Spin of the nucleon:
The COMPASS programme, present and future

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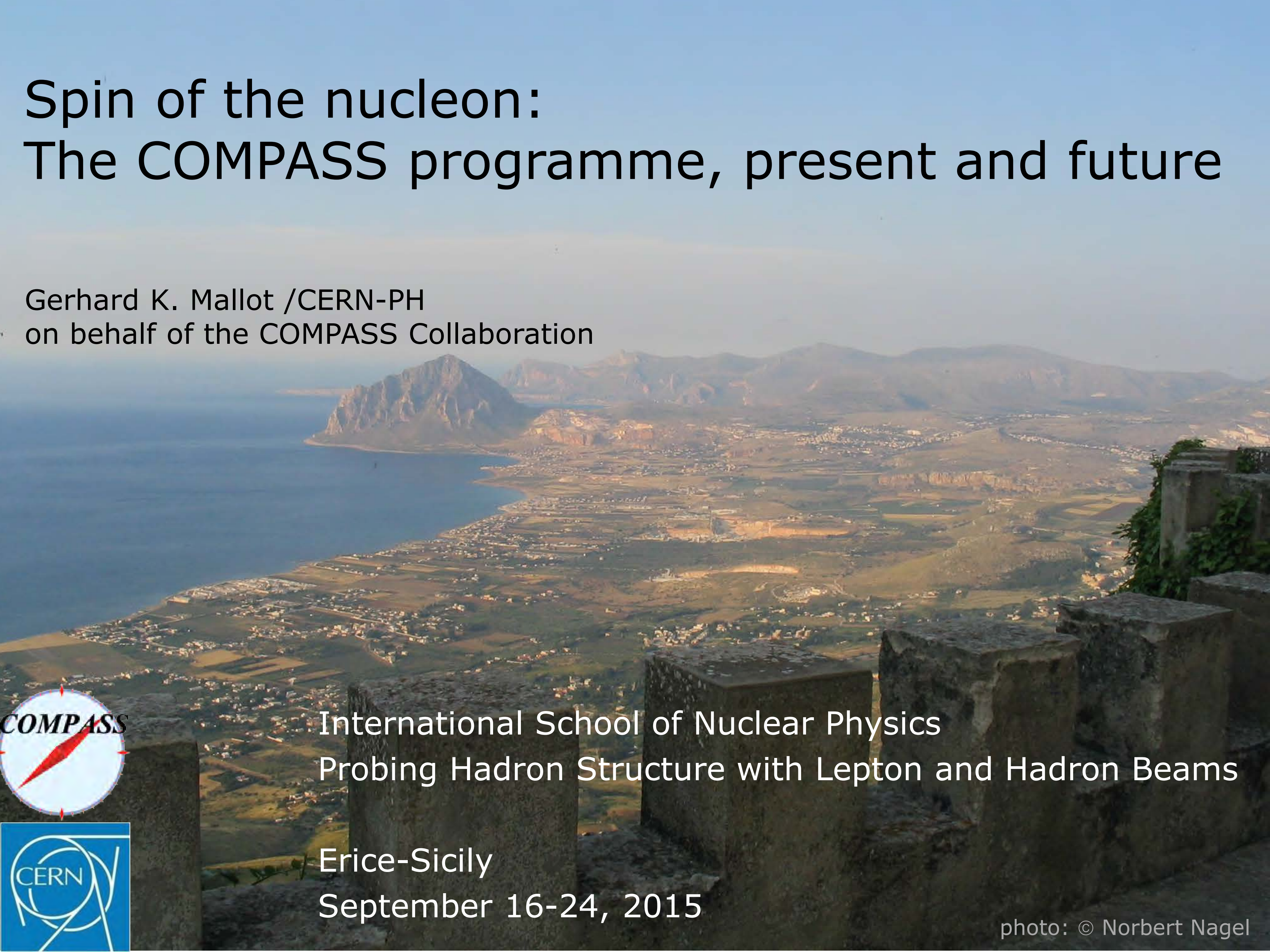
on behalf of the COMPASS Collaboration



International School of Nuclear Physics
Probing Hadron Structure with Lepton and Hadron Beams

Erice-Sicily
September 16-24, 2015

photo: © Norbert Nagel

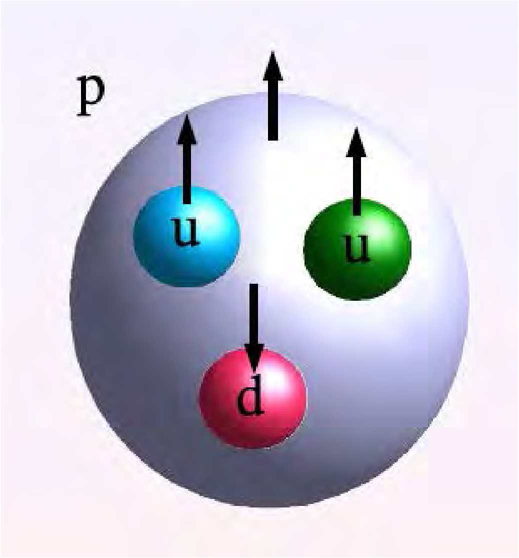
Outline

- Introduction
- Experiment
- Longitudinal spin: DIS results
- Longitudinal spin: SIDIS results
- COMPASS-II
- Add-on: Physics with hadrons beams

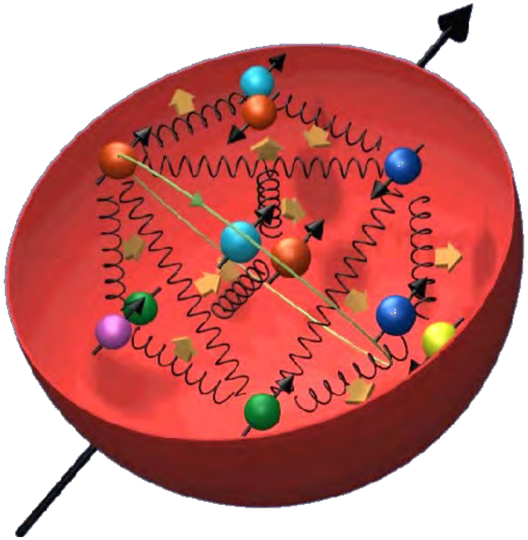
- Not covered ($\rightarrow$ F. Bradamante):
  - transverse spin, TMDs
  - hadron multiplicities and fragmentation functions

1. Introduction: nucleon spin

- Nucleon
  - 3 valence quarks
  - sea quark-antiquark pairs
  - gluons



- Spin
  - quark/antiquark spins
  - gluon spins
  - orbital angular momentum



Spin: Static Quark Model

- notation: $\Delta q = q^{+} - q^{-}$
- Proton: $\Delta u = \frac{4}{3}$ $\Delta d = -\frac{1}{3}$ $\Delta s = 0$ (in $\hbar$)

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

- EMC 1988: $\Delta\Sigma \approx 0.12$ "spin crisis"
- Now: $\Delta\Sigma \approx 0.30$
- Quark spins do not dominantly carry the nucleon spin

Where is the proton spin?

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

$\frac{1}{2}\Delta\Sigma$	ΔG	L_z
small	smallish, sign?	unknown, quark & gluon

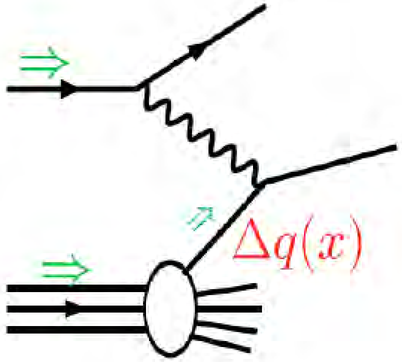
in infinite-momentum frame

Tools to study the partonic nucleon structure

Factorisation of hard interaction and nonperturbative nucleon structure/fragmentation:

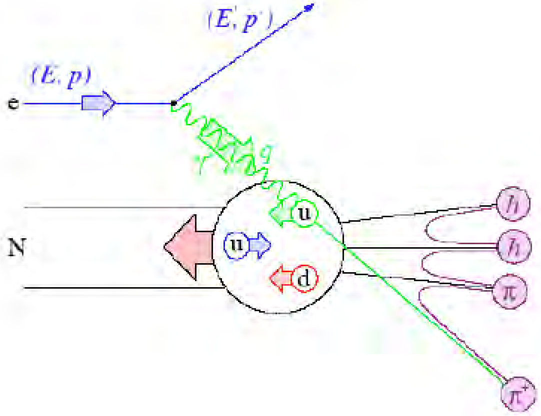
- PDF parton distribution functions
- FF fragmentation functions

DIS



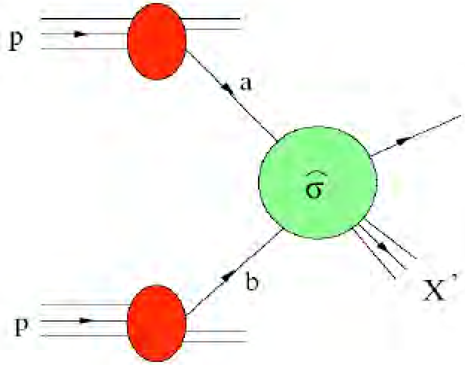
PDF

SIDIS



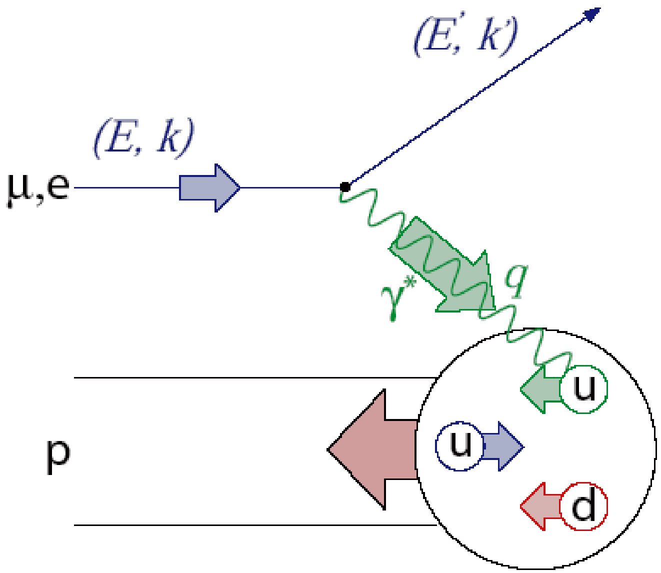
PDF⊗FF

pp



PDF⊗PDF

Deep inelastic scattering



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

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

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

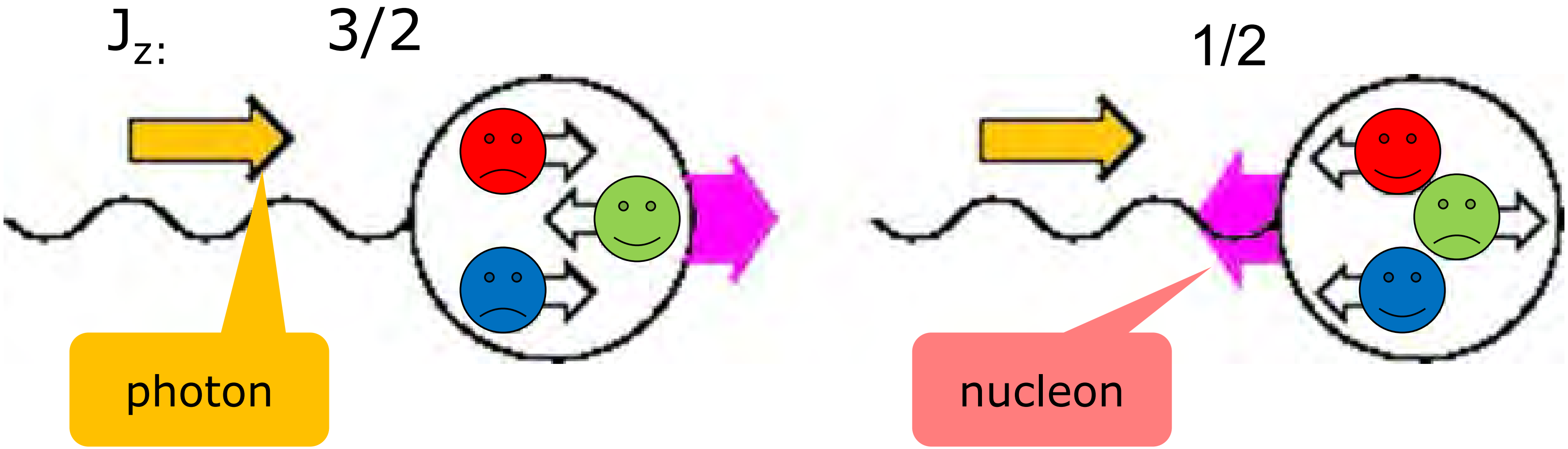
$$x \overset{lab}{=} \frac{Q^2}{2M\nu} = \frac{-q^2}{2P\cdot q}$$

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

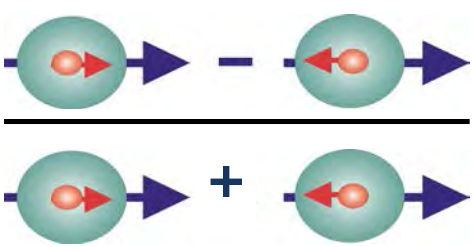
$$0 \leq x, y \leq 1$$

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

Structure Function asymmetry



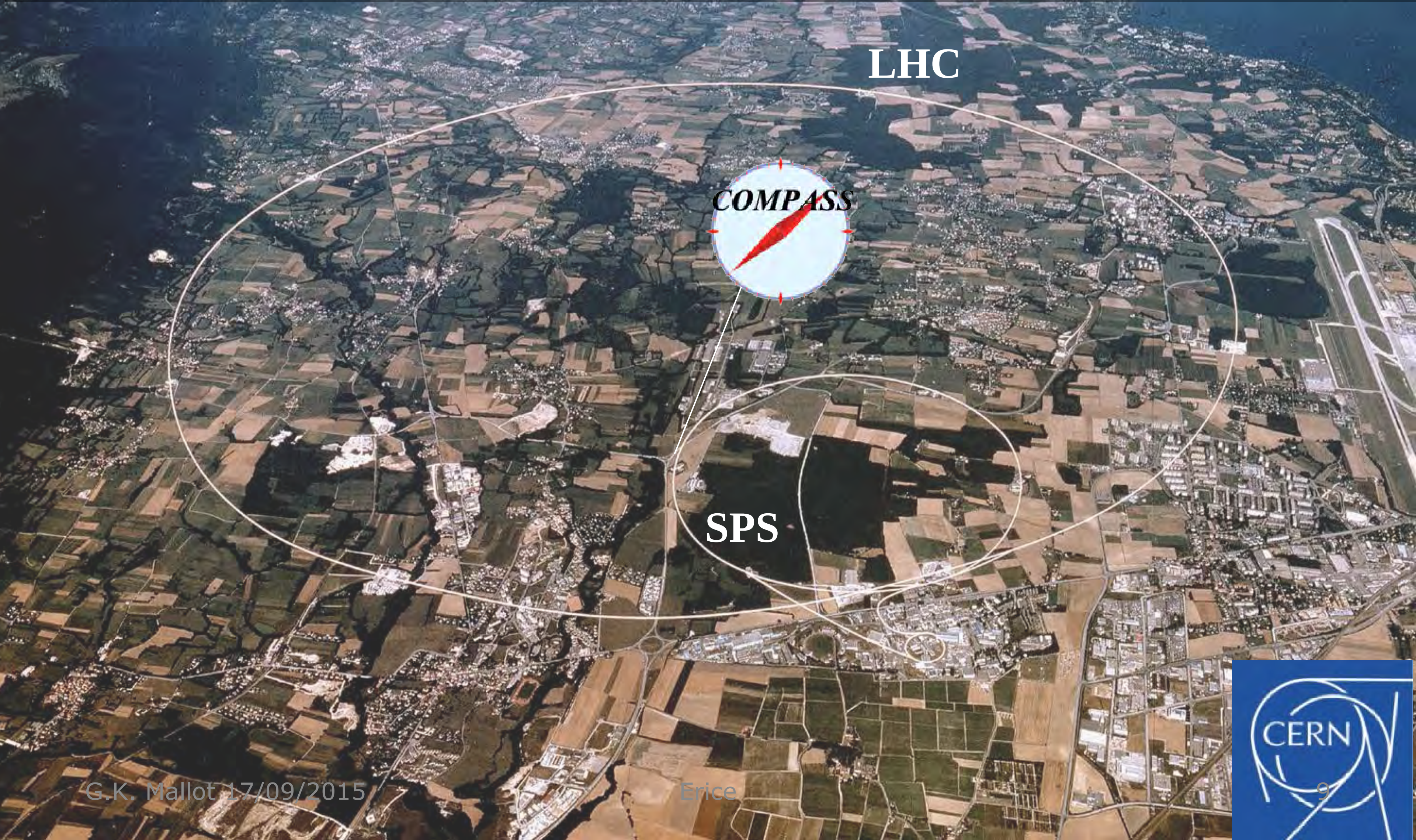
Measure longitudinal double-spin x-sect. asymmetries



$$A_1(x, Q^2) = \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)} = \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

2. The COMPASS experiment

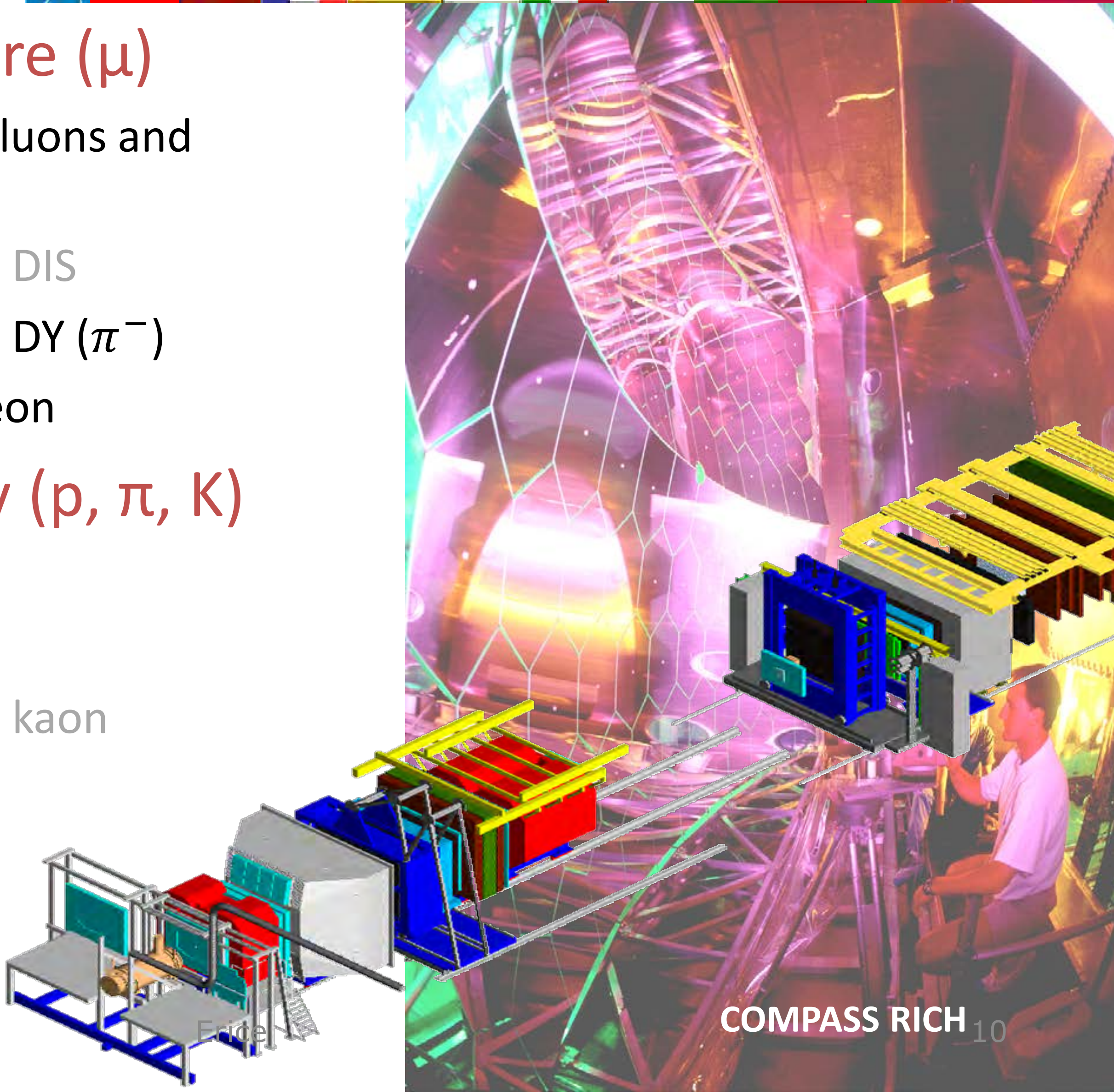
COmmon Muon and Proton Apparatus for Structure and Spectroscopy"



COMPASS: QCD structure of hadrons

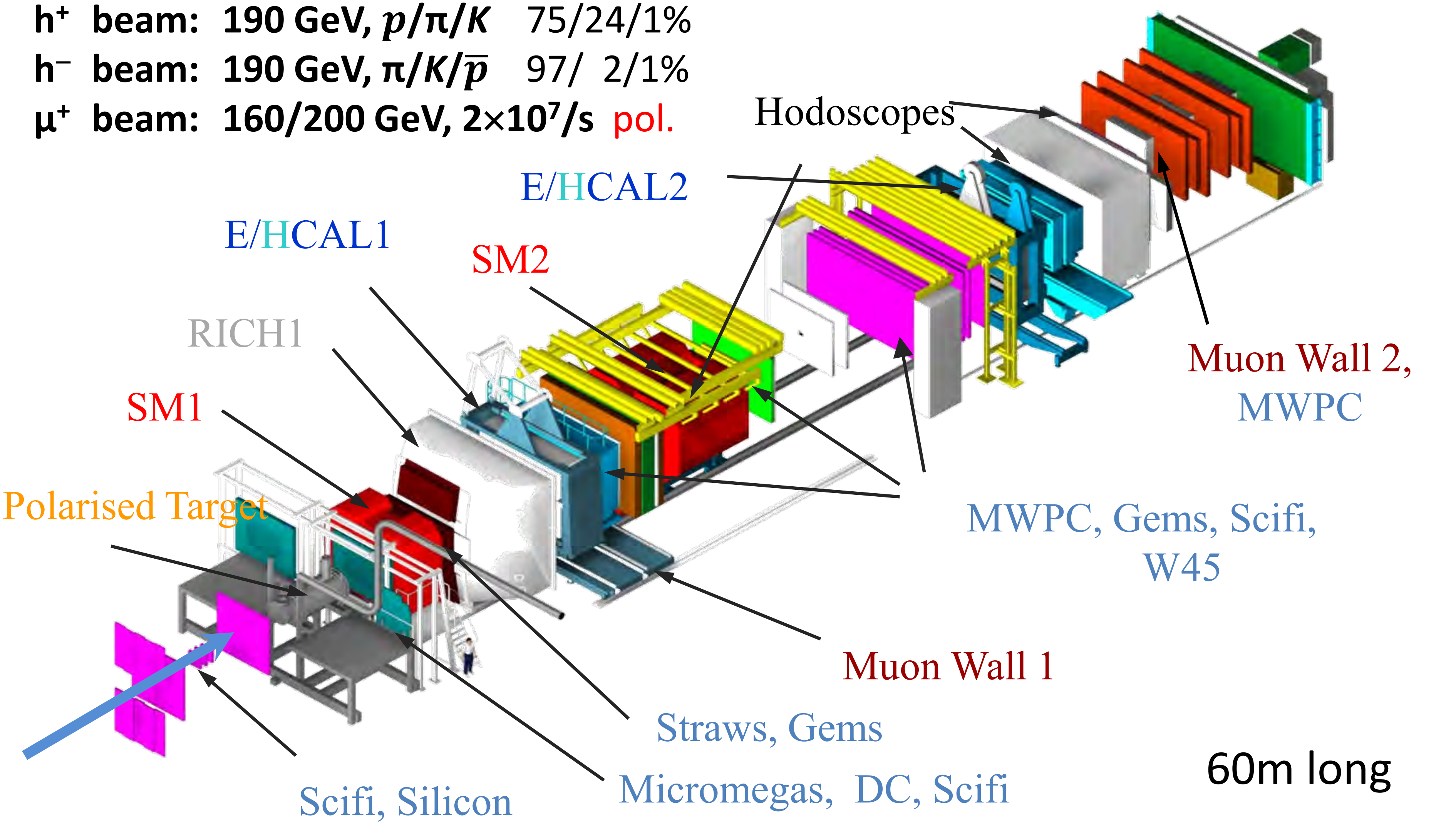
data taking since 2002

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



COMPASS spectrometer

h⁺ beam: 190 GeV, $p/\pi/K$ 75/24/1%
h⁻ beam: 190 GeV, $\pi/K/\bar{p}$ 97/ 2/1%
μ⁺ beam: 160/200 GeV, $2{\times}10^7$/s pol.



60m long

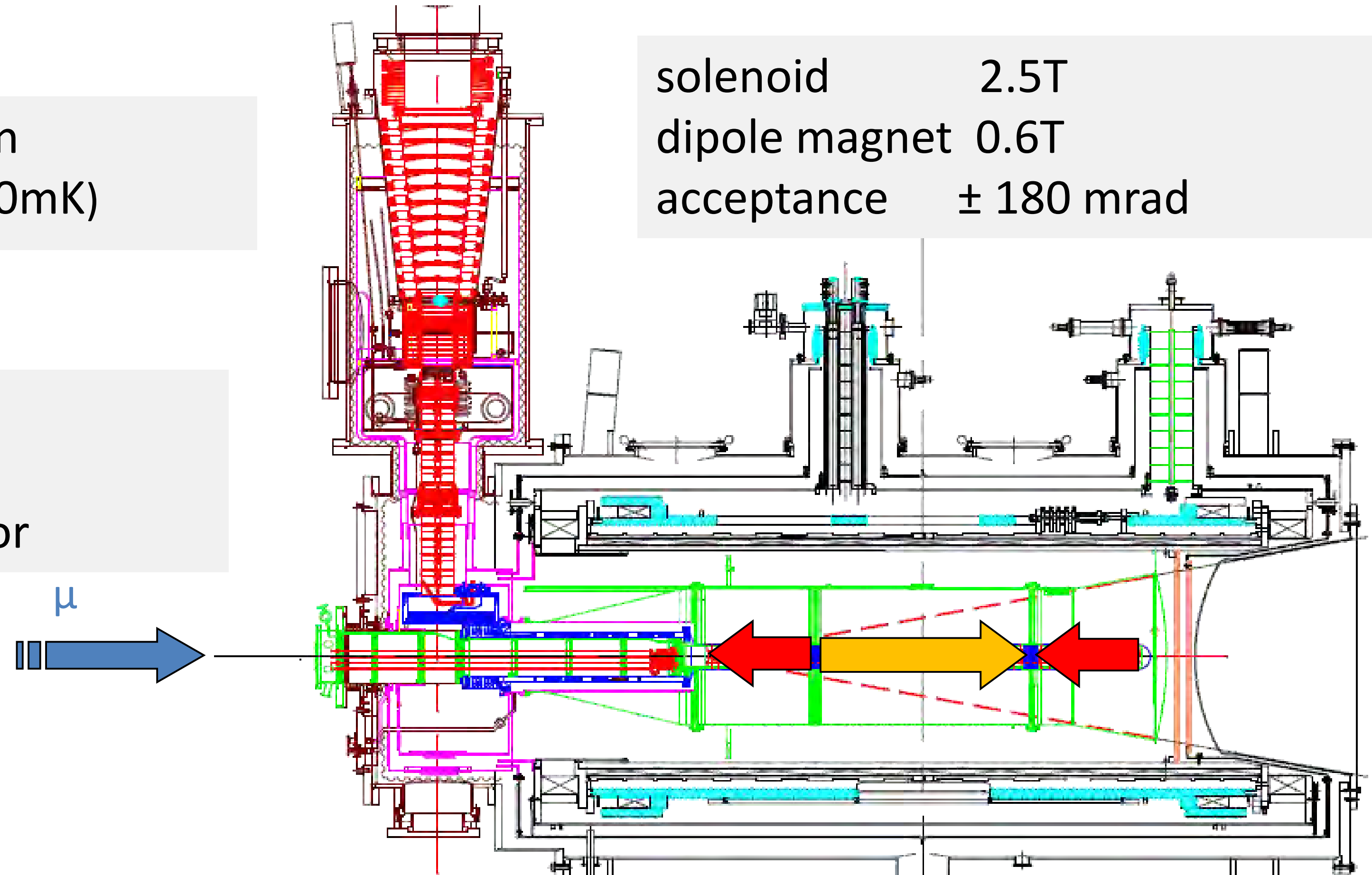
Polarized target system

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

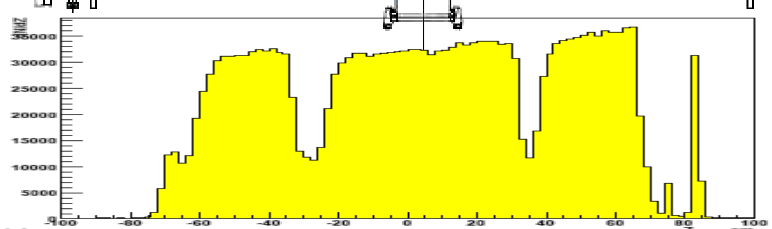
$^6LiD/NH_3$ (d/p)
50/90% pol.
40/16% dil. factor

solenoid 2.5T
dipole magnet 0.6T
acceptance ± 180 mrad

μ

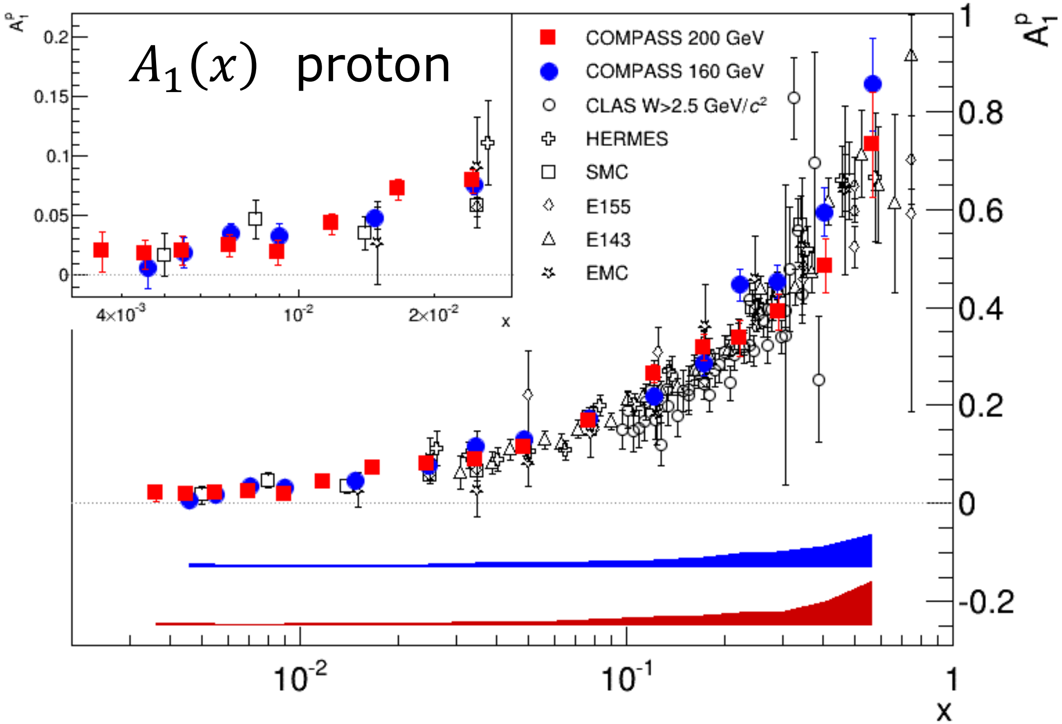


Recontructed interaction vertices

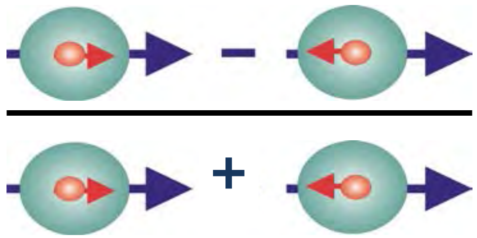


3. Longitudinal spin: DIS results

g1 and PDFs

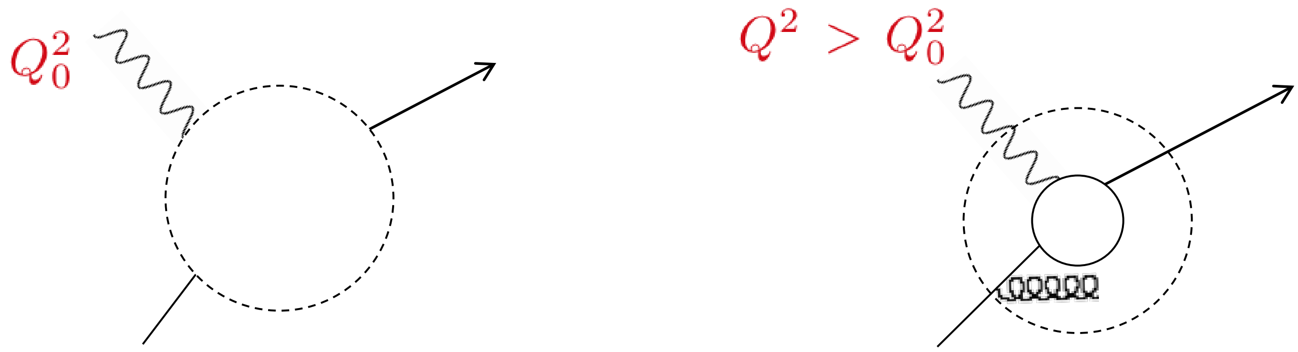


x: Bjorken x, fraction of nucleon mom. carried by struck quark in inf. mom. frame

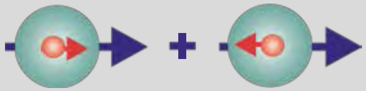
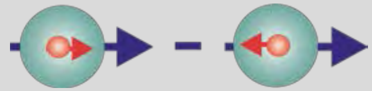


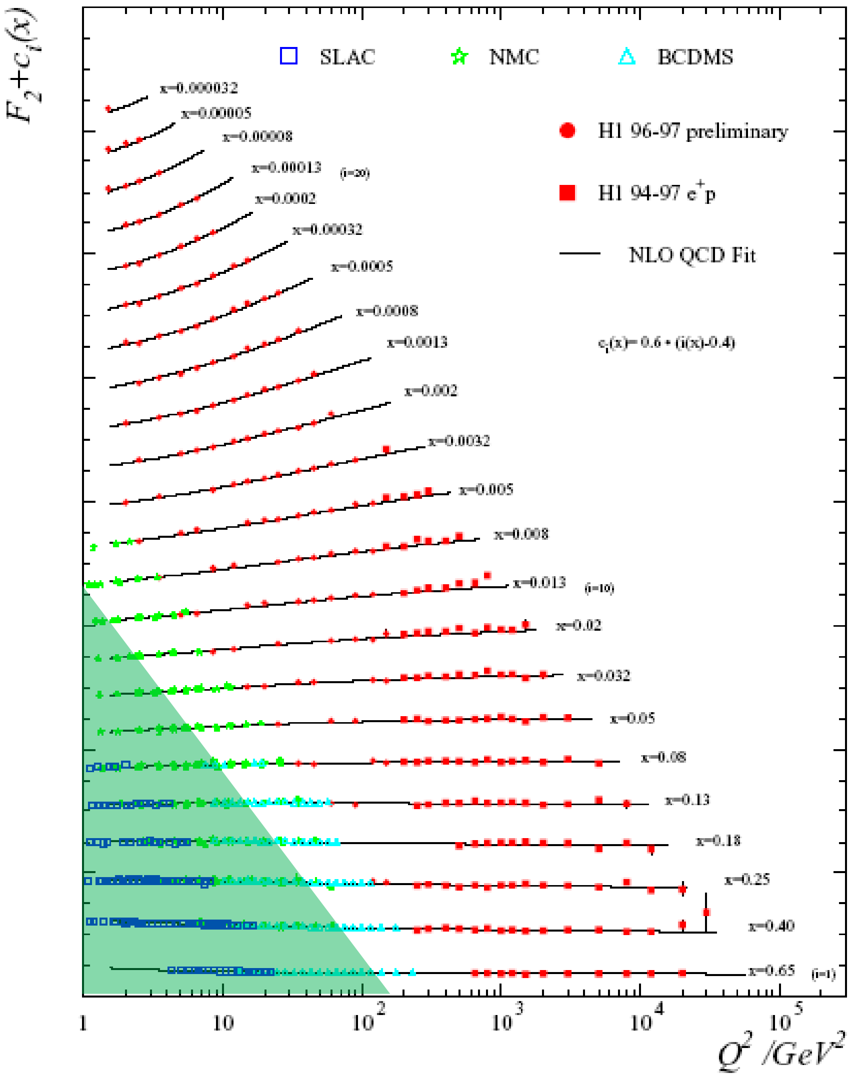
$$A_1(x,Q^2) = \frac{\Sigma_q e_q^2 \Delta q(x,Q^2)}{\Sigma_q e_q^2 q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

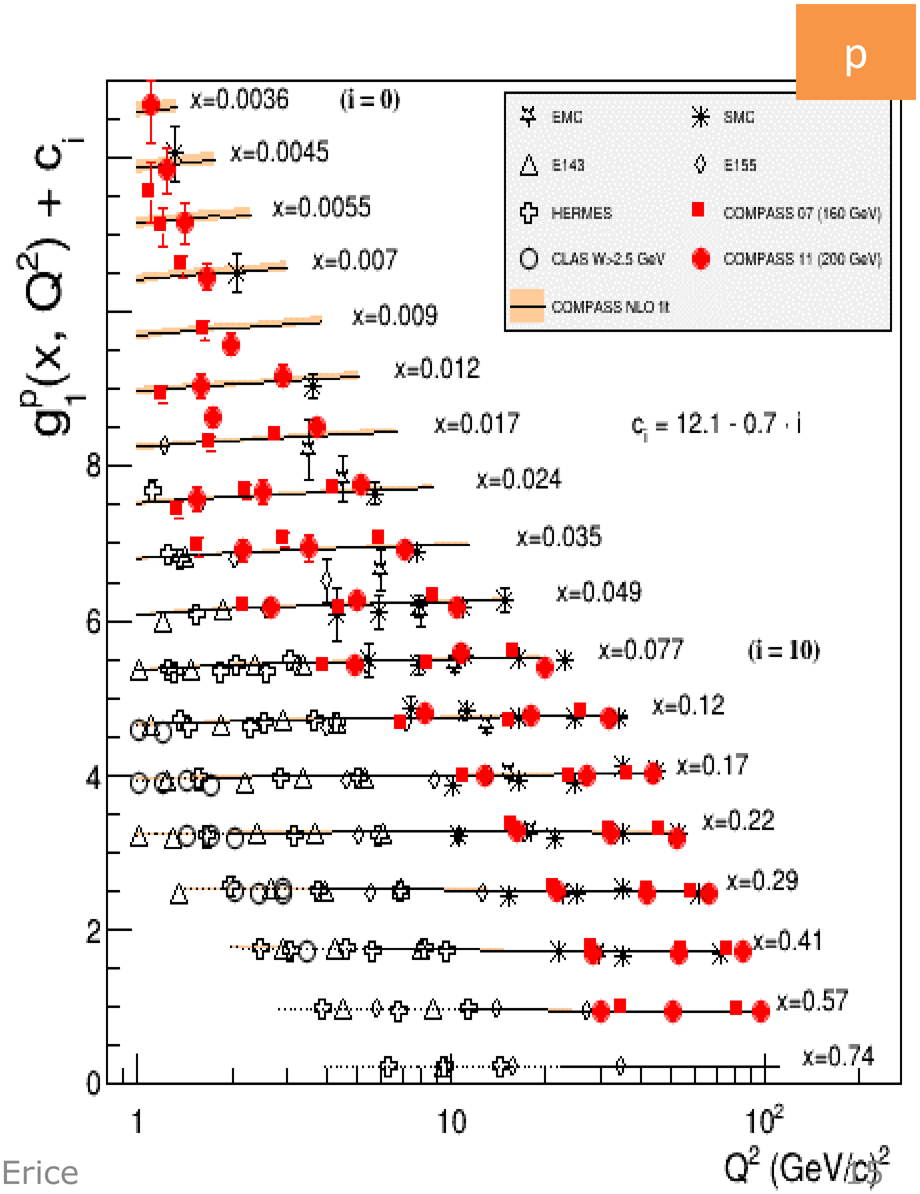
Scaling violations (gluons)



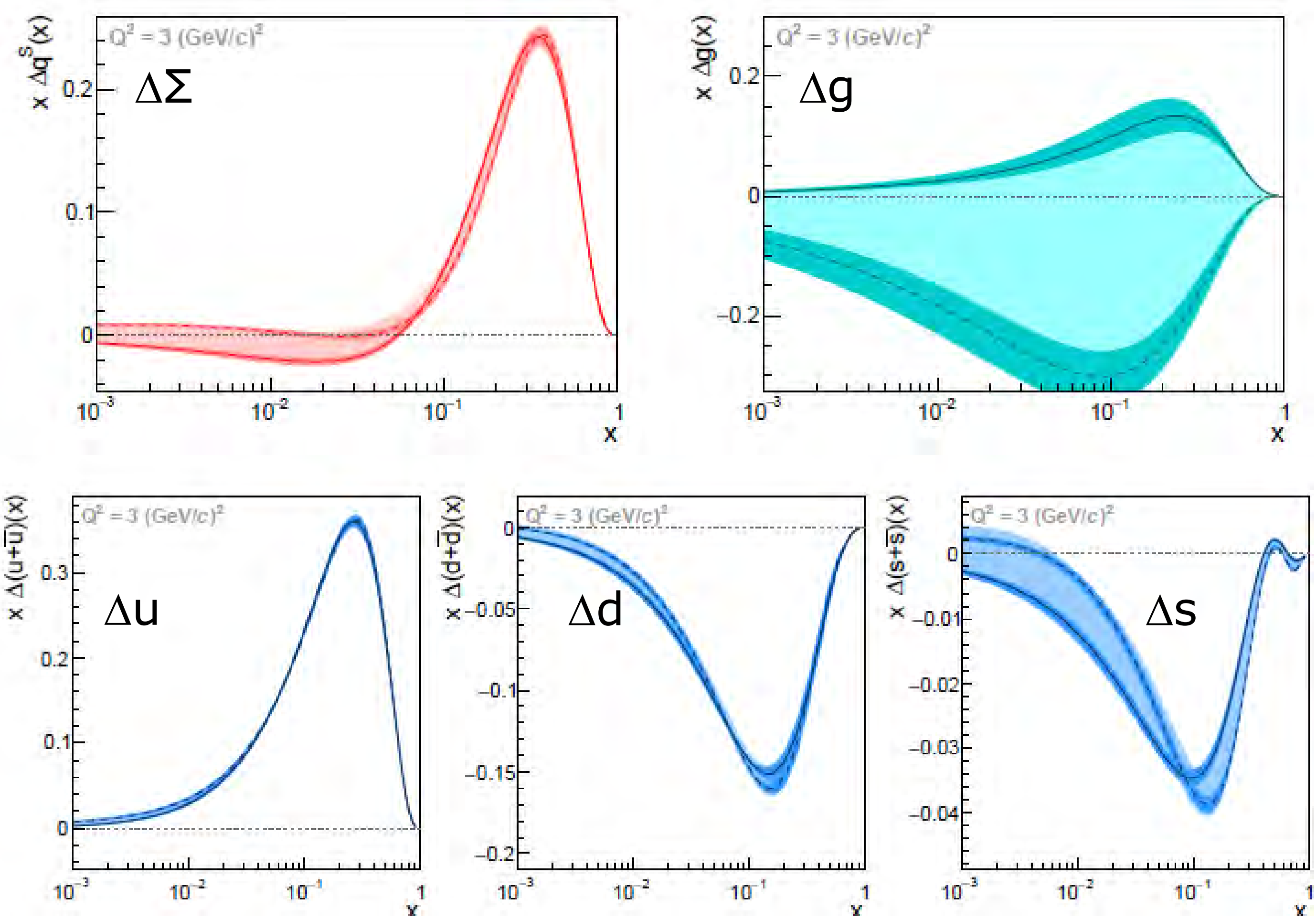
- with increasing Q^2 more and more details are resolved
- quarks/gluons split and produce more partons
- the 'new' partons have smaller *x*-Bjorken
- PDFs and SFs became functions of Q^2: $P(x) \rightarrow P(x,Q^2)$
- this Q^2 evolution is calculable in perturbative QCD, if the PDFs $P(x,Q^2_0)$ are known at some Q^2_0 (DGLAP equations)
- the x dependence is not described in pQCD
- The scaling violations depend on the gluon distribution

$F_2(x,Q^2)$  $g_1(x,Q^2)$ 


SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e+p
NLO QCD Fit
$c_i(x) = 0.6 \cdot (i(x) - 0.4)$
$F_2 + c_i(x)$
Q^2 / GeV^2


p
EMC
SMC
E143
E155
HERMES
COMPASS 07 (160 GeV)
CLAS W>2.5 GeV
COMPASS 11 (200 GeV)
COMPASS NLO fit
$c_i = 12.1 - 0.7 \cdot i$
$g_1^p(x, Q^2) + c_i$
Q^2 (GeV/c)^2

PDFs from NLO fit to world data



$Q^2 = 3\ \mathrm{GeV}^2$

integrals:

$0.27 \leq \Delta\Sigma \leq 0.39$

$-1.6 \leq \Delta G \leq 0.5$

$0.82 \leq \Delta U \leq 0.85$

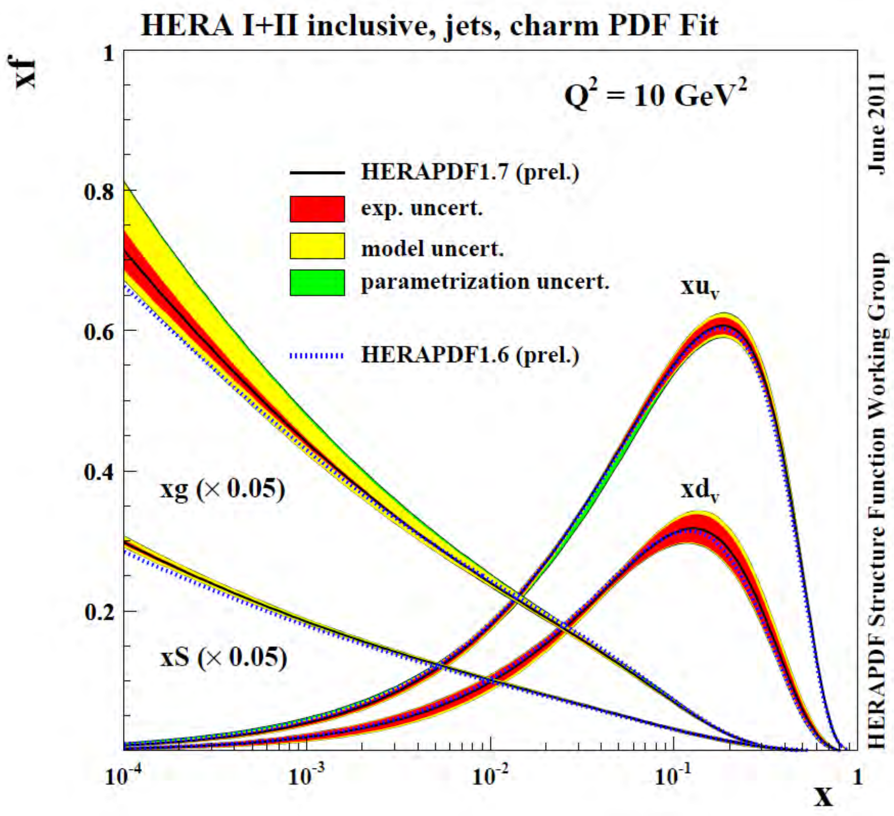
$-0.45 \leq \Delta D \leq -0.42$

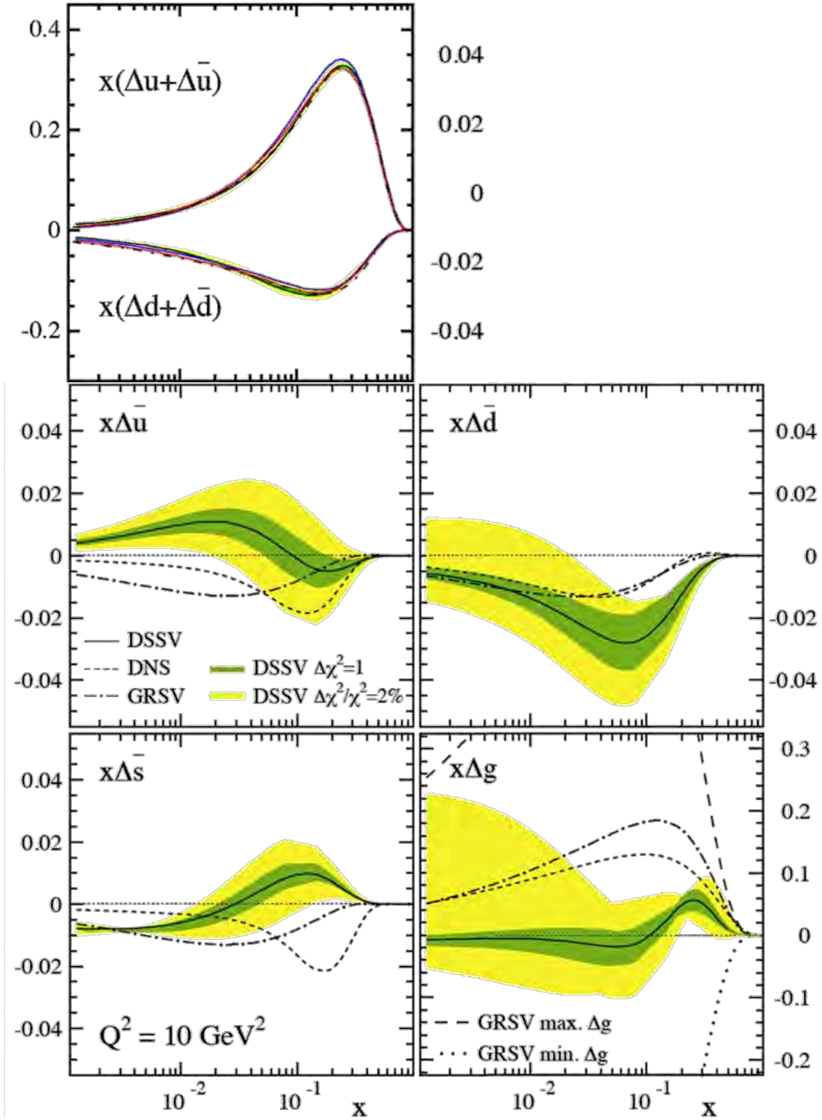
$-0.11 \leq \Delta S \leq -0.08$

using different functional shapes and Q_0^2

Status of PDFs: global analyses

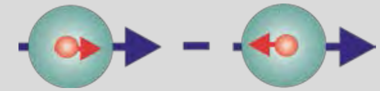
unpolarised





DSSV PPNP (2012) 251

Sum rules for g_1



- first moment Γ_1 of g_1 with $\Delta q = \int_0^1 \Delta q(x) + \Delta\bar{q}(x)\,\mathrm{d}x$

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

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

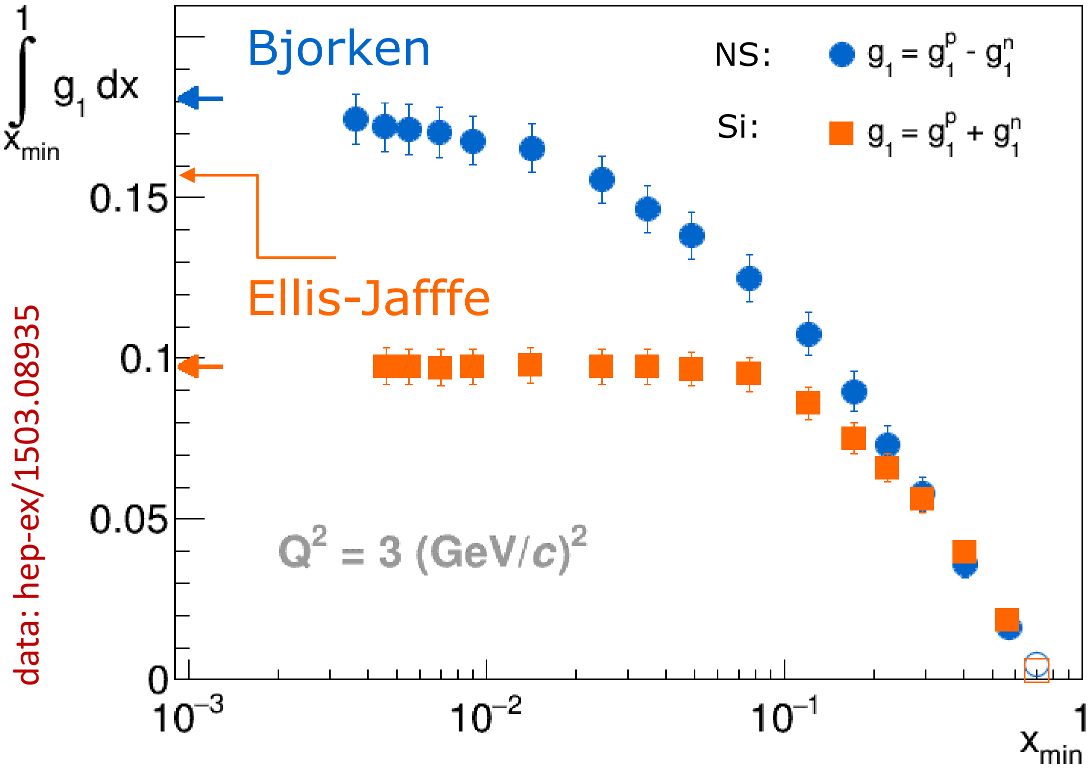
a_3 neutron decay $\quad$ a_8 hyperon decay $\quad$ $a_0 = \Delta\Sigma$

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

  if wrong $\Rightarrow$ QCD wrong
  but
  BJ: "worthless equation"

- Ellis-Jaffe 'SRs' for p and n assume : $\Delta s = 0$; $\Gamma_1 \Rightarrow \Delta u + \Delta d = \Delta\Sigma$

Sum rules



data: hep-ex/1503.08935

$$\Gamma_1^{NS}(Q^2) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Bjorken sum rule verified to 9%

- BJ SR major contribution from small *x*
- EJ SR no contribution at small *x*

COMPASS data only: $|g_A/g_V| = 1.22 \pm 0.05\ (\text{stat.}) \pm 0.10\ (\text{syst.})$

from neutron β decay: $|g_A/g_V| = 1.2723 \pm 0.0023$

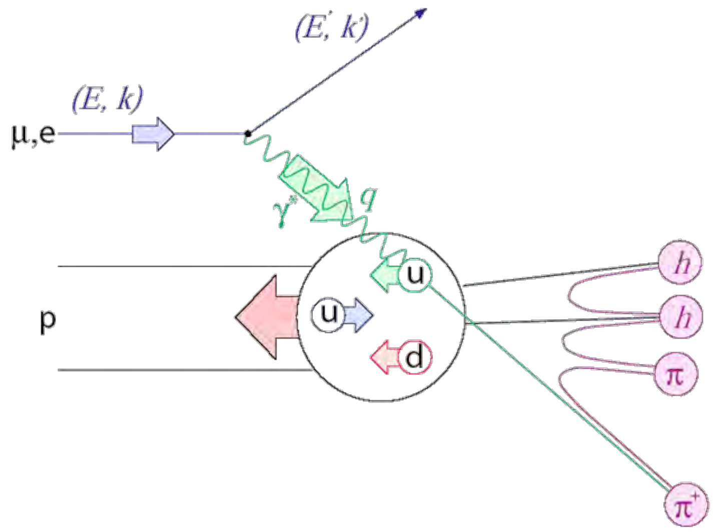
4. Longitudinal spin: SIDIS results

- additional hadron observed in FS

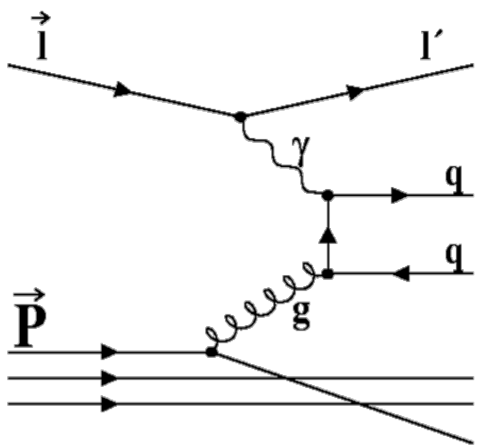
$$A_1^h = \frac{\sum_q e_q^2 g_1^q(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1q}^h(z,Q^2)}$$

$$z = E_h/\nu$$

- gives access to flavour information via the fragmentation functions *D*

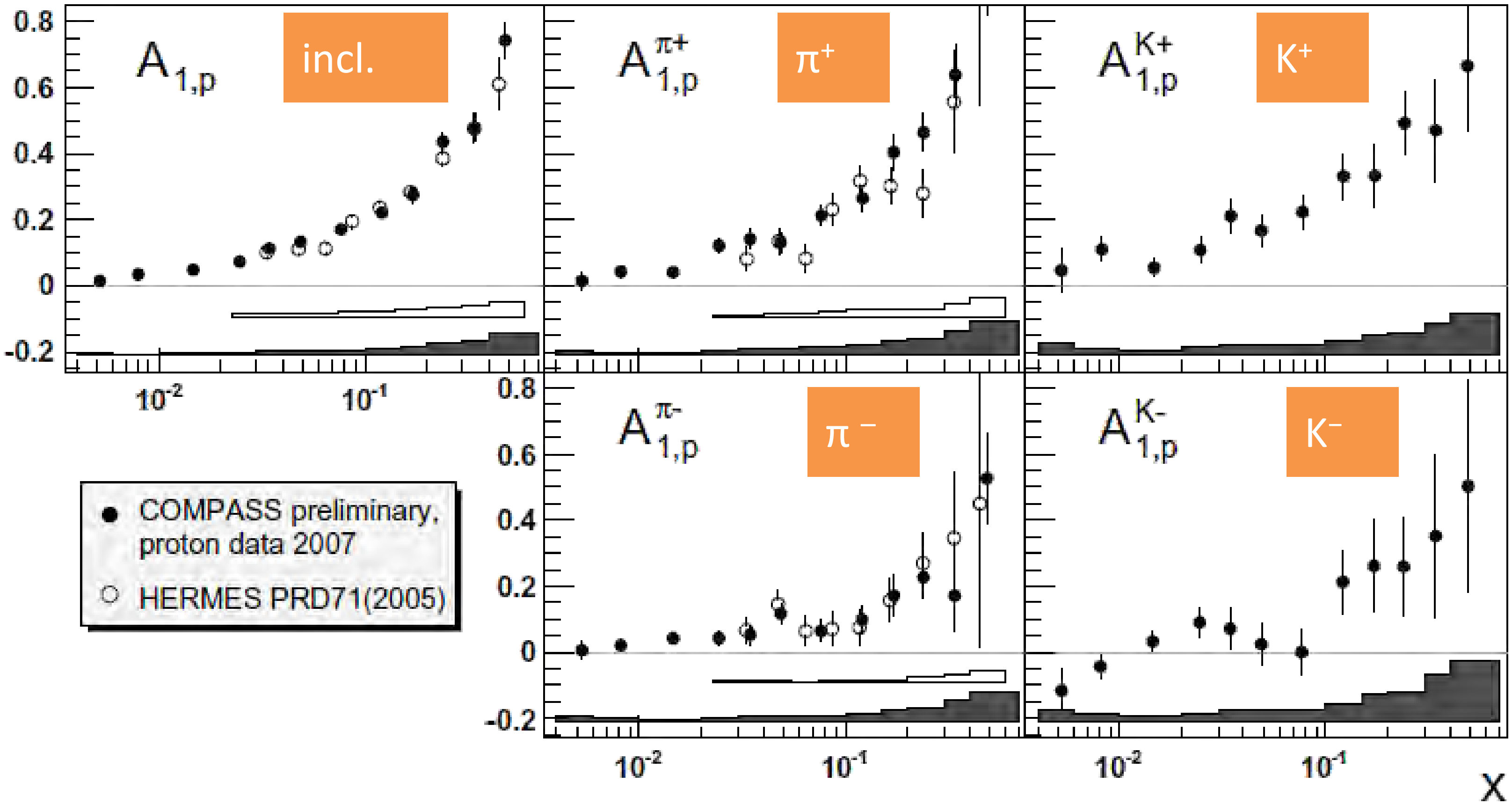


- photon–gluon fusion gives access to the gluon polarisation
- particularly interesting open charm production via $c\bar{c}$



Incl. & semi-incl. A_1

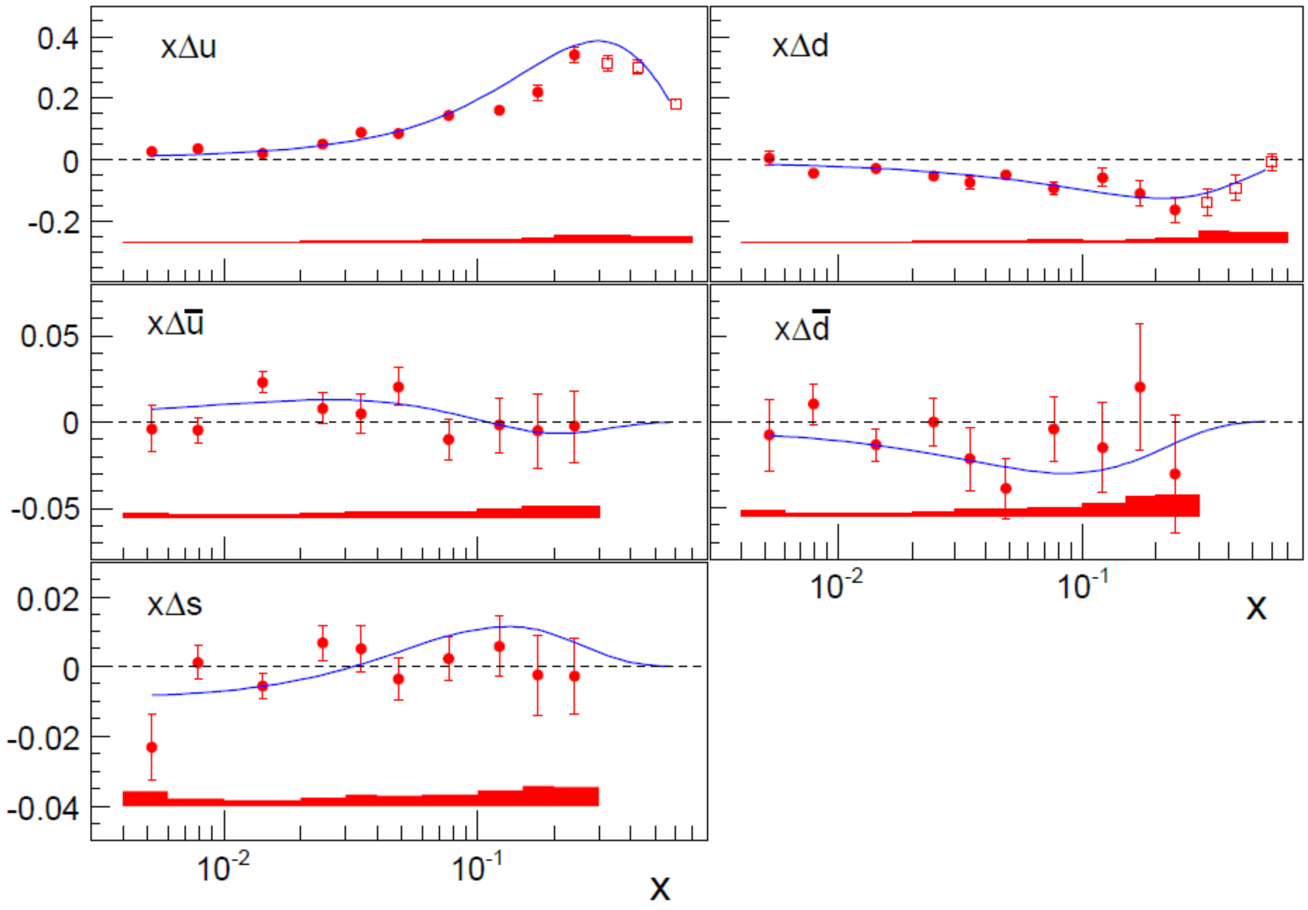
- proton



The role of quark flavours

LO analysis of 5p+5d asymmetries, DSS FF
Line: NLO DSSV not including these data

5-flavour fit,
assuming $\Delta s = \Delta\bar{s}$

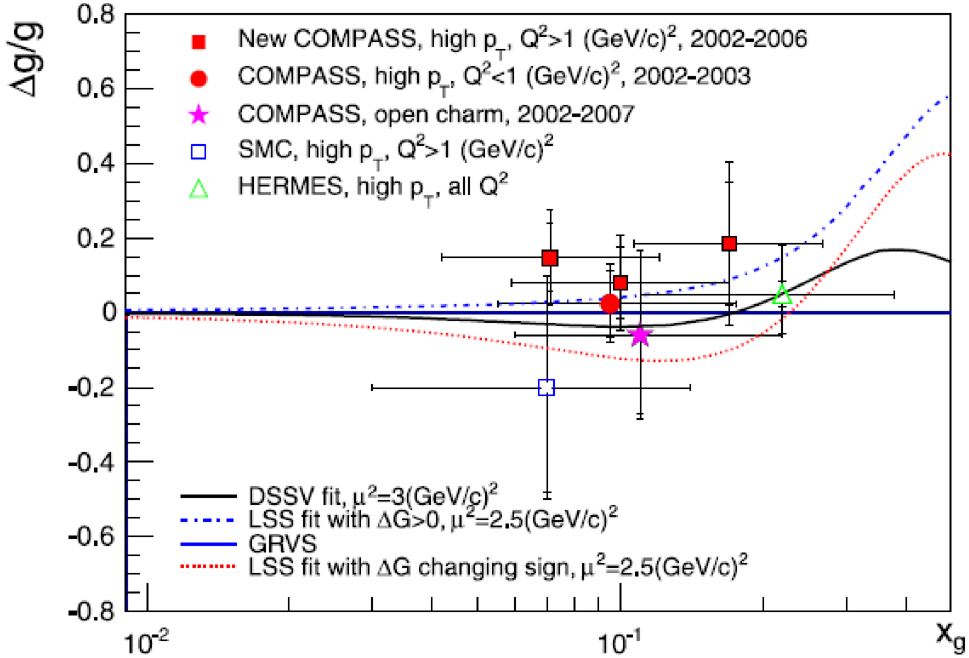


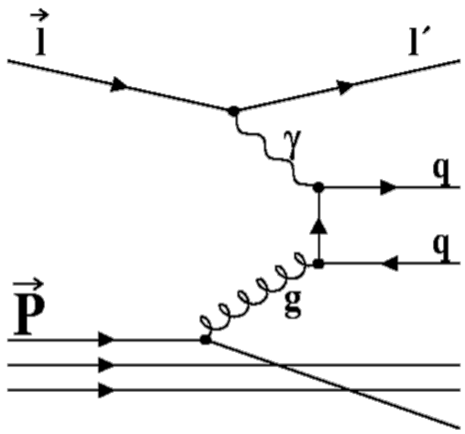
Data (LO analysis):

PLB693 (2010) 227

PRD80 (2009) 034030

Δg/g from PGF (LO)



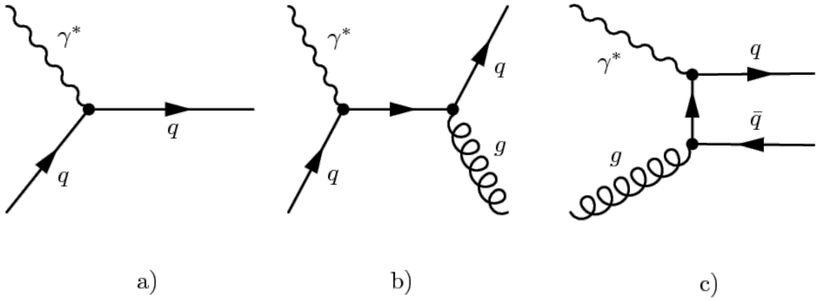


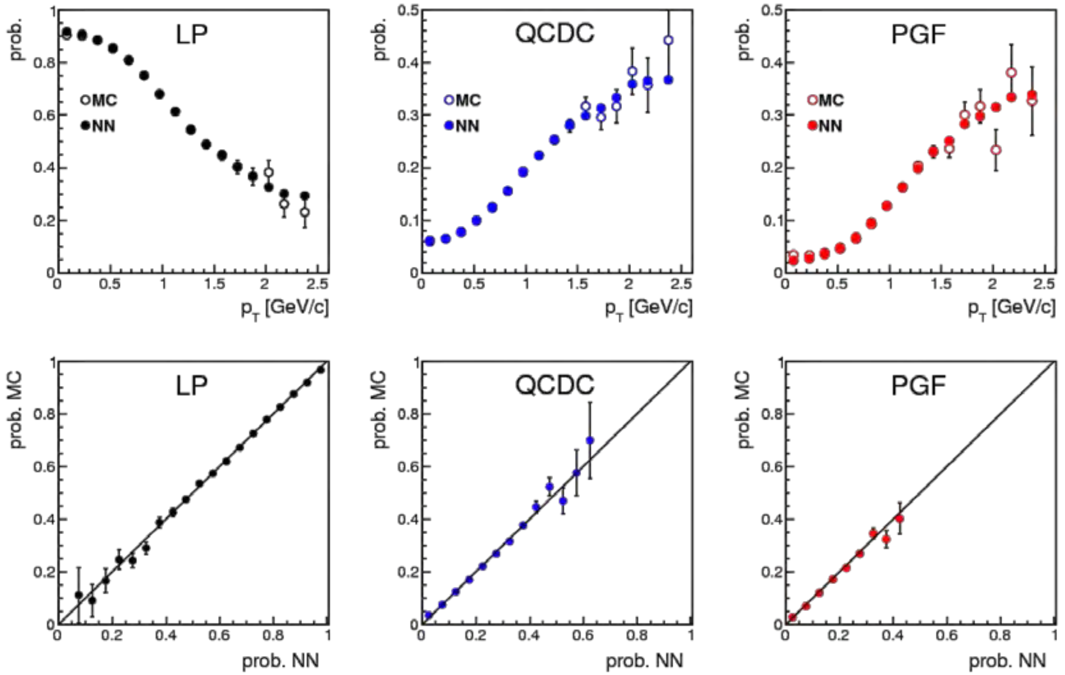
- $Q^2 > 1$ GeV^2
- $Q^2 < 1$ GeV^2
- open charm (D mesons)

- gluon polarisation is much smaller than thought in the 1990s by many theorists (around $2\hbar$ [even up to $6\hbar$], axial anomaly); various methods
- confirmed by polarised *pp* at RHIC
- Δg still can make a substantial contribution to nucleon spin

Gluon polarisation from PGF (LO)

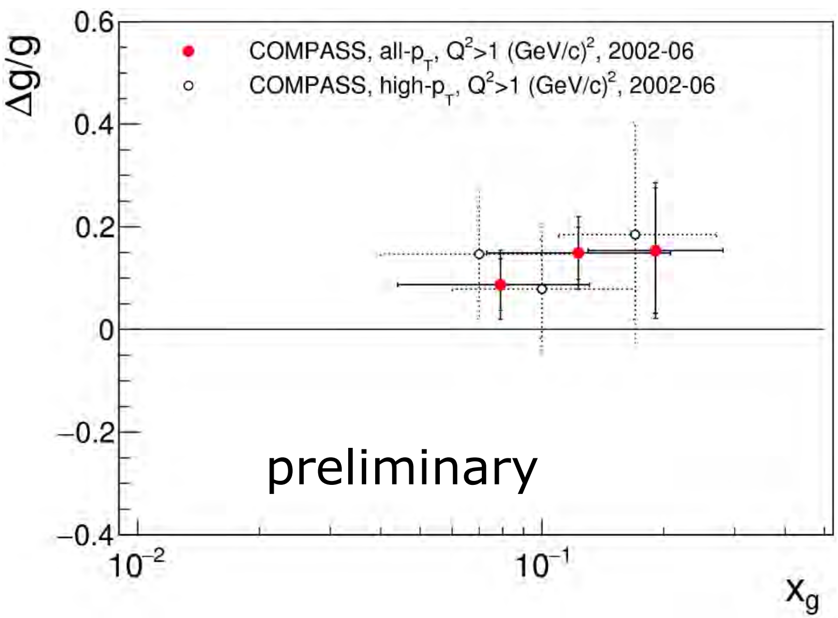
- LO reanalysis of 2002-2004, 2006 deuteron data
- $Q^2 > 1$ GeV^2
- novel method using events with any p_T and NN weights
- simultaneous determ. of leading order asym. reduces syst. uncertainty
- determination of $\Delta g(x)$ in 3 x ranges

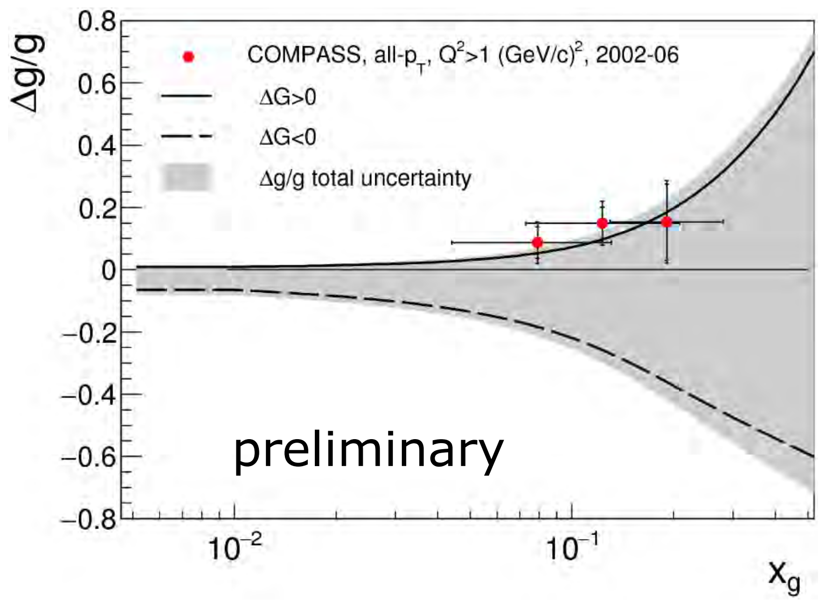




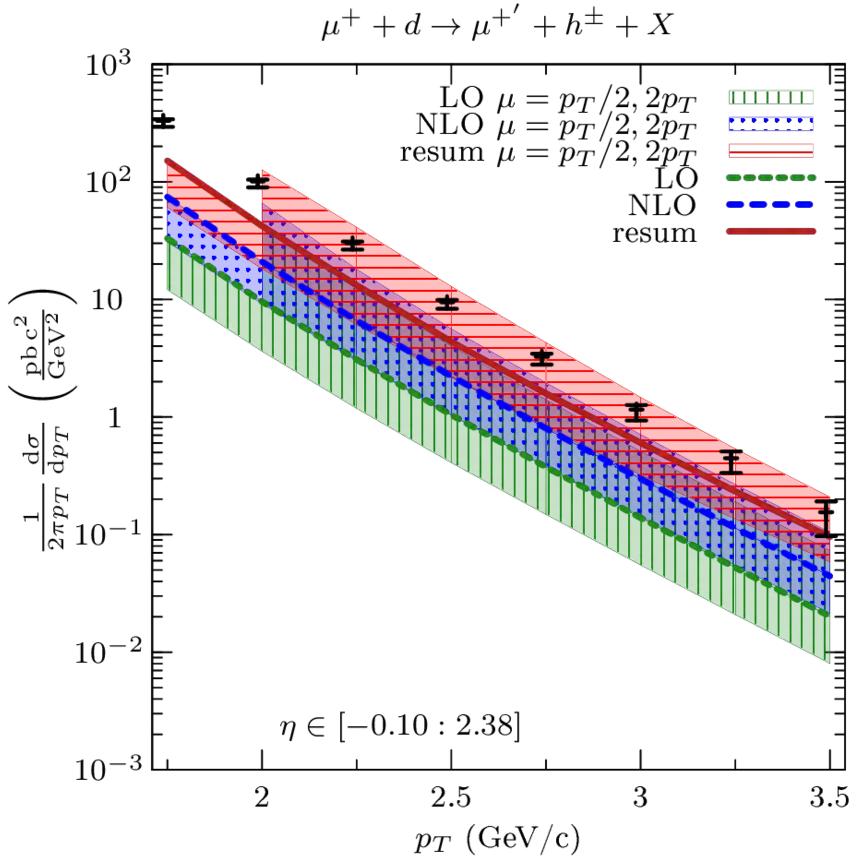
Gluon polarisation from PGF

- $\Delta g(x)$ = 0.113 ± 0.038 ± 0.036 with $\langle x_g \rangle$=0.10 at 3 GeV^2 prel.
- no x dependence visible
- error reduction factor: 1.6 stat, 1.8 syst
- positive $\Delta g(x)$ preferred





Spin independent cross-section



De Florian, Pfeuffer, Schaefer, Vogelsang, PRD 88 (2013) 014024

COMPASS, PRD 88 (2013) 091101

- semi-inclusive single hadron production
- COMPASS kinematics
- good agreement with NLL resummation

$\Rightarrow$ cross-section asymmetries can be used to determine the gluon polarisation

$\Rightarrow$ need NLL resummation for polarised case

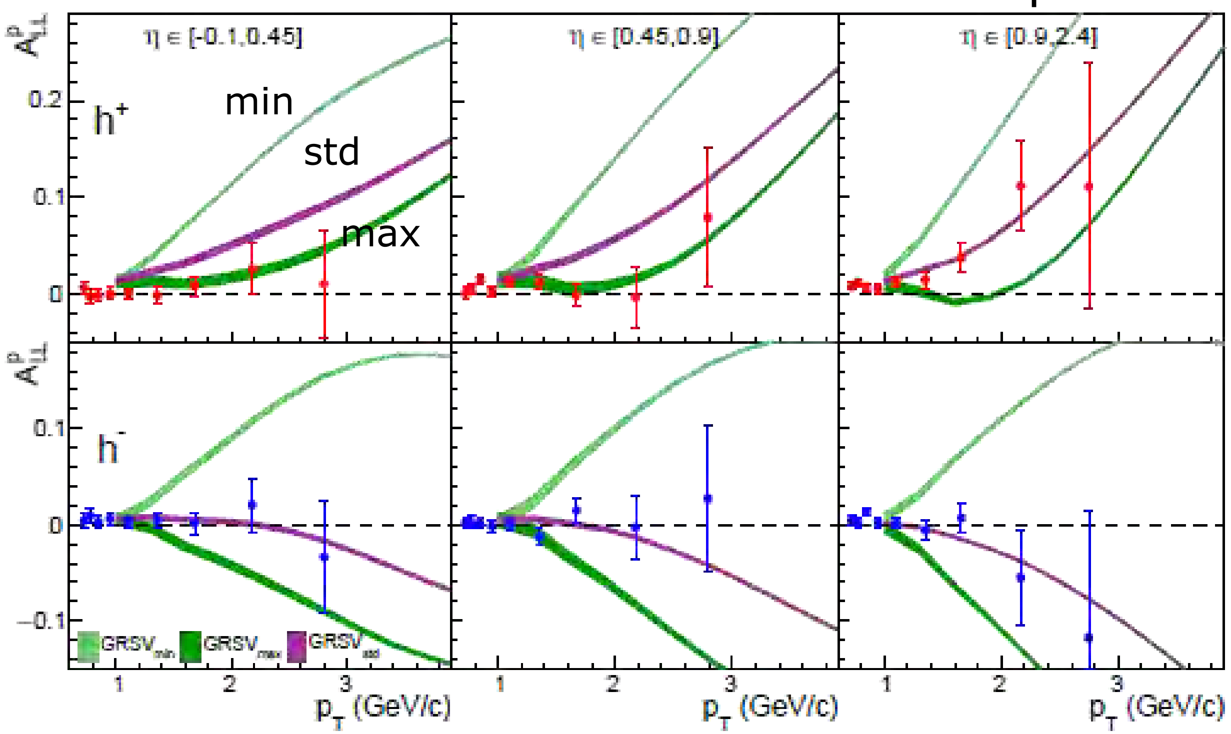
$\Delta g/g$ from single hadron (NLO)

- quasi-real photoproduction of single hadrons, à la RHIC π^0 prod.
- calc. by group of Vogelsang, agreement for unpolarised case
- caveat: NNL resummation missing for polarised case

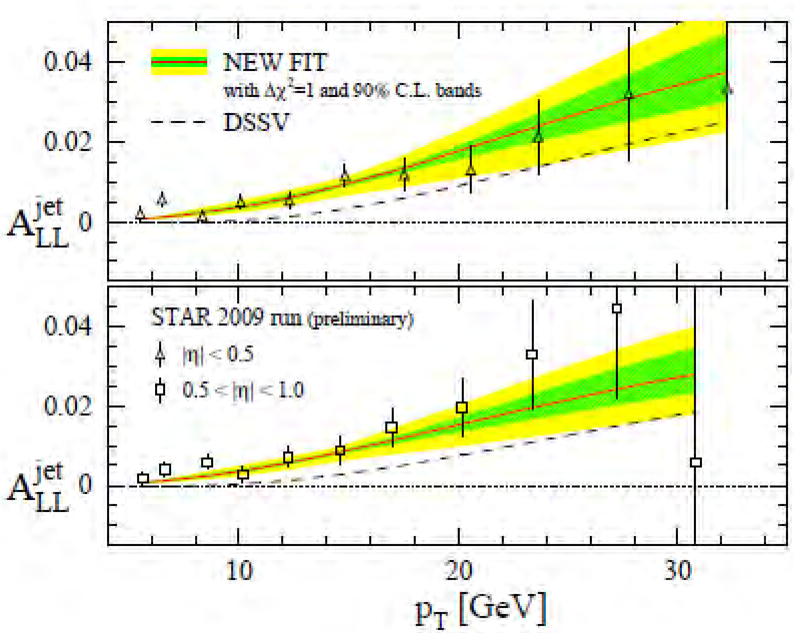
$$\eta_{cms} = -\ln\left(\tan\frac{\theta}{2}\right) - \frac{1}{2}\ln\left(\frac{2E}{M}\right)$$

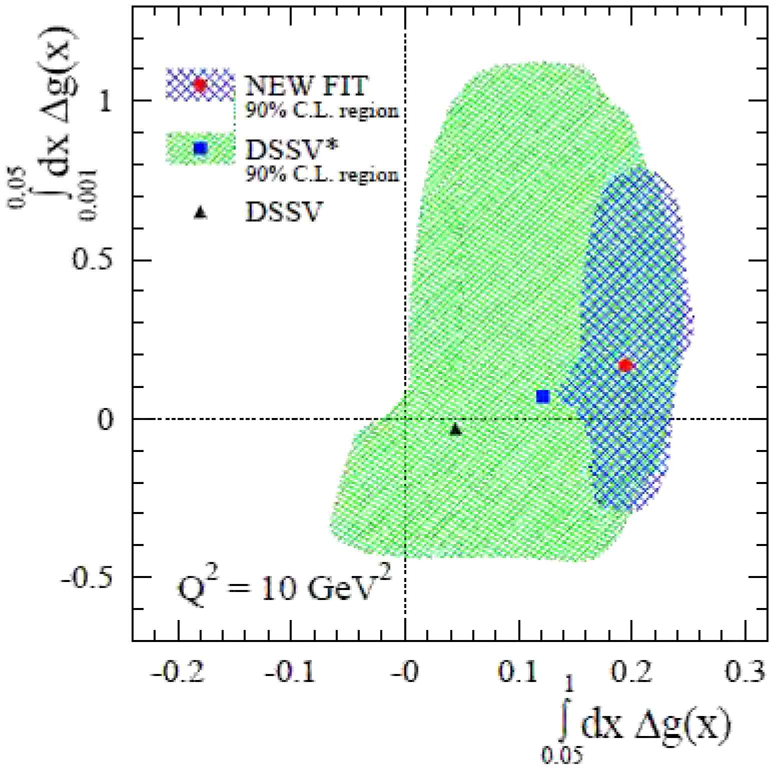
- 3 bins of pseudorapidity η
- FF important, using DSS (2015), agree best with meas. multiplicities
- data prefer positive gluon polarisation as also suggested by recent RHIC data

proton



RHIC STAR jet data & new DSSV fit (2014)





- clear preference for positive gluon distribution at $Q^2 = 10\ \mathrm{GeV}^2$

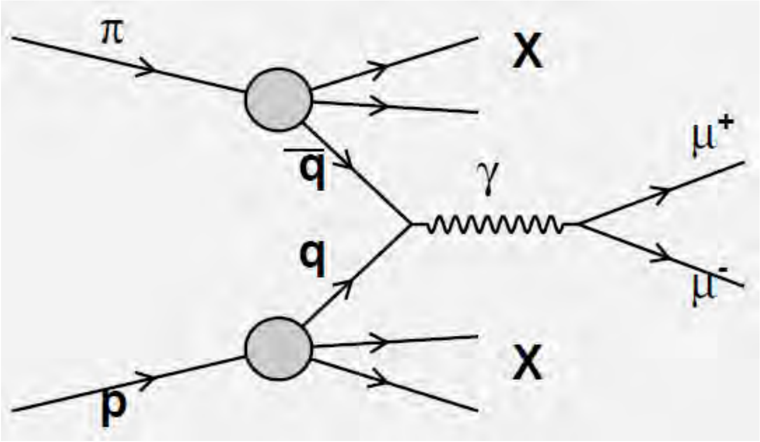
5. COMPASS-II

- Pion (and kaon) polarizabilities 2012
- TMD in $\pi^- + p$ transv. pol. Drell-Yan: 2015
- Generalised Parton Distr. (GPD)
  simult. unpol. SIDIS on proton: 2016/17
- new option, under discussion 2018

- proposal and scientific approval 2010
- first measurements 2012

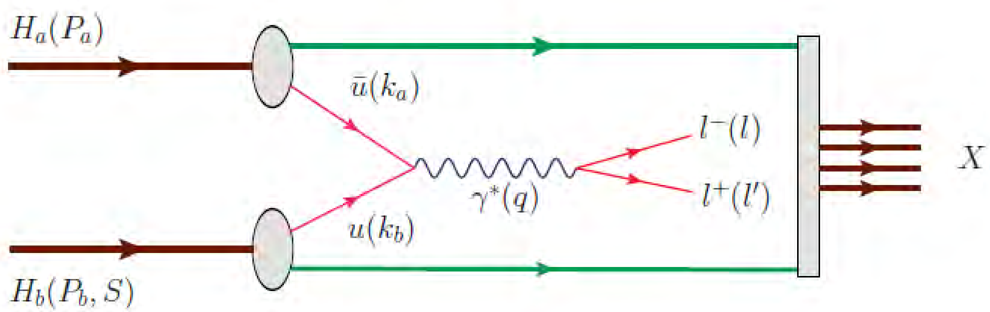
Drell–Yan Process

- No fragmentation function involved
- Convolution of two PDFs
- Best: pol. antiproton–proton (long-term)
- Simpler: negative pion on proton
- anti-u from neg. pion annihilates with proton u
- Transversely polarized proton target → access to transverse momentum dependent (TMD) PDFs like Sivers and Boer–Mulders functions → F. Bradamante
- Test of universally of PDFs, why interesting?

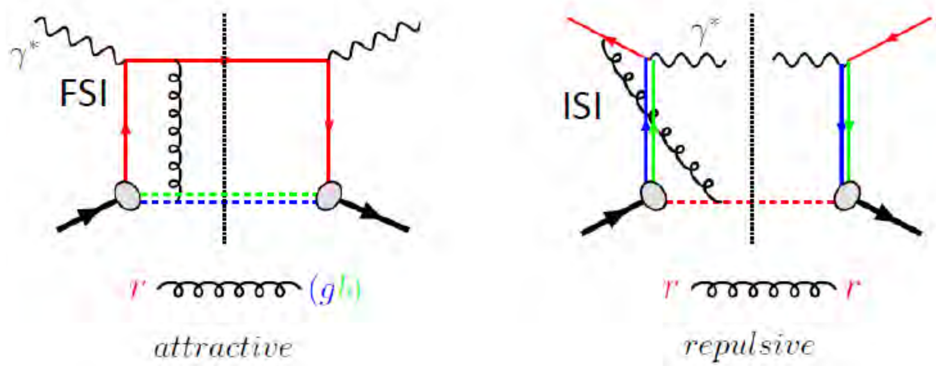


$$\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$$

Restricted universality in SIDIS and pol. DY



T-odd TMD



`gauge link changes sign for T-odd TMD', restricted universality of T-odd TMDs

J.C. Collins, PLB536 (2002) 43

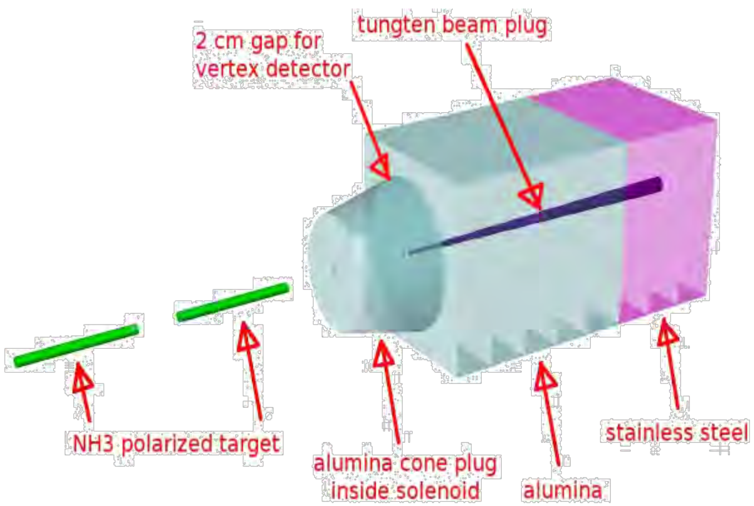
$$f_{1T}^{\perp}\Big|_{DY} = - f_{1T}^{\perp}\Big|_{DIS} \quad \text{and} \quad h_{1}^{\perp}\Big|_{DY} = - h_{1}^{\perp}\Big|_{DIS}$$

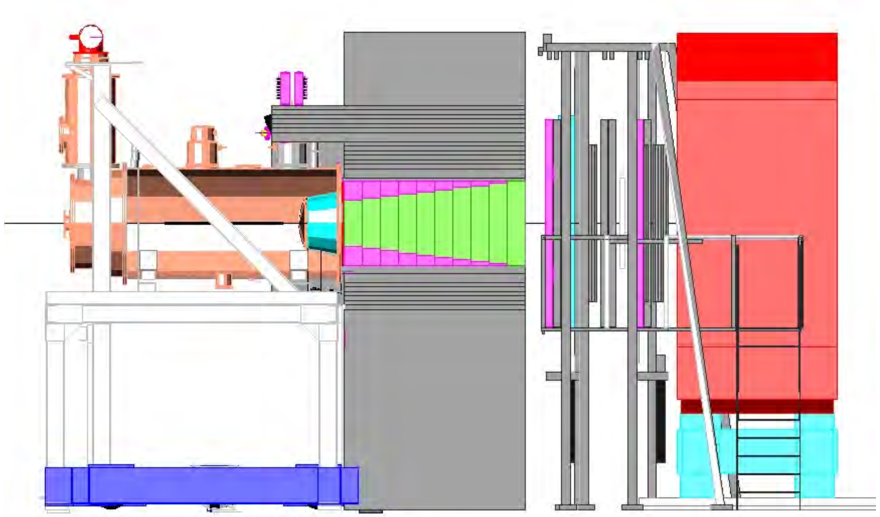
Sivers Boer-Mulders

- important prediction, needs to be verified

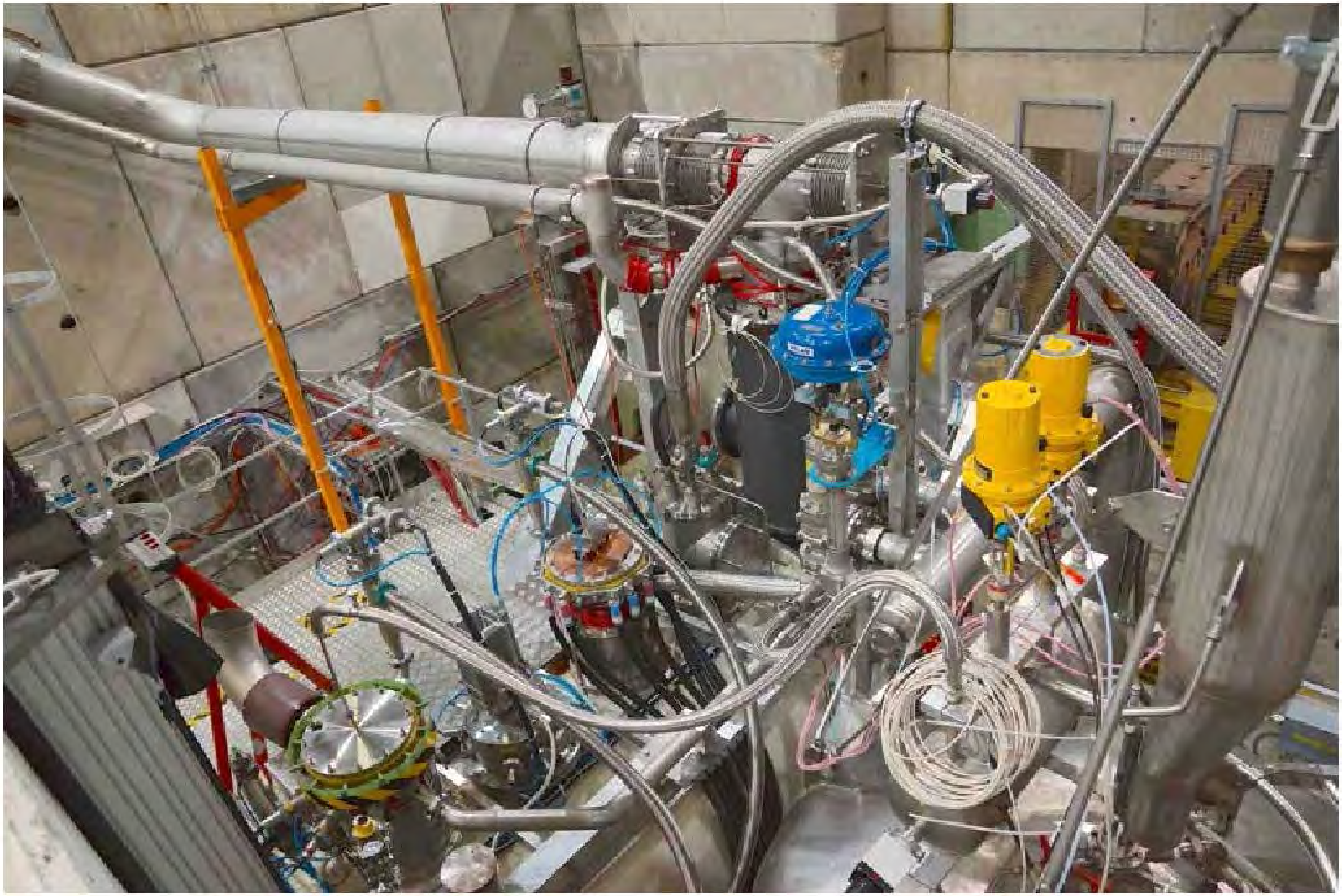
COMPASS-II Polarised Drell-Yan

- First ever polarized Drell–Yan experiment
- 190 GeV/*c* π^- beam on transv. pol. proton target
- Access to transversity , the T-odd Sivers and Boer–Mulders TMDs

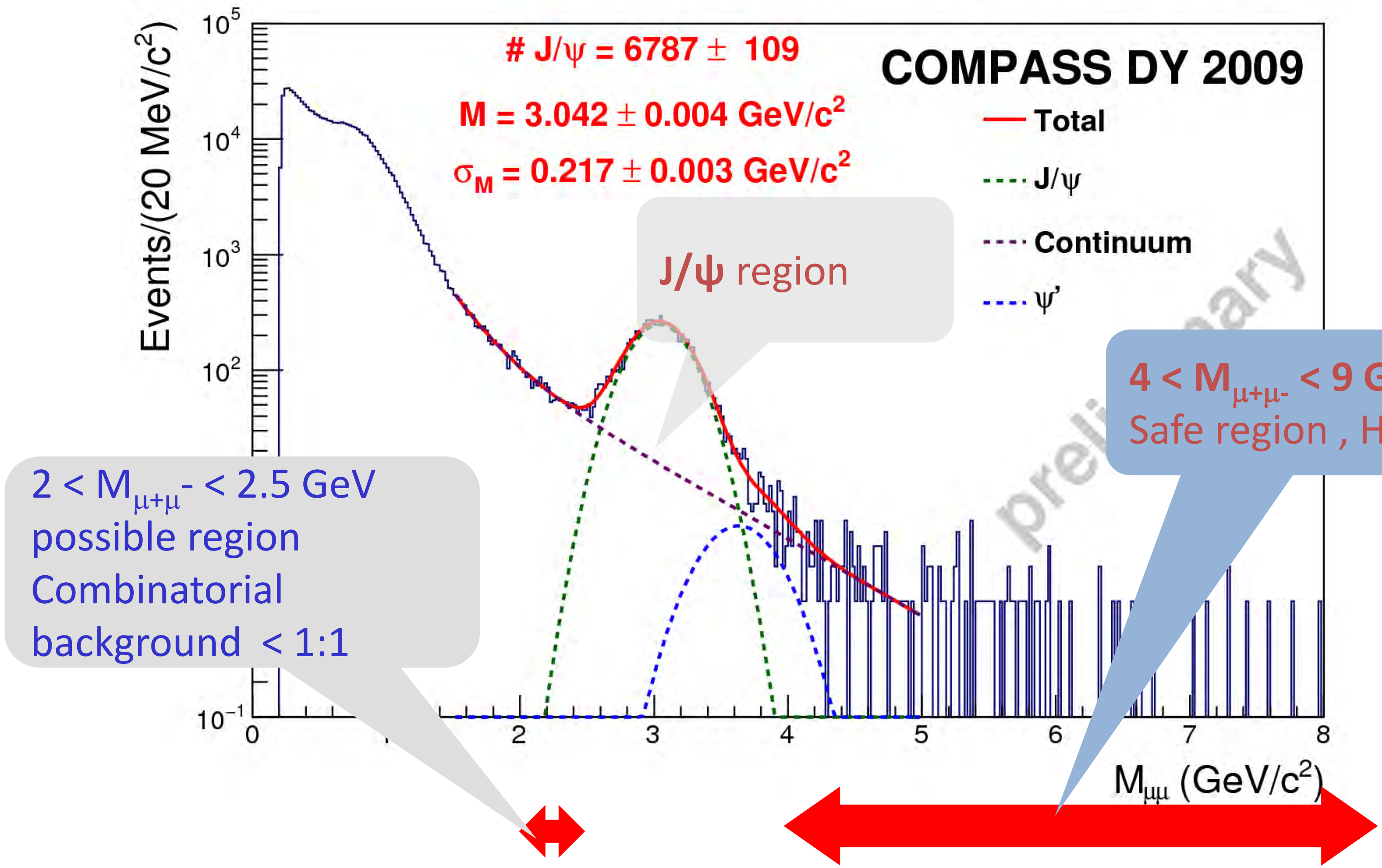




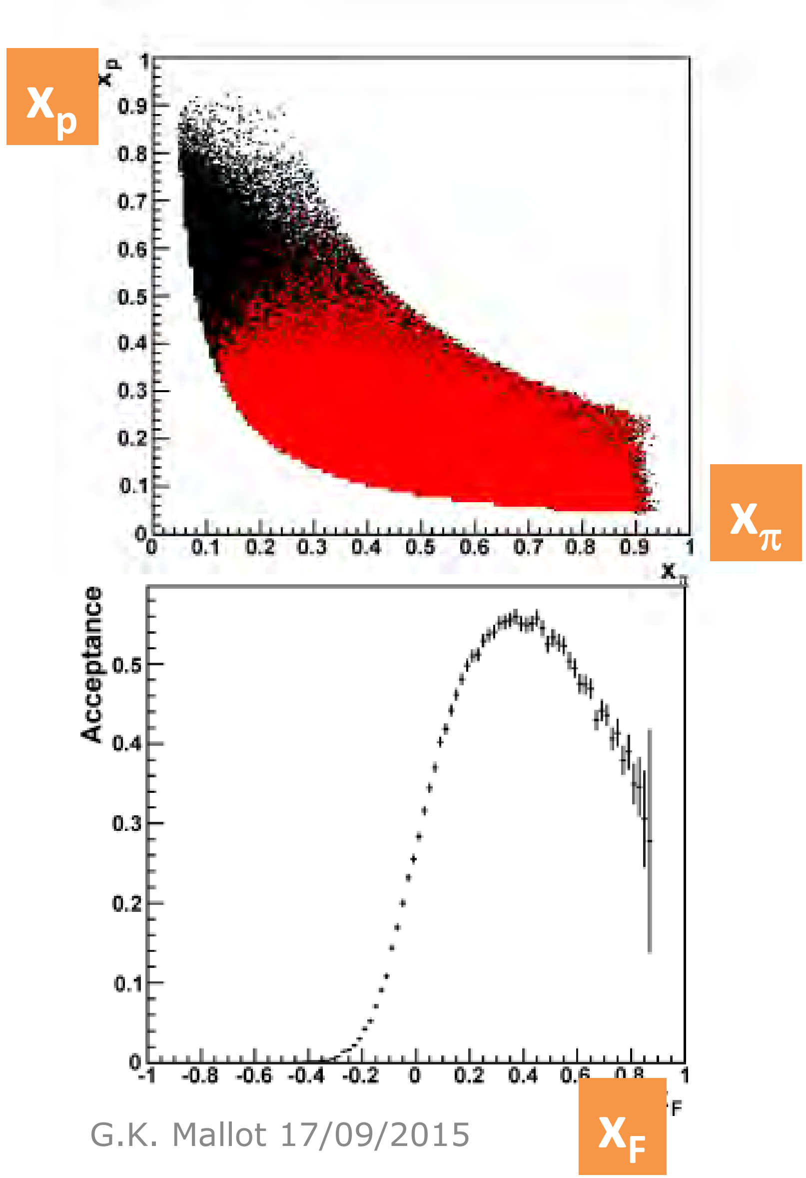
2015 run: polarised target

- 

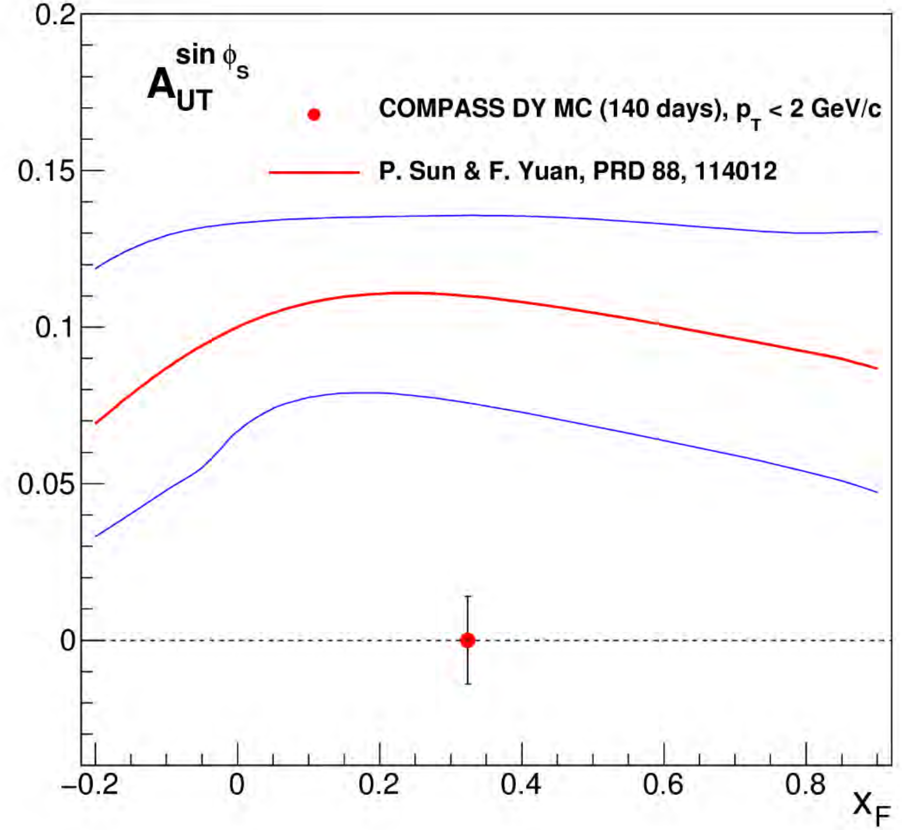
Drell–Yan muon pair mass regions



COMPASS polarized DY, projections HMR



Predictions vary strongly, e.g.



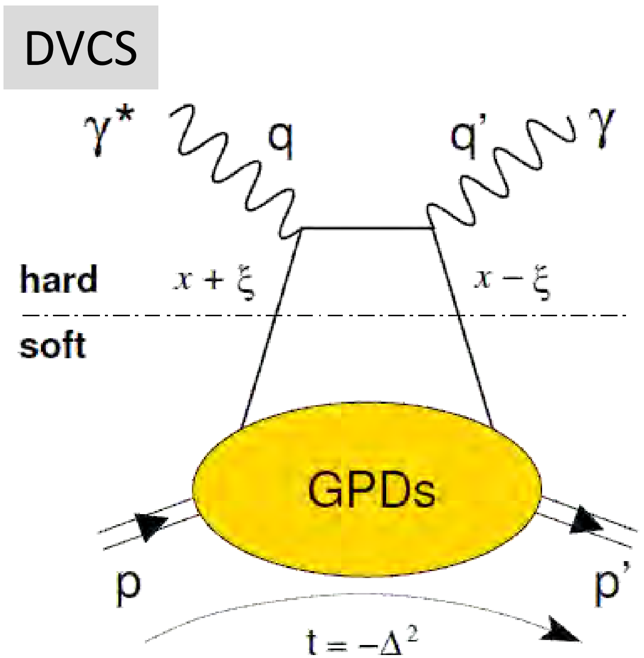
$x_F = x_\pi - x_p$

Generalized PDF's

- Correlating transverse spatial and longitudinal momentum degrees of freedom
- PDFs and elastic FF as limiting cases
- $H, \tilde{H} \rightarrow f_1, g_1$ for $\xi \rightarrow 0$;
- H (E) for nucleon helicity (non)conservation
- exclusive processes like DVCS, HEMP (vector & pseudoscalar)

$$H(x, \xi, t, Q^2); \quad Q^2 \text{ large, } t \text{ small}$$

$$H^f, E^f, \tilde{H}^f, \tilde{E}^f \text{ with } f = q, g$$

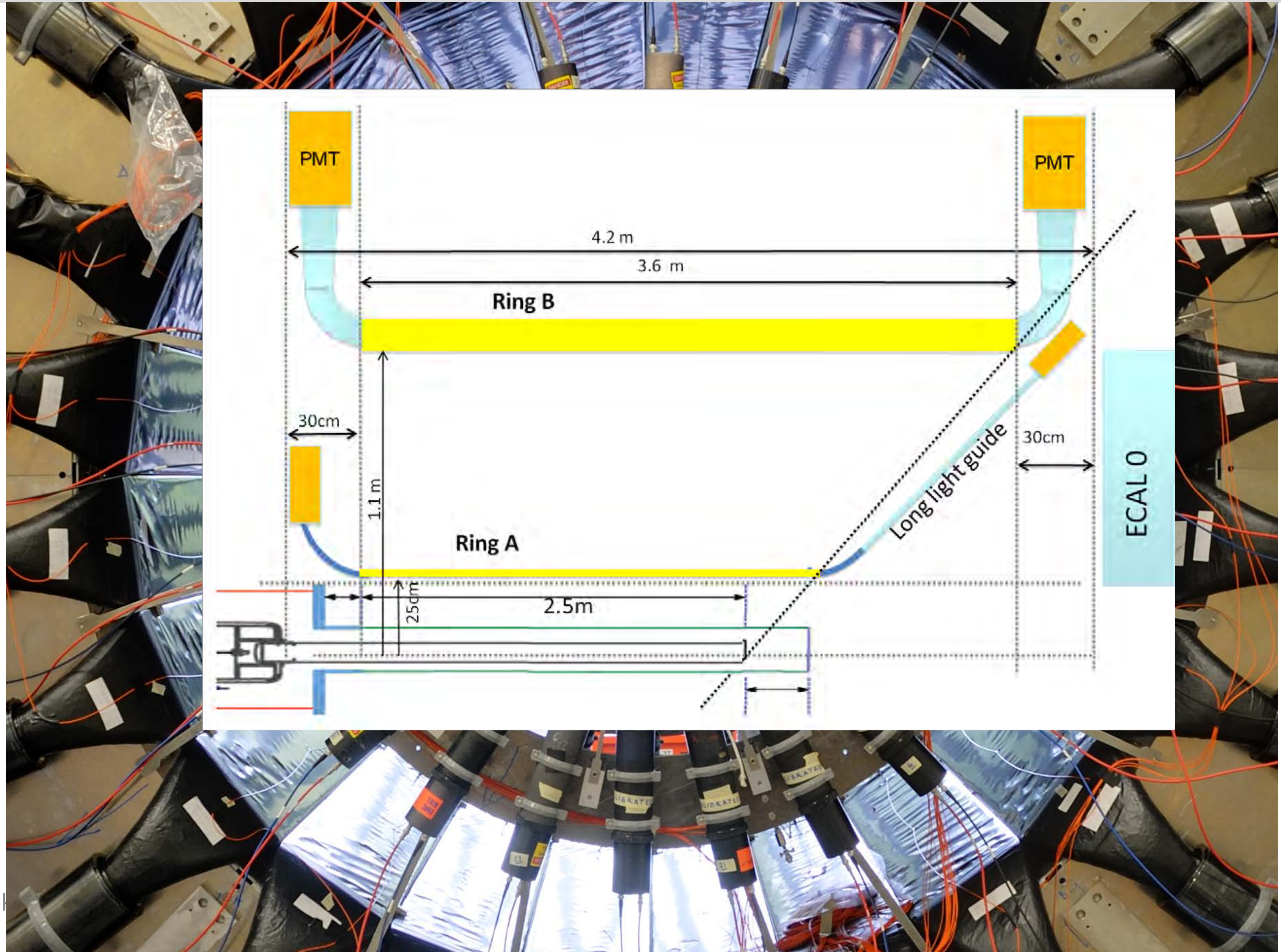


Total orbital momentum:

$$J^f(Q^2) = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \quad \left[H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2)\right]$$

X.-D. Ji, PRL 78 (1997) 610

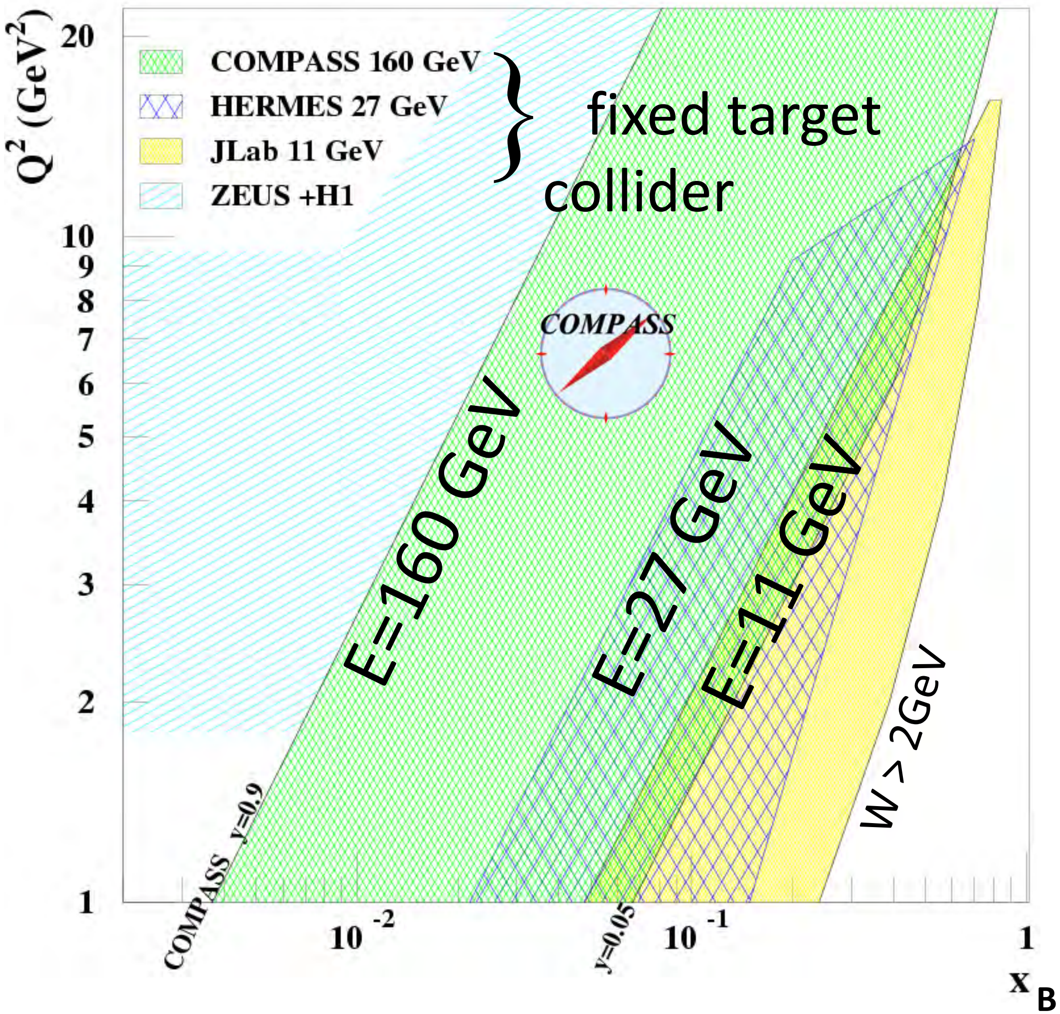
Camera detector for exclusivity



G.K

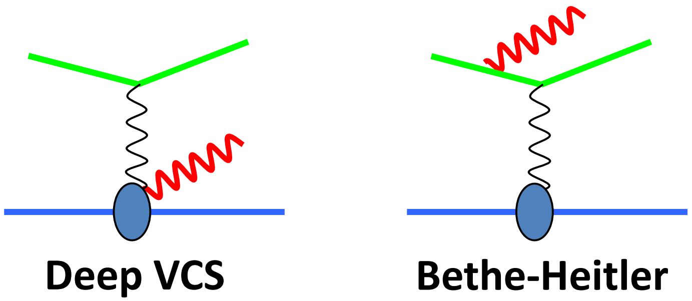
DVCS

- DVCS is the cleanest process to determine GPDs
- need a world-wide effort
- global analysis over large kinematic range mandatory
- COMPASS-II: bridges HERA to JLAB 11 GeV kinematics



DVCS–Bethe-Heitler interference *I*

- DVCS can be separated from BH and constrain the GPD *H* e.g. using different charge & spin (**e_μ** & **P_μ**) cross section combinations of the μ beam



- Note: $\mu^\pm$ beams have opposite polarisation at COMPASS

$$\mathrm{d}\sigma^{\mu p\to\mu p\gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma_0^{\mathrm{DVCS}} + P_\mu \mathrm{d}\Delta\sigma^{\mathrm{DVCS}} + e_\mu \mathrm{Re}\, I + P_\mu e_\mu \mathrm{Im}\, I$$

Charge & Spin sum and difference:

$$\mathcal{S} = \mathrm{d}\sigma^{\overset{+}{\leftarrow}} + \mathrm{d}\sigma^{\overset{-}{\rightarrow}} = 2(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma_0^{\mathrm{DVCS}} + \mathrm{Im}\, I)$$

$$\mathcal{D} = \mathrm{d}\sigma^{\overset{+}{\leftarrow}} - \mathrm{d}\sigma^{\overset{-}{\rightarrow}} = 2(\mathrm{d}\sigma_0^{\mathrm{DVCS}} + \mathrm{Re}\, I)$$

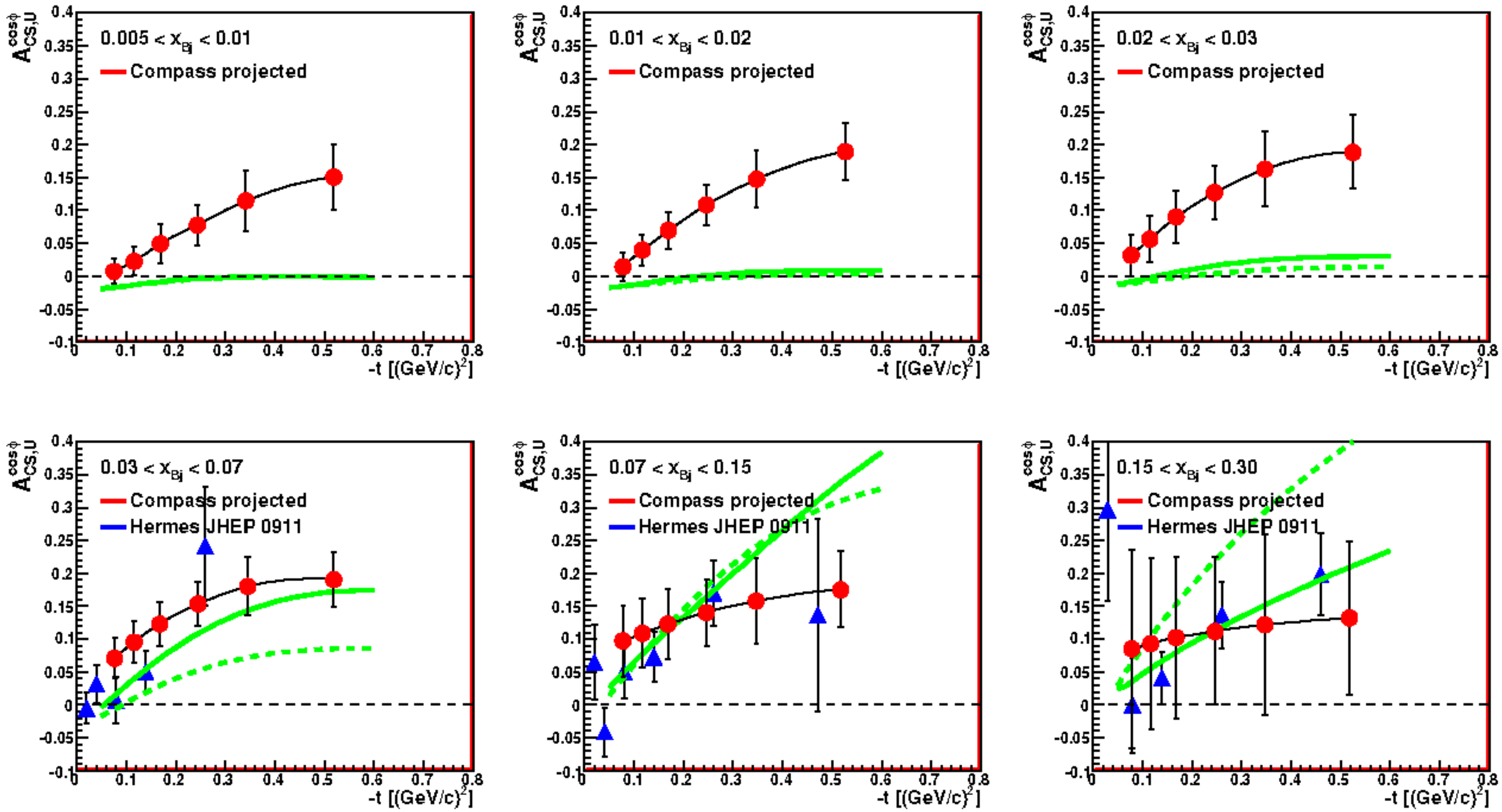
Im *I* and *Re* *I* related to

$$H(x=\xi,\xi,t)$$

$$\mathcal{P}\int \mathrm{d}x\, H(x,\xi,t)/(x-\xi)$$

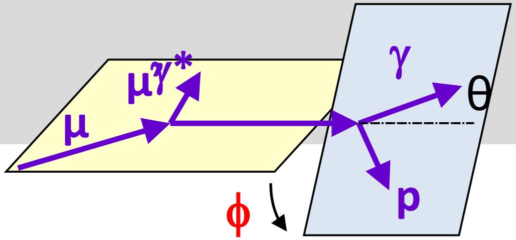
Projection for beam charge-and-spin asym.

Amplitude of cos ϕ modulation of $\mathcal{A}_{CS,U} \equiv \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$

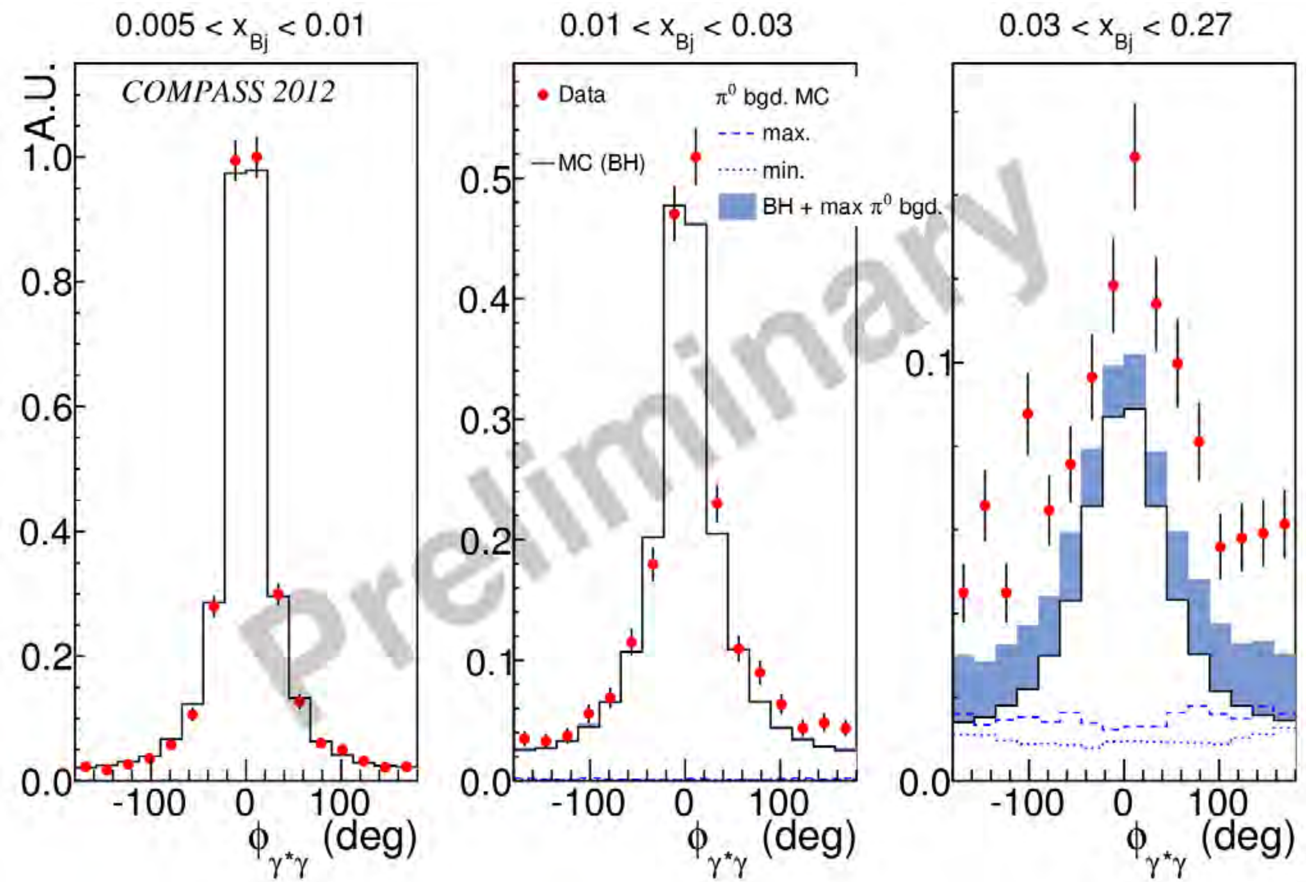


fits by Kumericki, Mueller

BH vs DVCS data

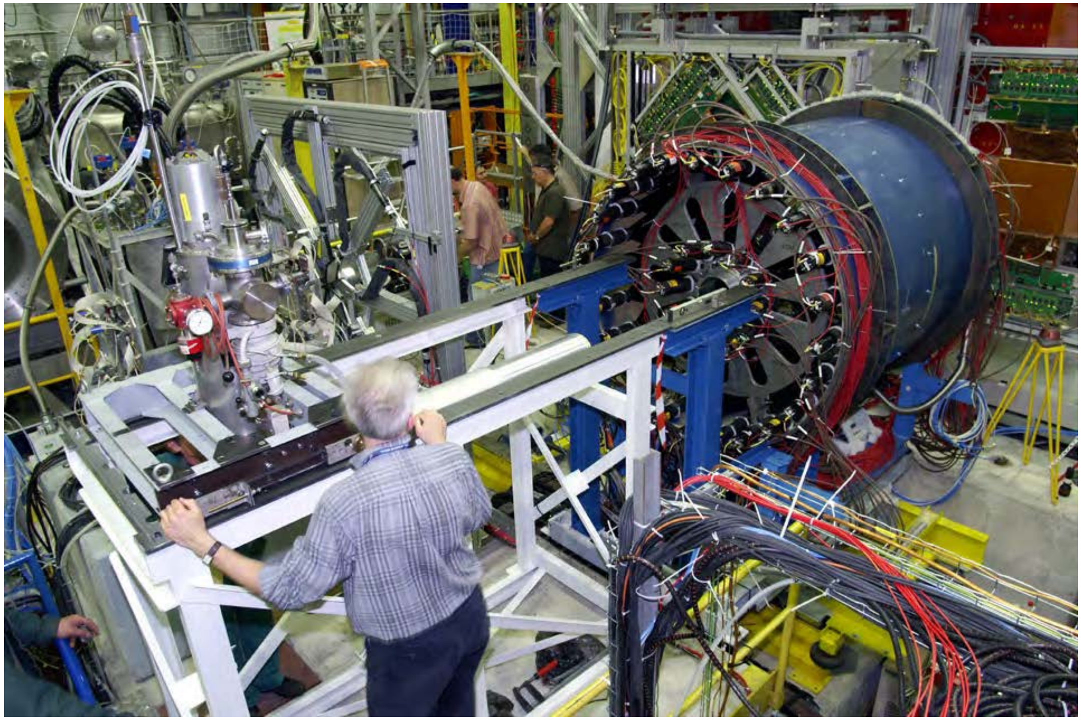


- Test runs in 2012 long LH target
- Clear DVCS signal, BH (- - - -) can subtracted



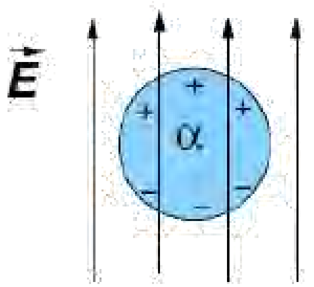
Add-on: Physics with hadron beams

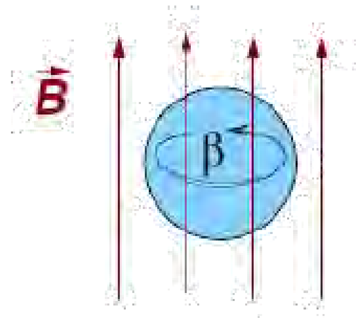
- Proton, pion (and kaon) beams
- hydrogen, nickel and lead targets

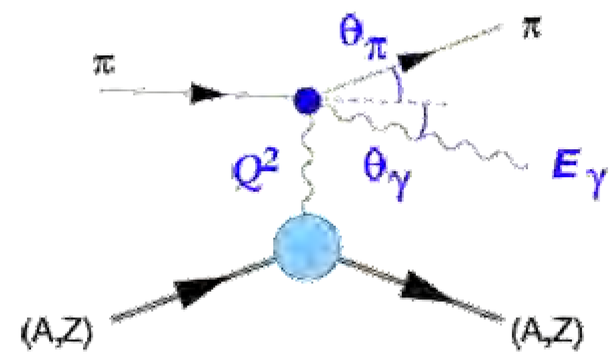


Inserting the liquid hydrogen target in the recoil detector

Pion el. & magn. polarisability

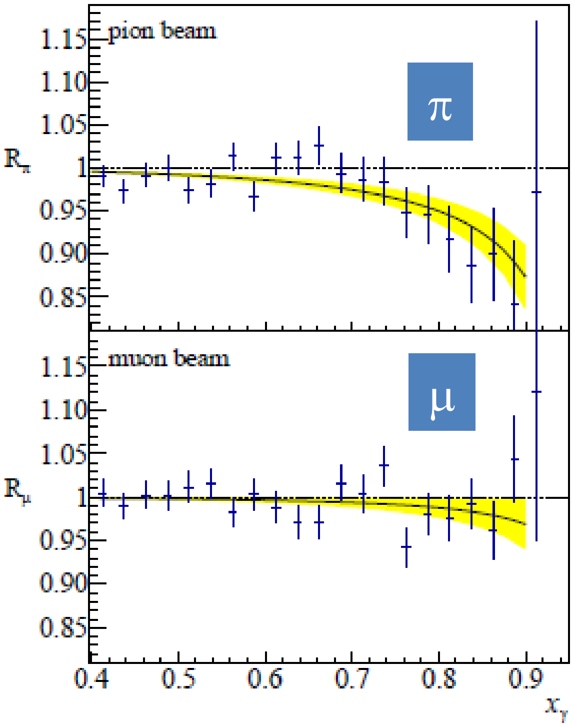


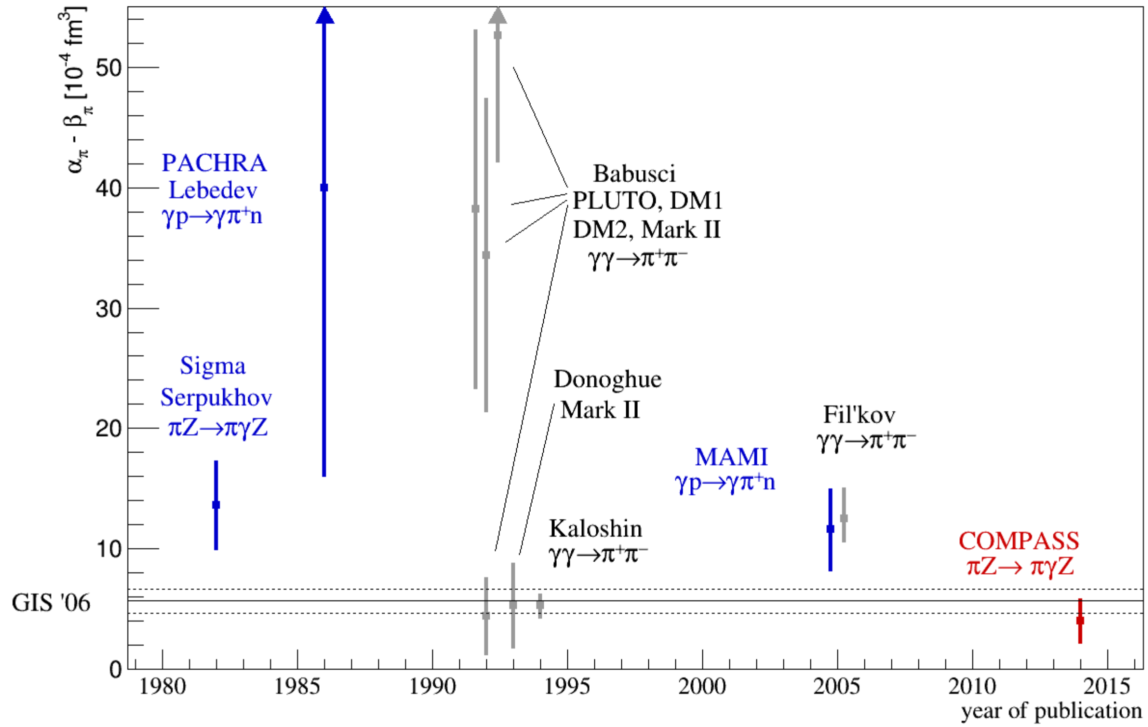




- deformation of a pion in el. & magn. fields
- prediction by chiral perturbation theory (χPT)
  $\alpha + \beta \simeq 0$
- pion polarisability measured via Primakoff scattering of pion in em. field of nucleus (Ni)
- control measurement using muons
- previously confused exp. situation

Pion polarisability



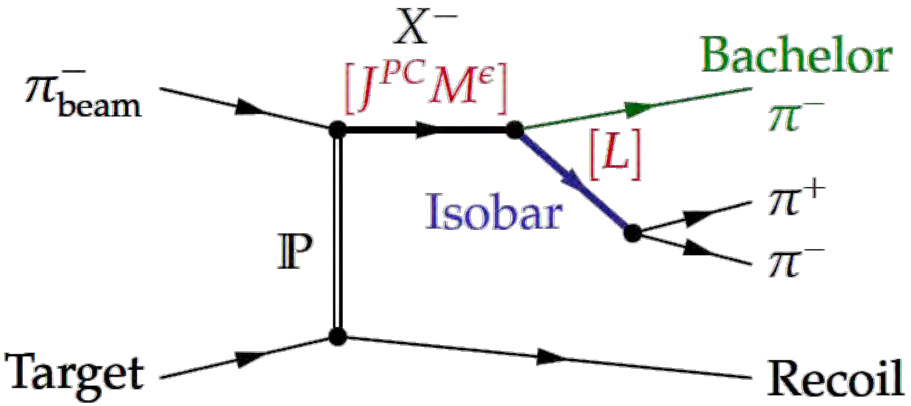


- predictions by χPT: $\alpha = (2.9 \pm 0.5)$ 10^{-4} fm^3
- exp with $\alpha + \beta = 0$ $\alpha = (2.0 \pm 0.6 \pm 0.7)$ 10^{-4} fm^3
- pion is very stiff! Neue Zürcher Zeitung : da schwabbelt nichts

  PRL 114 (2015) 062002

PWA of $\pi^- p \rightarrow \pi^- \pi^+ \pi^- p$

- Isobar model:

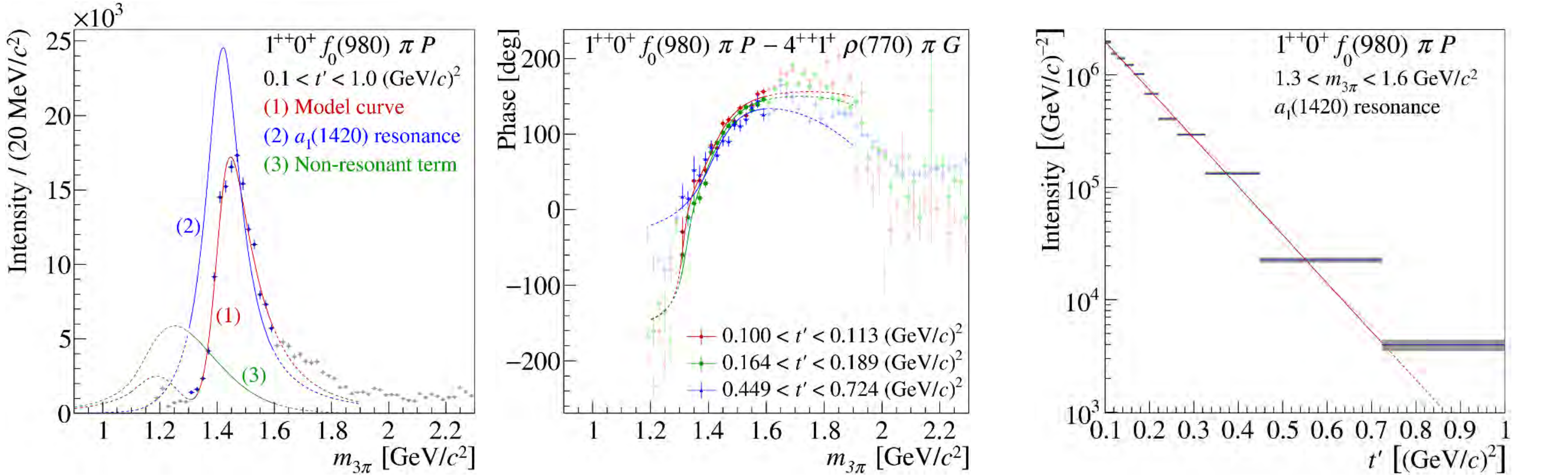


X decay is chain of successive two-body decays

- Analysis:
  - Partial wave analysis (PWA) in mass bins with 88 waves labelled J^{PC} M^{ε} Isobar L in 11 t′ bins
  - fit of spin-density matrix for major waves as function of mass
  - unprecedented statistical precision

- Discovery of $a_1(1420)$
  - 46 million events in 0.5 GeV < $m_{3\pi}$ < 2.5 GeV bin
  - unexpected narrow axial-vector state found
  - PRL 115 (2015) 082001

$a_1(1420)$ in $1^{++}0^+f_0(980)\ \pi P$ wave



- state of unknown nature
  - tetra-quark state
  - triangular diagram in $a_1(1260) \rightarrow K^*\bar{K}$; $K^*\pi$ and $K\bar{K} \rightarrow f_0(980)$
  - …

Summary and outlook

- A wealth of data from a decade of COMPASS-I
  - longitudinally polarised DIS and SIDS:
    - spin puzzle: first measurement of small gluon polarisation
    - PDFs, flavour separated quark distributions, BJ sum rule
  - transverse and unpolarised data → Bradamante
  - pion polarisability and other tests of chiral perturbation theory
  - a new quality of spectroscopy data, huge data sets
- Exciting new experiments of COMPASS-II
  - polarised DY, GPDs via DVCS and HEMP, SIDIS with LH2
- What's next? COMPASS-III?
  - until the advent of EIC the CERN COMPASS facility with the versatile M2 beam line remains unique.
  - physics case for 2021-202x after CERN LS2 being built up.

- **New Collaborators and ideas welcome!**

Thank you!