Spin dependent structure functions, TMDs and GPDs in COMPASS

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University of Warsaw

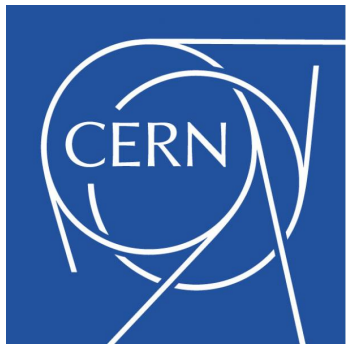
Low x

Rehovot/Eilat, May 30 – June 4, 2013

Outline

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

NA58, at the CERN SPS
$\sim$ 250 physicists
$\sim$ 30 institutes



Muon programme	Hadron programme
Spin dependent structure function g_1 Gluon polarisation in the nucleon Quark polarisation distributions Transversity Vector meson production Λ polarisation	Primakoff effect, π and K polarisabilities Exotic states, glueballs (Double) charmed barions Multiquark states
Future: Drell–Yan on a polarised target and DVCS	

Acceptance of high energy electroproduction experiments

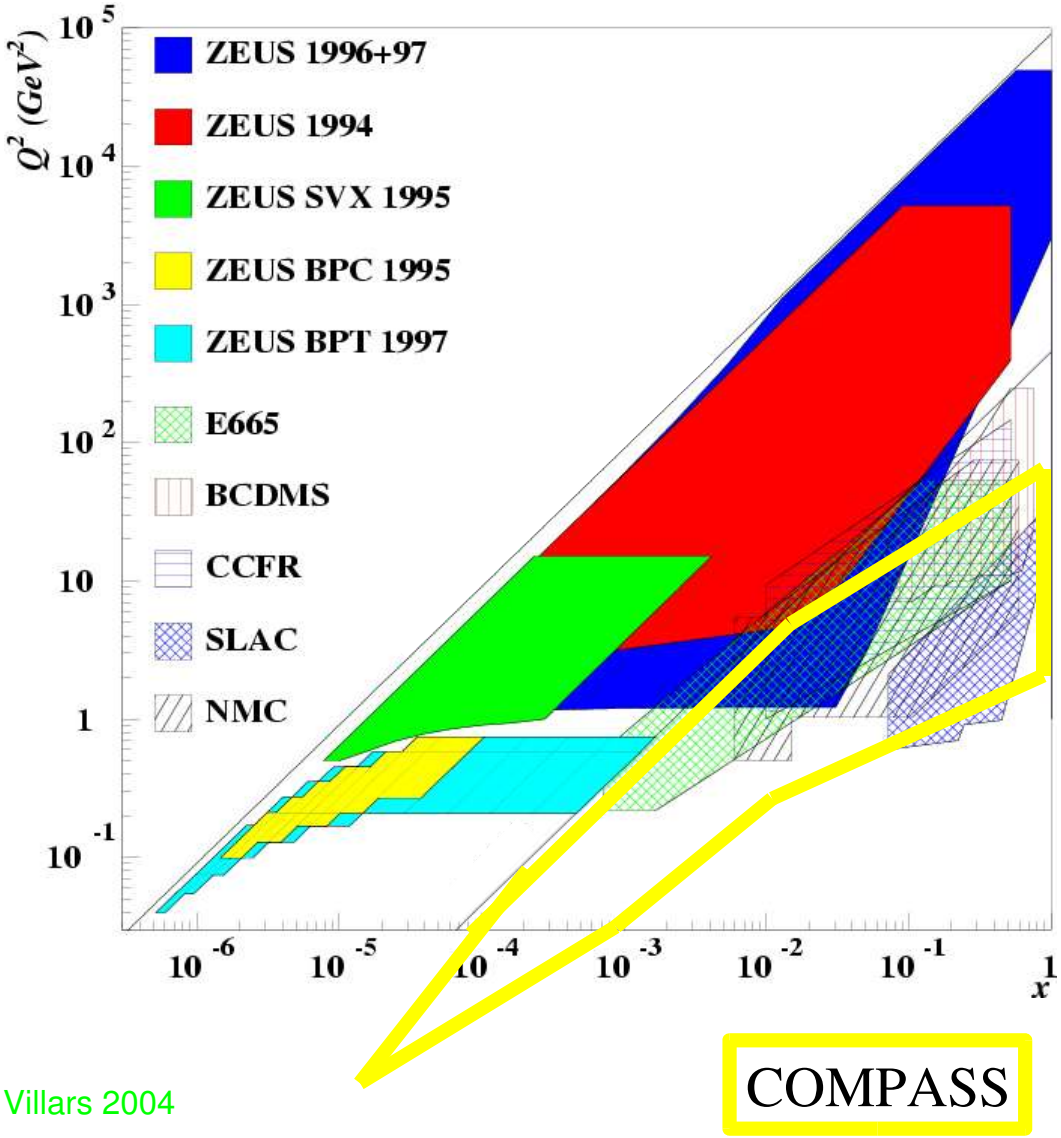
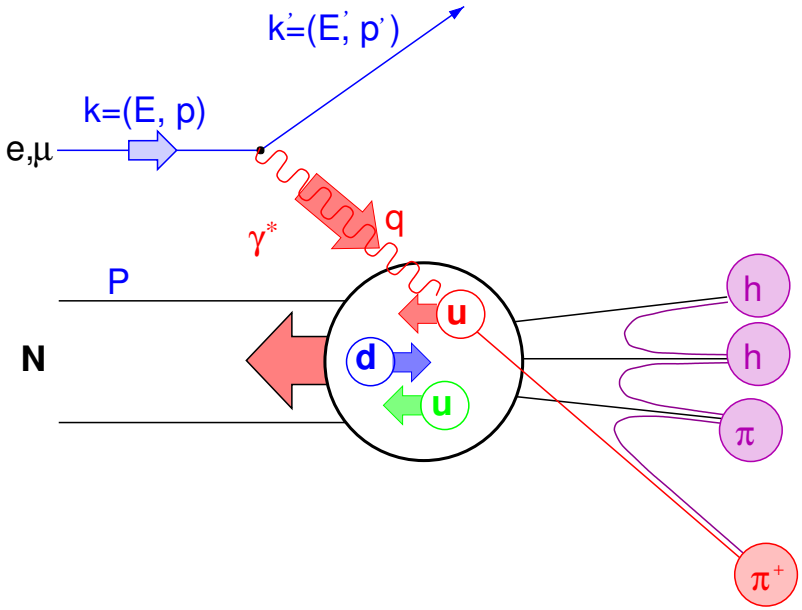


Figure from: N. D'Hose, Villars 2004

Outline

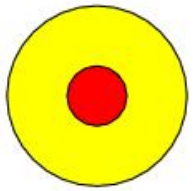
Nucleon spin structure in the electroproduction



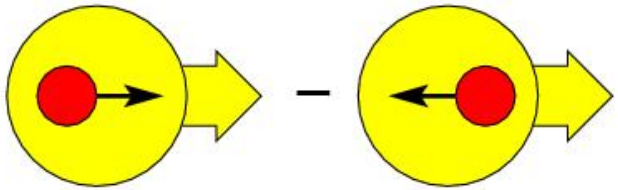
- $\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpol. DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}, \quad q(x) \longrightarrow g_{1,2}, \quad \Delta q(x)$ but...
- ...anomalous gluon contribution to $g_1(x)$
- ...$g_2(x)$ has no interpretation in terms of partons.

Partonic structure of the nucleon; distribution functions

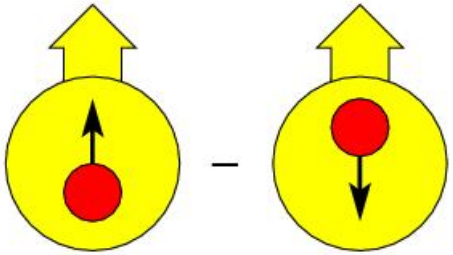
Three twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t)

$q(x) =$ 

Quark momentum DF;
well known (unpolarised DIS $\rightarrow F_{1,2}(x)$).

$\Delta q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known (polarised DIS $\rightarrow g_1(x)$).

$\Delta_T q(x) =$ 

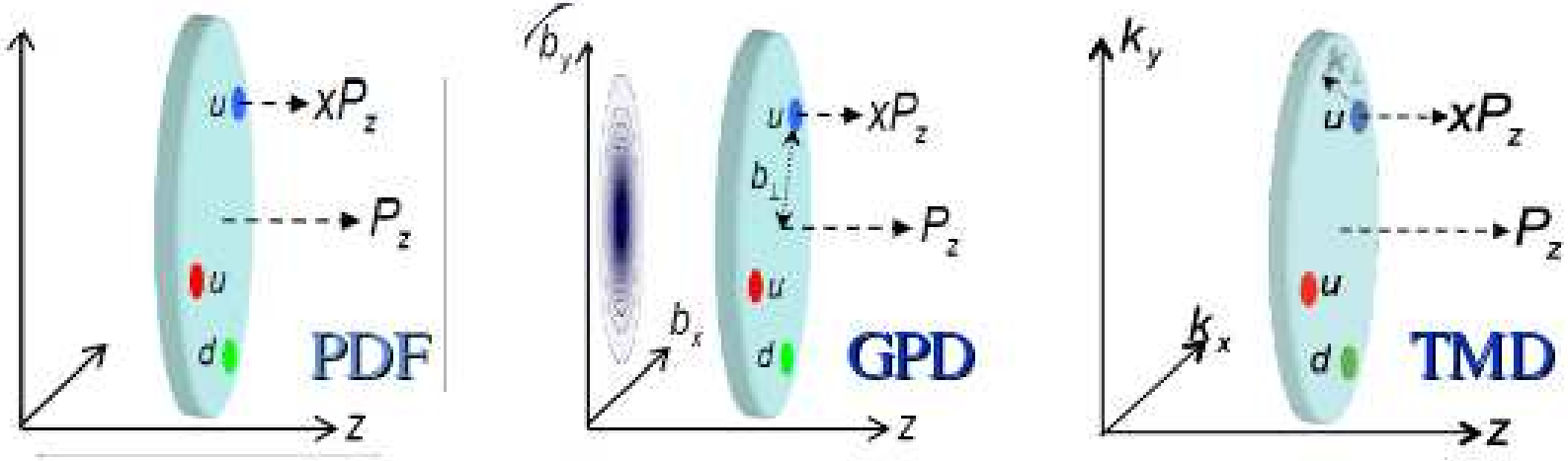
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
unknown (polarised DIS $\rightarrow h_1(x)$).

Nonrelativistically: $\Delta_T q(x) \equiv \Delta q(x)$. OBS.! $\Delta_T q(x)$ are C-odd and chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.

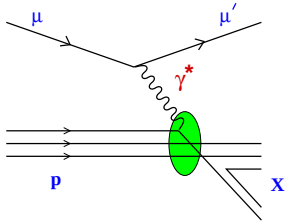
If the k_t taken into account $\Longrightarrow$ 8 TMD distr.; e.g. $f_{1T}^{\perp}$ (accessible through "Sivers asymmetry")

All determined in SIDIS by COMPASS.

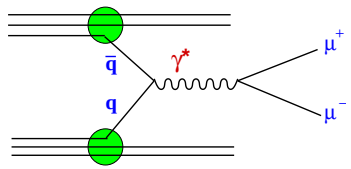
Transverse Momentum Dependent (TMD) distributions



- parton intrinsic k_{T} taken into account
- related to quark angular momentum, L!
- at COMPASS studied in 2 ways:
  - semi-inclusive DIS (polarised muons on unpolarised/transversely polarised target)
  - In the future: Drell-Yan process (π beam on unpolarised/transversely polarised tgt.)



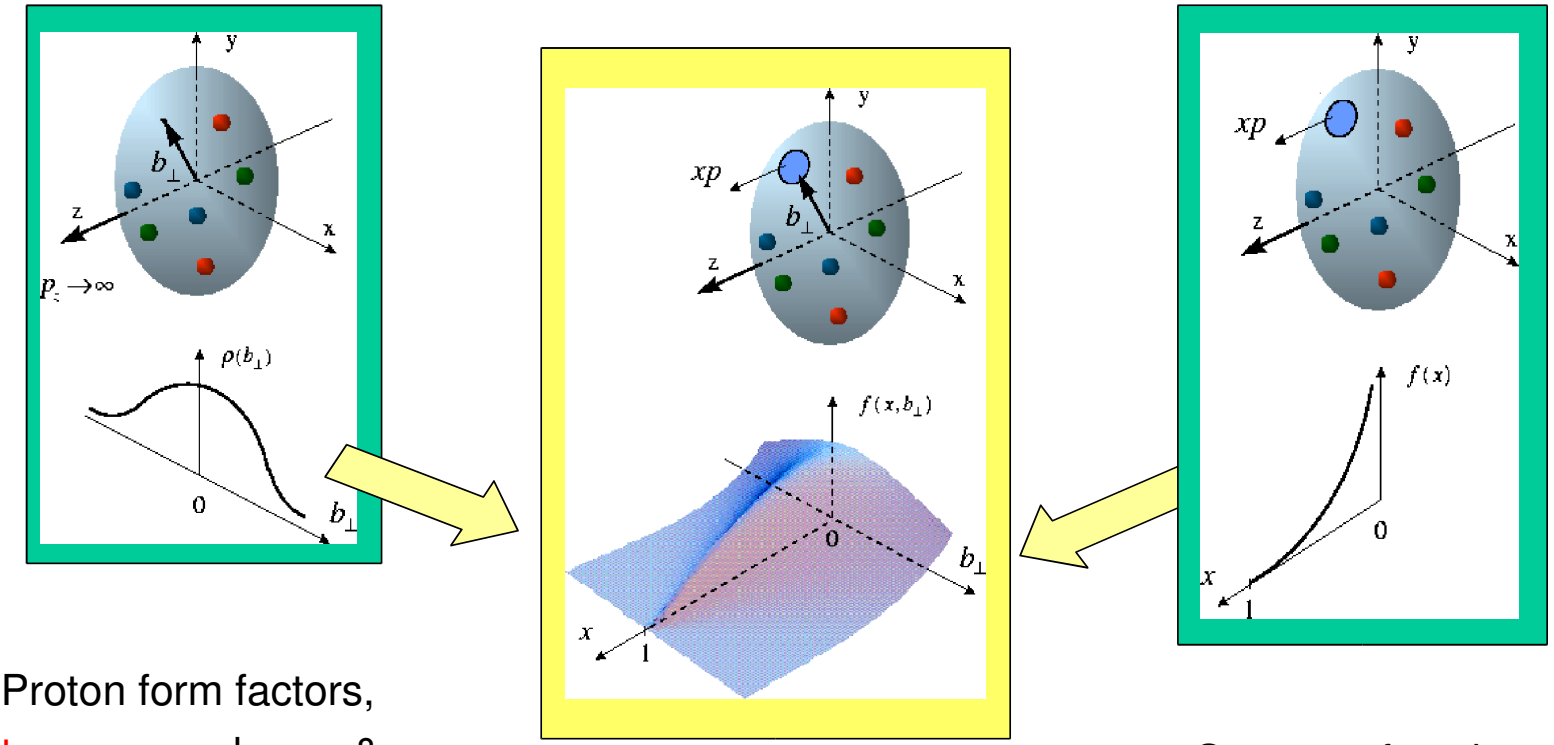
SIDIS



DY

3D picturing of the proton *via* GPD

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

Slide from V.D. Volker, LANL 2007

Nucleon spin structure: observables in $\vec{\mu}\vec{\mathrm{N}}$ scattering

- Inclusive asymmetry, A_{meas}:

$$A_{meas} = \frac{1}{f P_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\rightleftarrows}}{N^{\leftrightarrows} + N^{\rightleftarrows}}\right) \approx D A_1 = D\,\frac{g_1(x,Q^2)}{F_1(x,Q^2)} = D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

$$\Delta q = q^+ - q^-, \quad q = q^+ + q^-, \qquad g_1^d = g_1^N(1 - \frac{3}{2}\omega_D) = \frac{g_1^p + g_1^n}{2}(1 - \frac{3}{2}\omega_D);$$

$$\omega_D = 0.05 \pm 0.01$$

- At LO, semi–inclusive asymmetry, A_1^h:

$$A_1^h(x,z,Q^2) \approx \frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)} \qquad z = \frac{E_h}{\nu} \qquad D_q^h \neq D_{\bar{q}}^h$$

Outline

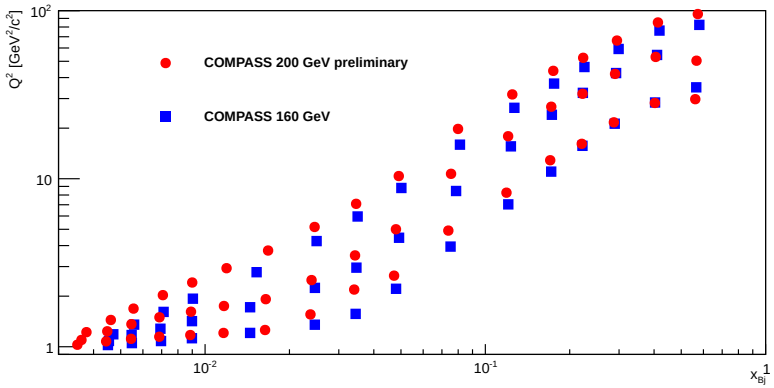
New, 2011 muon–proton data,

Taken at 200 GeV (160 GeV until then) to balance the amount of deuteron target data and thus:

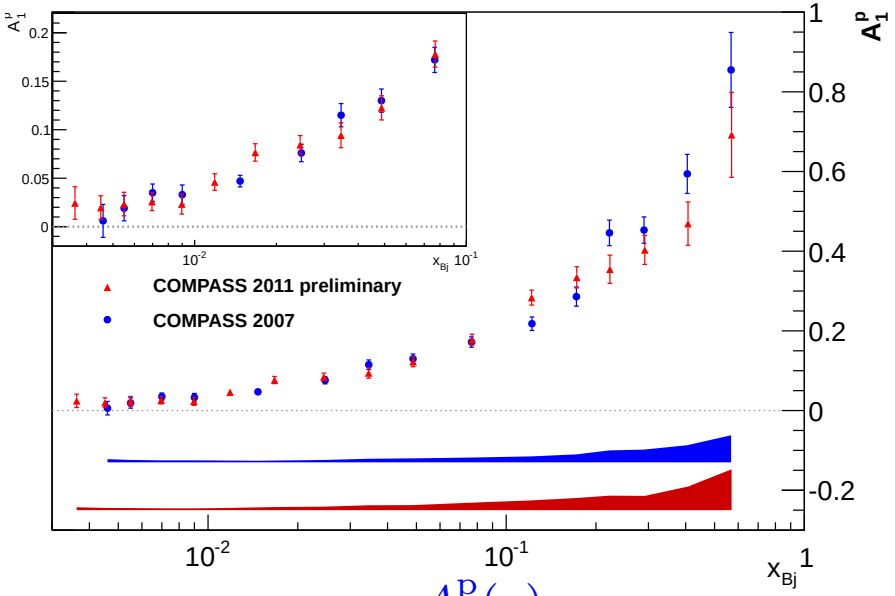
- to increase precision of the Bjorken sum determination, i.e. a precision of:

$$\int_{0.004}^{0.7} g_1^{\mathrm{NS}}(x)dx, \qquad g_1^{\mathrm{NS}} = g_1^{\mathrm{p}} - g_1^{\mathrm{n}} = 2g_1^{\mathrm{p}} - \frac{g_1^{\mathrm{d}}}{1 - \frac{3}{2}\omega_{\mathrm{D}}}, \qquad \omega_{\mathrm{D}} \approx 0.05$$

- to extend the range and increase precision of g_1^{p} measurements at low x
- better constrain the strange quark polarisation, Δs

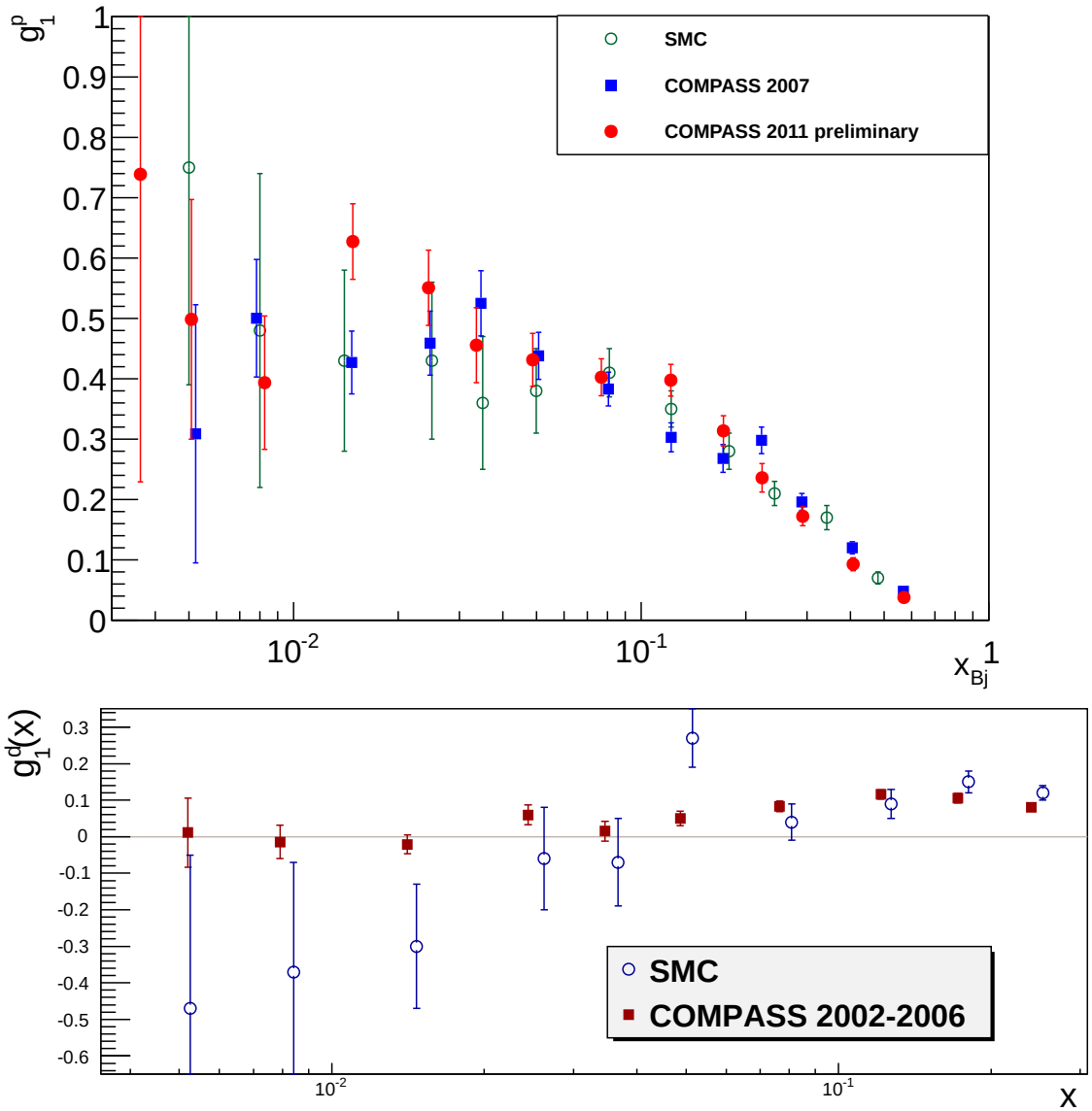


Q^2 vs x



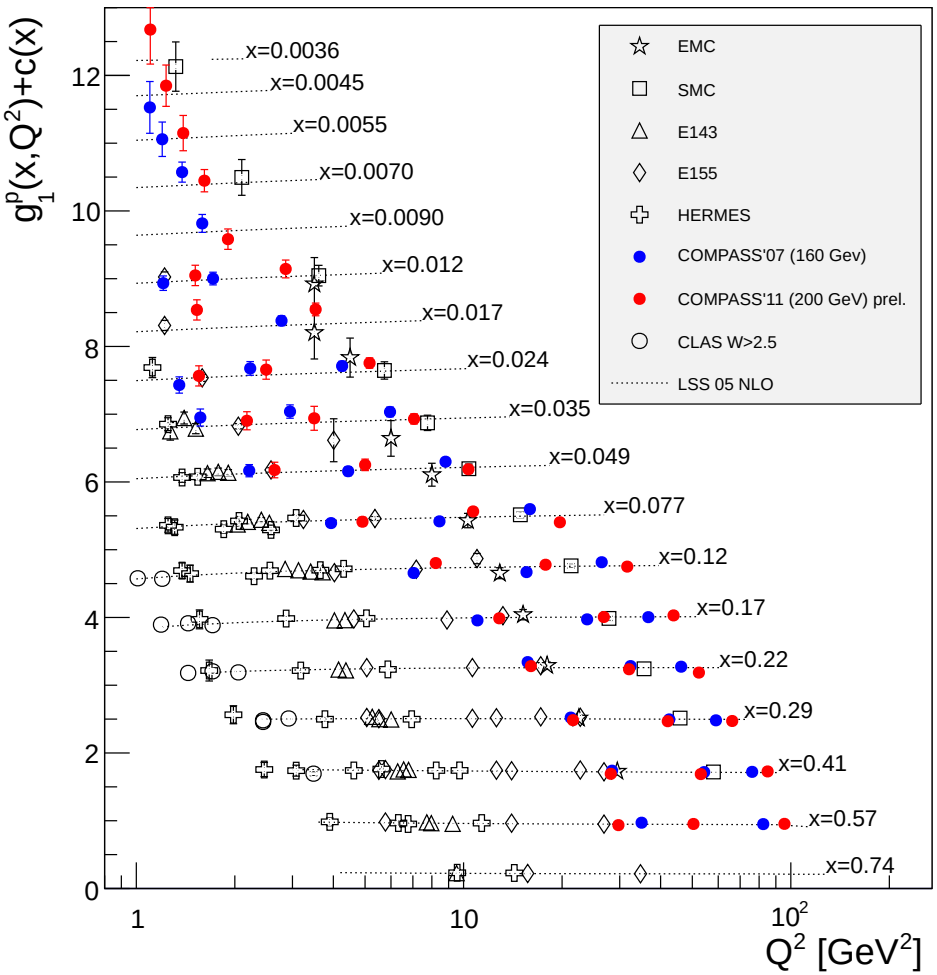
$A_1^{\mathrm{p}}(x)$

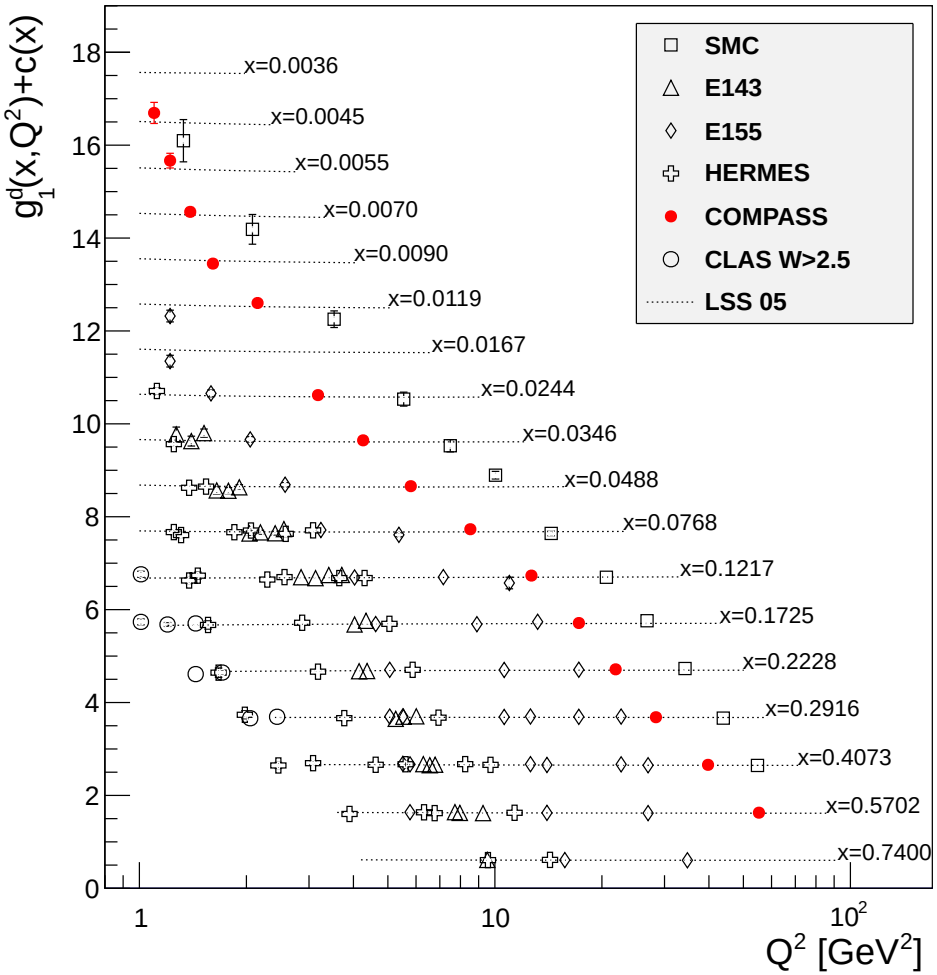
Structure functions g_1^p and g_1^d at low x



$g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)^2

NEW: proton data 2011 (preliminary); full deuteron statistics





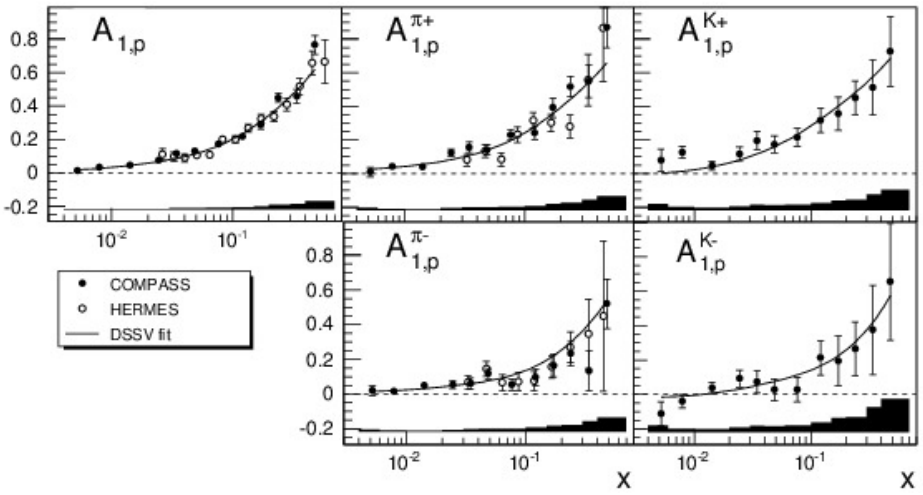
COMPASS measurements at high Q^2 important for the QCD analysis! but little sensitive to Δg

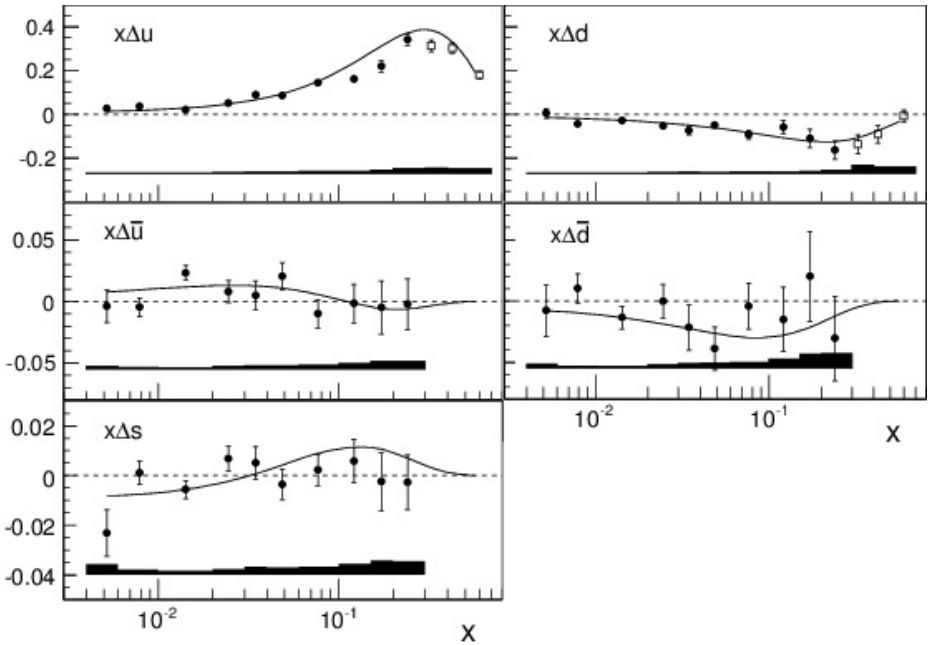
Semi-inclusive asymmetries and parton distributions

- Measured on both proton and deuteron targets
- for identified, positive and negative pions and (for the first time) kaons

COMPASS, Phys. Lett. B **680** (2009) 217

DSSV, Phys. Rev. D **80** (2009) 034030

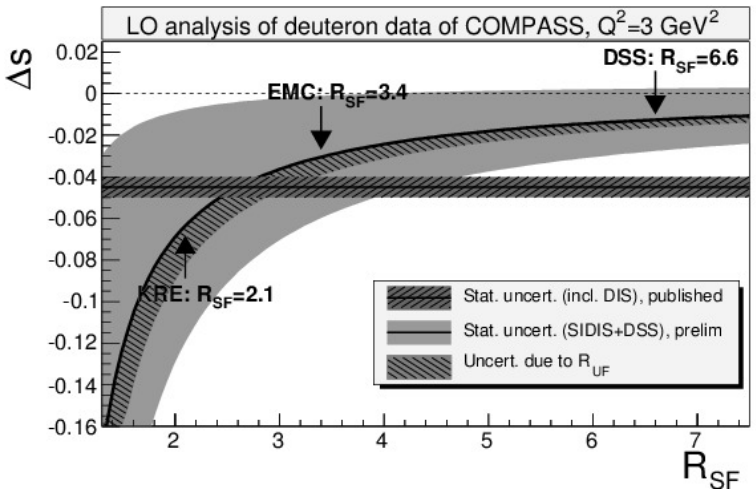


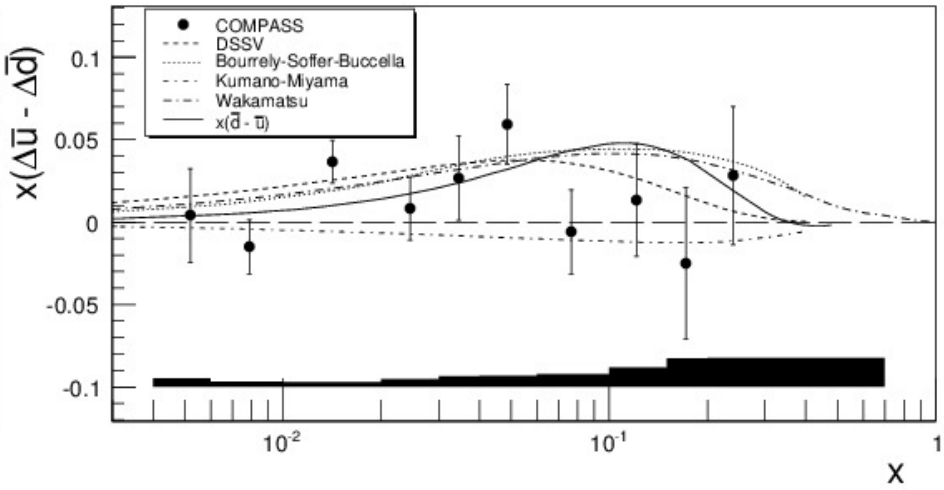


- LO DSS fragmentation functions and LO unpolarised MRST pdf assumed here.
- NLO parameterisation of DSSV describes the data well.

Polarisation of quark sea

- Δs puzzle. Strange quark polarisation:
  $2\Delta S = \int_0^1 (\Delta s(x) + \Delta \bar{s}(x))dx = -0.09 \pm 0.01 \pm 0.02$ from incl. asymmetries + SU_3,
  while from semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_{u}^{K^+}(z)dz}$
  $\Longrightarrow$ plan to extract it from COMPASS data on multiplicities.



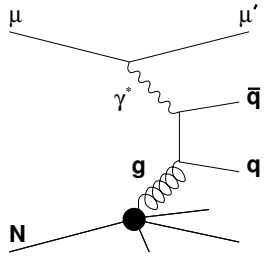


- The sea is not unsymmetric: COMPASS, Phys. Lett. B, **680** (2009) 217; ibid., **693** (2010) 227.
  $\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \;\; @ \;\; Q^2 = 3 \text{ (GeV/}c)^2$
  Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

Outline

Direct measurement of $\Delta g(x)$

Direct measurements – *via* the cross section asymmetry
for the photon–gluon fusion (PGF) with subsequent fragmentation into:

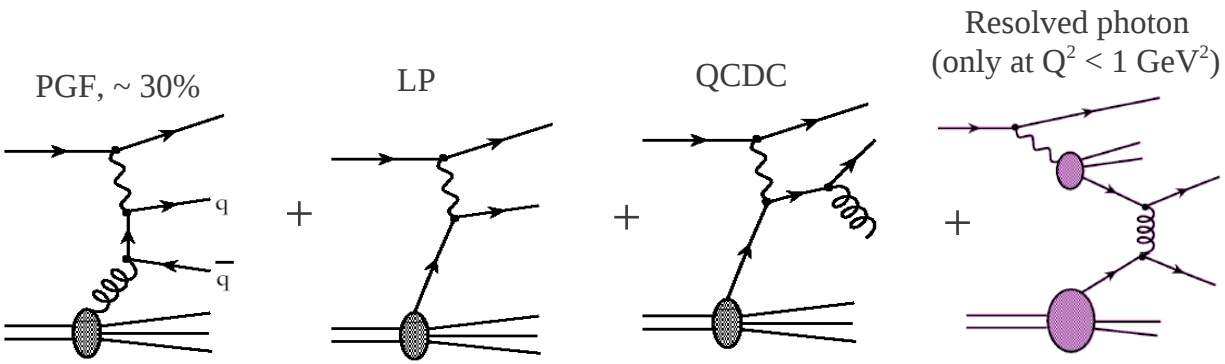


- charm mesons, q≡c, (max. @ low Q^2, perturbative scale: e.g. m_c): low statistics, few theoretical assumptions;

$$A_{meas} = p_B\, p_T\, f\, a_{LL}\, \frac{\sigma_{PGF}}{\sigma_{PGF} + \sigma_{BGD}}\, \frac{\Delta g}{g} + A_{BGD}$$

- a pair of hadrons of large p_T, q≡u, d, s, separately for low- and high Q^2 (perturbative scale: e.g. p_T): high statistics, several quantities from MC. At LO, for both 2-hadron and inclusive samples:

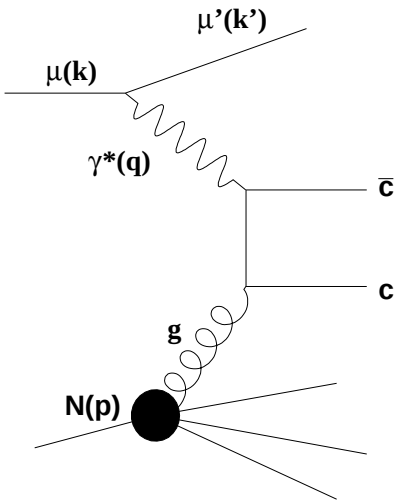
$$A_{meas} = p_B\, p_T\, f \left[R_{PGF} \cdot a_{LL}^{PGF} \cdot \frac{\Delta g}{g} + R_{LP} \cdot D \cdot A_1^{LP} + R_{QCDC} \cdot a_{LL}^{QCDC} \cdot A_1^{LP} \right]$$



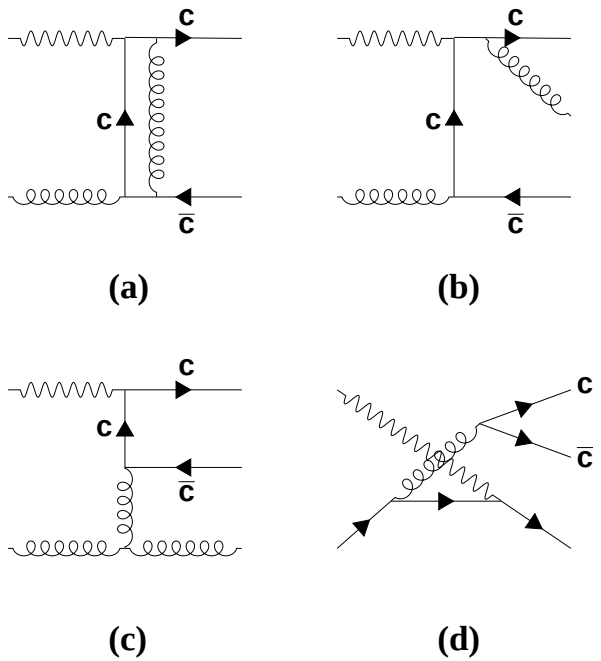
COMPASS NLO analysis of gluon polarisation

Based on I. Bojak and M. Stratmann, PL B**433** (1998) 411; NP B **540** (1999) 345; I. Bojak, PhD, hep-ph/0005120.

LO



Examples of NLO



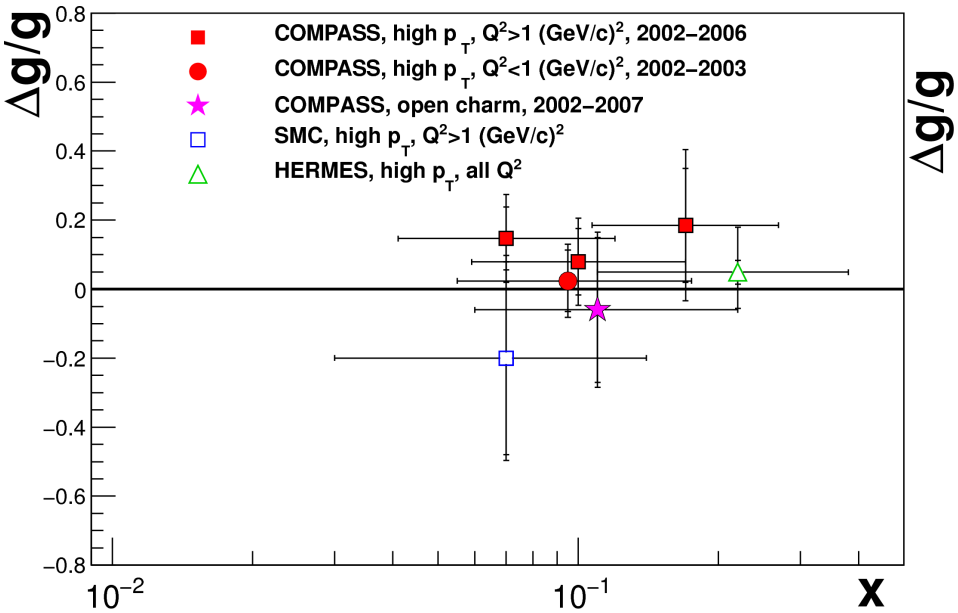
- AROMA with parton showers ON used for (event-by-event) simulation of PhSp for NLO
- Background NLO processes (e.g. diagram (d)) corrected for ($A_{\rm corr}$)
- $a_{\rm LL}^{\rm NLO}$ calculated event-by-event

$$A^{\gamma \rm N} = \frac{a_{\rm LL}}{D}\frac{\Delta g}{g} + A_{\rm corr}$$

Summary of $\langle \Delta g/g \rangle$ from COMPASS

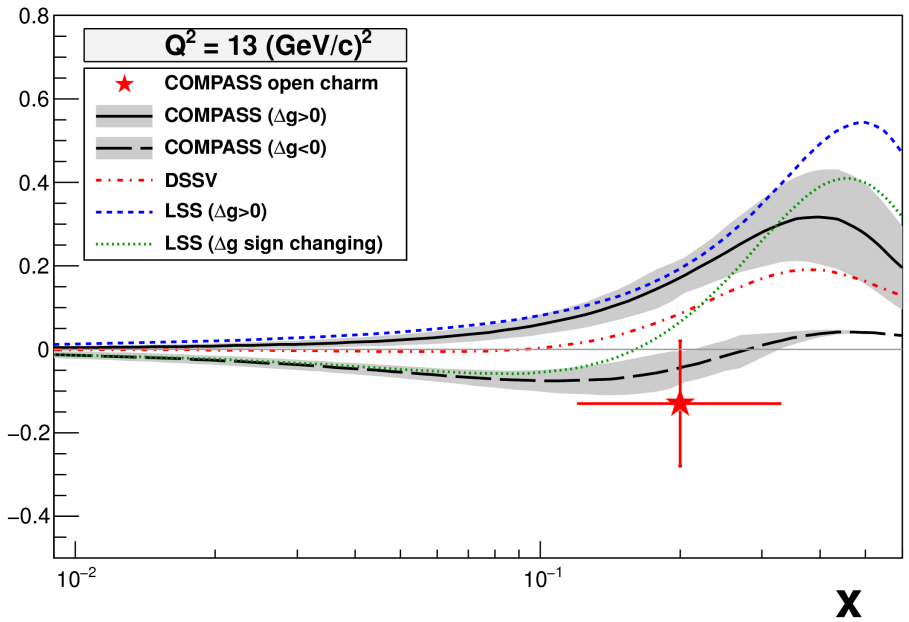
- All LO QCD data consistent and point toward small $\langle \Delta g/g \rangle$. ΔG also small ?
- Data do not permit to determine a sign of $\Delta g/g$.
- NLO QCD result of COMPASS, at $\langle x \rangle \approx 0.20$, influences a $\Delta g(x) > 0$ fit, reducing $\Delta G = 0.39 \pm 0.07$ (stat.) to 0.24 ± 0.09 (stat.) at Q^2 = 3 (GeV/c)^2.
- $\langle x \rangle^{\mathrm{NLO}} > \langle x \rangle^{\mathrm{LO}}$

LO



COMPASS, Phys. Lett. B **718** (2013) 922;

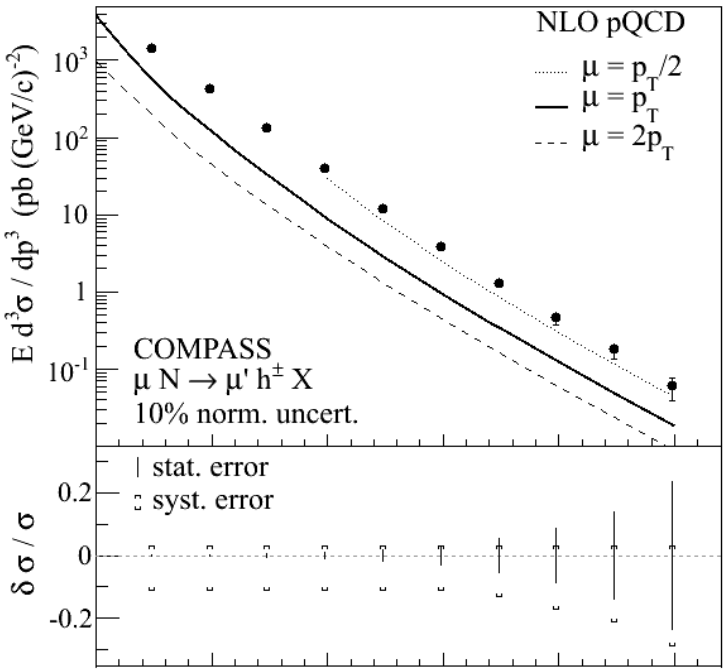
NLO

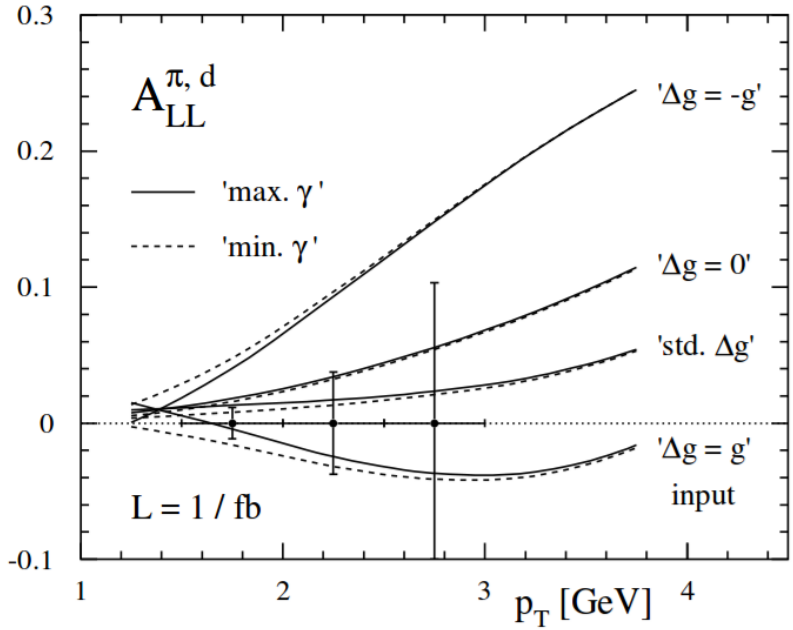


Phys.Rev. D **87** (2013) 052018

High-p_T hadron photoproduction

- Measured cross-section COMPASS hep-ex/1207.2022:
  Q^2 <0.1 (GeV/c)^2, -0.1 < $\eta_{\rm CMS}$ <2.4, $p_{\rm T}$ < 3.6 GeV/c.
- Photoproduction of inclusive hadrons at NLO QCD for the COMPASS kinematics
  B. Jäger, M. Stratmann and W. Vogelsang,EPJ C**44** (2005) 533.
- In perspective: constraining the Δg by the QCD calculations of the single high-$p_{\rm T}$ hadron asymmetries





NLO QCD calculations and

perspectives for COMPASS for 1/4 of its luminosity.

Outline

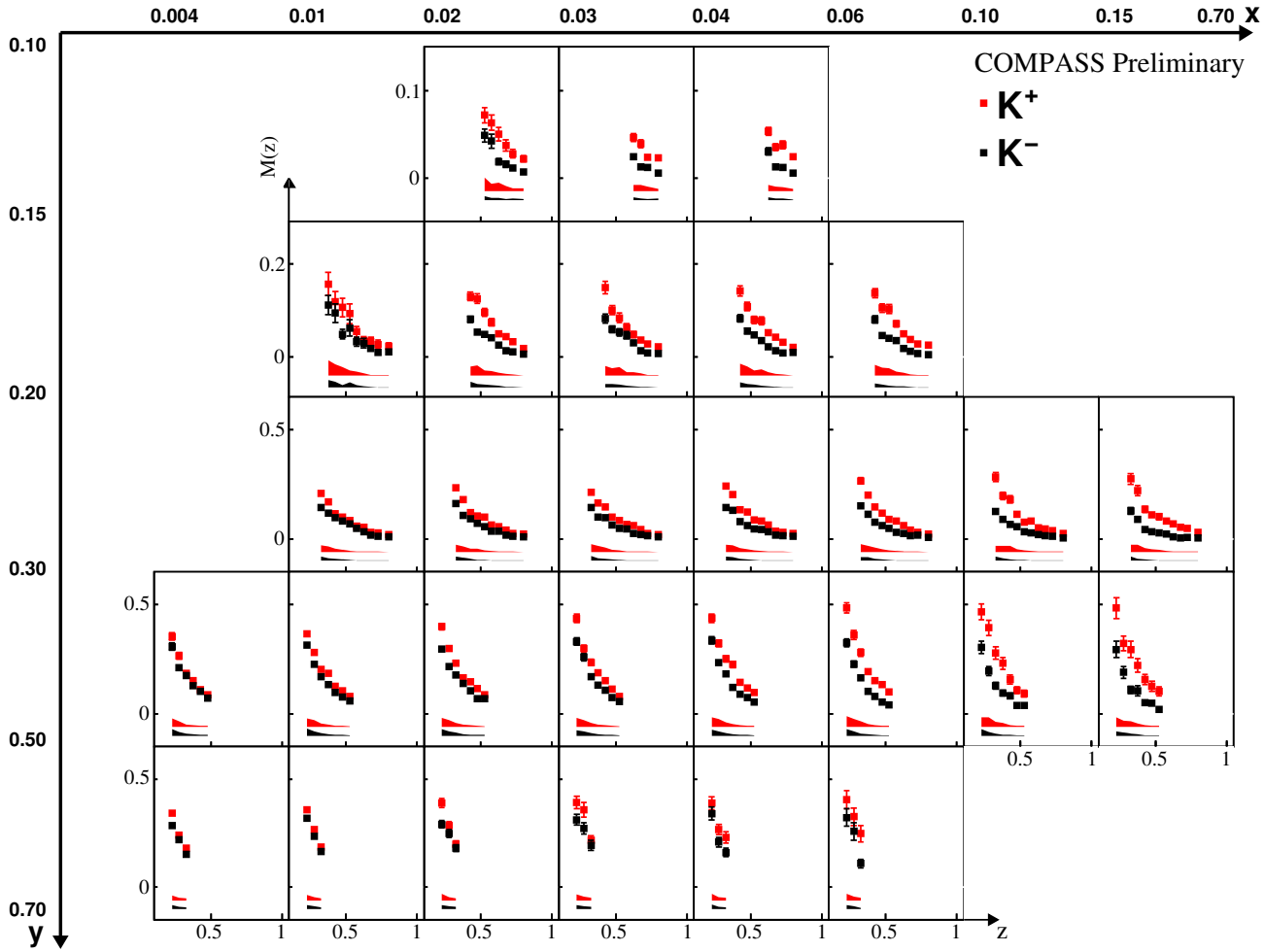
Charged (single-) hadron multiplicities,

- Studied to measure fragmentation functions (FF), $D_q^h(z, Q^2)$ ($\Longrightarrow$ cf. Δs).
  At LO:

$$M^h(x,z) = \frac{\frac{d\sigma_{\rm SIDIS}}{dxdz}}{\frac{d\sigma_{\rm DIS}}{dxdz}} = \frac{\Sigma_q e_q^2 \left[q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right]}{\Sigma_q e_q^2 \left[q(x) + \bar{q}(x)\right]}$$

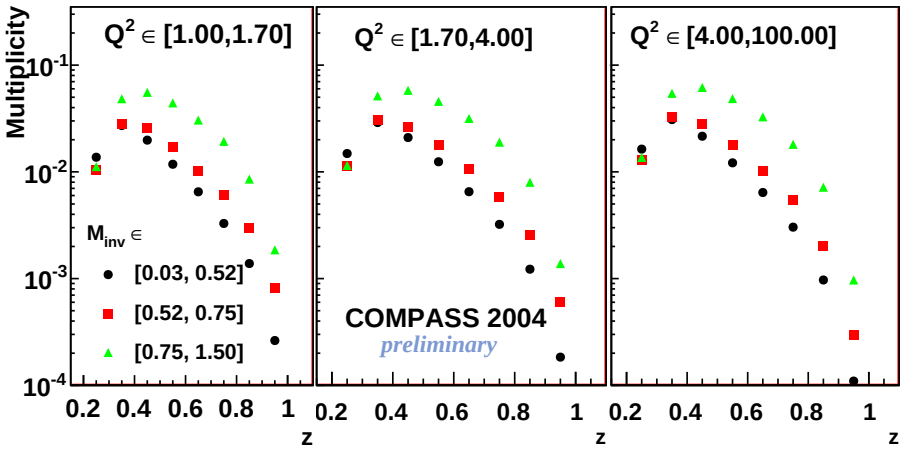
- Until now:
  - High precision Single Inclusive e^+e^- Annihilation data
    do not separate q and $\bar{q}$ and only access charge sum of FF for a hadron h.
  - Measurements at a fixed, large ($\sim M_Z$), scale,
    except BELLE (Q^2 ~10 GeV^2).
  - Inclusive single hadron production by RHIC $\Longrightarrow$ improve constraints on gluon FF.
  - Lepton–nucleon DIS: lower values and wide range of scales, sensitivity to parton flavour and hadron charge ($\Longrightarrow$ new data of HERMES).
  - Global NLO analyses, e.g.: DSS, Phys. Rev. D **75** (2007) 114010.
- New COMPASS results obtained on an isoscalar (d in ^{6}LiD) target (nuclear effects in ^{6}LiD small)...
- ...with K and π identification and measured x, y, z dependence.

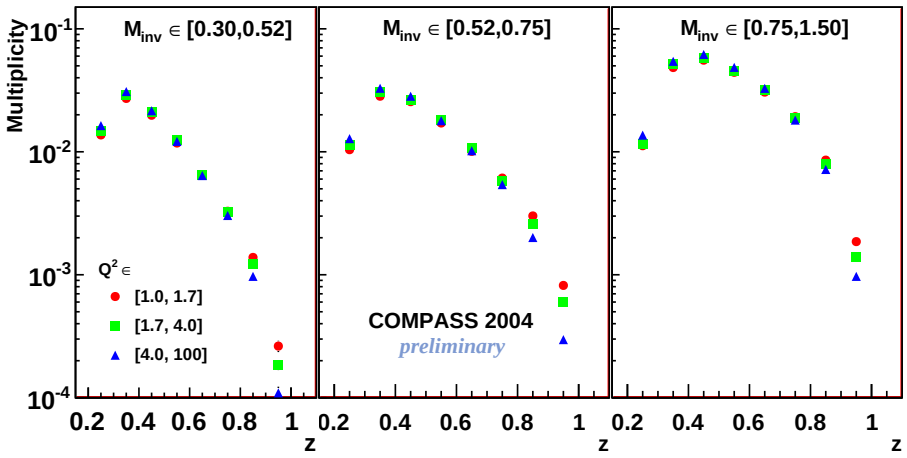
Charged (single-) hadron multiplicities; identified kaons



Charged (double-) hadron multiplicities

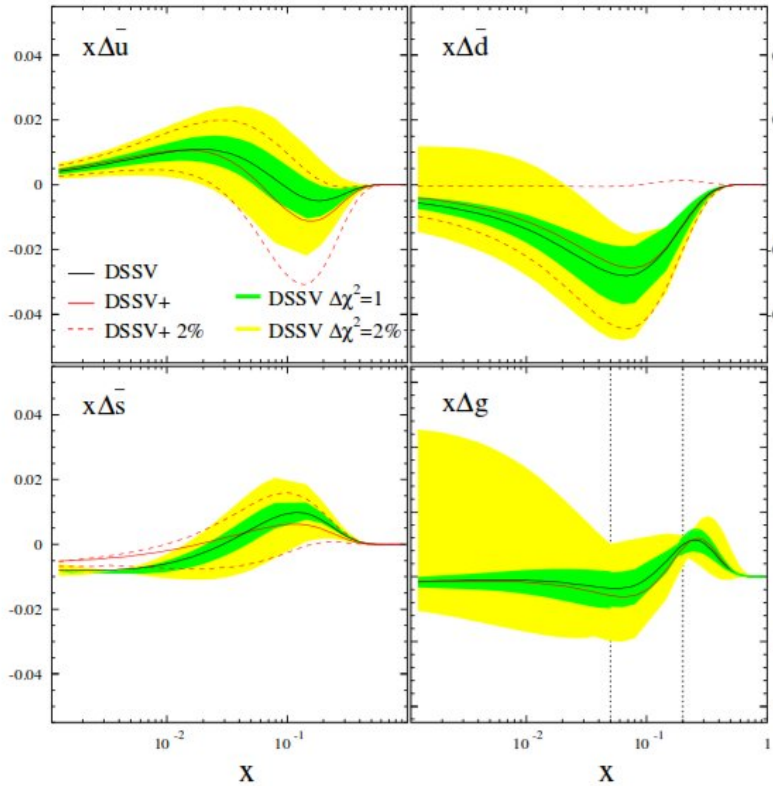
- Studied to measure $D_q^{h^+,h^-}(z^+, z^-, Q^2) = D_q^h(z, M_h^2, Q^2)$
- Needed in extracting asymmetries in SIDIS, e.g.: $A_{UT}^{\sin(\phi_R+\phi_S)}(z, M_h^2, Q^2)$
- Measured by COMPASS on d from LiD in bins of (z, M_h^2, Q^2).



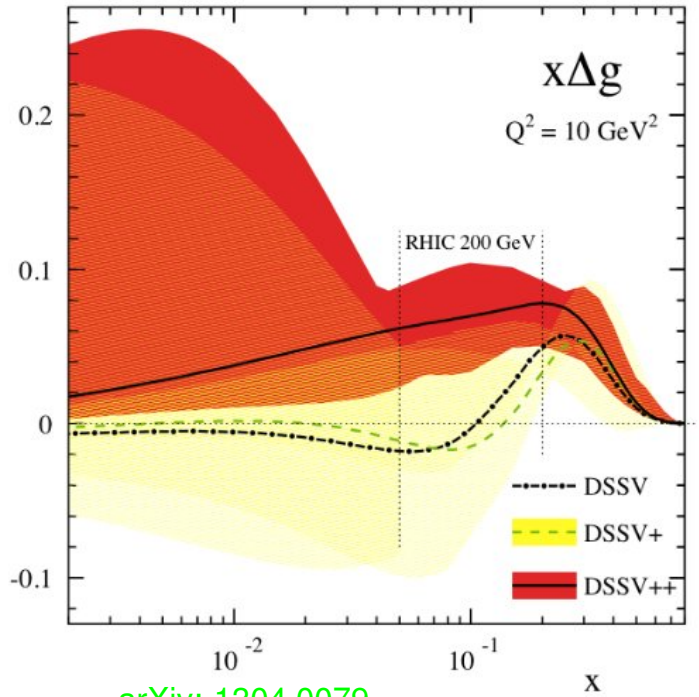


Status of helicity-dependent PDFs

- Global fits (DSSV/DSSV+/DSSV++) include: spin-dependent DIS data, SIDIS data with identified π and K, and proton-proton data $\Longrightarrow$ extracting PDFs at NLO. L_q and L_g decouple from this procedure $\Longrightarrow$ TMDs and GPDs ?.
  - Limited (x, Q^2) range $\Longrightarrow$ hard to get Δg from DIS
  - Separation of $q(x)$ and $\bar{q}(x)$ exclusively from SIDIS $\Longrightarrow$ FF needed!
    $\Longrightarrow$ COMPASS data crucial ($x_{\min} \approx 5 \cdot 10^{-3}$).

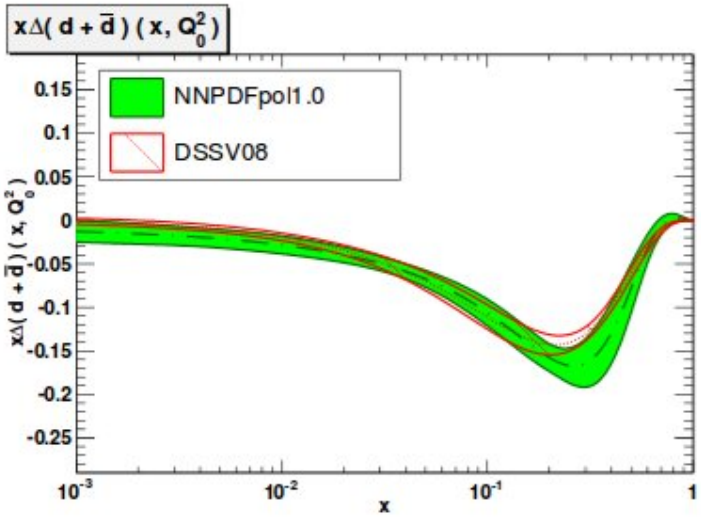


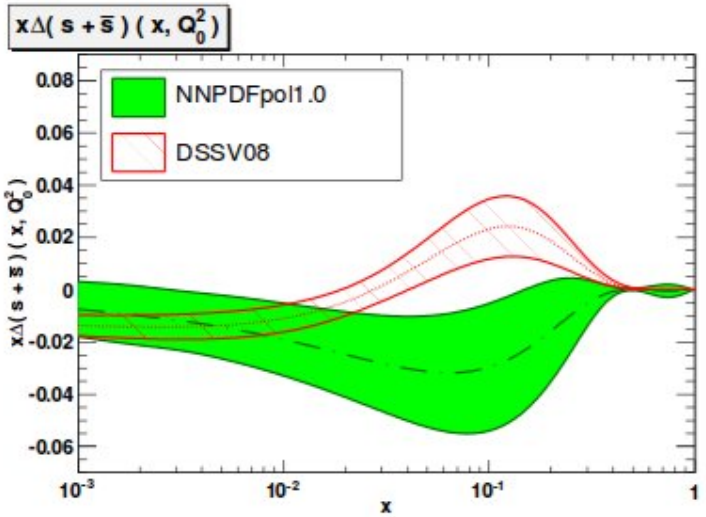
arXiv:1108.1713



arXiv: 1304.0079

Status of helicity-dependent PDFs,...cont'd





NNPDF, R.D. Ball et al., arXiv: 1303.7236

DSSV: DIS + SIDIS data; NNPDF: only DIS

- $\Delta s(x)$ conundrum: negative from DIS but zero (slightly positive ?) from all data
  $\Longrightarrow$ strong dependence on FF? Measurements coming from COMPASS, B–factories, LHC
  '3F-D' rule: $\int_0^1 dx[\Delta s(x) + \Delta\bar{s}(x)] \approx$ –0.1 Validity ???
  Lattice QCD: –0.020$\pm$ 0.010$\pm$ 0.001.

- The PDF status not likely to change befor the advent of EIC!

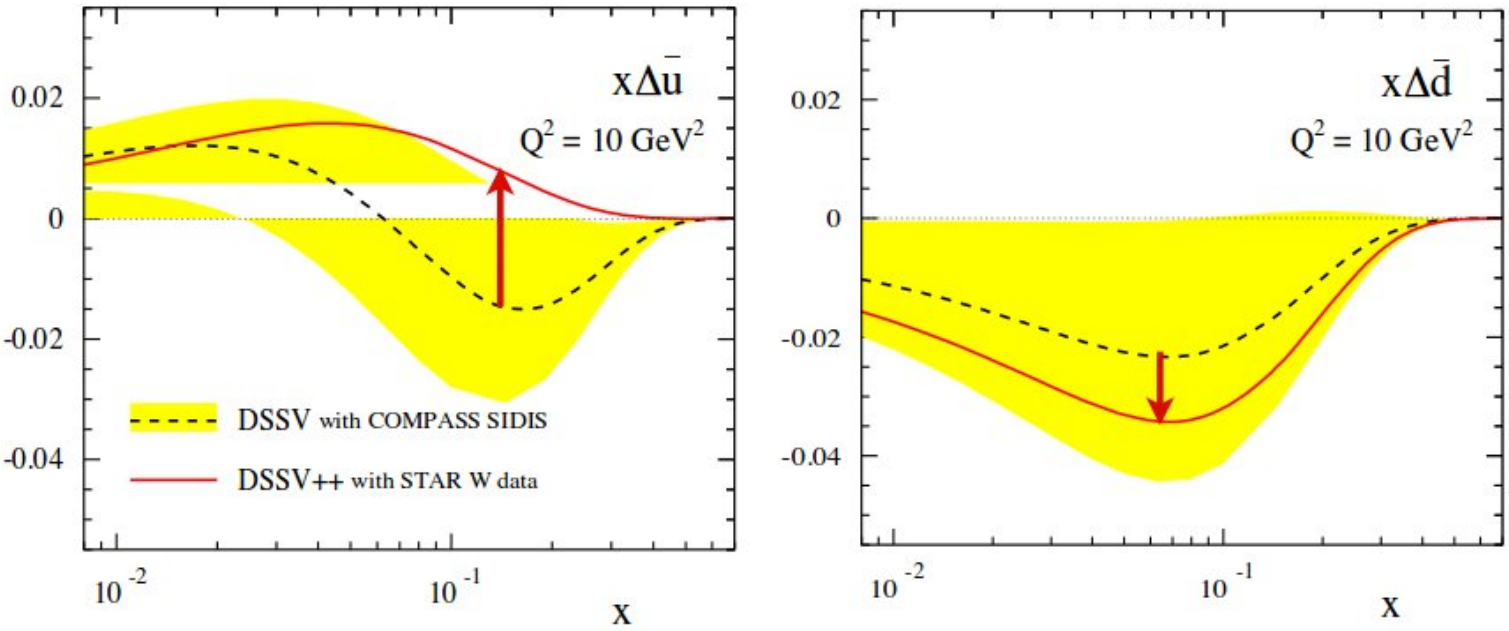
Status of helicity-dependent PDFs,...cont'd

Transparency from M. Stratmann, DIS2013

impact in terms of $\Delta\bar{u}(x)$ and $\Delta d(x)$

$\Delta\bar{u}$ $\Delta\bar{d}$

still very preliminary !



- starts to test of what we know about sea quarks from SIDIS with pions
- new fit points towards rather sizable $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ of interest for models

looming (mild ?) tension with SIDIS data

Outline

Measurements on a transversely polarised target,

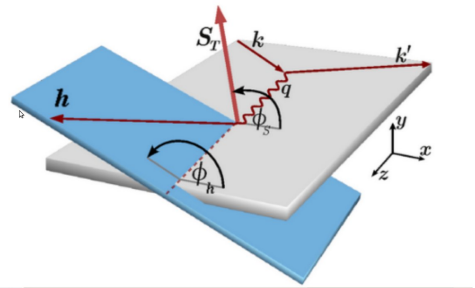
Collins asymmetry, TMD: Sivers asymmetry

Properties of $\Delta_T q(x)$:

- is chiral–odd $\Longrightarrow$ hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- related to GPD
- sum rule for transverse spin
- first moment gives "tensor charge" (now being studied on the lattice)

Transversity measured *e.g. via* the Collins asymmetry: $\perp$ polarised $q \Longrightarrow$ unpolarised h (asymmetry in the distribution of hadrons):

$$N_h^{\pm}(\phi_c) = N_h^0 \left[1 \pm p_T D_{NN} A_{Coll} \sin\phi_c\right]$$
$$\phi_C = \phi_h + \phi_S$$



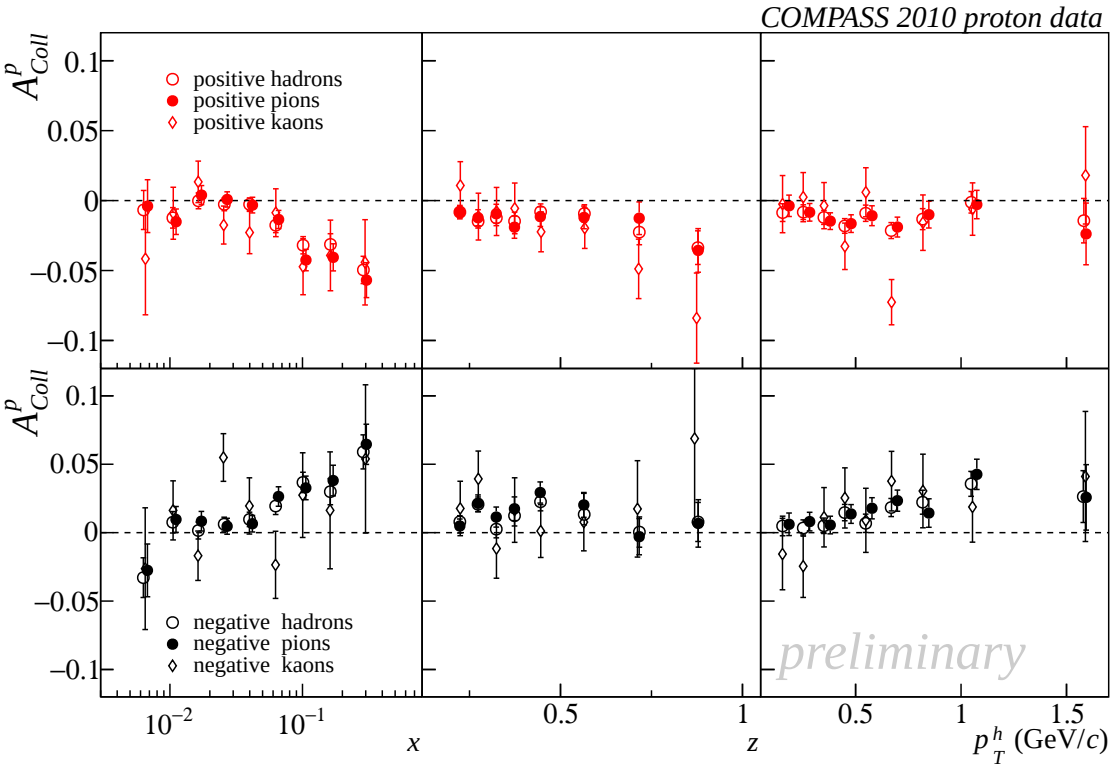
which in turn gives at LO:

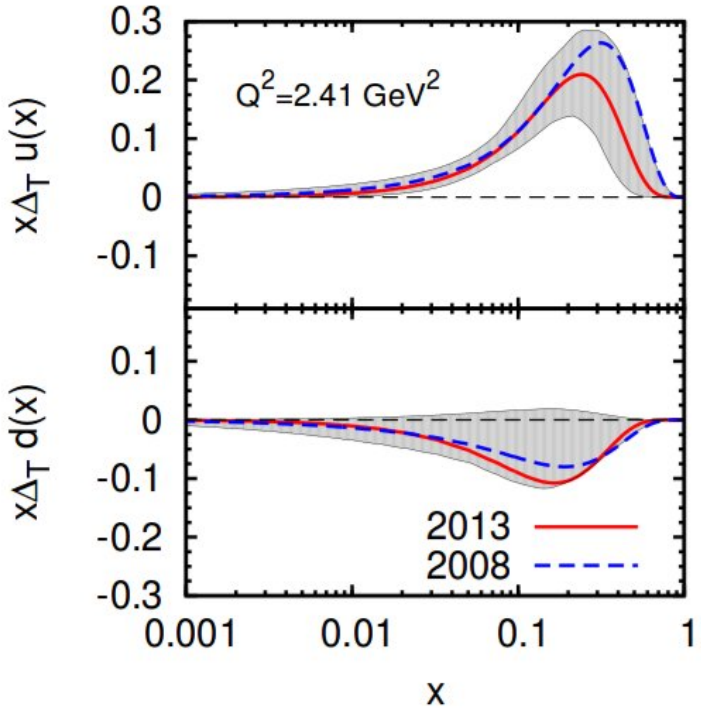
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

But transverse fragmentation functions $\Delta_T^0 D_q^h$ (universal!) needed to extract $\Delta_T q(x)$ from the Collins assymetry! Recently those FF measured by BELLE and BaBar.

Sivers process ($\phi_S = \phi_h - \phi_S$, correlation of $\perp$ nucleon spin with k_T of unpolarised q): related to L_q in the proton. Fundamental !

Results for the Collins asymmetry for protons

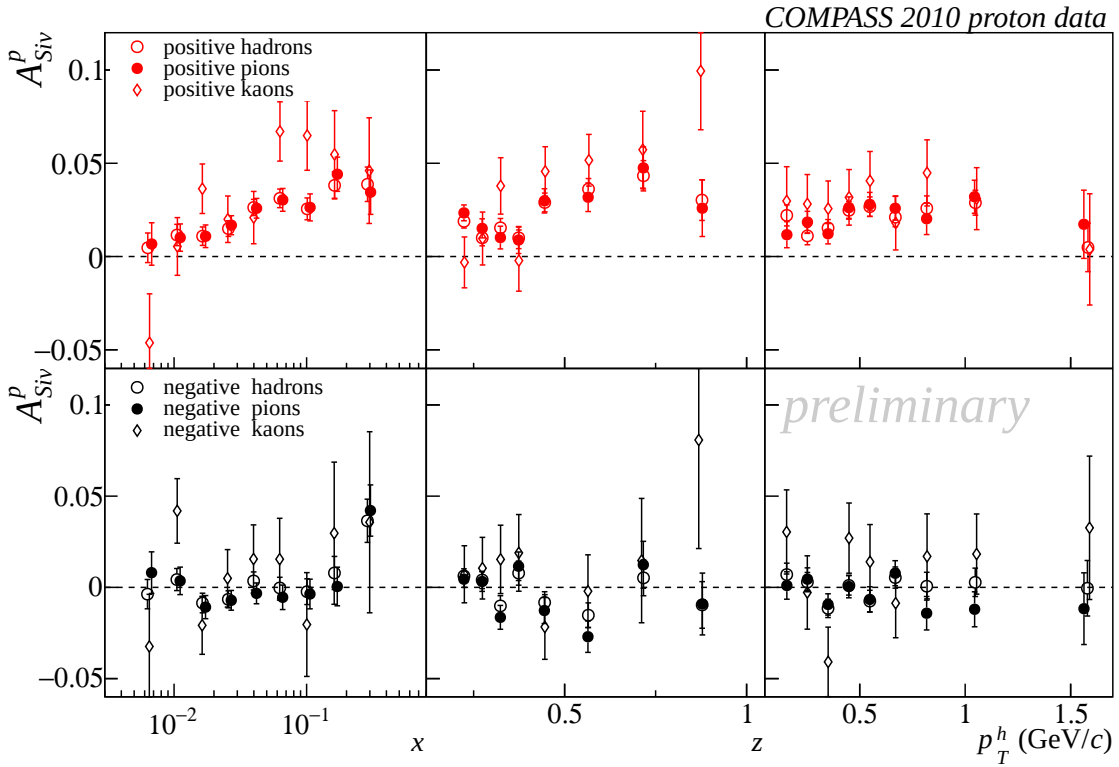




M. Anselmino et al., 1303.3822

- Collins asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are large at $x \gtrsim$ 0.1 and consistent with HERMES (in spite of different Q^2!)
- but negligible for the deuteron
- These data + HERMES + BELLE: $\Longrightarrow \Delta_T u + \Delta_T d \sim 0$
- Transversity also obtained from 2-hadron asymmetries (and “Interference Fragmentation Function”)

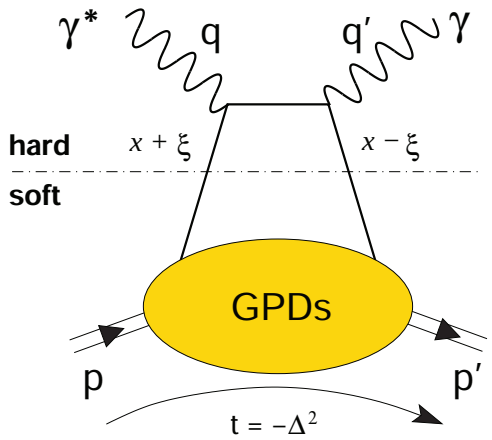
Results for the Sivers asymmetry for protons



- Sivers asymmetries for proton measured for +/– unidentified and identified hadrons...
- ...are larger at larger Q^2 (HERMES)
- COMPASS deuteron data show very small asymmetry
- Sivers functions ($f_{1T}^{\perp}$) for d and u quarks have opposite signs

Outline

Access GPD through the DVCS/DVMP mechanism

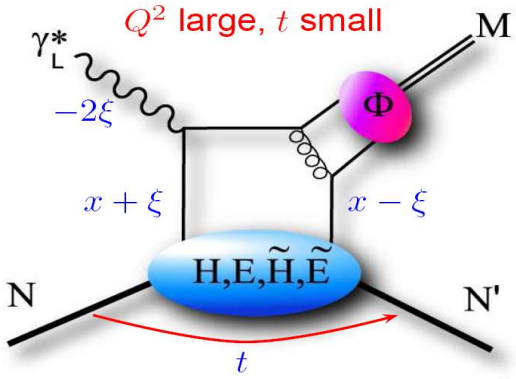


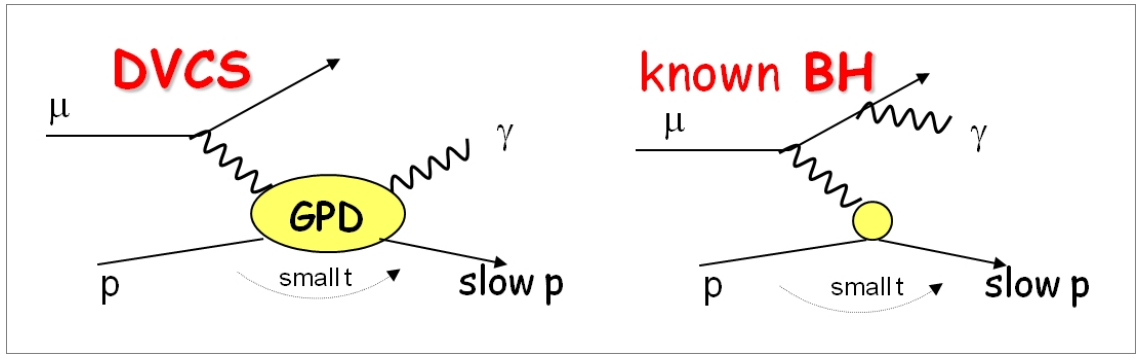
$Q^2 \to \infty$,
fixed $x_B, t \implies |t|/Q^2$ small

- 4 GDPs ($H, E, \widetilde{H}, \widetilde{E}$) for each flavour and for gluons
- Factorisation proven for σ_L only
- All depend on 4 variables: x, ξ, t, Q^2; DIS @ $\xi = t = 0$; Later Q^2 dependence omitted. Careful! Here $x \neq x_B$!
- $H, \widetilde{H}$ conserve nucleon helicity
  $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions
  $\widetilde{H}, \widetilde{E}$ refer to polarised distributions
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

- H, E accessed in vector meson production *via* A_{UT} asymmetries
- $\widetilde{H}, \widetilde{E}$ accessed in pseudoscalar meson production *via* A_{UT} asymmetries
- All 4 accessed in DVCS (γ production) in $A_C, A_{LU}, A_{UT}, A_{UL}$
- Integrals of $H, E, \widetilde{H}, \widetilde{E}$ over x give Dirac–, Pauli–, axial vector– and pseudoscalar vector form factors respectively.
- Important: $J_z^q = \frac{1}{2}\int dx\, x\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)] = \frac{1}{2}\Delta\Sigma + L_z^q$ (X. Ji)

DVCS/DVMP: $\mu p \to \mu p \gamma(M)$; what do we measure?

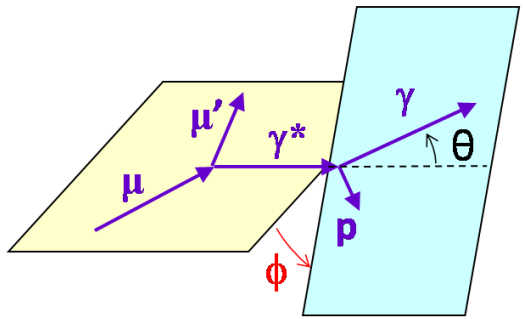




$$d\sigma^{\mu p \to \mu p \gamma} = d\sigma^{\rm BH} + (d\sigma^{\rm DVCS}_{\rm unpol} + P_\mu d\sigma^{\rm DVCS}_{\rm pol}) + e_\mu({\rm Re}I + P_\mu {\rm Im}I)$$

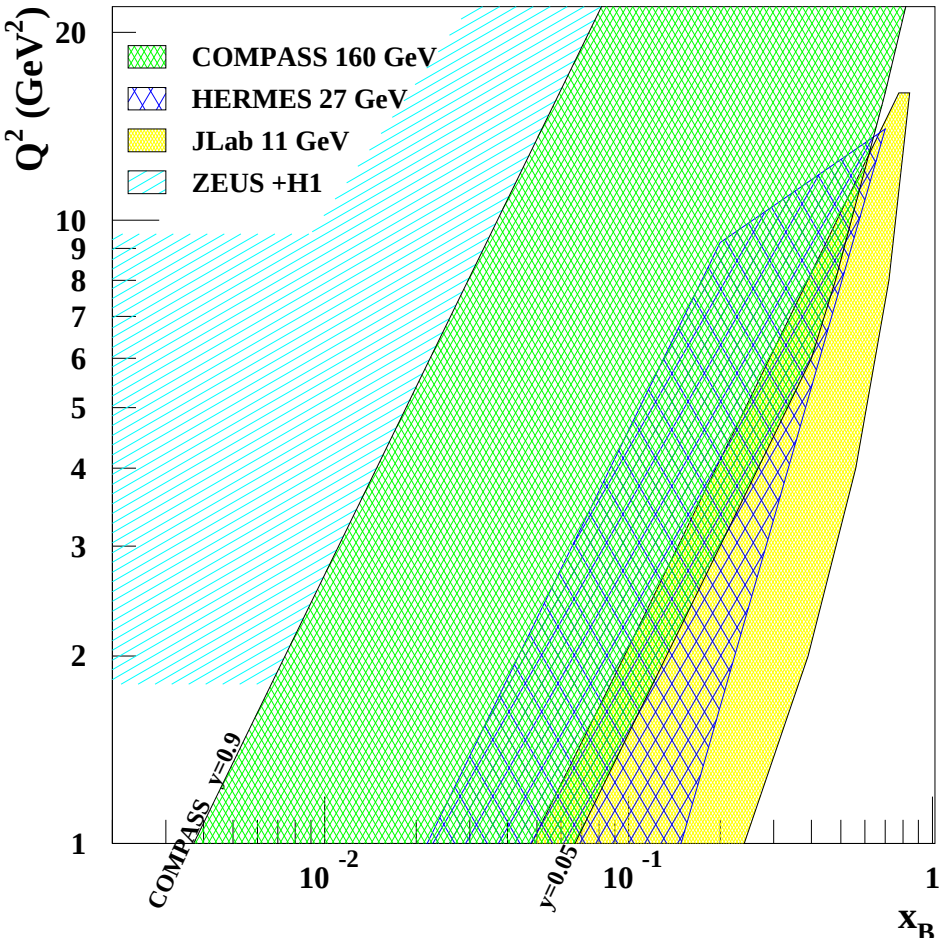
Observables (Phase 1):

- $S_{\rm CS,U} \equiv \mu^{+\leftarrow} + \mu^{-\rightarrow} = 2\left(d\sigma^{\rm BH} + d\sigma^{\rm DVCS}_{\rm unpol} + e_\mu P_\mu {\rm Im}I\right)$
- $D_{\rm CS,U} \equiv \mu^{+\leftarrow} - \mu^{-\rightarrow} = 2\left(P_\mu d\sigma^{\rm DVCS}_{\rm pol} + e_\mu {\rm Re}I\right)$
- $A_{\rm CS,U} \equiv \dfrac{\mu^{+\leftarrow} - \mu^{-\rightarrow}}{\mu^{+\leftarrow} + \mu^{-\rightarrow}} = \dfrac{D_{\rm CS,U}}{S_{\rm CS,U}}$
- Each term ϕ-modulated
  If ϕ-dependence integrated over $\Longrightarrow$ twist-2 DVCS contribution;
  if ϕ-dependence analysed: $\Longrightarrow$ Im $(F_1 H)$ and Re $(F_1 H)$



Analogously for transversely polarised target (Phase 2): $S_{\rm CS,T}, D_{\rm CS,T}, A_{\rm CS,T} \Longrightarrow E$

Why GPD at COMPASS ?



- CERN high energy muon beam
  - 100 - 190 GeV
  - 80% polarisation
  - $\mu^{+\leftarrow}$ and $\mu^{-\rightarrow}$ beams
- Kinematic range
  - between HERA and HERMES/JLab12
  - intermediate x (sea and valence)
- Separation
  - pure B-H @ low x_{B}
  - predominant DVCS @ high x_{B}
- Plans
  - DVCS
  - DVMP
- Goals
  - from unpolarised target: H (Phase 1)
  - from $\perp$ polarised target: E (Phase 2)

Test runs: 2008-9 and 2012; DVCS signal seen, full setup evaluated

Outline

Summary: nucleon structure @ COMPASS, now and in the future

- It is the only high-energy polarised lepton – nucleon experiment taking data
- longitudinally polarised muon beam of 160 (200) GeV/c
  off longitudinally and transversely polarised targets: ^{6}LiD (d), NH_3 (p)
- with hadron identification
- All three leading twist pdf (F_1, g_1, h_1) and TMD investigated
  - New proton (2011) data extend measurements of g_1^p to low x
    and will permit a more accurate extraction of polarised pdf
  - extraction of FF ratios from hadron multiplicities on the way
  - will help to solve the "Δs puzzle"
  - gluon polarisation, Δg updated in LO and (new) NLO suggest
    a small ΔG at the measured x with all world measurements compatible
  - In the transverse (and TMD) sector, clear signals on the proton
    and evidence of a strong Q^2 dependence of TMD observed
  - Expecting a new global analysis of HERMES and COMPASS data (with BELLE FF)
- In the future ($\geq$2014) a focus on transverse structure of the nucleon:
  - GPD, transverse size and parton orbital angular momentum
  - T-odd TMD (Sivers, Boer-Mulders distributions)
  - Drell-Yan process and TMD sign change SIDIS $\Longleftrightarrow$ DY
- Lots of data awaiting analysis!