# Longitudinale Spinphysik bei COMPASS

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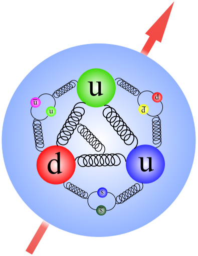
# Outline

# Motivation

**Longitudinal spin composition of the nucleon:**

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

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$

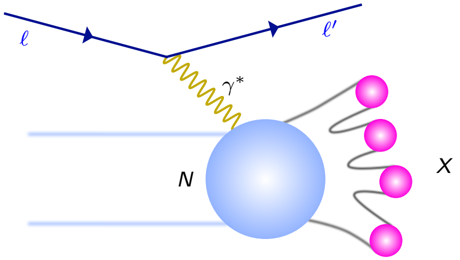



- Quark spin $\Delta\Sigma$ contributes only about 30% to the nucleon spin
- Gluon contribution $\Delta G$ some experimental constrains available
- Hardly any experimental information on orbital angular momentum $L$

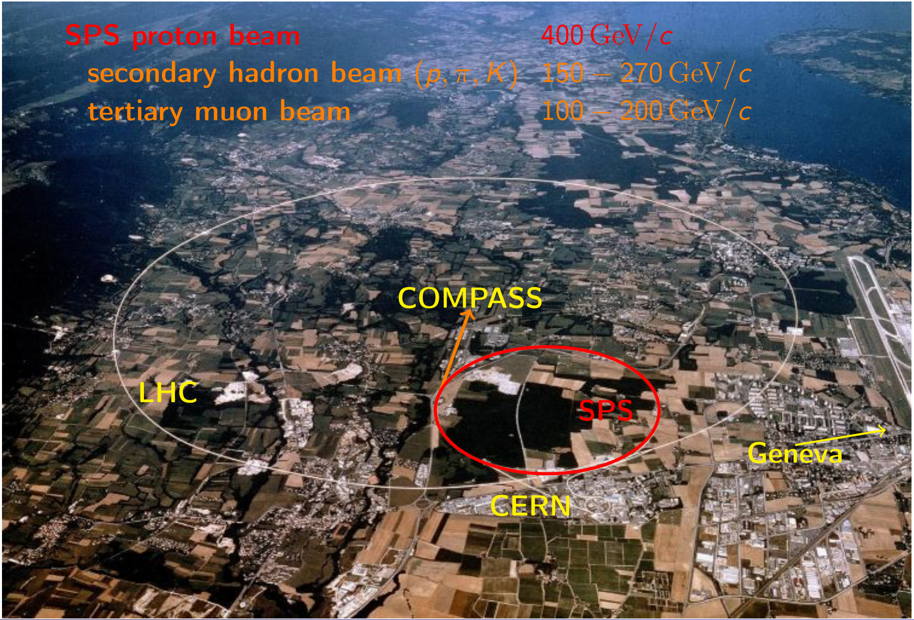
# Deep Inelastic lepton nucleon Scattering

$$\ell \; N \longrightarrow \ell' \; X$$

- Measurement of the nucleon structure
- Scattering of leptons on nucleons
- Kinematic domain with no individual resonances
- Measurement of the spin structure
  - Polarised nucleon
  - Polarised leptons
    $\rightarrow$ Polarised $\gamma$
  - High energetic beam



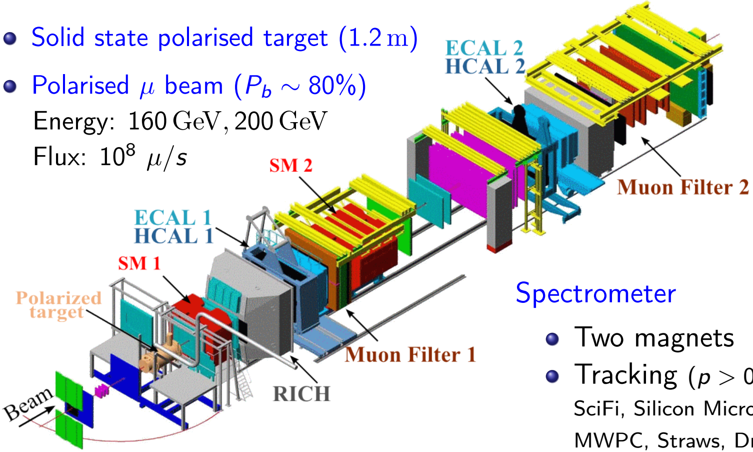
# COMPASS @ CERN



# The COMPASS experiment

**CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

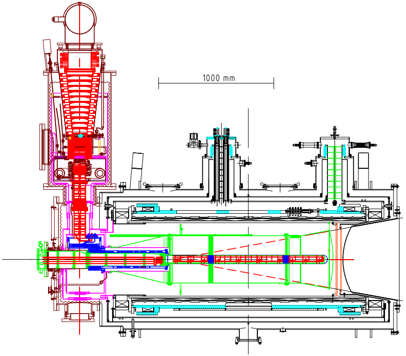
- M2 beamline
- Solid state polarised target ($1.2\,\mathrm{m}$)
- Polarised $\mu$ beam ($P_b \sim 80\%$)
  Energy: $160\,\mathrm{GeV}, 200\,\mathrm{GeV}$
  Flux: $10^8$ $\mu/s$




Spectrometer

- Two magnets
- Tracking ($p > 0.5\,\mathrm{GeV}/c$ )
  SciFi, Silicon MicroMega, Gem, MWPC, Straws, Drift tubes
- PID: RICH($\pi, K, p$)
  ECAL, HCAL, muon filters

# Polarised target

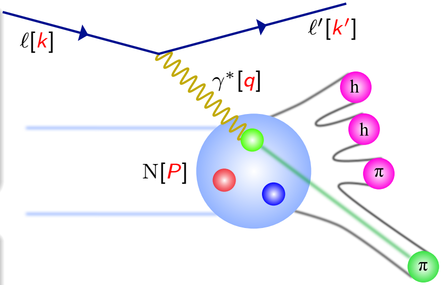



- Needed: polarised $p, d$
  → Solid state target
- Polarised via DNP
- High magnetic field:
  $2.5\,\mathrm{T}$ solenoid field
- Low temperature $50\,\mathrm{mK}$
- $^6$LiD (Longitudinal deuteron polarisation: $\sim 50\%$)
- $NH_3$ (Longitudinal proton polarisation: $\sim 90\%$)
- Large geometrical acceptance ($180\,\mathrm{mrad}$)

- DIS: $\ell + N \longrightarrow \ell' + X$
- SIDIS: $\ell + N \longrightarrow \ell' + h + X$

## DIS variables

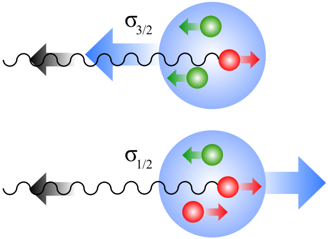
- Photon virtuality: $\mathbf{Q^2 = -q^2}$
- Bjorken scaling variable: $\mathbf{x = \frac{Q^2}{2 \cdot P \cdot q}}$
- Relative photon energy: $\mathbf{y = \frac{E - E'}{E}}$




## Hadron variables

- Hadron energy fraction: $\mathbf{z = \frac{E_h}{E - E'}}$
- Transverse momentum: $\mathbf{p_T}$
- Longitudinal momentum: $\mathbf{p_L}$

# Polarised Deep Inelastic Scattering




- Absorption of polarised photons
  $\sigma_{1/2} \sim q^+$
  $\sigma_{3/2} \sim q^-$
- $q(x) = q(x)^+ + q(x)^-$
  $\Delta q(x) = q(x)^+ - q(x)^-$

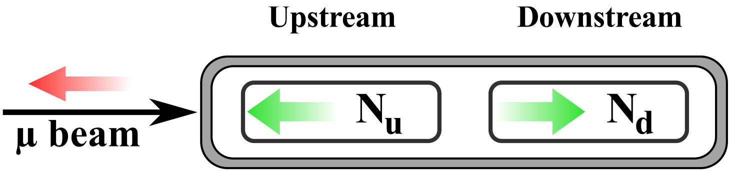
- Photon nucleon asymmetry

$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \overset{\text{LO}}{\approx} \frac{\sum_q e_q^2 (q(x)^+ - q(x)^-)}{\sum_q e_q^2 (q(x)^+ + q(x)^-)}$$

- Spin structure function

$$g_1(x, Q^2) = A_1(x, Q^2) \cdot F_1(x, Q^2) \overset{\text{LO}}{=} \frac{1}{2} \sum_q e_q^2 \Delta q(x)$$

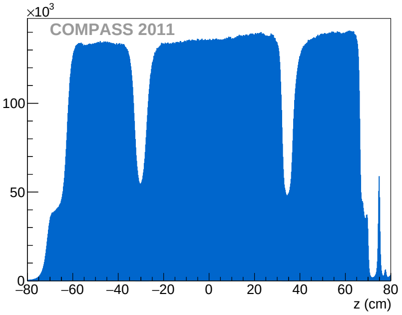
# Method (idea)

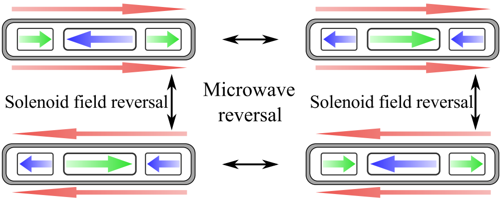



- Aim:
  $A = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$
- Measured:
  $A_{exp} = \frac{N_u - N_d}{N_u + N_d}$
- $N_i = a_i \phi_i n_i \overline{\sigma}(1 + P_\mathrm{B} P_\mathrm{T} f D A_1)$

- Needed:
  - Flux cancellation
  - Acceptance cancellation
    $\rightarrow$ polarisation rotation
    $\rightarrow$ 3 target cells

# Acceptance cancellation




- Acceptance changes with Z
- Two/Three target cells, oppositely polarised
- Measuring simultaneously both polarisations
- Flux cancels
- Regular polarisation reversals by field rotation
- Once by repolarisation

# Data selection

## 2007 and 2011 data taking

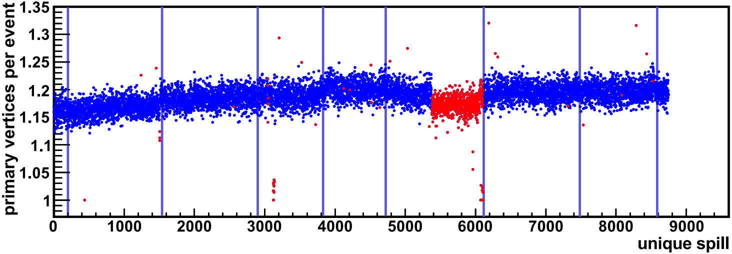
- Target material: $NH_3$
- Increased beam energy: $160\,\mathrm{GeV} \to 200\,\mathrm{GeV}$
  - Higher $Q^2$
  - Smaller $x$

## Event selection

- Kinematic cuts:
  - $Q^2 > 1\,(\mathrm{GeV}/c)^2$
  - $0.1 < y < 0.9$ remove hard to reconstruct/radiative events
- $0.0025(0.004) < x < 0.7$
- $W^2 > 10\,(\mathrm{GeV}/c^2)^2$
- Extrapolated beam track crosses all target cells

# Data quality studies

- Influence of small detector movements, detector problems ...
- Check mean values of different quantities (e.g. Number of tracks)
- Check stability of $K^0$ mass for all runs



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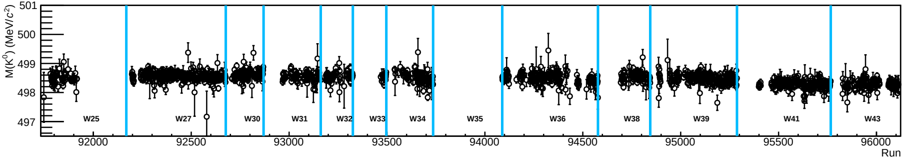
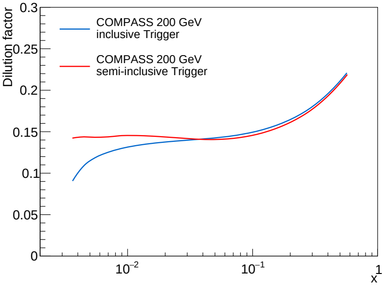
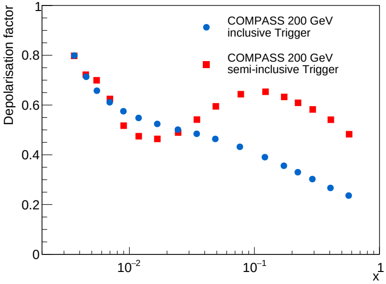
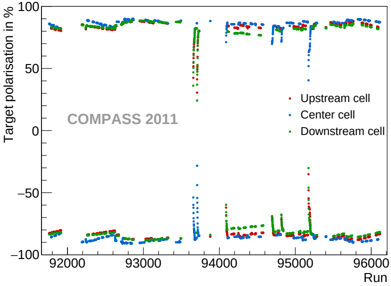


# Inputs to for asymmetry calculation



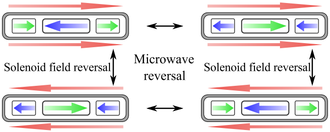



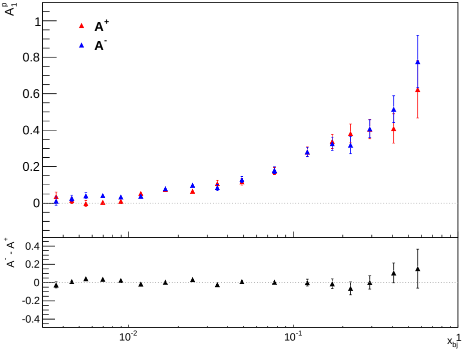




- $A_{exp} = A_1 \cdot P_{\mathrm{B}} \cdot P_{\mathrm{T}} \cdot f \cdot D$
- $D$: Depolarisation factor
- $f$: Dilution factor
- $P_{\mathrm{T}}$: Target polarisation
- $P_{\mathrm{B}}$: Beam polarisation
- Calculate average

# Systematic studies

- Most important contribution to the systematic uncertainty:
  → False asymmetries
  - Microwave reversal
  - Fake configuration (same spin orientation)
  - Several other test



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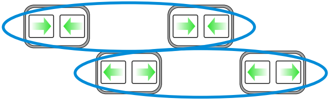
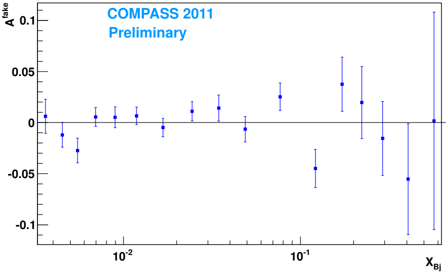
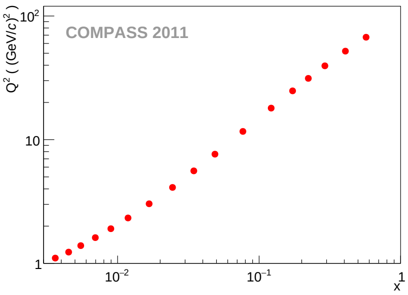
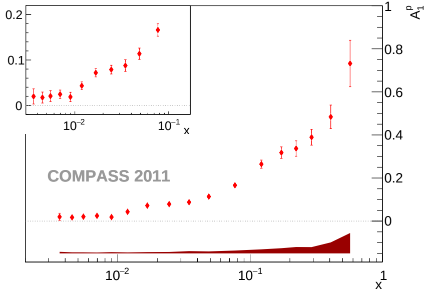


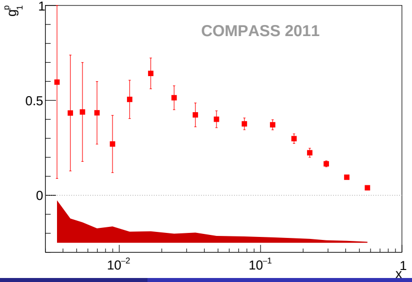


# Results on $A_1^{\mathrm{p}}$

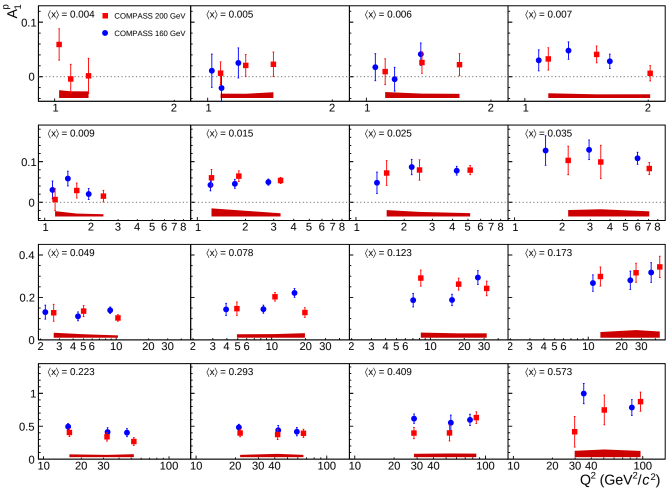



- $x$ dependence of the asymmetry
- Rise towards valence region
- $g_1^{\mathrm{p}}(x, Q^2) = F_1(x, Q^2) A_1^{\mathrm{p}}(x, Q^2)$

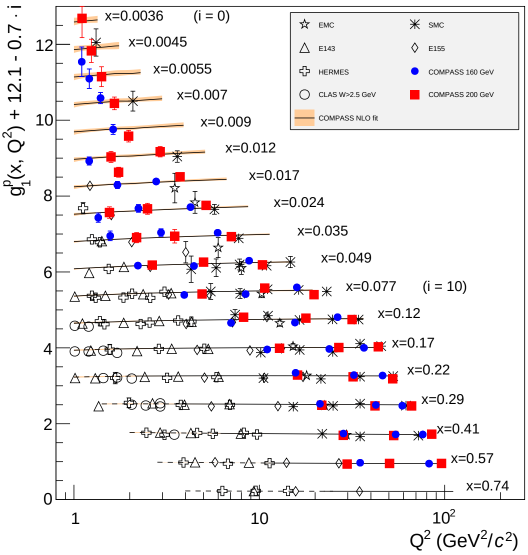


# $A_1^p$ in bins of $x$ and $Q^2$




- $^{14}$N correction and pol. rad. corrections included
- New data points at very small $x$
- Good agreement between COMPASS results at $160/200\,\mathrm{GeV}$

# Result compared to the world data




- World data
- COMPASS 2011 (200 GeV)
- COMPASS 2007 (160 GeV)
- COMPASS fit at NLO
- New data point at very low x
- Interpretation in QPM using pQCD
- Input for global QCD fit
- Indirect $\Delta G$ extraction

# NLO QCD analyses I

- DGLAP equations

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\Delta q_{\mathrm{NS}} = \frac{\alpha_s(Q^2)}{2\pi} \Delta P_{qq}^{\mathrm{NS}} \otimes \Delta q_{\mathrm{NS}}$$

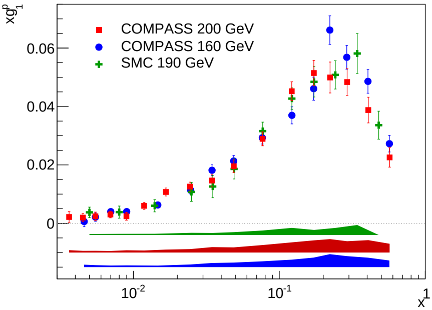
$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2}\begin{pmatrix}\Delta q_{\mathrm{Si}} \\ \Delta g\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}\Delta P_{qq}^{Si} & 2n_f\Delta P_{qg} \\ \Delta P_{gq} & \Delta P_{gg}\end{pmatrix}\otimes\begin{pmatrix}\Delta q_{\mathrm{Si}} \\ \Delta g\end{pmatrix}$$

- Structure function:

$$g_1 = \frac{1}{2}\langle e^2\rangle\left(C^{\mathrm{Si}}(\alpha_s)\otimes\Delta q_{\mathrm{Si}} + C^{\mathrm{NS}}(\alpha_s)\otimes\Delta q_{\mathrm{NS}} + C^{g}(\alpha_s)\otimes\Delta g\right)$$

- $\Delta q_{\mathrm{Si}} = \Delta U + \Delta D + \Delta S$, $\Delta q_3 = \Delta U - \Delta D$, $\Delta q_8 = \Delta U + 2\Delta D - \Delta S$
- Using only inclusive asymmetries quarks and anti-quarks cannot be disentangled *e.g.* determination of $\Delta(u+\overline{u})$, $\Delta(d+\overline{d})$, $\Delta(s+\overline{s})$ and $\Delta g$

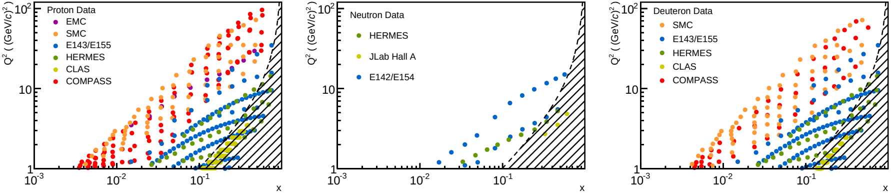
# NLO QCD analyses II




- No $x$ dependence given
- Input parametrisation at $Q_0^2 = 1\,(\mathrm{GeV}/c)^2$ needed
- Guess parametrisation
  - Low $x$: $x^\alpha$
  - High $x$: $(1-x)^\beta$
  - Allow for a node: $1+\gamma x$

$$f = \eta \frac{x^\alpha (1-x)^\beta (1+\gamma x)}{\int_0^1 x^\alpha (1-x)^\beta (1+\gamma x)\mathrm{d}x}$$

# Input and constraints

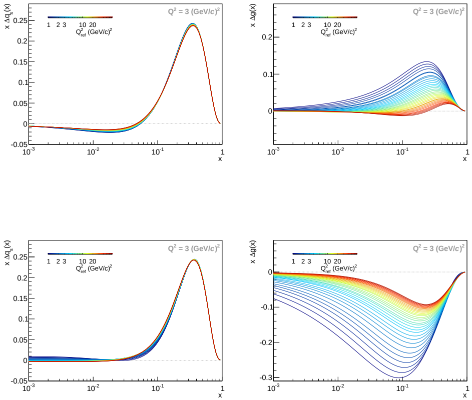



- $\chi^2 = \sum_{n=1}^{N_{exp}} \left[ \sum_{i=1}^{N_n^{data}} \left( \frac{g_1^{fit} - \mathcal{N}_n g_{1,i}^{data}}{\mathcal{N}_n \sigma_i} \right)^2 + \left( \frac{1 - \mathcal{N}_n}{\delta \mathcal{N}_n} \right)^2 \right] + \chi^2_{positivity}$
- Positivity: $|\Delta g(x)| < g(x)$ and $|\Delta(q(x) + \bar{q}(x))| < q(x) + \bar{q}(x)$
- Overall: 11 free parameters and 495 data points ($W^2 > 10\,\mathrm{GeV}^2$)
- Unpolarised parton distributions from MSTW2008

- Several equally good solutions
- Two extremes selected
- Systematic studies:
    - Different parametrisations
    - Reference scale $Q_0^2$
    - $\chi^2$ very stable

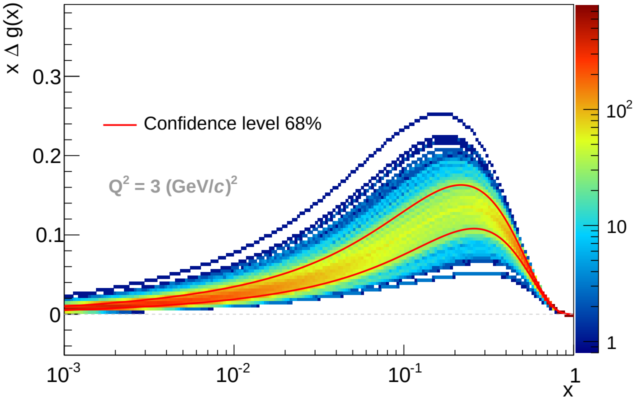
$\rightarrow$ Systematic uncertainty larger than statistical

Singlet Gluon

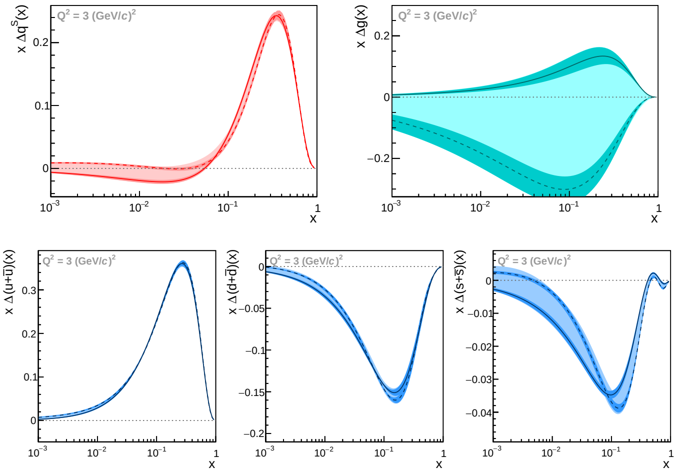


# Statistical uncertainty

- Generation of 1000 sets of pseudo data:
  Randomise data points according to a normal law
- Fit each data set
- Calculate mean and spread $\rightarrow 1\sigma$ interval



# Polarised parton distributions

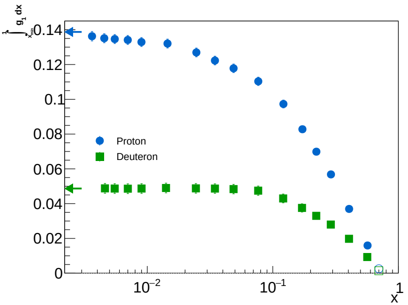



- Quark polarisation $0.26 < \Delta\Sigma < 0.36$
- Gluon polarisation $\Delta G = \int \Delta g(x) \mathrm{d}x$ Not well constrained
  $\rightarrow$ Direct measurement

# First moments from COMPASS data

$$\Gamma_1^{\mathrm{p,n}}(Q^2) = \int_0^1 g_1^{\mathrm{p,n}}(x, Q^2)dx = \frac{1}{36}\left[\left(a_8 \pm 3a_3\right) C^{\mathrm{NS}}(Q^2) + 3a_0\, C^{\mathrm{S}}(Q^2)\right]$$

- Evolve $g_1$ to $Q^2 = 3\,(\mathrm{GeV}/c)^2$
- Use results from QCD fit
- Calculate contributions from unmeasured region ($x \to 0, 1$)




$$\Gamma_1^{\mathrm{p}} = 0.139 \pm 0.003_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}} \pm 0.005_{\mathrm{evol}}$$

$$\Gamma_1^{\mathrm{N}} = 0.049 \pm 0.003_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.004_{\mathrm{evol}}$$

# Bjorken sum rule from COMPASS measurement

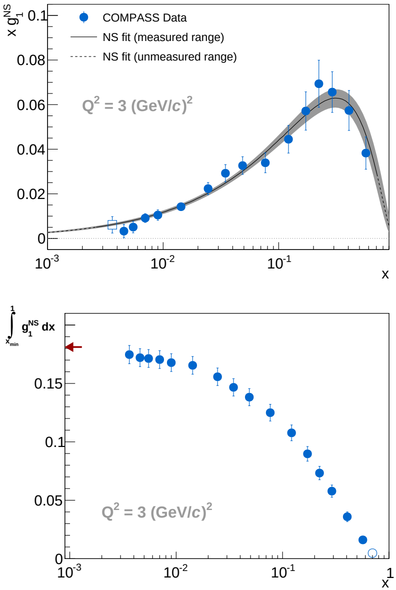
$$\int_0^1 g_1^{\mathrm{NS}}(x,Q^2)dx = \int_0^1 \left(g_1^{\mathrm{p}}(x,Q^2) - g_1^{\mathrm{n}}(x,Q^2)\right) dx = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{\mathrm{NS}}(Q^2)$$

- Non-singlet spin structure function
  $g_1^{\mathrm{NS}} = g_1^{\mathrm{p}} - g_1^{\mathrm{n}} = 2\left[g_1^{\mathrm{p}} - \frac{g_1^{\mathrm{d}}}{1-3/2\omega_D}\right]$, $\omega_D = 0.05$
- $g_1^{\mathrm{NS}}$ determined from COMPASS data only
  - 2007 & 2011 proton data
  - 2002 - 2004 deuteron data
- $\left|\frac{g_A}{g_V}\right| = 1.2701 \pm 0.0020$ obtained from neutron $\beta$-decay.
- Aim: Verification of the Bjorken sum rule

# Non-singlet structure function

- Calculate $g_1^{\mathrm{NS}}$
- Perform NLO QCD fit
  - Fit only $\Delta q_3$
  - 3 parameters needed
- Evolve $g_1^{\mathrm{NS}}$ to $Q^2 = 3\,(\mathrm{GeV}/c)^2$
- Extrapolation used for unmeasured region ($x \to 0, 1$)
- 94% in measured range
- Verification of the Bjorken sum rule:

$$\left|\frac{g_A}{g_V}\right|_{\text{NLO}} = 1.22 \pm 0.05_{(\text{stat.})} \pm 0.10_{(\text{syst.})}$$

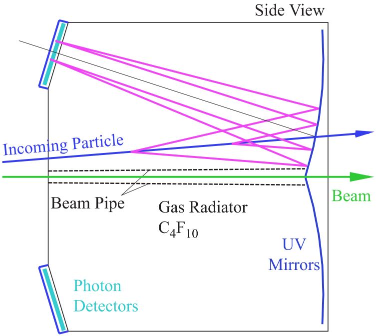


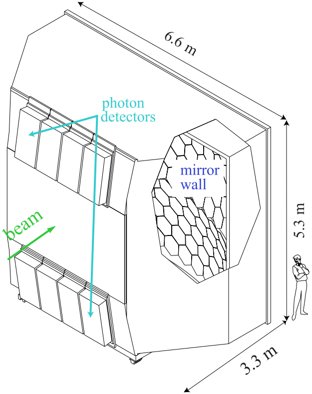
# Hadron Asymmetries

$$A_1^h(x,z) = \frac{\sum_q e_q^2\big(\Delta q(x) D_q^h(z) + \Delta\overline{q}(x) D_{\overline{q}}^h(z)\big)}{\sum_q e_q^2\big(q(x) D_q^h(z) + \overline{q}(x) D_{\overline{q}}^h(z)\big)}$$

- Calculate asymmetry for hadrons ($\pi^\pm, K^\pm$)
- Particle identification needed
- Use the RICH detector
- Determine identification efficiencies
- Access to all helicity distributions $\Delta q(x), \Delta\overline{q}(x)$
- Dependence on fragmentation functions $D_q^h(z)$

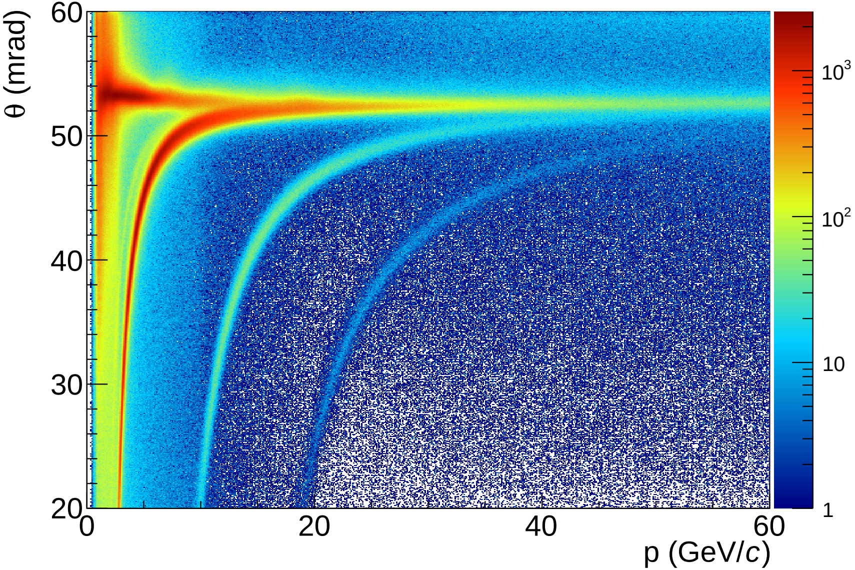
# The RICH detector




- Using the Cherenkov effect
- Ring projected on photo detectors
- Likelihood method for identification

# Momentum dependence of the Cherenkov angle



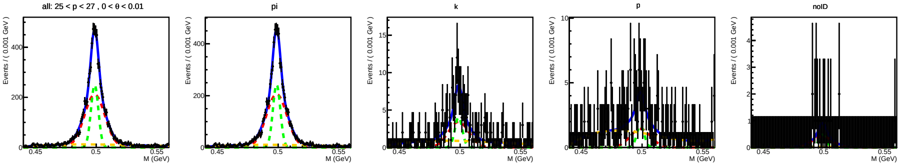
# Efficiency determination - method I

- Needed: Known particle ID without RICH information
- Use:
  - $K^0 \longrightarrow \pi^+\pi^-$
  - $\phi \longrightarrow K^+K^-$
  - $\Lambda \longrightarrow \pi^- p$
- Weak decays of $K^0/\Lambda$: secondary vertex seen
  $\rightarrow$ Cleaner sample
- Strong decays of $\phi$: secondary vertex not seen
  $\rightarrow$ Larger background

# Efficiency determination - method II

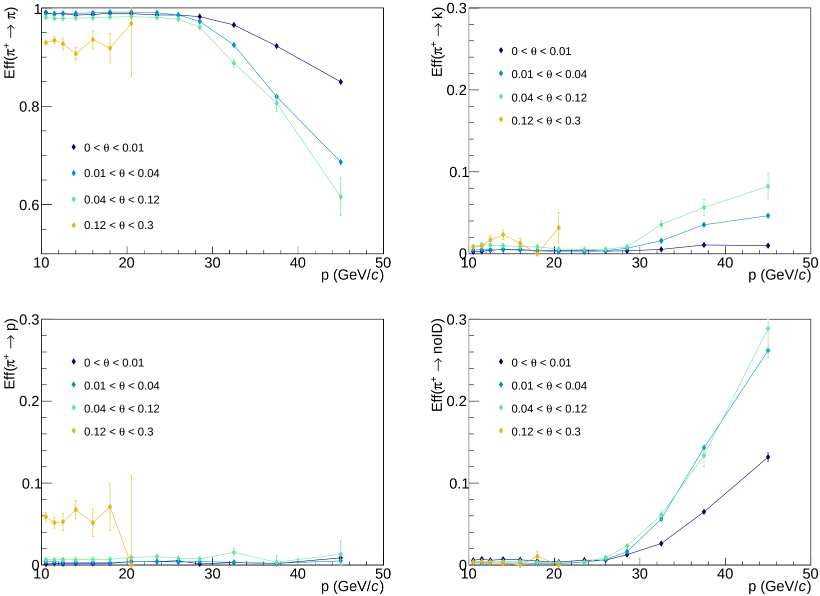
- Assumption Efficiency depends mainly on particle momentum and entry angle
  - Strong momentum dependence: 13 bins ($10 - 50\,\mathrm{GeV}/c$)
  - Weak angular dependence: 4 bins ($0 - 0.3\,\mathrm{rad}$)
- Tag one of the decay particles using the RICH (e.g. $\pi^-$ from $K^0$ decay)
- ID of the second particle known (must be $\pi^+$)
- Check the answer from the RICH (Identified as $\pi/K/p/\mathrm{noID}$)

# Efficiency determination - method III



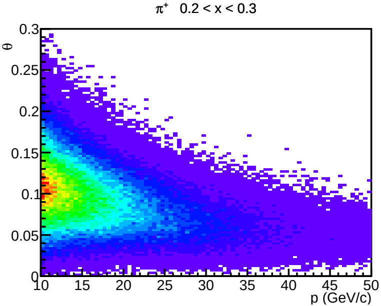

- Fit of the invariant mass spectra
- Fit simultaneously all five histograms
- Constrain on $N(all) = N(\pi) + N(K) + N(p) + N(\mathrm{noID})$
  $\rightarrow$ Efficiency between 0% and 100%
- Efficiency $\epsilon(\pi^+ \rightarrow K^+) = N(\pi \rightarrow K)/N(all)$
  - $N(all)$ constrained by first histogram (all particles)
  - $N(\pi \rightarrow K)$ from third histogram ($\pi$ identified as $K$)

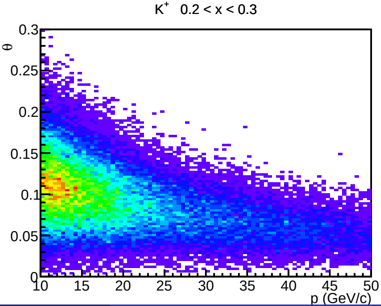
# RICH efficiency



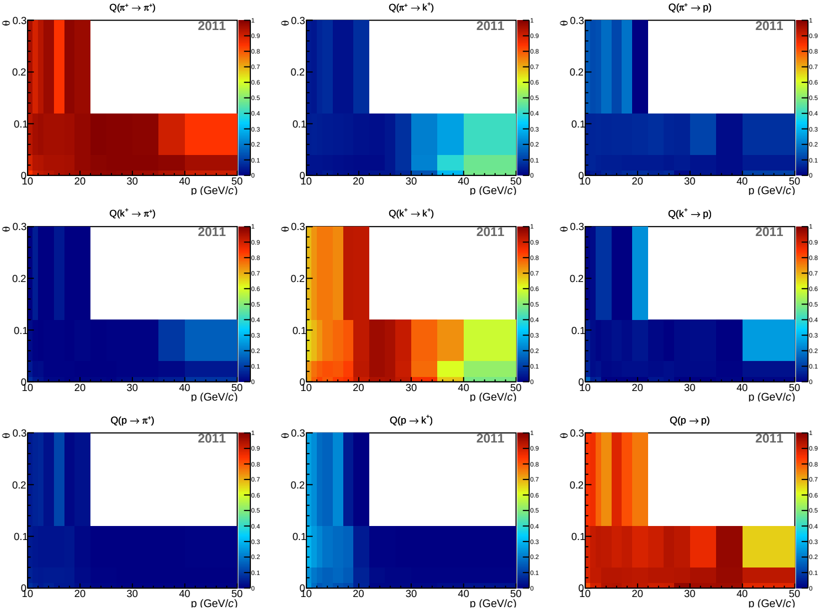
# Purity determination

- Coverage in the angle $\theta$ and momentum $p$
- Only one $x$-bin shown
- So far: RICH efficiency
  $\rightarrow$ detector property
- Needed: Purity/Contaminations
  $\rightarrow$ physics quantity
- Determined by:
  - Number of true hadrons
  - Number of Identified hadrons
  - RICH efficiency

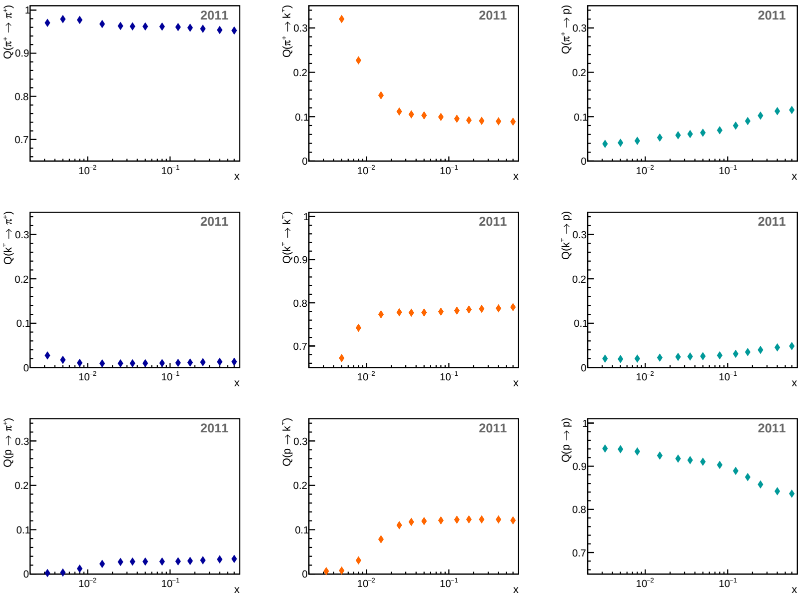


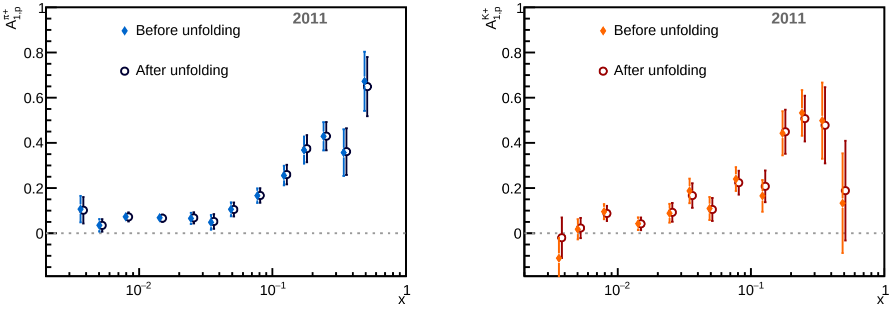
# Purity results



# Purity results



- First very preliminary results
- Unfolding: $A_1^{\text{true}} = \left(Q^T\right)^{-1} A_1^{\text{id}}$
- 2011: Take into account protons
- Small correction
- No correlations calculated so far
- Systematic studies ongoing



# Summary and Outlook

- New measurement of $A_1^{\mathrm{p}}$ and $g_1^{\mathrm{p}}$ at $200\,\mathrm{GeV}$
  - NLO QCD fit of world data
  - Update on the Bjorken sum rule from COMPASS data only
  - Verification of the Bjorken sum rule
- Identified hadron asymmetries
  - Method for extracting RICH efficiencies
  - Determination of the hadron purities
  - First results on the asymmetry
- Outlook
  - Further work on the identified hadron asymmetries
  - Extraction of polarised PDFs for each flavour