COMPASS, Longitudinal Spin of the Nucleon

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Spin crisis / Spin problem

- EMC spin crisis

$$\begin{aligned}
\int g_1^p(x)dx &= (\Delta u - \Delta d)/12 && \longleftarrow\ g_A^3 \text{ from neutron } \beta \text{ decay} \\
&+ (\Delta u + \Delta d - 2\Delta s)/36 && \longleftarrow\ g_A^8 \text{ from Hyperon } \beta \text{ decay} \\
&+ (\Delta u + \Delta d + \Delta s)/9 && = \Delta\Sigma \\
&+ \ \textit{perturbative QCD corrections.}
\end{aligned}$$

$\Delta\Sigma$ small (*compatible w/ 0 in EMC times*) whereas much higher in CQM.

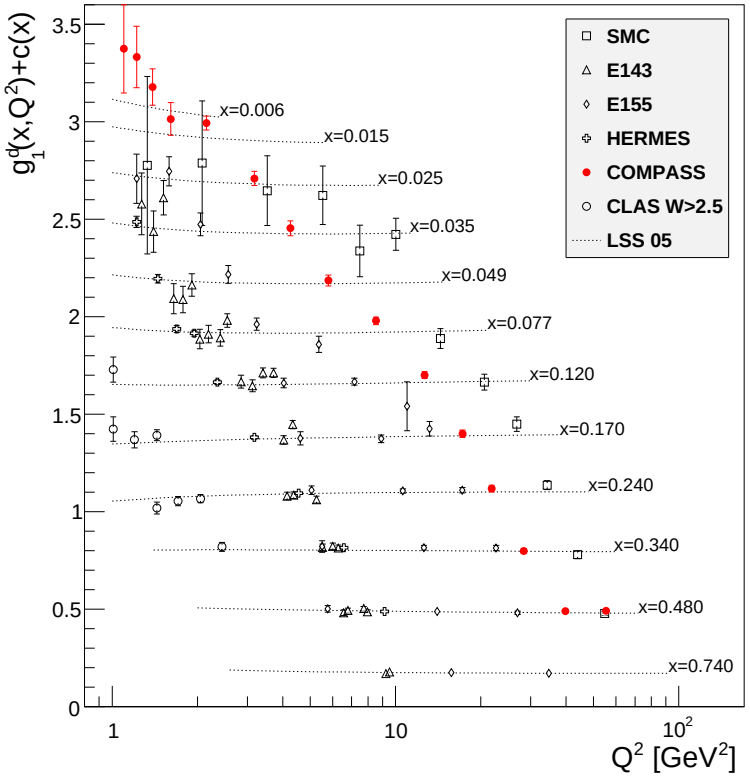
- Axial anomaly scenario
  - Gluonic contribution $-\,1/3\,\alpha_s/2\pi\,\Delta G$ (*does not vanish in the asymptotic limit*)
  - Large ΔG, $\sim$2$\div$3 at EMC Q^2, would mask quark spin

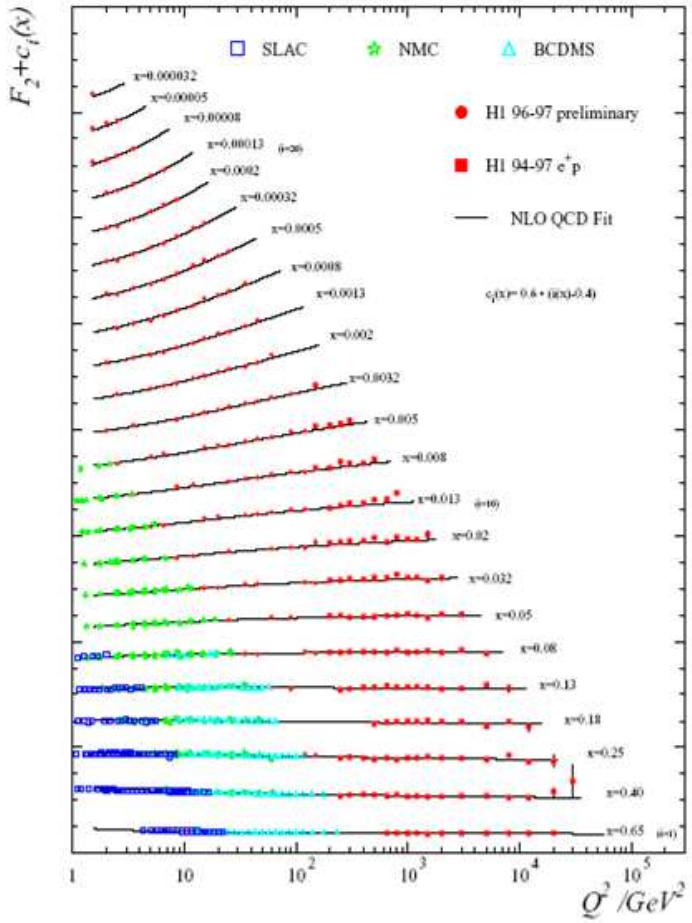
Efremov, Teryaev, JINR Report E2-88-287 (1988)
*Altarelli, Ross, Phys. Lett. B**212** (1988) 391.*

- More general spin problem

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q,g}$$

ΔG from scaling violation ?

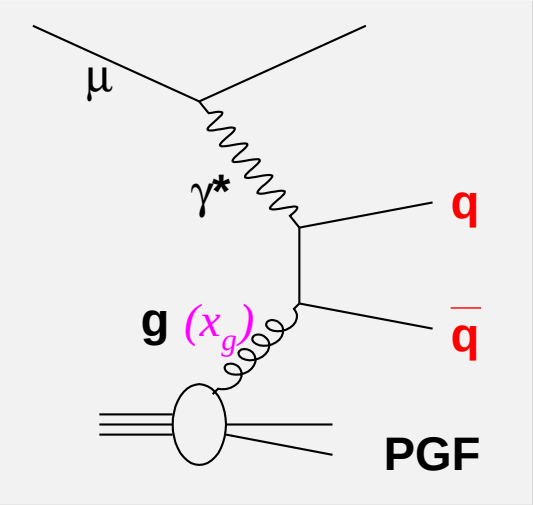


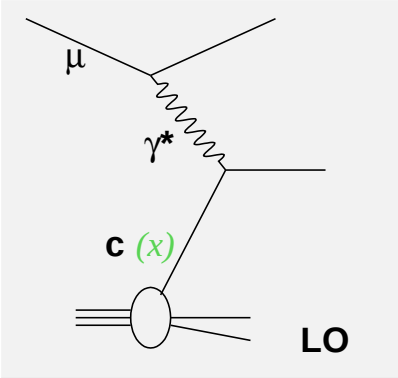


- Limited (x, Q^2) domain accessible

  as compared to unpolarized case
  for want of polarized $\vec{e}\vec{N}$ collider

ΔG from PGF





Intrinsic charm :
Expected at large x
(Brodsky et al., Phys.Lett. B ***93*** *(1980))*
Probed here at $x = 10^{-4} \div 10^{-2} \ll x_g$
$\Rightarrow$ *Neglect intrinsic charm*

q = c : **Open Charm** production
- Triggered by PGF at LO
- Resolved γ small (high x_γ)

$\Rightarrow$ Theory Golden Channel
- Experimentally difficult
- pQCD scale set by $\hat{s} > 4m_c^2$

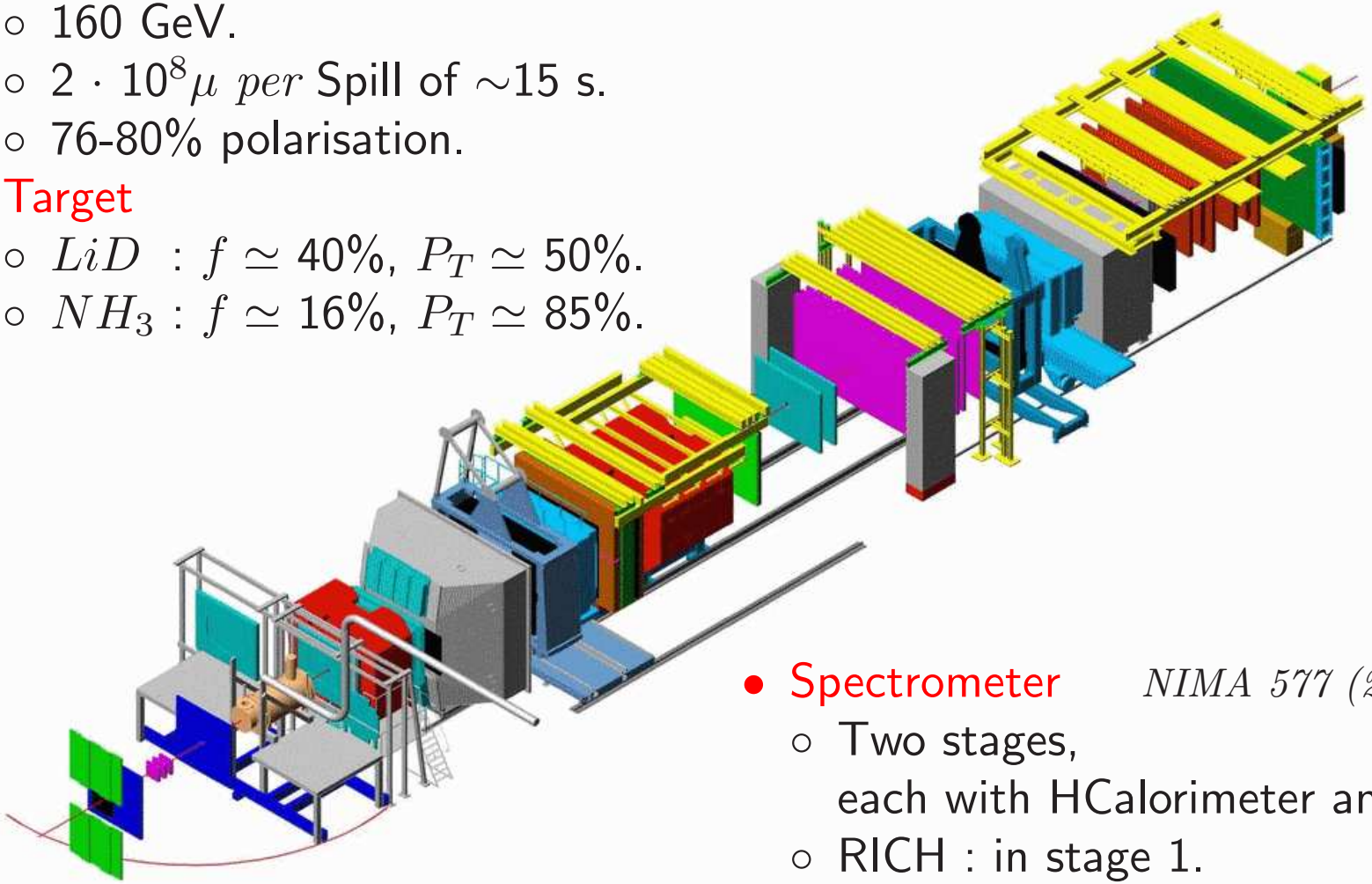
q = u,d,s,c : **High-p_T** Hadrons
- Competing LO-DIS, QCD-Compton
- Competing resolved γ processes.

$\Rightarrow$ Theoretical uncertainties.
- Higher statistics
- pQCD scale can be set by p_T

$\Rightarrow$ Explore all Q^2

COMPASS Spectrometer : All Q^2, SIDIS

- Muon Beam
  - 160 GeV.
  - $2 \cdot 10^8 \mu$ *per* Spill of ∼15 s.
  - 76-80% polarisation.
- Target
  - LiD : $f \simeq 40\%$, $P_T \simeq 50\%$.
  - NH_3 : $f \simeq 16\%$, $P_T \simeq 85\%$.



- Spectrometer *NIMA 577 (2007) 455*
  - Two stages,
    each with HCalorimeter and μ-filter.
  - RICH : in stage 1.
  - ECalorimeter : 2(*since mid-2004*), 1 (*in 2008*).

Asymmetry Measurement

- Two oppositely polarized target cells : $upstream$, $downstream$
- Polarization reversal by field rotation every 8 hours :

$$\frac{A^{\parallel}}{D} = \frac{1}{|P_\mu P_T| f D}\,\frac{1}{2}\left(\frac{N_u^{\Uparrow\downarrow} - N_d^{\Uparrow\uparrow}}{N_u^{\Uparrow\downarrow} + N_d^{\Uparrow\uparrow}} + \frac{N_d^{\Uparrow\downarrow} - N_u^{\Uparrow\uparrow}}{N_d^{\Uparrow\downarrow} + N_u^{\Uparrow\uparrow}}\right) \qquad D = Depolarization factor$$

$$P_\mu \times P_T \times f \times D \simeq 80\% \times 50\% \times 40\% \times 60\% \simeq 10\% \qquad (typical\ values)$$

- Weighted asymmetry

$$\frac{A^{\parallel}}{D} = \frac{1}{P_T}\,\frac{1}{2}\left(\frac{\sum_u^{\Uparrow\downarrow} w \; - \sum_d^{\Uparrow\uparrow} w}{\sum_u^{\Uparrow\downarrow} w^2 + \sum_d^{\Uparrow\uparrow} w^2} + \frac{\sum_d^{\Uparrow\downarrow} w \; - \sum_u^{\Uparrow\uparrow} w}{\sum_d^{\Uparrow\downarrow} w^2 + \sum_u^{\Uparrow\uparrow} w^2}\right) \qquad w = P_\mu\, f\, D$$

$\Rightarrow$ Gain in precision $= \sqrt{\langle w^2\rangle / \langle w\rangle^2}$

- Microwave reversal (once per ~month) cancels acceptance $vs.$ target field correlation.
- 2006 : 3-cell target $\Rightarrow$ Even better false asymmetry suppression. Rotation once per day.
- 2007 : NH_3 target $\Rightarrow$ $P_T \times f \simeq 85\% \times 16\%$

Data Taking

- Luminosity in the longitudinal mode :

	2002	2003	2004	2006
Integrated Luminosity (fb^{-1})	0.43	0.58	0.92	0.85

- [2002,2004] : ∼20% of data taking in tranversely polarised mode

- 2006 upgrade :
  - Larger acceptance : 70 mrd → 180 mrd.
  - Better RICH PID

- 2007 : NH_3 target. 1/2 longitudinal, 1/2 transverse.

- 2008,2009 : Hadron beam ($apart\ from\ short\ DVCS\ test\ runs$)

- 2010,2011 : NH_3 target. Electromagnetic calorimetry.

Physics results

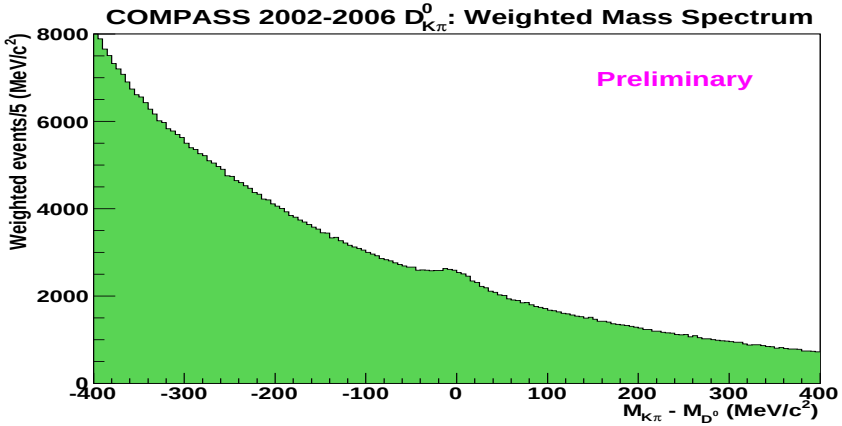
- **Muon program**
  - ΔG
    - Open Charm.
    - High p_T in DIS
    - High p_T in photoproduction
  - Spin dependent structure function and polarized PDFs
    - g_1^p, g_1^d.
    - Bjorken sum rule.
    - SIDIS : flavor separation.
  - Transversity and TMD DFs *cf. Christian Schill talk*
  - Λ polarization
  - Exclusive vector mesons

- **Hadron program**
  - Tests of χPT
  - Exotics (glueballs, hybrids, . . .)

$\Delta G/G$ Open charm : D^o meson reconstruction

- $D^o \to K\pi$
  - Thick target
    $\Rightarrow$ No Charm decay vertex reconstruction
  - RICH PID
  + Kinematical cuts
    - Momentum fraction z_{D^o}
    - D^o decay angle

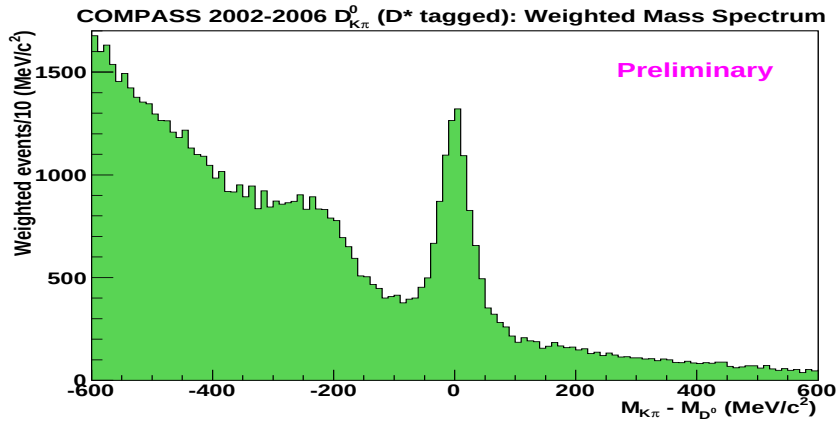
$\Longrightarrow$



$\sim 46k$ D^o's + $\sim 19k$ in 2007

- Favorable case : $D^* \to D^o\pi \to K\pi\,\pi$
  - 1/4 of D^o's
  - D^* tagging by cut on 3-body invariant mass
  - Bump $= D^o \to K\pi\pi^o$ missing π^o

$\Longrightarrow$



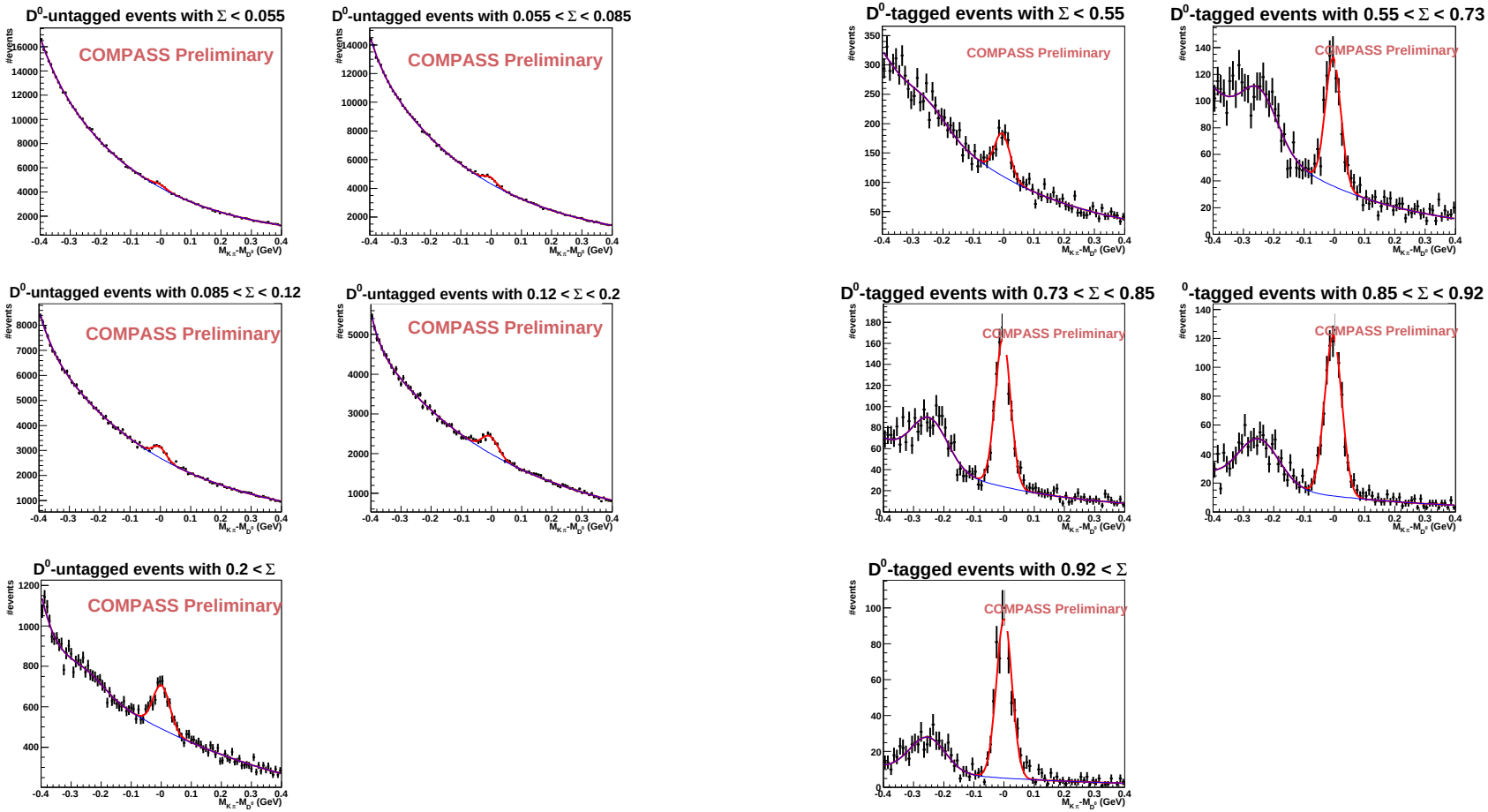
$\sim 8.5k$ D^*'s + $\sim 4.6k$ in 2007

- Also $D^* \to D^o\pi \to K3\pi\,\pi$ $(smaller\ contribution)$

$\Delta G/G$ Open charm : $S/S+B$ weighting

- $S/S+B$ parametrized in $fP_\mu a_{LL}, p^K, \theta^K, z^D, p_T^D, cos\theta^*$ and RICH likelihoods

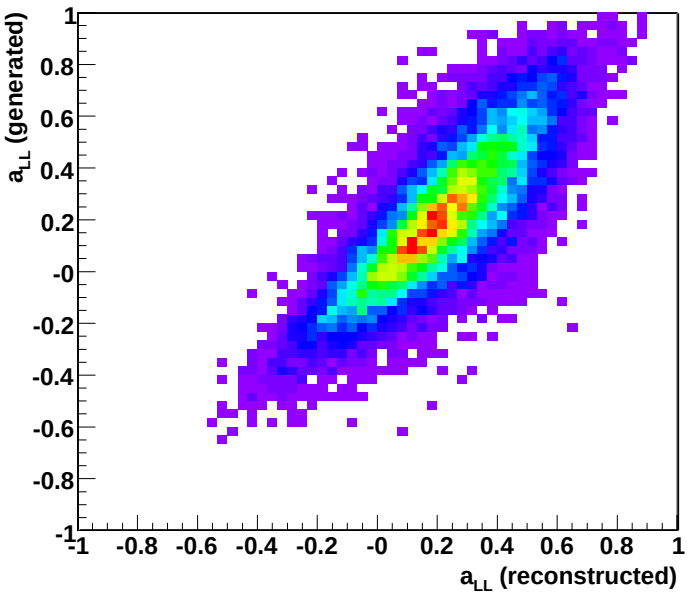
$\Rightarrow$ Mass distributions in bins of $S/S+B$



Open charm : LO interpretation of asymmetry measurement

$$\frac{\Delta G}{G} = \frac{1}{P_T P_\mu f\, a_{LL}\, S/S+B} \frac{N^{\Uparrow\downarrow} - N^{\Uparrow\uparrow}}{N^{\Uparrow\downarrow} + N^{\Uparrow\uparrow}}$$

- $S/S+B$ and a_{LL} parametrized and included in event weight



- a_{LL} parametrization
  - Indispensable given large variation
  - Hard scattering kinematics
    - Needs MC modelization $\Rightarrow$ LO
    - MC = AROMA. Checked $vs.$ data.
  - Parametrization with : $y, Q^2, z^{D^o}, p_T^{D^o}$
  - Using neural network
  - Correlation factor $\simeq$ 82%

$$\frac{\Delta G}{G} = \frac{1}{P_T} \frac{\sum^{\Uparrow\downarrow} w \; - \sum^{\Uparrow\uparrow} w}{\sum^{\Uparrow\downarrow} w^2 + \sum^{\Uparrow\uparrow} w^2} \qquad w = P_\mu\, f\, a_{LL}\, S/S+B$$

$\Delta G/G$ Open charm : Results

- LO interpretation

$$\frac{\Delta G}{G} = -0.08 \pm 0.21(stat.) \pm 0.11(syst.)$$

$$x_G = 0.11^{+0.11}_{-0.05}; \qquad \mu^2 \approx 13 GeV^2$$

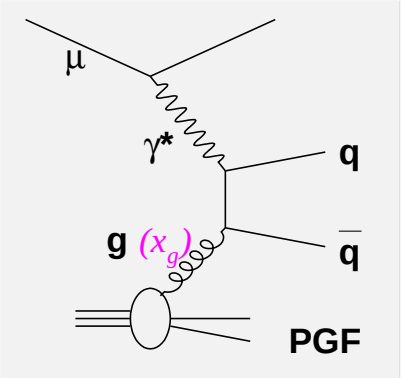
  - Systematics include false asymmetries, a_{LL} (charm mass) & signal extraction ($S/S{+}B$)

- Raw asymmetries

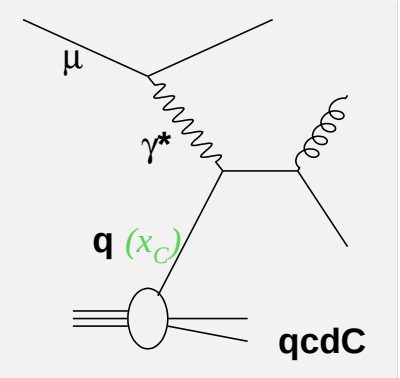
  - In bins of $(\boldsymbol{p_T}, \boldsymbol{E_D})$, w/in which LO a_{LL} is constant
  - Weighted by $\boldsymbol{S/S{+}B}$ and $\boldsymbol{D(y)}$

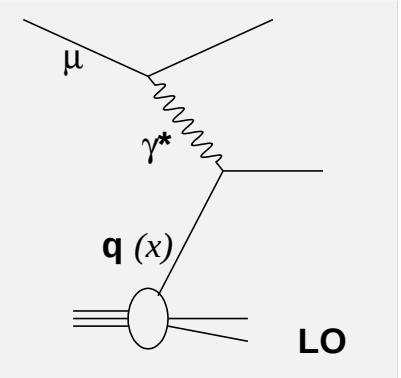
  $\Rightarrow$ NLO interpretation, *cf. Krzystof Kurek, SPIN2010.*

$\Delta G/G$: Direct extraction from high-p_T $Q^2 > 1$



+ background processes





$$A^S(x) \approx \frac{\Delta g}{g}(x_g)\langle \hat{a}_{LL}^{PGF}\rangle \mathcal{R}^S_{PGF} + A_1^{LO}(x_C)\langle \hat{a}^C_{LL}\rangle \mathcal{R}^S_C + A_1^{LO}(x) D \mathcal{R}^S_L$$

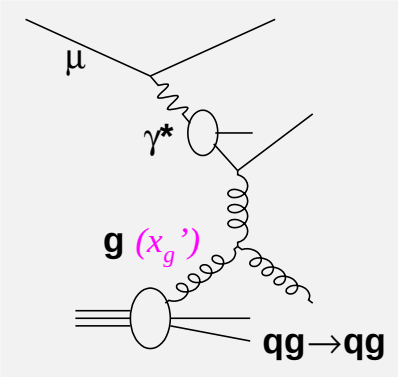
- S : high-p_T sample or inclusive sample
- $\mathcal{R}^S_P$: Fraction of process P = PGF, qcdC, LO in sample S

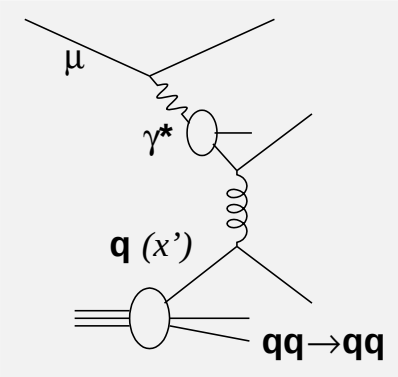
$\Rightarrow$ Input A_1^{LO} for background asymmetry retrieved from COMPASS data

- Derived from MC ($LEPTO$) modelization :
  - Fractions $\mathcal{R}$
  - Parametrization of $\hat{a}_{LL}$ in terms of muon and hadron kinematics

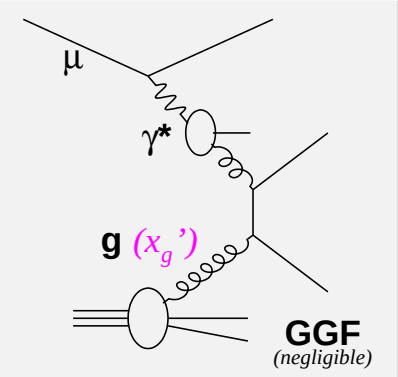
$\Delta G/G$: Extraction from high-p_T $Q^2 < 1$

- Large contribution of resolved photons. . .





etc. . .



etc. . .

$$\langle \frac{A^{h-p_T}}{D} \rangle = \frac{\Delta g}{g} \left(\mathcal{R}_{PGF} \langle \frac{\hat{a}_{LL}^{PGF}}{D} \rangle + \sum_{f^\gamma = q,g} \mathcal{R}_{gf^\gamma} \langle \hat{a}_{LL}^{gf^\gamma} \frac{\Delta f^\gamma}{f^\gamma} \rangle \right) + \mathcal{R}_C \langle \frac{\hat{a}_{LL}^{C}}{D} A_1 \rangle +$$
$$\sum_q \sum_{f^\gamma = q,g} \mathcal{R}_{qf^\gamma} \langle \hat{a}_{LL}^{qf^\gamma} \frac{\Delta q}{q} \frac{\Delta f^\gamma}{f^\gamma} \rangle + \mathcal{R}_{LO} A_{LO} + \mathcal{R}_{Low-p_T} A_{Low-p_T}$$

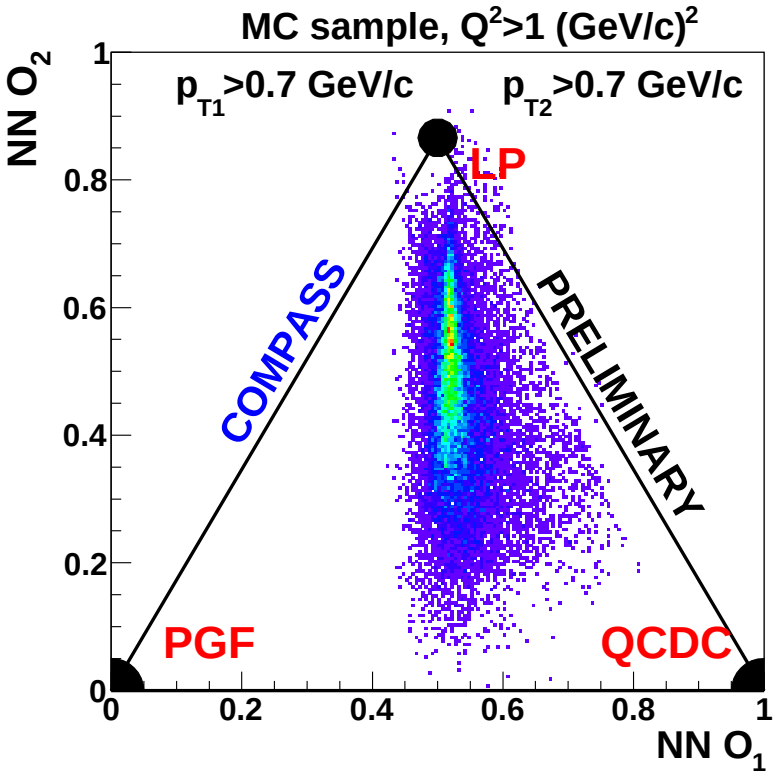
- Inputs $\Delta q/q, \Delta f^\gamma/f^\gamma$ for background asymmetry taken from PDFs (GRSV2000, GRV98)
  - For Δf^γ, max/minimal scenarios are used (*Glück, Reya and Sieg, Eur. Phys. J. C20 (2001)*)
- Fractions $\mathcal{R}$ and parametrizations of $\hat{a}_{LL}$: PYTHIA

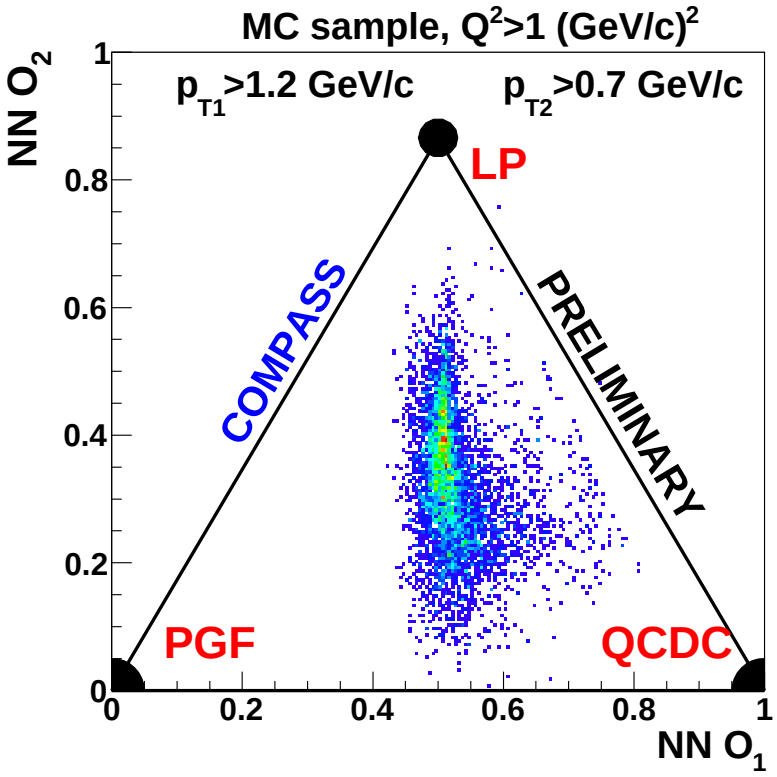
$\Delta G/G$ High p_T : $Q^2 > 1$ vs. $Q^2 < 1$

- **$Q^2 < 1$ GeV^2**
  - PYTHIA used :
    pQCD + resolved photon + model dependent low scale processes.
  - $\Sigma p_T^2 > 2.5$ GeV^2 ($p_T > 0.7$ GeV)
  - Hard scale defined by Σp_T^2
  - Highest statistics.

- **$Q^2 > 1$ GeV^2**
  - LEPTO used :
    pQCD alone $\Rightarrow$ better controlled.
  - $p_T > 0.7$ GeV
  - Hard scale defined by Q^2
  - Lower statistics.
  - Resolved photons assumed negligible.
  - No input from polarized PDFs
  - Fractions $\mathcal{R}$ parametrized by Neural Network and included in event weighting

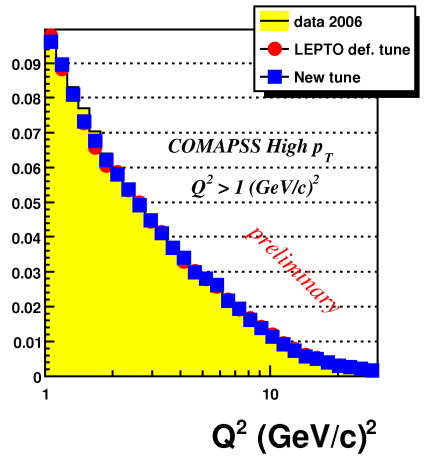
$\Delta G/G$ high-p_T $Q^2 > 1$: Parametrization of $\mathcal{R}$'s

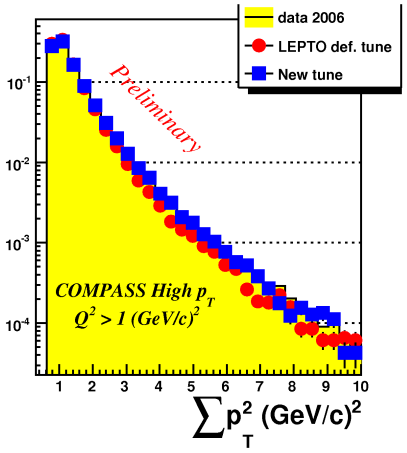


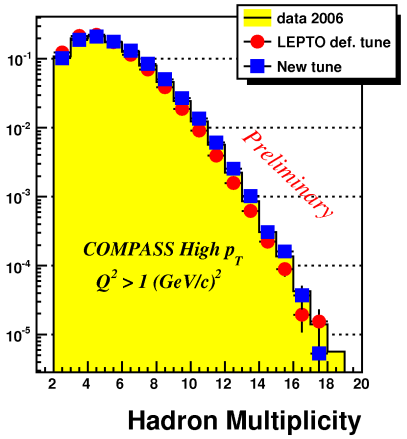


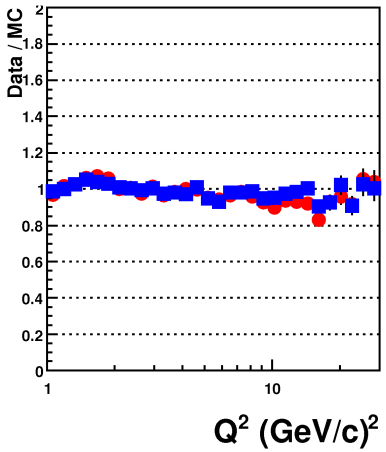
$$\mathcal{R}_{PGF} = 1 - O_1 - \frac{1}{\sqrt{3}}O_2, \quad \mathcal{R}_C = O_1 - \frac{1}{\sqrt{3}}O_2, \quad \mathcal{R}_L = \frac{2}{\sqrt{3}}O_2$$

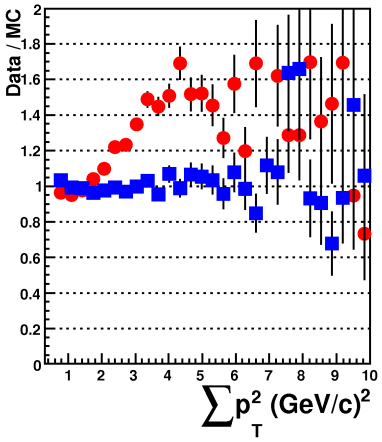
$\Delta G/G$ high-p_T $Q^2 > 1$: Data *vs.* MC

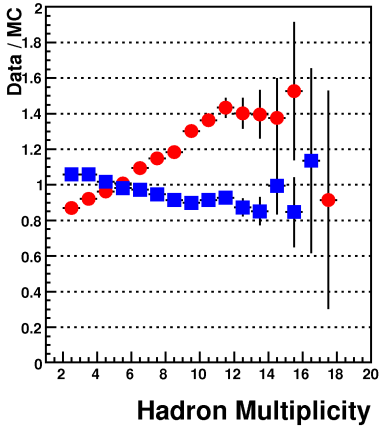












- Hadron distributions require a tuning of *JETSET* fragmentation
- The impact of this tuning is included in the systematics

$\Delta G/G$: high-p_T results

- $Q^2 > 1$ [2002,2006]

$$\frac{\Delta G}{G} = 0.125 \pm 0.060(stat). \pm 0.065(syst.)$$

$$x_G = 0.09^{+0.08}_{-0.04} \text{ @ } \mu^2 \simeq 3.4 \text{ (GeV/c)}^2$$

0.147 ± 0.091 $x_G = 0.07^{+0.05}_{-0.03}$ | 0.079 ± 0.096 $0.10^{+0.07}_{-0.04}$ | 0.185 ± 0.165 $0.17^{+0.10}_{-0.06}$

- Main contribution to systematics is MC generator
- Systematics also include false asymmetries, Neural Network stability, radiative corrections, simplifying assumptions regarding FF

- $Q^2 < 1$ [2002,2004]

$$\frac{\Delta G}{G} = 0.016 \pm 0.058(stat.) \pm 0.054(syst.)$$

$$x_G = 0.085^{+0.071}_{-0.035} \text{ @ } \mu^2 \simeq 3 \text{ (GeV/c)}^2$$

- Systematics include max./min. scenarios for polarized photon structure
- [2002-2003] published in *Phys. Lett.* ***B633*** *(2006)*

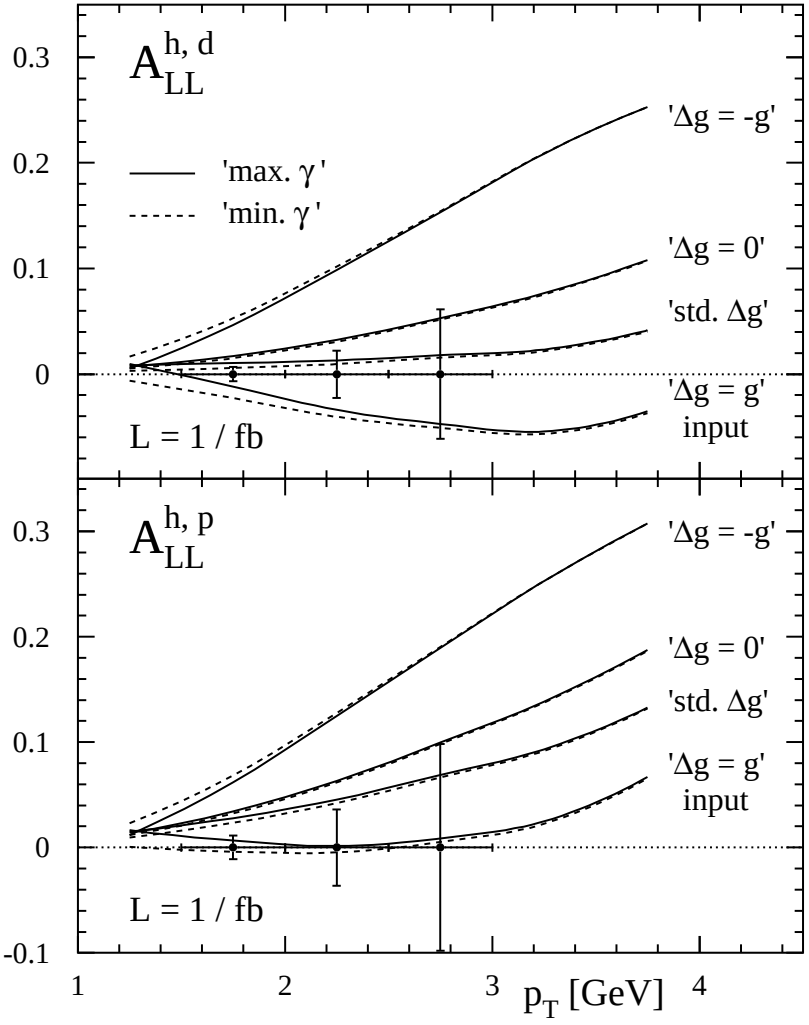
NLO calculation : high p_T photoproduction

- Calculations by group of *BNL/Regensburg*.
  - Single high p_T hadron

  Jäger, Stratmann, Vogelsang, Eur. Phys. J. C **44** *(2005) 533 [arXiv :hep-ph/0505157]*.
  - Pair of high p_T hadrons

  Hendlmeier, Schäfer, Stratmann, Eur. Phys. J. C **55** *(2008) 597 [arXiv :0803.1940 [hep-ph]]*
- Photoproduction : $Q^2 < 0.5$ GeV^2
- ΔG independent of MC model.
- Dependent upon functional shape $\Delta g(x)$
- Need to validate calculation on unpolarized cross section

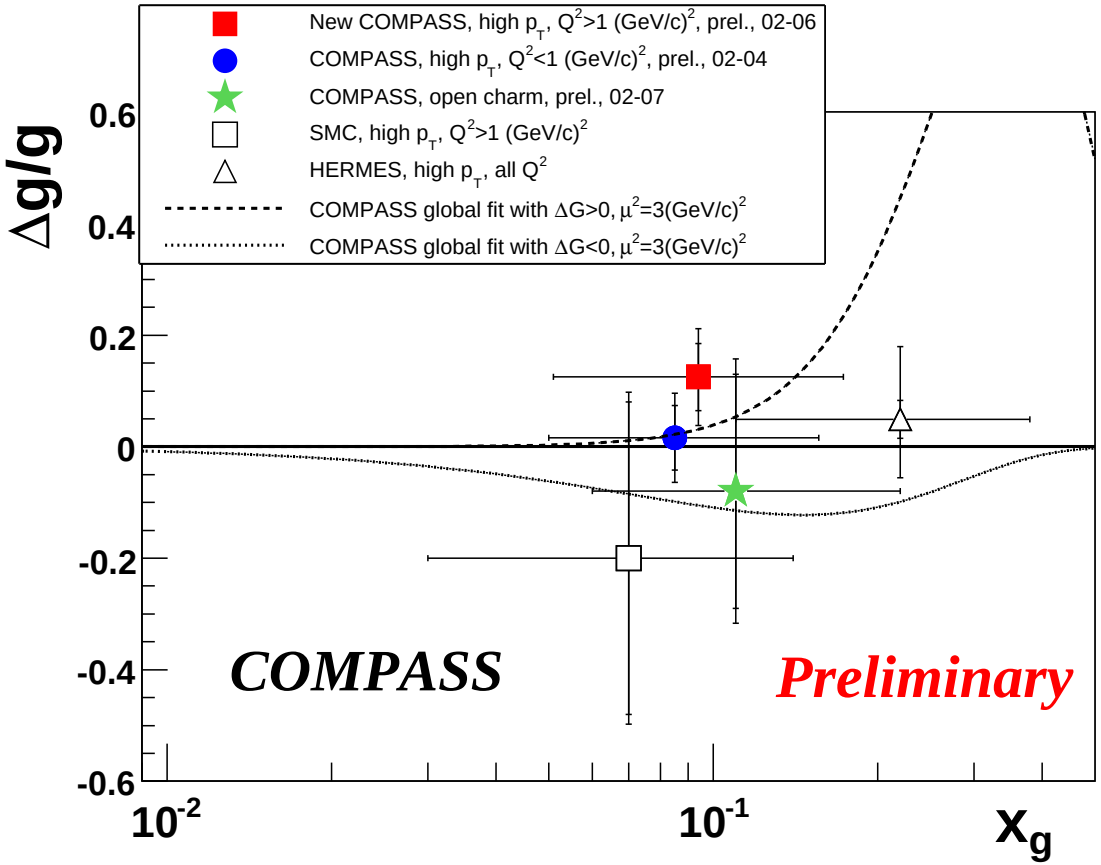
High p_T photoproduction : Projections



- Projections (*compared to GRSV scenarios*) :
  From : Jäger et al.,
  *Eur. Phys. J. C**44** (2005) 533 [arXiv :hep-ph/0505157].*

- Analysis of both unpolarized X-sections and asymmetries are under way.

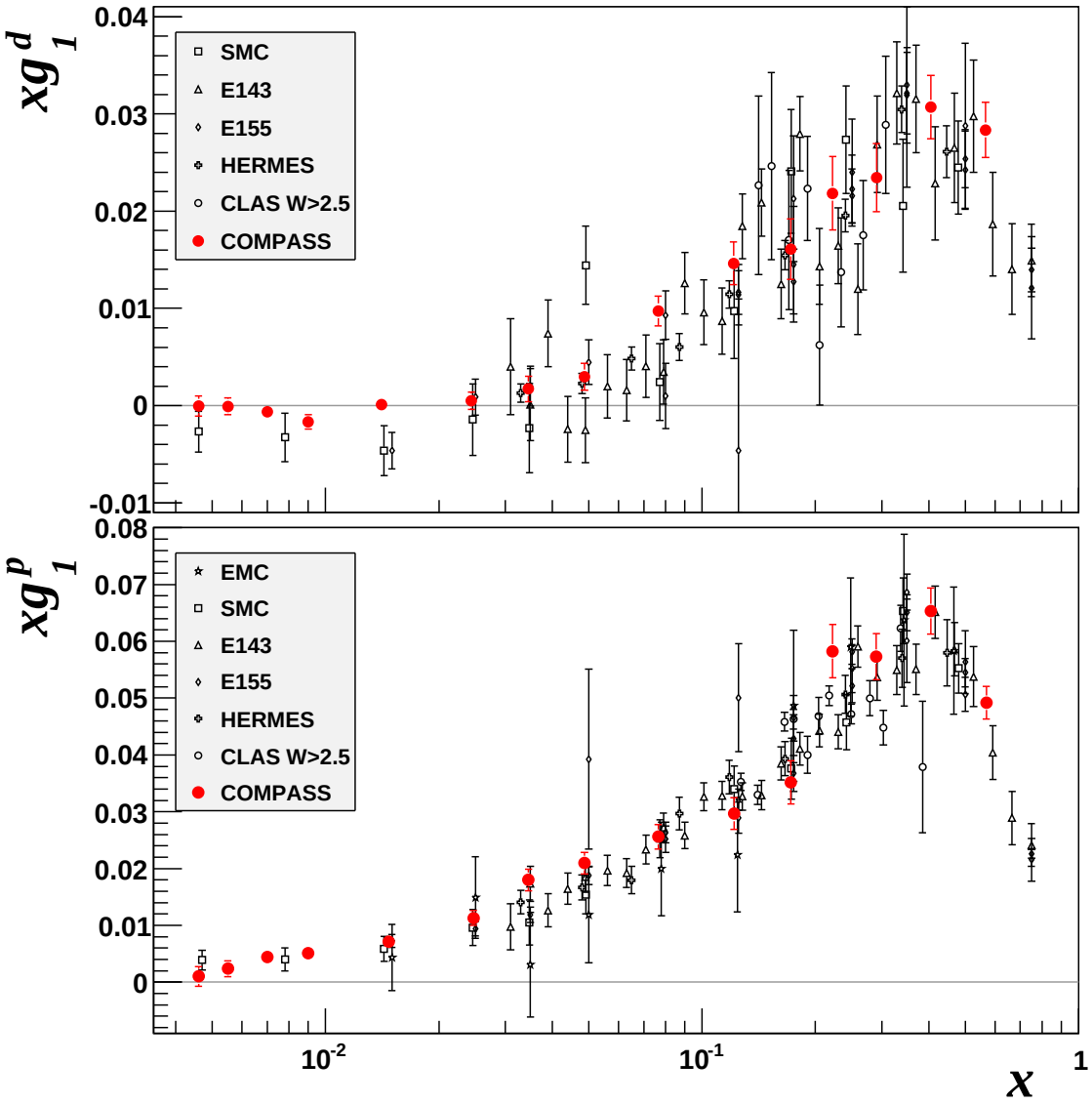
$\Delta G/G$: Summary of results



Caveat : LO data points, NLO curves

- Direct measurements show small value of $\Delta G/G$ at $x_g \simeq 0.1$
- Axial anomaly scenario ruled out
- Shape and sign of $\Delta G(x)$ not well constrained

g_1 : COMPASS measurements



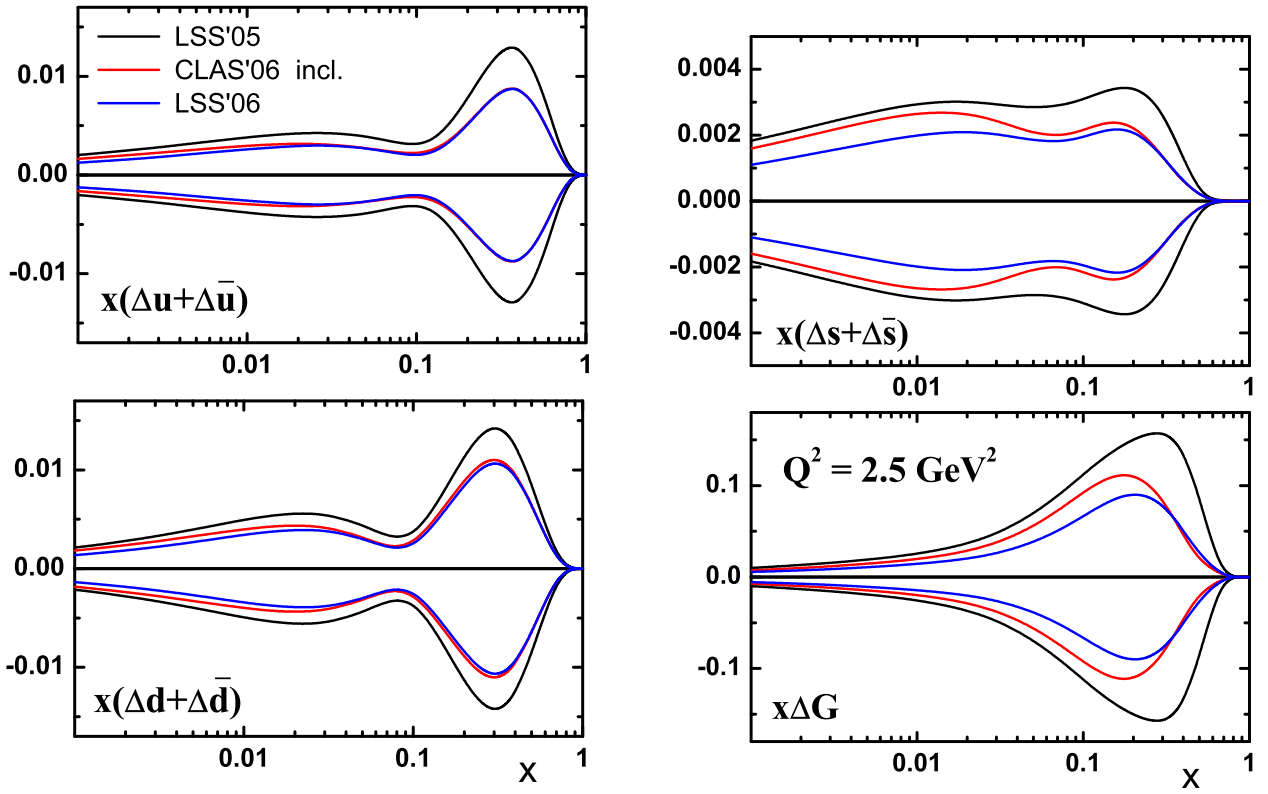
$g_1 \simeq A_{\parallel}/DF_1$ @ COMPASS $\sqrt{s}$

- [2002,2004], ^6LiD target
- 2007, NH_3 target

*Phys. Lett. B**690** (2010) 466*
[arXiv :1001.4654 [hep-ex]]

g_1 : QCD fit of (inclusive) world data

- Examples (*COMPASS p data not included yet*) :
  - COMPASS : *Phys. Lett.* B**647** *(2007) 8 [arXiv :hep-ex/0609038]*.
    $\Delta\Sigma = 0.30 \pm 0.01(stat.) \pm 0.02(evol.)$ @ $Q^2 = 3$ GeV^2
  - LSS : *Leader, Sidorov and Stamenov, Eur. Phys. J. ST***162** *(2008) 19.*

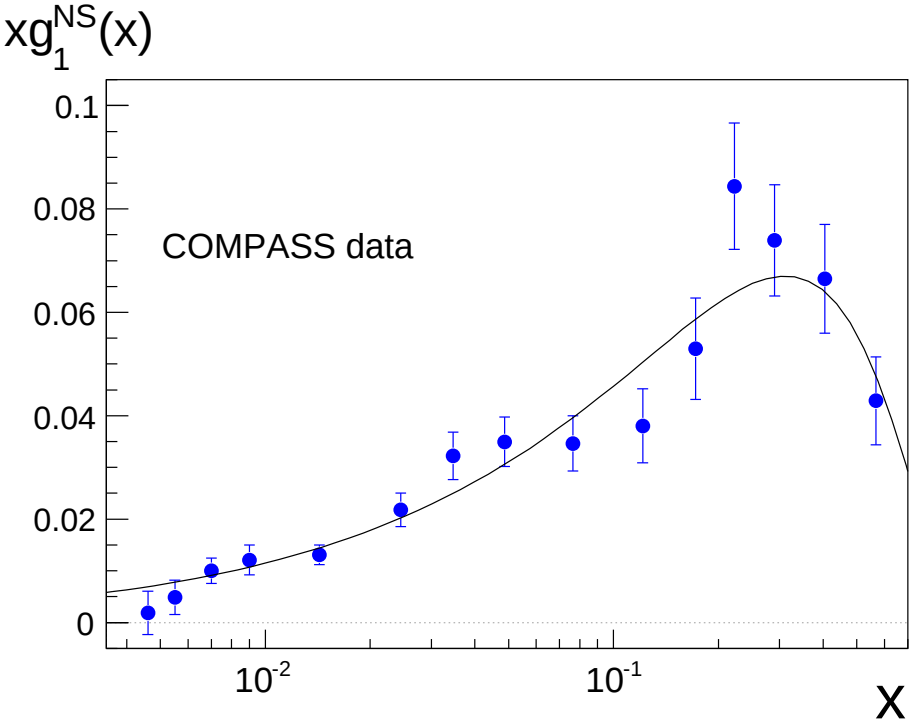


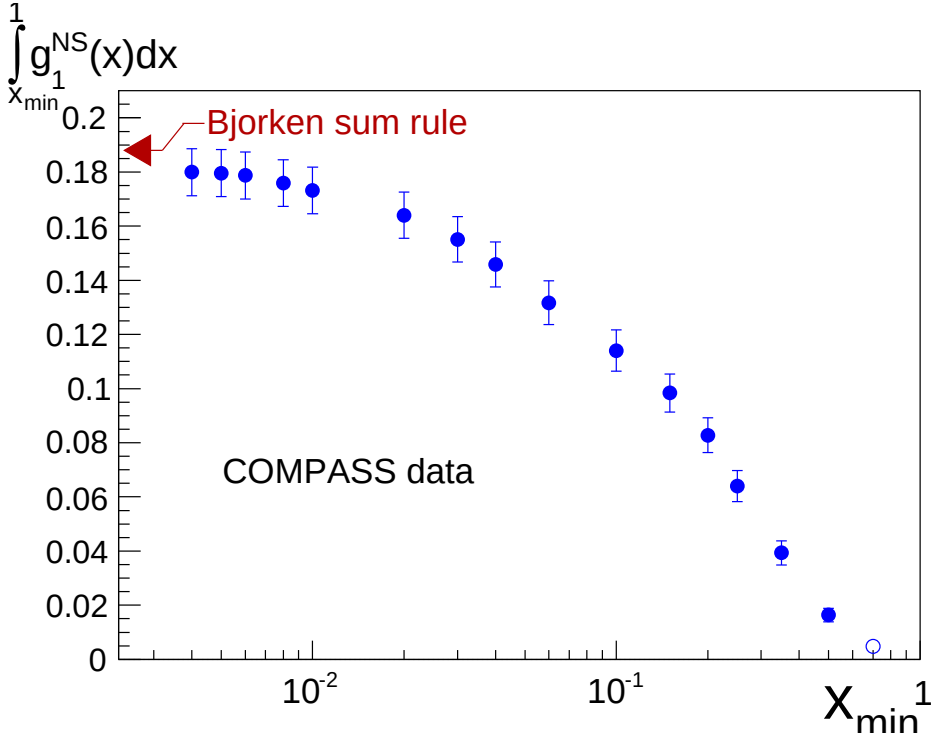
Impact of CLAS and COMPASS data on the uncertainties for NLO polarized PDFs.

- Yet, present inclus. DIS do not distinguish between >0, <0 and sign-changing $\Delta G(x)$

g_1^{NS} : Bjorken sum rule

- $g_1^{NS} = g_1^p - g_1^d \Rightarrow$ All distributions hard to handle $(\Delta s, \Delta G)$ cancel out.
- Bjorken sum rule : $\int g_1^p(x)dx(Q^2) = 1/6\, g_A/g_V C^{NS}(Q^2) + \ldots$ higher twist

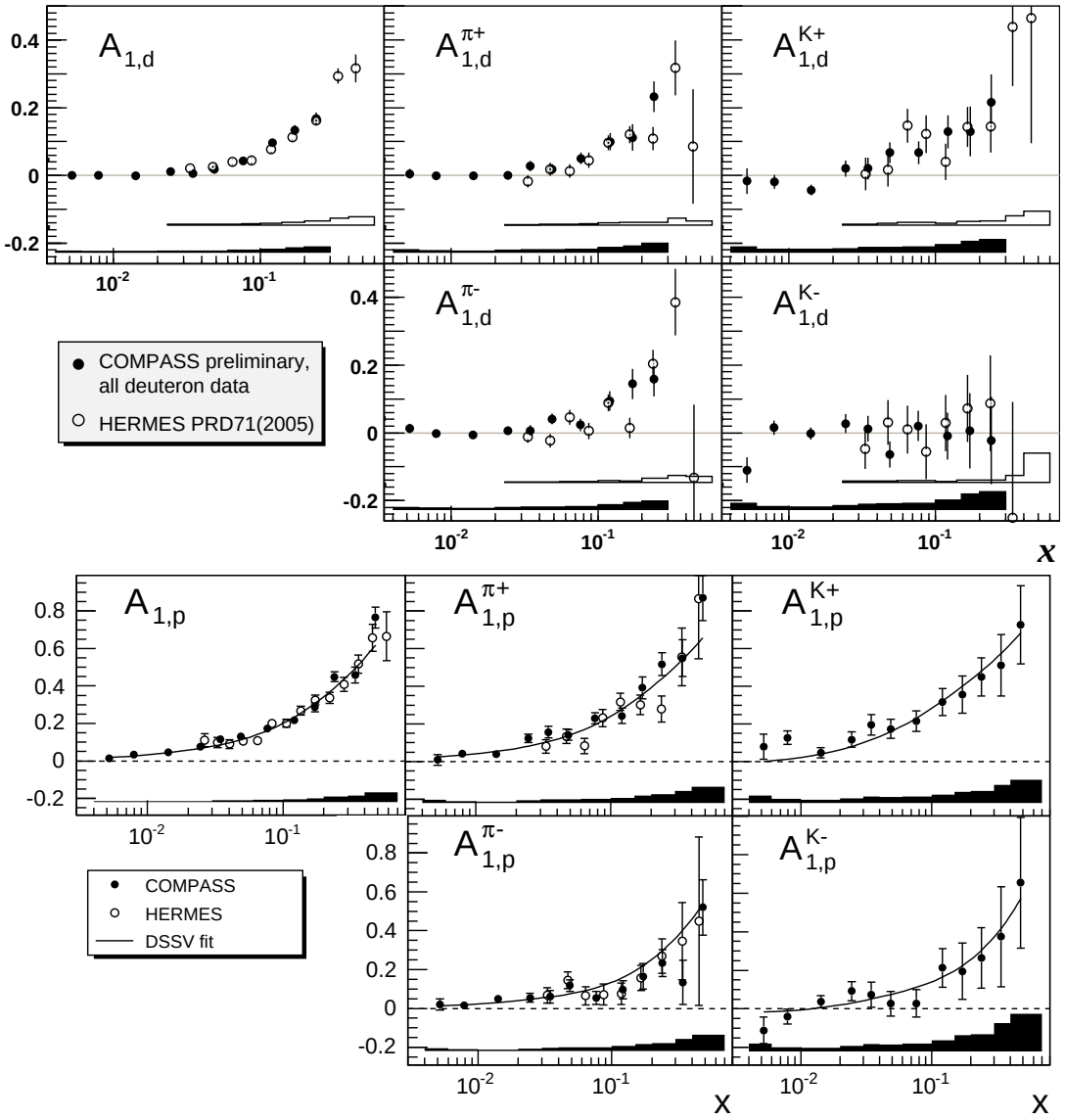




- Only COMPASS data $\Rightarrow$ Better control of systematics.
- NLO QCD fit to make for non measured x domain. $Q^2 = 3$ GeV^2.

$\Rightarrow$ $|g_A/g_V| = 1.28 \pm 0.07(stat.) \pm 0.10(syst.)$ *vs.* 1.2694 ± 0.0028 from neutron β decay.

SIDIS : $A_1^h, h = \pi, K$ measurements



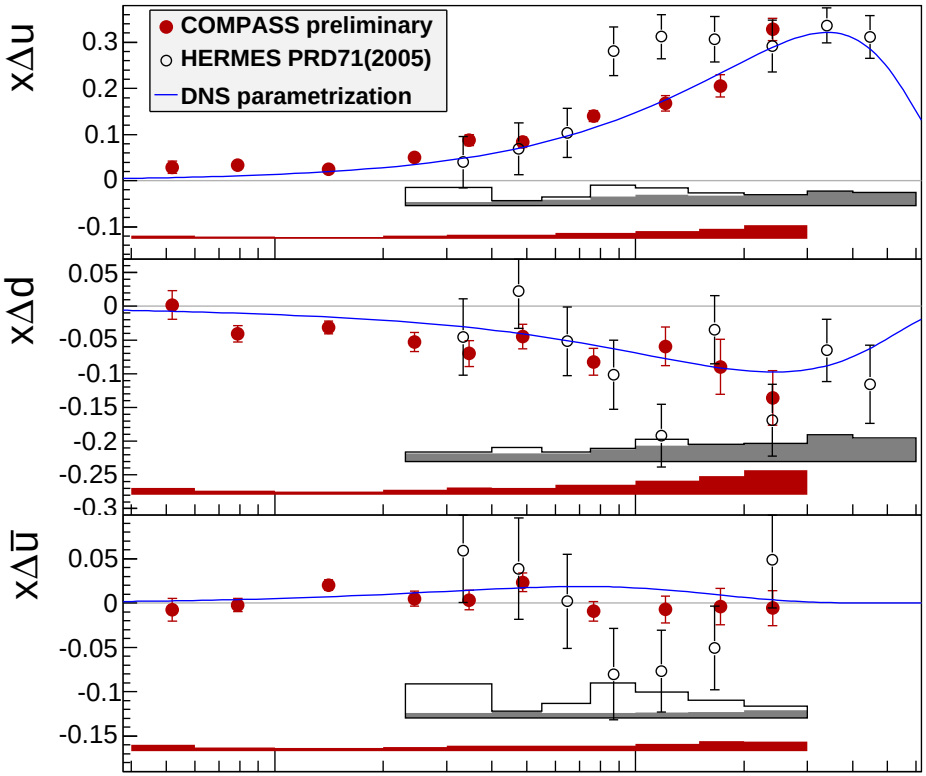
- *Phys. Lett. B* ***680*** *(2009) 217 [arXiv :0905.2828 [hep-ex]].*

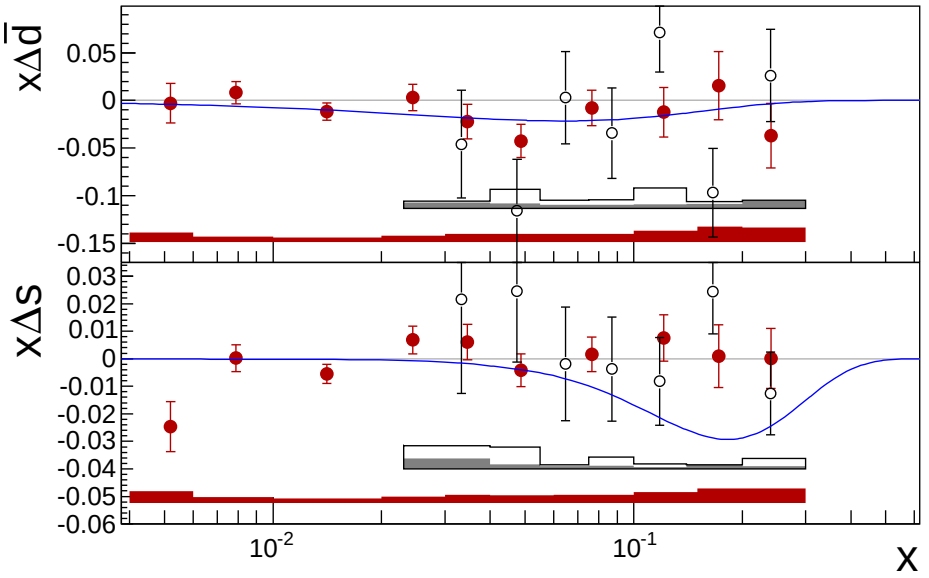
- *Phys. Lett. B* ***693*** *(2010) 227 [arXiv :1007.4061 [hep-ex]].*

  $A_{1,p}^K$: 1st measurement ever.

SIDIS : Flavor separation

- SIDIS can make up for lack of ν and Drell-Yan polarized data.
- QPM fit to COMPASS data, using LO unpolarized PDFs and FFs.

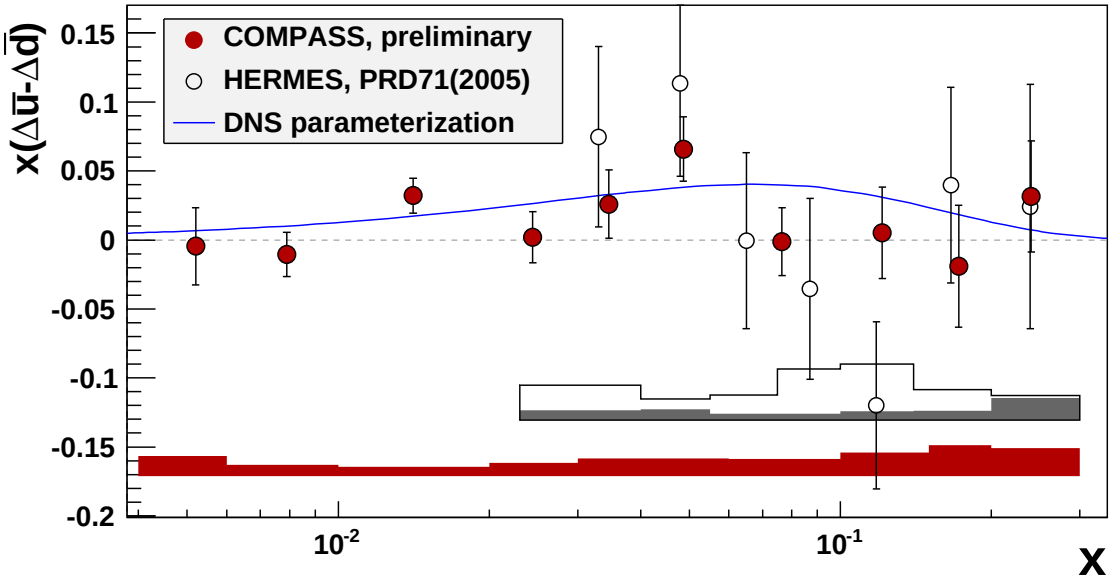




- Δs compatible w/ 0, at variance to QCD fit of Incl. data.
- Δs very sensitive upon choice of FF.

- Global QCD fit including SIDIS : DSSV *[arXiv :0904.3821 [hep-ex]]*.
  - Does not include COMPASS data yet.
  - ΔG and Δs w/ a pole.

Flavor asymmetry ? $\Delta\bar{u} - \Delta\bar{d}$



Summary and Outlook

- $\Delta G/G$
  - Axial anomaly scenario ruled out.
  - COMPASS direct measurements compatible W/ several global fit scenarios for ΔG.
  - $d\sigma/dp_T$ and $d\Delta\sigma/dp_T$ under way.

- Flavor separation from SIDIS.
  - Δs compatible w/ 0 @ high x.
  - Extraction very sensitive to FFs.
  - Measurement of hadron multiplicties from past and future 2012 data in order to contribute to global FF fit.
  - 2012 : Longitudinally polarized DIS and SIDIS w/ 190 GeV on p.

- Longer term (2013 on) : Measurement of Hard Exclusive Processes , *cf. talk of Nicole D'Hose*.