Measurements of the gluon polarisation in the nucleon at COMPASS

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COMPASS

Muon programme

Beam:

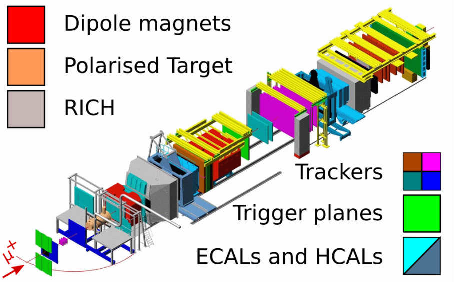
- Momentum: 160 GeV/c
- Polarisation μ^+: -80%

Target:

- Polarised both longitudinally and transversely
- Material: ^{6}LiD, (NH_3)
- Polarisation: ~50%, (90%)
- Two (three) target cells

Data taking

- 2002-2004, 2006-2007, (2008-2009 Hadron programme) . . .



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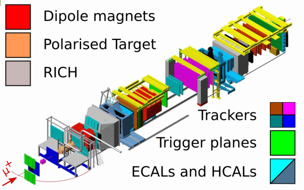
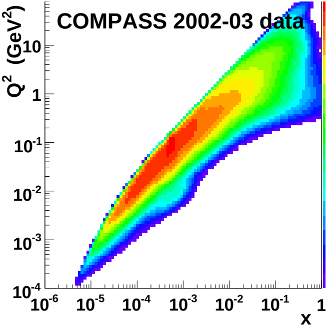
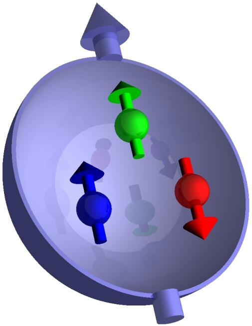




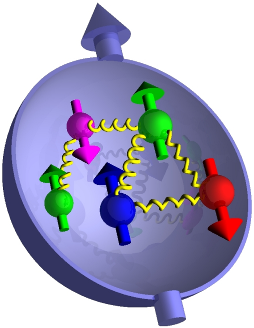
Physics motivation

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



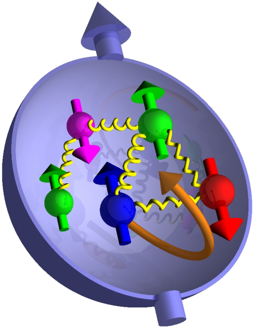
Physics motivation

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



Physics motivation

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

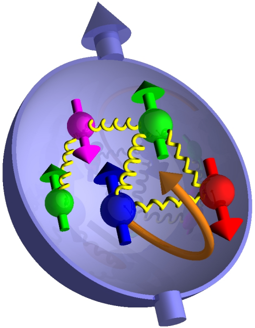


Physics motivation

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

"Spin Crisis"

- In a naive Quark Parton Model we expect: $\Delta\Sigma = 1$
- Taking into account relativistic effects: $\Delta\Sigma \approx 0.6$
- The EMC first measured quark contribution: $\Delta\Sigma = 0.12 \pm 0.17$ [1]
- COMPASS NLO QCD fit to the world data: $\Delta\Sigma = 0.30 \pm 0.01(\text{stat.}) \pm 0.02(\text{evol.})$ [2] @ $Q^2 = 3\,\text{GeV}^2$
- Direct measurements can answer what is the contribution of gluons and orbital momentum ...

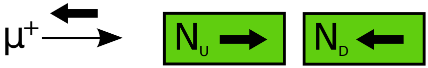


[1] Nucl. Phys. B 328 (1989) 1
[2] PLB 647 (2007) 8-17

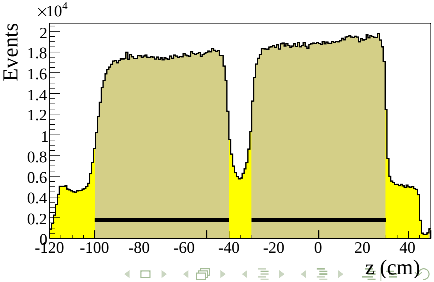
Experimental asymmetry

Asymmetries are a sensitive tool for measuring spin effects

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



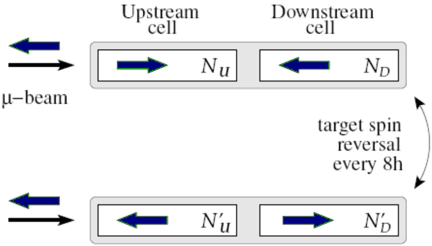
- One cell polarized parallel and one cell polarized antiparallel to the beam.
- Both cells exposed to same beam flux.
- Spectrometer acceptance is not the same for both cells.



Experimental asymmetry

Solution: reverse polarization every 8 hours.

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



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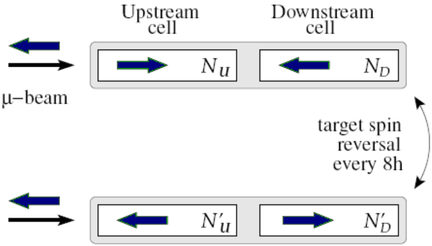


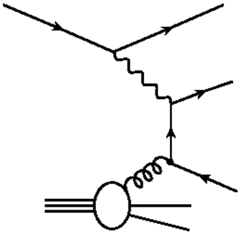
Experimental asymmetry is related to cross-section asymmetry:

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

Where:

- P_T - Target polarization
- P_B - Beam polarization
- f - dilution factor

Access to gluons

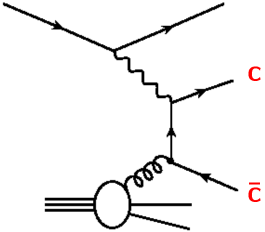


PGF

Photon Gluon Fusion

Access to gluons

- **Open Charm**
  - Search for D^0 meson in the final state
  - No charm in the nucleon in COMPASS kinematics
  - Charm is produced only via PGF (LO)
  - Perturbative region ensured by charm mass
  - Weakly depends on MC simulations
  - Low statistics



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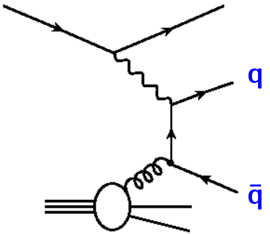

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  - Low statistics
- **High p_T hadron pairs** $(Q^2 > 1\,(\mathrm{GeV/c})^2)$
  - Search for two hadrons with high transverse momenta in the final state
  - Large statistics
  - Perturbative region - $Q^2 > 1\,(\mathrm{GeV/c})^2$
  - Background processes
  - MC simulations essential
- **High p_T hadron pairs** $(Q^2 < 1\,(\mathrm{GeV/c})^2)$
  - 2002-2003 result published [PLB 633 (2006) 25-32]
  - 2002-2004 presented on several conferences

Asymmetry calculation (LO)

$$A_{exp} = \frac{\Delta G}{G} P_t P_b a_{LL} f \frac{S}{S+B} + A_{BG}$$

ΔG — polarised, G — unpolarised: gluon distribution functions in nucleon

a_{LL} - partonic cross-section asymmetry - taken from Aroma MC

S - signal events (reconstructed D^0)
B - background events

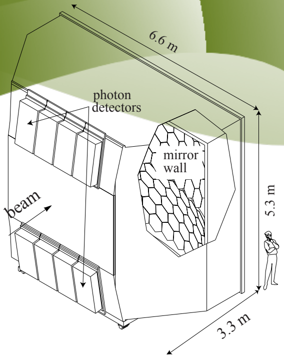
$\Rightarrow$ both obtained from fits to D mass spectra

Note: $A_{BG} = \frac{1}{P_t P_b f D \frac{B}{S+B}} A_{exp}$ is determined simultaneously and is found to be compatible with zero.

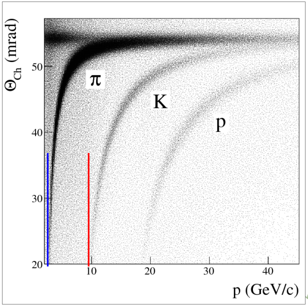
Selection

Channels

- $D^0 \to K\pi$
- $D^* \to D^0\pi_{soft} \to K\pi\pi_{soft}$
- BR($D \to K\pi$) ~3.8%
- 30% of D^0 tagged with D^*



- Selection to reduce combinatorial background
  - Kinematical cuts: z_D, D^0 decay angle, K and π momentum
  - RICH identification: K, π ID + e rejection from the π_{soft} sample



Statistical weights and $\frac{S}{S+B}$ parametrisation

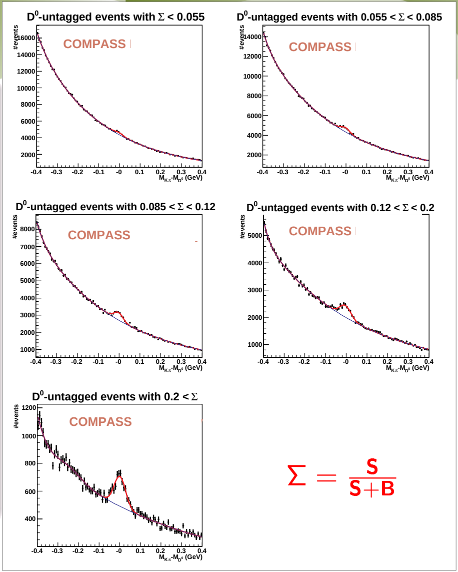
Statistical weights

To increase the statistical gain a weighted estimator is used. Each event is assigned a weight:

$$w = P_b f a_{LL} \frac{S}{S+B}$$

The $\frac{S}{S+B}$ is parametrised as a function of kinematic variables and RICH response:

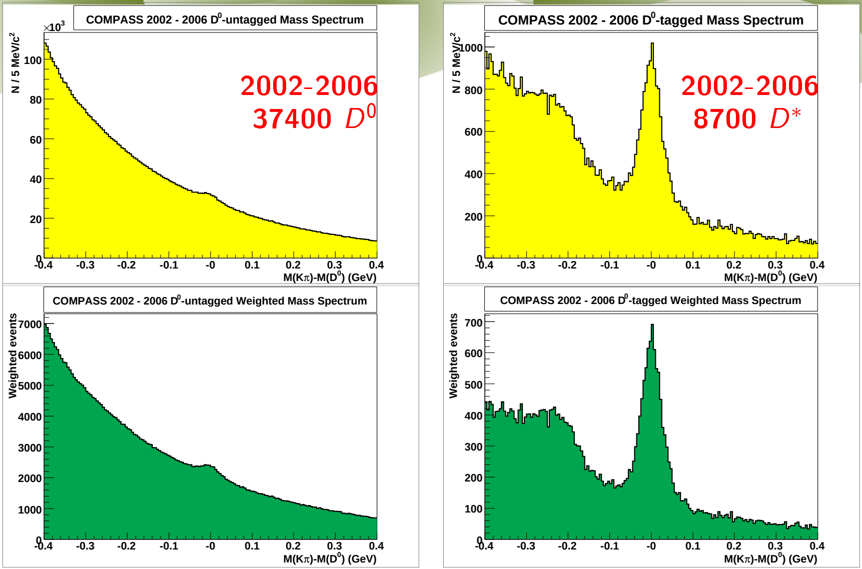
- available on event-by-event basis
- built from Data (fits to D spectra in bins of input variables)



Mass spectra

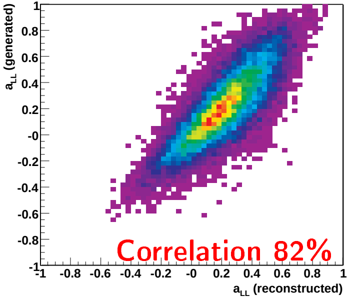
Raw histograms

Σ weighted histograms



a_{LL} parametrisation

- $a_{LL} = \frac{\Delta\sigma^{PGF}}{\sigma^{PGF}}$ depends on the full knowledge of partonic kinematics
- Cannot be obtained experimentaly - only one D meson observed
- a_{LL} is obtained from MC (in LO), to serve as an input to Neural Network parametrisation as a function of measured observables: y, x, Q^2, z_D, p_T



More contributions from the D^* channel [NEW]

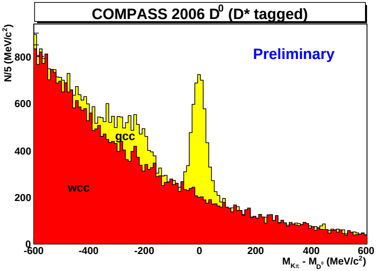
- The D^* channel is very clean from background contamination (*due to a 3-body mass cut*)
  $\Rightarrow$ the following contributions can be added:
  - π^0 reflection "bump": $D^0 \to K\pi\pi^0$
  - RICH sub-threshold Kaons events:
    - Candidates with $p < 9\,\mathrm{GeV/c}$ (no RICH ID for Kaon mass)
    - Recover D^0 if there is no positive pion or electron ID (for the Kaon candidate)
- Signal strength parameterization ($\Sigma = \frac{S}{S+B}$):

  Problem: Low purity samples with low statistics $\Rightarrow$ Very difficult to build Σ in several bins of several variables

  Solution: Multi-dimentional parameterization using a Neural Network (all kinematic and RICH dependences are taken into account at same time)

Neural Network qualification of events

- Two real data samples (with same cuts) are compared by the Neural Network (based on selected kinematic variables):
  - Signal model → $gcc = K^+\pi^-\pi^-_{soft} + K^-\pi^+\pi^+_{soft}$ (D^0 spectrum: signal + bg.)
  - Background model → $wcc = K^+\pi^+\pi^-_{soft} + K^-\pi^-\pi^+_{soft}$ (no D^0 is allowed)
- If the background model is good enough: Net is able to distinguish the signal from the combinatorial background on a event by event basis (inside gcc)



Σ is built in the simmilar way as for main channels

- Instead of set of kinematic variables only 1 variable is used: Neural Network output

Preliminary results including all channels

Final result
(including the main channels: D^0 and D^0 tagged with a D^*)

$$\Delta G/G = -0.39 \pm 0.24(stat) \pm 0.11(sys)$$

$$@ < x_g >= 0.11, < \mu^2 >= 13\,\text{GeV}^2$$

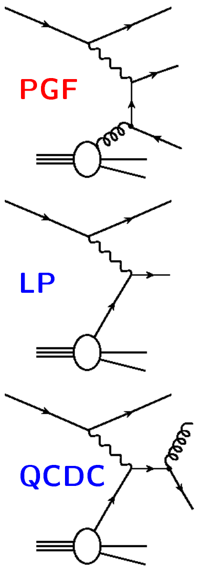
10% statistical improvement with regards to published result:

$$\frac{\Delta G}{G} = -0.49 \pm 0.27(stat.) \pm 0.11(sys.)$$

[PLB 676 (2009) 31-38]

High p_T asymmetries

$$\begin{cases} A_{||}^{2h} \approx \frac{\Delta G}{G} a_{LL}^{PGF} R_{PGF} + A_1^{LP} a_{LL}^{QCDC} R_{QCDC} + A_1^{LP} a_{LL}^{LP} R_{LP} \\ A_1 \approx \frac{\Delta G}{G} a_{LL}^{PGF,inc} R_{PGF}^{inc} + A_1^{LP} a_{LL}^{QCDC,inc} R_{QCDC}^{inc} + A_1^{LP} a_{LL}^{LP,inc} R_{LP}^{inc} \end{cases}$$



where:

$A_{||} = A_{exp}/P_t P_b f$

A_1 - inclusive asymmetry

R_n - fraction of process "n" (MC)

a_{LL}^n - partonic asymmetries (QCD)

$\frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i} \equiv A_1^{LP}$

$\Delta G/G$ extraction

Solving the set of equations we obtain the expression for $\Delta G/G$:

$$\frac{\Delta G}{G}(x_G^{avg}) = \frac{A_{\parallel} + A_{corr}}{\beta}; \quad \beta \sim a_{LL}^{PGF} R_{PGF} + \ldots$$

- $\Delta G/G$ extraction depends on knowledge of "Inclusive" and "High p_T" samples: R, R^{inc} and a_{LL}, a_{LL}^{inc}
- R fractions, a_{LL}, x_{QCDC} and x_G are parametrised using MC simulation

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To improve statistical sensitivity a weighted method is used

- For each event a weight is constructed based on: f, D, P_b
  R_{PGF}, R_{QCDC}, R_{LP}, R_{PGF}^{inc}, R_{QCDC}^{inc}, R_{LP}^{inc}
  a_{LL}^{PGF}, a_{LL}^{QCDC}, a_{LL}^{LP}, $a_{LL}^{PGF,inc}$, $a_{LL}^{QCDC,inc}$, $a_{LL}^{LP,inc}$
- Parametrisation: Neural Network
  - Obtained event-by-event
  - Input (Inclusive case): x_{Bj} and Q^2
  - Input (High p_T case): x_{Bj}, Q^2, $p_{L1,2}$ and $p_{T1,2}$

Data sample selection

Kinematic cuts

- $Q^2 > 1\,(\mathrm{GeV/c})^2$
  events are in perturbative region
- $p_{T1} > 0.7$ GeV/c; $p_{T2} > 0.7$ GeV/c
  enhance fraction of PGF events

Collected statistics

2002-2004: $\sim$ 500k events

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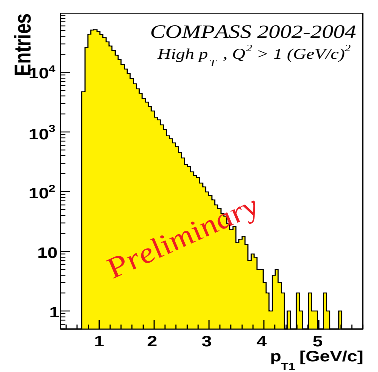
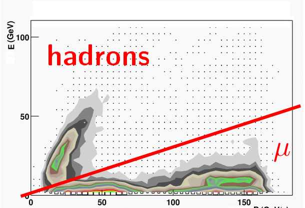
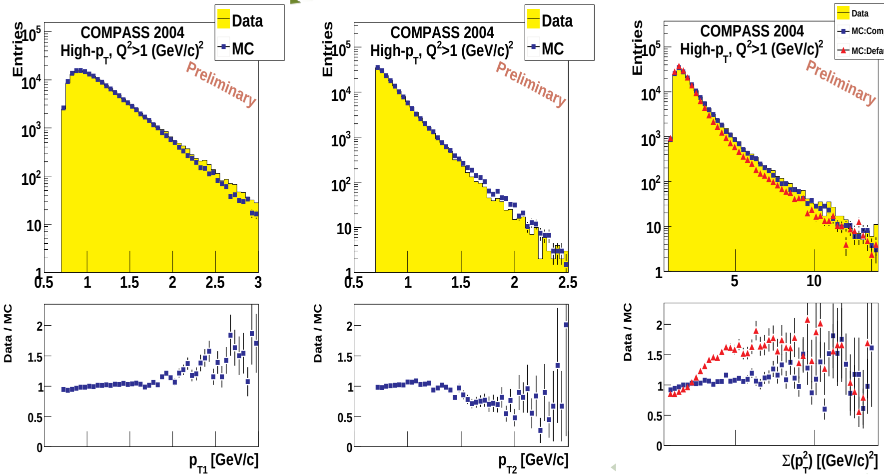
Hadron identification based on hadronic calorimeters and μ rejection in muon filters



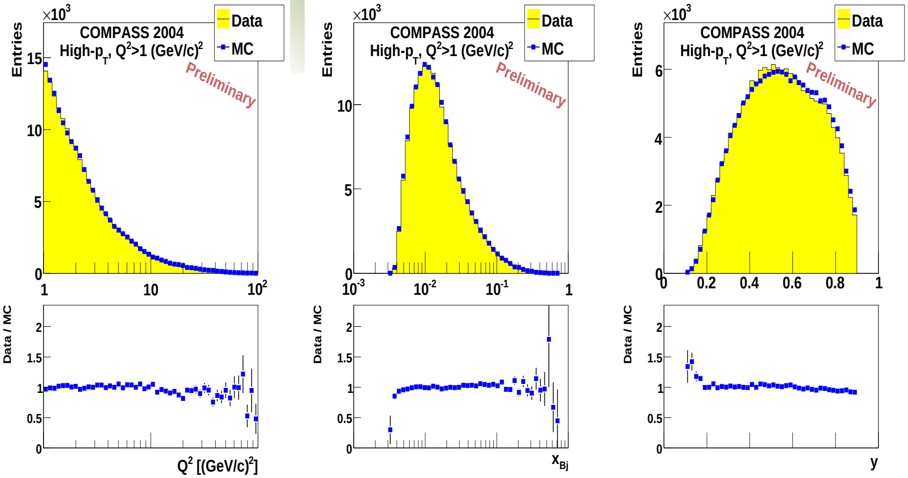


Monte Carlo

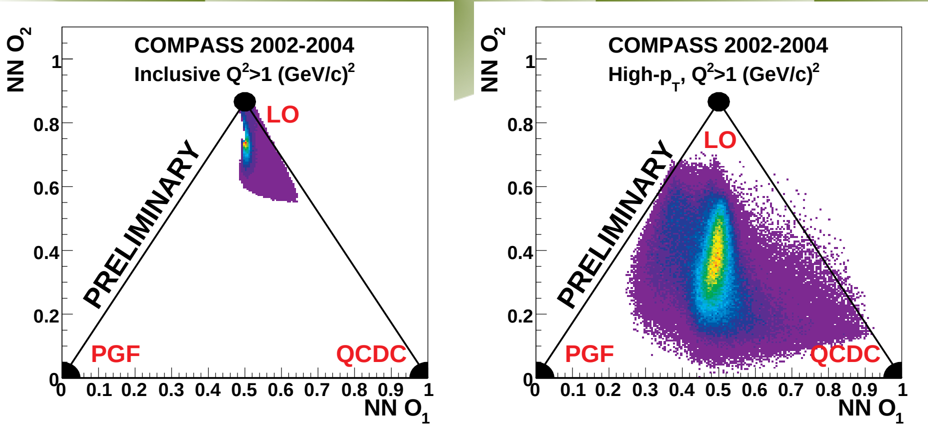
- LEPTO with JETSET fragmentation
- PDFs: MRST2004 LO
- Parton Shower - part of NLO corrections
- Tuning of JETSET fragmentation



High p_T Data/MC



Parametrisation of Rs



$$R_{PGF} + R_{QCDC} + R_{LP} = 1$$

$$R_{PGF} = 1 - o_1 - \frac{1}{\sqrt{3}} o_2; \;\; R_{QCDC} = o_1 - \frac{1}{\sqrt{3}} o_2; \;\; R_{LP} = \frac{2}{\sqrt{3}} o_2$$

Systematics studies

- false asymmetries
- NN stability
- systematic errors due to MC
- δf, δP_B, δP_T
- A_1^d parametrisation
- assumptions in formula extraction

$\delta(\Delta G/G)_{NN}$	0.006
$\delta(\Delta G/G)_{MC}$	0.040
$\delta(\Delta G/G)_{f,P_B,P_T}$	0.006
$\delta(\Delta G/G)_{false}$	0.011
$\delta(\Delta G/G)_{A1}$	0.008
$\delta(\Delta G/G)_{formula}$	0.013
Total	0.045

MC systematics

- 4 different MC have been used
  - COMPASS tuning PS on
  - COMPASS tuning PS off
  - Default tuning PS on
  - Default tuning PS off
- For each sample $\Delta G/G$ was calculated

Preliminary result for High p_T pairs $Q^2 > 1(\mathrm{GeV}/c)^2$

$$\frac{\Delta G}{G} = 0.08 \pm 0.10(stat.) \pm 0.05(syst.)$$

$$x_G = 0.082^{+0.041}_{-0.027} \quad @ \quad \mu^2 \approx 3(\mathrm{GeV}/c)^2$$

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$Q^2 < 1\,(\mathrm{GeV}/c)^2$ results

2002-2003 [PLB 633 (2006) 25-32]:

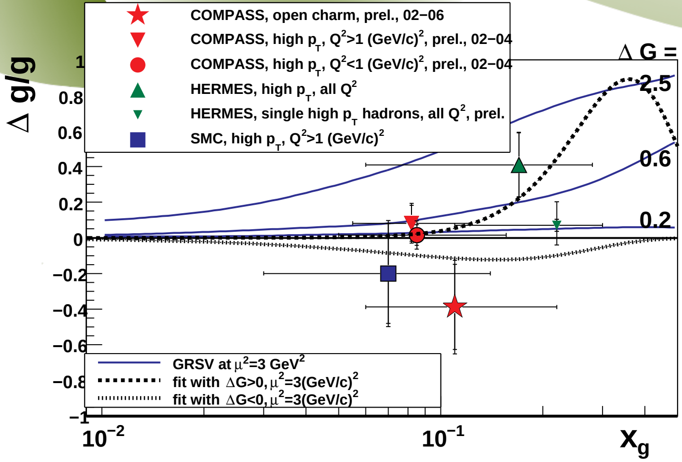
$$\frac{\Delta G}{G} = 0.024 \pm 0.089(stat.) \pm 0.057(syst.)$$

2002-2004 (preliminary):

$$\frac{\Delta G}{G} = 0.016 \pm 0.058(stat.) \pm 0.054(syst.)$$

- Additional background processes (e.g. resolved photon)
- Different MC → PYTHIA
- Hard scale ensured by p_T ($\Sigma p_T^2 > 2.5\,(\mathrm{GeV}/c)^2$)

Direct measurements summary



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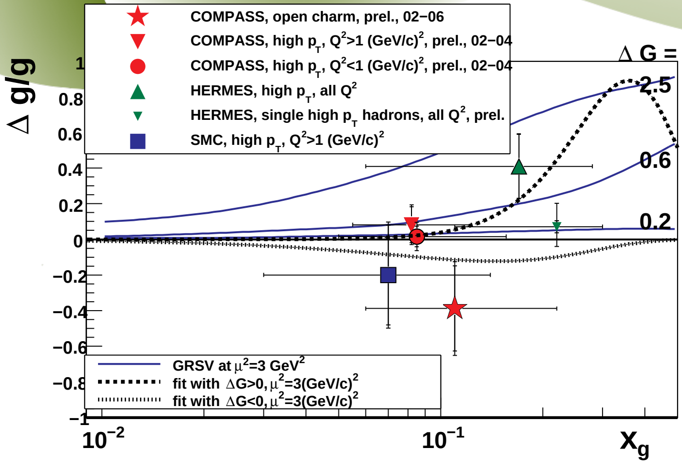


Results from RHIC experiments are compatible with small $\Delta G/G$ in the region covered by fixed target experiments

Summary

- Summary
  - Recent results of $\Delta G/G$ from COMPASS were presented
  - Errors of the measurements were significantly reduced due to usage of additional data and new methods of analysis
  - Present measurements indicate that $\Delta G/G$ is consistent with zero at $x_g \approx 0.1$
- Outlook Open Charm
  - Add 2007 data
  - Full neural networks analysis
  - NLO analysis (ongoing)
- Outlook High p_T pairs
  - Add 2006 and 2007 data ($Q^2 > 1\,(\mathrm{GeV/c})^2$) (ongoing)
  - Explore $0.4 < p_T < 0.7$ GeV/c region ($Q^2 > 1\,(\mathrm{GeV/c})^2$)
  - 1-hadron analysis
  - Add remaining data for $Q^2 < 1\,(\mathrm{GeV/c})^2$

Backup Slides

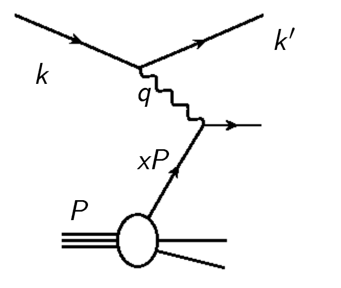
Deep Inelastic Scattering - DIS

Variables

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

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

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



Selection

Open Charm

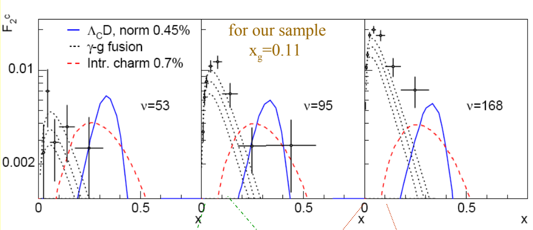
D^* event selection
$0.1 < y < 0.9$
$z_{D^0} > 0.2$
$\lvert cos(\theta^*)\rvert < 0.9$
3.2MeV $< m(K\pi\pi_{soft}) - m(D^0) - m(\pi) <$ 8.9MeV
π, K, e identification based on RICH
p<50 GeV/c
No other D^* in the same event

D^0 event selection
$0.1 < y < 0.9$
$z_{D^0} > 0.2$
$\lvert cos(\theta^*)\rvert < 0.65$
π, K, e identification based on RICH
>7 GeV/c for pions and for both <50 GeV/c
No other D^* or D^0 in the same event

High p_T

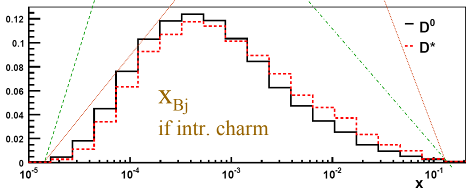
- $Q^2 > 1\ \mathrm{GeV}^2$
- $p_T > 0.7$ GeV (for both hadrons)
- $0.1 < y < 0.9$
- $x_F, z > 0.0$
- $m(h_1, h_2) > 1.5$ GeV: remove ρ resonance
- $\Sigma z < 0.95$: remove exclusive events

Intrinsic Charm



Ref. hep-ph/0508126 and hep-ph/9508403
Data from EMC:Nucl.Phys.B213, 31(1983)

For our data: average ν (70-120GeV),



Preliminary results including all channels

New channels contributions to $\Delta G/G$

- π^0 reflection "bump"
  $\Delta G/G = -0.15 \pm 0.63$
  $A_{BG} = 0.02 \pm 0.03$

- RICH sub-threshold Kaons
  $\Delta G/G = 0.57 \pm 1.02$
  $A_{BG} = -0.04 \pm 0.05$

Final result
(including the main channels: D^0 and D^0 tagged with a D^*)

$$\Delta G/G = -0.39 \pm 0.24(stat) \pm 0.11(sys)$$

$$@ < x_g >= 0.11, < \mu^2 >= 13\ \text{GeV}^2$$

10% statistical improvement with regards to published result:

$$\frac{\Delta G}{G} = -0.49 \pm 0.27(stat.) \pm 0.11(sys.)$$

[PLB 676 (2009) 31-38]

$\Delta G/G$ High p_T formula

Solving this set of two equations
we obtain expression for $\Delta G/G$:

$$\frac{\Delta G}{G}(x_G^{avg}) = \frac{A_{||} + A_{corr}}{\beta}; \quad \beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} \frac{R_{PGF}^{incl}}{R_{LP}^{incl}} \left(R_{LP} + a_{LL}^{QCDC} R_{QCDC} \right)$$

$$A_{corr} = -A_1(x_{Bjk}) \frac{R_{LP}}{R_{LP}^{incl}} - A_1(x_{QCDC})\alpha_1 + A_1(x'_{QCDC})\alpha_2$$

$$\alpha_1 = \frac{1}{R_{LP}^{incl}} \left(a_{LL}^{QCDC} R_{QCDC} - a_{LL}^{QCDC,incl} R_{QCDC}^{incl} \frac{R_{LP}}{R_{LP}^{incl}} \right)$$

$$\alpha_2 = a_{LL}^{QCDC,incl} \frac{R_{QCDC}^{incl}}{R_{LP}^{incl}} \frac{R_{QCDC}}{R_{LP}^{incl}} a_{LL}^{QCDC}$$

$\Delta G/G$ High p_T formula

Solving this set of two equations
we obtain expression for $\Delta G/G$:

$$\frac{\Delta G}{G}(x_G^{avg}) = \frac{A_{||} + A_{corr}}{\beta}; \quad \beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} \frac{R_{PGF}^{incl}}{R_{LP}^{incl}} \left(R_{LP} + a_{LL}^{QCDC} R_{QCDC} \right)$$

$$A_{corr} = -A_1(x_{Bjk}) \frac{R_{LP}}{R_{LP}^{incl}} - A_1(x_{QCDC})\alpha_1 + A_1(x'_{QCDC})\alpha_2$$

$$\alpha_1 = \frac{1}{R_{LP}^{incl}} \left(a_{LL}^{QCDC} R_{QCDC} - a_{LL}^{QCDC,incl} R_{QCDC}^{incl} \frac{R_{LP}}{R_{LP}^{incl}} \right)$$

$$\alpha_2 = a_{LL}^{QCDC,incl} \frac{R_{QCDC}^{incl}}{R_{LP}^{incl}} \frac{R_{QCDC}}{R_{LP}^{incl}} a_{LL}^{QCDC}$$

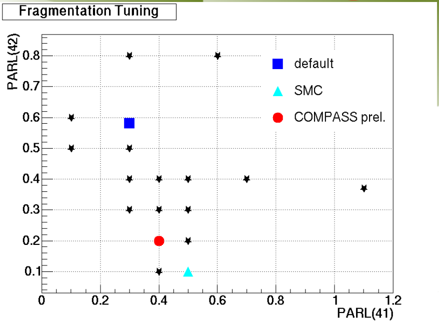
- a_{LL}^n, R_n - depend on partonic kinematics (not accessible in experiment)
- a_{LL}^n, R_n, x_C, x_G are parametrised using MC simulation
- In order to maximise the statistical efficiency a weighted estimator is used
- For each event a statistical weight is constructed
- Weights are constructed from: f, D, P_B, β, α_1, α_2

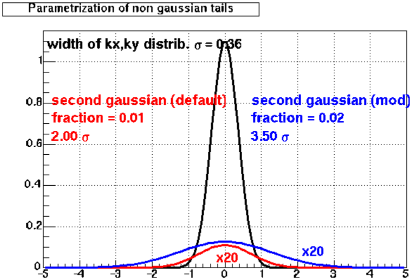
High p_T Monte Carlo

Avarage values of a_{LL}s and Rs	Final MC
$\langle a_{LL}^{LP} \rangle$	0.63
$\langle a_{LL}^{QCDC} \rangle$	0.50
$\langle a_{LL}^{PGF} \rangle$	-0.36
R_{LP}	0.40
R_{QCDC}	0.29
R_{PGF}	0.31

JETSET parameters	Default	COMPASS
PARJ(41)	0.3	0.6
PARJ(42)	0.58	0.1
PARJ(21)	0.36	0.3
PARJ(23)	0.01	0.02
PARJ(24)	2.0	3.5

Tuning of fragmentation





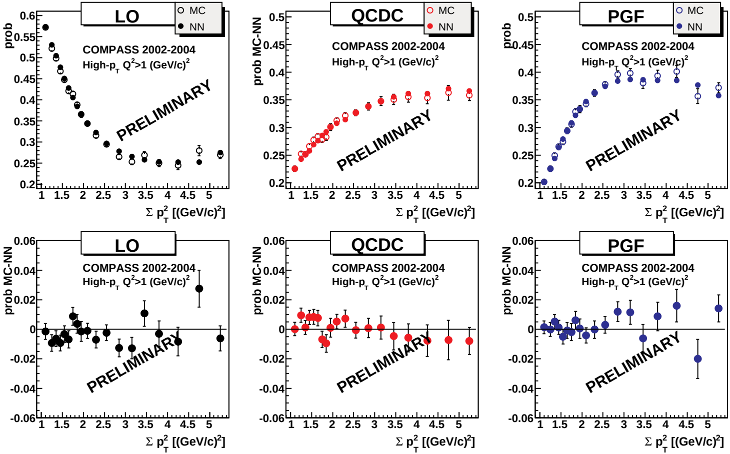
- LUND fragmentation
  $f(z) = z(1-z)^a e^{-bm_T^2/z}$
  $m_T^2 = m^2 + p_T^2$
- with variable parameters a (PARJ(41)) and b (PARJ(42))

- String between two outgoing quarks
- $q\bar{q}$ pairs created with transverse momentum k_T
- width of the gaussian $k_{x,y}$ PARJ(21) = 0.36
- non gaussian tails modelled by second broader gaussian
  - width = PARJ(24) x PARJ(21)
  - fraction PARJ(23) = 0.01 of first gaussian

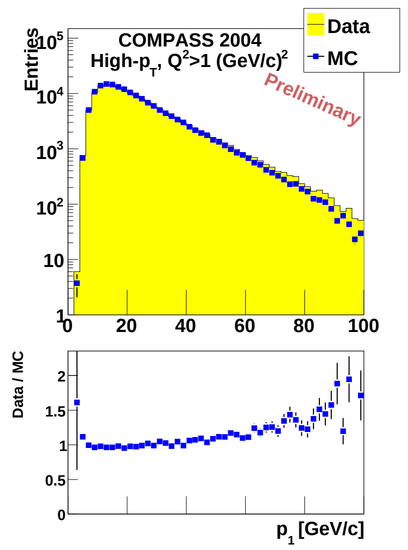
NN validity

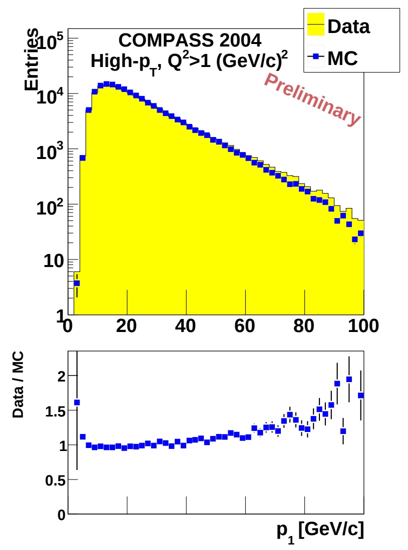
Fractions of the three processes as a function of $\sum p_T^2$

- Empty points - directly taken from MC
- Full points - estimated using NN



High p_T Data/MC





High p_T Data/MC