Latest Results from the COMPASS Experiment

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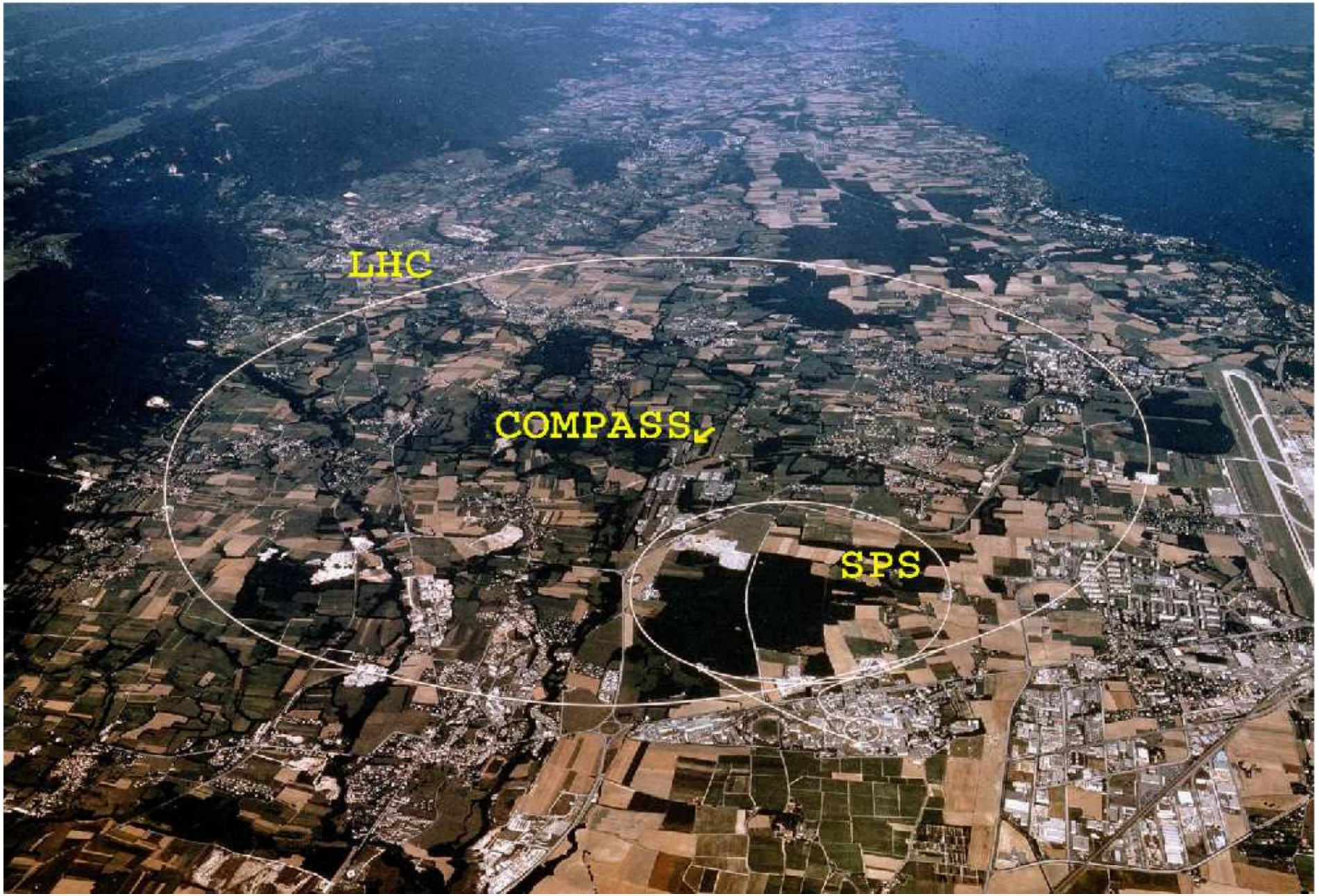
LIP

On behalf of the COMPASS Collaboration

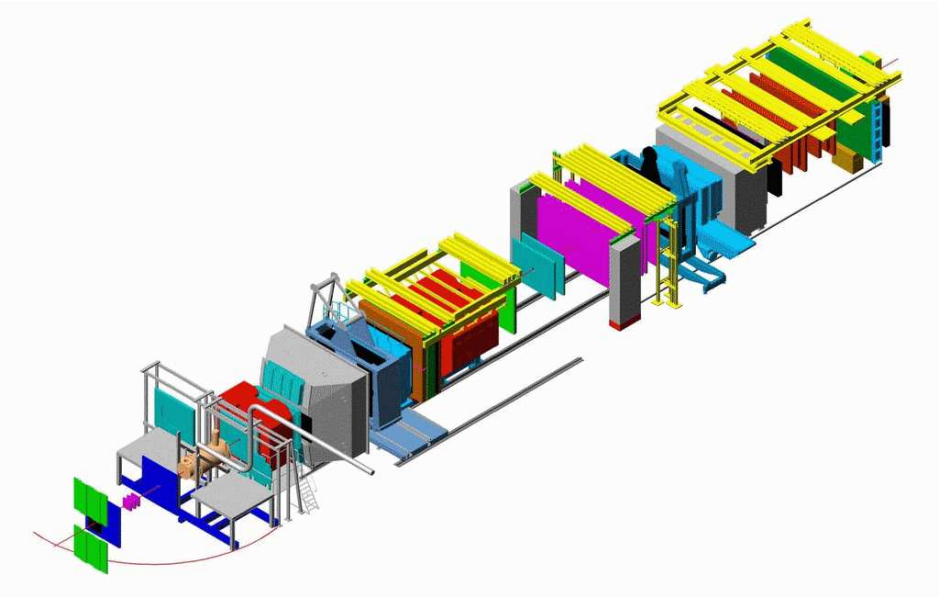
21-X-2014

Outline

COMPASS at CERN



COMPASS Spectrometer 2002-2012

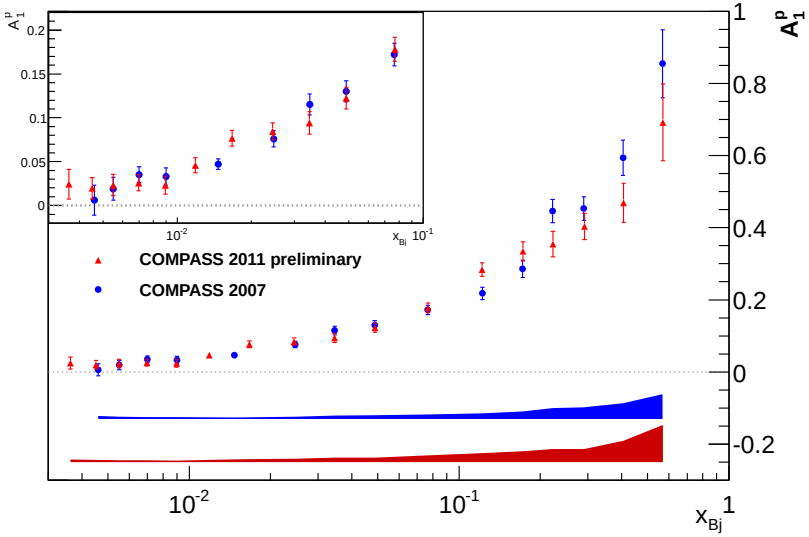


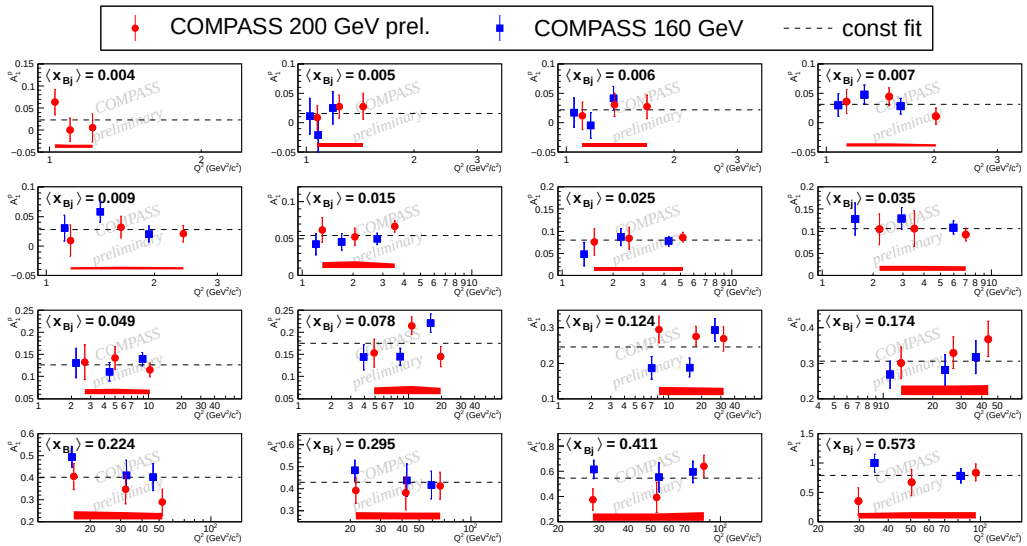
- COLLABORATION
  - about 210 physicists
  - 27 institutes
- DETECTOR
  - two stage spectrometer
  - 60 m length
  - about 350 detector planes

- POLARIZED TARGET
  - ^{6}LiD target (NH_3)
  - 2-3 cells (120 cm total length)
  - $\pm$ 50% (85%) polarization
  - pol. reversal every 8h-24h
- POLARIZED BEAM
  - μ^+ at 160 GeV/c
  - polarization –80 %
- FEATURES
  - angular acceptance: $\pm$70 mrad ($\pm$180 mrad from 2006)
  - track reconstruction: $p > 0.5$ GeV/c
  - identification h, e, μ: calorimeters and muon filters
  - identification: π, K, p (RICH) $p > 2$, 9, 18 GeV/c respectively

New Results on g_1^p

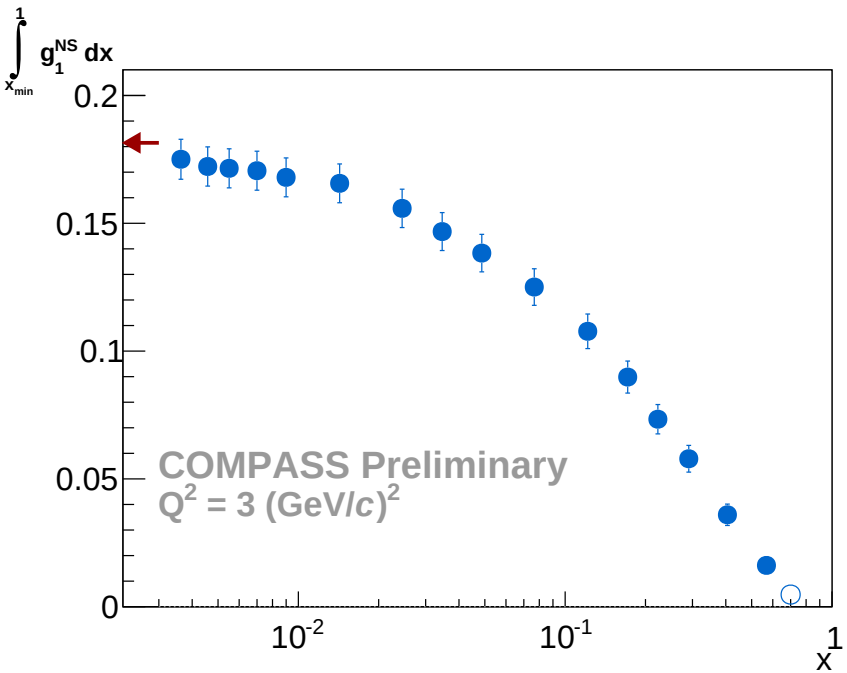
- In 2011 COMPASS collected data with 200 GeV/c muon beam
- The increased beam energy (160 $GeV/c \rightarrow$ 200 GeV/c) allows to access lower region of x for $Q^2 > 1$ (GeV/c)^2
- COMPASS extracted data in x, Q^2 grid for both A_1^p and g_1^p
- Good agreement is seen between 2007 and 2011 data
- Next step: SIDIS asymmetries for $h^{\pm}, K^{\pm}, \pi^{\pm}$

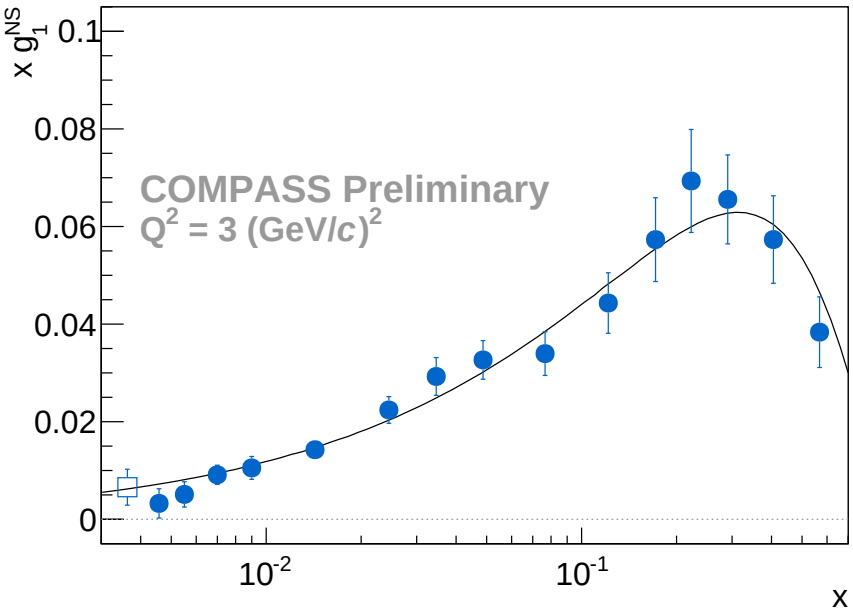




Test of the Bjorken Sum Rule

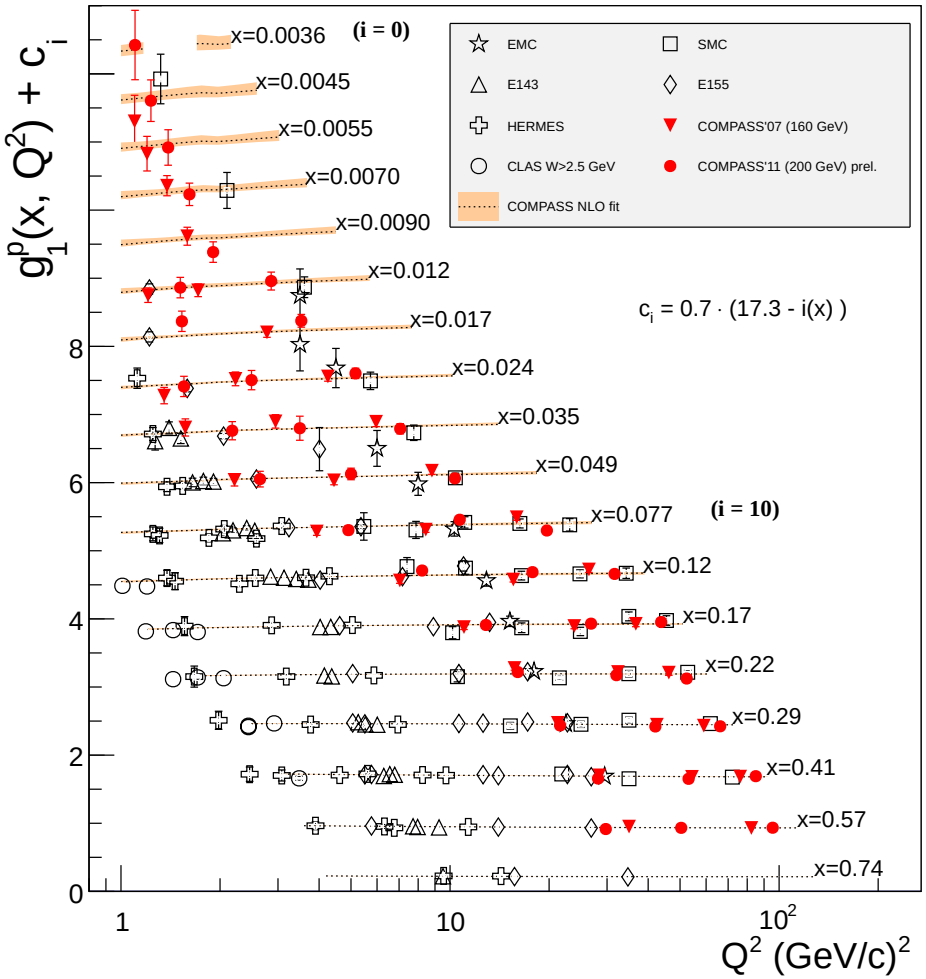
- $g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^d(x, Q^2)$
- $g_1^{NS}(x, Q^2)$ is interesting because its Q^2 dependence decouples from the singlet and gluon densities
- $\int_0^1 g_1^{NS}(x, Q^2) = \Gamma_1^{NS} = \frac{1}{6}\frac{g_A}{g_V} C_1^{NS}(Q^2)$,
  where $C_1^{NS}(Q^2)$ has been calculated in pQCD up to $\alpha_s^3(Q^2)$
- $\frac{g_A}{g_V}$ can be obtained from neutron beta decay, $\frac{g_A}{g_V} = 1.2694 \pm 0.0028$

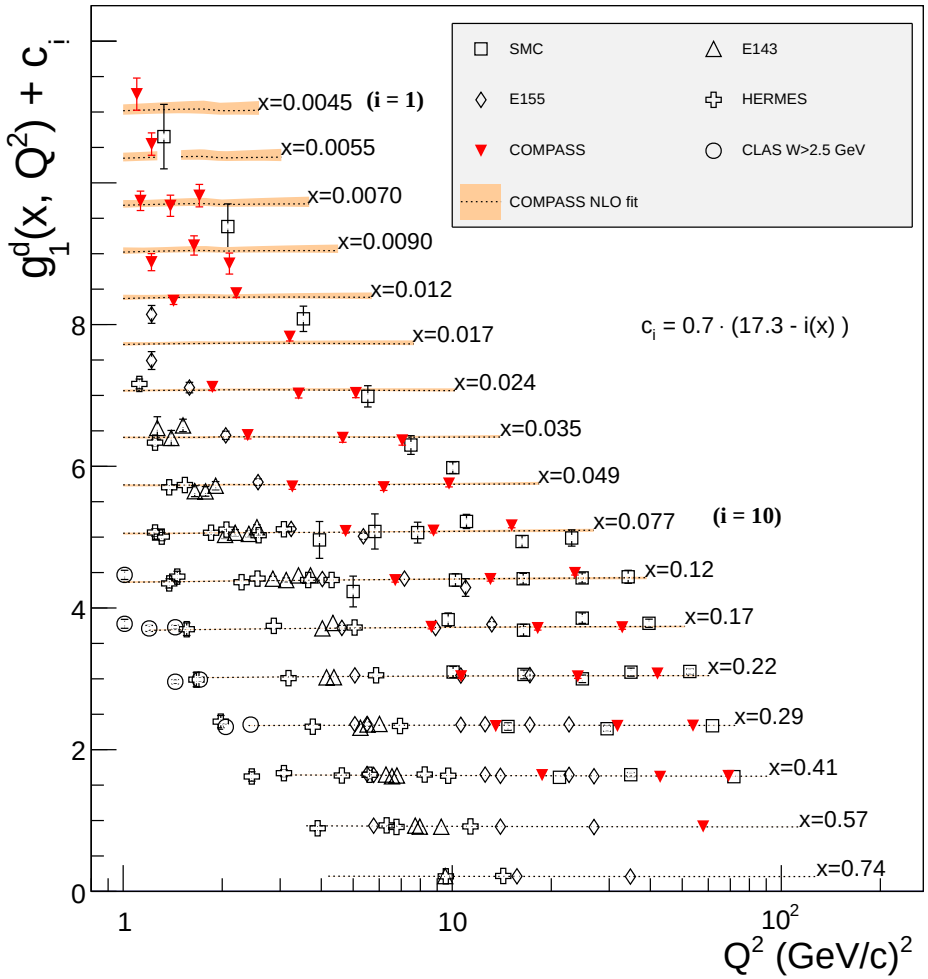




COMPASS results $\frac{g_A}{g_V} = 1.219 \pm 0.052 \pm 0.095$

NLO QCD fit of $g_1^{p,d}$ - Input

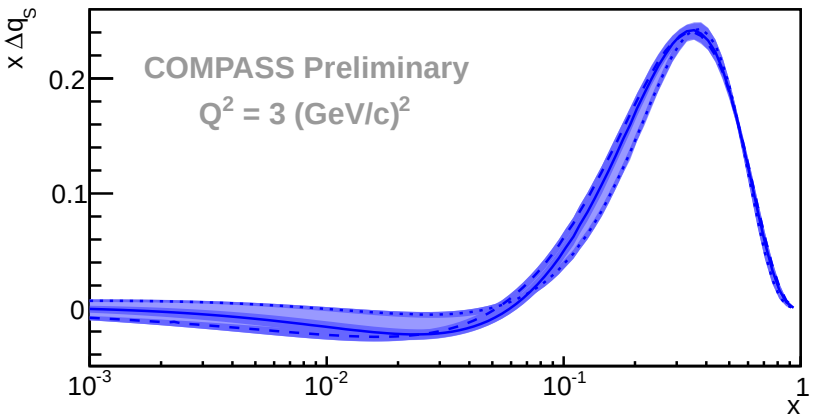


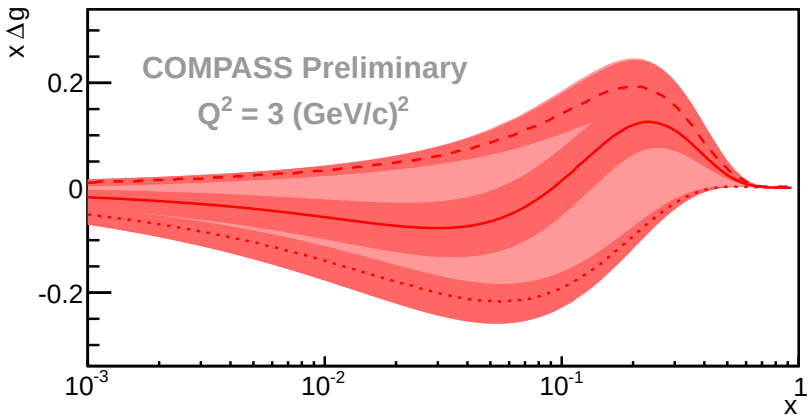


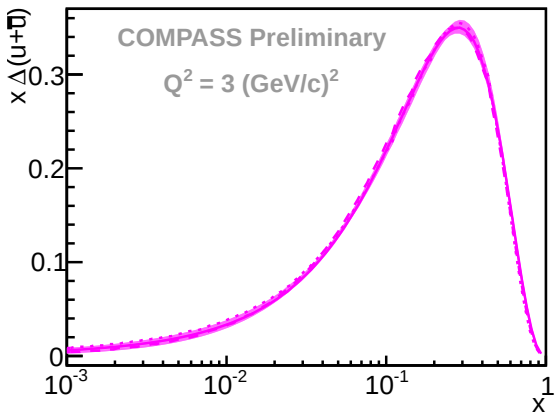
Limited (x, Q^2) coverage, as only fixed target DIS experiments were performed so far.

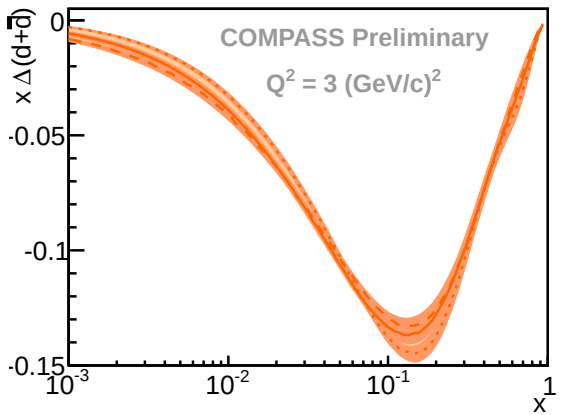
NLO QCD fit of $g_1^{p,d}$ - Results

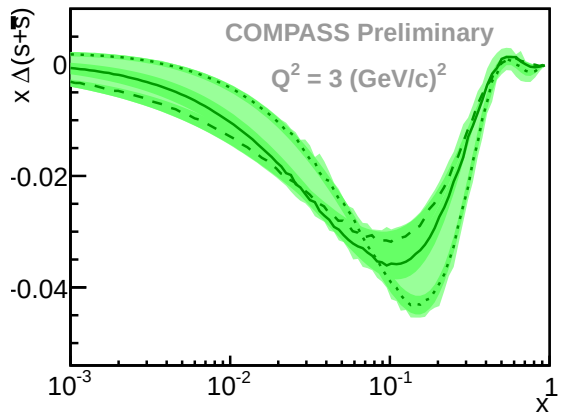
- Fit is performed in $\bar{M}S$ scheme
- $\chi^2/ndf \approx 1.05$
- $\Delta g/g$ is not constrained by the fit, although returned statistical errors are small
- Clear impact of poor $\Delta g/g$ knowledge on $\Delta\Sigma$





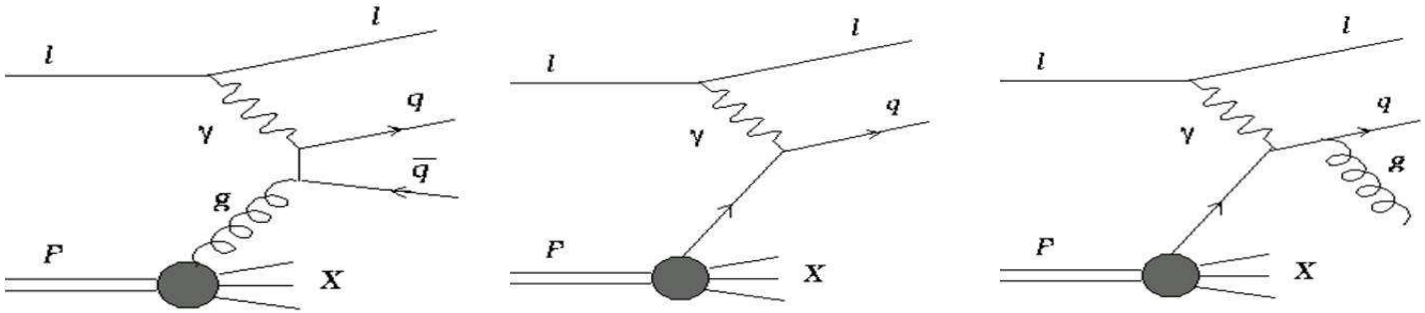






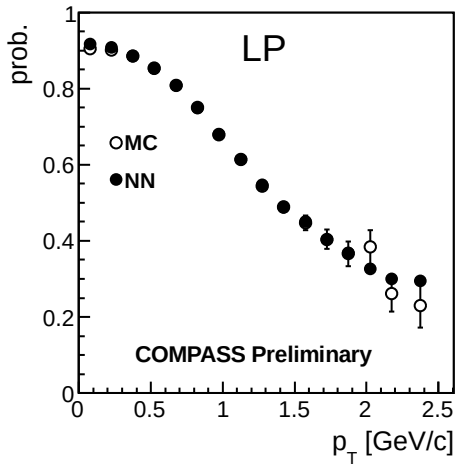
$\Delta g/g$ from All-p_T Method

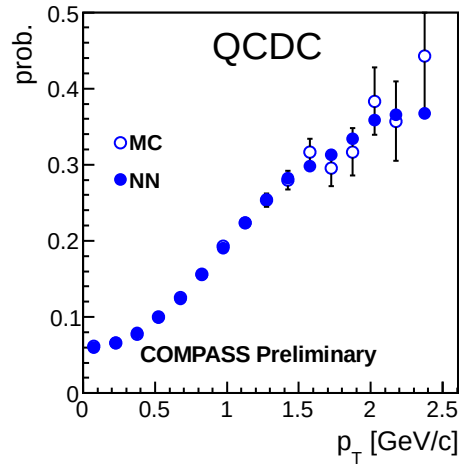
- Contribution from 3 processes to the observed asymmetry is assumed:

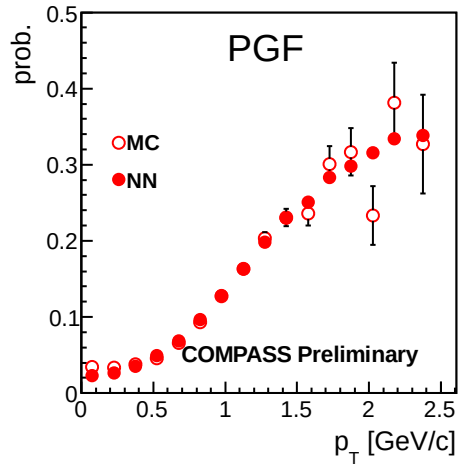


PGF LP QCDC

- $A_{LL}^h(x_{Bj}) = R_{PGF}\, a_{LL}^{PGF}\, \Delta g/g(x_G) + R_{LP}\, DA_1^{LO}(x_{Bj}) + R_{QCDC}\, a_{LL}^{QCDC}\, A_1^{LO}(x_C)$
  - the fraction of the processes (R_i) and partonic cross-section asymmetries (a_{LL}^i) are obtained from MC and parametrized by NN
- Idea: larger p_T $\rightarrow$ larger R_{PGF} $\rightarrow$ larger sensitivity to $\Delta g/g$

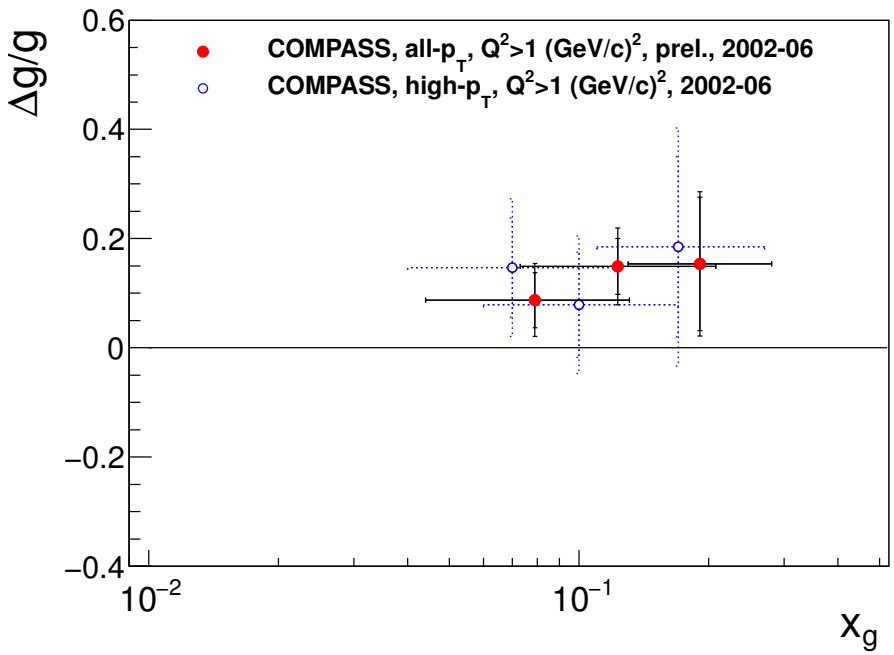


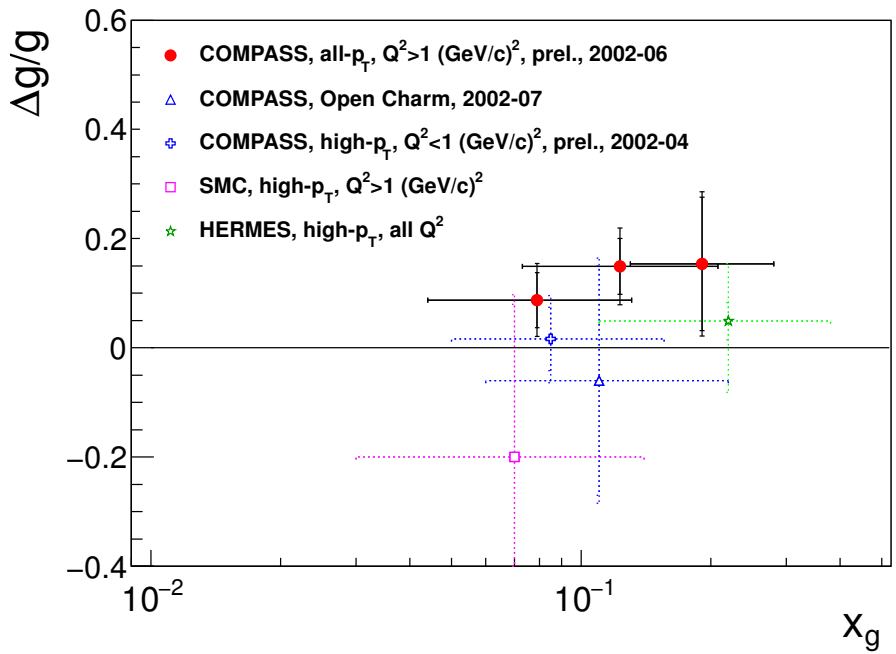




$\Delta g/g$ from All-p_{T} Method

- Reanalysis of data used for PLB 718 (2013) 922, now with a different method
- Presently, the A_1^{LO} and $\Delta g/g$ are extracted simultaneously from the same data set
  - low p_{T} data are needed as they are clean source of LP
  - certain systematic uncertainties are reduced w.r.t. previous method
  - some consistency tests of the model used for estimate of Rs, a_{LL}^is are possible.
- $\Delta g/g = 0.113 \pm 0.038 \pm 0.035$, $\langle \mu^2 \rangle = 3$ (GeV/c)^2, $\langle x_g \rangle = 0.10$
- In the measured x_g range $\Delta g/g$ maybe positive, similar conclusion is reached in recent DSS fits, which include RHIC data.

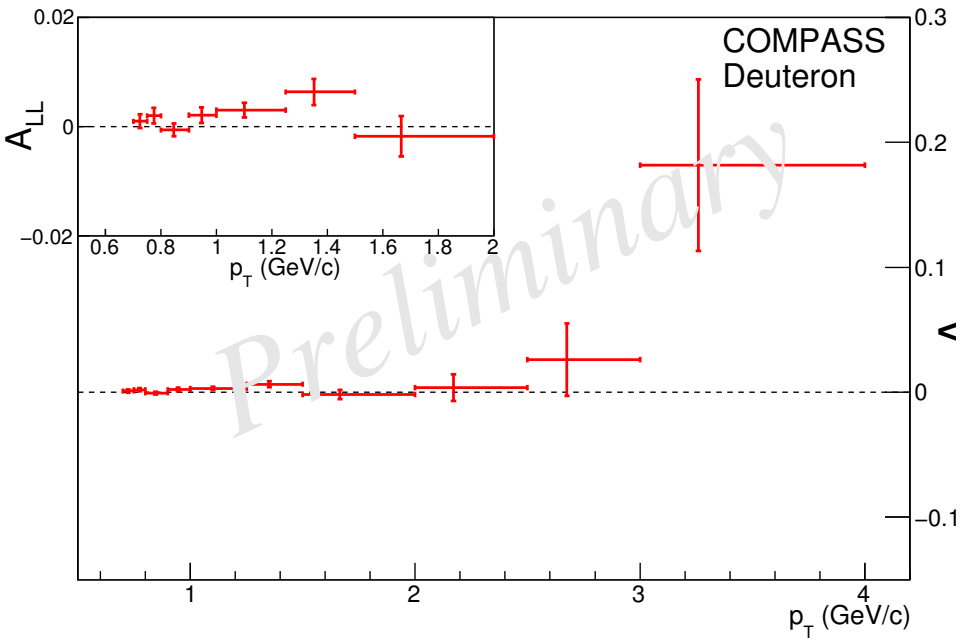


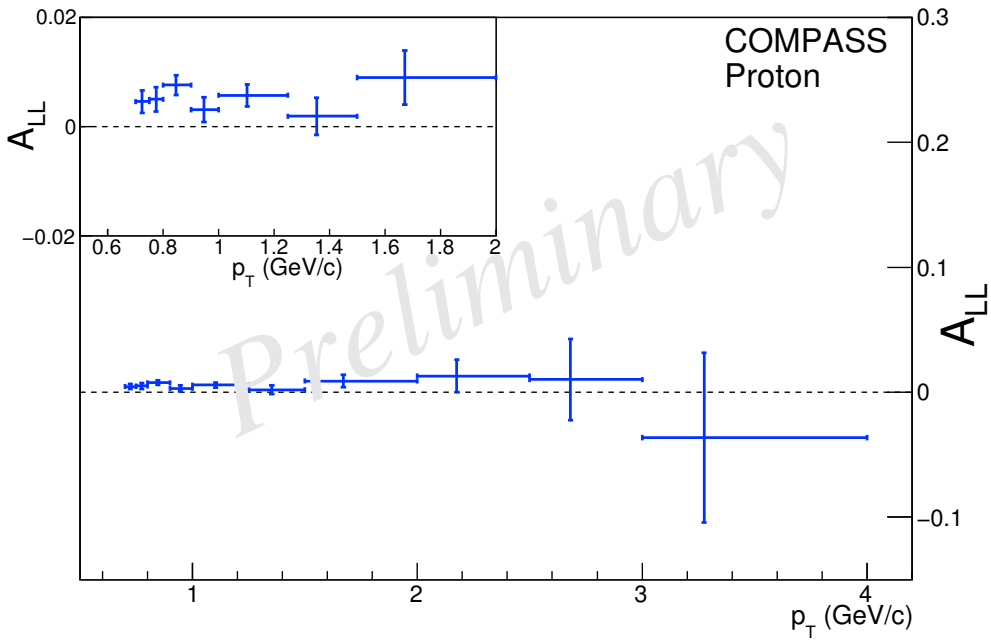


→ see talk by K. Kurek for more details

A_{LL} from Low Q^2, high-p_T Data

- The same idea as before: larger p_T $\rightarrow$ larger R_{PGF} $\rightarrow$ larger sensitivity to $\Delta g/g$
- In the low Q^2 region there is an additional complication: resolved photon processes
- NLO calculations in collinear pQCD by M. Stratmann, B. J?er and W. Vogelsang (EPJC 44 (2005) 533)

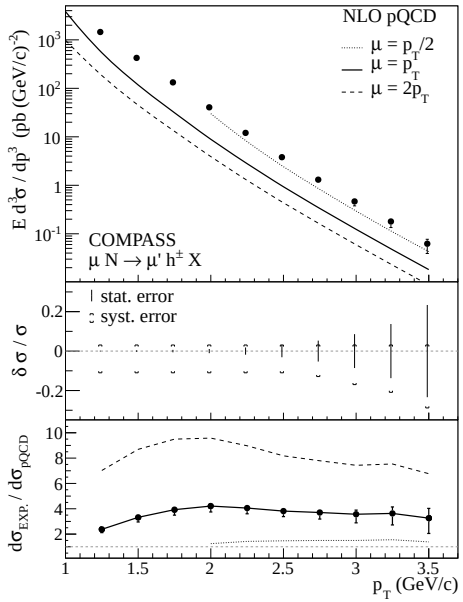


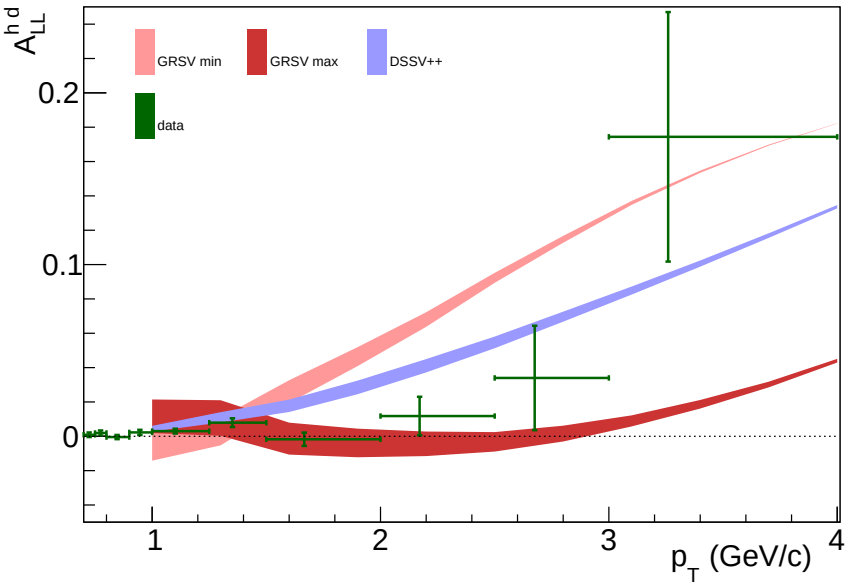


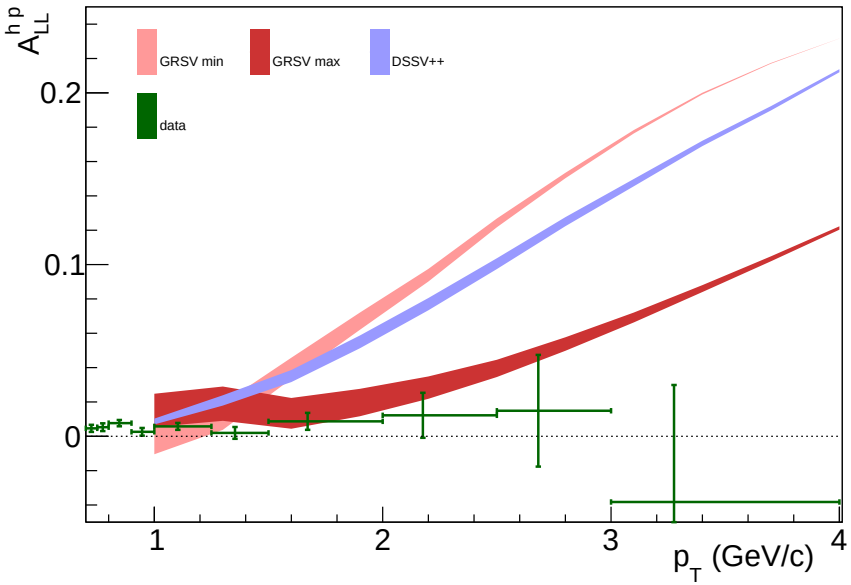
$\rightarrow$ see talk by K. Kurek for more details

A_{LL} from Low Q^2, high-p_T Data cont.

- COMPASS preliminary A_{LL}s are compared with various $\Delta g/g$ hypotheses
- Disagreement is seen between proton data and theory
- Possibly more resummations needed in the theory

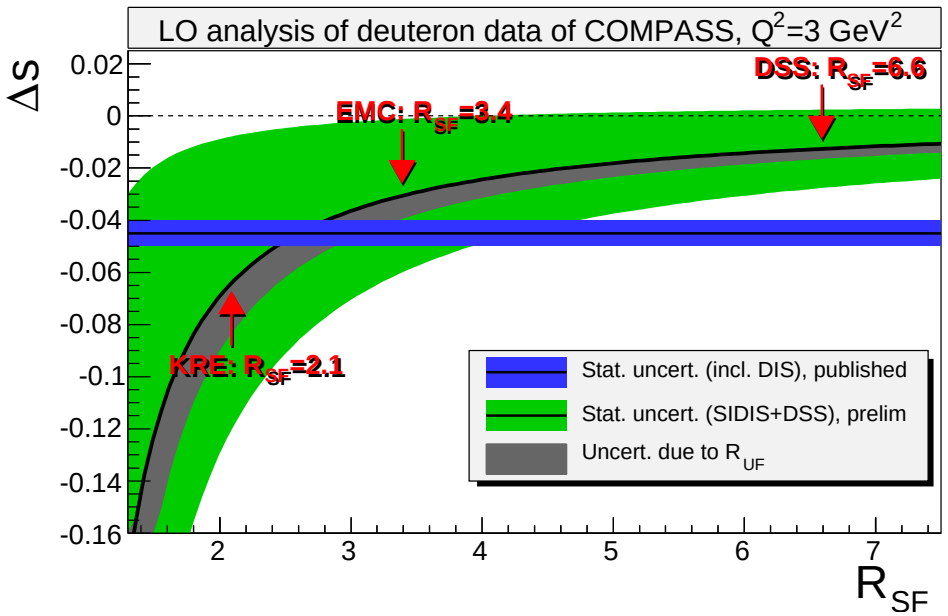


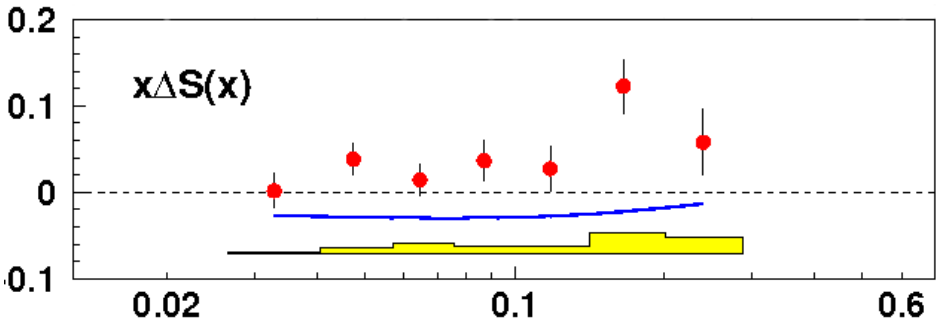




ΔS Puzzle

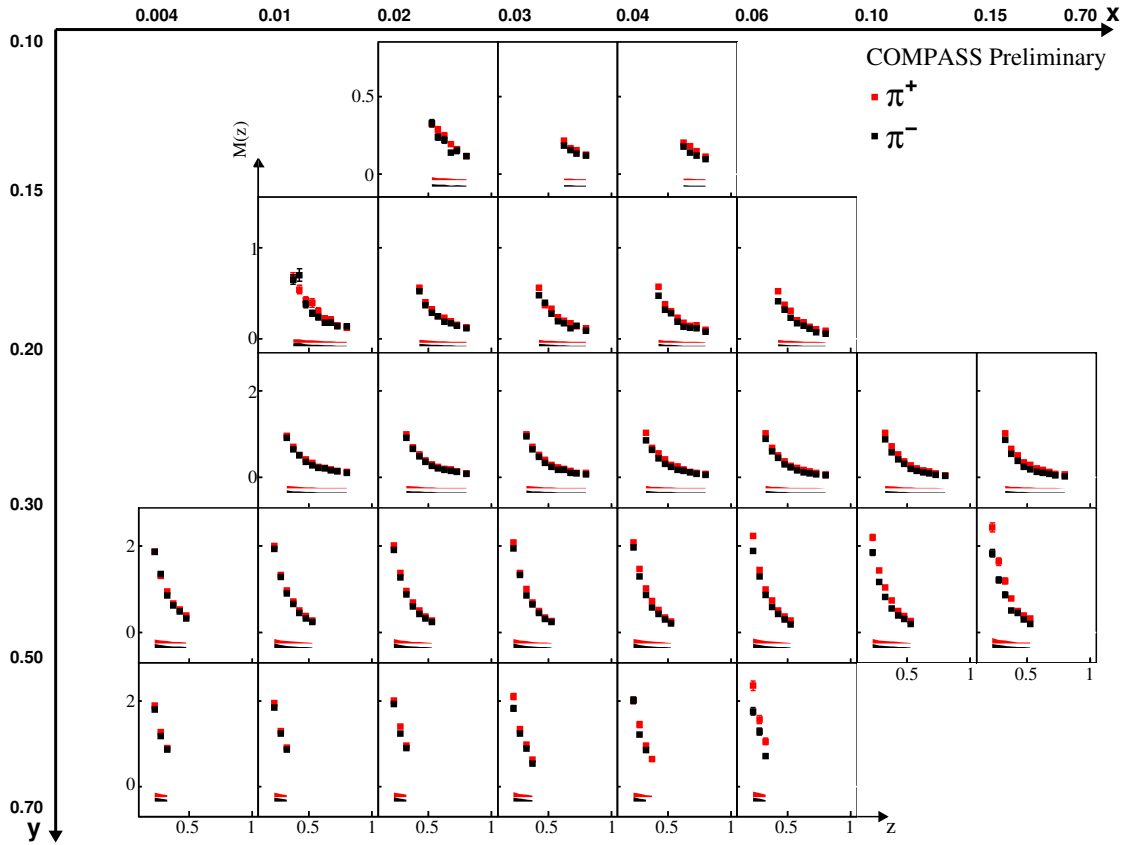
- ΔS from fits of g_1 and SIDIS π is negative in the whole x region
- However, SIDIS K data prefer zero or positive value at moderate x values
- Impact of Kaon data strongly dependent upon the choice of strange FF - D_S^K
- LSS group reported that problem disappears if HKNS FF set is used instead of DSS.





Charged Hadron Multiplicities

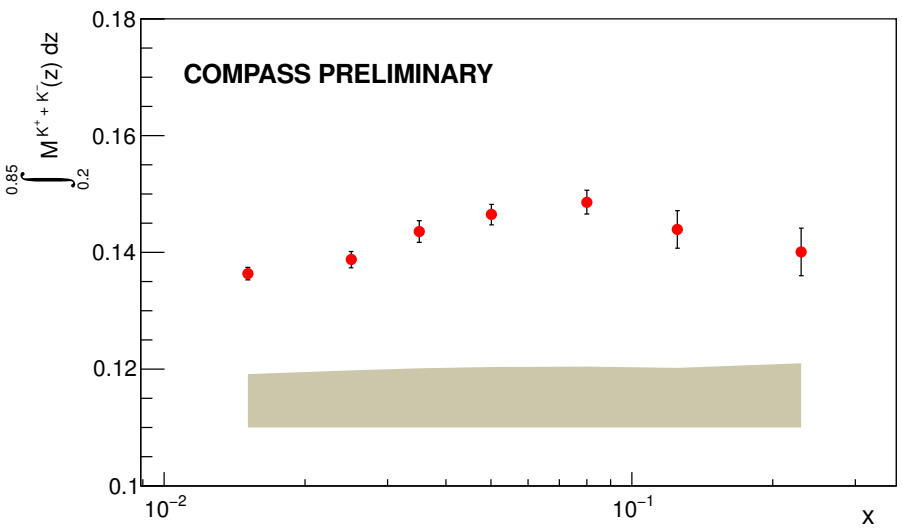
- Hadron multiplicities dN_h/dN_{DIS}, give access to FF
- In LO: $M^i(x, Q^2, z) = \frac{\sum_q e_q^2 q(x,Q^2) D_q^i(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$
- COMPASS extracted preliminary charged hadrons, π and K multiplicities in grid of (x, y, z)

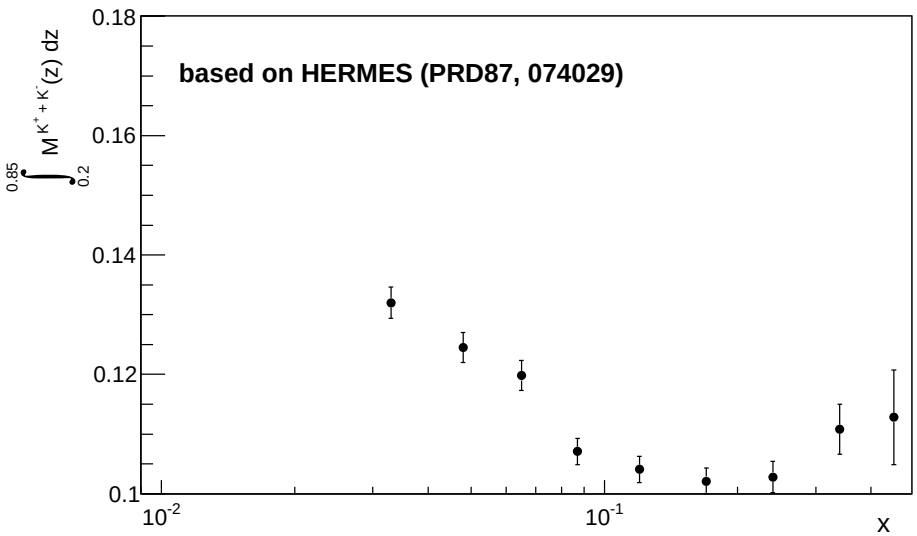


→ see talk by F. Kunne for more details

Kaon Multiplicity Sum

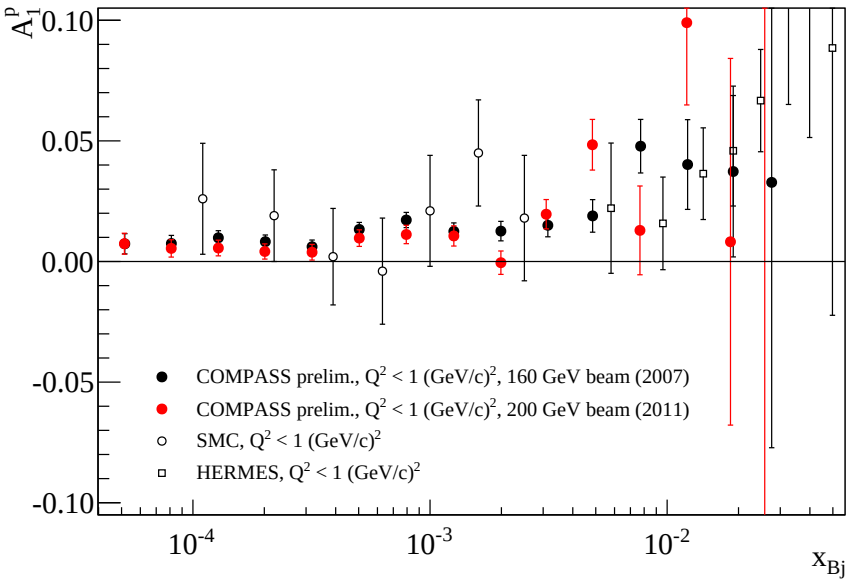
- Kaon multiplicity sum gives an easy access to $S \int D_S^K(z)dz$
- For the iso-scalar target:
- $5M^{K^+ + K^-} \approx \int D_Q^K + S/Q \int D_S^K$, where:
  - $D_Q^K = 4D_u^K + D_d^K$
  - $Q = u + \bar{u} + d + \bar{d}$; $S = s + \bar{s}$
- High x - low contribution of strange quarks $\rightarrow$ access to D_Q^K
- Low x- influence of $S \int D_S^K$ should be seen
- Problem: COMPASS and HERMES data have different shape of the $M^{K^+ + K^-}$ distribution as well as results do not agree for $x \approx 0.1 - 0.3$

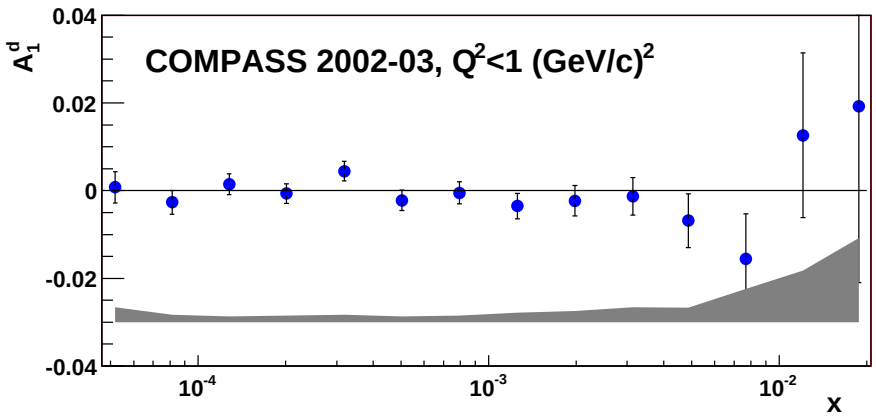




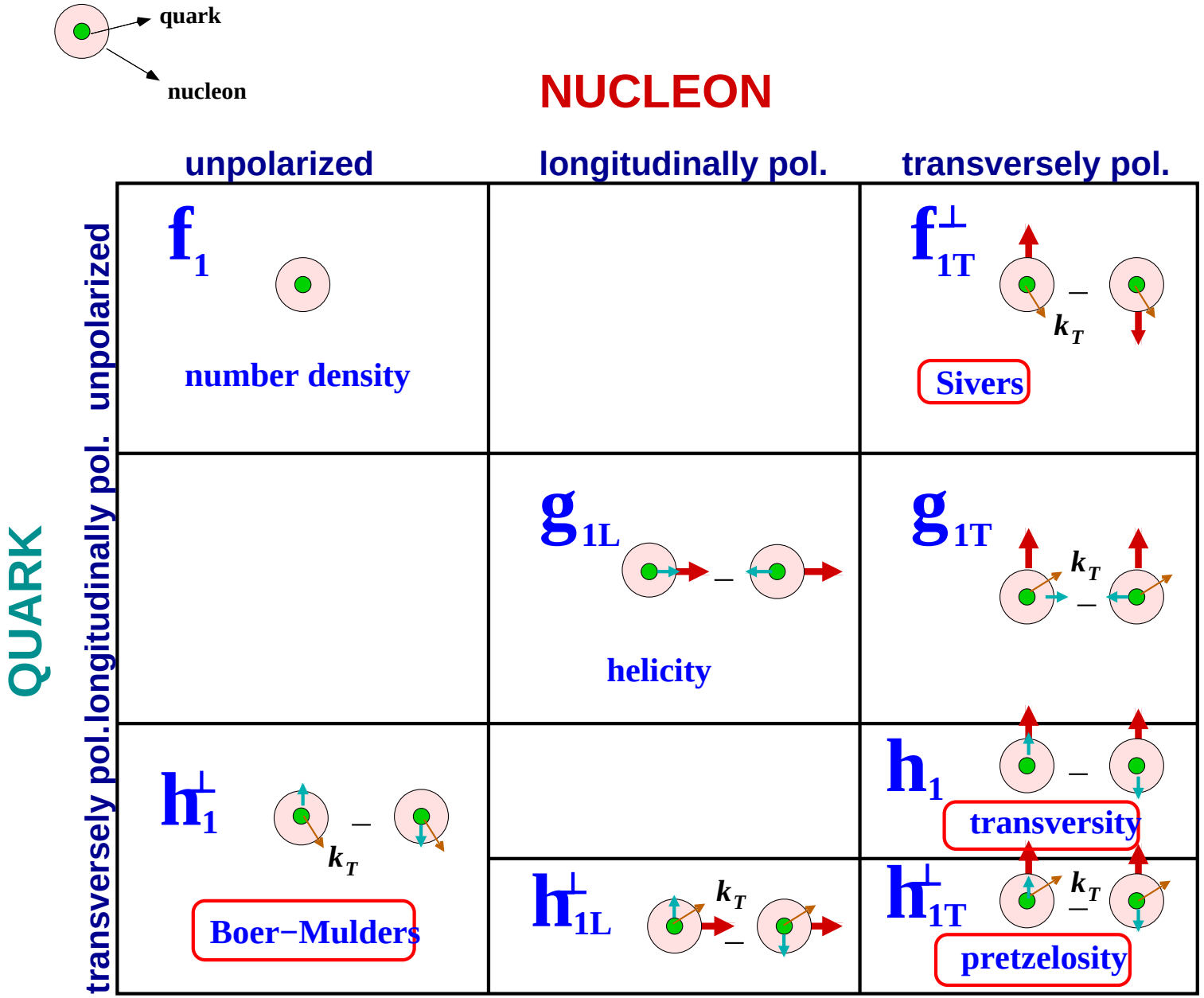
A_1^p at Low Values of x and Q^2

- Low x , high parton densities
- COMPASS (fixed target) strong correlation between x and Q^2
- $Q^2 < 1$ GeV/c - non perturbative region
- Some models that allow a smooth extrapolation to the low-Q^2 and high-Q^2 regions (J. Kwiecinski et al., B.I. Ermolaev et al.) can be confronted with data
- More than 10 fold increase of the precision w.r.t. previous experiments
- Clear non-zero signal is seen for the proton data even at low x , contrary to the deuteron data, where the result is consistent with zero.



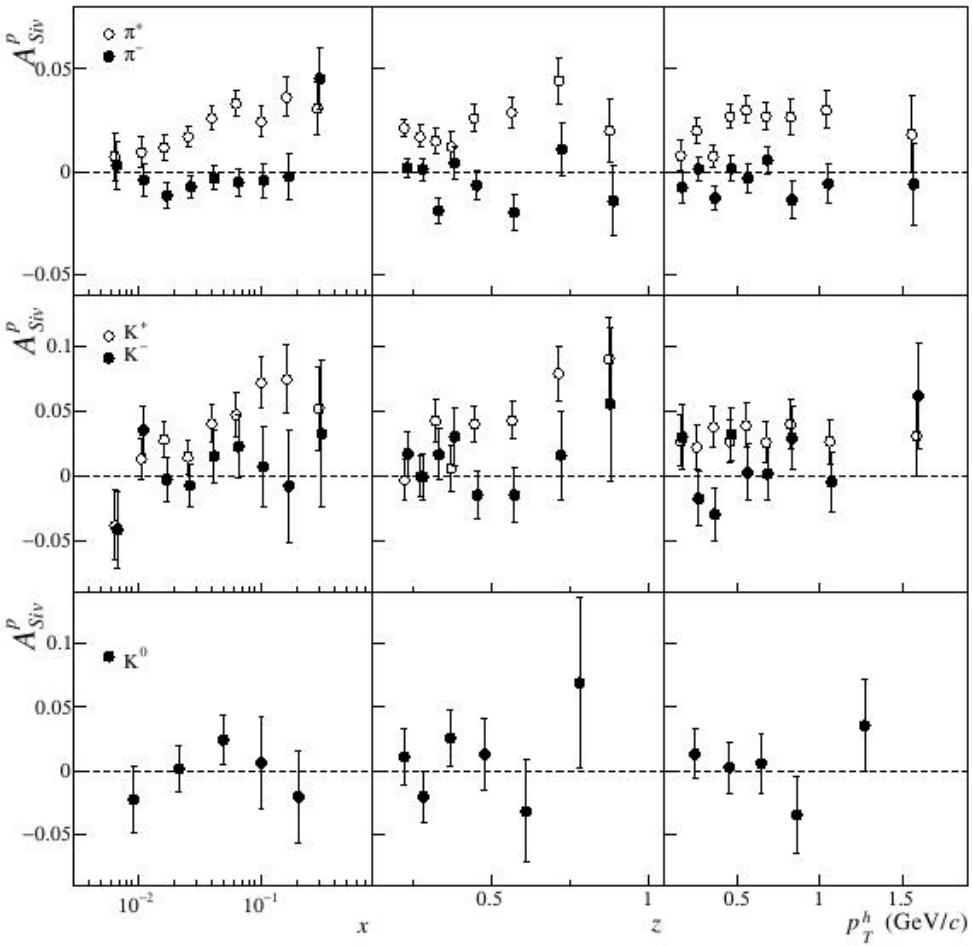


Beyond the Longitudinal Nucleon Structure



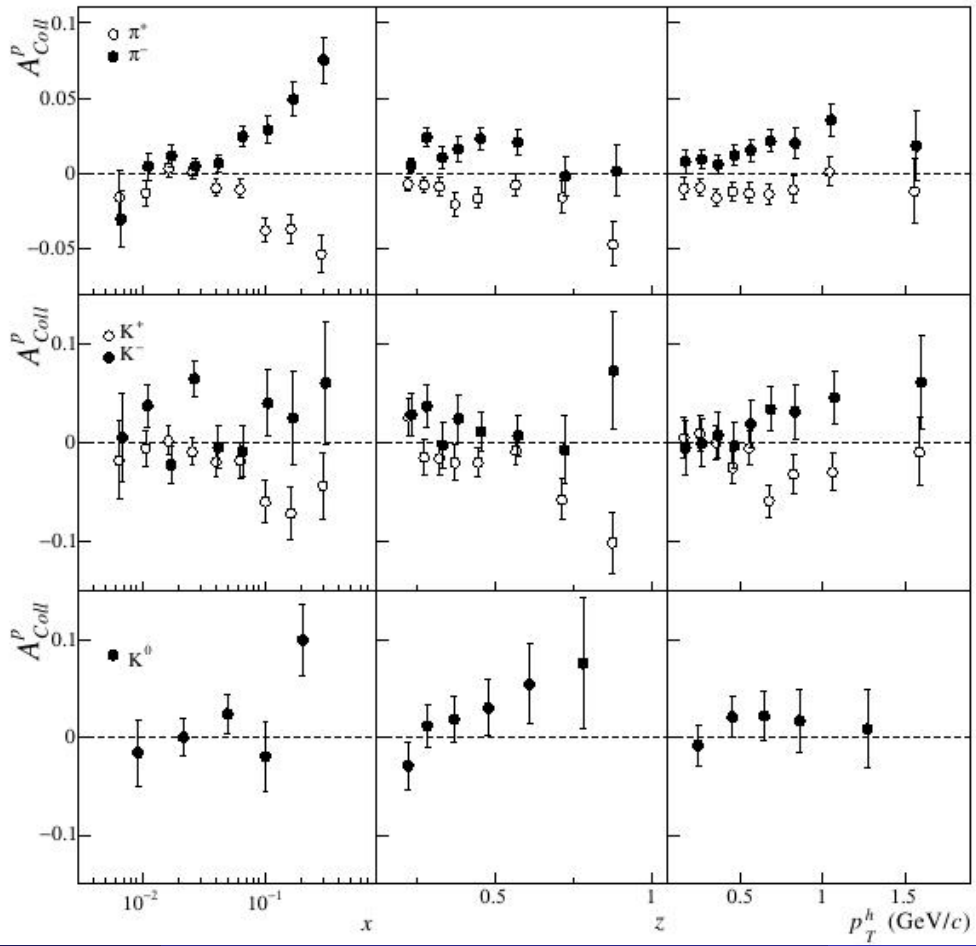
Sivers Effect

- Sivers effect - related with partons intrinsic k_T
- COMPASS, hep-ex/1408.4405, (subm. PLB)
- Non zero effect observed for π^+ and K^+



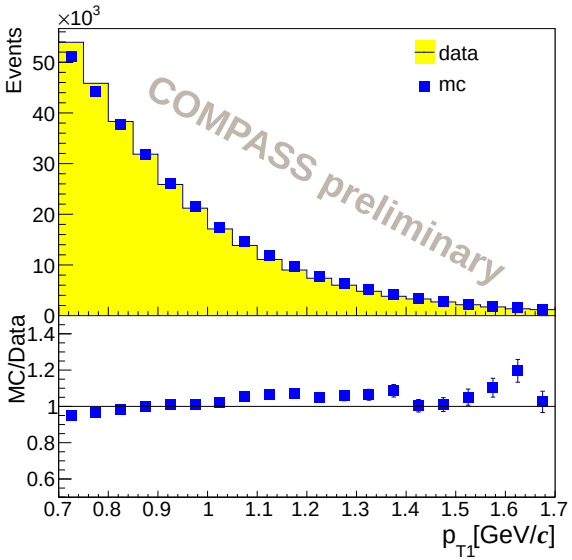
Collins Effect

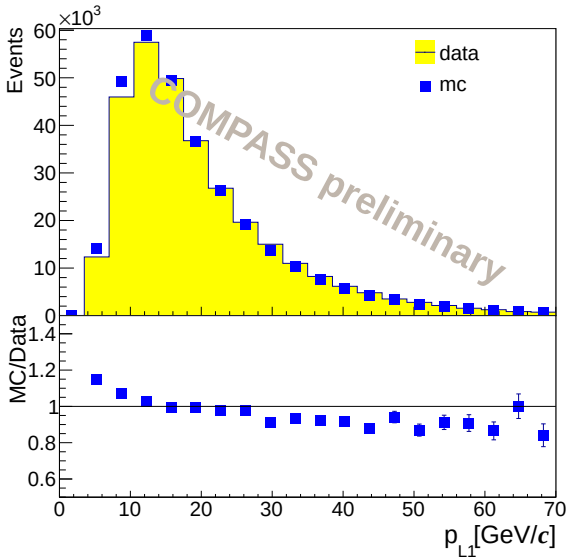
- Collins effect - related with fragmentation $p_\perp$
- COMPASS, hep-ex/1408.4405 (subm. PLB)
- Non zero effect observed for $\pi^\pm$
- More statistic needed for kaons, to make sound conclusions



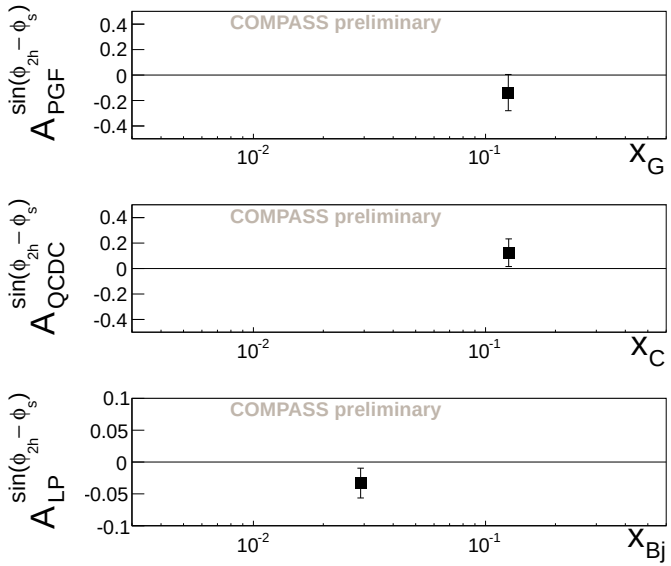
Gluon Sivers Measurement

- Idea & analysis method similar as in $\Delta g/g$ High-p_{T}:
  - three processes are considered LP,QCDC, PGF
  - select high-pT sample in order to increase contribution from PGF.
  - extract simultaneously the azimuthal asymmetries for the 3 processes
- Data 2003-2004 deuteron target
- Cuts: $Q^2 > 1$ GeV/c, $p_{\mathrm{T},1,(2)} > 0.7\,(0.4)$ GeV/c, $z_{1,2} > 0.1$
- Sivers effect for gluon as well as other asymmetries are compatible with zero, within experimental errors





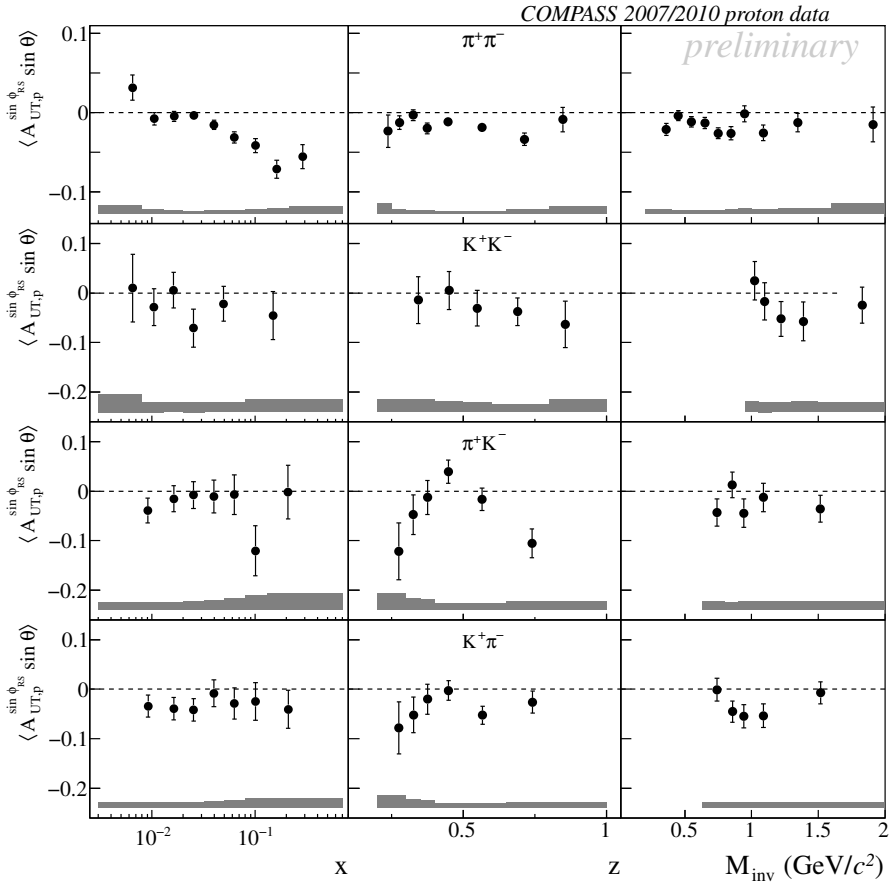
Sivers Asymmetry

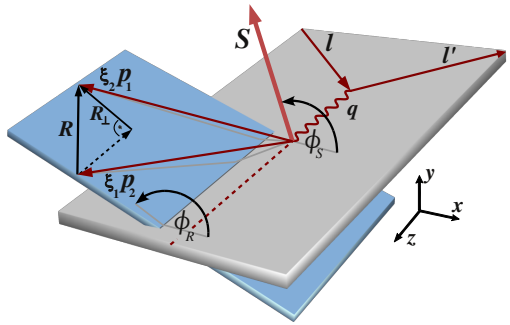


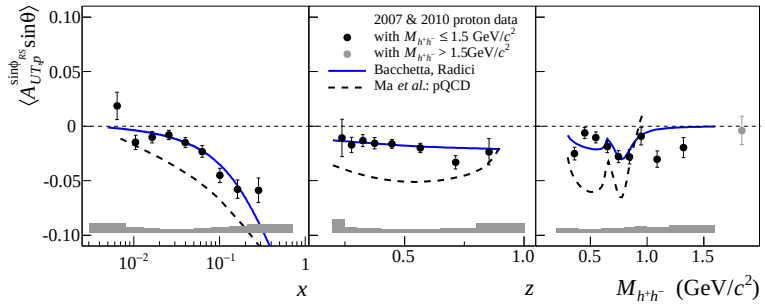
→ see talk by K. Kurek for more details

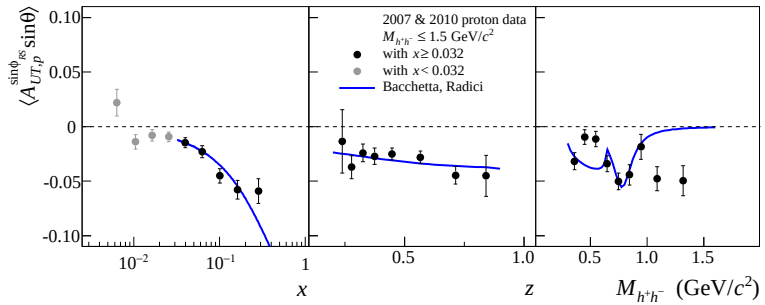
2h Asymmetries

- Two hadron asymmetry gives access to the interference FF
- They were extracted for h^+h^- pairs as well as for $\pi^+\pi^-, K^+K^-, \pi^+K^-, K^-\pi^+$
- Good agreement with the theory predictions





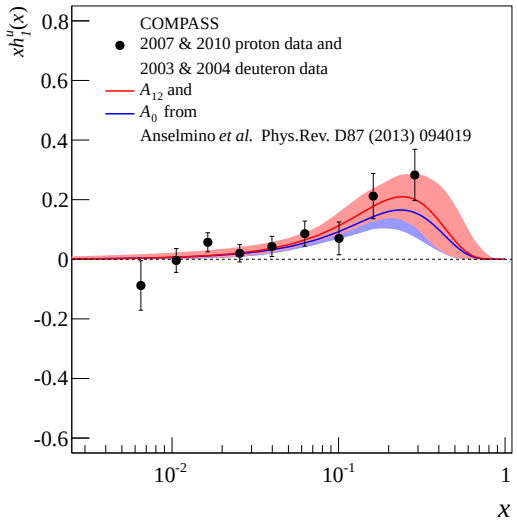


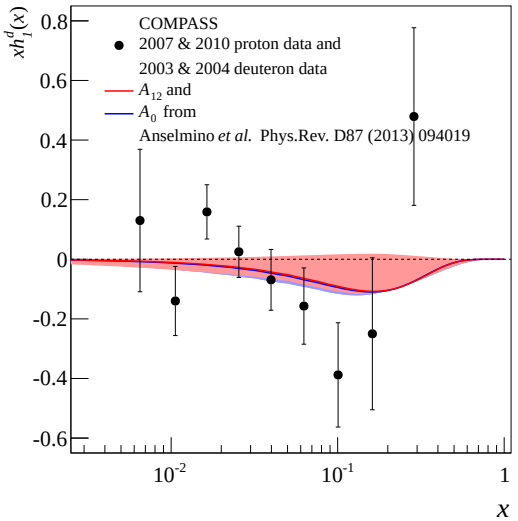


→ see talk by G. Sbrizzai for more details

Extraction of Transversity h_1

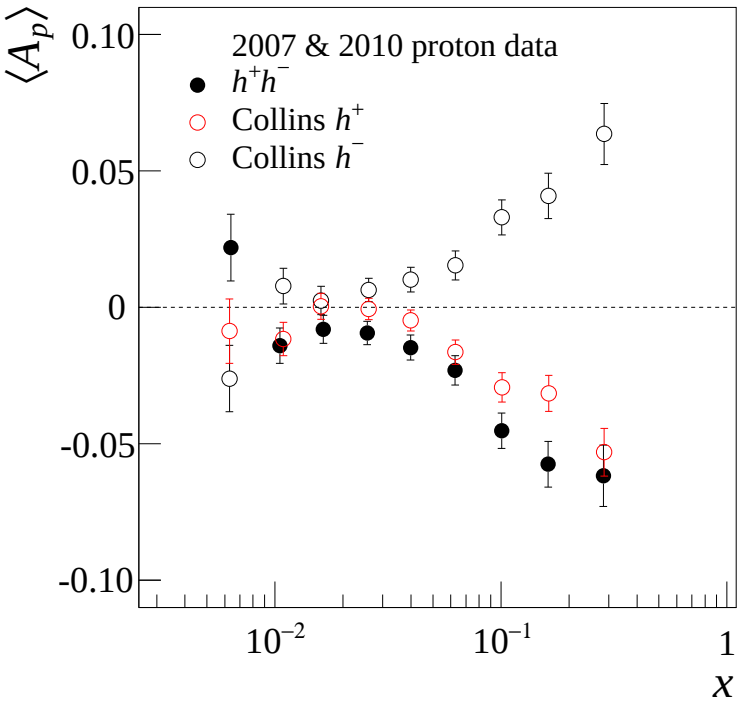
- Ingredients: 2h $\pi^+\pi^-$ asymmetries for proton and deuteron data
- Certain symmetry assumptions about dihadron FF
  - $D_1^q = D_1^{\bar{q}}$
  - $H_1^{\perp u} = -H_1^{\perp d} = -H_1^{\perp \bar{u}} = H_1^{\perp \bar{d}}$
  - $H_1^{\perp s,\bar{s},c,\bar{c}} = 0$
- $h_1^d = h_1^{u_v} + h_1^{d_v}$
- $h_1^p = h_1^{u_v} - 1/4 h_1^{d_v}$
- Extracted results from 2h case are compared with fit to the 1h Collins asymmetry

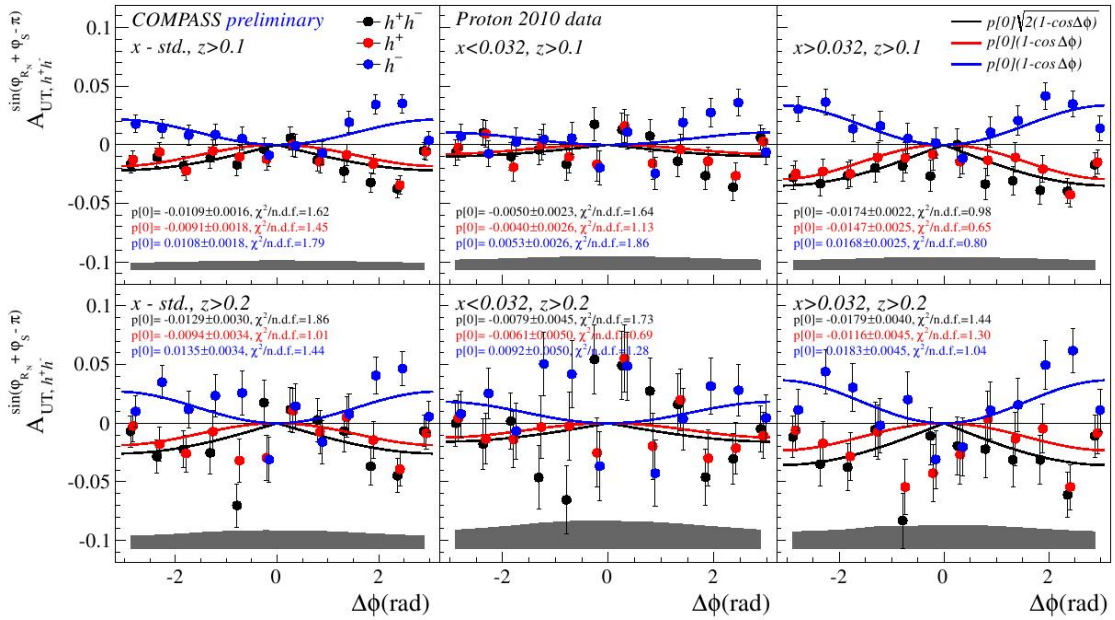




→ see talk by G. Sbrizzai for more details

2h vs 1h Asymmetries



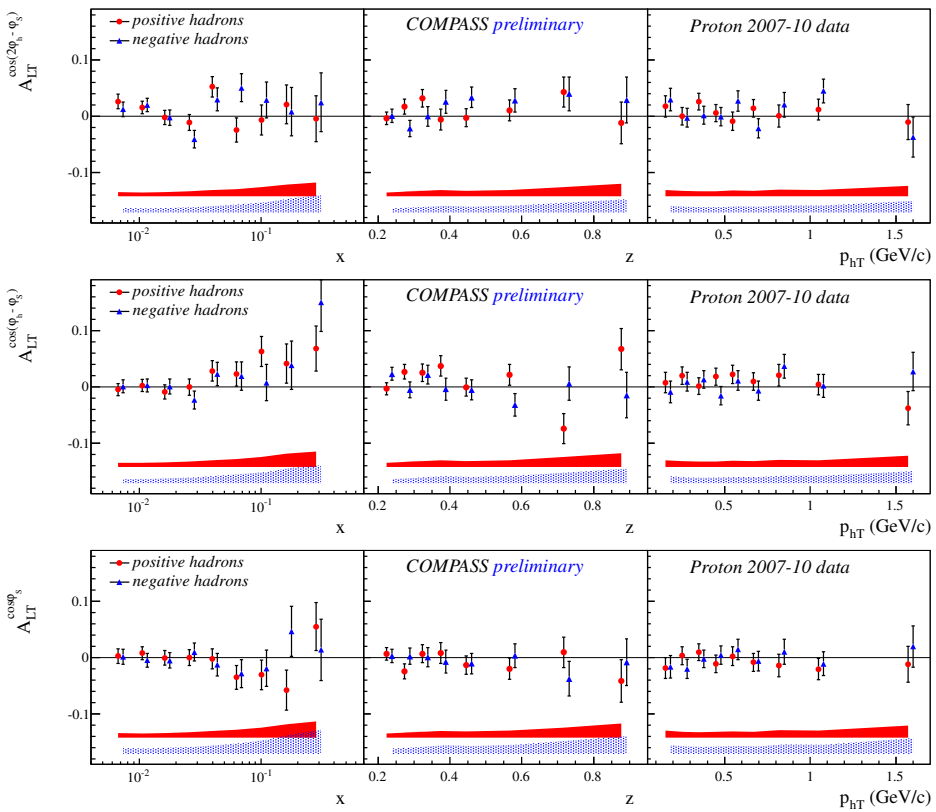


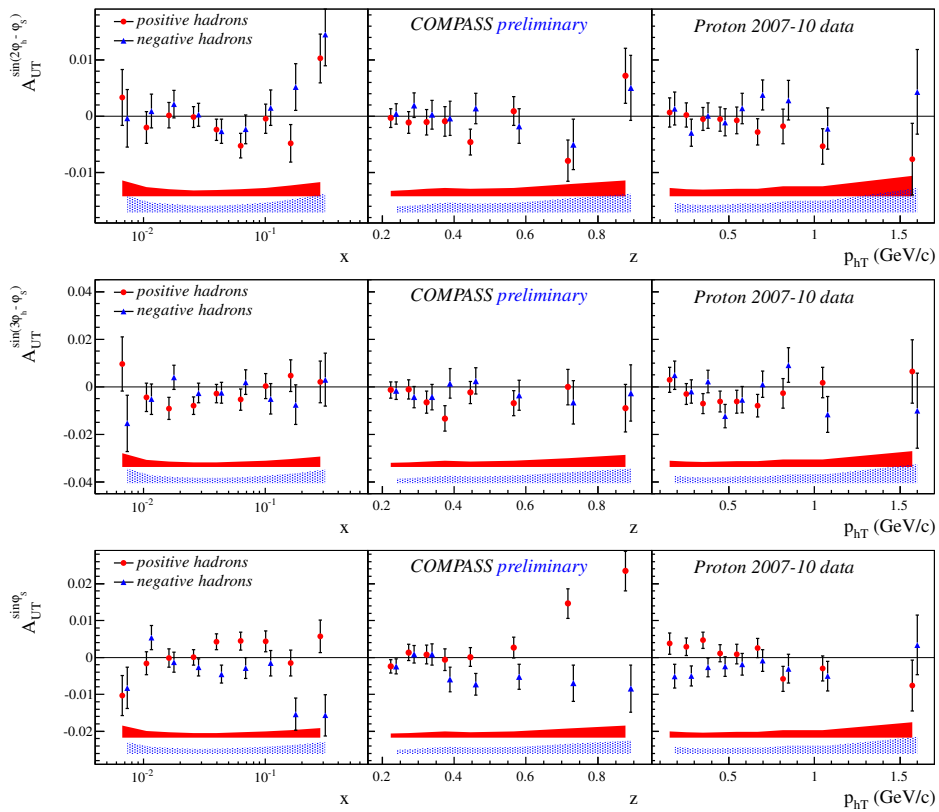
- Clear correlation between 2h asymmetry and Collins asymmetry is observed
- More general cross-section formula was written $lp \rightarrow 2h + X$ interaction
- It is interesting to study the asymmetries as a function of $\Delta\Phi$ $(\phi_h^+ - \phi_h^-)$
- It turns out that one can predict 2h asymmetry from the 1h Collins asymmetry. Expected ratio approx $4/\pi$

→ see talk by F. Bradamante for more details

Beyond Sivers & Collins I

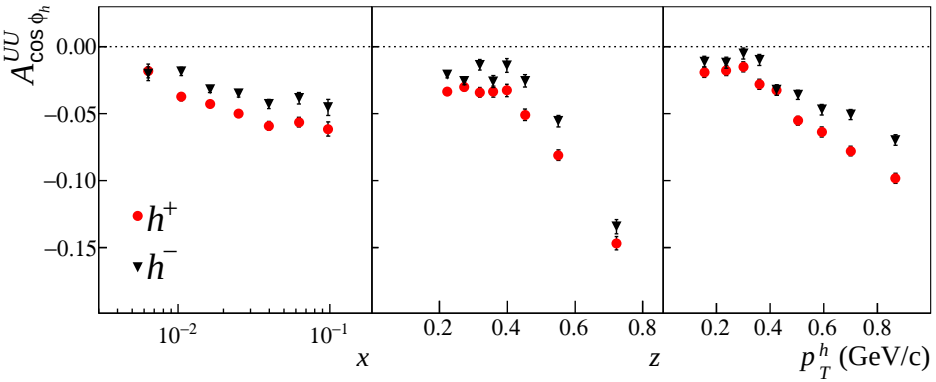
- Six other A_{LT} and A_{UT} asymmetries were measured
- Different combination of PDF, TMD and FF involved
- Asymmetries comparable with 0, but $A_{UT}^{\sin\phi_S}$
- $A_{UT}^{\sin\phi_S}$ related to Sivers $f_{1\perp}$ and transversity h_1

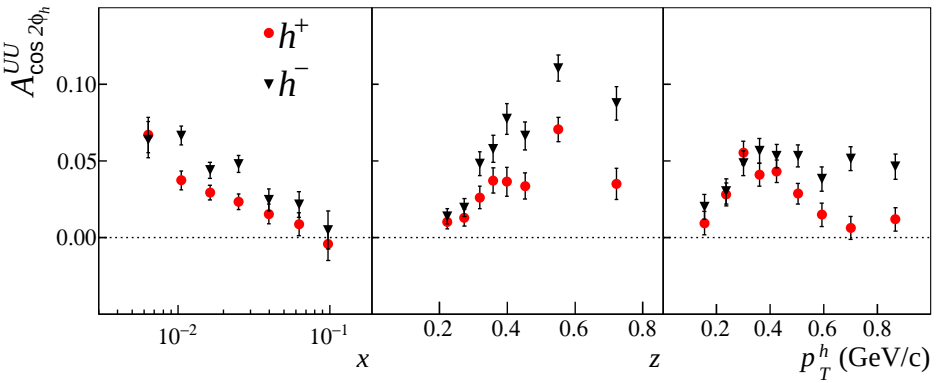




Beyond Sivers & Collins II

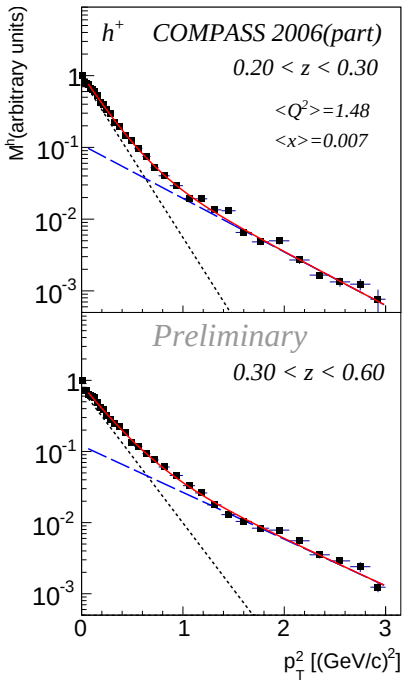
- Unpolarised azimuthal asymmetries were also measured
- $A_{UU}^{\cos\phi_h}$ related to Boer-Mulders PDF and Cahn effect (i.e. kinematic effect due quark k_T)
- $A_{UU}^{\cos 2\phi_h}$ related to Boer-Mulders PDF and Collins FF
- Sizable asymmetries observed
- Non-trivial dependence in all variables!
- These asymmetries were also extracted in 3D

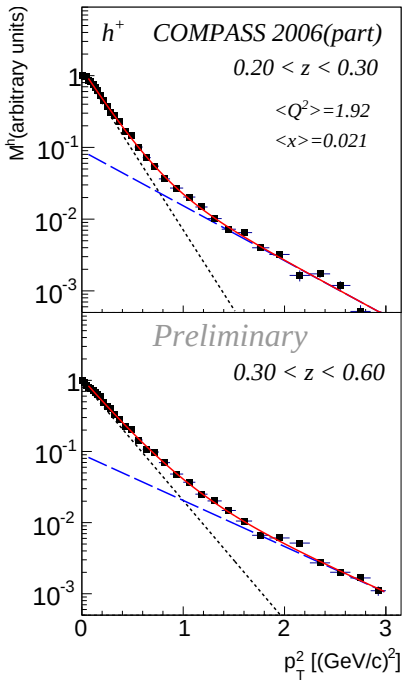


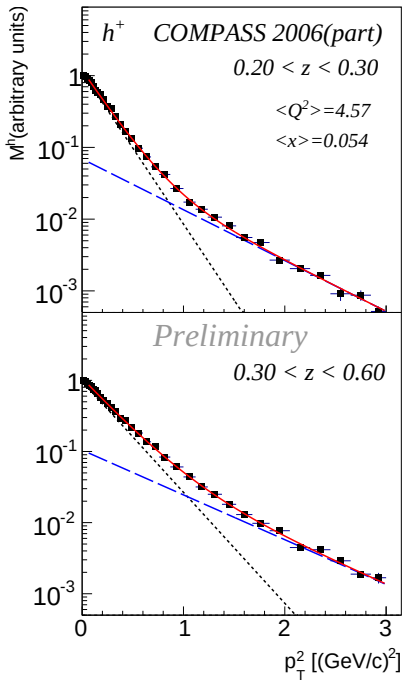


Transverse Momentum Dependent Multiplicities

- Both intrinsic k_T of quarks in the nucleon as well as $p_\perp$ of the fragmentation needs to be better understood
- Hadron multiplicities were extracted in 4D (x, Q^2, z, p_T^2) binning
- Main features:
  - the 2-exp fits give reasonable fits to the data,
  - 2nd exp become dominant event as low as $p_T^2 \approx 0.6$ GeV^2



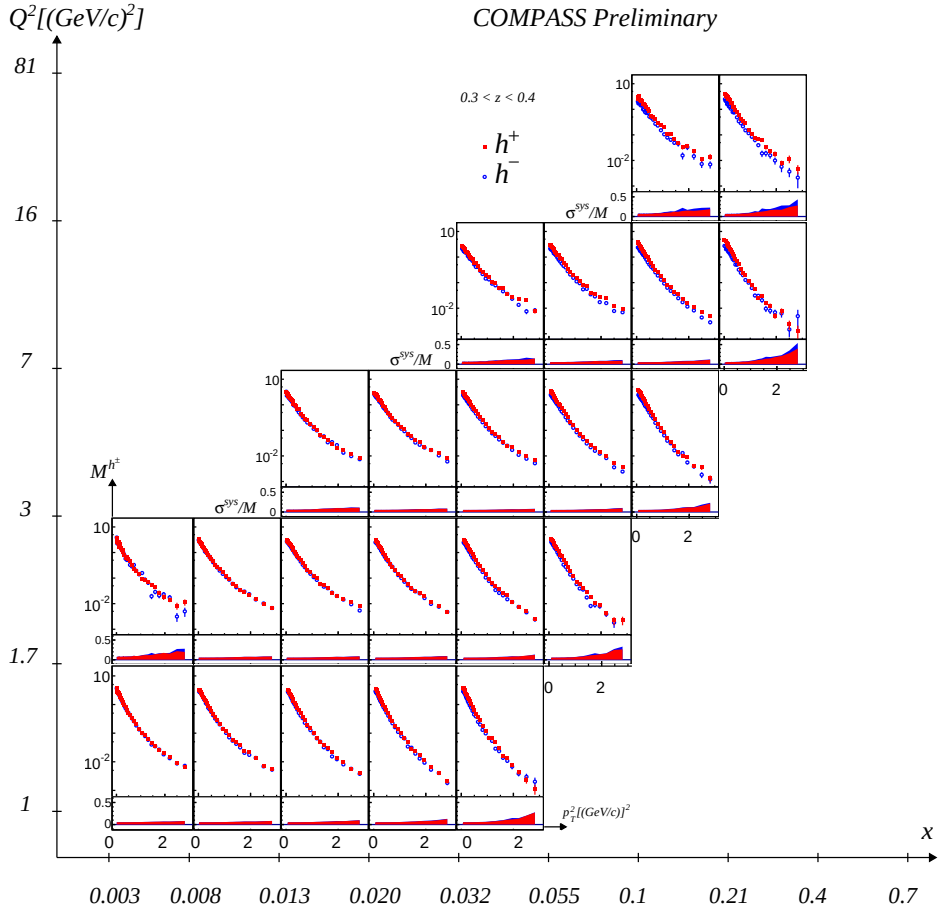




→ see talk by N. Makke for more details

Transverse Momentum Dependent Multiplicities cont.

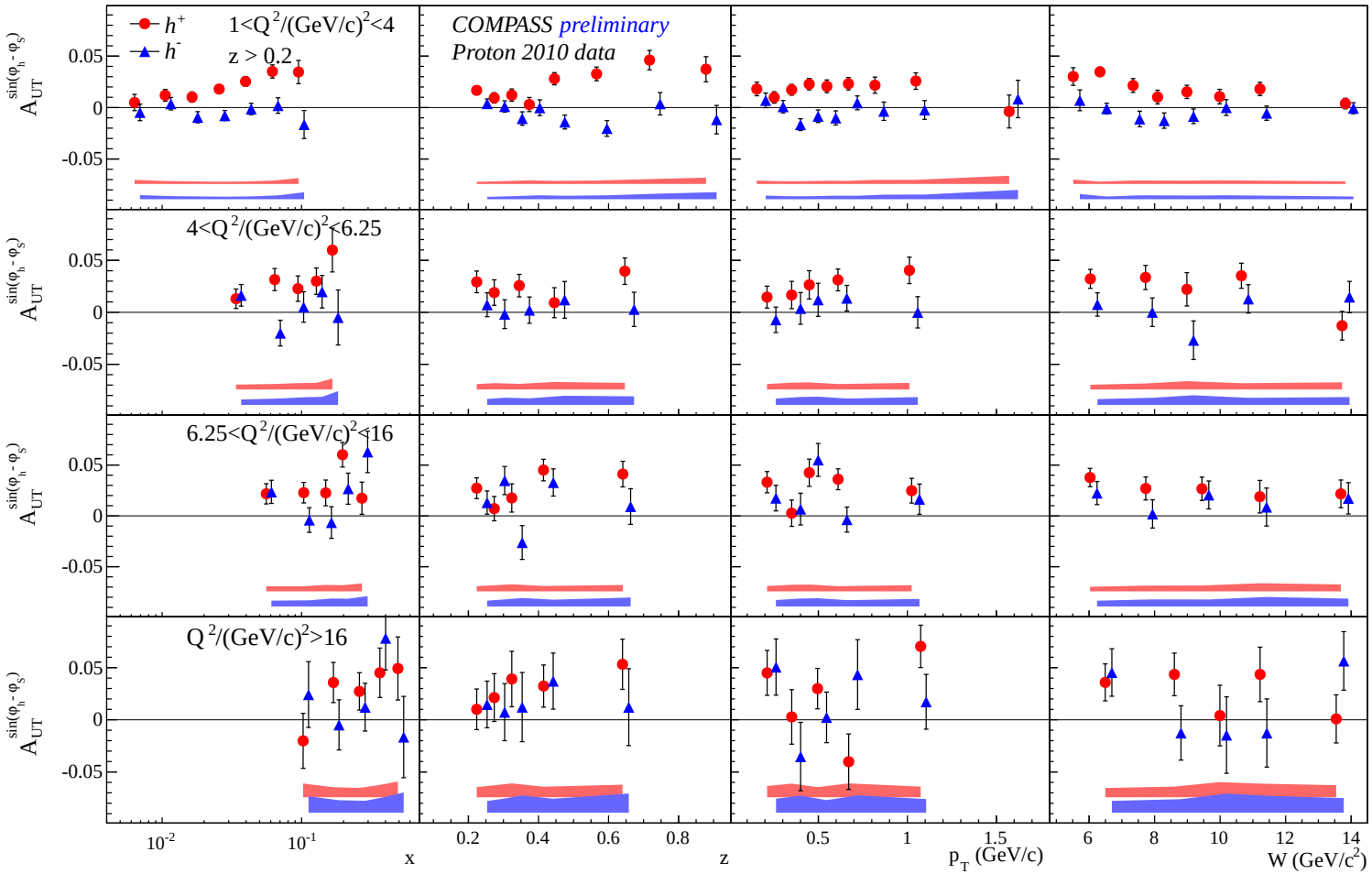
- New results without the arbitrary normalization:



- COMPASS has already published p_{T}^2 dependent multiplicities from 2004 data in EPJC 73 (2013) 2531
- However, issues in this analysis were detected, which can affect the overall x, y, z normalization of multiplicities up to 40%, but the shape as a function of p_{T}^2 are not significantly affected. Erratum in preparation

Multi-Dimensional Analyses

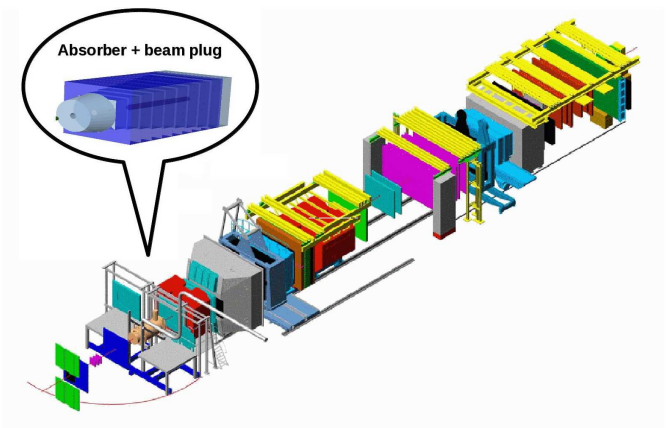
- Rapid theory advances asks for multidimensional analyses...
- Example: Sivers effect and the matter of TMDs Q^2 evolution

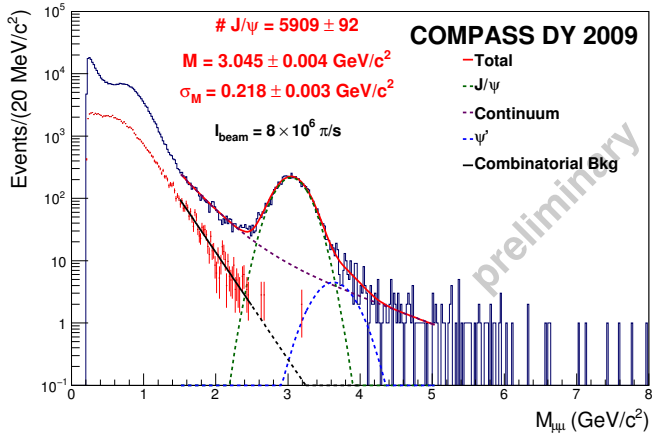


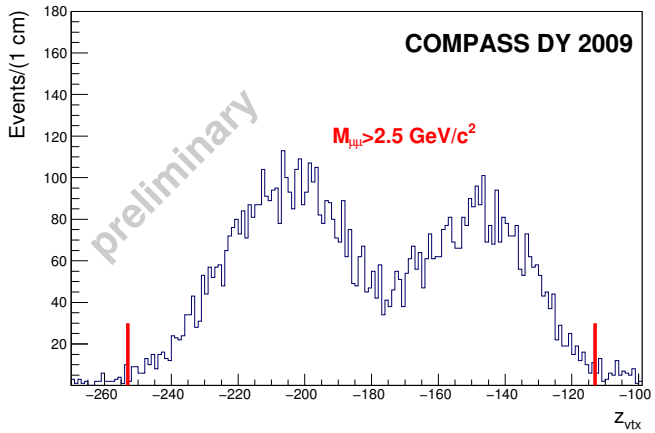
→ see talk by B. Parsamyan for more details

Polarized Drell-Yan Measurement @ COMPASS

- Polarized DY can give complementary information about TMDs to the SIDIS case
- It is expected that *e.g.* Sivers PDF changes sign in DY w.r.t SIDIS case
- Unpolarised studies will also be performed,
  - Boer-Mulders function will be extracted
  - DY will be measured on different Nuclear targets as well as different (π^-, K^-) beams
- COMPASS will measure DY events for $M_{\mu^+\mu^-} \in (4-9)$ GeV/c^2
- Large hadron absorber installed in the spectrometer



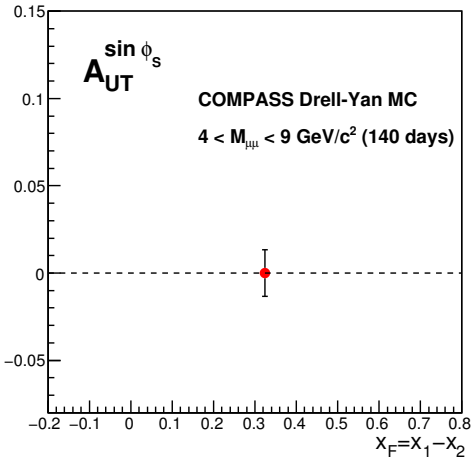


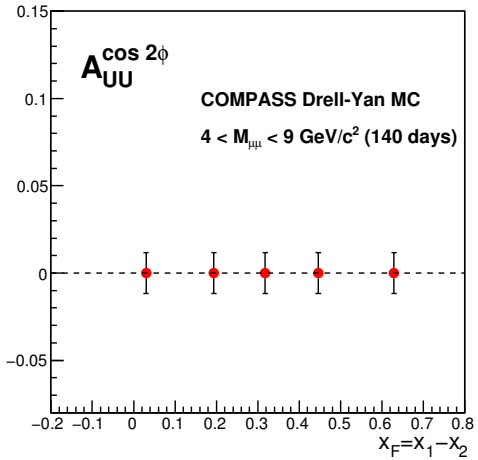


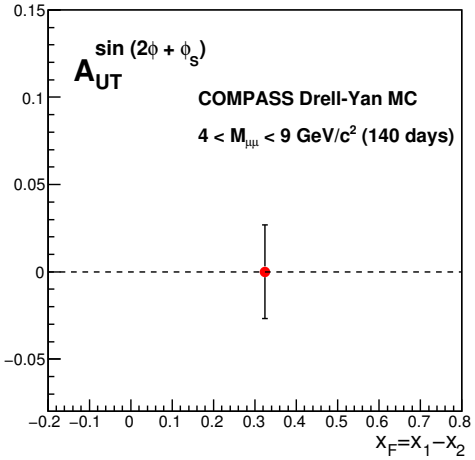
→ see talk by B. Parsamyan for more details (polarised)
→ see talk by W.-C. Chang for more details (unpolarised)

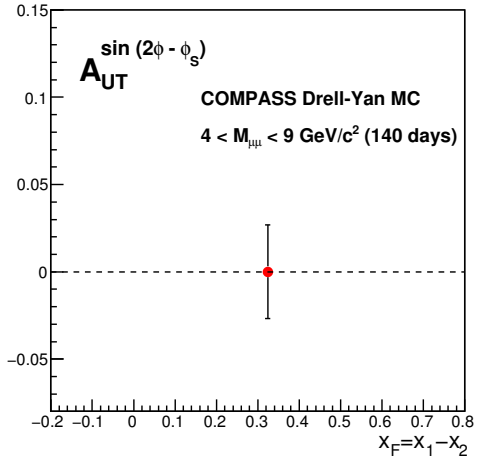
Expected Experimental Errors and Theory Expectations

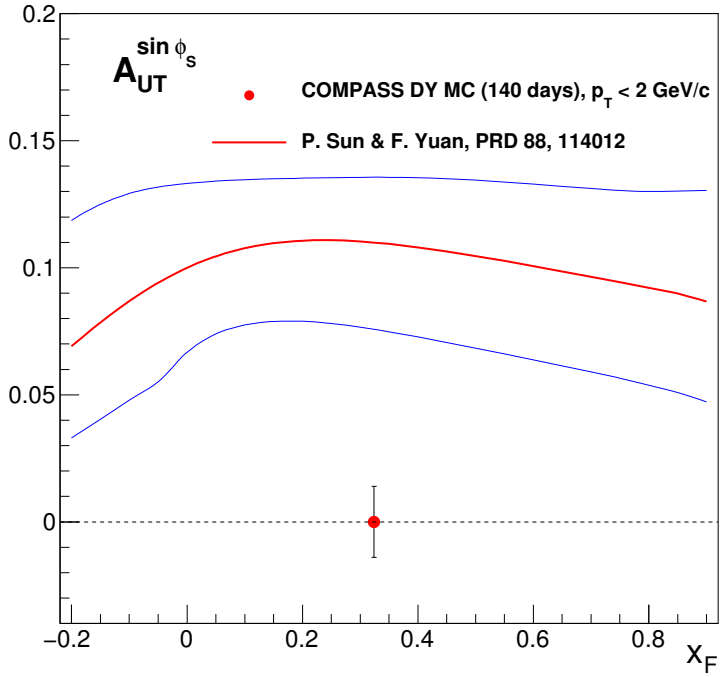
- COMPASS measurement is in valence region, non zero asymmetries are expected
- For example: the expected theory predictions (for Sivers) are several σ away from the zero









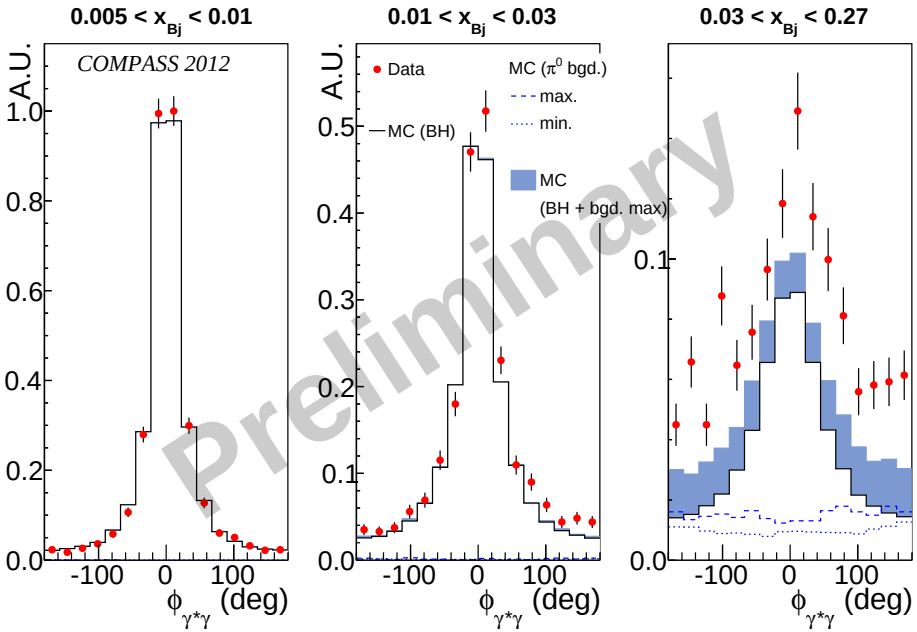


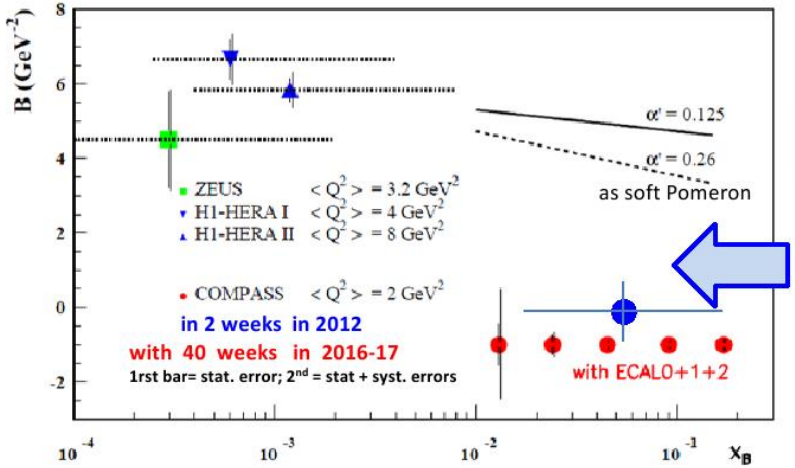
Polarized Drell-Yan Measurement @ COMPASS

- After the 2 years shut down for LHC,
  CERN accelerators restart their operation
- 1st beam already in COMPASS detectors
- DY pilot run will continue until Dec 2014
- Next year data taking fully dedicated to DY studies of TMDs

GDPs and DVCS

- GPDs: also give access to 3-D image of partons inside hadrons
  - 4 chiral-even GPDs $H^{q,g}$, $\tilde{H}^{q,g}$, $E^{q,g}$, $\tilde{E}^{q,g}$
  - 4 chiral-odd GPDs H_T^q, $\tilde{H}_T^q$, E_T^q, $\tilde{E}_T^q$
- Golden channel to study (some of) GPDs is DVCS $\mu p \to \mu' p \gamma$
- COMPASS DVCS measurement on LH target is foreseen for 2016 and 2017
- Short test runs were performed in 2009 and 2012
  - clear DVCS signal over BH background visible at high x
  - $B \sim 2\langle r_p \rangle^2$ can be extracted from 2012 test

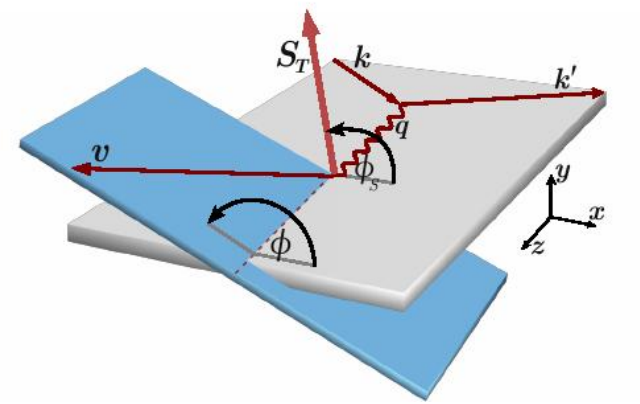


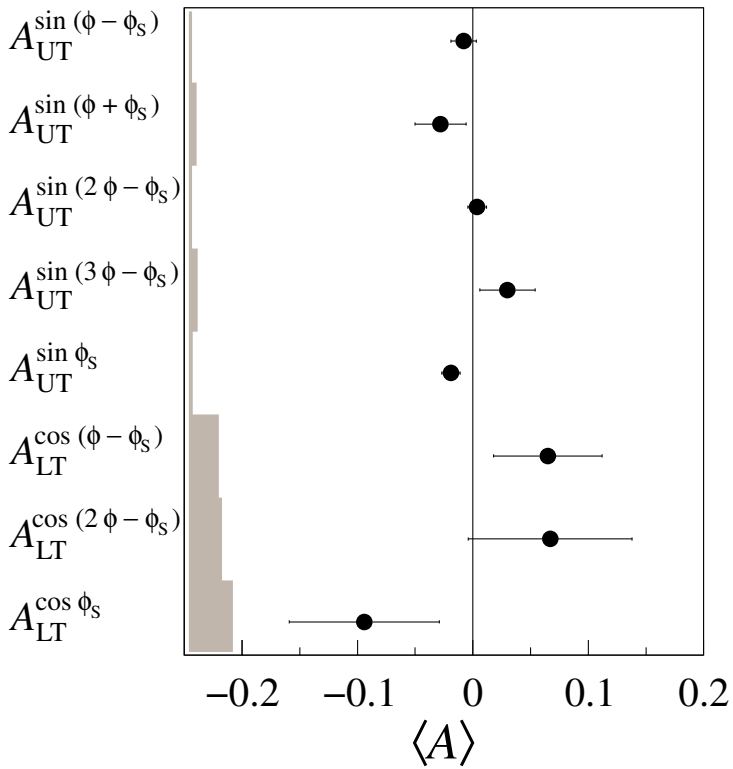


→ see talk by A. Ferrero for more details

GDPs and Hard Exclusive Meson Production

- GPDs can also be studied in Hard Exclusive meson production
- Different modulations of the x-section are sensitive to various combinations of GPDs, *e.g.* Non zero $A^{\sin\phi_S}$ means that $H_T \neq 0$
- Different vector meson are sensitive to different combinations of parton flavors
- Both single and double spin asymmetries were studied in COMPASS for ρ meson
- Most of the results are well compatible with zero

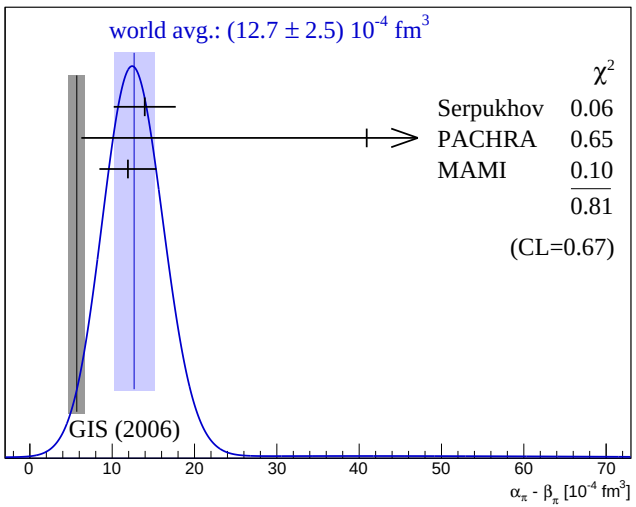


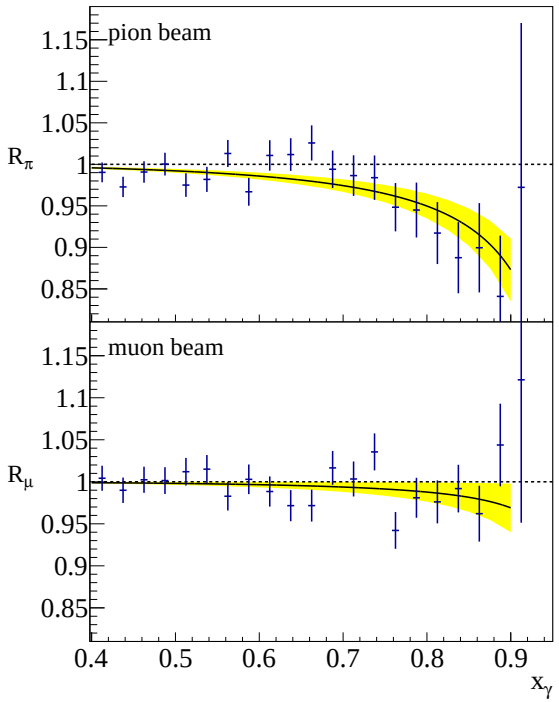


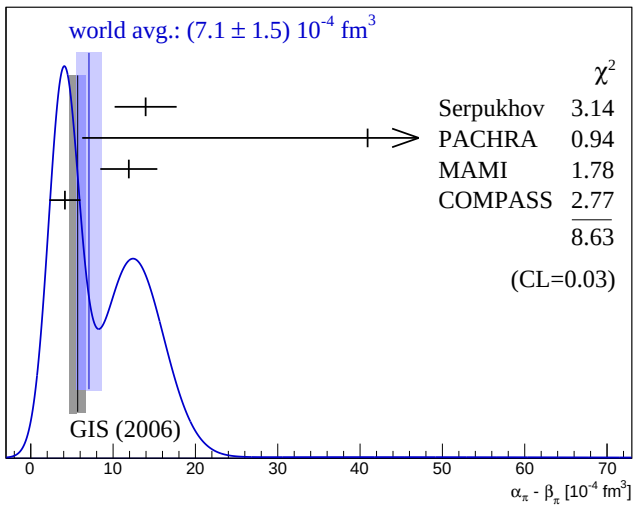
→ see talk by J. ter Wolbeek for more details

COMPASS HADRON Program

- COMPASS has rich program to study hadron-hadron interactions
- There is a lot of new results, but they are outside of the scope of this conference
- Highlight: Primakoff reaction - pion polarizability measurement, α_π
  - $\pi^- + p \rightarrow \pi^- p + \gamma$
  - studies of the pion polarizability as a crucial test of chiral perturbative theory
- COMPASS result from 2009 data:
  $\alpha_\pi = (2.0 \pm 0.6_{\text{stat.}} \pm 0.7_{\text{syst.}}) \times 10^{-4} fm^3$







Summary of COMPASS new Results

- COMPASS Longitudinal data - beginning of the end
  - some new data
  - more physics interpretations
    - currently Δg is not constrained by g_1 scaling violation
    - hints that $\Delta g/g$ is positive in the $x_g \in (0.05 - 0.28)$ from direct (model dependent) PGF measurements
- COMPASS Transverse data - end of the beginning
  - a lot of new data, more data expected
  - more and more physics interpretations
    - interplay of 1h and 2h asymmetries
    - extraction of transversity
  - both GPDs and TMDS are accessed are observed
- After a 2 years shutdown COMPASS restarted data taking!
- Main goal for 2014-2015: polarised Drell-Yan studies of TMDs