Nucleon longitudinal spin structure

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EINN2019 Workshop
The Road to the Electron-Ion Collider

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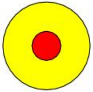
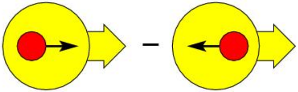
Partonic structure of the nucleon; distribution functions

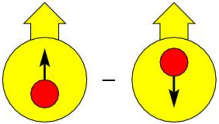
Three twist-two quark distributions in QCD and after integrating over the quark intrinsic k_t

$q(x) =$ 

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

$\Delta q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow \mathbf{g_1(x, Q^2)}$).

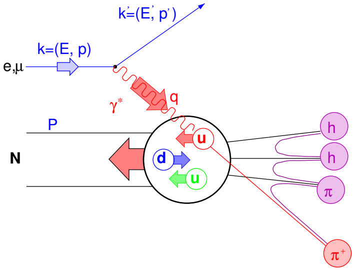
$\Delta_T q(x) =$ 

Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

Nonrelativistically: $\Delta_T q(x, Q^2) \equiv \Delta q(x, Q^2)$. OBS.! $\Delta_T q(x, Q^2)$ are C-odd and chiral-odd

Goal: measurement of $\mathbf{g_1(x, Q^2)}$ and determination of $\mathbf{\Delta q(x, Q^2)}$

Nucleon (spin) structure in DIS: $\vec{\mu} + \vec{\mathrm{N}} \rightarrow \mu' + \mathrm{X}$

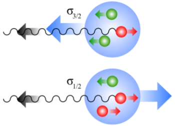


- $\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega \mathrm{d}E'} = \dfrac{\alpha^2}{2Mq^4}\dfrac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x, Q^2) \longrightarrow g_{1,2}$, $\Delta q(x, Q^2)$ where $q = q^+ +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

Definitions of DIS variables...

$Q^2 = -q^2$	γ^* virtuality
$x = Q^2/(2Pq)$	Bjorken variable
$y = Pq/(Pk)$	relative γ^* energy
$W = P + q$	γ^*-N cms energy

...and of the γ^*-N asymmetry (e.g. for γ^*-p):



$$A_1^p(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$A_2^p(x, Q^2) = \frac{2\sigma^{\mathrm{TL}}}{\sigma_{1/2} + \sigma_{3/2}}$$

Full hadronic tensor for proton

$$W_{\mu\nu} = (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2})F_1(x,Q^2) + \frac{\hat{P}_\mu \hat{P}_\nu}{P\cdot q}F_2(x,Q^2) - i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda P^\sigma}{2P\cdot q}F_3(x,Q^2)$$
$$+ i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda S^\sigma}{P\cdot q}g_1(x,Q^2) + i\varepsilon_{\mu\nu\lambda\sigma}\frac{q^\lambda(P\cdot q S^\sigma - S\cdot q P^\sigma)}{(P\cdot q)^2}g_2(x,Q^2)$$
$$+ [\frac{\hat{P}_\mu \hat{S}_\nu + \hat{S}_\mu \hat{P}_\nu}{2} - S\cdot q\frac{\hat{P}_\mu \hat{P}_\nu}{(P\cdot q)}]\frac{g_3(x,Q^2)}{P\cdot q}$$
$$+ S\cdot q\frac{\hat{P}_\mu \hat{P}_\nu}{(P\cdot q)^2}g_4(x,Q^2) + (-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2})\frac{(S\cdot q)}{P\cdot q}g_5(x,Q^2),$$

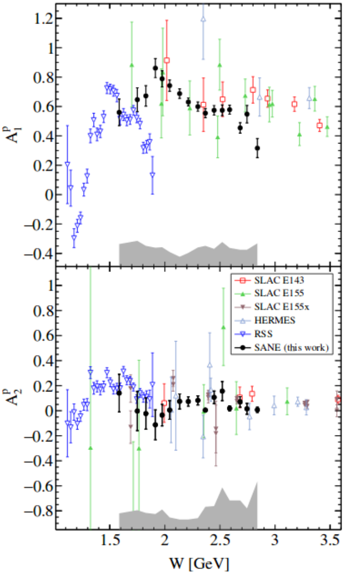
Blümlein, Kochelev, arXiv:hep-ph/9612318v2

- 5 spin-dependent structure functions: $g_1 \div g_5$; g_3, g_4, g_5 at CC
- 31 relations between them
- several sum rules (e.g. Burkhardt-Cottingham: $\int_0^1 \mathrm{d}x\, g_2(x,Q^2) = 0$)
- g_2 and g_3 have both twist-2 and twist-3 contributions
- if no target mass corrections then the twist-3 matrix element

  $\tilde{d_2} = \int_0^1 \mathrm{d}x\, x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]$

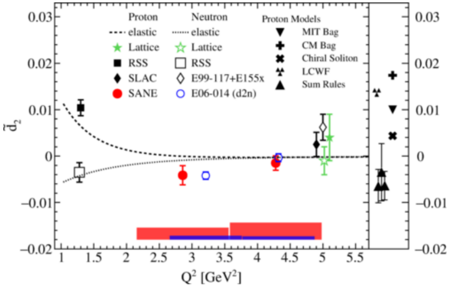
  may be measured experimentally; also accessed in LQCD

Measurement of $\tilde{d}_2$ by SANE (JLab/Hall C)



Color Lorentz force in the proton??

SANE PRL 122 (2019) 022002

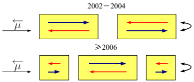


Method of extraction of g_1

- Inclusive asymmetry, $A_{meas}(x,Q^2)$, γ^*-N asymmetry, $A_1(x,Q^2)$, and $g_1(x,Q^2)$:

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

f, D: dilution and depolarisation factors; P_T, P_B: target and beam polarisations;
$N^{\leftrightarrows,\leftleftarrows}$: number of $\vec{\mu}$ interactions in each target cell:
(upstream, downstream) or (outer, central)



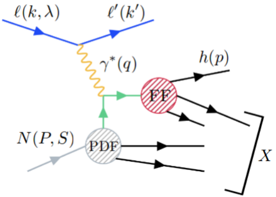
- Then $g_1(x,Q^2)$:

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

- For the deuteron target:

$$(\text{per nucleon})\, g_1^d = g_1^N\left(1-\frac{3}{2}\omega_D\right) = \frac{g_1^p+g_1^n}{2}\left(1-\frac{3}{2}\omega_D\right); \qquad \omega_D = 0.05 \pm 0.01$$

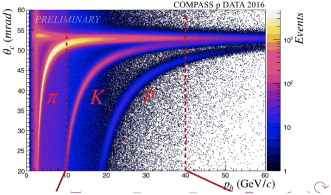
- At LO, semi–inclusive (SIDIS) asymmetry, A_1^h:



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

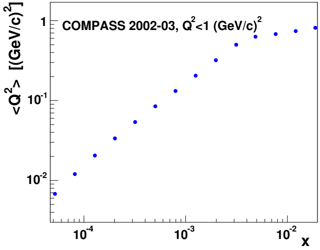
$$A^{\mathrm{SIDIS}} \sim \mathrm{pdf} \otimes \mathrm{FF}$$

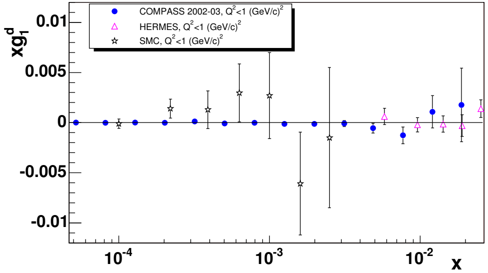
Nonperturbative fragmentation functions $D_q^h(z,Q^2)$ need to be determined from experiment!



$g_1^{\rm d}$ at low Q^2

g_1^{d} in the nonperturbative ($Q^2 < 1$ (GeV/c)^2 region)



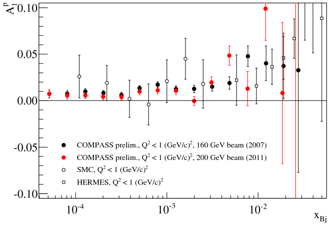


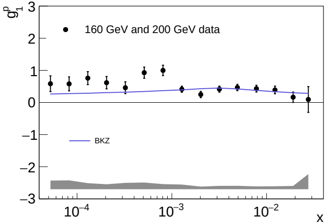
COMPASS PL B **647** (2007) 330

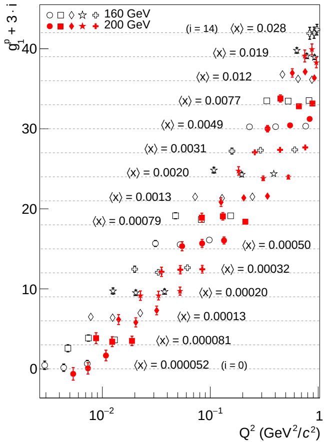
- More than ten-fold improvement over the statistical precision of SMC.
- Spin effects in g_1^{d} at low x and Q^2 absent ?

g_1^{p} at low Q^2

Low Q^2: results on $A_1^{\mathrm{p}}(x)$ and $g_1^{\mathrm{p}}(x, Q^2)$







- More than ten-fold improvement over the statistical precision of SMC.
- Very clear spin effects in g_1^{p} at low x and Q^2

COMPASS PLB 781 (2018) 464

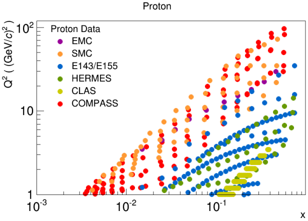
Importance of $g_1(x, Q^2)$ at low x, Q^2

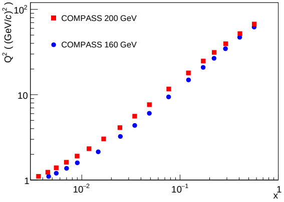
- At low x: strong increase of parton density with decreasing x
  $\Longrightarrow$ parton recombination effects
- Low x effects particularly visible in $g_1^{\rm NS} \Longrightarrow \ln^2(1/x)$ terms
- BUT: in fixed-target experiments low x correlated with low Q^2 region
  $\Longrightarrow$ nonperturbative effects must be considered
  and parton mechanisms have to be suitably extended to low Q^2.
- Attempts to describe that region phenomenologically:
  - B. B., J. Kwiecinski, J. Kiryluk, Phys. Rev. D61 (2000) 014009.
  - B. B., J. Kwiecinski, B. Ziaja, Eur. Phys. J. C26 (2002) 45.
  - B.I. Ermolaev, M. Greco, S.I. Troyan, Eur. Phys. J. C50 (2007) 823; *ibid.* C51 (2007) 859.
  - W. Zhu, J. Ruan, Int. J. Mod. Phys. E24 (2015) 1550077.

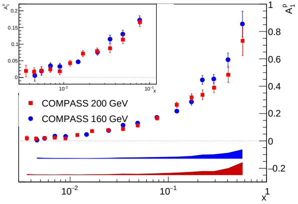
g_1^{p} at $Q^2 > 1\ (\mathrm{GeV}/c)^2$

g_1^{p}: data samples

- Measurements at incident E = 160 GeV (from 2007): PLB 690 (2010) 466
- Measurements at incident E = 200 GeV (from 2011): PLB 753 (2016) 18
  energy increased to reach lower x and higher Q^2
  (and to balance the amount of data from the deuteron target)
- Final sample: 85 million events @ 160 GeV + 77 million events @ 200 GeV
- Results on A_1^{p} at both energies agree very well

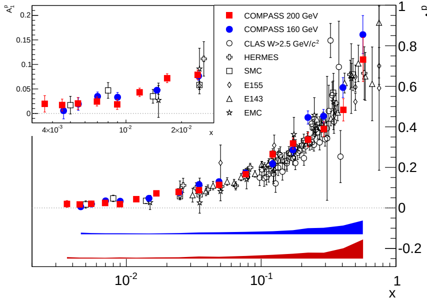


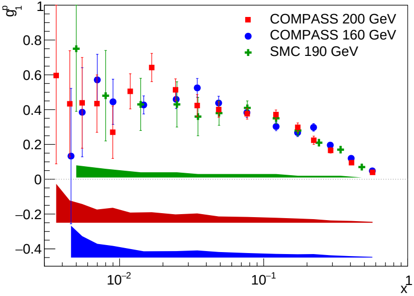




Results on $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$

- $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$ shown at the measured values of Q^2
- Bands of systematic uncertainties for each energy separately





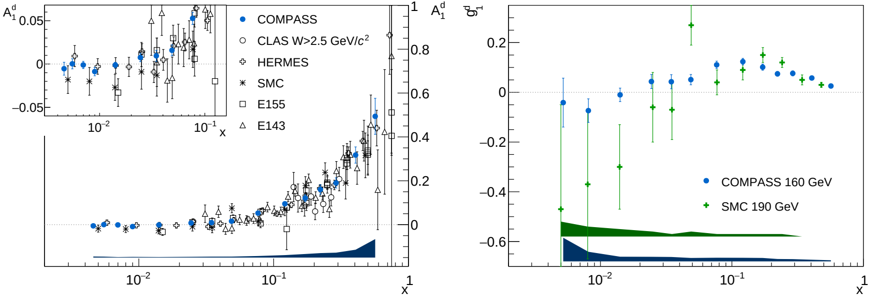
PLB 753 (2016) 18

- Good agreement of $A_1^{\rm p}(x)$ and $g_1^{\rm p}(x)$ with world data
- $g_1^{\rm p}(x)$ clearly positive at lowest measured values of x

g_1^{d} at $Q^2 > 1$ (GeV/c)^2

Results on $A_1^{\rm d}(x)$ and $g_1^{\rm d}(x)$

- Combined results from 2002–2004 and 2006
- $A_1^{\rm d}(x)$ and $g_1^{\rm d}(x)$ shown at the measured values of Q^2



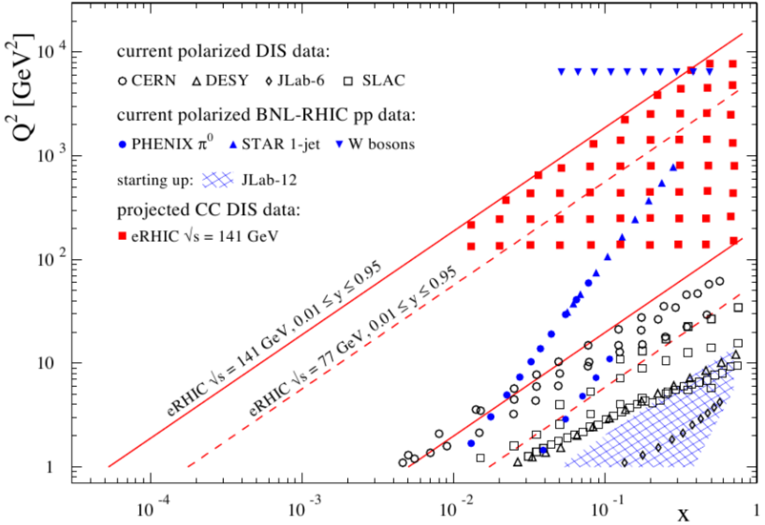
COMPASS PL B769 (2017) 034

- Good agreement of $A_1^{\rm d}(x)$ and $g_1^{\rm d}(x)$ with world data
- $g_1^{\rm d}(x)$ compatible with zero at lowest measured values of x, contrary to previous hints (SMC)

NLO QCD fit to p,d, ^{3}He world data

COMPASS, PLB 753 (2016) 18

Current polarised DIS data (including CC DIS)



arXiv: 1409.1633

NLO QCD fit: conditions

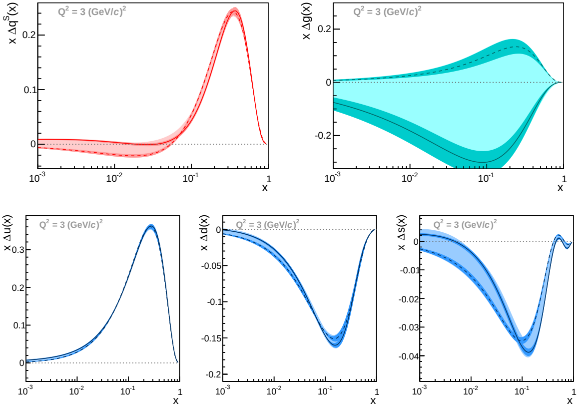
- A fit of the $g_1^{\rm p}$, $g_1^{\rm d}$, $g_1^{^3{\rm He}}$ inclusive data
- $\overline{\rm MS}$ scheme
- $W^2 < 10$ (GeV/c^2)^2 excluded
- Number of data points total/COMPASS: 495/138
- Fitted: Δg, $\Delta q^{\rm s} = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$, gluons, singlet
  $\Delta q_3 = \Delta(u+\bar{u}) - \Delta(d+\bar{d})$ nonsinglet
  $\Delta q_8 = \Delta(u+\bar{u}) + 2\Delta(d+\bar{d}) - \Delta(s+\bar{s})$ nonsinglet
- Parameterisation (at $Q_0^2 = 1$ (GeV/c)^2):

$$\Delta f_k(x) = \eta_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)\mathrm{d}x}, \qquad (k = s, 3, 8, g)$$

  η_k = first moment of $\Delta f_k(x)$ at Q_0^2

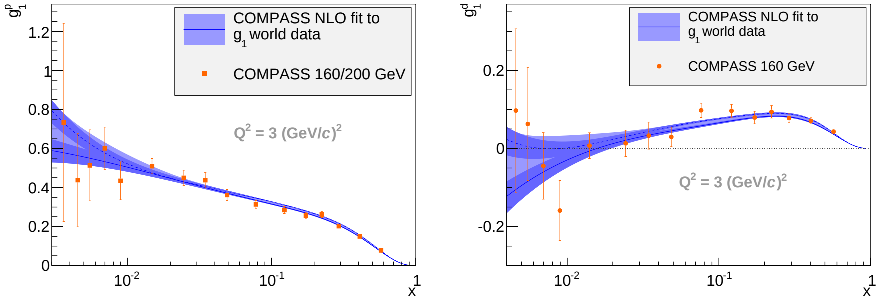
- Number of free parameters in the fitted pdfs: 11
- Only statistical errors taken, normalisations of each data set varied
- Required at every iteration:
  $|\Delta q(x) + \Delta\bar{q}(x)| \leq q(x) + \bar{q}(x)$, $|\Delta g(x)| \leq g(x)$ at $Q^2 = 1$ (GeV/c)^2
- Studied: parameterisation $\Delta f_k(x)$ dependence and Q_0^2 dependence of the fit.

NLO QCD fit: results



- Statistical uncertainties (dark bands) $\ll$ systematic (light bands)
- Gluon polarisation poorly constraint $\Longrightarrow$ “direct” methods
- Quark spin contribution to the nucleon spin: $0.26 < \Delta\Sigma < 0.36$ (due to poor Δg)

NLO QCD fit: results...cont'd

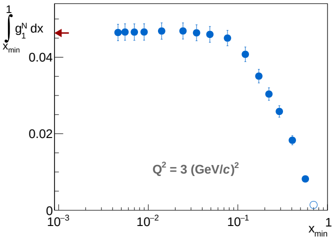


- g_1^{p} clearly positive at low x and raising with decreasing x
- g_1^{d} consistent with zero at low x ?

First moments of g_1 and singlet axial charge a_0

- First moments $\Gamma_1^{\rm p}, \Gamma_1^{\rm d}, \Gamma_1^{\rm N}$
  where $\Gamma_1^{\rm i} = \int_0^1 g_1^{\rm i}(x, Q^2){\rm d}x$

COMPASS PL B769 (2017) 034



- In particular:
  $$\Gamma_1^{\rm N}(Q^2) = \frac{1}{36}\left[4a_0 C_{\rm S}(Q^2) + a_8 C_{\rm NS}(Q^2)\right]$$
  $$= \int_0^1 \frac{g_1^{\rm d}(x, Q^2)}{1 - 1.5\omega_{\rm D}}{\rm d}x$$
- In the $\overline{\rm MS}$: $a_0 = \Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})$
- $\Gamma_1^{\rm N}$ approaches asymptotic value already at Q^2 = 3 (GeV/c)^2
- From COMPASS data alone:
  $\Gamma_1^{\rm N}(Q^2$ = 3 (GeV/$c)^2$) = 0.046 $\pm 0.002_{\rm stat.} \pm 0.004_{\rm syst.} \pm 0.005_{\rm evol.}$
- From COMPASS data alone (and a_8 from PRD 82 (2010) 114018):
  $a_0(Q^2$ = 3 (GeV/$c)^2$)= 0.32 $\pm 0.02_{\rm stat.} \pm 0.04_{\rm syst.} \pm 0.05_{\rm evol.}$
  (consistent with value from the COMPASS NLO QCD fit of world data).

Non-singlet structure function, $g_1^{\rm NS}(x,Q^2)$

COMPASS PL B753 (2016) 18

- Non-singlet structure function:

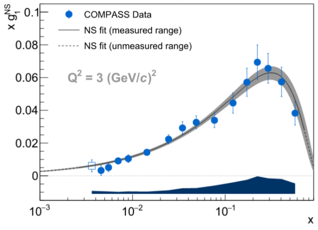
$$g_1^{\rm NS} = g_1^{\rm p}(x,Q^2) - g_1^{\rm n}(x,Q^2)$$
$$= 2\left[g_1^{\rm p}(x,Q^2) - g_1^{\rm N}(x,Q^2)\right]$$

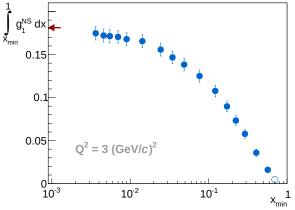
- Its moment connected to the Bjorken sum rule:

$$\Gamma_1^{\rm NS}(Q^2) = \int_0^1 g_1^{\rm NS}(x,Q^2){\rm d}x = \frac{1}{6}\left|\frac{g_{\rm A}}{g_{\rm V}}\right| C_1^{\rm NS}(Q^2)$$

- $g_1^{\rm NS}$ calculated, NLO QCD fitted (only Δq_3), evolved to Q^2= 3 (GeV/c)^2 and fit-extrapolated $x \to 0, 1$:

$$\Gamma_1^{\rm NS} = 0.192 \pm 0.007_{\rm stat.} \pm 0.015_{\rm syst.}$$
$$\left|\frac{g_{\rm A}}{g_{\rm V}}\right| = 1.29 \pm 0.05_{\rm stat.} \pm 0.10_{\rm syst.}$$





- Neutron β decay gives: $|g_{\rm A}/g_{\rm V}| = 1.2701 \pm 0.002$

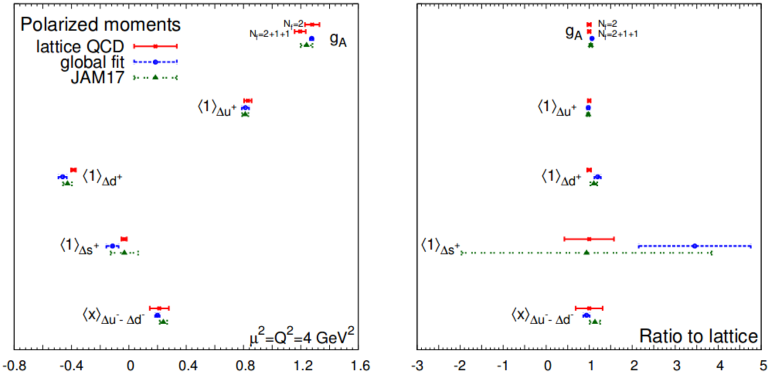
PDG, PRD86 (2012) 010001

- This validates the Bjorken sum rule with an accuracy of 9%

Comparison of spin-dependent moments to lattice QCD

$$\langle 1 \rangle_{\Delta q}(Q^2) = \int_0^1 dx[\Delta q(x,Q^2) - \Delta\bar{q}(x,Q^2)] = 0\text{-th moment}$$

$$\langle x \rangle_{\Delta q}(Q^2) = \int_0^1 dx\, x\Delta q(x,Q^2) = 1\text{-st moment}$$



Surprising agreement!

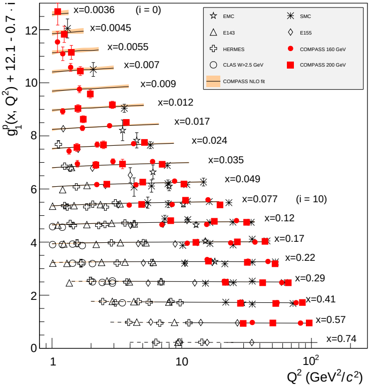
arXiv: 1711.07916

g_1^p and g_1^d, Q^2 >1 (GeV/c)^2, COMPASS full statistics

COMPASS NLO QCD fit to the world data at $W^2 > 10$ (GeV/c^2)^2

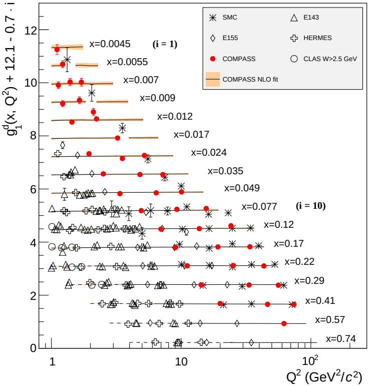
dashed line: extrapolation to $W^2 < 10$ (GeV/c^2)^2

proton



Phys.Lett.B753(2016)18

deuteron



COMPASS PL B769 (2017) 034

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

SIDIS measurements

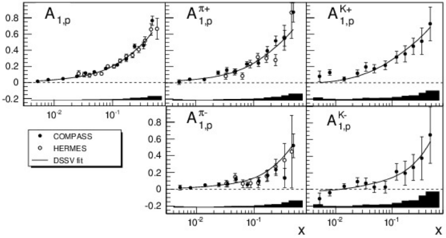
Semi-inclusive asymmetries, A_1^{h} and parton distributions

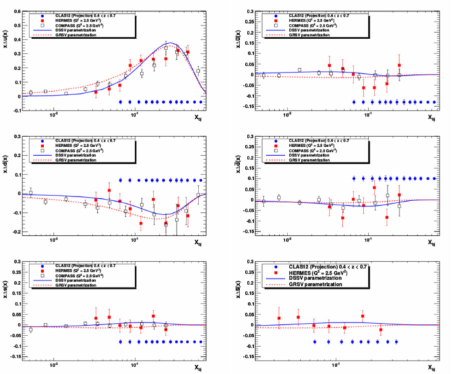
- COMPASS: measured on both proton and deuteron targets
  for identified, positive and negative pions and (for the first time) kaons

CLAS12, Update to E12-09-007

COMPASS, Phys. Lett. B **693** (2010) 227

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





- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

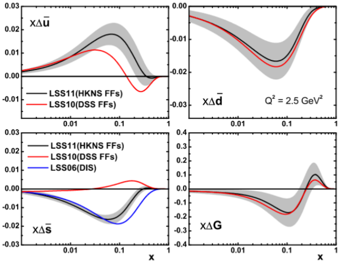
Polarisation of quark sea

- 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 SIDIS it is compatible with zero but depends upon chosen FFs.

  Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$

  $\Longrightarrow$COMPASS extracts it from multiplicities.

- Example of sensitivity to FFs at Q^2=2.5 (GeV/c)^2



LSS, PRD D84 (2011) 014002

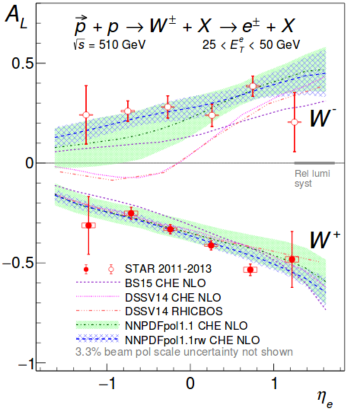
- The sea is not unsymmetric:

$$\int_{0.004}^{0.3} \left[\Delta\bar{u}(x,Q^2) - \Delta\bar{d}(x,Q^2)\right] dx = 0.06 \pm 0.04 \pm 0.02 \ \ @ \ \ Q^2 = 3 \text{ (GeV/}c)^2$$

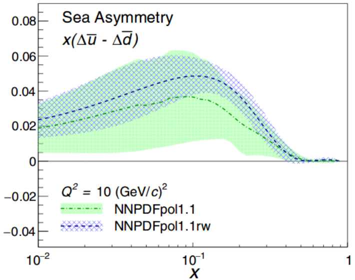
Thus the data disfavour models predicting $\Delta\bar{u} - \Delta\bar{d} \gg \bar{d} - \bar{u}$

COMPASS, PL B693 (2010) 227

Recent results from STAR on sea polarisation



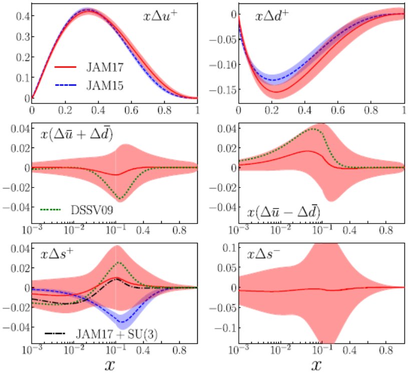
STAR, PR D99 (2019) 051102



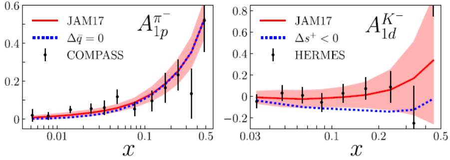
- The polarised sea is probably unsymmetric (STAR) contrary to COMPASS result
- This is opposite to spin-averaged quark sea asymmetry

Global QCD fits: JAM17

A global NLO $\overline{\mathrm{MS}}$ QCD analysis of DIS, SIDIS, e^+e^- data and of FFs



- Inclusion of SIDIS changes Δs^+
- Sensitivity to imposing SU_3!

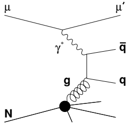


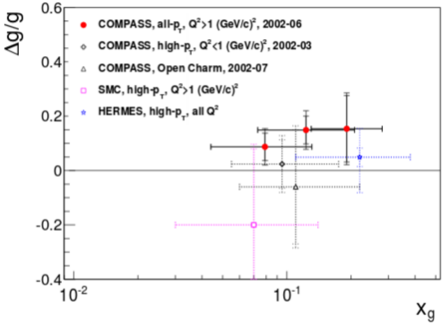
JAM PRL 119 (2017) 132001

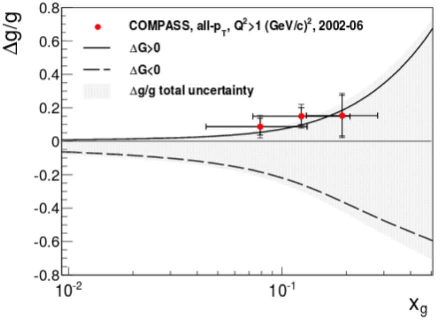
“Direct” measurements of Δg

Direct measurements of $\Delta g(x)$ by COMPASS

Direct measurements – *via* the cross section asymmetry for the photon–gluon fusion (PGF) with subsequent fragmentation into $c\bar{c}$ (LO, NLO) or $q\bar{q}$ (high p_{T} hadron pair (LO)): $A^{\mathrm{PGF}}_{\gamma \mathrm{N}} \approx \langle a^{\mathrm{PGF}}_{\mathrm{LL}} \rangle \dfrac{\Delta g}{g}$







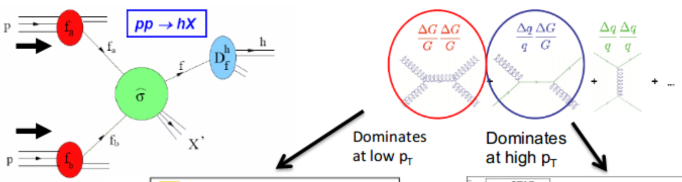
COMPASS from SIDIS on d for any $(p_{\mathrm{T}})_{\mathrm{h}}$ and at LO:

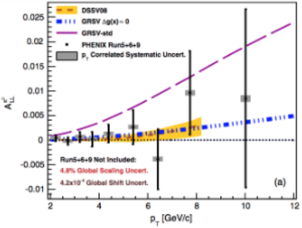
$$\Delta g/g = 0.113 \pm 0.038(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\mathrm{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

clearly positive gluon polarisation!

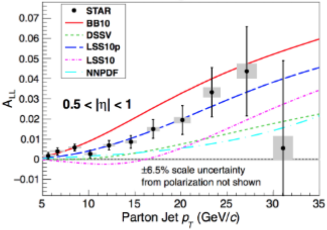
COMPASS, EPJC 77(2017) 209

Measurement of the gluon polarization Δg at RHIC





Phys. Rev. D 90 (2014) 012007



Phys. Rev. Lett. 115 (2015) 092002

D. de Florian *et al*, **PRL 113 (2014) 012001**

E. Nocera et al, **NPB 887 (2014) 276**

$$\int_{0.05}^{1} dx\Delta g(x,Q^2=10\,GeV^2) = 0.20^{+.06}_{-.07} \quad \text{DSSV++}$$

$$\int_{0.05}^{0.2} dx\Delta g(x,Q^2=10\,GeV^2) = 0.17 \pm 0.06 \quad \text{NNPDFpol1.1}$$

$$\int_{0.001}^{0.8} dx\Delta g(x,Q^2 = 1\,GeV^2) = 0.5 \pm 0.4 \quad \text{JAM15}$$

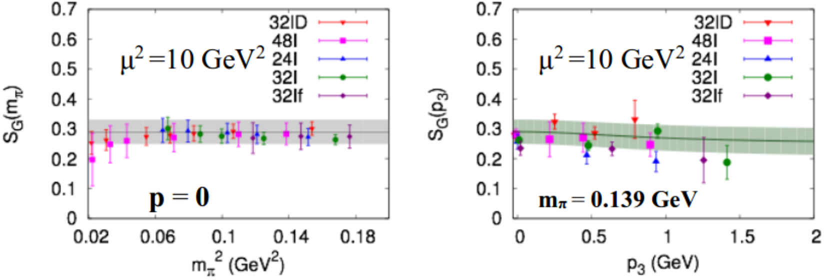
Surrow et al on sea quark spin from W production at RHIC

6

H.Gao, DIS2018

Gluon Spin From Lattice QCD

First lattice QCD calculation of the gluon spin in the nucleon



$$\Delta G \approx S_g\,(|\mathbf{p}|\rightarrow\infty): \quad 0.251(47)(16) \qquad (\mu^2 = 10\ \text{GeV}^2)$$

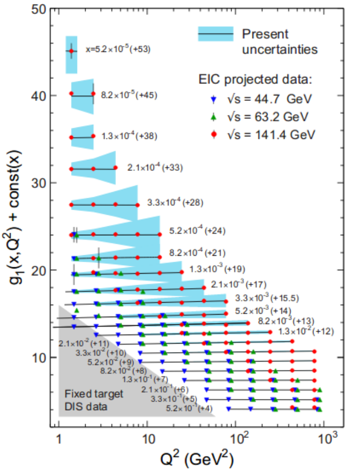
50(9)(3)% of the total proton spin

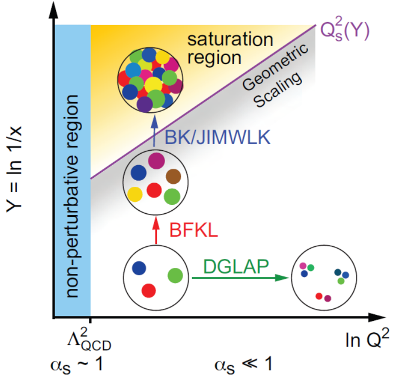
Y.-B. Yang *et al.* (χQCD Collaboration), Phys. Rev. Lett. 118, 102001 (2017).

8

H.Gao, DIS2018

Inclusive $g_1(x, Q^2)$ at EIC (pseudo-data)





Errors statistical (EIC: expected, modest parameters); bands: from gluon helicity uncertainty

arXiv:1708.01527v3

"White paper", arXiv:1212.1701

"Low x physics": gluon saturation

BFKL equation has $[\alpha_s \ln(1/x)]^n$ (DGLAP: $[\alpha_s \ln(Q^2)]^n$)

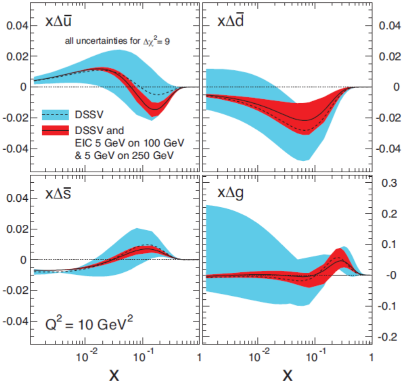
Even more, a new approach needed: non-linear QCD evolution

- Gluon splitting "infinite" $\longrightarrow$ recombination needed! (BFKL $\rightarrow$ BK)
- Saturation at certain scale Q_s^2
- New evolution equations to describe low x
- Colour Glass Condensate as an efective theory

Easy signature of BFKL in g_1: at low x it is sensitive to $\ln^2(1/x)$!!!!

Parton separation at EIC pseudo-data (inclusive and semi-inclusive)

DIS + SIDIS

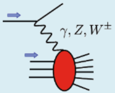


From "White paper", arXiv:1212.1701

EW DIS

- $\Delta g(x)$ from scaling violation
- $\Delta\bar{u}, \Delta\bar{d}, \Delta s$ from SIDIS
- Flavor separation at high Q^2 via CC DIS:

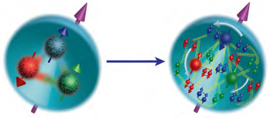
$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta\bar{c} + \Delta s$$
$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \Delta d + \Delta\bar{c} - \Delta s$$
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$



E. Aschenauer, SPIN2016

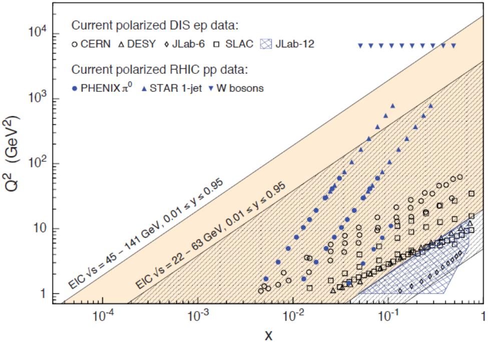
Spin "puzzle" ($>$ 30 years old!)

Nucleon spin "puzzle" at EIC

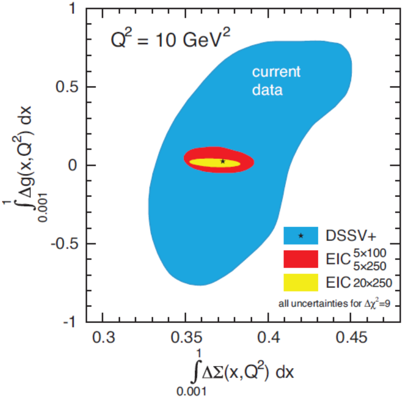


quark spins, gluon spins, quark&gluon orbital motion

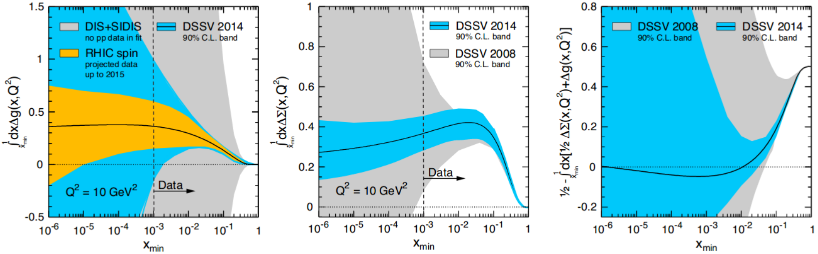
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$



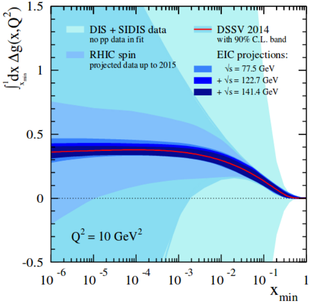
From "White paper2017", arXiv:1708.01527v3



From "White paper", arXiv:1212.1701



arXiv: 1708.01527



arXiv: 1509.06489

Accuracy of “spin puzzle” contributions improves with time

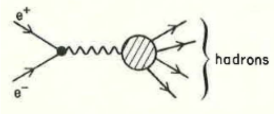
Hadron multiplicities

and

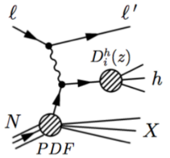
quark fragmentation functions

Nonperturbative component: Fragmentation Functions (FF)

FF for quarks



- e^+e^-: gives the cleanest access
  but sensitive only to fragmentation of $q + \bar{q}$;
  limited flavour separation



- SIDIS: a convolution of q distribution and FF

  $$\sigma^{\mathrm{lN}\to\mathrm{l'NX}} \propto \sum_q f(x) \otimes \sigma^{\mathrm{lq}\to\mathrm{lq}} \otimes D_q^{\mathrm{h}}(z)$$

  but separation to q and $\bar{q}$ and to flavours possible
  (in LO QCD, D has a sense of a probability density)
  SIDIS are crucial!

FF for gluons

- through high p_T hadron production in pp

Fragmentation Functions...cont'd

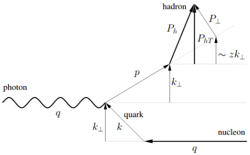
- Unpolarised SIDIS cross-section, σ^{h}, depends on 5 kinematic variables: $x, Q^2, z, P_{\mathrm{hT}}, \phi$

$$\frac{\mathrm{d}^4\sigma^{\mathrm{h}}(x,Q^2,z)}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}P_{\mathrm{hT}}^2} \sim \sum_q e_q^2 \int \mathrm{d}^2\vec{k}_{\mathrm{T}}\mathrm{d}^2\vec{p}_{\mathrm{h}\perp}\delta^{(2)}(\vec{P}_{\mathrm{hT}}-z\vec{k}_{\mathrm{T}}-\vec{p}_{\mathrm{h}\perp})q(x,Q^2,k_T)D_{\mathrm{q}}^{\mathrm{h}}(z,Q^2,p_{\mathrm{h}\perp})$$

(neglecting ϕ dependence); $\vec{p}_{\mathrm{h}\perp}$ - w.r.t. fragmenting q; $\vec{P}_{\mathrm{hT}}$ - w.r.t. γ^*

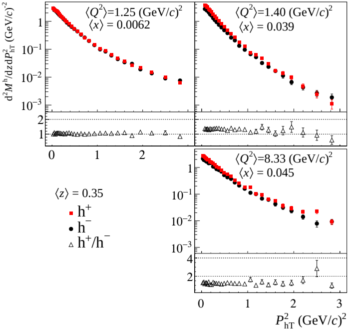
- This σ^{h} is accessed via multiplicities, $M^h(x, Q^2, z, P^2_{\mathrm{hT}}$

$$\frac{\mathrm{d}^2M^{\mathrm{h}}(x,Q^2,z,P^2_{\mathrm{hT}})}{\mathrm{d}z\mathrm{d}P^2_{\mathrm{hT}}} = \left(\frac{\mathrm{d}^4\sigma^{\mathrm{h}}}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}P^2_{\mathrm{hT}}}\right) \Big/ \left(\frac{\mathrm{d}^2\sigma^{\mathrm{DIS}}}{\mathrm{d}x\mathrm{d}Q^2}\right)$$

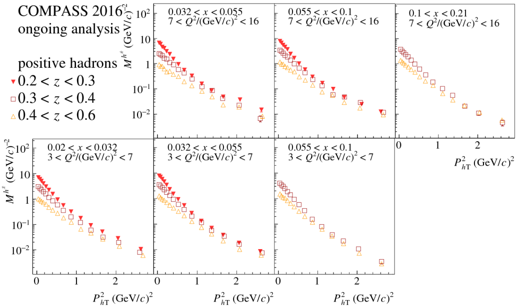


A.Bacchetta et al., JHEP06 (2017) 081

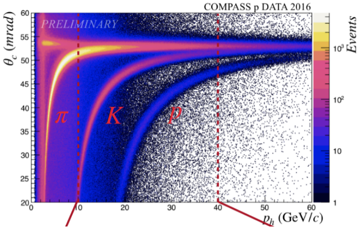
Multiplicities measurements at COMPASS in (x, Q^2, z, P_{hT}^2)



COMPASS, PR D97 (2018) 0322006

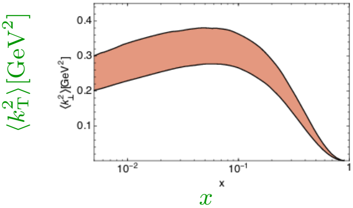


COMPASS, A. Moretti, DIS2019



Multiplicities in SIDIS $\Longrightarrow$ TMD QCD

- Transverse Momentum Dependent QCD has factorisation and evolution eqs different than collinear QCD!
- A process sensitive to TMD: if some transverse momentum component, p_{hT}, is much less than the hard scale of the process, $p_{\mathrm{hT}} \ll Q^2$.
- Possible processes: SIDIS, Drell-Yan, Z boson production
- First global analysis attempt

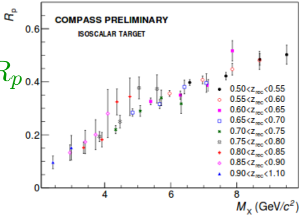


A. Bacchetta et al., JHEP 06 (2017) 081

Simultaneous fit of unpolarised TMD PDF (f_1^{q}) and of TMD FF ($D_{\mathrm{q}}^{\mathrm{h}}$); NLL accuracy.

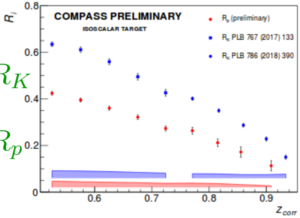
Multiplicity measurements: problems

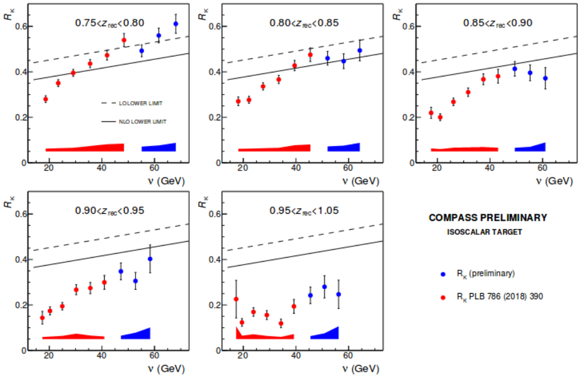
R_p



R_K

R_p





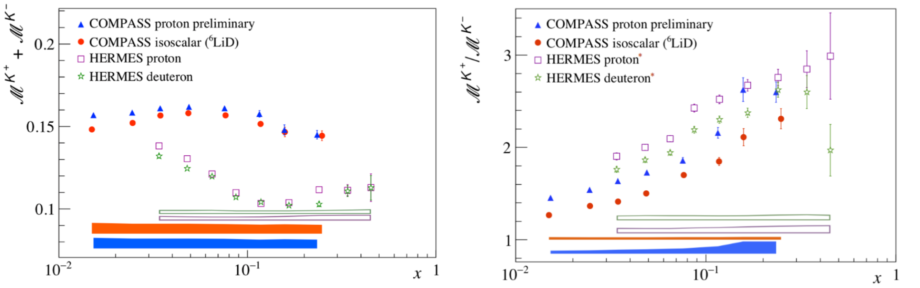
R_K vs ν in bins of z

$$R_h = \frac{M_{h^-}}{M_{h^+}} \quad \text{vs} \quad M_X, z$$

Sign of saturation at lower z?

M. Stolarski, DIS2019

Fragmentation Functions: problems...cont'd



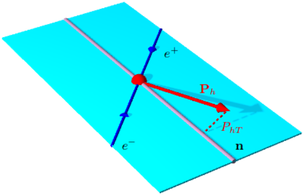
N.Pierre, DIS2019

M.Stolarski, DIS2019:

- In COMPASS the pQCD prediction fails in the corner of the phase space
- However, taking into account the observed ν and/or M_X dependence in experiments at lower energy much larger region of phase-space is affected
  - Note that selection of large Q^2 is not enough!
- This gives interesting insights:
  - It can be a reason for discrepancy between COMPASS and HERMES kaon multiplicity ratio and sum

SHOULD QCD in SIDIS BE REVISITED ?

Fragmentation Functions...cont'd; long time awaited

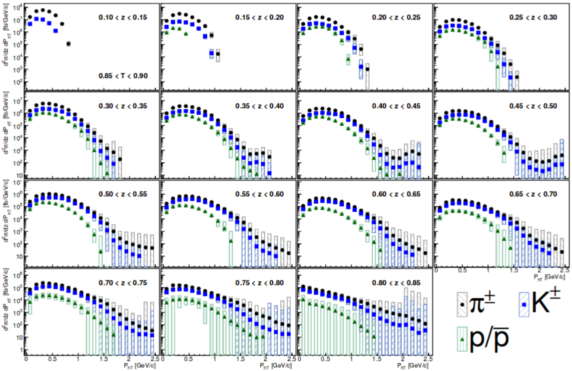


$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\rm CMS} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\rm CMS}|}$$

data of Belle Phys.Rev. D99 (2019) 112006

$$\frac{d^2\sigma}{dz dP_{\rm hT}} \text{ vs } P_{\rm hT}$$

(bins of z, T)



Take away menu

- Measurements of $g_1^{\mathrm{p}}(x, Q^2)$ and $g_1^{\mathrm{d}}(x, Q^2)$ for DIS ($Q^2 >$1 (GeV/c)^2) and nonperturbative ($Q^2 <$1 (GeV/c)^2) regions cannot be improved $\Longrightarrow$ EIC !
- The $g_1^{\mathrm{p}}(x)$ at low x and low Q^2 is clearly positive ($g_1^{\mathrm{d}}(x)$ is consistent with zero) $\Longrightarrow$ first observation of the spin effect at such low x
- The $g_1^{\mathrm{p}}(x)$ at low x is positive (and $g_1^{\mathrm{d}}(x) \approx 0$) also at $Q^2 >$1 (GeV/c)^2
- NLO QCD fit of g_1 world data gave well constrained quark distributions; gluons poorly determined. Quark helicity contribution to nucleon spin: $0.26 < \Delta\Sigma < 0.36$ but hope is in global fits (PDFs and FFs)
- Need to understand hadron multiplicites $\Longrightarrow$ FFs !
- From the COMPASS data alone:
  - first moments determined and Bjorken sum rule verified to 9% accuracy
  - flavour-singlet axial charge a_0 extracted: $a_0(Q^2$ = 3 (GeV/c)^2)= 0.32 $\pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$

    (in $\overline{\mathrm{MS}}$ identified with total contribution of quark helicities to the nucleon spin)