Semi–inclusive Deep Inelastic Scattering & Spin–flavour Decomposition

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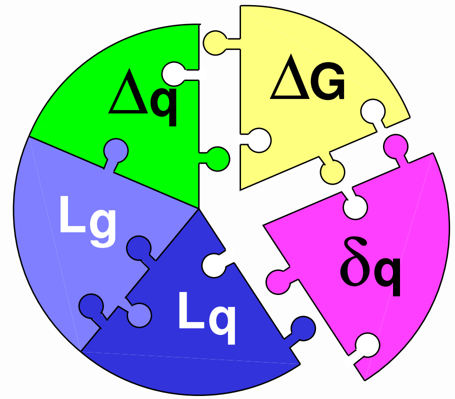
Outline

- The helicity structure of the nucleon
- Spin dependent DIS
- Why Semi–Inclusive DIS?
- The *Purity* Formalism
- Experiments on Polarised SIDIS:
  - SMC
  - HERMES
  - COMPASS
- Outlook

Helicity Structure of the Nucleon



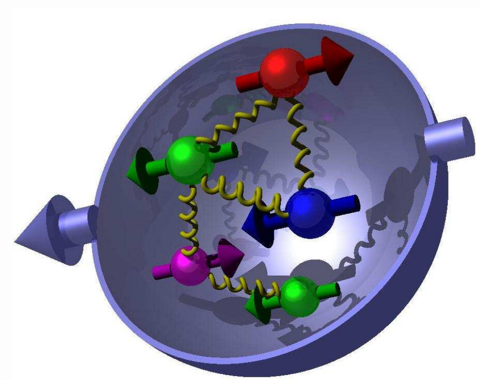
- Helicity Sum Rule for nucleons:

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

where

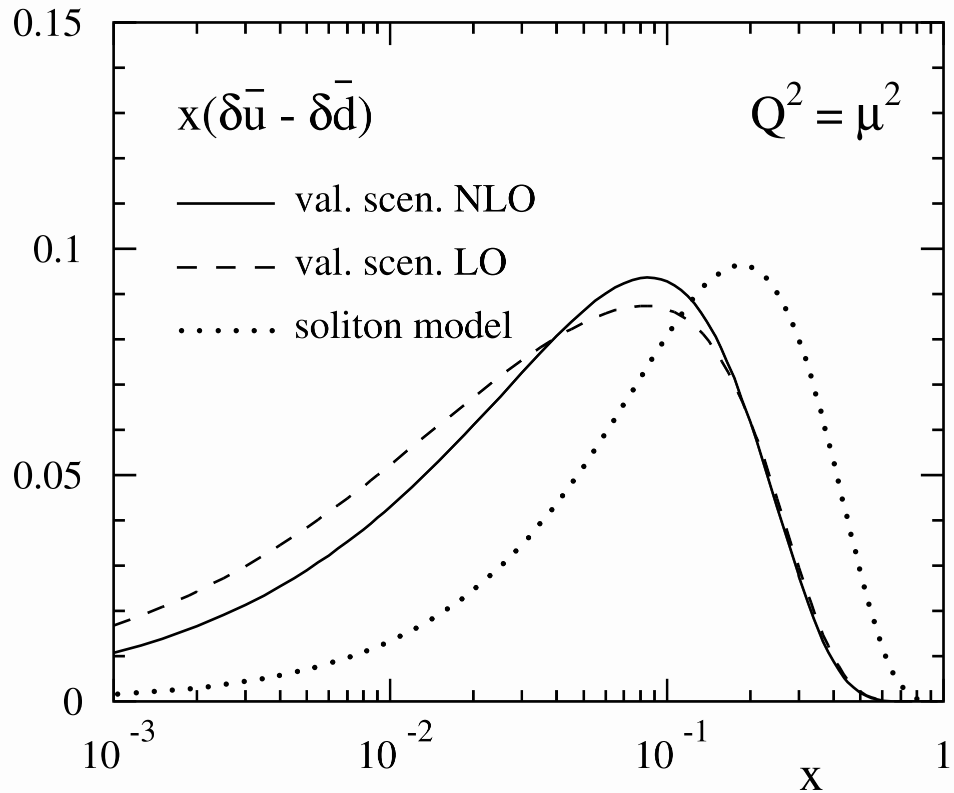
$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \simeq \begin{cases} 0.14\ldots 0.2 & \text{measured} \\ 0.58 & \text{expected} \end{cases}$$

- The $\Delta q = \Delta u, \Delta\bar{u}, \ldots$ are the first moments of the helicity densities $\Delta u(x), \Delta\bar{u}(x), \ldots$
- Helicity density: $\Delta q(x) = q^{+}(x) - q^{-}(x)$



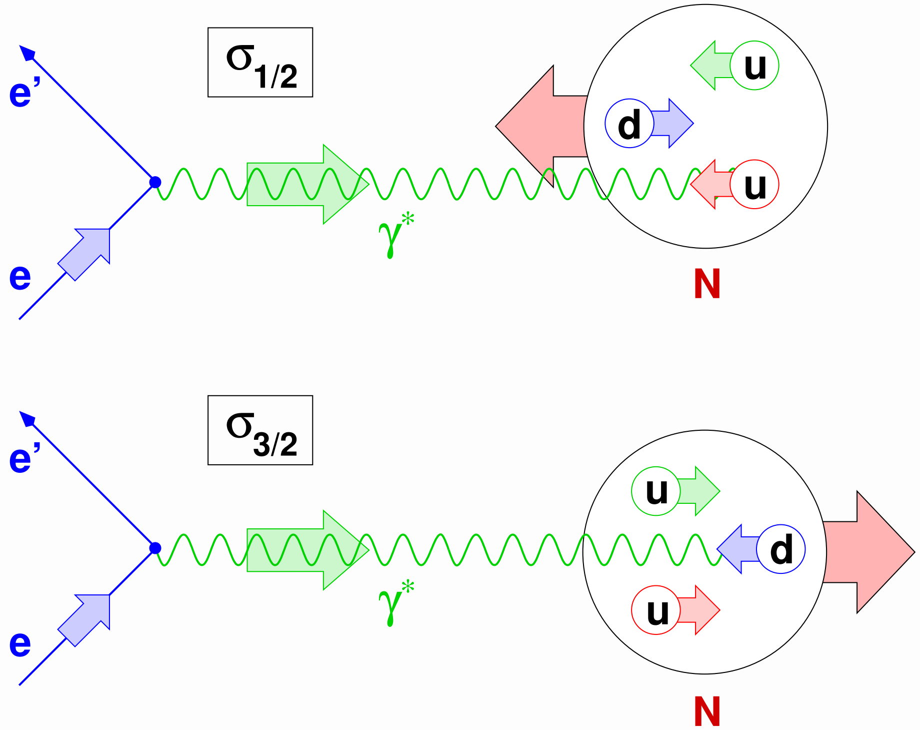
Models for Sea Quark Helicity Distributions

- Different models which predict $\Delta\bar{u}(x) \neq \Delta\bar{d}(x) \neq \Delta s(x)$
  - Chiral quark–soliton model (χQSM)
    [Dressler et al., EPJ C14 (2000) 147]
  - Pauli blocking ansatz
    [Glück et al., PRD 63 (2001) 094005]
  - Statistical model
    [Bourrely et al., EPJ C23 (2002) 487]
  - ⋮



[Glück et al., PRD 63 (2001) 094005]

DIS Cross Section Asymmetries



- DIS $e + N \rightarrow e' + X$ in lowest order mediated by one–photon exchange
- Virtual photon γ^* can only couple to quarks of opposite helicity
- Can select $q^+(x)$ or $q^-(x)$ by orientation of target nucleon spin or helicity of incident lepton beam
- Define cross section asymmetry A_1 in the $\gamma^* N$ system:

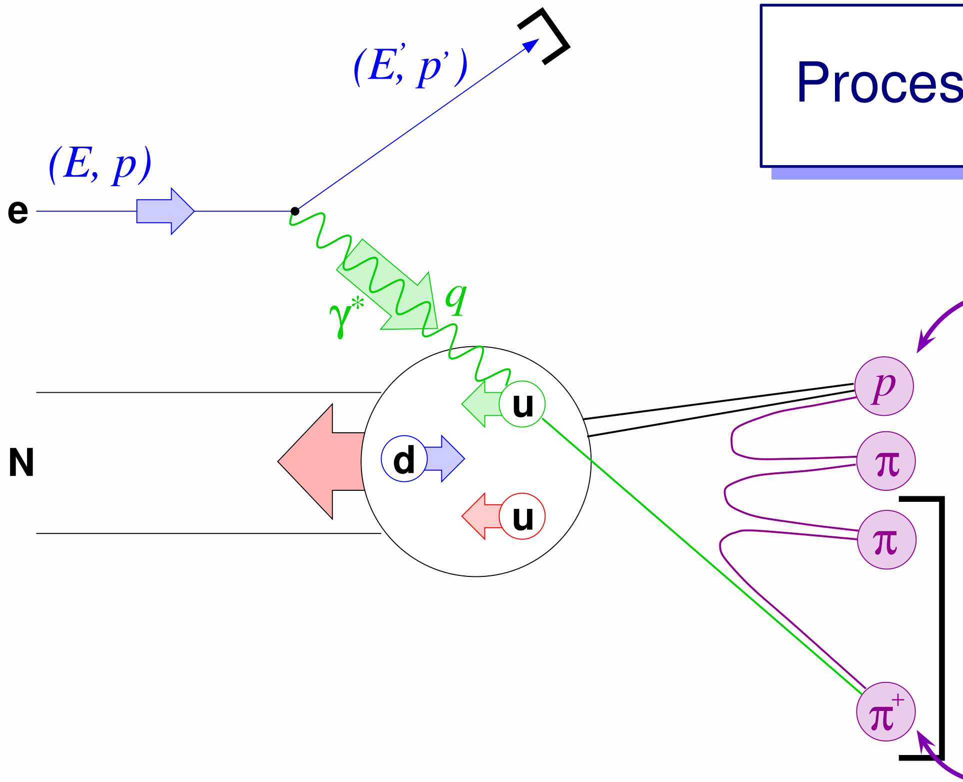
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

- In the QCD parton model:

$$A_1(x, Q^2) \overset{g_2=0}{\simeq} \frac{g_1(x, Q^2)}{F_1(x, Q^2)} = \frac{\sum_q e_q^2 \, \Delta q(x, Q^2)}{\sum_q e_q^2 \, q(x, Q^2)}$$

Weighted by e_q^2

SIDIS: Semi–Inclusive Deep Inelastic Scattering



Process: $\vec{e} + \vec{N} \longrightarrow e' + h + X$

Target fragments
($z = E_h/\nu$ small)

Current fragments

Factorisation ansatz for cross section:

$$\sigma^h(x, Q^2, z) \propto \sum_{q=u,\bar{u},\ldots} e_q^2\, q(x, Q^2)\, D_q^h(z, Q^2)$$

Different weights for
$h = \pi^{\pm}, K^{\pm}, \ldots$

SIDIS Cross Section Asymmetries

- Measured longitudinal cross section asymmetry

$$A_{\parallel} = \frac{1}{f\langle P_B\, P_T\rangle} \cdot \frac{(N/\mathcal{L})^{\overset{\rightarrow}{\Leftarrow}} - (N/\mathcal{L})^{\overset{\rightarrow}{\Rightarrow}}}{(N/\mathcal{L})^{\overset{\rightarrow}{\Leftarrow}} + (N/\mathcal{L})^{\overset{\rightarrow}{\Rightarrow}}},$$

N : Number of DIS events
$\mathcal{L}$: luminosity
P_B, P_T : beam and target polarisations
f : dilution factor

- Relation to asymmetry A_1:

$$\frac{A_{\parallel}(x,Q^2)}{D(x,Q^2)[1+\eta\gamma]} = A_1(x,Q^2) \overset{g_2=0}{\simeq} \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Contribution from F_L:

$$2x\,F_1 = F_2 \cdot \frac{1+\gamma^2}{1+R}$$

- With $D_{q^+}^{\pi,K}(z) = D_{q^-}^{\pi,K}(z)$:

$$A_1^h(x,Q^2) \overset{g_2=0}{\simeq} \frac{\sum_q e_q^2\, \Delta q(x,Q^2)\, \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_q^h(z,Q^2)}{\sum_q e_q^2\, q(x,Q^2)\, \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_q^h(z,Q^2)} \times \underbrace{\frac{1+R(x,Q^2)}{1+\gamma^2}}_{=:\,\mathcal{C}}$$

The Purity Formalism

- Rewrite photon–nucleon asymmetry $A_1^h(x, Q^2)$:

$$A_1^h(x,Q^2) = \sum_q \frac{e_q^2\, q(x,Q^2)\ \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2\, q'(x,Q^2)\ \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_{q'}^h(z,Q^2)} \cdot \frac{\Delta q}{q}(x,Q^2)$$

  where the "purity" is an unpolarised quantity.

- Need at least six independent asymmetry sets $A_1^h(x)$ to determine six unknown helicity distributions $\Delta u(x), \Delta\bar{u}(x), \Delta d(x), \Delta\bar{d}(x), \Delta s(x), \Delta\bar{s}(x)$

- Purity equation generally under–determined $\rightarrow$ add symmetry assumptions, e.g.

$$\Delta u_s(x) = \Delta\bar{u}(x) = \Delta d_s(x) = \Delta\bar{d}(x) = \Delta s(x) = \Delta\bar{s}(x) \quad \text{(SMC 1998)}$$

$$\frac{\Delta\bar{u}(x)}{\bar{u}(x)} = \frac{\Delta\bar{d}(x)}{\bar{d}(x)} = \frac{\Delta s(x)}{s(x)} = \frac{\Delta\bar{s}(x)}{\bar{s}(x)} \quad \text{(HERMES 1999)}$$

$$\frac{\Delta s(x)}{s(x)} = \frac{\Delta\bar{s}(x)}{\bar{s}(x)} \quad \text{(HERMES 2002)}$$

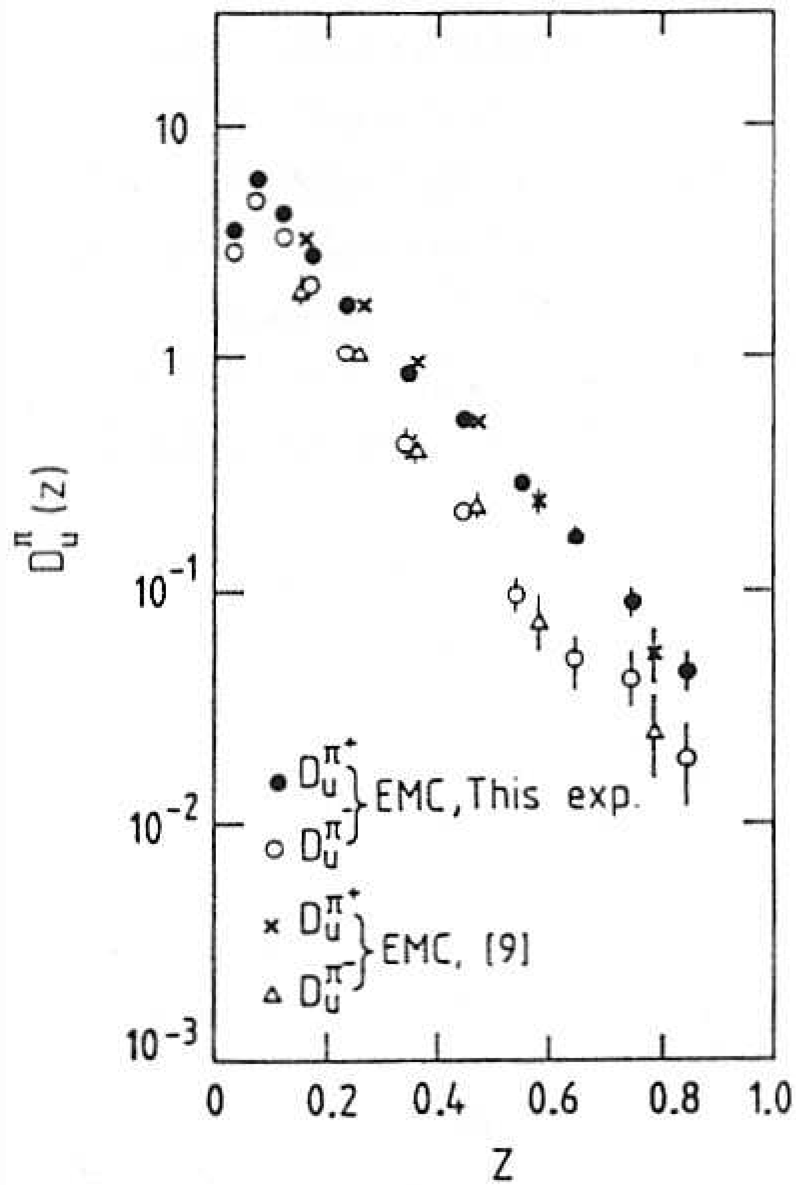
Generation of Purities (SMC)

$$\mathcal{P}_q^h(x,Q^2) = \frac{e_q^2\, q(x,Q^2)\, \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_q^h(z,Q^2)}{\sum_{q'} e_{q'}^2\, q'(x,Q^2)\, \int_{z_{\min}}^{z_{\max}} \mathrm{d}z\, D_{q'}^h(z,Q^2)}$$

- Unpolarised PDFs $q(x,Q^2)$ from GRV94LO or CTEQ3L
- Fragmentation functions $D_q^{h^\pm}(z,Q^2)$ from EMC
- Minimising

$$\chi^2 = \left(\vec{A} - \mathcal{P}\vec{Q}\right)^T (\mathrm{Cov}_A)^{-1} \left(\vec{A} - \mathcal{P}\vec{Q}\right)$$

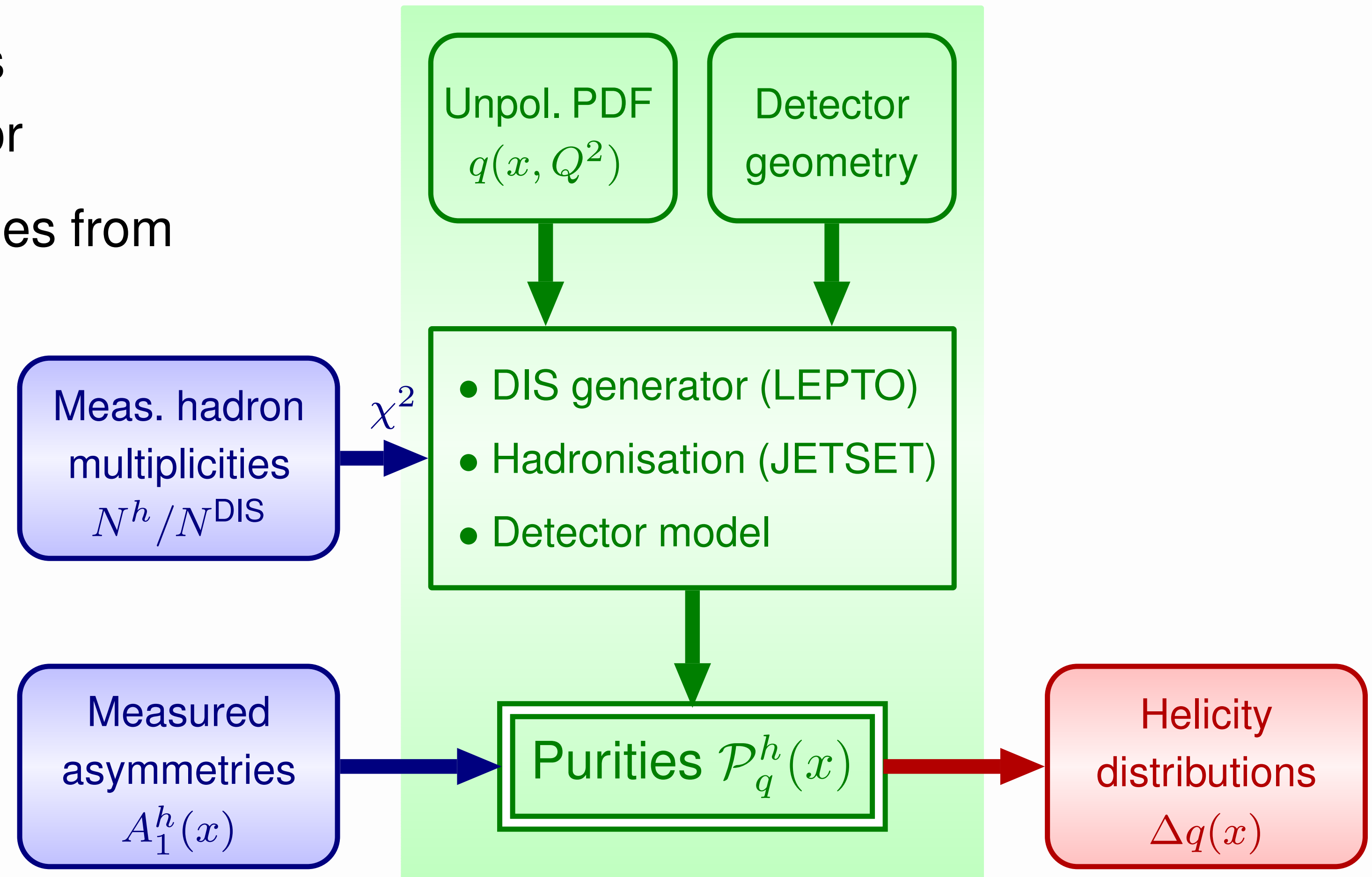
to obtain $\vec{Q} = \left(\frac{\Delta u_v}{u_v}(x), \frac{\Delta d_v}{d_v}(x), \frac{\Delta q_s}{q_s}(x)\right)$



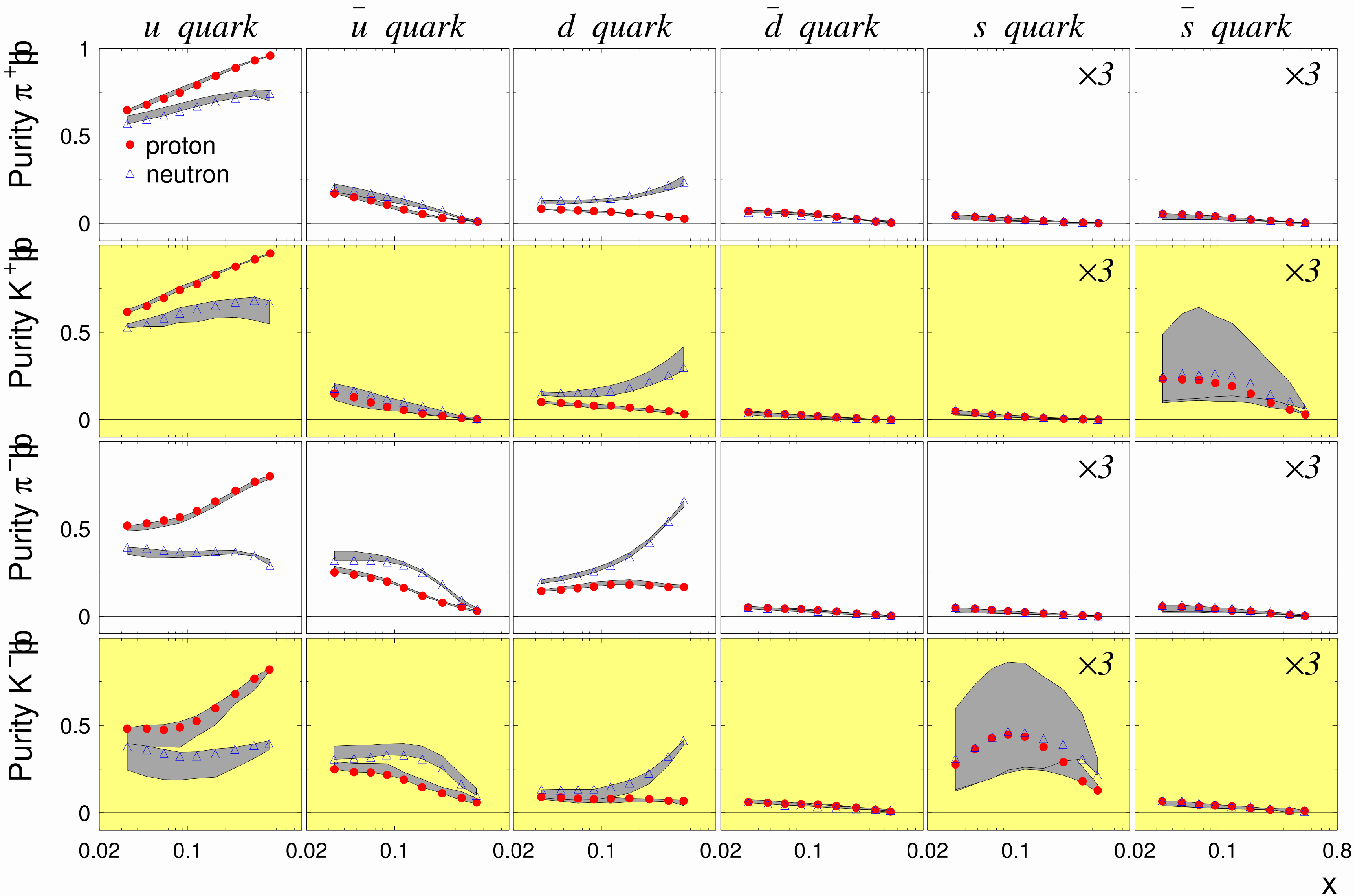
[M. Arneodo et al., Nucl. Phys. B321 (1989) 541]

Generation of Purities (HERMES)

- Use Monte Carlo model of DIS process (LEPTO), fragmentation process (JETSET) and detector
- Systematic uncertainties from
  - Variation of fragmentation parameters
  - Use of alternative PDF set GRV98LO vs. CTEQ5L



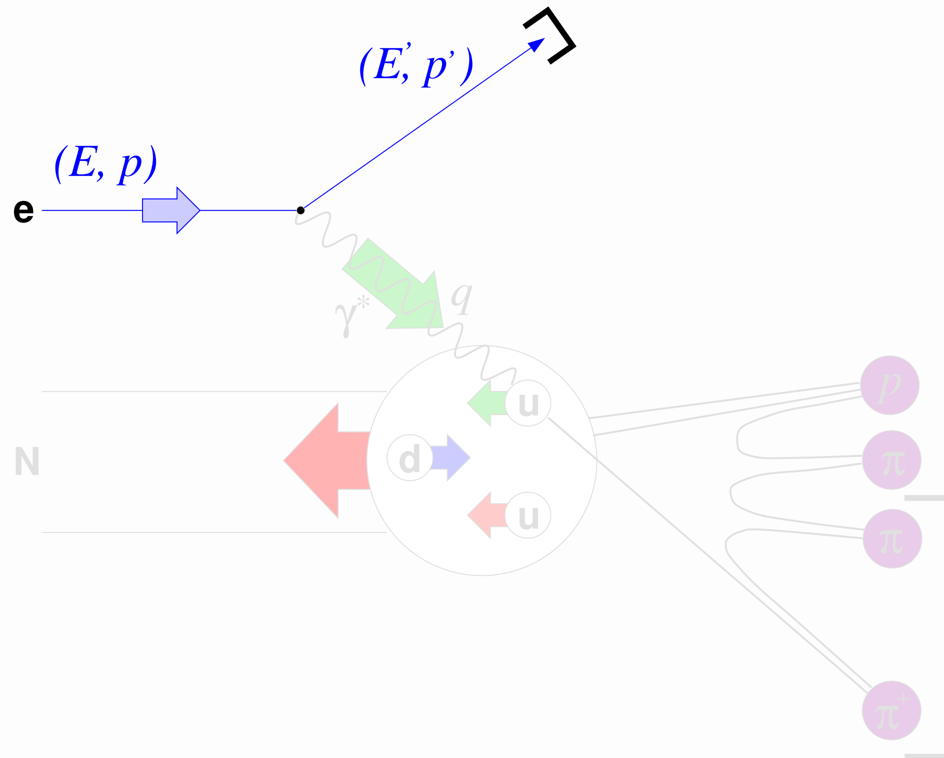
Purities (HERMES)



Syst. uncertainties from PDF sets (GRV98LO, CTEQ5L) and LUND parameters

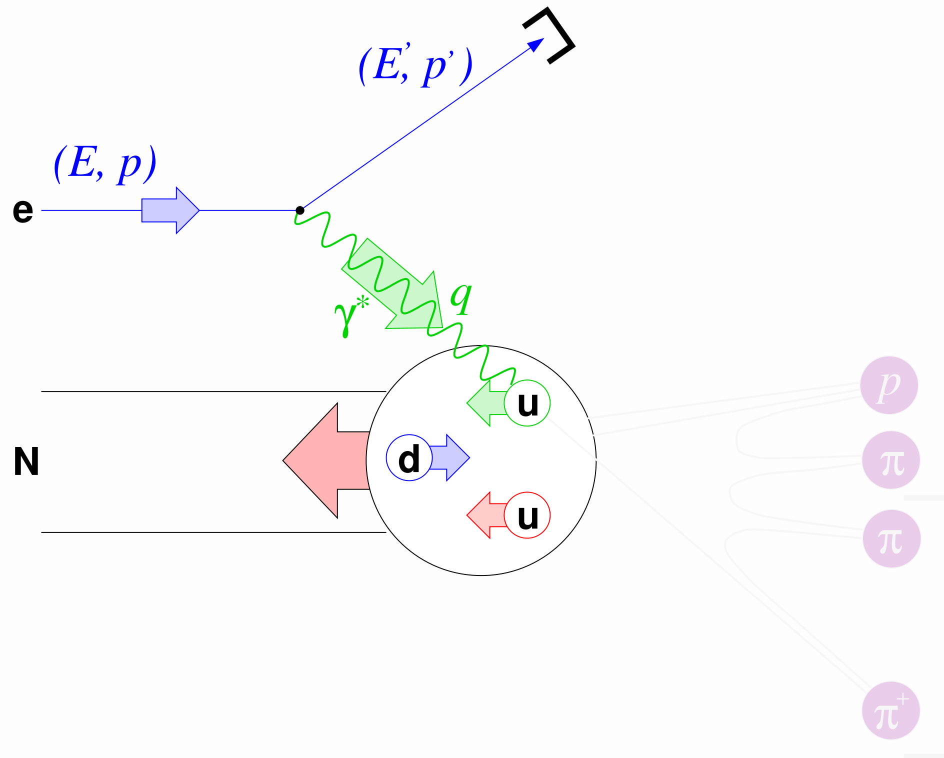
Experimental Prerequisites

- Longitudinally polarised lepton beam



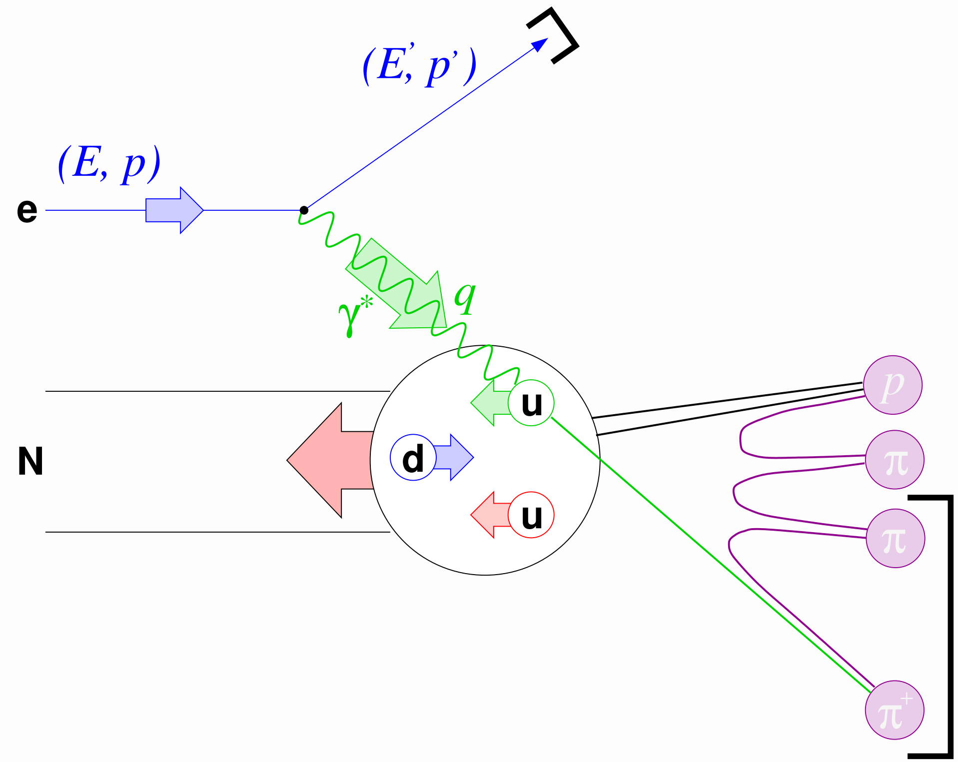
Experimental Prerequisites

- Longitudinally polarised lepton beam
- Longitudinally nuclear polarised target



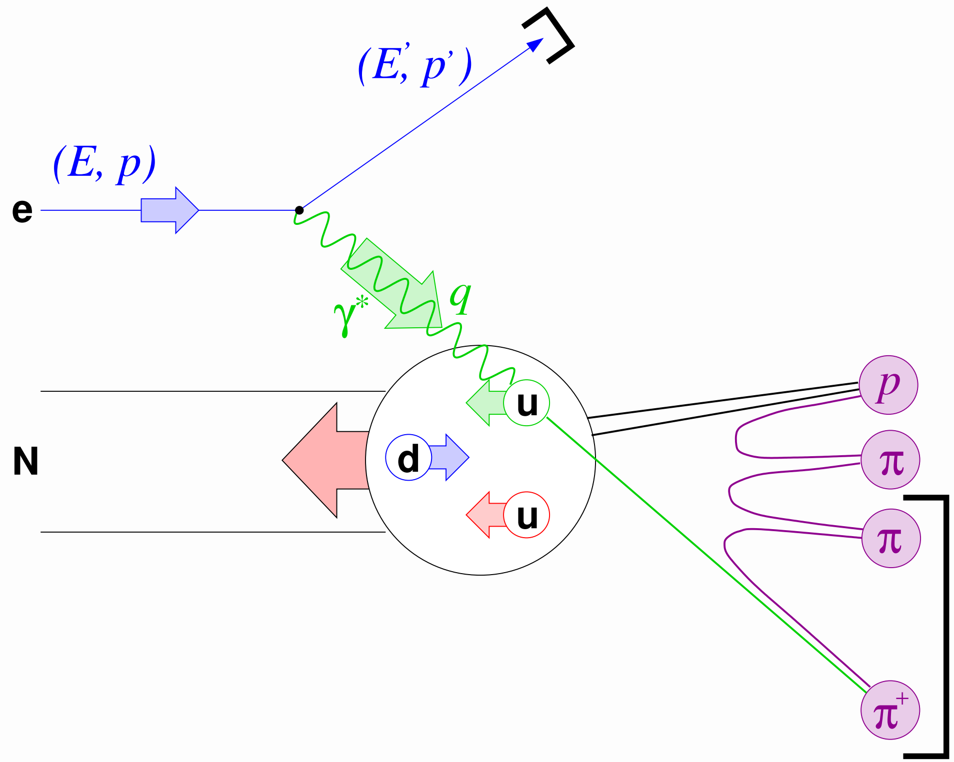
Experimental Prerequisites

- Longitudinally polarised lepton beam
- Longitudinally nuclear polarised target
- Large geometrical acceptance



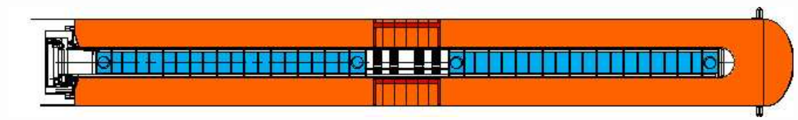
Experimental Prerequisites

- Longitudinally polarised lepton beam
- Longitudinally nuclear polarised target
- Large geometrical acceptance
- Good particle identification



The SMC Experiment at CERN

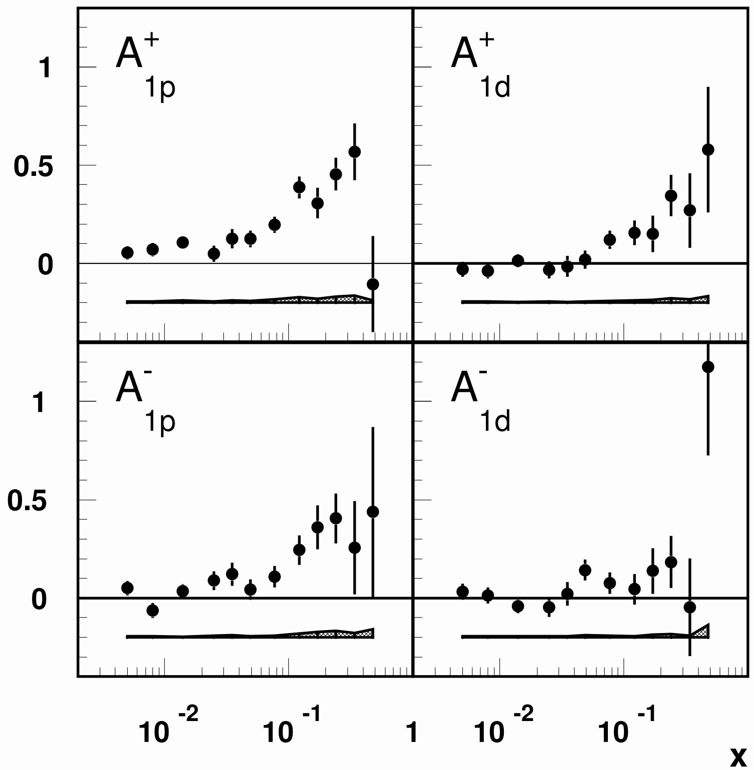
- Longitudinally polarised μ–beam
  - $E_{\text{Beam}} = 100$ / 190 GeV
  - $\langle P_{\text{Beam}} \rangle \approx 0.80$
- Longitudinally polarised solid state target
  - Target materials: Butanol (C_4H_9OH), d–Butanol (C_4D_9OD), Ammonia (NH_3)
  - $\langle P_{\text{Target}} \rangle \approx$ 0.88 (0.50) for p–, (d–)target
  - Dilution factor $f = 0.07 \ldots 0.16$

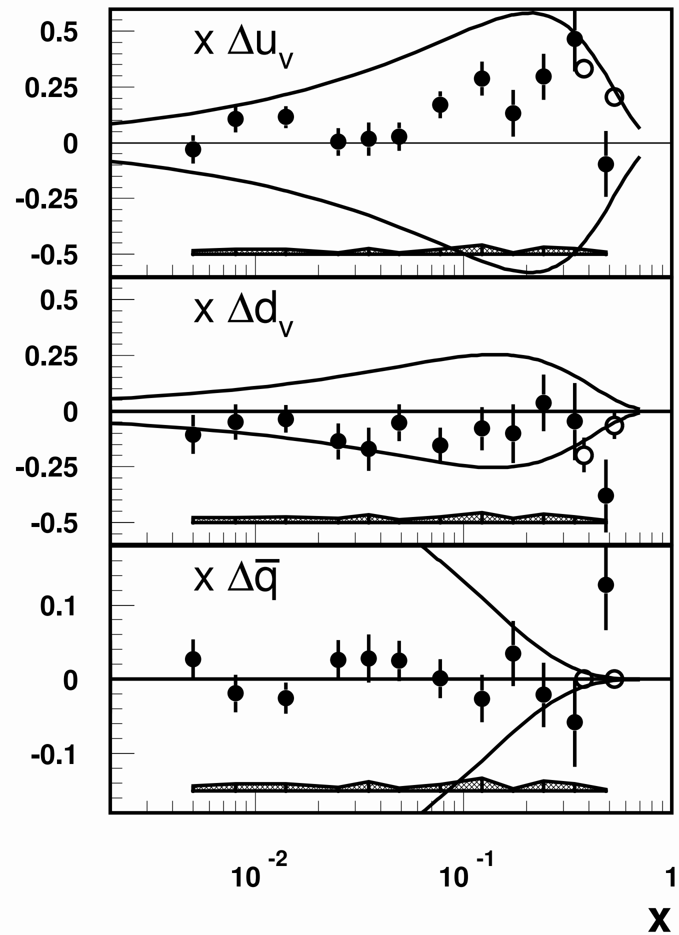


- Forward spectrometer with large acceptance and μ–h identification
- Data taking from 1993 to 1996

Results from the SMC Experiment

- Measured SIDIS asymmetries:



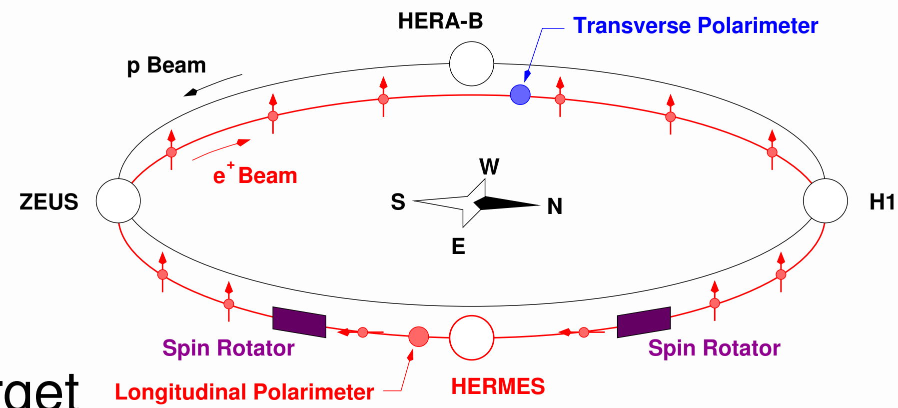


[B. Adeva et al., Phys. Lett. B420 (1998) 180]

- Covered range: $0.003 \le x \le 0.7$
- EMC fragmentation functions

$$\Delta\bar{q}(x) \equiv \Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta s(x) = \Delta\bar{s}(x)$$

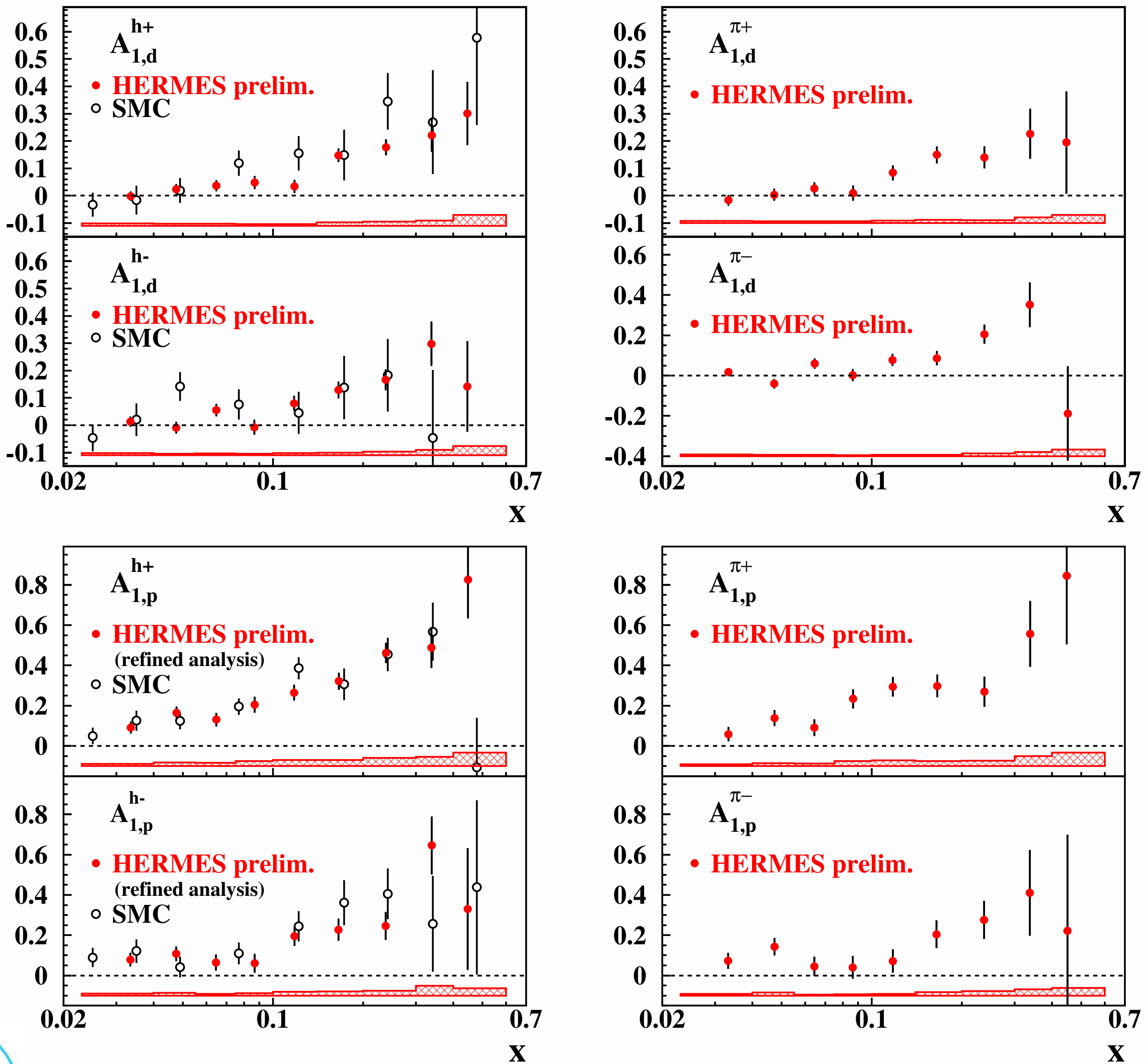
The HERMES Experiment at DESY



- Longitudinally polarised $e^{+/-}$–beam
  - $E_{\text{Beam}} = 27.5$ GeV
  - $\langle P_{\text{Beam}} \rangle \approx 0.52$
- Longitudinally polarised internal gas target
  - Target materials: $\vec{H}$, $\vec{D}$ (+ many unpolarised gas types)
  - $\langle P_{\text{Target}} \rangle \approx 0.88$ (0.82) for $\vec{H}$–, ($\vec{D}$–)target
  - Dilution factor $f = 1$
- Forward spectrometer with very good particle identification
  - Threshold Čerenkov detector until 1997: $\pi^{\pm}$ identification for $p_{\pi} > 4$ GeV
  - Dual radiator RICH detector since 1998: $\pi^{\pm}$, $K^{\pm}$, $p, \bar{p}$ identification over almost full momentum range
- Data taking with longitudinally polarised targets from 1996 to 2000 (*Run I*)

Results from the HERMES Experiment

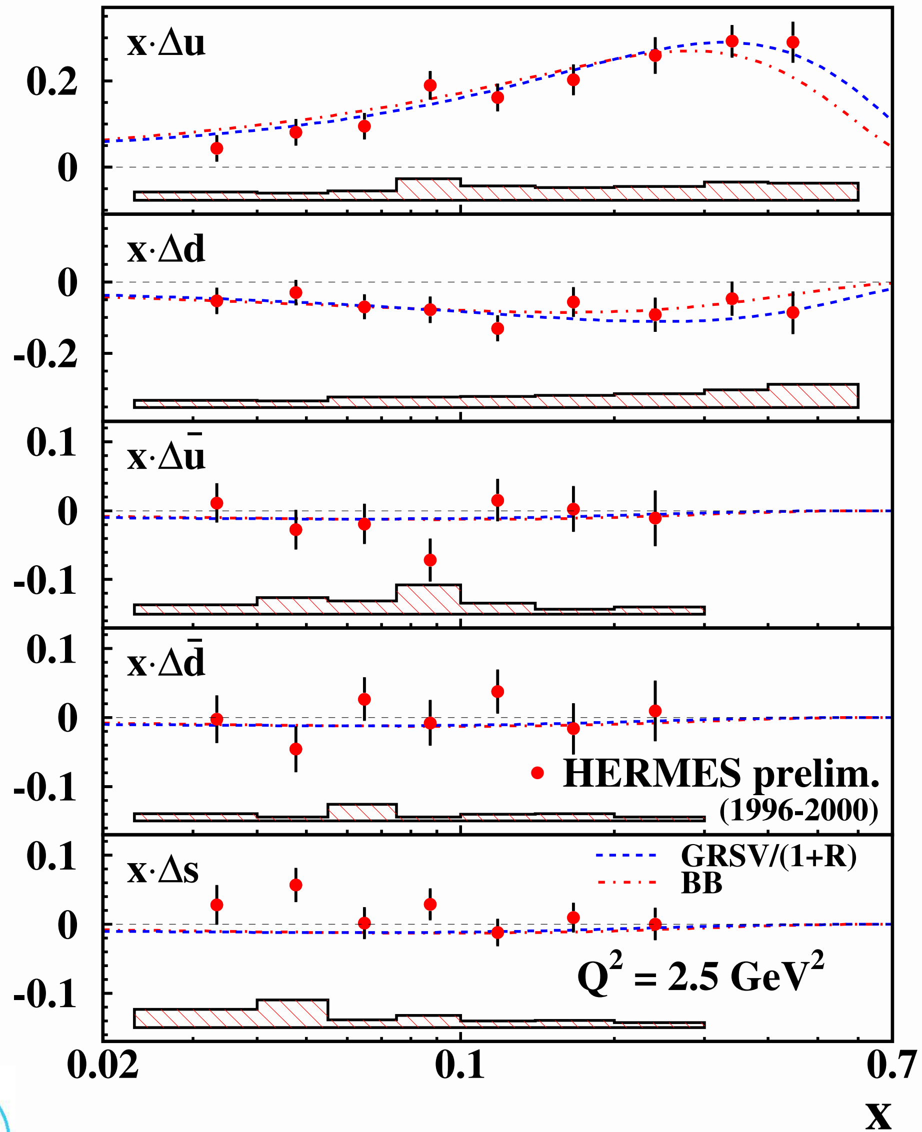
Measured SIDIS asymmetries (preliminary)

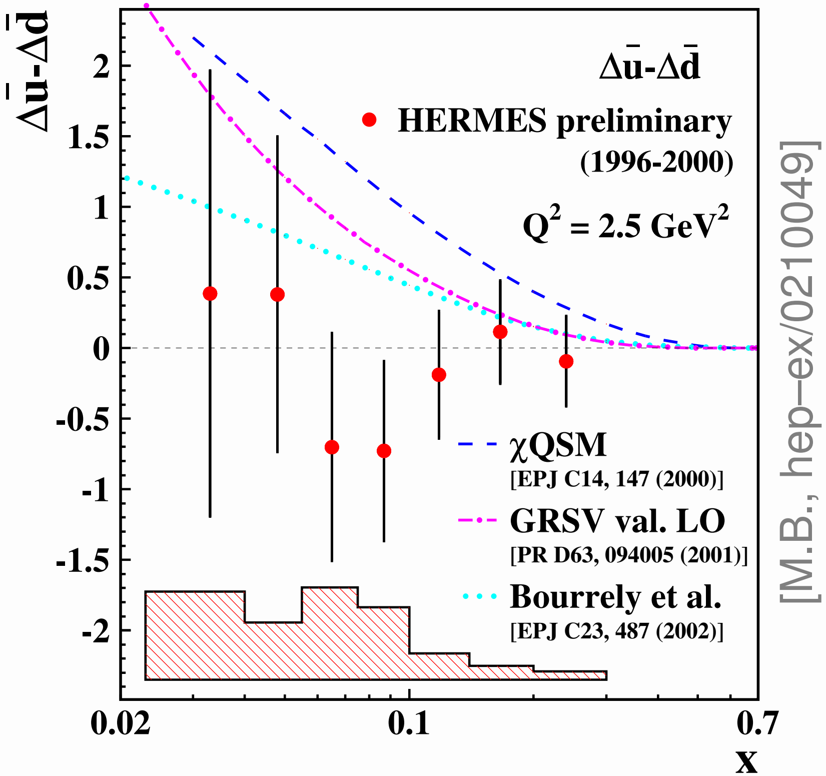


- $A_1^{K^-}(x) \approx 0$!
- $K^- = (\bar{u}s)$ is an all–sea object
- Covered range: $0.023 \le x \le 0.6$

Results from the HERMES Experiment (II)

Extracted helicity densities (preliminary)





- No indication for $\Delta s < 0$
- No significant $SU(2)$ breaking $\Delta\bar{u}(x) \neq \Delta\bar{d}(x)$

The COMPASS Experiment at CERN

- Beam and target setups similar to SMC experiment
- One RICH detector installed $\rightarrow$ good particle identification
- Higher $\sqrt{s}$ than HERMES
  - Extend x–range to smaller values
  - Cover larger range in Q^2 $\rightarrow$ lever arm for QCD evolution
- Data taking with longitudinally polarised target started

Where Do We Stand?

- After one decade of SIDIS experiments:
  - $\Delta u(x)$, $\Delta d(x)$ known to good precision, consistent with NLO fits to inclusive data
  - First direct extractions of $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$, $\Delta s(x)$ yield no significant polarisation of sea quarks
  - $\Delta s(x)$ not negative $\Leftrightarrow$ NLO fits to inclusive data
- Open questions:
  - Complementary results at higher $\sqrt{s}$ (COMPASS) and from different processes (RHIC)
  - What is $\Delta G(x)$?
- RHIC: $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$ to lower x at largely improved precision, complementary measurement
- **New, exciting experimental data expected soon!**