New COMPASS Results on Longitudinal Spin Effects

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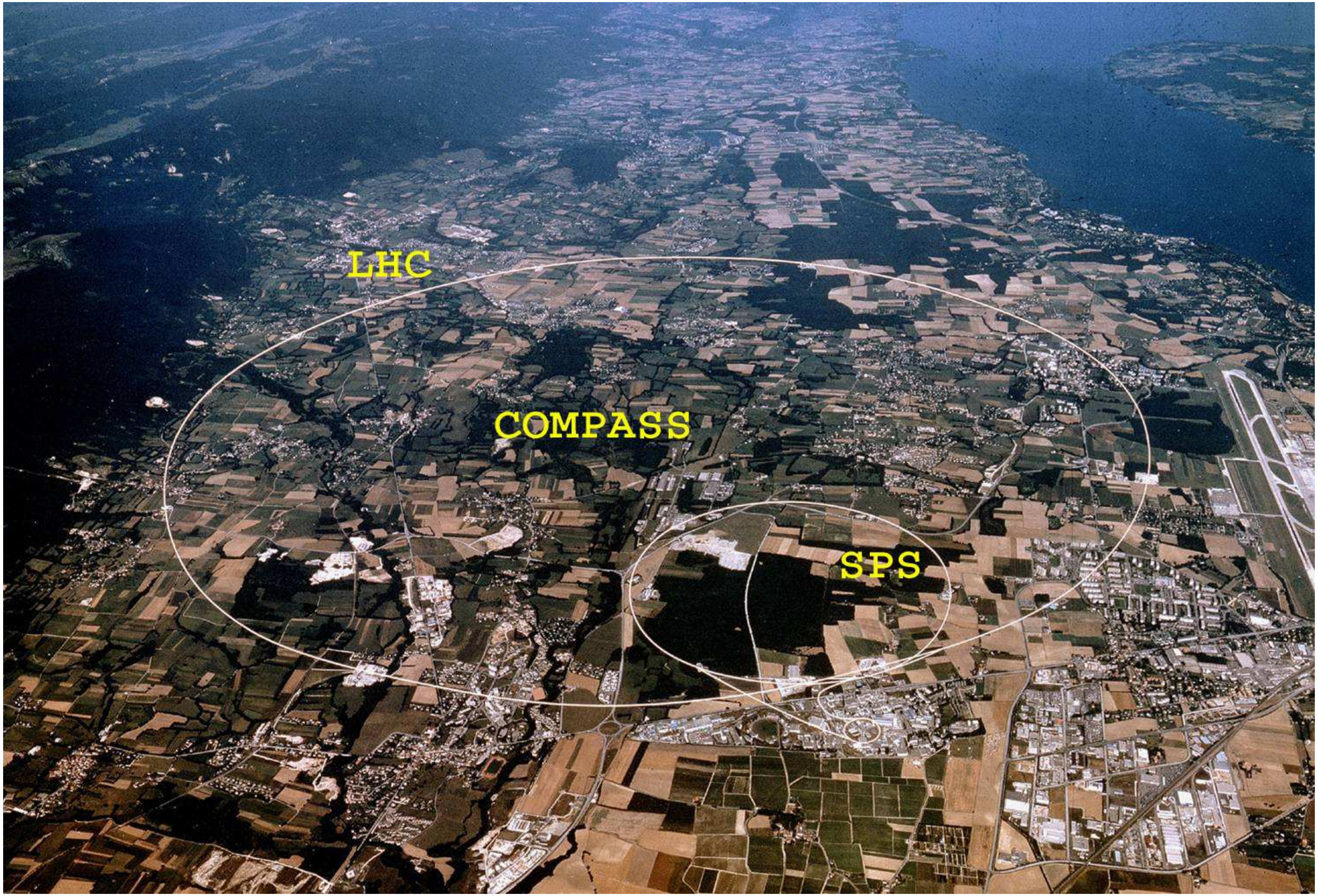
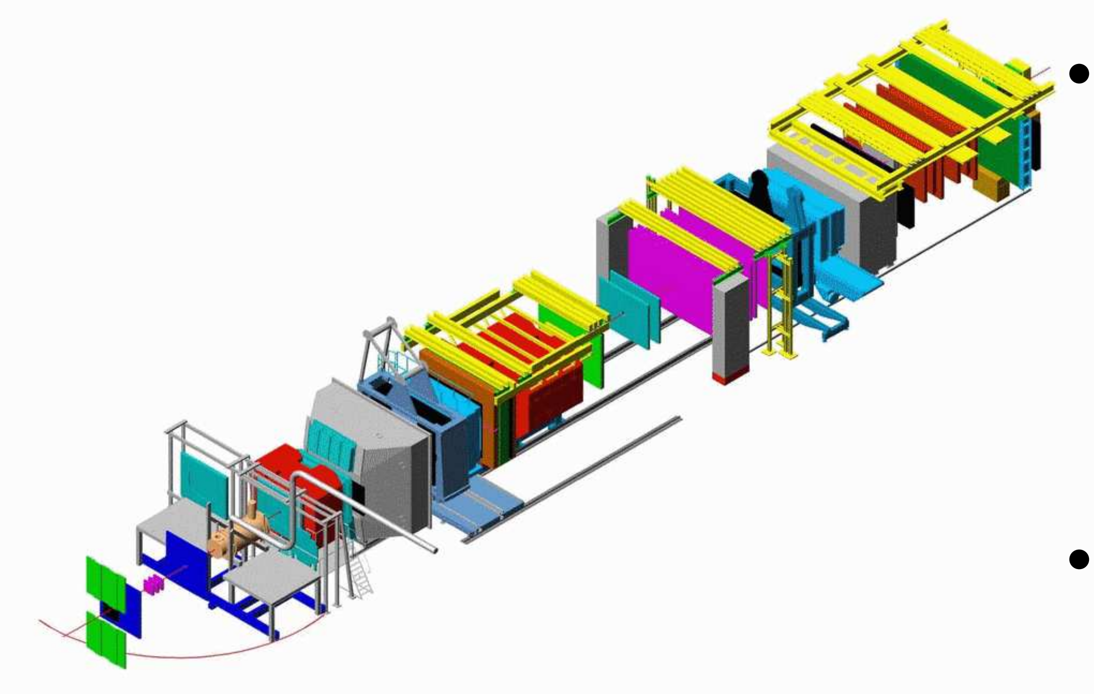
on behalf of the COMPASS collaboration

- $\Delta G/G$ measurements
  - open charm analysis
  - high-p_T 2h, $Q^2 <$ || >1 (GeV/c)^2 analyses
  - high-p_T 1h, $Q^2 <0.1$ (GeV/c)^2 analysis
- g_1^p and test of the Bjorken sum rule
- flavor separation

COMPASS @ CERN

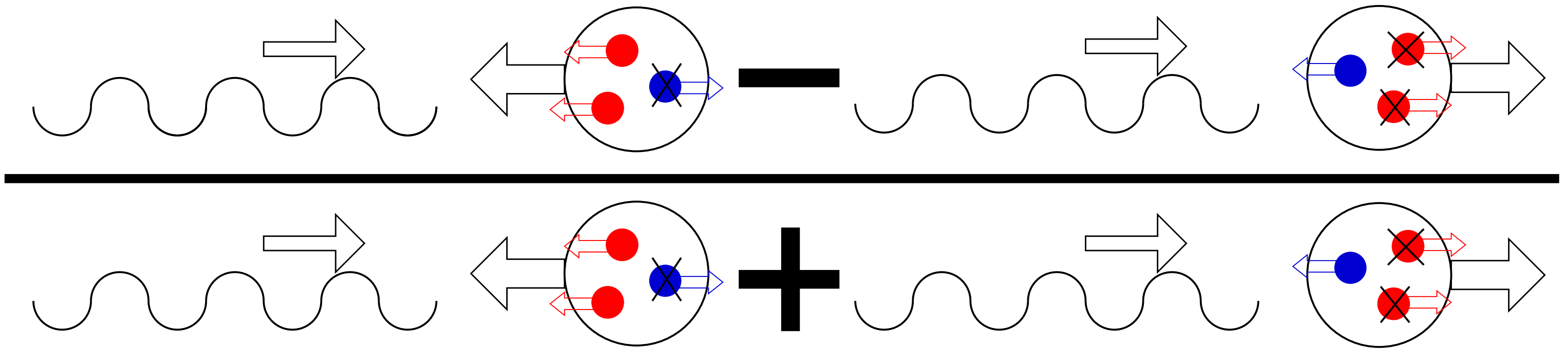




- POLARIZED TARGET
  - ^{6}LiD (NH_3) target
  - 2-3 cells (30,60 cm long each)
  - ± 50% (90%) polarization
  - polarization reversal every 8h-24h
- POLARIZED BEAM
  - positive muons at 160 GeV/c
  - polarization –80 %
- COLLABORATION
  - about 210 physicists
  - 27 institutes
- DETECTOR
  - 60 m length
  - 2 (3) magnets
  - about 350 detector planes
- FEATURES
  - acceptance: 70 → 130 mrad
  - track reconstruction: $p > 0.5$ GeV
  - identification: π, K, p (RICH) above 2, 9, 18 GeV respectively

Asymmetries

- the spin effects are small $\rightarrow$ precise methods of measurement are needed
- the asymmetry measurement is most commonly used
  - the asymmetry measurement allows to cancel many effects like acceptance, beam fluxes *etc.*
  - the physical asymmetry is diluted by the beam and target polarizations, and by the fraction of polarized nucleons in the target *etc.*
  - in COMPASS raw asymmetries are typically 10-100 smaller than the physics asymmetries



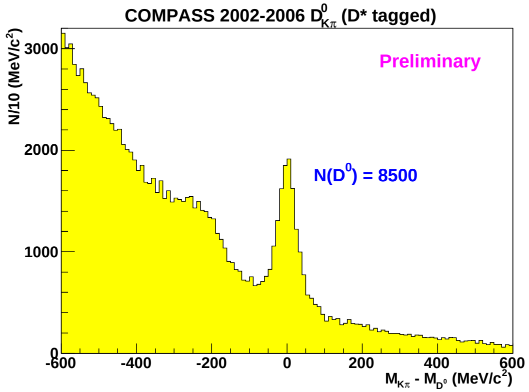
Gluon Polarization Inside the Nucleon

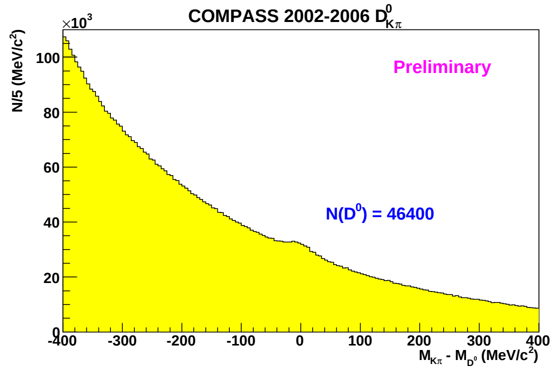
- spin of the proton ($S_p = 1/2\hbar$) can be decomposed as:
  - $\Delta\Sigma$ - quark contribution to the nucleon spin
  - ΔG - gluon contribution
  - ΔL_q,ΔL_g - orbital momentum of quarks and gluons
- $S_p = 1/2\hbar = 1/2\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$
- in the simplest QPM model: $S_p = 1/2\Delta\Sigma$
- the direct measurement: $\Delta\Sigma \approx 0.3$
- how much is then ΔG?
- possible measurement of ΔG in photon-gluon fusion
  - asymmetries in open-charm production
  - asymmetries for high transverse momentum hadrons

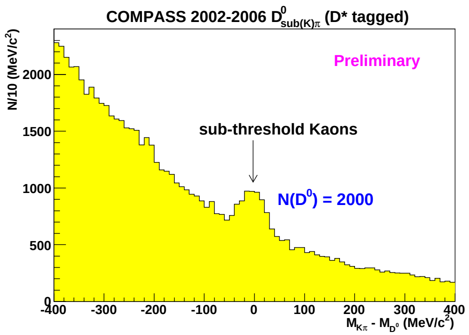
$\Delta G/G$ from Open Charm Analysis 2002-2007 Data

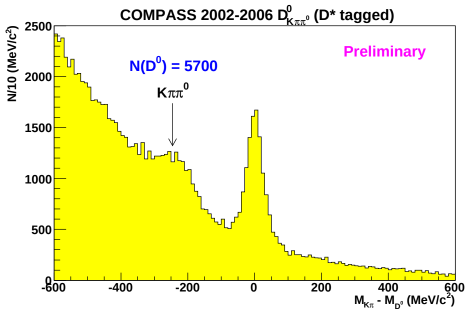
$\Delta G/G$ from Open Charm Analysis

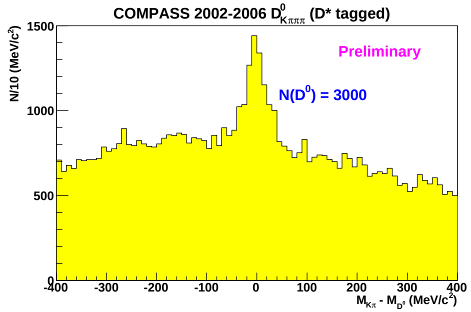
- open-charm - clean source of PGF
- hard scale $\approx 4m_c^2$, even though $Q^2 < 1$ (GeV/c)^2
- low statistics - various decay modes of Ds mesons analyzed











- Number of D^0 events : 65500
- Number of total D^* 29000 (13100 in the golden channel, $D^* \rightarrow K\pi\pi_{soft}$)

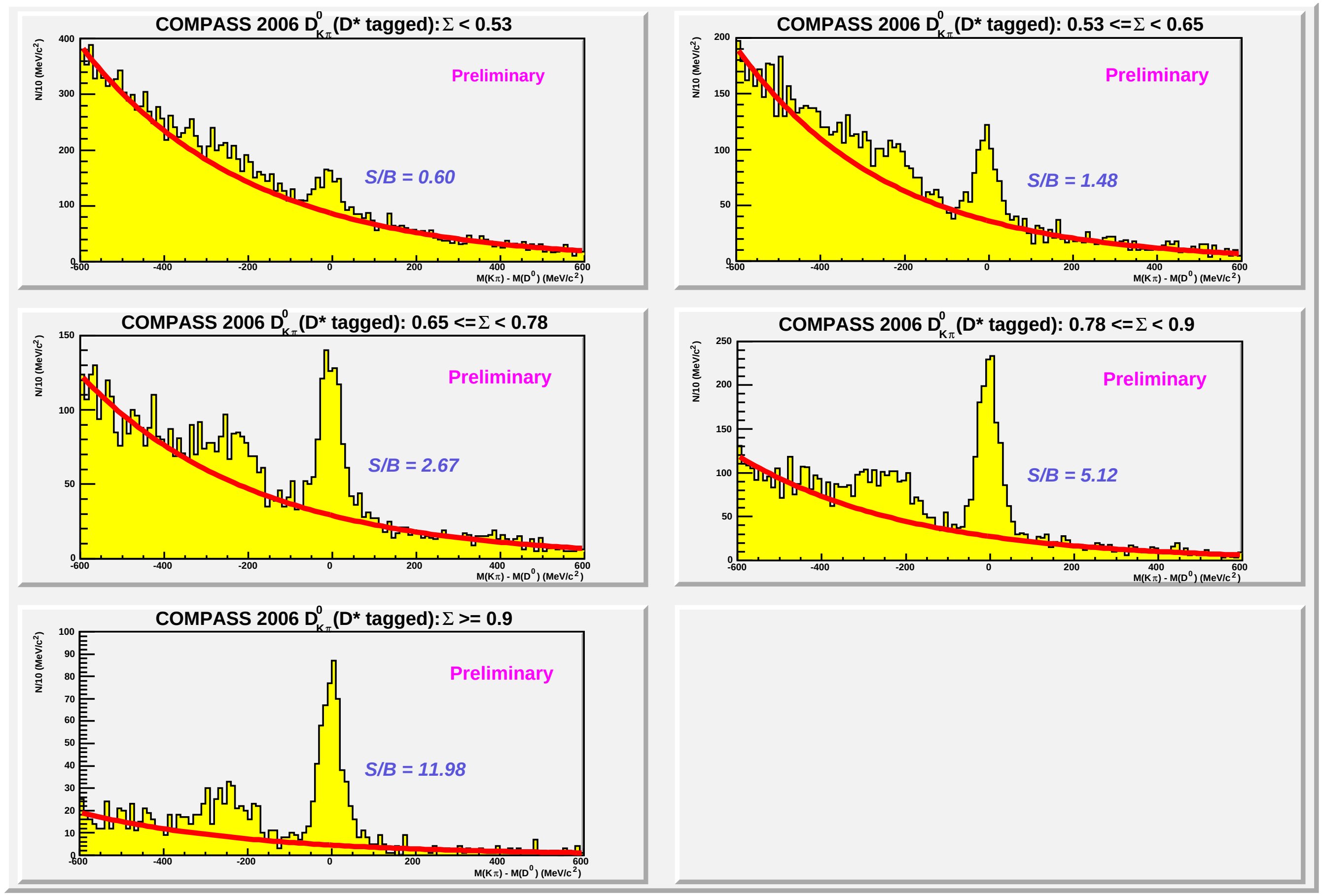
Gluon Polarization

$$\frac{\Delta G}{G} = \frac{1}{P_T P_b f a_{LL} \frac{S}{S+B}} A_{raw}$$

- in the analysis we use weight $P_b f a_{LL} \frac{S}{S+B}$ on the event by event basis to improve the statistical accuracy of the measurement.
- $\frac{S}{S+B}$ (Σ) is parametrized on data using a Neural Network (NN) approach
- analyzing power, a_{LL}, is taken from MC
- f - dilution factor, fraction of polarizable material in the target. Radiative corrections included, (NH_3: $f \approx 3/(3+14)$)
- P_b, P_T - beam and target polarizations
- NOTE: In reality a more complex $\Delta G/G$ extraction method is used.
- $A_{bakcgr} = \frac{1}{P_t P_b f D \frac{B}{S+B}} A_{raw}$ is extracted simultaneously with $\Delta G/G$, *c.f.* J. Pretz and J.M. Le Goff Nucl. Instr. Meth. A 602 (2009) 594

NN Approach for S/(S+B) Parametrization

- NN input variables: p_K, z_D, $p_{T,D}$ and RICH PID information
- background is simulated by the wrong charge combinations
- in bins of NN output the mass spectrum is fitted and the final parametrization is done

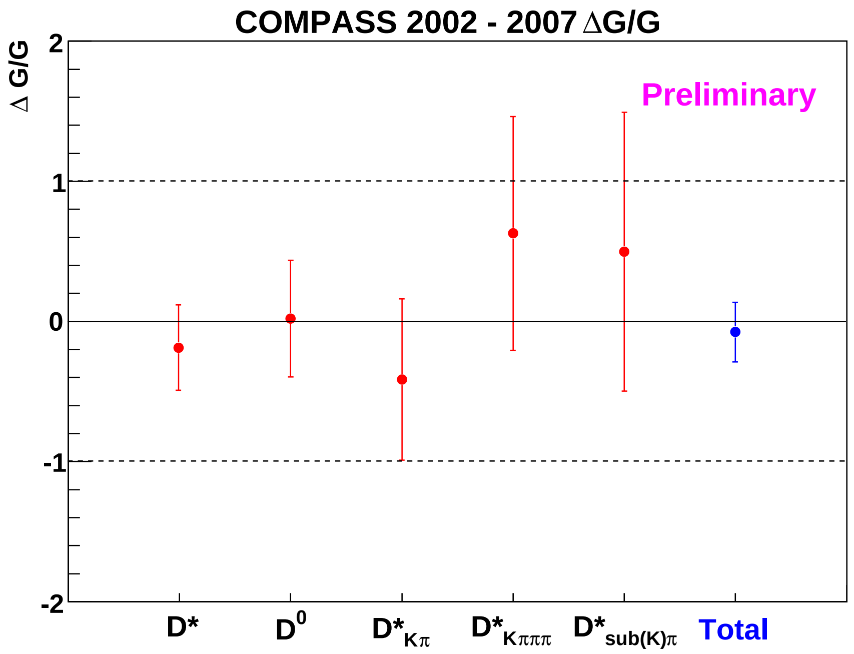


The $\Delta G/G$ Results

$$\Delta G/G = -0.08 \pm 0.21 \pm 0.11$$

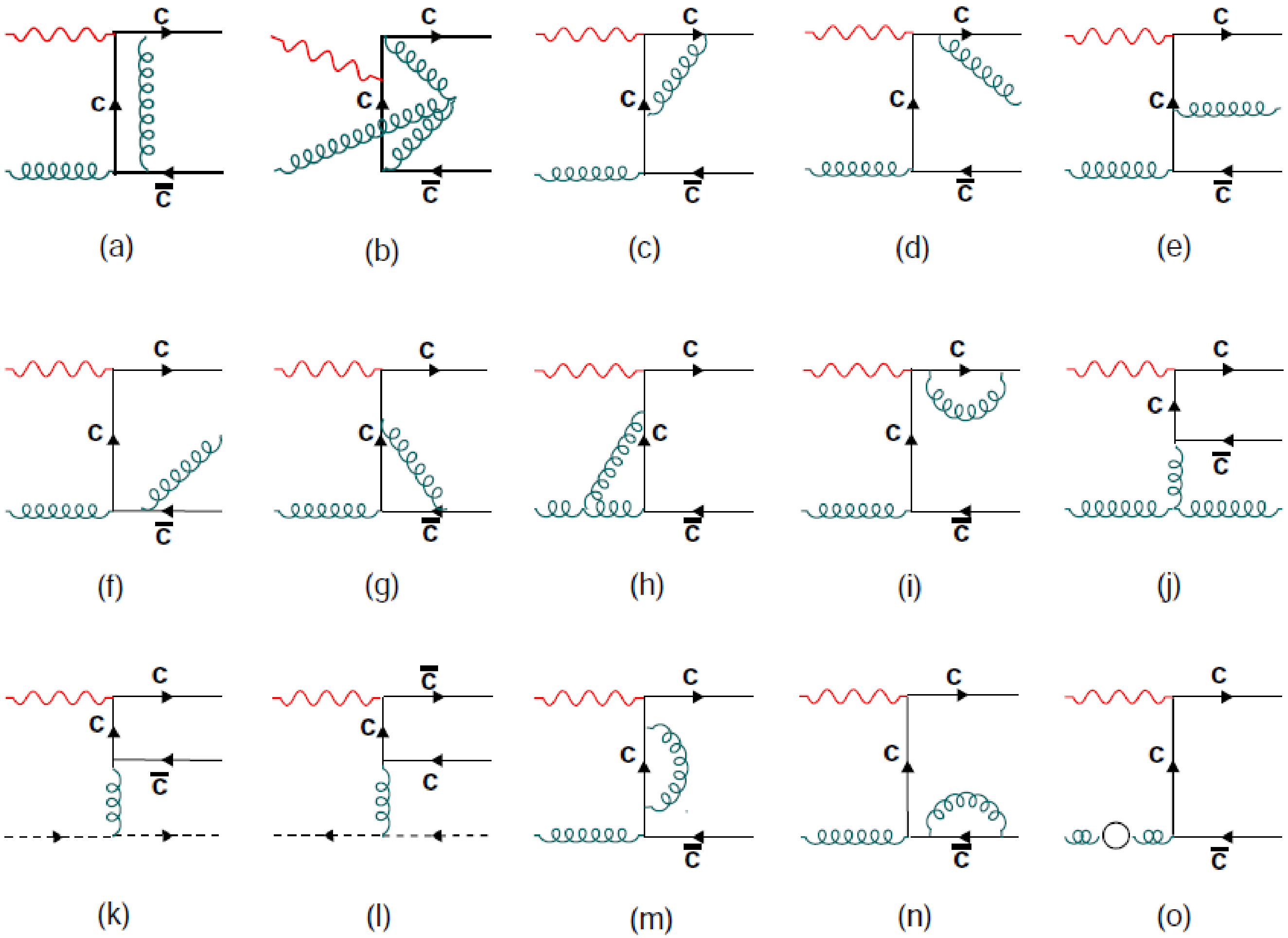
$< x_G >= 0.11^{+0.11}_{-0.05}$ $< \mu^2 > = 13$ (GeV/c)^2

channel	results
$D^* \rightarrow K\pi\pi_{slow}$	-0.19 ± 0.30
$D^0 \rightarrow K\pi$	0.02 ± 0.42
$D^* \rightarrow K\pi\pi^0\pi_{slow}$	-0.41 ± 0.58
$D^* \rightarrow K3\pi\pi_{slow}$	0.63 ± 0.83
$D^* \rightarrow K_{subth}\pi\pi_{slow}$	0.5 ± 1.0



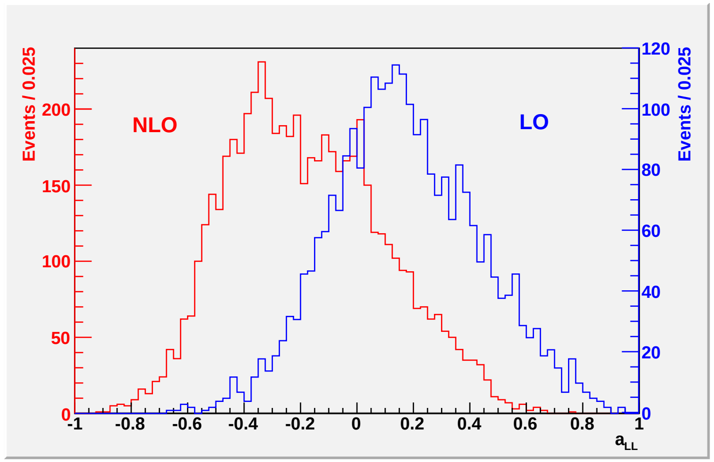
- large part of the systematic error is proportional $\delta\Delta G/G_{stat}$
- key point: $\sigma_{stat} >> \sigma_{sys}$

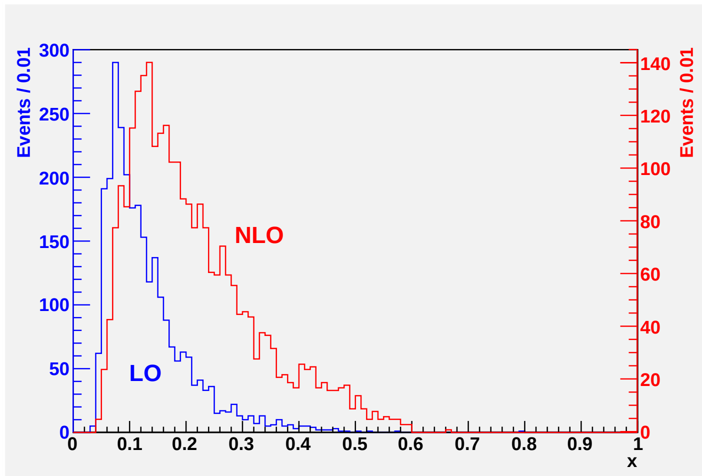
NLO Analysis of Open Charm Events



NLO Analysis of Open Charm Events cont.

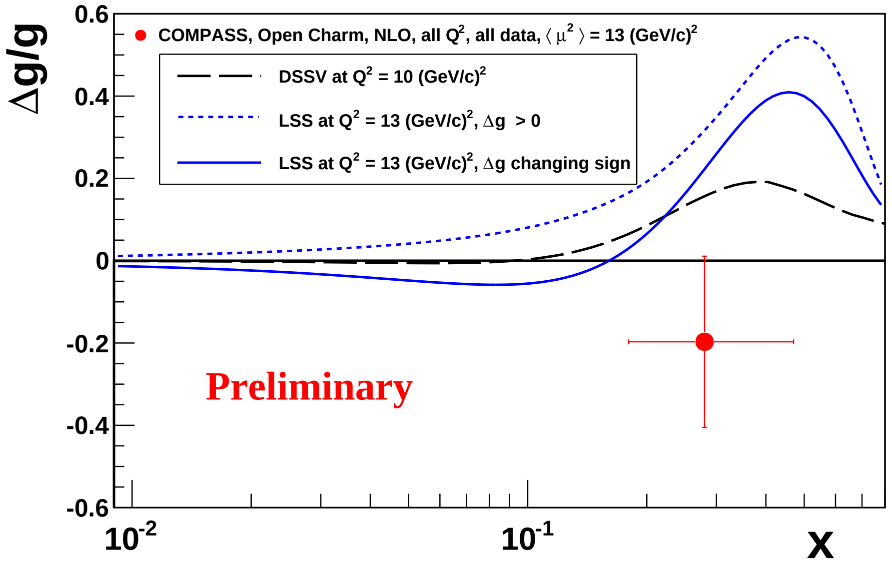
- based on I.Bojak, M.Stratmann, Nucl.Phys.B 540 (1999) 345
- AROMA generator is used with parton showers ON
- parton shower simulates the phase-space for NLO correction, which can be calculated on the event by event basis
- in addition in NLO part of the D_0's are not produced in PGF processes $\rightarrow A_{corr} \sim A_1^{d,p}$ term appears.
- large differences are observed between a_{LL}^{LO} and a_{LL}^{NLO} as well as between x_G^{LO} and x_G^{NLO}





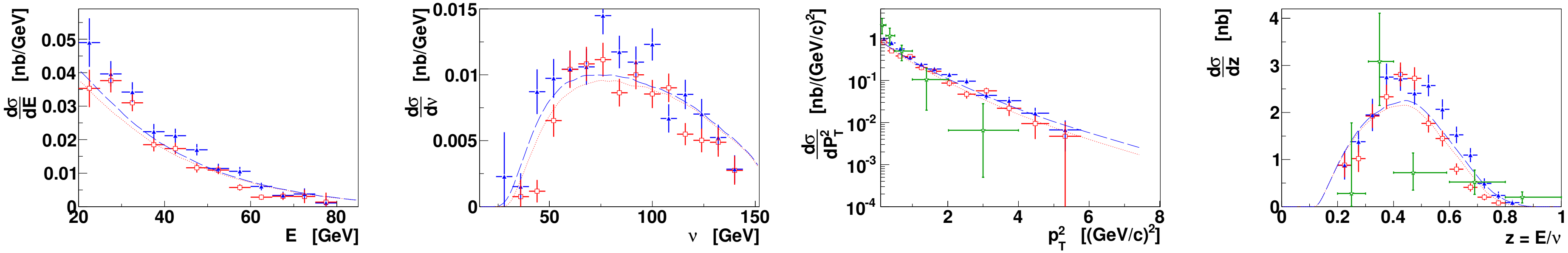
Results of NLO $\Delta G/G$ Extraction

- $\Delta G/G = \frac{ASY_{\gamma N} - A_{corr}}{<a_{LL}^{NLO}/D>}$
- the preliminary result is $\Delta G/G_{NLO} = -0.20 \pm 0.21 \pm 0.08$
- $\mu^2 = 13\ (\mathrm{GeV/c})^2$, $< x_{G,NLO} >= 0.28$
- publication of the $\Delta G/G$ results obtained in LO and NLO is being prepared



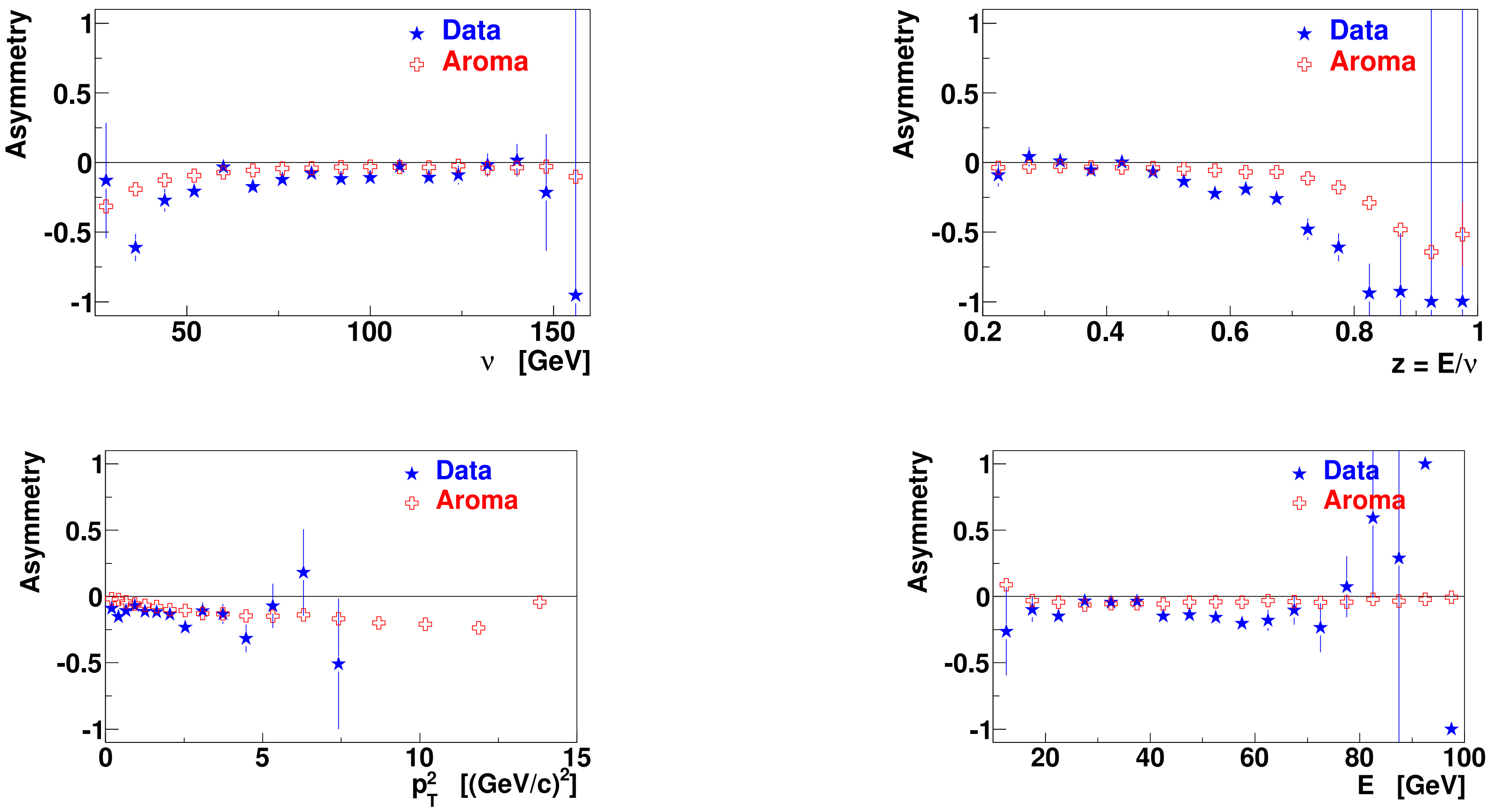
Properties of D^* Mesons

- COMPASS also studies unpolarized D^* production
- total observed production cross section for $D^{*\pm}$ mesons is $\sigma = 1.80 \pm 0.4$nb, to be compared with 2.6 nb from the AROMA generator.
- the cross section is for D^* mesons with laboratory energies between 22 and 86 GeV seen by the COMPASS experiment,
- differential cross sections have been measured:
  - they are compared with EMC results (green)
  - shape is compared with AROMA predictions



Properties of $D*$ Mesons cont.

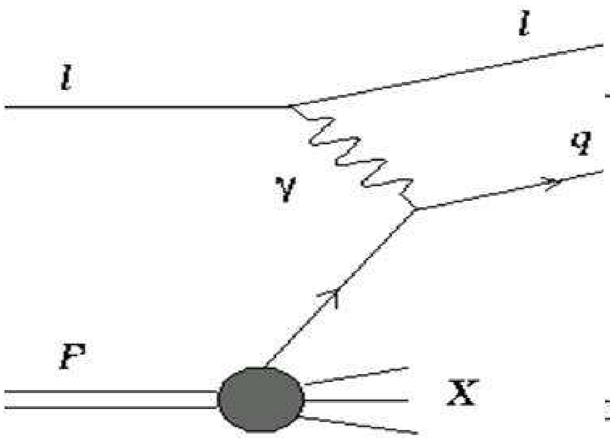
- non zero asymmetries are observed between D^{*+} and D^{*-} production,
- this result may suggest that other processes than PGF are also involved in the D* production
- separate publication is in progress



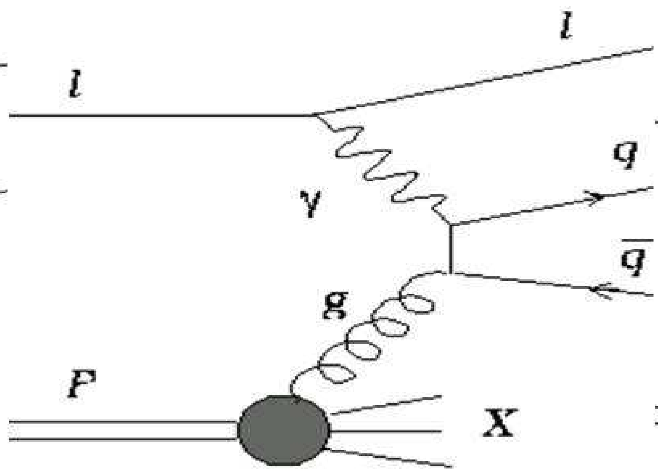
High-p_T Hadron Pairs Analysis 2002-2006 Data

High-p_T Hadron Pairs Analysis 2002-2006 Data, $Q^2 > 1$ (GeV/c)^2

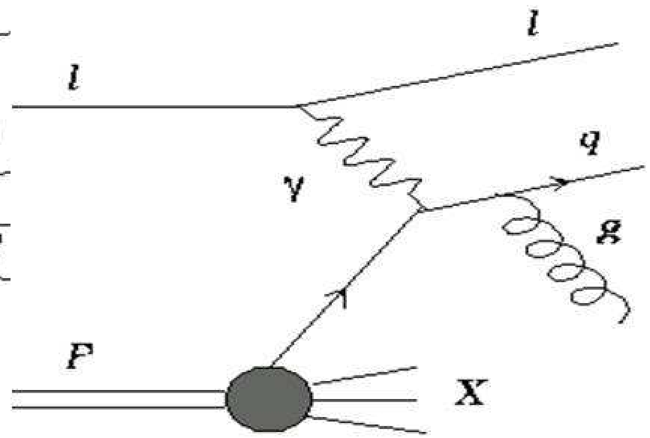
- in LO three processes are contributing: LP, PGF and QCDC
- the fraction of each process has to be estimated from MC
- in general, for higher p_T a larger fraction of PGF is expected
- the key point of the analysis is the good agreement between data and MC
- much larger statistics than in the open charm analysis



LP



PGF



QCDC

Data Selection

- cuts on inclusive variables
  - $Q^2 > 1$ (GeV/c)^2 (scale of the process)
  - $0.1 < y < 0.9$
- cuts on hadron variables
  - we can use lower p_T because the scale is determined by Q^2
  - $p_{T1} > 0.7$ GeV/c and $p_{T2} > 0.4$ GeV/c
  - $x_{F1,2} > 0,\ z_1 + z_2 < 0.95$
  - BTW, change of cut from $p_{T1} > 0.7$ GeV/c to $p_{T1} > 1$ GeV/c, increases the error of $\Delta G/G$ by 4 %, while the data sample is reduced by a factor of 3.

Total number of events in the selected sample: ≈ 7.3M

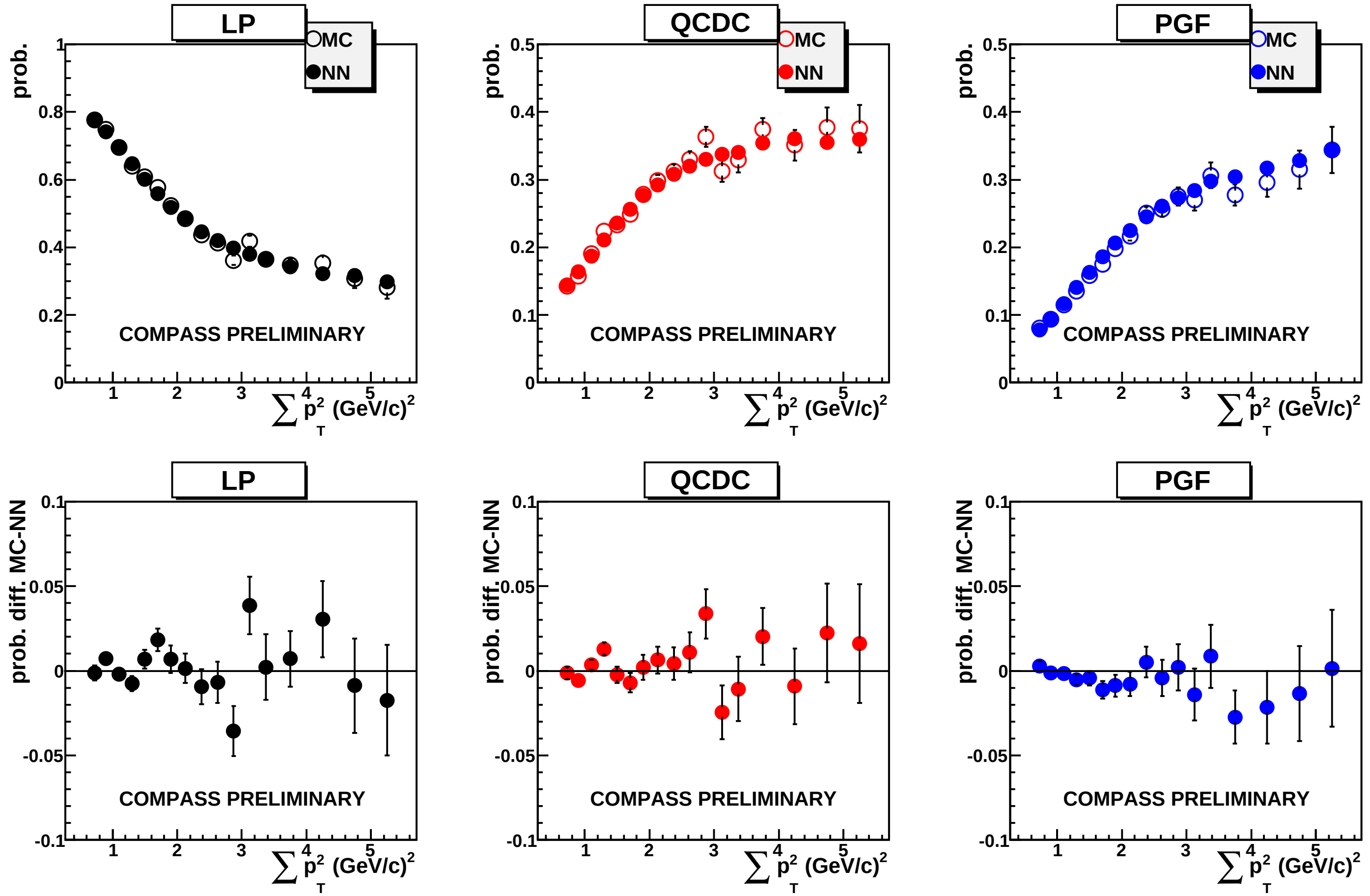
The Extraction of $\Delta G/G$

- observed asymmetry in 2 hadrons sample is:
- $A_{LL}^{2h}(x_{Bj}) = R_{PGF}\, a_{LL}^{PGF} \frac{\Delta G}{G}(x_G) + R_{LP}\, D\, A_1^{LO}(x_{Bj}) + R_{QCDC}\, a_{LL}^{QCDC} A_1^{LO}(x_C)$
  - $A_1^{LO} \equiv \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i}$
  - Rs - fractions of the sub-processes (LO, PGF, QCDC), taken from MC
  - a_{LL}s - analyzing powers for LO,PGF and QCDC, taken from MC
- we have two unknowns A_1^{LO} and $\Delta G/G$, and so far only equation...
- additional information is provided by the inclusive sample:

  $A_1^d(x_{Bj}) = R_{PGF}^{incl} a_{LL}^{incl,PGF} \frac{\Delta G}{G}(x_G) + R_{LP}^{incl} D A_1^{LO}(x_{Bj}) + R_{QCDC}^{incl} a_{LL}^{incl,QCDC} A_1^{LO}(x_C)$
- $\Delta G/G = \Delta G/G(x_G^{av}) = \frac{A_{LL}^{2h}(x_{Bj}) + A^{corr}}{\beta}$
- $\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF,incl} R_{PGF}^{incl} \left(\frac{R_L}{R_L^{incl}} + \frac{R_C}{R_L^{incl}} \frac{a_{LL}^C}{D}\right)$
- A^{corr} is a linear function of $A_1^d(x_{Bj} \sim 0.03)$ and $A_1^d(x_C \sim 0.11)$

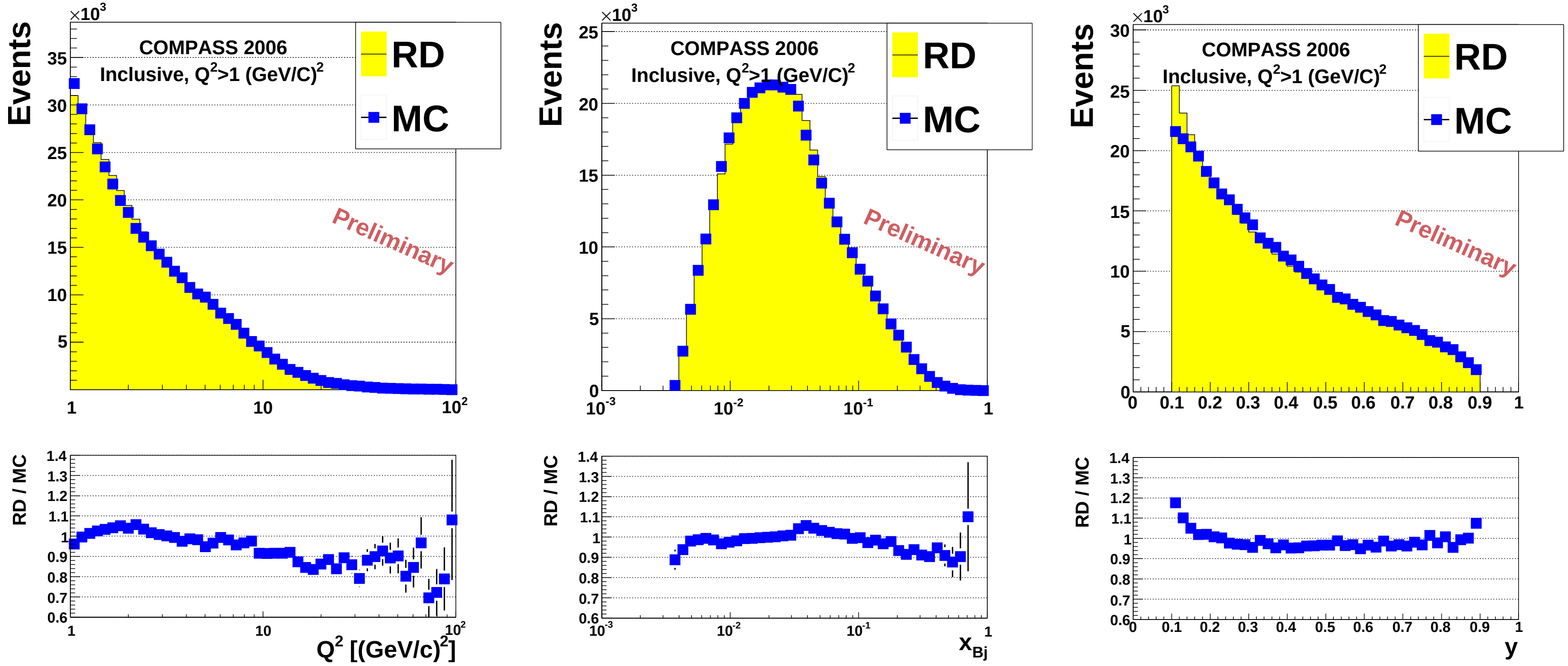
The Extraction of $\Delta G/G$ cont.

- to reduce statistical error we use a weighted method for the asymmetry extraction. We must know all Rs and a_{LL}s on the event by event basis
- we use a Neural Network trained on MC to obtain parametrizations which are used on data, $c.f.$ example below

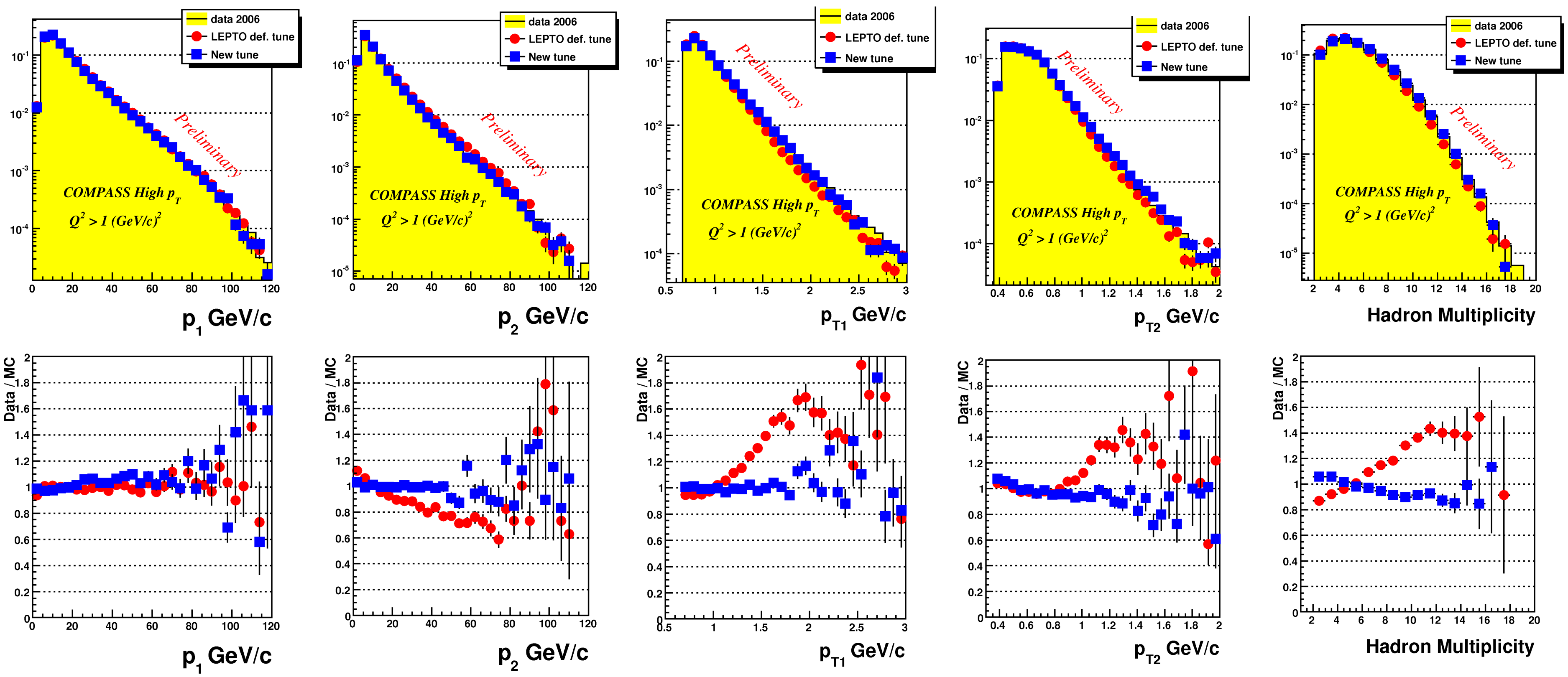


MC and Data Comparison

- LEPTO generator is used in the analysis
- parton Shower is ON, PDF set it MSTW08LO
- to improve data/MC agreement k_T and fragmentation parameters were adjusted, hadron variables affected
- below the comparison of inclusive variables is shown:



Ratio Data/MC for Hadron Variables



Results

- $\Delta G/G = 0.125 \pm 0.060 \pm 0.065$
- $< x_G >= 0.09$, $\mu^2 = 3$ (GeV/c)^2
- the dominating systematic contribution comes from the MC uncertainty

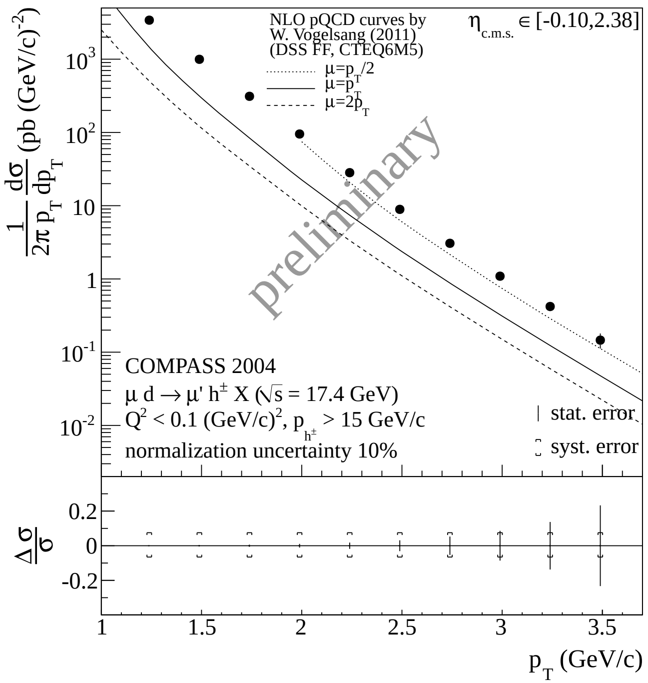
systematic error	value
$\delta(\Delta G/G_{NN})$	0.010
$\delta(\Delta G/G_{MC})$	**0.045**
$\delta(\Delta G/G_{f,P_t,P_b})$	0.004
$\delta(\Delta G/G_{false})$	0.019
$\delta(\Delta G/G_{A_1^d})$	0.015
$\delta(\Delta G/G_{formula})$	0.035
TOTAL	**0.065**

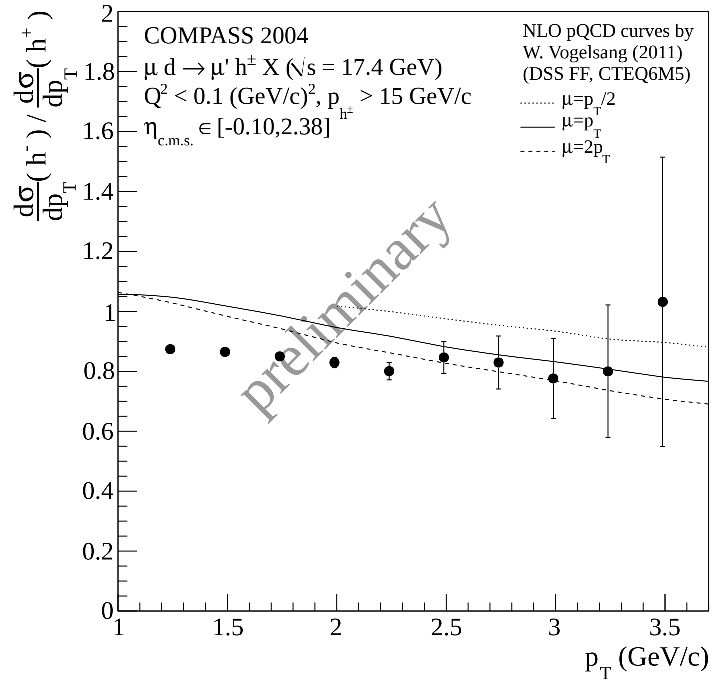
- COMPASS obtained results in 3 bins of x_G
  - we use NN to parametrize $x_{G,true}$
  - the correlation between $x_{G,param}$ and $x_{G,true}$ is about 60%
  - since the sample can be divided according to $x_{G,param}$, there is a partial overlap of the bins seen from $x_{G,true}$ perspective

$< x_G >$	$\Delta G/G$
$0.07^{+0.050}_{-0.029}$	$0.147 \pm 0.091 \pm 0.09$
$0.10^{+0.070}_{-0.041}$	$0.079 \pm 0.096 \pm 0.082$
$0.170^{+0.099}_{0.063}$	$0.185 \pm 0.165 \pm 0.144$

NLO $\Delta G/G$ from High$-p_T$ Hadrons for $Q^2 < 0.1$ (GeV/c)^2

- analysis in progress
- it uses as theoretical input the calculations of B.Jeager, M.Stratmann & W.Vogelsang, Phys. J. C44 (2005) 533-543
- the first step is done: hadron cross section is compared with theoretical expectations

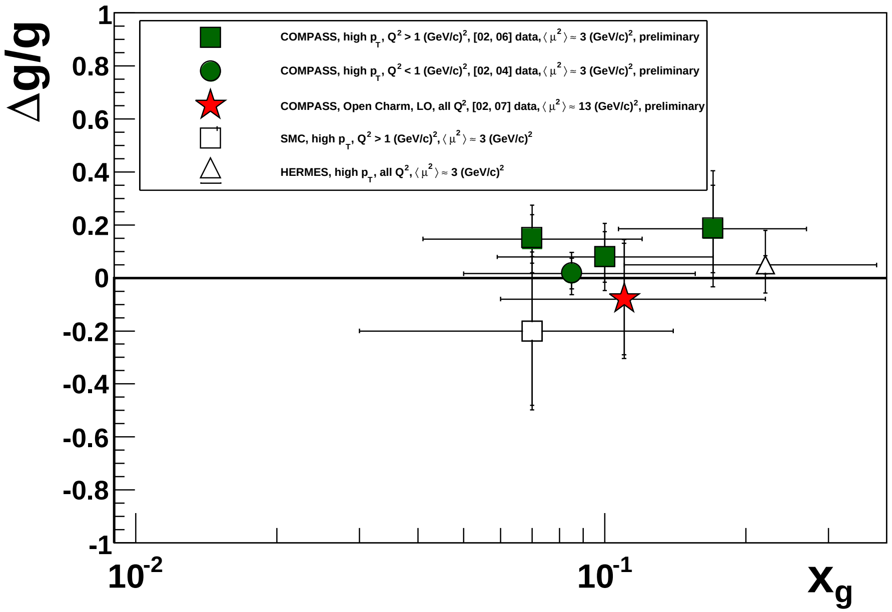


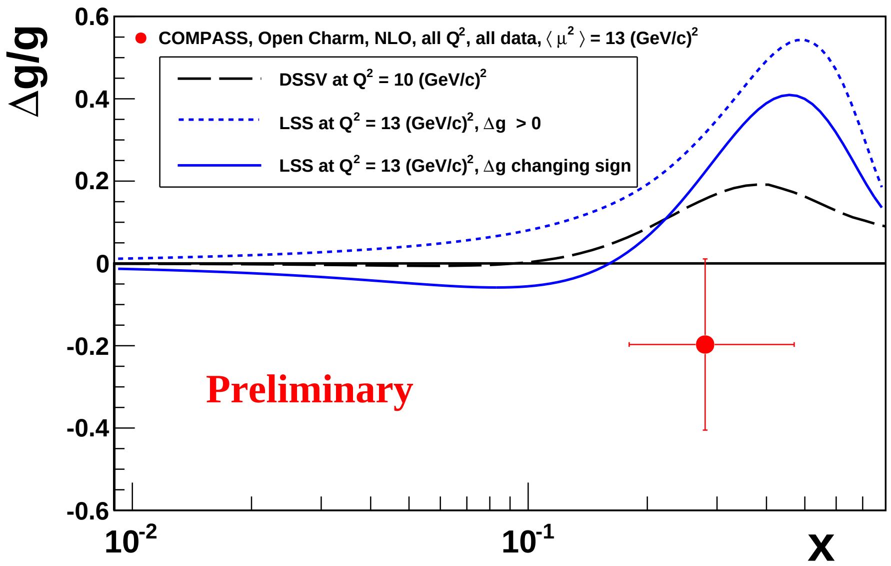


Results from High-p_T Hadron Pairs Analysis

- preliminary result for $Q^2 > 1$ (GeV/c)^2 2002-2006:
  - $\Delta G/G = 0.125 \pm 0.060 \pm 0.065$
- preliminary result for $Q^2 < 1$ (GeV/c)^2 2002-2004:
  - $\Delta G/G = 0.016 \pm 0.058 \pm 0.014 \pm 0.052 \pm 0.013$
  - includes the additional contribution from resolved photons
- published results $Q^2 < 1$ (GeV/c)^2, 2002-2003:
  - $\Delta G/G = 0.024 \pm 0.089 \pm 0.014 \pm 0.052 \pm 0.018$
  - PLB 633 (2006) 25-32
  - includes the additional contribution from resolved photons

Summary of $\Delta G/G$ from COMPASS





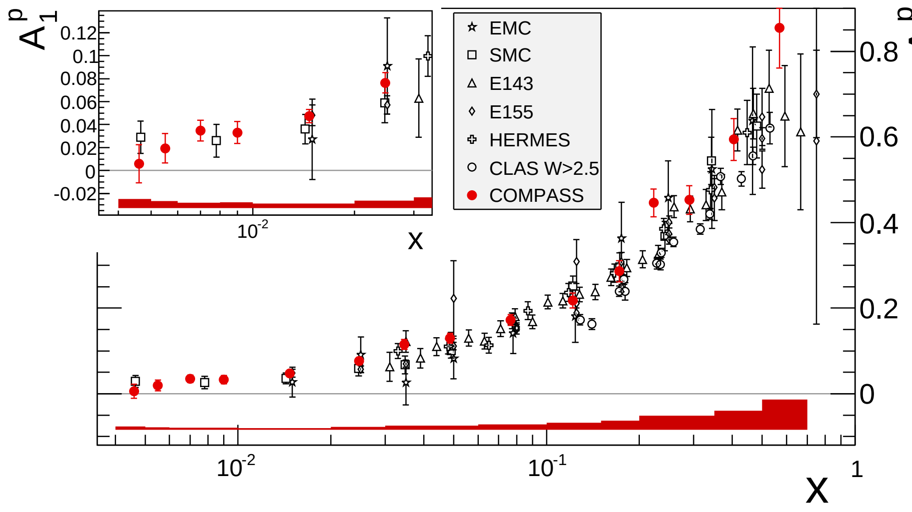
- all results agree with each other
- the ΔG is small, but the data are not precise enough to determine its sign

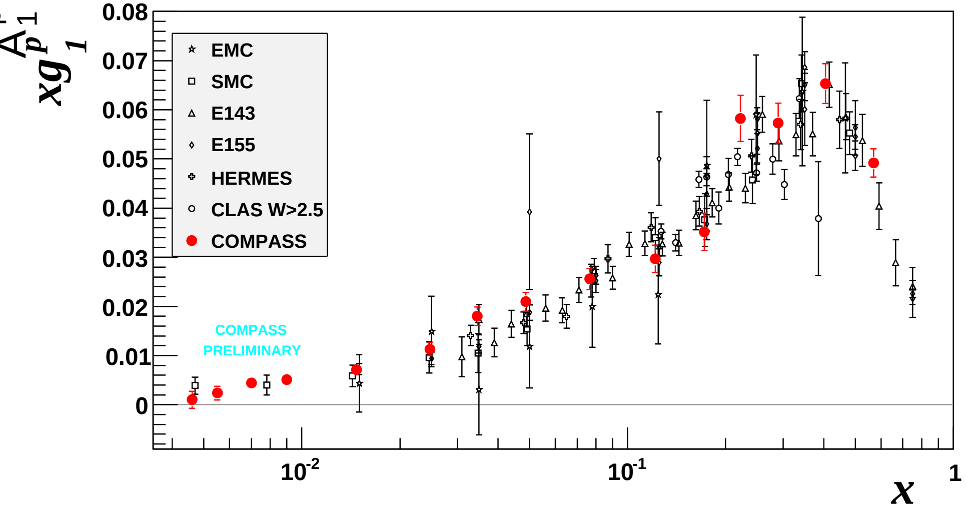
Spin Dependent Asymmetry A_1^p and Spin Dependent Structure Function g_1^p

analysis published in: PLB 690 (2010) 466

Asymmetry A_1^p and Structure Function g_1^p

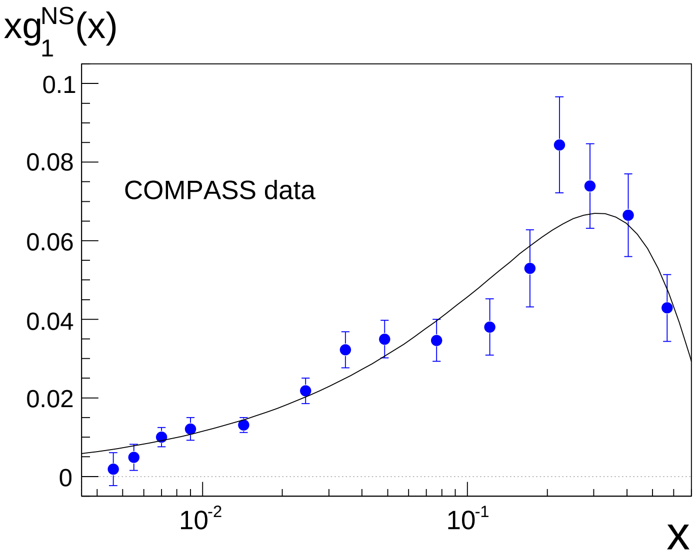
- 2007 data sample with $Q^2 > 1$ (GeV/c)^2
- reconstruction of μ and μ' and additional hadron for SI triggers
- $A_{raw} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$ $\quad A_1^p = \frac{1}{f D P_b P_T} A_{raw}$ $\quad g_1^p = \frac{F_2^p}{2x(1+R)} A_1^p$
- significant precision improvement in the low x region

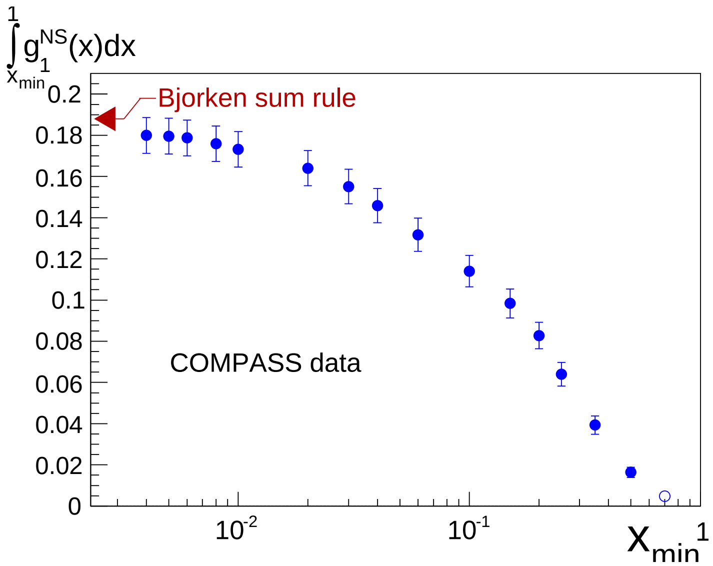




Test of the Bjorken Sum Rule

- $g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^d(x,Q^2)$
- $g_1^{NS}(x,Q^2)$ is interesting because its Q^2 dependence decouples from the singlet and gluon densities
- $\int_0^1 g_1^{NS}(x,Q^2) = \Gamma_1^{NS} = \frac{1}{6}\frac{g_A}{g_V} C_1^{NS}(Q^2)$,
  where $C_1^{NS}(Q^2)$ has been calculated in pQCD up to $\alpha_s^3(Q^2)$
- $\frac{g_A}{g_V}$ can be obtained from neutron beta decay: $\frac{g_A}{g_V} = 1.2694 \pm 0.0028$

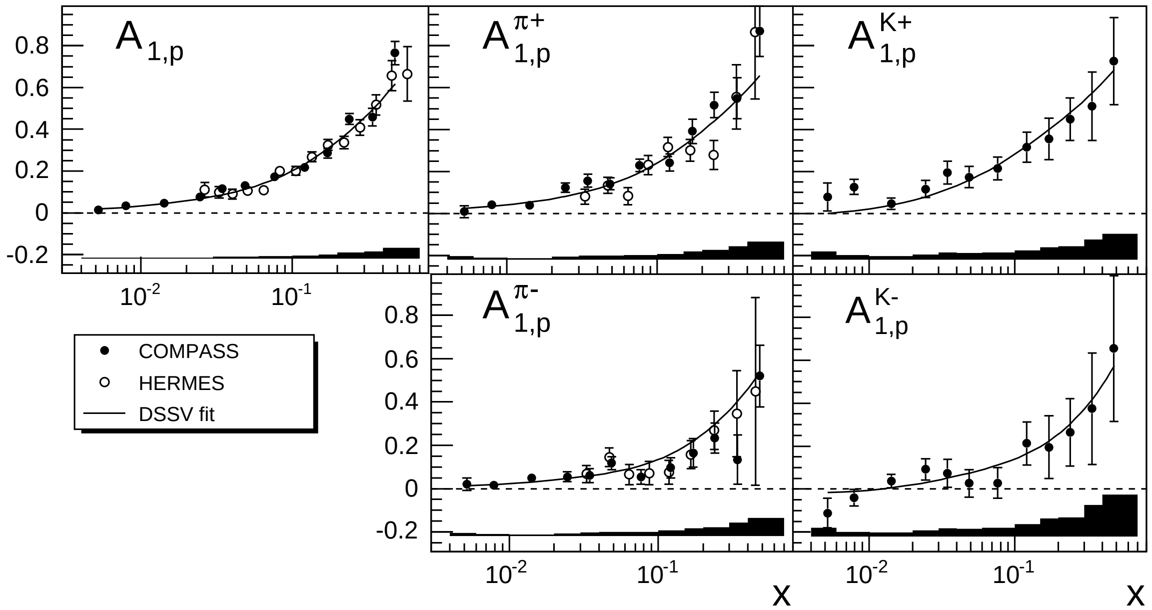




COMPASS result: $\frac{g_A}{g_V} = 1.28 \pm 0.07 \pm 0.10$

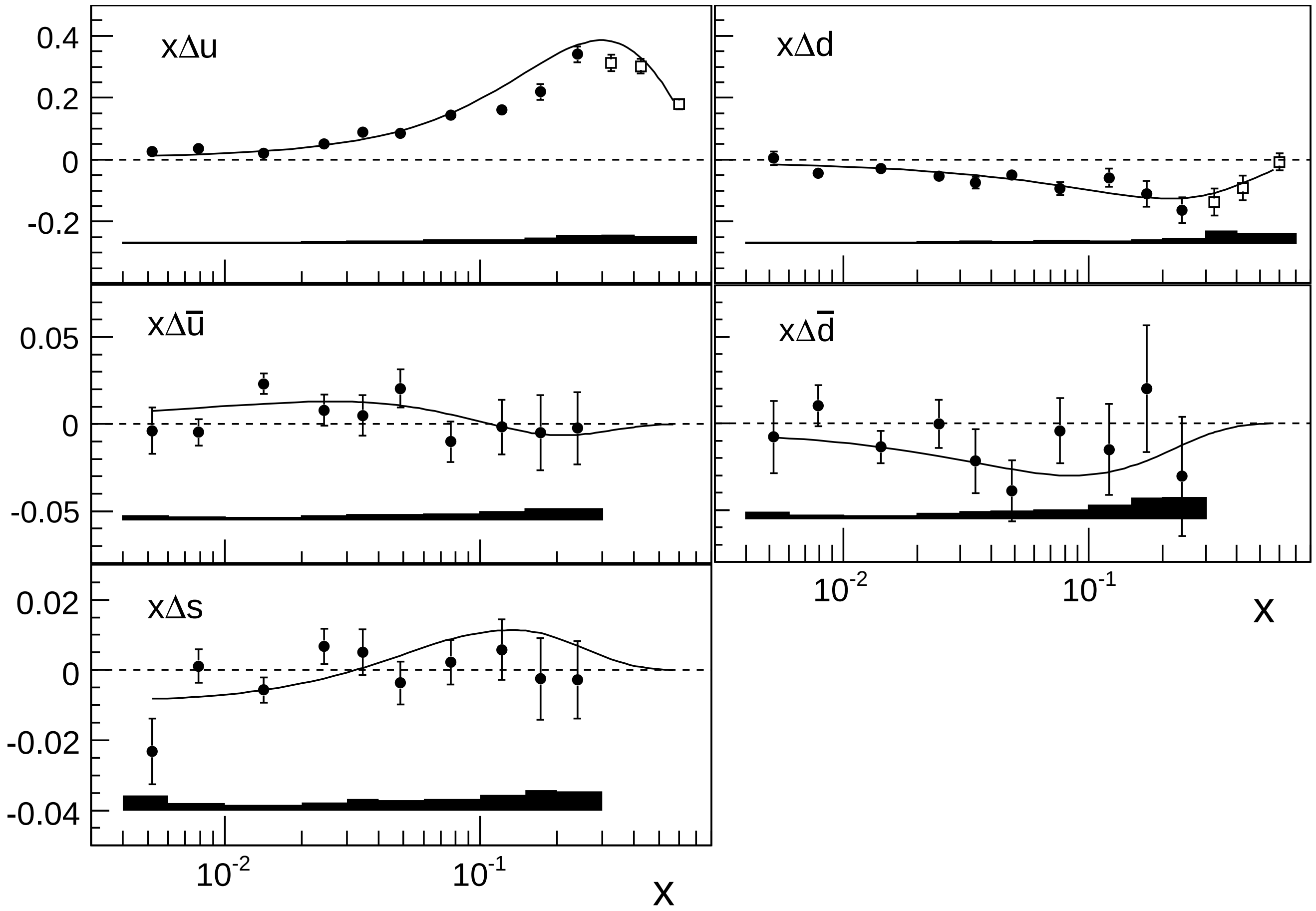
Semi-Inclusive Asymmetries and Flavour Separation

- semi-inclusive asymmetries were measured on both p and d targets
- for the first time Kaons asymmetries were measured on p target
- in the LO approximation $A_1^h(x, Q^2, z) = \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$
- D is a fragmentation Function (FF)
- with 10 asymmetries ($A_{1p,d}^{incl}, A_{1p,d}^{\pi\pm}, A_{1p,d}^{K\pm}$) and 5 unknown parameters ($\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s$) a flavor separation is possible



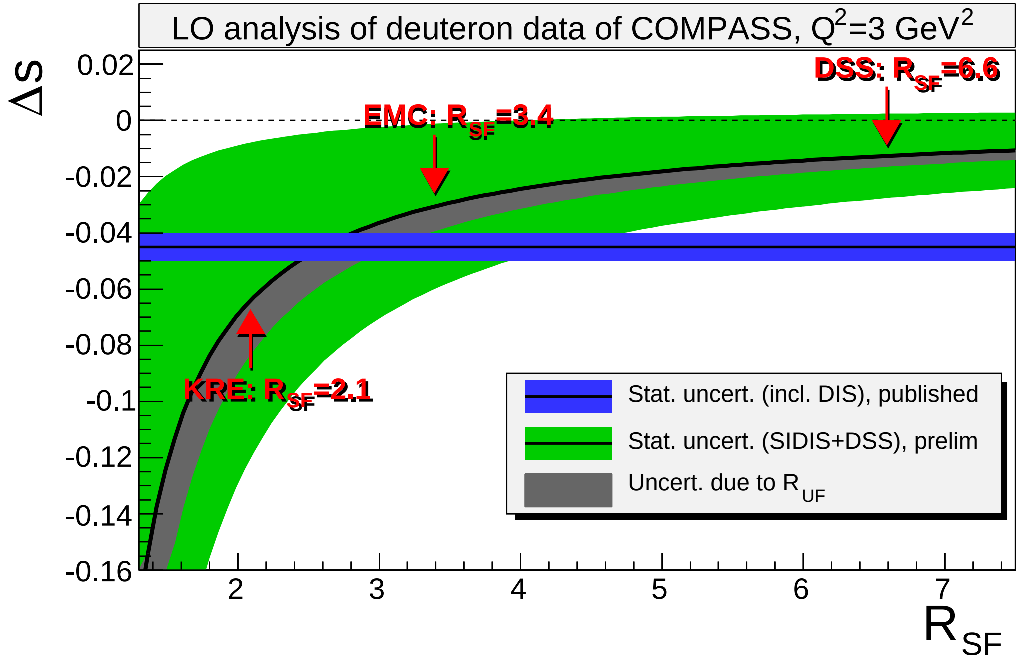
LO Flavour Separation

- results are published in PLB 693 (2010) 227
- curves are DSSV NLO parametrization Phys. Rev. Lett. 101 (2008) 072001; Phys. Rev. D80 (2009) 034030.
- good agreement between COMPASS data and DSSV parametrization



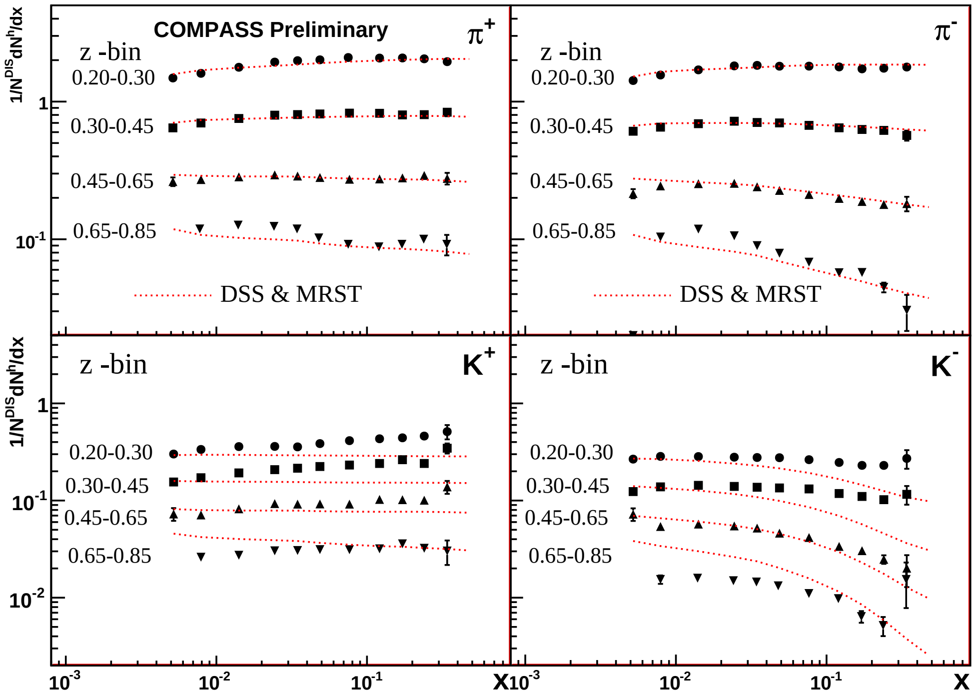
Strange Sea Polarization

- $\int_0^1 \Delta s(x) + \Delta \bar{s}(x) = \Delta S$ is negative from inclusive asymmetries
  $\Delta S = -0.09 \pm 0.01 \pm 0.02$
- ΔS obtained in semi-inclusive analysis strongly depends upon the choice of fragmentation functions used
- ratio $\frac{D(s \to K^-)}{D(\bar{u} \to K^-)} = \frac{D(\bar{s} \to K^+)}{D(u \to K^+)}$, known as R_{SF} is especially important
- try to extract R_{SF} from COMPASS data alone



Hadron multiplicities

- One way of extracting the fragmentation functions is to study hadron multiplicities *i.e.* number of hadrons produced per DIS event.
- various combinations of FF enter the K^+, K^- and K^0 multiplicities,
- so far charged K,π multiplicities are released
- good agreement between DSS parametrization and data is observed for π, discrepancies are seen for K.



Summary

- updated results for $\Delta G/G$ obtained in various analyses were presented
  - updated LO open charm analysis: $\Delta G/G = -0.08 \pm 0.21 \pm 0.08$
  - new NLO open charm analysis: $\Delta G/G = -0.20 \pm 0.21 \pm 0.08$
  - updated high-p_T hadron pairs, $Q^2 > 1$ (GeV/c)^2 analysis: $\Delta G/G = 0.125 \pm 0.060 \pm 0.065$
  - all world results agree with each other
  - ΔG is small, but the sign of it is still not determined
- The Bjorken sum rule is confirmed within the measured precision
- COMPASS is on the way to extract FF ratios, which are needed to understand better ΔS puzzle
  - if R_{SF} is small inclusive and Semi-Inclusive results agree with each other.