Longitudinal Spin Structure of the Nucleon
COMPASS Legacy

Yann Bedfer
CEA/DPhN Saclay

September 11, 2017

COMPASS @ *DSPIN*-17

- Longitudinal spin structure
  - Artem Ivanov: Tuesday AM
    Longitudinal target spin dependent azimuthal asymmetries in SIDIS
- Fragmentation
  - Nikolai Mitrofanov: Tuesday AM
    Multiplicities of charged hadrons, pions and kaons in DIS
- TMD
  - Franco Bradamante: TSAs in SIDIS
  - Michael Pešek: TSAs in Drell-Yan
  - Jan Matoušek: q_T-weighted TSAs in Drell-Yan
- GPD
  - Andrzej Sandacz: DVCS and exclusive π^o
  - Bohdan Marianski TSAs in exclusive vector meson production

Partonic structure of the nucleon

- Twist-2 PDFs, integrated over k_T ($k_T = parton\ intrinsic\ transverse\ momentum$)

  $\Rightarrow$ Three parton distributions:

  - Parton momentum DF $q(x)$
  - $\Delta q(x)$ for a longitudinally polarised Nucleon *via* Structure Function $g_1(x, Q^2)$
  - $\Delta_T q(x)$ for a transversally polarised Nucleon

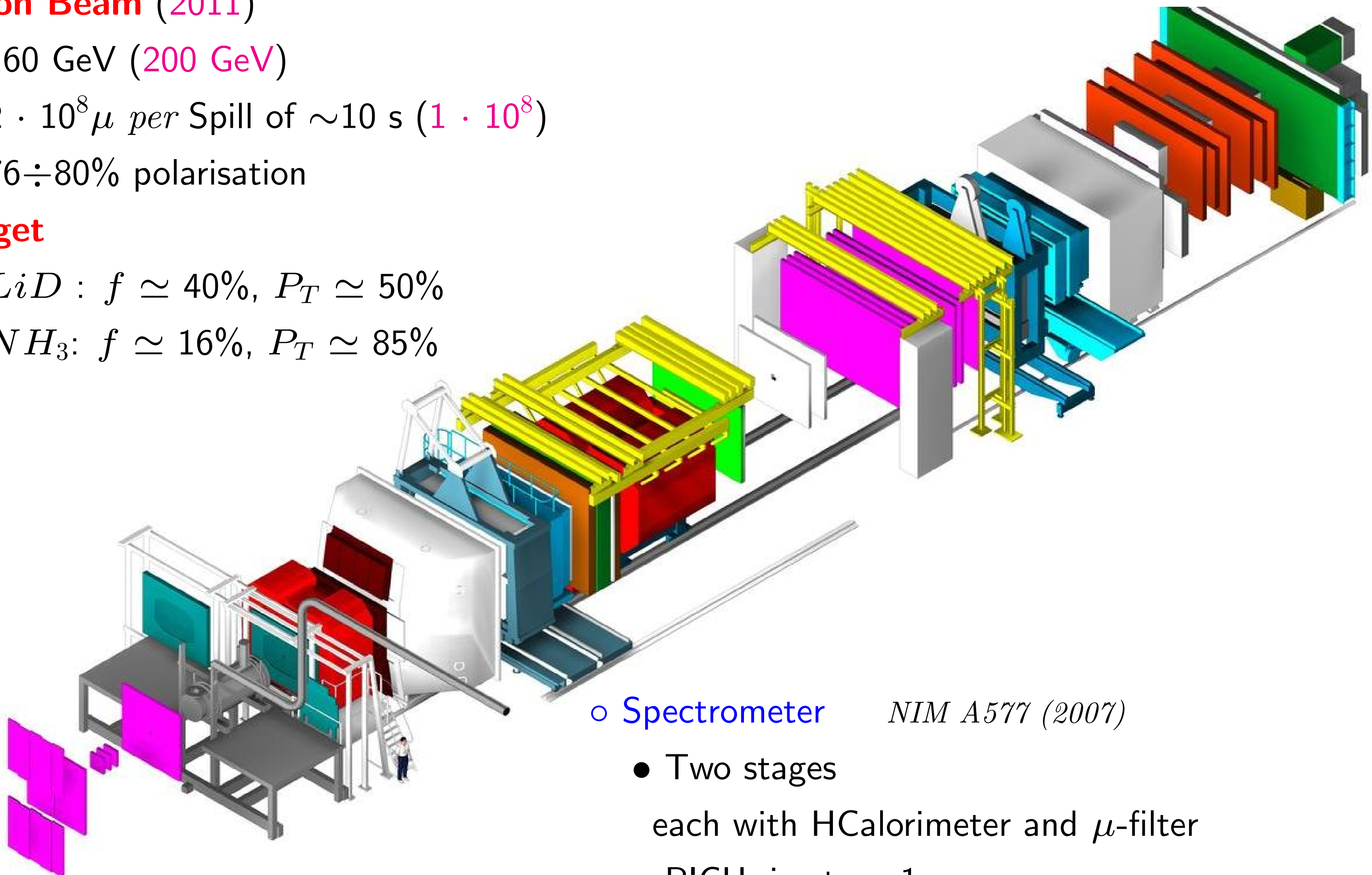
- $\Delta_T q(x)$: See talk by F. Bradamante at this conference

- Finite $A_{UL}^{sin\phi_R}$ in LSA of di-hadron production, sensitive to collinear twist-3 PDF and FF

  See talk by A. Ivanov at this conference

COMPASS: Spectrometer

- **Muon Beam** (2011)
  - 160 GeV (200 GeV)
  - $2 \cdot 10^8 \mu$ *per* Spill of ∼10 s ($1 \cdot 10^8$)
  - 76÷80% polarisation
- **Target**
  - LiD : $f \simeq 40\%$, $P_T \simeq 50\%$
  - NH_3: $f \simeq 16\%$, $P_T \simeq 85\%$



- Spectrometer *NIM A577 (2007)*
  - Two stages
    each with HCalorimeter and μ-filter
  - RICH: in stage 1
  - ECalorimeters(1&2): since 2008

Double Spin Asymmetry Measurement

- **Simultaneous** recording of the two spin states in oppositely polarised target cells. . .

. . . 2 cells: $\mathbf{1/2} \uparrow \mathbf{1/2} \downarrow \quad \Longleftarrow \; 8\, hours \; \Longrightarrow \quad \mathbf{1/2} \downarrow \mathbf{1/2} \uparrow$

. . . 3 cells: $\mathbf{1/3} \uparrow \mathbf{2/3} \downarrow \mathbf{1/3} \uparrow \quad \Longleftarrow \; 24\, hours \; \Longrightarrow \quad \mathbf{1/3} \downarrow \mathbf{2/3} \uparrow \mathbf{1/3} \downarrow$

  - Reversal by **target-field** rotation to cancel acceptance diff

$$\frac{\boldsymbol{A}^{\parallel}}{\boldsymbol{D}} = \frac{1}{|\boldsymbol{P_\mu P_T}|\,\boldsymbol{f}\,\boldsymbol{D}} \frac{1}{2} \left(\frac{\boldsymbol{N}^{\Uparrow\downarrow} - \boldsymbol{N}^{\Uparrow\uparrow}}{\boldsymbol{N}^{\Uparrow\downarrow} + \boldsymbol{N}^{\Uparrow\uparrow}} + \frac{\boldsymbol{N}^{\Uparrow\downarrow} - \boldsymbol{N}^{\Uparrow\uparrow}}{\boldsymbol{N}^{\Uparrow\downarrow} + \boldsymbol{N}^{\Uparrow\uparrow}} \right) \quad \boldsymbol{D} = Depolarisation\ factor$$

LiD: $\boldsymbol{P_\mu} \times \boldsymbol{D} \times \boldsymbol{P_T} \times \boldsymbol{f} \simeq$ 80% × 60% × 50% × 40% ≃ 10% *(typical values)*

NH_3: . . . $\boldsymbol{P_T} \times \boldsymbol{f} \simeq$ . . . 85% × 16% ≃ 6%

- Reversal *via* re-polarisation once per year to cancel **target-field**/acceptance correlation

- f corrected for spin-independent radiative processes: TERAD

- $A_1 \simeq A^{\parallel}/D$ corrected for spin-dependent radiative processes: POLRAD

Method of extraction

- $g_1^{\rm p,d}(x, Q^2)$ is extracted as:

$$g_1^{\rm p,d}(x, Q^2) = A_1^{\rm p,d}(x, Q^2)\frac{F_2^{\rm p,d}(x, Q^2)}{2x(1 + R(x, Q^2))}$$

- Input $F_2^{\rm p,d}(x, Q^2)$: from NMC parametrisation at $Q^2 > 0.2$ GeV^2 (*PRD 58 (1998) 112001*)

  at $Q^2 < 0.2$ GeV^2: from the model based on the GVMD concept (*PLB 295 (1992) 263*)

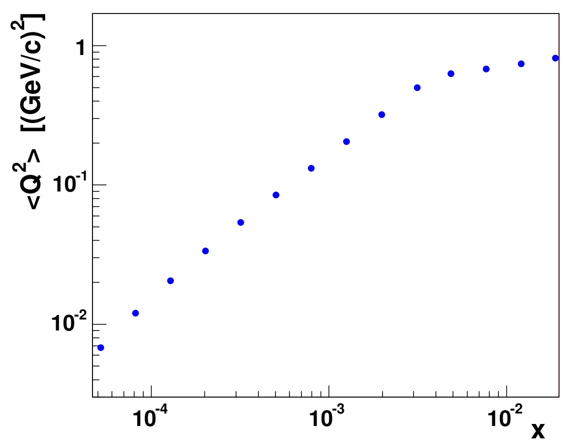
- $R(x, Q^2)$: R1998 from SLAC (*PLB 452 (1999) 194*)

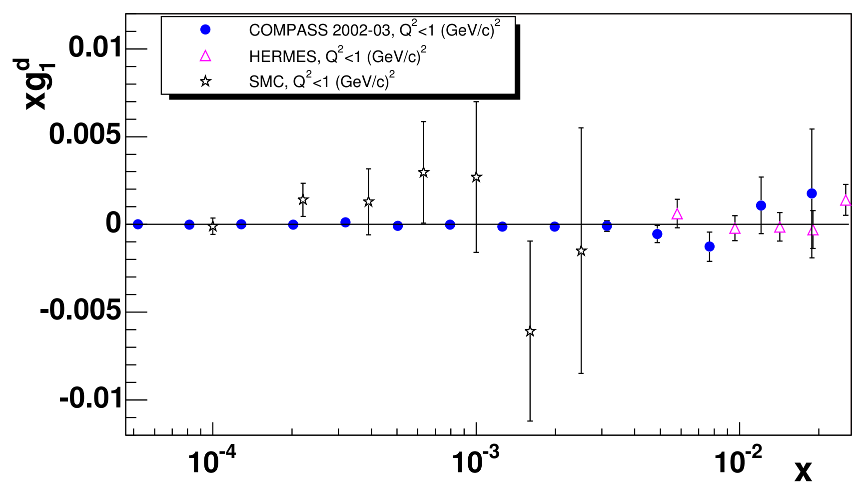
  suitably extended to low Q^2, (*PLB 647 (2007) 330*)

- Maximum systematic uncertainties on A_1
  - At low Q^2: from $D(R)$, ∼(0.01 - 0.39)D (mult.)
    and false asymm., 1.5$\sigma_{\rm stat.}$ (additive)
  - At high Q^2: from P_B, P_T, ∼0.05P_B, P_T (mult.)
    and false asymm., $< 0.8\sigma_{\rm stat.}$ (additive)

g_1^{d} at low Q^2

- COMPASS Coll., Phys. Lett. B **647** (2007)





- More than ten-fold improvement over SMC

- Consistent with 0 for $5 \times 10^{-}5 < x \lesssim 3 \times 10^{-}2$

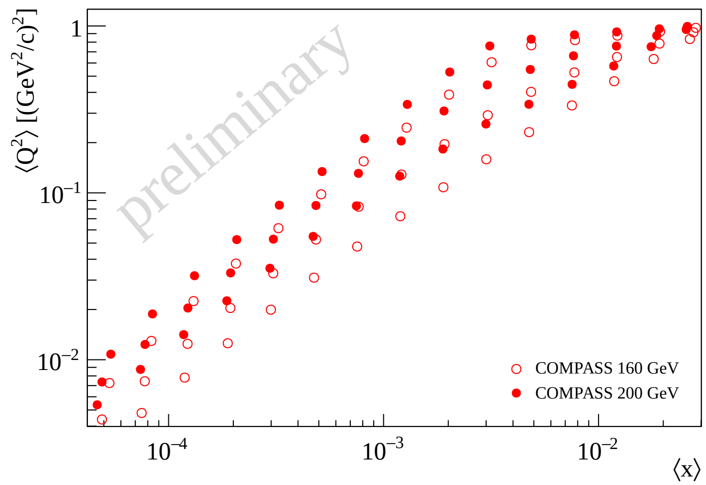
- Tend to indicate that ΔG is small. Would then rule out large ΔG solution to the spin crisis,

  via: $\Sigma = \Sigma_{naive\,QM} - N_f \alpha_S(Q^2)/2\pi \Delta G(Q^2)$

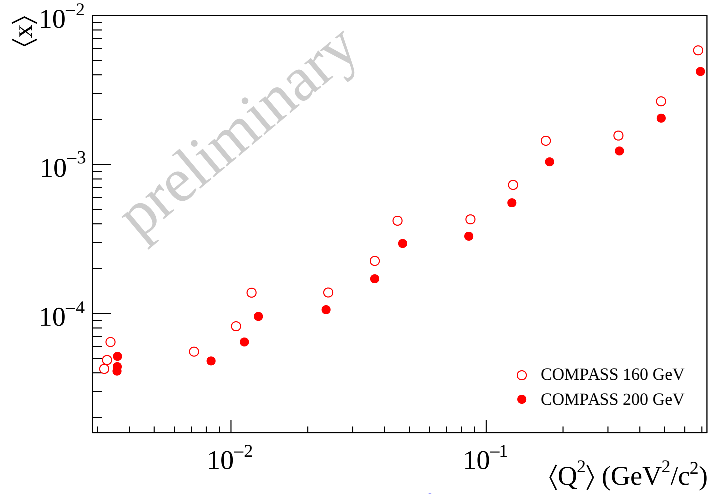
  (see *e.g.* A. Thomas, Int. J. Mod. Phys. E **18** (2009))

g_1^{p} at low Q^2

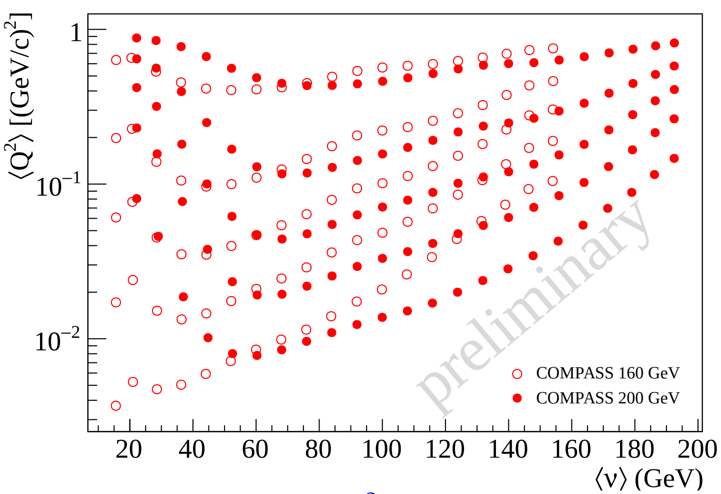
- Kinematic coverage:



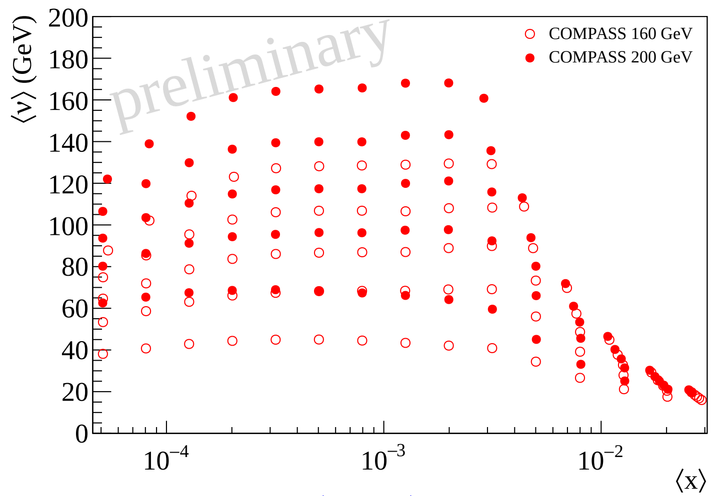
(Q^2, x)



(x, Q^2)



(Q^2, ν)



(ν, x)

g_1^{p} at low Q^2: data sample

- Reconstructed event: Small scattering angle
  - $\Rightarrow$ No way to be strictly inclusive and stay within polarised target cells
  - $\Rightarrow$ Require one extra outgoing charged particle

  Doesn't bias asymmetry at low x (see SMC Coll., Phys. Rev. D **58** (1998) 112001)

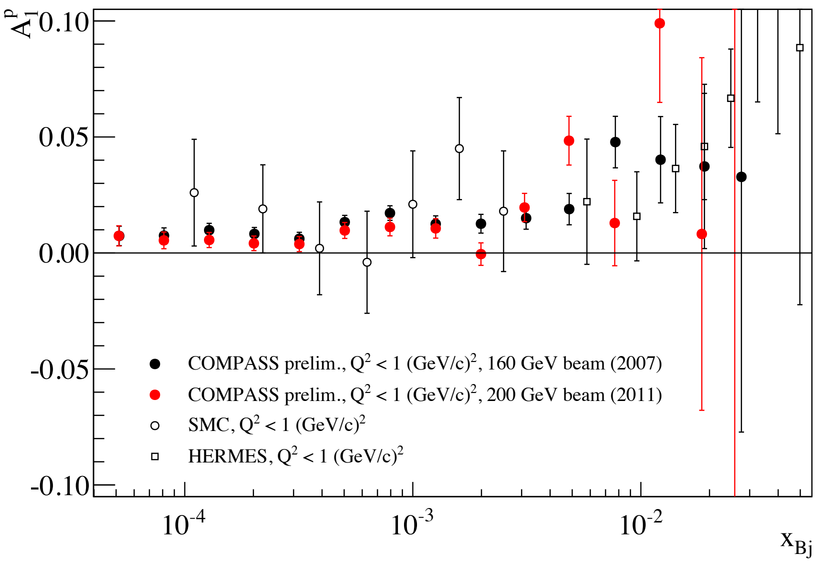
- Kinematic cuts
  - $x > 4 \times 10^{-5}$ (at smaller x uncertainties become too large)
  - $0.1 < y < 0.9$ (bad reconstruction @ low y, large rad. corr. at high y)
  - Above cuts result in: $W \gtrsim 5$ GeV

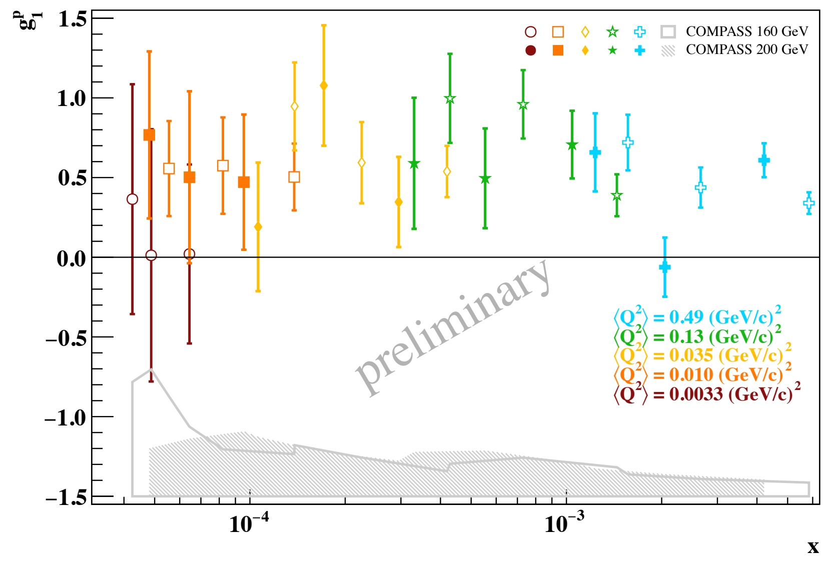
- Removed $\mu e \to \mu e$ events, around $x = m_e/M_p = 5.45 \times 10^{-4}$

- Final sample: 447 Mevnts @ 160 GeV + 229 Mevents @ 200 GeV

  $\sim$ 150 $\times$ SMC statistics

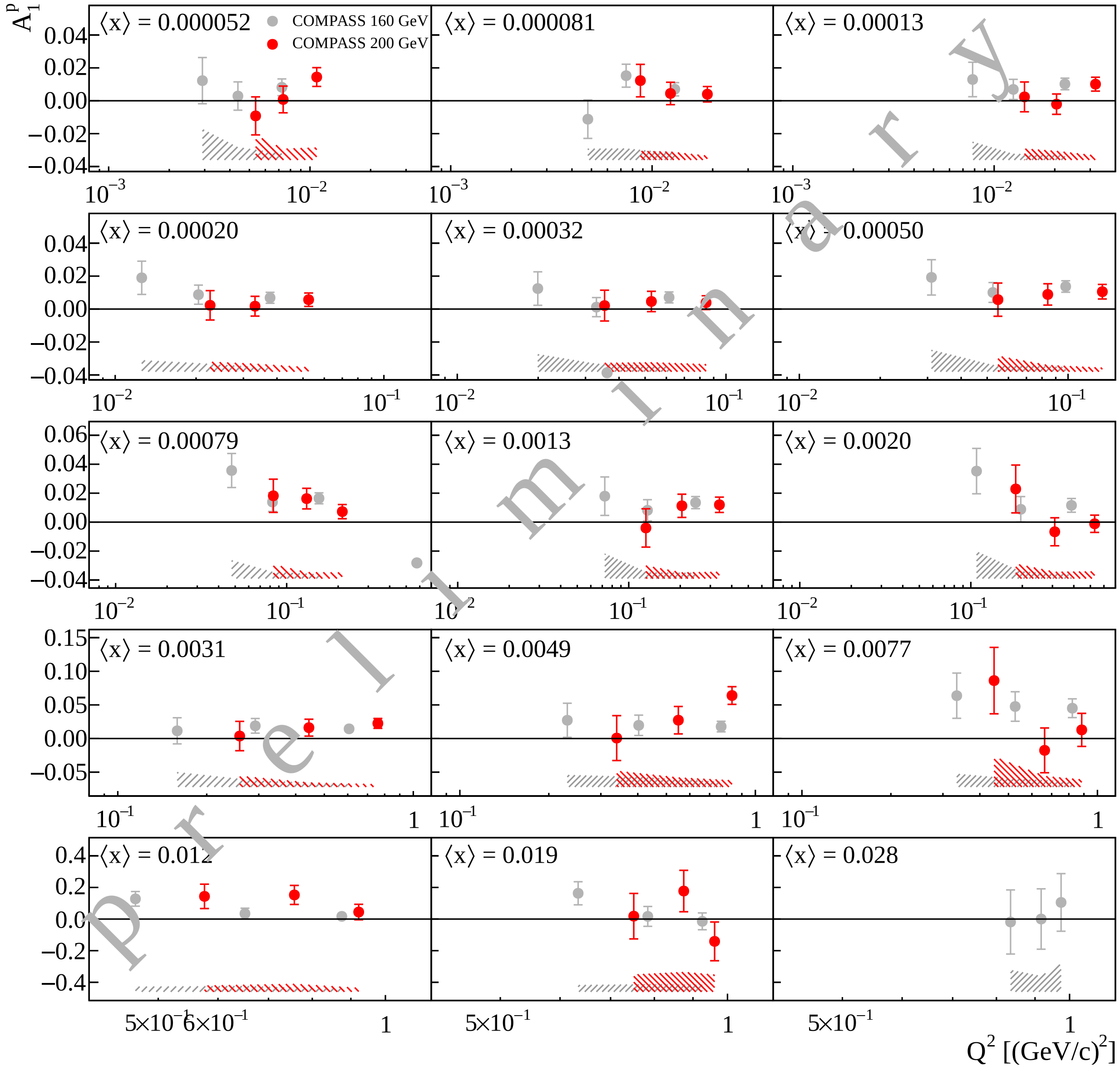
Low Q^2: results on $A_1^{\rm p}(x, Q^2)$





- More than ten-fold improvement over the statistical precision of SMC.
- Clear spin effects at low x and Q^2

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



Importance of g_1^{p} at low x, Q^2: results on $A_1^{\mathrm{p}}(x, Q^2)$

- At low x: strong increase of parton density with decreasing x
  $\Rightarrow$ parton recombination effects

- BUT: in fixed-target experiments low x correlated with low Q^2 region
  $\Rightarrow$ non-perturbative effects must be considered

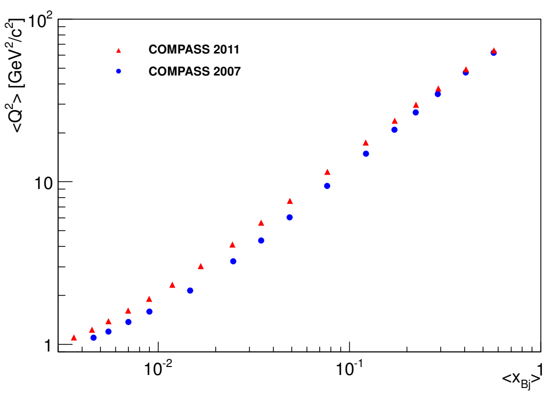
- Attempts to describe that region phenomenologically:
  - B. Badelek, J. Kiryluk, J. Kwiecinski, Phys. Rev. D**61** (2000) 014009.
  - B. Badelek, J. Kwiecinski, B. Ziaja, Eur. Phys. J. C**26** (2002) 45.
  - B.I. Ermolaev, M. Greco, S.I. Troyan, Eur. Phys. J. C**50** (2007) 823;
    ibid. C**51** (2007) 859.
  - W. Zhu, J. Ruan, Int. J. Mod. Phys. E **24** (2015) 1550077.

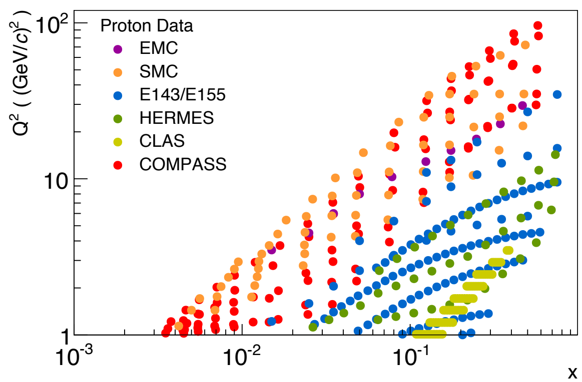
- g_1 at low Q^2 needed for Radiative Corrections

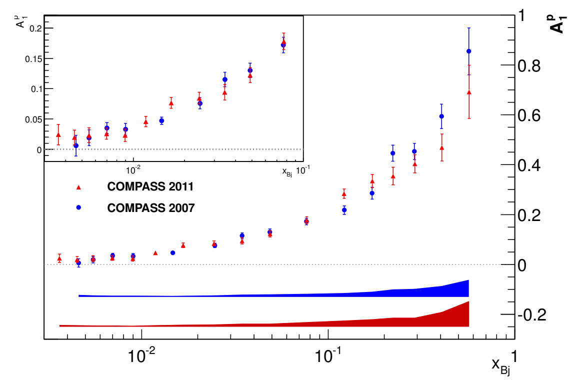
g_1^{p} at high Q^2: data samples

- Measurements at incident E $=$ 200 GeV: Phys. Lett. B **753** (2016) 18
- Complementing earlier data at E $=$ 160 GeV: (PLB 690 (2010) 466)

  Reaching lower x and higher Q^2



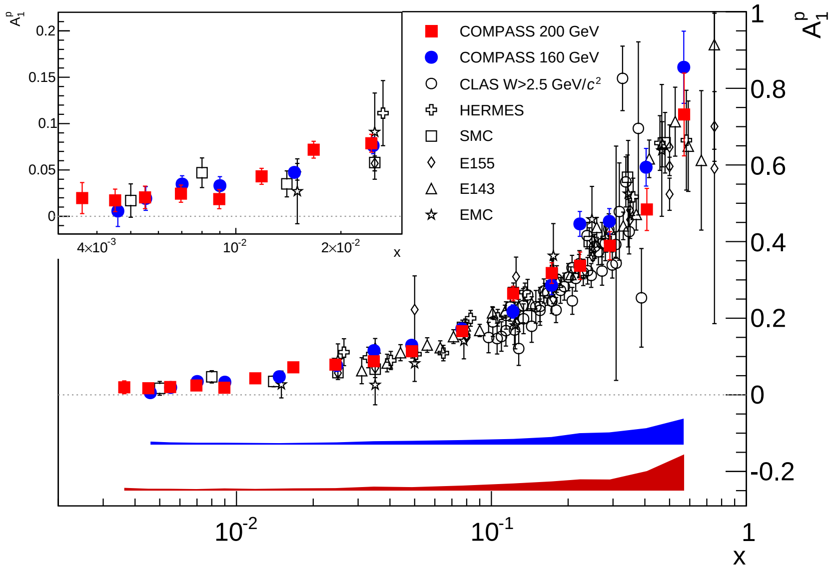


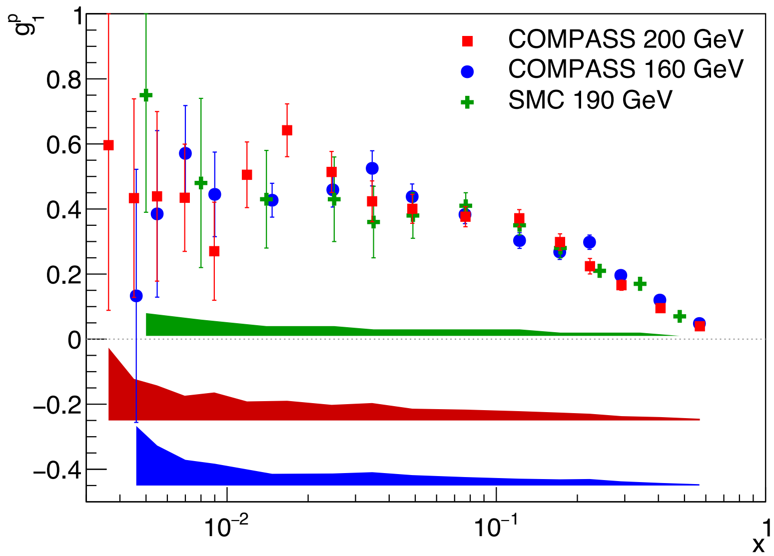


- Results on A_1^{p} at both energies agree well

Results on A_1^{p} and g_1^{p}

- A_1^{p} and g_1^{p} shown at the measured values of Q^2

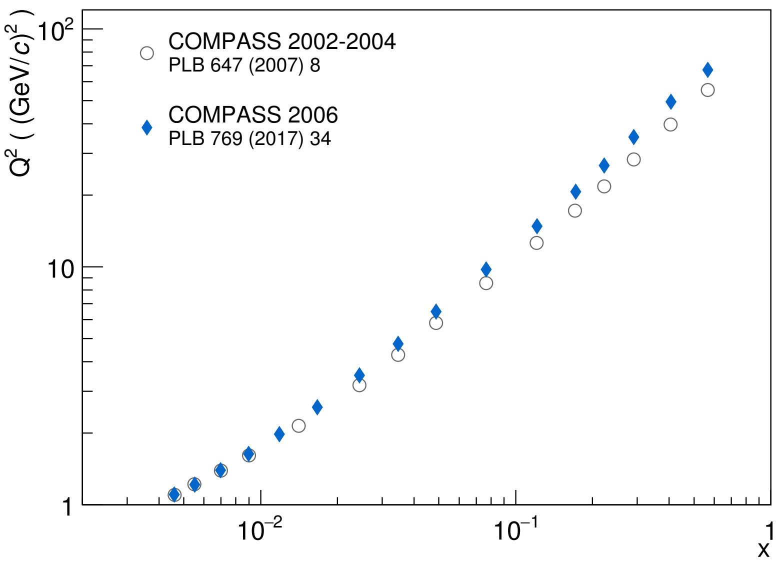


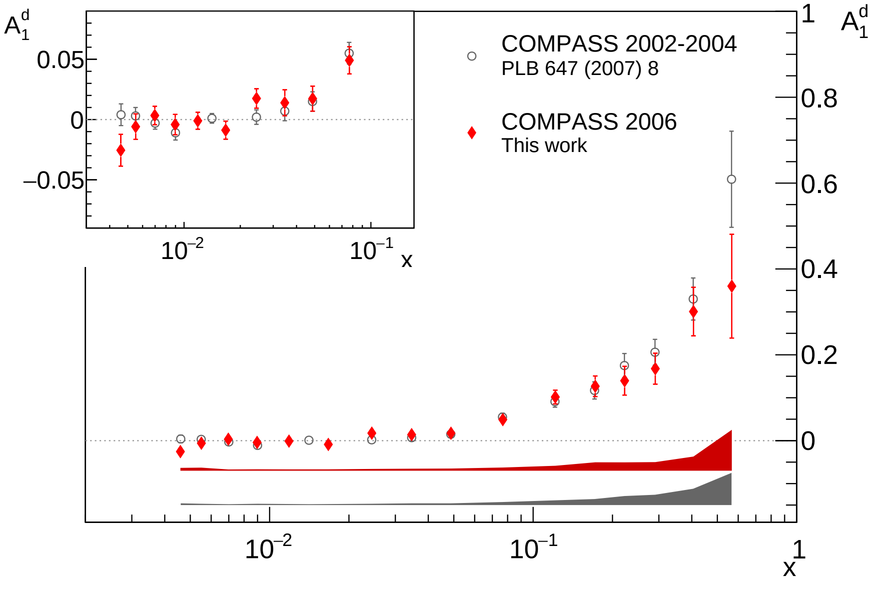


- Good agreement with world data
- g_1^{p} clearly positive at lowest measured values of x

$g_1^{\rm d}$ at high Q^2: data samples

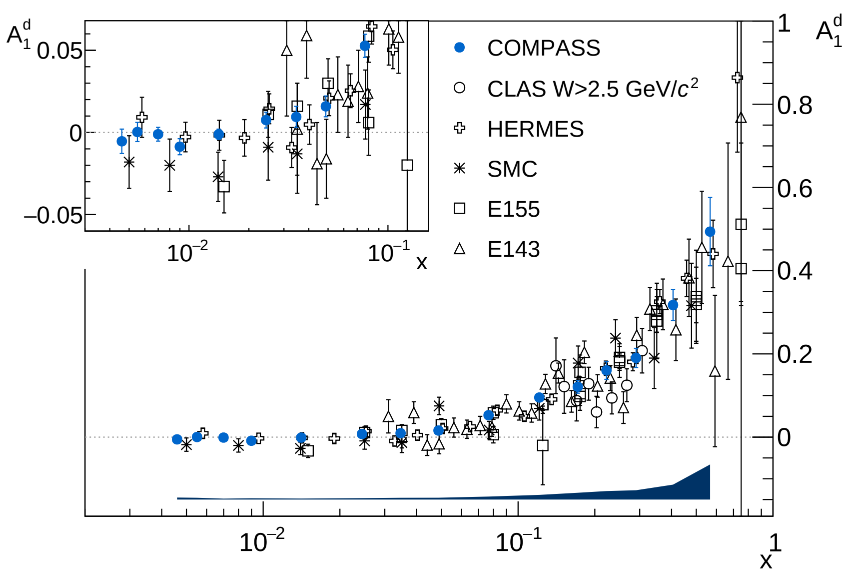
- Combined data, all @ 160 GeV: Phys. Lett. B **769** (2017) 34
- Results on $A_1^{\rm d}$ agree very well

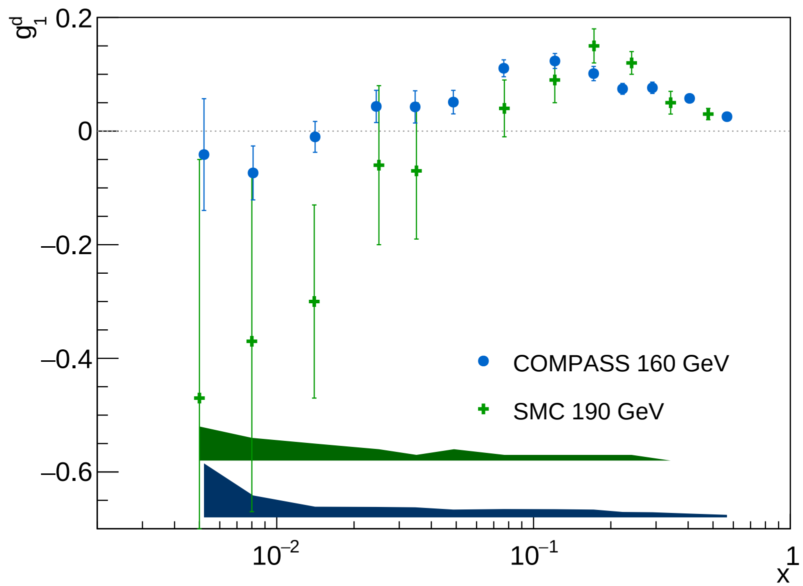




Results on A_1^d and g_1^d

- A_1^d and g_1^d shown at the measured values





- Good agreement of A_1^d and g_1^d with world data

- g_1^d compatible with zero at lowest measured values of x,

  contrary to hints from SMC

NLO QCD fit: conditions

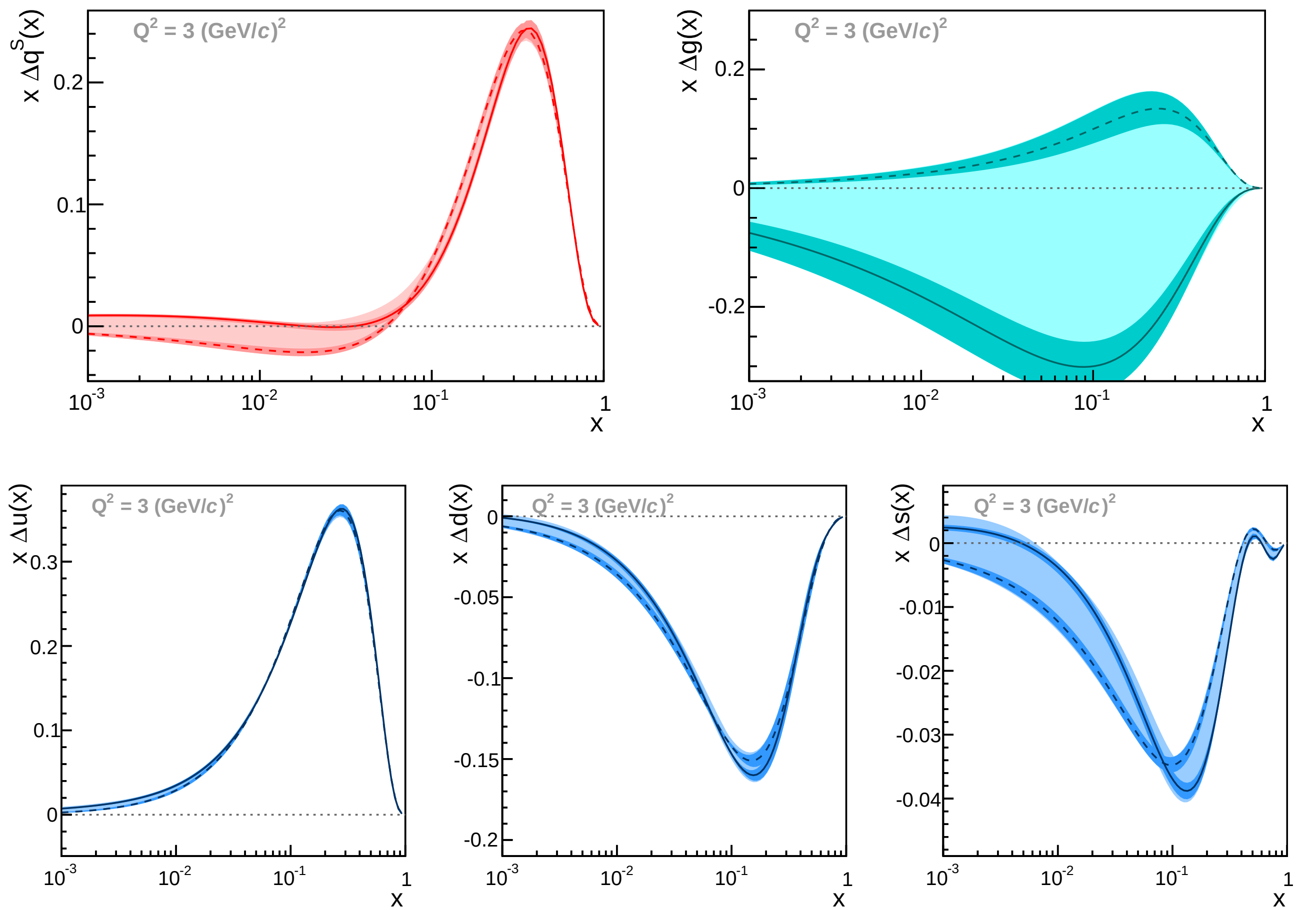
- Phys. Lett. B **753** (2016), updated by Phys. Lett. B **769** (2017)
- A fit of the g_1^{p}, g_1^{d}, $g_1^{{}^3\mathrm{He}}$ inclusive data
- $\overline{\mathrm{MS}}$ scheme
- $W^2 < 10$ GeV^2 excluded
- Number of data points total/COMPASS: 495/138
- Fitted: Δg, $\Delta q_0 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$, gluons, singlet
  $\Delta q_3 = \Delta(u+\bar{u}) - \Delta(d+\bar{d})$, nonsinglet
  $\Delta q_8 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) - 2\Delta(s+\bar{s})$ nonsinglet
- Parametrisation at input scale Q^{o}:

$$\Delta f_k(x) = \eta_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)\,dx}, \quad (k = 0, 3, 8, g)$$

$\eta_k =$ first moment of $\Delta f_k(x)$ at Q^{o}

- Number of free parameters in the fitted PDFs: 11
- Only statistical errors taken, normalisations of each data set varied
- Positivity required at every iteration: $|\Delta q+\bar{q}(x)| \leq |q+\bar{q}(x)|$, $|\Delta g(x)| \leq |g(x)|$ at Q^{o}
- Systematics: free/fix γ_k's, vary Q^{o}

NLO QCD fit: results



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

First moments of g_1 and singlet axial charge a_0

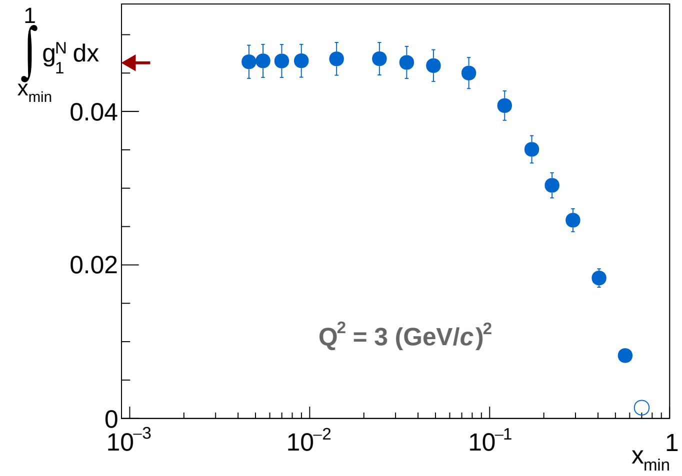
- First moments Γ_1^{p}, Γ_1^{d}, Γ_1^{N}

  where $\Gamma_1^{\mathrm{i}}(Q^2) = \int_0^1 g_1^{\mathrm{i}}(x,Q^2)\,dx$

- In particular:

$$\Gamma_1^{\mathrm{N}}(Q^2) = 1/36\,[4a_0\,C_{\mathrm{S}}(Q^2) + a_8\,C_{\mathrm{NS}}(Q^2)]$$

$$= \int_0^1 \frac{g_1^{\mathrm{d}}(x,Q^2)}{1-1.5\omega_D}\,dx$$



- In the $\overline{\mathrm{MS}}$: $a_0 = \Delta\Sigma = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$

- From COMPASS data alone:

  $\Gamma_1^{\mathrm{N}}(Q^2 = 3\mathrm{GeV}^2) = 0.046 \pm 0.002_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.005_{\mathrm{evol.}}$

- From COMPASS data alone (and still a_8 from Phys. Rev. D **82** (2010):

  $a_0(Q^2 = 3\mathrm{GeV}^2) = 0.32 \pm 0.02_{\mathrm{stat.}} \pm 0.04_{\mathrm{syst.}} \pm 0.05_{\mathrm{evol.}}$

  (consistent with value from the COMPASS NLO QCD fit of world data).

First moments of $g_1^{\rm NS}$ and Bjorken sum rule

- Non-singlet structure function:

$$g_1^{\rm NS} = g_1^{\rm p}(x, Q2) - g_1^{\rm n}(x, Q2)$$

- Bjorken sum rule:

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

- $g_1^{\rm NS}$ calculated, NLO QCD fitted (only Δq_3),

  evolved to $Q^2 = 3{\rm GeV}^2$

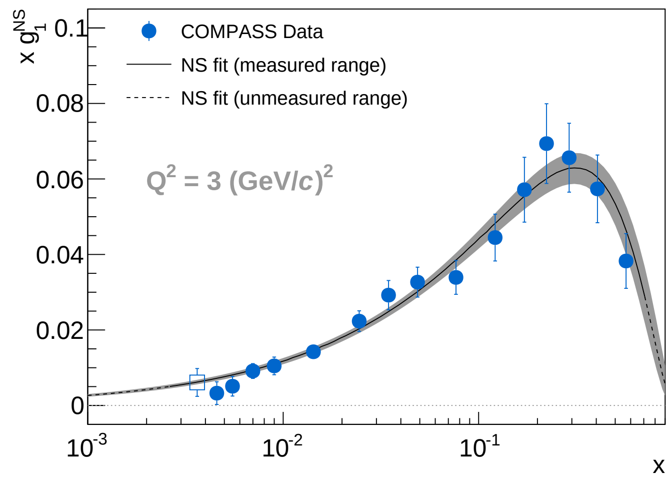
  and fit-extrapolated $x \to 0, 1$:

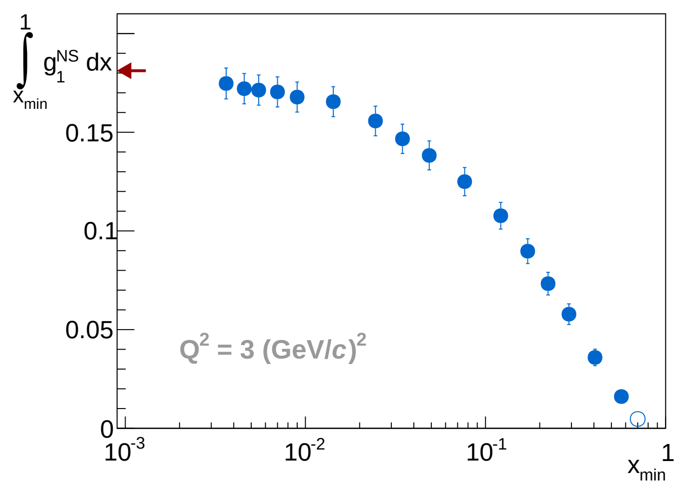
$$\Gamma_1^{\rm NS}(Q^2) = 0.192 \pm 0.007_{\rm stat.} \pm 0.015_{\rm syst.}$$

$$\left|\frac{g_{\rm A}}{g_{\rm V}}\right| = 1.29 \pm 0.05_{\rm stat.} \pm 0.10_{\rm syst.}$$

- Neutron β decay gives: $|gA/gV|$ =1.2701 $\pm$ 0.002

  PDG, PRD86 (2012) 010001

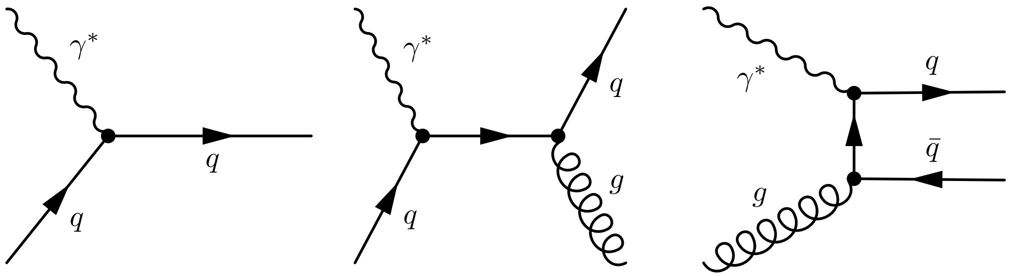




- This validates the Bjorken sum rule with an accuracy of 9%

Δg: "direct" measurement

- Re-analysis of polarised deuteron data: COMPASS coll., Eur. Phys. J. C **77** (2017) no.4, 209



- Δg accessed *via* PGF

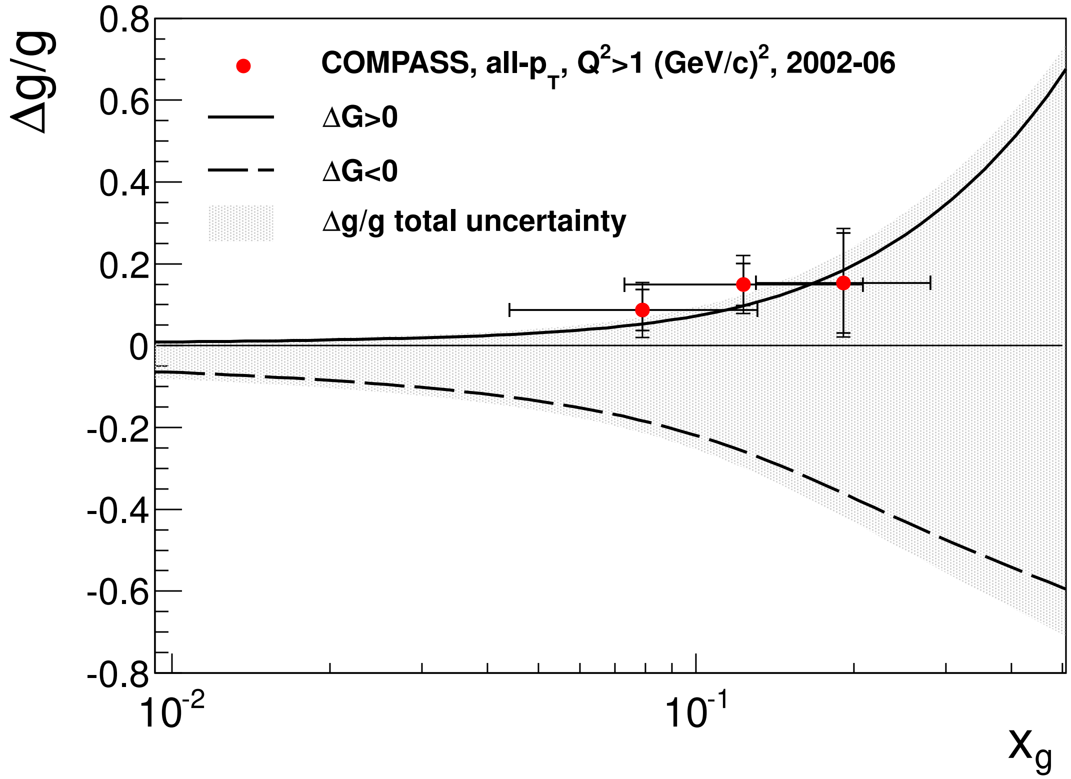
- Double spin asymmetries of single inclusive hadron in DIS
  over a wide range in p_T, $0.05 < p_T < 2.5$ GeV/c

- LO order interpretation:
  - Hadron level $\longrightarrow$ parton level *via* LEPTO Monte Carlo
  - 1.6 gain in statistical and systematics precision
  - $\Delta g/g = 0.113 \pm 0.038_{\text{stat.}} \pm 0.035_{\text{syst.}}$, $\langle Q^2 \rangle = 3\text{GeV}^2$, $\langle x_g \rangle = 0.10$

Δg: "direct" measurement (*cont'd*)

- LO "direct" measurement, here in 3 x_g bins, compared to NLO QCD fit

  (*Note: 1st and 2nd bin are correlated.*)



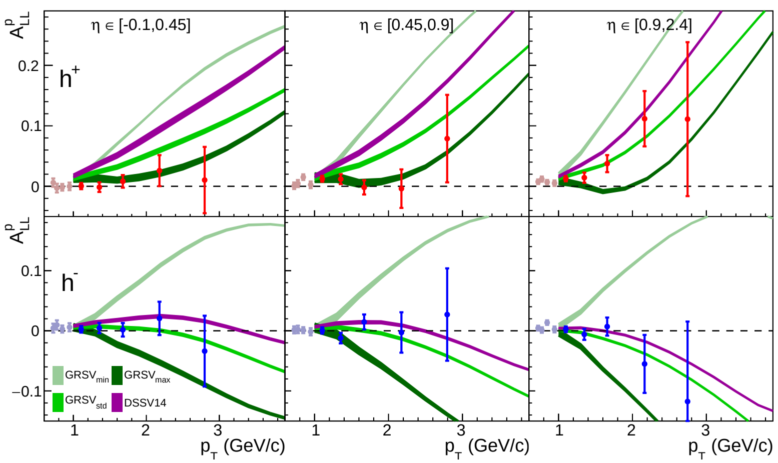
$\Rightarrow$ Illustrates the potential of "direct" asymmetry data.

(*But cannot be included in NLO fit.*)

Δg: "direct" measurement @ low Q^2

- "Direct" measurement at low Q^2: Phys. Lett. B **753** (2016) 573
  Double Spin asymmetry of single inclusive hadron @ $Q^2 < 1$ GeV^2

- Extra resolved subprocesses contribute: $gg, qg\ldots$



p data compared with NLO calculation from Jäger, Stratmann, Vogelsang, Eur. Phys. J. C **44** (2005)

- New calculation with resummation of large logarithms:
  Uebler, Schäfer, Vogelsang, arXiv:1708.08284 [hep-ph]
  $\Rightarrow$ Reasonable agreement with pPDF = DSSV2014 and FF = DSS14(π)+DSS17(K)

Conclusions

- COMPASS legacy on $g_1^{\mathrm{p}}(x,Q^2)$ and $g_1^{\mathrm{d}}(x,Q^2)$ presented for DIS and nonperturbative regions
  - g_1^{p} at low x and low Q^2 is clearly positive (g_1^{d} is consistent with zero)

    First observation of the spin effect at such low x
  - $g_1^{\mathrm{d}} \approx 0$ also at $Q^2 > 1$ GeV^{2}2
- From the COMPASS data alone:

  First moments determined and Bjorken sum rule verified to 9 %
- NLO QCD fit of $g_1 1$ world data gave well constrained quark distributions.

  Quark helicity contribution to nucleon spin: $0.26 < \Delta\Sigma < 0.36$
- "Direct" Δg measurement
  - In DIS, LO extraction: $\Delta g/g = 0.113 \pm 0.038_{\mathrm{stat.}} \pm 0.035_{\mathrm{syst.}}, \langle Q^2 \rangle = 3\mathrm{GeV}^2, \langle x_g \rangle = 0.10$
  - At low Q^2, rich asymmetry data, consistent with DSSV2014

Spares

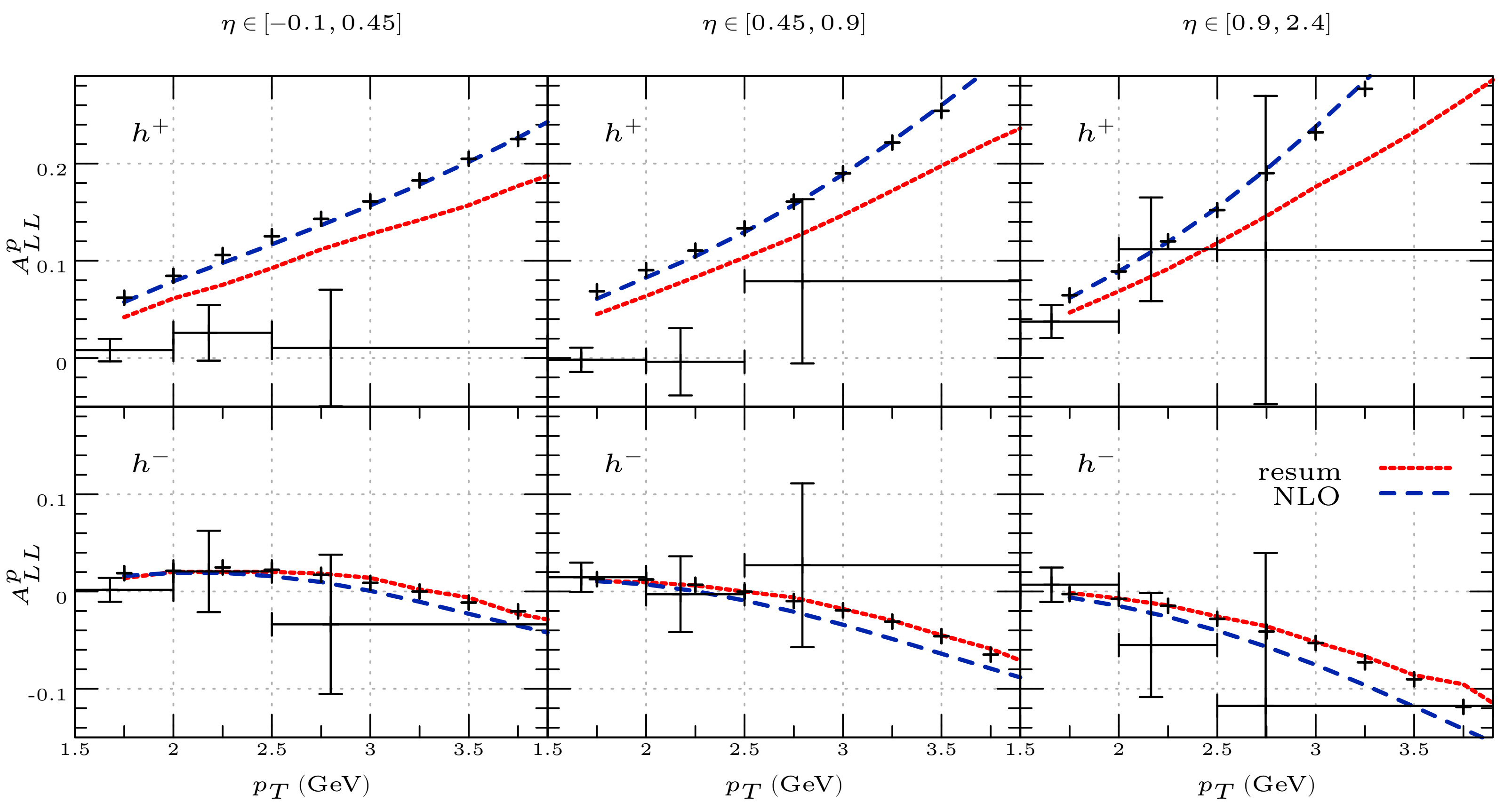
Uebler, Schäfer, Vogelsang

- arXiv:1708.08284 [hep-ph]

  NLO+resummation with pPDF = DSSV2014 and FF = DSS14(π)+DSS17(K)

  Still tension for h^+ off p, despite resummation of resolved processes.

  Improvement for h^- off p thanks to DSS14



Uebler, Schäfer, Vogelsang (*cont"d*)

- arXiv:1708.08284 [hep-ph]

  NLO+resummation with FF = DSS14(π)+DSS17(K)