Wkład eksperymentu COMPASS w badanie struktury nukleonu

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Zagadnienia fizyczne poruszone w referacie

- 1D obraz (w funkcji x) spinowej struktury nukleonu (dla ‘podłużnego spinu’)
  - całkowity wkład spinu kwarków
  - polaryzacja kwarków o różnych zapachach
  - polaryzacja gluonów

- 3D obraz nukleonu
  - rozkłady partonów zależne od pędu poprzecznego (TMDs) – $f(x, \vec{k}_T)$
  - uogólnione rozkłady partonów (GPDs) $\rightarrow$ $f(x, \vec{b}_T)$

- Rozkłady poprzeczności (transversity) kwarków

- Orbitalny moment pędu kwarków i gluonów

Plan referatu

- Krótka informacja nt. eksperymentu COMPASS

- Podsumowanie najważniejszych wyników dla ‘podłużnego spinu’ (1D)

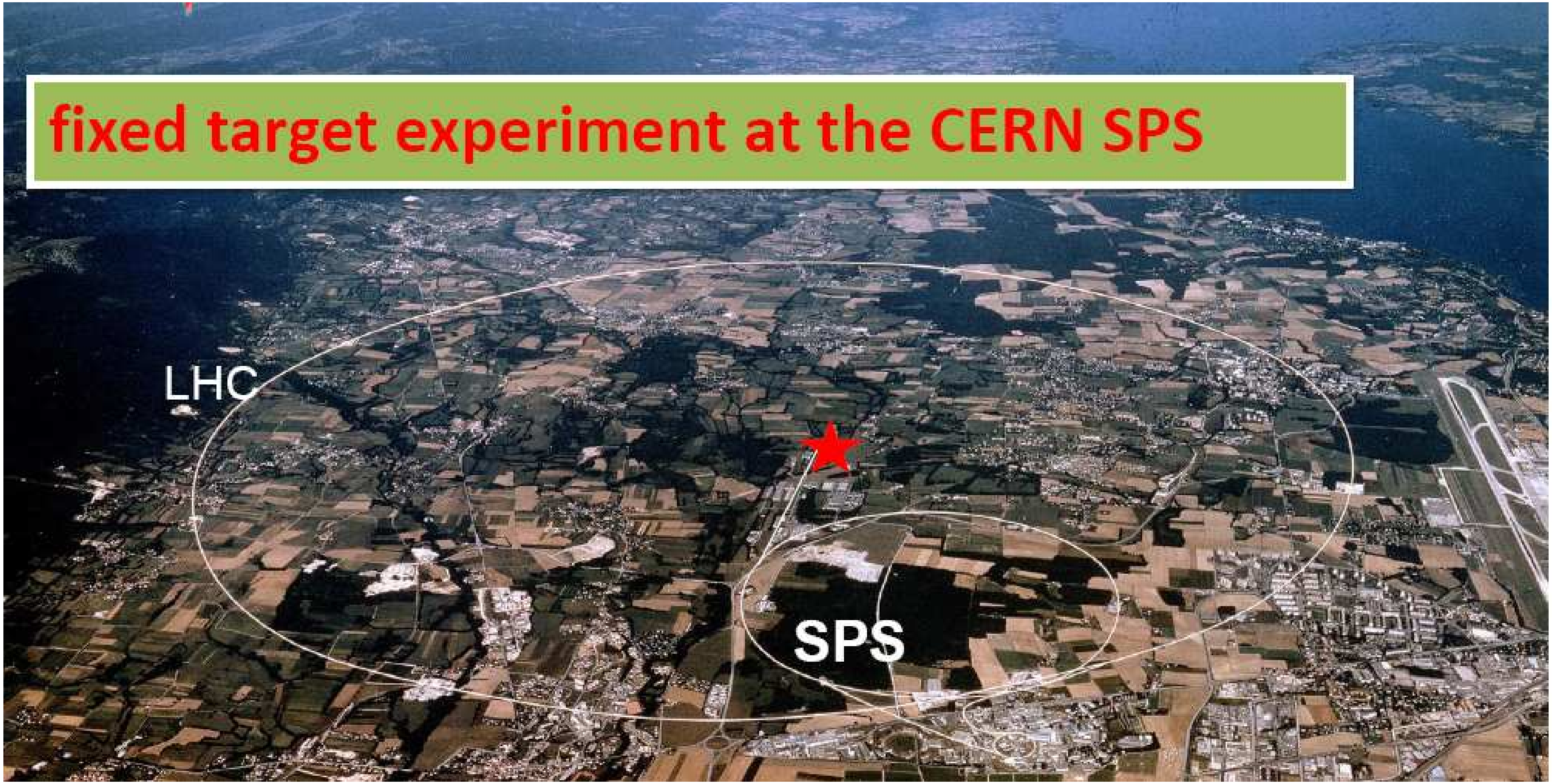
- Nowe, wybrane wyniki dla poprzecznie spolaryzowanych protonów i deuteronów
  - asymetrie Siversa i Collinsa (TMDs i transversity)
  - ekskluzywna produkcja mezonów ρ^0 (GPDs)

- Program badania GPDs w ramach projektu COMPASS-II

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

wide physics program carried on using both muon and hadron beam

fixed target experiment at the CERN SPS



COMPASS spectrometer

NIM A 577 (2007) 455

- **high energy beams**
- **large angular acceptance**
- **broad kinematical range**

two stages spectrometer

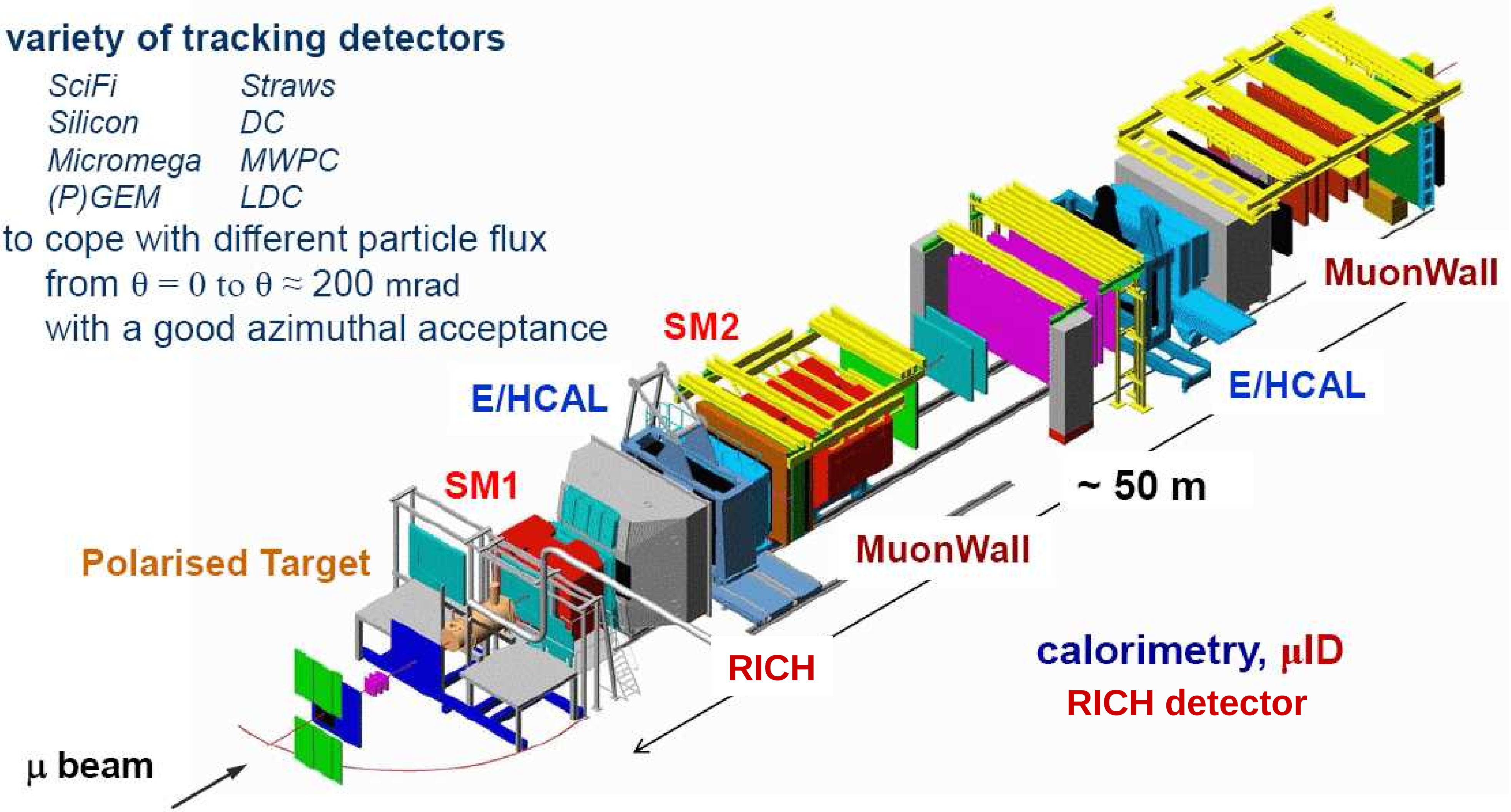
Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

SciFi	*Straws*
Silicon	*DC*
Micromega	*MWPC*
(P)GEM	*LDC*

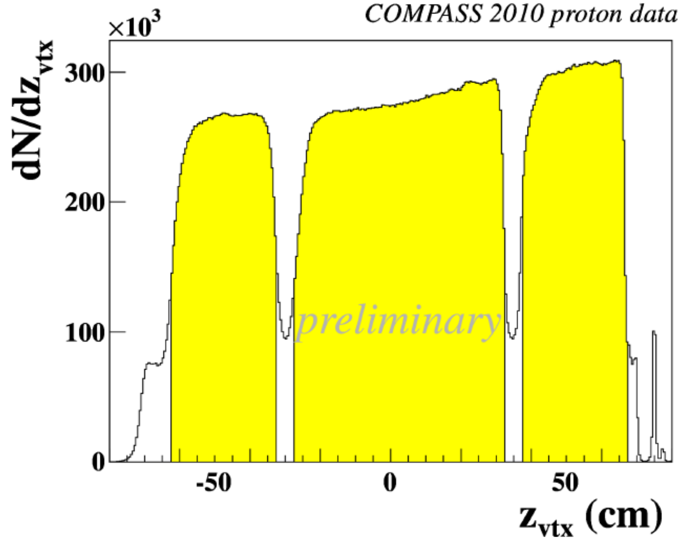
to cope with different particle flux
from $\theta = 0$ to $\theta \approx 200$ mrad
with a good azimuthal acceptance



calorimetry, μID

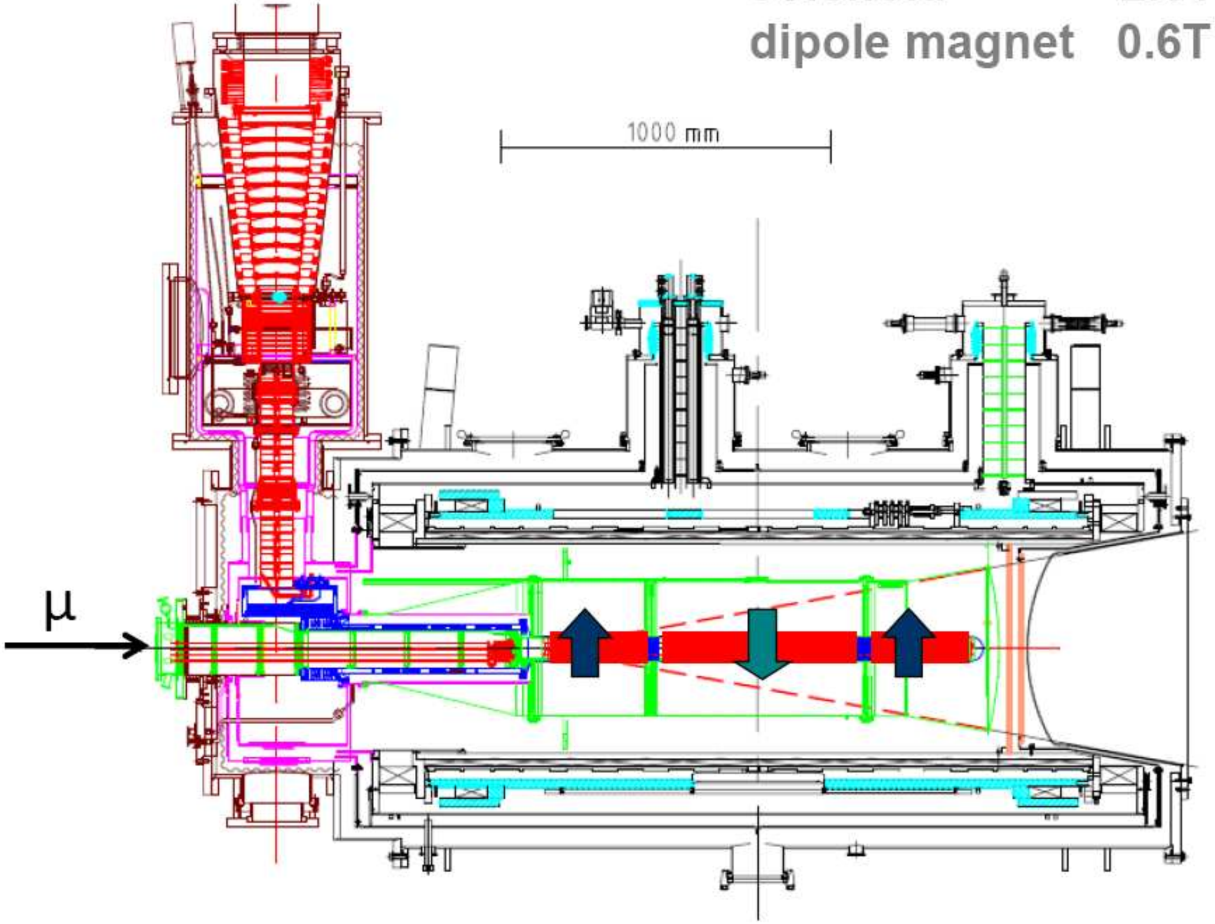
RICH detector

COMPASS polarised target



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

solenoid 2.5T
dipole magnet 0.6T



acceptance > ± 180 mrad

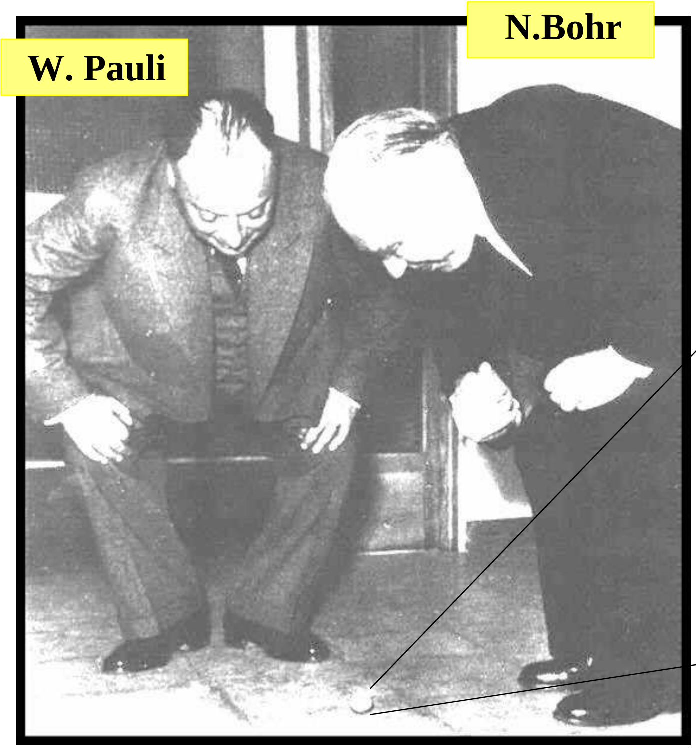
3 target cells
30, 60, and 30 cm long

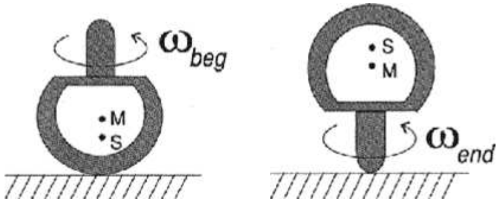
opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

transverse spin reversed every several days
longitudinal every 8 (or 24) hours

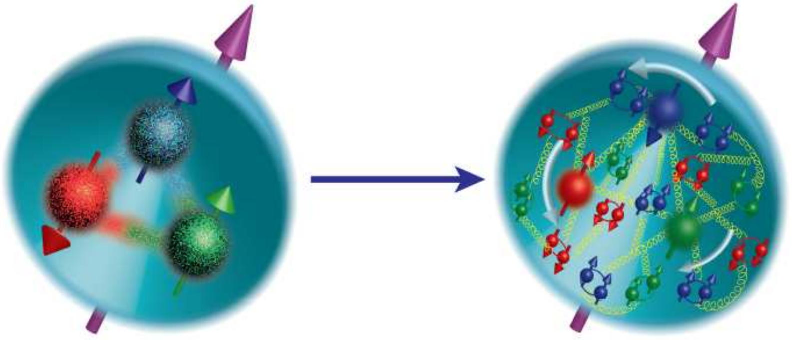
Fascynacje spinem



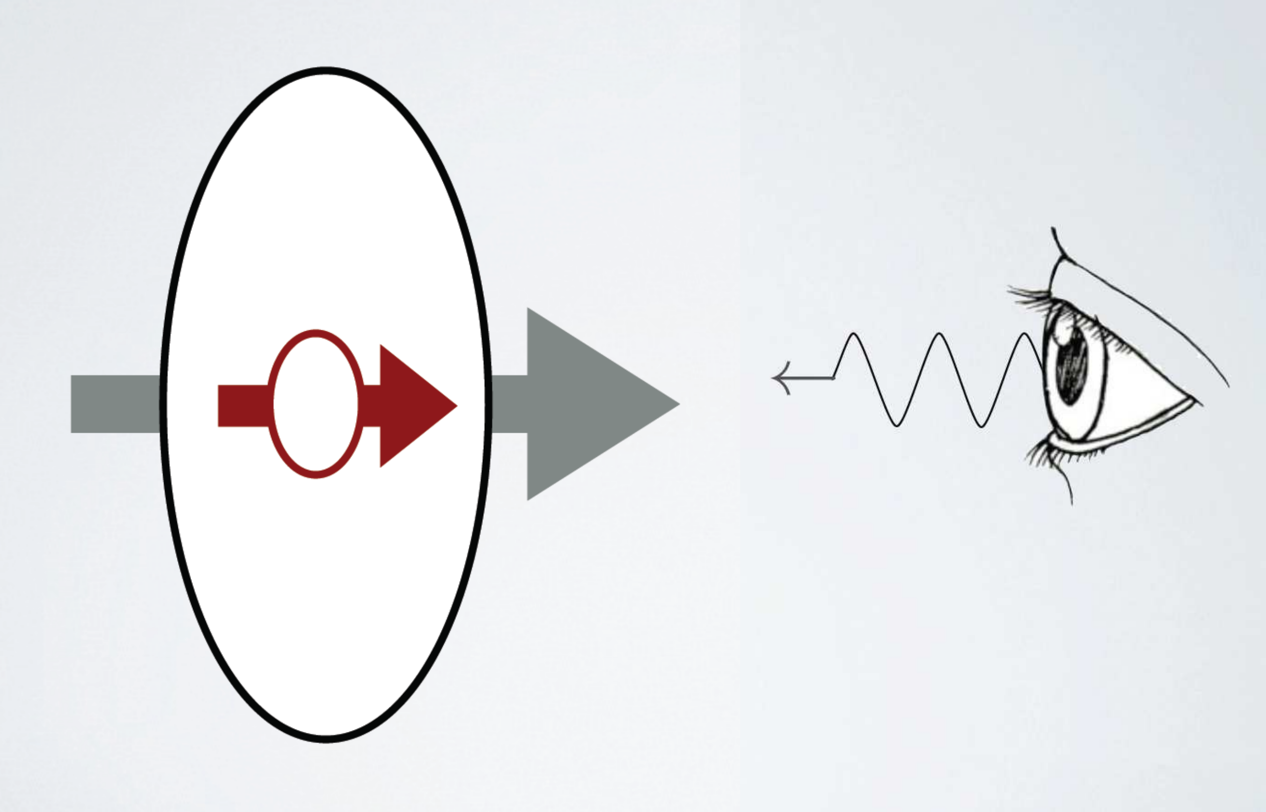


Odkrycie w SLAC (1969), że nukleon jest obiektem złożonym, uzasadniło intrygujące pytanie

Czy jest możliwe wyjaśnienie spinu nukleonu - skwantowanej wielkości = ½ poprzez jego składniki, kwarki i gluony ?



Nucleon structure - ‘longitudinal spin’

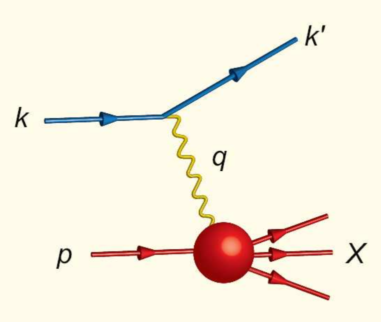


=> parton helicity distribution functions

Pioneer experiments

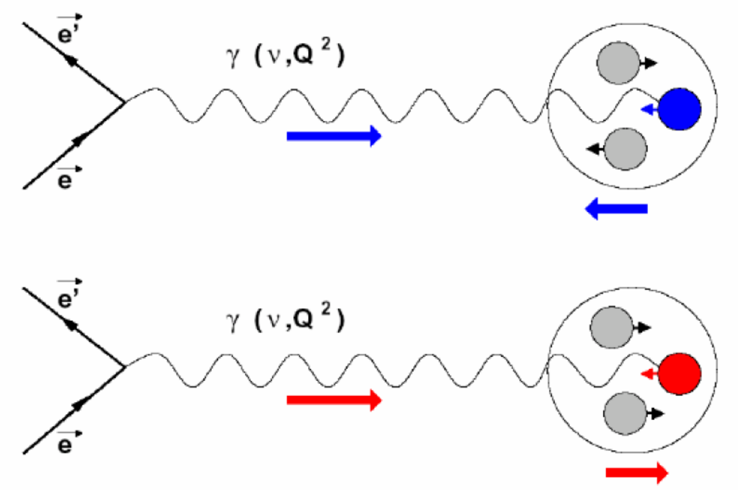
- SLAC (1976): polarised quarks in the polarised nucleon
- EMC (1988): ‘spin crisis’ – total contribution of quark helicities surprisingly small

Asymetrie zależnych od spinu przekrojów czynnych i spinowa funkcja struktury g_1



$$Q^2 = -q^2 = -(k-k')^2 \qquad x = Q^2/(2p\cdot q) \qquad y = (q\cdot p)/(k\cdot p)$$

$$\frac{1}{2}\left[\frac{d^2\sigma^{\uparrow\downarrow}}{dx\,dQ^2} - \frac{d^2\sigma^{\uparrow\uparrow}}{dx\,dQ^2}\right] \simeq \frac{4\pi\,\alpha^2}{Q^4} y\,(2-y)\,g_1(x,Q^2)$$



$\sigma_{\uparrow\downarrow} \sim q^+$

$\sigma_{\uparrow\uparrow} \sim q^-$

$\Delta q(x) = q(x)^+ - q(x)^-$

$q(x) = q(x)^+ + q(x)^-$

\+ quark ↑↑ nucleon

– quark ↑↓ nucleon

$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2)\,2x(1+R)}{F_2(x,Q^2)}$$

$A_1^{meas} \rightarrow A_1 \rightarrow g_1$

$F_2 \rightarrow$ param. SMC

$R = \sigma_L/\sigma_T \rightarrow$ param. SLAC

interpretacja w prostym modelu partonowym (LO)

$$g_1(x,Q^2) = \frac{1}{2}\sum e_q^2\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

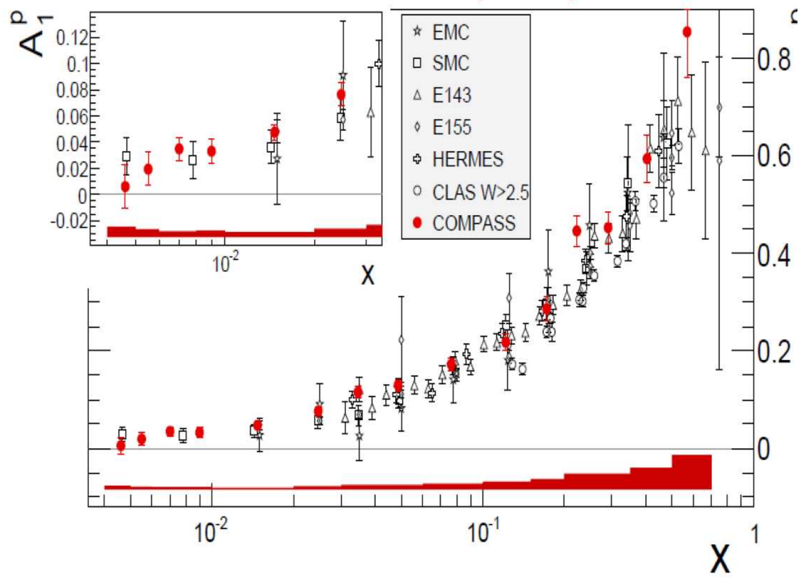
$$F_2(x,Q^2) = x\sum e_q^2\left[q(x,Q^2) + \bar{q}(x,Q^2)\right]$$

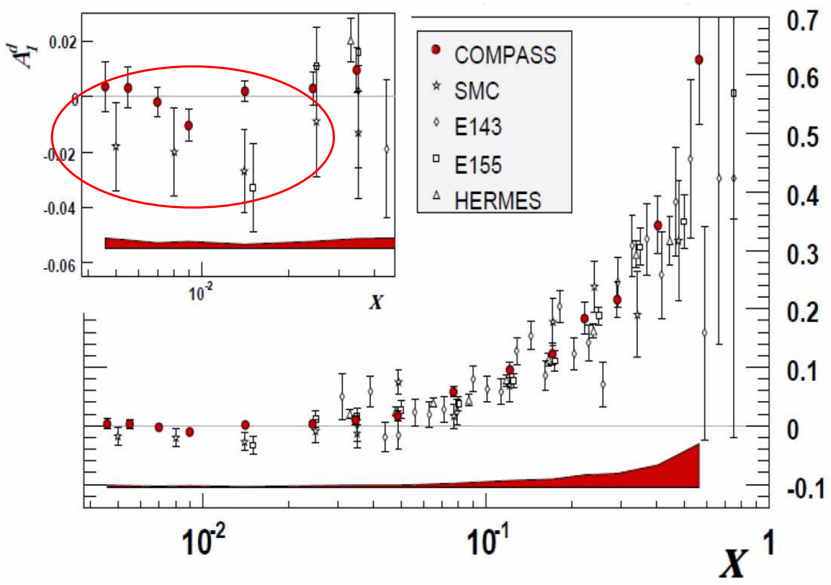
$R = 0$

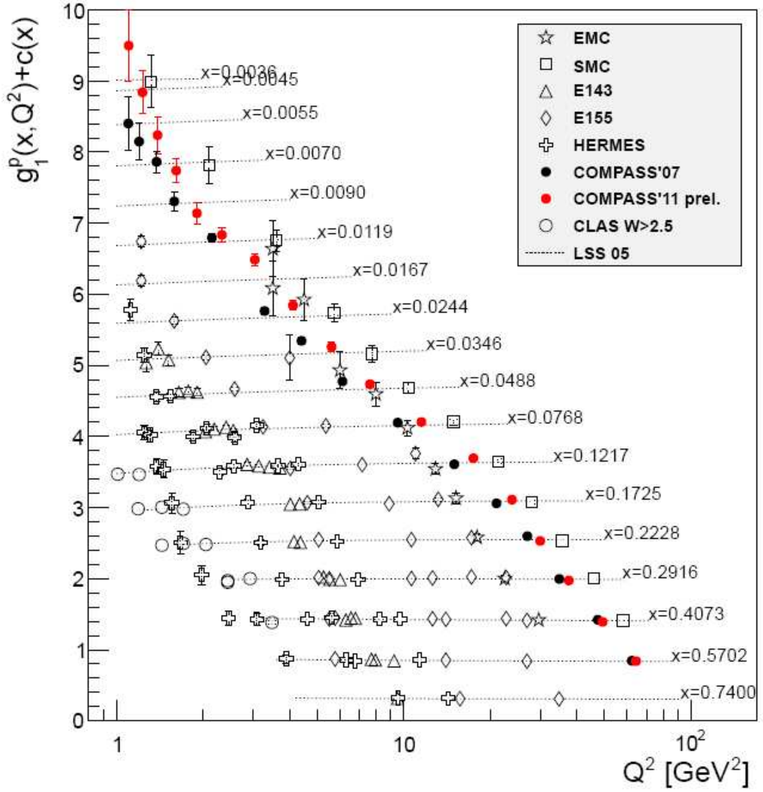
na gluony g_1 czuła poprzez ewolucję DGLAP

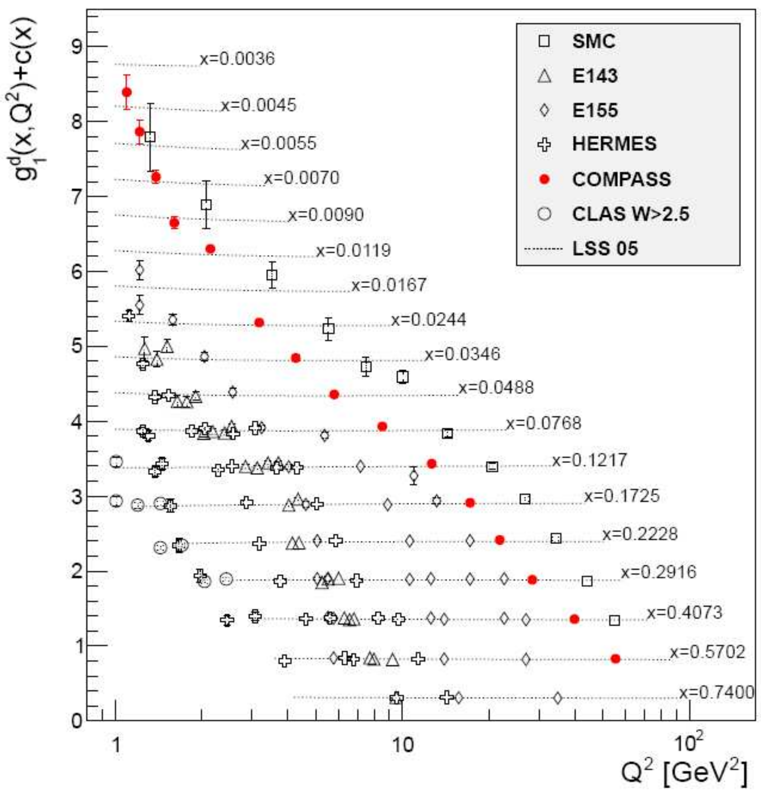
$$\frac{d\,g_1}{d\,Log(Q^2)} \propto -\Delta g(x,Q^2)$$

Results on g_1^p and g_1^d









Quark contribution ΔΣ to the proton spin

For each parton species $f = u, d, s, \bar{u}, \bar{d}, \bar{s}, g$ $\Delta f(x, Q^2) \equiv f^+(x, Q^2) - f^-(x, Q^2)$

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g}$$

$$\Delta\Sigma = \int_0^1 (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})(x, Q^2)\ dx \qquad \Delta G = \int_0^1 \Delta g(x, Q^2)\ dx$$

$\Delta\Sigma$ from NLO QCD fits to g_1 and $\Delta s + \Delta\bar{s}$ from the first moment of g_1 and SU$_F$(3)

COMPASS 2007 $\Delta\Sigma$ = 0.30 ± 0.01 (stat) ± 0.02 (evol)

fit to world data on $g_1^{p,\,n,\,d}$, $\overline{\text{MS}}$ scheme, $Q^2 = 3$ (GeV/c)^2

$\int(\Delta s + \Delta\bar{s})dx$ = -0.08 ± 0.01 (stat) ± 0.02 (evol) ⟵ COMPASS data on g_1^d

HERMES 2007 $\Delta\Sigma$ = 0.33 ± 0.011 (stat) ± 0.025 (theo) ± 0.028 (evol)

HERMES data on g_1^d, $\overline{\text{MS}}$ scheme, $Q^2 = 5$ (GeV/c)^2 , neglecting x < 0.02 contrib.

$\int(\Delta s + \Delta\bar{s})\ dx$ = -0.085 ± 0.008 (exp) ± 0.013 (th) ± 0.009 (evol)

ΔΣ accounts only for about 1/3 of the proton spin; rather high precision

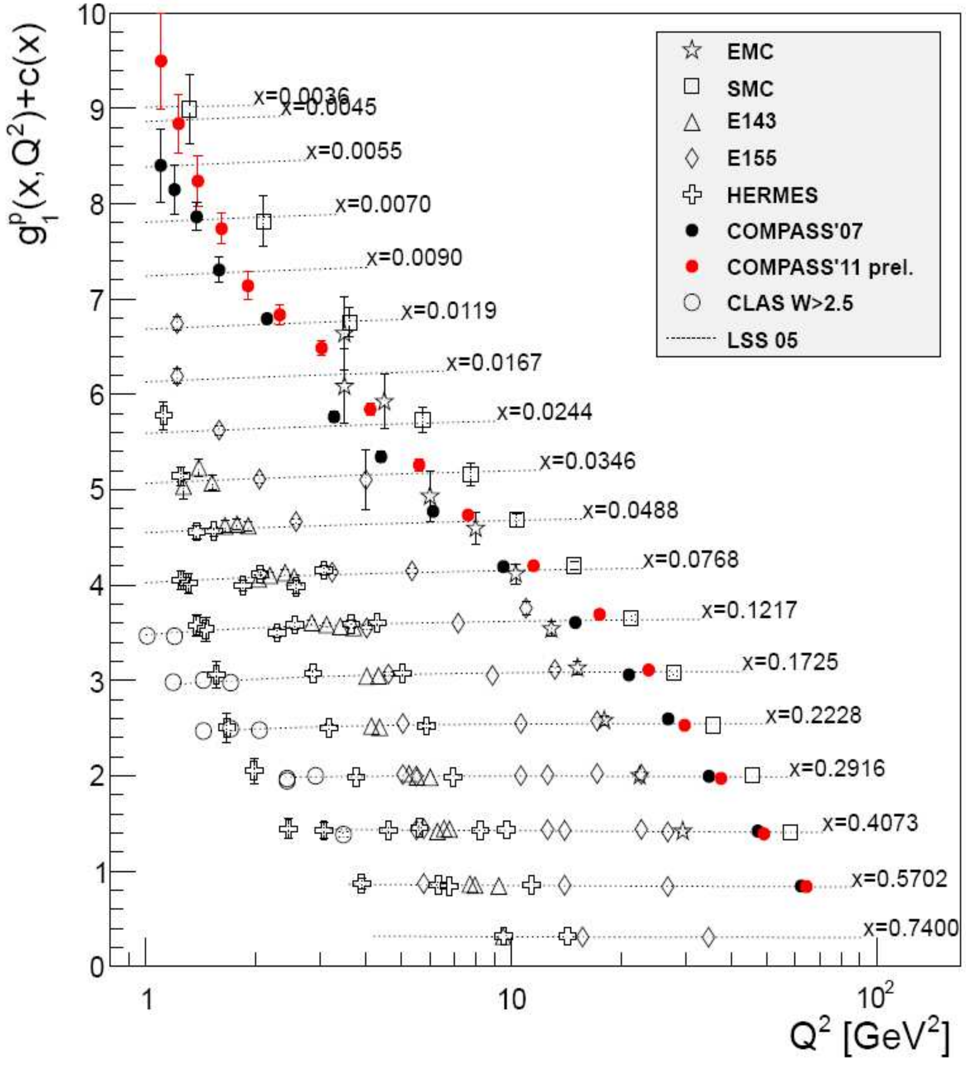
But …

- no quark – antiquark separation possible with inclusive measurements only
- limited sensitivity of g_1 to gluons with presently accessible kinematic range

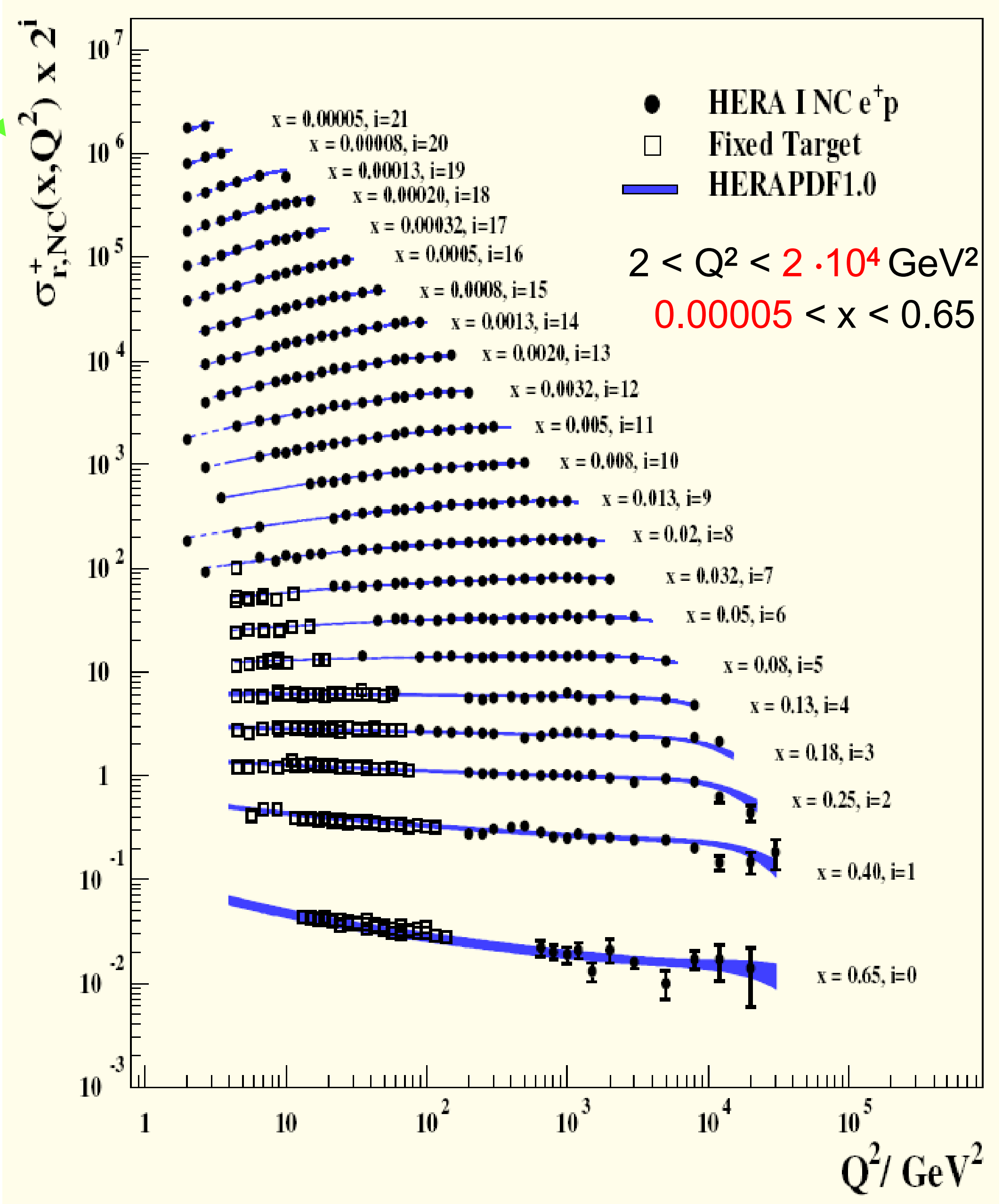
Kinematic ranges for polarised vs. unpolarised proton s.f.

1 < Q² < 7 ·10¹ GeV²

0.004 < x < 0.8



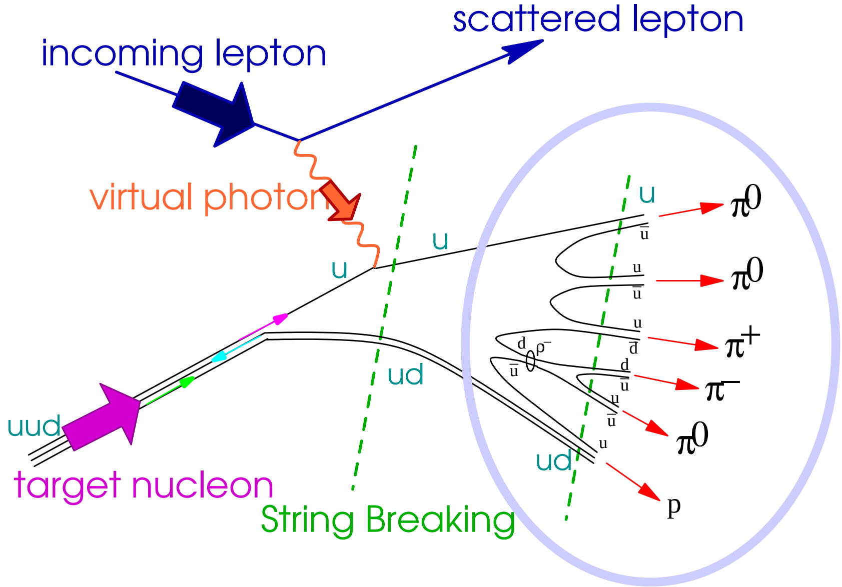
$$\sigma_r = \left(\frac{d^2\sigma}{dx\, dQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$



2 < Q² < 2 ·10⁴ GeV²

0.00005 < x < 0.65

SIDIS and flavour separation of quark helicity distributions

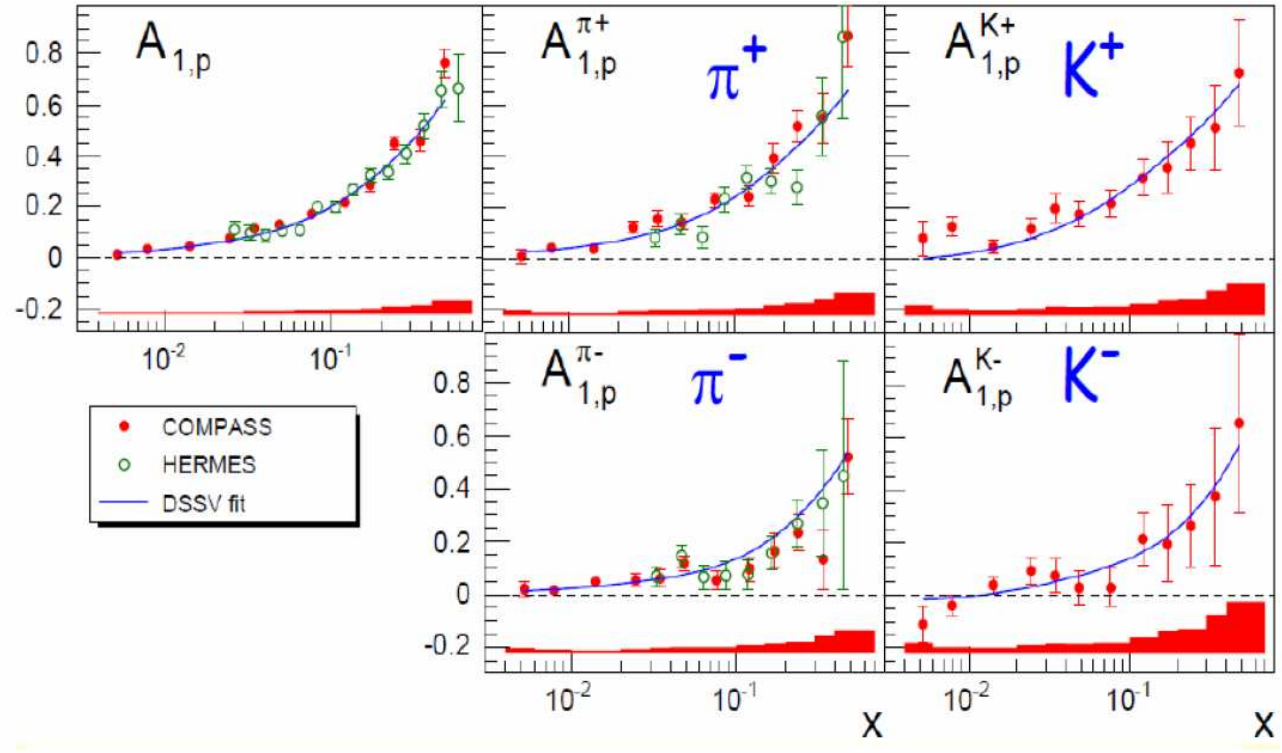


- the outgoing hadron 'tags' the quark flavour
- required fragmentation function of a quark q to a hadron h: $D_q^h(z, Q^2)$

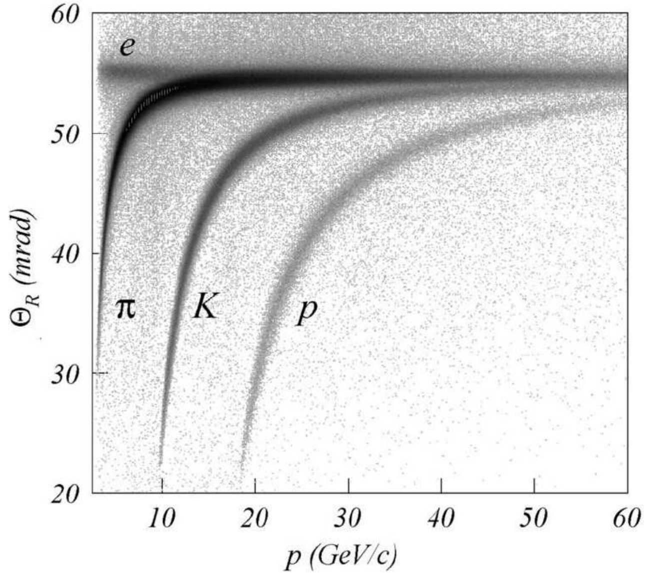
$z = E_h / (E_l - E_{l'})$

semi-inclusive DIS (SIDIS) $l\ N \to l'\ h\ X$

SIDIS spin asymmetry $A_1^h(x, Q^2, z)$ measured for production of a hadron h (analogously to inculsive A_1)



PID (RICH)



- $A_{1,p}^{K+,K-}$ measured for the first time
- 5 similar asymmetries for deuteron

Extraction of helicity distributions for all quark flavours

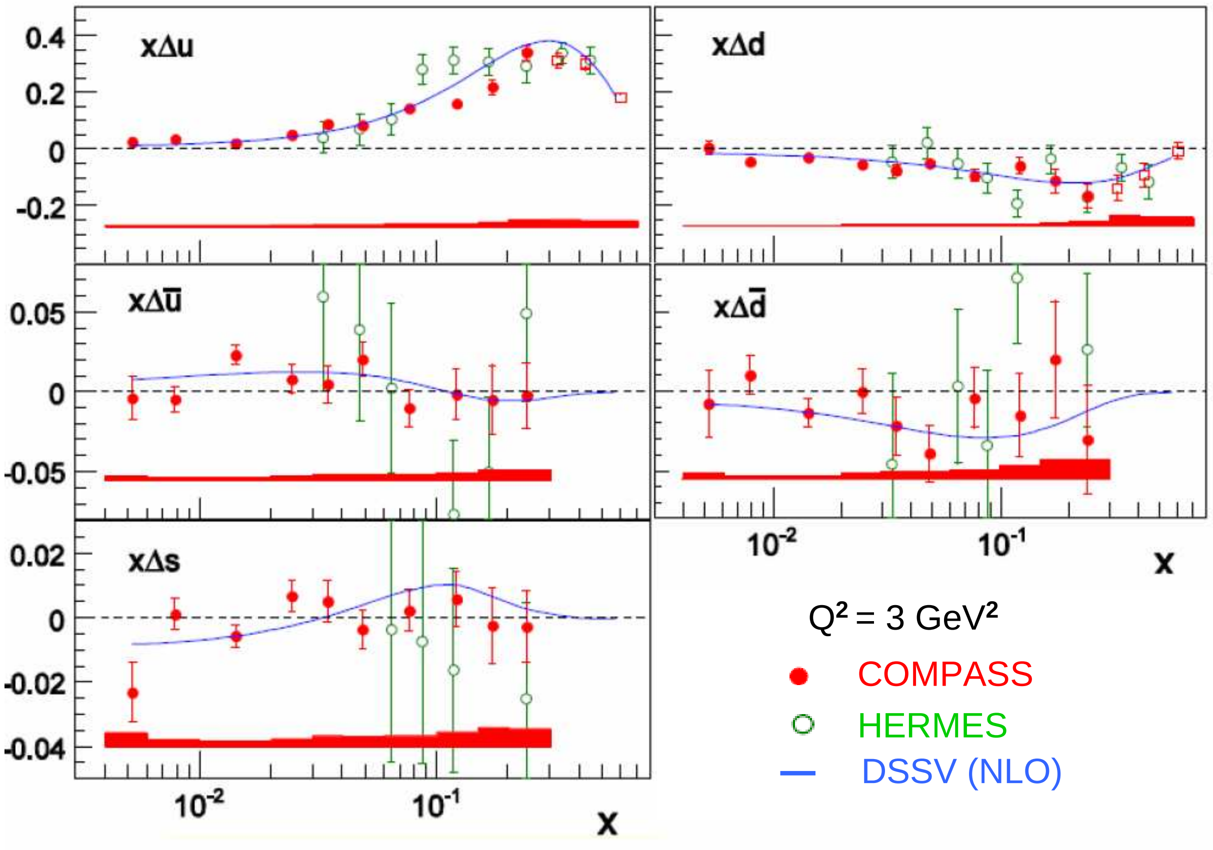
semi-inclusive asymmetries in LO approx.

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

needed inputs

- unpolarised PDFs (MRST04)
- D_q^h (DSS param.)

10 asymmetries ($A_{1p,d}^{incl}$, $A_{1p,d}^{\pi\pm}$, $A_{1p,d}^{K\pm}$) and 5 (6) unknown distributions ($\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta s$)

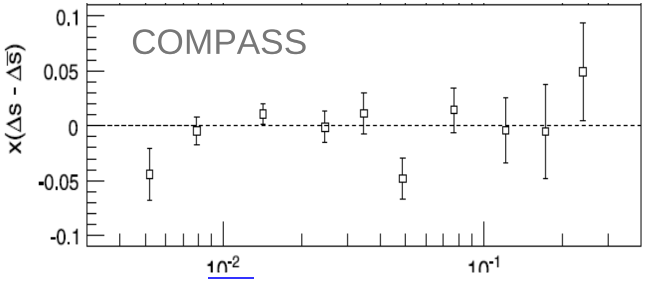


$$\int_{x\,\min}^{x\,\max} \Delta f(x)\,dx$$

x range	$0.004 < x < 0.3$	Extrapolation
Δu	$0.47 \pm 0.02 \pm 0.03$	$0.71 \pm 0.02 \pm 0.03$
Δd	$-0.27 \pm 0.03 \pm 0.02$	$-0.34 \pm 0.04 \pm 0.03$
$\Delta\bar{u}$	$0.02 \pm 0.02 \pm 0.01$	$0.02 \pm 0.02 \pm 0.01$
$\Delta\bar{d}$	$-0.05 \pm 0.03 \pm 0.02$	$-0.05 \pm 0.03 \pm 0.02$
$\Delta s(\Delta\bar{s})$	$-0.01 \pm 0.01 \pm 0.01$	$-0.01 \pm 0.01 \pm 0.01$

$\Delta\bar{u} - \Delta\bar{d}$	$0.06 \pm 0.04 \pm 0.02$
$\Delta\bar{u} + \Delta\bar{d}$	$-0.03 \pm 0.03 \pm 0.01$

cf. for unpolarised $\int (\bar{d} - \bar{u})dx = 0.118 \pm 0.012$



$\Delta s - \Delta\bar{s}$ compatible with 0

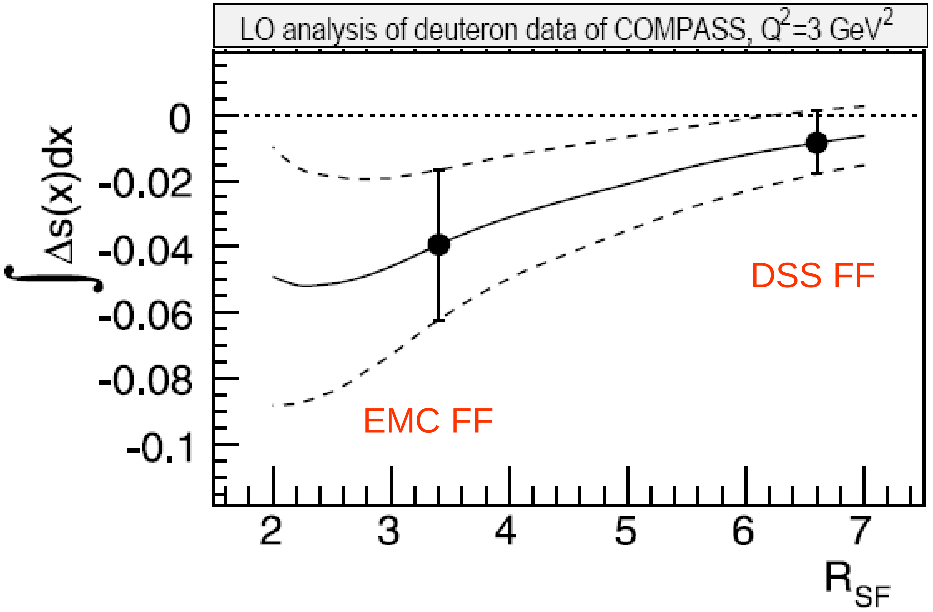
Δs puzzle

- DIS data g_1 moments and SU(3) symmetry → $\int \Delta s+\Delta\bar{s}$ = - 0.08 ± 0.01± 0.02
- SIDIS data   semi-inclusive (+ inclusive) asymmetries → Δs(x)≈ 0

Possible explanations of the discrepancy

- Violation of SU(3) in baryon decays;   assumed maximal 20% violation => $\int \Delta s+\Delta\bar{s} \approx -0.04$
- Global NLO QCD fits to DIS + SIDIS [+ RHIC] data (DSSV, LSS) suggest negative Δs at unmeasured low x region   may reconcile two approaches
- Uncertainty on strange quark fragmentation functions to kaons

Δs(x) extraction from asymmetries mostly sensitive to following ratios



$$R_{UF}=\frac{\int_{0.2}^{0.85} D_d^{K^+}(z)\,dz}{\int_{0.2}^{0.85} D_u^{K^+}(z)\,dz}, \quad R_{SF}=\frac{\int_{0.2}^{0.85} D_{\bar{s}}^{K^+}(z)\,dz}{\int_{0.2}^{0.85} D_u^{K^+}(z)\,dz}$$

try to extract R_{SF} (R_{UF}) from COMPASS data alone on hadron multiplicities

COMPASS results on hadron multiplicities and new parameterisation of FF

$\mu\, N \to \mu\, h\, X$ (SIDIS) $\mu\, N \to \mu\, X$ (DIS)

$$\frac{dM^h(x,Q^2,z)}{dz} = \frac{d^3N^h(x,Q^2,z)}{dxdQ^2dz} \Big/ \frac{d^2N^{DIS}(x,Q^2)}{dxdQ^2}$$

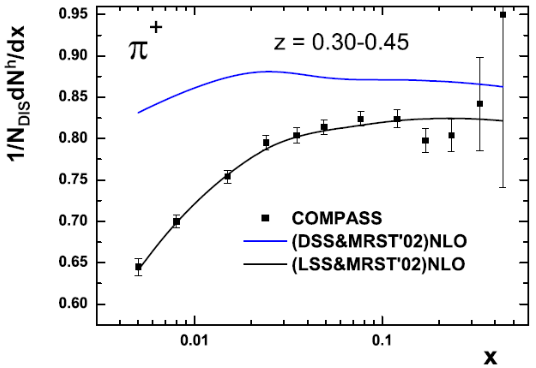
at LO

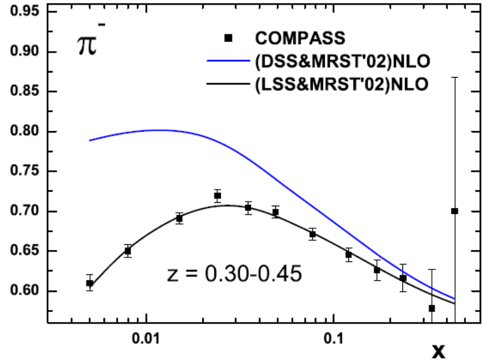
PDFs FFs

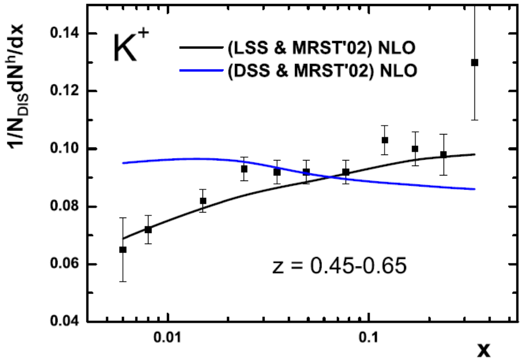
$$\frac{dM^h(x,Q^2,z)}{dz} \overset{\downarrow}{=} \frac{\sum_q e_q^2 f_q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 f_q(x,Q^2)}$$

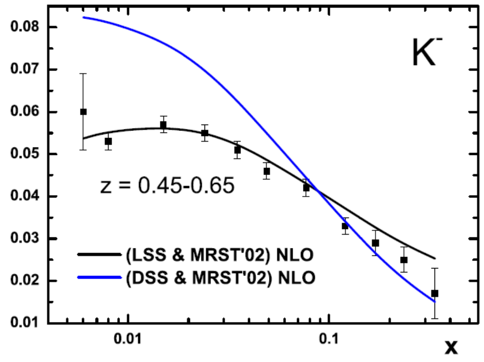
COMPASS preliminary results on $M^{\pi+,\,\pi-,\,K+,\,K-}$
from deuteron data (2004) in bins of x, Q^2 and z

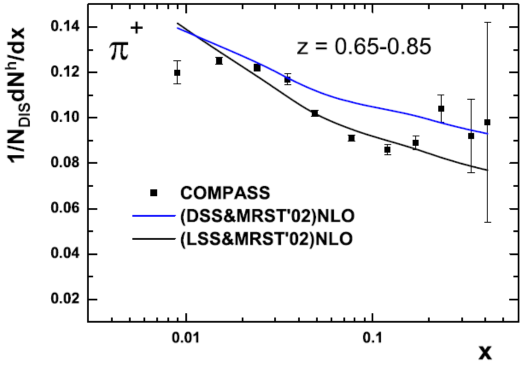
few examples shown here

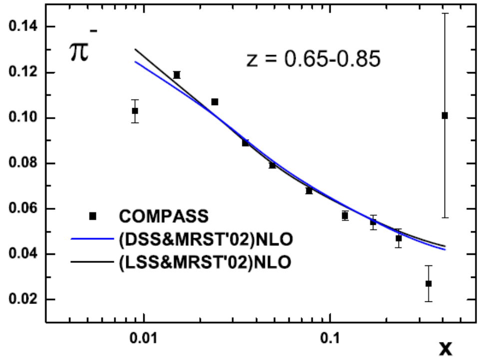












from NLO QCD fit to COMPASS data on M's
new FF obtained recently (2012)
Leader, Sidorov, Stamenov (LSS)

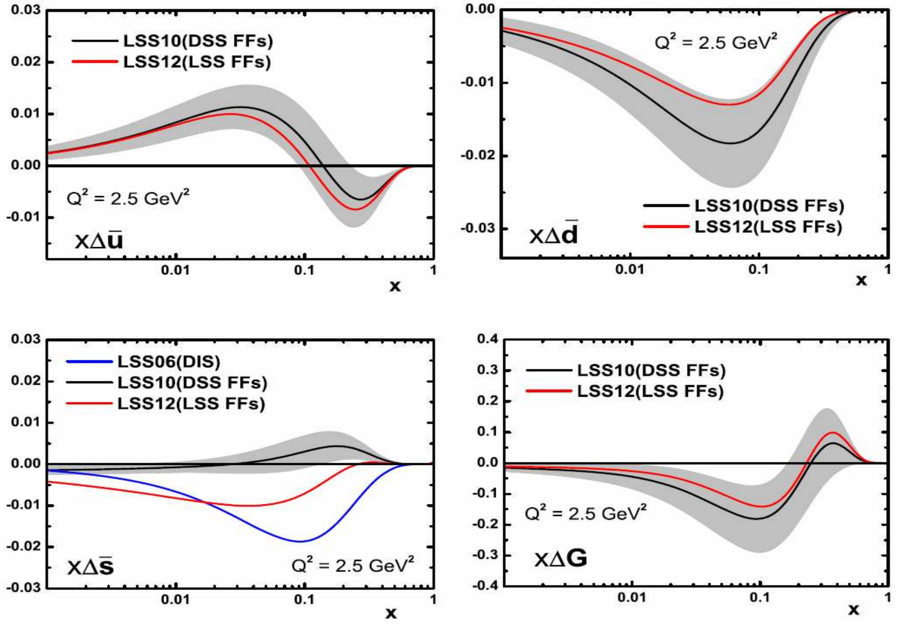
good agreement of LSS'12 with the data
big improvement wrt. previous parameterisations !

Recent estimates of R_{SF} : LSS'12 (NLO) ≈ 0.9, COMPASS (LO) (very preliminary) ≈ 2 - 2.5

➡ Larger negative (≈ - 0.05) Δs contribution preferred (cf. previous slide)

Possible reconcilation of Δs controversy between DIS and SIDIS (?)

Examples of parton helicity distributions from global NLO fits to world data



Leader, Sidorov, Stamentov (LSS)

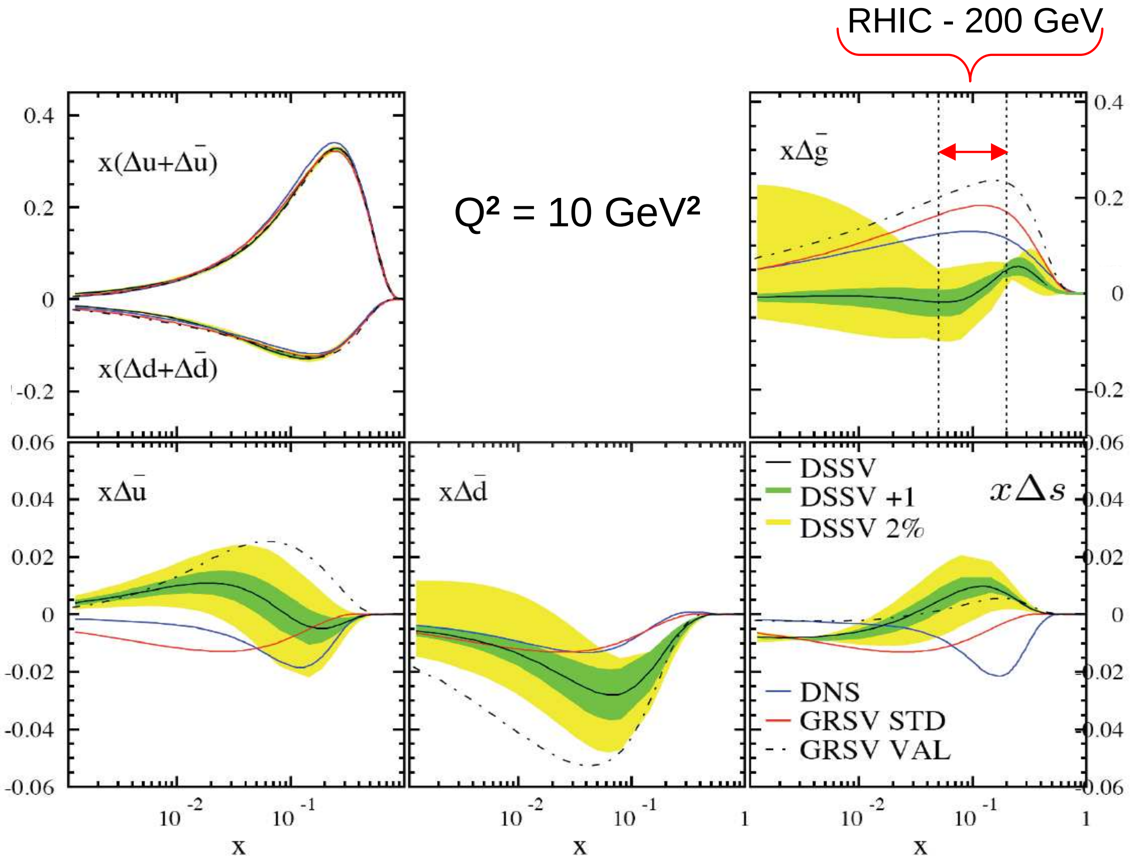
input: DIS + SIDIS data

- with LSS’12 significant change of $\Delta\bar{s}(x)$, negative for x < 0.2
- poor sensitivity to $\Delta g(x)$

de Florian, Sassot, Stratmann, Vogelsang (DSSV) 2008/09

input: DIS + SIDIS + RHIC data (2006)

- very well constrained $\Delta u+\Delta\bar{u}$ and $\Delta d+\Delta\bar{d}$ (as in all other global analyses)
- Δs becomes negative at small x
- improved sensitivity to $\Delta g(x)$ for 0.05 < x < 0.2, covered by RHIC

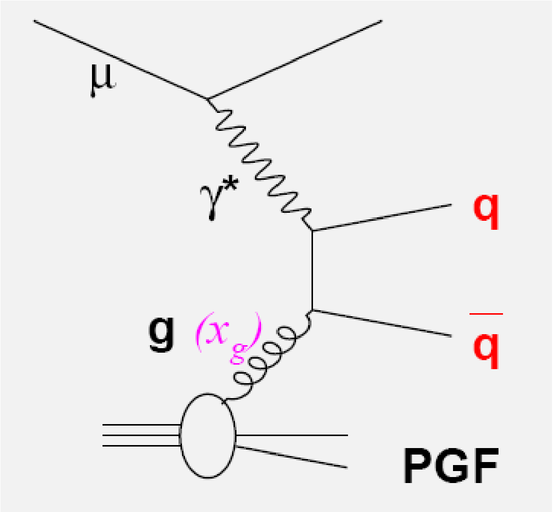

RHIC - 200 GeV

Q² = 10 GeV²

‘Direct’ access to the gluon polarisation Δg/g

From asymmetries of spin-dependent cross section for photon-gluon fusion (PGF)

$\gamma^* g \rightarrow q\ \text{qbar}$ (PGF)



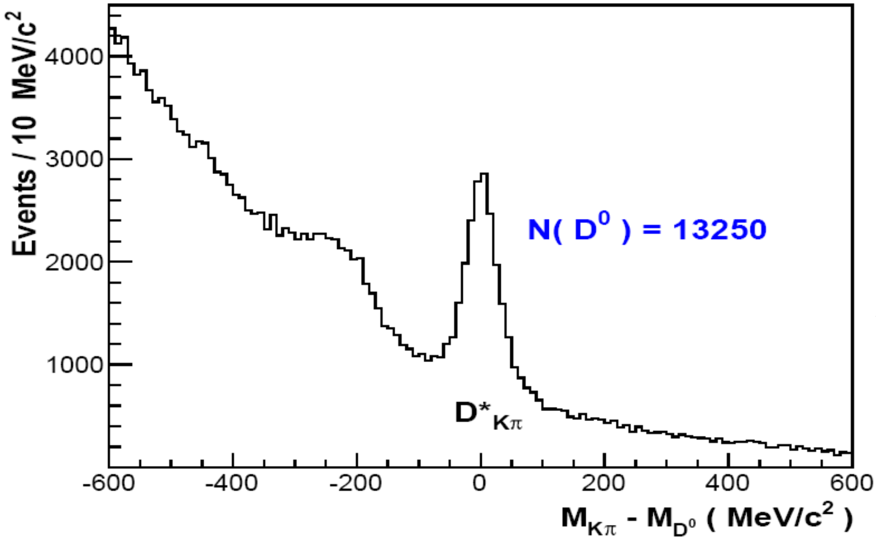
2 methods to select PGF events (both used in COMPASS)

- production of charm mesons D^0, D*
- production of high-p_T hadron pairs

In COMPASS charm mesons identified by invariant mass
PID of decay particles by RICH

Example for open charm: ‘golden channel’ D*-tagged D^0

$D^{*+} \rightarrow D^0\ \pi^+_{slow} \rightarrow K^-\ \pi^+\ \pi^+_{slow}$ (oraz kanał sprzężony ładunkowo)

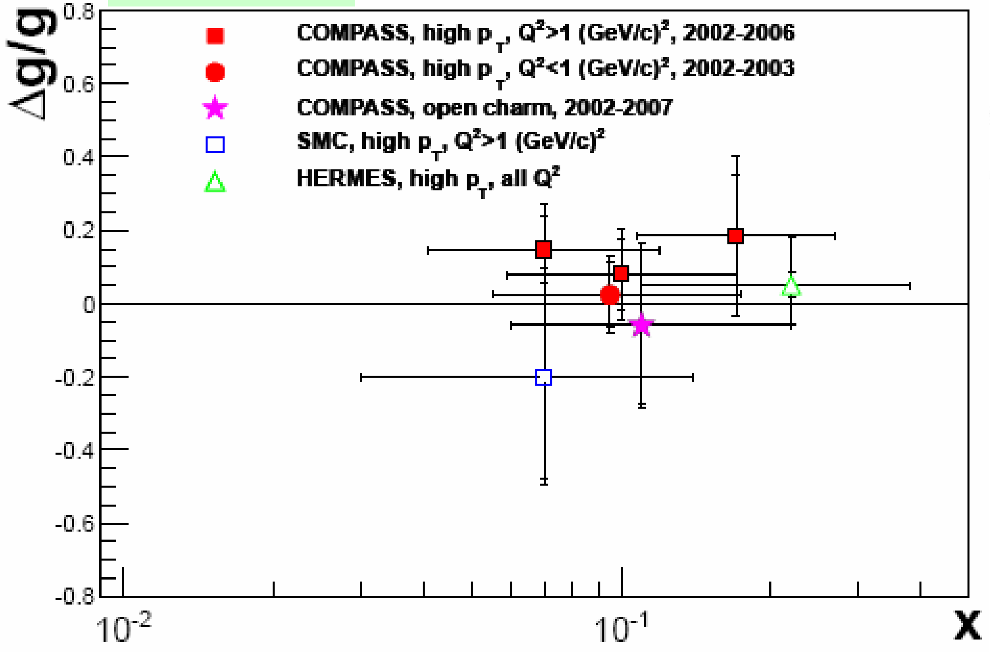


$p(\pi_{slow}) < 8$ GeV/c
$3.2 < \Delta M < 8.9$ MeV/c^2

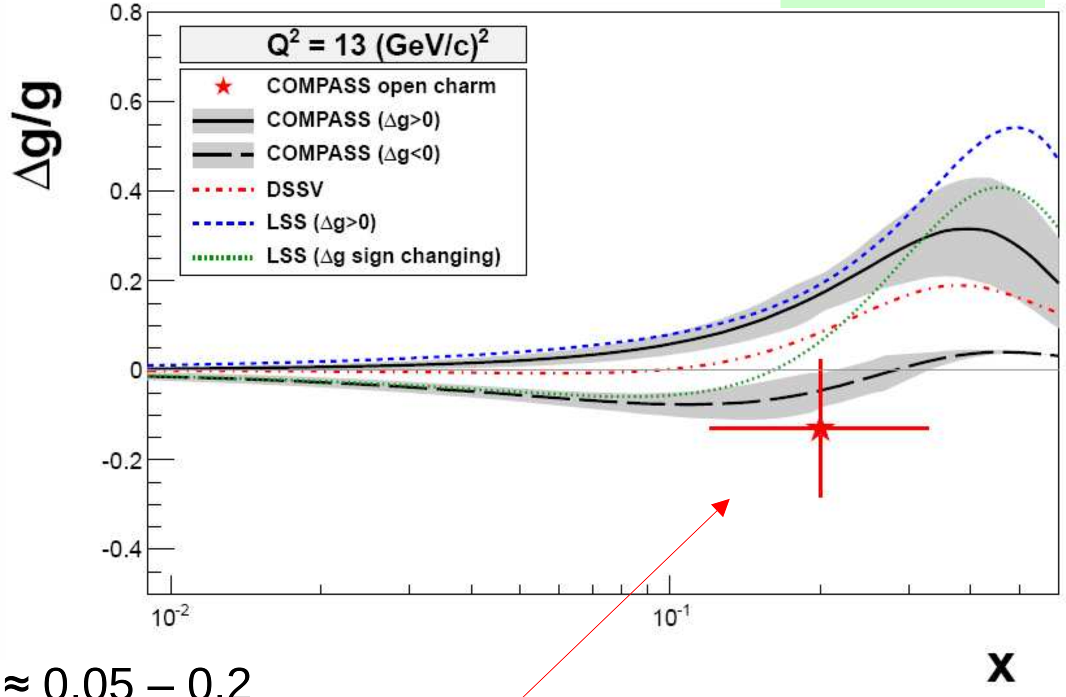
$$\Delta M = M_{K\pi\pi_{slow}} - M_{K\pi} - M_{\pi}$$

Results on Δg/g from PGF

LO QCD

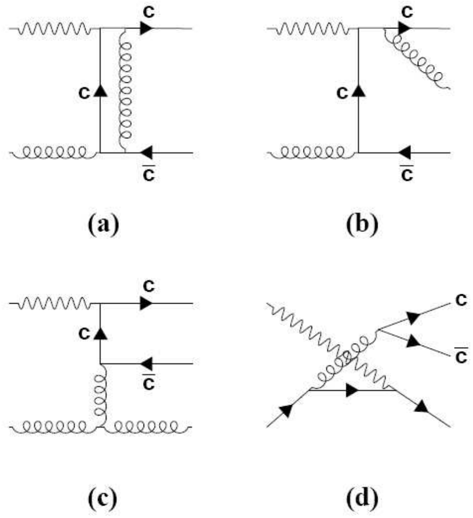


NLO QCD



- small gluon polarisation in the range $x_g \approx 0.05 - 0.2$
- first experimental estimate from PGF in NLO QCD

selected diagrams for PGF in NLO



Impact of the new NLO charm result on ΔG $\left(=\int_0^1 \Delta g(x,Q^2)\,dx\right)$

COMPASS ’12 global NLO fits to g_1 without/with charm result

$\Delta g(x)$ at Q_0^2 = 3 GeV^2	positive	negative
ΔG ‘without’	0.39 ± 0.07	-0.34 ± 0.12
ΔG ‘with’	0.22 ± 0.08	-0.34 ± 0.12

New result from DSSV+ with included precise 2009 RHIC data

$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$$

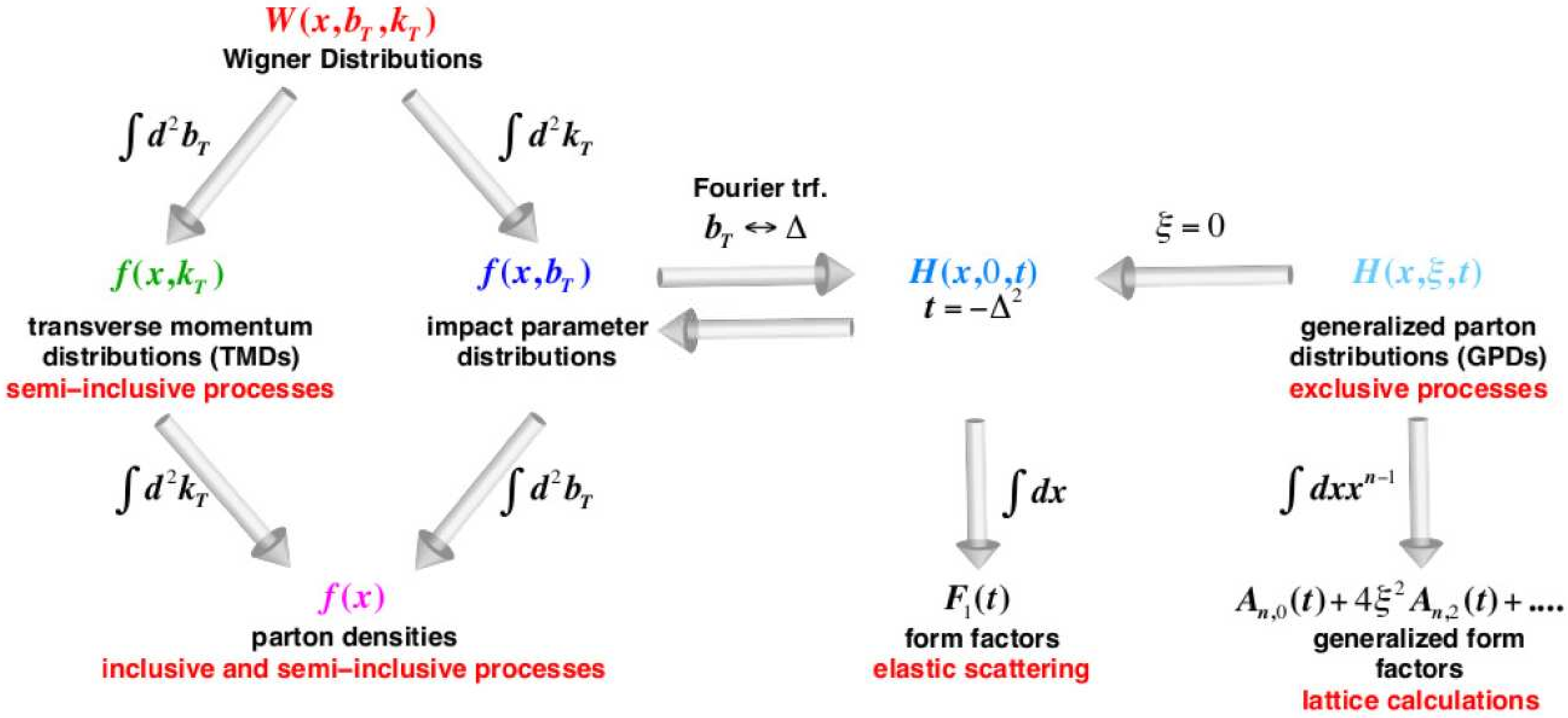
3D imaging of the proton

- transverse momentum dependent parton distributions (TMDs) – $f(x, \vec{k}_T)$
- general parton distributions (GPDs) → $f(x, \vec{b}_T)$

Connections between different distributions of partons inside the proton

The notation corresponds to the case of unpolarised partons in an unpolarised proton

Analogous connections hold for polarised quantities



$W(x,b_T,k_T)$
Wigner Distributions

$\int d^2b_T$

$\int d^2k_T$

Fourier trf.
$b_T \leftrightarrow \Delta$

$\xi = 0$

$f(x,k_T)$
transverse momentum distributions (TMDs)
semi–inclusive processes

$f(x,b_T)$
impact parameter distributions

$H(x,0,t)$
$t = -\Delta^2$

$H(x,\xi,t)$
generalized parton distributions (GPDs)
exclusive processes

$\int d^2k_T$

$\int d^2b_T$

$\int dx$

$\int dx x^{n-1}$

$f(x)$
parton densities
inclusive and semi–inclusive processes

$F_1(t)$
form factors
elastic scattering

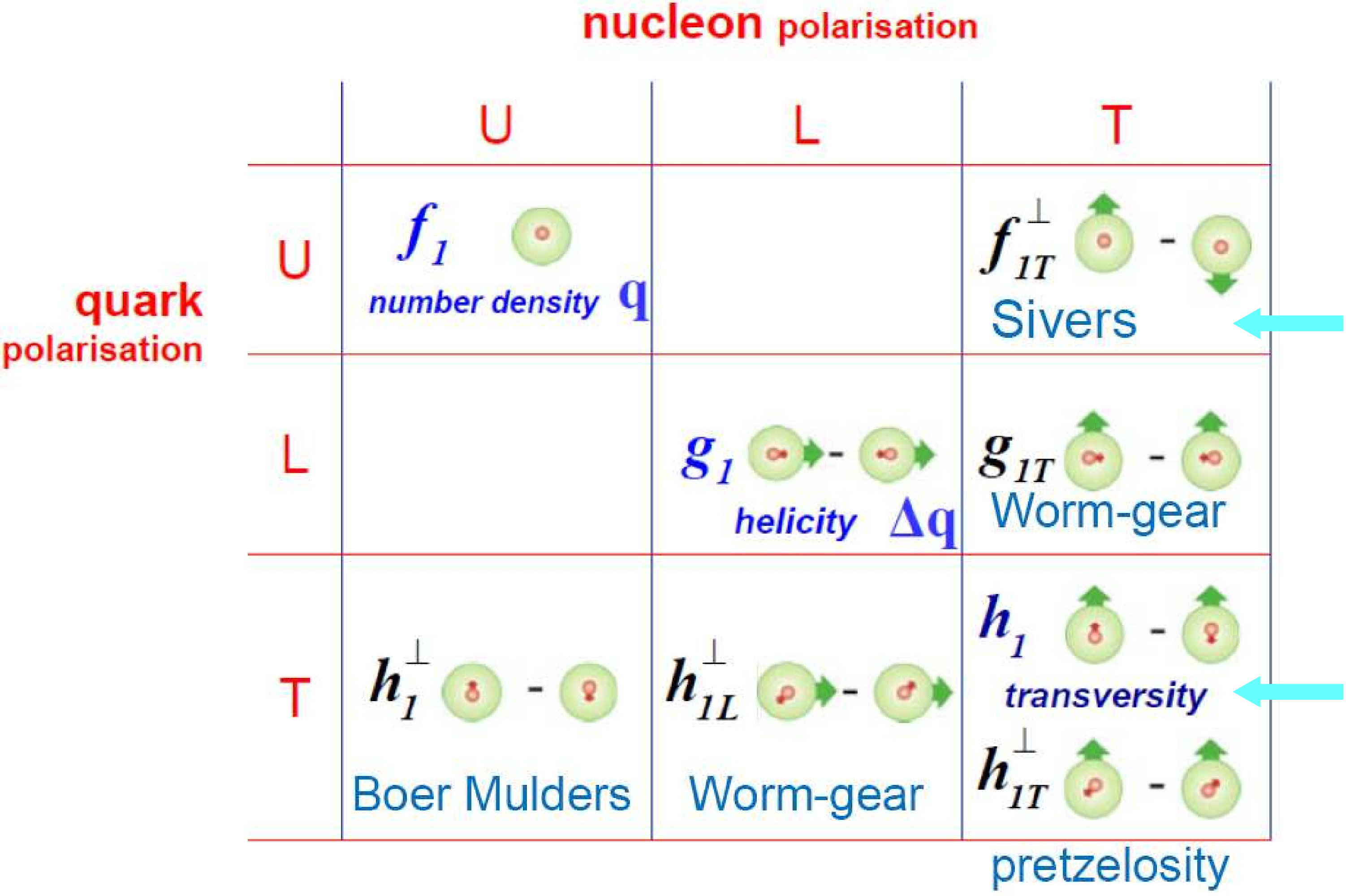
$A_{n,0}(t) + 4\xi^2 A_{n,2}(t) + ...$
generalized form factors
lattice calculations

Transverse momentum dependent structure of the nucleon

When intrinsic parton transverse momentum not neglected

8 TMD PDFs needed for complete description of the nucleon structure

Accessed via SIDIS

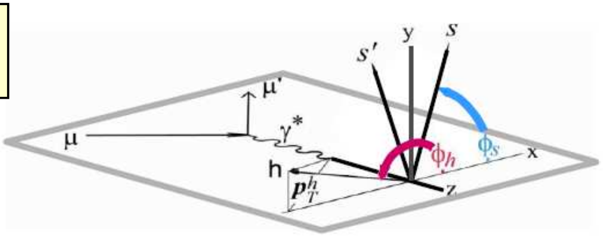


		nucleon polarisation		
		U	L	T
quark polarisation	U	f_1 number density q		$f_{1T}^{\perp}$ - Sivers
	L		g_1 - helicity Δq	g_{1T} - Worm-gear
	T	$h_1^{\perp}$ - Boer Mulders	$h_{1L}^{\perp}$ - Worm-gear	h_1 - transversity $h_{1T}^{\perp}$ - pretzelosity

upon integration over transverse momentum only f_1, g_1 and h_1 survive

transversity (h_1) is chiral-odd => in contrast to f_1 and g_1 cannot be measured in inclusive DIS possible in SIDIS, if coupled to a non-zero chiral-odd fragmentation function

SIDIS cross section



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$h_1^\perp H_1^\perp$

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

$h_{1L}^\perp H_1^\perp$

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

$f_{1T}^\perp D_1$

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

Sivers

$h_{1T}^\perp H_1^\perp$

$$+\varepsilon\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\boxed{\sin(3\phi_h-\phi_S)}\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

Collins

$h_1 H_1^\perp$

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

$g_{1T} D_1$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\boxed{\cos(\phi_h-\phi_S)}\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

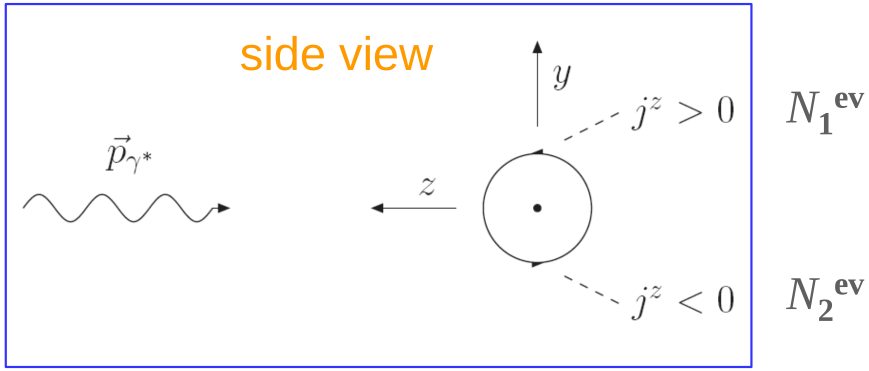
$$+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

18 structure functions
14 azimuthal modulations
all measured in COMPASS

A Bacchetta et al., 2006

Semi-classical explanation of connection between Sivers asymmetry and orbital angular momentum

proton polarised in $+x$ direction
assume L_q positive



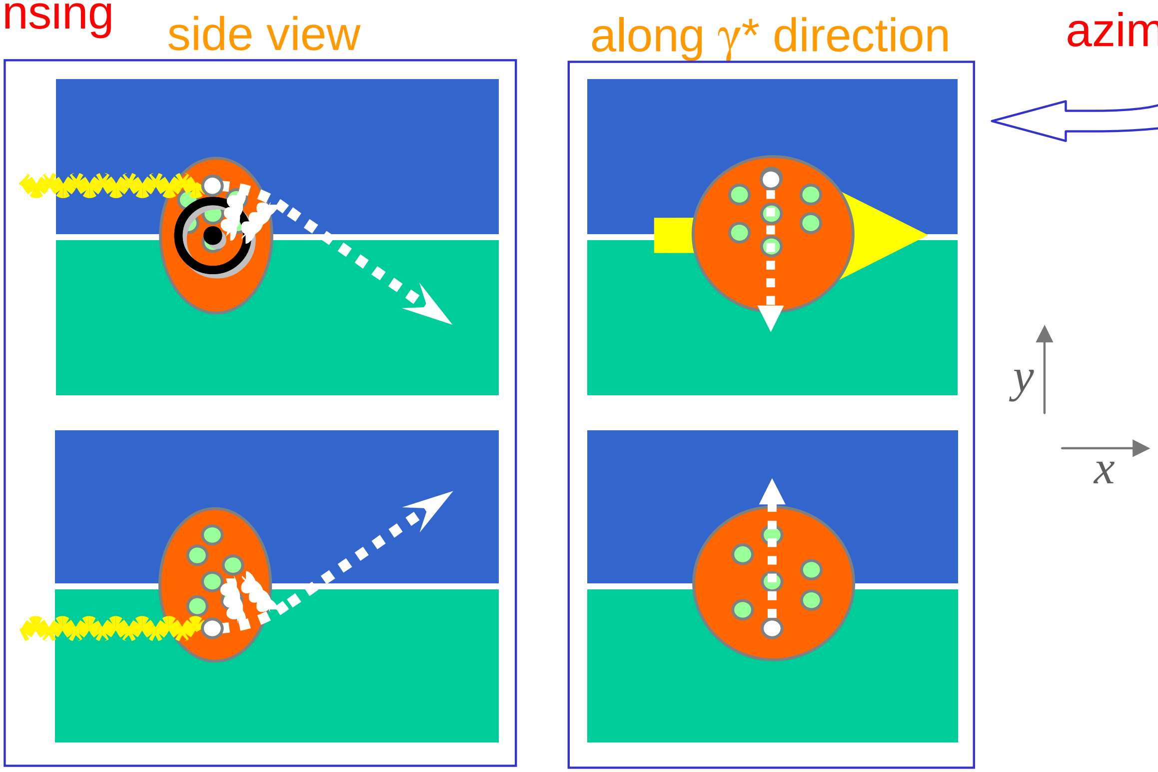
- electromagnetic interaction couples to vector current. In Bjorken limit γ^* 'sees' only $j^+ = j^0 + j^z$ component of quark current
- virtual photon 'sees' enhancement when quark current points in direction opposite to photon momentum

→ $N_1^{\mathrm{ev}} > N_2^{\mathrm{ev}}$

chromodynamic lensing

N_1^{ev}

N_2^{ev}



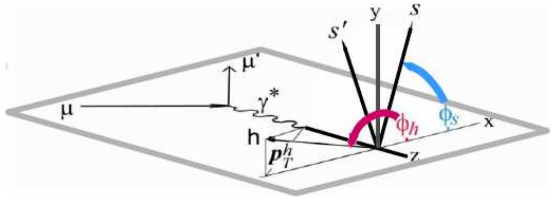
azimuthal asymmetry

$\sim \sin(\phi - \phi_s)$

Sivers asymmetries from 2010 run

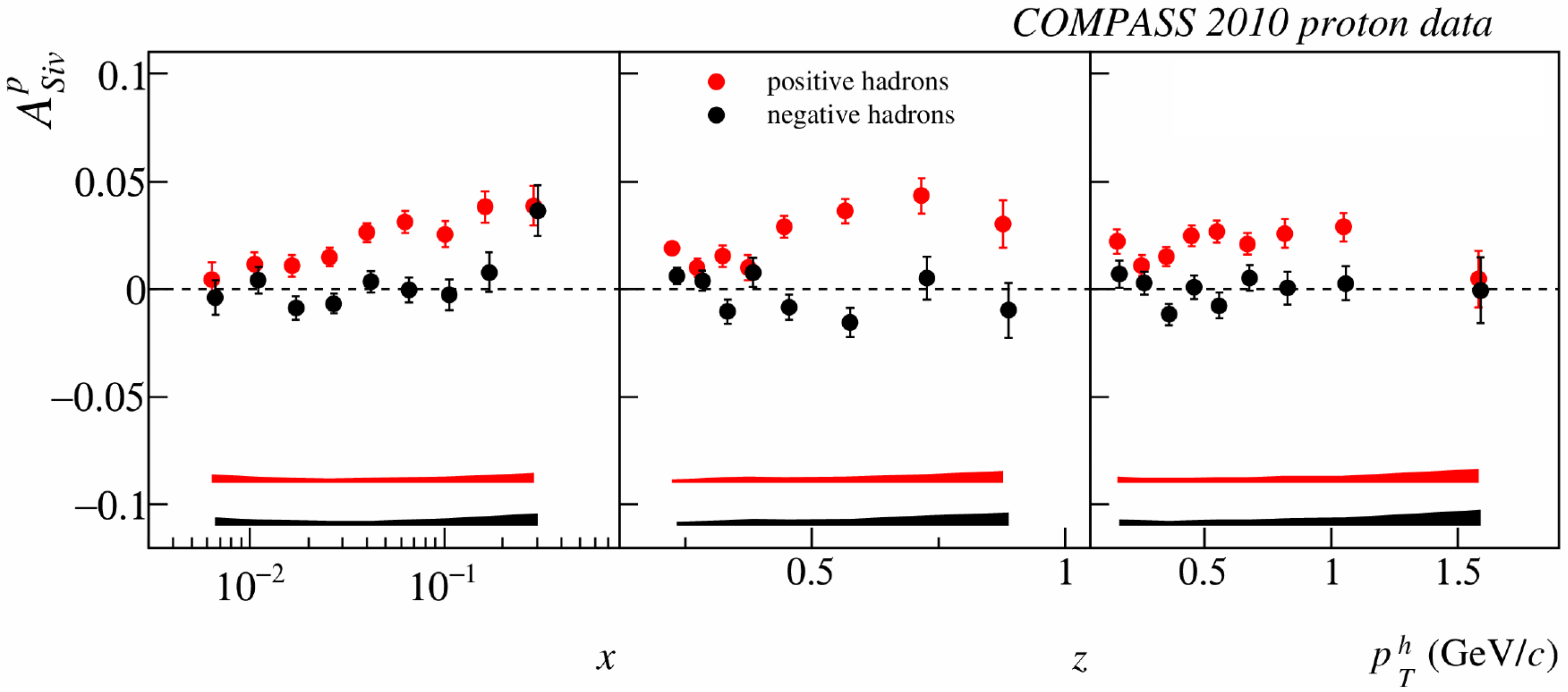
$$N_h^{\pm}(\Phi_S) = N_h^0(1 \pm A_S^h \sin(\Phi_S))$$

with $\Phi_S = \phi_h - \phi_s$



$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 f_{1T}^{\perp q}(x,k_\perp^2) \otimes D_{1,q}(z,p_\perp^2)}{\sum_q e_q^2 f_1^q(x,k_\perp^2) \otimes D_{1,q}(z,p_\perp^2)}$$

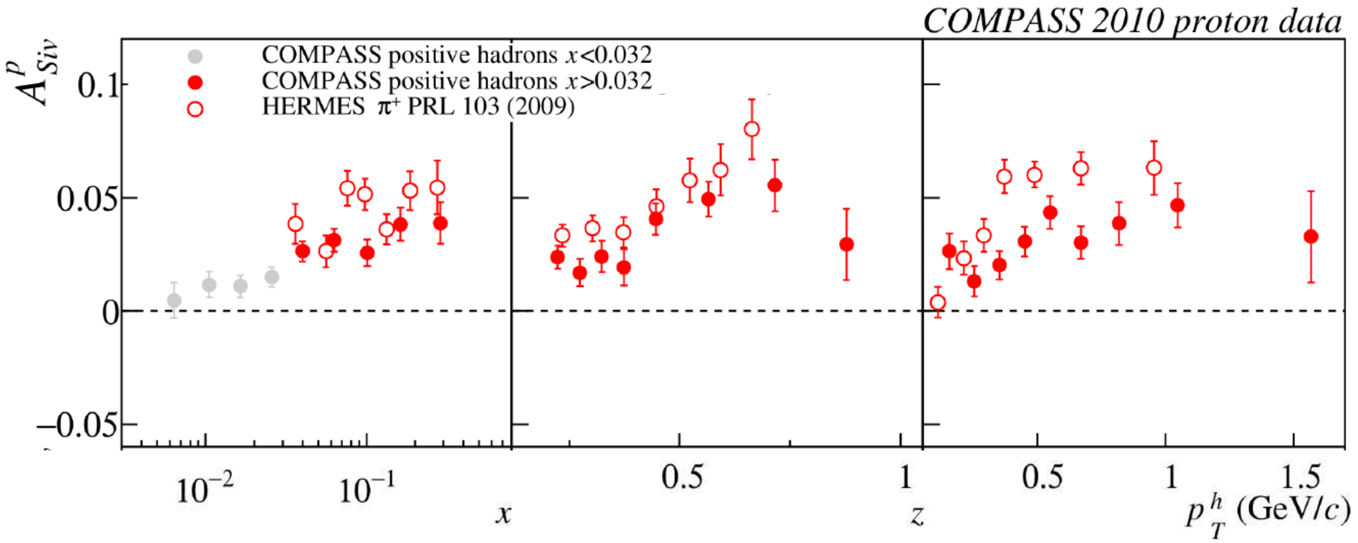
P_T – target polarisation, f – dilution factor

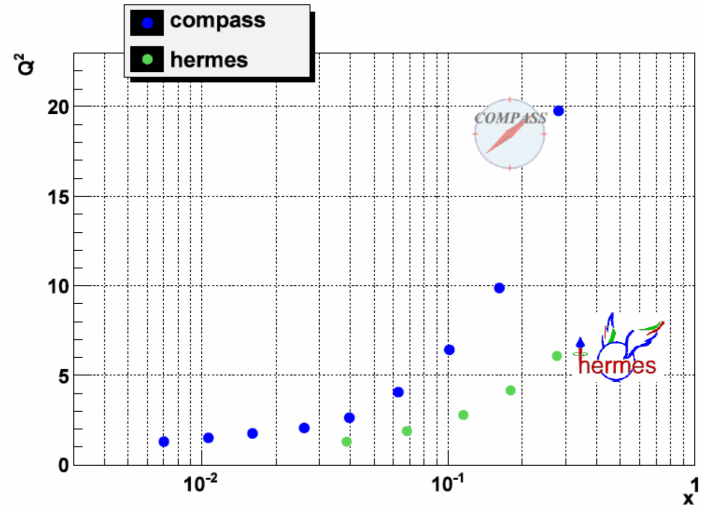


- positive asymmetry for h^+ , stays positive well below the valence region (down to $x \approx 10^{-2}$)
- for h^- the asymmetry compatible with zero
- good agreement with 2007 published results, significant reduction of statistical uncertainty

More on Sivers asymmetry

comparison to HERMES





clear increase of Sivers asymmetry for h^+ at low Q^2

Not shown comparison with HERMES for h^-
Results from both experiments on $A^p_{Siv,h-}$ compatible with zero

Also not shown COMPASS results on Sivers asymmetry for deuterons
Both $A^d_{Siv,h-}$ $A^d_{Siv,h-}$ compatible with zero

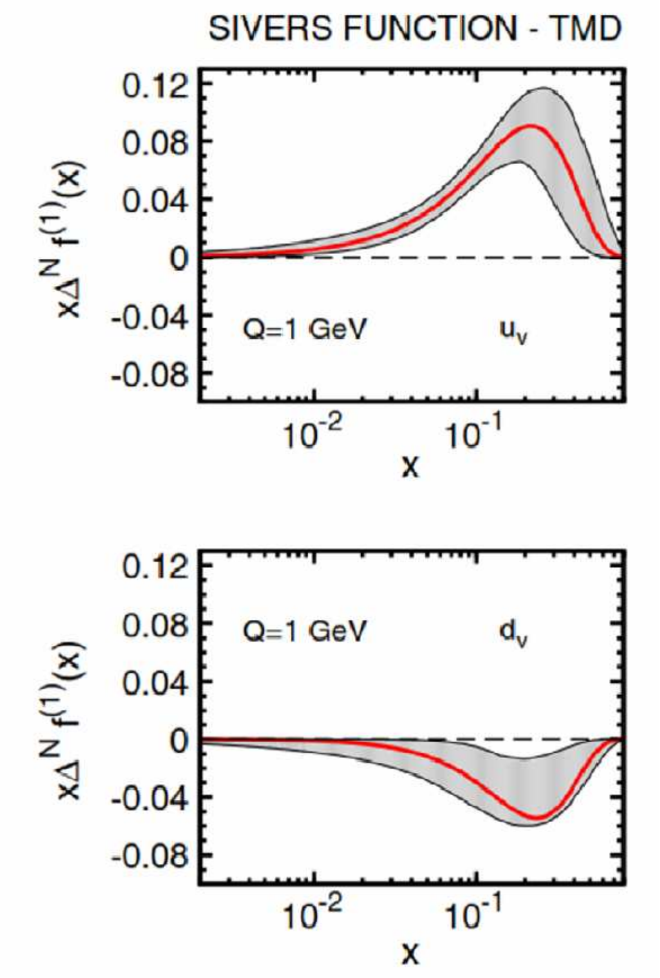
⬇

Important for quark flavour separation

Extraction of Sivers function from global analyses and TMD Q^2 evolution

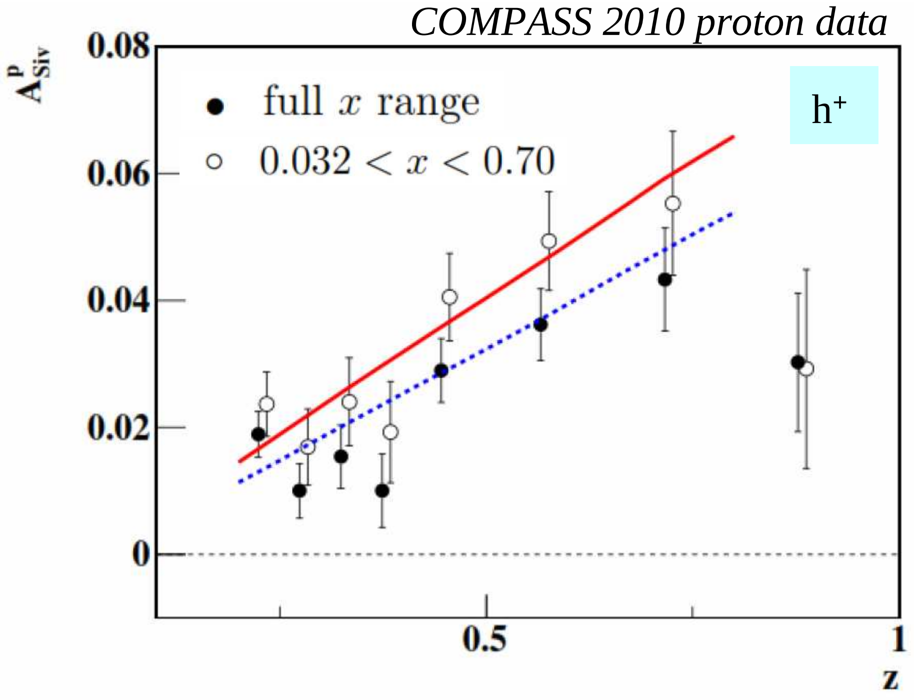
M. Anselmino, M. Boglione, S. Melis PRD86 (2012) 014028

Fits to HERMES p, COMPASS d, COMPASS p (2007) and Belle fragm. fct.



TMD evolution

S.M. Aybat, A. Prokhudin and T.C. Rogers (arXiv:1112.4423)



x > 0.032
$\langle Q^2 \rangle$ = 8.7 GeV/c^2
all x
$\langle Q^2 \rangle$ = 3.8 GeV/c^2

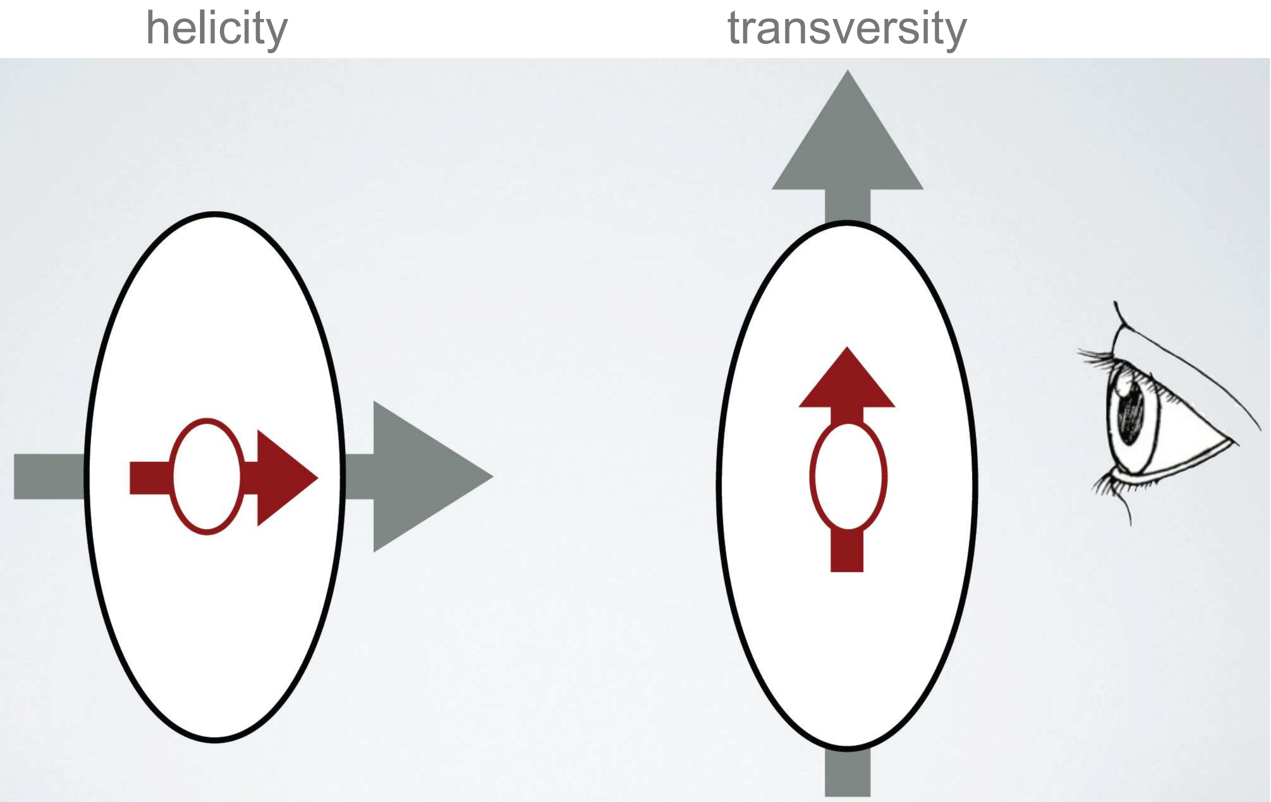
current TMD approach foresees a strong Q^2-dependence of the Sivers function

high precision of COMPASS 2010 proton results
expected to improve significantly future global fits of Sivers function

Nucleon structure - transversity

Transversity: distributions of transversely polarised quarks in transversely polarised nucleon

$$\boxed{h_1^q = \delta q = q^{\uparrow} - q^{\downarrow}}$$



Not the same as helicity, because rotations and boosts (nucleon) do not commute

Differences for transversity, h_1, compared to helicity, g_1, distribution function

- Chirally odd. Cannot be measurd in inclusive DIS. Possible to measure in a process where it couples to another chiral odd function, for example in SIDIS
- Do not couple to gluon spin Different DGLAP evolution than for g_1
- Different spin sum rule than for the longitudinal spin

Helicity

(big brother)

Transversity

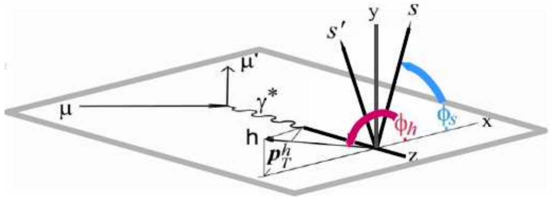
(little brother)

Courtesy of A. Bacchetta

Collins asymmetries from 2010 run

$$N_h^{\pm}(\Phi_C) = N_h^0(1 \pm A_C^h \sin(\Phi_C))$$

with $\Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$

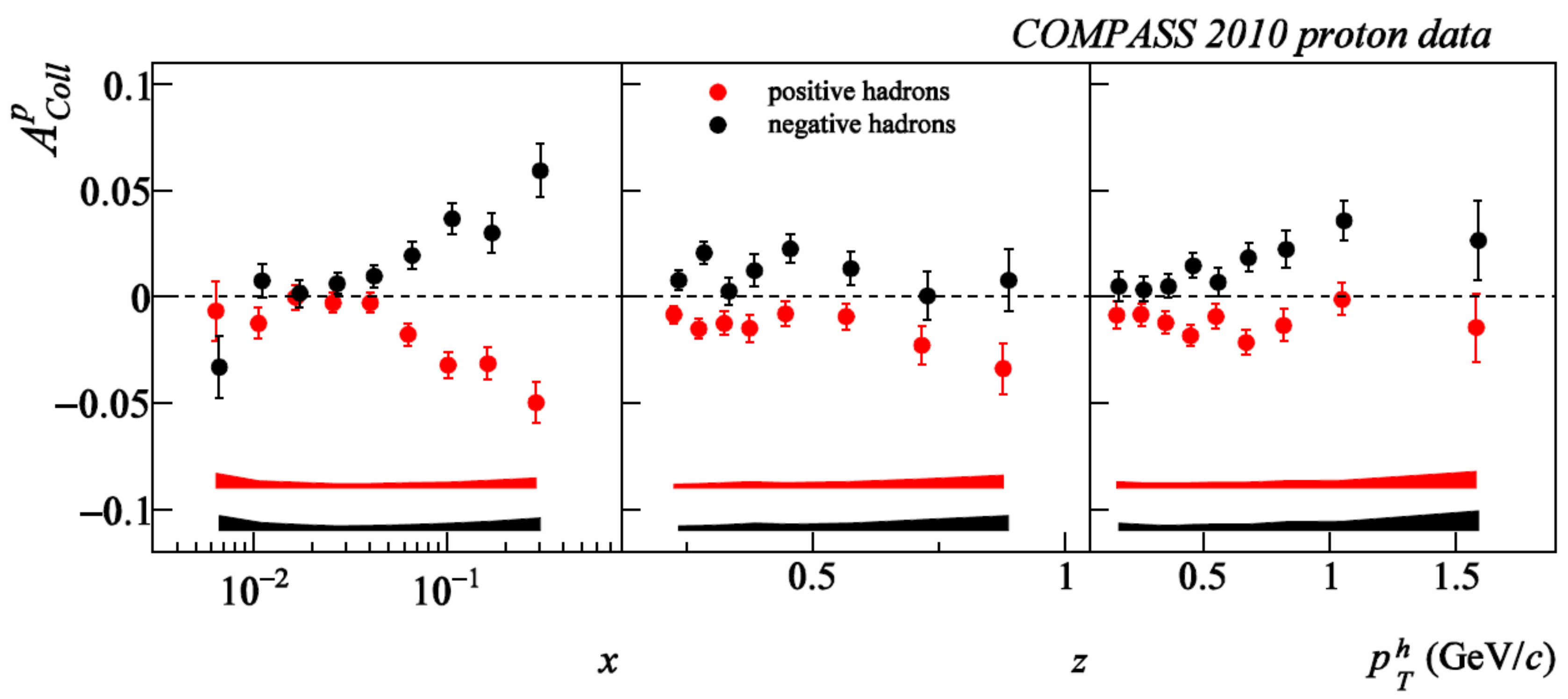


$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D_{nn}} = \frac{\sum_q e_q^2 h_1^q(x, k_\perp^2) \otimes H_{1,q}^\perp(z, p_\perp^2)}{\sum_q e_q^2 f_1^q(x, k_\perp^2) \otimes D_{1,q}(z, p_\perp^2)}$$

Collins FF

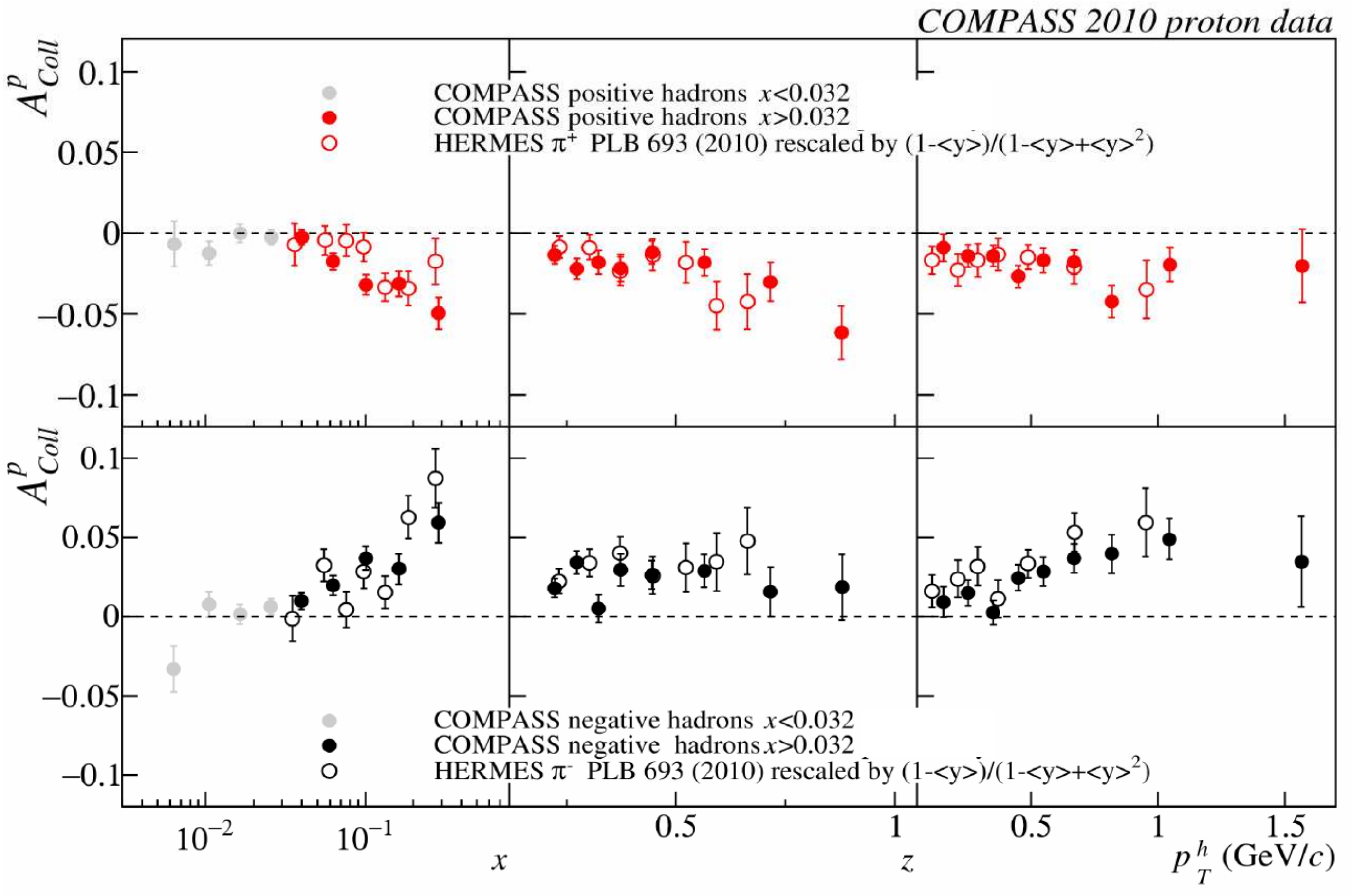
P_T – target polarisation, f – dilution factor

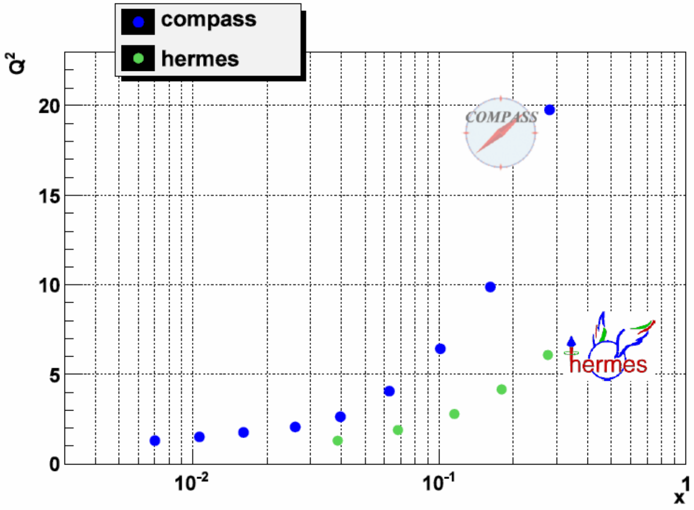
D_{nn} – spin transfer coeff. from initial to struck quark



- in valence region mirror symmetry wrt hadron charge => $H^\perp_{1,fav} \approx - H^\perp_{1,unf}$ (Collins FF)
- at small-x range (< 0.03), not covered by HERMES, asymmetries compatible with zero
- confirm published results from 2007 with statistical uncertainties improved by factor ~ 2

Comparison to HERMES and Q^2 dependence





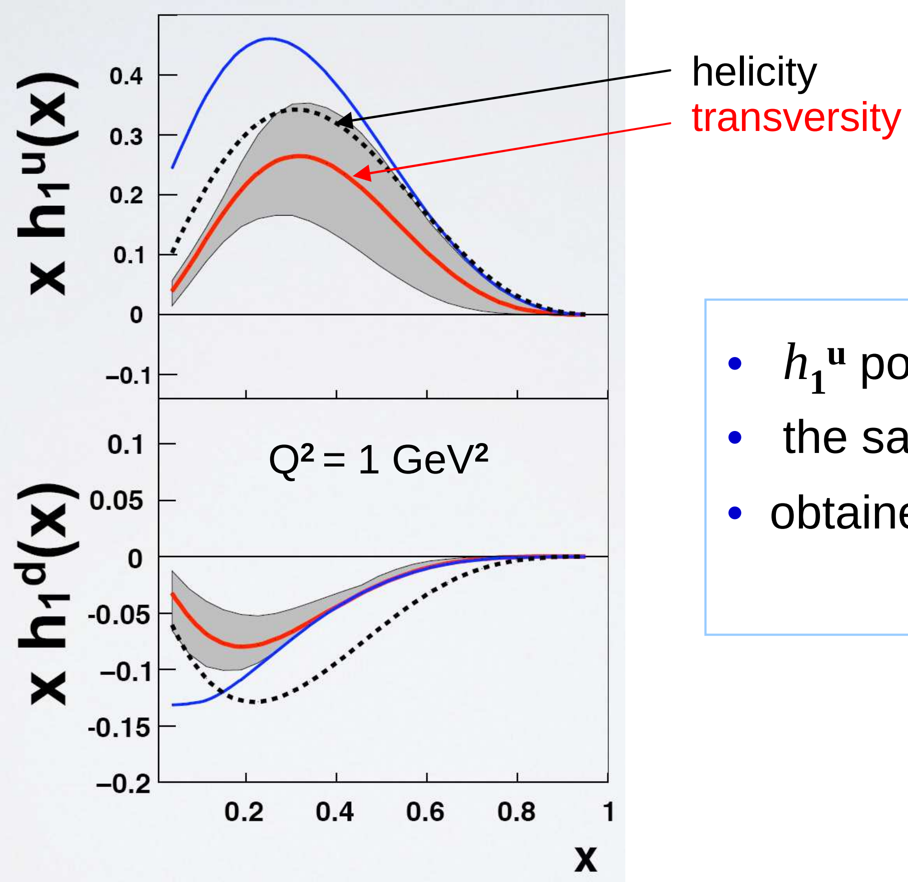
- in overlap region good agreement with HERMES
- non-trivial result; at COMPASS <Q^2> larger by a factor 2-3

→ weak Q^2> dependence of the Collins asymmetry

Extraction of transversity from global analyses

used data from HERMES p, COMPASS d and Belle fragm. fct. (not yet COMPASS p)

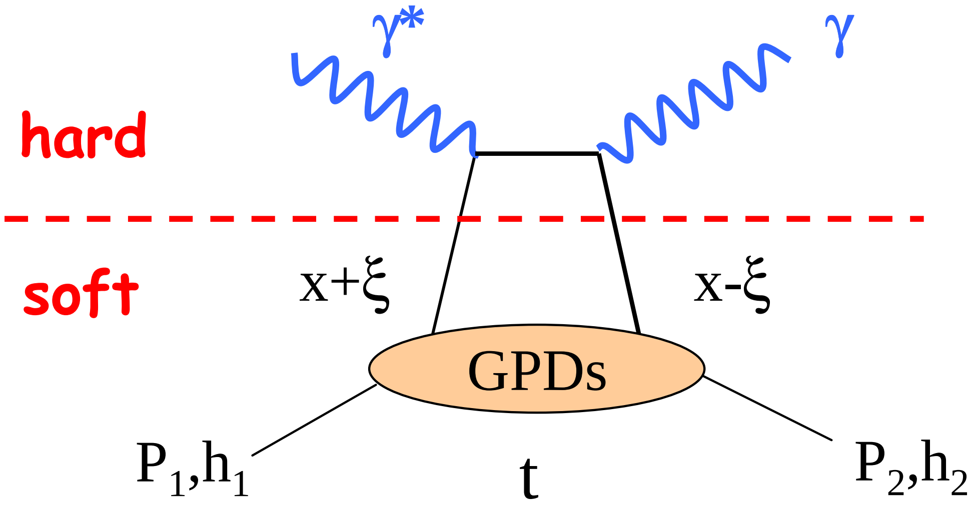
results from several analyses available
shown here are from M. Anselmino et al. (2008)



- h_1^u positive, h_1^d negative
- the same signs as for helicities, but h_1's smaller
- obtained also h_1's for sea quarks,
  considerably smaller than for u and d

observed agreement with HERMES and COMPASS supports
the weak Q^2 dependence of the Collins FF assumed in the model

Generalized Parton Distributions and DVCS



Factorisation:

Q^2 large, $-t<1$ GeV^2

$$\xi = \frac{x_B}{2 - x_B}$$

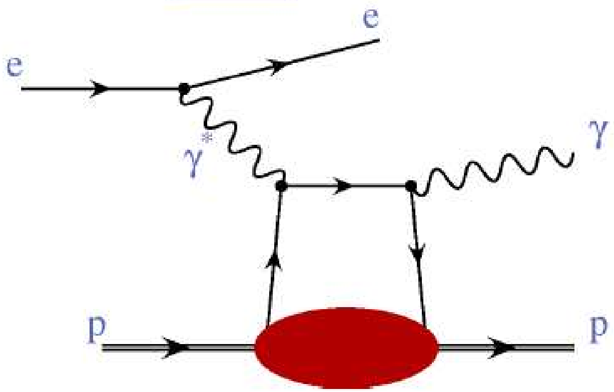
P_i, h_i – proton momentum and helicity

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ depending on 3 variables: x, ξ, t

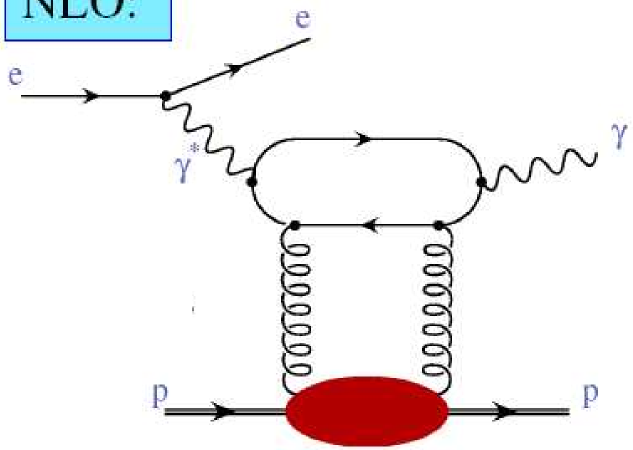
for each quark flavour and for gluons

for DVCS gluons contribute at higher orders in α_s

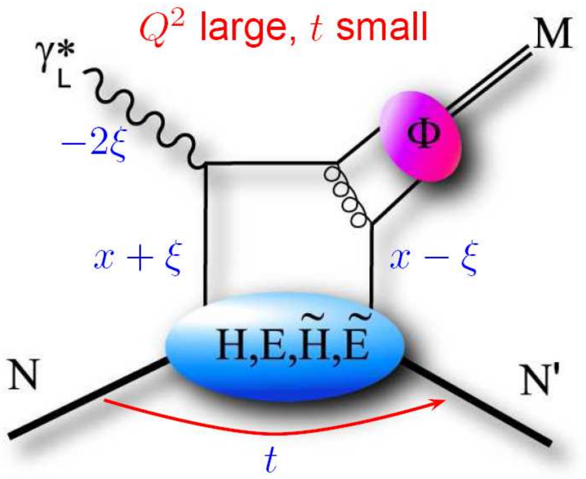
LO:



NLO:



Hard Exclusive Meson Production and GPDs



- 4 Generalised Parton Distributions (GPDs)

  for each quark flavour and for gluons

  GPDs depend on 3 variables: x, ξ, t

- collinear factorisation proven only for σ_L

  σ_T suppressed by $1/Q^2$

- quarks and gluons enter at the same order of α_S

- for vector mesons (ρ, ω, φ): H, E

  non-flip nucleon helicity flip

separation wrt quark flavours and gluons

ρ^0	2/3 u + 1/3 d + 3/8 g
ω	2/3 u – 1/3 d + 3/8 g
ϕ	s, g
ρ^+	u–d
J/ψ	g

LT observables in VM exclusive meson production relevant for GPDs

for longitudinal γ*

unpolarised
cross section $(\sigma_{00}^{++} \equiv \sigma_L)$

$$\frac{d\sigma_{00}^{++}}{dt} = (1-\xi^2)\,|\underline{H_M}|^2 - (\xi^2 + \frac{t}{4M_p^2})\,|E_M|^2 - 2\xi^2\,\mathrm{Re}\,(E_M^* H_M)$$

transverse target
spin dependent
cross section

$$\frac{1}{2}(\frac{d\sigma_{00}^{\uparrow\uparrow}}{dt} - \frac{d\sigma_{00}^{\downarrow\downarrow}}{dt}) = -\mathrm{Im}\frac{d\sigma_{00}^{+-}}{dt} = \Gamma'\sqrt{1-\xi^2}\,\frac{\sqrt{t_0 - t}}{M_p}\,\mathrm{Im}(\underline{E_M^*}H_M)$$

access to GPD E
related to orbital momentum

H_M , E_M are weighted sums of convolutions of the GPDs $H^{q,g}$, $E^{q,g}$
with hard scattering kernel and meson DA

weights depend on contributions of various quark flavours
and of gluons to the production of meson M

$$\Gamma' = \frac{\alpha_{\rm em}}{Q^6}\,\frac{x_B^2}{1-x_B} \qquad \xi = \frac{x_B}{2-x_B}, \qquad -t_0 = \frac{4\xi^2 M_p^2}{1-\xi^2}$$

(large Q^2 approximation)

$$\boxed{\frac{1}{2}\int_{-1}^{1} dx\; x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] \overset{t\to 0}{=} J_q = \frac{1}{2}\Delta\Sigma + L_q}$$

Ji's sum rule

So far GPD E poorly constrained by data (mostly by Pauli form factors)

Exclusive ρ^0 production on $p^\uparrow$ and $d^\uparrow$ at COMPASS

$\mu N \to \mu \rho^0 N$

i.e. incoherent process

Transversely polarised proton target (NH_3), 2007, 2010
Transversely polarised deuteron target (^6LiD), 2003-2004

note: there was no RPD for these data

only two tracks of opposite charge associated to the primary vertex

DIS cuts

$1 < Q^2 < 10$ GeV^2
$0.1 < y < 0.9$
$W > 5$ GeV

cuts specific for exclusive ρ^0 analysis

$0.5 < M_{\pi\pi} < 1.1$ GeV
$-2.5 < E_{miss} < 2.5$ GeV
$E_{\rho 0} > 15$ GeV
$0.05 < p_T^2 < 0.5$ GeV^2 [NH_3]
$0.1 < p_T^2 < 0.5$ GeV^2 [^6LiD]

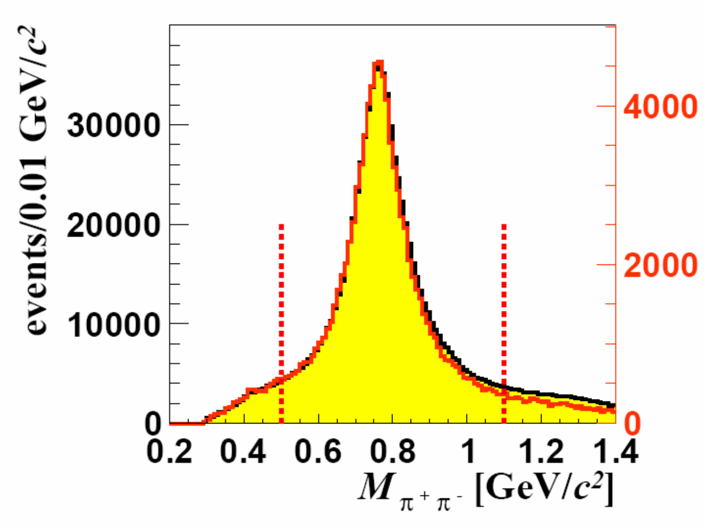
$E_{miss} = (M_X^2 - M_p^2)/(2M_p)$

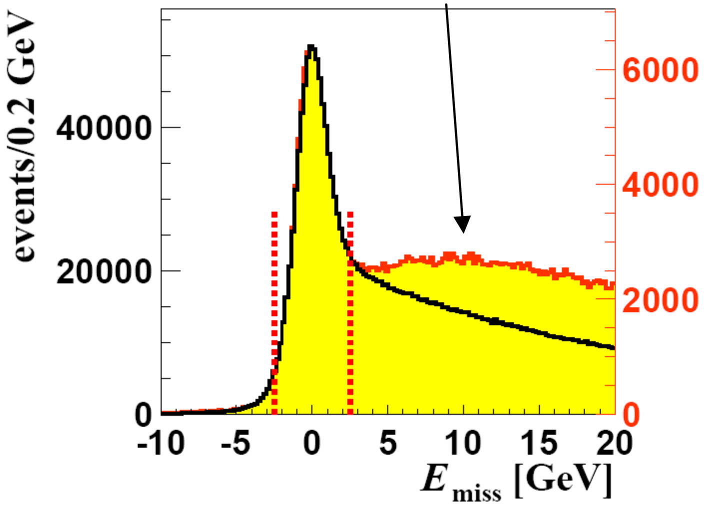
—	proton data	(797 000 evts)
—	deuteron data	(97 000 evts)

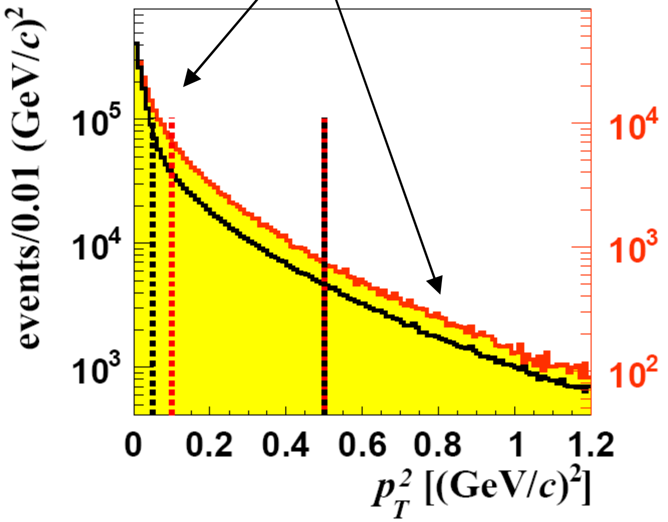
dominant non-excusive bkg.

dominant coherent contrib.

dominant non-exclusive bkg.

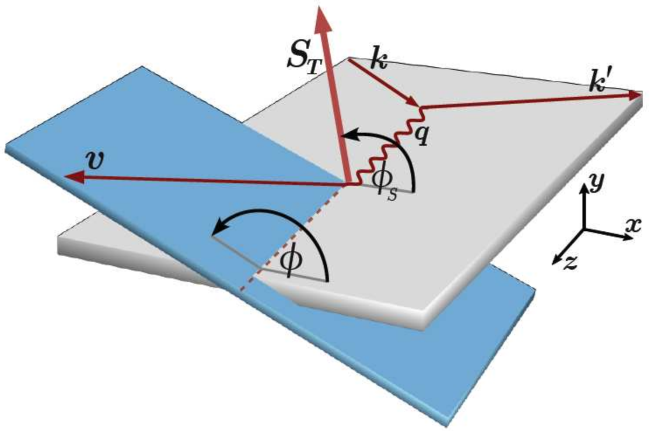






TTS asymmetry $A_{UT}^{\sin(\phi\text{-}\phi s)}$ for exlusive ρ^0 production from COMPASS

$\mu\, N \rightarrow \mu\, \rho^{0}\, N$



$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{\mathrm{d}\sigma}{\mathrm{d}x_{Bj}\mathrm{d}Q^2\mathrm{d}t\mathrm{d}\phi\mathrm{d}\phi_s} \simeq$$

$$\frac{1}{2}\left(\sigma^{++}_{++}+\sigma^{--}_{++}\right)+\epsilon\sigma^{++}_{00} - S_T\sin\left(\phi-\phi_s\right)\mathrm{Im}\left(\sigma^{+-}_{++}+\epsilon\sigma^{+-}_{00}\right)+\ \ldots$$

unpolarised cross section

interference terms with $E^*_M H_M$

$$A_{UT}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}(\sigma^{+-}_{++}+\epsilon\ \sigma^{+-}_{00})}{\frac{1}{2}(\sigma^{++}_{++}+\sigma^{--}_{++})+\epsilon\ \sigma^{++}_{00}}$$

index U refers to unpolarised target,
T to transversely polarised target

number of exclusive events
after bin-by-bin correction for SIDIS background

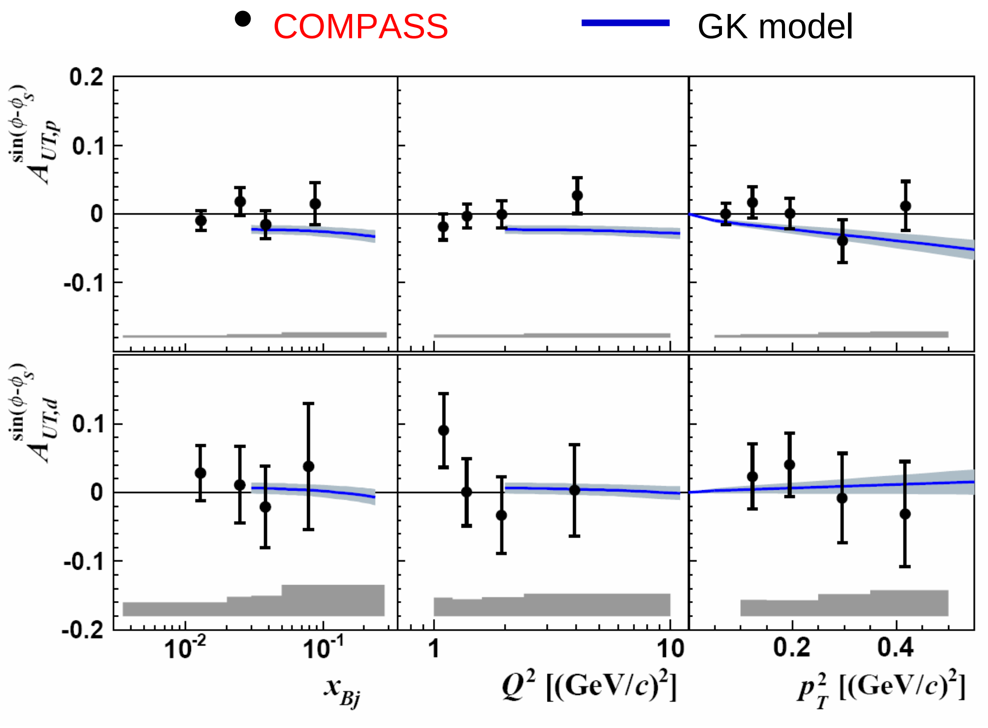
$$N(\phi-\phi_S)=F\,n\,a\,\sigma_0\left(1\pm f\,|P_T|\,A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S)\right)$$

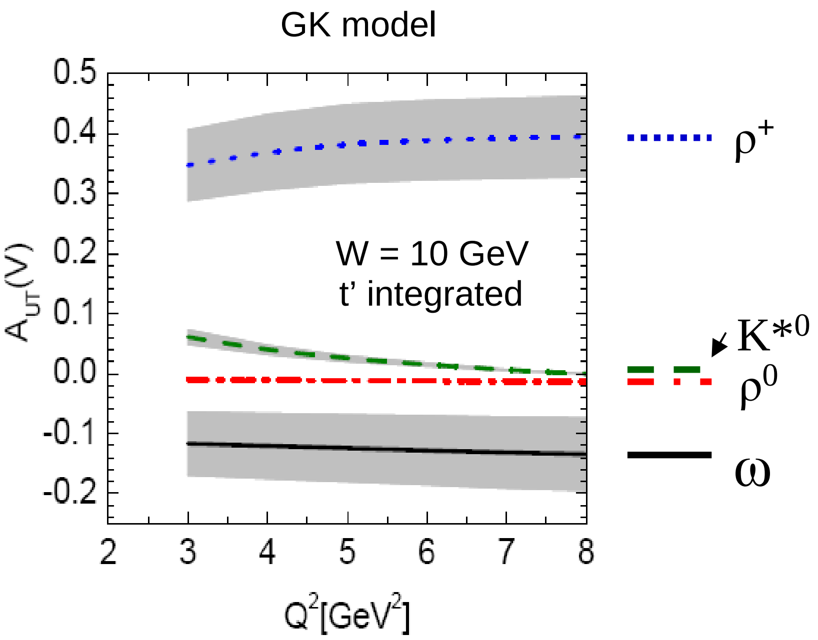
F – flux, n – number of nucleons, a – acceptance, σ_0 – unpolarised cross section
f – dilution factor, P_T – target transverse polarisation

asymmetry extracted form a fit of the number of events in 12 bins of ϕ - ϕ_s
for each of the two(*) target cells and polarisation state (+,-)

(*) for 3-cell target used for proton data (2007, 2010) upstream and downstream ones were combined

Results on $A_{UT}^{\sin(\phi-\phi s)}$ for exlusive ρ^0 production from COMPASS





- $A_{UT}^{\sin(\phi-\phi s)}$ for transversely polarised protons and deuterons compatible with 0
- reasonable agreement with predictions of the GPD model of Goloskokov - Kroll

[EPJ C59 (2009) 809]

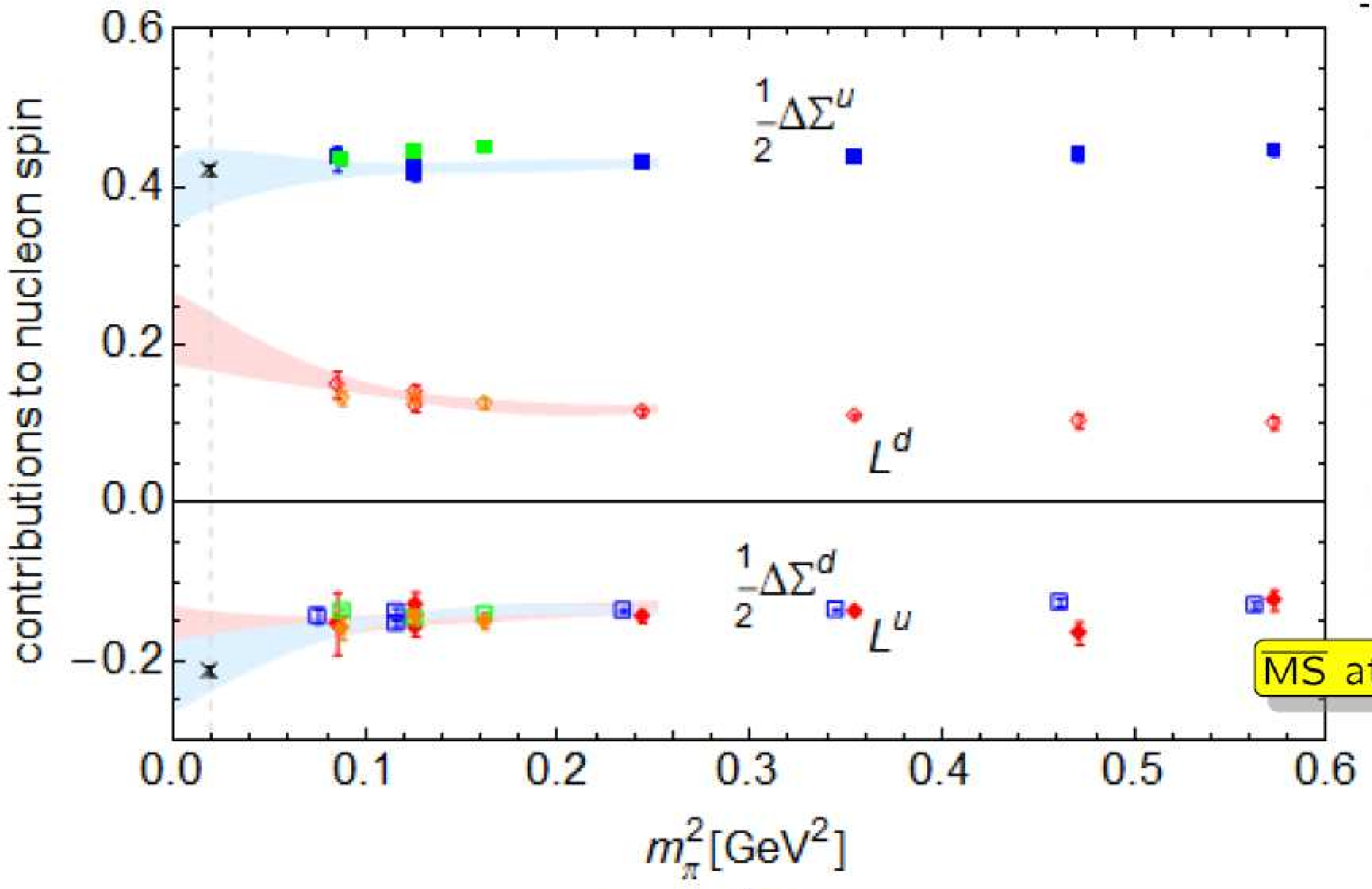
small values expected due to approximate cancellation of contributions from E^u and E^d, $E^u \approx -E^d$

$E^p_{\rho 0}$ ~ ⅔ E^u + ⅓ E^d + ⅜ E^g vs. E^p_{ω} ~ ⅔ E^u - ⅓ E^d + ⅜ E^g (cf. upper-right plot)

Interpretation in the framework of GPDs consistent with the Lattice QCD result: $L_u \approx - L_d$

Results from Lattice QCD (Ph. Hägler, MENU 2010)

Quark spin and orbital angular momentum



$\overline{\mathrm{MS}}$ at 4 GeV^2

$J^u \approx 0.236 \pm 0.006 \mathrel{\widehat{=}} 48\%$ of $1/2$
$J^d \approx 0.002 \pm 0.004$

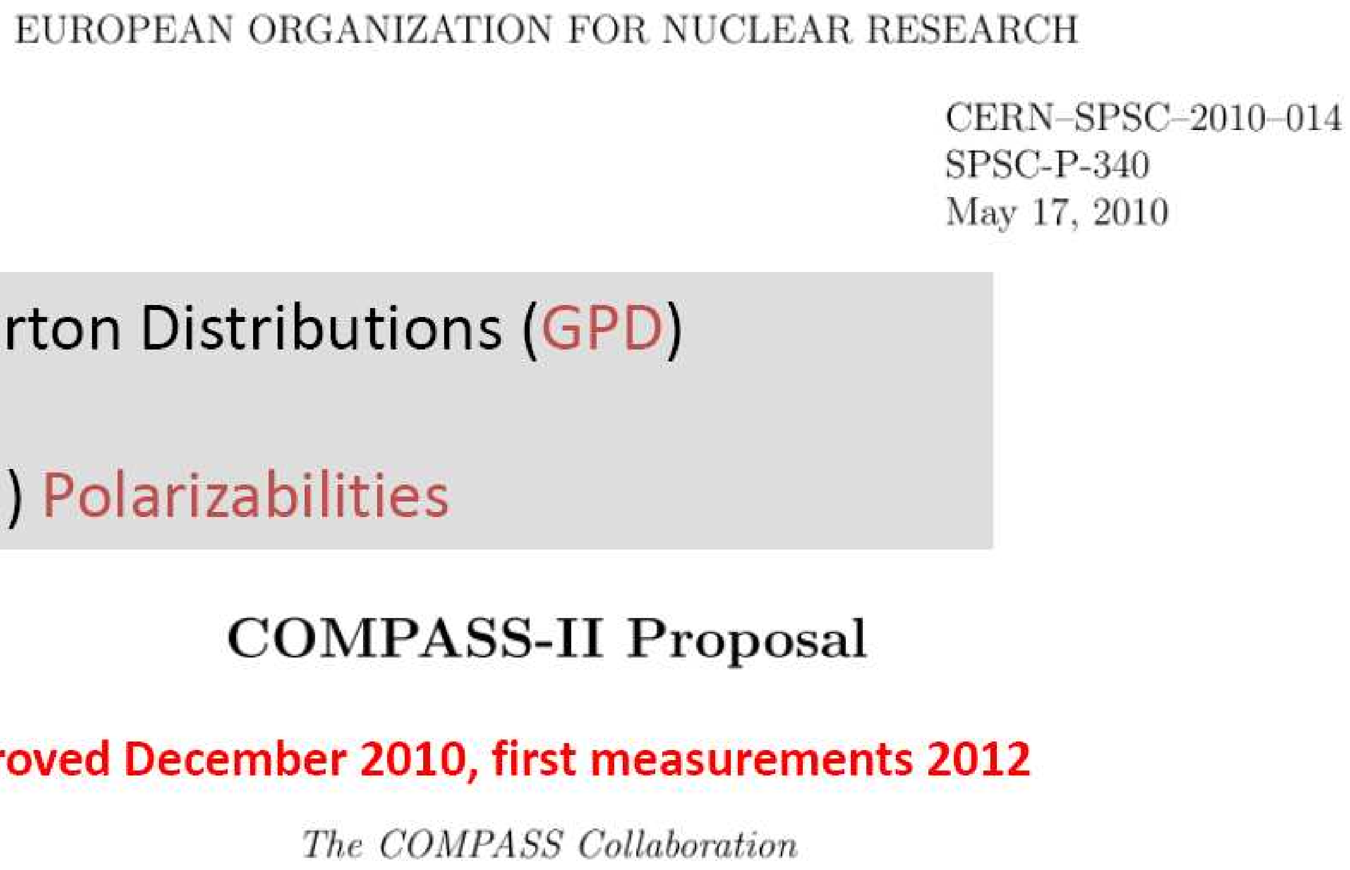
pioneering lattice calculations by Gadiyak, Ji and Jung in 2001

$L^d \approx -L^u \approx 0.185 \pm 0.06 \approx 36\%$ of $1/2$
$L^{u+d} \approx 0.030 \pm 0.012 \approx 6\%$ of $1/2$

$\kappa^{u+d} = 3\kappa^{p+n} = -0.36$

Ph. Hägler, MENU 2010, W&M

COMPASS-II



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–SPSC–2010–014
SPSC-P-340
May 17, 2010

- Generalized Parton Distributions (GPD)
- Drell-Yan
- Pion (and kaon) Polarizabilities

COMPASS-II Proposal

Approved December 2010, first measurements 2012

The COMPASS Collaboration

wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

Future GPD program in context of COMPASS-II time lines

Part of the COMPASS-II proposal scheduled presently by CERN

- 2012: pion and kaon polarisabilities (Primakoff) + comissioning and test run for DVCS
- 2013: long SPS shutdown
- 2015: Drell-Yann measurements with transversely polarised protons (NH_3 target)
- 2016-2017: stage 1 of GPD program and in parallel SIDIS (LH target)

Further subjects to be pursued at COMPASS-II > 2017

- ✓ additional year of Drell-Yann measurements
- ✓ stage 2 of GPD program (transversely polarised target and RPD)
- ✓ hadron program (spectroscopy in diffractive and central production)

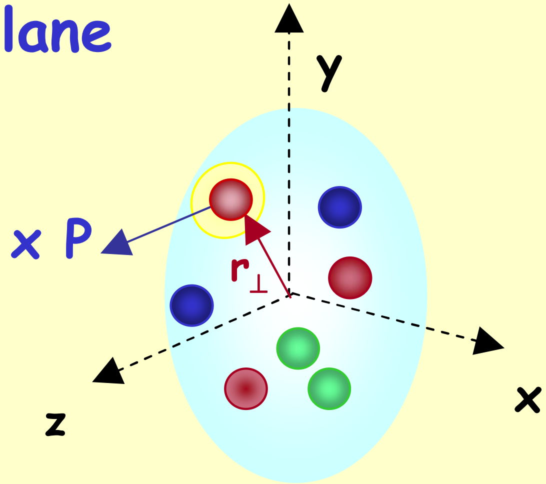
Main goal of ‘stage 1’ of COMPASS GPD program

DVCS and HEMP with unpolarised proton target
to constrain GPD H

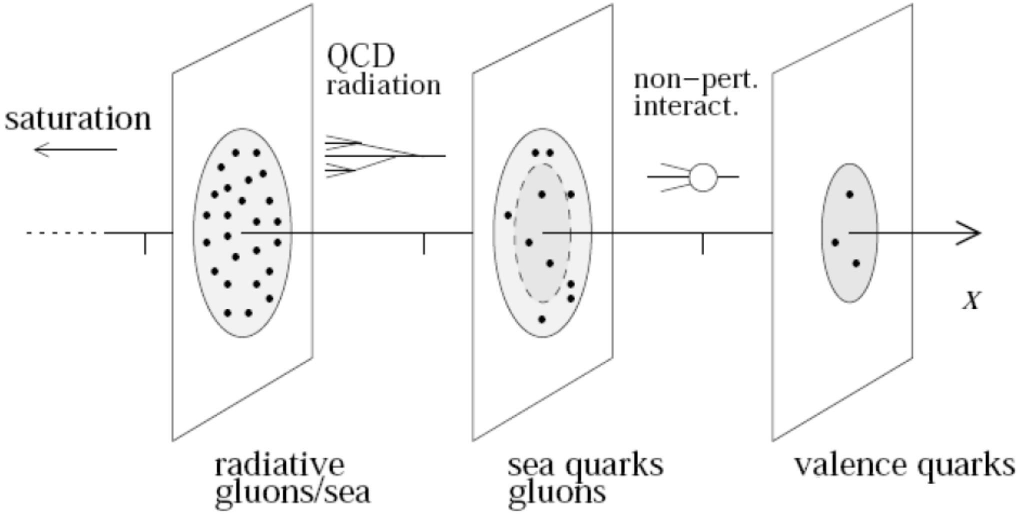
- GPD - 3-dimensional picture of the partonic nucleon structure or spatial parton distribution in the transverse plane

$$H(x,\ \xi=0,\ t) \rightarrow H(x,\ ,\ r_{x,y}\ )$$

probability interpretation
Burkardt



‘proton tomography’



Plot courtesy of Christian Weiss

‘Stage 2’ of COMPASS GPD program

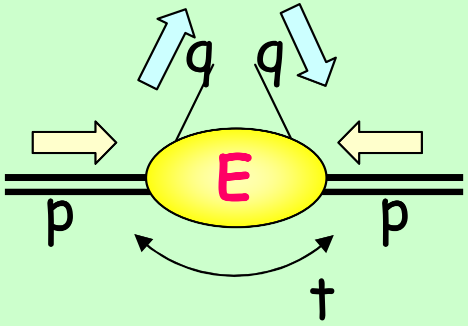
DVCS and HEMP with transversely polarised proton target (NH_3)

to constrain GPD E

- Contribution to the nucleon spin puzzle

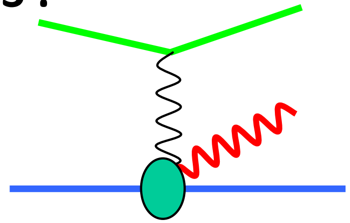
E related to the orbital angular momentum

$$J_q = \frac{1}{2} \int x \left(H^q(x,\xi,0) + E^q(x,\xi,0)\right) dx$$

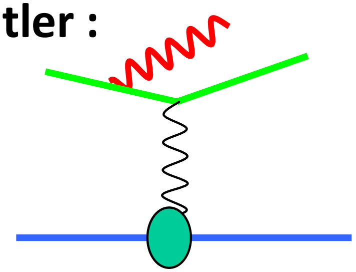


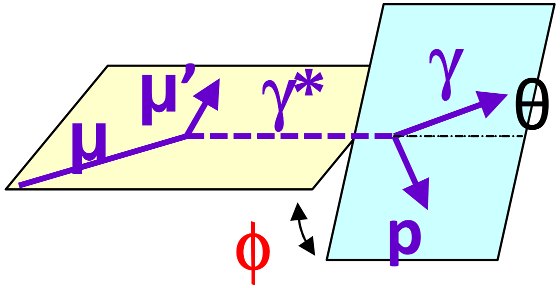
Interplay of DVCS and BH at 160 GeV

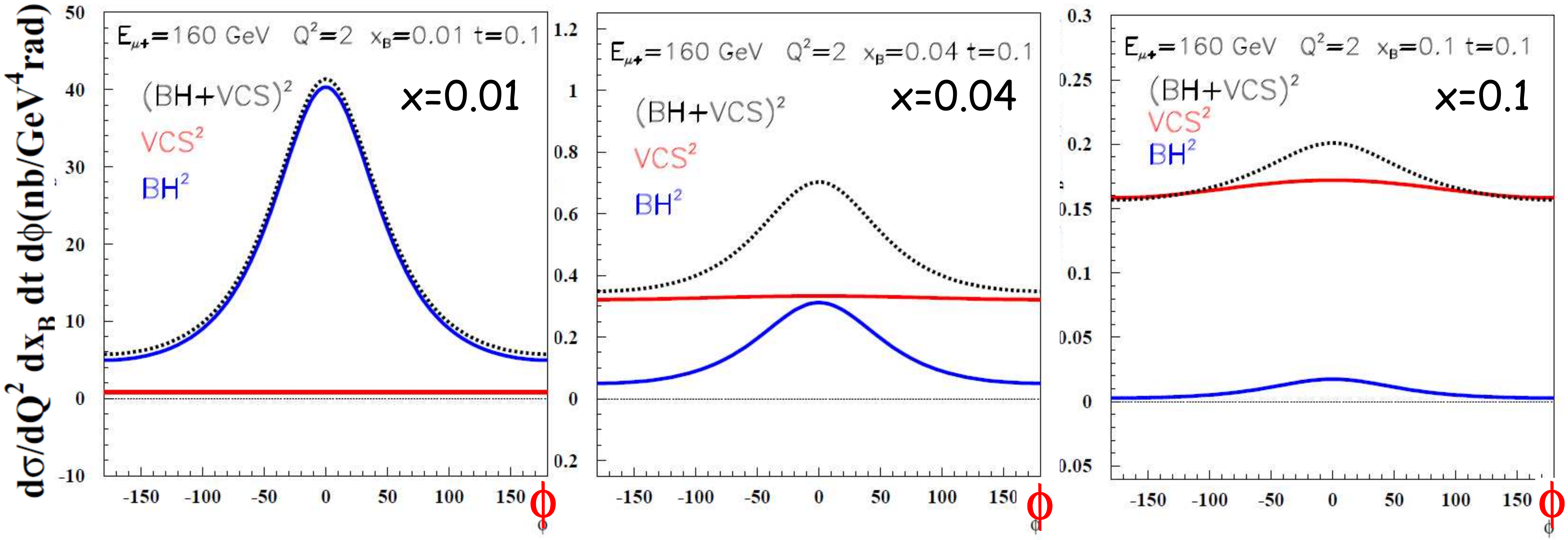
DVCS :



Bethe-Heitler :







BH dominates

excellent
reference yield

BH and DVCS at the same level

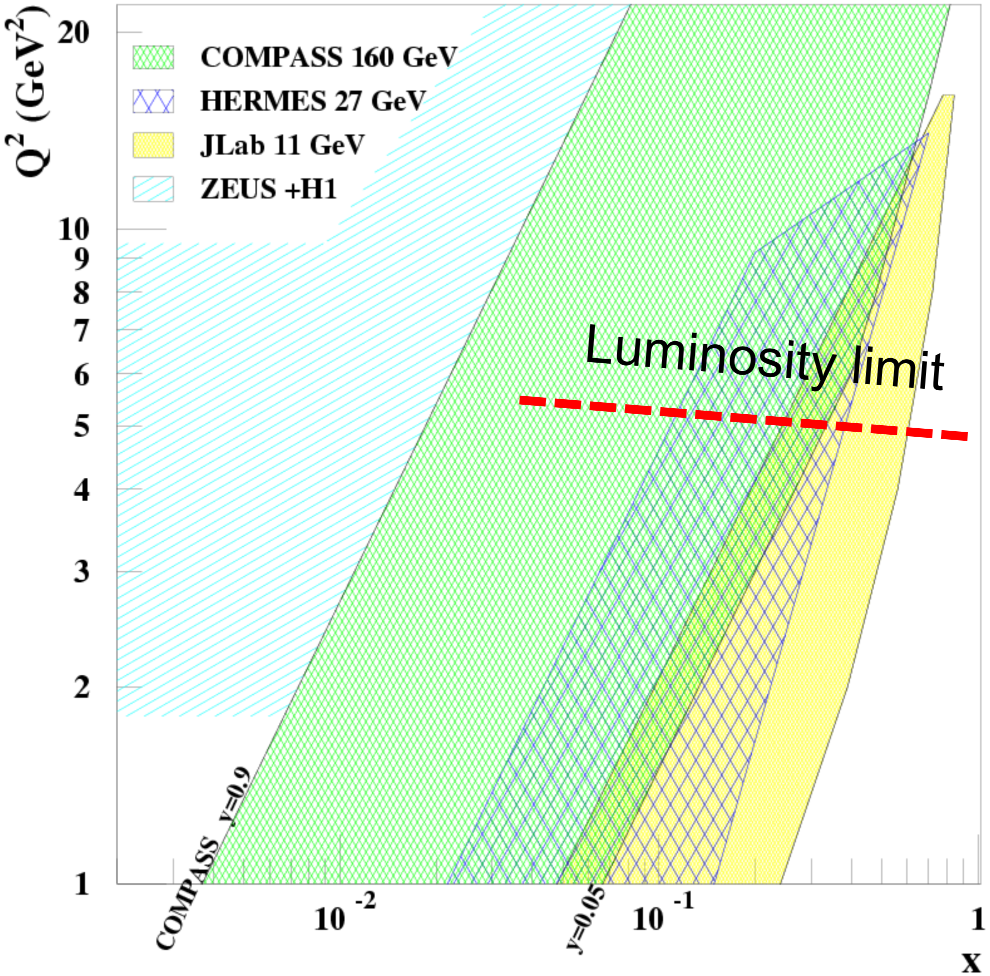
access to DVCS amplitude
through the interference

DVCS dominates

study of $d\sigma^{DVCS}/dt$

COMPASS kinematic coverage for DVCS

CERN SPS high energy polarised muon beams 100/190 GeV



with a 2.5m long LH_2 target
$L = 10^{32}$ cm^{-2} s^{-1}

$Q^2 \to 8$ GeV^2

$\to 16$ GeV^2 with possible luminosity increase by factor 4

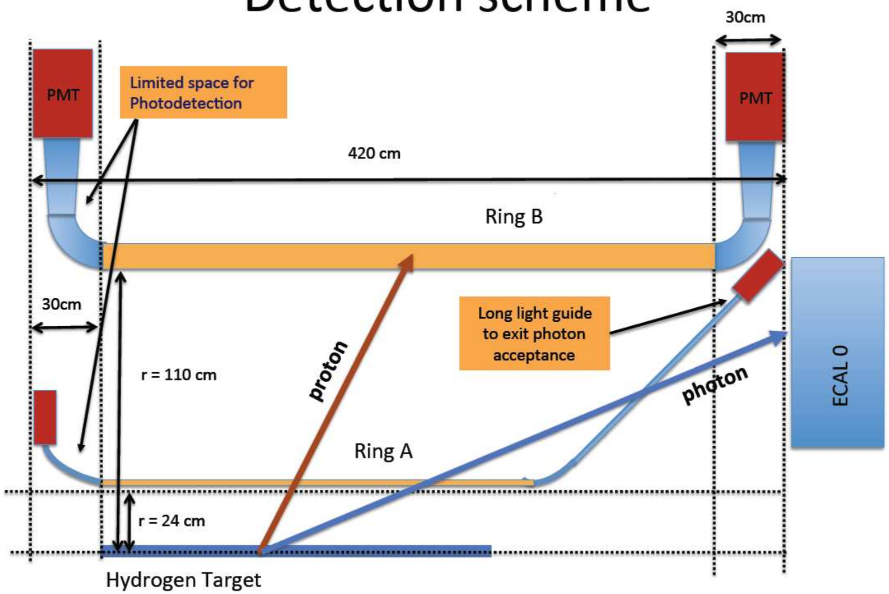
$\sim 10^{-2} < x < \sim 10^{-1}$

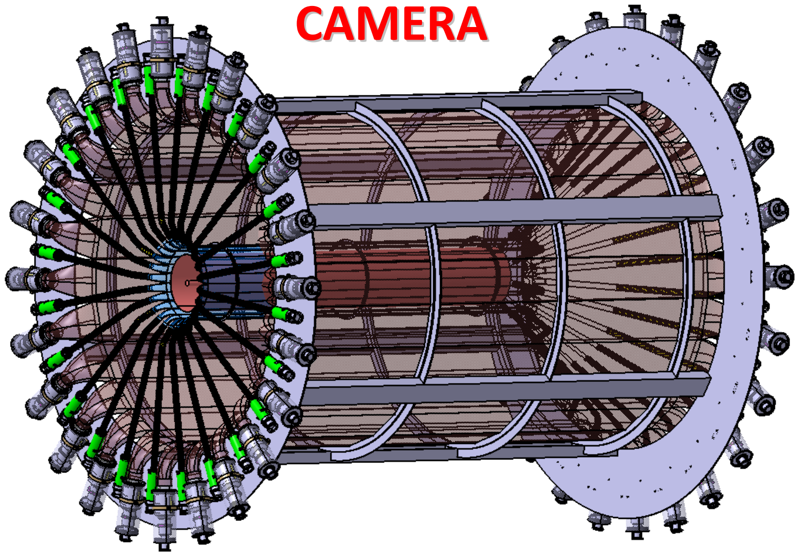
$x \to 0.20$ with an extension of present calorimetry

- COMPASS will be the only experiment in this range before availability of a new electron-hadron collider: eRHIC/ELIC (?) 2020+
- unique for several years, due to availability of lepton beams of both charges (for DVCS)

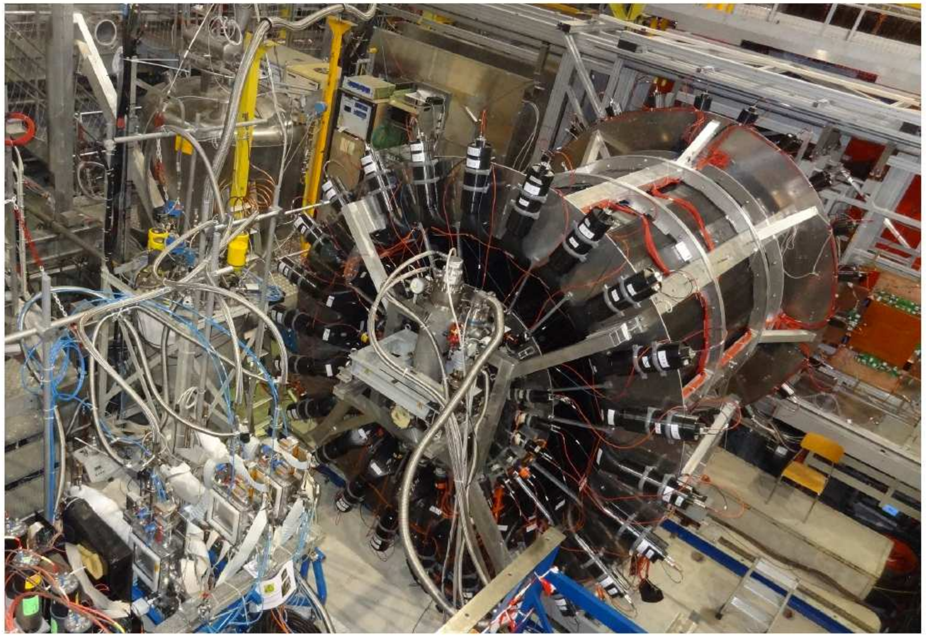
New developments - target and recoil detector

Detection scheme





Sept 26, ready for beam

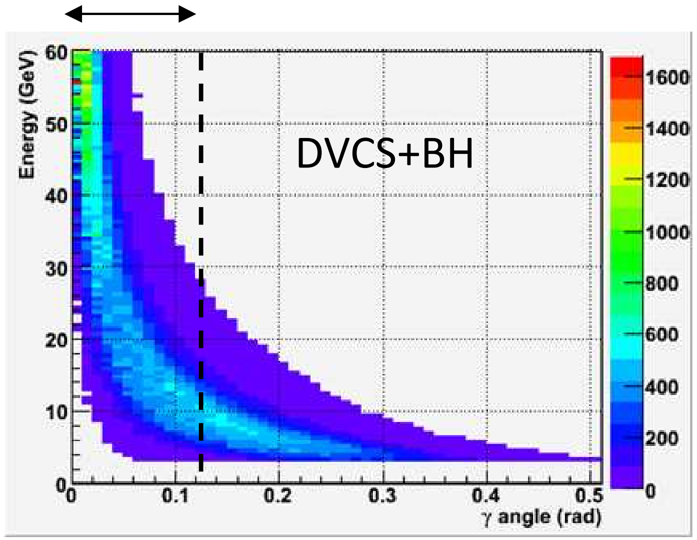


- 2.5m long LH target
- 4m long ToF barrel

  of 2 scintillator layers
- recoil proton ID by ToF and ΔE
- ≈ 300 ps time resolution
- full scale prototype tested

New developments - large-angle electromagnetic calorimeter ECAL0

existing
ECAL1&2



ECAL0 located downstream of CAMERA

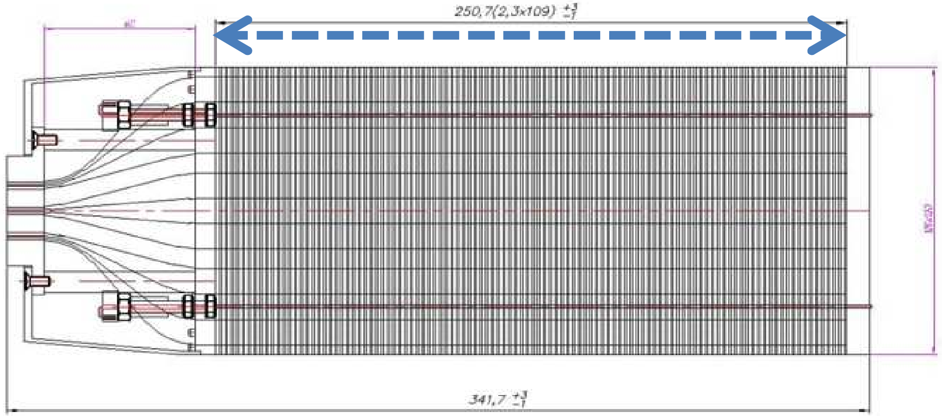
- transverse size 204x204 cm^2 (approx.)
- hole size 84x60 cm^2
- granularity 4x4 cm^2
- energy range 0.1 - 30 GeV
- polar angle range 0.15-0.5 rad
- insensitive to magnetic field

Total: 194 9-cell modules
1746 MAPDs and read out channels
the weight about 6 tons

Micropixel Avalanche Photo Diodes
3 x 3 mm², number of pixels ~ 135 000

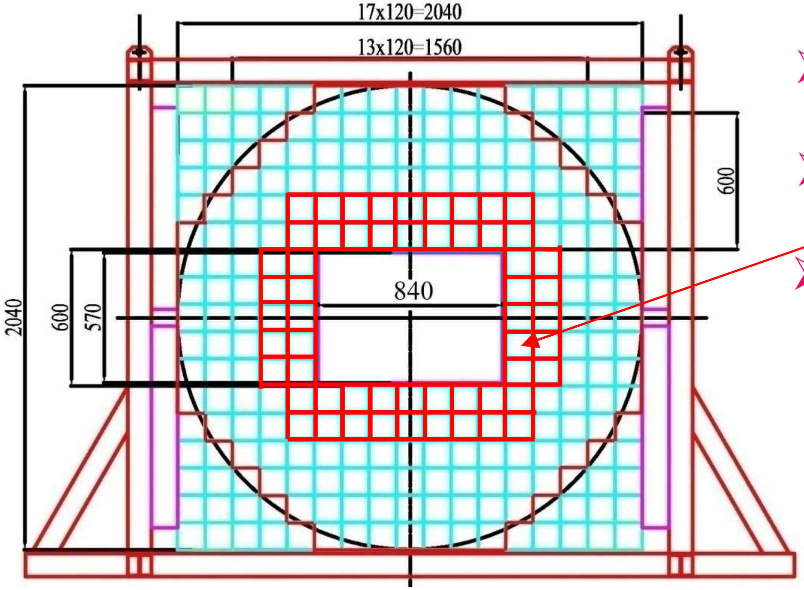
ECAL0 cell

252mm or 15 radiation length



shashlyk technology
109 plates made of Sc 1.5 mm /Pb 0.8 mm

Start of GPD program of COMPASS-II in 2012



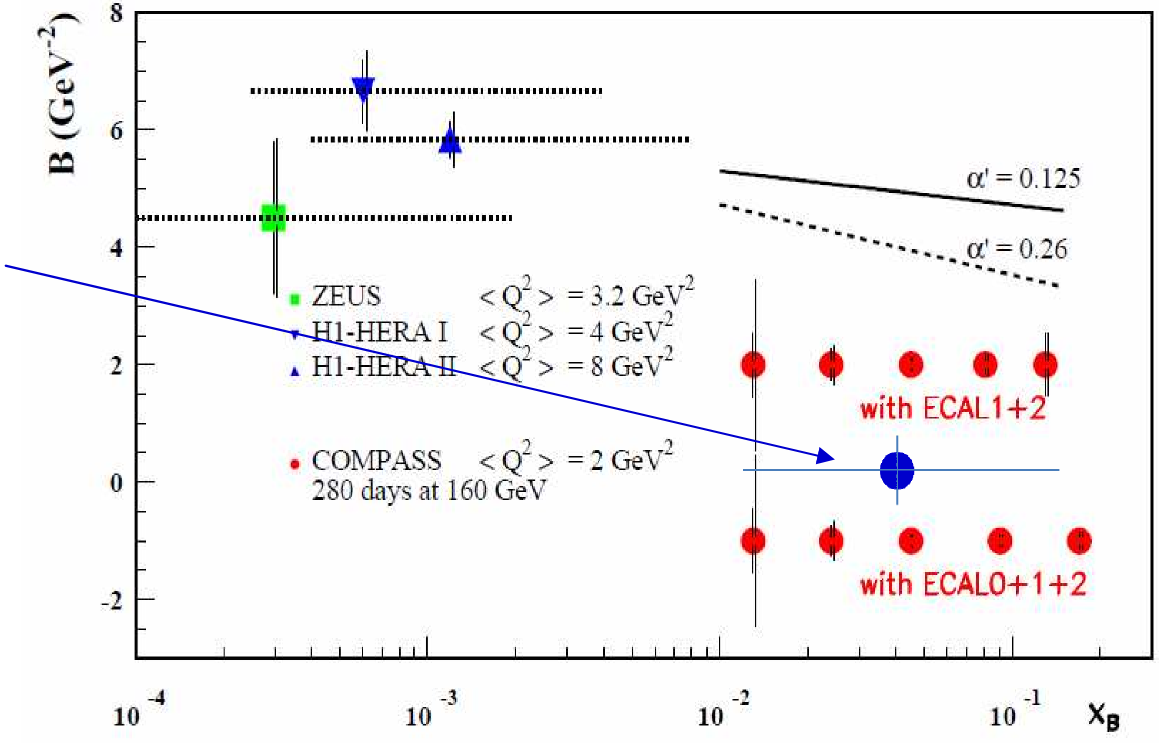
- 2.5m LH target and CAMERA ready in September 2012
- reduced ECAL0 (56 modules) at end of September 2012
- 4 weeks of comissioning and 4 of DVCS data taking

after 18 weeks of Primakoff measurements

- projection for a physics result

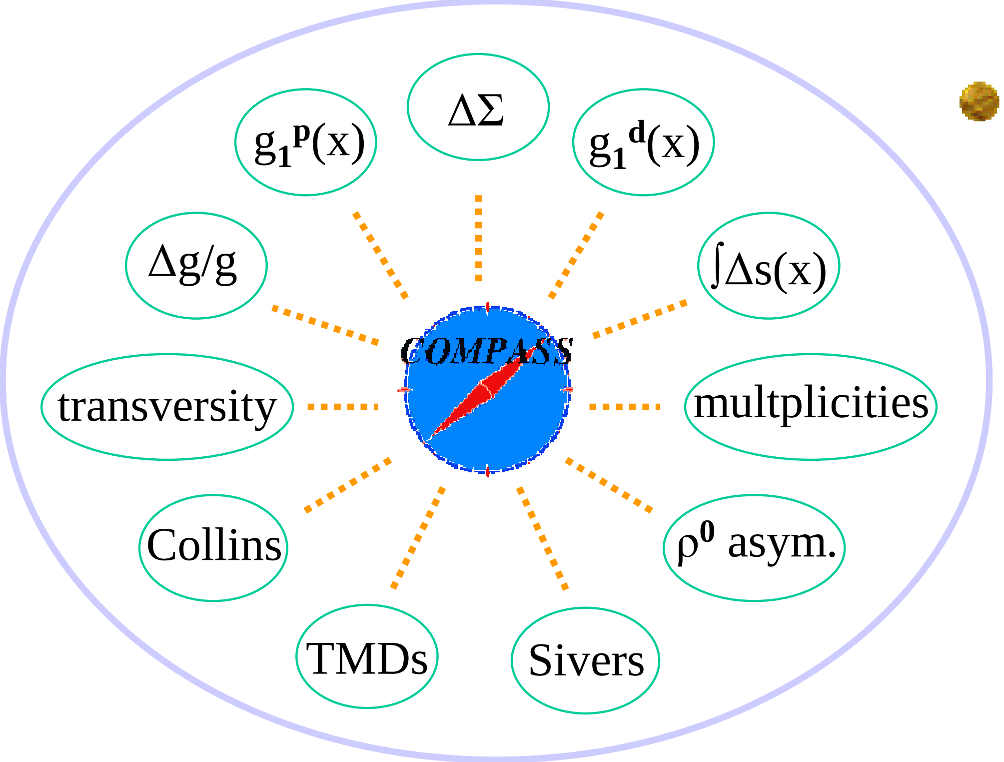
from 1 week of DVCS test in 2012

1/40 of the complete statistics



Complete GPD program of Stage 1 with complete ECAL0 scheduled for 2016-2017

Podsumowanie



- Bogaty plon 10-letniej działalności COMPASS-a

- Obiecująca perspektywa – COMPASS-II

Dziękuję