Latest results on longitudinal spin physics at COMPASS

CIPANP2012 – St. Petersburg, Florida

Celso Franco *(LIP – Lisboa)*

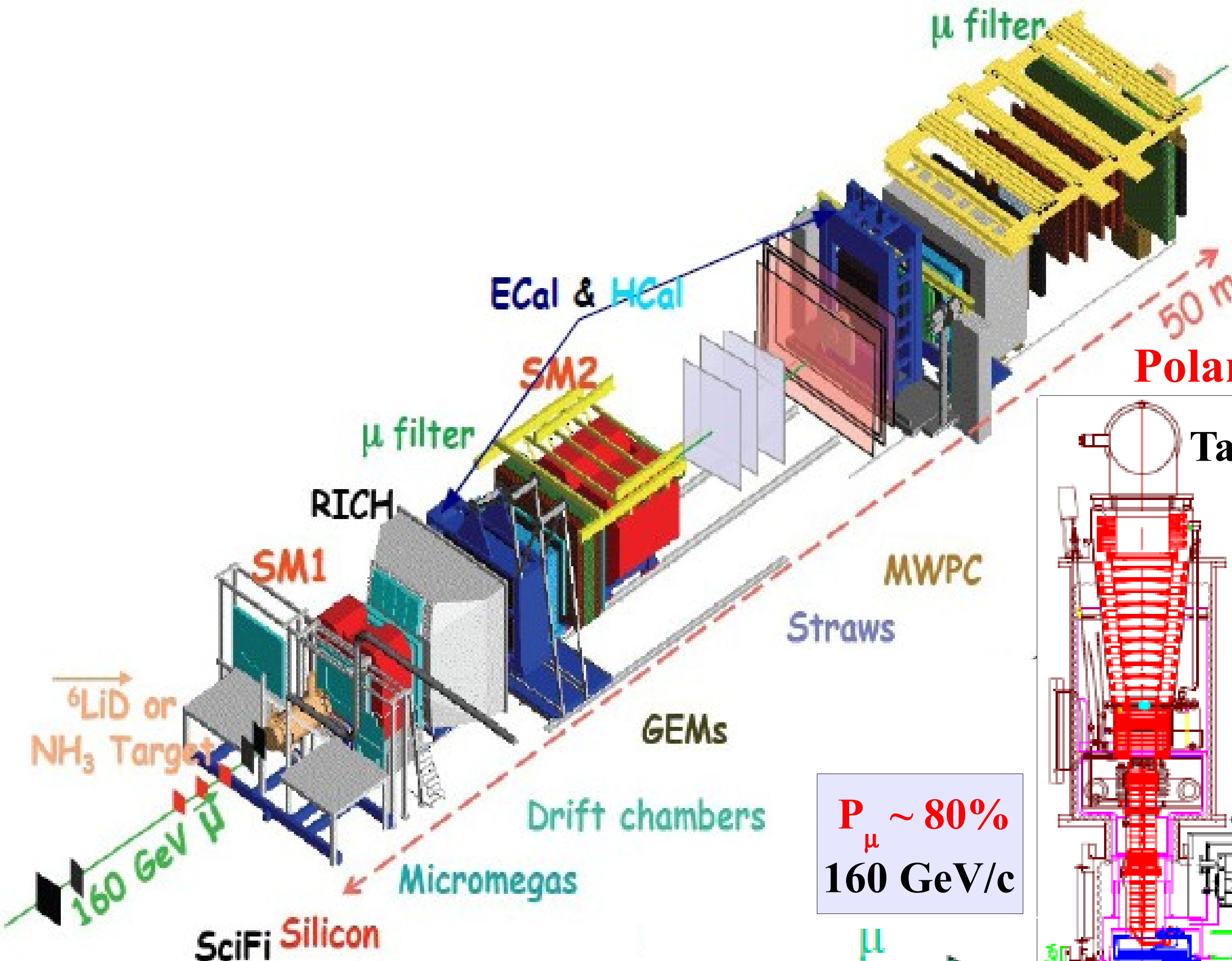
on behalf of the COMPASS collaboration

Outline

Results from longitudinally polarised nucleons:

- $A_1^{d/p}$, $g_1^{d/p}$, and first moments of g_1^d
- Semi-inclusive asymmetries and flavour separation
- Hadron multiplicities
- Gluon polarisation at LO in QCD:
  - Open Charm
  - High-p_T hadron pairs
- Gluon polarisation at NLO in QCD:
  - Open Charm

The spectrometer and polarised target



Polarised Target: 2006-2007 setup

Target: ^{6}LiD (2002-06) - NH_3 (2007)

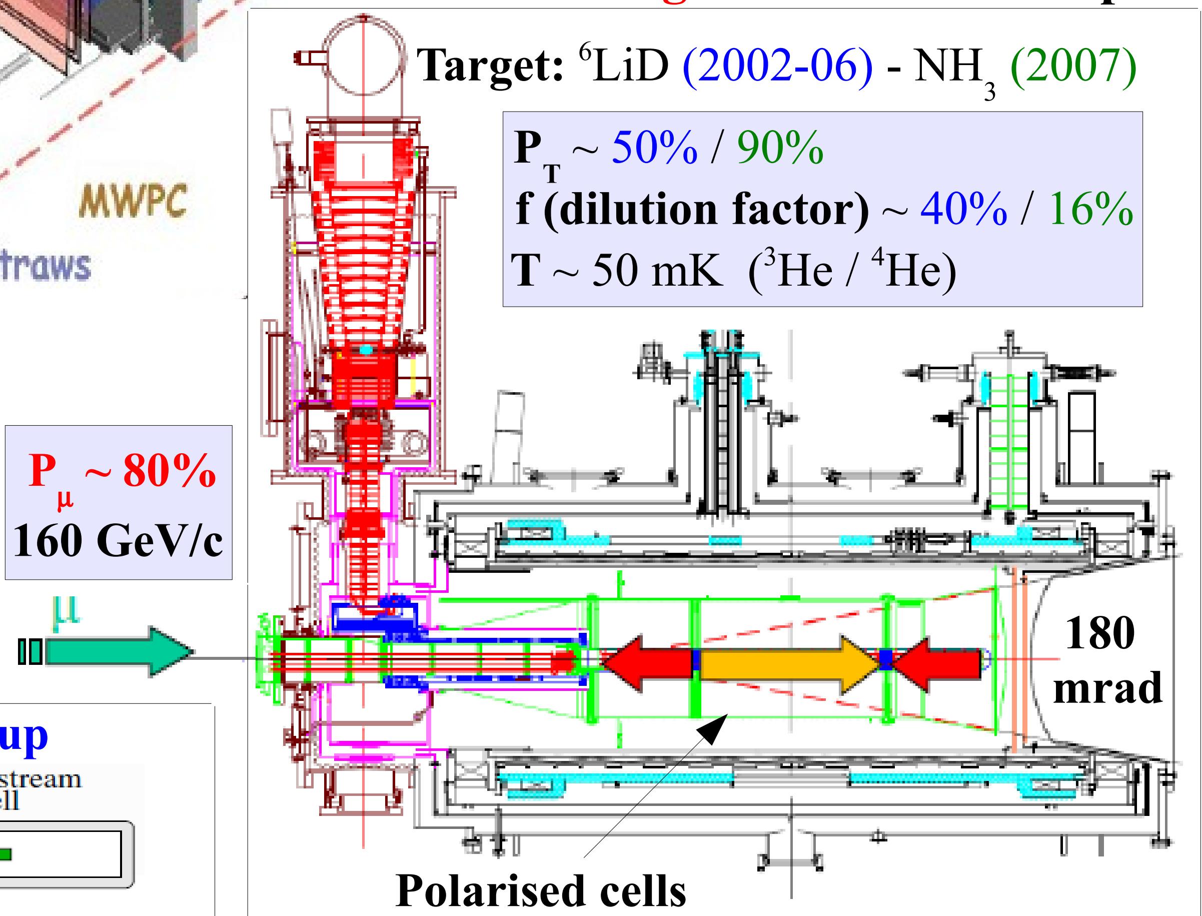
$P_T \sim$ 50% / 90%

f (dilution factor) ~ 40% / 16%

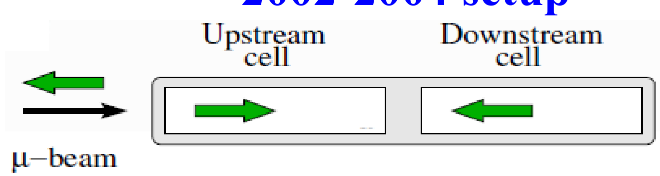
T ~ 50 mK (^{3}He / ^{4}He)

$P_\mu \sim 80\%$

160 GeV/c



2002-2004 setup



Inclusive asymmetries and spin structure functions

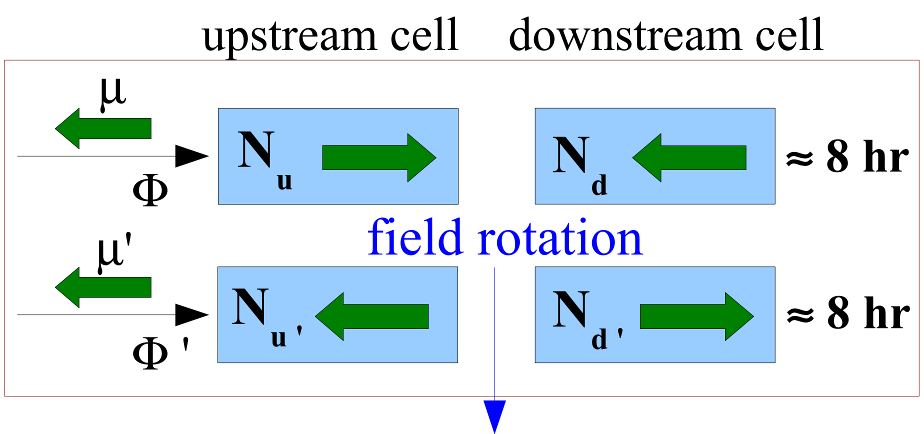
Asymmetry measurement: $A_1^N := \frac{\Delta\sigma_{\gamma*N}}{\sigma_{\gamma*N}} = \frac{\left(\sigma^{\rightleftarrows}_{\gamma*N} - \sigma^{\leftleftarrows}_{\gamma*N}\right)}{\sigma^{unpol}_{\gamma*N}}$

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

$$A^{exp} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N_{d'} - N_{u'}}{N_{d'} + N_{u'}}\right)$$

$$= f \cdot P_\mu \cdot P_T \cdot D \cdot A_1 \longrightarrow A^{\mu N}$$

D = Depolarisation factor



equal acceptance for both cells

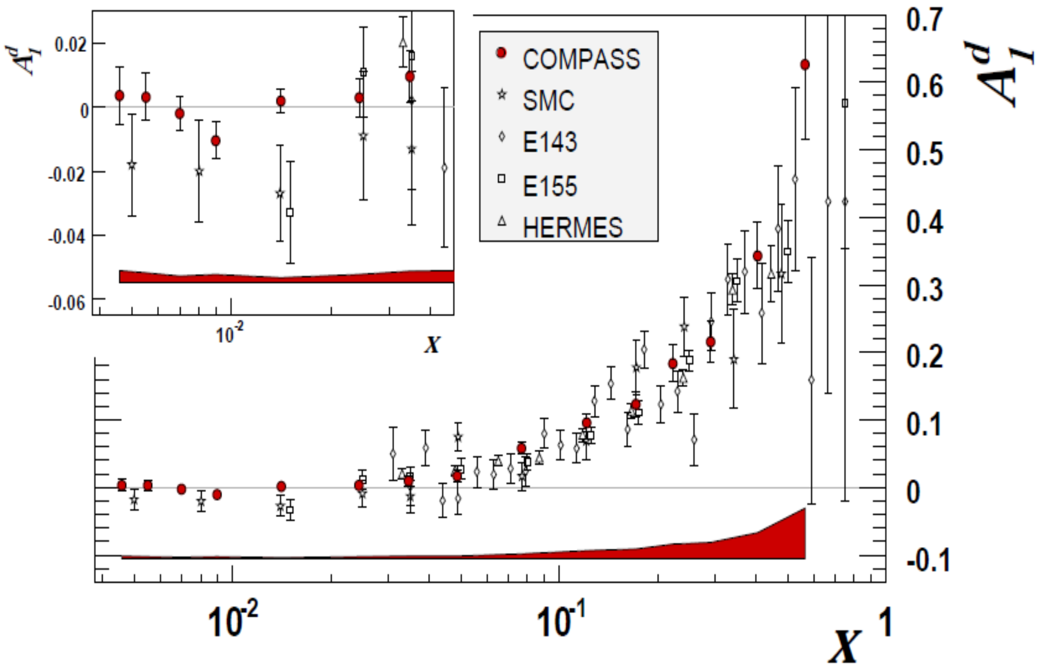
- **Weighting each event with $\omega = (fP_\mu D)$:**

$$A_1 = \frac{1}{2P_T}\left(\frac{\sum_{i=0}^{N_u}\omega_i - \sum_{i=0}^{N_d}\omega_i}{\sum_{i=0}^{N_u}\omega_i^2 + \sum_{i=0}^{N_d}\omega_i^2} + \frac{\sum_{i=0}^{N_{u'}}\omega_i - \sum_{i=0}^{N_{d'}}\omega_i}{\sum_{i=0}^{N_{u'}}\omega_i^2 + \sum_{i=0}^{N_{d'}}\omega_i^2}\right)$$

statistical gain: $\frac{\left\langle \sum_{i=0}^{N_{tot}} \omega_i^2 \right\rangle}{\left\langle \sum_{i=0}^{N_{tot}} \omega_i \right\rangle^2}$

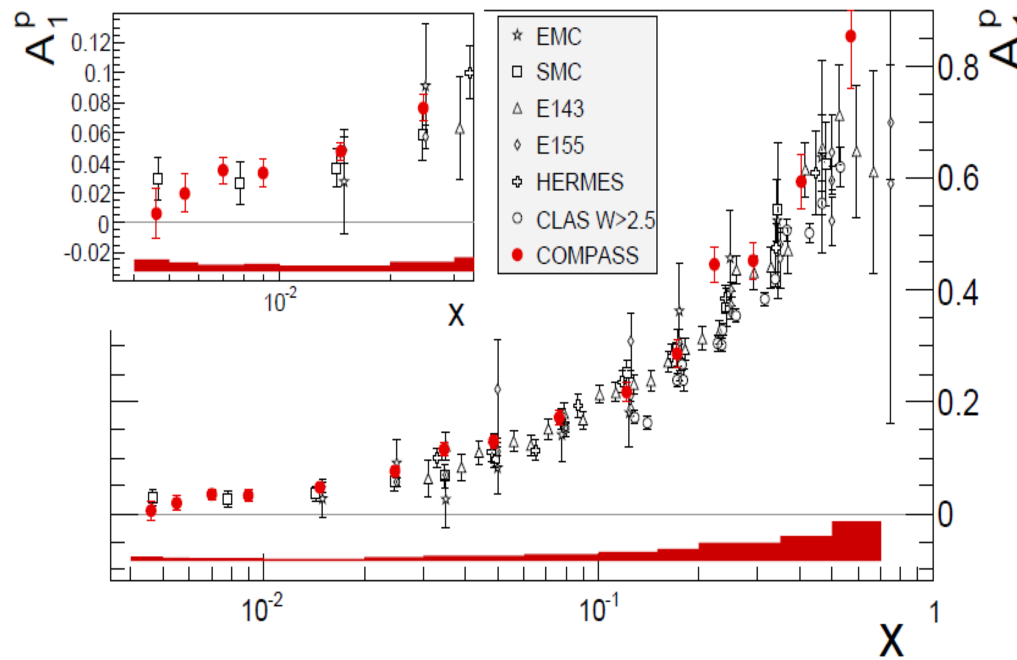
Inclusive asymmetries $A_1^{d/p}$: $Q^2 > 1\ (GeV/c)^2$

Deuteron data (2002-2006)



COMPASS, PLB 647 (2007) 330-340

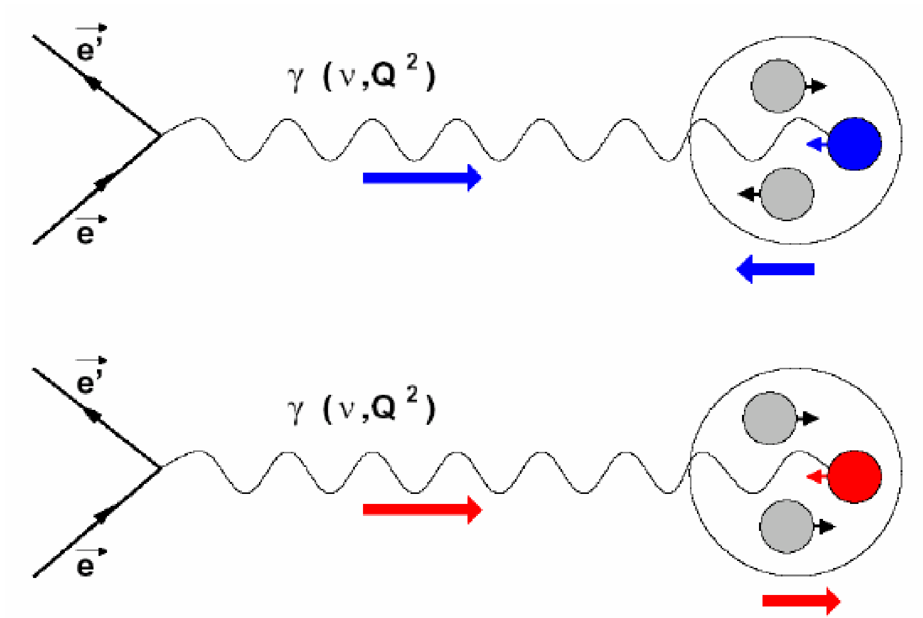
Proton data (2007)



COMPASS, PLB 690 (2010) 466-472

- Good agreement between all experimental points
- Significant improvement of precision in the low x region: A_1^d 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

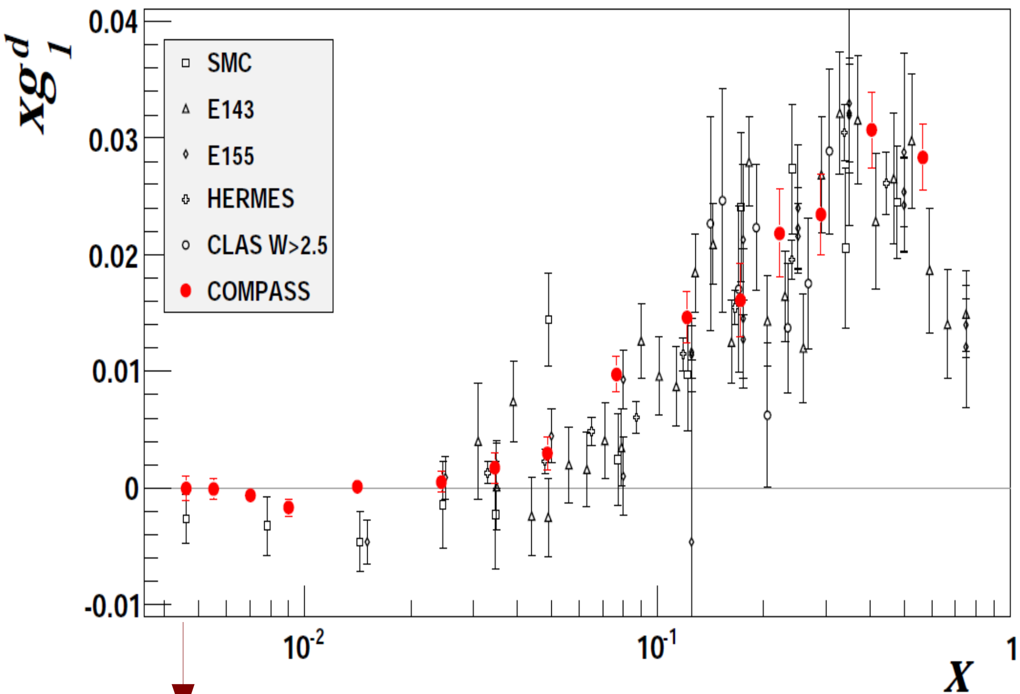
– quark ↑↓ nucleon

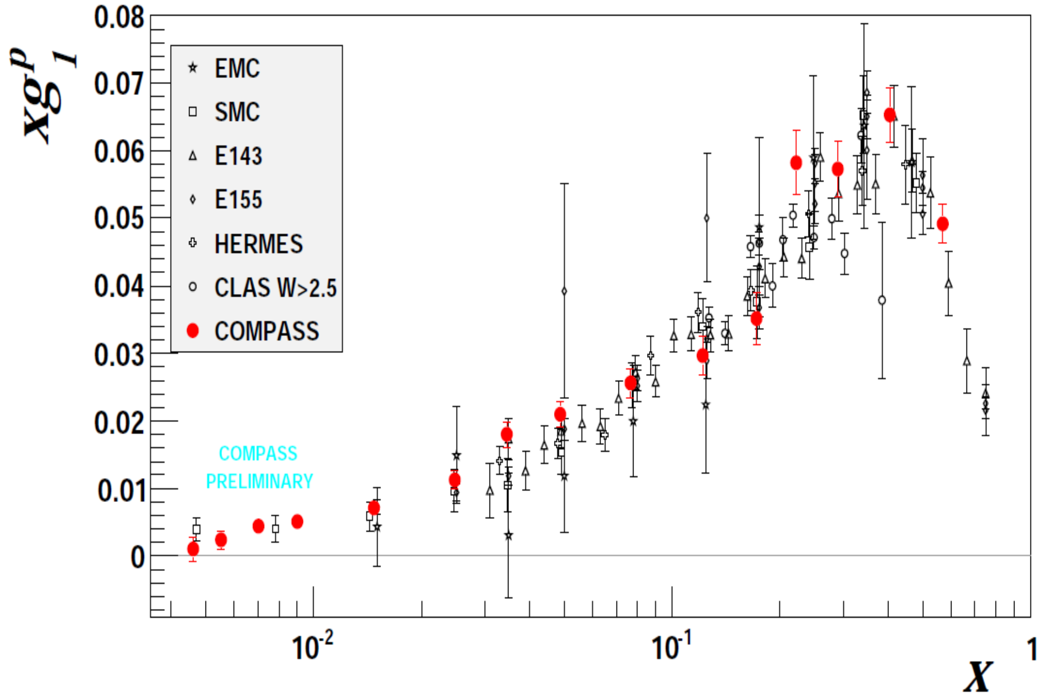
$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2)2x(1+R)}{F_2(x,Q^2)}$$

- 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





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

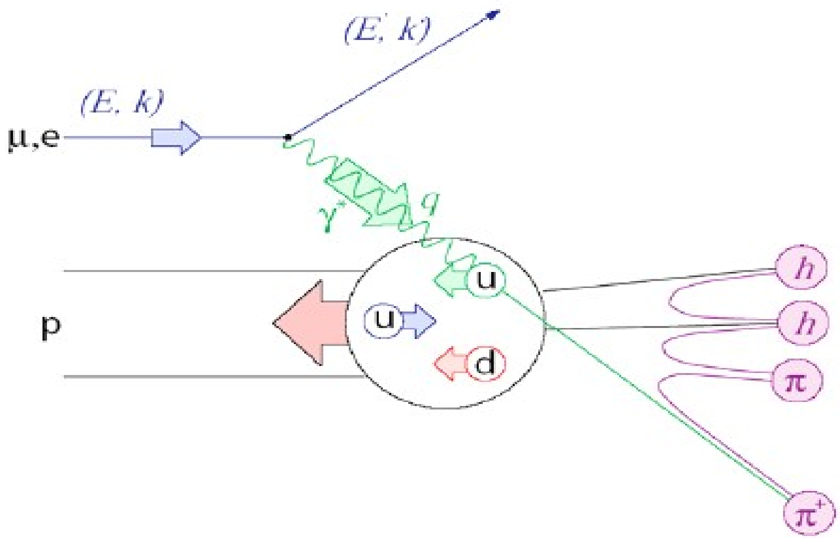
$$= \frac{1}{9}\left(1 - \frac{\alpha_s(Q^2)}{\pi} + O(\alpha_s^2)\right)\left(a_0(Q^2) + \frac{1}{4}a_8\right) \quad \Rightarrow \quad a_0 = 0.35 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst})$$

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

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

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: $D_q^{\,h}(z, Q^2)$

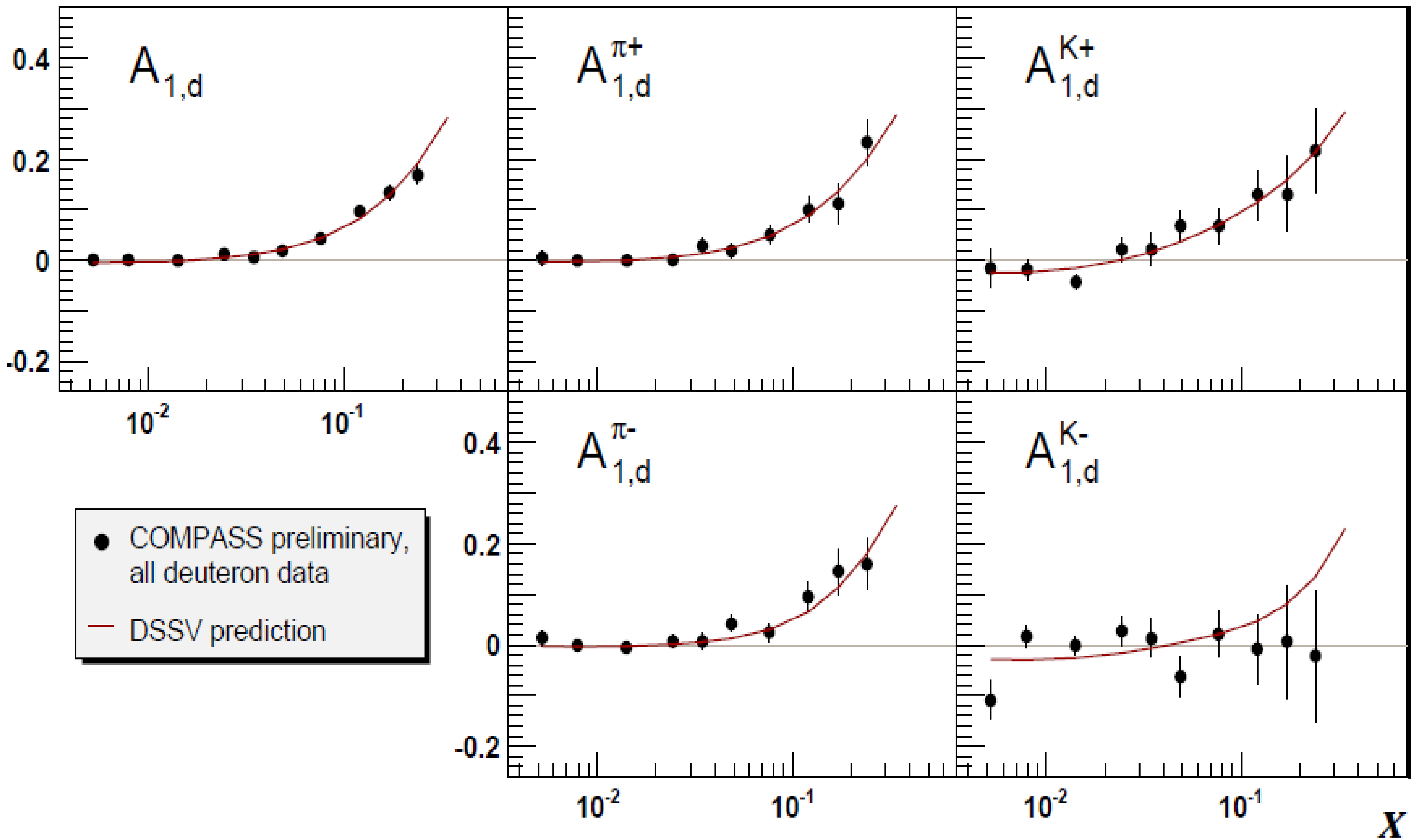
$$\mathbf{z = E_h/(E_\mu - E'_\mu)}$$

- **The semi-inclusive asymmetries have the following interpretation** (at 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 $\Delta q(x, Q^2)$:**
  - Unpolarised PDFs ($q(x, Q^2)$) $\rightarrow$ MRST04
  - $D_q^{\,h}(z, Q^2) \rightarrow$ DSS parameterisation

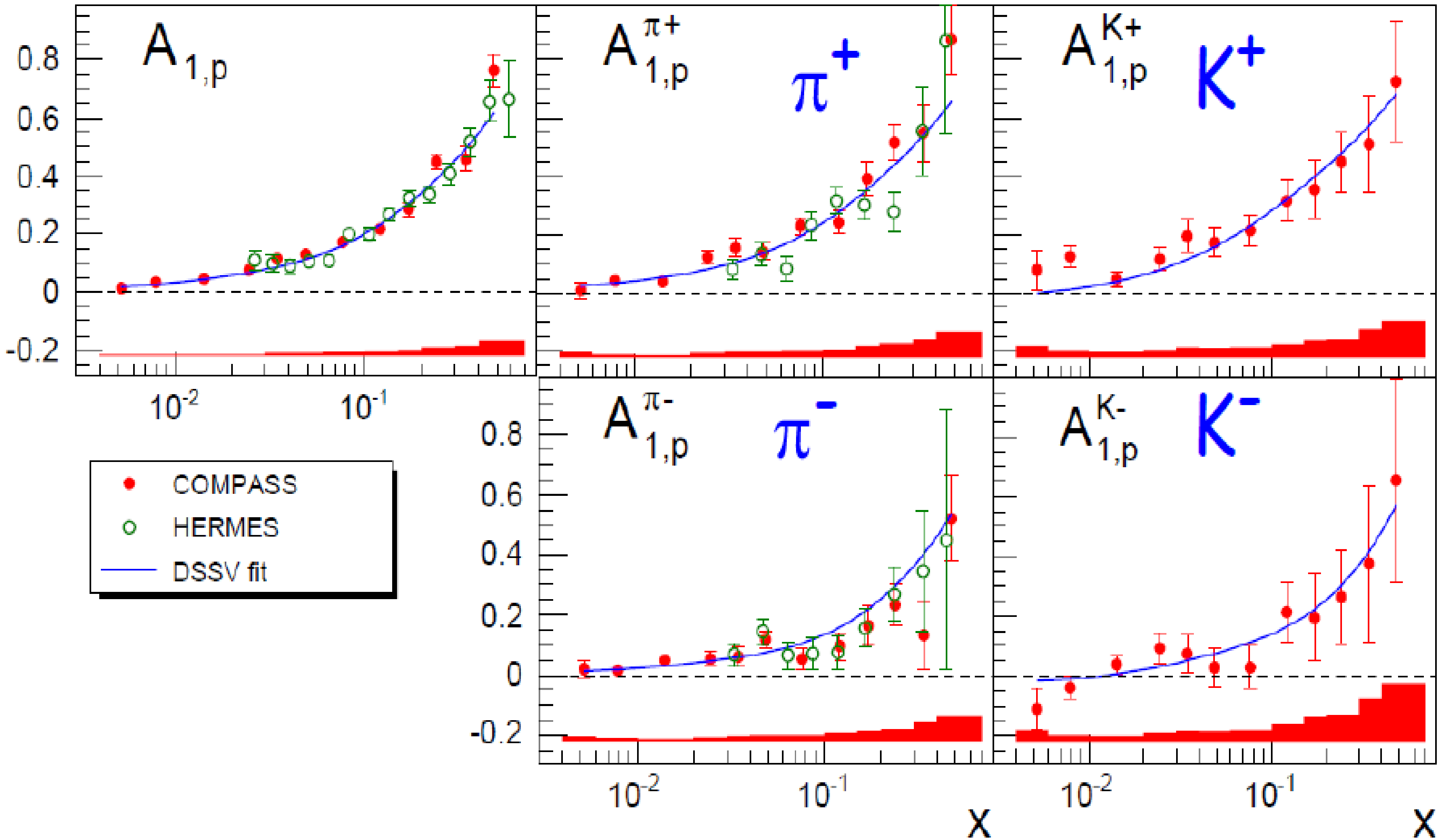
Inclusive and semi-inclusive spin asymmetries: Deuteron data



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

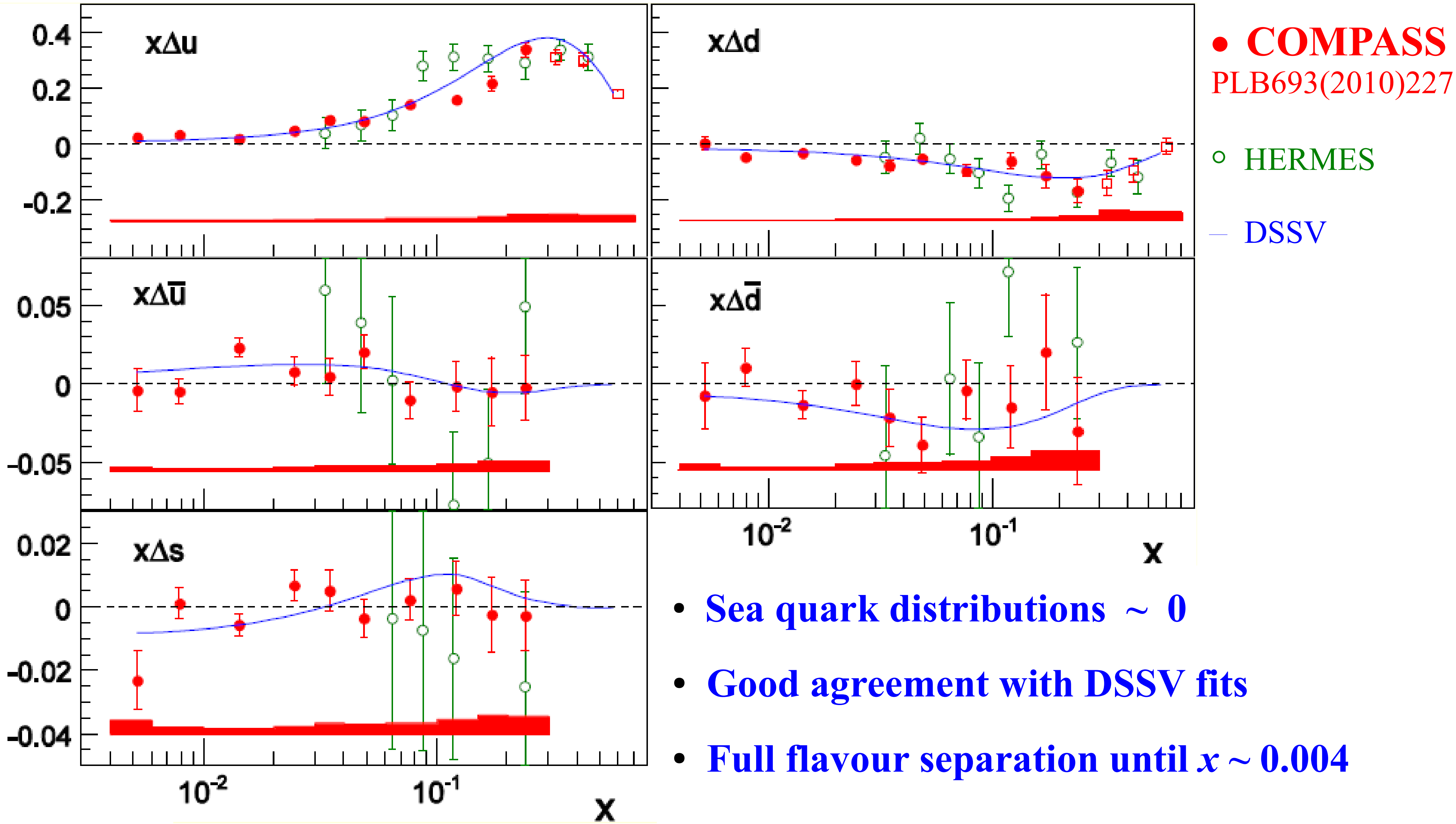
Inclusive and semi-inclusive spin asymmetries: Proton data

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



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

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



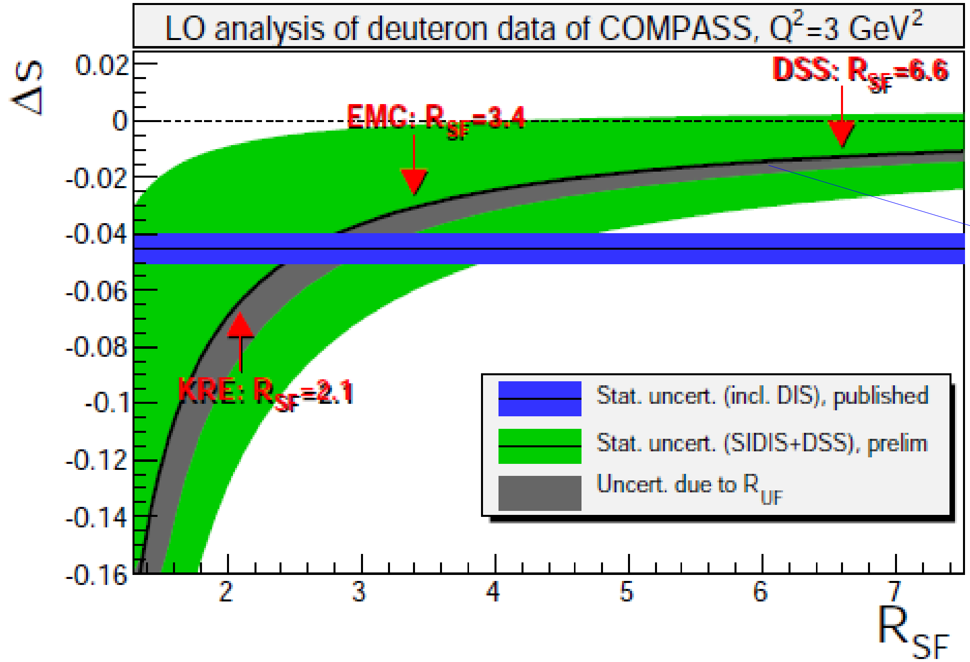
- **Sea quark distributions ~ 0**
- **Good agreement with DSSV fits**
- **Full flavour separation until *x* ~ 0.004**

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

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

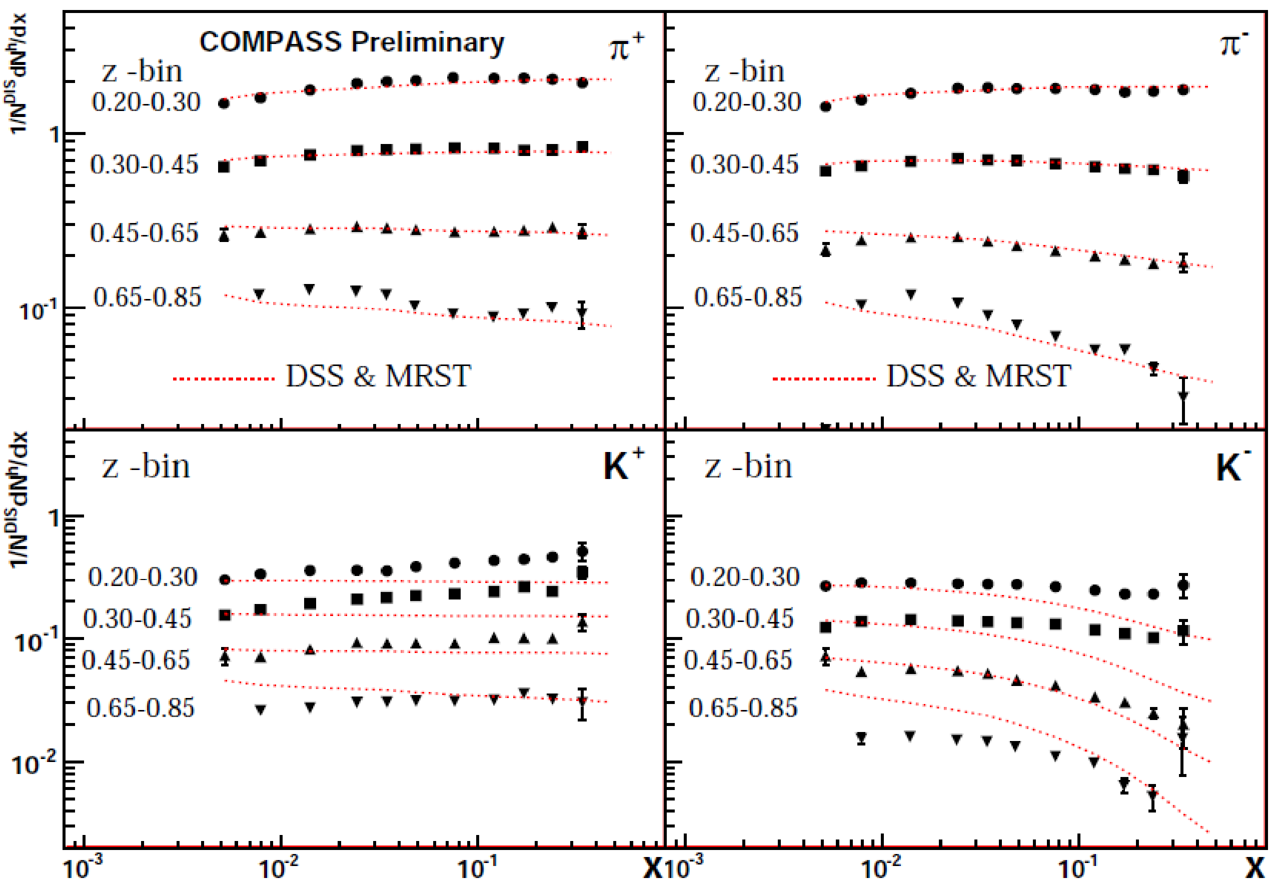
Hadron Multiplicities

A first look on hadron multiplicities

- **Assuming the quark parton model** (leading order):

$$\frac{dM^h(x,Q^2,z)}{dz} = \frac{\overbrace{\sum_q e_q^2 f_q(x,Q^2)}^{\text{PDF}}\ \overbrace{D_q^h(z,Q^2)}^{\text{FF}}}{\sum_q e_q^2 f_q(x,Q^2)} = \frac{\text{hadron yields}}{\text{DIS events yields}}$$

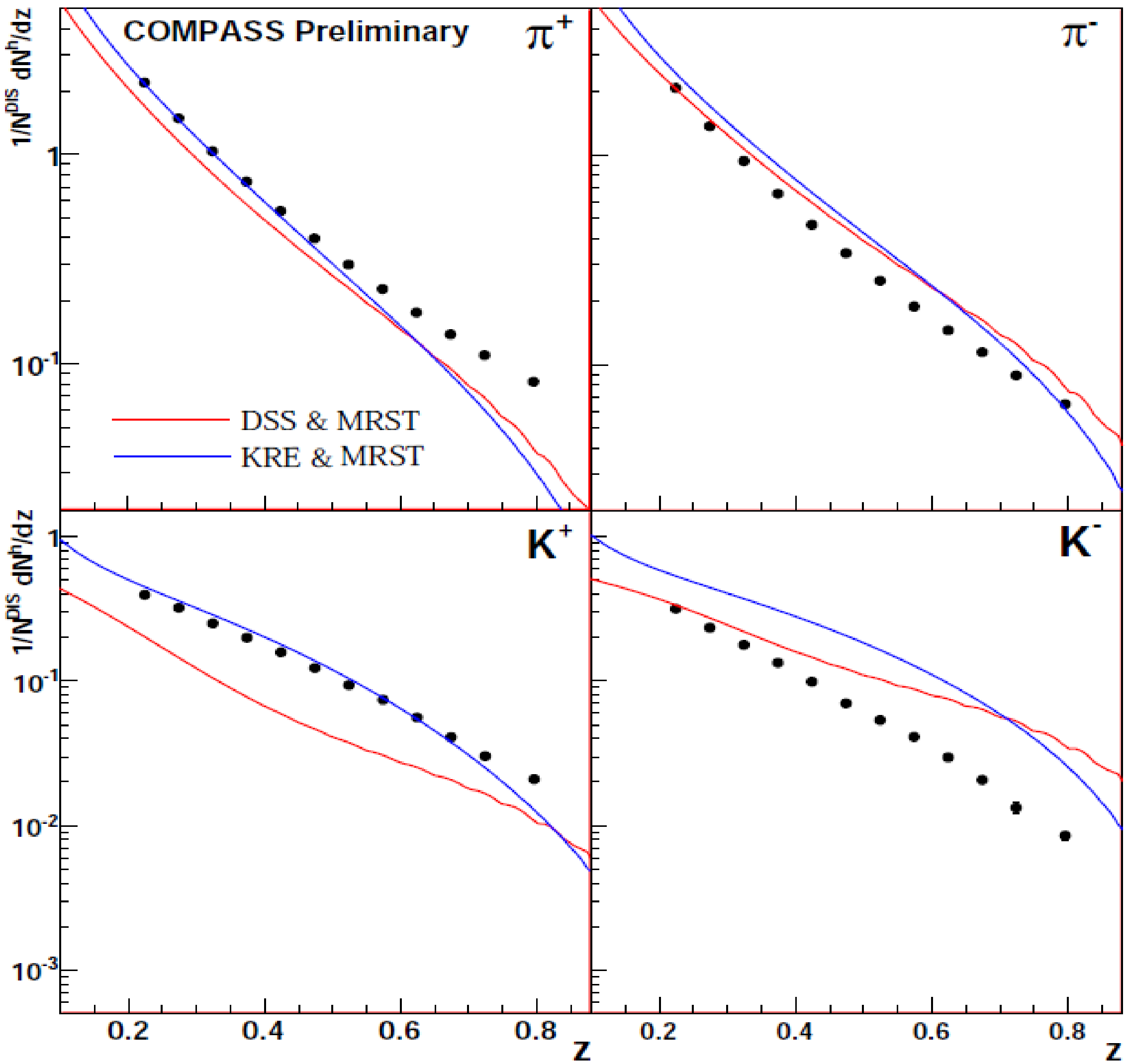
Experimental definition



X dependence of $\frac{1}{N_{DIS}}\frac{dN^h}{dzdx}$

Obtained from a small part of ^{6}LiD data

Comparison to parameterisations



- **The existence of discrepancies are evident** (<u>especially for K</u>)

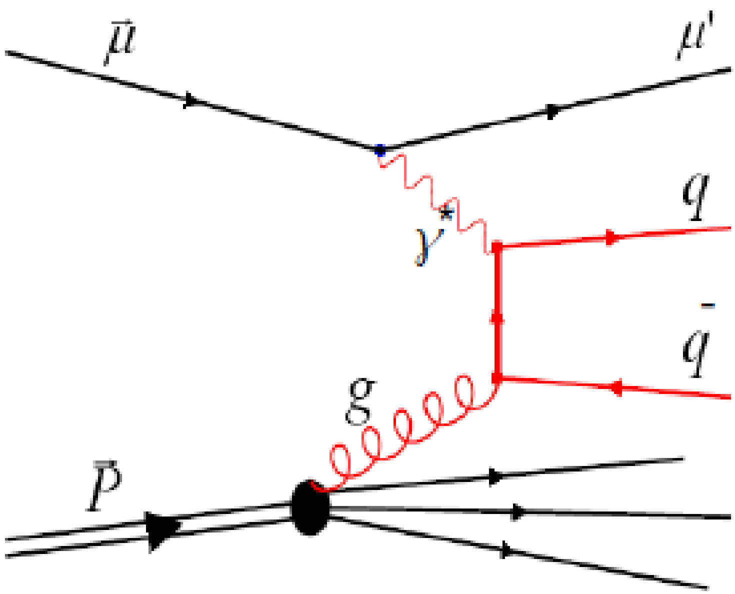
- Data can be used to improve our knowledge on FFs (<u>also good for Δs</u>) and also on poorly known PDFs (like s(x))

- It will contribute significantly to our knowledge of the hadronisation process

Gluon Polarisation

Direct measurement of ΔG/G at LO in QCD

photon-gluon fusion process (PGF)



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

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

Obtained from Monte Carlo and parameterised by a Neural Network (to be used on data)

There are two methods to tag this process:

- **Open Charm production**
  - $\gamma^* g \rightarrow c\bar{c}$ $\Rightarrow$ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly model dependent
  - Low statistics
- **High-p_T hadron pairs**
  - $\gamma^* g \rightarrow q\bar{q}$ $\Rightarrow$ 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 model dependent

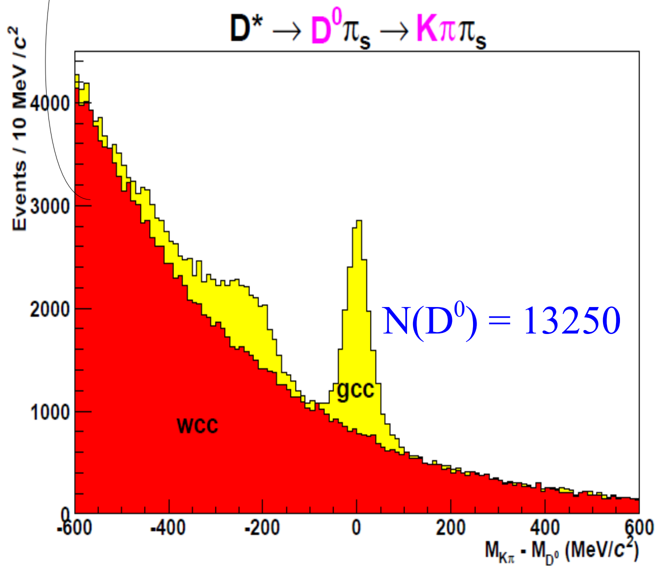
Open Charm

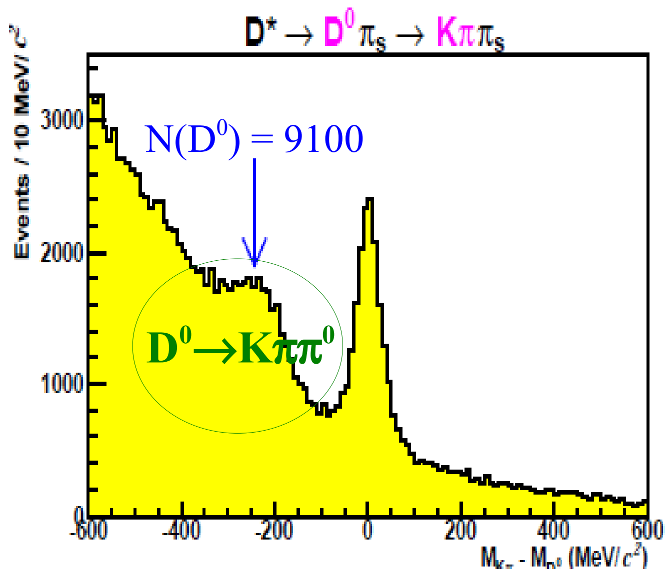
D^0 mass spectra (all samples):

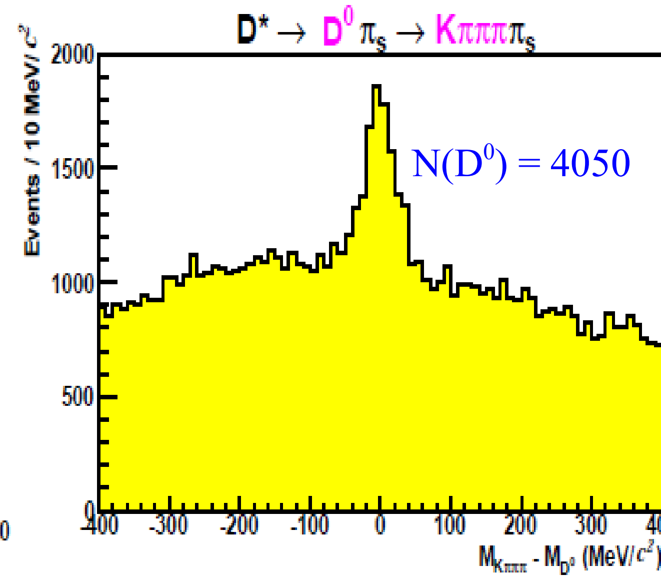
$$\left(A^{exp}_{D^0} = f P_\mu P_T \frac{S}{S+B} A^{PGF}_{\mu N} \right)$$

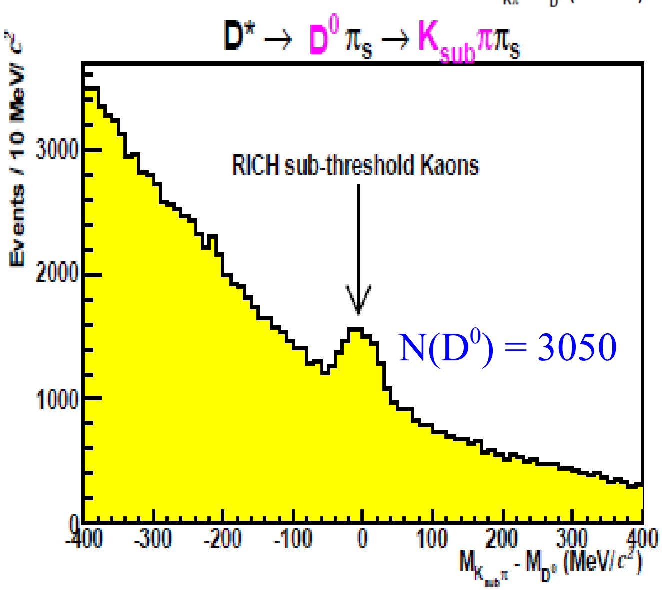
D^0 probability

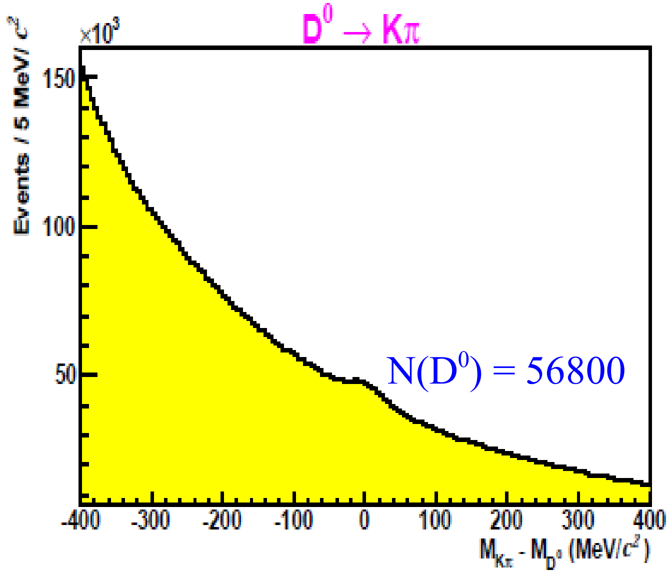
Wrong Charge Combination of Kπ pairs: Example of a background model used for the multidimensional kinematic parameterisation (performed by a Neural Network) of S/(S+B)









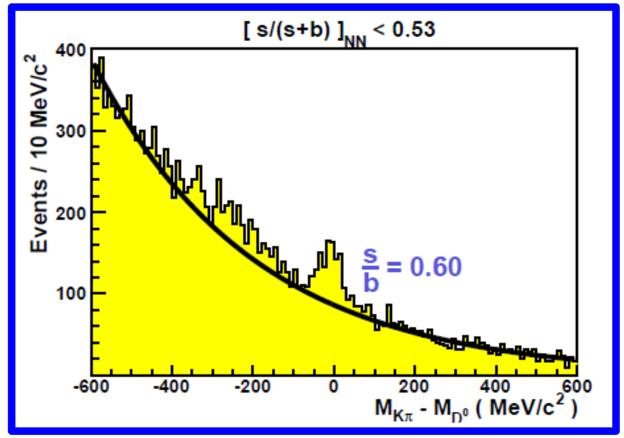


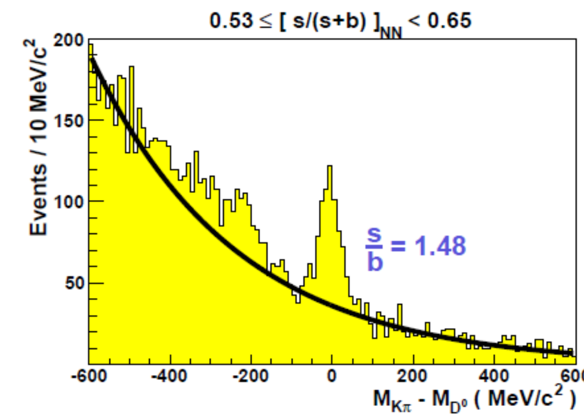
Number of D^0:

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

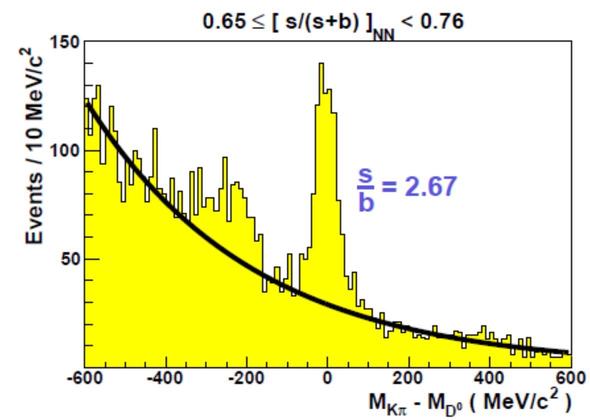
s/(s+b): Obtaining final probabilities for a D^0 candidate

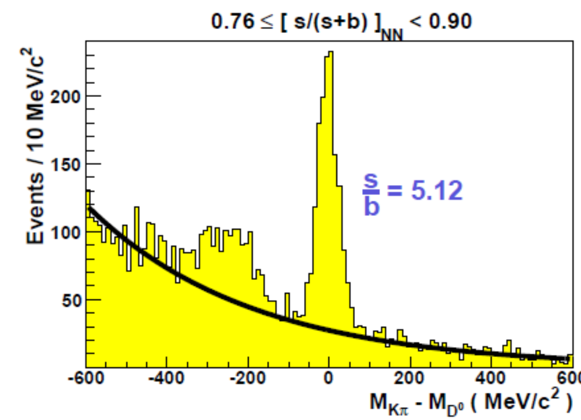
- **Events with small $[s/(s+b)]_{NN}$**
  - Mostly combinatorial background is selected



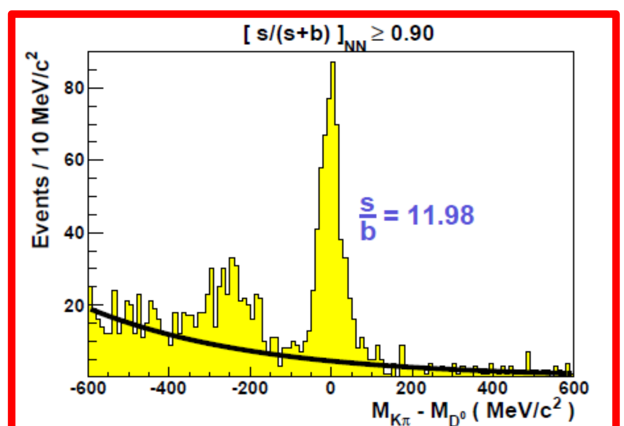


<u>s/(s+b) is obtained from a fit to these spectra</u> *(correcting all events with the corresponding values of $[s/(s+b)]_{NN}$)*





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



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

High-p_T hadron pairs

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

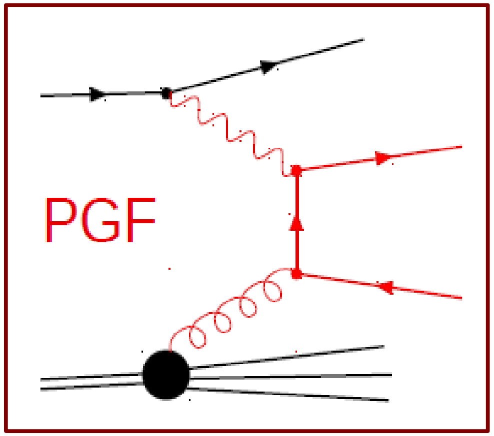
- **Two samples are considered** (fractions of the processes are estimated from MC):

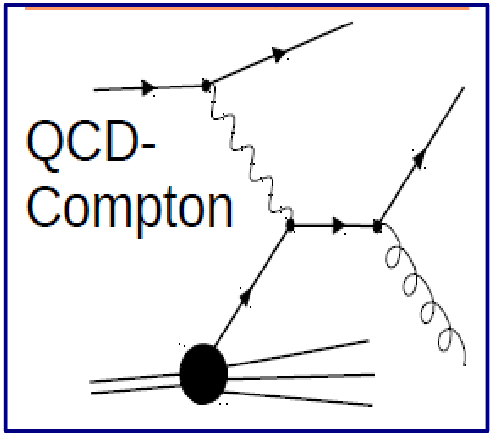
Inclusive asymmetry

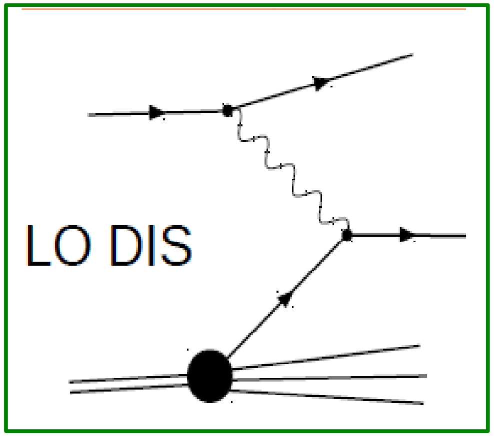
$$A_1^d(x) = \frac{\Delta G}{G}(x_g)\left(a_{LL}^{PGF,inc}\frac{\sigma^{PGF,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_C)\left(a_{LL}^{C,inc}\frac{\sigma^{C,inc}}{\sigma^{Tot,inc}}\right) + A_1^{LO}(x_{Bj})\left(D\frac{\sigma^{LO,inc}}{\sigma^{Tot,inc}}\right)$$

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

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

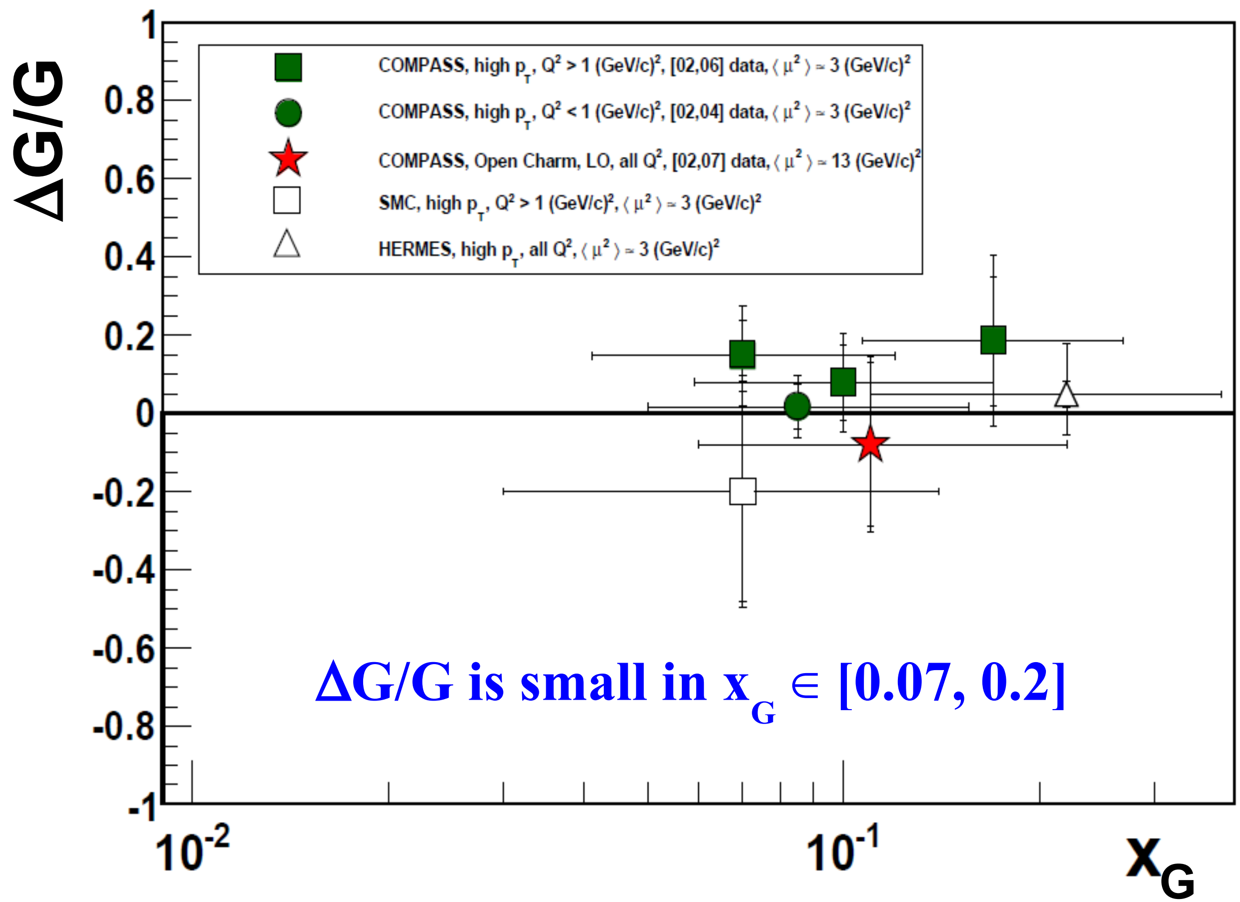






World measurements of ΔG/G at LO in QCD

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

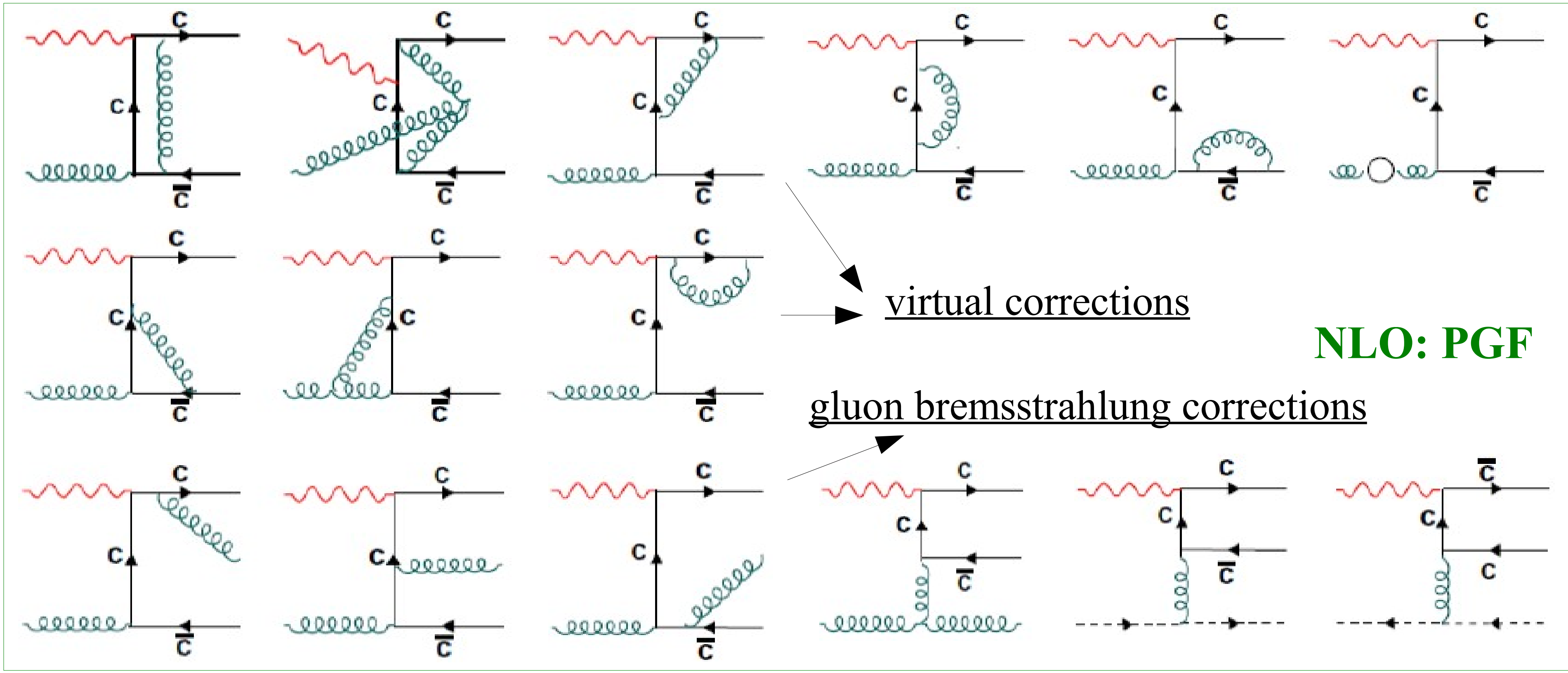


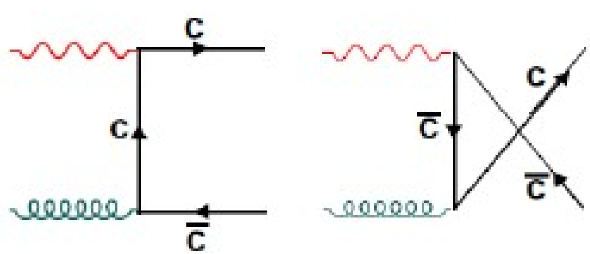
$\Delta G/G$ (high-p_T, $Q^2 > 1$) = 0.125 ± 0.060 (stat) ± 0.063 (syst) @$\langle x_G \rangle = 0.09^{+0.08}_{-0.04}$

$\Delta G/G$ (Open Charm) = -0.081 ± 0.213 (stat) ± 0.094 (syst) @$\langle x_G \rangle = 0.11^{+0.11}_{-0.05}$

NLO results from Open Charm

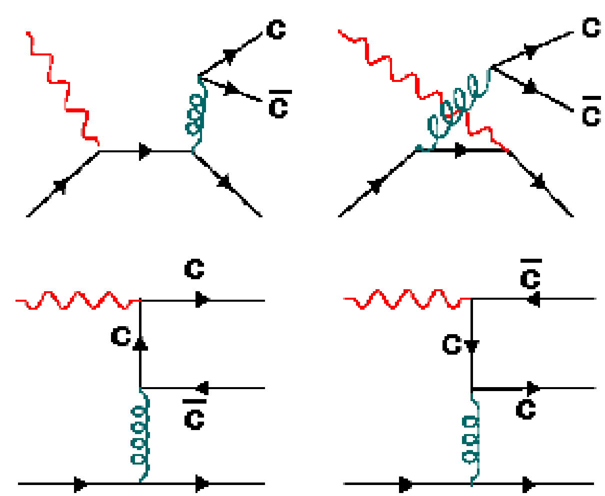
NLO corrections to the analysing power a_{LL}



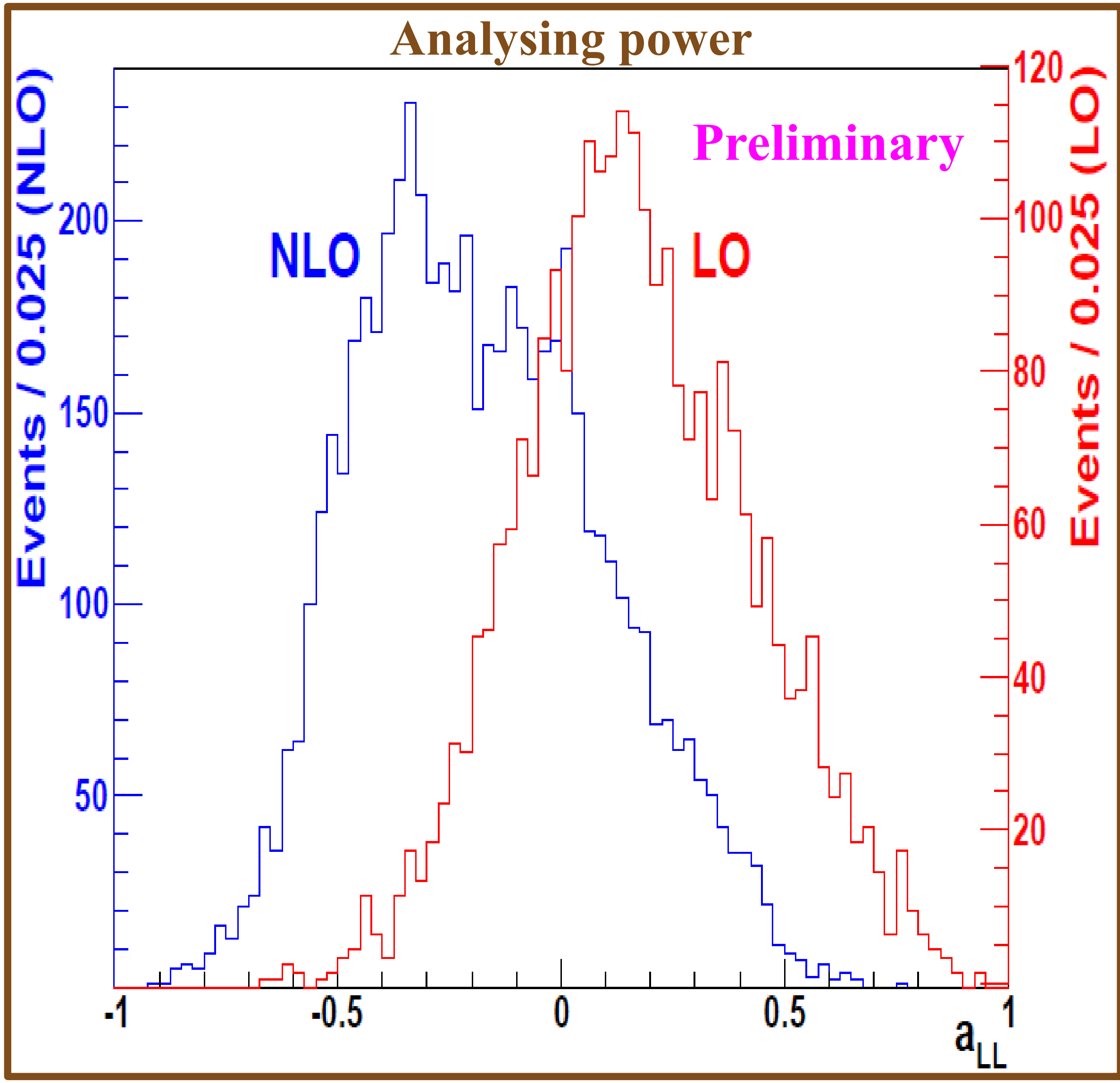


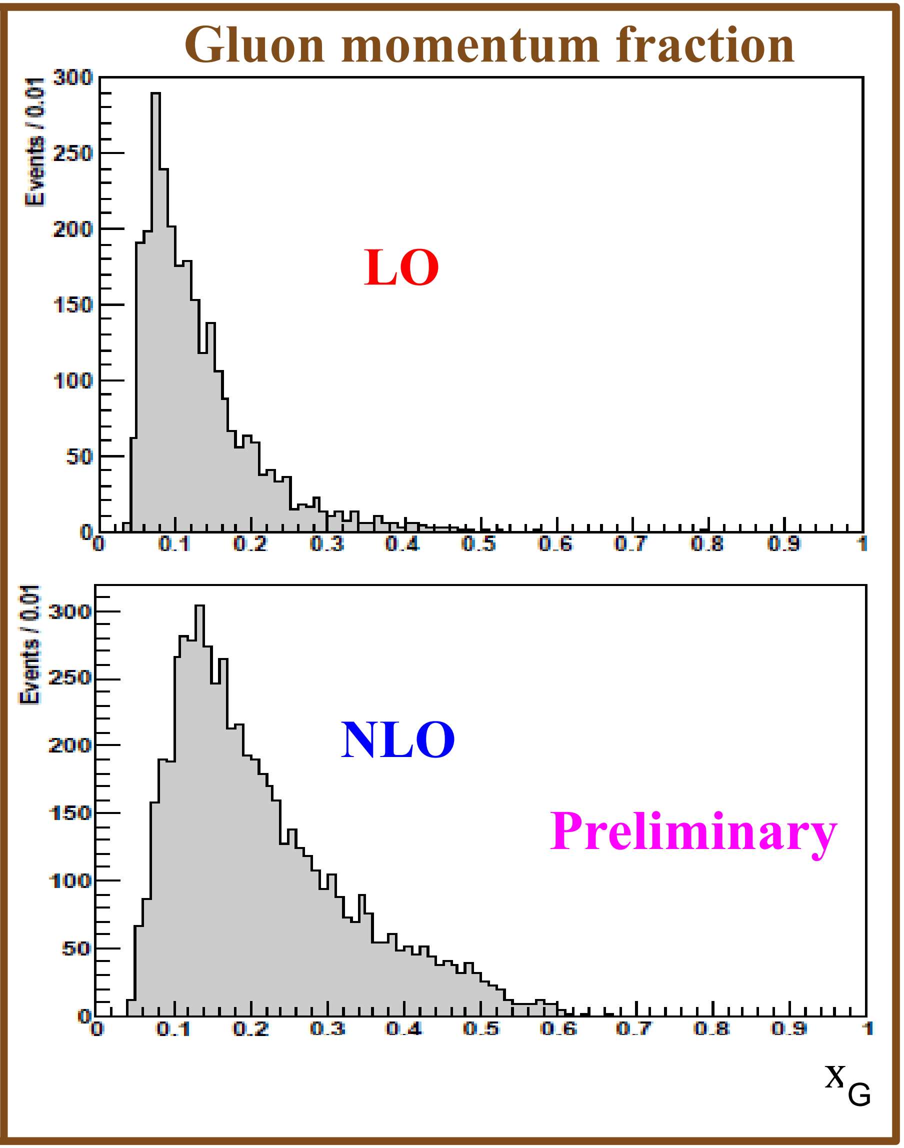
LO: PGF

NLO: bg

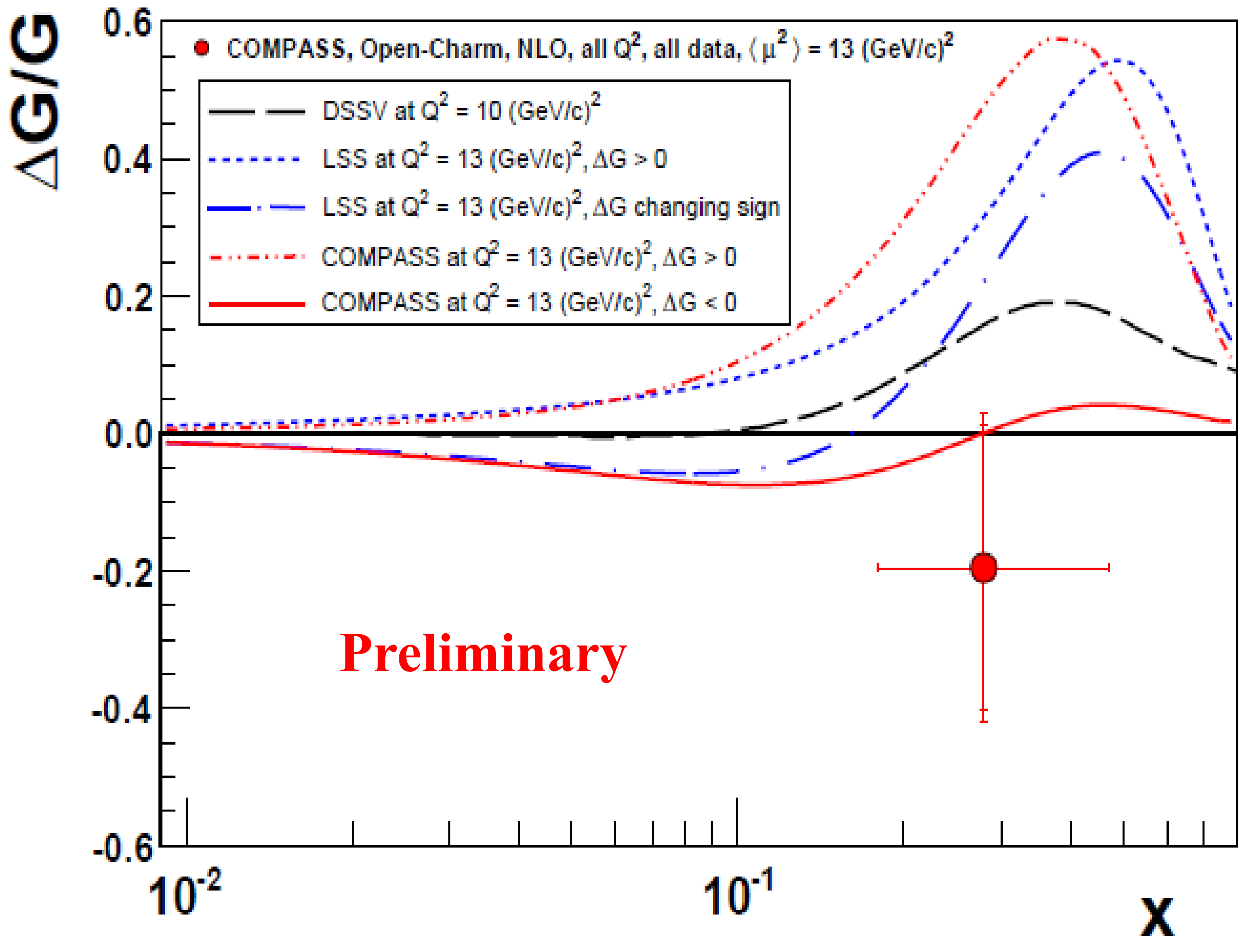


Distributions of a_{LL} and x_G at LO and NLO in QCD





ΔG/G result at NLO in QCD → first world measurement



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

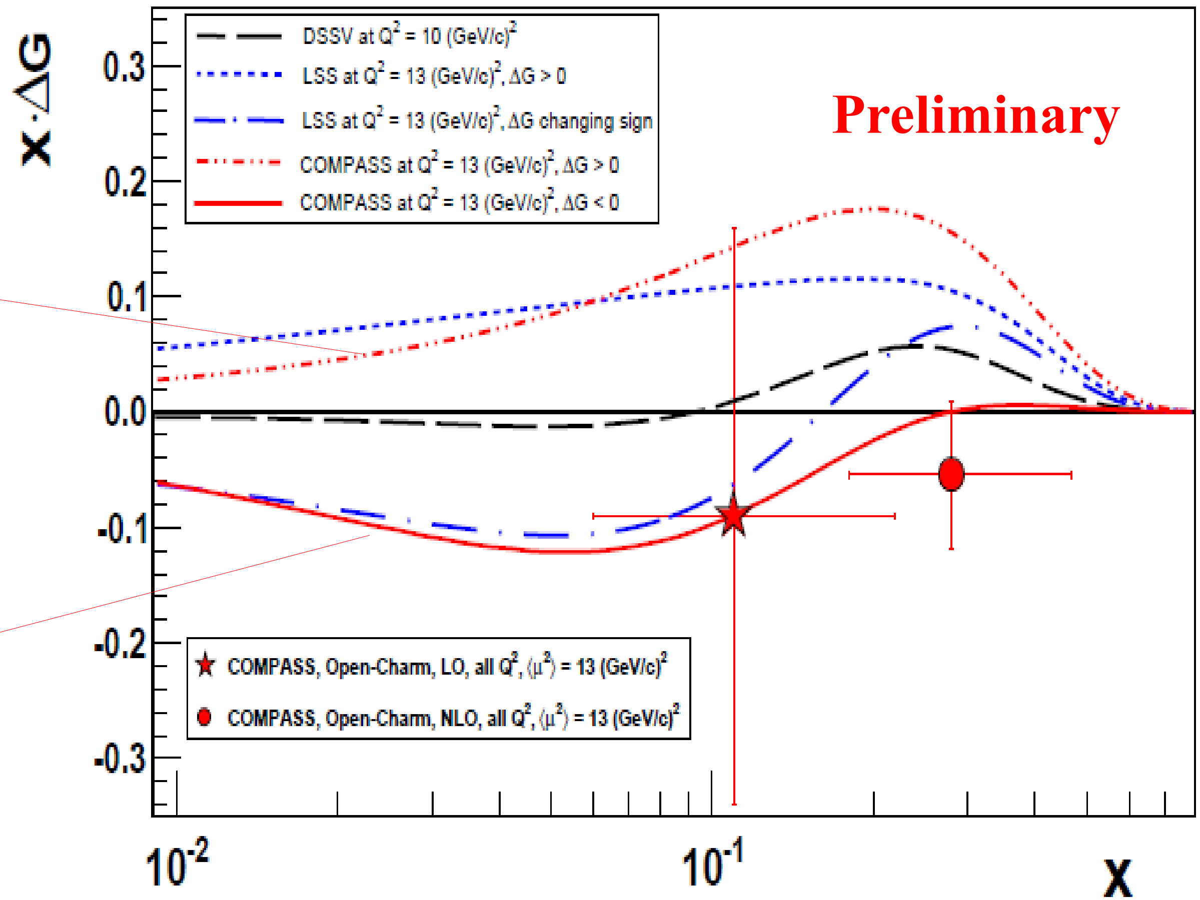
Only experimental: theoretical uncertainties associated with a_{LL} are still under study!

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)):

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

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



SPARES

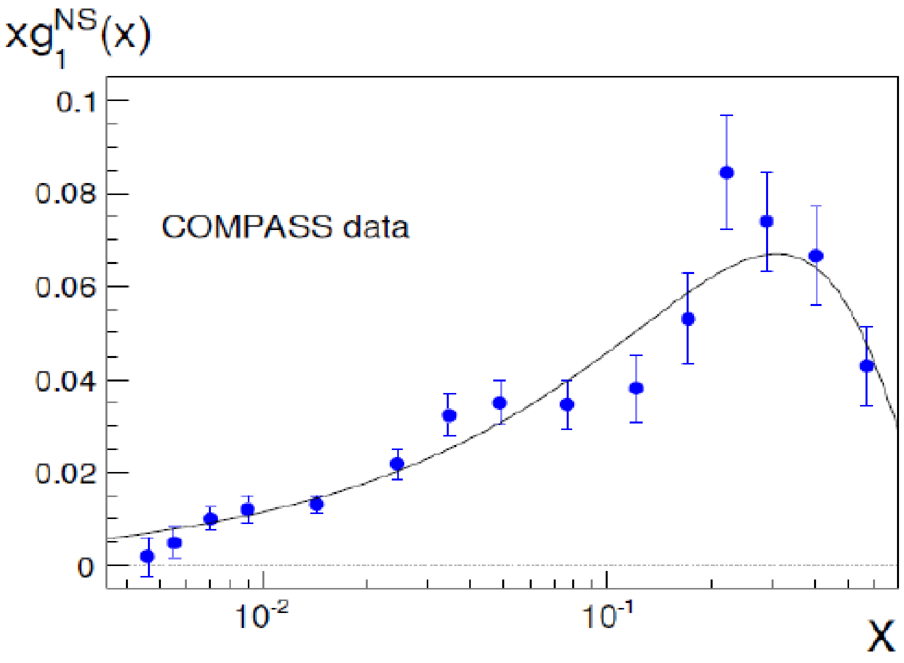
Bjorken sum rule

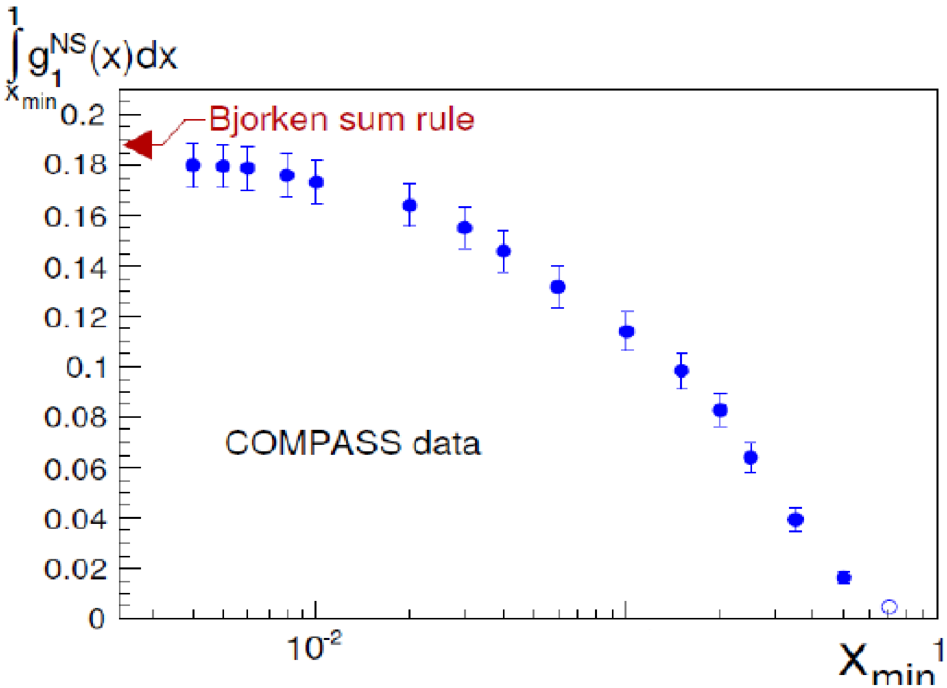
- According to the Bjorken sum rule the first moment of the non-singlet spin structure function, g_1^{NS}, is proportional to the ratio of axial and vector coupling constants g_A/g_V:

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

using

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



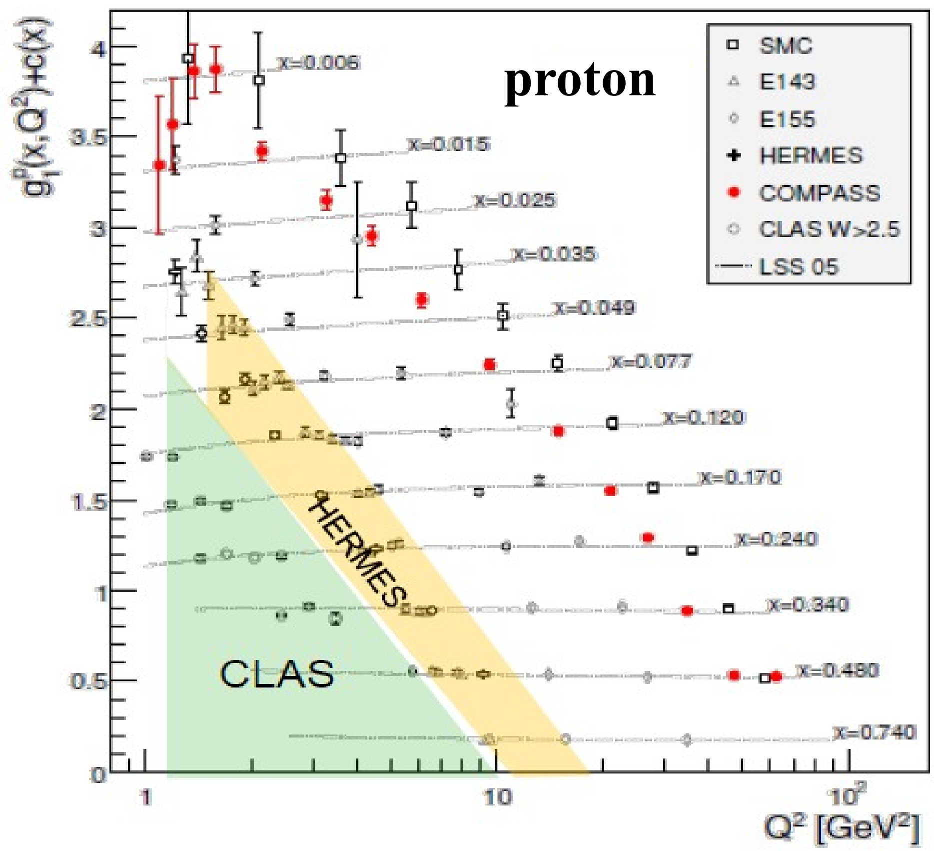


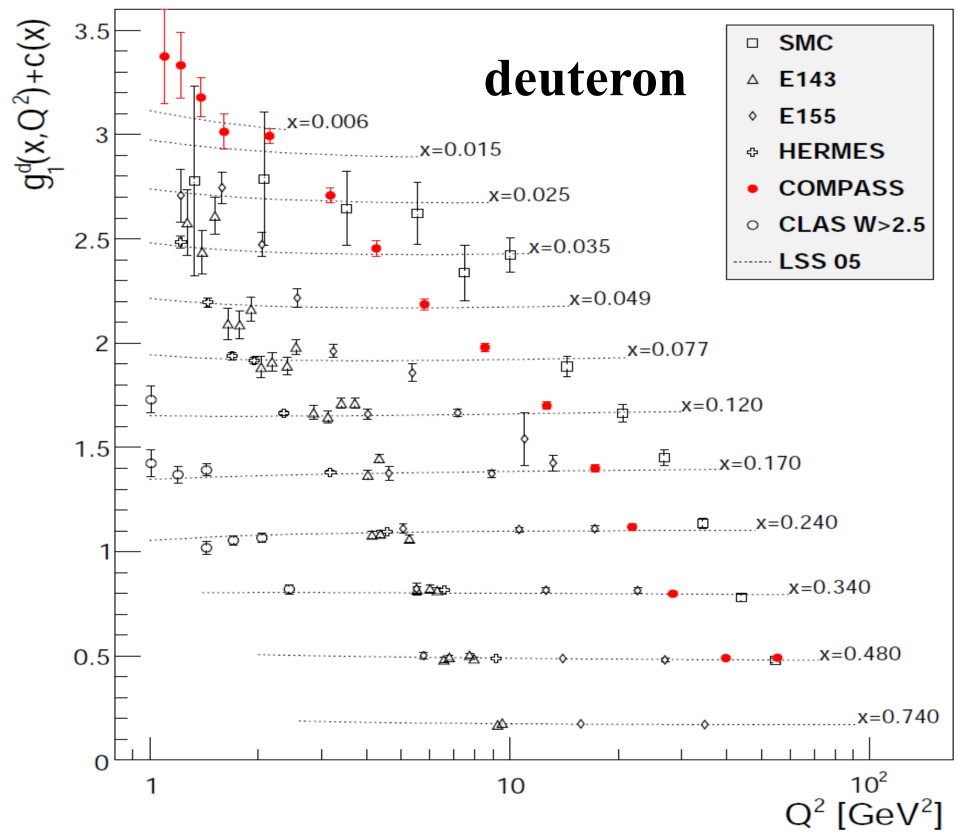
- QCD fit of COMPASS data using $\Delta q^{NS} = |g_A / g_V|\, x^{\alpha}(1 - x)^{\beta}$:

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

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

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

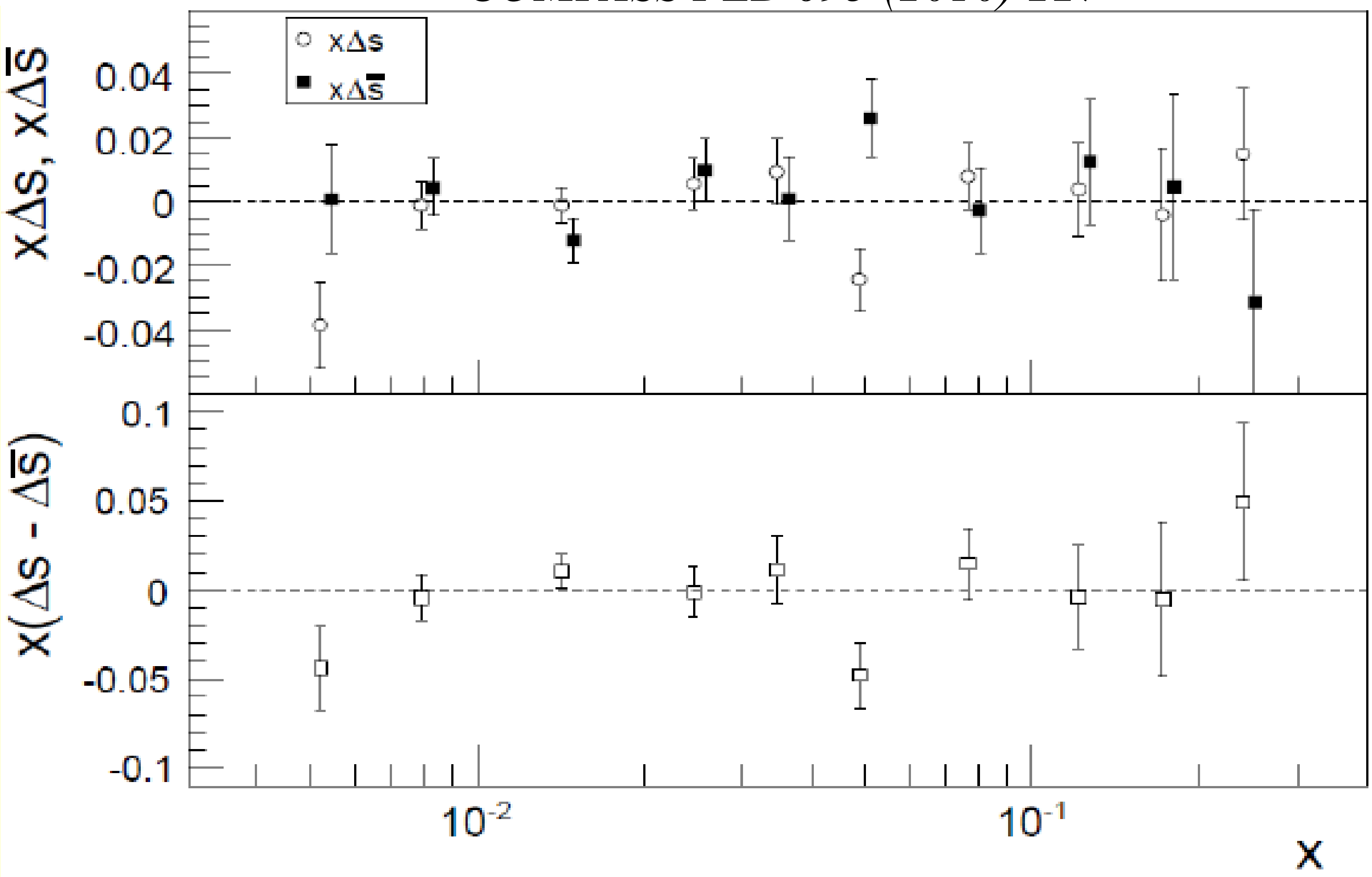




- The kinematic range is still limited (compared to the unpolarised F_2)
  → additional data from colliders is required !
- $(\Delta u + \Delta \bar{u})$ and $(\Delta d + \Delta \bar{d})$ are well constrained by the data (*LSS PRD 80 2009*)
- Δs comes out negative and Δg is small (< 0.5) → Still with large uncertainties

Comparison of Δs with $\Delta\bar{s}$

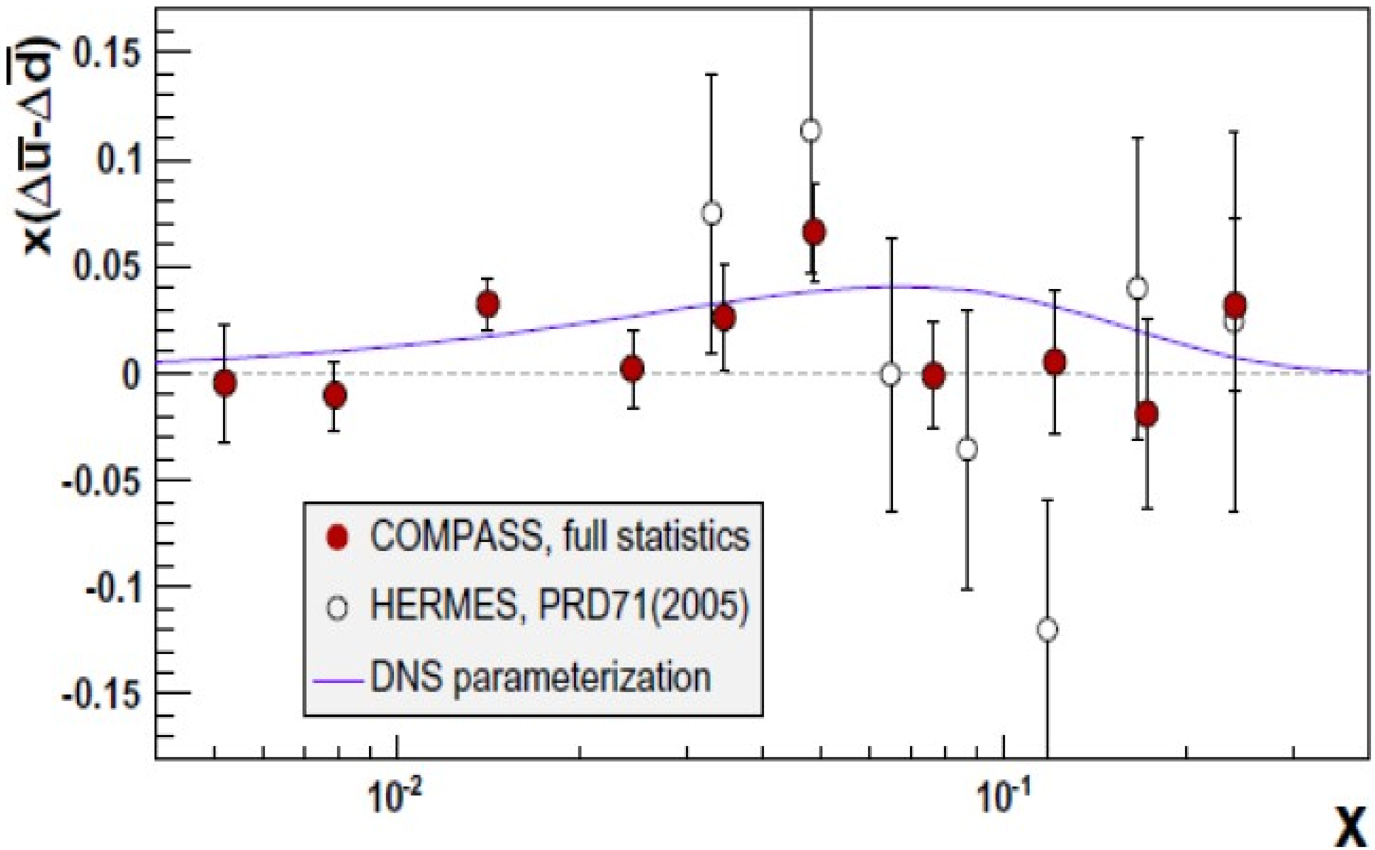
COMPASS PLB 693 (2010) 227



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

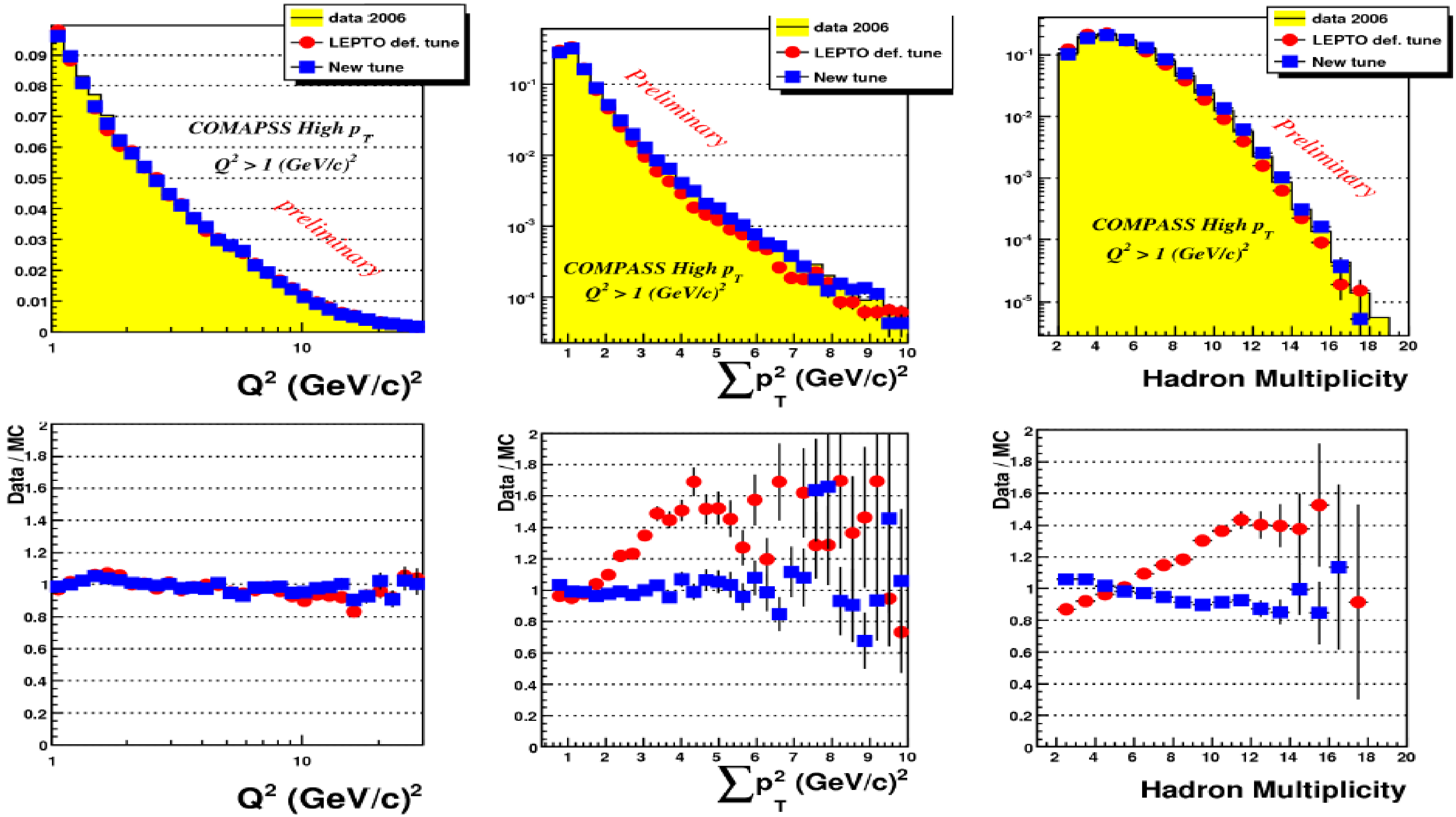
$\Delta\bar{u} - \Delta\bar{d}$: Flavour asymmetry?

- **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!



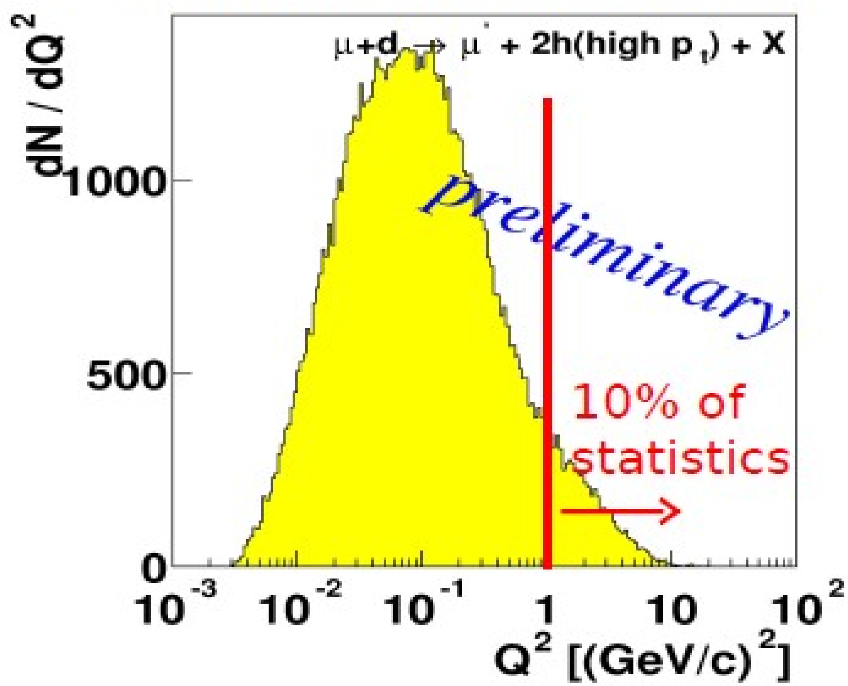
Data vs Monte Carlo: Comparison of Q^2 and hadron variables

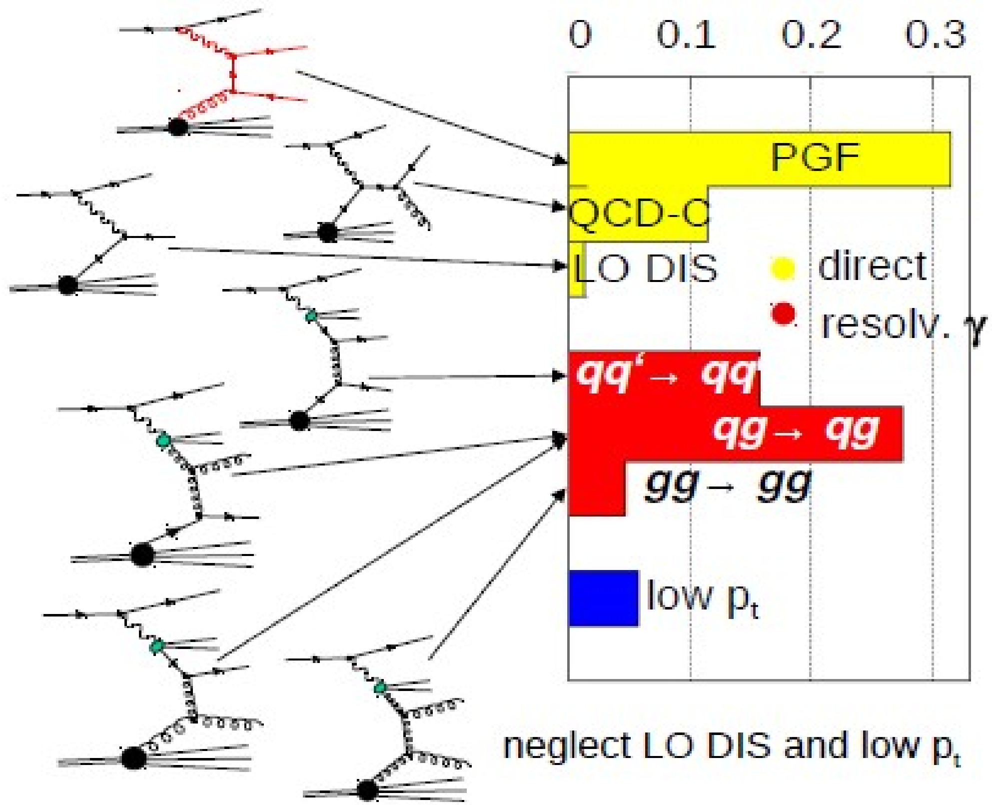
Monte Carlo (PS on): LEPTO generator with PDFs from MSTW2008LO



The impact of this tunning is included in the systematic error

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





2002-2004 Preliminary:

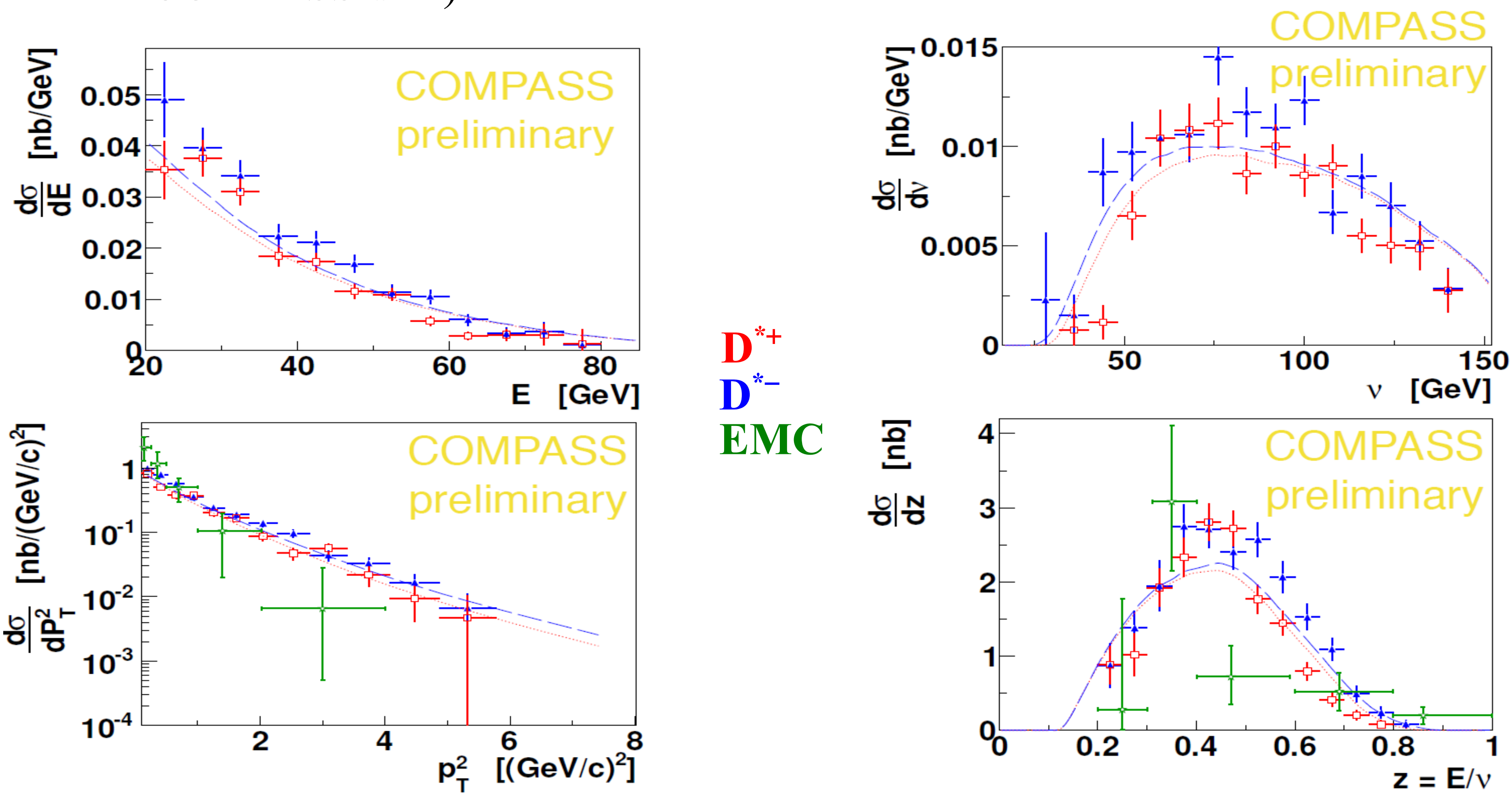
$\Delta G/G$ = 0.016 ± 0.058 (stat) ± 0.055 (syst)

2002-2003 Published:

$\Delta G/G$ = 0.024 ± 0.089 (stat) ± 0.057 (syst) → *Phys. Lett. B 633 (2006) 25 - 32*

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)**:**

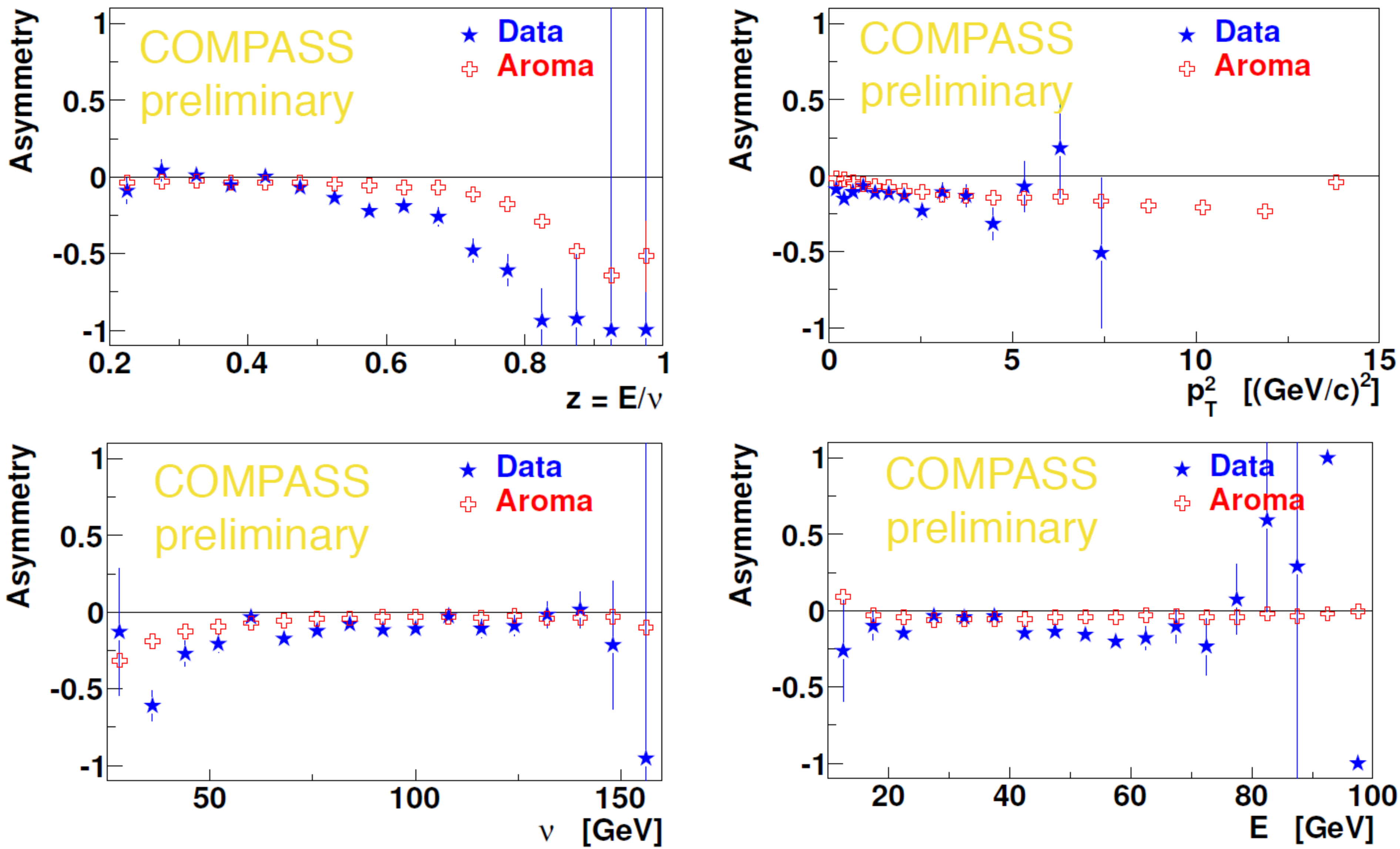


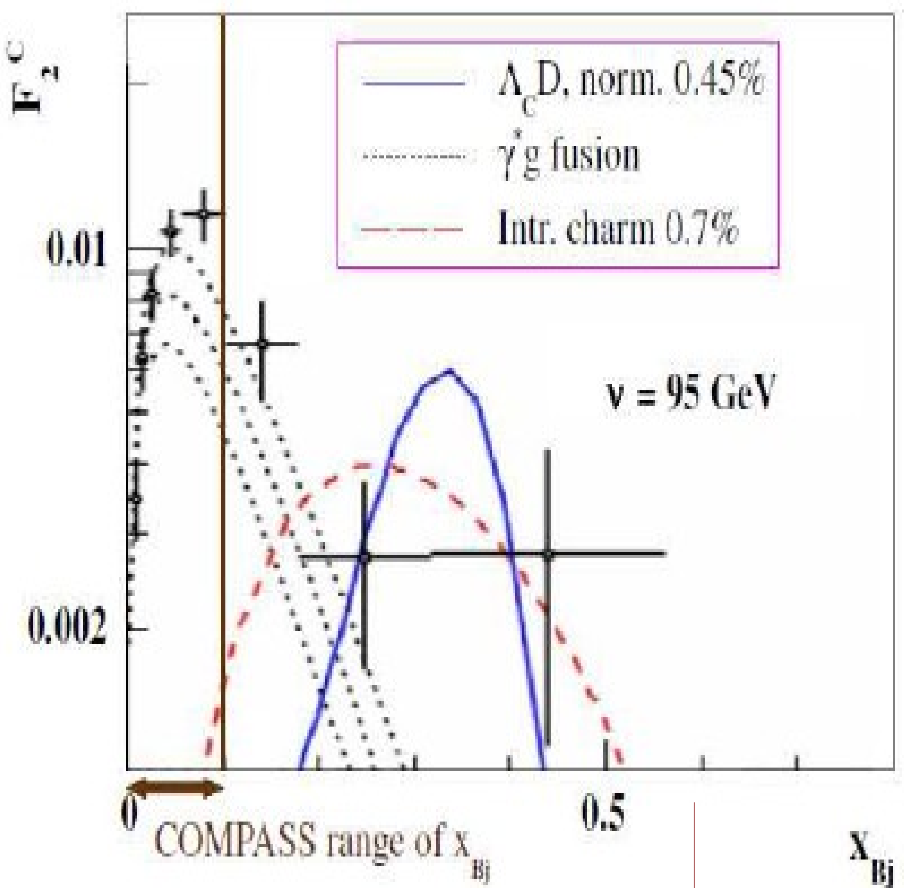
$\sigma(D^{*\pm}) = 1.8 \pm 0.4$ nb

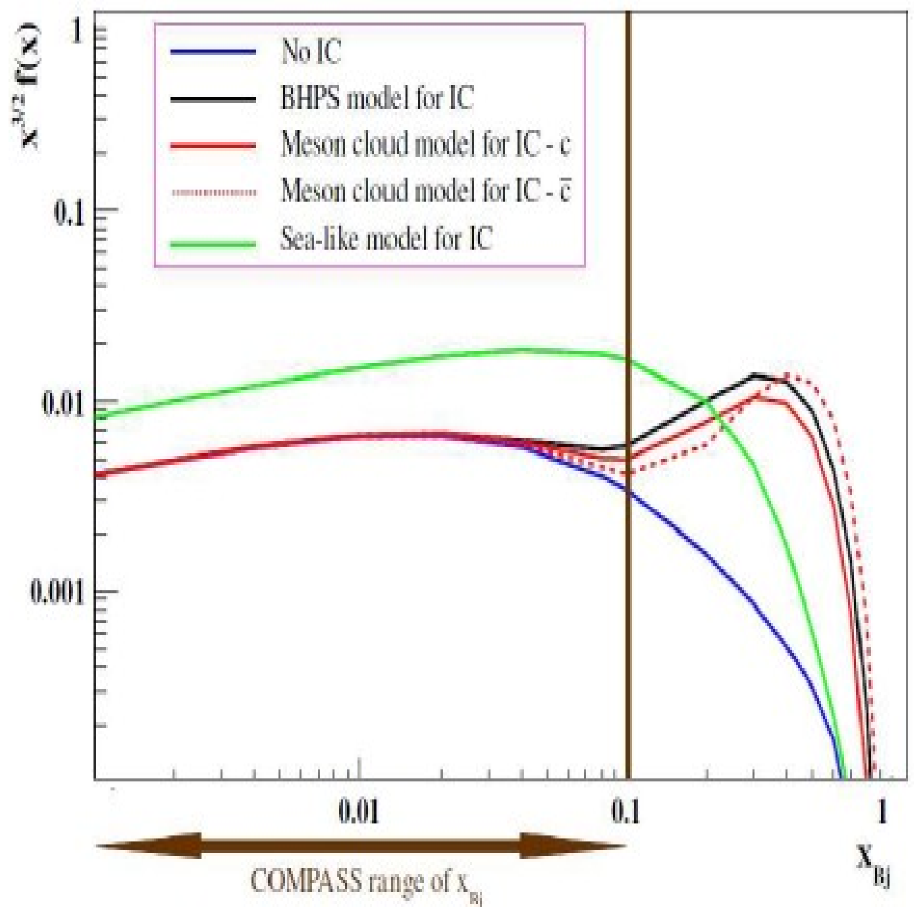
within 20 GeV < E_D < 80 GeV

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

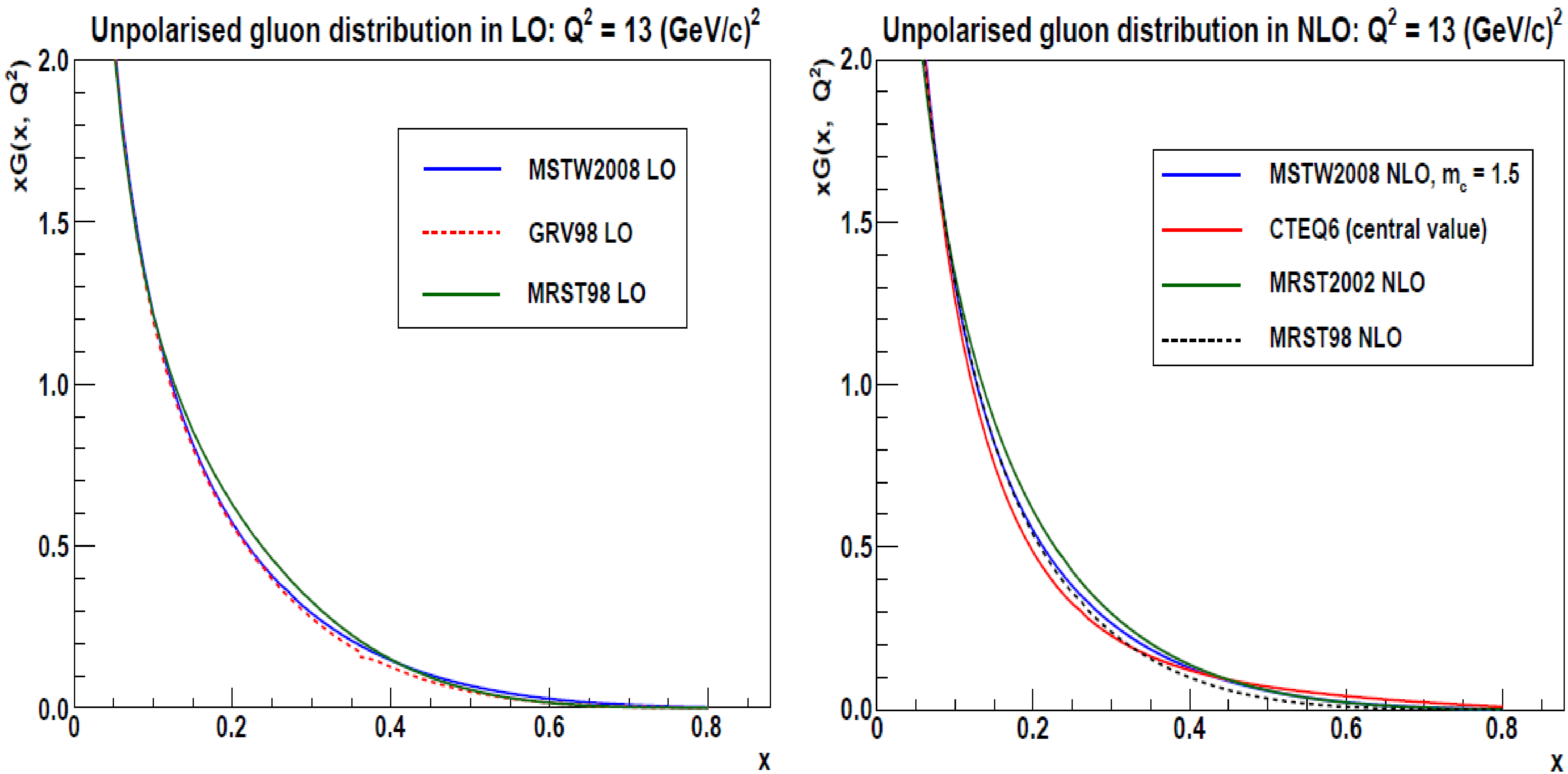
$$A(X) = \frac{d\sigma^{D^{*+}}(X) - d\sigma^{D^{*-}}(X)}{d\sigma^{D^{*+}}(X) + d\sigma^{D^{*-}}(X)}$$







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