Spin measurements in lepton scattering

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CERN/PH

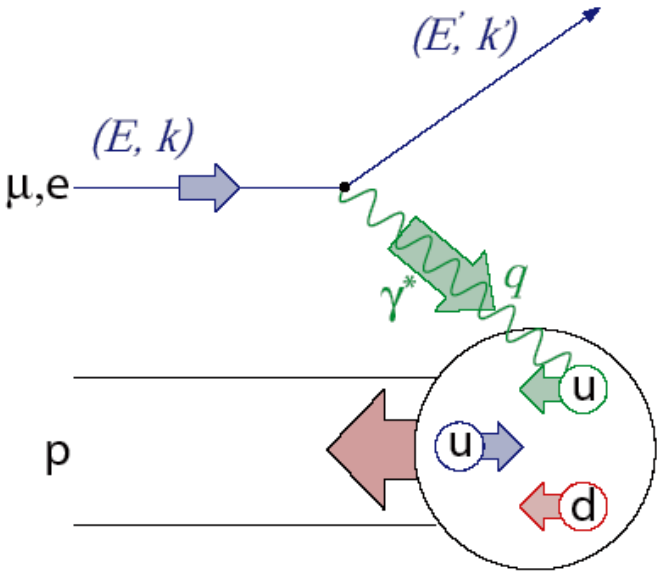
Workshop on
High-energy hadron physics with hadron beams

KEK, Tsukuba, January 2010

Plan

- Introduction
  - DIS
  - Experiments
- Helicity structure of the nucleon
  - Quarks
  - Gluons
- Transverse spin-structure of the nucleon
- Outlook

Deep Inelastic Scattering



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

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

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

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

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

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

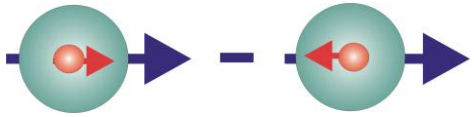
Parton Distribution Functions

Three twist-2 PDFs

q(x)
$f_1^q(x)$

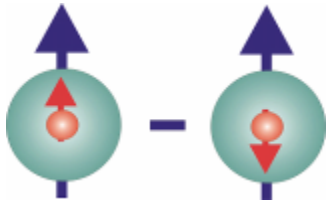
unpolarised PDF
quark with momentum *xP* in a nucleon
well known – unpolarised DIS

Δq(x)
$g_1^q(x)$



helicity PDF
quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon
known – polarised 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, poorly known

Longitudinal asymmetries

Inclusive scattering

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

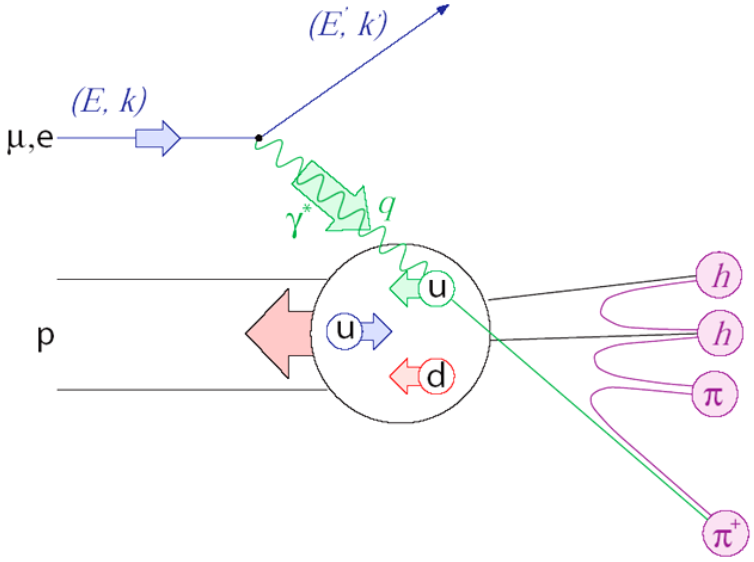
with

$$\Delta q = q^+ - q^-$$
$$A_1 = g_1 / F_1$$

Semi-inclusive scattering

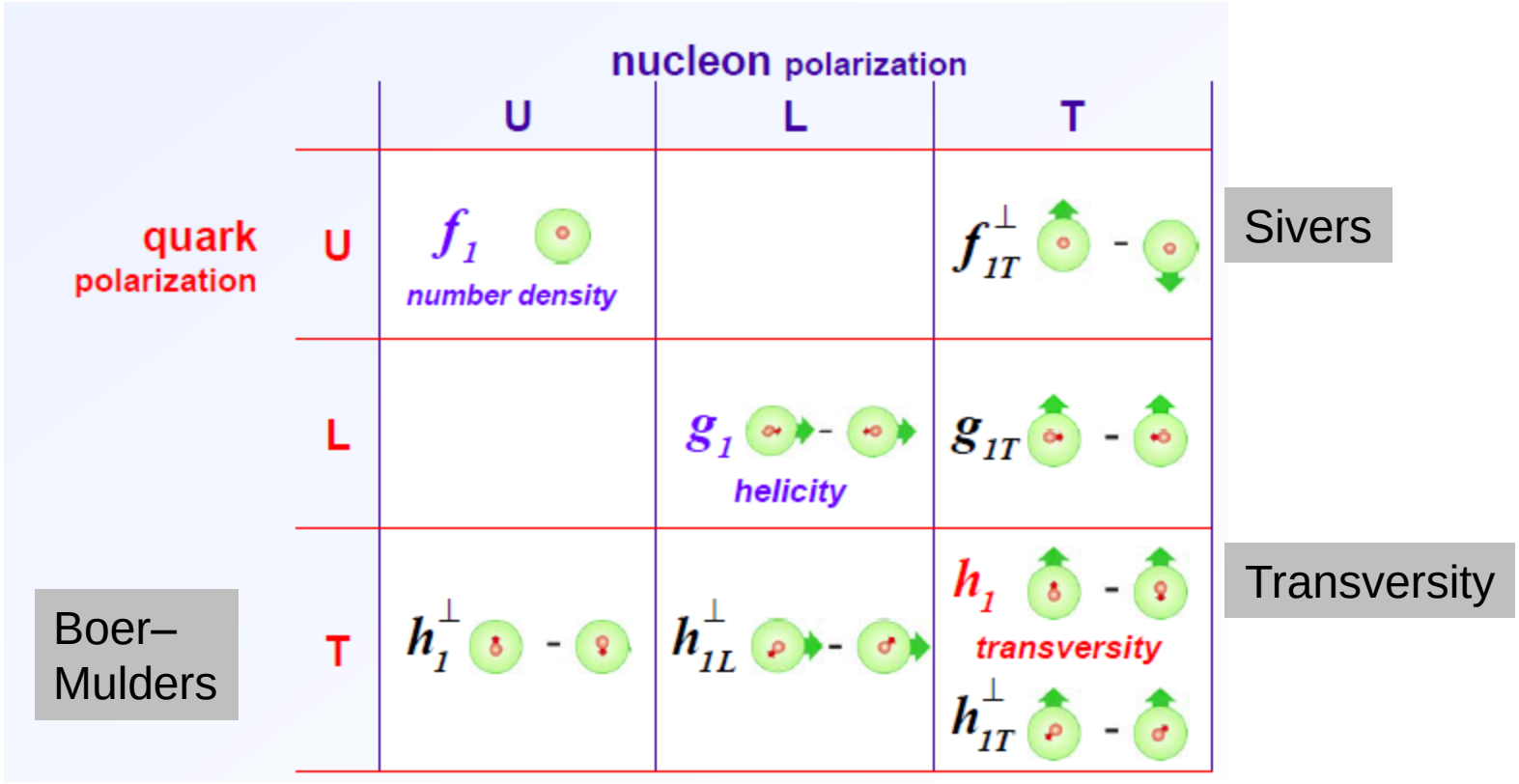
$$A_1^h = \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}$$

with $z = E_h / \nu$

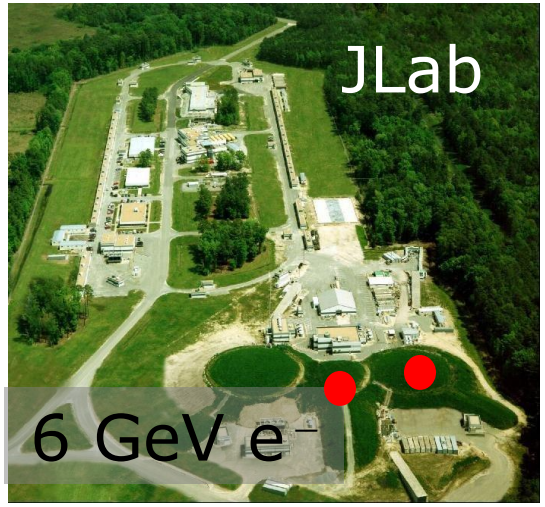


TMD parton distributions

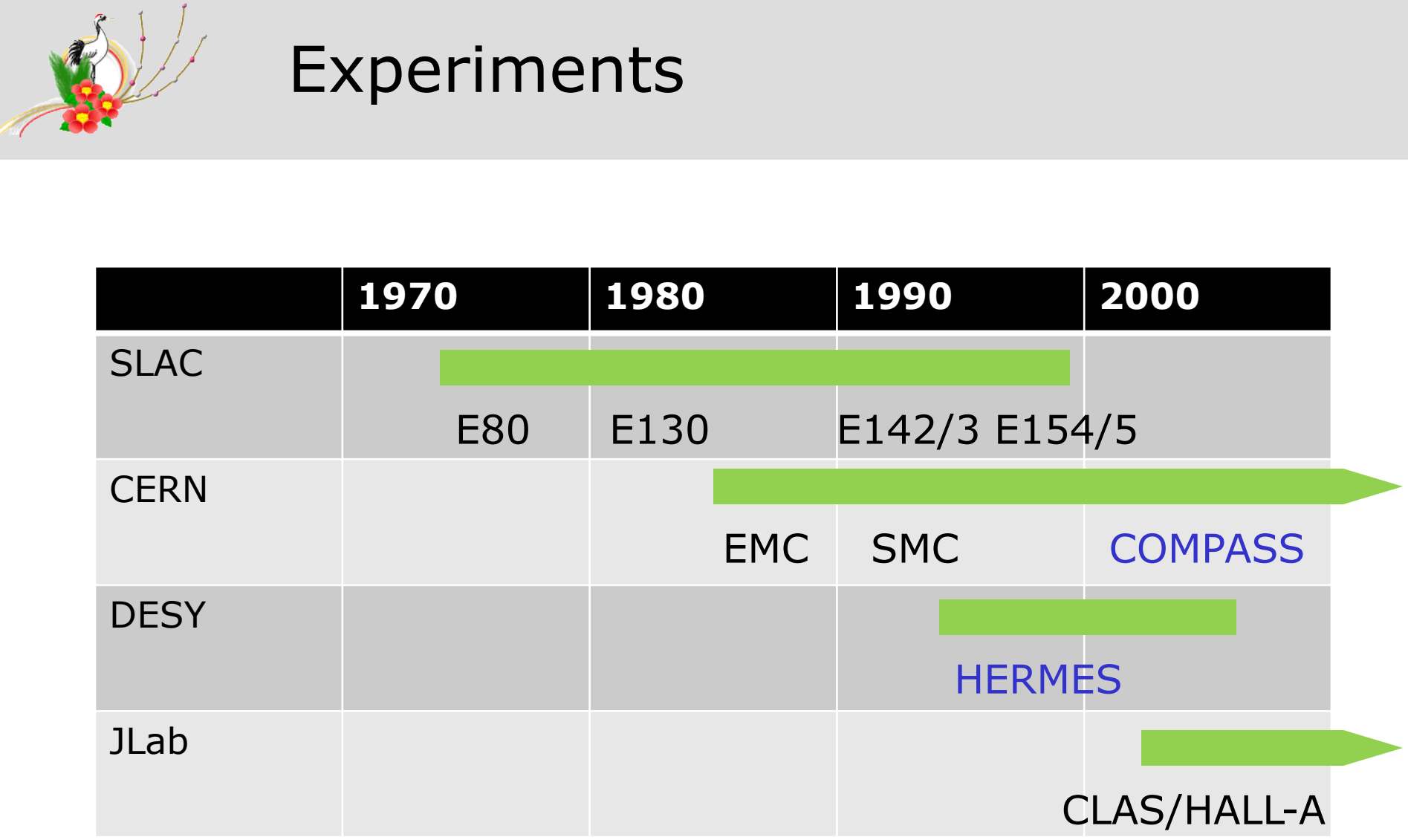
- 8 intrinsic transverse momentum dependent PDFs at LO
- Asymmetries with different angular dependences on hadron and spin azimuthal angles, Φ_h and Φ_s



Laboratories



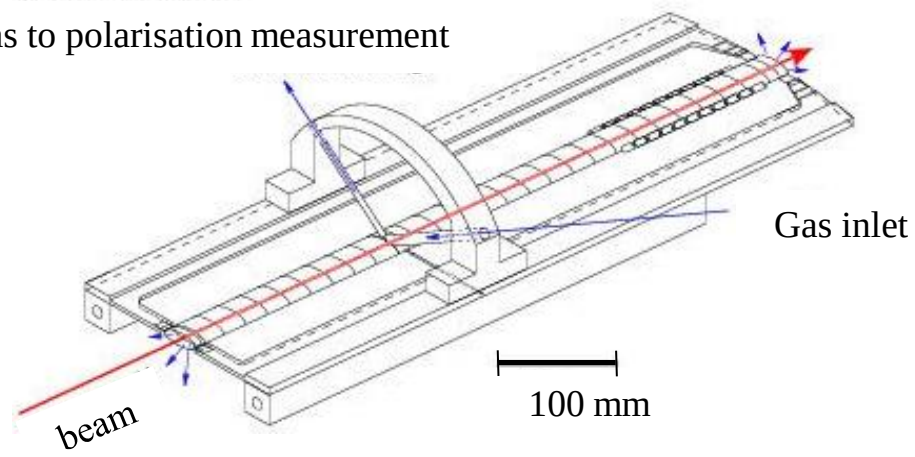
Experiments



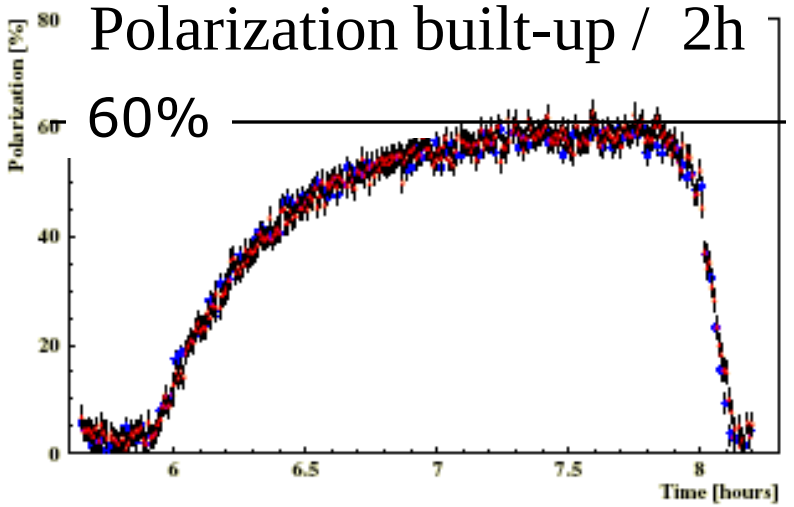
A worldwide effort since decades

HERMES

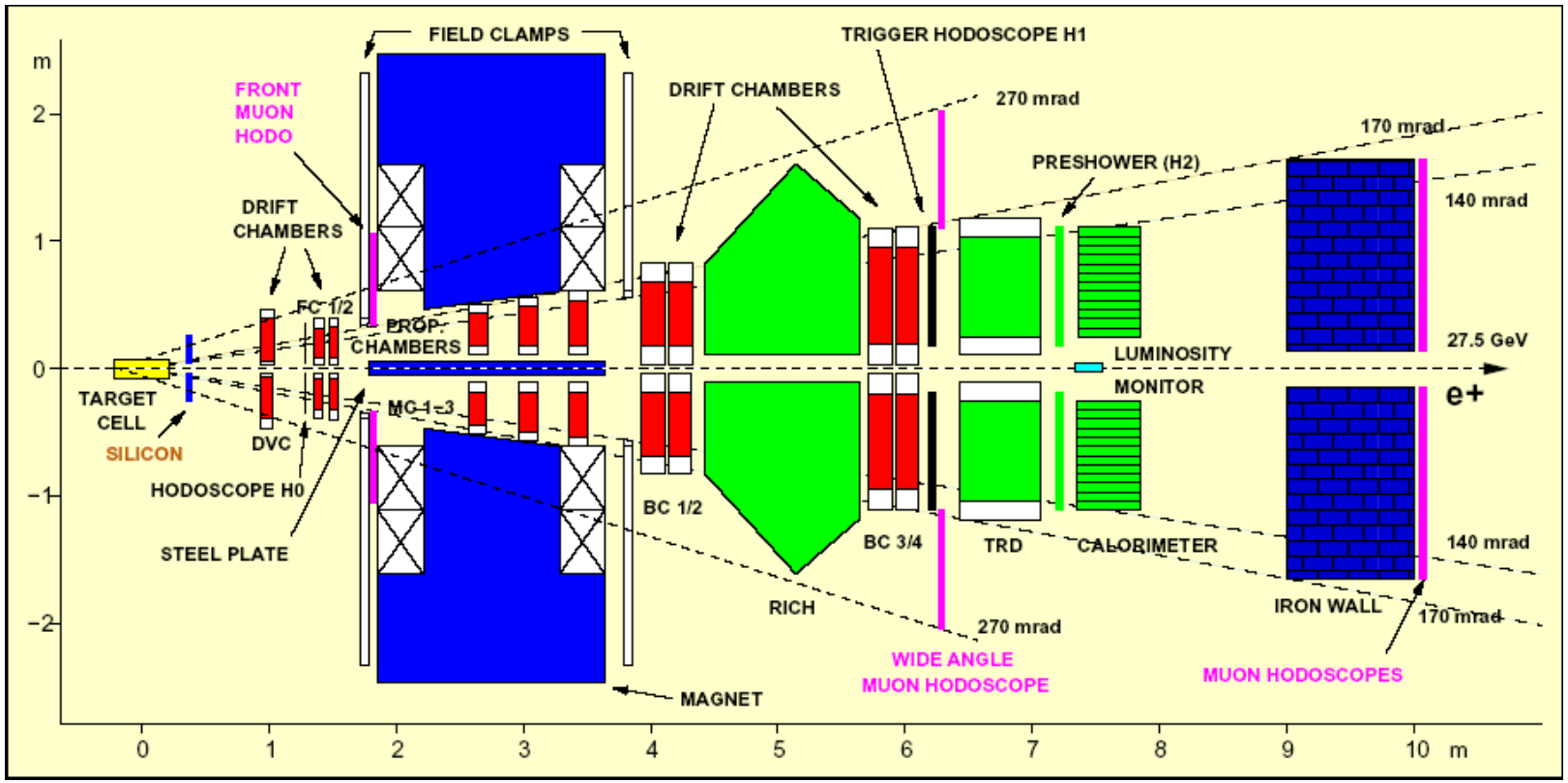
Target: atomic beam source + internal storage cell
10^{14} atoms/cm^2
p, d, ^{3}He (~90% pol.)



Beam: 27 GeV, electrons, polarized by the Sokolov-Ternov effect + spin rotators

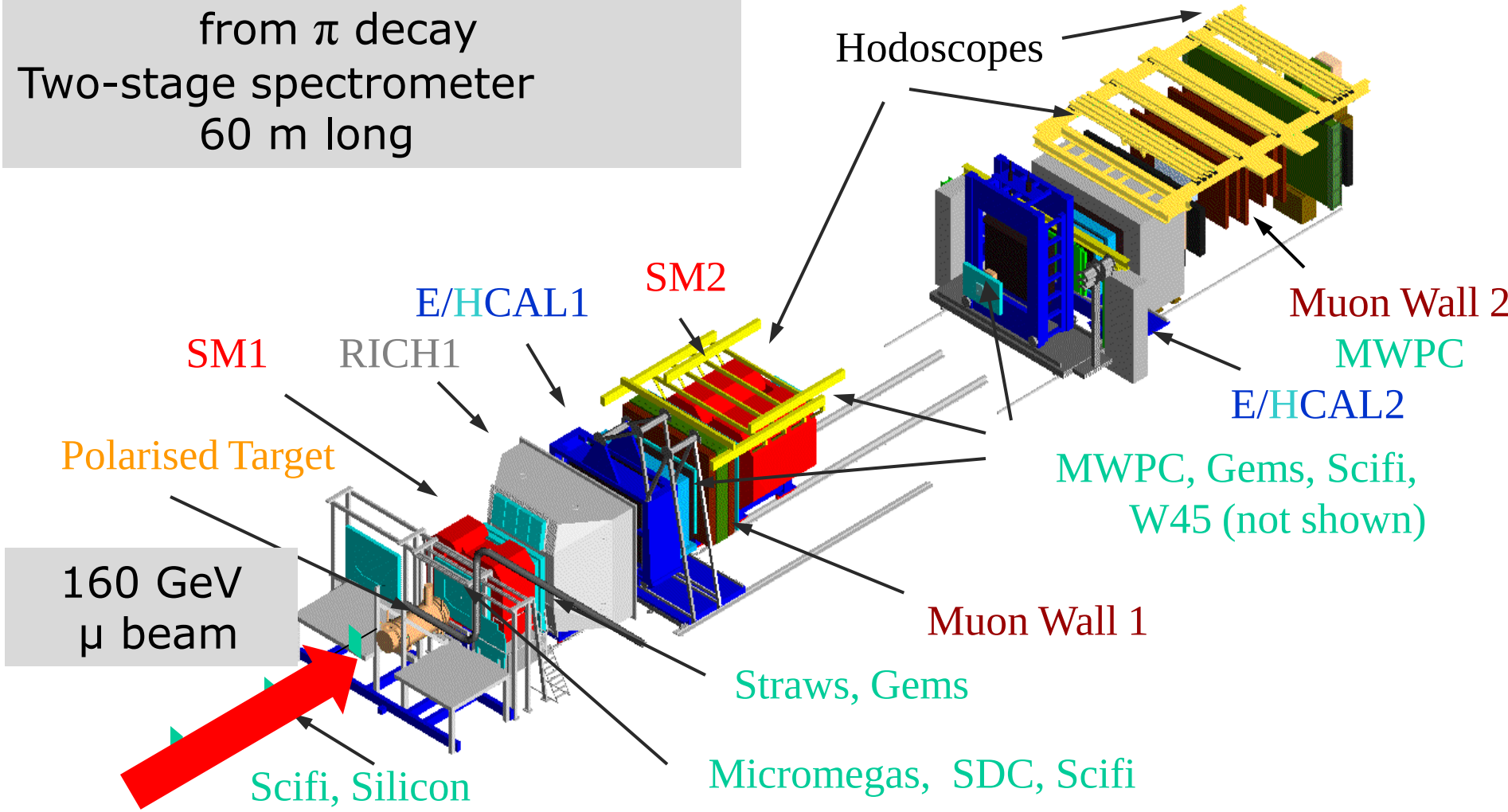


HERMES


FIELD CLAMPS
TRIGGER HODOSCOPE H1
m
FRONT MUON HODO
DRIFT CHAMBERS
270 mrad
170 mrad
PRESHOWER (H2)
DRIFT CHAMBERS
140 mrad
FC 1/2
PROP. CHAMBERS
27.5 GeV
LUMINOSITY MONITOR
e+
TARGET CELL
SILICON
MC 1-3
DVC
HODOSCOPE H0
STEEL PLATE
BC 1/2
BC 3/4
TRD
CALORIMETER
140 mrad
RICH
IRON WALL
170 mrad
270 mrad
WIDE ANGLE MUON HODOSCOPE
MUON HODOSCOPES
MAGNET
2
1
0
−1
−2
0
1
2
3
4
5
6
7
8
9
10 m

COMPASS

Beam: 160 GeV μ^+, pol. 80%
from π decay
Two-stage spectrometer
60 m long

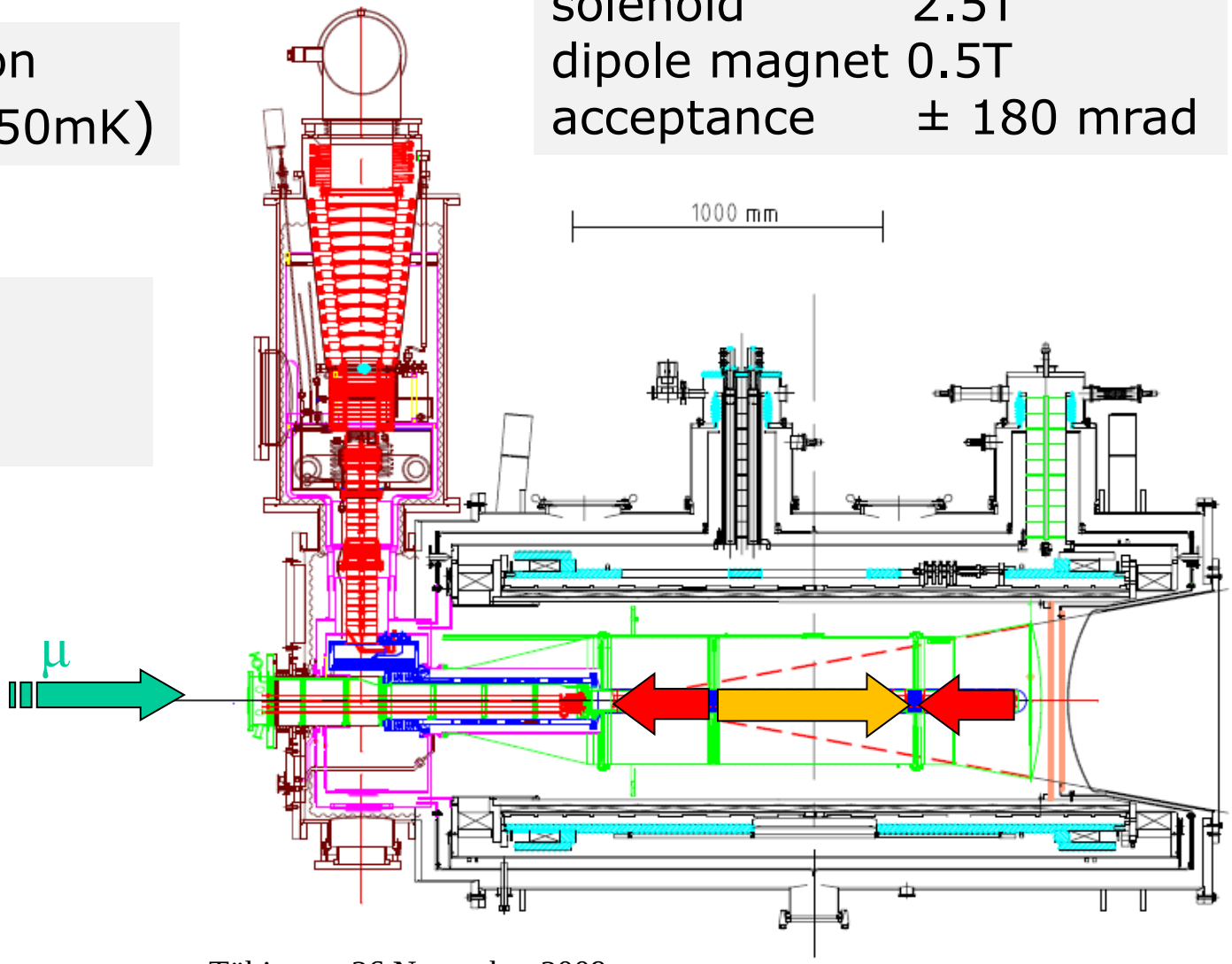


COMPASS Target system

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

^{6}LiD/NH_3
50/90% pol.
40/16% dil. f.

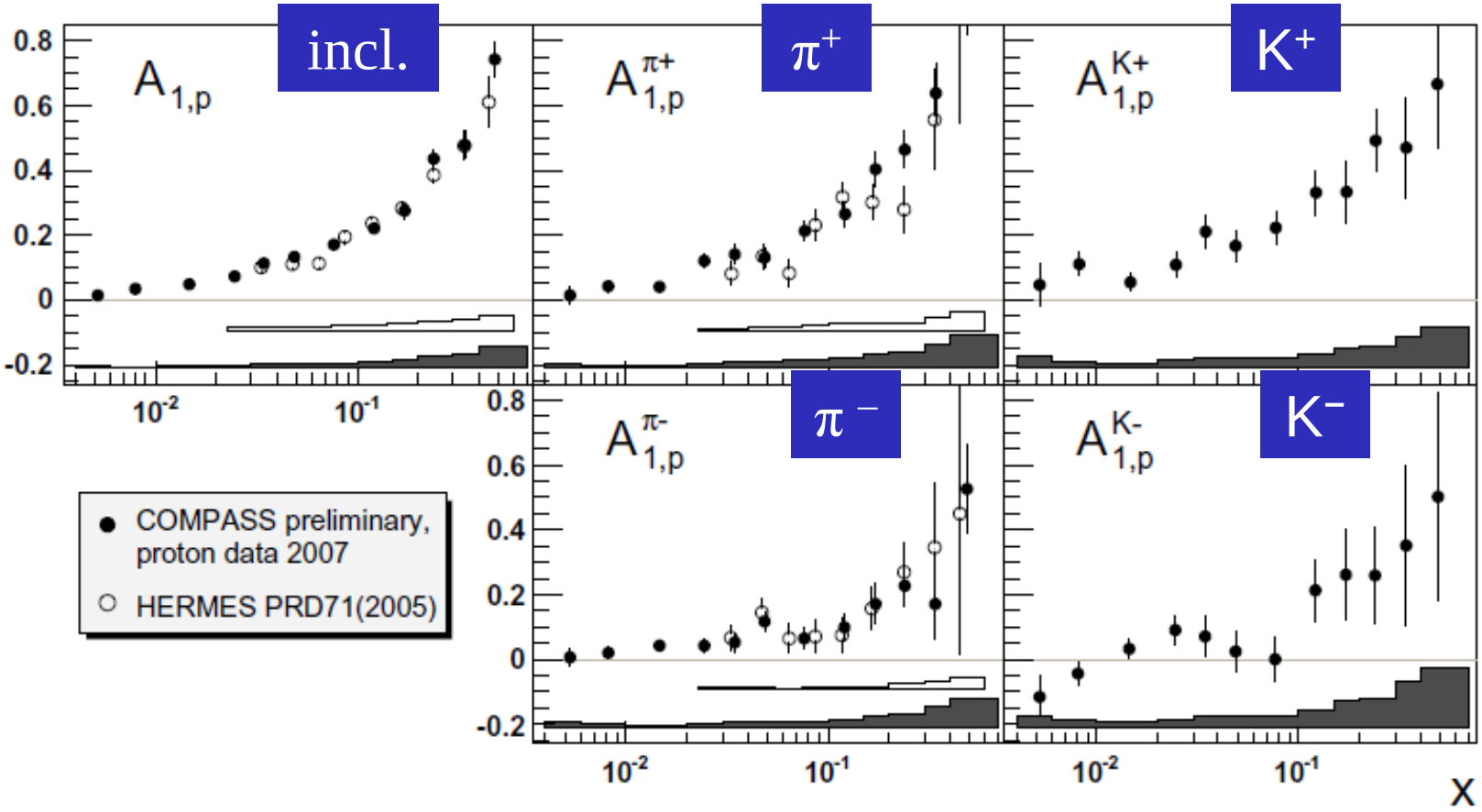
solenoid 2.5T
dipole magnet 0.5T
acceptance ± 180 mrad



Helicity structure

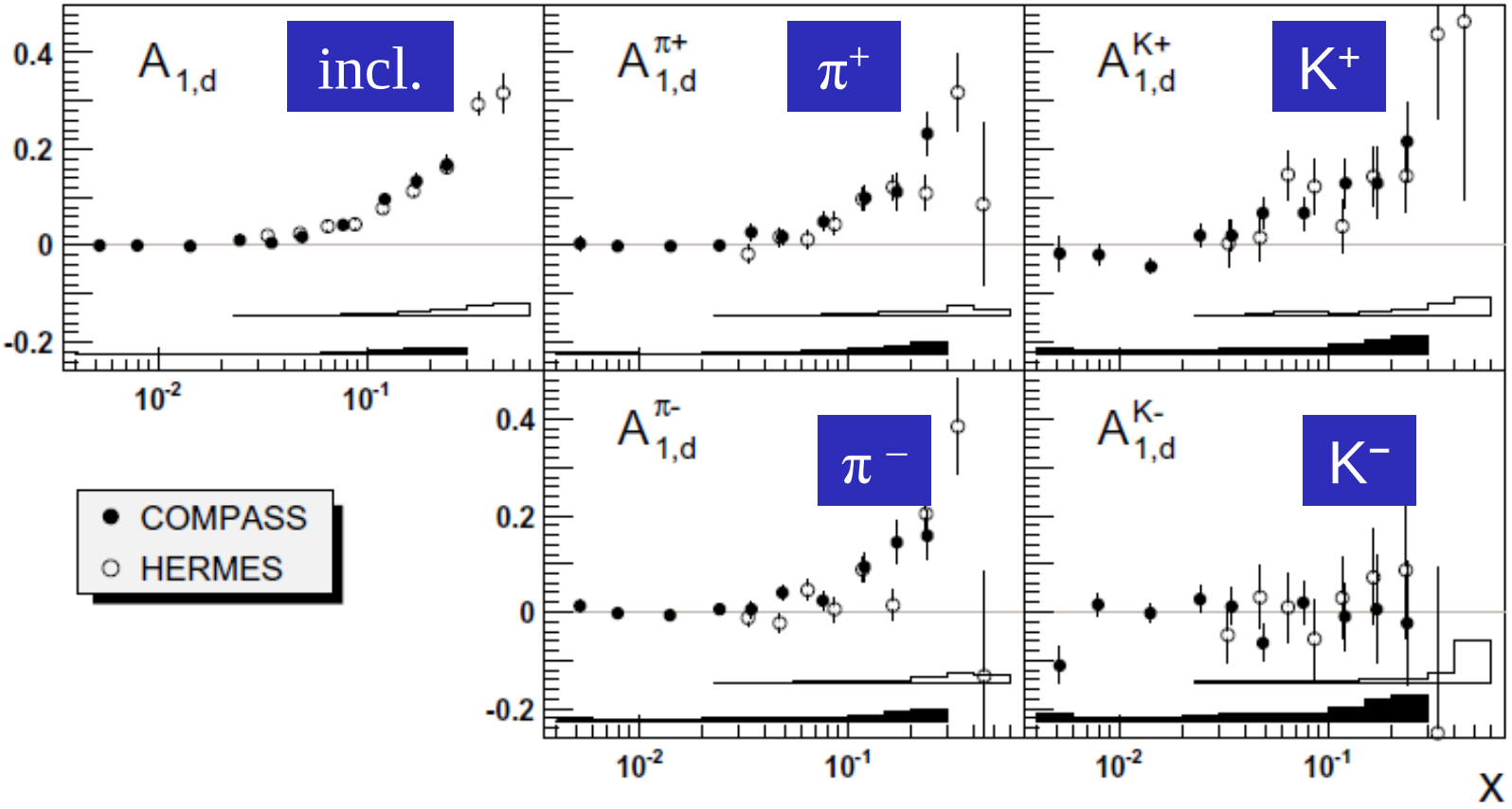
Proton helicity structure

- incl. & semi-incl. asymmetries,
- first measurement of A^K



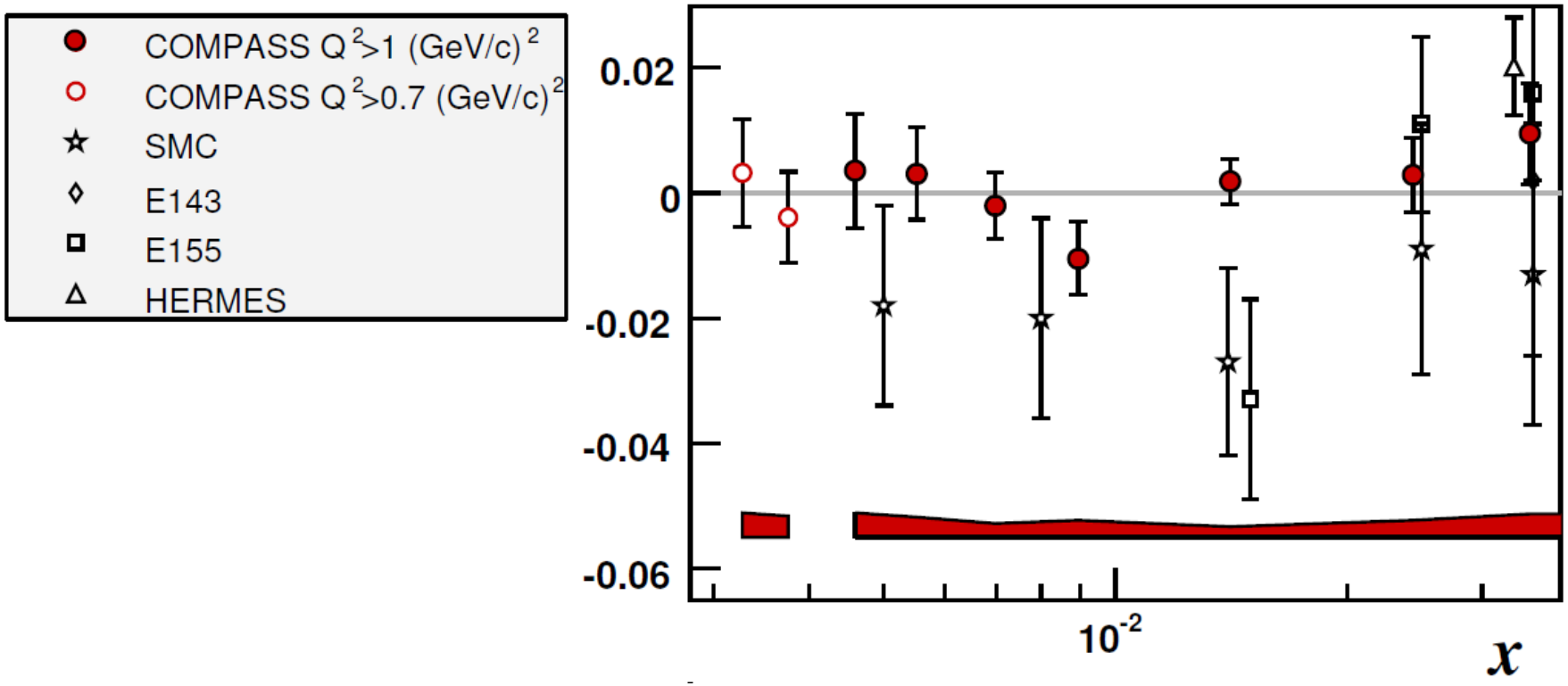
Deuteron helicity structure

- incl. & semi-incl. asymmetries



Incl. deuteron asymmetry

- most precise measurement for $x<0.03$ and $Q^2 > 1$ GeV^2



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

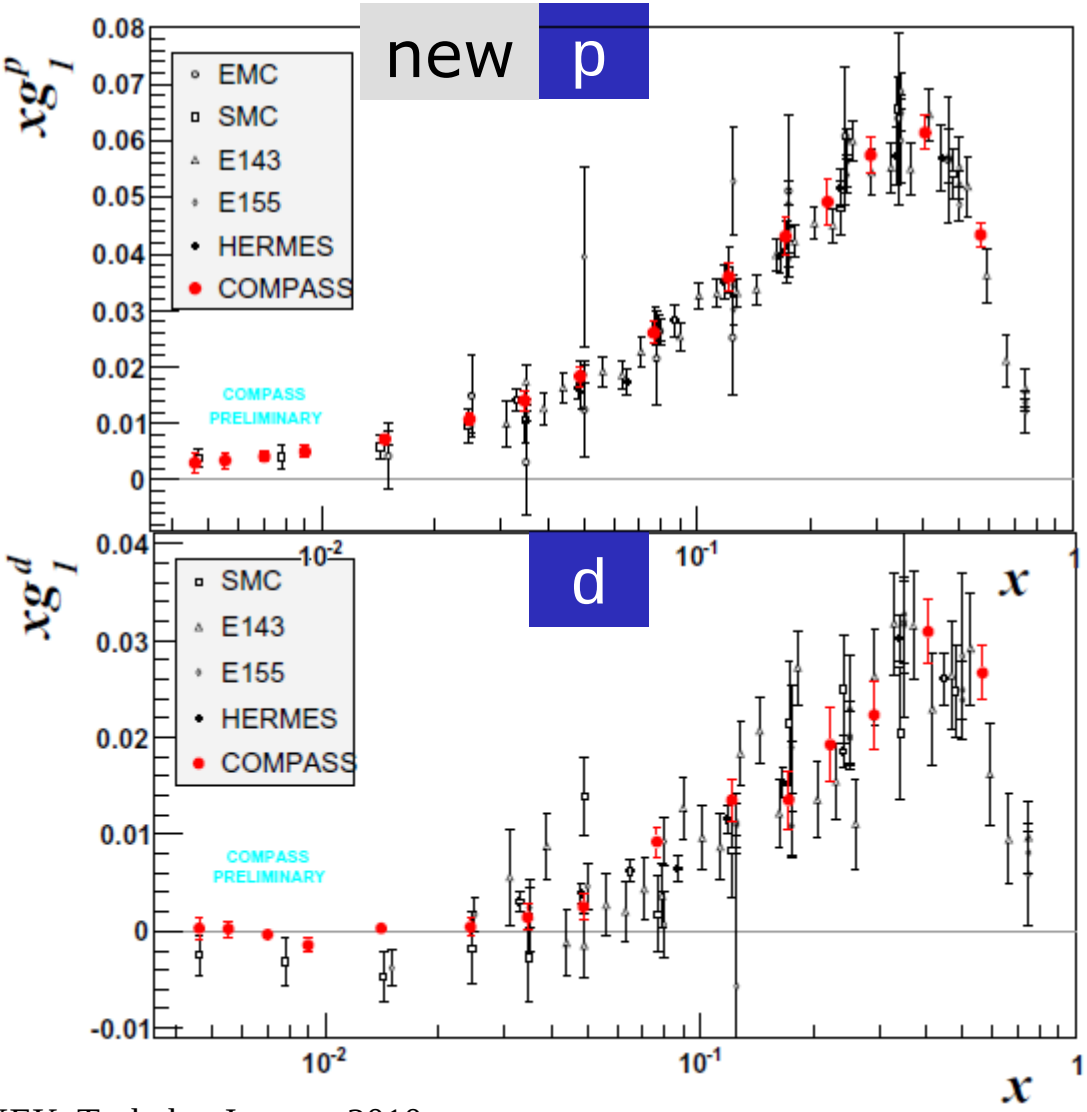
- very precise data
- only data below
  $x < 0.01$ ($Q^2 > 1$)

- deuteron data:

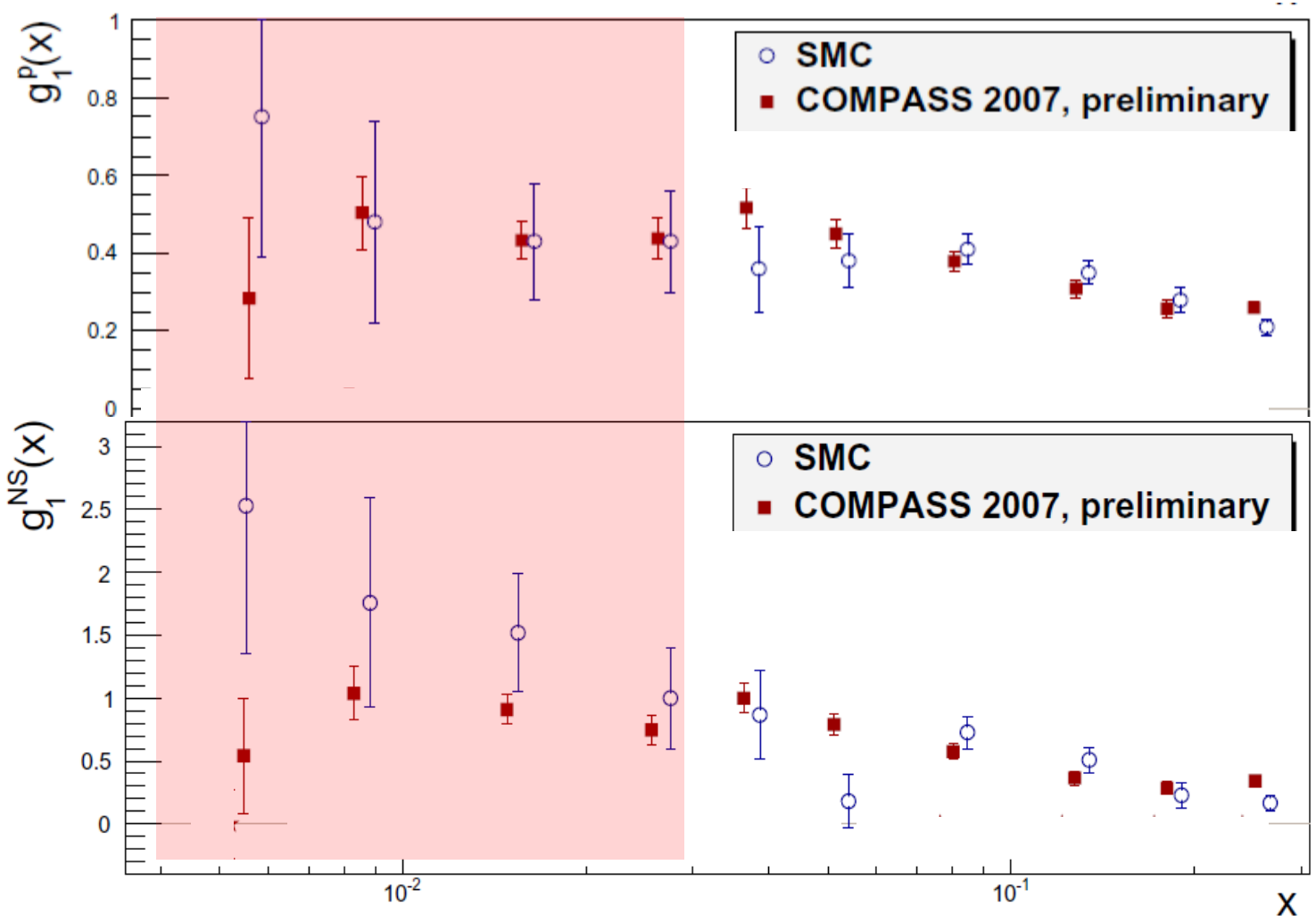
$a_0 = 0.33 \pm 0.03 \pm 0.05$

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

(evol. to $Q^2=\infty$)

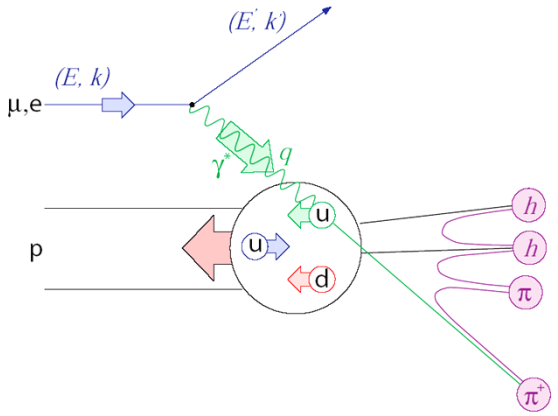


g_1 proton and g_1^{NS}

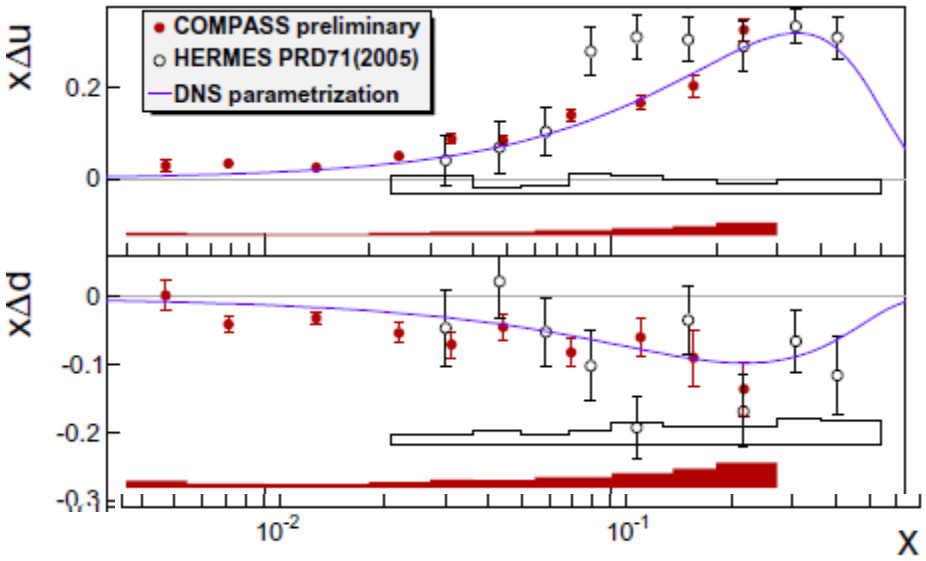


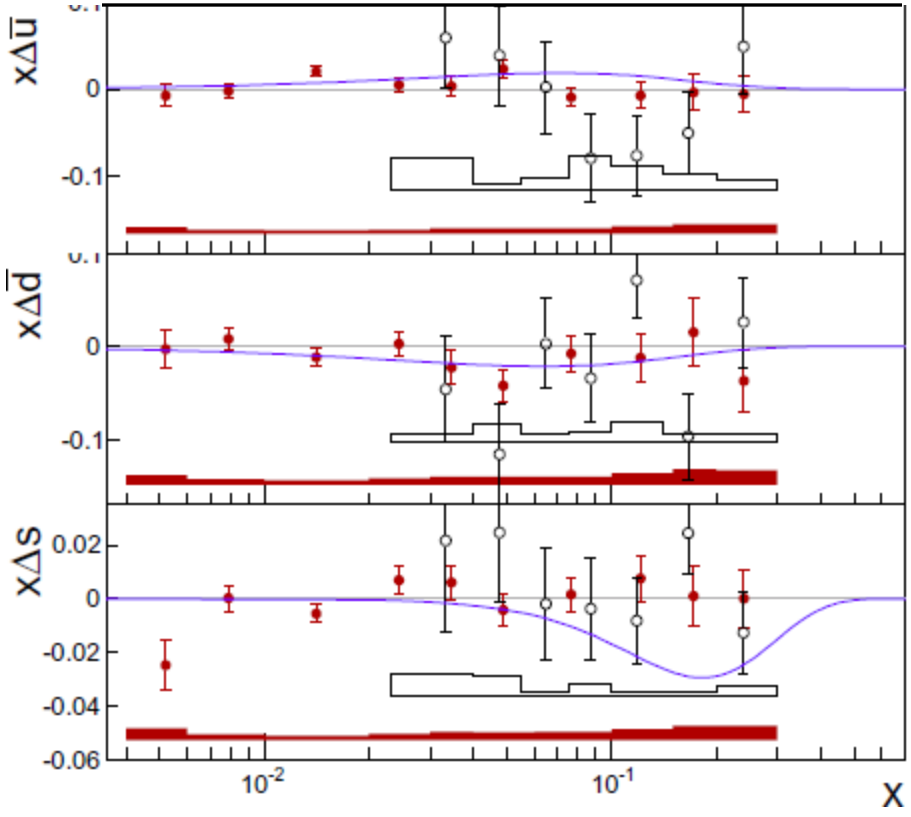
new

The role of quark flavours



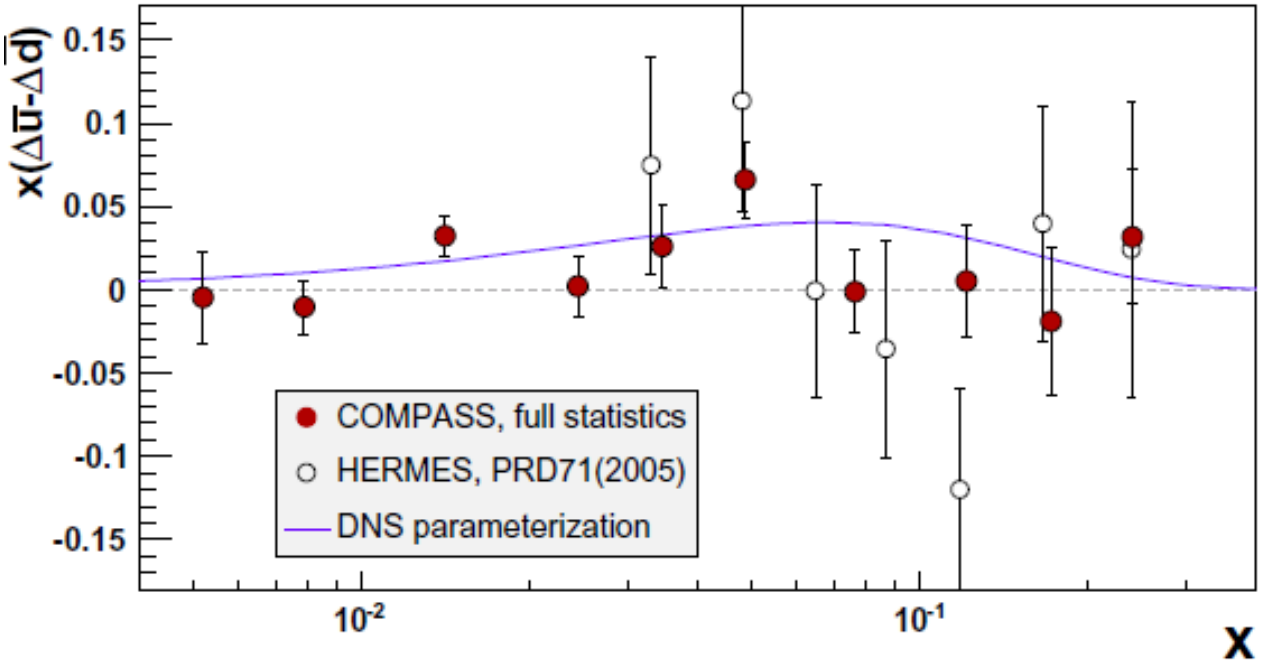
LO semi-inclusive data analysis





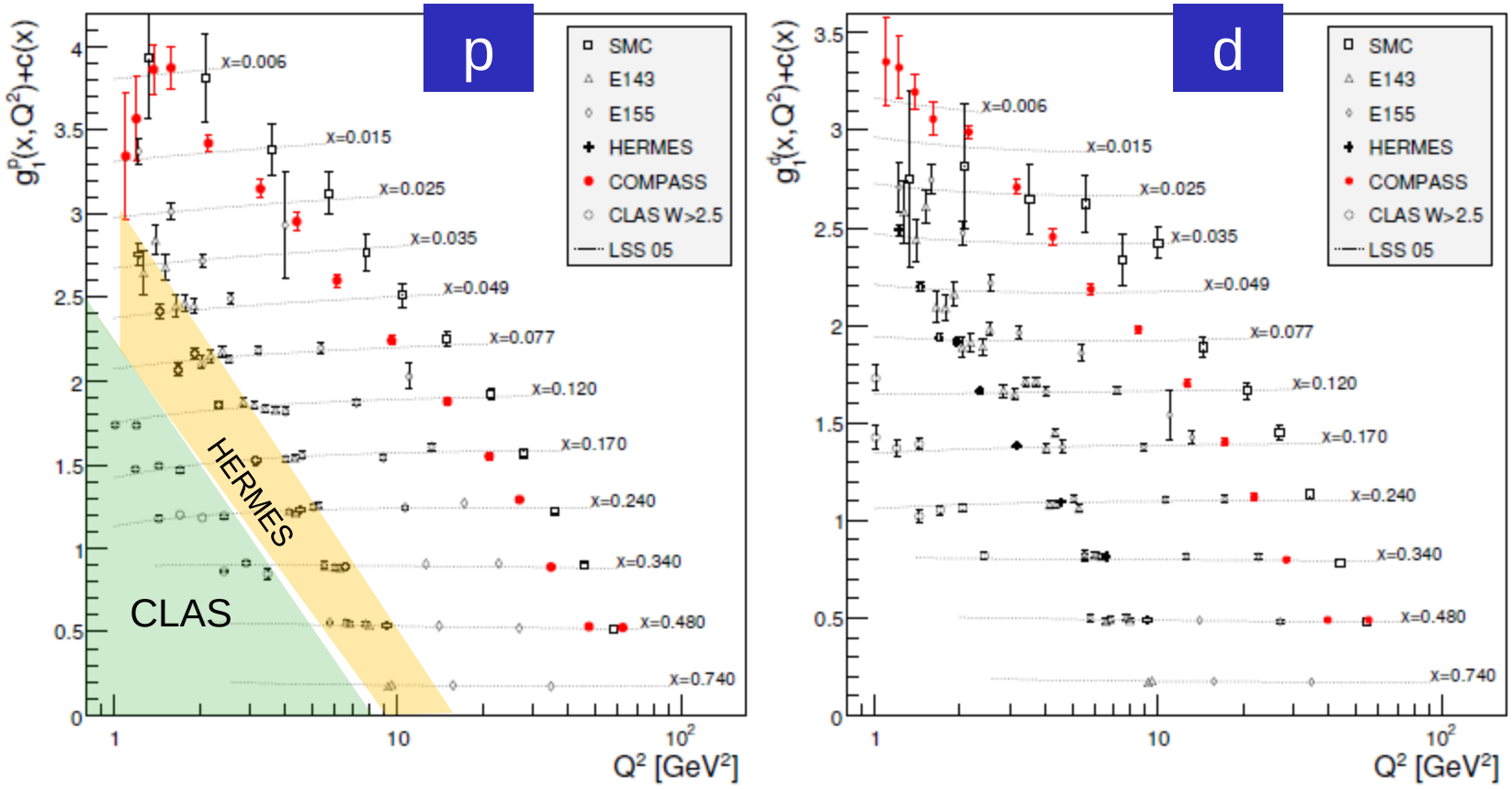
Flavour asymmetry? $\Delta\bar{u} - \Delta\bar{d}$

- considerable asymmetry in the unpolarised case
- model predicts naturally asymmetry for pol. case
- Rather small effect, u-bar > d-bar



QCD analyses

- *Q^2 dependence g_1* or A_1 data described in QCD
- Nice data, but limited kinematic rages (c.f. unpol. HERA)



Gobal NLO QCD analysis

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q^{\mathrm{ns}} = \Delta\mathcal{P}^{\mathrm{ns}}_{qq} \otimes \Delta q^{\mathrm{ns}}$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix} \Delta q^{\mathrm{s}} \\ \Delta g \end{pmatrix} = \begin{pmatrix} \Delta\mathcal{P}^{\mathrm{s}}_{qq} & \Delta\mathcal{P}^{\mathrm{s}}_{qg} \\ \Delta\mathcal{P}^{\mathrm{s}}_{gq} & \Delta\mathcal{P}^{\mathrm{s}}_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta q^{\mathrm{s}} \\ \Delta g \end{pmatrix}$$

DGLAP

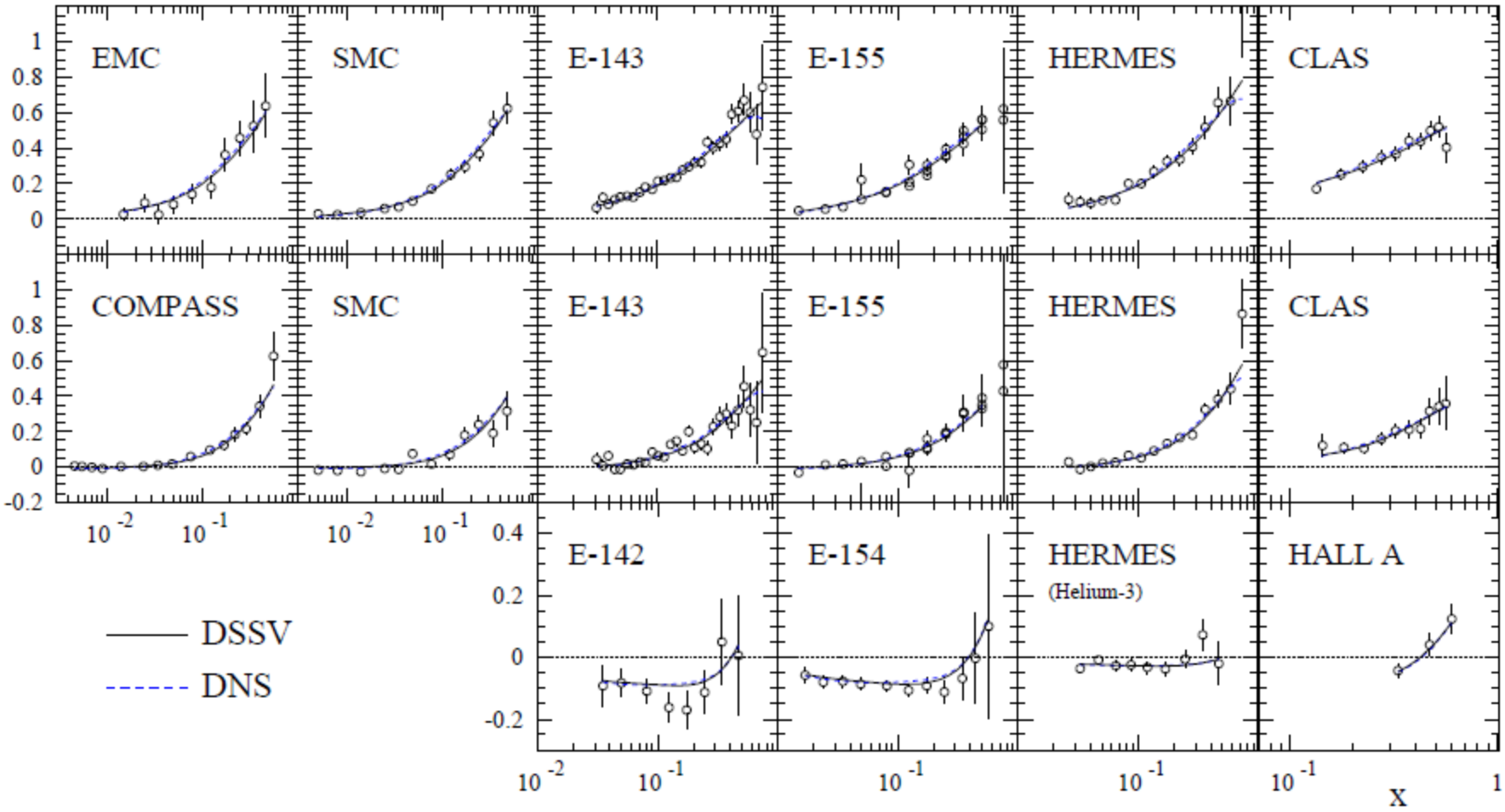
- choose scheme ($\overline{\mathrm{MS}}$, AB, jet) and Q_0^2
- optionally fix ns moments from hyperon decays (a_3, a_8)
- fit PDFs for quark non-singlet and singlet and gluon to data
- extra problems in polarized case
  no positivity condition, no momentum sum rule

- Recent analyses include semi-inclusive and RHIC data
  - DSSV 2009 arXiv:0904.3821
  - Hirai, Kumano arXiv:0808.0413

Global NLO QCD analyses

- Recent analyses of DIS and RHIC data
  - DSSV 2009 arXiv:0904.3821
    DIS and SIDIS data,
    RHIC π^0 and inclusive jets
  - Hirai, Kumano arXiv:0808.0413
    DIS data,
    RHIC π^0 data
  - Pol. gluon PDFs with node allowed
  - Detailed studies of systematic uncertainties
  - SIDIS data very sensitive to used fragmentation functions
  - "PGF" hadron data not yet included (s. below)

DSSV fit to inclusive asymmetries



A_1^p p

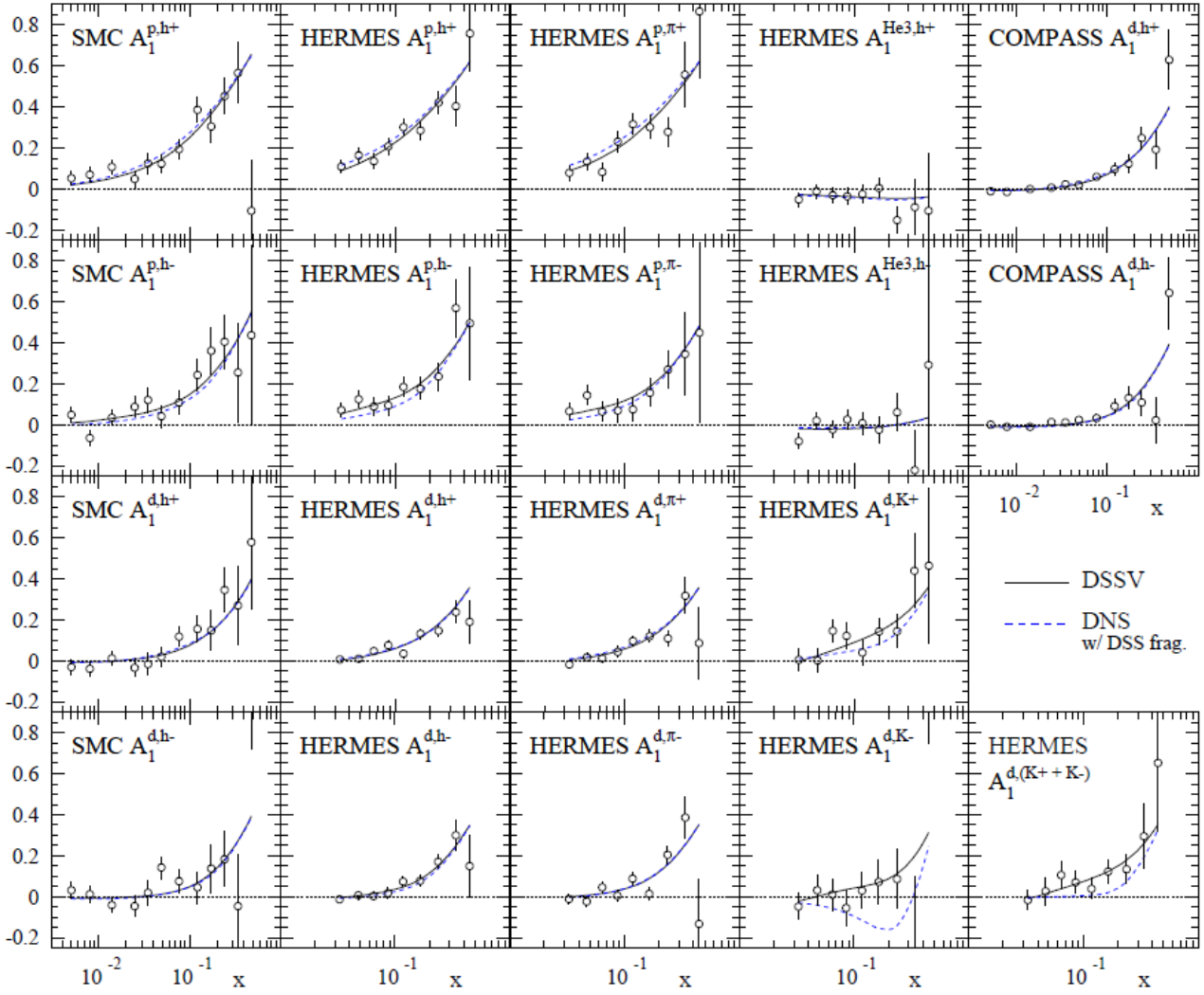
A_1^d d

A_1^n n

CERN | SLAC | DESY | JLab

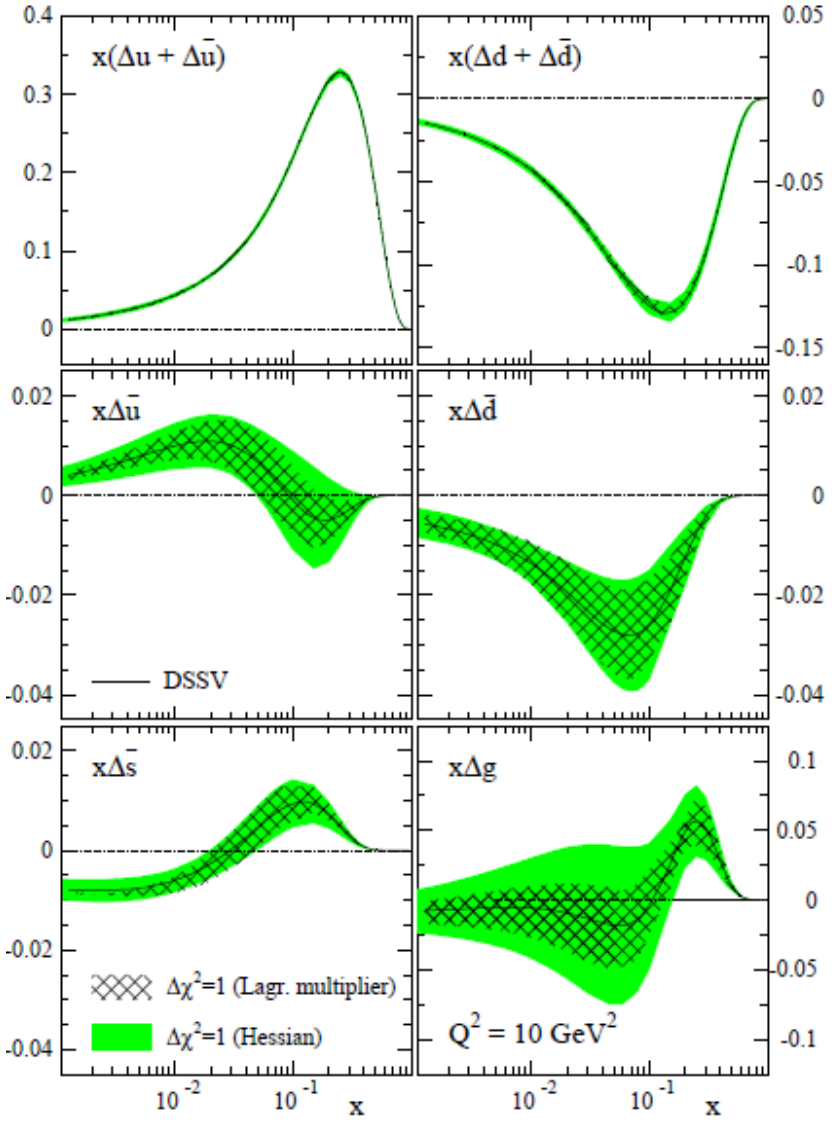
DSSV (semi-inclusive data)

- Most data from HERMES
- COMPASS proton data not yet in
- DSS fragmentation functions
  PRD 75, 114010
  PRD 76, 074033

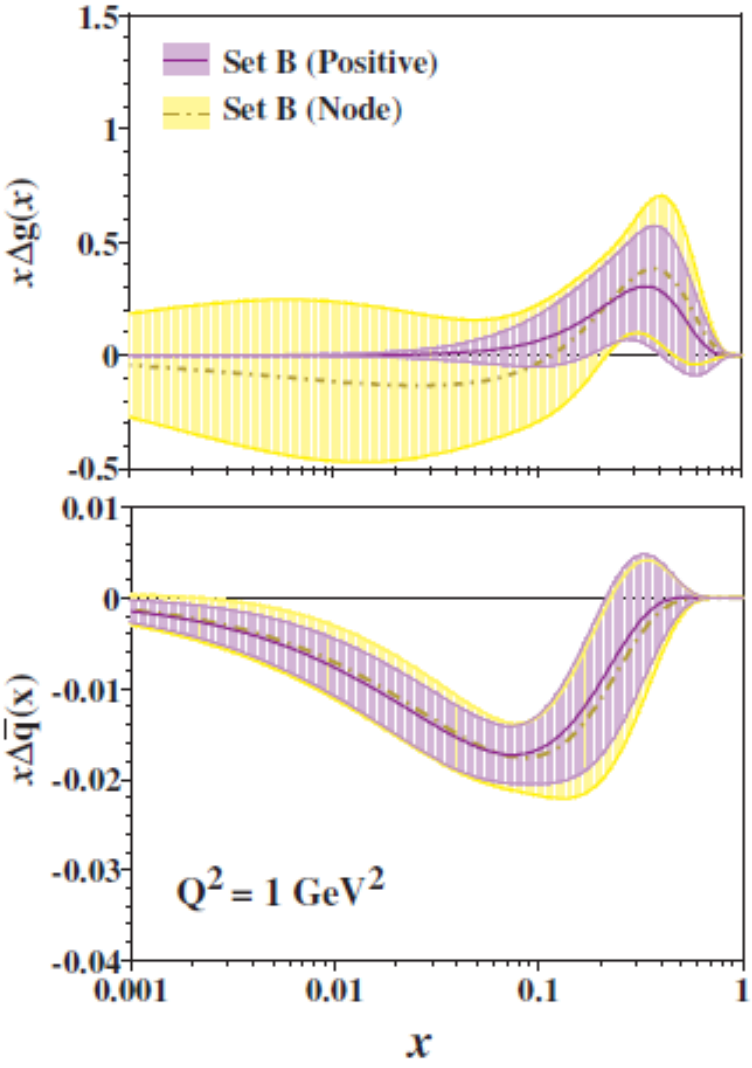


PDFs from global analyses

DSSV



Hirai, Kumano



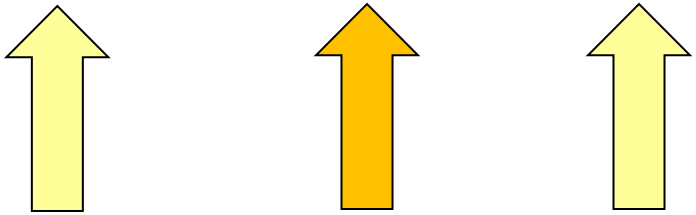
Global analyses

- Gluon polarization still poorly known but much smaller than expected in axial anomaly scenario for solving the spin puzzle.
- Gluons can still make a major contribution to the nucleon spin.
- Many analyses indicate the possibility of a node around x=0.1 in $\Delta g(x)$
- Quark distributions well determined (apart from anti-quarks)
- Strange quark distribution is indeed strange:
  SIDIS data prefer $\Delta s>0$ $(x>0.01)$ while incl data require with SU3 the first moment to be ~ –0.1 => node in DSSV

Angular momentum of the nucleon

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

quarks gluons orbital

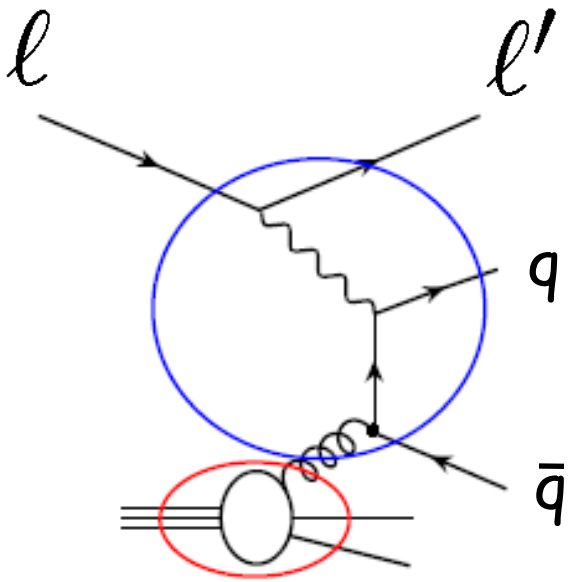


small ~0.15 unknown

Still poorly known

Gluon polarization from PGF

Principle: Gluon polarisation enters via photon-gluon fusion (PGF)



$$A_{\parallel} = R_{pgf} \langle \hat{a}_{pdf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle$$

- measure $A_{\parallel}$
- calculate R_{pgf}, $\langle \hat{a}_{pgf} \rangle$ and background by Monte Carlo

Analysed channels

analysed data sets:

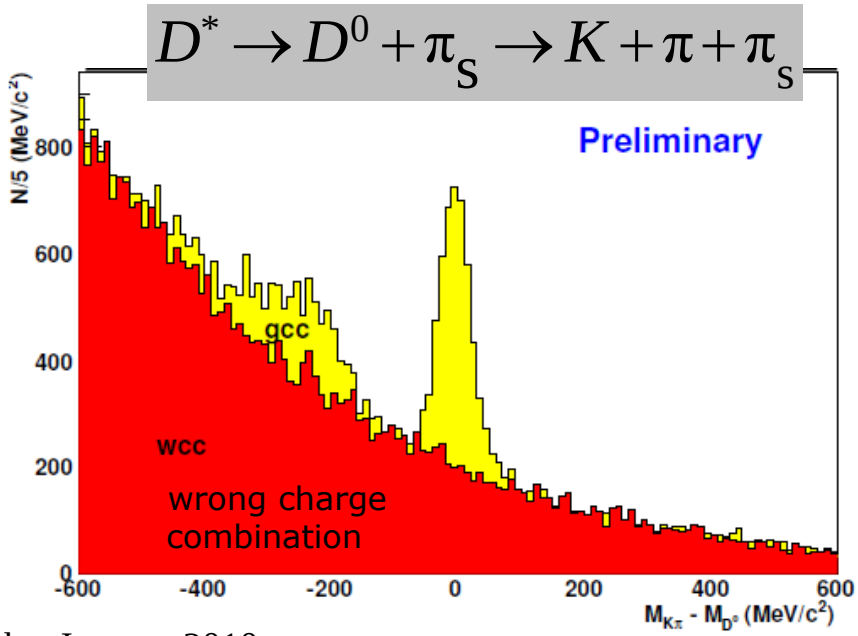
- high-p_T hadron pairs (no ID, pions/kaons)
  - $Q^2 > 1$ GeV^2 — LEPTO
  - $Q^2 < 1$ GeV^2 / unmeasured — PYTHIA
- high-p_T single hadron
  - small Q^2 / unmeasured — PYTHIA
- single charmed meson
  - quasi-real photons — AROMA, RAPGAP

All analyses in LO till now (plus parton showers)

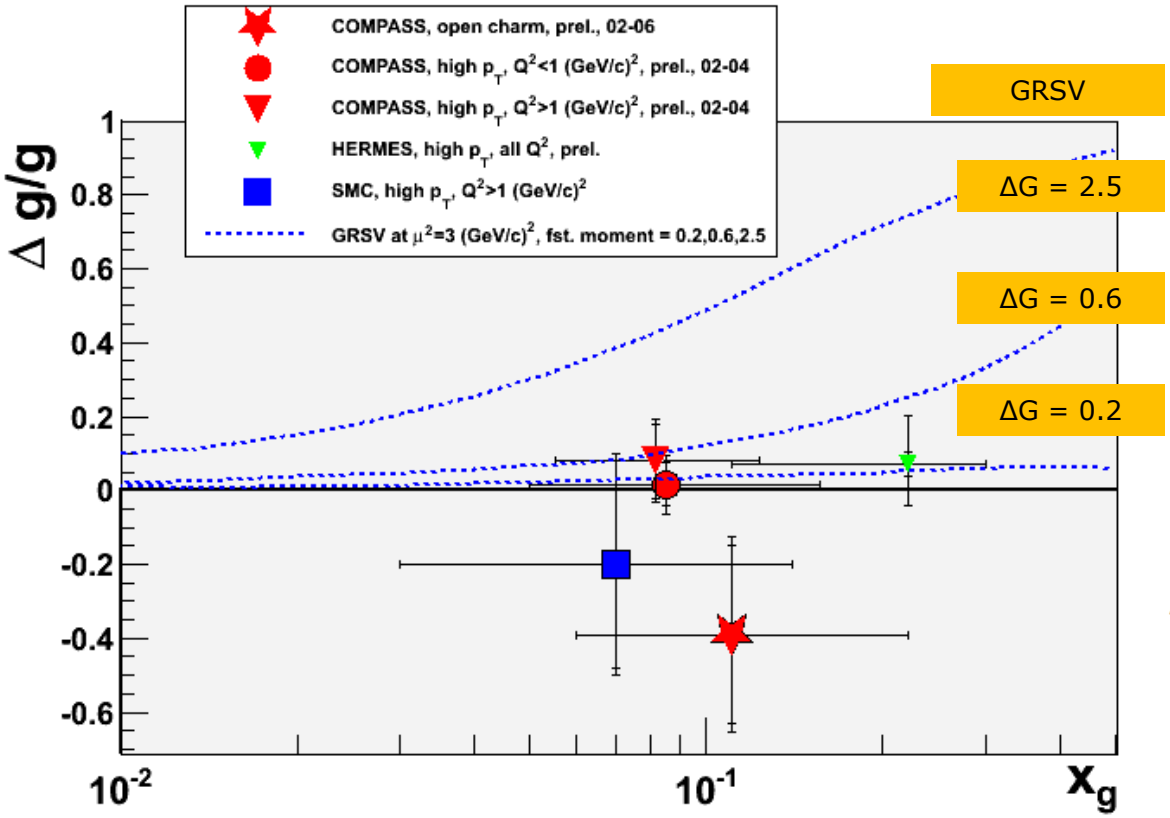
Δg/g from open charm

- Little physics background (LO, QCDC)
- Statistics limited, $D \to \pi K$ (BR ~ 4%)
- Large combinatorial background, drastically reduced in D^* channel with slow π_s
- All deuteron data
- new channels in D^* sample
  - sub-threshold kaons
  - 3-body decay with non-observed π^0 (bump)

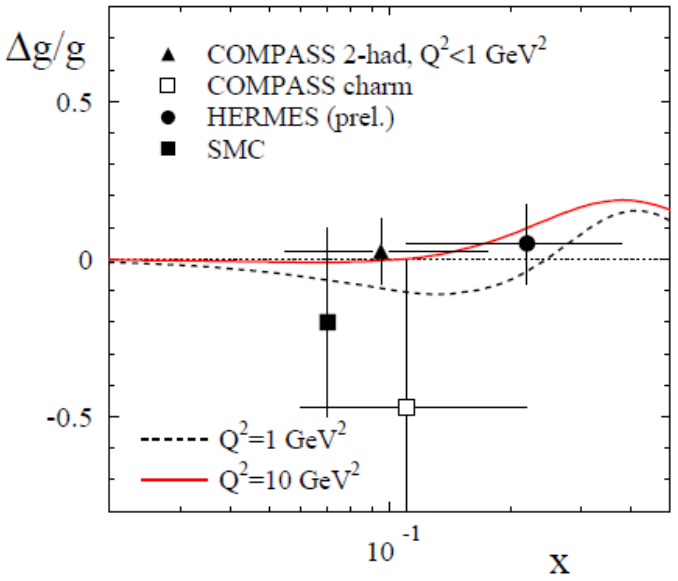
$$\langle \Delta g/g \rangle_x = -0.39 \pm 0.24\,(\text{stat.})$$



Gluon Polarization from LO PGF



Comparison with NLO DSSV



Transverse spin structure

Transversity PDF $\Delta_T^0 D_q^h$ or h_1

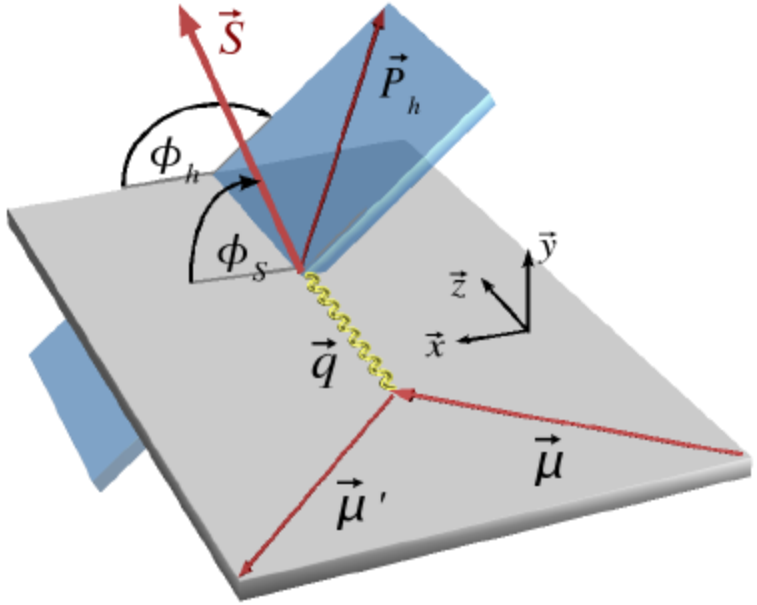
Couple $\Delta_T q$ to chiral odd Collins FF $\Delta_T^0 D_q^h$

$$A_{Coll} = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 q(x) D_q^h(z, p_T^h)}$$

Azimuthal cross-section asymmetry:

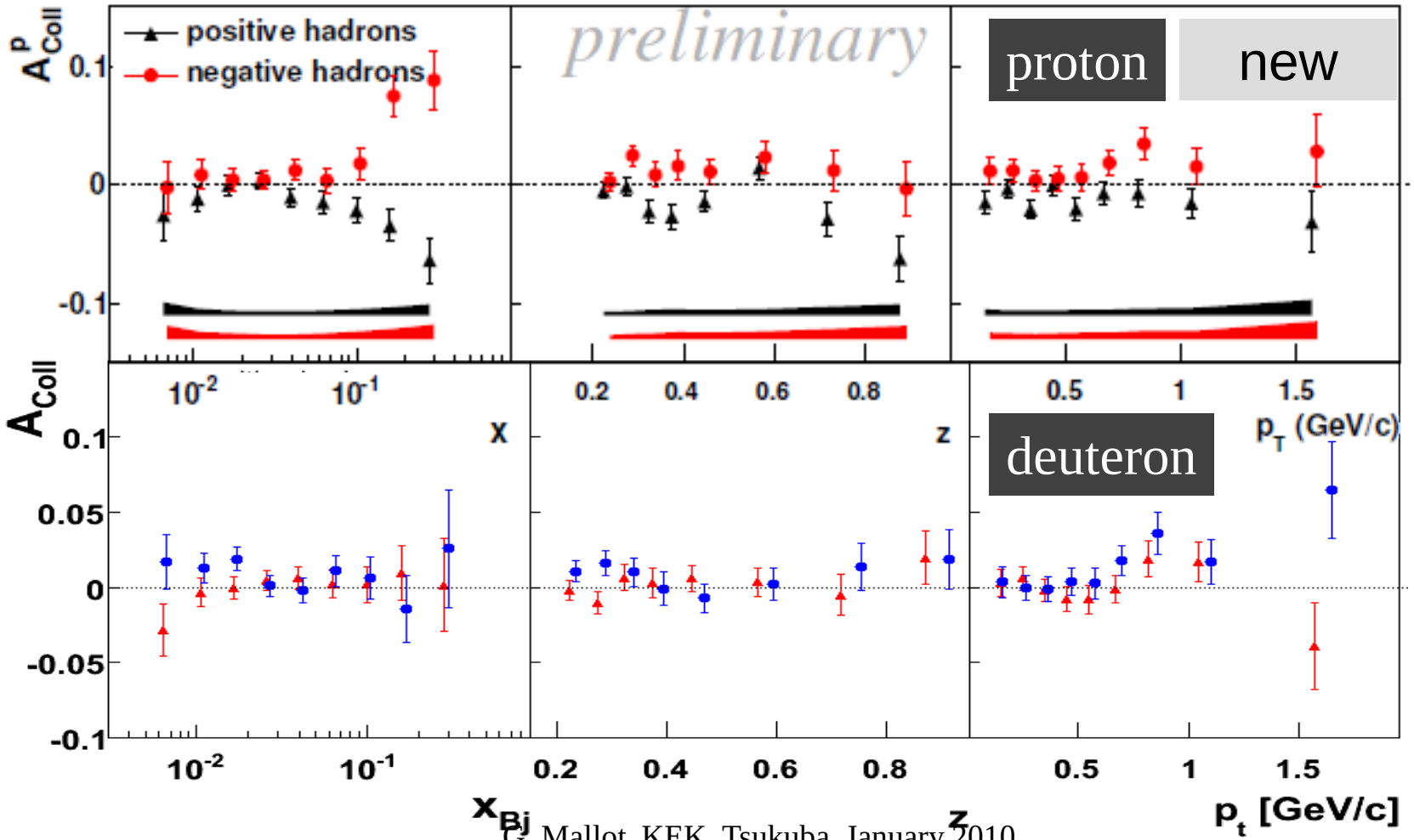
$$\frac{\Delta\sigma}{\sigma} \propto A_{Coll} \sin \Phi_C$$

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



Collins Asymmetries

New from COMPASS: full 2007 proton data set (statistics tripled)



h^+

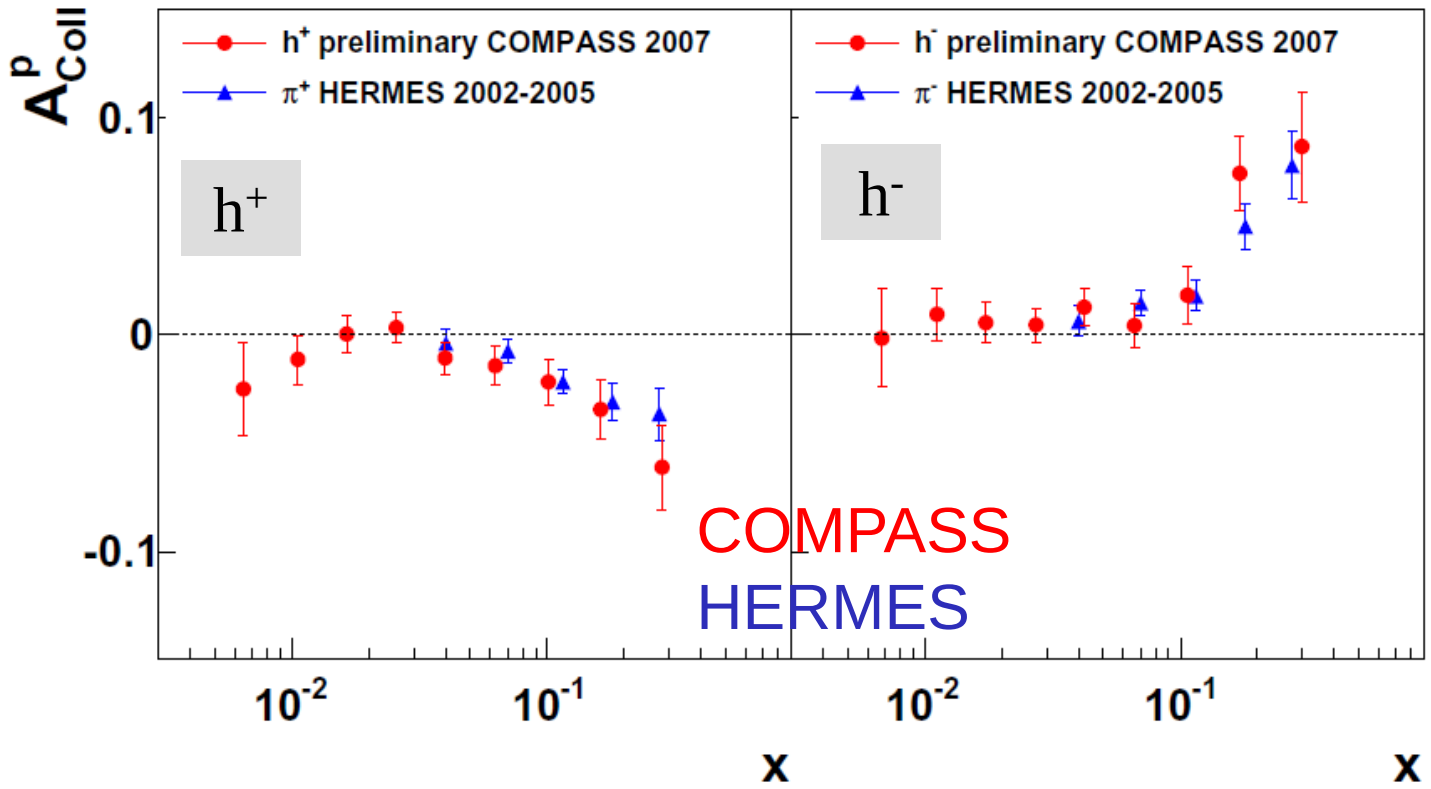
h^-

h^+

h^-

Comparison

proton



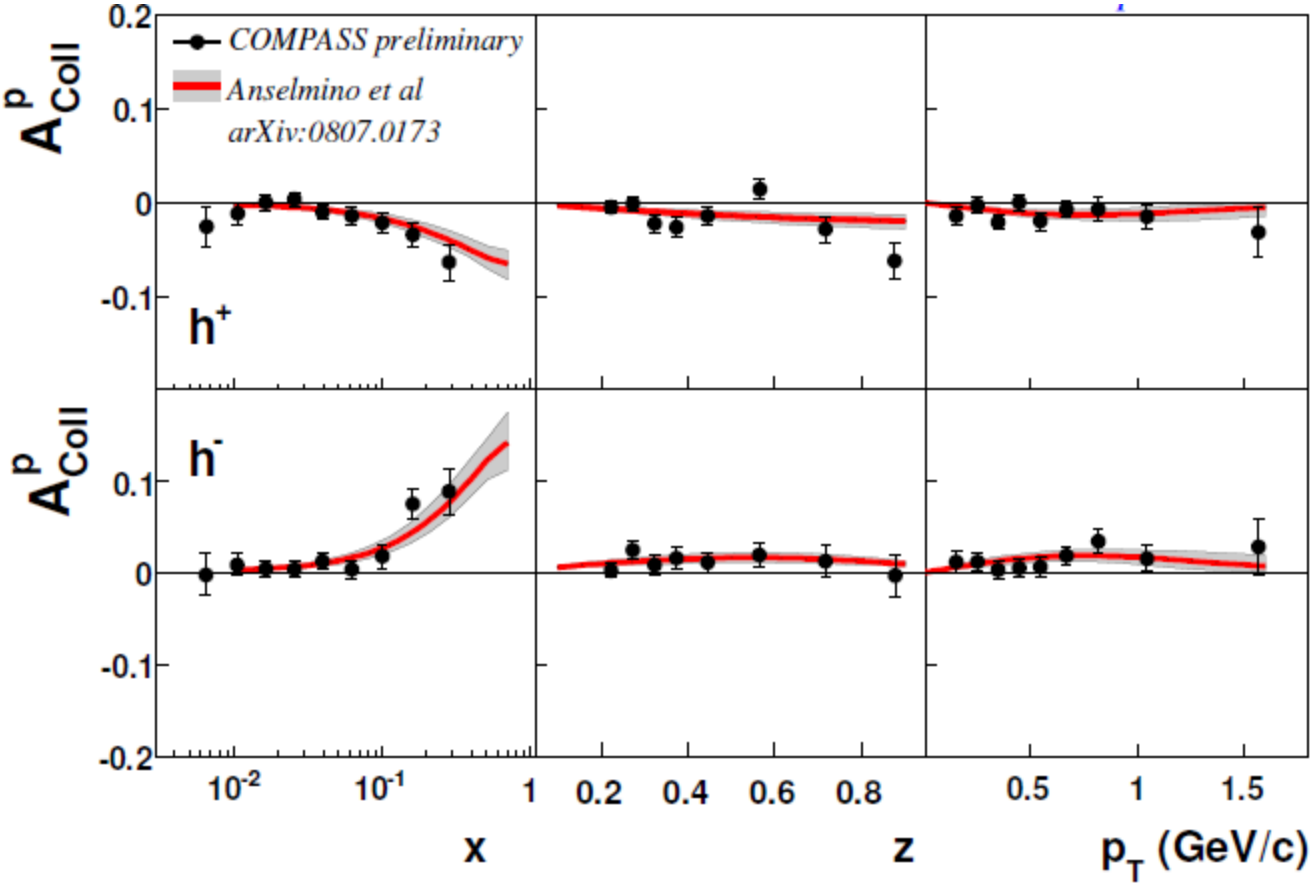
sign change and $D_{nn} \cong y$ applied for HERMES data

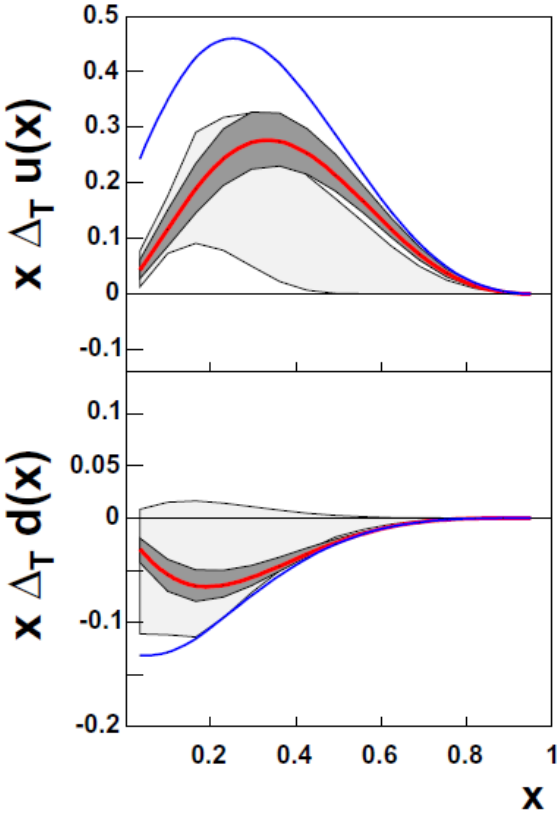
- large asymmetry ~10%
- good agreement in common *x* range
- zero deuteron result important ⇒ opposite sign of u and d quark transversity PDF

Global Fit

Fit to COMPASS *d*, HERMES, BELLE (FF, e^+e^-)

in good agreement with new proton data





Transversity PDF $\Delta_T q(x)$

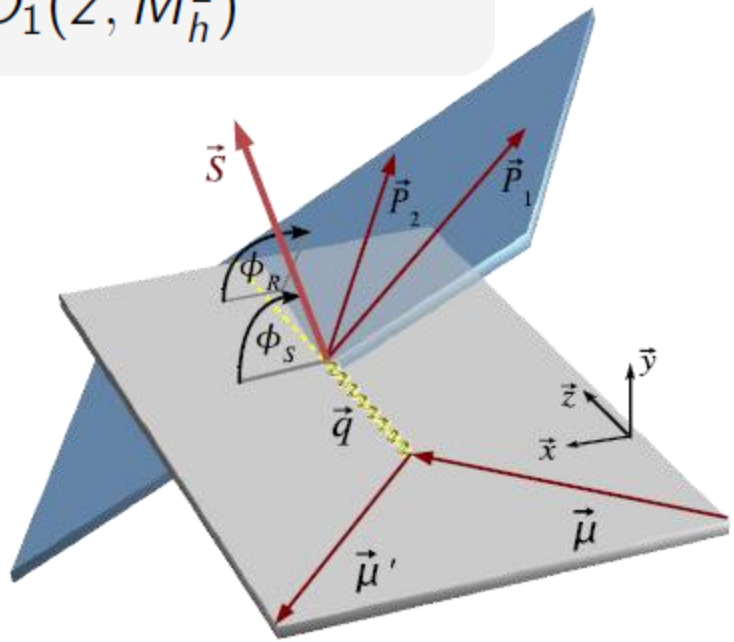
Alternative: couple $\Delta_T q$ to chiral odd 2-hadron interference FF $H_1^{\sphericalangle}$

$$A_{RS} \propto \frac{\sum_q e_q^2 \Delta_T q(x) H_1^{\sphericalangle}(z, M_h^2)}{\sum_q e_q^2 q(x) D_1(z, M_h^2)}$$

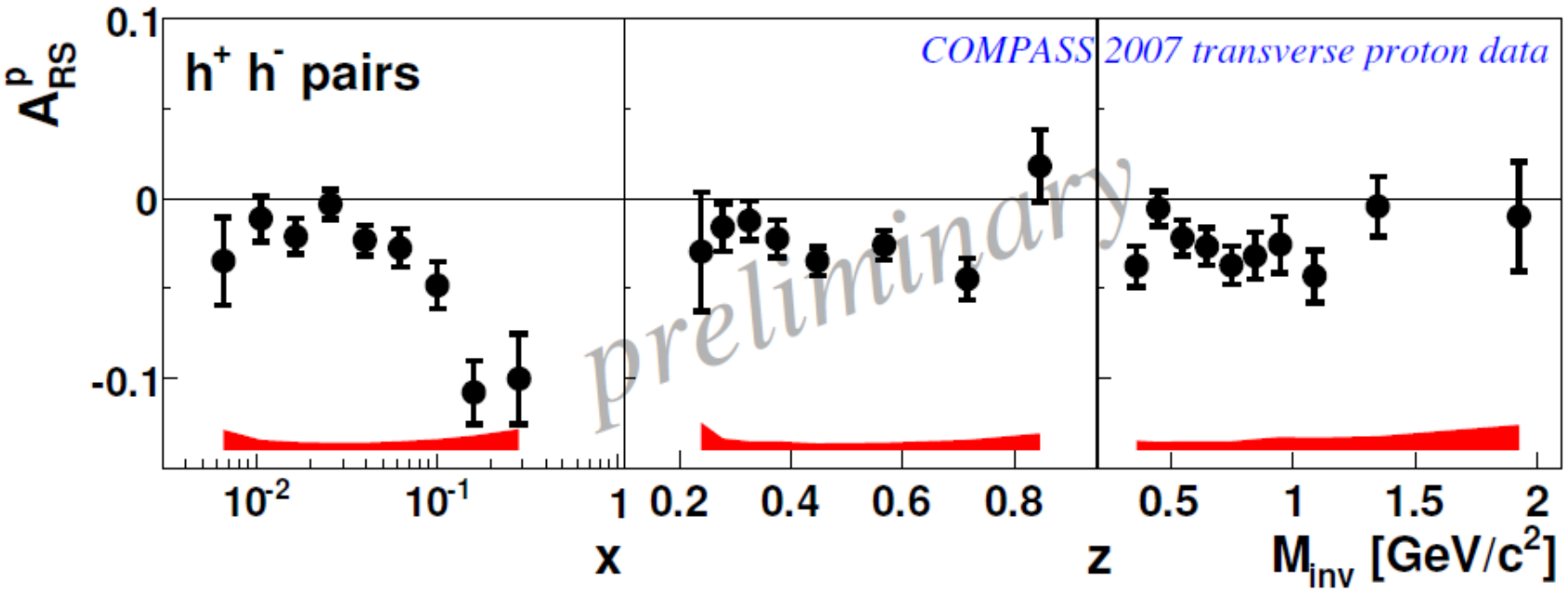
cross-section asymmetry:

$$\frac{\Delta\sigma}{\sigma} \propto A_{RS} \sin\phi_{RS} \sin\theta$$

$$\phi_{RS} = \phi_R + \phi_S - \pi; \quad \sin\theta \simeq 1$$



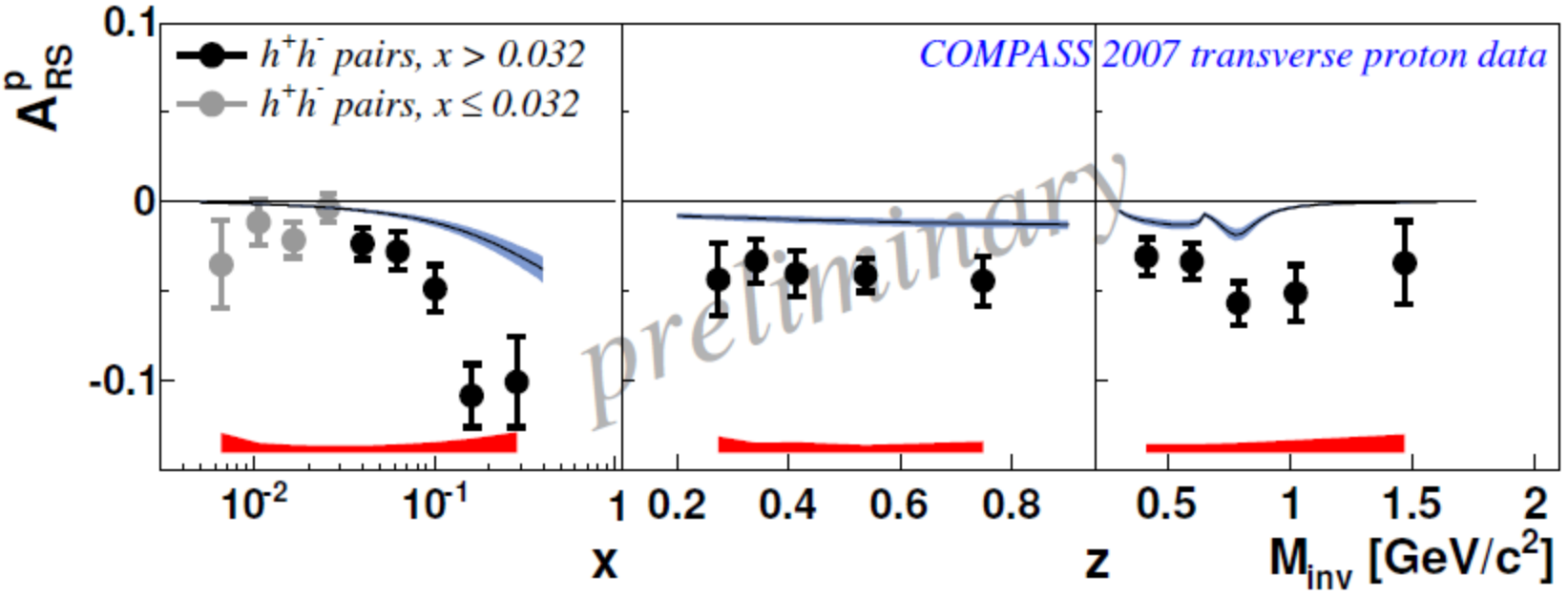
two-hadron asymmetry



- large asymmetries
- interference FF and transversity sizable

Comparison to a recent Fit

- Recent fit (dominated by HERMES, COMPASS *p* not yet in)



Very recent prediction (Bacchetta, Radici Phys.Rev.D79:034029,2009)

Sivers function $\Delta_0^T q$ or $f_{1T}^{\perp}$

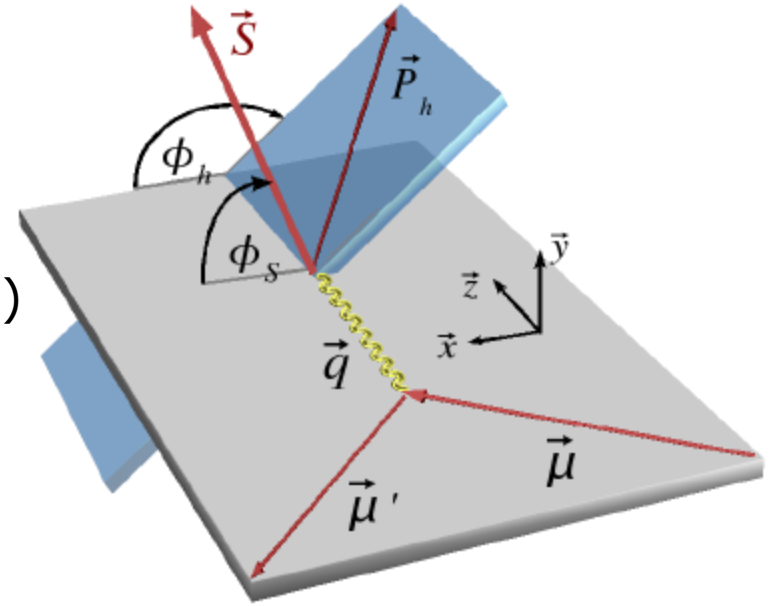
Sivers Asymmetry:

$$A_{Siv} = \frac{\sum_q e_q^2 \Delta_0^T q(x, p_T^h/z) D_q^h(z)}{\sum_q e_q^2 q(x, p_T^h/z) D_q^h(z)}$$

$$\frac{\Delta\sigma}{\sigma} \propto A_{Siv} \sin \Phi_S$$

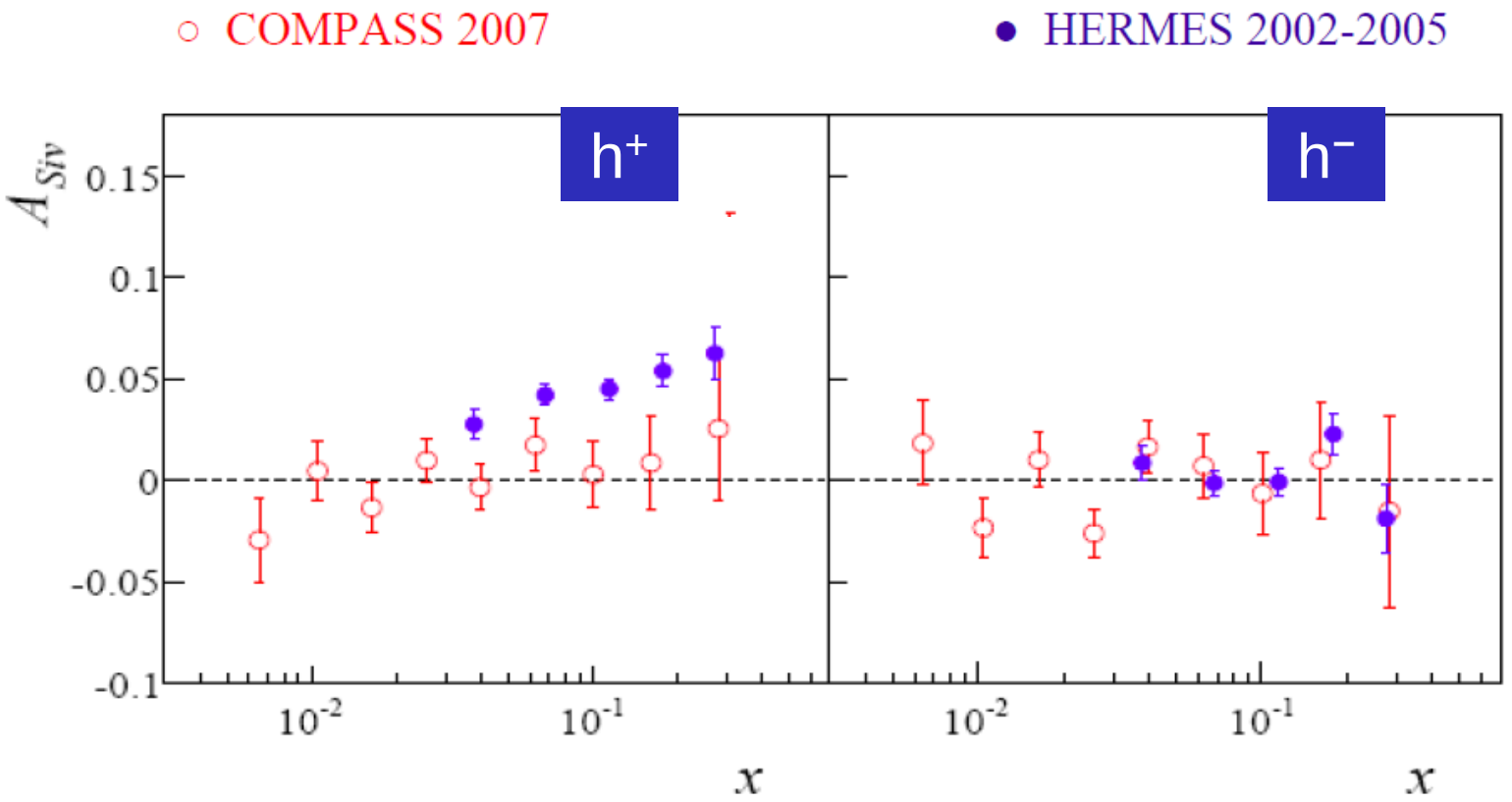
$$\Phi_S = \phi_h - \phi_S$$

- proposed (1990, Sivers)
- though to vanish (1993, Collins)
- resurrected (2002, Brodsky, Hwang, Schmitt)
- different sign in DY and SIDIS

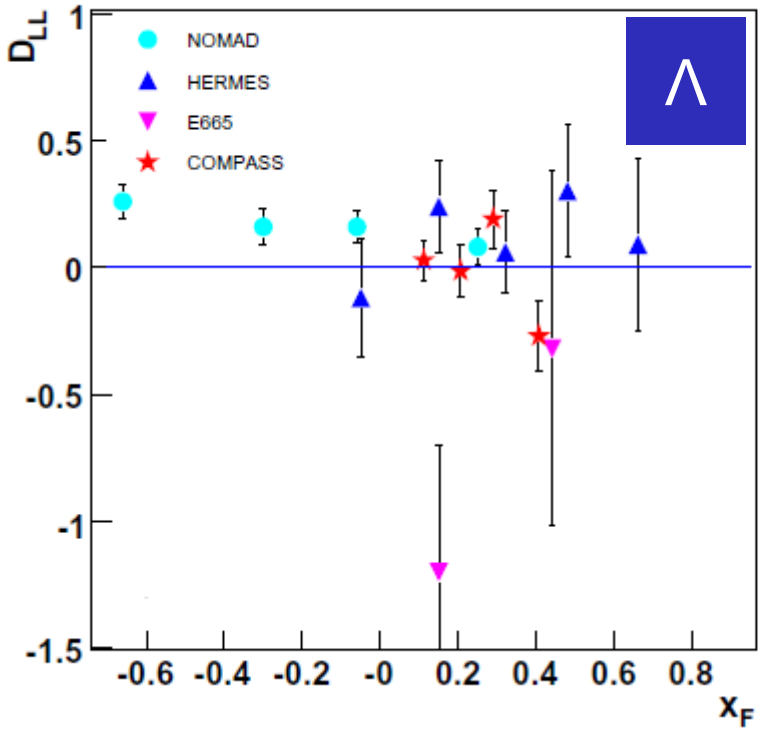


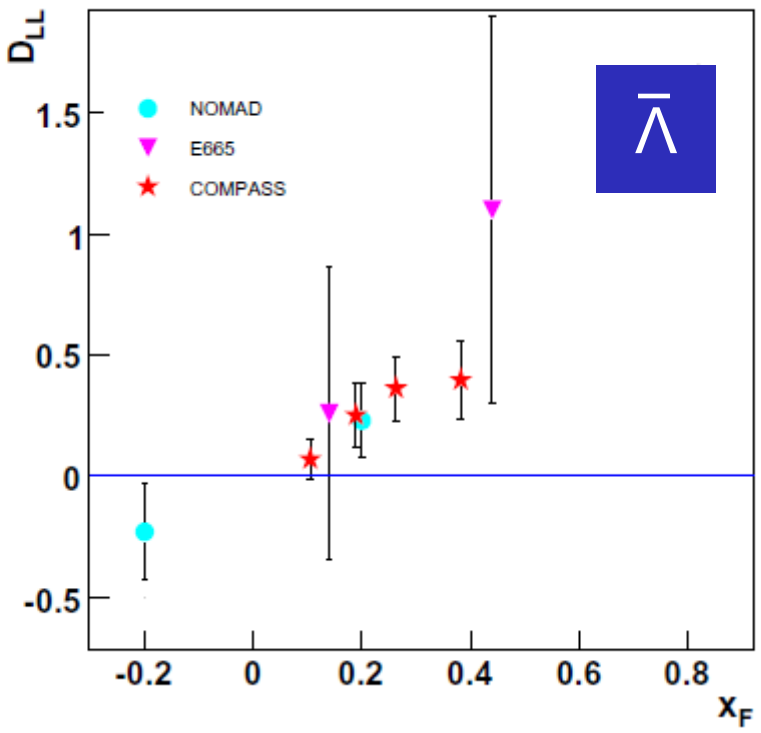
Proton Sivers Asymmetry

- compatible with zero for the deuteron
- large effect seen by HERMES, not confirmed by COMPASS
- clarification needed



Longitudinal spin transfer to Λ & $\bar{\Lambda}$





- non-zero D_{LL} related to polarisation of strange (anti) quarks (?)

Outlook

Goals: Precise determination of $\Delta g(x)$
Generalized parton distributions (GPD)
Orbital angular momentum

Experimental prospects:

Short term: More lepton data from COMPASS & Jlab
More hadron data from RHIC (500 GeV!)

Longer term: COMPASS GPD & DY programme
RHIC upgrade
JLab 12 GeV

Long term: Electron-Ion Colliders: eRHIC, ELIC, ENC