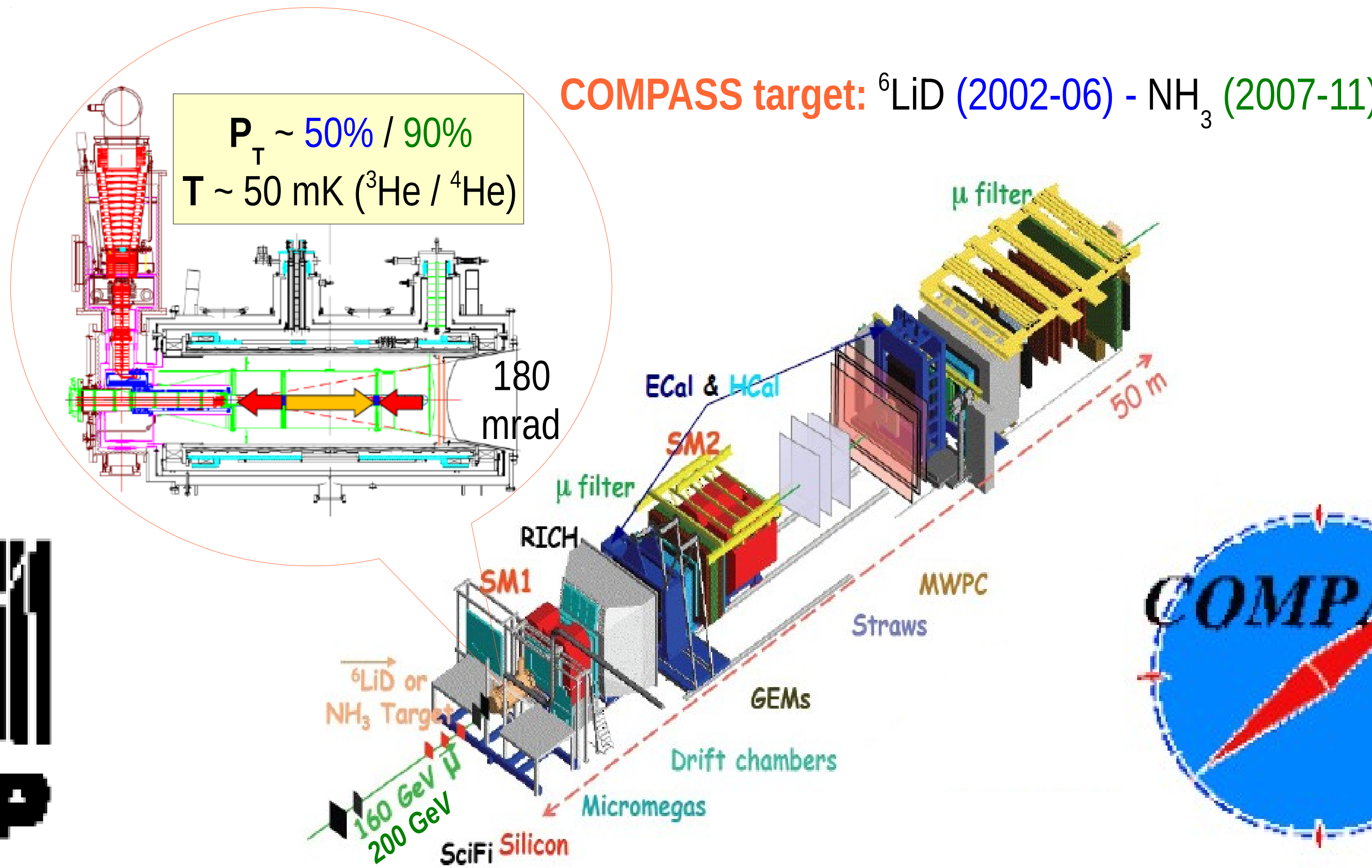
Overview of the COMPASS results on the nucleon spin

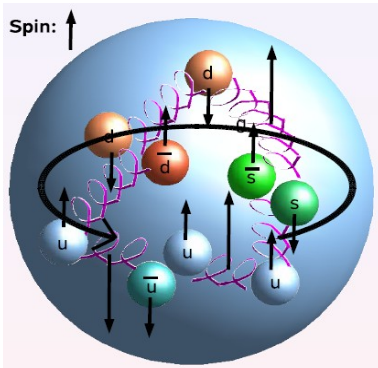


Celso Franco (LIP – Lisboa)

on behalf of the COMPASS collaboration

Motivation

• **Motivation I:** Nucleon spin structure



Where does the proton spin (complex structure in QCD) come from?

$$\left(\frac{2S_z^N}{\hbar}\right) = \frac{1}{2}\Delta\Sigma + L^q_{z,JM} + \Delta G + L^g_{z,JM} \longrightarrow \text{Jaffe-Manohar sum rule}$$

$$= \frac{1}{2}\Delta\Sigma + L^q_{z,Ji} + J^g_{Ji} = \frac{1}{2}\left(\lim_{t\to 0}\int_{-1}^{+1} dx\, x\,\underbrace{[H(x,\xi,t)+E(x,\xi,t)]}_{\text{GPDs}}\right) + J^g_{Ji}$$

Ji sum rule

Mostly studied in polarised Deep Inelastic Scattering (DIS)

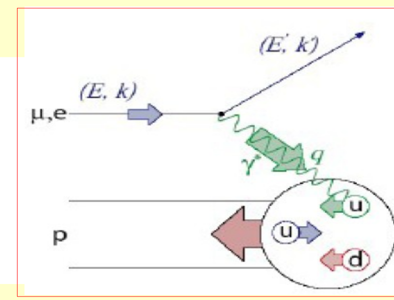
- $\Delta\Sigma = \int_0^1 \Delta u(x) + \Delta\bar{u}(x) + \Delta d(x) + \Delta\bar{d}(x) + \Delta s(x) + \Delta\bar{s}(x)\,dx$
- $\Delta G = \int_0^1 \Delta g(x)\,dx$
- L^q related to TMDs
- $\Delta\Sigma + L^q$ related to GPDs

$Q^2 = -q^2$

$\nu = E - E'$

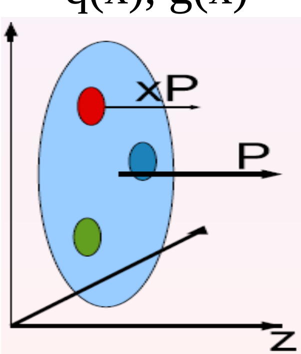
$x = Q^2 / 2M\nu$

$y = \nu / E$

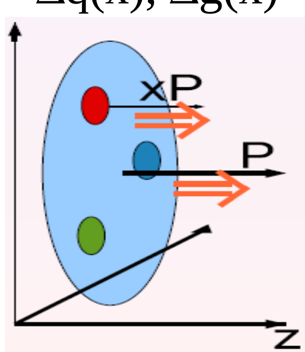


• **Motivation II:** Parton Distribution Functions (PDFs), TMDs and GPDs

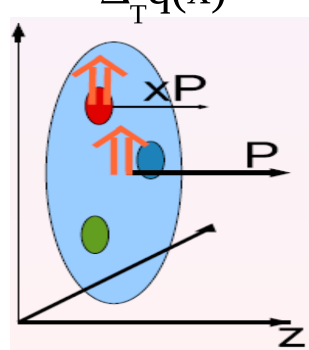
Unpolarised
q(x), g(x)



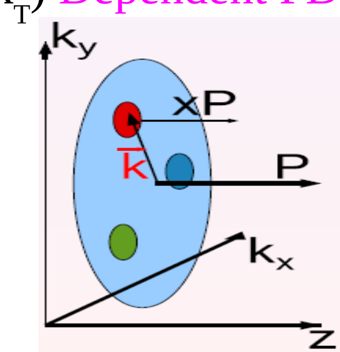
Helicity
Δq(x), Δg(x)



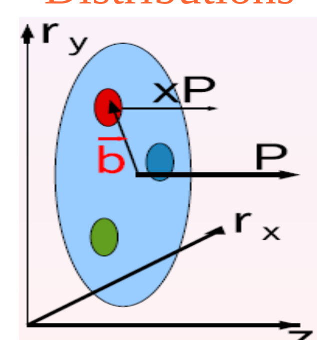
Transversity
$\Delta_T q(x)$



Transverse Momentum (k_T) Dependent PDFs



Generalized Parton Distributions



Description of the nucleon structure at leading twist

(when the intrinsic transverse momentum of quarks, k_T, is also taken into account)

8 TMD PDFs are required:

Nucleon \ Quark	Unpolarised	Longitudinal Polarisation	Transverse Polarisation
Unpolarised	f_1 *(Number density)*		$h_1^{\perp}$ *(Boer Mulders)*
Longitudinal Polarisation		g_1 *(Helicity)*	$h_{1L}^{\perp}$ *(Worm Gear)*
Transverse Polarisation	$f_{1T}^{\perp}$ *(Sivers)*	g_{1T} *(Worm Gear)*	h_1 $h_{1T}^{\perp}$ *(Pretzelosity)*

Study $q(x, Q^2)$ and $g(x, Q^2)$

Study $\Delta q(x, Q^2)$ and $\Delta g(x, Q^2)$

(Transversity) Study $\Delta_T q(x, Q^2)$

Surviving k_T integration

$$\Phi^{Tw-2}_{Coll}(x) = \frac{1}{2}\left\{q(x) + S_L\gamma_5\Delta q(x) + S_L\gamma_5\gamma^1\Delta_T q(x)\right\}$$

Contains information about the Orbital Angular Momentum (OAM) of quarks

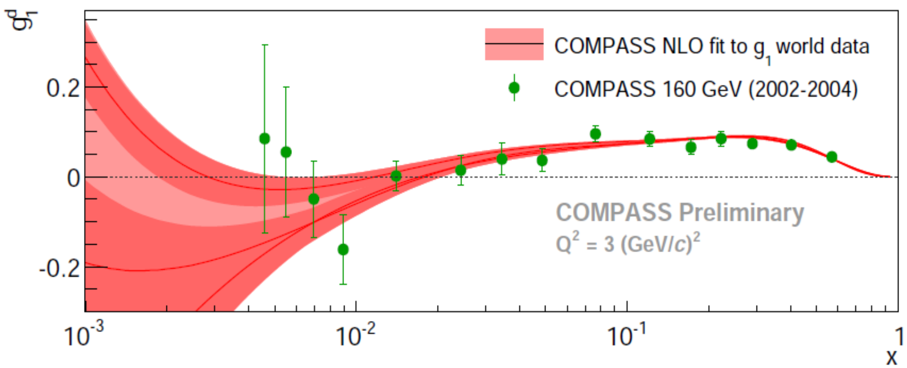
Investigated at COMPASS <u>via measurement of spin asymmetries</u>

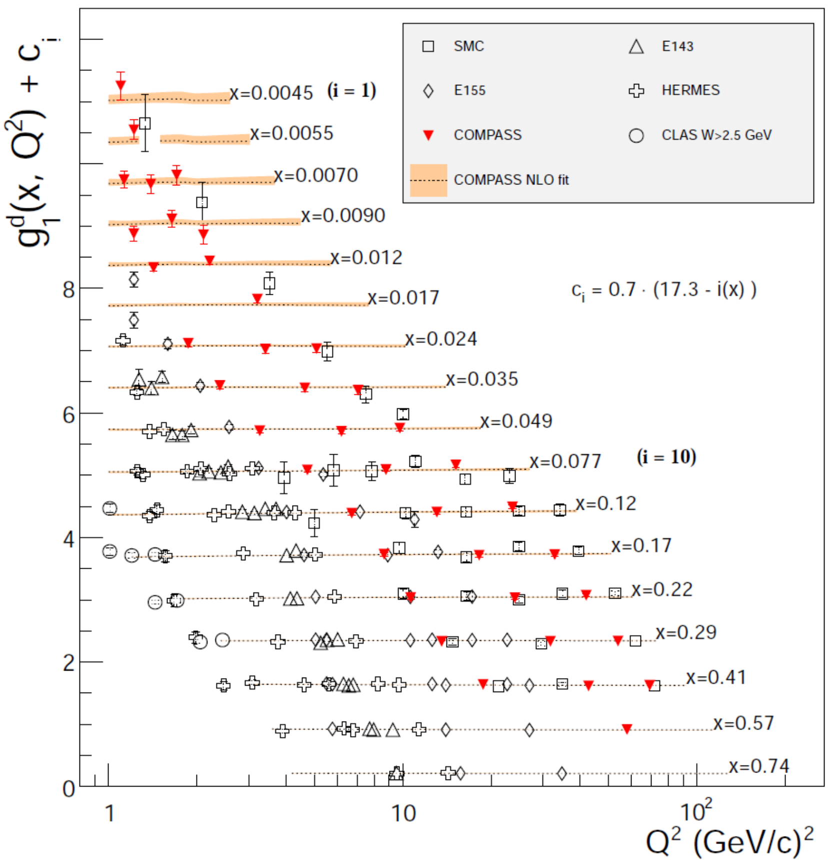
COMPASS results with a longitudinally polarised target

COMPASS results on g_1:

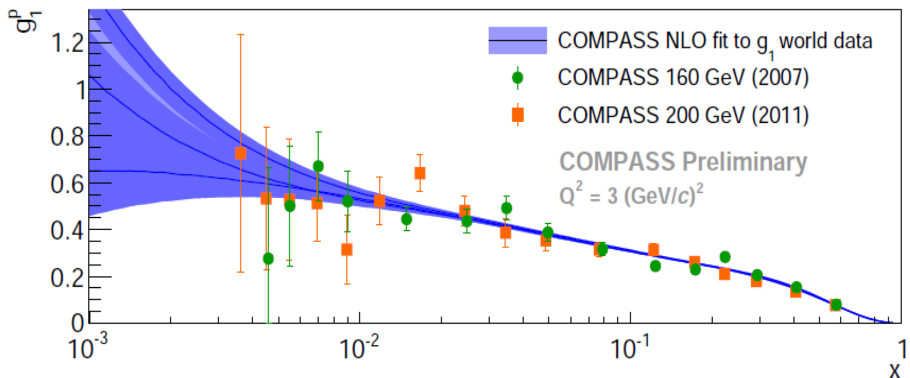
$$A_1(x,Q^2) = \frac{\sigma_{\gamma^* N}^{\leftarrow\rightarrow} - \sigma_{\gamma^* N}^{\rightarrow\rightarrow}}{\sigma_{\gamma^* N}} \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{f_1(x,Q^2)}$$

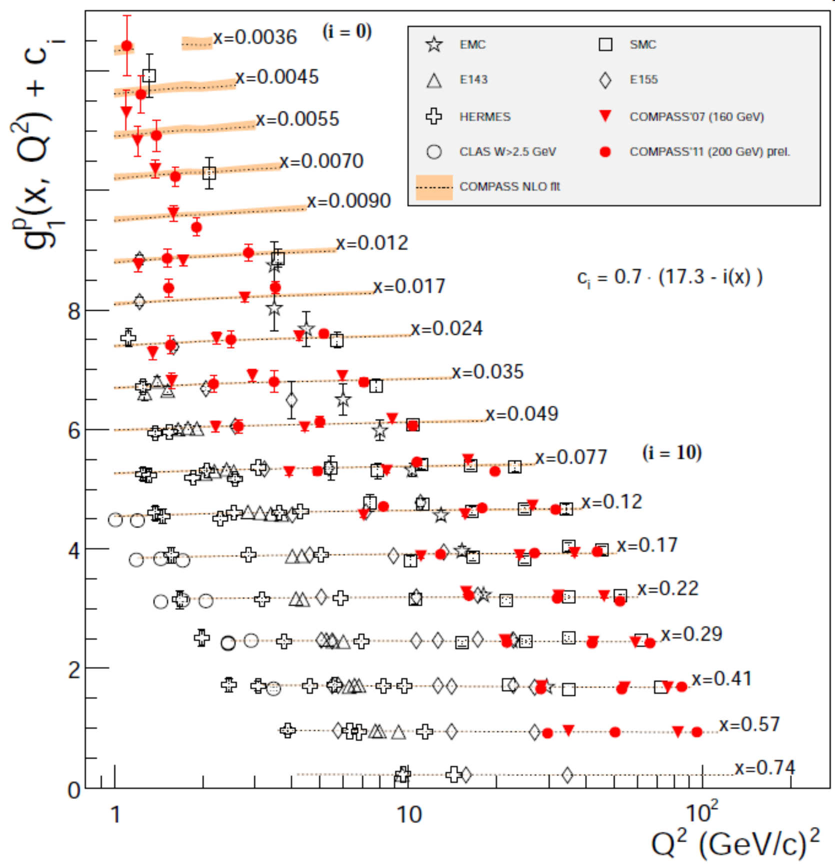
Deuteron





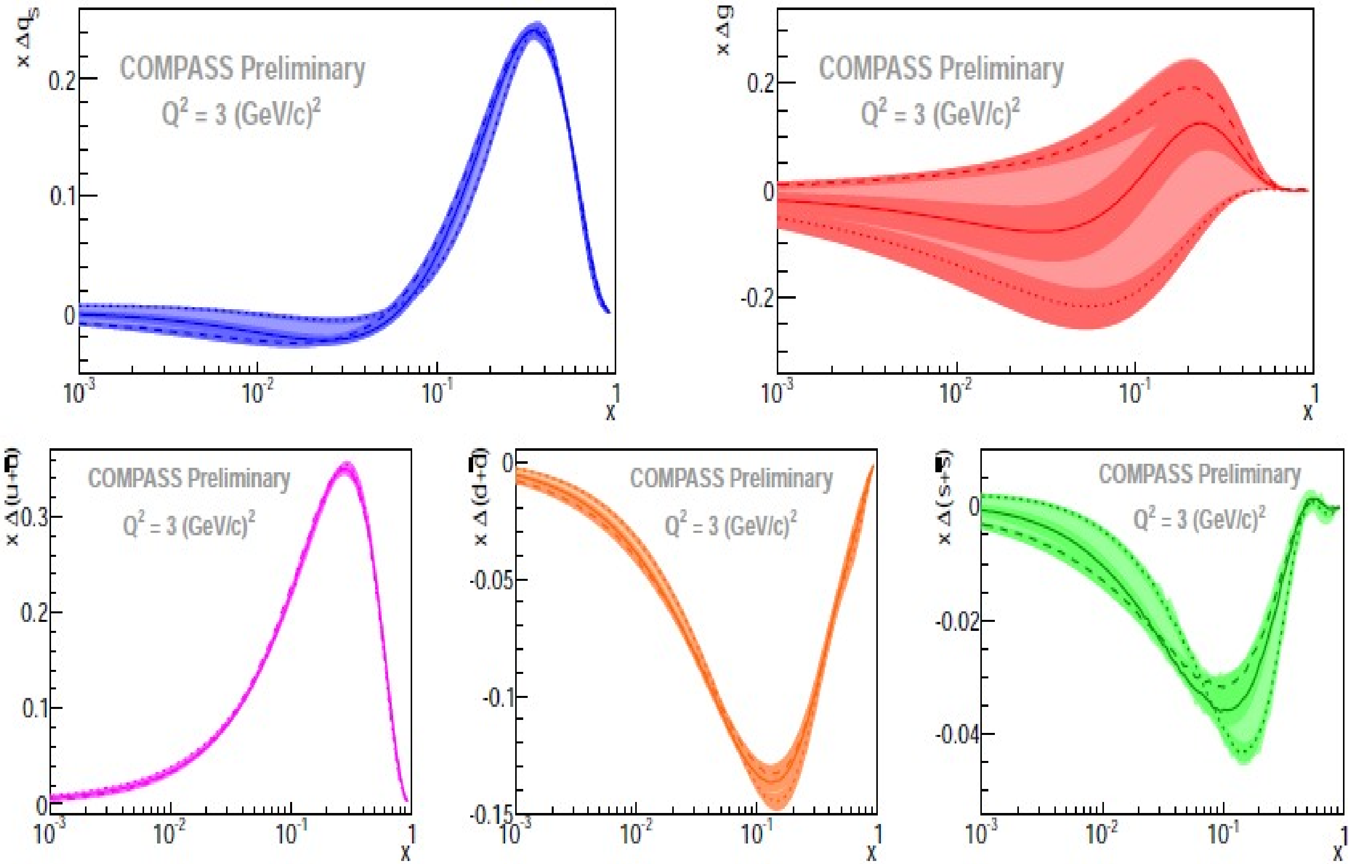
Proton





Polarised PDFs from the NLO-QCD fits to the g_1^d and g_1^p data

Three scenarios, ΔG < 0, ΔG ~ 0 and ΔG > 0, cover all possible results on the polarised PDFs *(the largest uncertainty arises from the choice of the functional forms)*:



QCD fits – Idea:

$$g_1 = \frac{1}{2}\langle e^2\rangle \left(C^{Si}(\alpha_s)\otimes\Delta q_{Si} + C^{NS}(\alpha_s)\otimes\Delta q_{NS} + C^{g}(\alpha_s)\otimes\Delta g\right)$$

$$\begin{cases} \frac{d}{d\ln Q^2}\Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi}\left(\Delta P_{qq}^{NS}\otimes\Delta q_{NS}\right) \\ \frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q_{Si}\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq}^{Si} & 2n_f\Delta P_{qg}\\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_{Si}\\ \Delta g\end{pmatrix}\end{cases}$$

Initial parametrisation in x at fixed Q^2:

$$\Delta q_{Si}(x|Q_0^2) = \eta_s x^{\alpha_s}(1-x)^{\beta_s}(1+\gamma_s x)/N_s$$
$$\Delta g(x|Q_0^2) = \eta_g x^{\alpha_g}(1-x)^{\beta_g}(1+\gamma_g x)/N_g$$
$$\Delta q_3(x|Q_0^2) = \eta_3 x^{\alpha_3}(1-x)^{\beta_3}/N_3$$
$$\Delta q_8(x|Q_0^2) = \eta_8 x^{\alpha_8}(1-x)^{\beta_8}/N_8$$

Minimisation procedure:

$$\chi^2 = \sum_{n=1}^{N_{exp}}\left[\sum_{i=1}^{N_n^{data}}\left(\frac{g_1^{fit}-\mathcal{N}_n g_{1,i}^{data}}{\mathcal{N}_n\sigma_i}\right)^2 + \left(\frac{1-\mathcal{N}_n}{\delta\mathcal{N}_n}\right)^2\right] + \chi^2_{positivity}$$

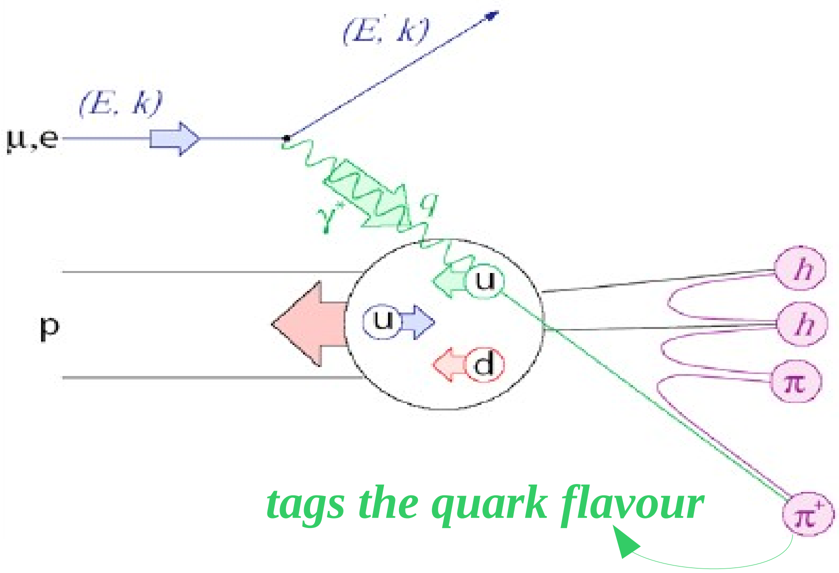
$$|\Delta g(x)| < |g(x)| \text{ and } |\Delta(s(x)+\bar{s}(x))| < |s(x)+\bar{s}(x)|$$

- Small sensitivity to light sea and gluon helicities
- Quark helicity: $\Delta\Sigma = \int \Delta q_s(x)dx \;\epsilon\; [0.256, 0.335]$
- Gluon helicity: $\Delta G = \int \Delta g(x)dx$ → Not well constrained

PLB 647(2007) 8-17 *(only g_1^d)*:

$\Delta\Sigma = +0.30 \pm 0.01 \pm 0.02$
$\Delta s = -0.08 \pm 0.01 \pm 0.02$

Extraction of the quark helicity distributions from Semi-Inclusive DIS (SIDIS)



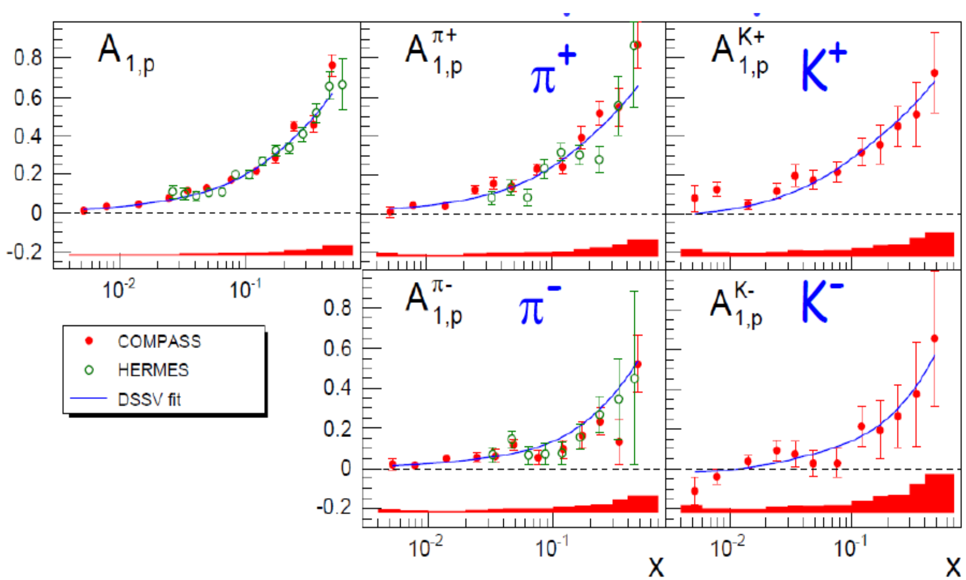
- **We have at Leading Order *(LO)* in QCD :**

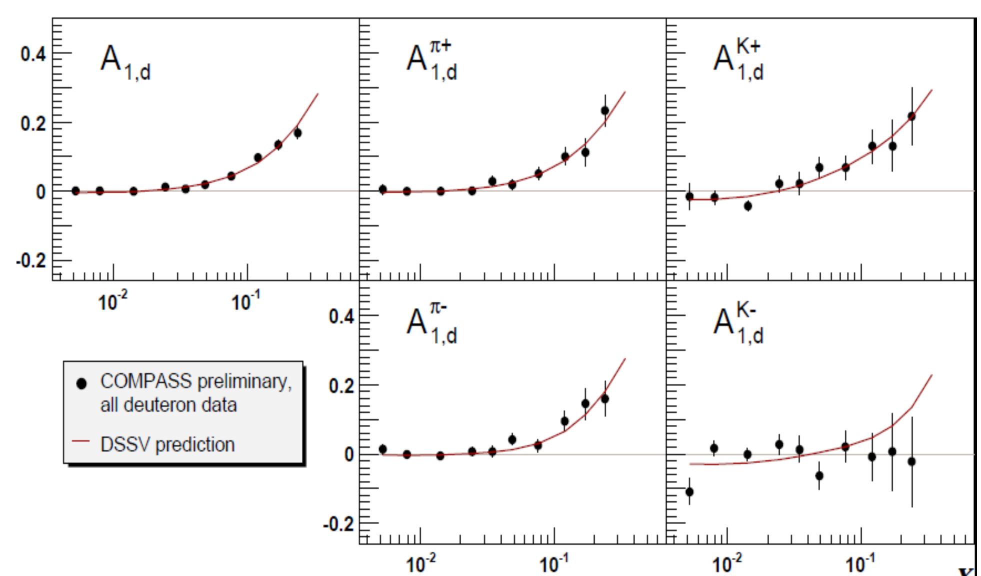
$$A^h_{1,(p/d)}(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}$$

– Unpolarised PDFs ($q(x, Q^2)$) → MRST04

– Fragmentation function of a quark to a hadron ($D_q^h(z, Q^2)$) → DSS parameterisation

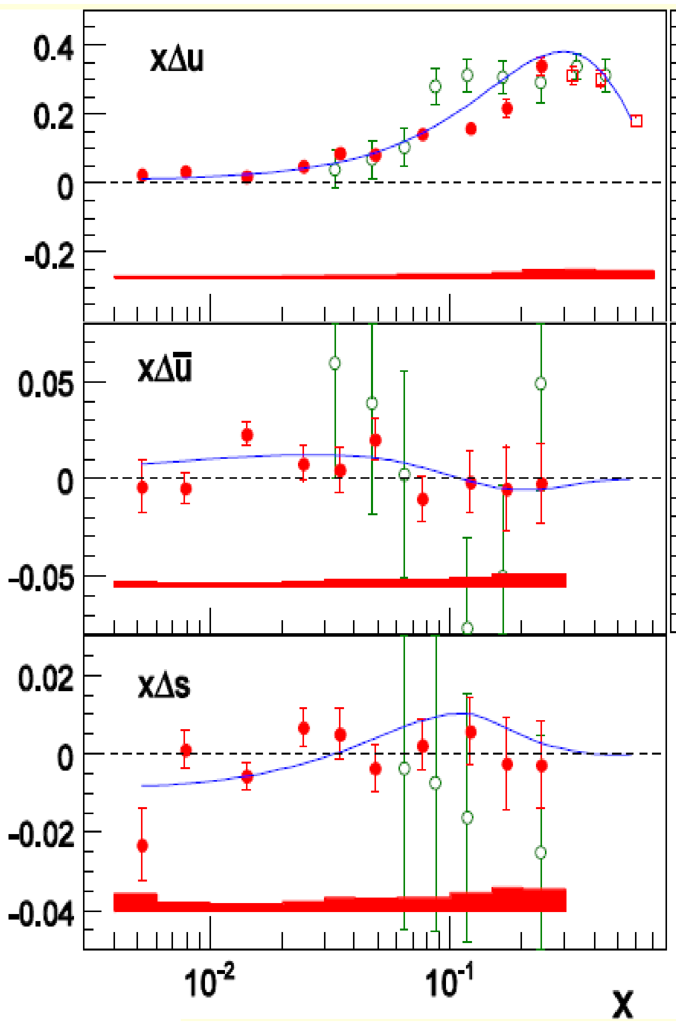
- **Results for $A^h_{1,(p/d)}$** (allows the separate extraction of **Δu, Δd, $\Delta \bar{u}$, $\Delta \bar{d}$, Δs** and **$\Delta \bar{s}$**):

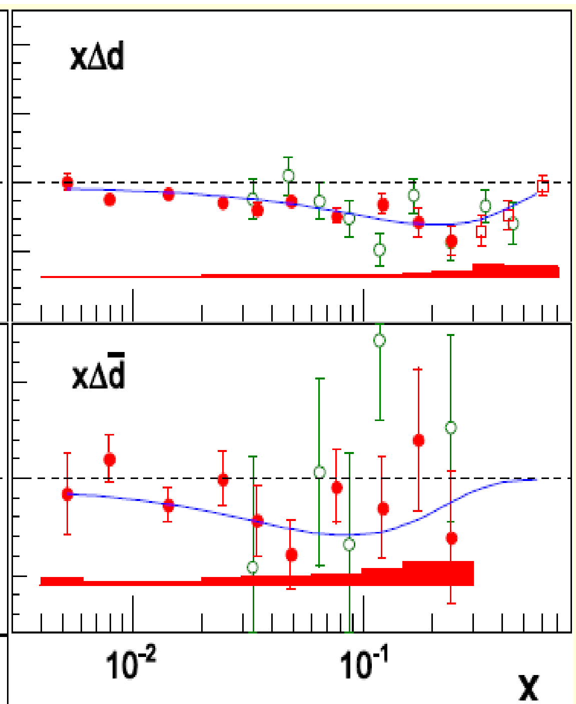




Quark helicities from SIDIS: $Q^2 = 3\ (GeV/c)^2$ and $x < 0.3$

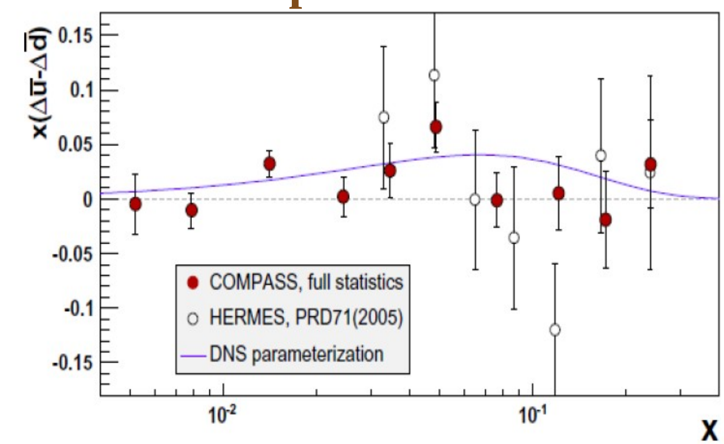
● COMPASS PLB693(2010)227, ○ HERMES, — DSSV



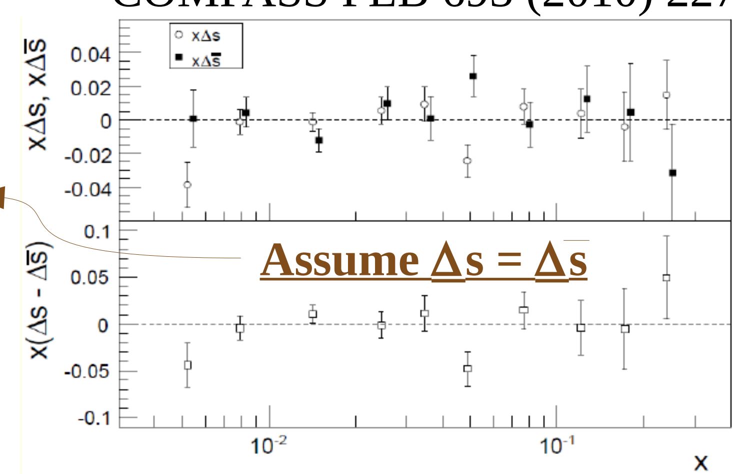


- **Sea distributions ~ 0**
- **Flavour separation until *x* ~ 0.004**

No flavour asymmetry in the polarised sea



COMPASS PLB 693 (2010) 227

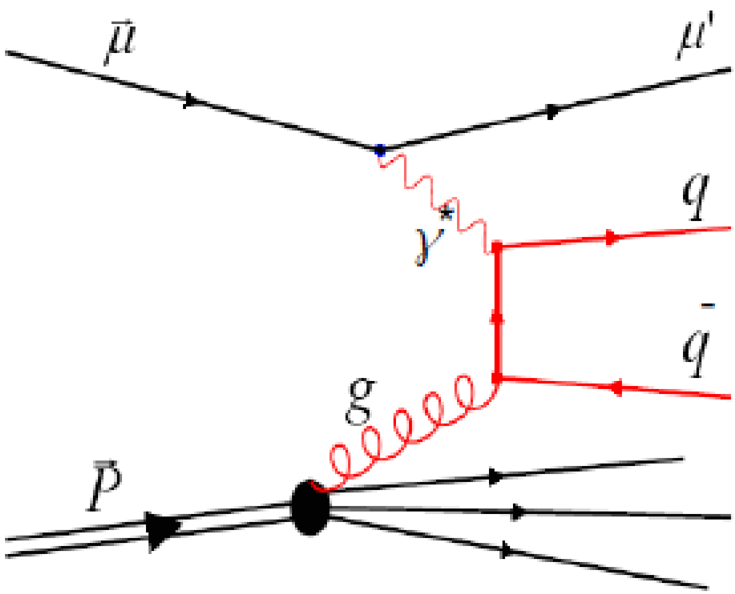


Assume $\Delta s = \Delta\bar{s}$

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

Direct measurement of the gluon polarisation (Δg/g) at LO in QCD

photon-gluon fusion process (PGF)



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

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

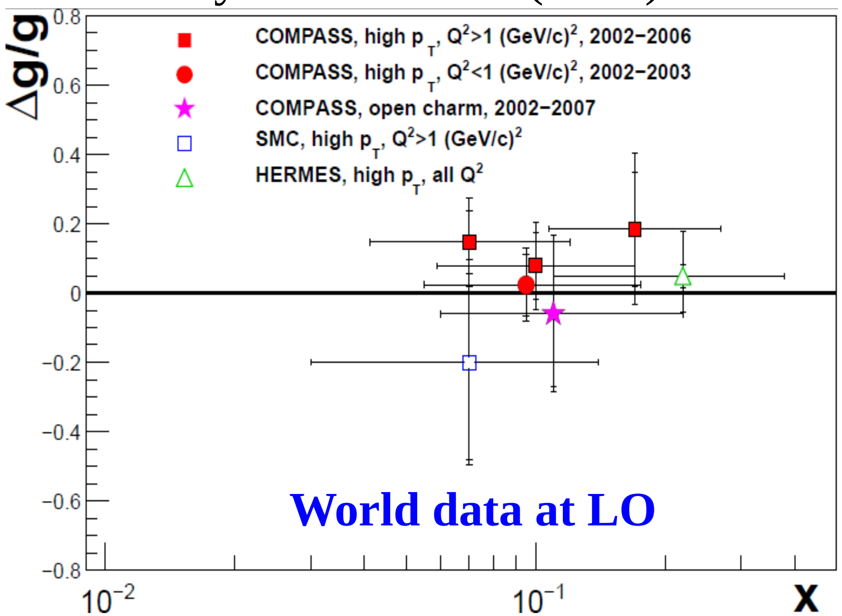
Obtained from Monte Carlo and parameterised by a Neural Network (to be used on data)

Two methods to tag this process are used:

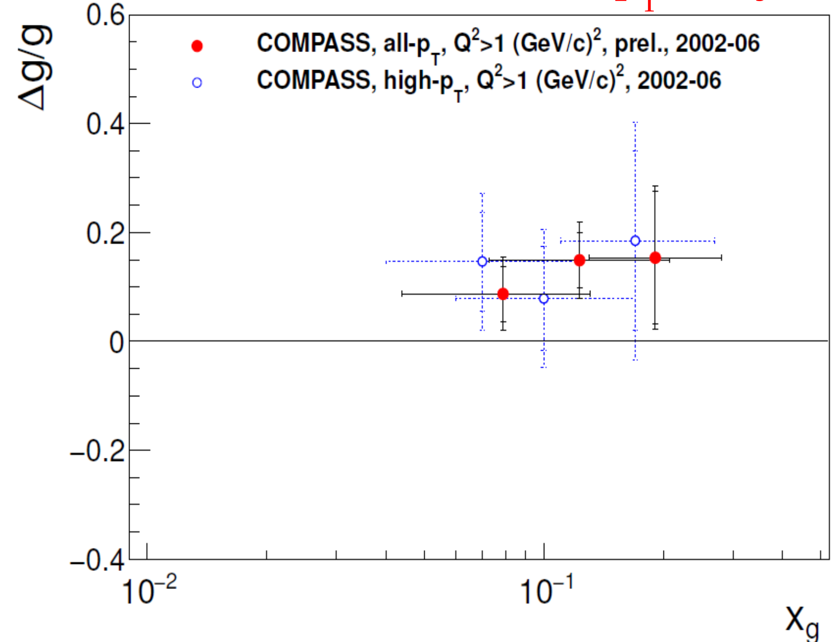
- **Open Charm production**
  - $\gamma^* g \to c\bar{c}$ ⇒ reconstruct D^0 mesons
  - Hard scale: M_c^2
  - No intrinsic charm in COMPASS kinematics
  - No physical background
  - Weakly model dependent
  - Low statistics
- **High-p_T hadron pairs**
  - $\gamma^* g \to q\bar{q}$ ⇒ reconstruct 2 jets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

Results on the gluon polarisation

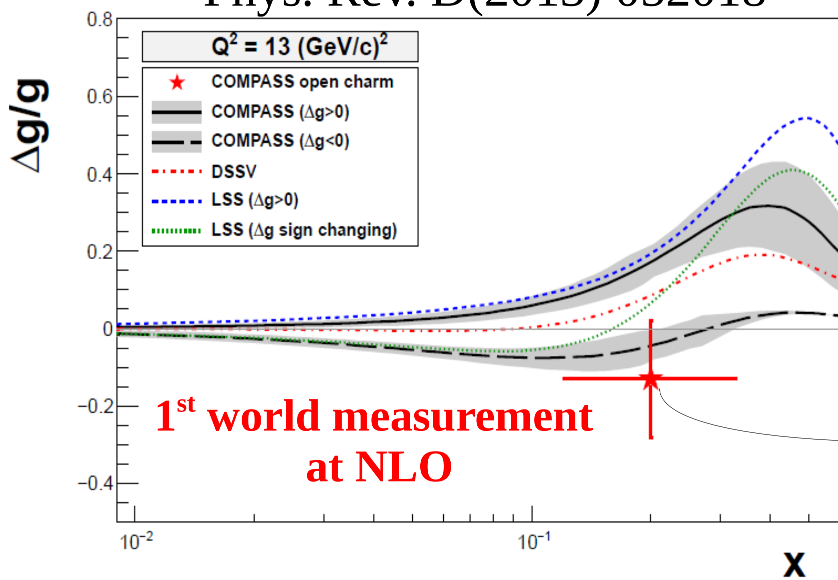
Phys. Lett. B 718 (2013) 922



New results from the all-p_T analysis



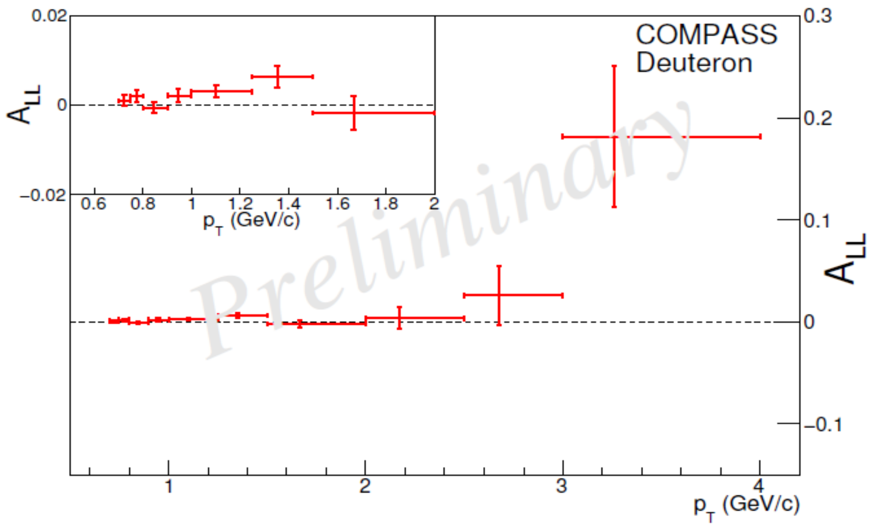
Phys. Rev. D(2013) 052018

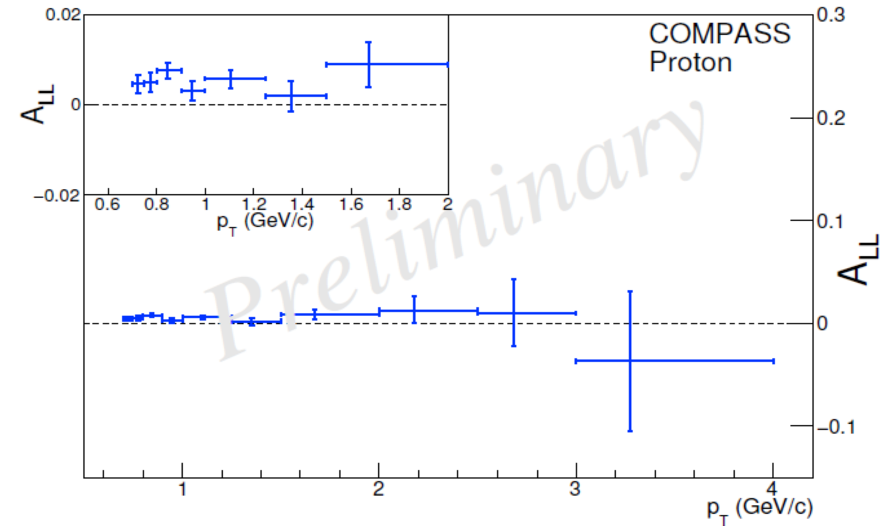


$$\Delta g/g = -0.13 \pm 0.15 \pm 0.15$$
$$@ \langle x_g \rangle = 0.20$$

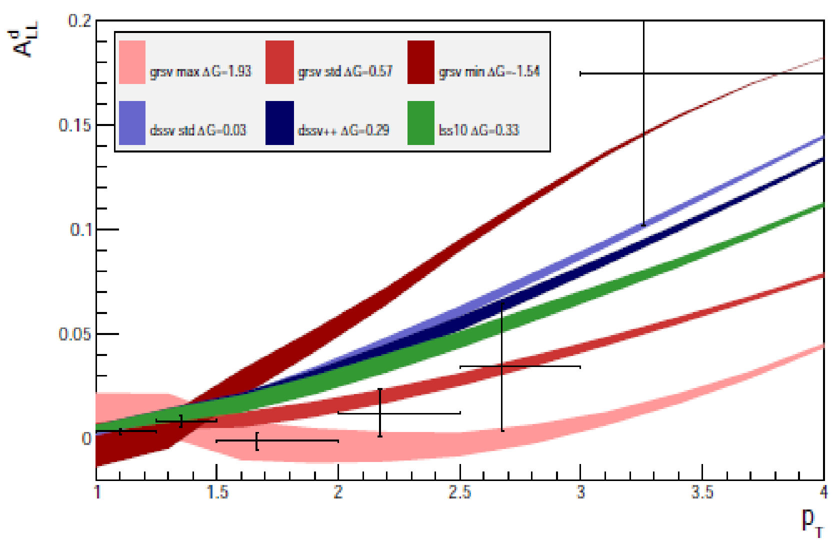
Spin asymmetries $\left(A_{LL} = \frac{\sigma_{\overset{\leftarrow}{\overrightarrow{\mu}N}} - \sigma_{\overset{\rightarrow}{\overrightarrow{\mu}N}}}{\sigma_{\mu N}} \right)$ at $Q^2 < 1\ \mathrm{GeV}^2/c^2$

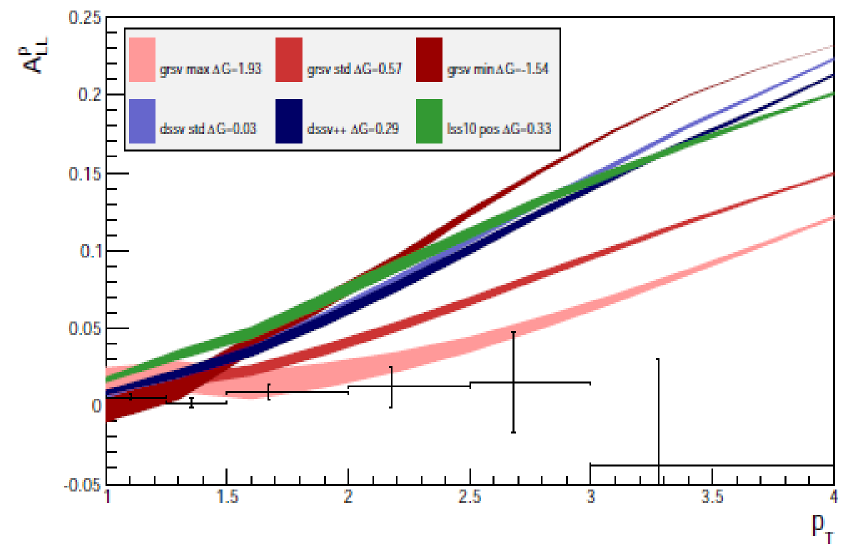
for an indirect extraction of ΔG





Comparison with calculations *(V. Vogelsang, M. Stratmann and B. Jäger)* of A_{LL} at NLO:





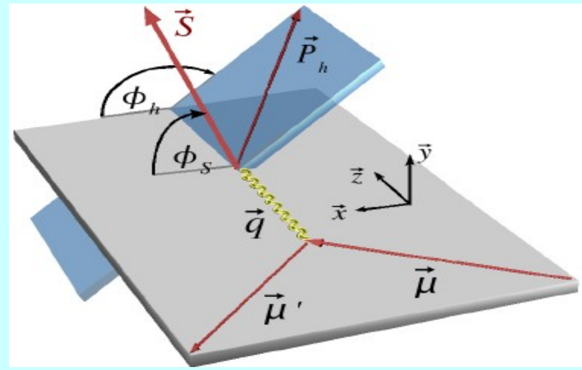
COMPASS results with a transversely polarised target

Interpretation of Collins & Sivers asymmetries in terms of TMDs

Studies from SIDIS

Depends on spin!

$$A_{Coll} \approx \frac{\sum_q e_q^2 \, h_1^q \otimes H_{1q}^{\perp h}}{\sum_q e_q^2 \, f_1^q \otimes D_{1q}^h}$$



$$A_{Siv} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \, f_1^q \otimes D_{1q}^h}$$

measured by fitting the corresponding (ϕ_h, ϕ_S) distributions (*from* σ^{SIDIS}) in different x, z, p_T^h bins

Collins Angle

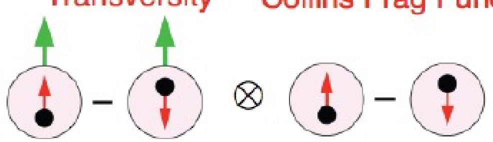
$\sin(\Phi_h + \Phi_S)$

Angle of hadron / initial quark spin

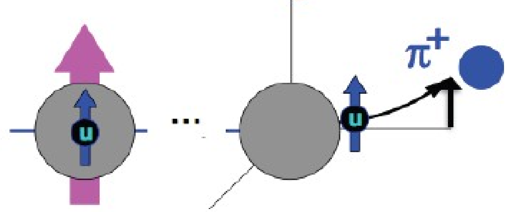
The "Collins Effect"

$h_1(x) \otimes H_1^{\perp}(z, p_T)$

Transversity   Collins Frag Funcⁿ



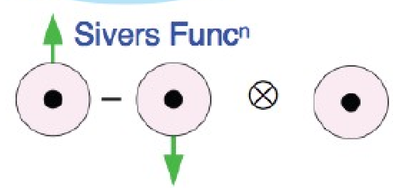
sensitive to ***transversity*** *and* ***spin-orbit*** *effects in* ***fragmentation***



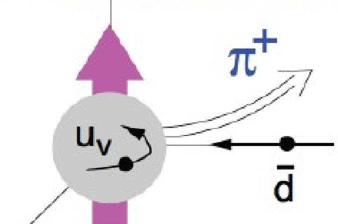
The "Sivers Effect"

$f_{1T}^{\perp}(x, k_T) \otimes D_1(z)$

Sivers Funcⁿ



sensitive to ***quark orbital motion***



Sivers Angle

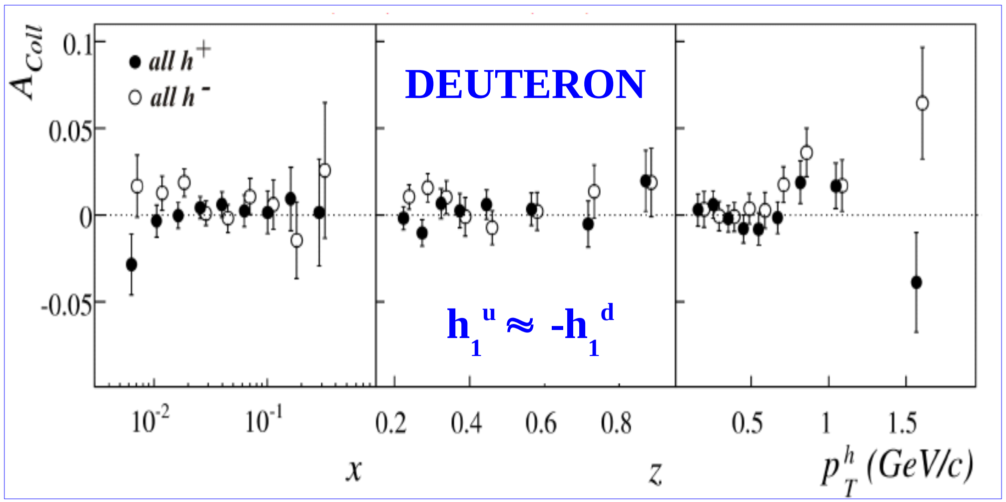
$\sin(\Phi_h - \Phi_S)$

Angle of hadron / final quark spin

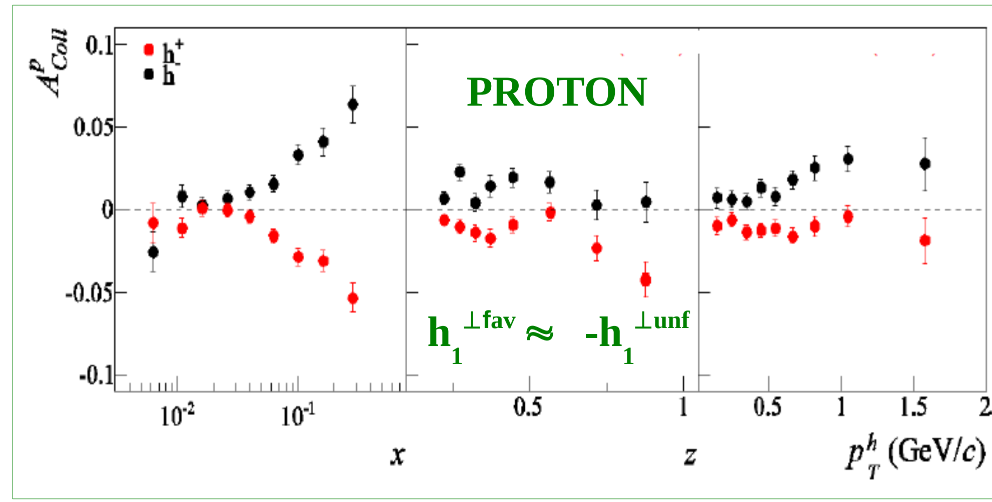
$\otimes$ denotes **convolution** over intrinsic quark k_T & fragmentation p_T

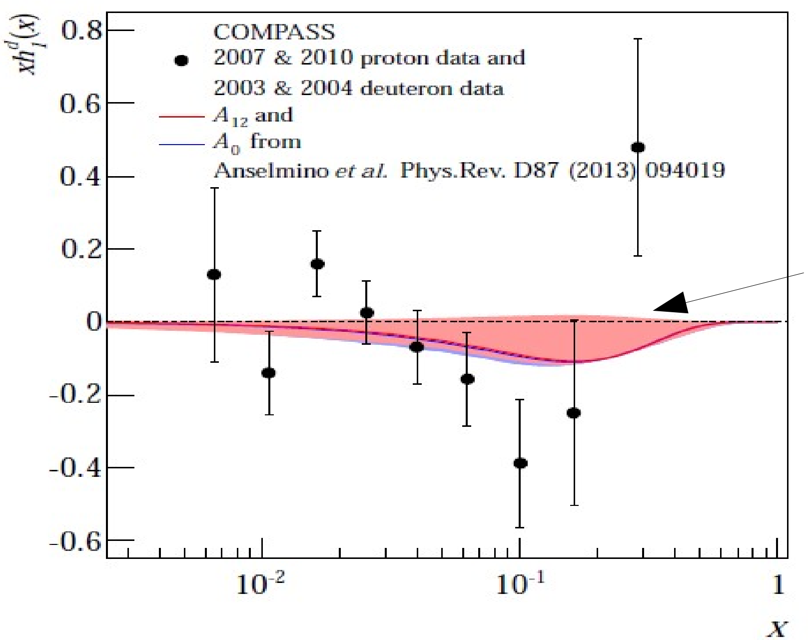
Results on the Collins asymmetry *(correlation between the hadron p_T & the quark transverse spin in a transversely polarised nucleon)*, **h_1^d and h_1^u**

NPB 765 (2007) 31

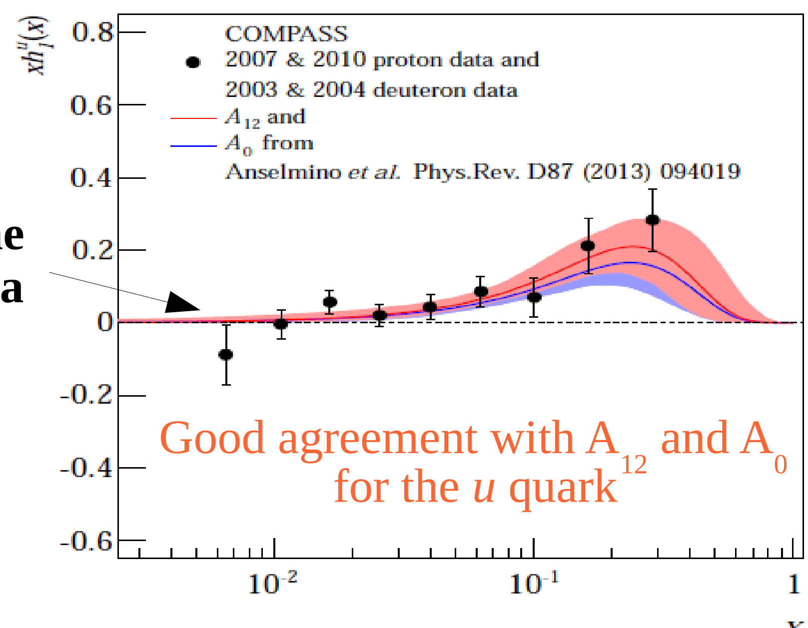


PLB 692 (2010) 240, PLB 717 (2012) 376





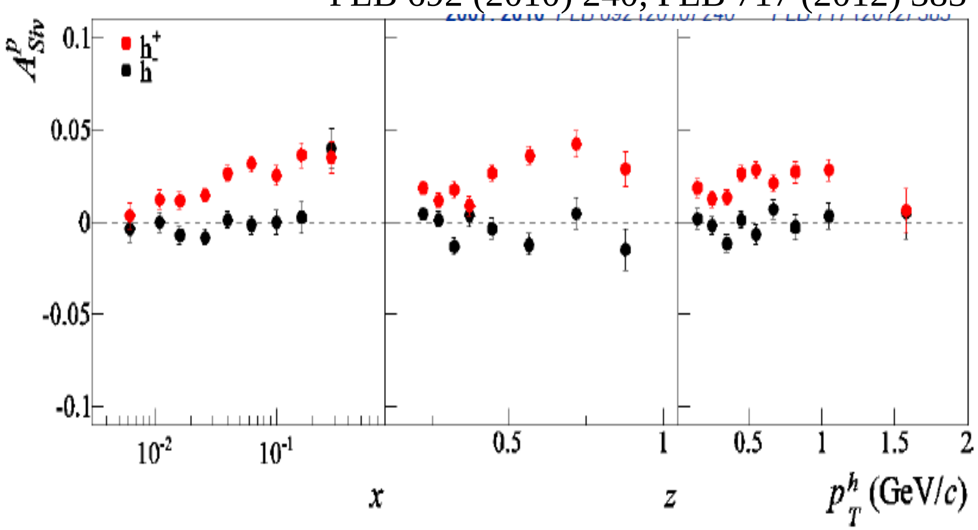
Fits to the Belle data



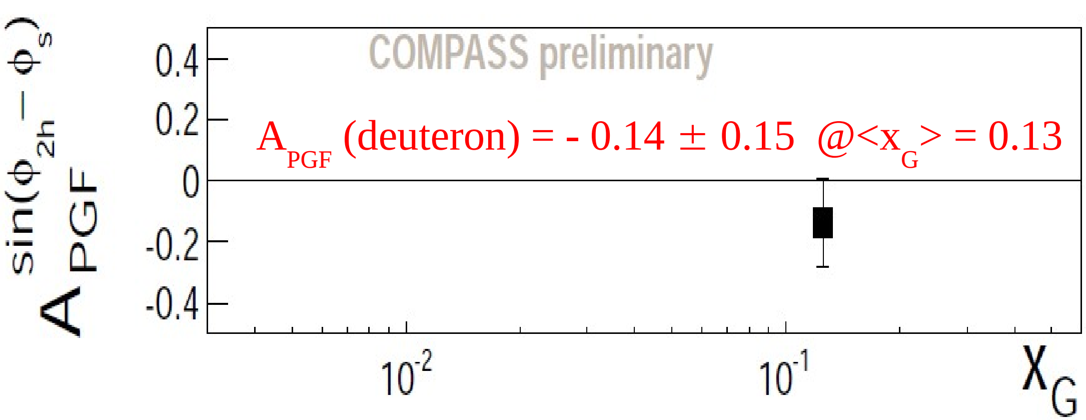
Results on the Sivers asymmetry *(correlation between the nucleon transverse spin and the quark/gluon k_T)* for quarks and gluons

- A clear A_{Siv}(quarks) signal is seen for h^+ proton data ($f_{1T}^{\perp u} \approx -f_{1T}^{\perp d}$ *on deuteron*):

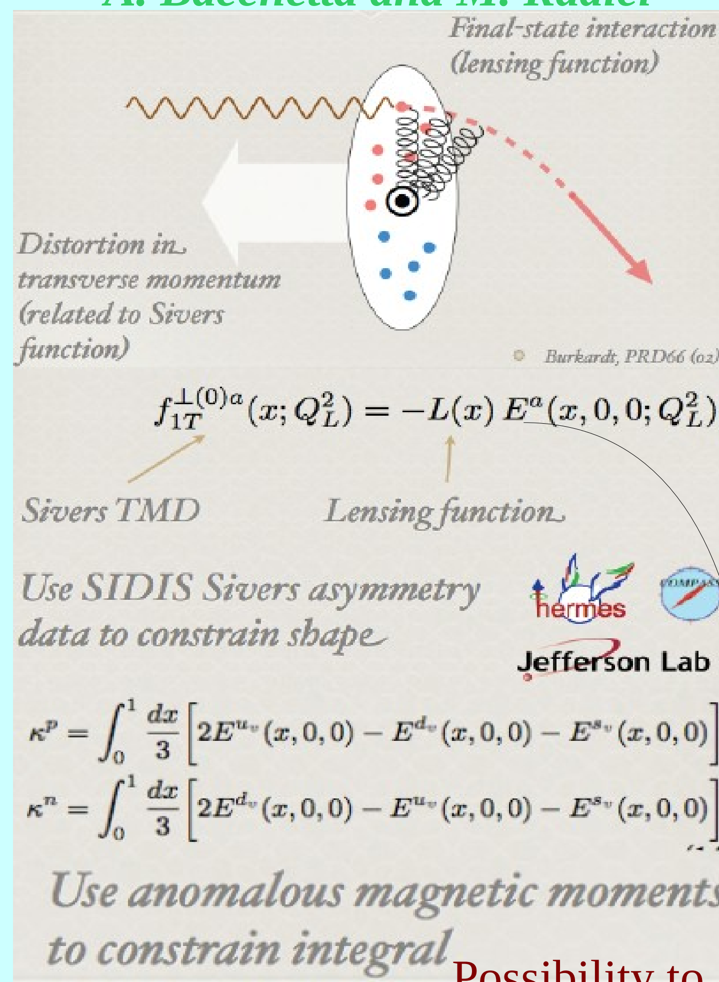
PLB 692 (2010) 240, PLB 717 (2012) 383



- **New result on the gluon Sivers asymmetry:**



A. Bacchetta and M. Radici



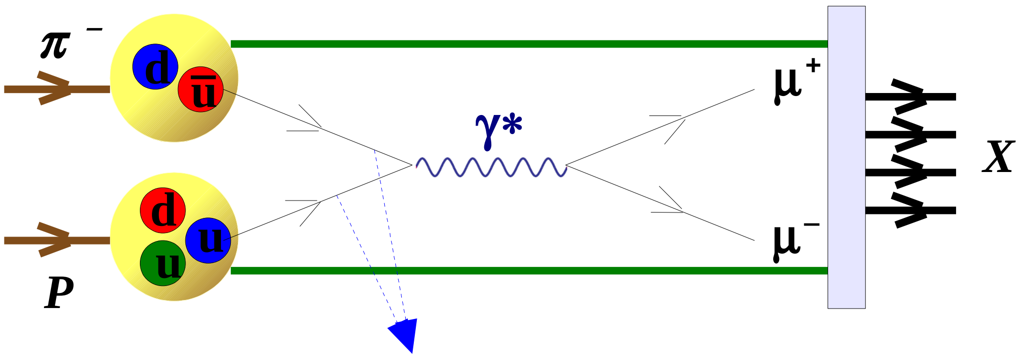
Possibility to access the OAM

$$J^q = (1/2)\Delta\Sigma + L^q$$
$$= \int_0^1 dx\, x\,[\underbrace{H^q(x,0,0)}_{q(x)} + E^q(x,0,0)]$$

Few examples of future measurements at COMPASS

COMPASS future I (2014-2015): TMDs from polarised Drell-Yan (DY)

DRELL-YAN PROCESS



Large acceptance in the valence region where large single spin asymmetries (SSA) are expected

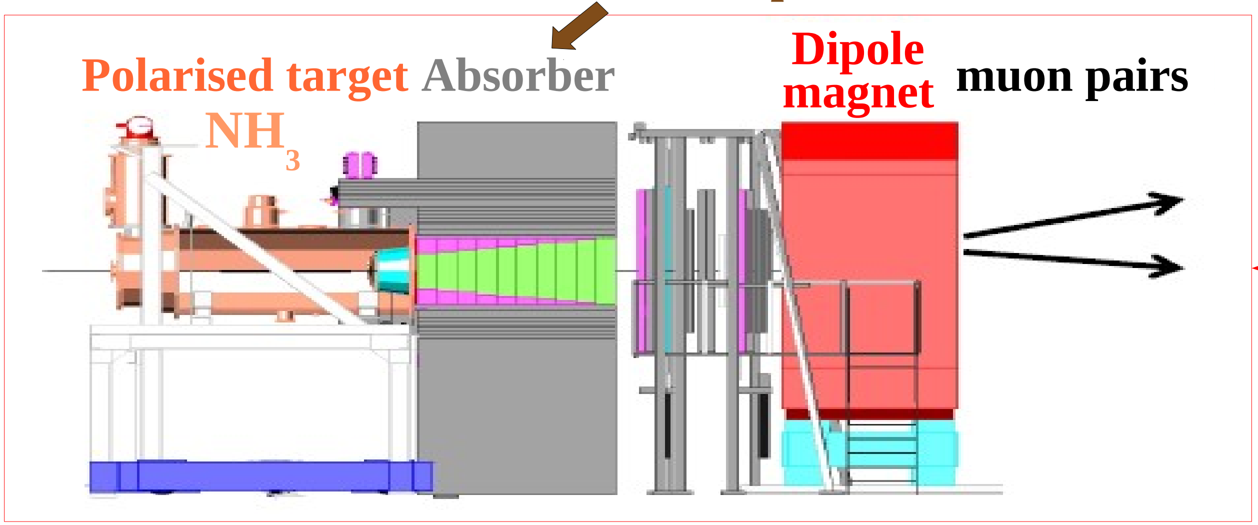
- **Convolution of 2 TMDs** *(no FF involved)*:

$$\sigma_{DY} \propto f_{\bar{u}/\pi^-} \otimes f'_{u/P}$$

- **Test of the TMD universality factorization approach** *(for the description of SSA)*:

$$f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{DIS} \;\;\&\;\; h_1^{\perp}\big|_{DY} = -h_1^{\perp}\big|_{DIS}$$

Main modifications in the spectrometer

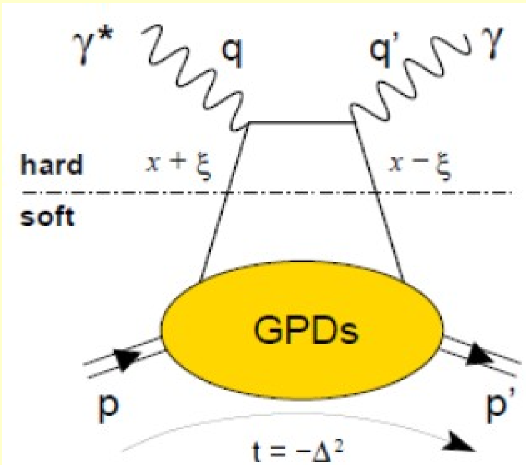


Clean access to 4 azimuthal modulations

(Boer-Mulders, Sivers, Pretzelosity and Transversity)

- **The production mechanism and the polarisation of *J/Ψ* will also be studied**

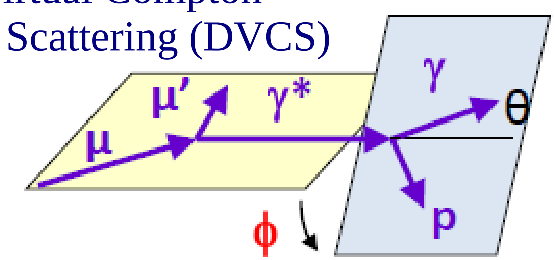
COMPASS future II (2016-2017): GPDs and nucleon tomography



- **Measurement of 4 generalised parton distributions** *(GPDs)* **for quarks:** $\boldsymbol{H}$, $\boldsymbol{E}$, $\boldsymbol{\tilde{H}}$, $\boldsymbol{\tilde{E}(x, \xi, t)}$
  - Contains normal PDF and elastic form factor as limiting cases: $q(x) = H(x,0,0)$ and $F(t) = \int dx\, H(x, \xi, t)$
  - Correlates transverse spatial and longitudinal momentum degrees of freedom *(nucleon tomography)*
  - Access the OAM of quarks via the Ji sum rule

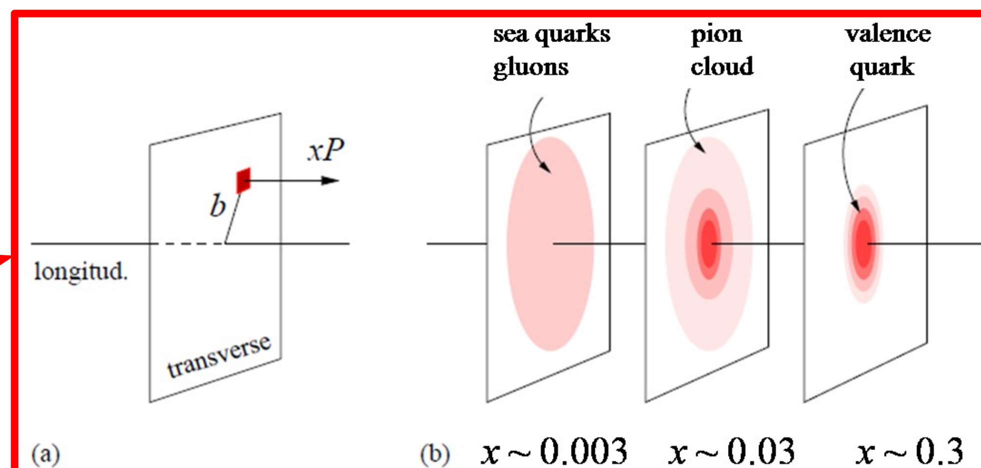
- The GPD ***H*** will be determined by studying the azimuthal dependence of the DVCS cross-section *(combining the data of μ^+ and μ^- beams on a liquid hydrogen target)*:

Deeply Virtual Compton Scattering (DVCS)



- **For the cases of $\xi = 0$, we have a purely transverse $\Delta_{\perp}^{2}$:**

Tomography!

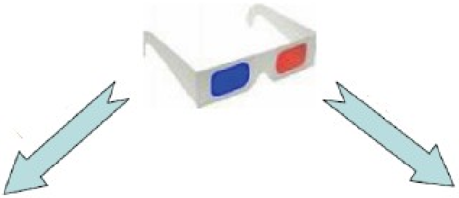


Summary

- **Contribution of the gluon helicity to the nucleon spin:**
  - All direct measurements point to zero or small contribution
  - ΔG is not well constrained by the NLO-QCD fits to the g_1 data
  - Present calculations of A_{LL} do not agree simultaneously with proton and deuteron data
- **Contribution of the quark helicity to the nucleon spin:**
  - Extraction for all flavours from SIDIS *(also from the NLO-QCD fits to the g_1 data)*
  - A global contribution of 30% was measured with good precision
- **Transversity and TMDs**
  - Precise measurements of the Collins and Sivers asymmetries
  - New result on the gluon Sivers asymmetry *(compatible with zero)*

- **Exciting future program in preparation:**

3D imaging of the nucleon



TMDs (DY) **GPDs** (DVCS)

Unpolarised SIDIS measurements

- Hadron multiplicities to improve the knowledge on: $D_q^h(z)$, $s(x)$ and $\Delta s(x)$
- Boer-Mulders TMD: $h_1^\perp(x, k_T)$