Results on COMPASS longitudinally polarised data from LIP

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Aknowledgements:

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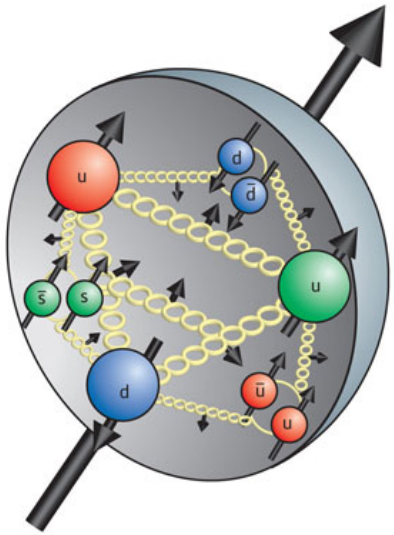
Outline

Nucleon spin

Decomposition

$$S = \frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluons}} + \underbrace{L_q + L_q}_{\text{orbital angular momenta}}$$

$$\begin{aligned} \Delta\Sigma &= \Delta u + \Delta d + \Delta s \\ &= \Delta u_v + \Delta d_v + 2\Delta\bar{u} + 2\Delta\bar{d} + \Delta s + \Delta\bar{s} \end{aligned}$$



$\Delta q \equiv \Delta(q + \bar{q})$
$\Delta q = \overrightarrow{q} - \overleftarrow{q}$ (parallel minus antiparallel to the nucleon spin)
$\mathbf{g_1(x, Q^2)} \simeq \sum_q e_q^2 \Delta q(x, Q^2)$

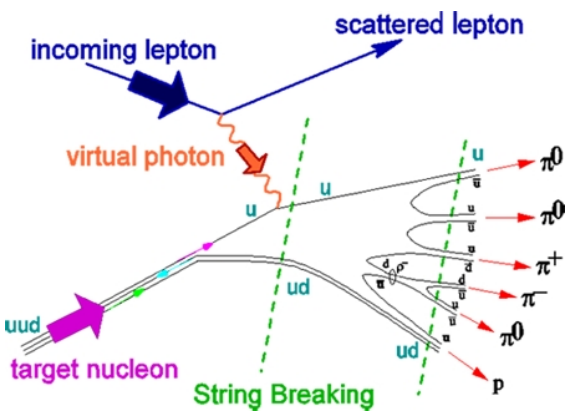
"Spin crisis"

- Relativistic quark model prediction: $\Delta\Sigma \simeq 0.6$
- EMC measurement (1988): $\Delta\Sigma = 0.12 \pm 0.17$

Recent status

- **Quarks spin** contributes only about 30% to the nucleon spin
- **Gluon** contribution constrained only for a limited x range
- Very few experimental results on orbital angular momentum

(SI)DIS and spin observables



$k_\mu = (E_\mu, \mathbf{k}_\mu)$
$k'_\mu = (E'_\mu, \mathbf{k}'_\mu)$
$P = (M, 0)$
$q = k_\mu - k'_\mu = (\nu, \mathbf{q})$
$Q^2 = -q^2$
$\nu = P \cdot q / M = E_\mu - E'_\mu$
$W^2 = M^2 + 2M\nu - Q^2$
$x = Q^2/(2M\nu)$
$y = \nu/E_\mu$
$z = E_h/(E_\mu - E_{\mu'})$

Experimental asymmetry

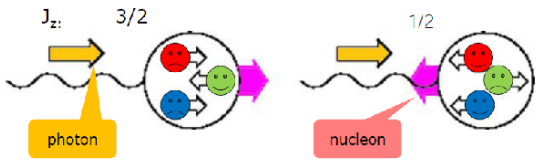
$$\mathbf{A_{exp}} = \frac{N^{\rightleftarrows} - N^{\rightrightarrows}}{N^{\rightleftarrows} + N^{\rightrightarrows}} = P_{\mathbf{beam}} P_{\mathbf{target}} f A_{\parallel}$$

Lepton-nucleon asymmetry

$$A_{\parallel} = \frac{d\sigma^{\rightleftarrows} - d\sigma^{\rightrightarrows}}{d\sigma^{\rightleftarrows} + d\sigma^{\rightrightarrows}} \simeq D A_1$$

$$\mathbf{A_1} \simeq \frac{1}{f D P_{\mathbf{beam}} P_{\mathbf{target}}} A_{\mathbf{exp}}$$

Virtual photon-nucleon asymmetry



$$A_1 = A_1^{\gamma^* N} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \simeq \frac{g_1}{F_1}$$

Spin dependent structure function g_1

$$\mathbf{g_1(x, Q^2)} \simeq \frac{F_2(x, Q^2)}{2x(1 + R(x, Q^2))} A_1(x, Q^2) \quad \textbf{with } R \equiv \frac{\sigma_L}{\sigma_T}$$

Gluon polarisation in the nucleon using a new method

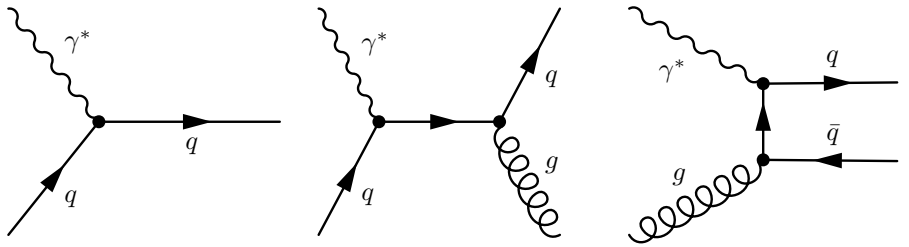
$$\frac{\Delta G}{G} = \int_0^1 \frac{\Delta g}{g}\, dx$$

Access to $\Delta g/g$ in COMPASS

Measuring longitudinal double spin asymmetries in:

- open charm meson production
  [PRD 87 (2013) 052018, Celso Franco's PhD]
- high-p_T hadron pair production in DIS
  [PLB 718 (2013) 922, Luís Silva's PhD]
- NLO QCD fits to g_1 world data
  [PLB 753 (2016) 18]
- high-p_T hadron quasi-real photoproduction
  [PLB 753 (2016) 573]
- all-p_T hadron production in DIS
  [hep-ex/1512.05053, Marcin Stolarski's analysis]

Photon-nucleon processes:

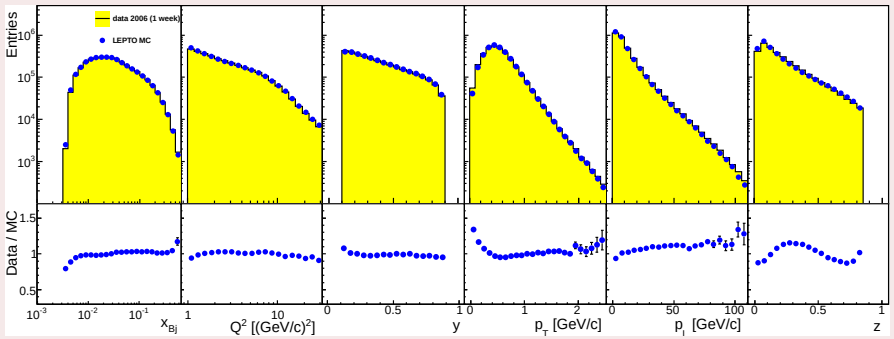


a) Leading process

b) QCD Compton

c) Photon-**gluon** fusion

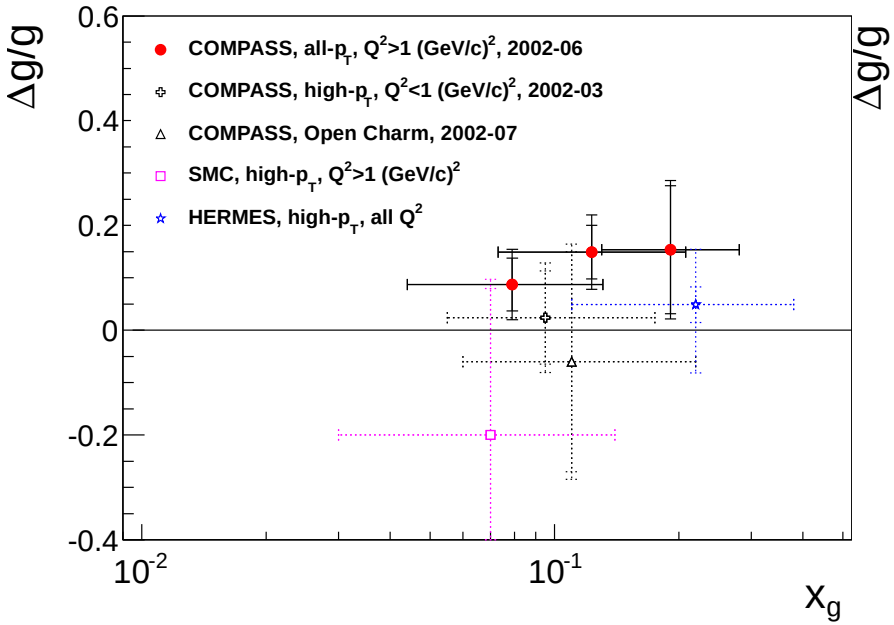
Monte Carlo vs data in the "all-p_T" method

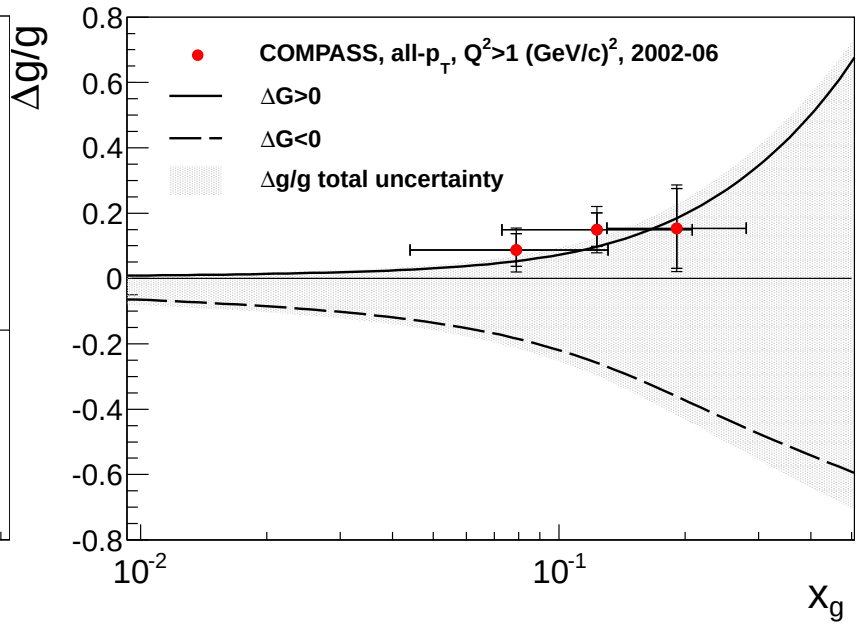


- High-p_T MC tuning (Luís Silva)
- Good description of the data achieved

Gluon polarisation in the nucleon: results

Data: 2002-2006, $\mu^+ d \to \mu^+ hX$





$$\langle \mathbf{\Delta g/g} \rangle = \mathbf{0.113 \pm 0.038}_{(\mathrm{stat.})} \pm \mathbf{0.036}_{(\mathrm{syst.})} \ @ \ \langle x_g \rangle \approx 0.10, \ Q_0^2 = 3 \ (\mathrm{GeV}/c)^2$$

- Improved statistical and systematic errors with respect to the high-p_T hadron pair analysis (by factors 1.6 and 1.8 respectively)
- **World's most precise** $\langle \Delta g/g \rangle$ extracted in LO
- Positive solution of ΔG favoured (out of two COMPASS NLO QCD fits of g_1 world data)

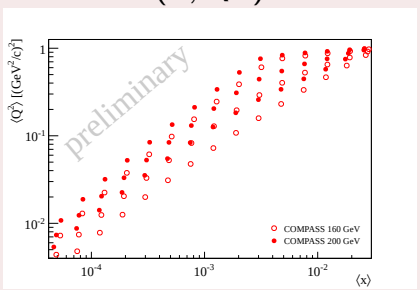
Spin structure of the proton in the non-perturbative region

Motivation

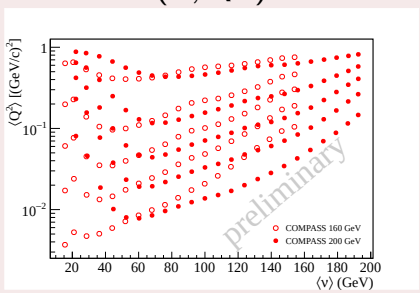
- low x corresponds to high parton densities
- the low x and low Q^2 region allows to access the **transition from the regime of photoproduction to the regime of DIS (described by pQCD)**
- extraction of A_1^p and g_1^p as functions of x and ν showed, **for the first time**, **positive spin effects at very low** x (*cf.* $A_1^d \sim 0$ at low x, and SMC sample - 150x smaller)
- theoretical models make predictions for g_1^p as function of two kinematic variables
  [Eur.Phys.J. C26 (2002) 45; Eur.Phys.J. C58 (2008) 29; Riv.Nuovo Cim. 33 (2010) 57]
- more than enough data ($\sim 7 \times 10^8$ events) for a 2D extraction
- extraction, for the first time, in 4 2D grids: (x, Q^2), (ν, Q^2), (x, ν), (Q^2, x)

Phase-space coverage

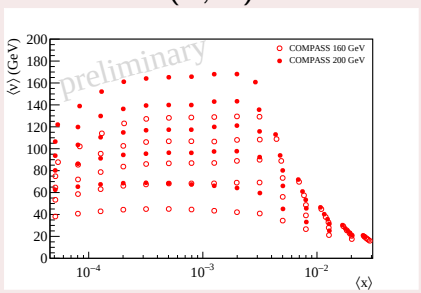
(x, Q^2)



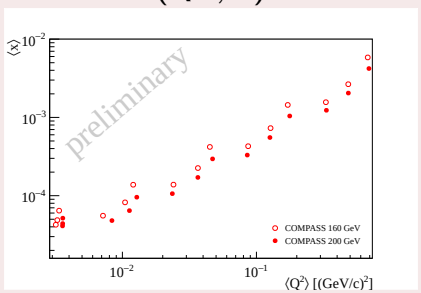
(ν, Q^2)



(x, ν)

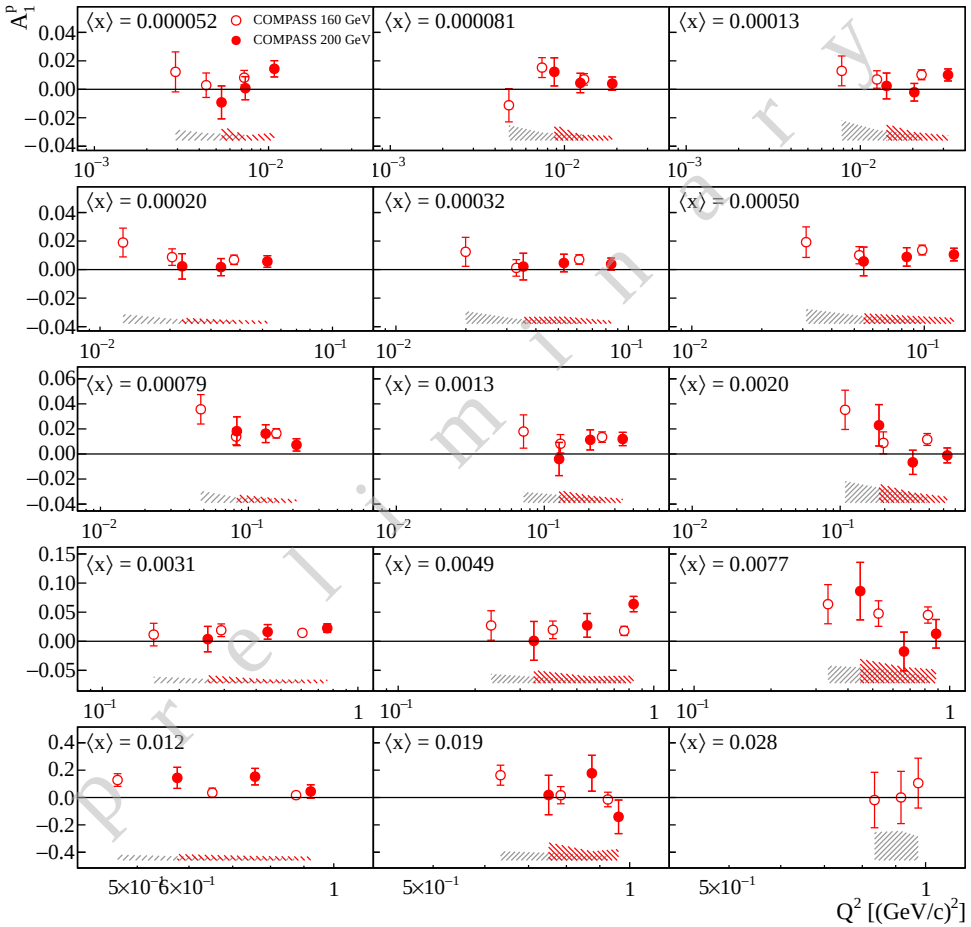


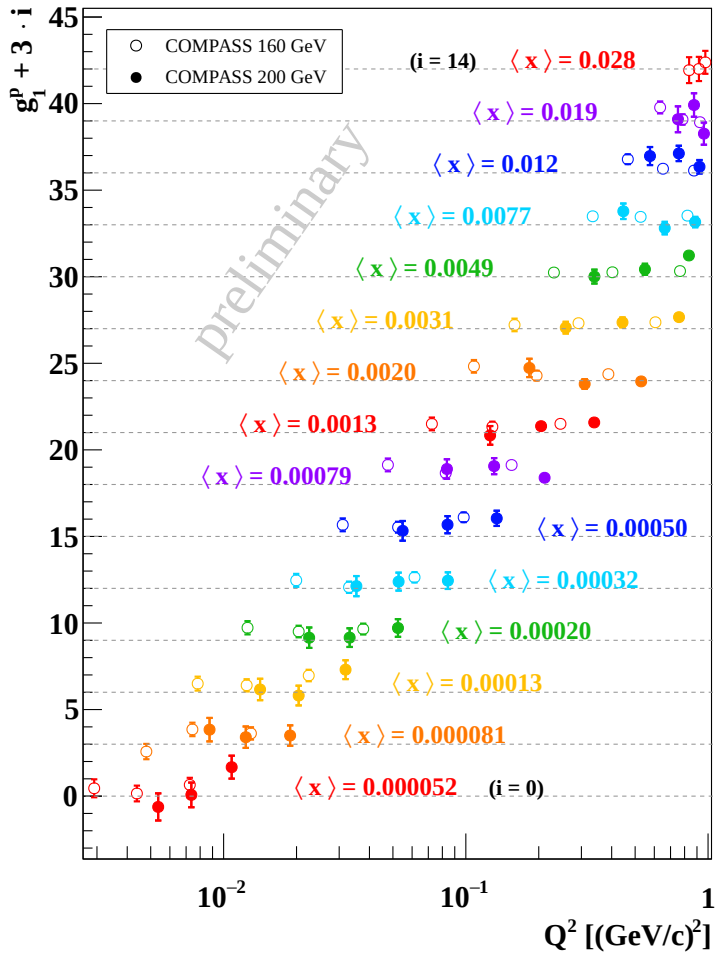
(Q^2, x)



A_1^p and g_1^p at low x and low Q^2: results for the grid (x, Q^2)

Data: 2007&2011, $\mu^+ p \to \mu^+ X$





- **no big dependence** with x or Q^2 (nor with the other variables)
- results **compatible with theoretical models** [Eur.Phys.J. C26 (2002) 45]

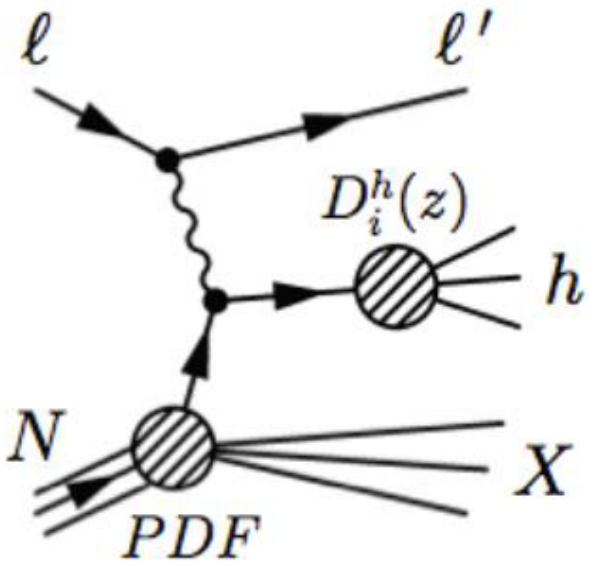
Hadron multiplicities in muon-deuteron scattering

Motivation

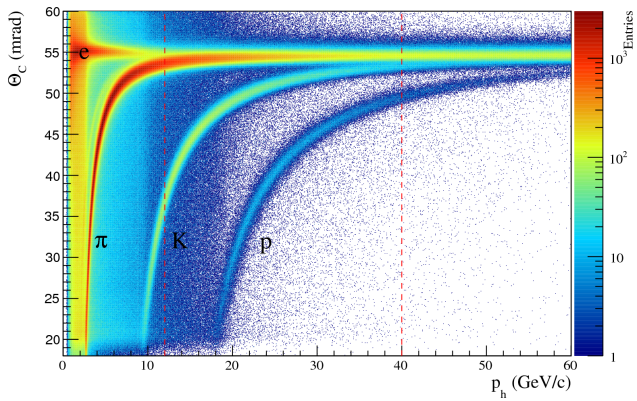
- The **quark fragmentation functions (FFs)** are non-perturbative, process independent objects
- FFs are needed for global pQCD fits
- COMPASS unpolarised data can give access to FFs via **pion and kaon multiplicities** in SIDIS:

$$\frac{dM^h}{dz} \underset{\text{at LO}}{=} \frac{\sum_q e_q^2 f_q(x,Q^2)\mathbf{D_q^h(z,Q^2)}}{\sum_q e_q^2 f_q(x,Q^2)}$$

- Hadron multiplicity $\equiv$ mean number of hadrons per DIS event



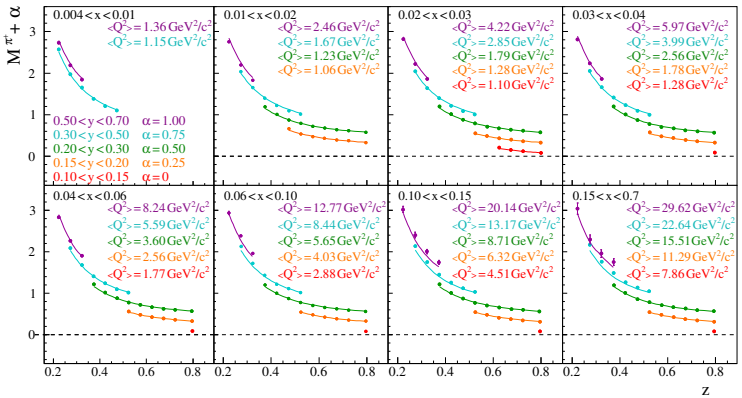
RICH: Θ_C vs momentum



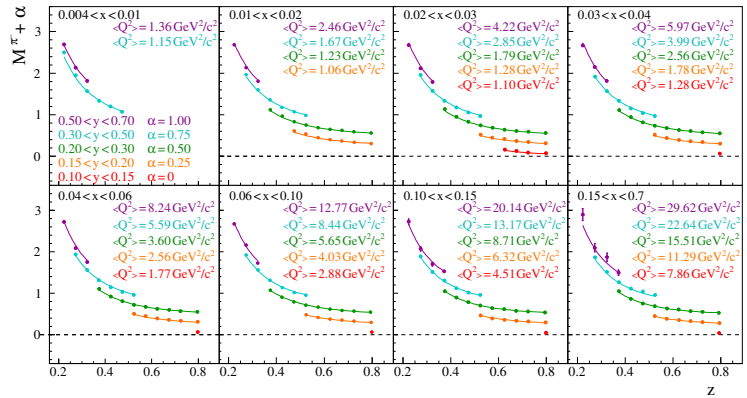
Hadron multiplicities: results

Data: 6 weeks of 2006, $\mu^+ d \to \mu^+ h^\pm X$

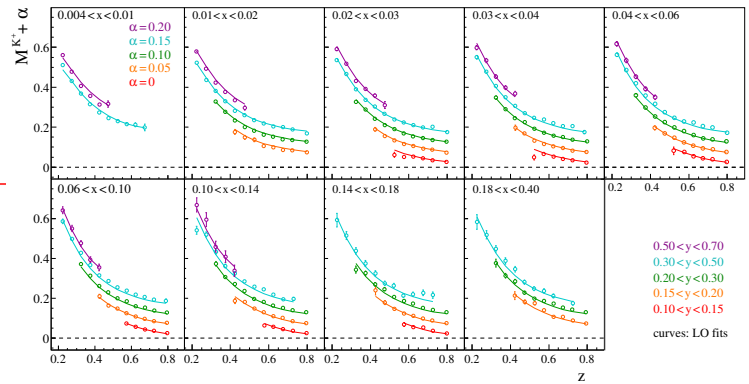
π^+



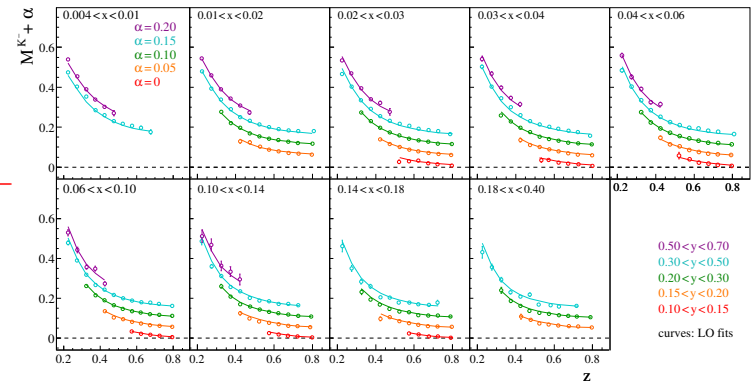
π^-



K^+



K^-



- $\sim$ 400 **data points** for π w/ strong z dependence, $M_{\pi^+} \gtrsim M_{\pi^-}$
- $\sim$ 400 **data points** for K w/ strong z dependence, $M_{K^+} > M_{K^-}$
- Also measured: p_T dependence

Summary and outlook

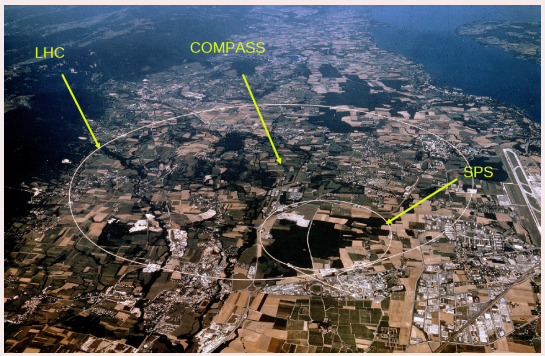
- The COMPASS group at LIP is **very active** in the analysis of the experiment's wealthy SIDIS data obtained with a longitudinally polarised target
- Important contributions have been given to the analysis of:
  - **gluon polarisation** in the nucleon obtained with a new method [MS]
    (2 peer-reviewed internal notes, **paper submitted to PLB**)
  - **spin structure of the proton in the non-perturbative region** [ASN, MS]
    (2 peer-reviewed internal notes, **writing of paper ongoing**)
  - **hadron multiplicities** in muon-deuteron SIDIS [MS]
    (4 peer-reviewed internal notes, **writing of 2 papers ongoing**)
- Much **more unpolarised SIDIS data** are available and will be collected in 2016 and 2017, and the LIP group can continue to contribute to it's analysis

BACKUP

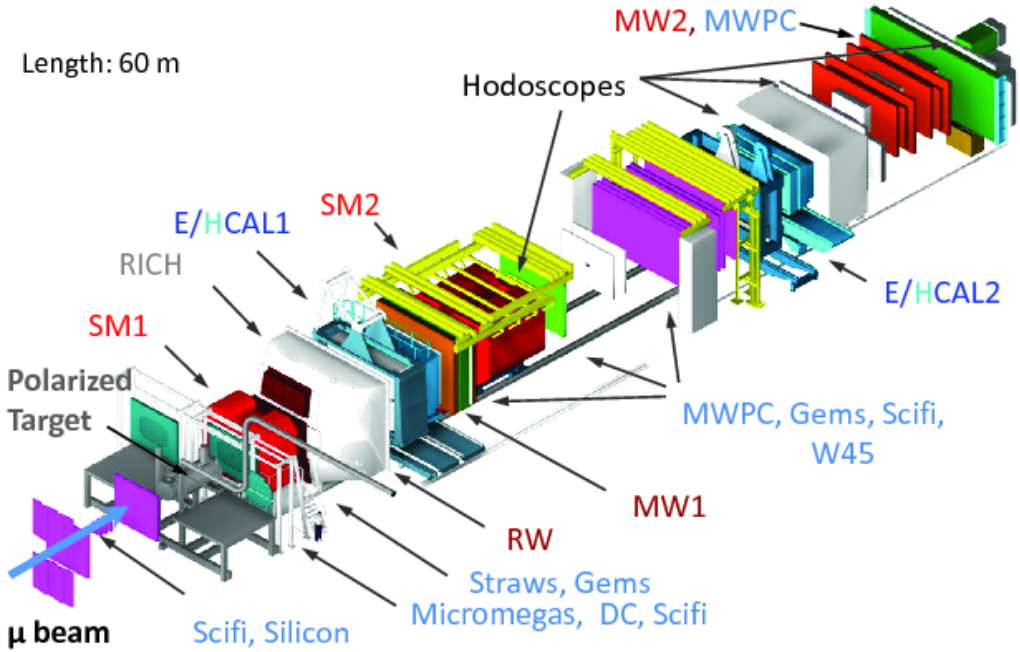
COMPASS experiment

COMPASS @ CERN

COmmon **M**uon **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



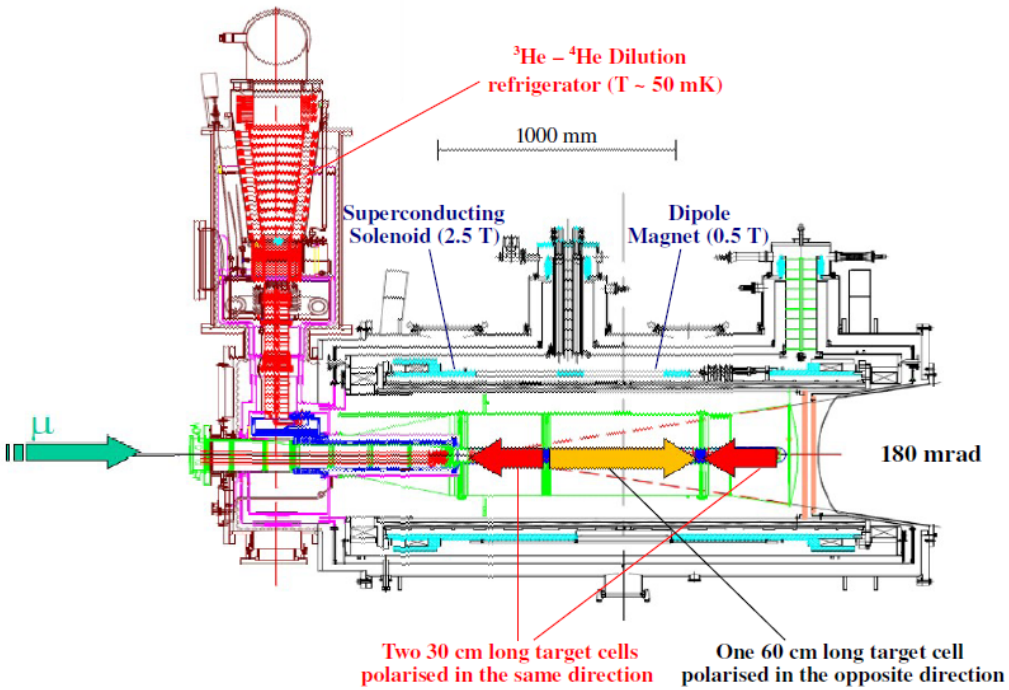
- **Fixed target experiment** at the SPS using a tertiary **muon beam**
- Collaboration of about 200 members from 11 countries and 23 institutions

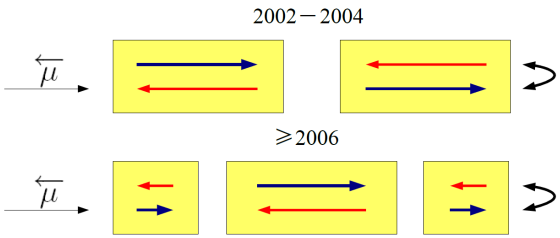


- 160/200 GeV μ^+ **polarised beam**, $P_b \sim -80\%$
- ^{6}**LiD** or N**H$_3$**, 1.2 m long, **polarised target** @ 2.5 T and 60 mK, $P_{target} \sim 50/85\%$

- large acceptance, two staged spectrometer
- tracking, calorimetry, RICH

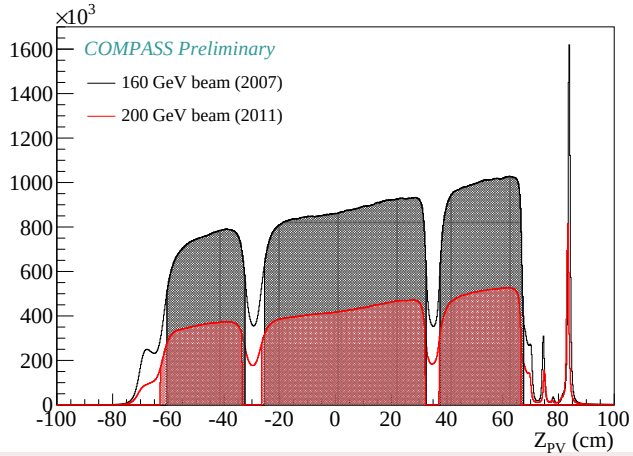
Polarised target



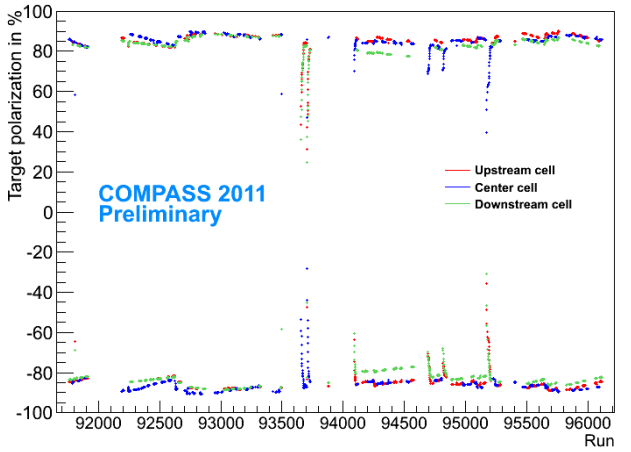


Material	Dilution factor	Polarisation
^{6}LiD	0.40	50%
NH_3	0.16	85%

Vertex coordinate z_{PV}



Target polarisation in 2011

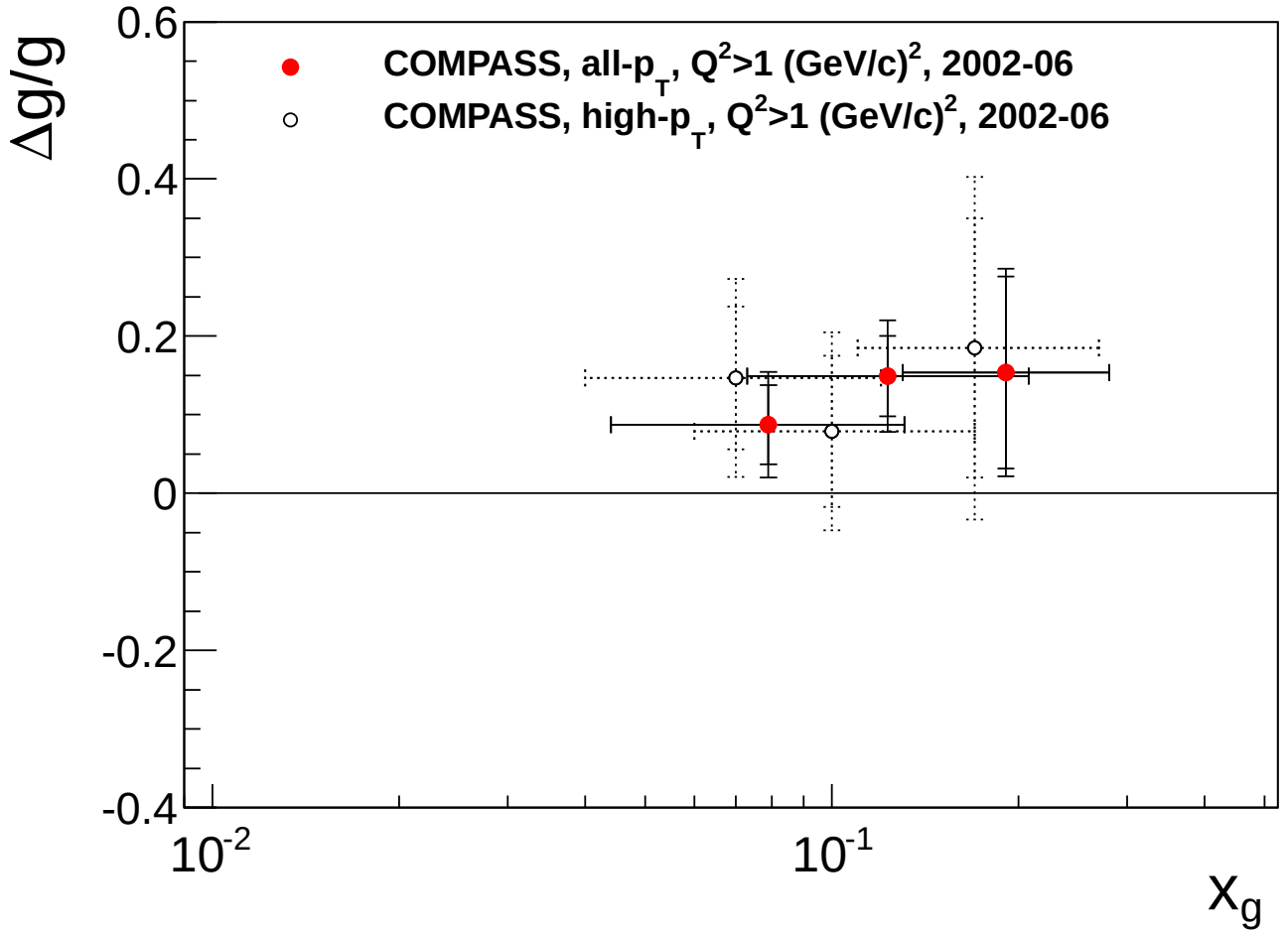


COMPASS data taking for the spin program

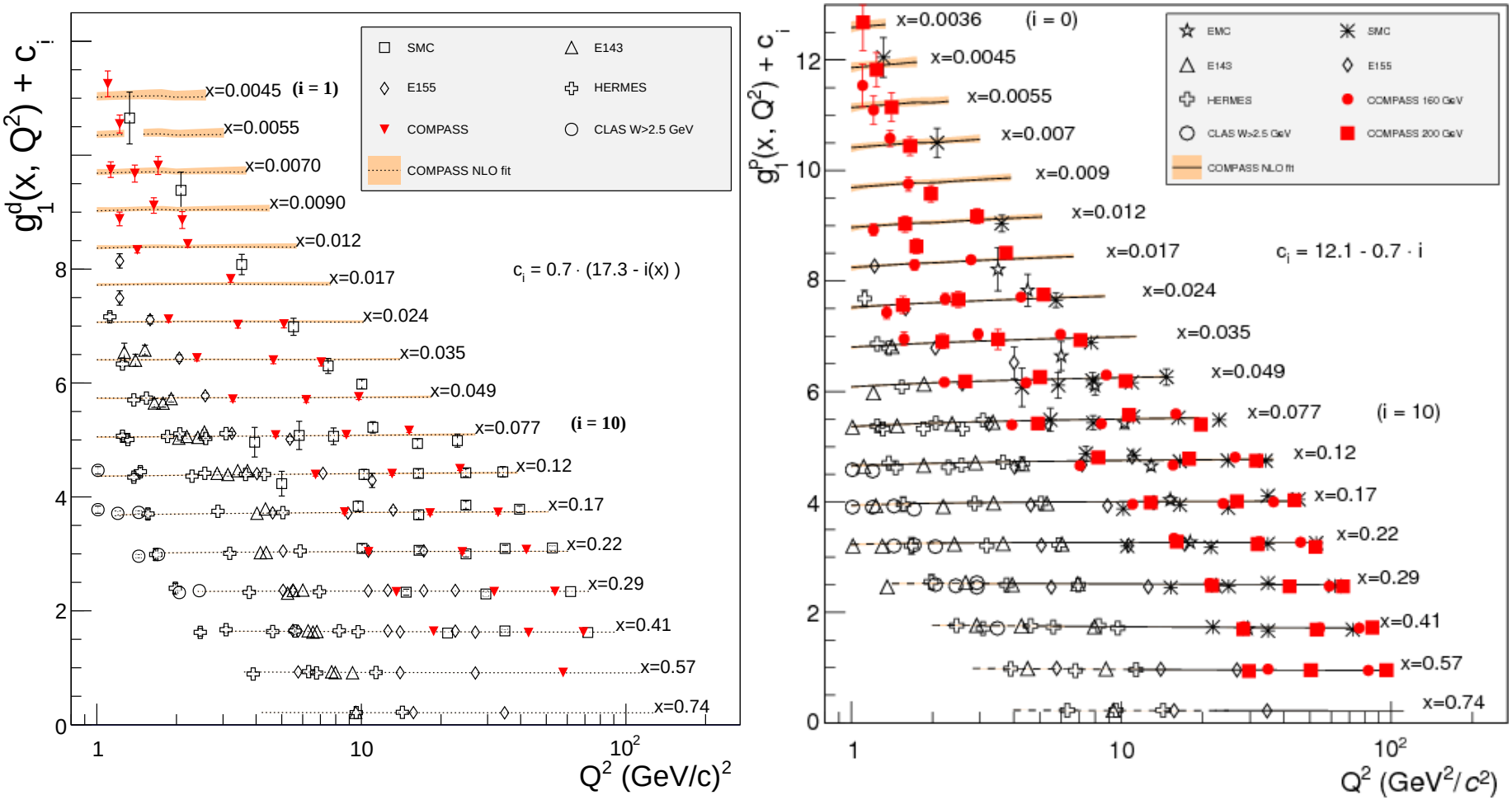
Year	Beam		Target		
	Particles	Energy (GeV)	Material	Cells	Magnetic field (T)
2002	**muons**	**160**	**^{6}LiD**	**2**	**long. $\pm$2.5**; transv. 0.42
2003	**muons**	**160**	**^{6}LiD**	**2**	**long. $\pm$2.5**; transv. 0.42
2004	**muons**	**160**	**^{6}LiD**	**2**	**long. $\pm$2.5**; transv. 0.42
2006	**muons**	**160**	**^{6}LiD**	**3**	**long. $\pm$1.0**
2007	**muons**	**160**	**NH_3**	**3**	**long. $\pm$1.0**; transv. 0.63
2010	muons	160	NH_3	3	transv. 0.63
2011	**muons**	**200**	**NH_3**	**3**	**long. $\pm$2.5**
2012	muons	160	H_2	1	0.0
2014	hadrons	190	NH_3	2	0.0
2015	hadrons	190	NH_3	2	transv. 0.63
2016	muons	160	H_2	1	0.0
2017	muons	160	H_2	1	0.0

Data covered in this talk, analysed @ LIP in 2014-2016 by Marcin Stolarski and ASN.

$\Delta G/G$ results: "all-p_T" vs high-p_T [hep-ex/1512.05053]

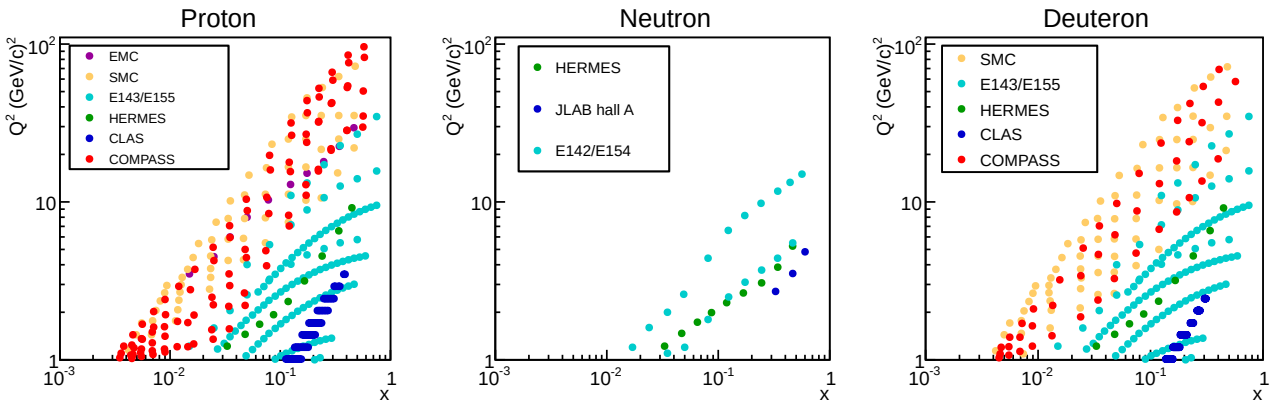


Results on g_1^d and g_1^p in DIS ($Q^2 > 1$ GeV$^2/c^2$) [PLB 753 (2016) 18]



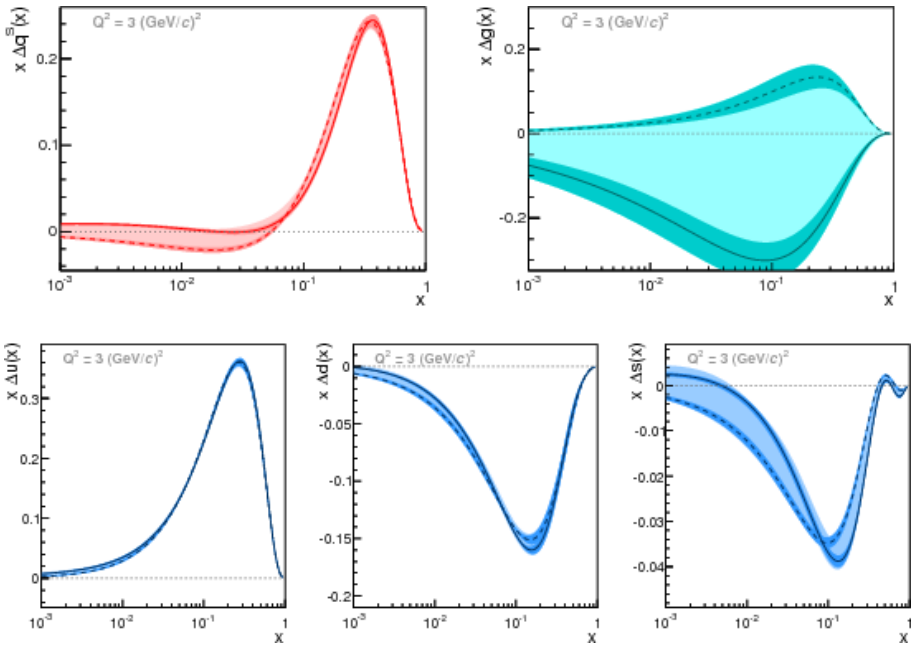
- New COMPASS point for the proton at **low x**
- **New COMPASS NLO QCD fit** describes the data well

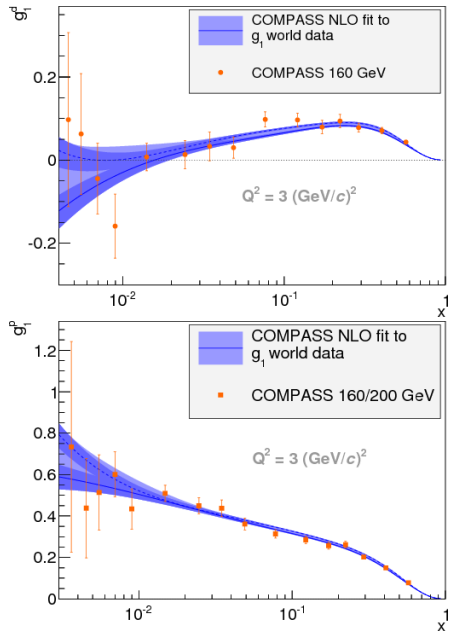
Inputs and constraints for NLO QCD fit



- 139 out of 674 points are from COMPASS
- $g_1^{p(n)} = \frac{1}{9}\left[C_S \otimes \mathbf{\Delta q_S} + C_{NS} \otimes \left(\pm\frac{3}{4}\mathbf{\Delta q_3} + \frac{1}{4}\mathbf{\Delta q_8}\right) + C_g \otimes \mathbf{\Delta g}\right]$
  - $\Delta q_S = \Delta u + \Delta d + \Delta s$ (spin singlet parton distribution)
  - $\Delta q_3 = \Delta u - \Delta d$ (triplet non-singlet spin distribution)
  - $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ (octet non-singlet spin distribution)
  - C_S, C_{NS}, C_g: Wilson coefficients associated to each distribution
- Functional forms are assumed at a given reference scale Q_0^2
- $SU(3)_f$ to fix the non-singlet distributions first moments:
  $\int_0^1 (\Delta u - \Delta d)\, dx = F + D = g_A/g_V$ and $\int_0^1 (\Delta u + \Delta d - 2\Delta s)\, dx = 3F - D$
- Positivity: $|\Delta g(x)| < |g(x)|$ and $|\Delta(s(x) + \bar{s}(x))| < |s(x) + \bar{s}(x)|$

NLO QCD fit results [PLB 753 (2016) 18]

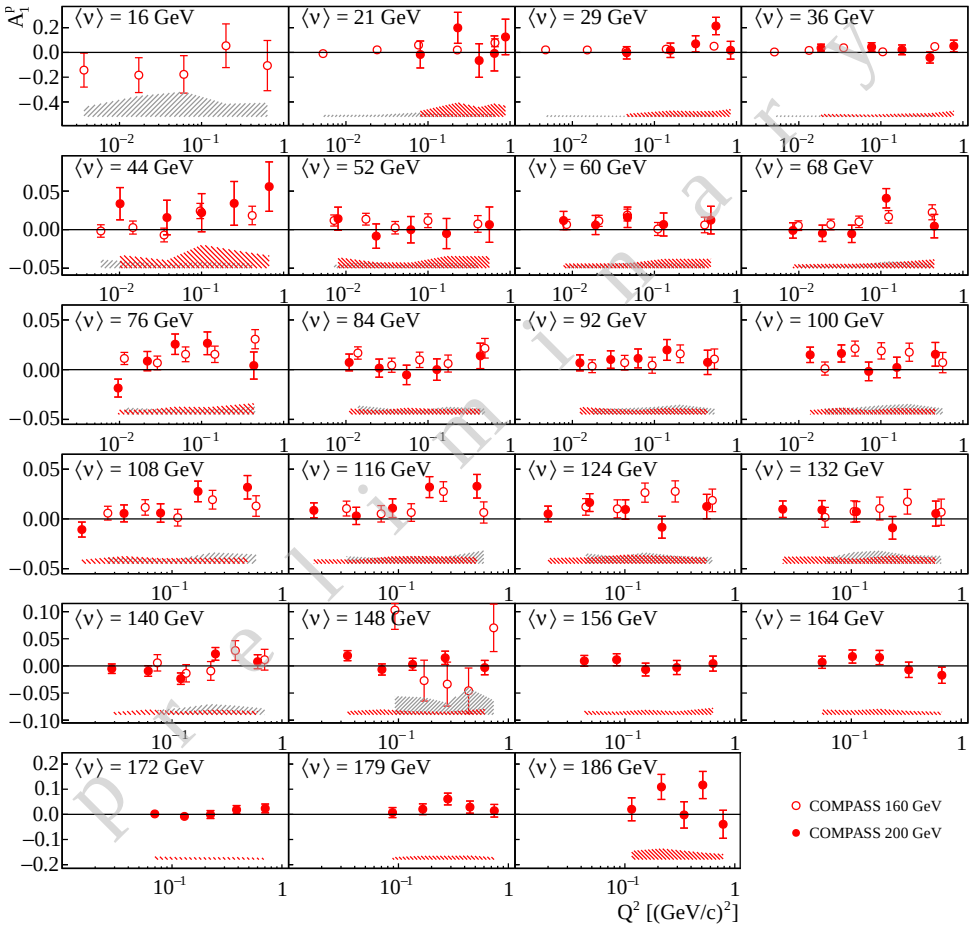


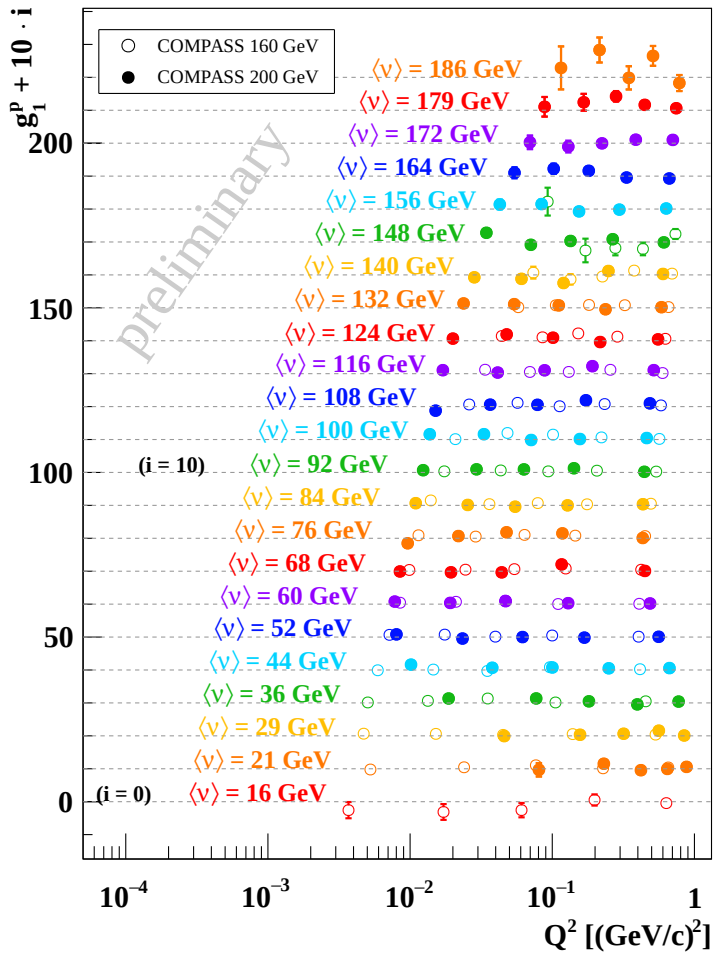


- Depending upon assumed functional forms, **2 categories of solutions**: $\Delta G > 0$ and $\Delta G < 0$
- Gluon polarisation: ΔG **not well constrained by the fit**
  $\hookrightarrow$ direct measurements needed
- Quark polarisation: $\mathbf{0.26 < \Delta\Sigma < 0.34}$ @ $Q_0^2 = 3\ (\mathrm{GeV}/c)^2$ $(\overline{\mathrm{MS}})$
  $\hookrightarrow$ largest uncertainty from functional forms
- Large uncertainty at very low x for g_1^p and g_1^d

A_1^p and g_1^p at low x and low Q^2: results for the grid (ν, Q^2)

Data: 2007&2011, $\mu^+ p \to \mu^+ X$





- **no big dependence** with ν or Q^2
- results **compatible with theoretical models** [Eur.Phys.J. C26 (2002) 45]

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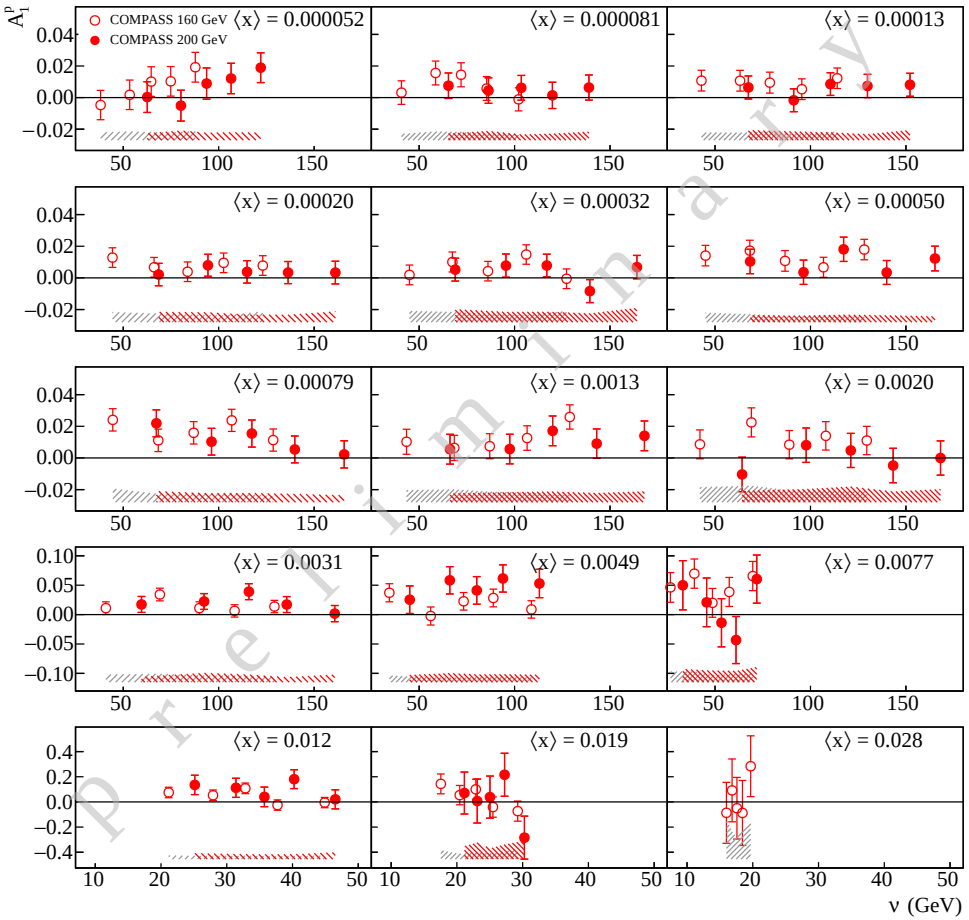
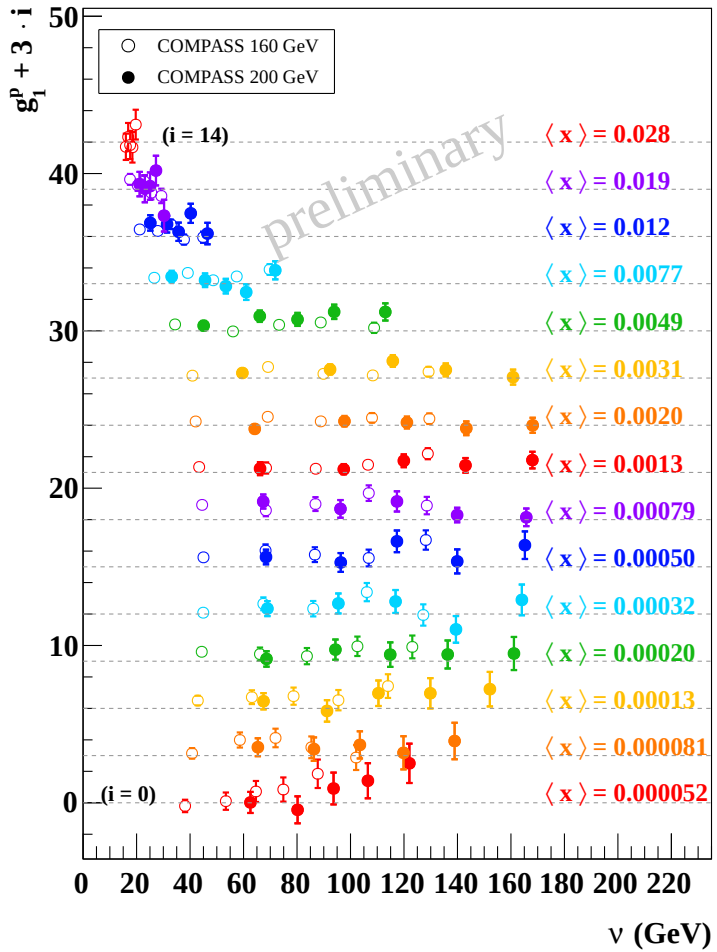
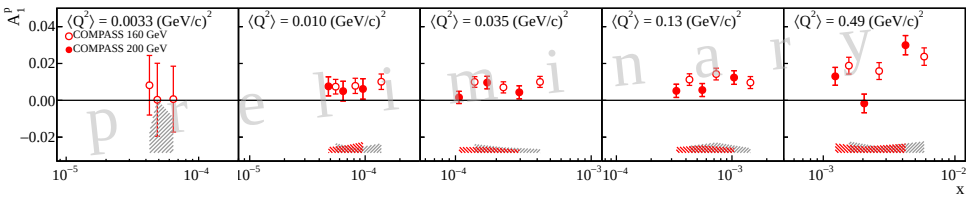


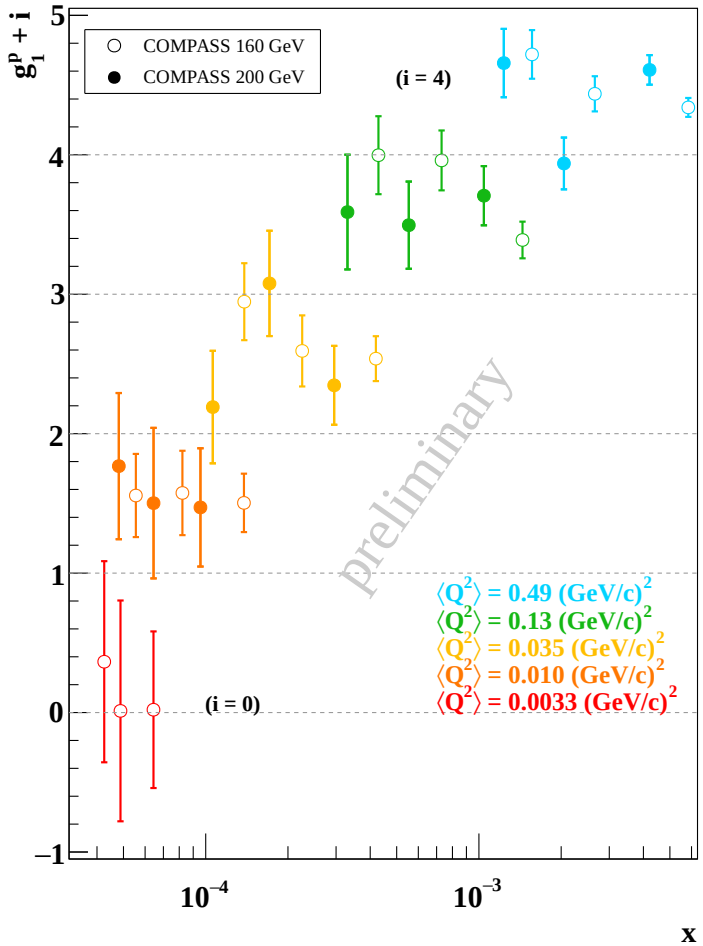


- **no big dependence** with ν or x
- results **compatible with theoretical models** [Eur.Phys.J. C26 (2002) 45]

A_1^p and g_1^p at low x and low Q^2: results for the grid (Q^2, x)

Data: 2007&2011, $\mu^+ p \to \mu^+ X$

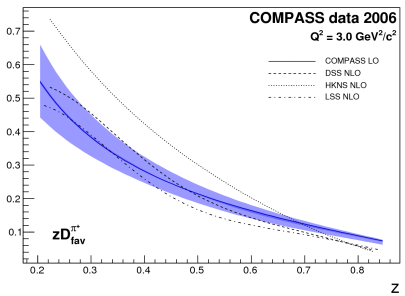


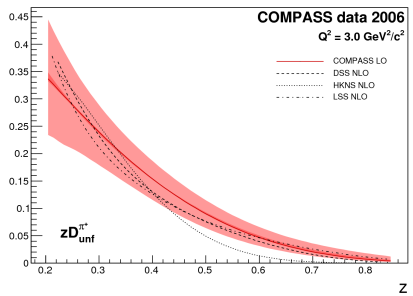


- **no big dependence** with x or Q^2
- results **compatible with theoretical models** [Eur.Phys.J. C26 (2002) 45]

Fragmentation functions: results

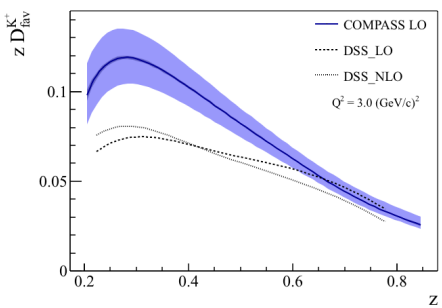
- Assuming isospin and charge symmetry:
  $\mathbf{D}_{\text{fav}}^{\pi^+} = D_u^{\pi^+} = D_{\bar{d}}^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-}$ $\qquad$ $\mathbf{D}_{\text{unf}}^{\pi^+} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_u^{\pi^-} = D_{\bar{d}}^{\pi^-}$
- Assuming $D_s^{\pi^+} = D_s^{\pi^-} = D_{\text{unf}}^{\pi^+}$, choosing funct. forms for FFs (z) and using DGLAP.
- Fitting π^+ and π^- multiplicities allows to extract the 2 independent FFs:

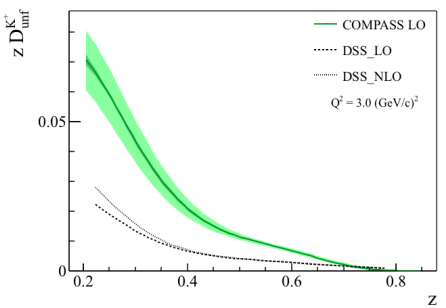




- As expected, $D_{\text{fav}}^{\pi^+} > D_{\text{unf}}^{\pi^+}$
- Results in fair agreement with DSS and LSS NLO fits (not shown)

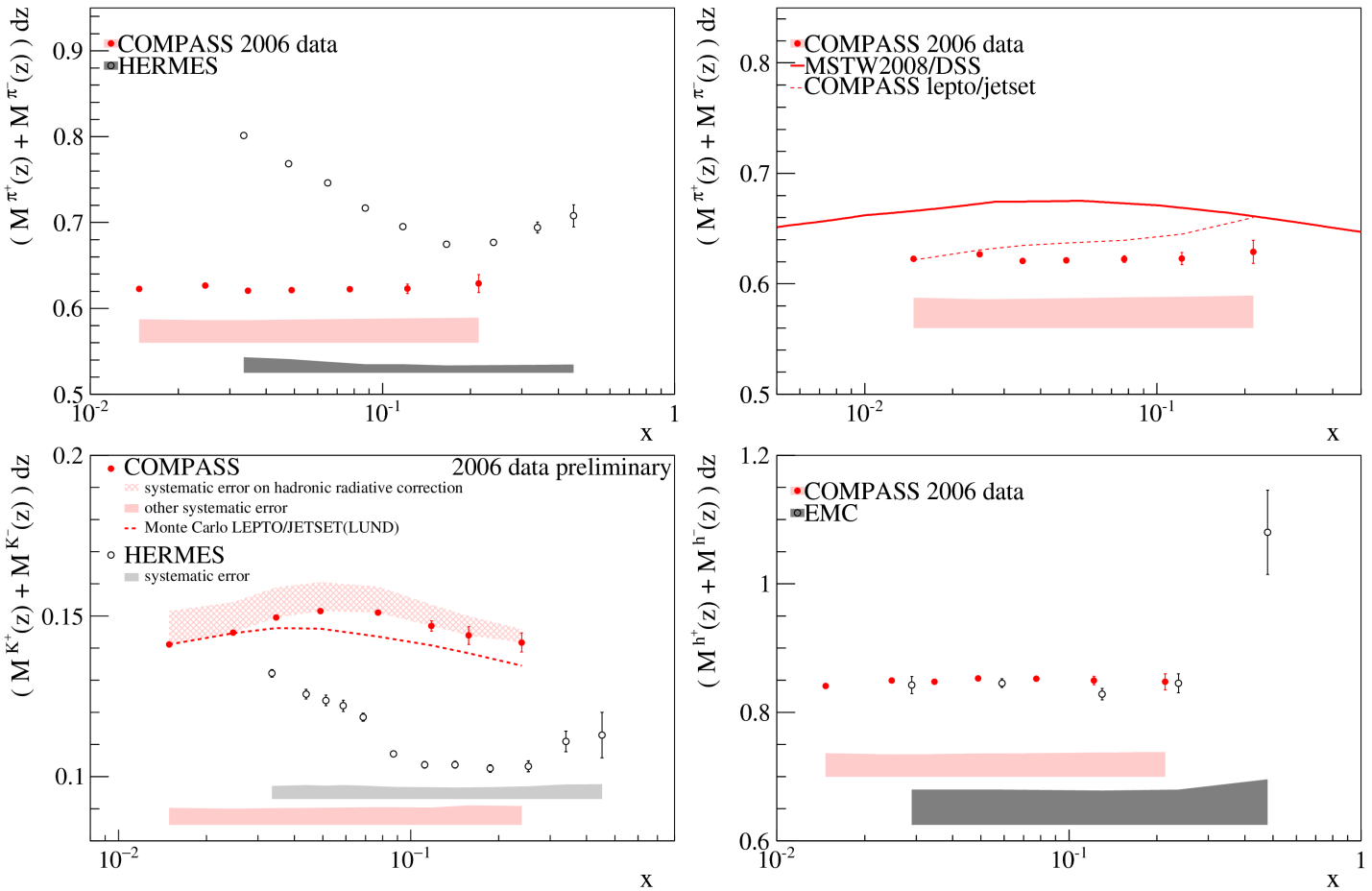
- Assuming isospin symmetry and 3 independent quark FFs: D_{fav}, D_{unf}^K, D_{str}^K





- As expected, $D_{\text{fav}}^{K^+} > D_{\text{unf}}^{K^+}$
- $D_{\text{fav}}^{K^+}$ and $D_{\text{unf}}^{K^+}$ significantly larger than DSS and LSS NLO fits (which do not include these kaon data)
- Results for D_{str}^K not shown. Unstable, depends on choice of functional form

Hadron multiplicities: comparison with HERMES



- The discrepancy COMPASS-HERMES is not yet understood
- Contribution by M. Stolarski, *Comment on "Reevaluation of the parton distribution of strange quarks in the nucleon"* [PRD 92 (2015) 098101]