COMPASS results on the gluon polarisation from the Open-Charm analysis

DSPIN-11: Dubna

Celso Franco *(LIP – Lisboa)*

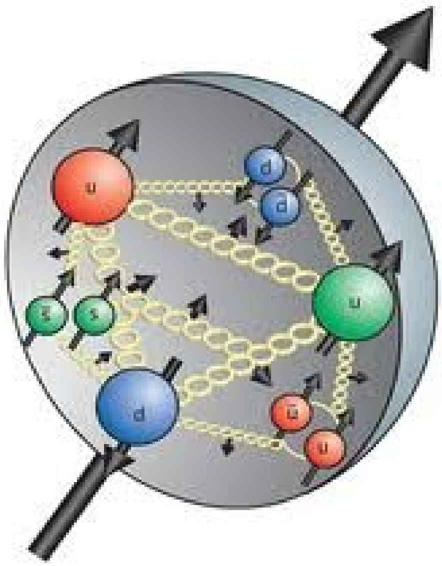
on behalf of the COMPASS collaboration

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:**

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

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

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

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

→ Up and Down quarks carry all the nucleon spin

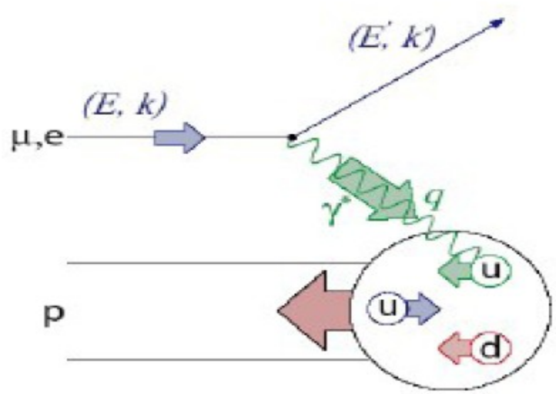
Spin crisis

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

  $\Delta\Sigma \sim 0.60$

- **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)*:



$Q^2 = -q^2$

$\nu = E - E'$

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

$y = \nu / E$

Phys. Lett. B447, (2007) 8

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

Much smaller than expected...

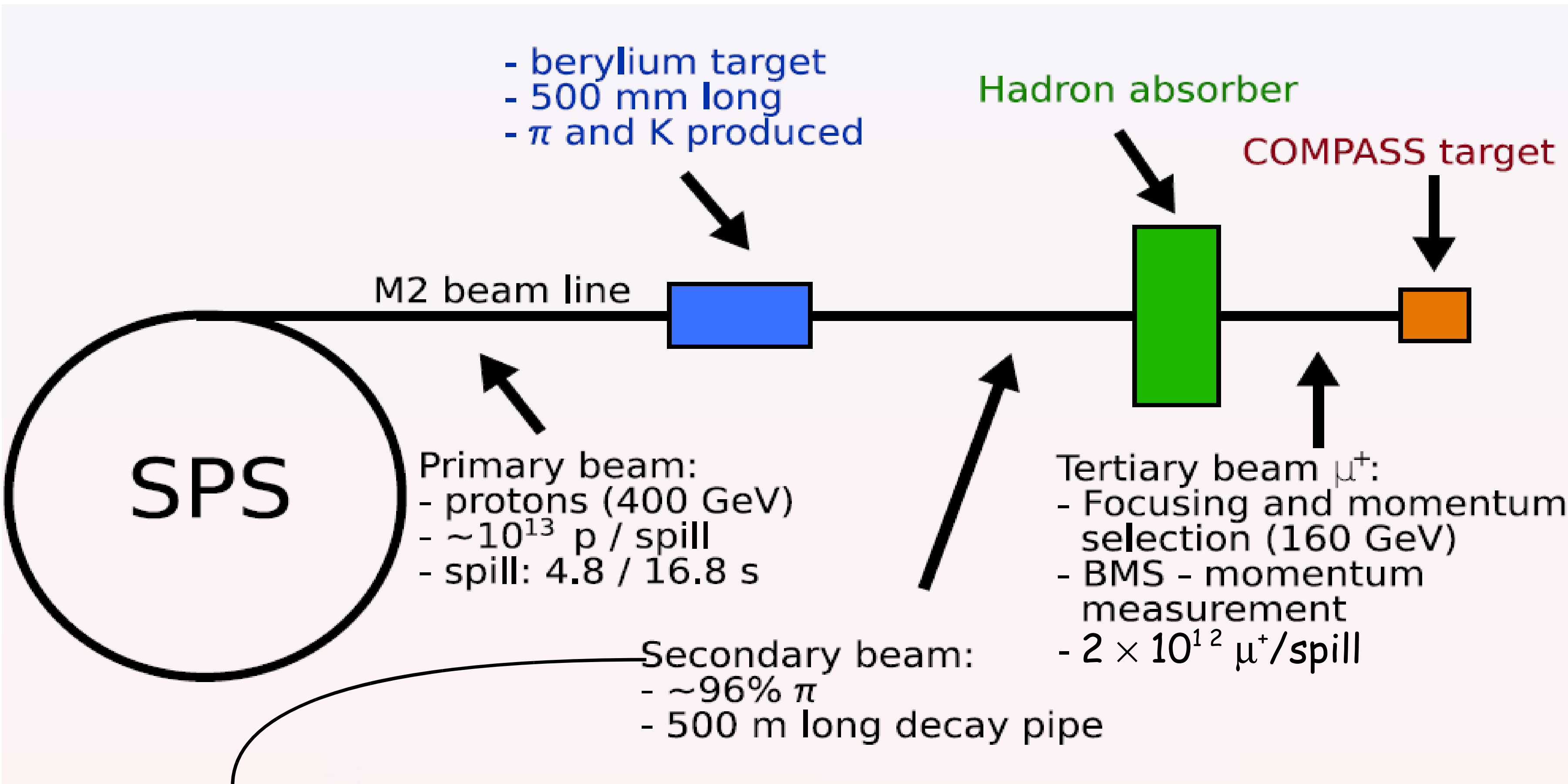
$\Downarrow$

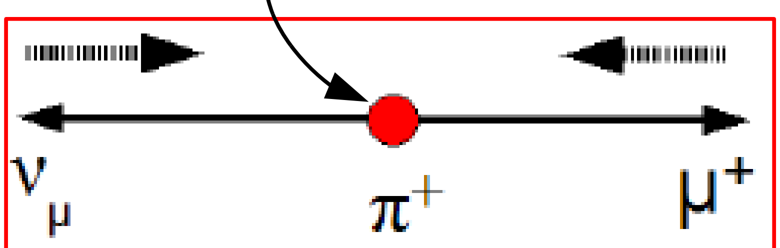
SPIN CRISIS!!!

- **Another reason for measuring the gluon spin contribution:**
  - <u>Due to the gluon axial anomaly</u>, if ΔG is large it could explain a small $\Delta\Sigma$

The COMPASS Experiment

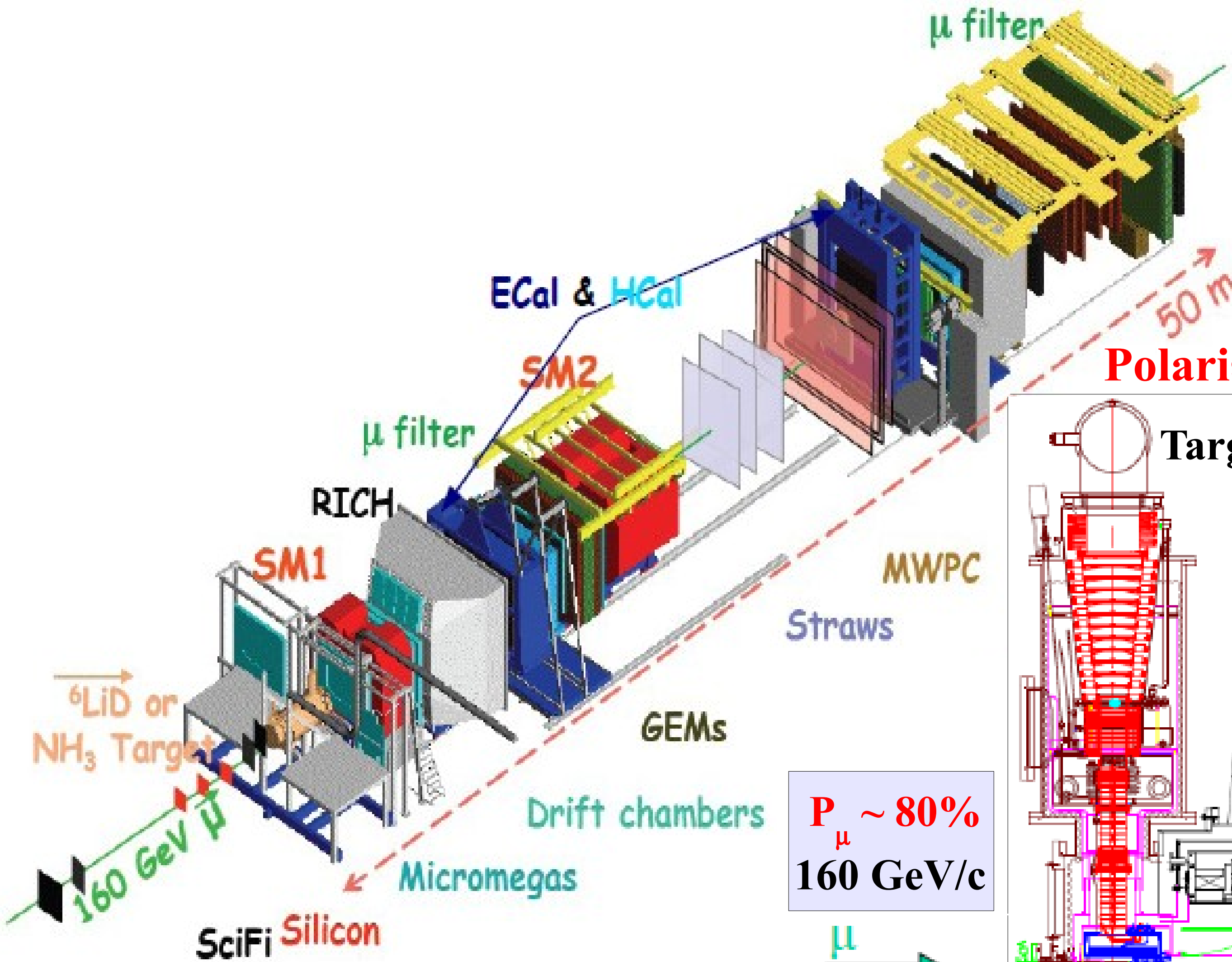
The polarised beam





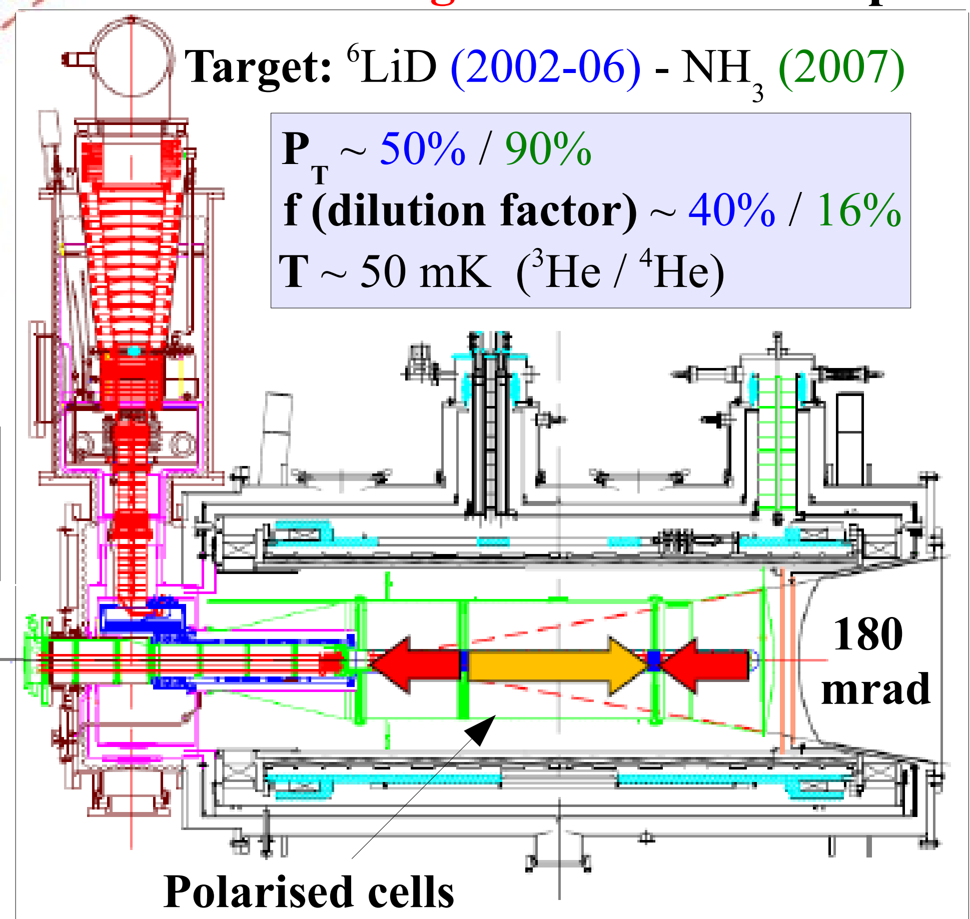
Naturally polarised muon beam: $P_\mu \sim 80\%$

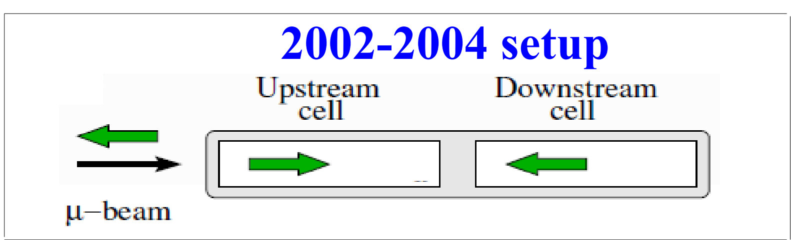
The spectrometer and polarised target



$P_\mu \sim 80\%$
160 GeV/c

Polarised Target: 2006-2007 setup





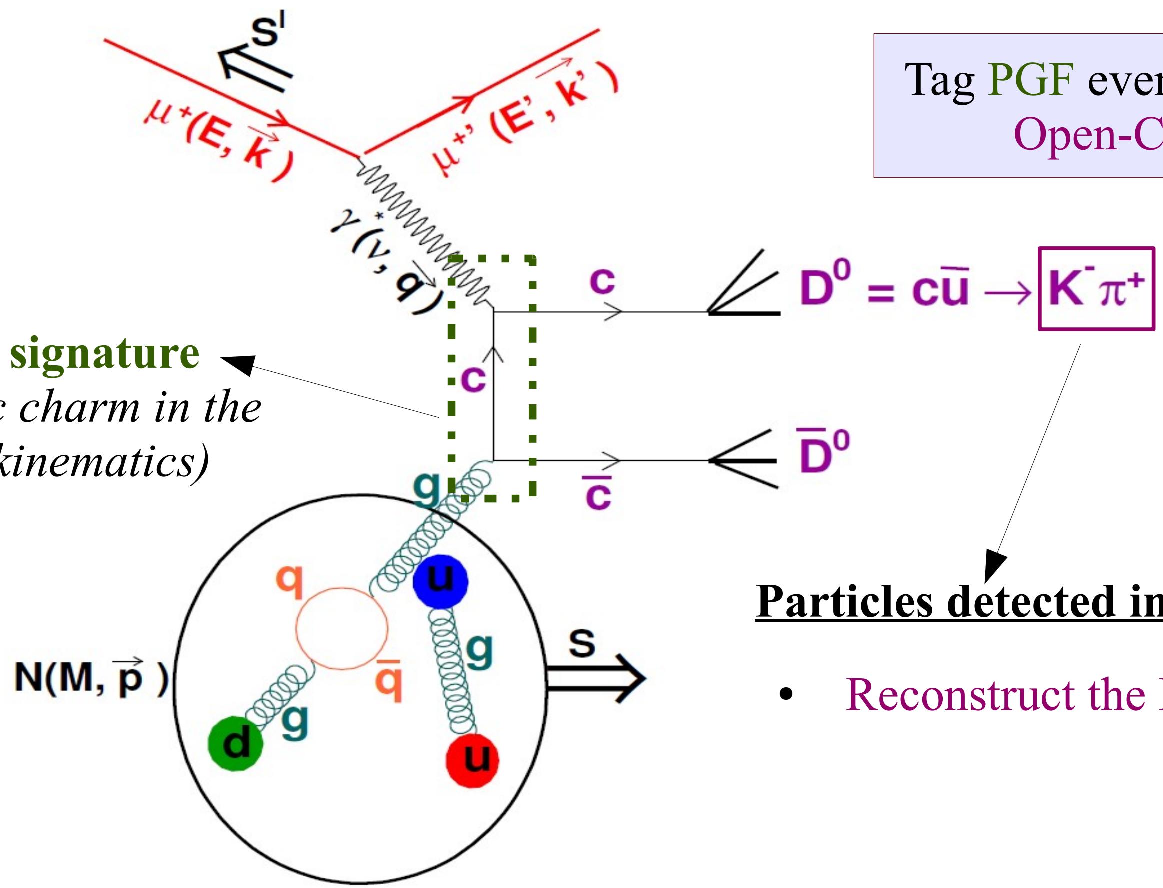
The Open-Charm analysis

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)

Particles detected in the spectrometer:

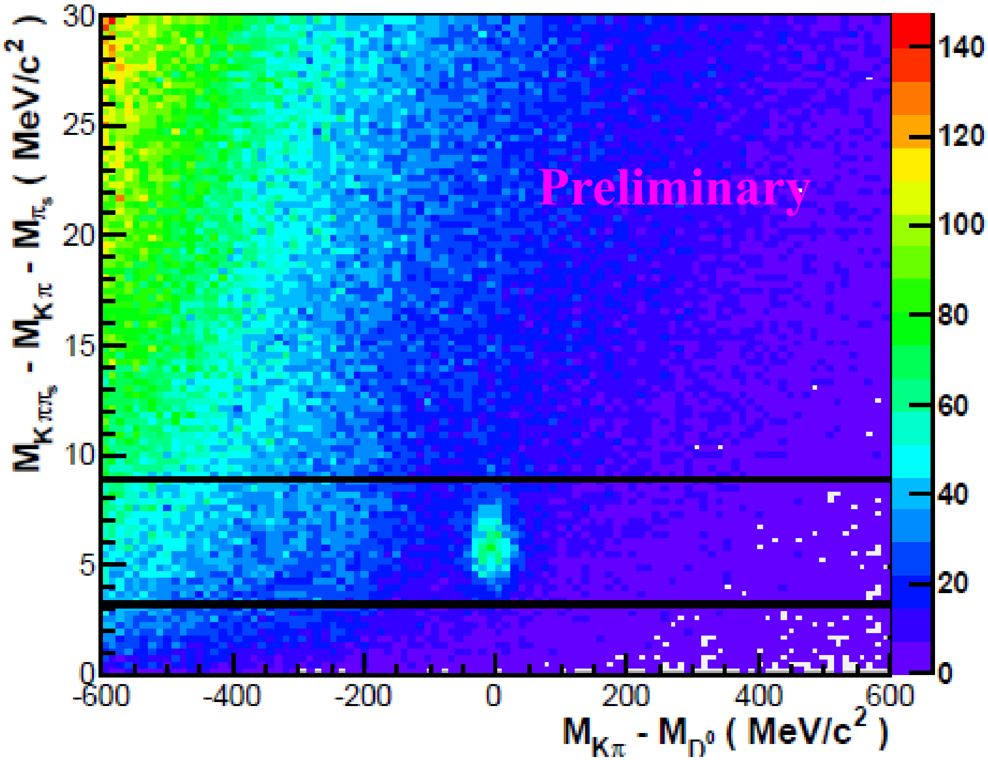
- Reconstruct the D^0 invariant mass!

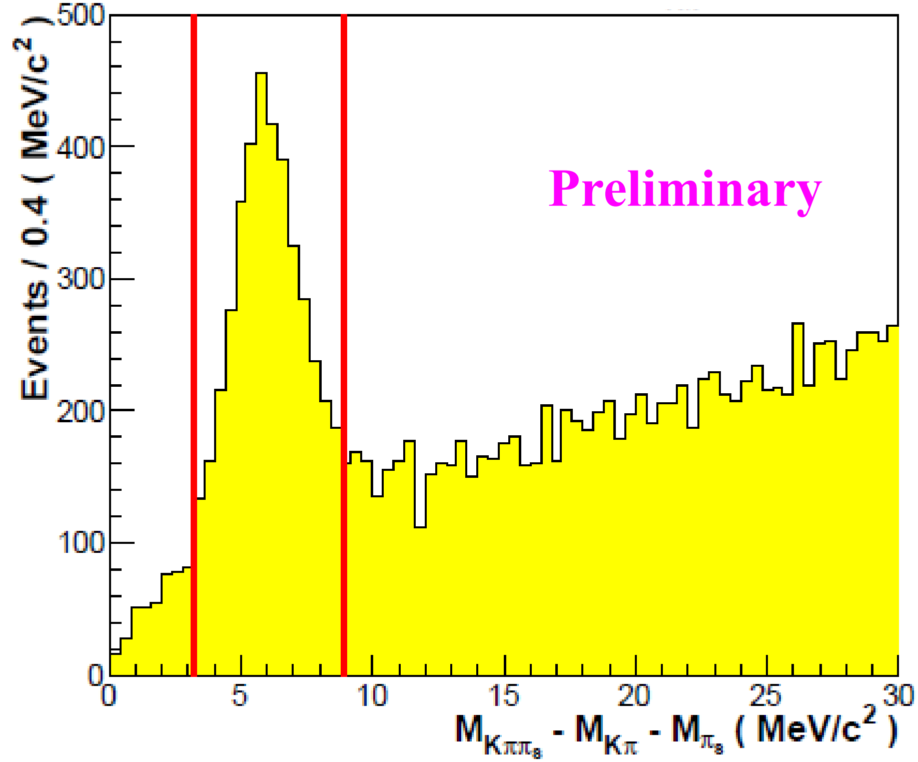
Reconstruction of Open-Charm mesons

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

- **Selection to reduce the combinatorial background:**
  - **Kinematic cuts:** Z_{D^0}, kaon angle in the D^0 centre-of-mass, K and π momentum
  - **RICH identification:** K and π ID + electrons rejected from the π_s sample
  - Mass cut for the D^* tagged channels $(M^{rec}[K\pi\pi_S] - M^{rec}[K\pi] - M[\pi])$
  - Use of a Neural Network to improve the purity of the D^0 spectra

The mass cut for the D* tagged channels

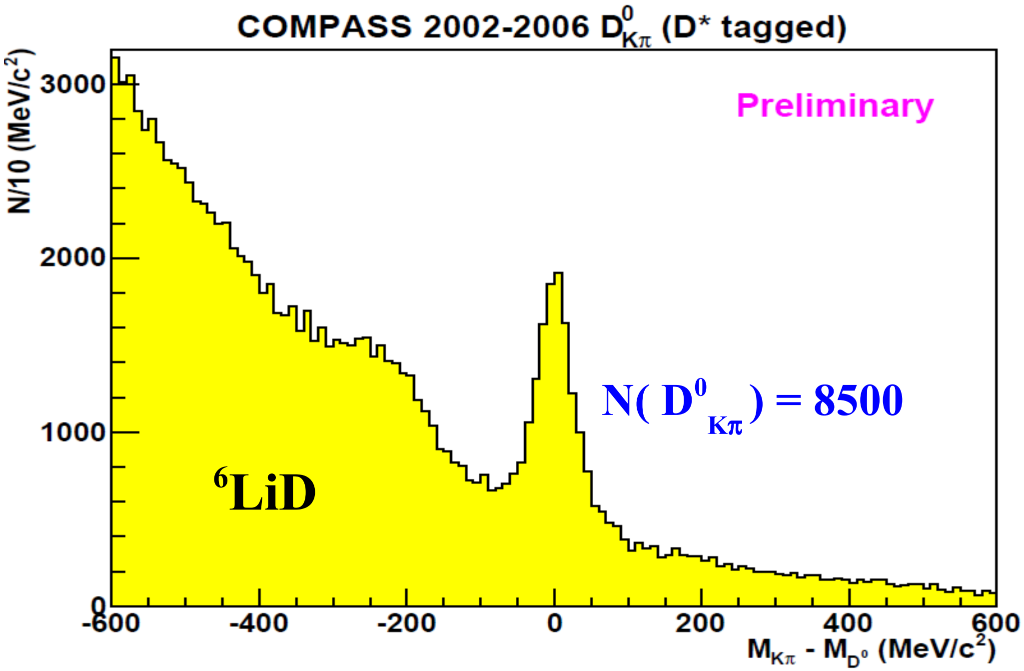


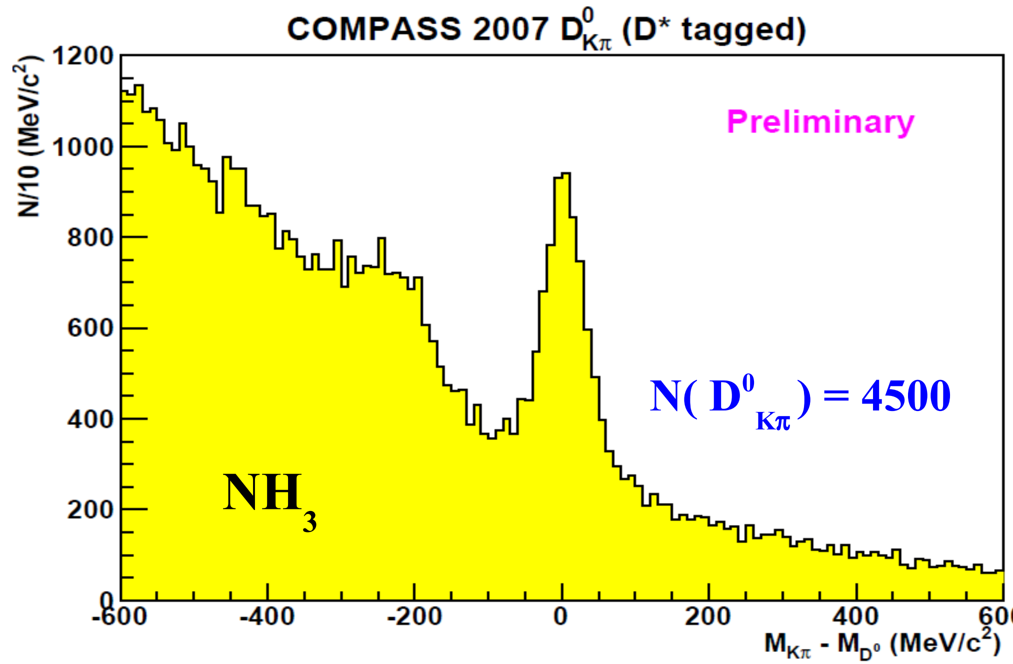


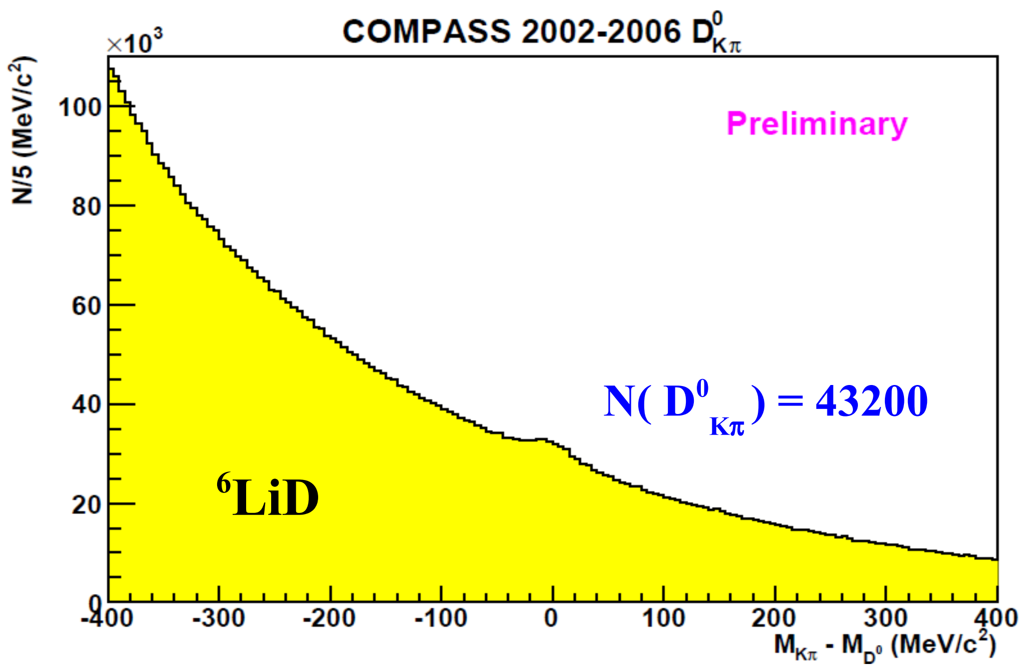
3.2 MeV/c^2 < ($M^{rec}[K\pi\pi_S] - M^{rec}[K\pi] - M[\pi]$) < 8.9 MeV/c^2

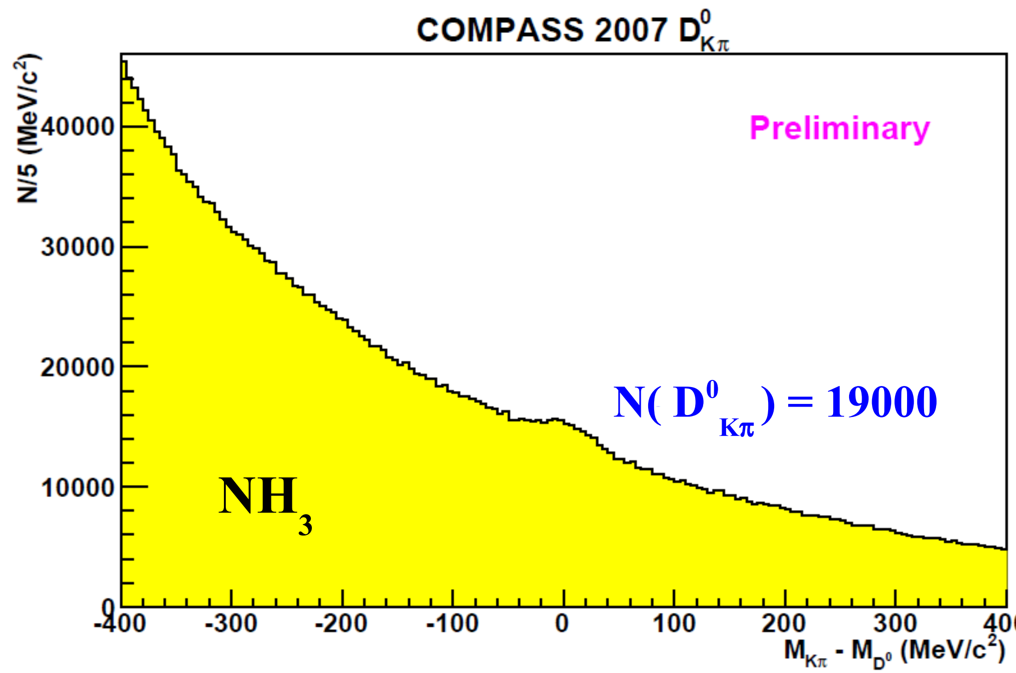
- Improves the FOM of the $D^0_{K\pi}$ sample <u>by a factor of 3</u>! *(tagged vs non-tagged)*
- Allows us to reconstruct low-purity channels of low statistics: $D^0_{K\pi\pi^0}$, $D^0_{K\pi\pi\pi}$ and $D^0_{K_{sub}\pi}$

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

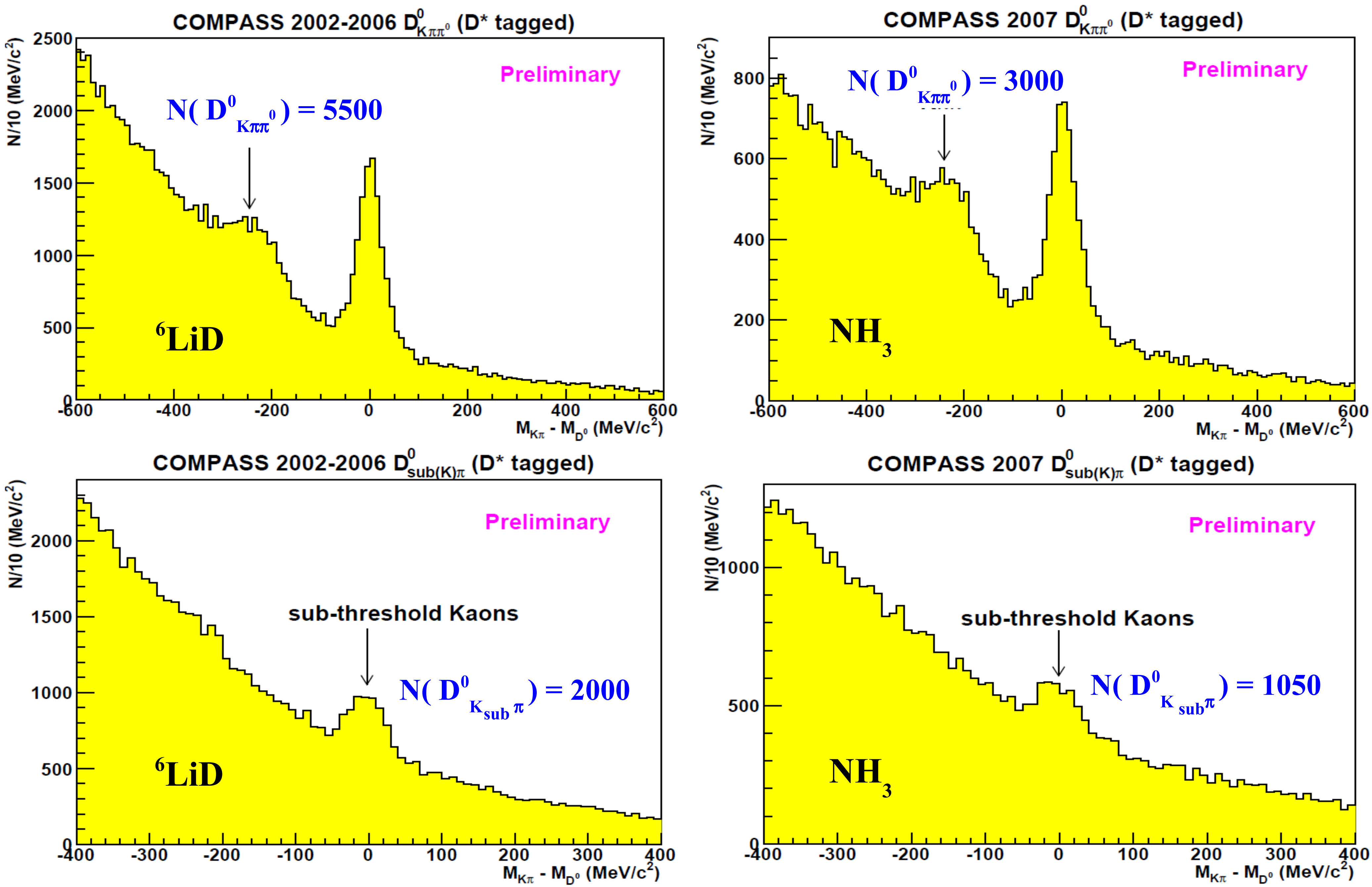




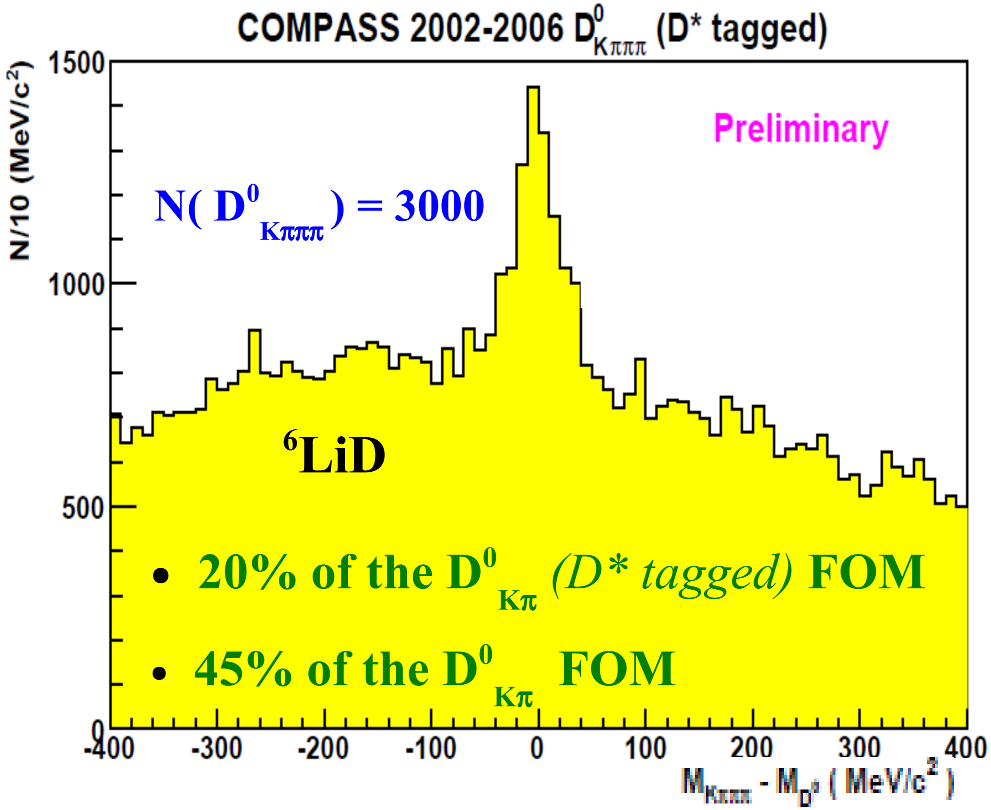


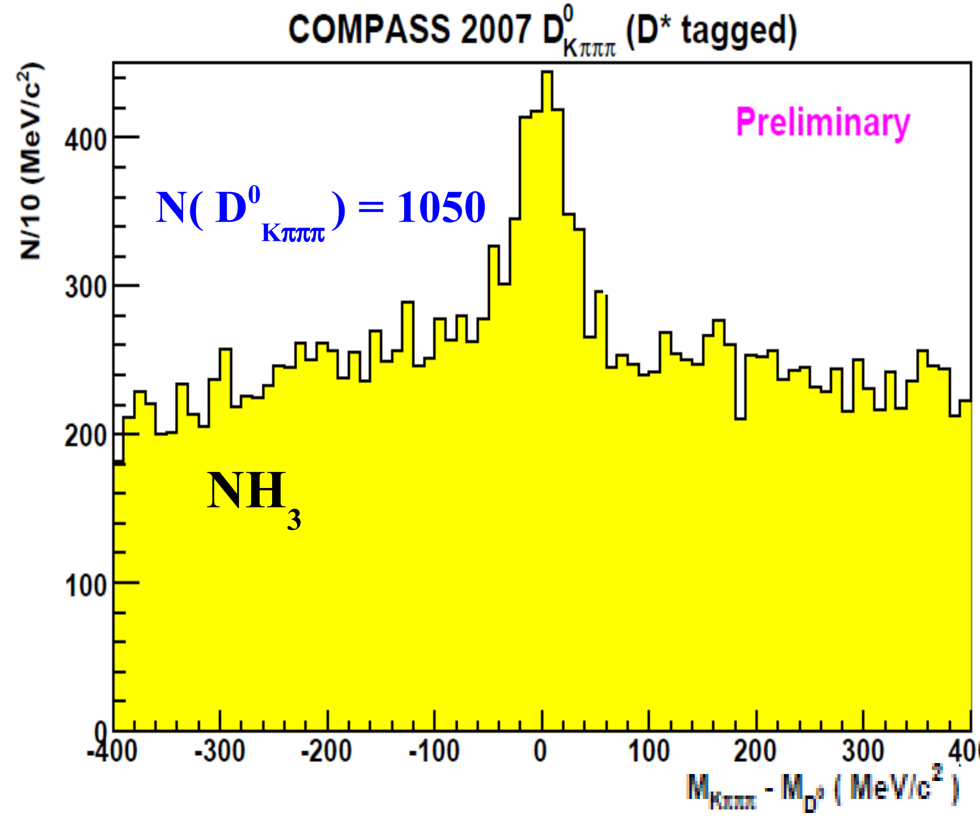


Invariant Mass Spectrum: $D^0_{K\pi\pi^0}$ and $D^0_{K_{sub}\pi}$ *(D* tagged channels)*



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





Total Number of D^0:

- ^{6}LiD → 65600
- NH_3 → 25000

90600

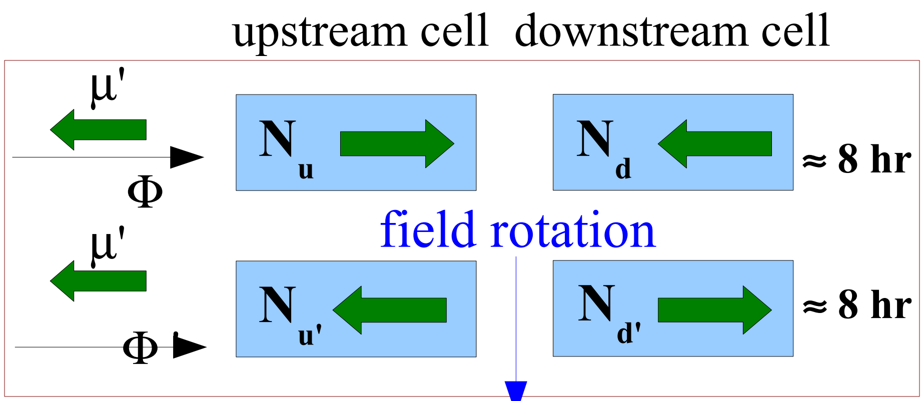
Measuring D^0 asymmetries to extract ΔG

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

Considering $A^{bg} = 0$

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

Open-Charm event probability



equal acceptance for both spin configurations

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

$$A^{\mu,N} = \langle a_{LL} \rangle \frac{\Delta G}{G} \quad \text{with} \quad a_{LL} = \left(\frac{\Delta \sigma^{PGF}}{\sigma^{PGF}}\right)$$

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

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

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

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

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

Open Charm event probability

- 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 also with a background weight, $\omega_B = f\,P_\mu\,D\,B/(S+B)$, and the weighted sums of events are taken:

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

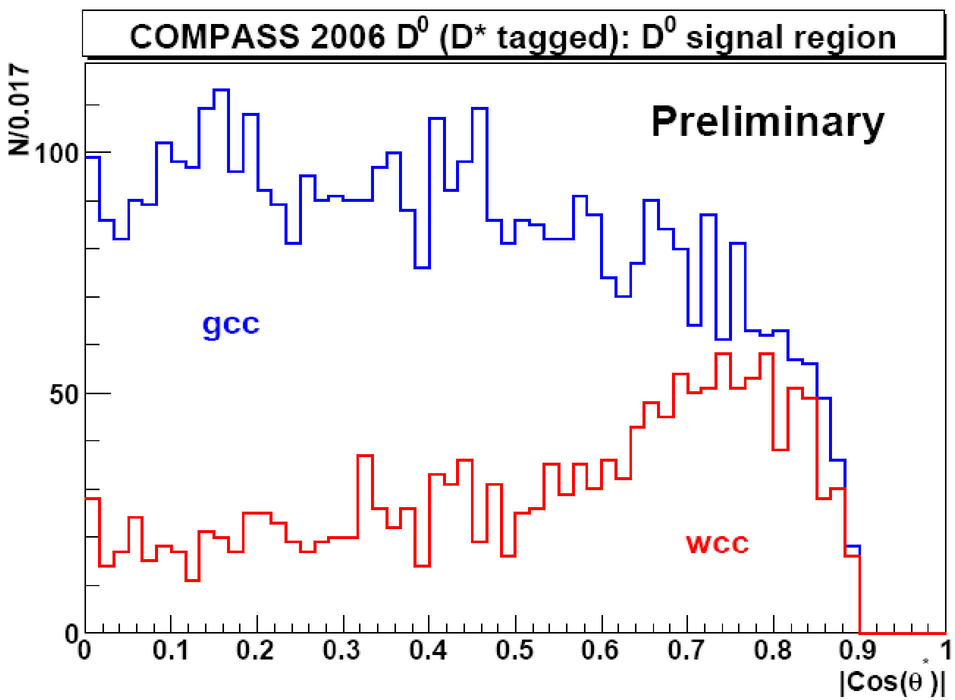
The system is solved by a χ^2 minimisation

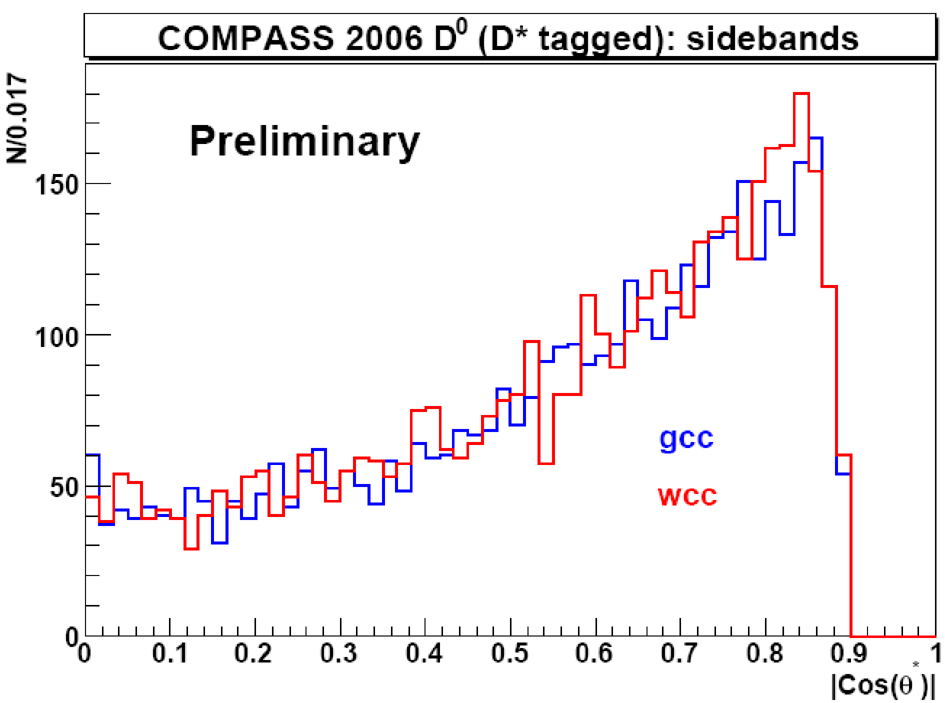
Determination of S/(S+B)

$s/(s+b)_{NN}$: Classification of events by a Neural Network

- **Two real data samples, selected with the same cuts, 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

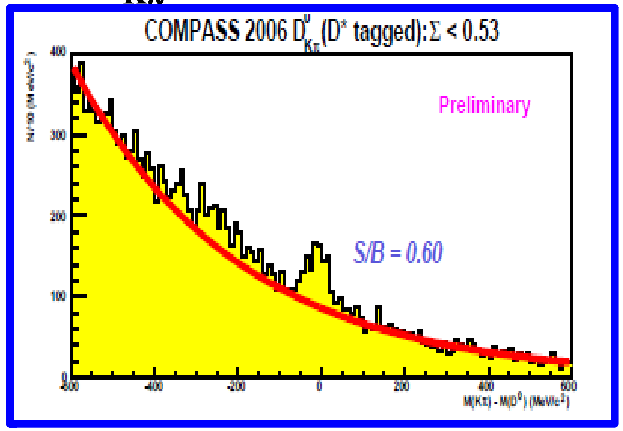


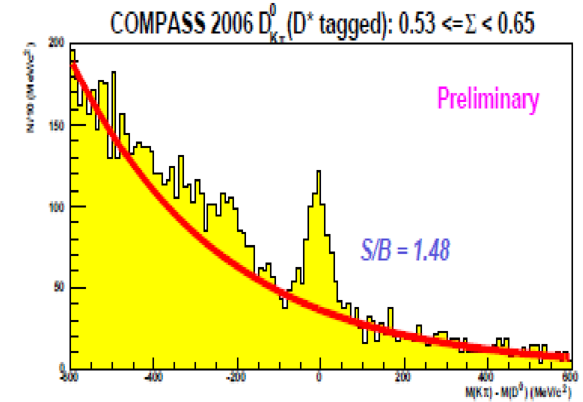


s/(s+b): Obtaining final probabilities for a D^0 candidate

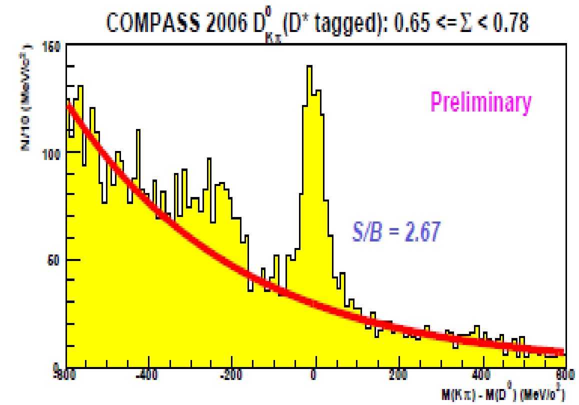
$D^0_{K\pi}$ (D* tagged) spectrum in bins of $\Sigma = s/(s+b)_{NN}$

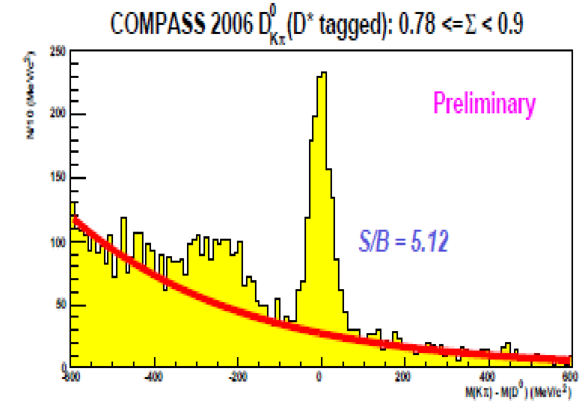
- **Events with small $s/(s+b)_{NN}$**
  - Mostly combinatorial background is selected



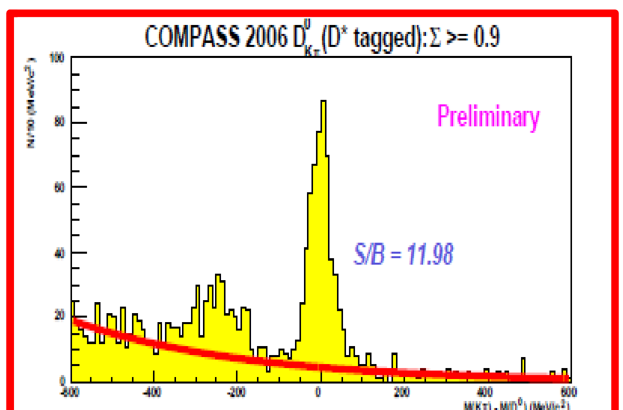


<u>s/(s+b) is obtained from a fit to these spectra</u> *(correcting with the NN parameterisation)*





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



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

Determination of a_{LL}

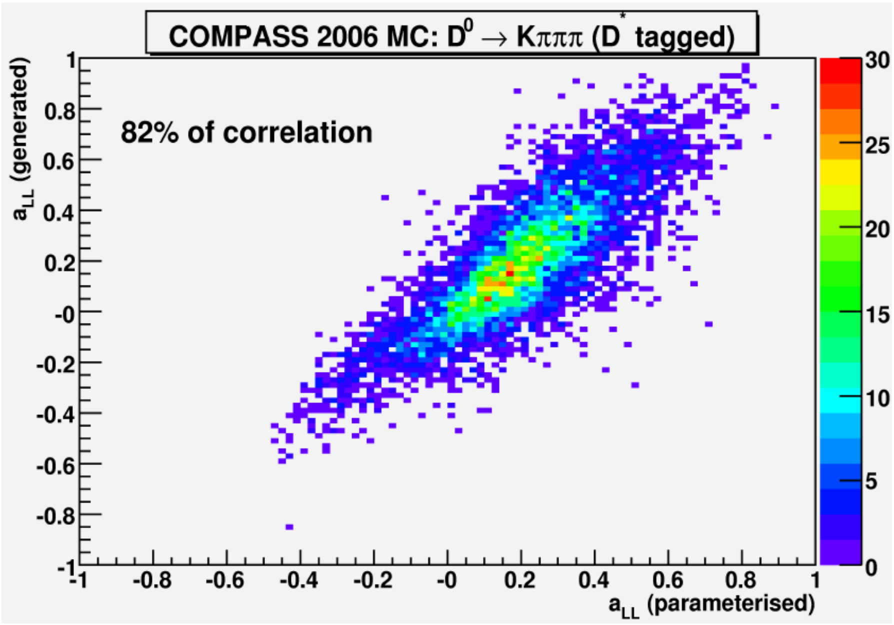
The muon-gluon analysing power

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

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

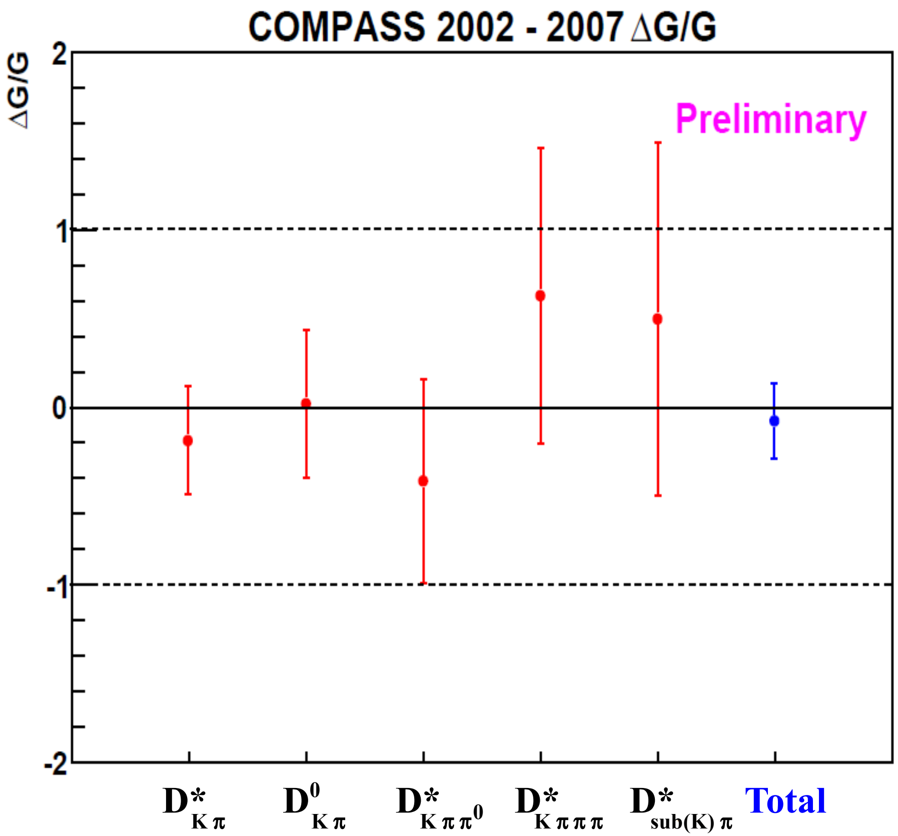
Can't be experimentally obtained: only one charmed meson is reconstructed

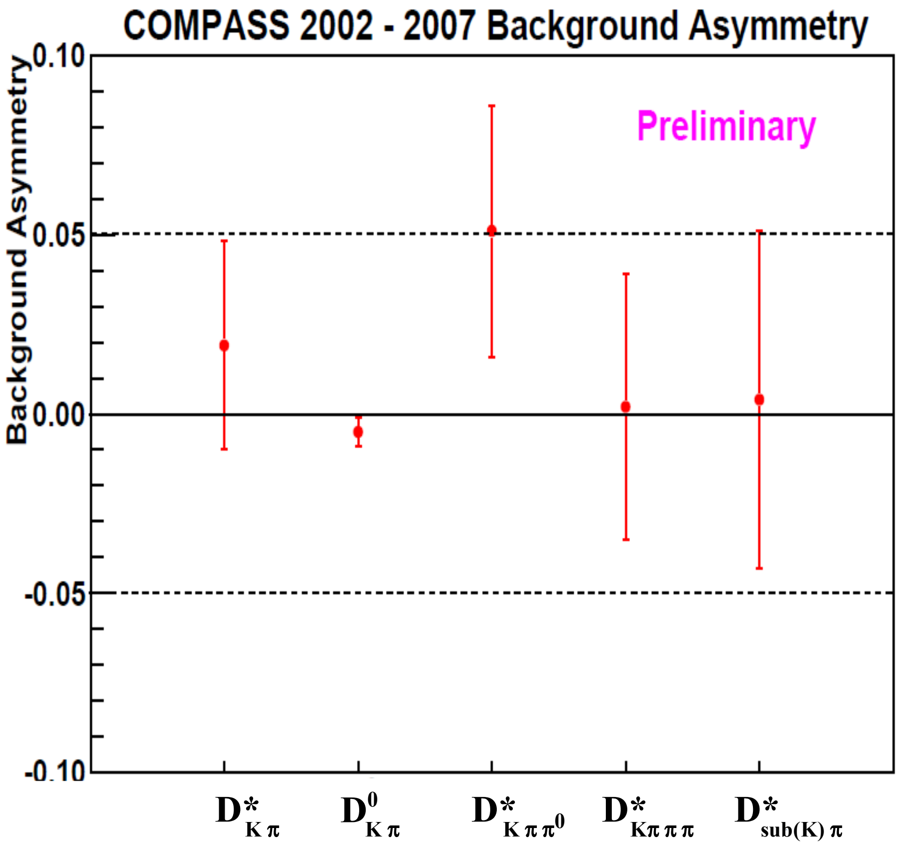
- a_{LL} is obtained from Monte-Carlo (in LO-QCD), to serve as input for a Neural Network parameterisation on some reconstructed kinematical variables: y, x_{Bj}, Q^2, z_D and p_T



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

Open-Charm results in LO-QCD

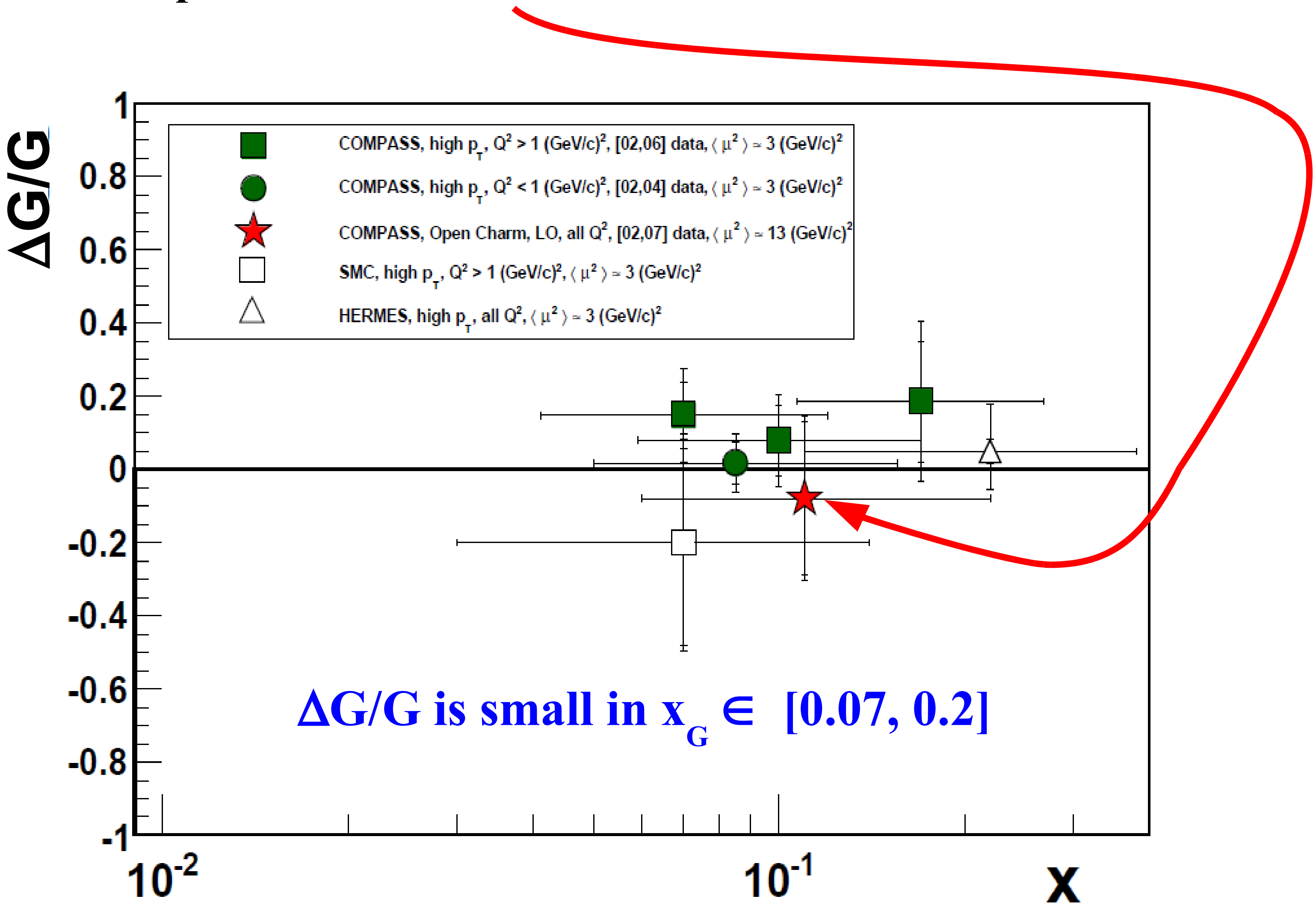




$$\frac{\Delta G}{G} = -0.08 \pm 0.21(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \quad @\langle x_g \rangle = 0.11^{+0.11}_{-0.05}, \quad \langle \mu^2 \rangle = 13\,(\mathrm{GeV}/c)^2$$

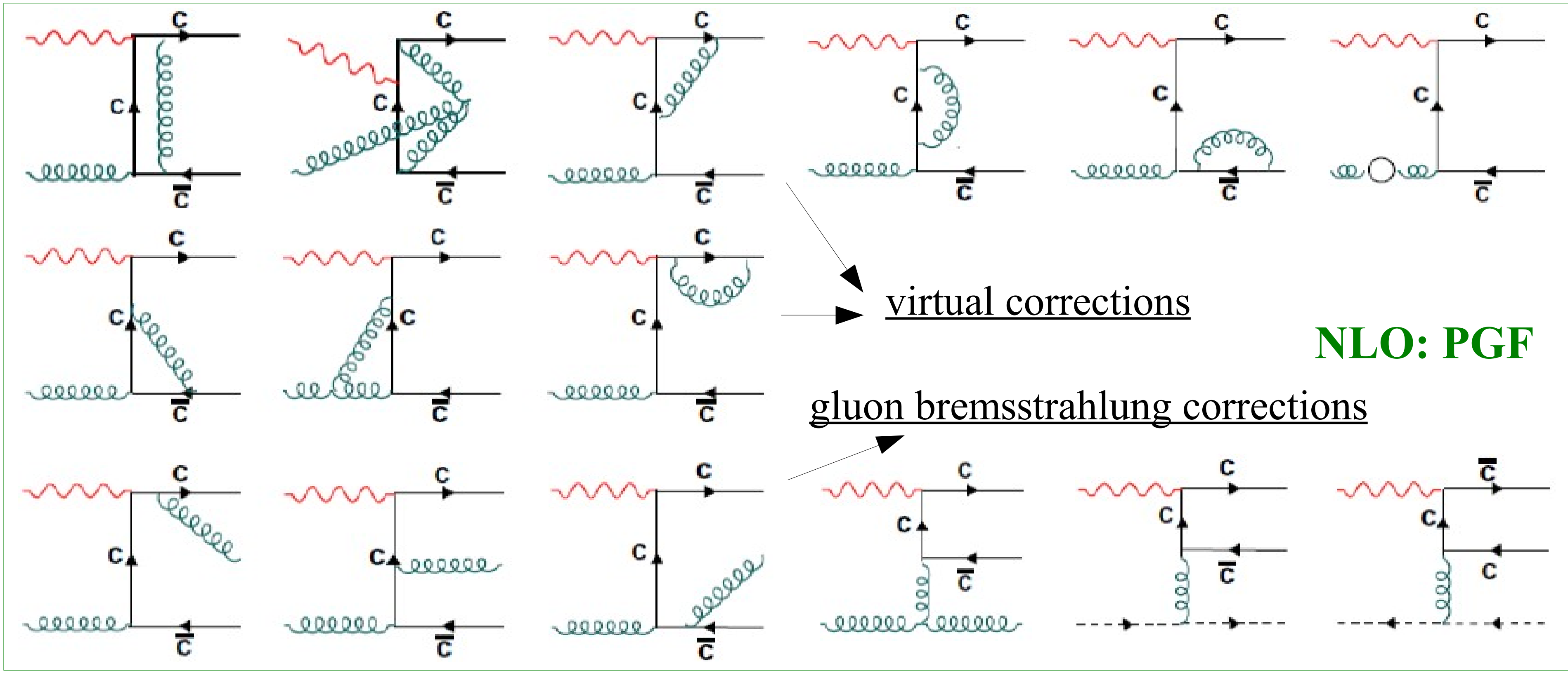
World measurements on ΔG/G in LO-QCD

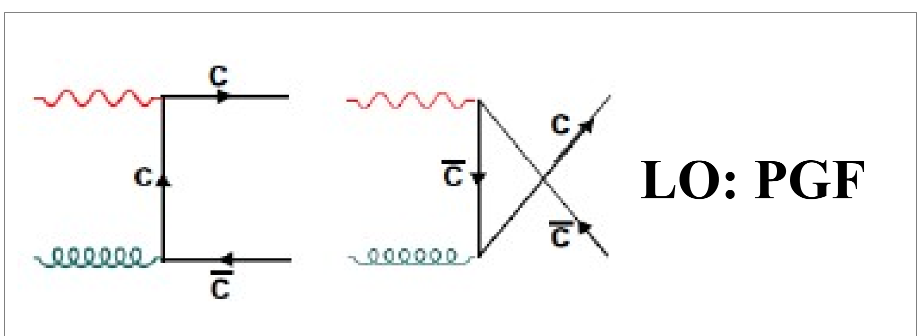
- **The gluon polarisation was obtained directly from the data, in LO, and was found to be compatible with zero**

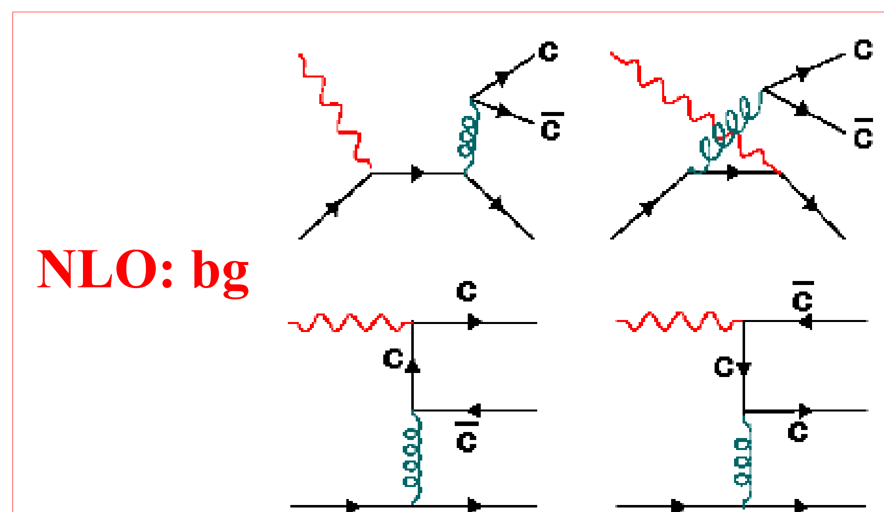


Determination of $\Delta G/G$ in NLO-QCD

NLO corrections to the analysing power $\langle a_{LL} \rangle$







Procedure for NLO calculations

- The AROMA generator with parton-shower-on (PS-on) describes the COMPASS data very well. Therefore, we can use the concept of PS to simulate the 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.
  - a_{LL} is calculated event-by-event from theoretical formulas (as in LO case)

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

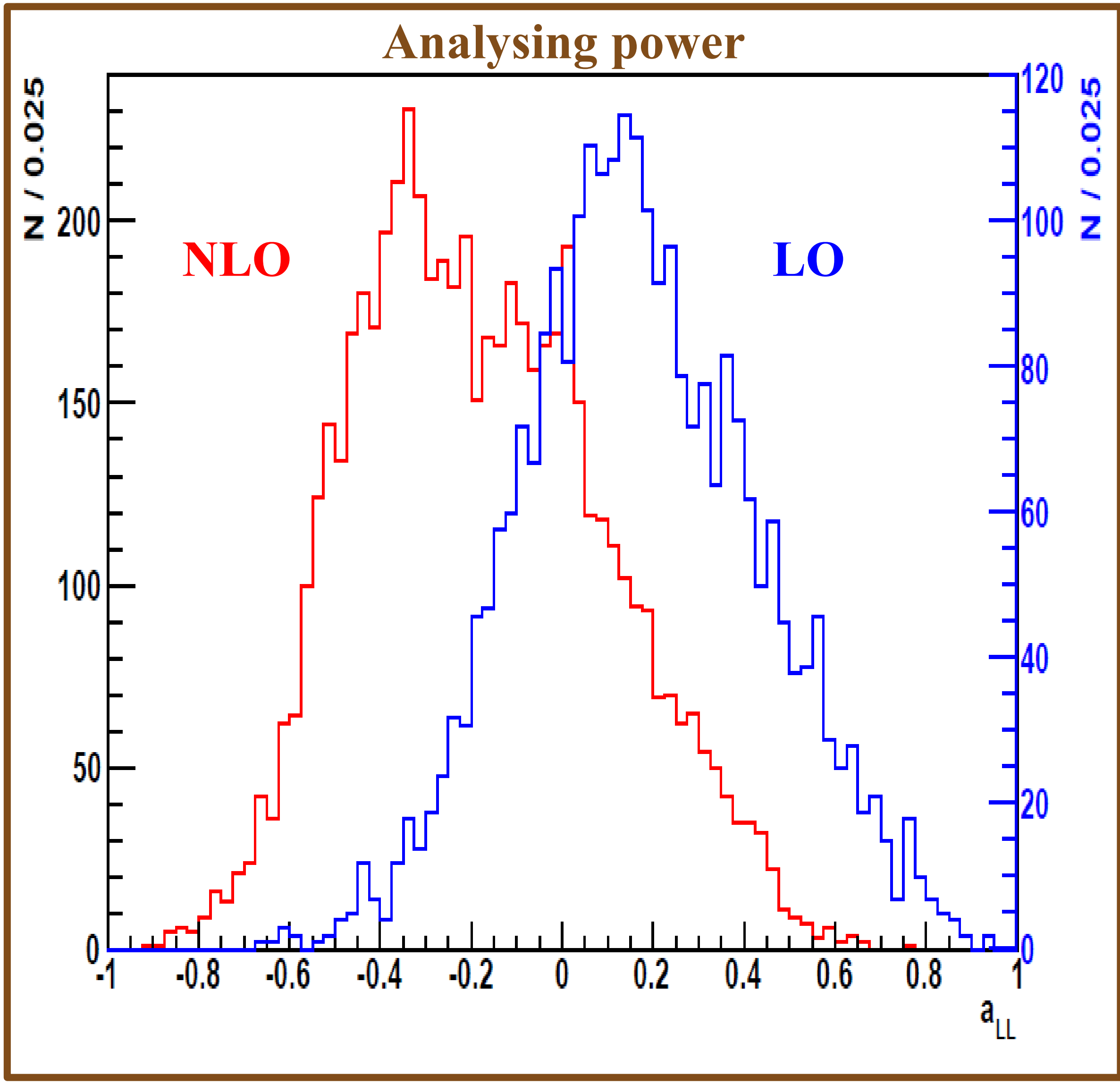
$$A^{\gamma N} = \left(\frac{a_{LL}^{PGF}(NLO)}{D} \frac{\Delta G}{G} + \frac{a_{LL}^{q}(NLO)}{D} A_1 \right)$$

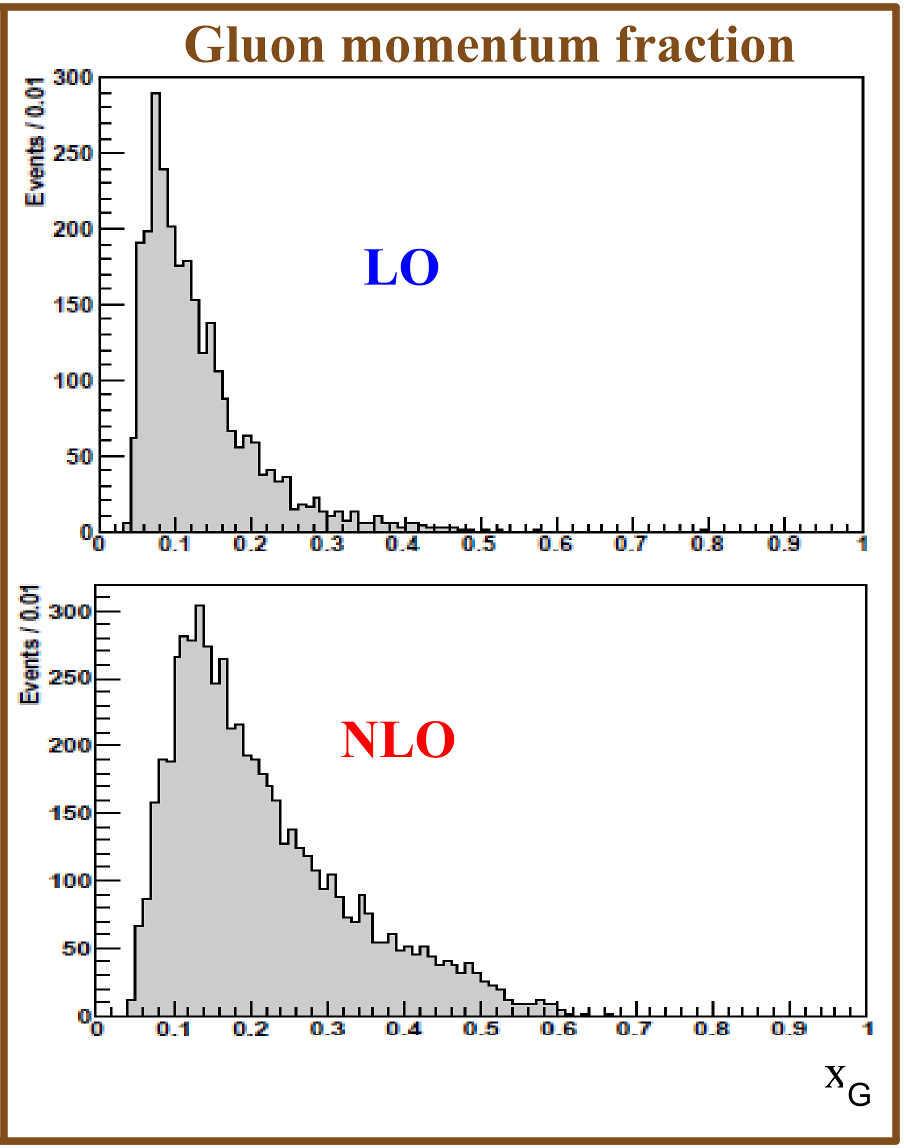
The replacement of a_{LL} by D in ω_s implies the extraction of $A^{\gamma N}$ instead of $\Delta G/G$

► **Independent of theoretical interpretations** → good for global fits of ΔG

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

Distributions of a_{LL} and x_g in LO-QCD and NLO-QCD

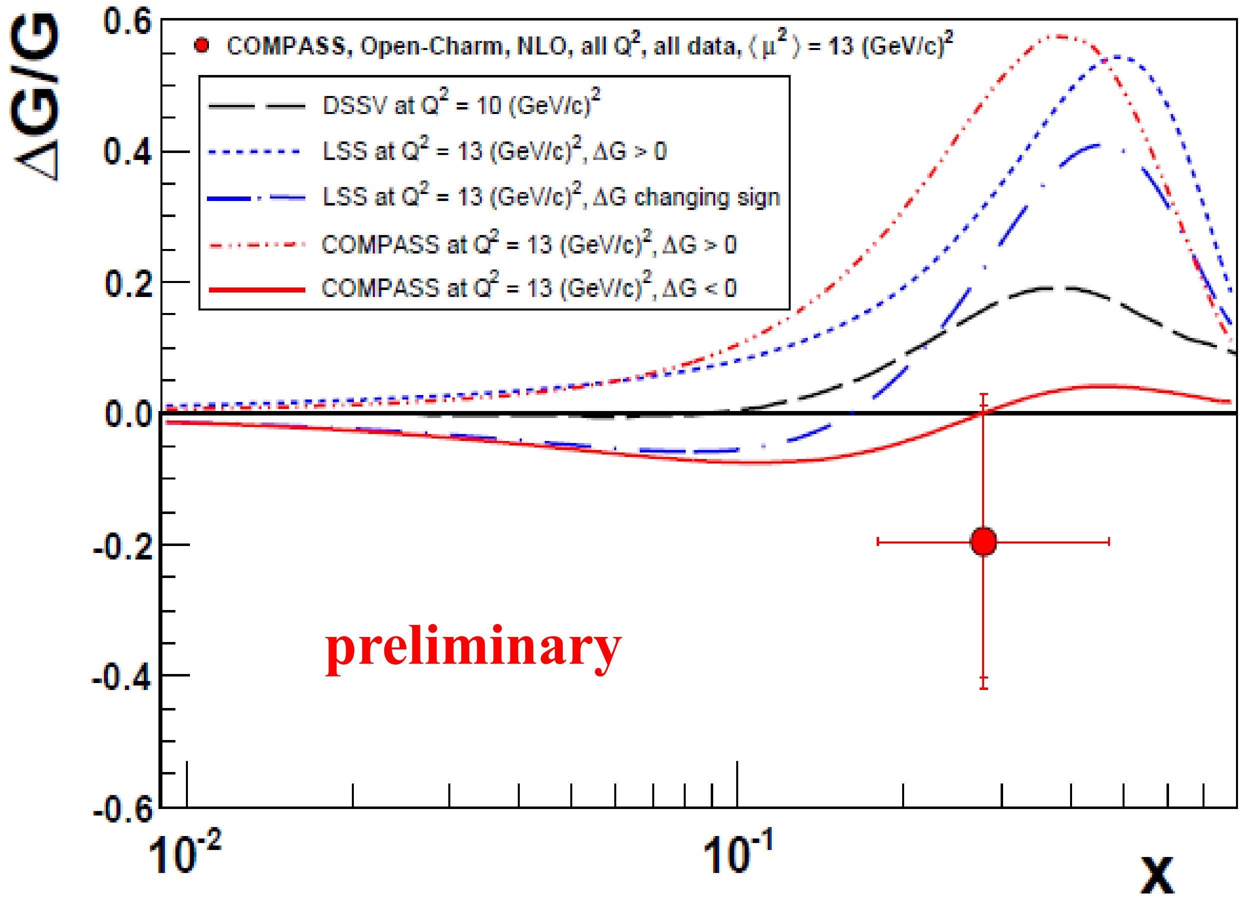




Results for $A^{\gamma N}$(PGF)

Bins		$D^0 \rightarrow K\pi$ samples			$D^0 \rightarrow K\pi\pi^0$ sample			$D^0 \rightarrow K\pi\pi\pi$ 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

ΔG/G result in NLO-QCD → NEW



$$\frac{\Delta G}{G} = -0.20 \pm 0.21 \pm 0.08\,(\mathbf{syst}) \qquad @\langle x_G\rangle = 0.28^{+0.19}_{-0.10}, \quad \langle \mu^2\rangle = 13\,(\mathrm{GeV/c})^2$$

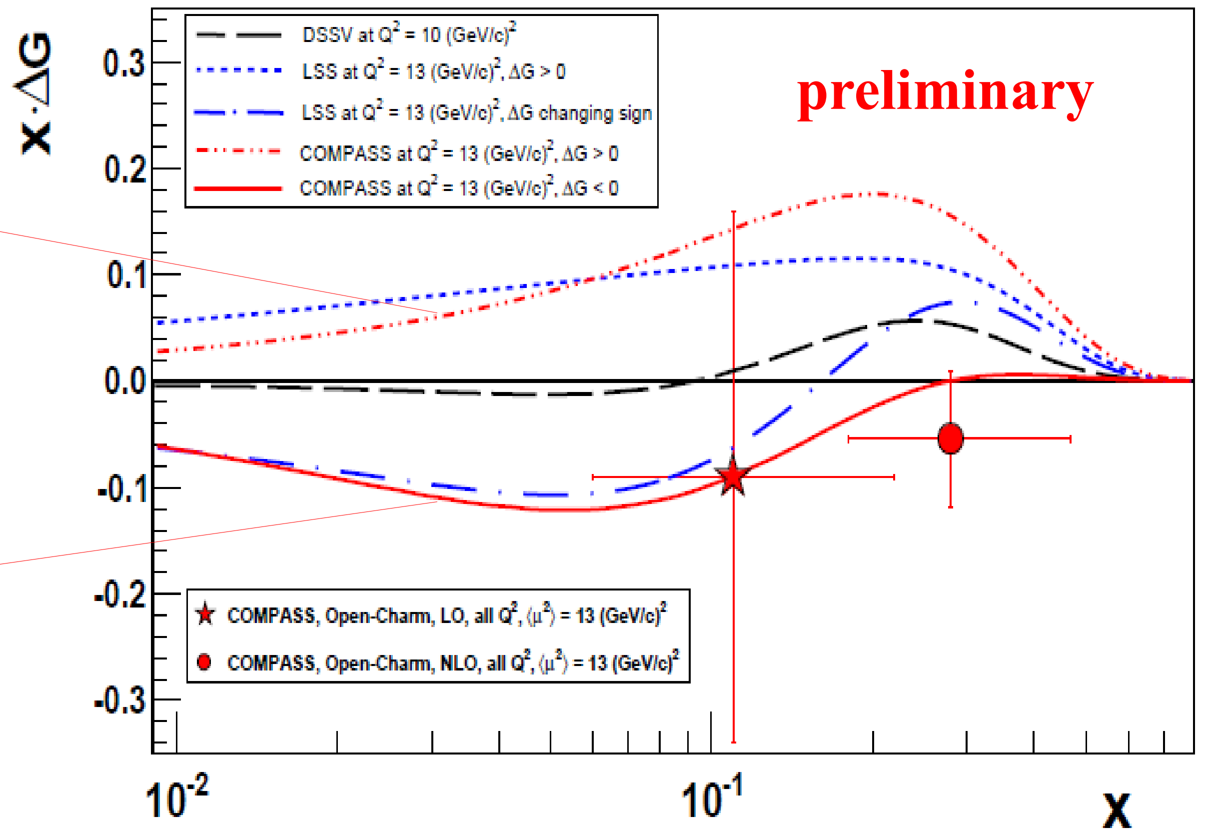
Preliminary: theoretical uncertainties still under study (a_{LL})

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 ΔG/G (the comparison of the LO point with the QCD fits is justified by xG(LO) ≈ xG(NLO)):

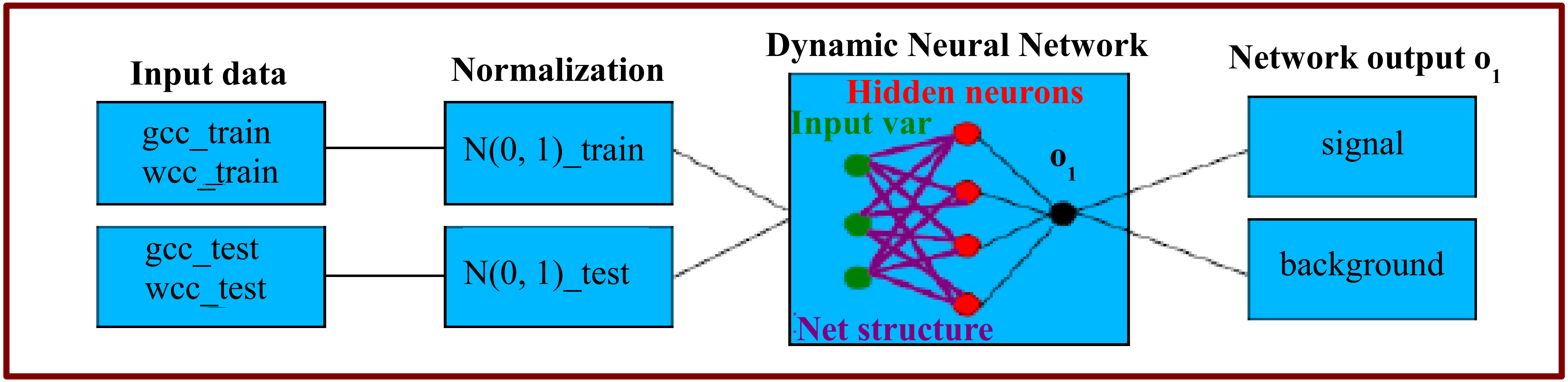
$$\int_0^1 \Delta \mathbf{G} d\mathbf{x} = 0.27 \pm 0.09$$

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



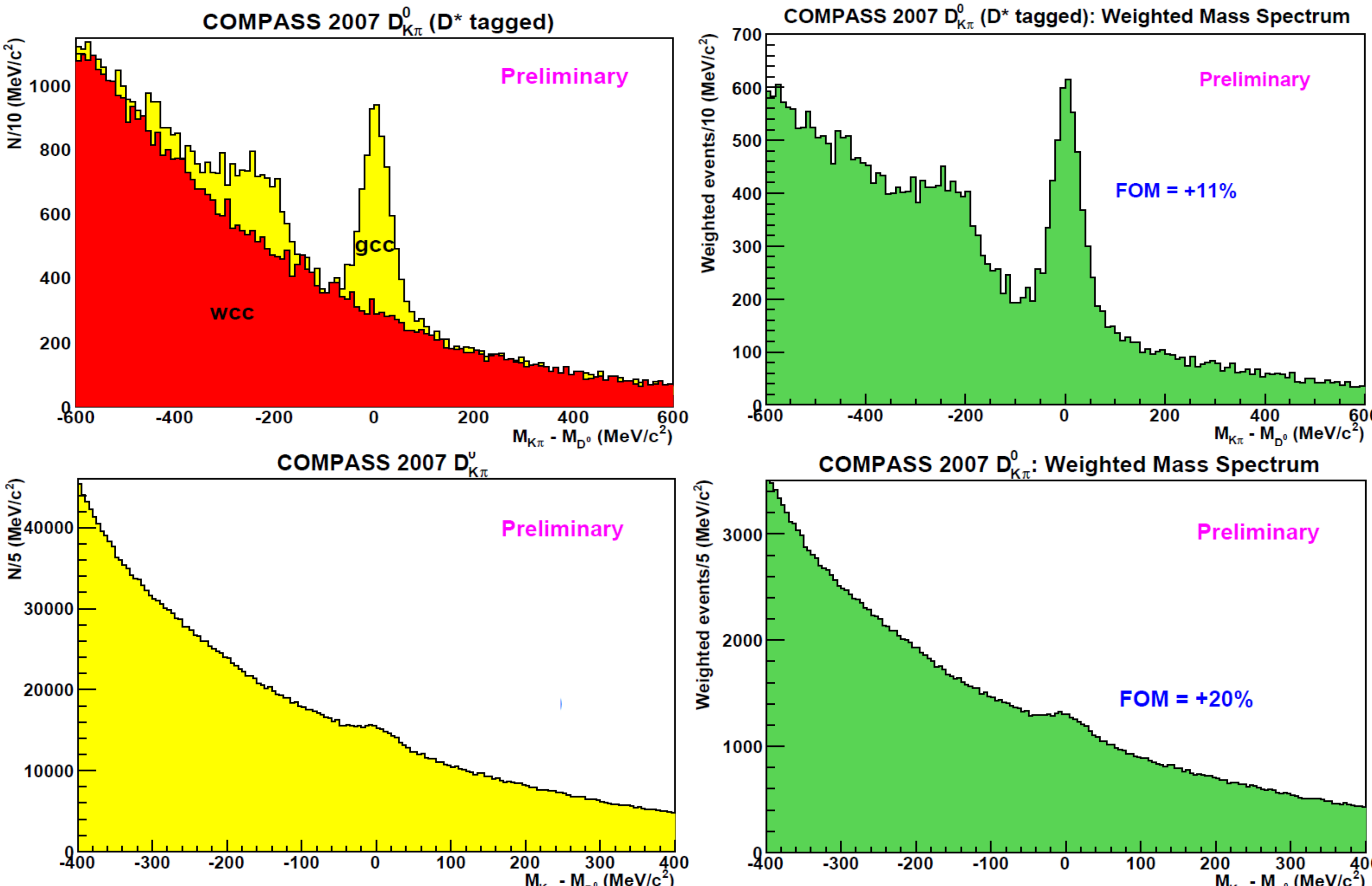
SPARES

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

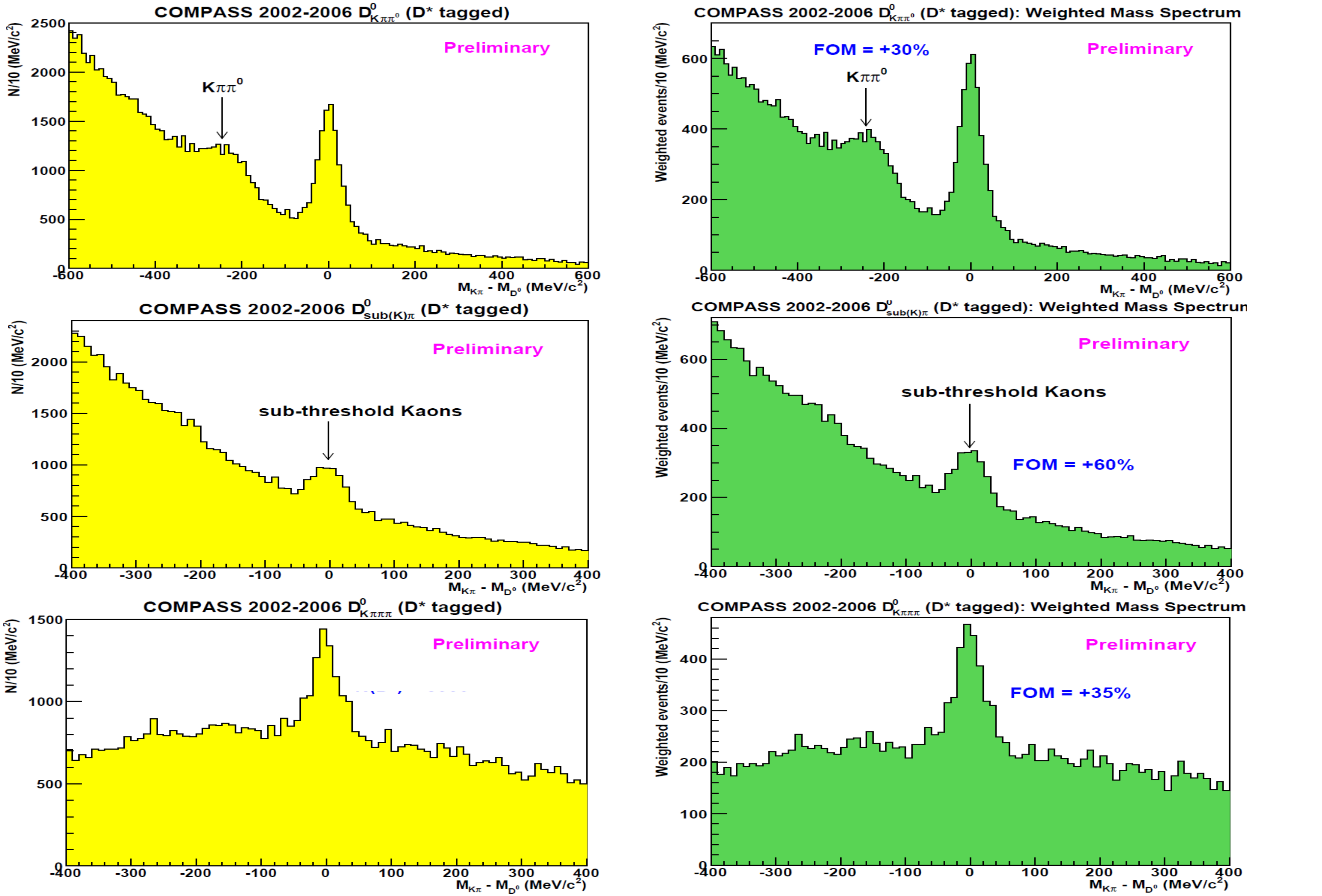


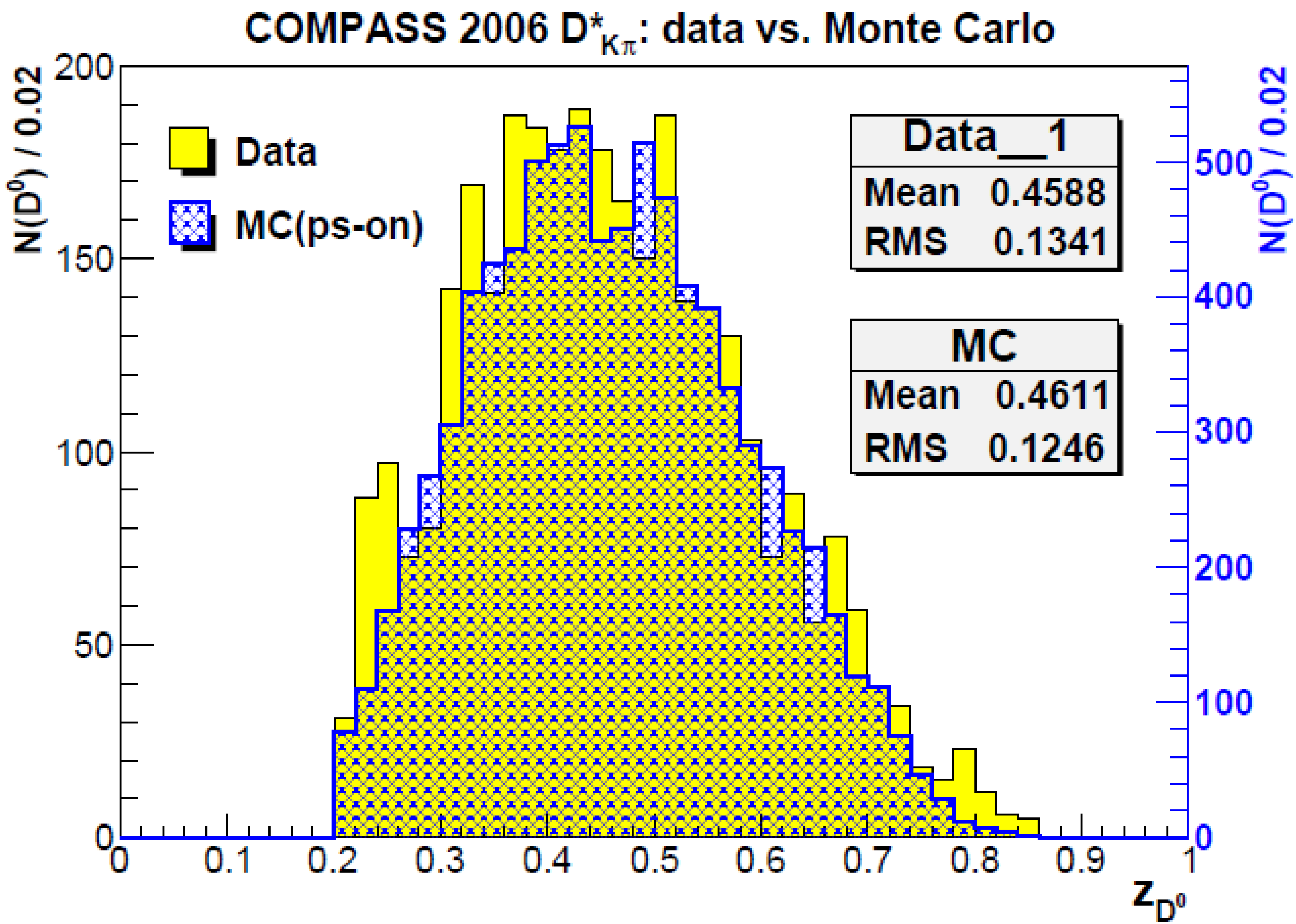
- **NN initialisation:** number of neurons + weights randomly assigned to the Net structure
- **<u>The goal is to tune the weights of each variable-neuron connection</u>:** They are iteratively adjusted to minimise the error between the expected answer *(1 for gcc and 0 for wcc)* and the neuron response *(modulated by a sigmoid activation function)*
- **To ensure universality, 2 data sets** *(train and test)* **are used:**
  - If their errors start to diverge the learning strategy is changed: Redundant neurons are killed *(new ones can born)* $\Rightarrow$ <u>Independence of precise initial conditions</u>!
- **D^0 probabilities are computed, <u>for every gcc event</u>, using the resulting multidimensional parameterisation** *(NN structure)*: **$f(o_1) = s/(s+b)_{NN}$**

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

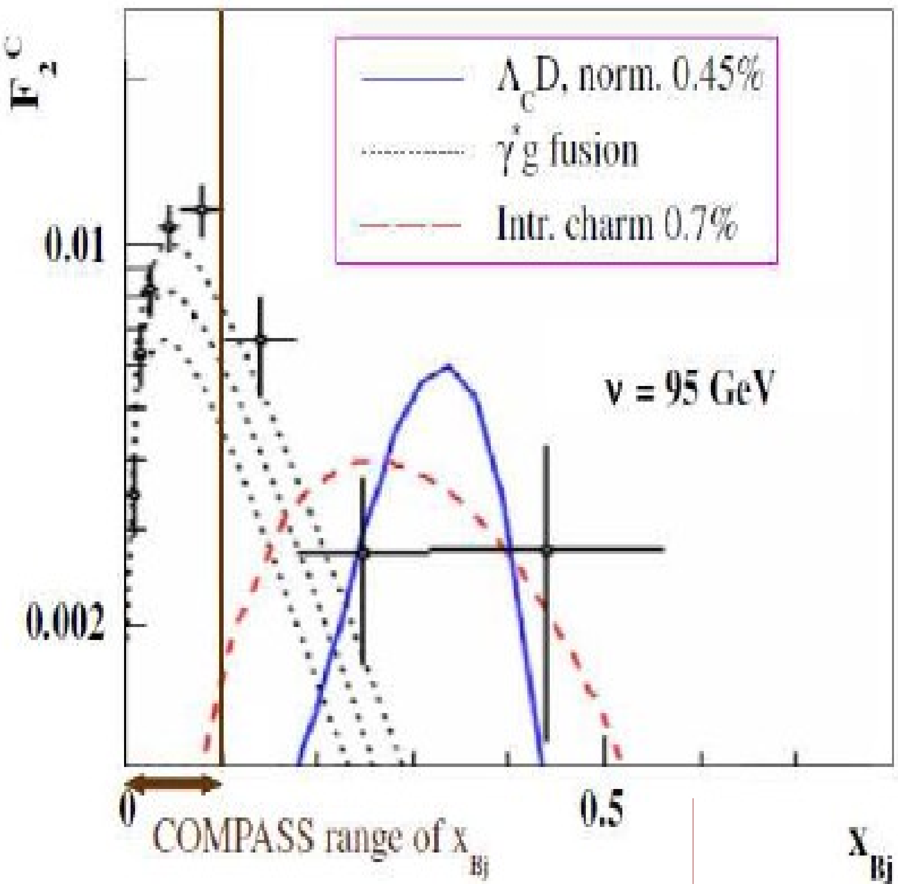


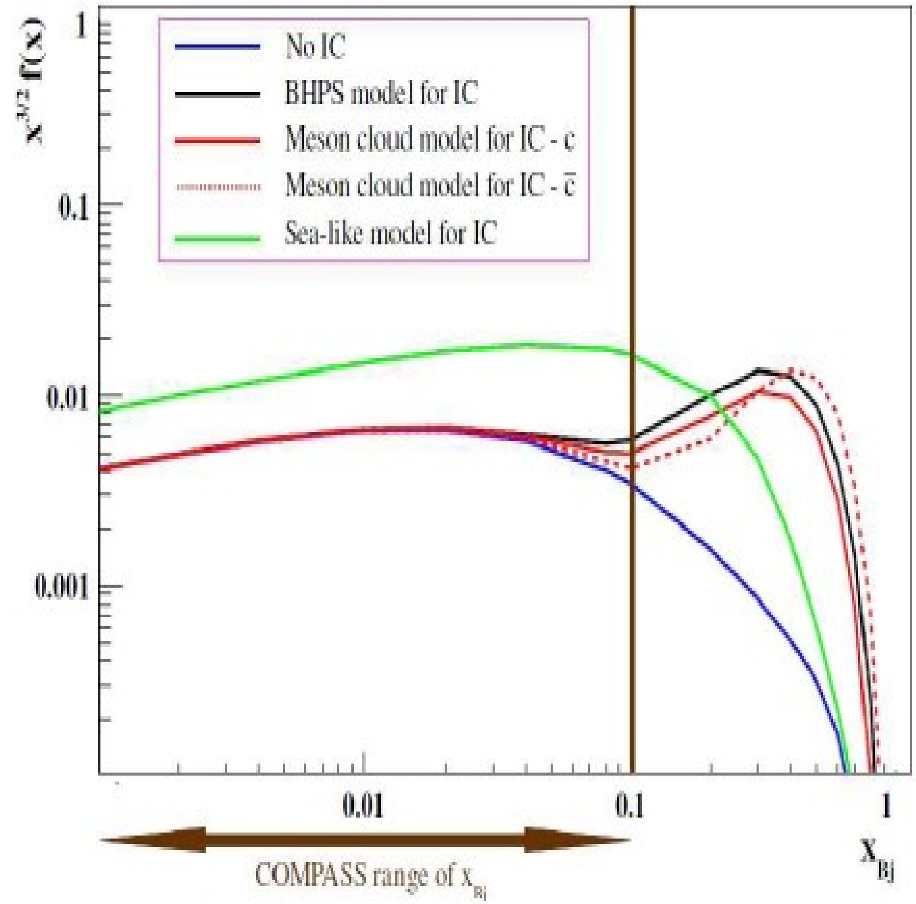
S/(S+B) parameterisation: FOM improvement *(low purity channels)*



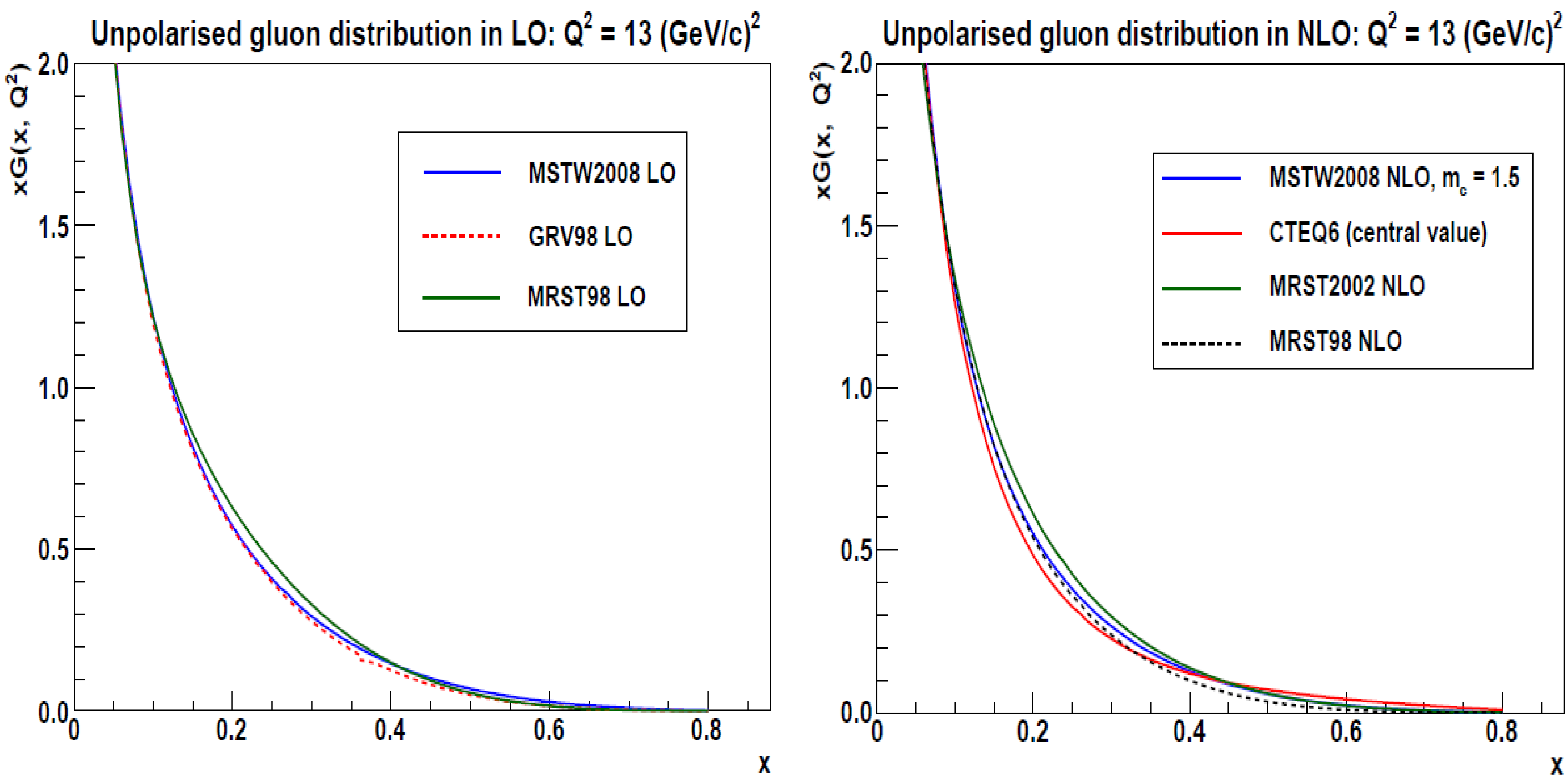


COMPASS 2006 D*Kπ: data vs. Monte Carlo
N(D0) / 0.02
Data
MC(ps-on)
Data__1
Mean 0.4588
RMS 0.1341
MC
Mean 0.4611
RMS 0.1246
0
50
100
150
200
0
100
200
300
400
500
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
zD0





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