

# The Spin-dependent Structure Function of the deuteron, $g_1(x, Q^2)$

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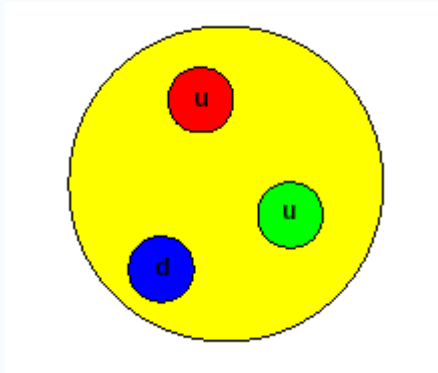
V Encontro Nacional de Física Hadrónica, FEUP-Porto, 18 de Maio de 2005

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# Outline

- The nucleon spin
- Generalities on Deep Inelastic Scattering
- The COMPASS experiment
- Inclusive asymmetries
- The  $g_1$  structure function

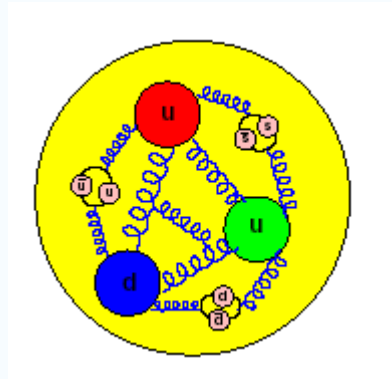
# The Nucleon Spin



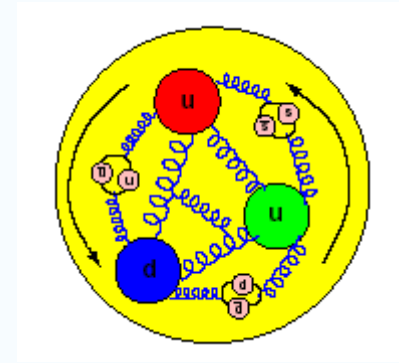
naïve parton model:

$$\Delta\Sigma = \Delta u + \Delta d = 1$$

EMC (1988):  $\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$



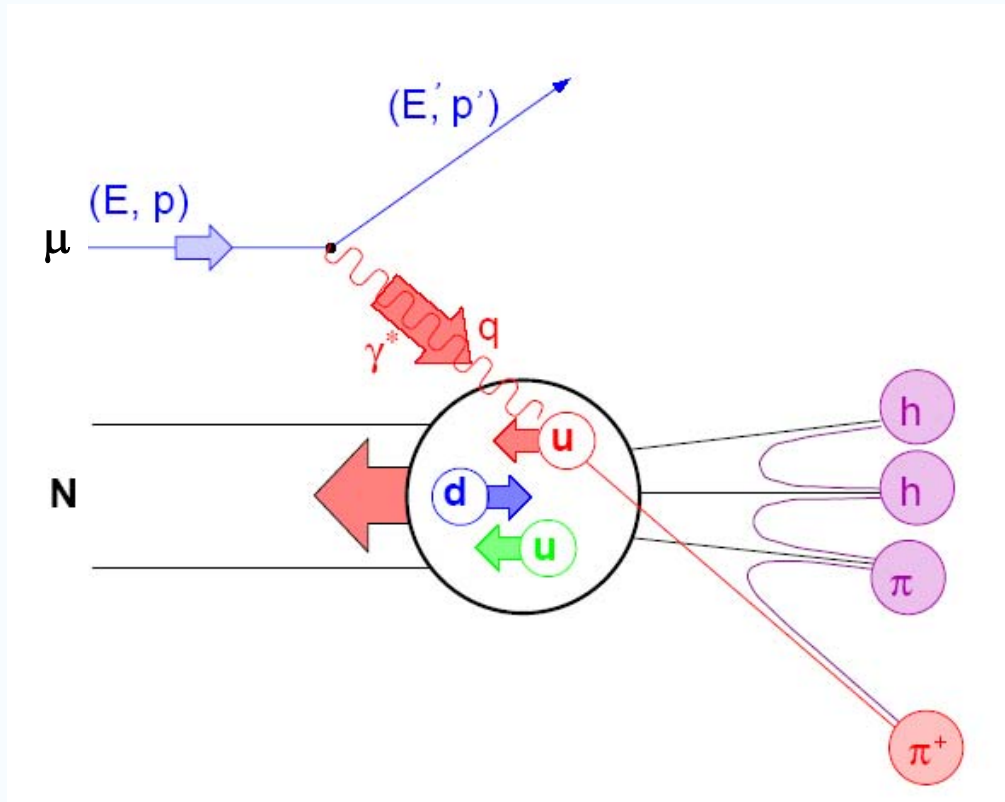
gluons are important



complete description:  
orbital angular momenta

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

# Deep Inelastic Scattering



$$Q^2 = -q^2$$

$$\nu = E - E'$$

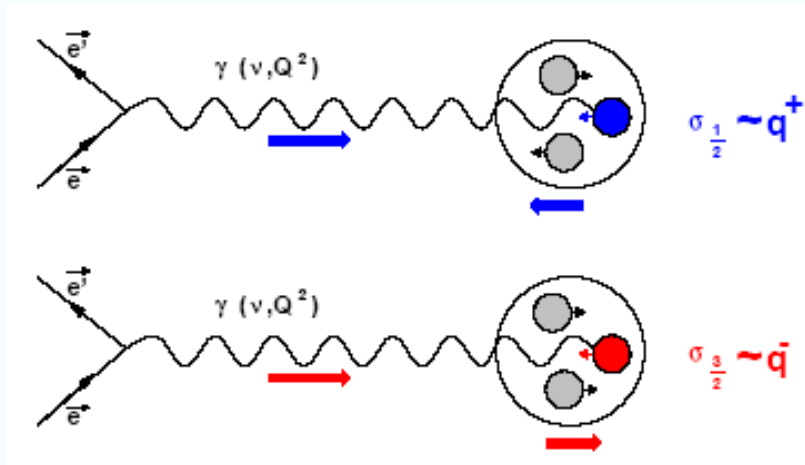
$$x = Q^2 / 2M\nu$$

$$y = \nu / E$$

$$z = E_h / \nu$$

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

# Polarised Deep Inelastic Scattering



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

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

+: quark  $\uparrow\uparrow$  nucleon

-: quark  $\uparrow\downarrow$  nucleon

photon-nucleon asymmetry

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

# The COMPASS Collaboration

(230 Physicists from 12 Countries)

Dubna (LPP and LNP), Moscow (INR, LPI, State University), Protvino



CERN



Bielefeld, Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Heidelberg, Mainz, München (LMU & TU)

Warsaw (SINS), Warsaw (TU)



Prag



Helsinki

Nagoya



Lisboa



CEA-Saclay

Torino (University, INFN), Trieste (University, INFN)



Tel Aviv



Burdwan, Calcutta

# COMPASS fixed target experiment at CERN

muons

$2 \cdot 10^8 \mu^+ / \text{spill}$  (4.8s / 16.2s)

hadrons  $\pi/K, p$

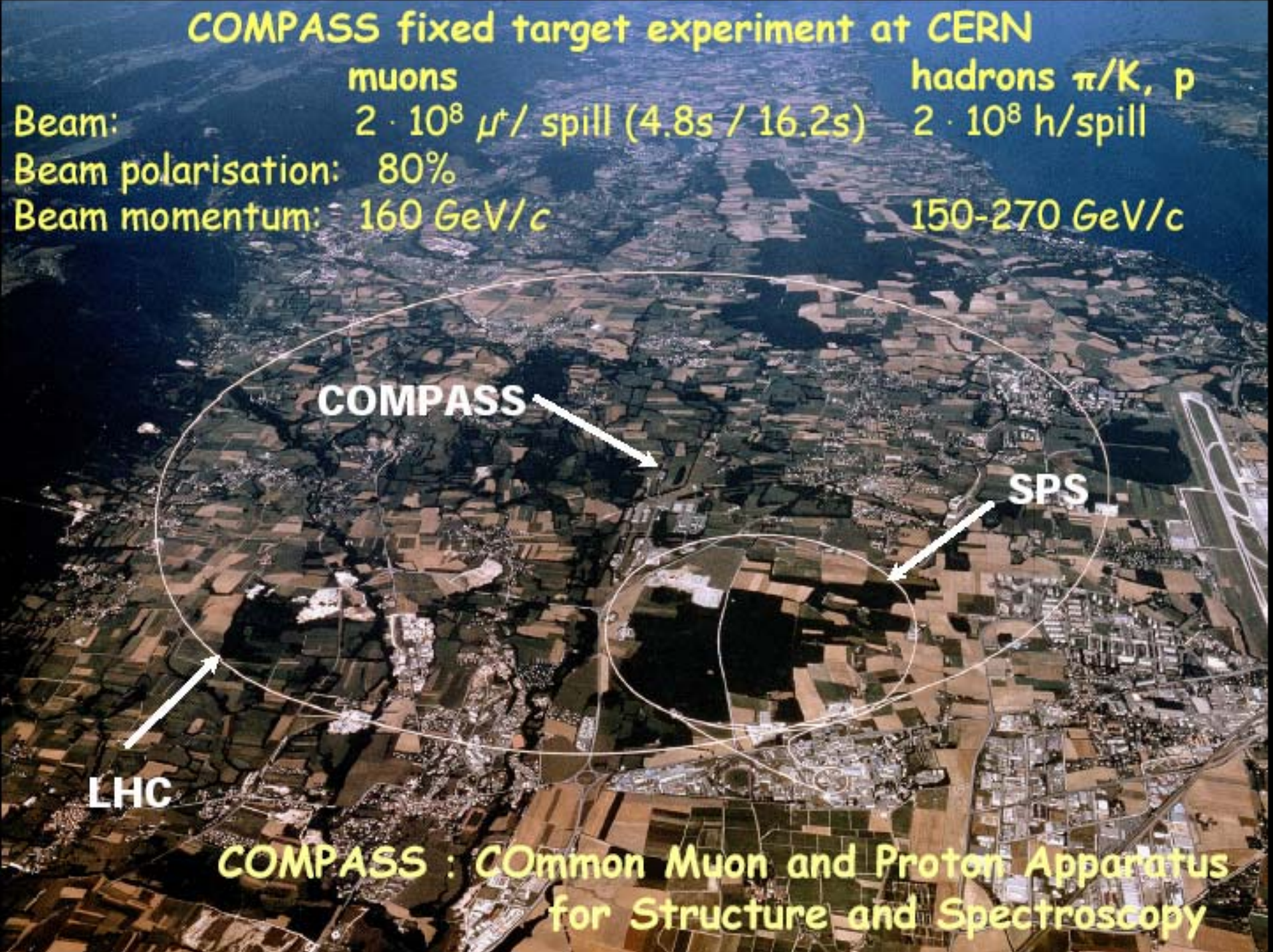
$2 \cdot 10^8 h / \text{spill}$

Beam:

Beam polarisation: 80%

Beam momentum: 160 GeV/c

150-270 GeV/c



COMPASS

SPS

LHC

COMPASS : COMMon Muon and Proton Apparatus  
for Structure and Spectroscopy

# The Compass Experimental Program

## muon beam

### nucleon spin structure

- Transversity
- $\Delta G$  (L. Silva talk)
- Semi-inclusive channels
- Inclusive  $\mu$  channel (this talk)
- vector-meson production
- Spin transfer in  $\Lambda$  production (C. Franco talk)

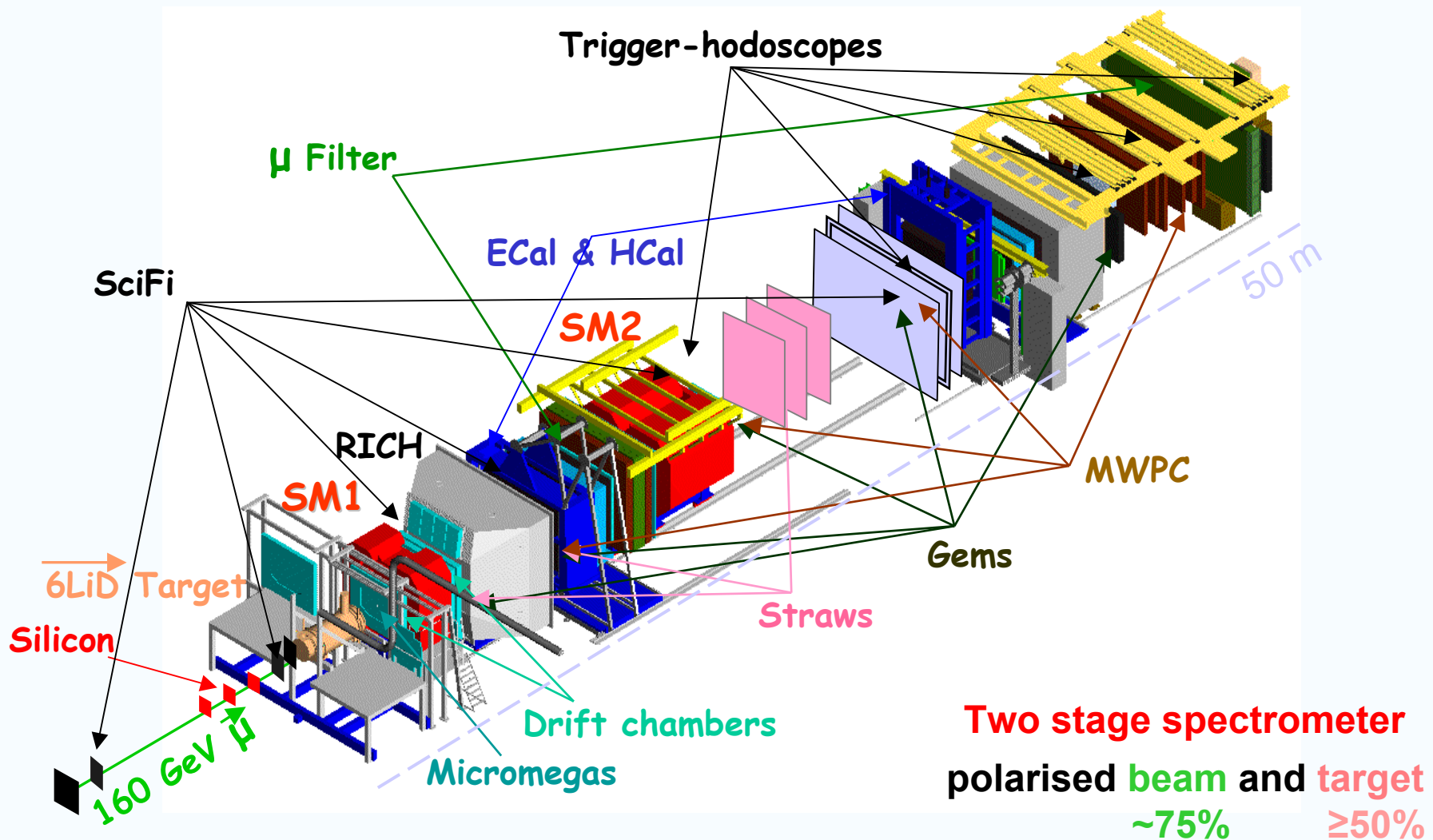
## hadron beam

### nucleon spectroscopy

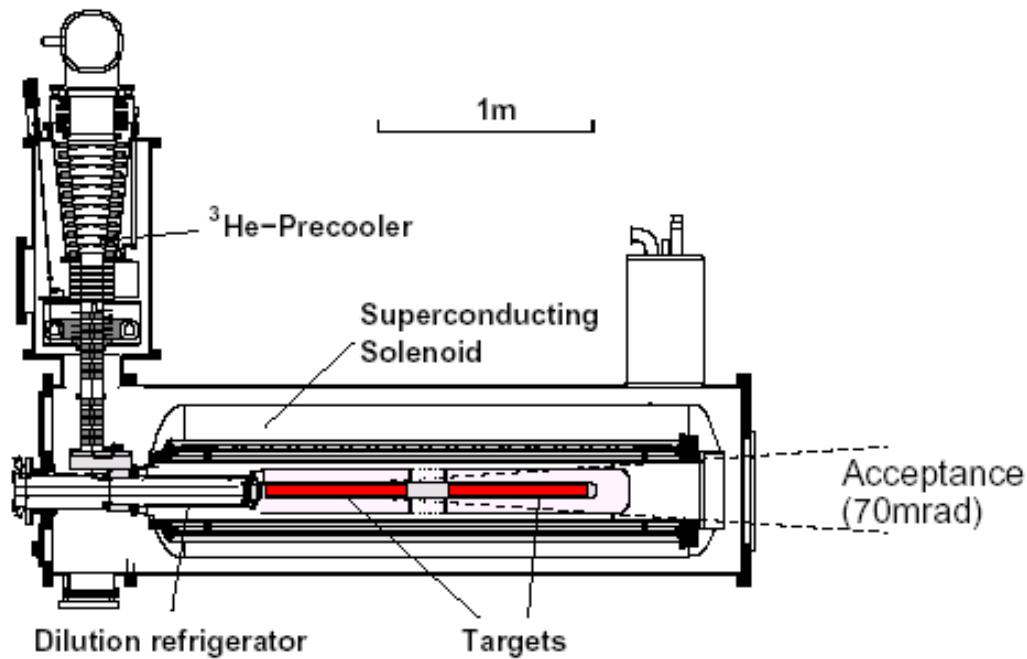
- Primakoff reactions:
  - Polarizability of  $\pi$  and K
- Exotics:
  - glue balls and hybrids
- Charmed mesons and baryons



# The COMPASS Spectrometer



# The Target System



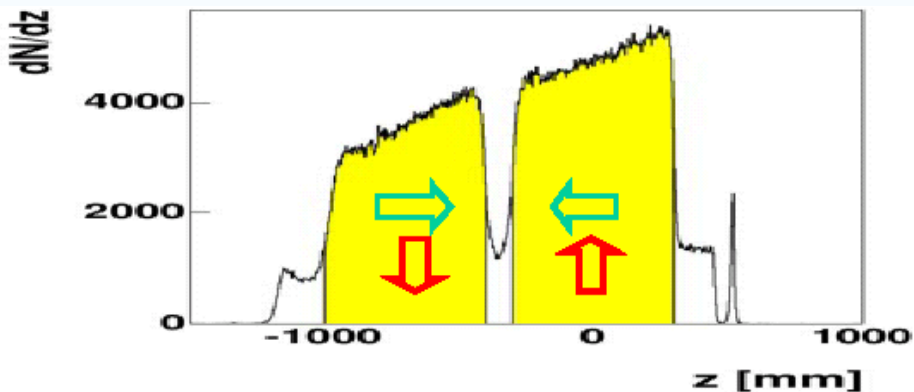
Two 60 cm long target cells with opposite polarisation

Target material:  $^6\text{LiD}$

Polarisation  $\sim 50\%$

Solenoid field: 2.5 T

$^3\text{He}/^4\text{He}$ :  $T_{\text{min}} \sim 50\text{mK}$



New solenoid with 180 mrad acceptance in 2006

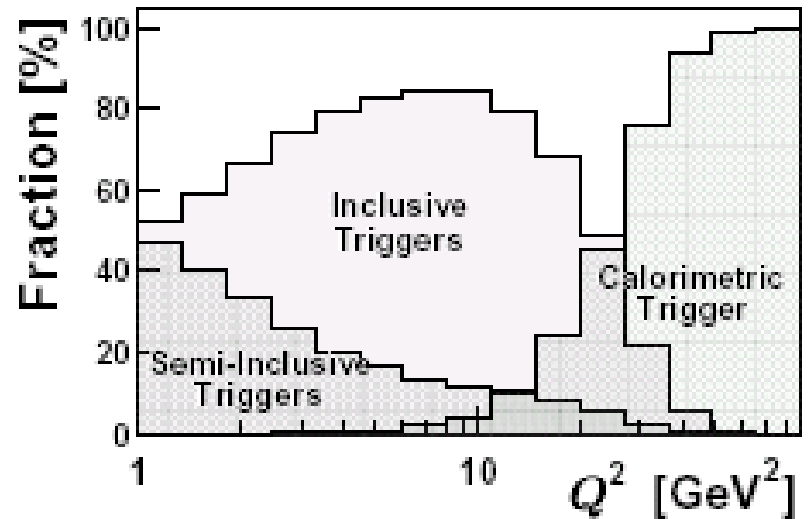
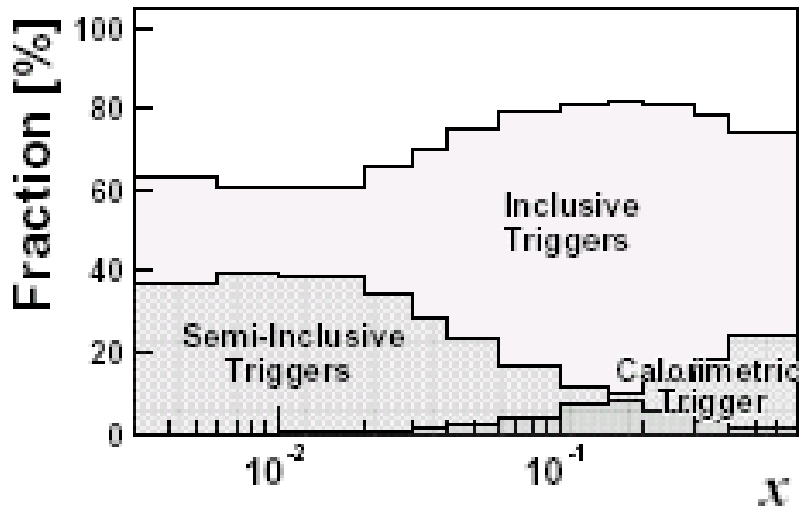
# The COMPASS Trigger System

- 3 types of triggers
  - Inclusive triggers: direction of scattered  $\mu$  behind SM2
  - Semi-inclusive triggers:  $\mu$  energy Loss + hadron signal in HCAL
  - Calorimetric triggers: hadron signal in calorimeter

for all cases: beam  $\mu$  + scattered  $\mu$  + interaction in target

for semi-inclusive and calorimetric triggers: in addition, at least 1 hadron at interaction point

# Fraction of the Various Triggers



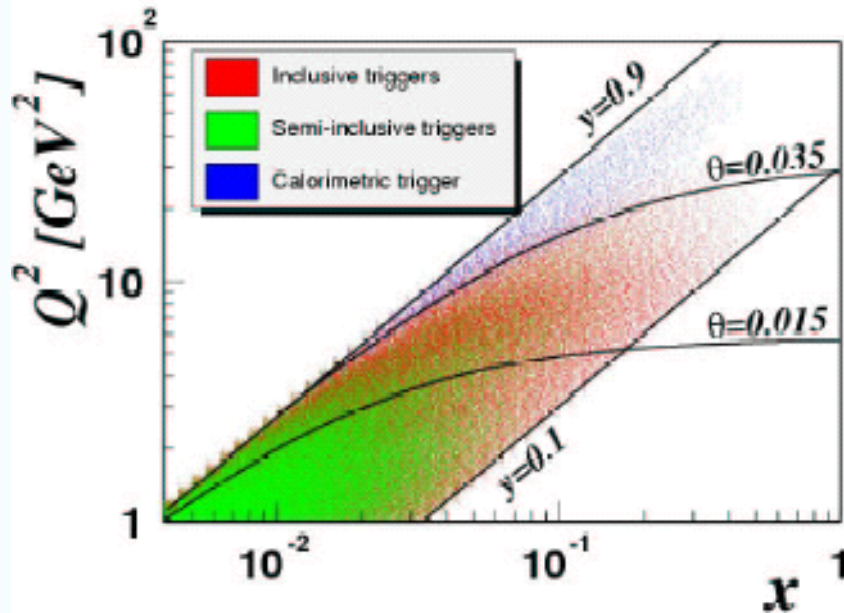
60–75% of inclusive triggers over the full range of  $x$

Semi-inclusive triggers dominant at low  $x$  and low  $Q^2$

Calorimetric triggers dominant for  $Q^2 > 30 \text{ GeV}^2$

# Kinematic Domain

- $E_{\mu} \in [140, 180] \text{ GeV}$
- (Invariant mass)<sup>2</sup> of the virtual photon:  $Q^2_{\min} > 1 \text{ GeV}^2$
- Fraction of the energy carried by the virtual photon,  
 $y = (E_{\mu} - E_{\mu'}) / E_{\mu} : 0.1 < y < 0.9$ 
  - $\Rightarrow E_{\text{lab}}$  of the virtual photon:  $v \in [14 - 162] \text{ GeV}$
  - $\Rightarrow$  Bjorken scaling variable:  $x_{Bj} = Q^2 / 2Mv : 0.003 - 0.7$



Statistics of DIS data (2002+2003):  
 $34 \times 10^6$  events

# Experimental Asymmetry

$$A^d = D(A_1^d + \eta A_2^d), \quad A_2^d = \sigma_{TL} / \sigma_T \quad (d \equiv \text{deuteron})$$

$$\eta = \frac{2(1-y)}{y(2-y)} \sqrt{Q^2} / E_\mu, \quad y = \frac{\nu}{E_\mu}$$

$\eta$  is small in the COMPASS kinematic range, as well as  $A_2$

$$A_1^d \simeq \boxed{A^d} / D$$

$$A_1^d = \frac{1}{D} \frac{1}{P_B P_T f} \left( \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} - \frac{N'^{\uparrow\downarrow} - N'^{\uparrow\uparrow}}{N'^{\uparrow\downarrow} + N'^{\uparrow\uparrow}} \right)$$

$P_B \equiv$  Beam polarisation

$P_T \equiv$  Target polarisation

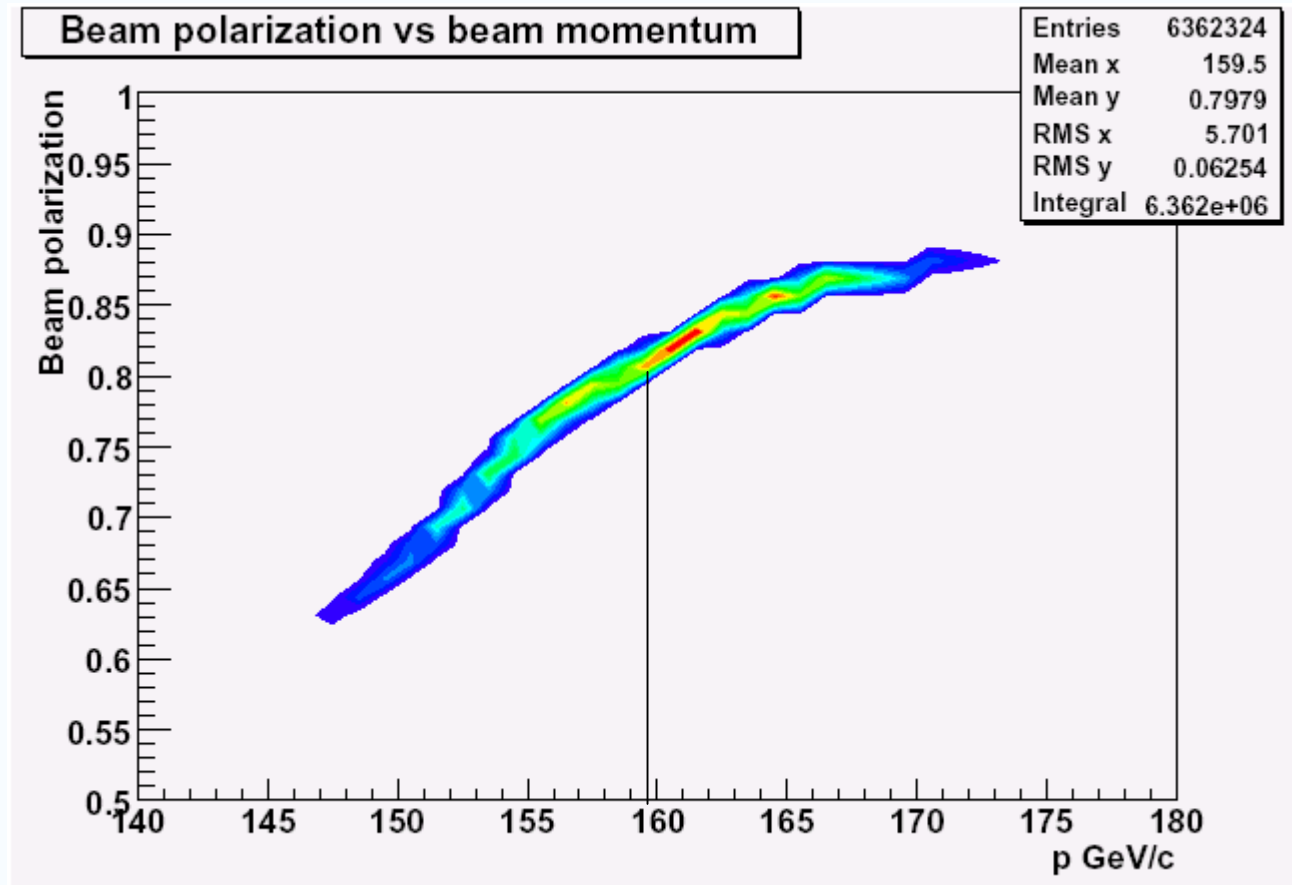
$f \equiv$  Dilution factor

$D \equiv$  Depolarisation factor

$\uparrow\downarrow \equiv$  1<sup>st</sup> cell (polarised anti-parallel to beam),  $\uparrow\uparrow \equiv$  2nd cell (polarised parallel to beam)

# The Beam Polarisation

As computed by MC simulations



The average beam polarisation is 80%

# The Dilution Factor of the COMPASS ${}^6\text{LiD}$ Target

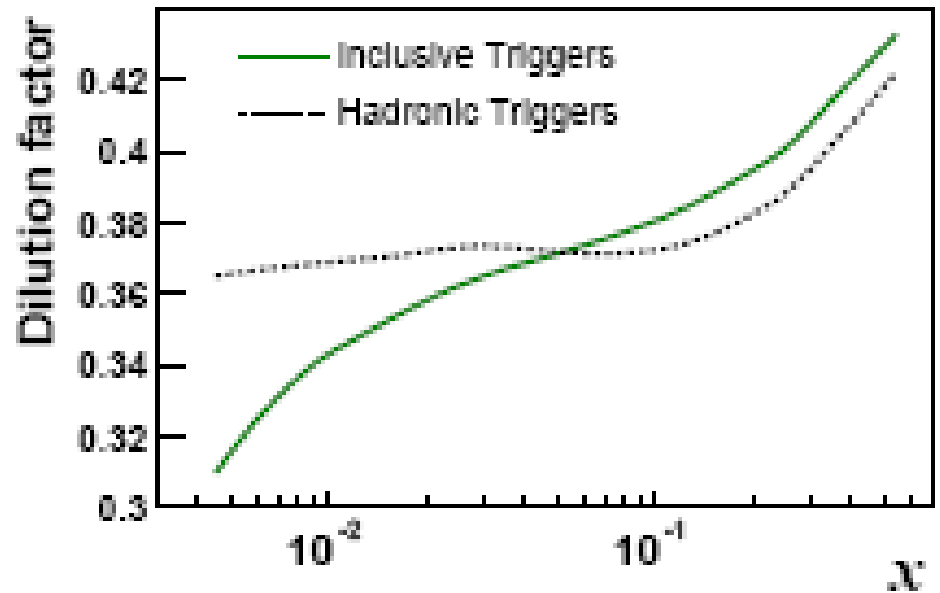
${}^6\text{LiD} \sim {}^4\text{He} + \text{D} \rightarrow$  naïve expectation  $f({}^6\text{LiD}) \sim 0.5$

$$f = \frac{n_d \bar{\sigma}_d^{\text{Tot}}}{n_d \bar{\sigma}_d^{\text{Tot}} - \sum_A n_A \bar{\sigma}_A^{\text{Tot}}} = \frac{n_d}{n_d - \sum_A n_A \frac{\bar{\sigma}_A^{\text{Tot}}}{\bar{\sigma}_d^{\text{Tot}}}}$$

$A = {}^1\text{H}, {}^2\text{H}, {}^3\text{He}, {}^4\text{He}, {}^6\text{Li}, {}^7\text{Li}, \text{C}, \text{F}, \text{Ni}$   
and  $\text{Cu}$

$$\bar{\sigma}^{\text{T}} = \bar{\sigma}^{\text{1}\gamma} + \bar{\sigma}^{\text{tail}}$$

$$\bar{\sigma}^{\text{tail}} = \bar{\sigma}_{\text{el}}^{\text{tail}} + \bar{\sigma}_{\text{qel}}^{\text{tail}} + \bar{\sigma}_{\text{inel}}^{\text{tail}}$$





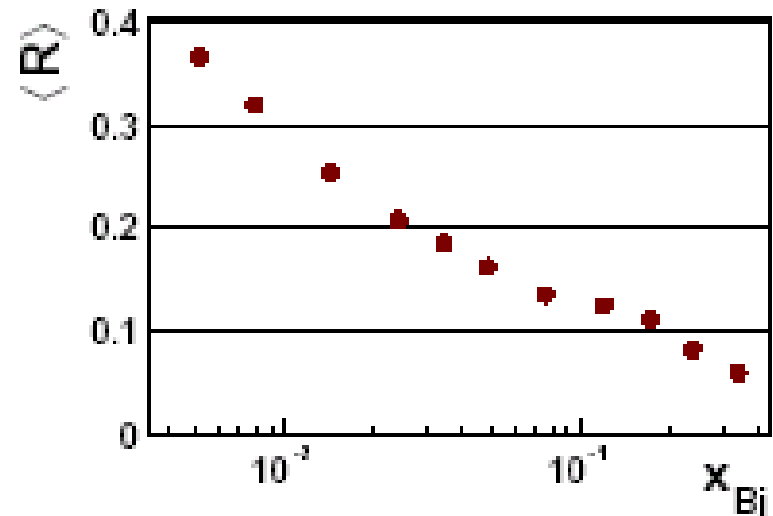
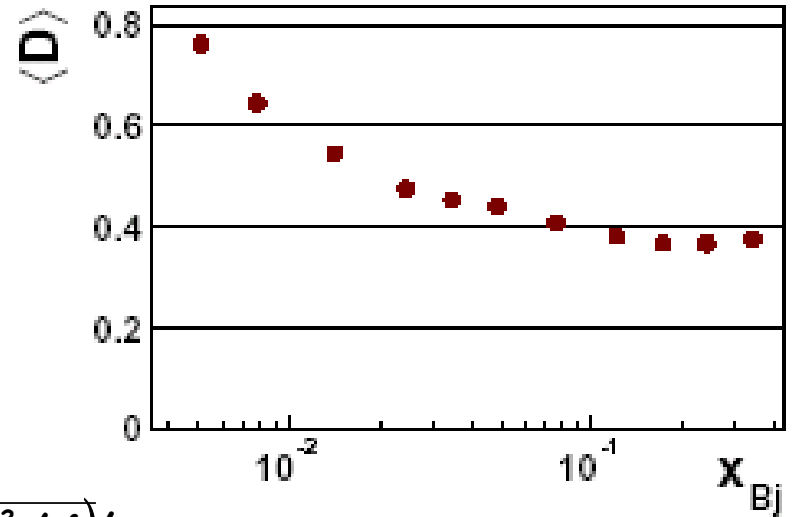
# The Depolarisation Factor

It accounts for polarisation transfer from  $\mu$  to virtual  $\gamma$

$$D = \frac{\gamma(1 + \gamma^2/2)(2 - \gamma) - 2\gamma^2 m_\mu^2 / Q^2}{\gamma^2(1 - 2m_\mu^2 / Q^2)(1 + \gamma^2) + 2(1 + R)(1 - \gamma - \gamma^2/4)}$$

$$\gamma = v / E_\mu, \quad \gamma = \frac{2m_p x_{Bj}}{\sqrt{Q^2}}$$

$$R \equiv R(x_{Bj}, Q^2) = \sigma_L / \sigma_T$$



# $A_1$ Calculation

$$A_1^d = \frac{1}{P_B P_T f D} \left( \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} - \frac{N'^{\uparrow\downarrow} - N'^{\uparrow\uparrow}}{N'^{\uparrow\downarrow} + N'^{\uparrow\uparrow}} \right)$$

Starting point: numbers of detected events, in **upstream** and **downstream** cells ( $N^{\uparrow\downarrow}$ ,  $N^{\uparrow\uparrow}$ )

$$u = \phi a_u n_u \sigma_0 (1 + \omega P_u A) \quad d = \phi a_d n_d \sigma_0 (1 + \omega P_d A)$$

$\phi \equiv$  incident  $\mu$ -flux

$a_u \equiv$  acceptance of the upstream cell,

$n_u \equiv$  number of nucleons in upstream cell

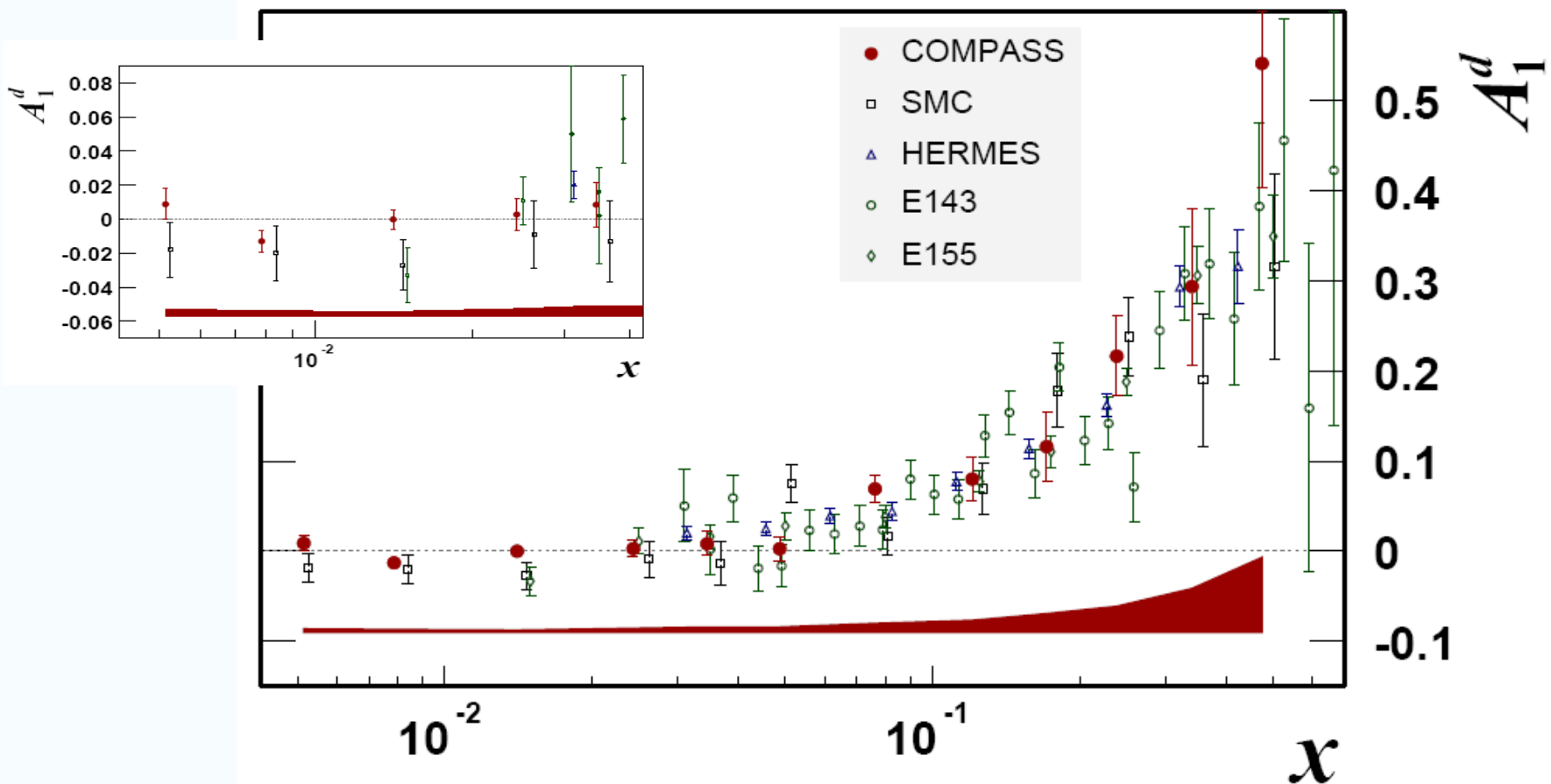
$P_u \equiv$  polarisation of the upstream cell

$\sigma_0 \equiv$  unpolarised cross section

$\omega \equiv P_B f D$

# Inclusive DIS Asymmetry - Results

data taken in 2002 and 2003

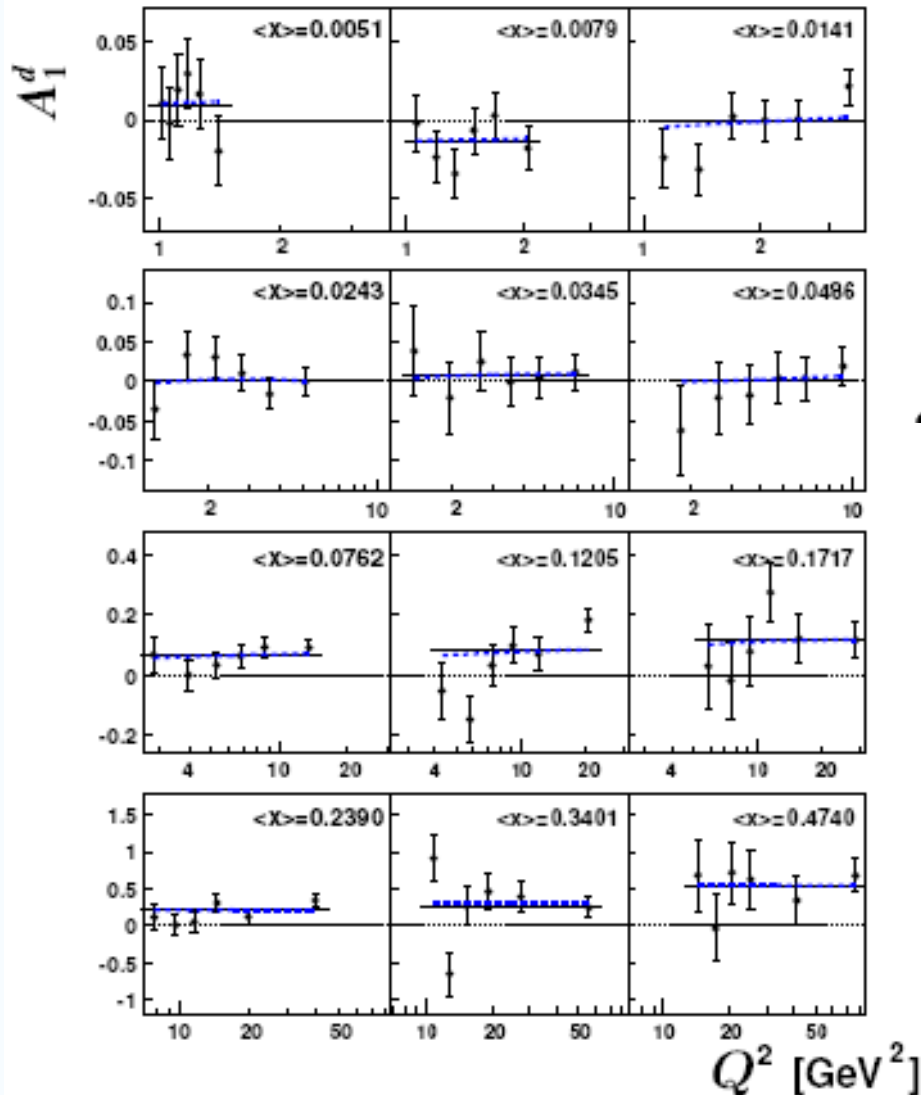


- Good agreement with previous experiments
- Improved statistics at low  $x$

# Main Sources of the Systematic Error

- Beam polarisation ~4-5%
- Target polarisation ~5%
- Dilution factor ~6%
- Depolarisation factor (R) ~4-5%
  
- $A_2$ , RC  $\rightarrow$  small effect
  
- False asymmetries  $< 0.5 \sigma(\text{stat})$

# Inclusive DIS Asymmetry - QCD Analysis



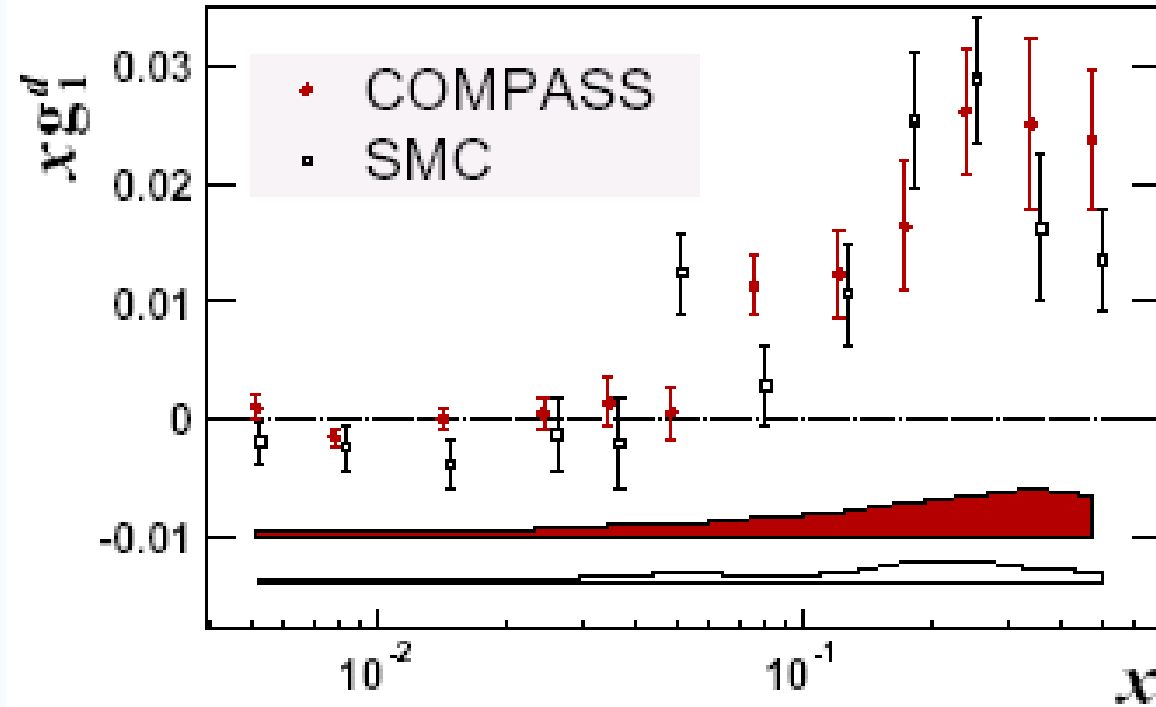
$A_1(x, Q^2)$  almost independent of  $Q^2$

Dashed lines are predictions from QCD perturbative

# The $g_1(x)$ Structure Function

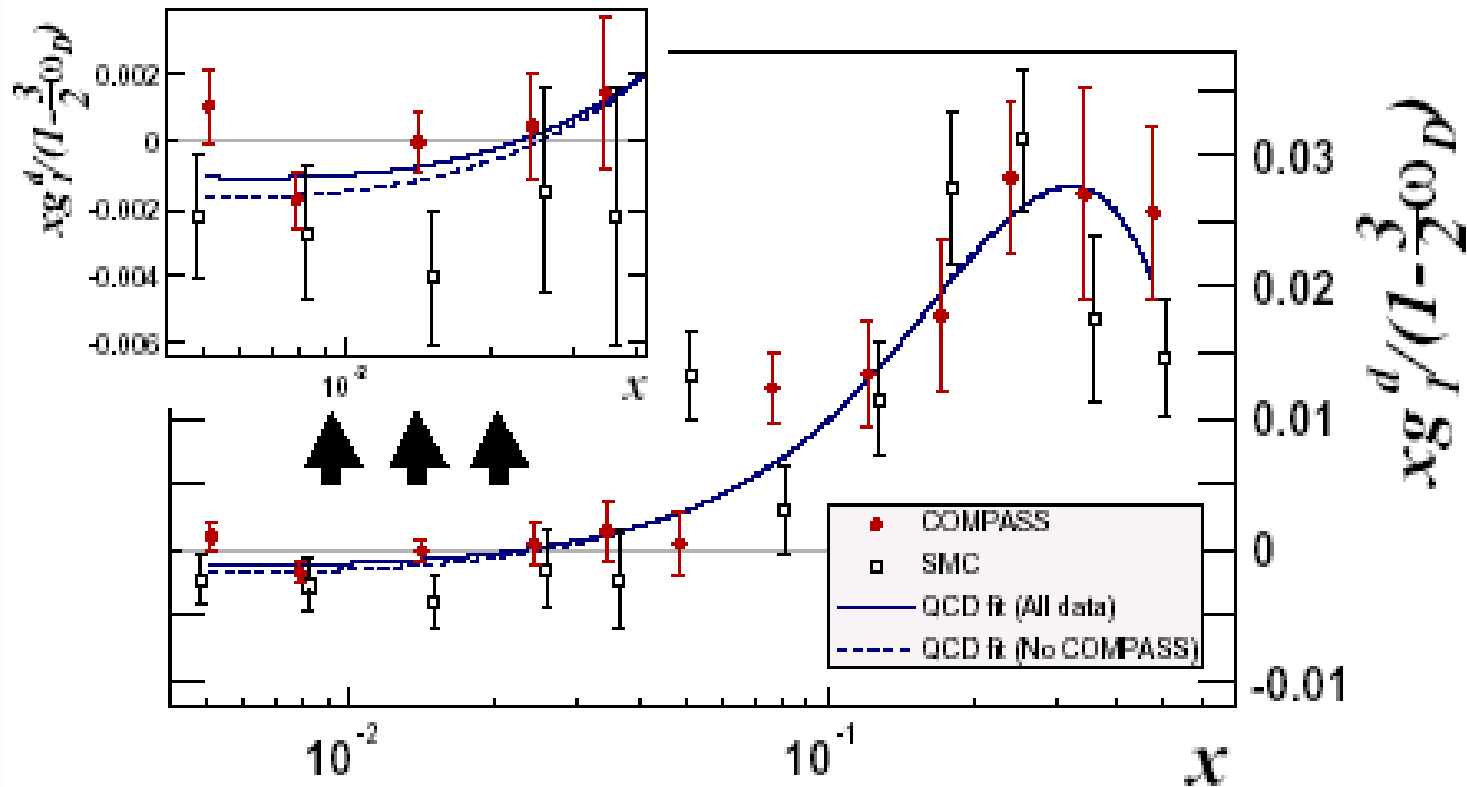
$$g_1(x) = A_1(x) \frac{F_2(x)}{2x(1+R)}$$

Phys.Lett. B612(2005)154



- For  $x < 0.03$  the statistical error is reduced by a factor of 2.5
- COMPASS results show no tendency toward negative values

# COMPASS QCD Fit to the World Data on $g_1(x)$ of the Nucleon



- 200 world data points, **12 from COMPASS**
- NLO analysis ( $\overline{\text{MS}}$  scheme)

# Results from the QCD Fit

➤ QCD fit to the world DIS data on  $g_1(x)$  at  $Q^2=3 \text{ GeV}^2$  and NLO:

$$\Delta\Sigma(\overline{\text{MS}}) = 0.22 \pm 0.03 \text{ without COMPASS data}$$

$$\Delta\Sigma(\overline{\text{MS}}) = 0.25 \pm 0.02 \text{ with COMPASS data}$$

➤ The QCD fit provides an indirect measurement of  $\Delta G$  through the  $Q^2$  evolution of the  $g_1$  structure function

- Needs input parameters from polarised PDFs
- Needs control of systematics

At  $Q^2=3 \text{ GeV}^2$  and from a NLO fit in  $\overline{\text{MS}}$  scheme:

$$\Delta G = 0.4 \pm 0.2 \text{ (stat)}$$



# Summary

- Longitudinal  $A_1$  inclusive asymmetries measured using 2002 & 2003 COMPASS data

→ Improved measurement of the  $g_1$  deuteron structure function giving

$$\Delta\Sigma(\overline{MS}) = 0.25 + 0.02(\text{stat})$$

2004 data analysis is finishing

Data taking continues on 2006