

# **Longitudinal Spin Structure of the Nucleon COMPASS Legacy**

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**On behalf of the COMPASS collaboration**

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## Scope of the presentation

- PDFs integrated over  $k_T$  ( $k_T = \text{parton intrinsic transverse momentum}$ )
  - ⇒ Three parton distributions at twist-2:
    - $q(x)$  parton momentum DF
    - $\Delta q(x)$  for a longitudinally polarised Nucleon → This talk.
    - $\Delta_T q(x)$  for a transversally polarised Nucleon
- Twist-3 collinear functions in azimuthal modulation

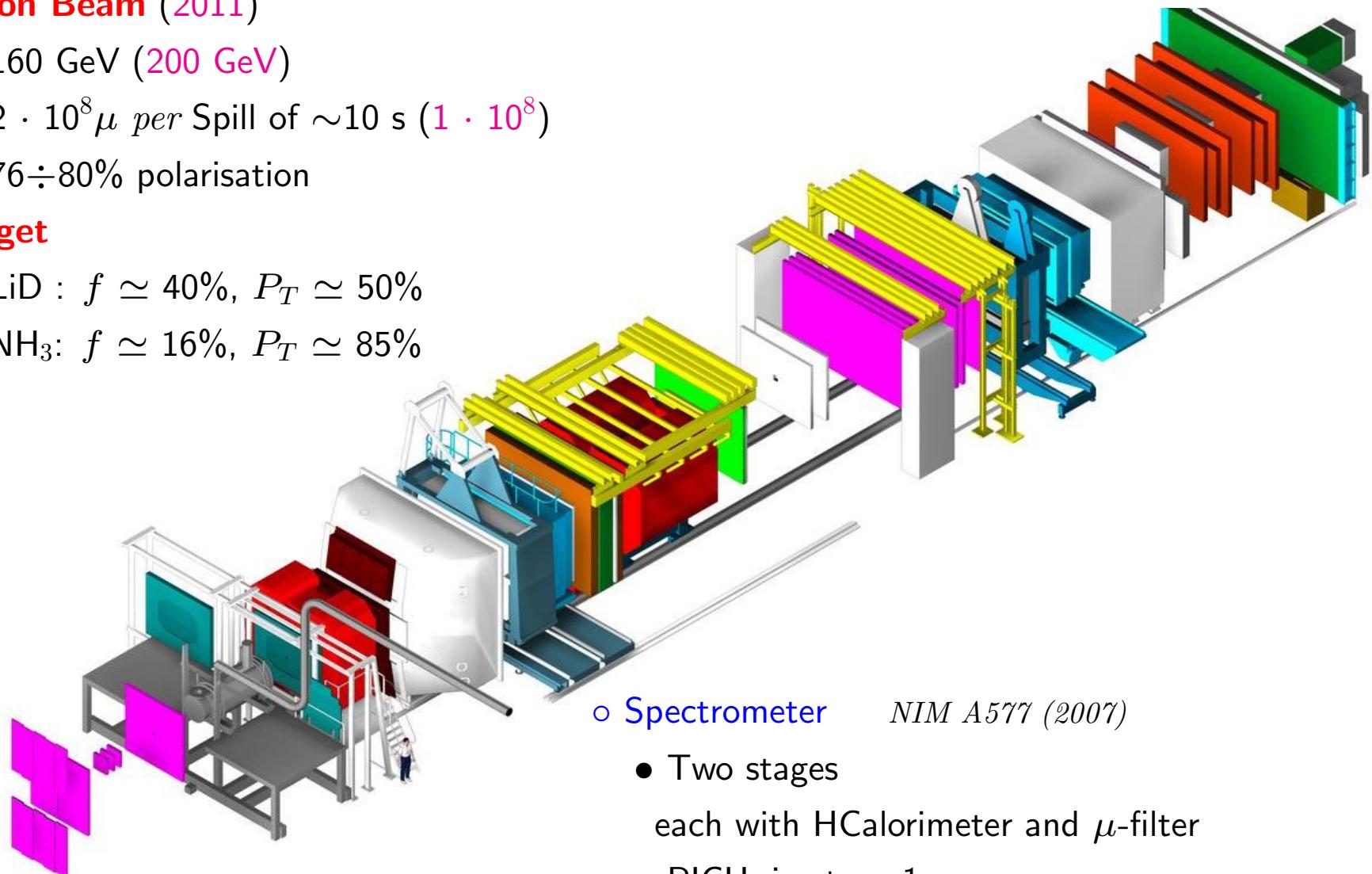
# COMPASS: Spectrometer

- **Muon Beam (2011)**

- 160 GeV (200 GeV)
- $2 \cdot 10^8 \mu$  per Spill of  $\sim 10$  s ( $1 \cdot 10^8$ )
- 76÷80% polarisation

- **Target**

- LiD :  $f \simeq 40\%$ ,  $P_T \simeq 50\%$
- NH<sub>3</sub>:  $f \simeq 16\%$ ,  $P_T \simeq 85\%$



- **Spectrometer**      *NIM A577 (2007)*

- Two stages  
each with HCalorimeter and  $\mu$ -filter
- RICH: in stage 1
- ECAL (1&2): since 2008

## Double Spin Asymmetry Measurement

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

. . . 2 cells:  $1/2 \uparrow 1/2 \downarrow \iff 8 \text{ hours} \Rightarrow 1/2 \downarrow 1/2 \uparrow$

. . . 3 cells:  $1/3 \uparrow 2/3 \downarrow 1/3 \uparrow \iff 24 \text{ hours} \Rightarrow 1/3 \downarrow 2/3 \uparrow 1/3 \downarrow$

- Reversal by **target-field** rotation to cancel spin-state/acceptance correlation

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

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

NH<sub>3</sub>: . . .  $P_T \times f \simeq . . . 85\% \times 16\% \simeq 6\%$

- **Target-field**/acceptance correlation: Reversal *via* re-polarisation once per year
- Radiative Corrections: Smaller than in electron scattering

## Method of extraction

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

$$A_1 \simeq A^{\parallel}/D$$

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

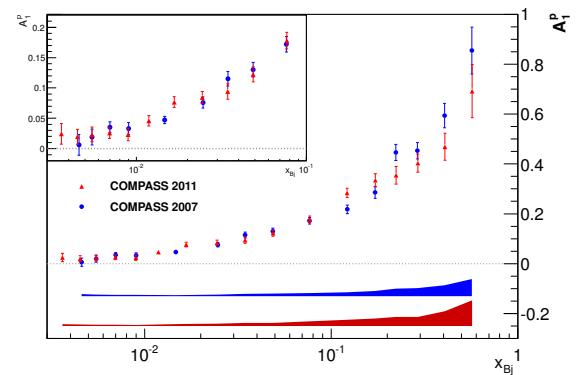
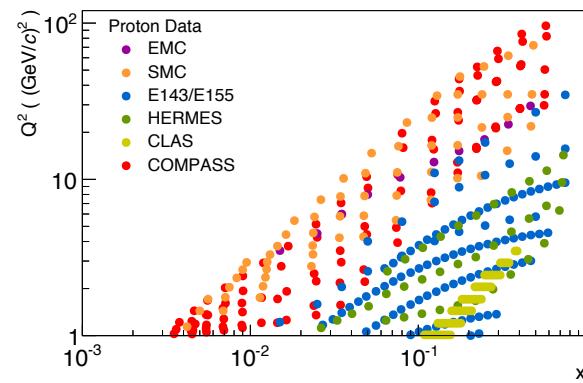
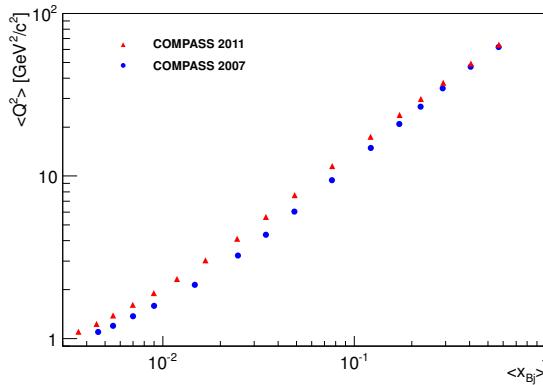
- Input  $F_2^{\text{p,d}}(x, Q^2)$ : from NMC parametrisation (*PRD 58 (1998) 112001*)
- $R(x, Q^2)$ : R1998 from SLAC (*PLB 452 (1999) 194*)
- Maximum systematic uncertainties on  $A_1$   
 from  $P_B, P_T, \sim 0.05P_B, P_T$  (multiplicative)  
 and false asymmetry,  $< 0.8\sigma_{\text{stat.}}$  (additive)

## $g_1^p$ : data samples

- Measurements at **incident  $E = 200 \text{ GeV}$** : PLB **753** (2016) 18

Reaching lower  $x$  and higher  $Q^2$

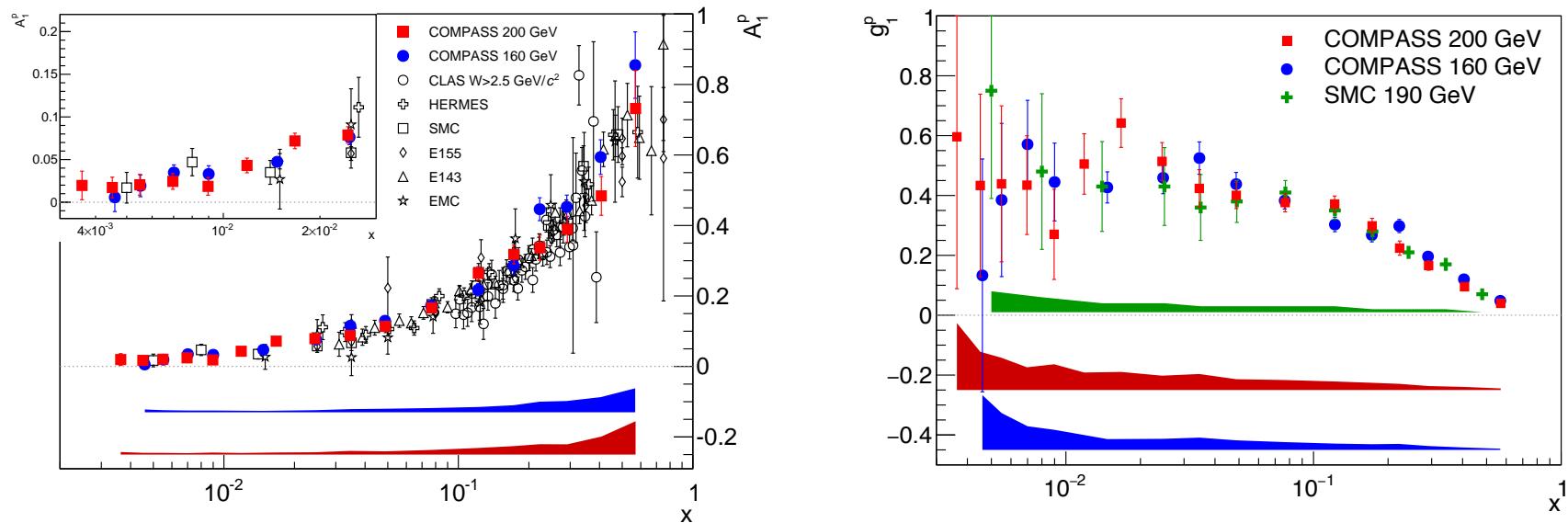
- Complementing earlier data **at  $E = 160 \text{ GeV}$** : (PLB **690** (2010) 466)



- Results on  $A_1^p$  at both energies agree well

## Results on $A_1^p$ and $g_1^p$

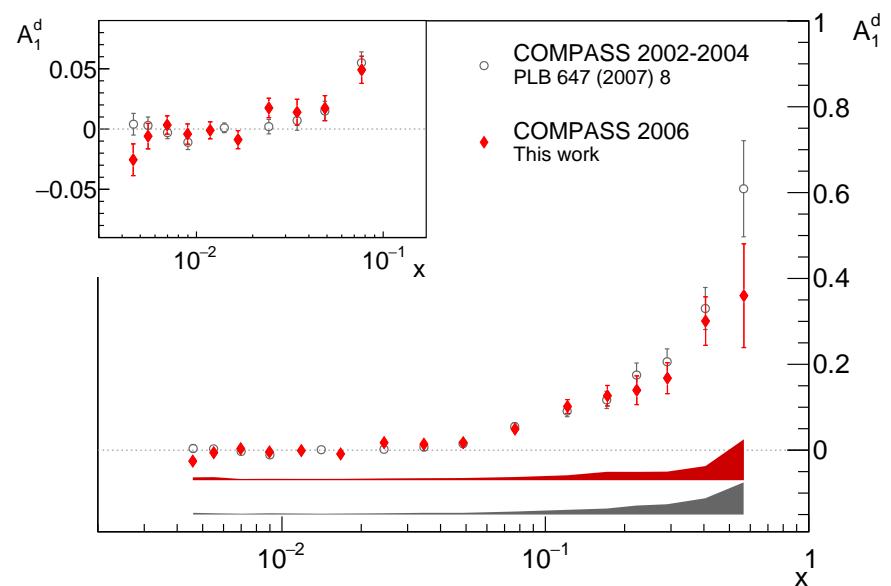
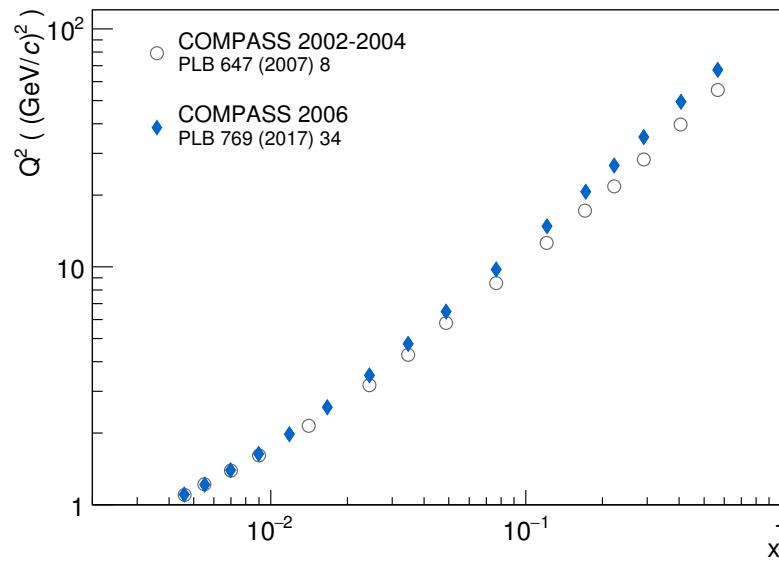
- $A_1^p$  and  $g_1^p$  shown at the measured values of  $Q^2$



- Good agreement with world data, despite diff. in  $Q^2$
- $g_1^p$  clearly positive at lowest measured values of  $x$

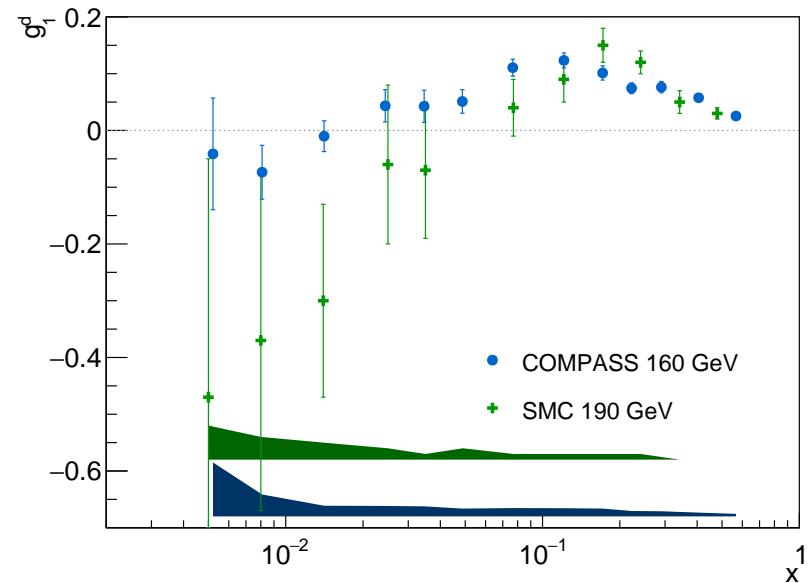
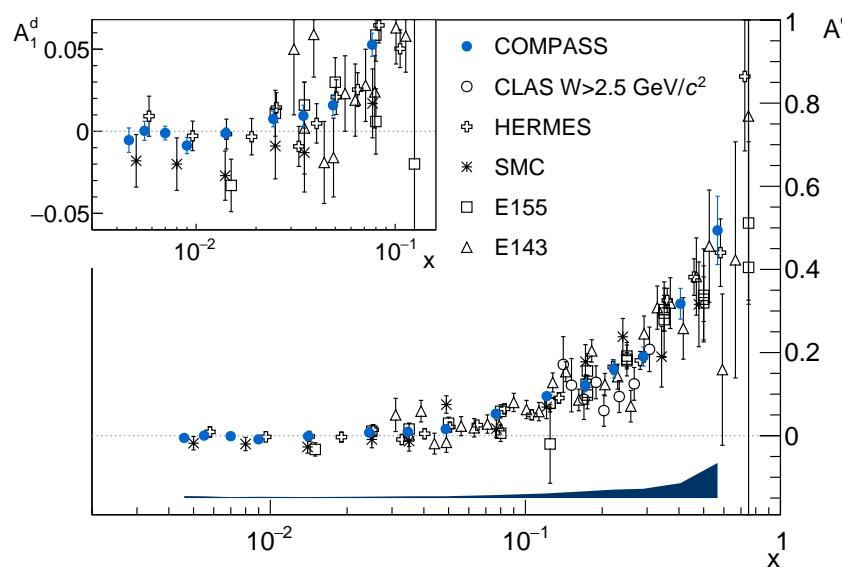
## $g_1^d$ : data samples

- Combined data, all @ 160 GeV: PLB **769** (2017) 34
- Results on  $A_1^d$  agree very well



## Results on $A_1^d$ and $g_1^d$

- $A_1^d$  and  $g_1^d$  shown at the measured values of  $Q^2$



- $g_1^d$  compatible with zero at lowest measured values of  $x$ ,  
contrary to hints from SMC . . .
- . . . Otherwise, good agreement with world data

## NLO QCD fit: conditions

- PLB **753** (2016), updated by PLB **769** (2017)
- A fit of the  $g_1^p$ ,  $g_1^d$ ,  $g_1^{^3\text{He}}$  inclusive data
- $\overline{\text{MS}}$  scheme
- $W^2 < 10 \text{ GeV}^2$  excluded

⇒ Number of data points total/COMPASS: 495/138

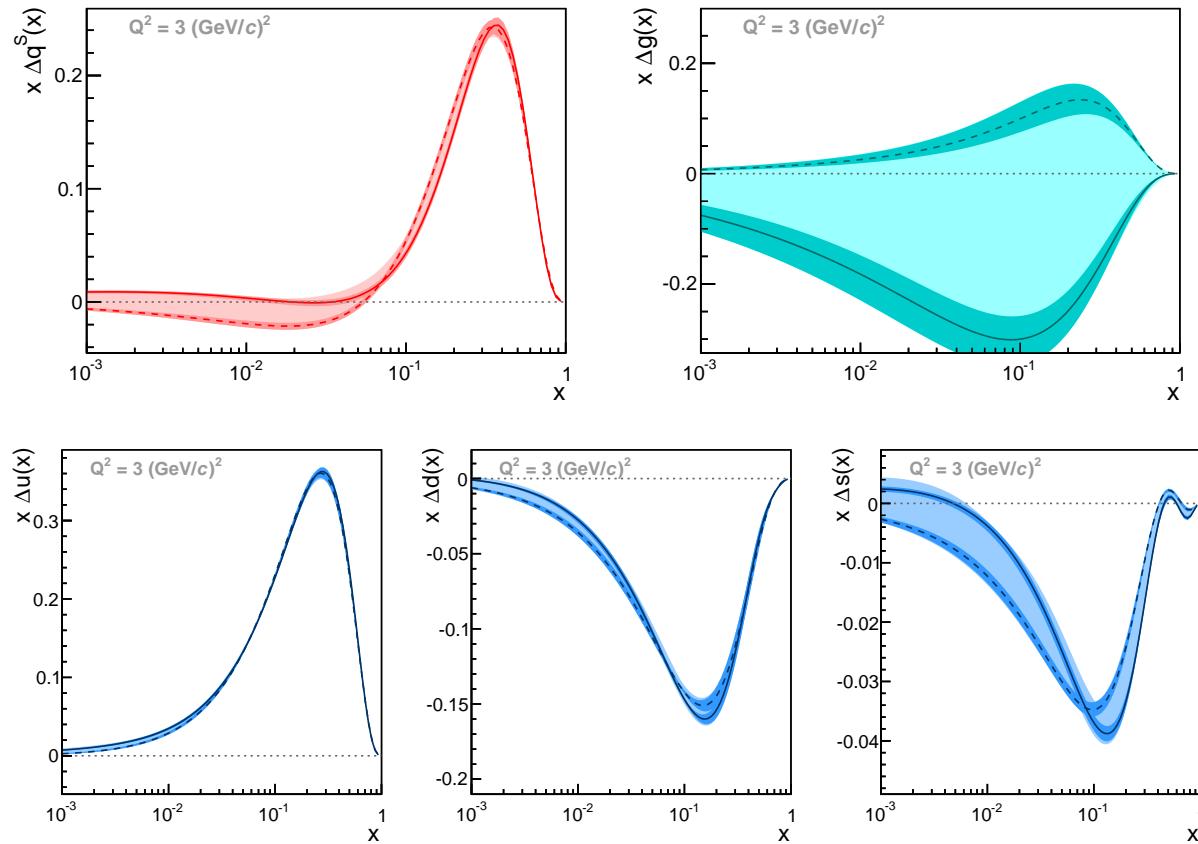
- Fitted:  $\Delta g$ ,  $\Delta q_0 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$ , gluons, singlet  
 $\Delta q_3 = \Delta(u+\bar{u}) - \Delta(d+\bar{d})$ , nonsinglet  
 $\Delta q_8 = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) - 2\Delta(s+\bar{s})$  nonsinglet
- Parametrisation at input scale  $Q^0$ :

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

$\eta_k$  = first moment of  $\Delta f_k(x)$  at  $Q^0$

- Number of free parameters in the fitted PDFs: 11 (*at most*)
- 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  $Q_0^2$
- Systematics: free/fix  $\gamma_k$ 's, vary  $Q_0^2$

## NLO QCD fit: results



- Two solutions (dark bands) and continuum in between (light bands = overall systematics) describing, almost, equally well the data.
- Gluon polarisation poorly constraint  $\Rightarrow$  Need “direct” methods
- Quark spin contribution to the nucleon spin:  $0.26 < \Delta \Sigma < 0.36$  (due to poor  $\Delta G$ )

# First moment of $g_1^{\text{NS}}$ and Bjorken sum rule

- Non-singlet structure function:

$$g_1^{\text{NS}} = g_1^{\text{p}}(x, Q^2) - g_1^{\text{n}}(x, Q^2)$$

- Bjorken sum rule:

$$\Gamma_1^{\text{NS}}(Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{\text{NS}}(Q^2)$$

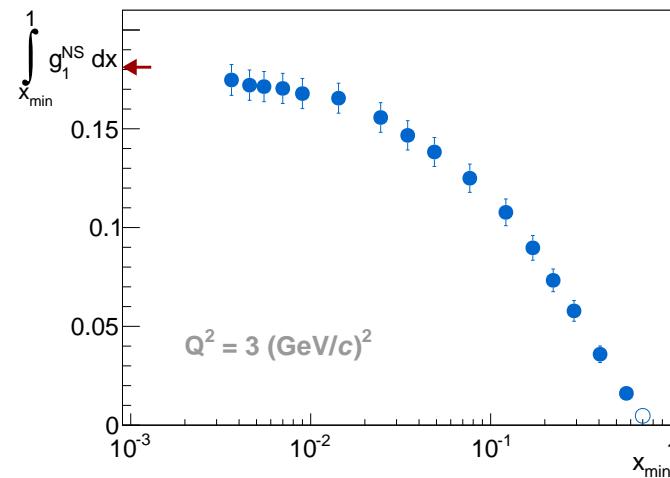
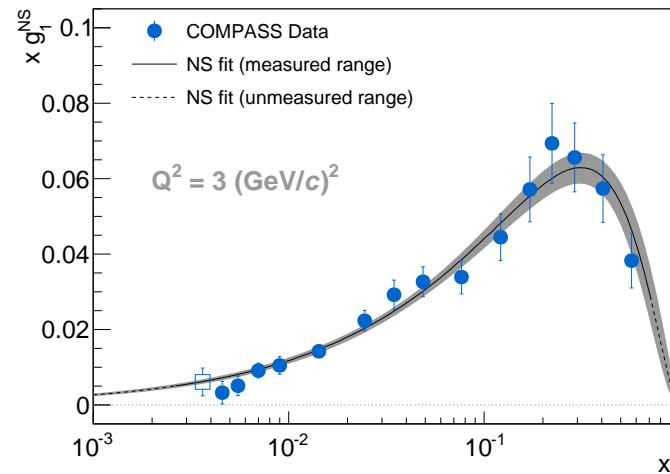
- $g_1^{\text{NS}}$  calculated, NLO QCD fitted (only  $\Delta q_3$ ), evolved to  $Q^2 = 3 \text{ GeV}^2$ , integrated, and fit-extrapolated  $x \rightarrow 0, 1$ :

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

$$\left| \frac{g_A}{g_V} \right| = 1.29 \pm 0.05_{\text{stat.}} \pm 0.10_{\text{syst.}}$$

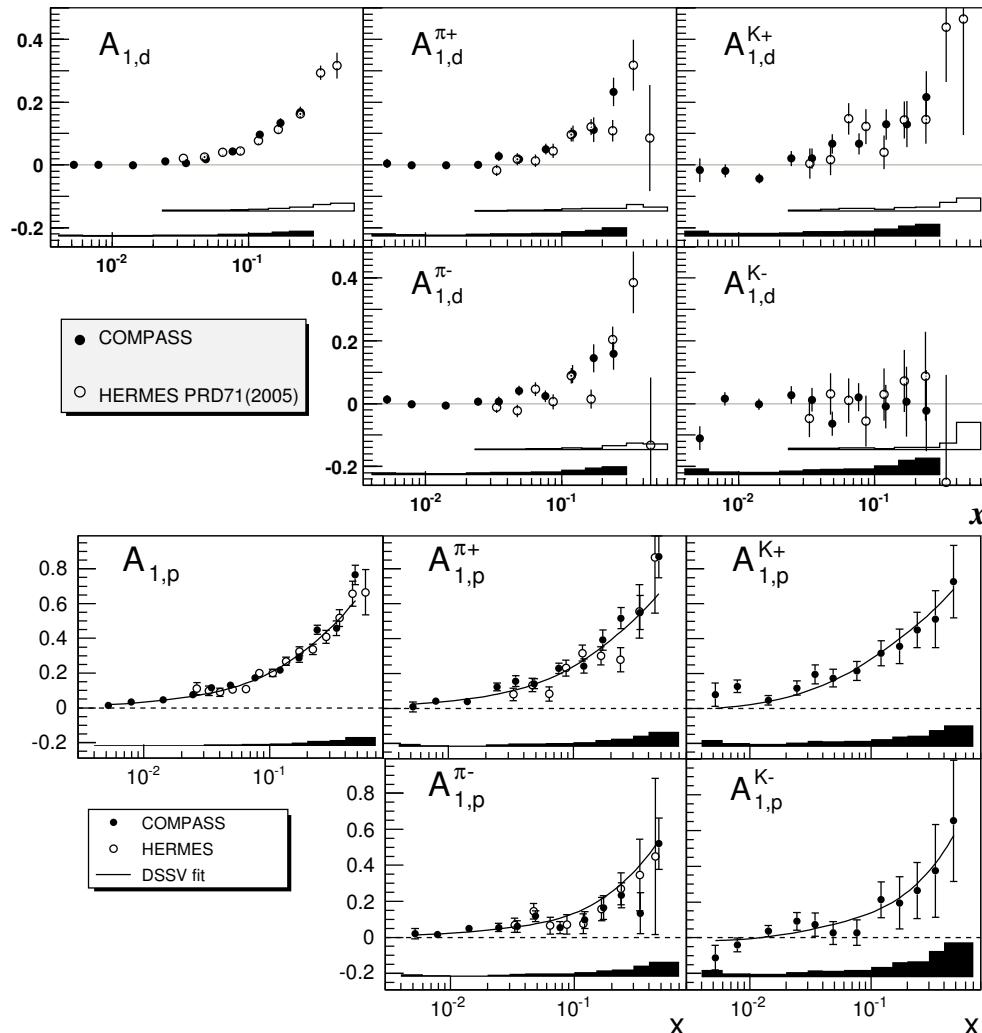
- Neutron  $\beta$  decay gives:  $|g_A/g_V| = 1.2701 \pm 0.002$

PDG, PRD86 (2012) 010001



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

# SIDIS: $A_1^h$ , $h = \pi, K$



● ○  $^6LiD$  target

PLB 680 (2009)

○  $NH_3$  target

PLB 693 (2010)

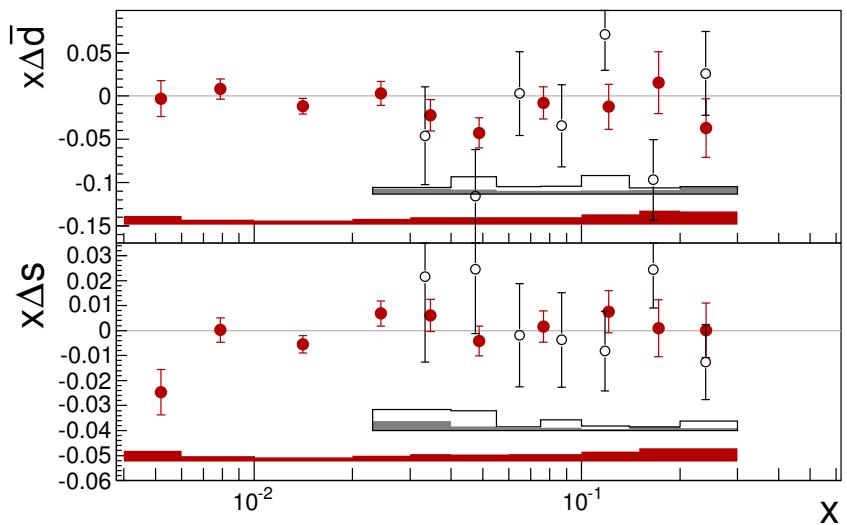
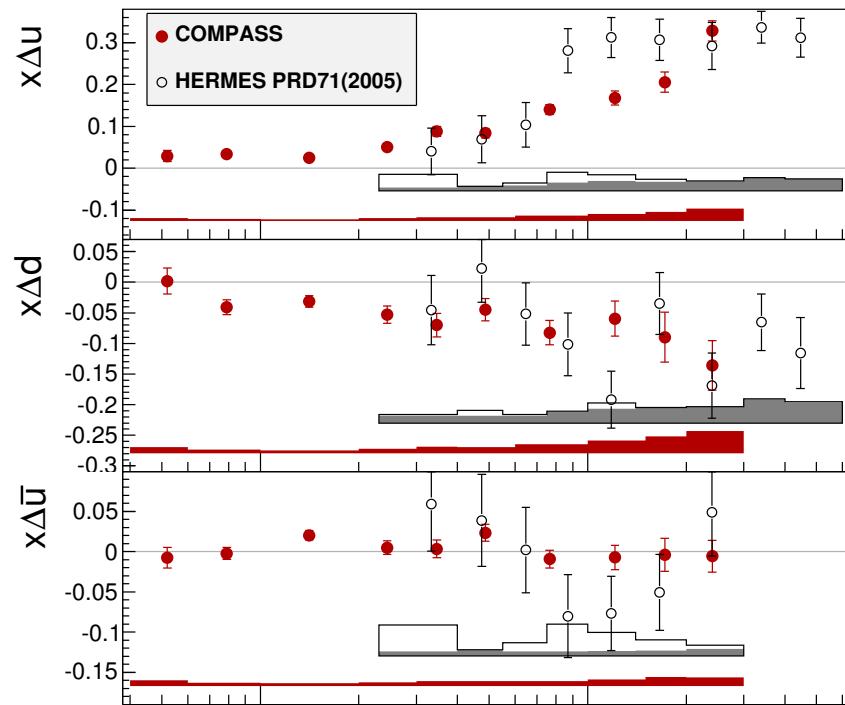
$A_{1,p}^K$ : 1st measurement ever.

⇒ Order of magnitude lower reach in  $x$  than HERMES

## SIDIS: $A_1^h$ , $h = \pi, K$ (cont'd)

- SIDIS provides  $q/\bar{q}$  flavour separation, relying on FFs.
- LO extraction by COMPASS, using DSS07:

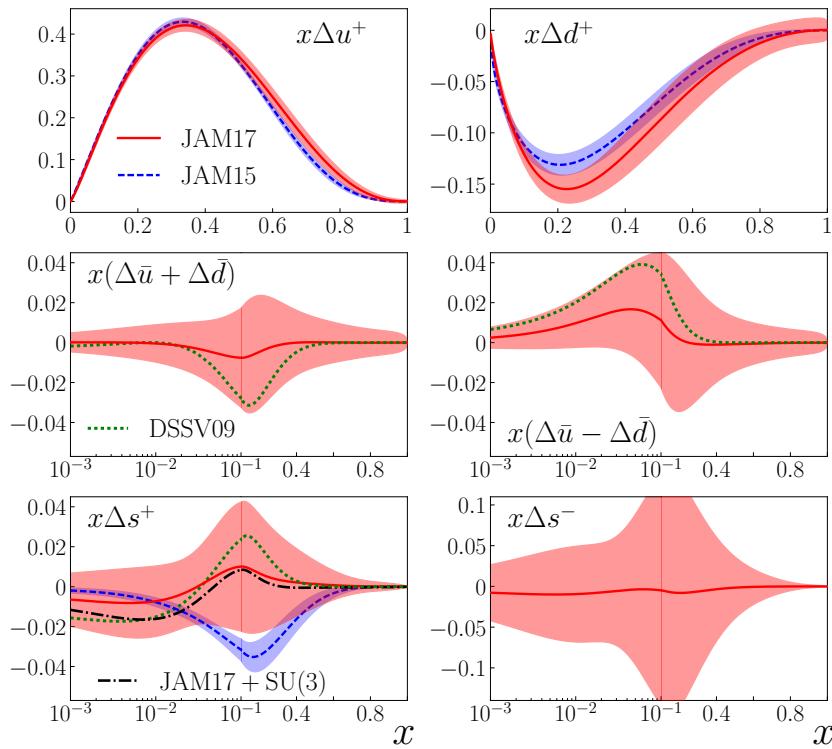
$$A_1^h(x, Q^2) = \frac{\sum_q e_q \Delta_q(x, Q^2) \int D_q^h(z, Q^2) dz}{\sum_q e_q q(x, Q^2) \int D_q^h(z, Q^2) dz}$$



*PLB 693 (2010)*

## $A_1^h$ in Global QCD Fits

- COMPASS SIDIS data included in several global QCD fits of pPDFs:  
*E.g. DSSV (see DSSV\*: PRL 113 (2014)) and JAM (see JAM17: PRL 119 (2017))*
- SIDIS (COMPASS+HERMES) plays essential role in flavor separation  
(particularly so in the absence of precise  $W^\pm$  data)

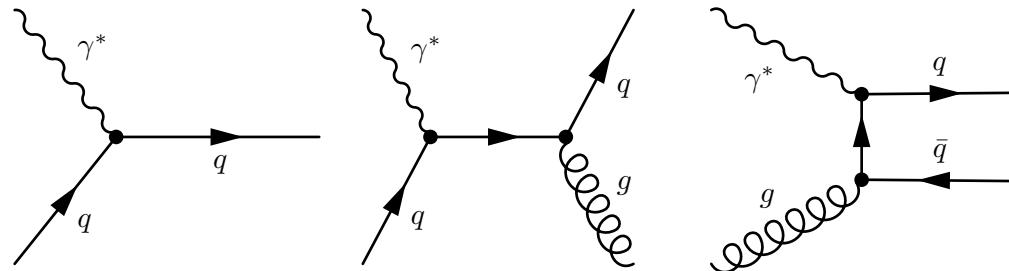


- $\Delta \bar{u} > 0, \Delta \bar{d} < 0$   
Some indication that  $|\Delta \bar{u}| > |\Delta \bar{d}|$
- Strangeness Polarisation:  $\Delta s^+ = \Delta s + \bar{s}$   
Sensitivity to  $D_s^K$  FF  
Either  $< 0$ , as for Incl. DIS (see JAM15)  
Or sign changing (see JAM17)
- Also sensitive to imposing of SU(3) or not

- Data at lower  $x$  needed to clarify polarised strangeness and test SU(3) breaking.

## $\Delta g$ : “direct” measurement

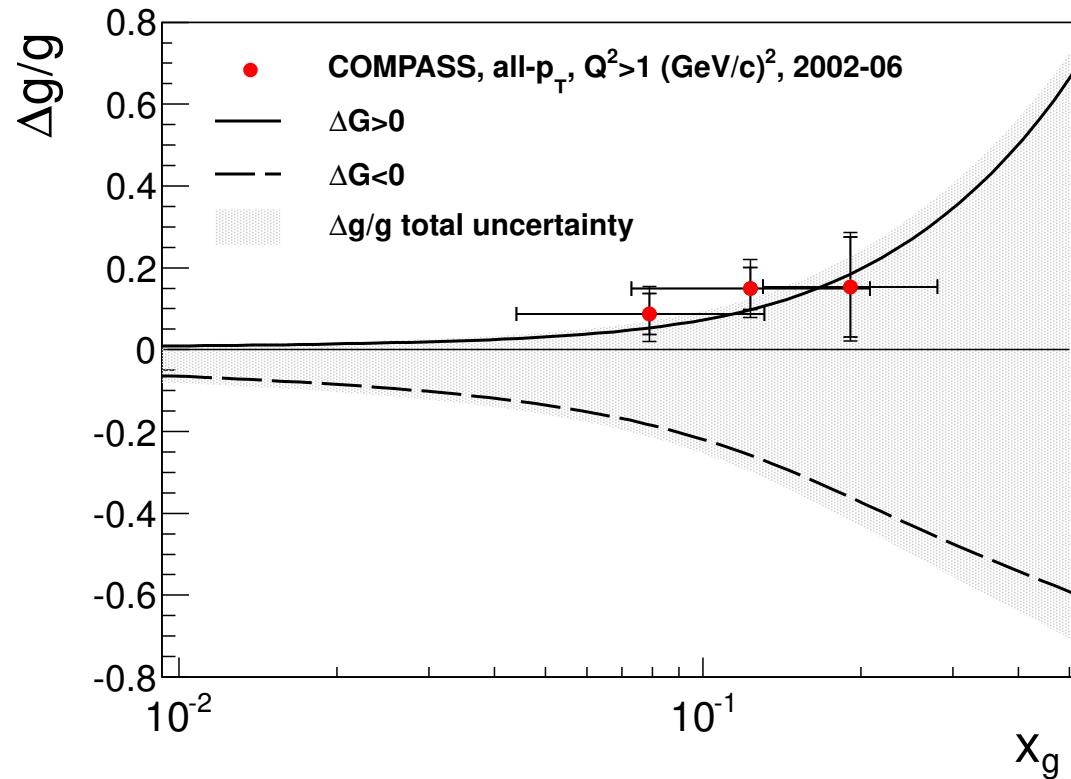
- Re-analysis of polarised deuteron data: COMPASS coll., EPJ C **77** (2017)



- $\Delta g$  accessed via PGF
- Double spin asymmetries of single inclusive hadron in DIS over a wide range in  $p_T$ ,  $0.05 < p_T < 2.5 \text{ GeV}/c$
- LO order interpretation (“*Leading*”, *in the gluon contribution*):
  - Hadron level → parton level via LEPTO Monte Carlo
  - 1.6 gain in statistical and systematics precision
  - $\Delta g/g = 0.113 \pm 0.038_{\text{stat.}} \pm 0.035_{\text{syst.}}, \langle Q^2 \rangle = 3 \text{ GeV}^2, \langle x_g \rangle = 0.10$

## $\Delta g$ : “direct” measurement (*cont’d*)

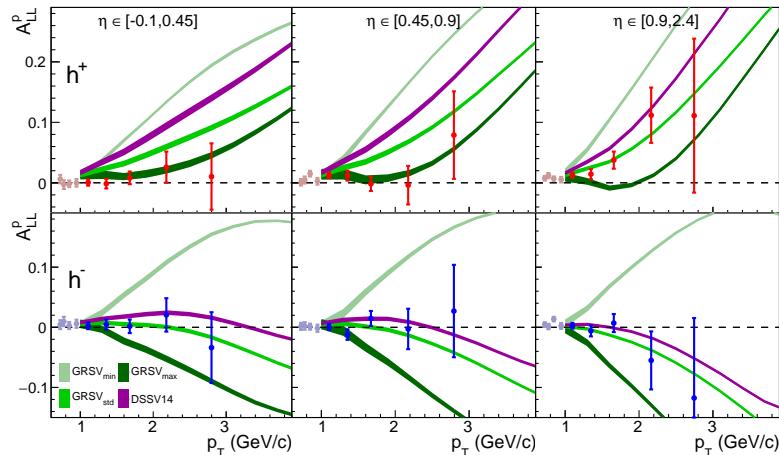
- LO “direct” extraction, here in 3  $x_g$  bins, compared to NLO QCD fit  
*(Note: 1st and 2nd bin are correlated.)*



⇒ Illustrates the potential of “direct” asymmetry data.  
*(But cannot be included in present-day global fits, all at NLO.)*

## $\Delta g$ : “direct” measurement @ low $Q^2$

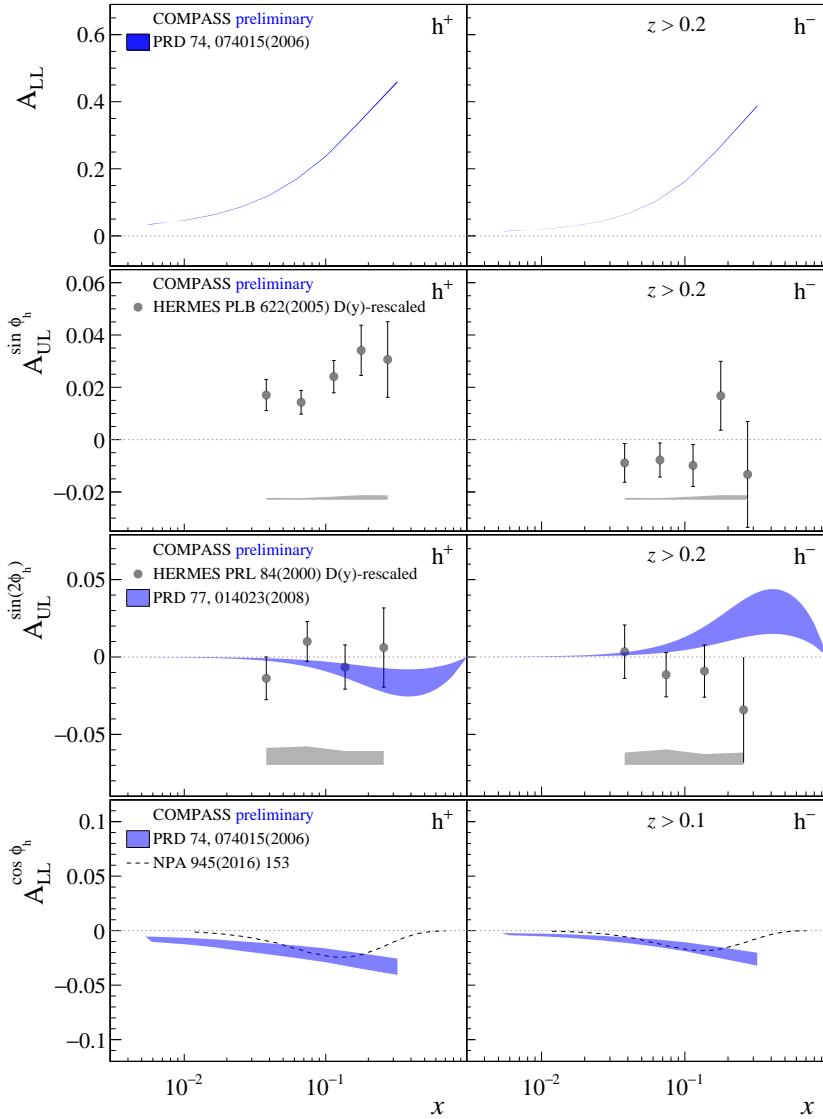
- “Direct” measurement at low  $Q^2$ : PLB **753** (2016) 573  
Double Spin asymmetry of single inclusive hadron @  $Q^2 < 1 \text{ GeV}^2$
- Extra resolved subprocesses contribute:  $gg, qg, \dots$



$p$  data compared with NLO calculation  
from Jäger, Stratmann, Vogelsang,  
EPJ C **44** (2005)

- New calculation with resummation of large logarithms:  
Uebler, Schäfer, Vogelsang, PRD **96** (2017)  
 $\Rightarrow$  Reasonable agreement with pPDF = DSSV2014 and FF = DSS14( $\pi$ ) + DSS17( $K$ )

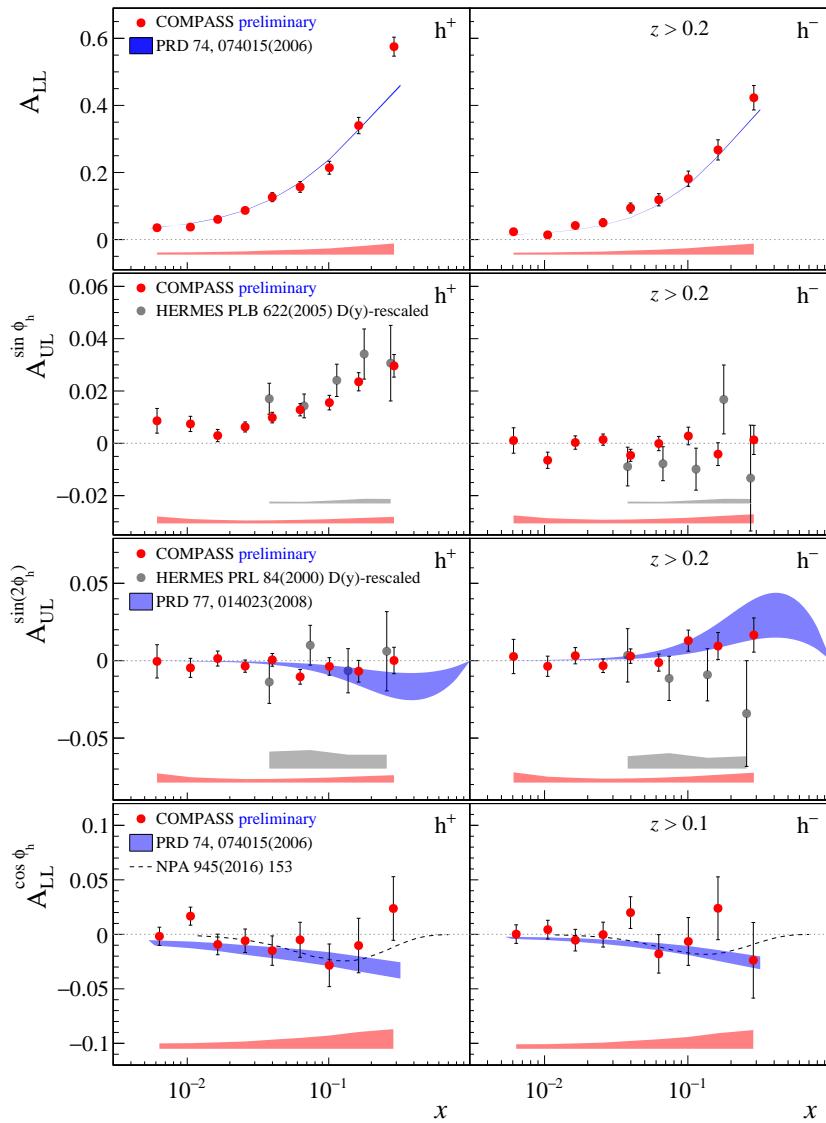
# Single Hadron Azimuthal Asymmetry on Logitudinal $\vec{p}$



- Expansion of SIDIS X-section as a  $f(\phi_h)$   
 $(\phi_h = \text{hadron plane w.r.t. lepton plane}):$

$$\frac{d\sigma}{dxdydzdp_Tdp_Td\phi_h} \propto \hat{\sigma}_U \left\{ 1 + \text{target spin indep. terms} \right. \\ \left. + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} A_{UL}^{\sin \phi_h} \sin \phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h \right] \right. \\ \left. + S_L \lambda \left[ \sqrt{1-\varepsilon^2} A_{LL}^{\cos \phi_h} + \sqrt{2\varepsilon(1-\varepsilon)} A_{LL}^{\cos \phi_h} \cos \phi_h \right] \right\}$$

# Single Hadron Azimuthal Asymmetry on Logitudinal $\vec{p}$ (*cont'd*)



- Expansion of SIDIS X-section as a  $f(\phi_h)$   
 $(\phi_h = \text{hadron plane w.r.t. lepton plane}):$

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# Single Hadron Azimuthal Asymmetry on Logitudinal $\vec{p}$ (*cont'd*)

- Structure functions in terms of distribution functions:

$$F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left[ -\frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x_{Bj} \mathbf{h}_L H_1^\perp + \frac{M_h}{M} g_{1L} \frac{\tilde{G}^\perp}{z} \right) + \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x_{Bj} f_L^\perp D_1 - \frac{M_h}{M} h_{1L}^\perp \frac{\tilde{H}}{z} \right) \right], \quad (1)$$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C} \left[ -\frac{2 (\hat{\mathbf{h}} \cdot \mathbf{p}_T) (\hat{\mathbf{h}} \cdot \mathbf{k}_T) - \mathbf{p}_T \cdot \mathbf{k}_T}{MM_h} h_{1L}^\perp H_1^\perp \right], \quad (2)$$

$$F_{LL} = \mathcal{C} [g_{1L} D_1], \quad (3)$$

$$F_{LL}^{\cos \phi_h} = \frac{2M}{Q} \mathcal{C} \left[ \frac{\hat{\mathbf{h}} \cdot \mathbf{p}_T}{M_h} \left( x_{Bj} \mathbf{e}_L H_1^\perp - \frac{M_h}{M} g_{1L} \frac{\tilde{D}^\perp}{z} \right) - \frac{\hat{\mathbf{h}} \cdot \mathbf{k}_T}{M} \left( x_{Bj} g_L^\perp D_1 + \frac{M_h}{M} h_{1L}^\perp \frac{\tilde{E}}{z} \right) \right], \quad (4)$$

## Conclusions

- COMPASS legacy on  $g_1^p(x, Q^2)$  and  $g_1^d(x, Q^2)$  presented for the DIS ( $Q^2 > 1 \text{ GeV}^2$ ) region
- From the COMPASS data alone:  
First moments determined and Bjorken sum rule verified to 9 %
- NLO QCD fit of  $g_{11}$  world data gave well constrained quark distributions.  
Quark helicity contribution to nucleon spin:  $0.26 < \Delta\Sigma < 0.36$
- SIDIS: High sensitivity to FFs, particularly  $D_s^K$ .  
 $\Rightarrow$  Have to keep fragmentation under control (*cf. F. Kunne's talk*)
- “Direct”  $\Delta g$  measurement
  - In DIS, LO extraction:  $\Delta g/g = 0.113 \pm 0.038_{\text{stat.}} \pm 0.035_{\text{syst.}}$ ,  $\langle Q^2 \rangle = 3 \text{ GeV}^2$ ,  $\langle x_g \rangle = 0.10$
  - At low  $Q^2$ , rich asymmetry data, consistent with DSSV2014

# Spares

# COMPASS Longitudinal Spin Structure @ SPIN18

- Related COMPASS talks at SPIN18 in the Nucleon helicity structure:
  - **Fragmentation:** Fabienne Kunne: Wednesday MM  
 $K^-/K^+$  multiplicity ration in SIDIS
  - **$g_2$ :** Andrea Bressan: Thursday PM  
Measurement of the spin-dependent structure function  $g2$
  - Andrea Moretti: Thursday PM  
Transversity and  $\Lambda$  polarisation in polarised SIDIS

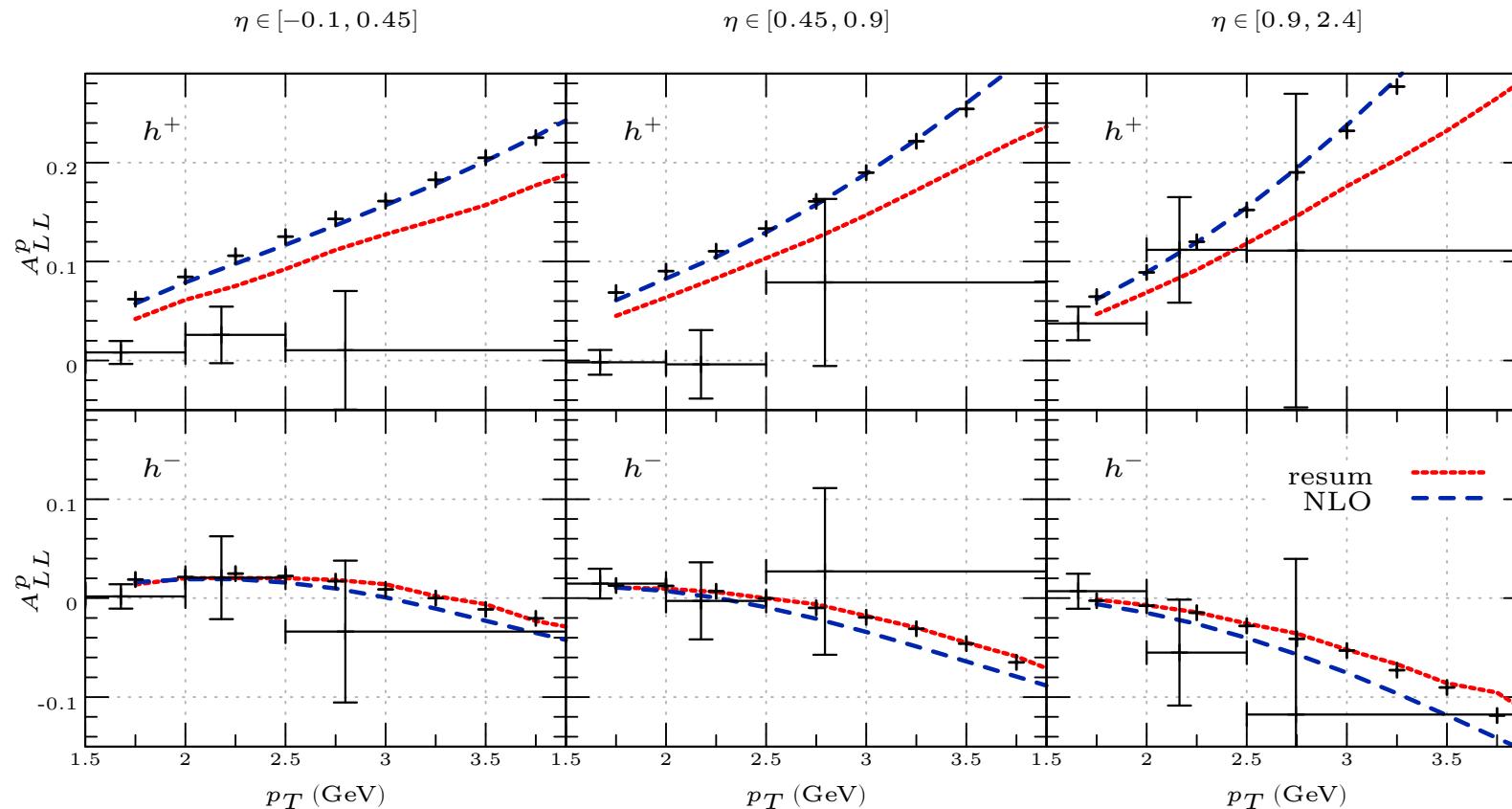
# Uebler, Schäfer, Vogelsang

- arXiv:1708.08284 [hep-ph]

NLO+resummation with pPDF = DSSV2014 and FF = DSS14( $\pi$ ) + DSS17( $K$ )

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

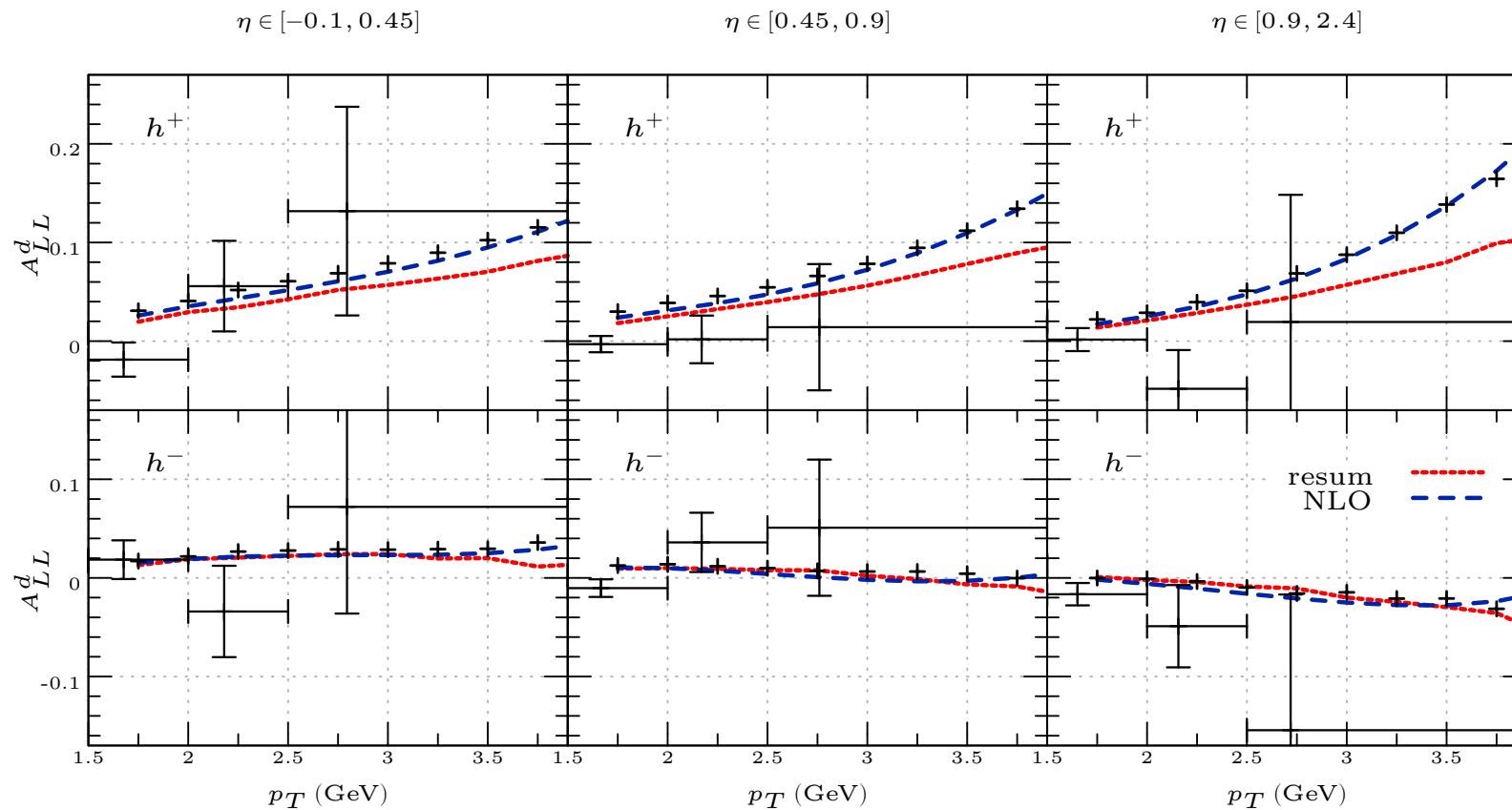
Improvement for  $h^-$  off  $p$  thanks to DSS14



## Uebler, Schäfer, Vogelsang (*cont'd*)

- PRD **96** (2017)

$$\text{NLO+resummation with FF} = \text{DSS14}(\pi) + \text{DSS17}(K)$$



## First moments of $g_1$ and singlet axial charge $a_0$

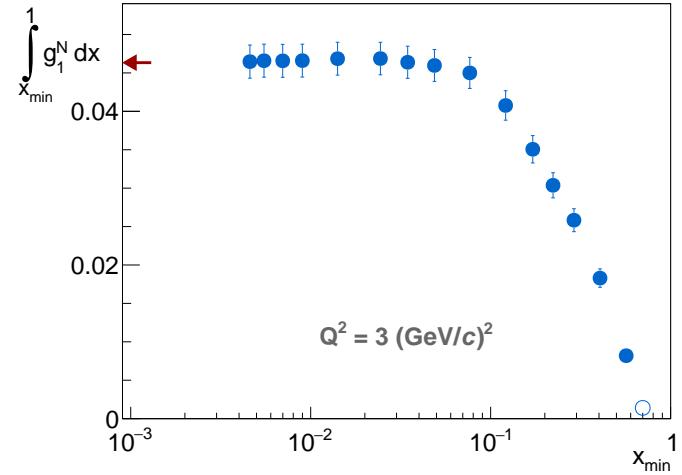
- First moments  $\Gamma_1^p$ ,  $\Gamma_1^d$ ,  $\Gamma_1^N$

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

- In particular:

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

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



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

- From COMPASS data alone:

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

- From COMPASS data alone (and still  $a_8$  from PRD **82** (2010)):

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

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