New results on transverse spin asymmetries from COMPASS Part **II**

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on behalf of the **COMPASS** collaboration

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Transverse Polarization Phenomena in Hard Processes
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GEFÖRDERT VOM
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NATURWISSENSCHAFTLICHE FAKULTÄT

Outline

1. Theoretical framework
2. Data selection
3. Results
   - deuteron data
   - proton data
4. Transversity extraction
5. Studies on the inter-relationship of Collins and dihadron asymmetries

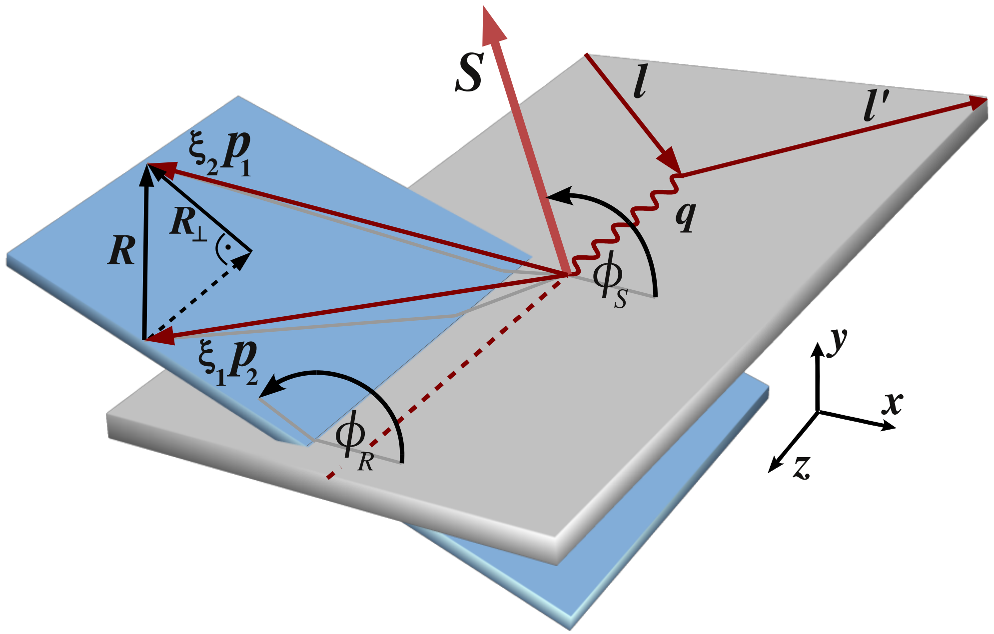
Theoretical framework

to the dihadron asymmetry

Theoretical framework ▶ angle definitions

$\ell\ N^{\uparrow} \rightarrow \ell'\ h_1\ h_2\ X$

Fragmentation of a transversely polarized quark into a pair of unpolarized hadrons



- $\boldsymbol{l}$, $\boldsymbol{l'}$ and $\boldsymbol{q}$ are 3-momenta of incoming, scattered lepton and virtual photon
- $\phi_{\boldsymbol{S}}$ azimuthal angle of the spin $\boldsymbol{S}$ of the fragmenting quark
- $\boldsymbol{p_i}$ is the 3-momenta of h_i
- z_i is the fraction of the virtual-photon energy carried by h_i
- $\boldsymbol{R} = \frac{z_2 \boldsymbol{p_1} - z_1 \boldsymbol{p_2}}{z_1 + z_2} = \xi_2 \boldsymbol{p_1} - \xi_1 \boldsymbol{p_2}$
- $\boldsymbol{R_T}$ is the component of $\boldsymbol{R}$ perpendicular to $\boldsymbol{q}$
- Azimuthal angle of $\boldsymbol{R}$:
  $\phi_R =$
  $\frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}}{|(\boldsymbol{q}\times\boldsymbol{l})\cdot\boldsymbol{R}|} \arccos\left(\frac{(\boldsymbol{q}\times\boldsymbol{l})\cdot(\boldsymbol{q}\times\boldsymbol{R})}{|\boldsymbol{q}\times\boldsymbol{l}||\boldsymbol{q}\times\boldsymbol{R}|}\right)$
- Difference of the azimuthal angles of the two hadrons:
  $\Delta\Phi = |\phi_{h^+} - \phi_{h^-}|$

The differential dihadron cross section is[1]:

$$\frac{\mathrm{d}^7\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_R\,\mathrm{d}\phi_S\,\mathrm{d}\cos\theta\,\mathrm{d}M_h^2} = \frac{2\alpha^2}{4\pi Q^2 y}\sum_q e_q^2 \Big[A(y) f_1^q(x) D_1^q(z, \cos\theta, M_h^2)$$
$$+\lambda_e S_L \frac{C(y)}{2} g_1^q(x) D_1^q(z, \cos\theta, M_h^2)$$
$$+B(y)\frac{|\boldsymbol{S}_T||\boldsymbol{R}_T|}{M_h} \sin\phi_{RS} h_1^q(x) H_1^{\sphericalangle q}(z, \cos\theta M_h^2)\Big]$$

with $\phi_{RS} = \phi_R + \phi_S - \pi$, $A(y) = \left(1 - y + \frac{y^2}{2}\right)$, $B(y) = (1 - y)$, and $C(y) = y(2 - y)$.

Where $h_1(x)$ is the Transversity PDF and $H_{1,q}^{\sphericalangle}$ is the dihadron fragmentation function, which describes the Fragmentation of a transversely polarized quark into two unpolarized hadrons. $D_{1,q}$ is the unpolarized dihadron fragmentation function, which is measured at *e.g.* BELLE[2].

[1] *cf.* talk by Marco Radici
[2] *cf.* talk by Francesca Giordano & Matthias GrossePerdekamp

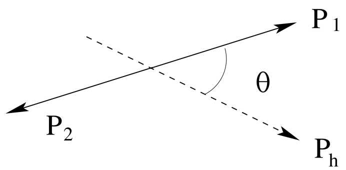
Theoretical framework ▶ asymmetries extraction

The dihadron asymmetry then is:

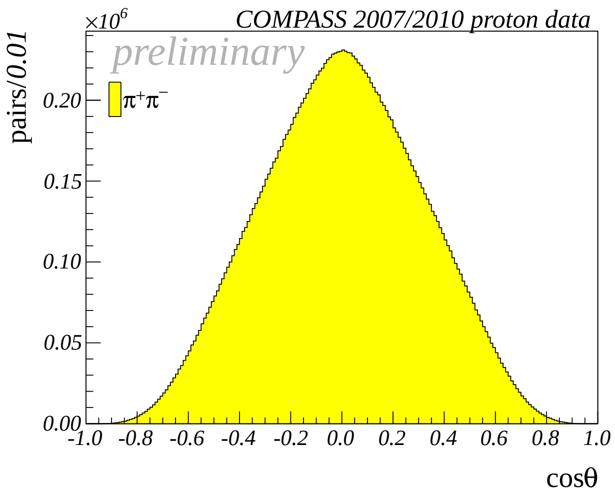
$$A_{UT}^{\sin\phi_{RS}} = |\boldsymbol{S}_T| \frac{B(y)}{A(y)} \frac{\sum_q e_q^2 h_1^q \int \mathrm{d}\cos\theta \frac{|\boldsymbol{R}_T|}{2M_h} H_1^{\sphericalangle,q}(z,\cos\theta,M_h^2)}{\sum_q e_q^2 f_1^q \int \mathrm{d}\cos\theta D_1^q(z,\cos\theta,M_h^2)}$$

We measure:

$$N_{2h}(x, y, z, M_{inv}^2, \theta, \phi_{RS}) \propto$$
$$\sigma_{UU}(1 \pm f P_T D_{NN} A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS})$$



in the pair's center of mass frame



σ_{UU} = unpolarized cross section

$\pm$ indicates nucleon spin orientation

f = target dilution factor

P_T = target polarization

D_{NN} = spin transfer coef.

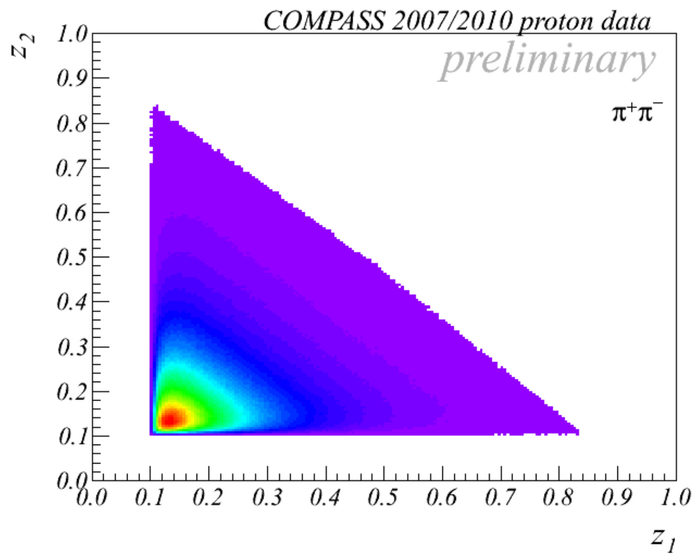
$D_{NN} = \frac{1-y}{1-y+\frac{y^2}{2}}$

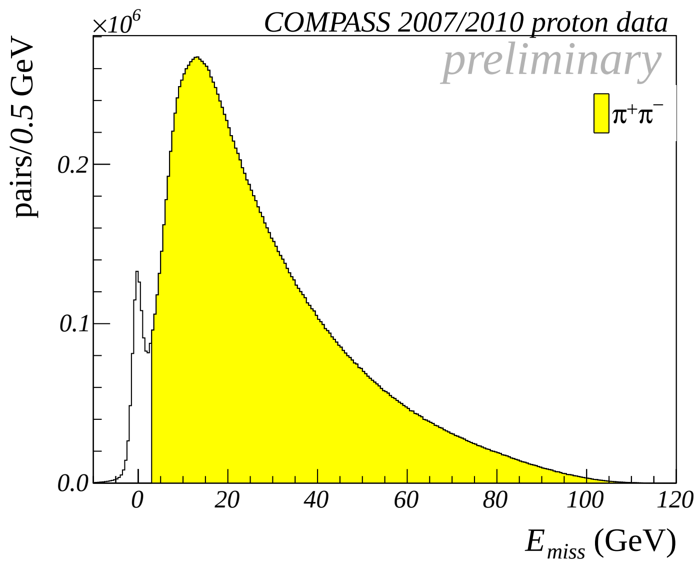
Data selection

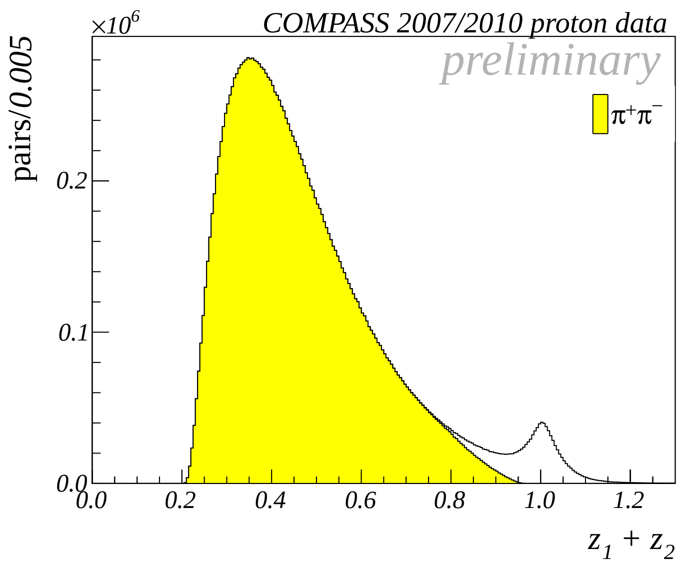
Data selection ▶ hadron & hadron pair cuts

hadron & hadron pair cuts:

- at least 2 outgoing hadrons with opposite charge
- $z > 0.1$ for each hadron
- $x_F > 0.1$ for each hadron
- $E_{miss} > 3$ GeV for each pair
- $R_T > 0.07$ GeV$/c$ for each pair



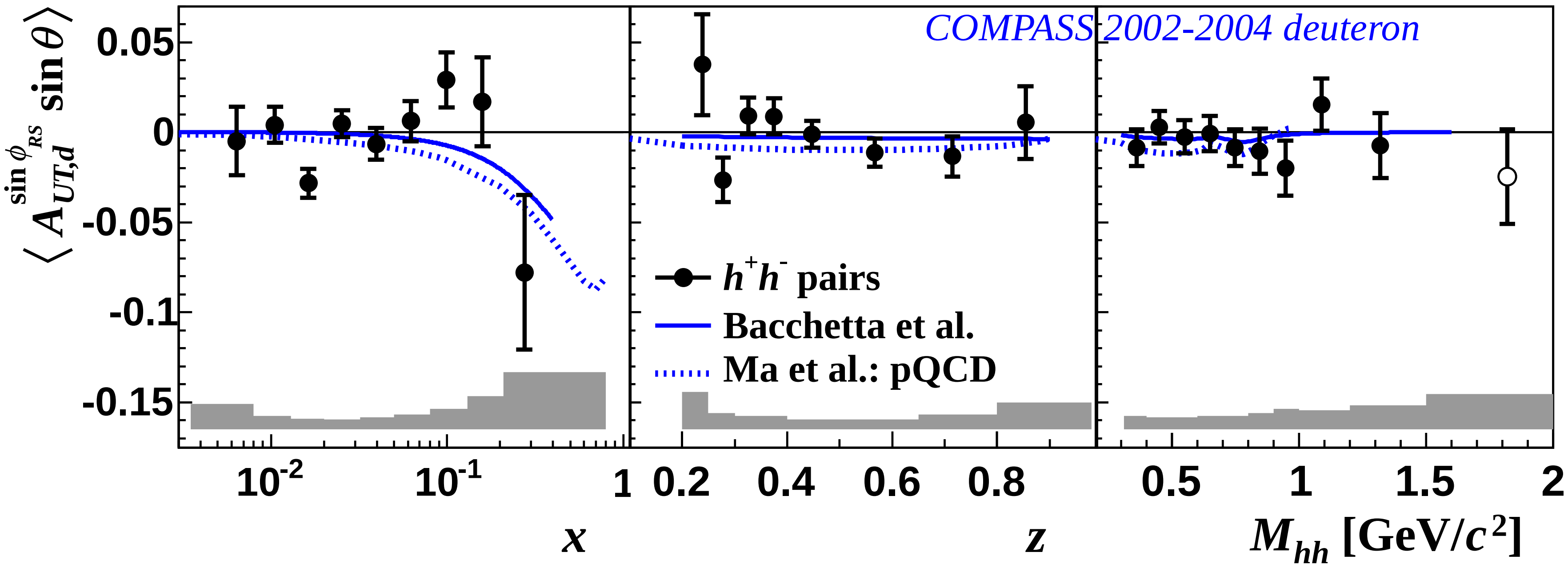




dihadron asymmetries:

deuteron data

Results ▶ deuteron data ▶ all hadron h^+h^- pairs

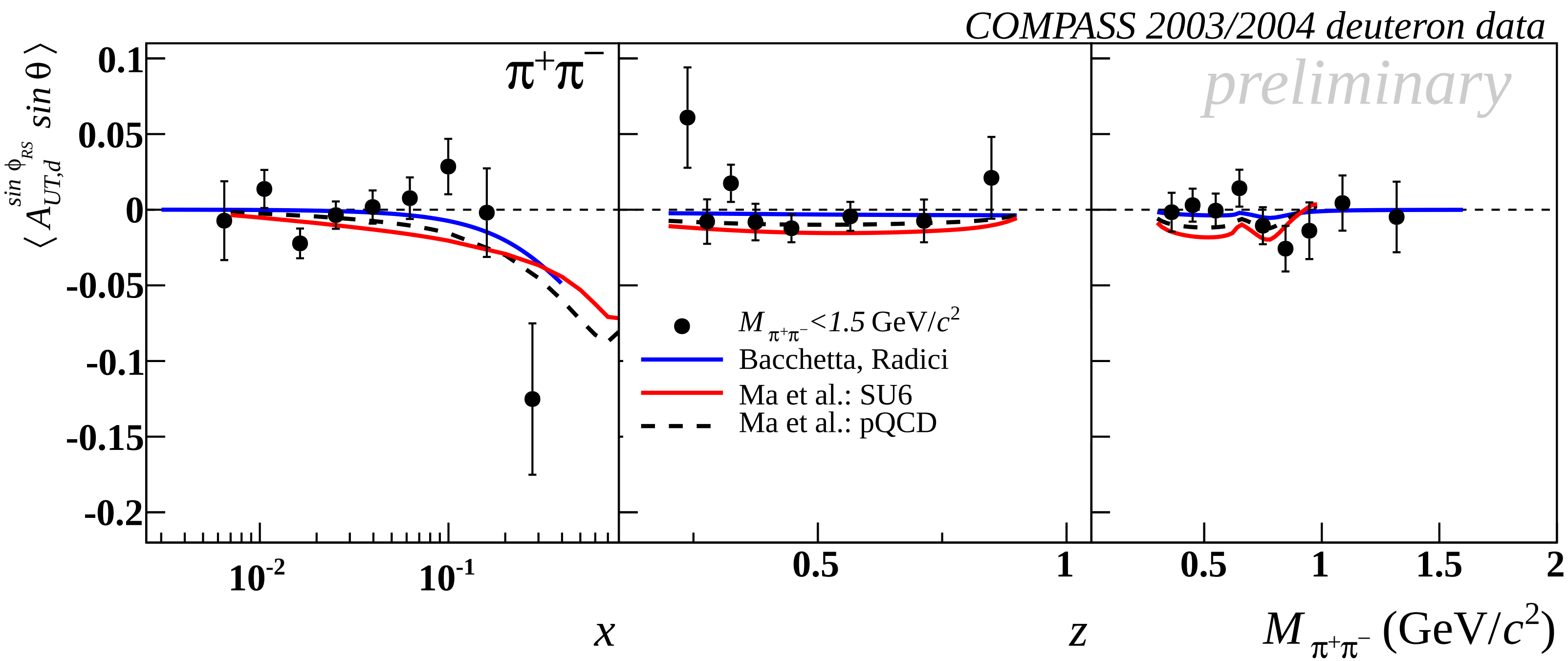


from: Adolph C. *et al.* [COMPASS Collaboration], Phys. Lett. B **713** (2012) 10
blue solid line: Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007
blue dashed line: Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

↪ Asymmetries of h^+h^- pairs from the deuteron target compatible with zero within the uncertainties

Interpreted as a close-to-complete cancellation of the u and d quark contributions from the transversity PDFs on the deuteron as an isoscalar target.

Results ▶ deuteron data ▶ $\pi^+\pi^-$ pairs



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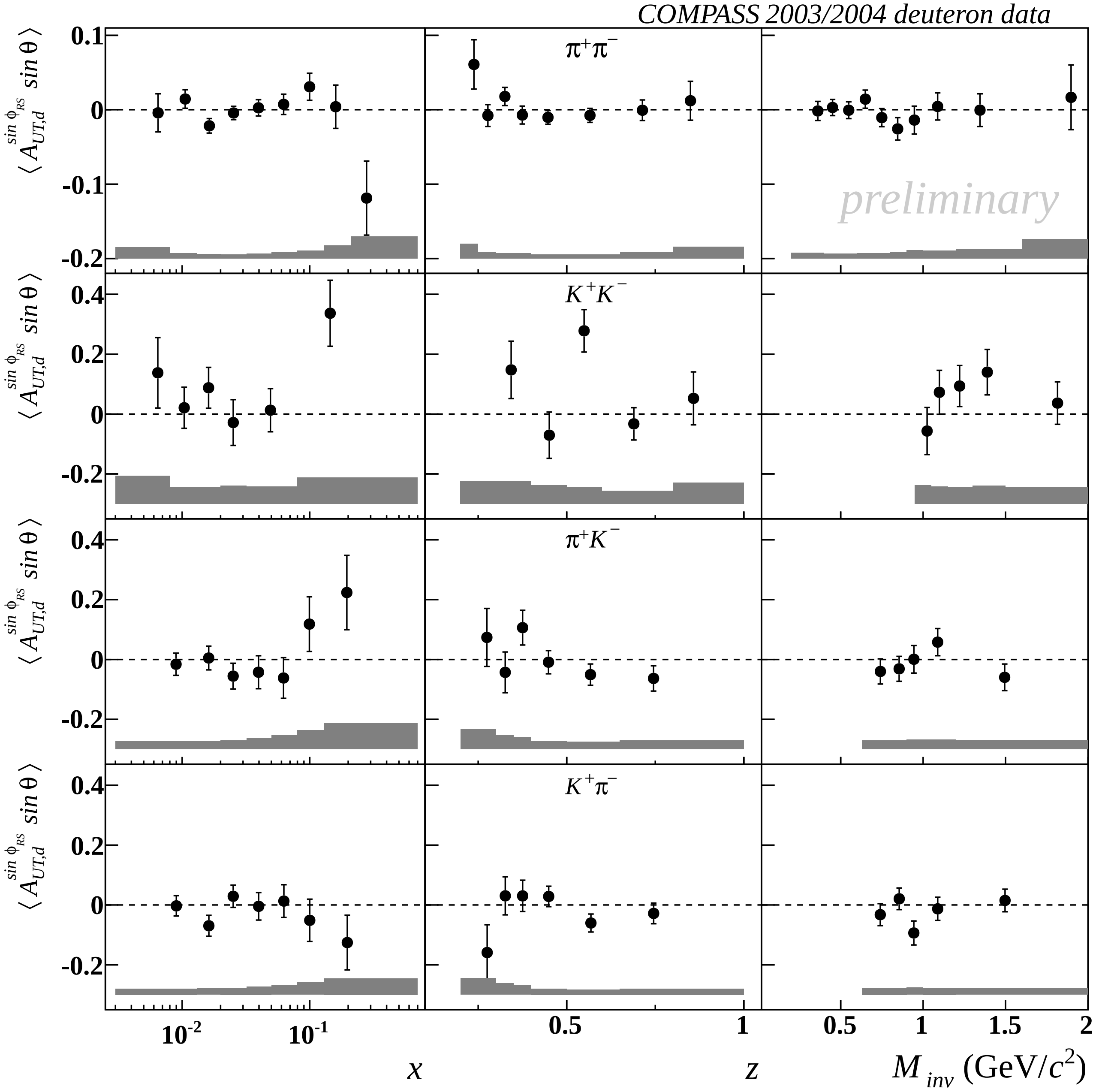
blue line: Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007

red and dashed lines: Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

Complete reanalysis of the deuteron data with unified cuts and methods w.r.t. to the proton data analysis!

↪ Asymmetries of $\pi^+\pi^-$ pairs from the deuteron target compatible with zero within the uncertainties.

Results ▶ deuteron data ▶ all identified pairs



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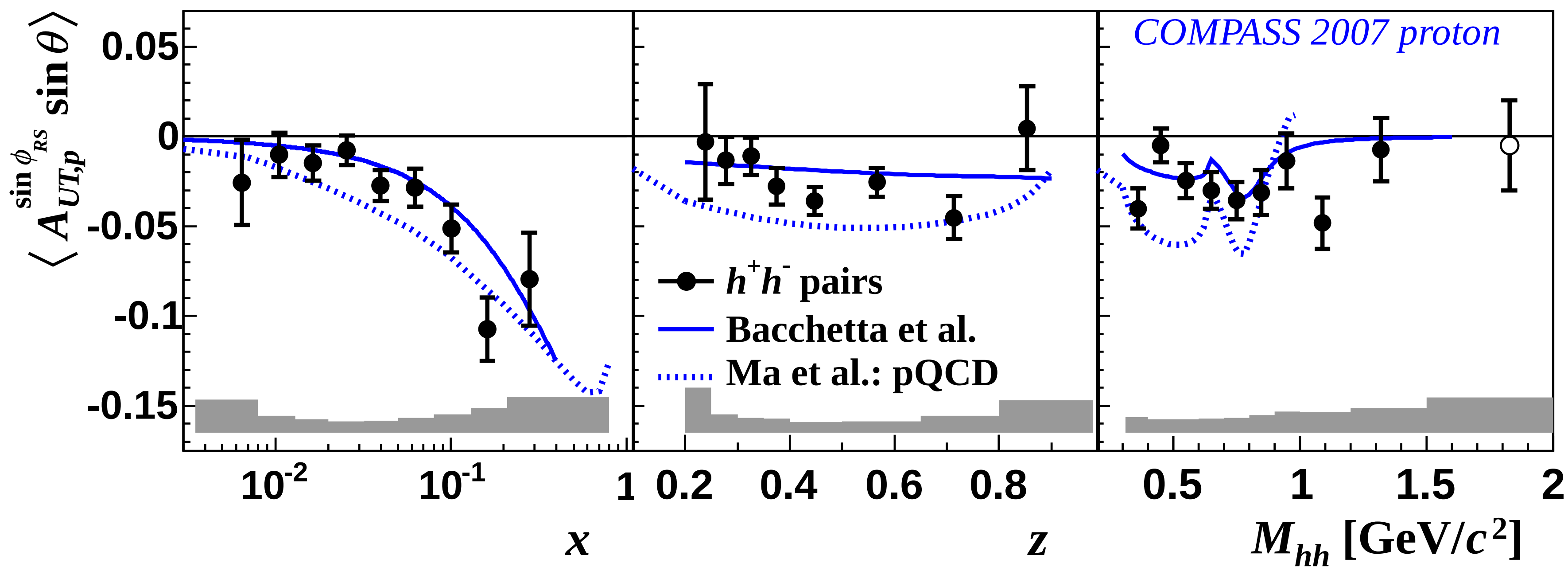
dihadron asymmetries:

proton data

Results ▶ proton 2007 data ▶ all hadron h^+h^- pairs

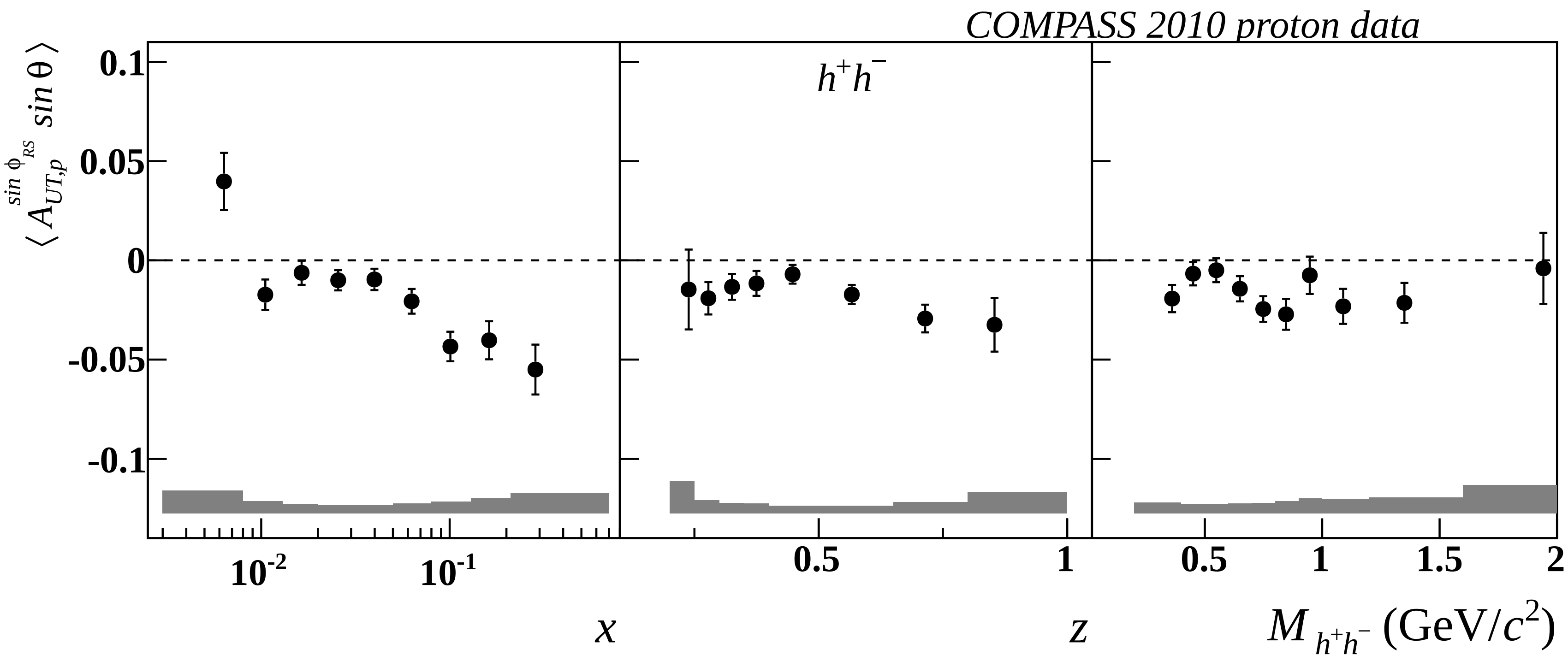


from: Adolph C. *et al.* [COMPASS Collaboration], Phys. Lett. B **713** (2012) 10

↪ Large asymmetries of h^+h^- pairs on the proton target in x dependence up to -10 %

Qualitative agreement with model predictions

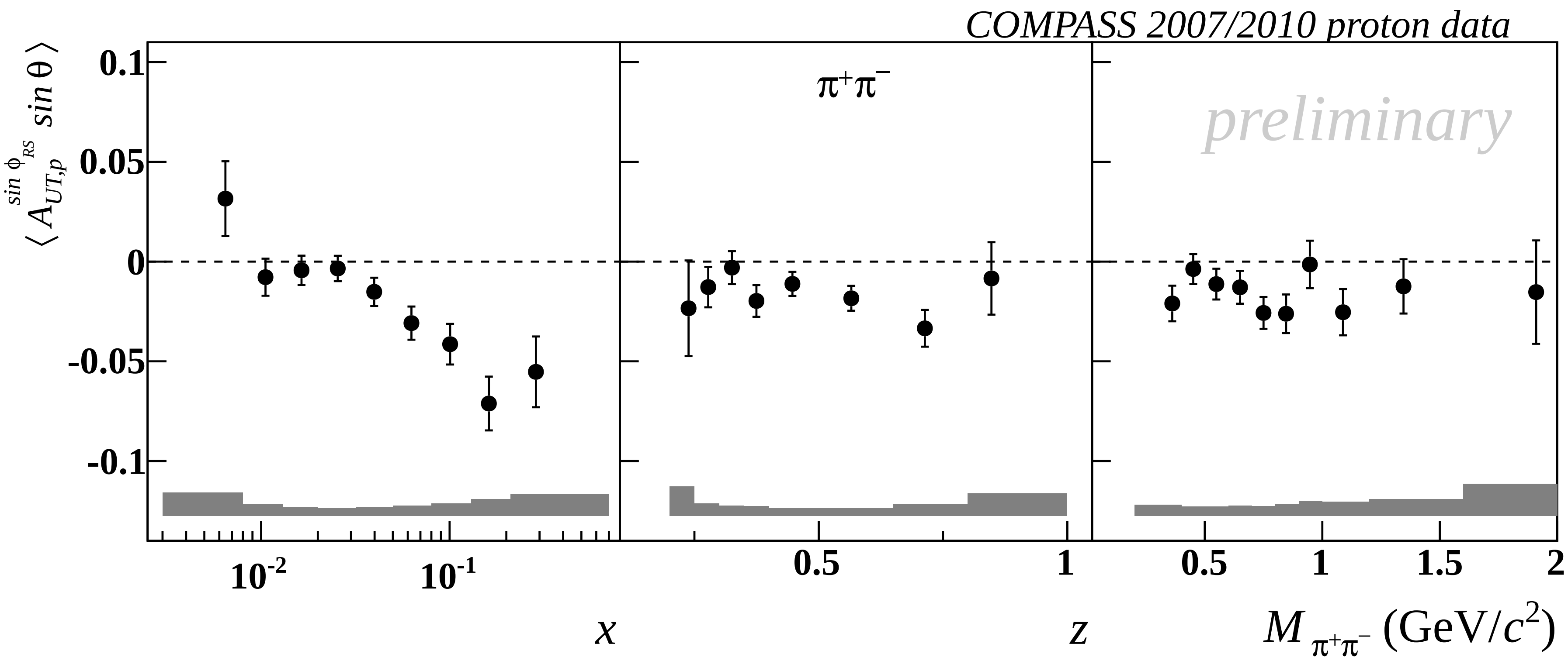
Results ▶ proton 2010 data ▶ all hadron h^+h^- pairs



from: Adolph C. *et al.* [COMPASS Collaboration], CERN preprint PH-EP-2014-013 [arXiv:1401.7873] accepted by Nucl.Phys.B.

↪ Large asymmetries of h^+h^- pairs on the proton target in the x dependence up to $-6\,\%$

Results ▶ proton data ▶ $\pi^+\pi^-$ pairs



$\hookrightarrow$ Clear asymmetries of $\pi^+\pi^-$ pairs

x up to -7 %

z no clear trend

M_{inv} indication of a dip around ρ^0 mass

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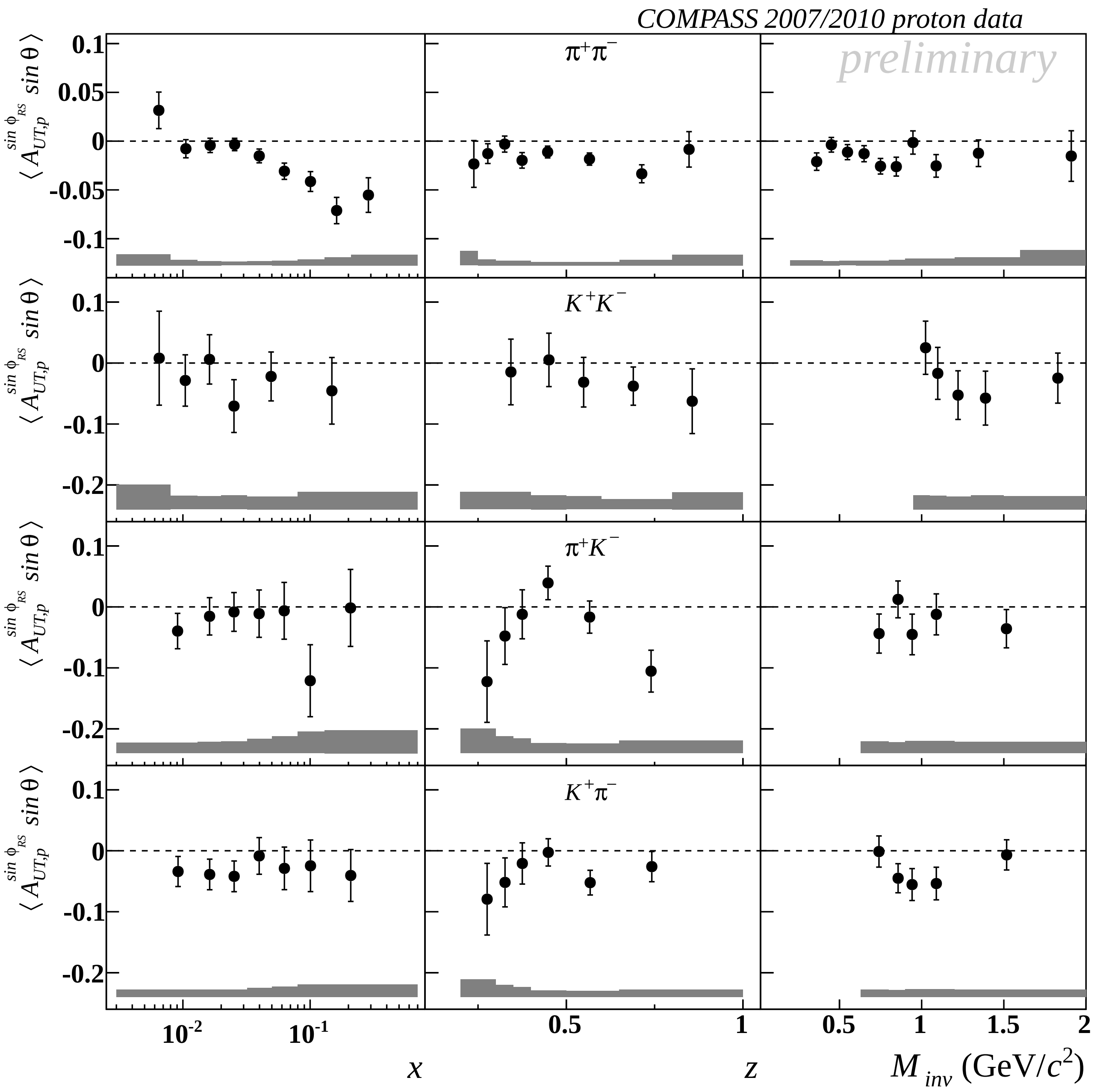
Results ▶ proton data ▶ all identified pairs



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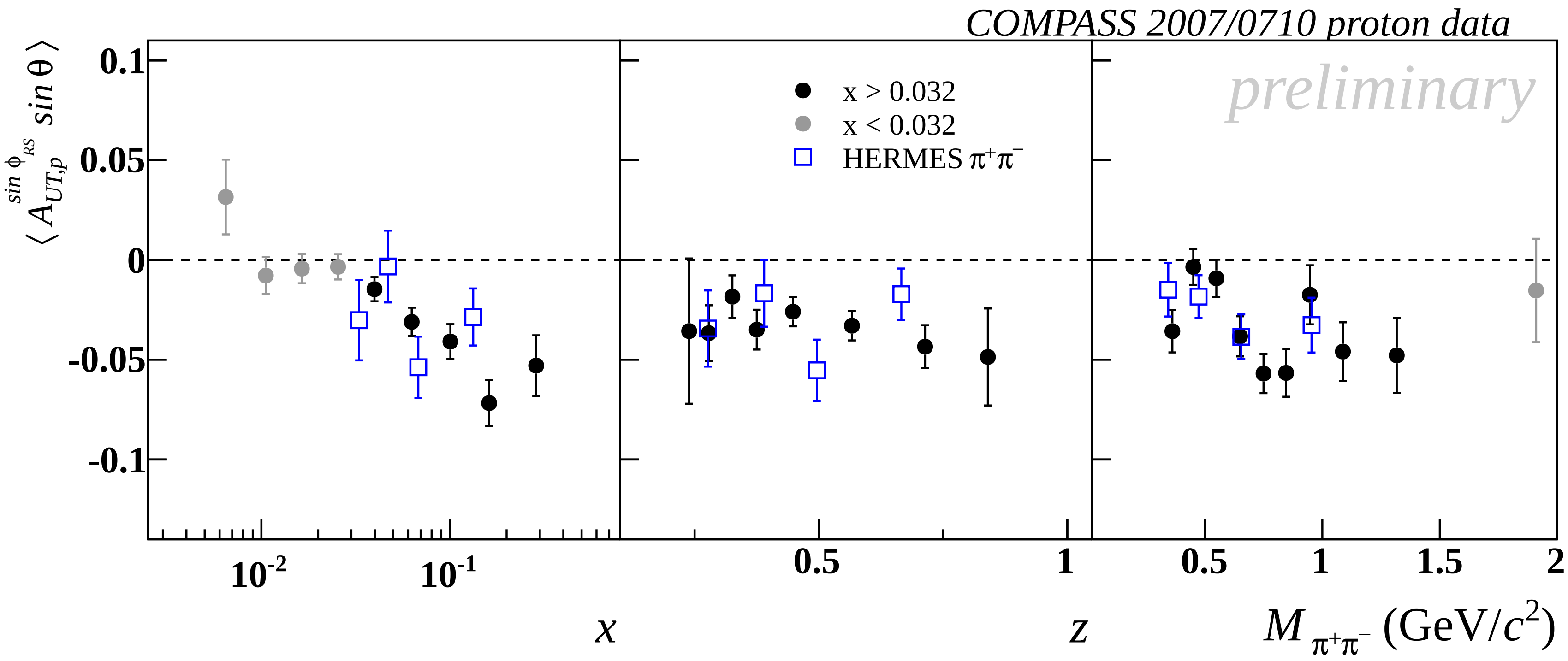
Results ▶ proton data ▶ comparison with HERMES



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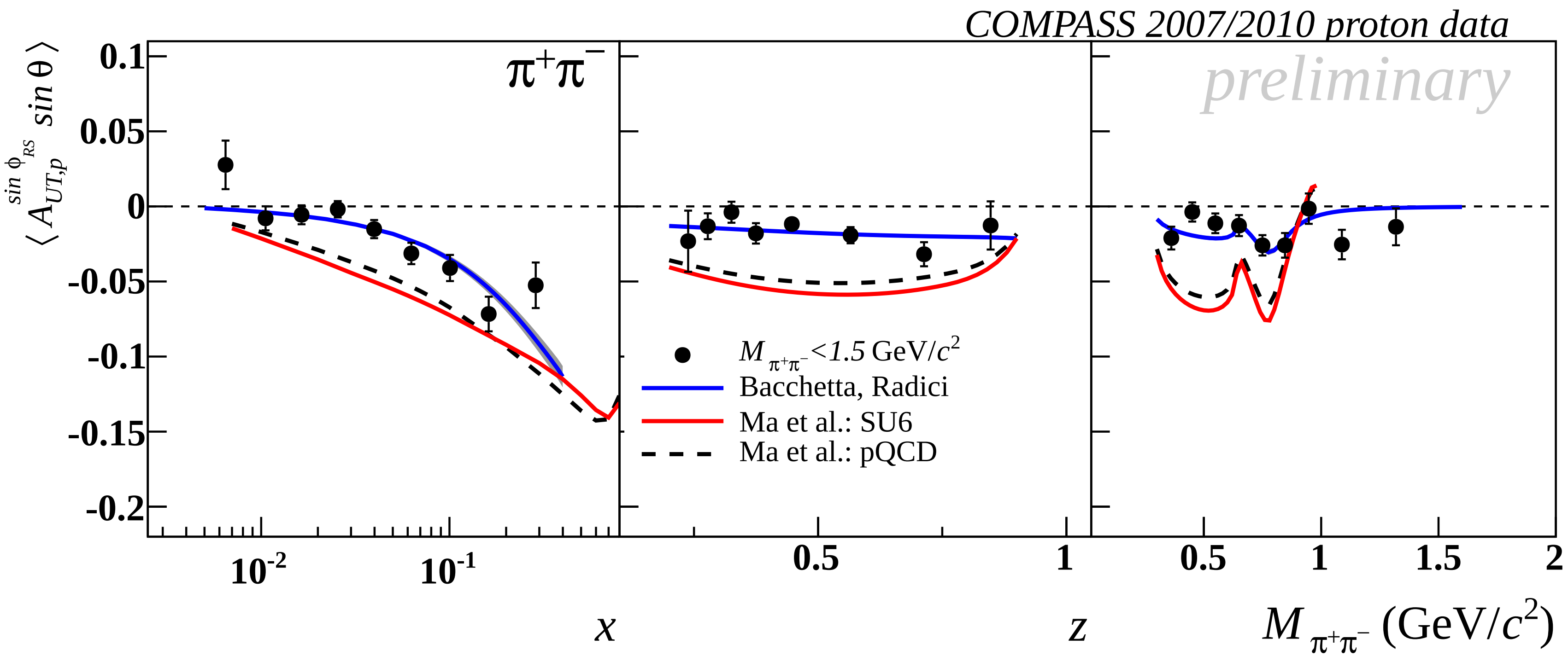
from: Airapetian A. et al. *et al.* [HERMES collaboration], J. High Energ. Phys. **06** (2008) 017

scaled with $\frac{1}{D_{nn}}$ [X.-R. Lu PhD thesis] and sign changed

↪ Good agreement within the uncertainties, bearing in mind the larger kinematic range of COMPASS

cf. talk by Charlotte Van Hulse

Results ▶ proton data ▶ $\pi^+\pi^-$ model predictions



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blue line: Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007

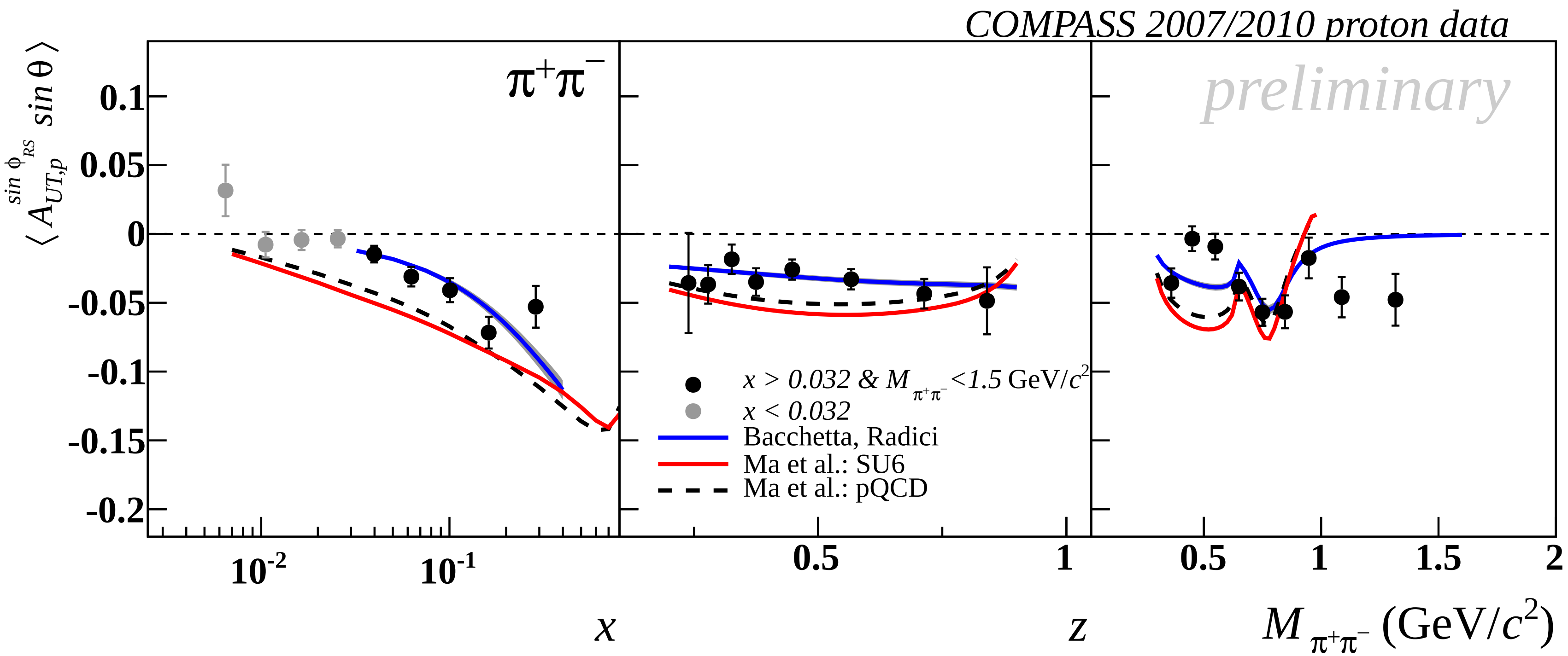
red and dashed lines: Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

$\hookrightarrow$ x: *Ma* trend confirmed | *Bachetta* good agreement

$\hookrightarrow$ z: *Ma* too large | *Bachetta* compatible

$\hookrightarrow$ M_{inv}: *Ma* too large | *Bachetta* good agreement around ρ^0 mass

Results ▶ proton data ▶ $\pi^+\pi^-$ model predictions



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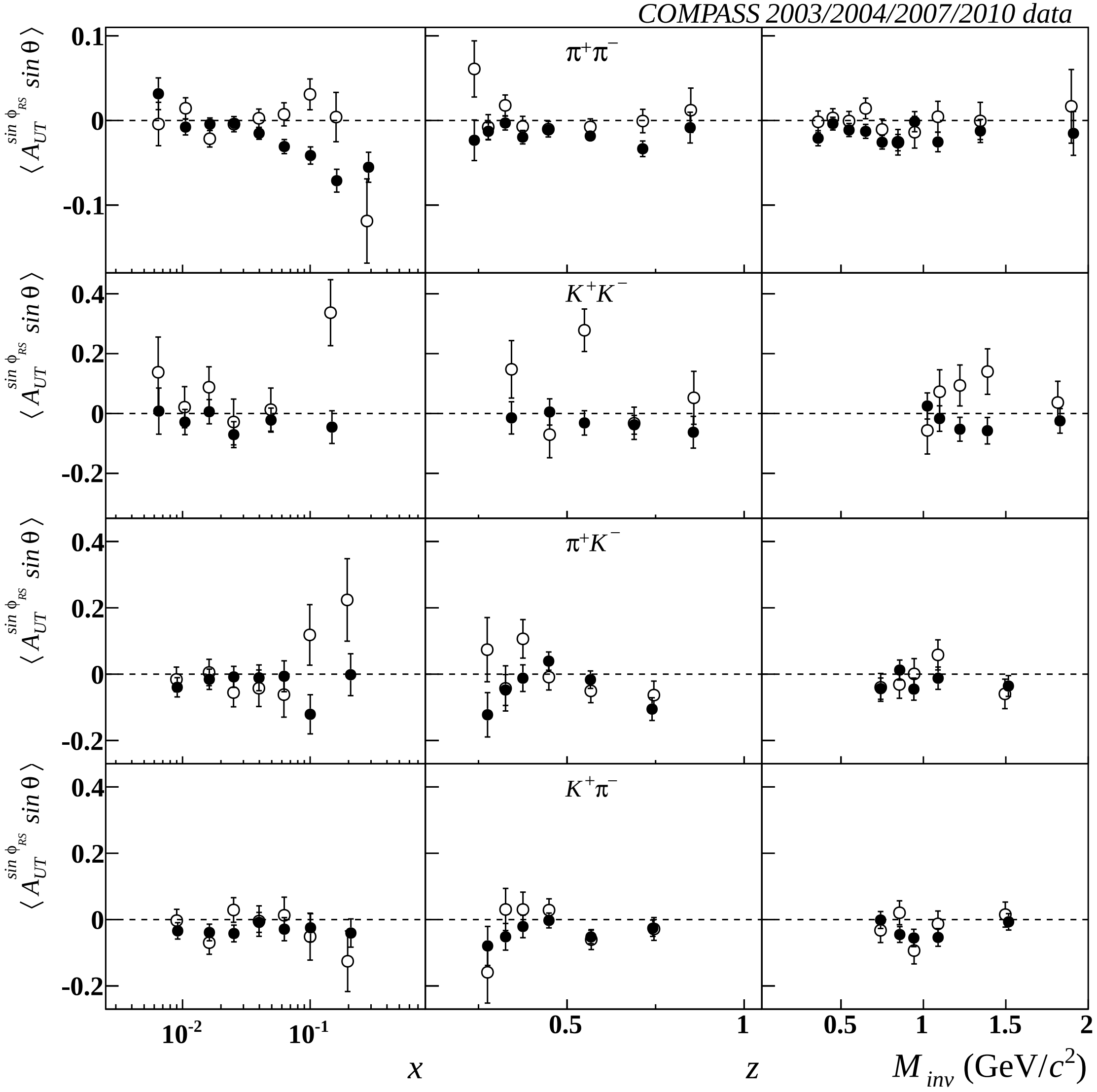
Improved agreement with Ma model if only the valence region is considered.

Transversity extraction

of u and d valence quarks

Results ▶ deuteron & proton data ▶ all identified pairs



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First complete set of identified dihadron asymmetries with unified cuts, binning and fit method from deuteron and proton targets.

Transversity extraction ▶ motivation & theory

A transversely polarized deuteron target gives access to:

$$xh_{1,d}(x;Q^2) = xh_1^u(x;Q^2) + xh_1^d(x;Q^2)$$

A transversely polarized proton target gives access to:

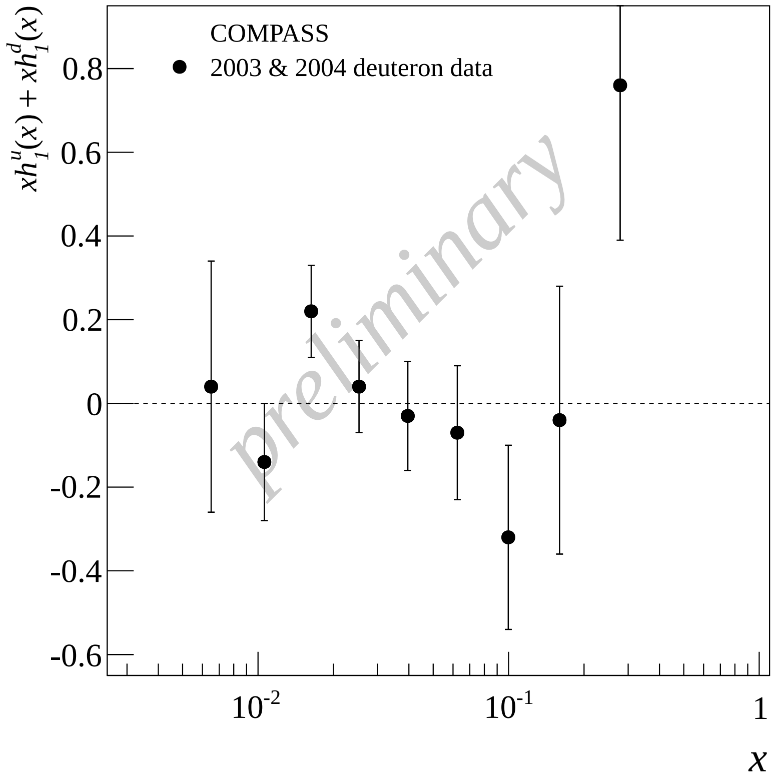
$$xh_{1,p}(x;Q^2) = xh_1^u(x;Q^2) - \tfrac{1}{4}xh_1^d(x;Q^2)$$

→ Bacchetta *et al.* in JHEP03 (**13**) 119 extracted $xh_{1,d}(x;Q^2)$ and $xh_{1,p}(x;Q^2)$ from HERMES $\pi^+\pi^-$ and COMPASS h^+h^- results [PLB **713** (12) 10].

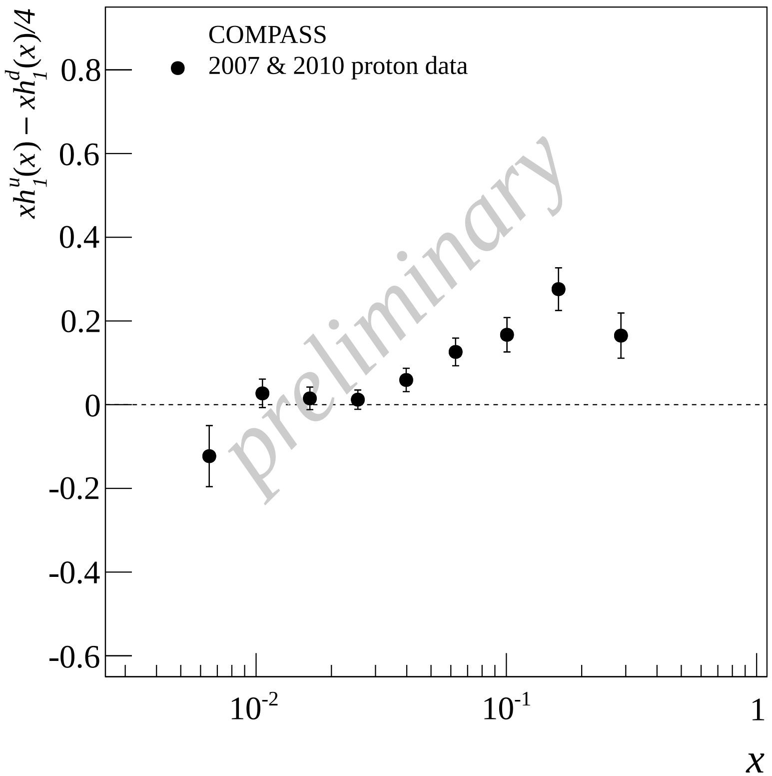
⇒ Use their method together with the new full set of $\pi^+\pi^-$ results to extract the u and d valence quark transversity distributions bin-by-bin.

Transversity extraction ▶ 1^{st} step ▶ results

$$xh_{1,d} = xh_1^u(x;Q^2) + xh_1^d(x;Q^2)$$
from deuteron data:



$$xh_{1,p} = xh_1^u(x;Q^2) - \frac{1}{4}xh_1^d(x;Q^2)$$
from proton data:



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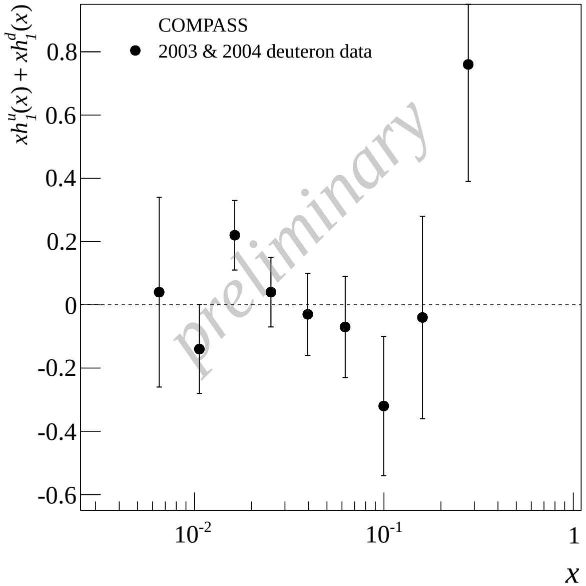
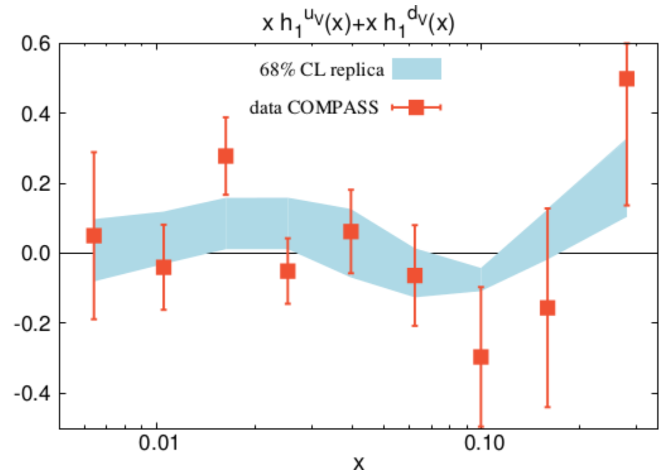
$\hookrightarrow$ $xh_{1,d}$ compatible with zero within the uncertainties
$\hookrightarrow$ $xh_{1,p}$ sizable signal at large x

Extraction of Transversities ▶ 1^{st} step ▶ comparison

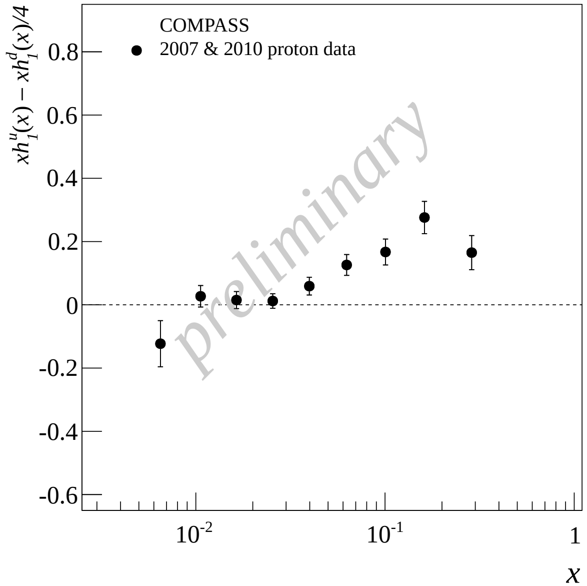
Comparison with results in JHEP03 (13) 119 Bacchetta *et al.*:
(2002/03/04/07 h^+h^- *data*)

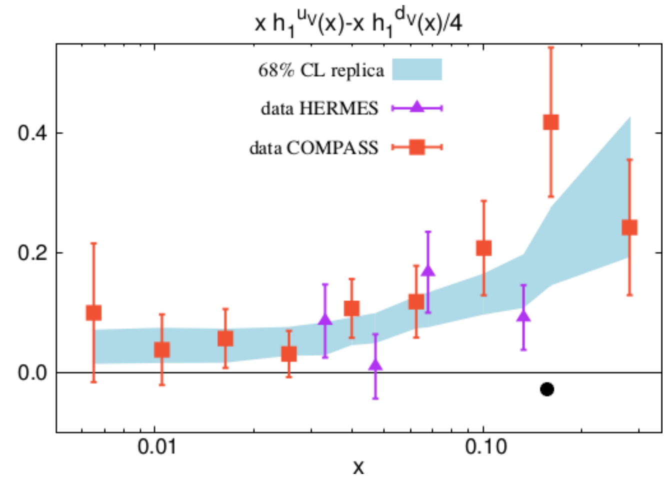
$xh_{1,d}$





$xh_{1,p}$

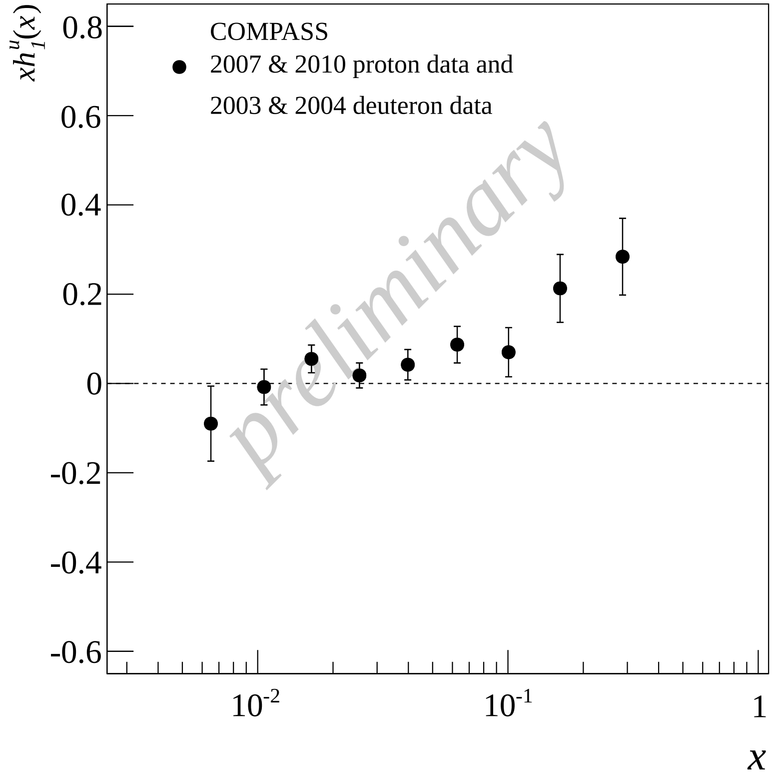




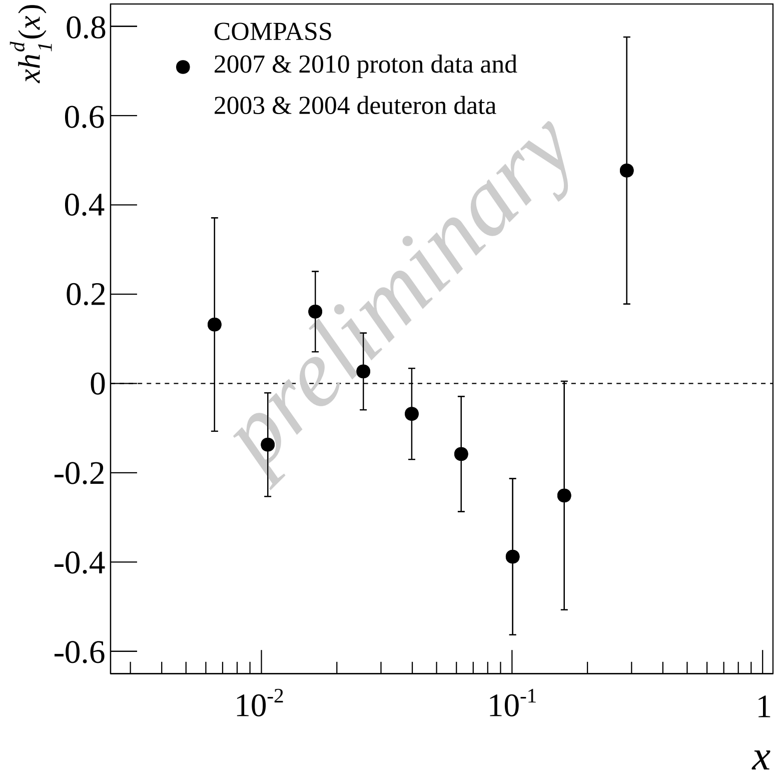
Extraction of Transversities ▶ 2^{nd} step ▶ results

xh_1^u and xh_1^d are obtained by solving the system of equations:

$xh_1^u(x;Q^2)$



$xh_1^d(x;Q^2)$



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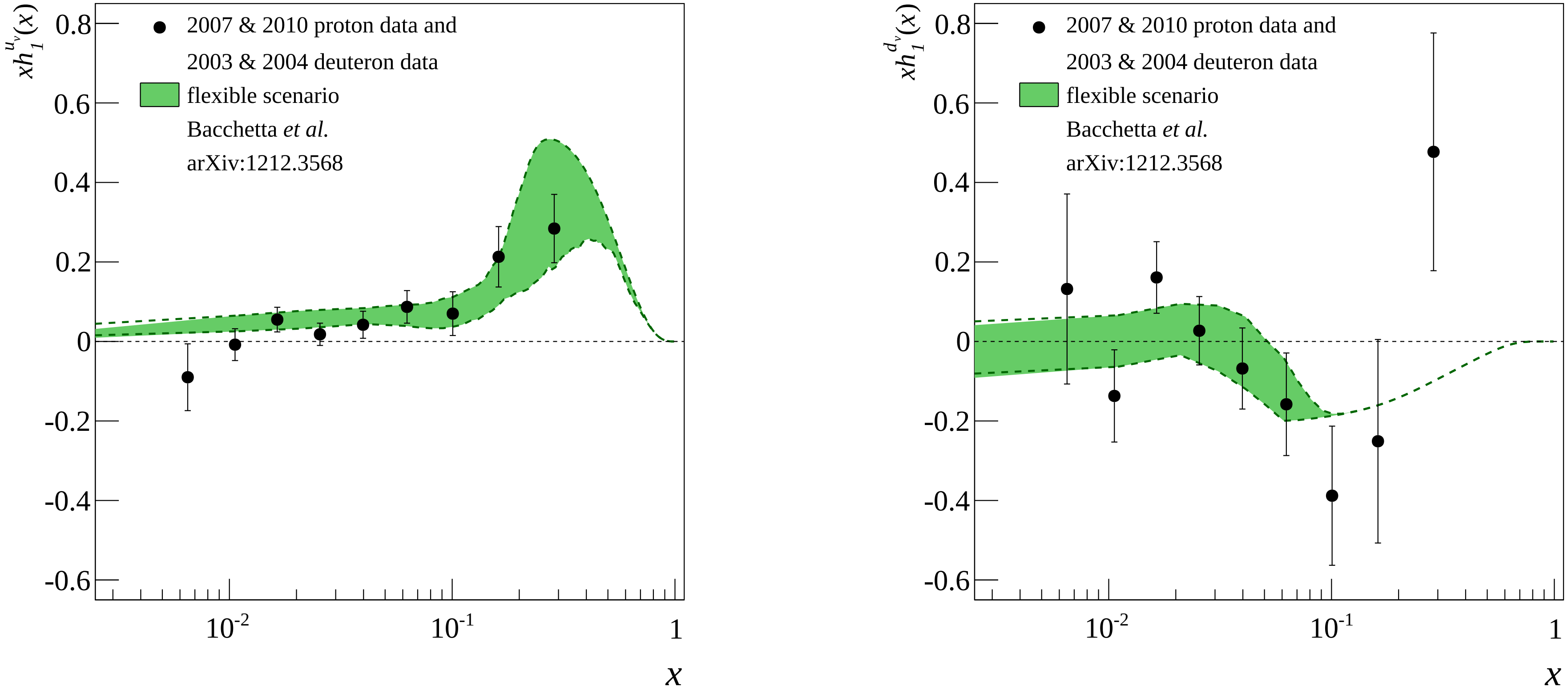
$\hookrightarrow$ xh_1^u clear transversity signal
$\hookrightarrow$ xh_1^d suffers from low deuteron data statistics

Comparison of new results with Bacchetta *et al.* JHEP03 (**13**) 119:

$xh_1^u(x;Q^2)$ $xh_1^d(x;Q^2)$



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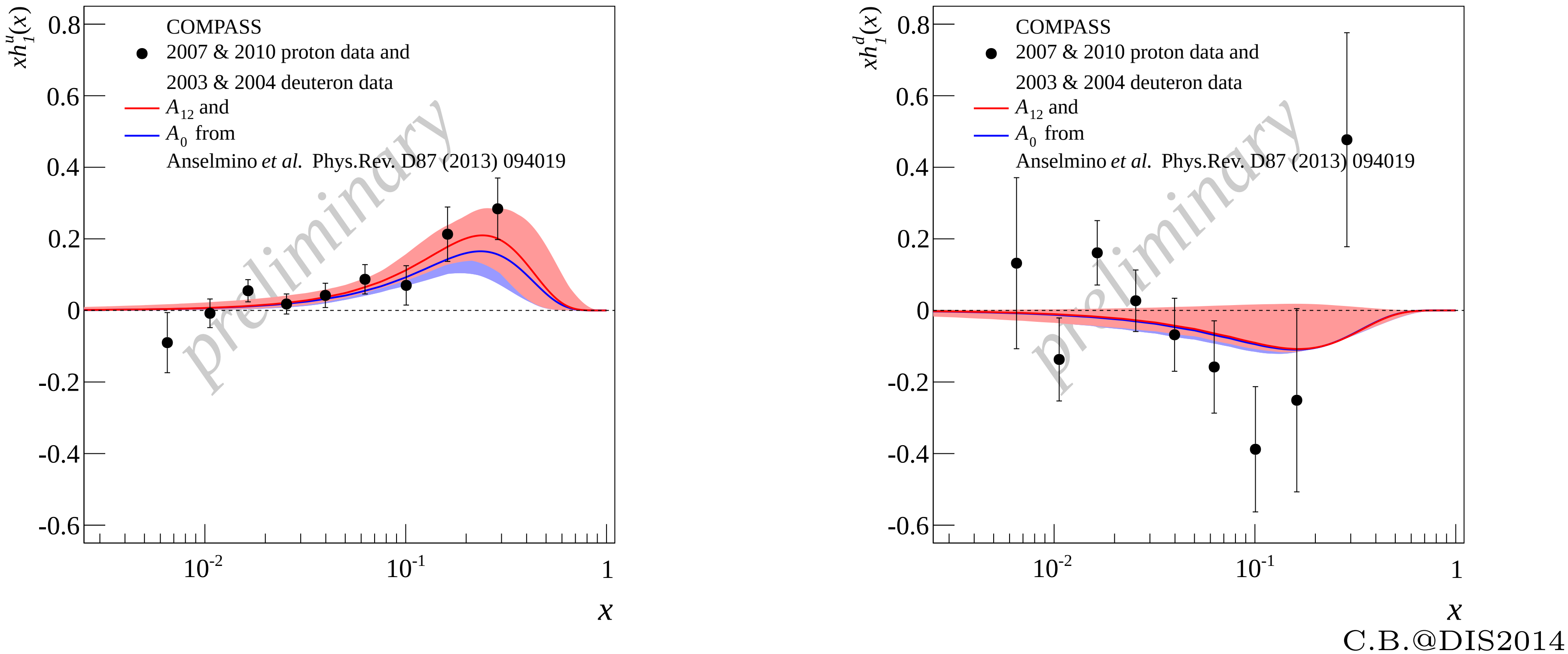
No surprise: New COMPASS data points are (still) very well compatible with the fit to the h^+h^- data.

Comparison of results from single hadron Collins asymmetry global fit by Anselmino *et al.* Phys.Rev.D **87** (2013) 094019 [arXiv:1303.3822]:

$xh_1^u(x;Q^2)$ $xh_1^d(x;Q^2)$



Very good agreement for the u-quark Transversity and fair agreement for d-quark.

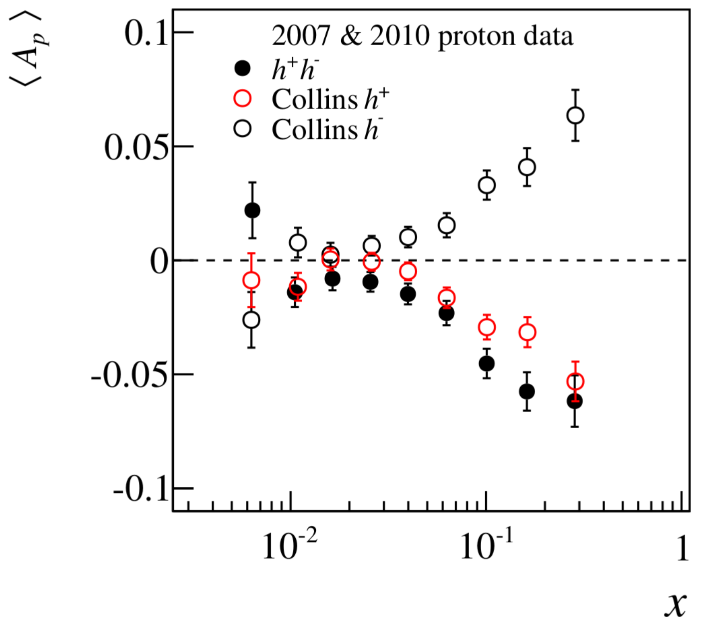
Better agreement with A_{12} BELLE e^+e^- results than A_0.

Studies on the inter-relationship of

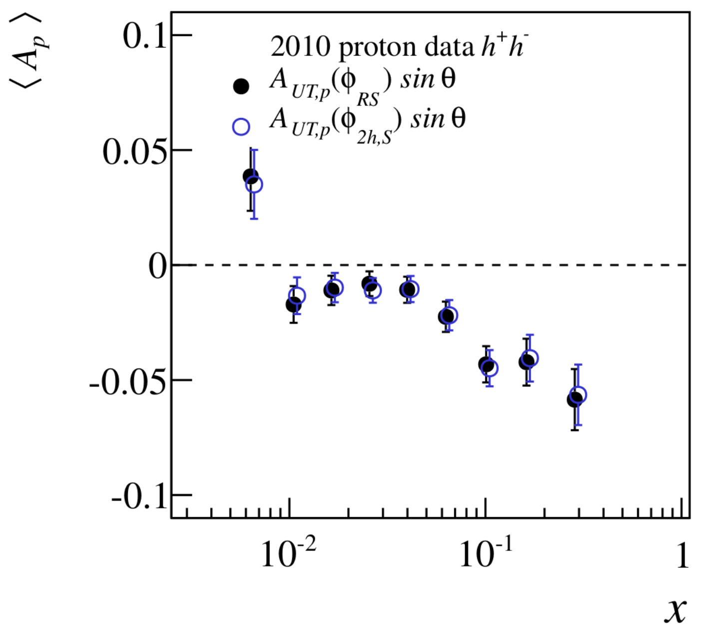
Collins and dihadron asymmetries

NEW

Collins vs. dihadron asymmetries ▶ motivation



1. Observation of almost equal shape and strength of the Collins asymmetry of h^+ and the dihadron h^+h^- asymmetry.

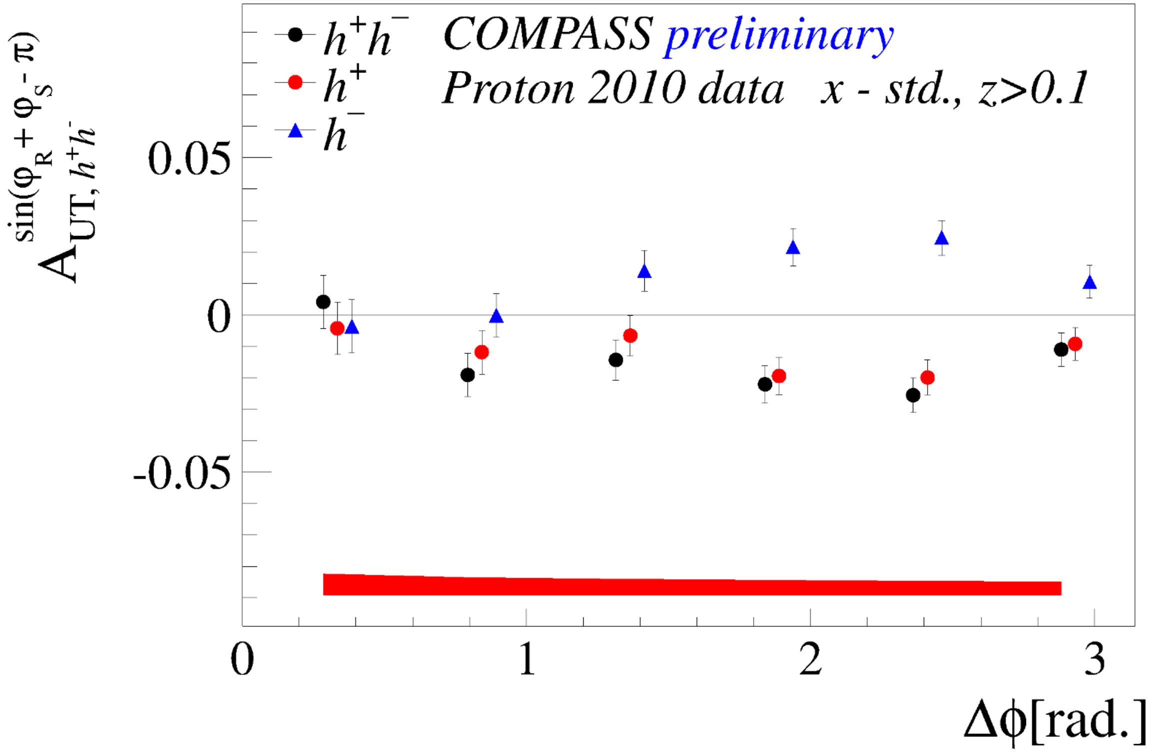


2. Construct a "Collins"-like dihadron angle $\phi_{2h,S}$ and compare the asymmetry obtained with the "classic" one from ϕ_{RS}:

ϕ_{2h} is the azimuthal angle of
$\boldsymbol{R}_N = \hat{\boldsymbol{p}}_{T,h^+} - \hat{\boldsymbol{p}}_{T,h^-}$
$\Rightarrow$ essentially the arithmetic mean of the azimuthal angles of the two hadrons

see Bradamante's talk at DSPIN13 and [arXiv:1401.6284]

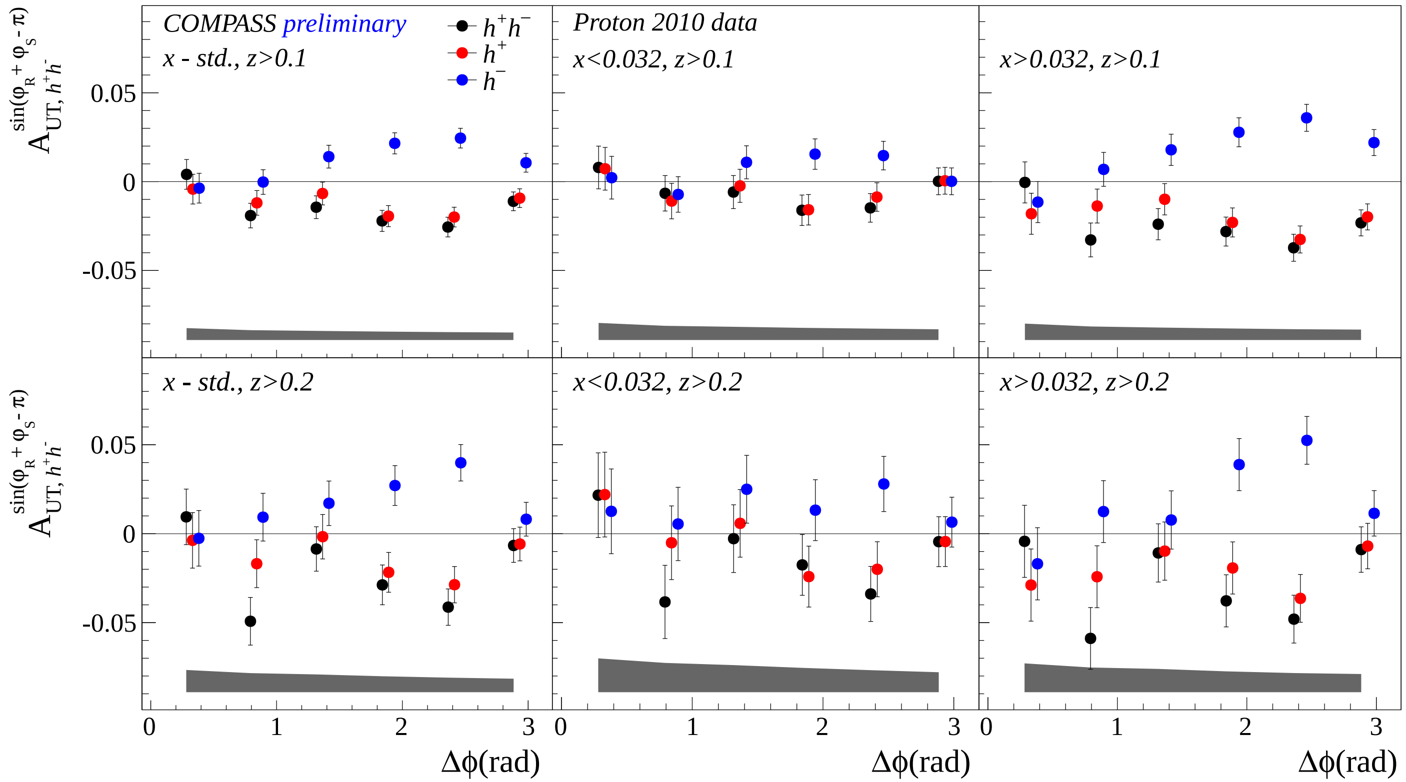
NEW Collins vs. dihadron asymmetries ▶ $\Delta\Phi$ dependence



- Clear mirror symmetry at larger $\Delta\Phi$ for Collins of h^+ and h^-
- Dihadron asymmetry well compatible with Collins asymmetry of h^+
- Increasing amplitudes with $\Delta\Phi$; except of highest bin
- Compatible with zero for $\Delta\Phi < 1$.

$\Rightarrow$ This is expected in the framework of the string fragmentation model and is also consistent with the small dihadron asymmetries measured at low invariant masses.

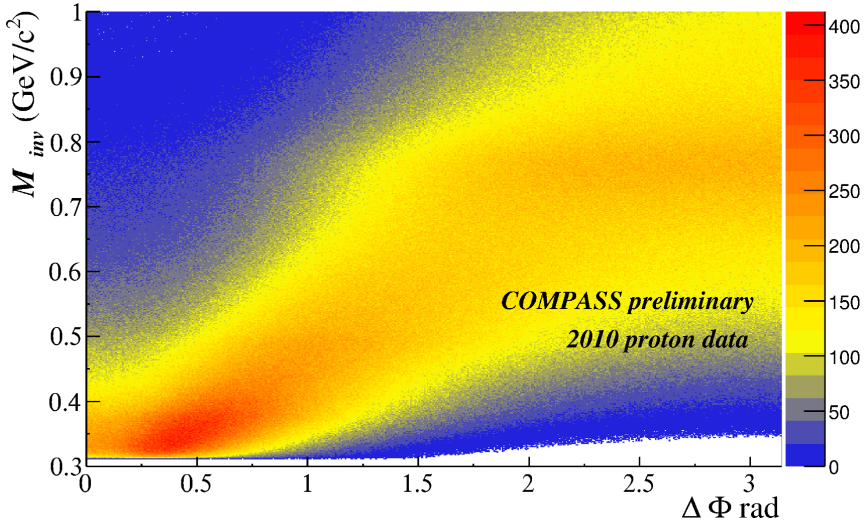
NEW Collins vs. dihadron asymmetries ► ΔΦ dependence

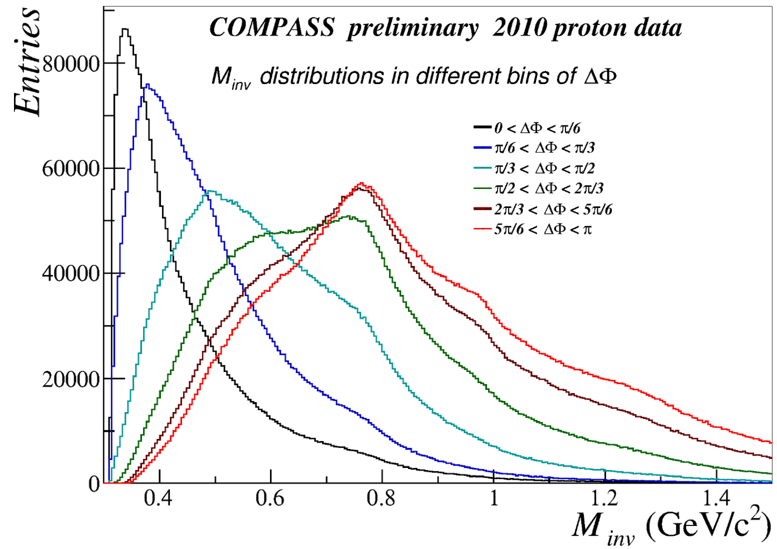


- Amplitudes for $z > 0.2$ sample are enhanced, but still compatible with the standard sample
- Increasing asymmetry amplitudes for the valence region sample
- But the asymmetry remains also in the $x < 0.032$ sample

NEW dihadron asymmetry ▶ $\Delta\Phi$ vs. M_{inv}

Is there a correlations between the invariant mass of the hadron pair and the difference of the azimuthal angles of the two hadrons?





$\rightarrow$ Correlation due to the fact that the difference of the azimuthal angles of the two hadrons is related to the opening angle of the pair and thus to its invariant mass.
$\Rightarrow$ Recursive string fragmentation model by Artru: A dependence of the asymmetry on $\Delta\Phi$, since the Artru's generalized Collins effect should be stronger for back-to-back emitted hadrons

$\Rightarrow$ Dihadron FF is also expected to depend on $M_{h^+h^-}$

Conclusions & Outlook

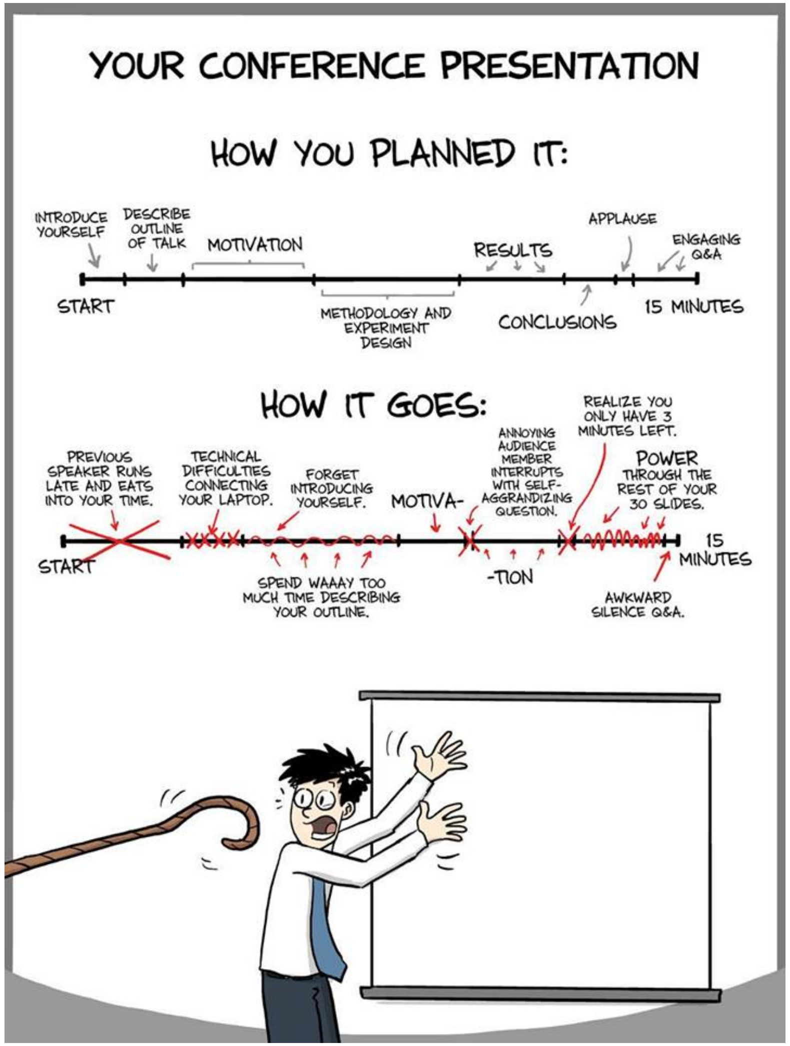
- Combined 2007/2010 proton h^+h^- results accepted by Nucl.Phys.B [arXiv:1401.7873]
- Preliminary 2003-2004 deuteron and 2007/2010 proton data identified pair

1. Complete sets of $\pi^+\pi^-$ asymmetries with unified cuts, binning and fit method from deuteron and proton targets
2. COMPASS $\pi^+\pi^-$ data is in good agreement with HERMES results and models
3. Bin-by-bin extraction with the final COMPASS results of the transversity distribution of u and d valence quarks using the method by Bacchetta *et al.* [JHEP03 (**13**) 119]
4. Clear Transversity signal at large $\Delta\Phi$

Outlook:

- Paper on all identified asymmetries: deuteron and proton data
- Multidimensional analysis of identified pairs
- Further investigations on dihadron vs. Collins asymmetries ongoing
- "Sivers" like asymmetry in the dihadron sample (cf. talk by Aram Kotzinian)
- Asymmetries of pairs including π^0

Thank you for your attention!



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