# Longitudinal spin physics at COMPASS

**Eva-Maria Kabuß,**
Institut für Kernphysik,
Mainz University
**on behalf of the COMPASS collaboration**

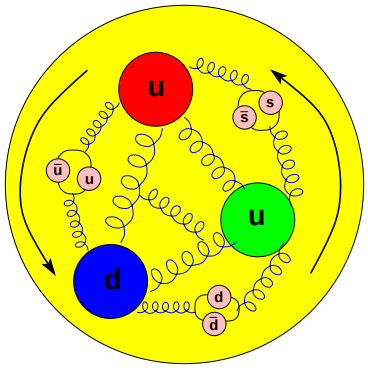
**International school on nuclear physics**
**33rd Course**
**From Quarks and Gluons to Hadrons**
**Erice, 16.9. – 24.9.2011**

bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# The spin of the nucleon

$$S_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$



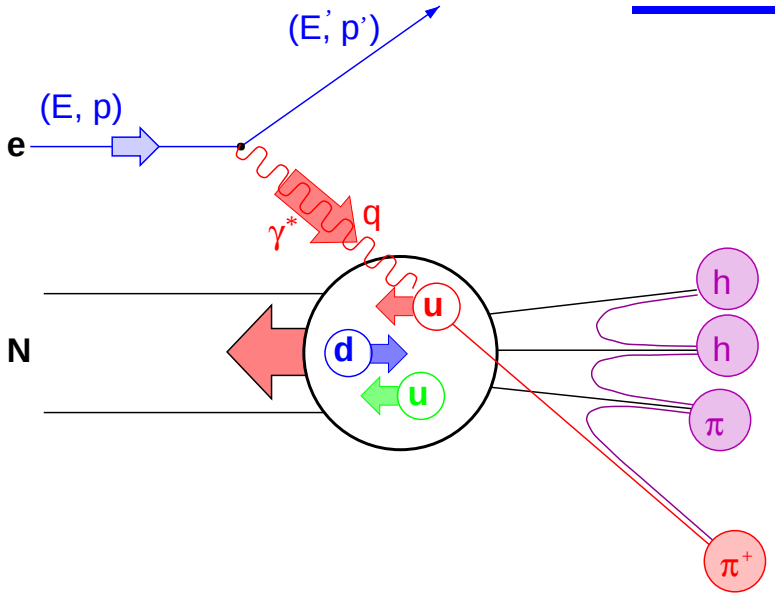

**Accessible in**

| | |
|---|---|
| $\Delta\Sigma$, $\Delta s$ | inclusive DIS |
| $\Delta u$,$\Delta d$,$\Delta s$ | semi-inclusive DIS |
| $\Delta G$ | PGF in DIS |
| $L_q$ | DVCS |

**Content**

- COMPASS experiment
- Longitudinal asymmetries
- Spin structure functions
- Flavourseparation
- Gluon polarisation

# Deep inelastic scattering




$$Q^2 = -q^2 \qquad z = E_\mathrm{h}/\nu$$

$$\nu = E - E' \qquad p_\mathrm{T}^\mathrm{h} : \text{transverse}$$

$$x = Q^2/2M\nu \qquad \text{momentum}$$

$$q(x) = q(x)^+ + q(x)^- \quad + \text{quark} \uparrow\uparrow \text{nucleon}$$

$$\Delta q(x) = q(x)^+ - q(x)^- \quad - \text{quark} \downarrow\uparrow \text{nucleon}$$

- **photon nucleon asymmetry**

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\Sigma_q\ e_q^2\ (q(x)^+ - q(x)^-)}{\Sigma_q\ e_q^2\ (q(x)^+ + q(x)^-)} = \frac{g_1(x)}{F_1(x)}$$

- **spin structure function**

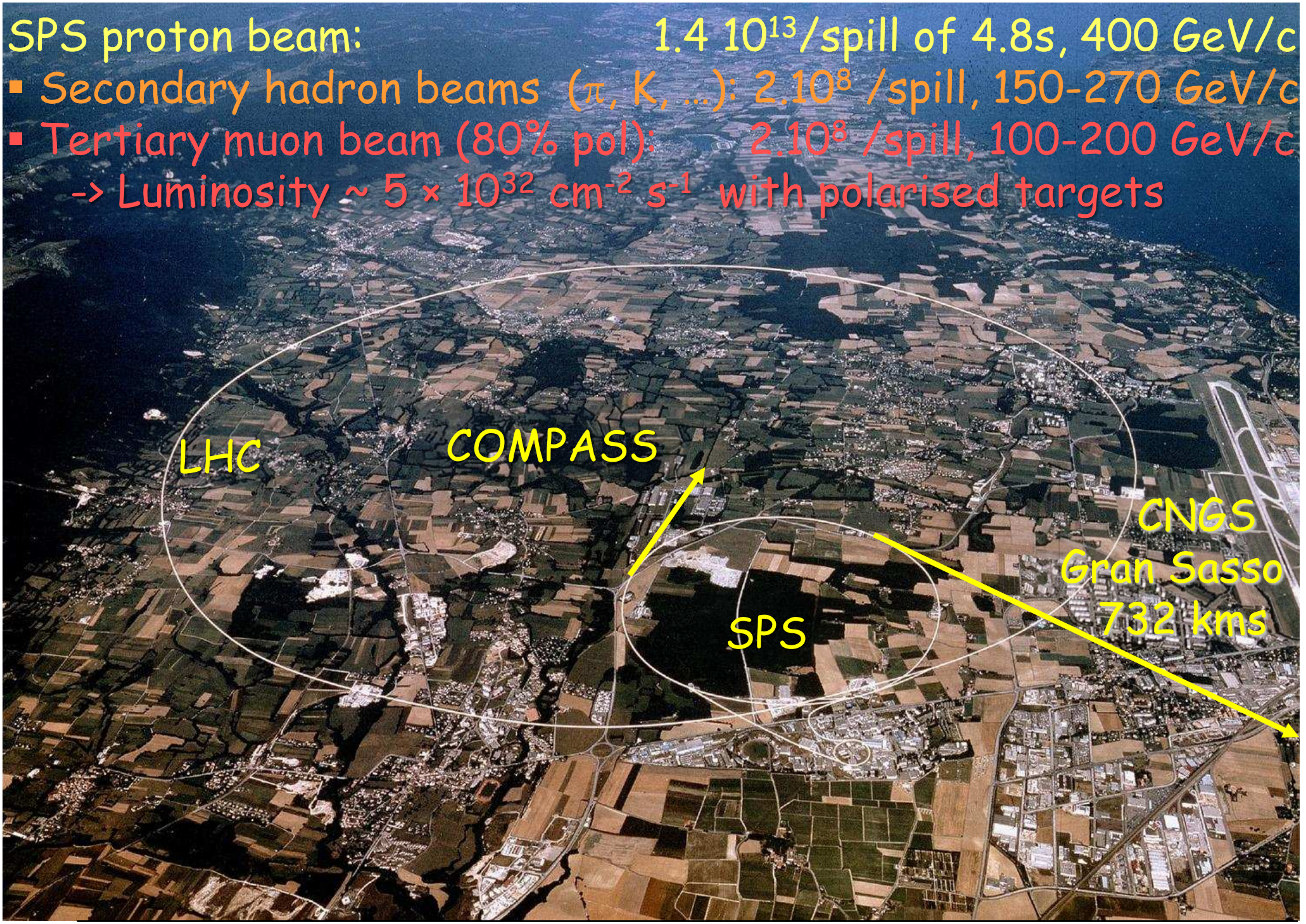
$$g_1 = \frac{1}{2}\Sigma_q\ e_q^2\ \Delta q(x) = A_1 \cdot \frac{F_2}{2x(1+R)} \approx \frac{A_\parallel}{D} \cdot \frac{F_2}{2x(1+R)}$$

# COMPASS at CERN

SPS proton beam: 1.4 $10^{13}$/spill of 4.8s, 400 GeV/c

- Secondary hadron beams ($\pi$, K, …): 2.$10^{8}$ /spill, 150-270 GeV/c
- Tertiary muon beam (80% pol): 2.$10^{8}$ /spill, 100-200 GeV/c

  -> Luminosity ~ 5 × $10^{32}$ $cm^{-2}$ $s^{-1}$ with polarised targets



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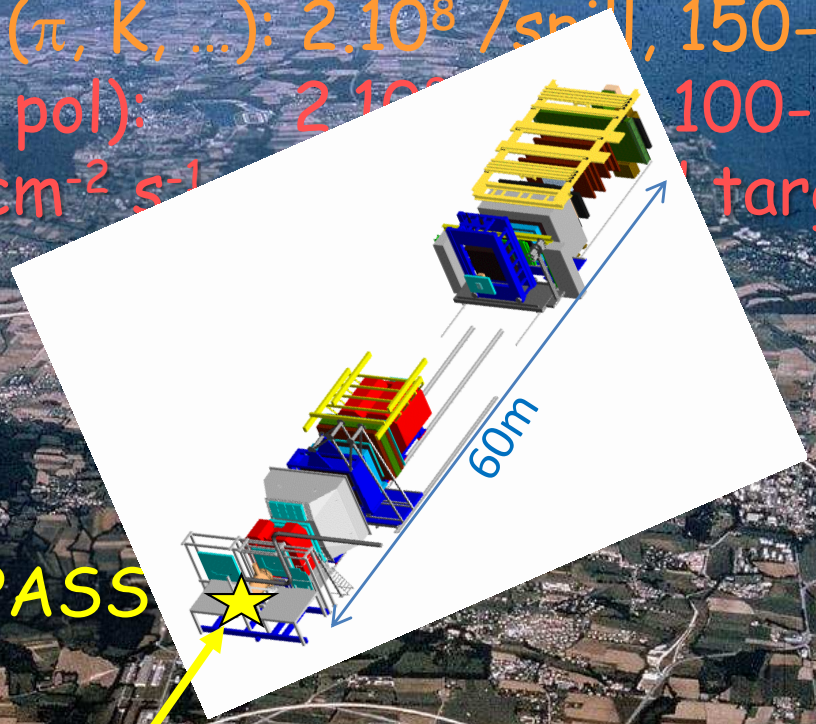



LHC

COMPASS

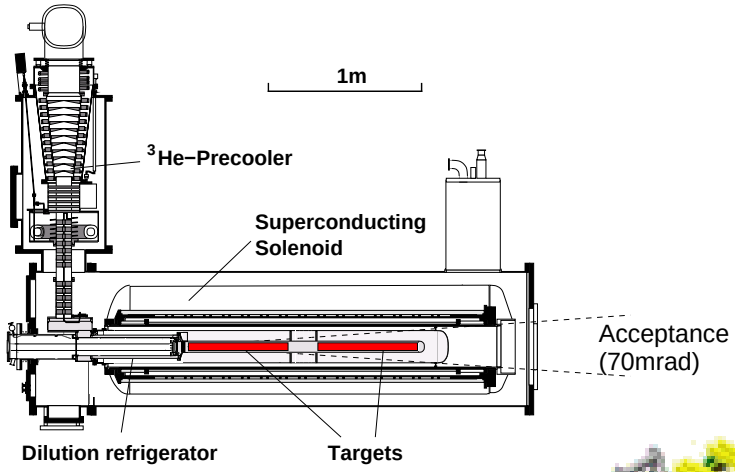
SPS

CNGS
Gran Sasso
732 kms

high energy beam(s), broad kinematic range, large angular acceptance

# COMPASS spectrometer

## Polarised target







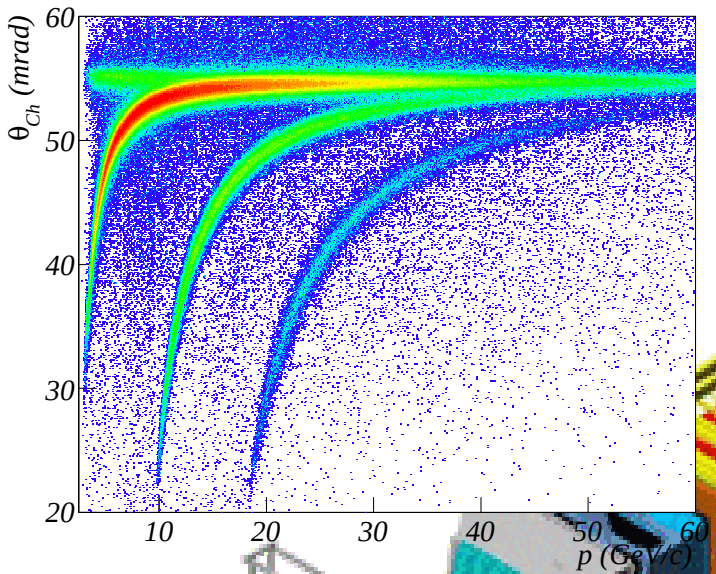
target material: $^6$LiD, $NH_3$
polarisation: 50%, 90%

## Spectrometer

- Two magnets (1 Tm, 4.5 Tm)
- Tracking ($p > 0.5$ GeV/c):
  SciFi, Silicon, MicroMega, GEM, MWPC, Drift, Straws, Driftubes
- PID: $\pi$, $K$, $p$ (RICH)
  above 2, 9, 18 GeV/c
- ECAL, HCAL, muon filter

# COMPASS spectrometer

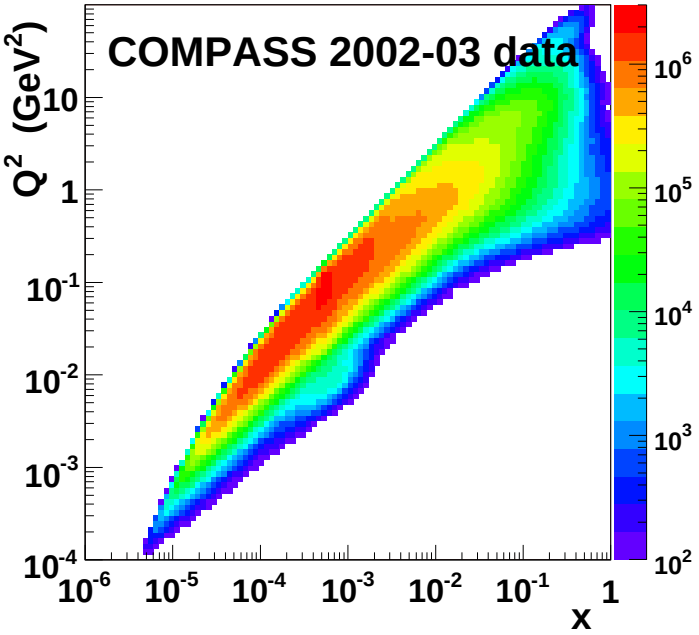
## Particle Id.







## Acceptance

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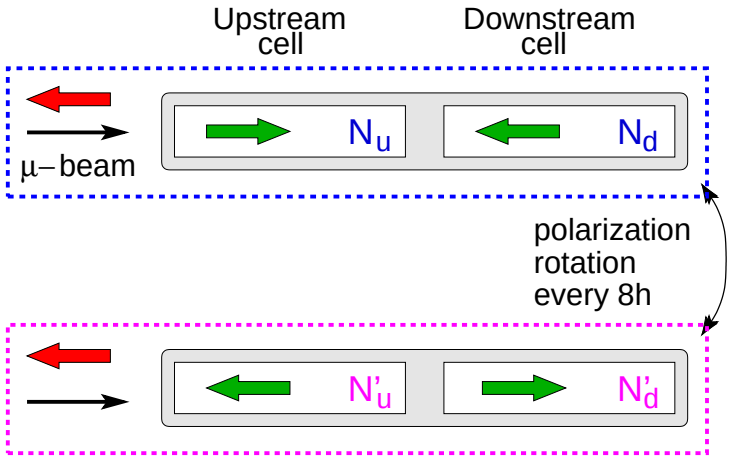
# Method

- **to be measured:**

$$A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$




- **flux normalization:**

$$A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d}$$

- **acceptance difference:**
  Polarisation rotation

- **take average asymmetry:**

$$\Rightarrow A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

  $\Rightarrow$ minimization of bias

- **experimental asymmetry**

$$A_{\text{exp}} = p_\mu \; p_{\text{T}} \; f \; A_{\parallel}$$

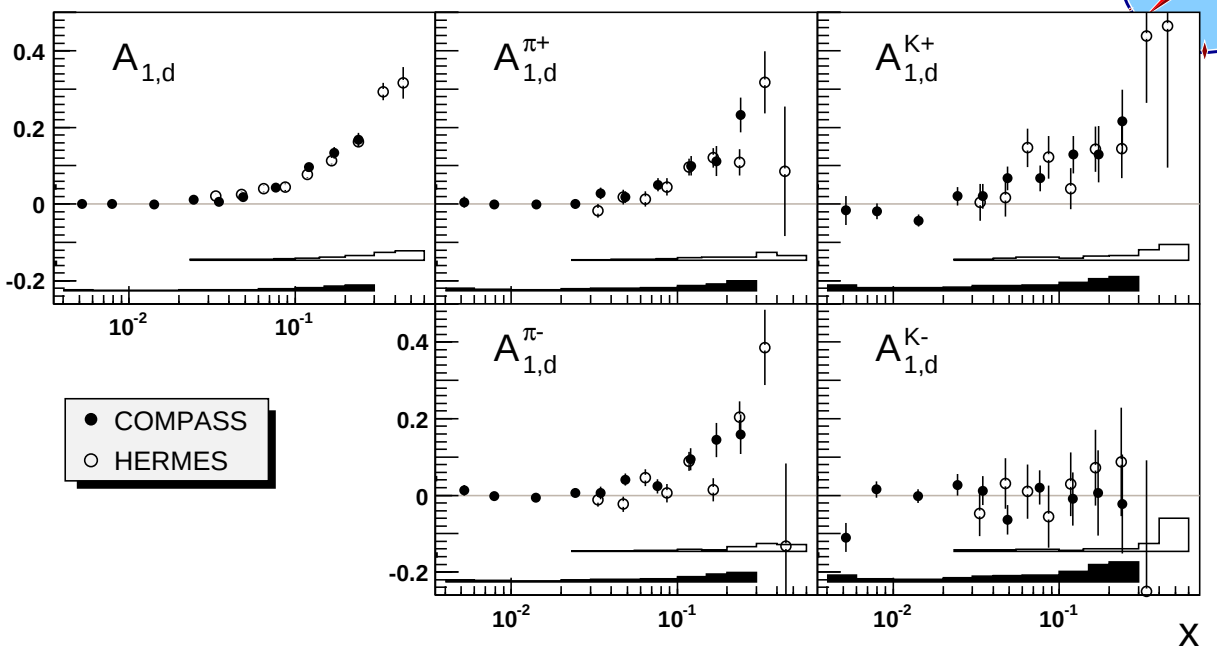
$p_\mu$, $p_{\text{T}}$ beam and target polarisation
$f$ dilution factor

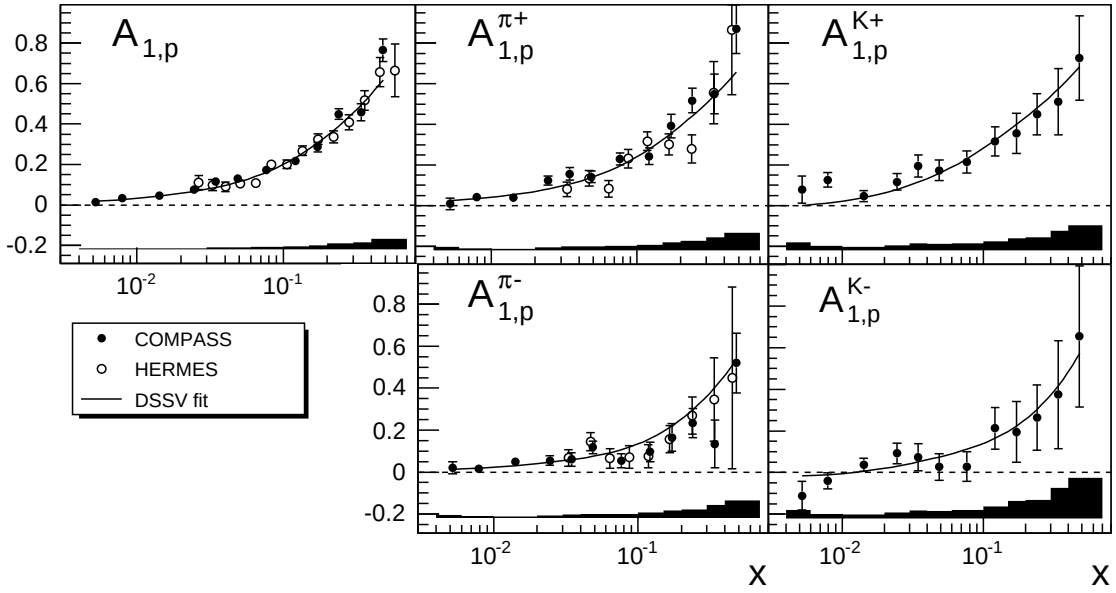
# Asymmetries

# Deuteron and Proton asymmetries

- **Kinematic domain:**

$Q^2 > 1\ (\mathrm{GeV}/c)^2$
$0.1 < y < 0.9$
$0.2 < z < 0.85$
$0.004 < x < 0.7$ DIS
$0.004 < x < 0.3$ SIDIS

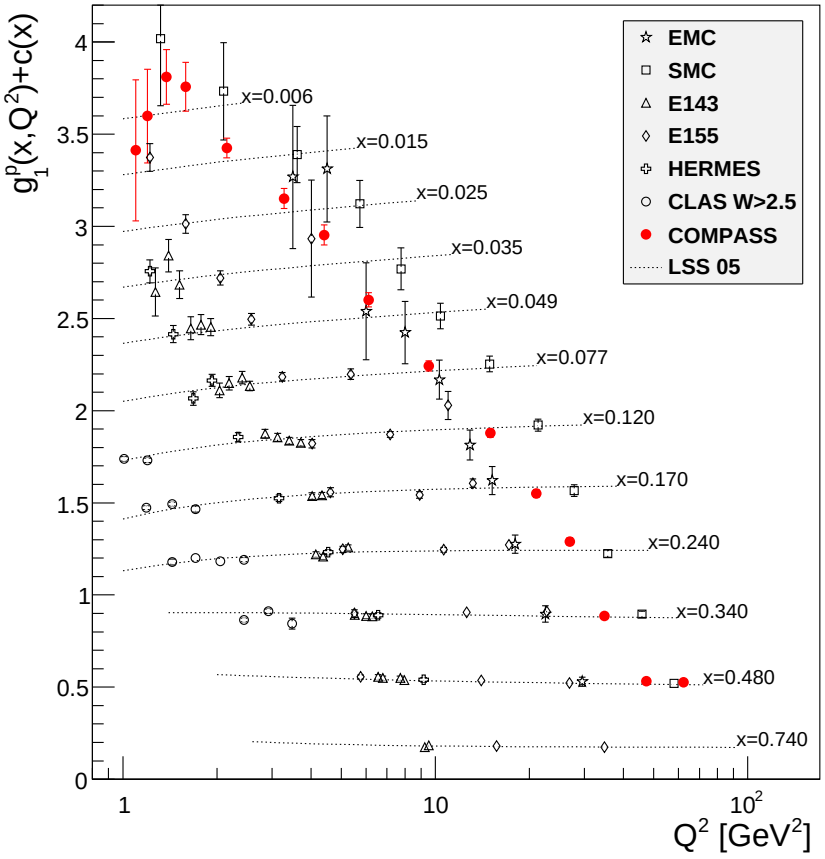


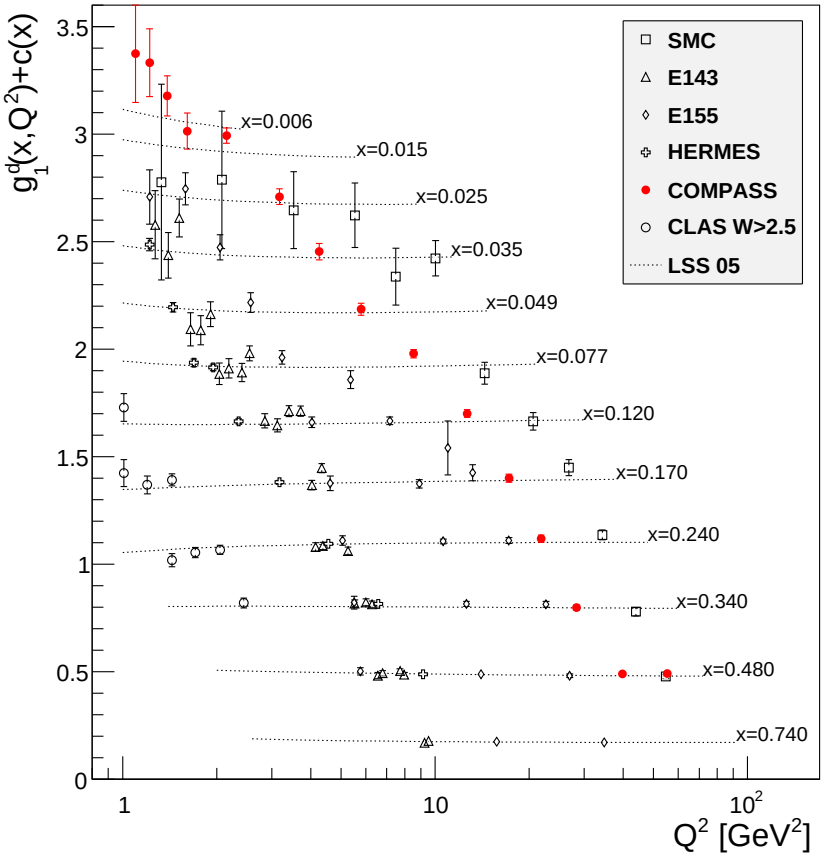

- **Deuteron**: 2002–2006
  PLB 647 (2007) 8, 680 (2009) 217
- **Proton**: 2007
  PLB 690 (2010) 466, 693 (2010) 227
- Identified pions and kaons

# World data on $g_1(x, Q^2)$

## Proton




## Deuteron




## pQCD analyses

- $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ well constrained by data (LSS PRD 80 (2009) 054026)
- $\Delta s$ and $\Delta g$ need other data in addition to inclusive data
- $\Delta s$ comes out negative
- $|\boldsymbol{\Delta G}|$ is small $(< 0.5)$ $\Longrightarrow$ **direct measurement needed**

# First moment of $g_1^{\mathrm{d}}$


## Can one learn something without pQCD fits?

- **First moment of $g_1^{\mathrm{d}}$** (at $Q^2 = 3(\mathrm{GeV/c})^2$)

$$\Gamma_1^{\mathrm{N}} = \int_0^1 \frac{g_1^{\mathrm{d}}(x)}{1 - 1.5\omega_{\mathrm{D}}}\,\mathrm{d}x = 0.0502 \pm .0028(\mathrm{stat}) \pm .0020(\mathrm{evol}) \pm .0051(\mathrm{syst})$$

  - data used in measured range, QCD fit used for extrapolation
  - contribution of unmeasured region few %

- **using**: $a_0^{\overline{\mathrm{MS}}} = \Delta\Sigma$ and $\Gamma_1^{\mathrm{N}} = \frac{1}{9}(a_0 \Delta C_{\mathrm{S}}^{\overline{\mathrm{MS}}} + \frac{1}{4} a_8 \Delta C_{\mathrm{NS}}^{\overline{\mathrm{MS}}})$

$$\Delta\Sigma(Q^2 = 3(\mathrm{GeV/c})^2) = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

- **assuming SU(3) symmetry**: $(\Delta s + \Delta\bar{s}) = \frac{1}{3}(a_0 + a_8)$

$$(\Delta s + \Delta\bar{s}) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

  - negative strange sea polarisation

## Is this supported by direct measurements?

# Flavour separation

# Flavour separation

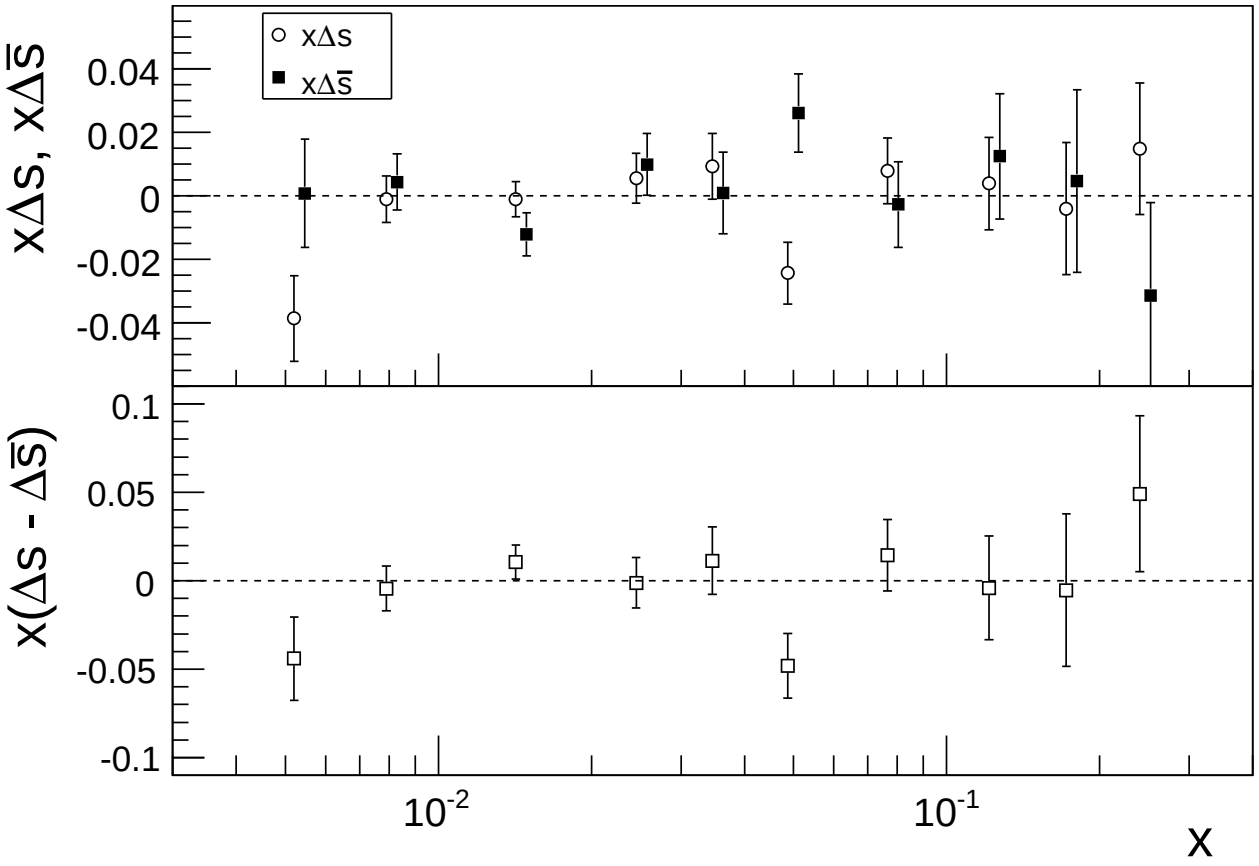
- **SIDIS**

$$A_1^h = \frac{\Sigma_q e_q^2 (\Delta q(x) \int D_q^h(z) \mathrm{d}z}{\Sigma_q e_q^2 q(x) \int D_q^h(z) \mathrm{d}z}$$

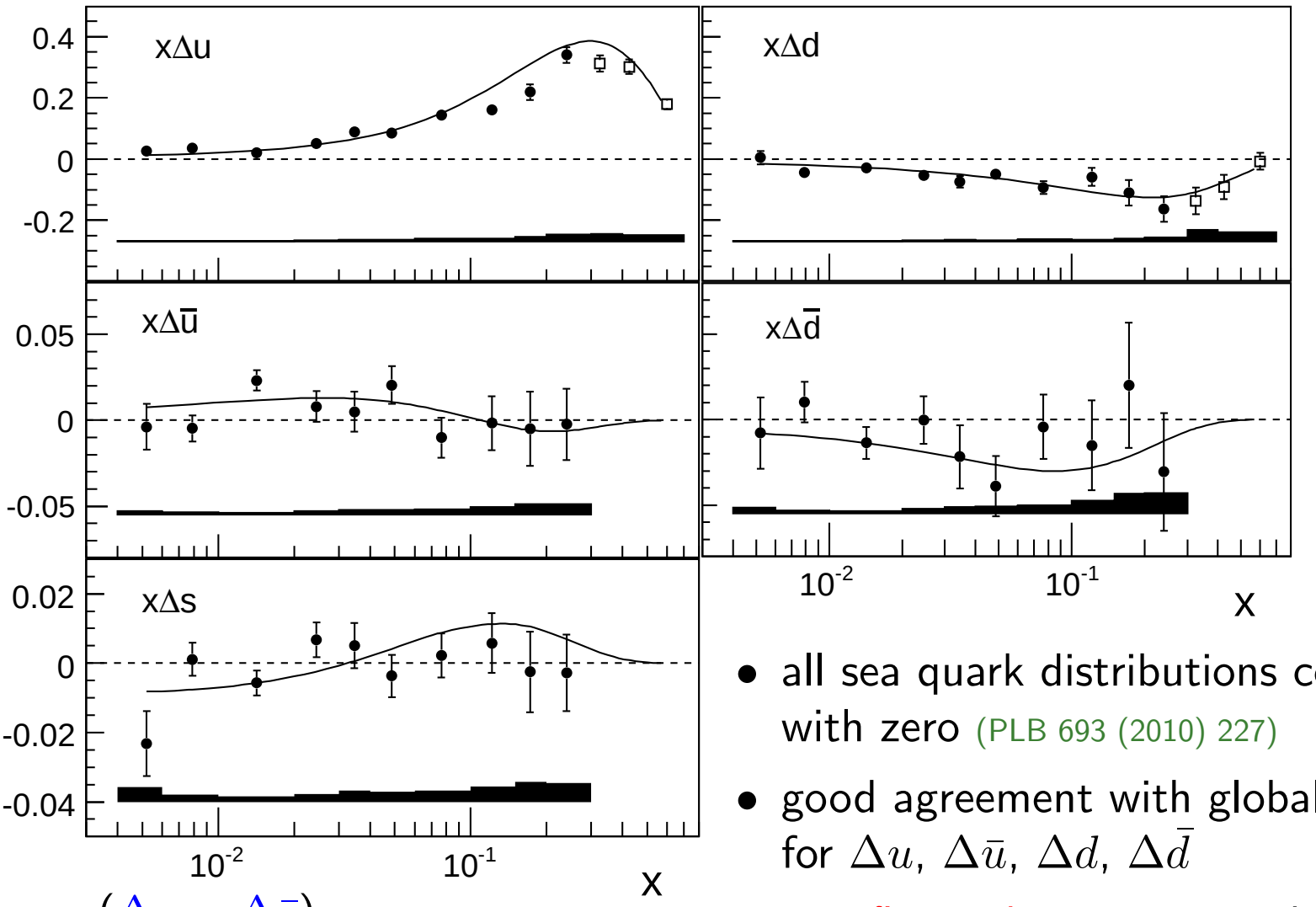
- **measured**:
  $A_1^{\mathrm{d}}$, $A_{1\mathrm{d}}^{K^\pm}$, $A_{1\mathrm{d}}^{\pi^\pm}$, $A_1^{\mathrm{p}}$, $A_{1\mathrm{p}}^{K^\pm}$, $A_{1\mathrm{p}}^{\pi^\pm}$

- **inputs**: MRST04 unpolarised LO PDFs, DSS parametr. of FFs

- **determined**:
  $\Delta u$, $\Delta \bar{u}$, $\Delta d$, $\Delta \bar{d}$, $\Delta s, \Delta \bar{s}$



# Polarised quark distributions at $Q^2 = 3\ \frac{\mathrm{GeV}}{c^2}$

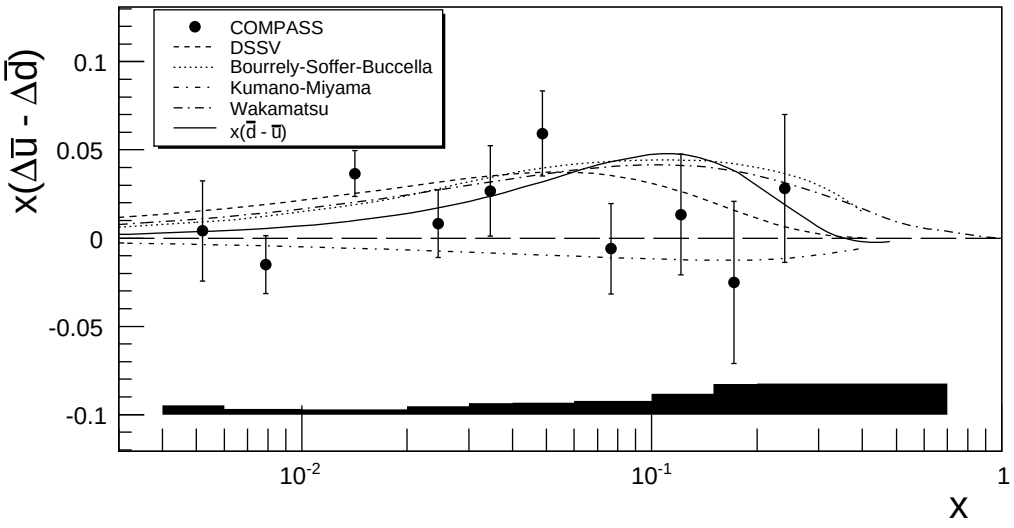


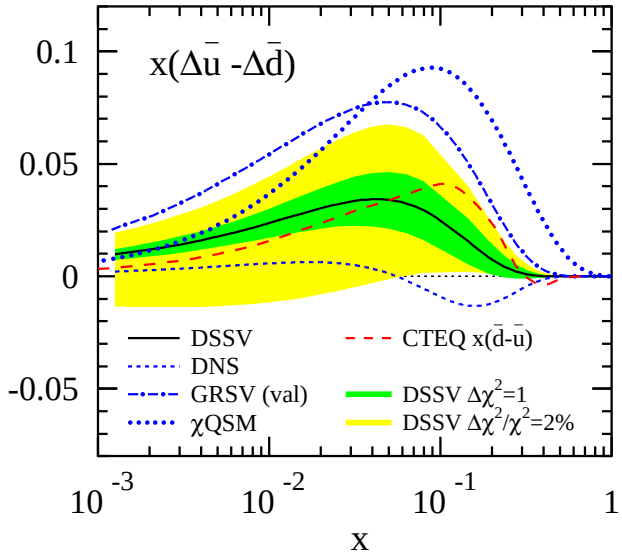

$(\Delta s = \Delta \bar{s})$

- all sea quark distributions compatible with zero (PLB 693 (2010) 227)
- good agreement with global fit for $\Delta u$, $\Delta \bar{u}$, $\Delta d$, $\Delta \bar{d}$
- significant discrepancy with $\Delta s$ obtained from QCD fits to $g_1$

$$\int_{0.004}^{0.3} \Delta s = -0.01 \pm 0.01 \pm 0.01$$

# Flavour symmetry breaking




- presently only accessible via SIDIS
- uncertainty from FFs not included
- result at $Q^2 = 3$ (GeV/$c$)$^2$:

$$\int_{0.004}^{0.3}(\Delta\bar{u} - \Delta\bar{d})\mathrm{d}x = 0.06 \pm 0.04(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

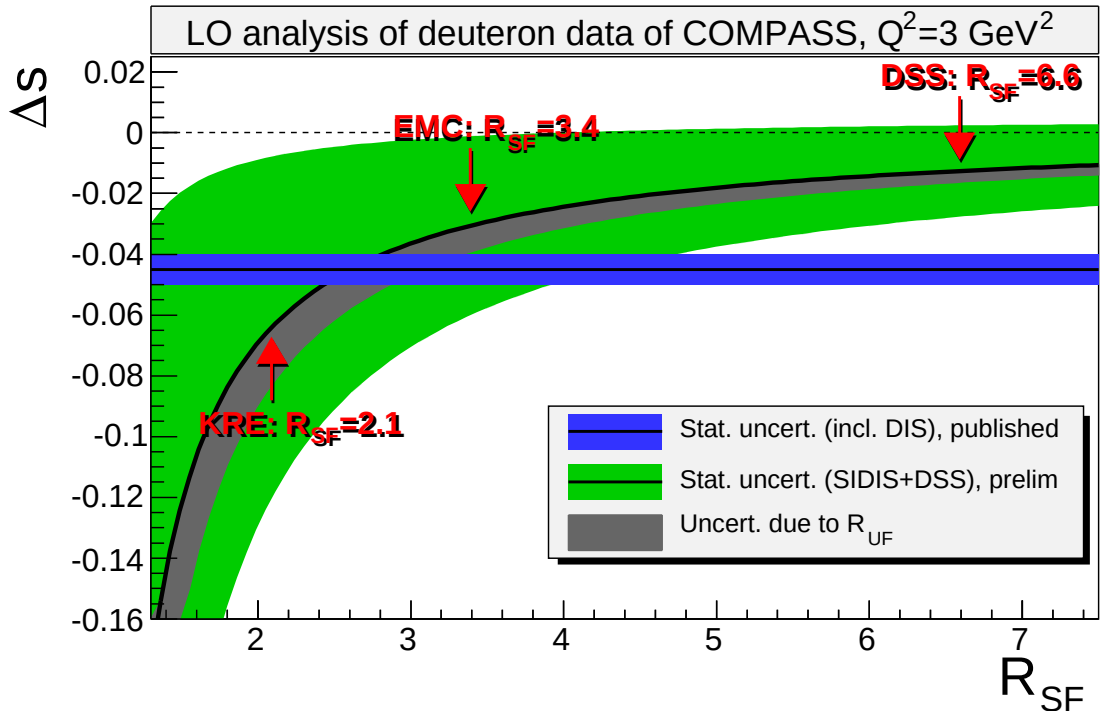
- compatible with HERMES result
- comparable with effect in unpolarised PDFs ($\int(\bar{u} - \bar{d})\mathrm{d}x = -0.118 \pm 0.012$)

# Dependence on fragmentation functions

- relation between SIDIS asymmetries and $\Delta s$ depends on

$$R_{UF} = \frac{\int D_d^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z} \qquad R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$$

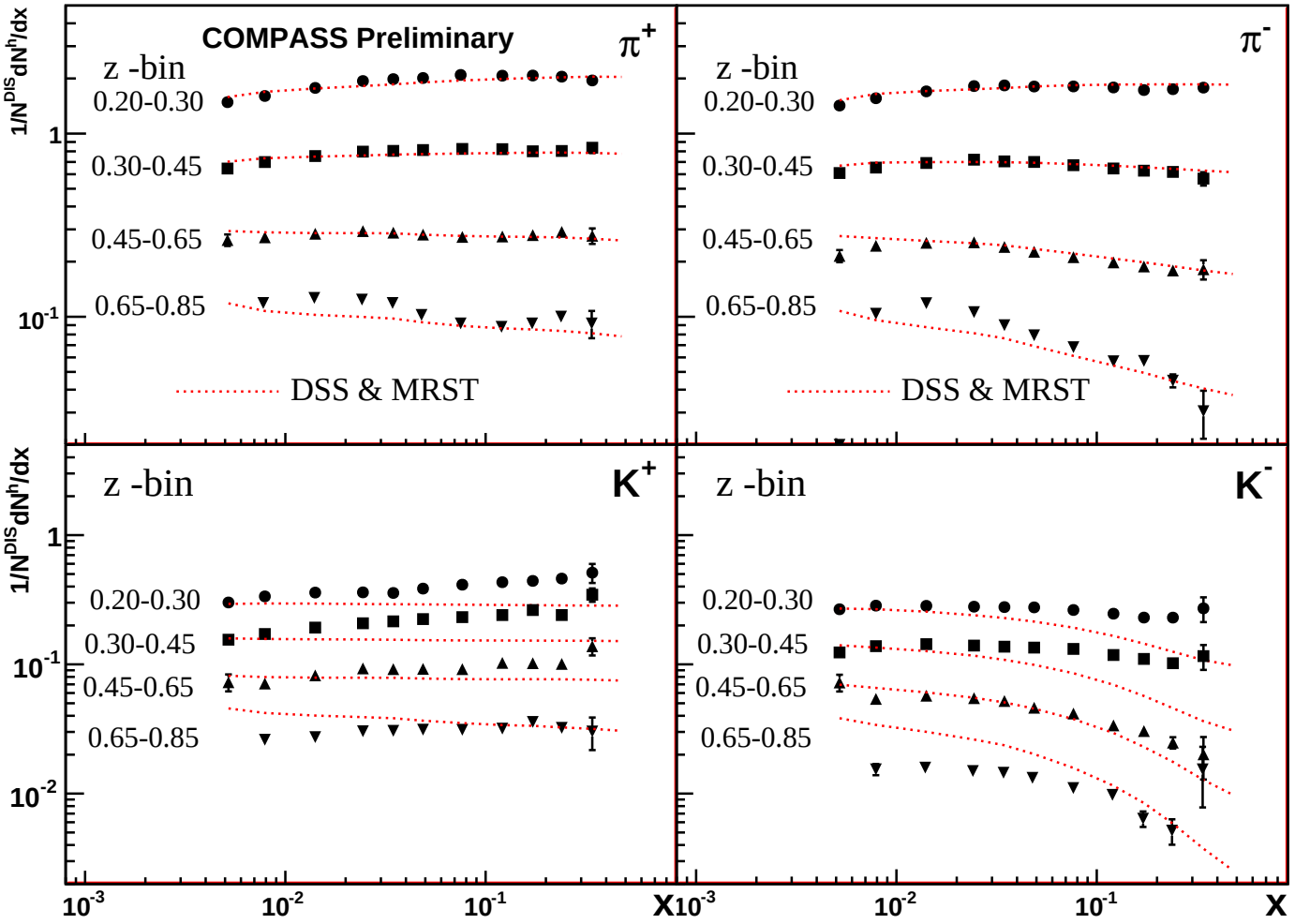
PLB 680 (2009) 217




- large dependence on $R_{SF}$, slight dependence on $R_{UF}$ for $\Delta s$
- determination of $R_{SF}$ from data needed hadron multiplicities on the way

# First look on multiplicities

$x$ dependence of $\dfrac{1}{N_{\mathrm{DIS}}} \cdot \dfrac{\mathrm{d}N^h}{\mathrm{d}z\mathrm{d}x}$

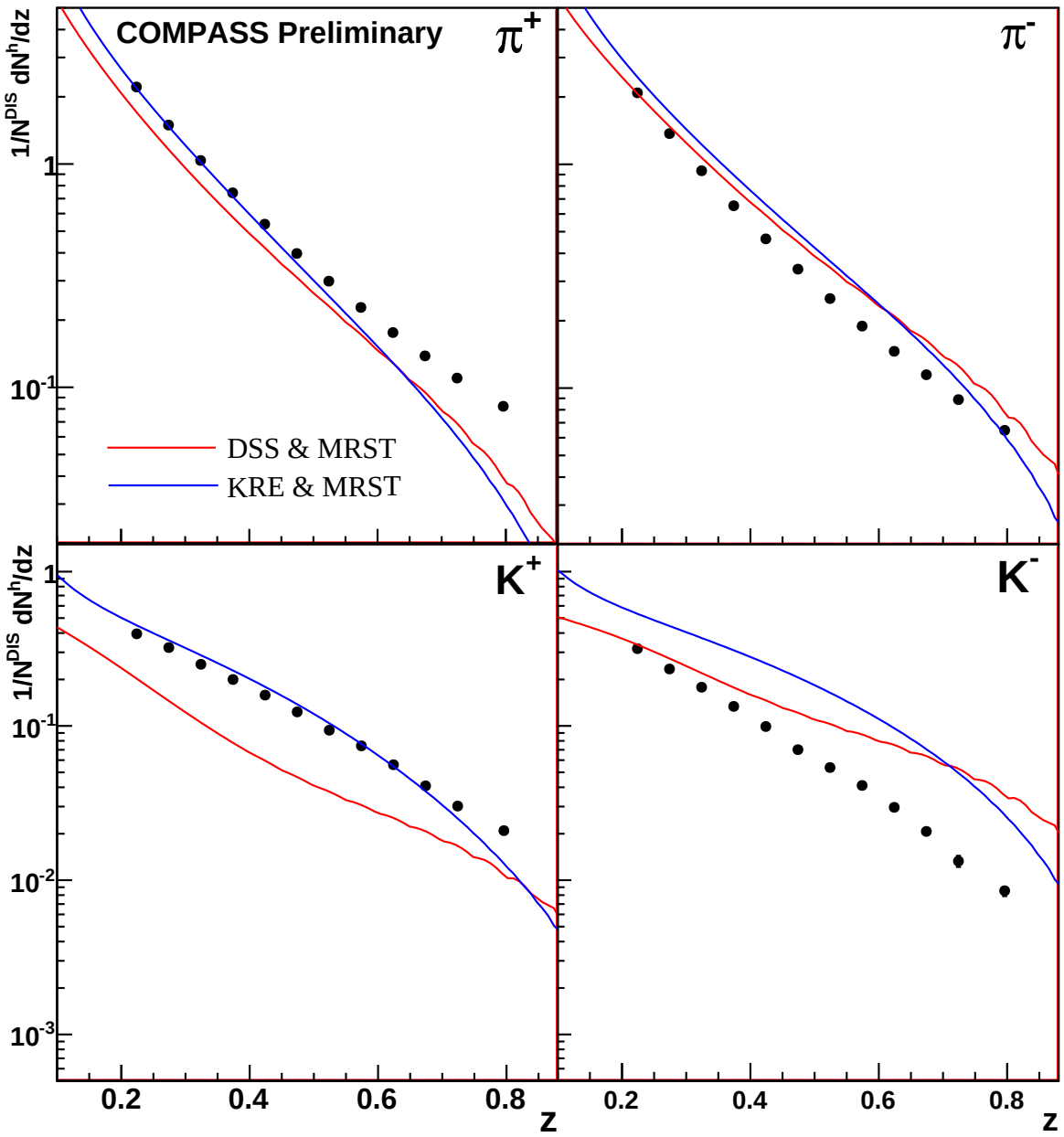



related in LO to product of PDFs and FFs

obtained from small part of $^6$LiD data

kaons and pions

# Comparison to parametrisations



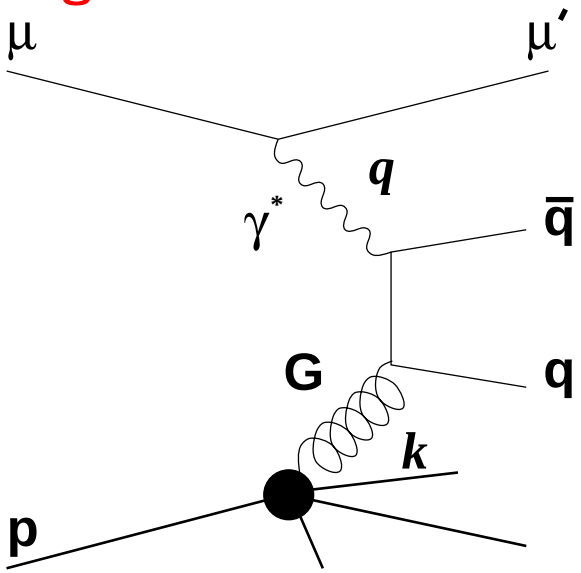

$$\frac{1}{N_{\mathrm{DIS}}} \cdot \frac{\mathrm{d}N^h}{\mathrm{d}z}$$

- some discrepancies, especially for kaons
- data can be used for LO extraction of FF and PDF
- will significantly contribute to knowledge on hadronisation process

# Gluon polarisation

# $\Delta G/G$ measurements in DIS

## Photon gluon fusion




$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\, \Delta\sigma^{PGF} \Delta G(x_g, \hat{s})}{\int d\hat{s}\, \sigma^{PGF} G(x_g, \hat{s})} \approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$

$\langle a_{LL}^{PGF} \rangle$ analysing power

## Direct methods

- **Open charm production**

  $\gamma g \rightarrow c\bar{c}$

  $\rightarrow D^0, D^*$

  hard scale: $M_c^2$
  theoretically clean channel,
  low staticstics

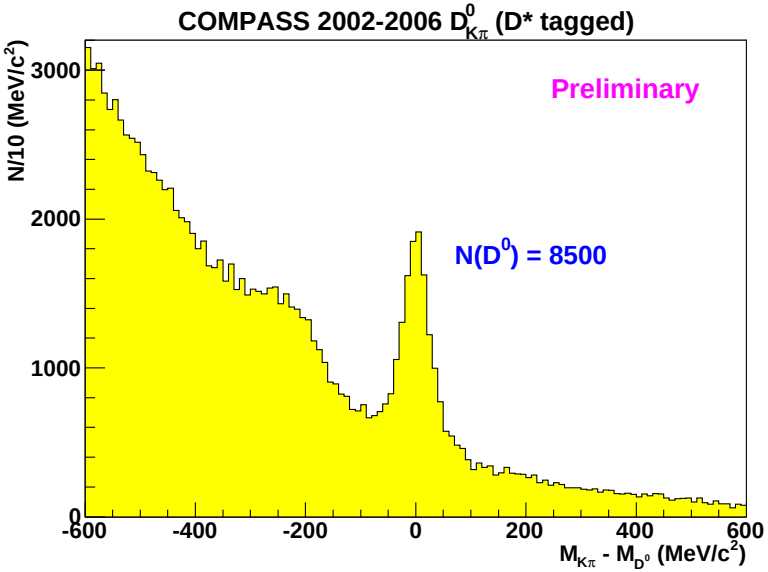
- **High $p_T$ hadron (pairs)**

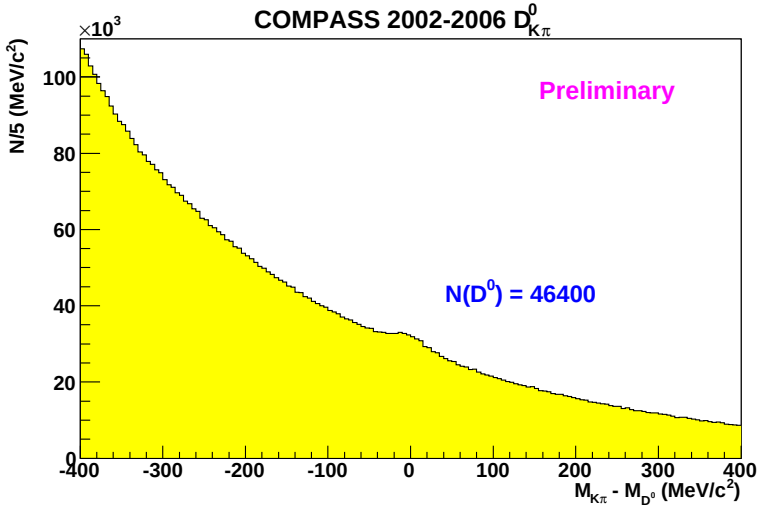
  $\gamma g \rightarrow q\bar{q}$

  $\rightarrow H^+H^-$ or H

  hard scale: $Q^2$ or $\Sigma p_T^2$
  high statistics
  contributions from background processes

# Open charm production




- **channels investigated**

$$D^* \rightarrow D^0\pi_{\rm slow} \rightarrow K\pi\pi_{\rm slow}$$
$$D^* \rightarrow D^0\pi_{\rm slow} \rightarrow K\pi\pi^0\pi_{\rm slow}$$
$$D^0 \rightarrow K\pi$$

- all deuteron data (PLB 676 (2009) 31)
- update with proton data (2007) and more channels (**preliminary**)

$$D^* \rightarrow D^0\pi_{\rm slow} \rightarrow K\pi\pi\pi_{\rm slow}$$

- improved analysis method
- all $Q^2$, $a_{\rm LL}$ in LO or NLO

$$\Delta g/g^{\rm LO} = -0.08 \pm 0.21({\rm stat}) \pm 0.08({\rm syst})$$

at $x_{\rm g} = 0.11$ and scale $\mu^2 \approx 13$ (GeV/$c$)$^2$

# High $p_{\mathrm{T}}$ hadron pairs

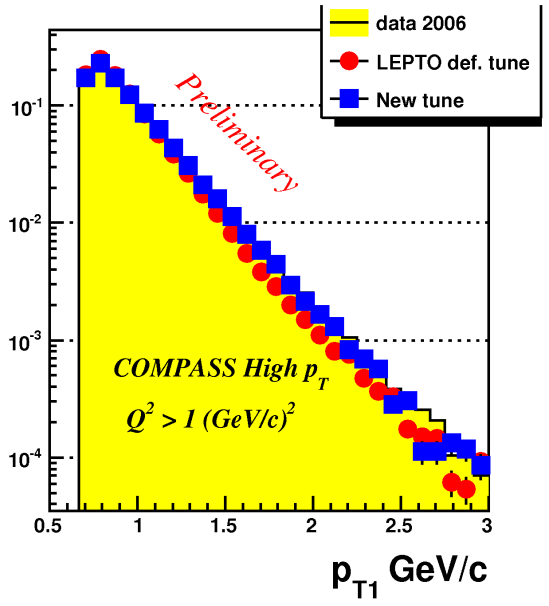
$$\Delta g/g(x_{\mathrm{g}}) = (A_{\mathrm{LL}}^{2h} + A^{\mathrm{corr}})/\beta$$

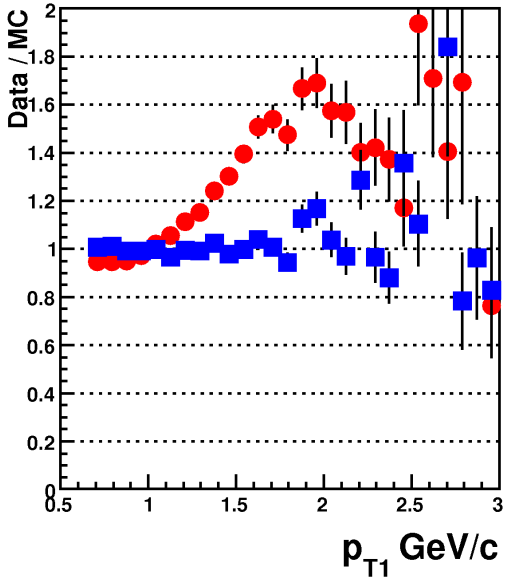
- **selection**
  $Q^2 > 1$ (GeV/$c$)$^2$, $p_{\mathrm{T}}^{h_1(h_2)} > 0.7(0.4)$ GeV/$c$
- **background processes**

  QCD-Compton, leading order
  (plus resolved photons for small $Q^2$)
- improved MC (Lepto) and NN method,
  new JETSET tuning
- **new preliminary result** from all deuteron data (2002–2006), three bins in $x_g$

$$\Delta g/g^{\mathrm{LO}} = 0.125 \pm 0.06(\mathrm{stat}) \pm 0.064(\mathrm{syst})$$

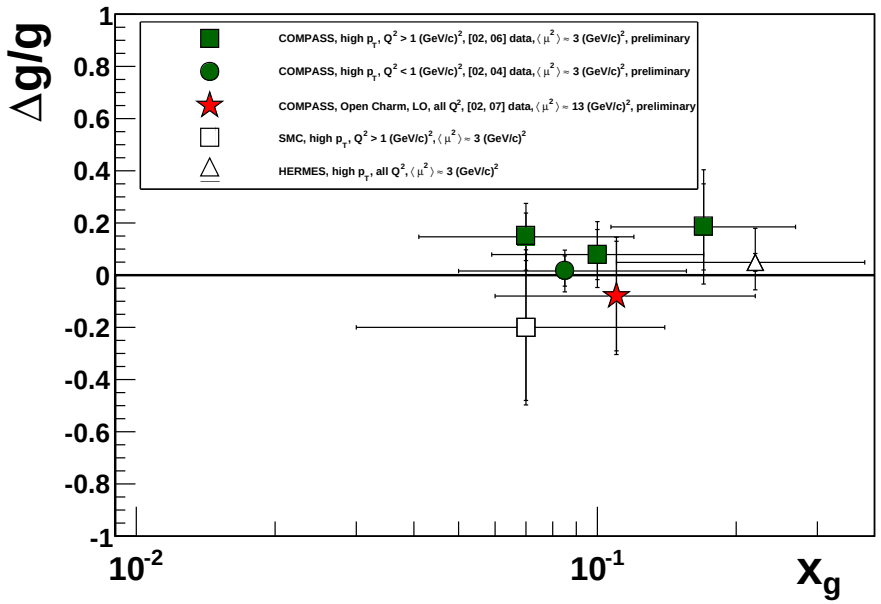
- at $x_{\mathrm{g}} = 0.09$ and scale $\mu^2 \approx 3.4$ (GeV/$c$)$^2$

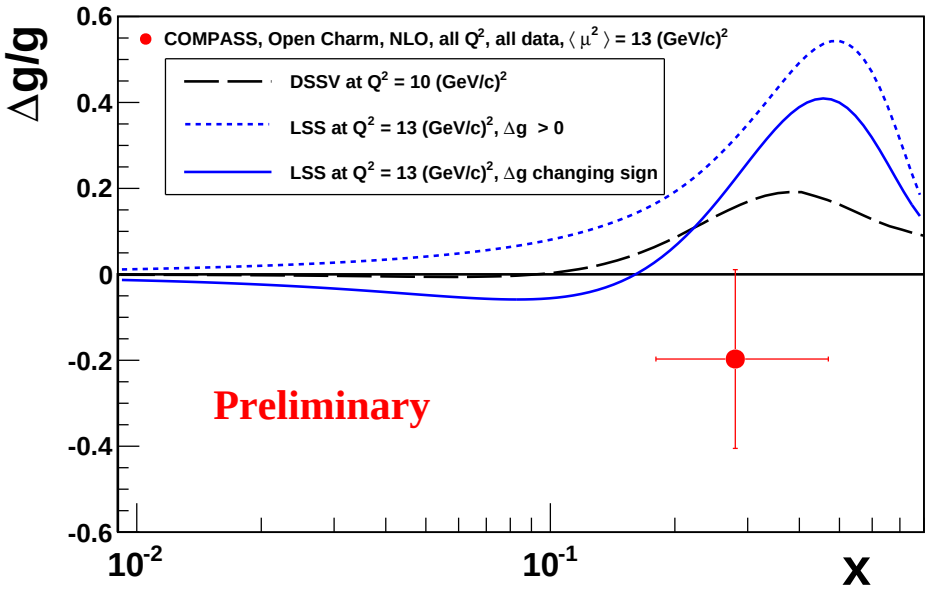



similar for other variables

# Results for $\Delta G/G$



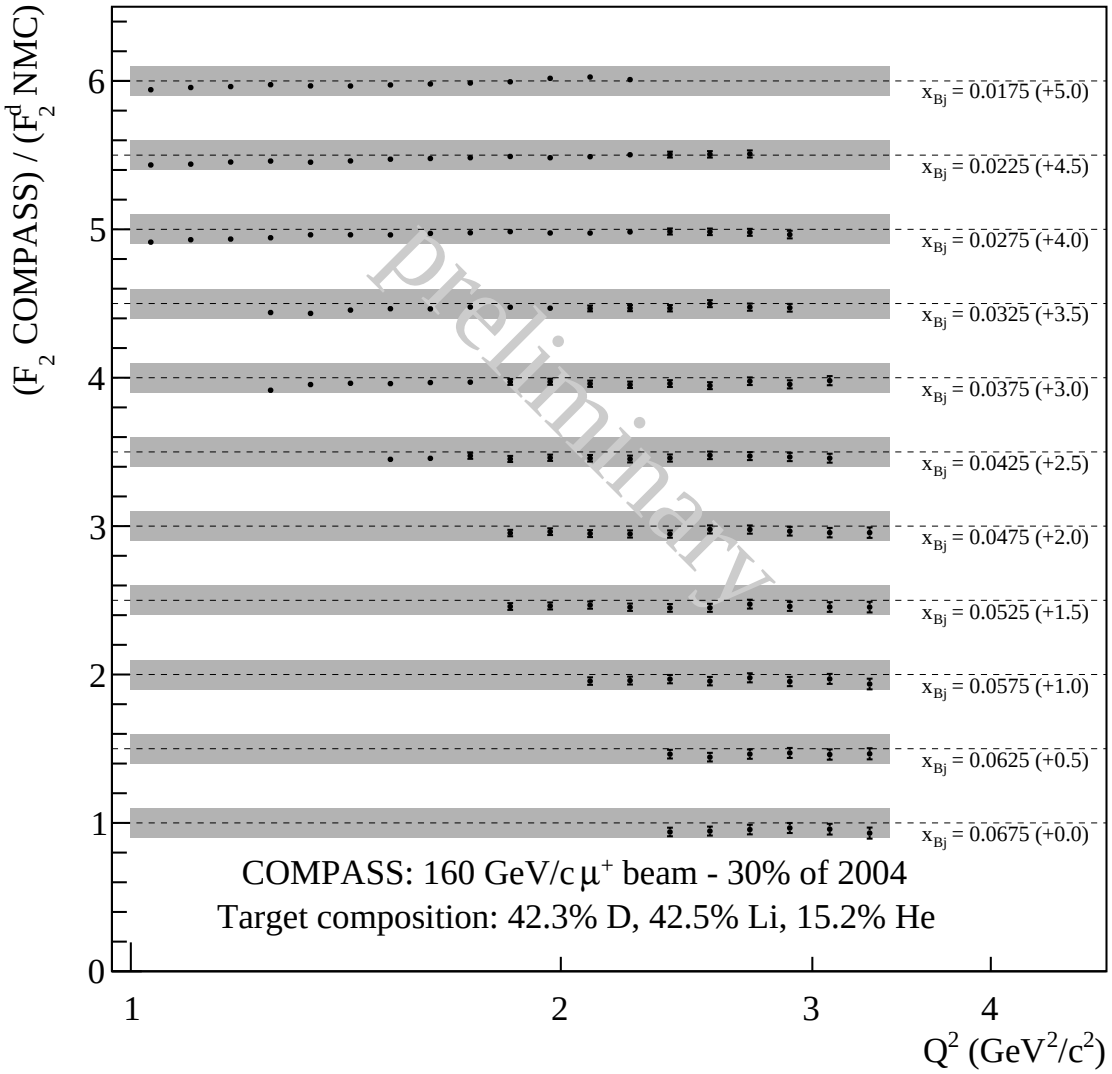




- LO results from high $p_{\mathrm{T}}$ hadrons (SMC, HERMES, COMPASS) and charm
- NLO result from charm (COMPASS): systematic error still under investigation

$$\Delta g/g^{\mathrm{NLO}} = -0.20 \pm 0.21(\mathrm{stat})$$

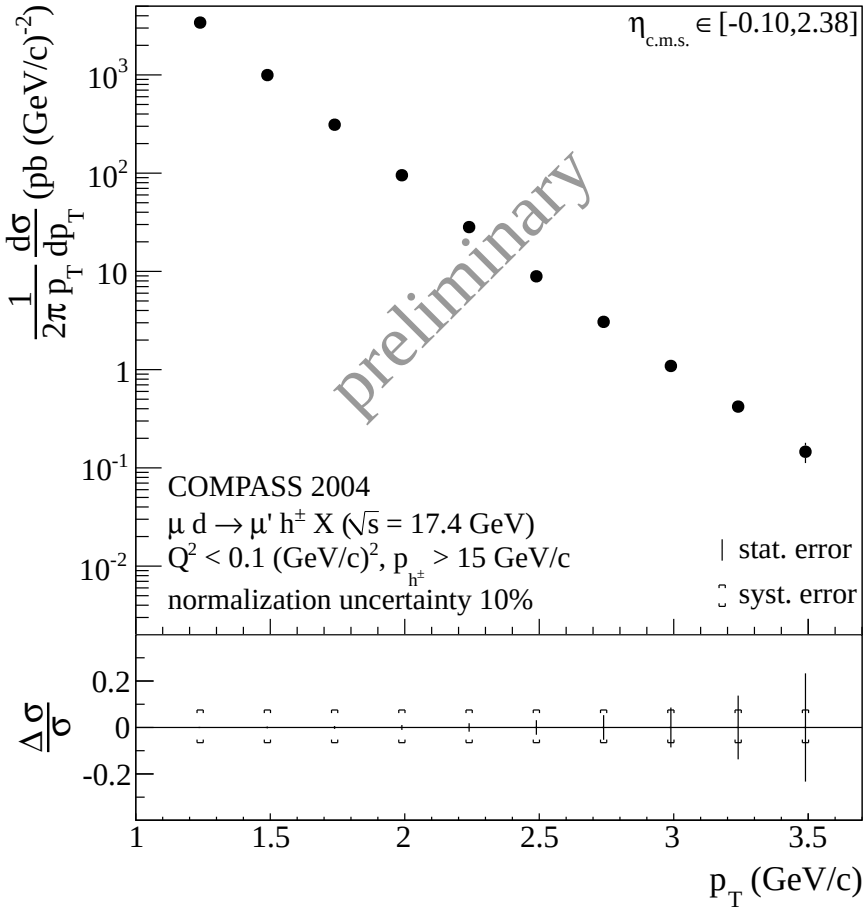
- **$\Delta G/G$ is small or has a node around $x_{\mathrm{g}} \approx 0.1$**

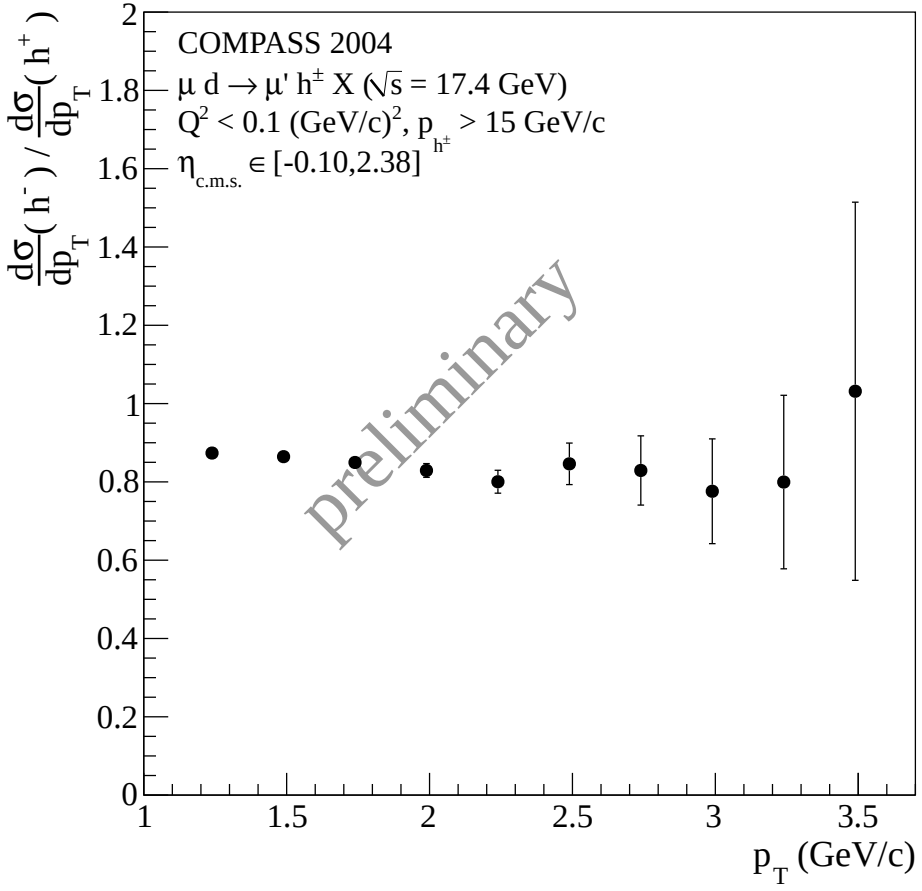
# What about cross sections?




- unpolarised PDFs much better known
- COMPASS optimised for asymmetries
- luminosity from beam flux and target density
- checked with **F2** from $^6$LiD
- $Q^2$ from 1 to 3 $(\mathrm{GeV}/c)^2$, $0.015 < x < 0.07$
- shaded areas correpond to 10% luminosity error
- comparison to **NMC $F_2$ parametrisation**

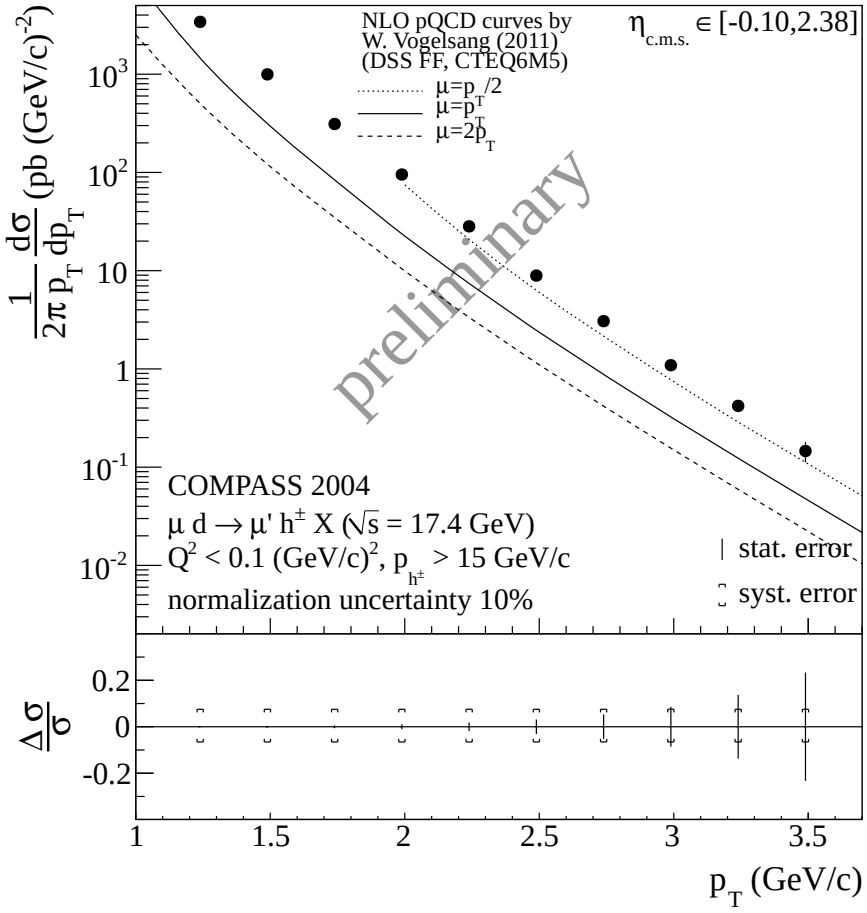
# Quasi-real photoproduction of hadrons

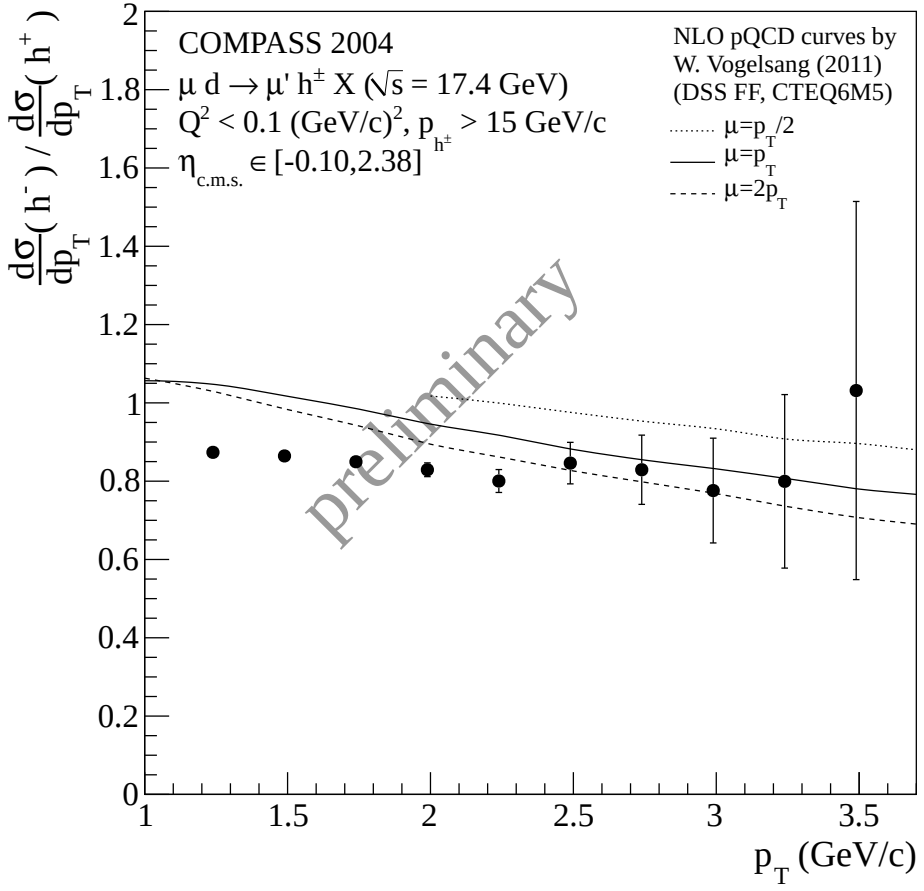



- cross section for $H^+ + H^-$ and charge ratio ($Q^2 < 0.1$ (GeV/$c$)$^2$)

# Comparison to pQCD prediction




some discrepancies observed

- experimental cross section larger than prediction, resummations needed?
- $p_T$ dependence of charge ratio from pQCD not confirmed, fragmentation functions?

# Summary and outlook


## Results

- results from all proton and deuteron data
- determination of quark contribution to nucleon spin
- full flavour separation from SIDIS data
- update of result for gluon polarisation
- more results on $\rho$ asymmetries, $\Lambda$ polarisation, azimuthal asymmetries

## Still to come

- study of fragmentation functions and strange quark distribution
- gluon polarisation from single hadrons
- more data with longitudinally polarised $NH_3$ in 2011
- proton $g_1$ at low $x$ and flavour separation
- future COMPASS II programme: DVCS and DVMP