ΔG/G Open-Charm results from COMPASS

SYMMETRIES AND SPIN *(SPIN - PRAHA - 2008)*

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on behalf of the COMPASS collaboration

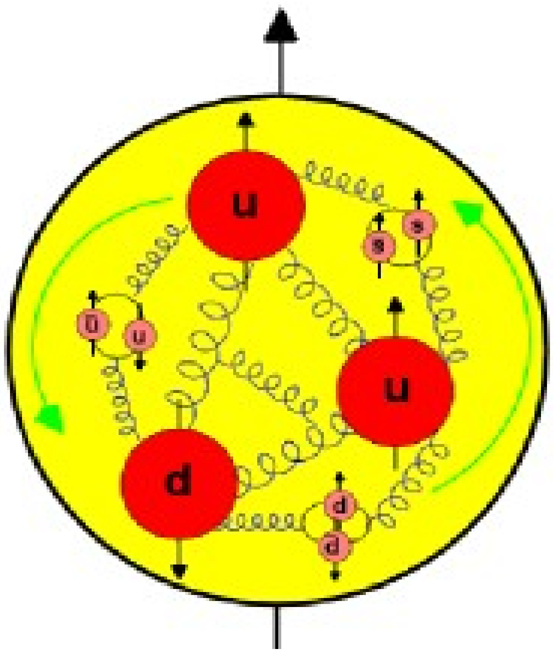
Outline

- **Nucleon spin structure:**
  - Physics motivation
- **The COMPASS experiment:**
  - Spectrometer + polarised target
  - Ring Imaging Cherenkov *(RICH)* for particle identification
- **COMPASS analysis and results on ΔG/G:**
  - Open-Charm channel

Nucleon spin structure

- **Nucleon spin** $\rightarrow$ $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$

quarks gluons orbital angular momentum *(quarks/gluons)*



- **Assuming the static quark model wave function:**

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\{2|u\uparrow u\uparrow d\downarrow\rangle - |u\uparrow u\downarrow d\uparrow\rangle - |u\downarrow u\uparrow d\uparrow\rangle + (u \leftrightarrow d)\}$$

$$\Delta u = \langle p\uparrow|N_{u\uparrow} - N_{u\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(10-2) = \tfrac{4}{3}$$

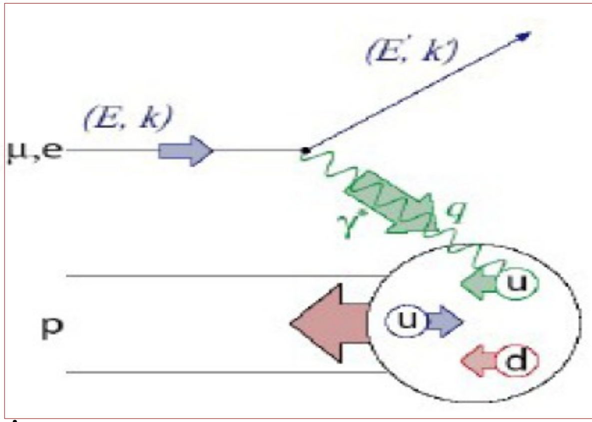
$$\Delta d = \langle p\uparrow|N_{d\uparrow} - N_{d\downarrow}|p\uparrow\rangle = \tfrac{3}{18}(2-4) = -\tfrac{1}{3}$$

- $\Delta\Sigma = \Delta u + \Delta d = 1$

$\Rightarrow$ Up and down quarks carry all the nucleon spin

Spin crisis

- **However, applying relativistic corrections** *(and assuming SU(3) symmetry)*:
  - $\Delta\Sigma \sim 0.60$
- **Where is the remaining part of the nucleon spin?** *(ΔG? $L_{q(G)}$?)*
  - Gluons solved the nucleon missing momentum problem:
    - Will they be the solution too for this missing spin? $\Rightarrow$ Measure ΔG!
- **Experimental $\Delta\Sigma$** *(from polarised DIS)*:



$Q^2 = -q^2$

$\nu = E - E'$

$x = Q^2 / 2M\nu$

$y = \nu / E$

Phys. Lett. B447, (2007) 8

$\Delta\Sigma = 0.30 \pm 0.01 \pm 0.02$ ***(world data)***
$@\ Q^2 = 3\ (GeV/c)^2$

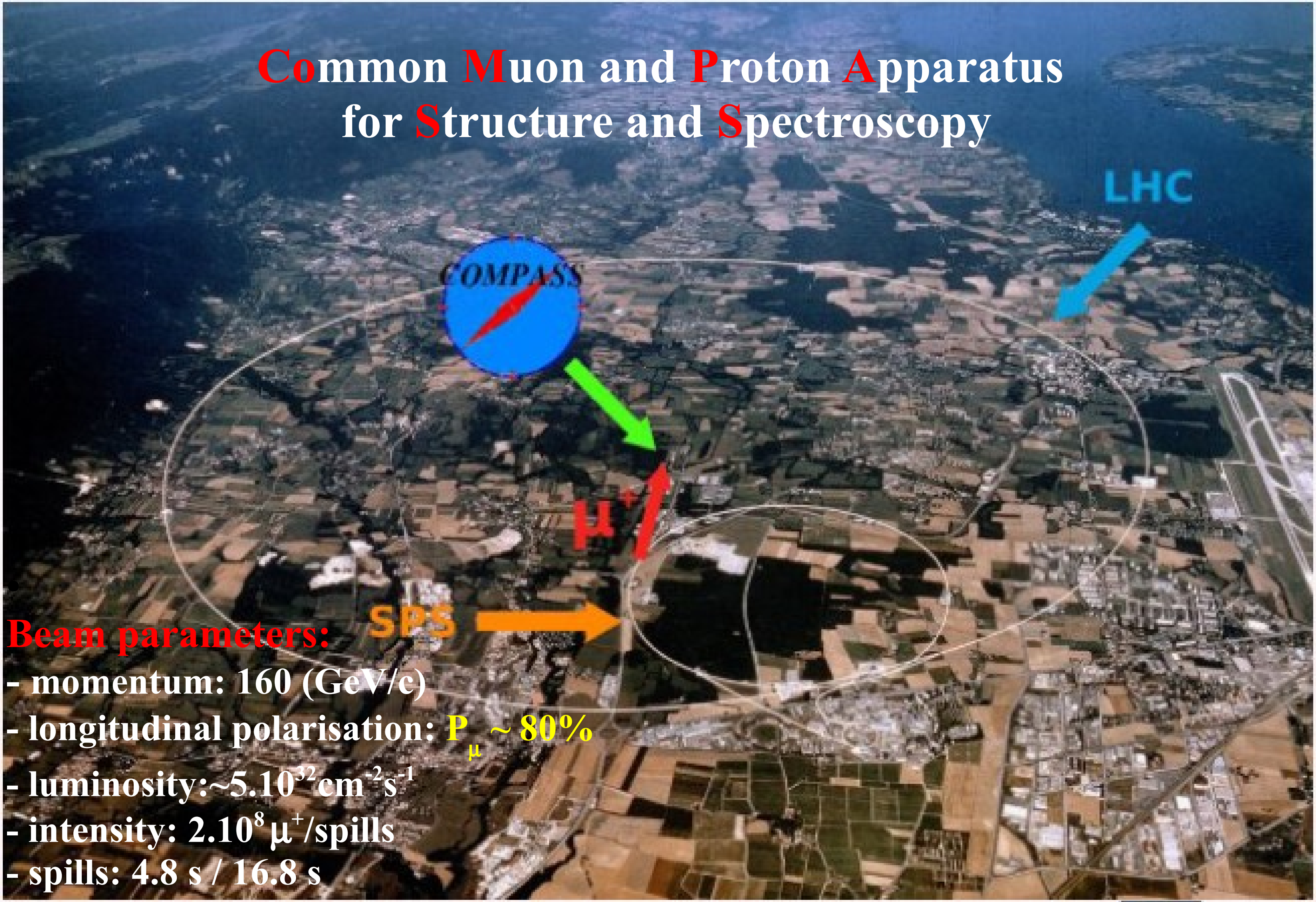
Much smaller than expected...

$\Downarrow$

SPIN CRISIS!!!

- **Another reason for measuring gluon spin contribution:**
  - Due to gluon axial anomaly, if ΔG is large *(~2.5)*, it could explain why $\Delta\Sigma$ was found so small

The COMPASS experiment at CERN

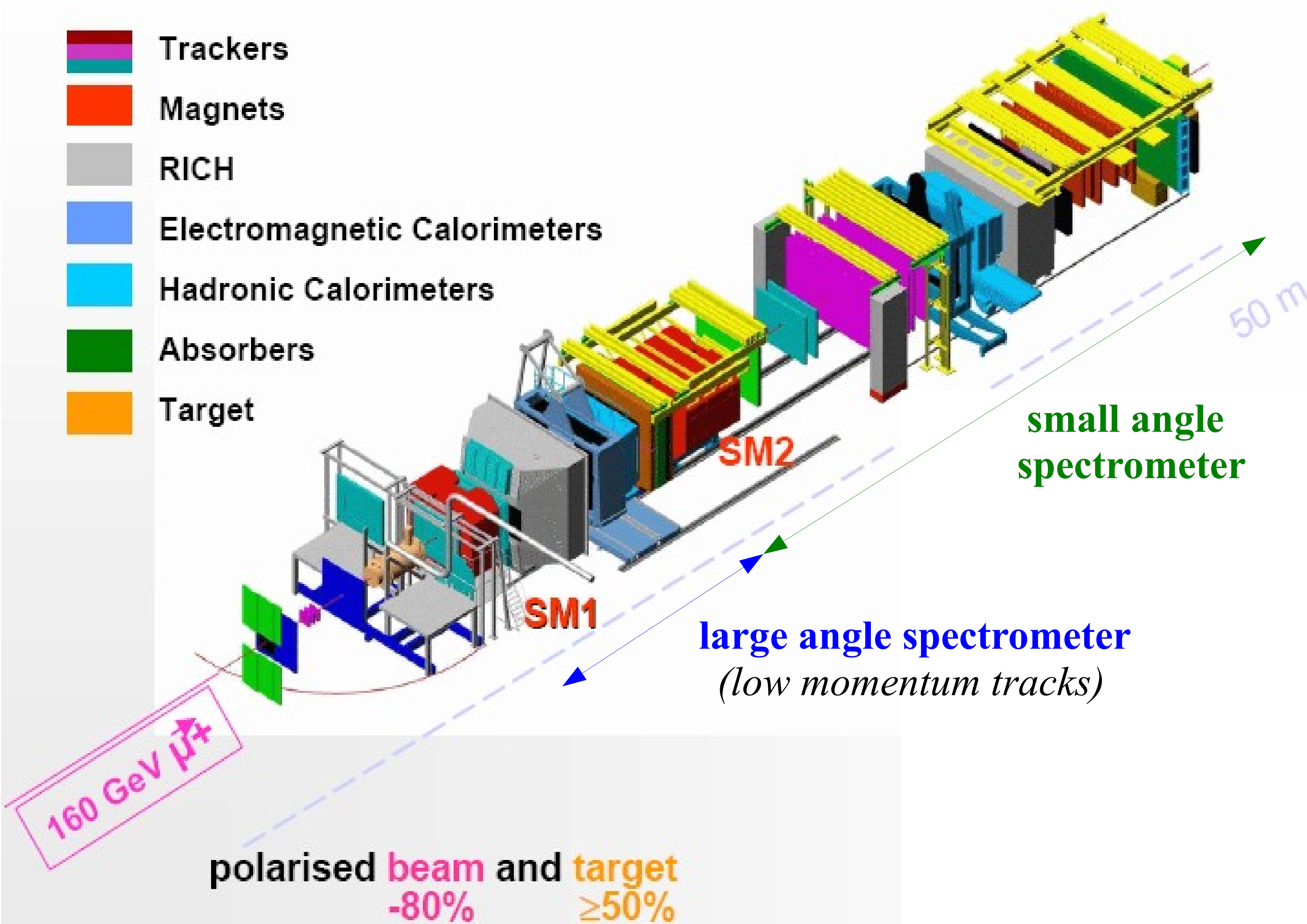


Common Muon and Proton Apparatus for Structure and Spectroscopy

Beam parameters:

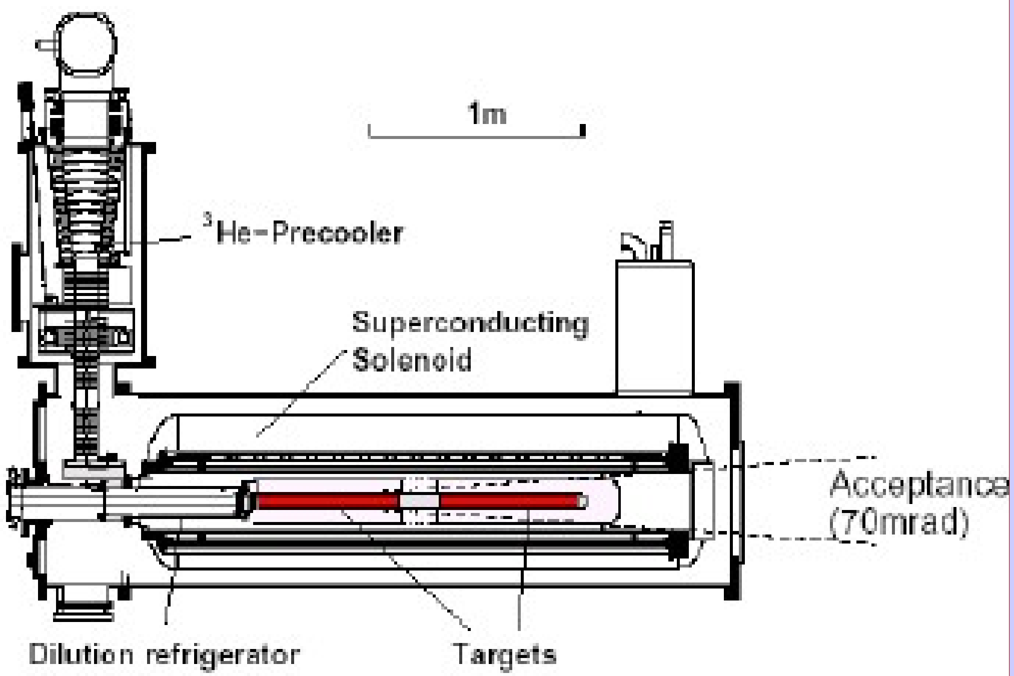
- momentum: 160 (GeV/c)
- longitudinal polarisation: $P_\mu \sim 80\%$
- luminosity: $\sim 5.10^{32} cm^{-2} s^{-1}$
- intensity: $2.10^{8}\ \mu^{+}$/spills
- spills: 4.8 s / 16.8 s

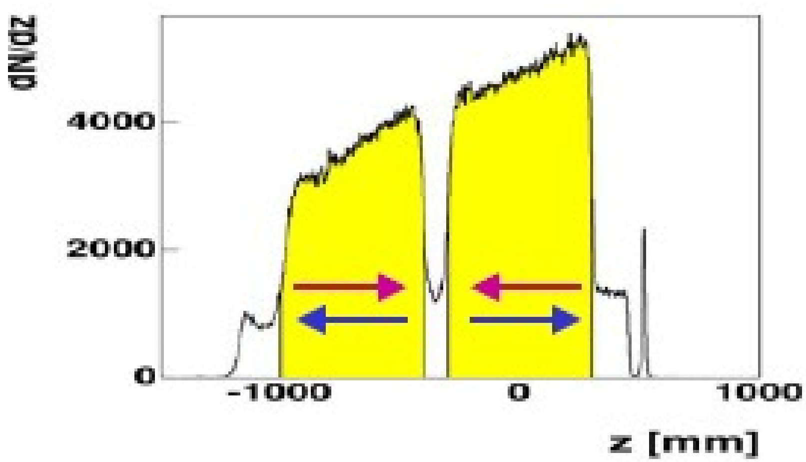
The COMPASS spectrometer



Polarised target *(2002-2004)*

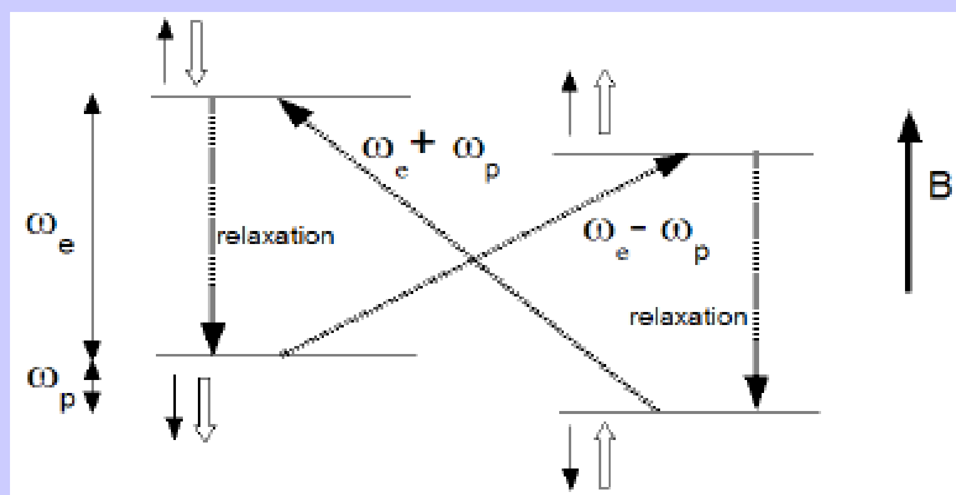
- Target material: ^{6}LiD
- Solenoid field: 2.5 T
- Dilution factor: f ~ 0.4
- Polarisation: $P_T > 50\%$
- ^{3}He/^{4}He: T_{min} ~ 50 mK





Dynamic nuclear polarisation:

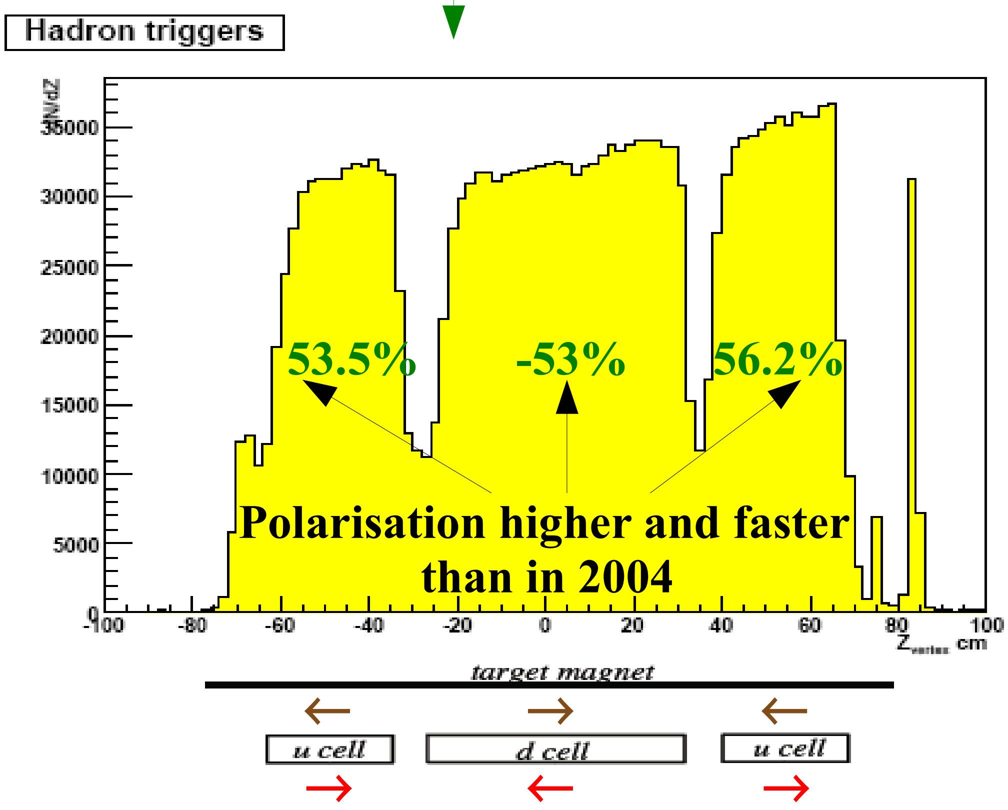
- High electron polarisation *(high magnetic moment)*
- Microwave irradiation of material, for simultaneous flip of electron and nucleon spin
- After spin flip, electron relaxates to lower energy state
- Nucleon has long relaxation time *(low magnetic moment)*

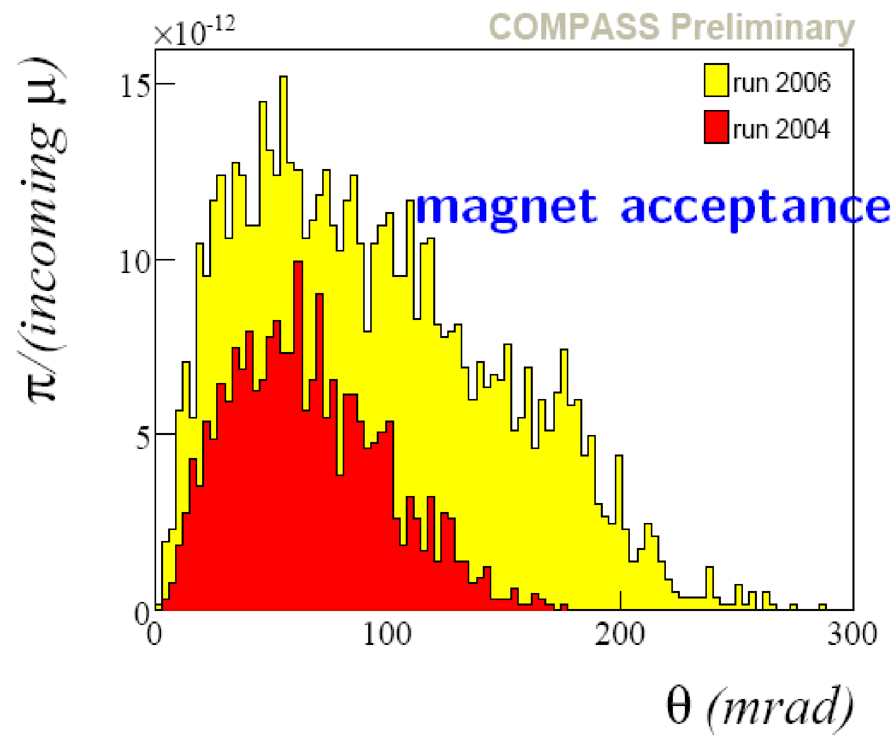


Target upgrade for 2006 data

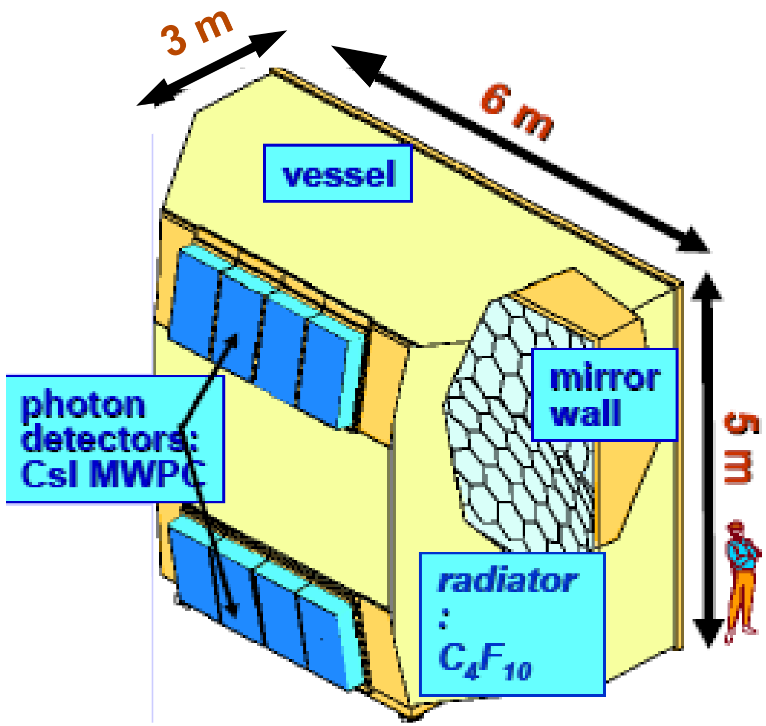
- **Larger solenoid acceptance**
  - 70 mrad $\Rightarrow$ 180 mrad
- **3 target cell for false asymmetries reduction**

  $\Rightarrow$ "same" acceptance *(u and d cells)* for asymmetry extraction

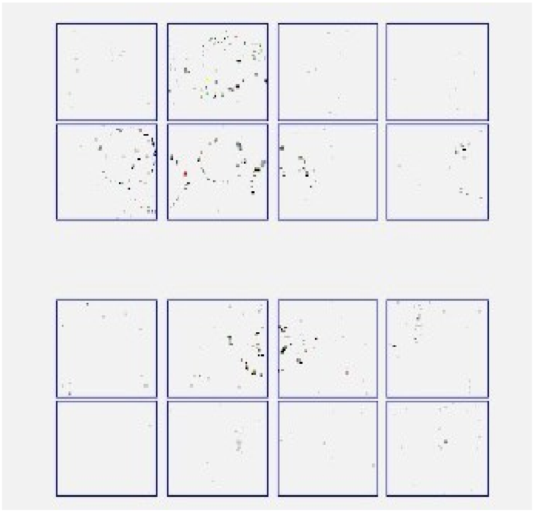


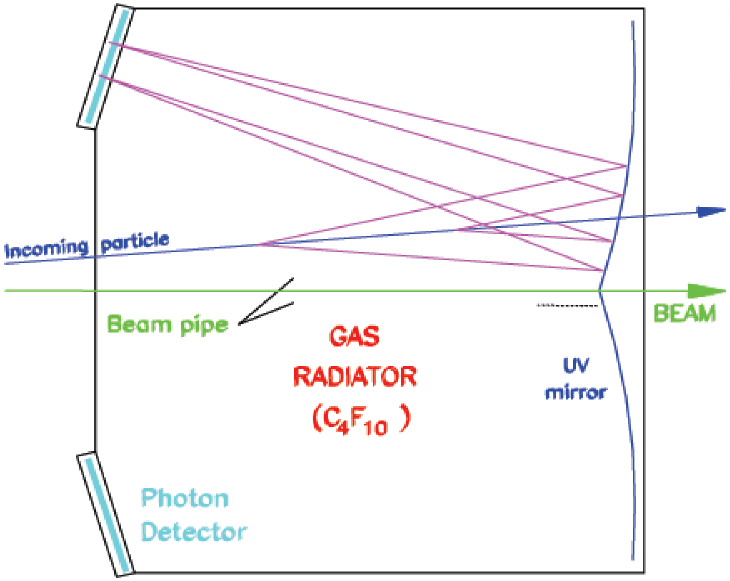


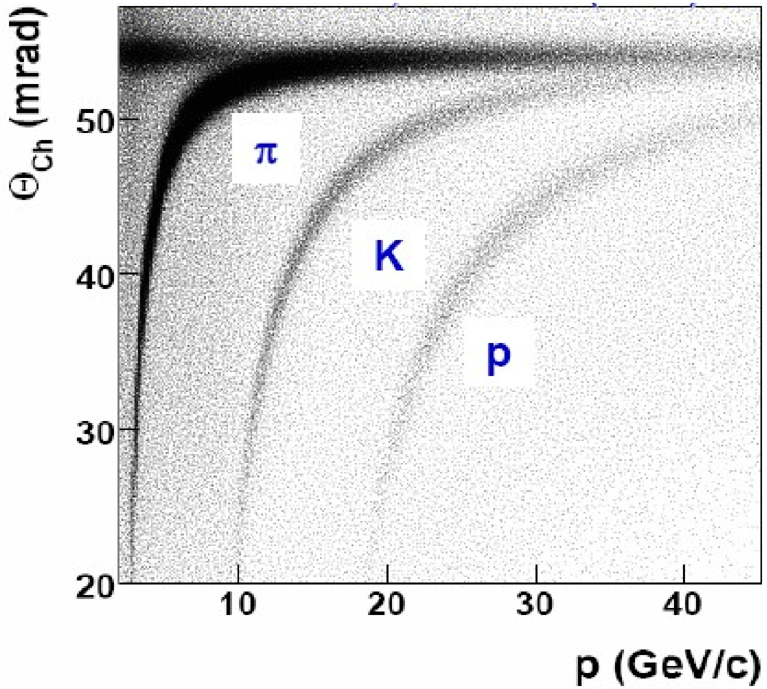
Particles identification: RICH *(2002-2004)*



- π , K separation until ~50 (GeV/c)
- 80 m^3 filled with C_4F_{10}: n = 1.00153
- 116 VUV spherical mirrors *(21 m^3)*
- 5.3 m^2 photodetectors: 82944 pixels



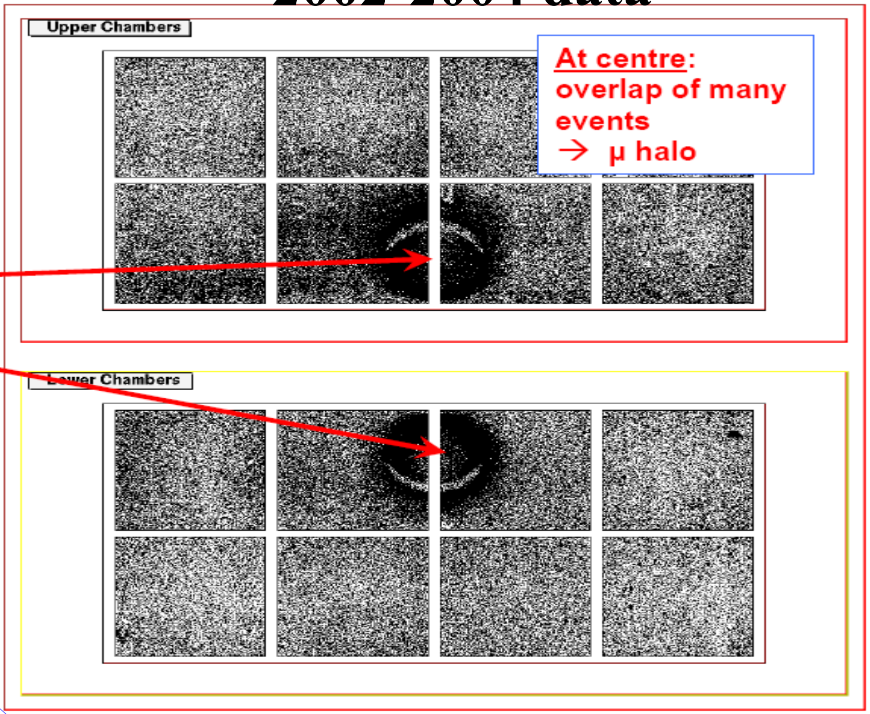


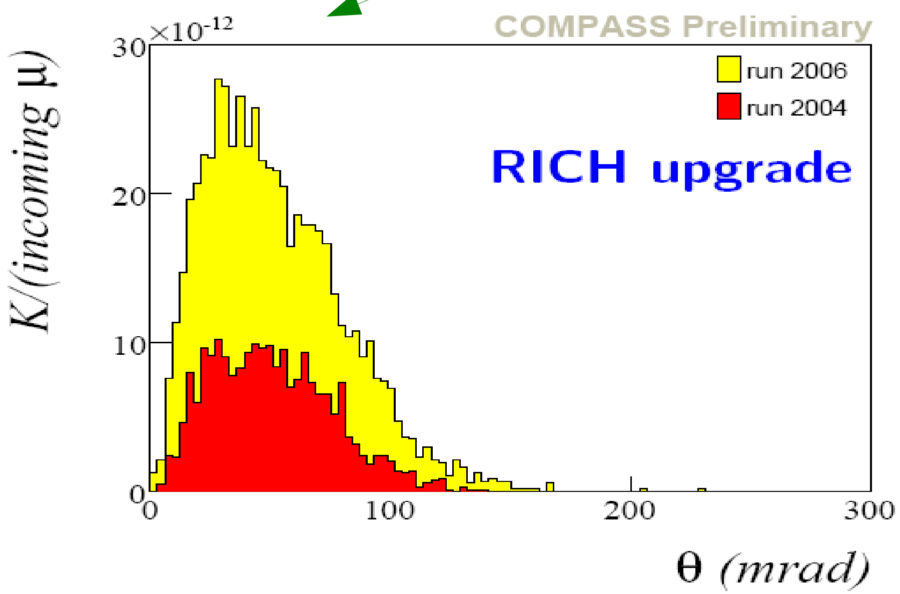


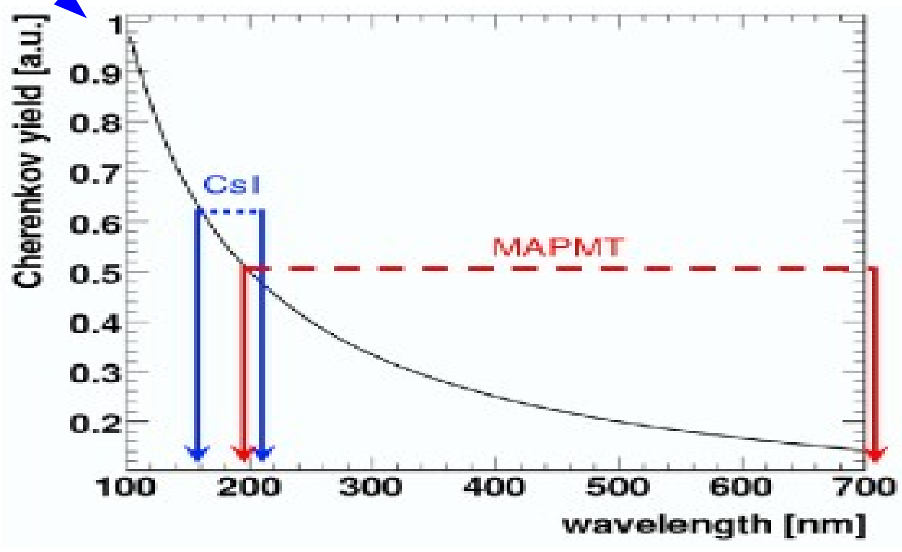
RICH upgrade for 2006 data

- **Electronic system refurbished:**
  - Faster photon detection
- **Central photon detector replaced by MAPMTs**
  - UV transparent + large number of photons detected *(increased wavelength range)*
  - Better efficiency of reconstruction

2002-2004 data



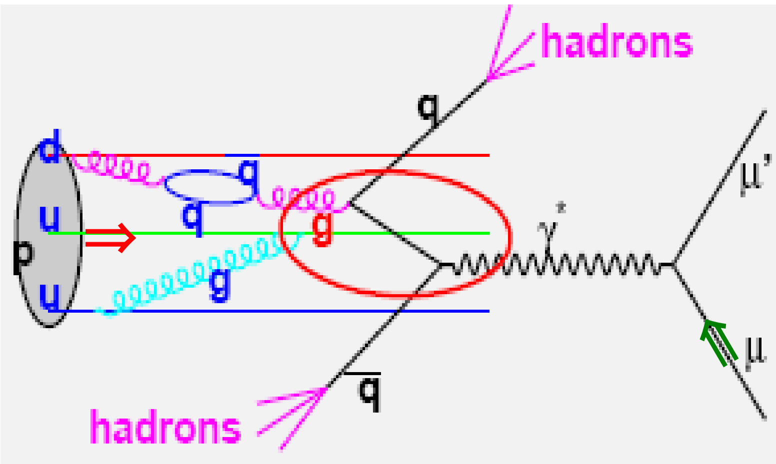




Open-Charm DIS production
The photon-gluon fusion process
(PGF)

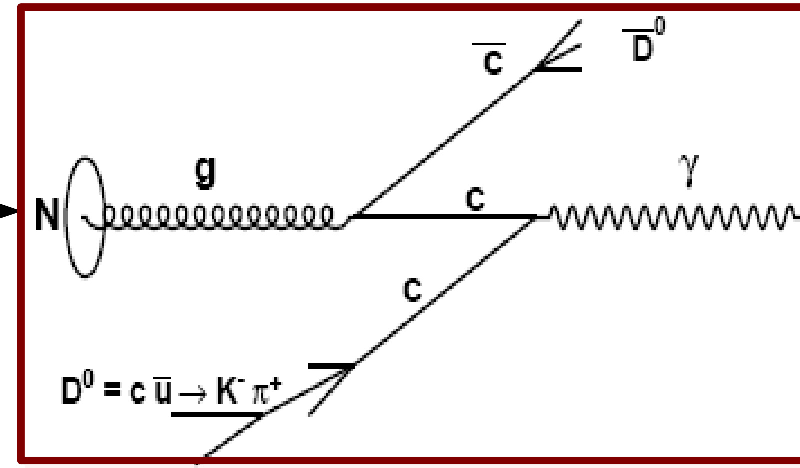
How to measure ΔG?

- **Polarised collision in DIS:**



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

via Open-Charm production



- **After gluon tag** *(reconstructing charmed mesons):*
  - Measure raw asymmetries for gluon spin information!

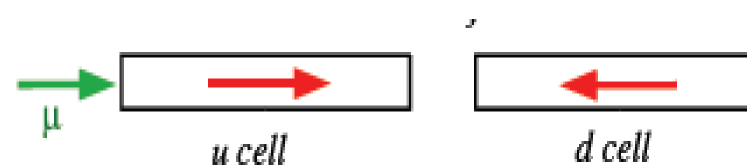
$$A^{exp} = \frac{N^u - N^d}{N^u + N^d} = f \cdot P_\mu \cdot P_T \cdot A^{\mu,T} + A^{bg}$$

Number of events

Depolarization from lepton to virtual photon

$$A^{\mu,T} = D \cdot A_1 = D \cdot \frac{\sigma^{\rightarrow\leftarrow}_{\gamma,T} - \sigma^{\rightarrow\rightarrow}_{\gamma,T}}{\sigma^{\rightarrow\leftarrow}_{\gamma,T} + \sigma^{\rightarrow\rightarrow}_{\gamma,T}}$$

Photon-target asymmetry

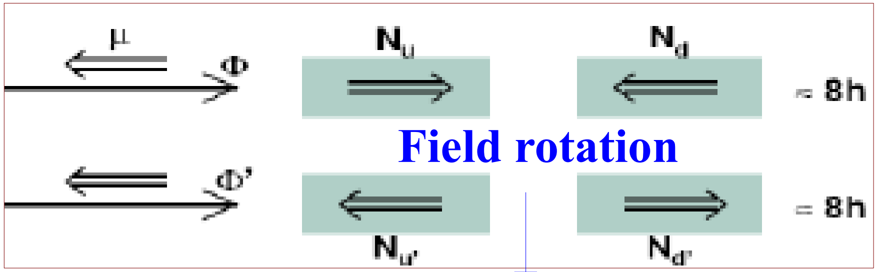


Why asymmetries for ΔG ?

Gluon polarisation from Open-Charm channel

Considering $A_B = 0$

$$\frac{\Delta G}{G} = \frac{1}{2P_T P_\mu f a_{LL} \frac{S}{S+B}} \times \left(\frac{N^u - N^d}{N^u + N^d} + \frac{N^{u'} - N^{d'}}{N^{u'} + N^{d'}} \right)$$



event weight

photon-gluon asymmetry

signal strength of Open-Charm events

equal acceptance for both cells

- **Using** → $A_1 \overset{LO}{=} \langle a_{LL} \rangle \frac{\Delta G}{G}$ with $a_{LL} = \frac{\Delta \sigma^{PGF}}{\sigma^{PGF}}$

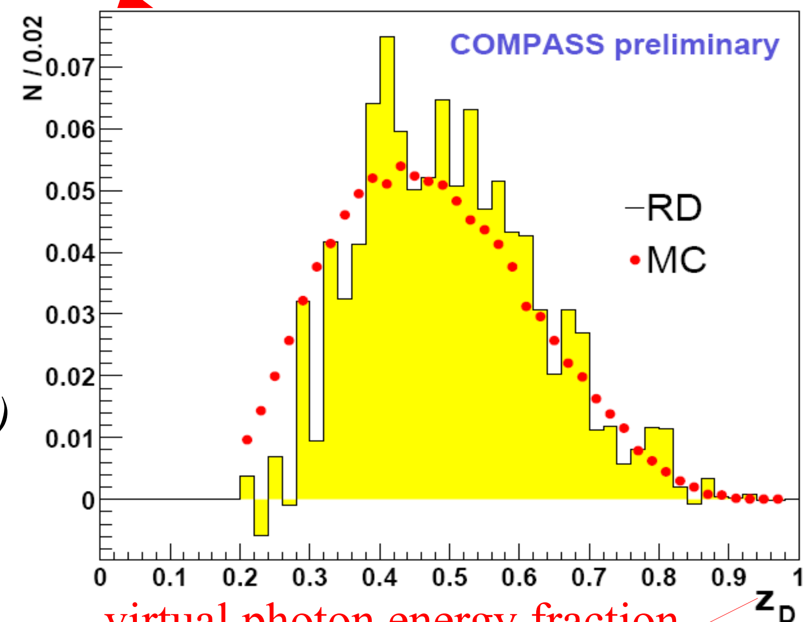
asymmetries are less sensitive to experimental changes than cross section differences

- **Events with small** *($P_\mu \cdot P_T \cdot f \cdot a_{LL} \cdot (S/S+B)$)* **factors contain less information about the asymmetry:**
  - Weighting the events with the option choosen minimizes de statistical error

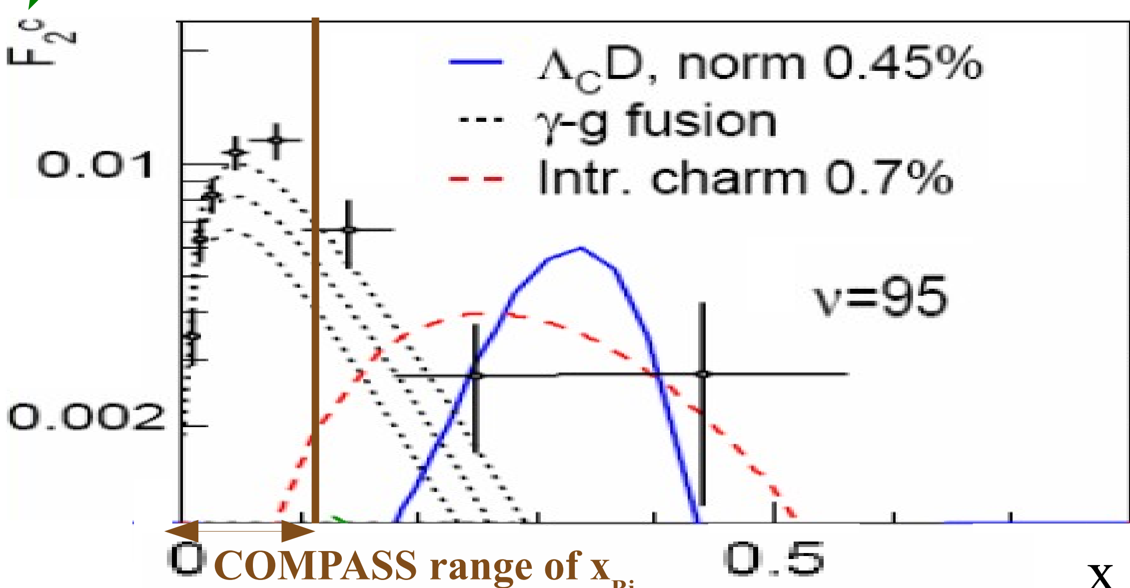
$$\frac{\Delta G}{G} = \frac{1}{2P_T} \times \left(\frac{\omega_u - \omega_d}{\omega_u^2 + \omega_d^2} + \frac{\omega_{u'} - \omega_{d'}}{\omega_{u'}^2 + \omega_{d'}^2} \right) \text{ with a statistical gain: } \frac{\langle \omega^2 \rangle}{\langle \omega \rangle^2}$$

Why measure gluon spin from Open-Charm?

- $c\bar{c}$ production is dominated by the PGF process, and <u>free from physical background</u> *(ideal for probing gluon polarisation)*
  - In our center of mass energy, the contribution from intrinsic charm *(c quarks not comming from hard gluons)* in the nucleon is negligible
  - Perturbative scale set by charm mass $4m_c^2$
  - Nonperturbative sea models predict at most 0.7% for intrinsic charm contribution
    - Expected at high x_{Bj} *(compass x_{Bj} < 0.1)*
  - $c\bar{c}$ supressed during fragmentation *(at our energies)*



virtual photon energy fraction carried by D^0 meson



COMPASS range of x_{Bj}

x_{Bj}

Ref. Hep-ph/0508126 and hep-ph/9508403
Phys. Lett. B93 (1980) 451
Data from EMC:Nucl.Phys.B213, 31(1983)

Open-Charm basic selection

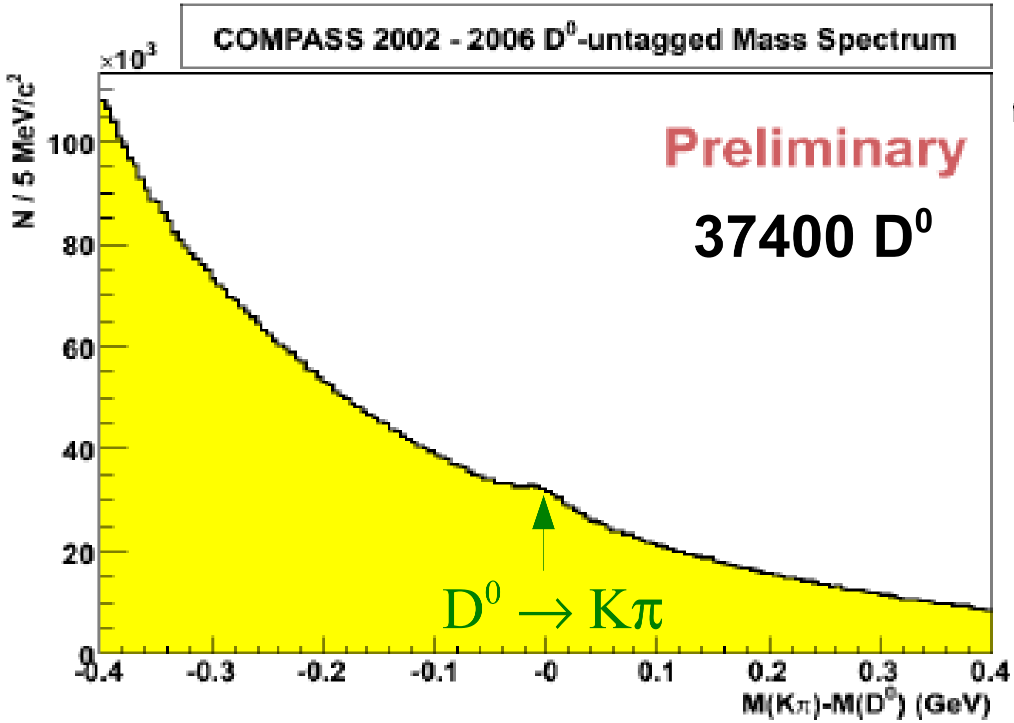
- **Open-Charm events considered** *(from c quarks fragmentation):*
  - $D^0 \to K\pi$ *(BR: 4%)*
  - $D^* \to D^0\pi_S \to K\pi\pi_S$ *(30% D^0 tagged with D^*)*
- **K and π are identified by RICH** ⇒ D⁰ invariant mass reconstructed!
- **In case of D^*, π_s sample is cleaned** *(slow pions: $p < 8$ (GeV/c))* **:**

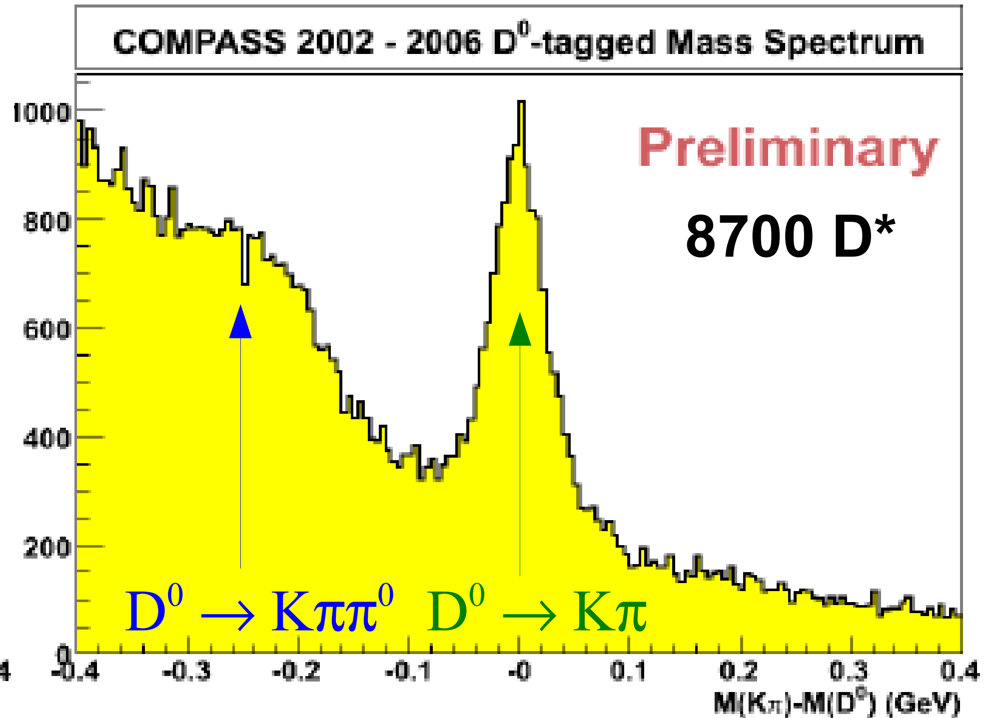
  ⇒ Rejecting electrons with RICH enhances S/B
- **Basic kinematic cuts for combinatorial background suppression:**
  - Reject colinear events with virtual photon *(meson angular cut)*
  - Reject events with very small z_D *(expected to be ~ 0.5 in PGF)*

.

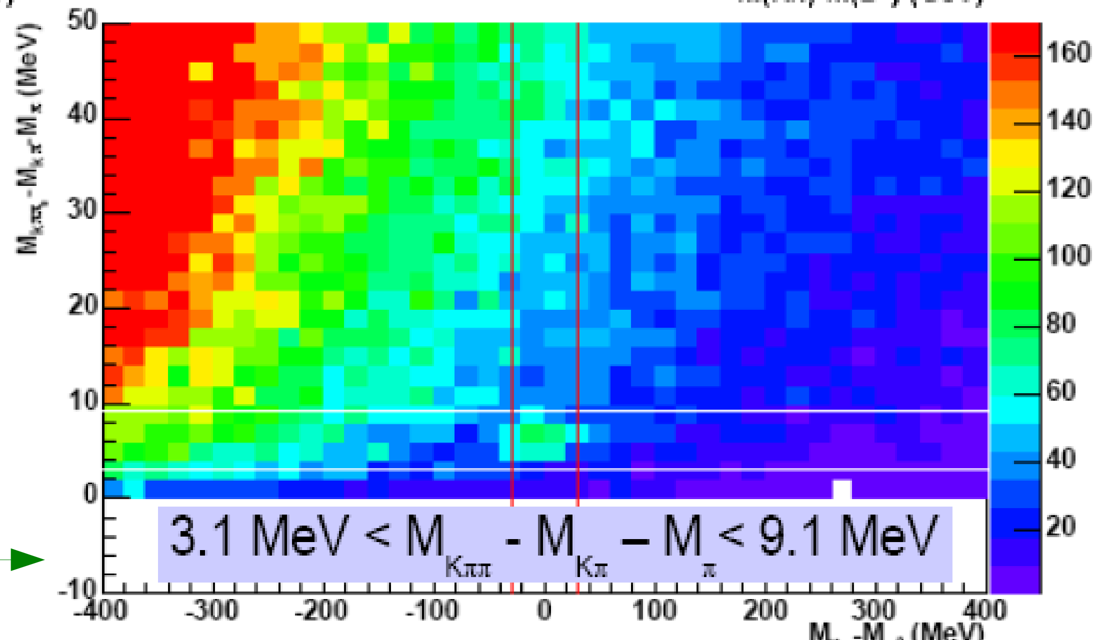
- **After selecting events** *(counting N_{cell} events)*
  - What is missing for ΔG/G? ⇒ S/S+B and a_{LL}

Invariant mass spectra on 2002-2006 data





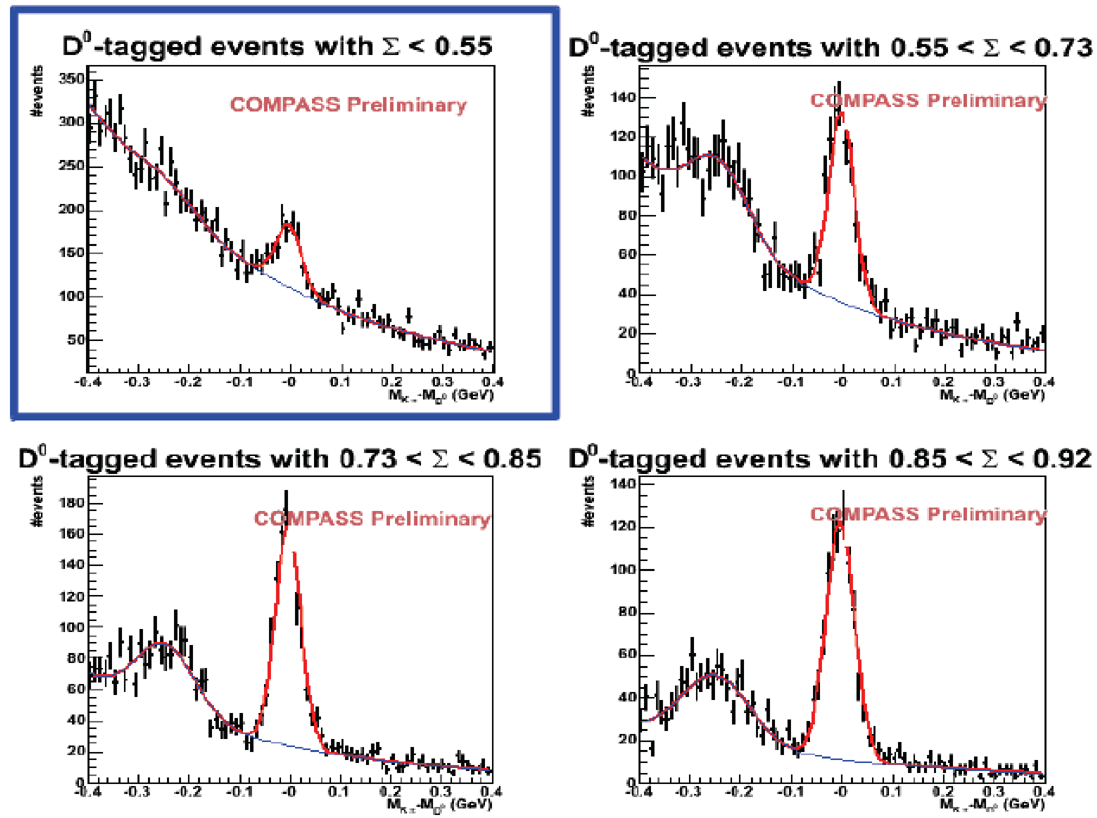
- **(S/S+B)** **<u>from fit to mass spectra</u>**
- **Problem: difficult $c\bar{c}$ production in PGF ⇒ low statistics!**
- **D^0** → big combinatorial background
- **D^*** → very good S/B, due to optimal mass reconstruction



Σ $(=S/S+B)$ as an Open-Charm event probability

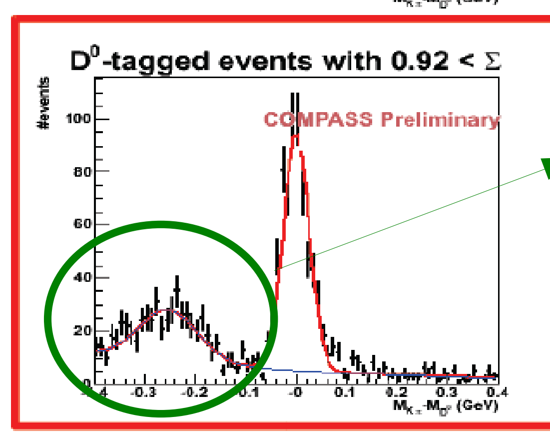
Why is better to have (S/S+B) for every event?

- **Events with small $\Sigma \Rightarrow$ low weight**
  - Mostly combinatorial background selected



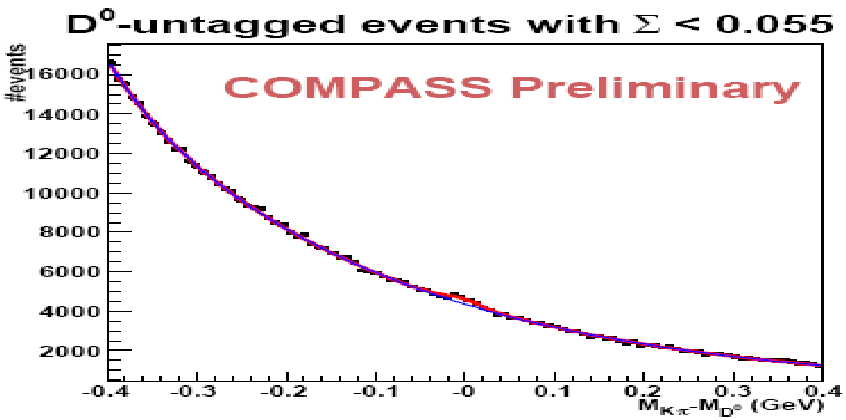
- **With Σ in the weight, the kinematical cuts can be loose:**
  - More background events
  - Preserve signal events

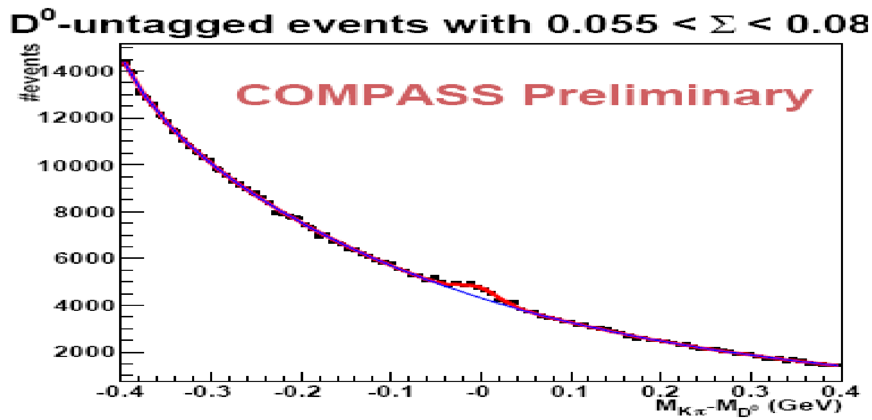
- **Events with large $\Sigma \Rightarrow$ high weight**
  - Mostly Open-Charm events selected

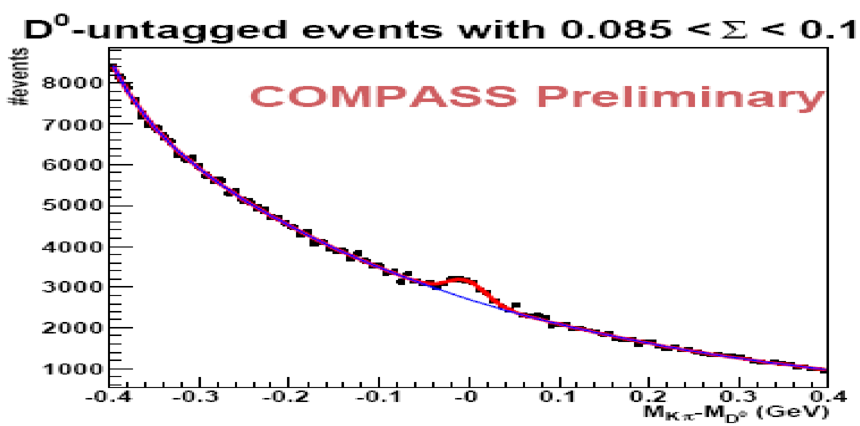


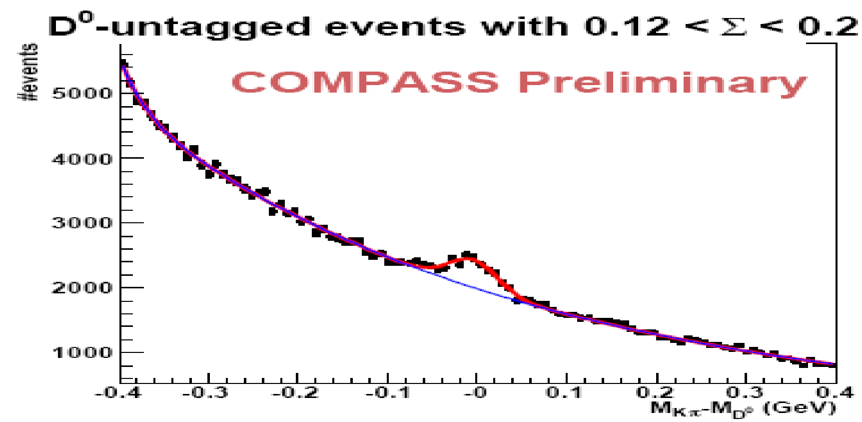
Possibility to include a new Open-Charm channel in the analysis for statistical error improvement

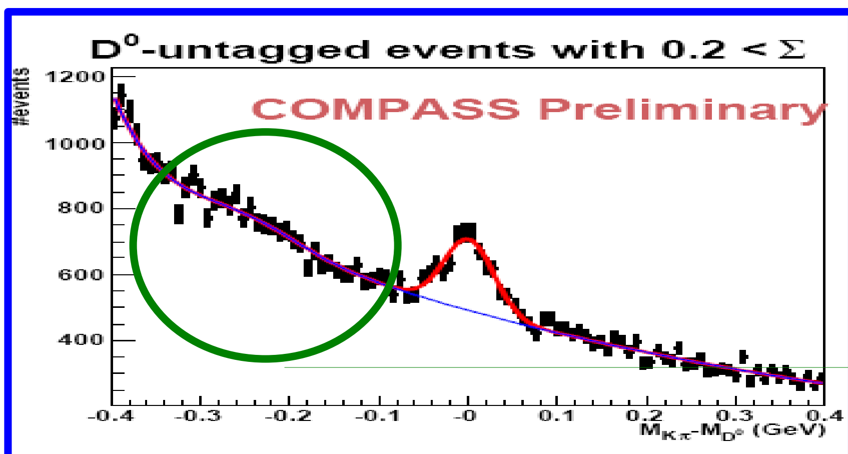
Σ (=S/S+B) effect in D^0 mass spectra











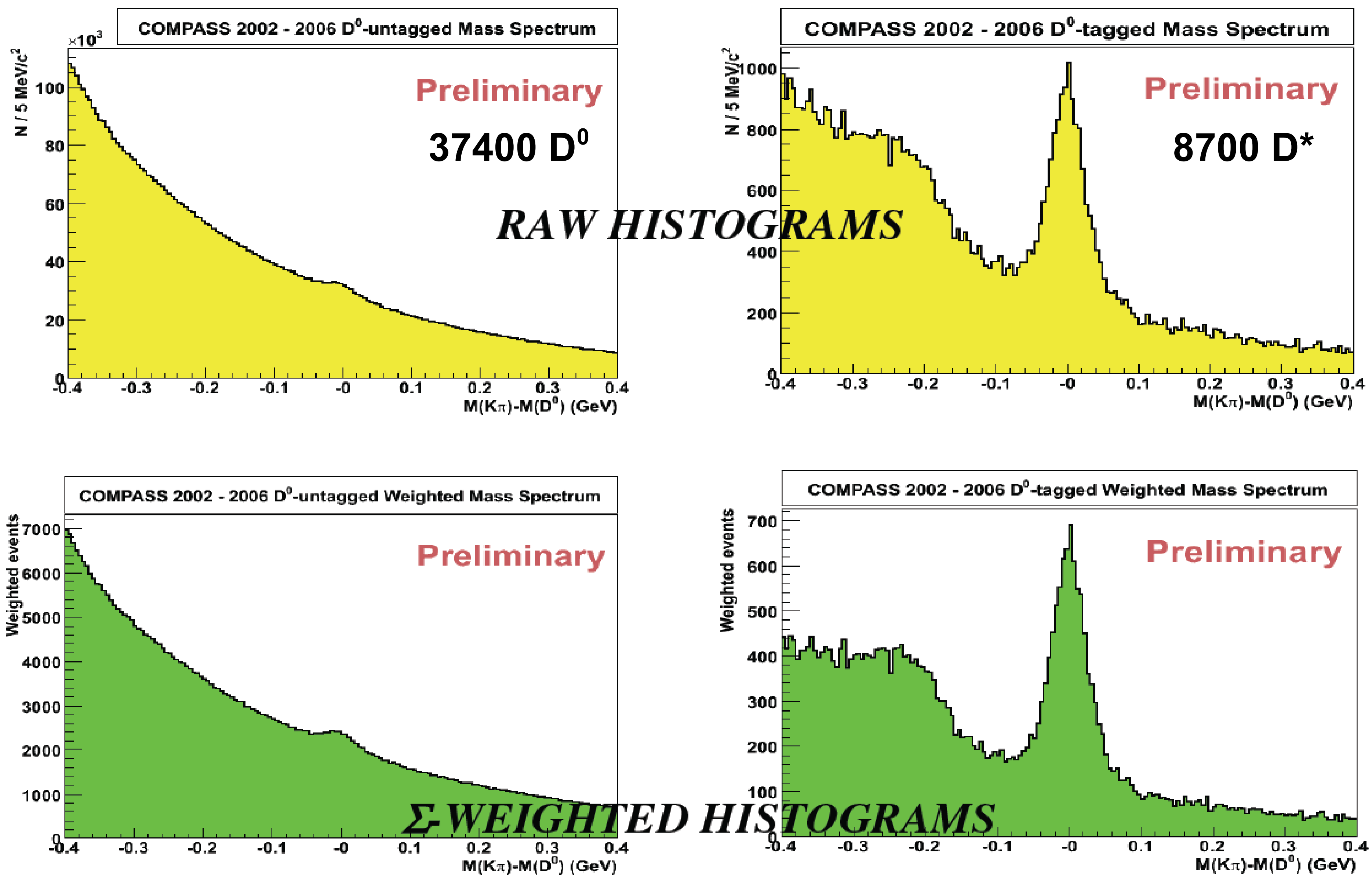
- **Improved S/B <u>for D^0 not tagged</u>**
  - For high Σ events, combinatorial background is reduced significatively
    - π^0 reflection is seen for high Σ

How to parameterize Σ ?

- **Σ_p = S/B is defined and parameterized for every event:**
  - Σ_p is built *(iteratively)* over some kinematic variables and RICH response:
    - $(\Sigma_p)_{initial} = 1$
    - Each variable is divided in mass bins *(binning needed for statistical gain)*
    - Fit all D^0 and D* mass spectra inside each bin of each variable
    - Σ_p is ajusted *(for every event inside each bin)* to $(S/B)_{fit}$
  - After convergence, parameterization is checked:
    - No artificial peak produced in wrong charge mass spectra
  - Mass dependence $\Rightarrow$ Included in Σ after convergence of Σ_p

- $(\Sigma = \Sigma_p / \Sigma_p + 1)$ in the weight → **probability for a given event to be background or Open-Charm**

S/B improvement with the parameterization

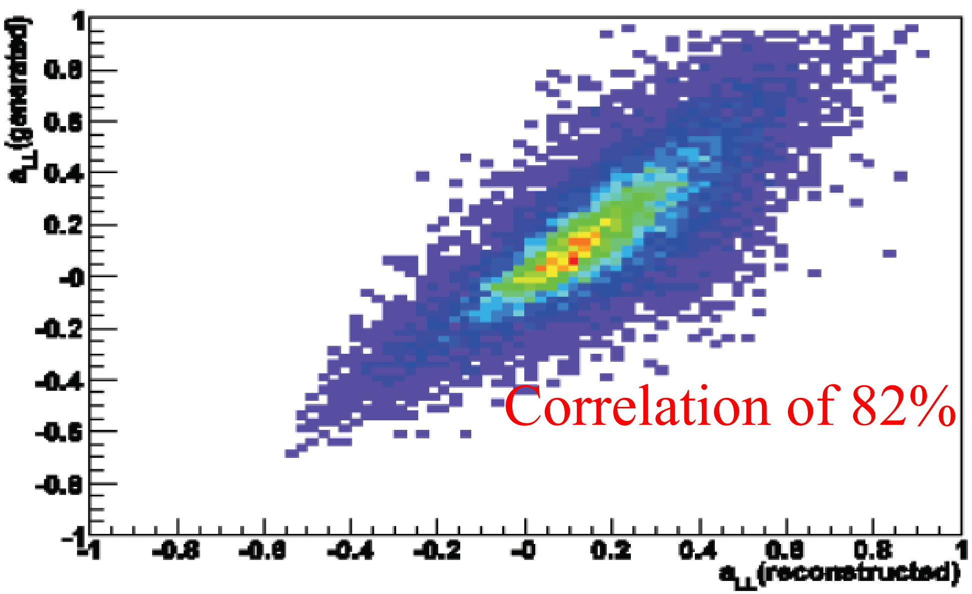


Partonic *(photon-gluon)* asymmetry a_{LL}

- **a_{LL} is dependent on full knowlege of 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 parameterization on reconstructed kinematical variables: y, x_{Bj}, q^2, z_D and $p_{T,D}$

- **ΔG/G is obtained <u>event by event also in LO</u>**



Parameterized a_{LL} *(by NN)*, shows a strong correlation with the generated one *(comparison with generated a_{LL} using AROMA)*

Method for ΔG/G and polarised A_B extraction

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

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

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 $\omega_B = P_\mu \cdot f \cdot D(y) \cdot (B/S+B)$

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

(cell = u , d , u' , d') **(ΔG/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

How to solve equations for simultaneous $\Delta G/G$ and A_B extraction?

- **Possible acceptance changes with time are the same for both cells** *(also the muon flux is the same for both cells):*

  10 ⇒ <u>8 unknowns</u>: 6 â , A_S and A_B →

$$\frac{\hat{a}_{u,S}\,\hat{a}_{d',S}}{\hat{a}_{u',S}\,\hat{a}_{d,S}} = 1 \quad , \quad \frac{\hat{a}_{u,B}\,\hat{a}_{d',B}}{\hat{a}_{u',B}\,\hat{a}_{d,B}} = 1$$

- **Signal and background events are affected in same way before and after a field reversal:**

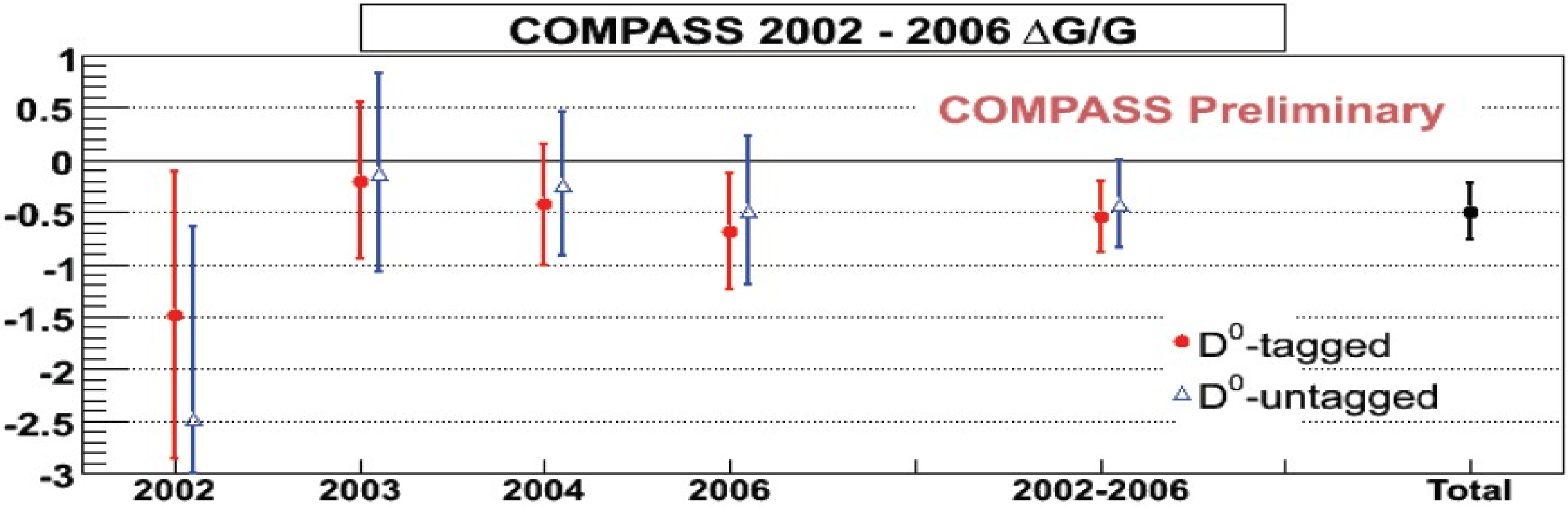
  8 ⇒ <u>7 unknowns</u>: 5 â , A_S and A_B →

$$\frac{\hat{a}_{u,S}}{\hat{a}_{u,B}} = \frac{\hat{a}_{u',S}}{\hat{a}_{u',B}} \quad , \quad \frac{\hat{a}_{d,S}}{\hat{a}_{d,B}} = \frac{\hat{a}_{d',S}}{\hat{a}_{d',B}}$$

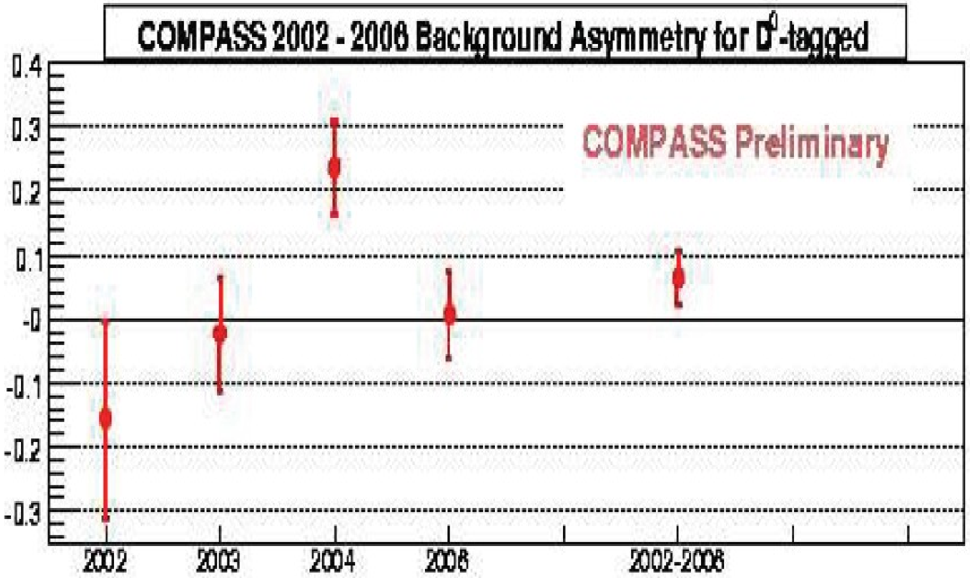
- **Unknowns are obtained by a χ^2 minimization:**

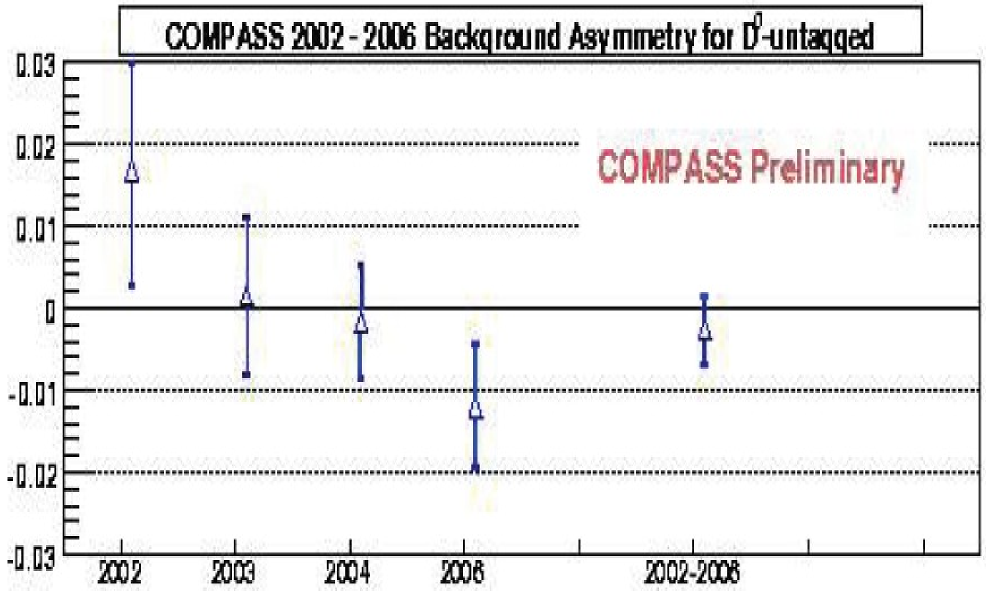
$$\chi^2 = (\vec{N} - \vec{f})^T \mathrm{Cov}^{-1} (\vec{N} - \vec{f})$$

Results



$$\frac{\Delta G}{G} = -0.49 \pm 0.27\ (stat) \pm 0.11\ (sys) \qquad \langle x_g \rangle = 0.11,\ \langle \mu^2 \rangle = 13\ GeV^2$$





Systematic errors

- **Possible errors of experimental systematics** *(false asymmetries)*, **Σ and a_{LL} in weights definitions:**
  - Results in an error which is proportional to ΔG/G
- **Σ was obtained in different mass windows** *(around the peak)*, **different fit functions were used, different order for the variables on which the parameterization is applied, and different number of iterations**
- **a_{LL} was estimated with different values for the charm quark mass and different pdf**
  - For a nominal analysis with weight w^0, and uncertainty in the weight w^i, the spread in ΔG/G is given by the spread of: $< w^0 w^i > / < (w^0)^2 >$

All systematic contributions for ΔG/G →

Source	D^0	D^*
Beam polarisation	0.025	0.025
Target polarisation	0.025	0.025
Dilution factor	0.025	0.025
False asymmetry	0.05	0.05
Σ	0.07	0.01
a_{LL}	0.05	0.03
Total	**0.11**	0.07

Conclusions

- **Our new $\Delta G/G$ measurement shows a significant statistical improvement as compared with our previous result:**

preliminary

- $(\Delta G/G)_{new} = -0.49 \pm 0.27 \pm 0.11$

@ $\langle x_g \rangle = 0.11$
$\langle \mu^2 \rangle = 13\ (GeV/c)^2$

- $(\Delta G/G)_{old} = -0.47 \pm 0.44 \pm 0.15$

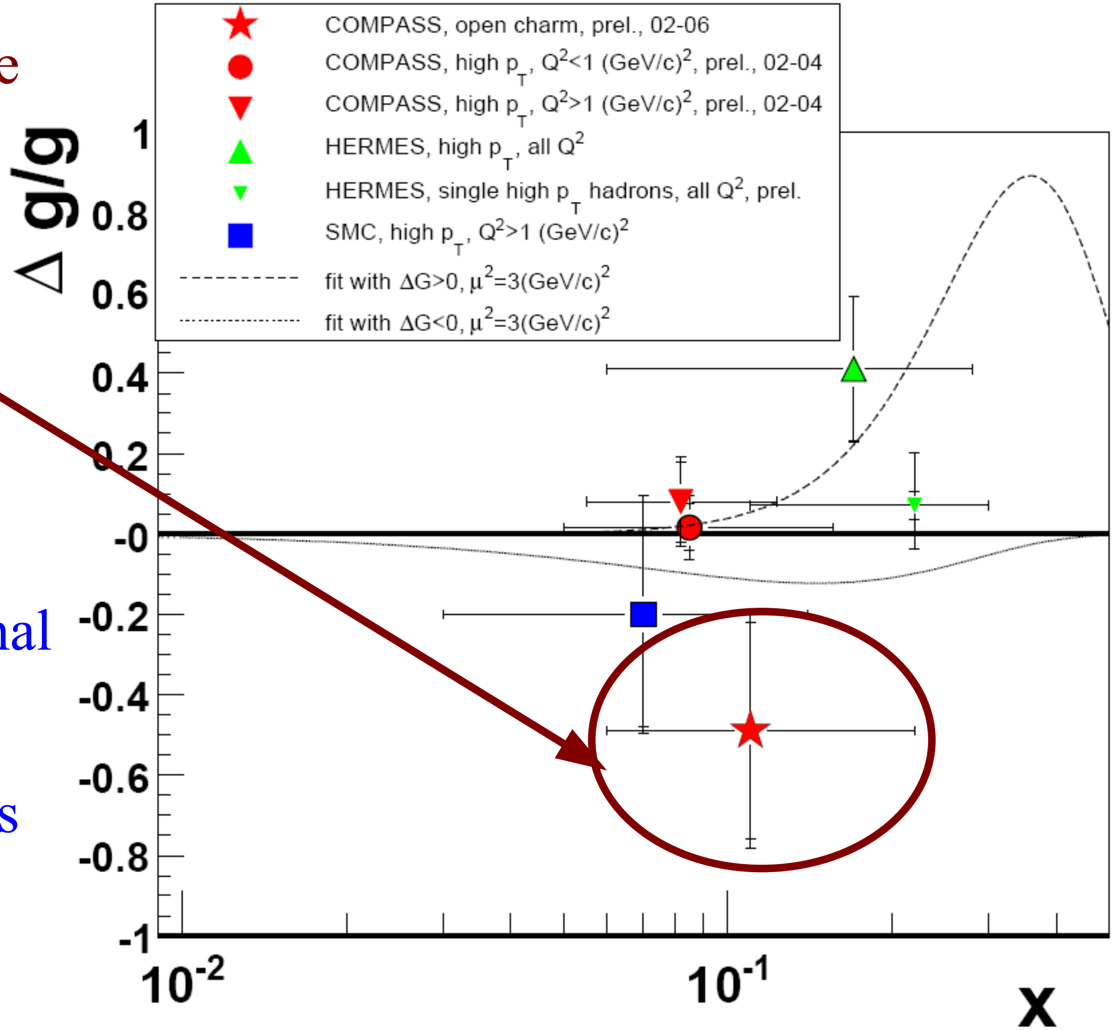
- **Main reasons for this new result:**

  - 2006 data included
  - New cut cleaning electrons from D^*
    (π_s more pure for $p < 8$ (GeV/c))
  - Parameterization of signal strength
  - Improved tracking

- **Gluon polarisation is obtained directly from data in a model independent way!**

Conclusions II

- **Small values of ΔG are preferred!**
  - Gluon polarisation compatible with zero within 2σ
- **Future studies:**
  - 2007 data
  - NLO analysis
  - Neural Network event selection, with multidimentional parameterization of Σ_p
  - RICH sub-threshold D^0 events recovery
  - D^* bump events recovery



SPARES

QCD analysis of the world data on structure function g_1

Method

- **In NLO QCD:**

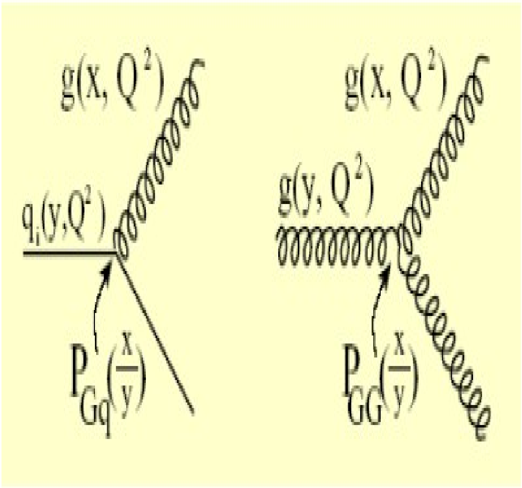
$$g_1(x,Q^2)=\frac{1}{2}<e^2>[C_q^S\otimes\Delta\Sigma+C_q^{NS}\otimes\Delta q^{NS}+2n_f C_G\otimes\Delta G]$$

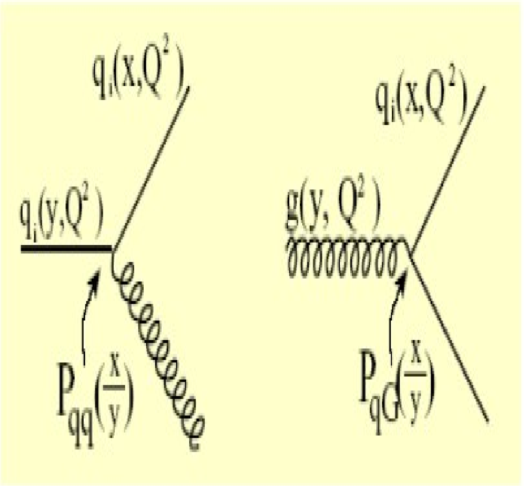
- **DGLAP evolution equations:**

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

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}=\frac{\alpha_S(t)}{2\pi}\begin{pmatrix}P_{qq}^S & 2n_f P_{qG}^S\\ P_{Gq}^S & P_{GG}^S\end{pmatrix}\otimes\begin{pmatrix}\Delta\Sigma\\ \Delta G\end{pmatrix}$$

$$\Delta q^{NS}(x,Q^2)=\Sigma_i\left(\frac{e_i^2}{<e_i^2>}-1\right)\Delta q_i(x,Q^2)$$





- **Parton distributions are parameterized at Q_0^2**

$$(\Delta\Sigma,\Delta q_3,\Delta q_8,\Delta G)=\eta\frac{x^\alpha(1-x)^\beta(1+\gamma x)}{\int_0^1 x^\alpha(1-x)^\beta(1+\gamma x)\,dx}$$

- **DGLAP evolution until measured Q^2**
  - Fit all data together

$$\chi^2=\Sigma_{i=1}^N\frac{[g_1^{calc}(x,Q^2)-g_1^{exp}(x,Q^2)]}{[\sigma_{stat}^{exp}(x,Q^2)]^2}$$

ΔG from QCD fits

- 230 points from 9 experiments: 43 from COMPASS

2 equally good solutions:

- ΔG > 0 preferred!
- ΔG < 0 preferred by small x points

$$\Delta\Sigma \approx 0.30 \pm 0.01\ (stat) \pm 0.02\ (evol)$$

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