COMPASS results on transverse spin dependent azimuthal asymmetries in two-hadron production in semi-inclusive deep-inelastic scattering

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on behalf of the **COMPASS** collaboration

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XXI INTERNATIONAL WORKSHOP on DEEP-INELASTIC SCATTERING and RELATED SUBJECTS
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GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

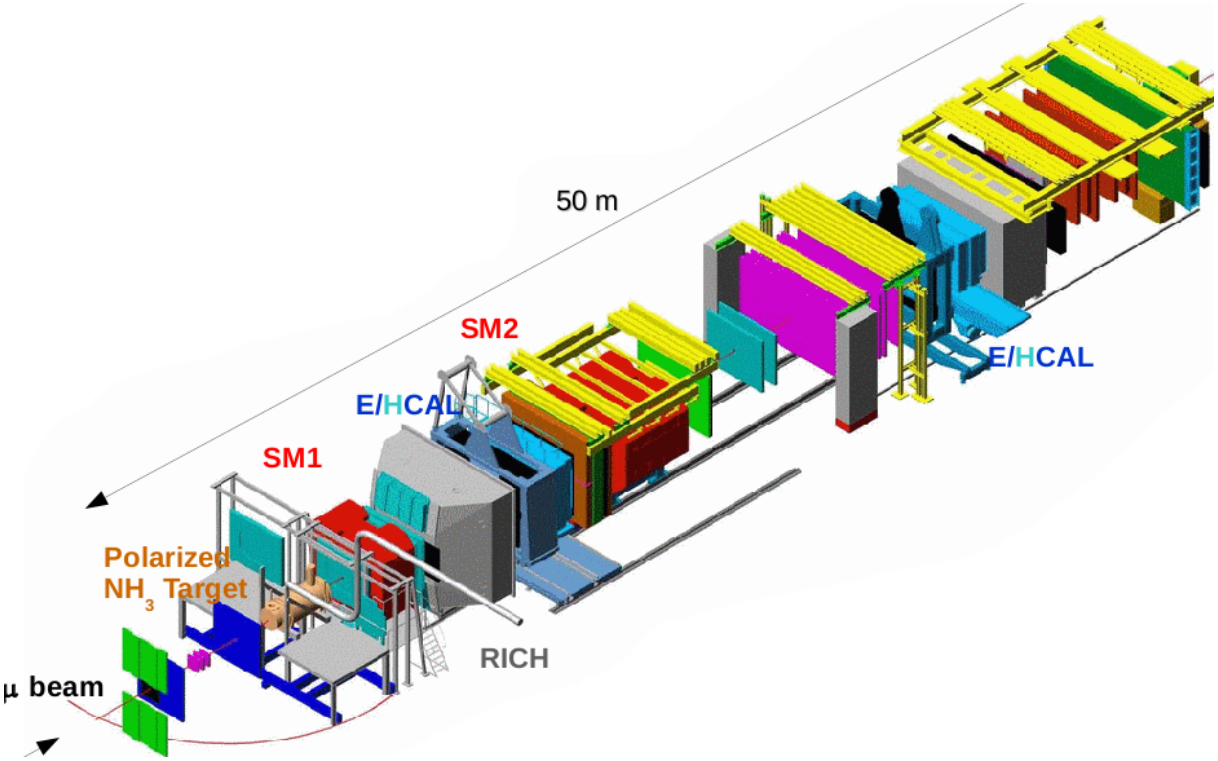
COMPASS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT

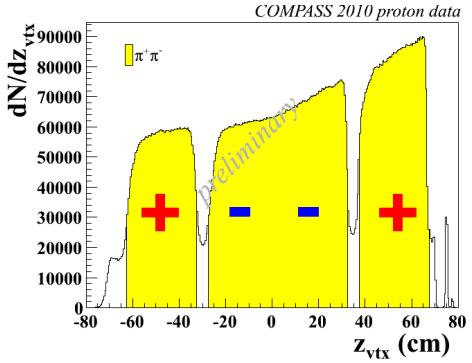
Outline

The COMPASS experiment at CERN

The COMPASS experiment



e.g. COMPASS setup 2007



deuteron (^{6}LiD):

- polarization $\approx 47\,\%$
- dilution factor ≈ 0.38

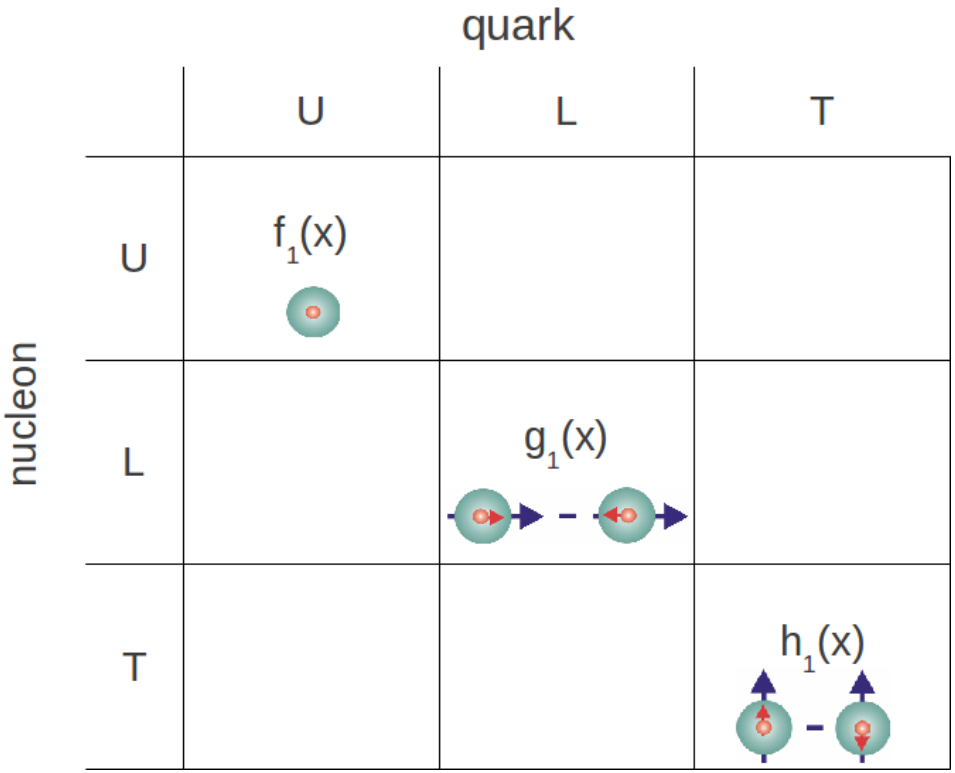
proton (NH_3):

- polarization $\approx 90\,\%$
- dilution factor ≈ 0.15

- 2-stage spectrometer with tracking, calo and PID (RICH)
- Longitudinally polarized 160 GeV/c μ^+-beam
- 2002-04 transversely polarized deuterium 2-cell target
- 2007 & 2010 transversely polarized ammonia 3-cell target
- Polarization reversed every week via microwave

Theoretical framework: from spin structure to Transversity

Three independent parton distribution functions (PDF) are necessary to describe the spin structure of the nucleon in leading twist in the collinear case:



unpol. quark distribution:
$f_1(x) = q^+(x) + q^-(x)$

Helicity distribution:
$g_1(x) = q^+(x) - q^-(x)$

Transversity distribution:
$h_1(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

Collins FF $\quad \ell N^\uparrow \to \ell' h X$

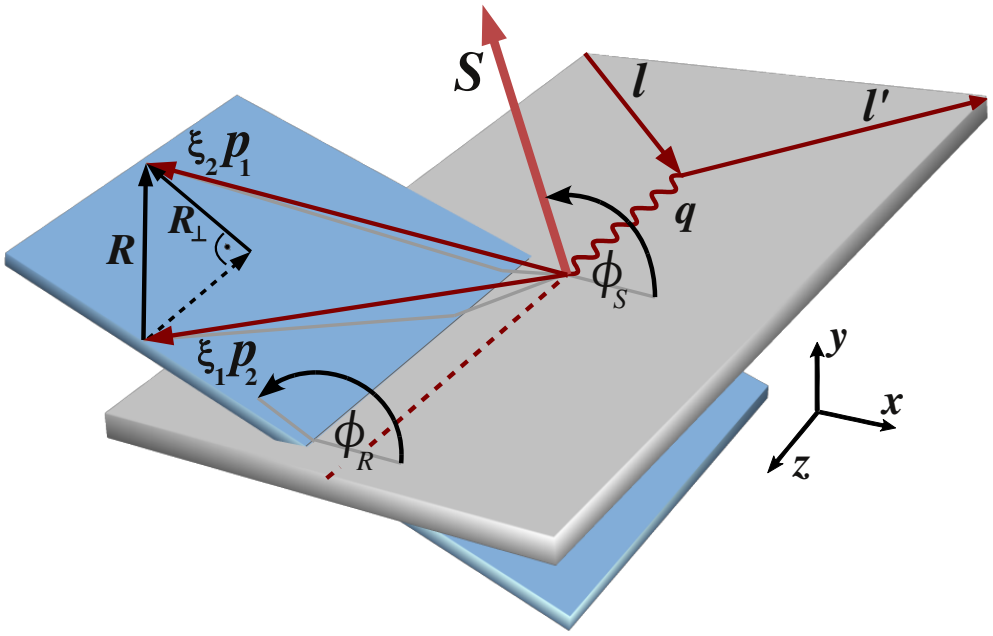
Interference FF $\quad \ell N^\uparrow \to \ell' h h X$

See also talks of A. Martin & B. Parsamyan

Theoretical framework: angle definitions

$\ell\, p^{\uparrow} \to \ell'\, h_1\, h_2$

Fragmentation of a transversely polarized quark into two unpolarized hadrons



- $\boldsymbol{\ell}$, $\boldsymbol{\ell'}$ and $\mathbf{q}$ are 3-momenta of incoming, scattered lepton and virtual photon
- $\phi_{\boldsymbol{S}}$ azimuthal angle of the spin $\boldsymbol{S}$ of the fragmenting quark
- $\mathbf{p_i}$ is the 3-momenta of h_i
- z_i is the fraction of the virtual-photon energy carried by h_i
- $\mathbf{R} = \frac{z_2\mathbf{p_1} - z_1\mathbf{p_2}}{z_1+z_2} = \xi_2\mathbf{p_1} - \xi_1\mathbf{p_2}$
- $\mathbf{R_T}$ is the component of $\mathbf{R}$ perpendicular to $\mathbf{q}$
- Azimuthal angle of $\mathbf{R}$:

$$\phi_R = \frac{(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}}{|(\mathbf{q}\times\mathbf{l})\cdot\mathbf{R}|} \arccos\left(\frac{(\mathbf{q}\times\mathbf{l})\cdot(\mathbf{q}\times\mathbf{R})}{|\mathbf{q}\times\mathbf{l}||\mathbf{q}\times\mathbf{R}|}\right)$$

Theoretical framework: two-hadron cross section

The differential two-hadron cross section is:

$$\frac{\mathrm{d}^7\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}M_{hh}^2\,\mathrm{d}\phi_R\,\mathrm{d}z\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y}\Big(\big(1-y+\tfrac{y^2}{2}\big)\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos\theta)$$

$$+S_\perp(1-y)\times\sum_q e_q^2 \tfrac{|\mathbf{p_1}-\mathbf{p_2}|}{2M_{hh}} \sin(\theta)\sin(\phi_{RS}) h_1^q(x) H_{1,q}^{\sphericalangle}(z, M_{hh}^2, \cos\theta)\Big)$$

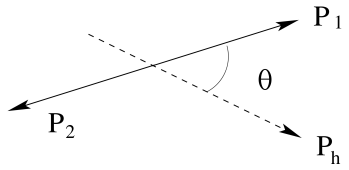
with $\phi_{RS} = \phi_R + \phi_S - \pi$

Where $h_1(x)$ is the Transversity PDF and $H_{1,q}^{\sphericalangle}$ is the two-hadron Interference FF.
$D_{1,q}$ is the unpolarized two-hadron fragmentation function,
which is measured at *e.g.* BELLE.

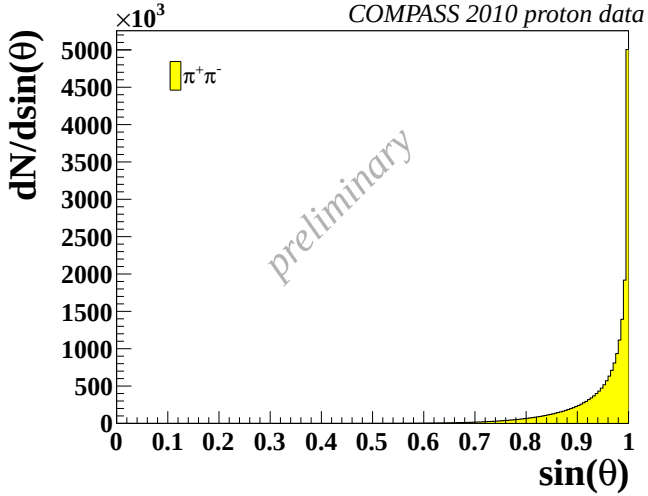
see talks by G. Karyan, N. Makke & C. van Hulse
A. Vossen *et al.* [BELLE Collaboration], Phys. Rev. Lett. **107** (2011) 072004 arXiv:1104.2425v3.

Theoretical framework: asymmetries extraction

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



h^+h^- center of mass frame



σ_{UU} = unpolarized cross section

$\pm$ indicates nucleon spin orientation

f = target dilution factor

P_T = target polarization

D_{NN} = transv. spin transfer coef.

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

$\langle \sin\theta \rangle = 0.94$
$\Rightarrow$ can be neglected

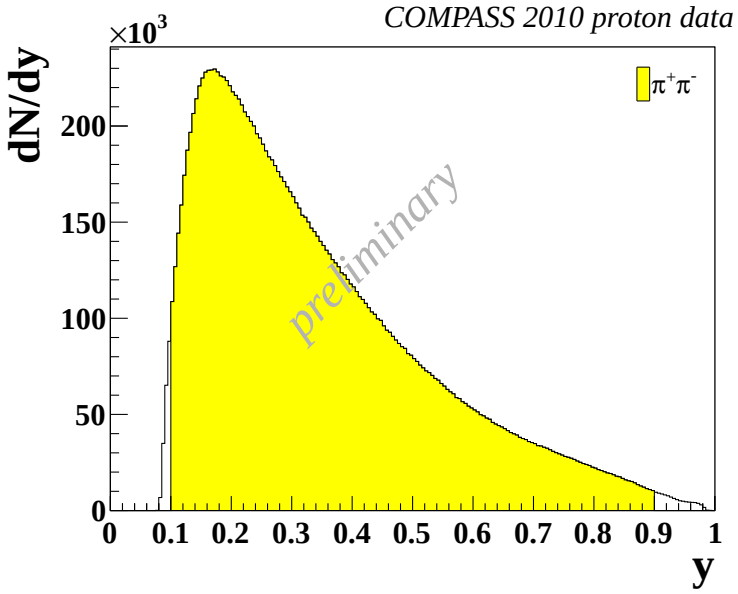
$$A_{UT}^{\sin\phi_{RS}} = \frac{|\mathbf{p_1} - \mathbf{p_2}|}{2M_{hh}} \frac{\sum_q e_q^2 h_1^q(x) H_{1,q}^{\sphericalangle}(z, M_{hh}^2, \cos\theta)}{\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{hh}^2, \cos\theta)}$$

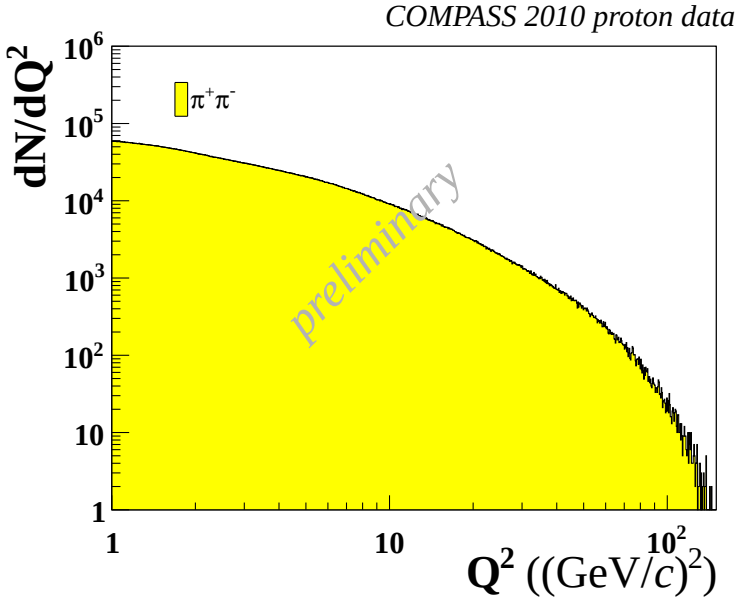
Data selection: DIS cuts

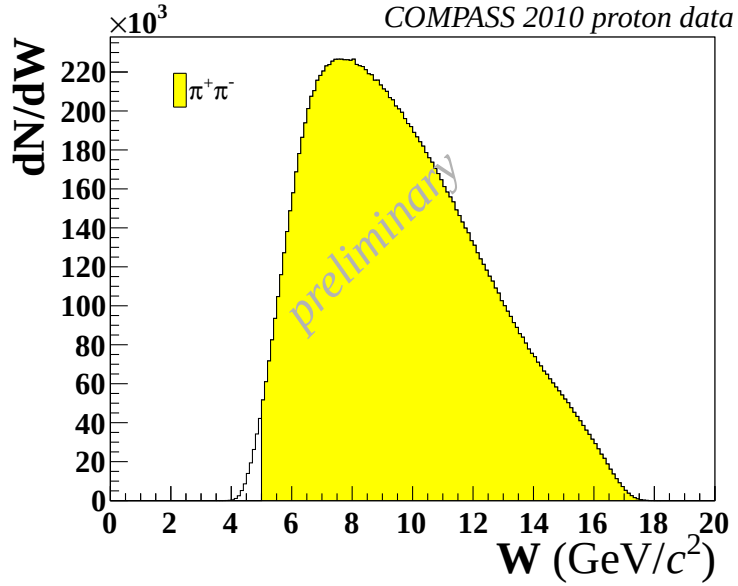
DIS cuts on events:

- $Q^2 > 1\,(\mathrm{GeV}/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ \mathrm{GeV}/c^2$

- spectrometer acceptance:
  $0.003 < x < 0.7$



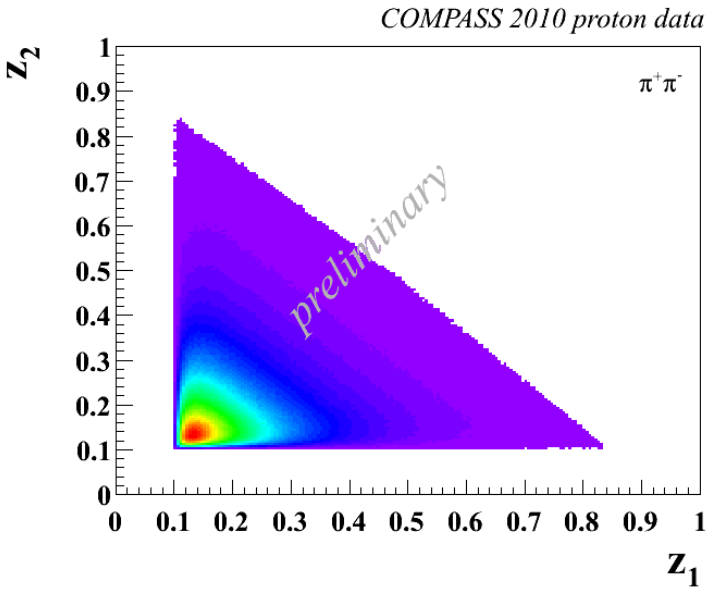


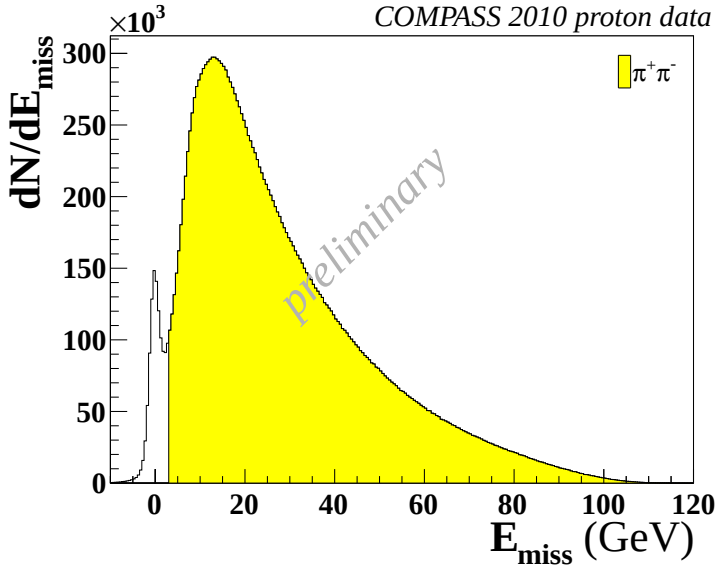


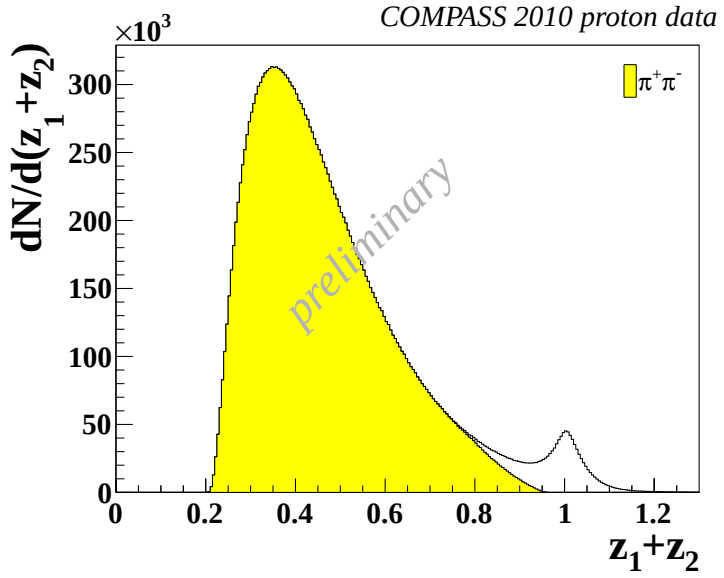
Data selection: hadron & hadron pair cuts

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



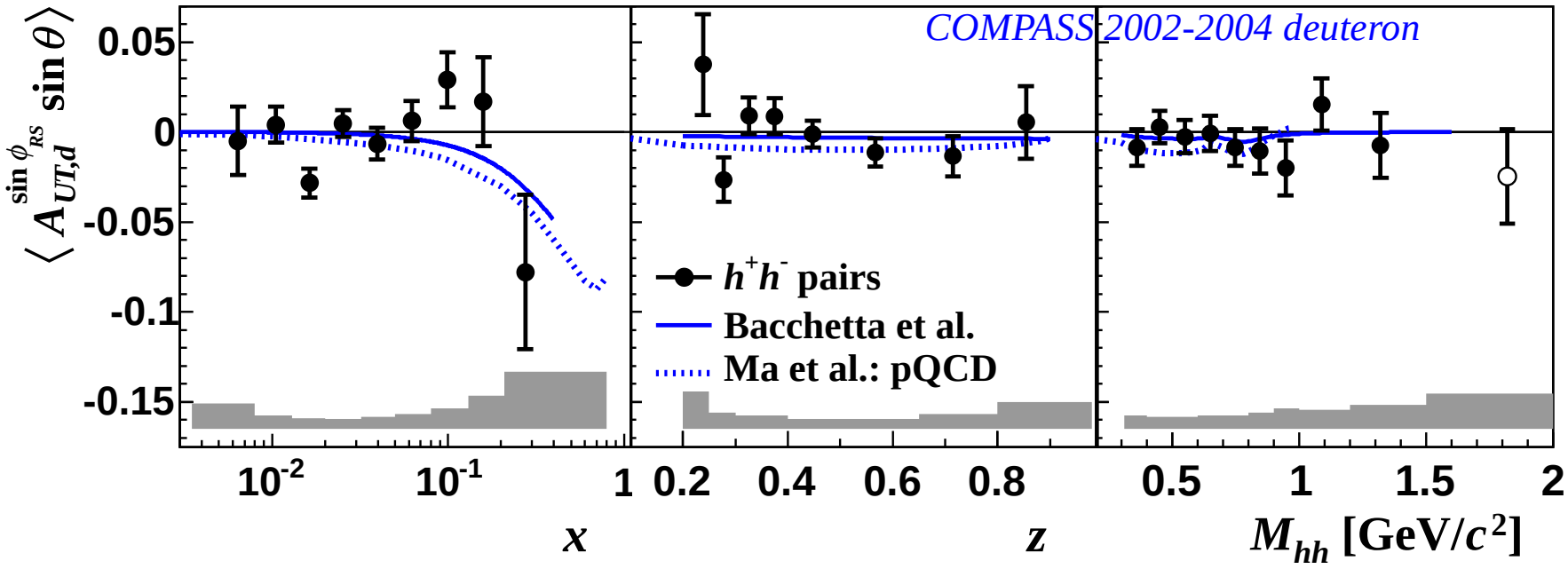




two-hadron asymmetries:

deuteron 2002-04 and proton 2007 data

deuteron data 2002-04: all h^+h^- pairs

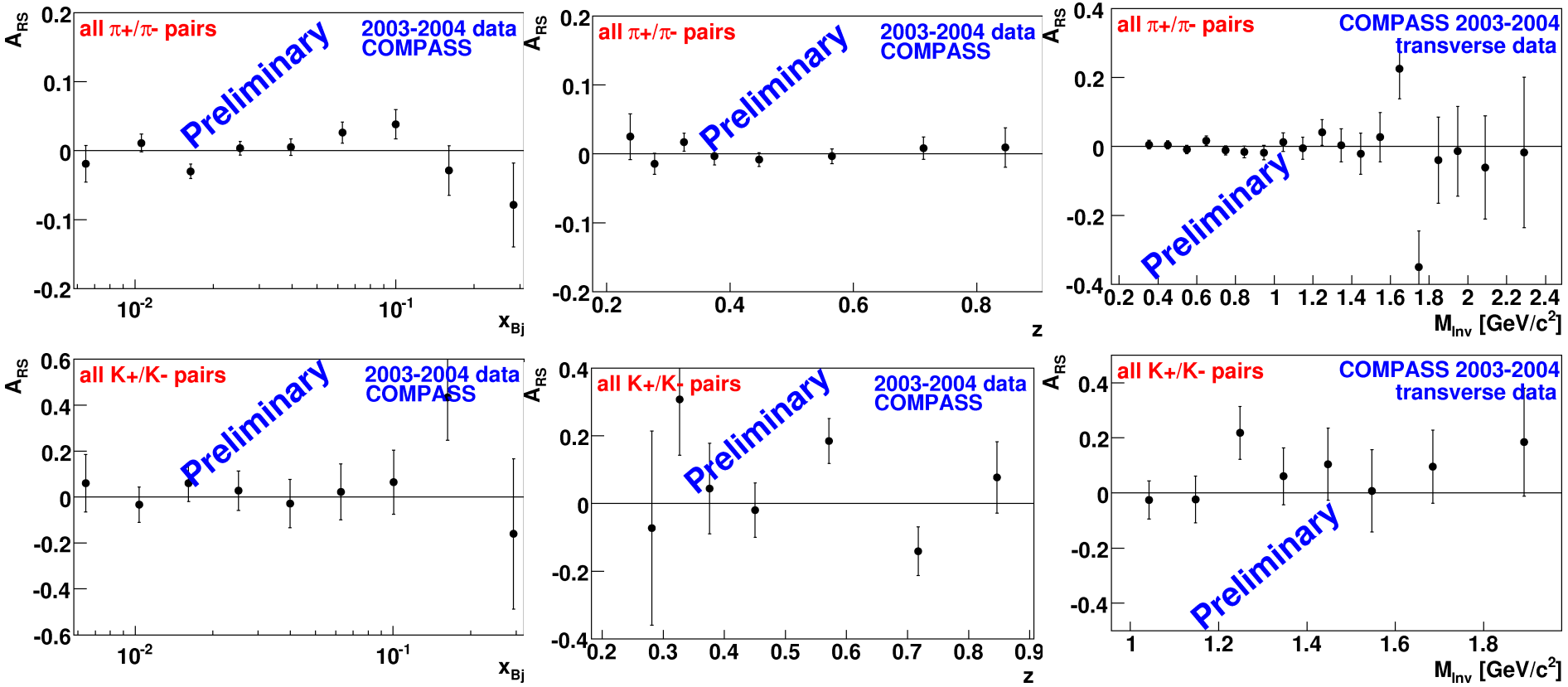


Adolph C. *et al.* [COMPASS Collaboration], Phys. Lett. B **713** (2012) 10
Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007
Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

↪ Asymmetries for deuteron target compatible with zero within the uncertainties

The models also predict a cancellation of the u and d quark transversity on the deuteron.

deuteron data 2002-04: $\pi^+\pi^-$ & K^+K^- pairs

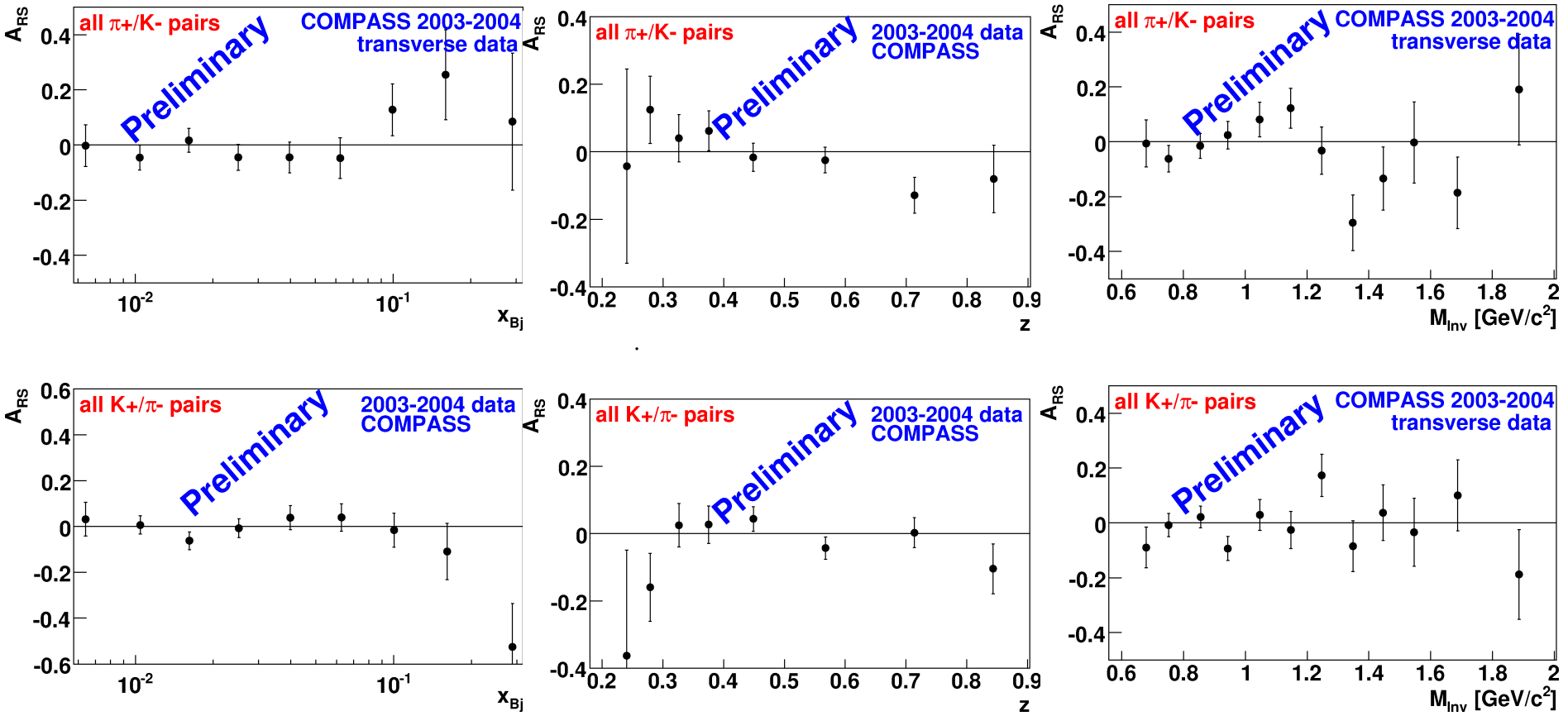


2002-04 deuteron data 2-hadron asymmetries: $\pi^+\pi^-$ pairs (top), K^+K^- pairs (bottom)

$\hookrightarrow$ h^+h^- asymmetries follow mostly $\pi^+\pi^-$ signal

$\pi^+\pi^-$ asymmetries are small and compatible with zero
K^+K^- no signal & low statistics

deuteron data 2002-04: π^+K^- & $K^+\pi^-$ pairs

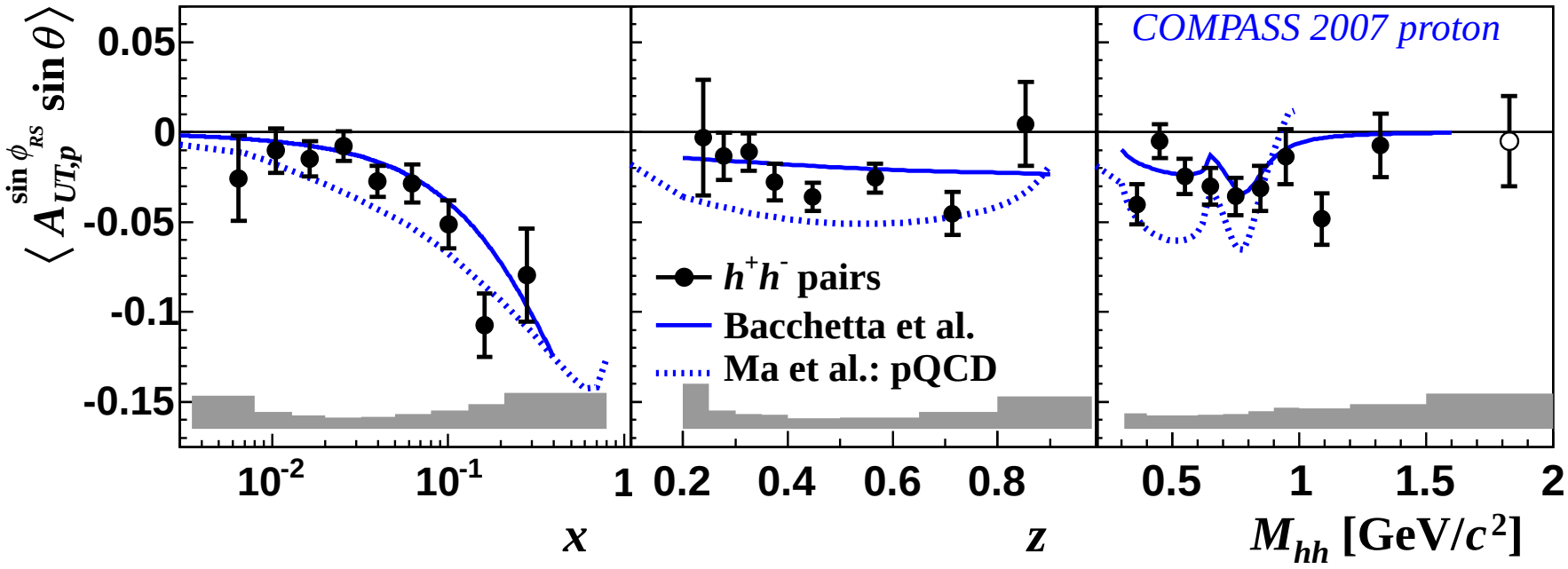


2002-04 deuteron data 2-hadron asymmetries: all π^+K^- pairs (top), $K^+\pi^-$ pairs (bottom)

$\hookrightarrow$ π^+K^- & $K^+\pi^-$ signal compatible with zero

weak indication of opposite sign of the signal in x dependence

proton data 2007: all h^+h^- pairs



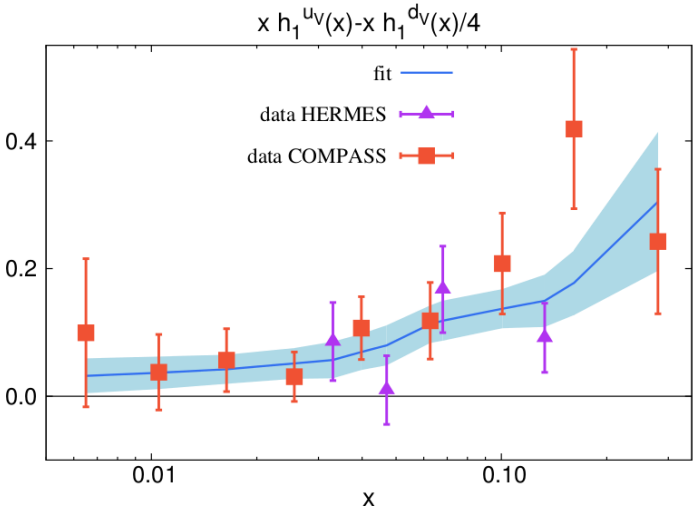
Adolph C. *et al.* [COMPASS Collaboration], Phys. Lett. B **713** (2012) 10
Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007
Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

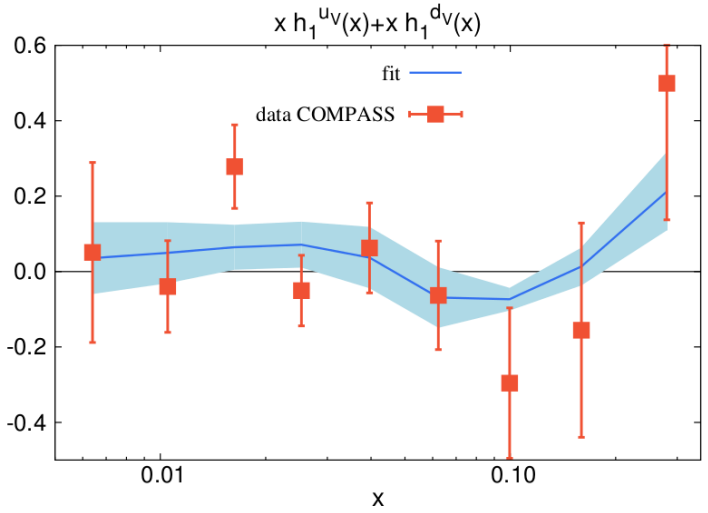
↪ Large asymmetries in x dependence up to -10 %

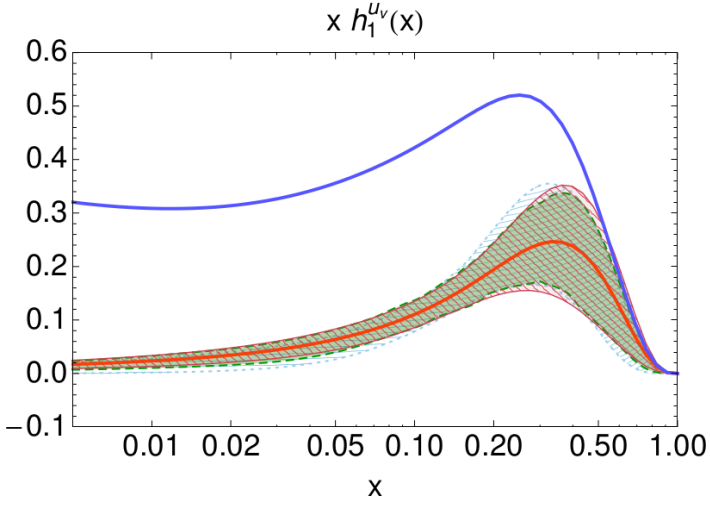
Good agreement with the model predictions

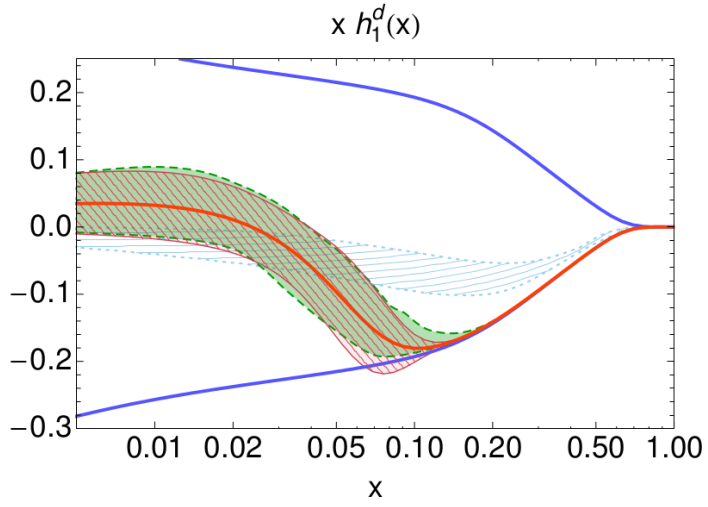
proton data 2007: extraction of u and d transversity

$\rightarrow$ h_1^u & h_1^d were extracted using **HERMES** proton and **COMPASS** 2007 proton & 2002-04 deuteron data







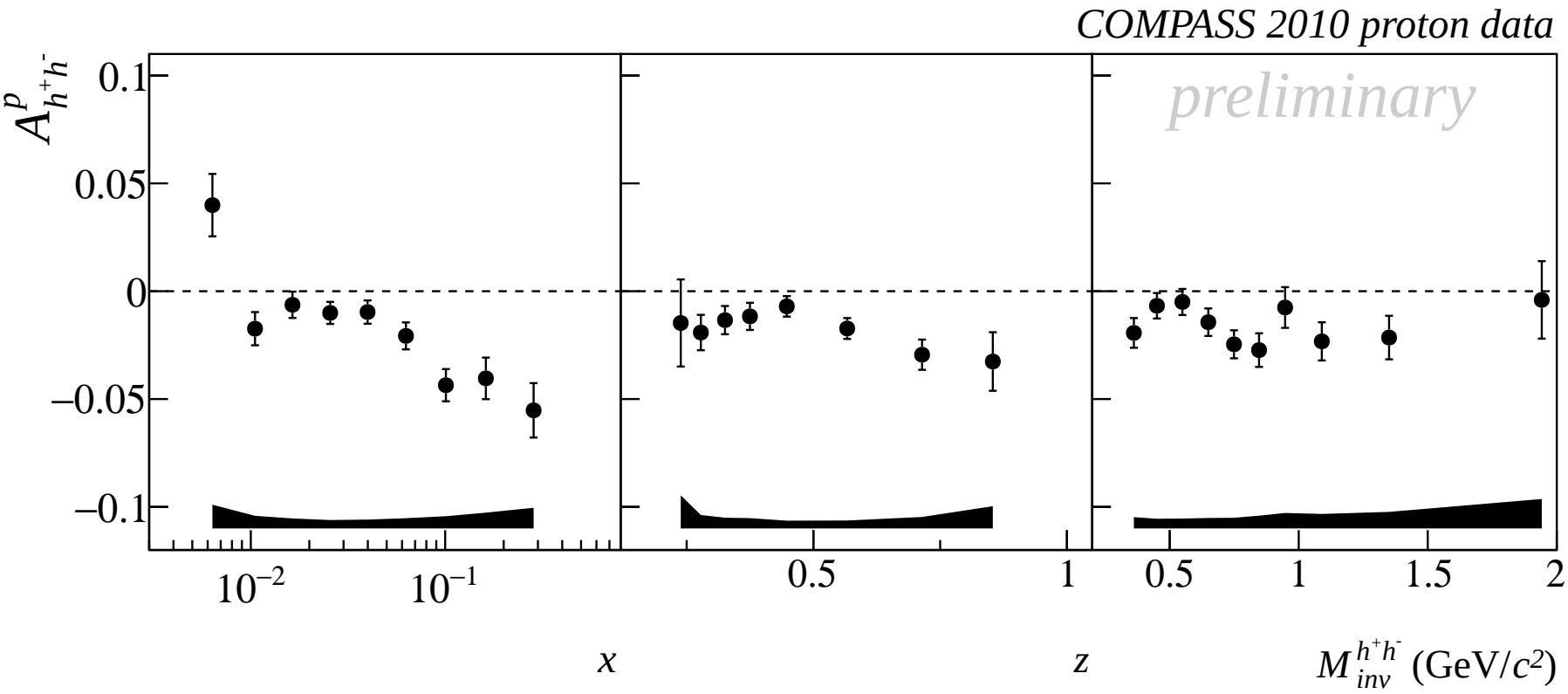


see talk by A. Courtoy | Bacchetta A., Courtoy A. and Radici M., JHEP **1303** (2013) 119

two-hadron asymmetries:

proton 2010 data

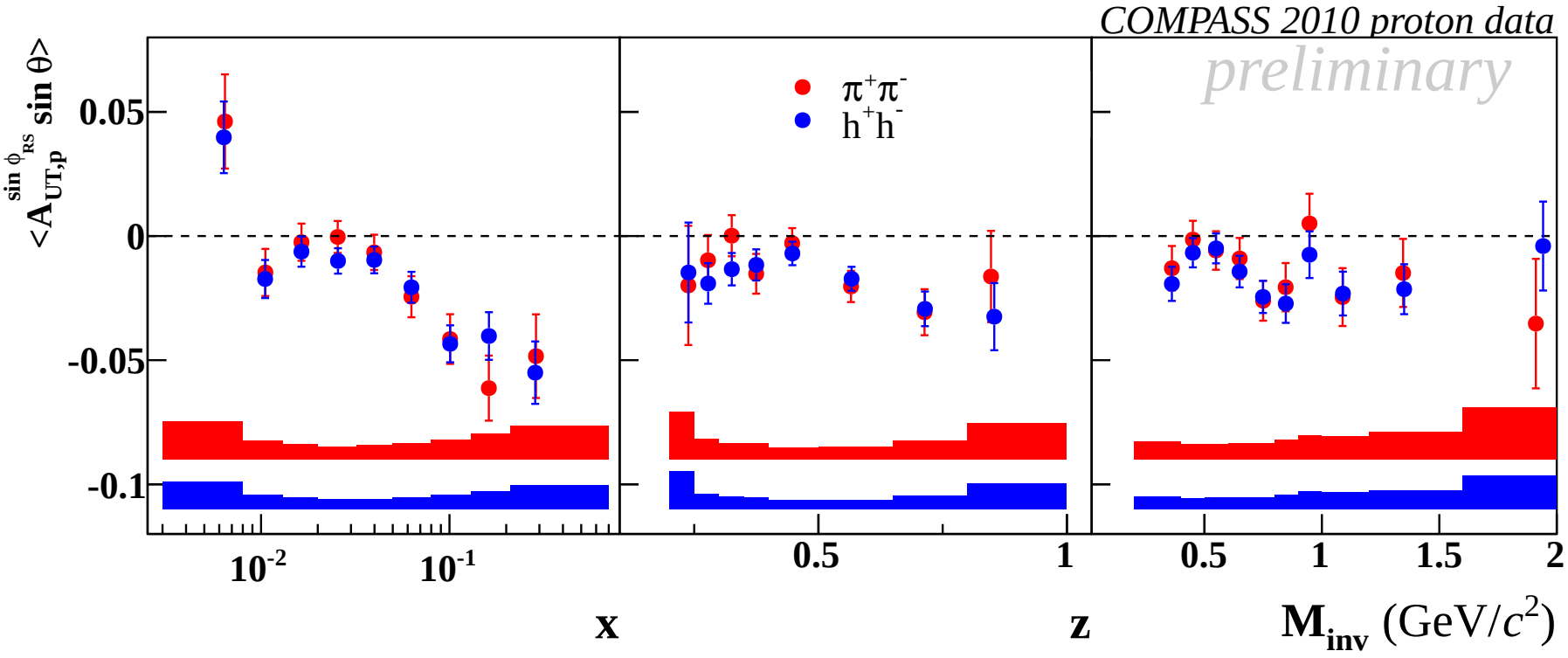
proton 2010 data: all h^+h^- pairs



C. Braun [COMPASS Collaboration], Nuovo Cimento C **035** (2012) 02

↪ Clear asymmetries of all hadron h^+h^- pairs

proton 2010 data: identified two-hadron asymmetries $\pi^+\pi^-$



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

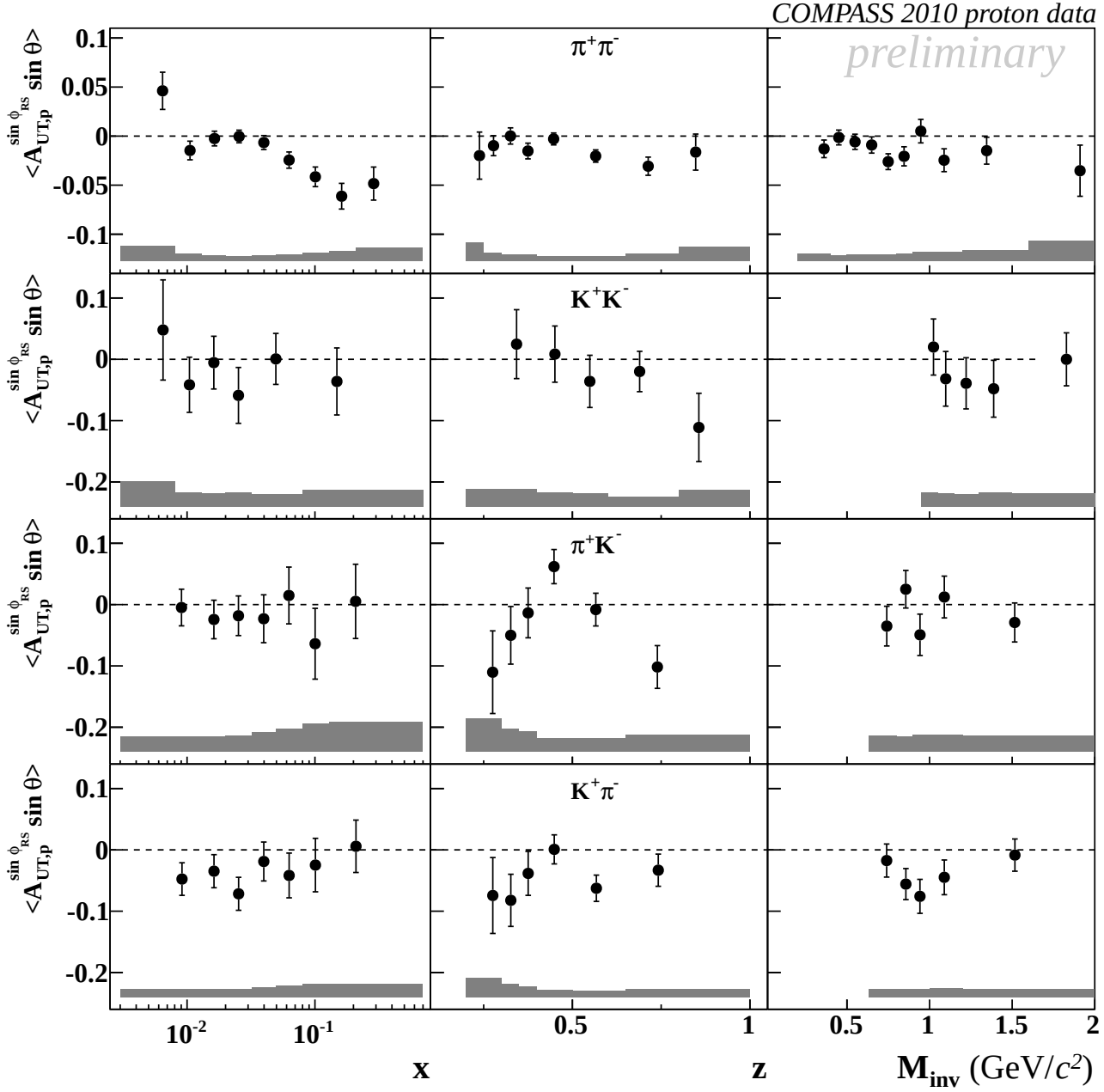
x up to -6 %

z no clear trend (compatible with a constant slope)

M_{inv} clear dip around ρ^0 mass

h^+h^- signal follows mostly $\pi^+\pi^-$ signal

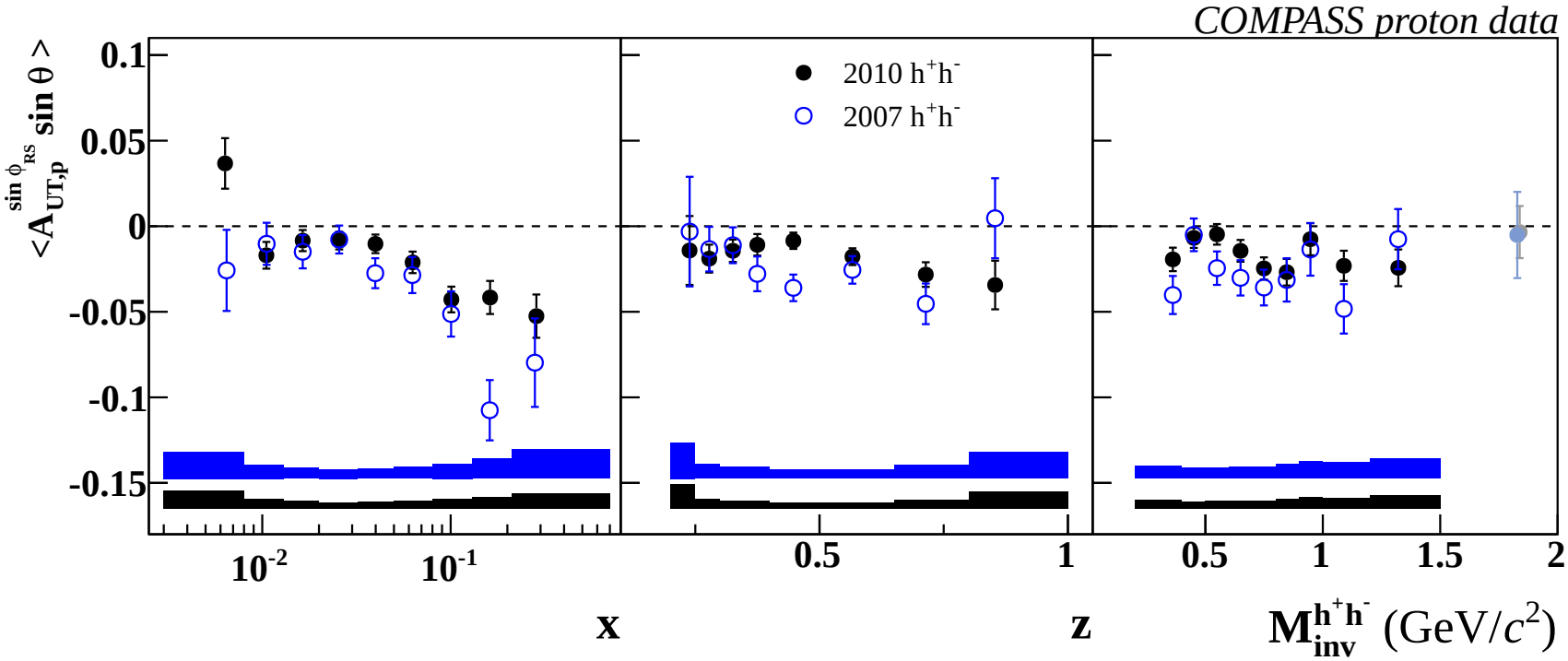
2010 proton data: identified two-hadron asymmetries all pairs



two-hadron asymmetries:

combined 2007/2010 data

comparison 2010 and 2007 proton data: all hadron h^+h^- pairs

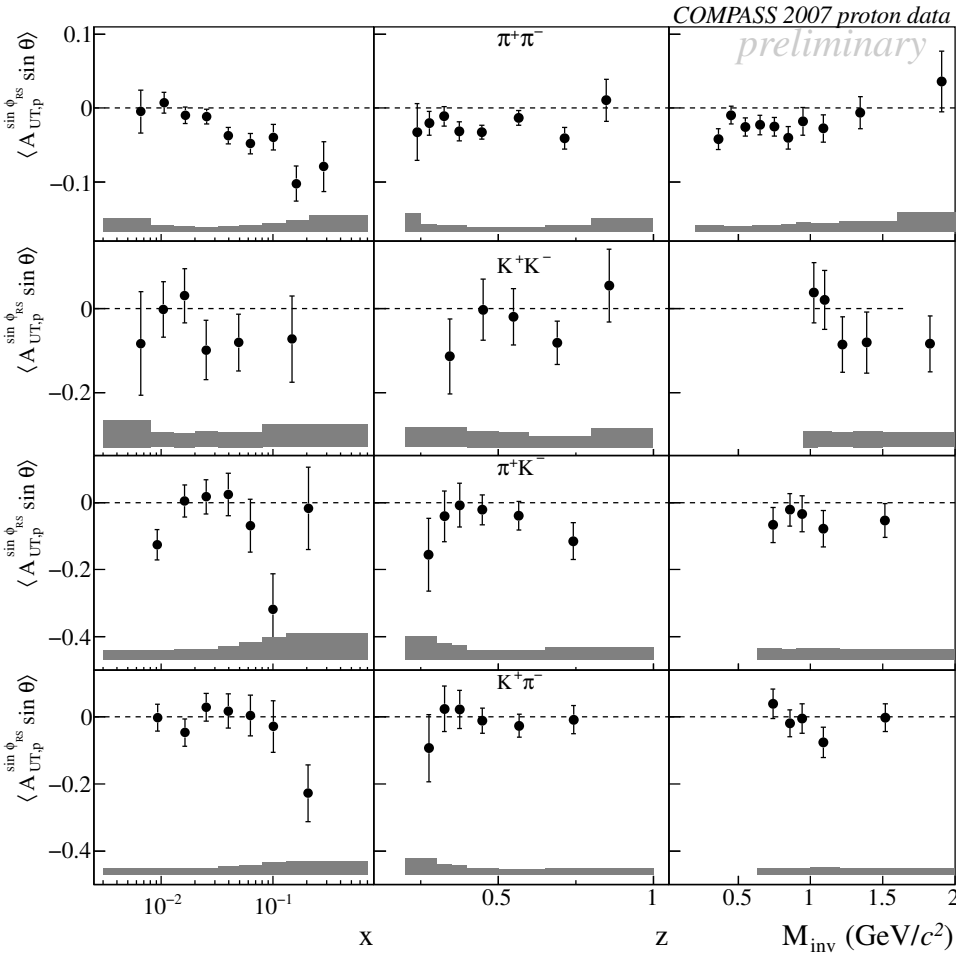


↪ Good agreement between 2007 and 2010 results within the uncertainties.

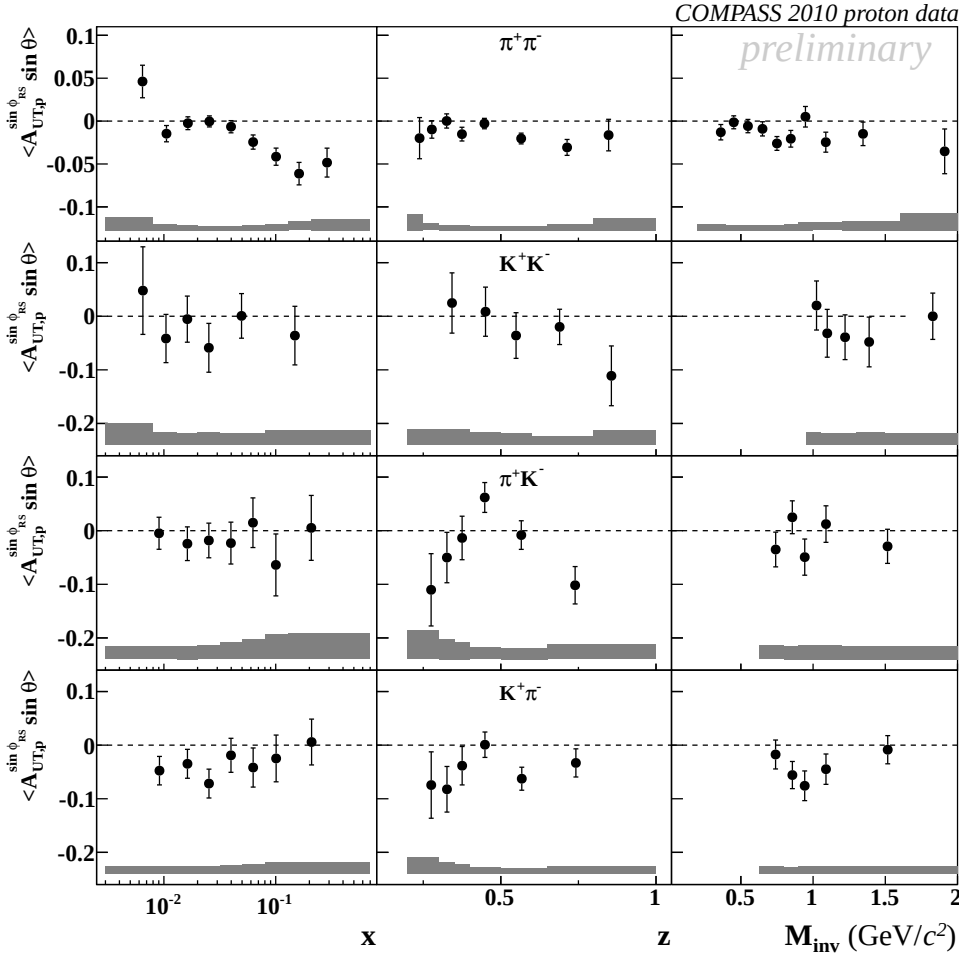
↪ Factor of gain in statistical uncertainty ~ 1.7

NEW: 2010 and 2007 proton data: all identified pairs

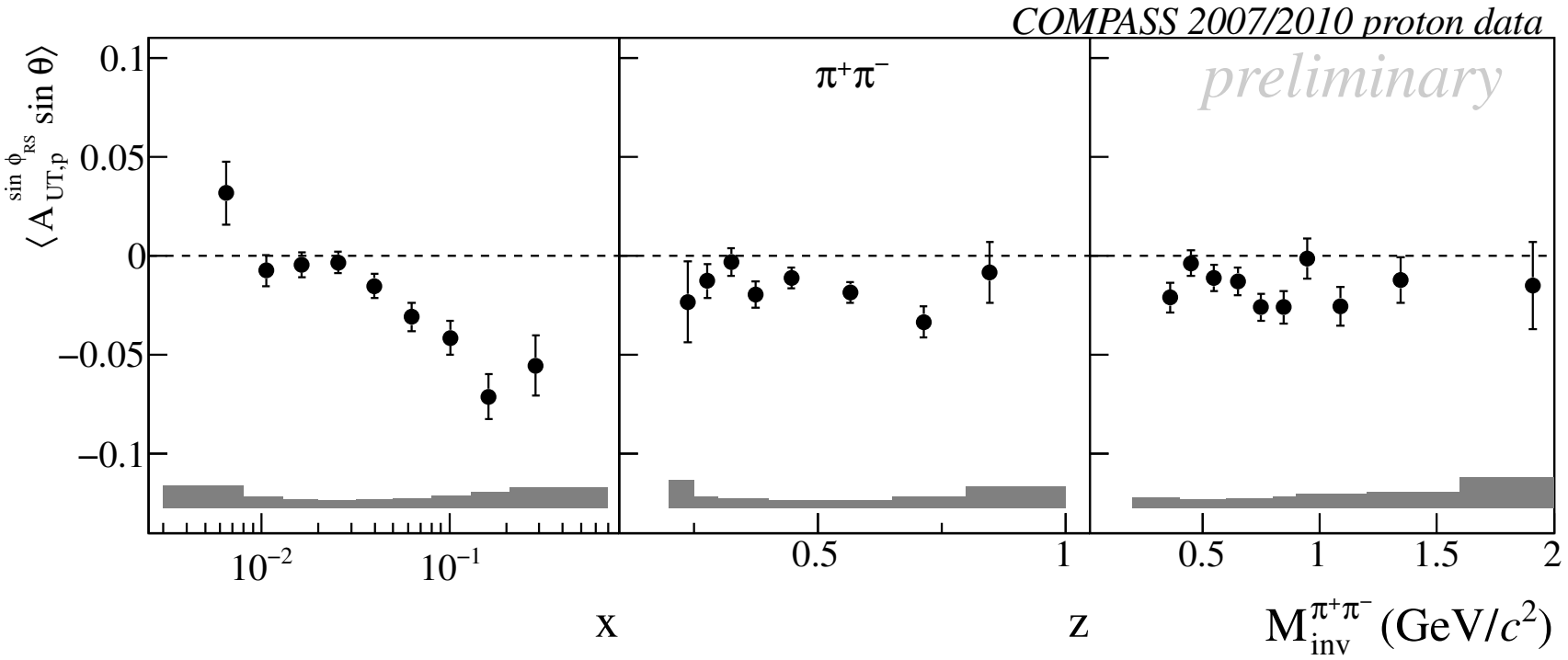
2007 data



2010 data



NEW: combined 2007/2010 data: $\pi^+\pi^-$ asymmetries



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

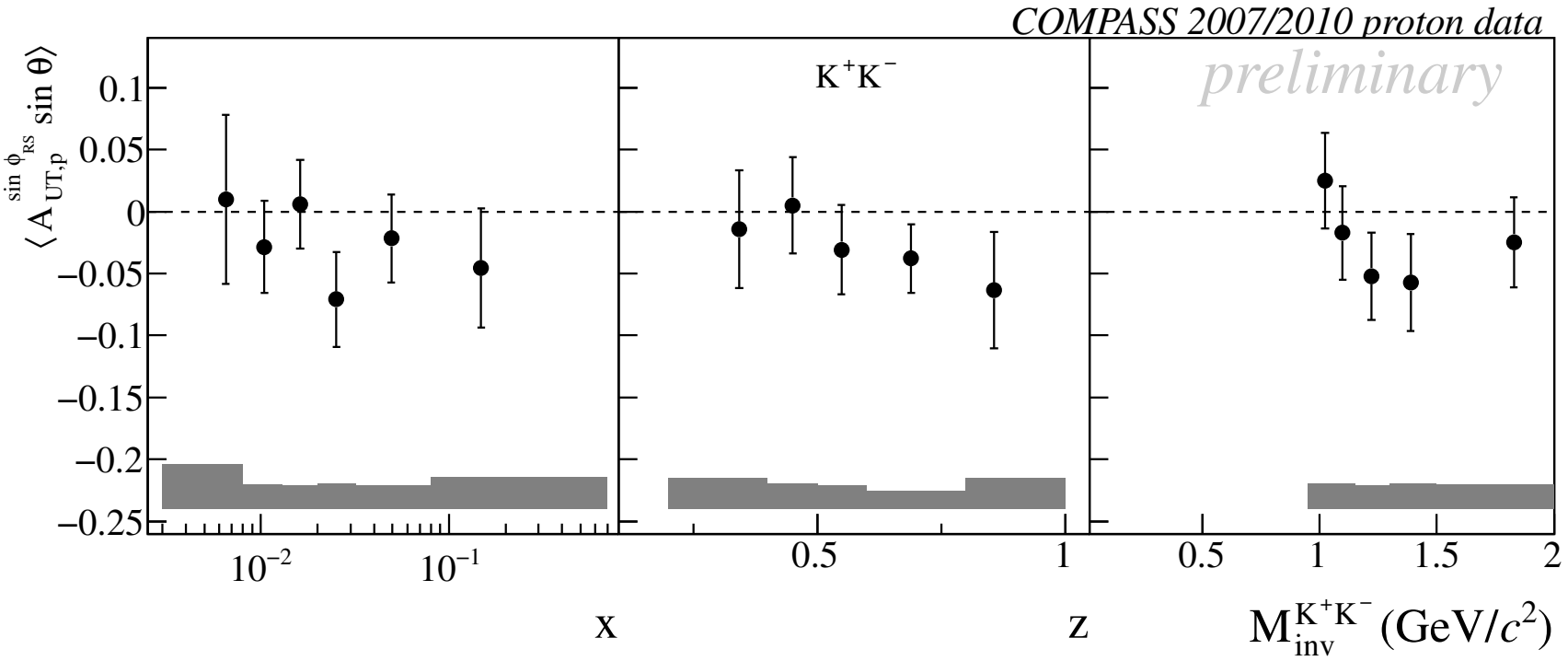
x up to $-6\,\%$

z no clear trend (compatible with a constant slope)

M_{inv} clear dip around ρ^0 mass

h^+h^- signal follows mostly $\pi^+\pi^-$ signal

NEW: combined 2007/2010 data: K^+K^- asymmetries



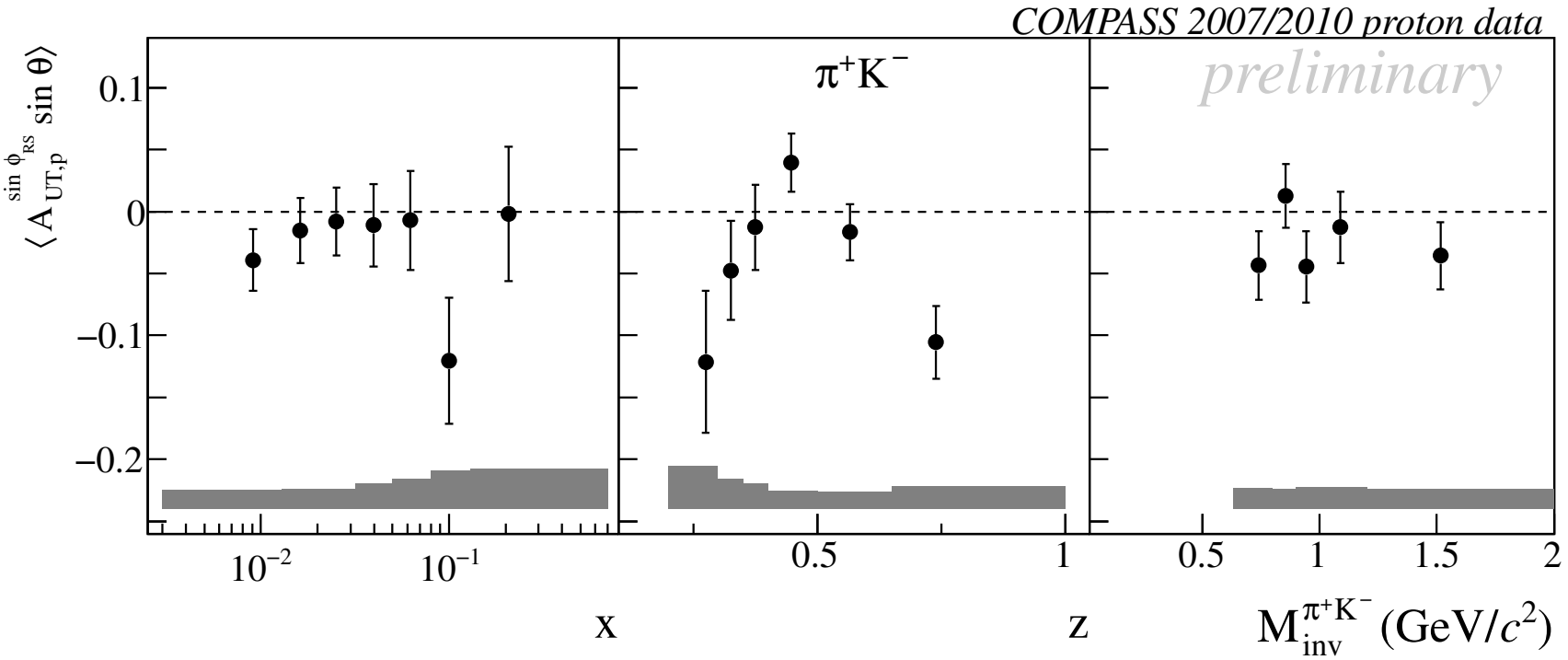
↪ no clear trend & compatible with zero within the statistical uncertainties

x no significant signal

z no significant signal

M_{inv} no significant signal

NEW: combined 2007/2010 data: π^+K^- asymmetries



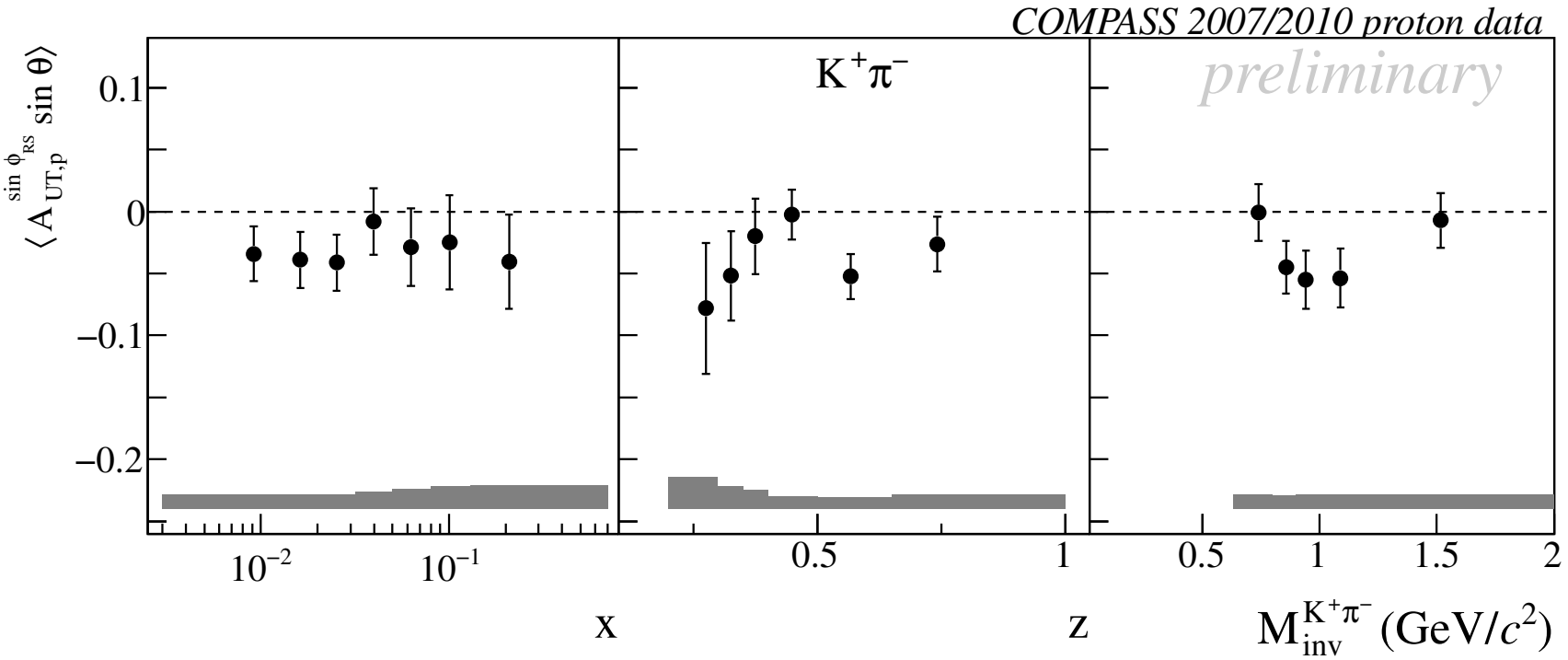
↪ compatible with zero within the statistical uncertainties

x no signal

z significant slope with a relative maximum around 0.45

M_{inv} no clear signal

NEW: combined 2007/2010 data: $K^+\pi^-$ asymmetries



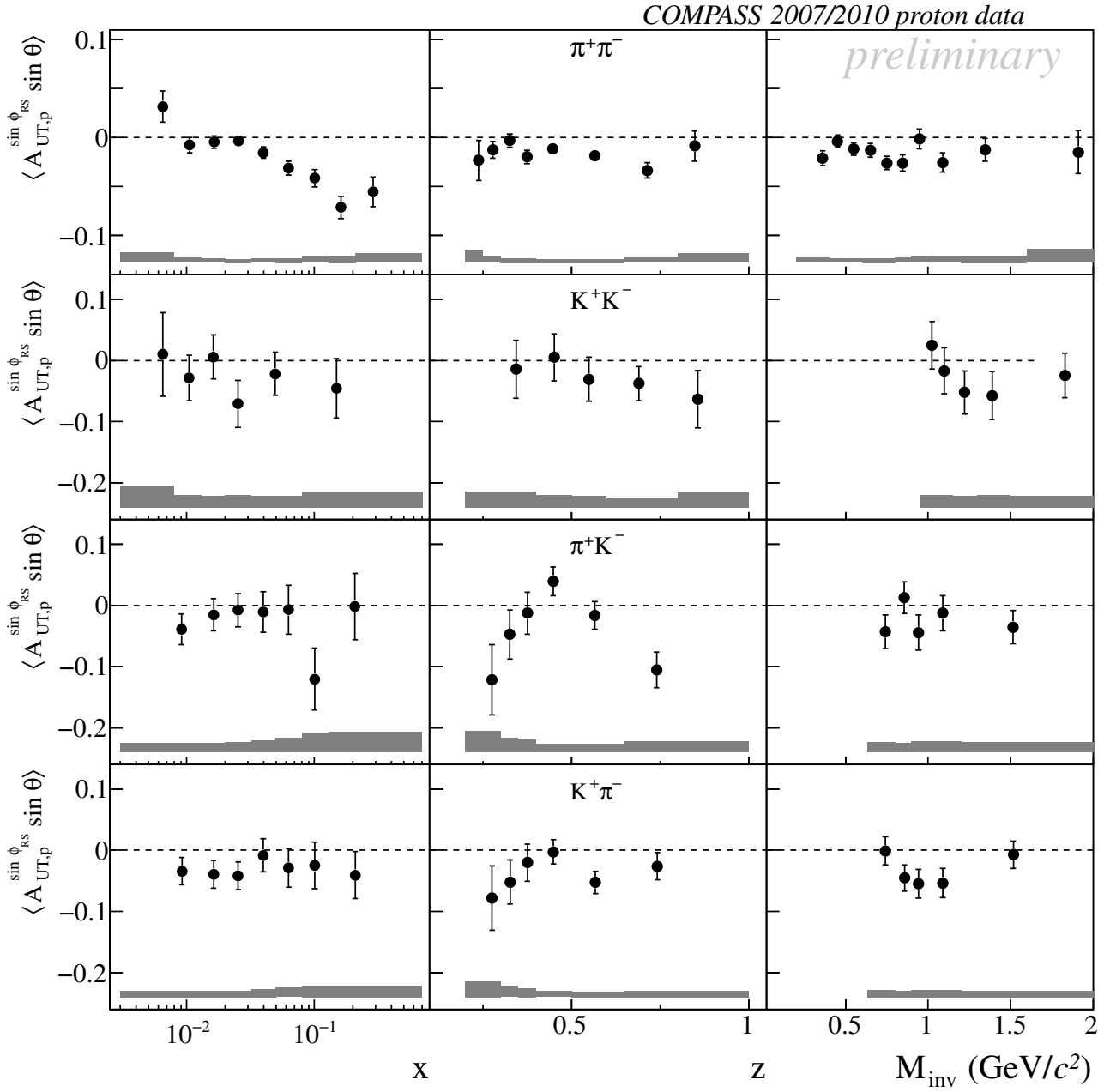
↪ compatible with zero within the statistical uncertainties

x no clear signal & negative mean value

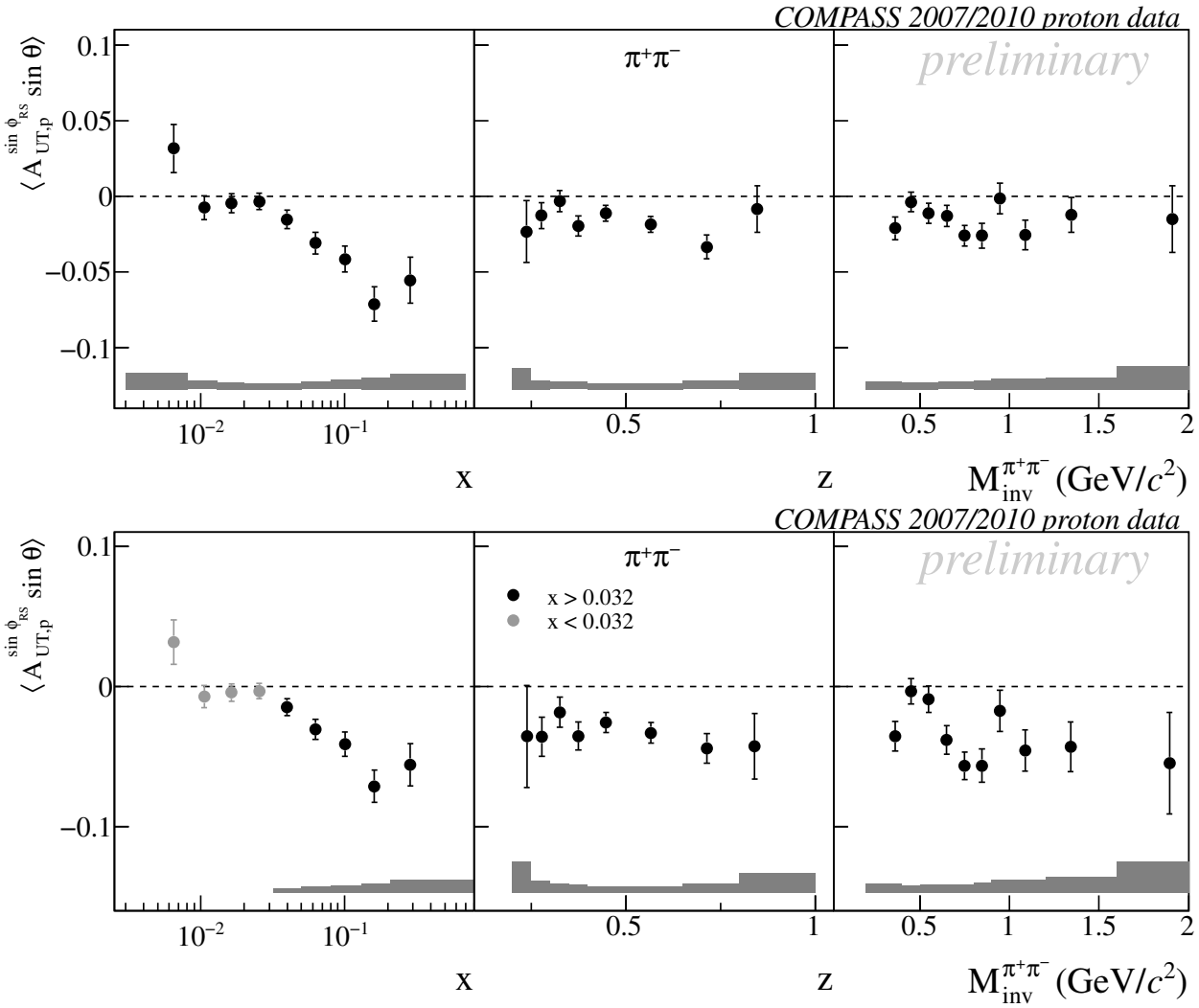
z no clear signal & negative mean value

M_{inv} minimum around 0.9 GeV/c^2

NEW: combined 2007/2010 data: all identified asymmetries



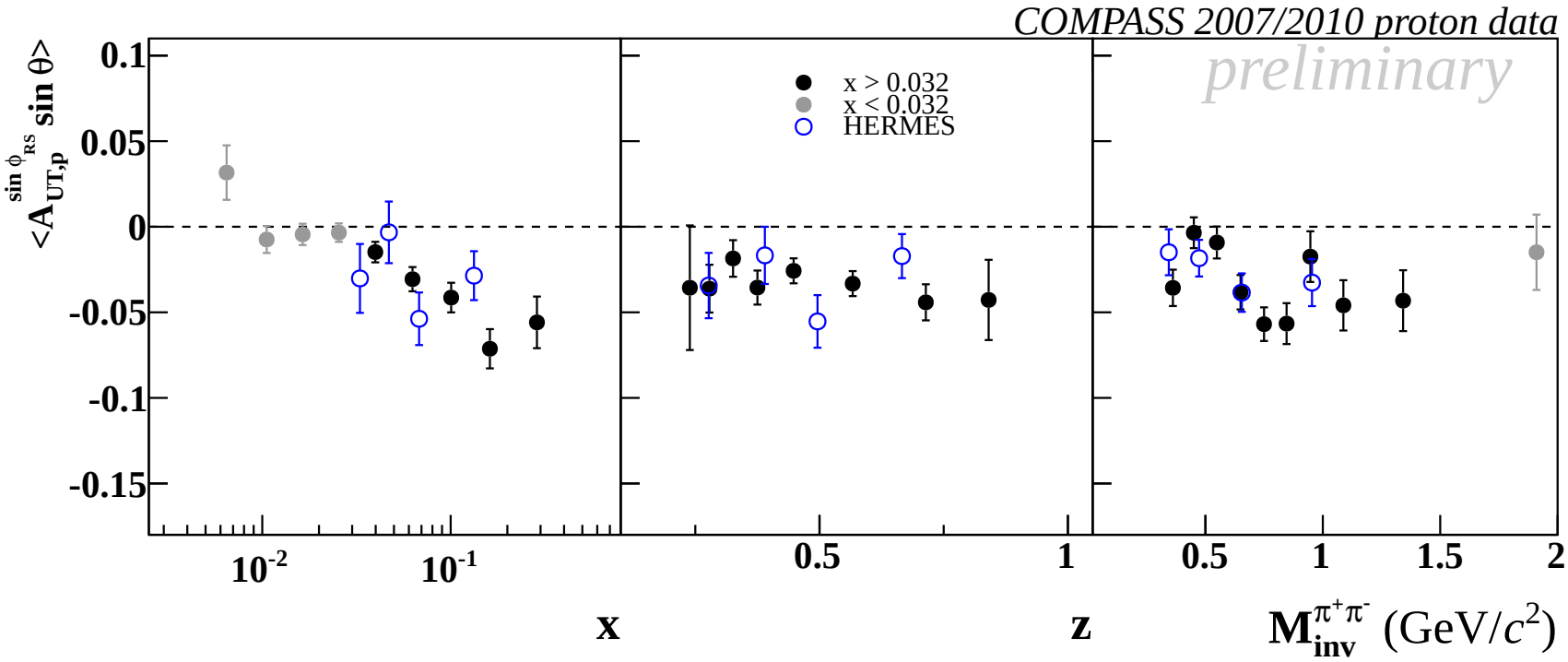
NEW: combined 2007/2010 data: $\pi^+\pi^-$ in valence region



$\hookrightarrow$ $\pi^+\pi^-$ valence region $x > 0.032$

Dip around the ρ^0 mass is pronounced in the valence region sample

NEW: combined 2007/2010 data: comparison of $\pi^+\pi^-$ with results from HERMES



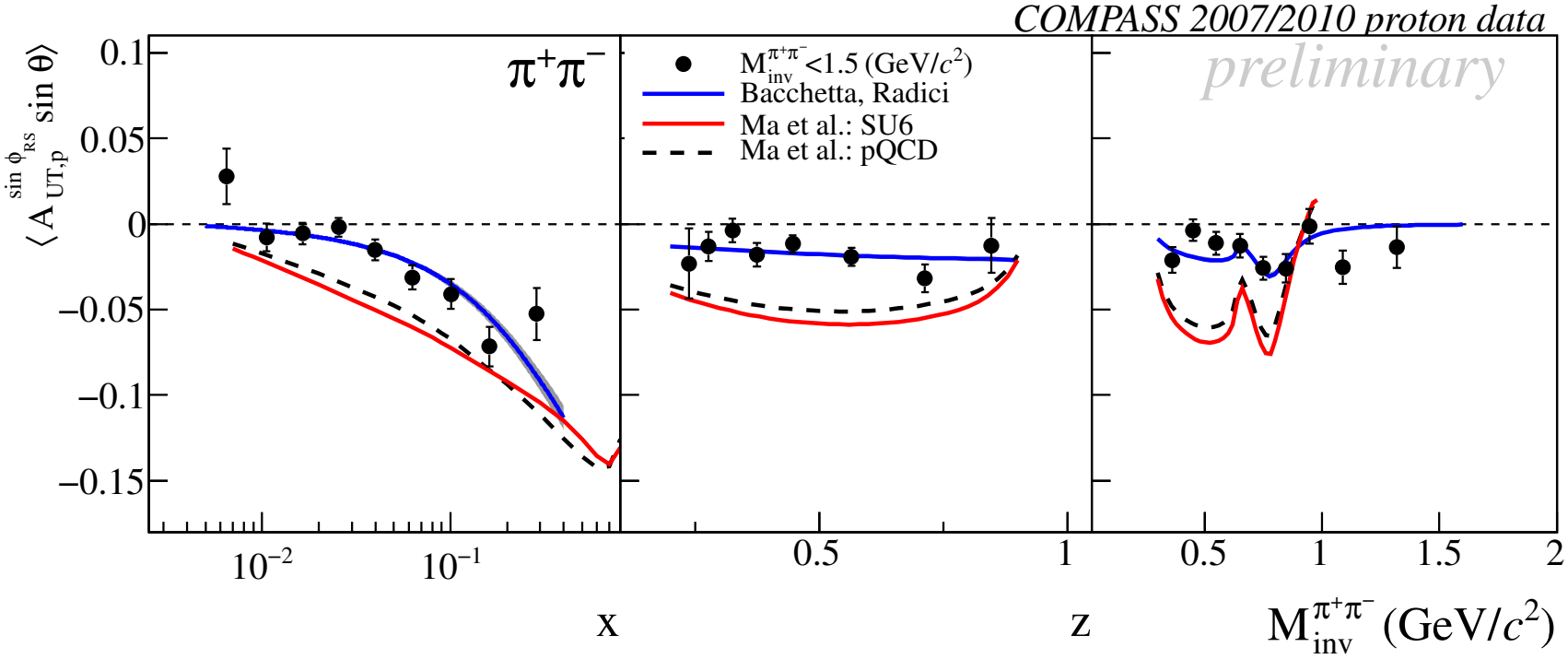
see talk of S. Gliske

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

scaled with $\frac{1}{D_{nn}}$ and sign changed

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

NEW: combined 2007/2010 data: comparison with model predictions



Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007
Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

↪ x: *Ma* trend confirmed | *Bachetta* good agreement
↪ z: *Ma* too large | *Bachetta* compatible
↪ M_{inv}: *Ma* too large | *Bachetta* good agreement around ρ^0 mass

Conclusions & Outlook

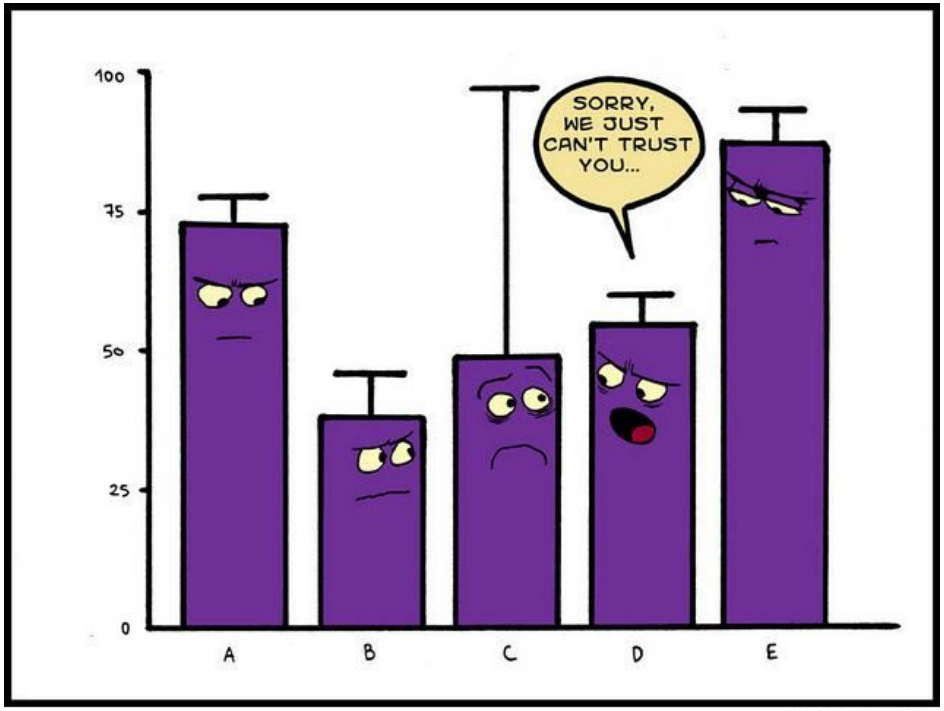
- COMPASS 2002-04 h^+h^- deuteron data published
- COMPASS 2007 proton data published
- preliminary results for 2010 COMPASS proton data
- preliminary combined results 2007/2010 COMPASS proton data

1. Recently: COMPASS **proton** data on transverse spin asymmetries in **identified** two-hadron production
   - $\pi^+\pi^-$ (also measured by HERMES)
   - K^+K^-, π^+K^- and $K^+\pi^-$ never measured before
2. COMPASS $\pi^+\pi^-$ data is in good agreement with HERMES data
3. Reasonable agreement with available model predictions
4. Important input for the extraction of transversity h_1

Outlook:

- Paper on proton 2010 data: h^+h^- asymmetries
- Paper on identified asymmetries: combined proton 2007 & 10 and deuteron 2002-04 data

Thank you for your attention!



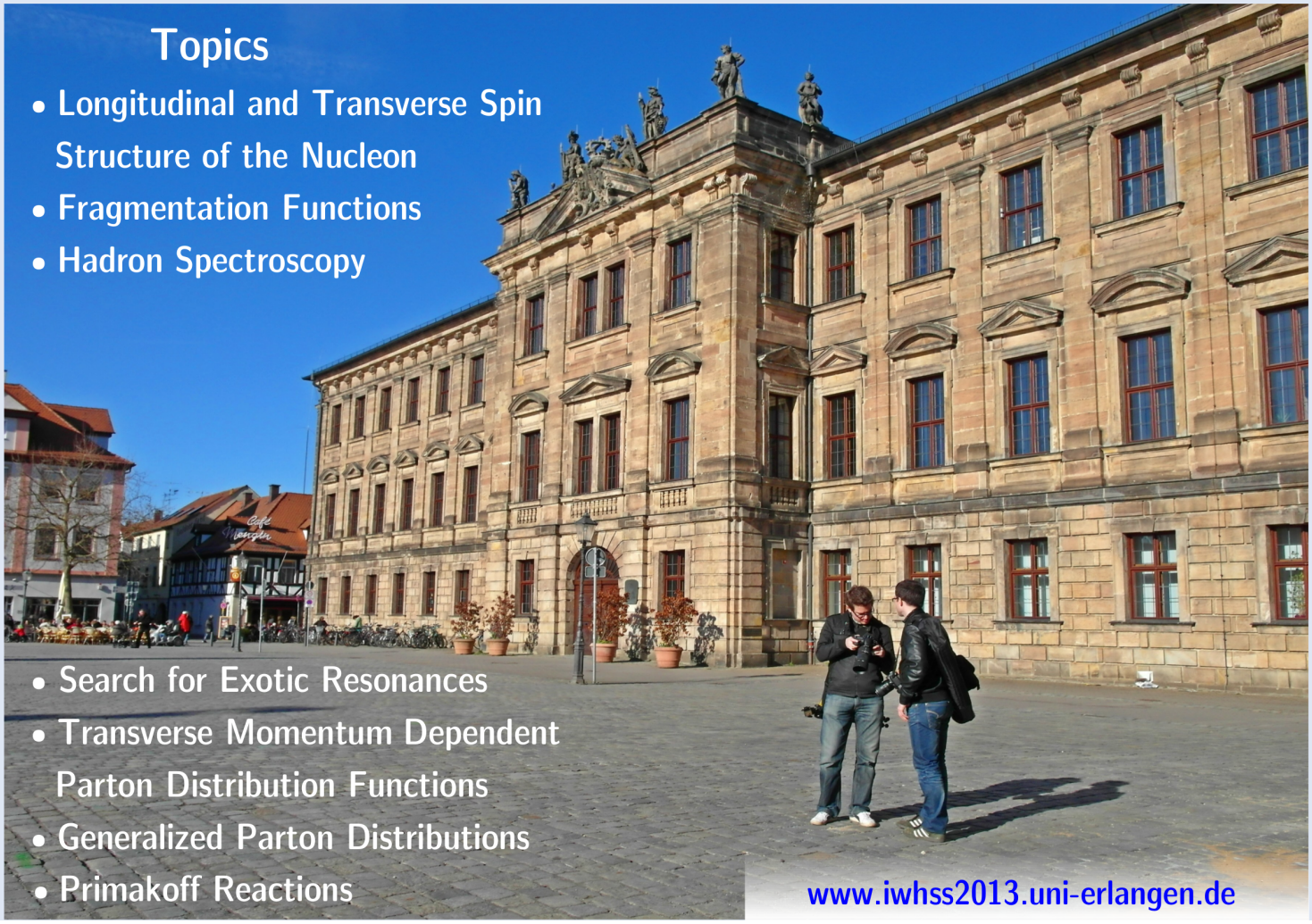
electronic address: christopher.braun@cern.ch

Invitation to IWHSS2013

IWHSS 2013

International Workshop on Hadron Structure and Spectroscopy,

Erlangen, 22-24 July 2013



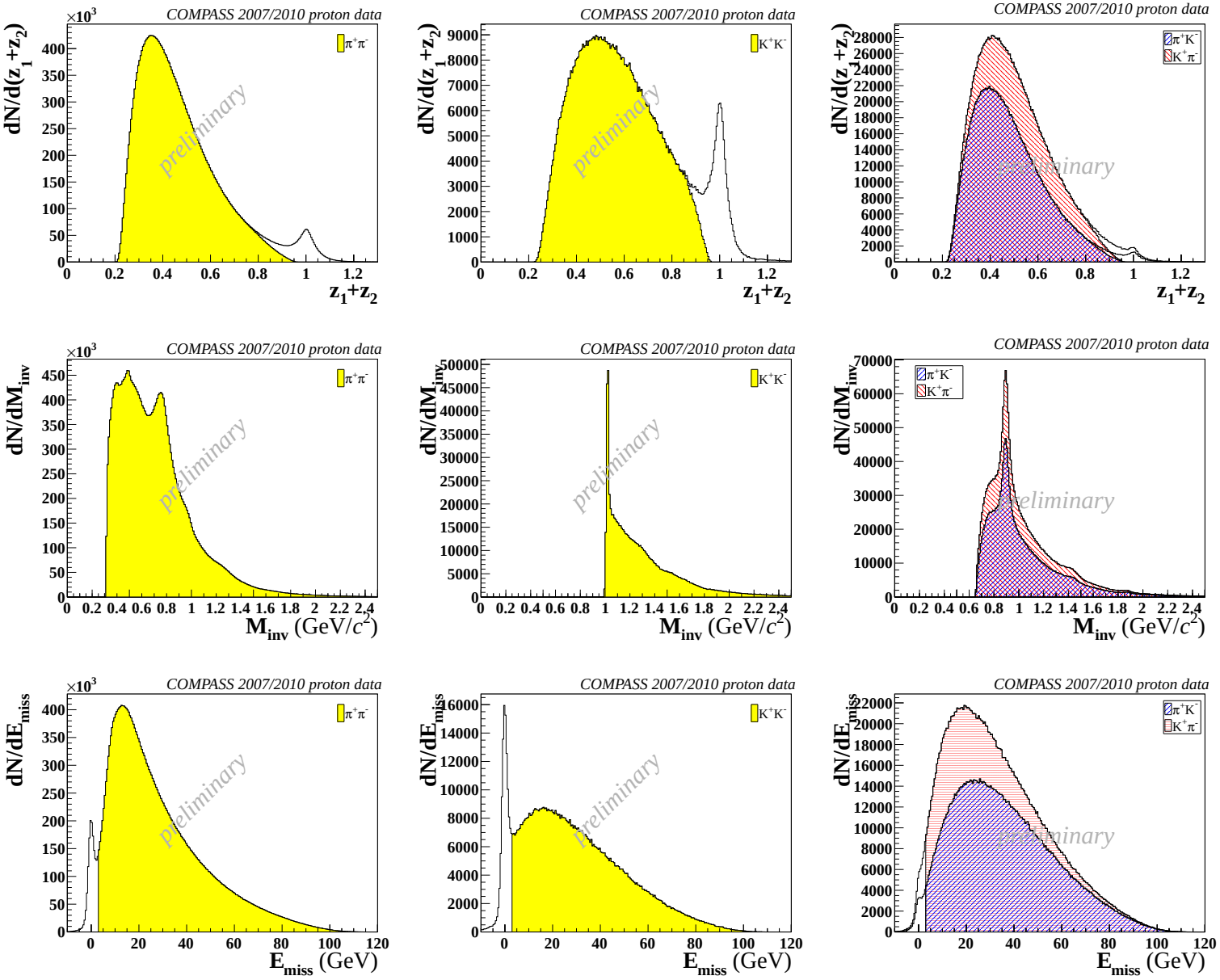
Invitation to IWHSS2013: Preliminary list of speakers and topics

E.-C. Aschenauer	Experimental review of hadron multiplicities and fragmentation functions
M. Boglione	Transverse momentum distributions – Q^2 evolution
F. Bradamante	Highlights of the workshop
V. Burkert	The JLAB 12 GeV project
V. Drach	Recent progress in Lattice QCD
A. Ferrero	COMPASS II: experiment and physics case
B. Grube	Spectroscopy at COMPASS and related Experiments
A. Guskov	Experimental review of Primakoff reactions
M. Kreps	Meson spectroscopy at LHCb
K. Kurek	Review of longitudinal spin physics
C. Lorce	The proton spin decomposition: observability and physical interpretation
H. Moutarde	Review of some recent developments on Deeply Virtual Compton Scattering
B. Parsamyan	Unpolarized azimuthal asymmetries in SIDIS
M. Pennington	Directions in Spectroscopy: COMPASS points the way
K. Peters	The FAIR project
M. Radici	Theoretical overview of transverse spin physics in SIDIS and Drell-Yan
C. Riedl	Review of Drell-Yan experiments
F. Ringer	QCD resummation for semi-inclusive hadronproduction processes
K. Rith	Deep inelastic scattering – an overview
G. Schnell	Experimental review of transverse spin physics
M. Stratmann	Theoretical review of fragmentation functions

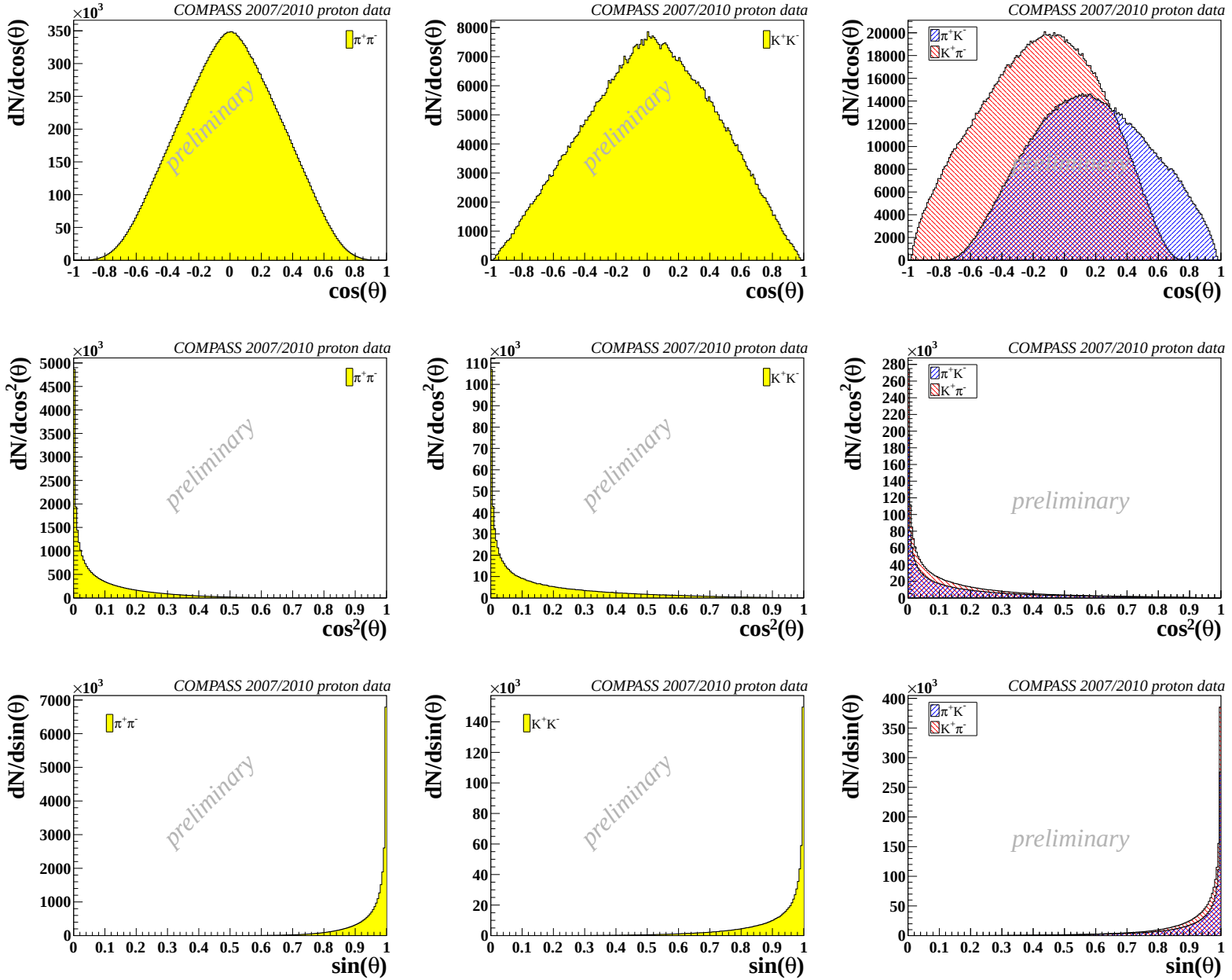
Back up

Identified hadron pairs: kin. distributions $z_1 + z_2$, M_{inv} and E_{miss}

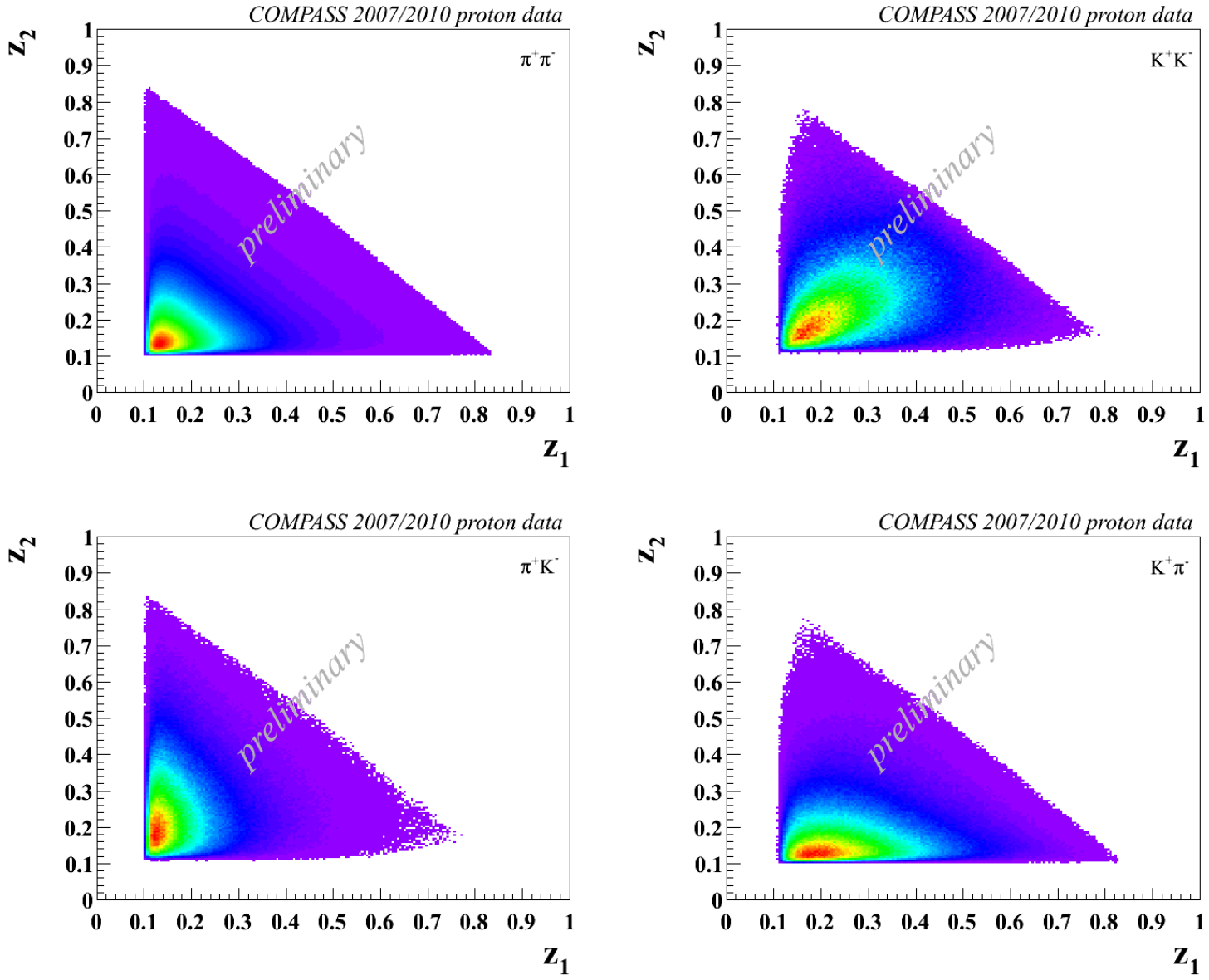
$\pi^+\pi^-$ K^+K^- $\pi^+K^- \,\&\, K^+\pi^-$



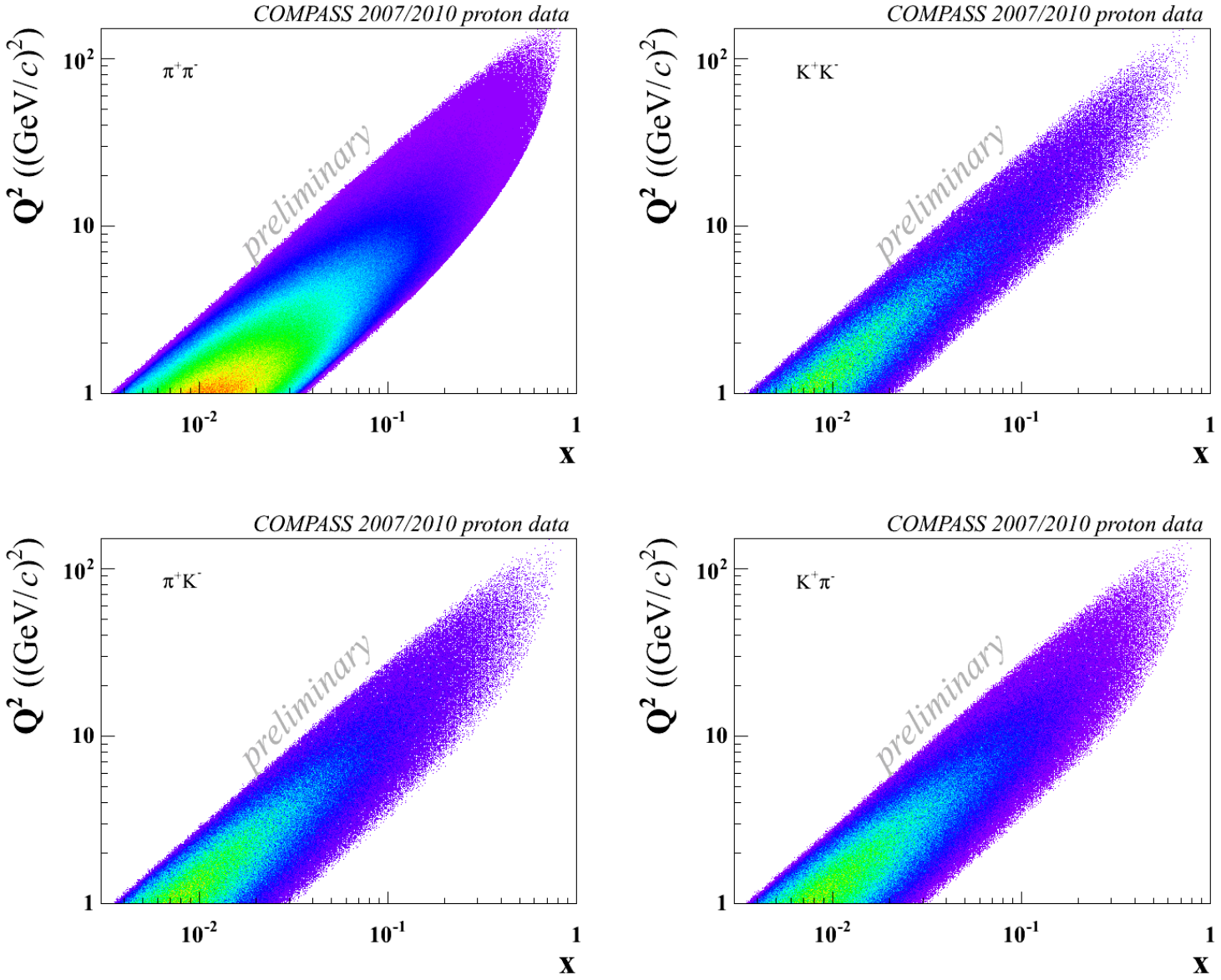
Kinematic distributions of DIS events: $\cos\Theta$, $\cos^2\Theta$ and $\sin\Theta$



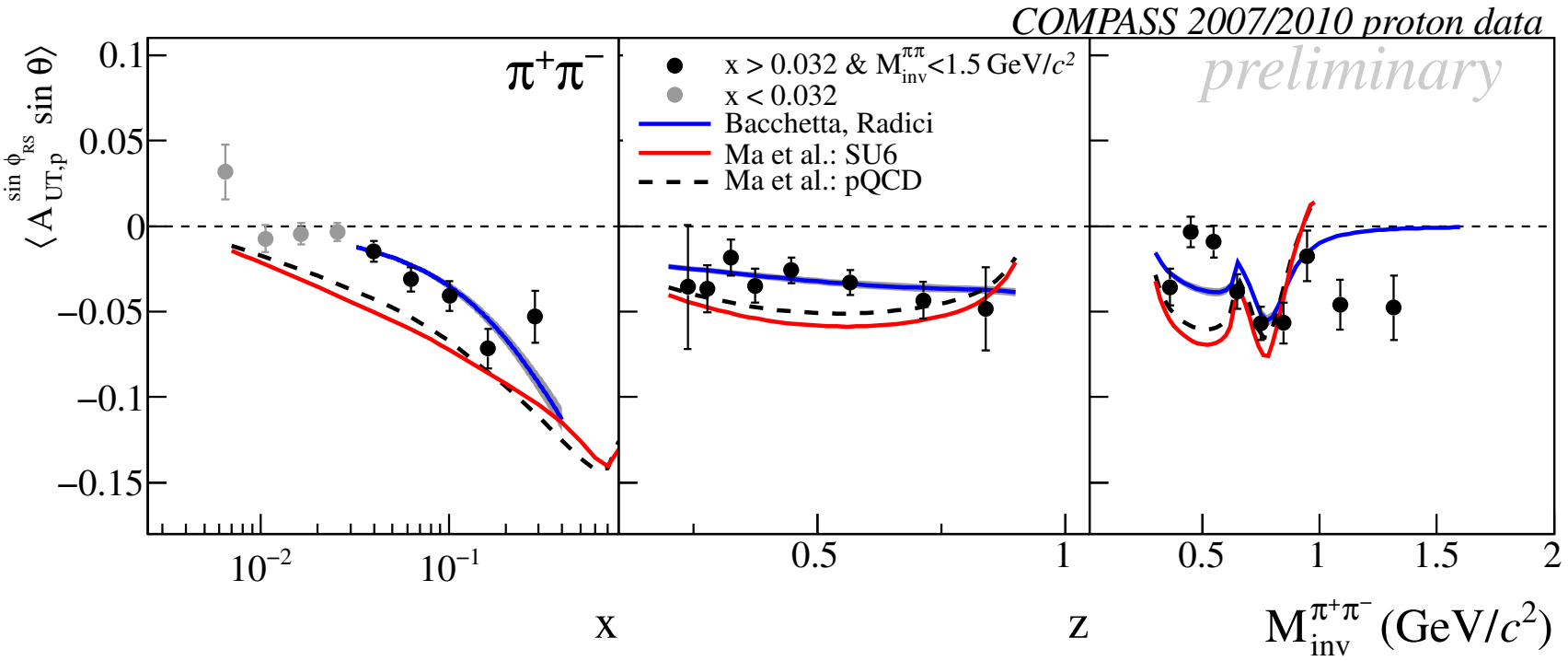
Kinematic distributions of DIS events: z_1 vs. z_2



Kinematic distributions of DIS events: Q^2 vs. x



comparison with model predictions in valence region



Bacchetta A. and Radici M., Phys. Rev. D **74** (2006) 114007
Ma B.-Q. *et al.*, Phys. Rev. D **77** (2008) 014035

↪ x: *Ma* trend confirmed | *Bachetta* good agreement
↪ z: compatible within the errors
↪ M_{inv}: good agreement in the region of the ρ^0 mass