Gluon Polarisation Results from the COMPASS Experiment

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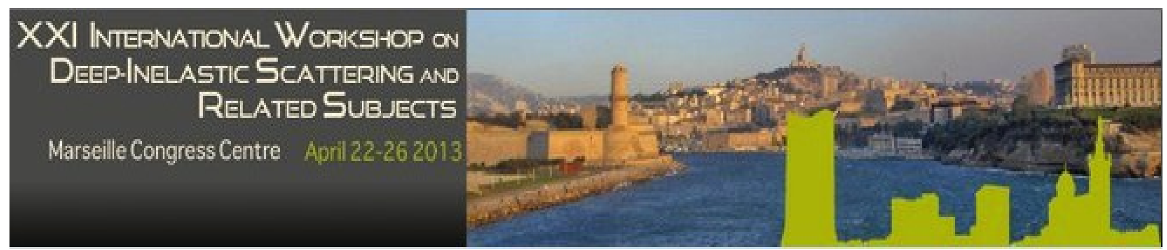
Outline:

- Motivation
- High p_T Analysis
- Open Charm (LO and NLO) Analyses
- $\Delta G/G$ Results
- Summary and Conclusions



co-financed by

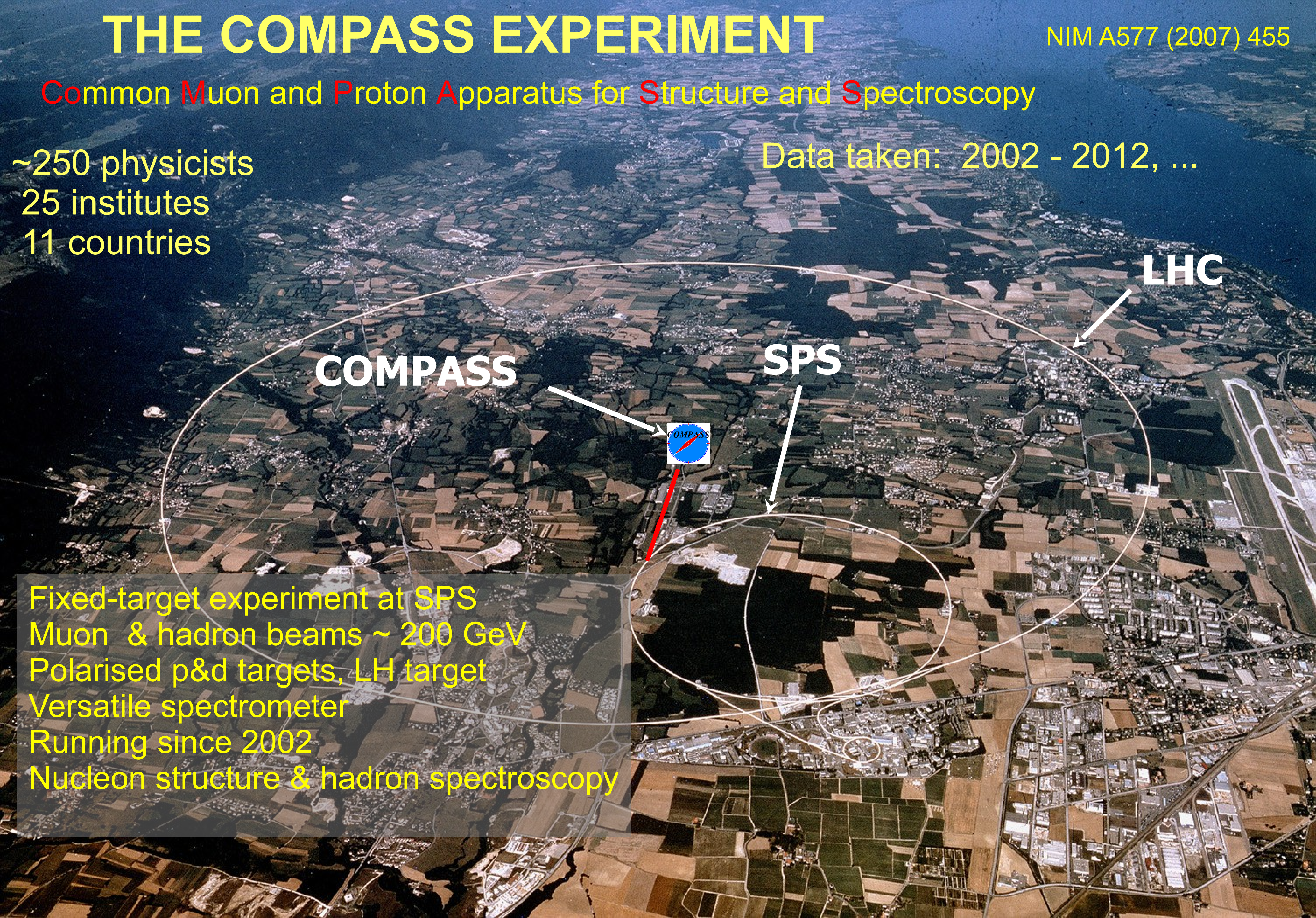
THE COMPASS EXPERIMENT

NIM A577 (2007) 455

Common Muon and Proton Apparatus for Structure and Spectroscopy

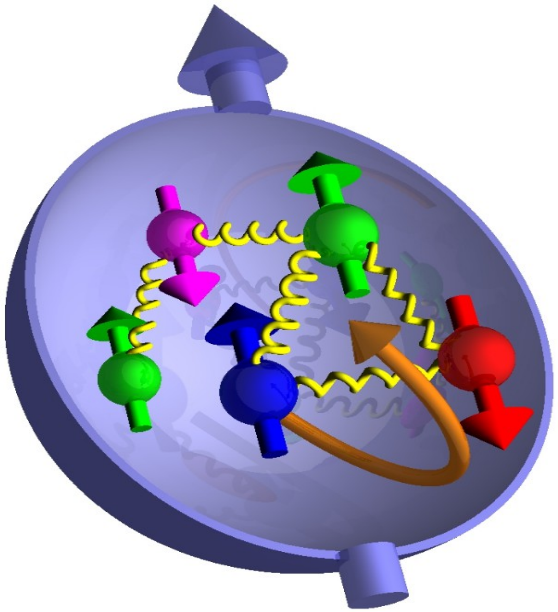
~250 physicists
25 institutes
11 countries

Data taken: 2002 - 2012, ...



- Fixed-target experiment at SPS
- Muon & hadron beams ~ 200 GeV
- Polarised p&d targets, LH target
- Versatile spectrometer
- Running since 2002
- Nucleon structure & hadron spectroscopy

The Nucleon Spin



$$S_N = \tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L$$

Partons Angular Orbital Momenta

Quarks

Gluons

Future !

GPDs

Well known !

In 1988 EMC measured

$\Delta\Sigma = 0.12 \pm 0.17$ (Phys.Lett.B206,364)

A recent result, including COMPASS, gives:

$\Delta\Sigma = 0.30 \pm 0.01$(stat.) ± 0.02(evol.) Phys.Lett.B647,8

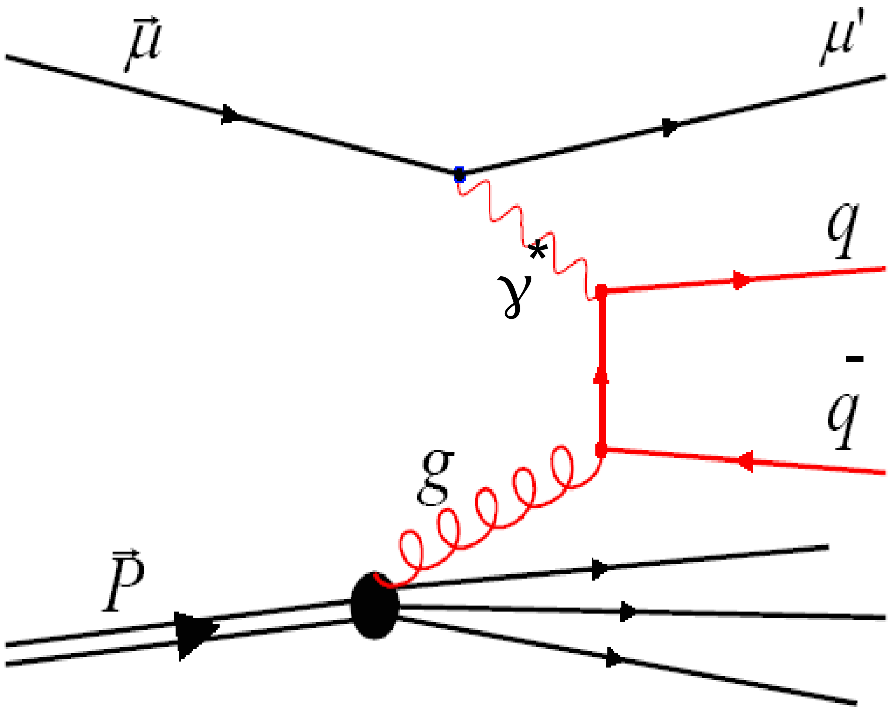
Not completely known

Exploratory and discovery stage. Some experiments and data might give hints.

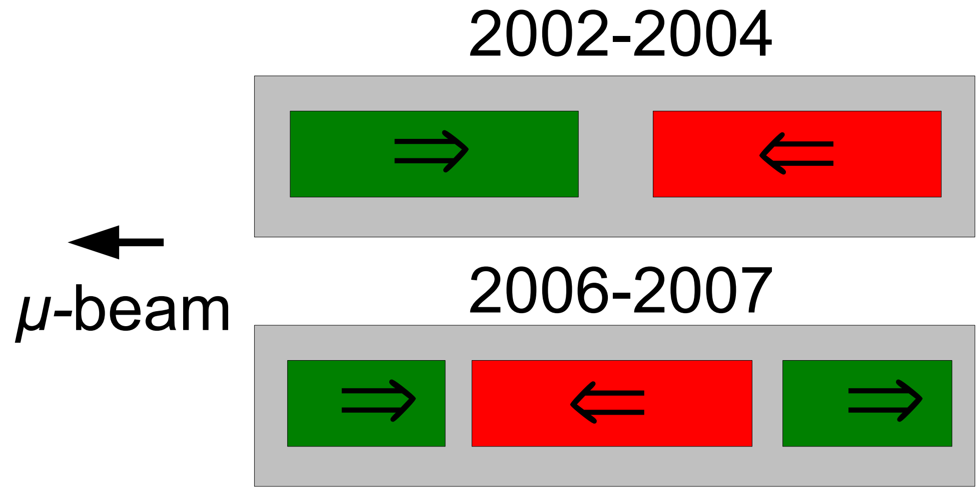
COMPASS, HERMES, CLAS, STAR, PHENIX, EIC.

Direct Measurement of ΔG/G

$\gamma^* g \rightarrow q \bar{q}$



Photon-gluon fusion (PGF) process

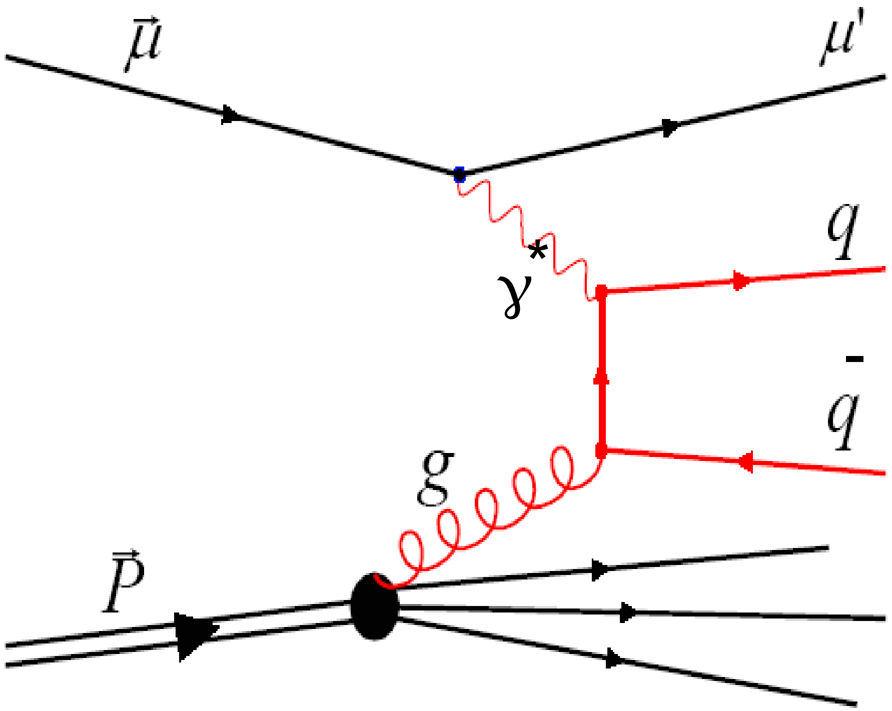


$$A_{PGF} = \frac{N^{\overleftarrow{\Rightarrow}}_{PGF} - N^{\overleftarrow{\Leftarrow}}_{PGF}}{N^{\overleftarrow{\Rightarrow}}_{PGF} + N^{\overleftarrow{\Leftarrow}}_{PGF}}$$

$\Rightarrow$ ΔG/G

Direct Measurement of $\Delta G/G$

$\gamma^* g \rightarrow q \bar{q}$



Photon-gluon fusion (PGF) process

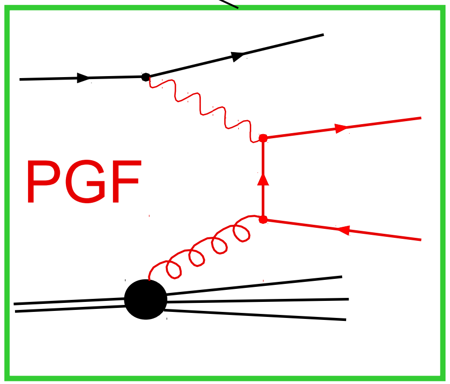
To select this process there are two methods :

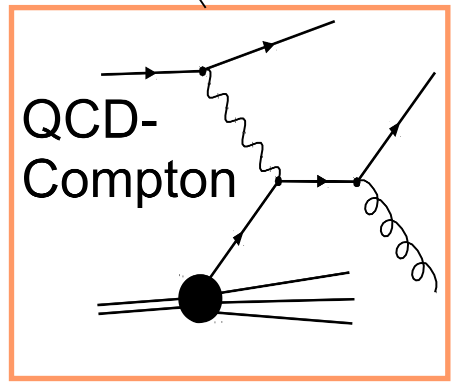
- High transverse momentum hadrons ($Q^2<1$ and $Q^2>1$ $(GeV/c)^2$)
  - ☺ Much more statistics.
  - ☹ Physical background: strongly model dependent requires a very good agreement between MC and Data.
- Open-charm meson (D mesons)
  - ☺ Provides the purest sample of PGF events, almost free from background contamination. Small dependence on MC.
  - ☹ Low statistics.

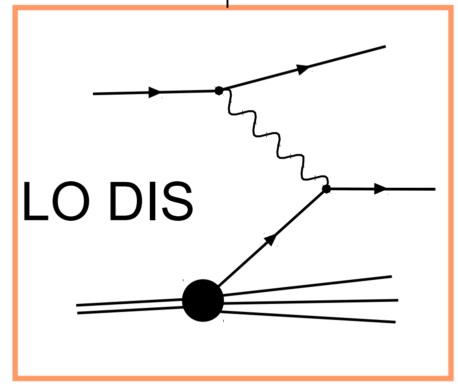
High p_T Analysis

$$A_{LL}^{2h}(x) = \frac{\Delta G}{G}(x_g)\, a_{LL}^{PGF} \frac{\sigma^{PGF}}{\sigma^{Tot}} + A_1^{LO}(x_C)\, a_{LL}^{C} \frac{\sigma^{C}}{\sigma^{Tot}} + A_1^{LO}(x_{Bj})\, D \frac{\sigma^{LO}}{\sigma^{Tot}}$$

A_1^{LO} : estimated by an inclusive sample







Final formula for the gluon polarisation

$$\frac{\Delta G}{G}(x_g^{av}) = \frac{1}{\beta}\left[A_{LL}^{2h}(x_{Bj}) + A_{corr} \right]$$

$$R_i = \frac{\sigma^i}{\sigma^{Tot}}$$

- A^{2h}_{LL} : measured from the two hadron sample.
- a^i_{LL} and R_i : estimated from MC and parametrised using a Neural Network.

$$\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} R_{PGF}^{incl} \frac{R_{LO}}{R_{LO}^{incl}} - a_{LL}^{PGF,incl} \frac{R_C R_{PGF}^{incl}}{R_{LO}^{incl}} \frac{a_{LL}^C}{D}$$

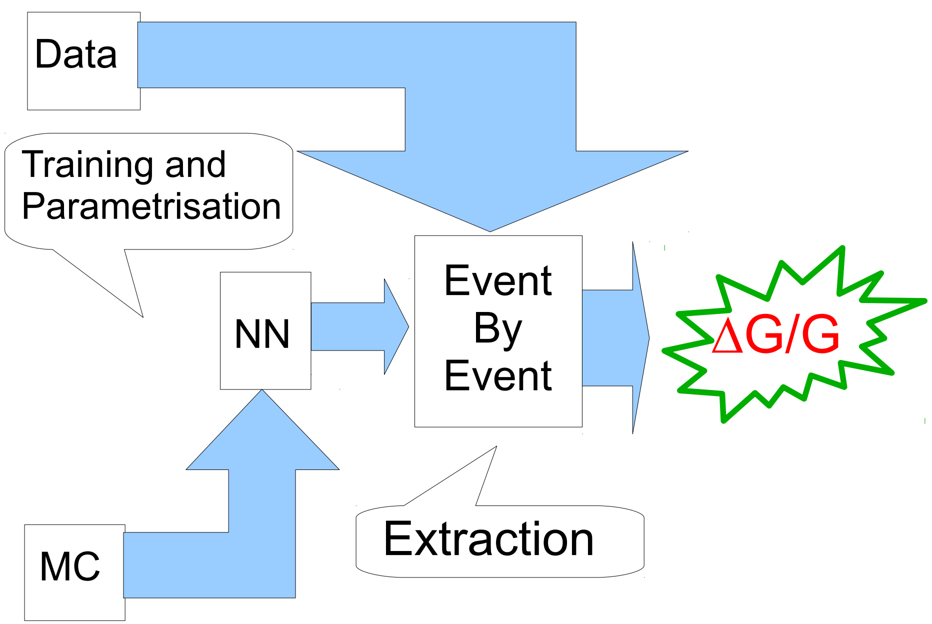
$$A_{corr} = -\left(A_1(x_{Bj}) D \frac{R_{LO}}{R_{LO^{incl}}} - A_1(x_C)\beta_1 + A_1(x_C')\beta_2 \right)$$

MC Simulation and Neural Network

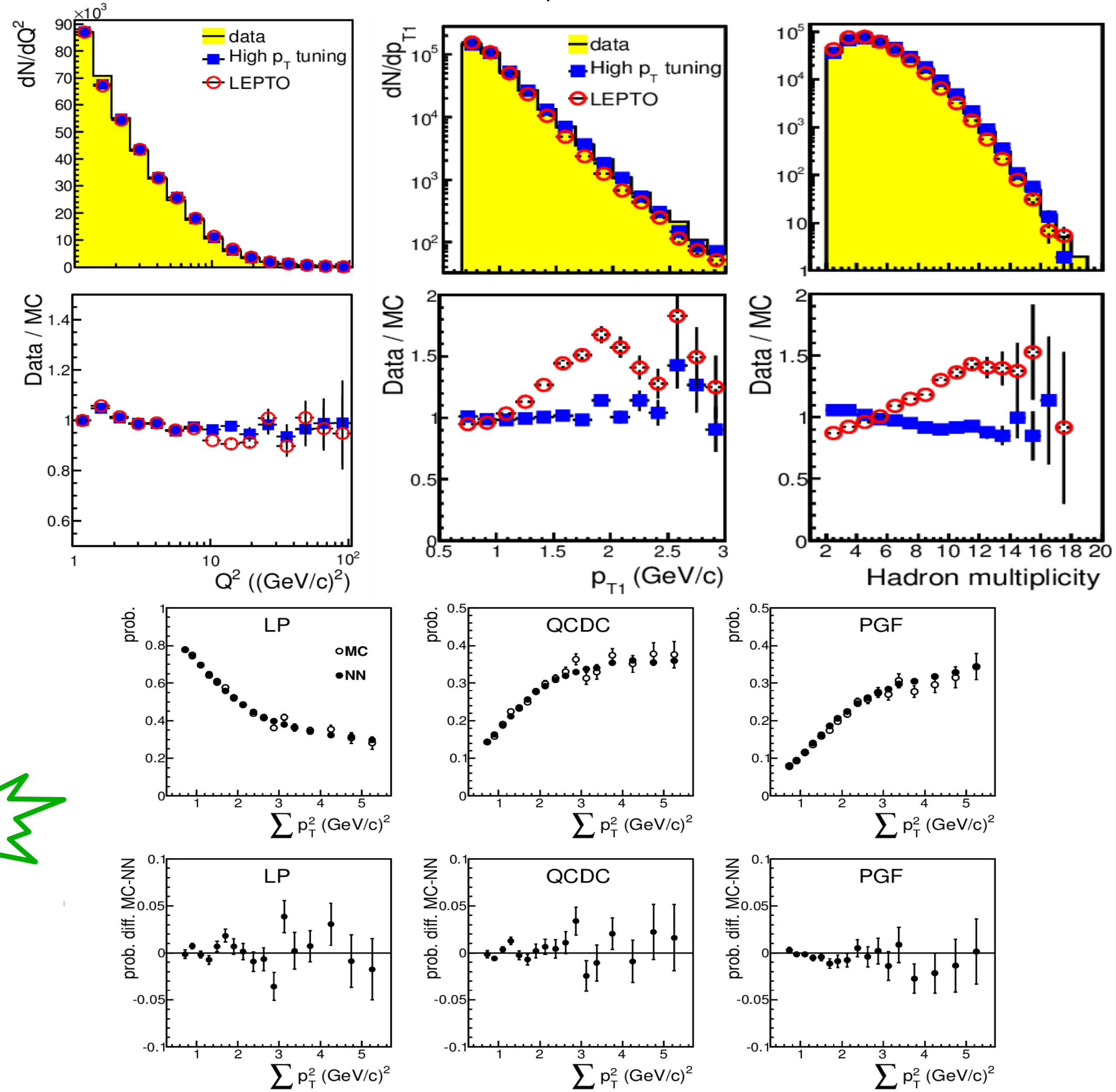
- Full chain of MC has been used:

Generator (LEPTO) + Apparatus Simulation (GEANT) + Reconstruction Program.

- PDF: MSTW2008LO.
- High p_T sample:
  - MC with parton shower ON.
  - A new tuning was performed to improve the hadron description.



Data-MC comparison: Q^2, p_T and hadron multiplicities.



Results

$$\frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063 \qquad x_g = 0.09^{+0.08}_{-0.05} \qquad \mu^2 = 3\ (\mathrm{GeV/c})^2$$

- The whole statistics was divided, for the first time, in 3 independent samples, having each one its own x_g distribution.

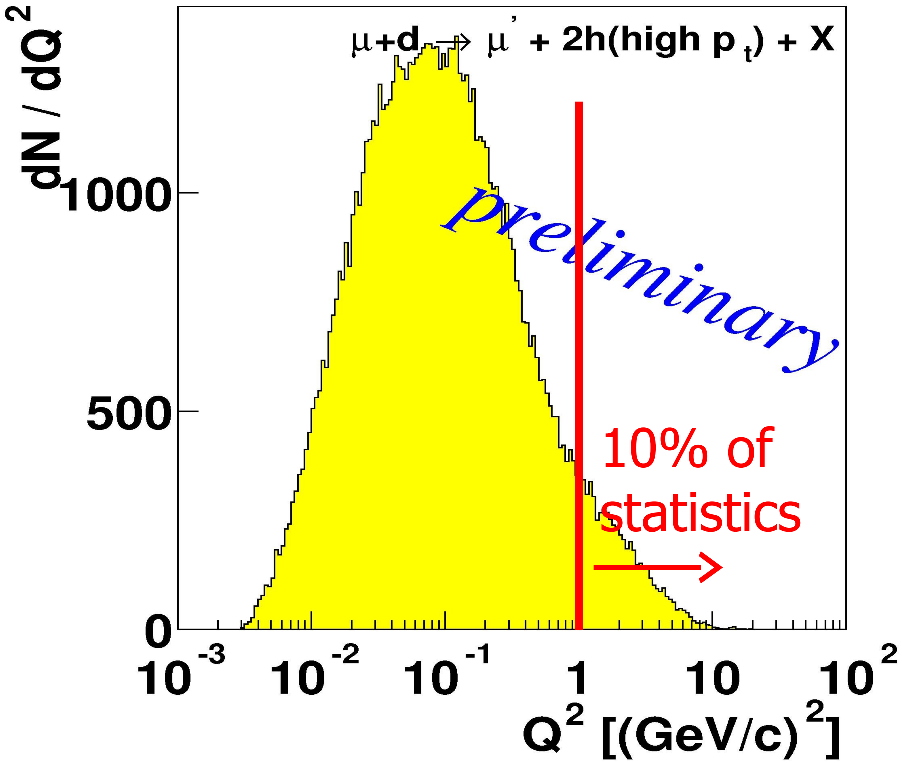
	1^{st} point	2^{nd} point	3^{rd} point
ΔG/G	0.147 ± 0.091 ± 0.088	0.079 ± 0.096 ± 0.082	0.185 ± 0.165 ± 0.143
$<x_g>$	$0.07^{+0.05}_{-0.03}$	$0.10^{+0.07}_{-0.04}$	$0.17^{+0.10}_{-0.06}$

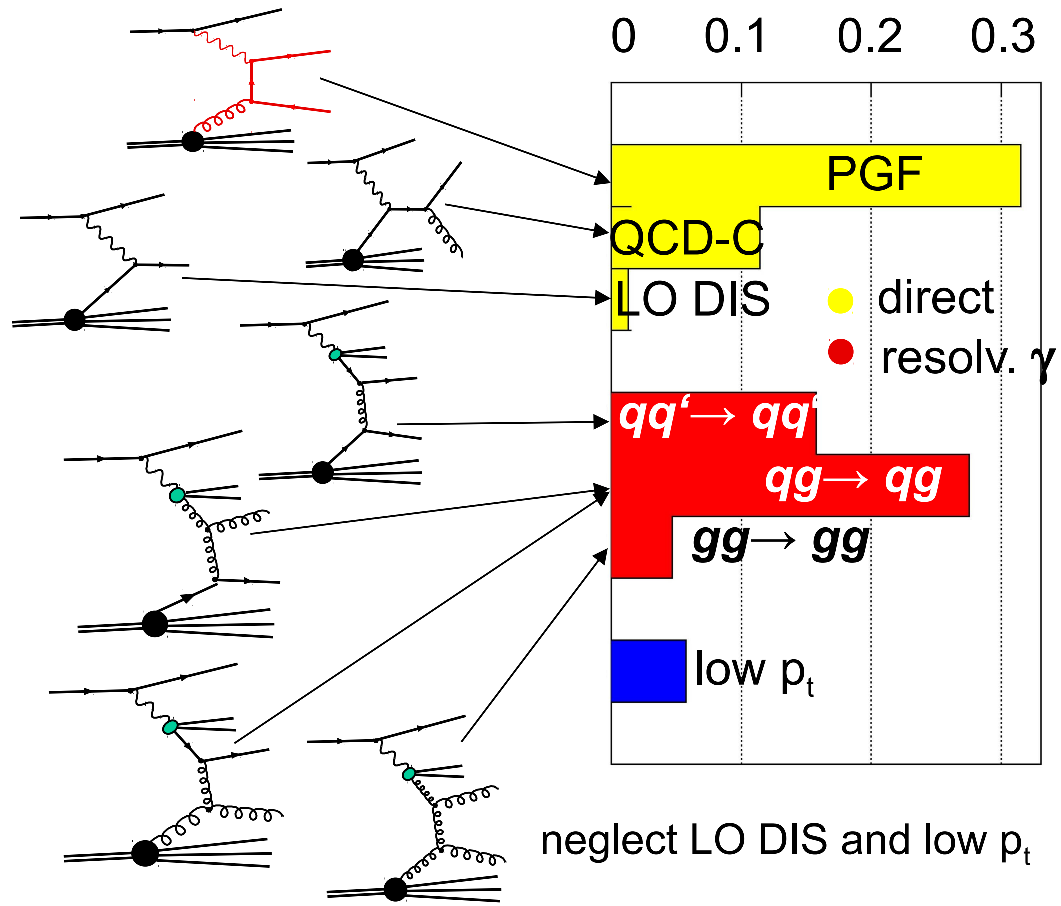
⇒ Within the errors the 3 points show no x_g dependence

Physics Letters B 718 (2013) 922–930

High p_T Analysis, $Q^2 < 1\ (GeV/c)^2$

~90 % of our statistics in this sample





neglect LO DIS and low p_t

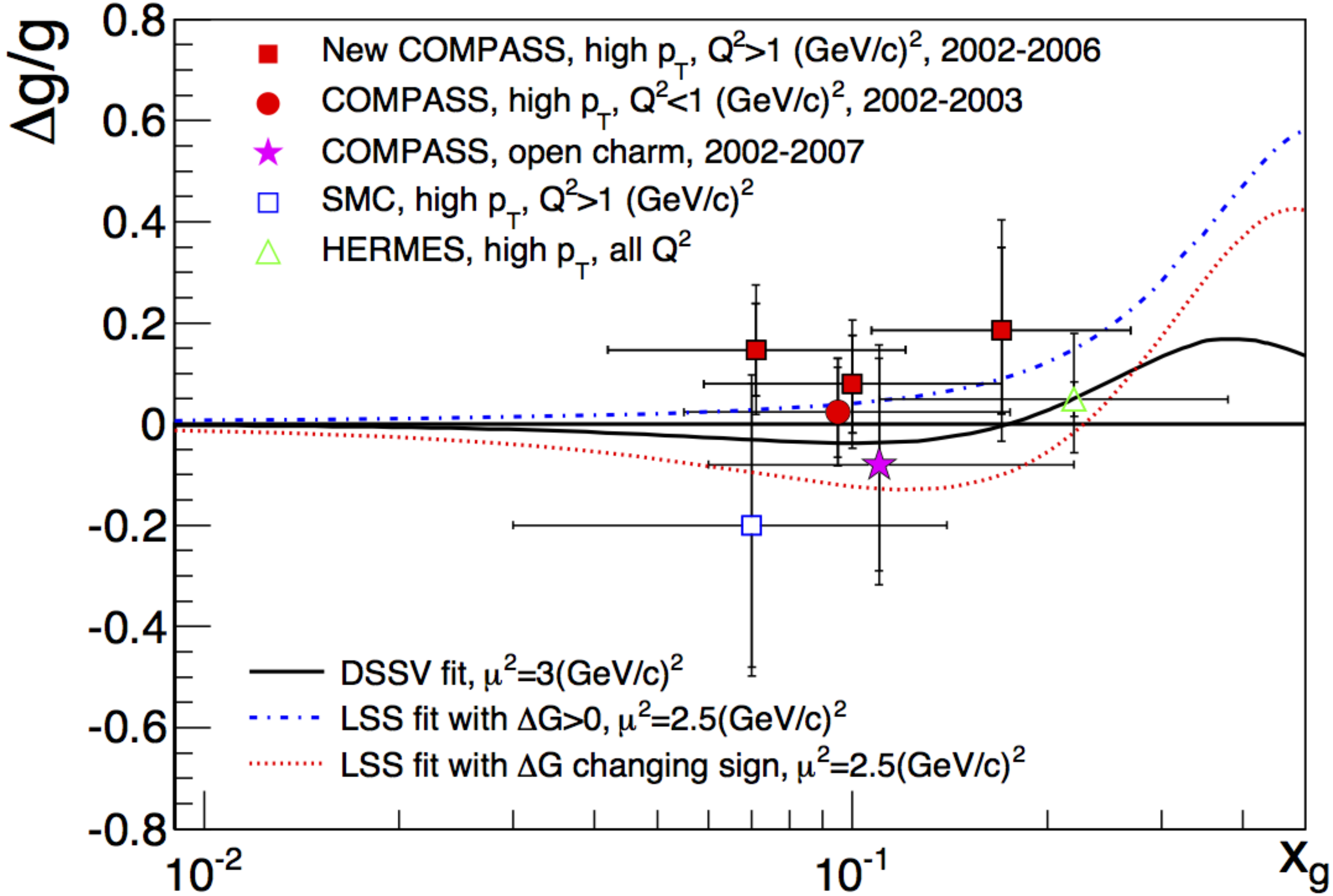
2002-2004 Preliminary:

$\Delta G/G = 0.016 \pm 0.058(stat) \pm 0.055(syst)$

2002-2003 Published:

$\Delta G/G = 0.024 \pm 0.089(stat) \pm 0.057(syst)$ *Physics Letters B 633,25 (2006)*

New ΔG/G Result from High p_T Analysis



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Open Charm

- The relation between the number of reconstructed D^0 (<u>for each target cell configuration</u>) and ΔG/G is given by:

$$N_t = a\,\phi\,n\,(S+B)\left(1 + f\,P_T\,P_\mu\left[a_{LL}\frac{S}{S+B}\frac{\Delta G}{G} + D\frac{B}{S+B}A^{bg}\right]\right),\quad t=(u,d,u',d')$$

acceptance, muon flux, number of target nucleons — Open Charm event probability

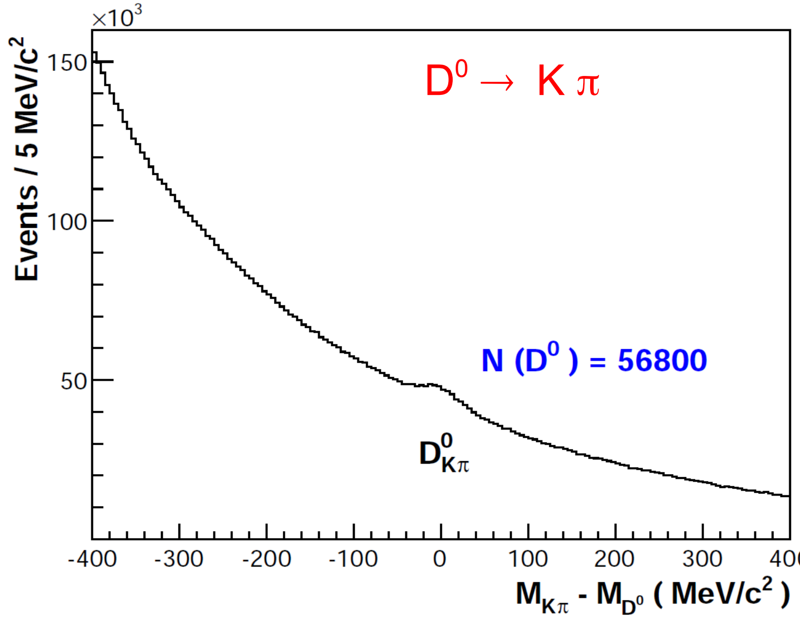
- <u>Each equation is weighted</u> with a signal weight $w_S = f\,P_m\,a_{LL}\,S/(S+B)$ and also with a background weight $w_B = f\,P_m\,D\,B/(S+B)$:

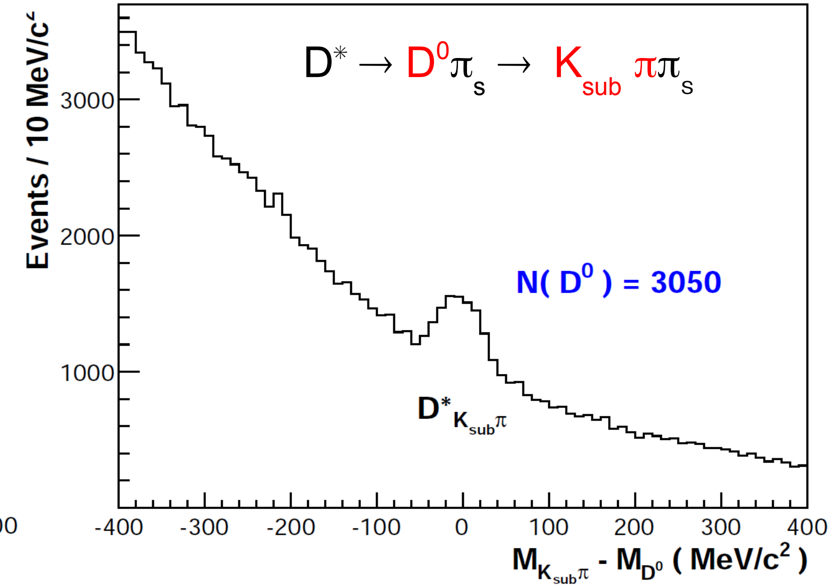
<u>8 equations with 7 unknowns</u>: ΔG/G, A^{bg} + 5 independent $\alpha = (a\phi n)$ factors

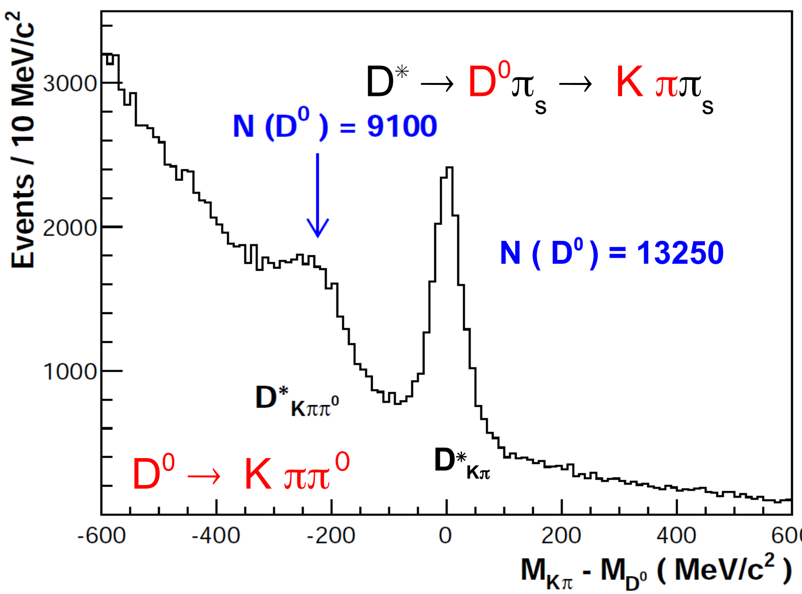
The system is solved by a χ^2 minimisation

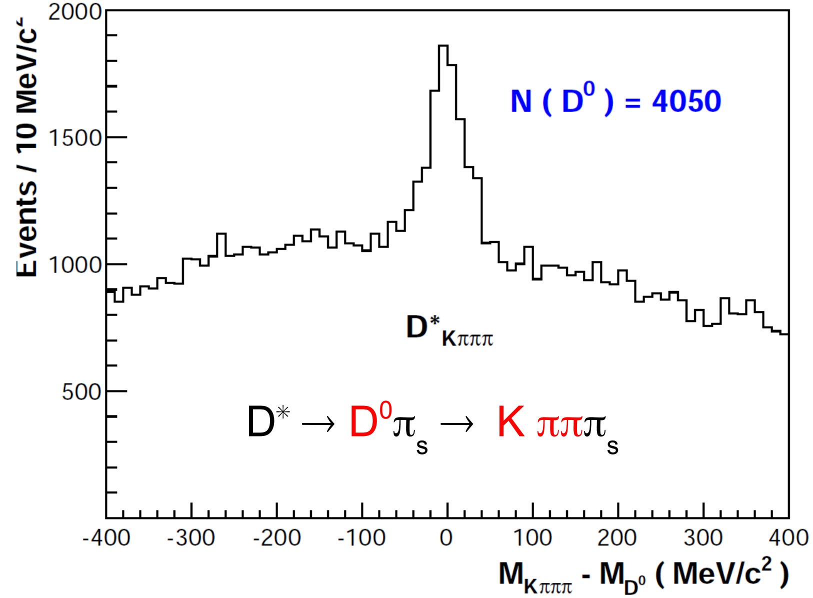
D^0 Invariant Mass Spectra: 2002-2007 Data

D^0 → $K\pi$, $K_{sub}\pi$, $K\pi\pi^0$, $K\pi\pi\pi$









Number of D^0:

- Total = 86250
- ^{6}LiD = 57400
- NH_3 = 28850

Neural Network Parametrisation

- **Two real data samples** (with the same cuts applied) **are compared by a Neural Network** (<u>using some kinematic variables as a learning vector</u>):
  - **Signal model gcc =**

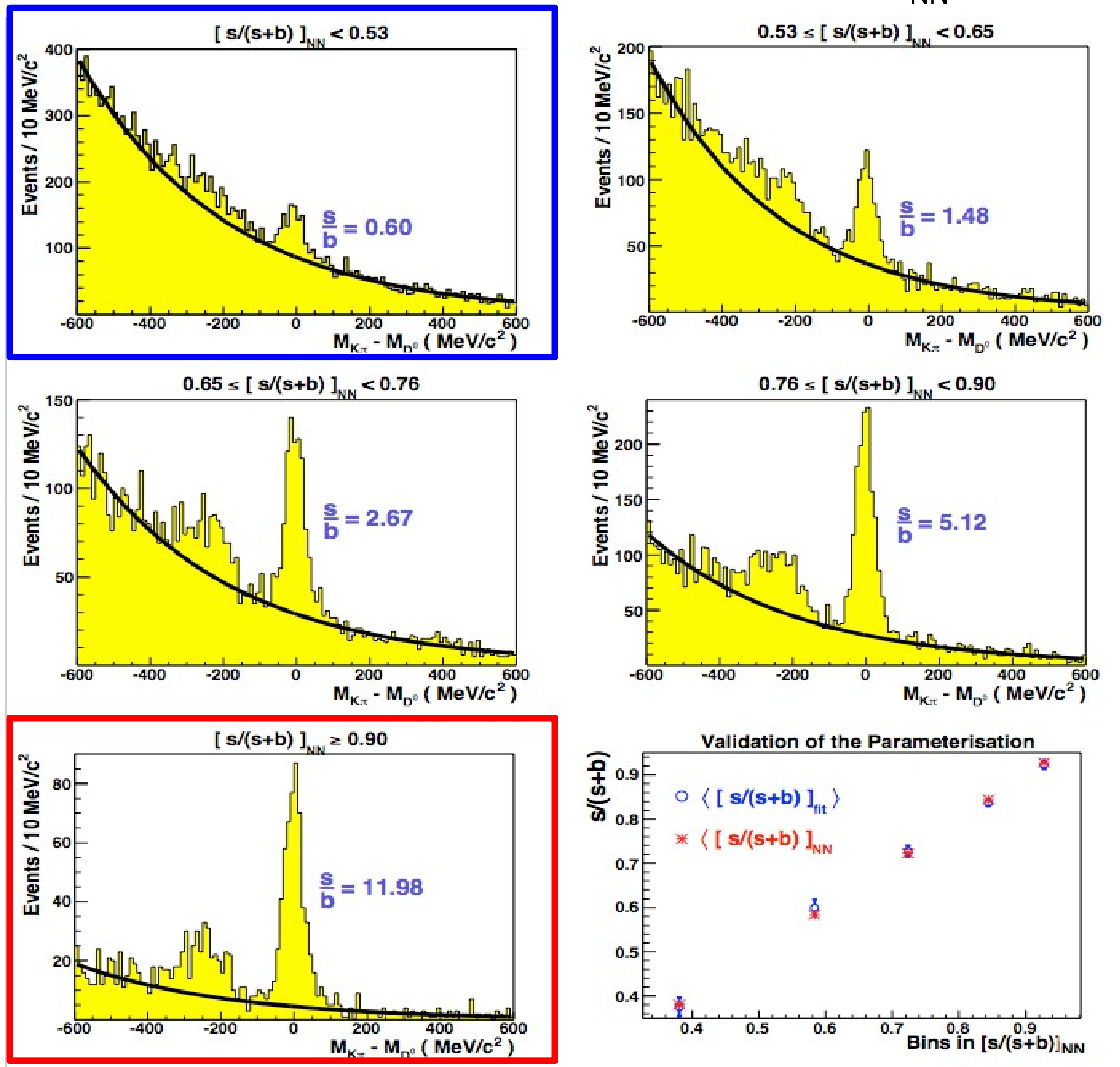
    $K^+\pi^-\pi_s^-$ + $K^-\pi^+\pi_s^+$

    (D^0 spectrum: signal + background)
  - **Background model**

    wcc = $K^+\pi^+\pi_s^-$ + $K^-\pi^-\pi_s^+$

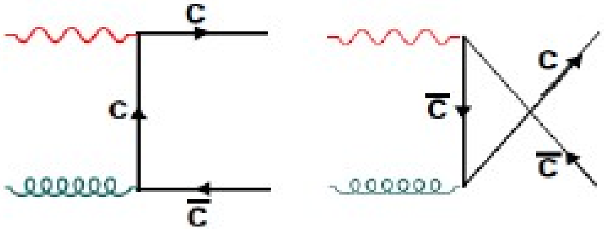
    (no D^0 is allowed)
- **If the background model is good enough,** <u>the Neural Network is able to distinguish the signal from the combinatorial background on a event by event basis</u> (inside gcc).

D^0 tagged spectrum in bins of $\sum = S/(S+B)_{NN}$



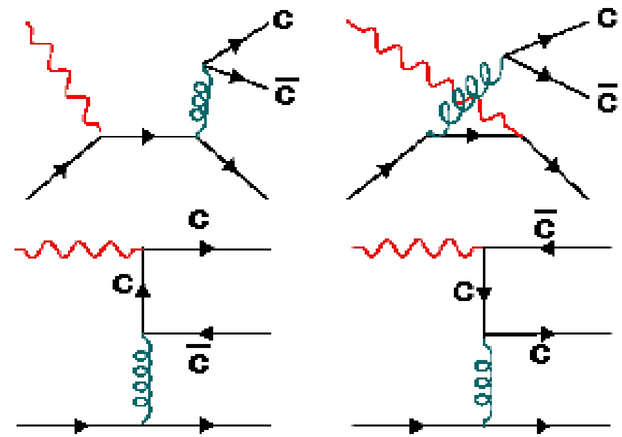
NLO Corrections for Open Charm Analysis

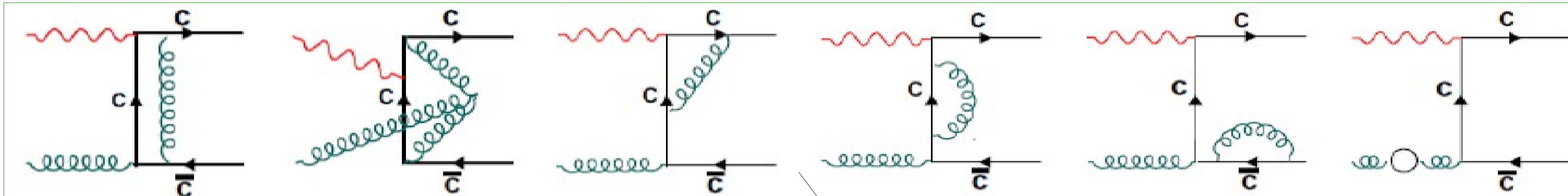
NLO corrections to the analysing power a_{LL}

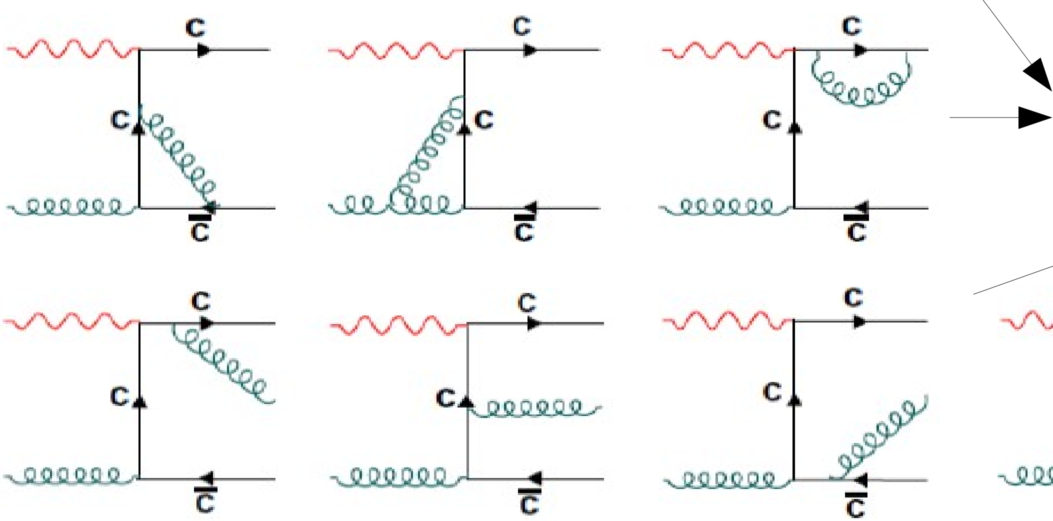


LO: PGF

NLO: bg



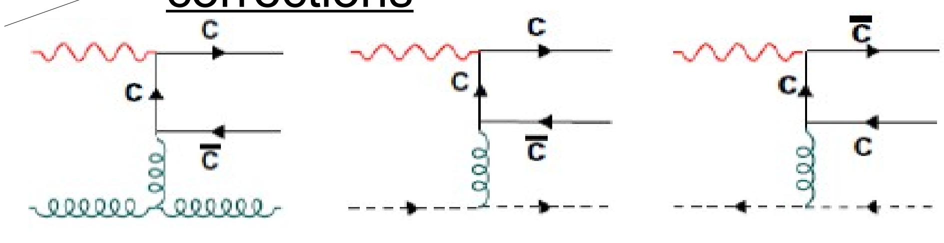




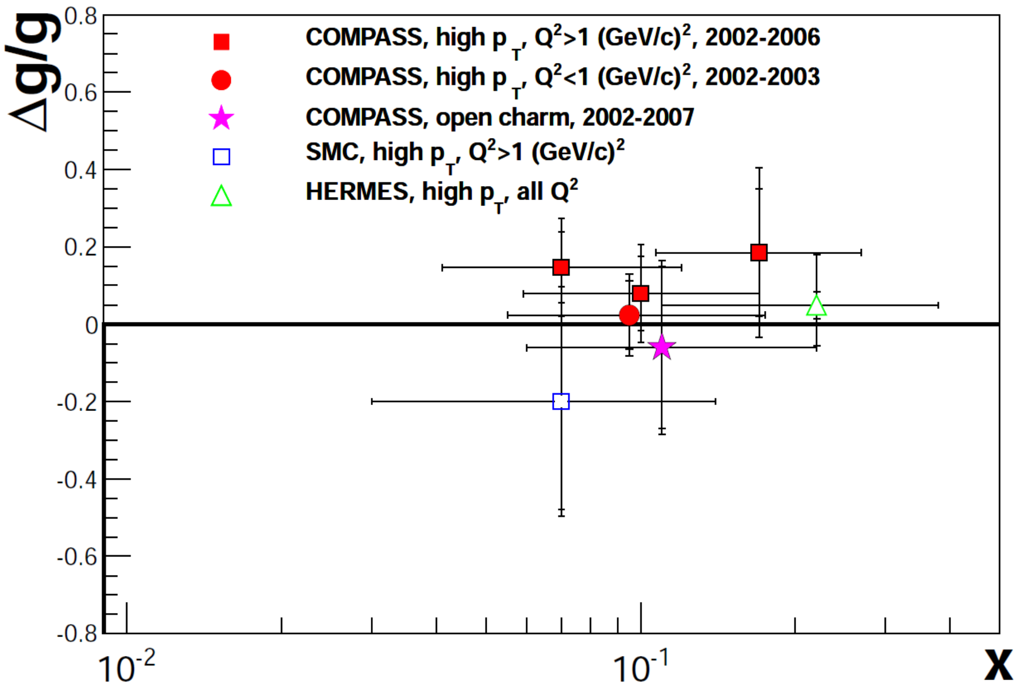
virtual corrections

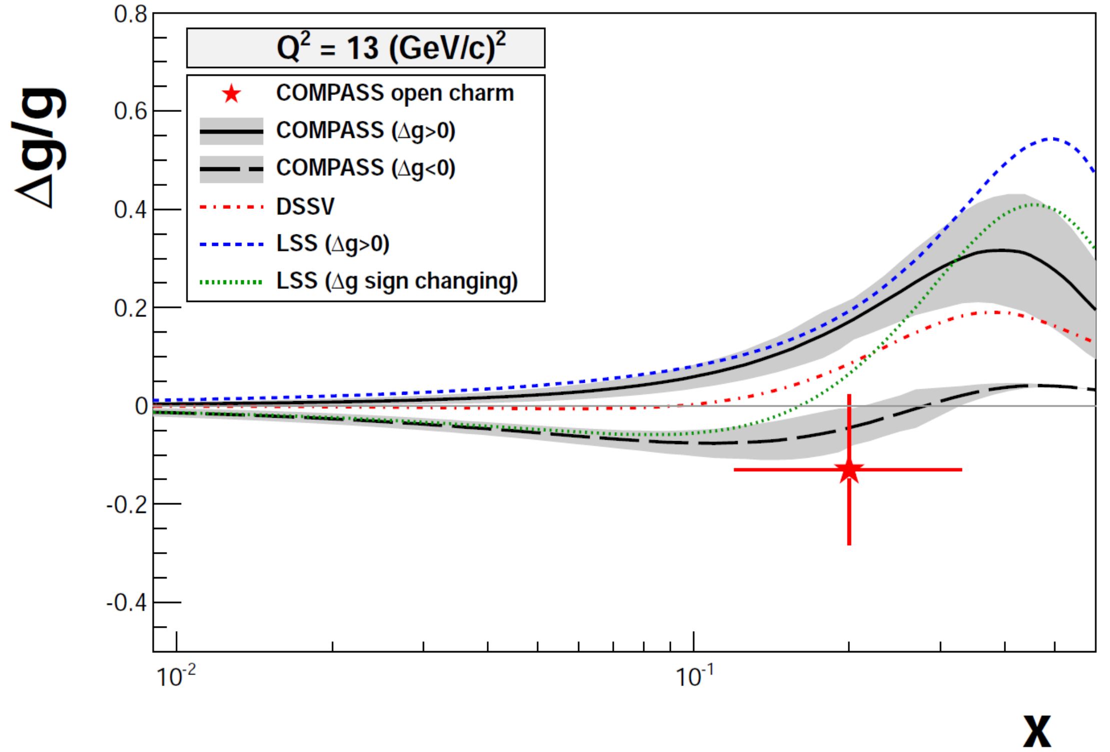
NLO: PGF

gluon bremsstrahlung corrections



Open Charm ΔG/G Results: LO and NLO





LO

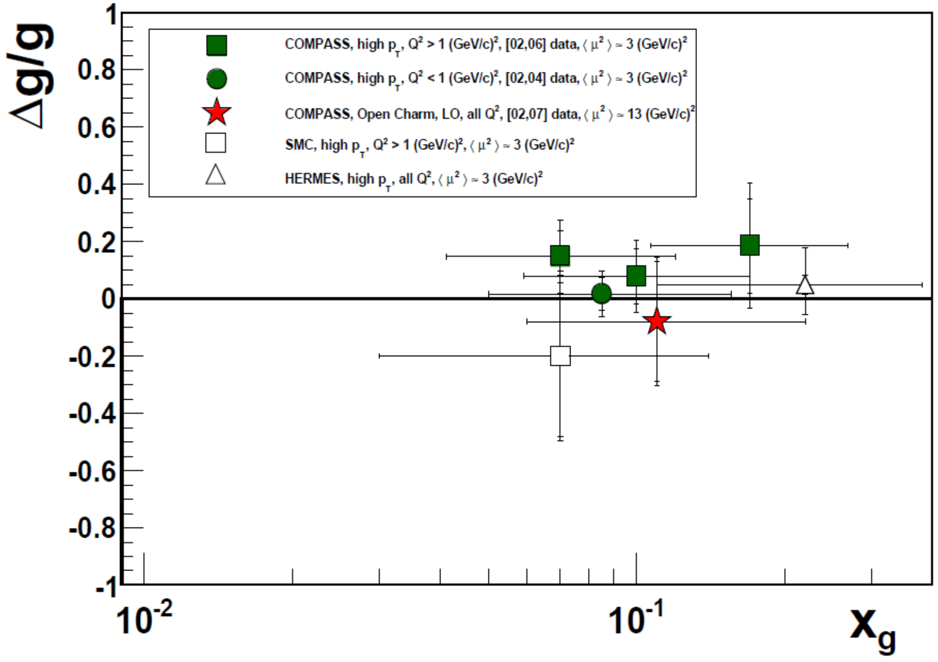
$$\frac{\Delta G}{G} = -0.06 \pm 0.21_{(stat)} \pm 0.08_{(syst)} \qquad \langle x_g \rangle = 0.11^{+0.11}_{-0.05}, \qquad \langle \mu^2 \rangle = 13\ (\mathrm{GeV}/c)^2$$

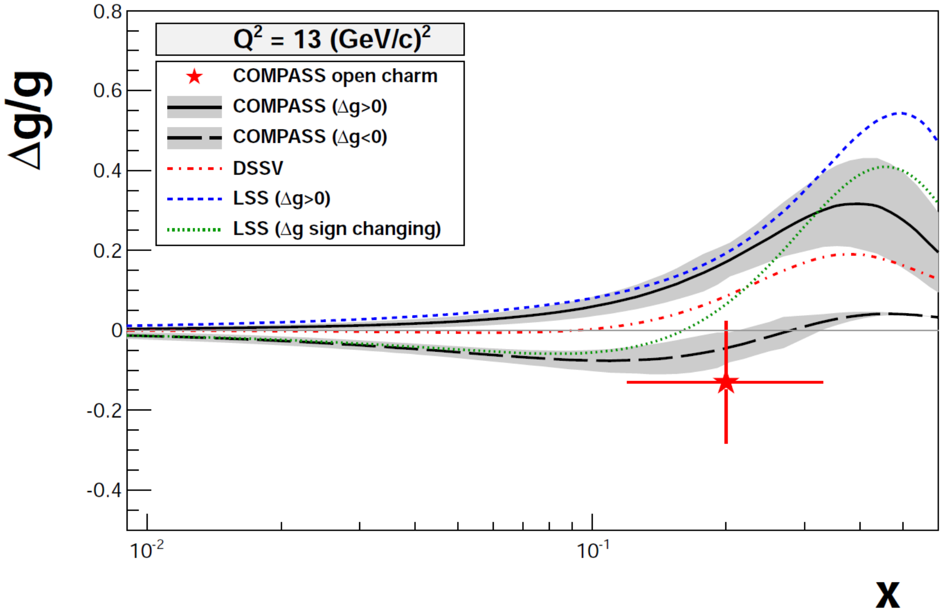
NLO

$$\frac{\Delta G}{G} = -0.13 \pm 0.15_{(stat)} \pm 0.15_{(syst)} \qquad \langle x_g \rangle = 0.20^{+0.13}_{-0.08}, \qquad \langle \mu^2 \rangle = 13\ (\mathrm{GeV}/c)^2$$

Physical Review D 87, 052018 (2013)

Summary and Conclusions





Summary:

- The importance of the gluon polarisation measurement concerning the nucleon spin structure was emphasised.
- The direct measurement methods were explained.
- The gluon polarisations results are presented.

Conclusions:

- Around $X_g \sim 0.1$ all measurements of ΔG/G are compatible with zero.
- Still there is the contribution of $L_{partons}$ to be taken into account.
- The COMPASS-II program foresees to measure $L_{partons}$ via GPDs.

Spares

High p_T Asymmetries

5 p_T bins x 5 X_{bj} bins

A_{LL}^{2h}/D asymmetries as a function of x_{Bj} and $\sum p_T^2$.

x_{Bj}	$p_{T_1}^2 + p_{T_2}^2$ $(GeV/c)^2$	$\langle x_{Bj} \rangle$	$\langle Q^2 \rangle$ $(GeV/c)^2$	$\langle p_{T_1}^2 + p_{T_2}^2 \rangle$ $(GeV/c)^2$	A_{LL}^{2h}/D
0.004–0.01	0.65–1.0	0.007	1.4	0.86	0.002 ± 0.011
0.004–0.01	1.0–2.0	0.007	1.4	1.35	-0.002 ± 0.009
0.004–0.01	2.0–3.0	0.007	1.4	2.39	-0.019 ± 0.020
0.004–0.01	3.0–4.0	0.007	1.4	3.41	-0.075 ± 0.037
0.004–0.01	4.0–	0.007	1.5	5.45	0.001 ± 0.045
0.01–0.02	0.65–1.0	0.014	2.4	0.86	-0.009 ± 0.012
0.01–0.02	1.0–2.0	0.014	2.4	1.35	-0.016 ± 0.010
0.01–0.02	2.0–3.0	0.014	2.5	2.39	0.007 ± 0.024
0.01–0.02	3.0–4.0	0.014	2.6	3.41	0.054 ± 0.045
0.01–0.02	4.0–	0.014	2.7	5.48	-0.033 ± 0.056
0.02–0.05	0.65–1.0	0.030	4.8	0.85	0.015 ± 0.016
0.02–0.05	1.0–2.0	0.030	5.0	1.35	0.018 ± 0.013
0.02–0.05	2.0–3.0	0.030	5.3	2.39	0.056 ± 0.031
0.02–0.05	3.0–4.0	0.030	5.5	3.41	0.054 ± 0.057
0.02–0.05	4.0–	0.031	5.9	5.52	0.066 ± 0.068
0.05–0.10	0.65–1.0	0.069	10.9	0.85	0.074 ± 0.029
0.05–0.10	1.0–2.0	0.068	11.4	1.35	0.038 ± 0.025
0.05–0.10	2.0–3.0	0.069	12.2	2.39	0.051 ± 0.057
0.05–0.10	3.0–4.0	0.068	12.9	3.40	-0.079 ± 0.105
0.05–0.10	4.0–	0.069	13.6	5.67	-0.087 ± 0.123
0.10–1.00	0.65–1.0	0.170	28.2	0.85	0.100 ± 0.043
0.10–1.00	1.0–2.0	0.172	29.9	1.35	0.143 ± 0.036
0.10–1.00	2.0–3.0	0.172	31.7	2.39	-0.037 ± 0.083
0.10–1.00	3.0–4.0	0.158	29.0	3.41	-0.191 ± 0.156
0.10–1.00	4.0–	0.168	32.8	5.67	0.593 ± 0.180

The COMPASS Spectrometer

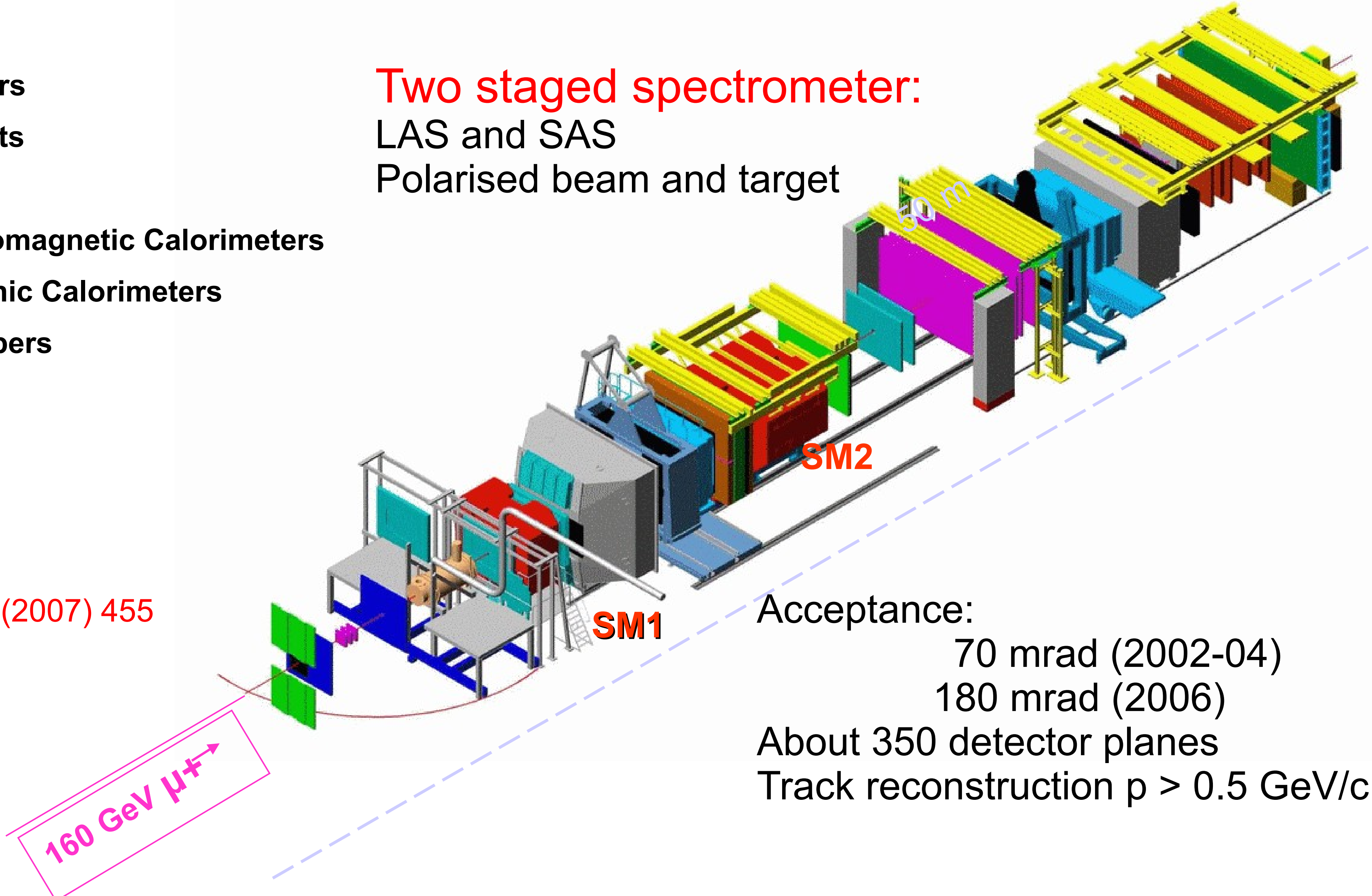
Common Muon and Proton Apparatus for Structure and Spectroscopy

- Trackers
- Magnets
- RICH
- Electromagnetic Calorimeters
- Hadronic Calorimeters
- Absorbers
- Target

Two staged spectrometer:

LAS and SAS

Polarised beam and target



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Acceptance:

70 mrad (2002-04)

180 mrad (2006)

About 350 detector planes

Track reconstruction p > 0.5 GeV/c

$\Delta G/G$ for High p_T, $Q^2 > 1$ GeV^2

The final formula for the gluon polarisation:

$$\frac{\Delta G}{G}(x_g^{av}) = \frac{A_{LL}^{2h}(x_{Bj})}{\beta} - \frac{A_1(x_{Bj})}{\beta} D \frac{R_{LO}}{R_{LO^{incl}}} - \frac{A_1(x_C)}{\beta}\beta_1 + \frac{A_1(x_C')}{\beta}\beta_2$$

$$\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} R_{PGF}^{incl} \frac{R_{LO}}{R_{LO}^{incl}} - a_{LL}^{PGF,incl} \frac{R_C R_{PGF}^{incl}}{R_{LO}^{incl}} \frac{a_{LL}^C}{D}$$

$$R_i = \frac{\sigma^i}{\sigma^{Tot}}$$

$$\beta_1 = \frac{1}{R_{LO}^{incl}}\left(a_{LL}^C R_C - a_{LL}^{C,incl} R_C^{incl} \frac{R_{LO}}{R_{LO}^{incl}}\right)$$

$$\beta_2 = a_{LL}^{C,incl} \frac{R_C R_C^{incl}}{(R_{LO}^{incl})^2} \frac{a_{LL}^C}{D}$$

- A^{2h}_{LL} is the measured 2-h asymmetry.
- a_{LL} and R are estimated using MC.
- The A_1 are taken using a parametrisation on inclusive data. (EPJ C52 (2007)255)

Monte Carlo Simulation

This analysis uses information from the MC, thus a strong effort and care to ensure that the MC simulation describes as good as possible the data was undertaken.

Two MC samples were used in the analysis: high p_T and inclusive samples.

- Full chain of MC has been used:

Generator (LEPTO) + Apparatus Simulation (GEANT) + Reconstruction Program.

- PDF: MSTW2008LO.
- High p_T sample:
  - MC with parton shower ON has been used in the analysis.
  - A new tuning was performed to improve the hadron description.

MC Tuning

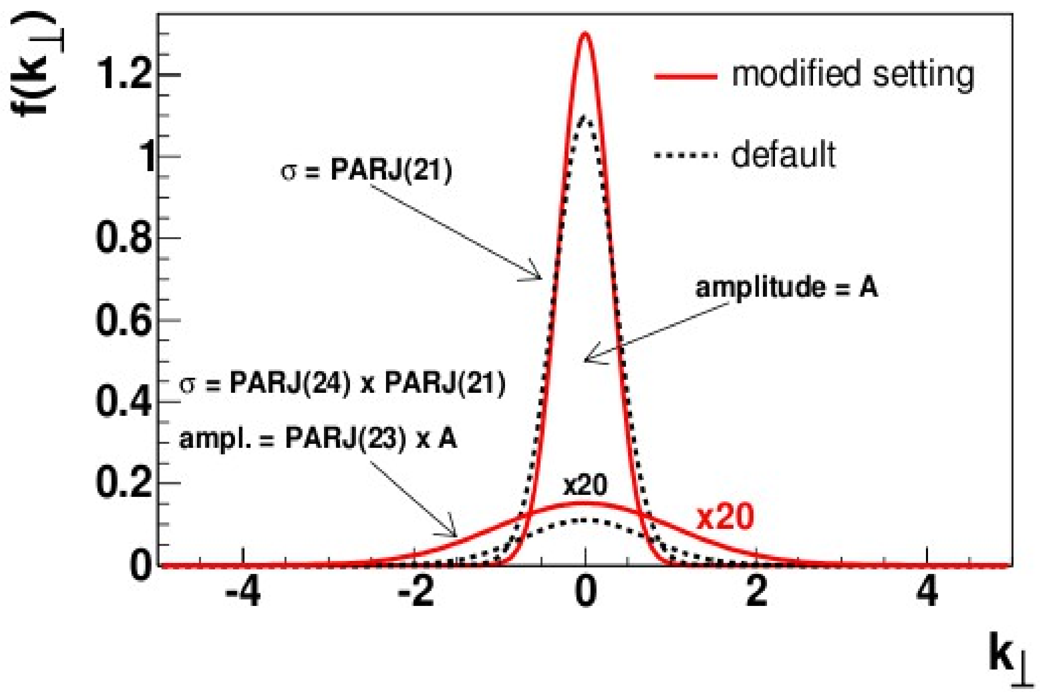
- The purpose of the MC tuning is to correct the shapes of the hadron variables (momenta) and fragmentation (multiplicity).
- In LEPTO this can be achieved by changing JETSET parameters:

PARJ(21)	PARJ(23)	PARJ(24)	PARJ(41)	PARJ(42)
Transverse momentum of the hadron fragmentation			Fragmentation function	

- These parameters can be divided into two sets regarding the component of the trajectory of the particles: transverse and longitudinal variable components.
- The sets can be tuned independently.

⇒The tuning improves substantially the Data-MC agreement.

Monte Carlo Simulation



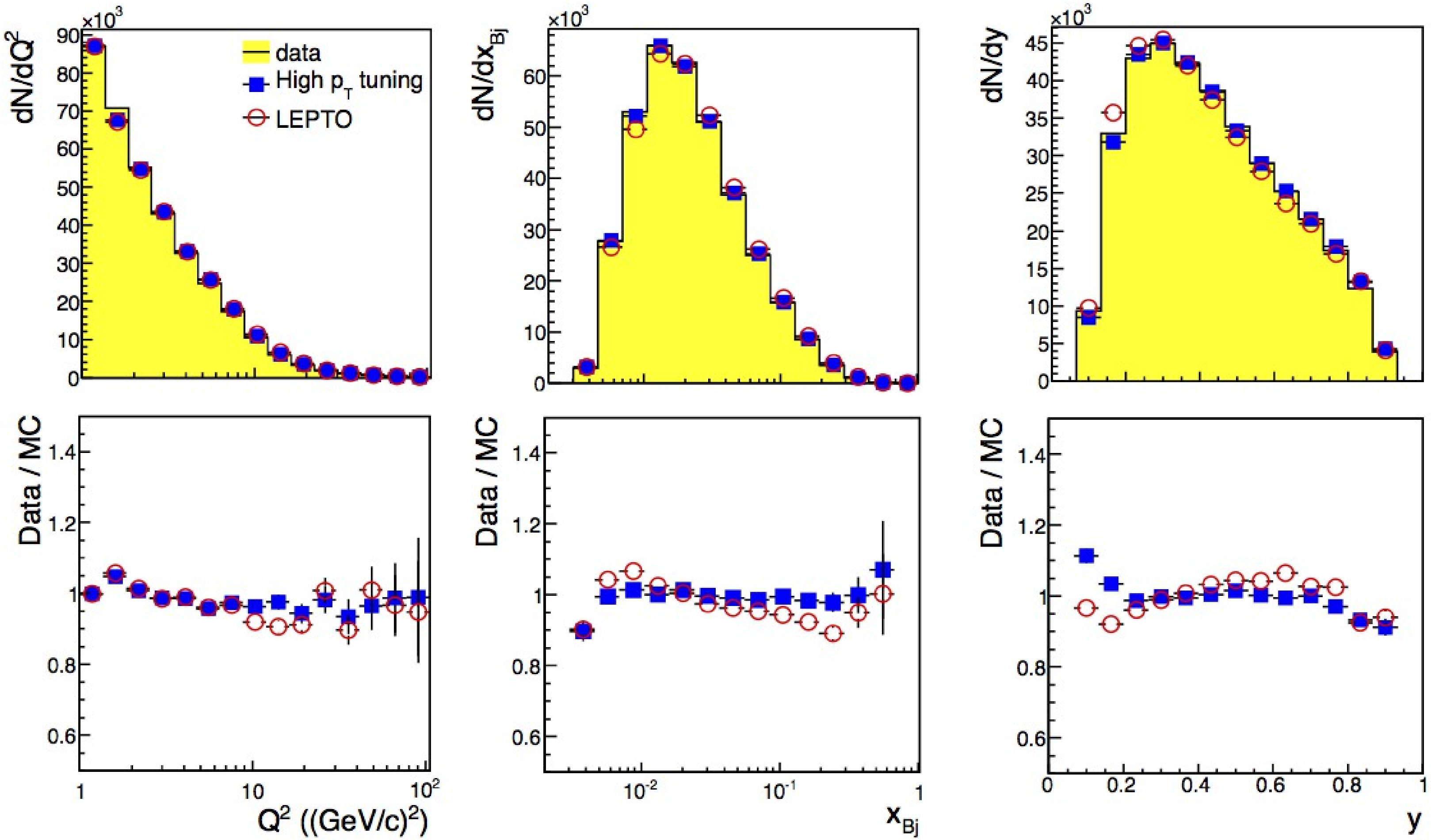
a = PARJ(41)

b = PARJ(42)

$$f(z) \propto \frac{1}{2}(1-z)^a \exp\left(-\frac{b\, m_T^2}{z}\right)$$

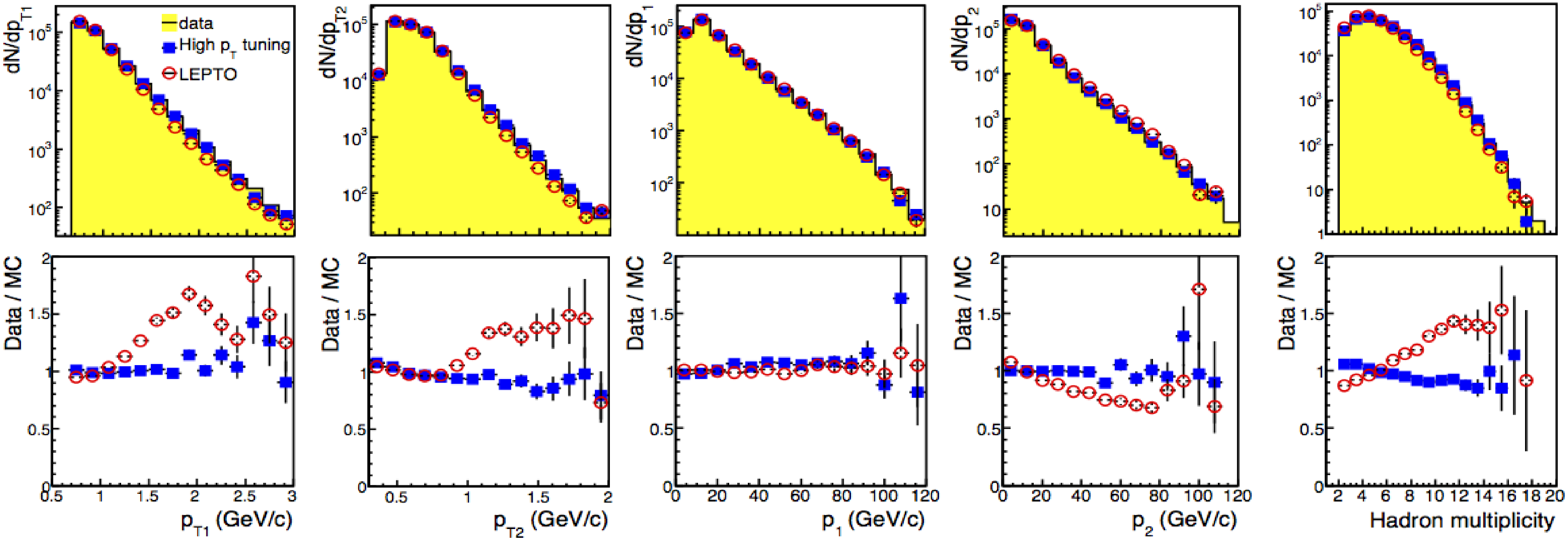
	PARJ(21)	PARJ(23)	PARJ(24)	PARJ(41)	PARJ(42)
COMPASS new tuning	0.34	0.04	2.8	0.025	0.075
LEPTO default tuning	0.36	0.01	2.0	0.3	0.58
	Transverse momentum of the hadron fragmentation			Fragmentation function	

Data – Monte Carlo comparison



Data – Monte Carlo comparison

high-p_T sample: hadron variables (p_{T1}, p_{T2} , p_1, p_2, and hadron multiplicity)



Weighted method

- A weight is applied on event-by-event basis:

$W = fDP_b\beta$, where β is a factor depending on a^i_{LL} and R^i

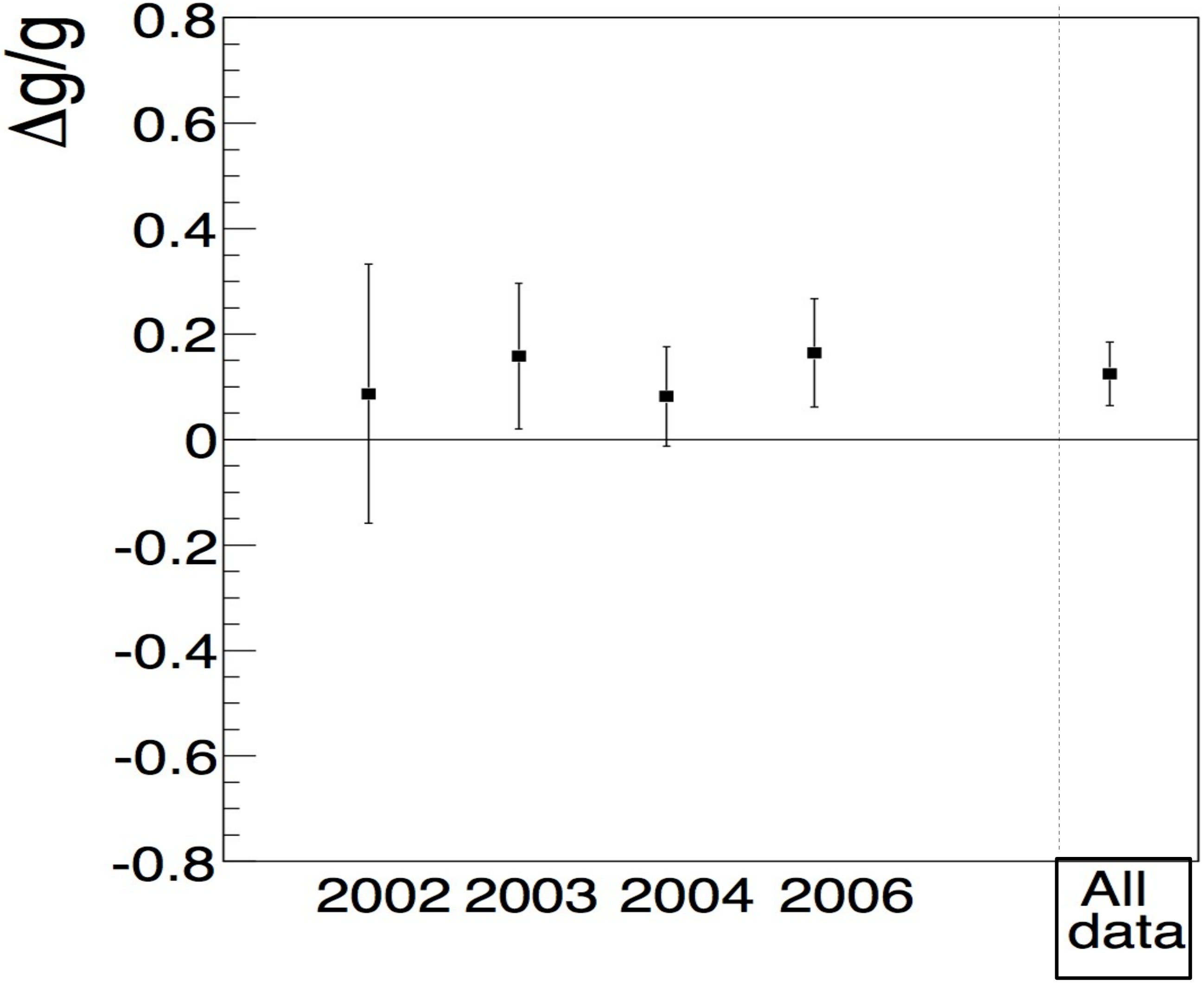
- Therefore for every event we have to know:

$$R_{PGF}, R_C, R_{LO}, R^{incl}_{PGF}, R^{incl}_C, R^{incl}_{LO},$$
$$a^{PGF}_{LL}, a^C_{LL}, a^{PGF,incl}_{LL}, a^{C,incl}_{LL},$$
$$x_C, x_G,$$
$$f, D, P_b$$

f,D,P_b are directly obtained from data.
The all the others variables have to be estimated/parametrised.

Results

$$\frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063 \qquad x_G = 0.09^{+0.08}_{-0.05} \qquad \mu^2 = 3 \ (\mathrm{GeV/c})^2$$



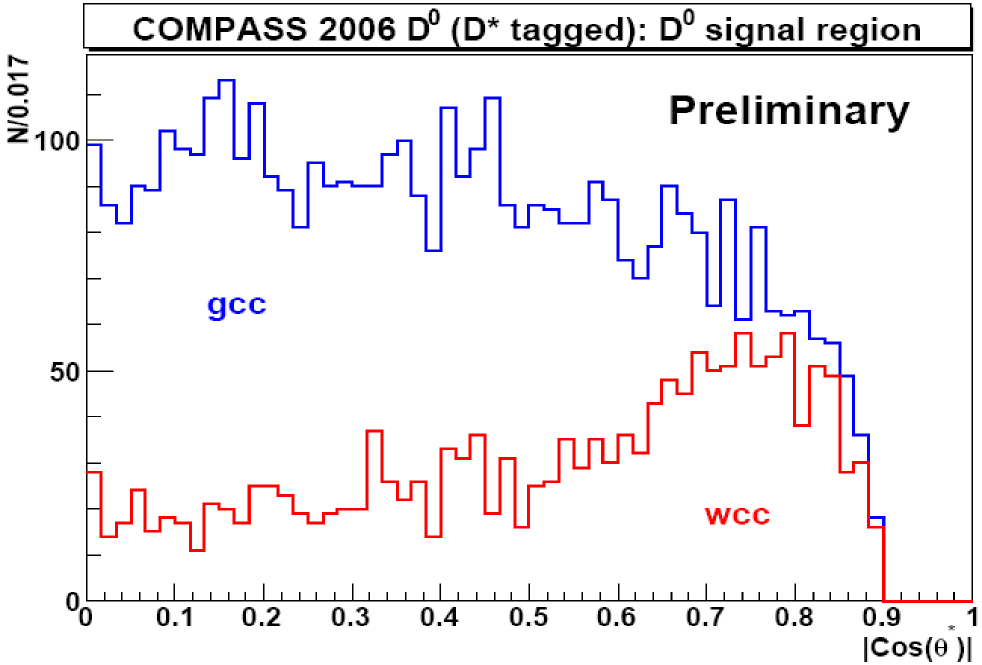
Systematic Uncertainties

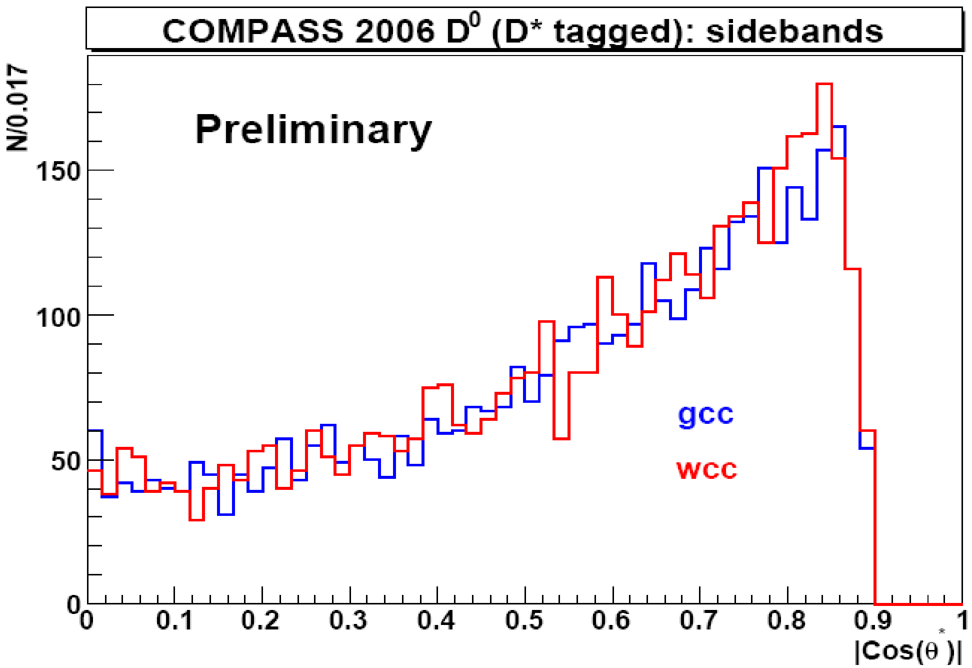
Sources of Systematic Uncertainties	δ(ΔG/G) High pT	δ(ΔG/G) Open Charm
MC Simulation	**0.045**	
Formula Simplification	**0.035**	0.025
False Asymmetries	0.019	**0.080**
A_1 Parametrisation	0.015	
NN Parametrisation	0.010	
P_B, P_T, f	0,004	0.009
a_{LL}		**0.119**
s/(s+b)		0.009
Total	0.063	0.146

Neural Network qualification of events

- **Two real data samples** (with the same cuts applied) **are compared by a Neural Network** (using some kinematic variables as a learning vector)**:**
  - **Signal model** → **gcc** = $K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+$ *(D^0 spectrum: signal + background)*
  - **Background model** → **wcc** = $K^+\pi^+\pi_s^- + K^-\pi^-\pi_s^+$ *(no D^0 is allowed)*
- **If the background model is good enough:** The Neural Network is able to distinguish the signal from the combinatorial background on a event by event basis (inside gcc)

Example of a good learning variable





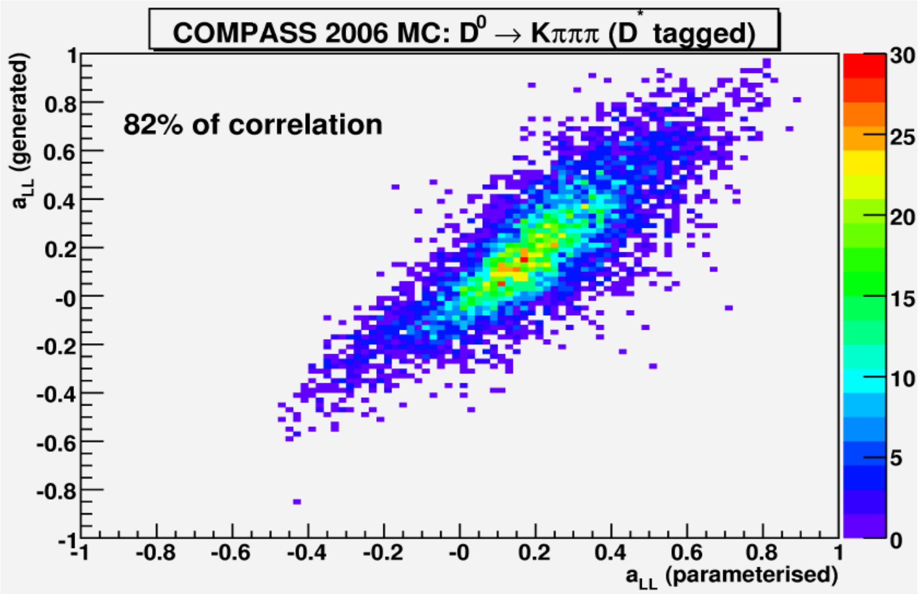
Analysing power (muon-gluon asymmetry a_{LL})

- a_{LL} is dependent on the full knowledge of the partonic kinematics:

$$a_{LL} = \frac{\Delta\sigma^{PGF}}{\sigma_{PGF}}(y, Q^2, x_g, z_C, \phi)$$

Can't be experimentally obtained: only one charmed meson is reconstructed

- a_{LL} is obtained from Monte-Carlo (in LO), to serve as input for a Neural Network parameterisation on some reconstructed kinematical variables: y, x_{Bj}, Q^2, z_D and p_T



Parameterised a_{LL}, shows a strong correlation with the generated one *(using AROMA)*

Comparison of a_{LL}(LO) with a_{LL}(NLO)

- **The AROMA generator is used to simulate the fase space for the NLO (PS on) / LO (PS off) calculations of a_{LL}**. The resulting D^0 mesons are reconstructed in the COMPASS spectrometer like real events. The respective a_{LL} distributions are: