COMPASS results on the gluon polarisation in the nucleon

Beata Pawlukiewicz

University of Warsaw
on behalf of the COMPASS collaboration

SYMMETRIES AND SPIN (Spin-Praha-2009)
Prague July 28, 2009

Overview

- The Spin Puzzle
- The COMPASS experiment
- Direct gluon polarisation measurements
  - Open Charm analysis
  - High p_T hadron pairs analysis
- Results
- Summary and Outlook

The Spin Puzzle 20 years later

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

Definitions:

$\Delta\Sigma = \Delta u + \Delta d + \Delta s$
$\Delta q = \int \Delta q(x) dx$
$\Delta G = \int \Delta g(x) dx$

- In the naive QPM: $\Delta\Sigma = 1$
- Taking into account relativistic corrections and $\Delta s = 0$: $\Delta\Sigma \approx 0.6$
- The EMC: $\Delta\Sigma = 0.12 \pm 0.17$ [Nucl. Phys. B **328** (1989) 1]
- COMPASS NLO QCD fit to the world data: $\Delta\Sigma = 0.30 \pm 0.01(\text{stat.}) \pm 0.02(\text{evol.})$ [PLB **647** (2007) 8-17]
- Direct measurements can answer what is the contribution of ΔG to the nucleon spin...

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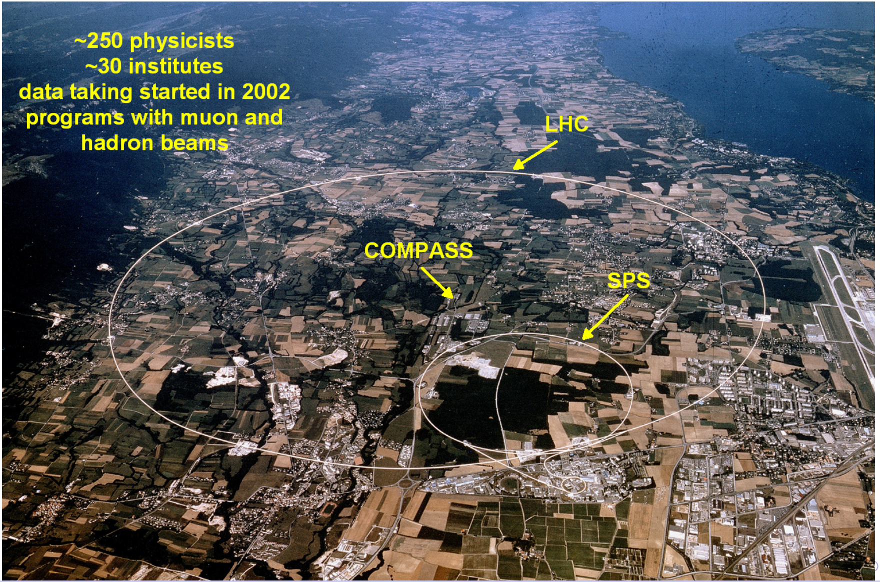
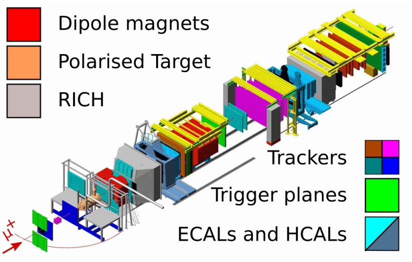
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

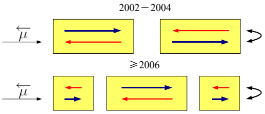


The COMPASS setup

- Two stages: LAS and SAS
- Tracking (p $>$ 0.5 GeV):
  Scifis, GEMs, Micromegas, Straws
- Particle identification:
  π, K, p separation
  (above 2, 9 and 18 GeV)
  with RICH, ECAL, HCAL, μFilter
- Beam: 160 GeV μ^+, $2 \cdot 10^8 \mu/5\text{s}$,
  naturally polarised $\sim$ 80 %
- Target (^{6}LiD): 2 (3) cells oppositely
  polarised $\sim$ 50 % $\Rightarrow$
  observables $\equiv$ cross-section asymmetries!

[NIMA **577** (2007) 455]





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How to access $\Delta g/g$?

- Register DIS scattering polarised μ on polarised nucleon:

$$\mu + \mathrm{N} \rightarrow \mu' + \mathrm{X}$$

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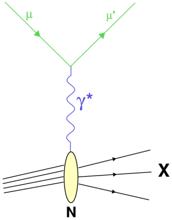

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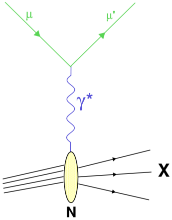

- Look for processes with Photon-Gluon-Fusion:

$$\gamma^* + \mathrm{g} \longrightarrow \mathrm{q}\ \overline{\mathrm{q}}$$

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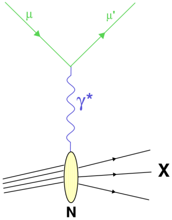

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  - hadrons with high transverse momenta (w.r.t. γ^*)

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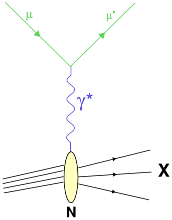

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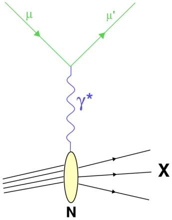

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beam target

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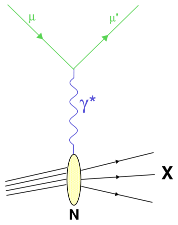

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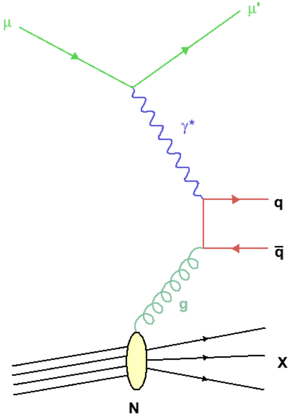
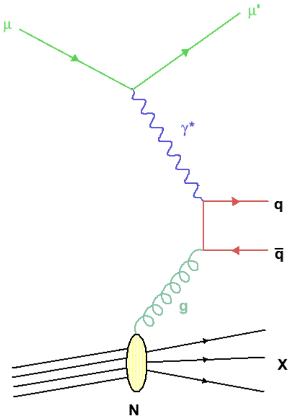
$$\Delta g \equiv \Delta g(x, \mu^2)$$
$$g \equiv g(x, \mu^2)$$

Tagging PGF process: charmed mesons



- $q \equiv c \Rightarrow$ D mesons in the final state
- clean channel:
  - intrinsic charm and charm in string fragmentation – suppressed
  - resolved photon – negligible
- perturbative scale: $4(m_c^2 + p_T^2)$
- difficult measurement:
  - low statistics
  - huge combinatorial background
- NLO effects may be important

Tagging PGF process: high p_T hadron pairs, $Q^2 > 1\ (\mathrm{GeV}/c)^2$



- q ≡ light quarks ⇒ a pair of hadrons with high transverse momenta in the final state
- perturbative scale: Q^2
- simple measurement: large statistics
- QCD background processes
- strong dependence on the MC simulations

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Interpretation of the charmed double spin asymmetry

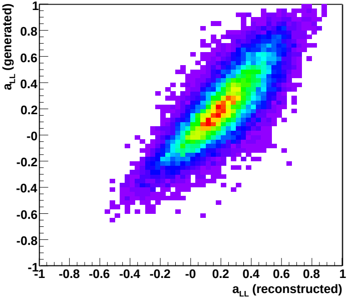
In the LO approximation:

$$A^{exp} = \frac{N^{\uparrow\Downarrow} - N^{\uparrow\Uparrow}}{N^{\uparrow\Downarrow} + N^{\uparrow\Uparrow}} = P_t P_b f a_{LL} \frac{S}{S+B} \frac{\Delta g}{g} + A^{bgd}$$

P_t	target polarisation: 50%
P_b	beam polarisation: 80%
f	target dilution factor: ≈ 0.4 for ^{6}LiD
a_{LL}	partonic cross-section asymmetry (analysing power)
$\frac{S}{S+B}$	fraction of the signal
A^{bgd}	extracted simultaneously with A^{exp}

Partonic cross-section asymmetry a_{LL}

- $a_{LL} \equiv \frac{\Delta\hat{\sigma}}{\hat{\sigma}}$: partonic cross-section asymmetry, not accessible in the measurement
- it is determined from Monte Carlo (AROMA LO) and parameterised using Neural Network
- the trained NN is applied to data $\Rightarrow$ obtain a_{LL} on the event-by-event basis



Data samples (2002 – 2006)

- standard channels: [PLB **676** (2009) 31-38]
  - $D^0 \longrightarrow K\pi$
    (D*-non-tagged; 37000 events)

Data selection:

- K, π identified using RICH
- 0.4 GeV/c^2 $<$ $M_{K\pi}$ - M_{D^0} $<$ 0.4 GeV/c^2

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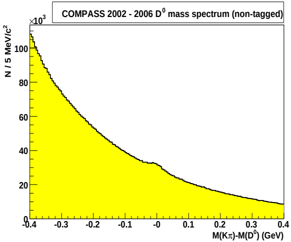

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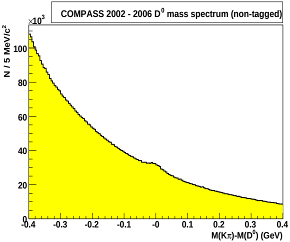

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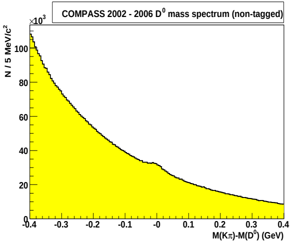

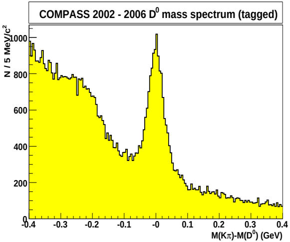

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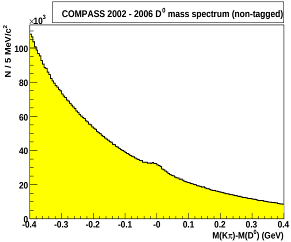
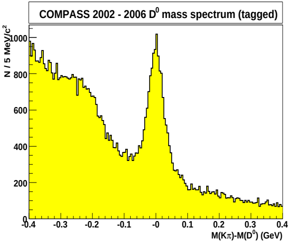


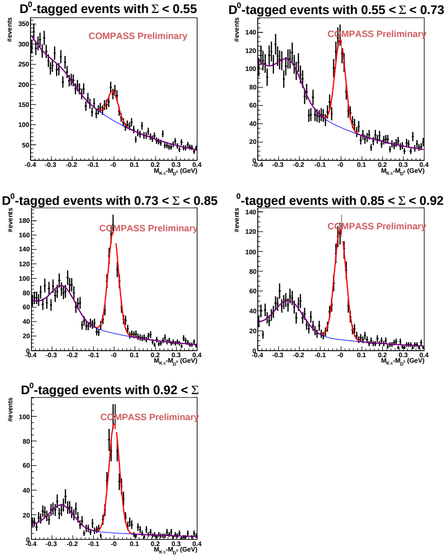


- new channels:
  - $D^* \longrightarrow D^0\pi_{slow} \longrightarrow K\pi(\pi^0)\ \pi_{slow}$ (D*-tagged; 6200 events)
  - $D^* \longrightarrow D^0\pi_{slow} \longrightarrow K_{sub}\pi\pi_{slow}$ (D*-tagged; 1800 events)

Event weight

To select the signal in more efficient way:

- each event is weighted with the full weight: $fP_b a_{LL} \frac{S}{S+B}$
- at the same time event is weighted with the background weight $(\dots \frac{B}{S+B})$
  $\Rightarrow$ simultaneous extraction of signal and background asymmetries
- $\Sigma \equiv \frac{S}{S+B}$ is parameterised event-by-event basis as a function of many variables (*e.g.* m_{D^0}, $p_{T_{D^0}}$, RICH likelihoods,...)



Open charm results (2002–2006)

sample	$\langle \Delta g/g \rangle_x$
D*-tagged and non-tagged [PLB **676** (2009) 31-38]	-0.47 ± 0.27 (stat.) ± 0.11 (sys.)
new! D^* with additional π^0	-0.15 ± 0.63 (stat.)
new! D^* with RICH–subtreshold kaons	$+0.57 \pm 1.02$ (stat.)

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$$\langle \frac{\Delta g}{g} \rangle_x = -0.39 \pm 0.24 \text{ (stat.) } \pm 0.11 \text{ (syst.)}$$

at $< x_g >= 0.11^{+0.11}_{-0.05}$, $< \mu^2 >= 13 \ (\mathrm{GeV}/c)^2$

SYSTEMATICS:

source	$\delta(\langle \Delta g/g \rangle_x) D^0(D^*)$	source	$\delta(\langle \Delta g/g \rangle_x) D^0(D^*)$
false asymmetry	0.05(0.05)	P_b	0.025
S/(S+B)	0.07(0.01)	P_t	0.025
a_{LL}	0.05(0.03)	f	0.025
Total: 0.11(0.07)			

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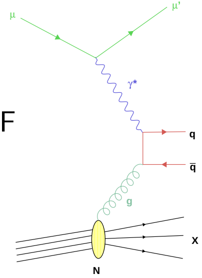
Interpretation of the high p_T hadron asymmetry, A^{2h}

In the LO approximation:

PGF



- R_i – fraction of sub-processes (PGF, LP, QCD-C)
- a^i_{LL} – analysing powers for PGF, LP and QCD-C
- D – a depolarisation factor
- $A_1^{LO} = \sum e_i^2 \Delta q_i / \sum e_i^2 q_i$

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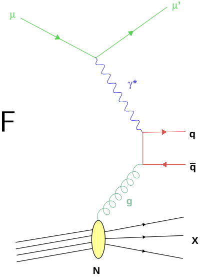
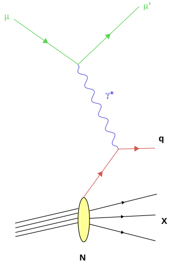


LP



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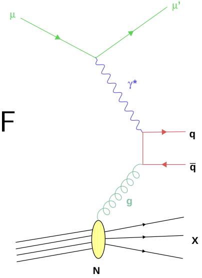

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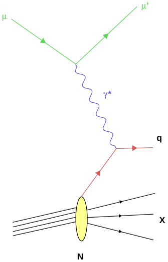
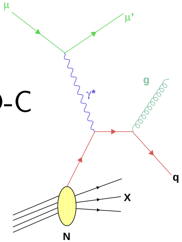


QCD-C



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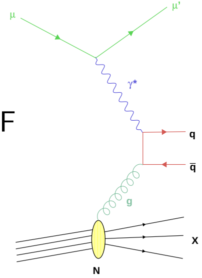

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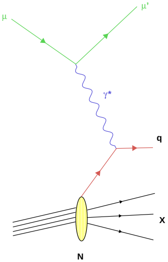

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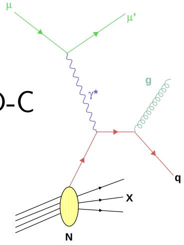

$$A^{2h} \sim \frac{\Delta g}{g}(x_g)a_{LL}^{PGF}R_{PGF} + A_1^{LO}(x_{Bj})DR_{LO} + A_1^{LO}(x_c)a_{LL}^{QCDC}R_{QCDC}$$

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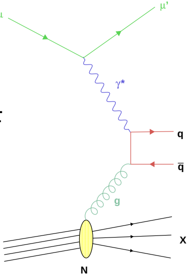

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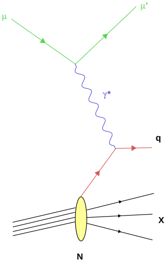

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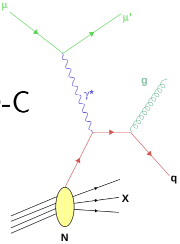

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$\Delta g/g$ extraction

$$\langle \frac{\Delta g}{g} \rangle_x = \frac{A^{2h} + A^{corr}}{\beta}$$

- $A^{2h} = A^{exp}/P_t P_b f$ – directly from data
- A^{corr} – combination of inclusive asymmetry A_1, R_i and a^i_{LL}
- β factor – a function of R_i and a^i_{LL}
- R_i and a^i_{LL} have to be obtained from MC simulation (LEPTO) for both inclusive and hight p_T samples
  $\Leftarrow$ good agreement between data and MC is crucial!

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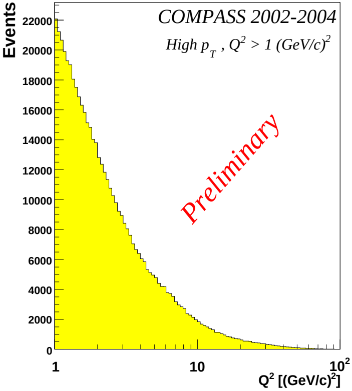
- Event weight: $fDP_b\beta$
- Parameterisation on the event-by-event basis: Neural Network

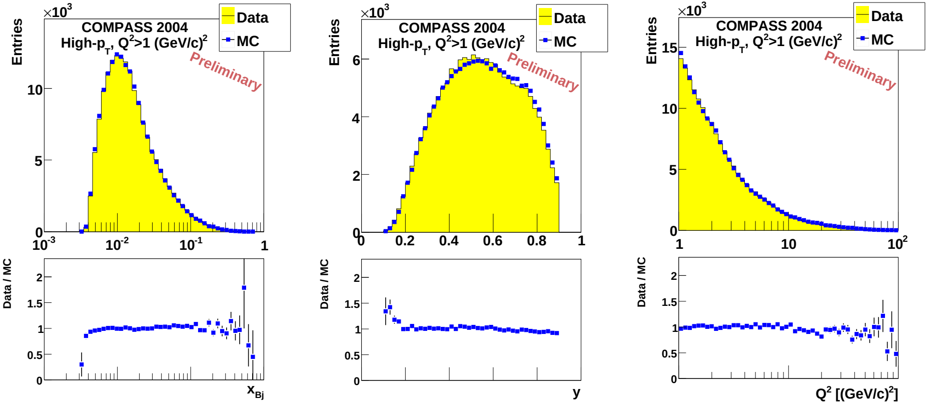
High p_T sample



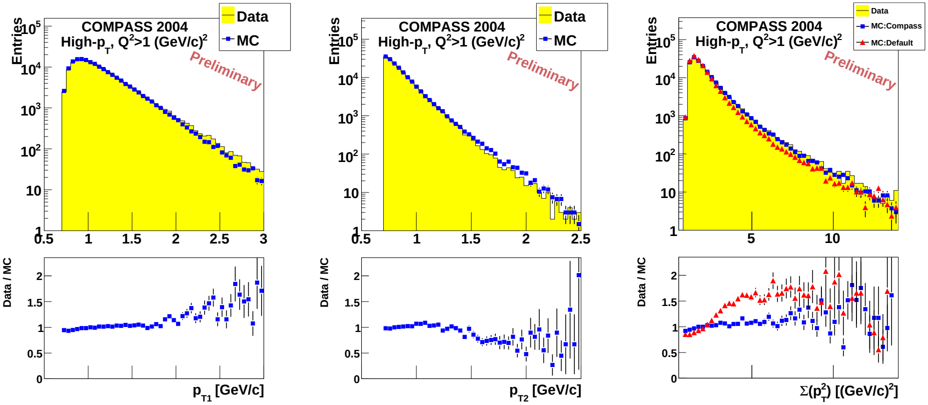
Data selection:

- $Q^2 > 1$ (GeV/c)^2 (cuts 90% of the statistics)
- $p_{T_1} > 0.7$ GeV/c and $p_{T_2} > 0.7$ GeV/c
- 2002 – 2004: 500k events

Data and MC comparison: x_{Bj}, y, Q^2



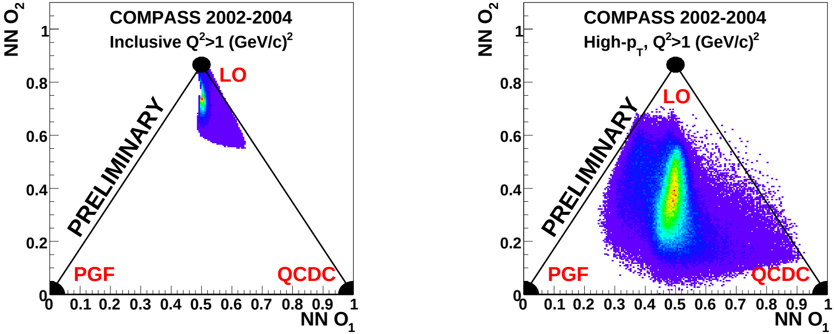
Data (2002-2004) and MC comparison: p_{T_1}, p_{T_2}, $\sum p_{T^2}$



LEPTO tuning: k_T and parameters of fragmentation

NN parameterisation of R_i

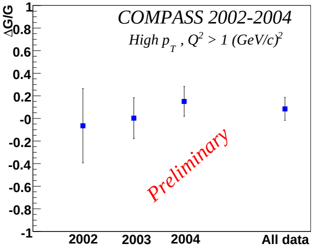
The event probability to be PGF, LP or QCDC is evaluated from a NN parametrising R_i (R_i sum up to 1):



$$R_{PGF} = 1 - O_1 - \frac{1}{\sqrt{3}} O_2 \qquad R_{QCDC} = O_1 - \frac{1}{\sqrt{3}} O_2 \qquad R_{LP} = \frac{2}{\sqrt{3}} O_2$$

High p_T hadron pairs results

$Q^2 > 1$ $(\text{GeV}/c)^2$ (2002 – 2004):



SYSTEMATICS:

source	$\delta(\langle \Delta g/g \rangle_x)$
NN	0.006
MC	0.040
fP_bP_t	0.006
false asymmetry	0.011
A_1	0.008
formula	0.013
Total	0.045

$$\langle \frac{\Delta g}{g} \rangle_x = 0.08 \pm 0.10 \text{ (stat.) } \pm 0.05 \text{ (sys.)} \quad < x_g >= 0.082^{+0.041}_{-0.027}, < \mu^2 >= 3 \ (\text{GeV}/c)^2$$

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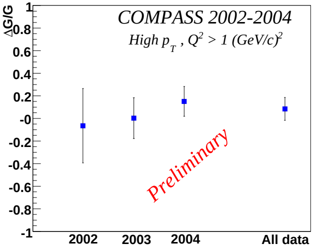

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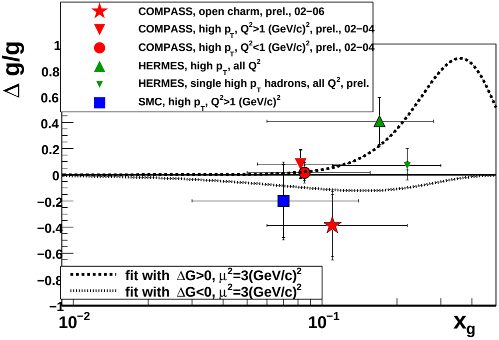
$Q^2 < 1\ (\mathrm{GeV}/c)^2$ (2002 – 2003): $\langle \frac{\Delta g}{g} \rangle_x = 0.024 \pm 0.089 \pm 0.057$ [PLB **633** (2006) 25-32]

$Q^2 < 1\ (\mathrm{GeV}/c)^2$ (2002 – 2004): $\langle \frac{\Delta g}{g} \rangle_x = 0.016 \pm 0.058 \pm 0.054$ preliminary

- The Spin Puzzle
- The COMPASS experiment
- Direct gluon polarisation measurements
  - Open Charm analysis
  - High p_T hadron pairs analysis
- Results
- Summary and Outlook

COMPASS results on $\Delta g/g$



- Direct COMPASS measurements on gluon polarisation: $\langle \Delta g/g \rangle_x$ compatible with 0 at $x_g \approx 0.1$
- The curves: COMPASS NLO QCD fits to world data on $g_1^d \Rightarrow$ fits with negative and positive ΔG describe data equally well

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  - Open charm: $\langle \Delta g/g \rangle_x = -0.39 \pm 0.24 \pm 0.11$ $(\mu^2 = 13\ (\text{GeV}/c)^2)$
  - High p_T, $Q^2 > 1\ (\text{GeV}/c)^2$: $\langle \Delta g/g \rangle_x = 0.08 \pm 0.10 \pm 0.05$ $(\mu^2 = 3\ (\text{GeV}/c)^2)$

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  - Open charm: $\langle \Delta g/g \rangle_x = -0.39 \pm 0.24 \pm 0.11$ ($\mu^2 = 13$ (GeV/c)^2)
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  - High p$_T$, Q$^2 < 1$ (GeV/c)^2: $\langle \Delta g/g \rangle_x = 0.016 \pm 0.058 \pm 0.054$ ($\mu^2 = 3$ (GeV/c)^2)
- The results indicate $\langle \Delta g/g \rangle_x$ consistent with 0 at $x_g \approx 0.1$

OUTLOOK

- Open Charm:
  - NLO analysis is going on
  - add 2007 data
- High p_T pairs:
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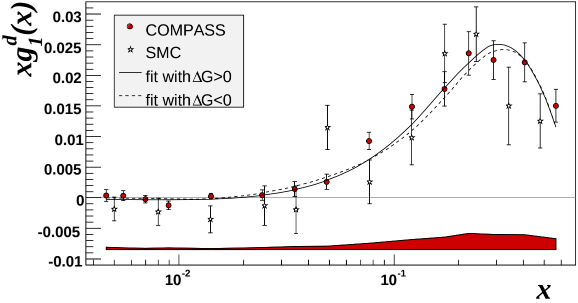
COMPASS has presented recently to the SPSC the addendum
to its original proposal and got positive feed-back.
It will run both longitudinal and transverse programs beyond 2009.

SPARES

Indirect $\Delta g/g$ Determination:

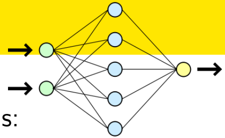
- World data: 9 experiments, 230 data points (43 from COMPASS)
- Both solutions: $\Delta G > 0$ and $\Delta G < 0$ describe data equally well

[PLB **647** (2007) 330–340]



ΔG from COMPASS data only: $\approx 0.2 - 0.3$

SPARES: Artificial Neural Network



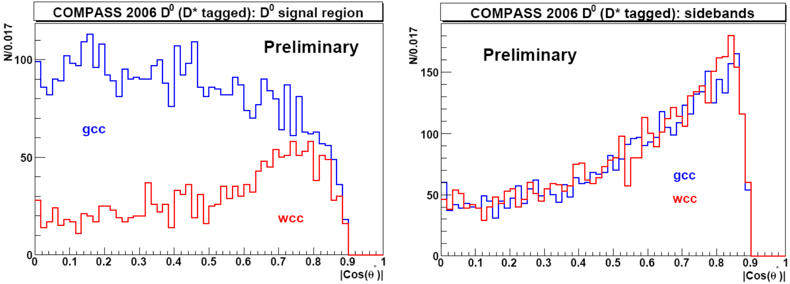
- a multidimensional structure of the interconnected neurons:
  - input layer: vector of variables on which the parameterisation will be built
  - hidden layers with the possibility to change the number of neurons
  - output layer: usually 1 exit neuron contained the desired output (e.g. a_{LL}^{par})
- the desired output is provided on the event-by-event basis (supervised learning)
- the connections are weighted
- the training process: the iterative procedure of weights adaptation
- the training goal: to minimise the difference between the desired and obtained NN output
- the training results are simultaneously checked using the testing set
- once the net is trained – frosen structure and weights – it can be applied to solve the problem for the new input sets!

SPARES: Neural Network qualification of events

the slide from C. Franco DIS 2009, Madrid, Spain

- **Two real data samples** *(with same cuts)* **are compared by the Neural Network** *(giving as input some kinematic variables as a learning vector)*:
  - **Signal model** → **gcc** = $K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+$ *(D^0 spectrum: signal + bg.)*
  - **Background model** → **wcc** = $K^+\pi^+\pi_s^- + K^-\pi^-\pi_s^+$ *(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)*

Example of a good learning variable



SPARES: The full formula for open-charm analysis

the slide from C. Franco DIS 2009, Madrid, Spain

- **The number of events comes from the asymmetries in the following way:**

$$N_{u,d}=a\,\phi\,n(S+B)\left(1+P_T P_\mu f\left(a_{LL}\frac{S}{S+B}\frac{\Delta G}{G}+a^{B}_{LL}\frac{B}{S+B}A_B\right)\right)$$

a = acceptance, ϕ = muon flux, n = number of target nucleons

- **We have 4 cell configurations** *(2 cells oppositely polarised + field reversal for acceptance normalization)*:
  - Weight the 4 $N_{u,d}$ equations by ω_s and by $\omega_B = P_\mu \cdot f \cdot D(y) \cdot (B/S+B)$:

$$<\Sigma_{k=1}^{N_{cell}}\omega_i^k>=\hat{a}_{cell,i}(1+(<\beta_{cell,S}>\omega_i)A_S+(<\beta_{cell,B}>\omega_i)A_B)=f_{cell,i}$$

(**cell = u , d , u' , d'**) **($\Delta G/G$)** **(i = S , B)**

$$\hat{a}=a\,\phi\,n\,\sigma=a\,\phi\,n(\sigma_{PGF}+\sigma_B)=a\,\phi\,n(S+B)$$

$$\beta_S=P_B P_T f\,a_{LL}\frac{S}{S+B} \qquad \beta_S=P_B P_T f\,D\frac{B}{S+B}$$

8 eq. with 10 unknowns

SPARES: Monte Carlo in high p_T analysis

- 2 MC samples were used: high p_T and inclusive
- the MC chain: LEPTO generator (PDFs: MRST2004LO) and the full simulation of the detector response and of the reconstruction
- the part of the NLO corrections taken into account: gluon radiations in final and initial states
- to improve data/MC agreement – LEPTO was tuned: k_T (transverse momentum of the $q\bar{q}$ pairs) and parameters of fragmentation (default parameters were used in the systematics studies)

	PARJ21	PARJ23	PARJ24	PARJ41	PARJ42
Default	0.36	0.01	2.0	0.3	0.58
COMPASS	0.3	0.02	3.5	0.6	0.1

SPARES: the full formula for high p_T analysis

the slide from K.Kurek SPIN 2008, Charlottesville, USA

$$\frac{\Delta G}{G}(x_G) = \frac{A_{LL}^{2h}(x_{Bj}) + A^{corr}}{\beta}$$

Note that inclusive sample also contains PGF and QCDC as well as LO process

$$\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} R_{PGF}^{incl} \left(\frac{R_L}{R_L^{incl}} + \frac{R_C}{R_L^{incl}} \frac{a_{LL}^C}{D}\right)$$

$$A^{corr} = -A_1(x_{Bj}) D \frac{R_L}{R_L^{incl}} - A_1(x_C)\beta_1 + A_1(x'_C)\beta_2$$

$$\beta_1 = \frac{1}{R_L^{incl}}\left(a_{LL}^C R_C - a_{LL}^{C,incl} R_C^{incl} \frac{R_L}{R_L^{incl}}\right) \qquad \beta_2 = a_{LL}^{C,incl} \frac{R_C R_C^{incl}}{(R_L^{incl})^2} \frac{a_{LL}^C}{D}$$