Measurements of the Longitudinal Spin Structure of the Nucleon at COMPASS

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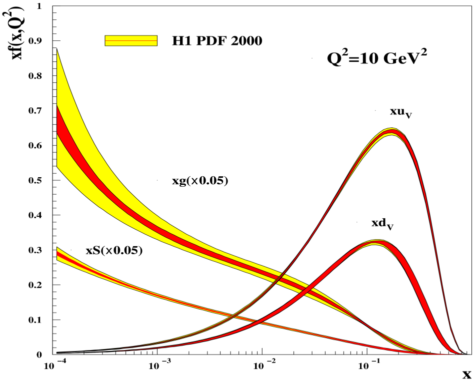
June 18, 2007

Supported by bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung and Maier-Leibnitz-Labor Garching bei München

Outline

1. Physics Introduction
2. The COMPASS Experiment
   - Polarized Muon Beam
   - Polarized Target
   - Asymmetry Extraction
3. Results
   - Inclusive DIS
   - Semi-Inclusive DIS
   - Delta G

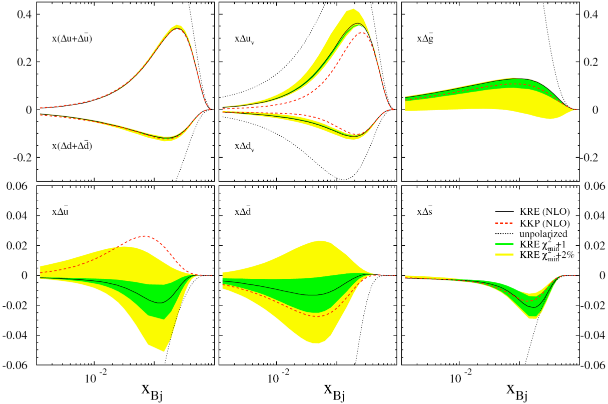
Unpolarized Nucleon Structure



[DIS talk by Olaf Behnke, April 2007]

- quite well known thanks to HERA

Polarized Nucleon Structure



[de Florian, Navarro, Sassot, Phys.Rev.D 71(2005), 094018]

- valence quark polarization quite well known
- direct measurement of strangeness and glue beginning

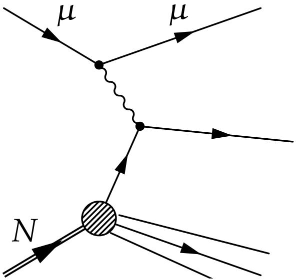
The Spin of the Nucleon

Decomposition of the Nucleon Spin

$$J_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q+g}$$

- only quark polarization well known, previously $\Delta\Sigma \approx 0.2 \div 0.3$
- gluon polarization extracted indirectly from QCD fits
- direct measurements of ΔG desirable

Deep Inelastic Lepton Scattering



DIS Variables

$$q = p_\mu - p'_\mu = (\nu, \vec{q})$$

$$Q^2 = -q^2 = \vec{q}^2 - \nu^2$$

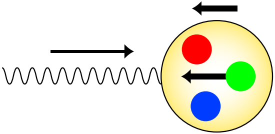
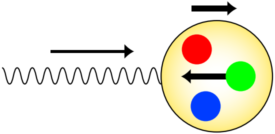
$$x_B = \frac{Q^2}{2M\nu} \qquad \in [0,1]$$

$$y = \frac{\nu}{E_\mu} \qquad \in [0,1]$$

Attention

p_T is the transverse momentum of the produced hadron with respect to the virtual photon direction

Leading Order Polarized DIS

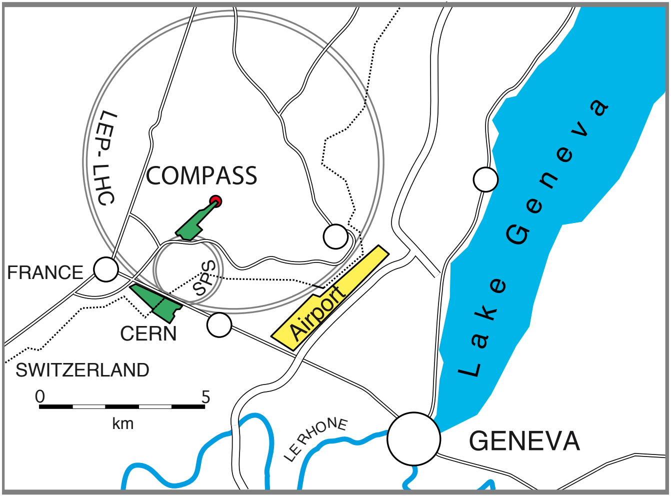
- lepton polarization is transferred to virtual photon, incurring depolarization factor D
- $\sigma^{\overset{\rightarrow}{\Leftarrow}}$ selects $q^{\uparrow}$: 
- $\sigma^{\overset{\rightarrow}{\Rightarrow}}$ selects $q^{\downarrow}$: 
- asymmetry A_1 between $\sigma^{\overset{\rightarrow}{\Leftarrow}}$ and $\sigma^{\overset{\rightarrow}{\Rightarrow}}$ related to $\frac{g_1}{F_1}$

The COMPASS Collaboration

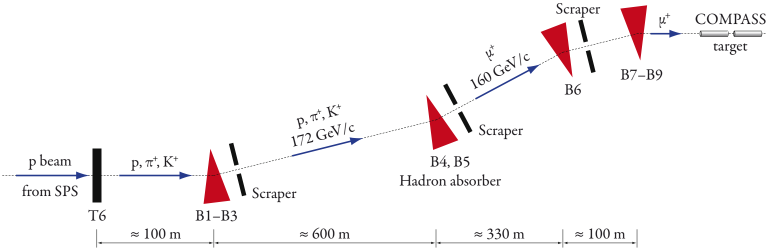
COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

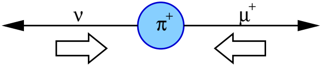
273 physicists, 24 institutes, located at CERN SPS

COMPASS at CERN



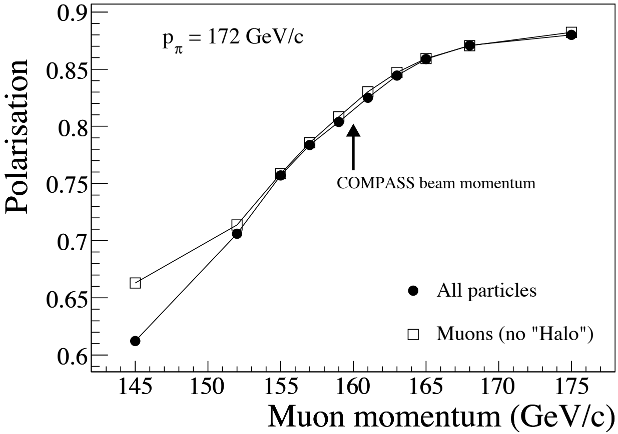
Production of Polarized Muon Beam





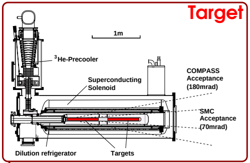
- only left-handed neutrino is produced in weak decay
- angular momentum conservation causes muon to be left-handed also
- selection of muon momentum for given pion momentum determines muon polarization

Beam Polarization

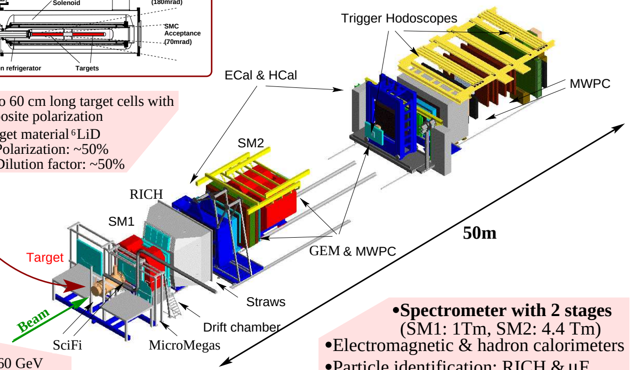


Monte Carlo simulation of the COMPASS beam line yields momentum dependent muon polarization

The COMPASS Experiment



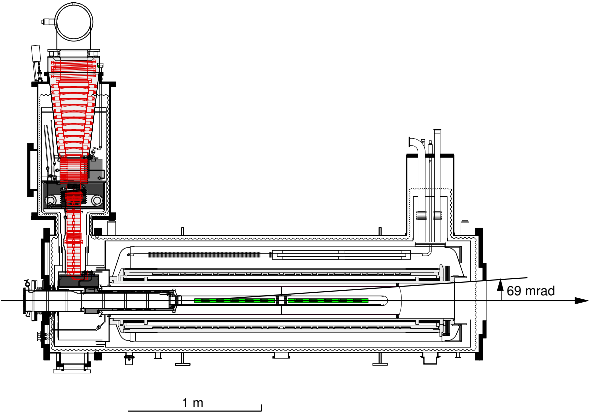
- Two 60 cm long target cells with opposite polarization
- Target material ^{6}LiD
  - Polarization: ~50%
  - Dilution factor: ~50%



- μ−beam
  - Energy: 160 GeV
  - Intensity: $2 \cdot 10^8 \mu$/spill
  - Polarization: −76%

- **Spectrometer with 2 stages** (SM1: 1Tm, SM2: 4.4 Tm)
- Electromagnetic & hadron calorimeters
- Particle identification: RICH & μF

Overview



- „Dilution Refrigerator“ for cooling
- superconductive coils for spin alignment
- microwave antenna for dynamic polarization
- both polarizations measured at the same time

Second Order Method

Count Rates in the Target Cells

$$u = \phi a_u n_u \sigma_0 (1 + P_u A_{\mathrm{phys}}) \qquad u' = \phi a'_u n_u \sigma_0 (1 - P_u A_{\mathrm{phys}})$$
$$d = \phi a_d n_d \sigma_0 (1 - P_d A_{\mathrm{phys}}) \qquad d' = \phi a'_d n_d \sigma_0 (1 + P_d A_{\mathrm{phys}})$$

- ϕ and σ_0 cancel in the asymmetry $A = \frac{u-d}{u+d}$
- field reversal yields u' and d'
- if the apparatus does not change during reversal, then

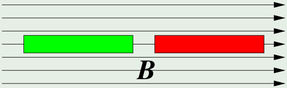
$$\frac{\langle a_u \rangle \langle a'_d \rangle}{\langle a'_u \rangle \langle a_d \rangle} = 1$$

and the set of two equations for the unknowns A_{phys} and $r = \frac{a_u n_u}{a_d n_d}$ simplifies to a quadratic equation in A_{phys}

Acceptance Bias Cancelling

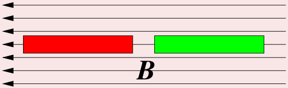
Polarization and Magnetic Field Layout

two target cells:

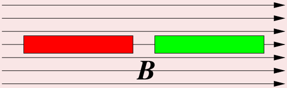


Two Possibilities for Polarization Reversal

solenoid field:



microwave:



Exploiting the Microwave Reversal

Combining the Asymmetries

$$A = \frac{w_+ A_+ + w_- A_-}{w_+ + w_-}, \qquad w_i = \frac{1}{(\delta A_i)^2}$$

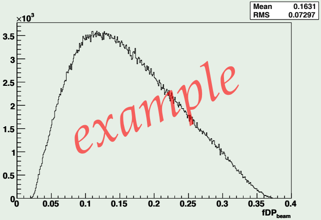
- systematic false asymmetry correlated to target dipole polarity cancel if $w_+ = w_-$
- luminosity is equalized between $+$ and $-$ better than 10%
- we are not systematics limited, so prefer to reduce statistical uncertainty
- after correcting for $A_{\text{false}} = \frac{1}{2}(A_+ - A_-)$, statistical checks for individual asymmetry measurements become available, e. g. pulls method, χ^2 probability, etc.

Event Weighting

The Idea

- every single event gives asymmetry ± 1 with error 1
- physics asymmetry usually greater by kinematic factors
- event-by-event evaluation of weight leads to optimum usage of statistics

Example Distribution of Weights



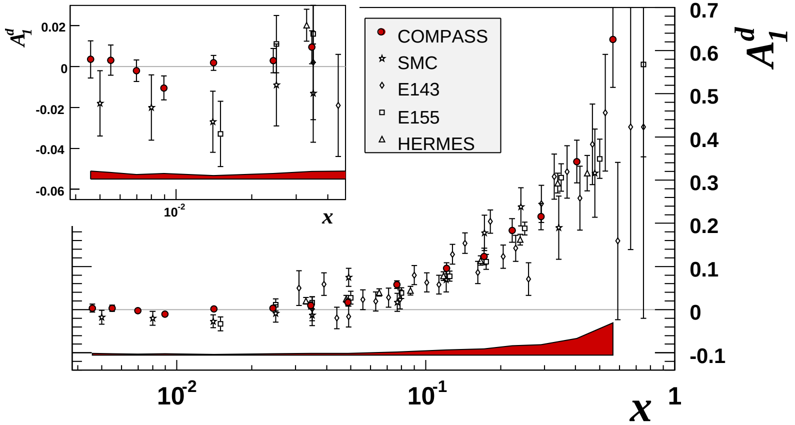
- statistical uncertainty reduced by $\sqrt{\frac{\langle w^2 \rangle}{\langle w \rangle^2}} = \sqrt{1 + \frac{\text{RMS}^2}{\text{Mean}^2}}$
- example: gain 10% in uncertainty, effective gain of 20% in statistics

Data Taking

- three beam times 2002–2004 (May–Nov)
- sharing *4:1* between longitudinal and transverse target polarization
- recorded 695 TB of raw data in longitudinal mode, integrated luminosity

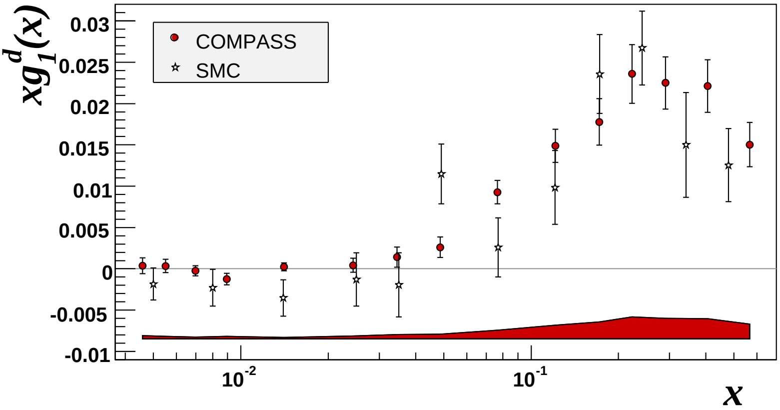
$$\mathcal{L} \approx 1.5\,\mathrm{fb}^{-1}$$

Measurement of A_1^d, $Q^2 > 1\,\mathrm{GeV}^2/c^2$



- good agreement with global data set
- significant improvement at low x_B

Extraction of g_1^d, $Q^2 > 1\,\mathrm{GeV}^2/c^2$

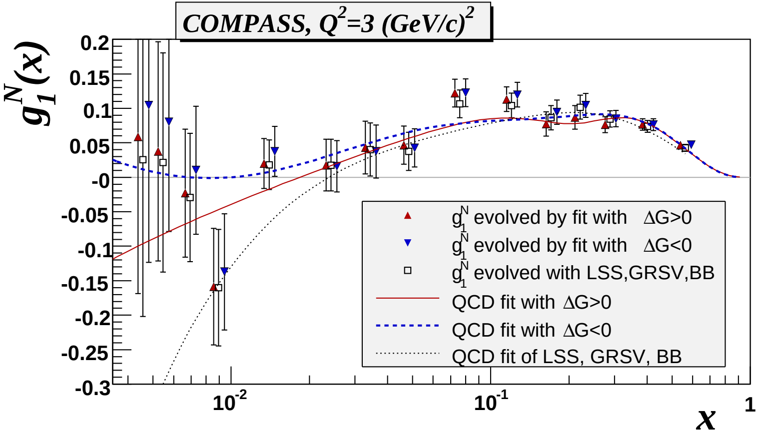


[Phys. Lett. B 647 (2007) 8–17]

Principle of QCD Fits

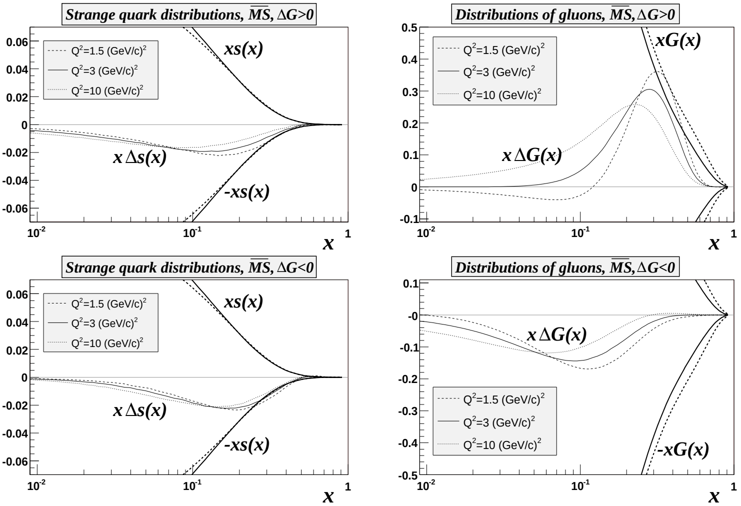
- set of parameterizations of the parton distribution functions are fitted to the available data points
- DGLAP evolution equations are used to transport the fitted functions to the scale Q^2 of the individual measurements
- ΔG enters via evolution, not direct measurement (so far)
- LO or NLO evolution kernels, depending on desired application of PDFs

QCD Fit to World Data



- two equally good solutions, with $\Delta G > 0$ or $\Delta G < 0$
- significant impact on extrapolation $x_B \to 0$

QCD Fit to World Data



QCD Fit Results

Results with World Data Set

$$\Delta\Sigma = 0.30 \pm 0.01_{\text{stat}} \pm 0.02_{\text{evol}}$$

$$|\Delta G| \approx 0.2 \div 0.3$$

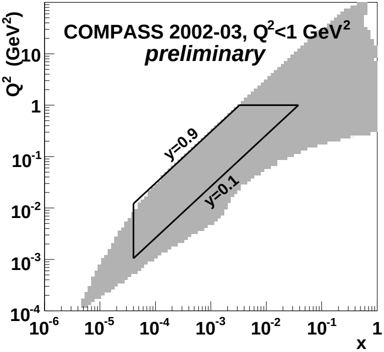
COMPASS g_1^d Only

$$\Gamma_1^d = 0.0502 \pm 0.0028_{\text{stat}} \pm 0.0020_{\text{evol}} \pm 0.0051_{\text{syst}}$$

$$\Delta\Sigma = 9\Gamma_1^d - \frac{a_8}{4} = 0.35 \pm 0.03_{\text{stat}} \pm 0.05_{\text{syst}}$$

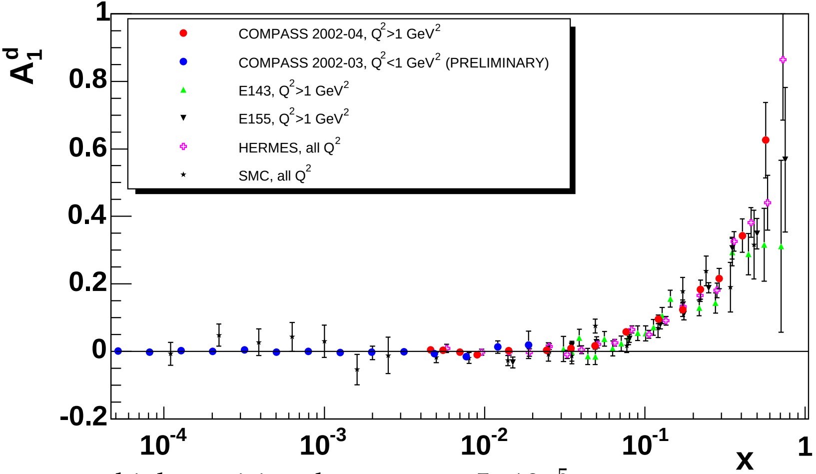
scale always $3\,\text{GeV}^2/c^2$

Measurement of A_1^d, $Q^2 < 1\,\mathrm{GeV}^2/c^2$



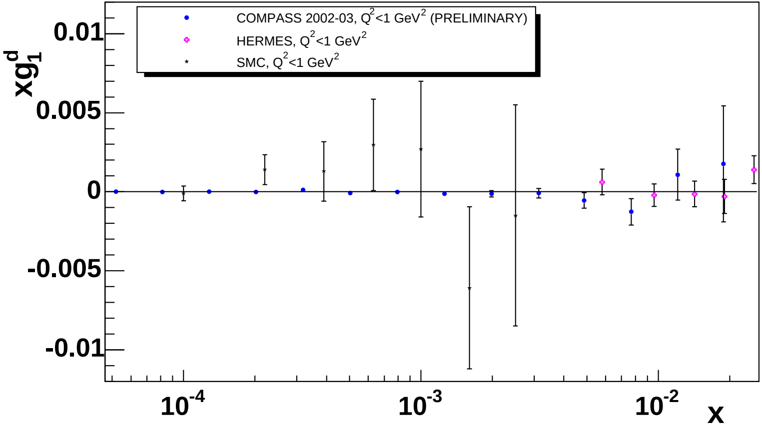
- low x, low Q^2
- very high statistics
- only 2002–2003

Measurement of A_1^d, $Q^2 < 1\,\mathrm{GeV}^2/c^2$



- very high precision down to $x = 5 \cdot 10^{-5}$
- asymmetry is zero for $x < 0.03$

Measurement of g_1^d, $Q^2 < 1\,\mathrm{GeV}^2/c^2$



- significant improvement over previous SMC results

[Phys. Lett. B 647 (2007) 330–340]

Accessing the Valence Quarks

Difference Asymmetry

$$A_N^{h^+-h^-} = \frac{(\sigma_{h+}^{\overleftarrow{\Leftarrow}} - \sigma_{h-}^{\overleftarrow{\Leftarrow}}) - (\sigma_{h+}^{\overrightarrow{\Rightarrow}} - \sigma_{h-}^{\overrightarrow{\Rightarrow}})}{(\sigma_{h+}^{\overleftarrow{\Leftarrow}} - \sigma_{h-}^{\overleftarrow{\Leftarrow}}) + (\sigma_{h+}^{\overrightarrow{\Rightarrow}} - \sigma_{h-}^{\overrightarrow{\Rightarrow}})}$$

$$= \frac{\Delta u_v + \Delta d_v}{u_v + d_v}$$

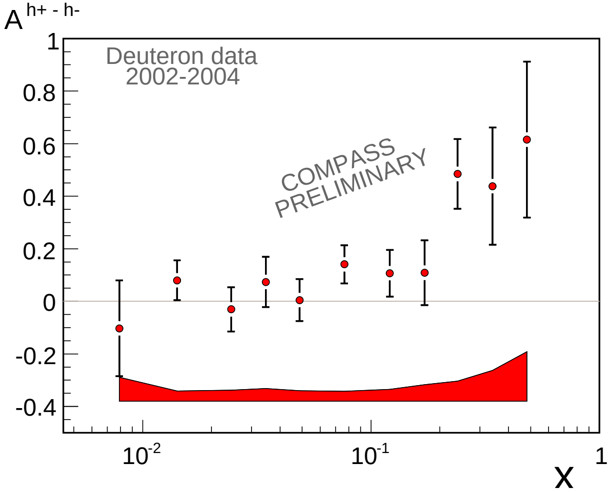
$$= \frac{1}{1-r}(A^{h^+} - rA^{h^-})$$

$$r = \frac{\sigma^{h-}}{\sigma^{h+}} = \frac{N^-}{N^+} \cdot \frac{a^+}{a^-}$$

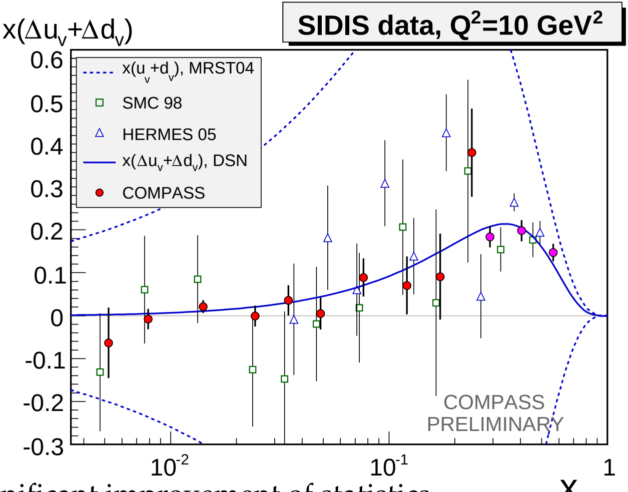
- fragmentation functions cancel in LO
- no PID required
- direct access to polarization of valence quarks, using MRST04 fit for $u_v + d_v$
- for $x > 0.3$, g_1 can also be used

[PLB 230(1989) 141]

Measurement of $A_N^{h^+-h^-}$, $Q^2 > 1\,\mathrm{GeV}^2/c^2$

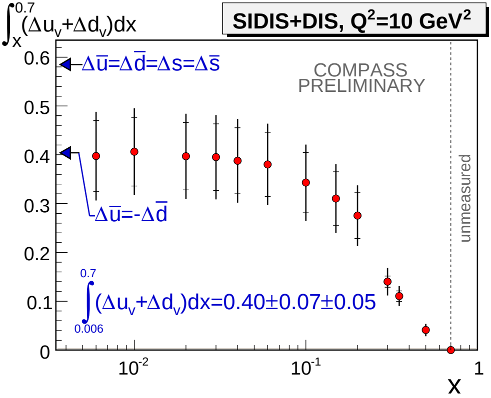


Measurement of Valence Quark Polarization



- significant improvement of statistics
- well compatible with DNS fit (does not include our data)

Spin Contribution of the Valence Quarks



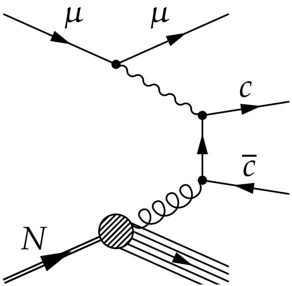
- x region $[0.7, 1]$ contributes 0.004 (DNS fit)
- antisymmetric light sea favored over symmetric sea

	x range	Q^2	$\Delta u_v + \Delta d_v$ measurement	$\Delta u_v + \Delta d_v$ DNS	$\Delta\bar{u} + \Delta\bar{d}$ measurement	$\Delta\bar{u} + \Delta\bar{d}$ DNS
SMC	$0.003 - 0.7$	10	$0.26 \pm 0.21 \pm 0.11$	0.386	$0.02 \pm 0.08 \pm 0.06$	-0.009
HERMES	$0.023 - 0.6$	2.5	$0.43 \pm 0.07 \pm 0.06$	0.363	$-0.06 \pm 0.04 \pm 0.03$	-0.005
COMPASS	$0.006 - 0.7$	10	$0.40 \pm 0.07 \pm 0.05$	0.385	–	-0.007
	$0 - 1$	10	$0.41 \pm 0.07 \pm 0.05$	–	$0.00 \pm 0.04 \pm 0.03$	–

Accessing the Gluon Polarization

- open charm
  - asymmetry in production of D mesons
- high transverse momentum
  - high p_T hadron pairs at $Q^2 > 1\,\mathrm{GeV}^2/c^2$
  - high p_T hadron pairs at $Q^2 < 1\,\mathrm{GeV}^2/c^2$
  - high p_T single hadrons at $Q^2 < 0.5\,\mathrm{GeV}^2/c^2$ (in preparation)

Accessing the Gluon Polarization: Open Charm

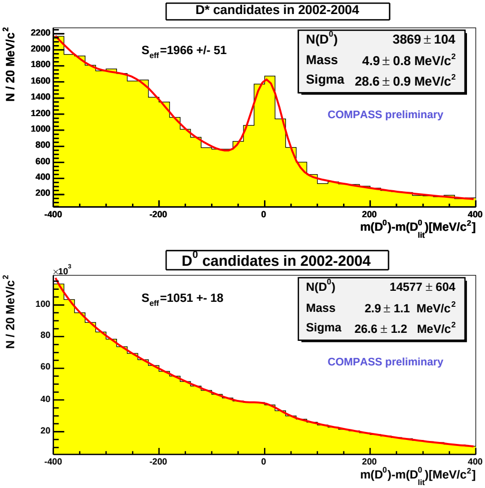


- negligible background from LO process
- reconstruct D mesons in the final state
  - requires PID
  - challenging at fixed target experiment
  - tagging with D^*
- analyzing power a_{LL} calculable
- MC needed for gluon kinematics

Extraction Formula

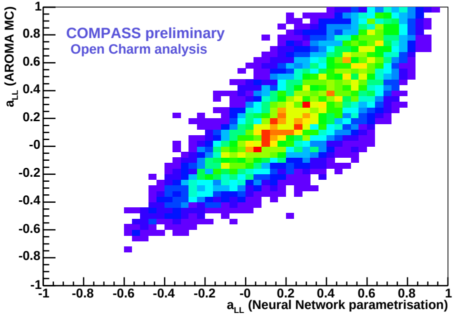
$$A_{\mathrm{exp}} = \frac{N^{\overrightarrow{\Rightarrow}} - N^{\overrightarrow{\Leftarrow}}}{N^{\overrightarrow{\Rightarrow}} + N^{\overrightarrow{\Leftarrow}}} = f P_{\mathrm{beam}} P_{\mathrm{target}} a_{LL} \frac{S}{S+B} \frac{\Delta G}{G} + A_{\mathrm{bk}}$$

Open Charm: Signal/Background



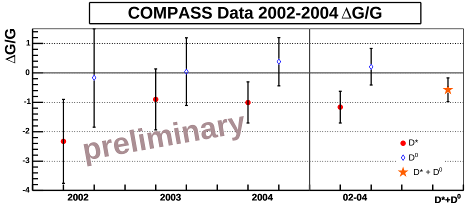
- two channels:
  - direct reconstruction from identified πK pair (RICH)
  - tagged by additional π from D^* decay
- $S/(S+B)$ parameterized by fitting spectra for event weighting

Open Charm: Analyzing Power



- hard scattering matrix element calculated in LO needs gluon kinematics
- AROMA Monte Carlo used for simulation
- a_{LL} directly extracted event-by-event from neural network parameterization and used in weighting

Open Charm: Result



Systematic Error

background asymmetry	0.07
binning procedure	0.04
false asymmetries	0.10
fitting procedure	0.09
AROMA parameters	0.05
target polarization	0.03
beam polarization	0.03
dilution factor	0.03

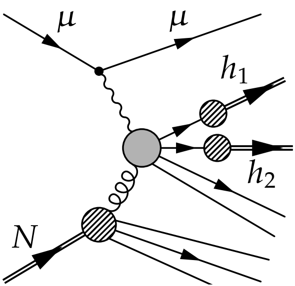
Result

$$\frac{\Delta G}{G} = -0.57 \pm 0.41_{\text{stat}} \pm 0.17_{\text{syst}}$$

$$x_g \approx 0.15$$

$$\mu^2 = 13\,\text{GeV}^2/c^2$$

Accessing the Gluon Polarization: High p_T

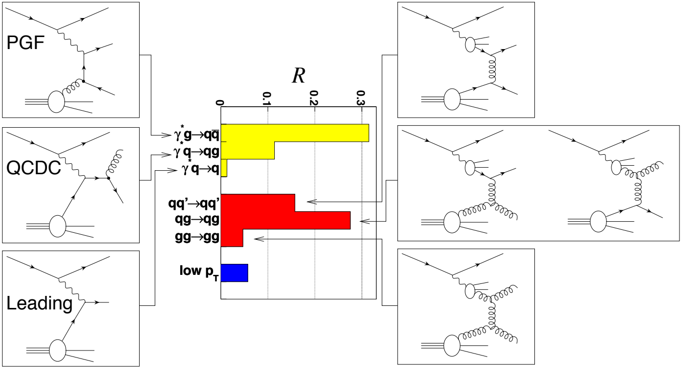


- selection
  - $p_{T,i} > 0.7\text{GeV}/c$
  - $\sum p_T^2 > 2.5(\text{GeV}/c)^2$
  - either $Q^2 < 1\,\text{GeV}^2/c^2$ or $Q^2 > 1\,\text{GeV}^2/c^2$
- very high statistics
- Monte Carlo simulation necessary for
  - fraction of photon–gluon fusion
  - background asymmetries
  - analyzing power

Extraction Formula

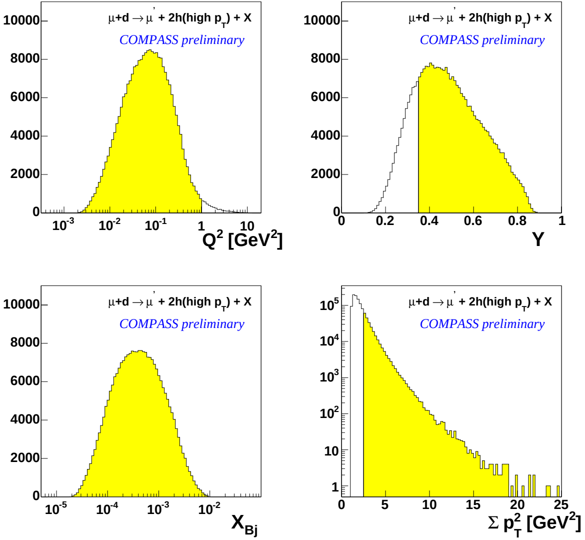
$$A_{\text{exp}} = \frac{N^{\overrightarrow{\Rightarrow}} - N^{\overrightarrow{\Leftarrow}}}{N^{\overrightarrow{\Rightarrow}} + N^{\overrightarrow{\Leftarrow}}} = f P_{\text{beam}} P_{\text{target}} a_{LL} R_{PGF} \frac{\Delta G}{G} + A_{\text{bk}}$$

High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: R_{PGF}



- PYTHIA simulation with pos. and neg. saturation of resolved photon polarized PDF
- $R_{PGF} = 0.32$

High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: Kinematic Distributions



High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: Result

Systematic Error

asymmetry extraction	0.014
R_{PGF} (MC)	0.052
resolved photon PDF	0.013

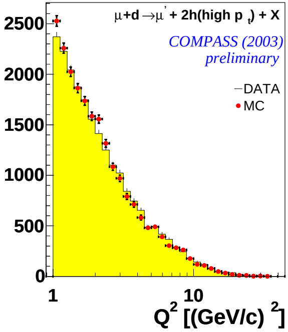
Result

$$\frac{\Delta G}{G} = 0.016 \pm 0.058_{\mathrm{stat}} \pm 0.055_{\mathrm{syst}}$$

$$x_g \approx 0.085$$

$$\mu^2 = 3\,\mathrm{GeV}^2/c^2$$

High p_T, $Q^2 > 1\,\mathrm{GeV}^2/c^2$

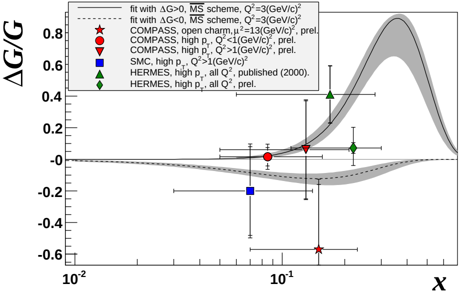


- resolved photon effects negligible
- simulation using LEPTO+RADGEN
- $R_{PGF} = 0.34 \pm 0.07$
- only 2002–2003 data
- new analysis with considerable improvement under way, using better cuts and full statistics

Result

$$\frac{\Delta G}{G} = 0.06 \pm 0.31_{\mathrm{stat}} \pm 0.06_{\mathrm{syst}} \qquad (x_g \approx 0.13, \mu^2 = 3\,\mathrm{GeV}^2/c^2)$$

Summary



ΔG Result

ΔG seems to be small

Quark Polarization Results

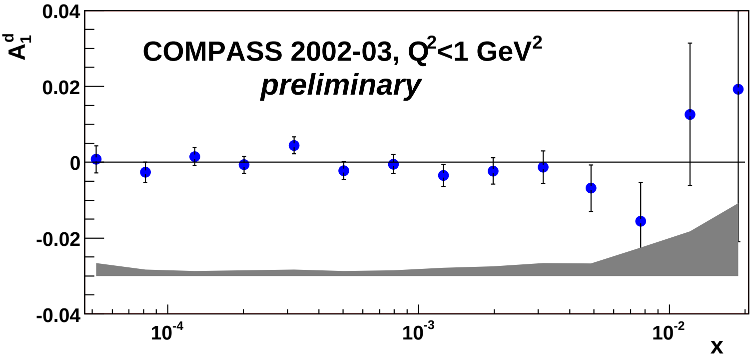
- $\Delta\Sigma = 0.30 \pm 0.01_{\text{stat}} \pm 0.02_{\text{syst}}$
- $\Gamma_1^d = 0.0502 \pm 0.0028_{\text{stat}} \pm 0.0020_{\text{evol}} \pm 0.0051_{\text{syst}}$
- $\Delta u_v + \Delta d_v = 0.40 \pm 0.07_{\text{stat}} \pm 0.05_{\text{syst}}$
- antisymmetric light sea favored over symmetric sea

Outlook

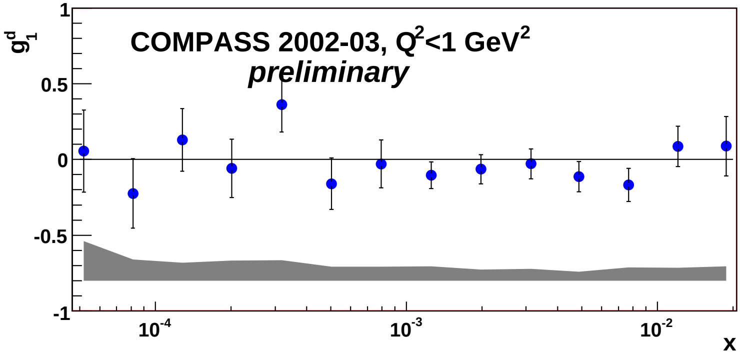
- measurement with proton target scheduled this year
- 2006 data hold significant improvement in statistics
- single-inclusive high p_T hadron analysis under way

Backup Slides

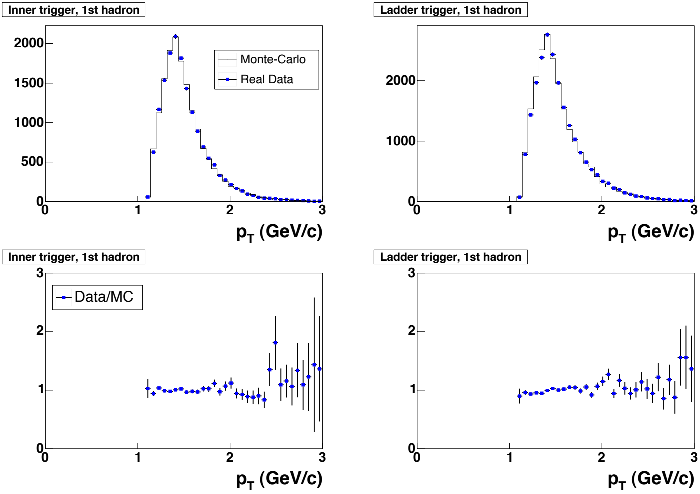
A_1^d, $Q^2 < 1\,\mathrm{GeV}^2/c^2$



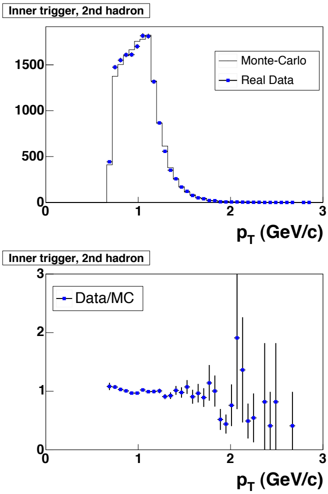
g_1^d, $Q^2 < 1\,\text{GeV}^2/c^2$



High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: Data/MC for $p_{T,1}$



High p_T, $Q^2 < 1\,\mathrm{GeV}^2/c^2$: Data/MC for $p_{T,2}$



High p_T, $Q^2 > 1\,\mathrm{GeV}^2/c^2$: Data/MC for p