Measurement of $A_{LL}(p_T)$ for single hadron photoproduction at *high* p_T at COMPASS

Maxime Levillain

on behalf of the COMPASS collaboration
CEA Saclay - SPhN

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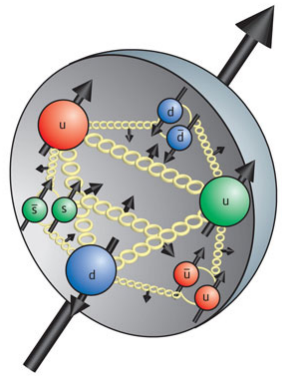
Nucleon Spin Structure

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

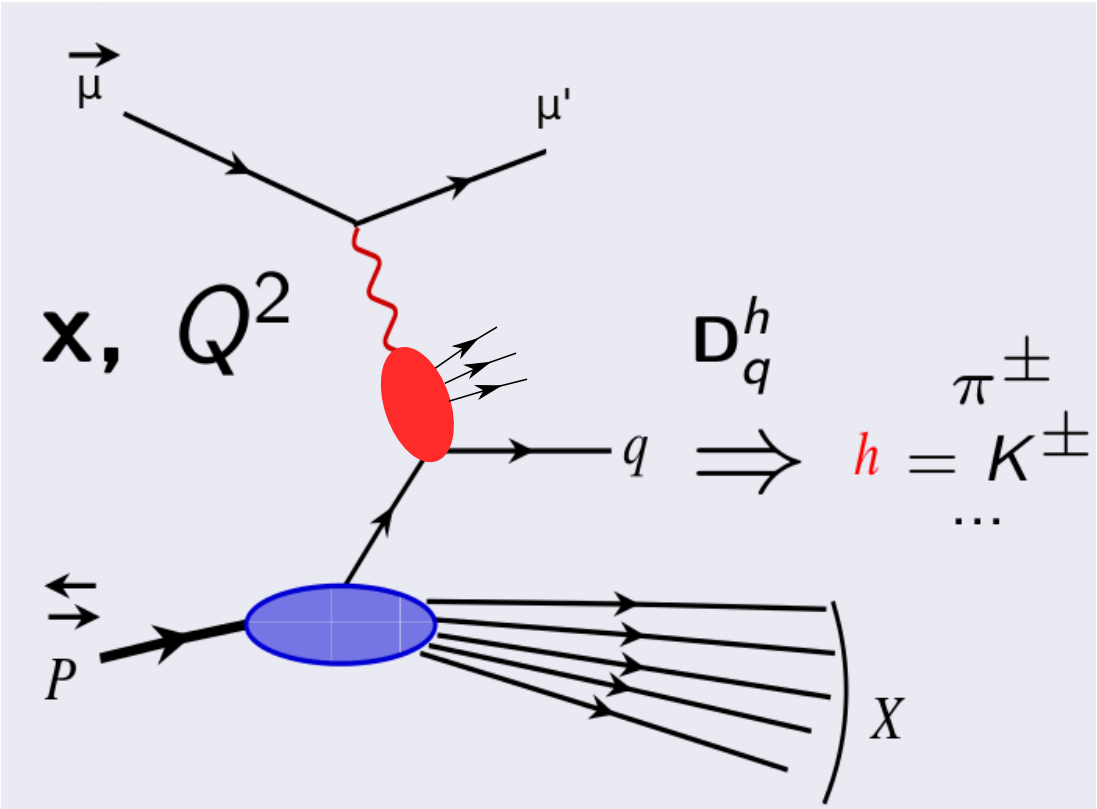


$$\Delta\Sigma \approx 0.3 \;\Rightarrow\; -0.1 \leq \Delta G \leq 0.3 \;\; ??$$

$\Rightarrow$ Purpose: Extraction of ΔG from $A_{LL}(p_T)$ at *high* p_T and *low* Q^2

Muon-Nucleon Scattering

$$\overleftarrow{\mu} + \overrightarrow{\overleftarrow{p}} \rightarrow \mu' + h + X$$



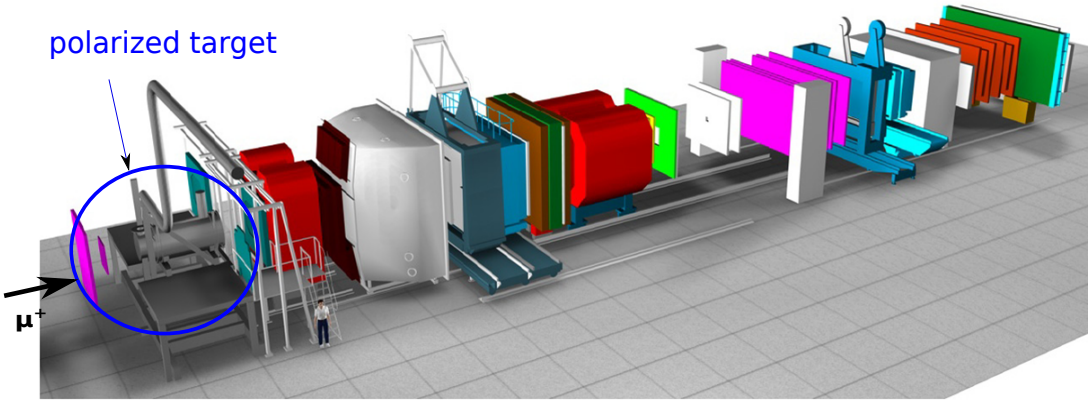
- photoproduction:

  $Q^2 < 1\ GeV^2/c^2$
- hard scale:

  high p_T

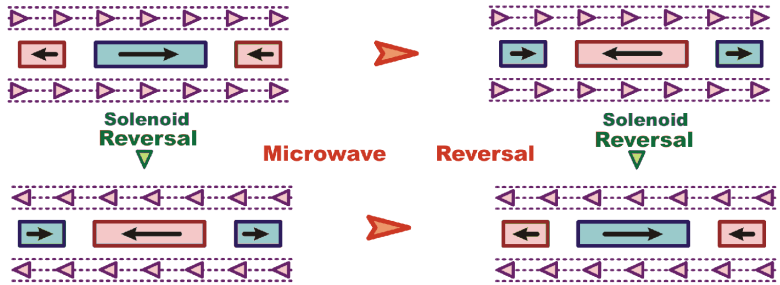
Important kinematical cuts:

- $0.2 < z < 0.8$
- $-0.1 < \eta_{cms} < 2.4$



- μ^+ polarized beam from SPS at 160 or 200 GeV
- 2 stages spectrometer with large acceptance

- polarized target with 2 (2002-2004) or 3 (2006-2011) cells
- 2 types of polarization reversal
- target material:
  - deuterons (^6LiD) from 2002 to 2006
  - protons (NH_3) from 2007 to 2011

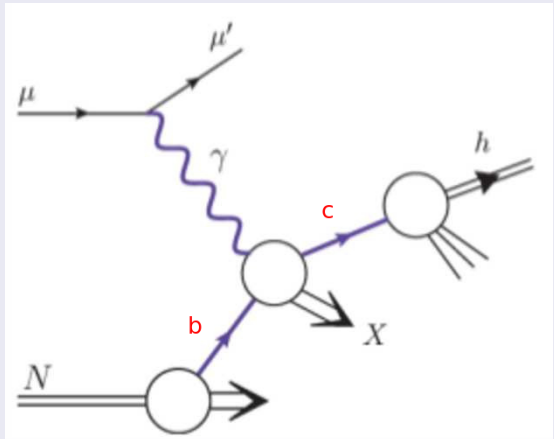


Purpose and Theoretical Framework

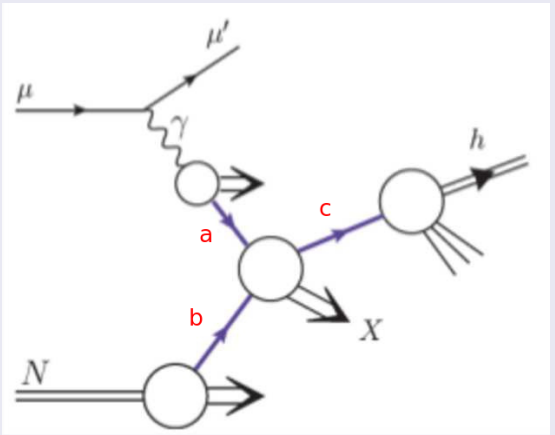
- Collinear pQCD analysis at NLO:

$$\frac{d\Delta\sigma^h}{d\sigma^h}(p_T,\eta) = \frac{\sum_{a,b,c} \Delta f_a^{\mu} \otimes \Delta f_b^{N} \otimes d\Delta\hat{\sigma}_{a,b\to c,X} \otimes D_c^h}{\sum_{a,b,c} f_a^{\mu} \otimes f_b^{N} \otimes d\hat{\sigma}_{a,b\to c,X} \otimes D_c^h} = \frac{d\Delta\sigma_{dir} + d\Delta\sigma_{res}}{d\sigma_{dir} + d\sigma_{res}}$$

direct γ-contribution



resolved γ-contribution

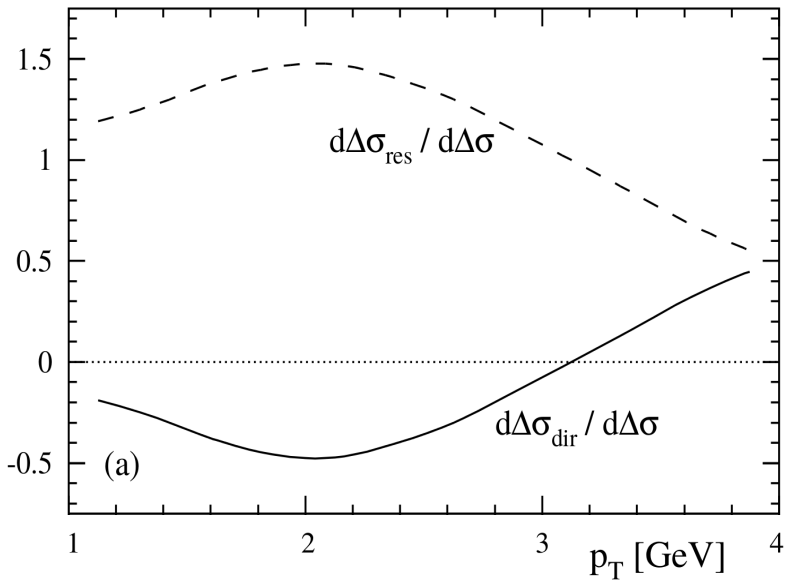


- $\Delta f_a^{\mu}(x_a,\mu_f) = \int_{x_a}^1 \frac{dy}{y} \Delta P_{\gamma\mu}(y) \Delta f_a^{\gamma}(x_\gamma = \frac{x_a}{y}, \mu_f)$ allows to take into account both γ-contributions
- Uncertainty for the polarization of the hadronic fluctuation of the virtual photon

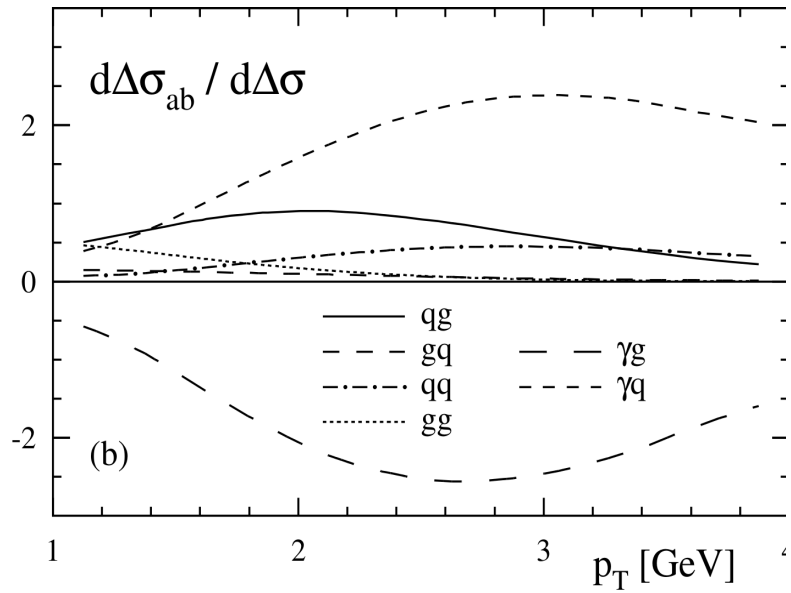
Contributions of the Different Processes

- Calculations by M. Stratmann, B. Jäger and W. Vogelsang (EPJC 44 (2005) 533)

direct and resolved contributions



subprocesses contributions

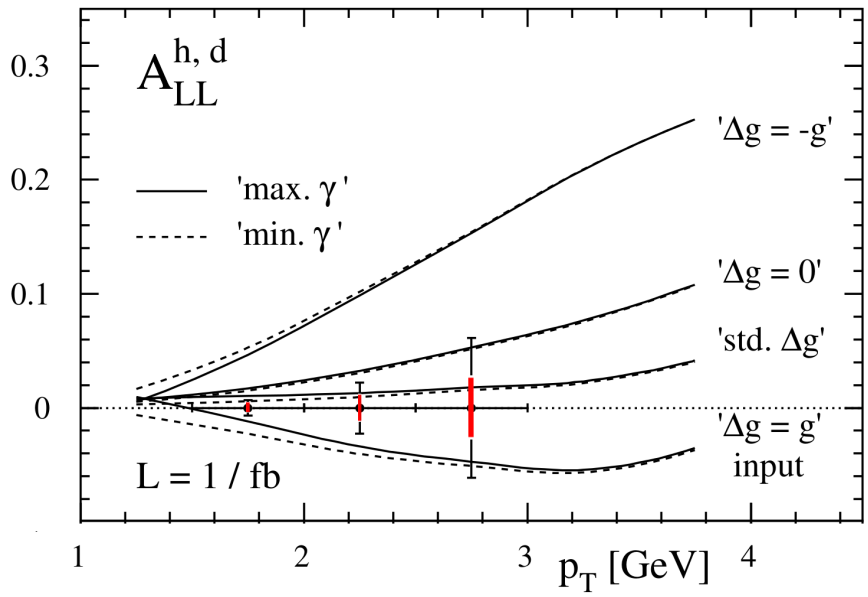


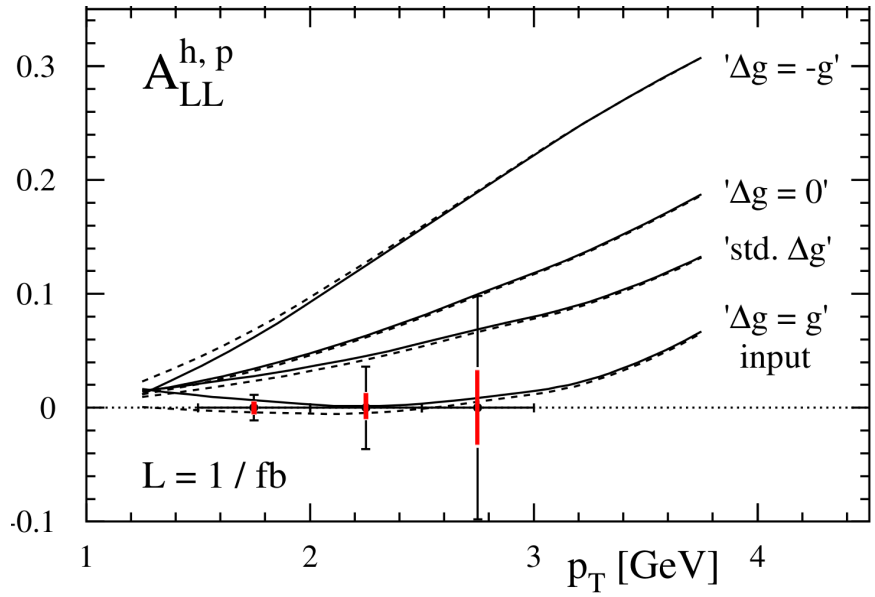
- cancelation of QCD Compton (γq) and PGF (γg)

  $\rightarrow$ more sensitive to resolved processes (especially at *low* p_T)

Theoretical Estimations of A_{LL}

- Estimation of COMPASS A_{LL} for deuteron and proton target, with COMPASS error projection for 1 fb^{-1} ($\sim 4 fb^{-1}$) (EPJC 44 (2005) 533)

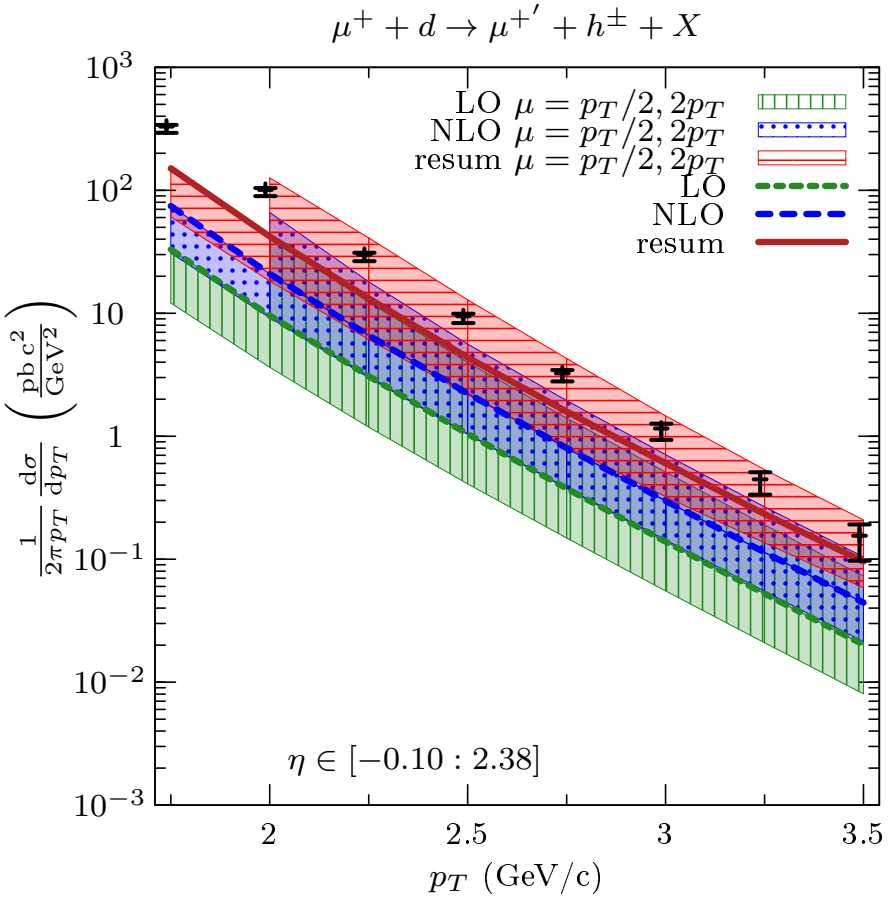




- Small impact of the resolved photon polarized structure uncertainty (only at *low* p_T)
- Discriminating power on ΔG

Unpolarized Cross-section Study

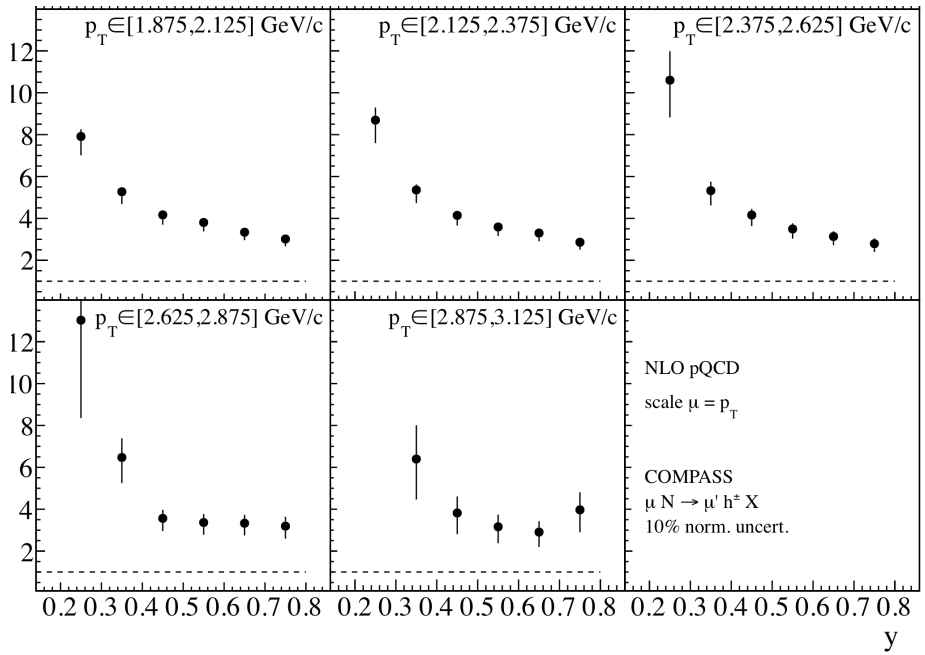
- COMPASS measurement (PRD 88 (2013) 091101)
- Comparison with theoretical calculations with gluon resummation (PRD 88 (2013) 014024)



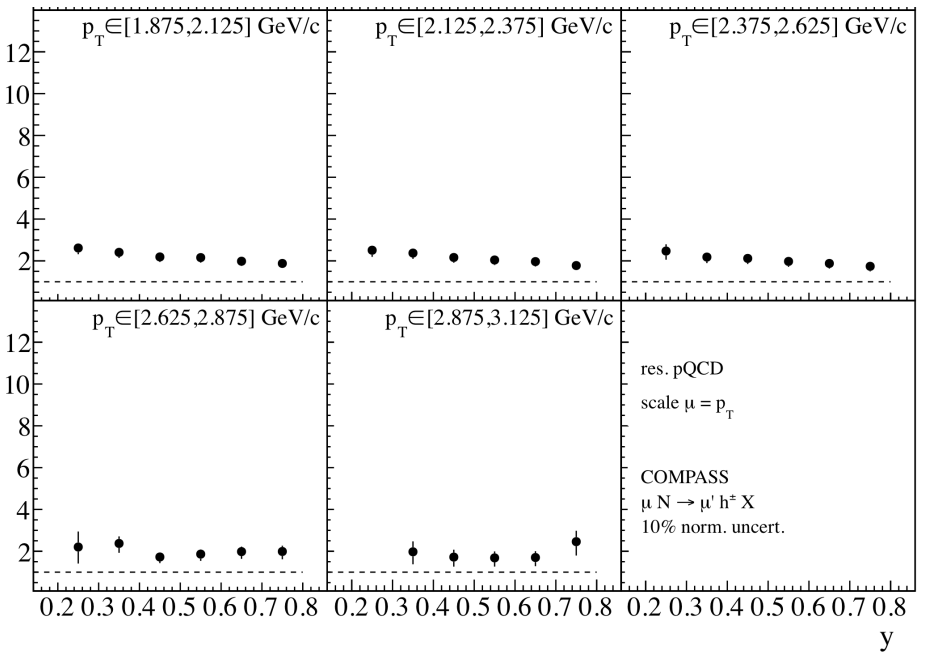
- close to threshold given a low energy range: $\sqrt{s} \approx 18\ GeV$ (RHIC: $\sqrt{s} \approx 200\ GeV$)
- needs resummation to explain unpolarized cross-section

y-dependent Unpolarized Cross-section

- Necessity to include gluon resummation to remove y-depedency to experimental over theoretical ratio of unpolarized cross-section



$d\sigma_{COMPASS}/d\sigma_{NLO}$



$d\sigma_{COMPASS}/d\sigma_{RES}$

- Validation of the applicability of the theory
  $\rightarrow$ Resummation for the polarized case needed (underway)

Method for Asymmetry Extraction

- Spin asymmetries based on hadron counts:

$$N_x = \phi a_x n_x \sigma_0 (1 + (f \cdot P_\mu \cdot P_x) A_{LL}) \quad \rightarrow \quad A_{raw} = \frac{N_u - N_d}{N_u + N_d}$$

- Removing acceptances effects with 2^{nd} order Method based on a geometric average:

$$\delta = \frac{N_u \cdot N_{d'}}{N_d \cdot N_{u'}} \approx \frac{(1 + \langle \beta_u \rangle A_{LL})(1 + \langle \beta_{d'} \rangle A_{LL})}{(1 + \langle \beta_d \rangle A_{LL})(1 + \langle \beta_{u'} \rangle A_{LL})}$$

$$\begin{aligned} \beta_x &= w \cdot P_{target,x} \\ &= f \cdot P_\mu \cdot P_{target,x} \end{aligned}$$

$\rightarrow$ leading to a second order equation

- By taking the weight w, one can statistically optimise $\langle A_{LL} \rangle$:

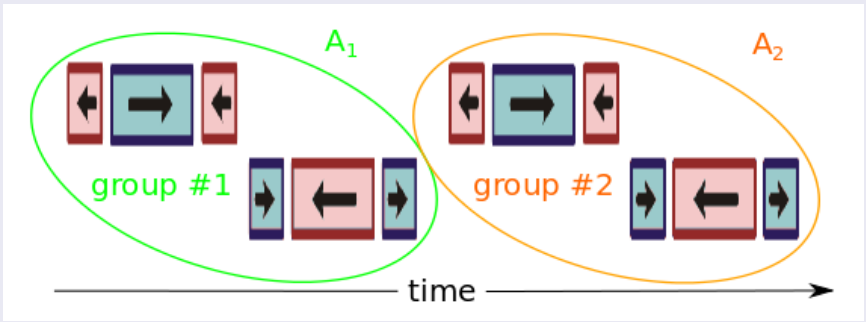
$$\delta = \frac{\sum w_u \cdot \sum w_{d'}}{\sum w_d \cdot \sum w_{u'}} \approx \frac{(1 + \langle \beta_u \rangle_w \cdot A_{LL})(1 + \langle \beta_{d'} \rangle_w \cdot A_{LL})}{(1 + \langle \beta_d \rangle_w \cdot A_{LL})(1 + \langle \beta_{u'} \rangle_w \cdot A_{LL})}$$

$$\rightarrow \frac{\sigma_{A_w}}{\sigma_{A_{st}}} \approx \sqrt{\frac{\langle w^2 \rangle}{\langle w \rangle^2}}$$

Data Grouping

Solenoid field rotation

- once a day
- remove acceptances differences between spin states
- Asymmetries computed with two consecutive groups (A_i) $\rightarrow$ remove long term instabilities



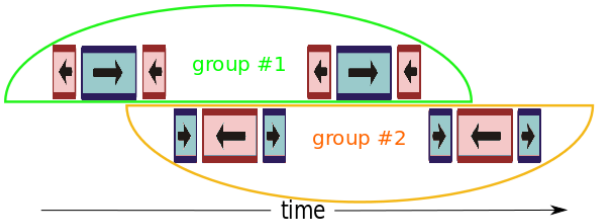
Microwave reversal

- once a year
- remove correlation between solenoid field and spin state
- A_+, A_- computed for each year with (A_{i+} and A_{i-})
- A small part of $A_+ - A_-$ must be taken into account due to unbalanced statistics:

$$A_{LL} = \langle A_i \rangle_{\sigma_{A_i}} + A_R(A_+ - A_-)$$

Estimation of some non-physical Asymmetries

- Misconfiguration Asymmetries
  $\rightarrow$ apparatus asymmetry



- Left-Right & Top-Bottom Asymmetries
  $\rightarrow$ efficiency anisotropy

- Upstream Cell - Downstream Cell Asymmetries
  $\rightarrow$ Acceptances effects and polarization inhomogeneity

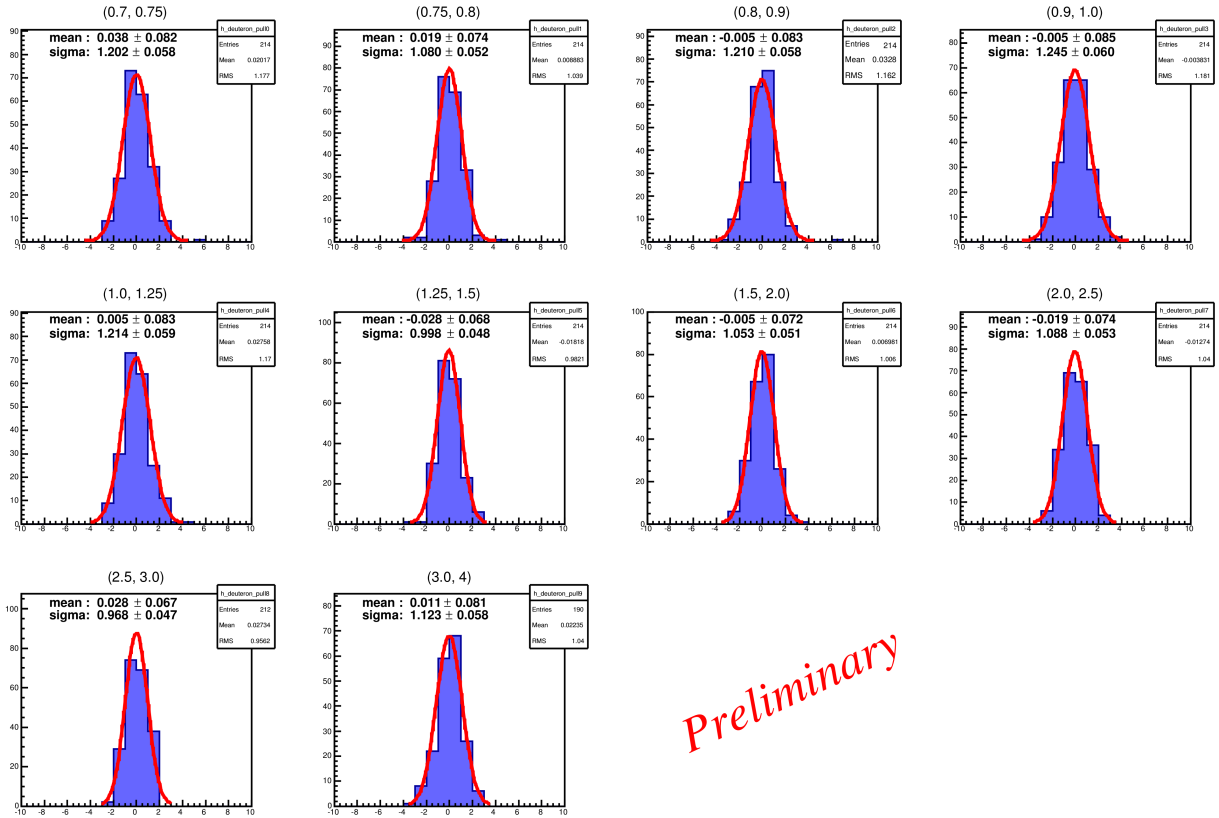
- Day-Night Asymmetries
  $\rightarrow$ Thermal expansion and electronic noise fluctuation

$\Rightarrow$ No false asymmetry detected

Random False Asymmetry via Time Stability Studies (*Pulls*)

Study of the deviation of the centred and normalised asymmetry distribution from the normal distribution $\Delta r = \frac{A_i - \bar{A}}{\sigma_A^{stat}}$

Δr for 10 p_T-bin



$\Rightarrow$ Systematics of the same order as statistics

Systematic Errors

- Multiplicative Errors

$$A_{LL} = \frac{1}{\langle f\, P_\mu \rangle P_t} A_{raw}$$

$$\Delta A_{LL}^{mult} = A_{LL} \sqrt{\left(\frac{dP_\mu}{P_\mu}\right)^2 + \left(\frac{dP_t}{P_t}\right)^2 + \left(\frac{df}{f}\right)^2}$$

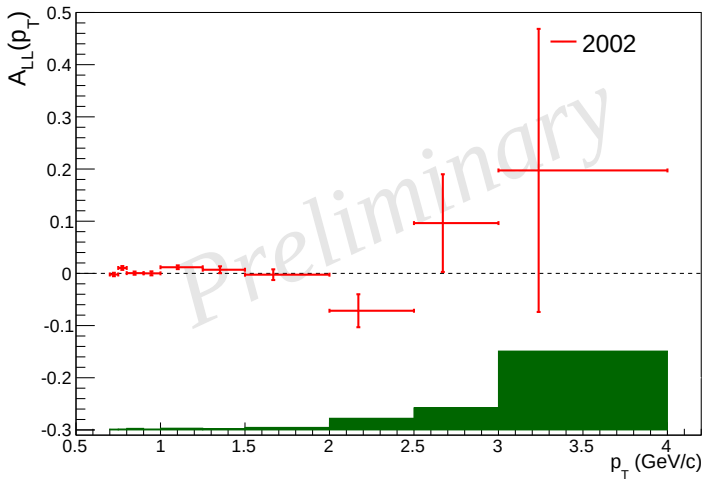
Beam Polarisation	dP_b/P_b	5%
Target Polarisation	dP_t/P_t	5%
Dilution Factor	df/f	2%
Total	ΔA^{mult}	$\approx 0.07\ A_{LL}$

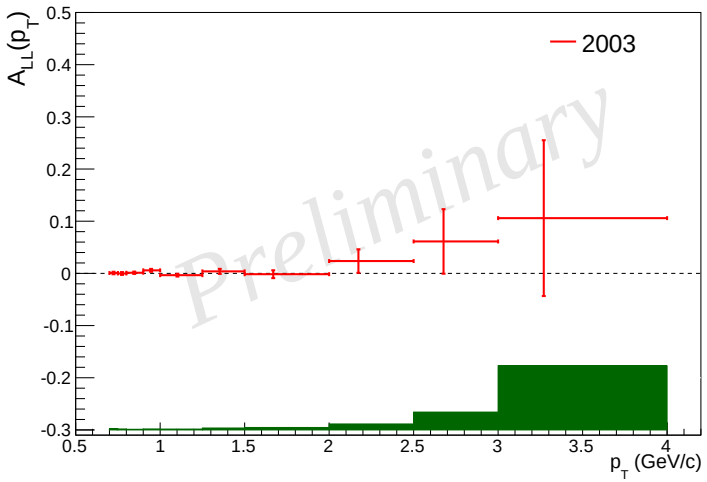
- $A_R(A_+ - A-)$ unbalanced statistics of the two microwave configurations

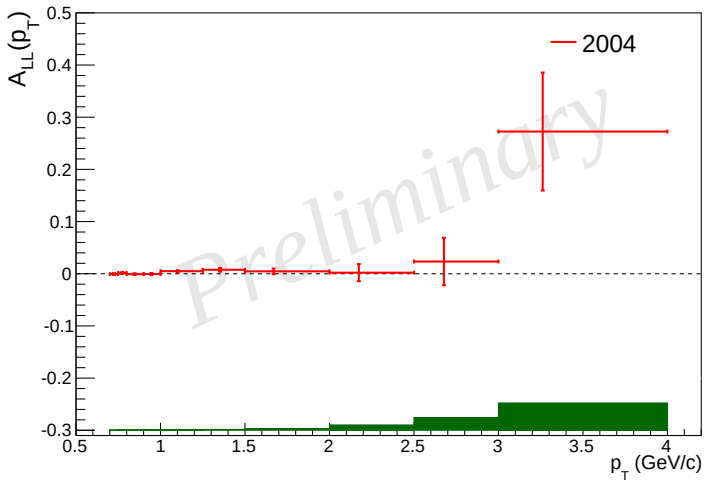
$$A_R = \frac{\sigma_{A_+}^2 - \sigma_{A_-}^2}{\sigma_{A_+}^2 + \sigma_{A_-}^2} \cdot \frac{A_+ - A_-}{2}$$

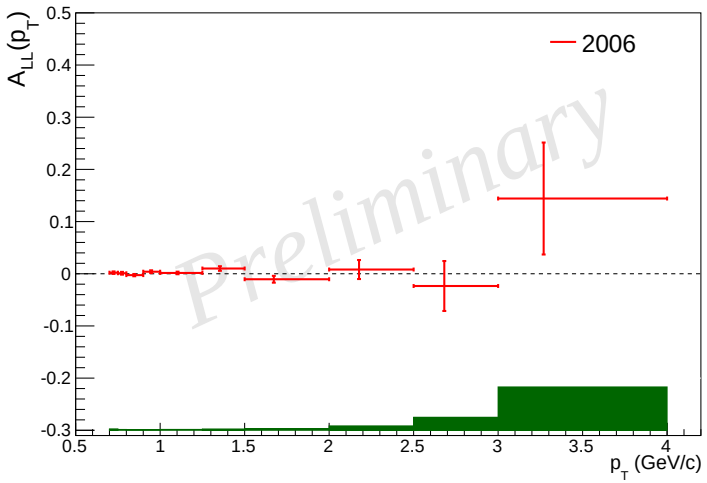
A_R remains small even when statistics between + and - configurations are relatively different

Year by Year Deuteron Results: 2002-2006





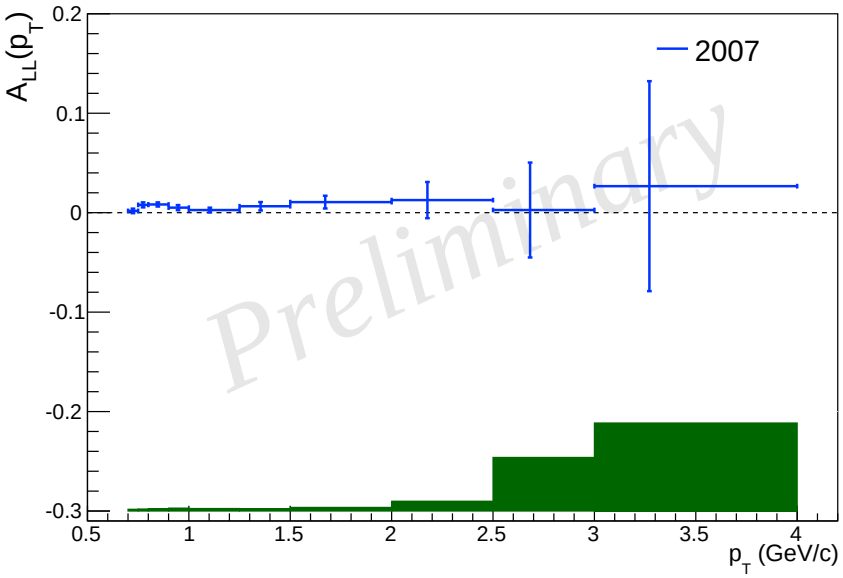


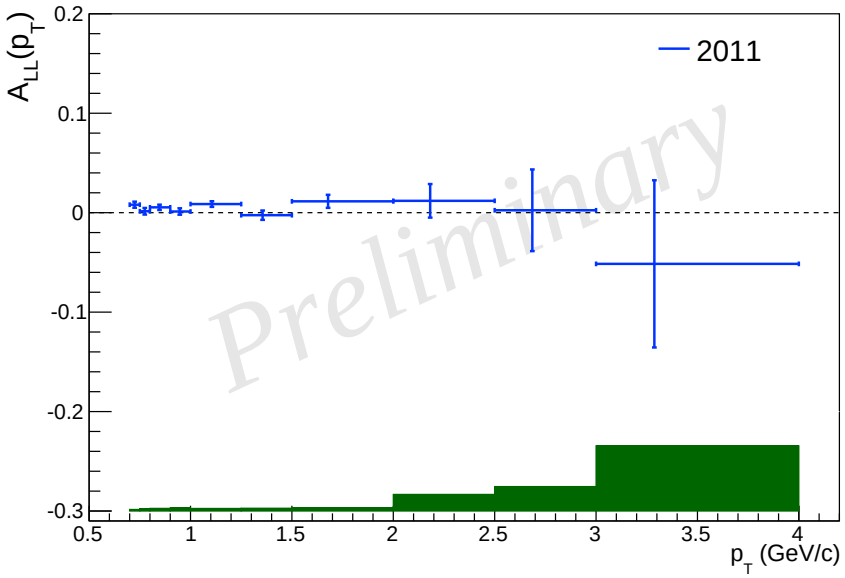


p_T	0.7 – 0.75	0.8	0.9	1.0	1.25	1.5	2.0	2.5	3.0 – 4.0	total
$\chi^2/3$ (ndf)	1.34	6.12	1.62	4.30	13.7	0.85	3.13	6.53	1.78	1.02	40.36/30

Table : compatibility χ^2 between the years

Year by Year Proton Results: 2007 and 2011

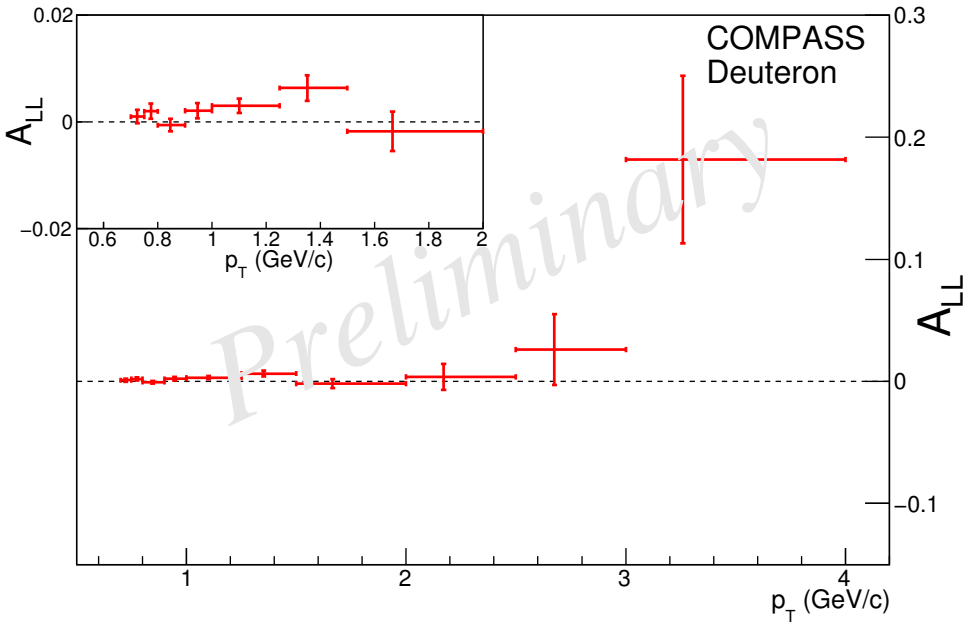


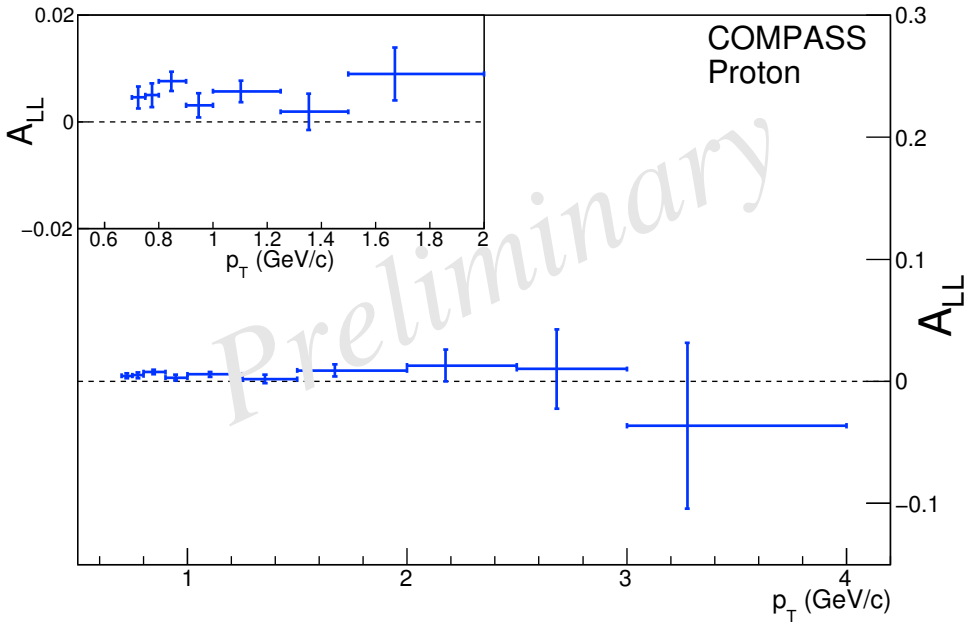


p_T	0.7 – 0.75	0.8	0.9	1.0	1.25	1.5	2.0	2.5	3.0 – 4.0	total
$\chi^2/1$ (ndf)	2.20	2.38	0.74	0.89	2.67	2.02	0.01	0.01	0.00	0.34	11.74/10

Table : compatibility χ^2 between the years

Results





- Asymmetries compatible with 0 except for:
  - *high* p_T for A_{LL}^d
  - *low* p_T for A_{LL}^p $\rightarrow$ shown by A. Nunes

1. Introduction
2. Theoretical Framework
3. Asymmetry Measurement
4. Systematics Studies
5. Results
6. Comparison with Theoretical Calculations
   - Different Sets of Polarized PDFs
   - Comparisons (without gluon resummation)

New Comparison with Theoretical Calculations

- Computations at NLO (without gluon resummation) cross-checked with W. Vogelsang
- Fragmentation functions (DSS) and unpolarized photon parton distribution (GRS) implemented
- Different sets of polarized PDFs:
  - 3 sets of GRSV (standard and extremes)
  - DSSV 2008, $\Delta G = 0.03$ (PRD 80 (2009) 034030)
  - new DSSV 2014, $\Delta G = 0.29$ (arXiv (2014) 1404.4293)
  - LSS 2010 pos, $\Delta G = 0.33$ (PRD 82 (2010) 11401)
- Gluon resummation for the polarized cross-section in progress

Different Sets of Polarized PDFs

grsv max ΔG=1.93

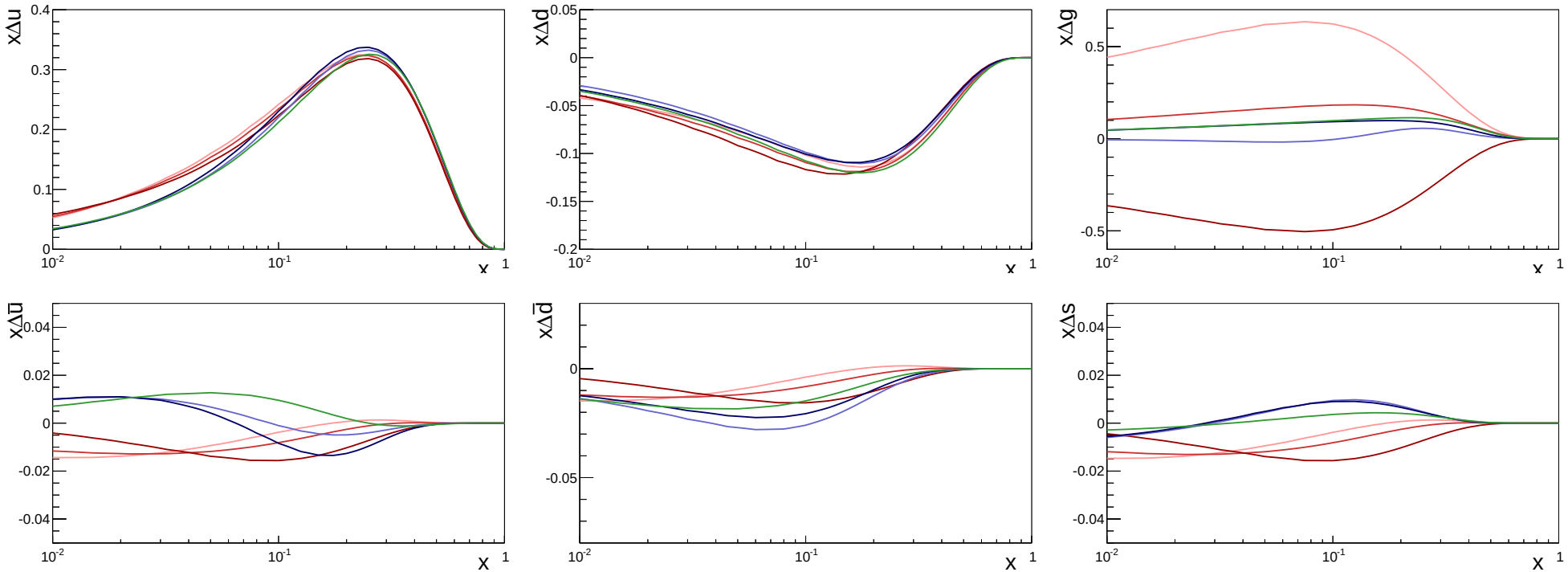
grsv std ΔG=0.57

grsv min ΔG=-1.54

dssv std ΔG=0.03

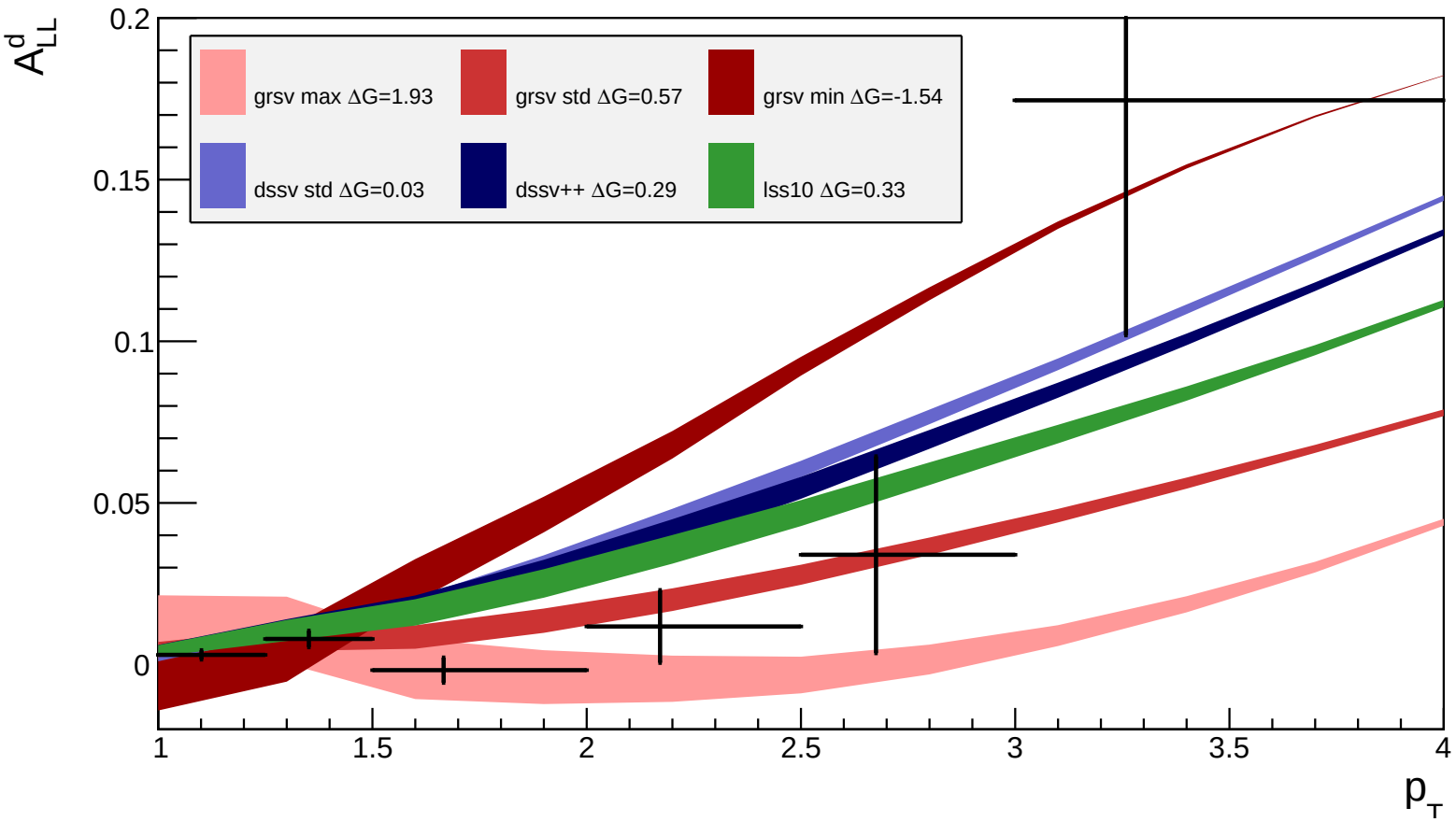
dssv++ ΔG=0.29

lss10 ΔG=0.33



Polarized PDFs for $Q^2 = 10\ GeV^2$

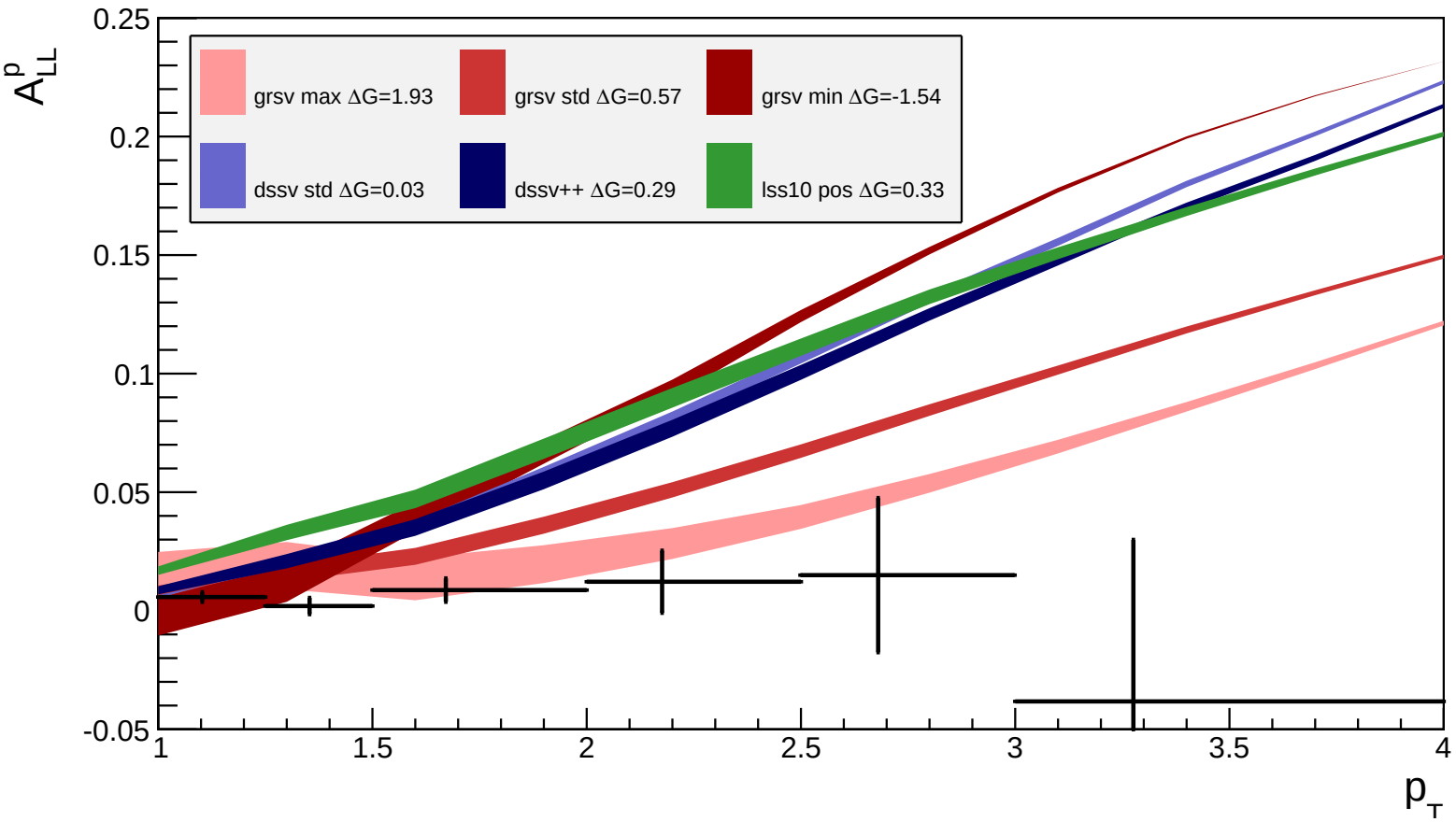
Deuteron A_{LL} (NLO from W. Vogelsang, M. Stratmann and B. Jäger codes)



→ NLO calculations of A_{LL}^d would suggest a high positive ΔG

→ No conclusion can be drawn before including the gluon resummation calculations

Proton A_{LL} (NLO from W. Vogelsang, M. Stratmann and B. Jäger codes)



→ At NLO, no PDF can yet explain A_{LL}^{p} except at really high ΔG

→ No conclusion can be drawn before including the gluon resummation calculations

Outlook

- New $A_{LL}(p_T)$ for single hadron photoproduction at *high* p_T on proton and deuteron targets at COMPASS, with $\approx 4 fb^{-1}$ integrated luminosity
- Present NLO calculations do not agree simultaneously with proton and deuteron data
- Inclusion of soft gluon resummation necessary before extracting ΔG from $A_{LL}(p_T)$ by global fit to world data
- Soon to come $A_{LL}(p_T)$ for +/- charges and also identified pions