COMPASS results on longitudinal spin physics

IWHSS11 - Paris

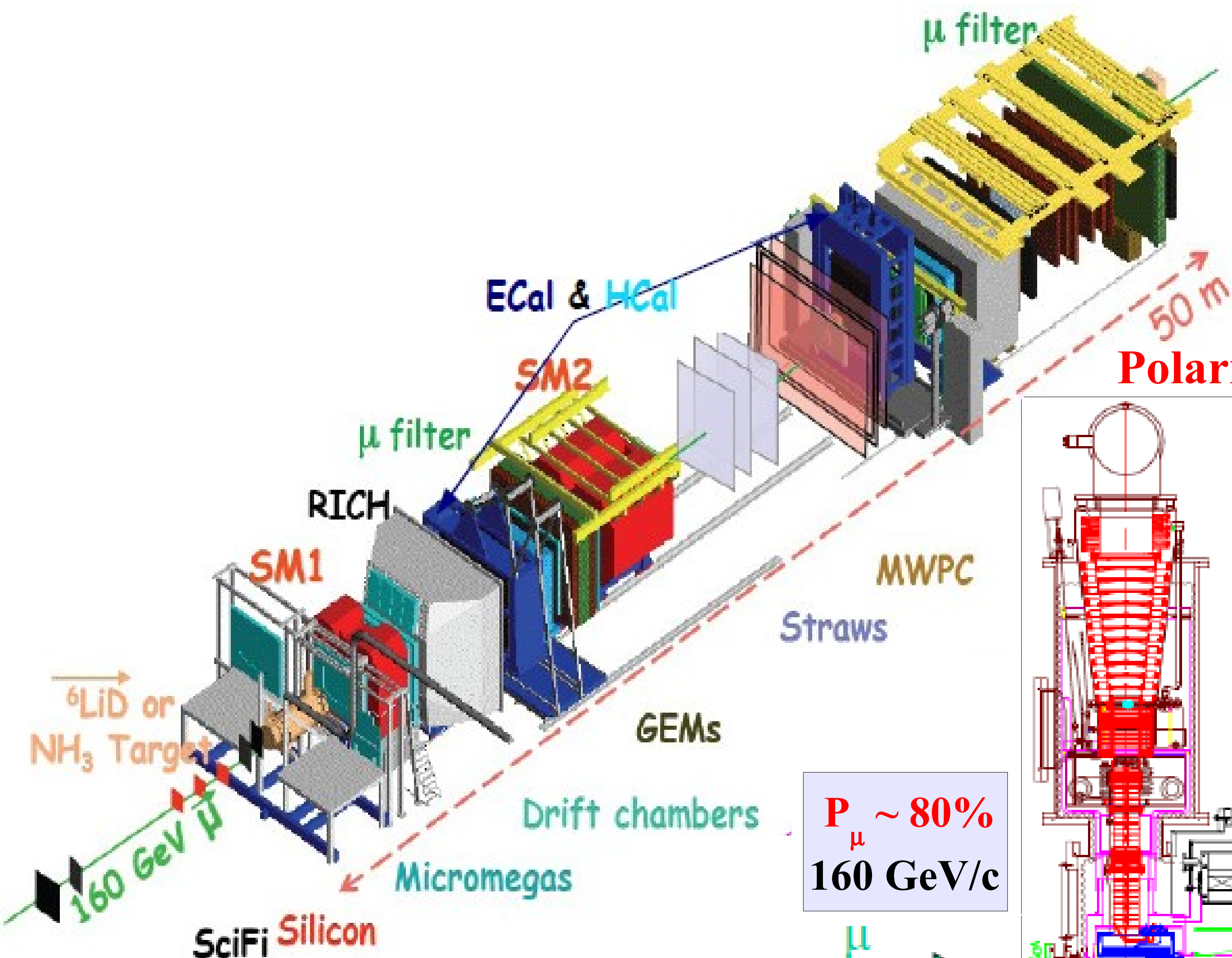
Celso Franco *(LIP – Lisboa)*
on behalf of the COMPASS collaboration

Outline

Longitudinally polarised DIS:

- $A_1^{d/p}$, $g_1^{d/p}$, first moments of g_1^d and the Bjorken sum rule
- Semi-inclusive asymmetries and flavour separation
- Gluon polarisation in LO:
  - Open Charm
  - High-p_T hadron pairs
- Gluon polarisation in NLO: $\rightarrow$ NEW
  - Open Charm

The COMPASS spectrometer and target

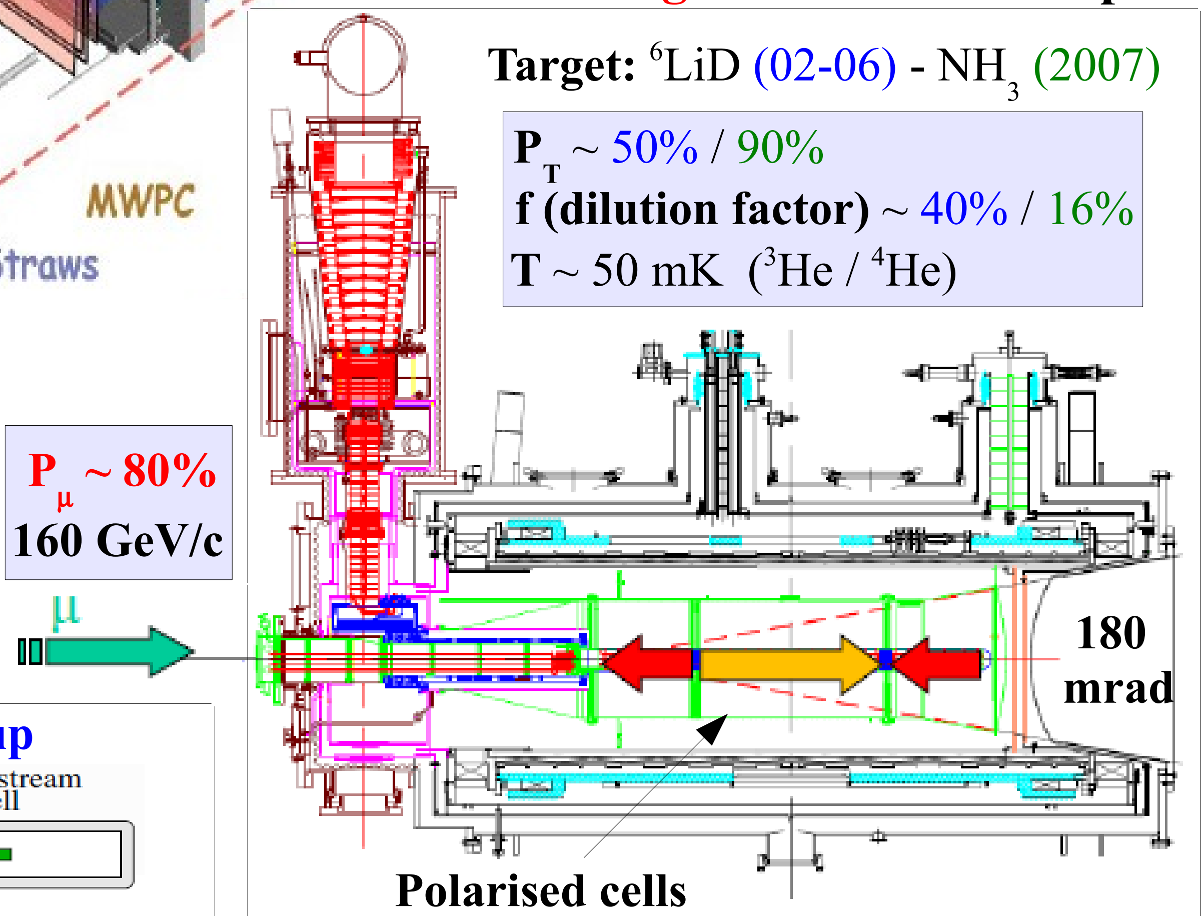


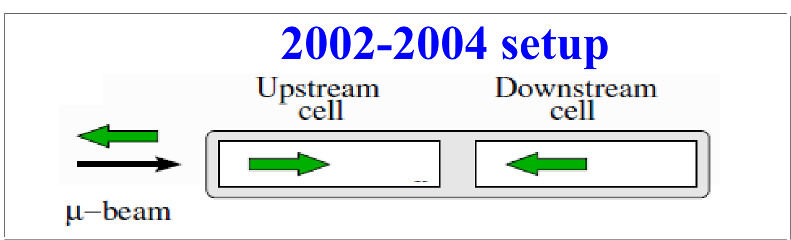
Polarised Target: 2006-2007 setup

Target: ^{6}LiD (02-06) - 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





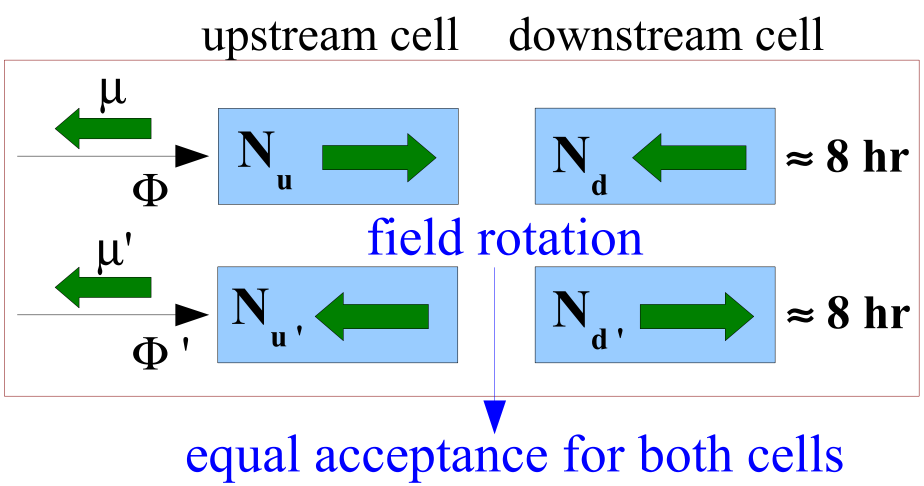
Inclusive asymmetries and spin structure functions

Asymmetry measurement: $A_1^N := \frac{\Delta\sigma_{\gamma^* N}}{\sigma_{\gamma^* N}} = \frac{\left(\sigma_{\gamma^* N}^{\rightleftarrows} - \sigma_{\gamma^* N}^{\leftleftarrows}\right)}{\sigma_{\gamma^* N}^{\mathbf{unpol}}}$

- **The number of reconstructed events inside each spin configuration,** N_t (t = u, d, u', d'), **can be used to extract the <u>γ*-deuteron / proton</u> (A_1^d / A_1^p) <u>asymmetries</u>:**

$$A^{\exp} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N_{d'} - N_{u'}}{N_{d'} + N_{u'}}\right)$$
$$= f \cdot P_\mu \cdot P_T \cdot D \cdot A_1 \longrightarrow A^{\mu N}$$

D = <u>Depolarisation factor</u>

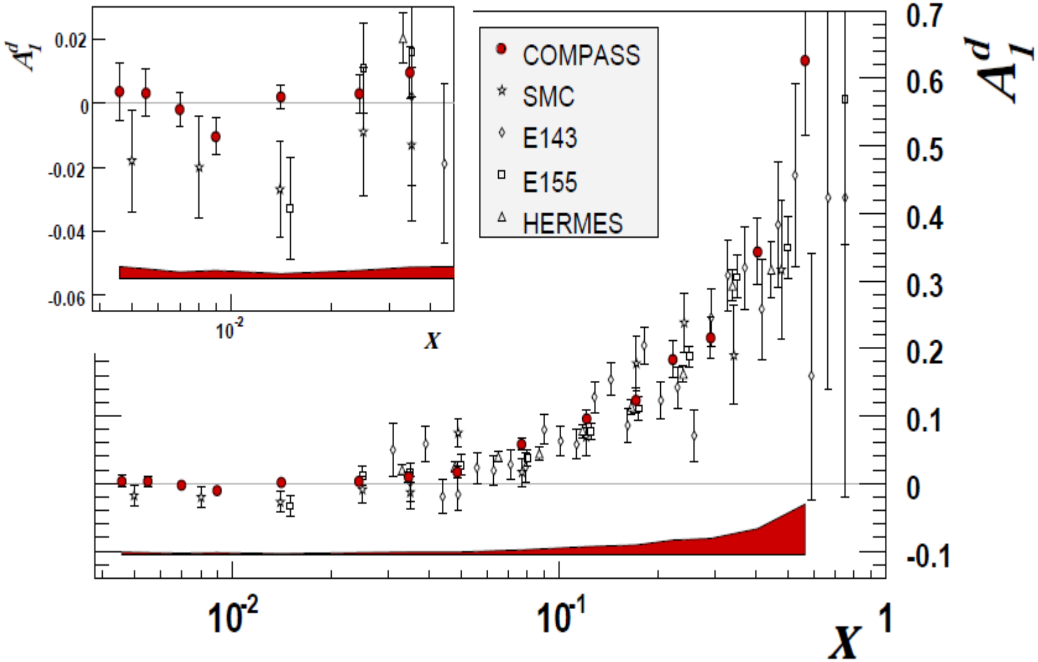


- **Weighting each event with** $\omega = (f\, P_\mu\, D)$**:**

$$A_1 = \frac{1}{P_T} \times \frac{1}{2}\left(\frac{\sum_u \omega - \sum_d \omega}{\sum_u \omega + \sum_d \omega} + \frac{\sum_{d'} \omega - \sum_{u'} \omega}{\sum_{d'} \omega + \sum_{u'} \omega}\right) \quad \text{with statistical gain:} \quad \frac{<\omega^2>}{<\omega>^2}$$

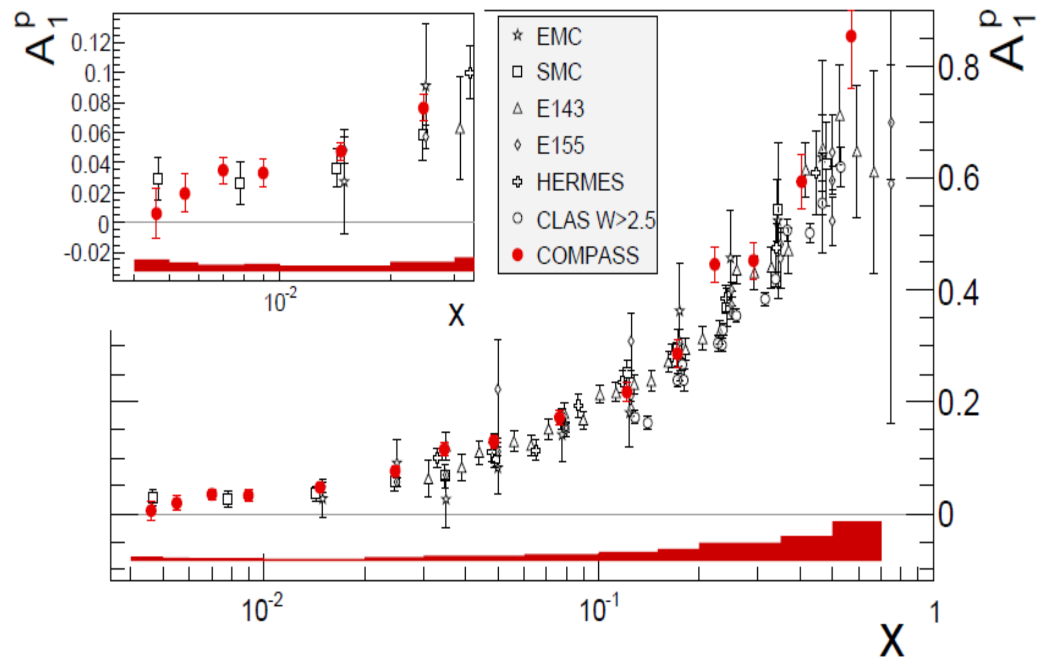
Inclusive asymmetries $A_1^{d/p}$: $Q^2 > 1\ (\mathrm{GeV}/c)^2$

Deuteron data (2002-2006)



COMPASS, PLB 647 (2007) 330-340

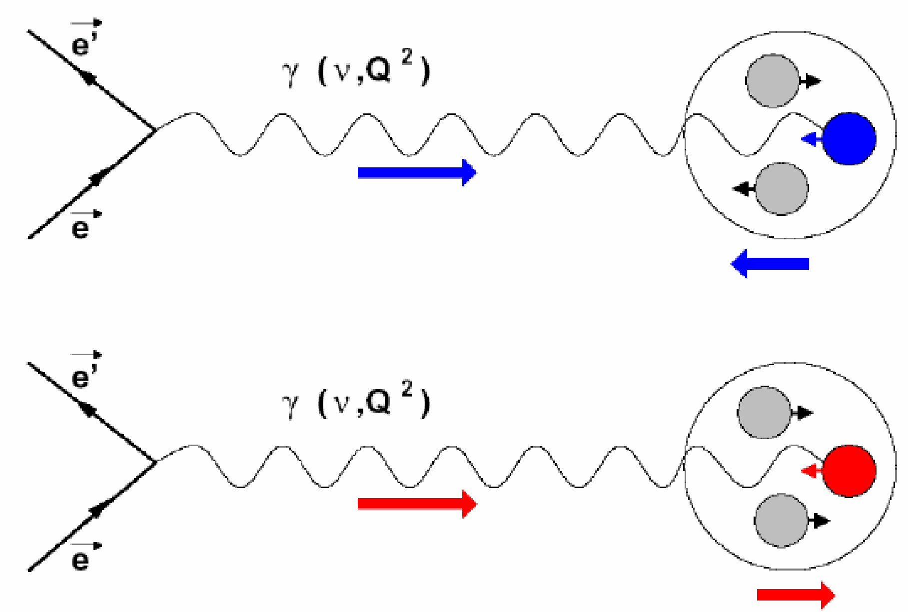
Proton data (2007)



COMPASS, PLB 690 (2010) 466-472

- Good agreement between all experimental points
- <u>Significant improvement of precision in the low x region</u>: compatible with zero for $x < 0.01$
- No negative trend for A_1^d

Interpretation of A_1 in terms of structure functions



$\sigma_{\uparrow\downarrow} \sim q^{+}$

$\sigma_{\uparrow\uparrow} \sim q^{-}$

$$\Delta q(x) = q(x)^{+} - q(x)^{-}$$

$$q(x) = q(x)^{+} + q(x)^{-}$$

\+ quark ↑↑ nucleon

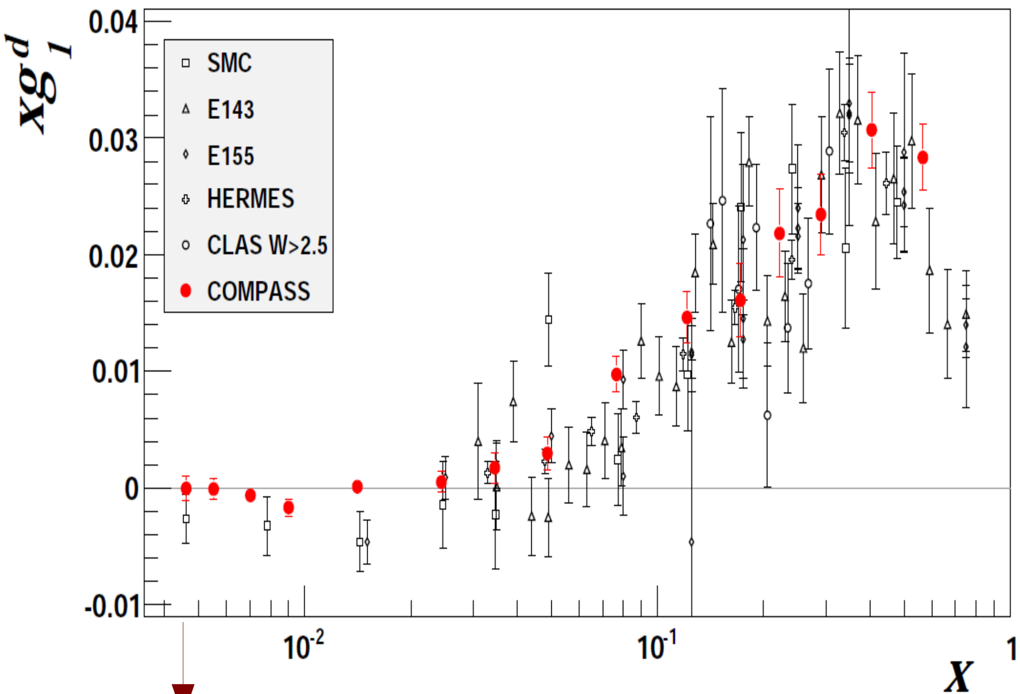
– quark ↑↓ nucleon

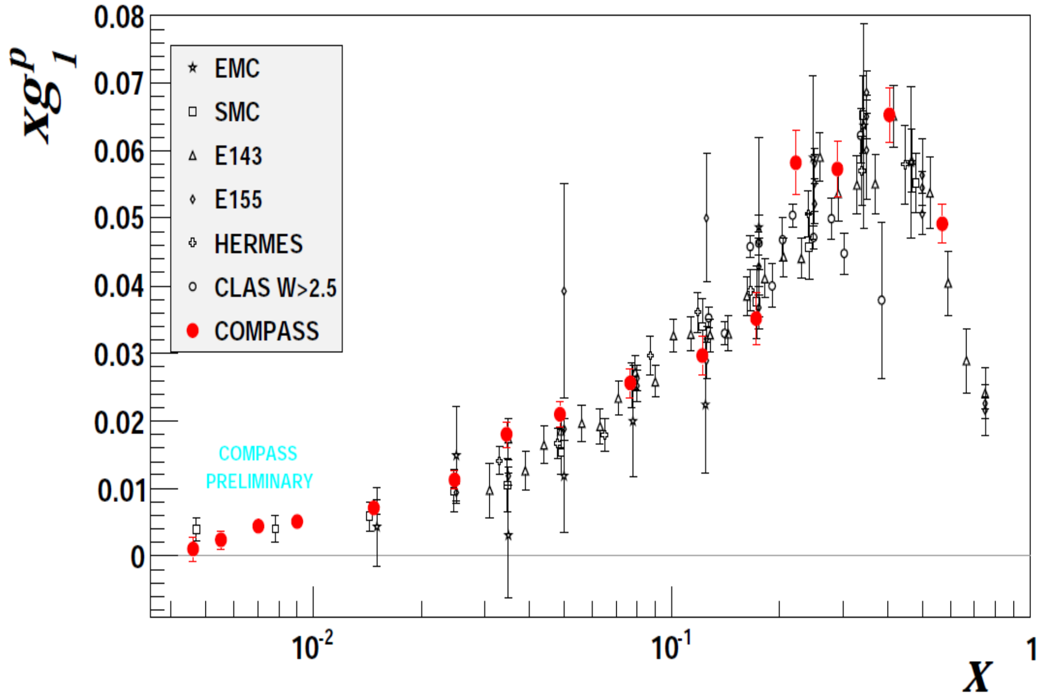
$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2)\,2x(1+R)}{F_2(x,Q^2)}$$

- g_1 (polarised structure function) **is obtained from the asymmetry A_1 using:**

$F_2 \rightarrow$ <u>SMC parameterisation</u> and $R = \sigma^L/\sigma^T \rightarrow$ <u>SLAC parameterisation</u>

COMPASS results for $g_1^{d/p}$ and first moments of g_1^d





$$\Gamma_1^N(Q_0^2=3(\mathrm{GeV}/c)^2) = \int_0^1 g_1(x)\,dx = 0.0502 \pm 0.0028(\mathrm{stat}) \pm 0.0020(\mathrm{evol}) \pm 0.0051(\mathrm{syst})$$

$$= \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right) \Rightarrow a_0 = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

$$\Delta\Sigma^{\overline{MS}} = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}) \qquad (\Delta\Sigma^{\overline{MS}} = a_0 \ @ Q^2 \to \infty)$$

$$(\Delta s + \Delta\bar{s}) = \frac{1}{3}(\Delta\Sigma^{\overline{MS}} - a_8) = -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

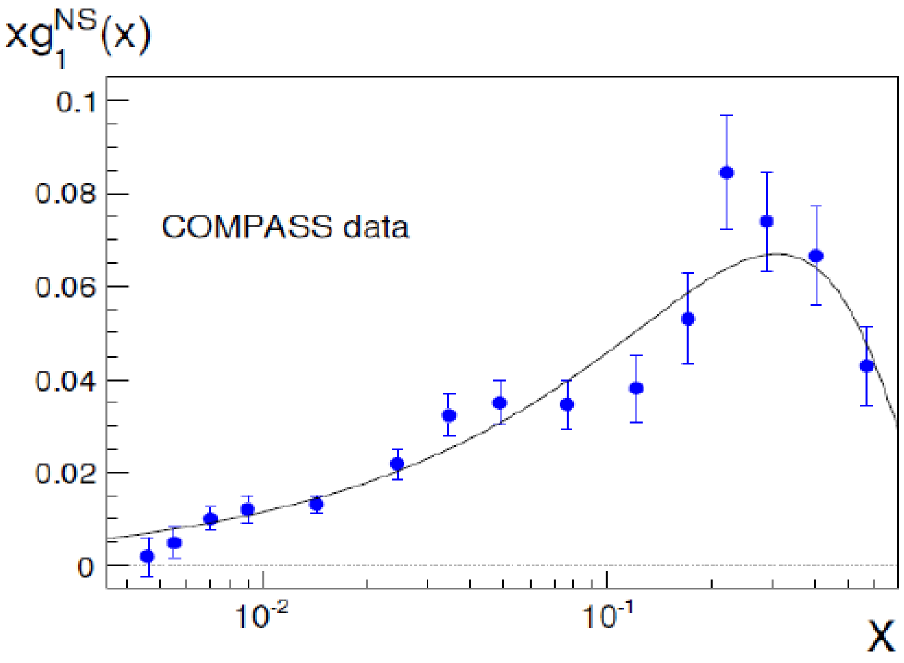
Bjorken sum rule

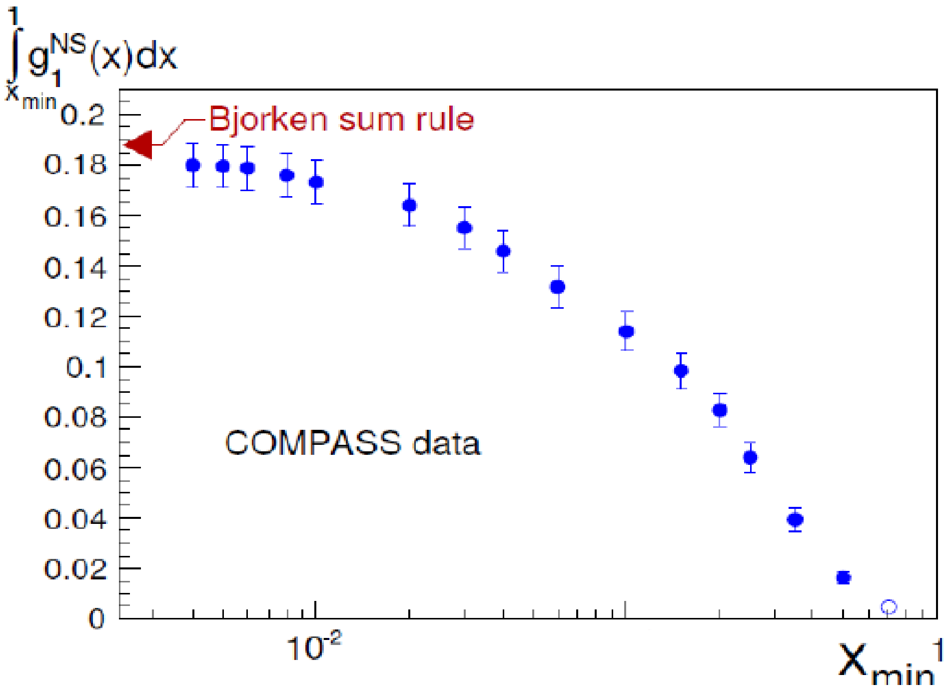
- According to the Bjorken sum rule the first moment of the non-singlet spin structure function, g_1^{NS}, is proportional to the ratio of axial and vector coupling constants g_A/g_V:

$$\int_0^1 \mathbf{g_1^{NS}(x,Q^2)\,dx} = \frac{1}{6}\left|\frac{\mathbf{g_A}}{\mathbf{g_B}}\right| \mathbf{C_1^{NS}(Q^2)}$$

using $\longrightarrow$

$$\mathbf{g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)}$$
$$= 2g_1^p - 2g_1^d/(1-1.5\,\omega_D)$$



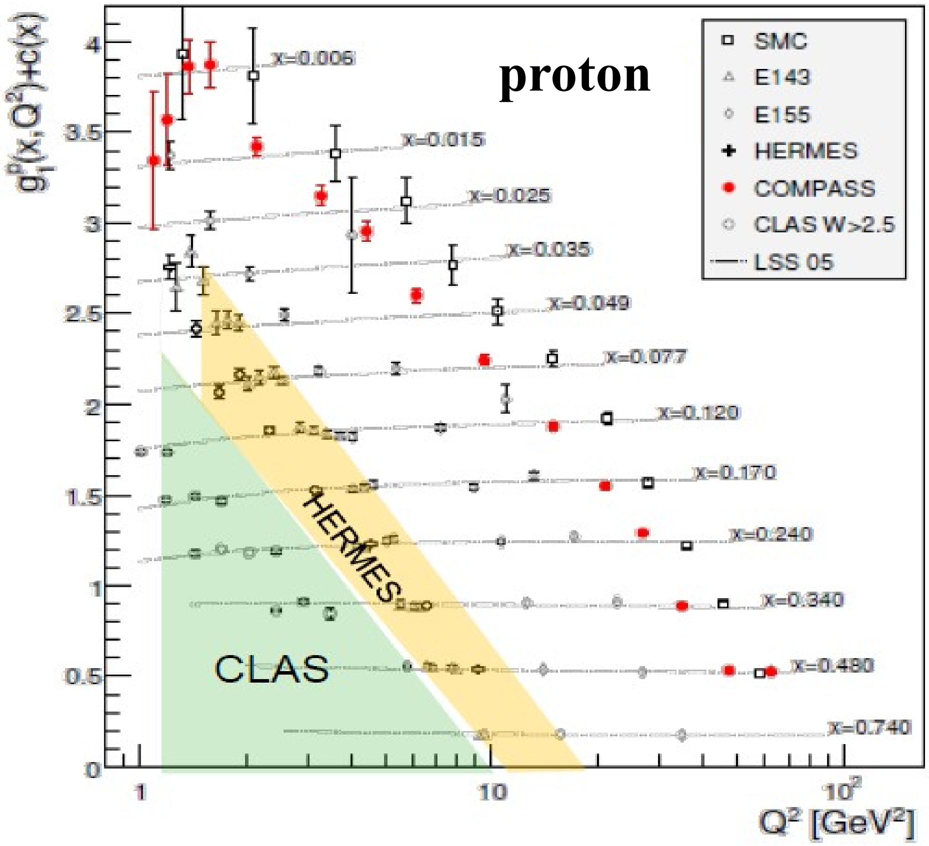


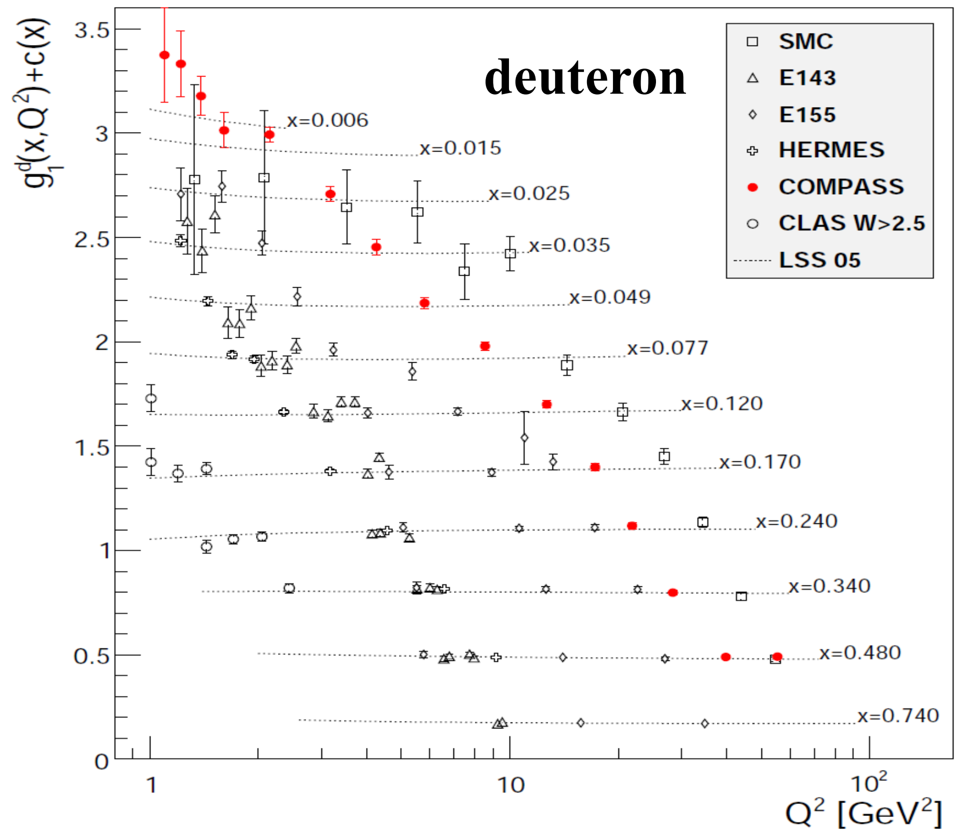
- QCD fit of COMPASS data using $\Delta q^{NS} = |g_A/g_V|\, x^{\alpha}(1-x)^{\beta}$:

$$\left|\frac{\mathbf{g_A}}{\mathbf{g_V}}\right| = 1.28 \pm 0.07(\mathbf{stat}) \pm 0.10(\mathbf{sys})$$

(PDG value: $|g_A/g_V| = 1.269 \pm 0.003$)

Q^2 dependence of $g_1(x, Q^2)$ for DGLAP evolution





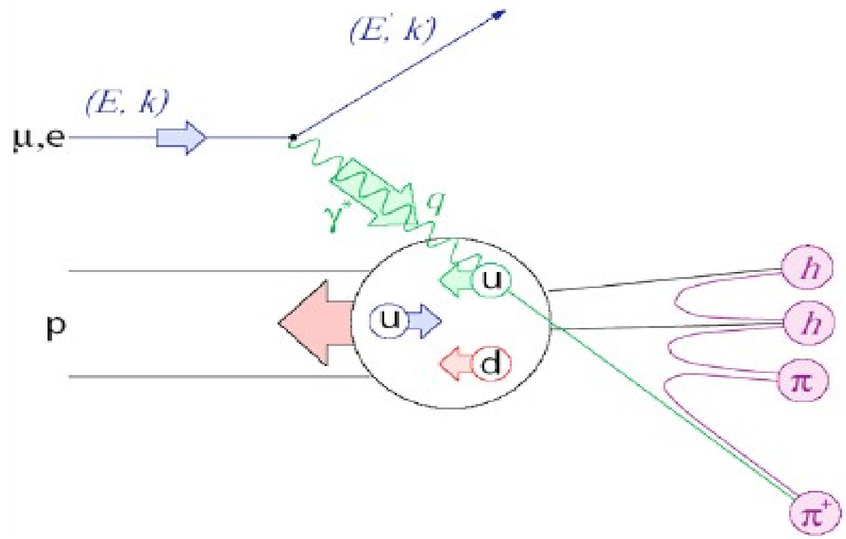
- The kinematic range is still limited (compared to the unpolarised F_2)

  → additional data from colliders is required !

- $(\Delta u + \Delta \bar{u})$ and $(\Delta d + \Delta \bar{d})$ are well constrained by the data (*LSS PRD 80 2009*)
- Δs comes out negative and Δg is small (< 0.5) → Still with large uncertainties

Semi-inclusive asymmetries and flavour separation

Extraction of the quark helicity distributions from SIDIS



- The outgoing hadron tags the quark flavour
- Required: fragmentation function of a quark q to a hadron h: $D_q^{\,h}(z, Q^2)$

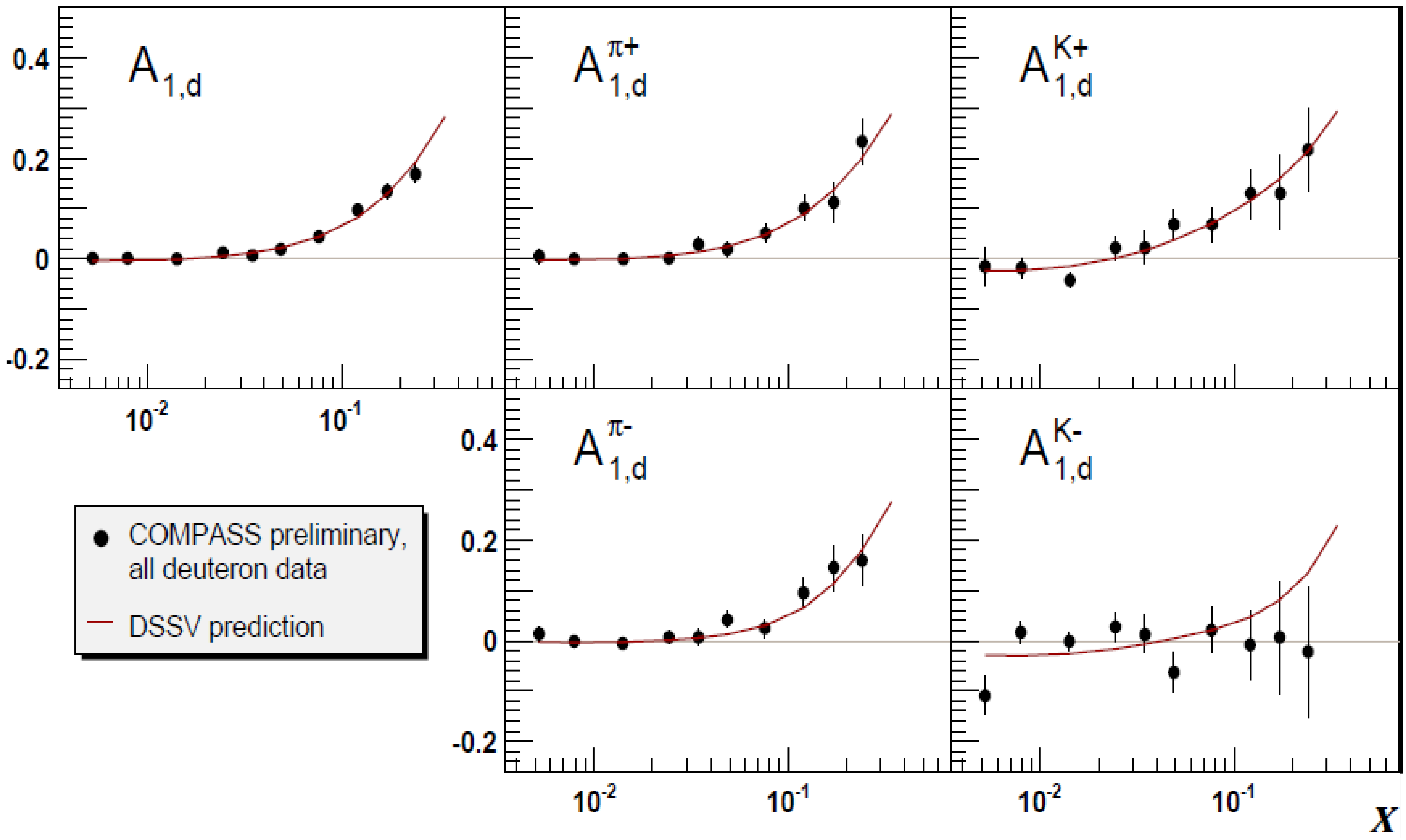
$z = E_h/(E_\mu - E'_\mu)$

- **The semi-inclusive asymmetries have the following interpretation** (in LO):

$$A_1^{h\,(p/d)}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}$$

- **Inputs needed for the extraction of Δq(x, Q²):**
  - Unpolarised PDFs ($q(x, Q^2)$) → MRST04
  - $D_q^{\,h}(z, Q^2)$ → DSS parameterisation

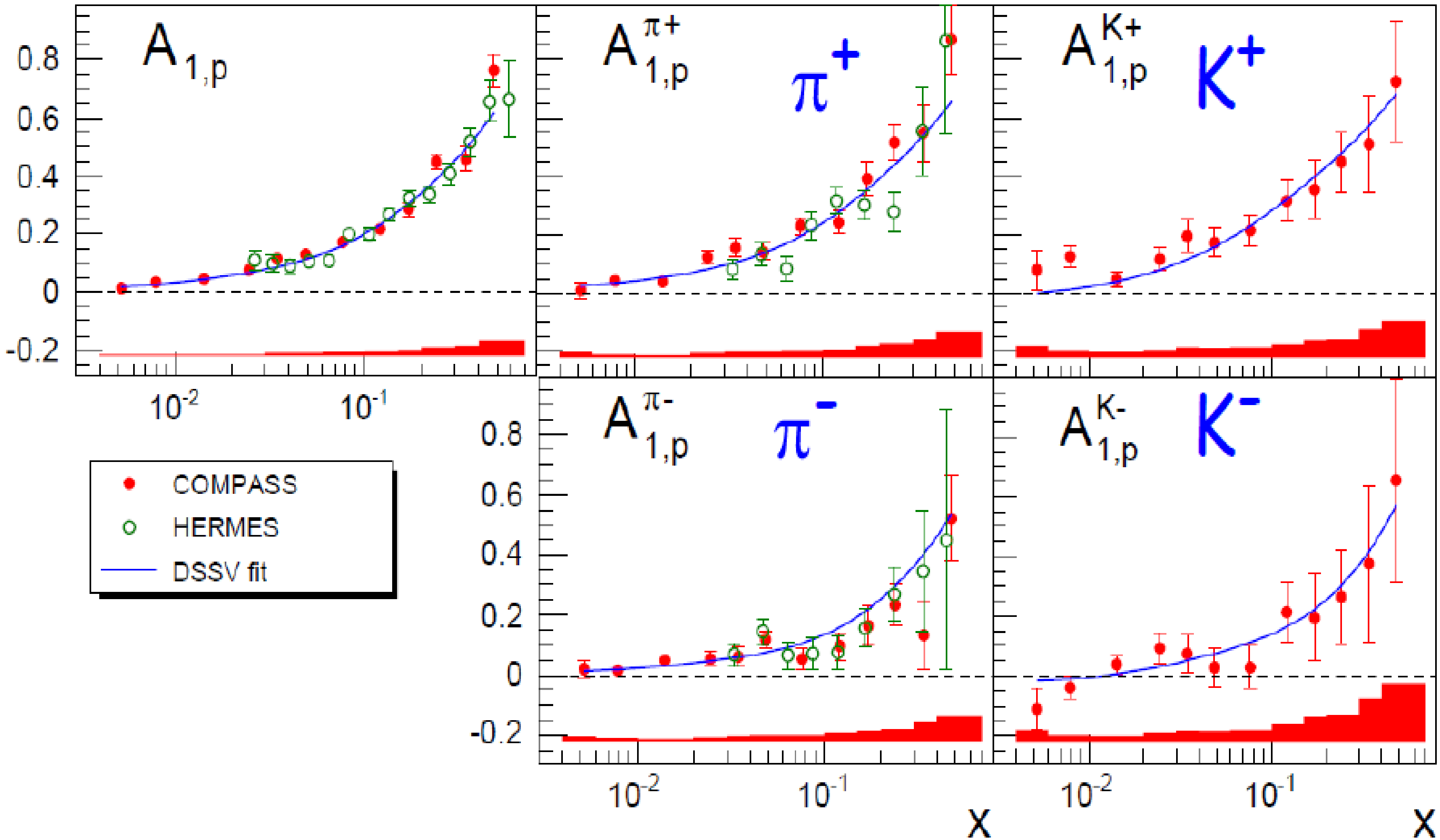
Inclusive and semi-inclusive spin asymmetries: Deuteron data



- **From these asymmetries one can extract:** $\Delta u + \Delta d$, $\Delta \bar{u} + \Delta \bar{d}$ and $\Delta s = \Delta \bar{s}$

Inclusive and semi-inclusive spin asymmetries: Proton data

First measurement ever of $A^{K}_{1,p}$



- **Using $A^{h}_{1,p}$ and $A^{h}_{1,d}$, <u>we can separately extract</u>:** Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs and $\Delta\bar{s}$

Comparison of Δs with $\Delta\bar{s}$

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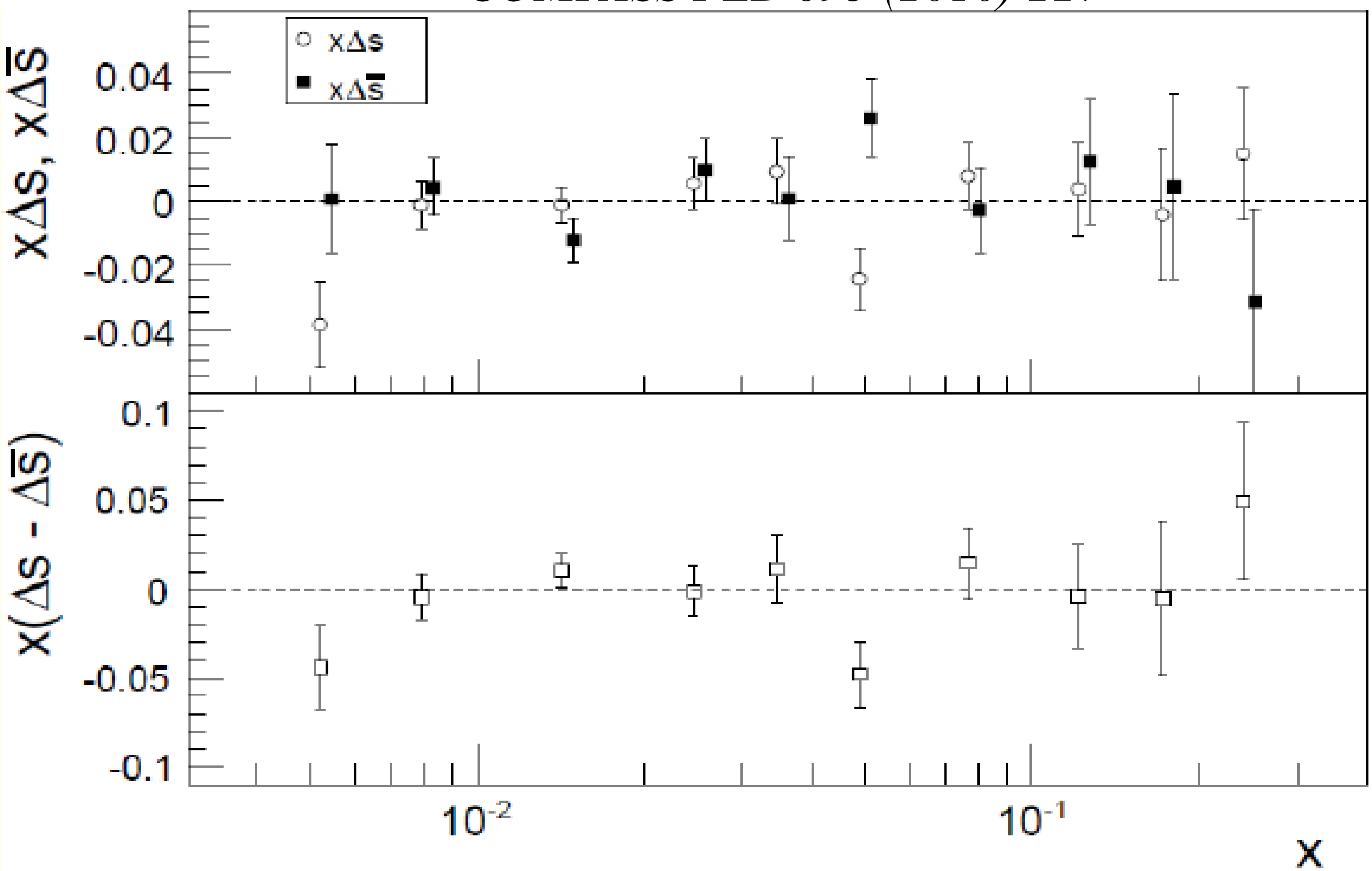
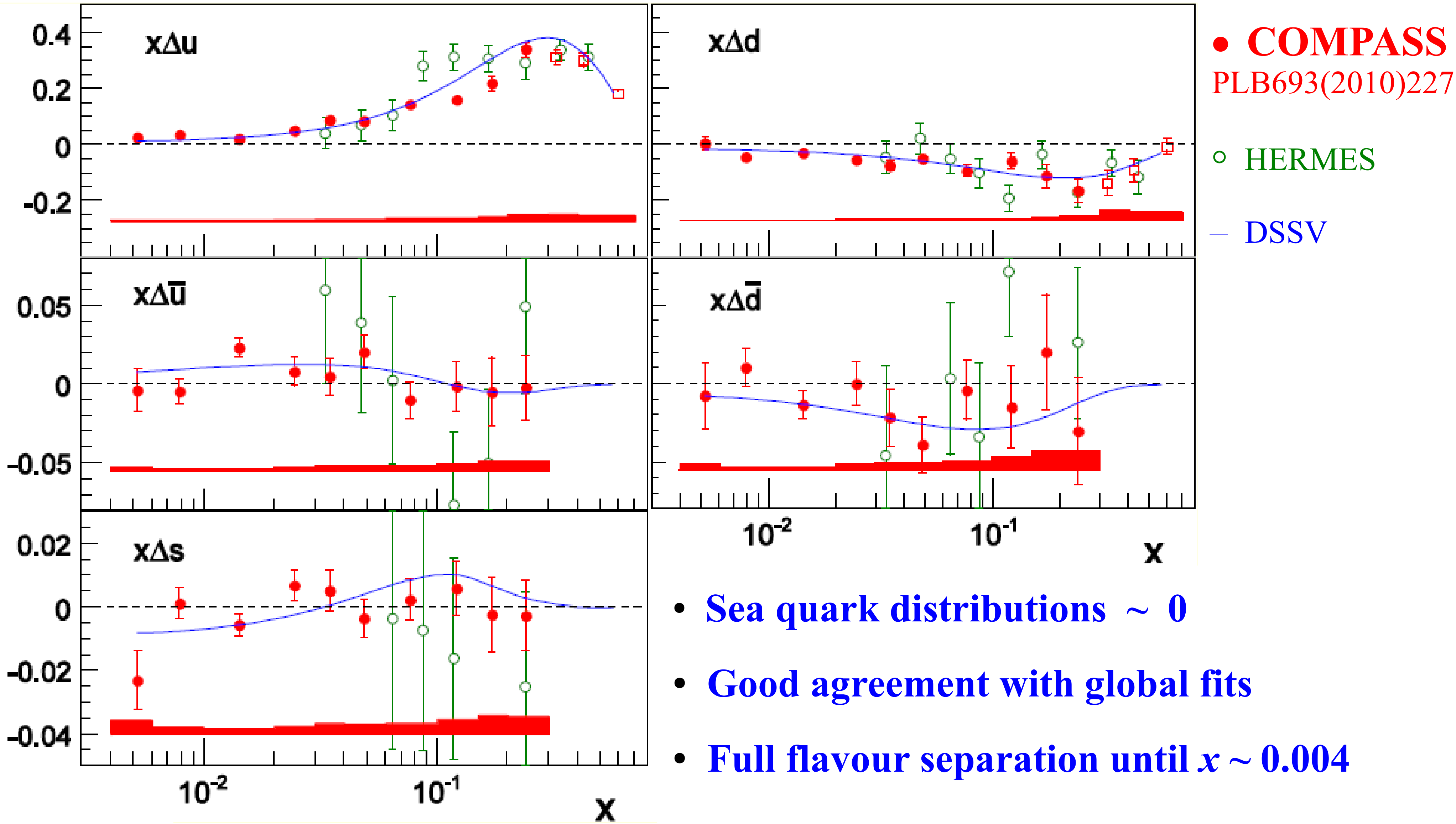


$\Delta s - \Delta\bar{s}$ is compatible with 0 $\rightarrow$ $\Delta s = \Delta\bar{s}$ is assumed in the subsequent analysis

Quark helicities from SIDIS ($Q^2 = 3\ (GeV/c)^2$ and $x < 0.3$)



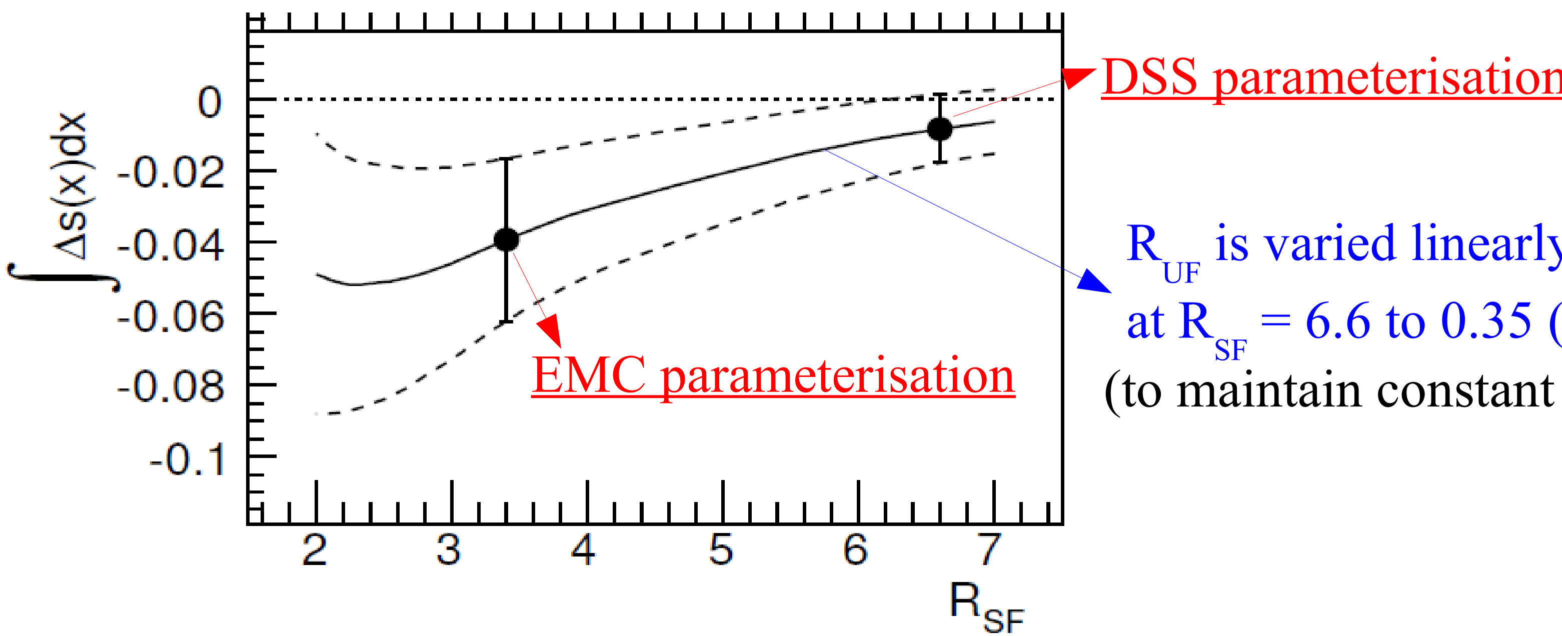
- **Sea quark distributions ~ 0**
- **Good agreement with global fits**
- **Full flavour separation until *x* ~ 0.004**

$$\Delta s(\text{SIDIS}) = -0.01 \pm 0.01(\text{stat}) \pm 0.01(\text{syst}) \quad @ \; 0.003 < x < 0.3$$

Δs dependence on FFs

- The relation between the semi-inclusive asymmetries and Δs depends only on the following ratios:

$$R_{UF} = \frac{\int_{0.2}^{0.85} D_d^{K^+}(z)\,dz}{\int_{0.2}^{0.85} D_u^{K^+}(z)\,dz}, \quad R_{SF} = \frac{\int_{0.2}^{0.85} D_{\bar{s}}^{K^+}(z)\,dz}{\int_{0.2}^{0.85} D_u^{K^+}(z)\,dz}$$

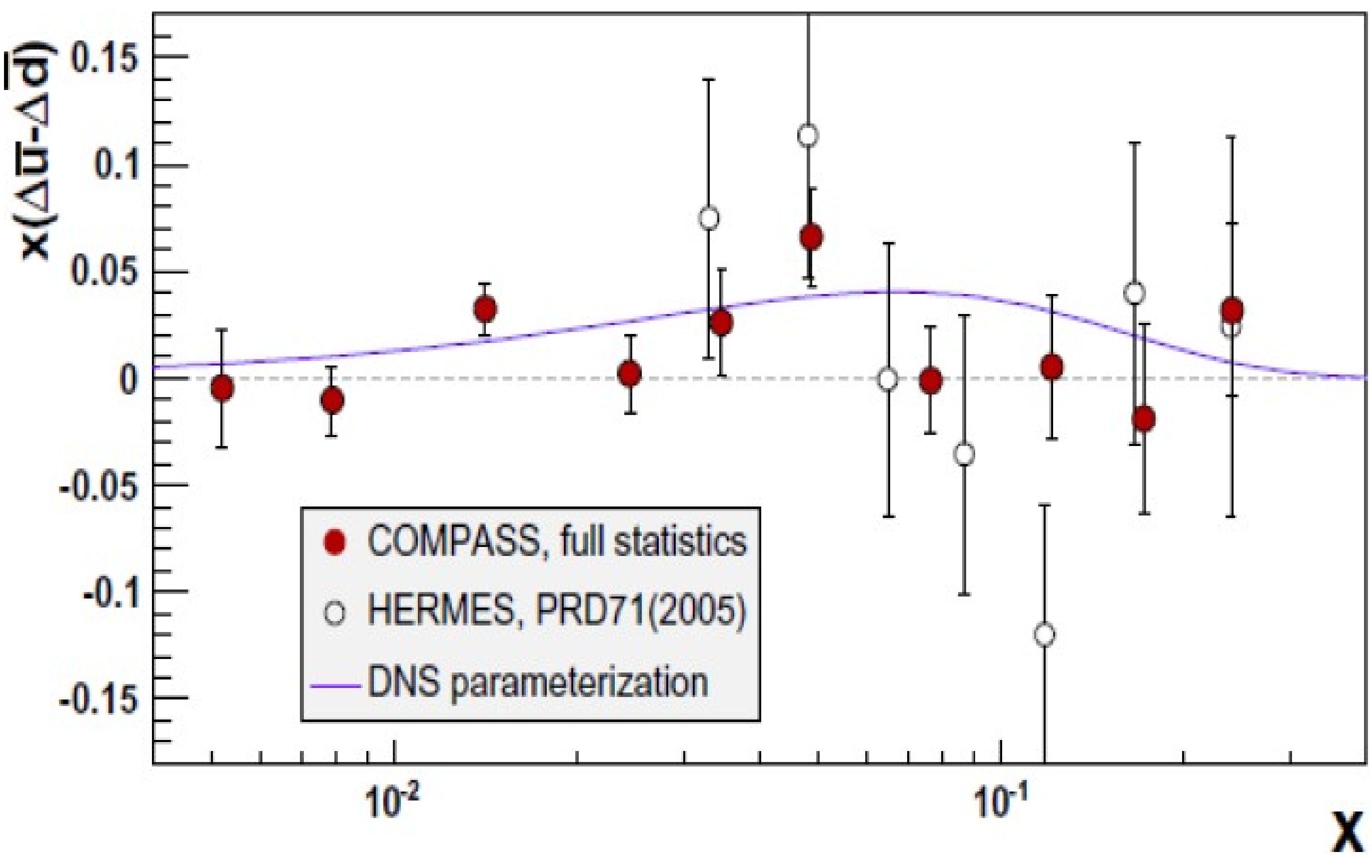


R_{UF} is varied linearly from 0.13 (DSS) at R_{SF} = 6.6 to 0.35 (EMC) at R_{SF} = 3.4 (to maintain constant the K^+ multiplicity)

- Determination of R_{SF} from hadron multiplicities on the way

$\Delta\bar{u} - \Delta\bar{d}$: Flavour asymmetry?

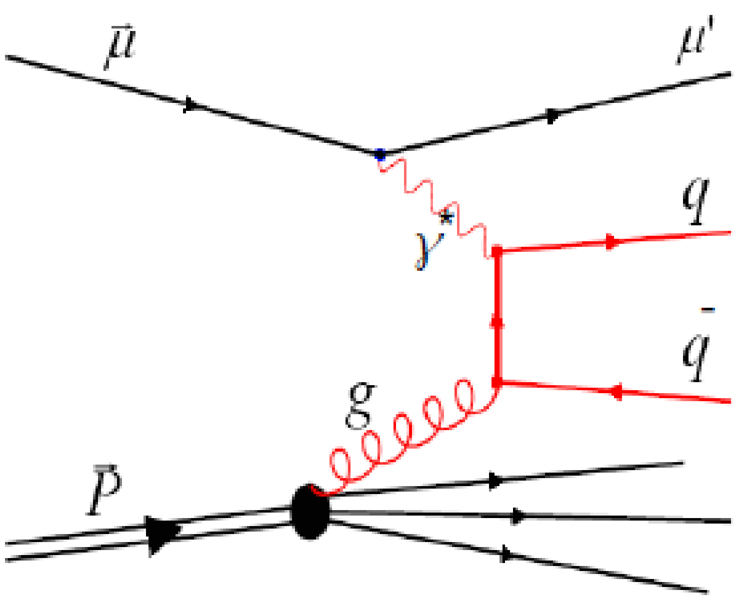
- The considerable asymmetry observed for $(\bar{u} - \bar{d})$ is not verified in the polarised case :
  - $\Delta\bar{u} - \Delta\bar{d}$ is slightly positive but compatible with zero!



Gluon Polarisation

Direct measurement of $\Delta G/G$ in LO

photon-gluon fusion process (PGF)



$$A_{\gamma N}^{PGF} = \frac{\int d\hat{s}\, \Delta\sigma^{PGF} \Delta G(x_G, \hat{s})}{\int d\hat{s}\, \sigma^{PGF} G(x_G, \hat{s})}$$

$$\approx \langle a_{LL}^{PGF} \rangle \frac{\Delta G}{G}$$

analysing power

There are two methods to tag this process:

- **Open Charm production**
  - $\gamma^* g \to c\bar{c} \Rightarrow$ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly Monte Carlo dependent
  - Low statistics
- **High-p_T hadron pairs**
  - $\gamma^* g \to q\bar{q} \Rightarrow$ reconstruct 2 jets or h^+h^-
  - Hard scale: Q^2 or Σp_T^2 [$Q^2 > 1$ or $Q^2 < 1$ $(GeV/c)^2$]
  - High statistics
  - Physical background
  - Strongly Monte Carlo dependent

Open Charm

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

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

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

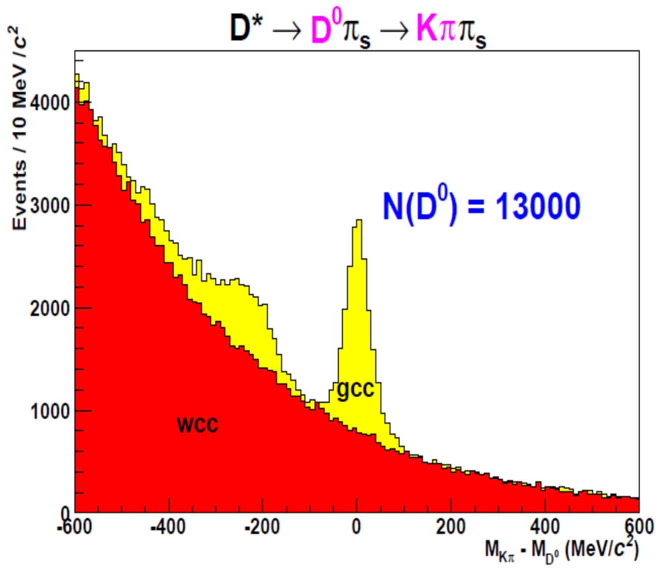
acceptance, muon flux, number of target nucleons Open Charm event probability

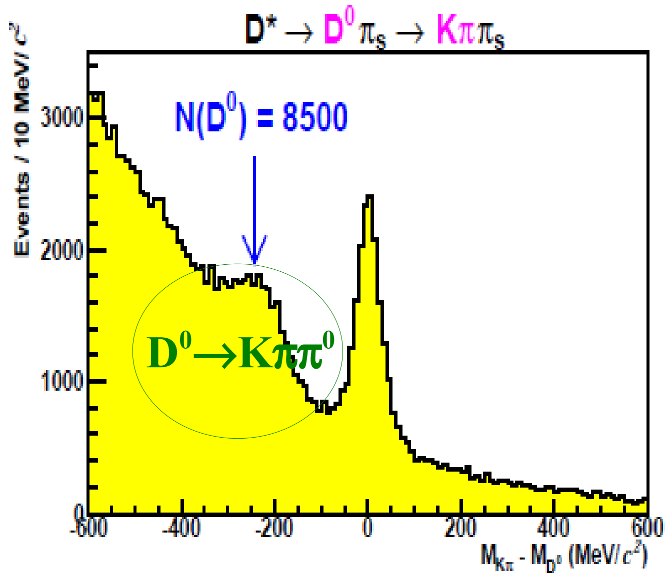
- Each equation is weighted with a signal weight $\omega_S = f\,P_\mu\,a_{LL}\,S/(S+B)$ and also with a background weight $\omega_B = f\,P_\mu\,D\,B/(S+B)$:

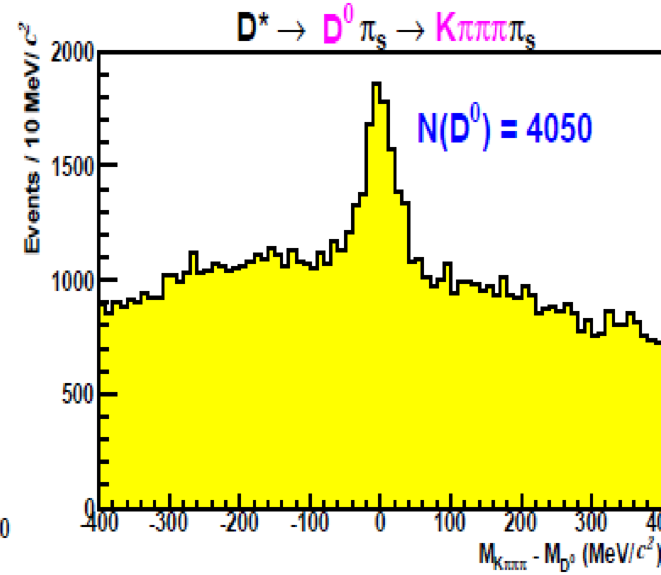
8 equations with 7 unknowns: $\Delta G/G$, A^{bg} + 5 independent $\alpha = (a\phi n)$ factors

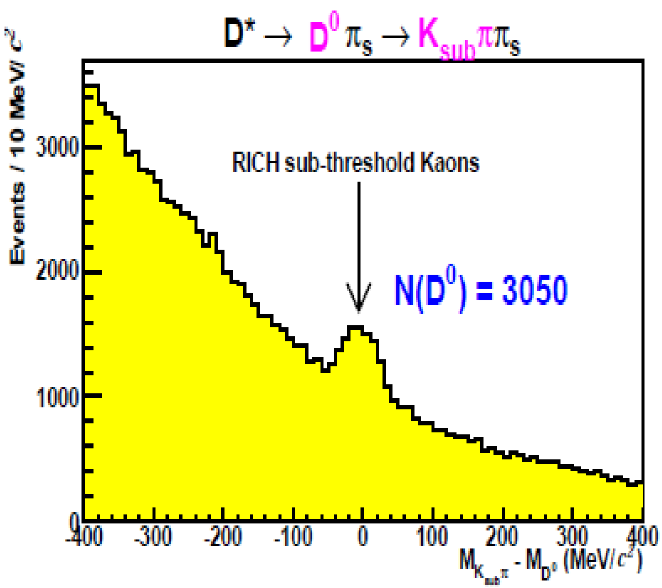
The system is solved by a χ^2 minimisation

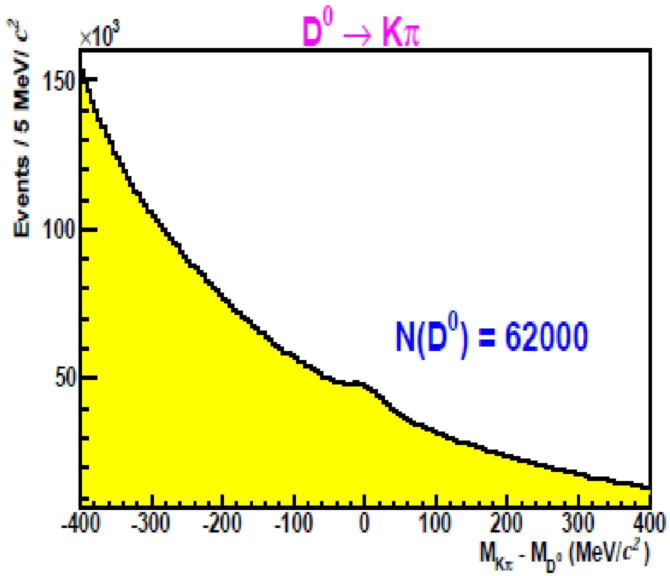
D^0 invariant mass spectra: All samples (2002-2007 data)











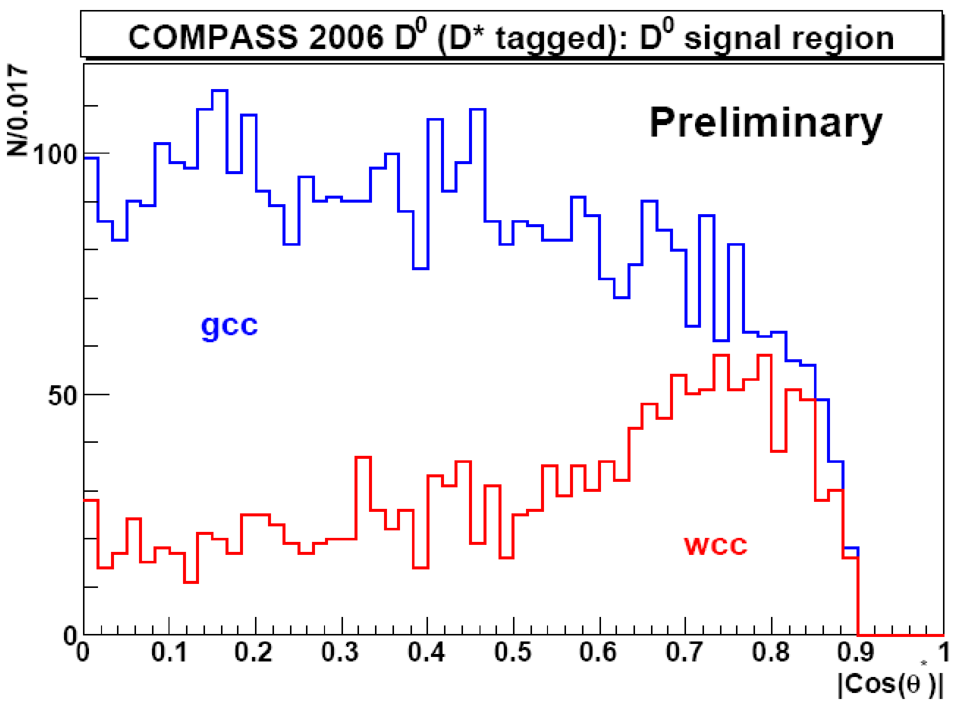
Number of D^0:

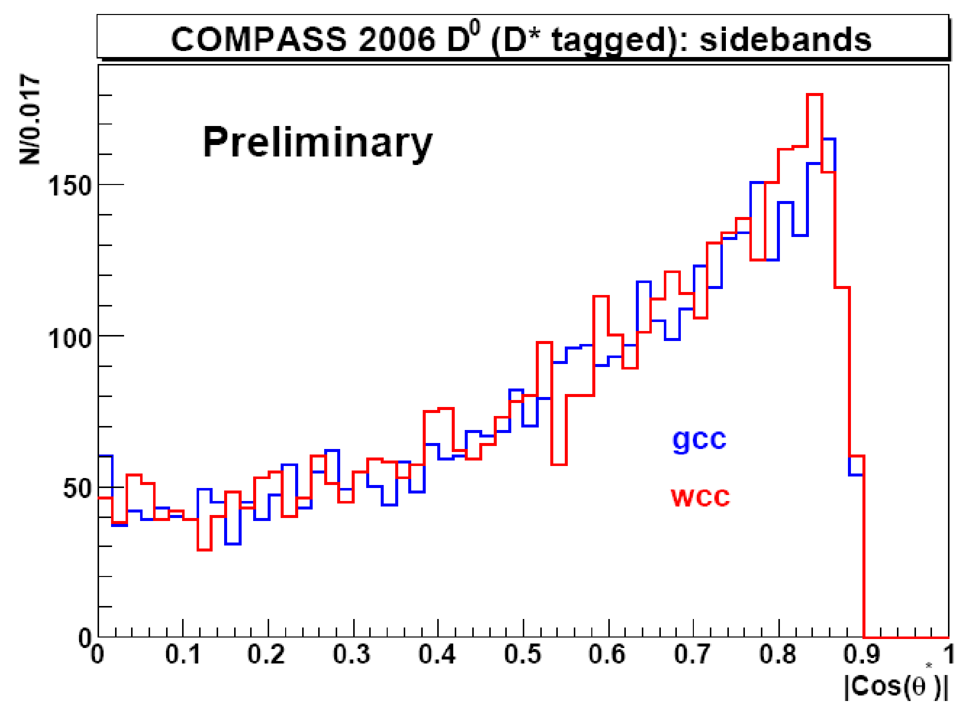
- Total → 90600
- ^{6}LiD → 65600
- NH_3 → 25000

Neural Network qualification of events

- **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)

Example of a good learning variable

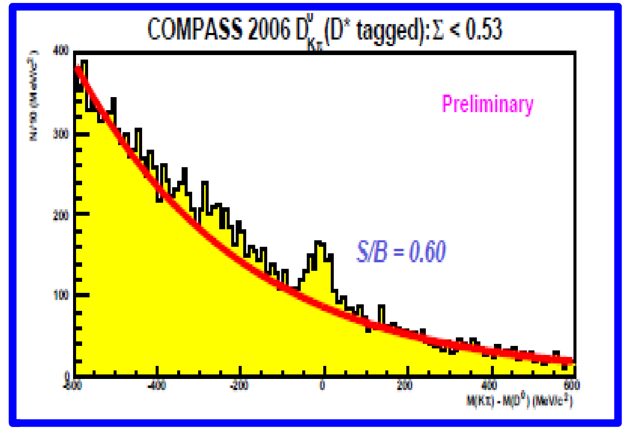


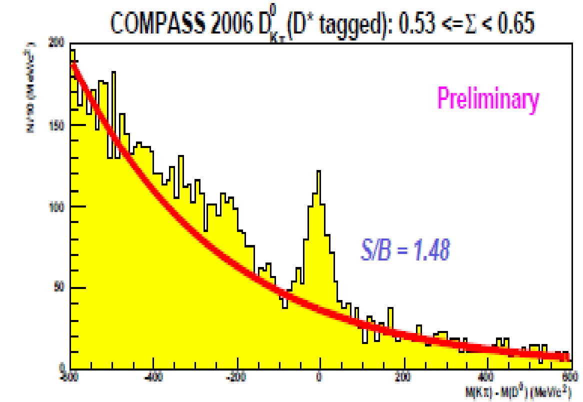


S/(S+B): Obtaining final probabilities for a D^0 candidate

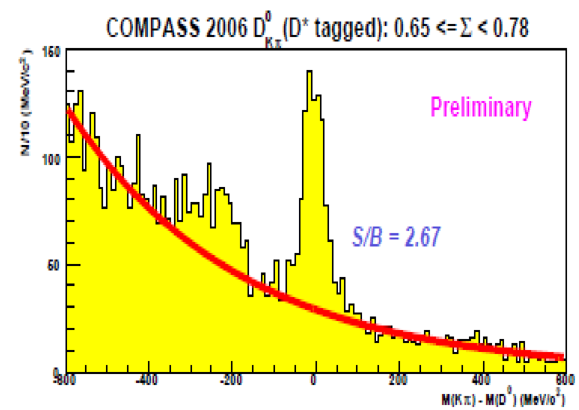
$D^0_{K\pi}$ tagged spectrum in bins of $\Sigma = S/(S+B)_{NN}$

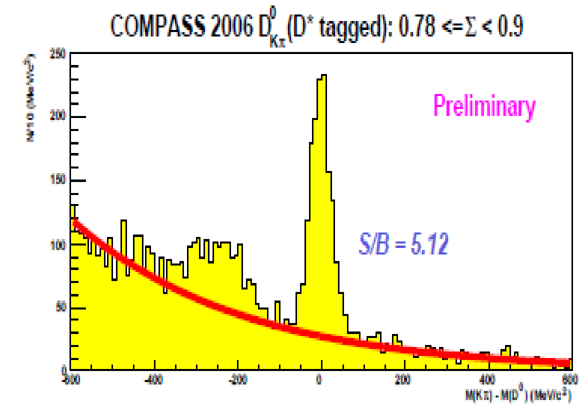
- **Events with small $S/(S+B)_{NN}$**
  - Mostly combinatorial background is selected



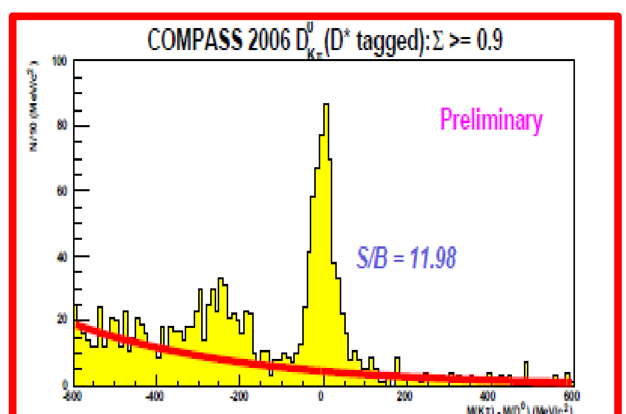


<u>S/(S+B) is obtained from a fit inside this bins</u> *(correcting with the NN parameterisation)*





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



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

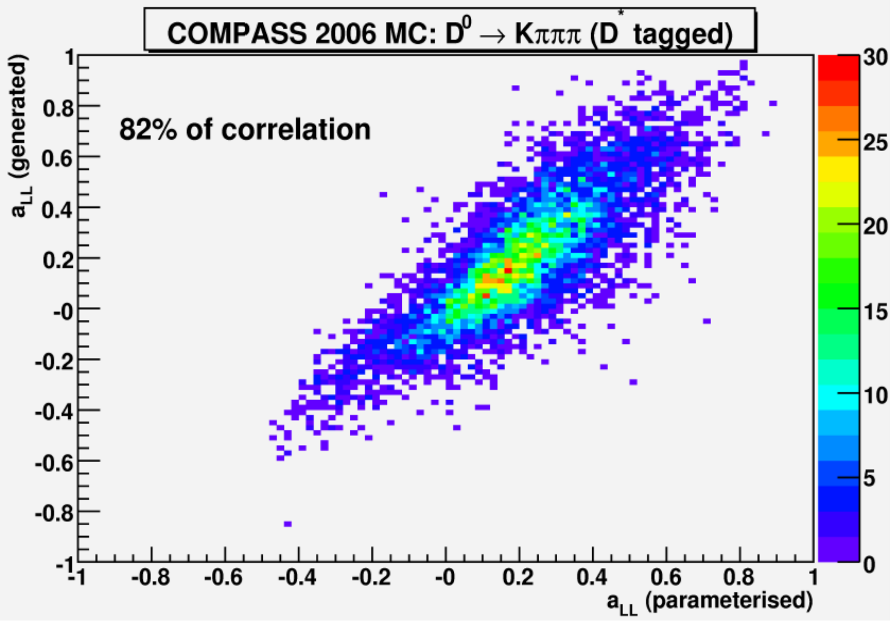
Analysing power (muon-gluon asymmetry a_{LL})

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

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

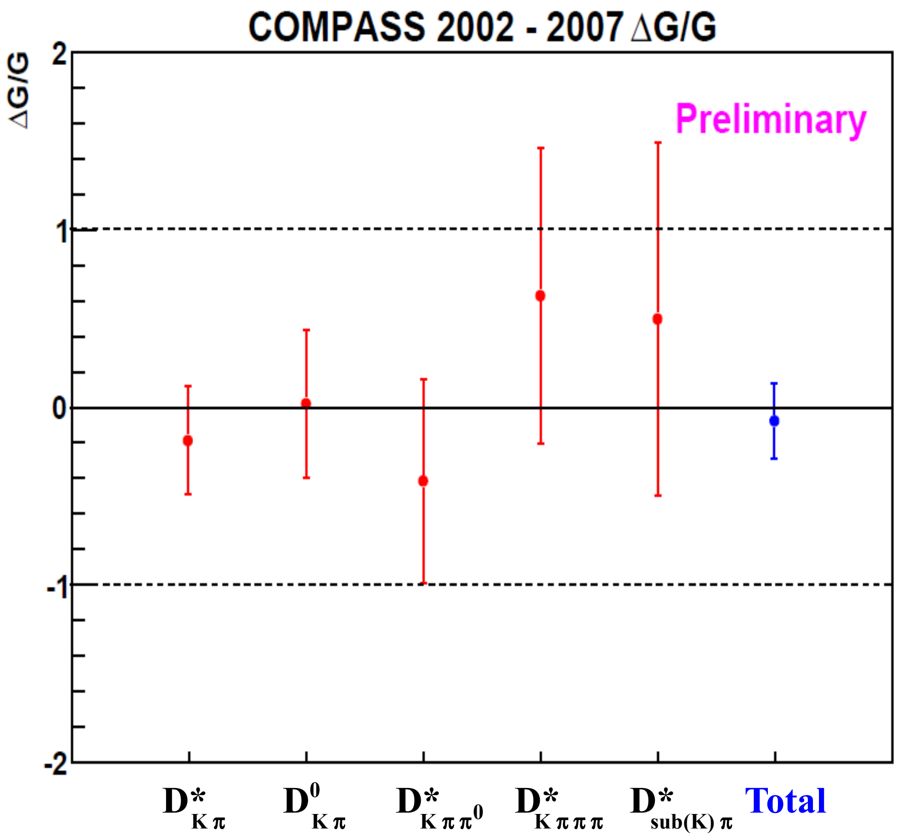
Can't be experimentally obtained: only one charmed meson is reconstructed

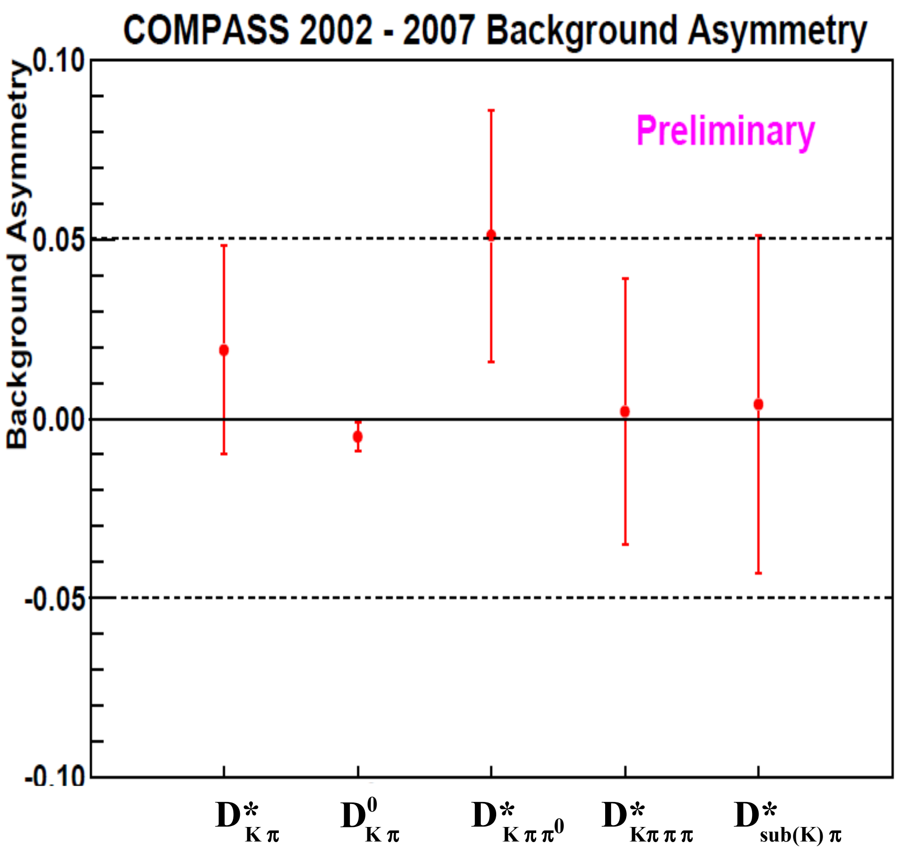
- a_{LL} is obtained from Monte-Carlo (in LO), to serve as input for a Neural Network parameterisation on some reconstructed kinematical variables: y, x_{Bj}, Q^2, z_D and p_T



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

Open Charm results in LO





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

High-p_T hadron pairs

High-p_T asymmetries (2002-2006): $Q^2 > 1\ (GeV/c)^2$

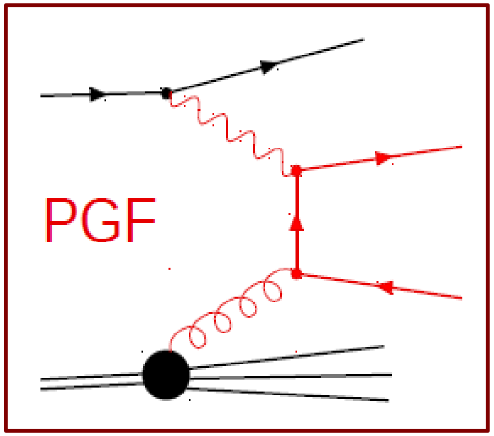
- **Two samples are considered:**

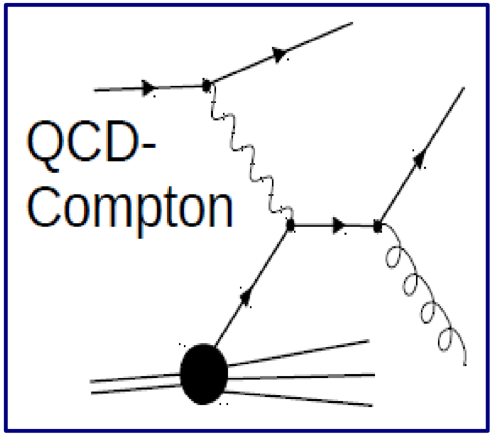
Inclusive asymmetry

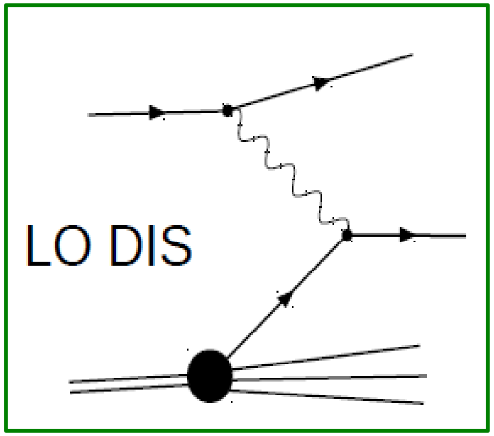
$$A_1^d(x) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF,inc}\frac{\sigma^{PGF,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C,inc}\frac{\sigma^{C,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO,inc}}{\sigma^{Tot,inc}}\right)$$

$$A_{LL}^{2h}(x) = \left(\frac{A^{exp}}{f P_\mu P_T}\right) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF}\frac{\sigma^{PGF}}{\sigma^{Tot}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C}\frac{\sigma^{C}}{\sigma^{Tot}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO}}{\sigma^{Tot}}\right)$$

high-p_T hadron pairs (p_{T1} / p_{T2} > 0.7 / 0.4 GeV/c) $\Rightarrow$ enhancement of the PGF contribution







Extraction of $\Delta G/G$ from high-p_T: $Q^2 > 1\ (GeV/c)^2$

- The gluon polarisation is determined from two asymmetry samples: the two high-p_T hadrons and the inclusive data samples. **The final formula is**:

$$\frac{\Delta g}{g}(x_g) = \frac{1}{\beta}\left[A_{LL}^{2h}(x) + A_{corr}\right] \qquad A_{corr} = -\left(A_1(x_{Bj})D\frac{R_{LO}}{R_{LO}^{inc}} - A_1(x_C)\beta_1 + A_1(x_C')\beta_2\right)$$

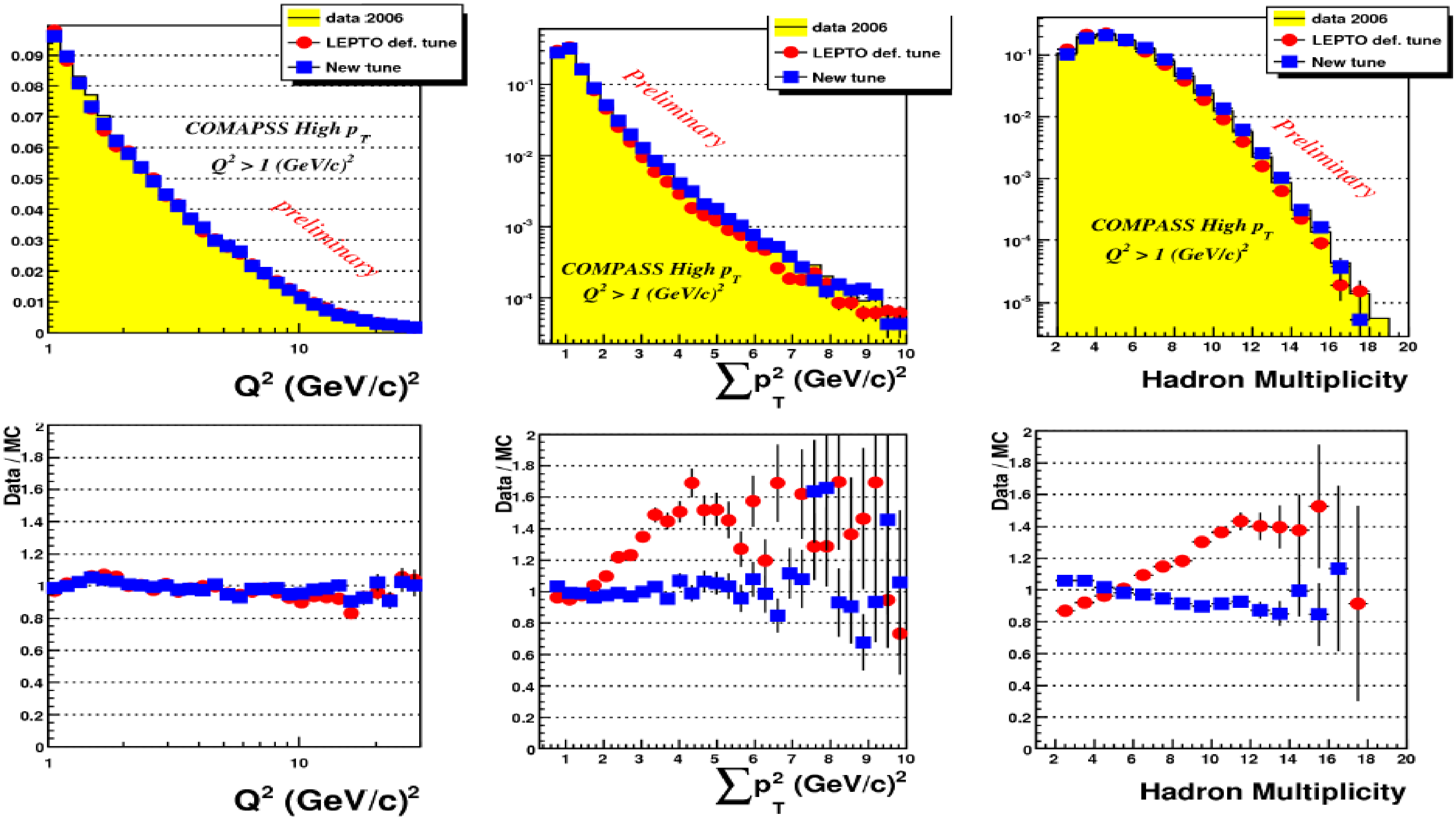
$$\beta = a_{LL}^{PGF}R_{PGF} - a_{LL}^{PGF,inc}R_{PGF}^{incl}\frac{R_{LO}}{R_{LO}^{inc}} - a_{LL}^{PGF,incl}\frac{R_C R_{PGF}^{inc}}{R_{LO}^{inc}}\frac{a_{LL}^{C}}{D}$$

- β_1 and β_2 are factors depending on a_{LL}^{i} and R_i
- Each event is weighted with $\omega = f\,D\,P_\mu\,\beta$ $\rightarrow$ statistical improvement!
- The following parameters are obtained from Monte Carlo, and then they are parameterised event-by-event by a Neural Network (to allow for their use in data):

R_{PGF}, R_C, R_{LO}, R_{PGF}^{inc}, R_C^{inc}, R_{LO}^{inc}, a_{LL}^{PGF}, a_{LL}^{C}, a_{LL}^{LO}, $a_{LL}^{PGF, inc}$, $a_{LL}^{C, inc}$ and $a_{LL}^{LO, inc}$

Data vs Monte Carlo: Comparison of Q^2 and hadron variables

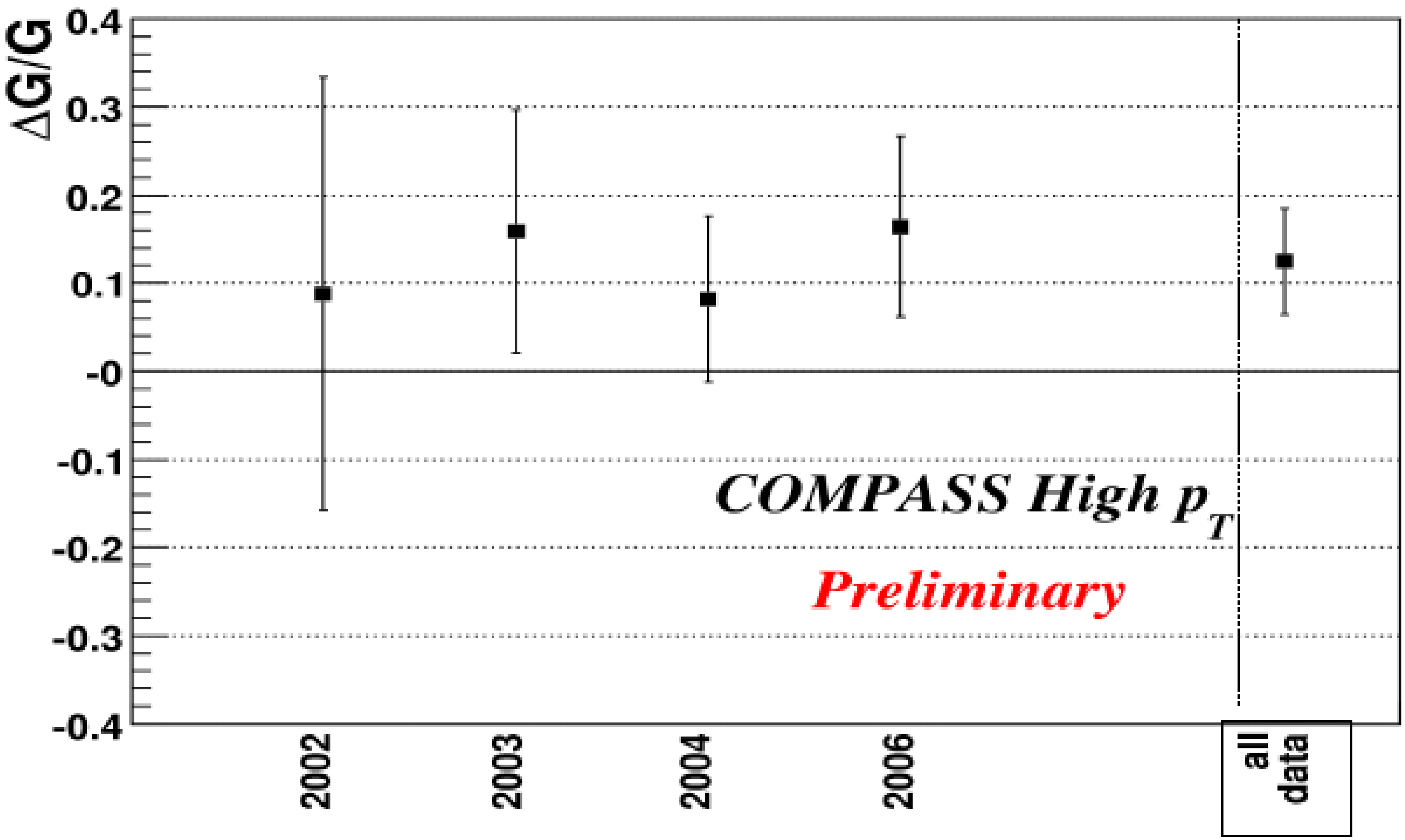
Monte Carlo (PS on): LEPTO generator with PDFs from MSTW2008LO



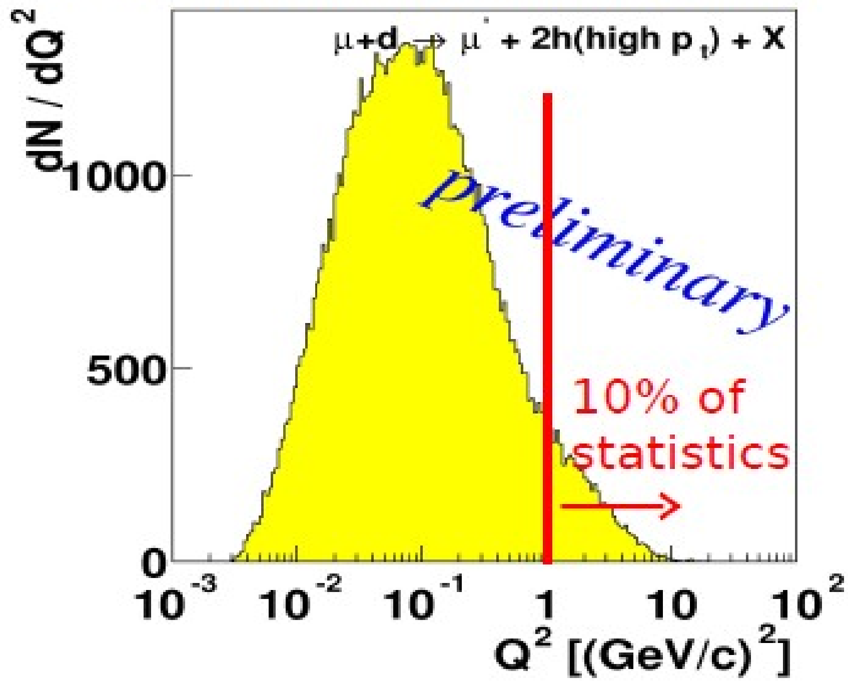
The impact of this tunning is included in the systematic error

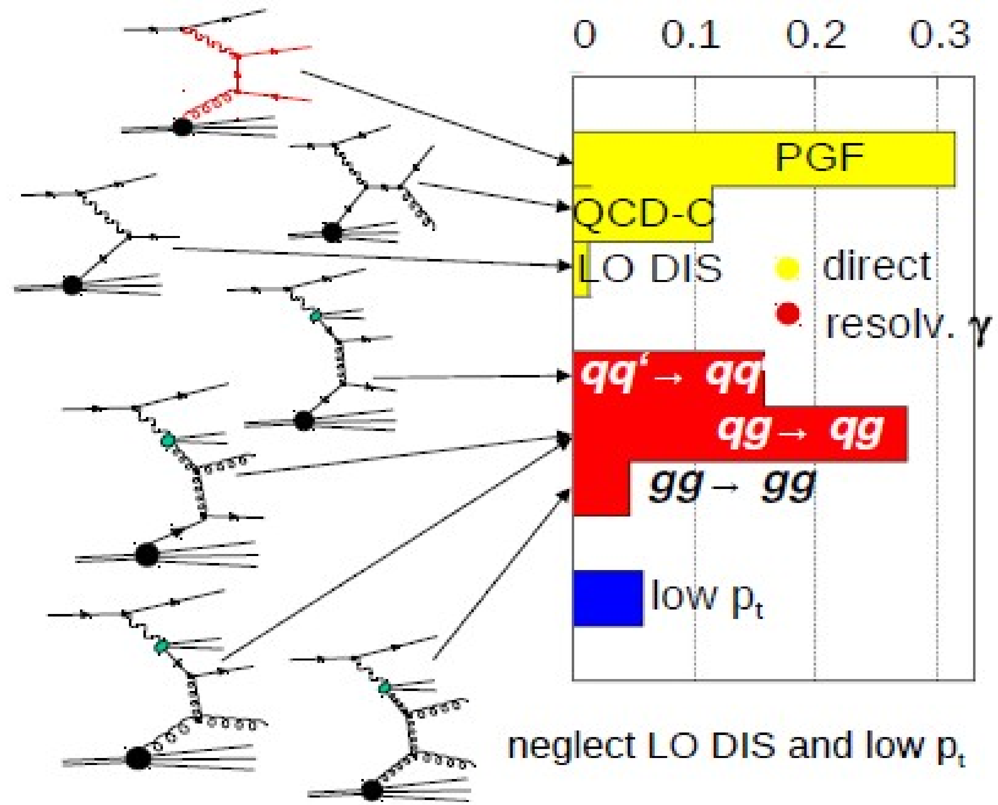
High-p_T results: $Q^2 > 1\ (\mathrm{GeV}/c)^2$

$$\frac{\Delta G}{G} = 0.125 \pm 0.060(\mathbf{stat}) \pm 0.063(\mathbf{syst}) \quad @ < x_g > = 0.09^{+0.08}_{-0.04}\ ,\ <\mu^2> = 3.4\ (\mathbf{GeV/c})^2$$



High-p_T analysis: $Q^2 < 1\ (\mathrm{GeV}/c)^2$





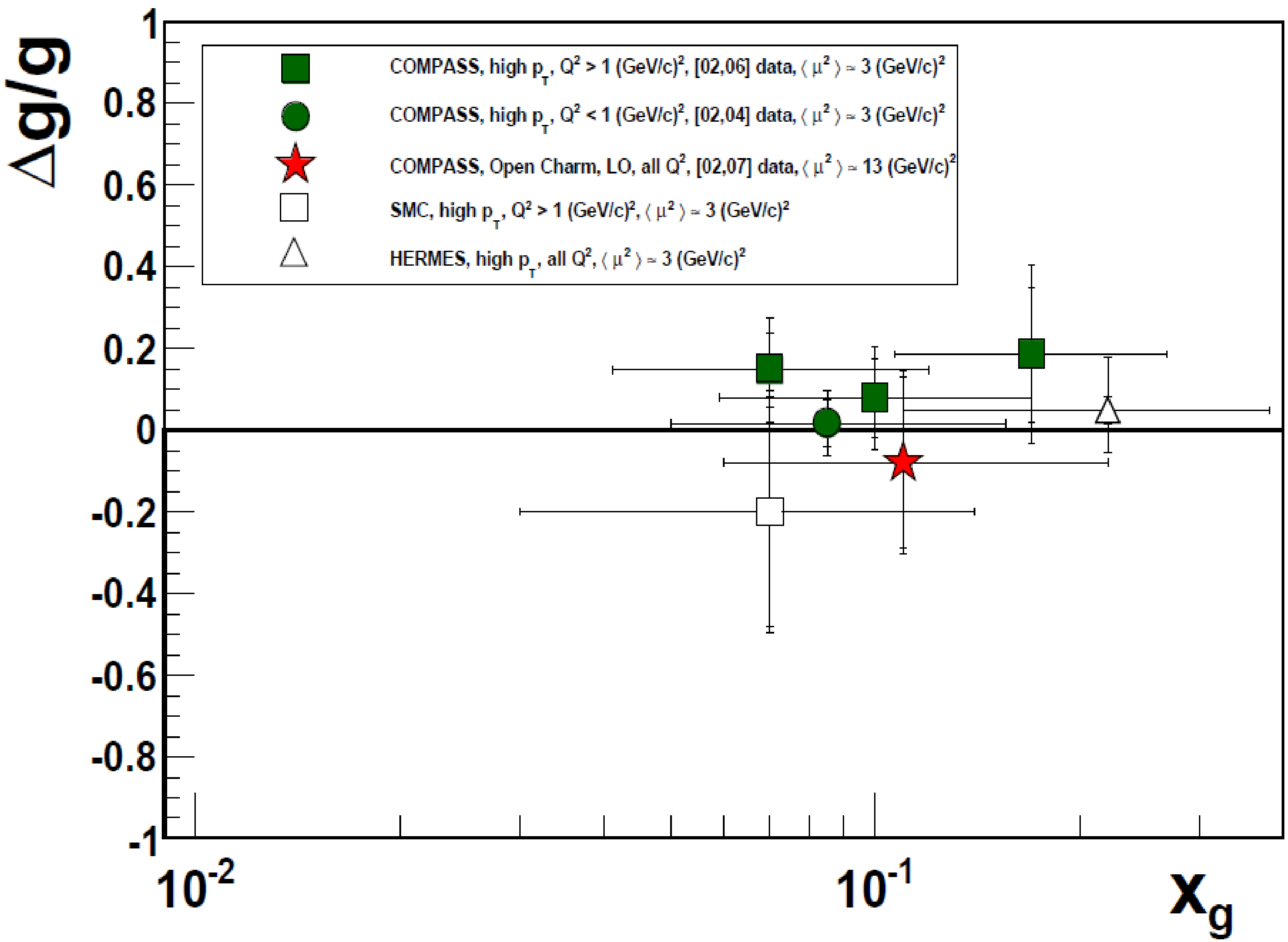
2002-2004 Preliminary:

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

2002-2003 Published:

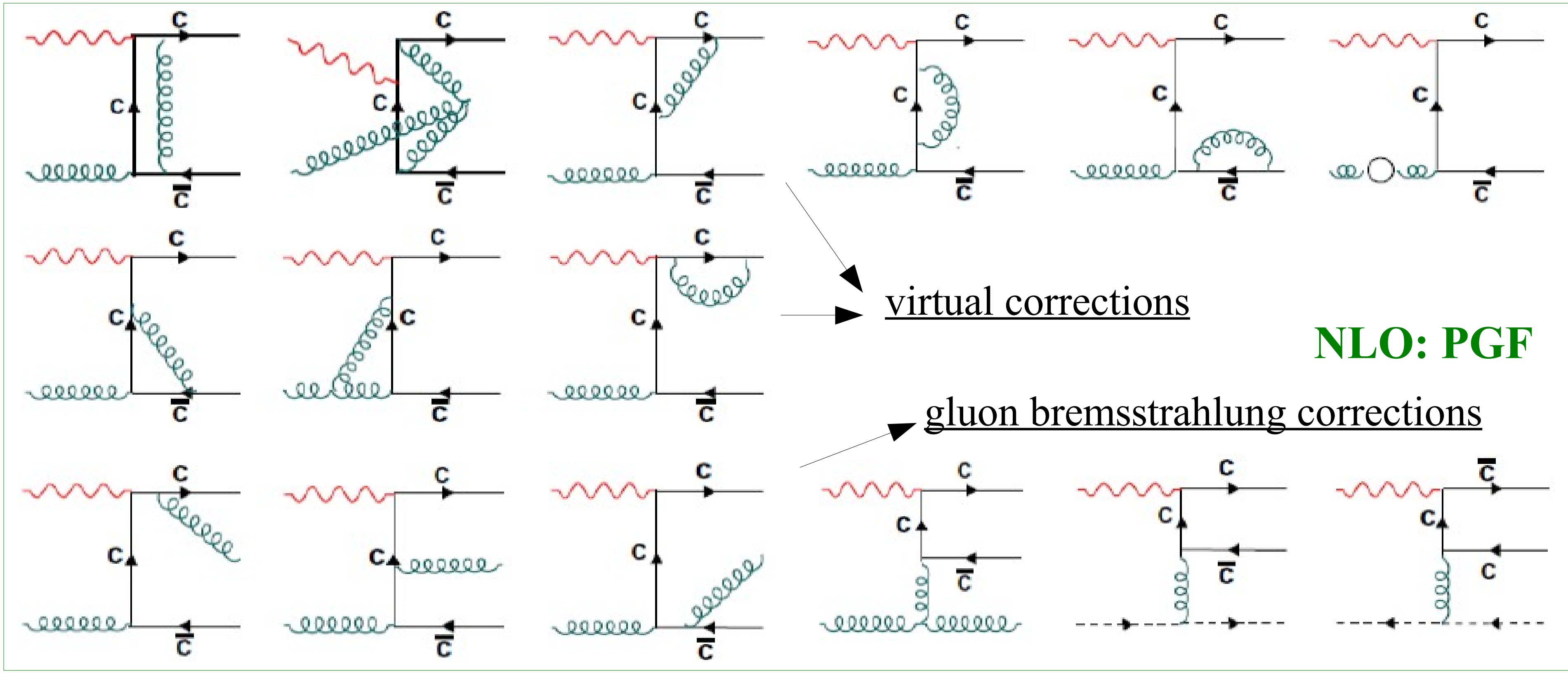
$\Delta G/G = 0.024 \pm 0.089\ (\mathrm{stat}) \pm 0.057\ (\mathrm{syst})$ $\rightarrow$ *Phys. Lett. B 633 (2006) 25 - 32*

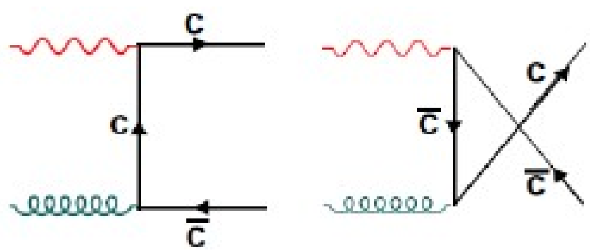
World measurements on ΔG/G in LO



NLO results from Open Charm

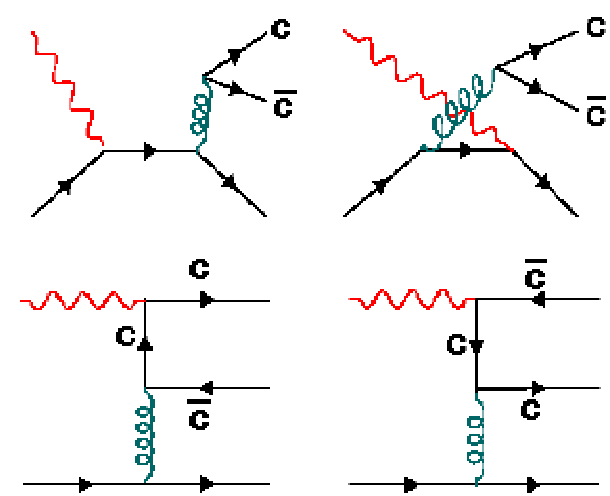
NLO corrections to the analysing power $\langle a_{LL} \rangle$





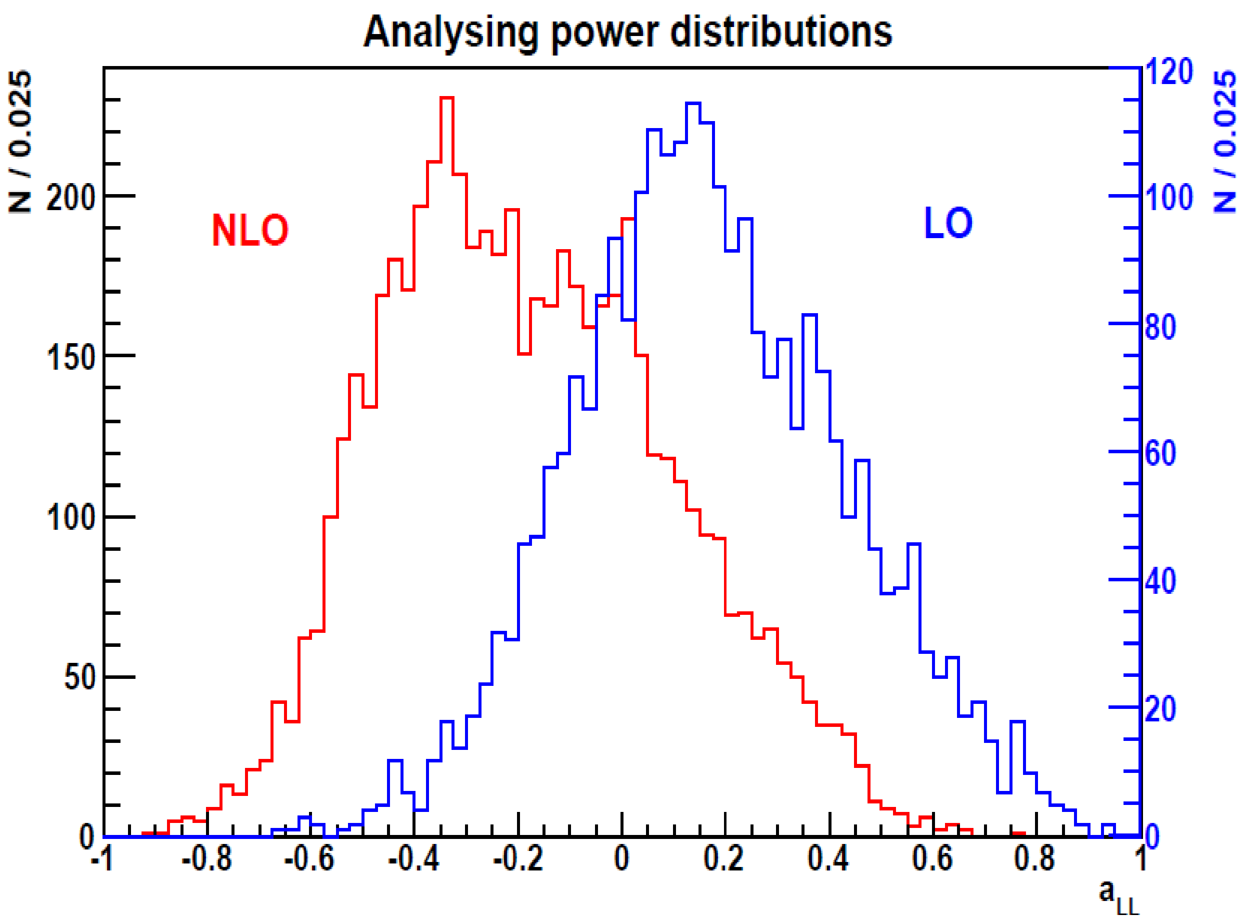
LO: PGF

NLO: bg



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

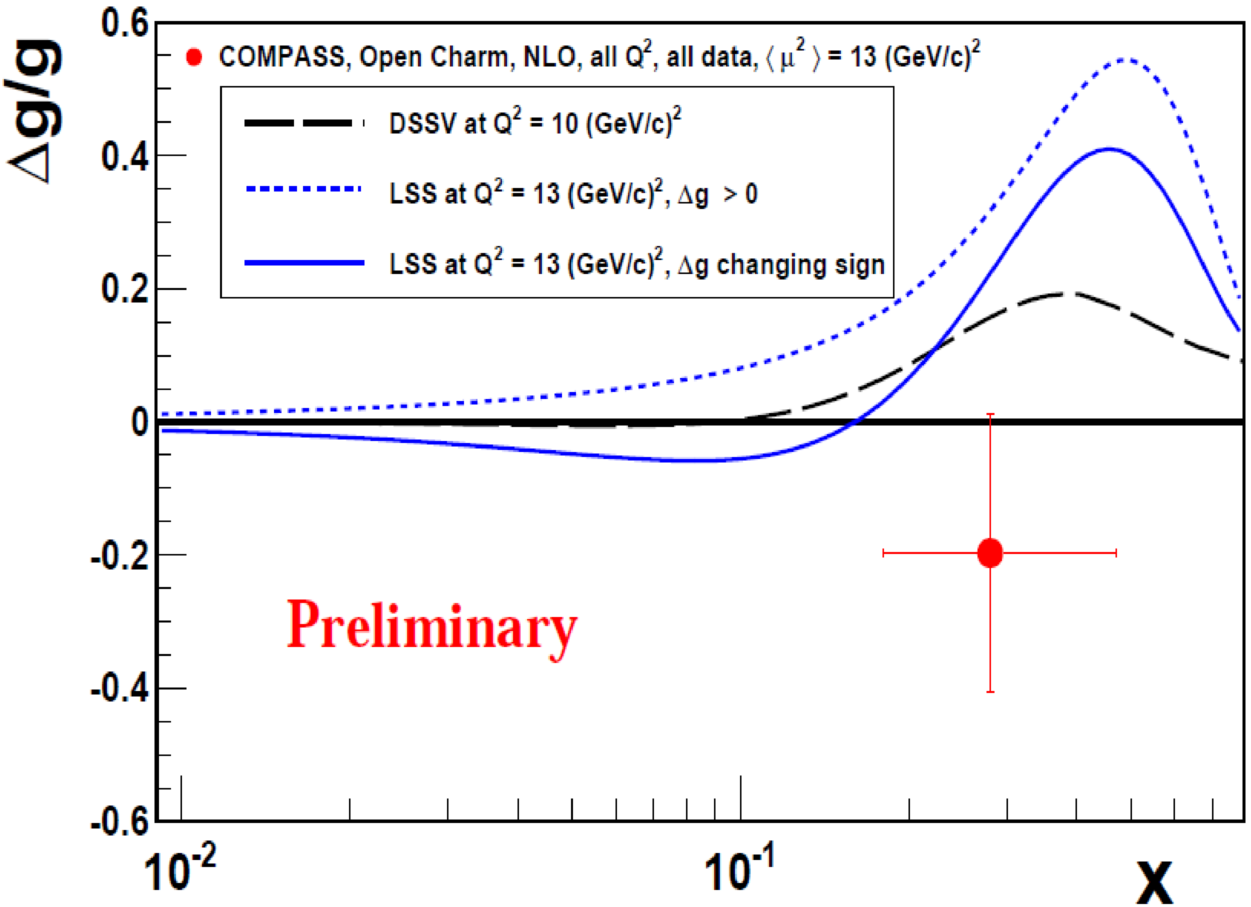
- **The AROMA generator is used to simulate the fase space for the NLO (PS on) / LO (PS off) calculations of a_{LL}.** The resulting D^0 mesons are reconstructed in the COMPASS spectrometer like real events. The respective a_{LL} distributions are:



NLO results for $A_{\gamma N}^{PGF}$: $A_{\gamma N} = \left(\frac{a_{LL}^{PGF}(NLO)}{D} \frac{\Delta G}{G} + \boxed{\frac{a_{LL}^{q}(NLO)}{D} A_1} \right)$ $\rightarrow A_{corr}$

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

$\Delta G/G$ result in NLO → NEW



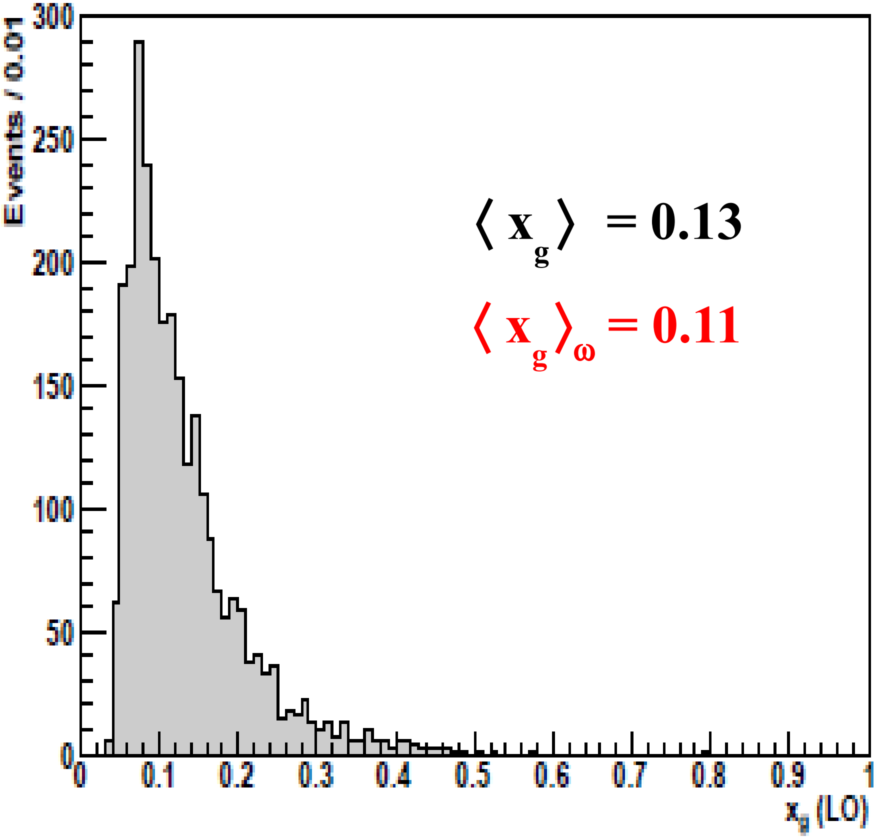
$$\frac{\Delta G}{G} = -0.20 \pm 0.21 \pm 0.08\,(\mathbf{syst}) \qquad @ <x_g> = 0.28^{+0.19}_{-0.10},\ <\mu^2> = 13\ (\mathbf{GeV/c})^2$$

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

SPARES

Open Charm: Comparison of the x_g(LO) and x_g(NLO) distributions

LO



NLO