Results from Inclusive and Semi-inclusive Asymmetries

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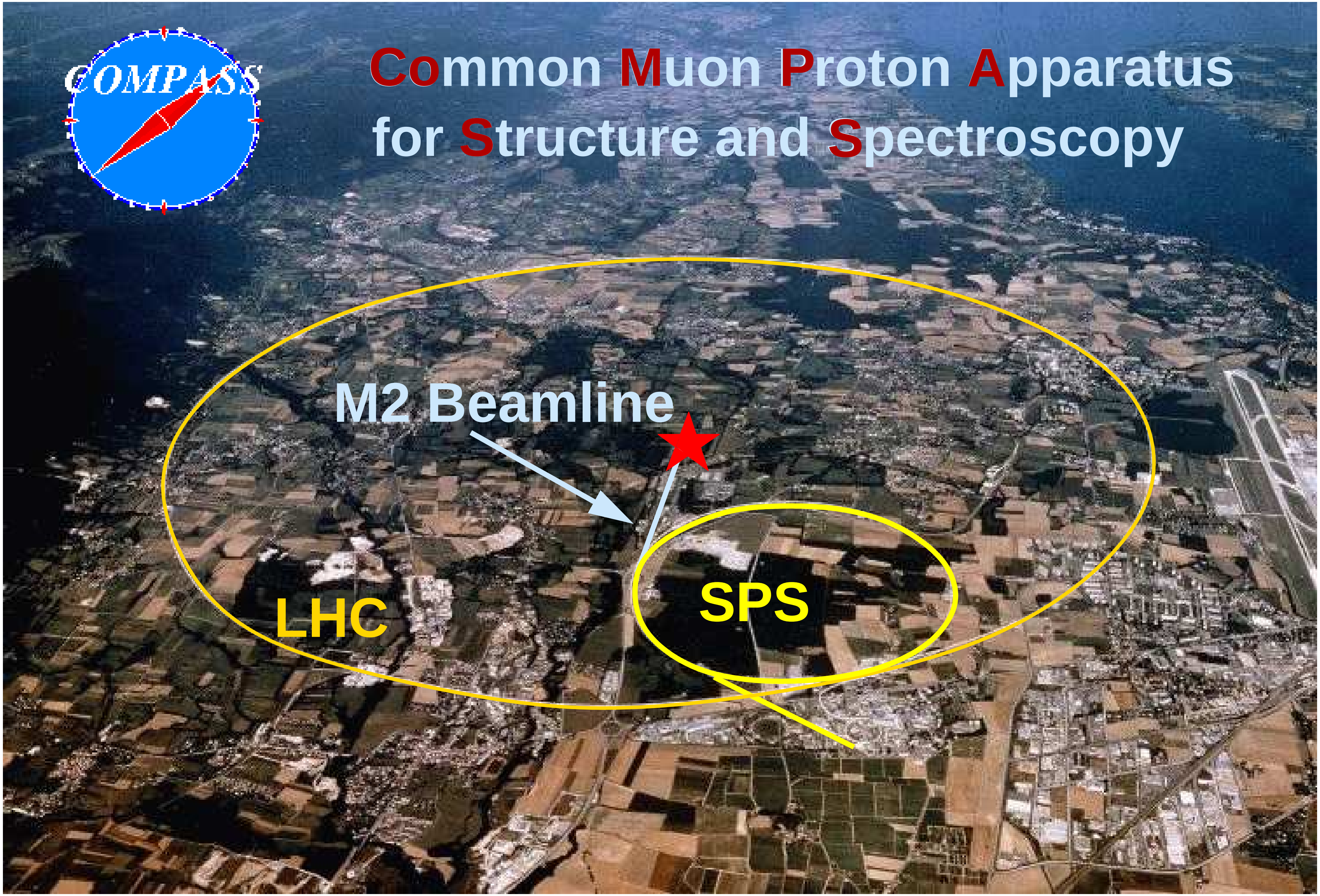
Int. Workshop on Hadron Structure and Spectroscopy 2008

- **COMPASS experiment**
- **Inclusive asymmetries**
- **Semi-inclusive asymmetries**
- **Data 2006/7**
- **Status and outlook**


COMPASS
Common Muon Proton Apparatus
for Structure and Spectroscopy
M2 Beamline
SPS
LHC

COMPASS

Bielefeld, Bochum, Bonn, Burdwan/Calcutta, CERN, Dubna, Erlangen, Freiburg, Lissabon, Mainz, Moscow, Munic, Prague, Protvino, Saclay, Tel Aviv, Turino, Trieste, Warsaw, Yamagata
(29 institutes, 240 physicists)

Muon beam

Spin dependent structure functions

Polarised quark distributions

Gluon polarisation

Transversity

Lambda polarisation

Vector meson production

DVCS

Hadron beam

Primakoff scattering

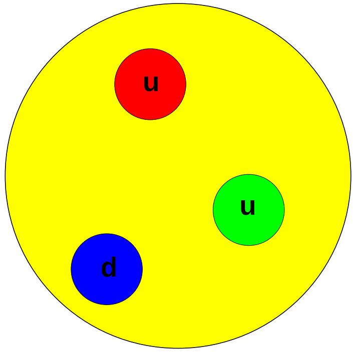
Exotic hadrons

- **Glueballs**
- **Hybrids**
- **Multi-quark states**

Charmed hadrons

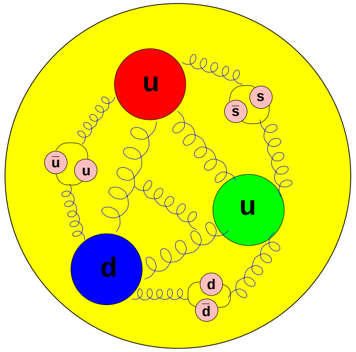
Drell Yan measurements

The spin of the nucleon

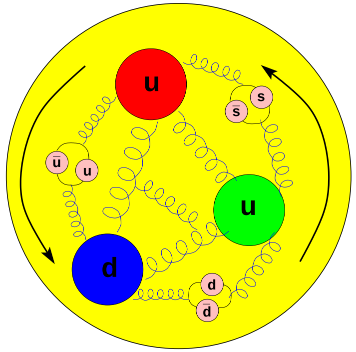


Naive parton model:
$\Rightarrow \Delta\Sigma = \Delta u_v + \Delta d_v = 1$

E155
$\Delta\Sigma = 0.23 \pm 0.07 \pm 0.19$



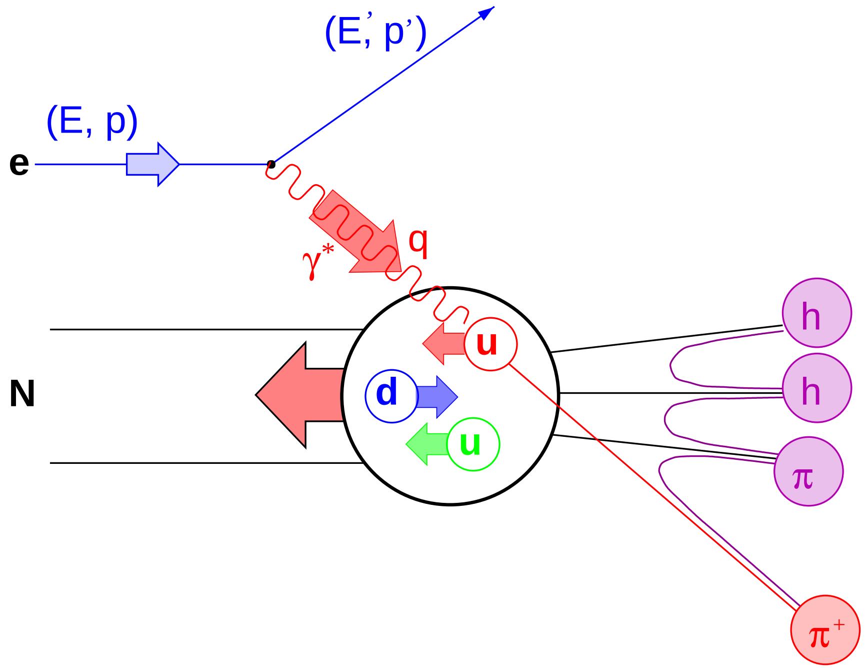
gluons important in unpolarized case
ΔG?



complete description:
orbital angular momenta

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

Deep inelastic scattering



$$Q^2 = -q^2$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$
$$y = \nu/E$$
$$z = E_\mathrm{h}/\nu$$

p_T : hadron transverse momentum

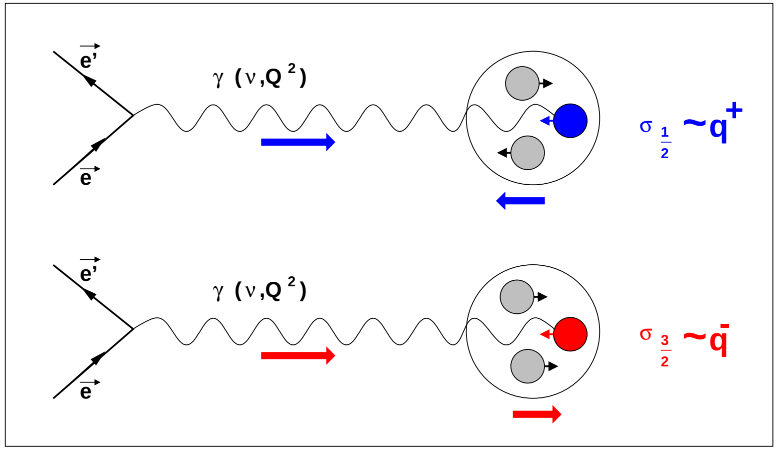
- **Inclusive cross section**

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E'} \sim \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{spin independent}} + \underbrace{c_3 g_1(x,Q^2) + c_4 g_2(x,Q^2)}_{\text{spin dependent}}$$

F_1, F_2, g_1, g_2 structure functions

Polarised deep inelastic scattering

- **absorption of polarised photons (QPM)**



$$q(x) = q(x)^+ + q(x)^-$$
$$\Delta q(x) = q(x)^+ - q(x)^-$$

$+$ quark $\uparrow\uparrow$ nucleon
$-$ quark $\downarrow\uparrow$ nucleon

- **photon nucleon asymmetry**

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

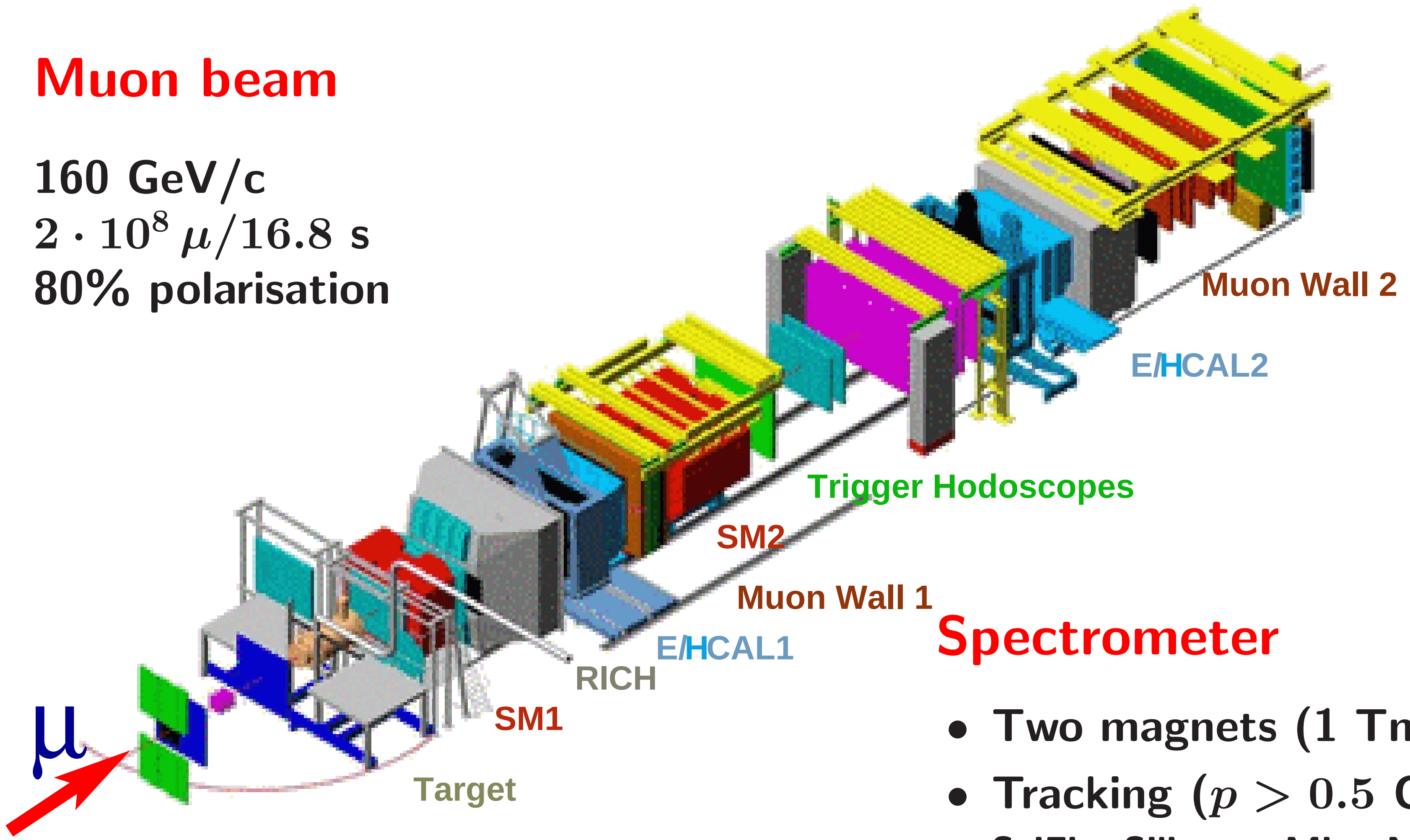
- **spin structure function**

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

COMPASS spectrometer

Muon beam

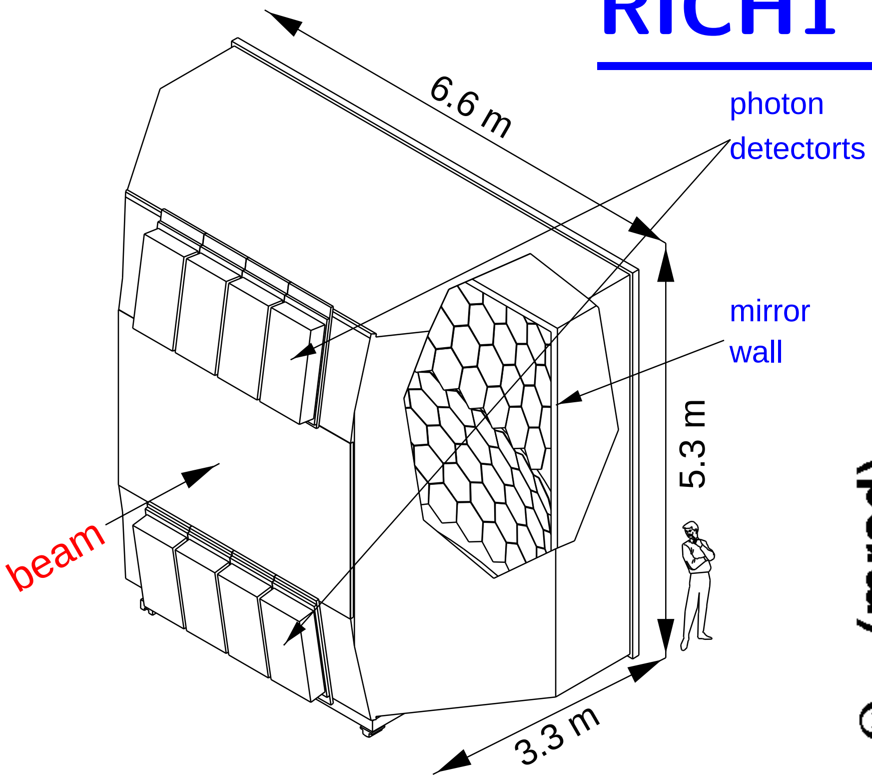
160 GeV/c
$2 \cdot 10^8\ \mu/16.8$ s
80% polarisation



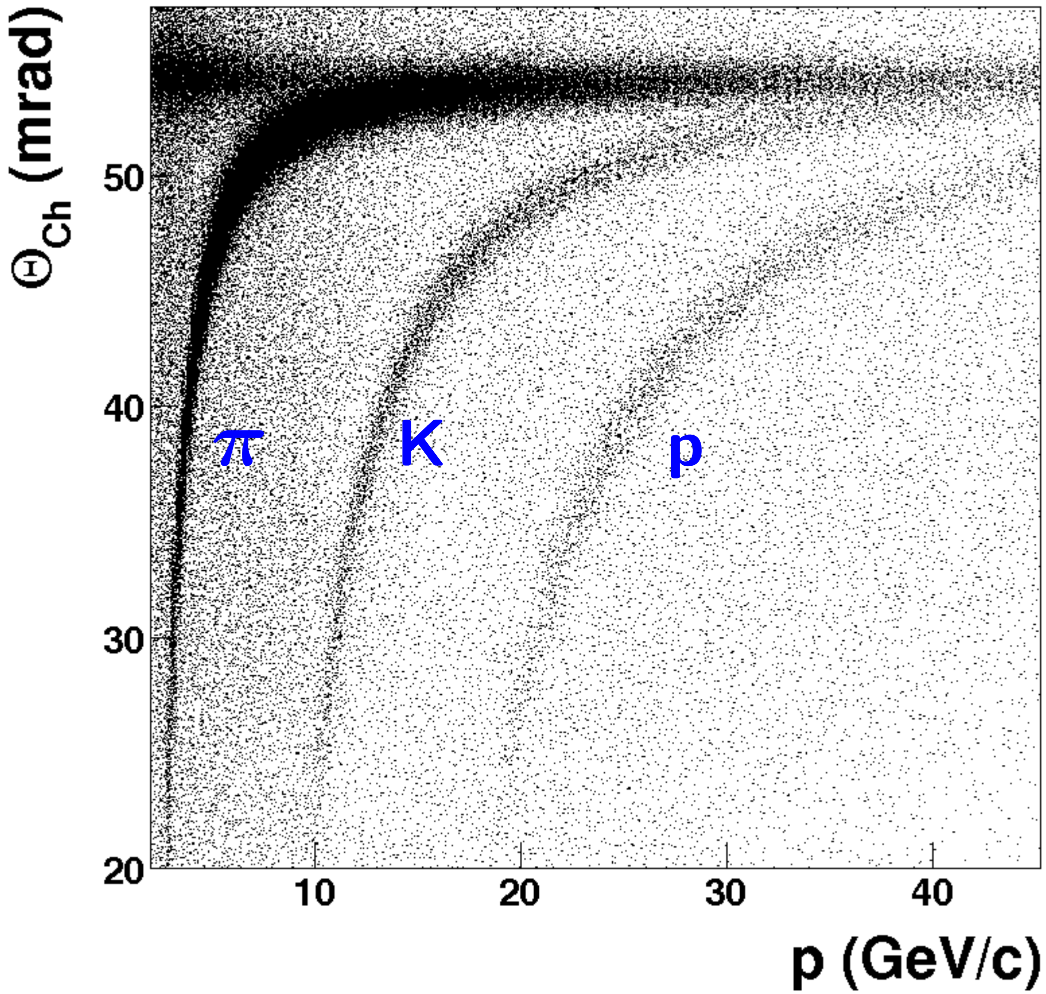
Spectrometer

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

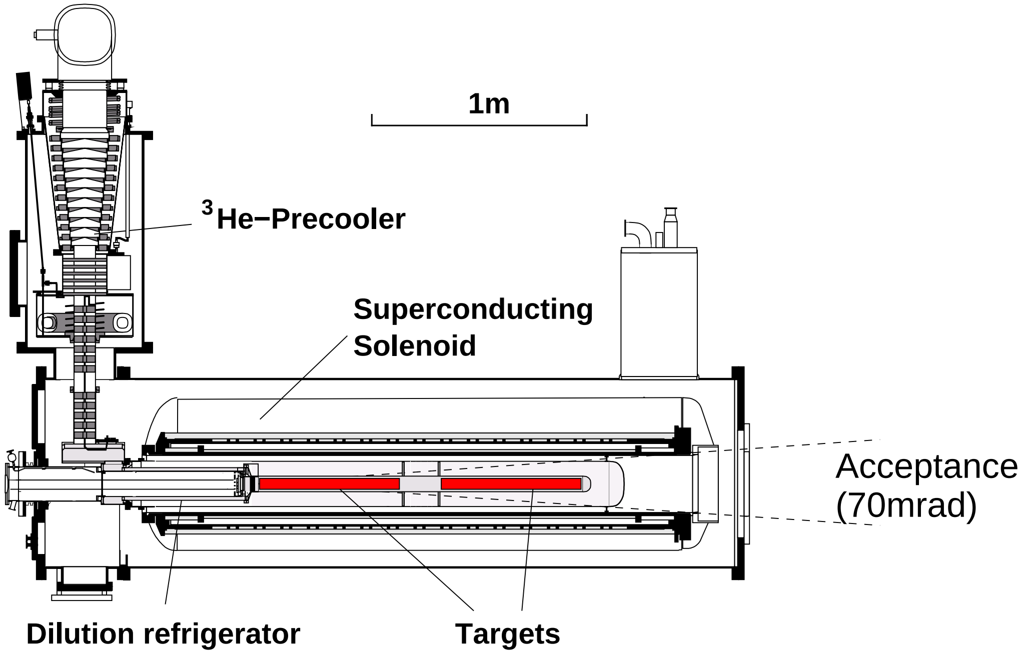
RICH1 (2002–2004)

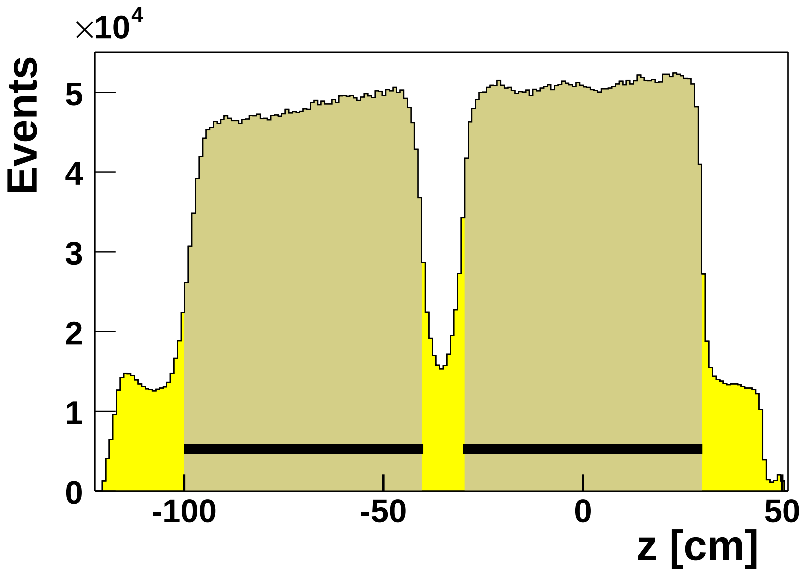


- π/K separation up to 50 GeV/c
- 80 m^3 C_4F_{10}, n=1.00153
- 116 VUV spherical mirrors (21 m^3)
- MWPCs with CsI cathodes, 8×8 mm^2
- $< n >= 15$ photons



The polarised target (2002–2004)

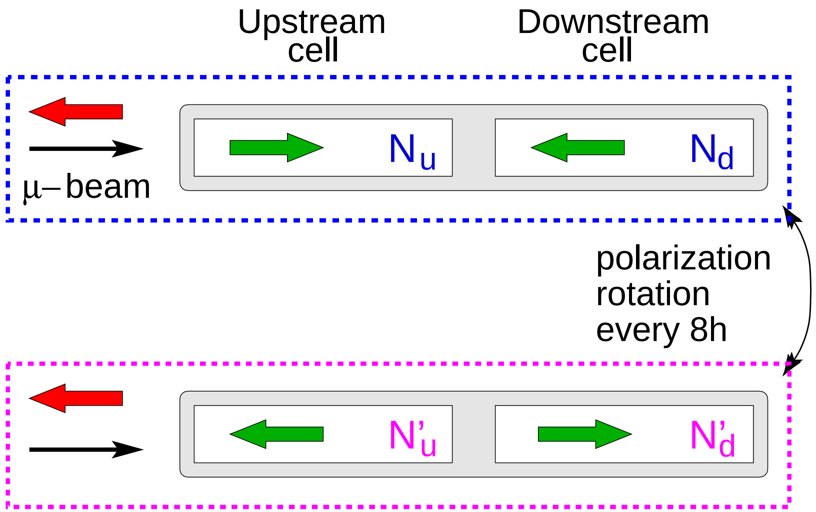




- target material: **^{6}LiD**
- polarisation: $> \mathbf{50\%}$
- dilution factor: $\sim \mathbf{0.4}$
- Dynamic Nuclear Polarization
- solenoid field: 2.5 T
  acceptance: 70 mrad
- ^{3}He/^{4}He: $T_{min} \approx 50\,\mathrm{mK}$
- two 60 cm long target cells with opposite polarisation
- regular polarisation reversal by field rotation

Method

- **to be measured:** $A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$
- **measured:** $N_u,\ N_d,\ N'_u,\ N'_d$
- **flux normalisation:** $\frac{\Phi_u}{\Phi_d} = 1$
- **acceptance:** $\frac{a_u \cdot a'_d}{a_d \cdot a'_u} = 1$
  (Polarisation rotation)



- **double ratio method:** $\delta = \frac{N_u \cdot N'_d}{N'_u \cdot N_d}$

  $\Rightarrow$ solve for A_{exp} (2nd order equation)

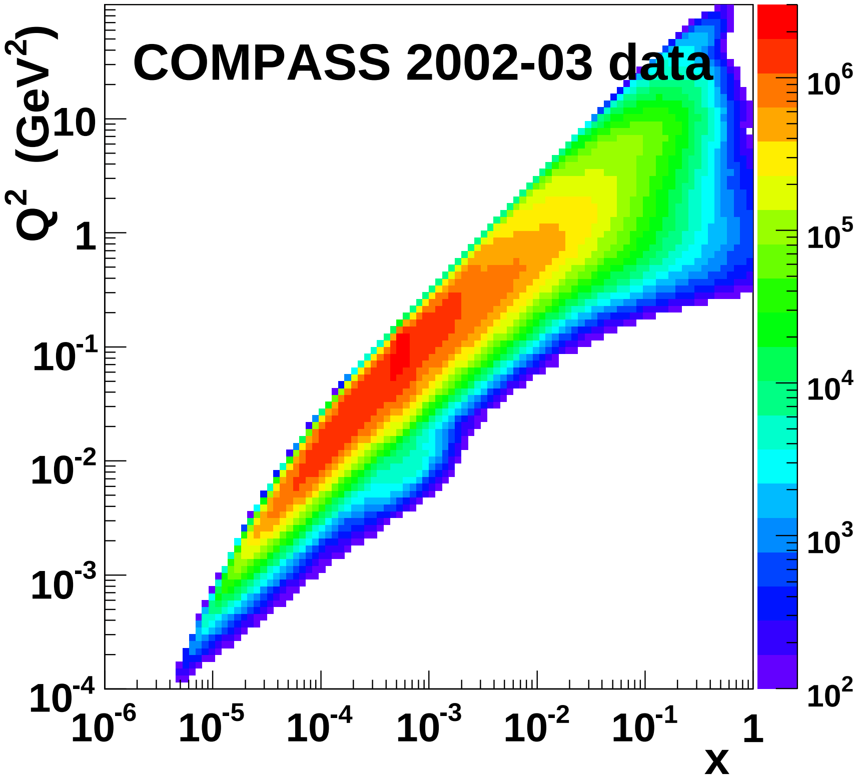
  $\Rightarrow$ minimization of bias

- **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

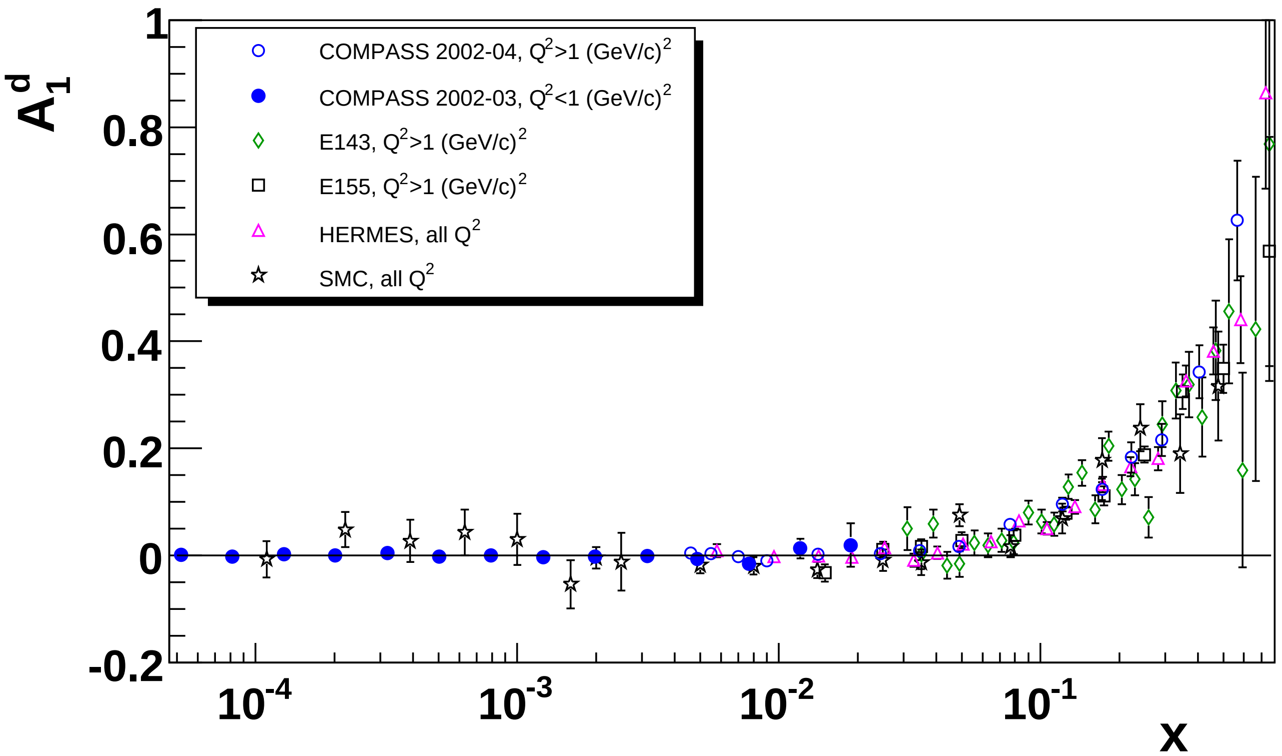
Data 2002–2004



- strong corellation between x and Q^2
- A_1^d and g_1^d for small Q^2
  small x physics
- A_1^d and g_1^d for high Q^2
  QCD analysis possible
  $\longrightarrow$ $\Delta\Sigma$, ΔG
- semi-incl. asymmetries
  A^{h^+}, A^{h^-}, A^{K^+}, A^{K^-}
  $\longrightarrow$ valence + strange quark pol.

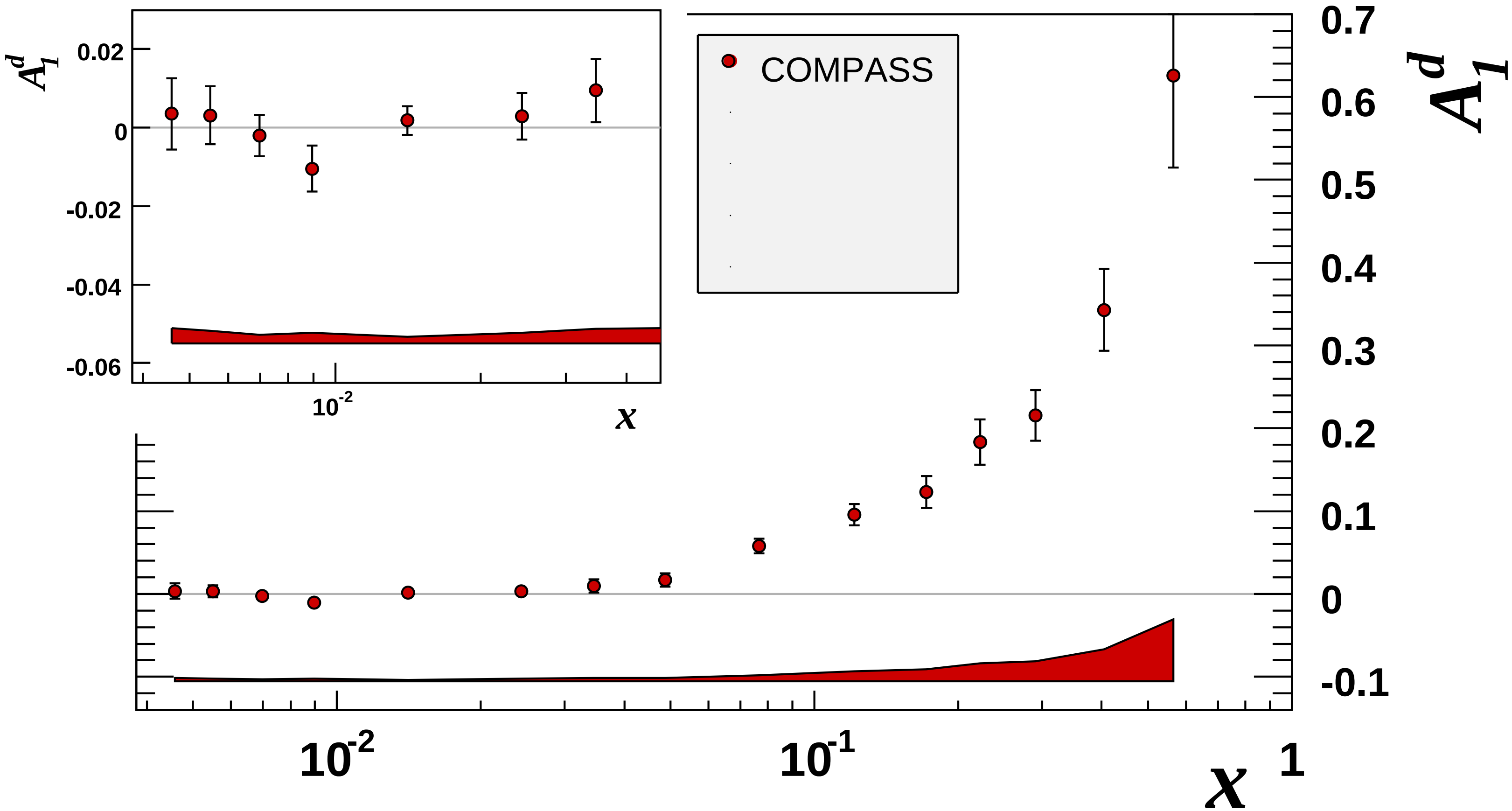
Inclusive asymmetries

Asymmetry for $Q^2 < 1$ (GeV/c)^2



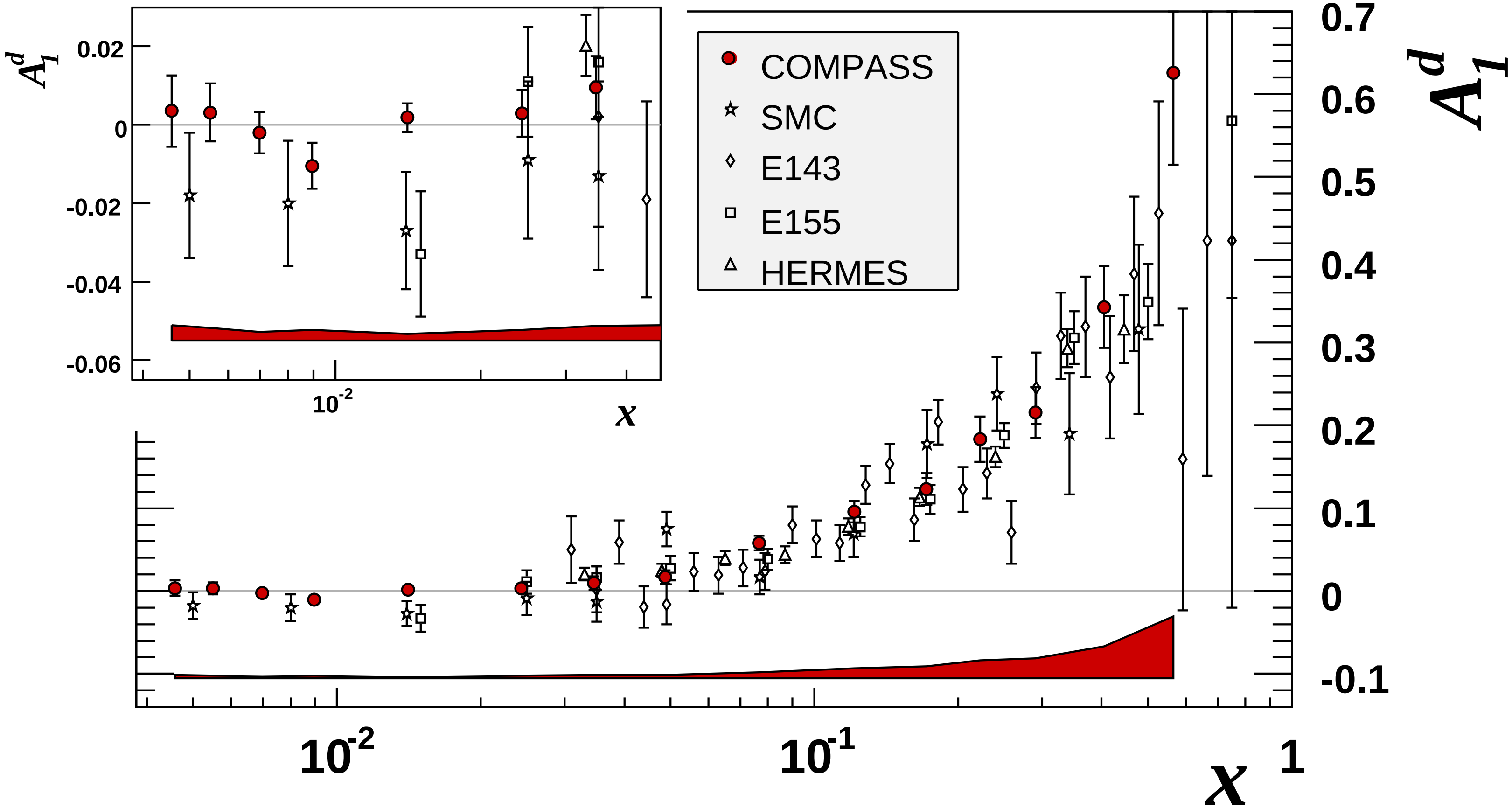
- results from 2002/2003 published (PLB 647(2007)330): $300 \cdot 10^6$ events
- systematic error mainly due to false asymmetries
- A_1^d is compatible with 0 at small x
- very good agreement with SMC (the only other experiment at low x)
- factor 10–20 improvement of statistical errors compared to SMC

Asymmetry for $Q^2 > 1$ (GeV/c)^2



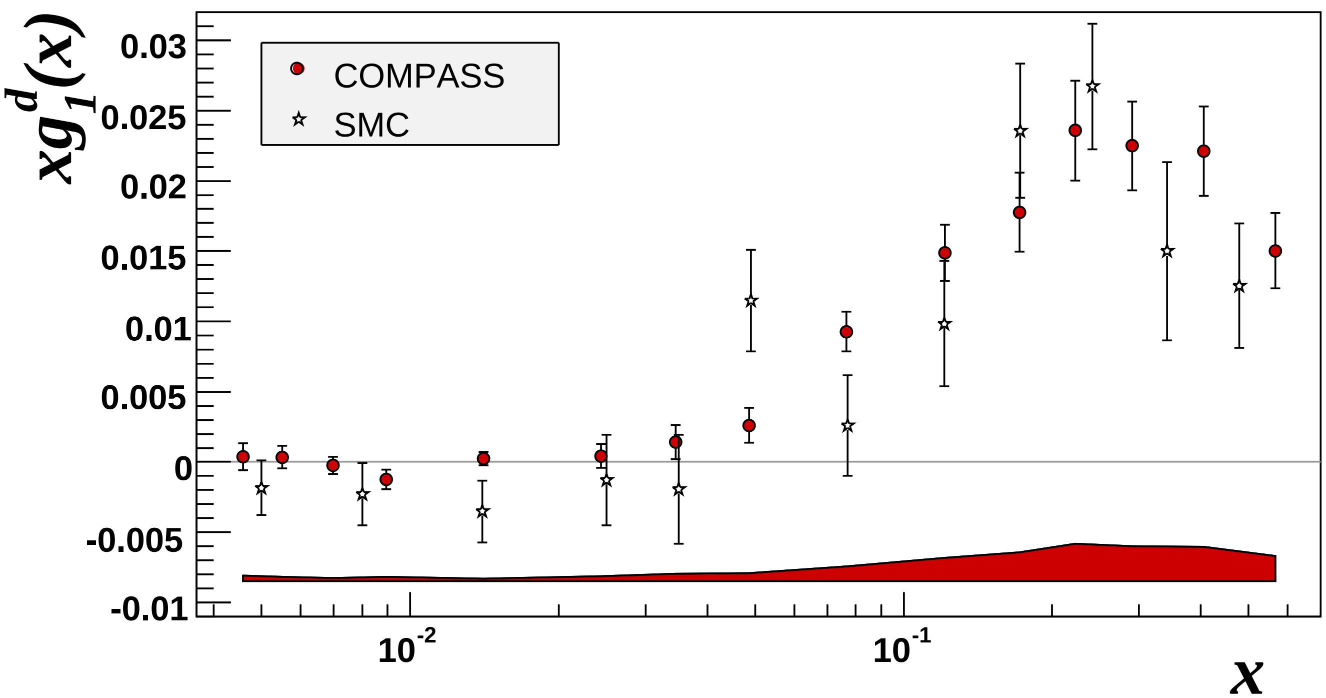
- results from 2002–2004 published in PLB 647 (2007) 8
- $88 \cdot 10^6$ events with $x > 0.004$, $0.1 < y < 0.9$
- systematic errors: p_μ (5%), p_T (5%, f (2–3%), D (6%) $\Longrightarrow \delta A_1 \approx 0.1 A_1$
- additional contributions from false asymmetries, radiative corrections

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

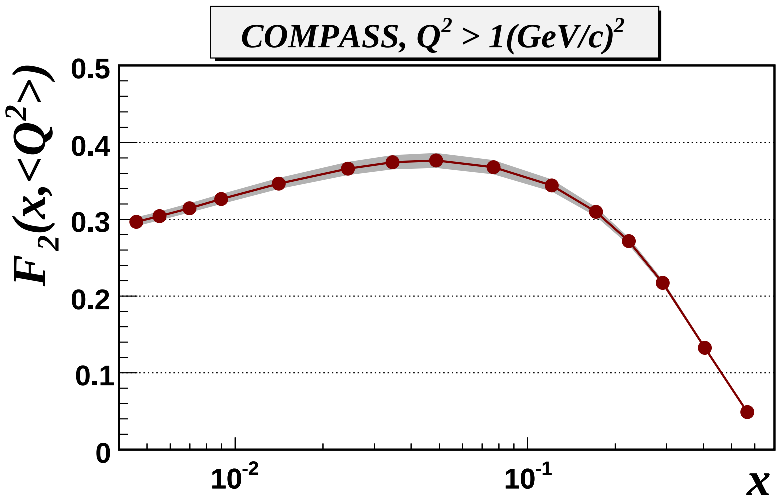


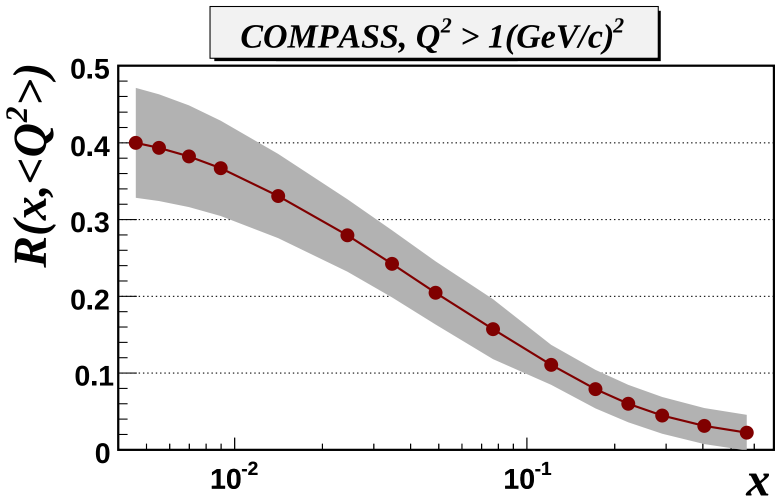
- results from 2002–2004 published in PLB 647 (2007) 8
- A_1^d compatible with 0 for $x < 0.05$
- good agreement with previous experiments
- significant improvement at low x, no tendency towards negative values

$g_1(x)$ at measured Q^2



$$g_1 = A_1 \cdot \frac{F_2}{2x(1+R)}$$





QCD analysis

- **spin structure function g_1**

$$g_1(x,Q^2) = \frac{1}{2}\langle e^2\rangle \left[C_{NS}\otimes\Delta q_{NS} + C_S\otimes\Delta q_{Si} + 2n_f C_g\otimes\Delta g\right]$$

- **DGLAP equations**

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi}\Delta P_{qq}^{NS}\otimes\Delta q_{NS}$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix}\Delta q_{Si}\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq}^{S} & 2n_f\Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_{Si}\\ \Delta g\end{pmatrix}$$

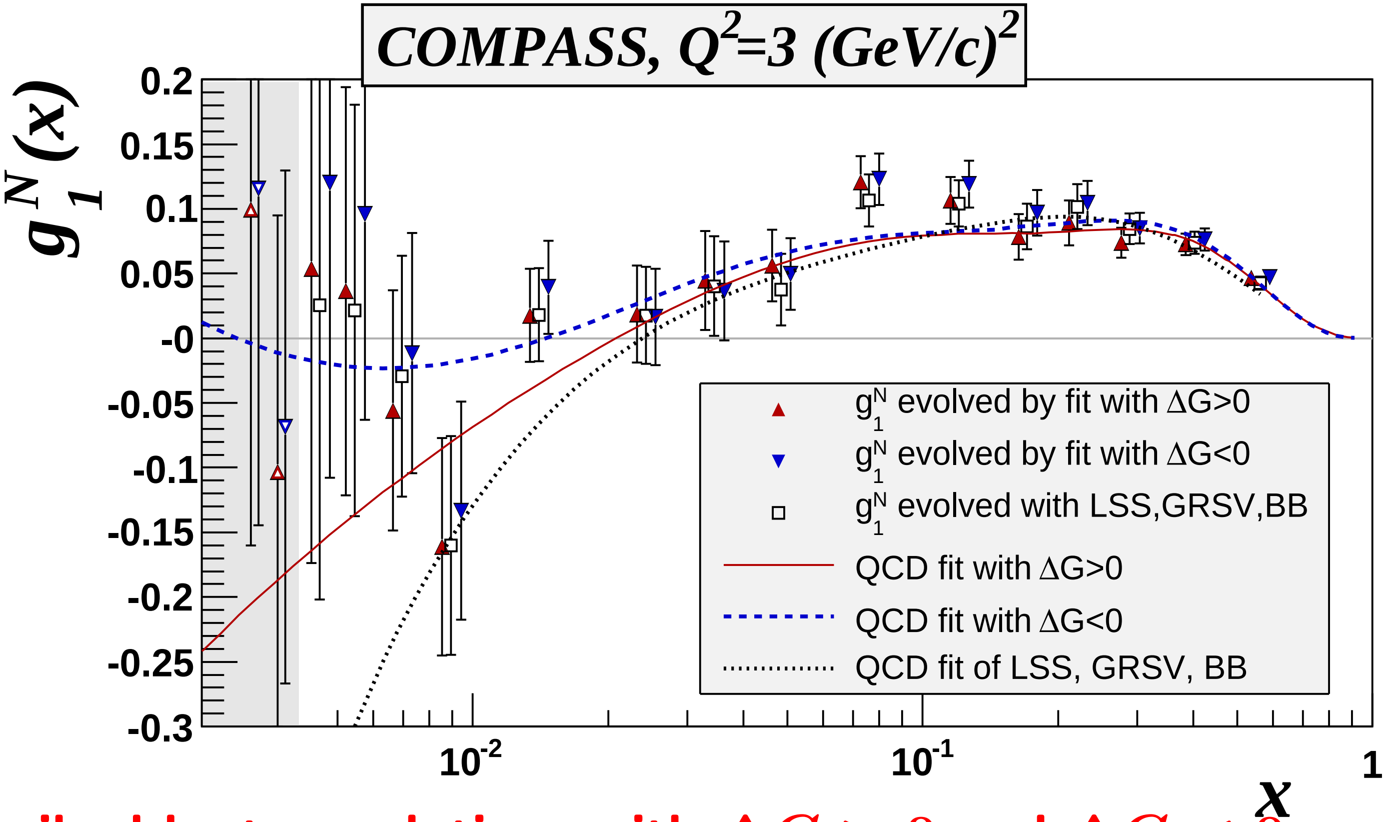
- **input parameterization at Q_0^2**

$$(\Delta q_{Si},\Delta q_3,\Delta q_8,\Delta g) = \eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)\mathrm{d}x}$$

with $\Delta q_{Si} = \Delta u + \Delta d + \Delta s$, $\Delta q_3 = \Delta u - \Delta d$, $\Delta q_8 = \Delta u + 2\Delta d - \Delta s$

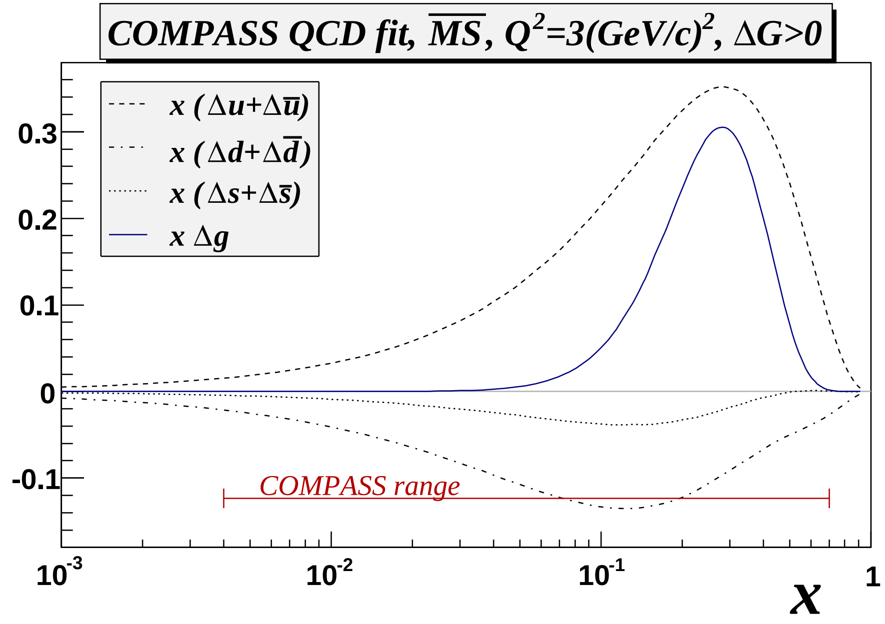
QCD fits

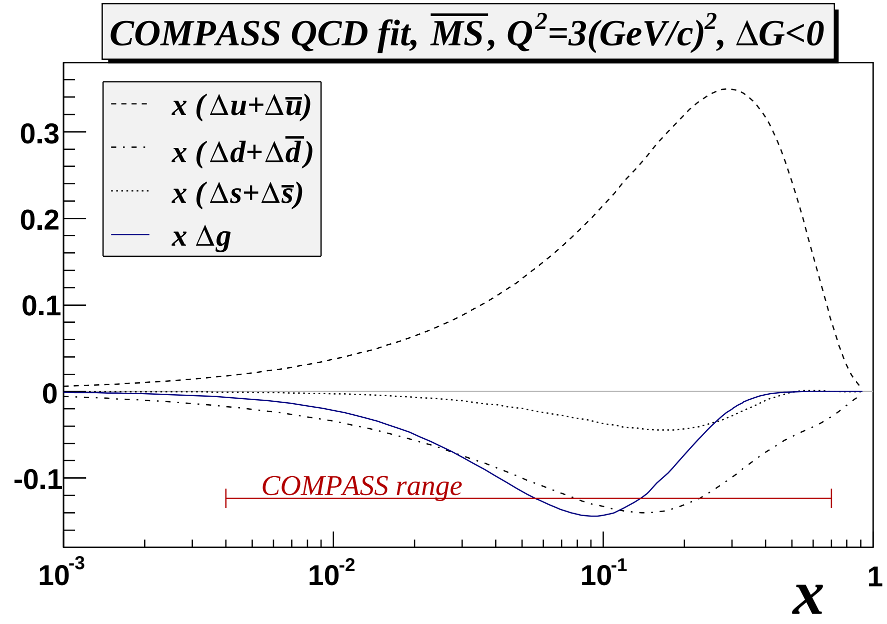
- **two different approaches**
  - numerical integration in (x,Q^2) space (PRD 58 (1998) 112002)
  - solution of DGLAP in space of moments (PRD 70 (2004) 074032)
- **fit to world data (except final g_1^d from HERMES)**
- **NLO analysis in $\overline{\mathrm{MS}}$ scheme**



- **well described by two solutions with $\Delta G > 0$ and $\Delta G < 0$**

Polarised parton distributions





- **small sensitivity to light sea and gluon polarisation**
- **quark polarisation** $\Delta\Sigma = \int q_{Si}(x)\mathrm{d}x$

$$\boldsymbol{\Delta\Sigma = 0.30 \pm 0.01(\text{stat}) \pm 0.02(\text{evol})}$$

(stat. error factor 2 larger without COMPASS)

- **gluon polarisation** $\Delta G = \int \Delta g(x)\mathrm{d}x$

$$\boldsymbol{|\Delta G| \approx 0.2 - 0.3} \quad \Longrightarrow \quad \textbf{direct measurement needed}$$

First moment of g_1

- COMPASS data only

$$\Gamma_1^{\mathrm{N}} \;(Q^2 = 3(\mathrm{GeV/c})^2) = \int_0^1 g_1^{\mathrm{N}}(x)\,\mathrm{d}x$$

$$= 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol.}) \pm 0.0051(\mathrm{syst.})$$

- data for $0.004 < x < 0.7$, QCD fit used for extrapolation
- contribution of unmeasured region about 3 %
- using: $\Gamma_1^{\mathrm{N}} = \frac{1}{9}(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha + s^2))(a_0(Q^2) + \frac{1}{4}a_8)$

$$a_0(Q^2 = 3(\mathrm{GeV/c})^2) = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

- extrapolating towards $Q^2 \to \infty$: $\boxed{\hat{a}_0 = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}) = \Delta\Sigma}$

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\hat{a}_0 + a_8) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

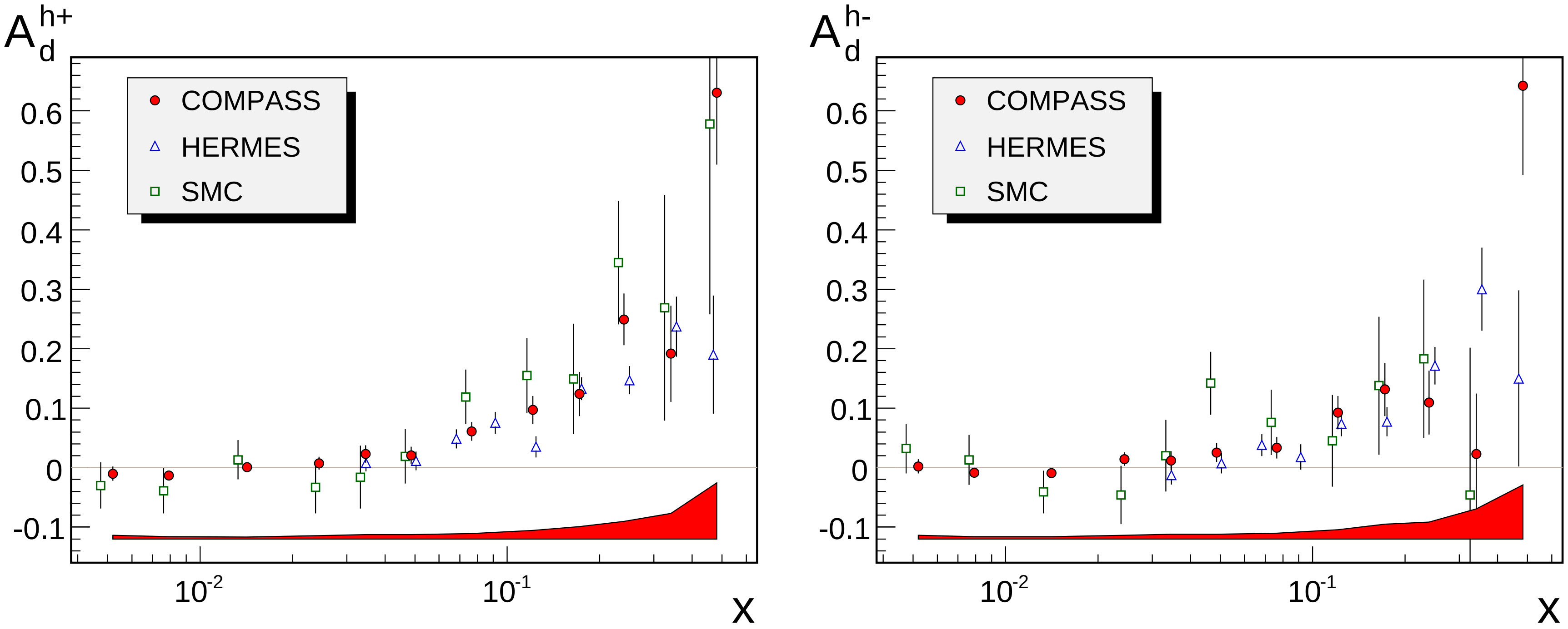
- negative strange sea polarisation

Semi-inclusive asymmetries

Hadron asymmetries

$$A_1^h(x) = \frac{\sum_q e_q^2(\Delta q(x) D_q^h + \Delta\bar{q}(x) D_{\bar{q}}^h)}{\sum_q e_q^2(q(x) D_q^h + \bar{q}(x) D_{\bar{q}}^h)}$$

$$A^+ = \frac{\sigma_{\uparrow\downarrow}^{h+} - \sigma_{\uparrow\uparrow}^{h+}}{\sigma_{\uparrow\downarrow}^{h+} + \sigma_{\uparrow\uparrow}^{h+}} \qquad A^- = \frac{\sigma_{\uparrow\downarrow}^{h-} - \sigma_{\uparrow\uparrow}^{h-}}{\sigma_{\uparrow\downarrow}^{h-} + \sigma_{\uparrow\uparrow}^{h-}}$$



- **selection:** $Q^2 > 1$ (GeV/c)^2, $0.1 < y < 0.9$, $0.2 < z < 0.85$
- **events:** $N^+ = 30 \cdot 10^6$, $N^- = 25 \cdot 10^6$, $corr(N^+, N^-) \approx 20\%$
  (PLB 660 (2008) 458)

Difference asymmetry

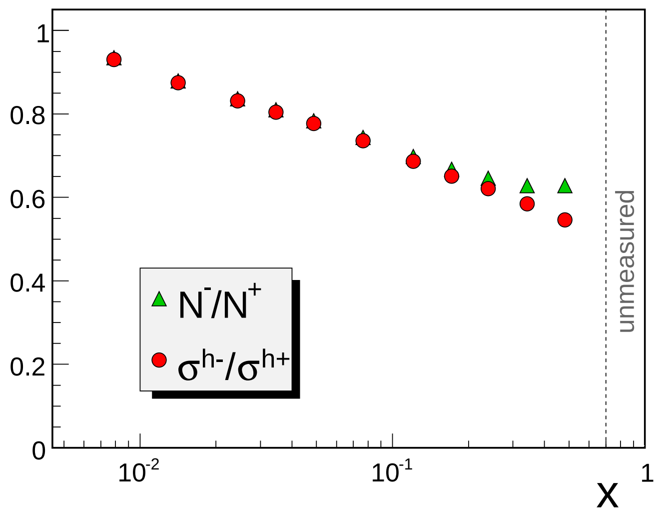
$$A^{+-} = \frac{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) - (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}{(\sigma^{h+}_{\uparrow\downarrow} - \sigma^{h-}_{\uparrow\downarrow}) + (\sigma^{h+}_{\uparrow\uparrow} - \sigma^{h-}_{\uparrow\uparrow})}$$

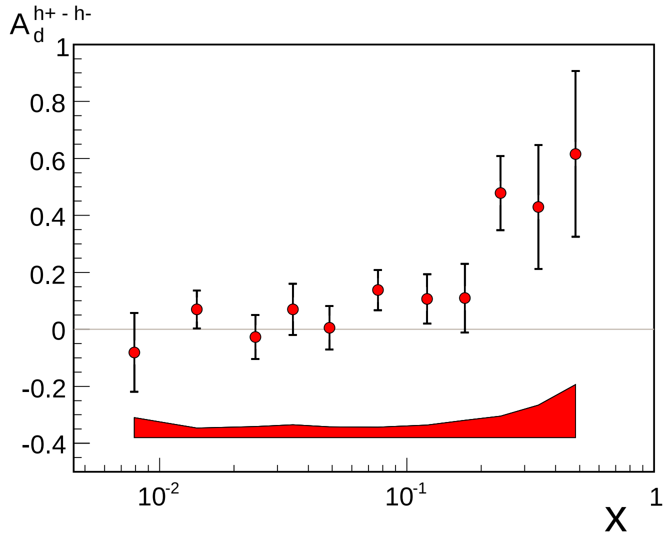
- LO analysis: fragmentation functions cancel, for deuteron PID not neccessary

$$A_d^{\pi^+-\pi^-}(x) = A_d^{K^+-K^-}(x) = \frac{\Delta u_v(x) + \Delta d_v(x)}{u_v(x) + d_v(x)}$$

- A^{+-} asymmetry obtained from A^+ and A^- asymmetries

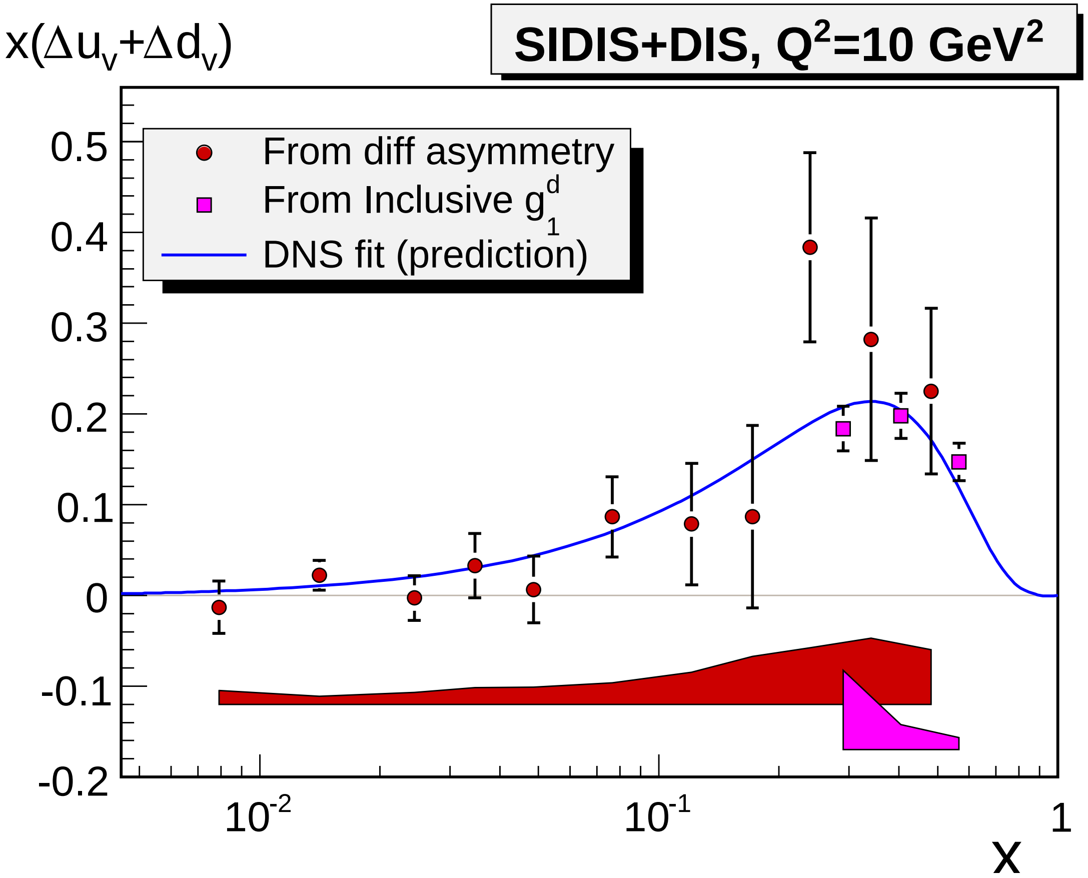
$$A^{+-} = \frac{1}{1-r}(A^+ - rA^-) \quad \text{with} \quad r = \frac{\sigma^{h-}_{\uparrow\downarrow} + \sigma^{h-}_{\uparrow\uparrow}}{\sigma^{h+}_{\uparrow\downarrow} + \sigma^{h+}_{\uparrow\uparrow}} = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-/a^-}{N^+/a^+}$$





Polarised valence distribution

$$x(\Delta u_v(x) + \Delta d_v(x)) = \frac{x(u_v(x) + d_v(x))}{(1 + R(x))(1 - 1.5\omega_{\mathrm{D}})} A^{+-}(x)$$



- evolved to $Q^2 = 10$ (GeV/c)^2
- using LO DNS parameterization (PRD 71(2005)094018)
- DNS predicts COMPASS data
- for $u_v + d_v$ MRST04(LO) used

- sea very small at large x, with inclusive asymmetry much better precision

$$\Delta u_v + \Delta d_v = \frac{36}{5} \frac{g_1^d(x, Q^2)}{(1 - 1.5\omega_{\mathrm{D}})} - \left[2(\Delta\bar{u} + \Delta\bar{d}) + \frac{2}{5}(\Delta\bar{s} + \Delta\bar{s})\right]$$

Polarised valence distribution

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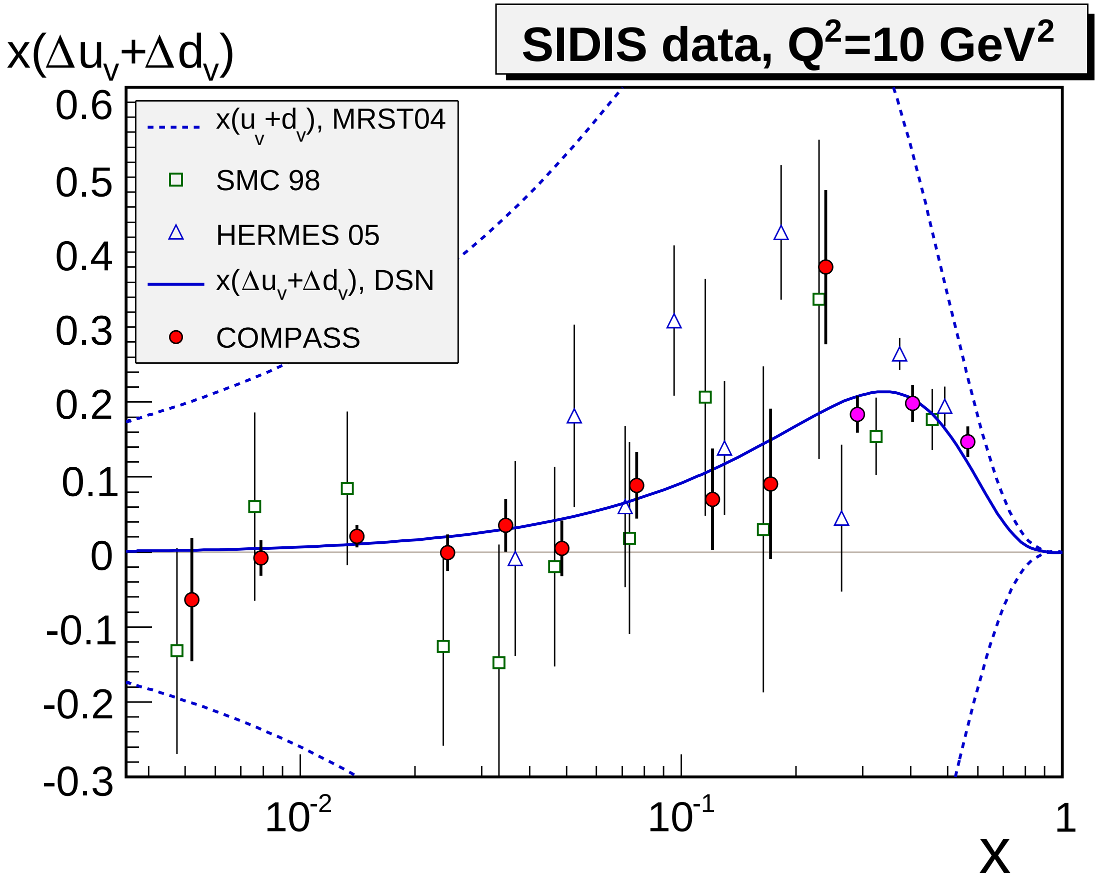

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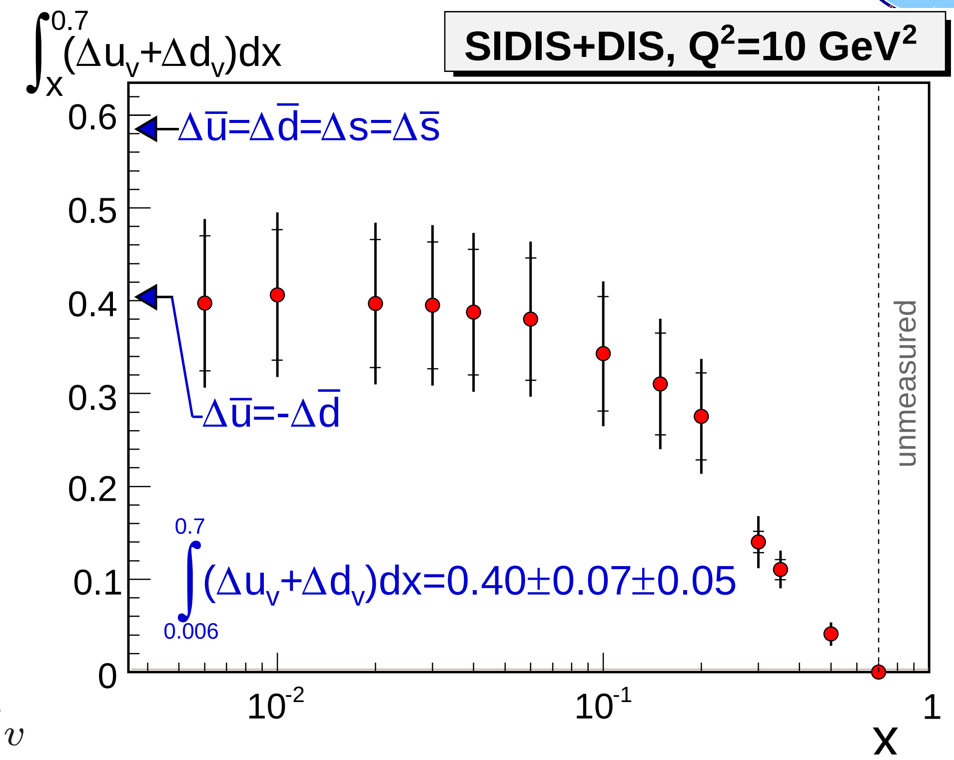
Towards polarised sea quarks

- first moment

$$\Gamma_v = \int_0^1 (\Delta u_v(x) + \Delta d_v(x))\mathrm{d}x$$



- contribution from $0.7 < x < 1$ about 0.004 (DNS fit)
- combining with Γ_1^{N} and a_8

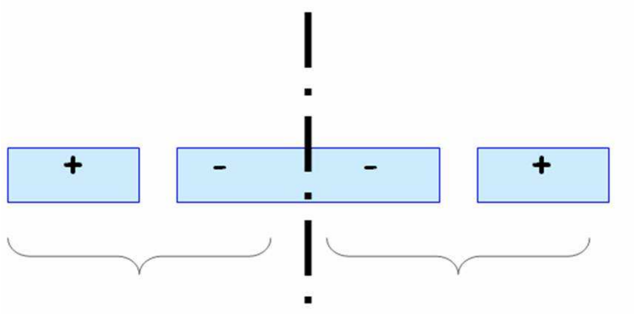
$$\Delta\bar{u} + \Delta\bar{d} = 3\,\Gamma_1^{\mathrm{N}} - \frac{1}{2}\Gamma_v + \frac{1}{12}a_8$$

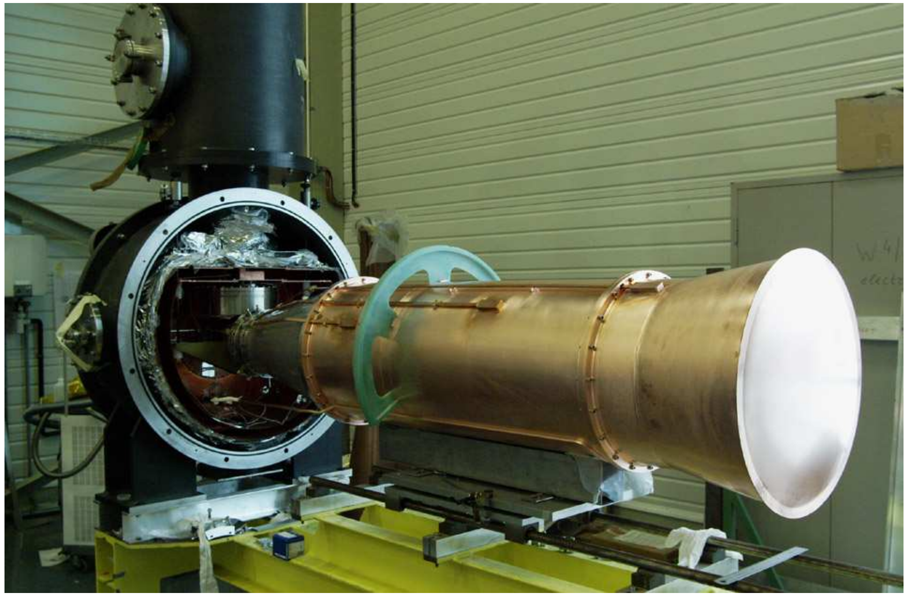
$$= (\Delta s + \Delta\bar{s}) + \frac{1}{2}(a_8 - \Gamma_v$$

- disentangle between flavour **symmetric** ($\Delta\bar{u}=\Delta\bar{d}=\Delta s=\Delta\bar{s}$) and **asymmetric** ($\Delta\bar{u}=-\Delta\bar{d}$) sea
- Γ_v is 2.5 σ_{stat} away from flavour **symmetric** sea scenario, **asymmetric** sea favoured
- next step: $\mathrm{K}^{\pm}$ asymmetries $\longrightarrow \Delta s$

Data 2006/7

Upgrade 2006: polarised target

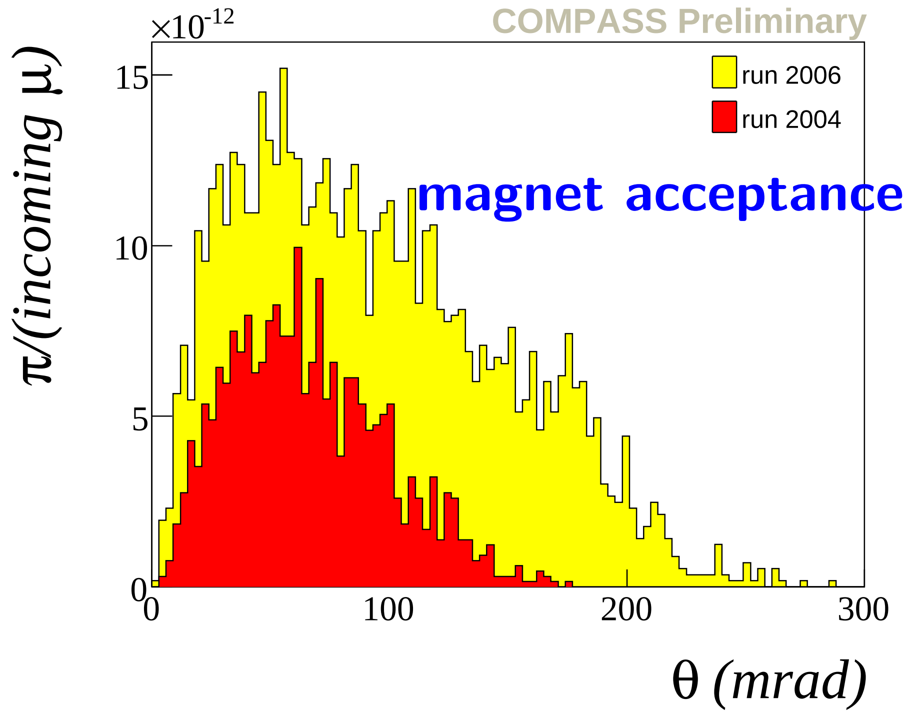


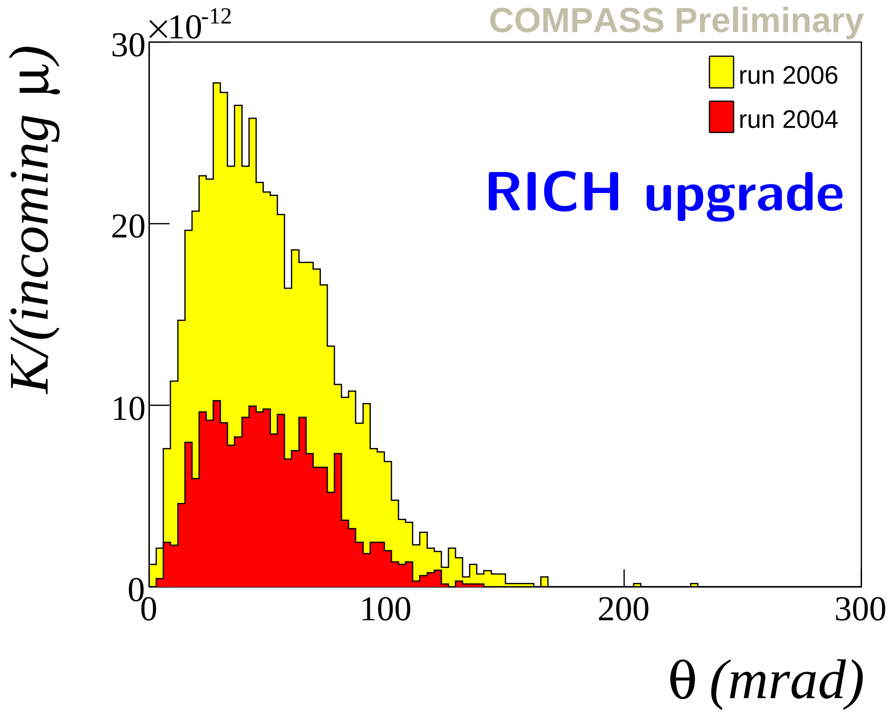


- new target magnet: COMPASS (180 mrad)
- gain in statistics at least 30%
- excellent field homogeneity
- to match larger acceptance: new microwave cavity
- 3 target cells: reduction of false asymmetries

Upgrade 2006: spectrometer

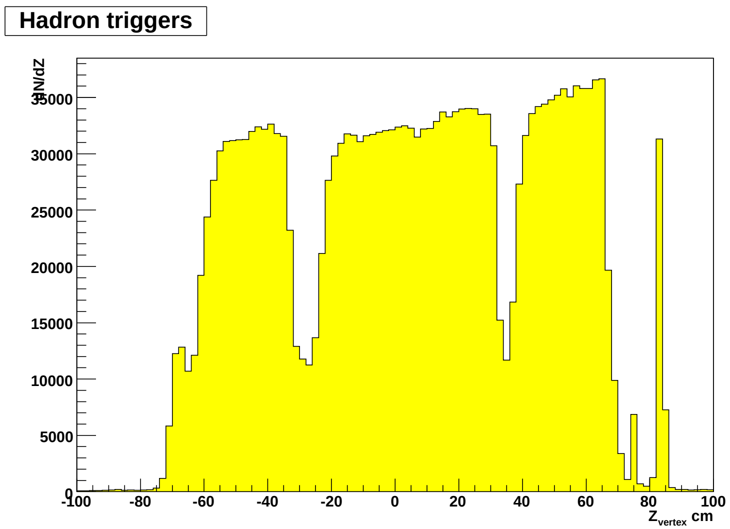
- **RICH1**:
  - central photon detectors replaced by MAPMTs
  - new read out using APVs for outer photon detectors
- **RICH wall**: preshower for ECAL1
- **ECAL1**: Electromagnetic calorimeter in first stage
- More **large angle tracking** in first stage
- **event gains**

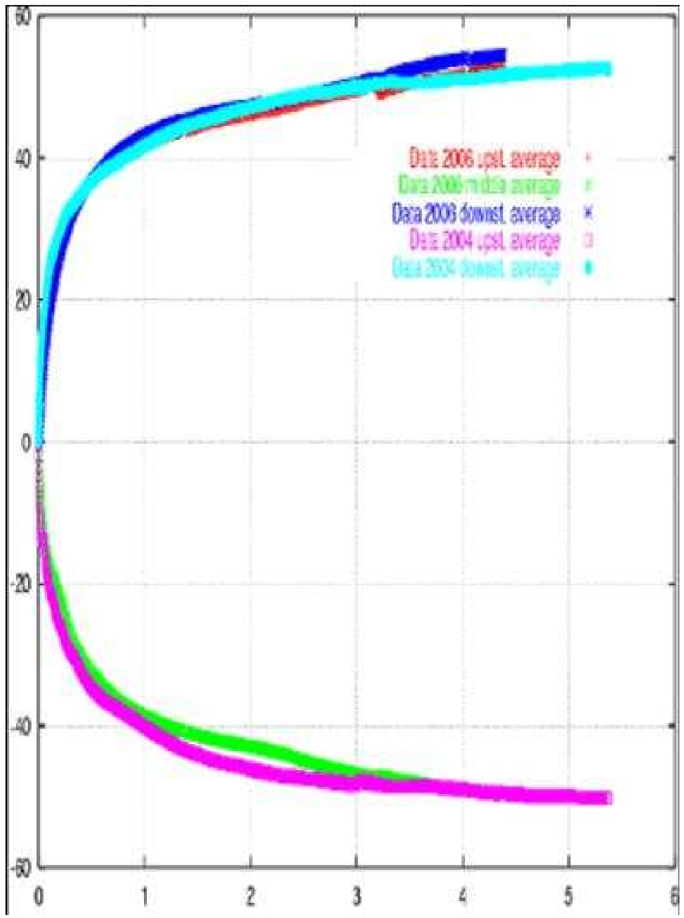




Data taking 2006

- target material: LiD
- longitudinal polarisation
- increase of 2002-2004 statistics by about 40%
- larger increase at high x and Q^2 (acceptance)
- reconstruction finished, first results



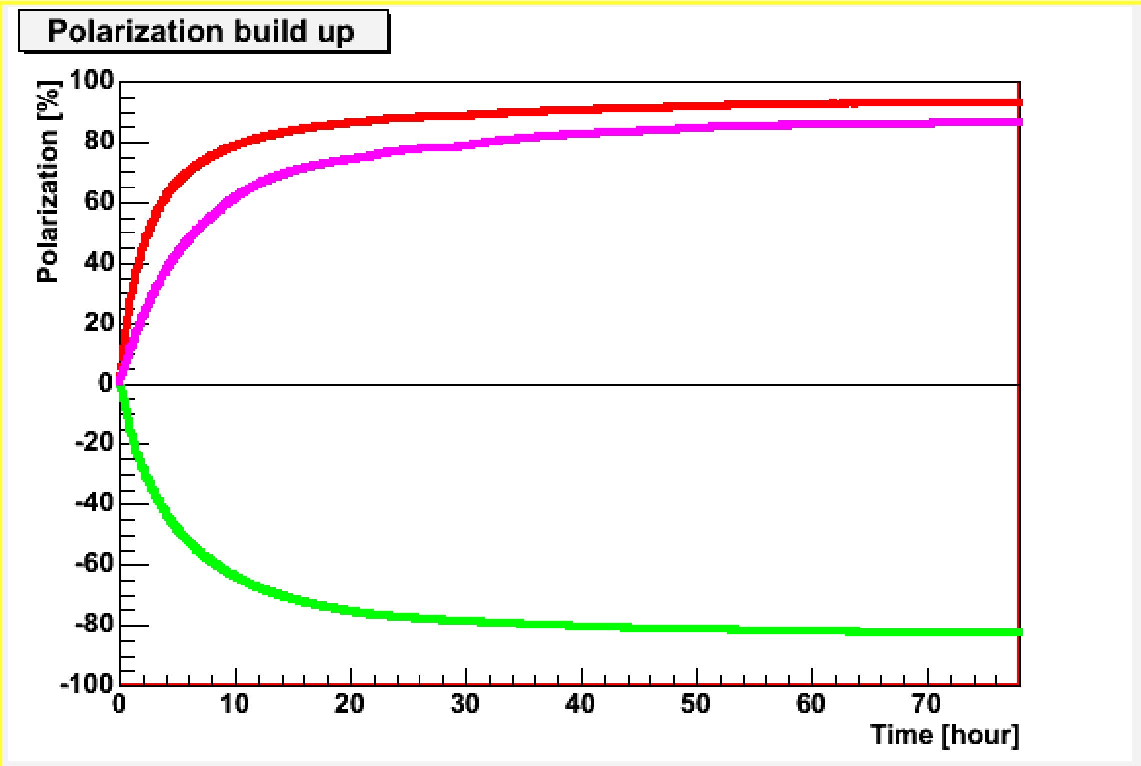


Polarisation of ^{6}LiD in 2006:
53.5%, -52%, 56.2%

higher and faster than in 2004

Data taking 2007

- longitudinal and transverse polarisation
- new trigger using ECAL1
- integrated beam flux about 30% of 2002–2006



- **target material: NH_3**
- difficult to handle
- high polarisation
- very long relaxation time (~ 4000 h)
- magnetic field rotation without polarisation loss

Polarisation of NH_3 in 2007: +92%, +88%, -83%

Main Goals

- **longitudinal target polarisation:**

  flavour separation of PDFs

  sign of **strange** sea polarisation at low x

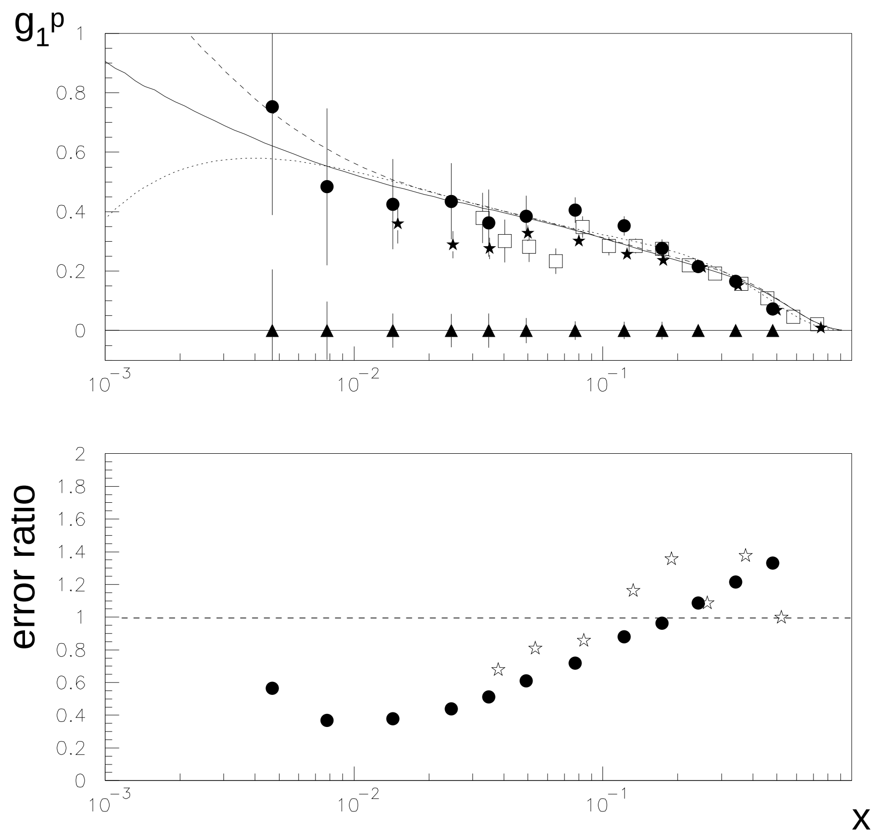
  shape of g_1^p at low x

- **transverse target polarisation:**

  Collins and **Sivers** asymmetries

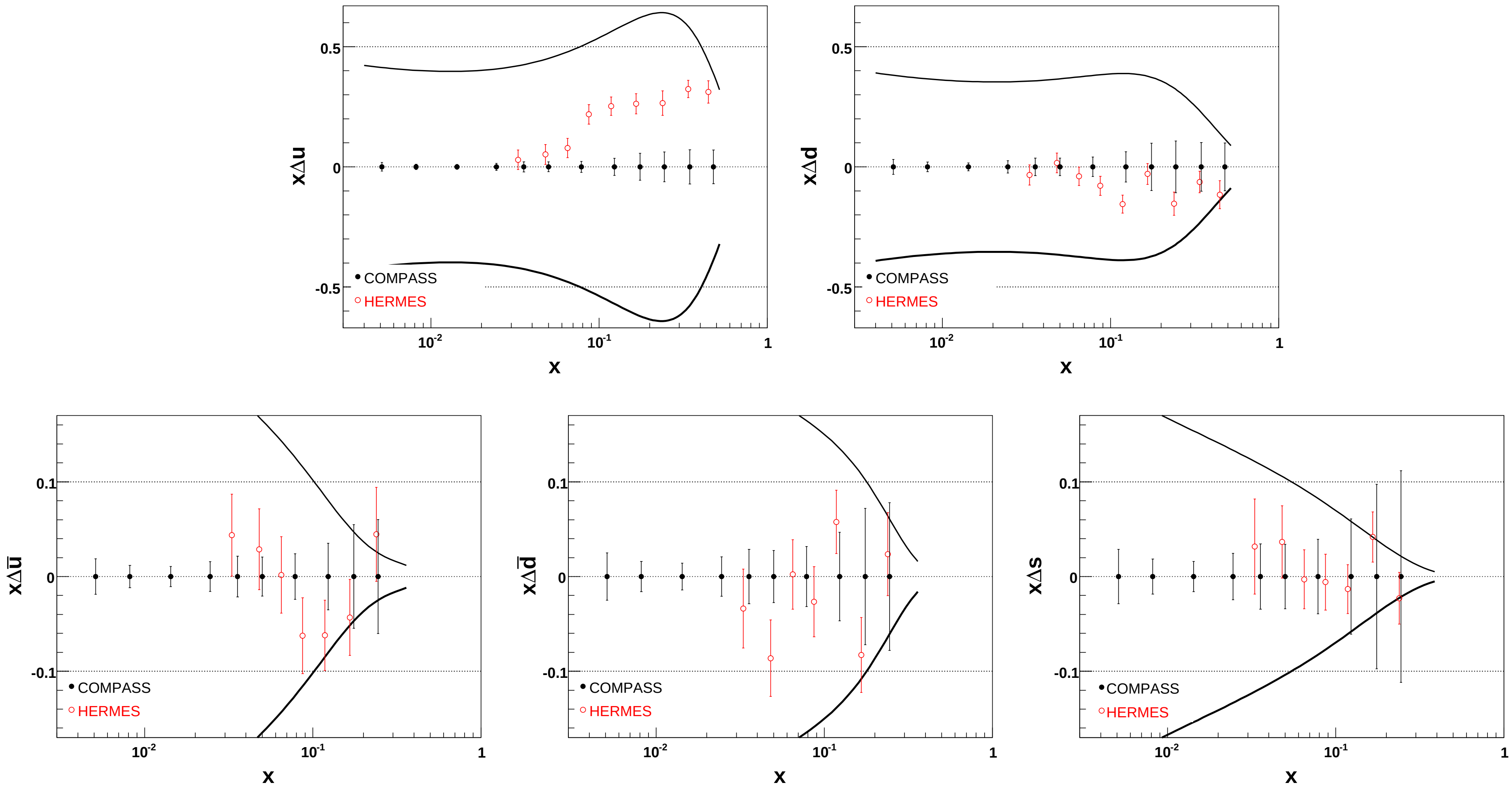
  flavour separation

g_1^p at low x



significant improvement in QCD evolution possible

Expectations with 2007 p and 2002–2006 d



COMPASS unique at small x

Summary

- Results from 2002–2004 deuteron data
- Inclusive and semi-inclusive data discussed
- First moment of g_1^{d} and QCD-analysis
- Valence quark polarisation from difference asymmetry
- many more results from 2006 and 2007 data to come

2007 p and 2002–2006 d

Expected precision of polarised PDF integrals:

range	$0.004 < x < 0.03$	$0.004 < x < 0.7$
$\delta(\delta u_V)$	0.020	0.07
$\delta(\delta d_V)$	0.036	0.11
$\delta(\delta \bar{u})$	0.013	0.04
$\delta(\delta \bar{d}$	0.017	0.05
$\delta(\delta s)$	0.03	0.09