Semi-Inclusive Deep-Inelastic Scattering

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TRIUMF

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New Results from JLAB and HERMES since SPIN 2000

Polarised Quark Distributions

- The complete HERMES data set on H and D from 1996-2000
- Extraction of quark polarisations based on Monte Carlo "purities"

Single-Spin Asymmetries

- A glimpse at the rich phenomenology
- SSAs from longitudinally polarised target protons at JLAB and HERMES
- Beam-helicity SSAs from unpolarised protons at JLAB and HERMES
- HERMES SSAs from longitudinally polarised deuterons

2000

2002

The $\vec{l} + \vec{p}$ Experiments

HERMES

- 27.5 GeV $\vec{e}^{\pm}$ (P=55%) on pure atomic $\vec{\mathrm{H}}$ or $\vec{\mathrm{D}}$ targets
- Luminosity = 0.16 fb^{-1} per year polarised + 0.5 fb^{-1} per year unpolarised
- Spectrometer has $\sim 1\%$ resolution, $\sim 20\%$ acceptance for semi-inclusive hadrons
- Complete hadron identification

JLAB

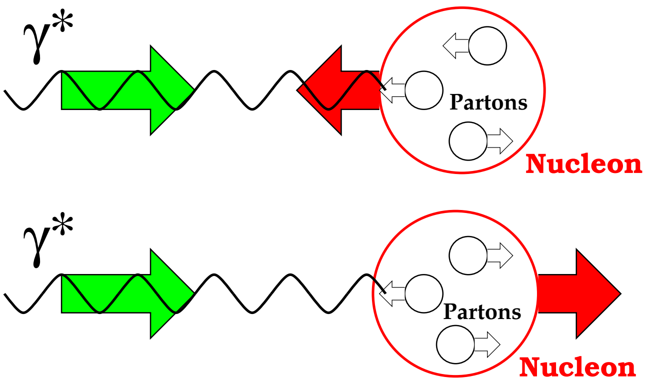
- 6 GeV $\vec{e}^{-}$ (P=70%) ,
- Large acceptance spectrometer (CLAS)
  - Only longitudinal target polarization
- High luminosity for unpolarised targets

COMPASS

- 100-200 GeV $\vec{\mu}^{\pm}$ (P=80%) on N$\vec{\mathrm{H}}_3$ ($f = 0.18$) or $^6\vec{\mathrm{L}}\mathrm{i}\vec{\mathrm{D}}$ (P=0.5, $f = 0.5$) targets
- Luminosity $\simeq$ 2 fb^{-1} per year
  - Target dilution $\Rightarrow$ Figure of merit similar to HERMES
- Complete hadron identification being stabilized

Spin-dependent Deep-Inelastic Scattering

In DIS with polarised lepton beams and polarised nucleon targets, one probes the polarisation of the quarks in the nucleon.



$\sigma_{1/2} \sim q^+(x)$

$\sigma_{3/2} \sim q^-(x)$

$$F_1 = \frac{1}{2}\sum_i e_i^2 q_i$$

$$g_1 = \frac{1}{2}\sum_i e_i^2 \Delta q_i$$

$$\Delta q_i = q_i^+ - q_i^-$$

Note: Inclusive DIS is sensitive only to e_i^2
There are no neutrino DIS measurements on polarised targets (yet!)
$\Rightarrow$ Inclusive DIS can't distinguish quark from anti-quark

Measurements of g_1 on both proton and neutron (deuteron) targets fix only the non-singlet distribution Δq_3 among:

$$\begin{aligned}
\Delta q_3(x,Q^2) &= \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} = 6(g_1^p - g_1^n), \\
\Delta q_8(x,Q^2) &= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} - 2(\Delta s + \Delta\bar{s}), \\
\Delta\Sigma(x,Q^2) &= \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}
\end{aligned}$$

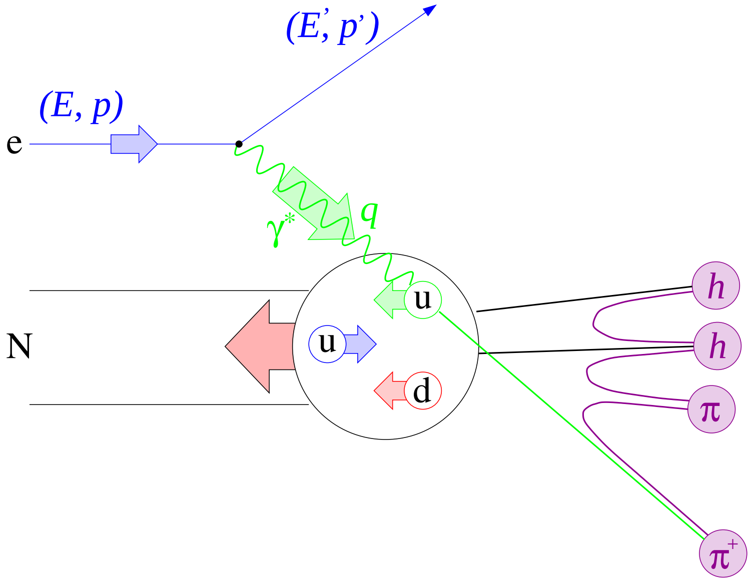
To the extent that $\Delta s + \Delta\bar{s}$ is negligible, $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ are also strongly constrained.

Hyperon **β-decay** + SU(3)-symmetry constrains **first moment** of Δq_8

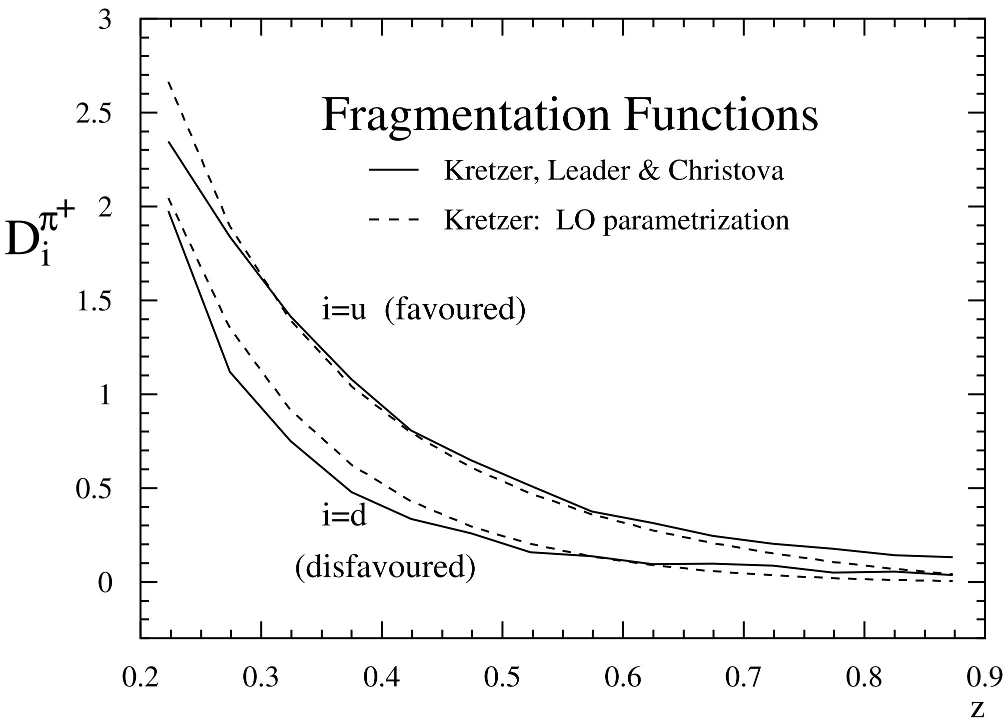
$\Rightarrow$ $\Delta\Sigma$ is small and Δs is negative.

Quark Polarisations from Semi-Inclusive DIS

In semi-inclusive DIS, a hadron h is also detected in the kinematic regime associated with hadronization of the struck quark:
$z \equiv E_h/\nu > 0.2$

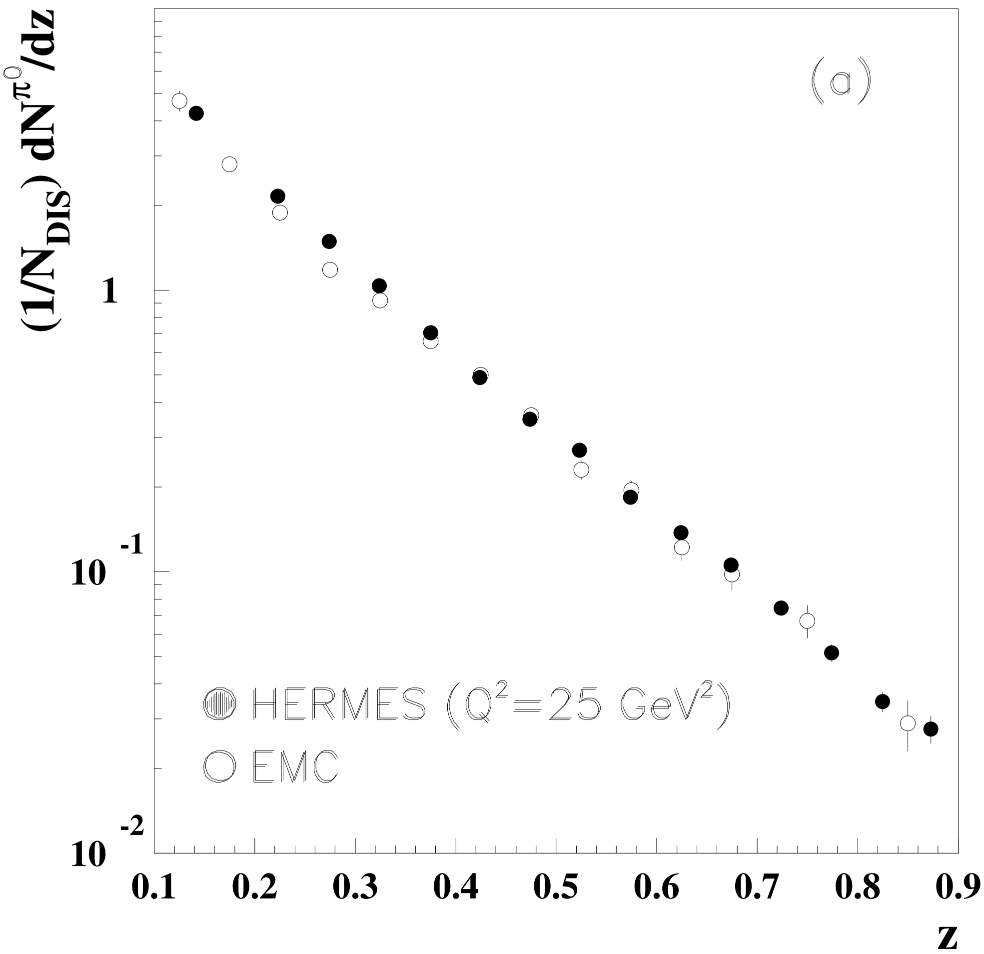


Flavour Tagging The flavour content of the final state hadrons is related to the flavour of the struck quark through the agency of the **fragmentation functions** $D_q^h(z, Q^2)$.



Is HERMES Fragmentation "Universal"?

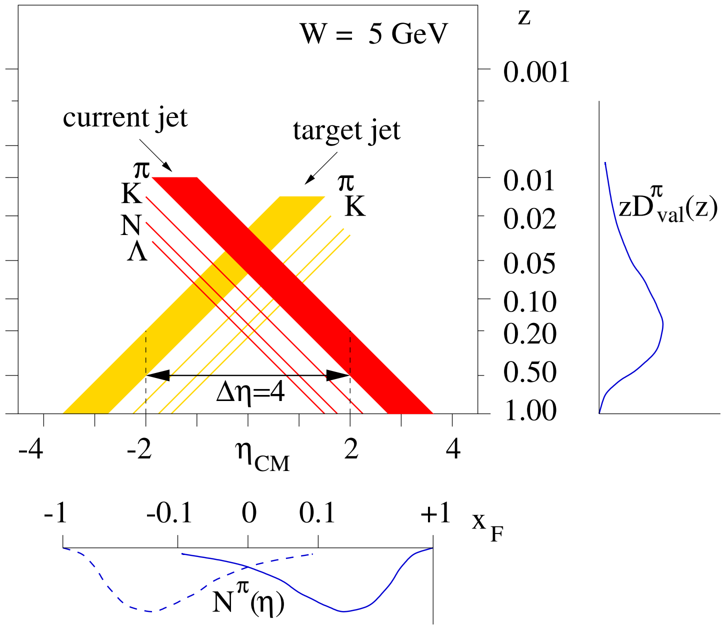
Compare pion multiplicities: HERMES versus EMC

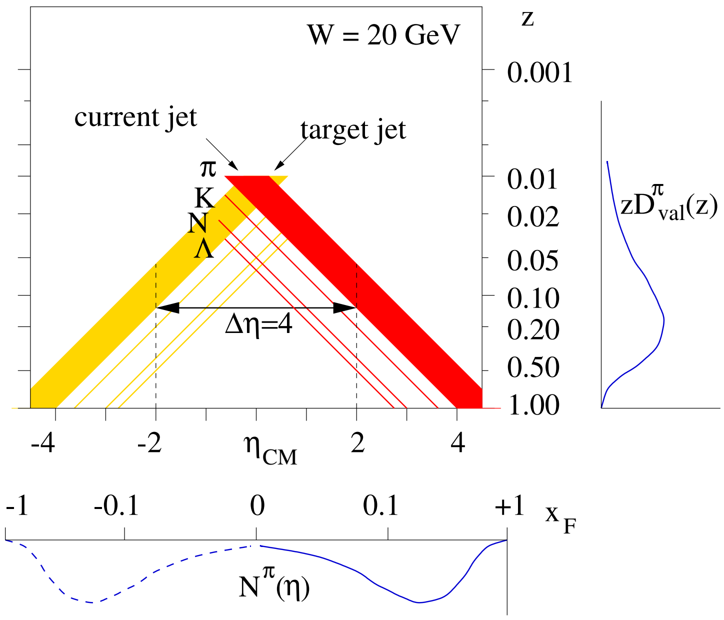


Good agreement, despite order of magnitude difference in energy

Contamination from Target Fragmentation?

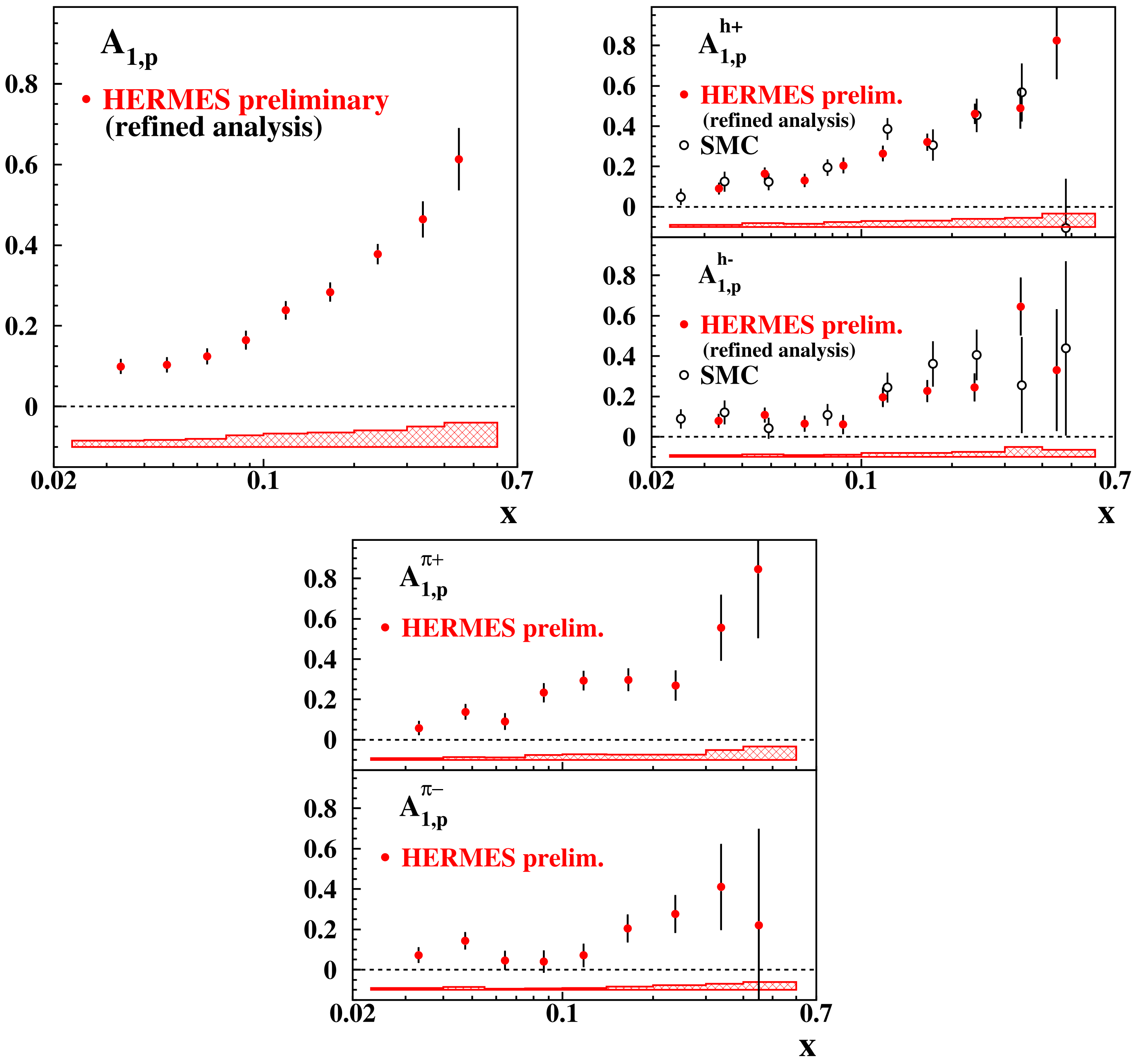
Thanks to Piet Mulders. . .





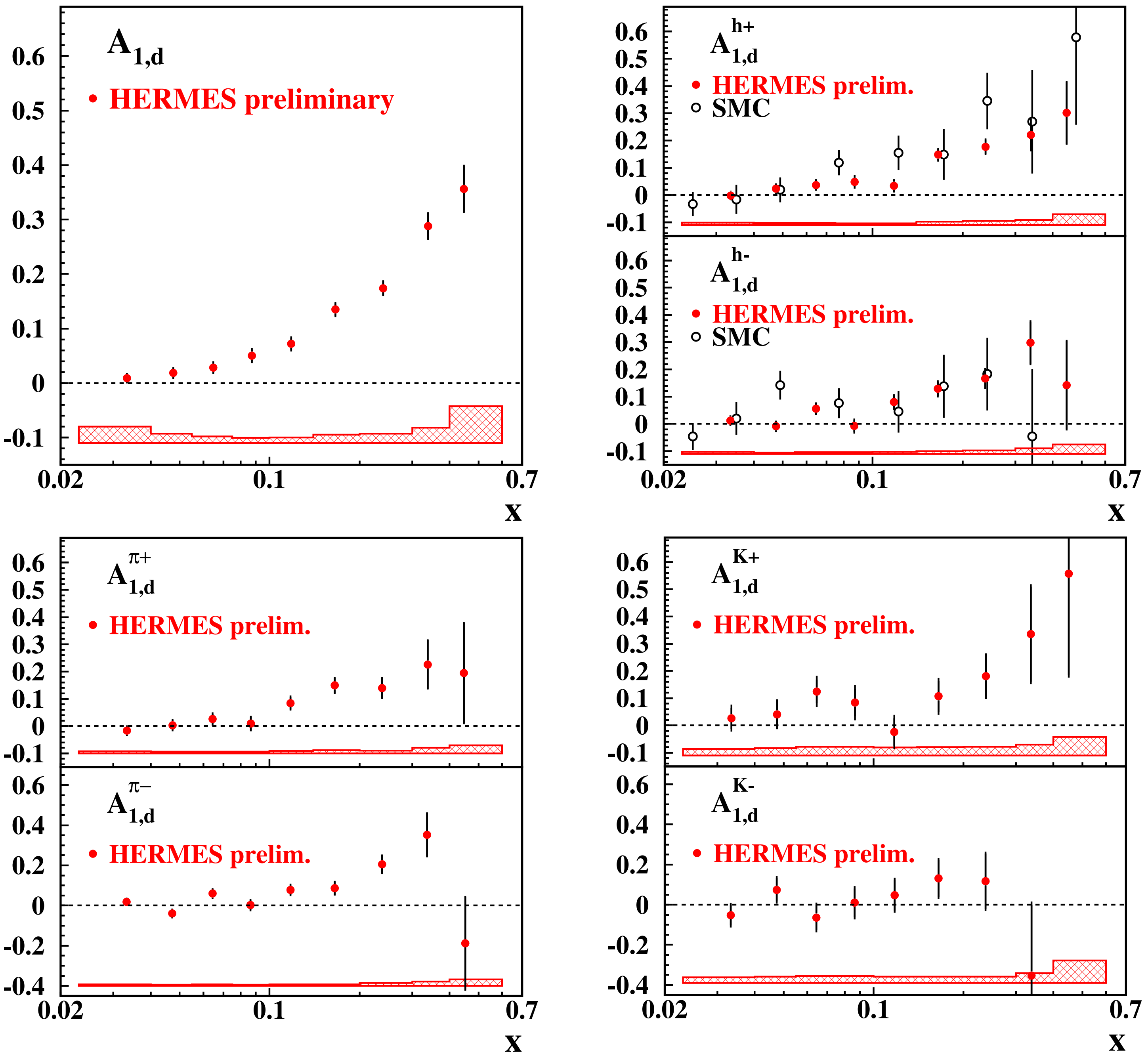
- Usual Berger criterion for separation of current and target fragmentation is $\delta\eta > 2$
- This is compatible with HERMES cut $z > 0.2$ for pions

Asymmetries On The Proton



- 1996–97 data: threshold Čerenkov counter identifies $\pi^{\pm}$
- $0.2 < z < 0.7$
- Asymmetries are independent of z in this range
  $\Rightarrow$ No evidence of target fragmentation

Asymmetries On The Deuteron



- 1998–2000 data: RICH detector identifies $\pi^{\pm}$ and $K^{\pm}$
- $0.2 < z < 0.7$
- Asymmetries are independent of z in this range

Unfolding Kinematic Migration

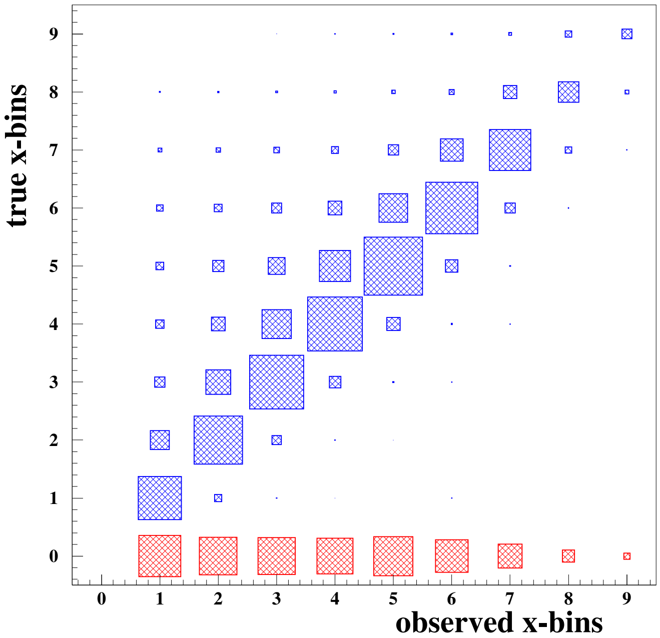
hermes

Radiative and instrumental smearing

Inclusive data:

Smearing within acceptance →

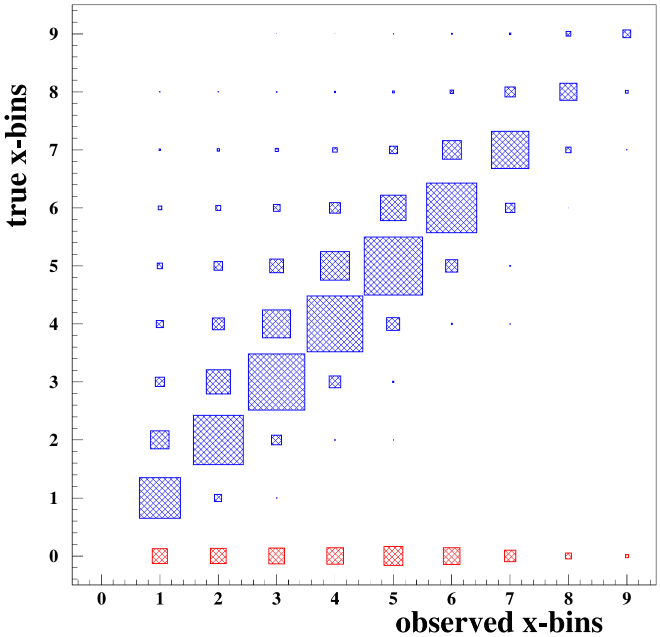
Mostly radiative elastic tail →



Semi-Inclusive data:

Smearing within acceptance →

Smearing into acceptance →



- Bin fractions are shuffled back to their “true parentage” as identified by MC simulation
- No parametric fits to the data are involved
- Resulting (small) statistical correlations between bins are known
- Statistical uncertainties are increased by up to a factor of 2

Quark Polarisations Extracted via Purities

In leading order:

$$F_1(x,Q^2) = \frac{1}{2}\sum_f e_f^2\, q_f(x,Q^2) \qquad g_1(x,Q^2) = \frac{1}{2}\sum_f e_f^2\, \Delta q_f(x,Q^2)$$

Semi-inclusive asymmetry of hadron h:

$$A_1^h(x) \overset{g_2=0}{\simeq} \frac{\sum_f e_f^2\, \Delta q_f(x)\, \int \mathrm{d}z\, D_f^h(z)}{\sum_{f'} e_{f'}^2\, q_{f'}(x)\, \int \mathrm{d}z\, D_{f'}^h(z)}$$

$$= \sum_f \underbrace{\frac{e_f^2\, q_f(x) \int \mathrm{d}z\, D_f^h(z)}{\sum_{f'} e_{f'}^2\, q_{f'}(x)\, \int \mathrm{d}z\, D_{q_{f'}}^h(z)}}_{\mathcal{P}_f^h(x)\ \equiv\ \text{Purity}} \frac{\Delta q_f(x)}{q_f(x)}$$

Purities are *spin-independent*

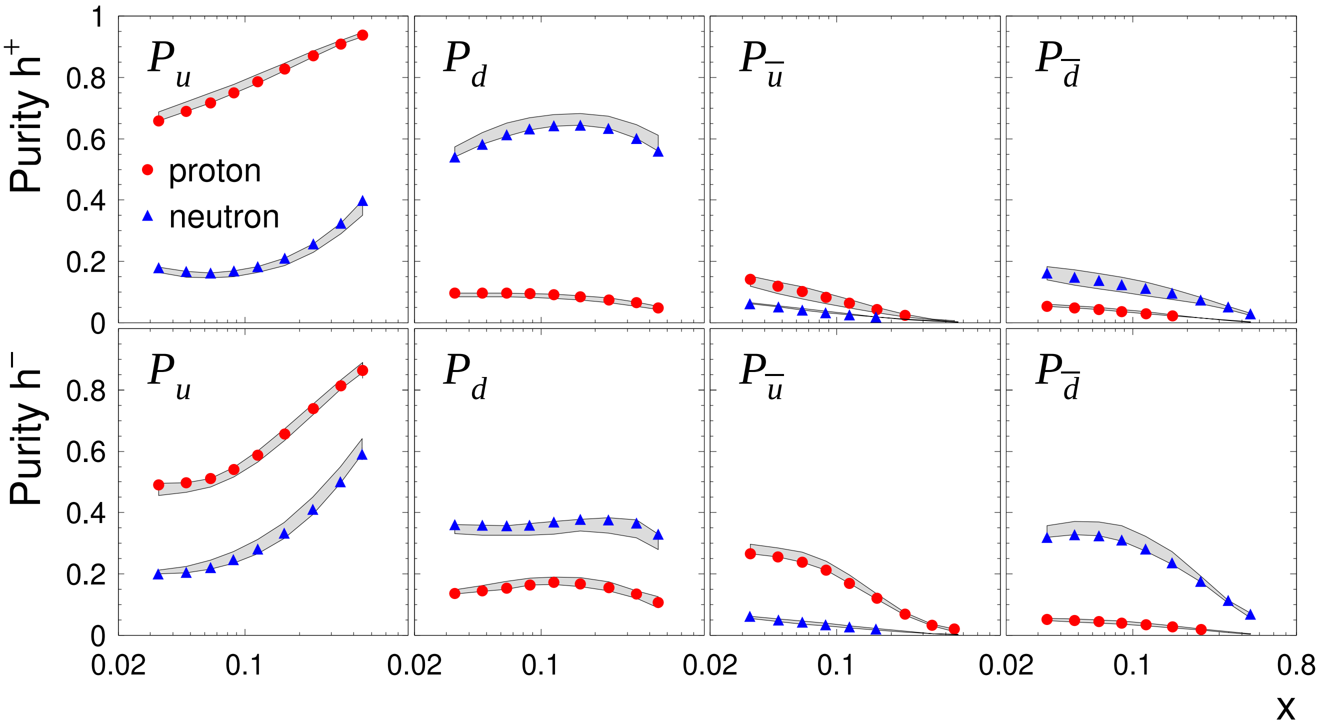
Effective Purities accounting for experimental acceptance may be computed via Monte Carlo based on the JETSET model for fragmentation

Solve linear system for $\vec{Q}$ with $\vec{A} = (A_{1,\mathrm{p}}, A_{1,\mathrm{d}}, A_{1,\mathrm{p}}^{\pi^\pm}, A_{1,\mathrm{d}}^{\pi^\pm}, A_{1,\mathrm{d}}^{\mathrm{K}^\pm})$:

$$\boxed{\vec{A}(x) = \mathbf{P}_f^h(x)\cdot\vec{Q}(x)}$$

$$\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta\bar{u}}{\bar{u}}, \frac{\Delta\bar{d}}{\bar{d}}, \frac{\Delta s+\Delta\bar{s}}{s+\bar{s}}\right)$$

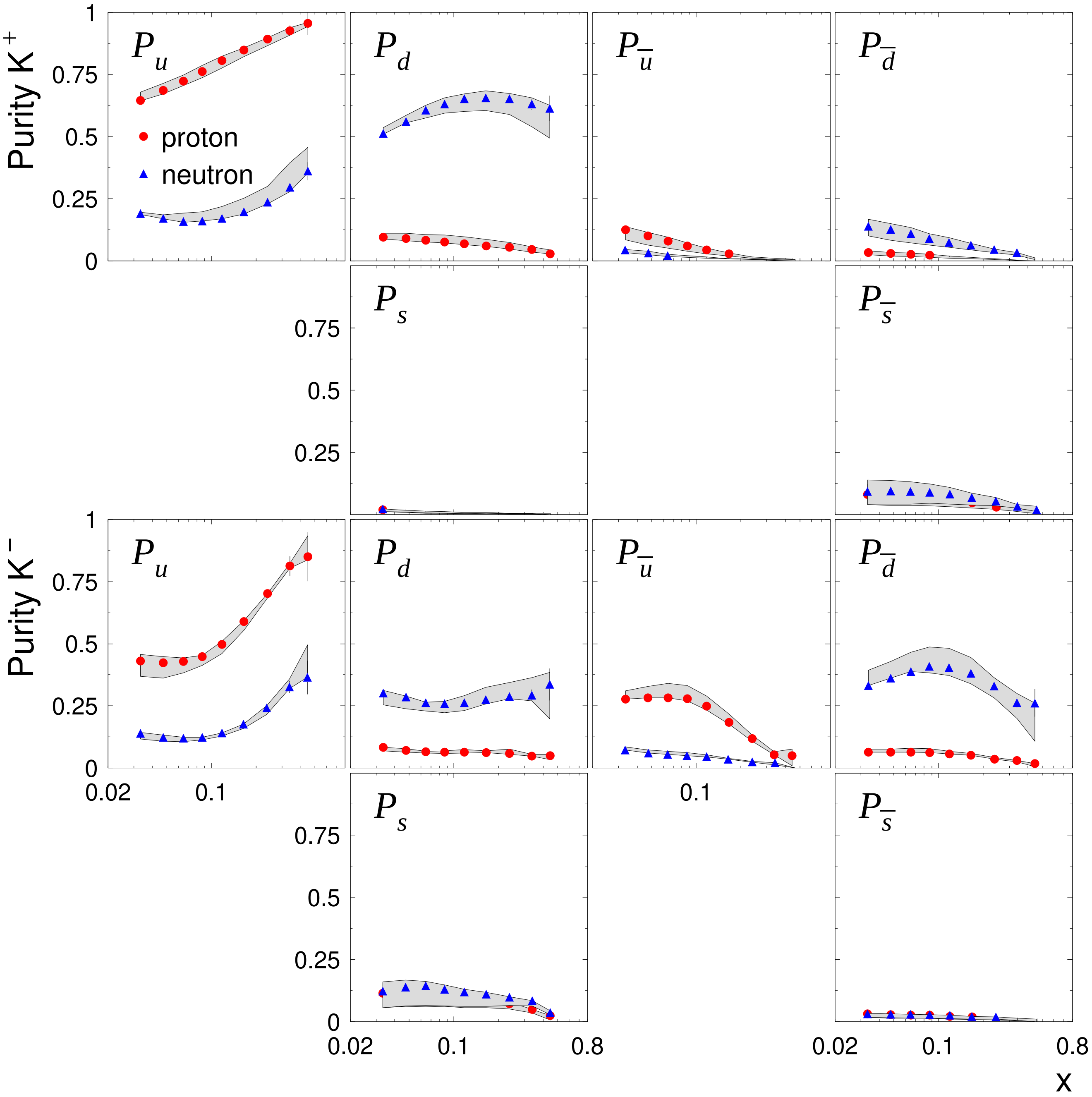
Purities for Charged Hadrons



Shaded bands indicate the systematic uncertainties

- An adequate degree of orthogonality is provided:
  - u versus d from h$^+$
  - valence versus sea from hadron charge
  - $\bar{u}$ versus $\bar{d}$ from h$^-$
- The u-quark dominates h$^+$ production from both proton and neutron targets (which is good!)
- Production of h$^-$ from sea quarks is relatively larger than h$^+$, and again dominated by $\bar{u}$ quarks

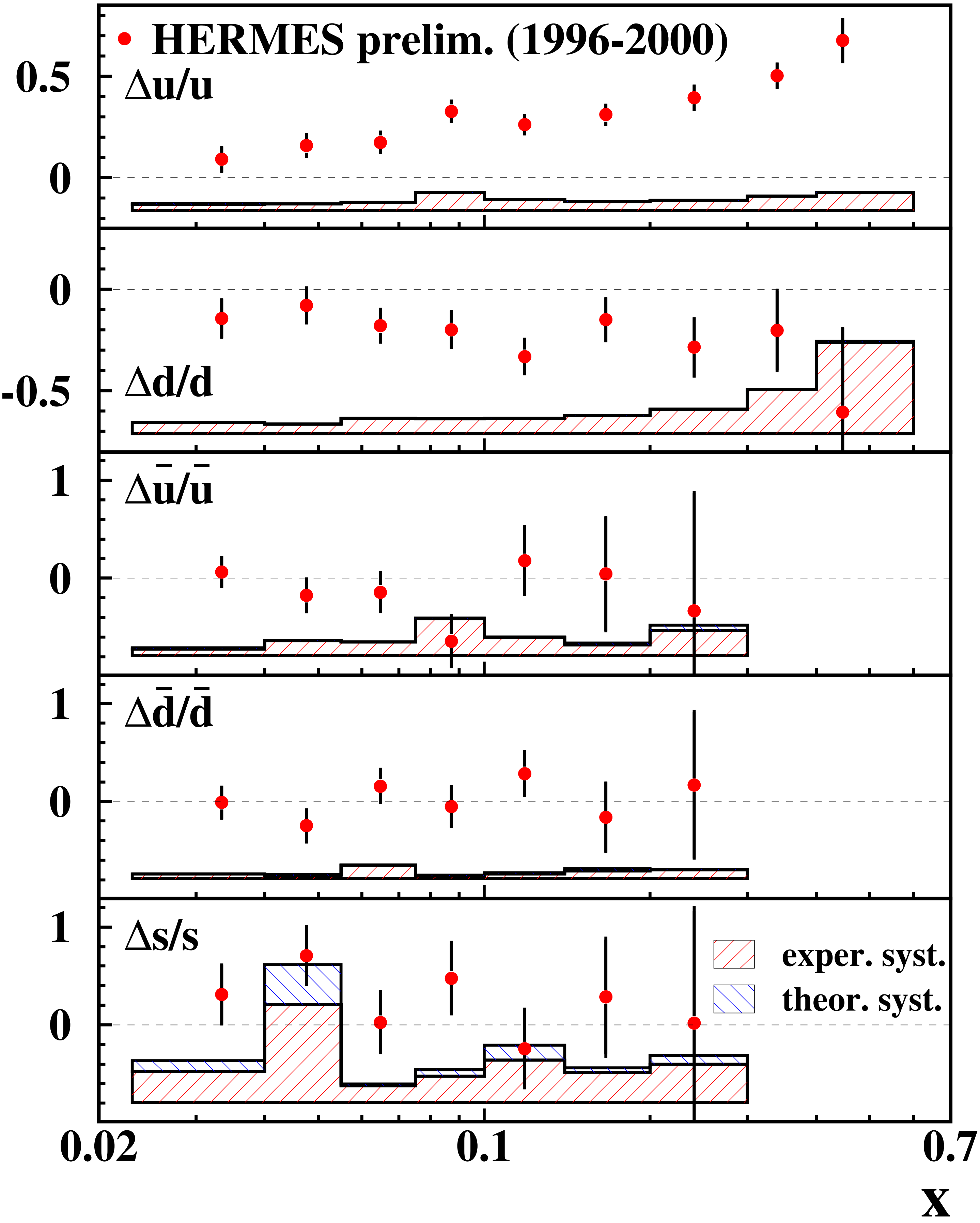
Purities for Charged Kaons



Shaded bands indicate the systematic uncertainties

- Kaons have about 10% sensitivity to the strange sea
- Systematic uncertainties are presently large due to both fragmentation functions and unpolarised parton densities

Quark Polarisations at LO



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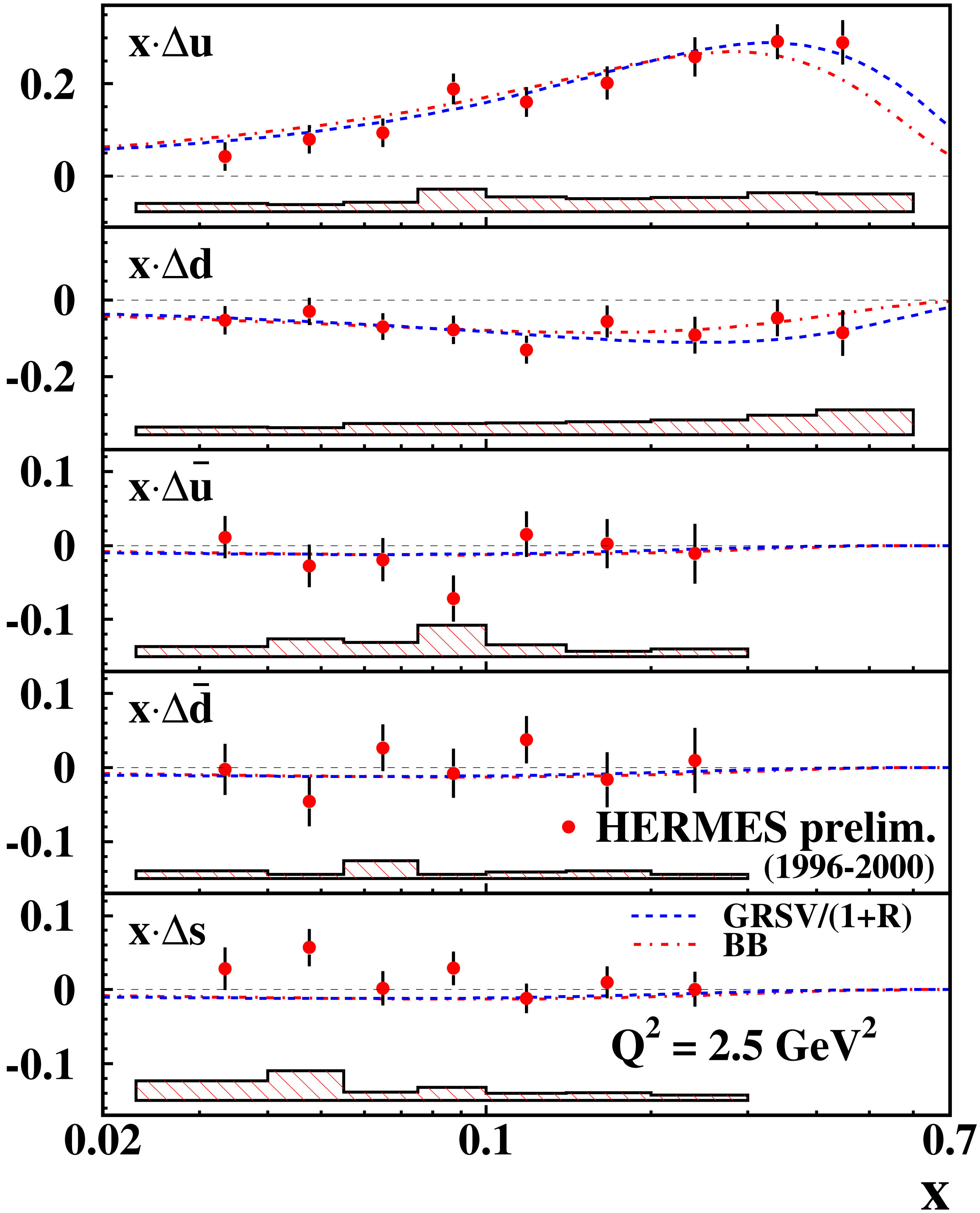
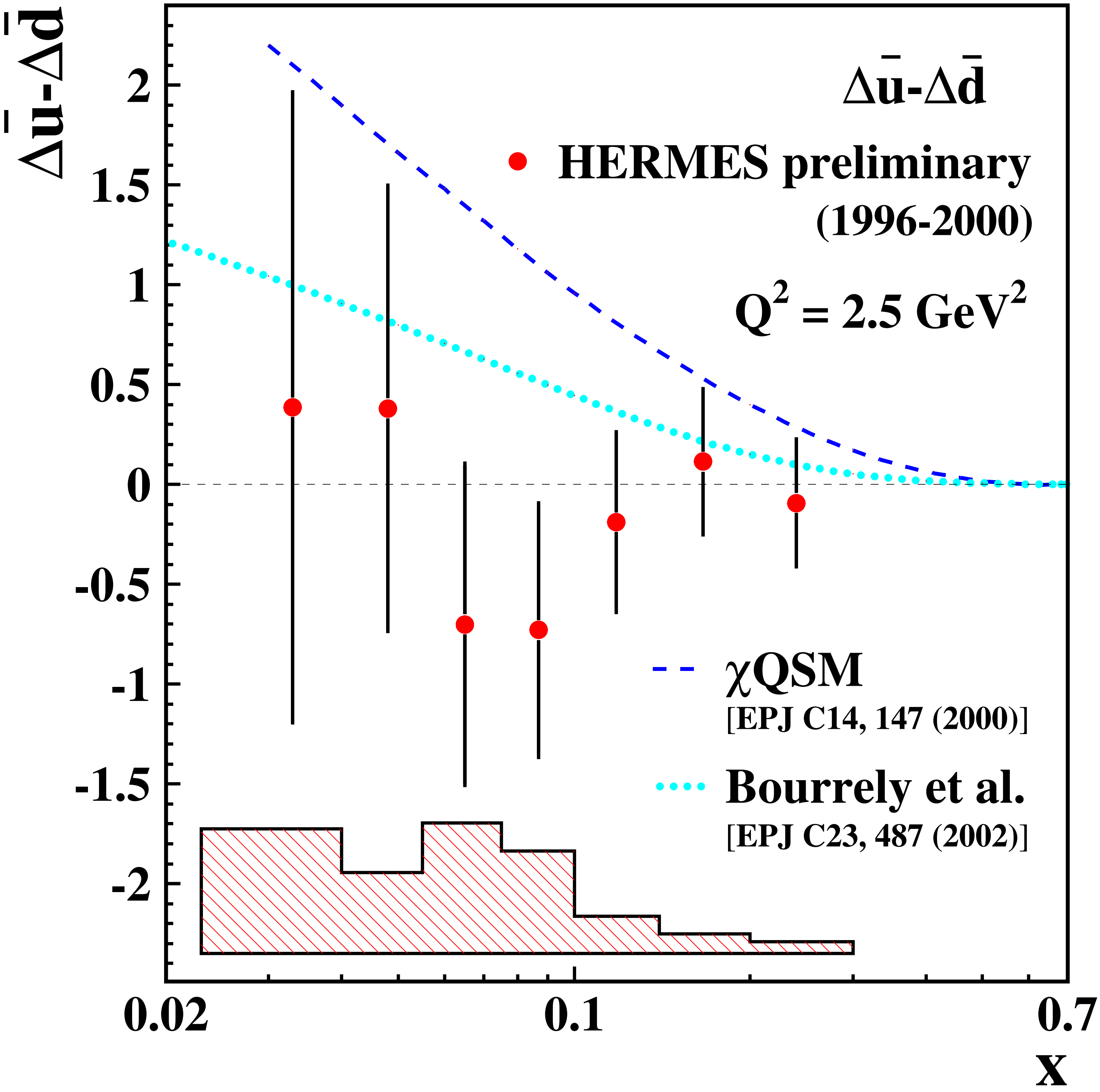
Polarised Quark Densities at LO



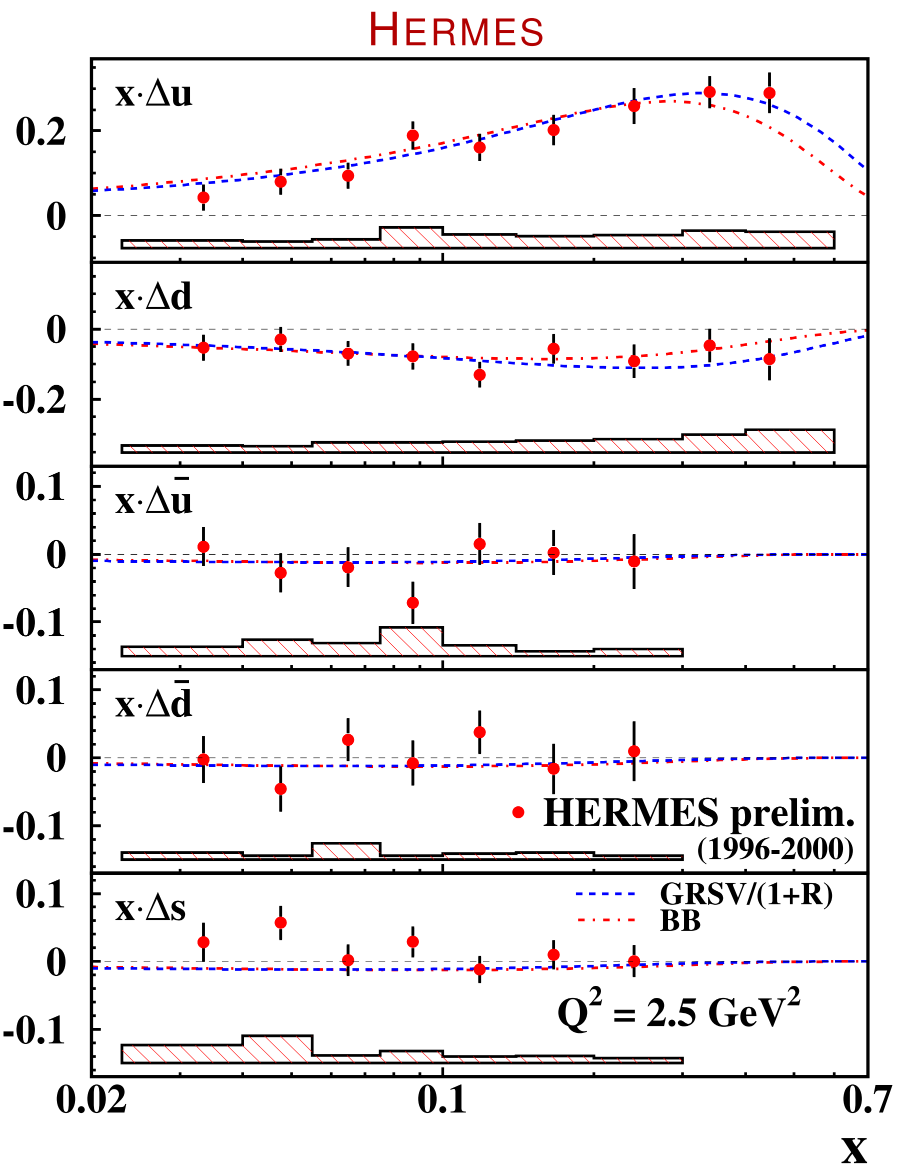
- Unpol. PDF: CTEQ5 LO
- Strange sea polarisation: $\Delta s \gtrsim 0$

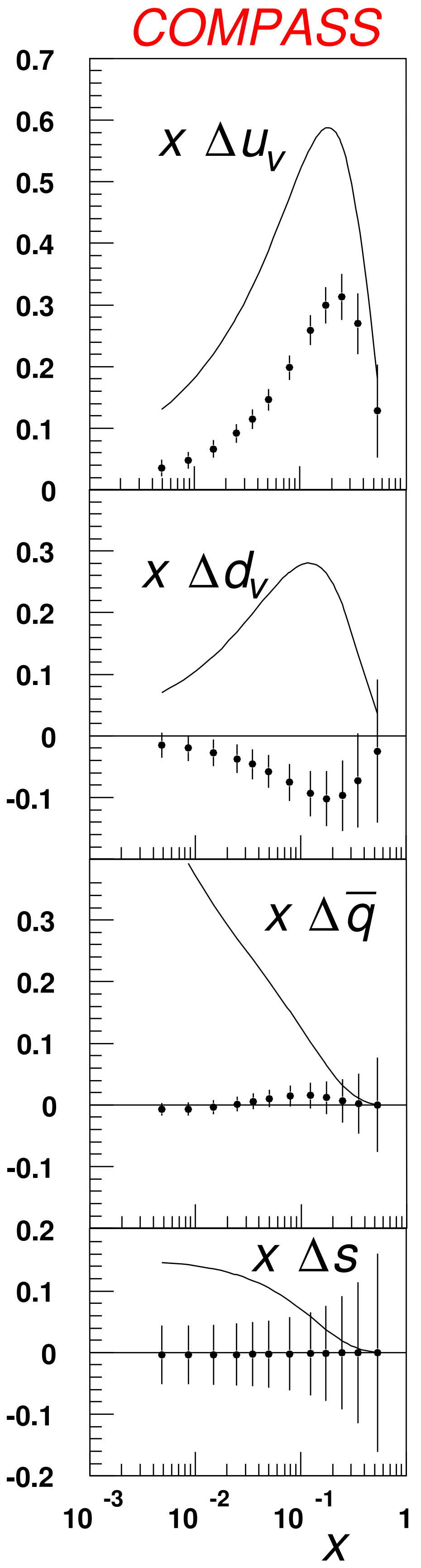
Symmetry of the Polarised Light Sea



- The HERMES data are consistent with flavour symmetry
- The data disfavour χQSM of Dressler *et al.*

COMPASS Projections





- SMC results consistent with HERMES 96-00, but extend to $x = 0.04$.
- COMPASS will also extend to lower x, test systematics (fragmentation model)
- See contributed talk by F. Tessarotto on Wednesday afternoon

Quark Polarisations: Summary

Semi-inclusive Deep-Inelastic Scattering (flavour tagging)

- HERMES has released 1998–2002 SIDIS asymmetries on deuterium for identified $\pi^\pm$ and $K^\pm$
- In combination with 1996–97 data on hydrogen, the statistics is sufficient to extract the polarisations of all 3 sea flavours
- The results from a preliminary LO extraction using tuned JETSET fragmentation are consistent with previous inclusive and SIDIS analyses, but have much improved precision
- Δs extracted in LO is non-negative
- The extracted light sea flavour asymmetry $\Delta\bar{u} - \Delta\bar{d}$ disfavours the χQSM model
- This extraction is unaffected by exclusion of the inclusive data set
  $\Rightarrow$ supports this model for pure current fragmentation
- See contributed talk by Antje Brüll on Tuesday afternoon

Quark Polarisations: Outlook

- Pion and Kaon multiplicities will become available from a much larger HERMES unpolarised data set to better constrain the fragmentation functions

- HERMES with COMPASS will span a large Q^2 range to test systematics

- COMPASS will cover the small-x range to $x = 0.004$

- Quality of existing SIDIS data represents nearly the limit for the present generation of facilities

- Should the **Next-Generation Facility** be designed to measure the ratios of cross section differences that provide stronger constraints on parton polarisations and fragmentation functions?

  (Christova & Leader, Nucl. Phys. B 607 (2001) 369)

  e.g.

$$\frac{\Delta\sigma_p \pm \Delta\sigma_n}{\sigma_p \pm \sigma_n}$$

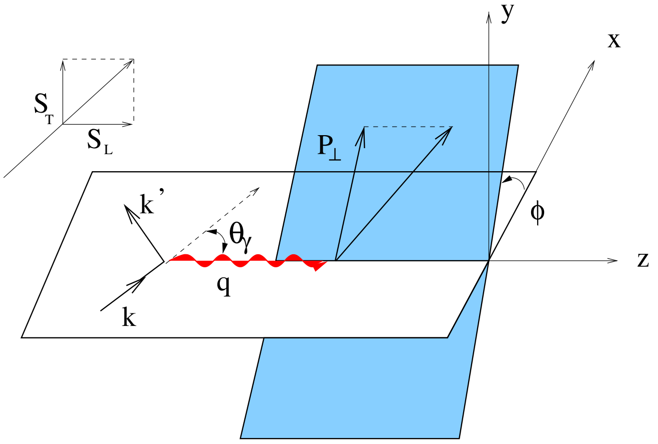
  and

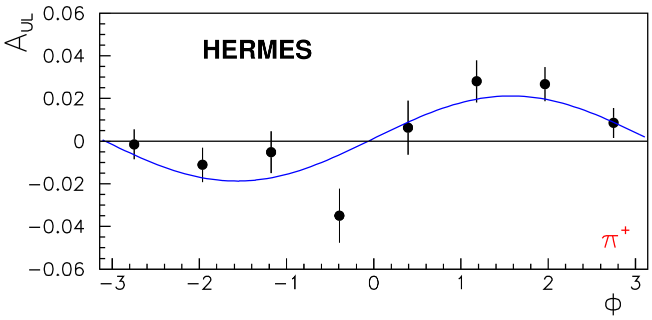
$$\frac{\sigma_p^{h\pm\bar{h}} \pm \sigma_n^{h\pm\bar{h}}}{\sigma_p^{DIS} \pm \sigma_n^{DIS}}$$

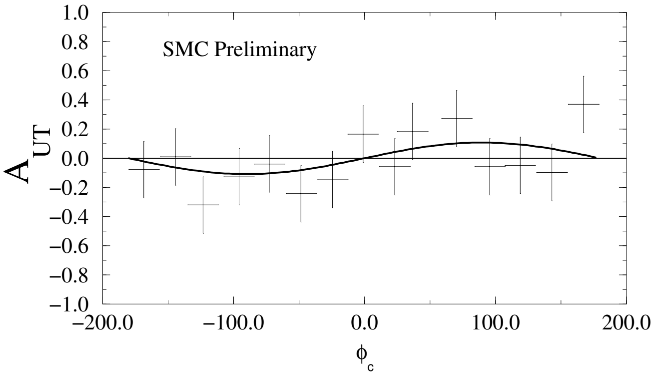
Single-Spin Asymmetries in SIDIS

A brief review

- In 1999, HERMES and SMC released single-spin asymmetries that depend on the azimuthal orientation of the hadron's $P_\perp$
- The target polarisation was "transverse" for SMC, "longitudinal" for HERMES
- In either case, the linear polarisation of the virtual photon in the lepton plane selects transverse polarisation of the struck quark



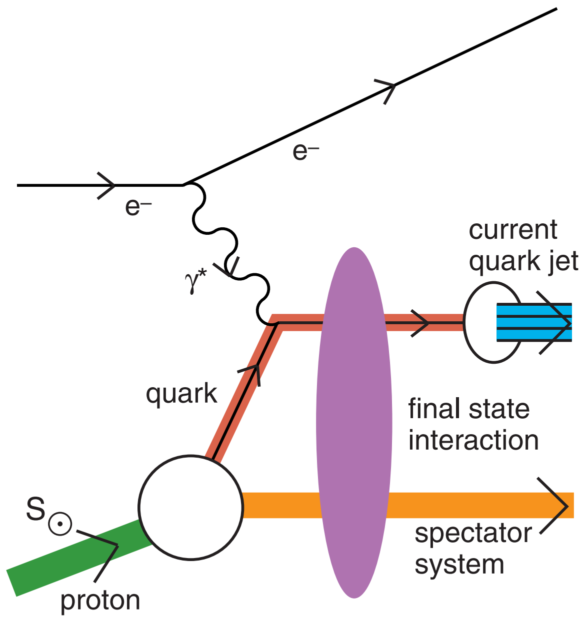




- In leading twist, $P_\perp$ can arise from two sources:
  - Primordial p_T of the quark in the target
  - k_T produced in the fragmentation process
- A single-spin asymmetry requires the participation of some Time-Odd object correlating that p_T or k_T with some spin
- Theoretical explanations of the SIDIS asymmetries have focussed on a T-odd fragmentation process (Collins Effect)
- Wonderful implication! This "quark polarimeter" can provide access to the otherwise-inscrutable transversity distribution

The SIDIS SSA Plot Thickens

Brodsky, Hwang & Schmidt present a model calculation including a short-distance "final state interaction" between struck quark and spectator:



- They show that this mechanism can generate a single-(transverse)spin azimuthal asymmetry

- Contrary to appearances, it's leading twist

John Collins' Revelation:

- This mechanism is the old Sivers Effect in disguise.

- The model calculation reveals that this mechanism does not violate fundamental time reversal invariance

- Ergo the Sivers mechanism is allowed after all !

Resolution and Reconciliation

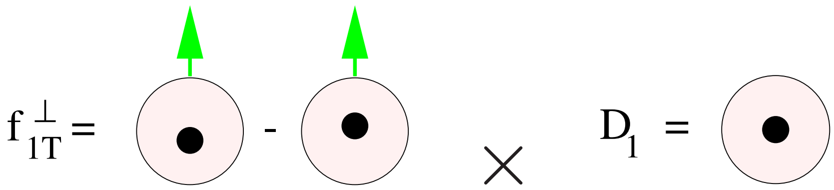
New Theoretical Understanding

There exist three leading-twist mechanisms that can generate single-spin asymmetries (*John Collins*):

- Transversity $\times$ "Collins effect": Finding in a polarised target nucleon a transverse-polarised quark, which fragments with a transverse momentum correlated with that quark polarisation

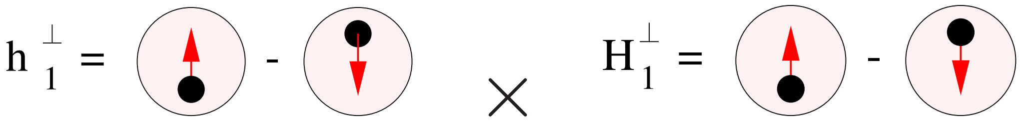
chiral-odd, T-even   chiral-odd, T-odd

- "Sivers effect": Finding in a transverse-polarised target nucleon a quark with correlated primordial transverse momentum



chiral-even, T-odd   chiral-even, T-even

- (Boer & Mulders) Finding in an unpolarised target nucleon a quark with correlated transverse polarisation and primordial transverse momentum



chiral-odd, T-odd   chiral-odd, T-odd

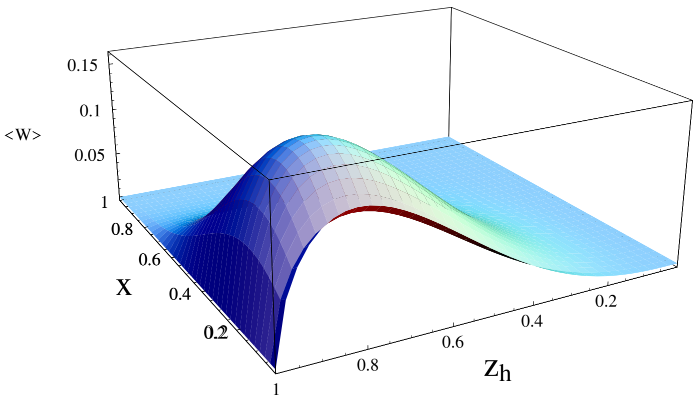
Only the first two mechanisms can generate target spin asymmetries

SSAs: Which is the Responsible Mechanism?

- Model calculations show distinctive kinematic signatures
- Boglione & Mulders, Phys. Rev. D 60 (1999) 054007
- Based on parameterizations fitted to $\mathrm{p}\bar{\mathrm{p}} \to \pi X$ SSAs

Collins Effect

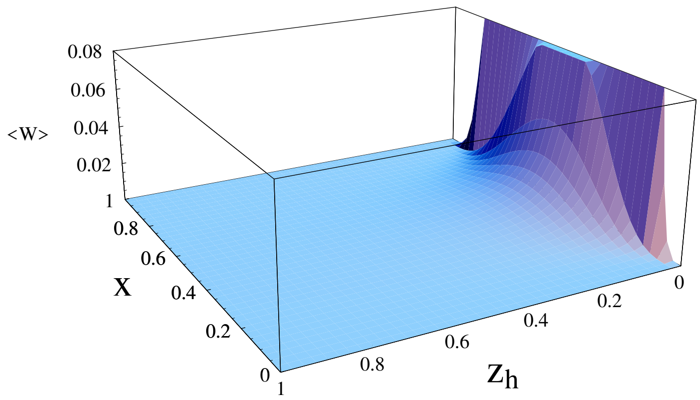
$h_1(x) \times H_1^{\perp(1)}(z)$



Strength is at large z

Sivers Effect

$f_{1T}^{\perp}(x) \times D_1(z)$



Strength is at small z

Sorting Out the Azimuthal Moments

- Chiral structure of DF $\times$ FF : even
- Time reversal structure of DF $\times$ FF : odd

		T-even DF		T-odd FF	
		chirality		chirality	
		even	odd	even	odd
twist 2	U	$\mathbf{f}_1$			$H_1^\perp$
	L	$\mathbf{g}_{1L}$	$h_{1L}^{\perp(1)}$		
	T	g_{1T}	$\mathbf{h}_1$ $h_{1T}^\perp$	$D_{1T}^\perp$	
twist 3	U	$f^\perp$	$\mathbf{e}$		H
	L	$g_L^\perp$	$\mathbf{h}_L$	$D_L^\perp$	E_L
	T	$\mathbf{g}_T$ $g_T^\perp$	h_T $h_T^\perp$	$\mathbf{D_T}$	E_T

$$\langle \sin\phi\rangle_{UL} \propto S_L \frac{M}{Q}\sum_{a,\bar{a}} e_a^2 x [h_L^a(x) H_1^{\perp(1)a}(z) - x h_{1L}^{\perp(1)a}(x)\frac{\tilde{H}^a(z)}{z}]$$
$$- \quad S_T \sum_{a,\bar{a}} e_a^2 x h_1^a(x) H_1^{\perp(1)a}(z)$$

$$\langle \sin 2\phi\rangle_{UL} \propto S_L \textstyle\sum_{a,\bar{a}} e_a^2 x h_{1L}^{\perp(1)a}(x) H_1^{\perp(1)a}(z)$$

Lorentz covariance:
$$h_L(x) = h_1(x) - \frac{\mathrm{d}}{\mathrm{d}x} h_{1L}^{\perp(1)}(x)$$
$$\frac{\tilde{H}(z)}{z} = \frac{\mathrm{d}}{\mathrm{d}z}[z H_1^{\perp(1)}(z)]$$

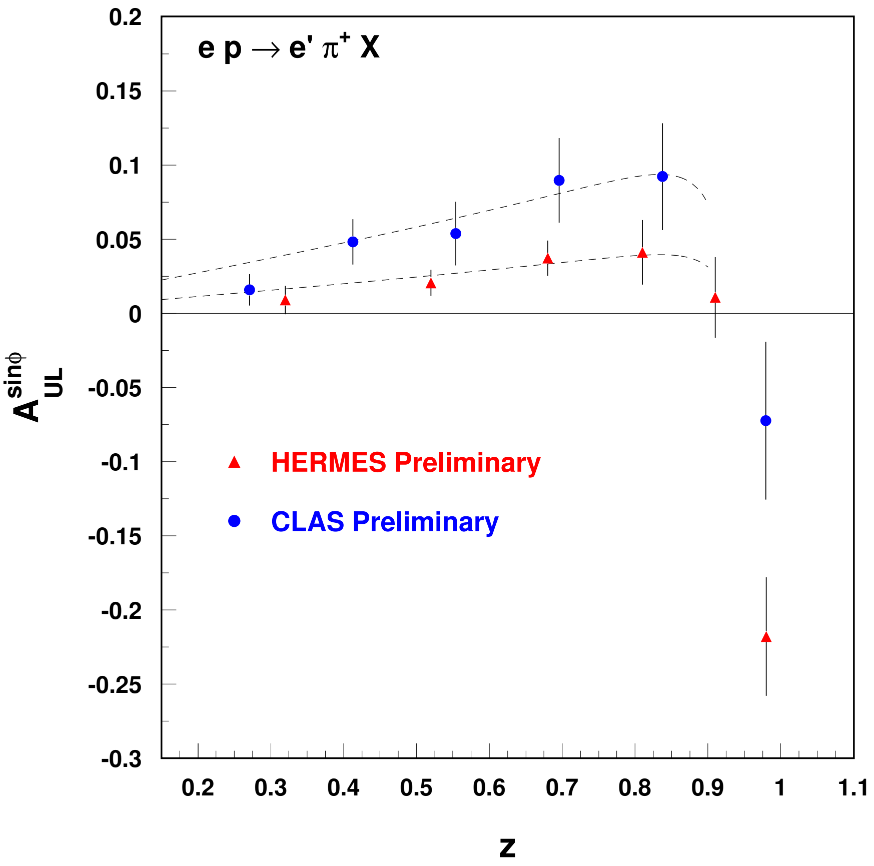
'Longitudinally' polarised target: $S_T << S_L$

From a Dictionary

Phenomenology (noun):

A philosophical doctrine proposed by Edmund Husserl based on the study of human experience in which considerations of objective reality are **not** taken into account.

z dependence of the SSAs

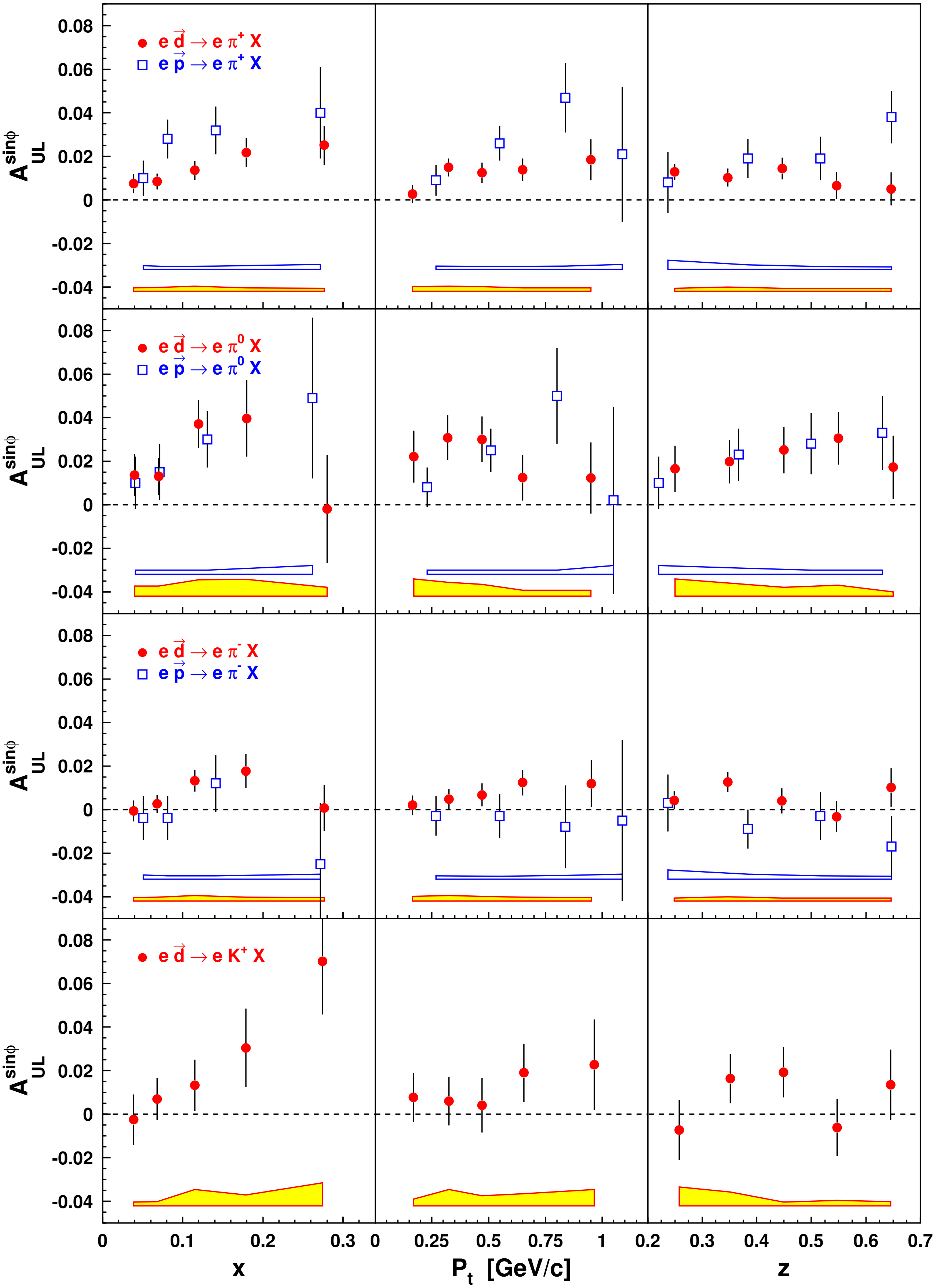


The arbitrarily normalized curves are from **Bacchetta, Kundu, Metz & Mulders** hep-ph/0206309

- They calculate the Collins function $H_1^{\perp(1)}(z)$ at the one-loop level in a chiral-invariant model
- Their z-dependence is consistent with the data
- Their model predicts azimuthal asymmetries for $e^+e^- \rightarrow 2$ jets up to of order 5%.

The model of **Oganessyan** *et al.* Nucl.Phys. A689 (2001) 784, assuming $h_{1L}^{\perp(1)} = 0 \Rightarrow h_L = h_1$ and using a parametric model for $H_1^{\perp(1)}(z)$, results in a very similar curve for the HERMES kinematics

SSAs on Proton and Deuteron



Deuteron Data is Preliminary

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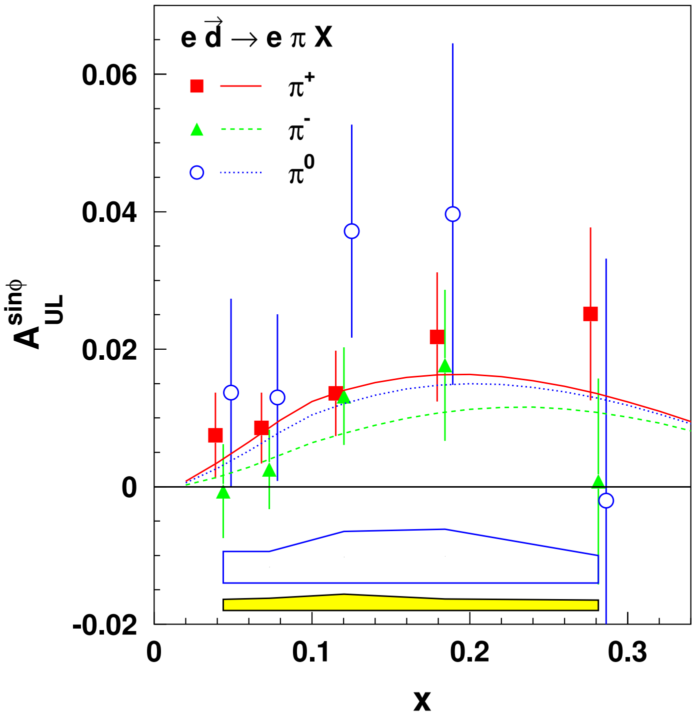
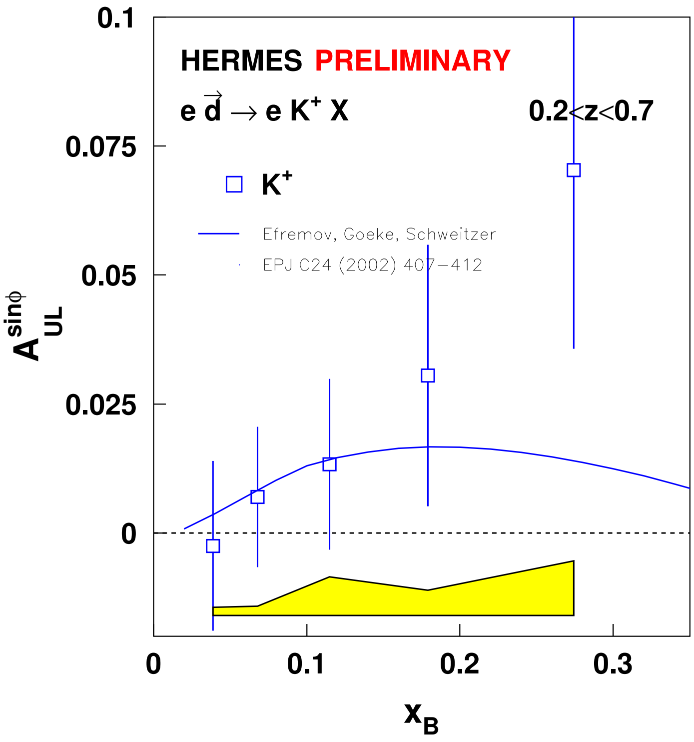
Model Calculations

χ Quark Soliton Model:

Efremov, Goeke & Schweitzer (Eur. Phys. J. C 24 (2002) 407)





Assumptions for the calculations:

- h_1 from the χ Quark Soliton Model
- $h_1^s = h_1^{\bar{s}} = 0$
- $\tilde{h}_L = 0$ (neglect interaction-dependent part of h_L)
- Collins function parameterised to fit HERMES proton data (and "optimistic" result from DELPHI $e^+e^- \rightarrow 2$ jets):

$$\frac{\langle H_1^{\perp(1)} \rangle}{\langle D_1 \rangle} = (12.5 \pm 1.4)\%$$

- N.B. There was previously a sign error, resulting in a Collins function only half this size

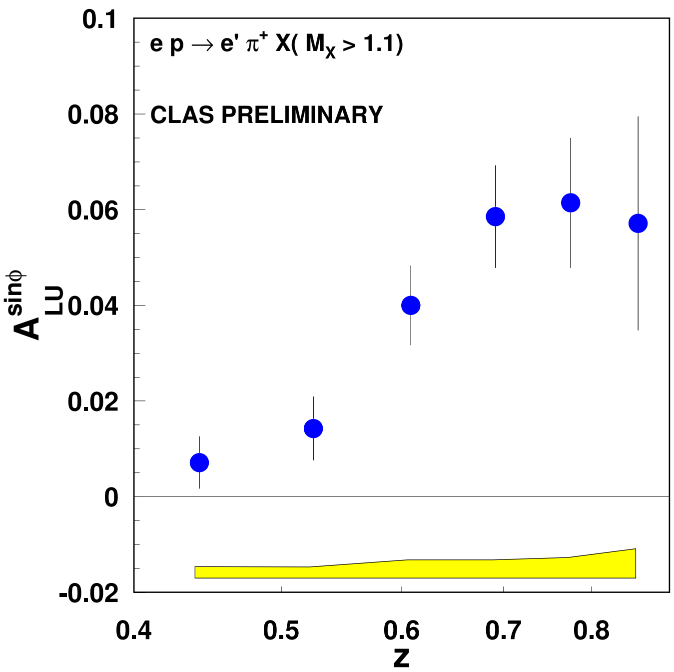
Beam Helicity Asymmetries

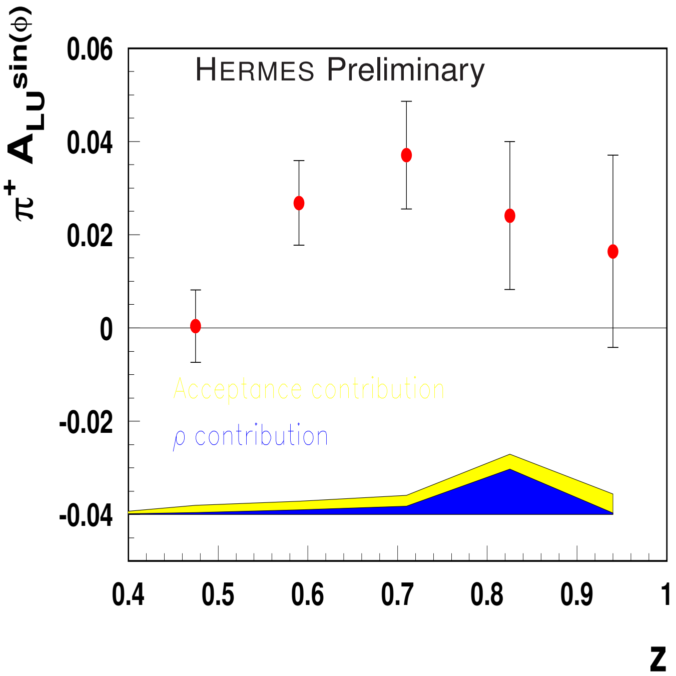
- $A_{LU}^{\sin\phi}$ is also understood to be generated by the Collins fragmentation function: $\propto e(x) \times H_1^{\perp(1)}(z)$

- e(x) is a twist-3 chiral-odd distribution function whose first moment is related to the pion-nucleon σ term

$$\int_{-1}^{1} \mathrm{d}x [e^u + e^d](x) = \frac{\sigma}{m_{av}}$$

$$m_{av} \equiv \frac{1}{2}(m_u + m_d) \simeq 5\,\mathrm{MeV}$$





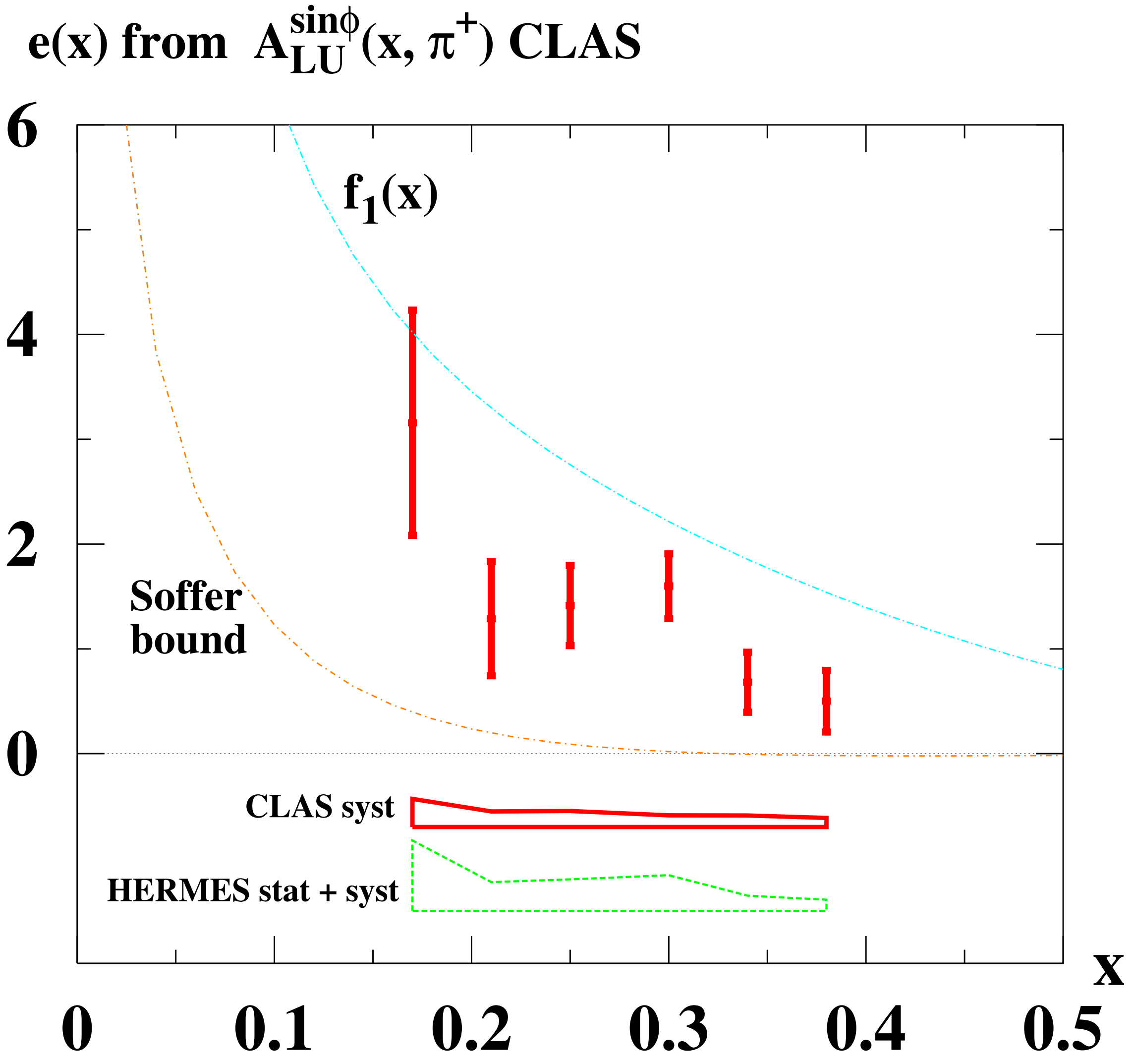
No x-dependence of the asymmetry is observed.

Extracting $e(x)$

Efremov, Goeke & Schweitzer (hep-ph/0208124)

- As before, used $H_1^{\perp(1)}(z)$ from analysis of HERMES $A_{UL}^{\sin\phi}$ and DELPHI $e^+e^- \to 2$ jets:

- e(x) was extracted from the CLAS data for $A_{LU}^{\sin\phi}$:



Status: Single-Spin Asymmetries

- SIDIS SSAs measured up to now involving "longitudinal" target spin have ambiguous interpretations

- Their z dependence suggest that the Collins fragmentation function is the responsible T-odd object

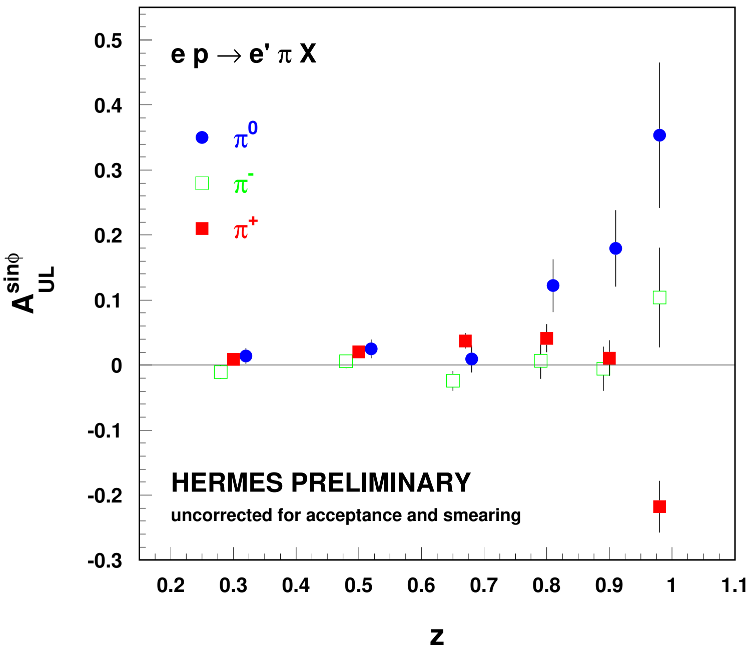
- Data being recorded now by HERMES and COMPASS with transverse target polarisation can distinguish leading-twist mechanisms through azimuthal dependence of the asymmetry:

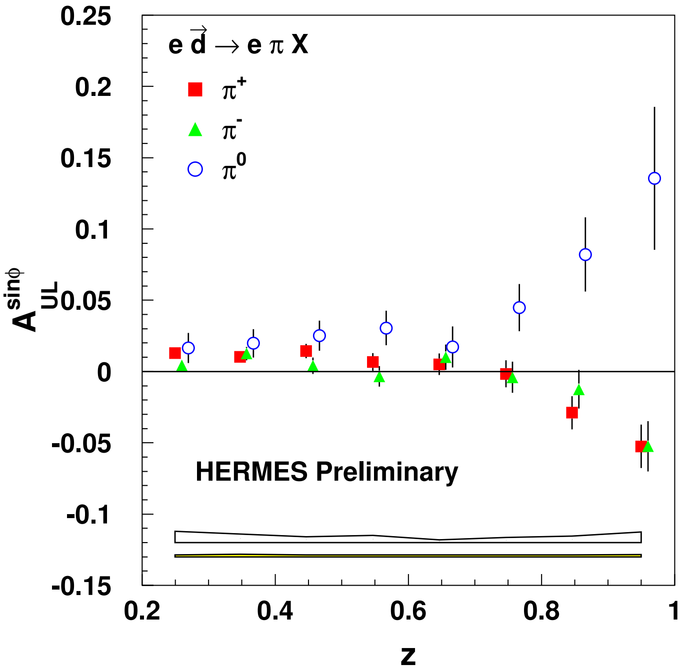
  – Sivers effect depends on the azimuthal angle difference between the target spin axis and hadron plane $\propto \sin(\theta_h^l - \theta_S^l)$
  – Collins effect depends on the sum of these angles relative to the lepton scattering plane: $\propto \sin(\theta_h^l + \theta_S^l)$

- If the Collins effect is confirmed to be dominant, the first measurements of transversity can be extracted

- For more theoretical details, please see the plenary talk by Phillip Ratcliffe on Friday morning

Semi-Exclusive Asymmetries





- There exists no factorization theorem for exclusive meson production by transverse photons
- A_{UL} at the exclusive limit involves non-leading twist and longitudinal-transverse interference
- One gets the impression that non-leading twist becomes dominant as z increases above 0.7
- For a full explanation of other exclusive reactions, please see the plenary talk by Marc Vanderhaeghen on Thursday morning
- Even larger asymmetries A_{UT} are predicted for exclusive pion production from a transversely-polarised target
- They arise in leading twist and can be interpreted in the light of a factorization theorem for longitudinal production

Conclusions

- The present DIS facilities are just adequate to reveal **abundant evidence for a rich future for this field**

- The interplay of experiment and phenomenology is wonderfully fertile

- There is an urgent need for a **new high-energy high-luminosity facility** designed for precise measurements of SIDIS and exclusive reactions