Spin-dependent parton distributions

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University of Warsaw

Low x 2017

Bari, June 13 – 17, 2017

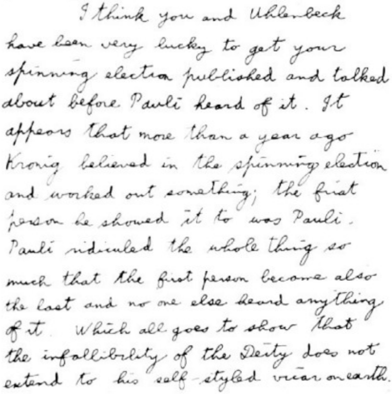
In spite of Stern–Gerlach experiment (1922)...

UPPSALA UNIVERSITET

Electron spin

Theory of the electron spin by Uhlenbeck & Goudsmit (1925)

George Uhlenbeck, Hendrik Kramers & Samuel Goudsmit



I think you and Uhlenbeck have been very lucky to get your spinning electron published and talked about before Pauli heard of it. It appears that more than a year ago Kronig believed in the spinning electron and worked out something; the first person he showed it to was Pauli. Pauli ridiculed the whole thing so much that the first person became also the last and no one else heard anything of it. Which all goes to show that the infallibility of the Deity does not extend to his self-styled vicar on earth.

Letter of B.L. Thomas to Sam Goudsmit (1926)

Read the story in:
http://lorentz.leidenuniv.nl/history/spin/goudsmit.html

Slide from Peter Oppeneer, UU

European Muon Collaboration CERN, Phys. Lett. B**206** (1988) 364:

An Investigation of the Spin Structure of the Proton in Deep Inelastic Muon–Proton Scattering

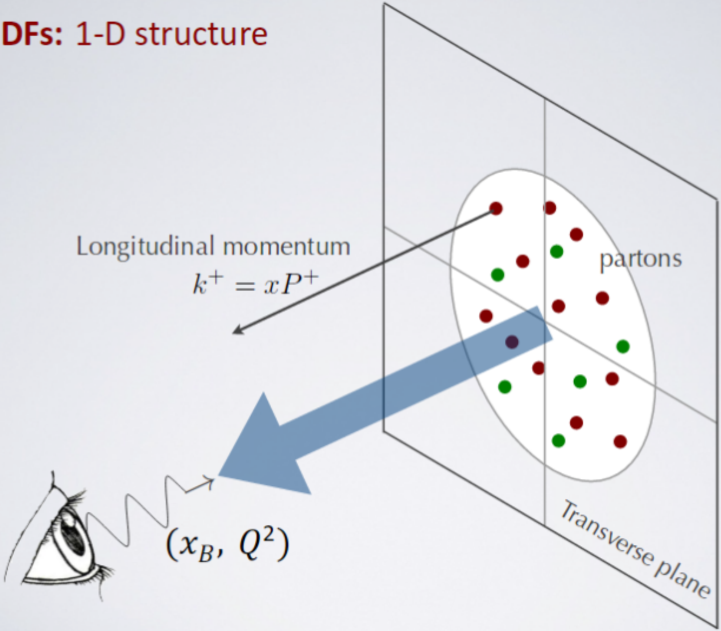
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta \mathrm{G} + \mathrm{L_q} + \mathrm{L_g}$$ **Jaffe–Manohar**

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

EMC measured: $\Delta\Sigma \sim 0.1!$

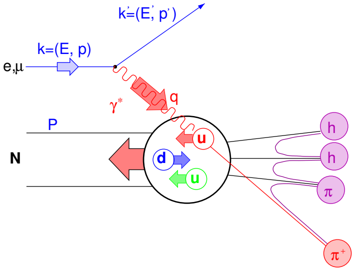
paper cited **1000+** times (exactly **1954**)

PDFs: 1-D structure



11 A. Bacchetta (Baryon 2013 Conference)

Nucleon spin structure in DIS: $\mu + \mathrm{N} \to \mu' + \mathrm{X}$

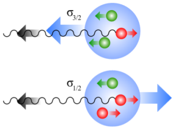


- $\dfrac{d^2\sigma}{d\Omega dE'} = \dfrac{\alpha^2}{2Mq^4}\dfrac{E'}{E}L_{\mu\nu}W^{\mu\nu}$
- Symmetric part of $W^{\mu\nu}$ – unpolarised DIS, antisymmetric – polarised DIS
- Nominally $F_{1,2}$, $q(x,Q^2) \longrightarrow g_{1,2}$, $\Delta q(x,Q^2)$ where $q = q^+ + q^-$, $\Delta q = q^+ - q^-$, but...
- ...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):



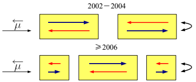
$$A_1(x,Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

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)



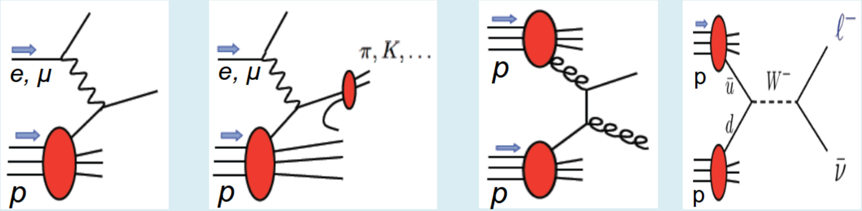
- Then $g_1(x,Q^2)$:

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

- For the deuteron target:

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

Processes available for parton helicity distributions



DIS:

$\Delta q + \Delta\bar{q}$

Δg (From Q^2 evolution of g_1)

SIDIS:

$\Delta q, \Delta\bar{q}$

Δg

pp:

$\Delta q, \Delta\bar{q}$

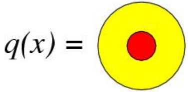
Δg

A. Bazilevsky, SPIN2016

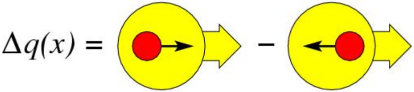
L_q??? via GPD; hints in TMD

Partonic structure of the nucleon; distribution functions

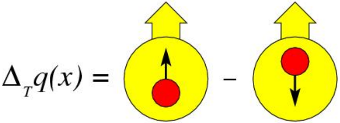
Three twist-two quark distributions in QCD and after integrating over the quark intrinsic k_t



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



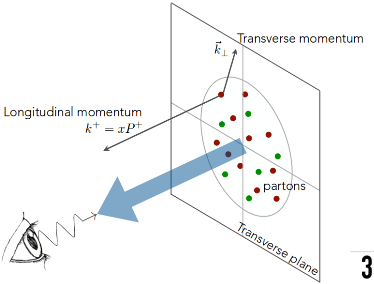
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a longitudinaly polarised nucleon;
less well known (polarised DIS $\rightarrow \mathbf{g_1(x, Q^2)}$).

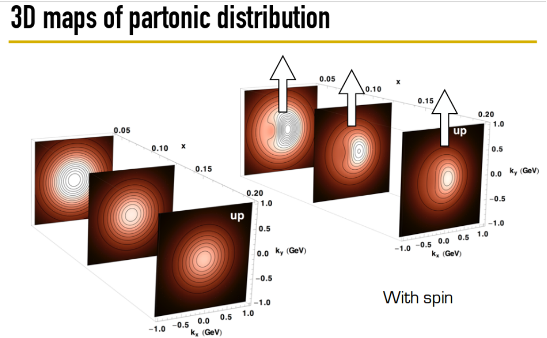


Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in a transversely polarised nucleon;
poorly known (polarised DIS $\rightarrow \mathbf{h_1(x, Q^2)}$).

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

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

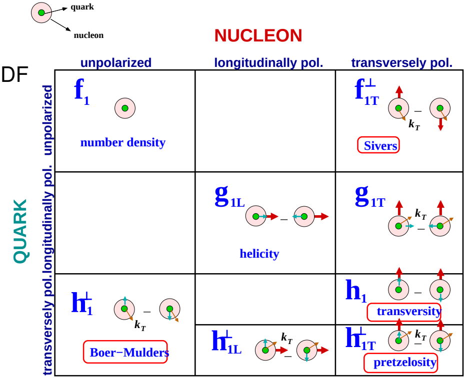




A. Bacchetta, DIS2017

Partonic structure of the nucleon; distribution functions

- In LT and considering k_{T},
  8 PDF describe the nucleon
  $\Longrightarrow$ Transverse Momentum Dependent PDF
- QCD-TMD approach valid $k_{\mathrm{T}} \ll \sqrt{Q^2}$
- After integrating over k_{T}
  only 3 survive: f_1, g_1, h_1
- TMD accessed in SIDIS and DY
  by measuring azimuthal asymmetries
  with different angular modulations
- SIDIS: e.g. $A_{\mathrm{Sivers}} \propto$ PDF $\otimes$FF
- DY: e.g. $A_{\mathrm{Sivers}} \propto$ PDF$^{\mathrm{beam}} \otimes$ PDF$^{\mathrm{target}}$



- OBS! Boer-Mulders and Sivers PDF are T-odd, i.e. process dependent

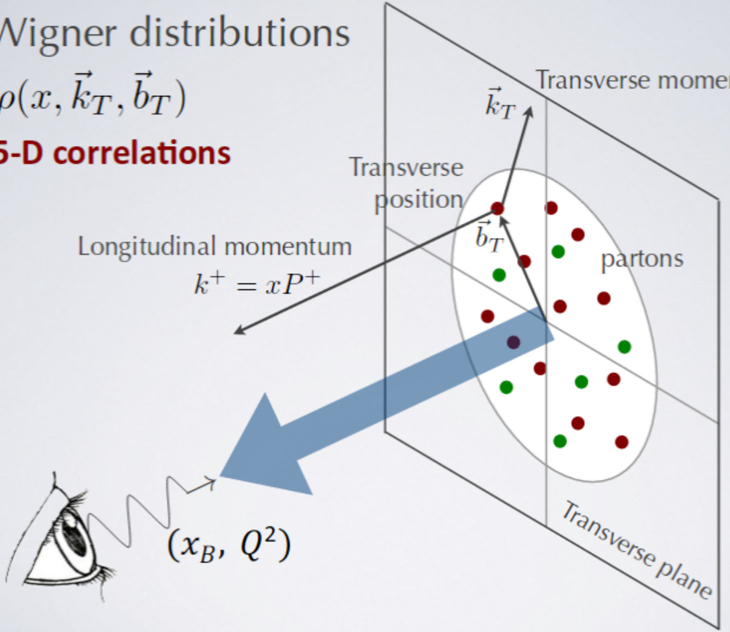
$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY}) \qquad f_{1\mathrm{T}}^{\perp}(\mathrm{SIDIS}) = -f_{1\mathrm{T}}^{\perp}(\mathrm{DY})$$

- OBS! transversity PDF is chiral-odd; may only be measured with another chiral-odd partner, e.g. fragmentation function.
- TMD parton distributions need TMD Fragmentation Functions!

Wigner distributions

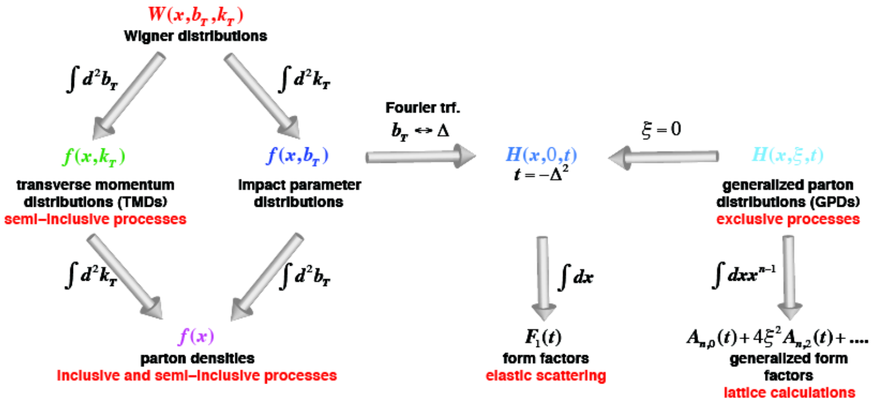
$$\rho(x, \vec{k}_T, \vec{b}_T)$$

5-D correlations



11 A. Bacchetta (Baryon 2013 Conference) *see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)*

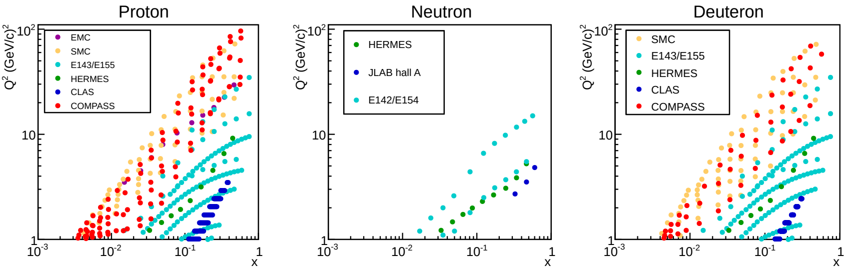
Descriptions of *pdf*^{s} in the nucleon



From “White paper”, arXiv:1212.1701

The (spin) players

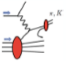
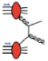
- Fixed target spin experiments:
  - JLab (Hall A, CLAS (Hall B)): polarised e of $\lesssim$ 12 GeV, polarised targets
  - CERN (COMPASS): polarised μ^+ of 160-200 GeV, polarised protons, deuterons
  - (completed) DESY (HERMES): polarised e of 27 GeV, polarised targets
- Collider spin experiments: BNL (STAR, PHENIX) polarised protons, $\sqrt{s} \lesssim$ 510 GeV



Global NLO fits

Compilation by M.Stratmann (2015 Jlab Users Meeting)

overview of recent helicity PDF fits @ NLO

latest paper					uncertainties	features & focus
NNPDF 1406.5539 Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo	✓	✗	✓	jets W's	100 MC replicas stat. approach	pp data w/ reweighing method
DSSV 0904.3821 1404.4293 de Florian, Sassot, MS, Vogelsang	✓	✓	✓	jets pions	Lagrange mult. (Hessian)	pp data fitted fast Mellin method
JAM 1403.3355 Jimenez-Delgado, Accardi, Avakian, Melnitchouk, Sato, ...	✓	✗	✗		Hessian	large x / JLab region pp soon
LSS 1010.0574 Leader, Sidorov, Stamenov	✓	✓	✗		Hessian	higher twist, Δs
BBS 1502.02517 1408.7057 Bourrely, Buccella, Soffer	✓	✗	✗		Hessian	statistical approach unpol/pol simult. fit
BB 1010.3113 Blumlein, Bottcher	✓	✗	✗		Hessian	α_s, higher twist
⋮		⋮				⋮
GRSV 9508347 0011215 Gluck, Reya, MS, Vogelsang	✓	✗	✗		✗	1st NLO analysis 1995

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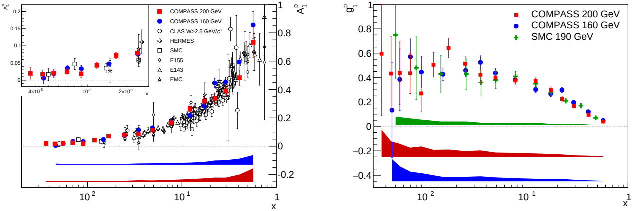
Moving towards NNLO

Higher Twist

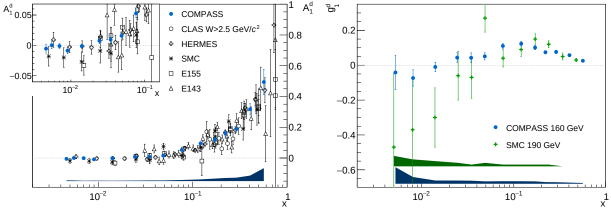
Including more probes

A. Bazilevsky, SPIN2016

Results on $A_1(x)$ and $g_1(x)$ at the measured values of Q^2



PLB 753 (2016) 18



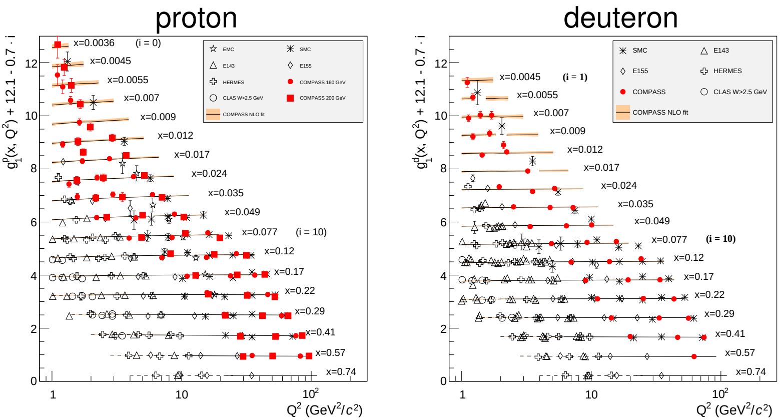
PLB 769 (2017) 034

- Good agreement of new COMPASS $A_1(x)$ and $g_1(x)$ with world data
- $g_1^{\mathrm{p}}(x)$ clearly positive at lowest measured x; $g_1^{\mathrm{d}}(x)$ compatible with zero

World data on $g_1^{\rm p}$ and $g_1^{\rm d}$, $Q^2 > 1$ (GeV/c)^2

Continuous line: 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

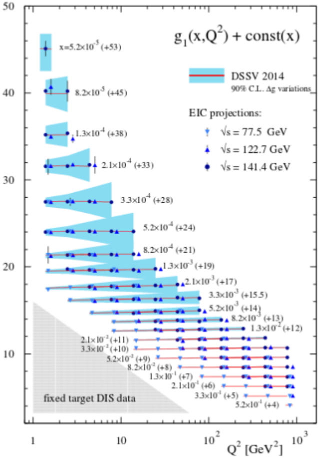


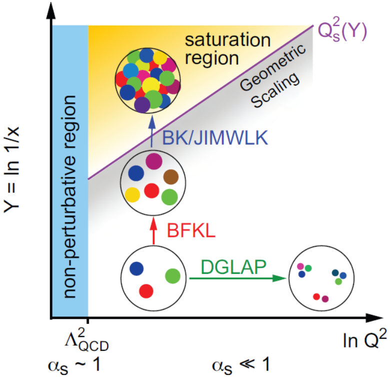
Phys.Lett.B753(2016)18

Phys.Lett.B769(2017)034

Data little sensitive to Δg

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





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

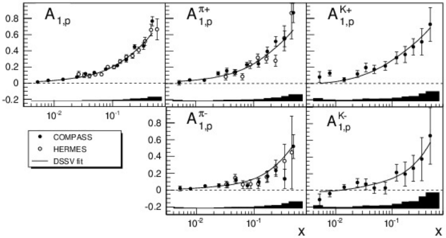
arXiv:1509.06489 "White paper", arXiv:1212.1701

Semi-inclusive asymmetries and parton distributions

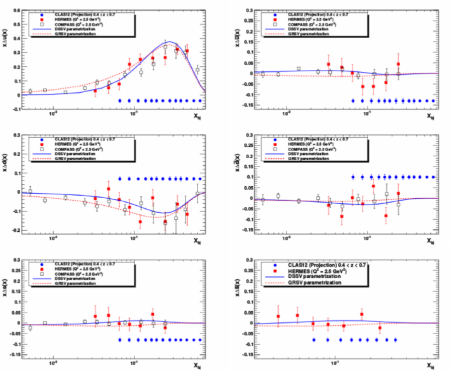
- SIDIS permits to separate q and $\bar{q}$ distributions
- COMPASS: measured on both proton and deuteron targets
  for identified, positive and negative pions and (for the first time) kaons

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

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



CLAS12. Update to E12-09-007

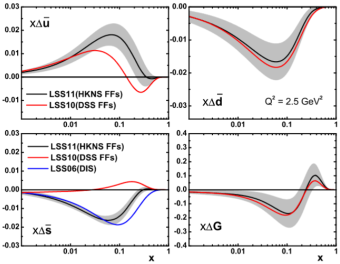


- COMPASS: LO DSS fragm. functions and LO unpolarised MRST assumed here.
- NLO parameterisation of DSSV describes the data well.

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 semi-inclusive asymmetries it is compatible with zero
  but depends upon chosen fragmentation functions. Most critical: $R_{SF} = \frac{\int D_{\bar{s}}^{K^+}(z)dz}{\int D_u^{K^+}(z)dz}$
  $\Longrightarrow$ COMPASS extracts it from multiplicities.

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

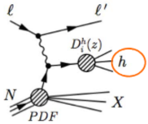


LSS, PRD D84 (2011) 014002

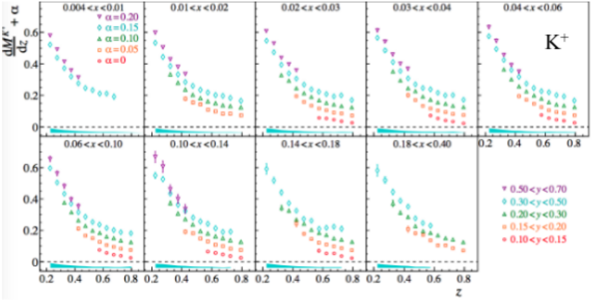
Charged hadron ($h^\pm$, $\pi^\pm$, $K^\pm$) multiplicities; identified kaons

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

$$\frac{dM^h(x,z,Q^2)}{dz} = \frac{\left(\frac{d\sigma}{dx\,dz\,dQ^2}\right)_{\rm SIDIS}}{\left(\frac{d\sigma}{dx\,dQ^2}\right)_{\rm DIS}} \stackrel{\rm LO}{=} \frac{\Sigma_q e_q^2 \left[q(x,Q^2)D_q^h(z,Q^2) + \bar{q}(x,Q^2)D_{\bar{q}}^h(z,Q^2)\right]}{\Sigma_q e_q^2 \left[q(x,Q^2) + \bar{q}(x,Q^2)\right]}$$

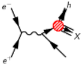


- New COMPASS results on isoscalar target, 3D bins of (x, y, z)
- Large samples; very important input for future FF global analyses

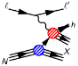


COMPASS, PLB 764 (2017) 001, PLB 767 (2017) 133

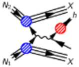
Update on Fragmentation Functions



$e^+ + e^- \to h + X$
single-inclusive annihilation (SIA)



$\ell + N \to \ell' + h + X$
semi-inclusive deep-inelastic scattering (SIDIS)



$N_1 + N_2 \to h + X$
high-p_T hadron production in pp collisions (PP)

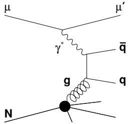
	DHESS	HKNS	JAM	NNFF1.0
SIA	☑	☑	☑	☑
SIDIS	☑	☒	☒	☒
PP	☑	☒	☒	☑
statistical treatment	Iterative Hessian 68% - 90%	Hessian $\Delta\chi^2 = 15.94$	Monte Carlo	Monte Carlo
hadron species	$\pi^\pm$, $K^\pm$, $p/\bar{p}$, $h^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$	$\pi^\pm$, $K^\pm$	$\pi^\pm$, $K^\pm$, $p/\bar{p}$
latest update	PRD 91 (2015) 014035; 1702.06353	PTEP 2016 (2016) 113B04	PRD 94 (2016) 114004	in preparation

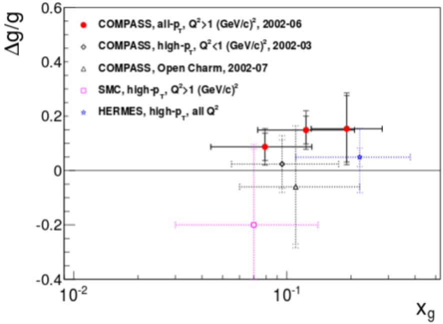
New data: BELLE [PRL 11 (2013) 062002], BABAR [PRD 88 (2013) 032001] (SIA)
HERMES [PRD 87 (2013) 074029], COMPASS [PLB 764 (2017) 1; PLB 767 (2017) 133] (SIDIS)

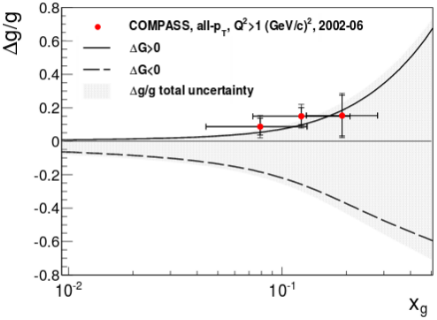
E. Nocera, DIS2017

Direct measurements of $\Delta g(x)$

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)): $A_{\gamma\mathrm{N}}^{\mathrm{PGF}} \approx \langle a_{\mathrm{LL}}^{\mathrm{PGF}} \rangle \frac{\Delta g}{g}$







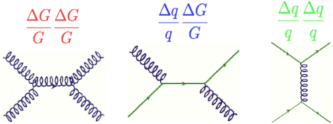
COMPASS from SIDIS on d for any $(p_{\mathrm{T}})_{\mathrm{h}}$ and at LO:

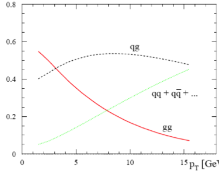
$$\Delta g/g = 0.113 \pm 0.038(\mathrm{stat.}) \pm 0.036(\mathrm{syst.}) \quad \text{at} \quad \langle Q^2 \rangle \approx 3\ (\mathrm{GeV}/c)^2, \quad \langle x_g \rangle \approx 0.10$$

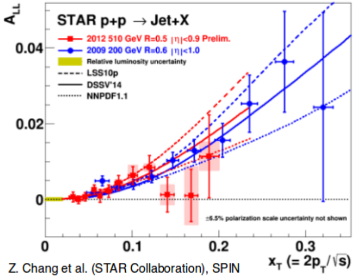
clearly positive gluon polarisation!

COMPASS, EPJC 77(2017) 209

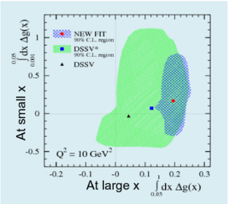
$\Delta g(x)$ from A_{LL} for π^0 production at $\sqrt{s}$=200 and 510 GeV @ RHIC

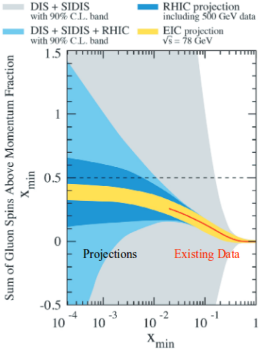






Z. Chang et al. (STAR Collaboration), SPIN 2014. (Run 12 / 510GeV)





DSSV, PRL 113 (2014) 012001
Surrow, DIS2017

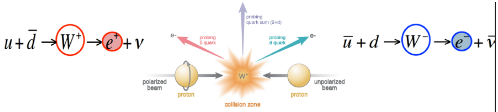
DSSV++ with 200 GeV data:

$$\int_{0.05}^{1.0} \Delta g(x)dx = 0.2^{+0.06}_{-0.07}$$

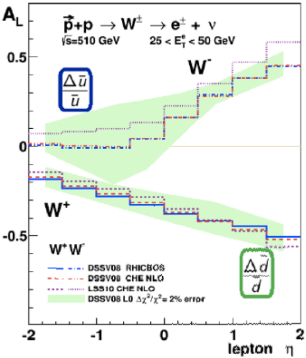
Wealth of new data on single-, double jets, π^0 prod., J/Ψ agree with this estimate DSSV14, NNPDF1.1

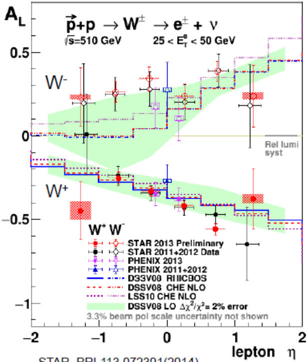
$\Delta q(x)$ from A_L for W$^{\pm}$ production at $\sqrt{s}$ = 510 GeV @ RHIC

- Direct coupling to $q\bar{q}$ of interest
- Scale set by W mass
- Efficient spin separation
- Easy detection

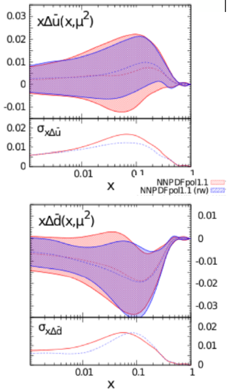


Cartoons from D.Gunarathne, DIS2015



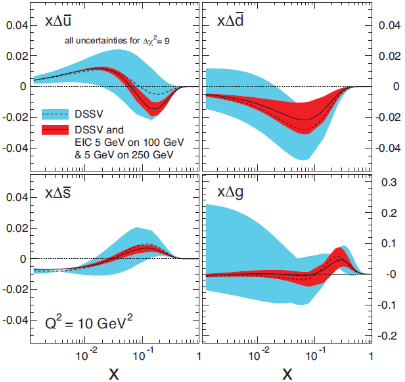


- STAR, PRL113,072301(2014)
- PHENIX, PRD93,051103(2016)



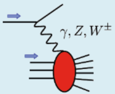
STAR, Q.Xu, DIS2017

E. Nocera, arXiv:1702.05077



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

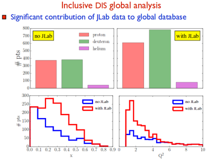
$$g_1^{W^+} = \Delta\bar{u} + \Delta d + \Delta\bar{c} + \Delta s$$
$$g_1^{W^-} = \Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}$$
$$g_5^{W^+} = \Delta\bar{u} - \Delta d + \Delta\bar{c} - \Delta s$$
$$g_5^{W^-} = -\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}$$



From "White paper", arXiv:1212.1701

E. Aschenauer, SPIN2016

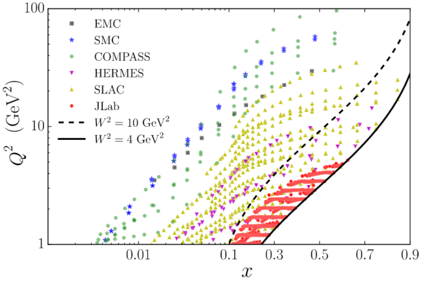
JAM NLO fit to world inclusive data ($A_\parallel$, $A_\perp$)

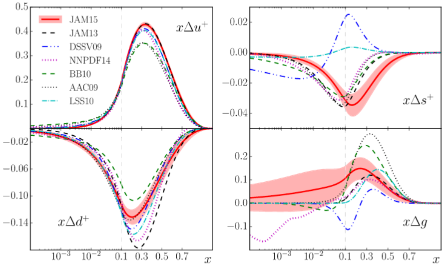


JAM: JLab Angular Momentum Collaboration

Included JLab data $W^2 > 4$ GeV^2
$\Longrightarrow$ reduced errors for valence & sea at $x > 0.1$
TMC and HT included in the fit

helicity distributions at Q^2 = 1 (GeV/c)^2



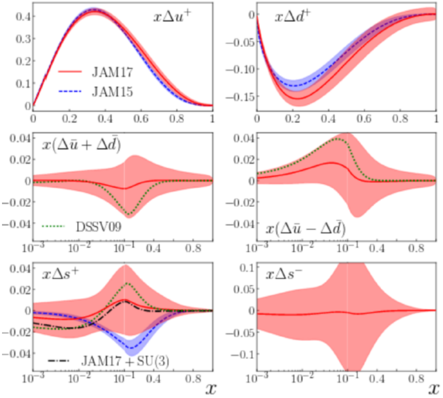


JAM, PRD 93 (2016) 074005

- $\Delta u, \Delta d$ well constraint
- Δs small and negative
- Δg poorly constraint

JAM: recent update (JAM17)

- first global QCD analysis of polarised DIS, SIDIS, SIA data to get PDFs and FF (SIA $\equiv$ Single Inclusive Annihilation, $e^+e^- \to hX$)

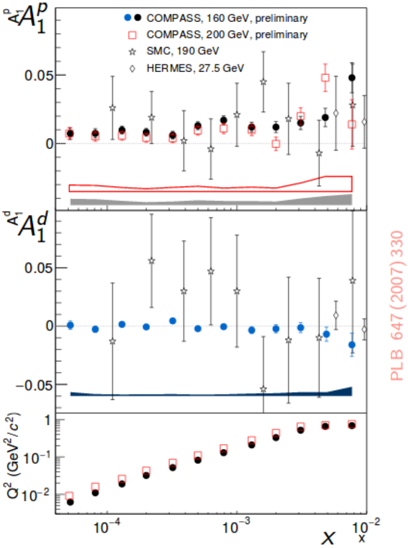


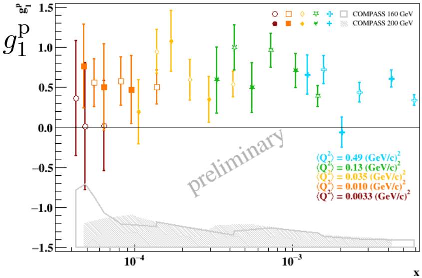
Without imposing the SU(3):

- $\Delta s \sim 0$
- $a_8 = 0.46$, i.e. 20% smaller
- $\Delta\Sigma(Q_0^2 = 1\ \mathrm{GeV}^2) = 0.36$, i.e. 25% larger

JAM, arXiv: 1705.05889

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



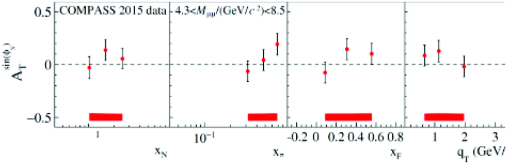


- more than 10-fold improvement over the statistical precision of the SMC
- Spin effects at low x and Q^2 absent in g_1^d but very clear in g_1^p
- Nonperturbative effects apart of parton mechanisms

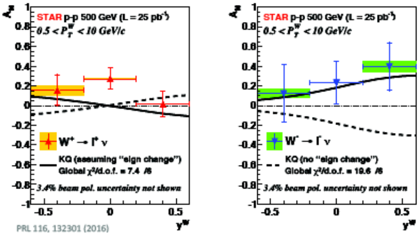
Sivers asymmetries from SIDIS and Drell-Yan processes

(slide from T. Horn, DIS2017, Spin Physics Summary talk

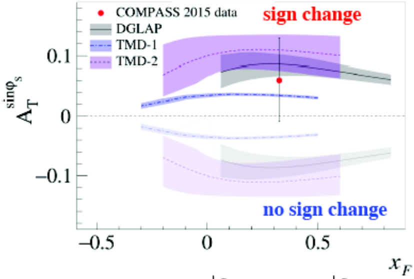
- COMPASS: first Sivers Drell-Yan measurement



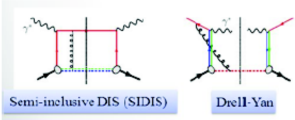
- STAR: exploratory Sivers sign-change measurement



COMPASS, arXiv:1704.00488, to appear in PRL



$$f_{1T}^{\perp q}|_{SIDIS} = -f_{1T}^{\perp q}|_{DY}$$



- Measurements from PHENIX to come

7

Take-away menu (for **now** and the future)

- **Inclusive DIS** $\Longrightarrow$ many data sets; COMPASS legacy on $g_1^{\mathrm{p,d}}(x, Q^2)$;
  NLO QCD: gluons poorly constraint
- **Gluon helicity:** nonzero evidence from jets and hadron production in pp
- **Parton helicity flavour separation:** SIDIS, W production in pp
- **Strange quark "helicity puzzle":** DIS vs SIDIS results; FFs ?
- **New multiplicity measurements** (COMPASS) $\Longrightarrow$ new FFs fits?
- **Proton "spin puzzle":** $\Delta\Sigma \sim$ 30%, ΔG substantial ?
- **New data on transversity, TMDs,...**
- **Spin effects clearly seen** in the $g_1^{\mathrm{p}}(x, Q^2)$ at low x, $Q^2 < 1$ (GeV/c)^2
- Nearest future: orbital angular momentum constraint by DVCS ?
- Nearest future: new data at large x from JLab at 12 GeV
- More distant future: low x data from EIC

Spin-dependent parton distributions: outlook

Per analogiam:

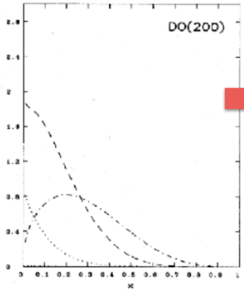
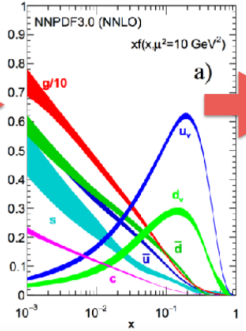


FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_s(x)$ (dotted line).



From M. Ubiali, DIS2017