ΔG/G results from the Open-Charm production at COMPASS

CHARM2012 – Honolulu

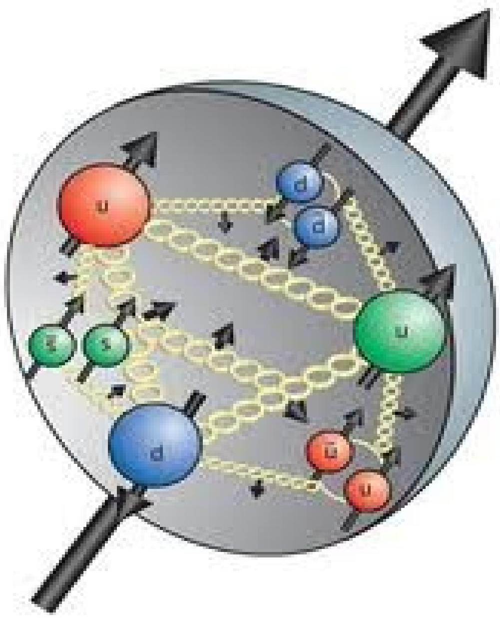
Celso Franco *(LIP – Lisboa)*

on behalf of the COMPASS collaboration

Nucleon spin structure

- **Nucleon spin** ⟶ $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

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



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

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

$$\boxed{\begin{aligned}\Delta u &= \langle p\uparrow|N_{u\uparrow} - N_{u\downarrow}|p\uparrow\rangle = \frac{3}{18}(10-2) = \frac{4}{3}\\ \Delta d &= \langle p\uparrow|N_{d\uparrow} - N_{d\downarrow}|p\uparrow\rangle = \frac{3}{18}(2-4) = -\frac{1}{3}\end{aligned}}$$

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

⟶ Up and Down quarks carry all the nucleon spin

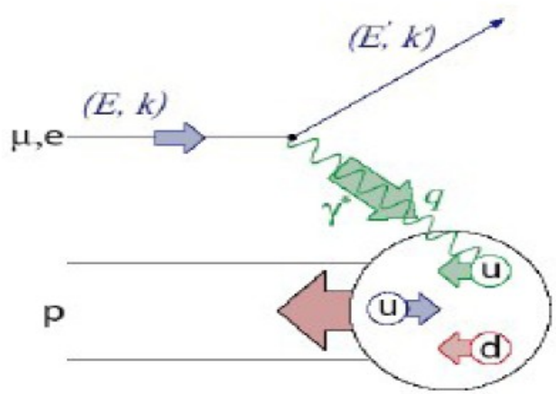
Spin crisis

- **However,** **by applying relativistic corrections** *(<u>and assuming SU(3) symmetry</u>)*:

$\boxed{\Delta\Sigma \sim 0.60}$

- **Where is the remaining part of the nucleon spin?** *(ΔG ? $L_{q\,(g)}$?)*
  - <u>Gluons solved the problem of the missing momentum in the nucleon</u>:
    - Will they be the solution too for this missing spin? $\Rightarrow$ Measure ΔG!

- **Experimental $\Delta\Sigma$** *(from polarised DIS)*:



$Q^2 = -q^2$

$\nu = E - E'$

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

$y = \nu / E$

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

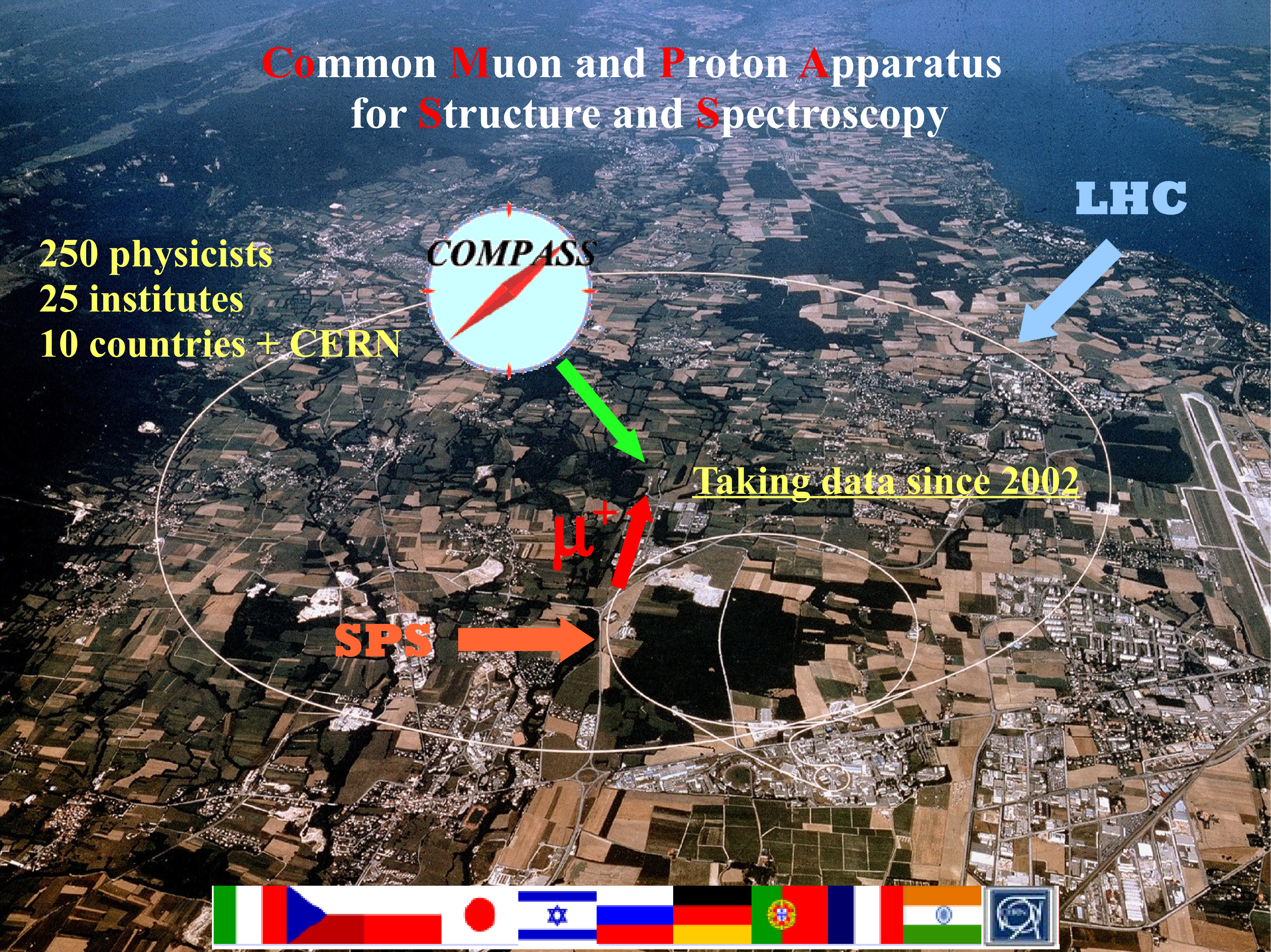
Much smaller than expected...

$\Downarrow$

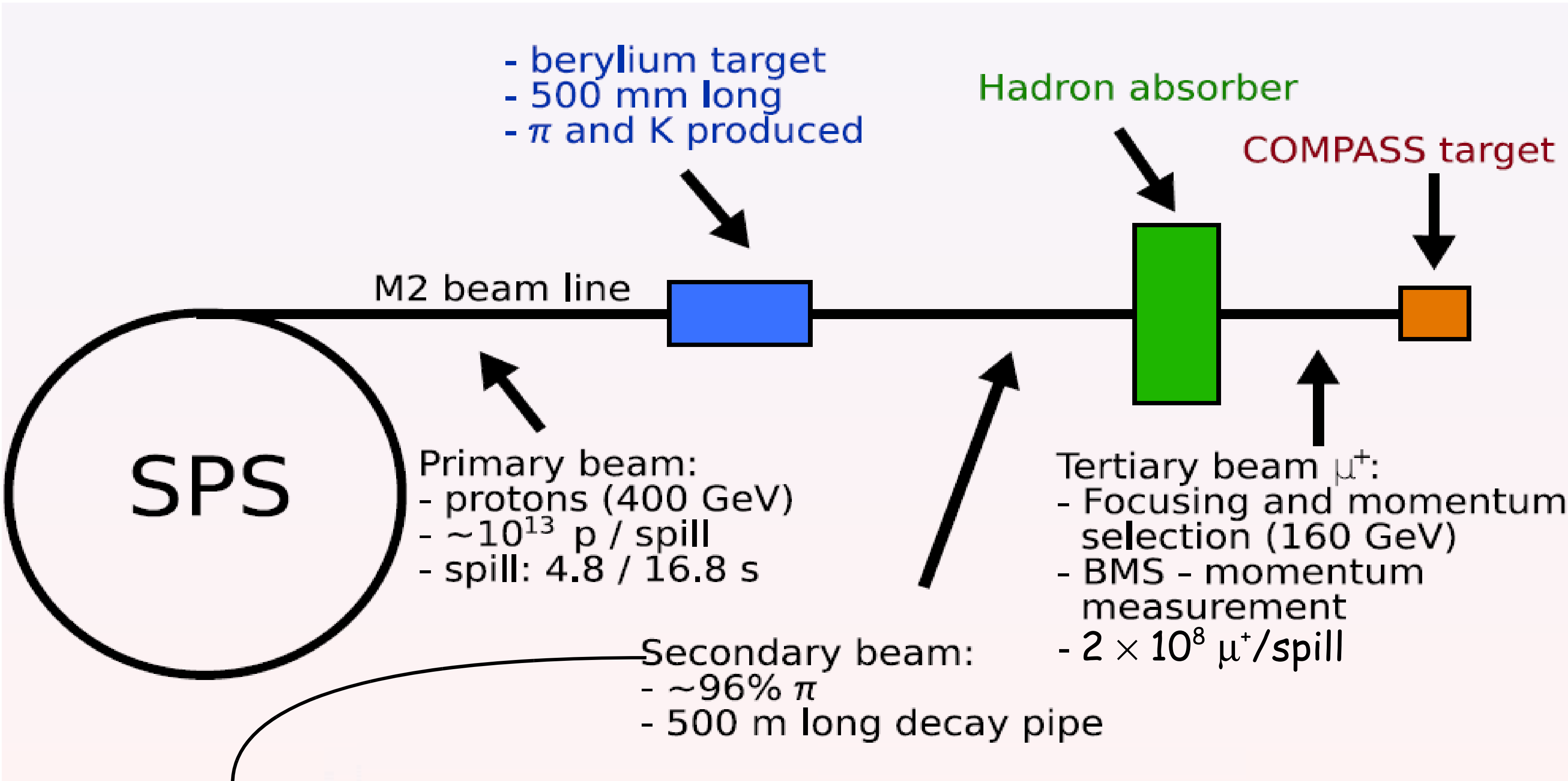
SPIN CRISIS!!!

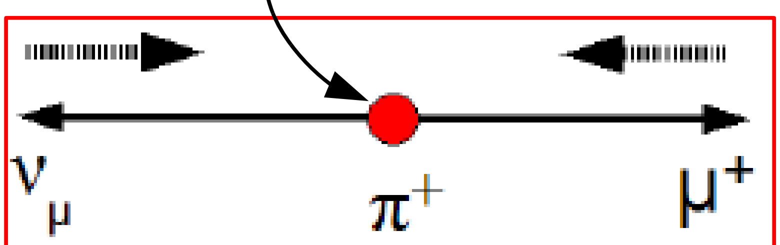
- **Another reason for measuring the gluon contribution to the nucleon spin:**
  - <u>Due to the gluon axial anomaly</u>, a large ΔG could explain why $\Delta\Sigma$ was found so small

The COMPASS Experiment


Common Muon and Proton Apparatus
for Structure and Spectroscopy
LHC
250 physicists
25 institutes
10 countries + CERN
COMPASS
Taking data since 2002
μ^+
SPS

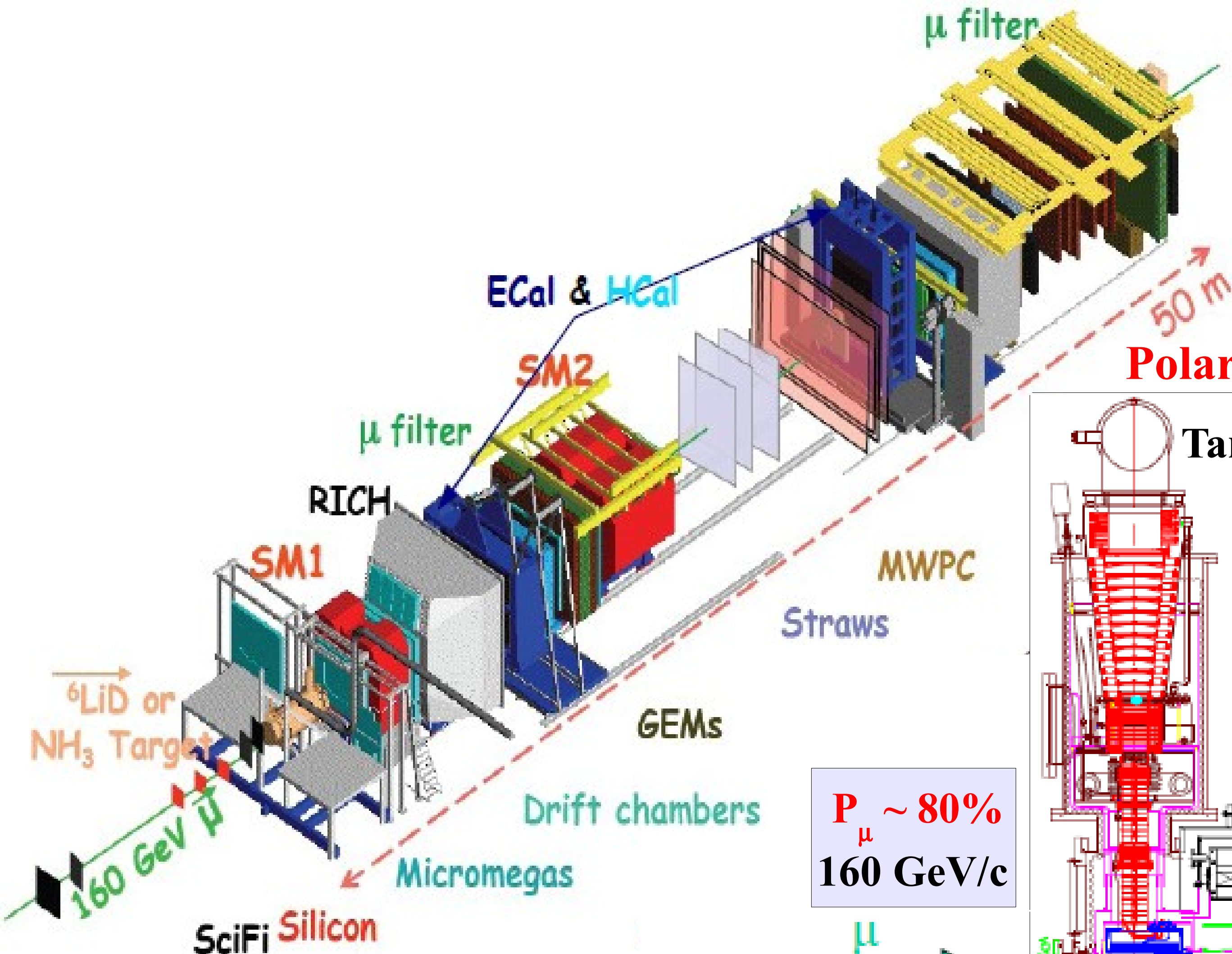
The polarised beam





Naturally polarised muon beam: $P_\mu \sim 80\%$

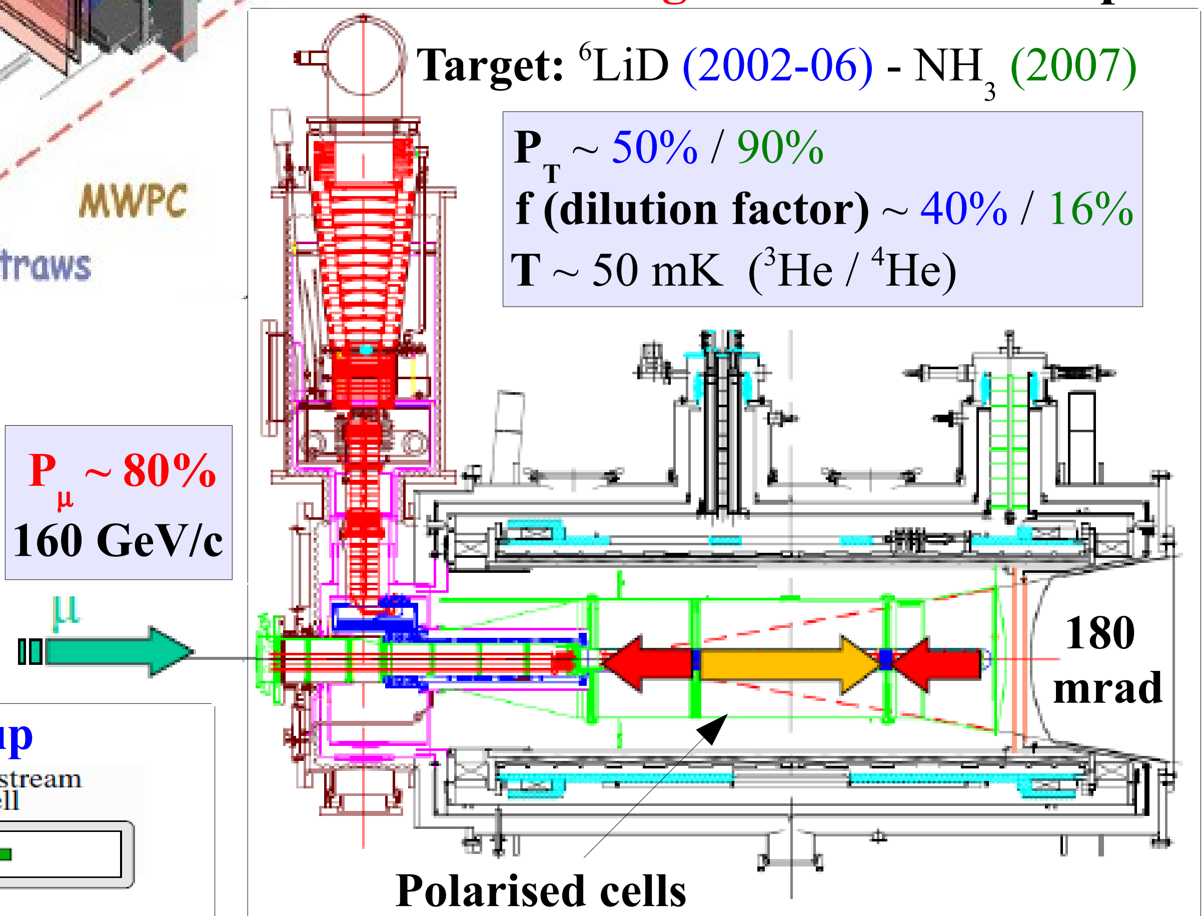
The spectrometer and polarised target



Polarised Target: **2006-2007 setup**

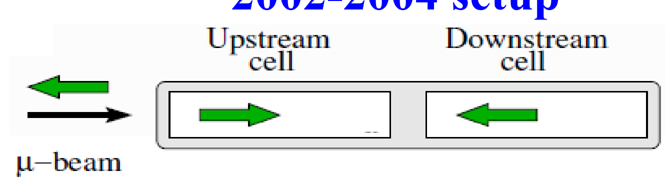
Target: ^{6}LiD (2002-06) - NH$_3$ (2007)

P_T ~ 50% / 90%
f (dilution factor) ~ 40% / 16%
T ~ 50 mK (^{3}He / ^{4}He)



P_μ ~ 80%
160 GeV/c

2002-2004 setup



The Open-Charm analysis

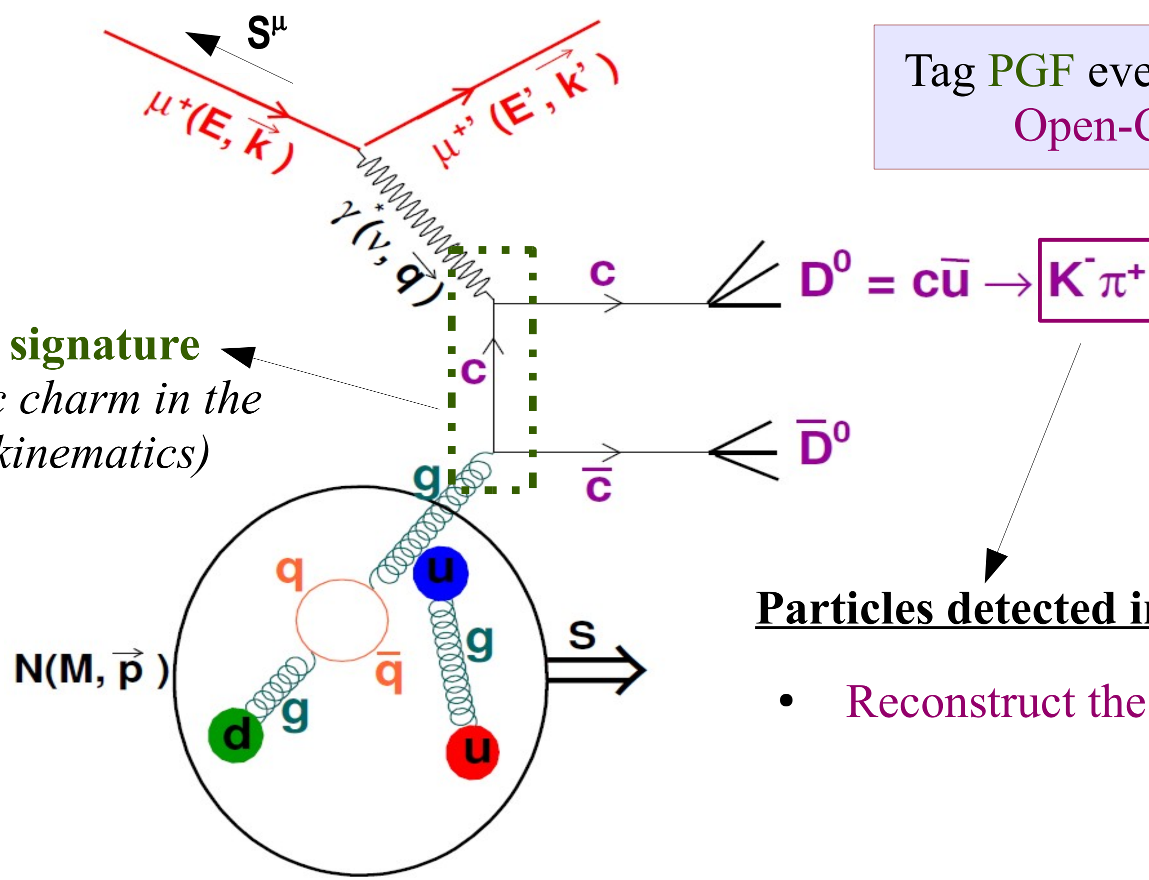
How to tag a polarised gluon?

- In COMPASS, we can probe directly the gluons using the following interaction:

The photon-gluon fusion process *(LO-PGF)*

Tag PGF events via selection of Open-Charm mesons

Clean PGF signature
***(**no intrinsic charm in the COMPASS kinematics)*



<u>Particles detected in the spectrometer</u>:

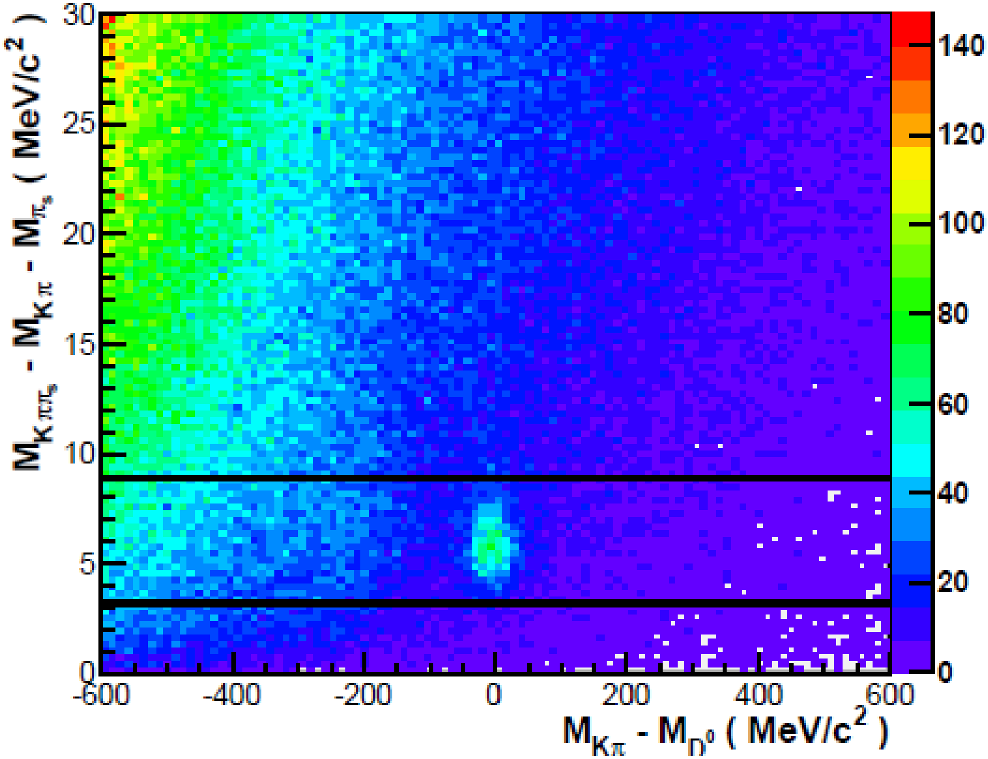
- Reconstruct the D^0 invariant mass!

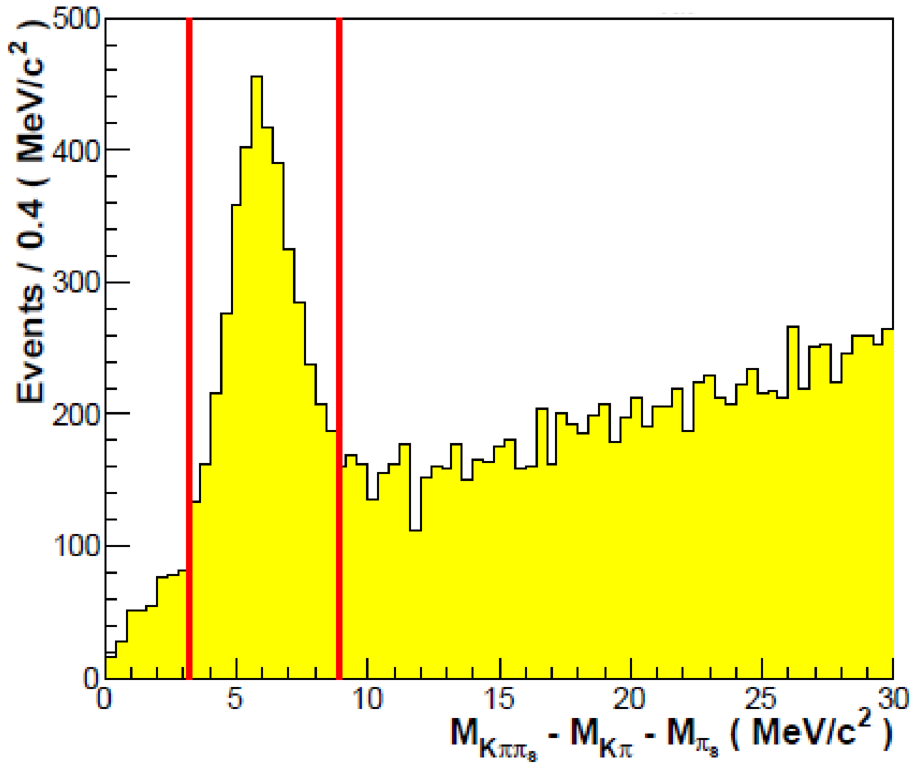
Reconstruction of Open-Charm mesons

- **Events considered** *(resulting from the c-quarks fragmentation)*:
  - $D^0 \to K\pi$ *(BR: 4%)*
  - $D^* \to D^0\pi_{slow}$ *(30% of D^0 are tagged with a D^*)*
    - $D^0 \to K\pi$
    - $D^0 \to K\pi\pi^0$ *(BR: 13%)* ⟶ **not directly reconstructed**
    - $D^0 \to K\pi\pi\pi$ *(BR: 7.5%)*
    - $D^0 \to K_{sub}\pi$ ⟶ **no RICH ID for kaons** *(p(K) < 9 GeV/c)*

- **Selection to reduce the combinatorial background:**
  - **Kinematic cuts:** Z_{D^0} ($= E_{D^0} / E_{\gamma^*}$) and polar angle of kaon in the D^0 center-of-mass *(to reject collinear events with the γ^* direction)*, K and π momentum
  - **RICH identification:** K and π ID + rejection of electrons from the π_{slow} sample
  - Mass cut for the D^* tagged channels ($M^{rec}[\,K\pi\pi_{slow}\,] - M^{rec}[\,K\pi\,] - M[\,\pi\,]$)
  - Use of a Neural Network to improve the purity of the D^0 mass spectra

The mass cut for the D* tagged channels

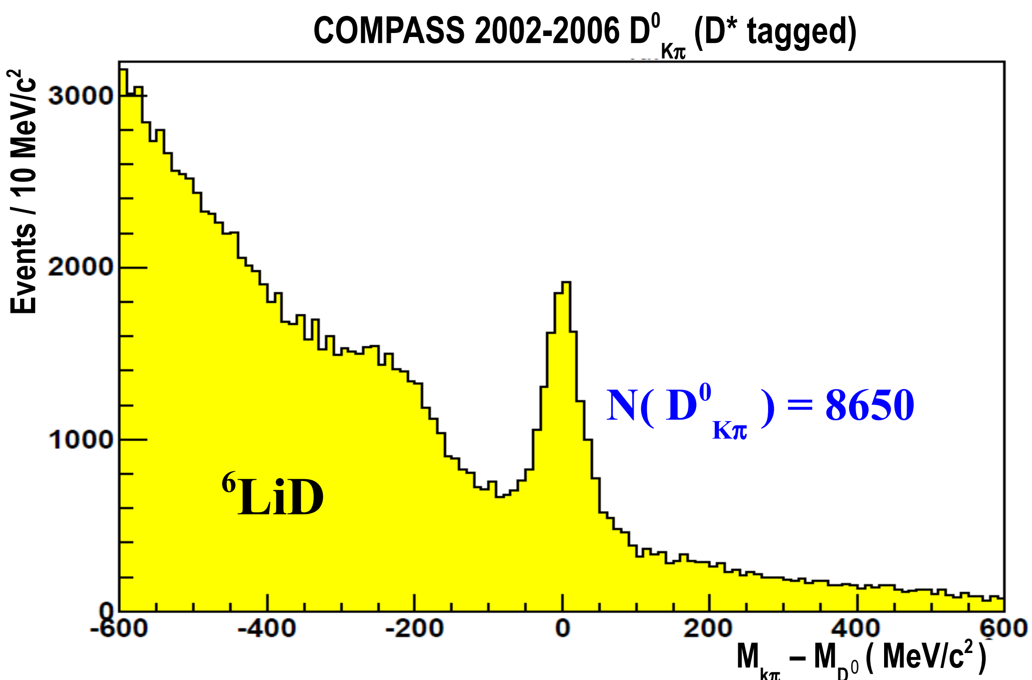


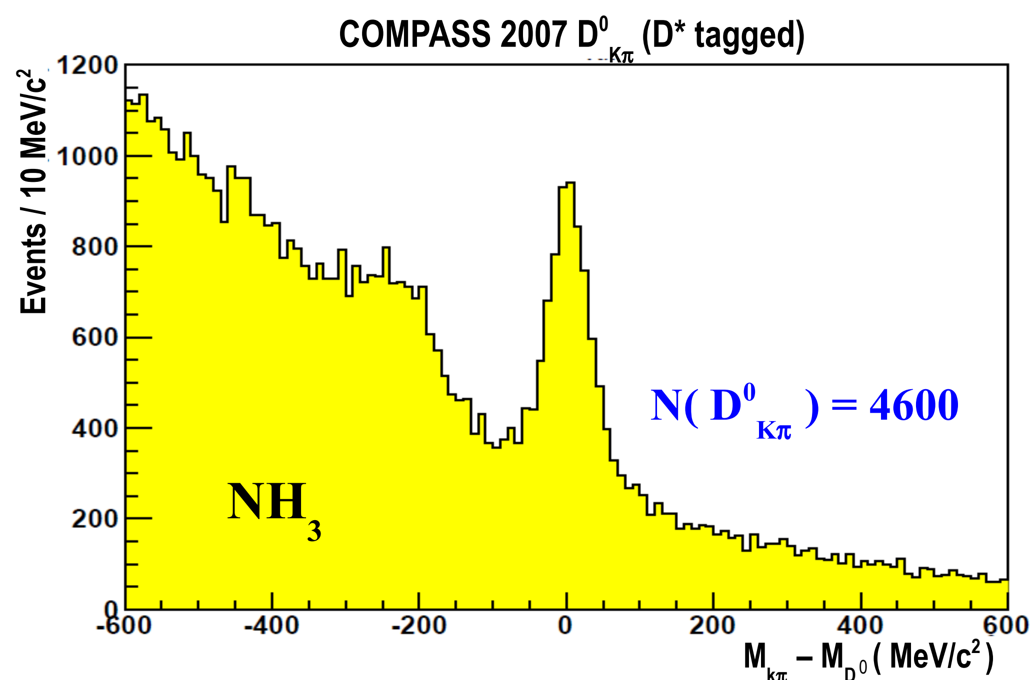


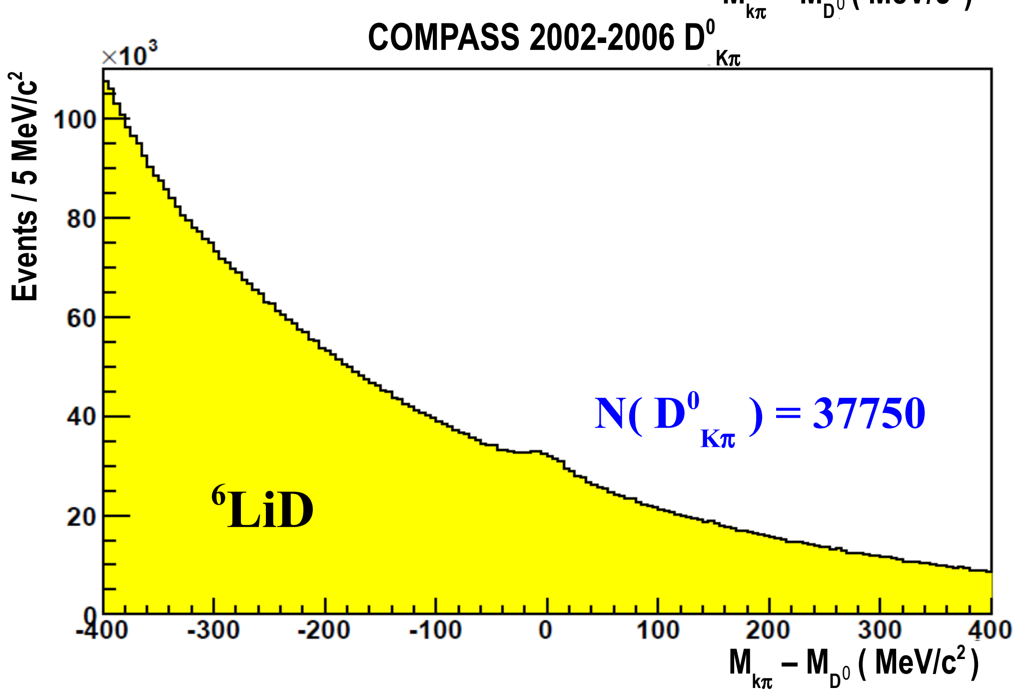
3.2 MeV/c^2 < ($M^{rec}[K\pi\pi_{slow}] - M^{rec}[K\pi] - M[\pi]$) < 8.9 MeV/c^2

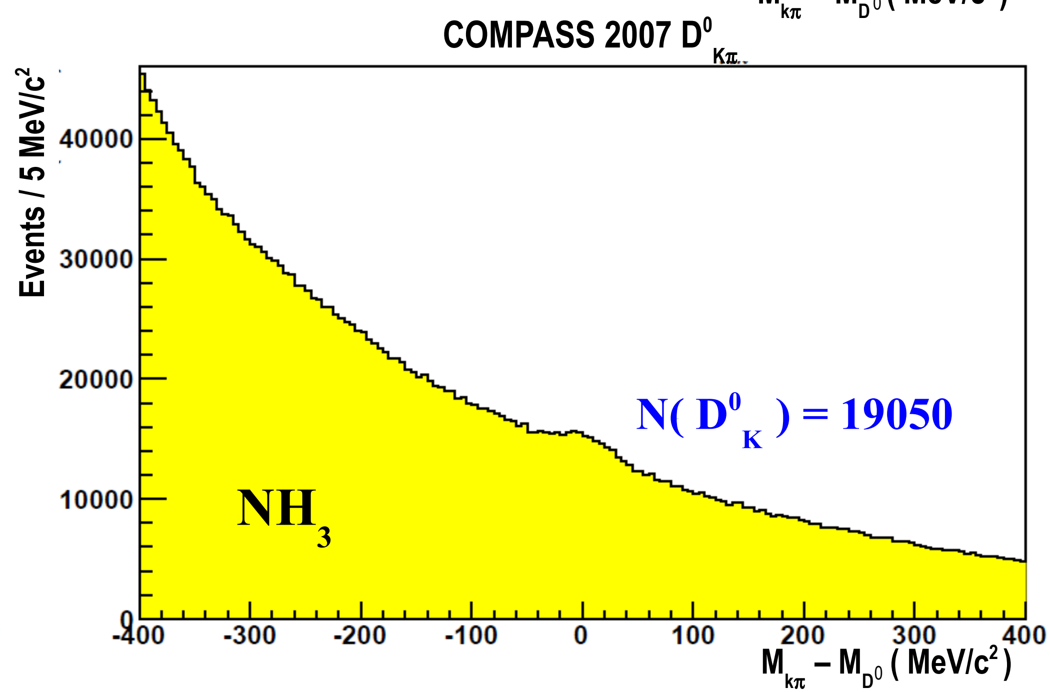
- Improves the Figure-of-Merit (FOM = $N^2_{D^0} / N_{tot}$) of the $D^0_{K\pi}$ resonance by a factor of 3!
- Allows us to reconstruct low-purity channels of low statistics: $D^0_{K\pi\pi^0}$, $D^0_{K\pi\pi\pi}$ and $D^0_{K_{sub}\pi}$

Invariant mass spectrum: $D^0_{K\pi}$ (D* tagged and untagged channels)

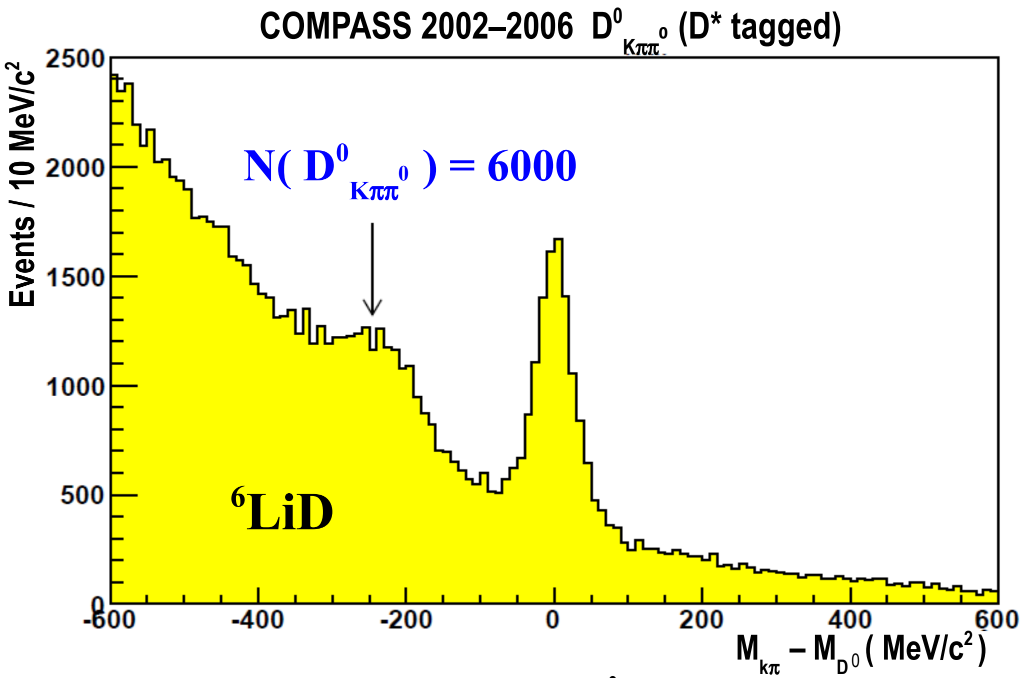


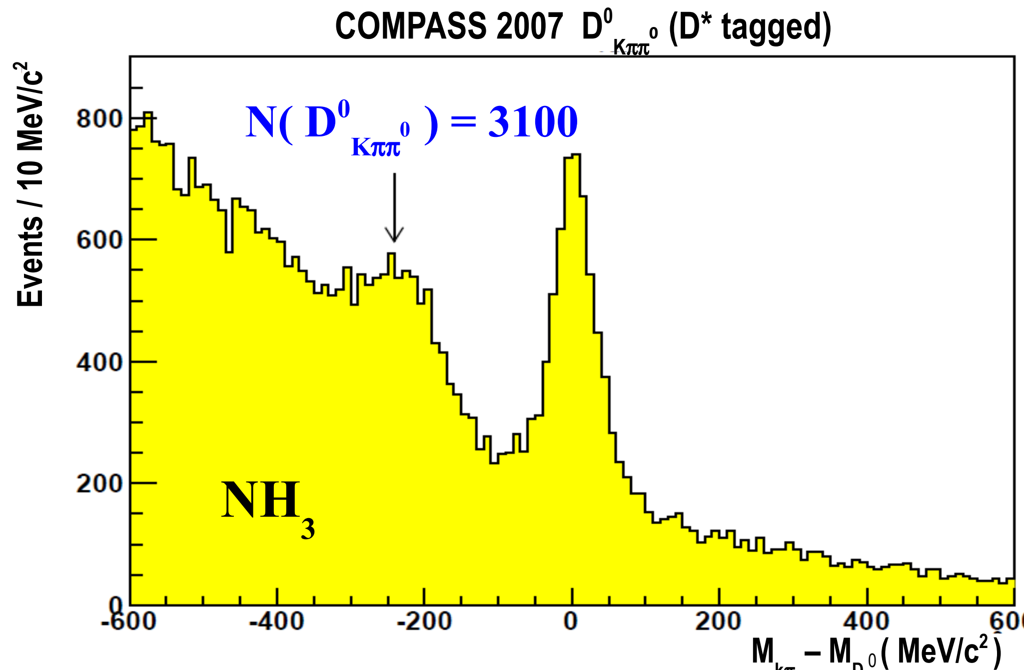


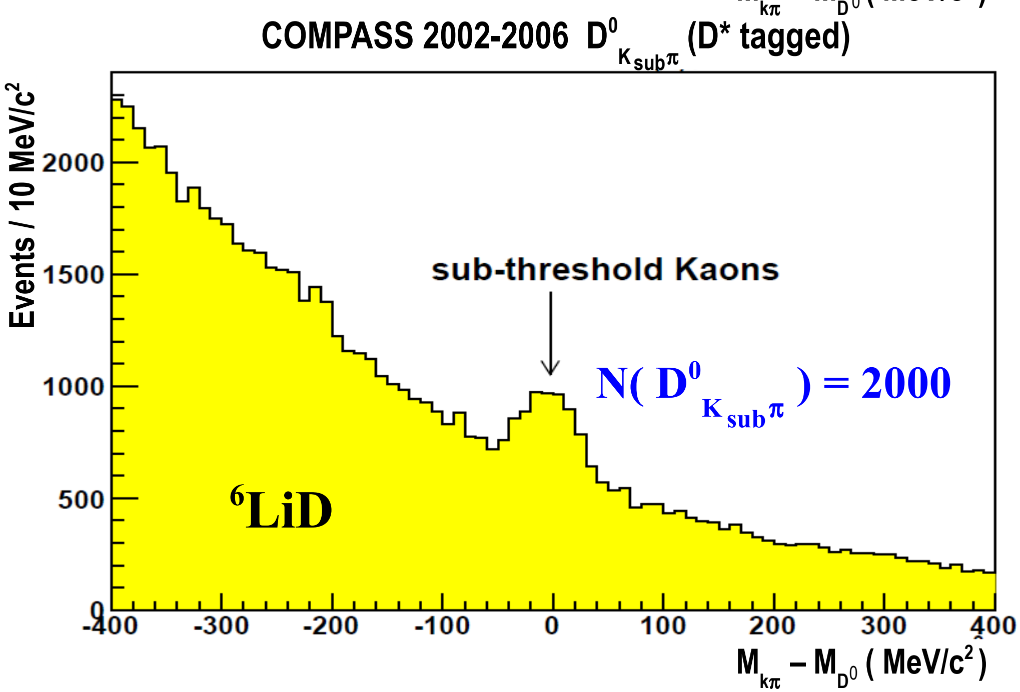


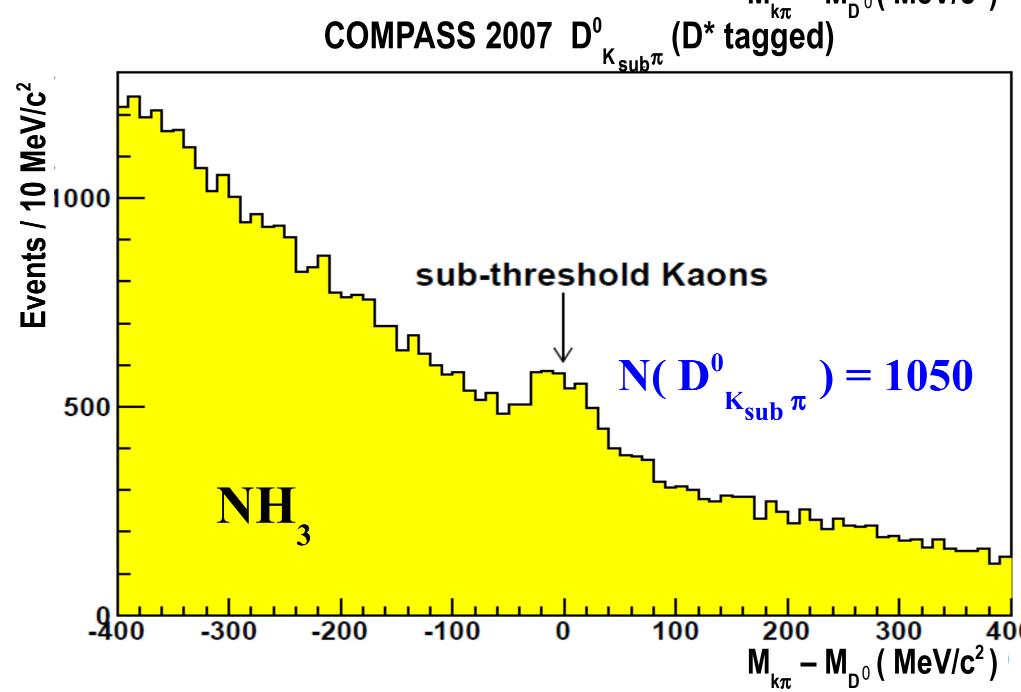


Invariant mass spectrum: $D^0_{K\pi\pi^0}$ and $D^0_{K_{sub}\pi}$ (D* tagged channels)

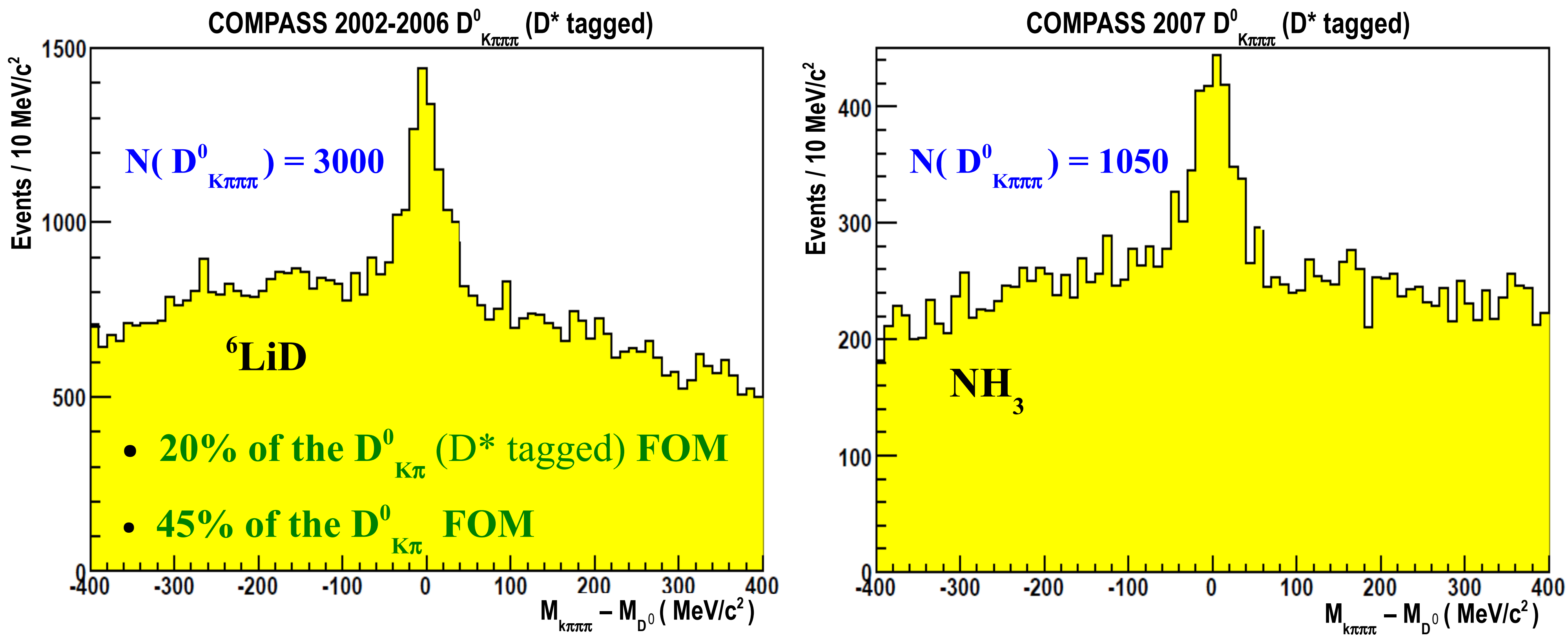








Invariant mass spectrum: $D^0_{K\pi\pi\pi}$ (D* tagged)



Total Number of D^0:

- ^{6}LiD → 57400
- NH_3 → 28850

86250

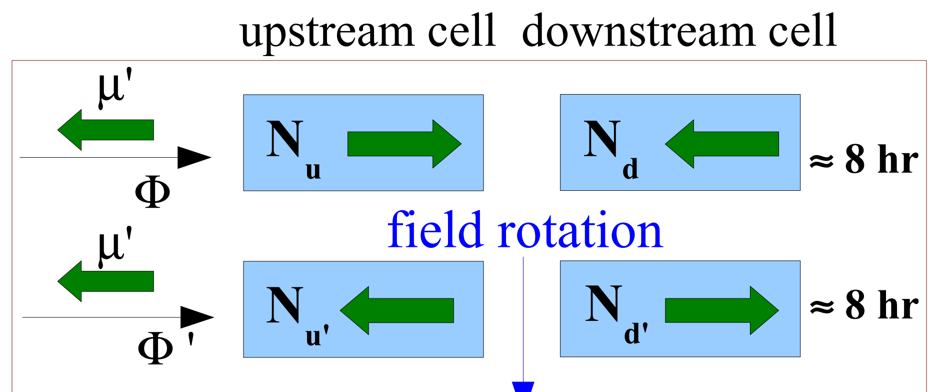
Measuring D^0 asymmetries to extract ΔG

- The number of reconstructed D^0 inside each spin configuration of the target, N_t (t = u, d, u', d'), can be used to extract an Open-Charm asymmetry from the PGF interaction:

Considering $A^{bg} = 0$

$$A^{exp} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N_{d'} - N_{u'}}{N_{u'} + N_{d'}}\right) = f \cdot P_\mu \cdot P_T \cdot \frac{S}{S+B} \cdot A^{\mu,N}$$

Probability of an event to be a D^0



equal acceptance for both spin configurations

- **<u>In LO-QCD</u>, we have for $A^{\mu,N}$:**

$$\boxed{A^{\mu,N} = \langle \hat{a}_{LL} \rangle \frac{\Delta G}{G} \; ; \; \hat{a}_{LL} \equiv \left(\frac{\Delta \hat{\sigma}_{\mu g}}{\hat{\sigma}_{\mu g}}\right) = \frac{\hat{\sigma}^{\leftrightarrows}_{\mu g} - \hat{\sigma}^{\leftleftarrows}_{\mu g}}{\hat{\sigma}^{\rightrightarrows}_{\mu g} + \hat{\sigma}^{\leftleftarrows}_{\mu g}}}$$

- Weighting each event with $\omega = [\, f P_\mu \, S/(S+B)\, a_{LL} \,]$: → **needed for every event**

$$\frac{\Delta G}{G} = \frac{1}{2P_T}\left(\frac{\sum_{i=0}^{N_u}\omega_i - \sum_{i=0}^{N_d}\omega_i}{\sum_{i=0}^{N_u}\omega_i^2 + \sum_{i=0}^{N_d}\omega_i^2} + \frac{\sum_{i=0}^{N_{u'}}\omega_i - \sum_{i=0}^{N_{d'}}\omega_i}{\sum_{i=0}^{N_{u'}}\omega_i^2 + \sum_{i=0}^{N_{d'}}\omega_i^2}\right)$$

<u>statistical gain</u>: $\dfrac{\langle \sum_{i=0}^{N_{tot}} \omega_i^2 \rangle}{\langle \sum_{i=0}^{N_{tot}} \omega_i \rangle^2}$

Open-Charm analysis: Simultaneous extraction of $\Delta G/G$ and A^{bg}

- The relation between the number of reconstructed D^0 and $\Delta G/G$ is given by (<u>for each spin configuration of the target cells</u>):

depolarisation factor

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

acceptance, muon flux, number of target nucleons probability of an event to be a D^0

- Each event contributing to one of 4 equations is weighted with a signal weight, $\omega_S = [f\,P_\mu\,a_{LL}\,S/(S+B)]$, and thereafter the weighted sums of events are taken. This procedure is repeated using a background weight, $\omega_B = [f\,P_\mu D\,B/(S+B)]$, thereby giving rise to a system of:

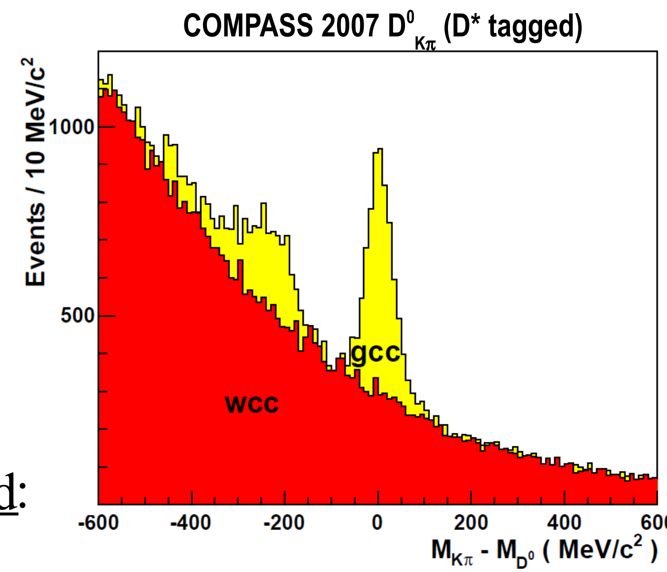
<u>8 equations with 7 unknowns</u>: $\Delta G/G$, A^{bg} + 5 independent $\alpha = (a\phi n)$ factors

The system is solved by a χ^2 minimisation

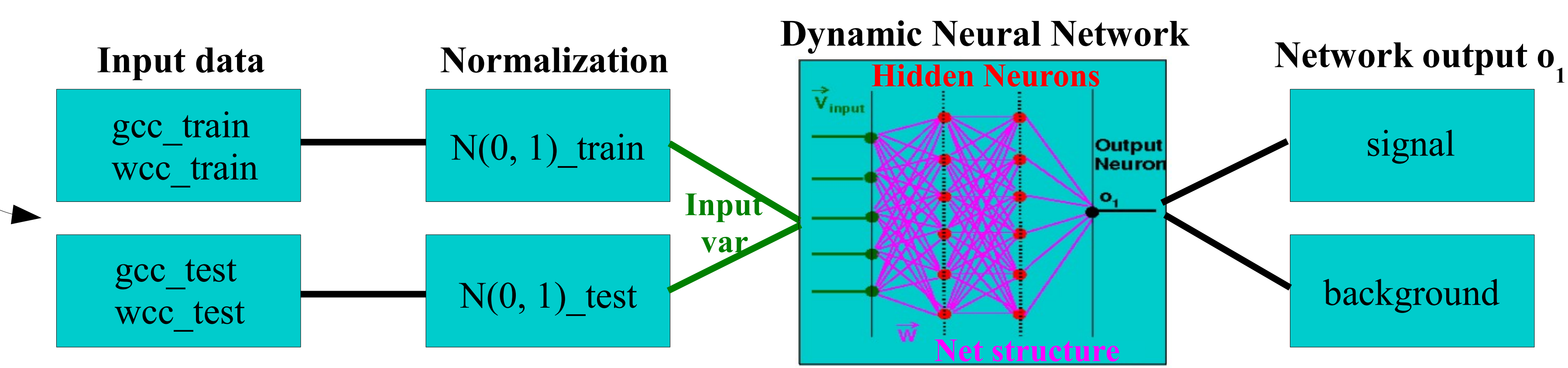
Determination of S/(S+B)

$s/(s+b)_{NN}$: Neural Network (NN) parameterisation

- Two real data samples are compared by a NN, using some kinematic variables as a learning vector:
  - **Signal model** $\rightarrow$ **gcc** $= K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+$ *(D^0 spectrum)*
  - **Background model** $\rightarrow$ **wcc** $= K^+\pi^+\pi_s^- + K^-\pi^-\pi_s^+$

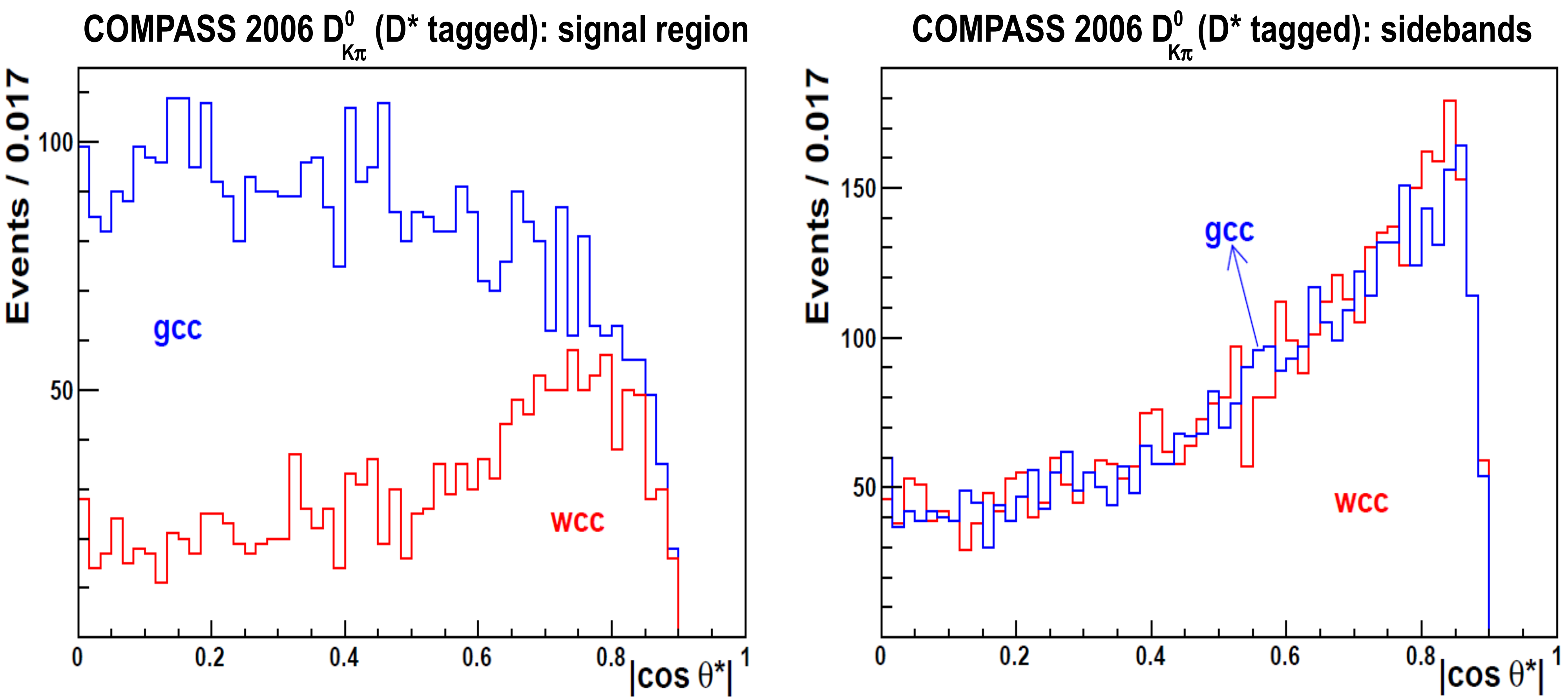


- To ensure an unbiased parameterisation, 2 data sets are used:
  - If the minimisation of errors in the train & test (control sample) sets begin to diverge during the learning process, the NN changes its strategy: some neurons can be killed and others can be born
- D^0 probabilities are computed, for every gcc event, using the resulting multidimensional parameterization *(weights of each variable-neuron connection)*: $f(o_1) = [s/(s+b)]_{NN}$



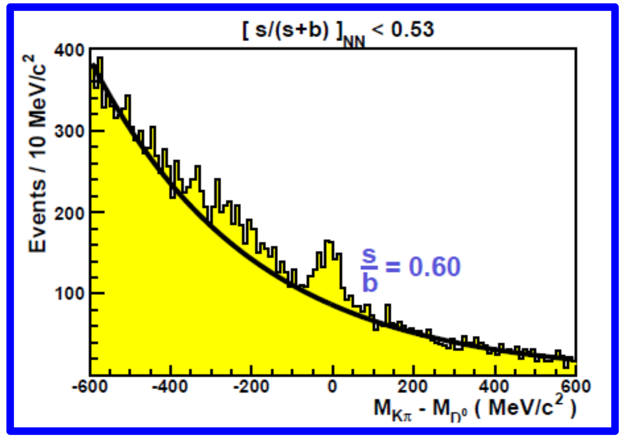
Example of a good kinematic variable to use in the training of the Neural Network

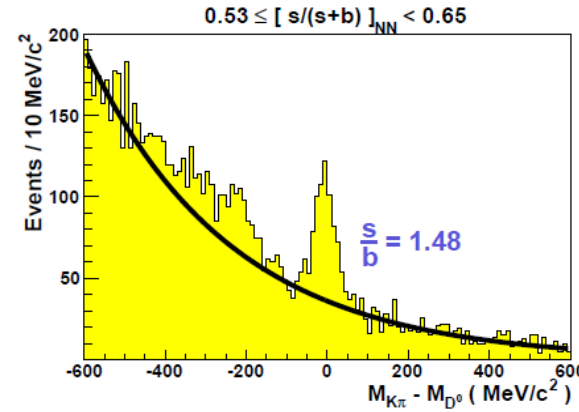
- Cosine of the polar angle of kaon in the D^0 center-of-mass relative to the D^0 momentum:



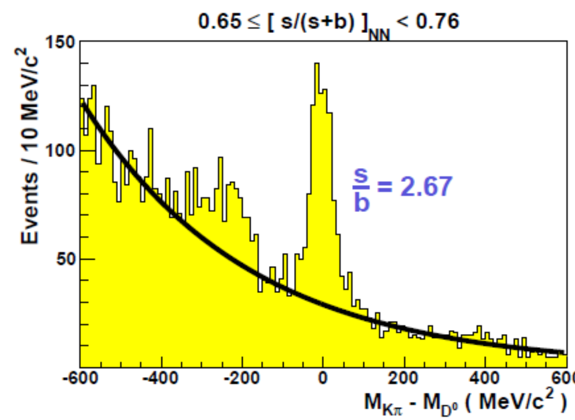
s/(s+b): Obtaining final probabilities for a D^0 candidate

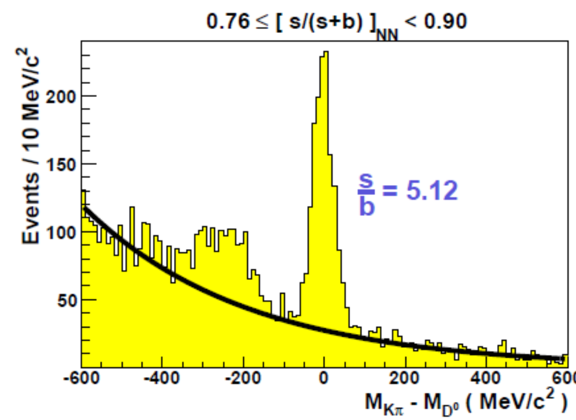
- **Events with small $[s/(s+b)]_{NN}$**
  - Mostly combinatorial background is selected



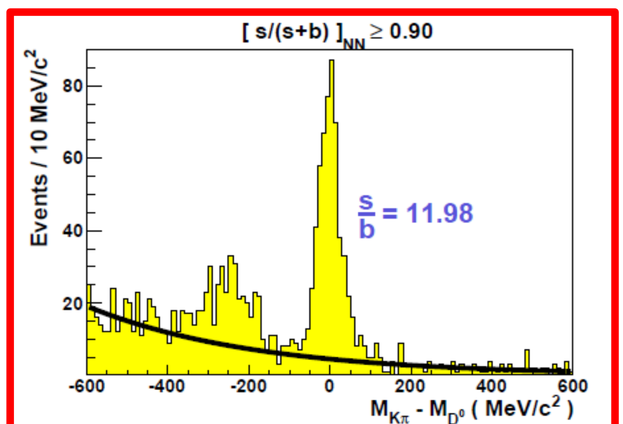


<u>s/(s+b) is obtained from a fit to these spectra</u> *(correcting all events with the corresponding values of* ***[s/(s+b)]***$_{NN}$ *)*





- **Events with large $[s/(s+b)]_{NN}$**
  - Mostly Open-Charm events are selected



$$\delta\left(\frac{\Delta G}{G}\right) = \frac{1}{FOM}$$

Determination of a_{LL} at LO in QCD

The muon-gluon analysing power

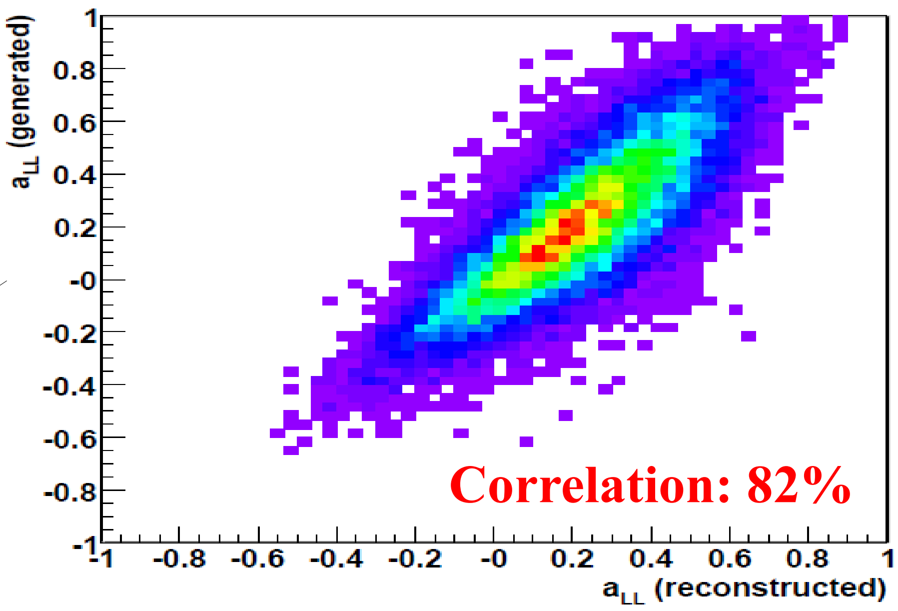
- a_{LL} is dependent on the full knowledge of the partonic kinematics:

$$a_{LL} = \left\langle \frac{\Delta \hat{\sigma}_{\mu g}}{\hat{\sigma}_{\mu g}}(y, Q^2, x_g, z_C, \phi) \right\rangle$$

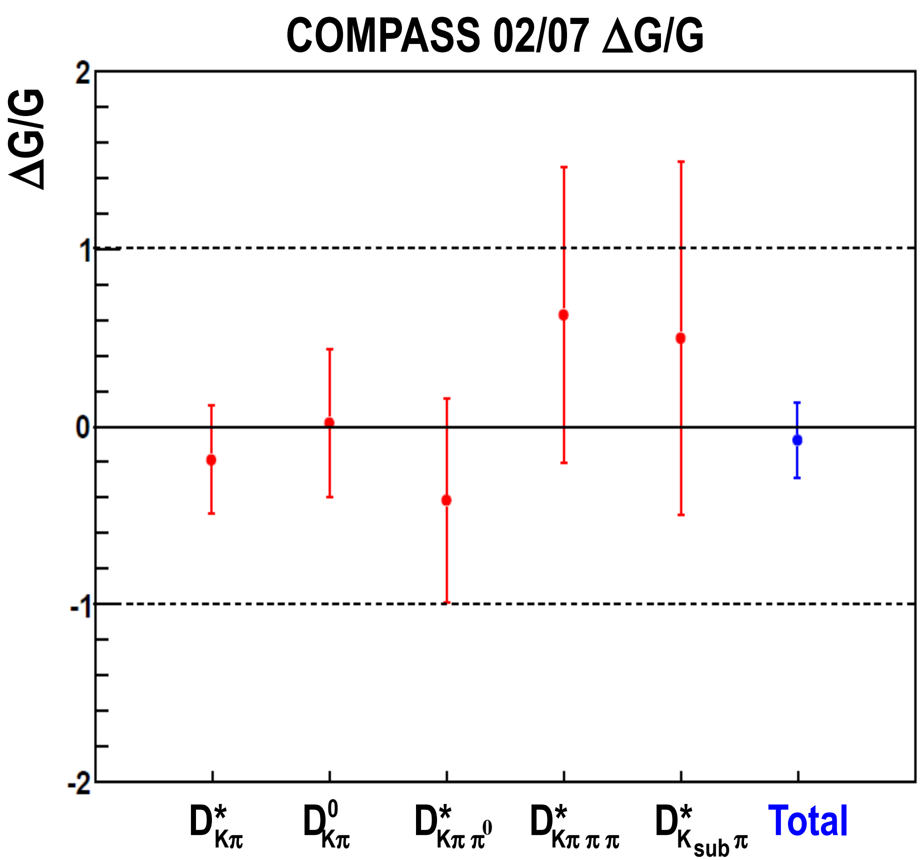
Can't be experimentally obtained: only one charmed meson is reconstructed

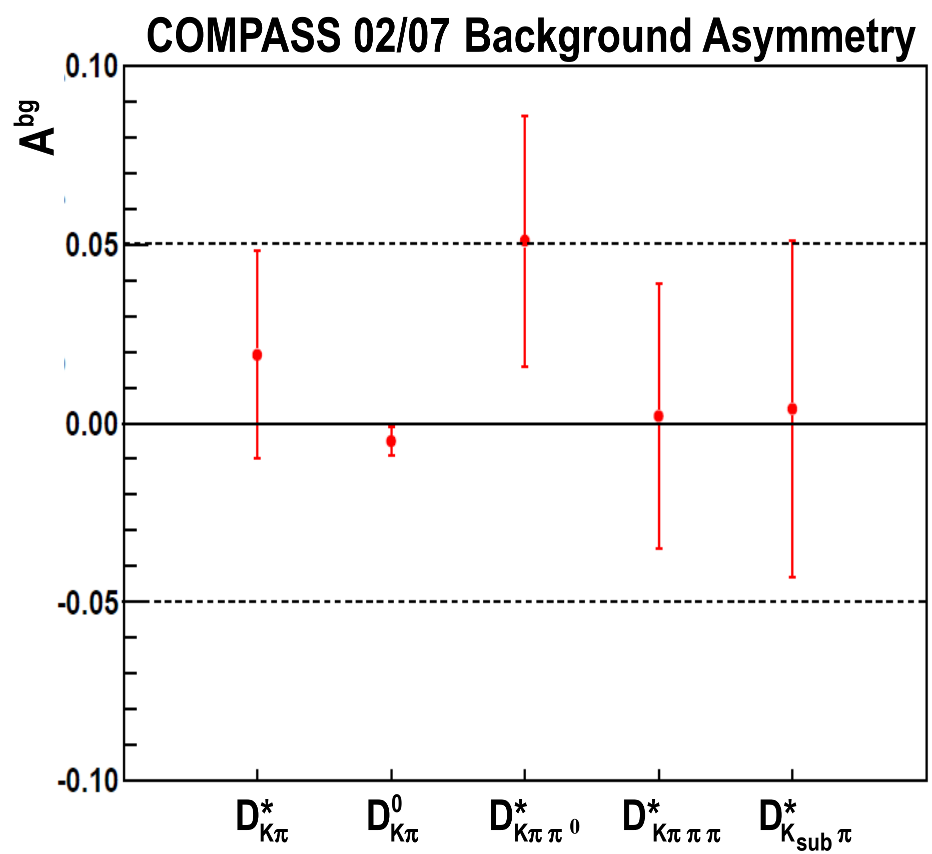
- a_{LL} is determined from a Monte-Carlo simulation of the Open-Charm production in the COMPASS experiment, using the AROMA generator without parton-showers. Thereafter, the obtained values are used as an input for a NN parameterisation on some experimentally accessible kinematical variables: y, x_{Bj}, Q^2, z_D and p_T

Parameterised a_{LL} shows a strong correlation with the generated one



Open-Charm results at LO in QCD

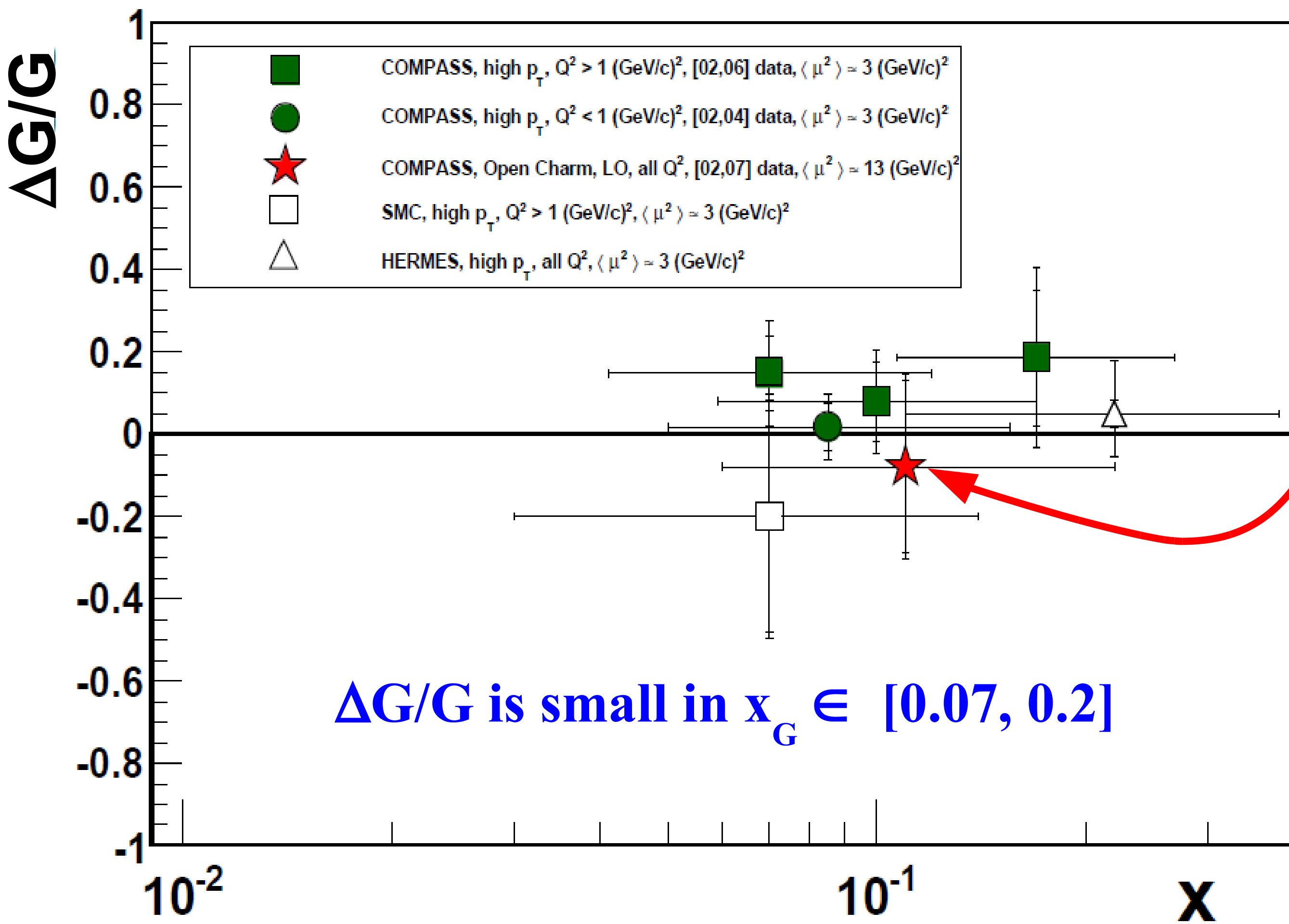




$$\frac{\Delta G}{G} = -0.08 \pm 0.21(\mathbf{stat}) \pm 0.09(\mathbf{syst}) \quad @\langle x_g \rangle = 0.11^{+0.11}_{-0.05}, \ \langle \mu^2 \rangle = 13(\mathrm{GeV}/c)^2$$

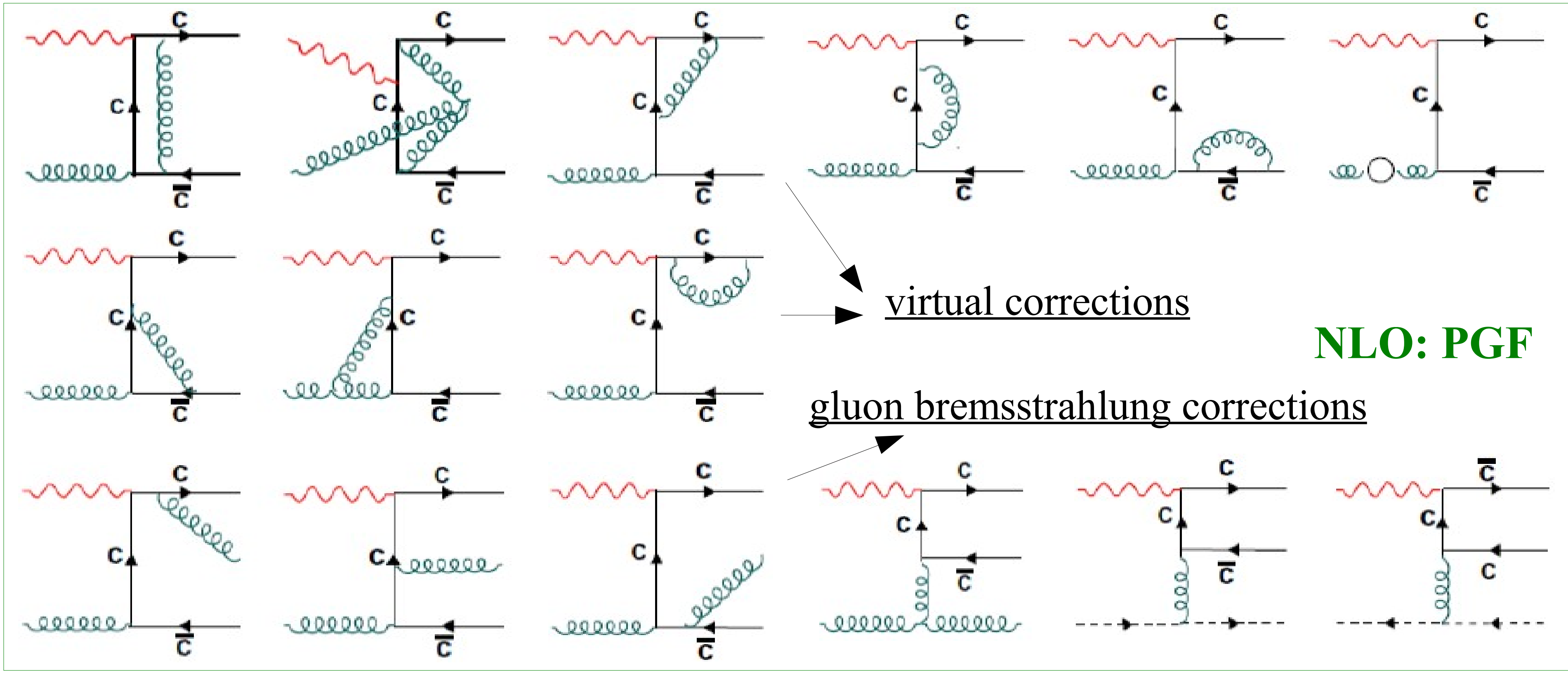
World measurements of ΔG/G at LO in QCD

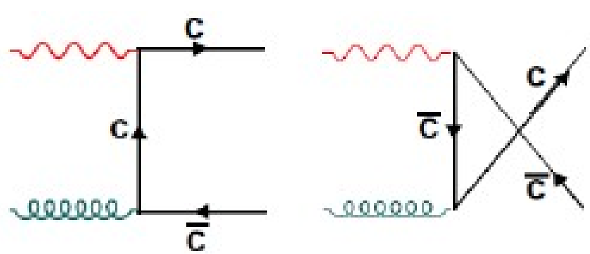
- **The gluon polarisation was obtained directly from the data, at LO, and was found to be <u>compatible with zero</u>**



Determination of $\Delta G/G$ at NLO in QCD

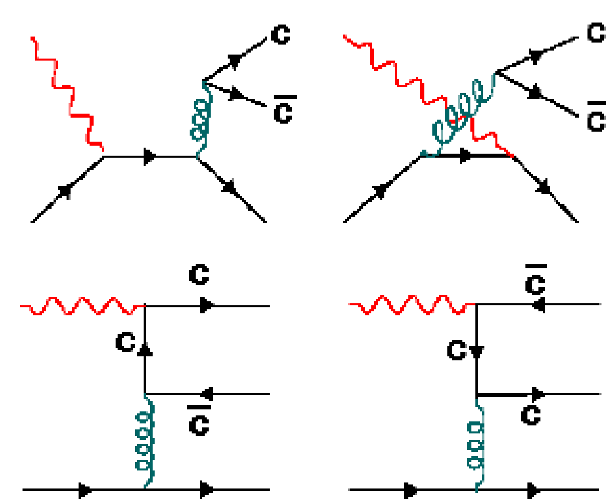
NLO corrections to the analysing power a_{LL}





LO: PGF

NLO: bg



Procedure for NLO calculations

- The AROMA generator with parton-shower-on (PS-on) describes the COMPASS data very well. Therefore, the concept of PS was used to simulate the needed phase space for NLO corrections:

  – The energy of parton-showers defines the upper limit of integration over the energy of the unobserved gluon/quark, in the NLO emission process

This procedure guarantees a correct infra-red divergence cancellation. Consequently, a_{LL} is calculated event-by-event from theoretical formulas *(as in LO case)*

- The following photon-nucleon asymmetries were used to determine $\Delta G/G$:

$$A^{\gamma N} = \left(\frac{a_{LL}^{PGF}(NLO)}{D} \frac{\Delta G}{G} + \boxed{\frac{a_{LL}^{q}(NLO)}{D} A_1} \right)$$

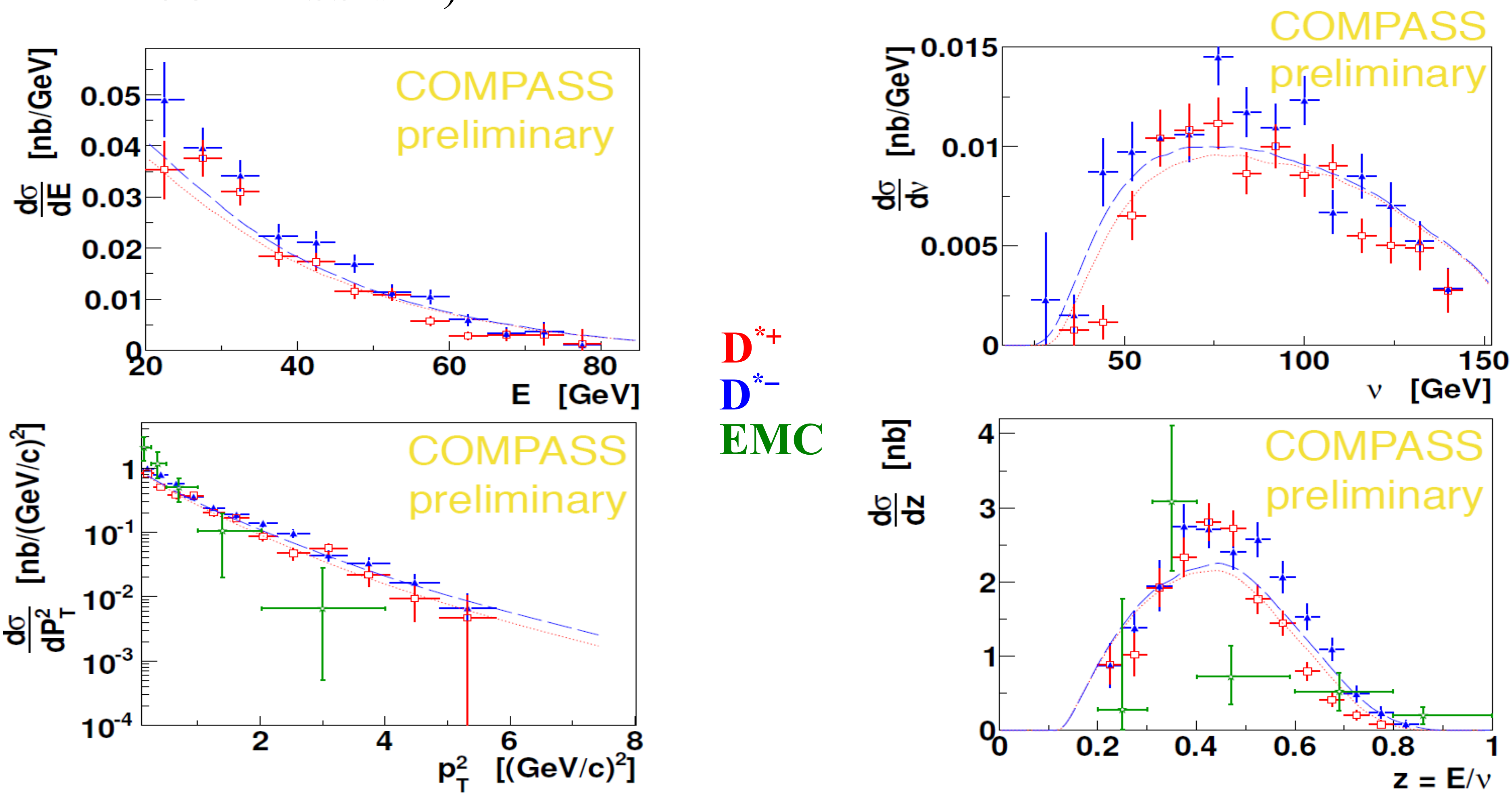
The replacement of a_{LL} by D in ω_S implies the extraction of $A^{\gamma N}$ instead of $\Delta G/G$

► **Independent of theoretical interpretations** $\rightarrow$ good for global fits of ΔG

- The quantity A_1 belonging to the light-quark correction, A_{corr}, is taken directly from data

AROMA with PS-ON versus COMPASS data

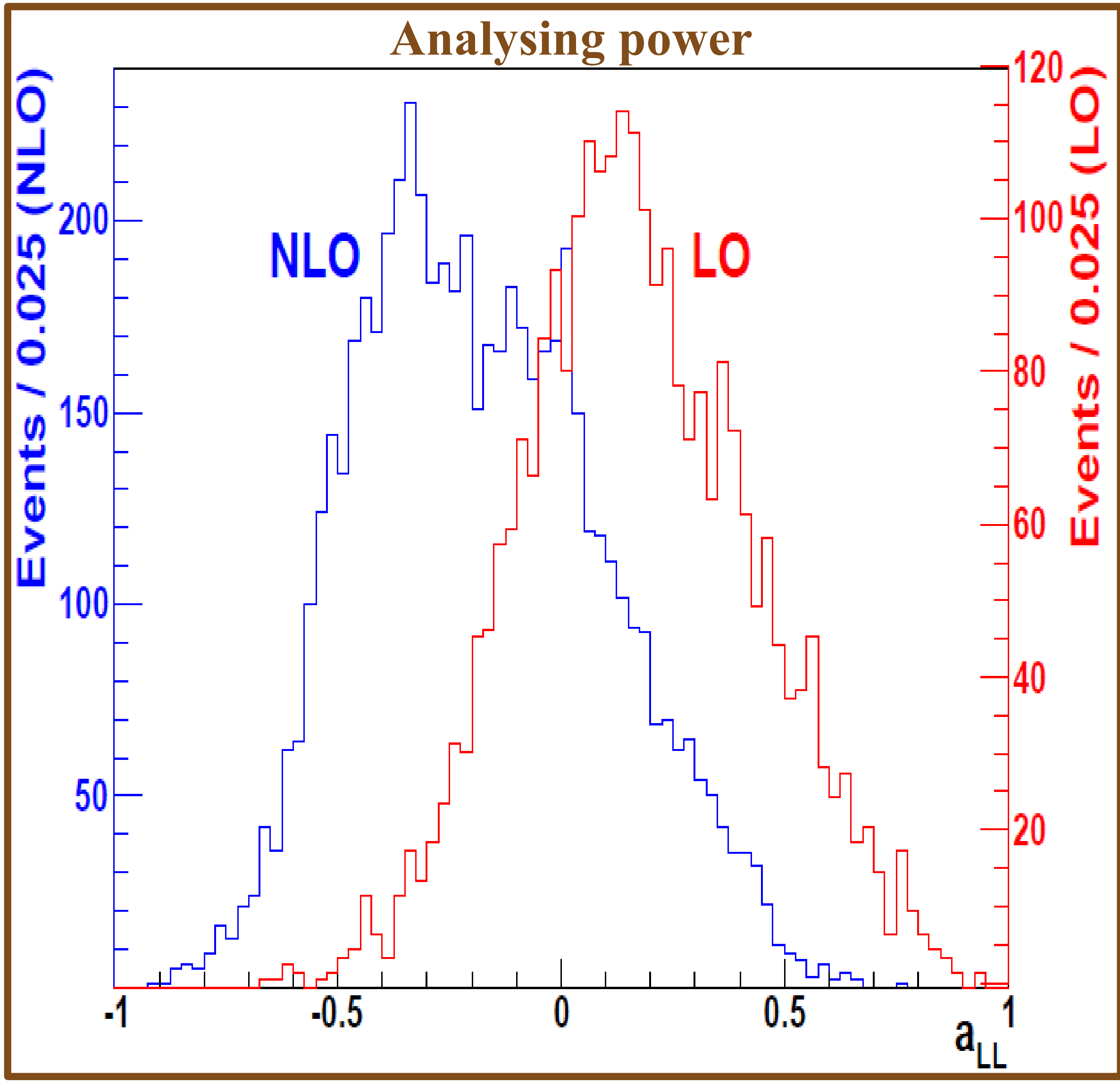
- **Differential cross section for D* meson production** ($D^0_{K\pi}$(2004) from D^{*+} and D^{*-} COMPASS data)**:**

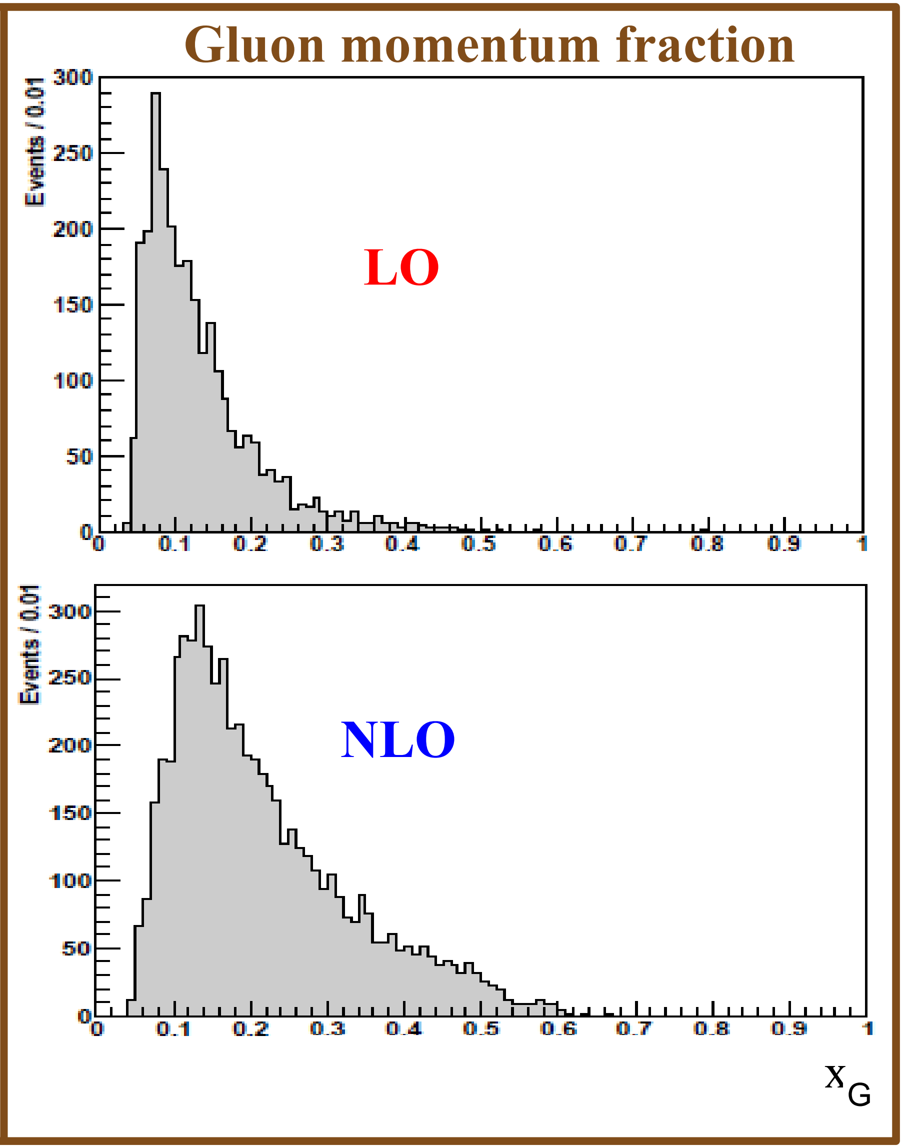


$\sigma(D^{*\pm}) = 1.8 \pm 0.4$ nb

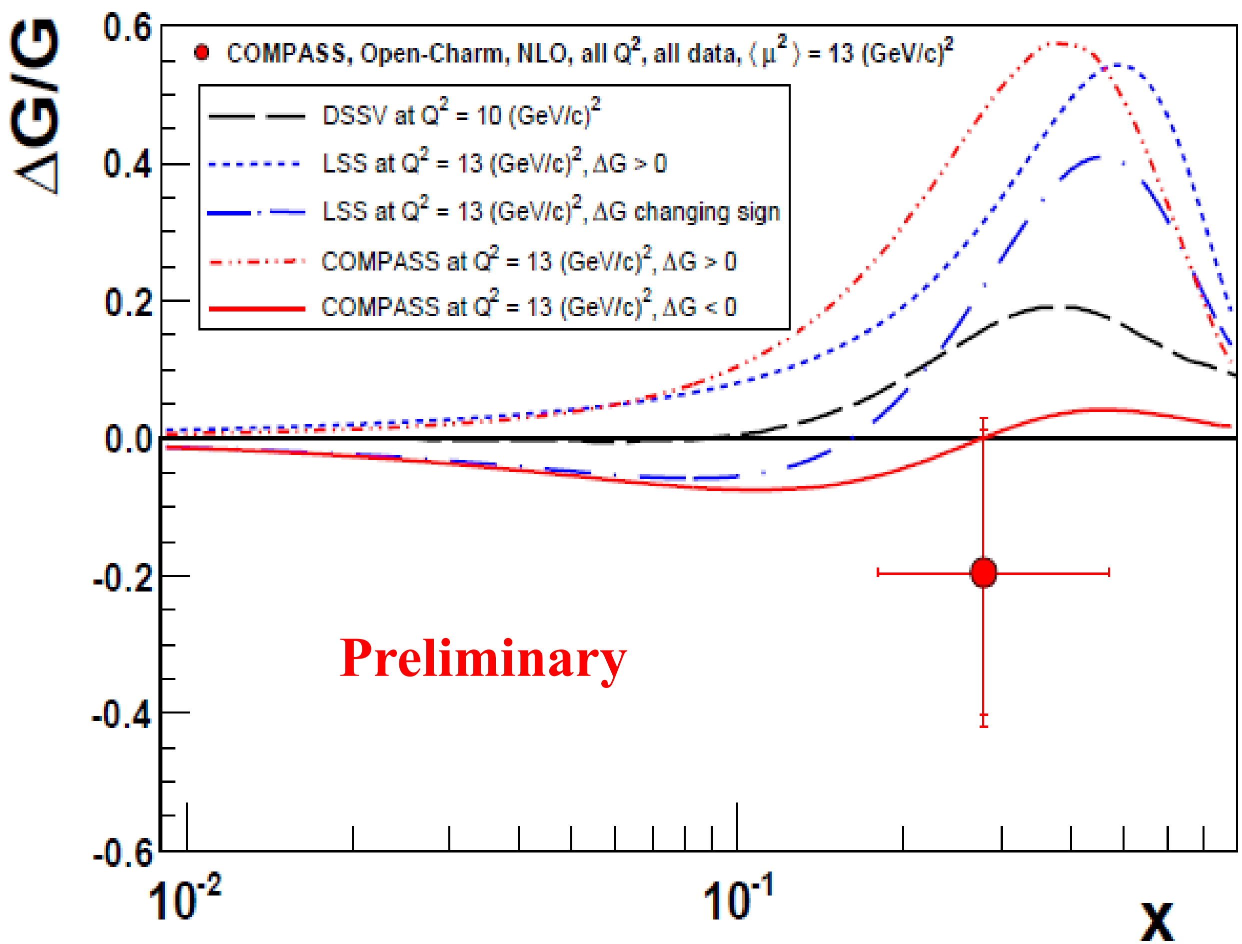
within 20 GeV < E_D < 80 GeV

Distributions of a_{LL} and x_G at LO and NLO in QCD





$\Delta G/G$ result at NLO in QCD $\rightarrow$ first world measurement



$$\frac{\Delta G}{G} = -0.20 \pm 0.21\ (\mathbf{stat}) \pm 0.09\ (\mathbf{syst}) \quad @\langle x_G \rangle = 0.28^{+0.19}_{-0.10}, \quad \langle \mu^2 \rangle = 13\,(\mathrm{GeV}/c)^2$$

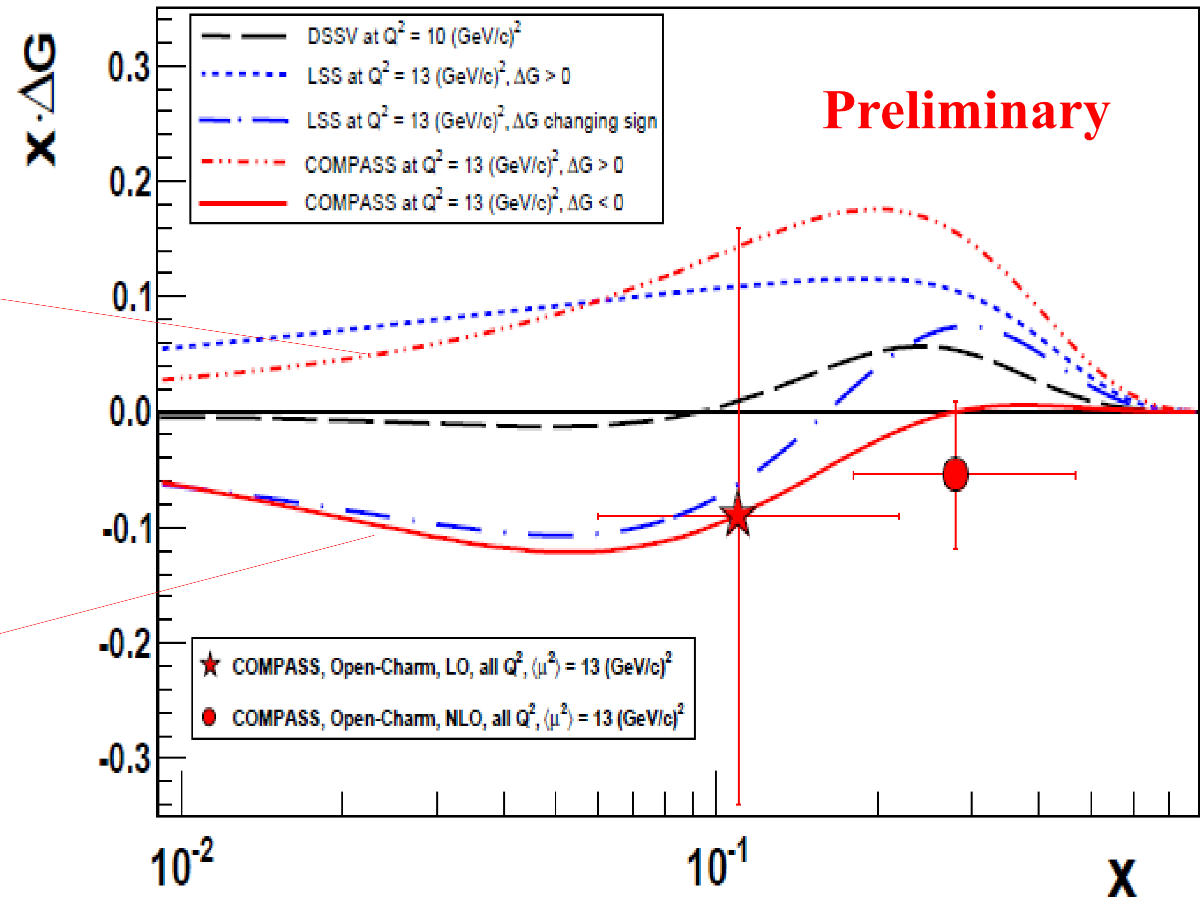
Only experimental: theoretical uncertainties associated with a_{LL} are still under study!

Open-Charm results for xΔG

- Using the LO and NLO parameterisations of xG corresponding to the ones used in the calculations of a_{LL}, we obtain the following results from $\Delta G/G$ (the comparison of the LO point with the QCD fits is justified by xG(LO) ≈ xG(NLO)):

$$\int_0^1 \Delta\mathbf{G}dx = 0.27 \pm 0.09$$

$$\int_0^1 \Delta\mathbf{G}dx = -0.34 \pm 0.12$$



SPARES

Systematic errors

What has been checked?

- S/(S+B)
- a_{LL} *(Monte Carlo + NN stability)*
- Beam Polarisation
- Target Polarisation
- Dilution Factor
- False Asymmetries *(FA)*
- Assumption on $\left\langle \frac{\Delta G}{G} \right\rangle^{\omega_S} \approx \left\langle \frac{\Delta G}{G} \right\rangle^{\omega_B}$

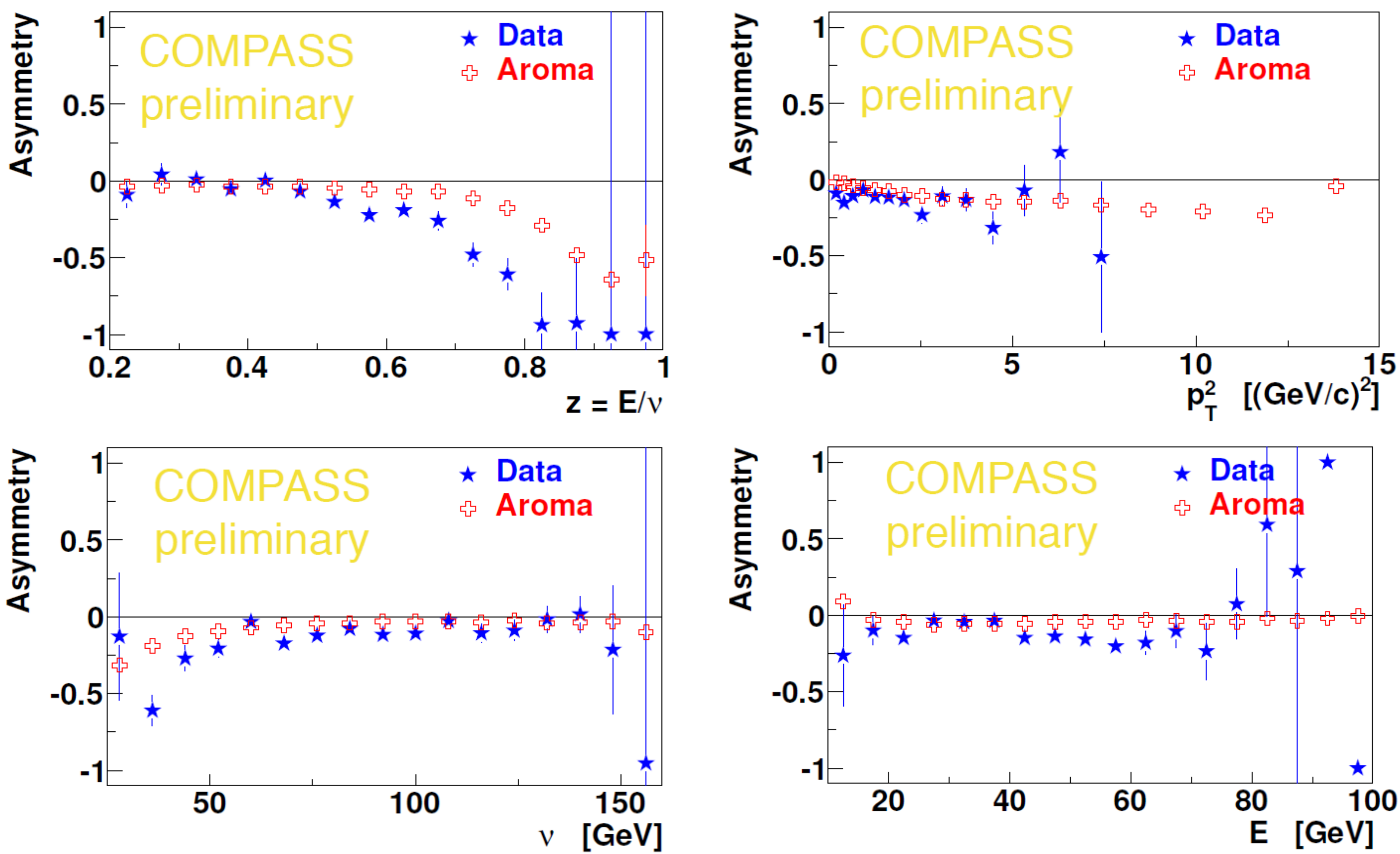
	LO	NLO
$\delta(\Delta G/G)_{S/(S+B)}$	0.022	0.031
$\delta(\Delta G/G)_{a_{LL}}$	0.025	???
$\delta(\Delta G/G)_{P_\mu}$	0.015	0.021
$\delta(\Delta G/G)_{P_t}$	0.015	0.021
$\delta(\Delta G/G)_{f}$	0.006	0.008
$\delta(\Delta G/G)_{FA}$	0.080	0.080
$\delta(\Delta G/G)_{A_S^{\omega_S} = A_S^{\omega_B}}$	0.025	0.025
Total	0.094	???

Results for $A^{\gamma N}$(PGF)

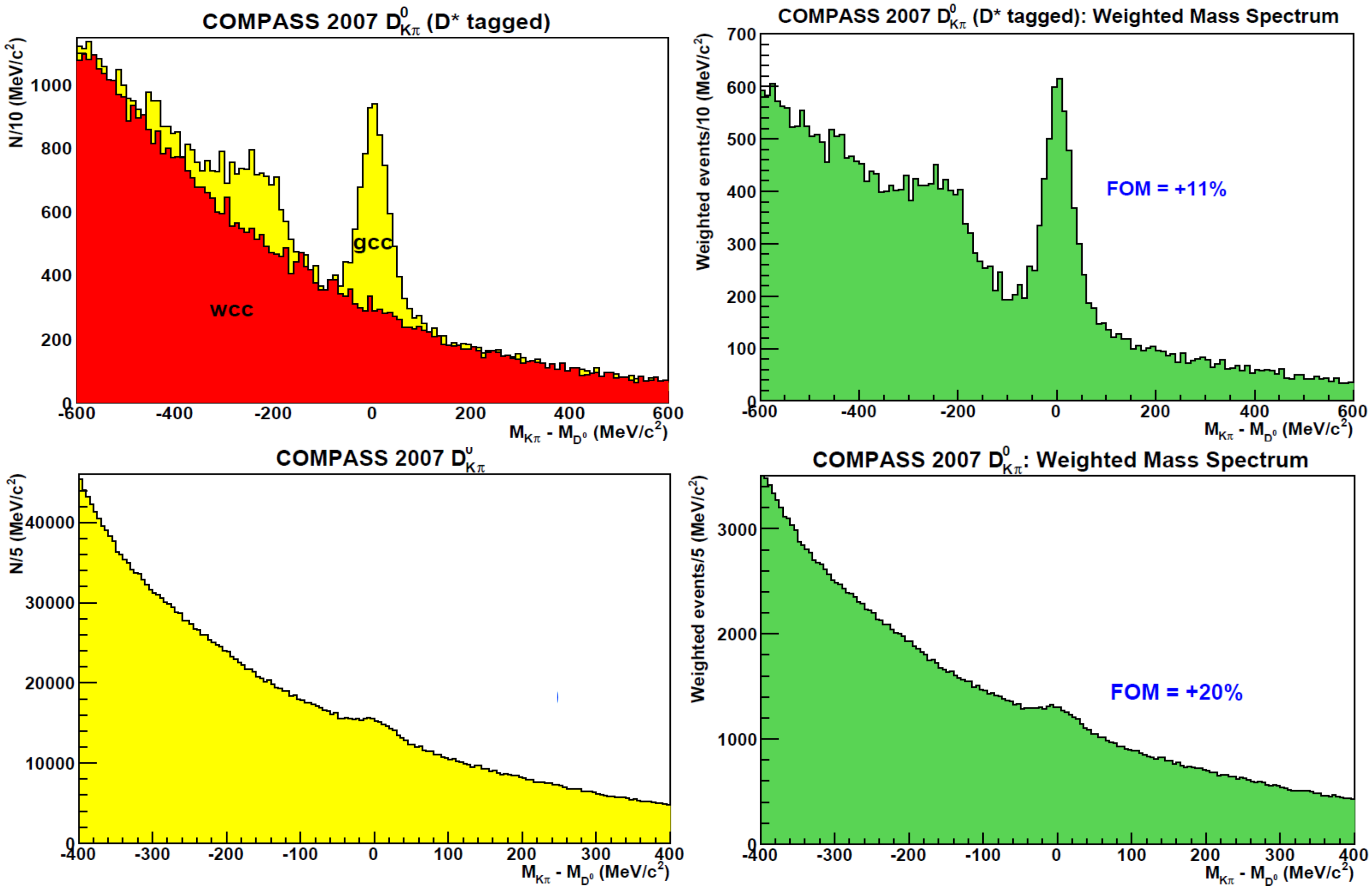
Bins		$D^0 \to K\pi$ samples			$D^0 \to K\pi\pi^0$ sample			$D^0 \to K\pi\pi\pi$ sample		
p_T (D^0) (GeV/c)	E (D^0) (GeV)	$A^{\gamma N}$	a_{LL}^{PGF}/D	A_{corr}	$A^{\gamma N}$	a_{LL}^{PGF}/D	A_{corr}	$A^{\gamma N}$	a_{LL}^{PGF}/D	A_{corr}
[0, 0.3[	[0, 30[	-0.90±0.63	0.00	0.01	-0.63±1.29	-0.11	0.01	7.03±4.74	-0.09	0.01
	[30, 50[	-0.19±0.48	-0.06	0.01	0.27±1,17	-0.08	0.01	-2.05±1.10	-0.08	0.01
	> 50	0.07±0.68	-0.12	0.02	-2.55±2.00	-0.11	0.02	0.17±1.83	-0.09	0.01
[0.3,0.7[	[0, 30[	-0.18±0.37	-0.08	0.01	-0.24±0.80	-0.17	0.01	-0.59±1.74	-0.10	0.02
	[30, 50[	0.10±0.26	-0.19	0.02	0.49±0.69	-0.23	0.02	1.00±0.54	-0.20	0.02
	> 50	-0.04±0.36	-0.22	0.02	-1.28±1.03	-0.18	0.02	-1.75±0.84	-0.21	0.02
[0.7,1.0[	[0, 30[	-0.42±0.44	-0.26	0.01	0.55±0.95	-0.29	0.02	2.91±2.61	-0.19	0.01
	[30, 50[	-0.36±0.29	-0.29	0.01	-0.53±0.76	-0.32	0.02	1.42±0.57	-0.31	0.02
	> 50	1.49±0.42	-0.33	0.03	-0.17±1.00	-0.36	0.03	1.69±0.81	-0.32	0.03
[1.0,1.5[	[0, 30[	-0.30±0.35	-0.35	0.01	1.35±0.86	-0.40	0.02	-1.89±2.64	-0.36	0.02
	[30, 50[	0.13±0.23	-0.40	0.02	-0.11±0.51	-0.44	0.03	-0.45±0.51	-0.41	0.02
	> 50	-0.20±0.33	-0.43	0.03	-0.05±0.78	-0.42	0.04	1.06±0.66	-0.45	0.03
> 1.5	[0, 30[	0.38±0.49	-0.49	0.02	-0.19±1.14	-0.52	0.02	1.64±3.52	-0.49	0.03
	[30, 50[	-0.00±0.25	-0.53	0.03	-0.23±0.51	-0.50	0.04	0.44±0.68	-0.54	0.03
	> 50	0.36±0.33	-0.53	0.04	0.26±0.90	-0.49	0.05	0.08±0.63	-0.54	0.05

D^{*+}/D^{*-} asymmetry:

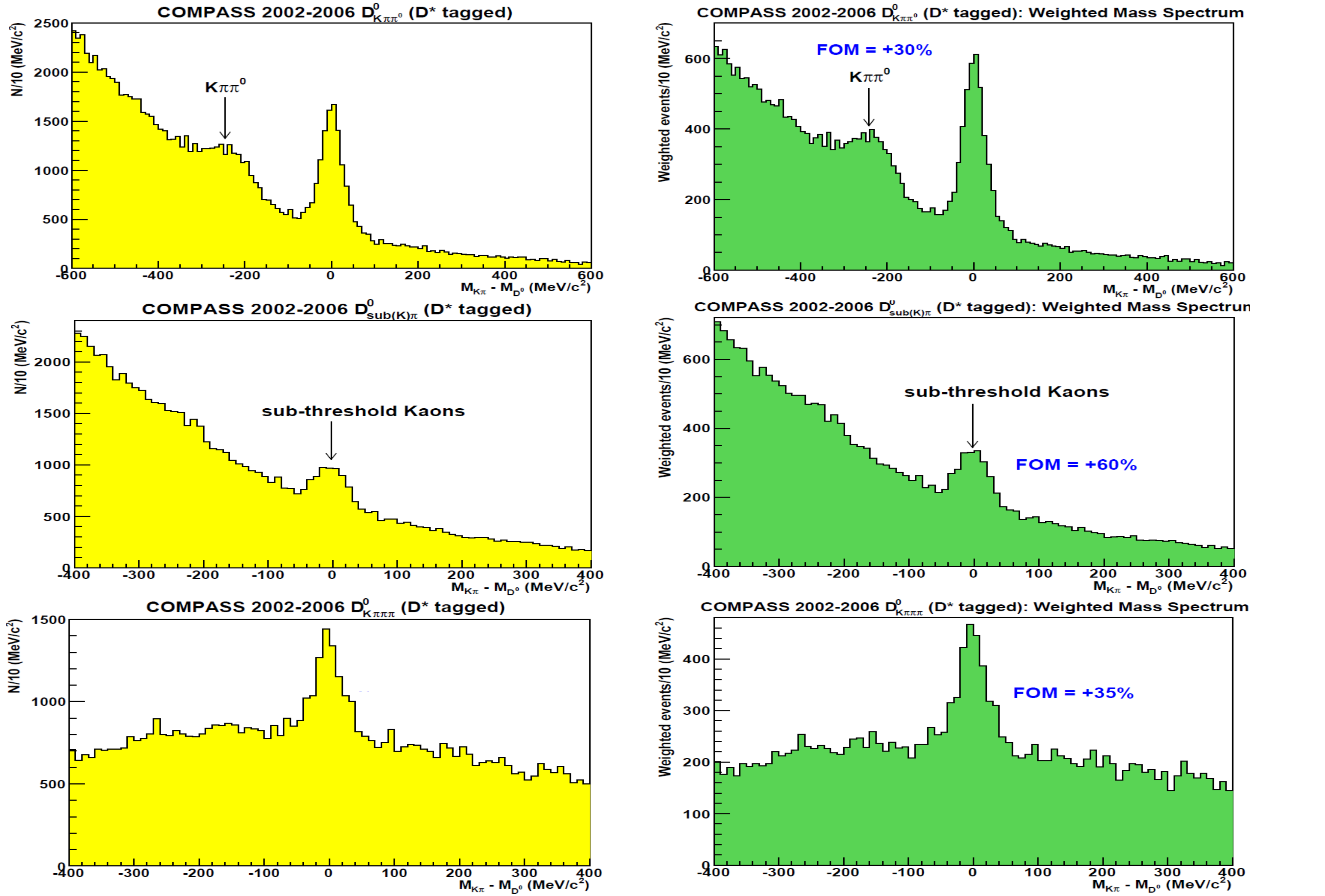
$$A(X) = \frac{d\sigma^{D^{*+}}(X) - d\sigma^{D^{*-}}(X)}{d\sigma^{D^{*+}}(X) + d\sigma^{D^{*-}}(X)}$$

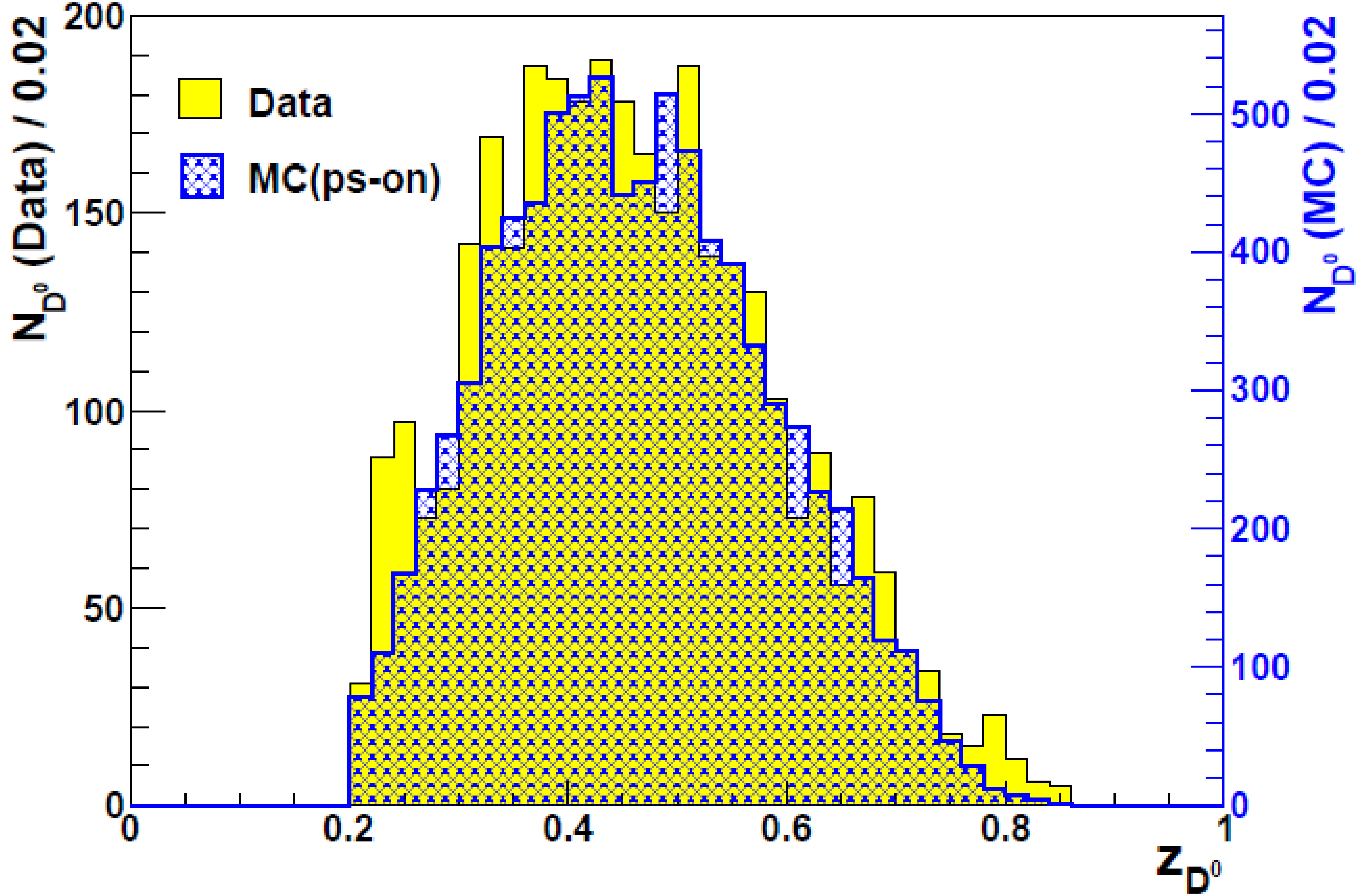


S/(S+B) parameterisation: FOM improvement *(main channels)*

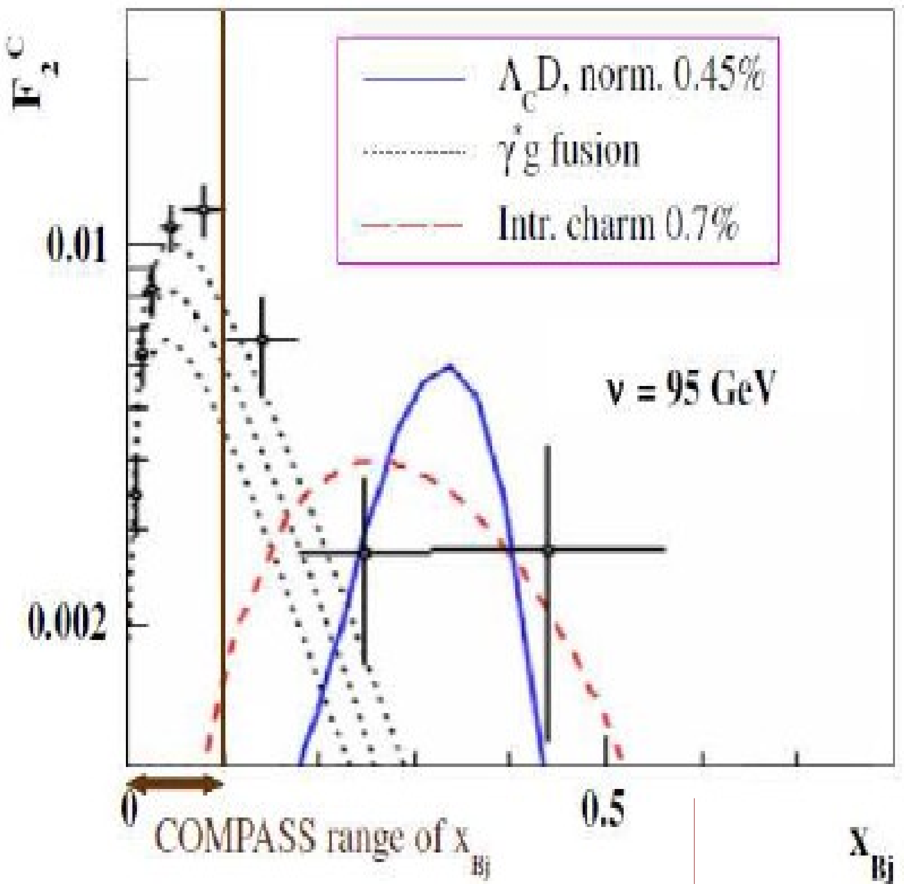


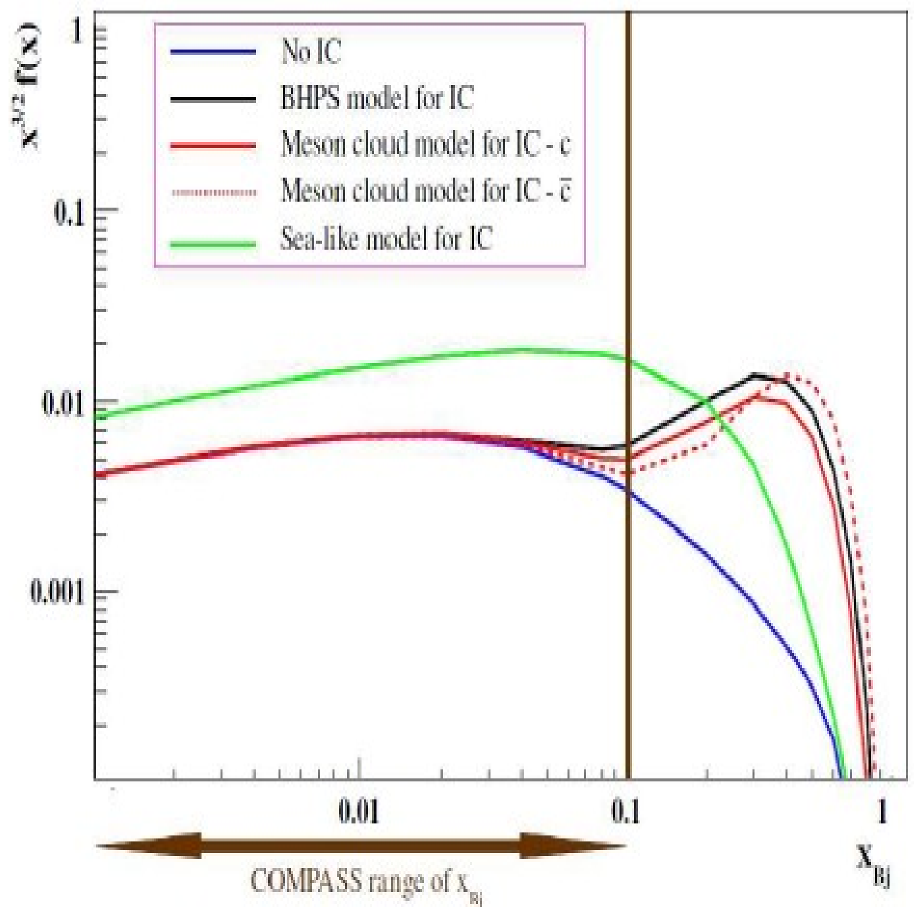
S/(S+B) parameterisation: FOM improvement *(low purity channels)*



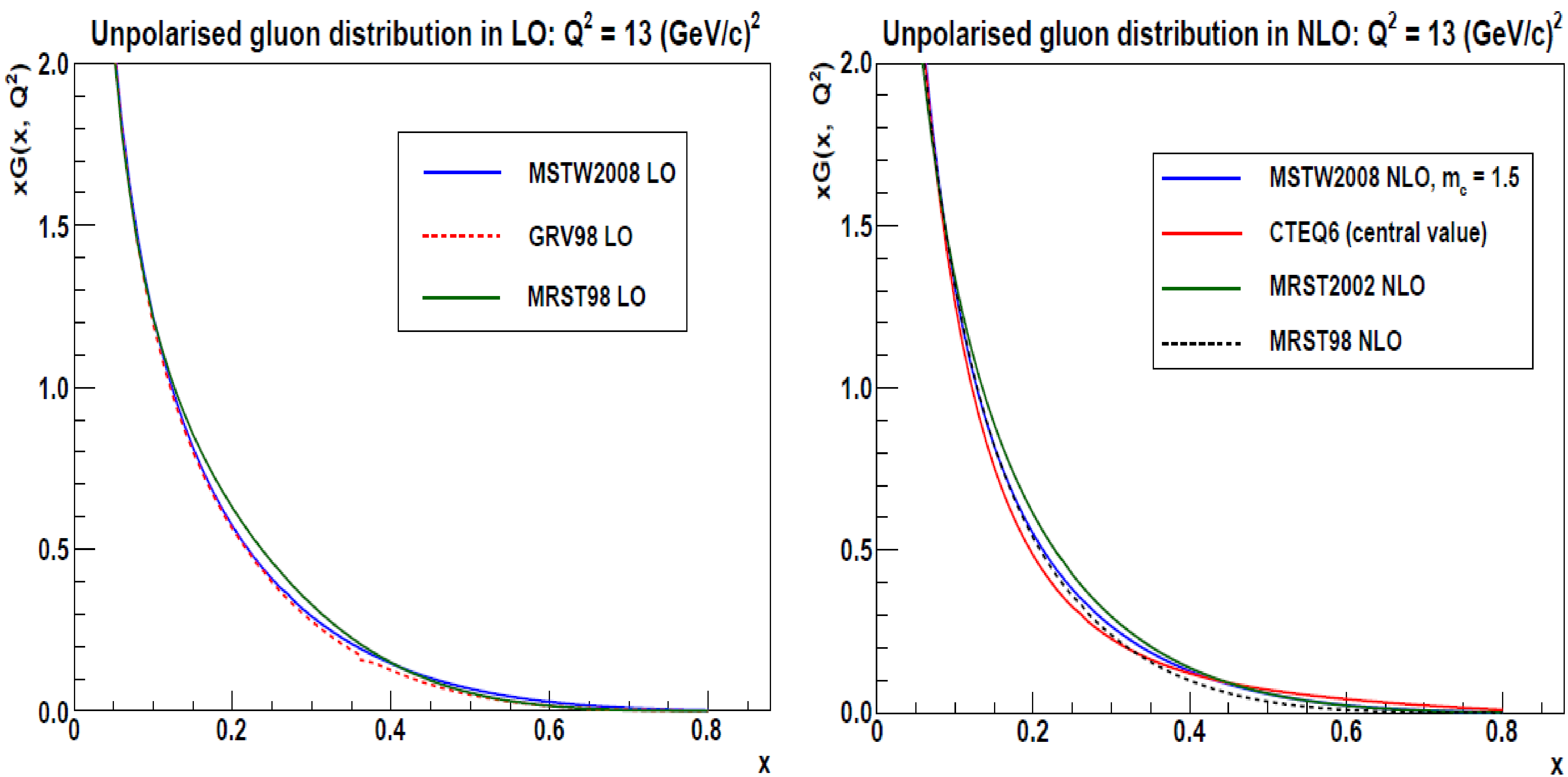


Data
MC(ps-on)
N_{D^0} (Data) / 0.02
N_{D^0} (MC) / 0.02
z_{D^0}
0
50
100
150
200
0
100
200
300
400
500
0
0.2
0.4
0.6
0.8
1





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



Unpolarised gluon distribution in LO: Q2 = 13 (GeV/c)2
xG(x, Q2)
2.0
1.5
1.0
0.5
0.0
0
0.2
0.4
0.6
0.8
x
MSTW2008 LO
GRV98 LO
MRST98 LO
Unpolarised gluon distribution in NLO: Q2 = 13 (GeV/c)2
MSTW2008 NLO, mc = 1.5
CTEQ6 (central value)
MRST2002 NLO
MRST98 NLO