Measurement of $\Delta G/G$ at COMPASS

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on behalf of the COMPASS collaboration

SYMMETRIES AND SPIN (SPIN-Praha-2007)
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Outline

1. COMPASS experiment
   - Polarized Beam
   - COMPASS Spectrometer
   - Polarized Target
2. Gluon Polarization
   - Nucleon spin puzzle
   - Direct measurement of gluon polarization
3. $\Delta G/G$ at COMPASS
   - Open Charm
   - High p_T hadrons

COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

- ~250 physicists
- 28 institutes
- 12 countries

Muon programme

Beam:

- Polarization μ^+: -80%
- Luminosity: $5 \cdot 10^{32} cm^{-2} s^{-1}$
- Intensity: $2 \cdot 10^8 \mu^+$/spill
- Momentum: 160 GeV

Target:

- Polarized both longitudinally and transversely
- Material: ^6LiD, (NH_3)
- Polarization: ~50%, (90%)

COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

- ~250 physicists
- 28 institutes
- 12 countries

Muon programme

Goals:

- Gluon contribution to nucleon spin
- Quark polarization
  (g_1, $\Delta\Sigma$, Δq, flavor separation)
- Transversity
- Production of ρ, Φ, J/Ψ, Λ, ...

Data taking

- 2002-2004, 2006-2007, ...

COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Hadron programme

Beam:

- p, K, π
- Intensity: $5 \cdot 10^7$/spill
- Momentum: 100 - 250 GeV

Target:

- Pb, C, Cu, (H)

- ~250 physicists
- 28 institutes
- 12 countries

COMPASS experiment

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

Hadron programme

Goals:

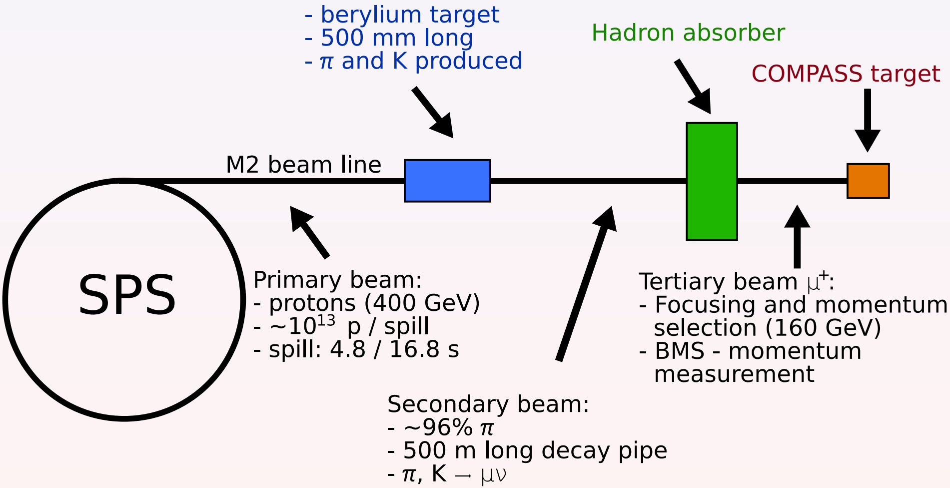
- Primakoff reaction $\longrightarrow \pi$, K polarisabilities
- Exotic q-states, glueballs
- Charmed hadron spectroscopy

Data taking

- 2004, 2008, ...

- $\sim$250 physicists
- 28 institutes
- 12 countries

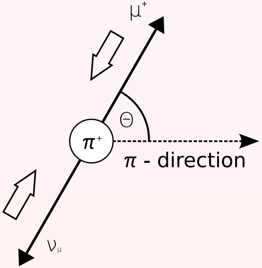
Muon beam line

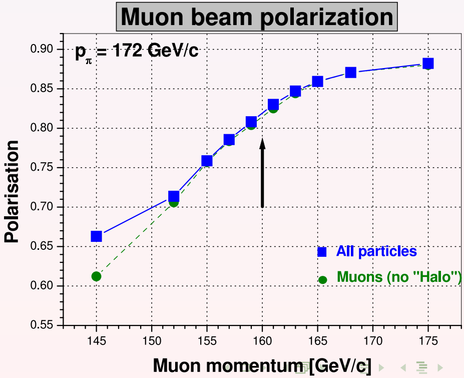


Beam Polarization

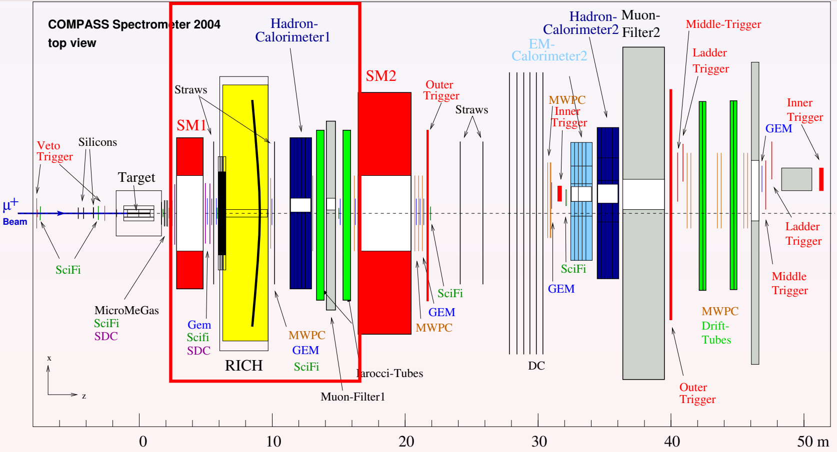
- $\pi^+ \rightarrow \mu^+ \nu_\mu$ is a parity violating decay
- In π rest frame μ are 100% polarized
- In laboratory frame μ polarization depends on decay angle and π momentum in laboratory frame

$$P_\mu = \frac{m_\pi^2 + (1 - 2E_\pi/E_\mu)\, m_\mu^2}{m_\pi^2 - m_\mu^2}$$



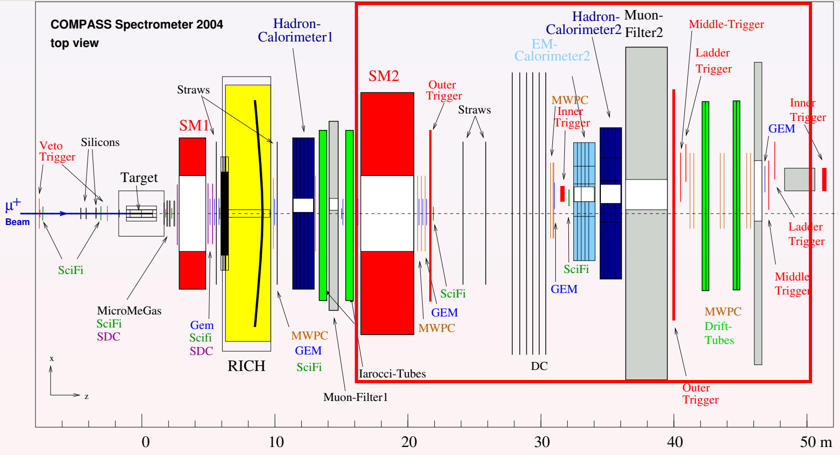


Spectrometer



- Two stage spectrometer
  - Large Angle Spectrometer - LAS (SM1 magnet)
  - Small Angle Spectrometer - SAS (SM2 magnet)

Spectrometer



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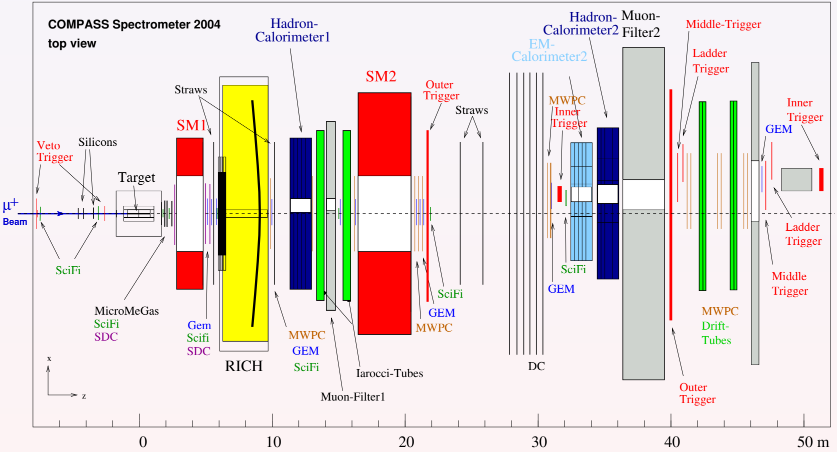
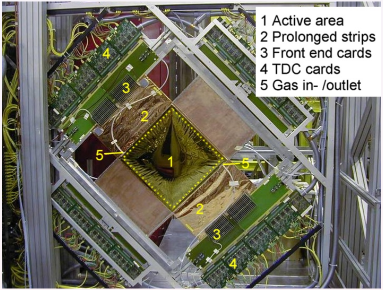
Spectrometer

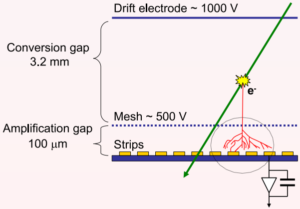


- $\sim$ 350 detector planes
- Track reconstruction for momenta > 0.5 GeV
- Broad spectrum of trackers: SciFis, Silicon Microstrips, GEMs, MicroMegas, Drift Chambers, Straw Tubes, MWPCs

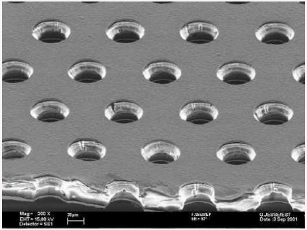
MicroMegas and GEMs

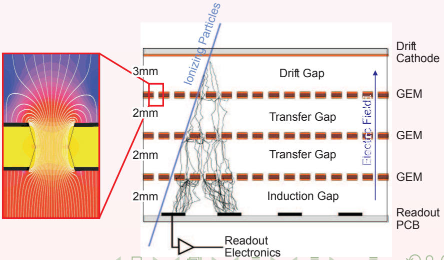
Micro Mesh Gasous detector - MicroMega





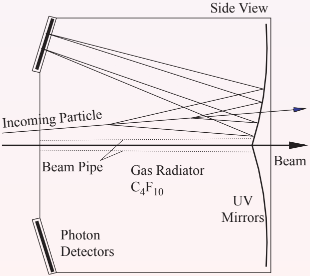
Gas Electron Multiplier - GEM

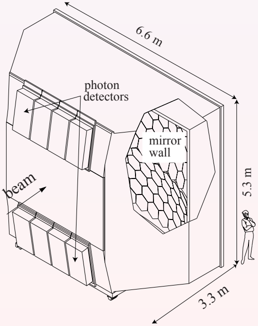


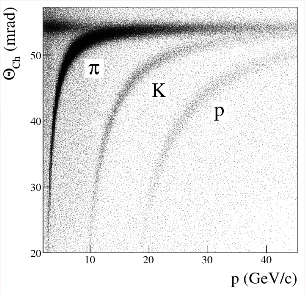


Particle Identification
Ring Image CHerenkov detector

- RICH
  - >80 m^3 filled with C_4F_{10}
  - π/K/p identification up to 50 GeV from 2.5/9/17 GeV





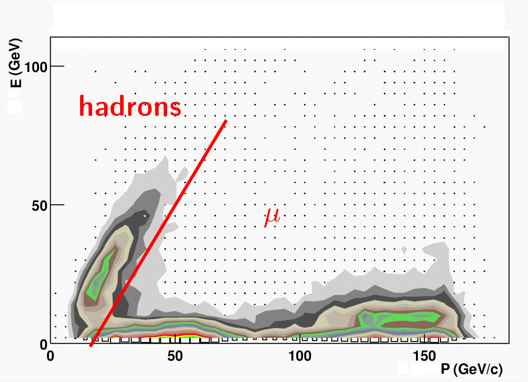


Particle Identification

Ring Image CHerenkov detector

Particle Identification
Calorimeters and muon filters

- Two Hadron Calorimeters
- One Electromagnetic Calorimeter (since 2006 two)
- Muon identification via muon filters



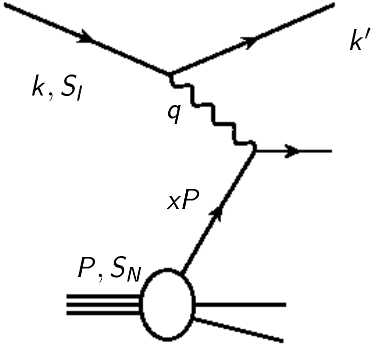
Deep Inelastic Scattering - DIS

Variables

$$Q^2 = -q^2 = -(k-k')^2$$

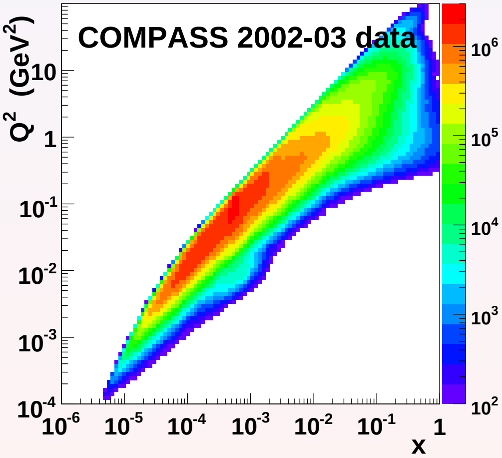
$$y = \frac{P \cdot q}{P \cdot k} \overset{lab}{=} \frac{E-E'}{E} = \frac{\nu}{E}$$

$$x = \frac{Q^2}{2P \cdot q} \overset{lab}{=} \frac{Q^2}{2M\nu}$$



Triggers

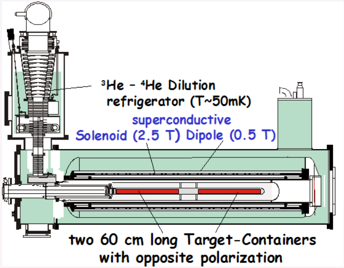
- Trigger:
  - Dedicated hodoscopes
  - Hadron calorimeters

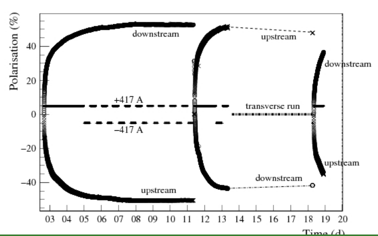


Target

Target

- Two cells (since 2006 three cells)
- Material ^{6}LiD (since 2007: NH_3)
- Dilution factor: ~ 0.4 (~ 0.15 for NH_3)
- Acceptance: ± 70 mrad (since 2006: ± 180 mrad)
- Cooling system: 50 mK
- Cells oppositely polarized $\sim 50\%$ ($\sim 90\%$ for NH_3)
- Beam goes through both cells

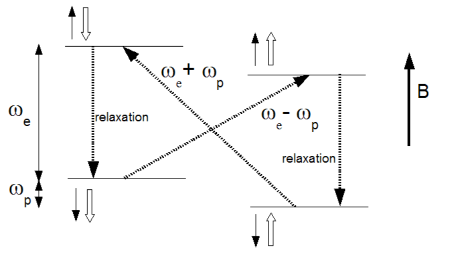




The Dynamic Nuclear Polarization (DNP)

- Target material kept in low temperature (0.4K) and in strong magnetic field (2.5T)
  - High electron polarization achieved (high magnetic moment)
- Material irradiated with microwaves (MW)
  - MW energy set so that simultaneous spin flip of electron and nucleon is possible
  - This energy depends on the value of total spin of the electron-proton system

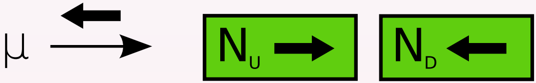
- After spin flip electron relaxes to lower energy state
- Relaxation time of nucleon is long (low magnetic moment - low probability of spin flip)
- Separate MW system for both cells
- MW stopper between cells
- Polarization measured via NMR coils



Experimental asymmetry

- Extract asymmetry (asymmetries are sensitive to small effects):

$$A_{exp} = \frac{N_U - N_D}{N_U + N_D}$$



- One cell polarized parallel and one cell polarized antiparallel to the beam.
- Both cells exposed to same beam flux.
- Spectrometer acceptance is not the same for both cells.

Experimental asymmetry

- Solution: reverse polarization every 8 hours.

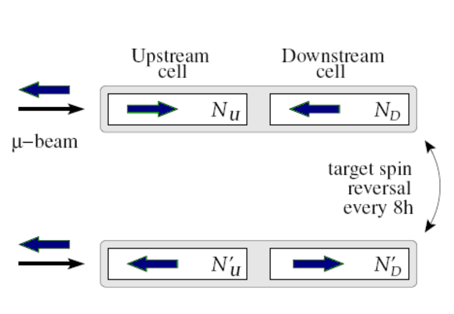
$$A_{exp} = 1/2 \left(\frac{N_U - N_D}{N_U + N_D} + \frac{N'_D - N'_U}{N'_D + N'_U} \right)$$

- Experimental asymmetry is related to cross-section asymmetry:

$$A_{exp} = P_T P_B f A_{||}$$

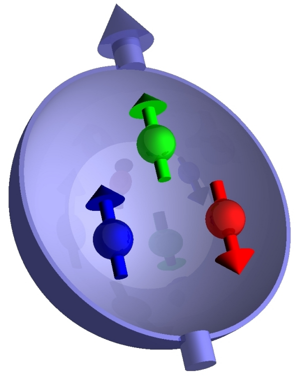
Where:

  - P_T - Target polarization (measured with NMR probes)
  - P_B - Beam polarization (parameterization)
  - f - dilution factor (parameterization)



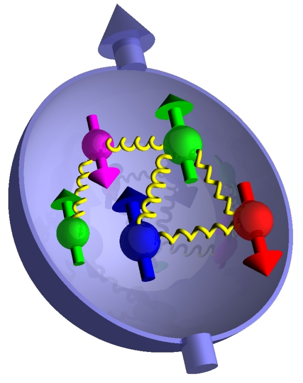
Nucleon spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$



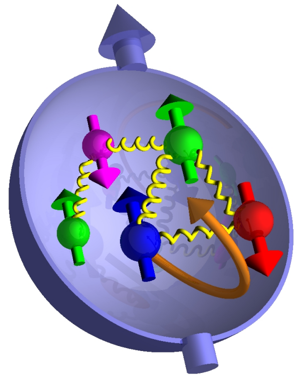
Nucleon spin

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



Nucleon spin

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



Nucleon spin

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

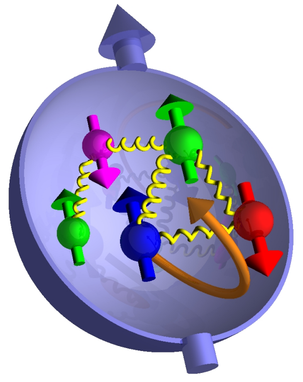
where (in LO):

- $\Delta\Sigma = \int_0^1 \Delta\Sigma(x)dx$

  $\Delta\Sigma(x)$ - polarized quark distribution
- $\Delta\Sigma(x) = \sum_f [\Delta q_f(x) + \Delta\overline{q_f}(x);]$ f - flavors (u,d,s)
- $\Delta q_f(x) = q_f^+(x) - q_f^-(x)$; f - flavors (u,d,s)

  $q_f^{+/-}(x)$ - quarks polarized parallel / antiparallel to nucleon spin
- $\Delta G = \int_0^1 \Delta g(x)dx$

  $\Delta g(x)$ - polarized gluon distribution
- $L_{q/g}$ –orbital momentum of quarks / gluons

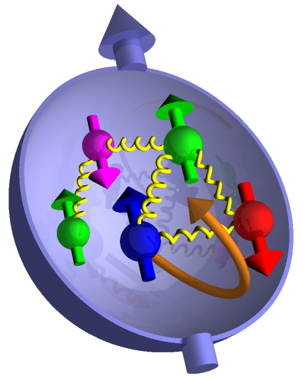


Nucleon spin

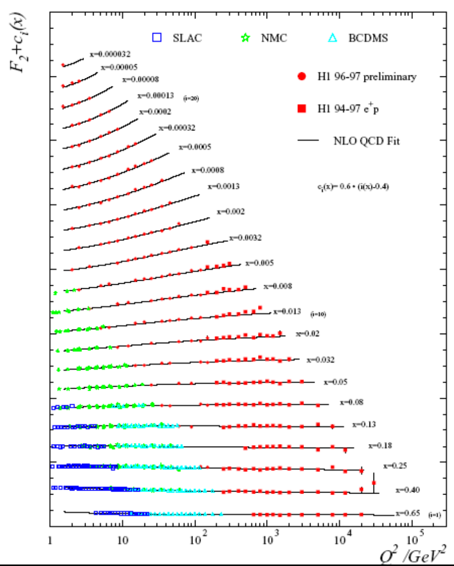
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

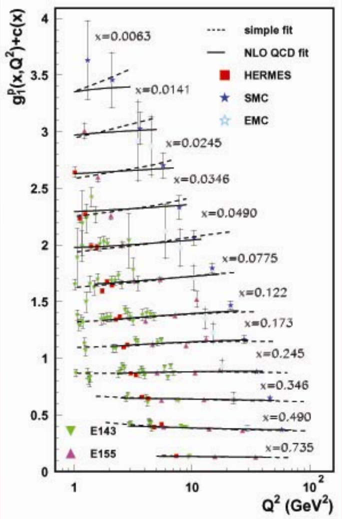
"Spin Crisis"

- Only a small fraction of nucleon spin is carried by quarks
  $\Delta\Sigma = 0.30 \pm 0.01(\text{stat.}) \pm 0.02(\text{evol.})$
  (QCD NLO fits)
- How big is the contribution of gluons and orbital momentum?
- Solution: measure polarization of the gluons and orbital momentum of partons (see talk by Etienne Burtin).



$\Delta G/G$ from g_1 measurement





$\Delta G/G$ from g_1 measurement

In NLO QCD:

$$g_1(x,\, Q^2) = \frac{1}{2} < e^2 > \left[C_q^S \otimes \Delta\Sigma + C_q^{NS} \otimes \Delta q^{NS} + 2n_f C_g \otimes \Delta G\right]$$

DGLAP evolution equations:

$$\frac{d}{dt}\begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta G \end{pmatrix}, \quad t = log\left(\frac{Q^2}{\Lambda^2}\right)$$

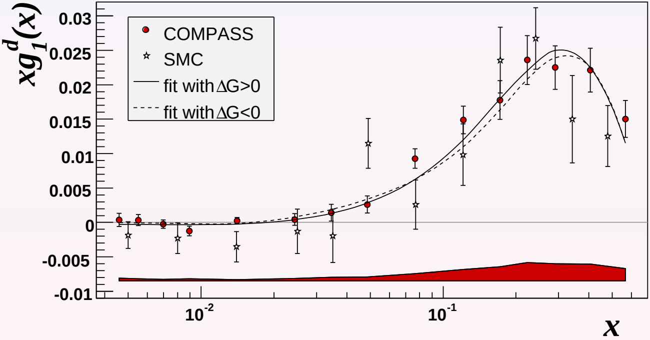
$$\frac{d}{dt}\Delta q^{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q^{NS}$$

Distributions (ΔG, $\Delta\Sigma$, Δq^{NS}) are parametrized. Values of the parameters are obtained from a fit to data.

where:

C_i - Wilson coefficients
P_{ij} - QCD splitting functions
$\Delta q^{NS}(x, Q^2) = \sum_i \left(e_i^2 / < e_i^2 > -1\right) \Delta q_i(x, Q^2)$

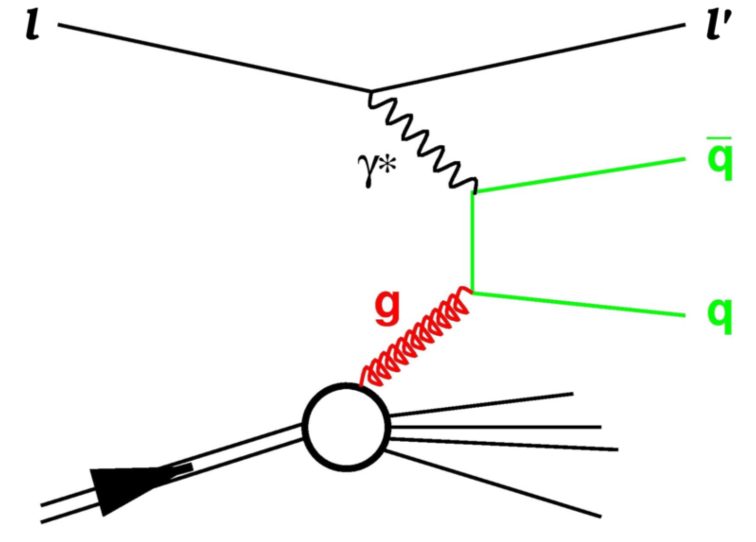
$\Delta G/G$ from g_1 measurement



Results (COMPASS fit to global data [PLB 647 (2007) 8-17])

$\Delta\Sigma = 0.30 \pm 0.01(\text{stat.}) \pm 0.02(\text{evol.})$
Two equally good solutions were found with $\Delta G > 0$ and $\Delta G < 0$:
$|\Delta G| \approx 0.2 - 0.3$

Photon Gluon Fusion - PGF



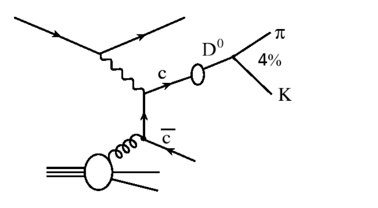
PGF selection

- Open charm production
  - $c\bar{c}$ production
  - hard scale set by $4m_c^2$
  - no background asymmetry
  - limited statistics
- 2 high p_T hadrons ($Q^2 > 1\text{GeV}^2$)
  - hard scale set by Q^2
  - large statistics
  - contamination by other processes
- 2 high p_T hadrons ($Q^2 < 1\text{GeV}^2$)
  - hard scale set by p_T
  - very large statistics
  - contamination by other processes (resolved photon not negligible)

D^0selection

- Thick and long target enclosed in the solenoid and cooling system $\longrightarrow$
- Lack of vertex detector$\longrightarrow$
- Very high combinatorial background

- RICH identification of kaons essential
  - Kaons identification for momenta > 9 GeV
  - do not count as π particles that have a positive K id
- Kinematic cuts :
  - $z_{D^0} > 0.25$ where $z_{D^0} = E_{D^0}/\nu$
  - $|\cos\Theta^*_K| < 0.5$



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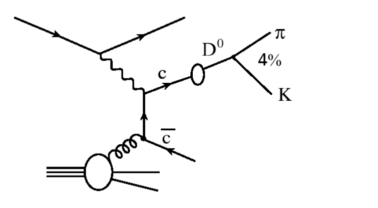

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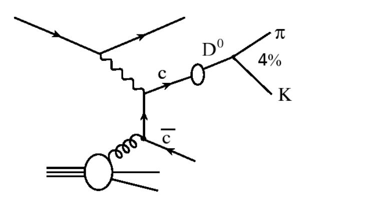

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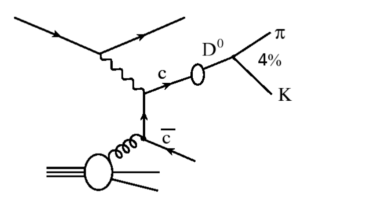
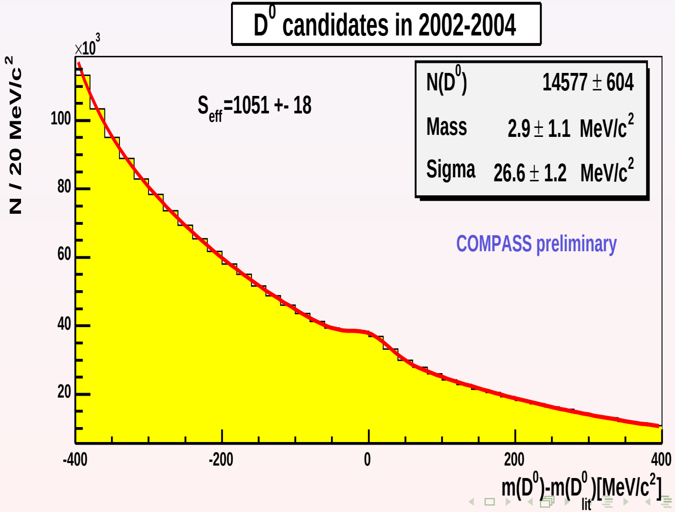
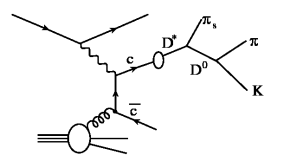


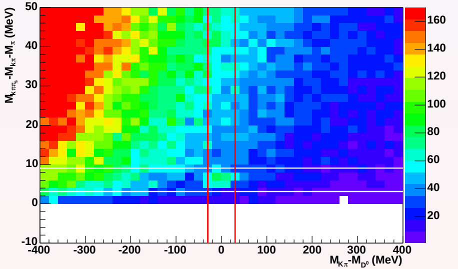
D^0


D0 candidates in 2002-2004
x10^3
N / 20 MeV/c^2
S_eff=1051 +- 18
N(D^0) 14577 ± 604
Mass 2.9 ± 1.1 MeV/c^2
Sigma 26.6 ± 1.2 MeV/c^2
COMPASS preliminary
100
80
60
40
20
-400
-200
0
200
400
m(D^0)-m(D^0_lit)[MeV/c^2]

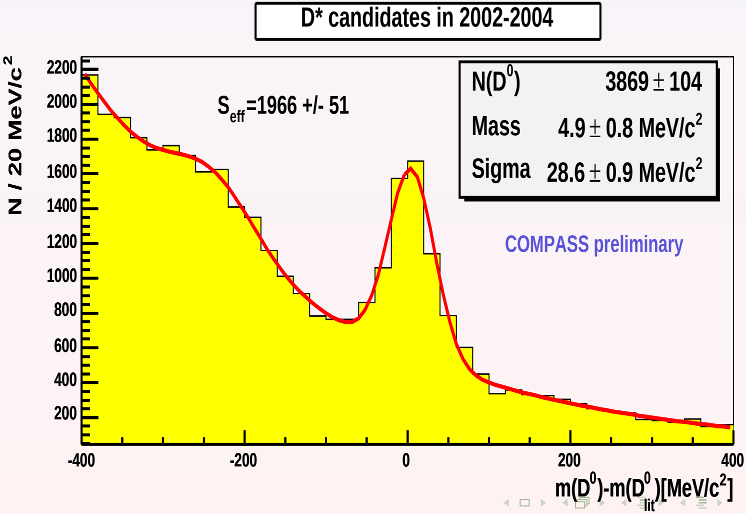
D^*

- $\sim$30% D^0 comes from D* decays
- Cut on a mass difference:
  3.1 MeV $< M_{K\pi\pi} - M_{K\pi} - M_\pi <$ 9.1 MeV
- Cuts on kinematics:
  - $z_{D^0} > 0.20$
  - $|\cos\Theta^*_K| < 0.85$





D^*


D* candidates in 2002-2004
N / 20 MeV/c²
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
-400
-200
0
200
400
m(D⁰)-m(D⁰lit)[MeV/c²]
S_eff=1966 +/- 51
N(D⁰) 3869 ± 104
Mass 4.9 ± 0.8 MeV/c²
Sigma 28.6 ± 0.9 MeV/c²
COMPASS preliminary

ΔG/G from open charm

$$A^{IN} \equiv A_{||} \equiv \frac{\Delta\sigma}{\sigma} \equiv \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\downarrow\Downarrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\downarrow\Downarrow}}$$

- $\Delta\sigma = \Delta F \otimes \Delta\hat{\sigma} \otimes D$; $\sigma = F \otimes \hat{\sigma} \otimes D$
- where:
  - ΔF, F: ΔG, Δq, G, q
  - $\Delta q = \sum_f e_f^2 \left(\Delta q_f(x) + \Delta \bar{q}_f(x)\right)$
  - $\Delta q = \sum_f e_f^2 \left(q_f(x) + \bar{q}_f(x)\right)$
  - D - fragmentation functions

- Selecting D mesons we ensure that we select only PGF events
- $A_{||} = \frac{S}{S+B} < a_{LL} > \frac{\Delta G}{G}$
- where:
  - $< a_{LL} > = < \Delta\hat{\sigma}/\hat{\sigma} >$
  - $\Delta\hat{\sigma}$, $\hat{\sigma}$ - hard process cross-sections

$$\frac{\Delta G}{G} = \frac{1}{< P_T P_B a_{LL} f \frac{S}{S+B} >} A_{exp}$$

- To minimize statistical error a weighting method is used
  - Events are weighted with $w = P_B f \frac{S}{S+B} a_{LL}$ instead of using mean values

ΔG/G from open charm

$$A^{IN} \equiv A_{||} \equiv \frac{\Delta\sigma}{\sigma} \equiv \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\downarrow\Downarrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\downarrow\Downarrow}}$$

- $\Delta\sigma = \Delta F \otimes \Delta\hat{\sigma} \otimes D$; $\sigma = F \otimes \hat{\sigma} \otimes D$
- where:
  - ΔF, F: ΔG, Δq, G, q
  - $\Delta q = \sum_f e_f^2 \left(\Delta q_f(x) + \Delta \bar{q}_f(x)\right)$
  - $\Delta q = \sum_f e_f^2 \left(q_f(x) + \bar{q}_f(x)\right)$
  - D - fragmentation functions
- Selecting D mesons we ensure that we select only PGF events
- $A_{||} = \frac{S}{S+B} < a_{LL} > \frac{\Delta G}{G}$
- where:
  - $< a_{LL} >=< \Delta\hat{\sigma}/\hat{\sigma} >$
  - $\Delta\hat{\sigma}, \hat{\sigma}$ - hard process cross-sections

$$\frac{\Delta G}{G} = \frac{1}{< P_T P_B a_{LL} f \frac{S}{S+B} >} A_{exp}$$

- To minimize statistical error a weighting method is used
  - Events are weighted with $w = P_B f \frac{S}{S+B} a_{LL}$ instead of using mean values

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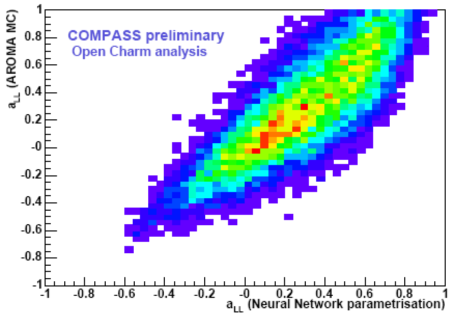
- To minimize statistical error a weighting method is used
  - Events are weighted with $w = P_B f \frac{S}{S+B} a_{LL}$ instead of using mean values

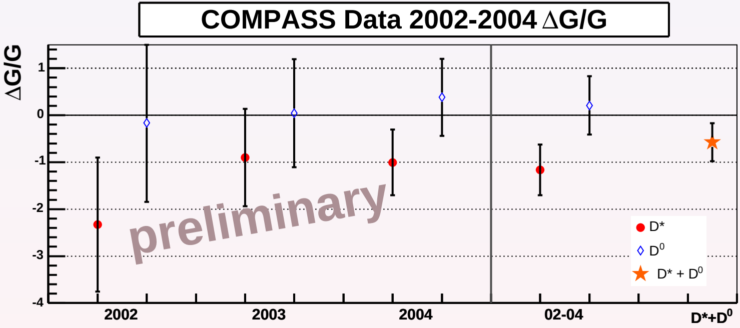
a_{LL} parametrization

- Only one measured charmed meson in event - not enough information to calculate a_{LL} directly
- Parametrization is based on AROMA Monte Carlo generator
- Neural Networks are used for the parametrization
- Variables used for parametrization: $z_{D^0}, p_{T_{D^0}}, x, Q^2, y$



Correlation factor 82%

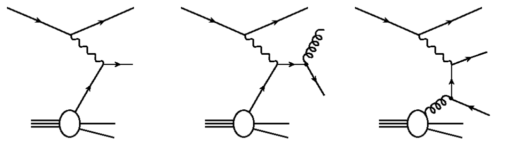
Open charm result



- Based on data collected in 2002-2004
- $\frac{\Delta G}{G} = -0.57 \pm 0.41(stat.) \pm 0.17(syst.)$
- $x_g \approx 0.15$ (RMS 0.8)
- Scale $\approx 13\text{GeV}^2 (\approx 4m_c^2)$

High p_T background processes

Contributing diagrams ($Q^2 > 1\text{GeV}^2$)



LP

Leading Process

QCDC

QCD Compton

PGF

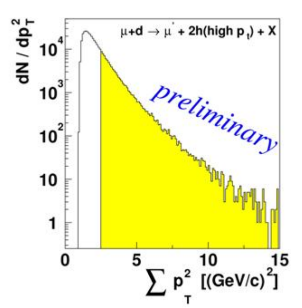
Photon Gluon Fusion

- For Leading Process struck quark goes along photon direction
- p_T of hadron in the final state is small
- Non zero p_T can originate from fragmentation or intrinsic p_T of quark
- Selection of events with high p_T suppresses Leading Process

High p_T ($Q^2 > 1$) selection

Cuts:

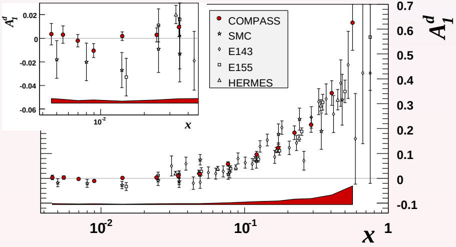
- Hadrons detected via hadronic calorimeters
- $p_T > 0.7$ GeV
- $\Sigma p_T^2 > 2.5$ GeV^2
  - suppress LP contribution
- $x_F, z > 0.1$: current fragmentation region
- $m(h_1, h_2) > 1.5$ GeV : avoid ρ resonance



$\Delta G/G$ from High p_T ($Q^2 > 1$ GeV^2)

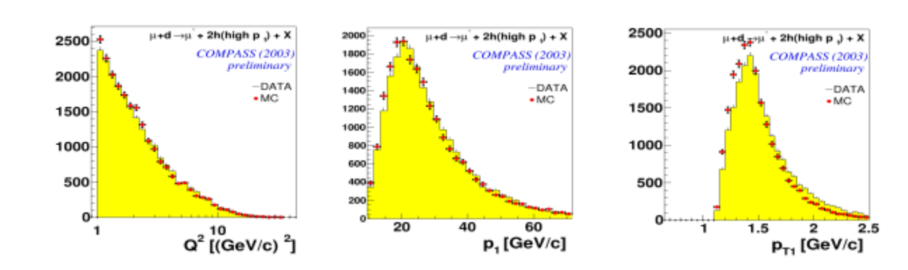
$$A_{||} = \frac{\Delta q}{q}(< a_{LL}^{LP} > R_{LP} + < a_{LL}^{QCDC} > R_{QCDC}) + \frac{\Delta G}{G} < a_{LL}^{PGF} > R_{PGF}$$

- $\frac{\Delta q}{q}$ approximated by A_1 asymmetry
- For region x < 0.05 A_1 is small - we can neglect contribution from LP and QCDC (included in systematic error)
- R_{PGF} - fraction of PGF events - determined from MC simulations



Monte Carlo for High p_T ($Q^2 > 1$ GeV^2)

- Monte Carlo generator: LEPTO
- Obtained reasonable agreement with data



High p_T ($Q^2 > 1$ GeV^2) result

- Result based on data collected in 2002-2003:

$$\frac{\Delta G}{G} = 0.06 \pm 0.31(stat.) \pm 0.06(syst.)$$

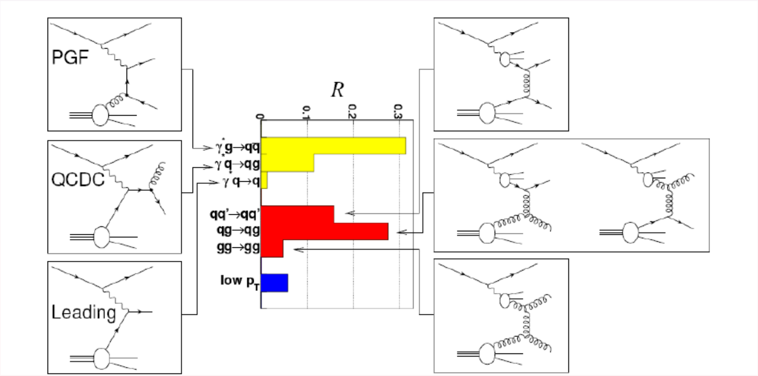
$$R_{PGF} = 0.34 \pm 0.7$$

$$< x_g >= 0.13$$

- Analysis of 2004 and 2006 data ongoing.
- We are working o methods to improve sample selection.

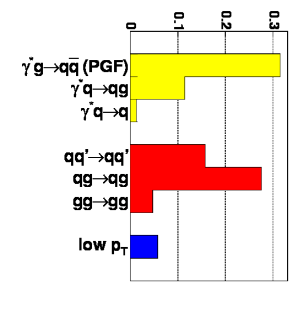
High p_T ($Q^2 < 1$ GeV^2) additional processes

Direct processes	Resolved Photon processes



High p_T ($Q^2 < 1$ GeV^2) additional processes

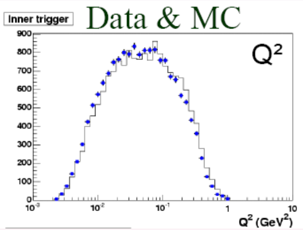
$$
\begin{aligned}
A_{||} &= R_{PGF}\, a_{LL}^{PGF} \frac{\Delta G}{G} \\
&+ R_{QCDC}\, a_{LL}^{QCDC} \frac{\Delta q}{q} \\
&+ R_{qq}\, a_{LL}^{qq} \frac{\Delta q}{q} \frac{\Delta q^{\gamma}}{q} \\
&+ R_{gq}\, a_{LL}^{gq} \frac{\Delta q}{q} \frac{\Delta G^{\gamma}}{G} \\
&+ R_{qg}\, a_{LL}^{qg} \frac{\Delta G}{G} \frac{\Delta q^{\gamma}}{q} \\
&+ R_{gg}\, a_{LL}^{gg} \frac{\Delta G}{G} \frac{\Delta G^{\gamma}}{G}
\end{aligned}
$$

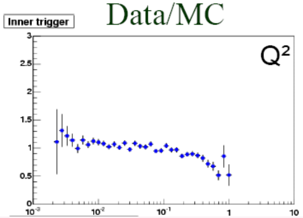


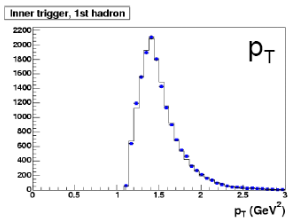
- R_i - process fraction (MC).
- a_i - hard process asymmetry (QCD).
- q, G, Δq, ΔG - parton distributions in nucleon (parametrization).
- q^{γ}, G^{γ} - unpolarized parton distributions in photon (parametrization).
- Δq^{γ}, ΔG^{γ} - polarized parton distributions in photon (min - max

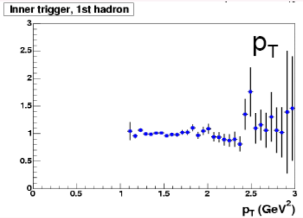
High p_T ($Q^2 < 1$ GeV^2) Monte Carlo

Monte Carlo generator: PYTHIA
Agreement with Real Data (blue points) and Monte Carlo

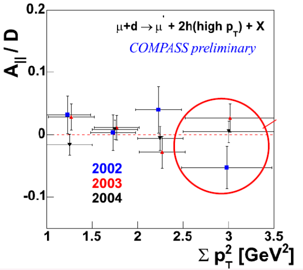






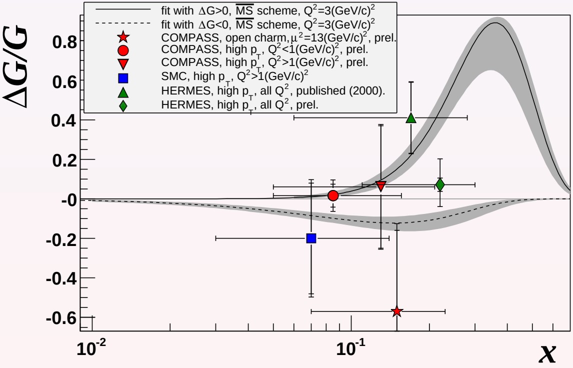


High p_T ($Q^2 < 1$ GeV^2) result



- Based on data collected in 2002-2003 (PLB 633 (2006) 25-32)
- $\frac{\Delta G}{G} = 0.024 \pm 0.089(stat.) \pm 0.057(syst.)$
- $x_g \approx 0.095^{+0.08}_{-0.04}$ (RMS 0.8)
- Scale 3GeV^2
- Preliminary result based on 2002-2004 data:
  $\frac{\Delta G}{G} = 0.016 \pm 0.058(stat.) \pm 0.055(syst.)$

$\Delta G/G$



QCD fits:

- Lines obtained from NLO QCD fits including a new COMPASS deuteron results on g_1^d (PLB 647 (2007) 8-17).
- Two equally good solutions for$\Delta G/G$ were found. For both $|\Delta G| = 0.2 - 0.3$.

Prospects

- 2006 and 2007 data to be analyzed
- Increased statistics in 2006 and 2007 due to new COMPASS magnet
- Upgraded RICH detector will increase Kaon identification efficiency
- 2004 data for High p_T ($Q^2 > 1$ GeV^2) sample is being analyzed
- Usage of neural networks is studied as a tool for selecting PGF events (for both channels)

Summary

- Recent results of $\Delta G/G$ from COMPASS were presented
- Present measurements indicate that $\Delta G/G$ is consistent with zero at $x_g \approx 0.1$
- We are working on further analysis and hope to show new results with even better precision in near future
- Measurement of orbital momentum of partons in nucleon is needed to solve "nucleon spin puzzle"

Spares

Spares

Open charm systematics

A number of potential systematic effects studied:

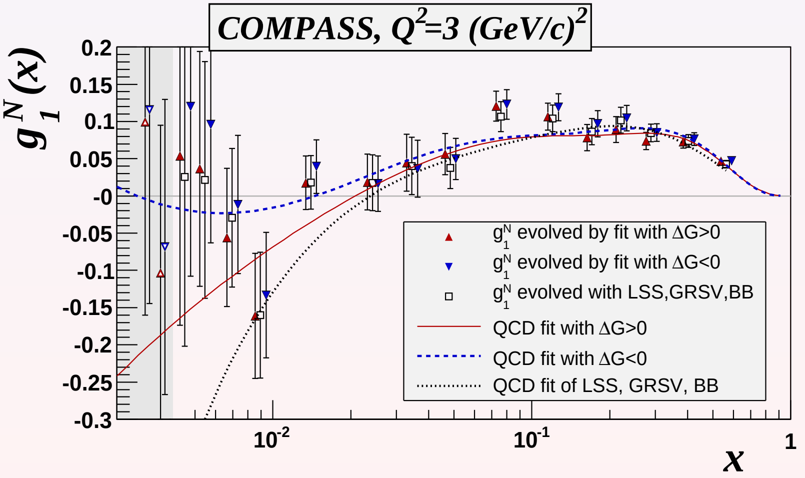
Source of uncertainty	$\delta(\Delta G/G)$
Background asymmetry	0.07
Binning procedure	0.04
False asymmetries (pulls method)	0.10
Fitting	0.09
Parameters of Aroma	0.05
Target polarization	0.03
Beam polarization	0.03
Dilution factor	0.03
Combined systematic error	0.17

$$\Delta G/G = -0.57 \pm 0.41(stat.) \pm 0.17(syst.)$$

High p_T hadrons $Q^2 < 1\,\mathrm{GeV}^2$ systematics

- The systematical error can be decomposed:
  - False asymmetries (experimental systematics): 0.014
  - Resolved photon contribution: 0.013
  - Monte Carlo tuning: 0.052
    - The MC parameters were changed in a range where the resonable agreement between the data and MC remains
    - 30% difference in R found PGF

$\Delta G/G$ from g_1 measurement



$\Delta G/G$ from g_1 measurement