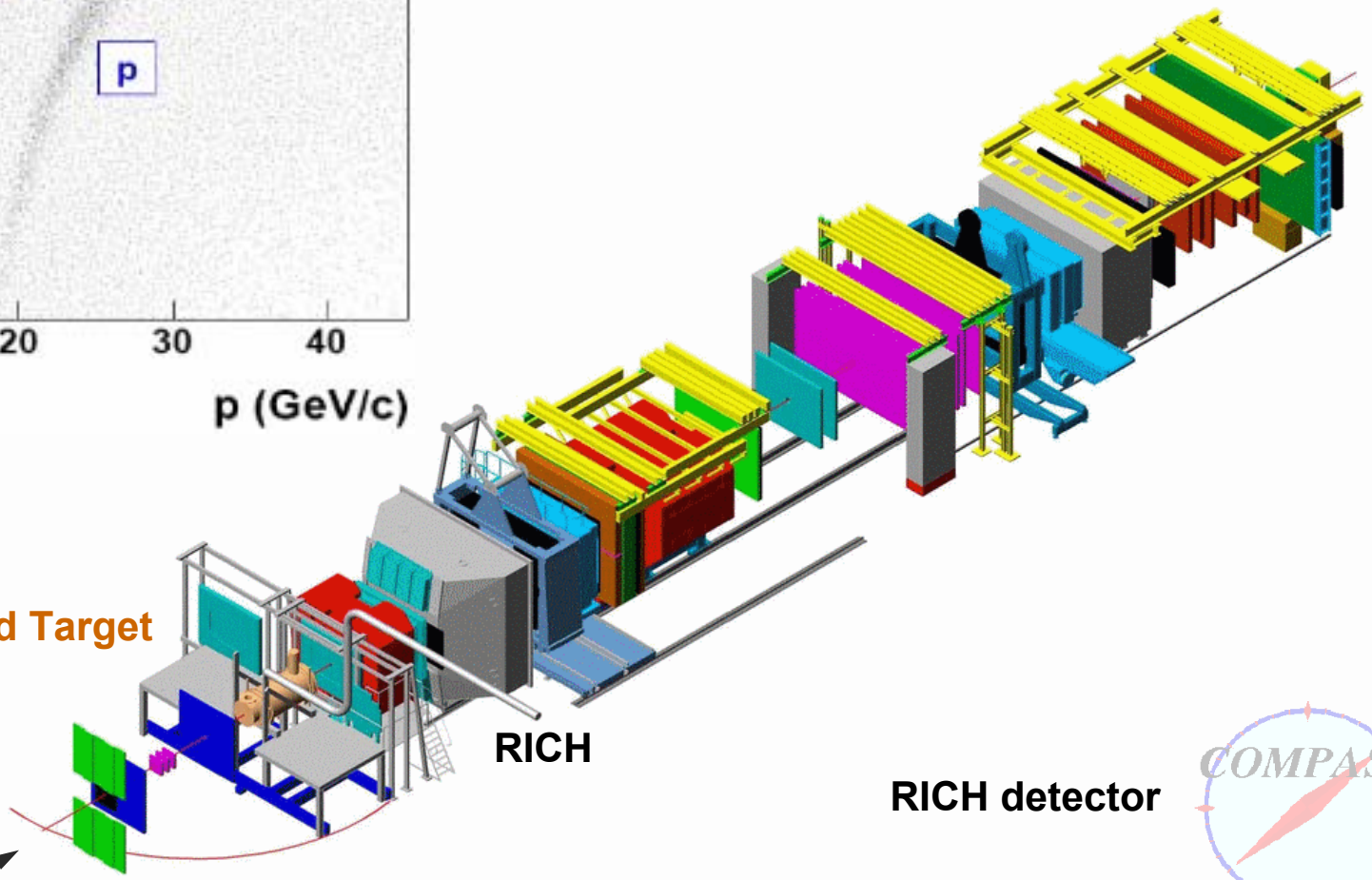
RICH detector

COMPASS



radiator C_4F_{10}

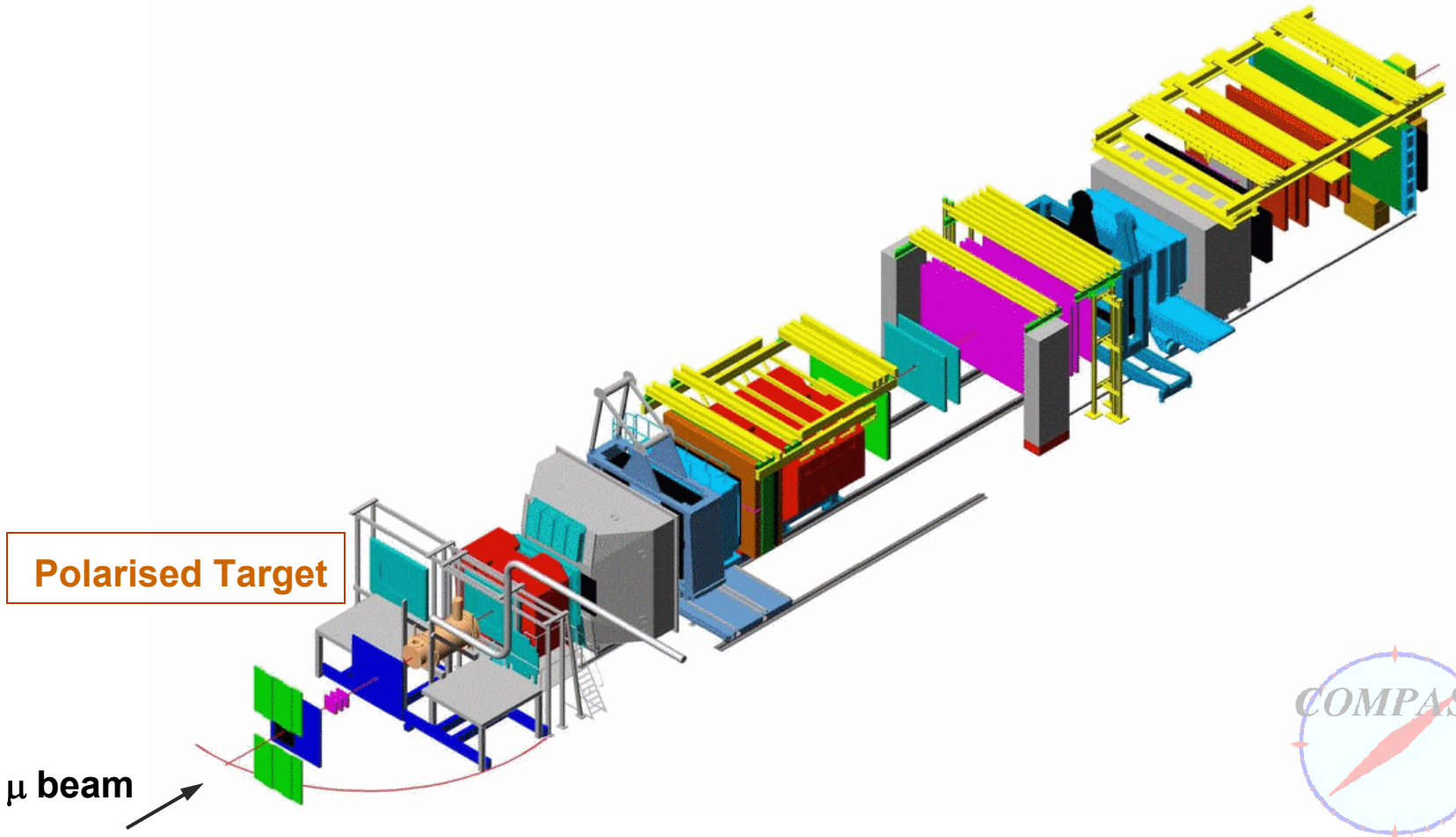
threshold: π ~2 GeV/c
K ~ 10 GeV/c



RICH detector

COMPASS

COMPASS



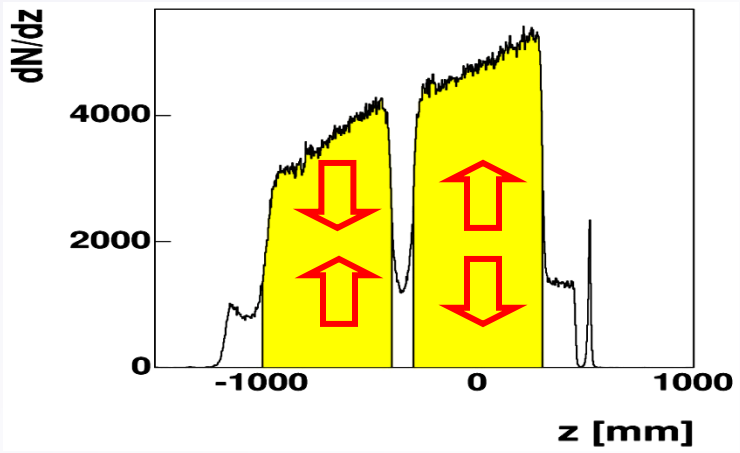
The Target System

solid state target operated in frozen spin mode

during data taking with transverse polarization, polarization reversal after ~ 4-5 days

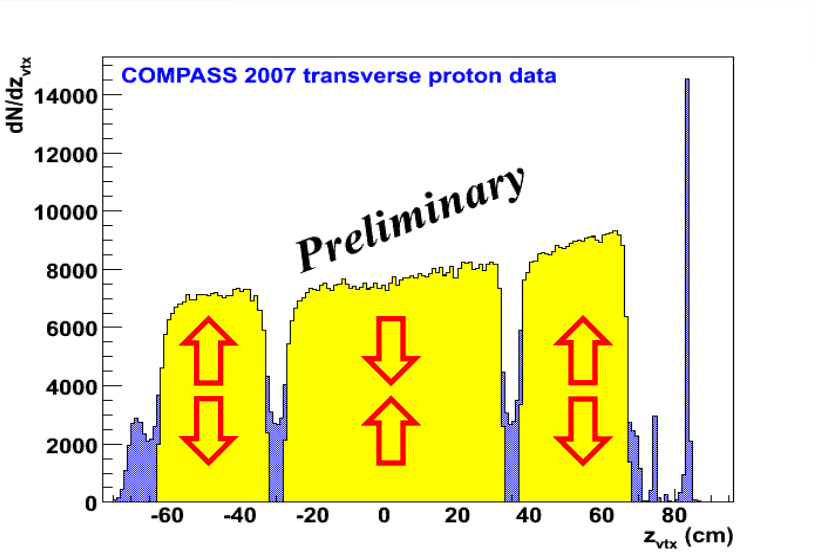
2002-2004: ^{6}LiD (polarised deuteron)
dilution factor f = 0.38
polarization P_T = 50%

two 60 cm long cells with opposite polarization



2006:
- **PTM replaced with the large acceptance COMPASS magnet (180 mrad)**
- **2 target cells ➔ 3 target cells**

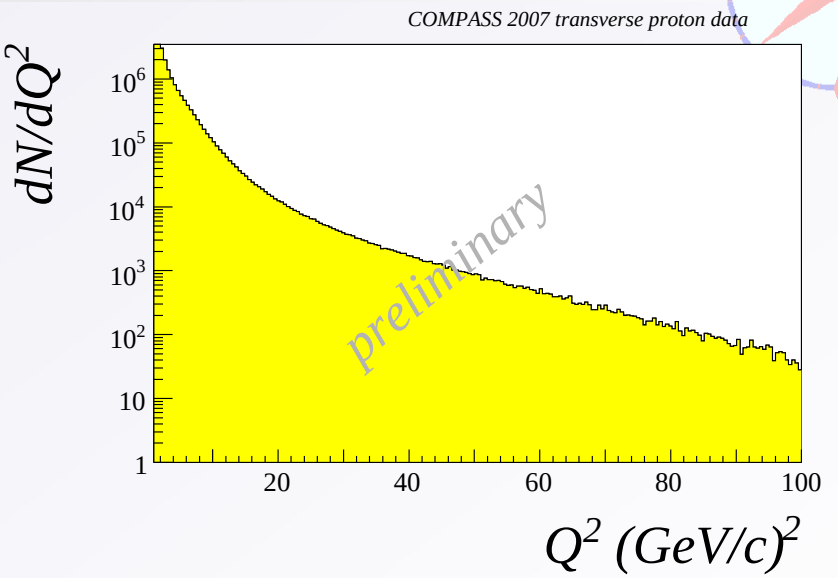
2007: NH_3 (polarised protons)
dilution factor f = 0.14
polarization P_T = 90%

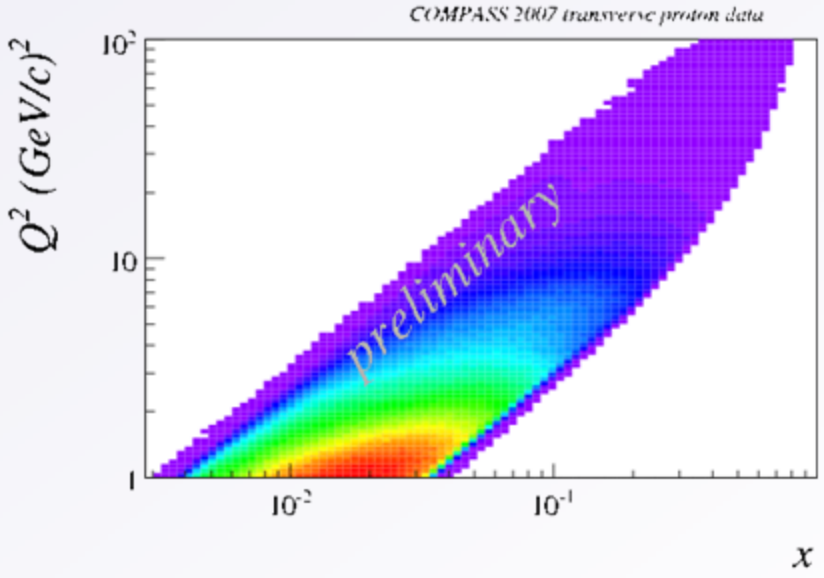


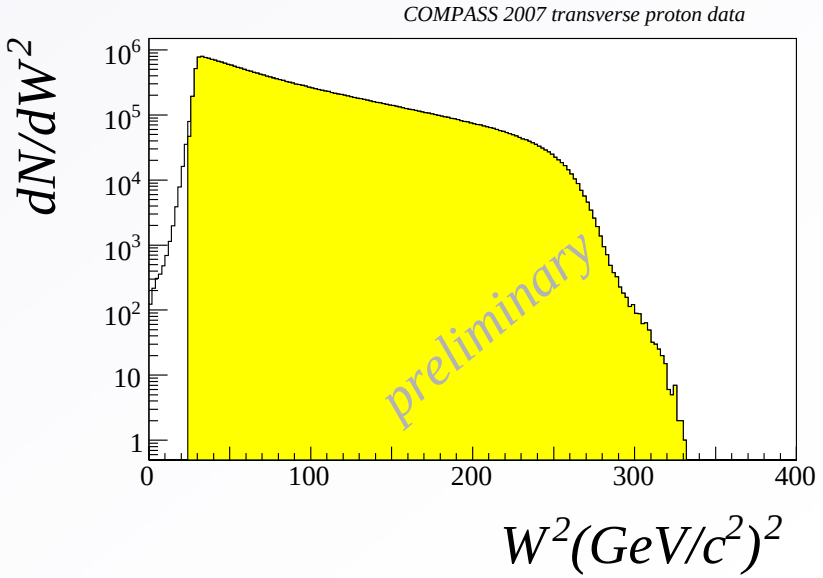
SIDIS event selection and kinematics

DIS event selection:

- $Q^2>1$ (GeV/c)^2
- $0.1<y<0.9$
- $W>5$ GeV/c^2







SIDIS event selection and kinematics

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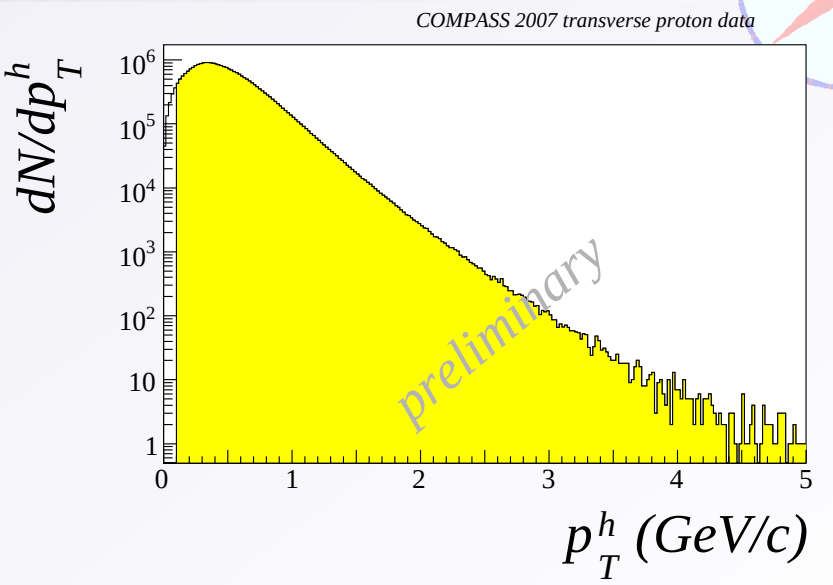
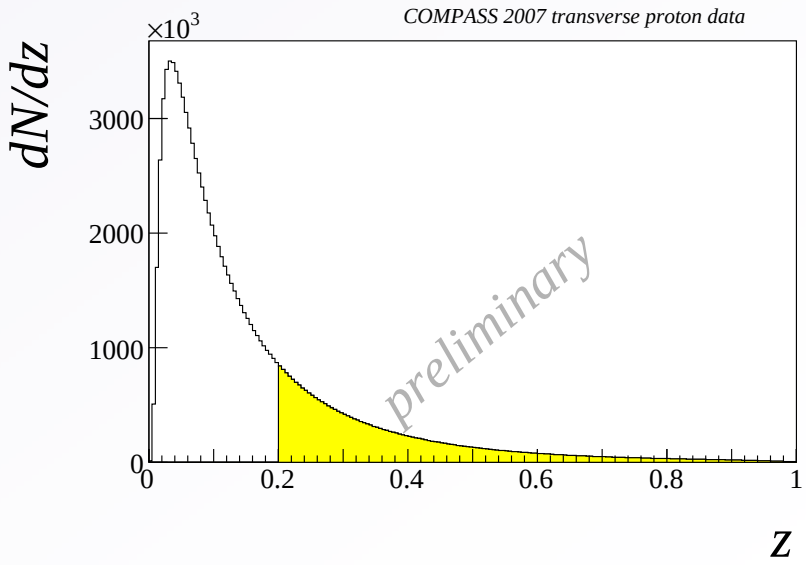
- $W>5$ GeV/c^2

Hadron selection

- $p_T>0.1$ GeV/c
- $z>0.2$





OUTLOOK

the COMPASS experiment

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conclusions

Transversity Distribution Function

is chiral-odd:

observable effects are given only by the
product of $\Delta_T q(x)$ and an other chiral-odd function

can be measured in SIDIS on a transversely polarised target
via "quark polarimetry"

$l\, N^{\uparrow} \rightarrow l'\, h\, X$	"Collins" asymmetry "Collins" Fragmentation Function
$l\, N^{\uparrow} \rightarrow l'\, h\, h\, X$	"two-hadron" asymmetry "Interference" Fragmentation Function
$l\, N^{\uparrow} \rightarrow l'\, \Lambda\, X$	Λ polarisation Fragmentation Function of $q^{\uparrow} \rightarrow \Lambda$

all explored in COMPASS

Collins Asymmetry

Collins effect

→ azimuthal distribution of the hadrons produced in $l\,N^{\uparrow} \rightarrow l'\,h^{\pm}\,X$

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$

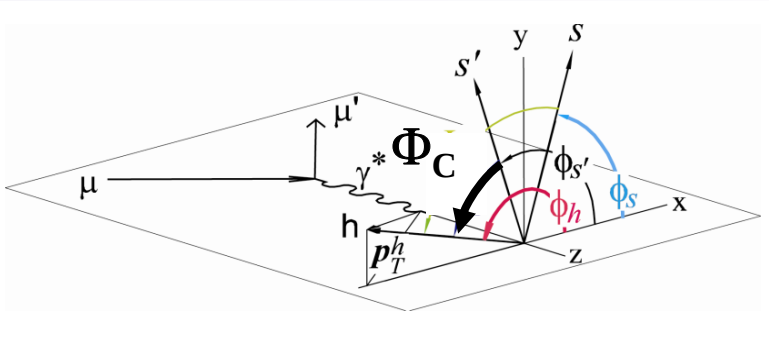
± refer to the opposite orientation of the transverse spin of the nucleon

P_T is the target polarisation; D_{NN} is the transverse spin transfer coefficient initial → struck quark

"Collins angle"

$$\Phi_C = \phi_h - \phi_{s'} = \phi_h + \phi_S - \pi$$

$\phi_{h,s',S}$ azimuthal angles of hadron momentum, of the spin of the fragmenting quark and of the nucleon in the GNS



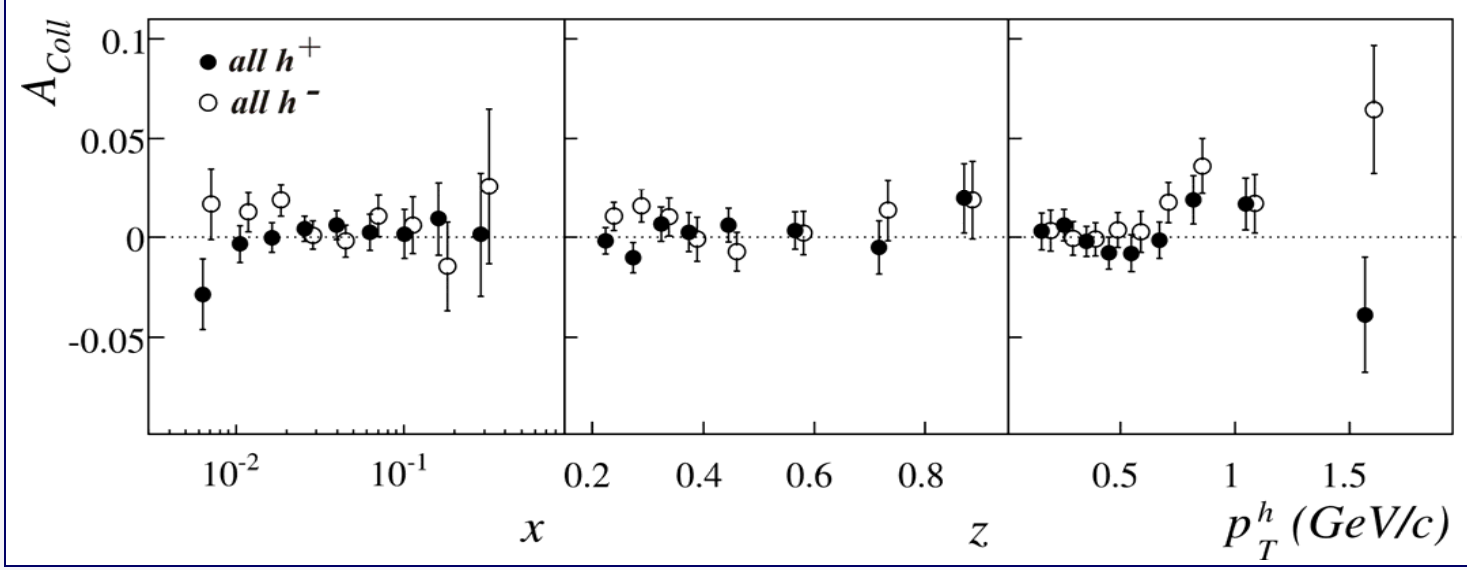
from the azimuthal distribution of the hadrons one measures the "Collins Asymmetry"

the convolution of TRANSVERSITY and COLLINS FF

$$A_{Coll} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

Collins Asymmetry - Deuteron data

final results from 2002-2004 data



charged hadrons

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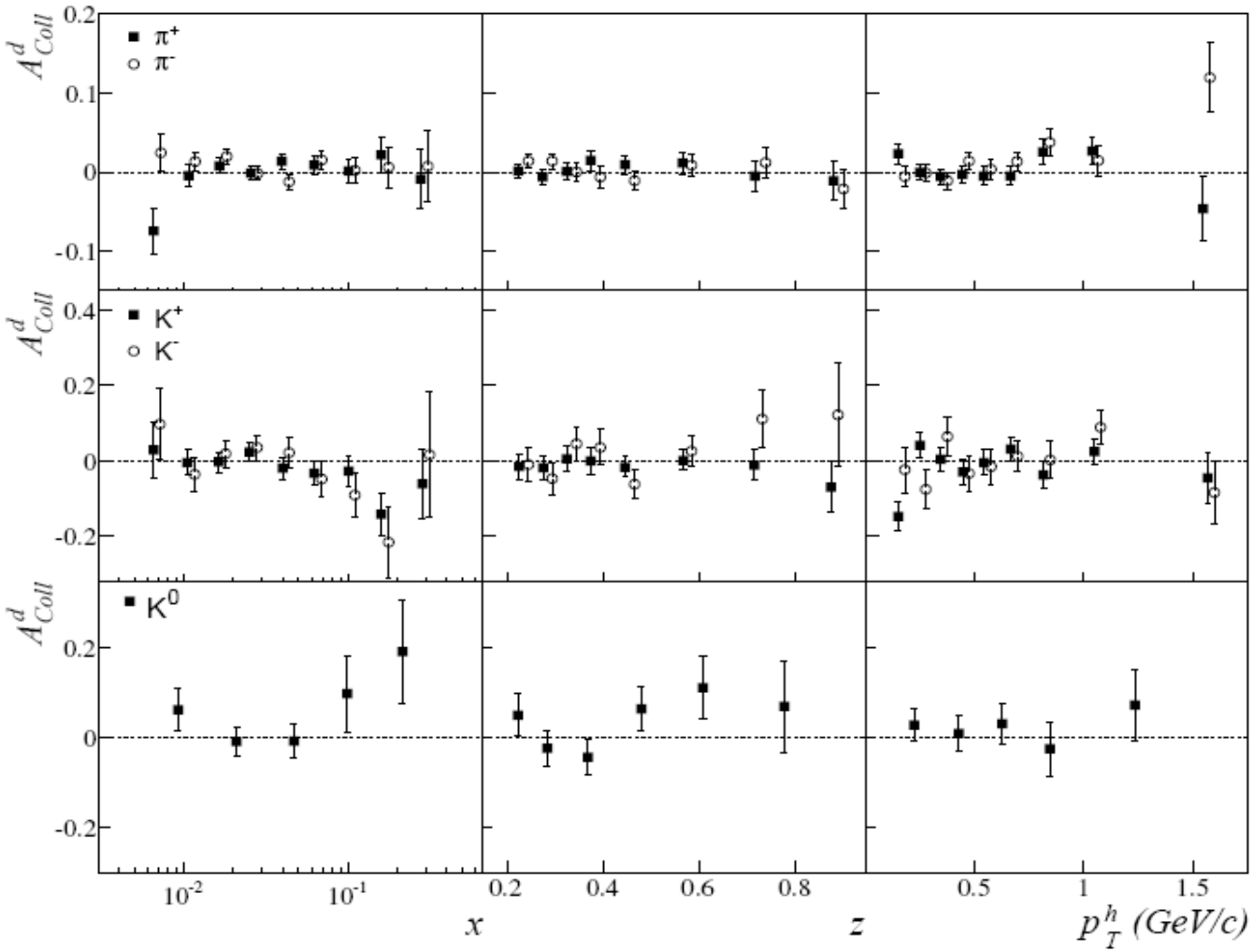
asymmetries compatible with zero within the statistical errors

(syst. errors much smaller)

Collins Asymmetry - Deuteron data

final results from 2002-2004 data



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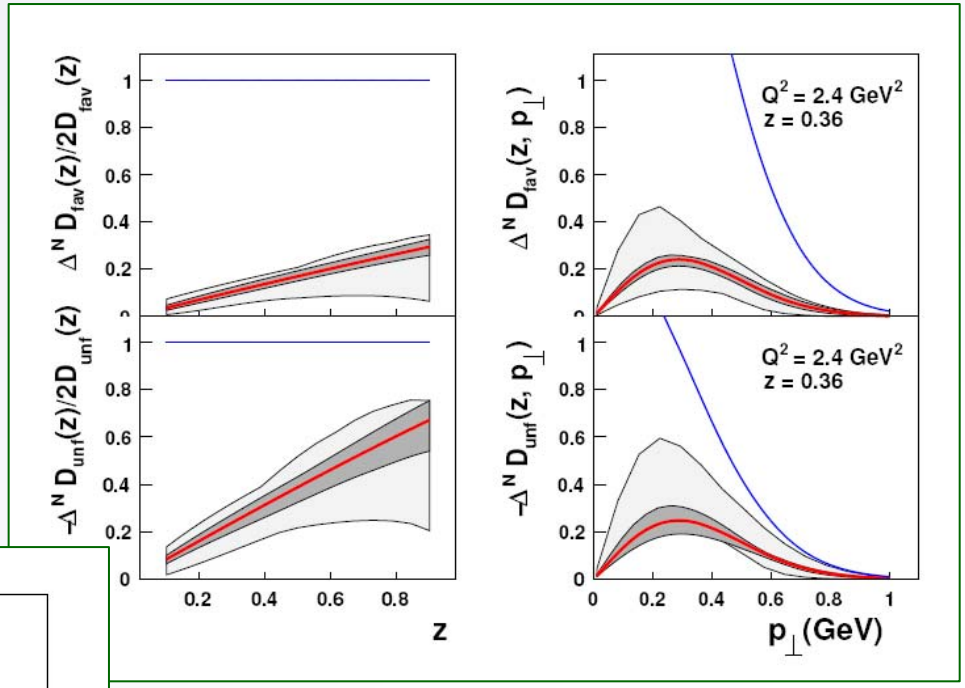
$\pi^{\pm}$

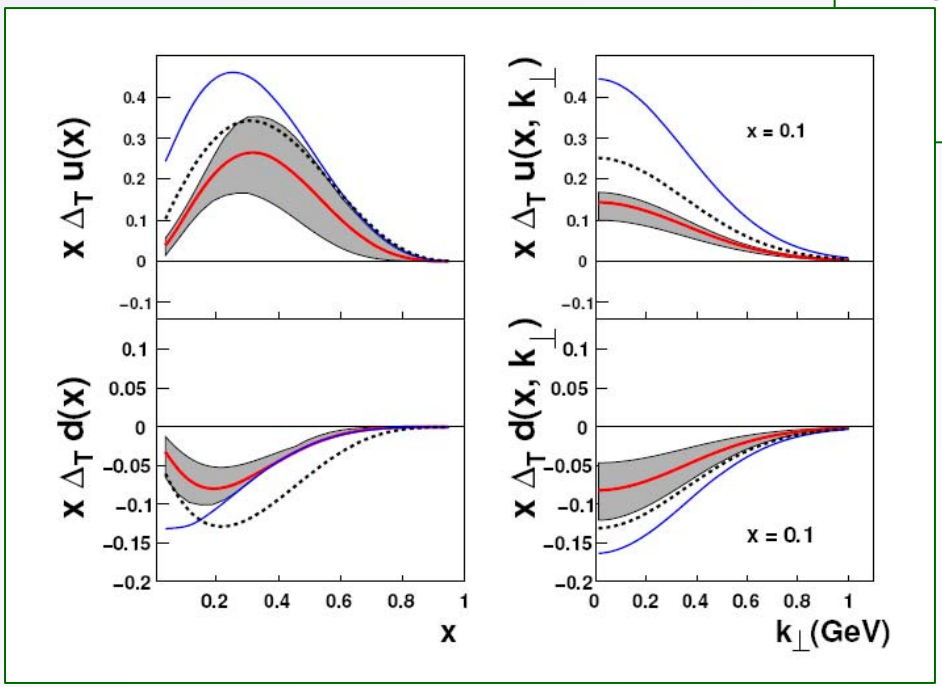
$K^{\pm}$

K^0

Collins Asymmetry - Fits to Data

new results using
HERMES (p) and
COMPASS (d) pion data,
and BELLE data





M. Anselmino et al.,
Ringberg Workshop on New Trends in HERA Physics 2008
Nucl.Phys.Proc.Suppl.191 (2009) 98

Collins Asymmetry - Proton Data

COMPASS

2007 run: transversely polarized NH_3 target

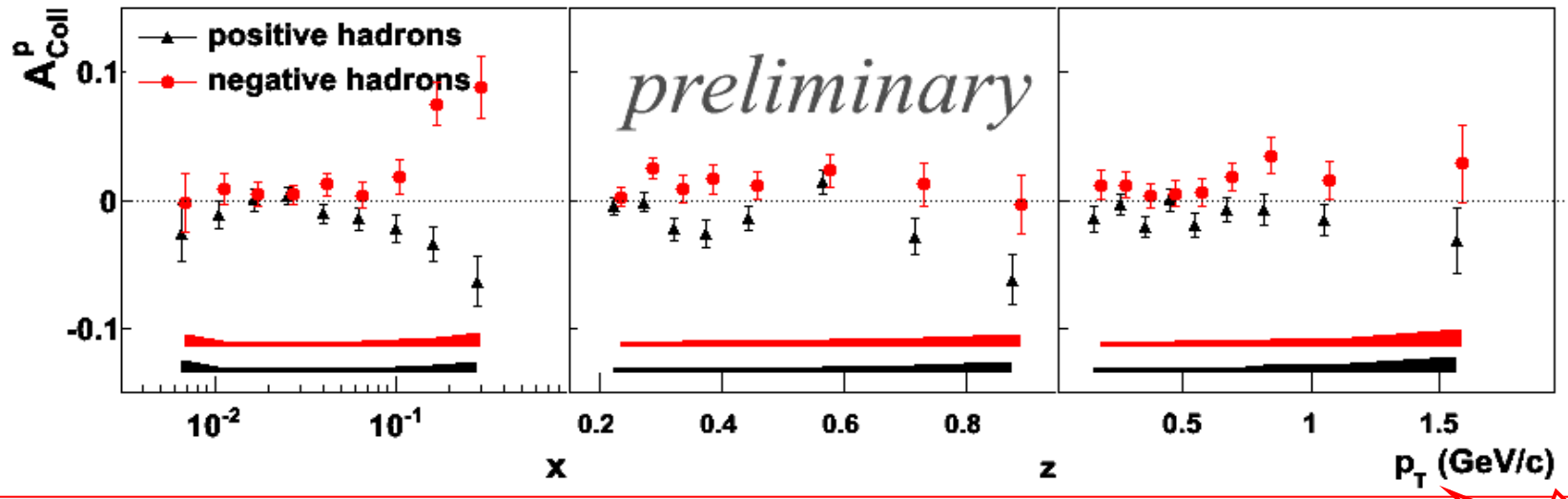
data taking equally shared between transverse and longitudinal

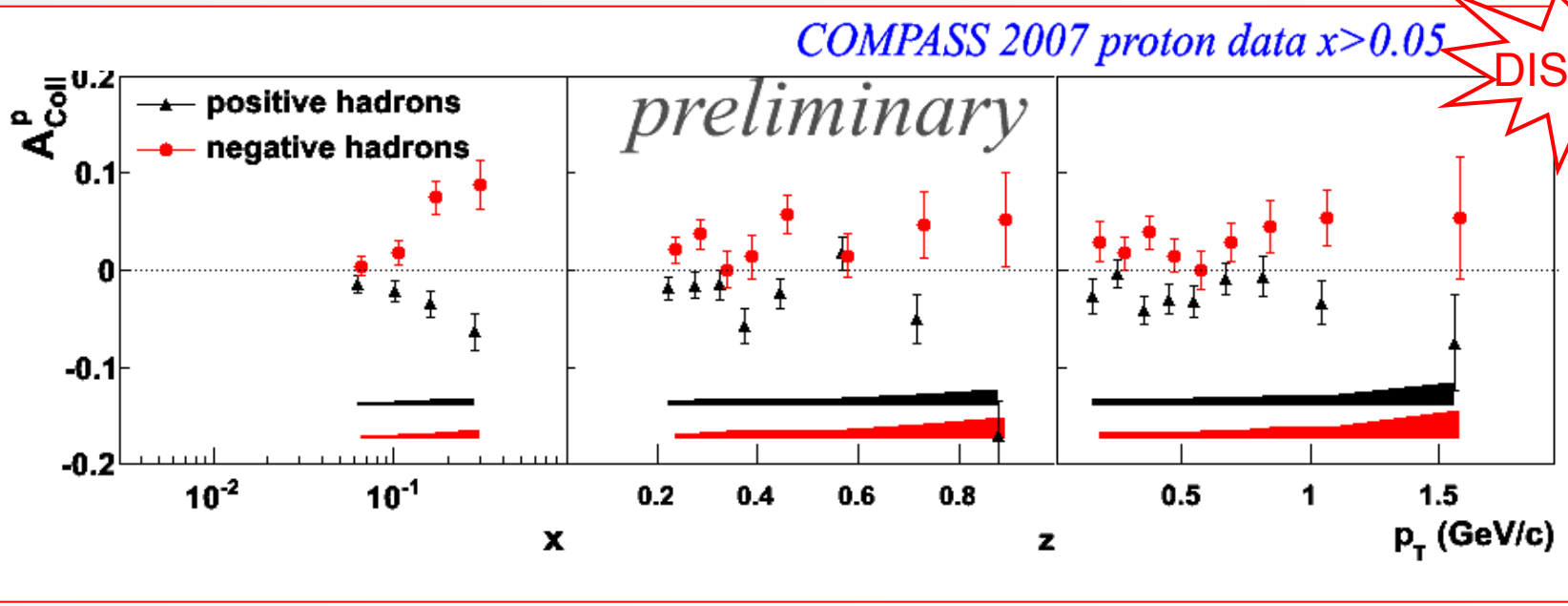
first results: Transversity 2008 in Ferrara

new release: DIS 2009 in Madrid

~2 times more statistics

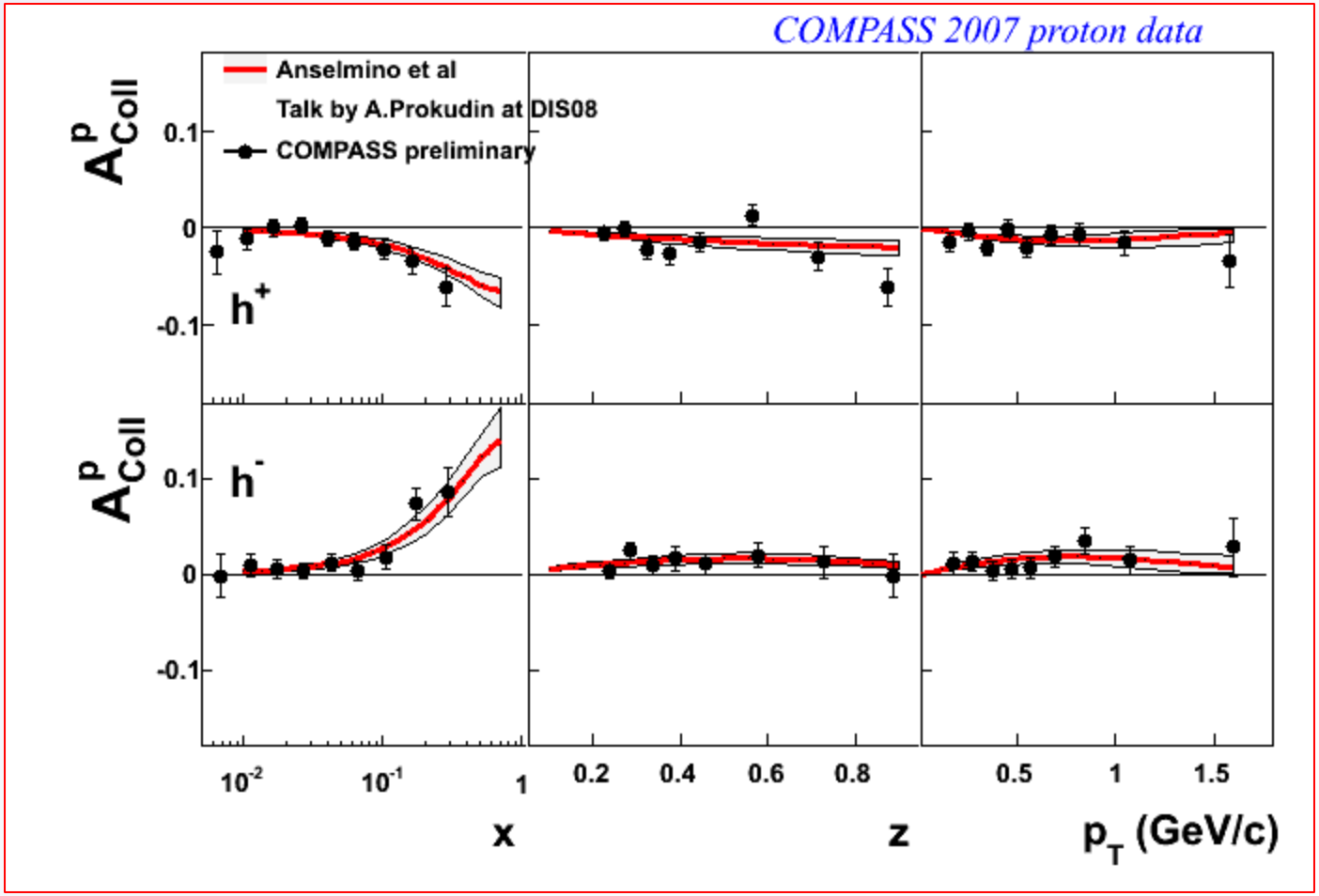
Collins Asymmetry - Proton Data





Collins Asymmetry - Proton Data

comparison with predictions



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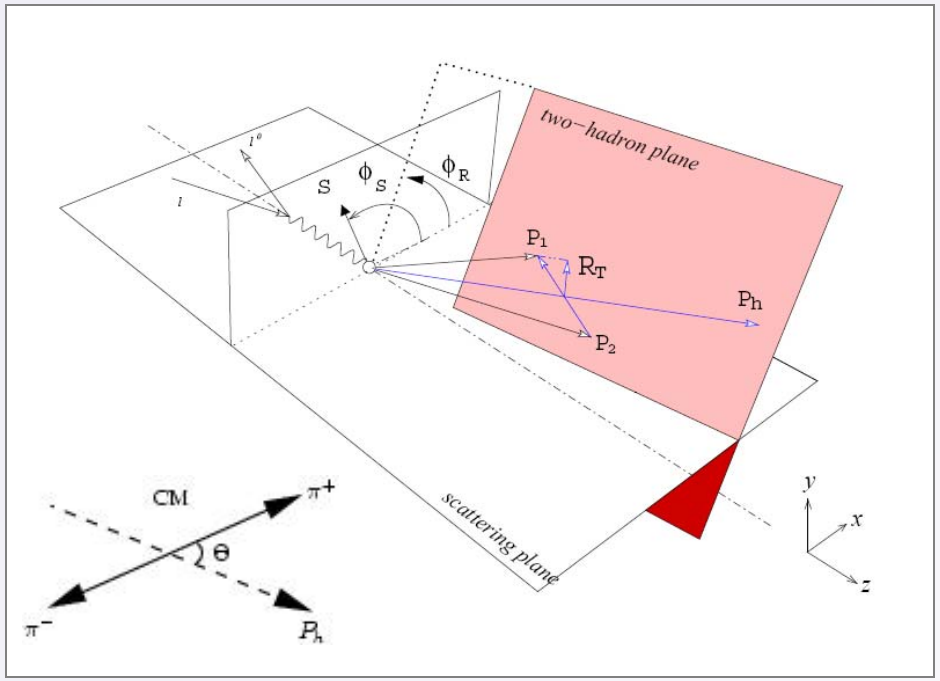
Two Hadron Asymmetries



azimuthal asymmetry in

$$\phi_{RS} = \phi_{R\perp} - \phi_S ,$$

$\phi_{R\perp}$ **is the azimuthal angle of the plane defined by the two hadrons**

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{ 1 \pm A \cdot \sin\Phi_{RS} \}$$

Interference Fragmentation Function

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

A. Bacchetta, M. Radici, hep-ph/0407345
X. Artru, hep-ph/0207309

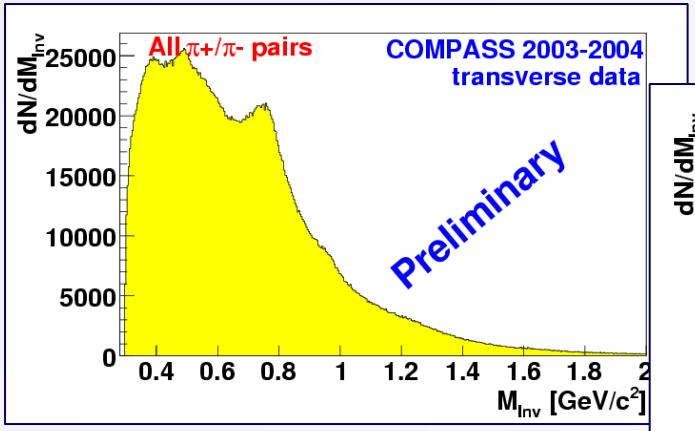
Two Hadron Asymmetries – Deuteron data

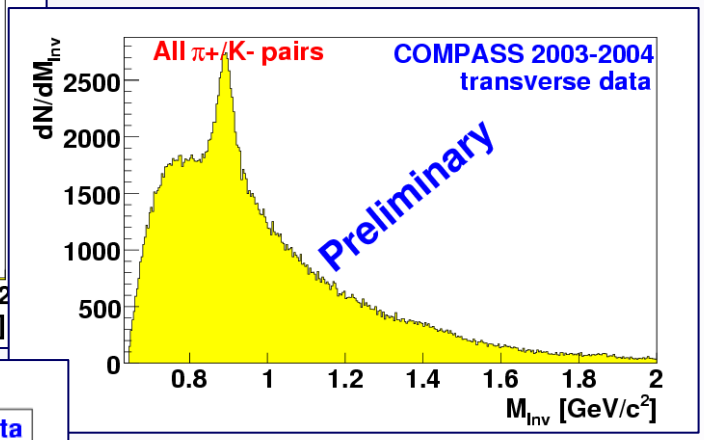
$x_F > 0.1$

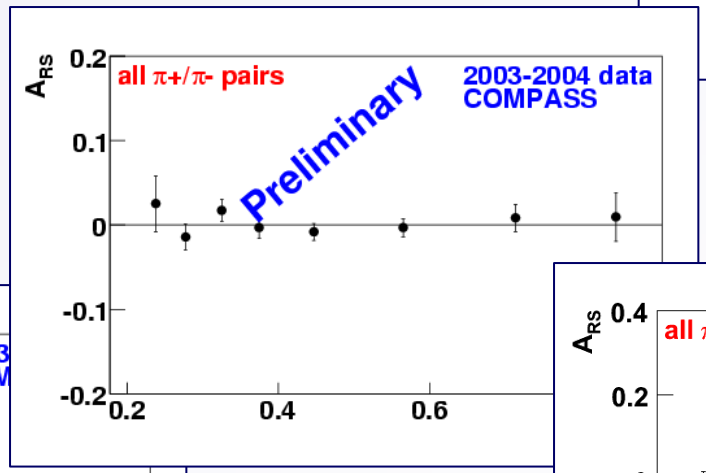
$z_{1,2} > 0.1$

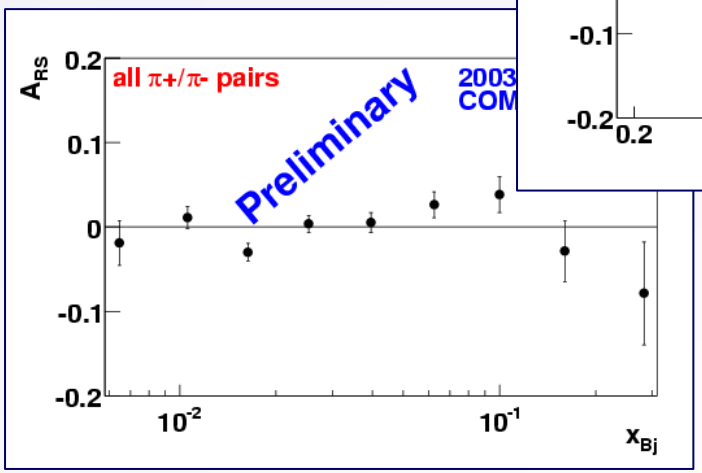
$Z = z_1 + z_2 < 0.9$

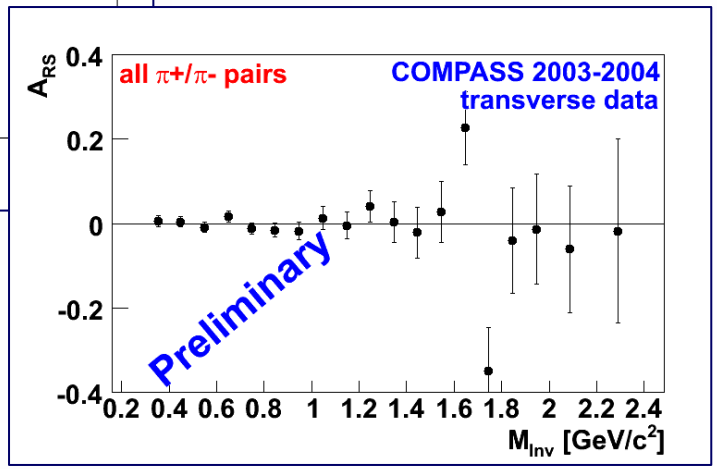
$R_T > 0.05$ GeV/c











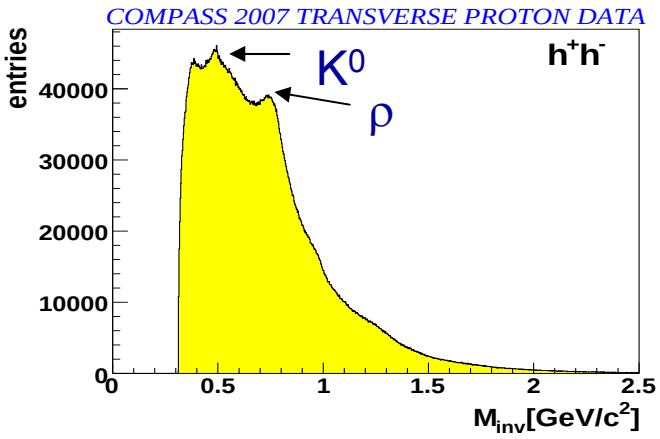
Two Hadron Asymmetries – Proton data

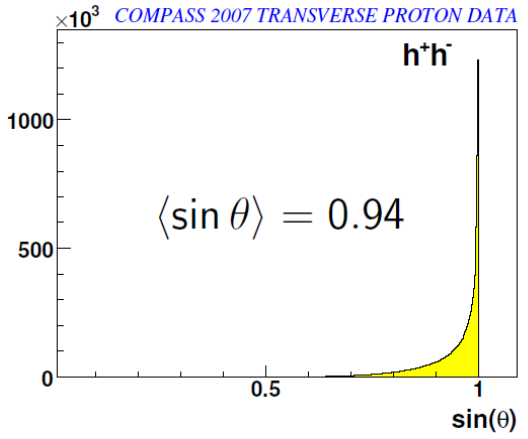
$x_F > 0.1$

$z_{1,2} > 0.1$

$Z = z_1 + z_2 < 0.9$

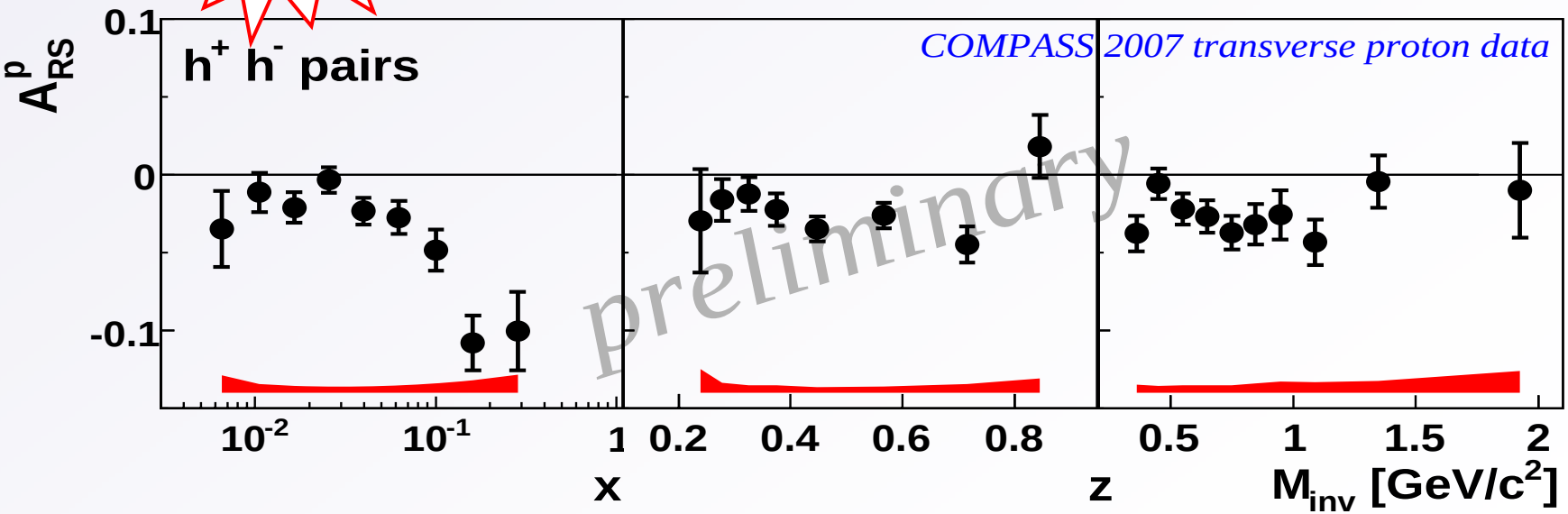
$R_T > 0.07$ GeV/c





COMPASS

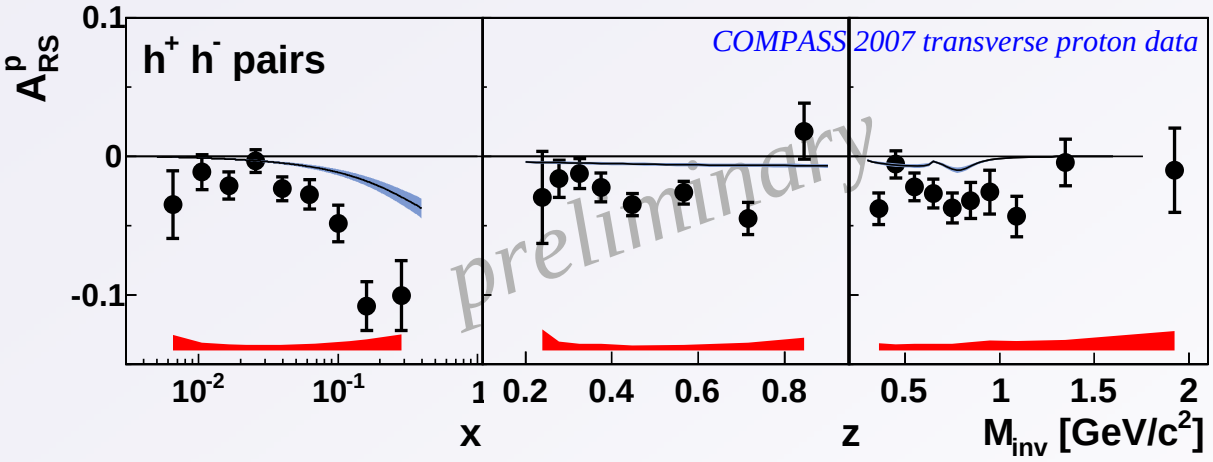
DIS2009

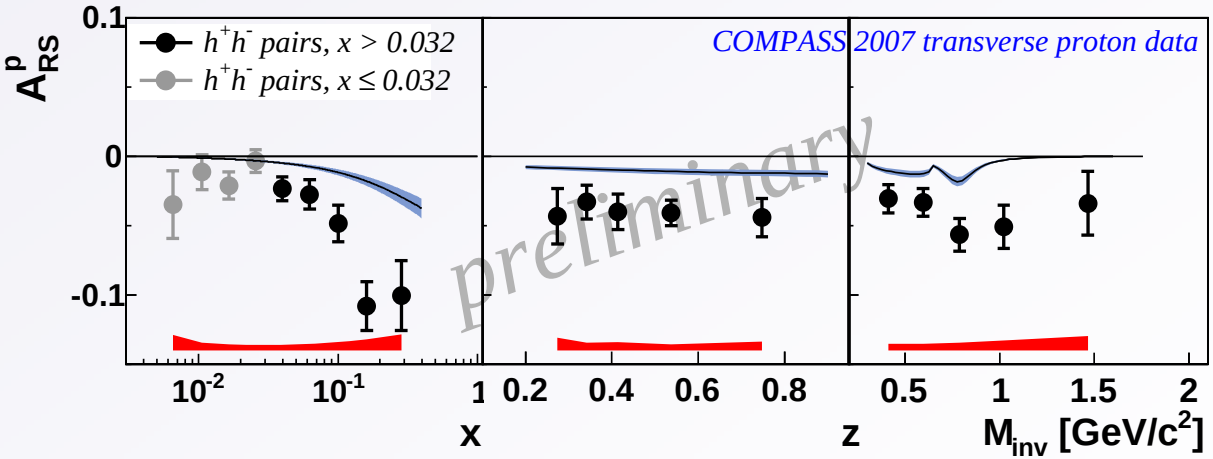


in the valence region signal larger than measured by HERMES

Two Hadron Asymmetries – Proton data

comparison with predictions





courtesy of A.Bacchetta

still waiting for the BELLE measurement of the IFF

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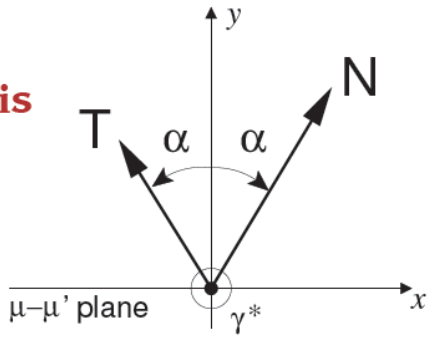
Λ asymmetries

Information on $\Delta_T q$ can be accessed in $\mu N^{\uparrow} \to \mu' \Lambda X$ $\mu N^{\uparrow} \to \mu' \bar{\Lambda} X$

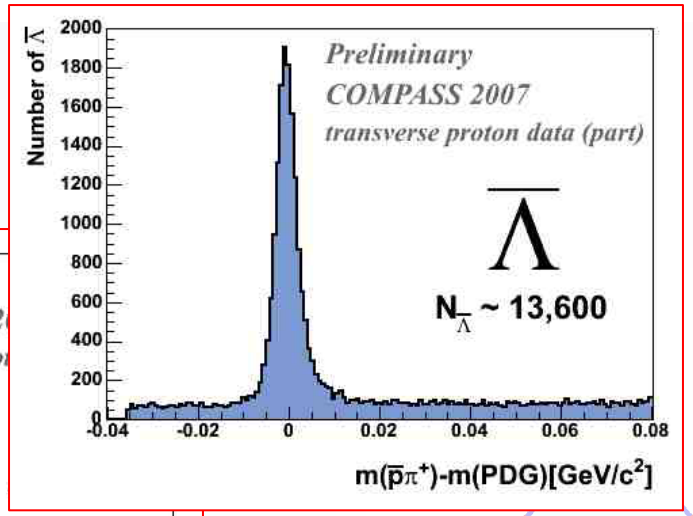
Λ polarization axis

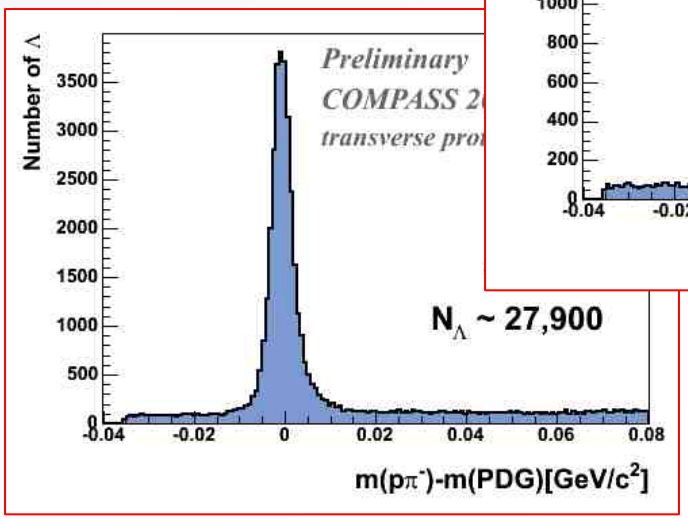


$$P_{T,exp}^{\Lambda} = f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$

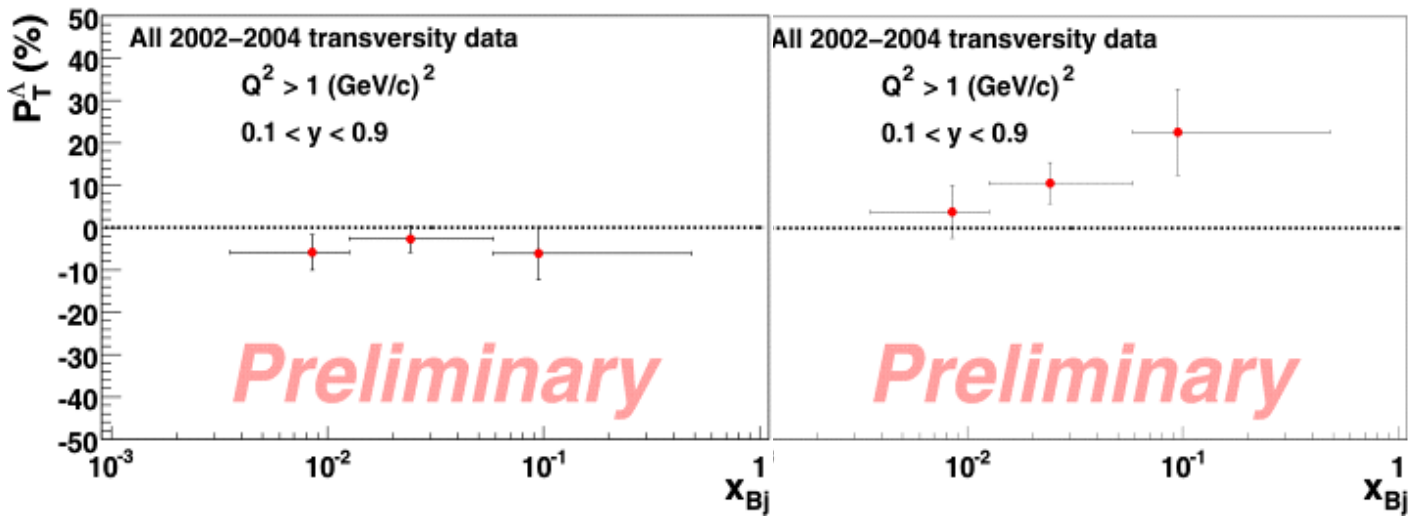
2007 proton data

- p_T > 23 MeV/c to exclude e^+e^- pairs
- Proton and pion momenta > 1 GeV/c
- Q^2 > 1 (GeV/c)^2
- 0.1 < y < 0.9
- Use of RICH (2007 data)
- Λ decay distance $D_\Lambda > 7\ \sigma_D$
- Collinearity < 10 mrad

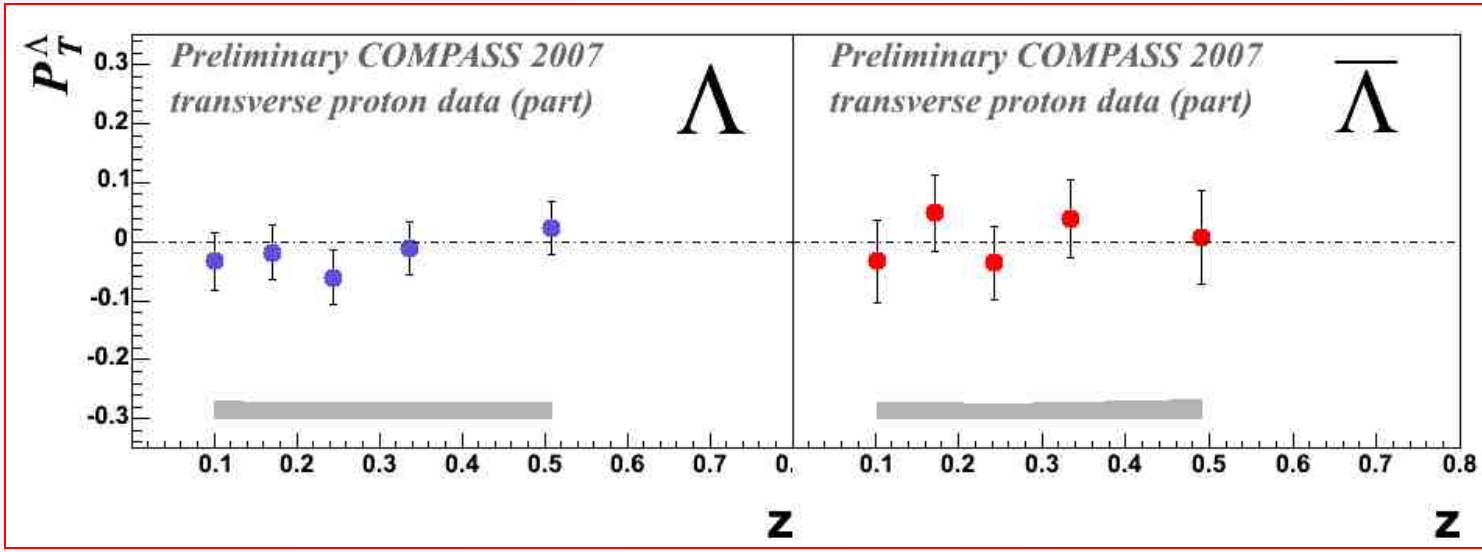




Λ asymmetries



deuteron



proton

systematic errors smaller than statistical errors from false polarization
no dependence on *x*

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Sivers Asymmetry

appears in SIDIS as a modulation in the "Sivers angle" $\Phi_S = \phi_h - \phi_S$

$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left[1 \pm P_T \cdot A_{Siv} \cdot \sin\Phi_S \right]$$

ϕ_h azimuthal angle of hadron momentum
ϕ_S azimuthal angle of the spin of the nucleon

the "Sivers angle" Φ_S and the "Collins angle" Φ_C are independent

→ the Collins and Sivers asymmetries can be disentangled and extracted from the same data in SIDIS on a transversely polarised target

$$A_{Siv} \approx \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

the "Sivers DF" (or $\Delta^N f_{q/N\uparrow}$ or $f_{1T}^{\perp q}$ or q_T)

the most famous of the TMD parton DF

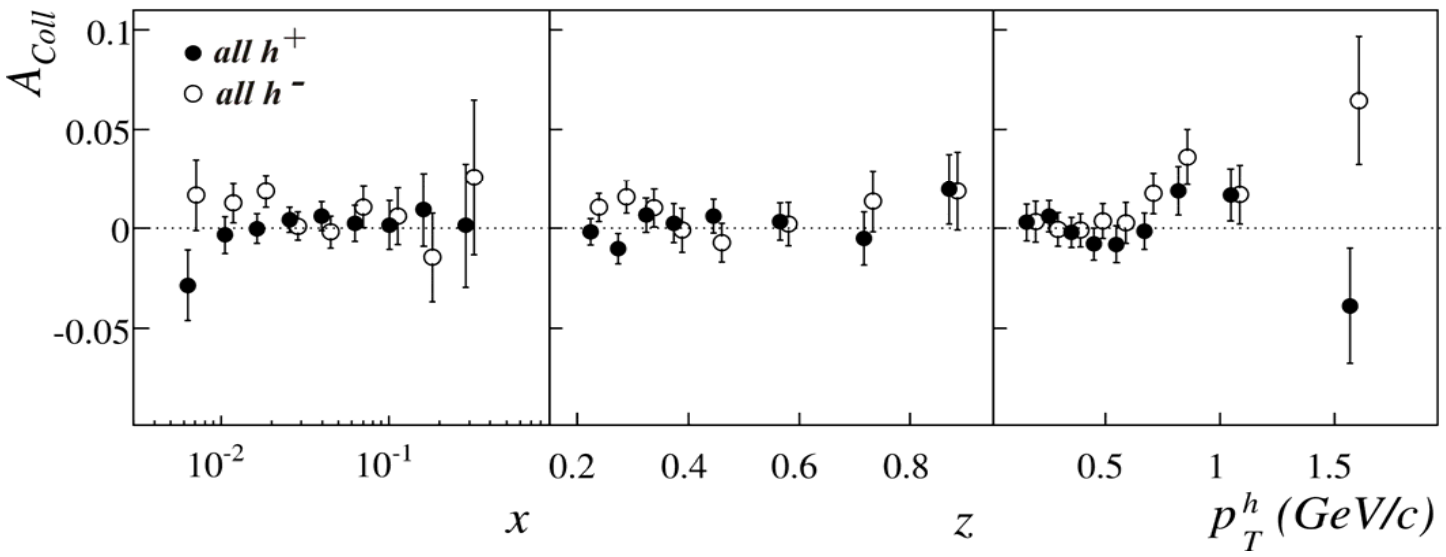
the Sivers asymmetry

has been measured by the HERMES experiment on proton

- **different from zero for positive charge particles**
- **compatible with zero for negative charge particles**

Sivers Asymmetry - Deuteron data

final results from 2002-2004 data



charged hadrons

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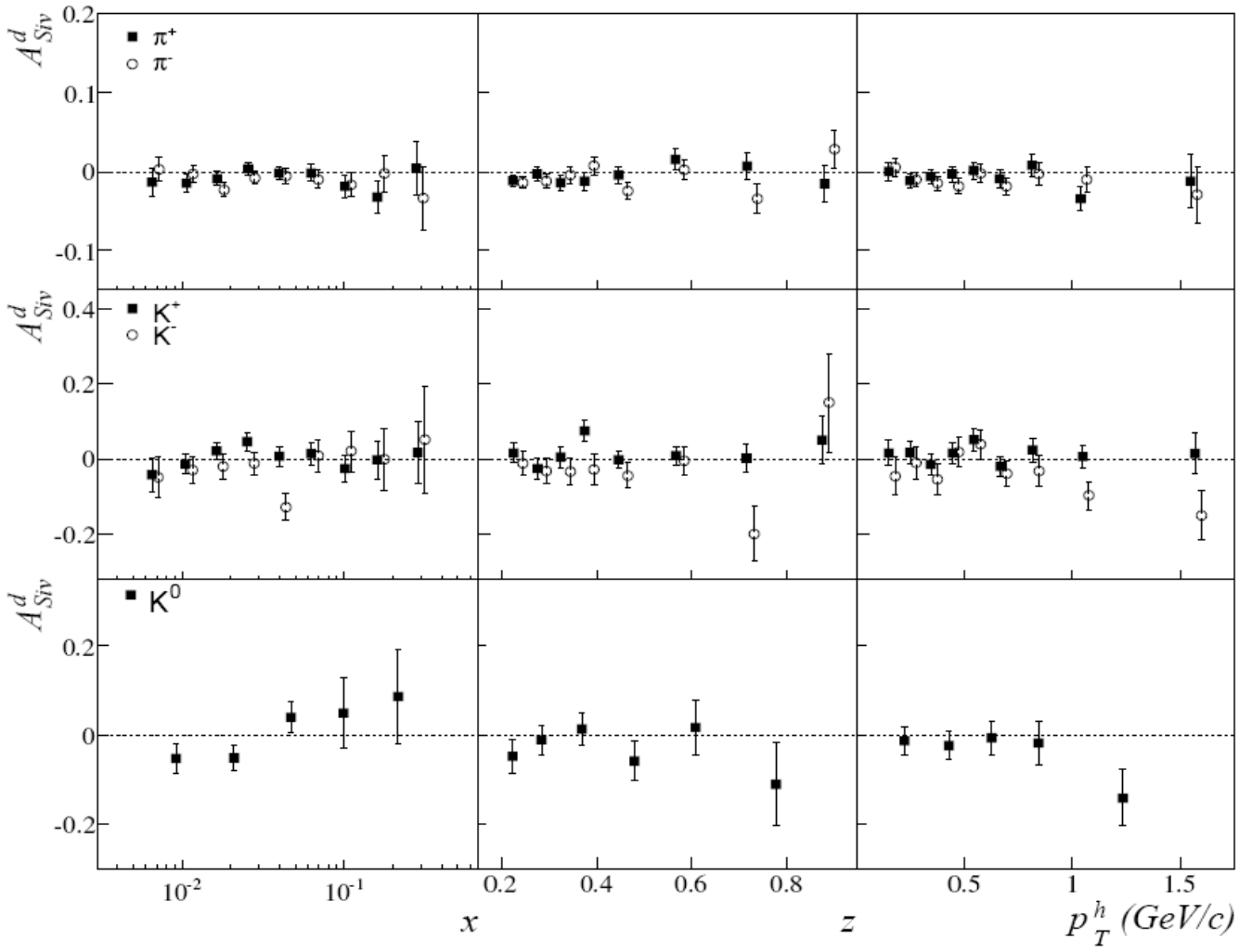
cancellation between u and d quark contributions in the dueteron

Sivers Asymmetry - Deuteron data

final results from 2002-2004 data



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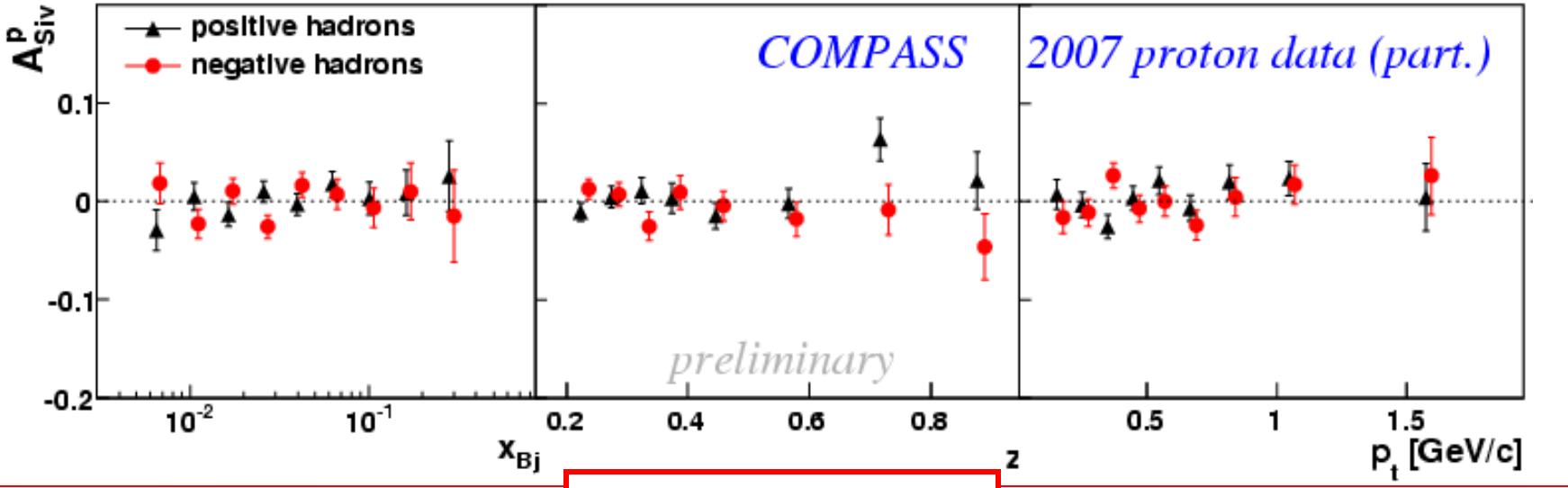
$\pi^{\pm}$

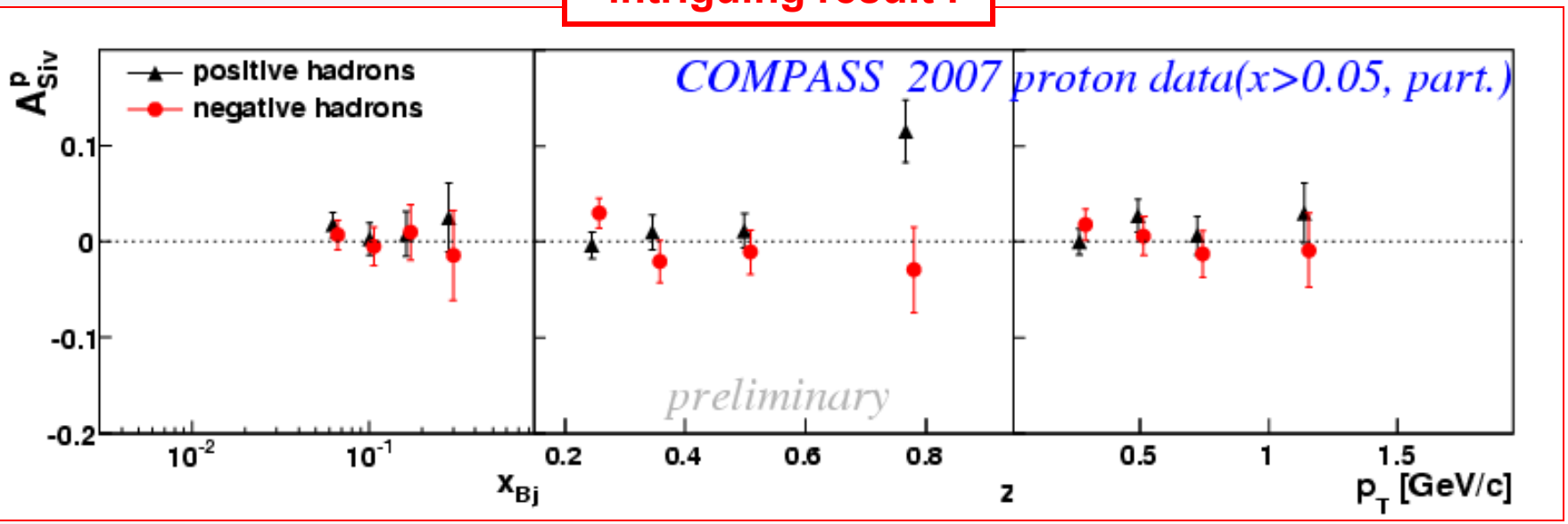
$K^{\pm}$

K^0

Sivers asymmetry – proton data



intriguing result !

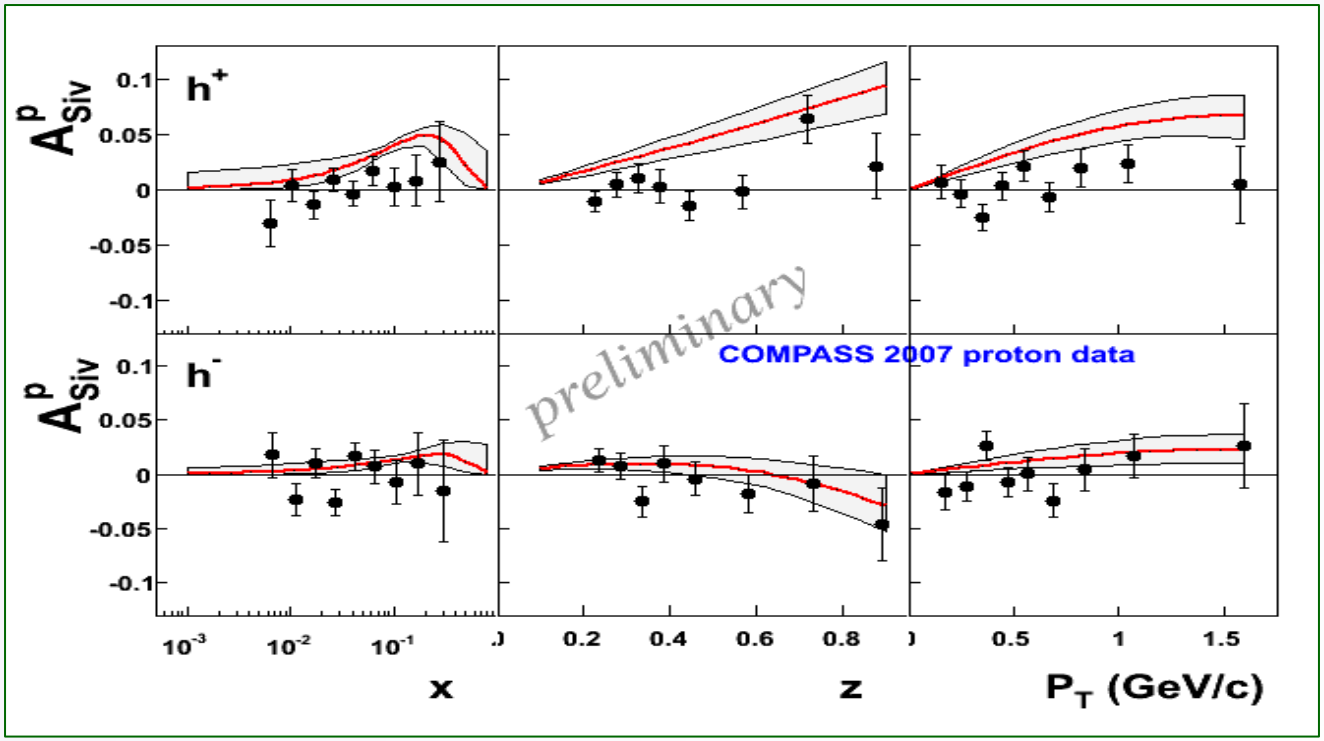


Sivers asymmetry – proton data

comparison with recent predictions

- **from M. Anselmino et al.**

  arXiv:0807.0166



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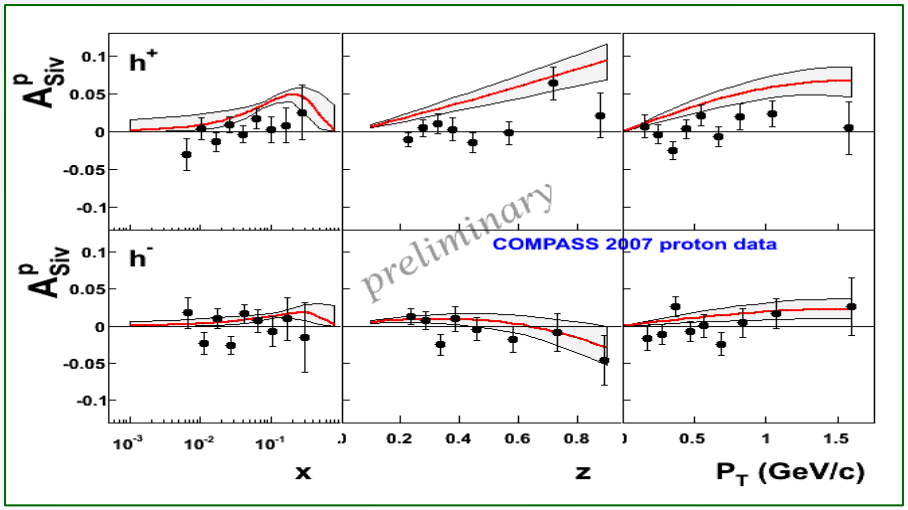
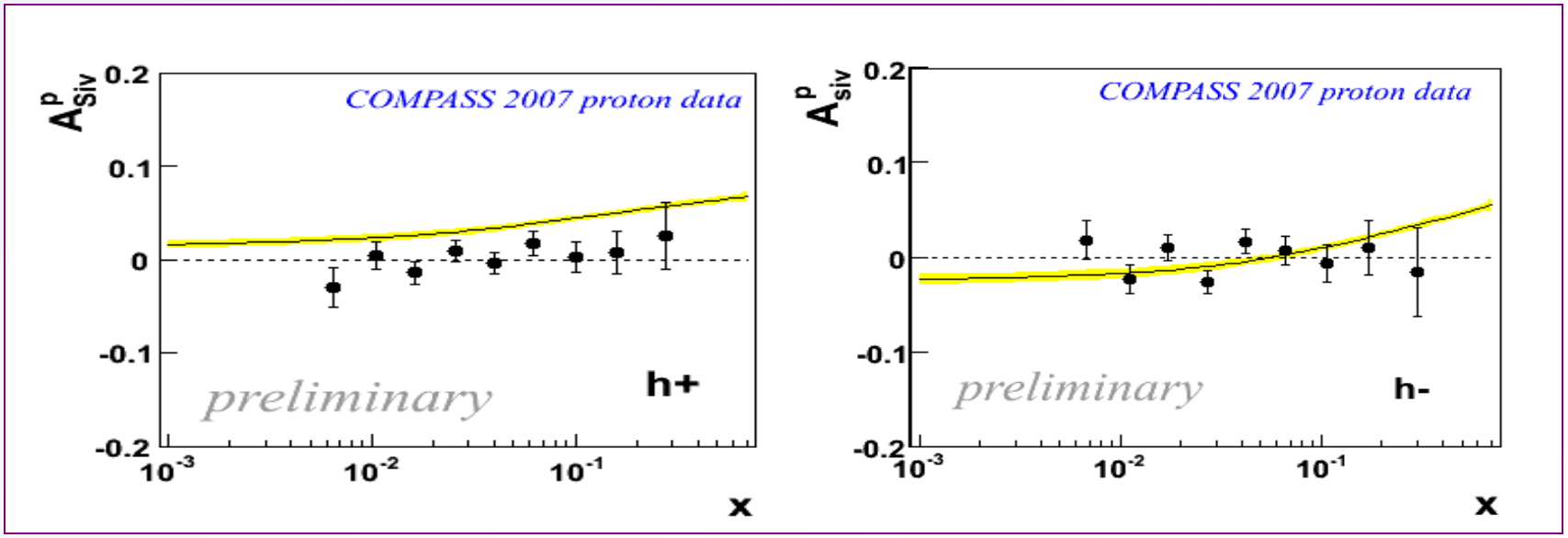


- **from S. Arnold et al.**
  arXiv:0805.2137



OUTLOOK

the COMPASS experiment

results on

- transversity : Collins asymmetries
  2 hadron asymmetries
  Λ polarization
- Sivers asymmetries
- **other TMD asymmetries**
- unpolarised azimuthal asymmetries
- exclusive ρ asymmetries

conclusions

SIDIS cross-section

18 structure functions

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

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

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

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

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

Sivers

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

Collins

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

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

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

8 modulations (4 LO)

all measured by COMPASS on deuteron

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

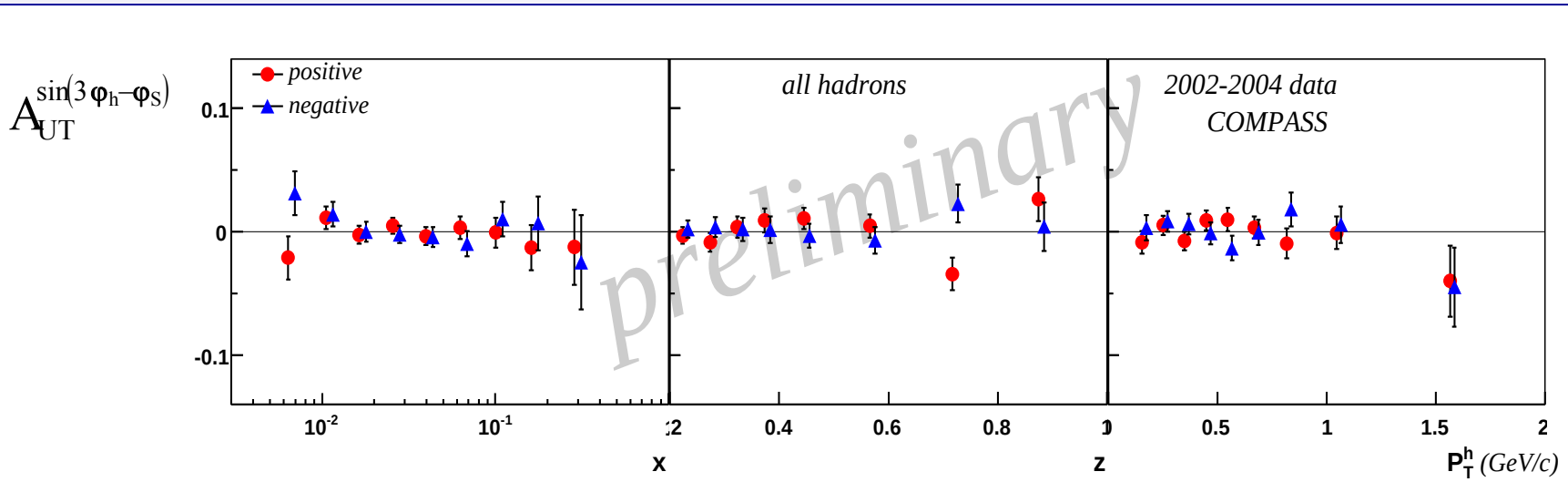
Other SSAs - Deuteron data

$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

two twist-2 asymmetries can be interpreted in QCD parton model and will allow to extract unexplored DFs

– “pretzelosity” ⊗ Collins FF



on deuteron asymmetries compatible with zero :
again cancellation between proton and neutron?

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

Collins

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

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

8 modulations (4 LO)

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

Unpolarised Target SIDIS Cross-Section

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e\, H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right]$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h\, H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{H}}{z}\right)\right]$$

Cahn effect + Boer-Mulders DF

$$xh = x\tilde{h} + \frac{p_T^2}{M^2} h_1^\perp \qquad F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_1 D_1\right]$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M\,M_h} h_1^\perp H_1^\perp\right]$$

Boer- Mulders x Collins FF
+ Cahn effect

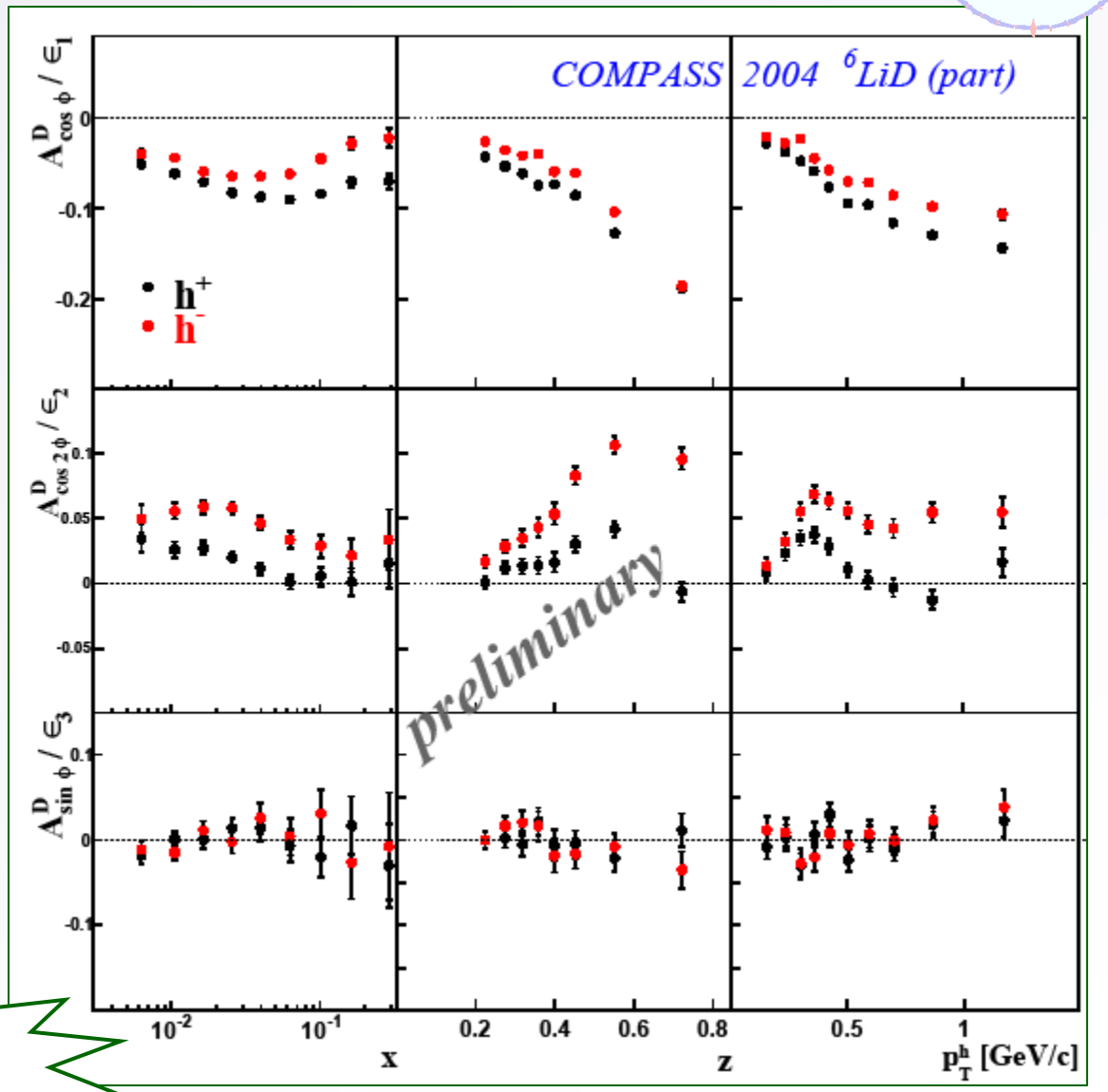
Unpolarised Azimuthal Asymmetries

summary

positive hadrons

negative hadrons

error bars:
statistical errors only

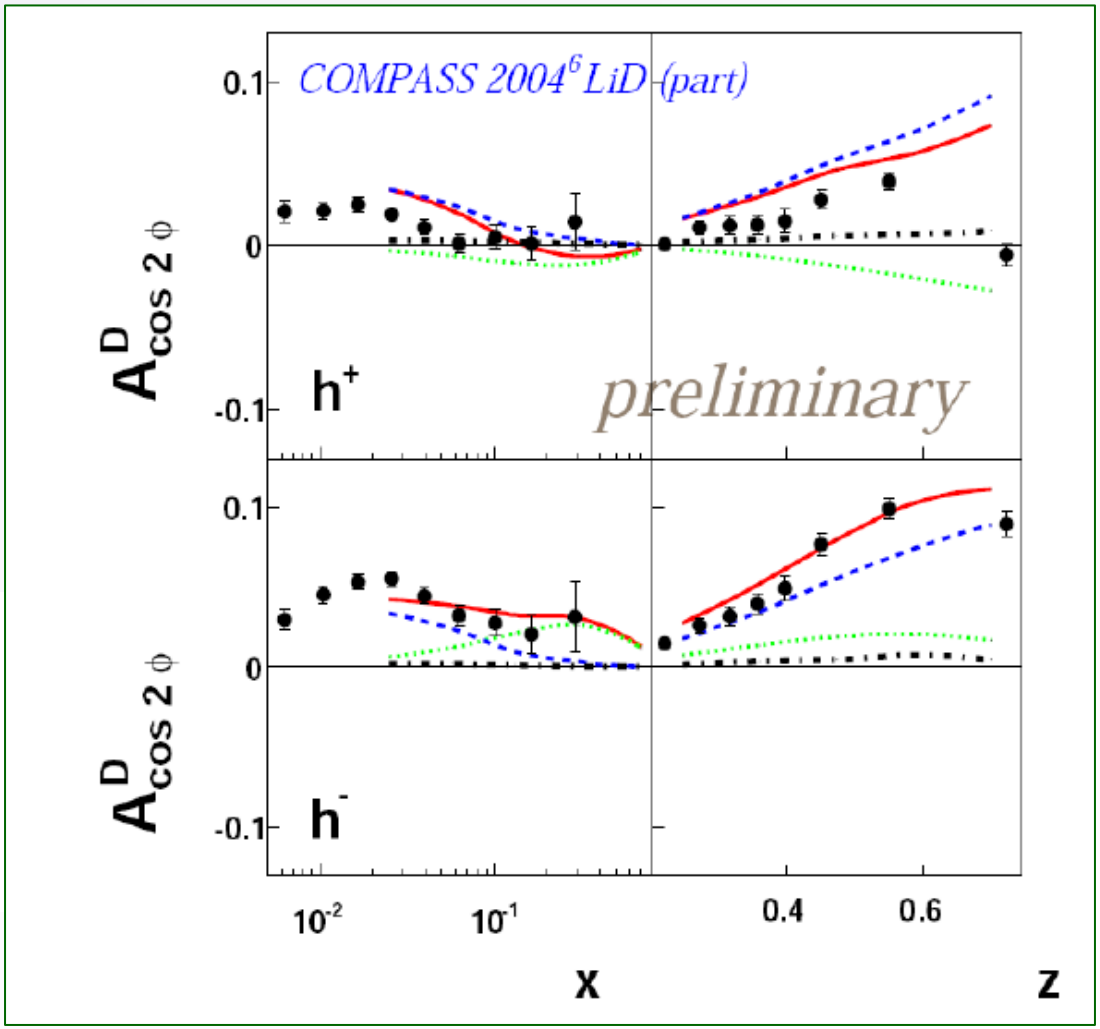


Transversity 2008

Unpolarised Azimuthal Asymmetries

cos2ϕ modulation

comparison with theory



total
Cahn
Boer Mulders
pQCD

V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

OUTLOOK

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- **exclusive ρ asymmetries**

conclusions

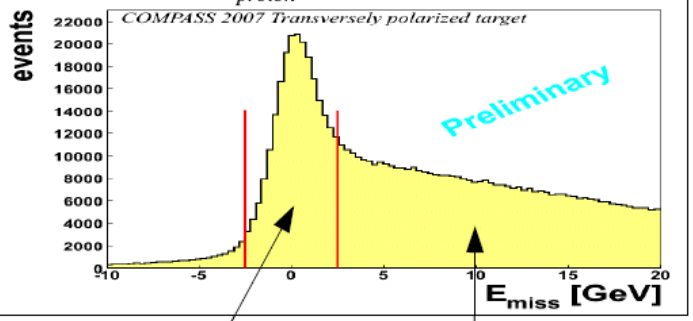
exclusive ρ_0 asymmetries

proton data analysis

- **selection of exclusive ρ_0 production**

Recoil proton (p') is not detected,
Check if the proton is intact :

$$E_{miss} = \frac{M_X^2 - M^2_{proton}}{2\,M_{proton}} \in [-2.5, 2.5]\,GeV$$



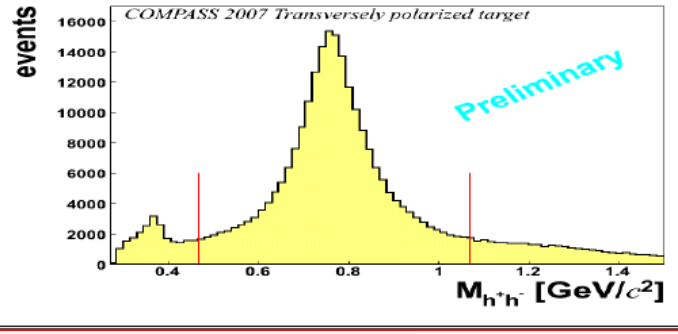
Exclusive peak

Non exclusive background

Exclusive ρ_0 Production

Invariant mass selection

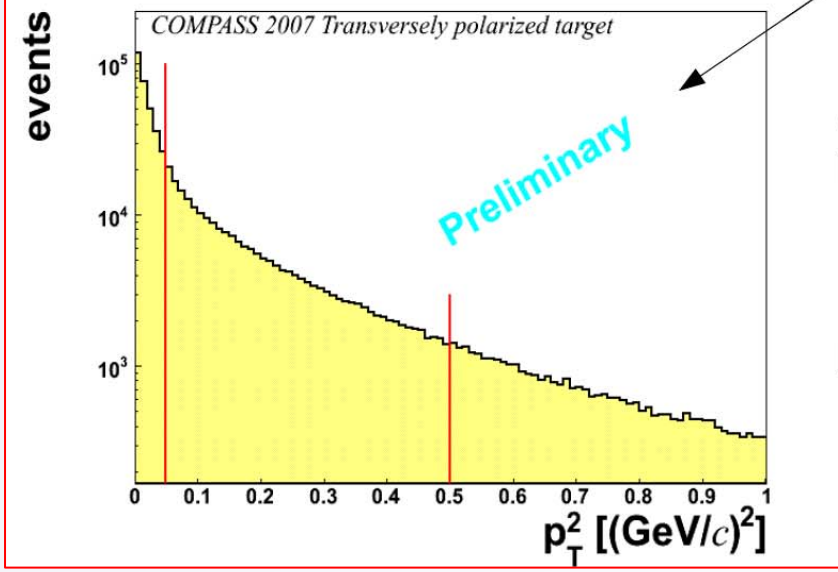
$$0.3 < M_{h^+h^-} - M_\rho < 0.3\,GeV$$



exclusive ρ_0 asymmetries

proton data analysis

- **selection of exclusive ρ_0 production**
- **selection of incoherent ρ_0 production**



Incoherent ρ_0 Production

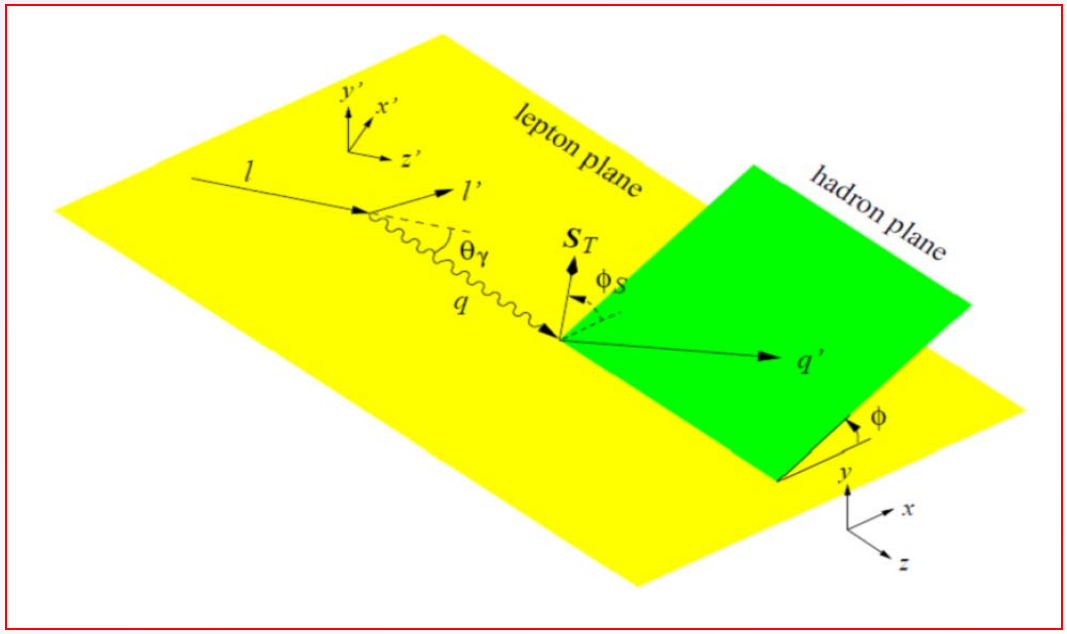
Coherent scattering on nitrogen rejected by selecting events with $p_T^2 > 0.05$ (GeV/c)^2

Non-exclusive background reduced by selecting events with $p_T^2 < 0.5$ (GeV/c)^2

exclusive ρ_0 asymmetries

proton data analysis

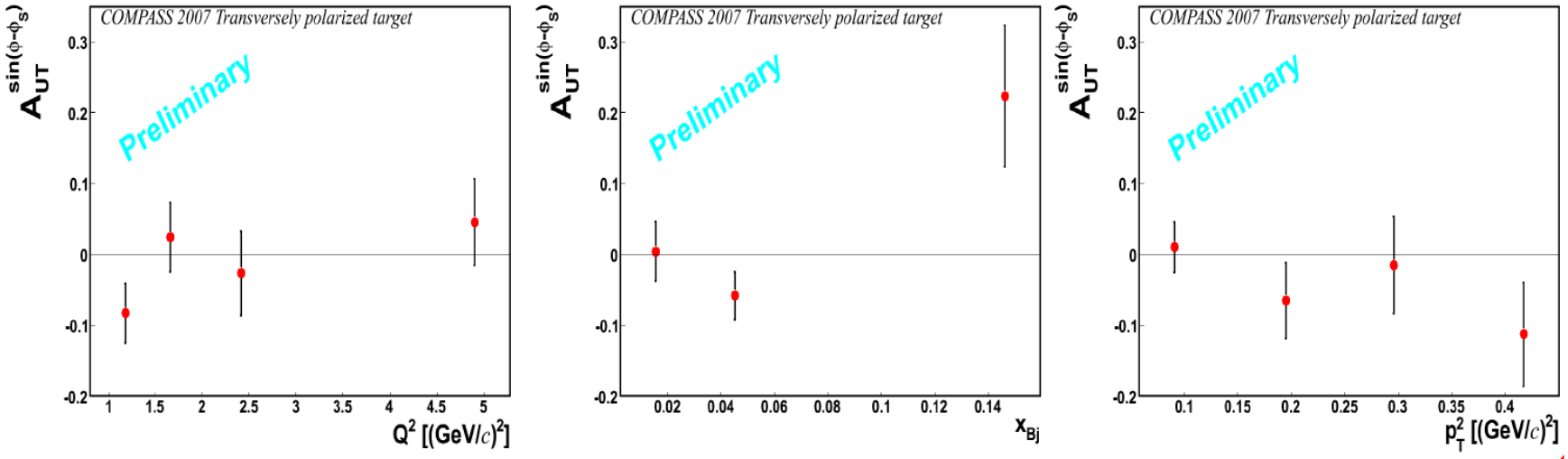
- selection of exclusive ρ_0 production
- selection of incoherent ρ_0 production
- measured asymmetry



$$N(\phi-\phi_S)=F\,a(\phi-\phi_S)\sigma_0(1\pm f\langle P_T\rangle A_{UT}^{\exp}\sin(\phi-\phi_S))$$

exclusive ρ_0 asymmetries – proton data

$\langle Q^2 \rangle \simeq 2.2\,(GeV/c)^2$ $\langle x_{Bj} \rangle \simeq 0.04$ $\langle p_T^2 \rangle \simeq 0.18\,(GeV/c)^2$



$A_{UT}^{\sin(\phi-\phi_s)}$ compatible with 0

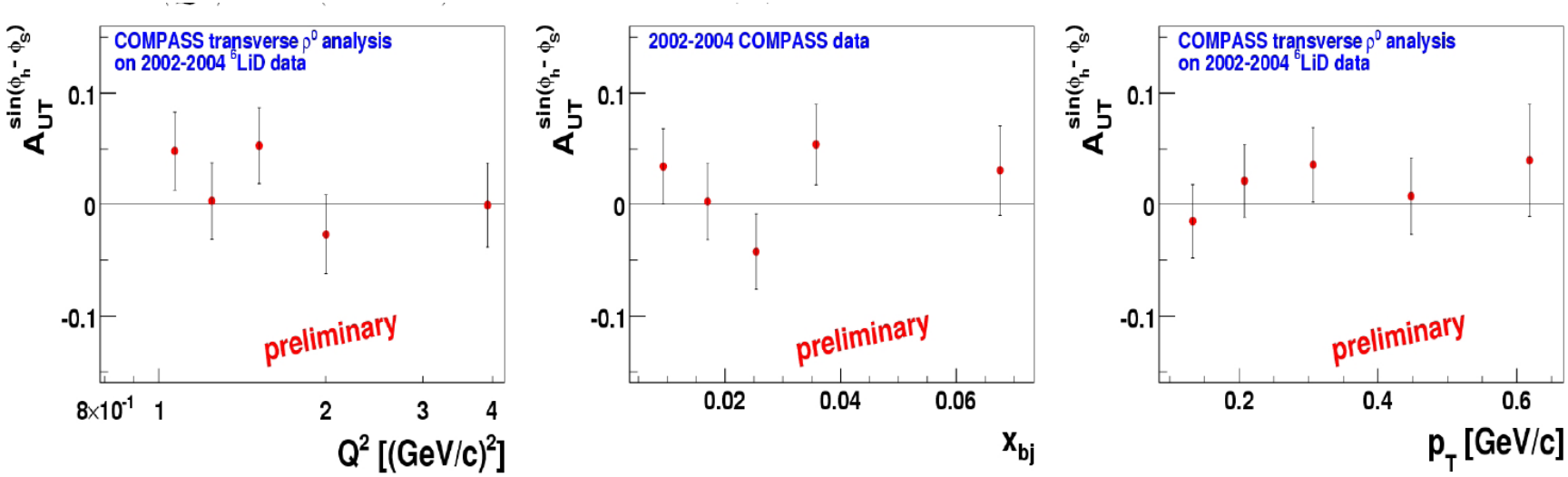
DIS2009

Small value ($A_{UT}(\rho) \simeq 0.02$) predicted by Goloskokov and Kroll (EPJC59 2009) (hep-ph/0809.4126)

Larger value ($A_{UT}(\omega) \simeq 0.1$) predicted by Goloskokov and Kroll

exclusive ρ_0 asymmetries – deuteron data

$\langle Q^2 \rangle \simeq 2.0\,(GeV/c)^2$ $\langle x \rangle \simeq 0.03$ $\langle p_T \rangle \simeq 0.11\,GeV/c$



without coherent/incoherent scattering separation

CONCLUSIONS

interesting COMPASS results for

- unpolarised hadron asymmetries on deuteron
  for positive and negative hadrons
- Collins and Sivers asymmetries on protons and deuterons
- Two hadron asymmetries
- ….

near future:

- identified hadron asymmetries
- all TMD asymmetries from 2007 data

longer term:

- the study of transverse spin effects needs further precise measurements and the COMPASS facility is the only place where SIDIS can be measured at high energy

→ *Anna Martin (SIDIS), Yann Bedfer (GPD), Catarina Quintans (DY) talks*

THANK YOU !