Tatranská Štrba, June 27th - July 1st, 2011

COMPASS results on the nucleon spin structure

I.A. Savin, JINR, Dubna

OUTLINE

1. Introduction
2. DIS from longitudinally polarised targets
3. DIS from transversely polarised targets
4. Summary

1. INTRODUCTION

1.1. What is COMPASS?

1.2. COMPASS physics goals.

1.1. COMPASS: THE new fixed target facility at CERN !

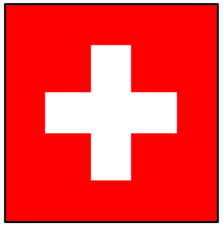
COMPASS - History

- 1996 COMPASS proposal
- 1997 conditional approval
- 1998 MoU

- 1999 – 2001 construction & installation
- 2001 technical run

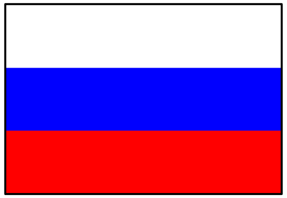
- 2002 - 2011 data taking
- COMPASS-II @CERN at least until 2015

The COMPASS Collaboration
(230 Physicists from 12 Countries)

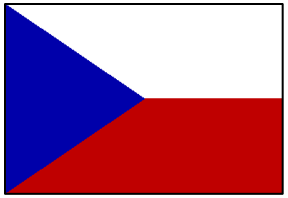


CERN

- Dubna (LPP and LNP), Moscow (INR, LPI, State University), Protvino

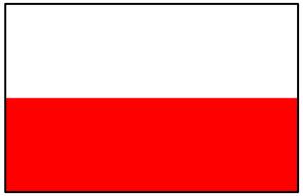


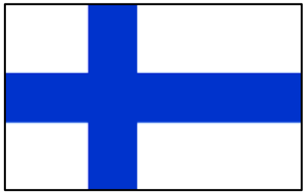
- Bielefeld, Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Heidelberg, Mainz, München (LMU & TU)



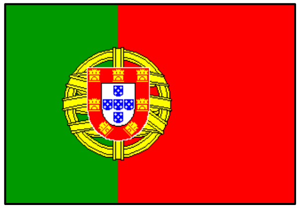
Prague

- Warsaw (SINS), Warsaw (TU)



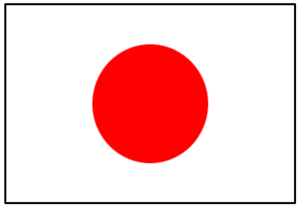


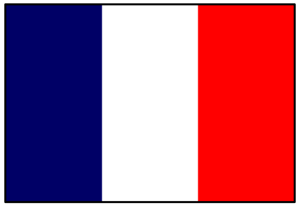
Helsinki



Lisboa

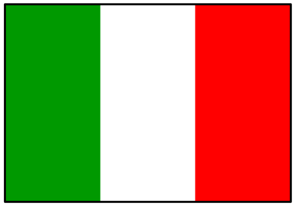
Nagoya





Saclay

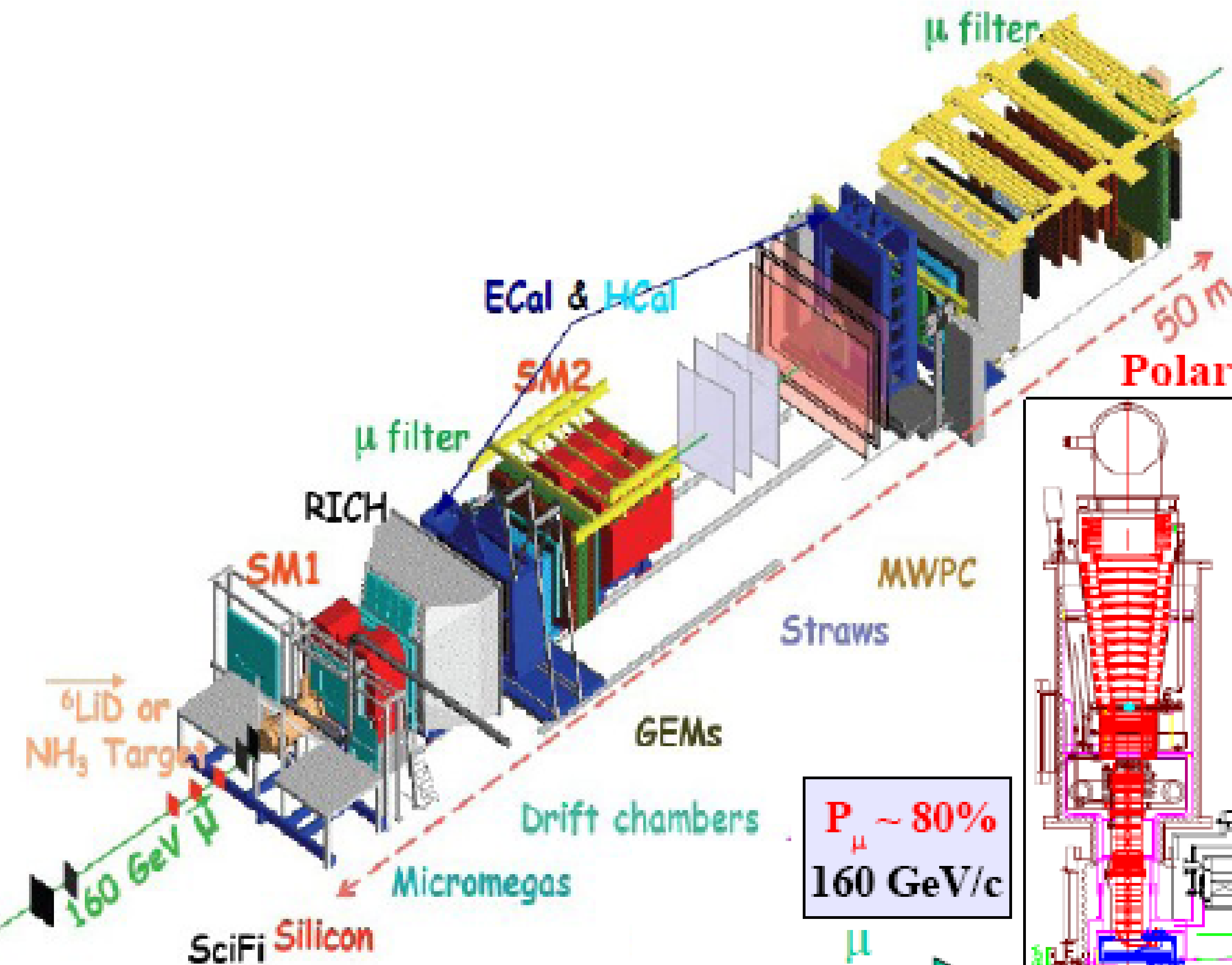
Torino(University,INFN), Trieste(University,INFN)



Tel Aviv

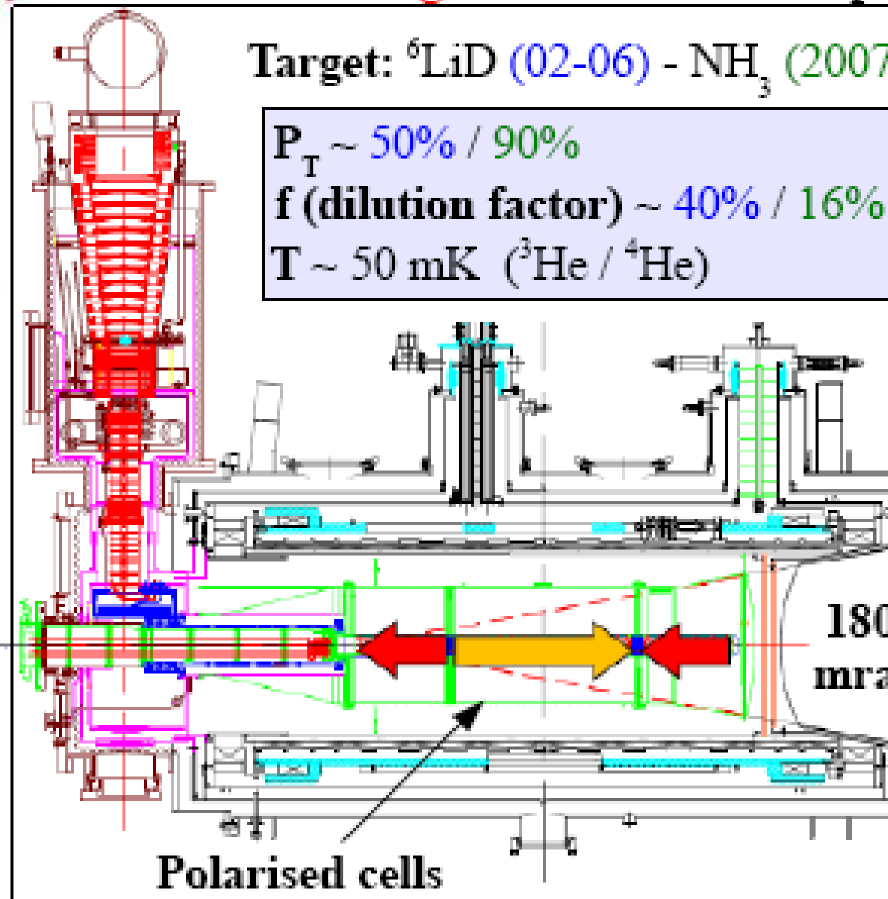
- Burdwan,
- Calcutta

The COMPASS spectrometer and target



$P_\mu \sim 80\%$
160 GeV/c

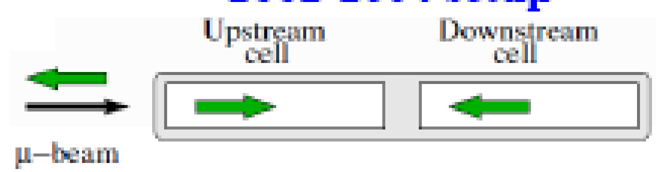
Polarised Target: 2006-2007 setup



Target: ^{6}LiD (02-06) - NH_3 (2007)

$P_T \sim 50\% / 90\%$
f (dilution factor) ~ 40% / 16%
T ~ 50 mK (^{3}He / ^{4}He)

2002-2004 setup



1.2. COMPASS Physics Goals

With muon beam:

nucleon spin structure

- **Gluon Polarization $\Delta G/G$**
- Transverse spin structure function $h_1(x)$
- Flavor dependent polarized quark helicity densities $\Delta q(x)$
- Spin dependent fragmentation functions
- Diffractive VM-Production

With hadron beam:

hadron spectroscopy

- **Primakoff-Reactions**
  -polarizability of π and K
- **Glueballs and hybrids**
- **Charmed mesons and baryons**
  -semi-leptonic decays
  -double-charmed baryons

The COMPASS starting point

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

small
EMC, SMC

unknown
in 1997

unknown
up to now

Smallness (<30%) of $\Delta\Sigma$ confirmed by SMC!

"Where, oh where is the proton spin?" Elliot Leader

Theory Input 1988

CHIRAL SYMMETRY AND THE SPIN OF THE PROTON *

Stanley J. BRODSKY [a], John ELLIS [a,b] and Marek KARLINER [a]
[a] *Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305, USA*
[b] *CERN, CH-1211 Geneva 23, Switzerland*

Received 22 February 1988

PLB 206 (1988) 309

A crisis in the parton model: where, oh where is the proton's spin?

E. Leader[1] and M. Anselmino[2]
Birkbeck College, University of London, London, UK
Dipartimento di Fisica Teorica, Università di Torino, I-10125 Torino, Italy

Received 18 March 1988

ZPC 41 (1988) 239

E2-88-287

A.V.Efremov, O.V.Teryaev*

SPIN STRUCTURE OF THE NUCLEON AND TRIANGLE ANOMALY

THE ANOMALOUS GLUON CONTRIBUTION TO POLARIZED LEPTOPRODUCTION

G. ALTARELLI and G.G. ROSS [1]
CERN, CH-1211 Geneva 23, Switzerland

Received 29 June 1988

PLB 212 (1988) 391

Large gluon contributions have been advocated and COMPASS planned to see it.

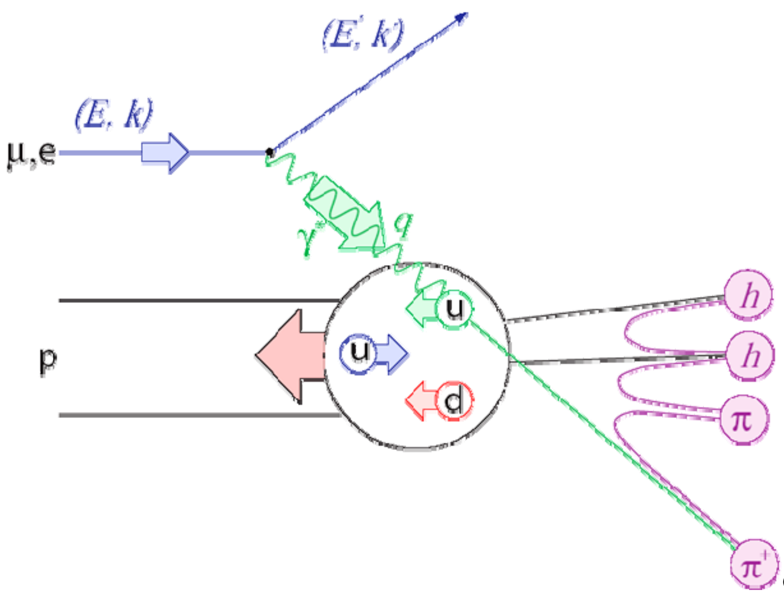
2. DIS from longitudinally polarised targets

2.1. DIS x-sections & asymmetries

2.2. Inclusive asymmetries and spin structure functions

2.3. Semi-inclusive asymmetries and helicity PDF

2.1. DIS x-section for Inclusive & Semi-Inclusive Deep Inelastic Scattering



$$x = \frac{Q^2}{2P\cdot q} \qquad y = \frac{P\cdot q}{P\cdot \ell} =_{LAB} \frac{E-E'}{E}$$

$$Q^2 = -q^2 \qquad W^2 = (P+q)^2$$

$$z = \frac{P\cdot P_h}{P\cdot q} =_{LAB} \frac{E_h}{E-E'}$$

Inclusive: $l + N \rightarrow l' + X$

Semi-Inclusive: $l + N \rightarrow l' + N + nh + X$, $n=1,2,..$

Incusive x-section : product of contributions from the lepton vertex, which is described in QED, and nucleon vertex, which is expressed via nucleon Structure Functions (SF). In QPM structure functions are expressed via Parton Distribution Functions (PDF) – factorisation theorem.

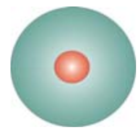
Semi-Inclusive x-section: product of contributions from lepton and nucleon vertexes and from the Fragmentation Function (FF) of quarks into hadrons.

Structure functions & Parton Distribution Functions

Three twist-2 (LO) SF & PDFs, equally important for description of the nucleon structure:

q(x)

$f_1^q(x)$



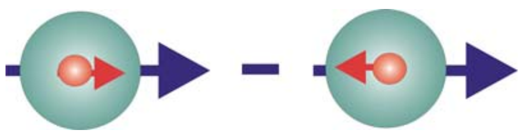
unpolarised PDF

quark with momentum *xP* in a nucleon

(well known – unpolarized DIS)

Δq(x)

$g_1^q(x)$



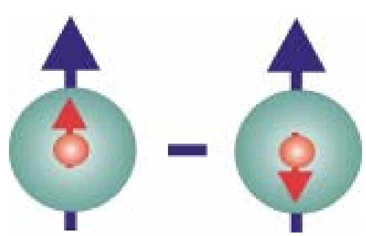
helicity PDF

quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon

(known – polarized DIS)

Δ_Tq(x)

$h_1^q(x)$



transversity PDF

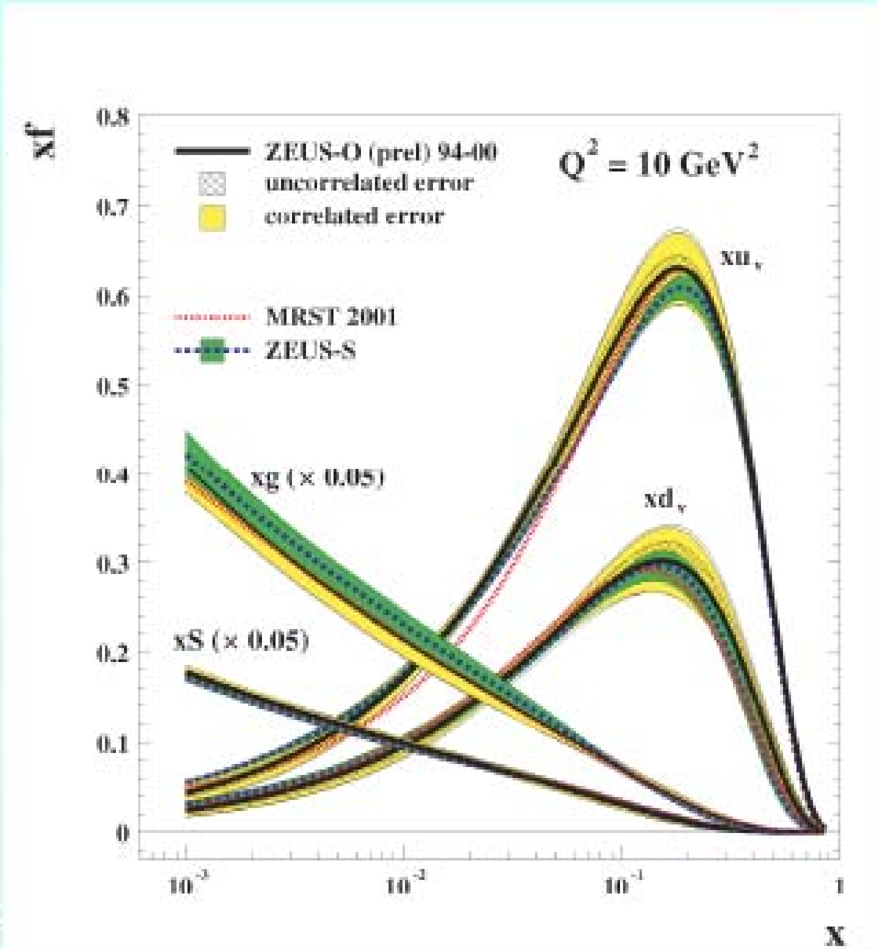
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

(chiral odd, poorly known)

PDF AND STRUCTURE FUNCTIONS

Inclusive DIS: unpolarised

$$\frac{d\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2} \cdot \left\{ \frac{y}{2} \cdot F_1 + \frac{1}{2xy} \cdot \left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot F_2 \right\}$$



$F_2(x) = 2x \cdot F_1(x)$ Callan-Gross

in the parton model

$$F_1(x) = \frac{1}{2} \sum_q e_q^2 \cdot \left[q(x) + \bar{q}(x) \right]$$

$q = u, d, s$

⇒ q(x) from global analysis of DIS and hard scattering data (QCD fits)

2.2. Inclusive asymmetries and spin structure functions

2.2.1. World data on A1(x)

2.2.2. g1(x,Q2)

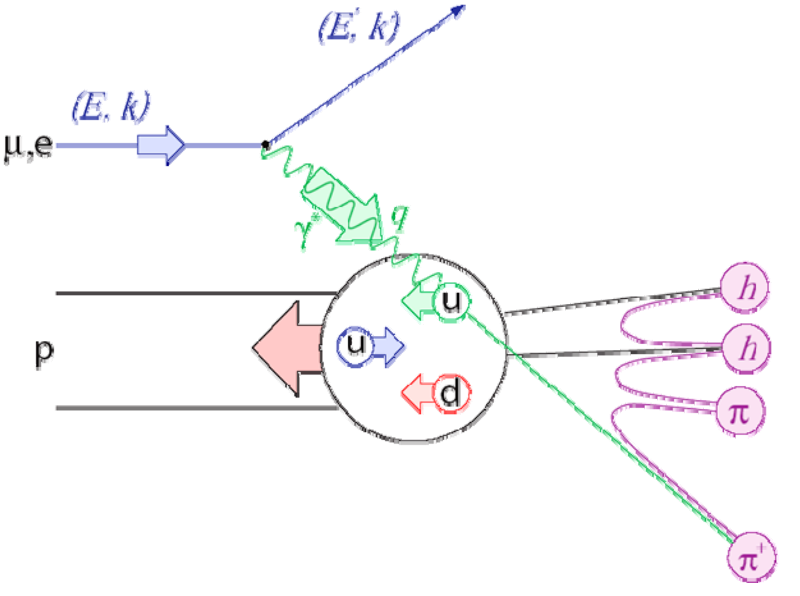
2.2.3. Test of the Bjorken sum rule

2.2.4. QCD fits and preliminary data on gluon polarisation

X-section asymmetries are measurable values for studies of polarised SF and PDF

Inclusive scattering

$$A_1 = \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$



Semi-inclusive scattering

$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}$$

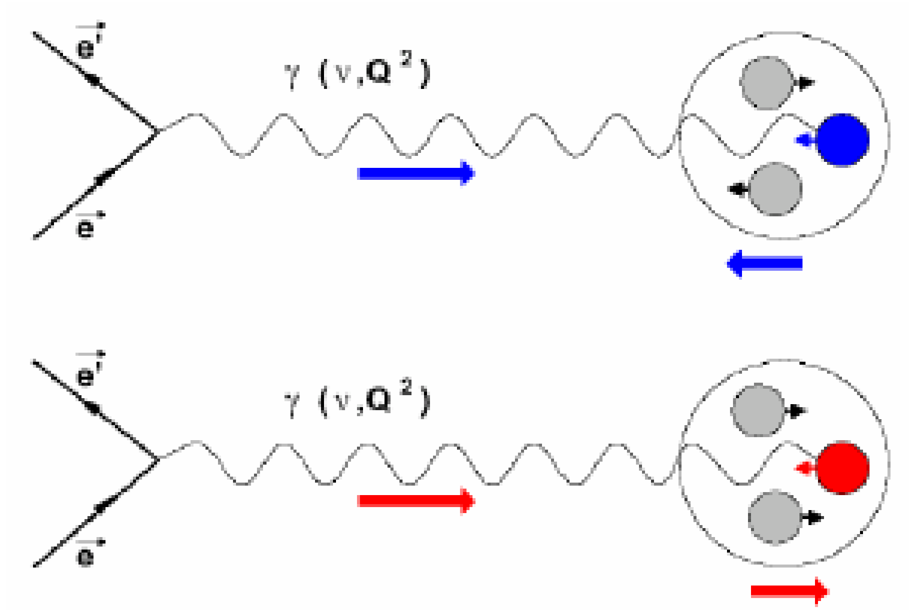
long. double spin asymmetry

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

transverse single asymmetry

$$z = E_h/\nu$$

Interpretation of A_1 in terms of structure functions



$\sigma_{\uparrow\downarrow} \sim q^{+}$

$\sigma_{\uparrow\uparrow} \sim q^{-}$

$$\Delta q(x) = q(x)^{+} - q(x)^{-}$$

$$q(x) = q(x)^{+} + q(x)^{-}$$

+ quark ↑↑ nucleon

– quark ↑↓ nucleon

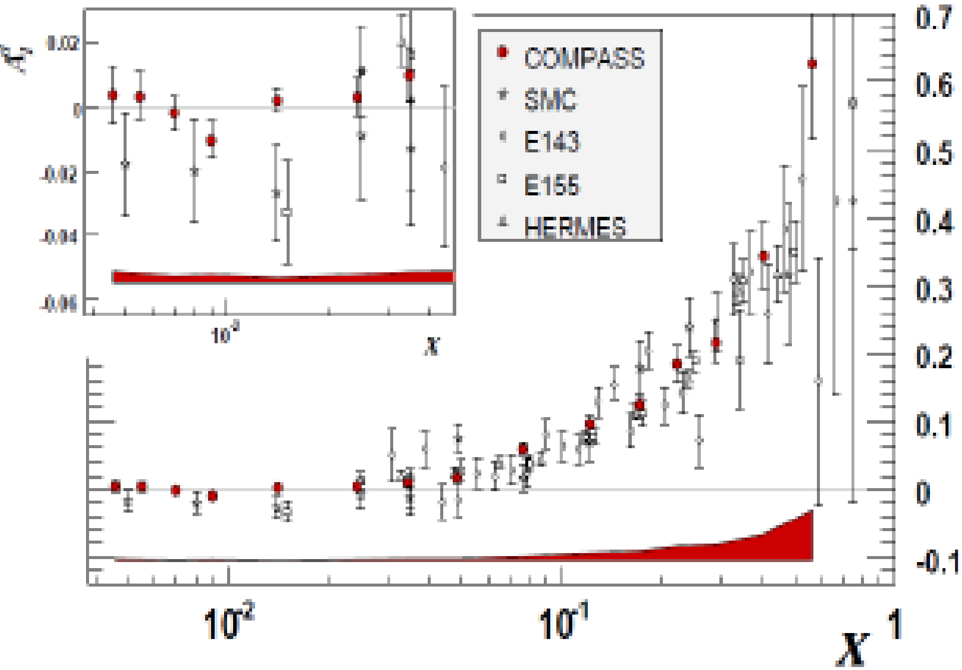
$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2)\,2x(1+R)}{F_2(x,Q^2)}$$

- g_1 (polarised structure function) **is obtained from the asymmetry A_1 using:**

$F_2 \rightarrow$ <u>SMC parameterisation</u> and $R = \sigma^L/\sigma^T \rightarrow$ <u>SLAC parameterisation</u>

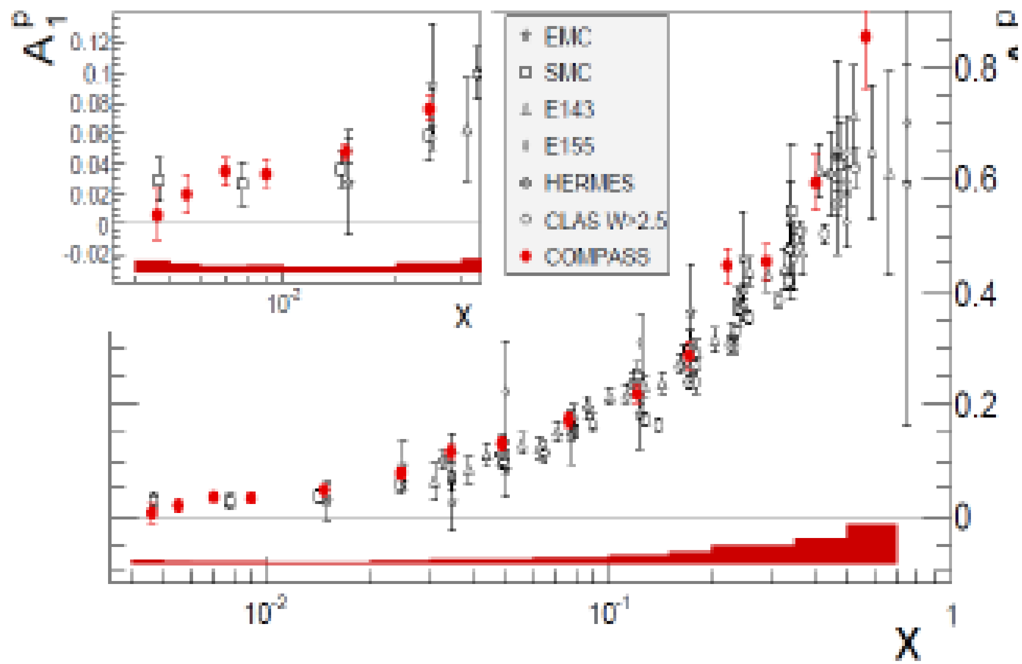
2.2.1. Inclusive asymmetries $A_1^{d/p}$: $Q^2 > 1\ (GeV/c)^2$

Deuteron data (2002-2006)



COMPASS, PLB 647 (2007) 330-340

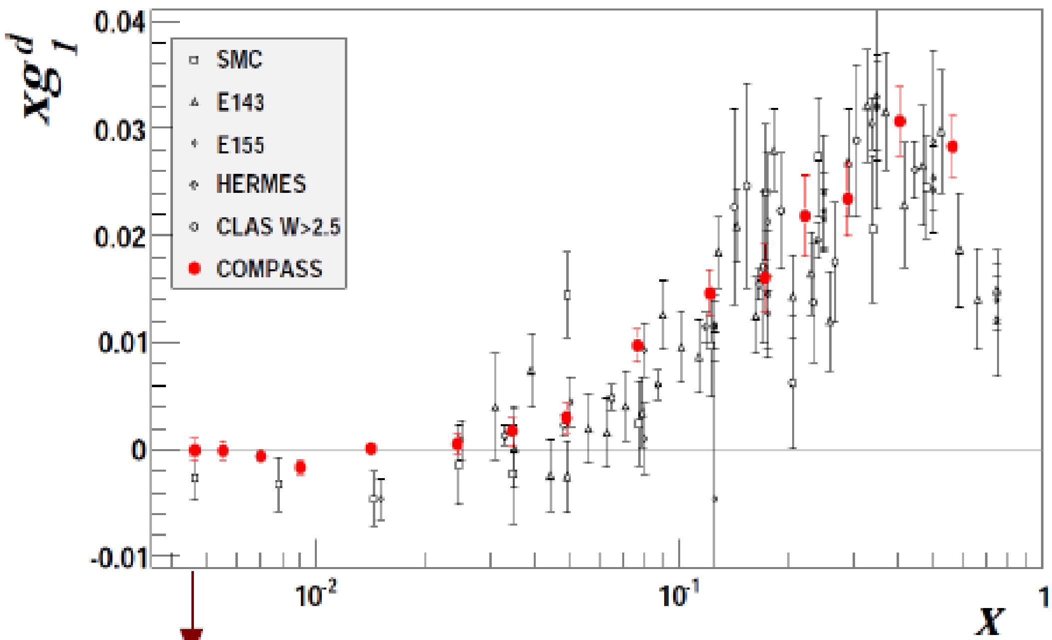
Proton data (2007)

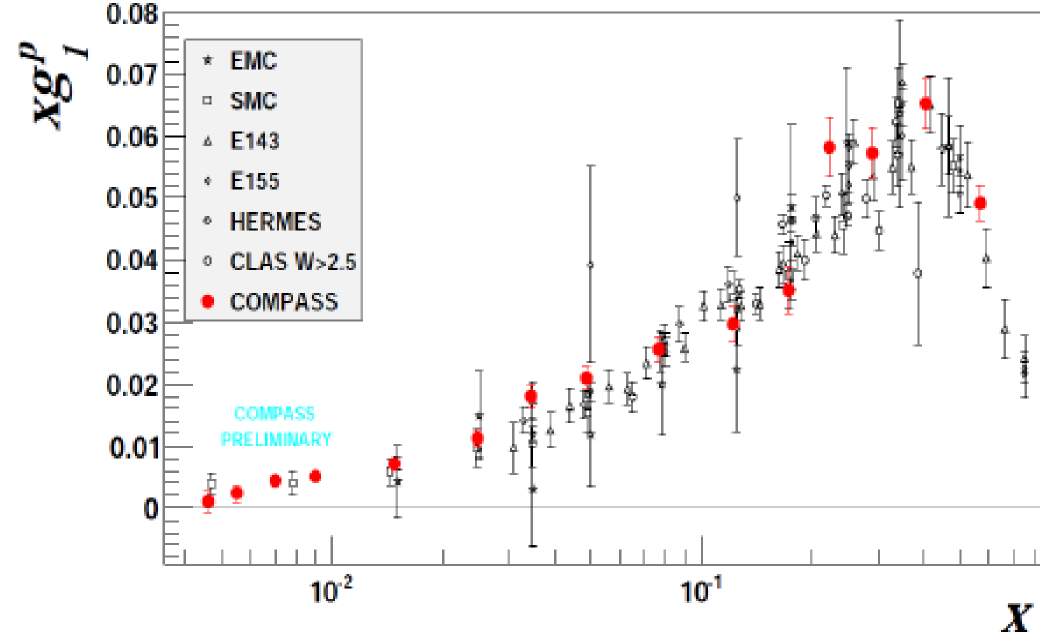


COMPASS, PLB 690 (2010) 466-472

- Good agreement between all experimental points
- Significant improvement of precision in the low x region: compatible with zero for $x < 0.01$
- No negative trend for A_1^d

COMPASS results for g_1 and first moments of g_1





$$\Gamma_1^N(Q_0^2 = 3(\mathrm{GeV}/c)^2) = \int_0^1 g_1(x)\,dx = 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol}) \pm 0.0051(\mathrm{syst})$$

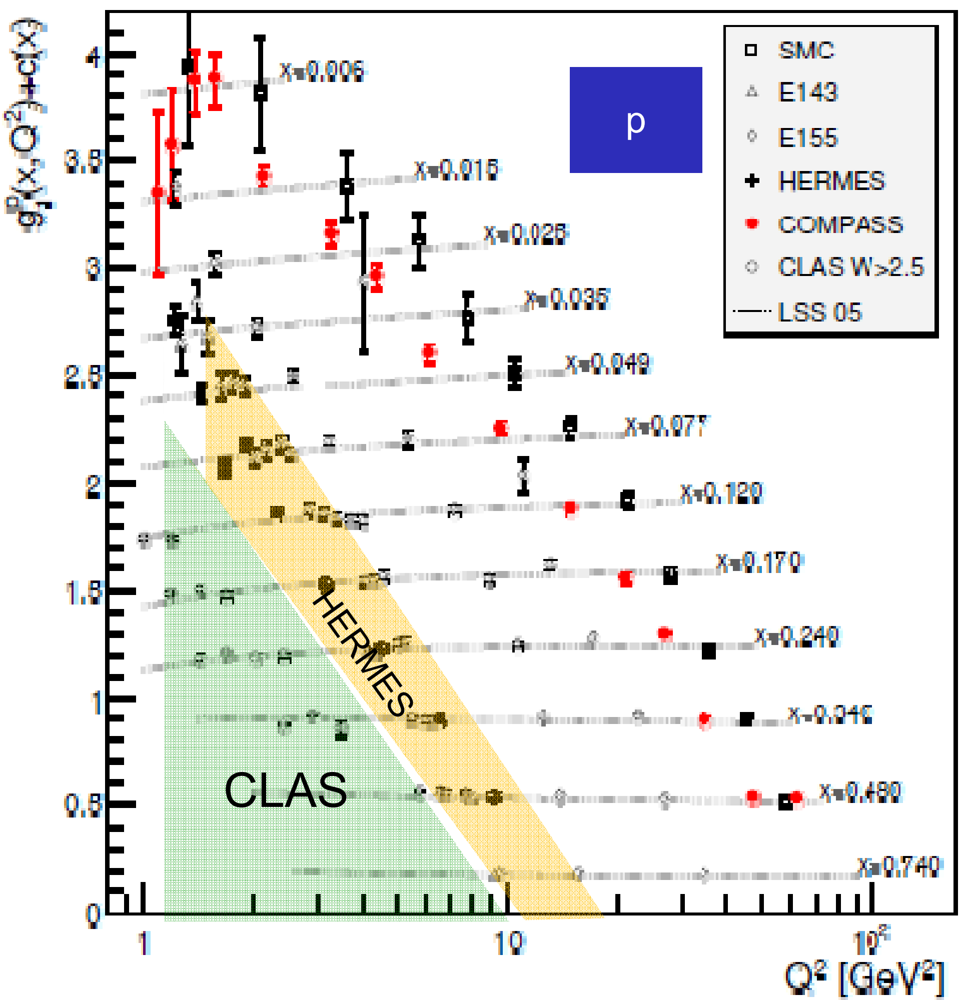
$$= \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right) \quad \Rightarrow \quad a_0 = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

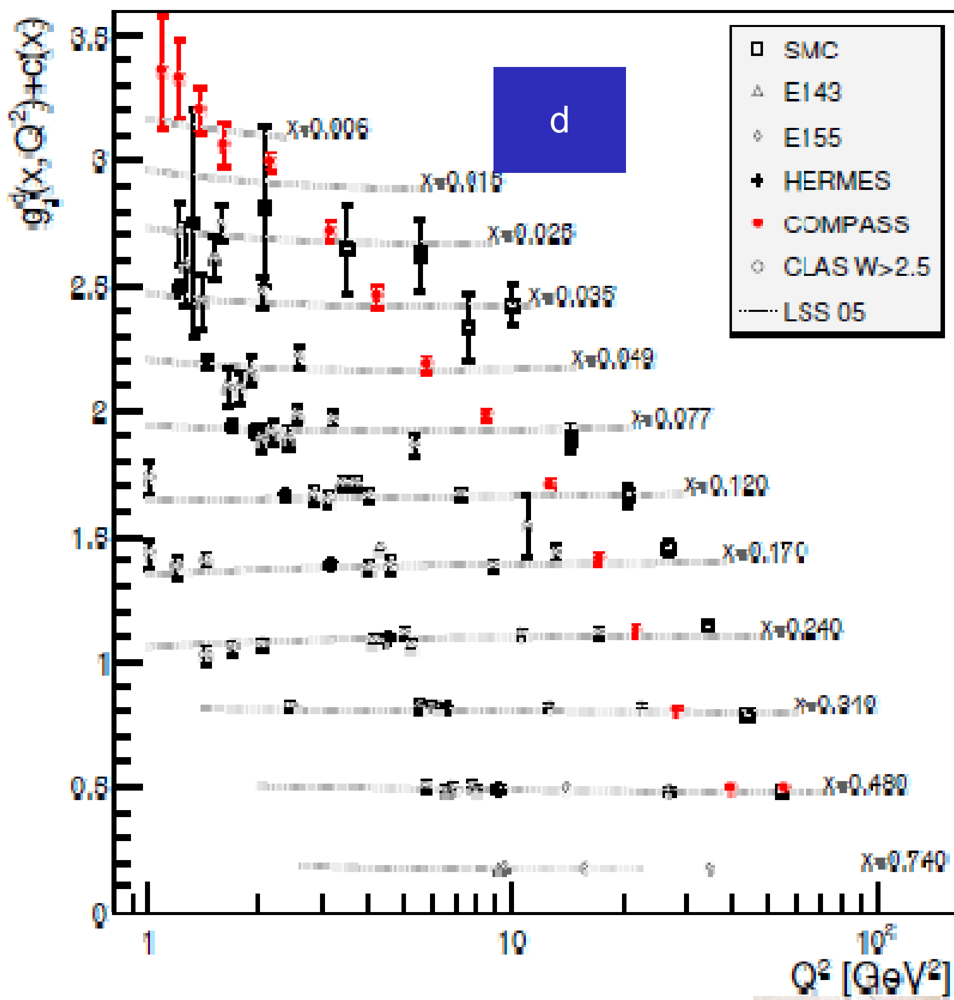
$$\Delta\Sigma^{\overline{MS}} = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}) \qquad (\Delta\Sigma^{\overline{MS}} = a_0 \;\; @Q^2 \to \infty)$$

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\Delta\Sigma^{\overline{MS}} - a_8) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

2.2.2. Q^2 evolution of $g_1(x,Q^2)$

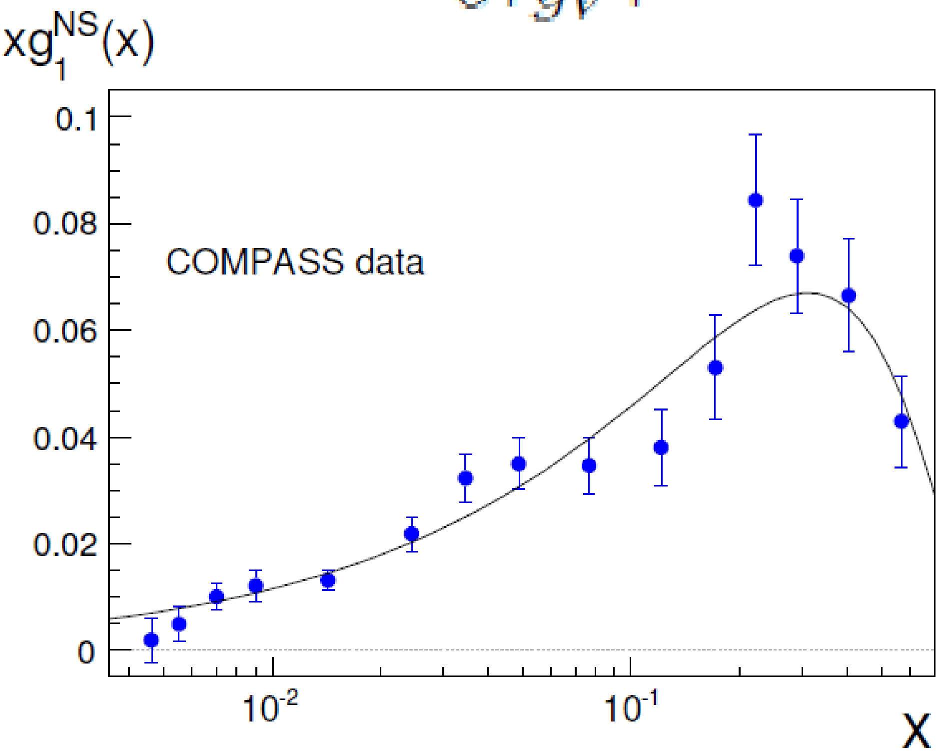
- Q^2 dependence *of* g_1 data related to gluon polarization (DGLAP)
- Limited kinematic range (c.f. unpol. HERA)
- Proton data will be updated in 2011

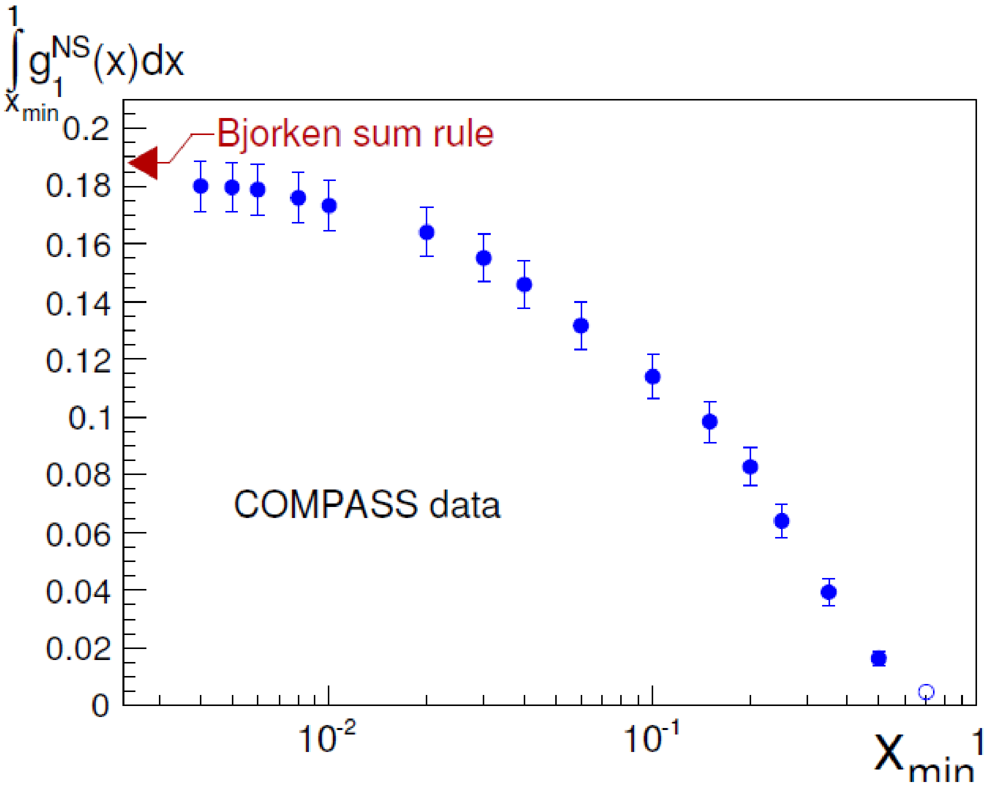




2.2.3. Bjorken sum rule test

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2) \qquad g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$$





$$|g_A/g_V| = 1.28 \pm 0.07(\text{stat.}) \pm 0.10(\text{syst.})$$

$|g_A/g_V| = 1.269$ from neutron β decay

2.2.4. QCD fits and preliminary data on the gluon polarisation

g_1 @ NLO

In QPM g_1 is related to the polarized parton distribution functions (PDF):

$$g_1^{p(n)}(x,Q^2) = \frac{1}{9}\left(C_{NS} \otimes \left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S \otimes \Delta\Sigma + C_G \otimes \Delta G\right)$$

Where C_{NS}, C_S and C_G are Wilson coefficients,

Δq_3, Δq_8 - non-singlet polarized quark DF,

$\Delta \Sigma$ - singlet polarized quark DF,

ΔG - polarized gluon DF,

$\otimes$ - convolution: $a(x) \otimes b(x) = \int_x^1 \frac{dy}{y} a\left(\frac{x}{y}\right) \cdot b(y)$.

In the 3 quark limits:

$\Delta\Sigma = \Delta u + \Delta d + \Delta s$,

$\Delta q_3 = \Delta u - \Delta d$,

$\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

FITTING PROGRAMS

PROGRAM 1 [SMC, P.R. D58 (1998) 112002]

numerical solutions of the DGLAP evolution equations for PDF's.

PROGRAM 2 [Refered to in P.R. D70 (2004) 074032].

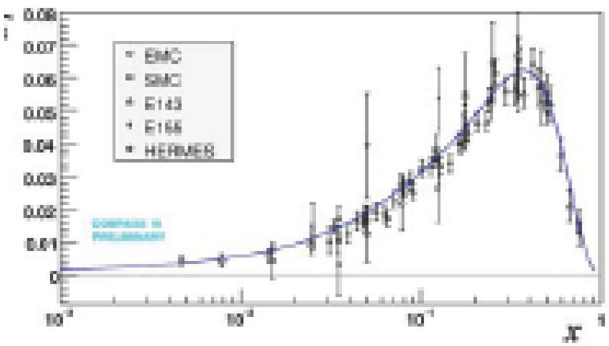
Works in two steps:

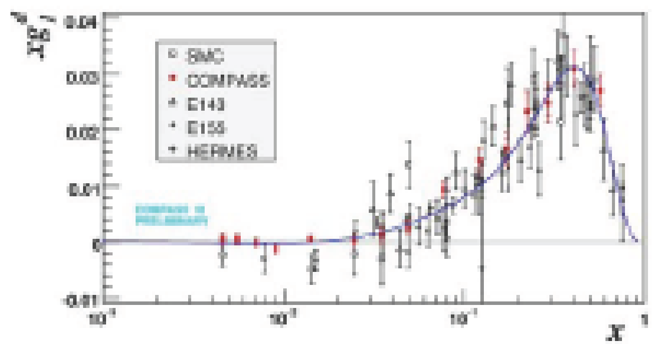
1. Analytical solution of the evolutions equations for the PDF moments,
2. Inverse Mellin transformation of moments for PDF's reconstruction
   (similar to one developed for the QCD analysis of $F_2(x, Q^2)$, [Krivokhizhin et al., Z.Phys. C36 (1987) 51])

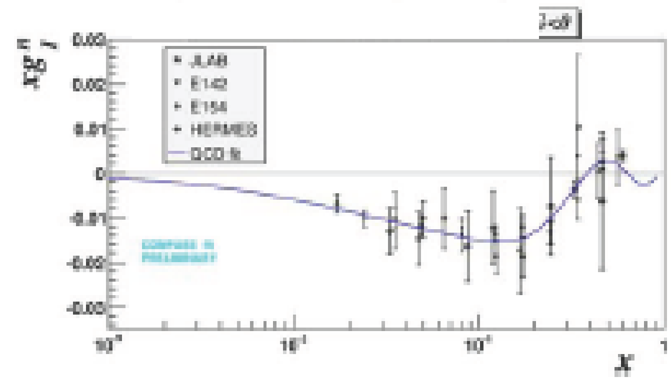
Both programs work in the $\overline{MS}$ renormalization and factorization scheme in next-to-leading (NLO) approximation and require input parametrizations of PDF's

FITTED xg_1 & WORLD DATA

The world data on $xg_1(x)$ at Q_0^2=3 GeV^2 are shown in this slide together with the QCD fit for $\Delta G < 0$ (blue lines).

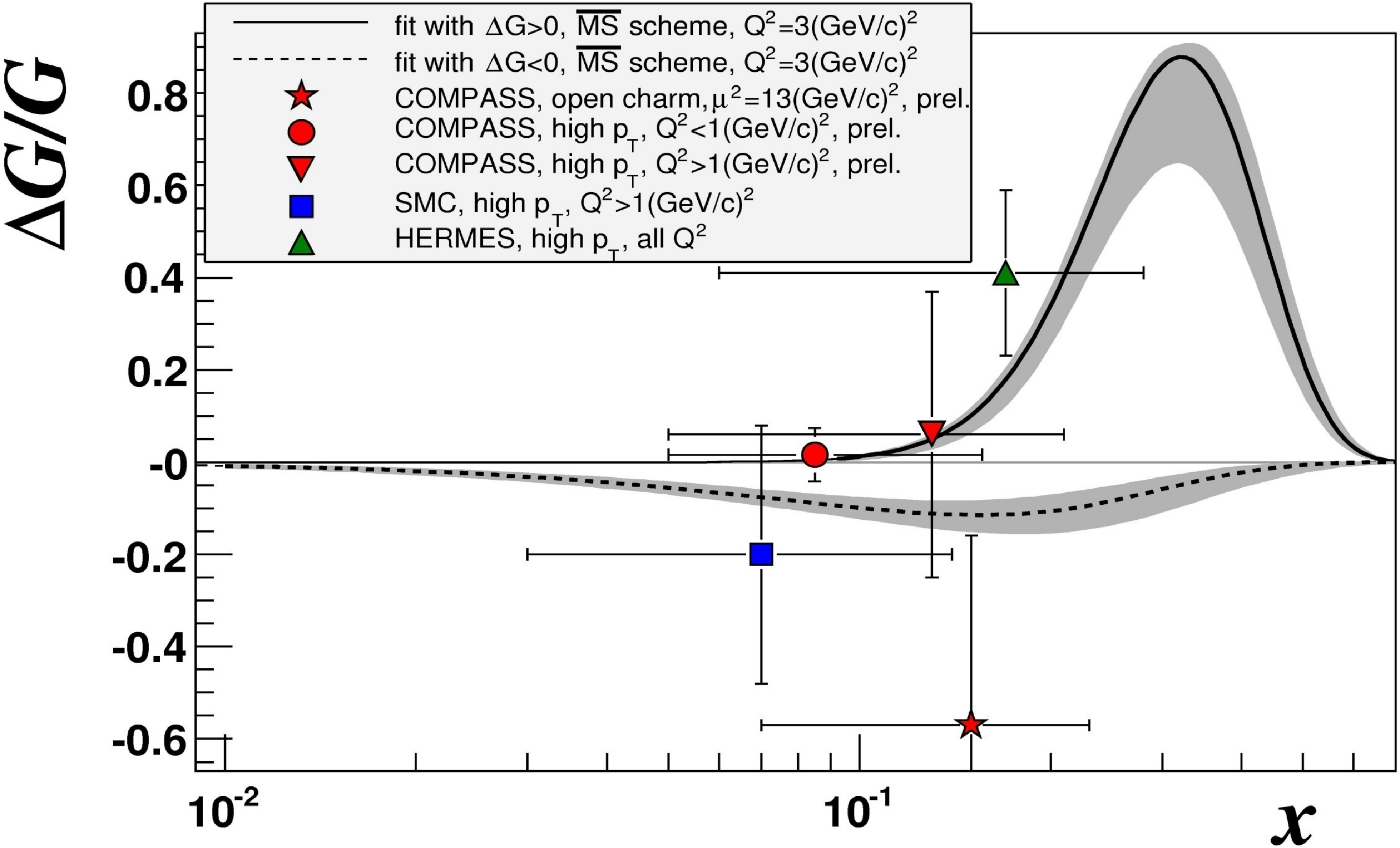






The fit reproduce trends of data rather well. But precisions of present measurements, especially for g_1^d and g_1^n, are still poor.

Preliminary data on gluon polarisation and the QCD fits of the world data on g1(x,Q2): two solutions, positive and negative values of gluon polarisation are possible.



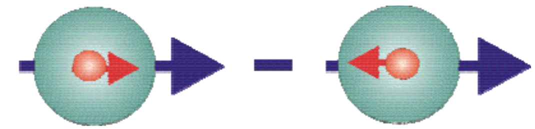
2.3. Semi-inclusive asymmetries and helicity PDF

2.3.1. Proton & deuteron asymmetries

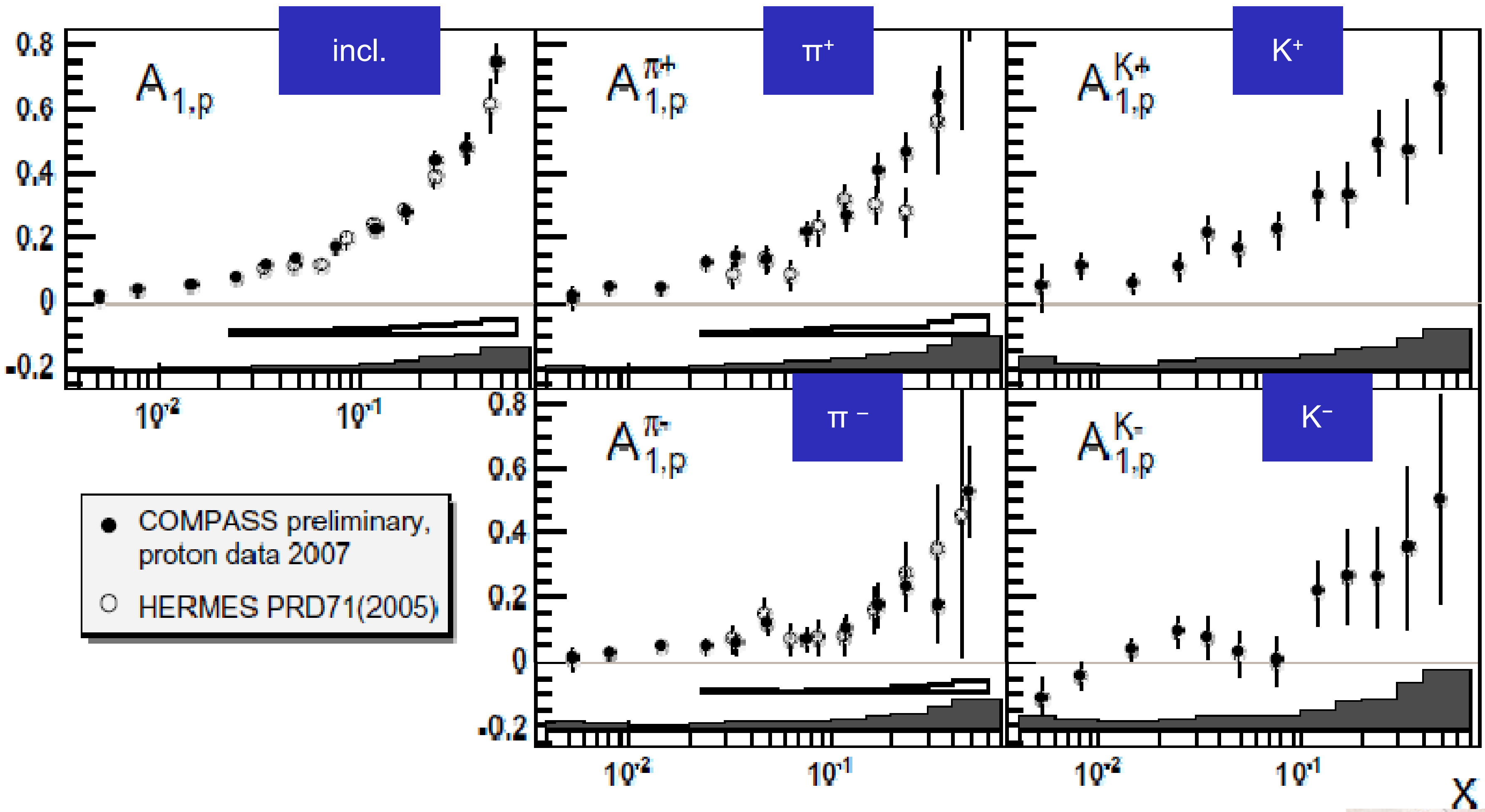
2.3.2. Helicity PDF

2.3.3. Gluon polarisation, direct measurements

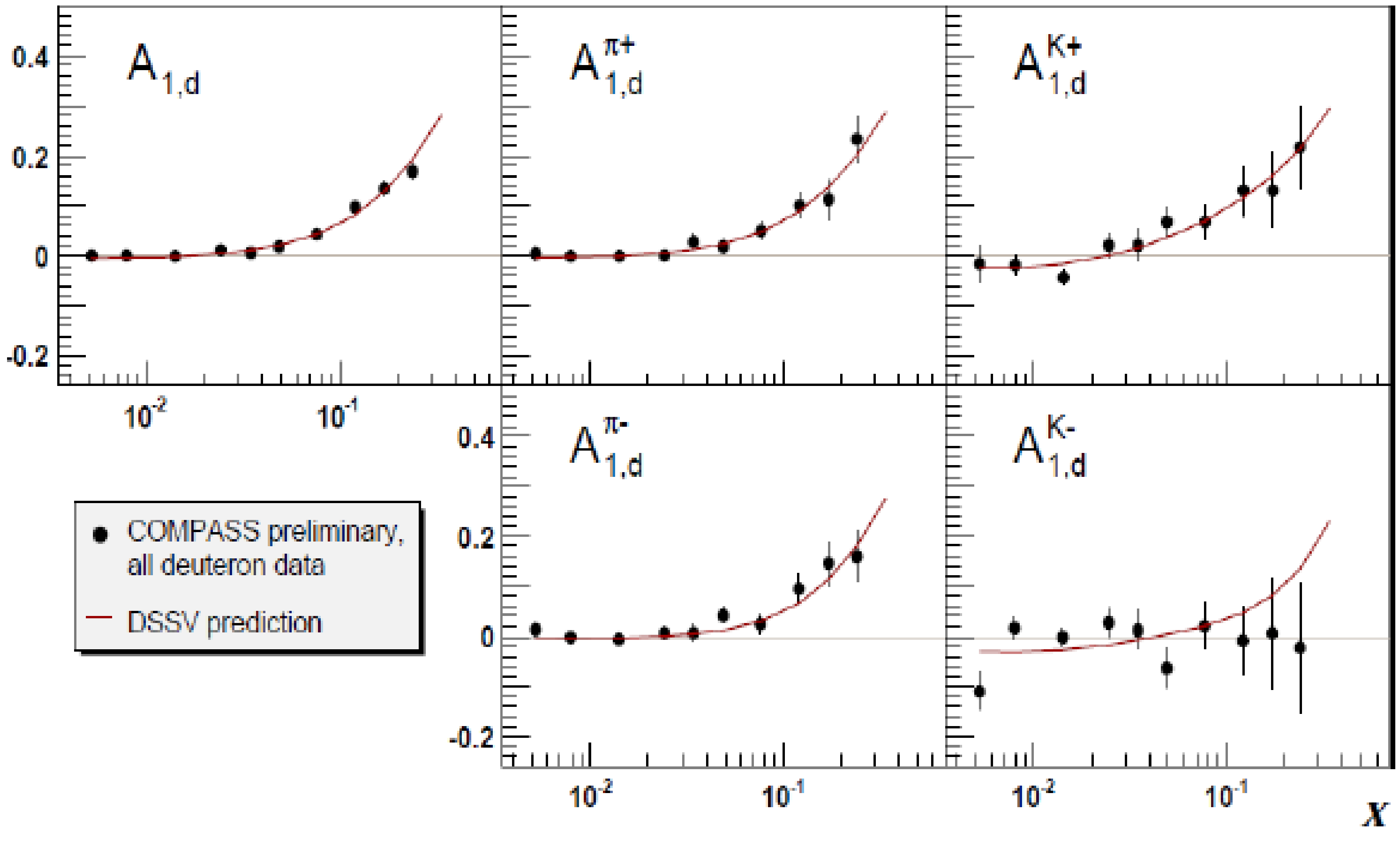
2.3.1. Proton asymmetries and......



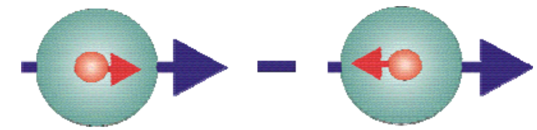
- incl. & semi-incl. asymmetries,
- similar data for deuteron

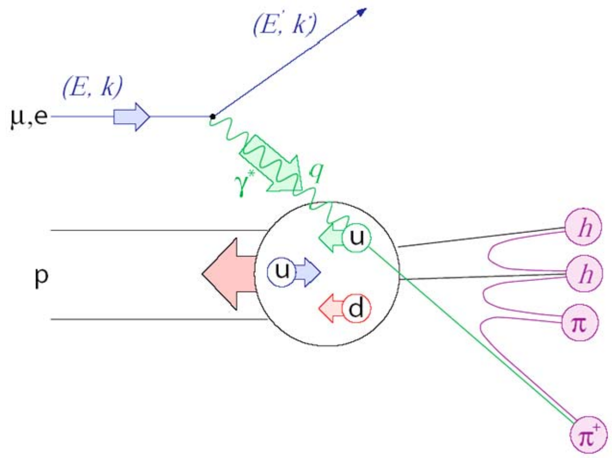


Deuteron asymmetries

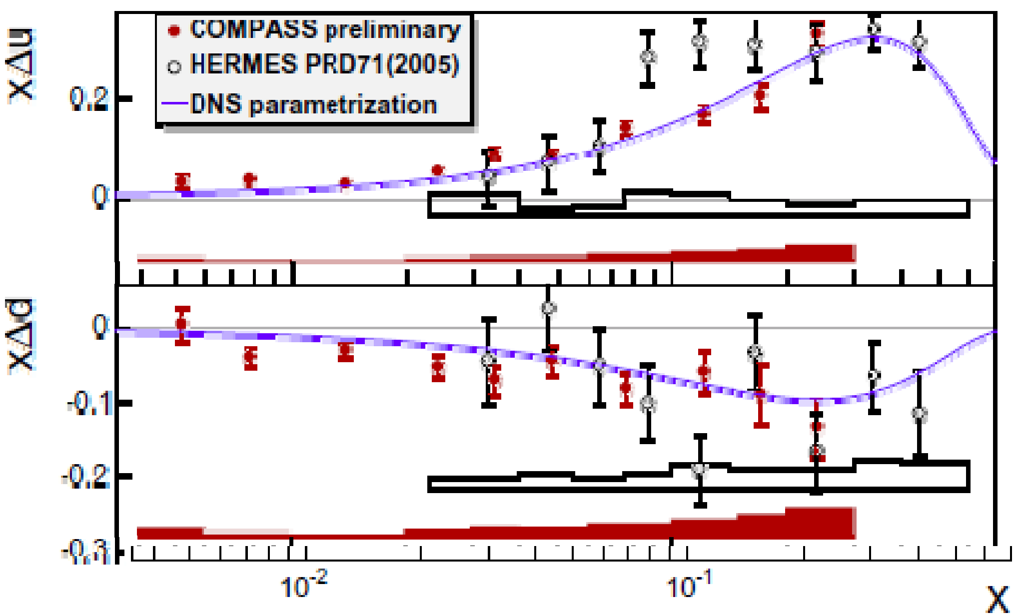


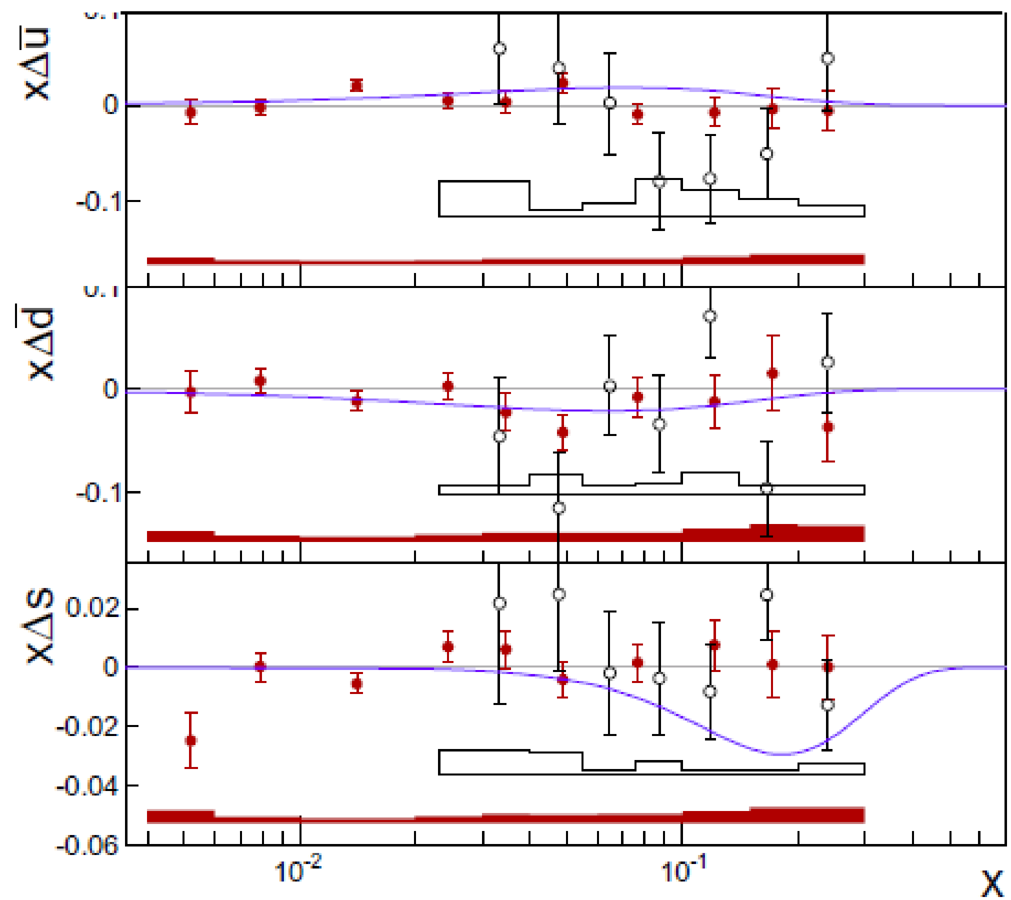
2.3.2. Helicity PDF and the role of quark flavours



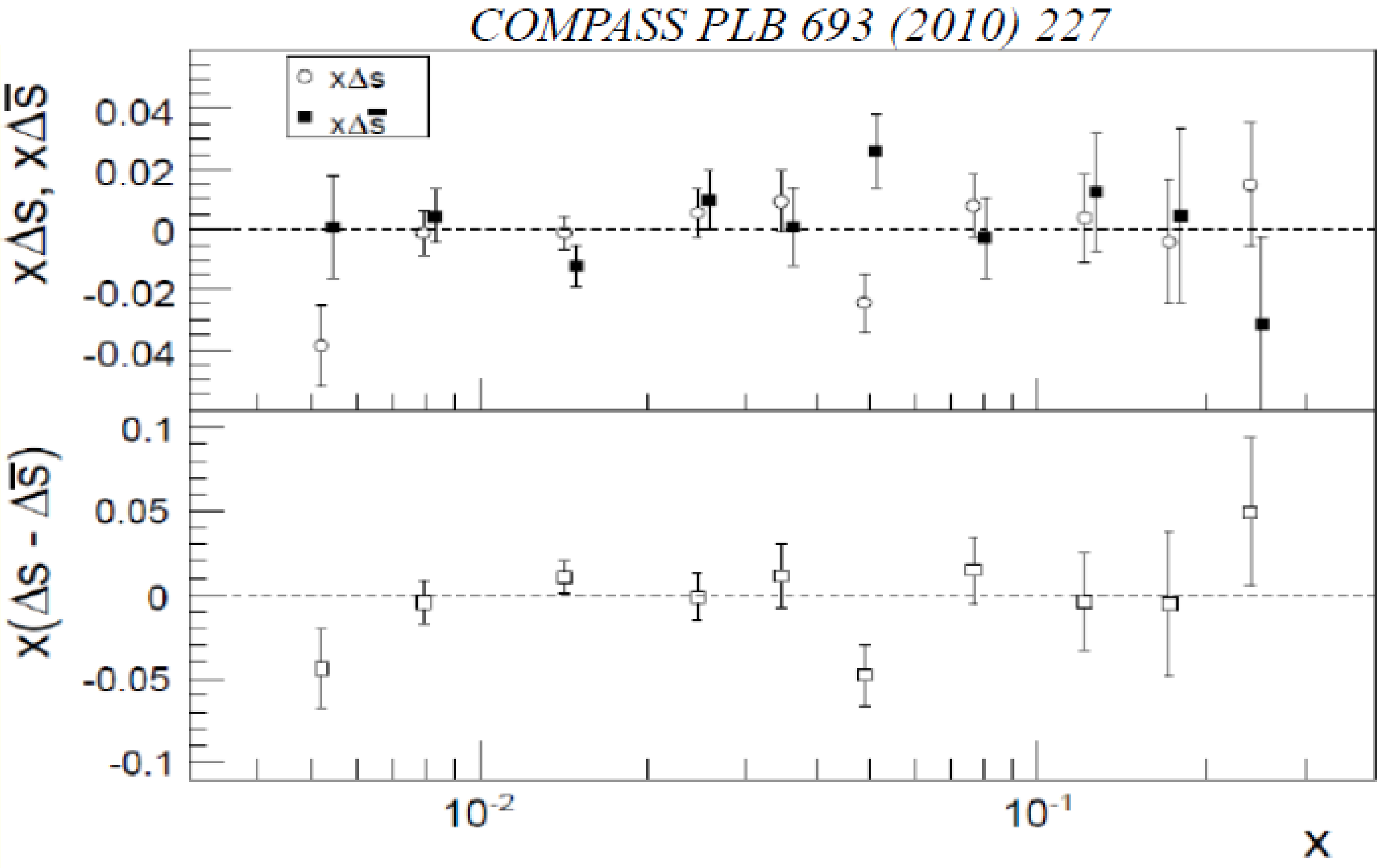


LO semi-inclusive data analysis



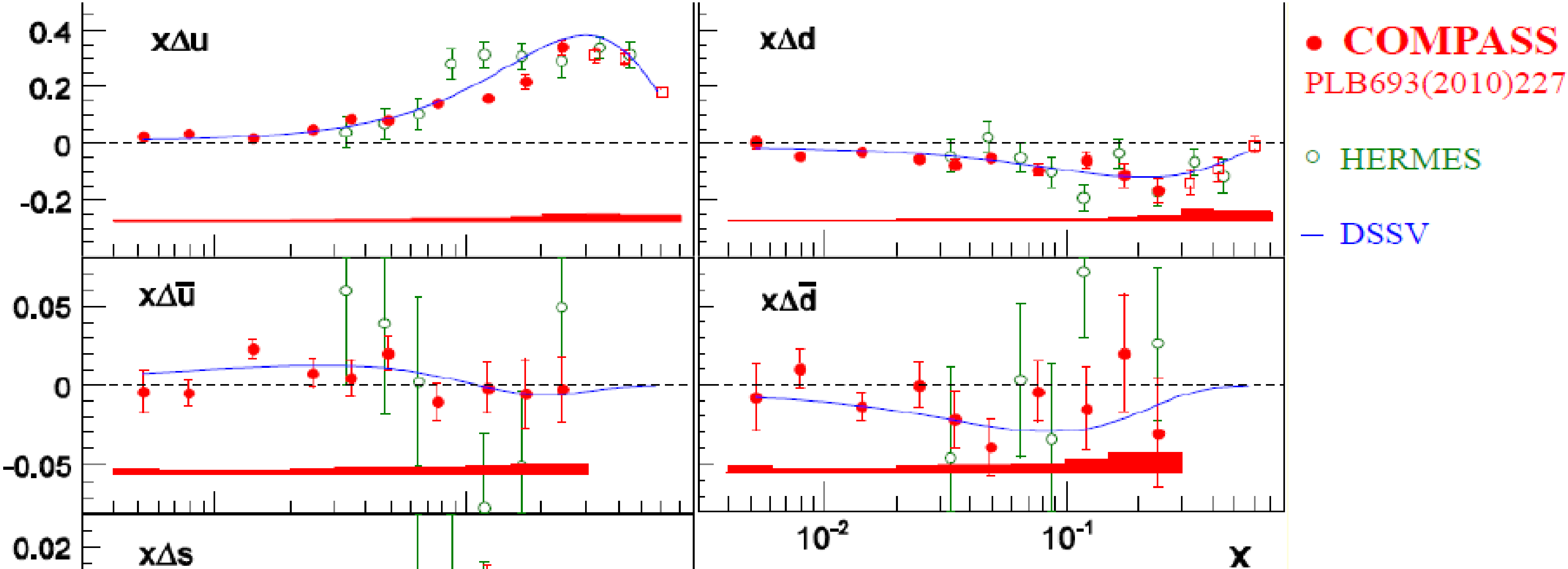


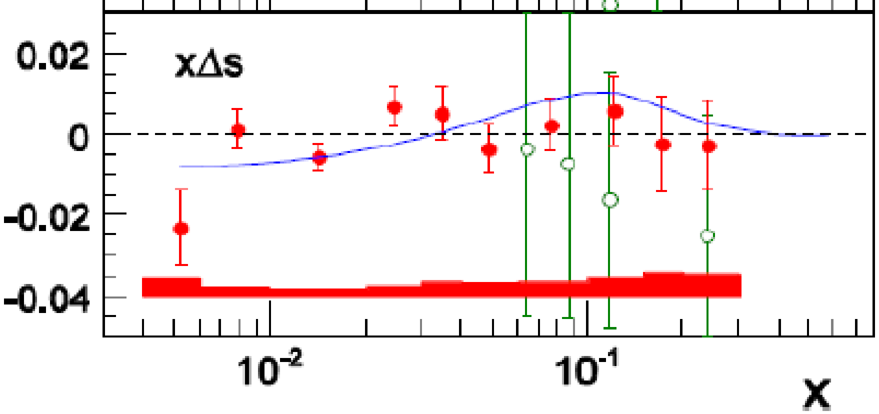
Comparison of Δs with $\Delta\bar{s}$



$\Delta s - \Delta\bar{s}$ is compatible with 0 $\rightarrow$ $\Delta s = \Delta\bar{s}$ is assumed in the subsequent analysis

Quark helicities from SIDIS ($Q^2 = 3\ (\mathrm{GeV}/c)^2$ and $x < 0.3$)



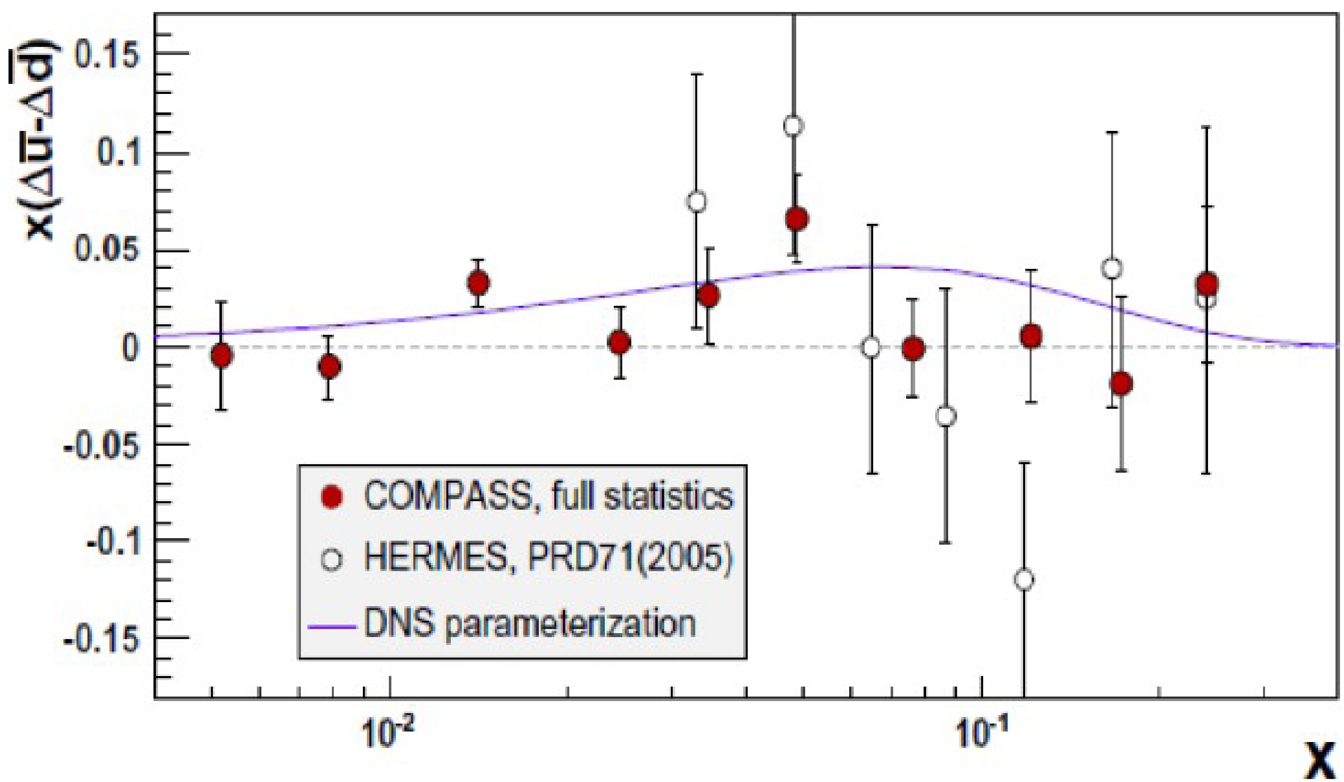


- **Sea quark distributions ~ 0**
- **Good agreement with global fits**
- **Full flavour separation until *x* ~ 0.004**

$$\Delta s(\mathbf{SIDIS}) = -0.01 \pm 0.01(\mathbf{stat}) \pm 0.01(\mathbf{syst}) \quad @ \quad 0.003 < \mathbf{x} < 0.3$$

$\Delta\bar{u} - \Delta\bar{d}$: Flavour asymmetry?

- **The considerable asymmetry observed for $(\bar{u} - \bar{d})$ is not verified in the polarised case :**
  - $\Delta\bar{u} - \Delta\bar{d}$ is slightly positive but compatible with zero!



2.3.2. Gluon polarisation

2.3.2.1. Direct measurements

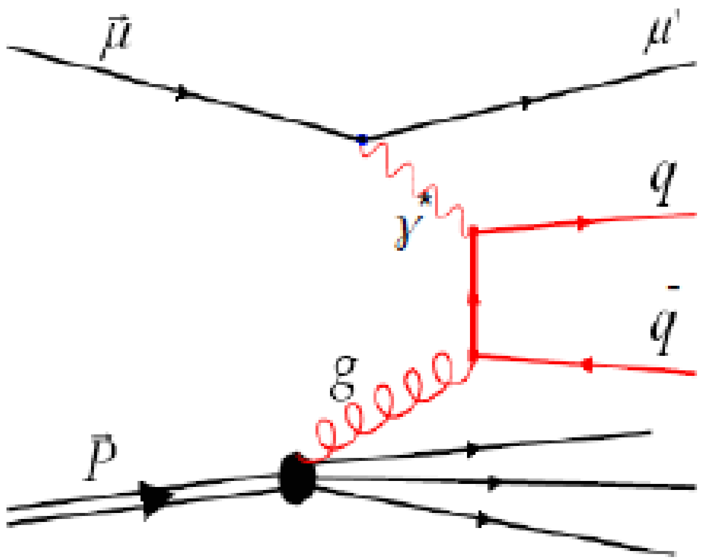
2.3.2.2. Open charm analysis

2.3.2.3. High-pT analysis

2.3.2.4. World data

2.3.2.1. Direct measurement of ΔG/G in LO

photon-gluon fusion process (PGF)



$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\, \Delta\sigma^{PGF} \Delta G(x_G, \hat{s})}{\int d\hat{s}\, \sigma^{PGF} G(x_G, \hat{s})}$$

$$\approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$

analysing power

There are two methods to tag this process:

- **Open Charm production**
  - $\gamma^* g \rightarrow c\bar{c} \quad \Rightarrow$ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly Monte Carlo dependent
  - Low statistics
- **High-p_T hadron pairs**
  - $\gamma^* g \rightarrow q\bar{q} \quad \Rightarrow$ reconstruct 2 jets or h^+h^-
  - Hard scale: Q^2 or Σp_T^2 [$Q^2 > 1$ or $Q^2 < 1$ $(GeV/c)^2$
  - High statistics
  - Physical background
  - Strongly Monte Carlo dependent

2.3.2.2. Open Charm analysis: Simultaneous extraction of ΔG/G and A^{bg}

- The relation between the number of reconstructed D^0 (for each target cell configuration) and ΔG/G is given by:

$$N_t = a\,\phi\,n\,(S+B)\left(1 + f\,P_T\,P_\mu\left[a_{LL}\frac{S}{S+B}\frac{\Delta G}{G} + D\frac{B}{S+B}A^{bg}\right]\right), \quad t=(u,d,u',d')$$

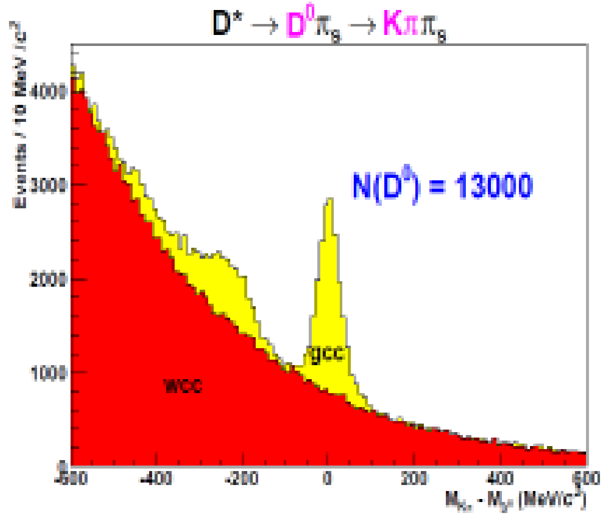
acceptance, muon flux, number of target nucleons — Open Charm event probability

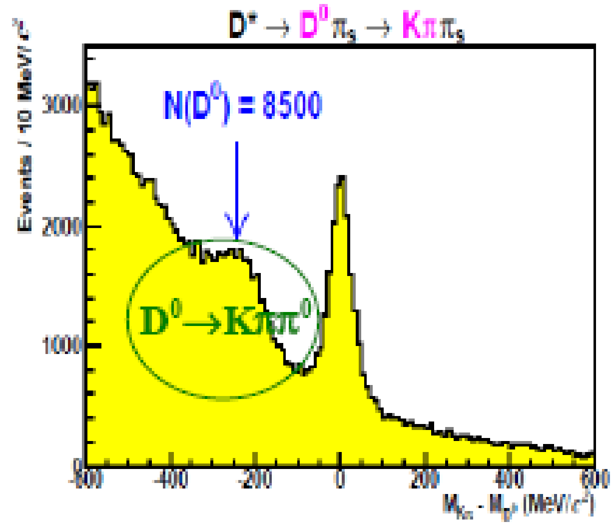
- Each equation is weighted with a signal weight $\omega_S = f\,P_\mu\,a_{LL}\,S/(S+B)$ and also with a background weight $\omega_B = f\,P_\mu\,D\,B/(S+B)$:

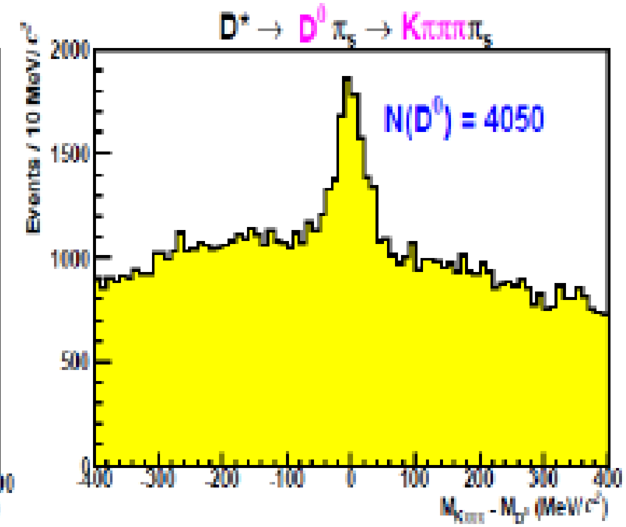
8 equations with 7 unknowns: ΔG/G, A^{bg} + 5 independent $\alpha = (a\phi n)$ factors

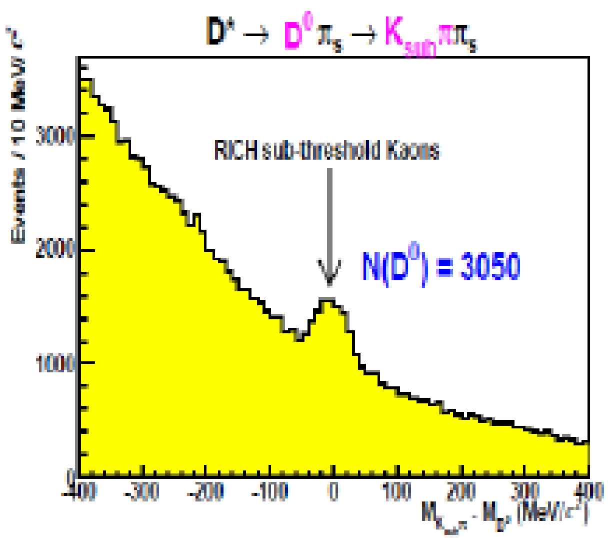
The system is solved by a χ^2 minimisation

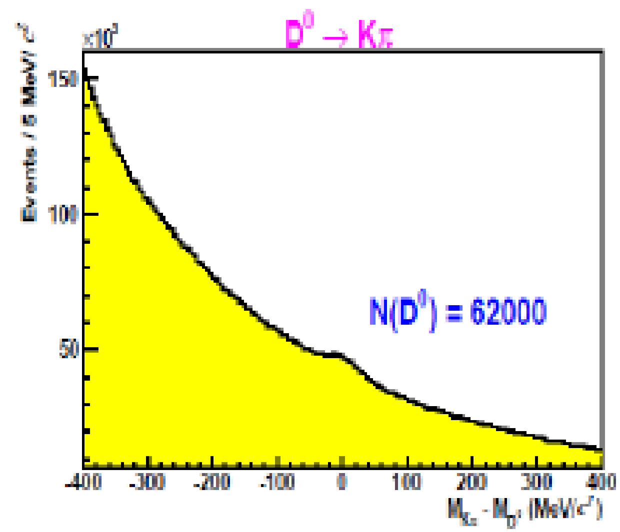
D^0 invariant mass spectra: **All samples** (2002-2007 data)







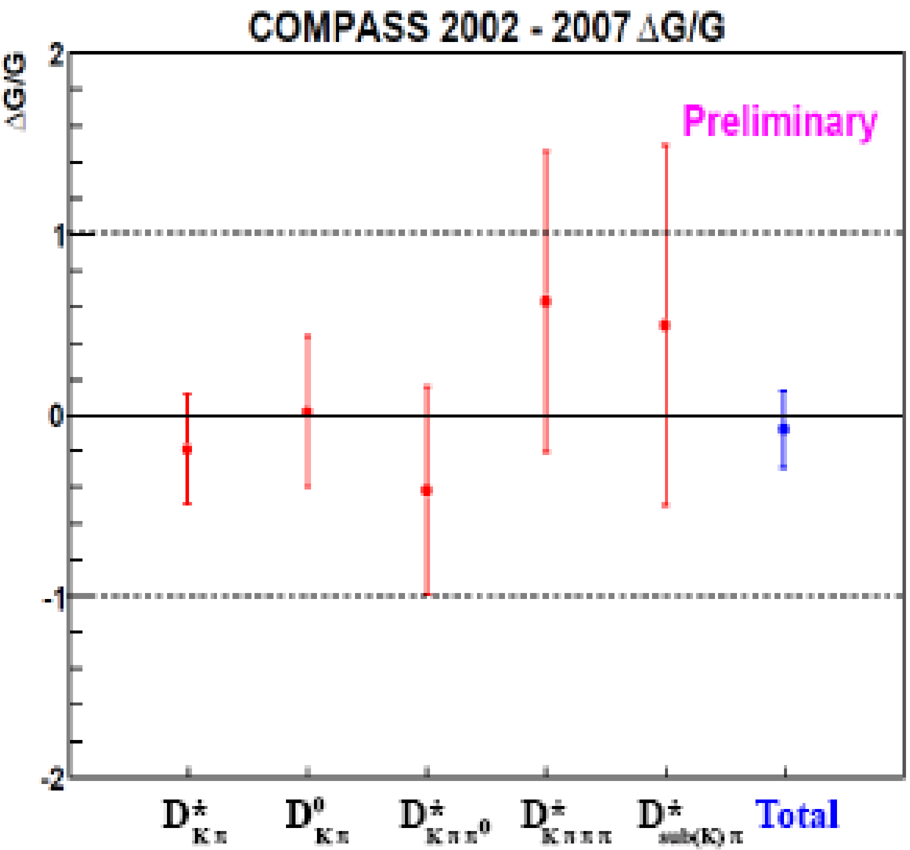


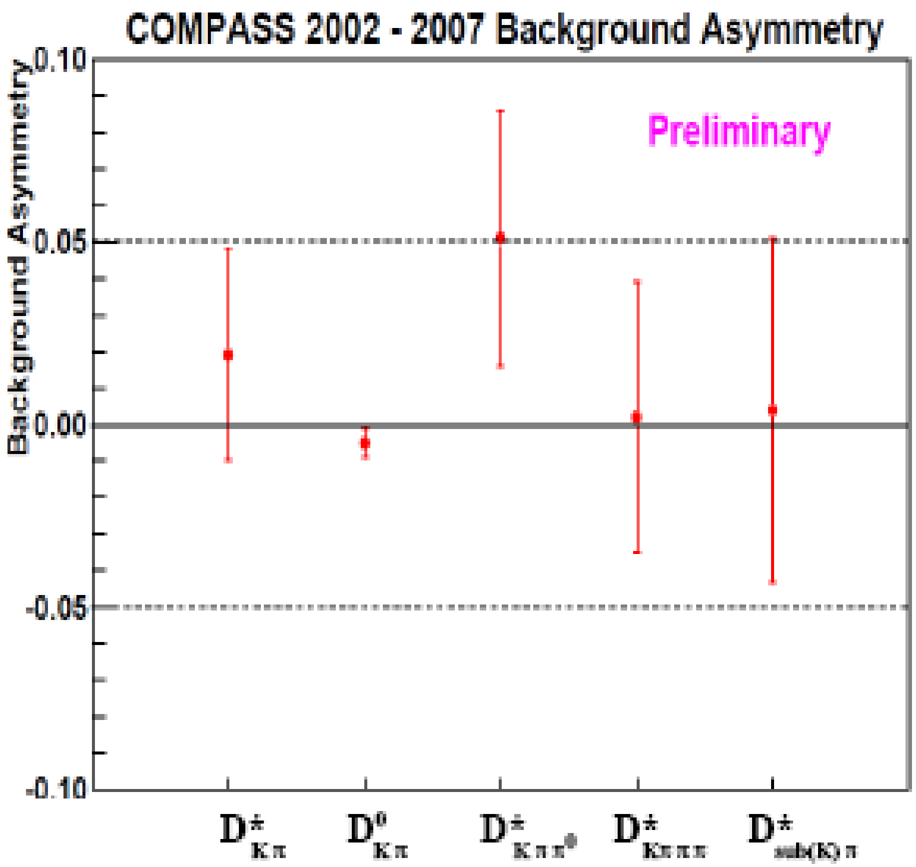


Number of D^0:

- Total → 90600
- ^6LiD → 65600
- NH_3 → 25000

Open Charm results in LO





$$\frac{\Delta G}{G} = -0.08 \pm 0.21(\mathbf{stat}) \pm 0.08(\mathbf{syst}) \quad @ < x_g > = 0.11^{+0.11}_{-0.05}, \ <\mu^2> = 13\ (\mathbf{GeV/c})^2$$

2.3.2.3. High-p_T asymmetries (2002-2006): $Q^2 > 1\ (GeV/c)^2$

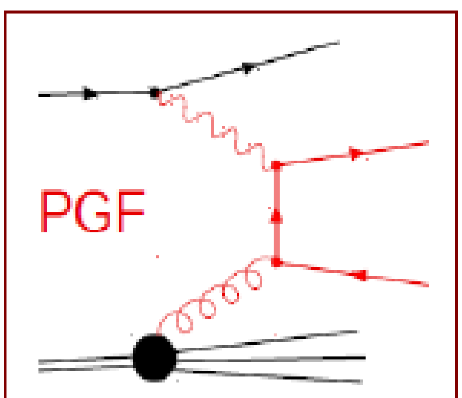
- **Two samples are considered:**

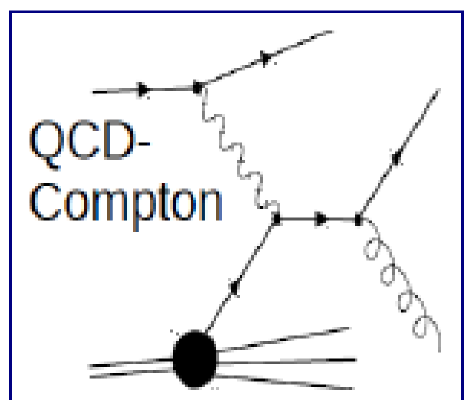
Inclusive asymmetry

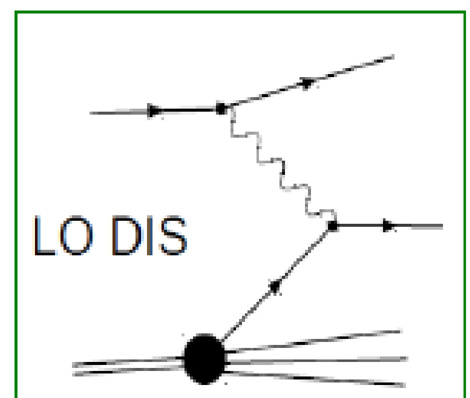
$$A_1^d(x) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF,inc}\frac{\sigma^{PGF,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C,inc}\frac{\sigma^{C,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO,inc}}{\sigma^{Tot,inc}}\right)$$

$$A_{LL}^{2h}(x) = \left(\frac{A^{exp}}{f\,P_\mu P_T}\right) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF}\frac{\sigma^{PGF}}{\sigma^{Tot}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C}\frac{\sigma^{C}}{\sigma^{Tot}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO}}{\sigma^{Tot}}\right)$$

high-p_T hadron pairs (p_{T1} / p_{T2} > 0.7 / 0.4 GeV/c) $\Rightarrow$ enhancement of the PGF contribution







Extraction of ΔG/G from high-p_T: $Q^2 > 1\ (\mathrm{GeV}/c)^2$

- The gluon polarisation is determined from two asymmetry samples: the two high-p_T hadrons and the inclusive data samples. **The final formula is:**

$$\frac{\Delta g}{g}(x_g) = \frac{1}{\beta}\left[A_{LL}^{2h}(x) + A_{corr}\right] \qquad A_{corr} = -\left(A_1(x_{Bj})D\frac{R_{LO}}{R_{LO}^{inc}} - A_1(x_C)\beta_1 + A_1(x_C')\beta_2\right)$$

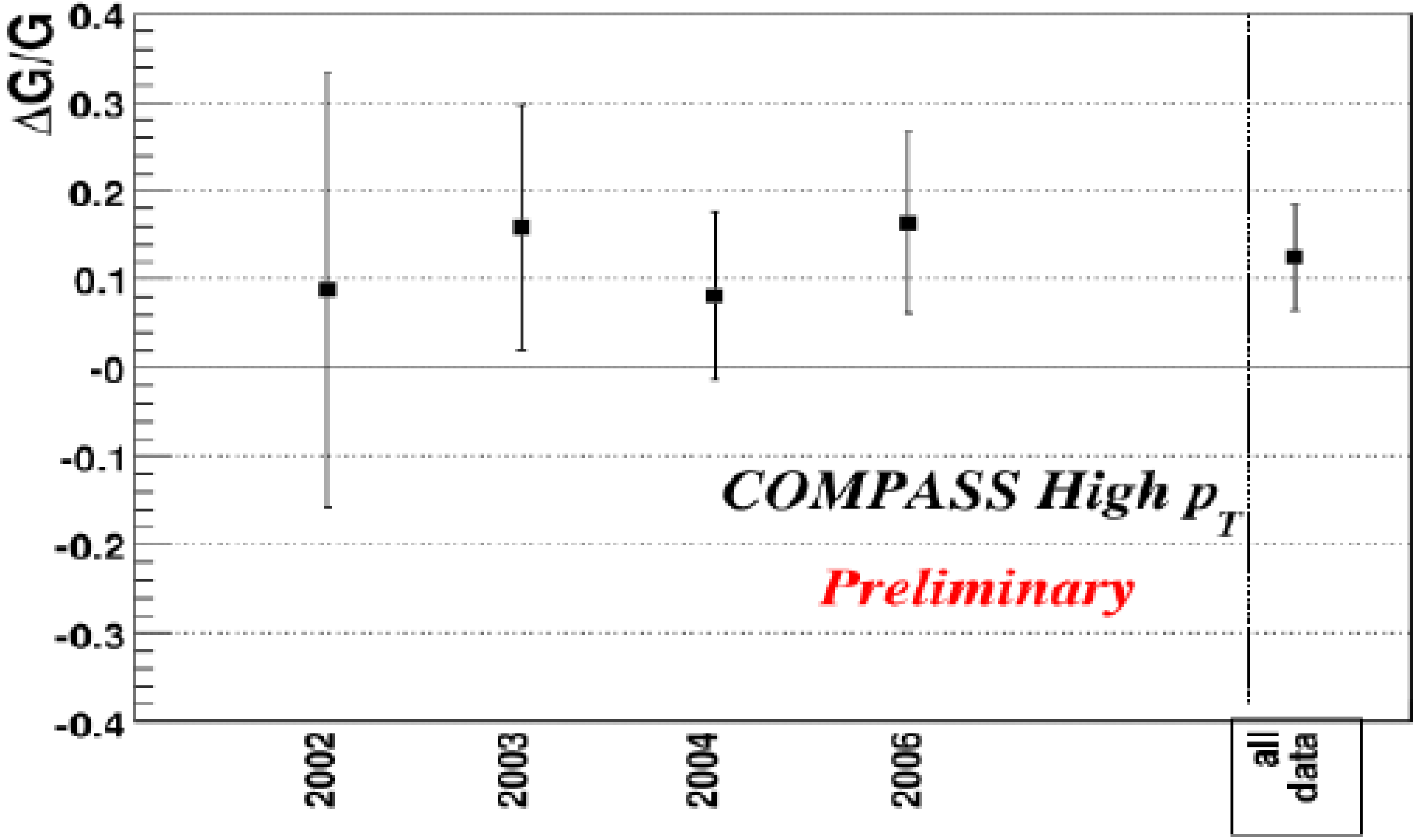
$$\beta = a_{LL}^{PGF}R_{PGF} - a_{LL}^{PGF,inc}R_{PGF}^{incl}\frac{R_{LO}}{R_{LO}^{inc}} - a_{LL}^{PGF,incl}\frac{R_C R_{PGF}^{inc}}{R_{LO}^{inc}}\frac{a_{LL}^{C}}{D}$$

- β_1 and β_2 are factors depending on $a_{LL}{}^{i}$ and R_i
- Each event is weighted with $\omega = f\,D\,P_\mu\,\beta$ → statistical improvement!
- The following parameters are obtained from Monte Carlo, and then they are parameterised event-by-event by a Neural Network (to allow for their use in data):

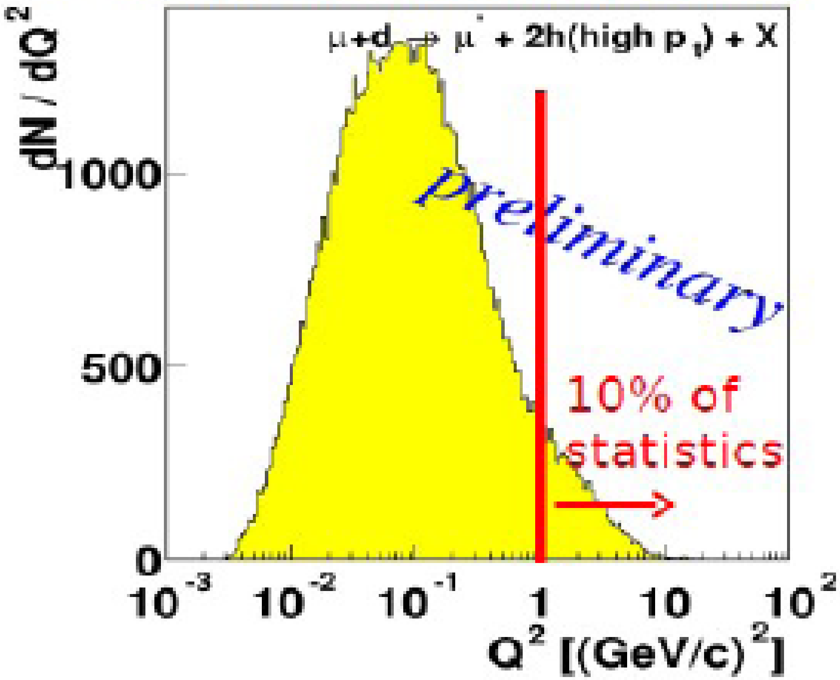
R_{PGF}, R_C, R_{LO}, R_{PGF}^{inc}, R_C^{inc}, R_{LO}^{inc}, a_{LL}^{PGF}, a_{LL}^{C}, a_{LL}^{LO}, $a_{LL}^{PGF,\,inc}$, $a_{LL}^{C,\,inc}$ and $a_{LL}^{LO,\,inc}$

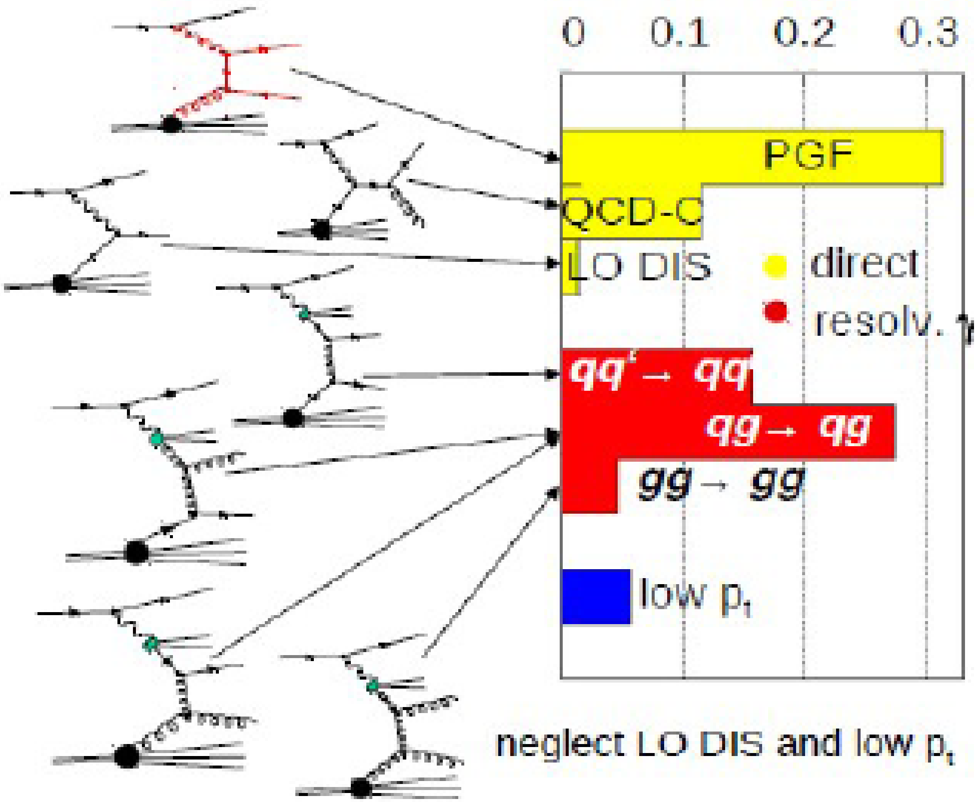
High-p_T results: $Q^2 > 1\ (GeV/c)^2$

$$\frac{\Delta G}{G} = 0.125 \pm 0.060(\mathrm{stat}) \pm 0.063(\mathrm{syst}) \quad @ <x_g> = 0.09^{+0.08}_{-0.04}\ ,\ <\mu^2> = 3.4\ (\mathrm{GeV/c})^2$$



High-p_T analysis: $Q^2 < 1\ (GeV/c)^2$





2002-2004 Preliminary:

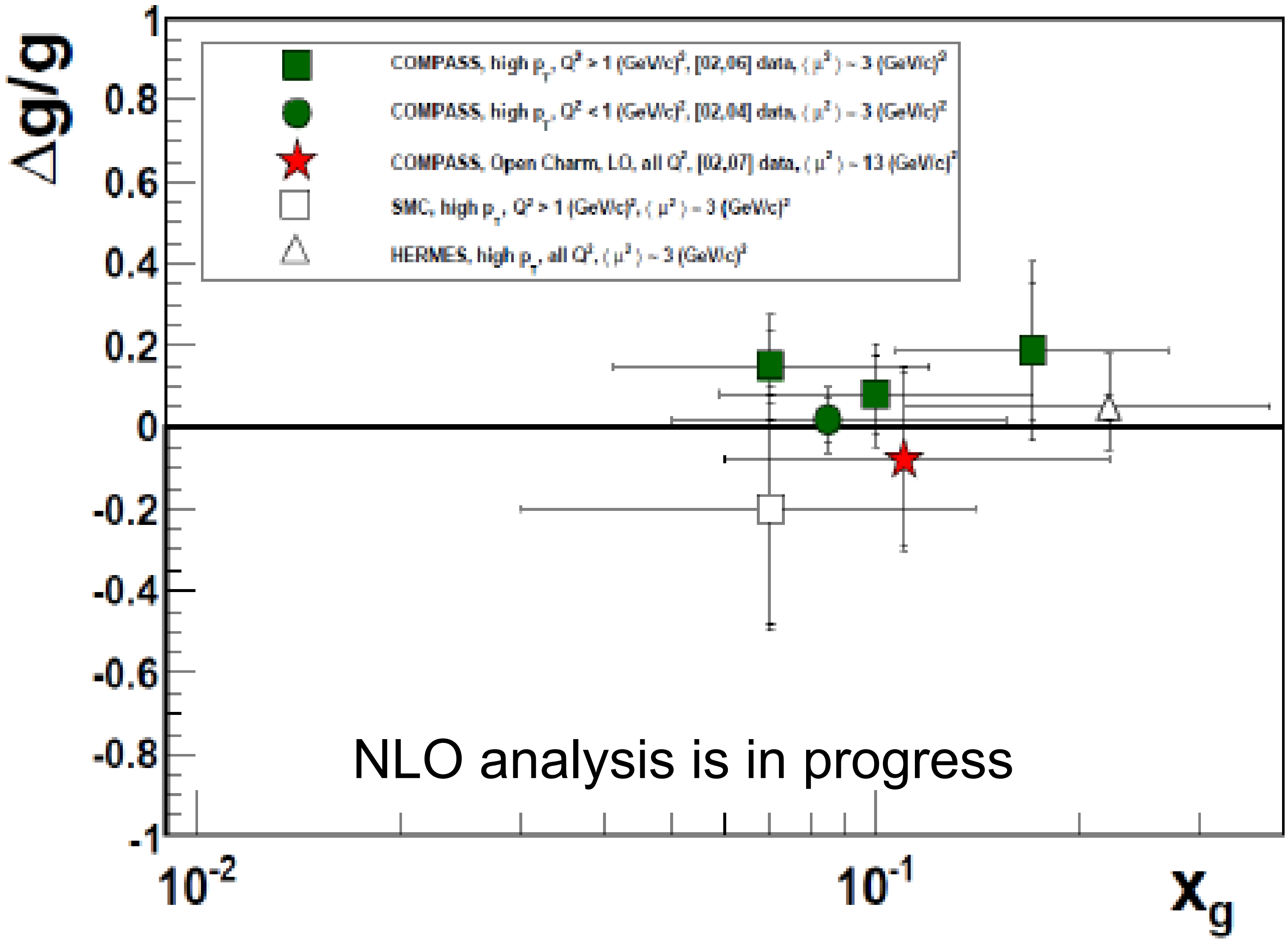
$\Delta G/G = 0.016 \pm 0.058\ (stat) \pm 0.055\ (syst)$

2002-2003 Published:

$\Delta G/G = 0.024 \pm 0.089\ (stat) \pm 0.057\ (syst)$ → *Phys. Lett. B 633 (2006) 25 - 32*

2.3.2.4. World measurements on ΔG/G in LO

Gluon contributions to the nucleon spin are small.



3. DIS from transversely polarised targets. Transverse Spin and Transverse Momentum effects in SIDIS.

3.1.Transverse Spin & Momentum structure of nucleons

3.2. Results on the Azimuthal modulations (AM) with T-targets

3.3. Results on the AM with L-targets

3.1.Transverse Spin and Momentum structure of the Nucleon

Three distribution functions are necessary to describe the quark structure of the nucleon at Twist-2 (LO) in the **collinear case:** f_1 , g_1 *and* h_1

Transversity PDF, h_1 or $\Delta_T q$, describes correlation between the transverse spin of the nucleon and the transverse spin of the quark.

Taking into account the **quark intrinsic transverse momentum,** k_T, additionally 5 PDFs ("TMDs") are needed for a full description of the nucleon structure at LO….

		nucleon polarisation		
		U	L	T
quark polarisation	U	f_1 *number density* q		
	L		g_1 - *helicity* Δq	
	T			h_1 - *transversity* $\Delta_T q$

....additional to the "colinear" are PDFs:

Sivers function $f_{1T}^{\perp}$, correlation between the transverse spin of the nucleon and the transverse momentum of the quark in T-polarised nucleons,

Boer-Mulders function $h_1^{\perp}$ - correlation between the transverse spin and the transverse momentum of the quark in unpolarised nucleons,

$h_{1L}^{\perp}$ ($h_{1T}^{\perp}$) - similar to Boer-Mulders, but in L (T) polarised nucleons,

g_{1T} - similar to g_1 , but

in T- polarised nucleons .

nucleon polarisation

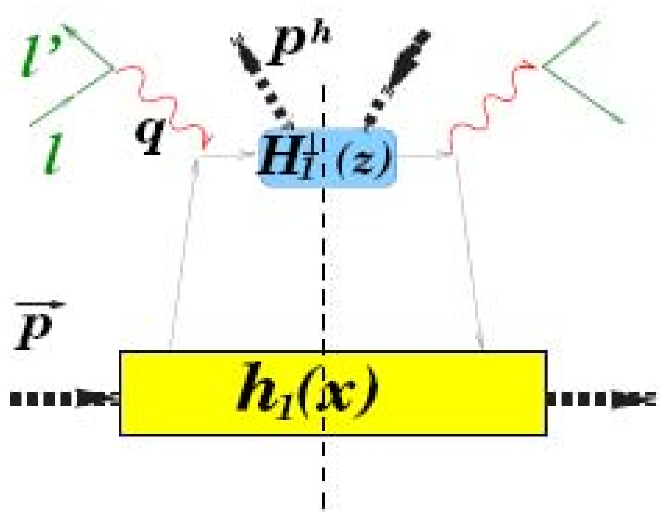
quark polarisation	U	L	T	
U	f_1 *number density* q		$f_{1T}^{\perp}$ - *Sivers*	$\Delta_0^T q$
L		g_1 - *helicity* Δq	g_{1T} -	
T	$h_1^{\perp}$ - *Boer - Mulders*	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ -	$\Delta_T q$

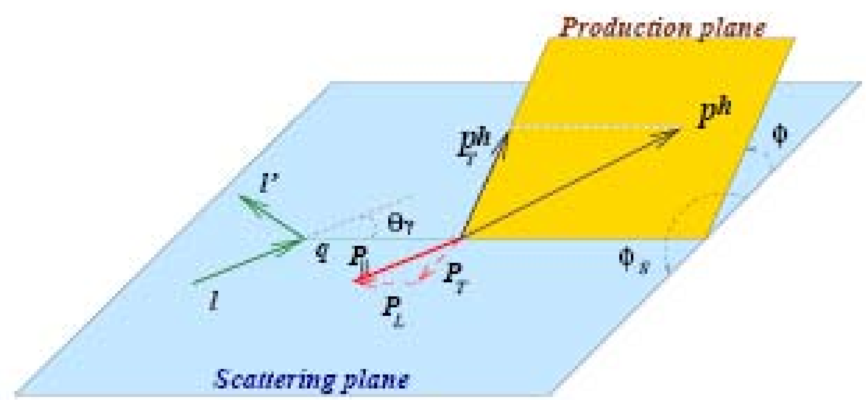
T-odd TMDs

The azimuthal distributions of hadrons in SIDIS of leptons off T-, L- and Un-polarised targets are sources of information on new PDFs and PFFs, characterizing the longitudinal and transverse spin structure of nucleons, e.g.:

$$d\sigma_h / d\phi \sim h_1(x) \otimes H_1^{\perp}(z) \cdot \sin\phi + \ldots$$

$$\ell + \overline{N} \rightarrow \ell' + X + h$$





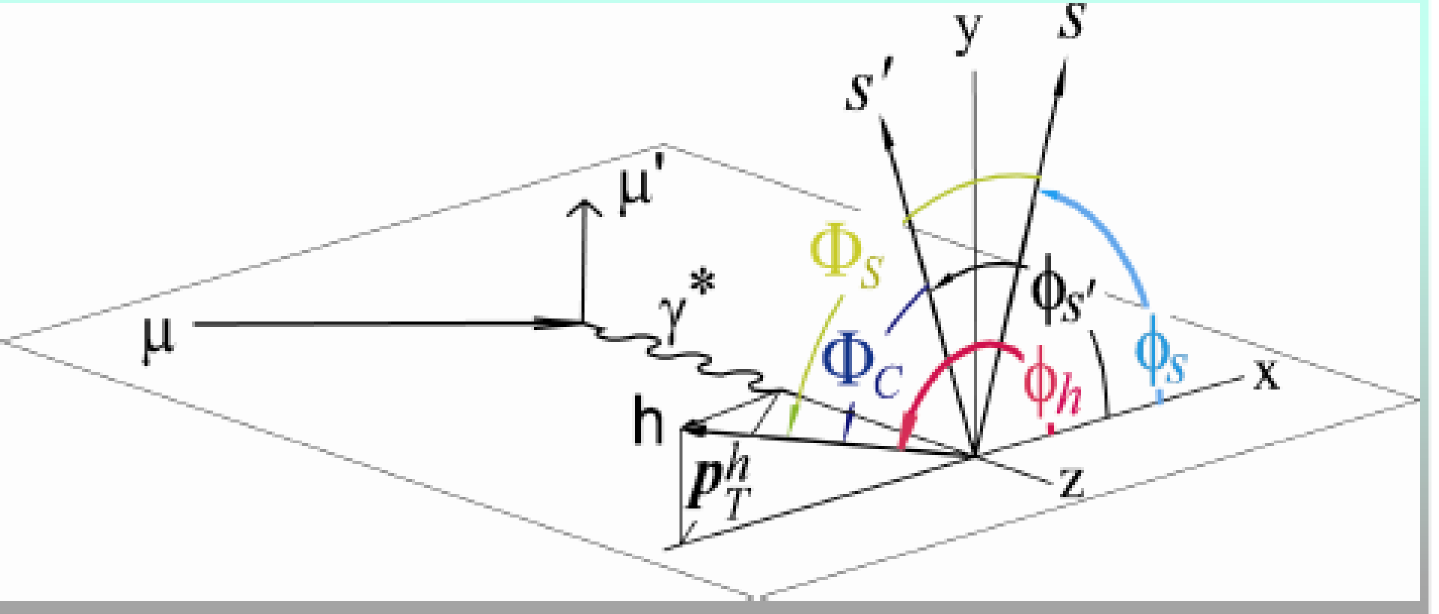
A number of PDF's and PFF's enter in total SIDIS cross section. They are characterizing by modulations vs. various azimuthal angles, particulary vs. Collins or Sivers angles.

Azimuthal modulations

Collins and Sivers angles

$\Phi_C = \phi_h - \phi_{S'}$

$\Phi_S = \phi_h - \phi_S$



$\phi_{S'}$ azimuthal angle of spin vector of fragmenting quark ($\phi_{S'} = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

The amplitudes of modulations have forms:

$$F_{BT}^{mod} \propto x \sum_q e_q^2 \; f^q \otimes D_q^h$$

any TMD PDF (f^q)

corresponding FF (D_q^h)

The measurements of the modulation amplitudes using different targets with different polarizations and looking at different final state hadrons give information on the different TMD PDFs for the different quark flavors q

General expression for the SIDIS cross section

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

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

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

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

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

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

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

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

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

14 azimuthal modulations

$\phi_{h\,(S)}$ hadron (nucleon spin) azimuthal angle in GNS

3 with **unpolarised** target

3(5) with **L polarised** target

8 with **T polarised** target

they can be measured from the same data

A Bacchetta et al., 2006

3.2.Results on azimuthal modulations with transverse target polarization:

3.2.1. "Collins asymmetry"

"Collins asymmetry":

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

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

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

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

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

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

$h_1 H_1^\perp$

“Collins” asymmetry is characterised by the

amplitude $F_{UT}^{\sin(\phi_h+\phi_S)}$ of the $\sin(\phi_h+\phi_S-\pi)$ modulation in the azimuthal distribution of the final state hadrons

transversity

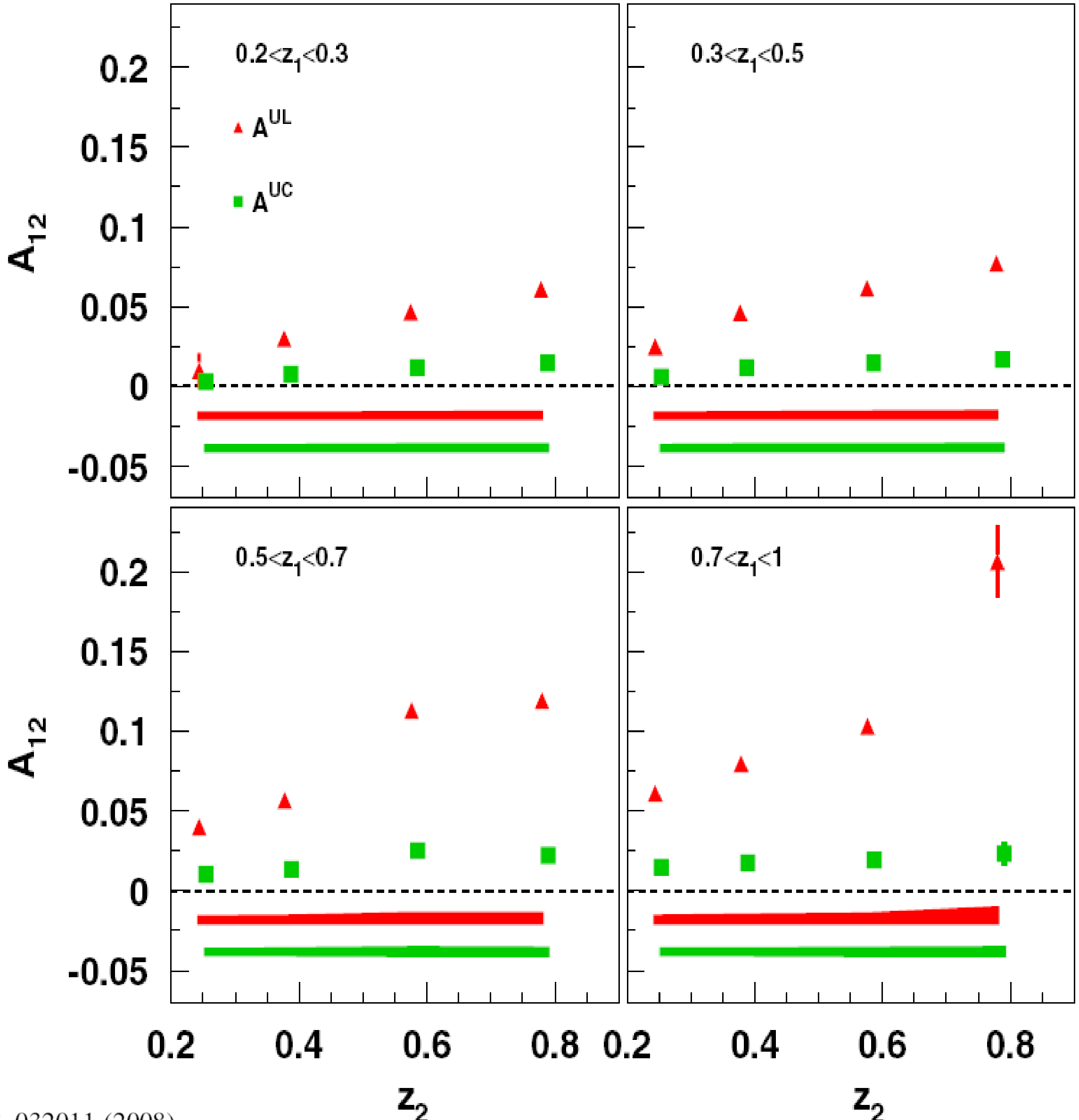
“Collins FF”

$$A_{Coll} \approx \frac{\sum_q e_q^2\, \Delta_T q \otimes \Delta_T^0 D_q^h}{\sum_q e_q^2\, q \otimes D_q^h}$$

It can be measured from one hadron , two hadron azimuthal modulations and Lambda polarisation in SIDIS and from the data on $e^+e^- \rightarrow \pi^+\pi^- X$ at Belle,where pions are from two differend jets.

"Collins" @ Belle

Asymmetries are proportional to the product of two Collins FFs



PHYSICAL REVIEW D **78,** 032011 (2008)

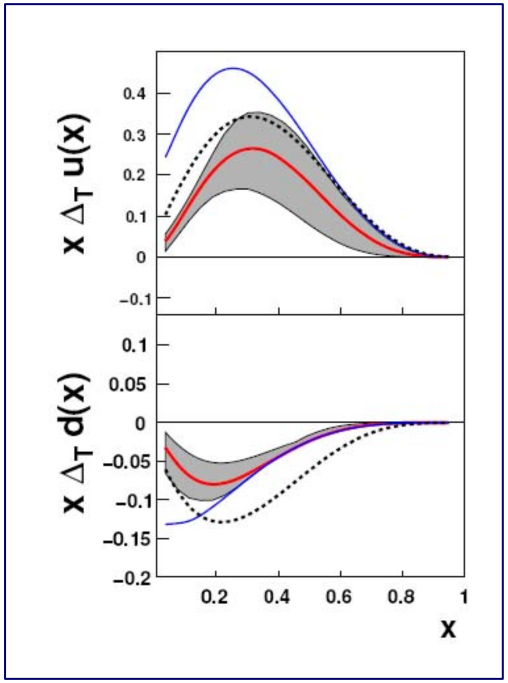
“Collins” asymmetry

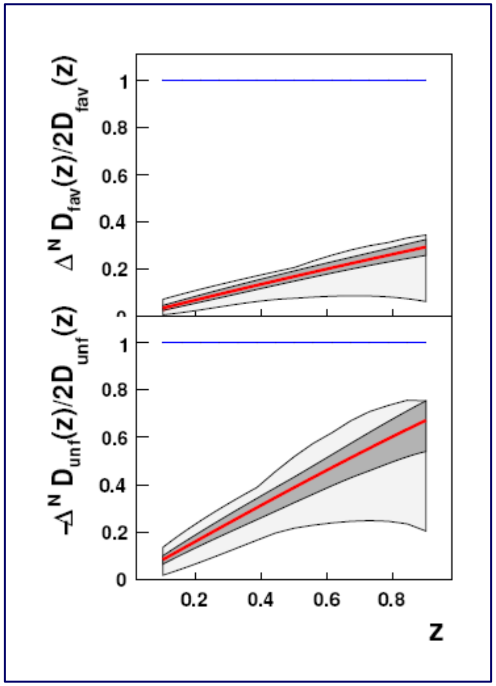
2005

- **first strong signals seen by HERMES on protons: MILESTONE!**
- **no signal seen by COMPASS on deuterons**

the COMPASS d, HERMES p, and BELLE data are well described in global fits

→ *first extractions of the Collins FFs and the transversity PDFs*

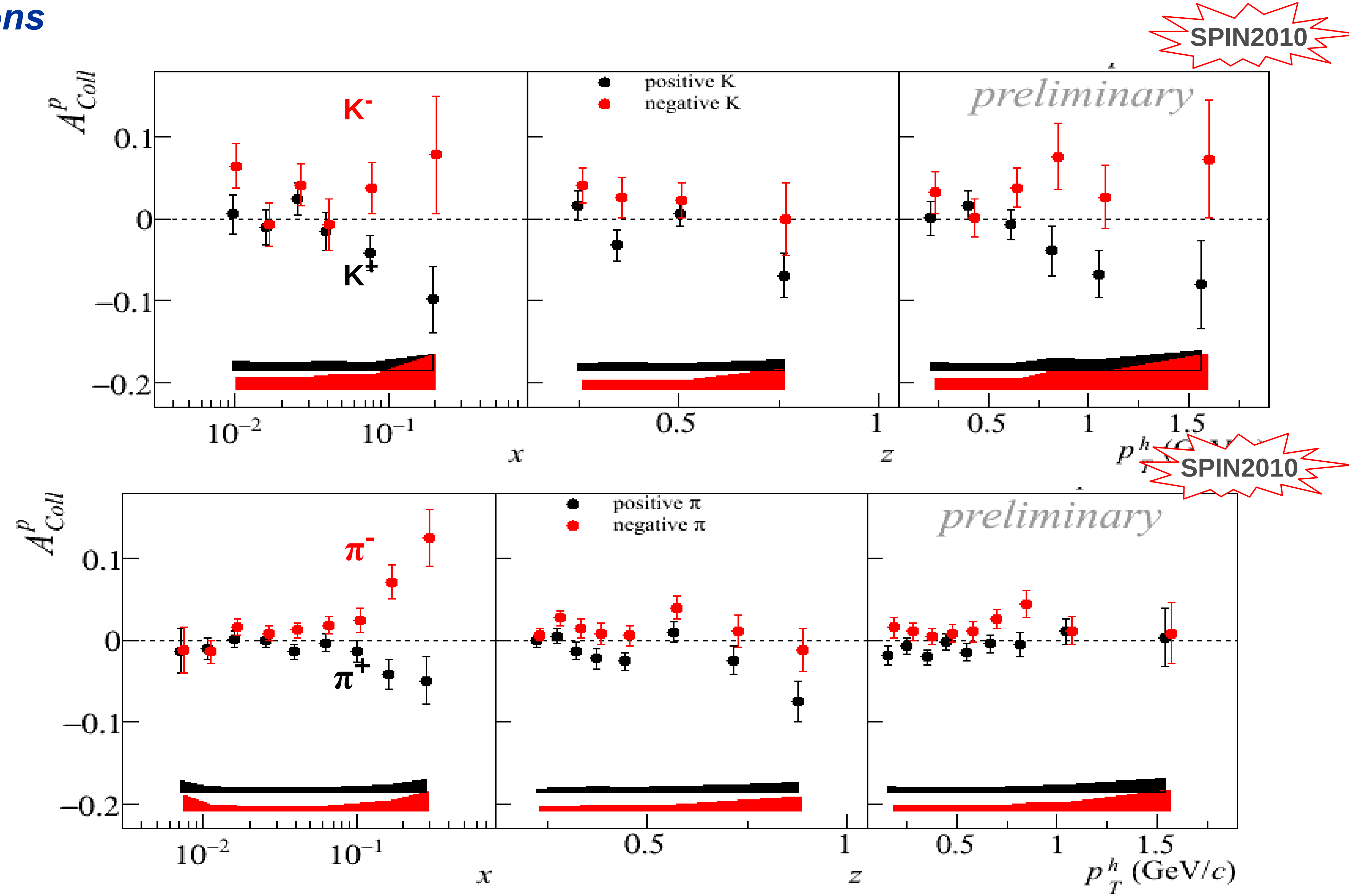




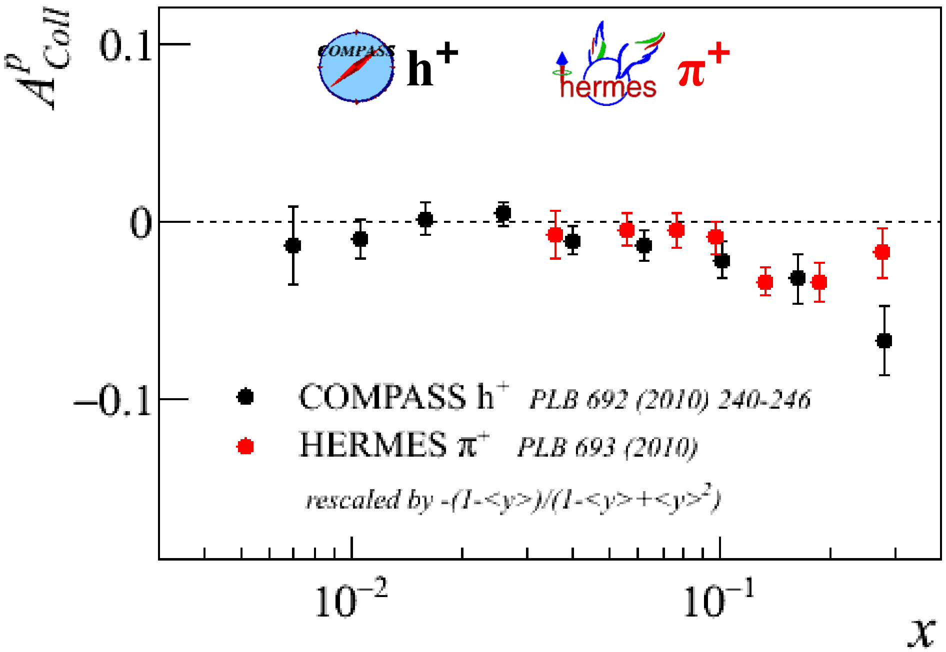
M. Anselmino et al.,
Nucl.Phys.Proc.Suppl.191 (2009) 98

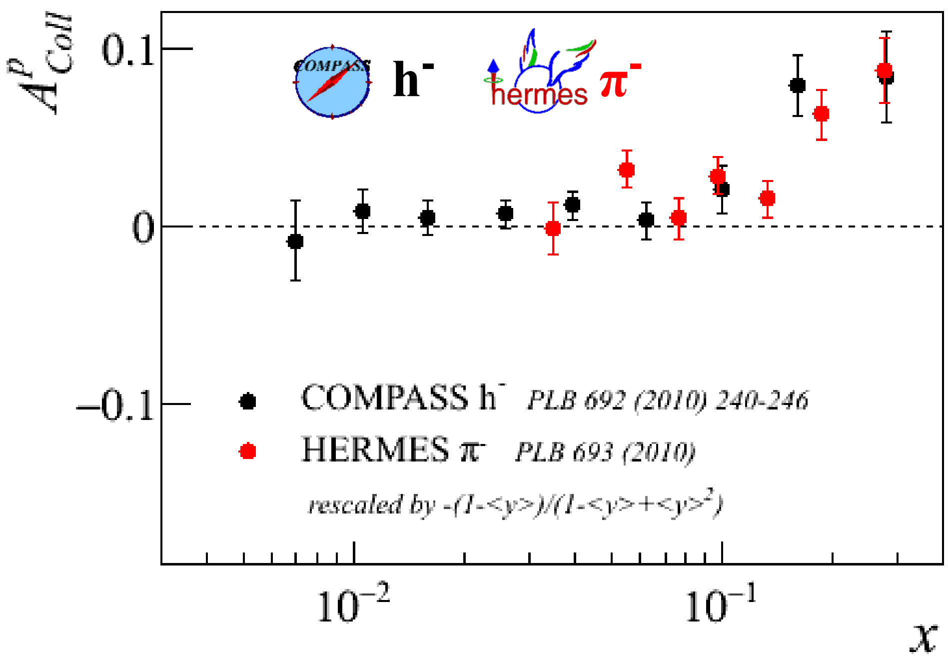
"Collins" asymmetry - proton

COMPASS results from 2007 data for Kaons and pions: compatible with ze
at small x, large signal in valence region of opposite signs for pos and neg hadrons



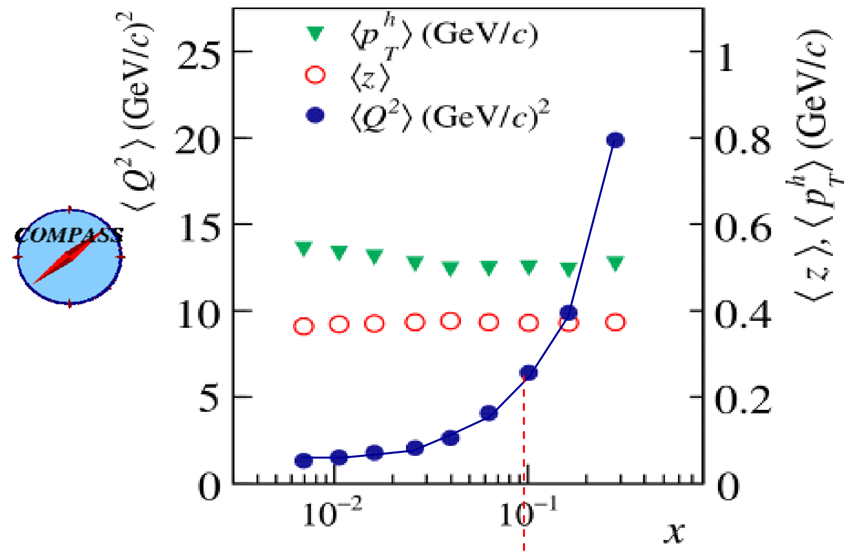
“Collins” asymmetry – proton: Hermes vs. COMPASS

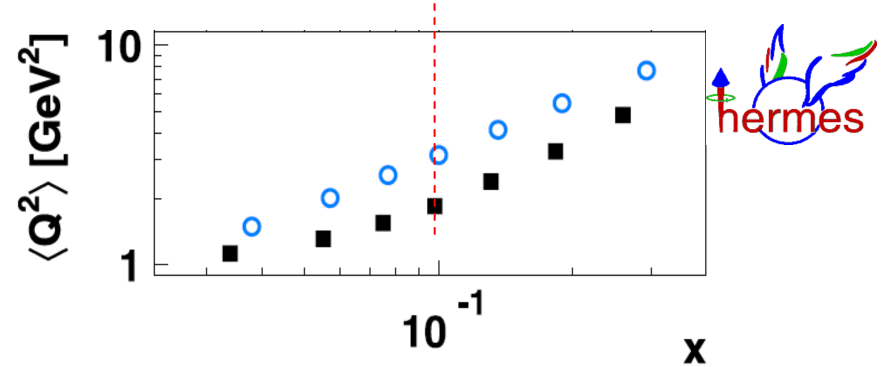




same sign and strength:
a very important, not obvious result!

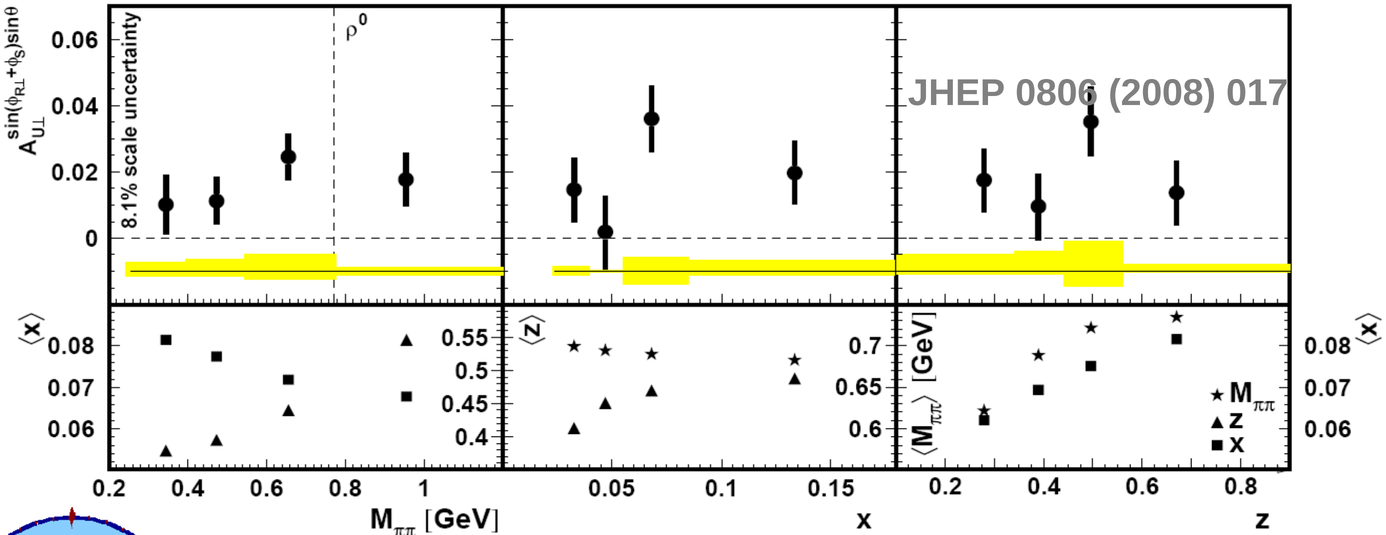
indication for: not a higher twist effect,
weak Q^2 dependence of the Collins FF





COMPASS sign convention

Two Hadron Asymmetry



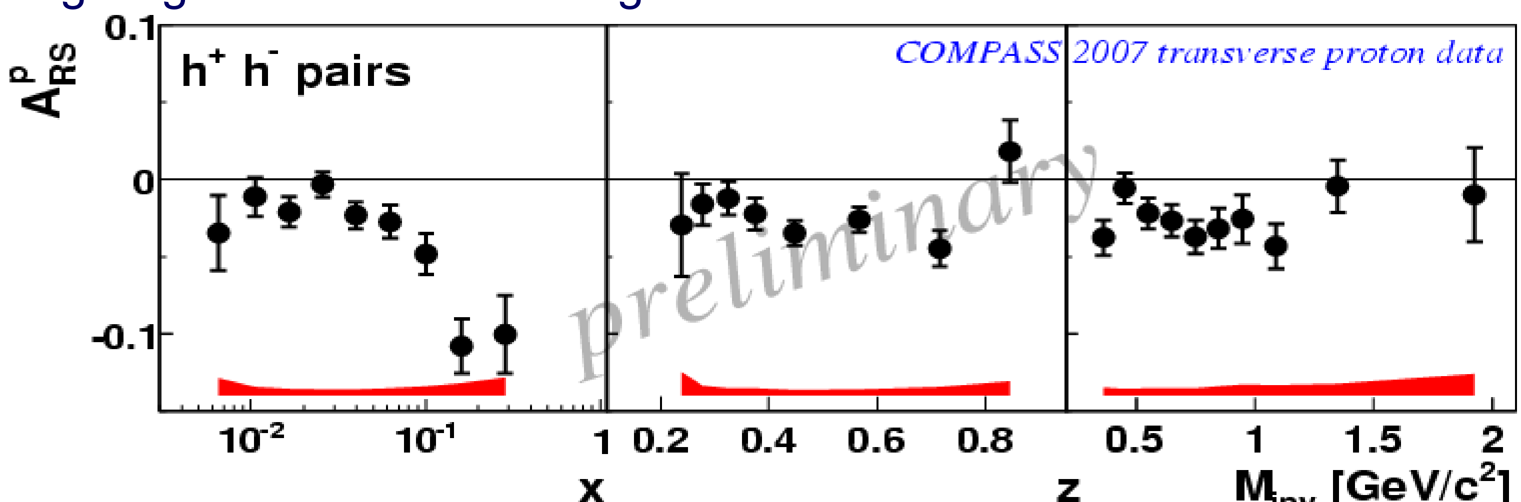
transversely polarised protons:

first evidence for a different from zero interference FF

deuteron: compatible with zero at all x, for all the used combinations

proton: large signal in the valence region

- sign in agreement with the Collins asymmetry
- strength ~ larger than the Collins asymmetry



same sign, higher values from COMPASS than from HERMES

different kinematics and extraction

difficult to describe both sets of data at the same time

Results on azimuthal modulations with transverse target polarization

3.2.4. “Sivers” asymmetry

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

“Sivers” asymmetry: $A_{Siv} \approx \dfrac{\sum_q e_q^2\, f_{1T}^{\perp q} \otimes D_1^q}{\sum_q e_q^2\, f_1 \otimes D_1^q}$

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

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

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

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

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

“Sivers” asymmetry

$$F_{UT,T}^{\sin(\phi_h - \phi_S)}$$

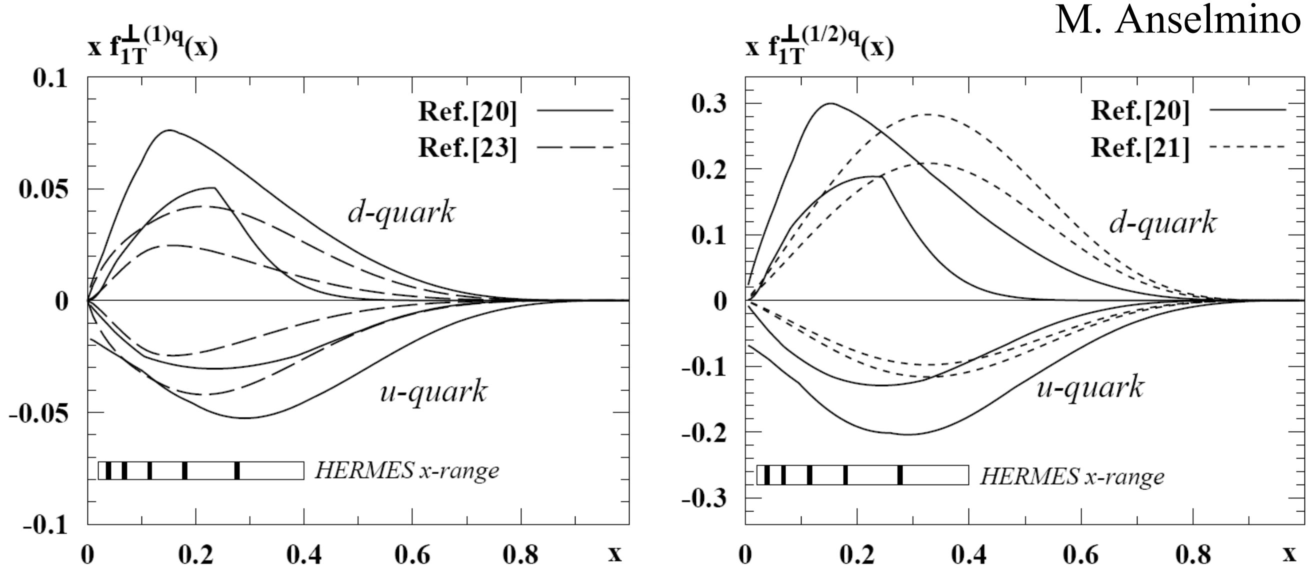
2005

- **first strong signal seen by HERMES for π^+ on protons**
- **no signal seen by COMPASS for h^+ and h^- on deuterons**

→ first extractions of the Sivers function from HERMES p (and COMPASS d) data

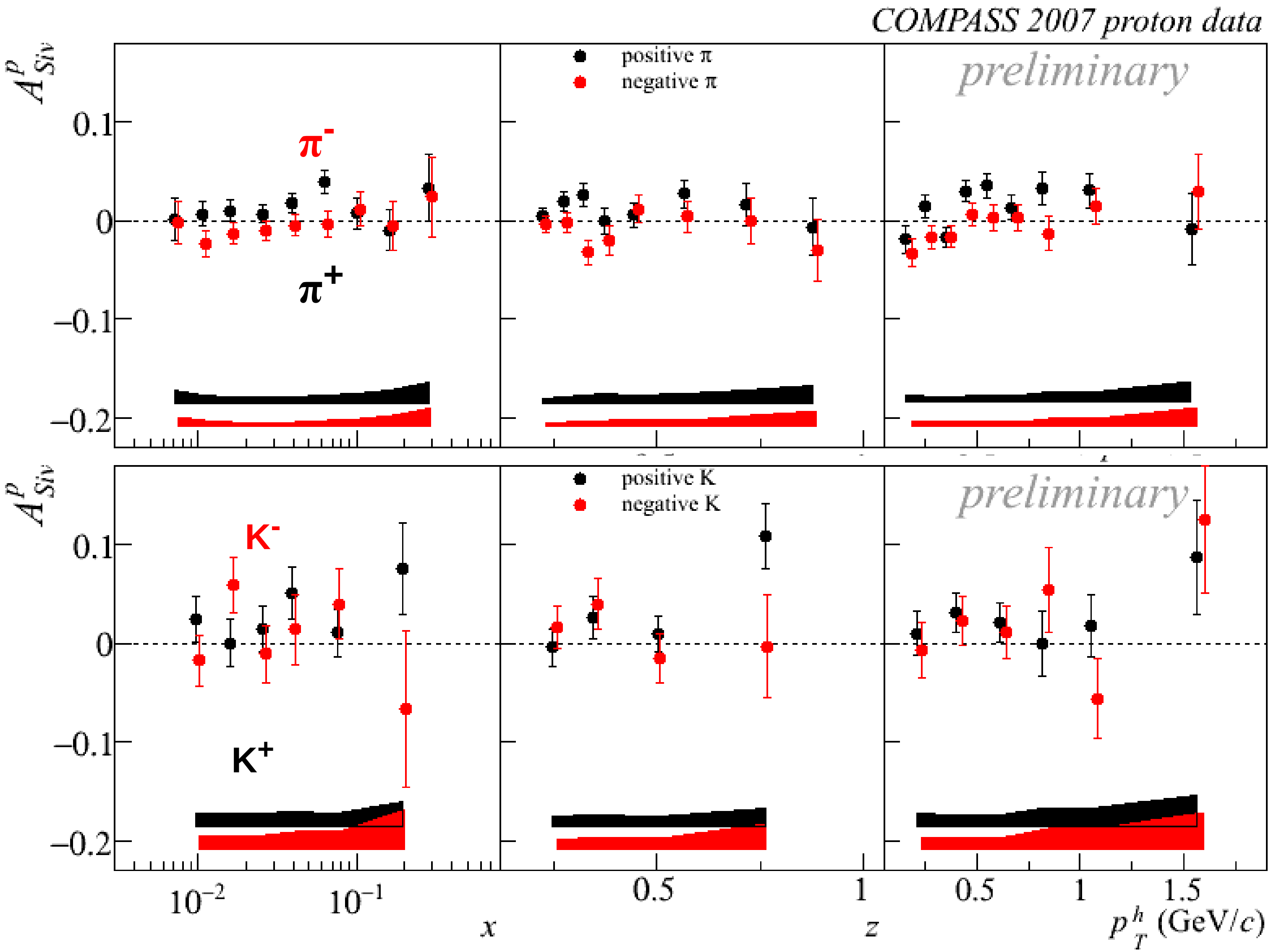
good description of the experimental results

M. Anselmino et al., Transversity2005



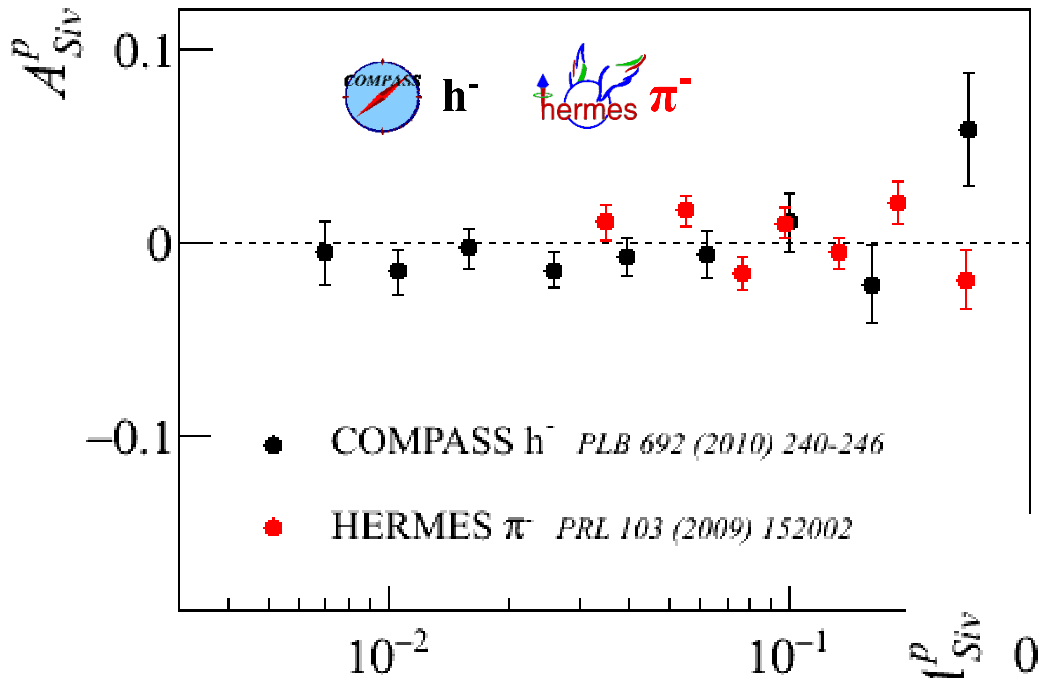
“Sivers” asymmetry - proton

COMPASS results from 2007 data

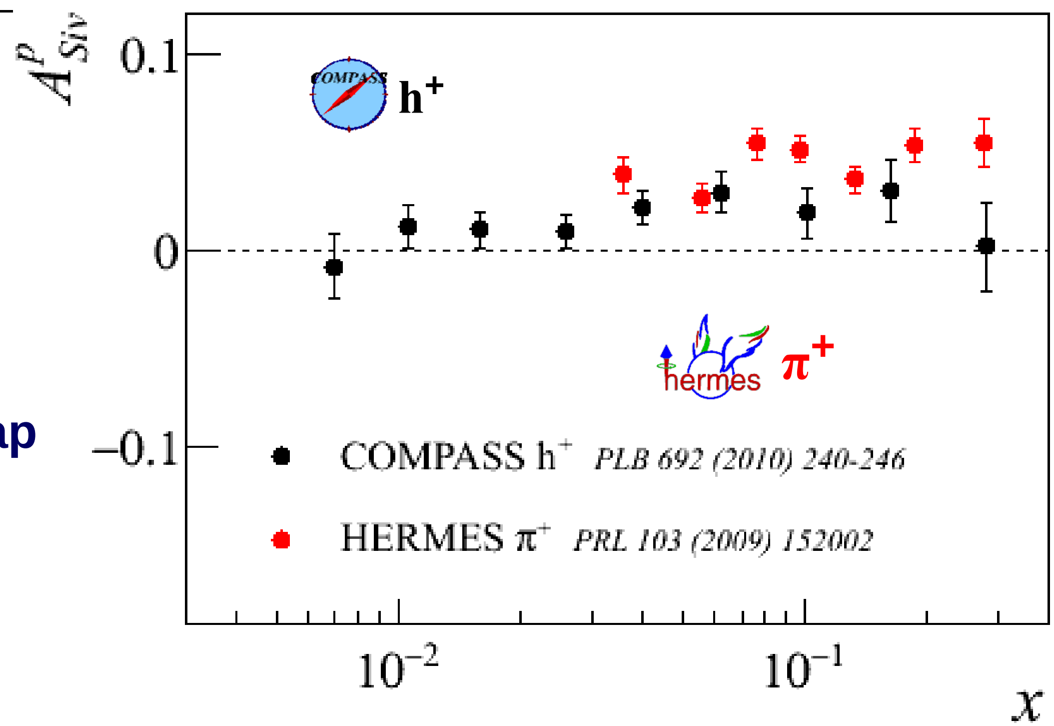


SPIN2010

Sivers asymmetry - proton



good agreements



- **same sign**
- **COMPASS results in the overlap region smaller by a factor ~ 2**

Results on azimuthal modulations with transverse target polarisation.

3) 6 other asymmetries

preliminary results

all the other 6 are small, compatible with zero both on p and d

$F_{LT}^{\cos(\phi_h-\phi_S)}$ **positive for π- on ^{3}He at JLab E06-010**

hermes $F_{UT}^{\sin\phi_S}$ **different from zero**

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

$$+ |\boldsymbol{S}_\perp| \Big[\sin(\phi_h-\phi_S) \Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon \ldots \Big)$$

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

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

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

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

$g_{1T} D_1$

Results on azimuthal modulations with longitudinal target polarisation

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

twist 3

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

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

twist 3

$h_{1L}^{\perp} H_1^{\perp}$

worm-gear

COMPASS: **no clear signal** (on deuteron)	EPJC 70 (2010) 39
$F_{UL}^{\sin 2\phi_h}$ **from CLAS**	arXiv:1003.4549
$F_{UL}^{\sin\phi_h}$ **from HERMES** (hermes)	... PLB 562(2003)182 PLB 622(2005)14

The cross section and L-asymmetry of the h production in SIDIS:

$$d\sigma = d\sigma_{00} + P_\mu d\sigma_{L0} + P_L\left(d\sigma_{0L} + P_\mu d\sigma_{LL}\right) + \left|P_T\right|\left(d\sigma_{0T} + P_\mu d\sigma_{LT}\right),$$

$$a(\phi) = \frac{d\sigma^{\leftarrow\Rightarrow} - d\sigma^{\leftarrow\Leftarrow}}{d\sigma^{\leftarrow\Rightarrow} + d\sigma^{\leftarrow\Leftarrow}} \sim \left|P_L\right|\left(d\sigma_{0L} + P_\mu d\sigma_{LL}\right) + \left|P_L\right| tg(\theta_\gamma)(d\sigma_{0T} + P_\mu d\sigma_{LT}) \ ,$$

where contributions to σ_{ij} (i=beam, j= target polarizations) from each quark and antiquark (up to the order of (M/Q)) have forms:

Twist 3

$$d\sigma_{0L} \propto \ \in x h_{1L}^{\perp}(x) \otimes H_1^{\perp}(z)\sin(2\phi) + \sqrt{2\in(1-\in)}\,\frac{M}{Q}x^2\left[h_L(x)\otimes H_1^{\perp}(z) + f_L^{\perp}(x)\otimes D_1(z)\right]\sin(\phi),$$

helicity | Twist 3

$$d\sigma_{LL} \propto \sqrt{1-\in^2}\quad x g_{1L}(x)\otimes D_1(z) + \sqrt{2\in(1-\in)}\,\frac{M}{Q}x^2\left[g_L^{\perp}(x)\otimes D_1(z) + e_L(x)\otimes H_1^{\perp}(z)\right]\cos(\phi),$$

transversity | pretzelosity

$$d\sigma_{0T} \propto \quad \in[x h_1(x)\otimes H_1^{\perp}(z)\sin(\phi+\phi_S) + x h_{1T}^{\perp}(x)\otimes H_1^{\perp}(z)\sin(3\phi-\phi_S)$$

Sivers

$$-x f_{1T}^{\perp}(x)\otimes D_1(z)\sin(\phi-\phi_S)]\ ,$$

Mulders&Tangerman
Boer&Mulders
Bucchetta et al.

$\otimes$=convolution in k_T

$$d\sigma_{LT} \propto \quad \sqrt{1-\in^2}\, x g_{1T}(x)\otimes D_1(z)\cos(\phi-\phi_S). \quad ,$$ $\phi_S = 0$ for L-target

Method of the analysis

$$R_f(\phi) = \frac{N^U_{+f}(\phi)}{N^D_{-f}(\phi)} \cdot \frac{N^D_{+f}(\phi)}{N^U_{-f}(\phi)} = \frac{C^U_f(\phi) L^U_{+f} \sigma_+(\phi)}{C^D_f(\phi) L^D_{-f} \sigma_-(\phi)} \cdot \frac{C^D_f(\phi) L^D_{+f} \sigma_+(\phi)}{C^U_f(\phi) L^U_{-f} \sigma_-(\phi)} = \frac{\sigma_+(\phi)^2}{\sigma_-(\phi)^2},$$

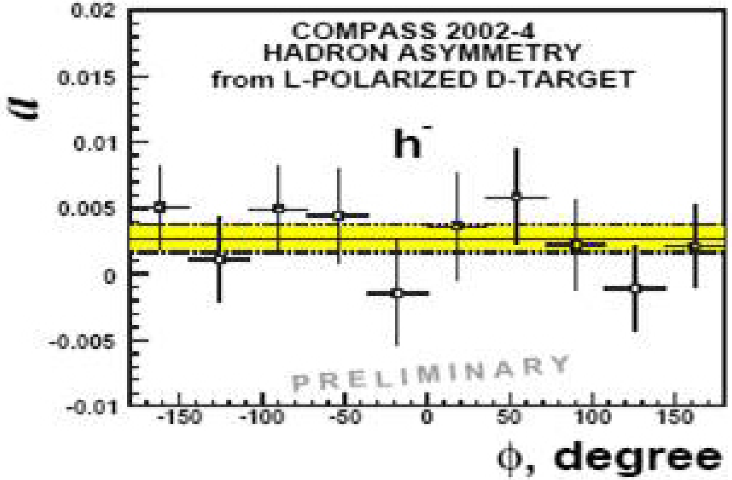
$$R_f(\phi) = \frac{\left(1 + P^U_{+,f} a_f(\phi)\right)\left(1 + P^D_{+,f} a_f(\phi)\right)}{\left(1 - P^D_{-,f} a_f(\phi)\right)\left(1 - P^U_{-,f} a_f(\phi)\right)},$$

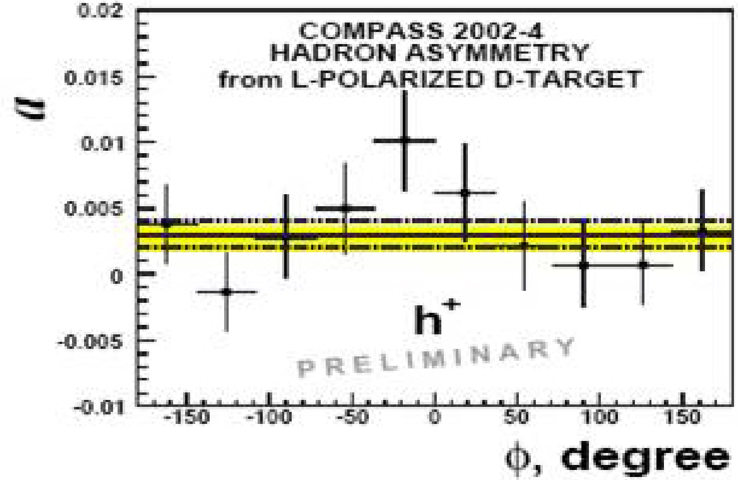
$$a_f(\phi) \approx \frac{R_f(\phi) - 1}{P^U_{+,f} + P^D_{+,f} + P^U_{-,f} + P^D_{-,f}}$$

$$a_+(\phi) \approx a_-(\phi)$$

$$a(\phi) = a_+(\phi) \otimes a_-(\phi) \rightarrow \mathit{final\ results}$$

The weighted sum of azimuthal asymmetries $a(\phi)=a_+(\phi) \otimes a_-(\phi)$ for h^- and h^+ averaged over all kinematical variables :



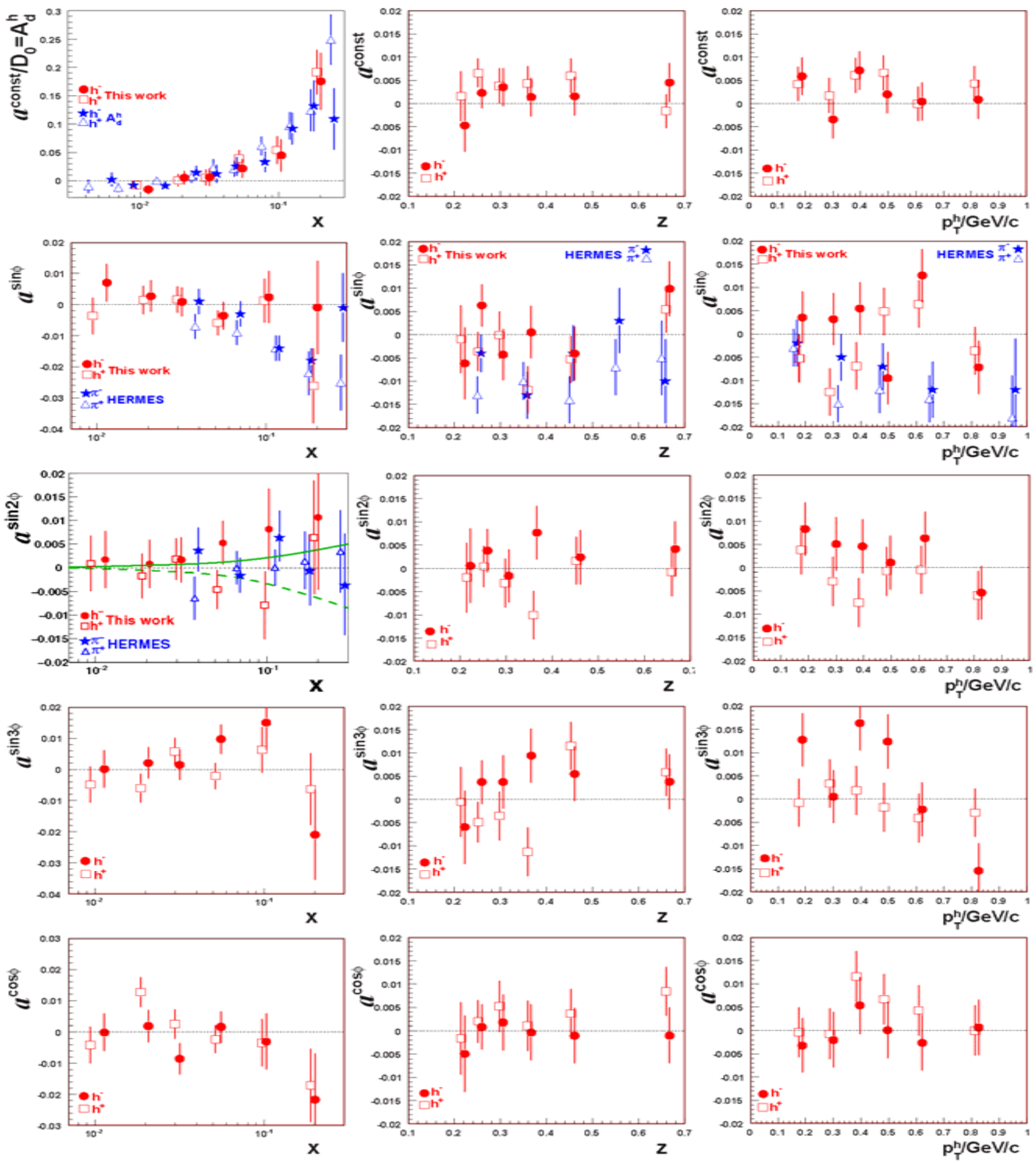


$$a(\phi) = a^{const} + a^{\sin\phi}\sin(\phi) + a^{\sin 2\phi}\sin(2\phi) + a^{\sin 3\phi}\sin(3\phi) + a^{\cos\phi}\cos(\phi) \quad or \quad a(\phi) = a^{const}$$

Fit parameters in units 10^{-4} :

	h^-	h^+	h^-	h^+
$a^{\rm const}$	23 ± 11	35 ± 11	27 ± 11	30 ± 11
$a^{\sin\phi}$	-1 ± 16	-13 ± 15	0	0
$a^{\sin 2\phi}$	20 ± 16	-15 ± 15	0	0
$a^{\sin 3\phi}$	6 ± 16	3 ± 15	0	0
$a^{\cos\phi}$	10 ± 16	24 ± 15	0	0
$\chi^2/n.d.f.$	$3.42/5$	$5.18/5$	$4.82/9$	$8.03/9$

Modulations from L-target. Amplitudes vs . x, z and pT



Agree with data on inclusive asymmetry

Compatible with HERMES

Consistent with zero within statistics

Consistent with zero within statistics

Consistent with zero within statistics

These are data from deuterium. Data from proton will follow.

Azimuthal asymmetries from the unpolarised target

3 independent azimuthal modulations :

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

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

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

twist-3

Preliminary results on sin

COMPASS: positive for positive hadrons (d)

hermes: positive for positive pions (p,d)

CLAS: positive for positive pions (p)

Azimuthal asymmetries from the unpolarised target

3 independent azimuthal modulations

Cahn effect — **Boer - Mulders × Collins FF**

$$\propto \frac{1}{Q}\left(f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp}\right)$$

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

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

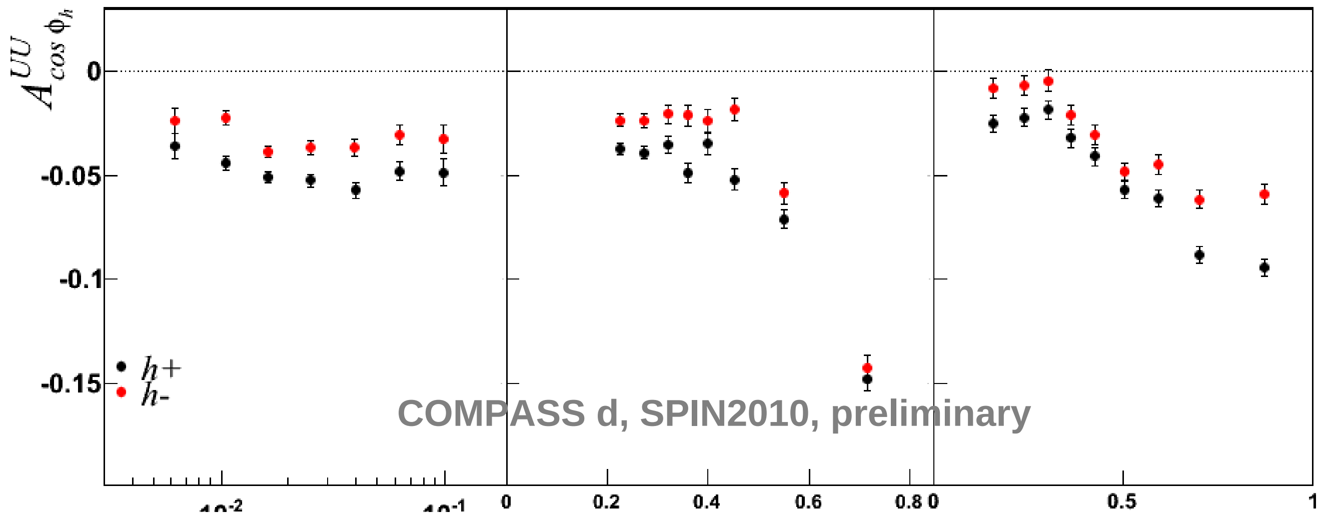
$$\propto h_1^{\perp} \otimes H_1^{\perp} + \frac{1}{Q^2} f_1 \otimes D_1$$

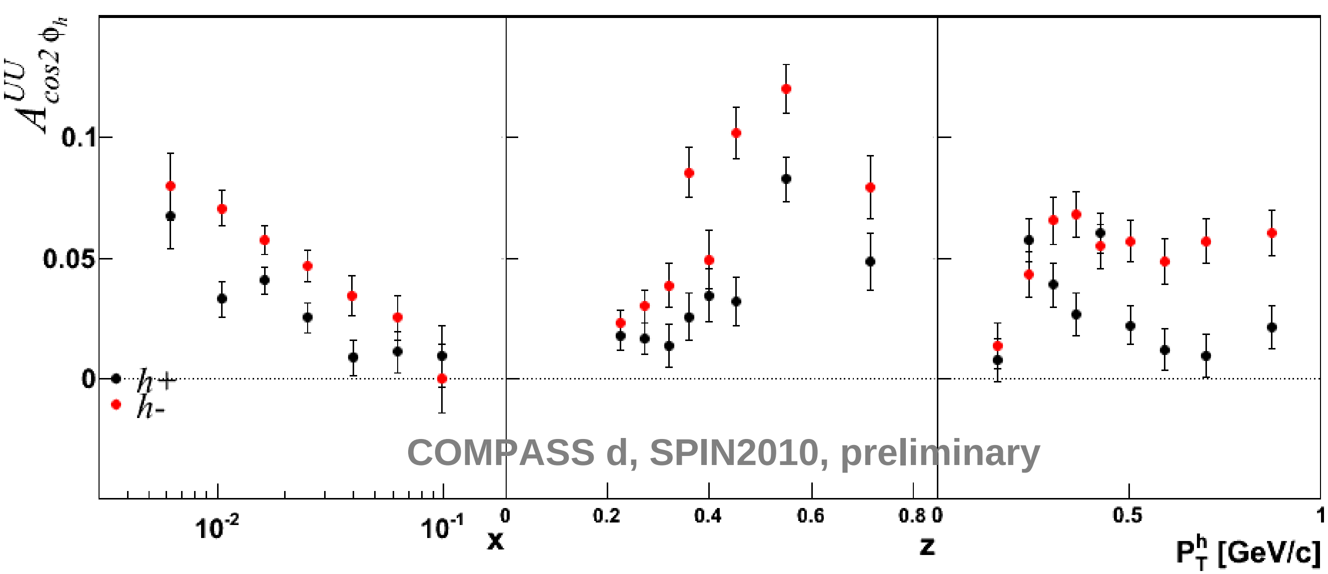
Boer - Mulders × Collins FF — **Cahn effect**

Preliminary results on **cos *(phi)* and cos (2*phi)* modulations are available**

cos ϕ and cos 2ϕ modulations

first results for h+ and h- from COMPASS in 2008





cos ϕ

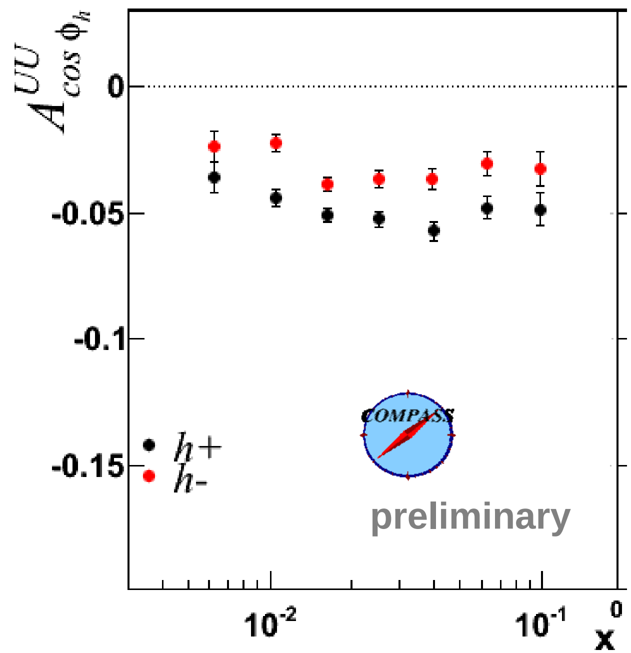
- large signals over all the x range
- strong dependence on x, z, P_T^h
- surprising, different for h^+ and h^-

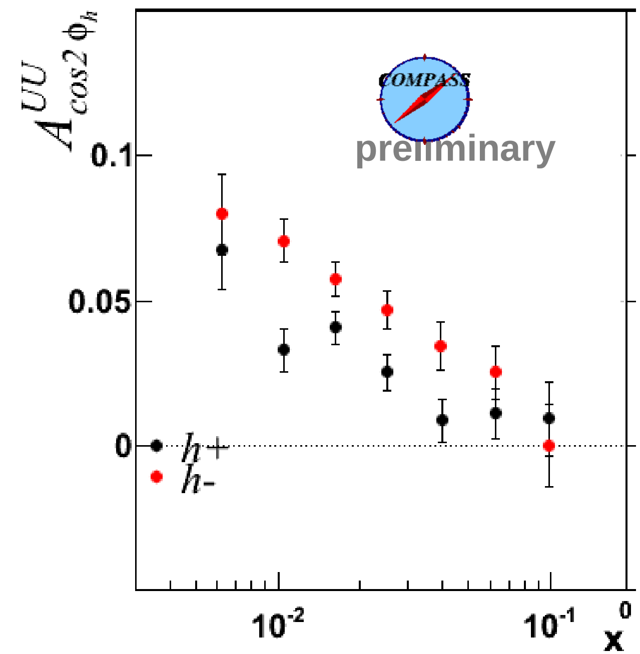
Boer-Mulders contribution?

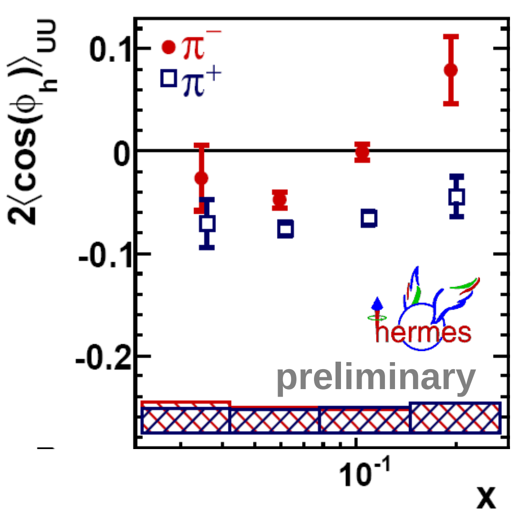
cos 2ϕ

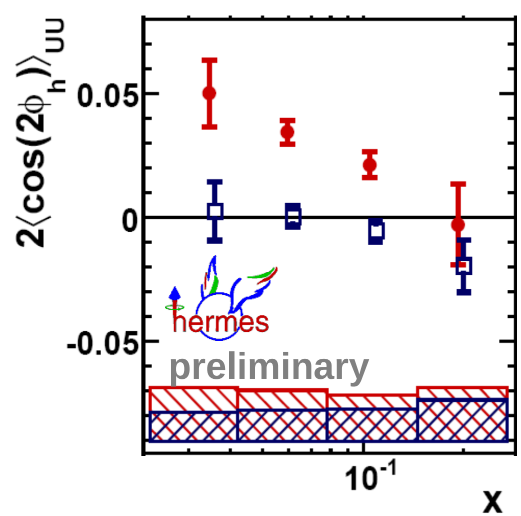
- large signals at small x
- strong dependence on x, z, P_T^h
- different for h^+ and h^-

cos ϕ and cos 2ϕ modulations: COMPASS vs. hermes









deuteron data

different contributions of the Boer-Mulders term at HERMES and COMPASS?

from first fits to extract the B-M function (Barone et al.)

- **difficult to fit all the data**
- **Cahn contribution not negligible**

Summary

A lot of SIDIS results have been produced by COMPASS and other experiments since 2005 from L- , T- , and Un-polarised targets, with some surprises.

L: QCD fits describe rather well the structure functions g1(x,Q2) but produce ambiguous results for parton distributions.
Bjorken sum rule is OK up to NNLO.
“Spin crises” is not over, qurks and gluons do not account for spin of of nucleons. Next step – GPDs.

T : solid evidence for transversity PDF to be different from zero and Sivers function to be different from zero.
Still, important points to be clarified concerning other TMD PDFs.

to know more: Transverity 2011
http://www.ecsac.ictp.it

Un : data on azimuthal modulations and corresponding PDFs are still preliminary.

Back up slides

DGLAP EVOLUTION EQUATIONS

$$\frac{d}{dt}\Delta q_{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q_{NS}$$ (non – singlet),

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix}P_{qq}^{S} & 2n_f P_{qG}^{S} \\ P_{Gq}^{S} & P_{GG}^{S}\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta G\end{pmatrix}$$ (singlet & gluon),

where $t = \log\left(Q^2 / \Lambda^2\right)$ and P_{qq}, P_{qG}, P_{Gq} are polarized splitting functions.

EVOLUTION OF MOMENTS

1. $$\frac{d}{dt}\Delta q_{3(8)}^{(n)}(Q^2) = \frac{\alpha_s(t)}{2\pi}\gamma_{NS}\Delta q_{3(8)}^{(n)}(Q^2)$$ *(non-singlet sector),*

$$\frac{d}{dt}\begin{pmatrix} \Delta\Sigma^{(n)}\left(Q^2\right) \\ \Delta G^{(n)}\left(Q^2\right) \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix} \gamma_{qq} & \gamma_{qg} \\ \gamma_{gq} & \gamma_{gg} \end{pmatrix} \times \begin{pmatrix} \Delta\Sigma^{(n)}\left(Q^2\right) \\ \Delta G^{(n)}\left(Q^2\right) \end{pmatrix}$$ (singlet & gluon sector),

where $$\Delta q^{(n)}\left(Q^2\right) = \int_0^1 dx x^n \Delta q\left(x, Q^2\right),$$

γ_{ij} - anomalous dimensions.

2. $$\Delta q\left(x, Q^2\right) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dn x^{-n} \Delta q^{(n)}$$

INPUT PARAMETRIZATIONS

-The PDF $\Delta\Sigma$, Δq_3, Δq_8 and ΔG at $Q_0^2 = 3$ GeV^2 are parametrized as:

$$\Delta F_k(x) = \eta_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)\,dx}, \qquad \eta_k = \int \Delta F_k(x)\,dx$$

-η_3, η_8 are fixed by the barion octet constants F&D assuming $SU(3)_f$ flavor symmetry:

$\eta_3 = F+D$, $\eta_8 = 3F-D$.

-The linear term $\gamma_k x$ used for $\Delta\Sigma$ only.

-Positivity limits $|\Delta s(x)| \le s(x)$ & $|\Delta G(x)| \le G(x)$ imposed at each step.

-Unpolarized PDF's are taken from MRST parametrizations

(Martin et al., Eur.Phys. J.C4(1998) 463).

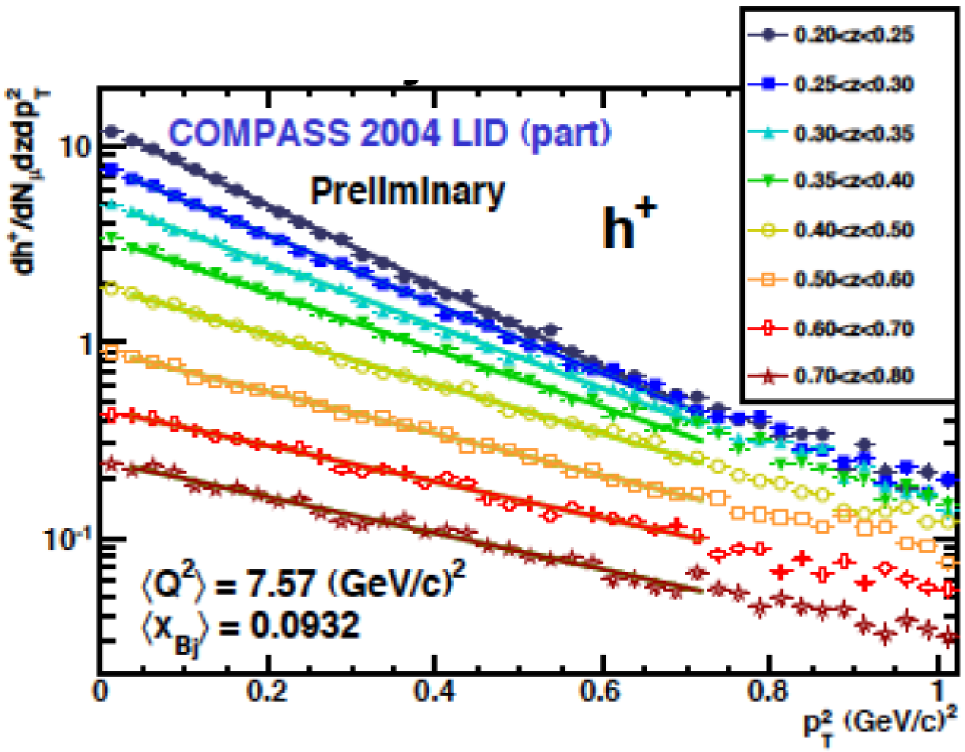
- Finally, there are 10 free parameters determined by minimizations of the sum (MINUIT):

$$\chi^2 = \sum_{i=1}^{230} \frac{\left[g_1^{fit}(x_i, Q_i^2) - g_1^{\exp}(x_i, Q_i^2)\right]^2}{\left[\sigma(x_i, Q_i^2)\right]^2}.$$

unpolarised target
SIDIS differential cross-section

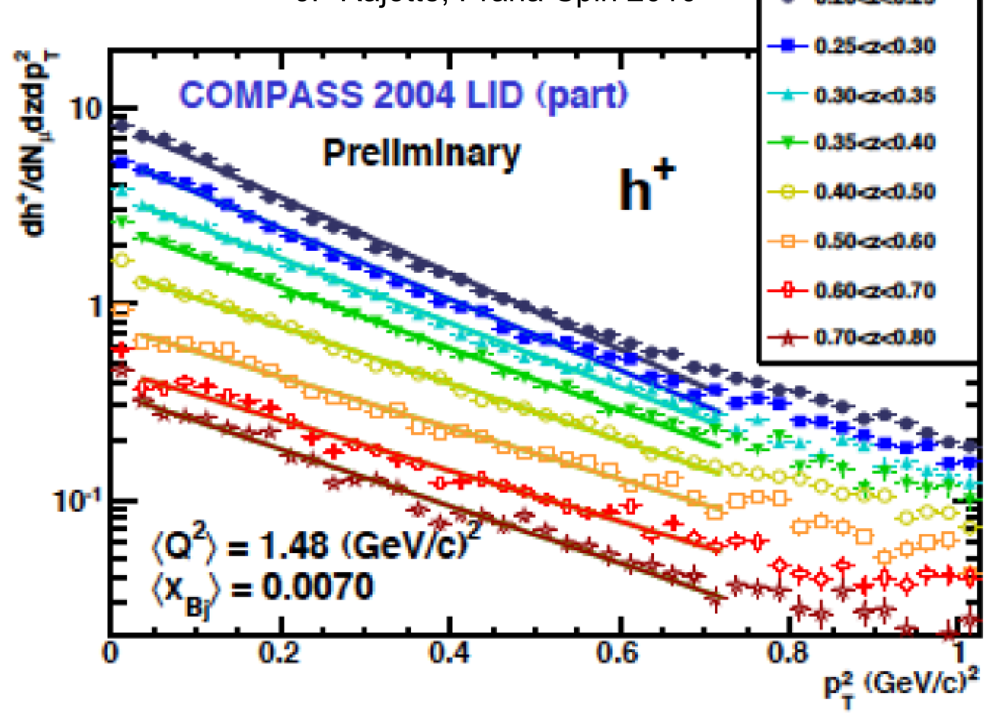
unpolarised target
SIDIS differential cross-section

deuteron



hadron multiplicity
vs transverse momentum of
the final state hadrons

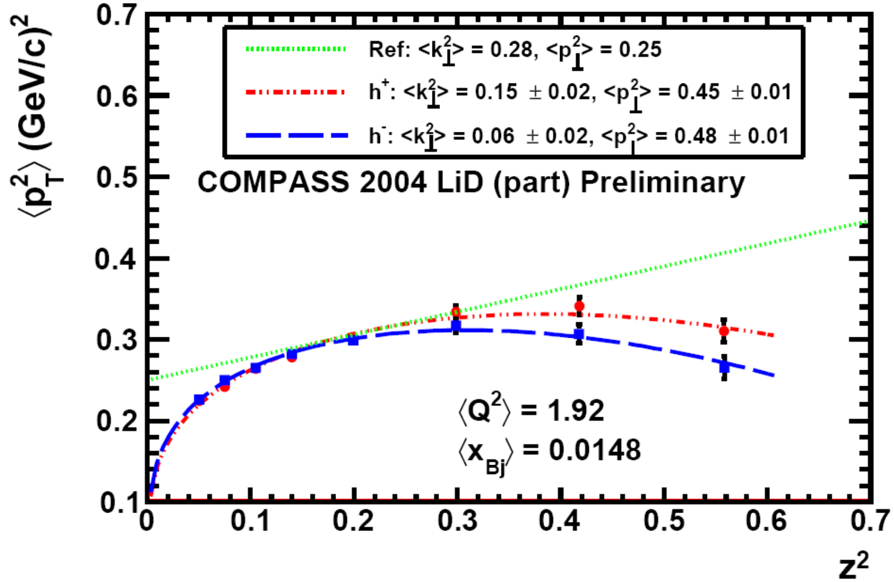
JF Rajotte, Praha-Spin 2010



as well as the $\cos\phi_h$ asymmetry,
these data can be used to extract
the intrinsic transverse momentum

unpolarised target
SIDIS differential cross-section

JF Rajotte, Praha-Spin 2010



the expected behaviour

$$\langle p_T^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

final state hadron → $\langle p_T^2 \rangle$; FF → $\langle p_\perp^2 \rangle$; PDF → $\langle k_\perp^2 \rangle$

does not reproduce the data

as already known

using $$\langle p_T^2 \rangle = z^\alpha (1-z)^\beta \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle$$

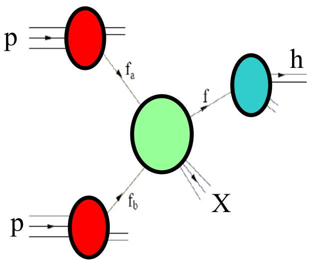
the extracted $\langle k_\perp^2 \rangle$ **is**

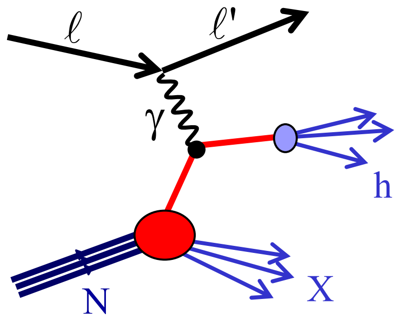
- **smaller than in previous extractions**
- **different for h+ and h-**
- **Q^2 dependent**

a lot of interpretation work on the transverse momenum is ongoing: news soon ?

Transverse Spin and Momentum Structure of the Nucleon is studied from:

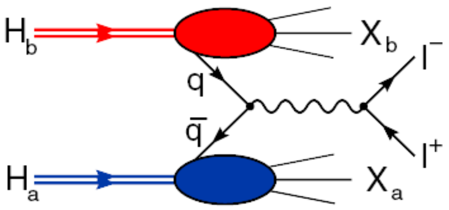
- the hard polarised **pp scattering**
RHIC / BNL,





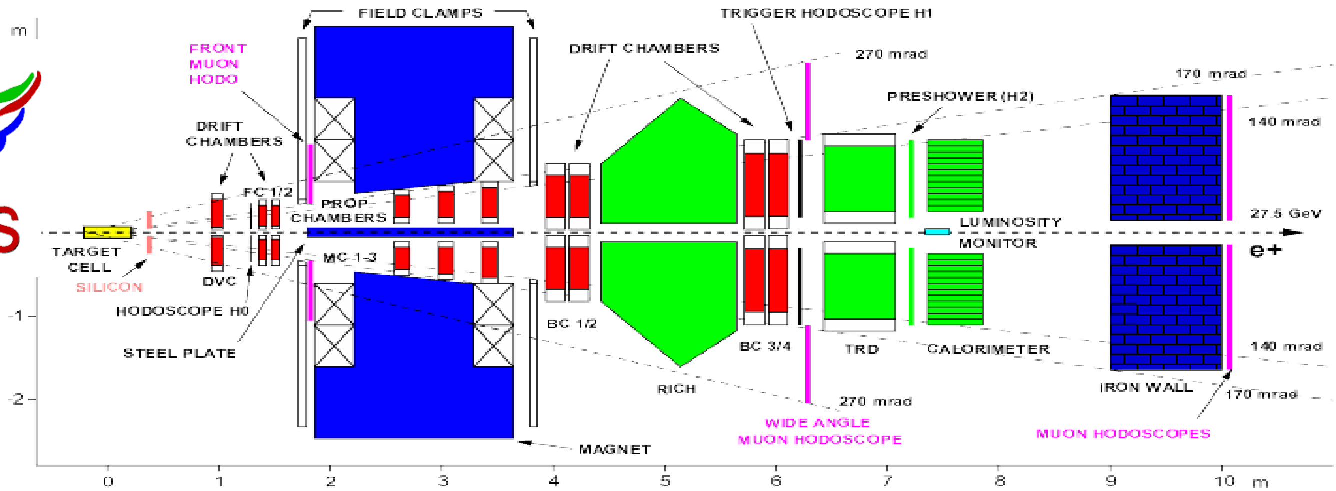
- SIDIS off transversely and longitudinally polarised targets:
DESY (HERMES)
CERN (COMPASS)
JLab ,

- and several (future) projects for (polarised) Drell-Yan:
CERN *(COMPASS)*
FNAL, *JParc, RHIC, JINR(NICA), IHEP, GSI .*

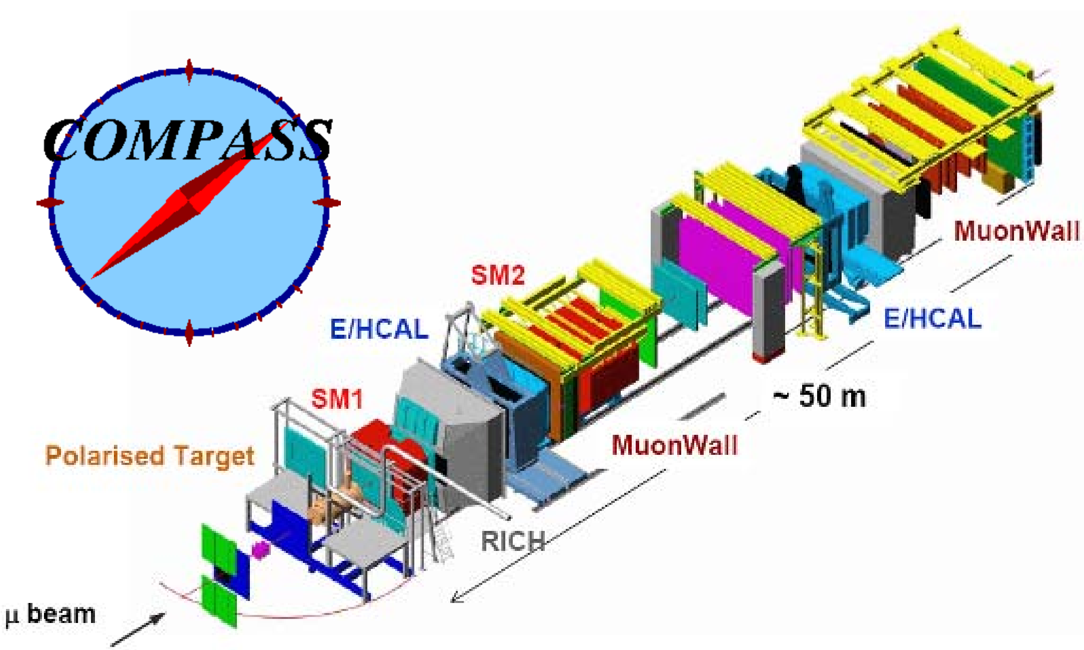


Leading DIS experiments

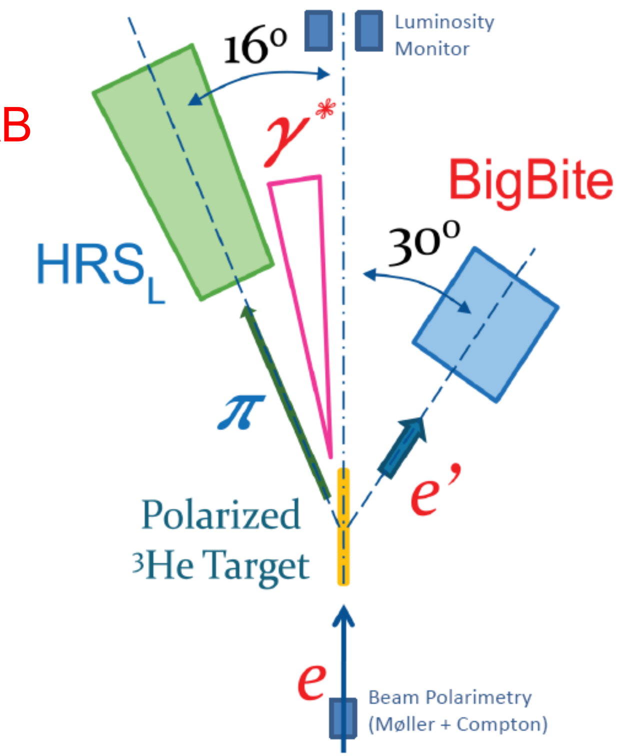
hermes



COMPASS



JLAB



data taking with
T polarised target:
2002-2005 (p)

hermes

- polarized (<60%) e^+/e^- beam of **27 GeV**, both helicity states
- pure gas targets with T (**p**) and L (**p,d**) polarization,
  fast spin-flip of target
- RICH PID K: 2-15 GeV

COMPASS

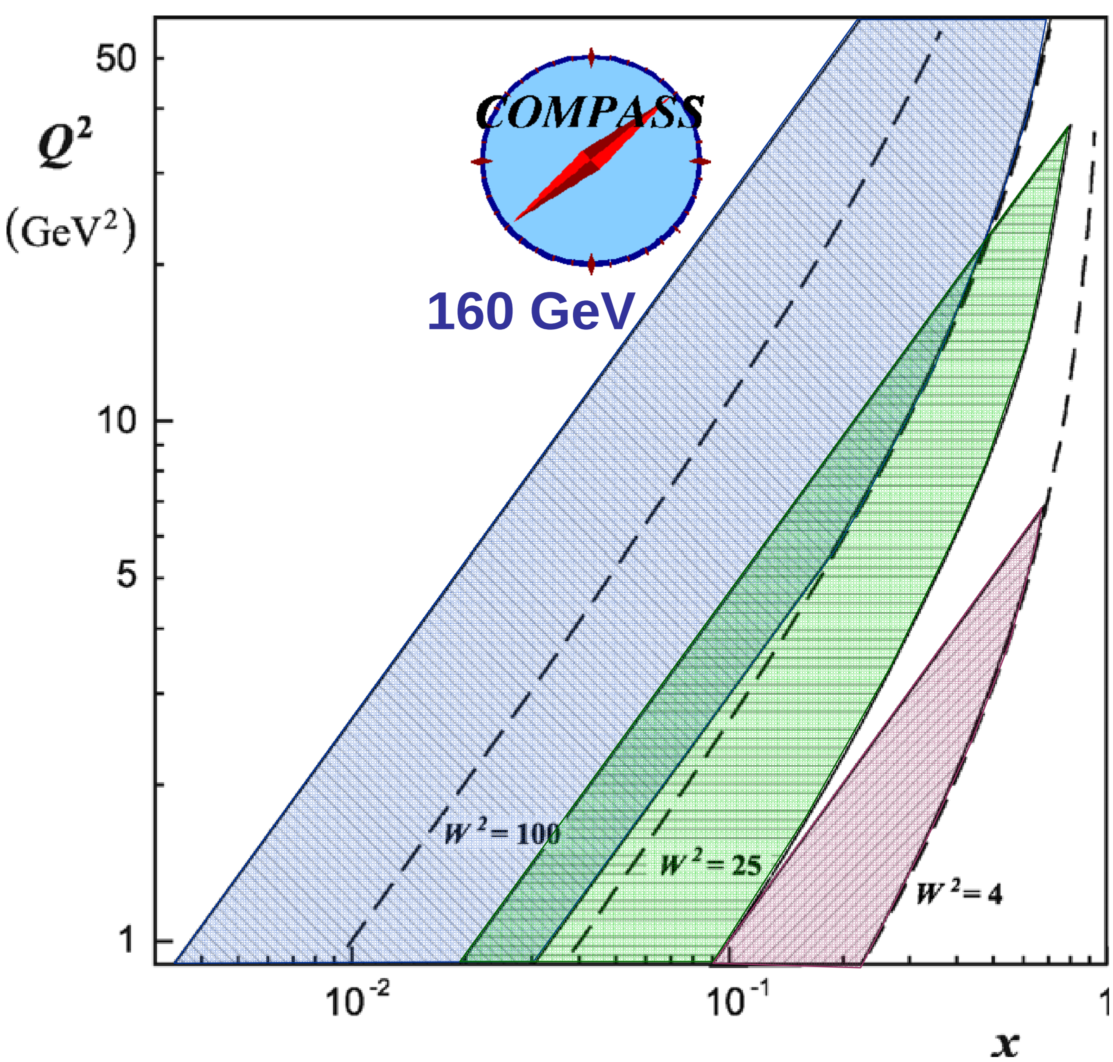
data taking with
T polarised target:
2002-2004 (d)
2007 (p)
2010 (p)

- polarized (~-80%) μ^+ of **160 GeV**
- **NH_3** (p) and **^{6}LiD** (d) targets with T and L polarization, 2 (3) cells with opposite P, polarisation reversal every ~8h
- RICH PID K: 9-50 GeV

Jefferson Lab
E06-010 Collaboration

- **6 GeV** electron beam
- transversely polarised **^{3}He** target
- identified final state hadrons

kinematical regions



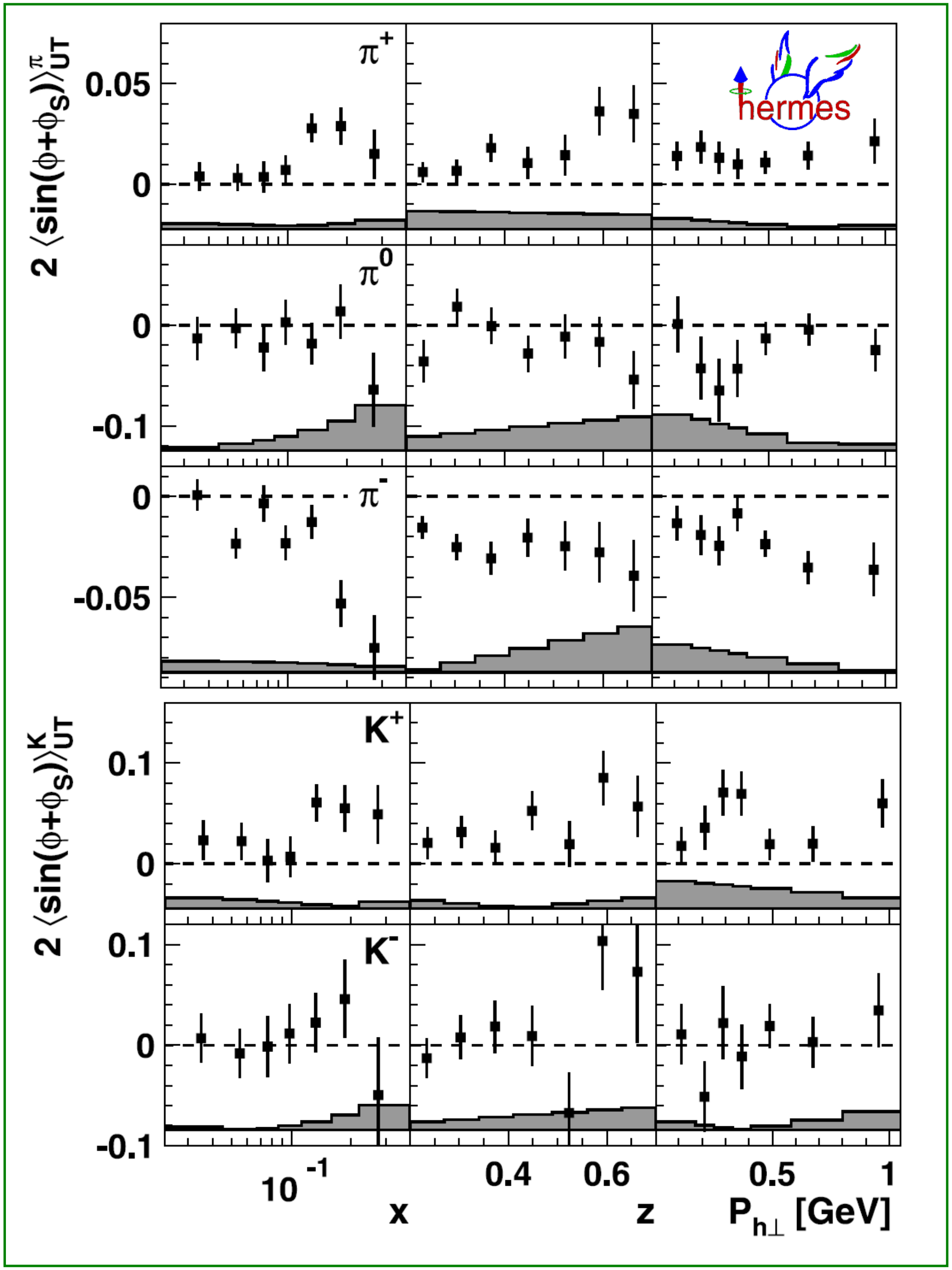
hermes

27.5 GeV

JLab 6 GeV

Collins asymmetry - proton

PLB 693 (2010) 11



HERMES results:

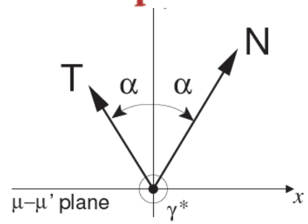
- **clear signal for π^+ and π^- at x>0.1, opposite sign**
- **K^+ signal larger than π^+: role of sea quarks?**
- *higher twist effects? limited statistics and range to study the Q^2 dependence*

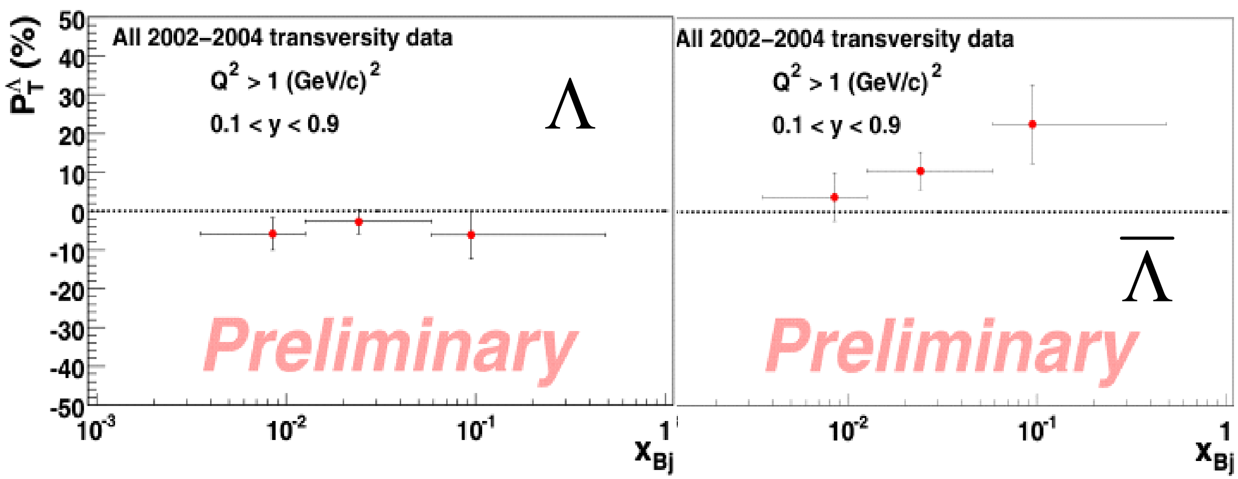
Λ polarisation

$\mu N^{\uparrow} \rightarrow \mu' \Lambda X$ $\mu N^{\uparrow} \rightarrow \mu' \bar{\Lambda} X$

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

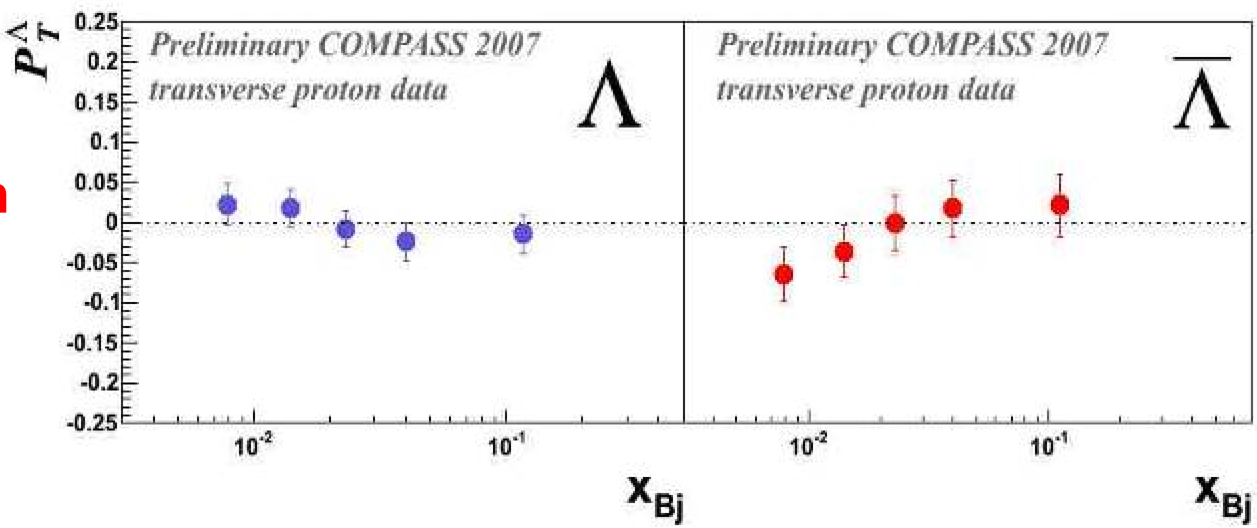
Λ polarization axis





deuteron

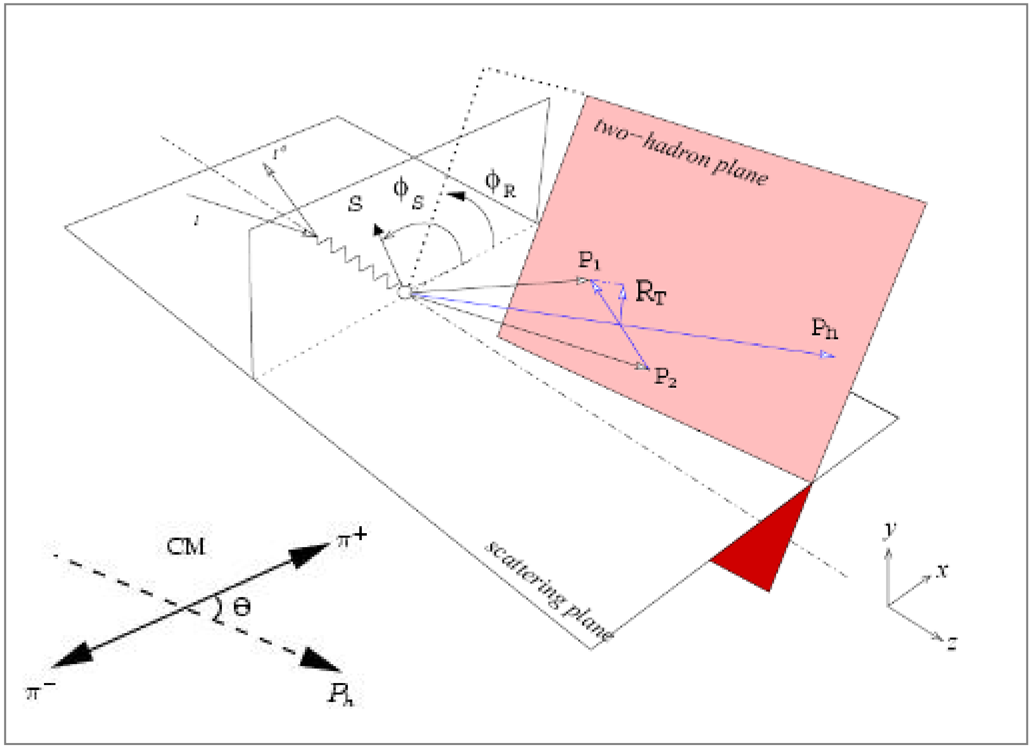
proton



compatible with zero

more statistics is needed

Two Hadron Asymmetry



azimuthal asymmetry in

$$\phi_{RS} = \phi_{R\perp} - \phi_{s'}$$

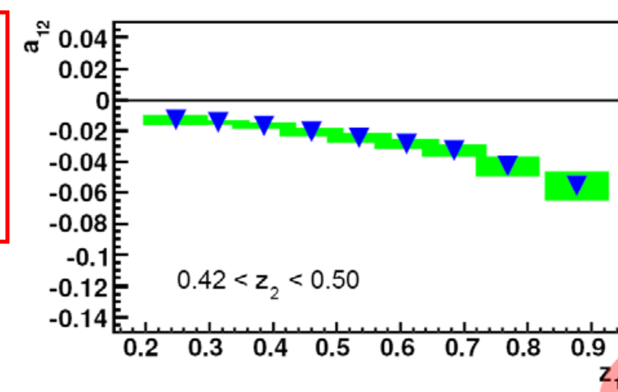
$\phi_{R\perp}$ **is the azimuthal angle of the plane defined by the two hadrons**

$\boldsymbol{R} = (z_1 \boldsymbol{p_2} - z_2 \boldsymbol{p_1})/(z_1+z_2)$

Interference Fragmentation Function

BELLE

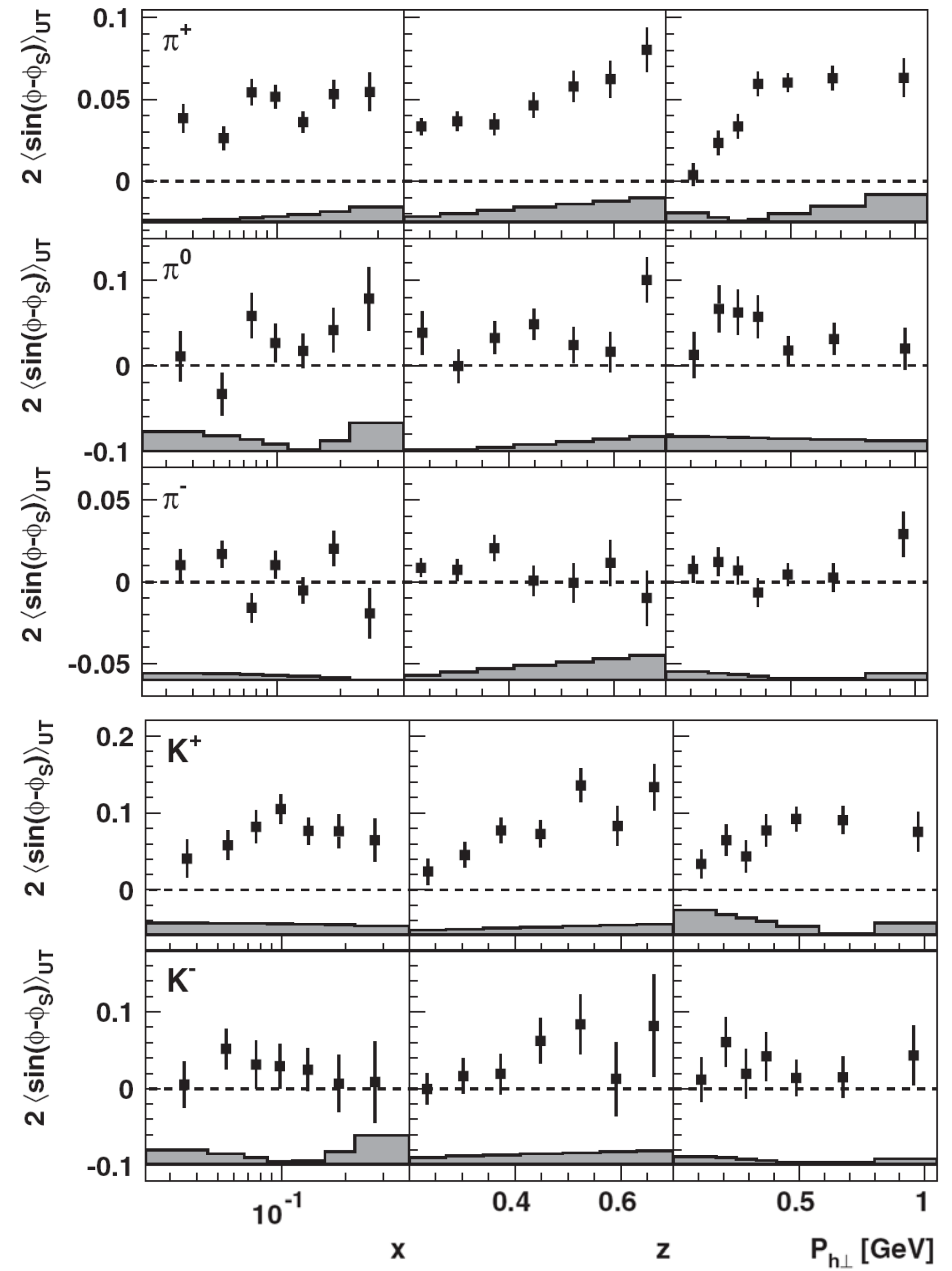
$$A_{RS} = \frac{1}{f \cdot P_T \cdot D_{NN}} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{2h}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_h^2)}$$



Sivers asymmetry - proton

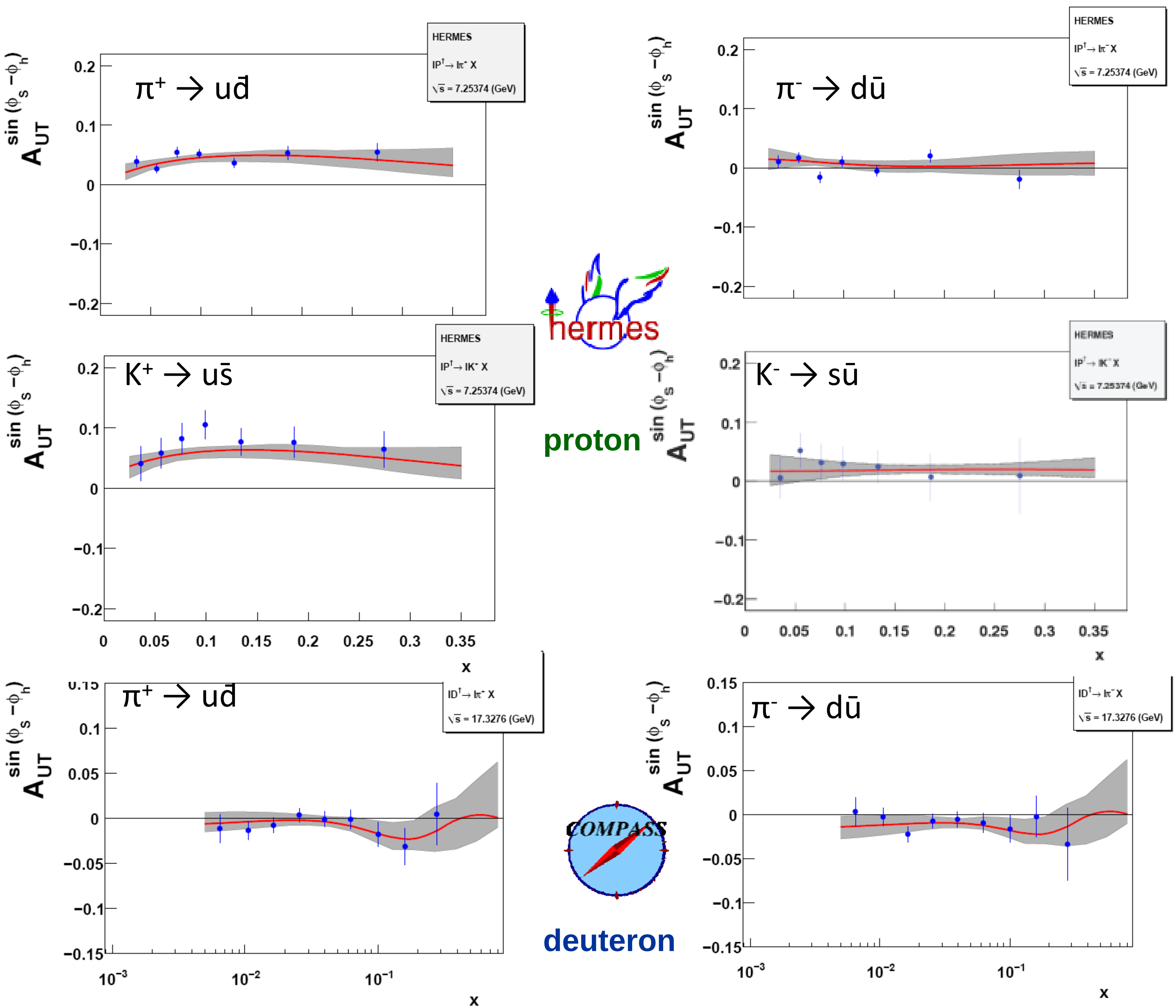
final hermes results

- **clear signal for π^+ and K^+ over all the measured x range**
- **saturation for $P_T^h > 0.4$ GeV/c**
- **difference between K^+ and π^+:**
  role of sea quarks?
  larger at lower Q^2
  higher twist effects
  in K production?



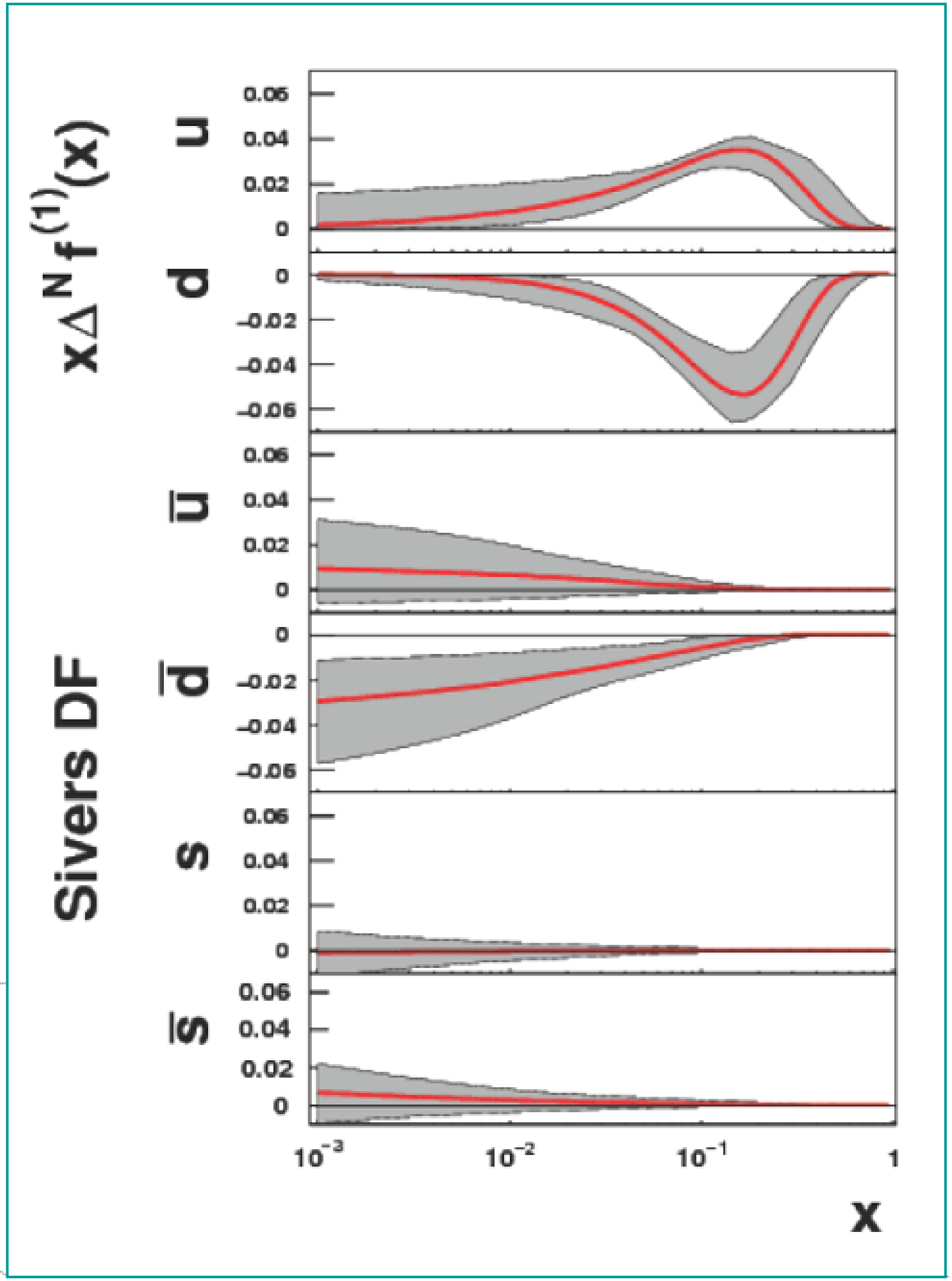
PRL **103,** 152002 (2009)

Sivers asymmetry



New fit – valence + sea

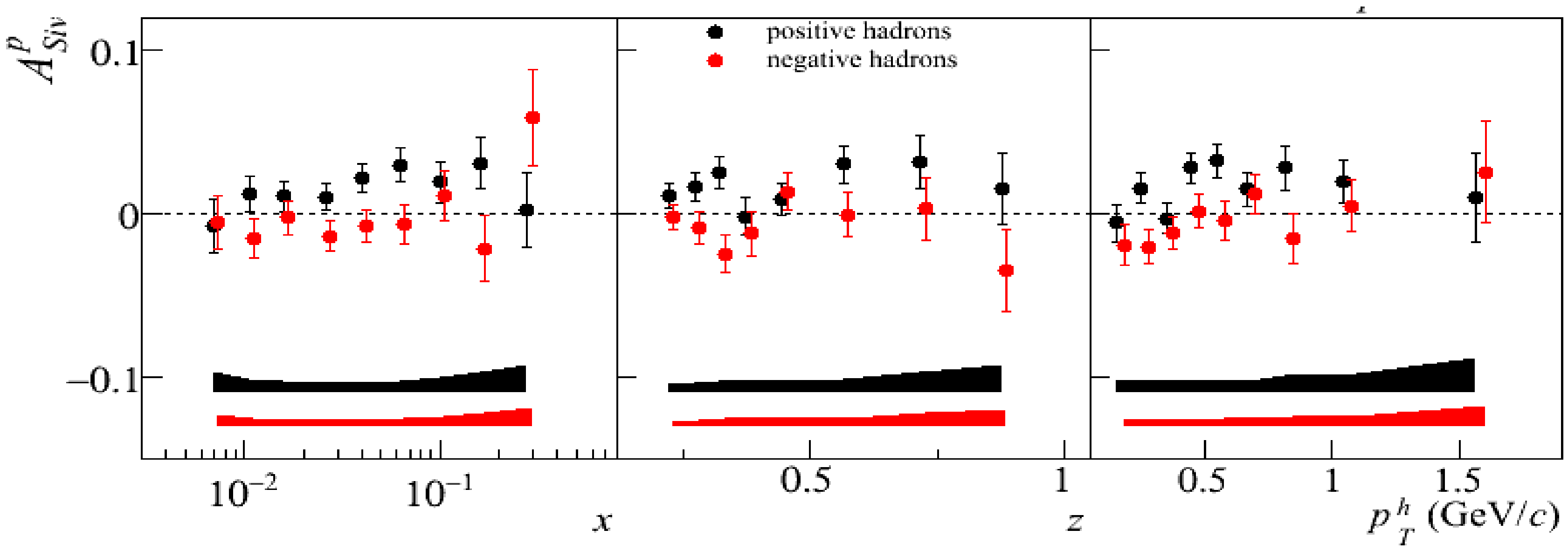
M. Boglione


Sivers DF
$x\Delta^N f^{(1)}(x)$
u
d
$\bar{u}$
$\bar{d}$
s
$\bar{s}$
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
10^{-3}
10^{-2}
10^{-1}
1
x

Sivers asymmetry - proton

final COMPASS results from 2007 data

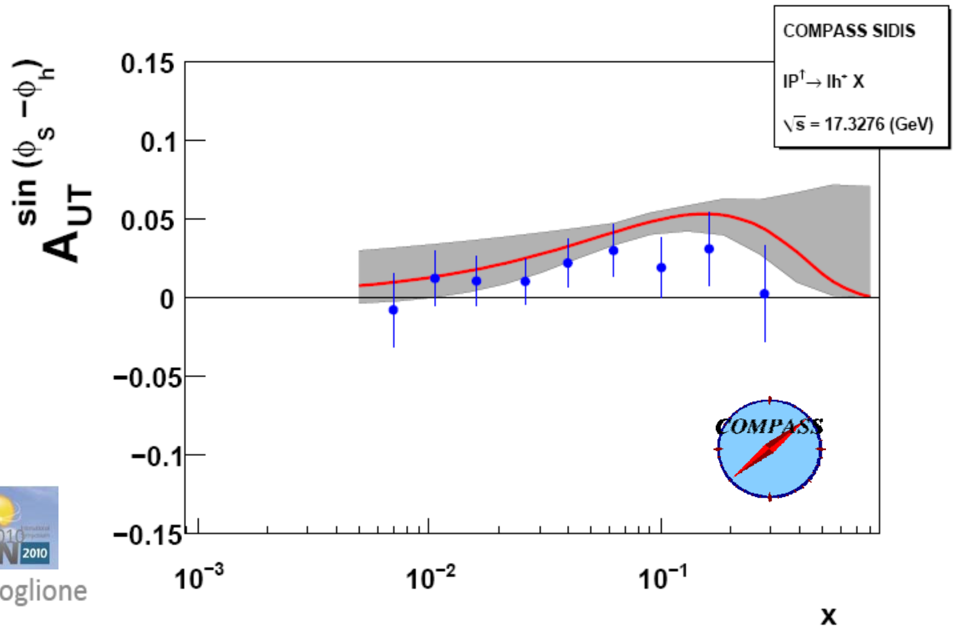
PLB 692 (2010) 240

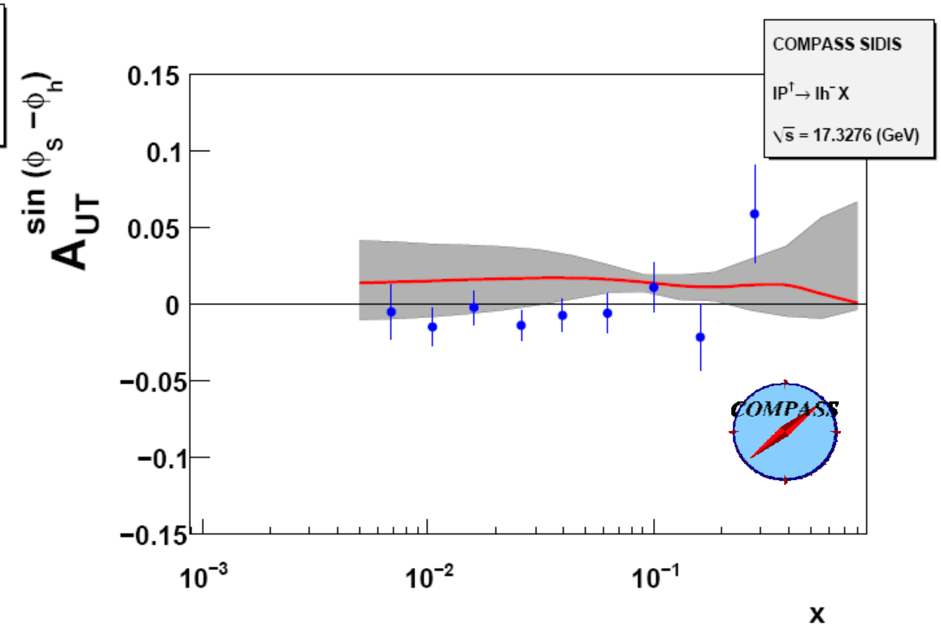


evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

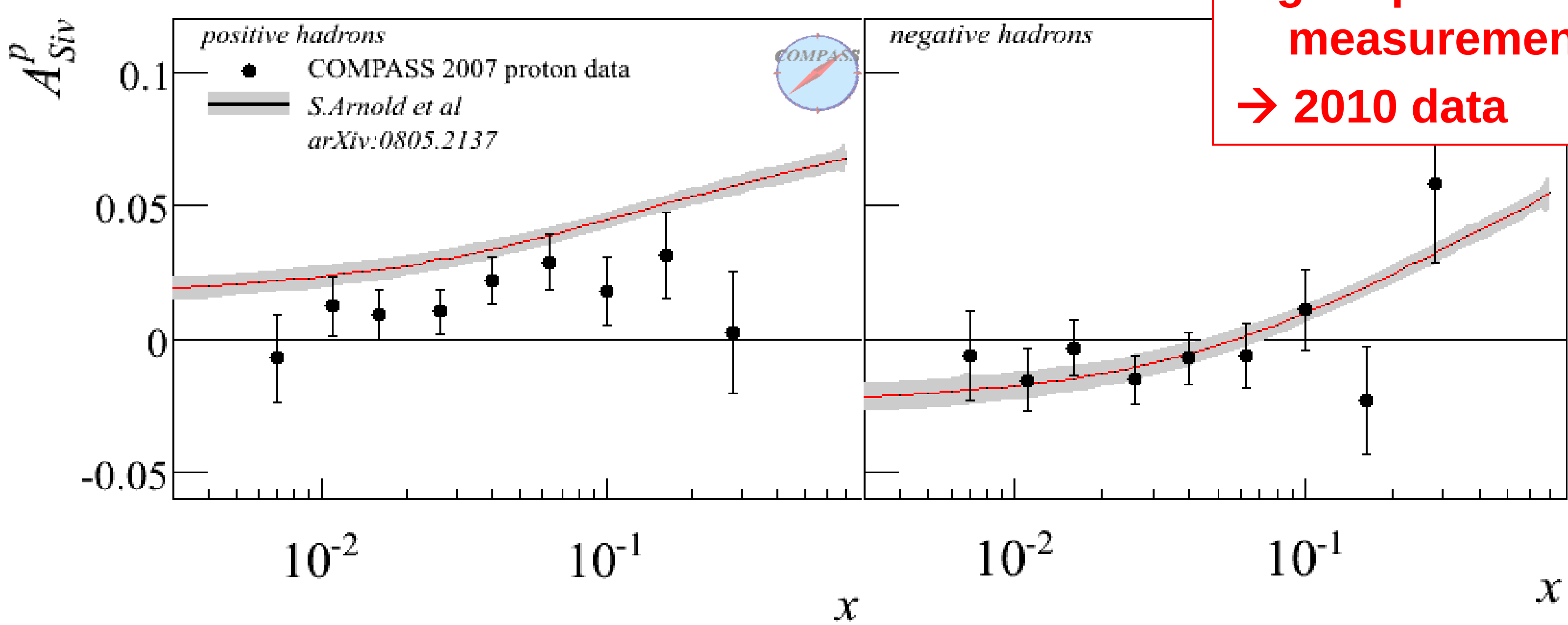
systematic errors $h^- \sim 0.5\ \sigma_{stat}$
$h^+ \sim 0.8\ \sigma_{stat}$ plus a scale (abs) uncertainty of ± 0.01

Sivers asymmetry - proton





M. Boglione



higher precision measurements needed

→ 2010 data

Sivers asymmetry - proton

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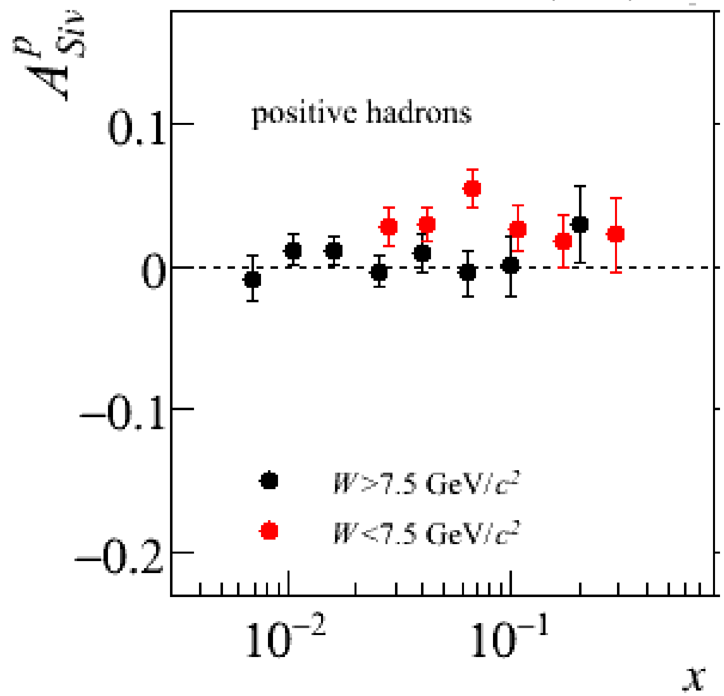
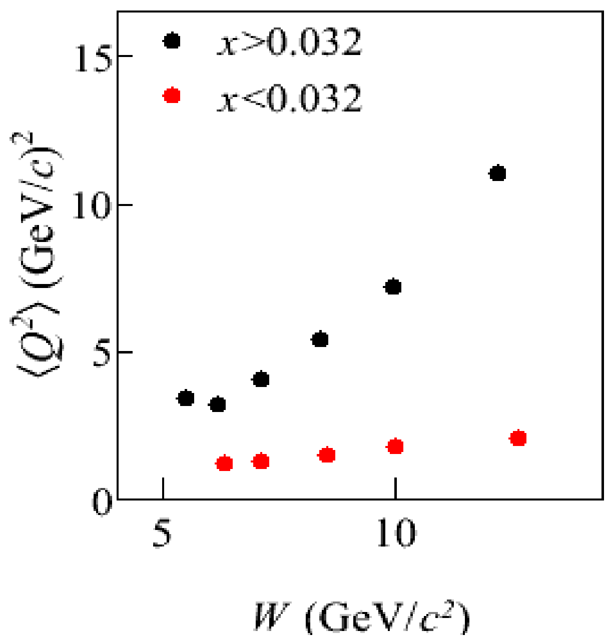


hints for a possible **unexpected**
W dependence of the h^+ Sivers asymmetr

same effect in K^+ asymmetry (SPIN2010)

Q^2 dependence?



no definite conclusion with the present accuracy:
higher precision measurements are needed
→ 2010 data

azimuthal asymmetries

unpolarised target

3 independent azimuthal modulations

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

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

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

twist-3

preliminary results

COMPASS: **positive for positive hadrons** (d)

hermes: **positive for positive pions** (p,d)

CLAS: positive for positive pions (p)

azimuthal asymmetries
unpolarised target

3 independent azimuthal modulations

Cahn effect

Boer - Mulders
× Collins FF

$$\propto \frac{1}{Q}(f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp)$$

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

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

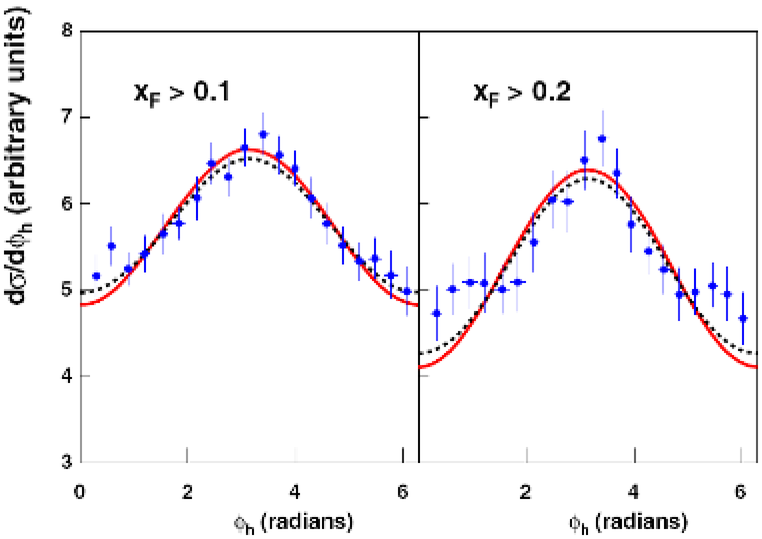
$$\propto h_1^\perp \otimes H_1^\perp + \frac{1}{Q^2} f_1 \otimes D_1$$

Boer - Mulders
× Collins FF

Cahn effect

cosϕ modulation

EMC 1987

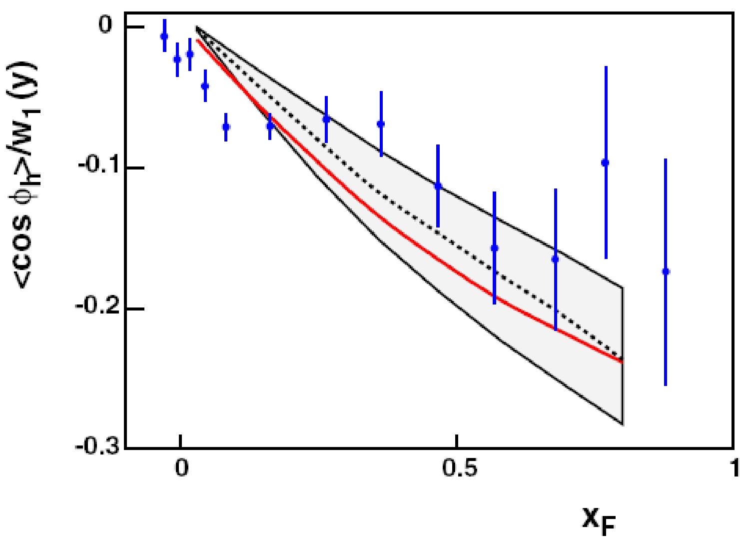


large effects

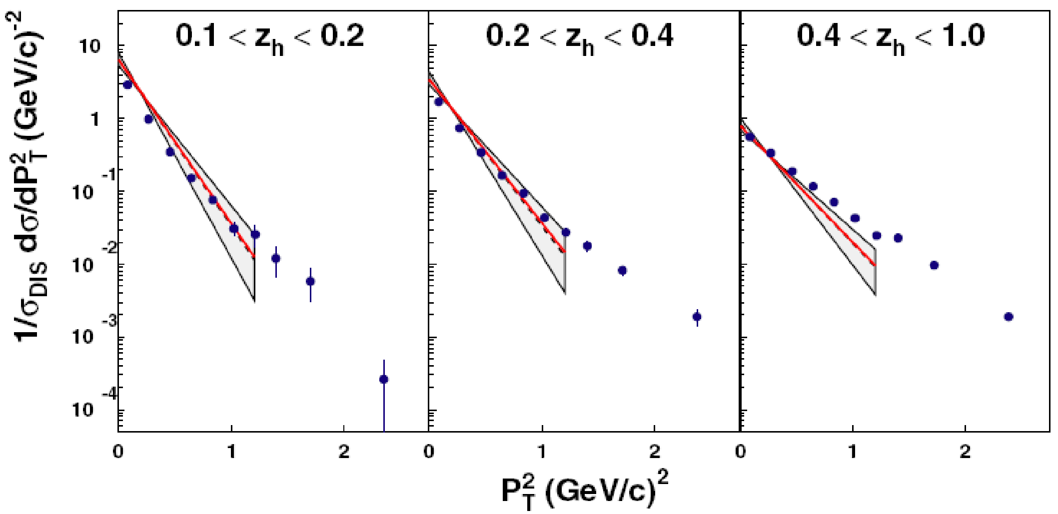
for $h^+ + h^-$ asymmetries

used to extract $\langle k_T^2 \rangle$

M. Anselmino et al., PRD 71 (2005) 074006

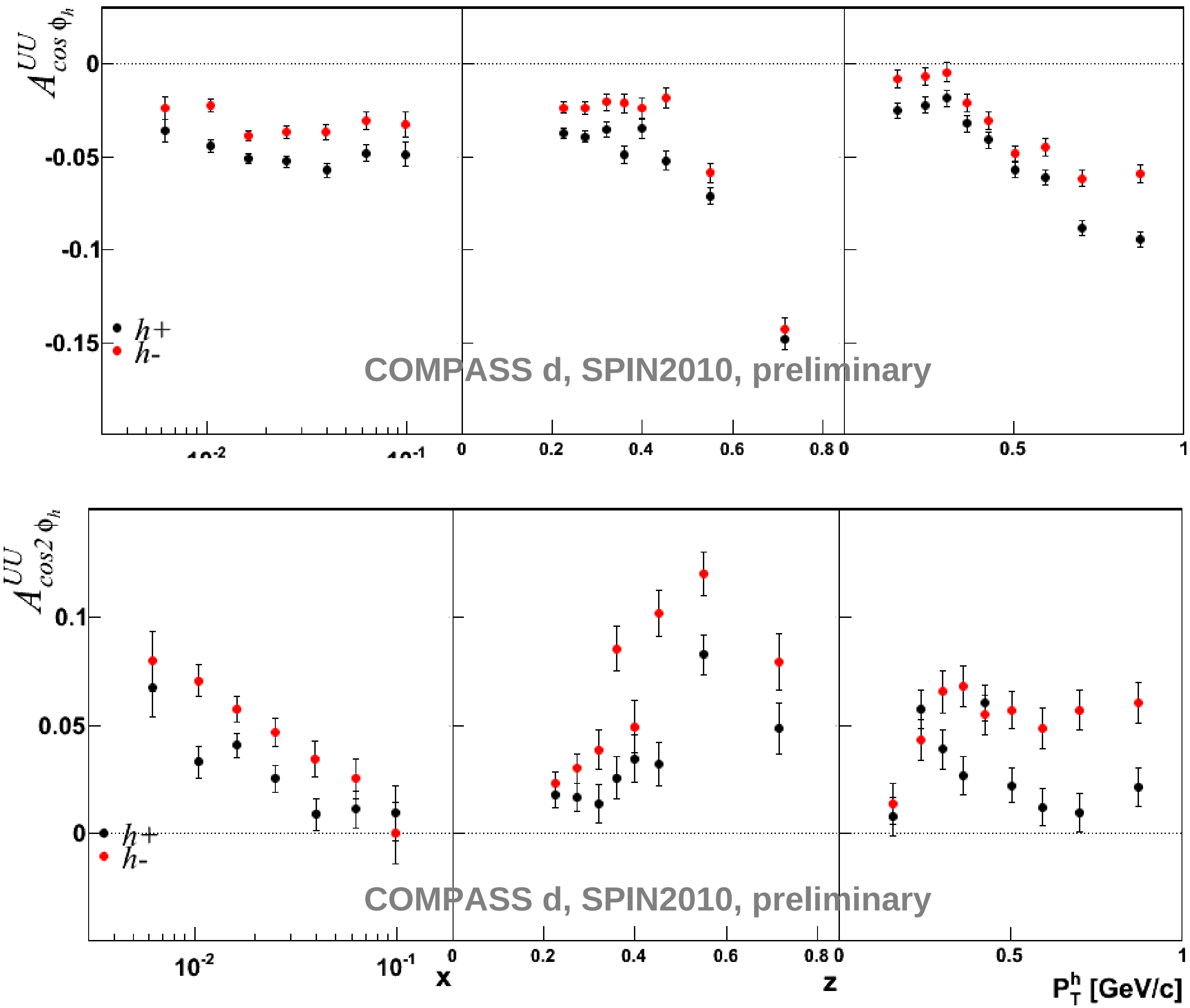


EMC 1991



cos ϕ and cos 2ϕ modulations

first results for h+ and h- from COMPASS in 2008



cos ϕ

large signals over all the x range

strong dependence on x, z, P_T^h

surprising, different for h^+ and h^-

Boer-Mulders contribution?

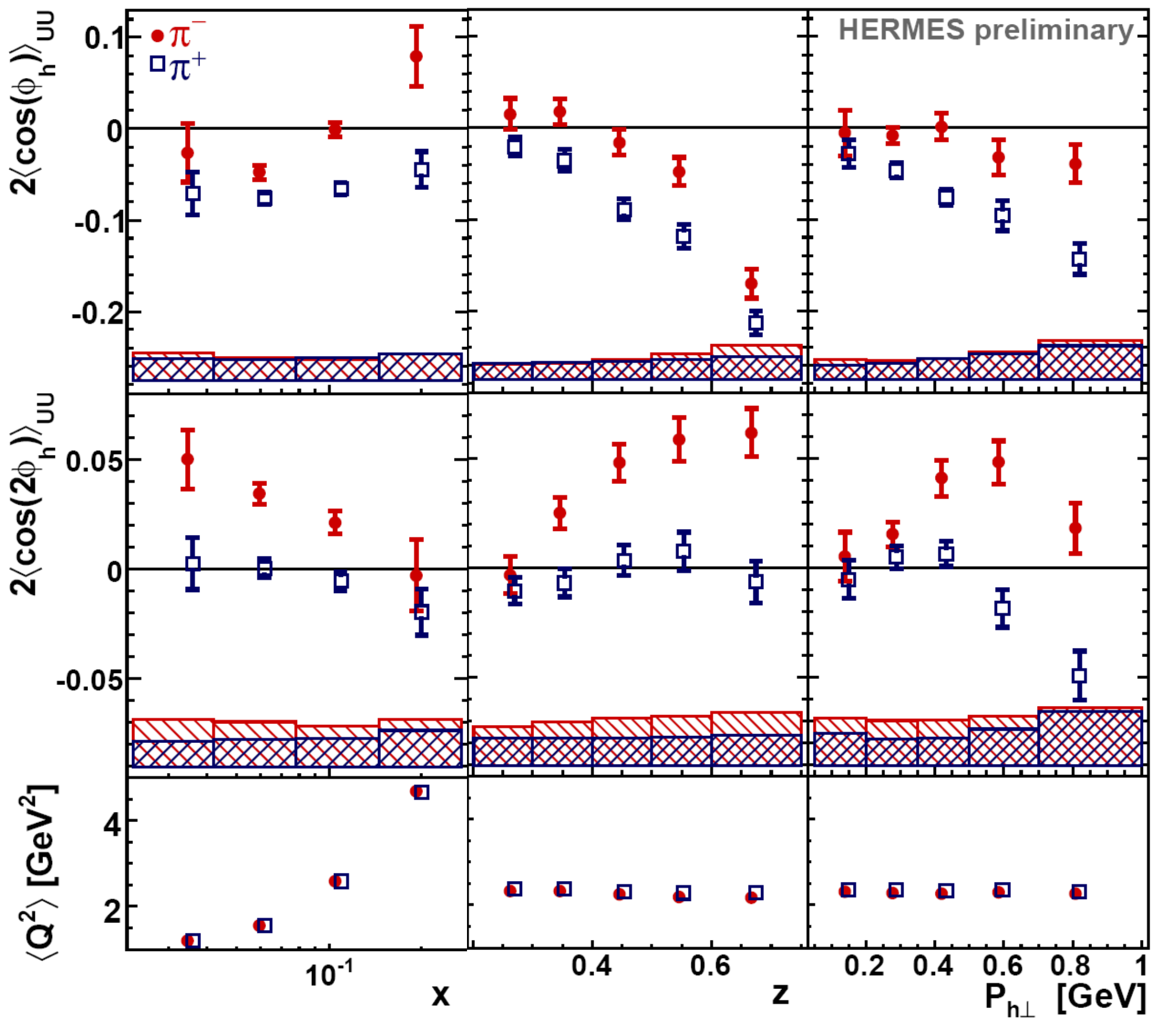
cos 2ϕ

large signals at small x

strong dependence on x, z, P_T^h

different for h^+ and h^-

cos ϕ and cos 2ϕ modulations



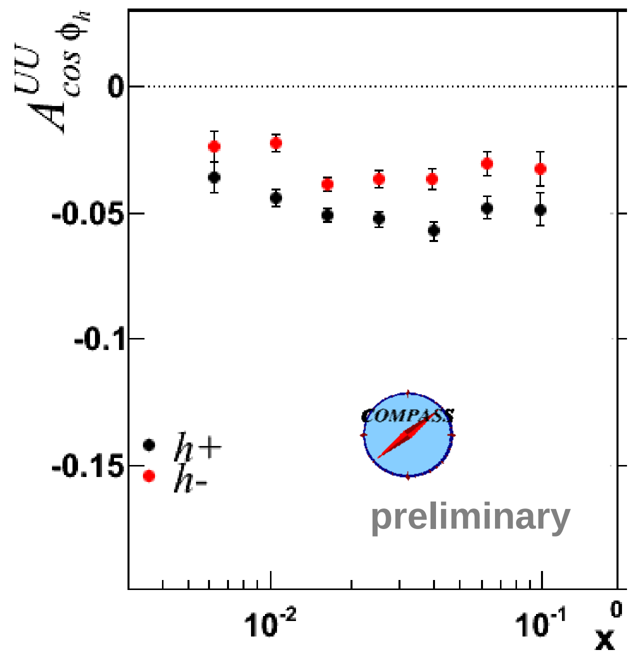
large signals

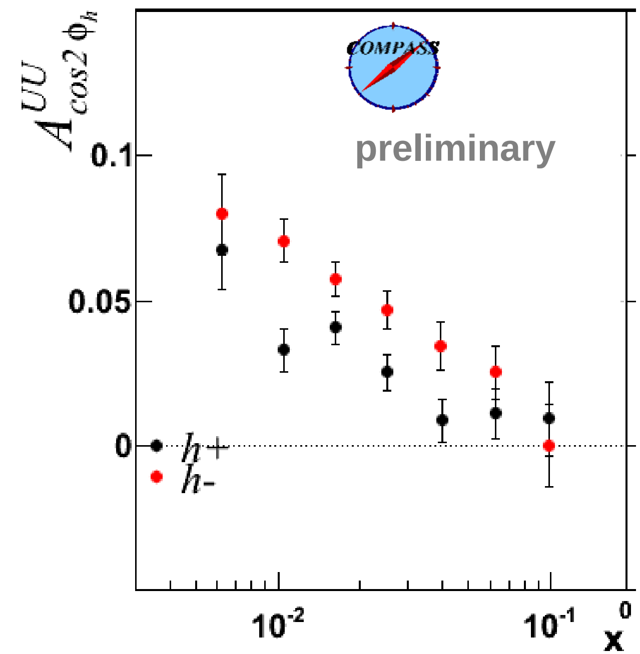
strong dependence on x, z, P_T^h

different values for π+ and π-

deuteron (very similar for proton)

cos ϕ and cos 2ϕ modulations

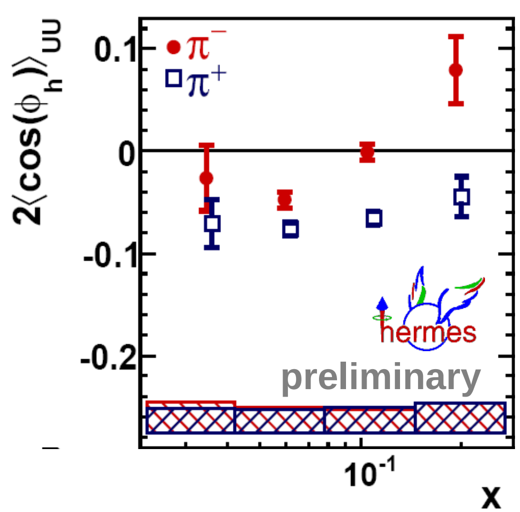


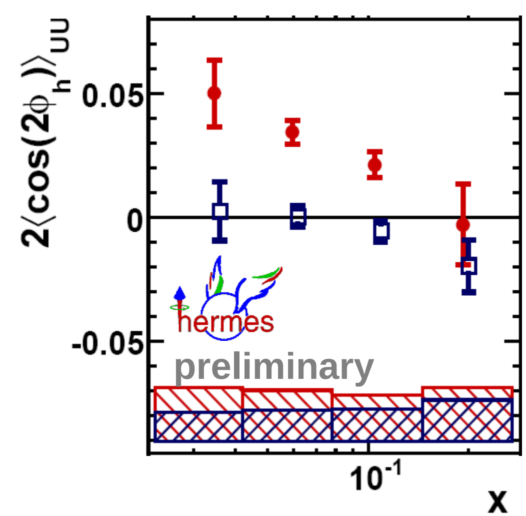


different contributions of the Boer-Mulders term at HERMES and COMPASS?

from first fits to extract the B-M function (Barone et al.)

- difficult to fit all the data
- Cahn contribution not negligible

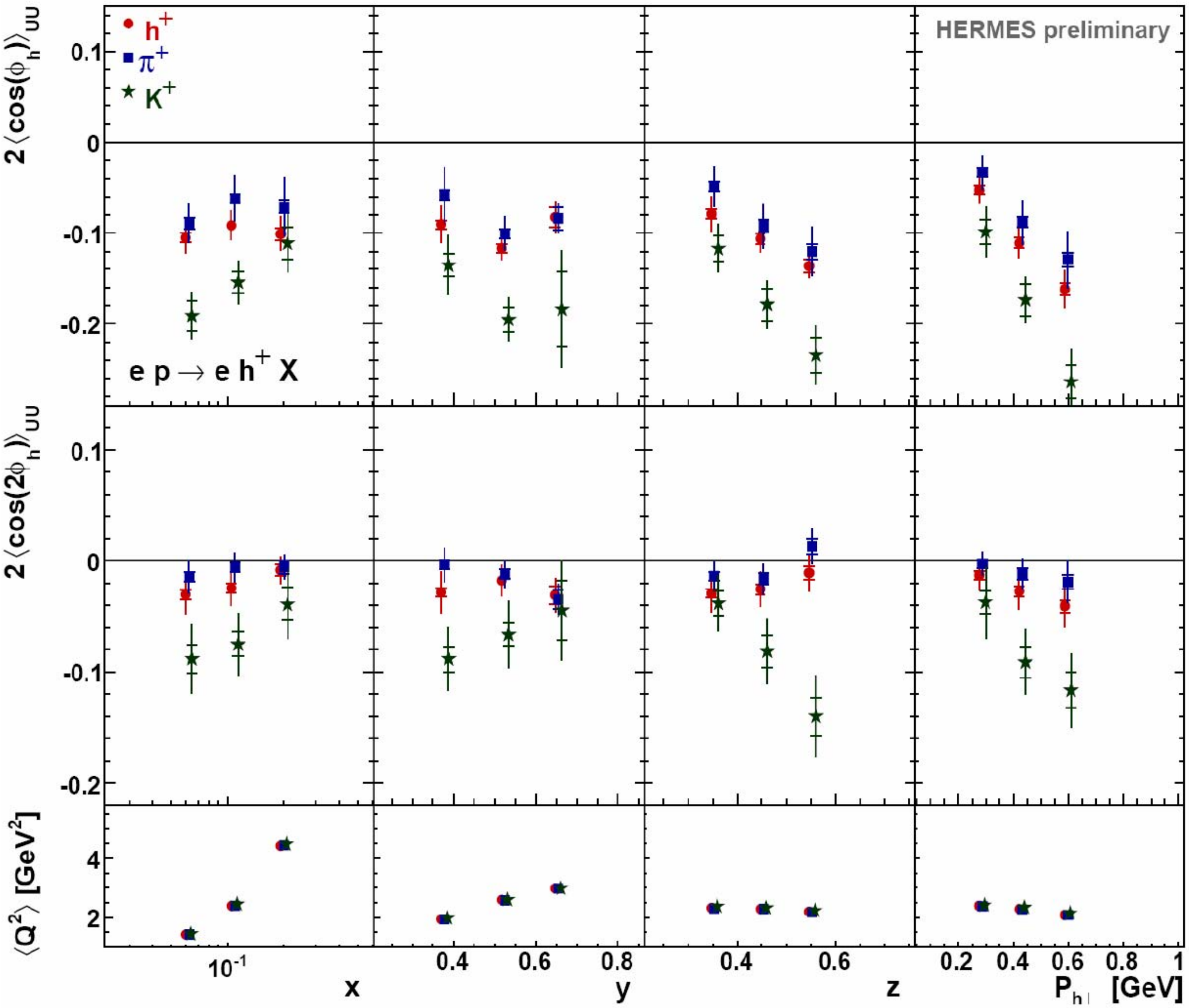




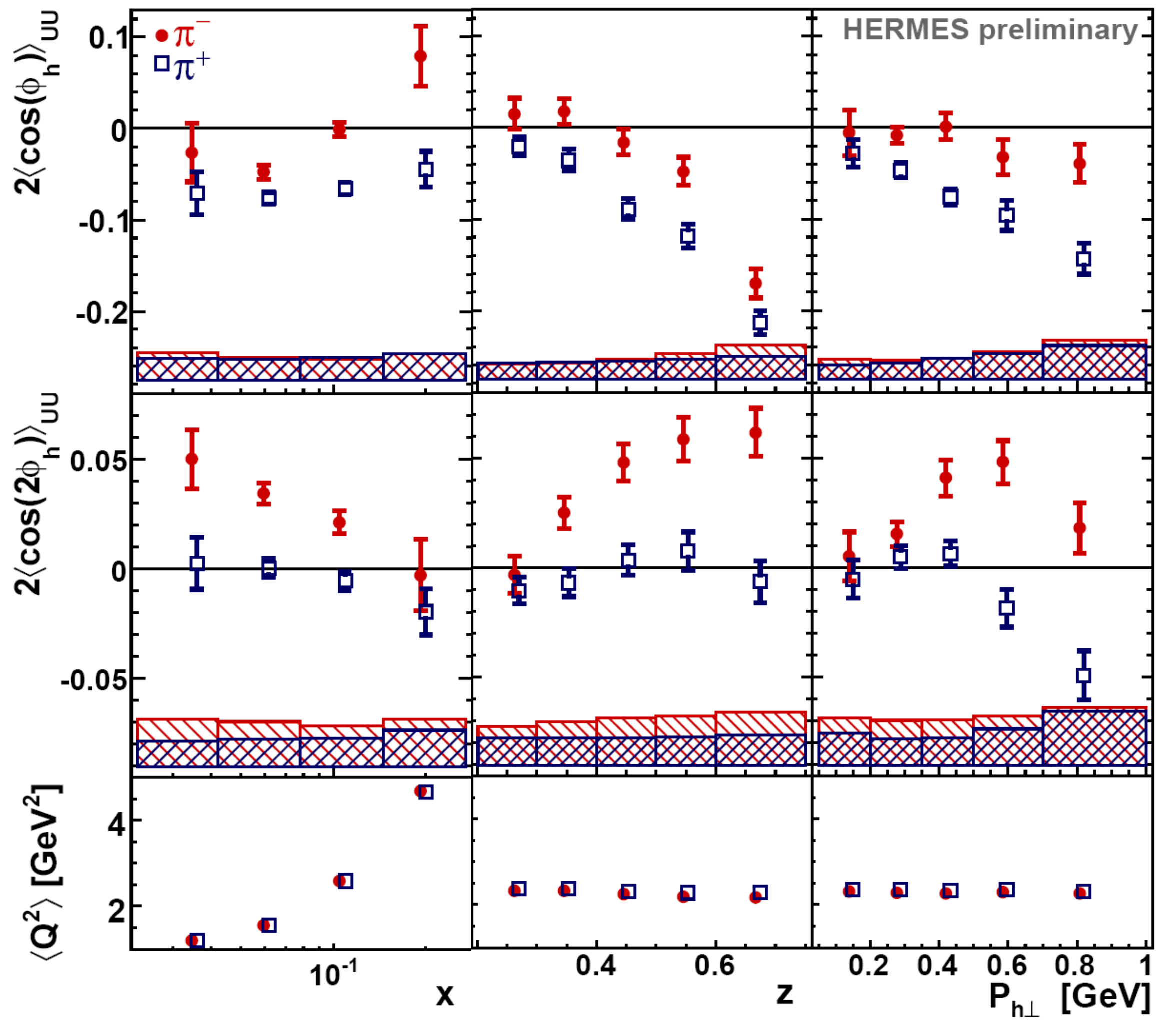
deuteron data

cos ϕ and cos 2ϕ modulations

surprising ...!



cos ϕ and cos 2ϕ modulations



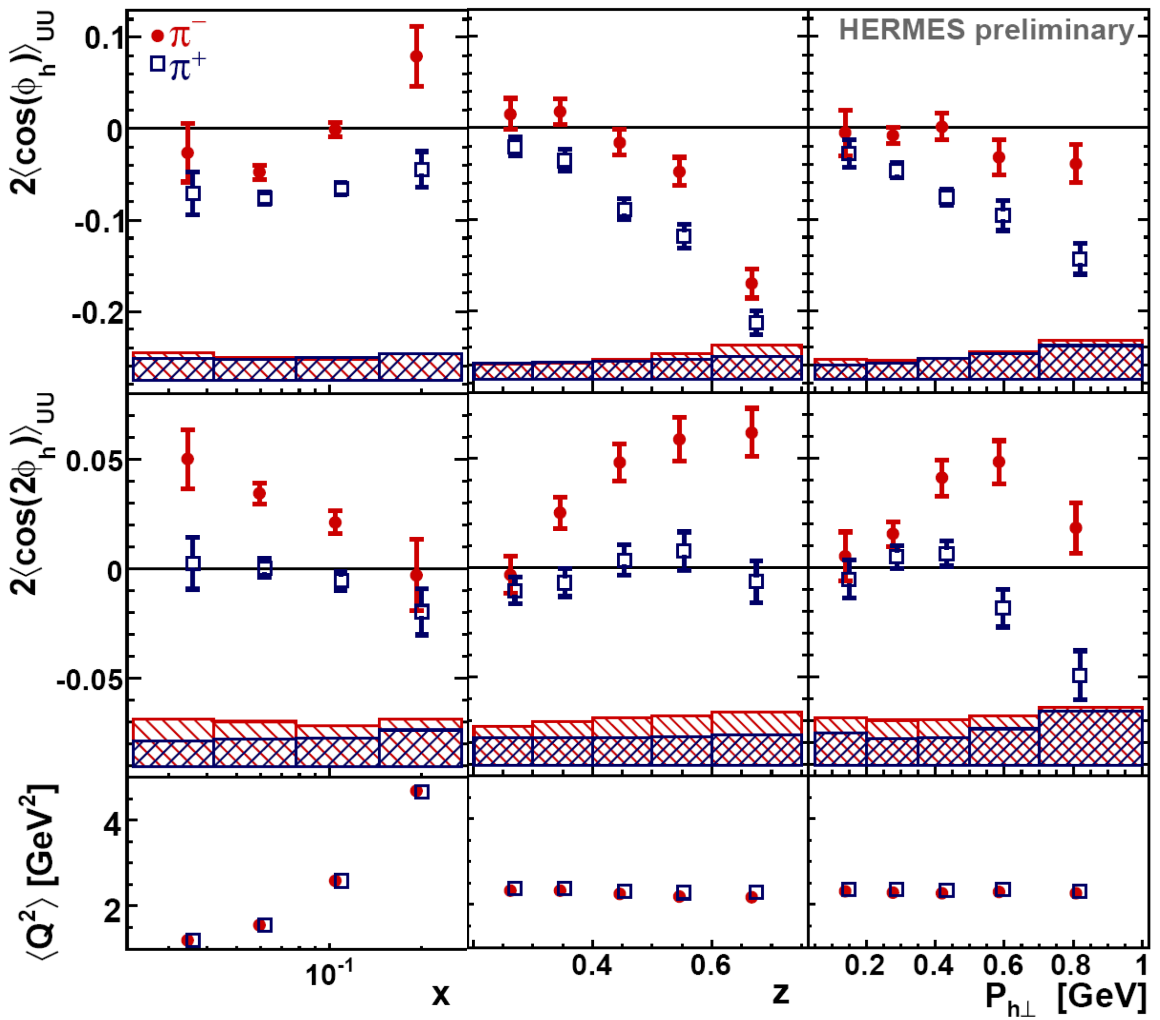
large signals

strong dependence on x, z, P_T^h

different values for π+ and π-

deuteron (very similar for proton)

cos ϕ and cos 2ϕ modulations



large signals

strong dependence on x, z, P_T^h

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deuteron (very similar for proton)