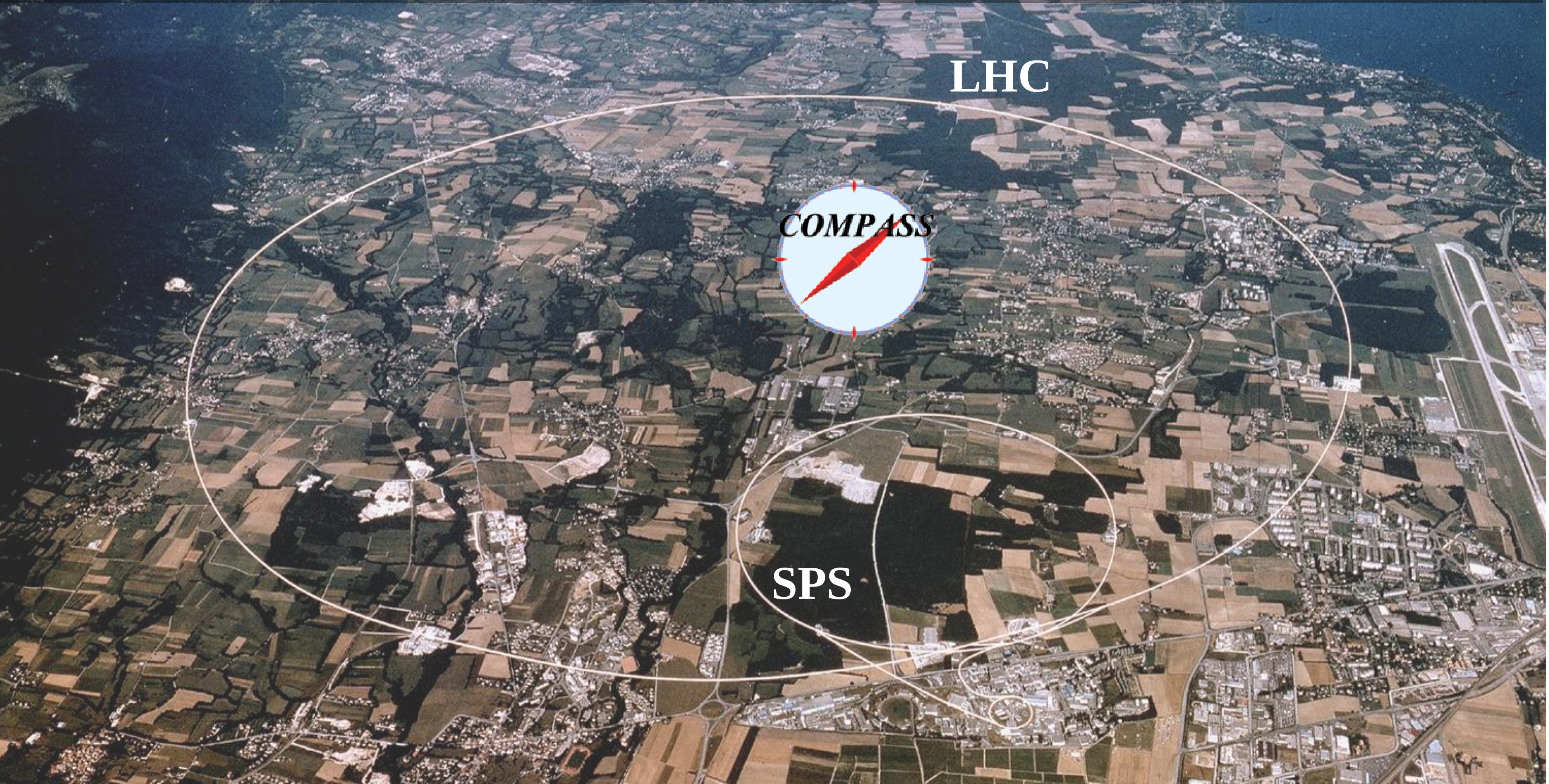
# COMPASS results

**COmmon Muon and Proton Apparatus for Structure and Spectroscopy"**

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on behalf of the COMPASS Collaboration

# Historical Introduction

**"…We understand the proton spin structure via the quark parton model and measuring the spin structure functions would not be fruitful…"**

## BARYON MAGNETIC MOMENTS

| BARYON | WAVE FUNCTION | QUARK MODEL MAG. MOMENT | EXPERIMENT ($\mu_N$) |
|---|---|---|---|
| $\Omega^-$ | $\uparrow s \uparrow s \uparrow s$ | $\mu_{\Omega^-} = 3\mu_s = -2.1\mu_N$ | $-2.02 \pm .05$ |
| $\Lambda^0$ | $\uparrow s \uparrow u \downarrow d$ | $\mu_\Lambda = \mu_s = -0.7\mu_N$ | $-0.613 \pm .005$ |
| $\Xi^0$ | $\uparrow s \uparrow s \downarrow u$, $\uparrow s \downarrow s u\uparrow$, $s\downarrow s\uparrow u\uparrow$ ---- KNOWN WEIGHTS | $\mu_{\Xi^0} = \frac{4\mu_s - \mu_u}{3} = -1.6\mu_N$ | $-1.25 \pm .014$ |
| $\Xi^-$ | $\uparrow s \uparrow s \downarrow d$ ----- | $\mu_{\Xi^-} = \frac{4\mu_s - \mu_d}{3} = -0.6\mu_N$ | $-0.651 \pm .003$ |
| $\Sigma^+$ | $\uparrow s \uparrow u \downarrow u$ ----- | $\mu_{\Sigma^+} = \frac{4\mu_u - \mu_s}{3} = +2.9\mu_N$ | $+2.458 \pm .010$ |
| $\Sigma^-$ | $\uparrow s \uparrow d \downarrow d$ ---- | $\mu_{\Sigma^-} = \frac{4\mu_d - \mu_s}{3} = -1.1\mu_N$ | $-1.16 \pm .025$ |
| p | $\uparrow u \downarrow u \uparrow d$ ---- | $\mu_p = \frac{4\mu_u - \mu_d}{3} = 3.0\mu_N$ | 2.793 |
| n | $\uparrow d \downarrow d \uparrow u$ --- | $\mu_n = \frac{4\mu_d - \mu_u}{3} = -2.0\mu_N$ | $-1.913$ |

# FRACTION OF NUCLEON'S SPIN CARRIED BY QUARKS:-

$$\int_0^1 g_1^p dx = \Gamma_1^p = +\frac{g_A}{12} f(\alpha_s) + a_8 \frac{f(\alpha_s)}{36} + \Delta\Sigma \frac{h(\alpha_s)}{9}$$

$$\int_0^1 g_1^n dx = \Gamma_1^n = -\frac{g_A}{12} f(\alpha_s) + a_8 \frac{f(\alpha_s)}{36} + \Delta\Sigma \frac{h(\alpha_s)}{9}$$

$f(\alpha_s)$; $h(\alpha_s)$ – QCD Radiative correction factors ~ 1

SU3:-

$a_8 = \frac{1}{\sqrt{3}}(3F - D)$; $g_A = F + D = 1.26$ (= $G_V/G_A$ From $n\ \beta$ Decay)

($F, D$ Symmetric, antisymmetric SU(3) couplings from hyperon decay, $F = 0.48 \pm 01$, $D = 0.76 \pm 01$)

In QPM

$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$

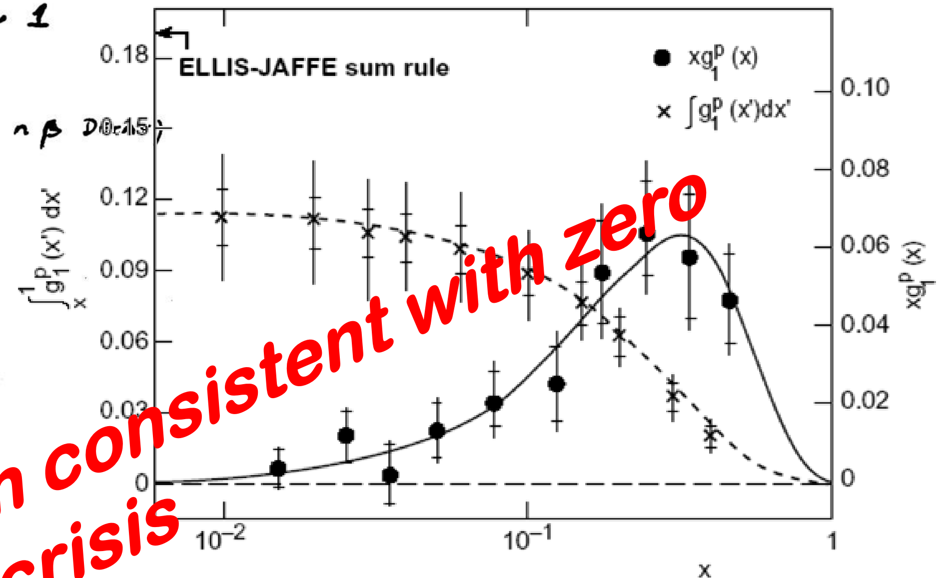
= Total fraction of proton spin carried by quarks

$a_8 = \frac{1}{\sqrt{3}}\{\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s})\}$

$g_A = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}$

- use $\Gamma_1^p, \Gamma_1^n$ to obtain $\Delta\Sigma$; then $g_A$ and $a_8$ to solve for $\Delta u$, $\Delta d$, $\Delta s$.
- previously Ellis - Jaffe sum rule obtained by assuming $\Delta s = 0$ to get predictions for $\Gamma_1^p, \Gamma_1^n$
- the modern data shows that the Ellis - Jaffe sum rule is violated, so the strange sea is polarised.

EMC, J. Ashman et al., PLB 206 (1988) 364 (> 1660 citations)




**Quark spin contribution consistent with zero**

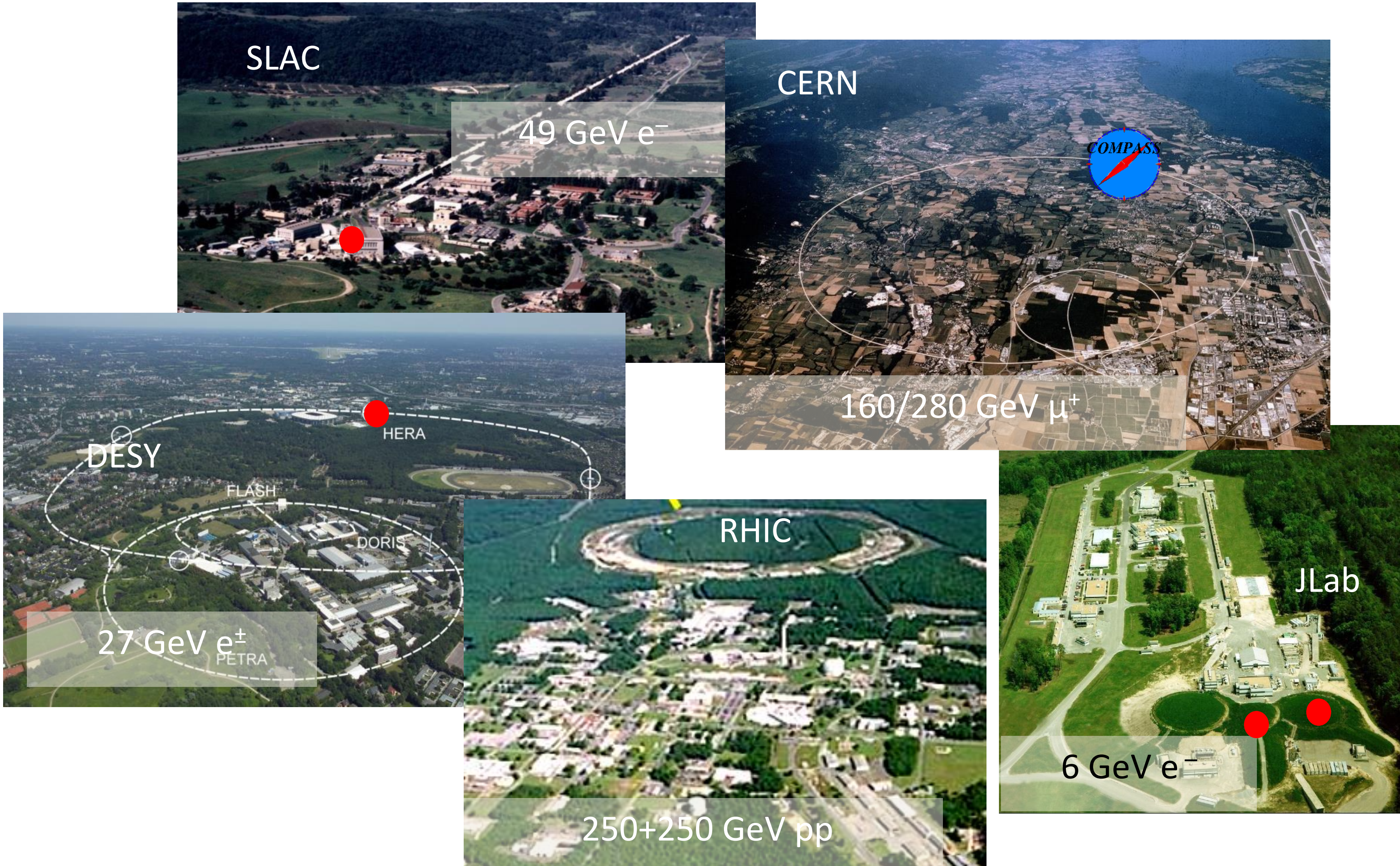
**spin crisis**

EMC MEASURED $\int_0^1 g_1^p dx = 0.126 \pm .010 \pm .015$

ie $\Delta\Sigma = 0.12 \pm .09 \pm .14$.

i.e. ~12% OF SPIN OF PROTON CARRIED BY QUARKS

# Laboratories &



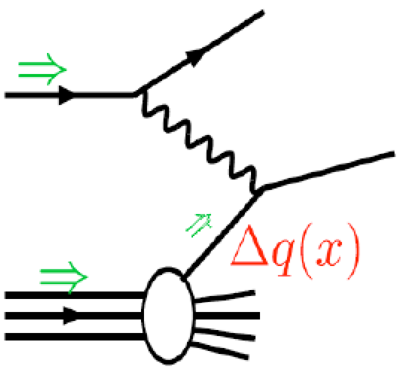
# & Experiments

| | 1970 | 1980 | 1990 | 2000 |
|---|---|---|---|---|
| SLAC | E80 | E130 | E142/3 E154/5 | |
| CERN | | EMC | SMC | COMPASS |
| DESY | | | HERMES | |
| JLab | | | | CLAS/HALL-A |
| RHIC | | | | Phenix/Star |

**A worldwide effort since decades**

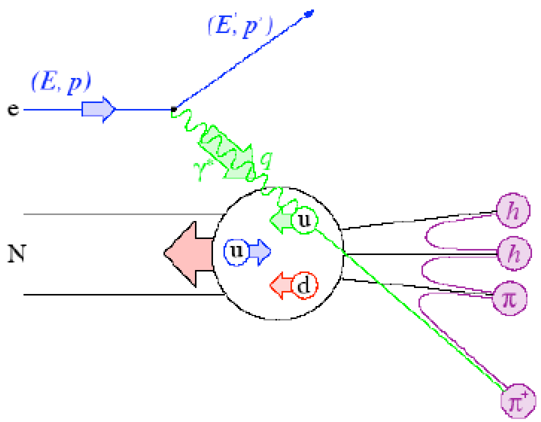
# Tools to study the nucleon structure

DIS




PDF

SIDIS

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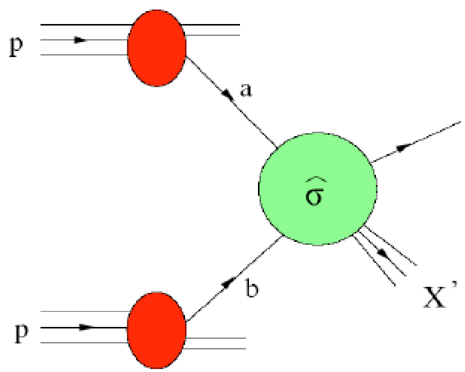


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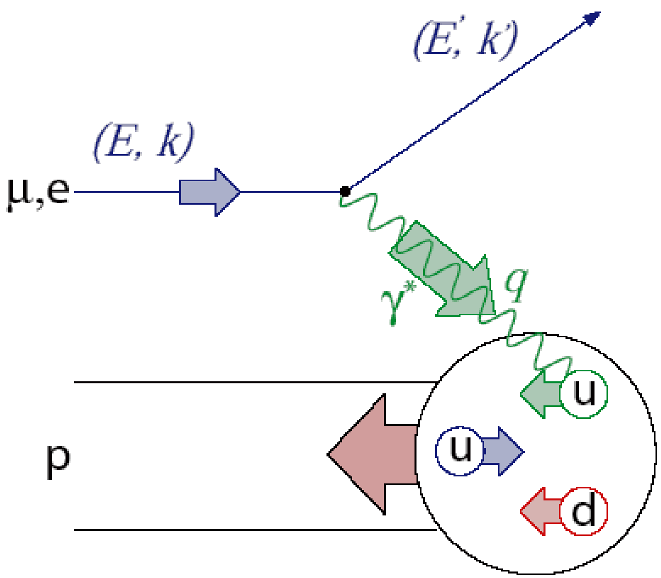
# Deep inelastic scattering




$$Q^2 = -(k-k')^2 \stackrel{lab}{=} 4EE'\sin^2\frac{\vartheta}{2}$$

$$P\cdot q \stackrel{lab}{=} M\nu = M(E-E')$$

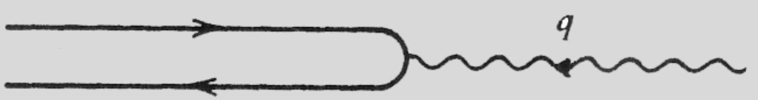
$$P\cdot k \stackrel{lab}{=} ME$$

$$x \stackrel{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

$$y \stackrel{lab}{=} \frac{\nu}{E} = \frac{P\cdot q}{P\cdot k}$$

$$0 \leq x, y \leq 1$$

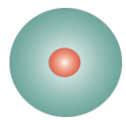
Bjorken-*x*: fraction of longitudinal momentum carried by the struck quark in infinite- momentum frame (Breit)



# Structure: Parton Distribution Functions

**$q(x)$**

$f_1^q\ (x)$



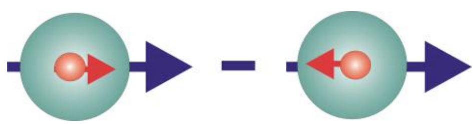
**unpolarised PDF**

quark/gluon with momentum *xP* in a nucleon

*well known – unpolarized DIS*

**$\Delta q(x)$**

$g_1^q(x)$



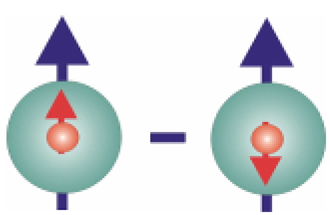
**helicity PDF**

quark/gluon with spin parallel to the nucleon spin in a longitudinally polarised nucleon

*known – polarized DIS*

**$\Delta_T q(x)$**

$h_1^q(x)$

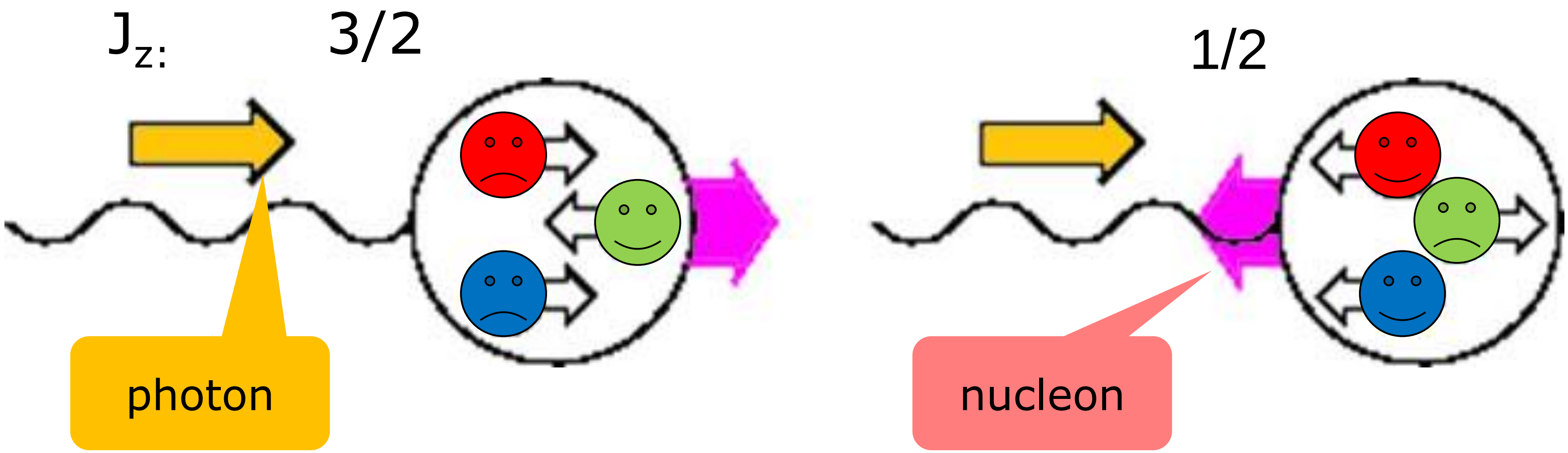


**transversity PDF**

quark with spin parallel to the nucleon spin in a transversely polarised nucleon

*chiral odd, fairly known*

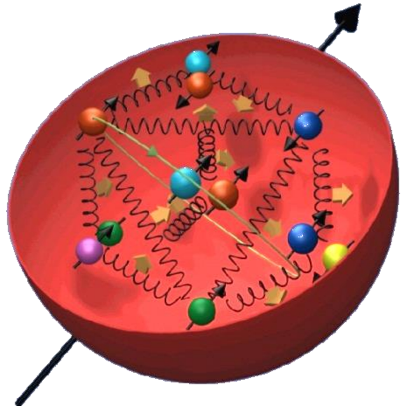
# Photoabsorption & long. spin structure




- Measure cross-section asymmetry

$$\frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

- Need polarised beam & target
  (for longitudinal spin structure)



$$\frac{A_{\rm exp}}{f\ P_\mu\ P_T\ D} \simeq A_1$$

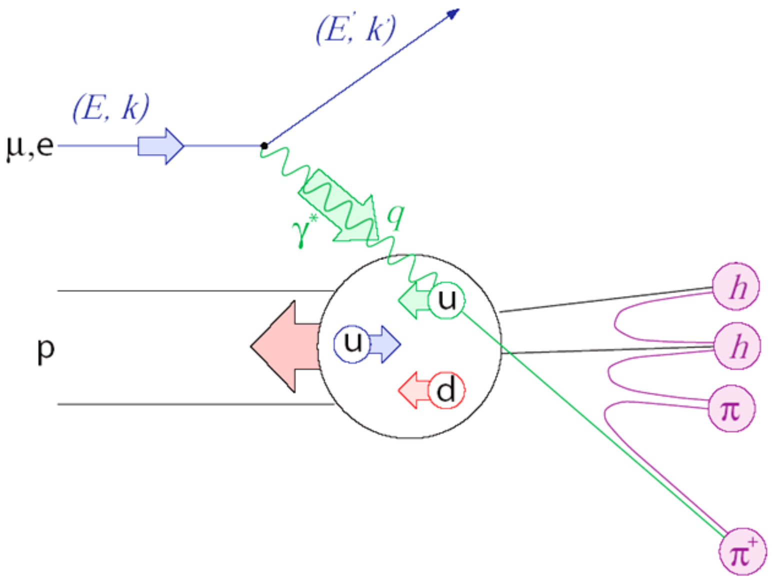
- Inclusive scattering

$$A_1 = \frac{\sum_q e_q^2 g_1^q(x,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2)}$$

- Semi-inclusive scattering

$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

$$z = E_h/\nu$$



# Questions:

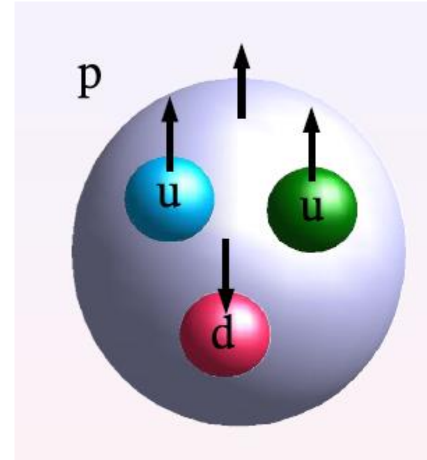
- **What is helicity contribution of quarks to nucleon spin $\Delta\Sigma$?**

- **How do contributions of different flavours $\Delta q(x)$ , q=u,d,s and antiquarks look like?**

- **Is gluon helicity distrbution $\Delta G = \int \Delta g(x)dx$ small or not?**

- **How does $\Delta g(x)$ look like?**

# After almost 40 years

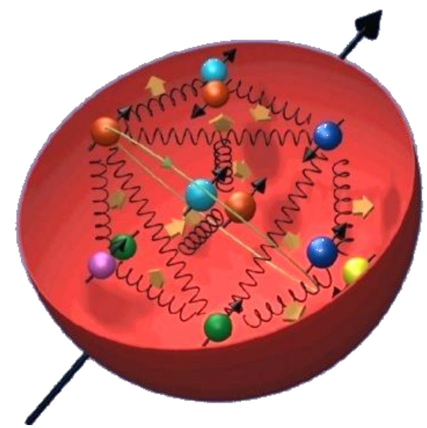



$$\Delta\Sigma = \Delta u + \Delta d = 1$$

SQM: valence quarks carry the nucleon spin!

EMC: Quarks spins contribute little (1987/88)

$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$

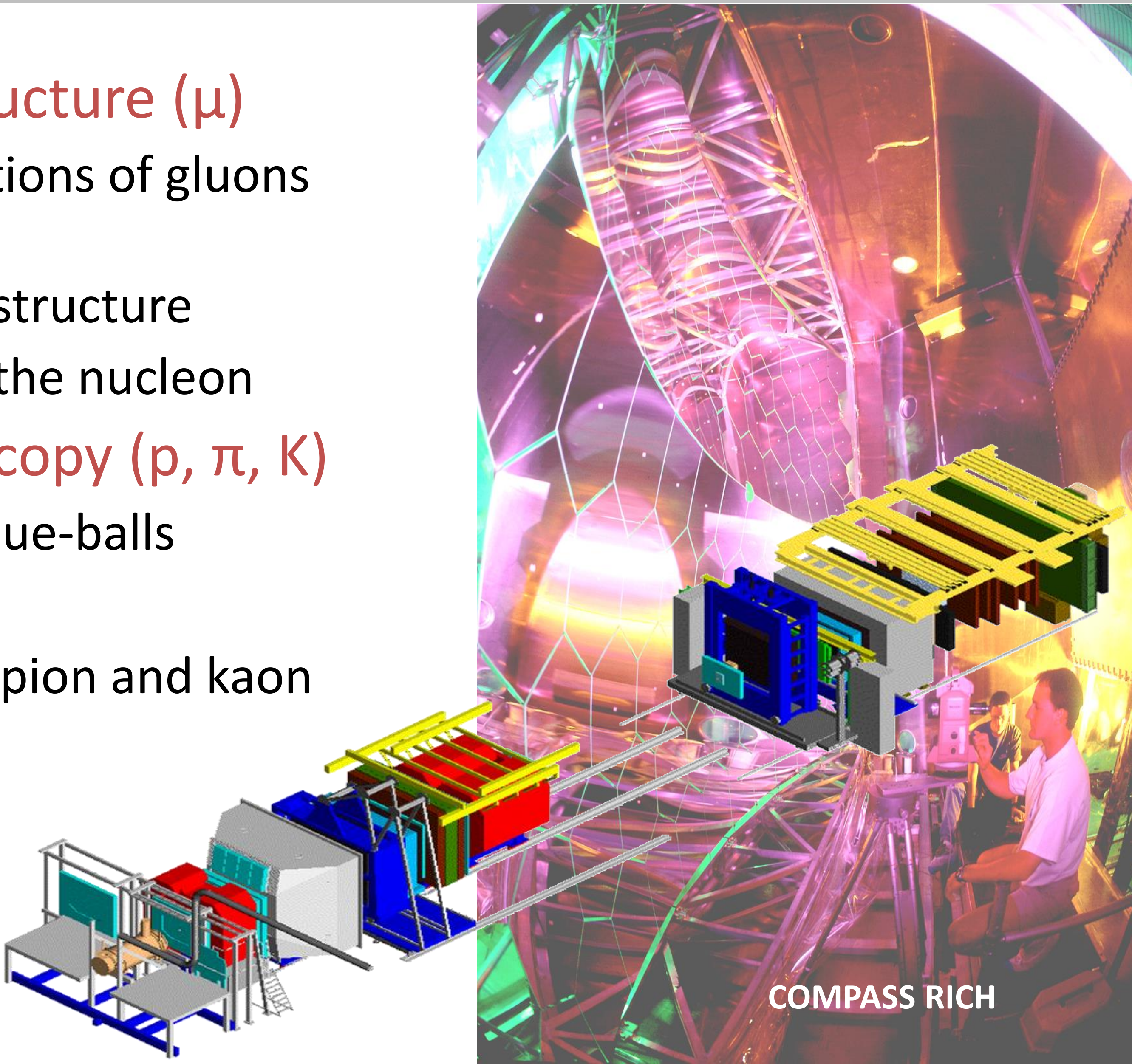


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

| quarks | gluons | orbital |
| --- | --- | --- |
| small ~0.25 | Still poorly known | unknown |

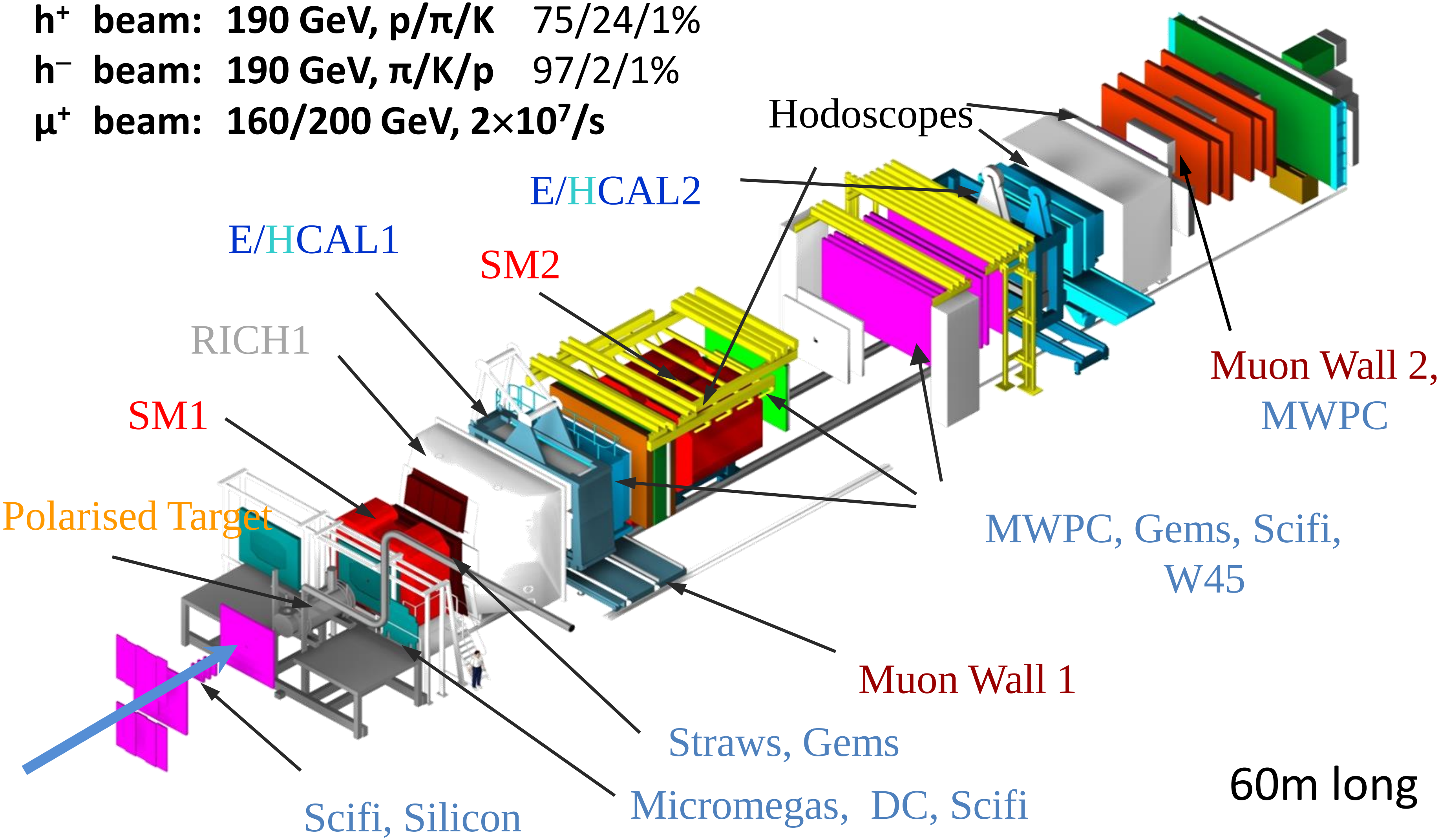
# COMPASS experimeent

- nucleon spin-structure (μ)
  - helicity distributions of gluons and quarks
  - transverse spin structure
  - 3D structure of the nucleon
- hadron spectroscopy (p, π, K)
  - light mesons,  glue-balls
  - exotic mesons
  - polarisability of pion and kaon
- members:
  - 220 physicists, 23 institutes, 12 countries

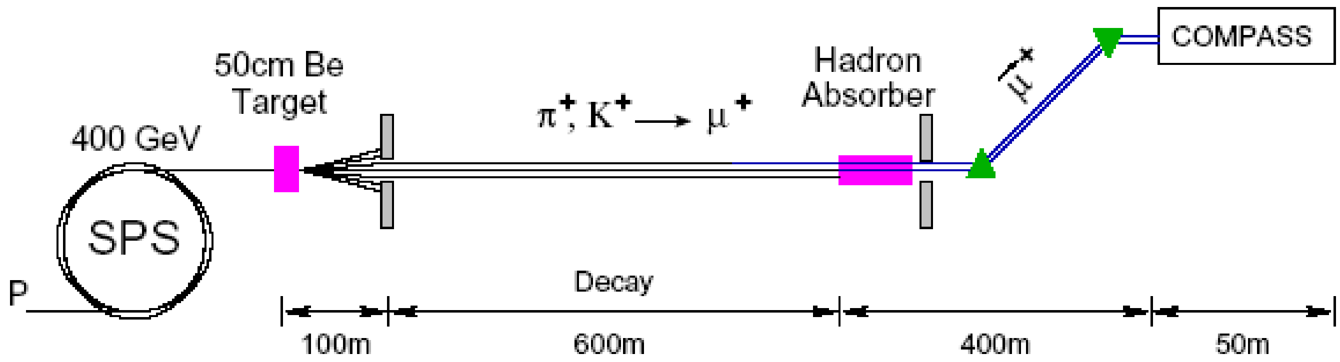


# COMPASS spectrometer

$h^+$ beam: 190 GeV, p/π/K 75/24/1%
$h^-$ beam: 190 GeV, π/K/p 97/2/1%
$\mu^+$ beam: 160/200 GeV, $2\times10^7$/s



# COMPASS Beams




**Muon beam**

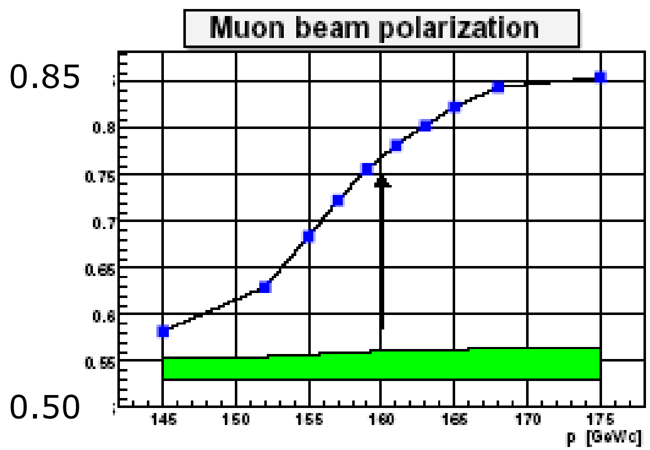
- Energy: 160 GeV
- Intensity: $2\text{x}10^8$/spill
- Polarization: 80%

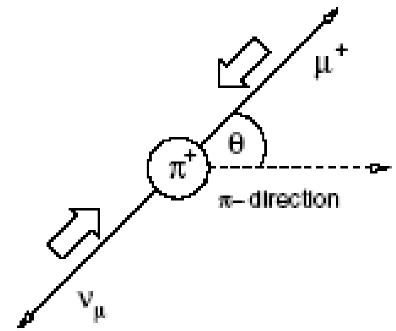
**Hadron beams**

- Pions(97%), kaons(2.6%), anti-p(0.6%)
- Energy: 190 GeV
- Intensity: up to $10^8$/spill

**Electron beam**

- 40 GeV, few $10^3$/spill, used for calibration



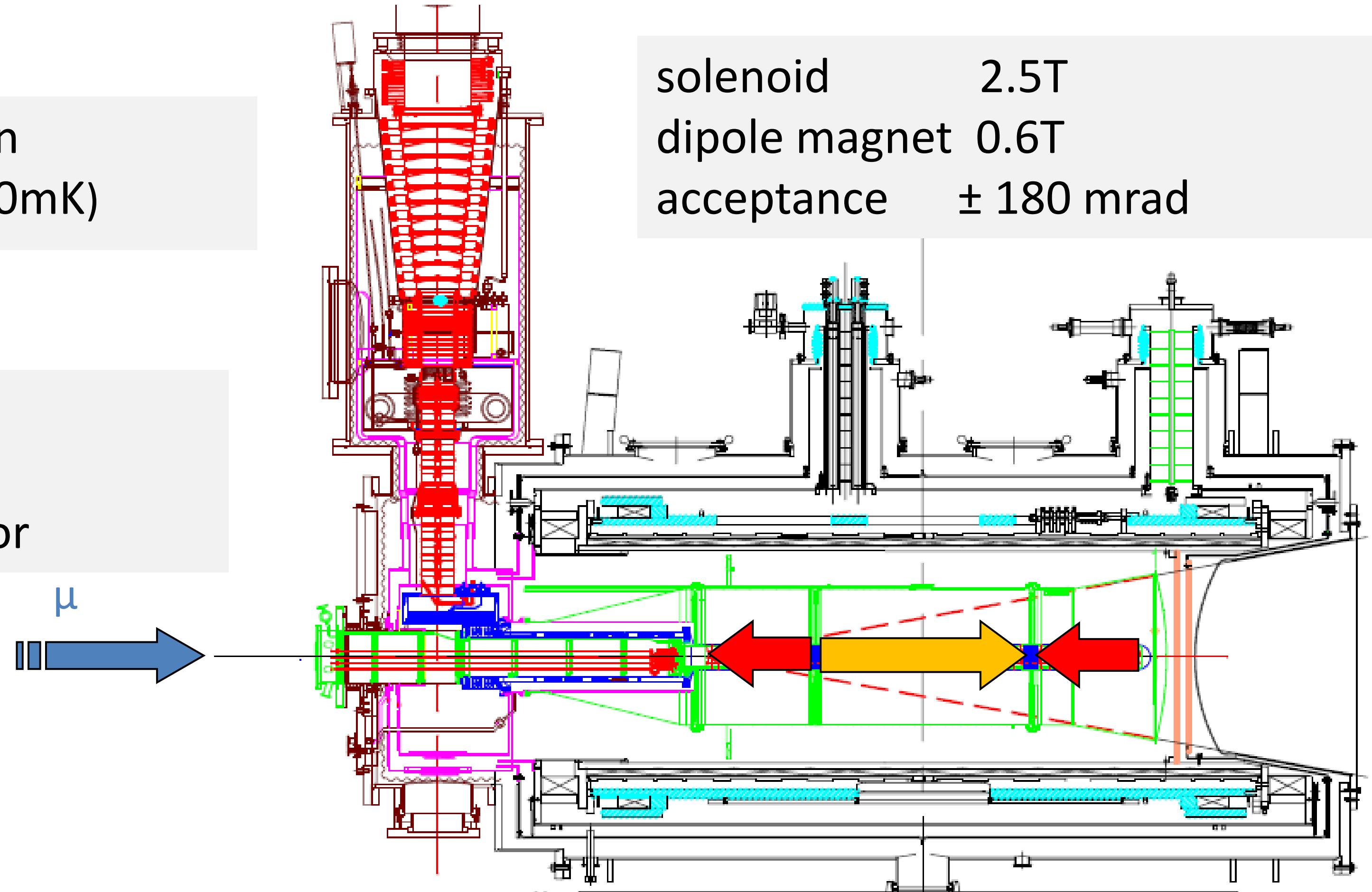

| | |
|---|---|
| Energy | 160 GeV |
| Intensity | $2 \cdot 10^8 \mu /$ Spill |
| Polarisation | $\approx 76\,\%$ |

# Polarized target system

$^3He$ – $^4He$ dilution refrigerator (T~50mK)

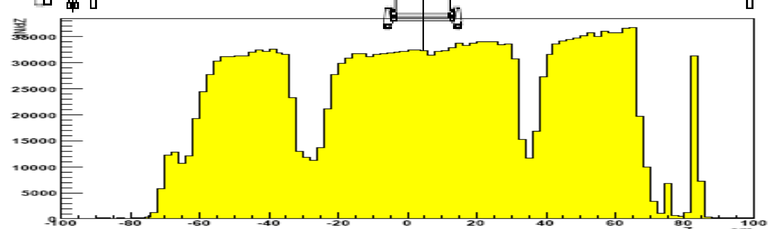
$^6LiD/NH_3$ (d/p)
50/90% pol.
40/16% dil. factor

μ



solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

Recontructed interaction vertices



# Helicity structure of the nucleon

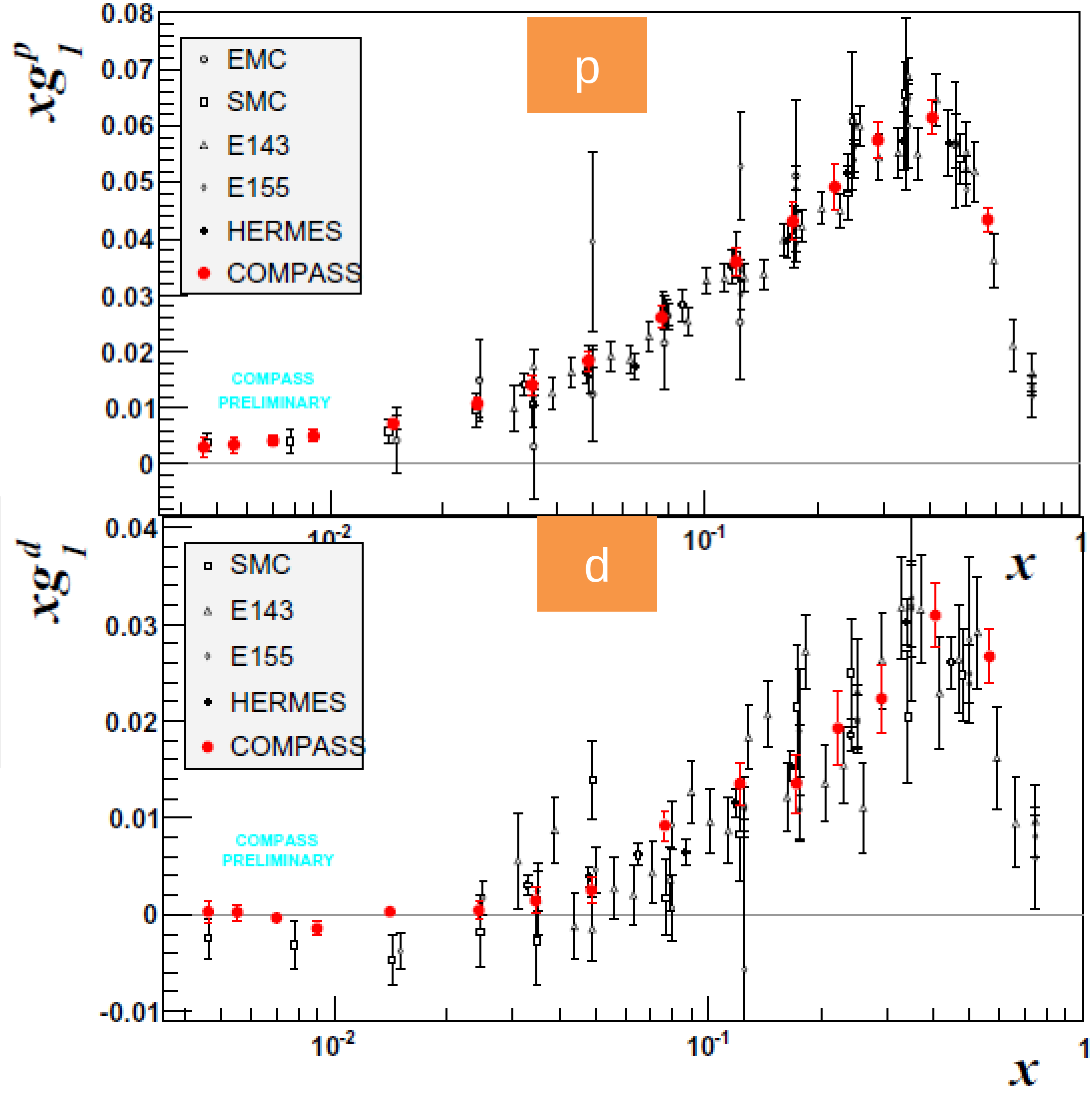
# Structure function $g_1(x,Q^2)$

- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)

- deuteron data:

$\Delta\Sigma = 0.33 \pm 0.03 \pm 0.05$

$\Delta s + \Delta\bar{s} =$
$= -0.08 \pm 0.01 \pm 0.02$



# Sum rules

- first moment $\Gamma_1$ of $g_1$ with $\Delta q = \int_0^1 \Delta q(x)\mathrm{d}x$

$$\Gamma_1 = \int_0^1 g_1(x)\mathrm{d}x \overset{proton}{=} \frac{1}{2}\left\{\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right\}$$

$$\Gamma_1^{\mathrm{p}} = \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{\sqrt{3}a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

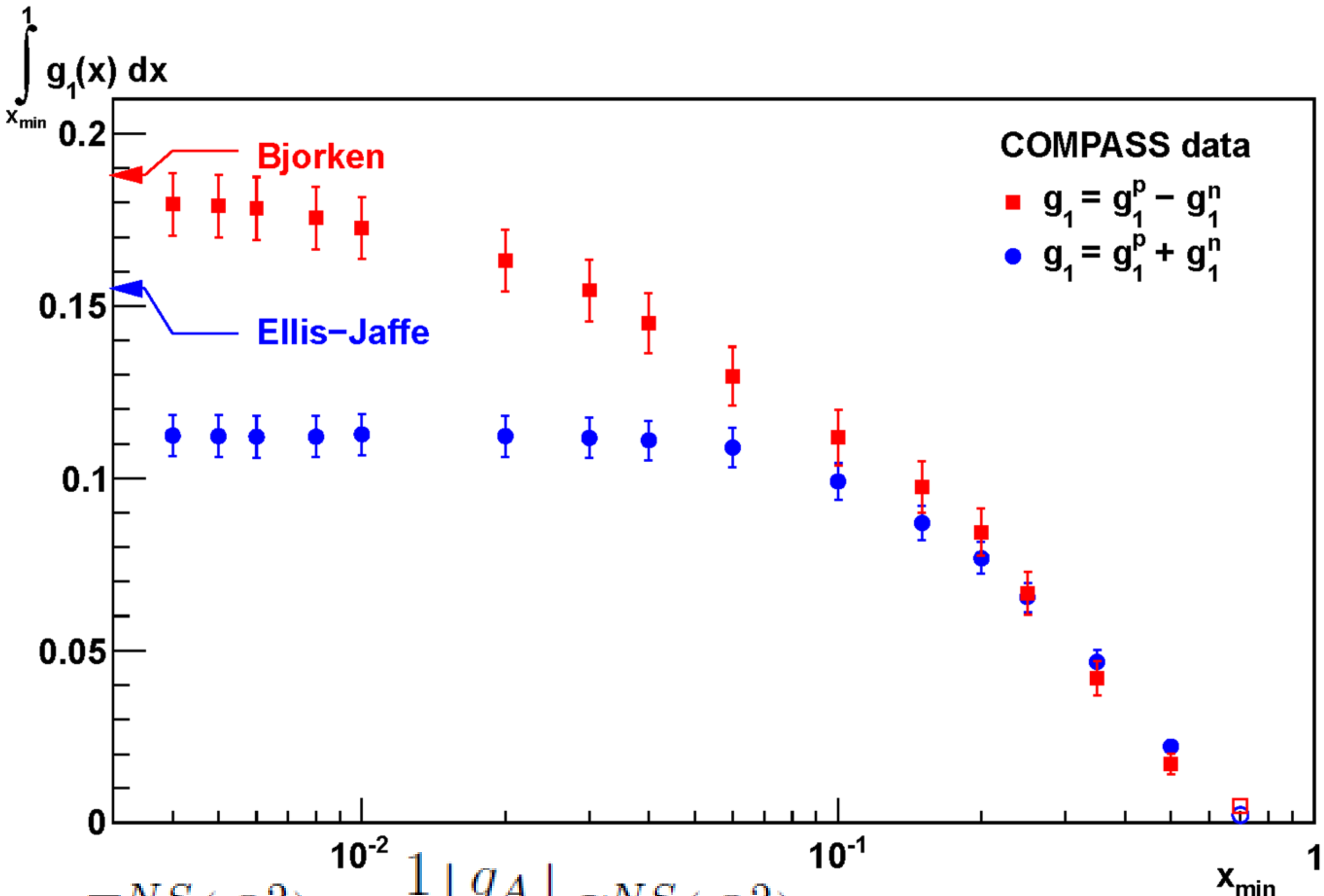
Neutron decay
**$a_3 = |g_a/g_v|$**

Hyperon decay
**(3F-D)/3**

**$\Delta\Sigma$**

- **Bjorken sum rule:**

$$\Gamma_1^{\mathrm{p}} - \Gamma_1^{\mathrm{n}} = \frac{1}{6}(\Delta u - \Delta d)$$



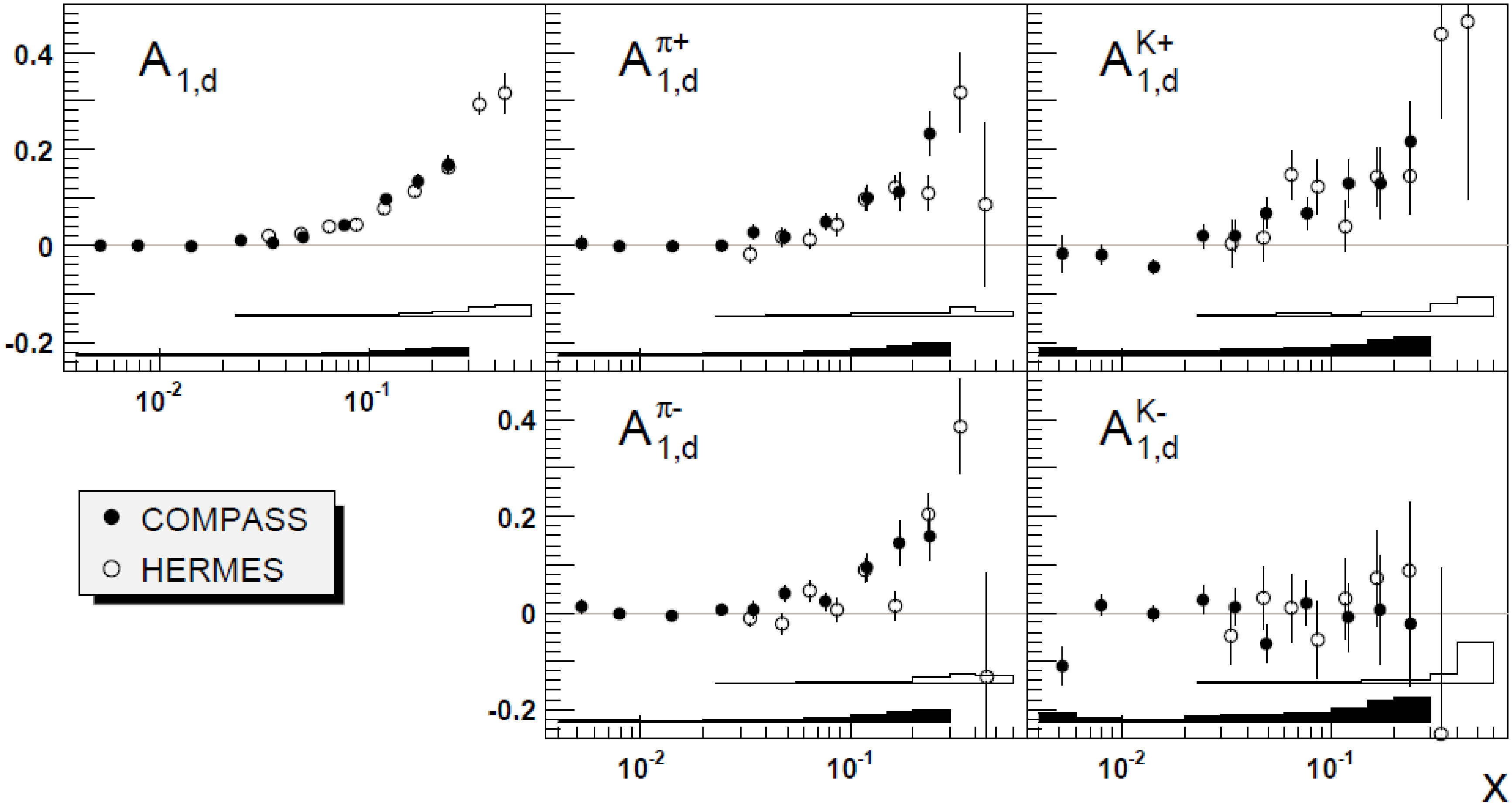

PLB 690 (2010) 466

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2) \qquad g_1^{NS}(x,Q^2) = g_1^p(x,Q^2) - g_1^n(x,Q^2)$$

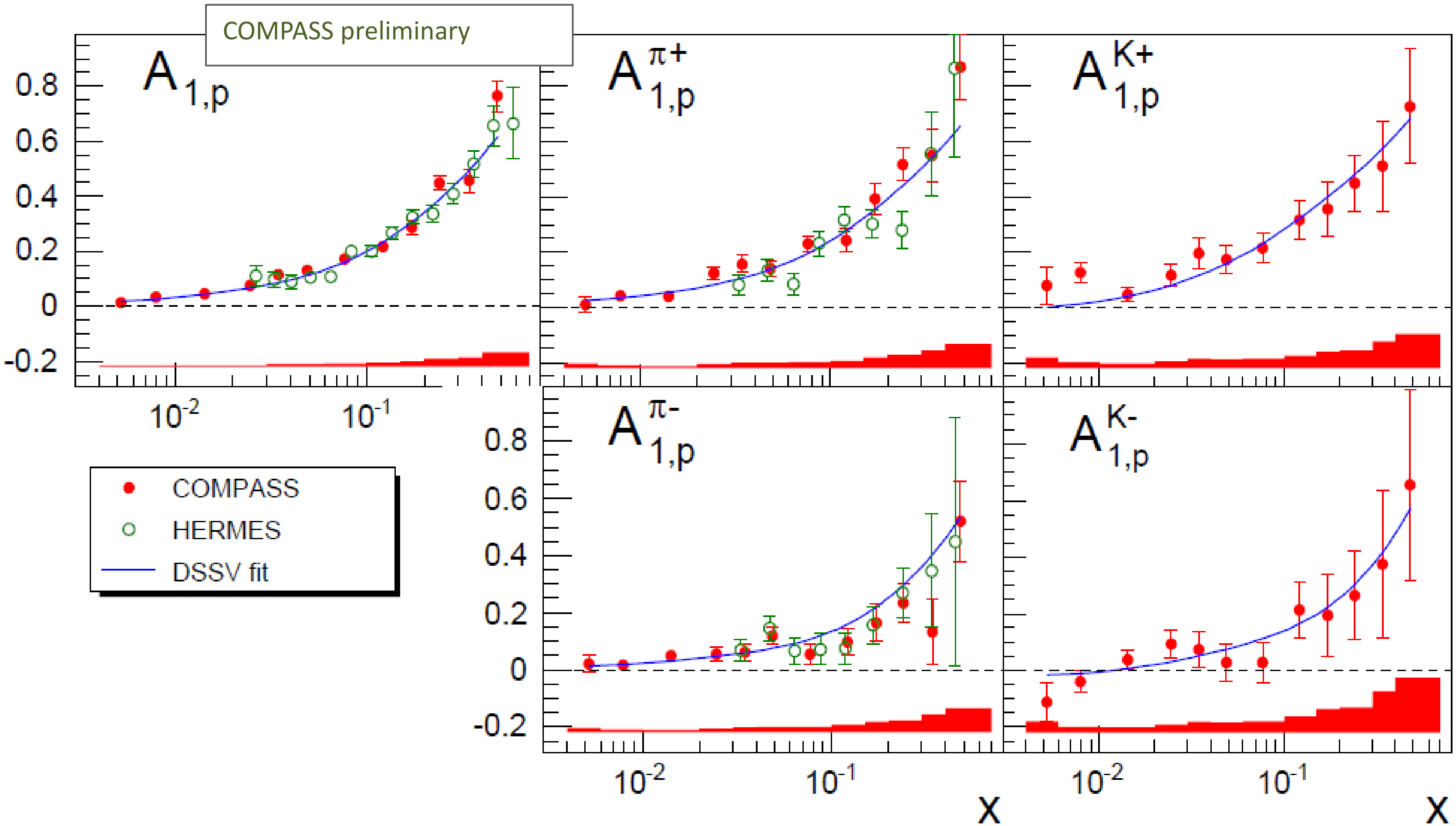
$$|g_A/g_V| = 1.28 \pm 0.07(\mathrm{stat.}) \pm 0.10(\mathrm{syst.})$$

from neutron β decay $|g_A/g_V| = 1.269$

# DIS & SIDIS asymmetries - deuteron

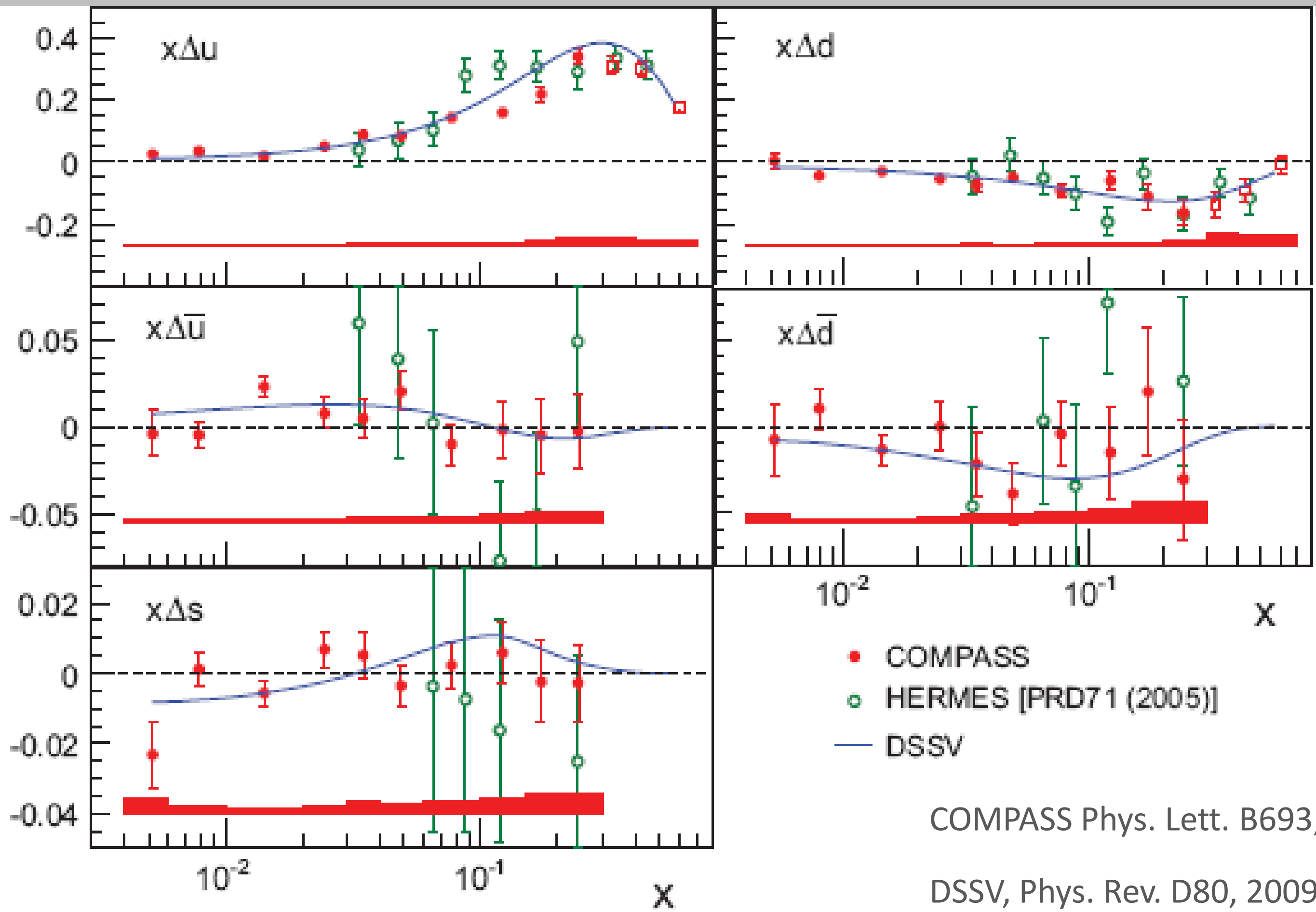


# DIS & SIDIS asymmetries - proton




- Leading Order (LO) fit of the 10 asymmetries (2x5)
- Determine 6 flavor separated PDFs : $\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s}$

# Helicity distributions



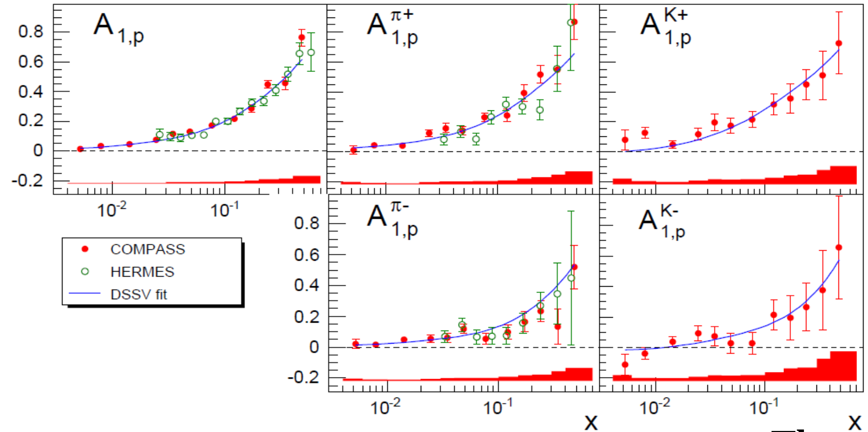

COMPASS Phys. Lett. B693, 2010.

DSSV, Phys. Rev. D80, 2009

**Δs: Truncated first moment:**
*(with DSS FF )*

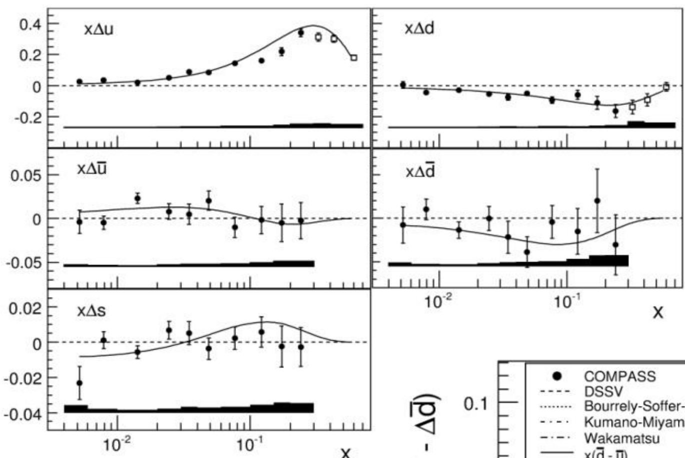
$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$

# Results

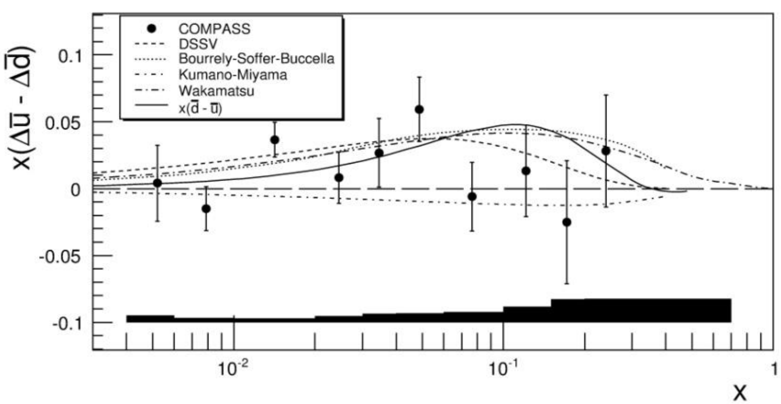



Double spin asymmetries for production of charged pions and kaons in semi inclusive deep inelastic muon scattering off longitudinally polarized protons have been measured.

A leading order evaluation of the helicity distributions for the three lightest quarks and anti-quark flavors, derived from these asymmetries and from previous deuteron data, are performed

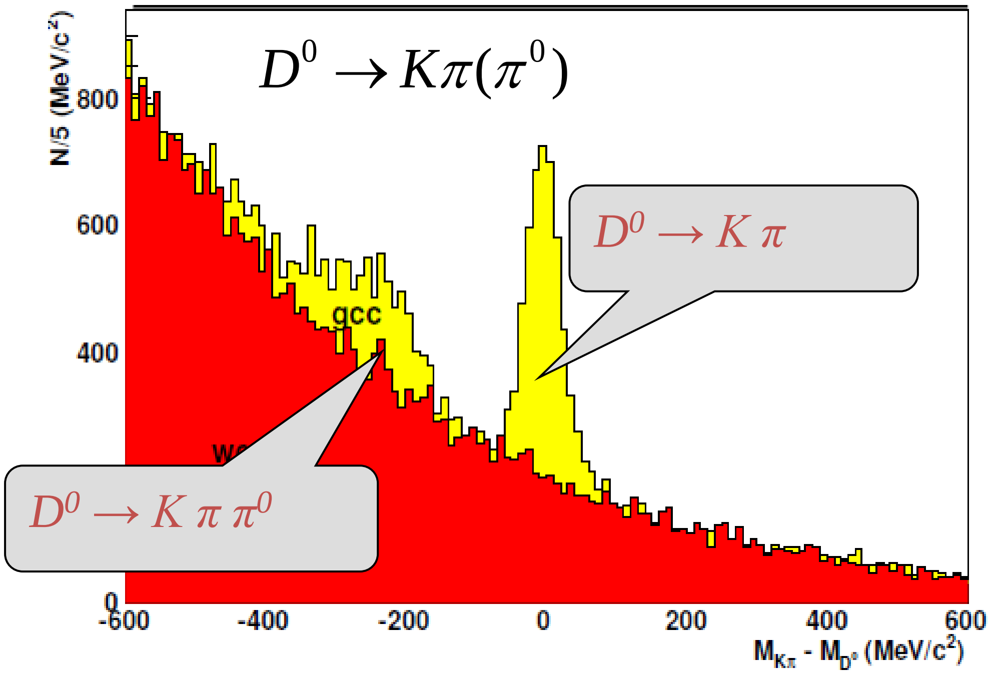


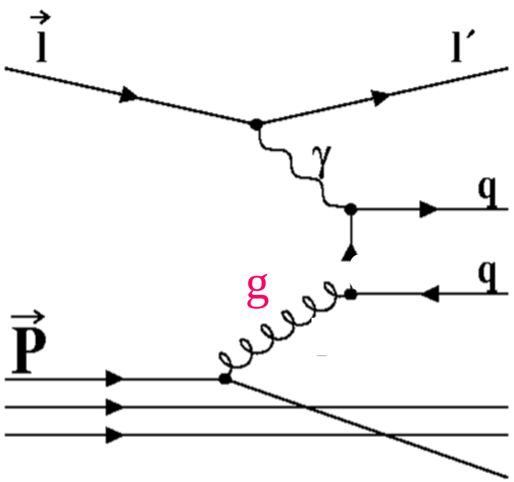

The resulting values for *u* and *d* quarks have opposite signs. The sea quark distributions are small and do not show sizable dependence on x in the range of the measurements. No significant difference is observed between the strange and anti-strange helicity distributions, both compatible with zero. The integrated value of the flavor asymmetry of the helicity distribution of the light quark sea, $\Delta\bar{u}$-$\Delta\bar{d}$, is found to be slightly positive, about 1.5 standard deviations away from zero.



# Gluon polarization measurements

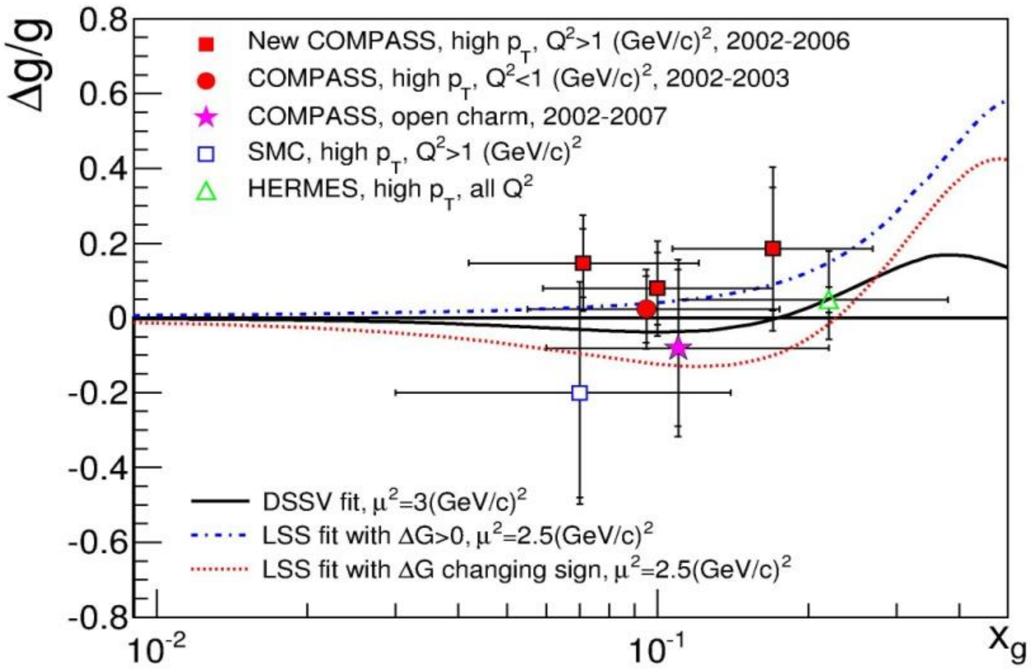
- open charm: single $D$ meson
  cleanest process wrt physics background




- high-$p_T$ hadron pairs with $Q^2 > 1$ GeV²
  high-$p_T$ hadron pairs with $Q^2 < 1$ GeV²
  single hadron production $Q^2 < 0.1$ GeV²

# ΔG: summary for open charm & high $p_T$




**The gluon polarization, $\Delta g/g$, in the nucleon is measured by several methods. One of them is based on the longitudinal double spin asymmetry of SIDIS events with a pair of large transverse momentum hadrons in the final state. The gluon polarization is evaluated at leading order OCD by a Neural Network approach for three intervals of the gluon momentum fraction $x_g$ covering the range $0.04<x_g<0.27$. The values obtained do not show significant dependence on $x_g$.**

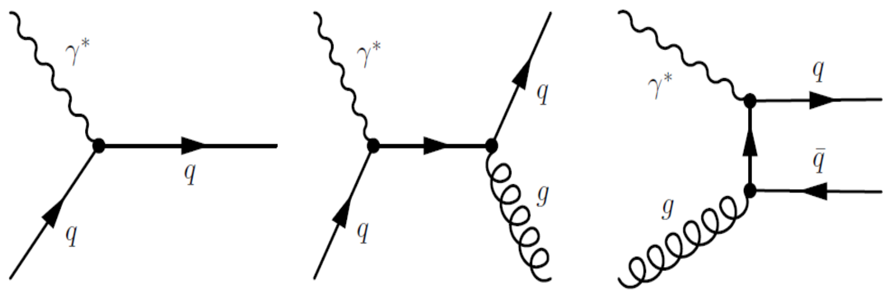
| | $x_g$ range | | | |
|---|---|---|---|---|
| | [0.04, 0.27] | [0.04, 0.12] | [0.06, 0.17] | [0.11, 0.27] |
| $x_g^{av}$ | 0.09 | 0.07 | 0.10 | 0.17 |
| $\Delta g/g$ | $0.125 \pm 0.060$ | $0.147 \pm 0.091$ | $0.079 \pm 0.096$ | $0.185 \pm 0.165$ |

**The average is: $\Delta g/g$=0.125 ± 0.060 (stat.) ± 0.063 (syst.) at $x_g$=0.09 and at a scale of $\mu^2 = 3\ (GeV/c)^2$ .**
**($\Delta g/g$ evaluations in NLO QCD are in preparation for publication)**

# $\Delta g/g$ using "all $p_T$" events

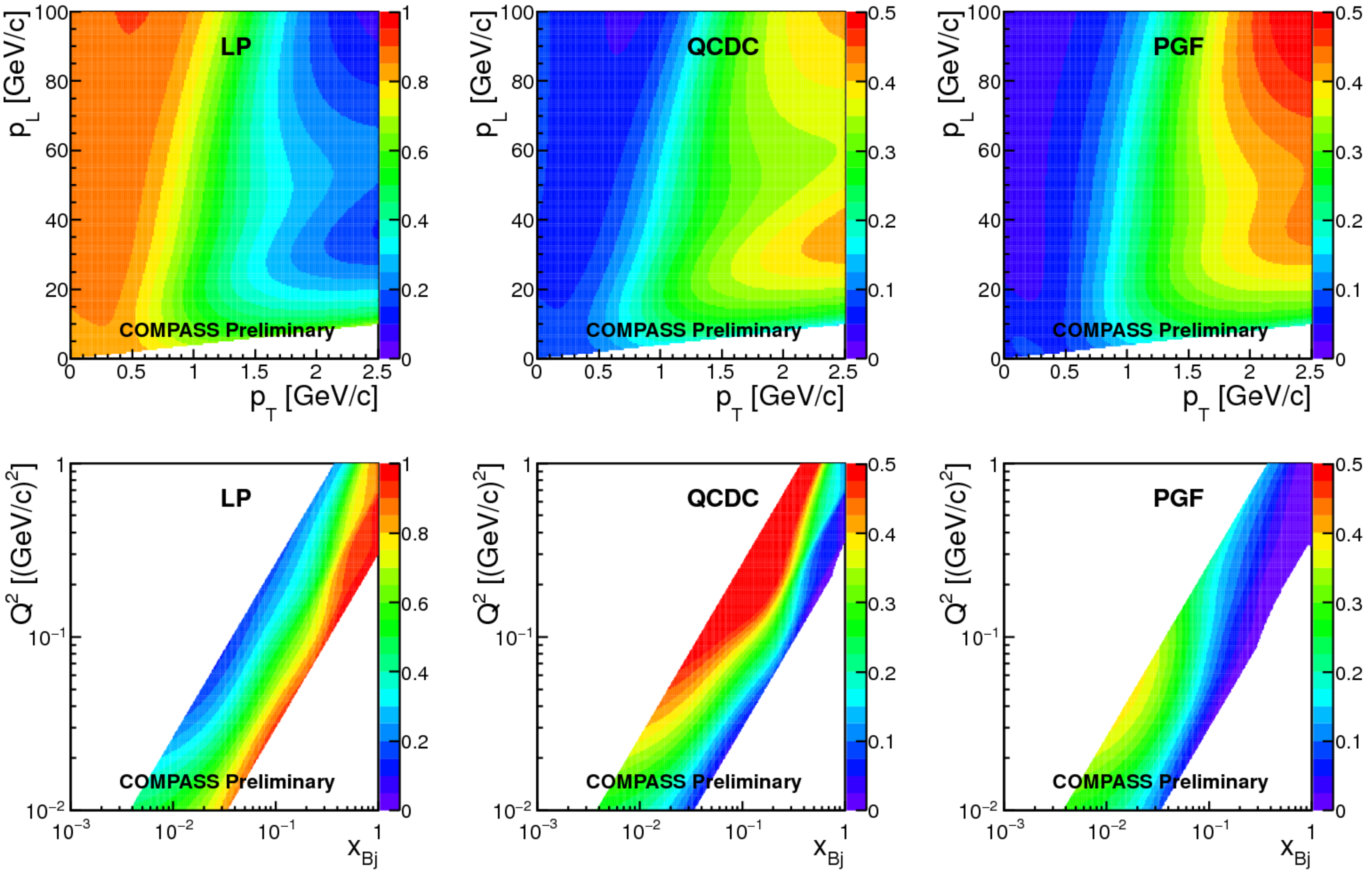
- The main goal is to improve the extraction by removing few sources of systematic effects.
- However, also a considerable reduction of the statistical error of $\Delta g/g$ was achieved.
- Three processes contribute to the cross-section

$$A_{LL}^{h}(x) = R_{LO} D A_1^{LO}(x) + R_{PQCD} a_{LL}^{QCDC} A_1^{LO}(x_C) + R_{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x_g)$$

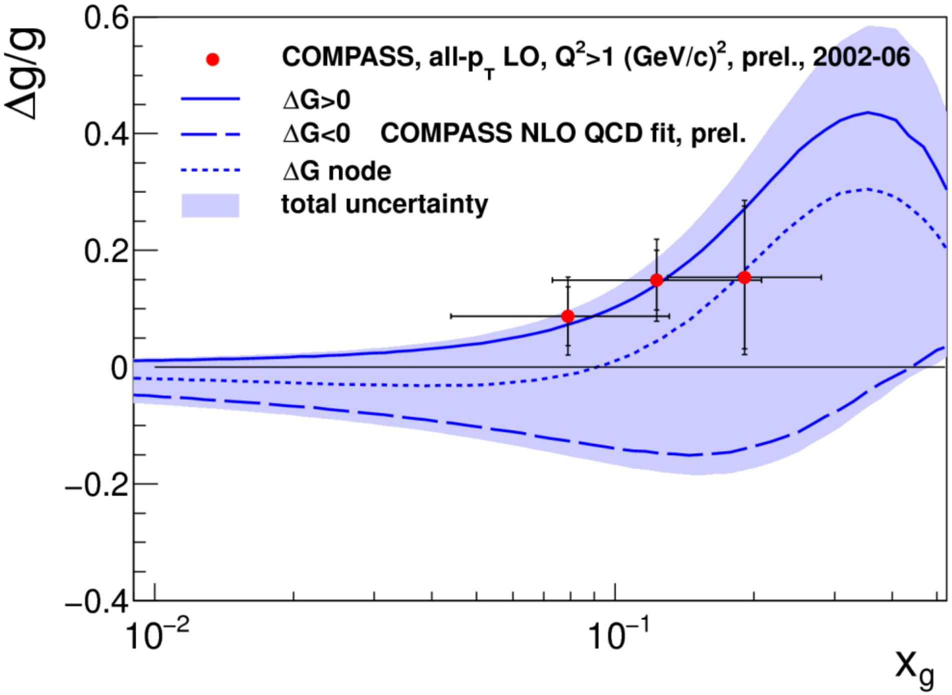



- Simultaneous extraction of $\Delta g/g$, and $A_1^{LO}$
- Extraction based on effective Monte Carlo description of all processes giving the relative weights ($R_i$) and analyzing powers ($a_{LL}^{i}$)
- Process weights depends on $p_T$ (at small $p_T$ LO contribution is > 0.95)

# $\Delta g/g$ using “all $p_T$” events: correlations



# $\Delta g/g$ using "all $p_T$" events: results

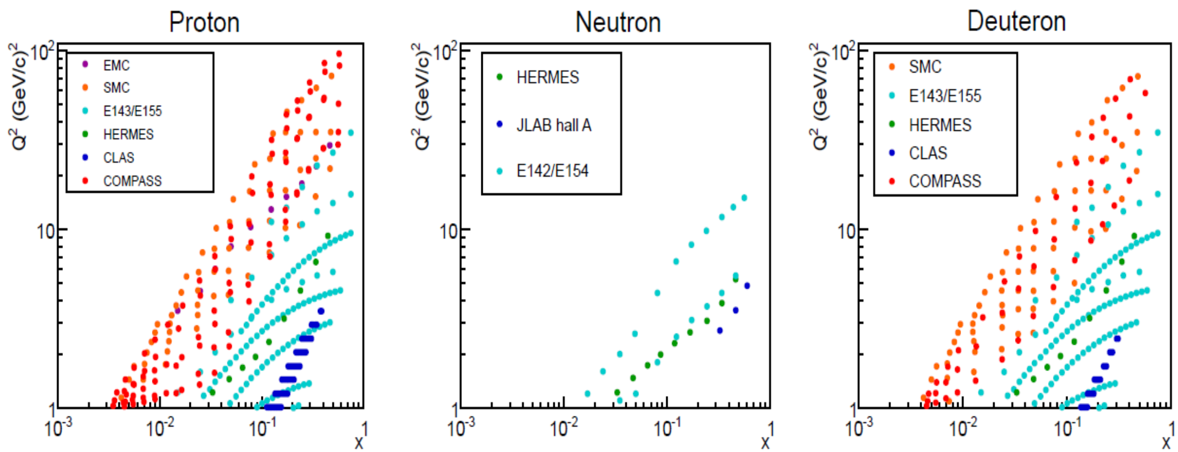



$$\Delta g/g\Big|_{\langle x_g\rangle=0.10} = 0.113 \pm 0.038 \pm 0.035$$

| $\langle x_g \rangle$ | $x_g$ range | $\Delta g/g$ |
|---|---|---|
| $x_g = 0.08$ | $0.04 - 0.13$ | $0.087 \pm 0.050$ |
| $x_g = 0.12$ | $0.07 - 0.21$ | $0.149 \pm 0.051$ |
| $x_g = 0.19$ | $0.13 - 0.28$ | $0.154 \pm 0.122$ |

# Global NLO QCD fits to world data on $g_1$

- 138 out of 679 points are from COMPASS




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

$\Delta q_S = \Delta u + \Delta d + \Delta s$; $\Delta q_{NS}$ is a combination of $\Delta q_3 = \Delta u - \Delta d$ and $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$

Evolving as

$$\frac{d}{d\ln Q^2}\Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi} \Delta P_{qq} \otimes \Delta q_{NS}$$

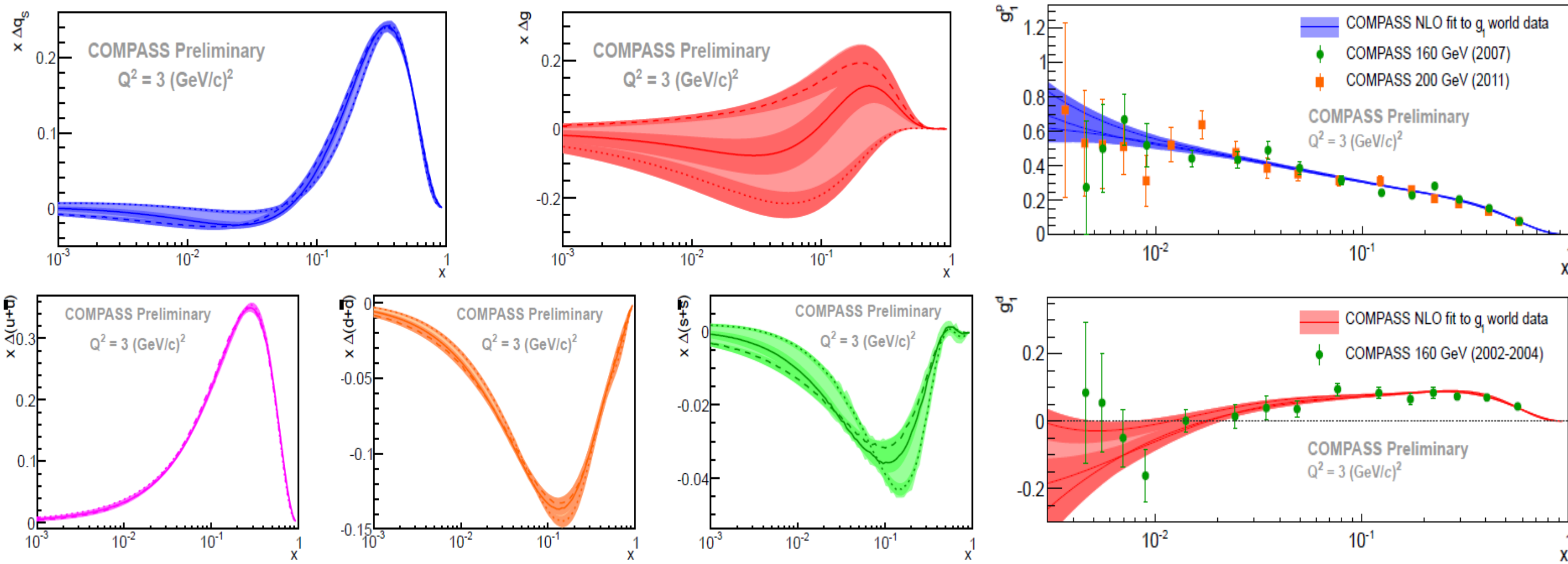
$$\frac{d}{d\ln Q^2}\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq} & 2n_f\Delta P_{qg}\\ \Delta P_{qg} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_S\\ \Delta g\end{pmatrix}$$

First moments of $\Delta q_3$ and $\Delta q_8$ fixed by baryon decay constants $(F + D)$ and $(3F - D)$ assuming $SU(2)_f$ and $SU(3)_f$ symmetries.

$$\Delta f_k(x) = \Delta q_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x + \rho\sqrt{x})}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x + \rho\sqrt{x})}$$

# Results

3 initial $\Delta g$ shapes; positive, negative with node.

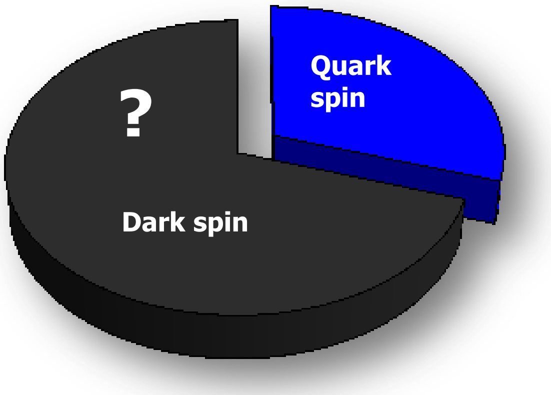



| Distribution | First moment at $Q^2 = 3\ (\mathrm{GeV}/c)^2$ |
|---|---|
| $\Delta\Sigma$ | [ 0.25 , 0.34] |
| $\Delta u + \Delta\bar{u}$ | [ 0.82 , 0.85 ] |
| $\Delta d + \Delta\bar{d}$ | [ −0.45 , −0.42 ] |
| $\Delta s + \Delta\bar{s}$ | [ −0.11 , −0.08 ] |

Range in $\Delta\Sigma$ driven by uncertainty on initial $\Delta g$ shape

# Summary I

- Many results on the helicity distributions Δq and Δg
- Full flavor decomposition Δu, Δd, Δs and antiquarks
  - Δu and Δd are rather well-known
  - open questions: Δu=Δd and Δs=Δs ?
- $\Delta\Sigma = 0.25 \pm 0.05$;  $\Delta G \approx 0 \pm 0.5$
- Nucleon spin puzzle is still not solved



# Transverse spin structure

# TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at leading twist
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, $\Phi_h$ and $\Phi_s$
- Vanish upon integration over $k_T$ except $f_1$, $g_1$, and $h_1$

| quark polarization \ nucleon polarization | U | L | T |
|---|---|---|---|
| U | $f_1$ number density | | $f_{1T}^{\perp}$ |
| L | | $g_1$ helicity | $g_{1T}$ |
| T | $h_1^{\perp}$ | $h_{1L}^{\perp}$ | $h_1$ transversity<br>$h_{1T}^{\perp}$ |

| | aka |
|---|---|
| Sivers | $\Delta_0^T q$ |
| Transversity | $\Delta_T q$ |

Boer–Mulders

chiral odd

# TMD effects in nucleon structure
# Sivers and Collins asymmetries

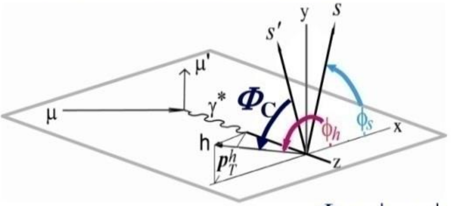
## Collins asymmetry (used for extraction Transversity PDF)

amplitude of the $\sin\Phi_C$ modulation
in the azimuthal distribution
of the final state hadrons

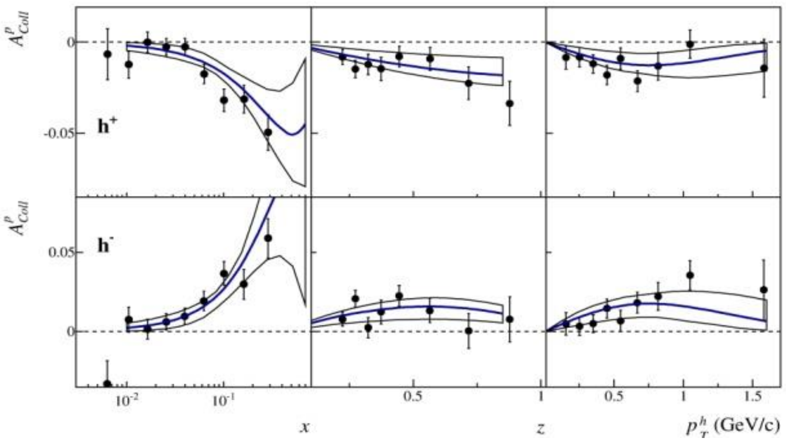
$$N_h^{\pm}(\Phi_C) = N_h^0\left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$

transversity — "Collins FF"

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




$\Phi_C = \phi_h + \phi_s - \pi$




The Collins asymmetries for negative and positive hadrons are similar in magnitude and opposite in sign. They are compatible with model calculations in which the *u*-quark transversity is opposite in sign and somewhat larger than the *d* quark transversity distribution function. The high statistics of the data also allow for more detailed investigations of the dependence on the kinematic variables. These studies confirm the leading-twist nature of the Collins asymmetry.

## Sivers asymmetry

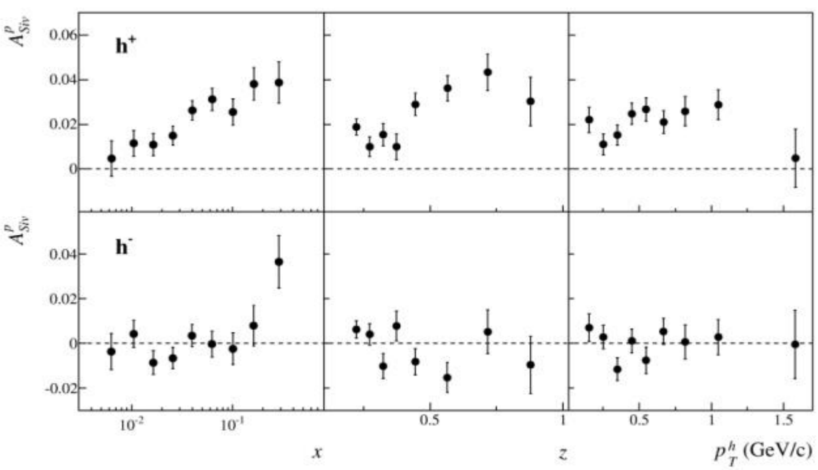
amplitude of the $\sin\Phi_S$ modulation
in the azimuthal distribution
of the final state hadrons

$$N_h^{\pm}(\Phi_S) = N_h^0\left[1 \pm P_T \cdot A_{Siv} \cdot \sin\Phi_S\right]$$

Sivers PDF

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

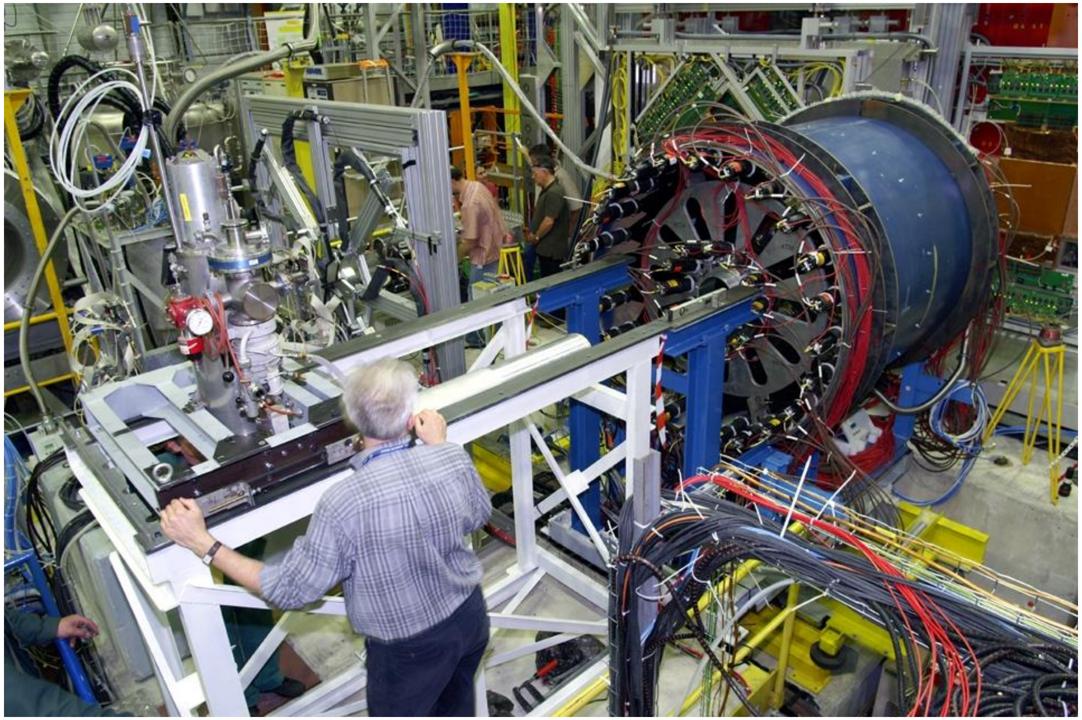
$\Phi_S = \phi_h - \phi_s$




The Sivers asymmetry is found to be compatible with zero for negative hadrons and positive for positive hadrons, a clear indication of a spinorbit coupling of quarks in a transversely polarised proton .

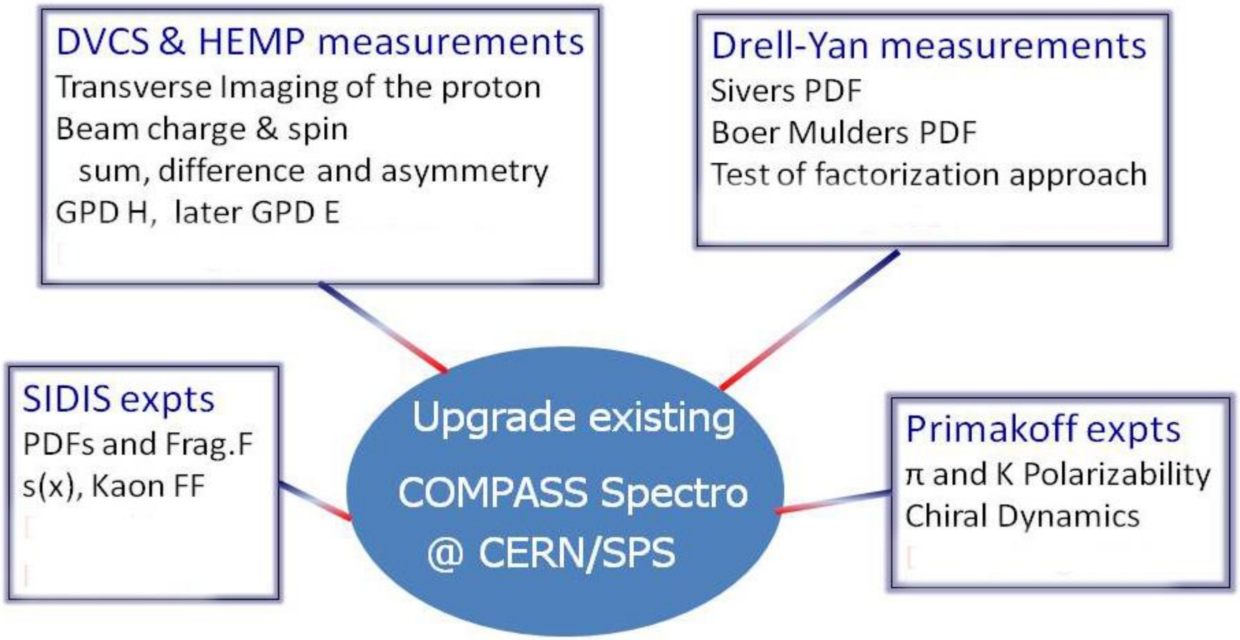
# Physics with hadron beams

- **Proton, pion (and kaon) beams**
- **hydrogen, nickel and lead targets**



**Not discussed today**

# COMPASS-II (2012-2016)



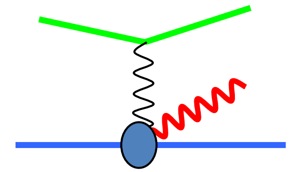

**The COMPAS-II measurements have started in 2012 with a pion/kaon polarisability via Primakoff reactions and with GPD feasibility test using partially upgraded COMPASS-II spectrometer.**

**The further measurements will start in 2014 after the accelerator shutdown.**
**They will be focused on studies of transverse momentum dependent (TMD) distributions of partons in nucleons via Drell-Yan lepton pair production and measurements of generalized parton distributions (GPDs) via hard exclusive meson production and DVCS .**

**In parallel with the GPD program, high statistic data for unpolarized SIDIS will be taken.**

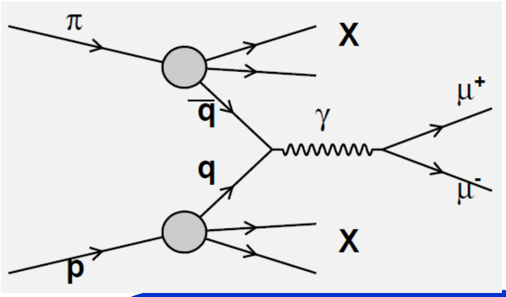
# Exploring the 3-dimensional phase-space structure of the nucleon

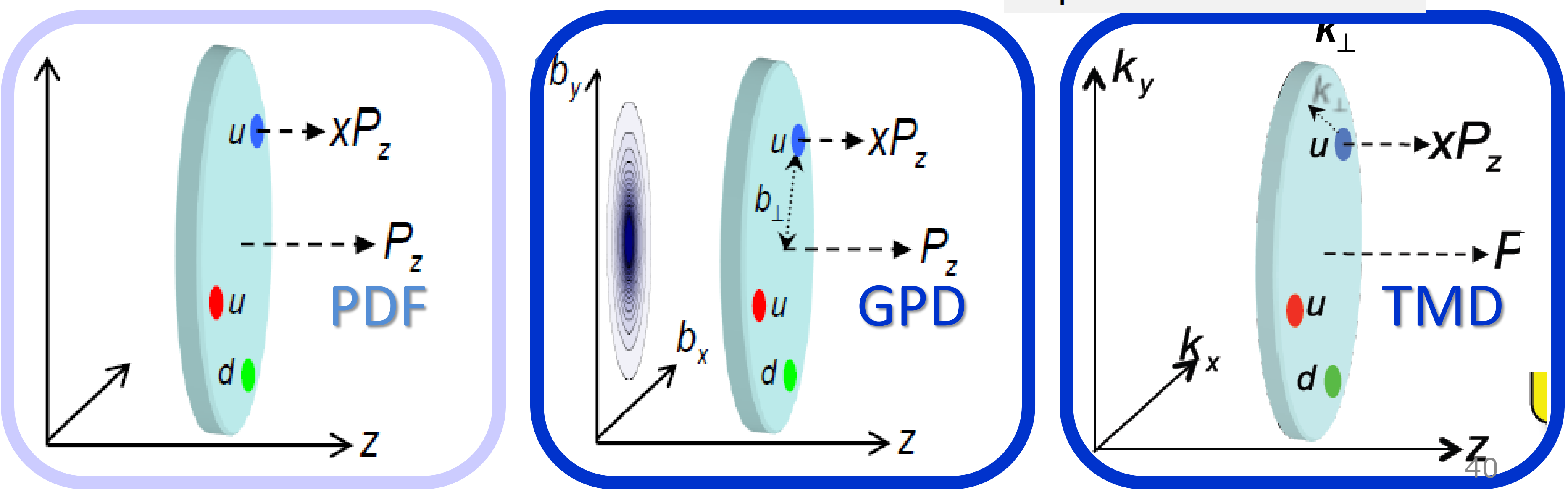
- **GPD: Generalised Parton Distribution (position in the transverse plane)**



**Deep VCS**

- **TMD:Transverse Momentum Distribution (momentum in the transv. plane)**



# COMPASS-II schedule

| | | |
|---|---|---|
| 2012 | Primakoff scattering: | Polarizabilities of p and K |
| | DVCS pilot run: | *t*-slope, transverse size |
| 2013 | Accelerator shutdown | |
| 2014/15 | Drell-Yan: | Universality of TMDs |
| 2016/17 | DVCS and DVMP: | Study GPDs, "nucleon tomography" |
| | Unpolarized SIDIS: | FF, strangeness PDF, TMDs |

# Summary II

- COMPASS has a rich programme on QCD and hadron physics
- Nucleon spin
  - Essential contributions to clarify the spin structure of the nucleon both longitudinal and transverse
  - Gluon polarisation
  - Flavour separation (SIDIS)
- Huge data set on hadron spectroscopy
  - tests of chiral perturbation theory
  - new meson discovered, exotic mesons being studied
  - many more channels, e.g. $\pi^0$, $\eta$, $\eta'$, $pp \to p_{\text{fast}}\pi^+\pi^- p_{\text{slow}}$
  - just the beginning...
- Future experiments
  - Starting future program on GPDs and TMD PDFs
  - Maybe come back to spectroscopy

# Thank you!

# Backup

# Sum Rules

Bjorken sum rule

PR 148 (1966) 1467

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_a$$

if wrong $\Rightarrow$ QCD wrong, "worthless equation", needs neutron measurement

Ellis-Jaffe sum rule

PR D9 (1974) 1444

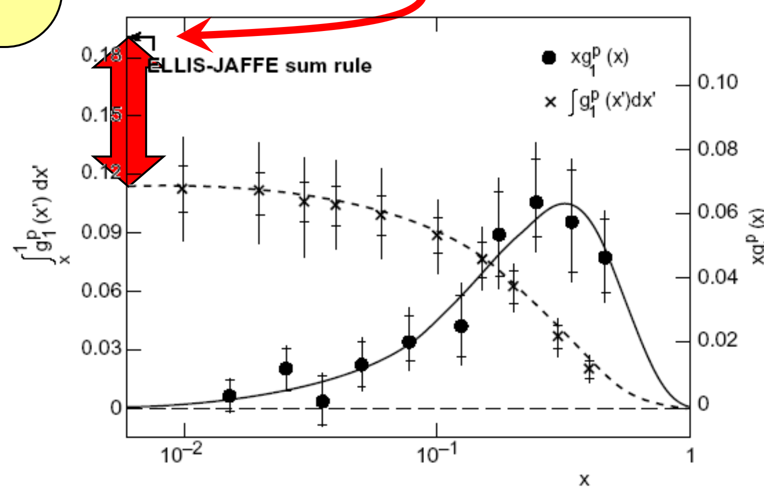
$$\Gamma_1^p = \frac{1}{12} g_a + \frac{5}{36}\sqrt{3} a_8 + \frac{1}{3}\Delta s \Rightarrow \Delta\Sigma \simeq 0.6$$

formulated for $\Delta s=0$, unpolarised strange quarks

Consequences of violation:

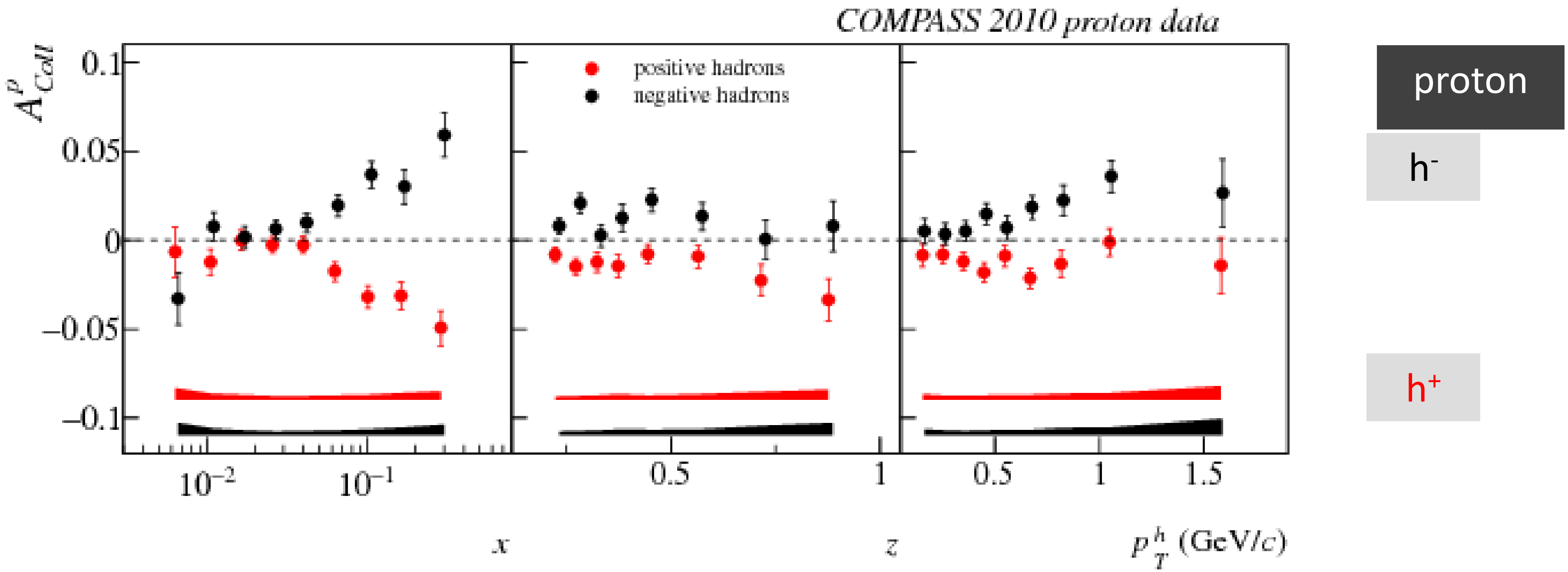
$$\begin{aligned} \Delta s &= -0.19 \pm 0.06 \\ \Delta\Sigma &= 0.12 \pm 0.17 \end{aligned}$$

EMC 1987



# Collins Asymmetries

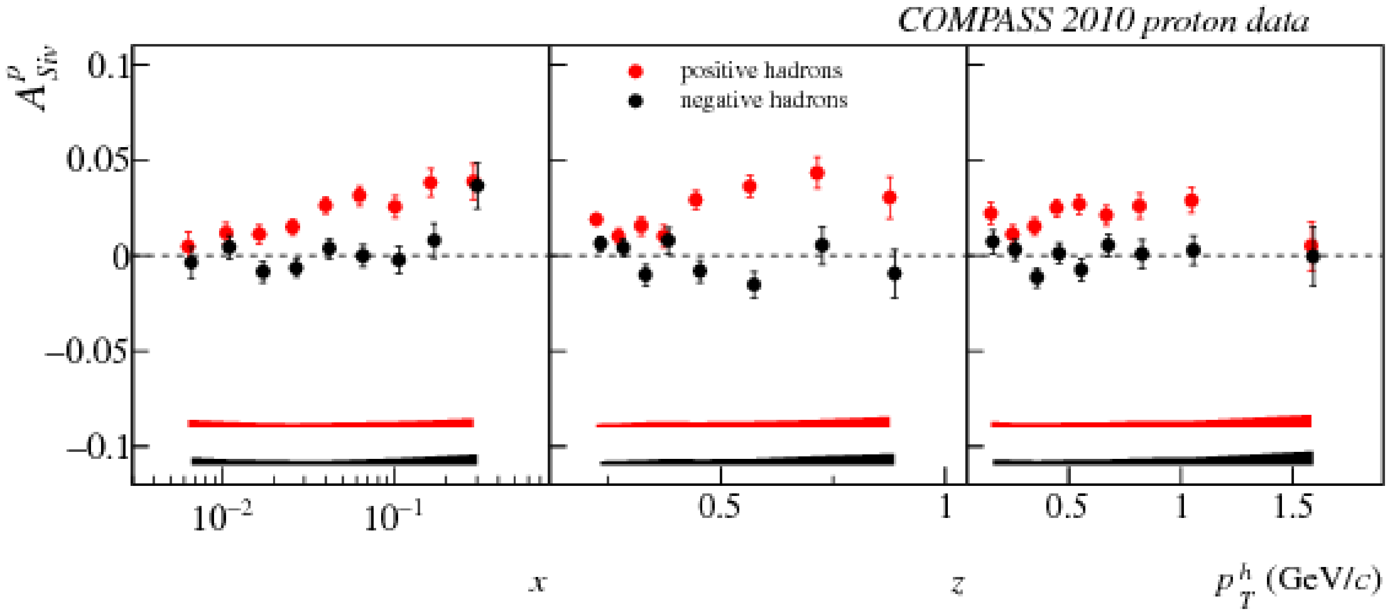
- large asymmetry for proton ~10%
- zero deuteron result important ⇒ opposite sign of u and d




PLB717 (2012) 326

# Proton Sivers Asymmetry

- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons




h+

h-

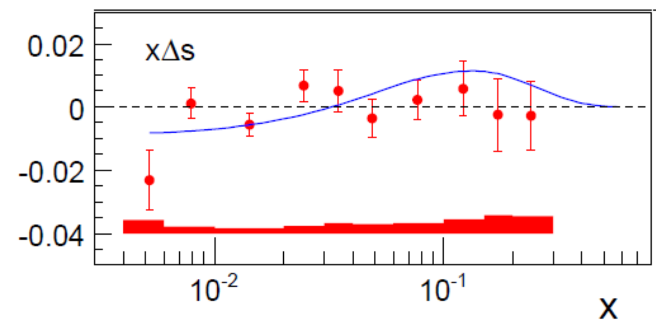
# The strange quark polarization puzzle

- DIS (only) data:
  - Sensitive to the integral value of Δs(x); assuming that SU(3) is valid and using hyperon decay data:

$$\int_0^1 \left[\Delta s(x) + \Delta \bar{s}(x)\right] dx = 0.08 \pm 0.01 \pm 0.01$$

- SIDIS data:
  - Measures the Δs(x) directly; assuming that the fragmentation functions, specifically $D_s^K$, is known:

$$\Delta s(x) \approx 0$$




- Possible explanations:
  1. Changing sign of Δs(x)
     DSSV and LSS global QCD fits
  2. Assume strong SU(3) violation
     Bass and Thomas, PLB 684(2010)216.
  3. Large uncertainty on the $D_s^K$ fragmentation function
     2013: data from Hermes and Compass