RECENT RESULTS FROM COMPASS

Andrea Bressan
University of Trieste and INFN

(on behalf of the COMPASS Collaboration)

OUTLOOK

- the COMPASS experiment
- Longitudinal spin
  - Quark helicity distributions
  - ΔG
- Transverse spin and TMD PDF and FF
  - transversity
  - Sivers asymmetries
  - other TMD asymmetries
- future plans for DVCS and DY

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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**
		2006	**L target polarisation**
	proton (NH_3) polarised target	**2007**	**L /T target polarisation**
hadron beam	**LH target**	**2008 2009**	
muon beam	**proton (NH_3) polarised target**	**2010**	**T target polarisation**
		2011	**L target polarisation**

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

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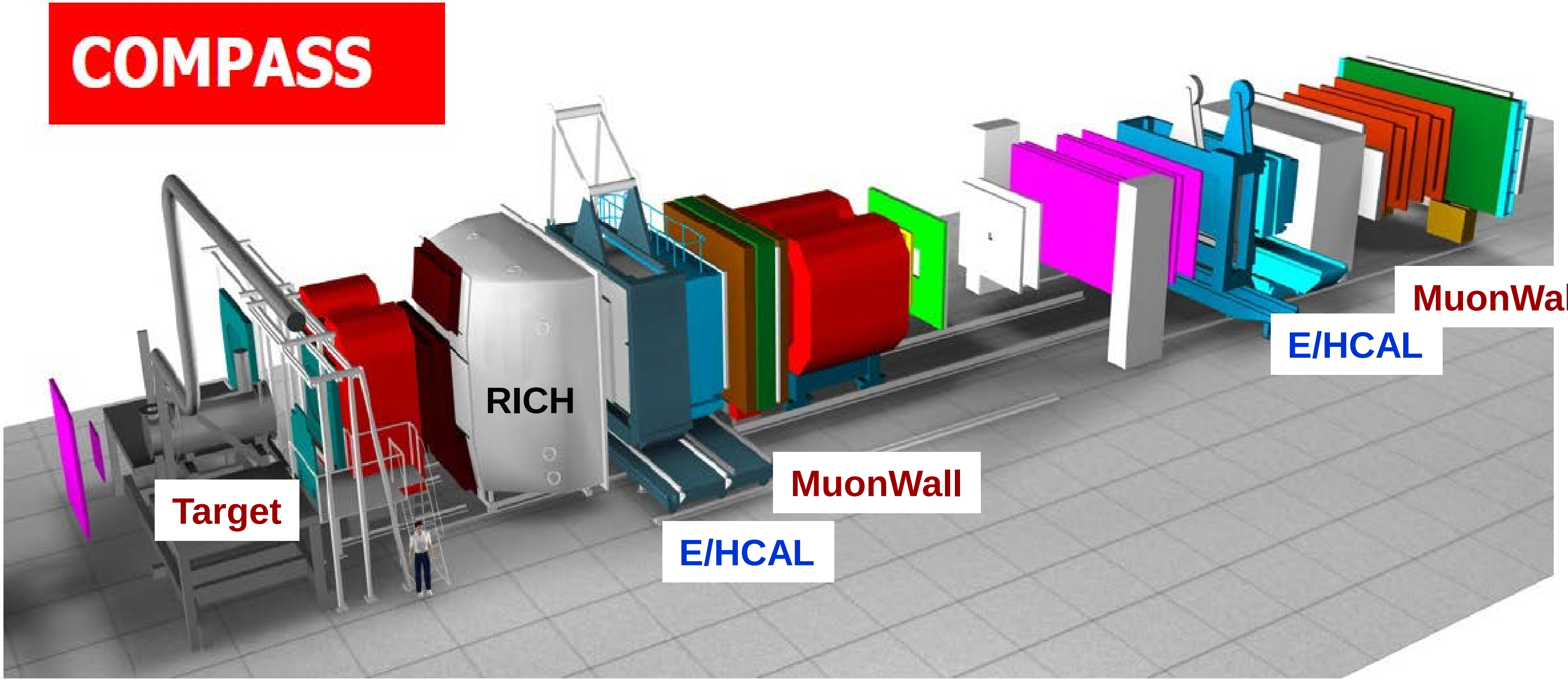
COMPASS

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

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

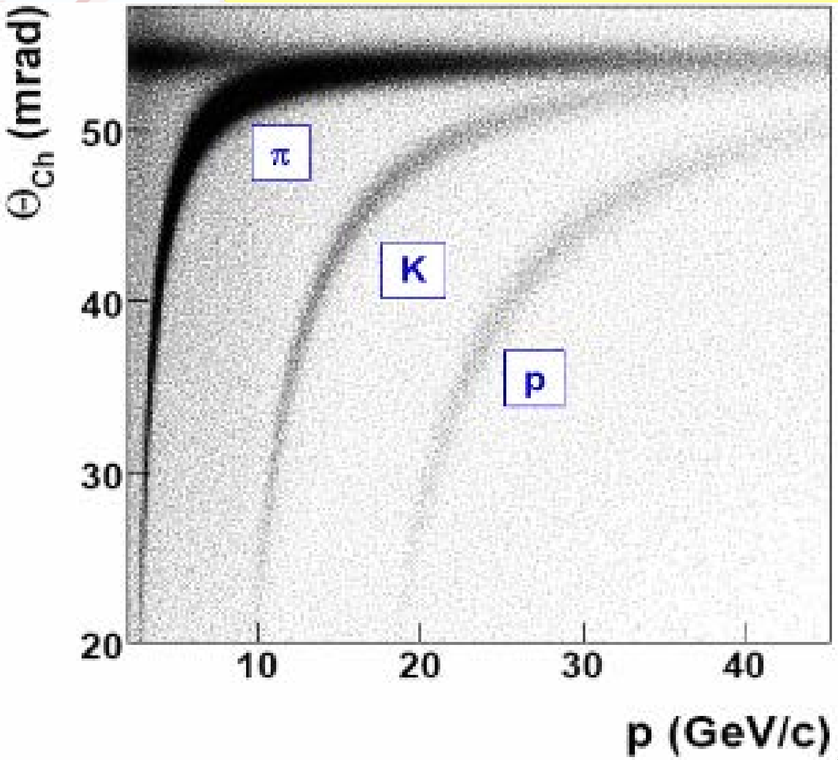


variety of tracking detectors

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

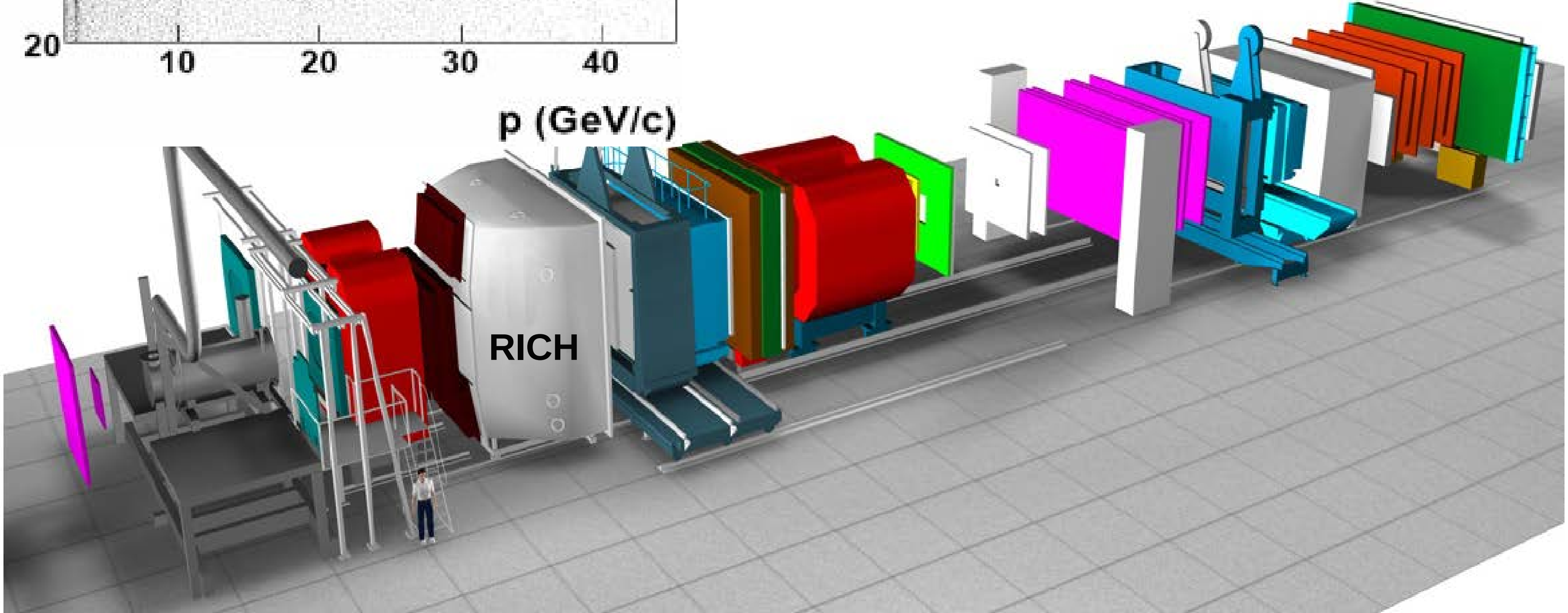
SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*

COMPASS



radiator C_4F_{10}

threshold: π ~2 GeV/c
K ~ 10 GeV/c



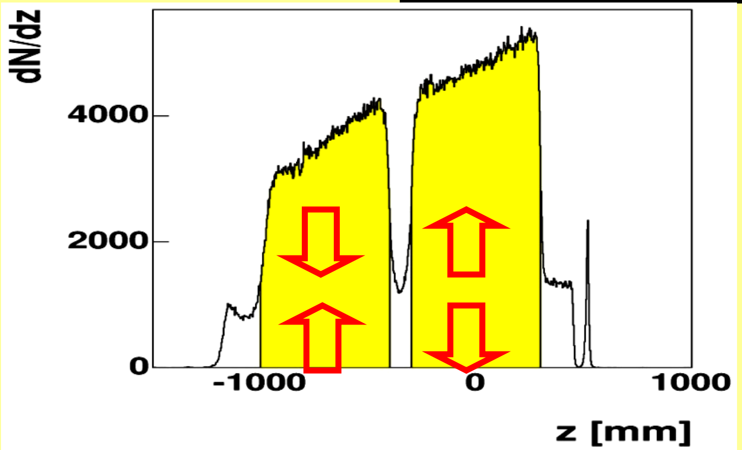
The Target System

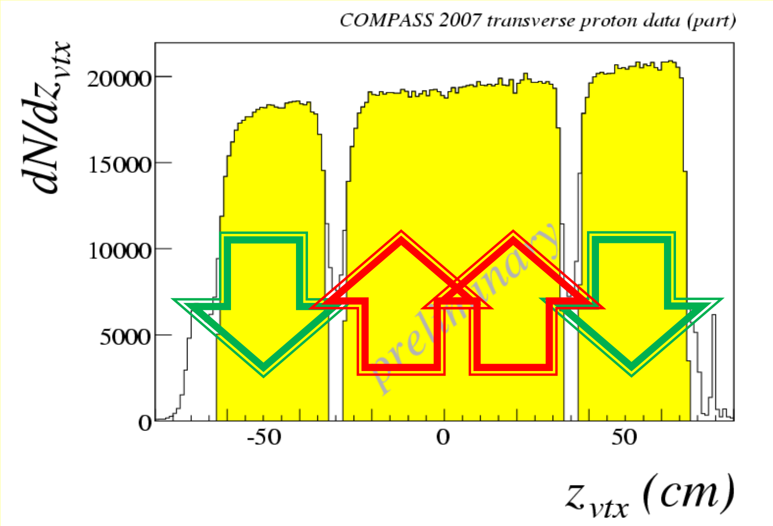
2002-2004: ^{6}LiD (polarised deuteron)
dilution factor f = 0.38
polarization P_T = 50%

two 60 cm long cells with opposite polarization

during data taking:
polarization reversal after ~ 6 h for LP
polarization reversal after ~ 4-5 days for TP

New COMPASS target magnet:
→180 mrad geometrical acceptance
→excellent field homogeneity
To match larger acceptance:
→new microwave cavity
→3 target cells: reduction of false asymmetries
NH3 Target material:
→high polarisation (80-90%)
→very long relaxation time (~ 4000 h)
→magnetic field rotation without polarisation loss





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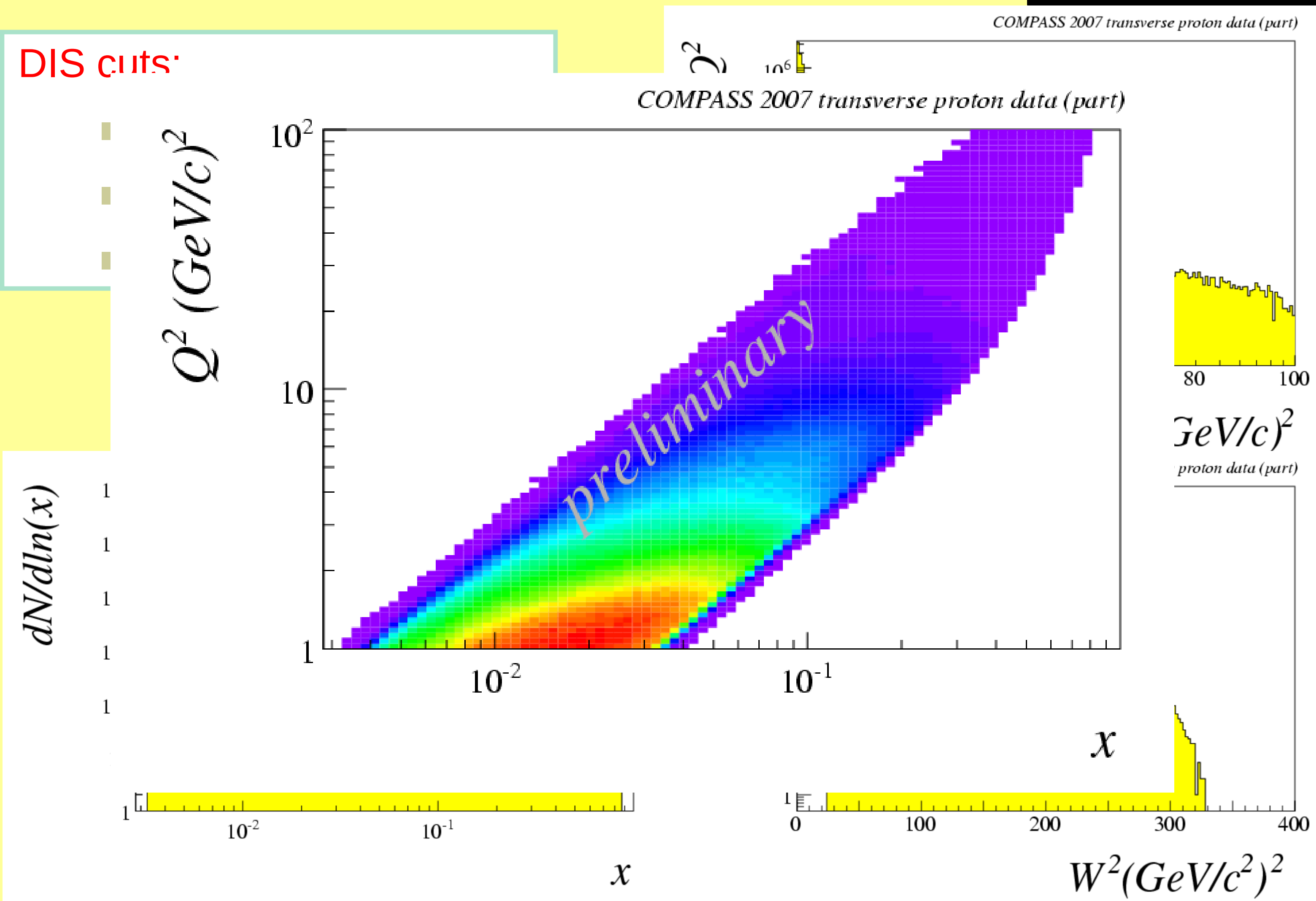
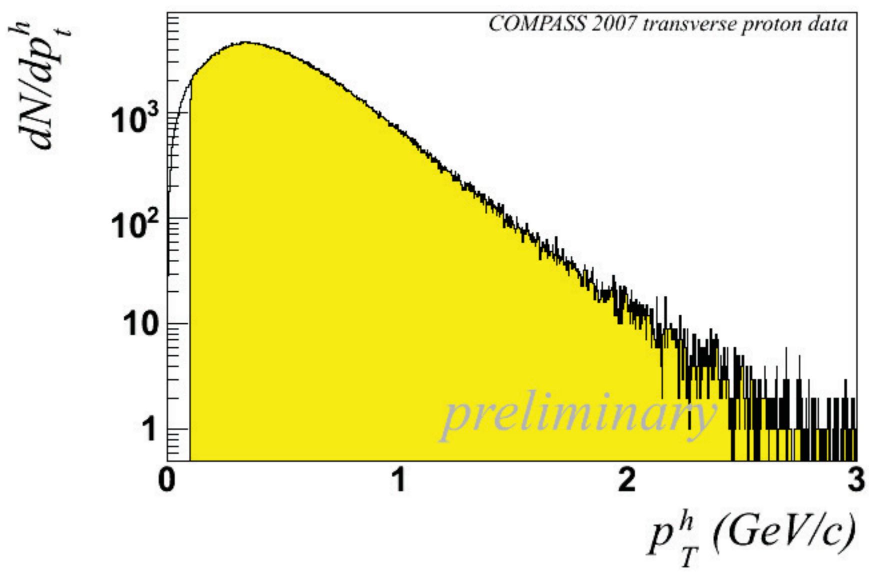
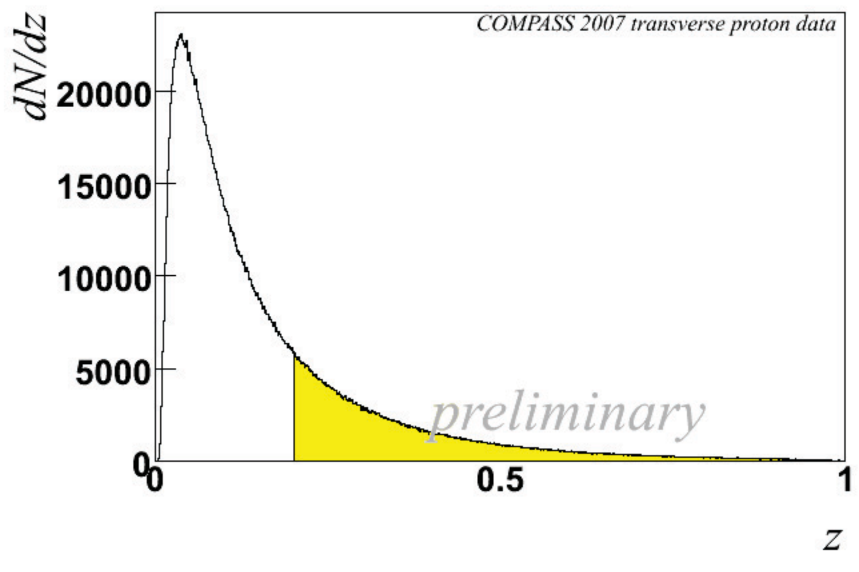
DIS Events

DIS cuts:



Hadrons





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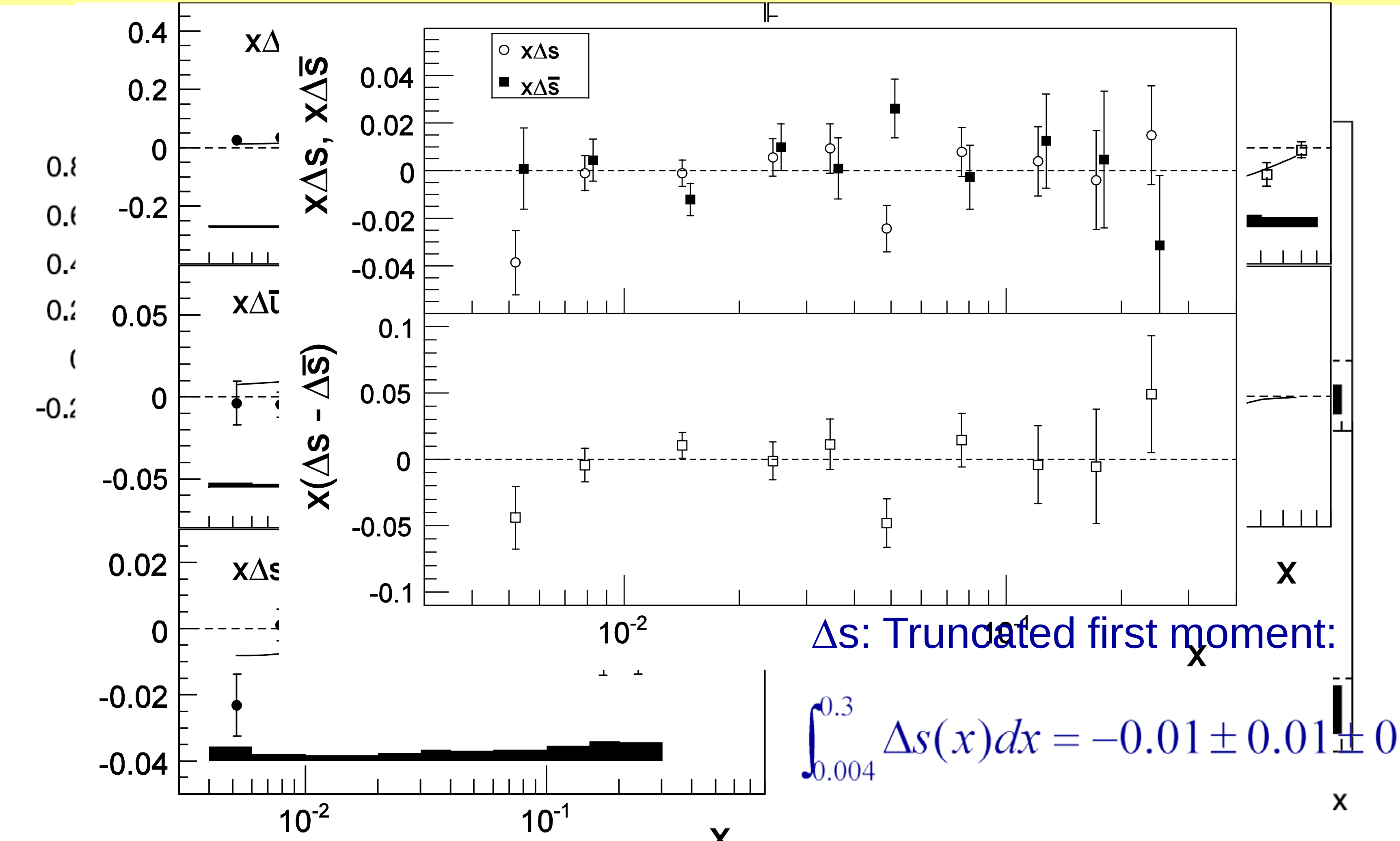
Flavor separation



Δs: Truncated first moment:

$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$

Δs: dependence on the Fragmentation Functions

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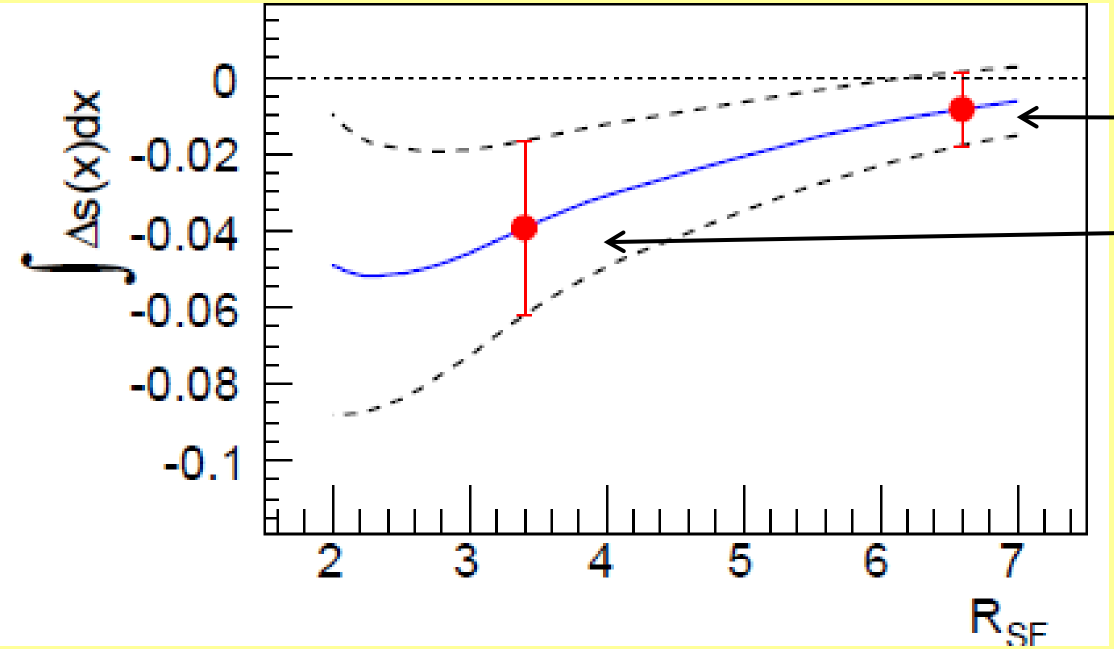


DSS: De Florian, Sassot, Stratman, Phys. Rev. D75, 2007

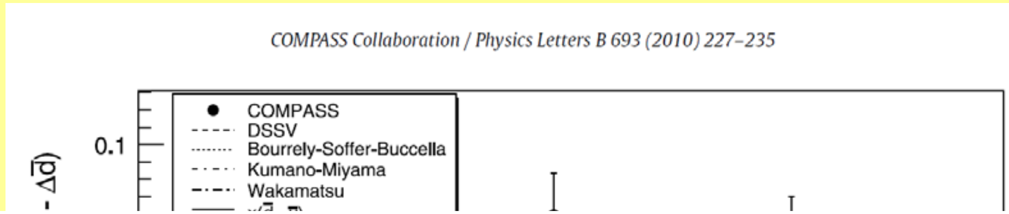
EMC: EMC collaboration, Arneodo et al, Nucl. Phys. B321, 1989

$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$$

First moments: FF from DSS Δs= -0.01 0.01 0.01

FF from EMC Δs= -0.04 0.03 0.01

Flavor symmetry of the polarized sea



Talk of R. Windmolders "Quark-helicity distributions from longitudinal spin asymmetries in μp e μd scattering"

COMPASS $\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d})dx = 0.06 \pm 0.04 \pm 0.02 \quad @ \quad Q^2 = 3\,(GeV/c)^2$

HERMES $\int_{0.023}^{0.6} (\Delta\bar{u} - \Delta\bar{d})dx = 0.048 \pm 0.057 \pm 0.028 \quad @ \quad Q^2 = 2.5\,(GeV/c)^2$

FNAL E866, Phys. Rev. D64 (2001) 052002

unp. E866 $\int_{0}^{1} (\bar{u} - \bar{d})dx = -0.118 \pm 0.012 \quad @ \quad Q^2 = 54\,(GeV/c)^2$

MEASUREMENTS OF THE GLUON POLARIZATION

FOUR LINES OF ATTACK:

1. **Double spin asymmetry of the OPEN CHARM cross-section in high energy µD scattering**

2. **Double spin asymmetry of the HIGH-p_t HADRON PAIRS in high energy µD DIS ($Q^2 > 1$ GeV^2)**

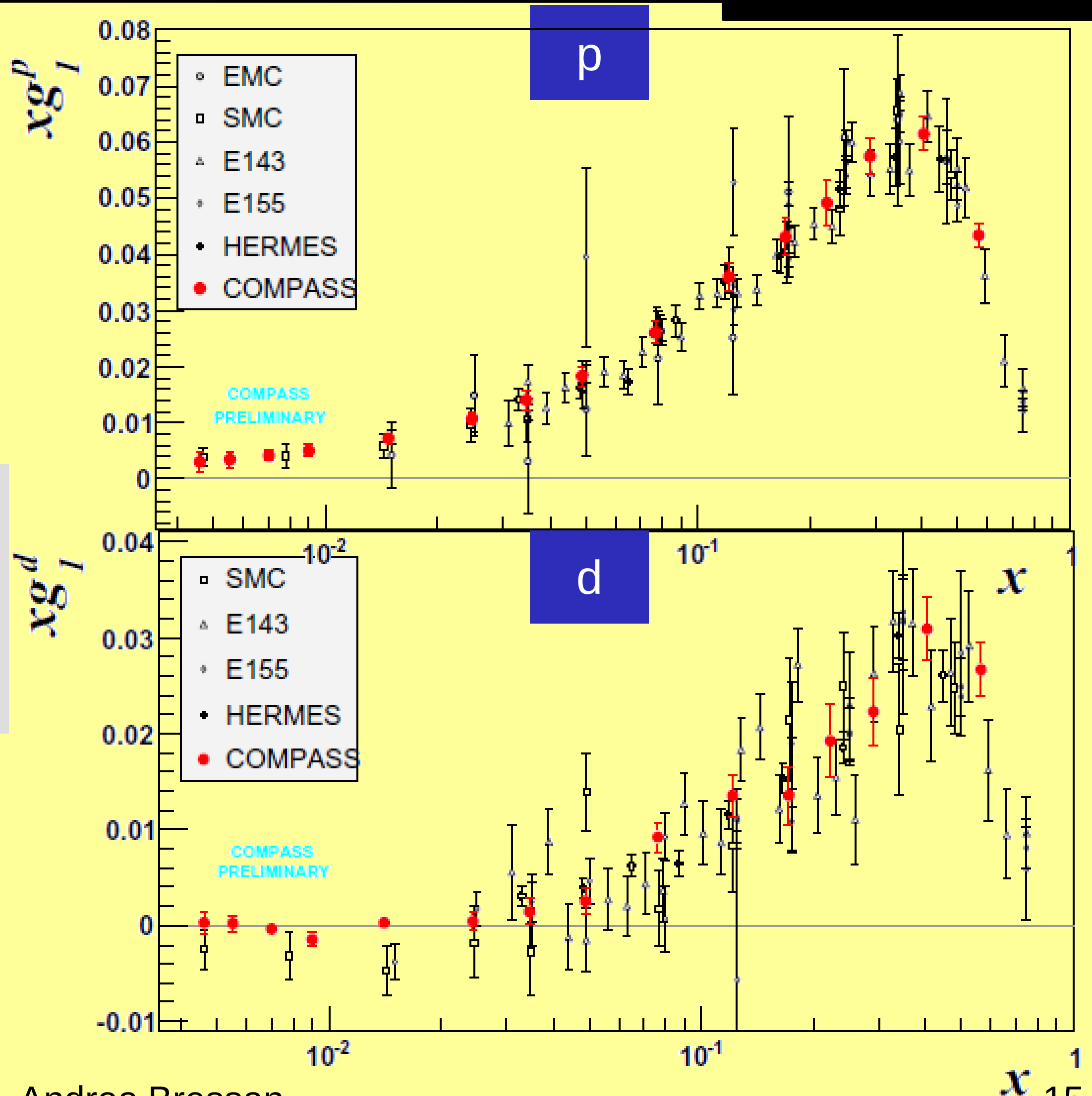
3. **Double spin asymmetry of the high-p_t hadron pairs in high energy µD scattering ($Q^2 < 1$ GeV^2)**

4. **Measurement of g_1 of the deuteron and QCD fit of all the world data**

Structure function $g_1(x,Q^2)$

- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)

- deuteron data:
  - $\Delta\Sigma = 0.33\ \ 0.03\ \ 0.05$
  - $\Delta s+\Delta\bar{s}$ $= -0.08\ \ 0.01\ \ 0.02$



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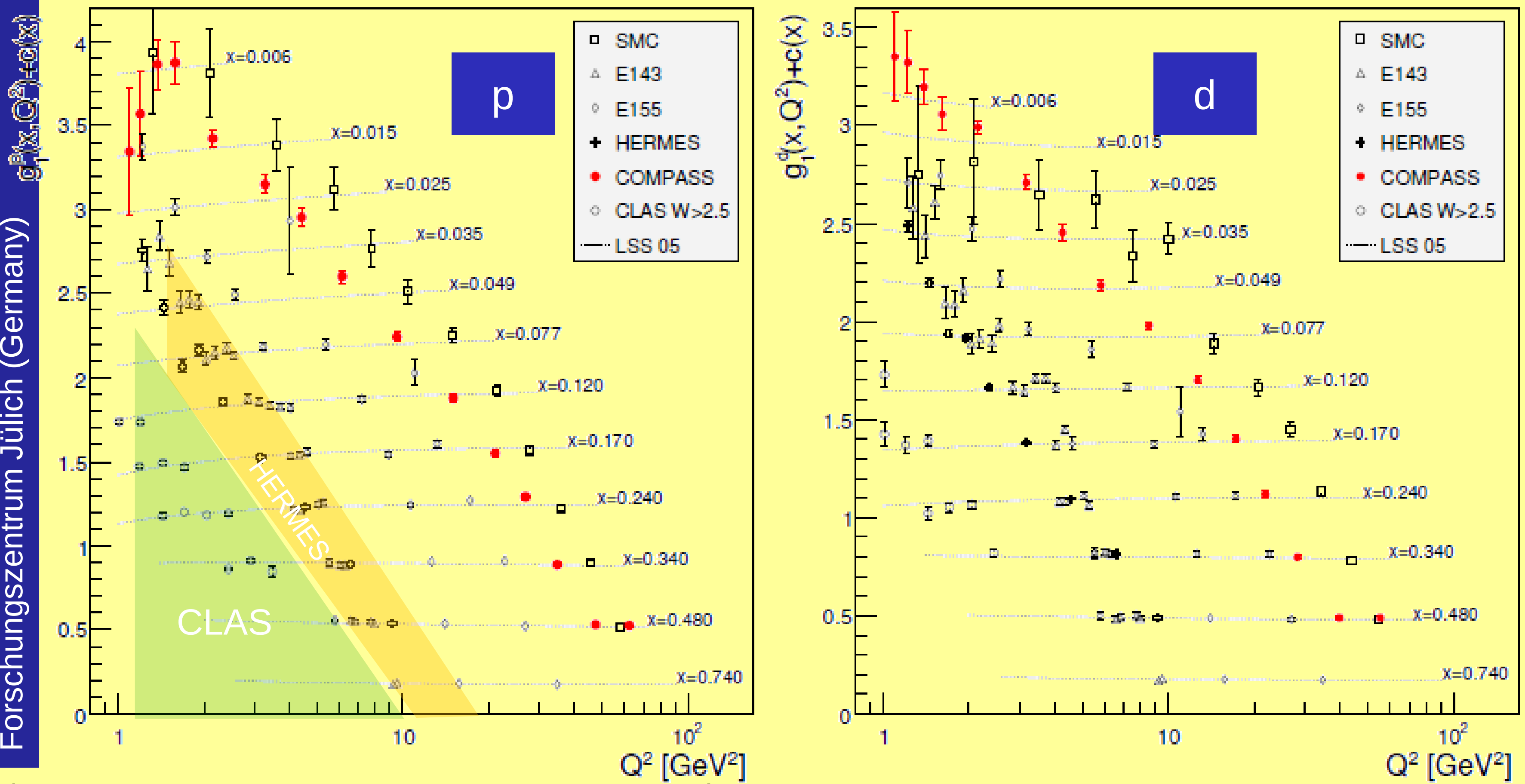
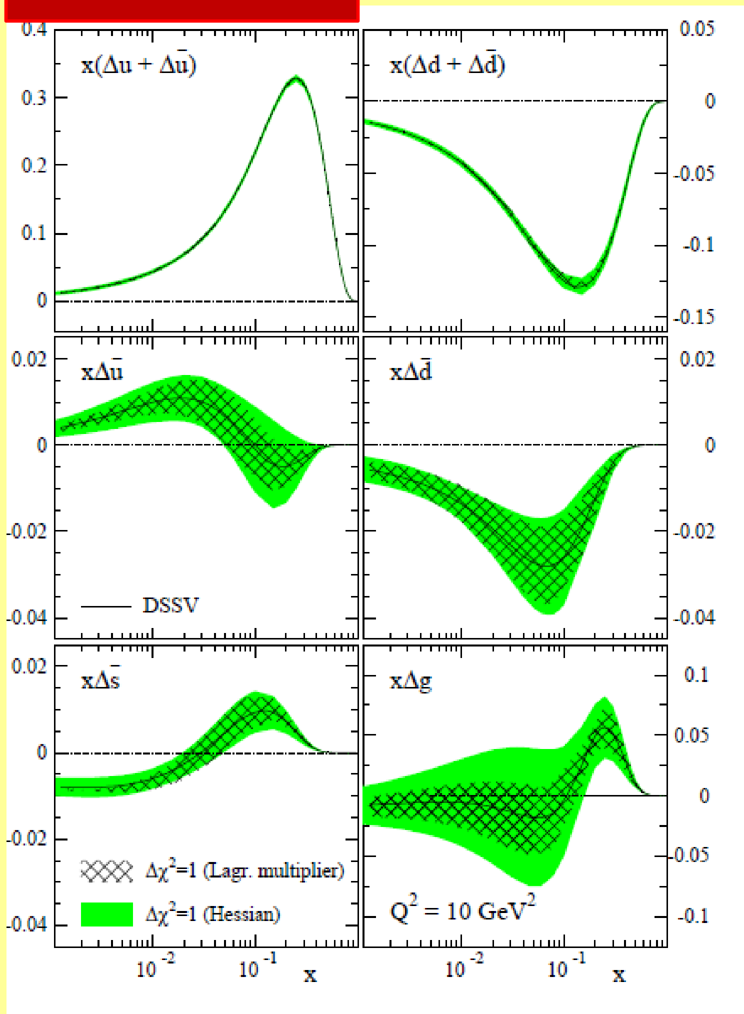
Q^2 evolution and gluon polarization

- Q^2 dependence g_1 data related to gluon polarization (DGLAP)
- Limited kinematic range (c.f. unpol. HERA)

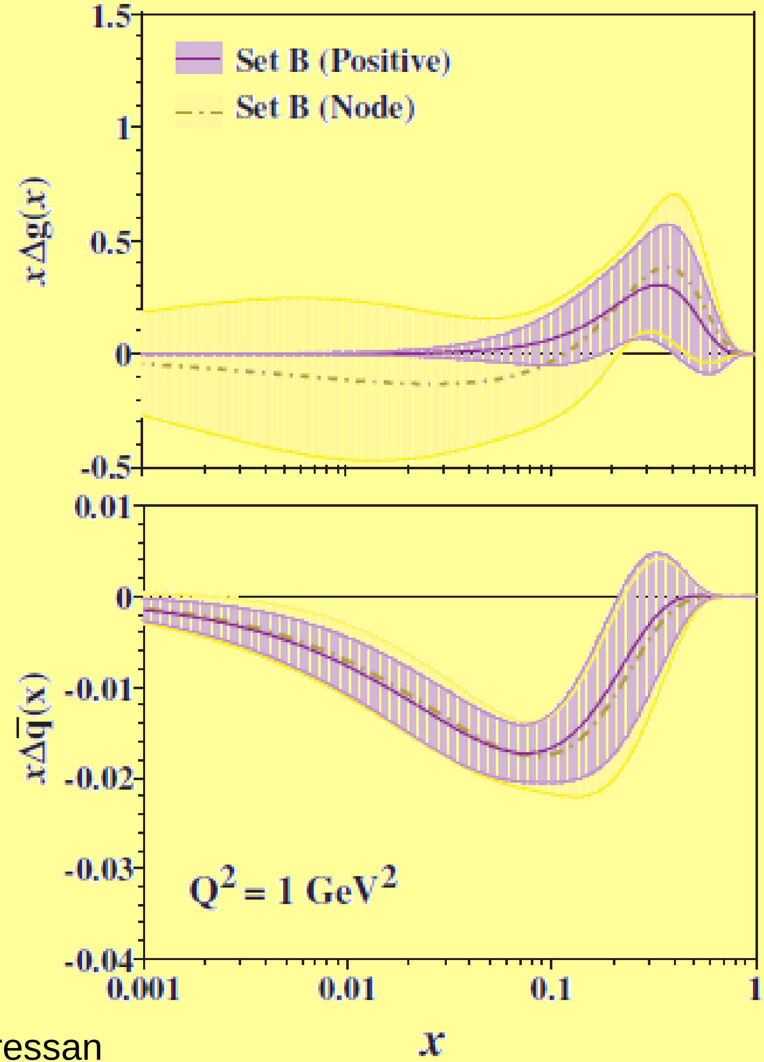


PDFs from global analyses

DSSV

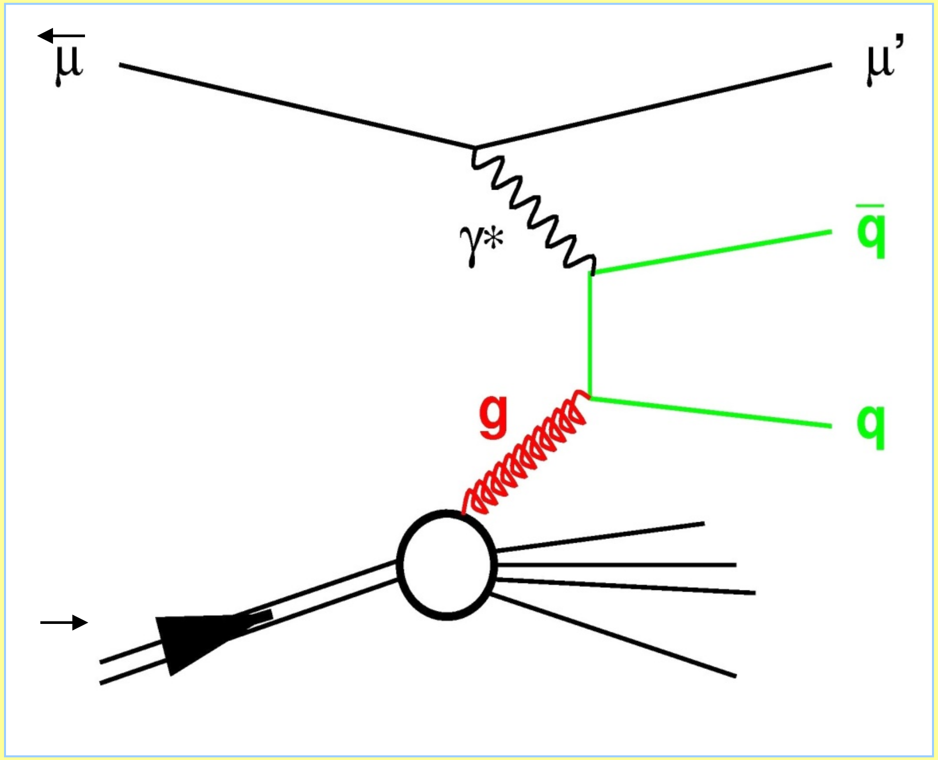


Hirai, Kumano



ΔG/G at COMPASS

Photon Gluon Fusion



q = c **cross section difference in *charmed meson production***

→ ***theory well understood***

→ ***experiment challenging***

q = u,d,s **cross section difference in 2+1 jet production in COMPASS: events with 2 hadrons with high-p_t**

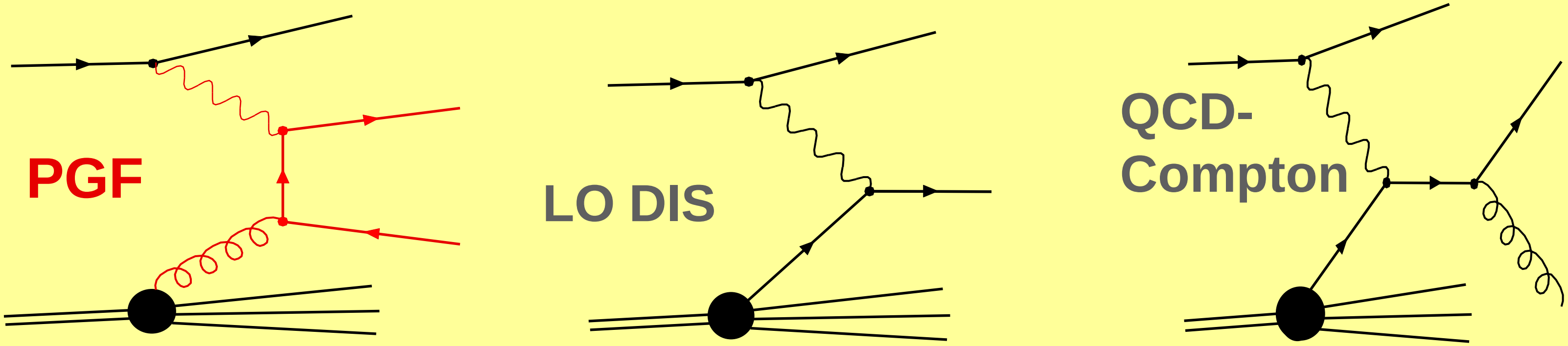
→ ***experiment easy***

→ ***theory more difficult***

ΔG from PGF – high-p_T

$$A_{LL}^{p_T}(x) \approx \frac{\Delta G}{G}(\bar{x}_G)\left\langle \hat{a}_{LL}^{PGF} \right\rangle_G R_{PGF} + A_1^{LO}(\bar{x}_C)\left\langle \hat{a}_{LL}^{C} \right\rangle_C R_C + A_1^{LO}(\bar{x}_{Bj})\left\langle \hat{a}_{LL}^{C} \right\rangle DR_L$$

$$A_{LL}^{inc}(x) \approx \frac{\Delta G}{G}(\bar{x}_G)\left\langle \hat{a}_{LL}^{PGF,inc} \right\rangle_G R_{PGF}^{inc} + A_1^{LO}(\bar{x}_C)\left\langle \hat{a}_{LL}^{C,inc} \right\rangle_C R_C^{inc} + A_1^{LO}(\bar{x}_{Bj})\left\langle \hat{a}_{LL}^{C} \right\rangle DR_L^{inc}$$



- R(fraction of process) and a_{LL}(analysing power) calculated from effective model in Monte-Carlo for all processes
- Parameterized on event basis by Neural Network trained on MC

Results

ΔG/G values in bins of x_G

	$0.041 < x_G < 0.120$	$0.059 < x_G < 0.170$	$0.107 < x_G < 0.269$
$\Delta G/G =$	0.147 ± 0.091	0.079 ± 0.096	0.185 ± 0.165
$\langle x_G \rangle$	$0.07^{+0.05}$	$0.10^{+0.07}$	$0.17^{+0.10}$

Talk of L. Silva "ΔG/G results from COMPASS for $Q^2>1$ $(GeV/c)^2$ using High-p_T hadrons"

$\delta(\Delta G/G_{formula})$	0.035
TOTAL	0.063

FULL DEUTERON DATA i.e. 2002-2006

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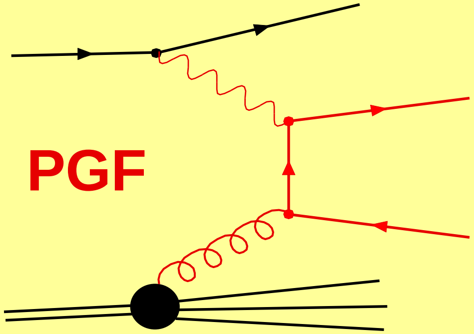
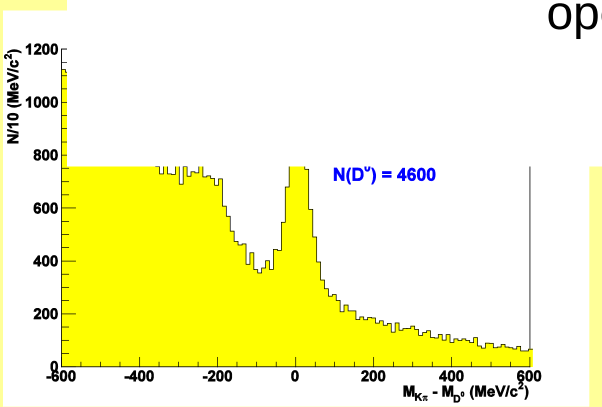
COMPASS

ΔG from PGF–open charm

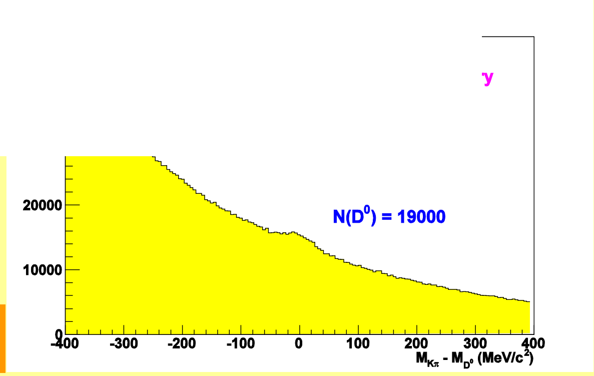


$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

This is LO … NLO analysis ongoing:talk of K. Kurek “NLO results from open-charm D^0 at COMPASS”



$D^0 \rightarrow K\pi \Rightarrow$



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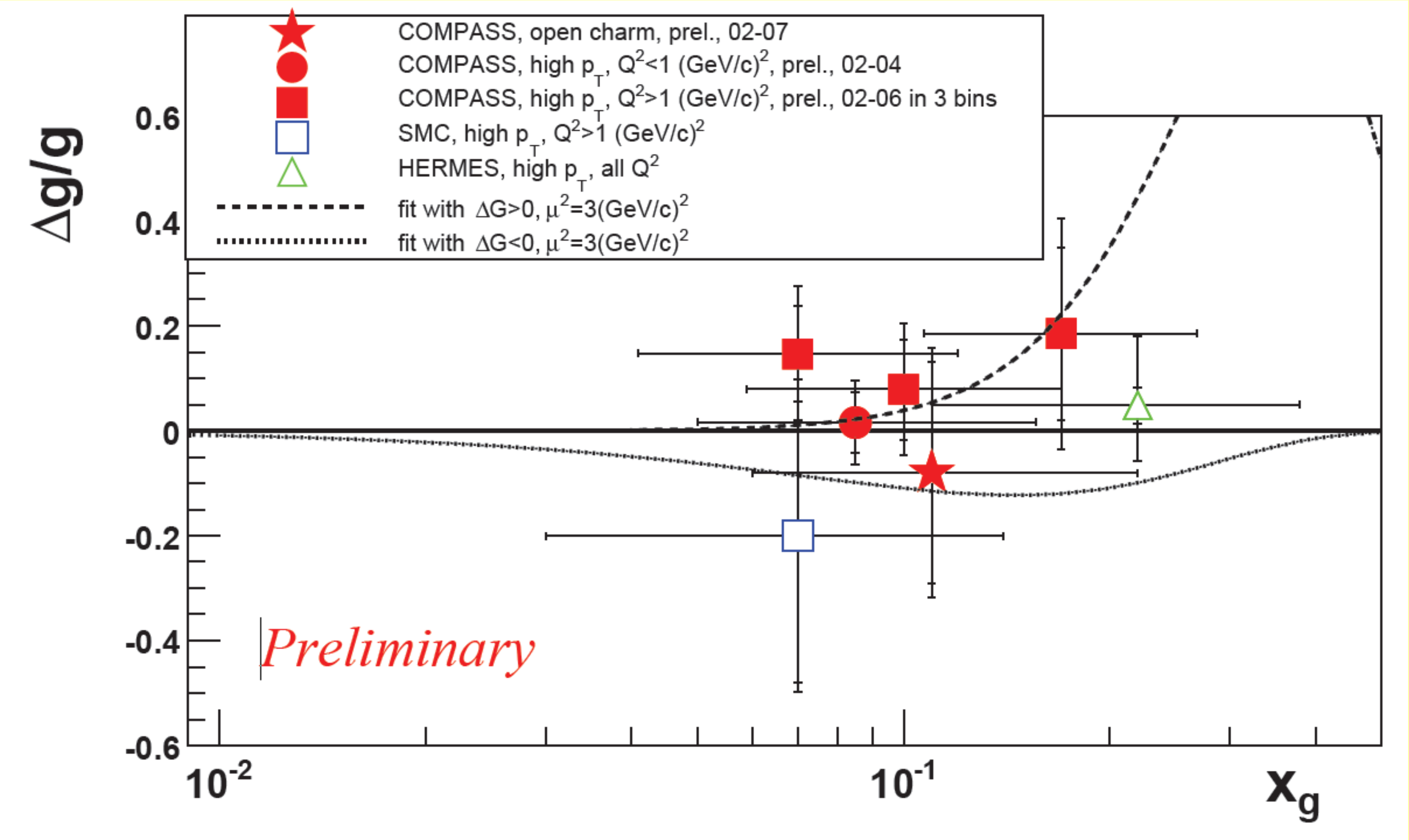
Gluon polarization



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SIDIS LT azimuthal asymmetries

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ \; \ldots$$

$$+ |S_\perp| \Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+ \varepsilon \sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon \sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)} \Big]$$
$$+ |S_\perp|\lambda_e \Big[\sqrt{1-\varepsilon^2}\, \cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos\phi_S\, F_{LT}^{\cos\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\, \cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)} \Big] \Big\},$$

Sivers

Collins

6 further Modulations

All possible 8 azimuthal asymmetries extracted at once.

From **A. Bacchetta** et al., **JHEP 0702:093,2007**. e-Print: **hep-ph/0611265**

Nucleon Structure

eight leading twist PDFs shows up,
when taking into account the quark intrinsic transverse momentum k_T

quark polarization \ nucleon polarization	U	L	T
U	f_1 number density		$f_{1T}^{\perp}$ Sivers (T)
L		g_1 helicity	g_{1T} Worm-gear 2
T	$h_1^{\perp}$ Boer Mulders (TC)	$h_{1L}^{\perp}$ Worm-gear1(C)	h_1 Transversity (C); $h_{1T}^{\perp}$ Pretzelosity(C)

COMPASS

spin

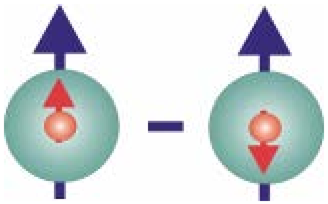
Transversity DF

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

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



$q = u_v, d_v, q_{sea}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

Properties:

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound……………..$2|\Delta_T q| \leq q + \Delta q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………$\Delta_T q \equiv \int dx\ \Delta_T q(x)$
- sum rule for transverse spin
  in Parton Model framework…………$\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$
  Bakker, Leader, Trueman, PRD 70 (04)
- it is related to GPD's
- is chiral-odd: decouples from inclusive DIS

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↑→Λ**

all explored in COMPASS

Collins asymmetry

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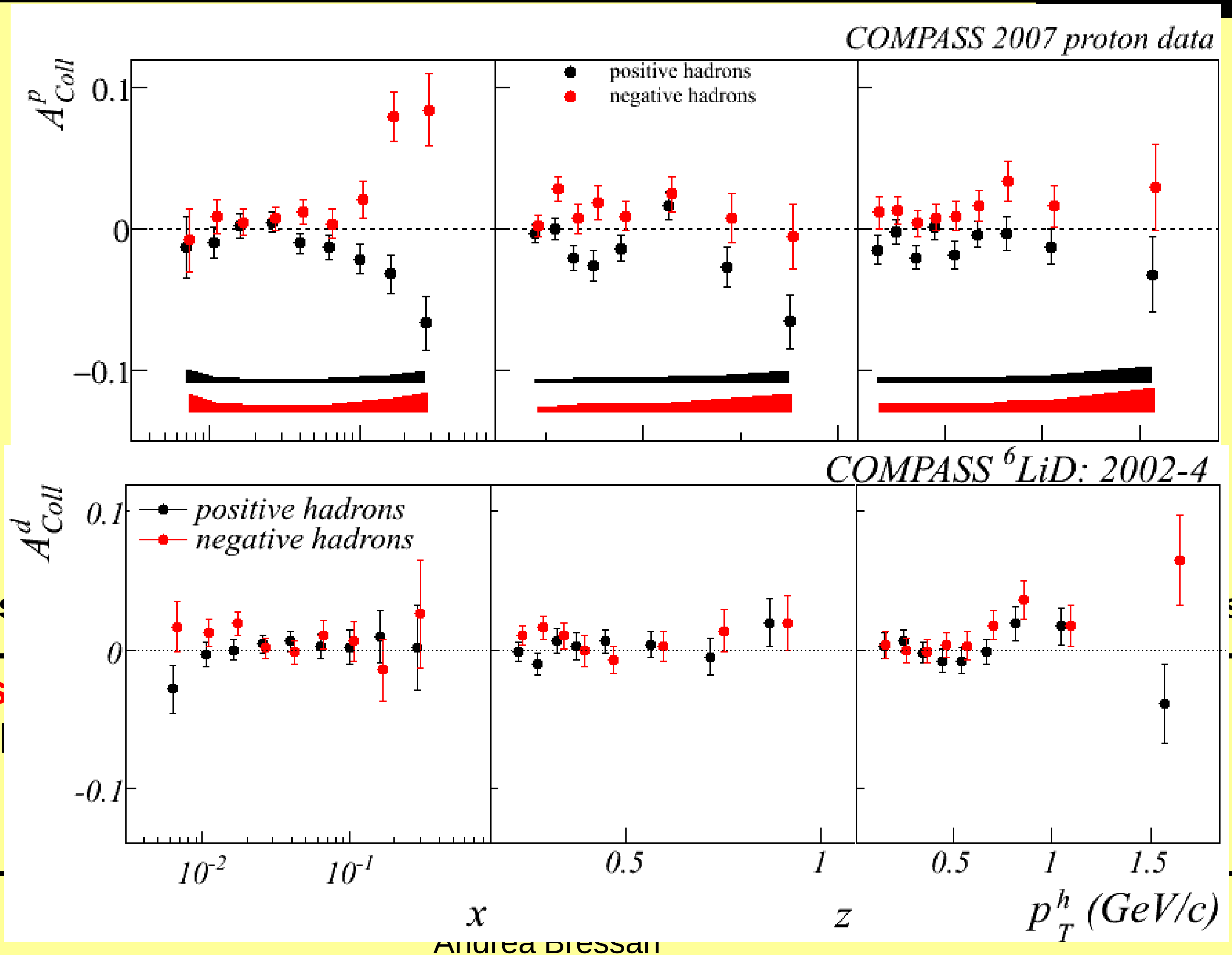


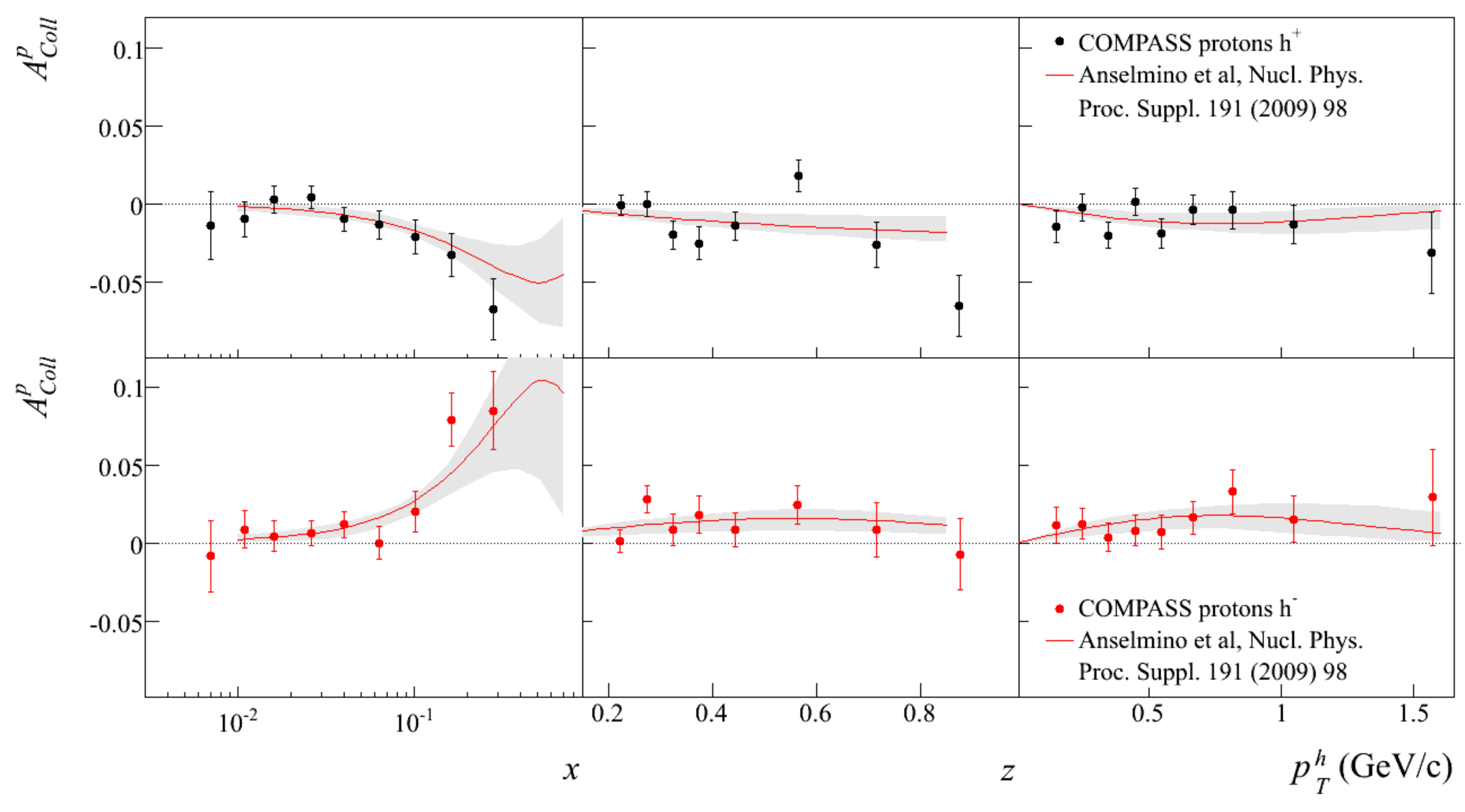
sy… …s

at s…

in th…

Compass proton data

comparison with M. Anselmino et al. predictions



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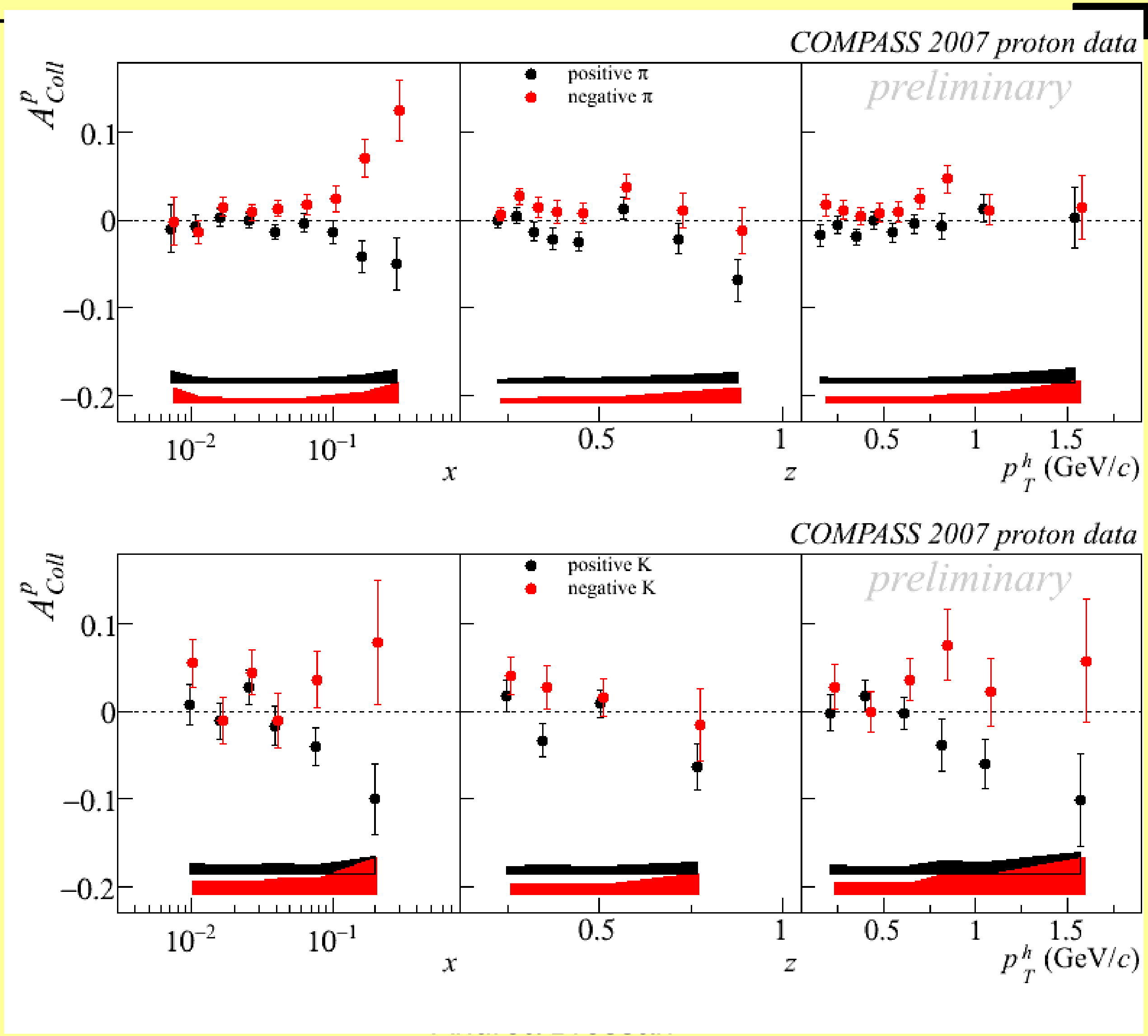
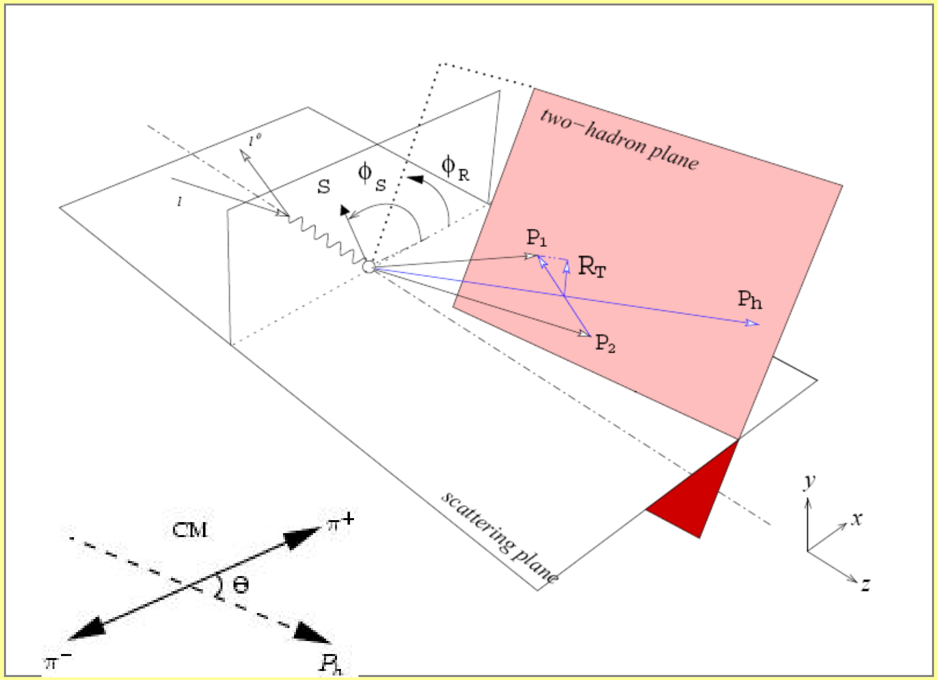
Collins asymmetry ID



COMPASS

Two Hadron Asymmetries

spin



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**

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

Interference Fragmentation Function

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

ϕ_{RS} defined by:

$R = (z_1 p_2 - z_2 p_1)/(z_1 + z_2)$

(X. Artru, hep-ph/0207309)

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

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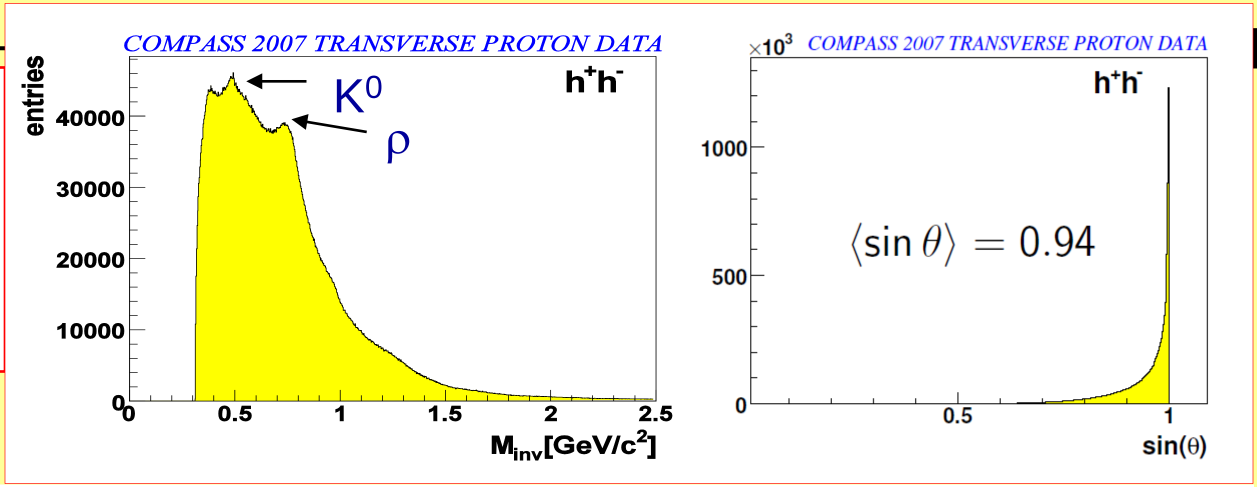
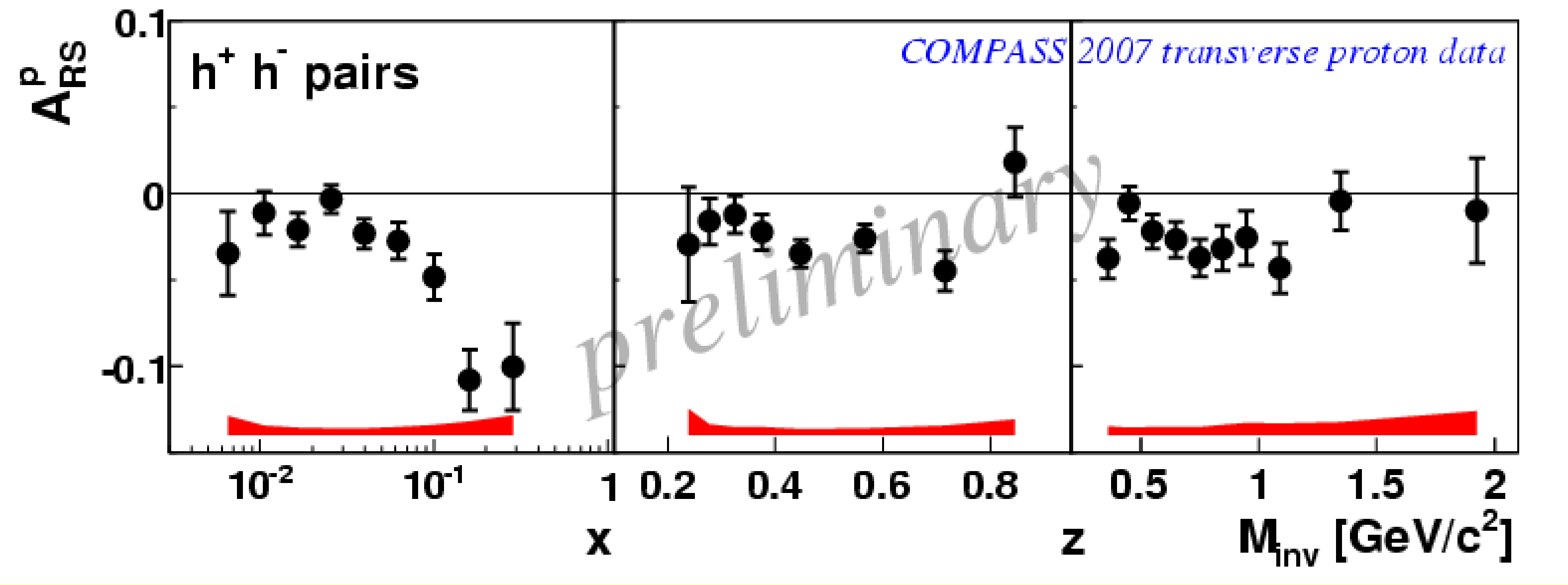
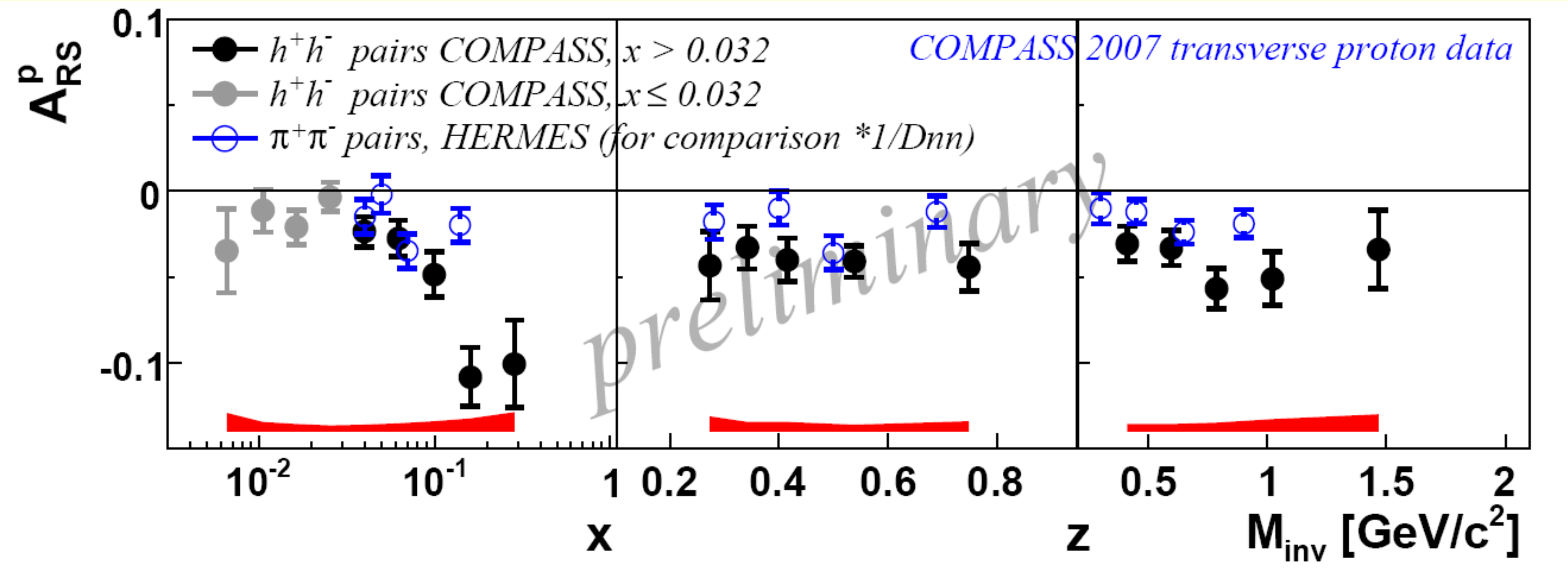
2H Asymmetries – Proton

- $x_F > 0.1$
- $z_{1,2} > 0.1$
- $Z = z_1 + z_2 < 0.9$
- $R_T > 0.07$ GeV/c





2H Asymmetries – Proton



COMPARISON WITH HERMES

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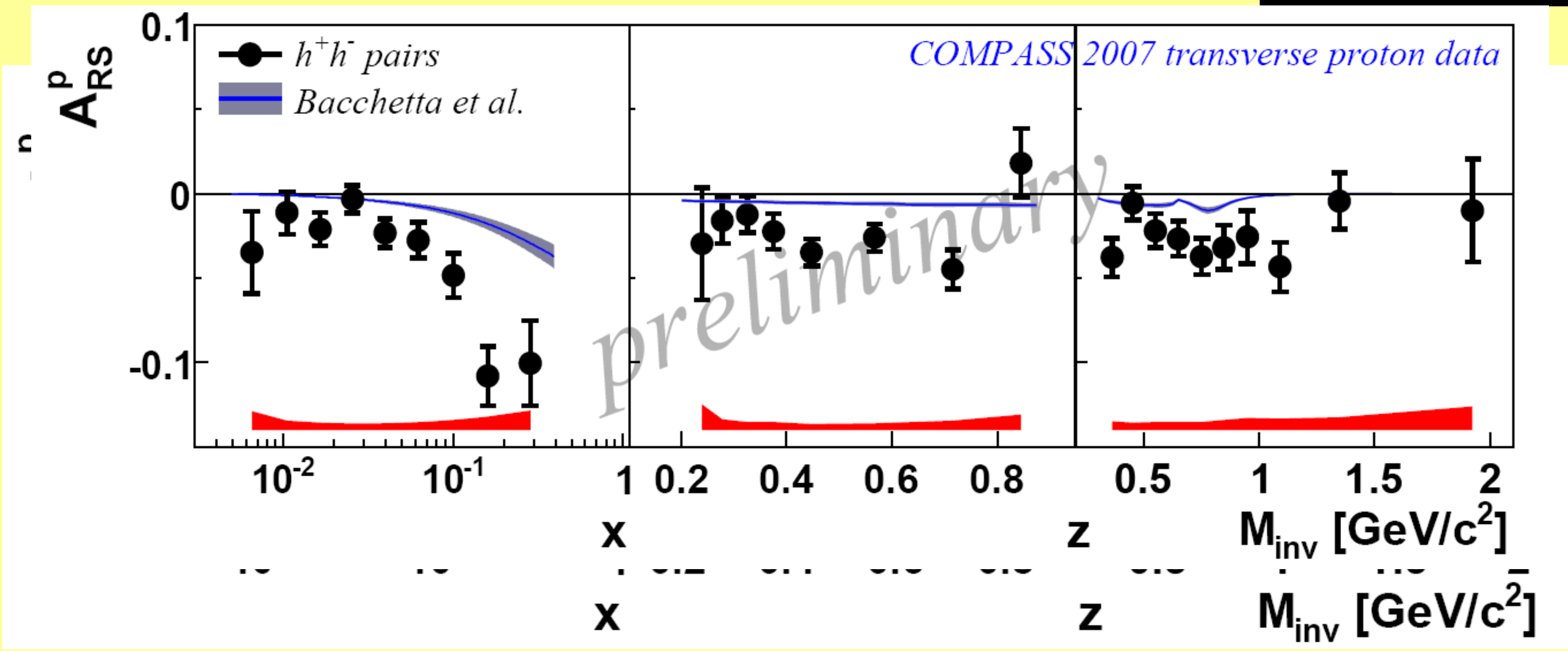
2H Asymmetries – Proton



Prediction by Bacchetta, Radici, hep-ph/0608037

Calculation by Ma et al., TEPSPIN09, Armenia, June 2009.

(Interference Fragmentation function scaled down to fit HERMES data)

Recent BELLE measurement of the IFF

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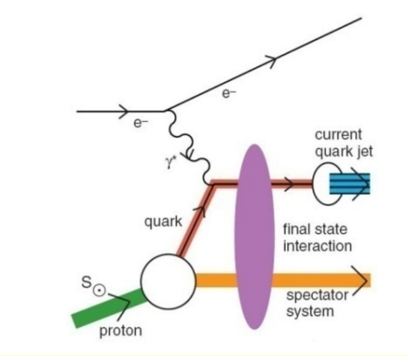
SIVERS Mechanism

- The Sivers DF $\Delta_0^T q$ is probably the most famous between TMDs…
- gives a measure of the correlation between the transverse momentum and the transverse spin
- Requires final/initial state interactions of the struck quark with the spectator system and the interference between different helicity Fock states to survive time-reversal invariance
- Time-reversal invariance implies:

$$\Delta_0^T q(x,k_T^2)_{SIDIS} = -\Delta_0^T q(x,k_T^2)_{DY}$$

…to be checked



- In SIDIS:

$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left\{ 1 \pm A_S^h \cdot \sin\Phi_S \right\}$$

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

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Sivers – proton

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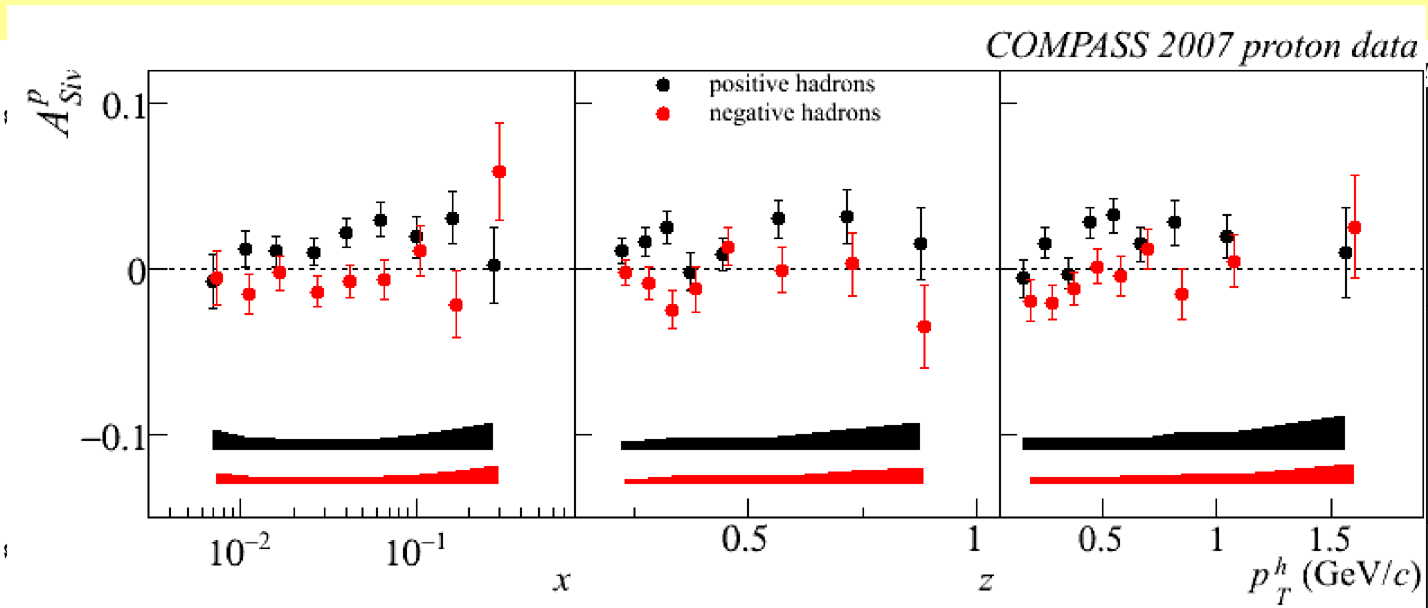
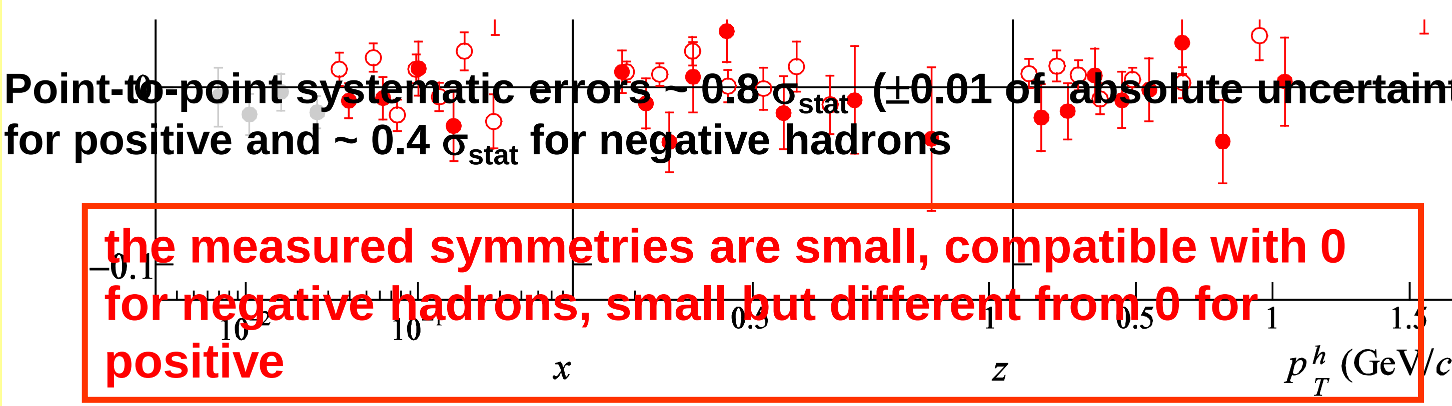


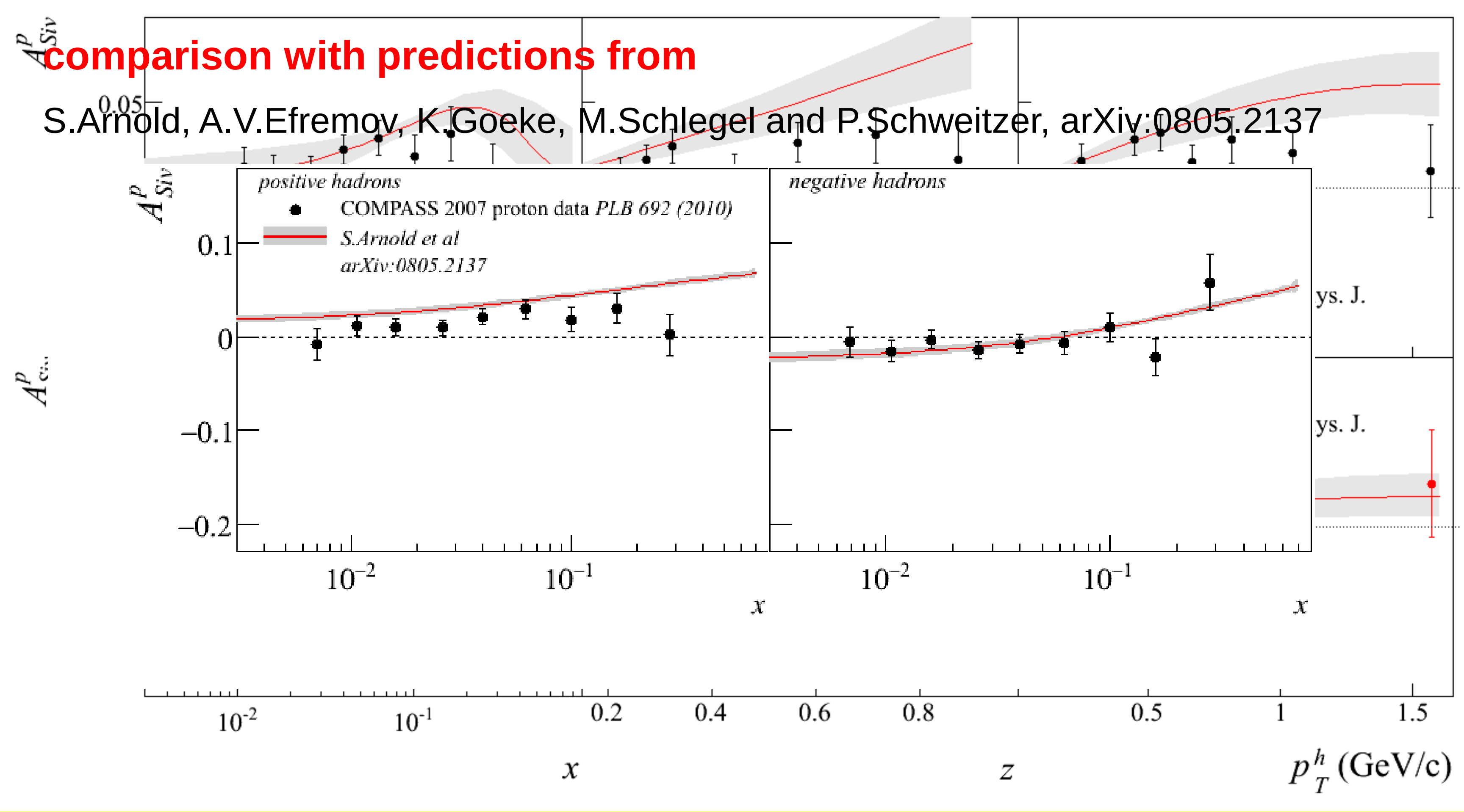


Point-to-point systematic errors ~ 0.8 σ_{stat} (±0.01 of absolute uncertainty) for positive and ~ 0.4 σ_{stat} for negative hadrons

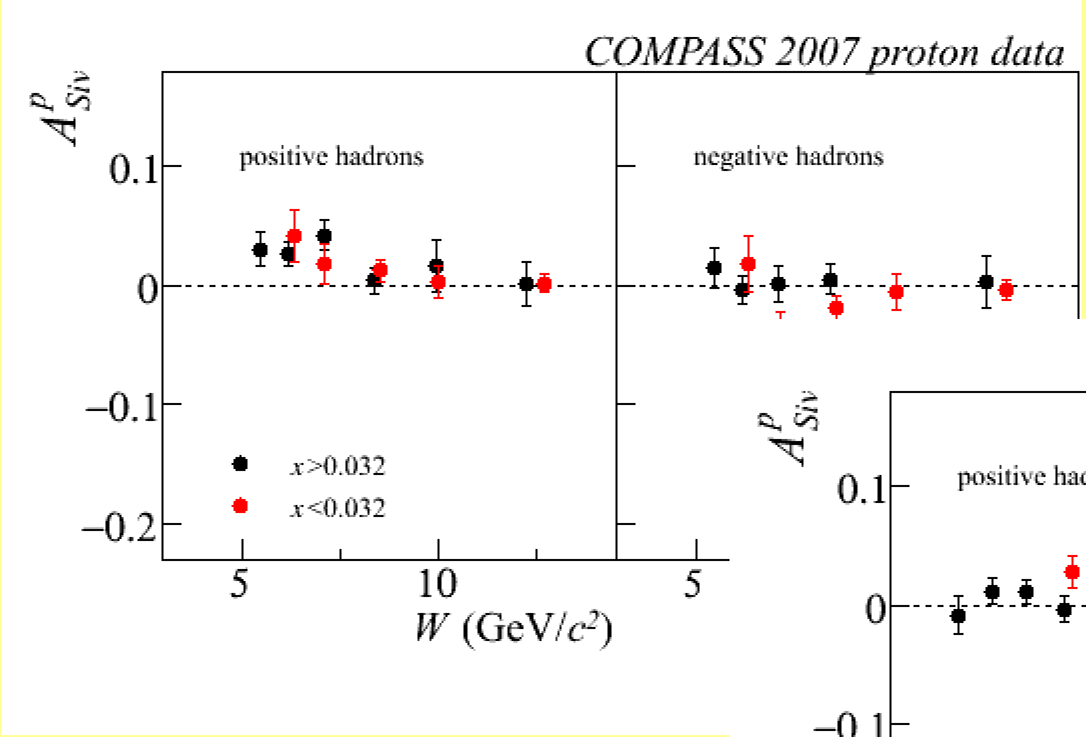
the measured symmetries are small, compatible with 0 for negative hadrons, small but different from 0 for positive

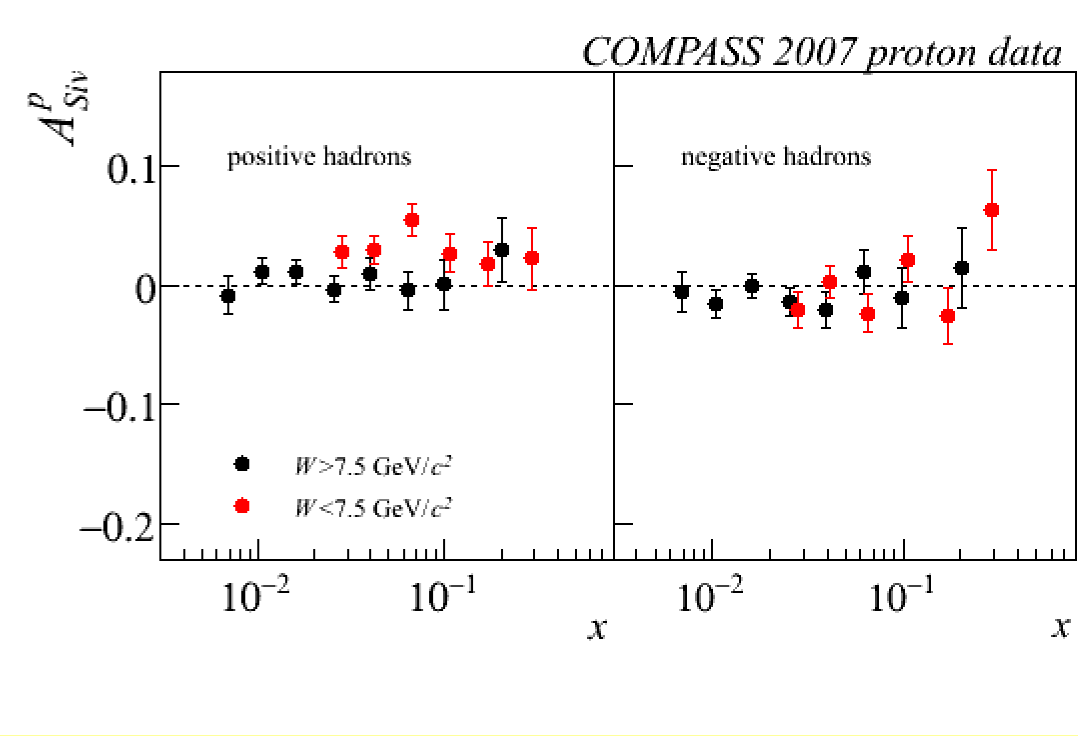
Sivers asymmetry– proton data

comparison with the predictions from M. Anselmino et al.

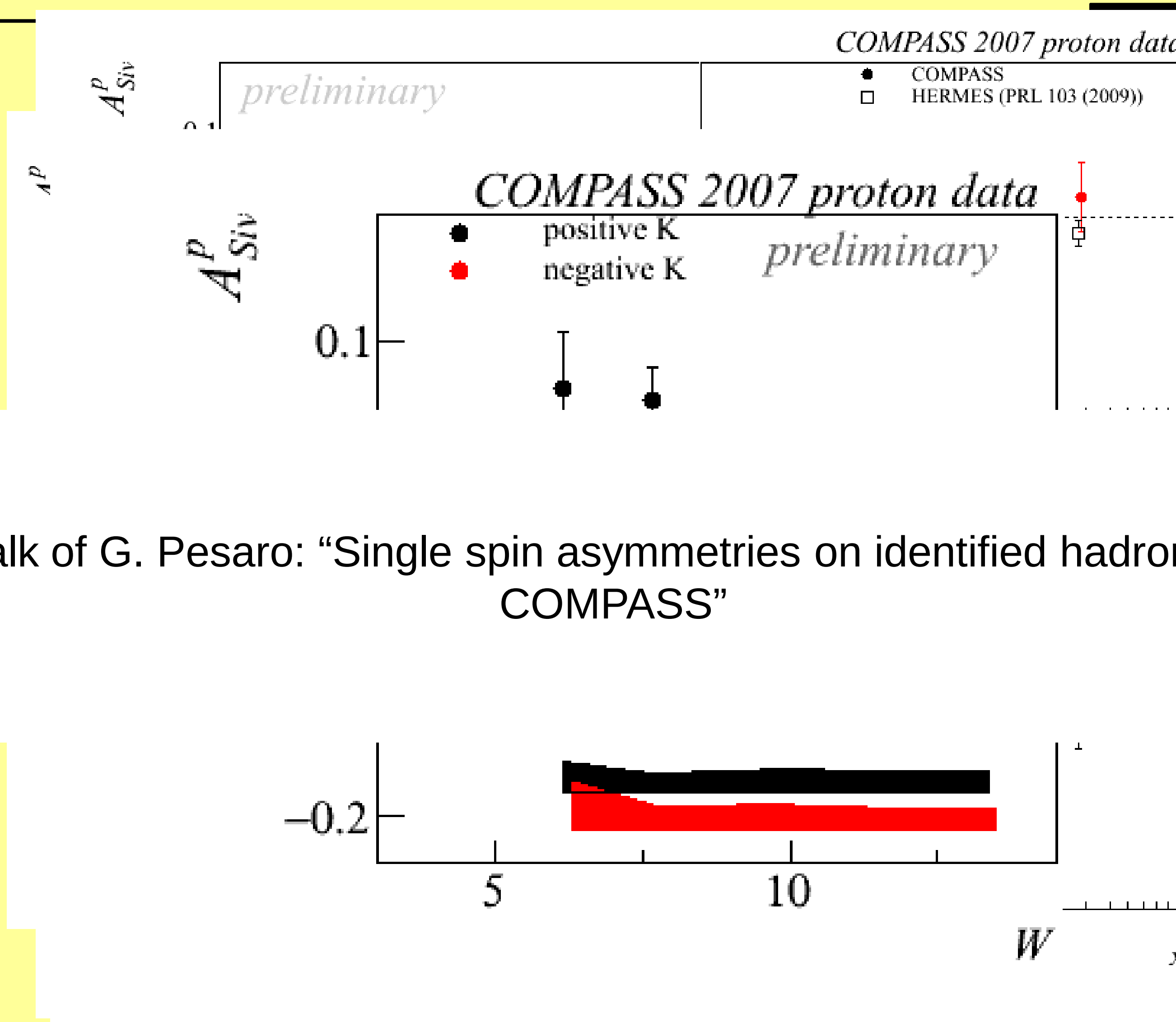


Sivers asymmetry – W ?





Sivers – proton ID



Talk of G. Pesaro: “Single spin asymmetries on identified hadrons at COMPASS”

COMPASS

Other SSAs - Proton/D data

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

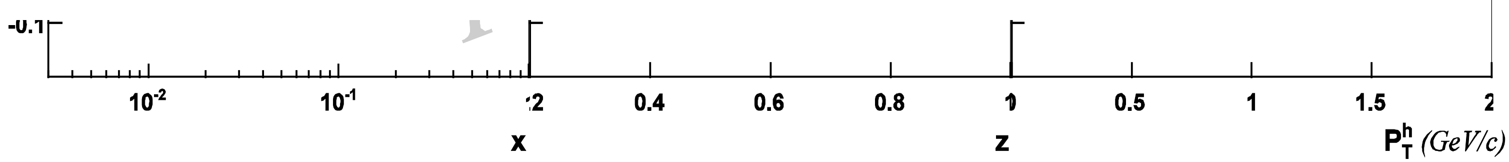
$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

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

"pretzelosity" ⊗ Collins FF

$A_{UT}^{\sin}$

Talk of B. Parsamyan "Transverse spin dependent azimuthal asymmetries from 2007 proton data"



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Unpolarised target SIDIS cross-section

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

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

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

$$F_{LU}^{\sin\phi_h}=\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xe\,H_1^{\perp}+\frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{h}\cdot p_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Cahn effect

Cahn effect + Boer-Mulders DF

Boer-Mulders DF

$$F_{UU}^{\cos\phi_h}=\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xh\,H_1^{\perp}+\frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\right)-\frac{\hat{h}\cdot p_T}{M}\left(xf^{\perp}D_1+\frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

he

nucleon spin in an unpolarised

cleon

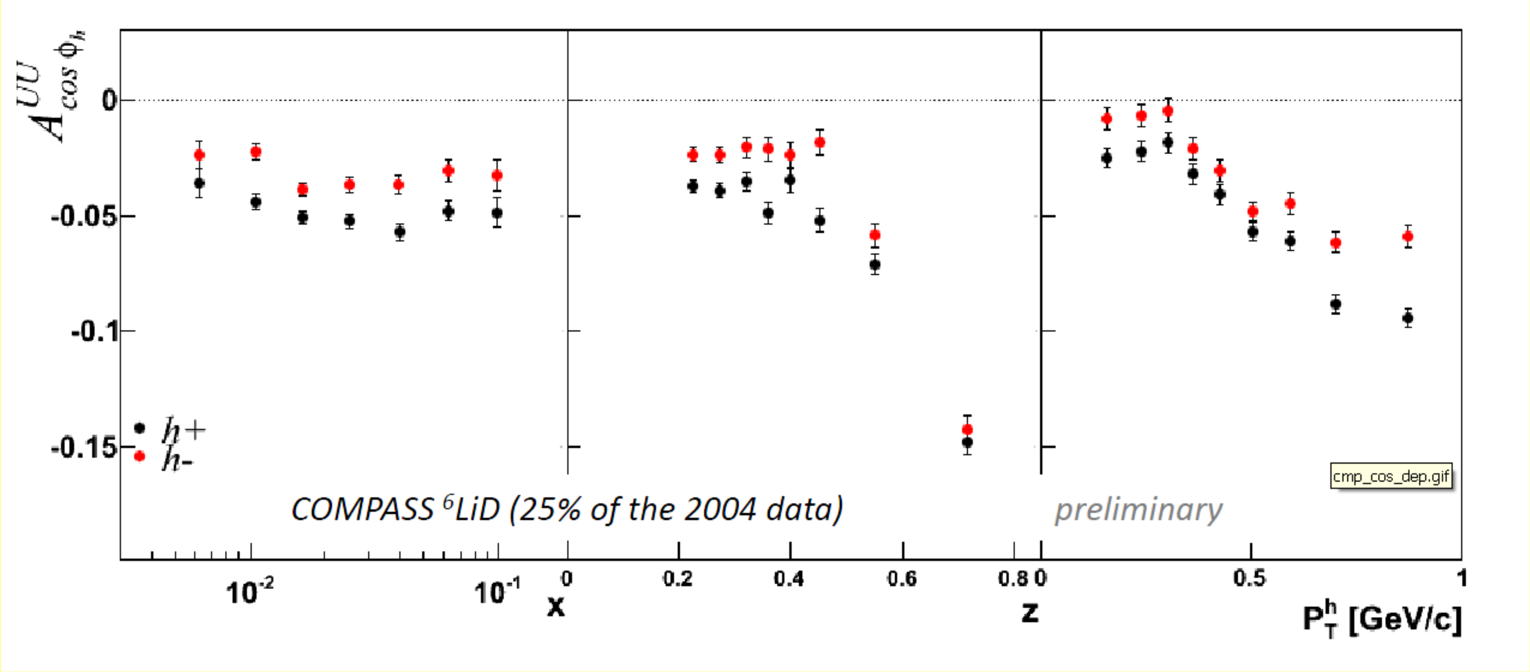
$$F_{UU}^{\cos 2\phi_h}=\mathcal{C}\left[-\frac{2\left(\hat{h}\cdot k_T\right)\left(\hat{h}\cdot p_T\right)-k_T\cdot p_T}{M\,M_h}\,h_1^{\perp}H_1^{\perp}\right]$$

Boer- Mulders x Collins FF

+ Cahn effect

and R. Sassot. PR D71

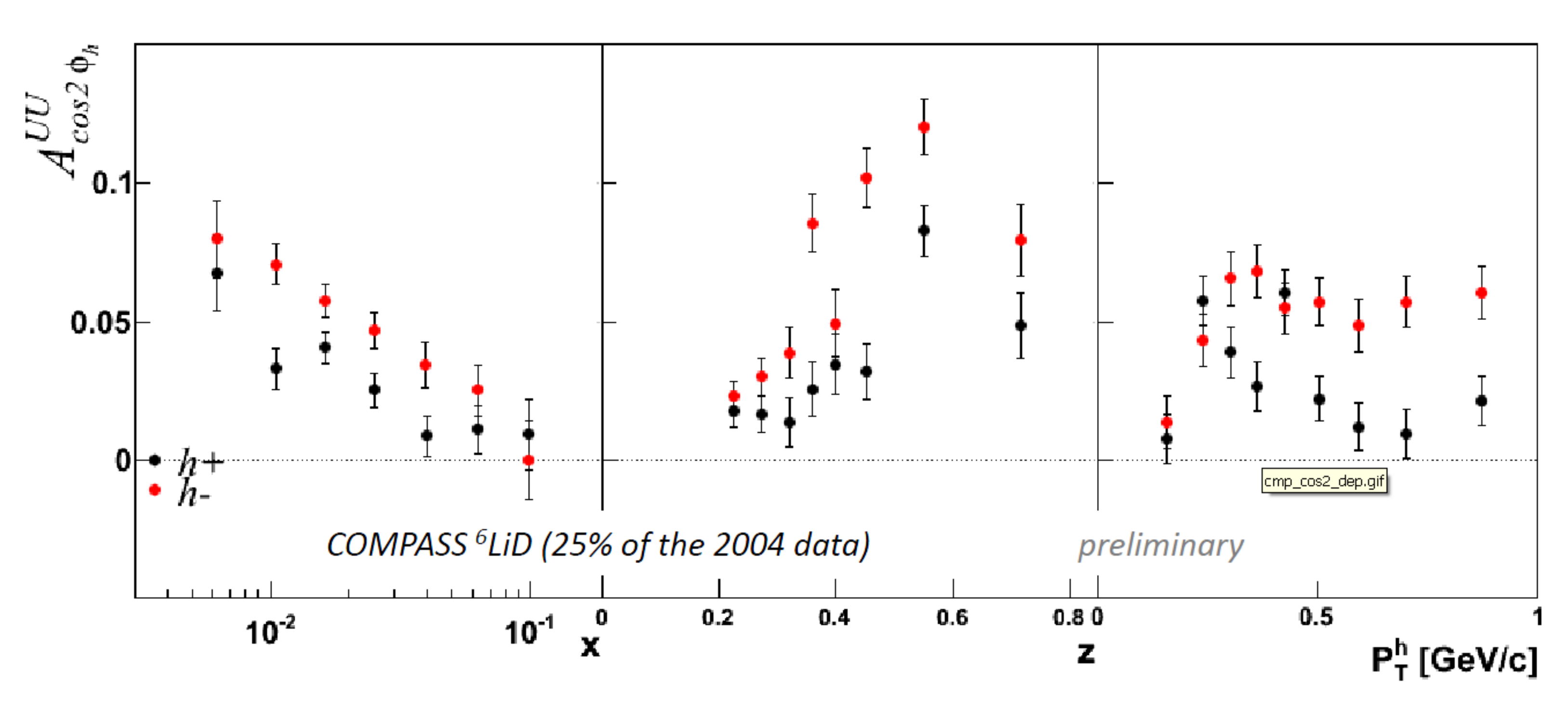
Results: cosϕ modulation



Sistematic error ~ 2x Statistical Error
Positive and negative hadrons differ:

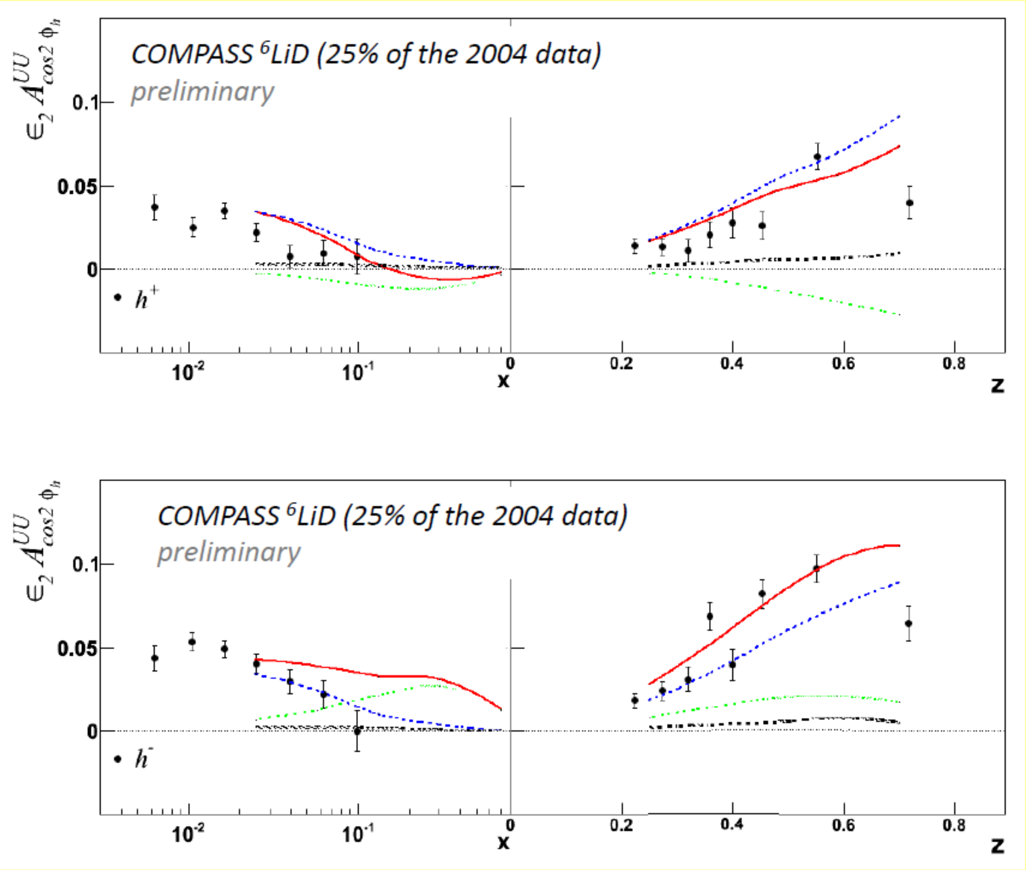
- k_T different for the u and d quarks
- non zero Boer-Mulders PDF

cos 2ϕ modulation



There is a difference between +h and –h asymmetries on cosϕ/cos2ϕ
⇒ Boer-Mulders

Predictions



total		Boer Mulders	
Cahn		pQCD	

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

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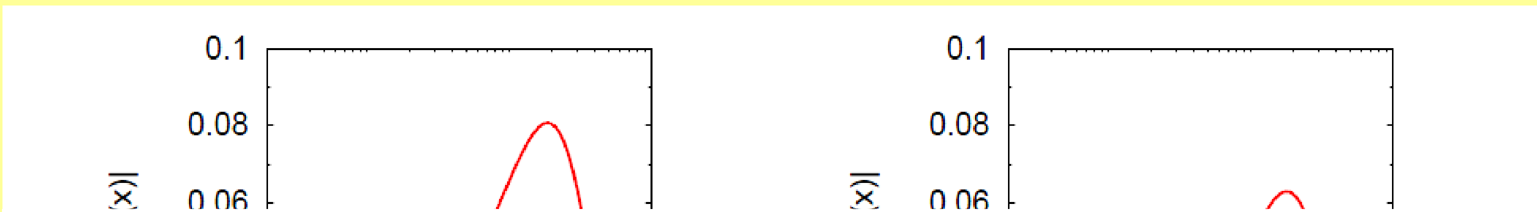
First extraction of BM PDF



Talk of G. Sbrizzai: “Azimuthal modulations in the unpolarized SIDIS μd cross-section at COMPASS”

V. Barone arXiv:0912.5194v1 [hep-ph]

COMPASS Plans

Starting in 2010:
- **SIDIS measurements with transversely pol. protons (1 year)**
- **SIDIS measurements with longitudinally pol. protons (1year)**

Proposal SPSC-2010-014/P-340 **presented in May to SPSC**
- **DY on transversely polarised p target (C. Quintanans)**
- **DVCS with LH target and polarised p target (A. Ferrero)**

Hadron program: not over
further measurements mainly depending on the results from the 2008-2009 data taking

Thank You