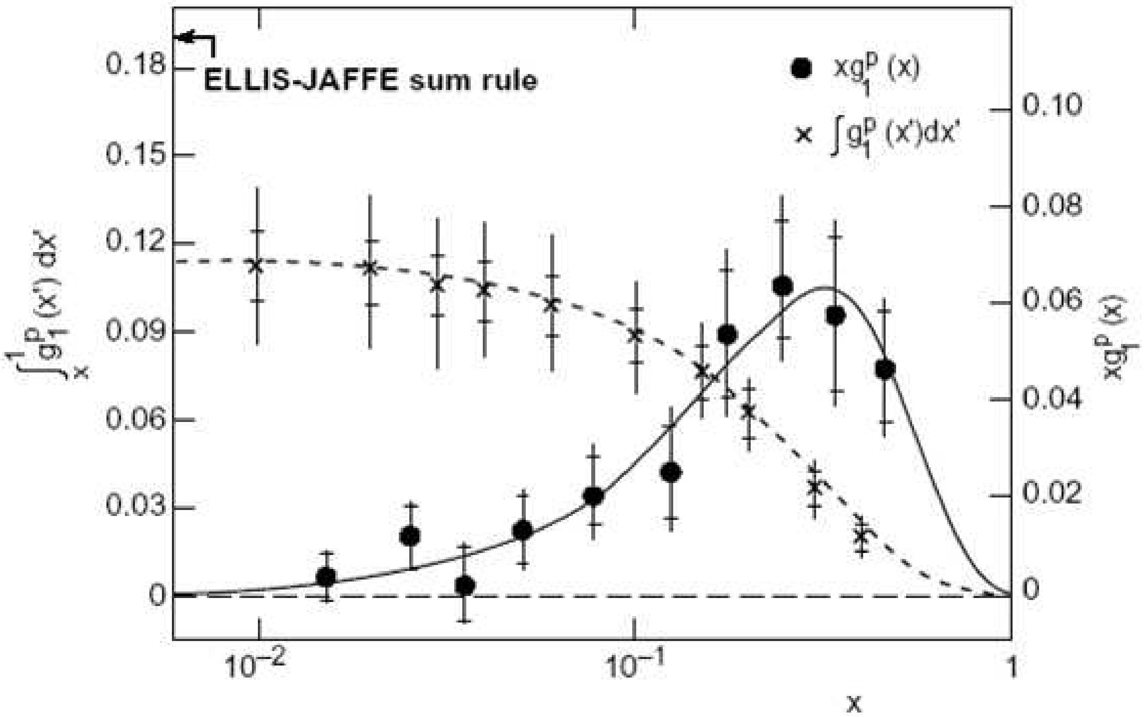
COMPASS, $\Delta G/G$, transverse polarization

COMPASS

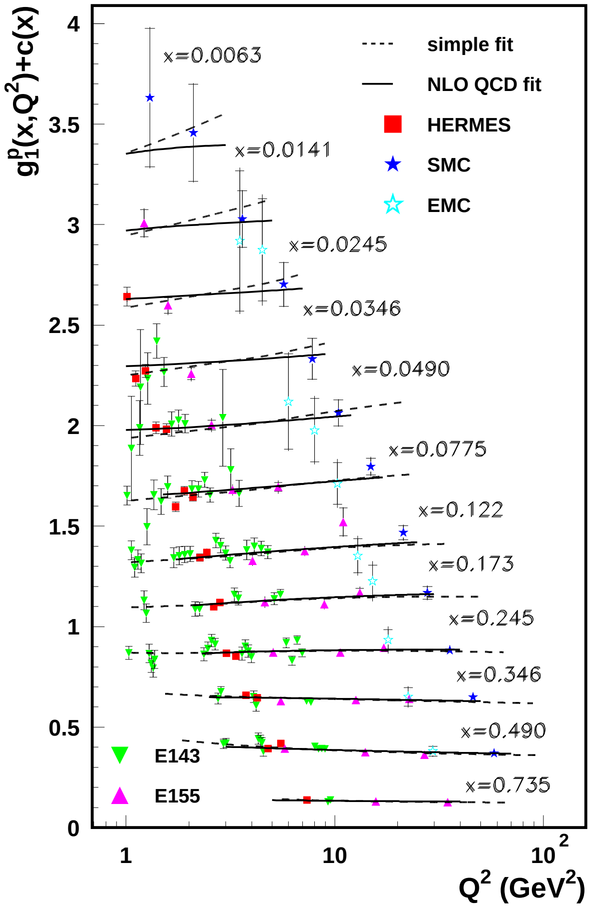
Yann Bedfer
Saclay - IRFU/SPhN
On behalf of the COMPASS collaboration

EMC 1987/88 : 20th Anniversary

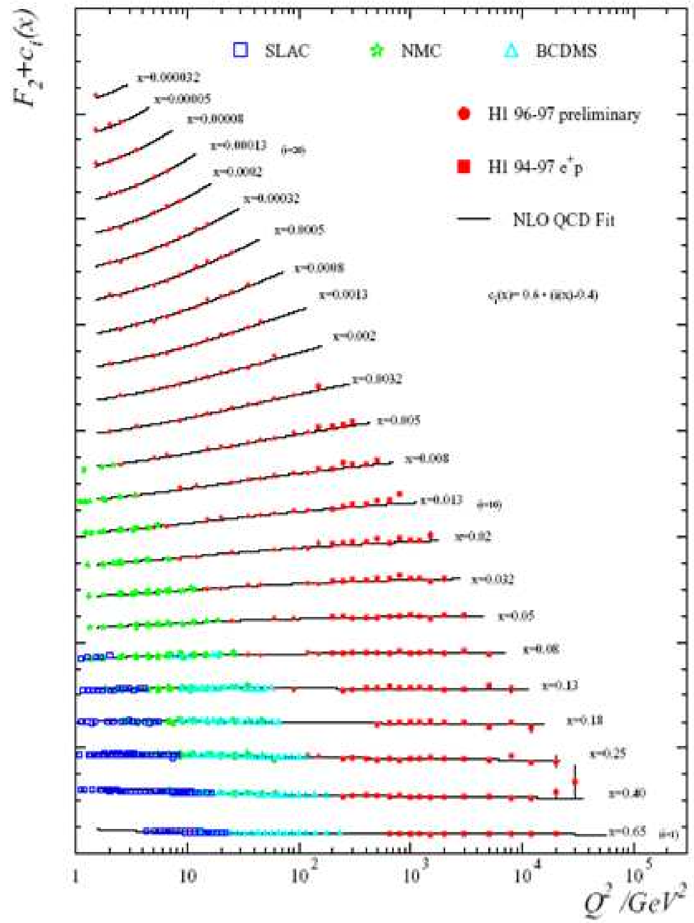


EMC, Phys. Lett. **B** *206 (1988)*

1988-2000 : Confirmation of EMC result



Bass, Rev. Mod. Phys. **77** *(2005)*



- Contribution of quark spin to nucleon spin, $\Delta\Sigma \simeq 30\%$ @ EMC Q^2
- World data cover limited (x, Q^2) domain (as compared to unpolarized case)

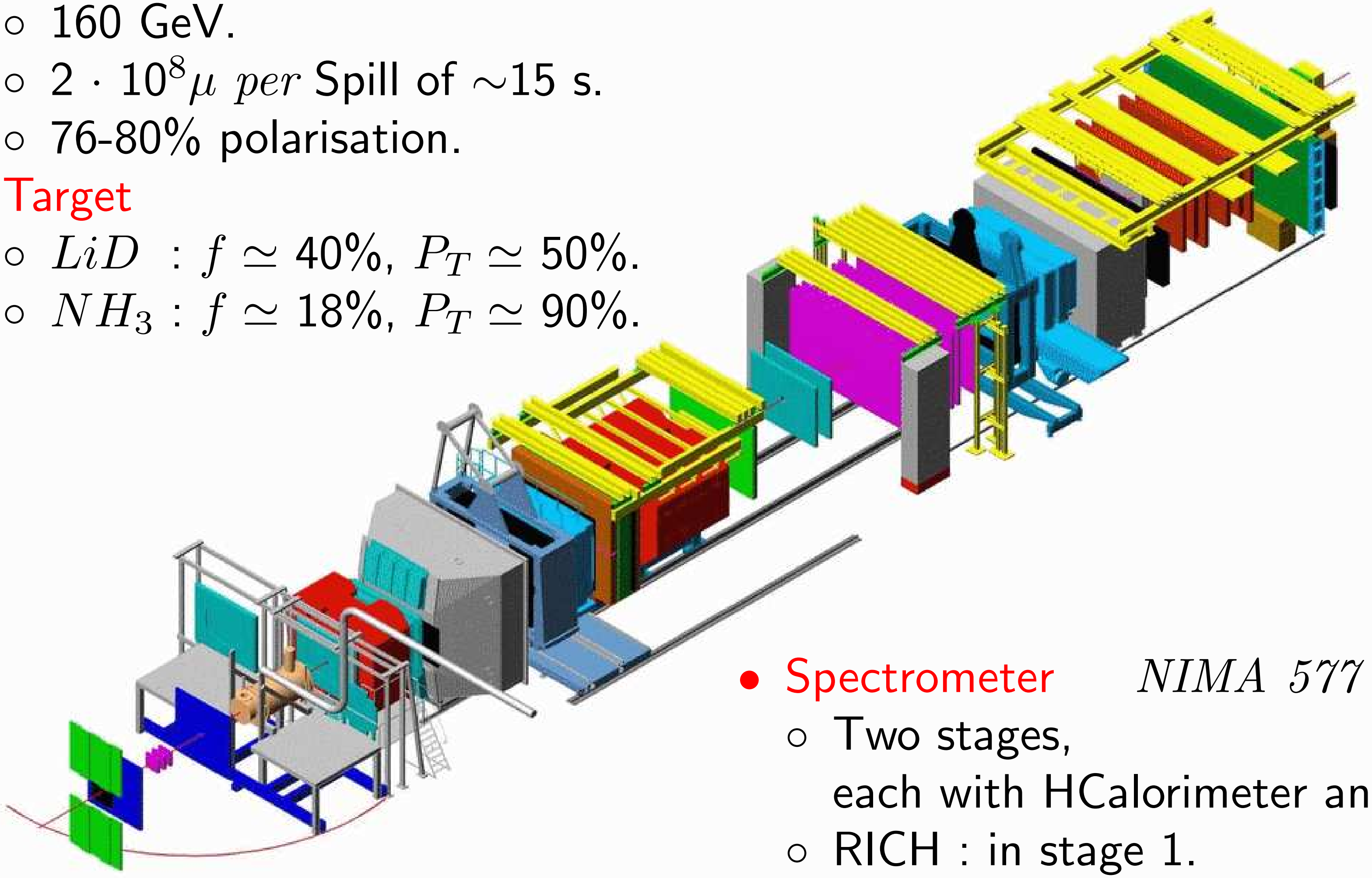
COMPASS scientific program

- **Muon program**
  - $\Delta G : 1/2 = 1/2\Delta\Sigma + \Delta G + L_z$
    Large ΔG, ~2-3 at SMC Q^2 would mask quark spin via axial anomaly
    Efremov, Teryaev, JINR Report E2-88-287 (1988)
    Altarelli, Ross, Phys.Lett. B212 (1988)
  - Spin dependent structure function and polarized PDFs,
    cf. D. Peshekhonov's and E. Zemlyanichkina's talks
  - Transversity and TMD DFs
  - Λ polarization *cf. M. Sapozhnikov's talk*
  - Exclusive vector mesons

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

COMPASS Spectrometer

- 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 : $f \simeq$ 18%, $P_T \simeq$ 90%.



- Spectrometer *NIMA 577 (2007) 455*
  - Two stages,
    each with HCalorimeter and μ-filter.
  - RICH : in stage 1.
  - ECalorimeter : 2(*since mid-2004*), 1 (*in 2006*).

Asymmetry Measurement

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

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

$$P_T \times P_\mu \times f \times D \simeq 50\% \times 80\% \times 40\% \times 60\% \simeq 10\%$$

- 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.

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

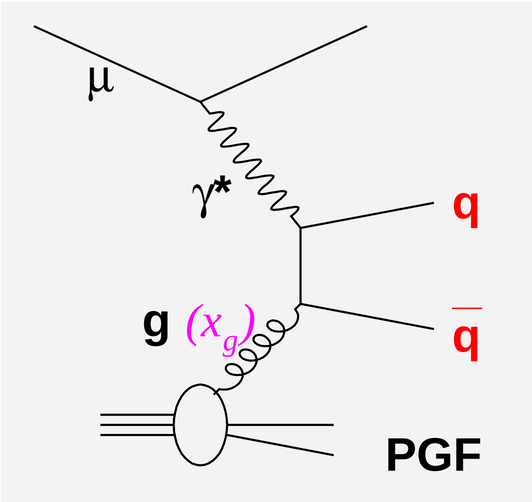
- 2006 upgrade :
  - Larger acceptance : 70 mrd → 180 mrd.
  - Better RICH PID
  - Electromagnetic calorimetry.

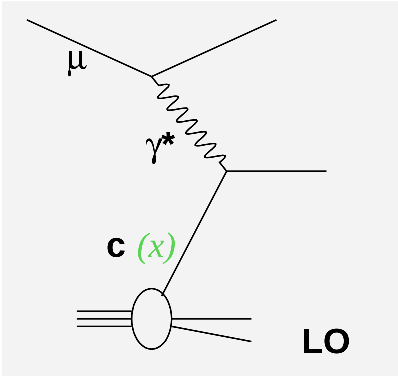
- 2007 : NH_3 target, 1/2 longitudinal, 1/2 transverse.

- Only partially analyzed : [2002,2004] *or* [2002,2006] depending upon channel

- 2008 : Data taking resumed, w/ a pion beam

$\Delta G/G$: 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.

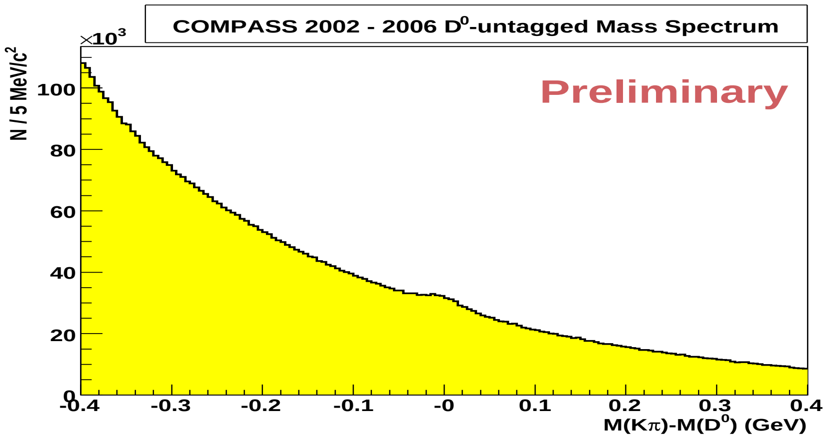
$\Rightarrow$ Theoretical uncertainties.
- Higher statistics
- pQCD scale can be set by p_T

$\Rightarrow$ Explore all Q^2

$\Delta G/G$ 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

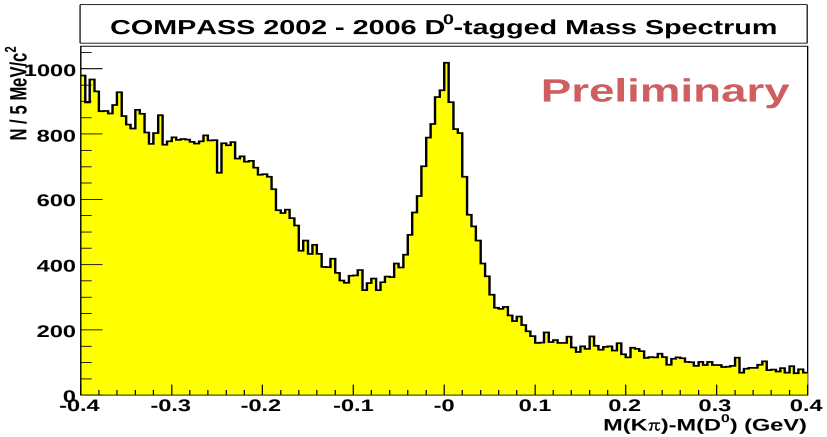
$\Longrightarrow$



$\sim 37k\ D^o$'s

- Favorable case : D^o from $D^* \to D^o\pi \to K\pi\pi$
  - 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

$\Longrightarrow$

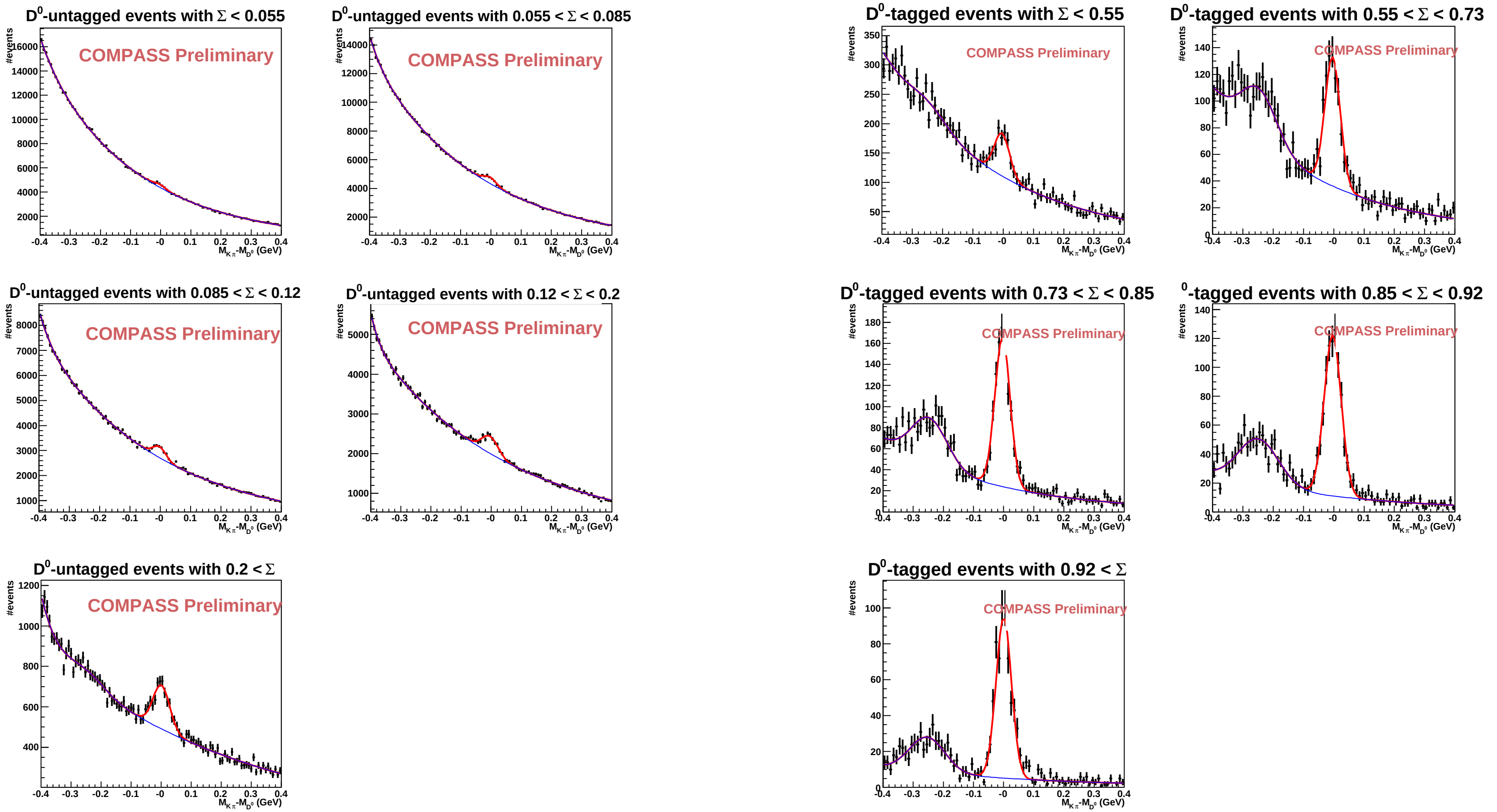


$\sim 8.7k\ D^*$'s

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

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

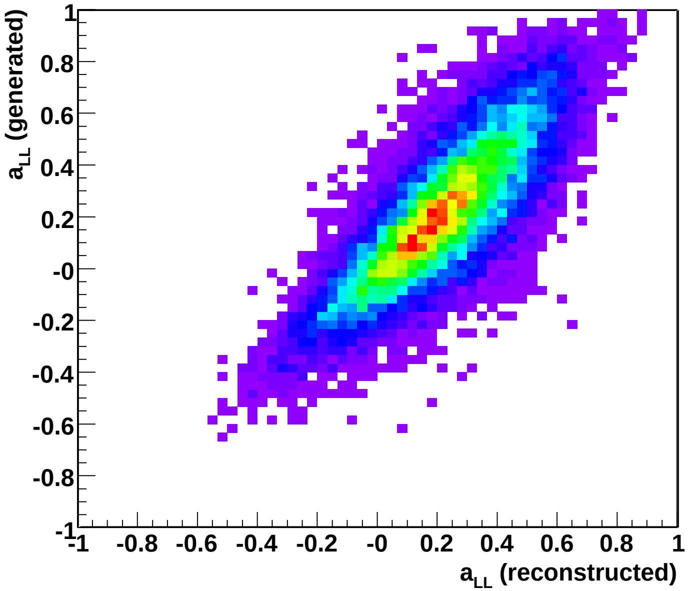
$\Rightarrow$ Mass distributions in bins of $\boldsymbol{S/S+B}$



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} parameterized and included in event weight



- a_{LL} parameterization
  - 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

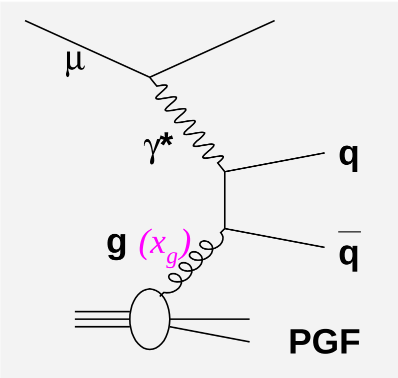
$$\frac{\Delta G}{G} = -0.49 \pm 0.27(stat.) \pm 0.11(syst.)$$

$$x_G = 0.11^{+0.11}_{-0.05}\,; \qquad \mu^2 \approx 13\ (\mathrm{GeV/c})^2$$

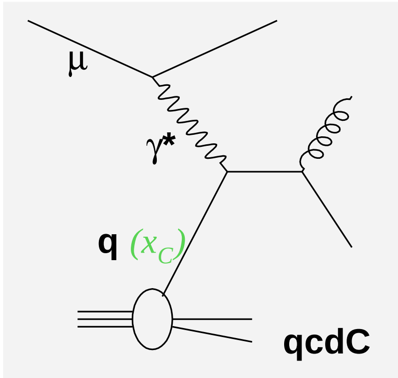
  - Systematics include false asymmetries, a_{LL} (charm mass) & signal extraction ($S/S{+}B$)

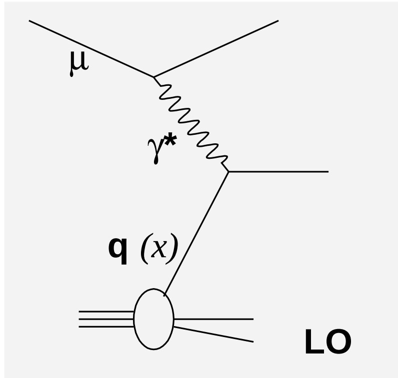
- Raw asymmetries
  - *Yet to be released*
  - In bins of $(\boldsymbol{p_T}, \boldsymbol{E_D})$, w/in which LO a_{LL} is constant
  - Weighted by $\boldsymbol{S/S+B}$ and $\boldsymbol{D(y)}$

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



+ background processes





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

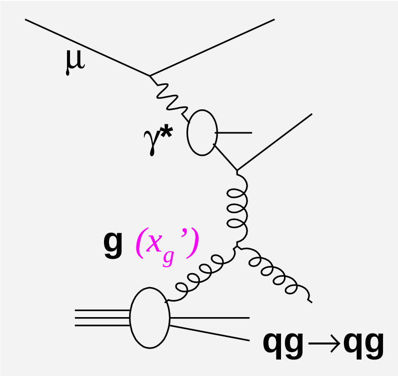
- S : high-p_T sample *or* inclusive sample
- $\mathcal{R}_P^S$: Fraction of process P = PGF, qcdC, LO in sample S

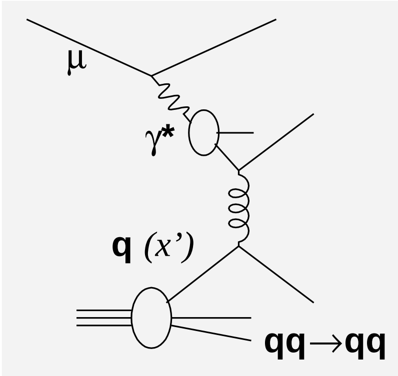
⇒ Input A_1^{LO} for background asymmetry retrieved from COMPASS data

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

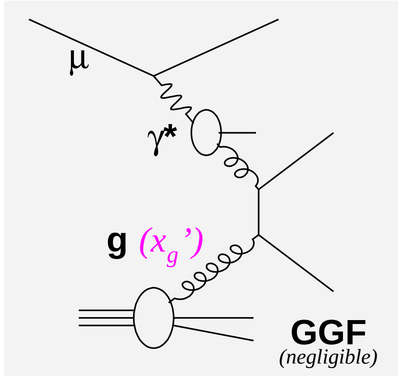
$\Delta G/G$: Extraction from high-p_T $Q^2 < 1\text{GeV}^2$

- Large contribution of resolved photons. . .





etc. . . .



etc. . . .

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

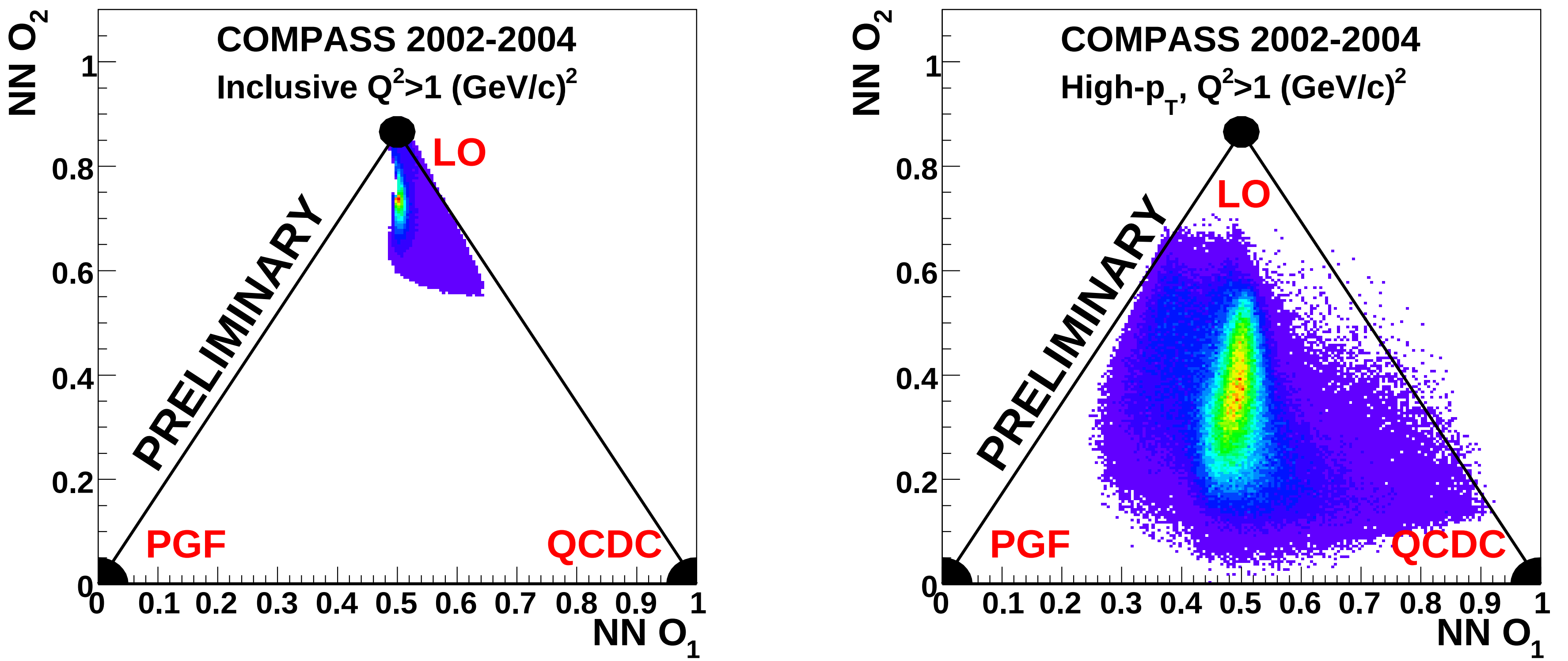
- Inputs $\Delta q/q, \Delta f^\gamma/f^\gamma$ for background asymmetry taken from PDFs (GRSV2000, GRV98)
  - For Δf^γ, max/minimal scenarios are used (*Glück, Reya and Sieg, Eur. Phys. J. C20 (2001)*)
- Fractions $\mathcal{R}$ and parameterizations of $\hat{a}_{LL}$: PYTHIA

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

- **$Q^2 < 1$ 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.

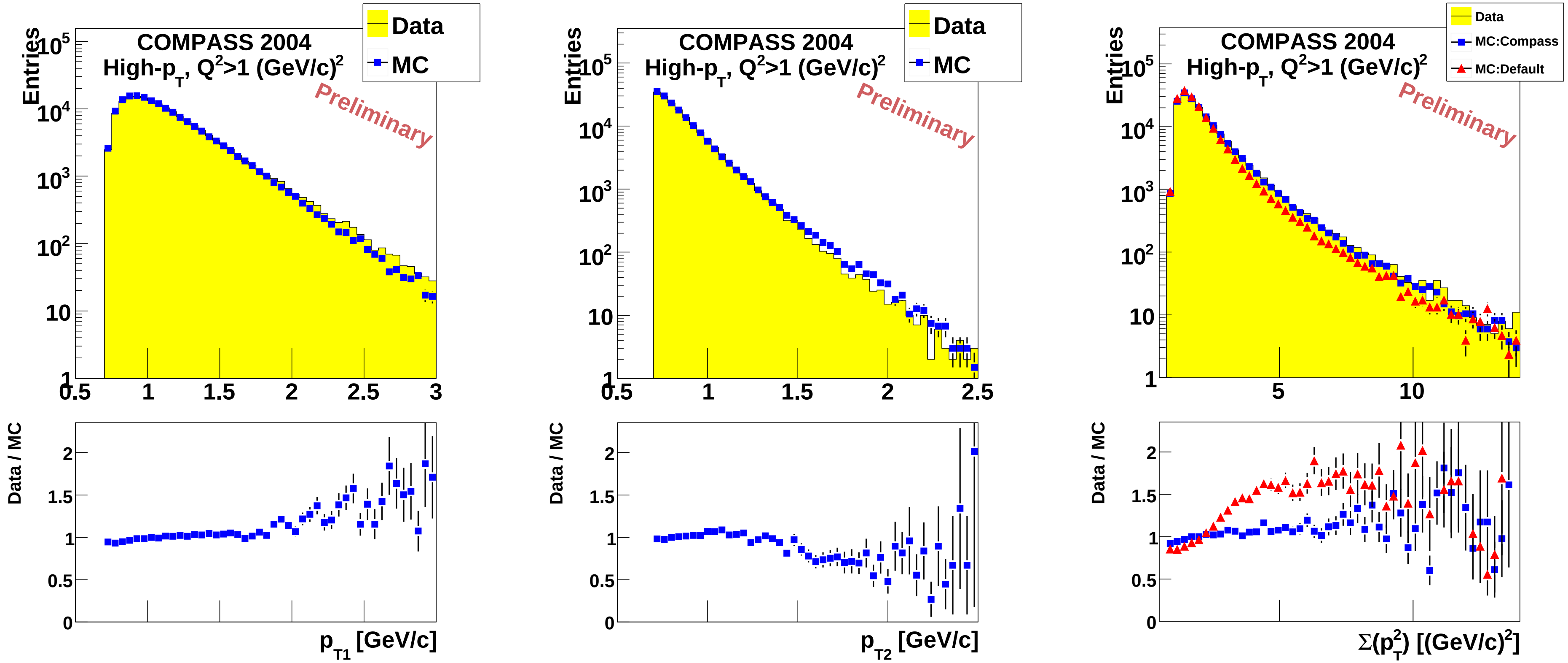
- **$Q^2 > 1$ GeV^2**
  - LEPTO used :
    pQCD alone $\Rightarrow$ better controlled.
  - $p_T > 0.7$ GeV
  - Hard scale defined by Q^2
  - Lower statistics.
  - Resolved photons assumed negligible.
  - No input from polarized PDFs
  - Fractions $\mathcal{R}$ parameterized by Neural Network and included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

$\Delta G/G$ high-p_T $Q^2 > 1$GeV^2 : Parameterization 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 $Q^2 > 1\text{GeV}^2$: 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

∘ $Q^2 > 1$ [2002,2004]

$$\frac{\Delta G}{G} = 0.08 \pm 0.10(stat). \pm 0.05(syst.)$$
$$x_G = 0.082^{+0.041}_{-0.027} \text{ @ } \mu^2 \simeq 3 \text{ (GeV/c)}^2$$

- 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]

$$\frac{\Delta G}{G} = 0.016 \pm 0.058(stat.) \pm 0.054(syst.)$$
$$x_G = 0.085^{+0.071}_{-0.035} \text{ @ } \mu^2 \simeq 3 \text{ (GeV/c)}^2$$

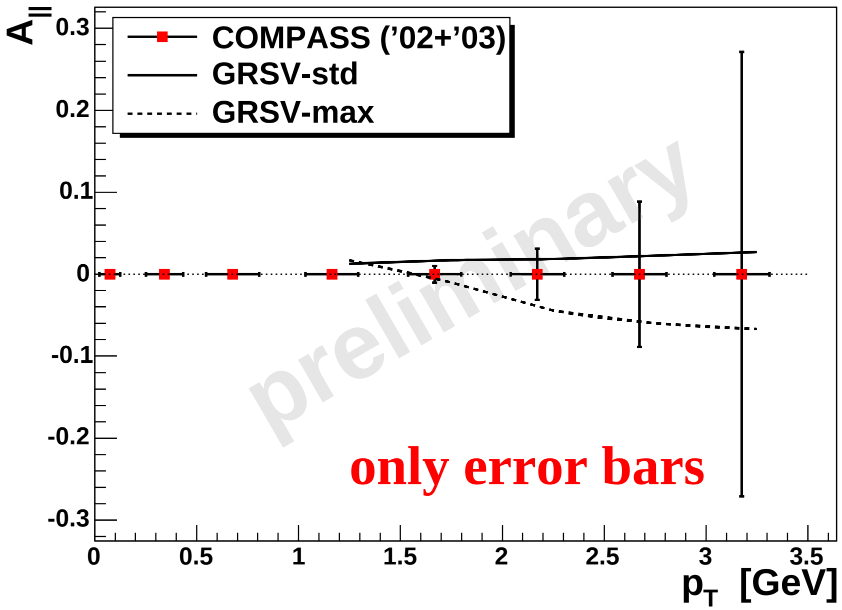
- Systematics include max./min. scenarios for polarized photon structure
- [2002-2003] published in *Phys. Lett. B* **633** *(2006)*

NLO calculation : high p_T photoproduction

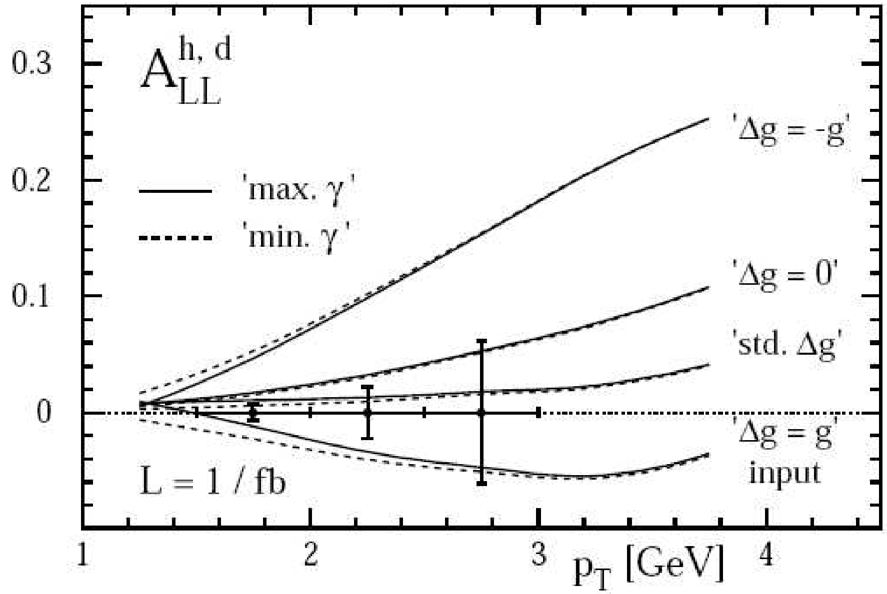
- Calculations by group of *BNL/Regensburg*.
  - Single high p_T hadron
    Jäger, Stratmann, Vogelsang, Eur.Phys.J. C44 (2005) 533-543.
  - Pair of high p_T hadrons
    Hendlmeier, Schäfer, Stratmann, arXiv :0803.1940v1 [hep-ph]
- Photoproduction : $Q^2 < 0.5$ GeV^2
- ΔG independent of MC model.
- Dependent upon functional shape $\Delta g(x)$
- Need to validate calculation on unpolarized cross section

High p_T photoproduction : Projections

- Measurement not released yet.
- Projections (*compared to GRSV scenarios*) :

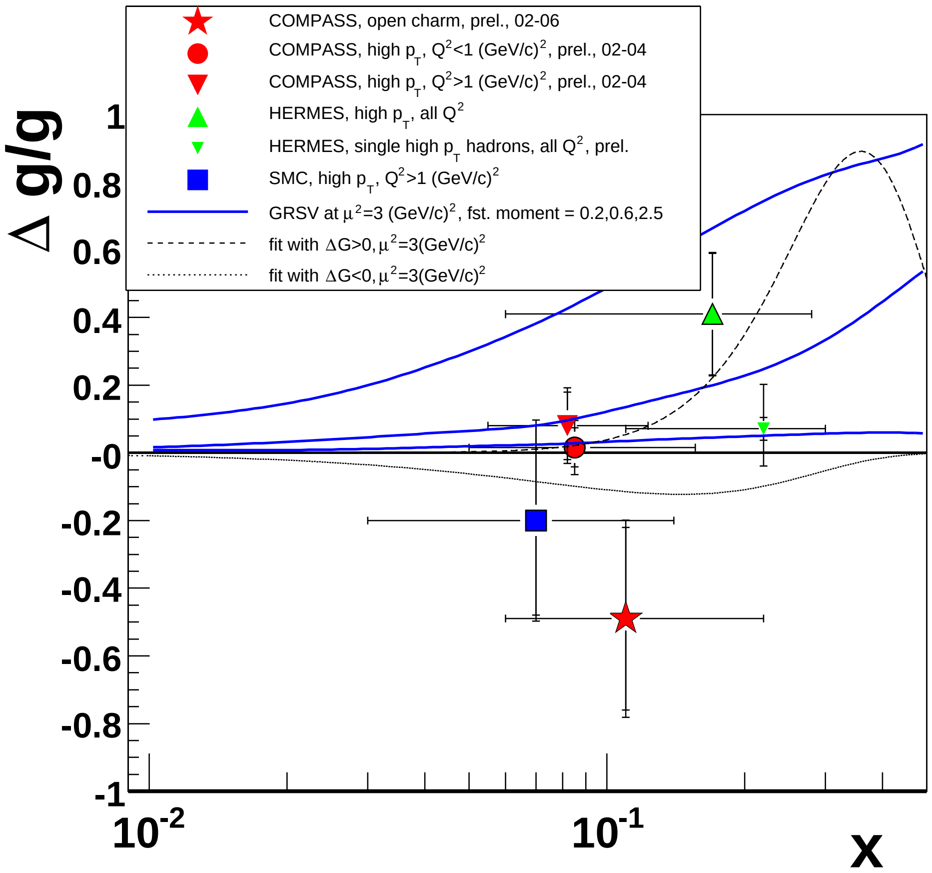


Single hadron : Data analysis of ~1/3 of recorded data.



Single hadron : Jäger et al., Eur.Phys.J. C44 (2005) 533-543

$\Delta G/G$: Summary of results



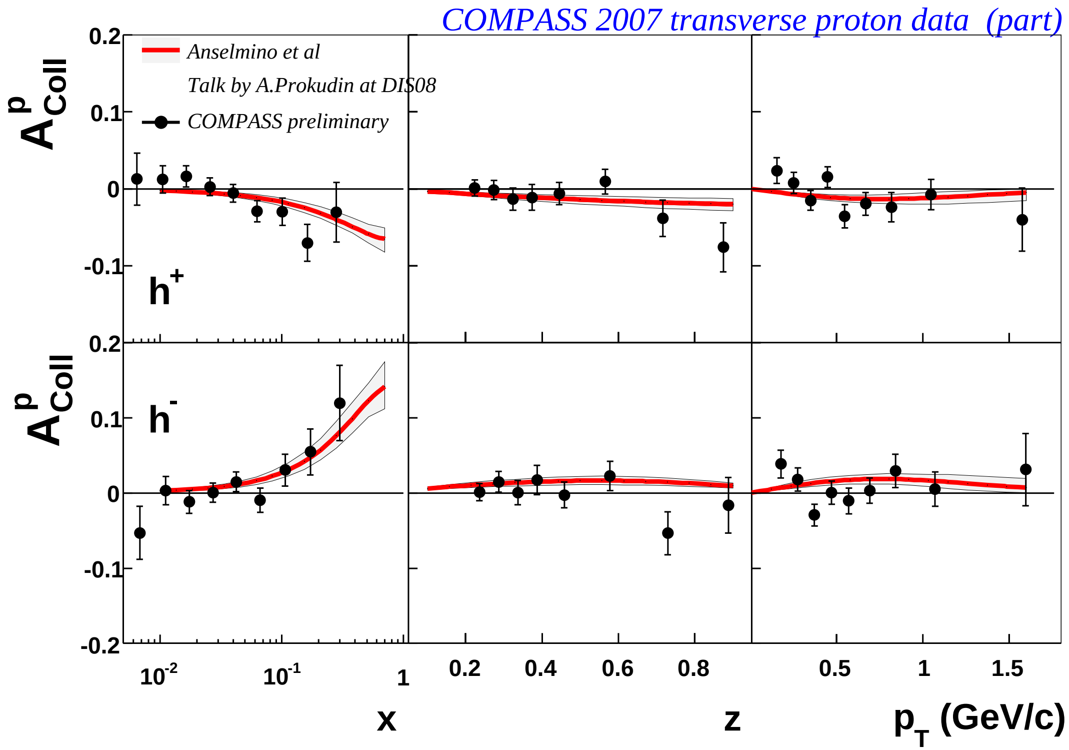
Caveat : LO data, NLO fits

- Direct measurements show small value of $\Delta G/G$ at $x_g \simeq 0.1$
- In agreement w/ global fits of DIS data and $\vec{p}\,\vec{p}$ @ $RHIC$
- Axial anomaly scenario ruled out
- Shape and sign of $\Delta G(x)$ not well constrained

Transversity

- 3rd fundamental PDF. Completes leading twist, integrating over k_T
- Chiral-odd Collins FF (measured @ *BELLE*) $\Rightarrow$ Single spin azimuthal asymmetry in SIDIS

- Preliminary results from **COMPASS 2007 proton** data (partial : $\sim 1/4$ of 2007 total) :



$\Rightarrow$ Agreement w/ predictions of *Anselmino, Prokudin et al., DIS08*
(based on global fit of HERMES, COMPASS deuteron and BELLE data)

Semi-Inclusive X-section : 18 structure functions

$$\frac{d\sigma}{dx_{\rm Bj}\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_{\rm Bj}yQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_{\rm Bj}}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+S_L\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+|\boldsymbol{S}_T|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+|\boldsymbol{S}_T|\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}+\sqrt{2\,\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}$$

Kotzinian, Nucl. Phys. **B441** *(1995)* *Bacchetta et al.,JHEP* **0702** *(2007)*

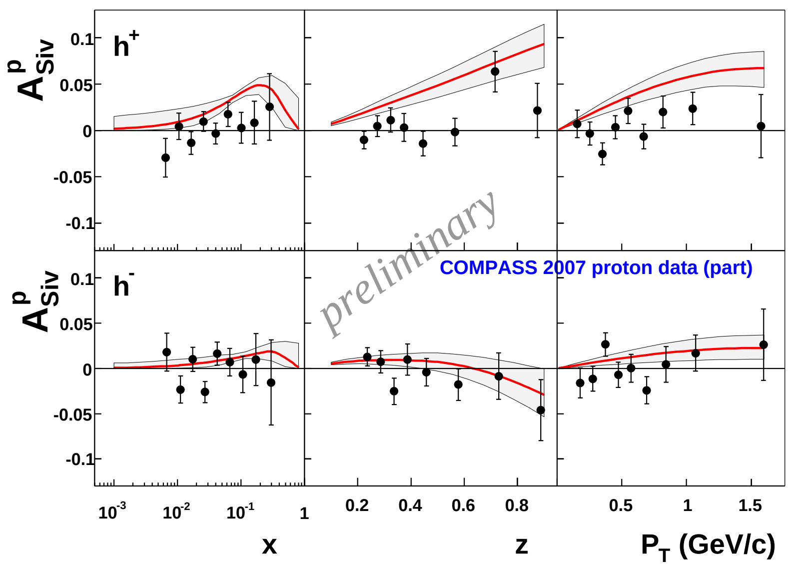
⇒ Collins, Sivers and 6 extra target Transverse spin dependent modulations.
All measured on deuteron target @ COMPASS

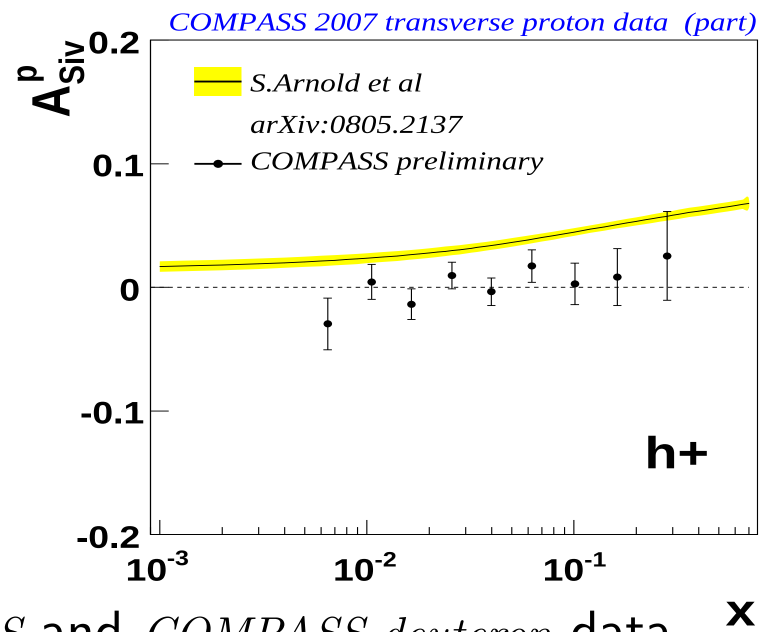
Sivers Effect

- Correlation between nucleon spin and quark k_T. Described by Sivers TMD DF
- Would explain large transverse single spin asymmetries measured @ *E704* and *STAR*

  Anselmino et al., Phys. Rev. D **73** *(2006)*
- Finite effect measured @ *HERMES*

- Preliminary results from **COMPASS 2007 proton** data (partial : $\sim 1/4$ of 2007 total) :





$\Rightarrow$ Disagreement w/ global fit of *HERMES* and *COMPASS deuteron* data

Anselmino et al., arXiv :0805.2677 [hep-ph] *Arnold et al., arXiv :0805.2137 [hep-ph]*

Outlook

- $\Delta G/G$
  - 2007 longitudinal data : Polarized proton target : Not optimum since fP_T reduced
  - Open charm : Include $D^o \rightarrow K\pi\pi^o$
  - High-p_T $Q^2 > 1$: Double statistics w/ 2006/2007 data and lower p_T cut
    $\Rightarrow$ 2 bins in x_g
  - High-p_T photoproduction : σ and $\Delta\sigma$ as a f(p_T)

- Transverse proton data
  - Full 2007 statistics $\Rightarrow$ $\times$2 in precision
  - π/K identification, π^o/K^o
  - Λ and hadron pairs polarimeters
  - Other unpolarized and target transverse spin dependent azimuthal modulations

- 2008 : Search for exotics in diffractive and central production w/ pion beam

- Long term : Working on proposal for GPD @ *COMPASS*