Recent results from COMPASS

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HiX2014

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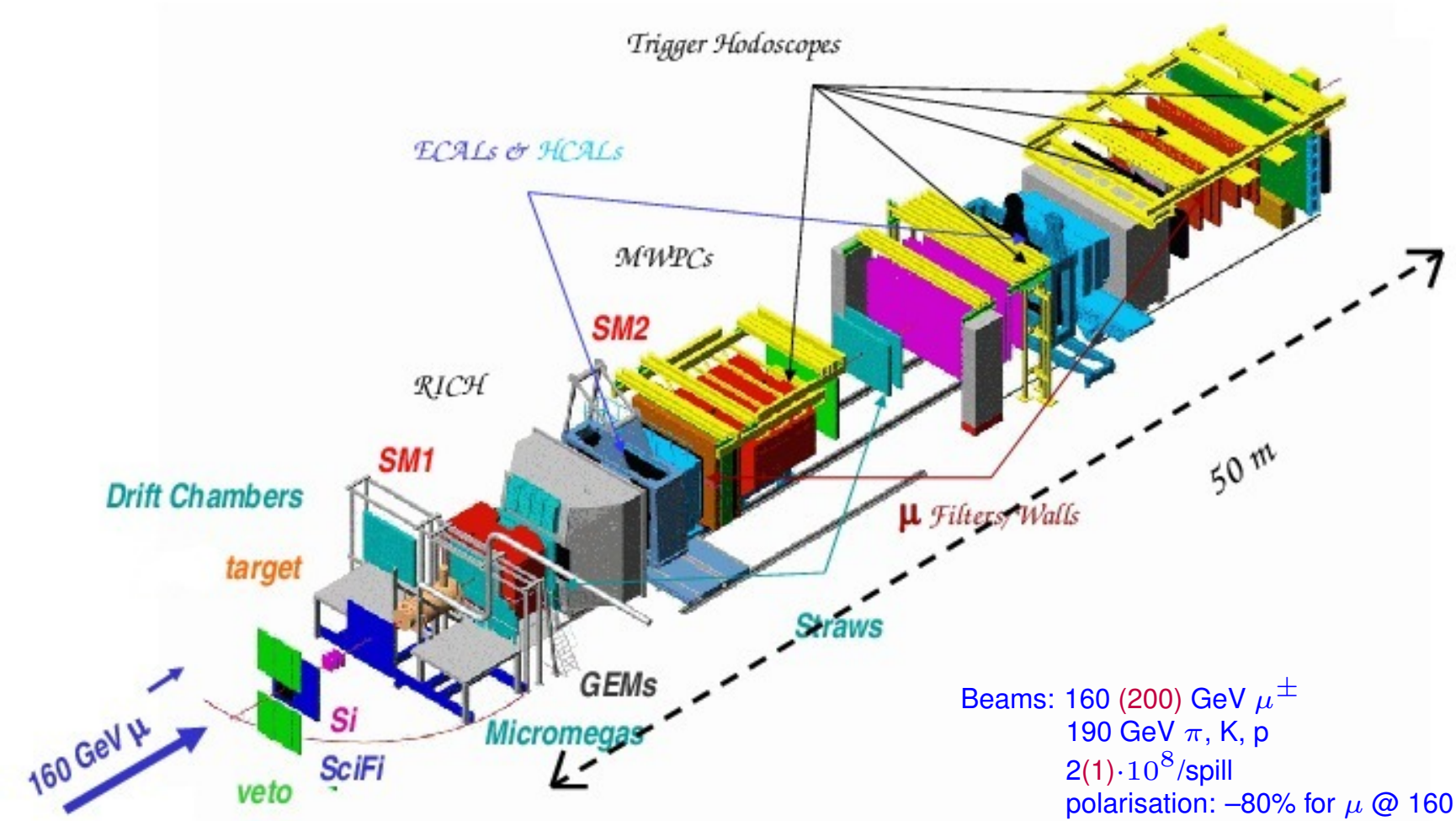
COMPASS Spectrometer (2002–2012)

muon runs: Nucl. Instr. Meth. A577 (2007) 455

Two stages, $\sim$ 350 planes
Particle identification (RICH, calos, μ filters)

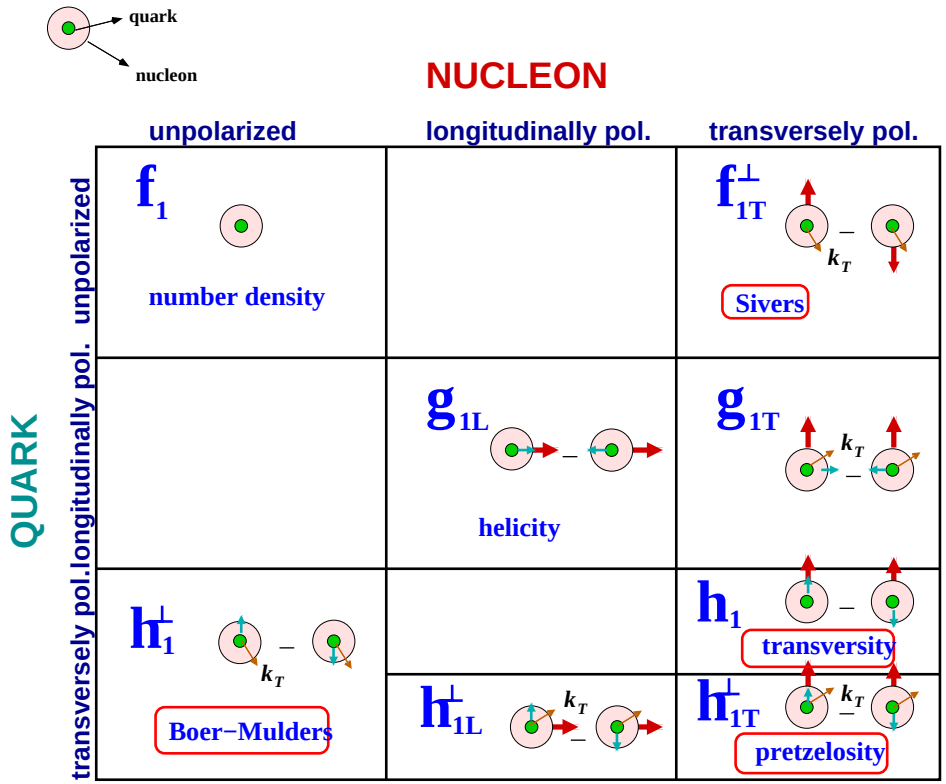


Beams: 160 (200) GeV $\mu^{\pm}$
190 GeV π, K, p
$2(1)\cdot 10^8$/spill
polarisation: –80% for μ @ 160 GeV

Targets: large, solid state, polarised ^{6}LiD (NH_3)
polarisation: $\pm$50% (85%)

Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T},
  8 PDF describe the nucleon
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto \mathrm{PDF} \otimes \mathrm{FF}$
- DY: e.g. $A_{\mathrm{Sivers}} \propto \mathrm{PDF}^{\mathrm{beam}} \otimes \mathrm{PDF}^{\mathrm{target}}$



- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

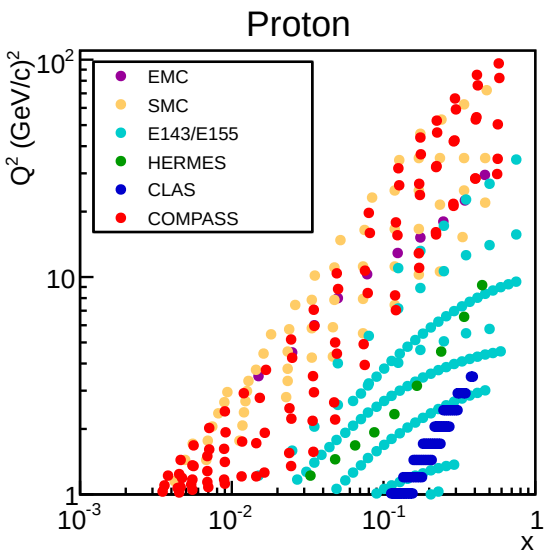
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

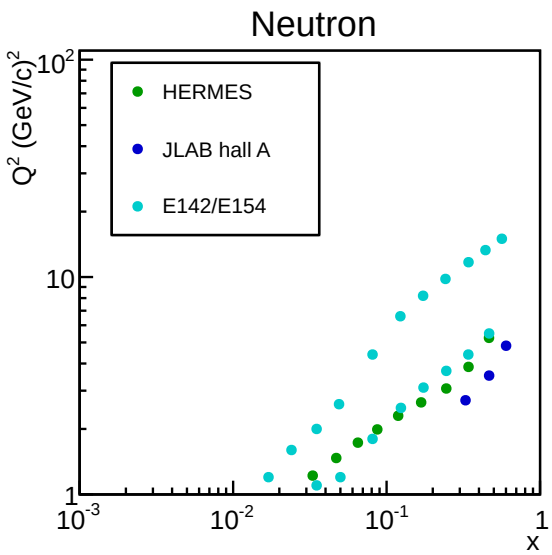
- OBS! transversity PDF is chiral-odd (may only be measured with another chiral-odd partner, e.g. fragmentation function.
- Boer-Mulders, Sivers and transversity $(h_1^{\perp}, f_{1\mathrm{T}}^{\perp}, h_1)$ will be measured in COMPASS II

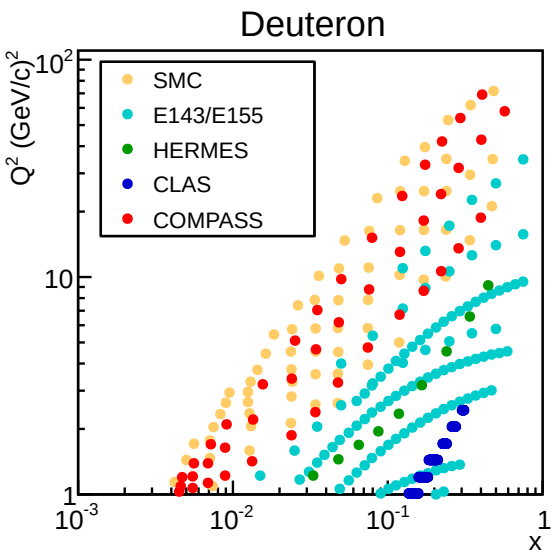
Outline

Acceptance of spin experiments: different targets

$$Q^2 > 1\ (\mathrm{GeV}/c)^2$$

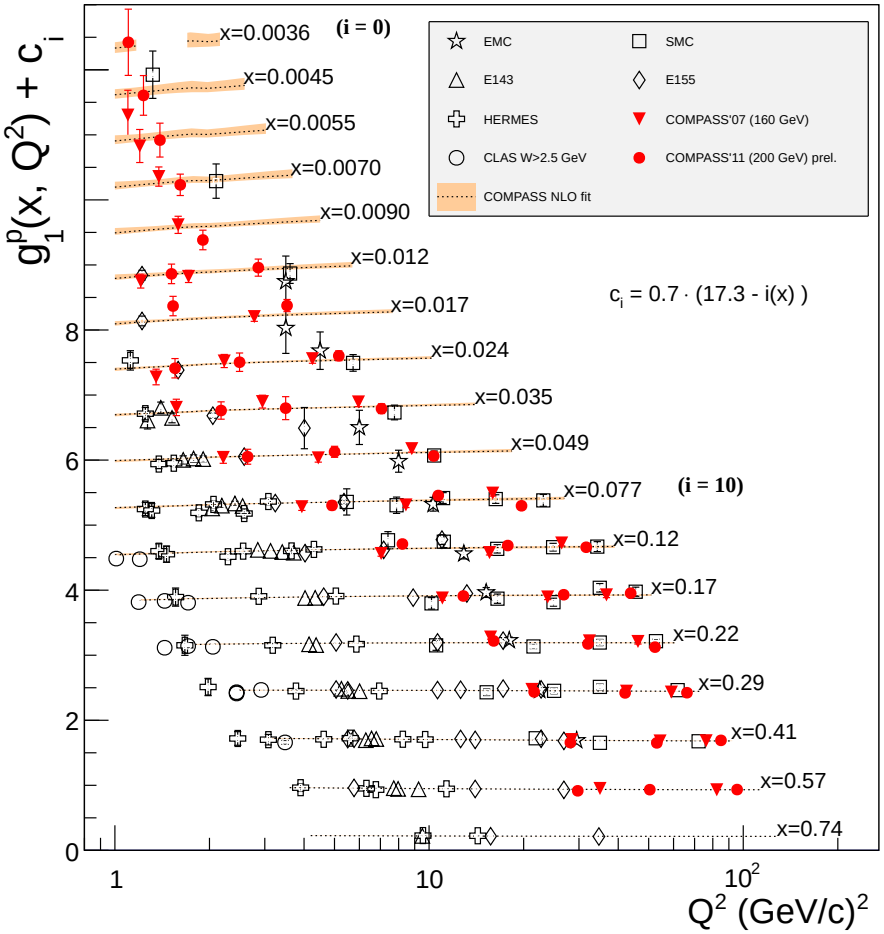


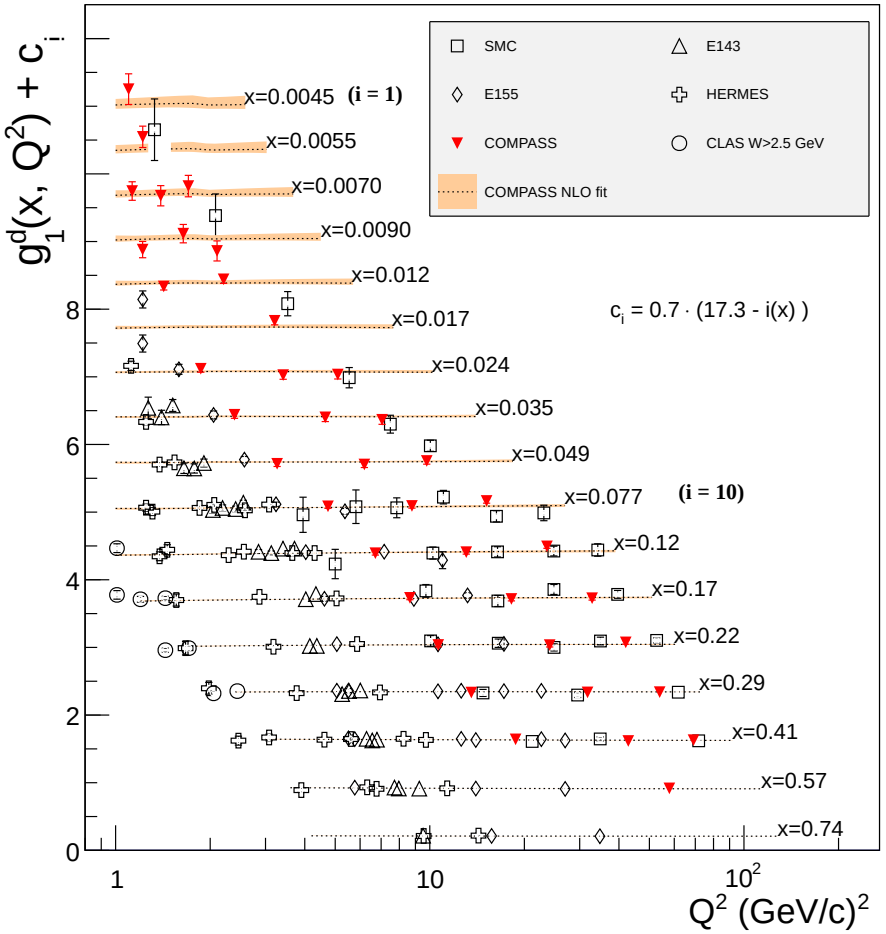




Measurements of $g_1^p(x)$ and $g_1^d(x)$

COMPASS p data 2007 @ 160 GeV + NEW: p data 2011 @ 200 GeV (prelim.);
full deuteron statistics

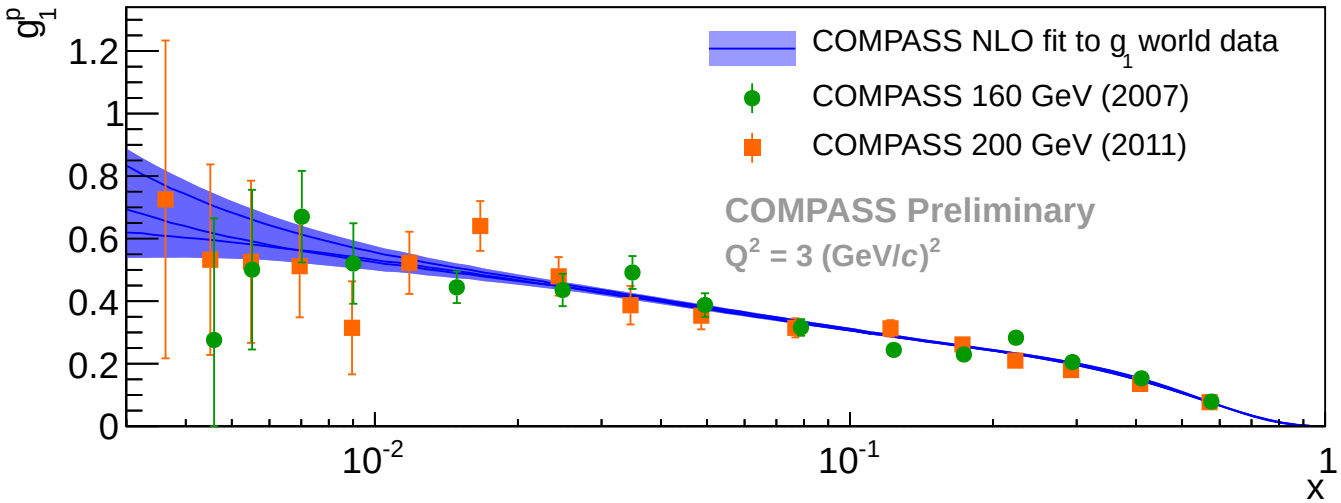


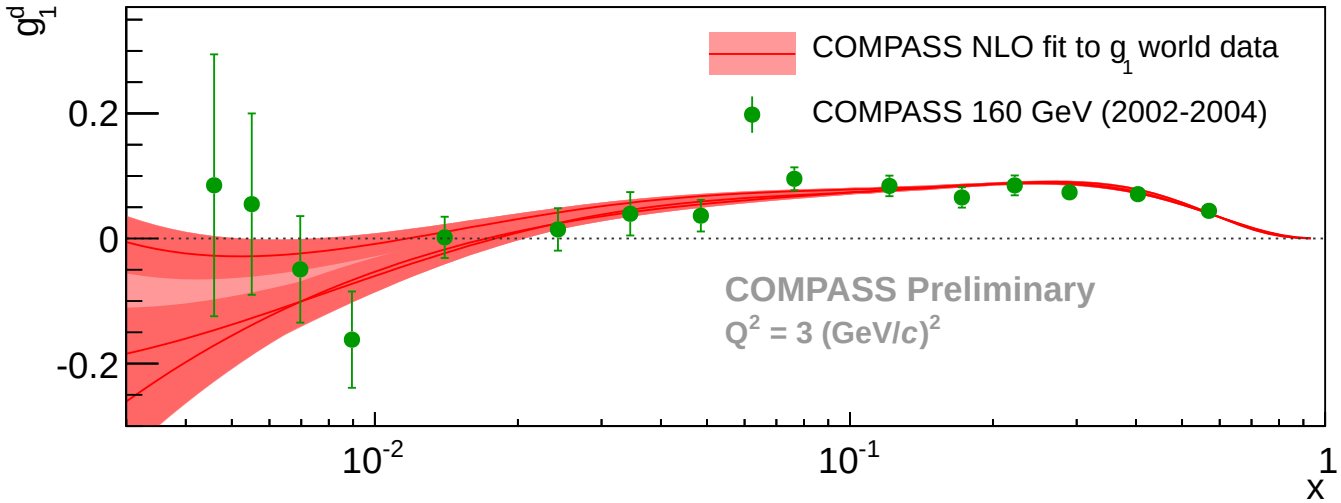


COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

COMPASS NLO fit to g_1 world data; Q^2 = 3 (GeV/c)^2

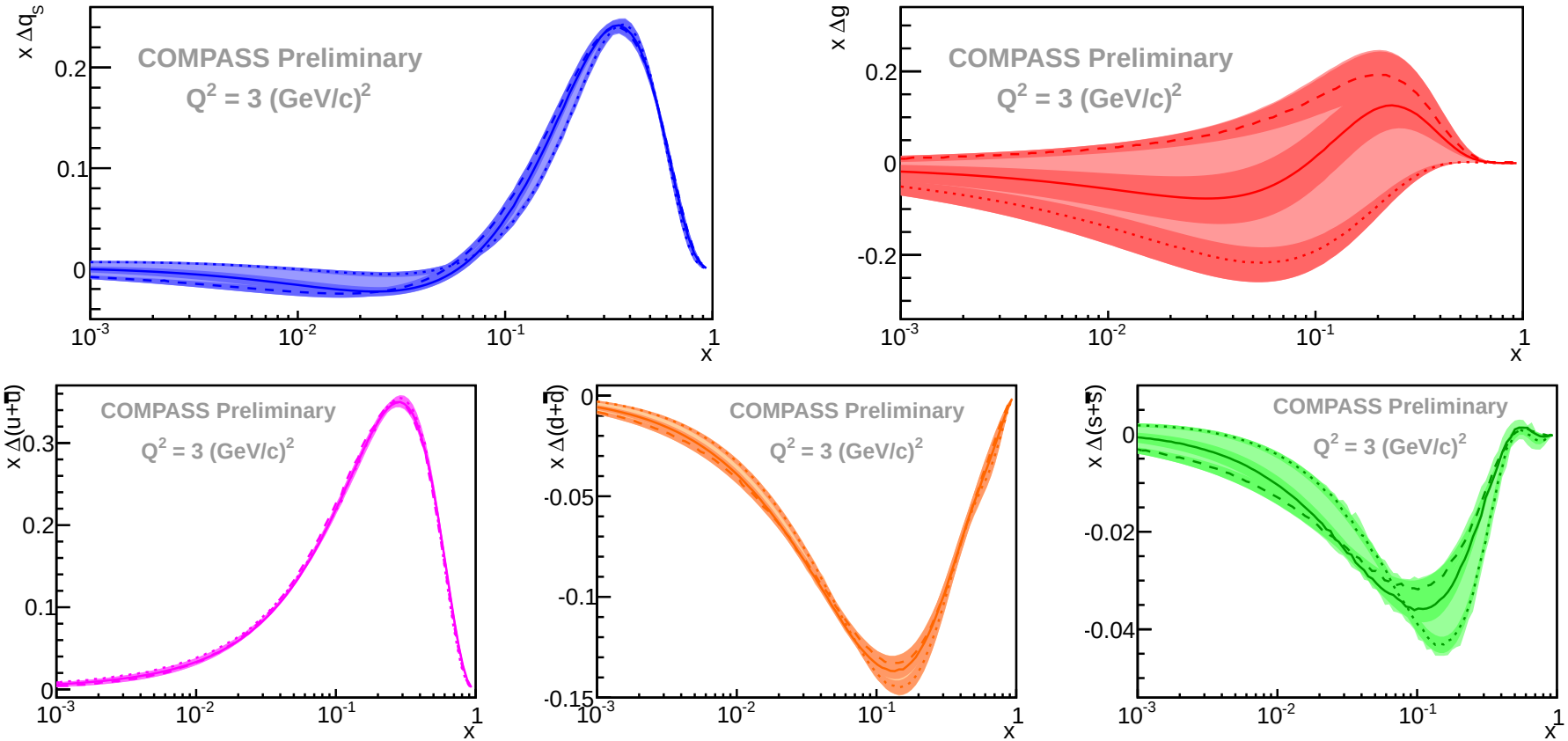
Fitted: $\Delta q_{\rm SI}, \Delta q_3, \Delta q_8, \Delta g$ at Q_0^2 = 1 (GeV/c)^2; 679 points, 28 params; $\overline{\rm MS}$ scheme





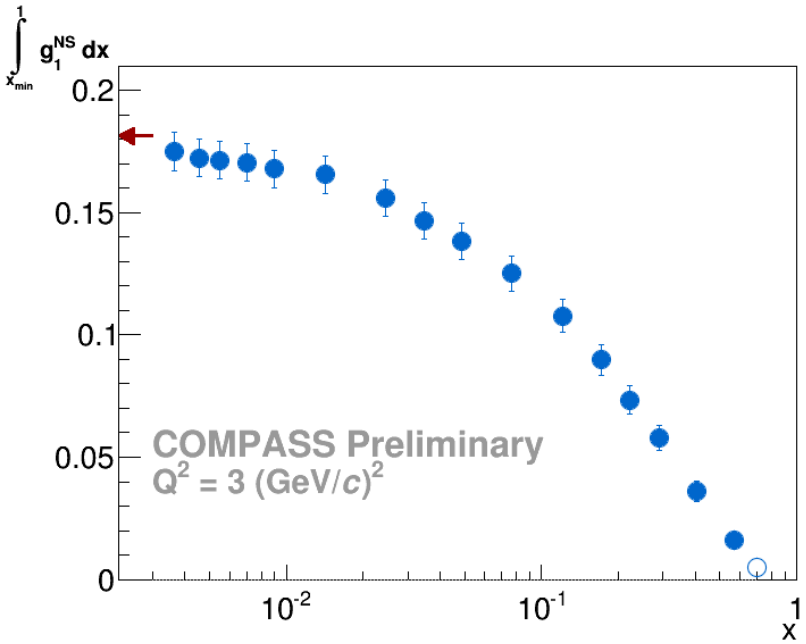
COMPASS NLO fit to g_1 world data... cont'd

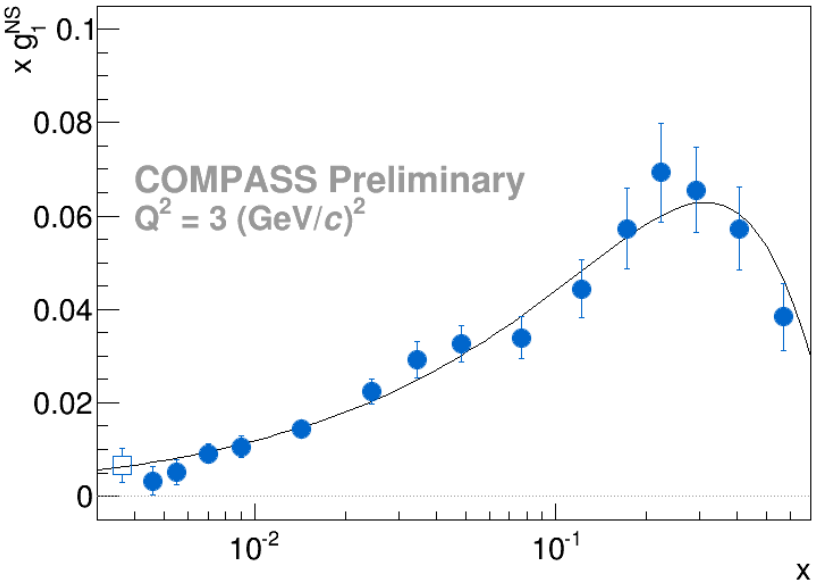
- Little sensitive to gluon polarisation
- Quark polarisation: $\Delta\Sigma = \int \Delta q_{\mathrm{SI}}(x)dx \sim 0.3$



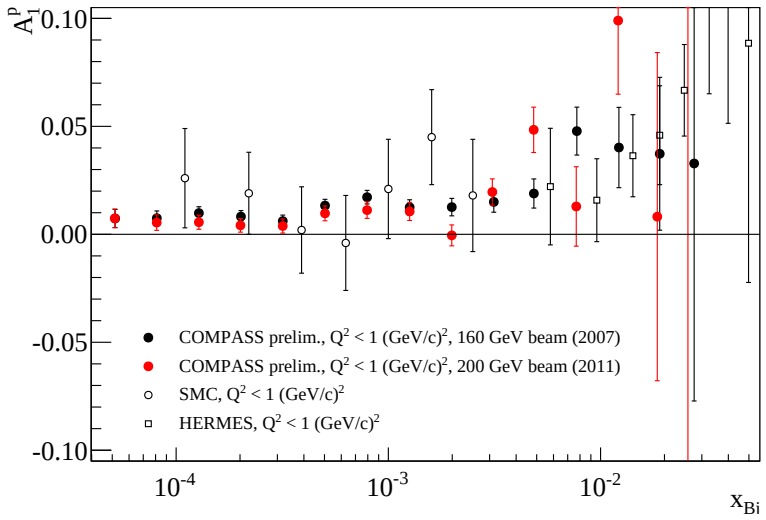
Update on Bjorken Sum Rule test

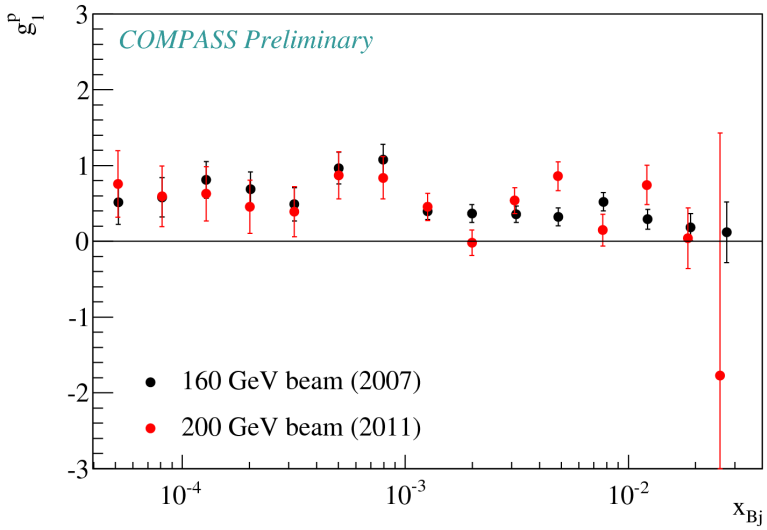
- $$\int_0^1 g_1^{\mathrm{NS}}(x,Q^2)dx = \int_0^1 g_1^{\mathrm{p}}(x,Q^2)dx - \int_0^1 g_1^{n}(x,Q^2)dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{\mathrm{NS}}(Q^2)$$
- $\left|\frac{g_A}{g_V}\right| = 1.2694 \pm 0.0028$ (neutron β decay) C_1^{NS} known to α_s^3
- g_1^{NS} from COMPASS data only
- COMPASS: $|g_A/g_V| = 1.219 \pm 0.052 \pm 0.095$ (8% verification)

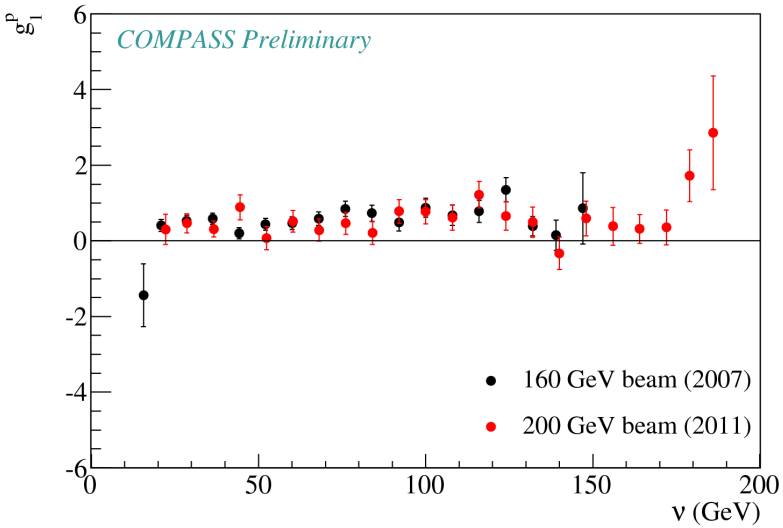




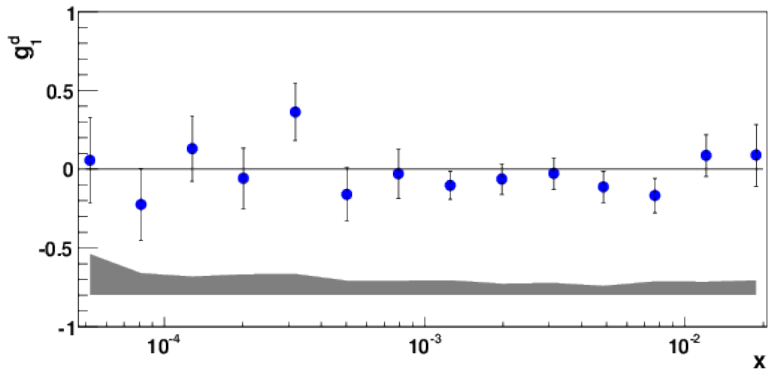
g_1^p and g_1^d measurements; Q^2 <1 (GeV/c)^2 region







$g_1^p(x)$, $g_1^p(\nu)$ significantly positive, $g_1^d(x) \approx 0$



A.S.Nunes, DIS2014

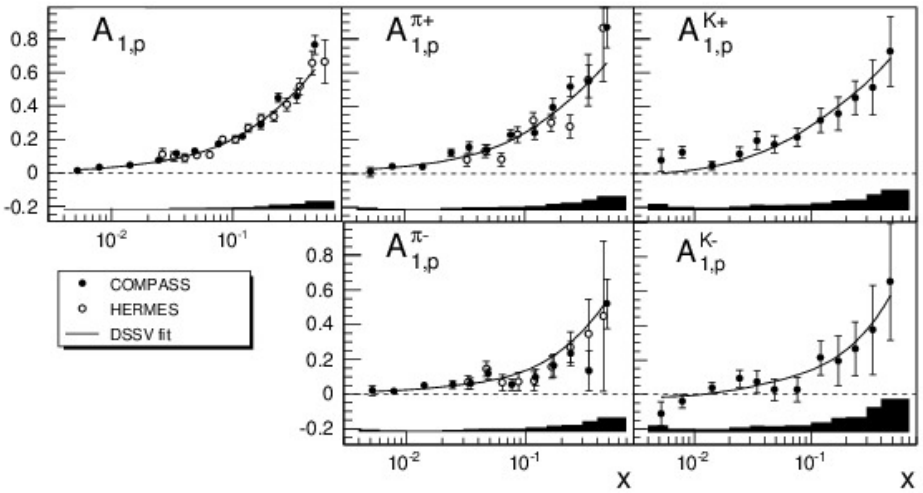
Figure above is from Phys.Lett. B647 (2007) 330

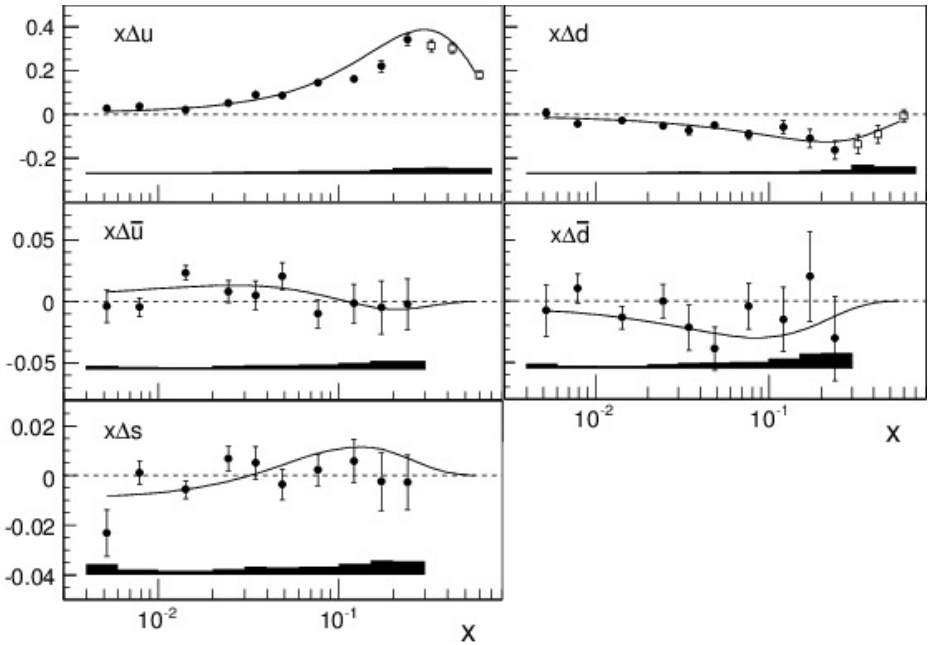
Semi-inclusive asymmetries and parton distributions

- Measured on both proton and deuteron targets
- for identified, positive and negative pions and (for the first time) kaons

COMPASS, Phys. Lett. B **693** (2010) 227

DSSV, Phys. Rev. D **80** (2009) 034030

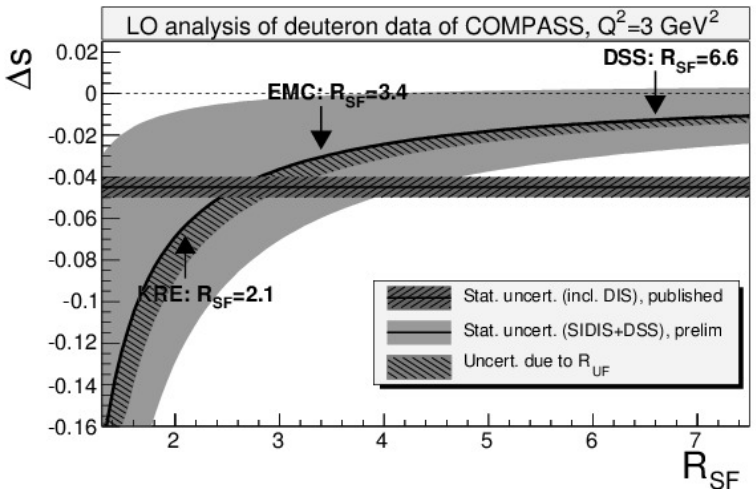


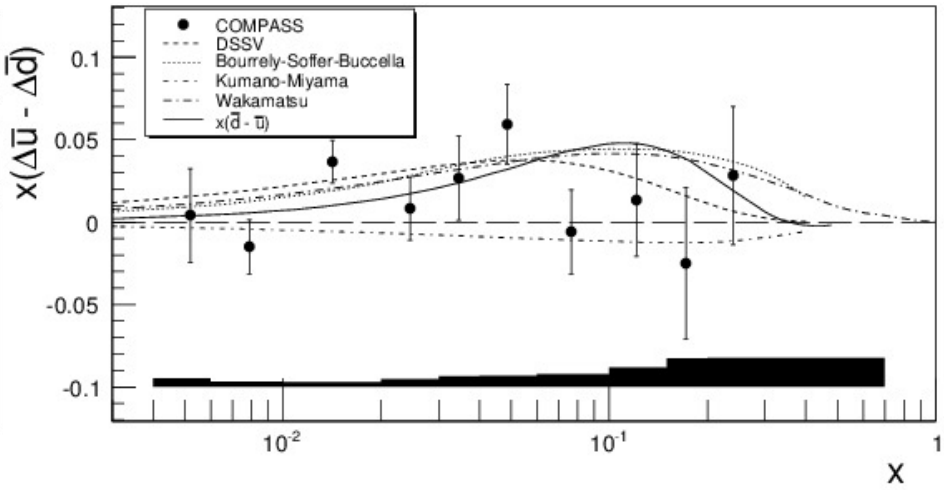


- LO DSS fragmentation functions and LO unpolarised MRST pdf assumed here.
- NLO parameterisation of DSSV describes the data well.

Polarisation of quark sea

- Δs puzzle. Strange quark polarisation:
  $2\Delta S = \int_0^1 (\Delta s(x) + \Delta \bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU_3,
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_{u}^{K^+}(z)dz}$
  $\Longrightarrow$ plan to extract it from COMPASS data on multiplicities.

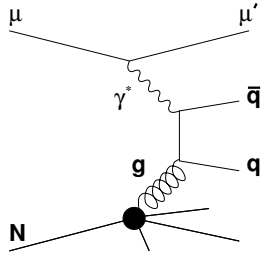




- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ibid., **693** (2010) 227.
  $$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \;\; @ \;\; Q^2 = 3 \text{ (GeV/}c)^2$$
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

Direct measurements of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry
for the photon–gluon fusion (PGF) with subsequent fragmentation into:

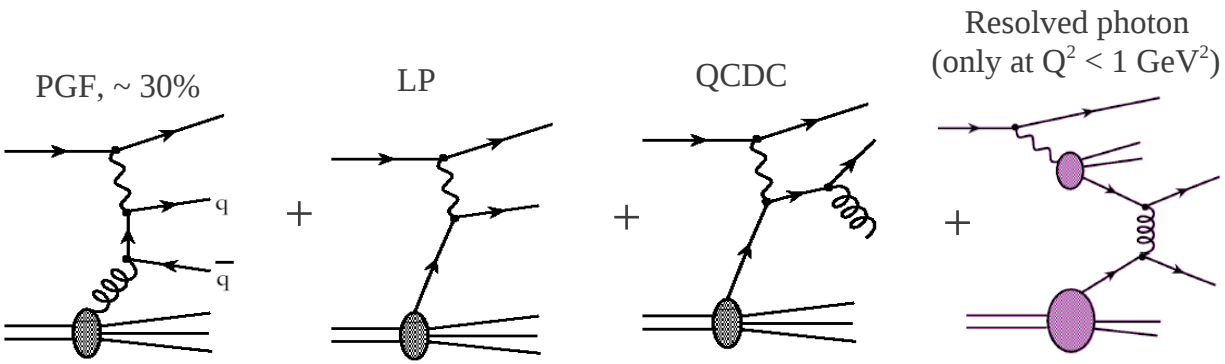


- charm mesons, q≡c, (max. @ low Q^2, perturbative scale: e.g. m_c): low statistics, few theoretical assumptions;

$$A_{meas} = p_B\, p_T\, f\, a_{LL}\, \frac{\sigma_{PGF}}{\sigma_{PGF} + \sigma_{BGD}}\, \frac{\Delta g}{g} + A_{BGD}$$

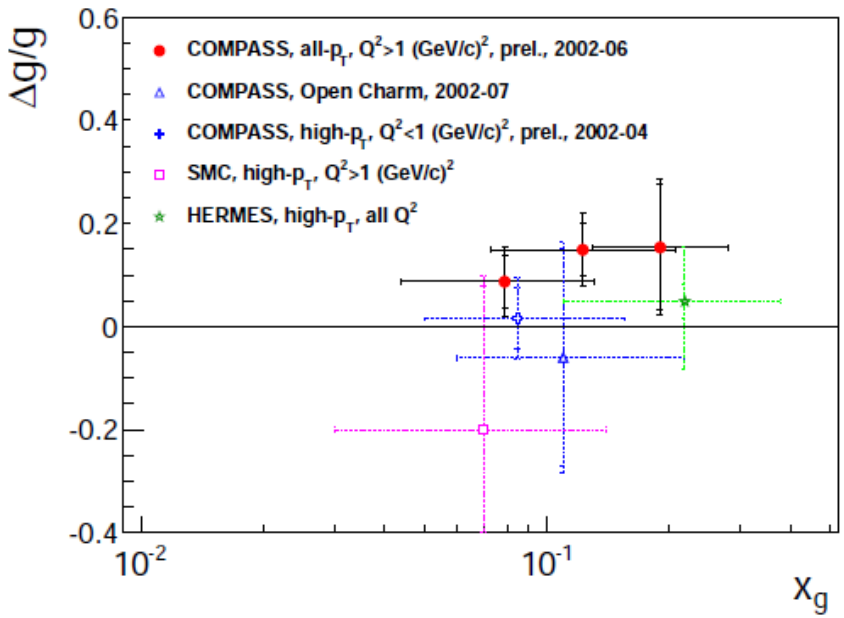
- a pair of hadrons of large p_T, q≡u, d, s, separately for low- and high Q^2 (perturbative scale: e.g. p_T): high statistics, several quantities from MC. At LO, for both 2-hadron and inclusive samples:

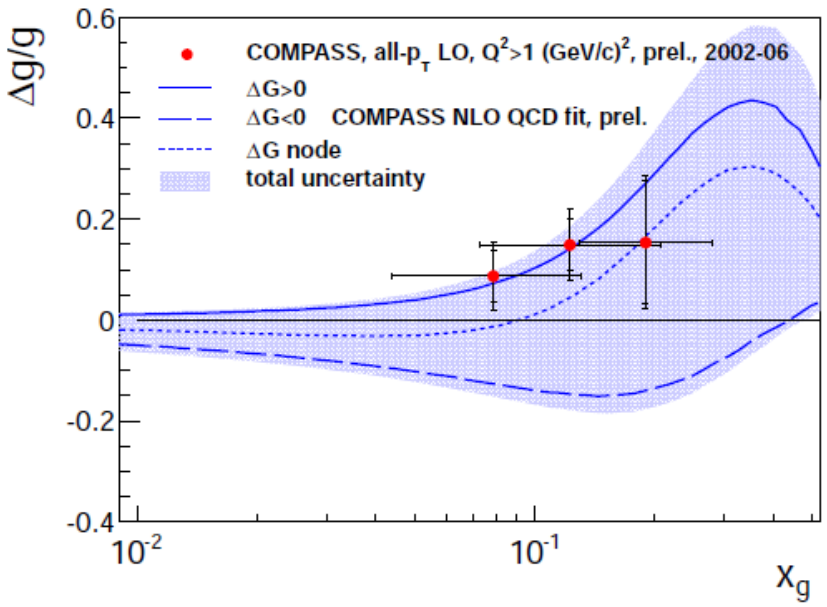
$$A_{meas} = p_B\, p_T\, f \left[R_{PGF} \cdot a_{LL}^{PGF} \cdot \frac{\Delta g}{g} + R_{LP} \cdot D \cdot A_1^{LO} + R_{QCDC} \cdot a_{LL}^{QCDC} \cdot A_1^{LO} \right]$$



New determination of $\Delta g(x)$ at LO: all-p_T method

- New approach (as compared to Phys.Lett. B718 (2013)922):
  hadrons with all p_T values are accepted
- A_1^{LO} and $\Delta g/g$ are extracted simultaneously from the same data set
  certain systematic uncertainties are reduced and consistences checked
- $\Delta g/g = 0.113 \pm 0.038 \pm 0.035$ at $\langle Q^2 \rangle$ = 3 (GeV/c)^2, $\langle x_g \rangle$ = 0.10
  (cf. with 0.125 $\pm$ 0.060 $\pm$ 0.063 in the old approach)





M.Stolarski, DIS2014

Summary of double longitudinal results

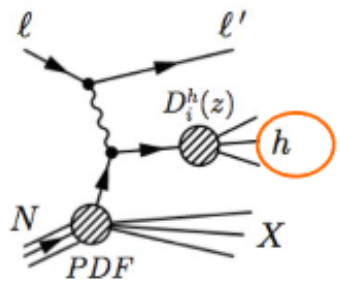
- Measurements of g_1^p at $x > 0.0036$ for $Q^2 > 1$ (GeV/c)^2; large statistical improvement compared to SMC
- NLO QCD fit to the g_1 world data with a detail analysis od systematics; $0.26 < \Delta\Sigma < 0.34$ @ 3 (GeV/c)^2; gluons poorly constrained
- Bjorken Sum Rule verified to 8% (p and d data)
- g_1^{p} in nonperturbative ($Q^2 < 1$ (GeV/c)^2) region clearly positive
- The Δs puzzle needs precise FF determination
- New determination of $\Delta g/g$ (all-p_T method) gives a positive value around $x_g \sim 0.1$
- Soon: new semi-inclusive asymmetries and helicity flavour separation

Outline

Charged (single-) hadron multiplicities,

- Studied to measure fragmentation functions (FF), $D_q^h(z,Q^2)$ ($\Longrightarrow$ cf. Δs).
  At LO:

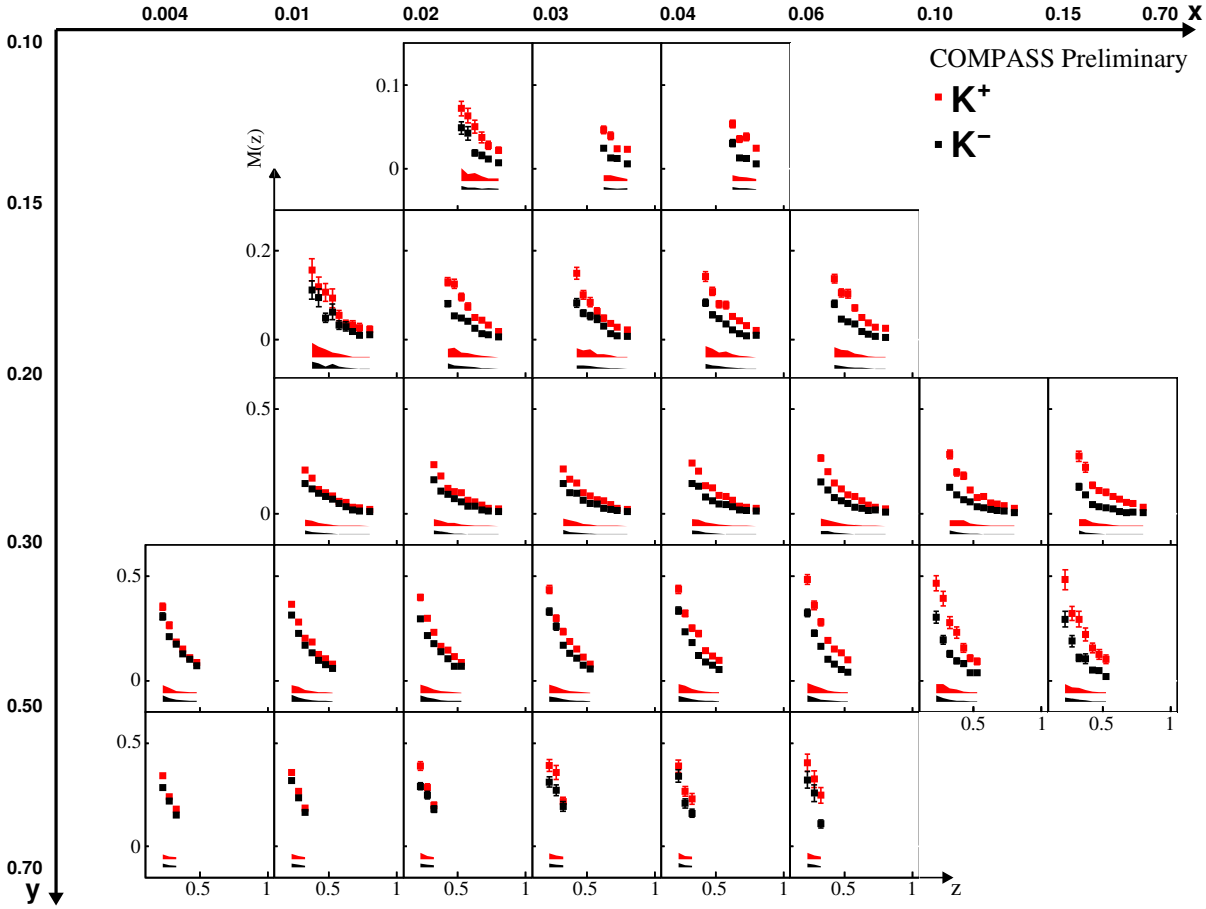
$$M^h(x,z,Q^2) = \frac{\frac{d\sigma_{\rm SIDIS}}{dxdzdQ^2}}{\frac{d\sigma_{\rm DIS}}{dxdzdQ^2}} = \frac{\Sigma_q e_q^2 \left[q(x,Q^2)D_q^h(z,Q^2) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]}{\Sigma_q e_q^2 \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]}$$



- Until now:
  - High precision Single Inclusive e^+e^- Annihilation data
    do not separate q and $\bar{q}$ and only access charge sum of FF for a hadron h.
  - Measurements at a fixed, large ($\sim M_Z$), scale,
    except BELLE (Q^2 ~10 GeV^2).
  - Inclusive single hadron production by RHIC $\Longrightarrow$ improve constraints on gluon FF.
  - Lepton–nucleon DIS: lower values and wide range of scales, sensitivity to parton flavour and hadron charge ($\Longrightarrow$ new data of HERMES).
  - Global NLO analyses, e.g.: DSS, Phys. Rev. D **75** (2007) 114010.
- New COMPASS results obtained on an isoscalar (d in ^{6}LiD) target (nuclear effects in ^{6}LiD small)...
- ...with K and π identification and measured x, y, z dependence; $\langle Q^2 \rangle$ in each bin.

Charged (single-) hadron multiplicities; identified kaons

- 2006 data (25% of sample); ^{6}LiD target.
- $Q^2 > 1$ (GeV/c)^2, $0.1 < y < 0.7$, $0.004 < x < 0.07$
  $0.2 < z < 0.85$, $10 < p_h < 40$ GeV/c (coverage in W: 5 –17 GeV).



N.Makke, DIS2013

Charged (single-) hadron multiplicities; identified pions

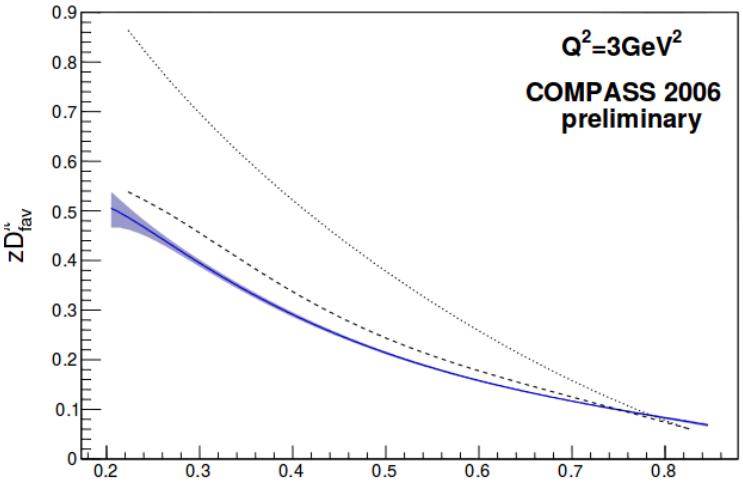
- Assume isospin and charge symmetry:

$$D_{\rm fav}^{\pi^+} = D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-}, \qquad D_{\rm unf}^{\pi^+} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-}$$

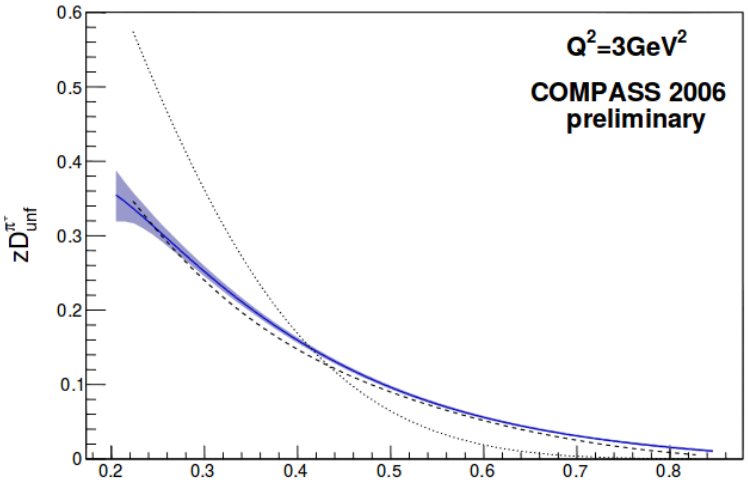
and $D_s^{\pi^+} = D_s^{\pi^-} = D_{\rm unf}^{\pi^+}$

- Assume a functional form of a FF $\Longrightarrow$ fit e.g. $\pi^\pm$ mutiplicities (DGLAP) $\Longrightarrow$ extract 2 FFs

$zD_{\rm fav}^{\pi^+}$



$zD_{\rm unf}^{\pi^+}$



- - - - HNKS NLO

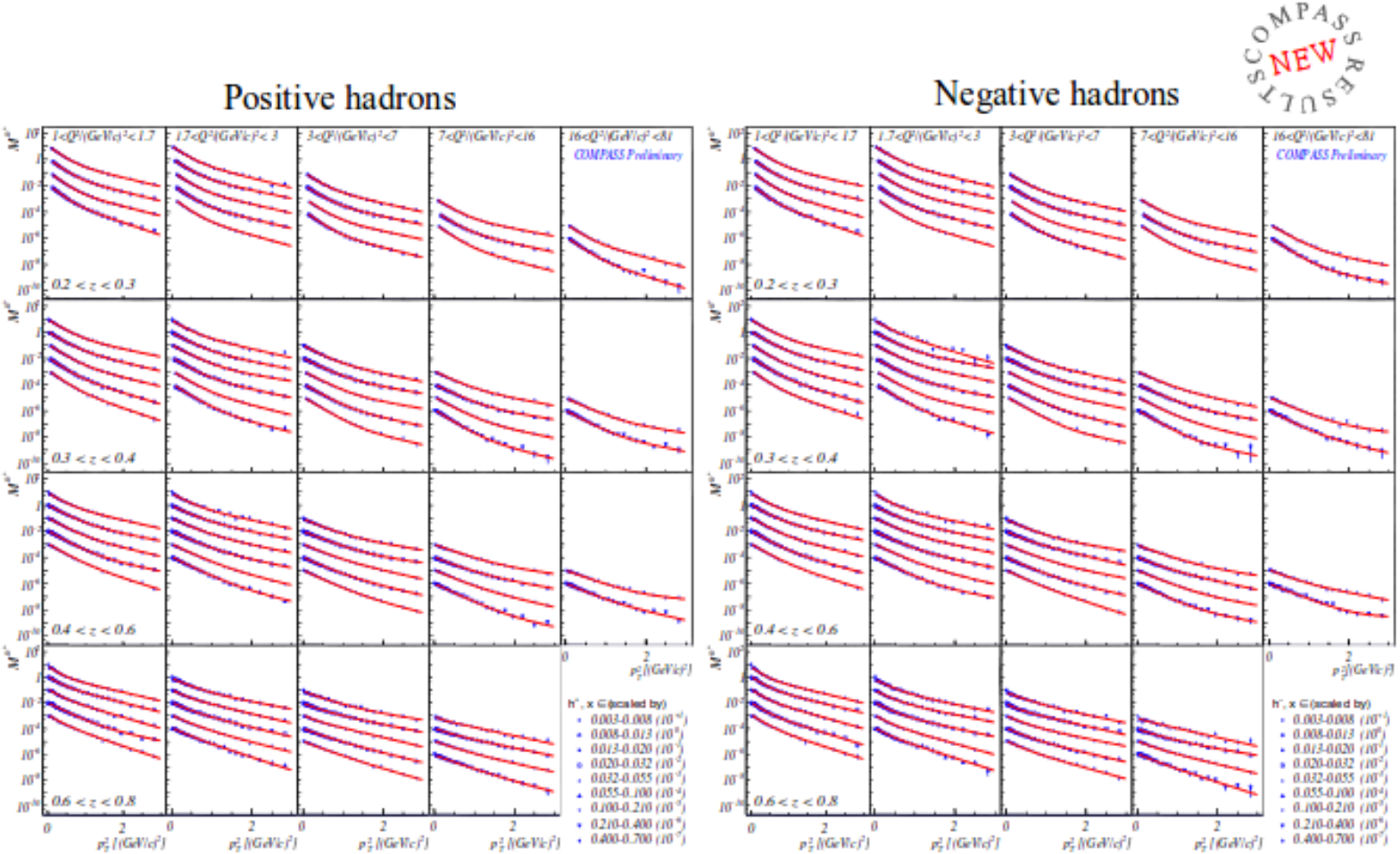
· · · · DSS NLO

- Analysis continues with $K^\pm$ multiplicites/FFs and with proton data
- 2016-2017 proton data will be taken parallely to GPD programme and upgraded RICH

N. du Fresne von Hohenesche, DIS2014

Charged (single-) hadron multiplicities; p_T dependence

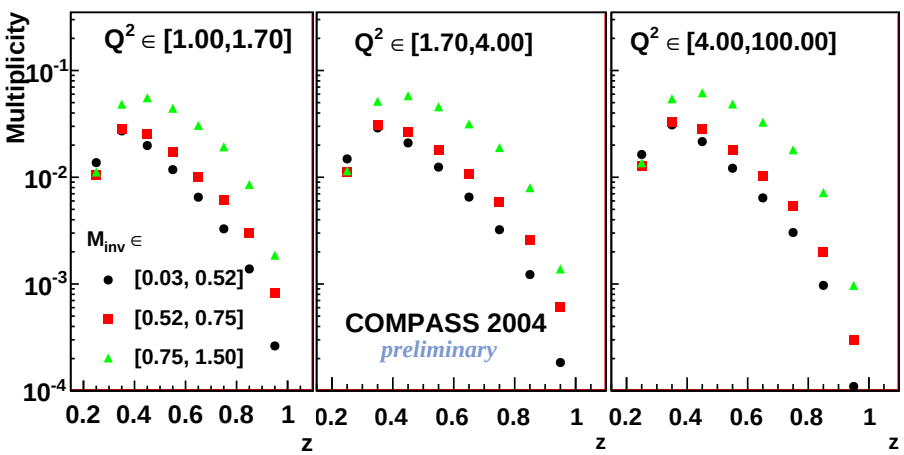
p_T^2 – dependent multiplicities vs. (x, Q^2, z, p_T^2) for $h^{\pm}$

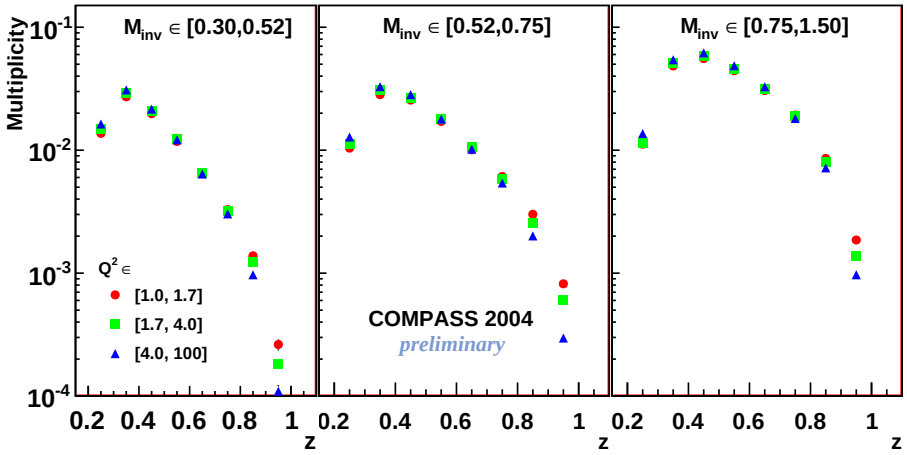


Very good description of shape of experimental data fitting with $a.e^{-\alpha pt2} + b.e^{-\beta pt2}$

Charged (double-) hadron multiplicities

- Studied to measure $D_q^{h^+,h^-}(z^+, z^-, Q^2) = D_q^h(z, M_h^2, Q^2)$
- Needed in extracting asymmetries in SIDIS, e.g.: $A_{UT}^{\sin(\phi_R+\phi_S)}(z, M_h^2, Q^2)$
- Measured by COMPASS on d from ^{6}LiD in bins of (z, M_h^2, Q^2).





N.Makke, SPIN2014

Summary of multiplicity results

- Measurement of h^+, h^-, π^+, π^-, K^+, K^- in bins of (x, y, z), $5 < W < 17$ GeV.
- LO determination of FFs into pions ($D^{\pi}_{\rm fav}$, $D^{\pi}_{\rm unfav}(z, Q^2)$) from 2006 d data
- Soon: improved analysis and FFs into kaons; analysis 2012 p data
- New determination of $p_{\rm T}^2$–dependent multiplicities in (x, z, Q^2) bins for h^+ and h^- (2006 d data); visible h^+/h^- differences @ large x and large z.
- Hadron pair multiplicities in $(z, Q^2, M_{\rm inv})$ bins, 2004 d data.
  Soon: $p_{\rm T}^2$–dependent multiplicities for pions and hadron pair multiplicities (2006 data)
- 2016 – 2017 measurements planned (parallely to DVCS) on p target and with improved RICH.

Outline

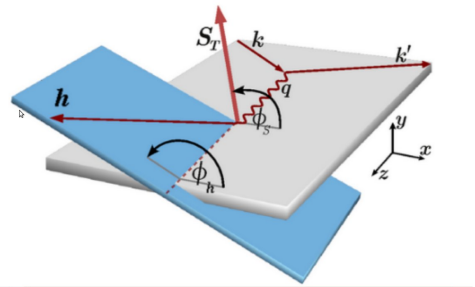
Measurements on a transversely polarised target

Properties of transversity $\Delta_T q(x)$:

- is chiral–odd $\Longrightarrow$ hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- related to GPD
- sum rule for transverse spin
- first moment gives "tensor charge" (now being studied on the lattice)

Transversity measured *e.g. via* the Collins asymmetry: $\perp$ polarised $q \Longrightarrow$ unpolarised h (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0 \left[1 \pm p_T D_{NN} A_{Coll} \sin \phi_c\right]$$
$$\phi_C = \phi_h + \phi_S$$



which in turn gives at LO:

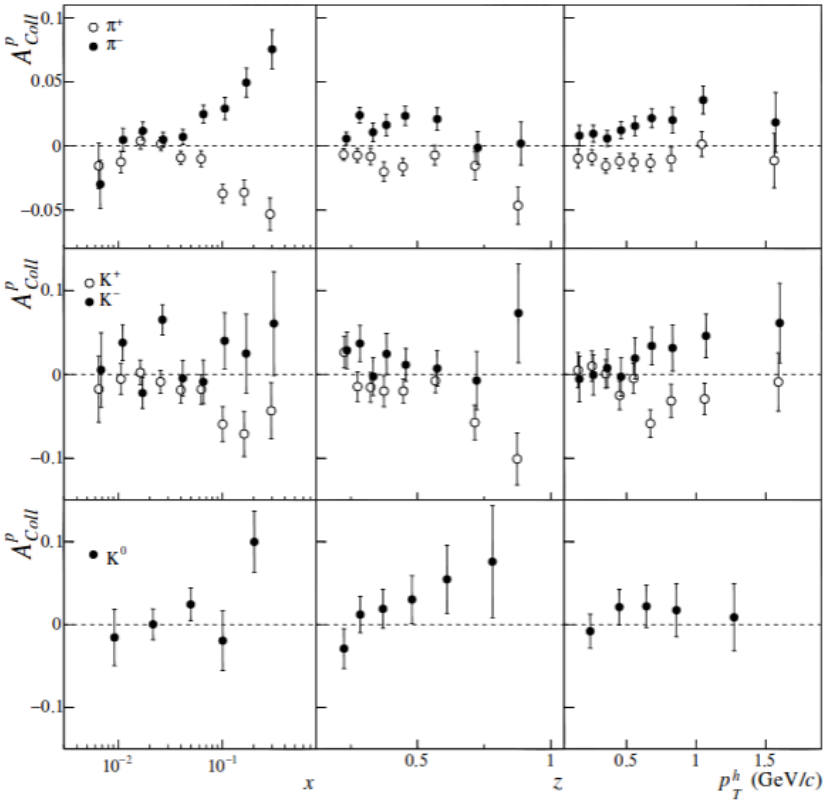
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ (universal!) needed to extract $\Delta_T q(x)$ from the Collins assymmetry! Recently those FF measured by BELLE and BaBar.

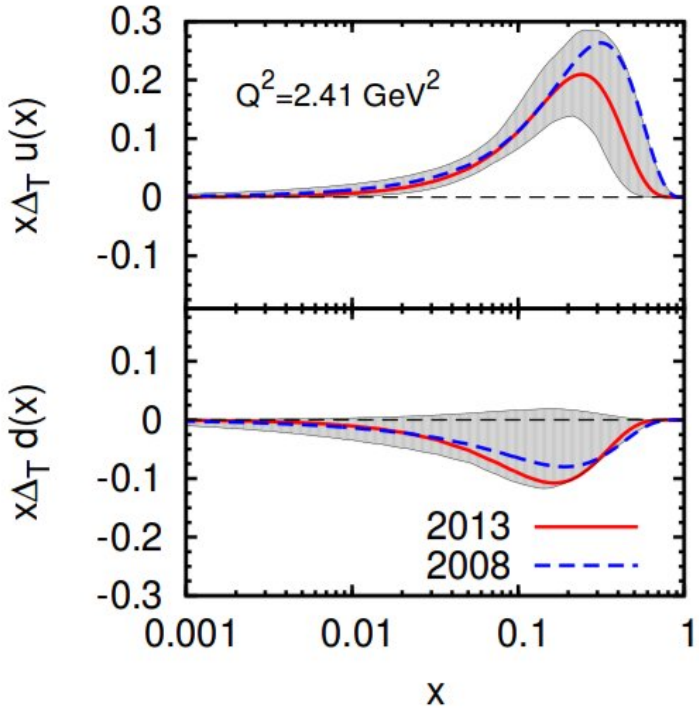
Sivers process ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q):

related to L_q in the proton. Fundamental !

Results for the Collins asymmetry for protons



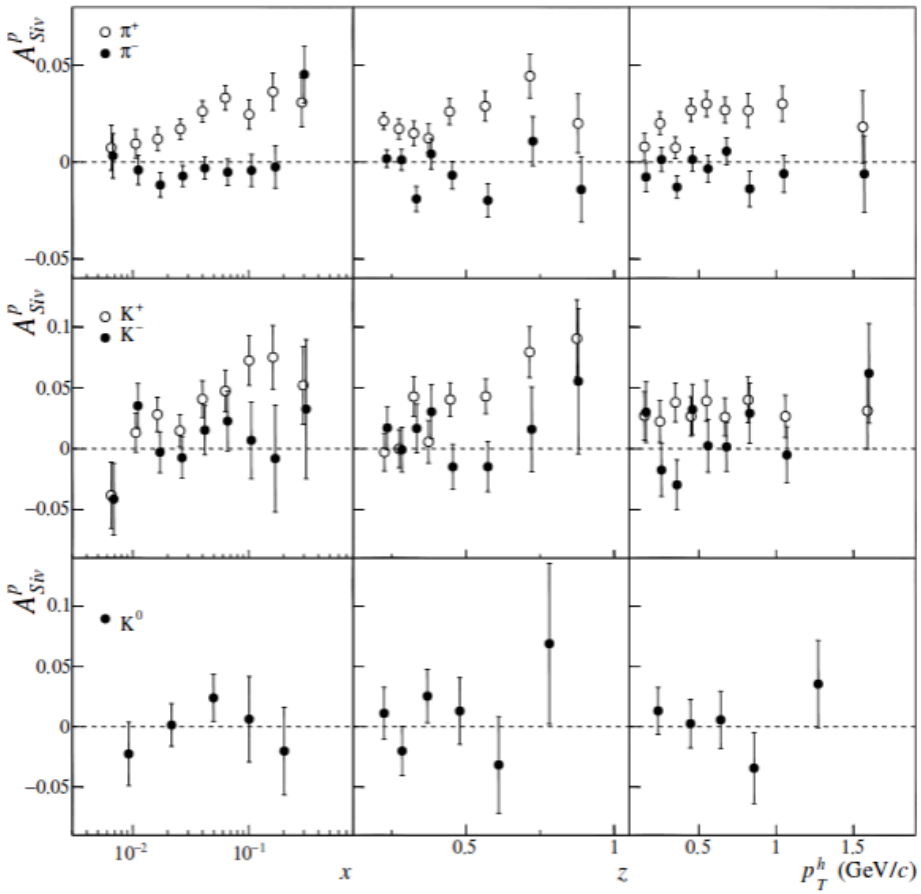
COMPASS, arXiv:1408.4405, submitted to PL B



M. Anselmino et al., Phys.Rev. D87 (2013) 094019

- Collins asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are large at $x \gtrsim$ 0.03 and consistent with HERMES (in spite of different Q^2!)
- but negligible for the deuteron
- COMPASS + HERMES data on p,d + BELLE on e^+e^-: $\Longrightarrow \Delta_T u,\ \Delta_T d$
- Transversity also obtained from 2-hadron asymmetries (and “Interference Fragmentation Function”)

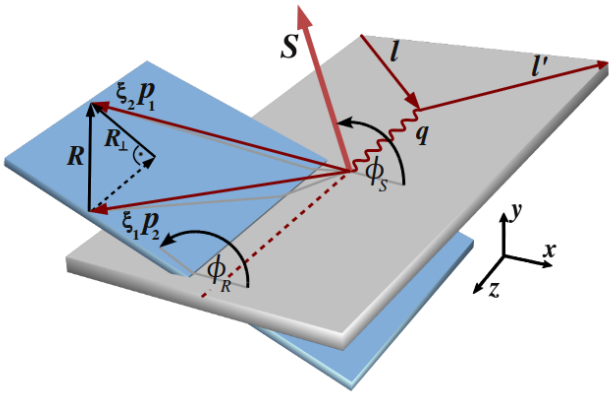
Results for the Sivers asymmetry for protons



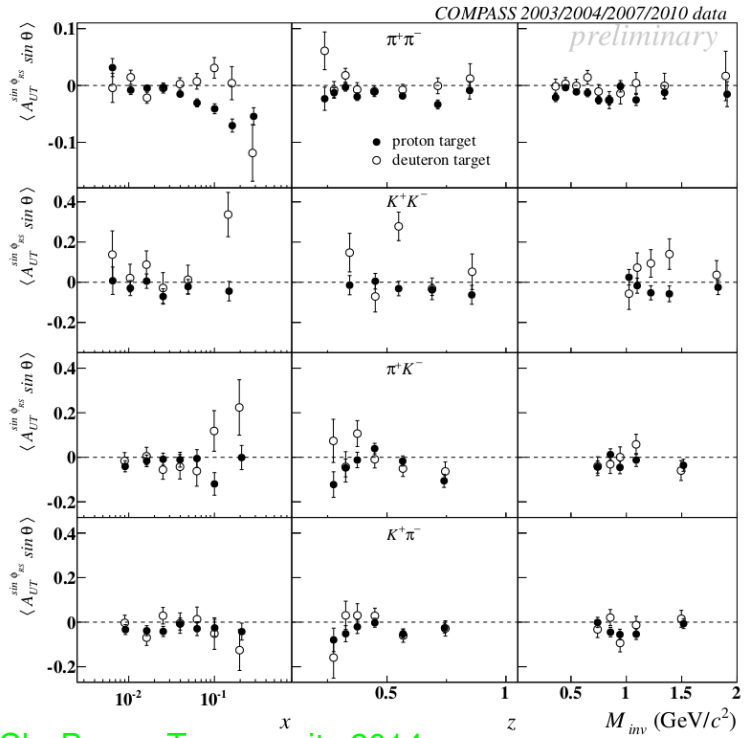
COMPASS, arXiv:1408.4405, submitted to PL B

- Sivers asymmetries for proton measured for +/– identified hadrons are large for π^+, K^+...
- ...and even larger at smaller Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry

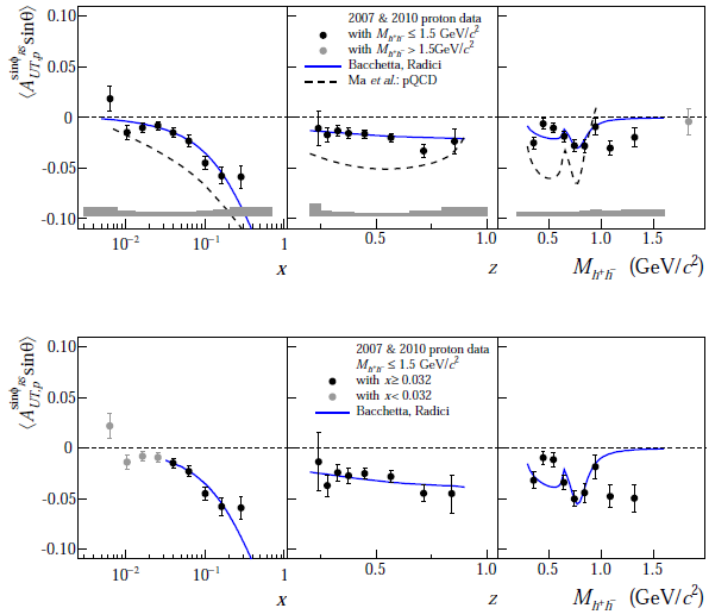
Di-hadron ($lN^{\uparrow} \to l' h_1 h_2 X$) asymmetries, p and d



- Fragmentation of $q\uparrow$ into unpolarised $h_1 h_2$
- Di-hadron asymmetry: $A_{UT}^{\sin\phi_{RS}}$ $(\phi_{RS} = \phi_R + \phi_S - \pi)$
- measured from $N_{2h}(x, y, z, M_{inv}^2, \theta, \phi_{RS})$
- gives access to transversity $\Delta_T q$
- ...and to a corresponding FF, $H_1^{\sphericalangle q}$



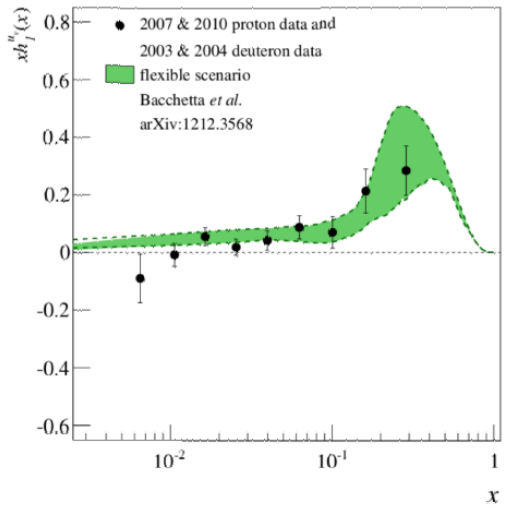
Ch. Braun, Transversity 2014

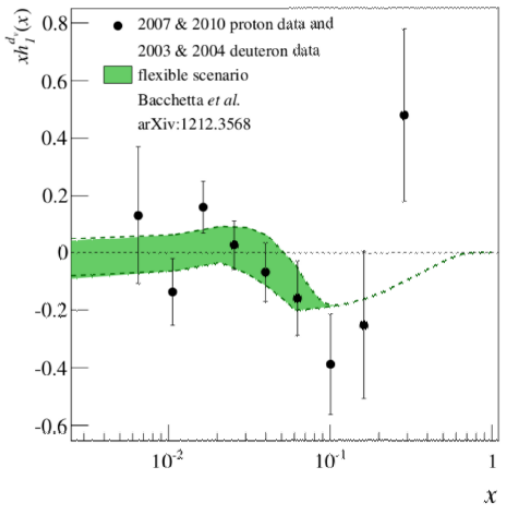


COMPASS, Phys.Lett. B736 (2014) 124

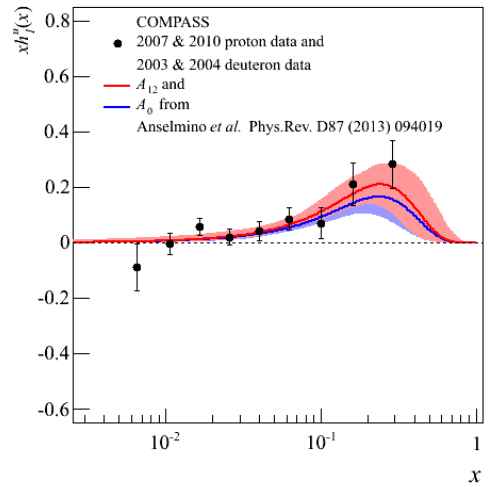
Transversity, $\Delta_T q(\equiv h_1)$, from 2h; p and d targets

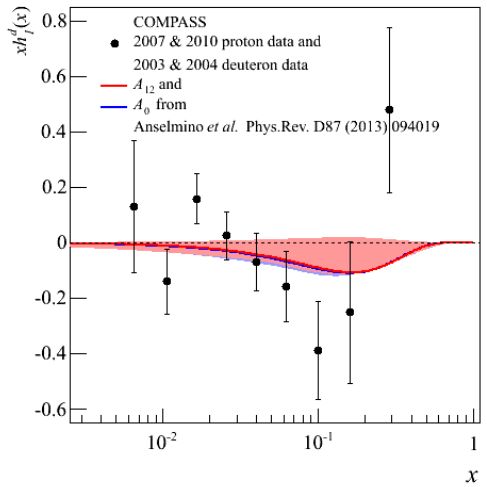
Comparison with a global fit (Bacchetta *et al.* JHEP 03 (2013) 119)





...and with a global fit of 1h Collins asymmetry (Anselmino *et al.* Phys.Rev. D87 (2013) 094019)

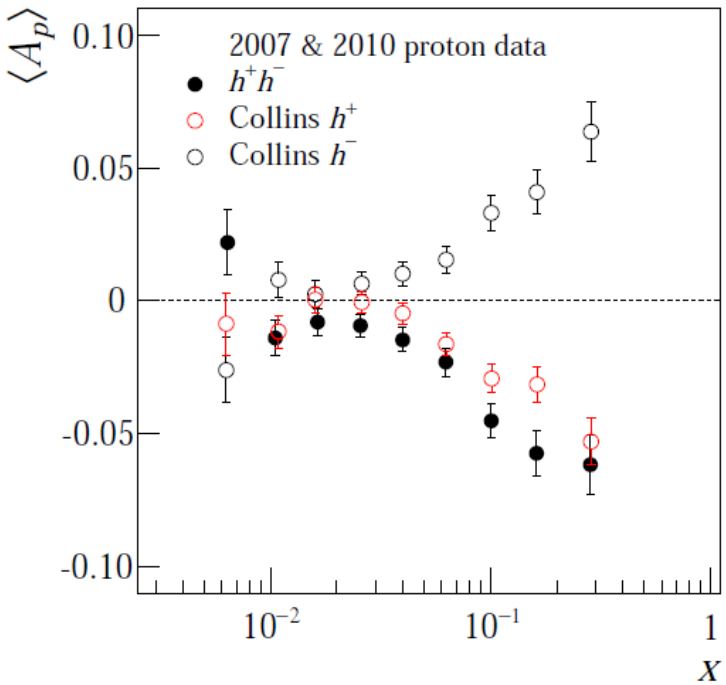




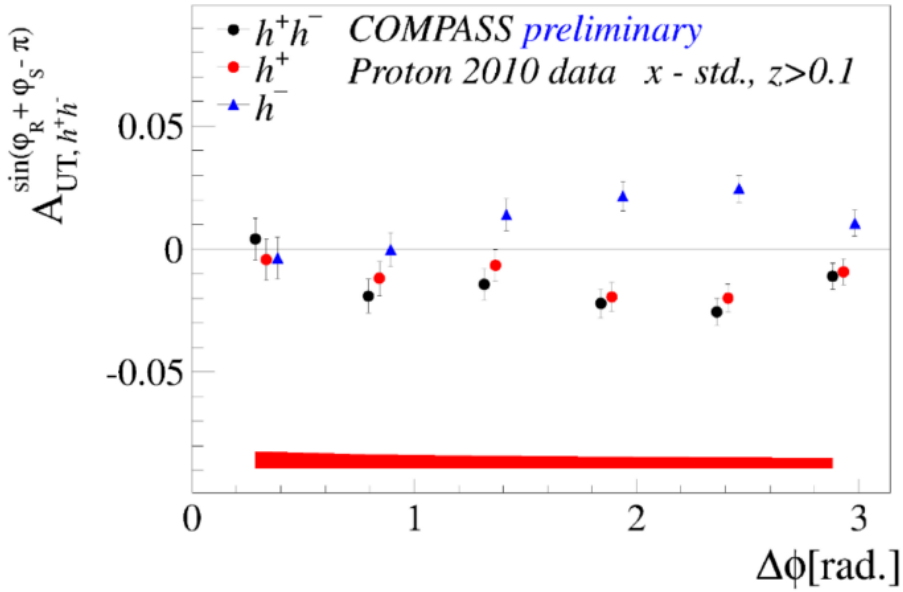
Two–hadron *vs* Collins asymmetries

Interesting observations:

- Shape and strength of 2h and Collins h^+ asymmetries almost identical as functions of x and $\Delta\Phi = |\phi_{h+} - \phi_{h-}|$
- Expected within the string fragmentation model and consistent with 2h asymmetries at low M^2_{inv}
- Work is going on



COMPASS, Phys.Lett. B736 (2014) 124



Other azimuthal asymmetries

SIDIS x-section

A. Kotzinian, Nucl. Phys. B441, 234 (1995).
Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007).

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\varphi_h\,d\psi} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\times$$

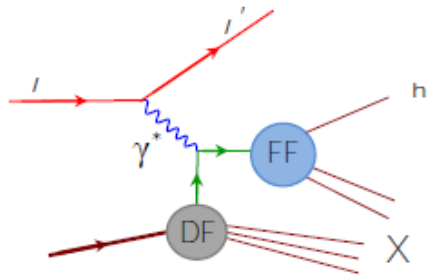
$$\left\{\begin{array}{l}
1+\cos\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UU}^{\cos\phi_h}\right)+\cos 2\phi_h\left(\varepsilon A_{UU}^{\cos 2\phi_h}\right)\\
\quad+\lambda\sin\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LU}^{\sin\phi_h}\right)\\
\quad+S_L\left[\sin\phi_h\left(\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UL}^{\sin\phi_h}\right)+\sin 2\phi_h\left(\varepsilon A_{UL}^{\sin 2\phi_h}\right)\right]\\
\quad+S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\cos\phi_h\left(\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LL}^{\cos\phi_h}\right)\right]\\
\quad+S_T\left[\begin{array}{l}
\sin(\phi_h-\phi_S)\left(A_{UT}^{\sin(\phi_h-\phi_S)}\right)\\
\quad+\sin(\phi_h+\phi_S)\left(\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\right)\\
\quad+\sin(3\phi_h-\phi_S)\left(\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\right)\\
\quad+\sin\phi_S\left(\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin\phi_S}\right)\\
\quad+\sin(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1+\varepsilon)}\,A_{UT}^{\sin(2\phi_h-\phi_S)}\right)
\end{array}\right]\\
\quad+S_T\lambda\left[\begin{array}{l}
\cos(\phi_h-\phi_S)\left(\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\right)\\
\quad+\cos\phi_S\left(\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos\phi_S}\right)\\
\quad+\cos(2\phi_h-\phi_S)\left(\sqrt{2\varepsilon(1-\varepsilon)}\,A_{LT}^{\cos(2\phi_h-\phi_S)}\right)
\end{array}\right]
\end{array}\right.$$

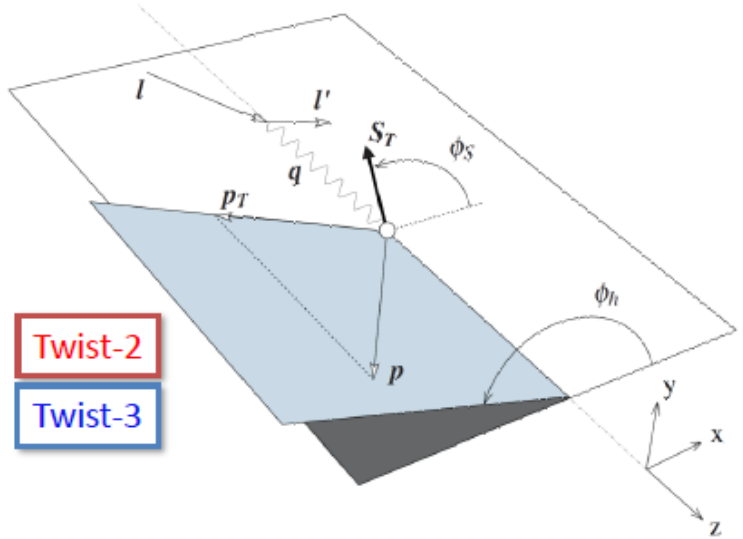
SSA

DSA

Twist-2

Twist-3



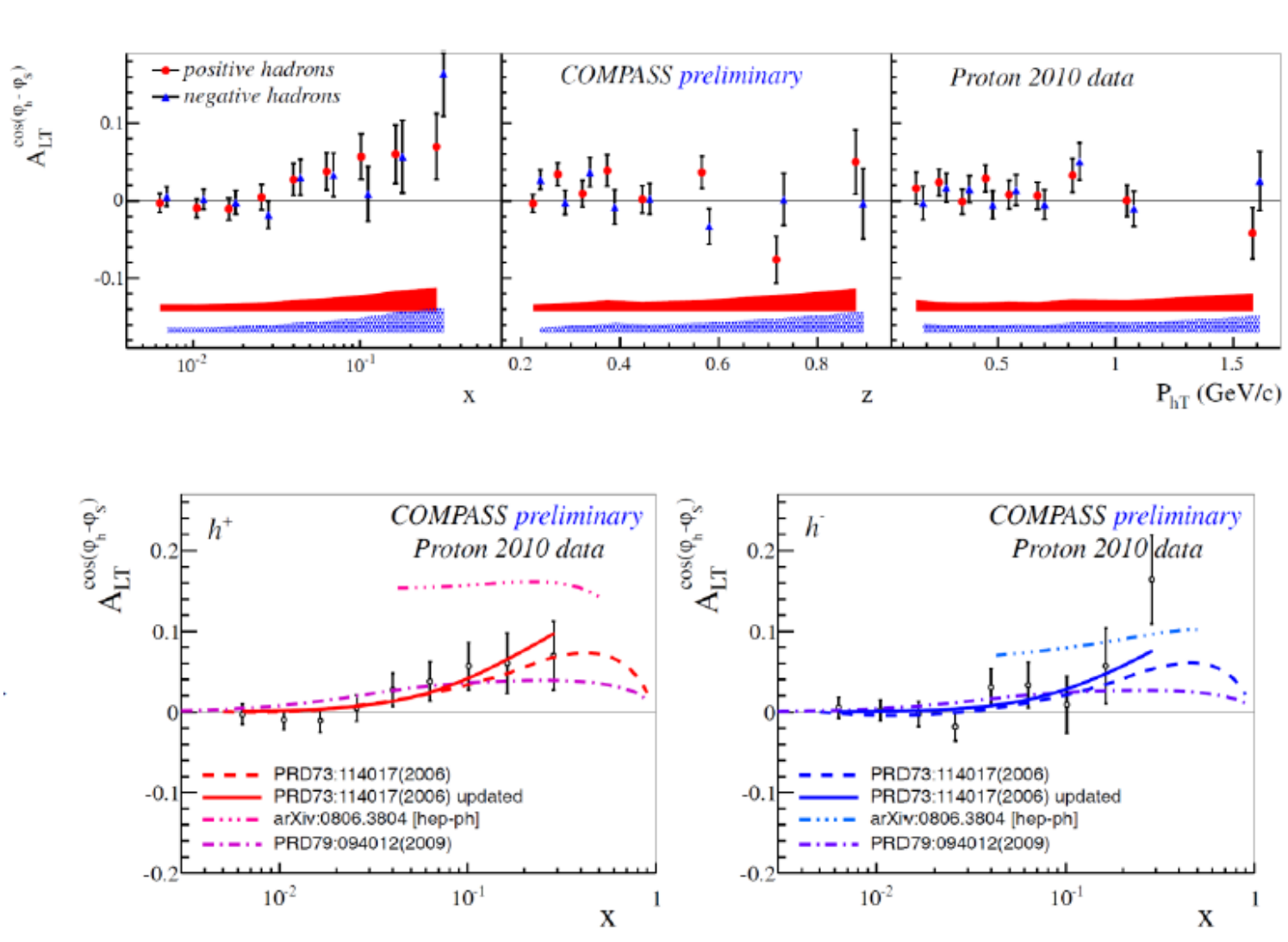


$$A_{U(L),T}^{w(\varphi_h,\varphi_S)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}};\qquad \varepsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2},\qquad \gamma=\frac{2M_x}{Q}$$

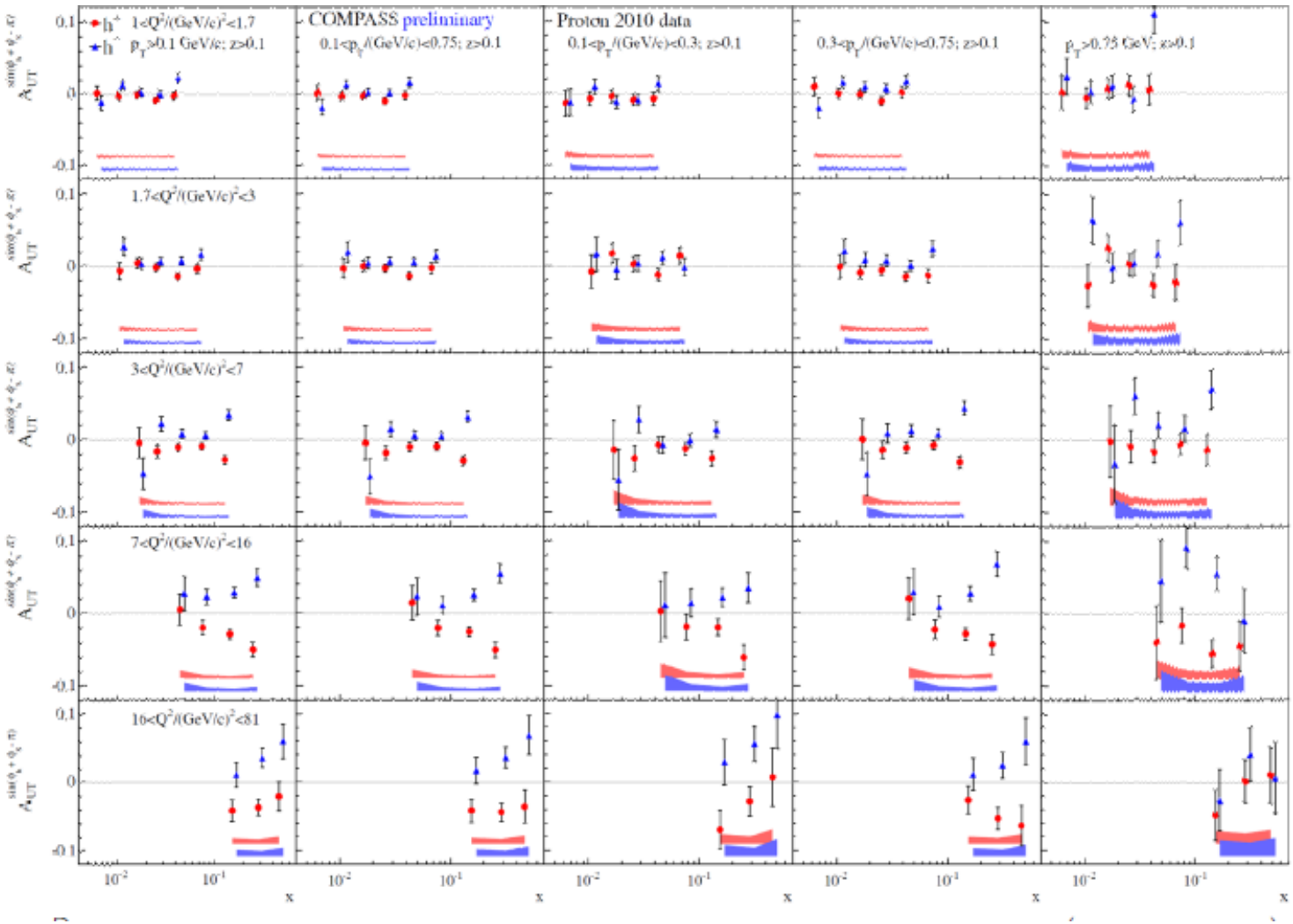
22 October 2014 Bakur Parsamyan 8

Other TSAs: e.g. $A_{LT}^{\cos\phi_h-\phi_s}$ sensitive to g_{1T}^q

- g_{1T}^q: the only T-even, chiral-even, off-diagonal, twist-2 TMD



Multidimensional analyses: Collins asym. 3D (Q^2, p_T, x), $z > 0.1$



⟸ DY!

Summary of measurements on a transversely polarised target

- Collins and Sivers: completed analysis of combined 2007/2010 proton identified pions and kaons data (arXiv:1408.4405).
  Collins exhibits a non-zero signal for pions; Sivers: positive for π^+, K^+ (zero otherwise).
- Di-hadrons: combined 2007/2010 proton h^+h^- data (Phys. Lett.B736 (2014) 124).
  Preliminary 2003/2004 d and 2007/2010 p identified 2h
- Di-hadrons: $\pi^+\pi^-$ asymm. with unified analysis (cuts, binning,...) for p and d
- $\Delta_T u^v$ and $\Delta_T d^v$ extracted bin-by-bin from final COMPASS data according to method of Bacchetta *et al.*.
- A transversity signal at large $\Delta\phi$.
- Multidimensional (2D, 3D, 4D) analysis of unidentified h^+/h^- hadrons
- Correlation between Collins for di-hadrons and 1 hadron is being investigated

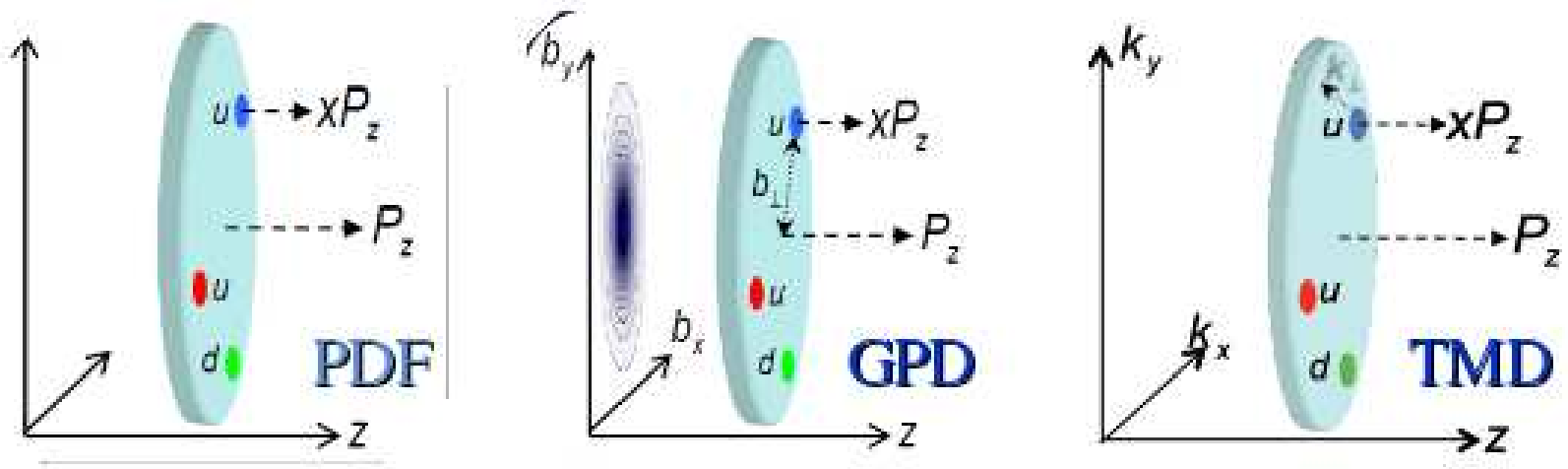
Outline

COMPASS II Proposal

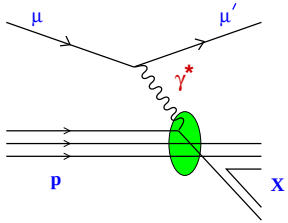
- CERN–SPSC–2010–014 (SPSC–P–340) of May 17, 2010
  wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf
- Approved in December 2010 initially 3 years data taking (Phase 1)
- Flavour separation and fragmentation in spin-averaged SIDIS (strange sector !)
- Focus on transverse structure of the nucleon
  - T-odd TMD (Sivers, Boer-Mulders distributions)
  - Drell-Yan process and TMD sign change SIDIS $\Longleftrightarrow$ DY
  - GPD, transverse size and parton orbital angular momentum
- π/K polarisabilities and tests of ChPT
  in the Compton scattering via Primakoff reaction.
- Addendum foreseen (spin-dependent GPD), Phase 2.

Outline

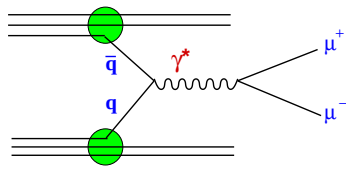
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_{T} taken into account
- related to quark angular momentum, L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - Drell-Yan process (π beam on unpolarised/transversely polarised tgt.)



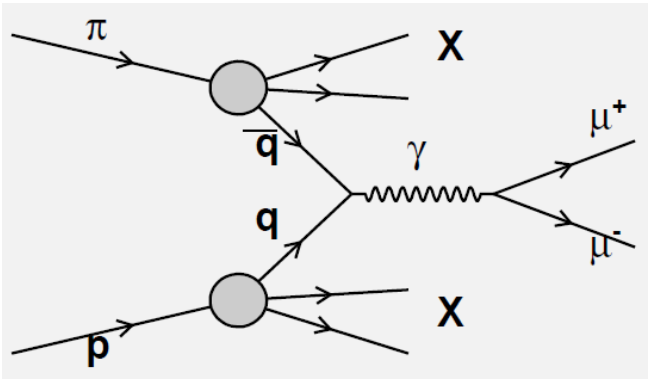
SIDIS
Obs.: final state interactions!

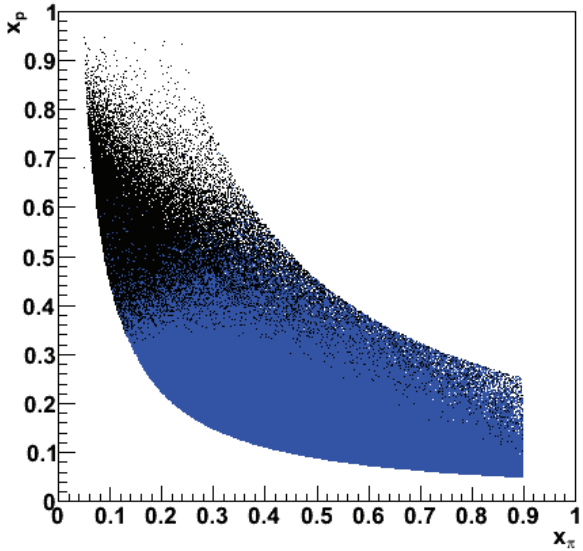


DY
Obs.: initial state interactions!

Drell-Yan process: $\pi^- p^\uparrow \to \mu^+\mu^- X$ @ COMPASS

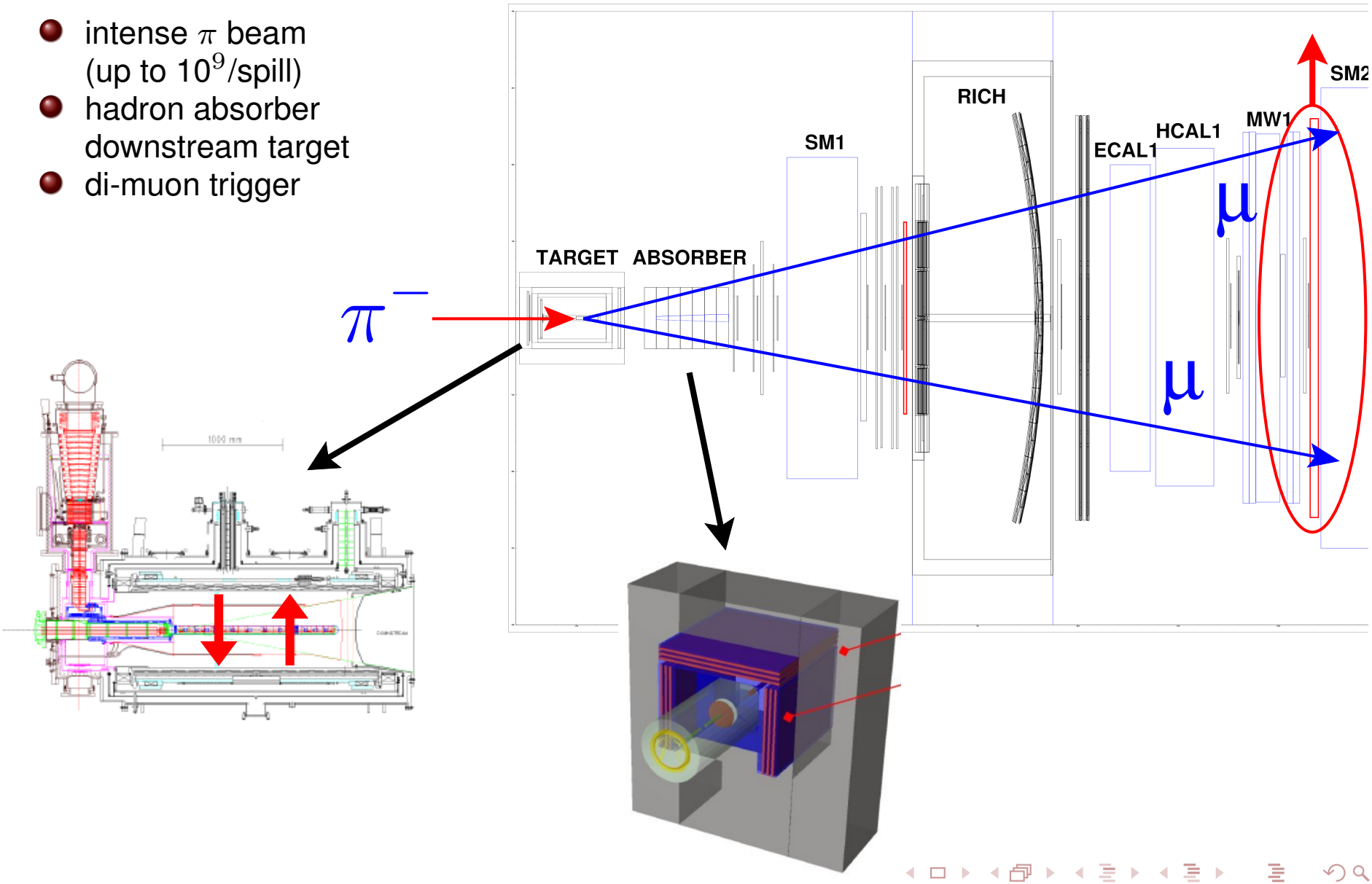
- Clean partonic process
- No fragmentation functions involved!
- Convolution of two Parton Distribution Functions
  $\sigma^{\mathrm{DY}} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|\mathrm{p}}, \quad \sigma^{\mathrm{DY}} = \sigma^{\mathrm{DY}}(x_\pi, x_\mathrm{p})$
- Gives an access to azimuthal modulations of 4 PDF: transversity, pretzelosity, Boer–Mulders and Sivers.
- Ideal: $\bar{\mathrm{p}}\mathrm{p}$; good compromise: $\pi^-\mathrm{p}$
- Here dominated by annihilation of valence $\bar{u}$ from π^- and valence u from p
- COMPASS has large acceptance in the valence region of p and π (large SSA expected). Example of covered kinematics (in blue): π^- beam, 190 GeV/c, NH_3 target, $\perp$ polarised dimuon mass range: $M_{\mu\mu}$: 4 – 9 GeV/c^2 (low bckg.)
- QCD TMD approach justified by: $M_{\mu\mu} \gg p_{\mathrm{T}}^{\mu\mu} \approx 1$ GeV



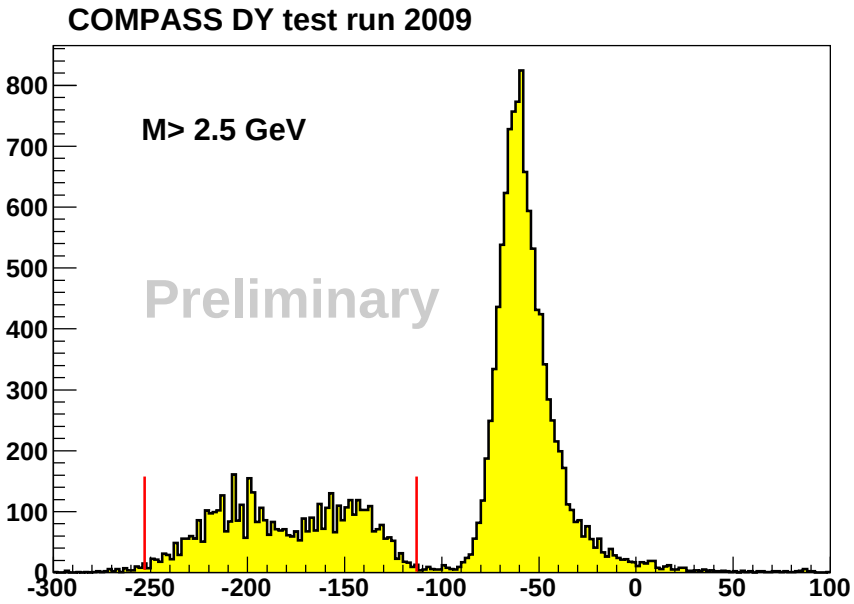


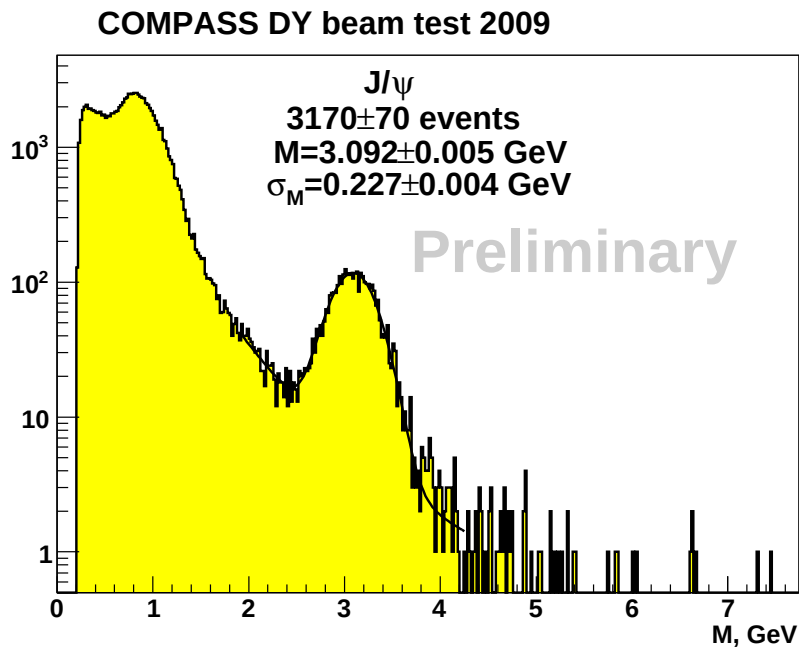
Drell–Yan @ COMPASS: experimental requirements

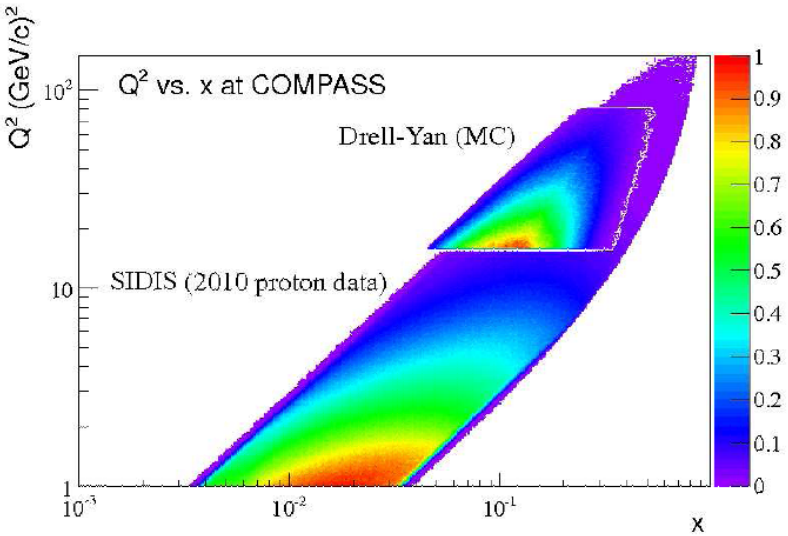
- intense π beam (up to 10^9/spill)
- hadron absorber downstream target
- di-muon trigger



Drell–Yan @ COMPASS: Results from 2009 beam test



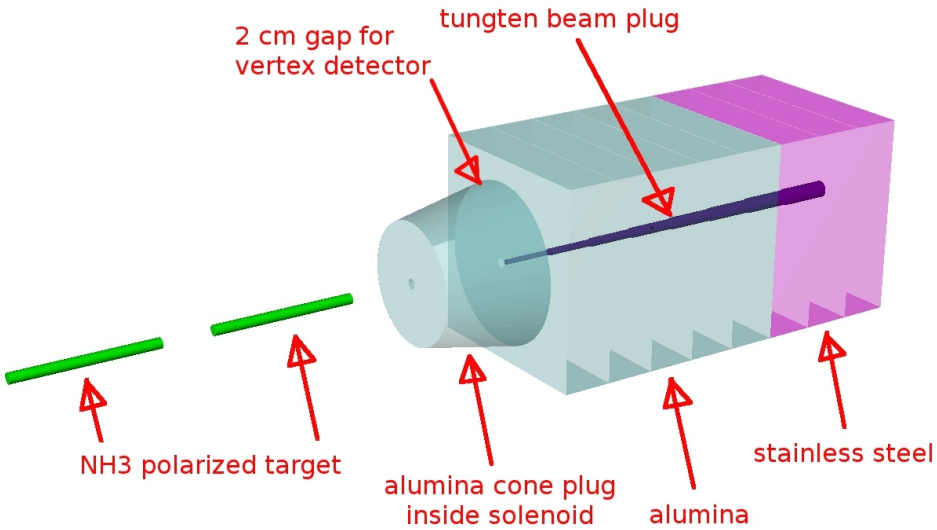




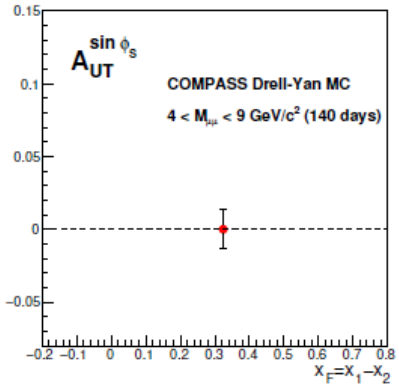
DY & SIDIS have overlapping acceptance!

Drell–Yan @ COMPASS: Projections for azimuthal asymmetries

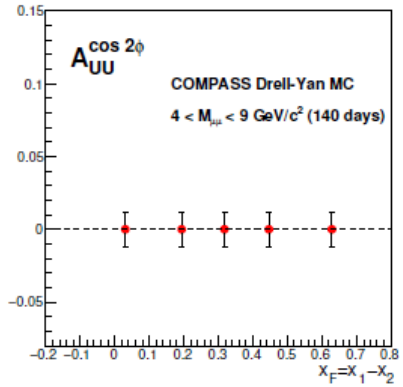
- projections for 4 GeV/c^2 $< M_{\mu\mu} <$ 9 GeV/c^2
- 2014 – test; 2015 – 140 days of data taking
  $>$ 200 kevents expected
- 10^8 pions /9.6 s spill; 33.6 s cycle
- 1.1 m long, polarised NH_3 target



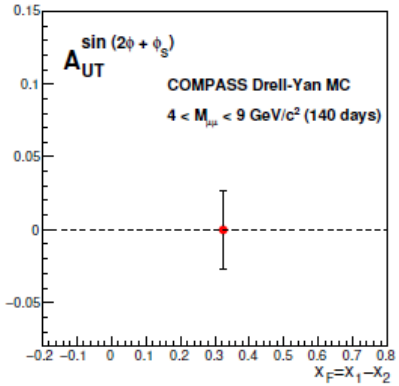
$f_1^\pi \otimes \text{Sivers}^p$



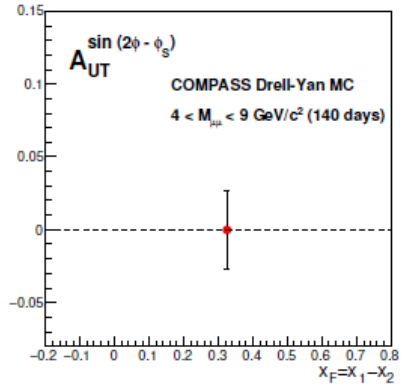
$\text{BM}^\pi \otimes \text{BM}^p$



$\text{BM}^\pi \otimes \text{pretzel.}^p$



$\text{BM}^\pi \otimes \text{transv.}^p$



Goals: change of sign between DIS and SIDIS in $h_1^\perp$,
J/Ψ production mechanism,...

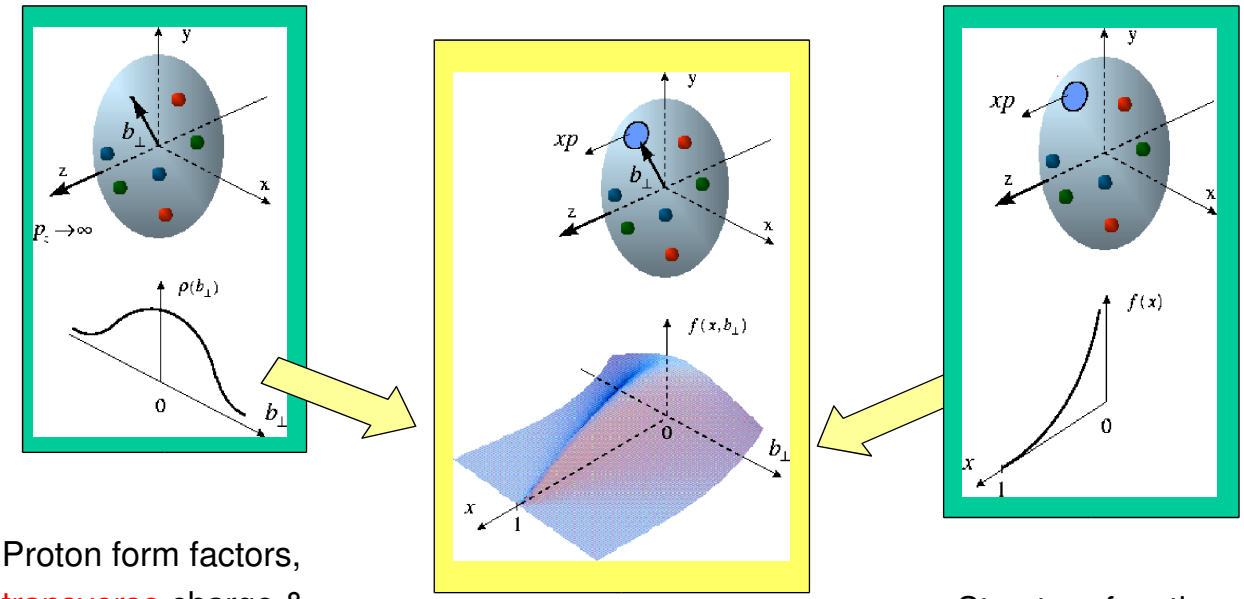
Drell–Yan measurement: status

- (Transversely) Polarised DY COMPASS just started taking the test data ($\sim$ until end of 2014);
  In 2015, 140 days of TMD dedicated DY data taking.
  Possible continuation in 2018 ?
- Simultaneously the relevant azimuthal asymmetries will be extracted in the region $4 < M_{\mu\mu} < 9$ GeV/c^2.
- Expected $\delta A_{\mathrm{Sivers}} \sim 1\%$ after 1 year of running
- Parallely: unpolarised DY on nuclear targets for studies of EMC effect (flavour dependence)

Outline

3D picturing of the proton *via* GPD

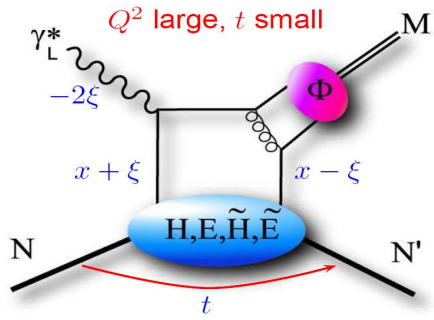
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

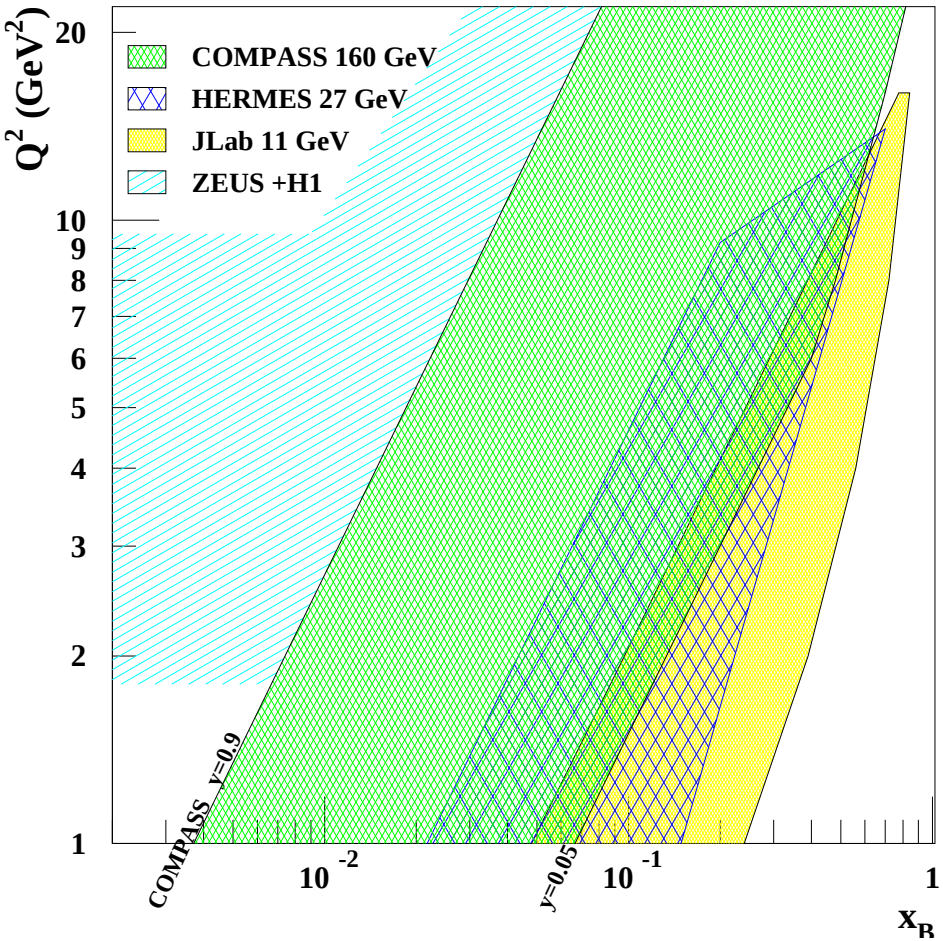
Structure functions, quark longitudinal momentum & helicity distributions



- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- All depend on 3 variables: x, ξ, t; DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity; $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions; $\widetilde{H}, \widetilde{E}$ refer to polarised distr.

After V.D. Volker, LANL 2007

GPD at COMPASS: data taking in 2016-17



- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_{B}
  - predominant DVCS @ high x_{B}
- Plans
  - DVCS
  - DVMP
- Goals
  - from unpolarised target: H (Phase 1)
  - from $\perp$ polarised target: E (Phase 2)

Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated