Longitudinal Spin Results with COMPASS

before OAM investigation

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

$$\Delta\Sigma = \int_0^1 \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x) + \Delta s(x) + \Delta\bar{s}(x)\,\mathrm{d}x$$

$$\Delta G = \int_0^1 \Delta g(x)\,\mathrm{d}x$$

Inclusive asymmetries :

$g_1^{d,p}$, $\int g_1^N$ dx and $\Delta\Sigma$, $\Delta s + \Delta\bar{s}$, $\int g_1^{NS}$ dx and Bjorken sum rule

Semi-inclusive asymmetries:

Flavour separation: Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$

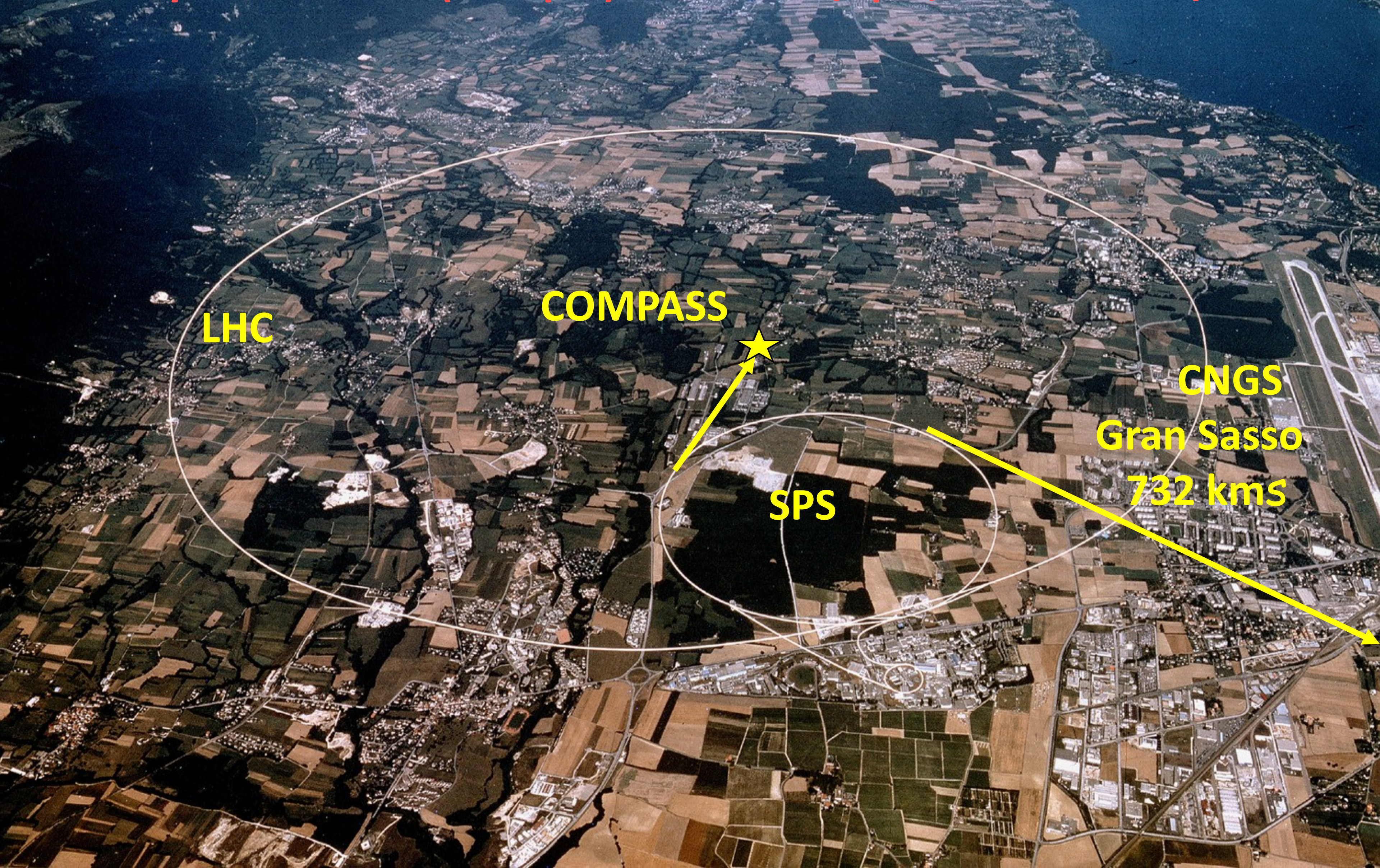
Photon-Gluon Fusion asymmetries: ΔG

Nicole d'Hose (CEA Saclay) on behalf of the COMPASS collaboration

INT Workshop, OAM in QCD, February 6-27, 2012

SPS proton beam: 2.6 10^{13}/spill of 9.6s each 48s, 400 GeV/c

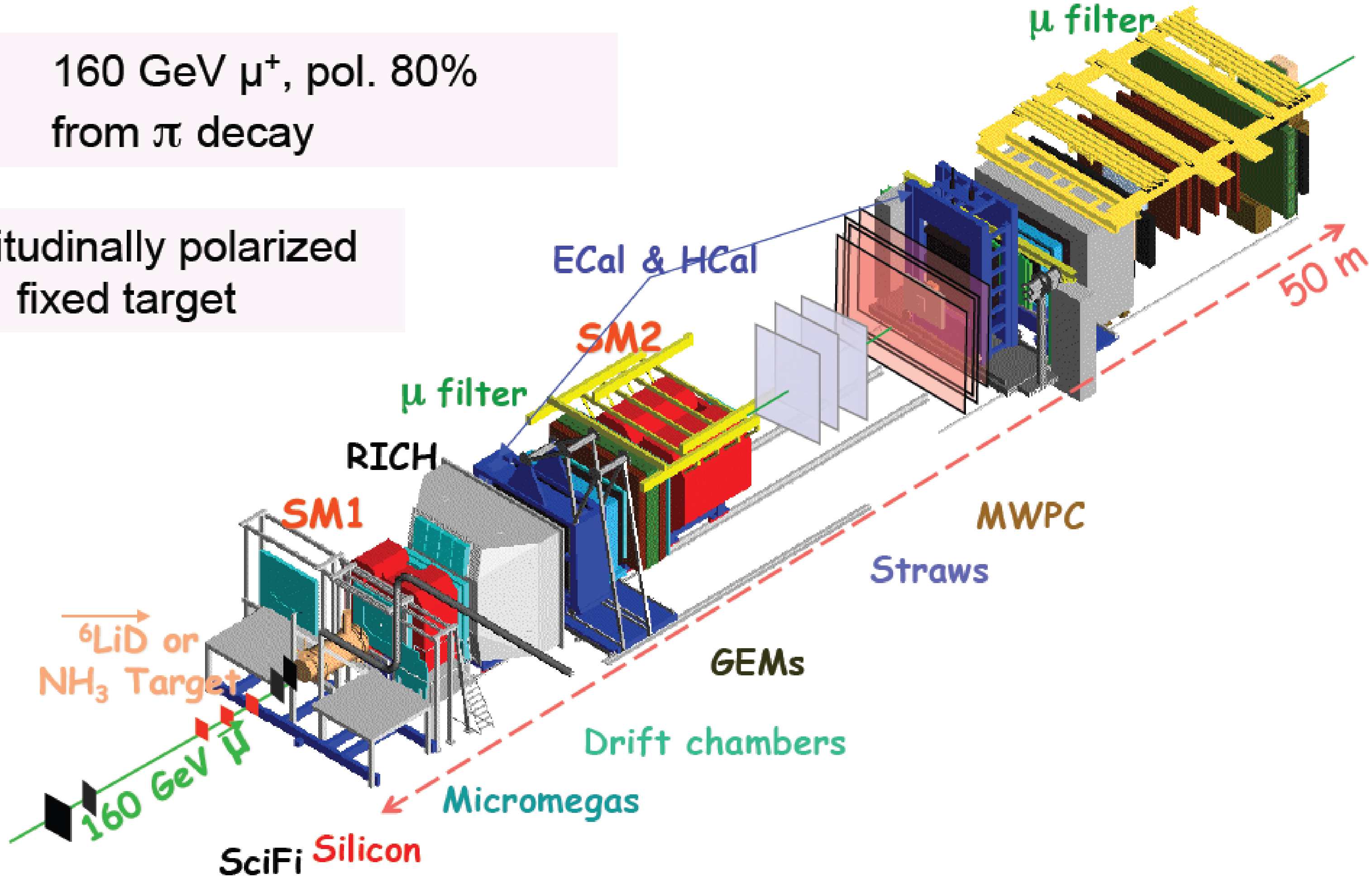
- Secondary hadron beams (π, K, …): 6.10^{8} /spill, 50-200 GeV/c
- Tertiary muon beam (80% pol): 4.6 10^{8} /spill, 100-200 GeV/c



The COMPASS experiment

Beam: 160 GeV μ^+, pol. 80% from π decay

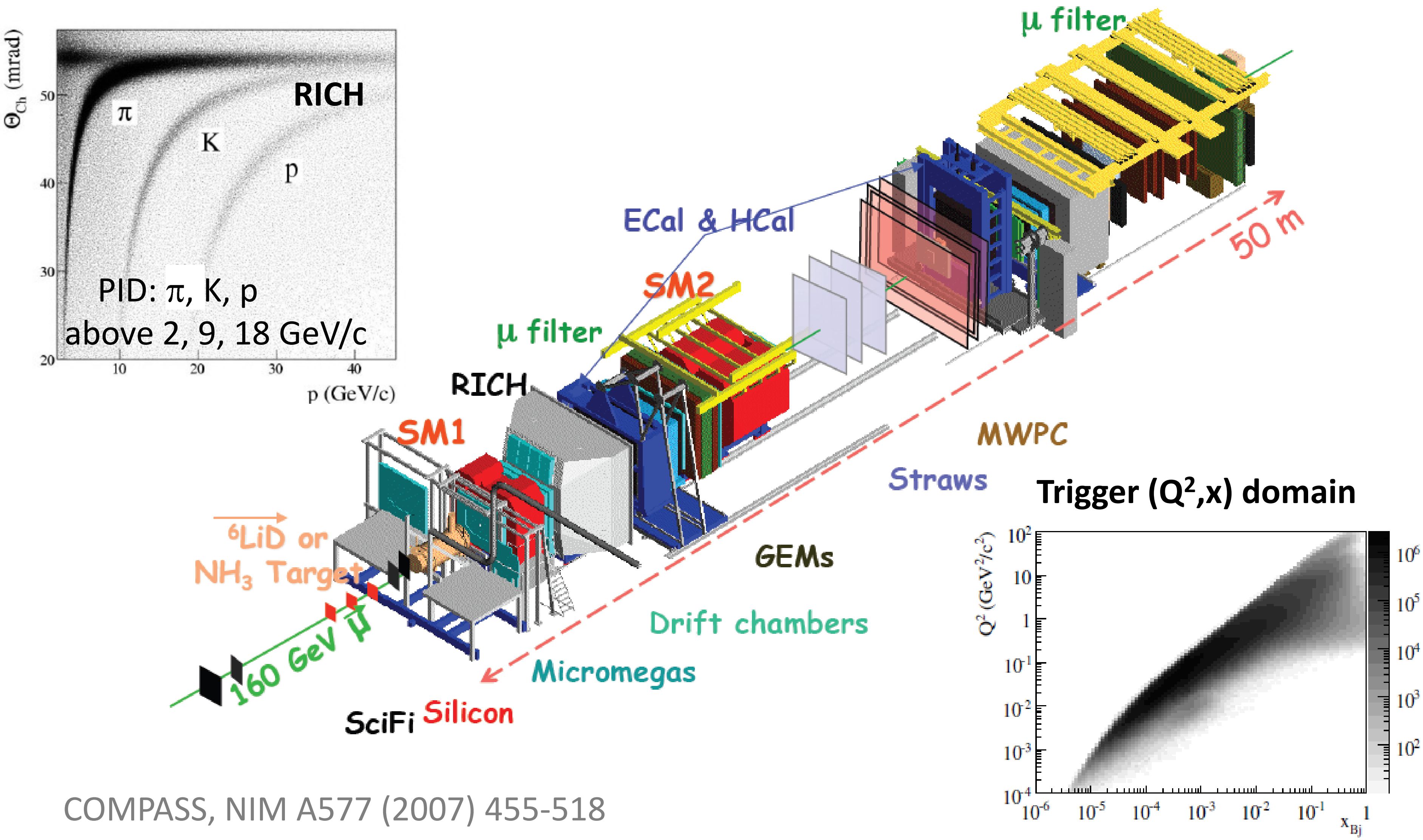
Longitudinally polarized fixed target



COMPASS, NIM A577 (2007) 455-518

The COMPASS experiment

two stages spectrometer for Large and Small Angles around SM1 and SM2



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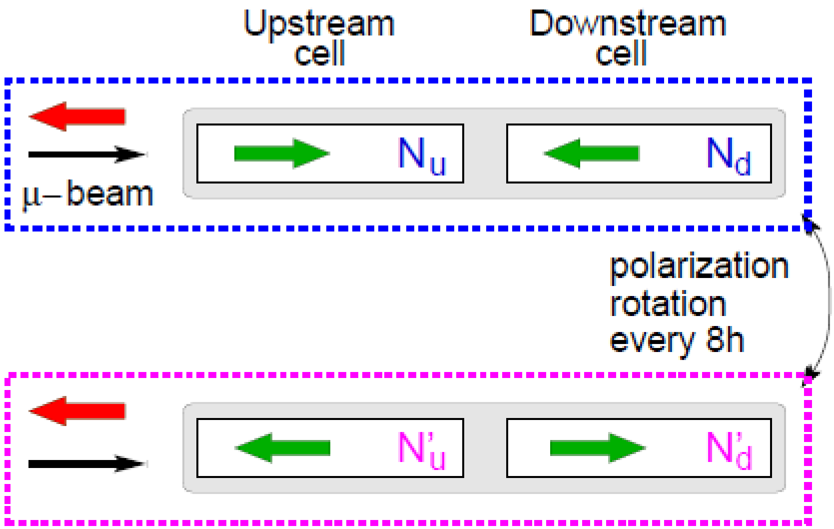
Asymmetry measurement

To be measured

$$A_{\parallel}^{\mu N} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$



Flux normalisation

$$A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d}$$

Acceptance difference: polarisation rotation

Take average asymmetry (with minimization of bias)

$$A_{\text{exp}} = \frac{A + A'}{2} = \frac{1}{2}\left(\frac{N_u - N_d}{N_u + N_d} + \frac{N'_d - N'_u}{N'_u + N'_d}\right)$$

Experimental asym. related to lepton-nucleon asym. or to photon-nucleon asym.

$$A_{\text{exp}} = p_\mu \, p_{\mathrm{T}} \, f \, A_{\parallel}^{\mu N}$$

$$A_{\text{exp}} = p_\mu \, p_{\mathrm{T}} \, f \, D \, A_1^{\gamma^* N}$$

p_μ, p_{T} beam and target polarisation

f dilution factor

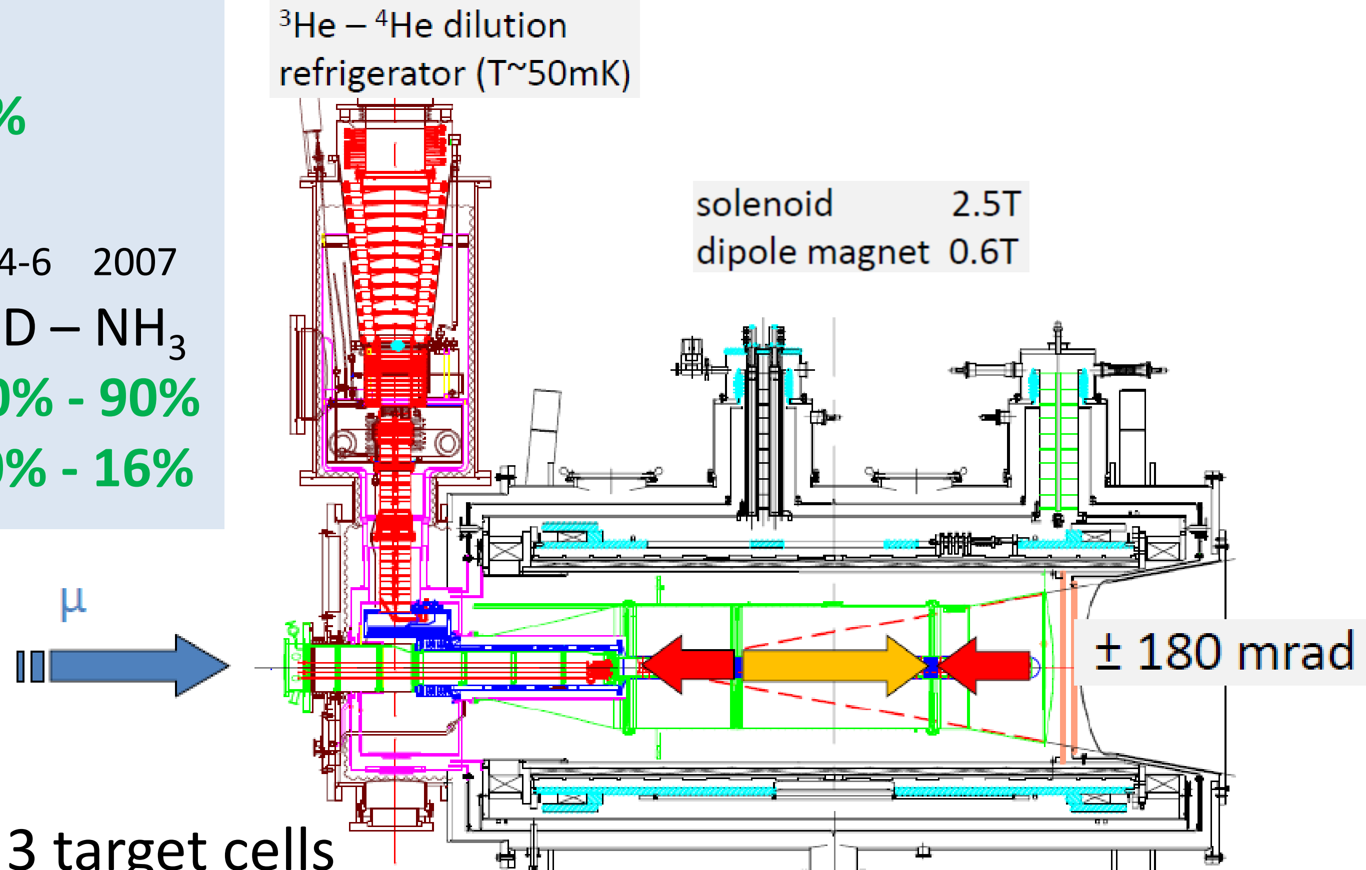
D depolarisation factor

weighting each event with $\omega = p_\mu f D$ for statistical gain

the COMPASS polarized beam and target

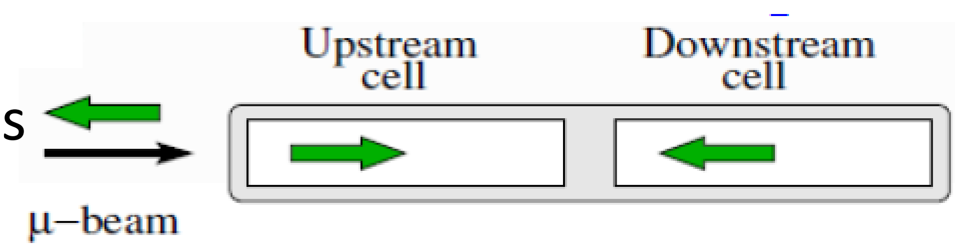
Muon 160 GeV
Polarisation P_μ = 80%

	2002-3-4-6	2007
Target material:	^6LiD –	NH_3
Polarisation P_T =	50% -	90%
Dilution factor f =	40% -	16%



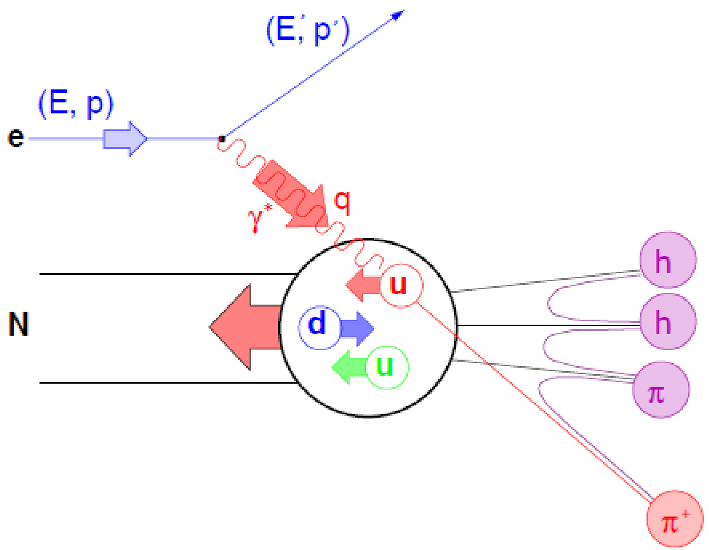
2006-7-10-11 setup: 3 target cells

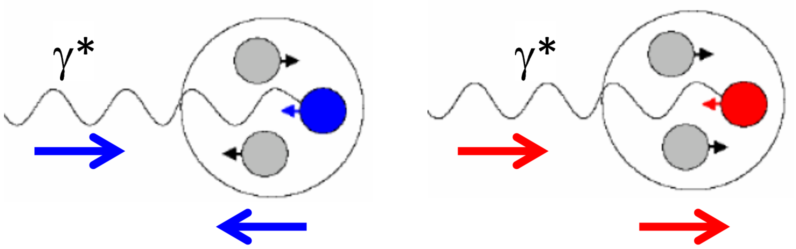
2002-3-4 setup: 2 target cells



Inclusive asymmetries in DIS and spin structure functions

inclusive asymmetries in DIS





$\sigma_{1/2} \sim q^{+}$ $\sigma_{3/2} \sim q^{-}$

$q(x) = q(x)^{+} + q(x)^{-}$ + quark ↑↑ nucleon

$\Delta q(x) = q(x)^{+} - q(x)^{-}$ − quark ↓↑ nucleon

photon-nucleon asymmetry

$$A_1^{\gamma^* N} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{\Sigma_q\ e_q^2\ (q(x)^{+} - q(x)^{-})}{\Sigma_q\ e_q^2\ (q(x)^{+} + q(x)^{-})} = \frac{g_1(x)}{F_1(x)}$$

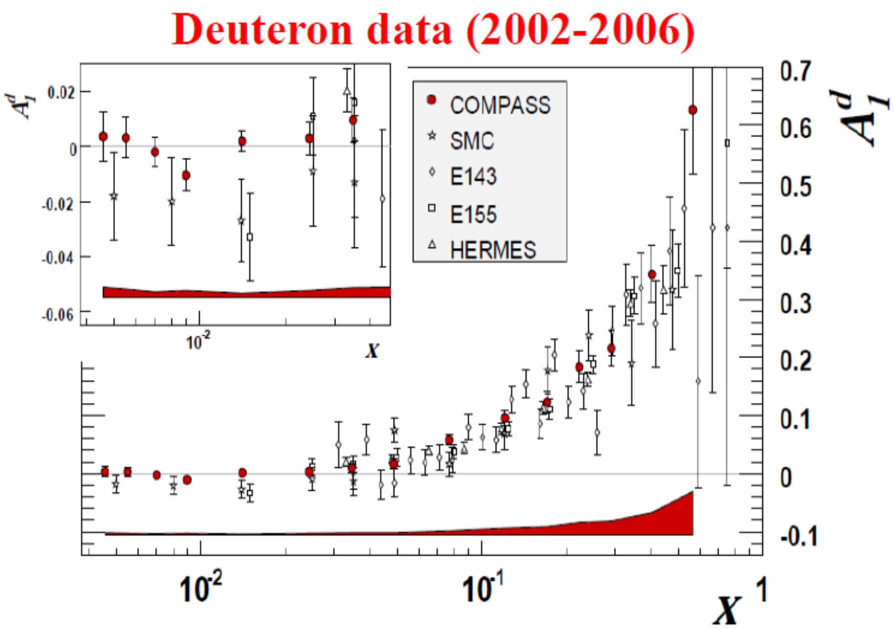
spin structure function

$$g_1 = \frac{1}{2}\Sigma_q\ e_q^2\ \Delta q(x) = A_1 \cdot \frac{F_2}{2x(1+R)} \approx \frac{A_{\parallel}}{D} \cdot \frac{F_2}{2x(1+R)}$$

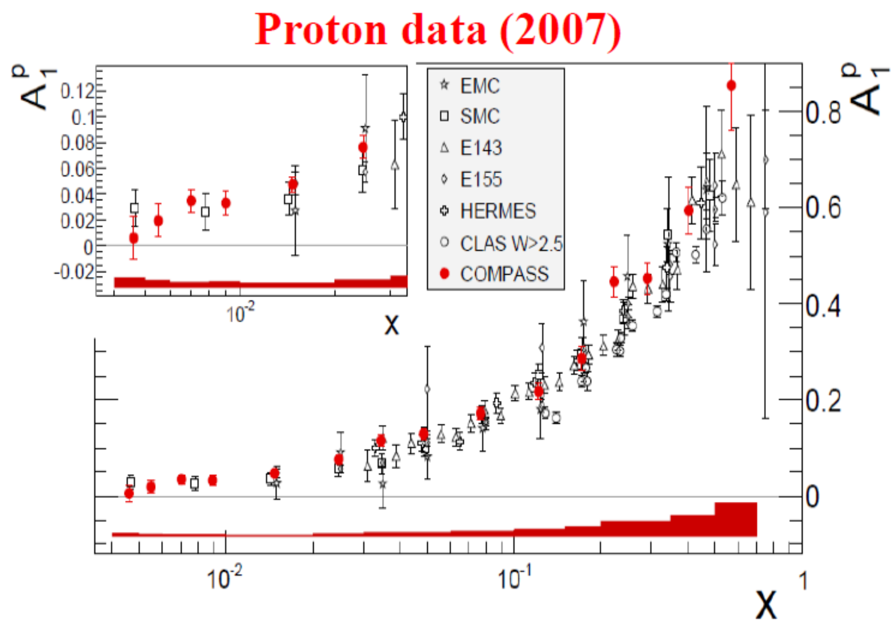
F_2 from the SMC parametrization

$R = \sigma_L / \sigma_T$ from SLAC parametrization

inclusive asymmetries $A_1^{d,p}$: $Q^2 > 1$ GeV^2



COMPASS, PLB 647 (2007) 8-17



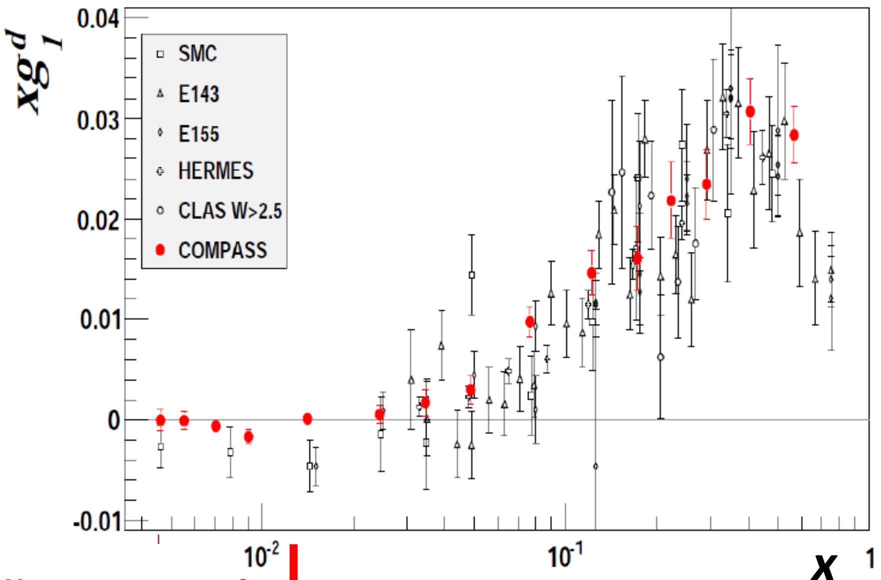
COMPASS, PLB 690 (2010) 466-472

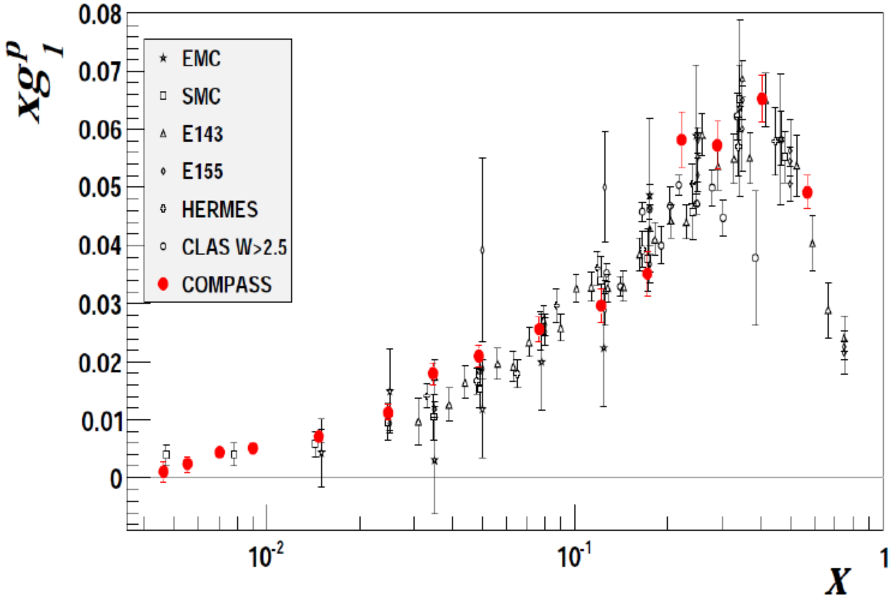
Good agreement between all experimental points

Significant improvement of precision in the low x region

No negative trend for A_1^d

COMPASS results for $g_1^{d,p}$ and first moment of g_1^N





$g_1^N = (g_1^p + g_1^n)/2$

$$g_1^N(x, Q^2) = g_1^d(x, Q^2)/(1 - 1.5\omega_D)$$

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

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

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

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

COMPASS, PLB 647 (2007) 8-17

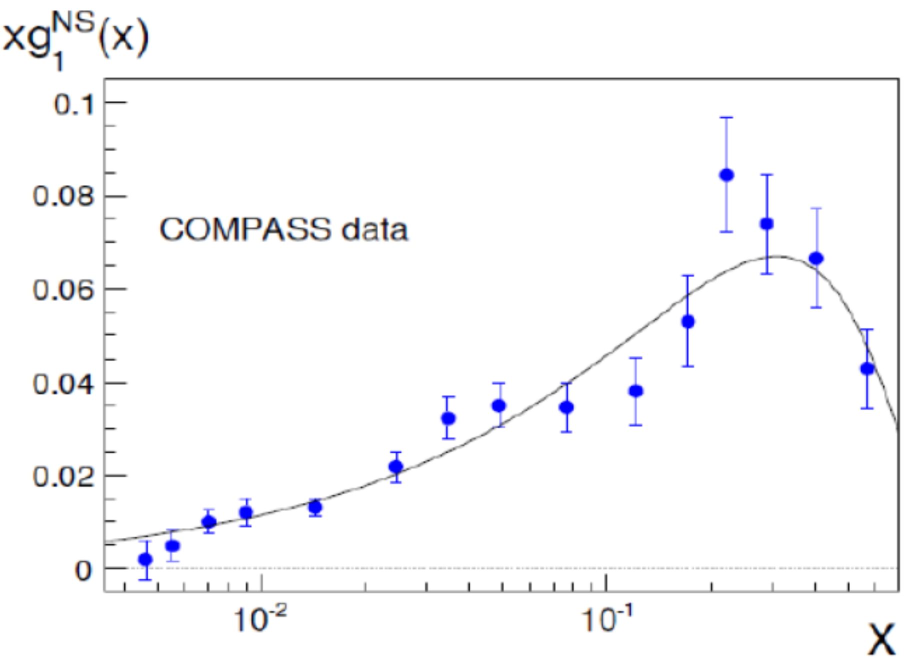
Bjorken sum rule from COMPASS g_1^p and g_1^d

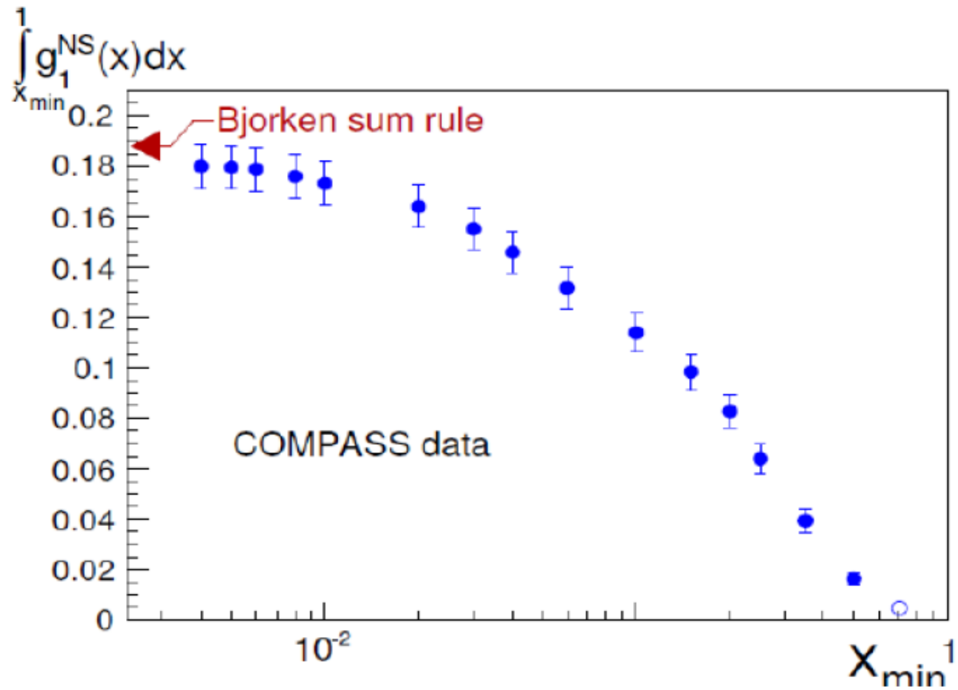
the non-singlet spin structure

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

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 $\Delta q^{NS} = |g_A / g_V|\, x^{\alpha}(1 - x)^{\beta}$

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

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

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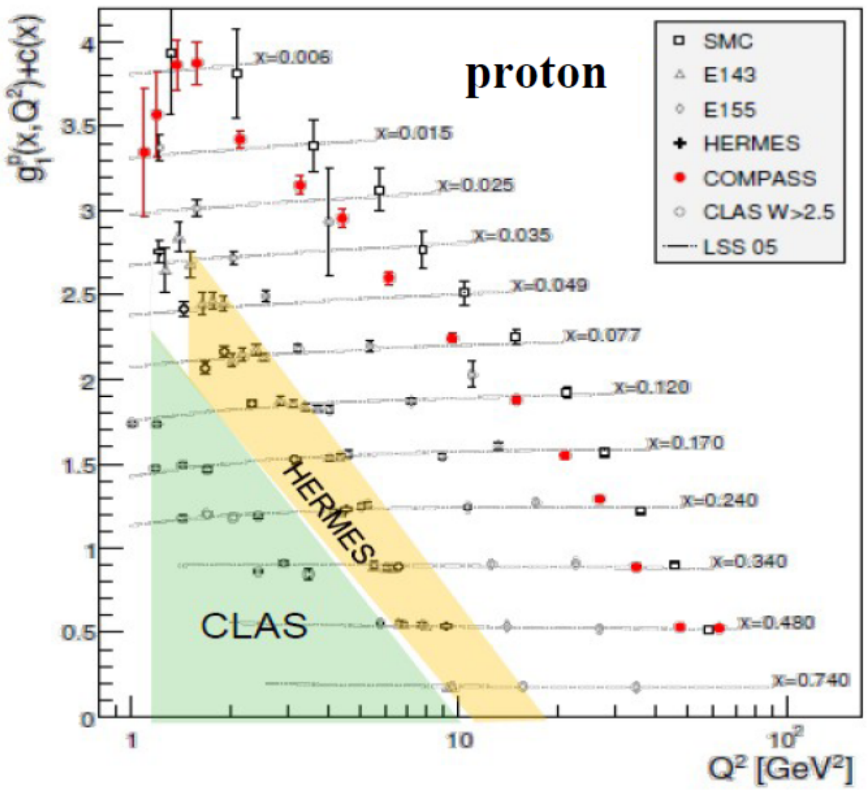
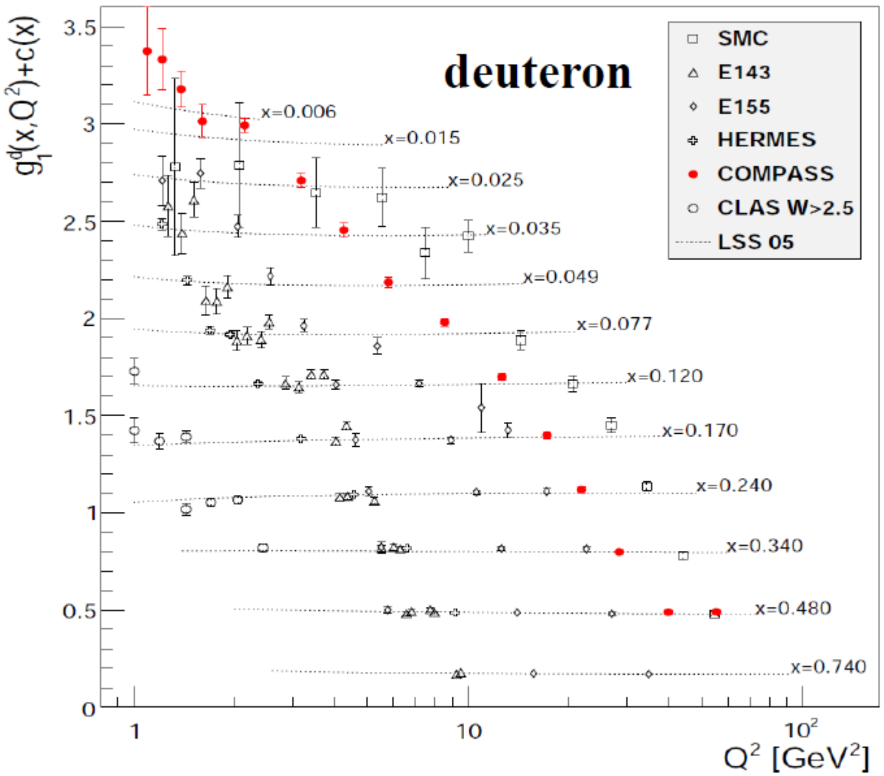
the Q^2 dependence of g_1 for DGLAP evolution





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

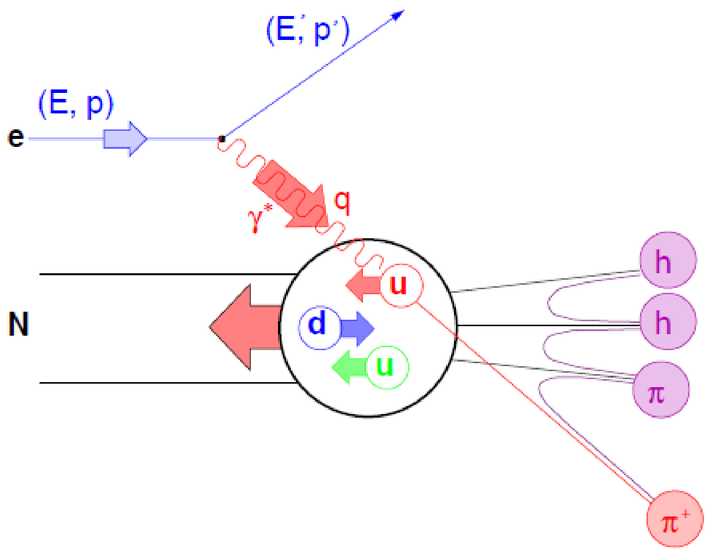
➔ additional data from colliders are required

pQCD analyses:

- $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ well constrained by data (LSS PRD 80 (2009) 054026)
- Δs and Δg need other data in addition to inclusive data
- Δs comes out negative
- $|\Delta g|$ is small (<0.5) still with large incertainties ➔ direct measurement needed

Semi-Inclusive asymmetries and flavour separation

Extraction of quark helicity distribution from SIDIS



The outgoing hadron tags the quark flavour

Requirement of the fragmentation function FF of a quark q to a hadron h

$$D_q^h(z,Q^2) \quad \text{with} \quad z=E_h/E_{\gamma^*}$$

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

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

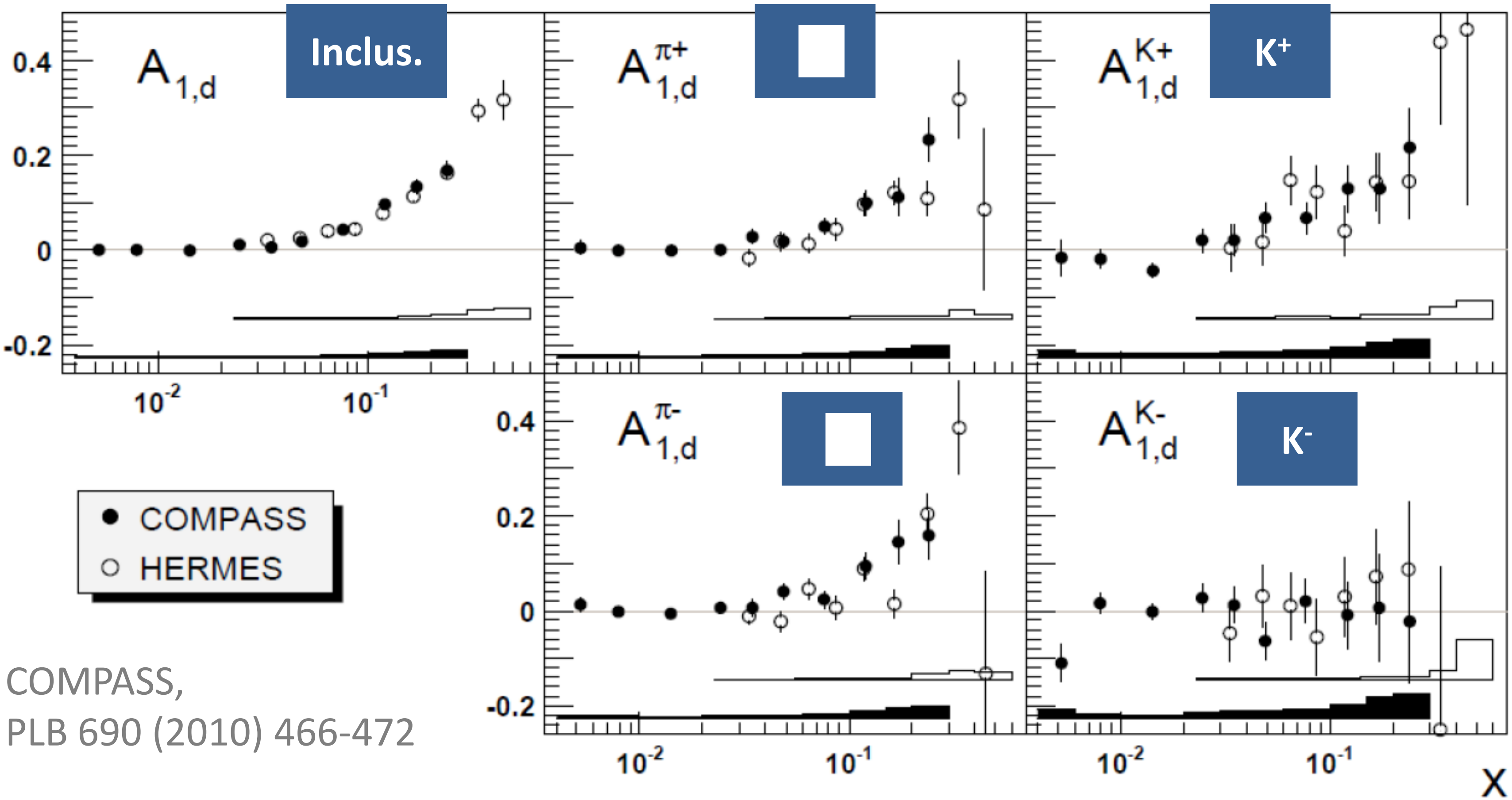
Inputs needed to extract quark helicity:

Unpolarized PDFs from MRST04

FF from DSS parametrisation

Inclusive and semi-inclusive spin asymmetries for **deuteron** data

Inclusive & semi-inclusive asymmetries
for identified π's and *K's*



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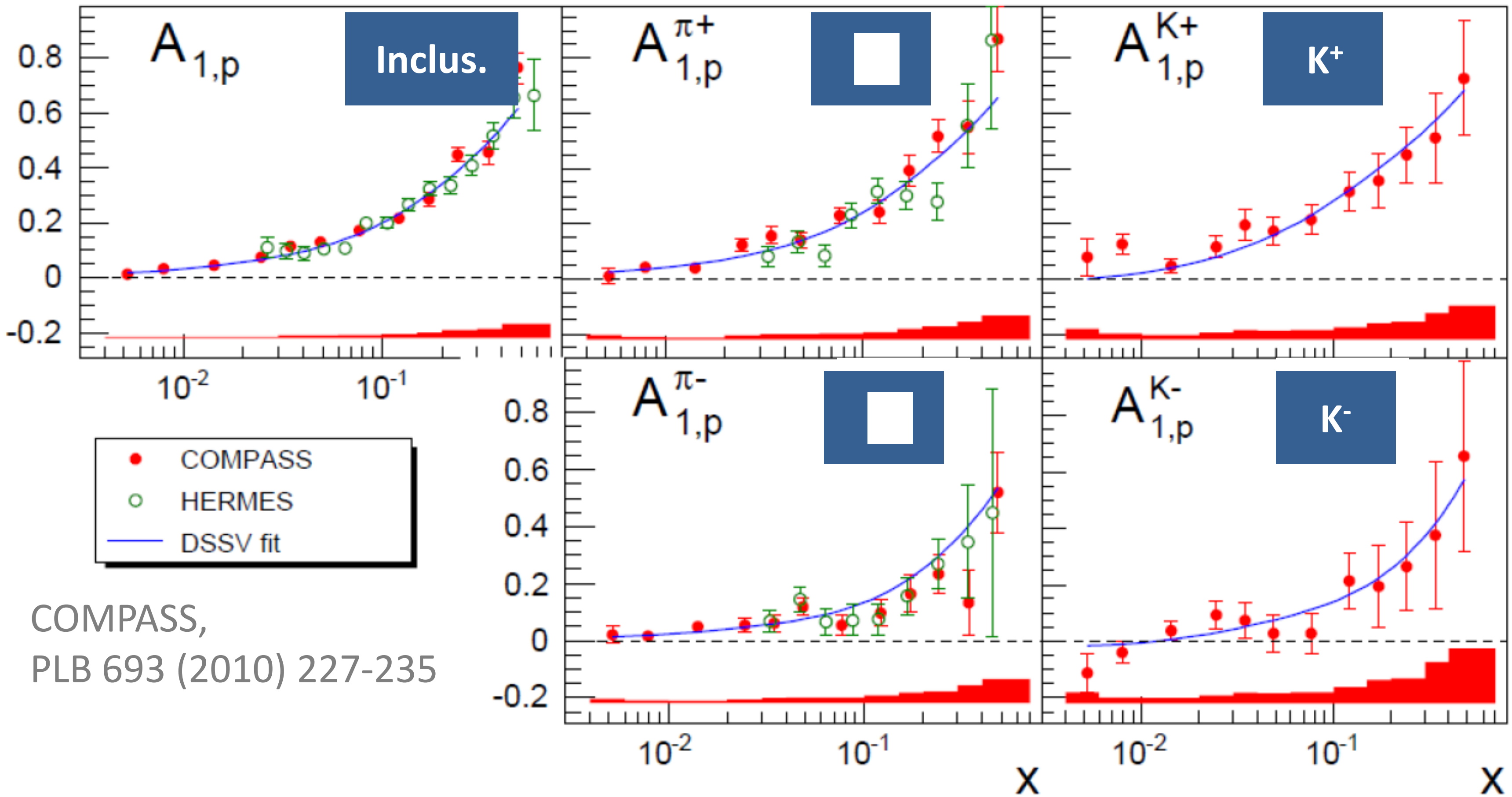
PLB 690 (2010) 466-472

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 for **proton** data

incl. & semi-incl. asymmetries
for identified π's and *K's*



COMPASS,
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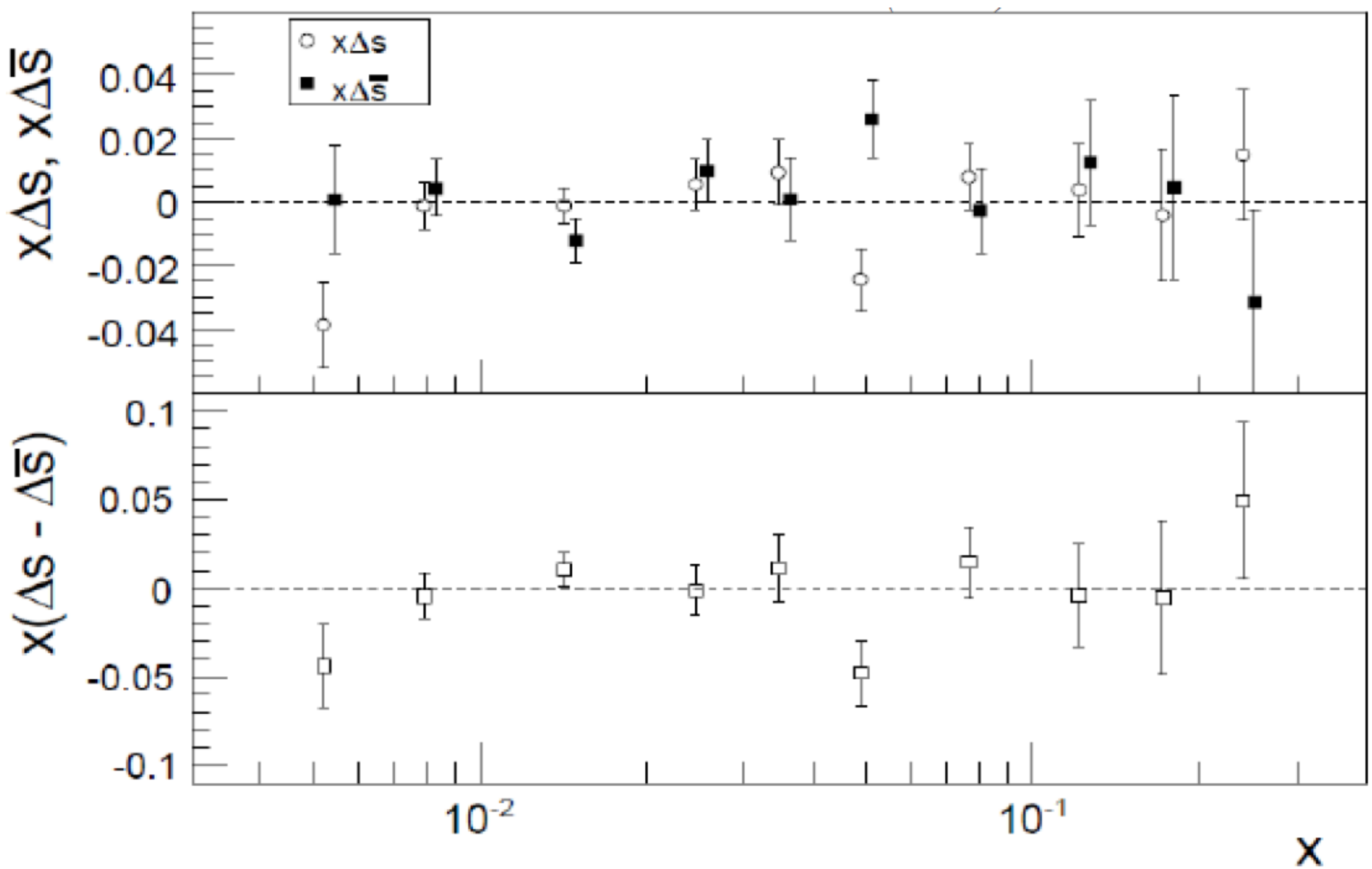
Using $A_{1,p}^{h}$ and $A_{1,d}^{h}$ one can extract separately $\Delta u,\ \Delta d,\ \Delta\bar{u},\ \Delta\bar{d},\ \Delta s$ and $\Delta\bar{s}$

Comparison of with

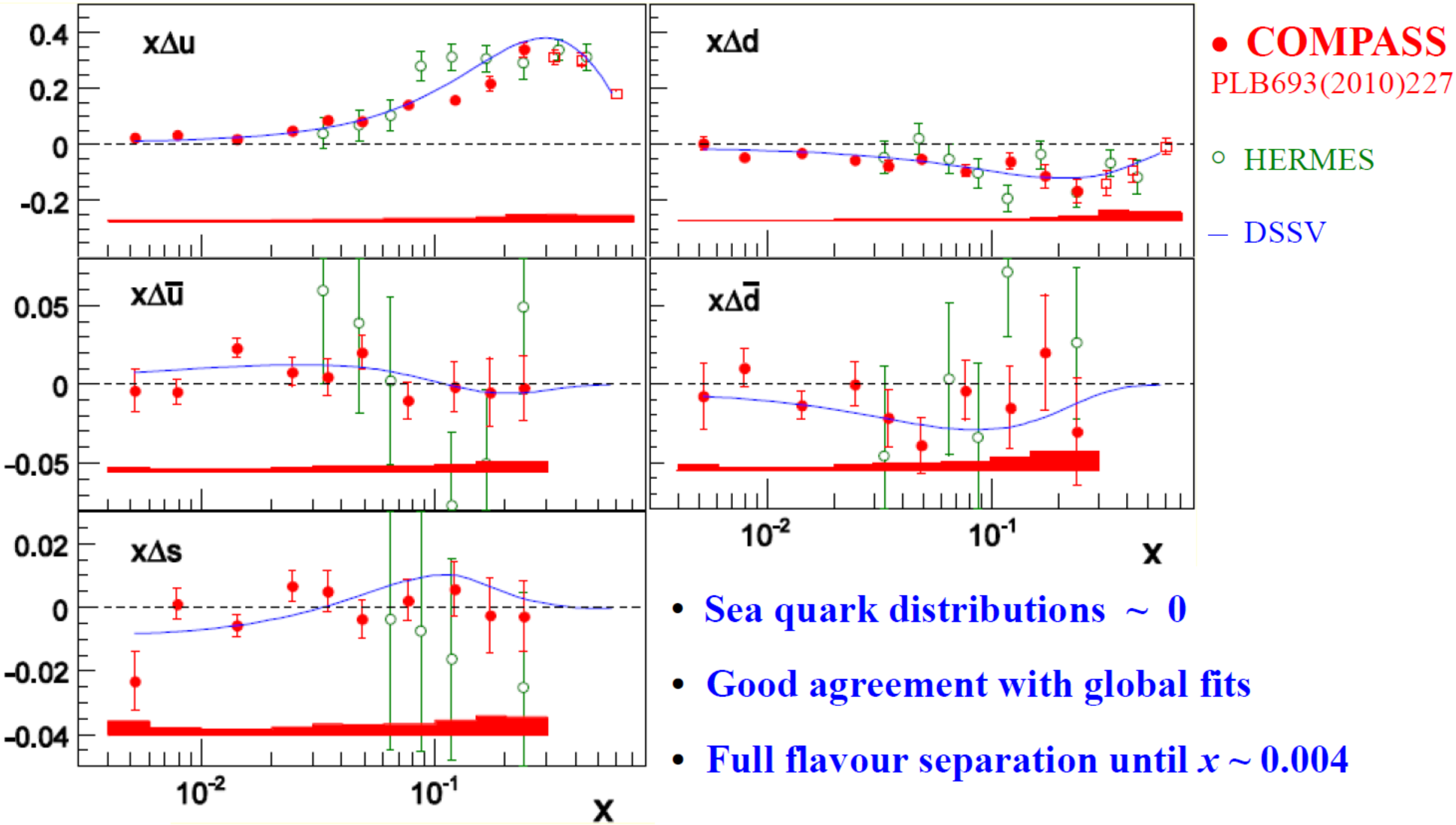
COMPASS, PLB 693 (2010) 227-235



$\Delta s - \Delta\bar{s}$ is compatible with 0

$\Delta s = \Delta\bar{s}$ is assumed in the following analysis

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



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

$$\int_{0.004}^{0.3} \Delta s \, dx = \Delta s(\text{SIDIS}) = -0.01 \pm 0.01(\text{stat}) \pm 0.01(\text{syst})$$

puzzle?

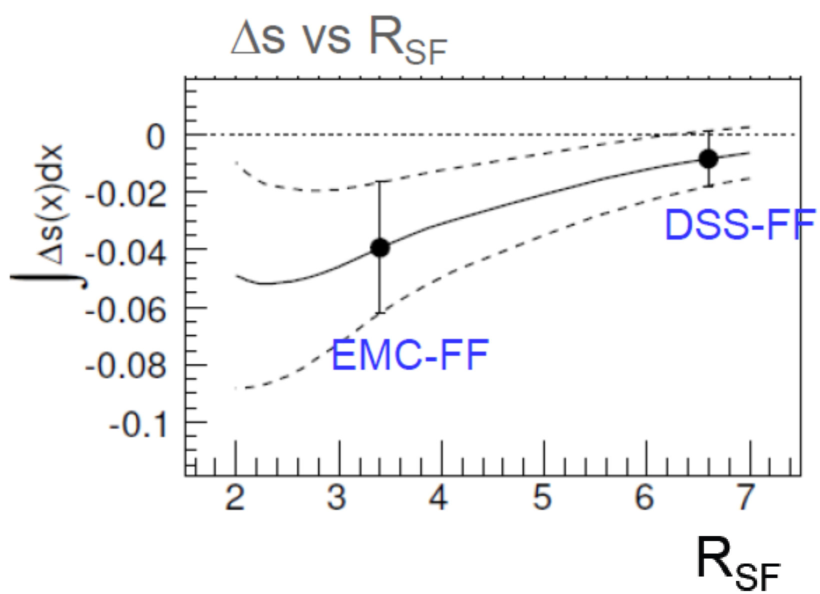
From DIS first moment of g_1 + (neutron and hyperon β decay + SU3):

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

From SIDIS: $\Delta s(\mathrm{SIDIS}) = -0.01 \pm 0.01(\mathrm{stat}) \pm 0.01(\mathrm{syst})$

The relation between SIDIS asymmetries and Δs depends on
R_{SF} the ratio of strange to favoured fragmentation functions FF for kaons

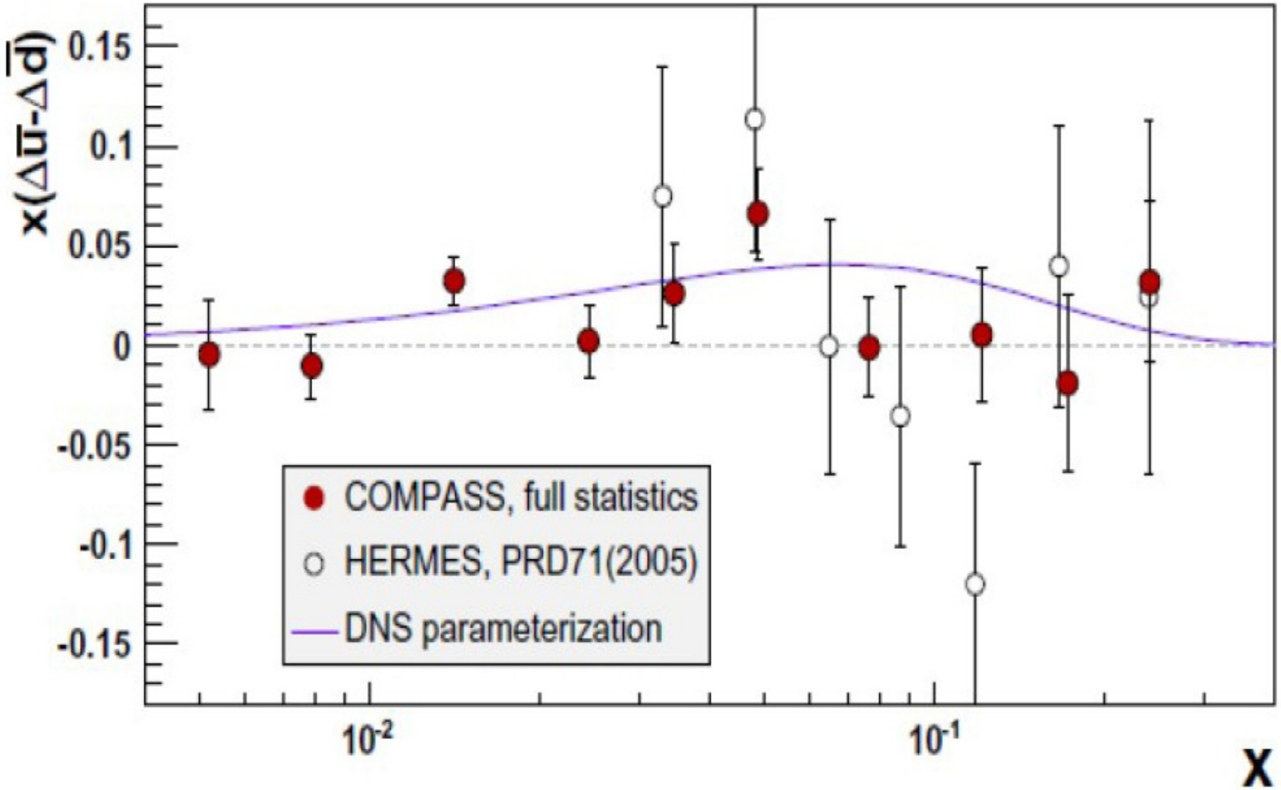
$$R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)\mathrm{d}z}{\int D_u^{K^+}(z)\mathrm{d}z}$$



➔Need more data on FF

Flavour symmetry breaking

The considerable asymmetry observed for $(\bar{u} - \bar{d})$ is not verified for the polarized case



$$\int_{0.004}^{0.3}(\Delta\bar{u} - \Delta\bar{d})\mathrm{d}x = 0.06 \pm 0.04(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$

sightly positive but compatible with zero

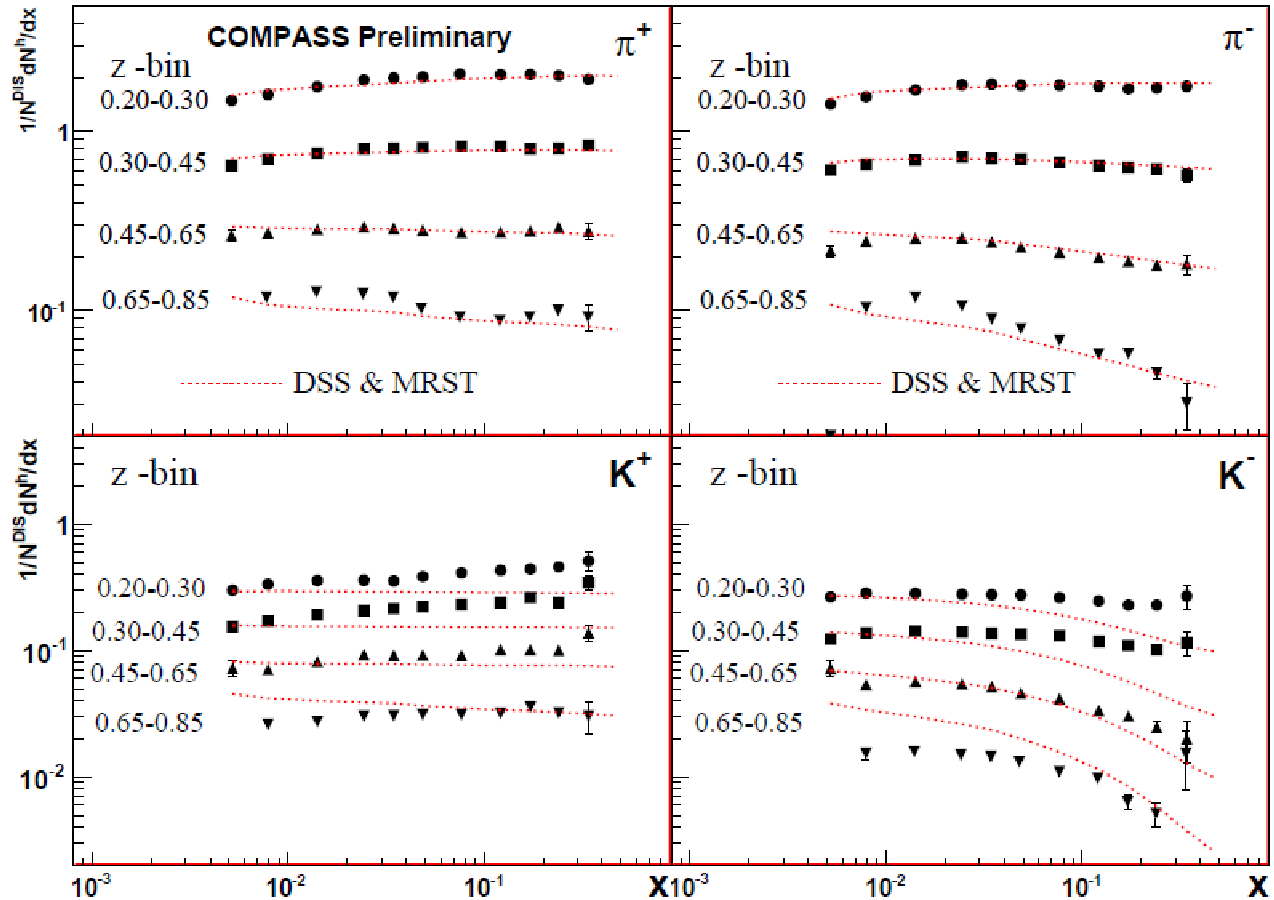
$$\int(\bar{u} - \bar{d})\mathrm{d}x = -0.118 \pm 0.012$$

First look on multiplicities

x dependence of $\frac{1}{N_{\mathrm{DIS}}} \cdot \frac{\mathrm{d}N^h}{\mathrm{d}z\mathrm{d}x}$

PDF FF

$$\frac{dM^h(x, Q^2, z)}{dz} = \frac{\sum_q e_q^2 f_q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 f_q(x, Q^2)}$$



related in LO to product of PDFs and FFs

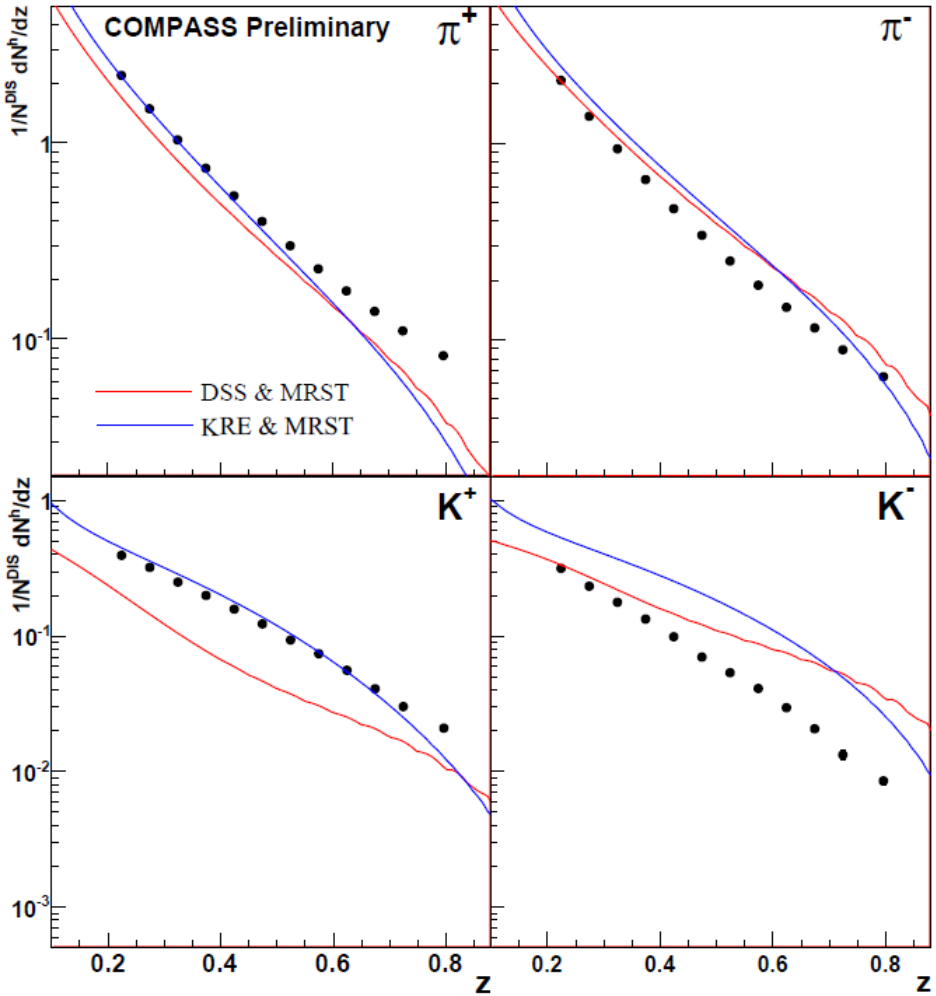
obtained from small part of ^{6}LiD data

kaons and pions

Comparison to parametrisations

PDF FF

$$\frac{dM^h(x, Q^2, z)}{dz} = \frac{\sum_q e_q^2 f_q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 f_q(x, Q^2)}$$



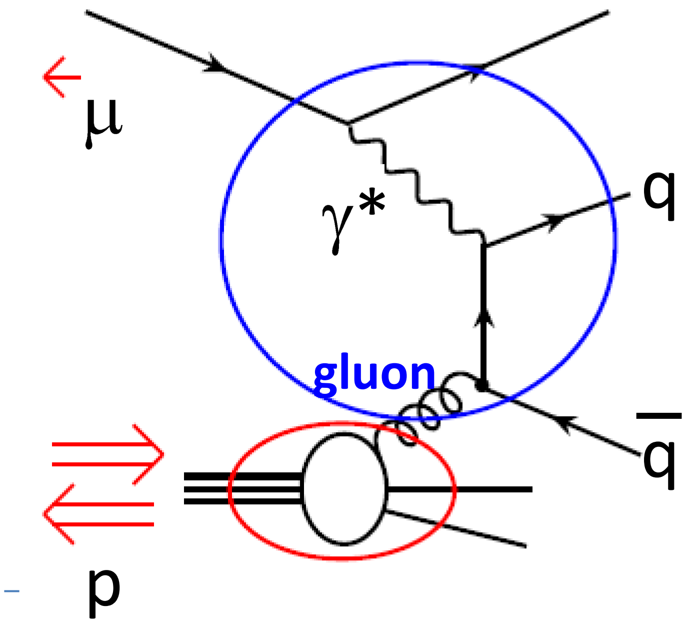
$$\frac{1}{N_{\rm DIS}} \cdot \frac{{\rm d}N^h}{{\rm d}z}$$

- some discrepancies, especially for kaons
- data can be used for LO extraction of FF and PDF
- will significantly contribute to knowledge on hadronisation process

Gluon Polarization

Direct measurement of /G

photon-gluon fusion (PGF)



$$A_{\parallel} = R_{pgf}\,\hat{a}_{LL}^{pgf}\,\frac{\Delta G}{G} + A_{bdf}$$

- R_{pgf}: Fraction of process
- $\hat{a}_{LL}^{pgf}$: Analyzing power calculable at LO and NLO
- A_{bdf}: Background

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 Monte Carlo 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 Monte Carlo dependent
- **and single hadron production at high-p_T?**

High p_T hadron pairs

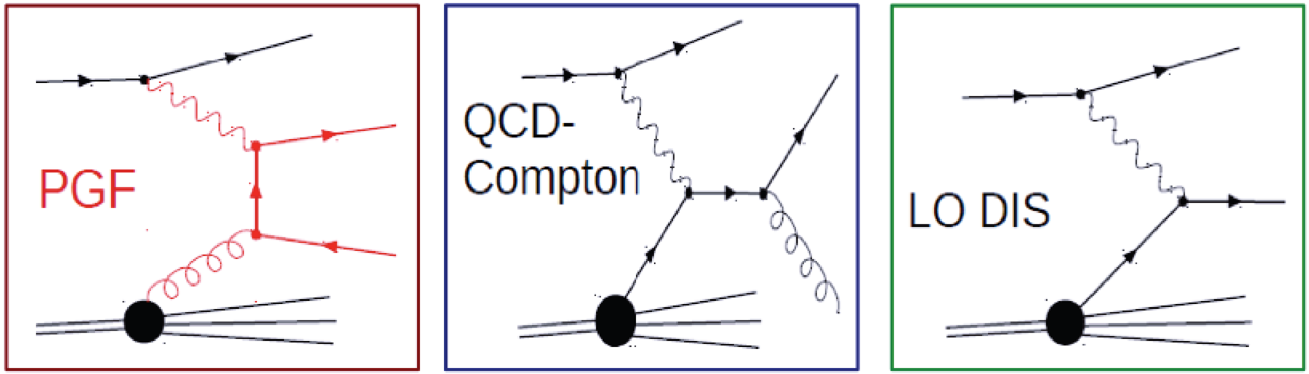
High-p_T asymmetries $Q^2 > 1$ GeV^2

The values of $R=\sigma^i/\sigma^{tot}$ and a^i_{LL} estimated using MC based on LEPTO generator

A_1^{LO} polarized and unpolarized PDF? JETSET parameter tuning for fragmentation ?

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

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



High-p_T asymmetries $Q^2 > 1$ GeV^2

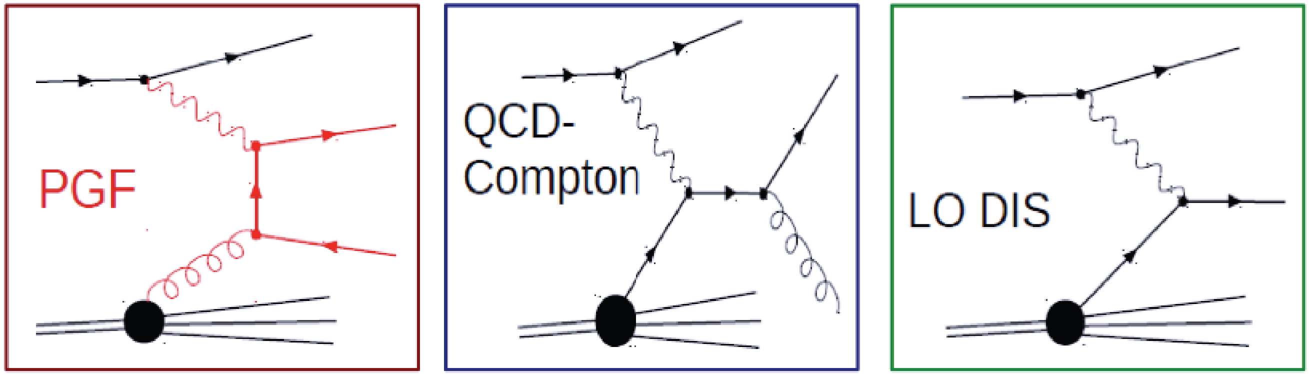
- **Two samples are considered:**

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) ⇒ enhancement of the PGF contribution



High-p_T asymmetries $Q^2 > 1$ GeV^2

The gluon polarization is determined from two asymmetry samples:
the high-p_T hadron pairs $\mathbf{A}_{\mathbf{LL}}^{2h}(\mathbf{x})$ and the inclusive data $\mathbf{A}_1^{\mathbf{d}}(\mathbf{x})$

$$\frac{\Delta G}{G}(x_g) = \frac{1}{\beta}\left[A_{LL}^{2h}(x) + A_{corr}\right]$$

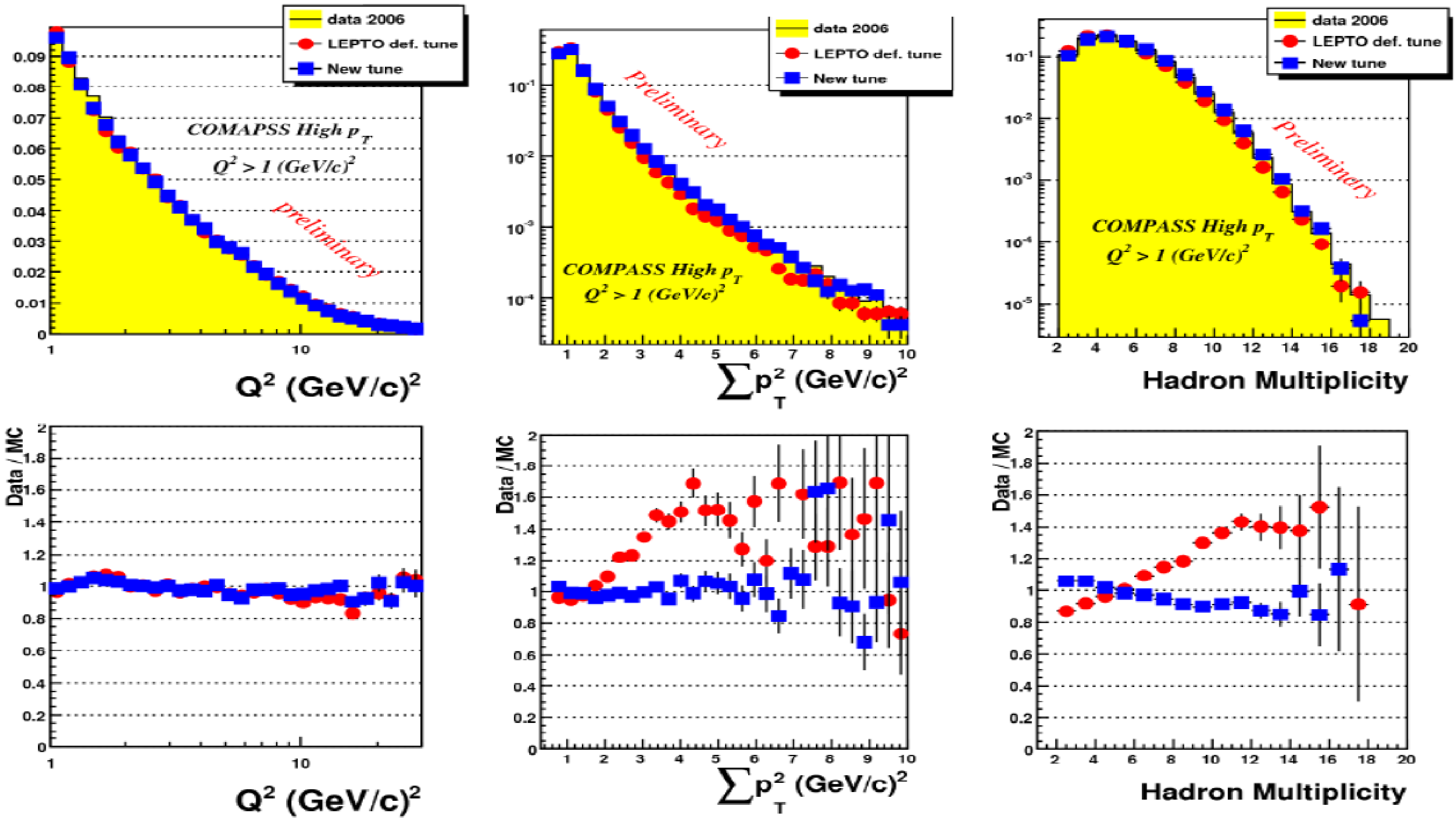
The MC based on LEPTO generator is improved, JETSET is tuned, and all the following parameters to evaluate β and A_{corr}

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

are parametrized event by event using a Neural Network approach

Data vs MC: comparison of Q^2 and hadron variables

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



High-p_T results $Q^2 > 1\ GeV^2$

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

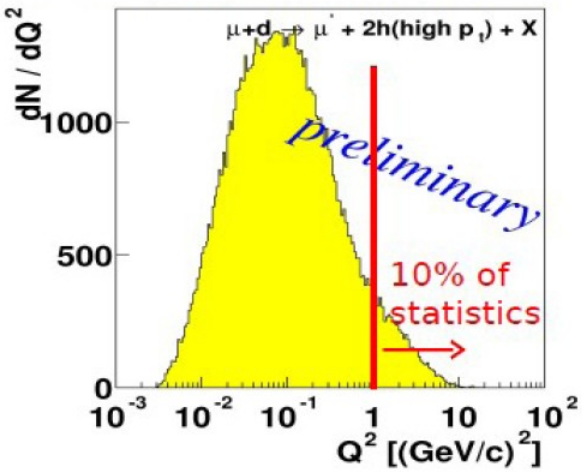
Very good statistics to allow 3 bins in x_g

1st point : $\mathbf{0.147 \pm 0.091_{stat} \pm 0.088_{sys}}$ $@\ x_g = 0.07^{+0.05}_{-0.03}$

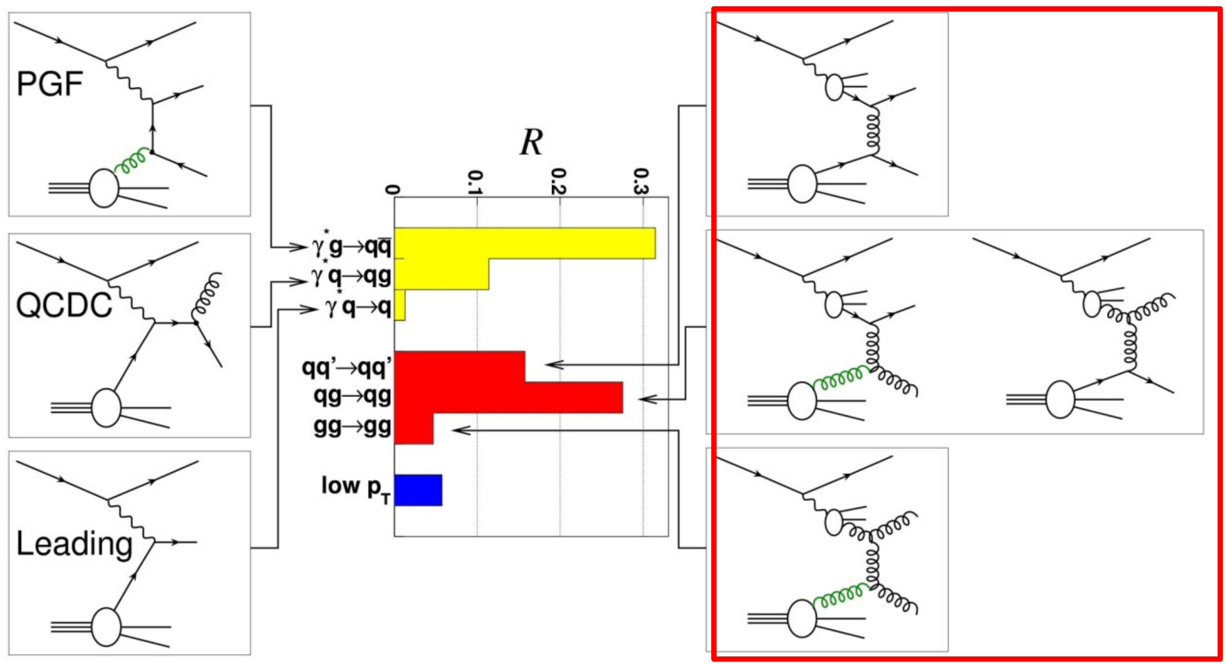
2nd point : $\mathbf{0.079 \pm 0.096_{stat} \pm 0.082_{sys}}$ $@\ x_g = 0.10^{+0.07}_{-0.04}$

3rd point : $\mathbf{0.185 \pm 0.165_{stat} \pm 0.143_{sys}}$ $@\ x_g = 0.17^{+0.10}_{-0.06}$

High-p_T results $Q^2 < 1$ GeV^2



+ Resolved photons



2002-2004 Preliminary:

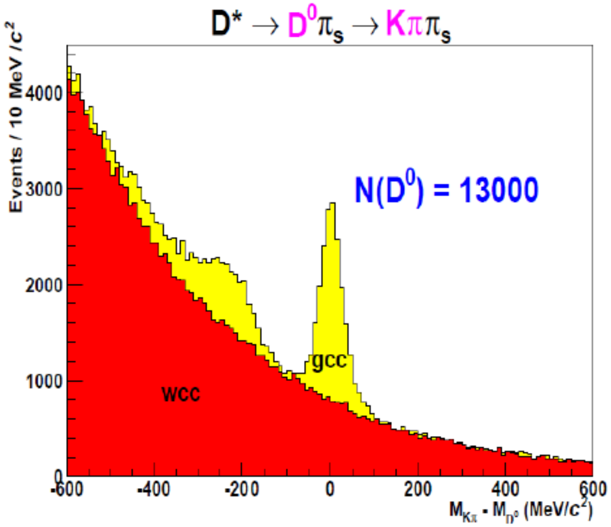
$\Delta G/G = 0.016 \pm 0.058\ (\text{stat}) \pm 0.055\ (\text{syst})$

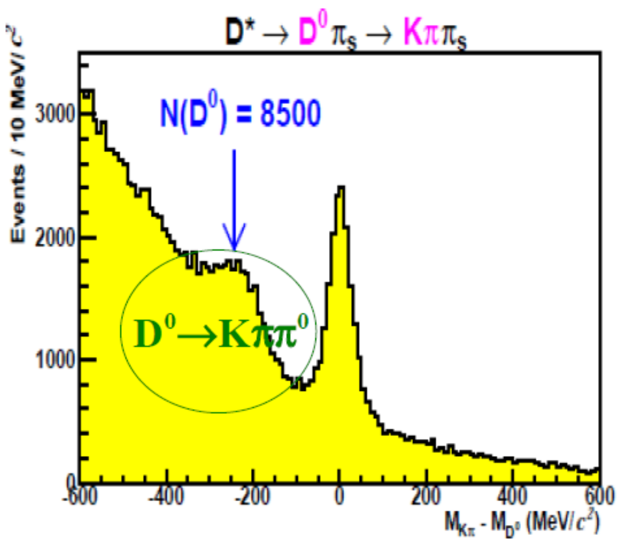
2002-2003 Published:

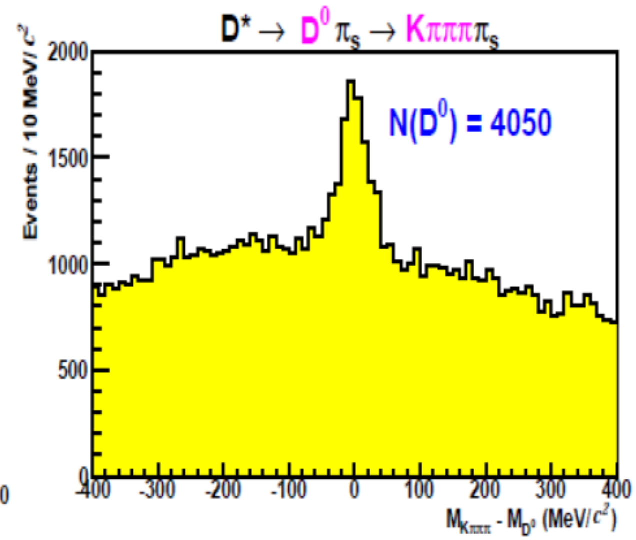
$\Delta G/G = 0.024 \pm 0.089\ (\text{stat}) \pm 0.057\ (\text{syst})$ COMPASS, PLB 633 (2006) 25-32

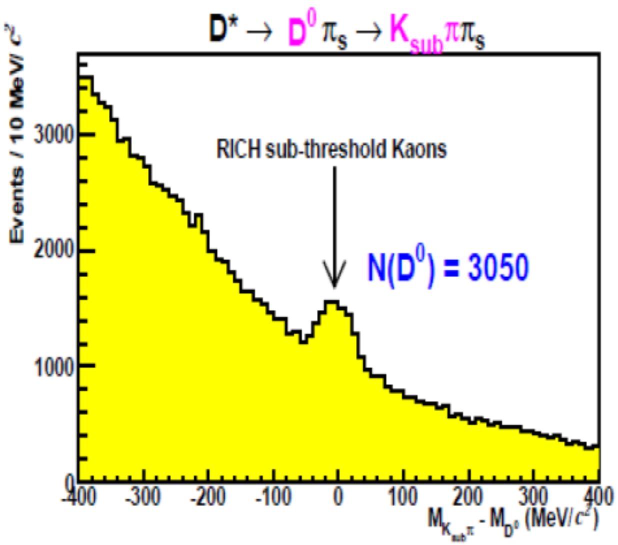
Open Charm production

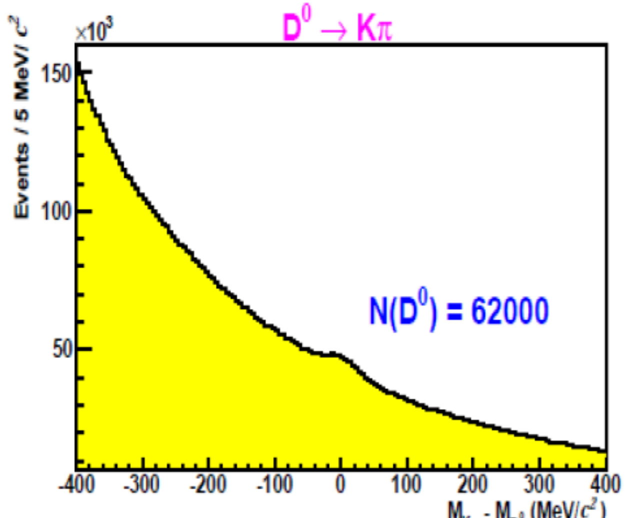
D^0 invariant mass spectra











Number of D^0:

2002-2007

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

Refined analysis for open charm selection

The D^0 meson is selected using the invariant mass distribution for identified K and π

The selection is performed with the help on a Neural Network which is trained on two data samples (with signal and pure background)

The Neural Network is able to distinguish the signal from the combinatorial background on a event by event basis

➔ **Determination of open charm probability = S/(S+B) event by event**

Analysis Power in LO

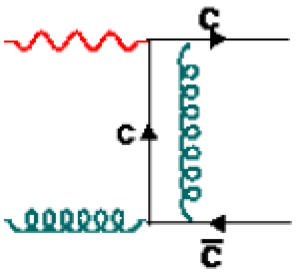
$$a_{LL} = \frac{\Delta \sigma^{PGF}}{\sigma_{PGF}}(y, Q^2, x_g, z_C, \phi)$$

a_{LL} depends on the knowledge of the partonic kinematics and cannot be experimentally obtained

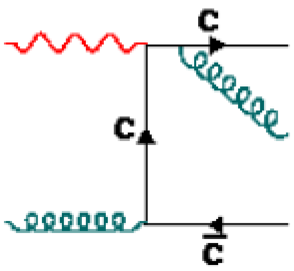
a_{LL} is calculated with a MC using the AROMA generator (in LO QCD) and parametrized using a Neural Network approach on the reconstructed kinematic variables y, x_B, Q^2, $z_{D°}$, p_T

Analysis Power in NLO

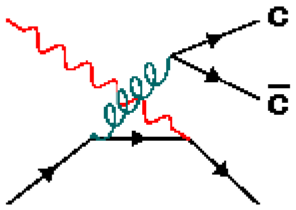
a_{LL} is also calculated event by event using theoretical formulas for NLO



virtual gluon correction



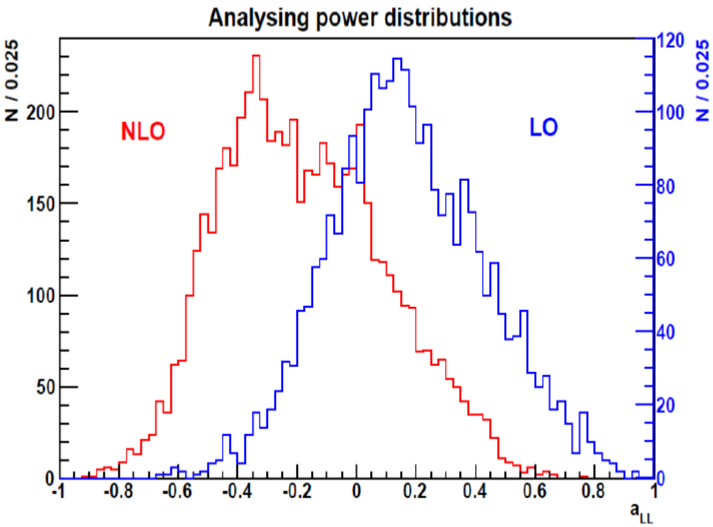
real gluon emission



gluon originating from light quark producing a $c\bar{c}$ pair

The phase space needed for NLO real gluon emission is generated through parton showers included in the standard LO AROMA generator

Light quark correction using the direct measurement of A_1



/G with open charm in LO and NLO

In LO

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

In NLO

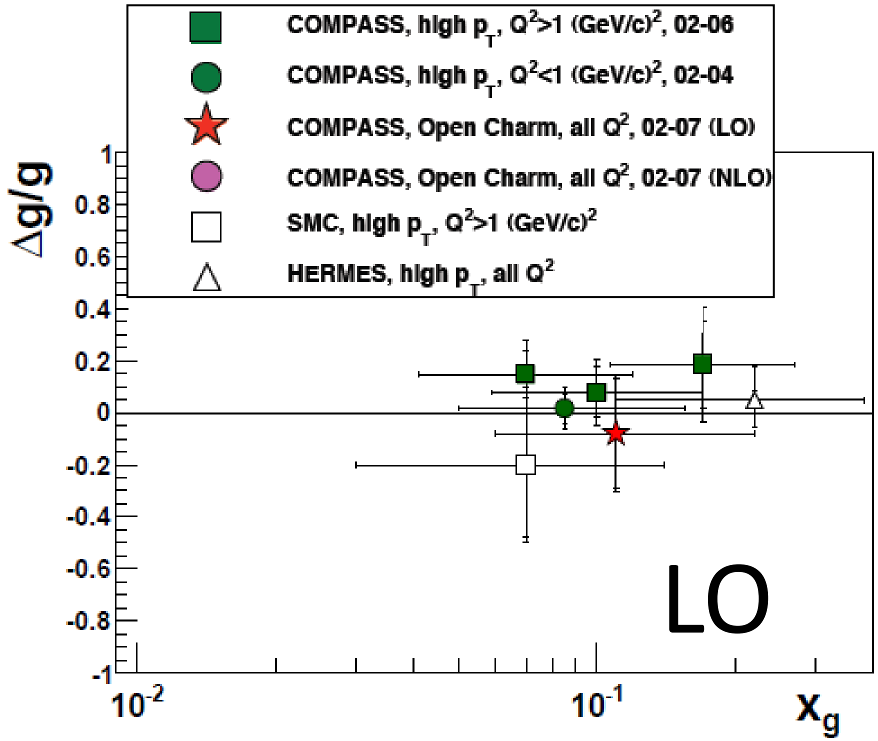
$$\frac{\Delta G}{G} = -0.20 \pm 0.21 \pm 0.08\ (\mathbf{syst}) \quad @<\mathbf{x_g}> = 0.28^{+0.19}_{-0.10},\ <\mu^2> = 13\ (\mathbf{GeV/c})^2$$

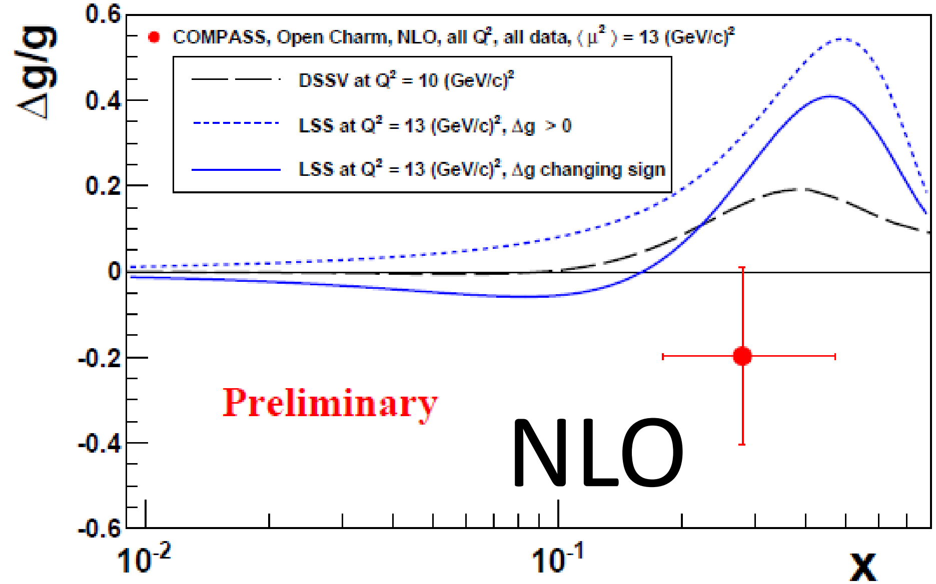
still preliminary

$<x_g>$ shifted to higher values

- depends on the order of the QCQ calculation of a_{LL} causing a change in the relative weight of the each event
- due to the real gluon emission at NLO, the energy of the photon-gluon system is higher

Results for /G





LO results from:

- ✓ High pT hadron pairs: COMPASS compared to SMC, HERMES
- ✓ Open charm from COMPASS

NLO result from charm at COMPASS (systematic error still under investigation)

ΔG/G predicted small, with a node around $x_g \sim 0.1$? and $\int \Delta G(x)\,dx$ =?

Single hadron production for $Q^2 < 0.1$ GeV^2 and high p_T

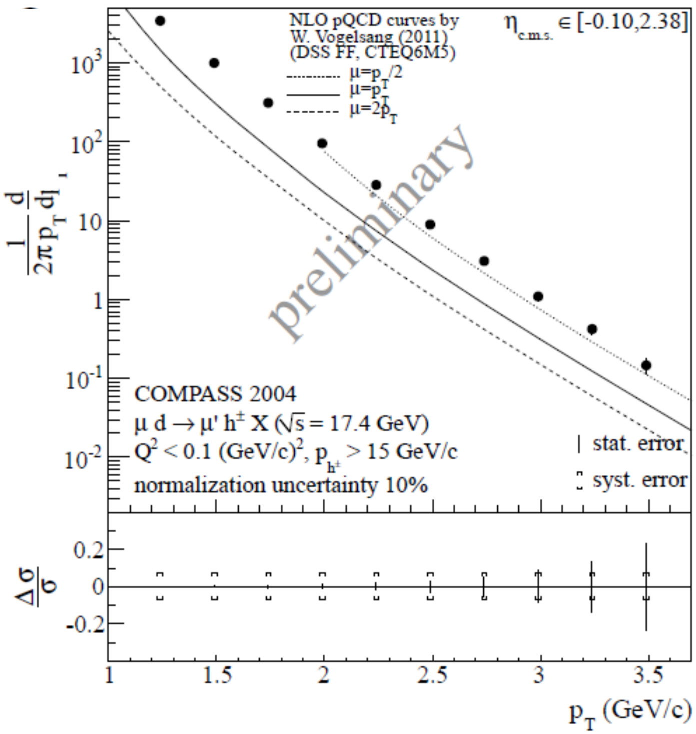
$\mu^+ d \rightarrow \mu^+ h^\pm X$

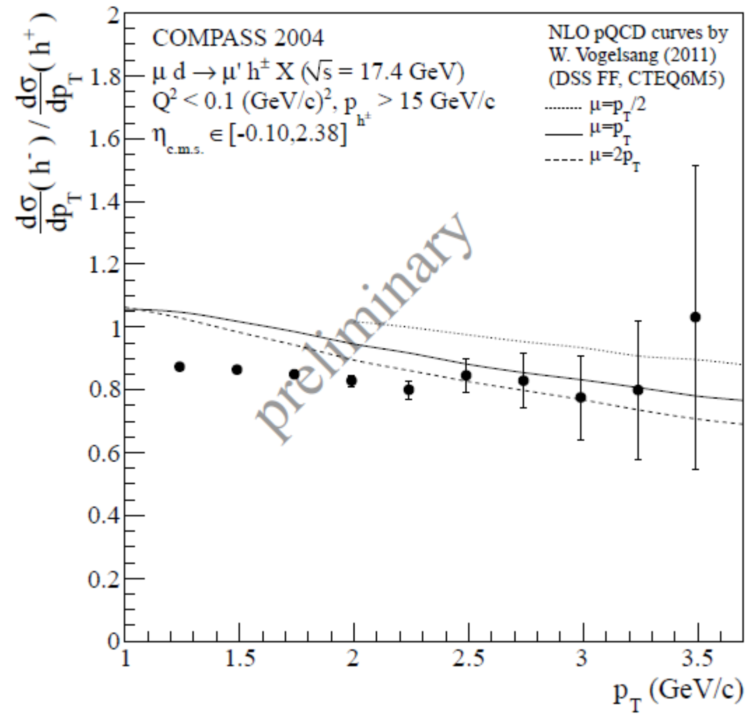
$Q^2 < 0.1$ GeV^2

$P_h > 15$ GeV

COMPASS

$\sqrt{s} = 17$GeV





Calculations exist in NLO for small Q^2 and large p_T

However is theory applicable at COMPASS?

- experimental cross section > prediction: preferred scale $\mu = p_T/2$, resummation needed?
- p_T dependence of charge ratio from pQCD not confirmed, pb of fragmentation functions?

Next steps: much more data on tape for ΔG determination

Summary and Outlook

Results from COMPASS:

- ✓Quark spin contribution to nucleon spin: $\Delta\Sigma$ = 0.33±0.03(stat)±0.05(syst)
- ✓ Flavour separation Δq from SIDIS data for $0.004 < x < 0.3$
- ✓Update of gluon polarization: ΔG is small

Still to come:

- ✓Study of fragmentation and strange quark distribution
- ✓Gluon polarization from single hadrons
- ✓More data with longitudinal polarized NH_3 and $E\mu$=200 GeV in 2011
- ✓Proton g_1 at low x and flavour separation
- ✓Future COMPASS-II: DVCS, DVMP for GPD , DY for TMD ➔ OAM ?
  still unpolarized measurements to improve the unpol. PDF and FF