Latest results on nucleon spin and QCD fits from COMPASS

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on behalf of the COMPASS Collaboration

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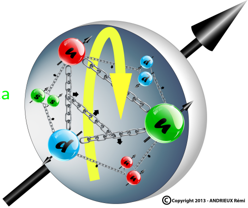
QCD@Work 2014

Outline

What is the nucleon spin made up of?

Nucleon spin $\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quarks}} + \underbrace{\Delta G}_{\text{gluon}} + \underbrace{L_g + L_q}_{\text{orbital momenta}}$



Where:

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

$\Delta q = \overrightarrow{q} - \overleftarrow{q}$

Parton spin parallel and anti-parallel to the nucleon spin

Historically: From relativistic quarks in QM: $\Delta\Sigma \sim 0.6$

In 1988, EMC measured $\Delta\Sigma = 0.12 \pm 0.17 \rightarrow$ "Spin crisis"

- $\Delta\Sigma$ unexpectedly small $\rightarrow \Delta G$ surprisingly large
- $\Delta\Sigma \approx 0.58 + 3\Delta s \rightarrow \Delta s$ is negative and large

} New era of spin physics

Covered in this talk:

→ Extraction of $\Delta\Sigma$ and ΔG via QCD fits of the spin structure functions

→ Dedicated measurements for ΔG via gluon sensitive processes

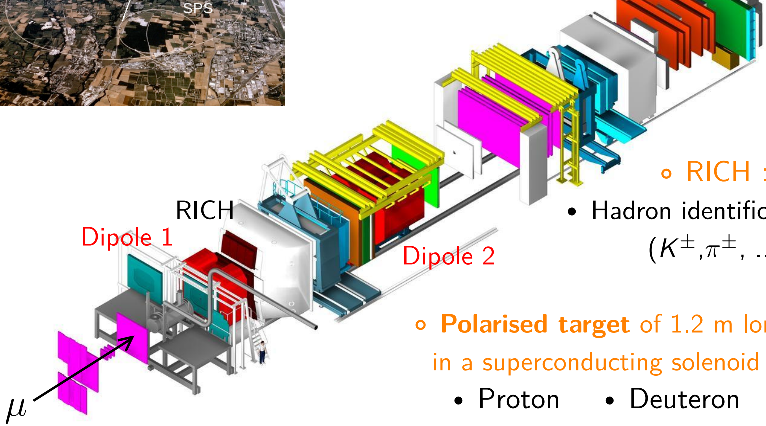
→ Extractions of inputs to improve Δs measurement

COMPASS Spectrometer

- **Polarised μ^+ beam** from CERN SPS

  200 GeV/160 GeV

  P_μ=80%

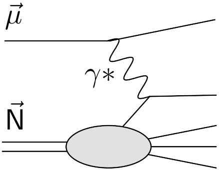


- RICH :
  - Hadron identification ($K^\pm$,$\pi^\pm$, ...)

- **Polarised target** of 1.2 m long in a superconducting solenoid
  - Proton
  - Deuteron

Polarised DIS and spin structure functions

$$\mu N \rightarrow \mu X$$



Q^2: photon virtuality (hard scale)

x: Bjorken scaling variable

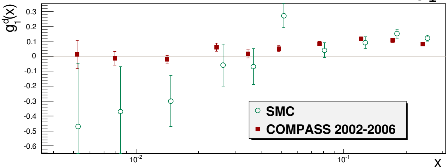
fraction of nucleon mometum carried by the struck quark

$\sigma^{inc.}_{DIS} \propto g_1$: spin structure function

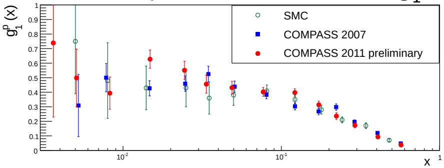
$$g_1^p(x, Q^2) \underset{LO}{=} \frac{1}{2} \sum_q e_q^2 (\Delta q(x) + \Delta \bar{q}(x))$$

COMPASS legacy including lattest 200 GeV data

Deuteron spin structure function g_1^d



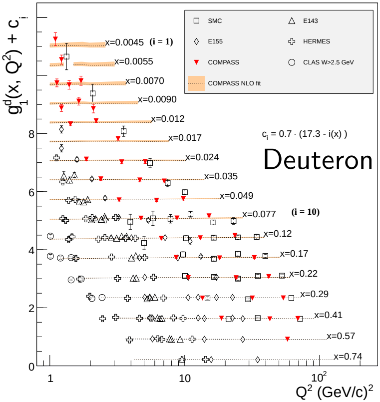
Proton spin structure function g_1^p

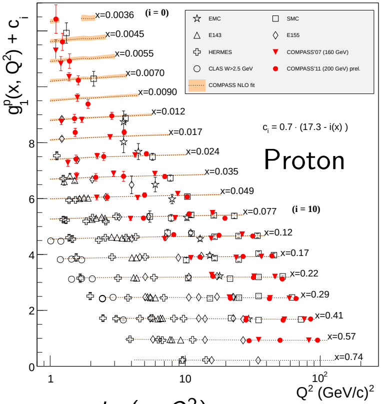


Improved statistical precision compared to previous experiment SMC:
The only two experiments in this kinematic domain

World data on spin structure functions g_1

COMPASS data extends high Q^2 and low x domain





Input for NLO QCD fit of polarised world data: $\dfrac{dg_1(x,Q^2)}{dlog(Q^2)} \propto \Delta g(x,Q^2)$

NLO QCD fit of g_1^p, g_1^n and g_1^d world data

$$g_1 \underset{NLO}{=} \frac{1}{2}\langle e^2\rangle \Big(\underbrace{C_S \otimes \Delta q_S}_{\substack{\text{singlet}\\ \Delta u+\Delta d+\Delta s}} + \underbrace{C_{NS} \otimes \Delta q_{NS}}_{\substack{\text{2 non-singlets}\\ \Delta u-\Delta d \ \&\ \Delta u+\Delta d-2\Delta s}} + \underbrace{C_g \otimes \Delta g}_{\text{gluon}}\Big)$$

$\Delta q \equiv \Delta(q + \bar{q})$

Assumptions:

- Functional forms at a Q^2 reference scale for: $\Delta q_S(x)$, $\Delta g(x)$ and $\Delta q_{NS}(x)$
- $\mathrm{SU}(3)_f$ to fix the non-singlet distribution first moments:
  $\int_0^1 \Delta u - \Delta d \, dx = F + D$
  $\int_0^1 \Delta u + \Delta d - 2\Delta s \, dx = 3F - D$

with F and D the parameters describing the weak axial-vector/vector coupling contants

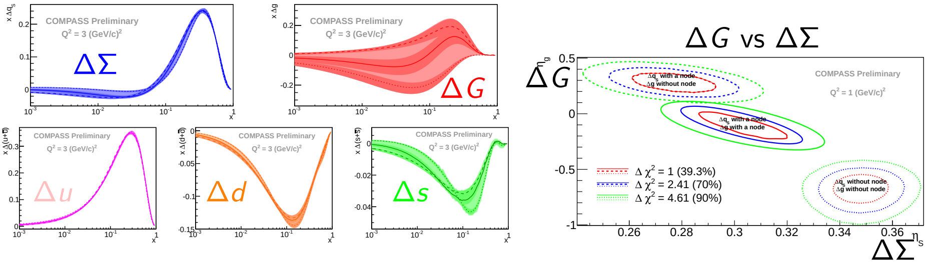
DGLAP equations:

- Evolution of the polarised PDF to the Q^2 of the data points

$\Rightarrow$ Fit the spin structure functions to the data

Polarised parton distribution functions

Depending upon assumed fonctional forms, 3 categories of solutions:
$\Delta G > 0$, $\Delta G \sim 0$ and $\Delta G < 0$



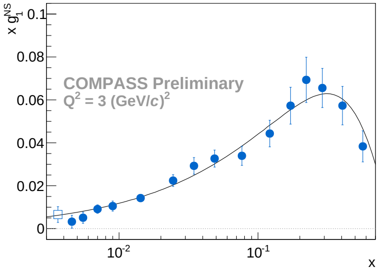
- 0.26< $\Delta\Sigma$ <0.34 at $Q^2 = 3$ (GeV/c)^2 ($\overline{\text{MS}}$)
  → Largest uncertainty coming from the choice of functional forms
- ΔG not much constrained by DIS data alone
  → Direct measurements needed (RHIC spin, COMPASS)

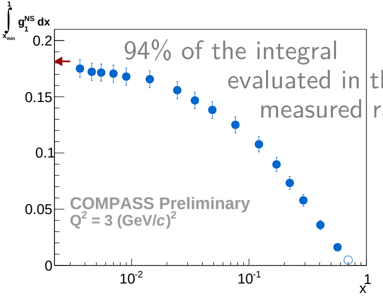
Bjorken sum rule

Fundamental QCD prediction relating p and n:

$$\int_0^1 g_1^p - g_1^n dx = \frac{1}{6} C^{NS}(\alpha_s) \frac{g_A}{g_V}$$

- Test of $SU(2)_{flavour}$
- Decorrelated from ΔG





94% of the integral evaluated in the measured range

From COMPASS data alone:

$$\boldsymbol{g_A/g_V|_{NLO} = 1.220 \pm 0.052 \pm 0.095}\ \textbf{(prel.)} \qquad g_A/g_V|_{NNLO} = 1.251$$

PDG: $g_A/g_V|_\beta = 1.2701 \pm 0.0025$

Better statistics and systematics compared to previous COMPASS determination

Dedicated measurements to constrain ΔG

Same data, semi-inclusive channels:

Extract $\langle \Delta g \rangle$ directly:

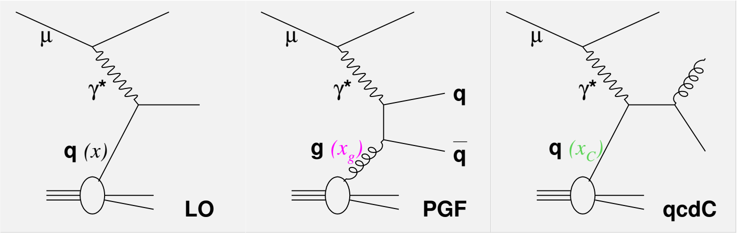
- Based on Monte-Carlo generator with Lund fragmentation
- Channels studied at COMPASS:
  - **Production of charged hadron at high p_T (LO)**
  - Open charmed mesons production (LO & NLO not shown)

Supply Δg sensitive measurements to global fits:

- pQCD calculation with collinear fragmentation
- Channel studied at COMPASS:
  - **Photo-production of charged hadrons at high p_T (NLO)**

Δg at LO from high-p_T hadron production in DIS

Double spin asymmetry of hadron production cross-section comprises 3 subprocesses:



$$A_{LL}^{h}(x_{Bj}) \underset{LO}{=} R_{PGF}\, a_{LL}^{PGF}\, \Delta g/g(x_g) + \underbrace{R_{LP}\, D A_1^{LO}(x_{Bj}) + R_{QCDC}\, a_{LL}^{QCDC}\, A_1^{LO}(x_C)}_{background}$$

R_i Fraction of the process; a_{LL}^{i} partonic cross-section asymmetry

R_i and a_{LL}^{i} are extracted from MC and parametrised by Neural Network

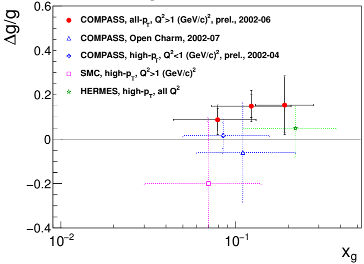
Signature for Photon Gluon Fusion (PGF) via high p_T hadrons (R_{PGF} ~30%)

Δg at LO from high-p_T hadron production in DIS

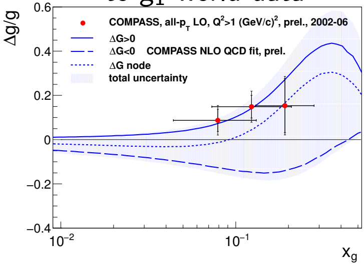
DIS 2014, M. Stolarsky

- COMPASS high-p_T hadron production compared to:

Direct extractions of $\Delta g/g$ at LO: World data



COMPASS NLO QCD fit to g_1 world data



$\Delta G > 0$
$\Delta G \sim 0$
$\Delta G < 0$

$\langle \Delta g/g \rangle = 0.113 \pm 0.035 \pm 0.035$ (Prel.) for $x_g \in [0.04, 0.28]$

- The smallest stat.+syst. uncertainty among LO direct extractions
- In agreement with COMPASS NLO QCD fit and DSSV arχiv:1404:4293
- Favours ΔG>0 or ~ 0
- Δg is small in the measured range

Δg at NLO from high-p_T hadron photoproduction

Double spin asymmetry of hadron production cross-section:
NLO interpretation available for:

- Single hadron at high p_T
- Photoproduction regime ($Q^2 < 1 (\mathrm{GeV/c})^2$)

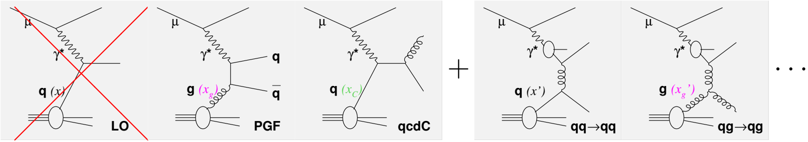
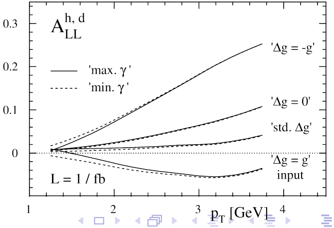
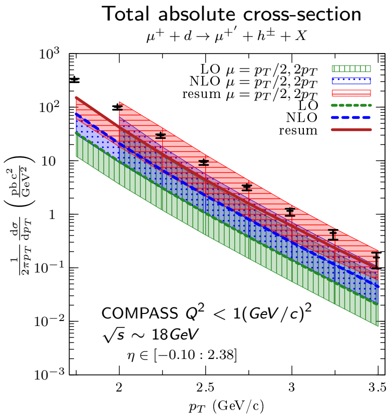


Illustration of the sensitivity to Δg for 4 pPDF scenarii (GRSV)

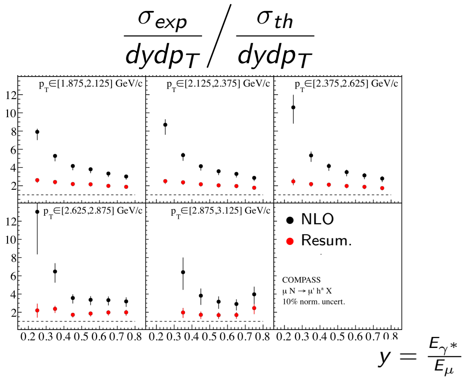


B. Jäger *et al.* EPJC 44 (2005) 533

Hadron photoproduction cross-section



COMPASS, PRD 88 (2013) 091101
D. de Florian *et al.*, PRD 88 (2013) 014024



- Data/Theory in agreement over 4 orders of magnitude
- No dependence on y after gluon resummation

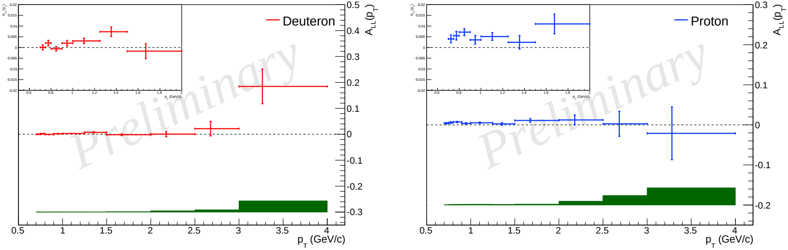
→ Validates the applicability of the theory framework for ΔG

Single hadron photoproduction asymmetry $A_{LL}(p_T)$

DIS 2014, M. Levillain

COMPASS polarised data $\sim$ 4 fb^{-1}

Spin asymmetry $A_{LL}(p_T)$



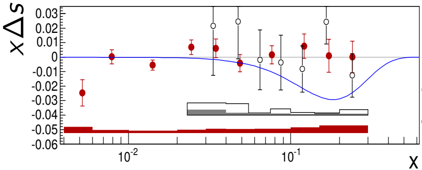
- New inputs for QCD fits
- Waiting for gluon resummation before concluding on Δg

Work in progress

Strange quark polarisation: Δs puzzle

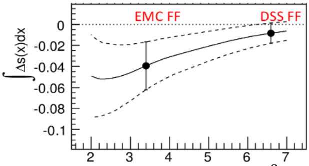
Inclusive DIS channel:
$\int_0^1 g_1\, dx$ with SU(3)$_f$
$\Delta s \simeq -0.8$

Semi-inclusive DIS channel:
Quark fragmentation functions needed
$\Delta s(x) \sim 0$ for 0.003<x<0.3



Possible explanations:

- **Lack of knowledge on fragmentation functions:** $D_s^K \rightarrow$
- No data at very low x
- SU(3)$_f$ breaking ?



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

COMPASS, PLB 693 (2010) 227-225

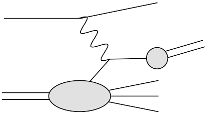
Quark fragmentation functions (FF)

Universal quantities modelling the process of hadronisation

$\rightarrow$ Accessible through several reactions

COMPASS: Hadron multiplicity measurements in SIDIS reaction

$\mu d \rightarrow \mu h X$



$$M^h(x, Q^2, z) = \frac{d\sigma^h/dz}{d\sigma^{DIS}}$$

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

Hadrons tag the quark flavour

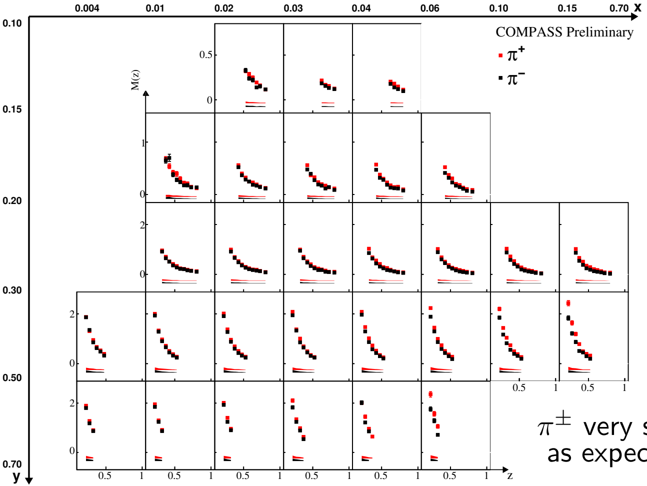
$z = \frac{E_h}{E_{\gamma *}}$: fractional hadron energy

M^π and M^K $\rightarrow$ Inputs to global QCD analyses to extract quark FF

Pion multiplicities $M^{\pi^\pm}$

DIS 2013, N. Makke

$\sim$ 500 data points in a 3D wide kinematic domain



$\pi^\pm$ very similar as expected

Extraction of quark FF into pions

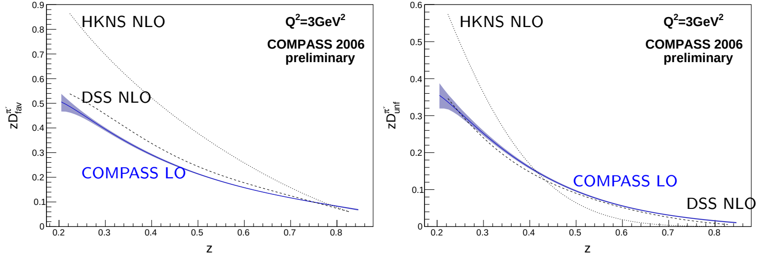
DIS 2014, N. Dufresnes

Fit of $M^h(x, Q^2, z) \underset{LO}{=} \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$

Assumptions:

- $D^{\pi}_{fav} = D^{\pi^+}_{u} = D^{\pi^+}_{\bar{d}} = D^{\pi^-}_{b} = D^{\pi^-}_{\bar{u}}$
- $D^{\pi}_{unf} = D^{\pi^+}_{d} = D^{\pi^+}_{\bar{u}} = D^{\pi^-}_{u} = D^{\pi^-}_{\bar{d}}$ and with $D^{\pi}_{unf} = D^{\pi^+}_{s} = D^{\pi^-}_{s}$
  $\rightarrow$ 2 independent FF into π

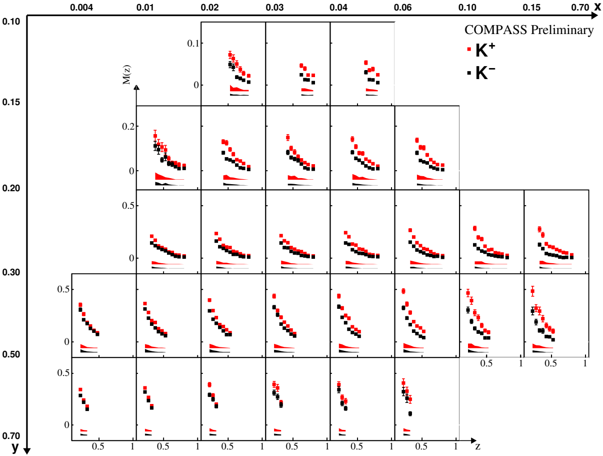
D^{π}_{fav} D^{π}_{unf}



Agreement as expected of FF from LO fit of COMPASS data alone and DSS NLO fit

Kaon multiplicities $M^{K^{\pm}}$

$\sim$ 500 data points in a 3D wide kinematic domain



To be included in a QCD fit to extract the coveted D_s^K

Conclusion and Outlook

- Improved precision on g_1^p and g_1^d by at least a factor of $\sim$3 compared to the previous experiment SMC
- Verification of the Bjorken sum rule at 4%
- $\langle \Delta g(x) \rangle |_{LO} > 0$ at $\sim 3\sigma_{stat}$ in hadron high-p_T measurement

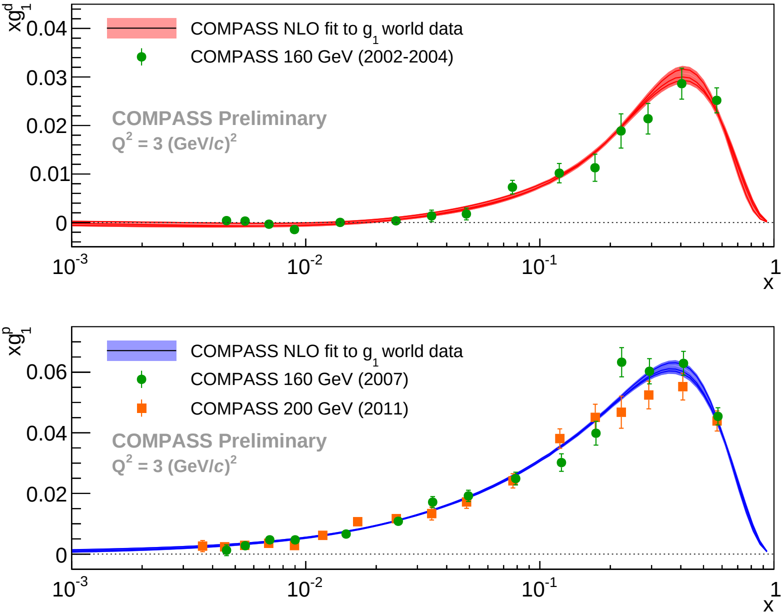
◦ NLO Δg extraction via $A_{LL}(p_T)$ in photoproduction (in progress)

◦ Quark fragmentation function extractions from pion and kaon multiplicities

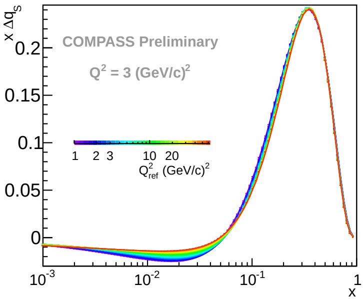
Future of COMPASS (2014-2017):

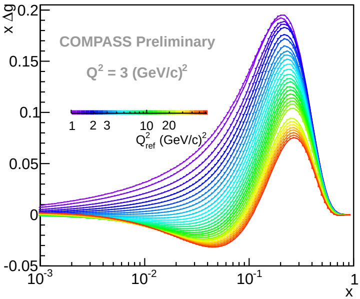
$\Rightarrow$ TMDs via polarised Drell-Yan reaction
$\Rightarrow$ GPDs via Deeply virtual Compton scattering

BACKUP



xg_1^d
0.04
0.03
0.02
0.01
0
COMPASS NLO fit to g_1 world data
COMPASS 160 GeV (2002-2004)
COMPASS Preliminary
Q^2 = 3 (GeV/c)^2
10^{-3}
10^{-2}
10^{-1}
1
x
xg_1^p
0.06
0.04
0.02
0
COMPASS NLO fit to g_1 world data
COMPASS 160 GeV (2007)
COMPASS 200 GeV (2011)
COMPASS Preliminary
Q^2 = 3 (GeV/c)^2
10^{-3}
10^{-2}
10^{-1}
1
x


COMPASS Preliminary
Q2 = 3 (GeV/c)2
1 2 3 10 20
Q2ref (GeV/c)2
x Δqs
0.2
0.15
0.1
0.05
0
10-3
10-2
10-1
1
x


COMPASS Preliminary
Q2 = 3 (GeV/c)2
1 2 3 10 20
Q2ref (GeV/c)2
x Δg
0.2
0.15
0.1
0.05
0
-0.05
10-3
10-2
10-1
1
x

$\Delta\Sigma$ evolution with Q^2

$$
\begin{aligned}
\Delta\Sigma &\in [0.264,\ 0.356] \text{ at } Q^2 = 1\ (GeV/c)^2 \\
\Delta\Sigma &\in [0.256,\ 0.335] \text{ at } Q^2 = 3\ (GeV/c)^2 \\
\Delta\Sigma &\in [0.258,\ 0.299] \text{ at } Q^2 = 10\ (GeV/c)^2
\end{aligned}
$$