Single-Spin/Azimuthal Asymmetries in Semi-Inclusive and Exclusive DIS

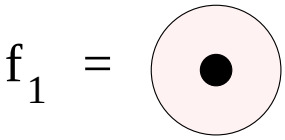
Andy Miller, TRIUMF

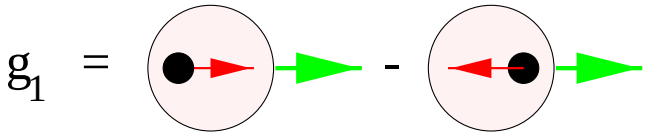
for the hermes Collaboration

- Parton distributions involving transverse spin
- Single-spin/azimuthal asymmetries in semi-inclusive deep-inelastic scattering
- Single-spin/azimuthal asymmetries in semi-exclusive deep-inelastic scattering
- (Double-spin asymmetry in exclusive ρ^0 leptoproduction)

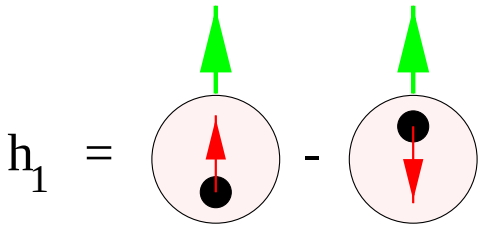
Transversity

A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution $\delta q(x)$.





transversity:
$h_1(x) \sim \delta q(x)$



Features of $h_1(x)$:

- in the absence of relativistic effects,
$$\delta q(x) = \Delta q(x)$$
- unlike for g_1, the gluon polarization does not mix with quark polarization in $h_1 \longrightarrow$ different Q^2 evolution
- h_1 predominantly sensitive to valence quark polarization
- first moment of h_1 = tensor charge of the nucleon $\longrightarrow$ possible comparison with lattice QCD
- $h_1(x)$ is a chiral-odd distribution function, related to spin flip of transversely polarized quark

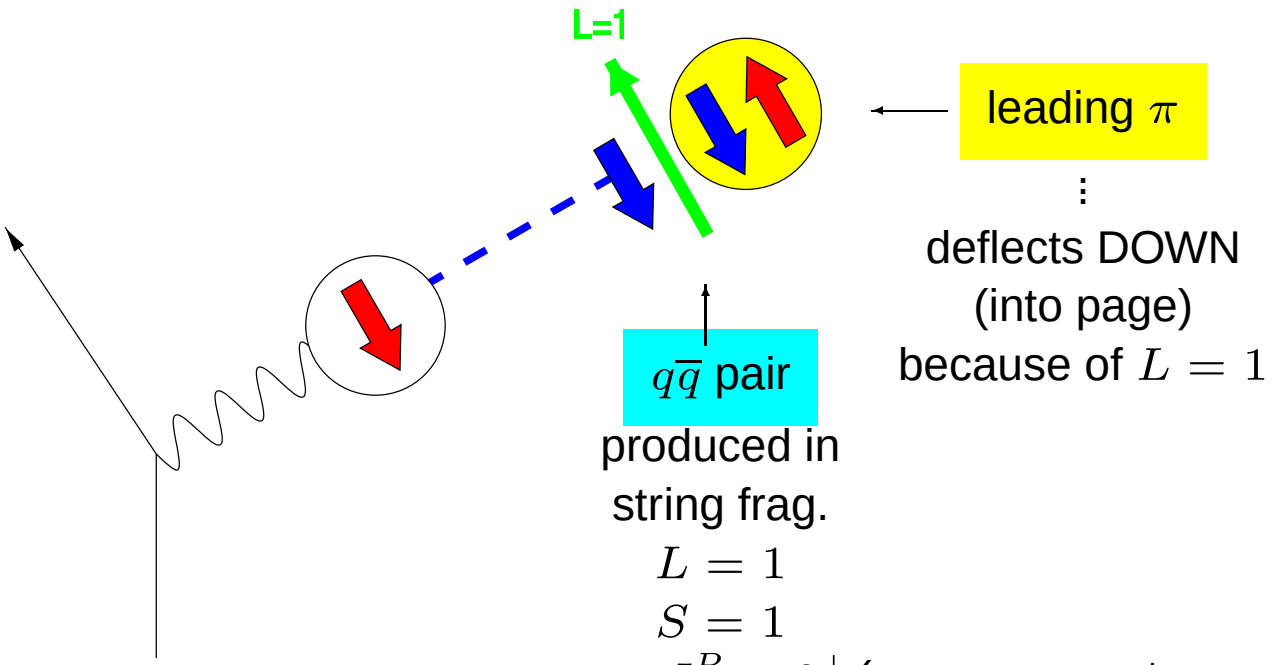
Measurement approach:

Transversity is inaccessible in inclusive DIS, but can be probed via azimuthal distributions in polarized semi-inclusive DIS, especially from a transversely polarized target.

The Collins Effect in the String Fragmentation Model

Collins Fragmentation Function $H_1^\perp(z)$

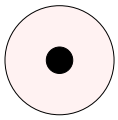
- **Leading Twist**
- **chiral-odd** like $h_1(x)$ ... chiral-odd dist. and frag. functions appear in pairs in DIS cross-section
- **T-odd** ... one T-odd function required to produce single-spin asymmetry in semi-inclusive DIS
- **'polarimeter'** for transverse polarization of struck quark



Collins Angle ϕ_c = hadron azimuth about γ^* momentum, relative to transverse target spin axis.

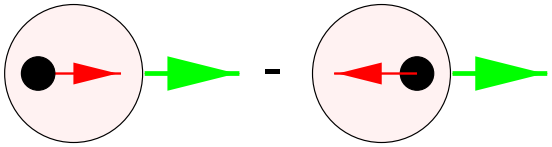
$$\langle \frac{Q_T}{M_h} \sin\phi_c \rangle \sim -h_1(x) \cdot H_1^\perp(z)$$

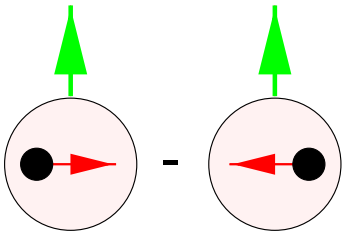
Twist-2 Parton Distribution Functions.

f_1 = 

Unpolarized quark in unpolarized nucleon.

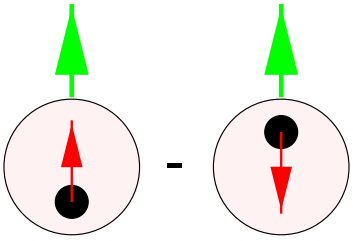
Longitudinal quarks in. . .

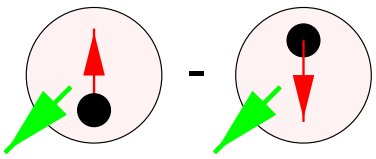
g_{1L} = 

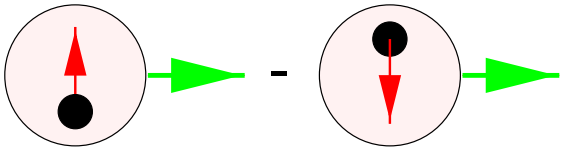
g_{1T} = 

longitudinal and transverse nucleons.

Transverse quarks in. . .

h_1 = 

$h_{1T}^{\perp}$ = 

$h_{1L}^{\perp}$ = 

transverse and longitudinal nucleons.

Contributions to Azimuthal Moments

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

		T-even DF		T-odd FF	
		chirality		chirality	
		even	odd	even	odd
twist 2	O	$\mathbf{f}_1$		$\mathbf{D}_1$	$H_1^\perp$
	L	$\mathbf{g}_{1L}$	$h_{1L}^{\perp(1)}$		
	T	g_{1T}	$\mathbf{h}_1 \;\; h_{1T}^\perp$	$D_{1T}^\perp$	
twist 3	O	$f^\perp$	$\mathbf{e}$		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

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

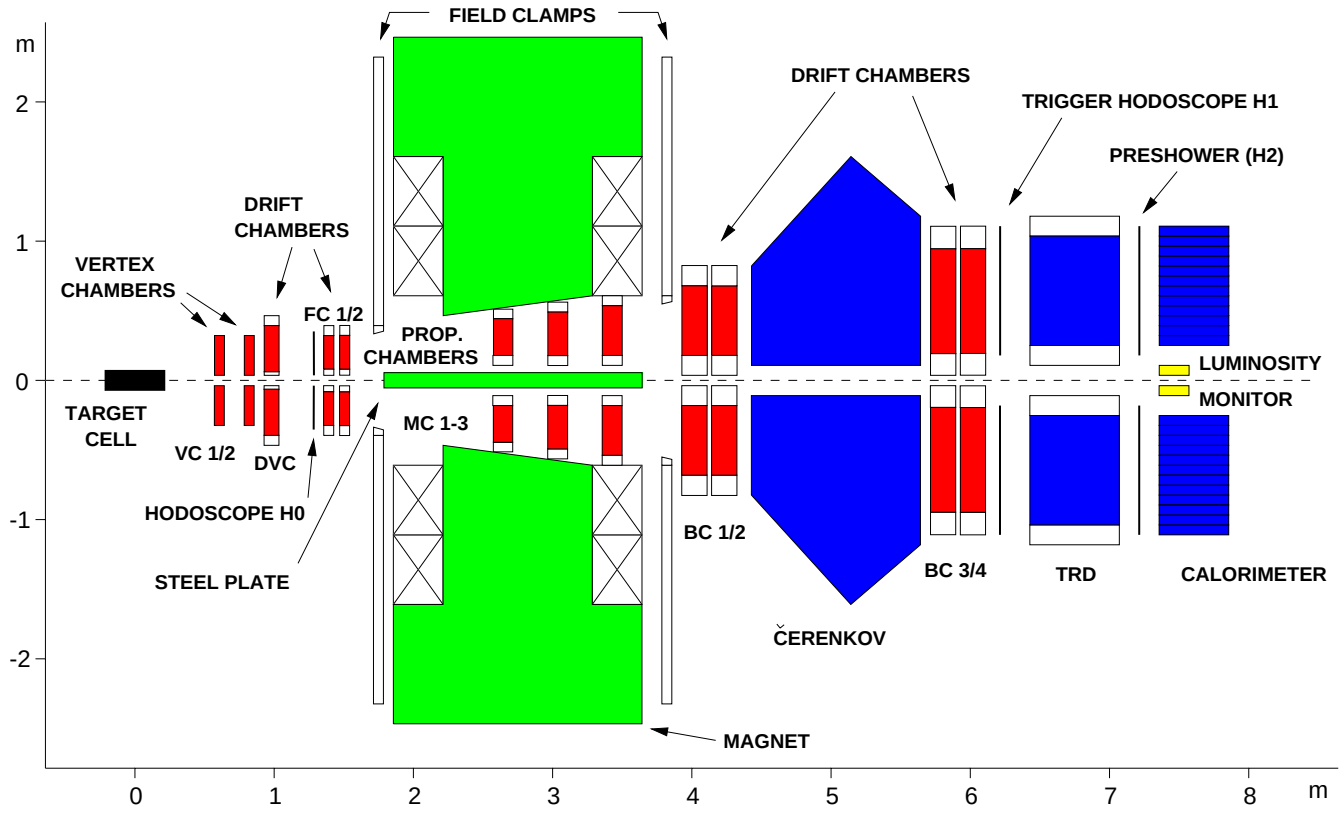
$$\langle \sin 2\phi \rangle_{UL} \propto S_L \textstyle\sum_{a,\bar{a}} e_a^2 x h_{1L}^{\perp(1)a}(x) H_1^{\perp(1)a}(z)$$

Lorentz covariance:

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

HERMES 'Longitudinally' polarized target: $S_T << S_L$

The HERMES Experiment (in 97)



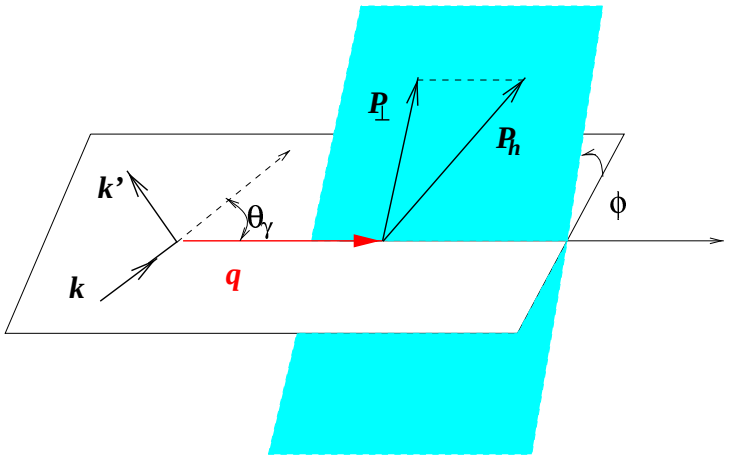
- **Beam** 27.5 GeV HERA e^+ beam
- **Target**: Internal storage cell gas target $P_{\vec{H}} \approx 86\%$
- **kinematic:** $0.02 < x < 0.8$ for $Q^2 > 1$ and $W^2 > 4$
- **Tracking**: 57 tracking planes,
  $\delta P/P = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ mrad
- **Particle identification**: Čerenkov (RICH98), TRD, Preshower, Calorimeter.

$$4.5 \text{ GeV} < P_{\pi^\pm} < 13.5 \text{ GeV}$$

$$3 \text{ GeV} < P_{\pi^0} < 18 \text{ GeV}$$

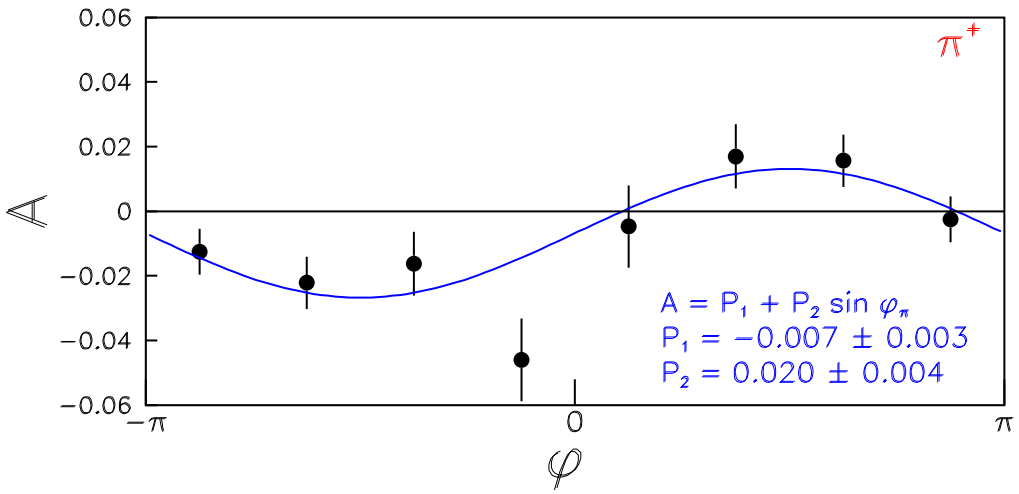
Spin-Azimuthal Asymmetry

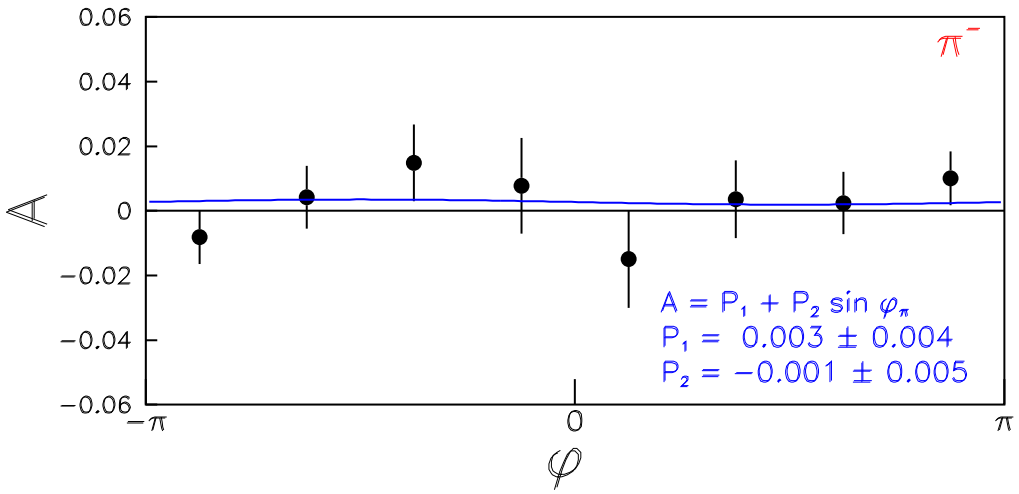
Consider distribution of pions in angle ϕ = pion azimuthal angle around the q vector, relative to lepton scattering plane (containing 'Longitudinal' target spin axis).



'Longitudinal' target single-spin asymmetry:

$$A_{UL}(\phi) = \frac{1}{P}\frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$





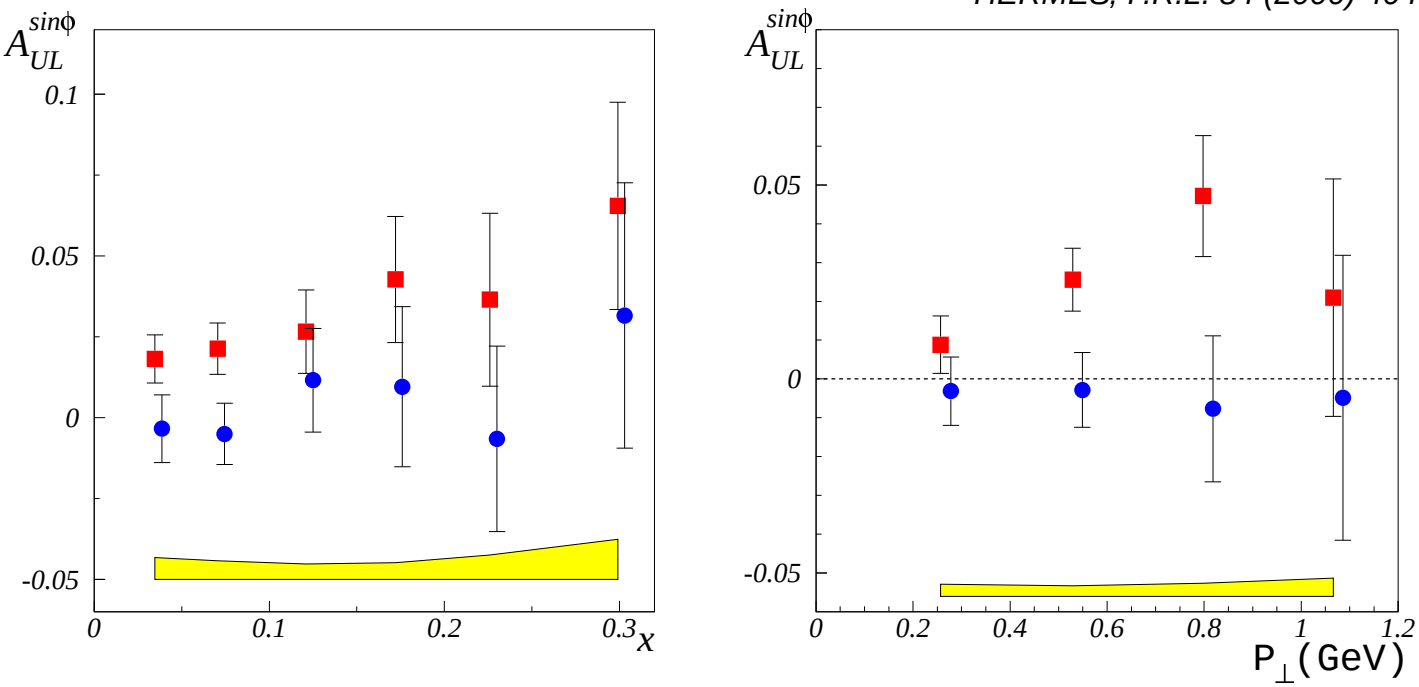
$A_{UL}^{\sin\phi}$ Behaviour

$A_{UL}^{\sin\phi} = \langle \sin\phi \rangle$ moment of longitudinal target asymmetry

$\rightarrow$ related to product of $h_L(x)$ and $H_1^{\perp}(z)$

Red squares = π^+, blue circles = π^-

HERMES, P.R.L. 84 (2000) 4047



Original Predictions of Collins

Collins, NP B396 (1993) 161

- Effect should peak at $x \simeq 0.3$ (valence region)
- Effect should be stronger for π^+ than π^- (u-quark dominance)
- Effect should grow with p_T and peak at $p_T \simeq 1$ GeV/c

Future Measurements of Transversity

This effect is due to **transverse** quark polarization. . . already visible using a longitudinally polarized target $\Rightarrow$ good promise for future **transverse target programs** , e.g. at HERMES and COMPASS.

Azimuthally Weighted Asymmetries

$$\mathcal{A}_{UL}^{\sin\phi} = \frac{\frac{L^+}{L_P^+}\int_0^{2\pi}\sin\phi\,\mathrm{d}N_+ - \frac{L^-}{L_P^-}\int_0^{2\pi}\sin\phi\,\mathrm{d}N_-}{\frac{1}{2}[\int_0^{2\pi}\mathrm{d}N_+ + \int_0^{2\pi}\mathrm{d}N_-]} = 2 < \sin\phi >$$

- $\pm$ target spin state
- $L^{\pm}$ dead-time corrected luminosities
- $L_P^{\pm}$ luminosities wighted by the target polarization

$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} = 0.022 \pm 0.005(stat) \pm 0.003(syst)$$
$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} = -0.005 \pm 0.008(stat) \pm 0.004(syst)$$

$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} \propto \frac{4}{9}h_L^u \mathbf{H_1^{\perp u\to\pi^+}} + \frac{1}{9}h_L^d H_1^{\perp d\to\pi^+}$$
$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} \propto \frac{4}{9}h_L^u H_1^{\perp u\to\pi^-} + \frac{1}{9}h_L^d \mathbf{H_1^{\perp d\to\pi^-}}$$

$e^+ + e^- \to \mathrm{Z}^0 \to$ 2 jets

A. V. Efremov *et al.* (DELPHI), hep-ph/9812522

- $\mathrm{Z}^0 \to q\bar{q} \to$ 2 jets
- (Very small) transverse polarizations of quark and antiquark are highly correlated near the Z^0 peak.
- Collins FF leads to an asymmetry in the production of a hadron in one jet around the axis of a second in the opposite jet.

Result:

$$\left| \frac{\overline{H_1^\perp}}{D_1} \right| = 6.3 \pm 1.7\% \; .$$

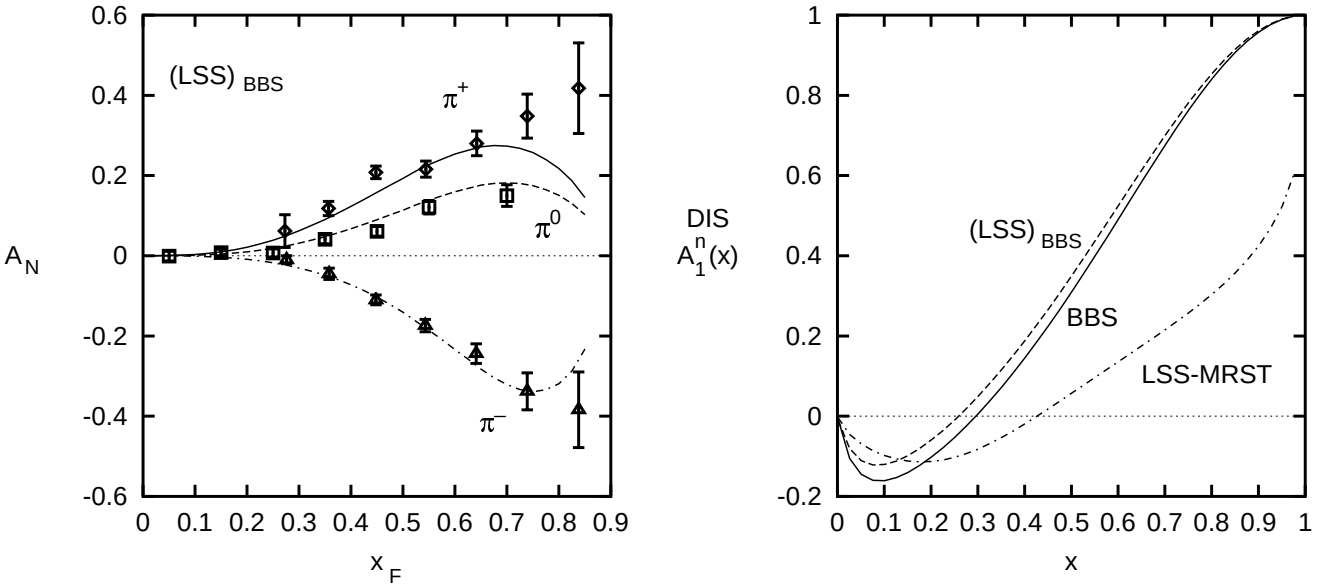
(with large and poorly-understood systematic uncertainty)

$p^{\uparrow}p$ **or** $\bar{p}^{\uparrow}p \rightarrow \pi^{\pm} + X$

$$A_N(x_F, p_T) = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$A_N(\bar{p}^{\uparrow}p \rightarrow \pi^{\pm}) \simeq A_N(p^{\uparrow}p \rightarrow \pi^{\mp})$$

E704 Data



Curves from Boglione and Leader hep-ph/9911207 assuming Collins FF is responsible for the effect

Their transversity fit now satisfies Soffer inequality:

$$|\delta q(x)| \leq \tfrac{1}{2}[q(x) + \Delta q(x)]$$

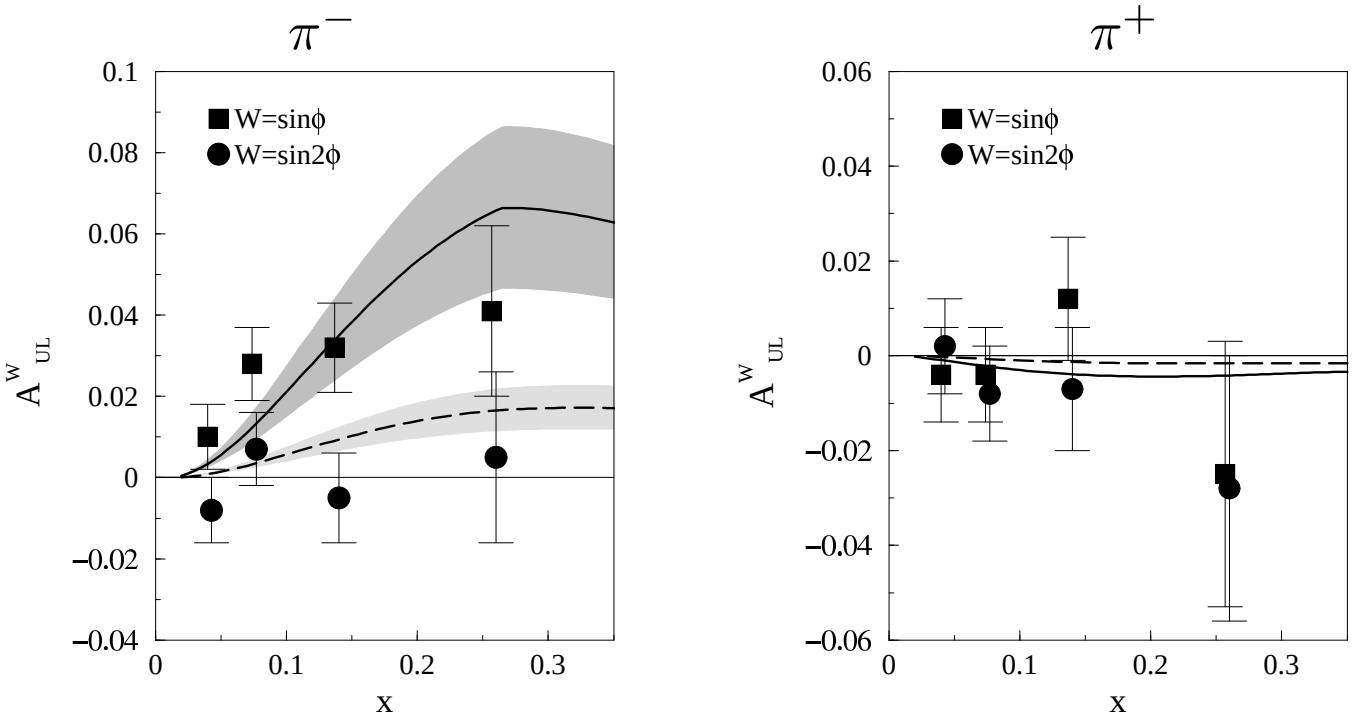
Consistent with effects of Collins FF

SSA $\mathcal{A}_{UL}^{\sin\phi}$ x dependence: THEORY

Efremov, Goeke, Polyakov & Urbino, hep-ph/0001119

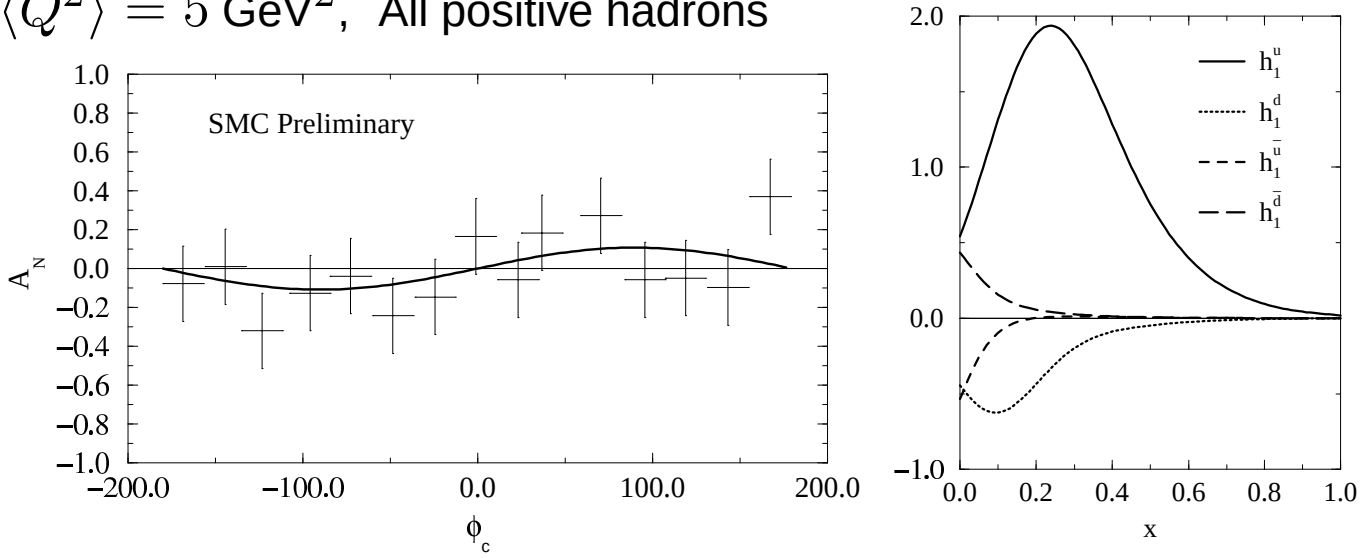
- Neglect twist-3: $h_{1L}^{\perp(1)}(x) \simeq -\frac{x}{2} h_L(x) \simeq -x^2 \int_x^1 dy \frac{h_1(x)}{y^2}$
- Transversity $h_1(x)$ from Chiral-Soliton model

HERMES data: 'longitudinal' target polarization, $\langle Q^2 \rangle = 2.5$ GeV^2



SMC data: 'transverse' target polarization

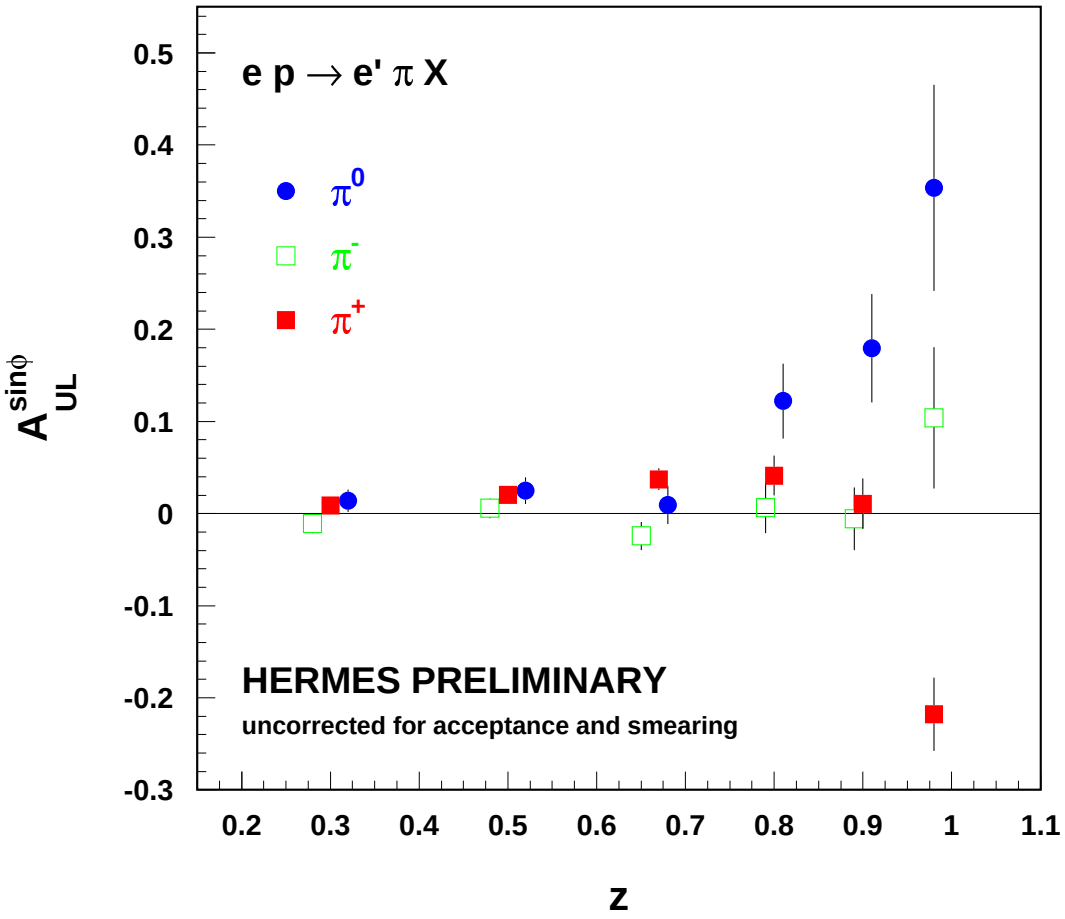
$\langle Q^2 \rangle = 5$ GeV^2, All positive hadrons

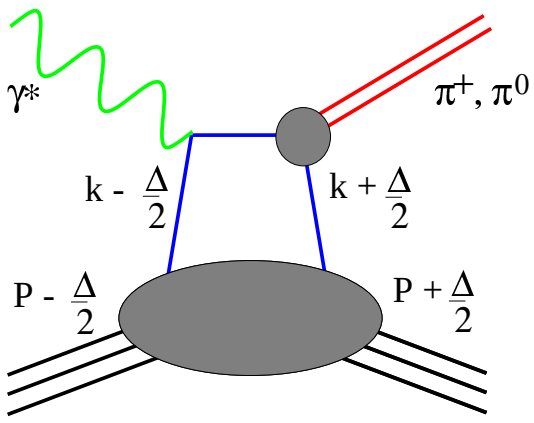


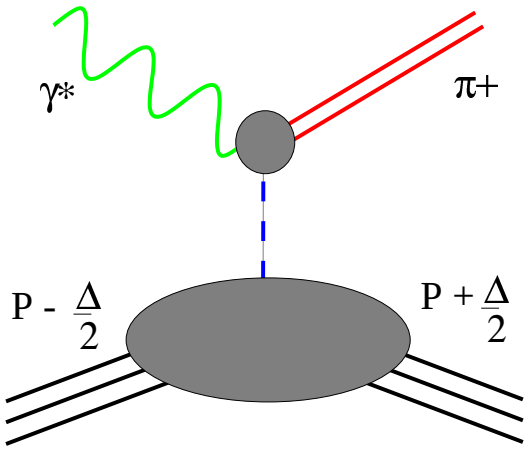
Exclusive Pion Production

Factorization Theorem found to apply to hard exclusive longitudinal production of mesons, via SPD's. *Collins, Frankfurt and Strikman (1997)*

First look at spin-azimuthal asymmetry $A_{UL}^{\sin\phi}$ for pion production on proton target, in the exclusive limit $z \longrightarrow 1$:

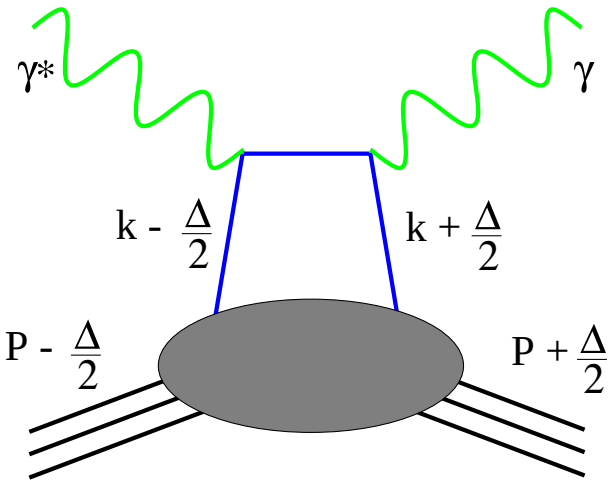






Skewed Parton Distributions

Analysis of **hard exclusive processes** leads to a new class of parton distributions. Simplest example is Deeply Virtual Compton scattering:



On the lightcone:

$$x \equiv k^+/P^+$$
$$\xi \equiv -\Delta^+/2P^+$$
$$t \equiv \Delta^2$$
$$\Delta \neq 0 \rightarrow \textbf{correlations}$$

$$\langle P'S'|\overline{\psi}(-\frac{y}{2})\gamma^\alpha\psi(\frac{y}{2})|PS\rangle \quad \Rightarrow \quad H(x,\xi,t), E(x,\xi,t)$$

$$\langle P'S'|\overline{\psi}(-\frac{y}{2})\gamma^\alpha\gamma_5\psi(\frac{y}{2})|PS\rangle \quad \Rightarrow \quad \tilde{H}(x,\xi,t), \tilde{E}(x,\xi,t)$$

Connection with **DIS structure functions** : forward limit

$$q(x) = H^q(x,\xi=0,t=0), \quad \Delta q(x) = \tilde{H}^q(x,\xi=0,t=0)$$

Connection with **elastic form factors** : first moments

$$G_M(t) = \int_{-1}^{1} dx \sum_q [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

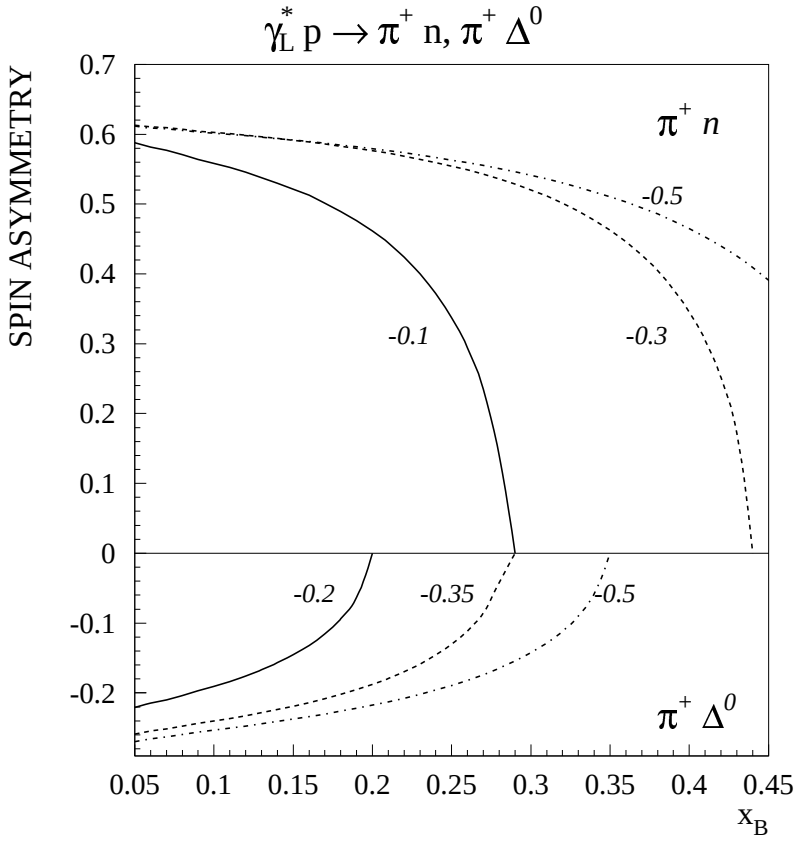
$$G_E(t) = \int_{-1}^{1} dx \sum_q [H^q(x,\xi,t) + \frac{t}{4M^2}E^q(x,\xi,t)]$$

Connection with **quark angular momentum** : second moments

$$J^q = \frac{1}{2}\Delta\Sigma + L^q = \frac{1}{2}\int_{-1}^{1} x\, dx\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

SPD Model Predictions

For transverse polarised target

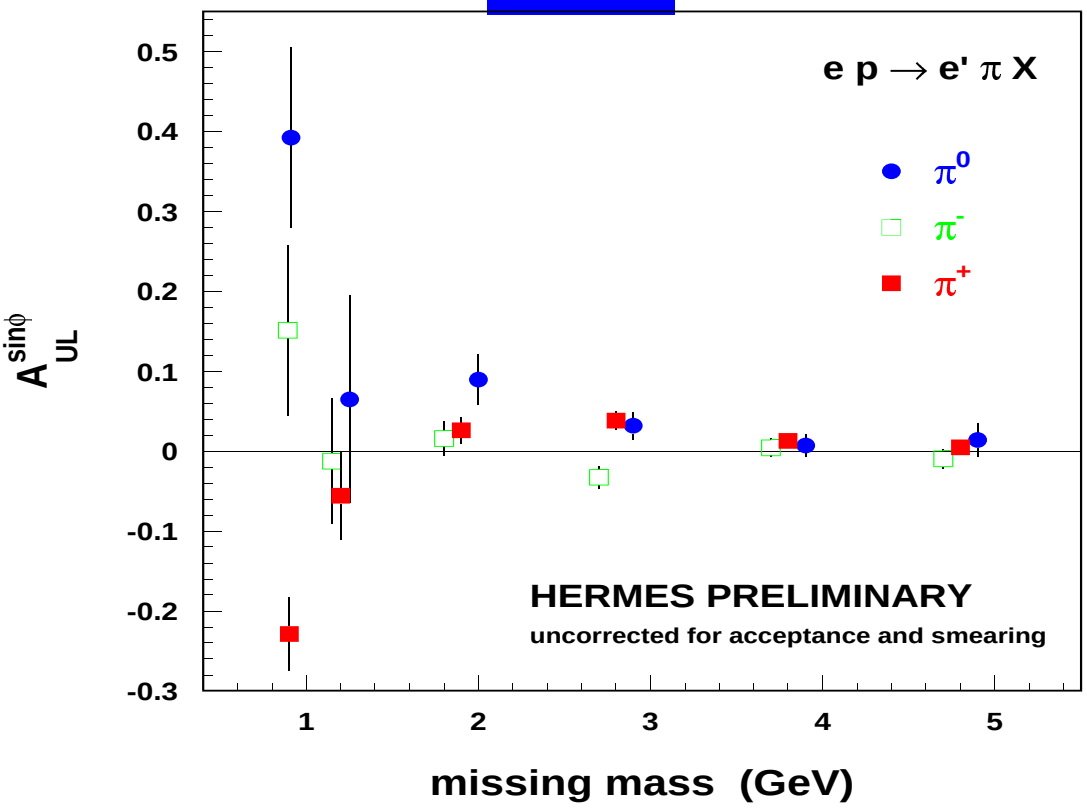


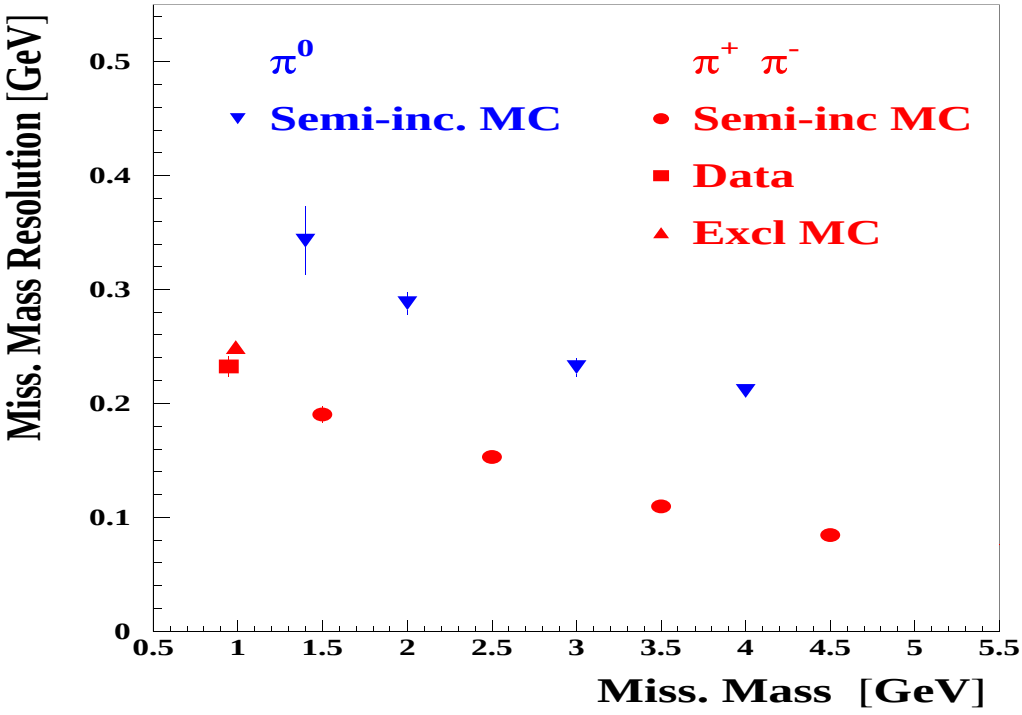
L. L. Frankfurt, M. V. Polyakov, M. Strikman, M. Vanderhaeghen; Phys.Rev.Lett. 84 (2000) 2589-2592

- No predictions for **longitudinally** polarised target.

HERMES longitudinally polarized target: $S_T << S_L$

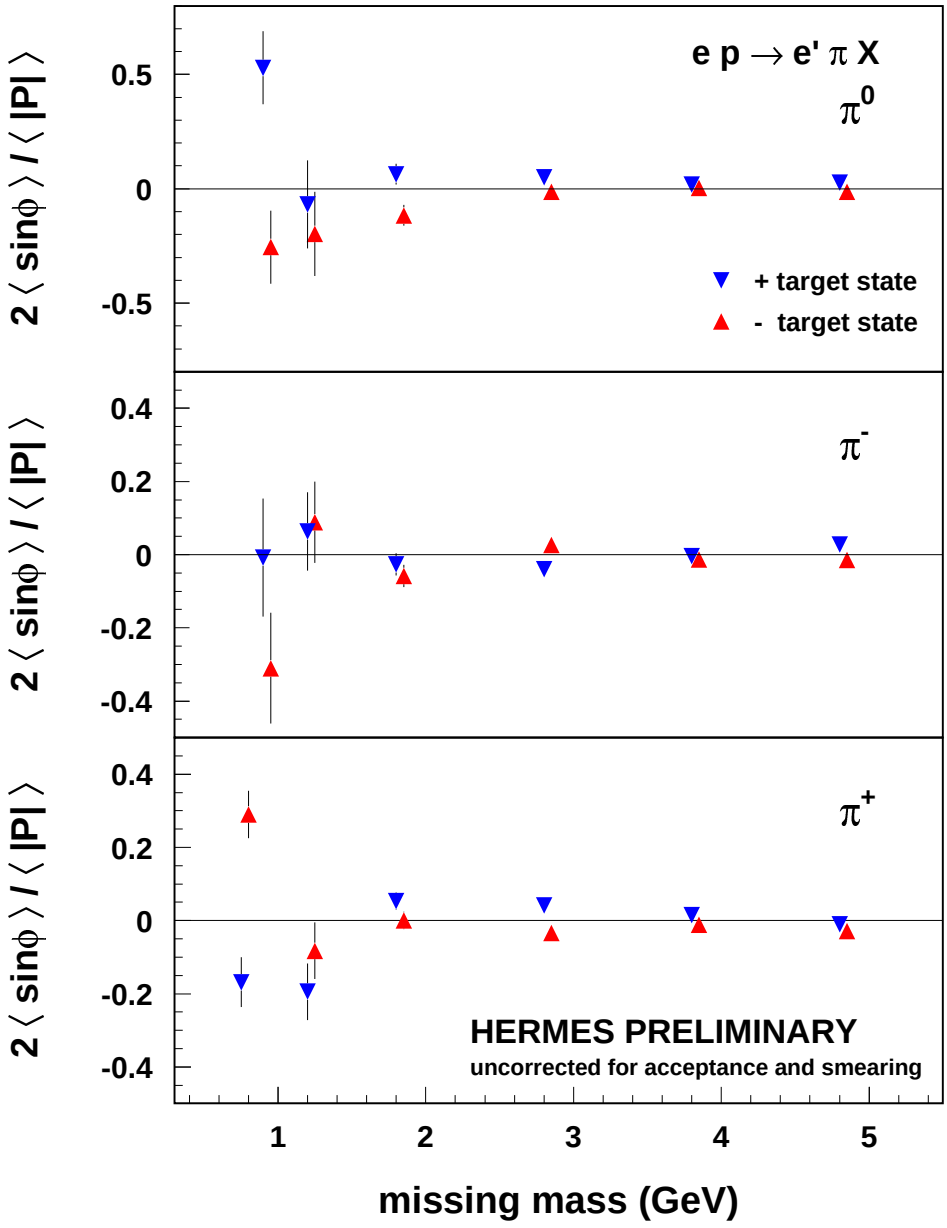
$\mathcal{A}_{UL}^{\sin\phi}$





In excl. region, sign of A^{π^+} is opposite to predictions for transverse target polarization. Also expect $A^{\pi^0} << A^{\pi^+}$

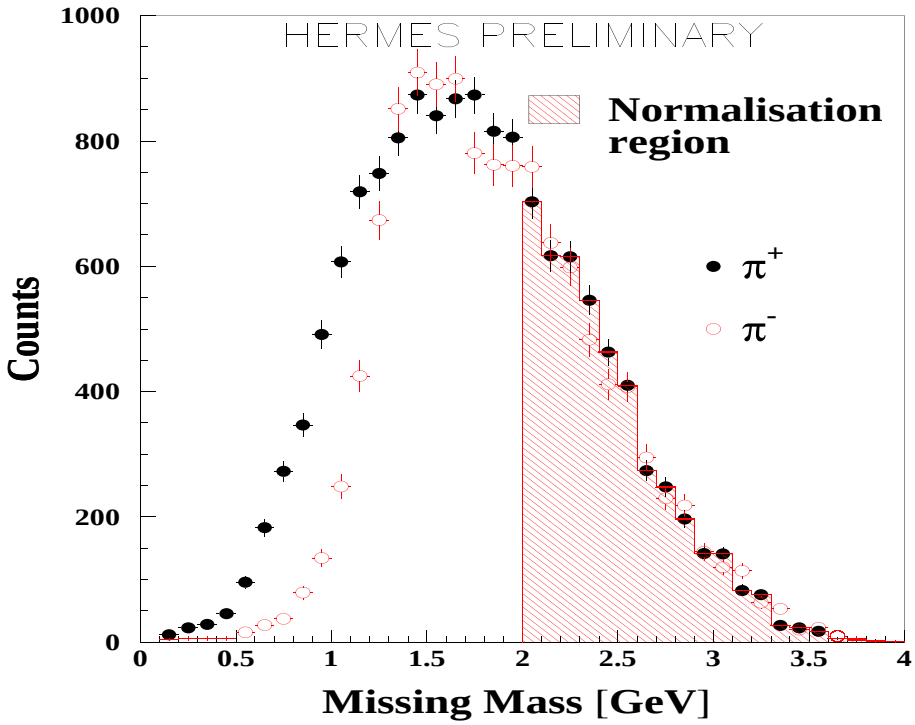
Flip target polarisation

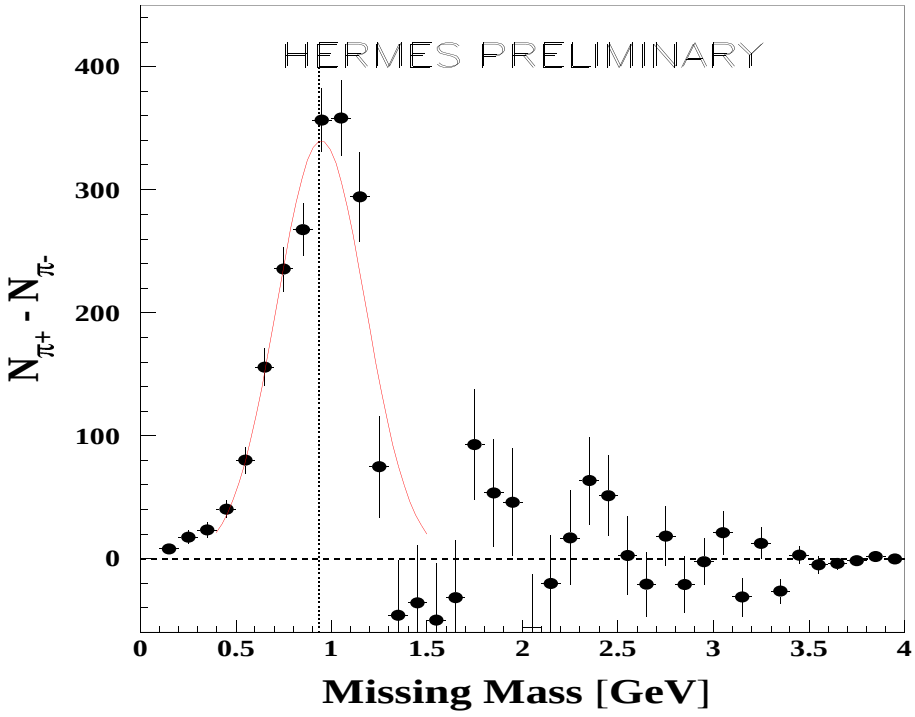


⇒ effect comes from target polarisation only

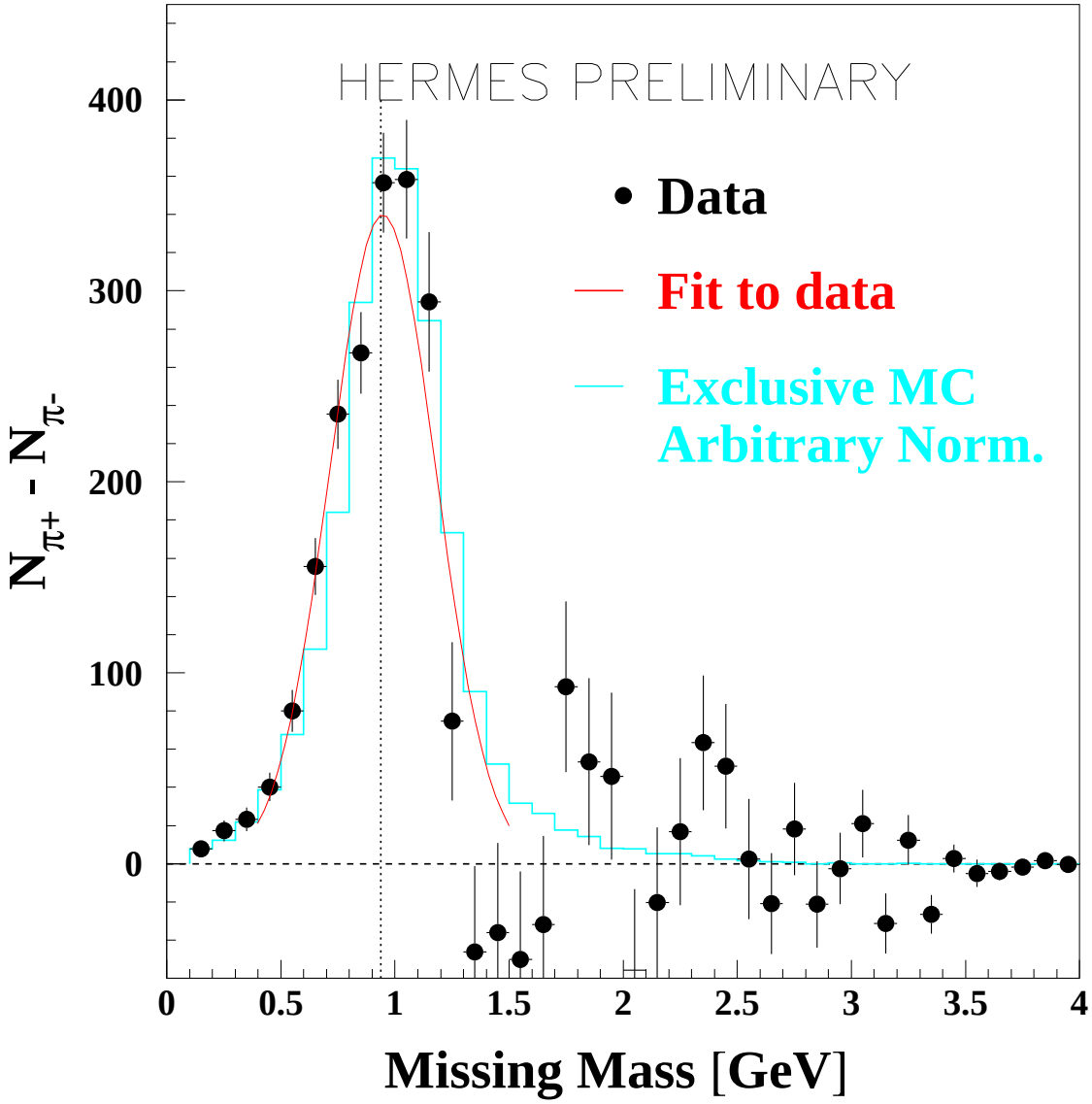
Missing Mass

$$e\ P \rightarrow e'\ \pi^{\pm}\ X$$



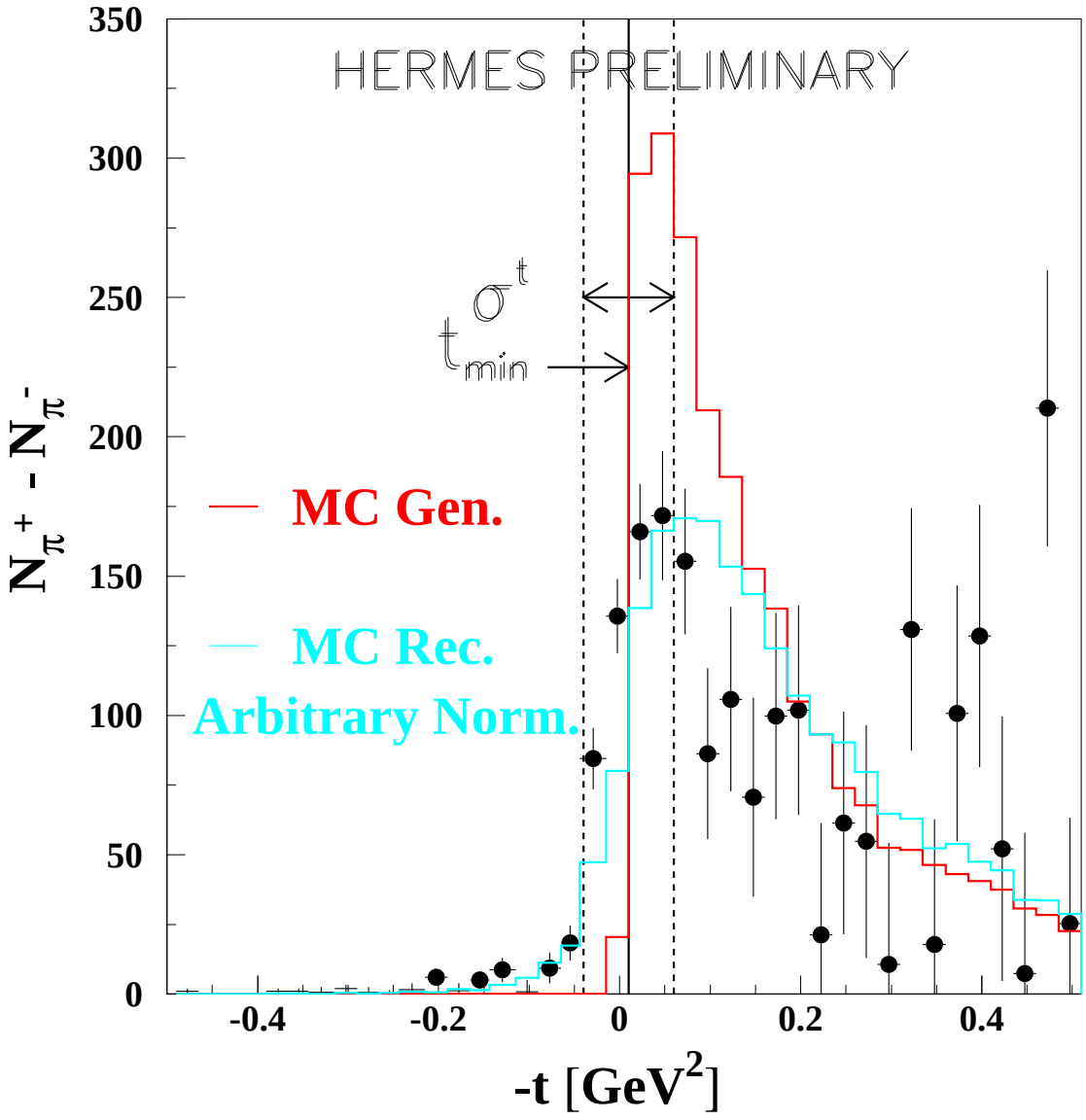


Missing mass distribution



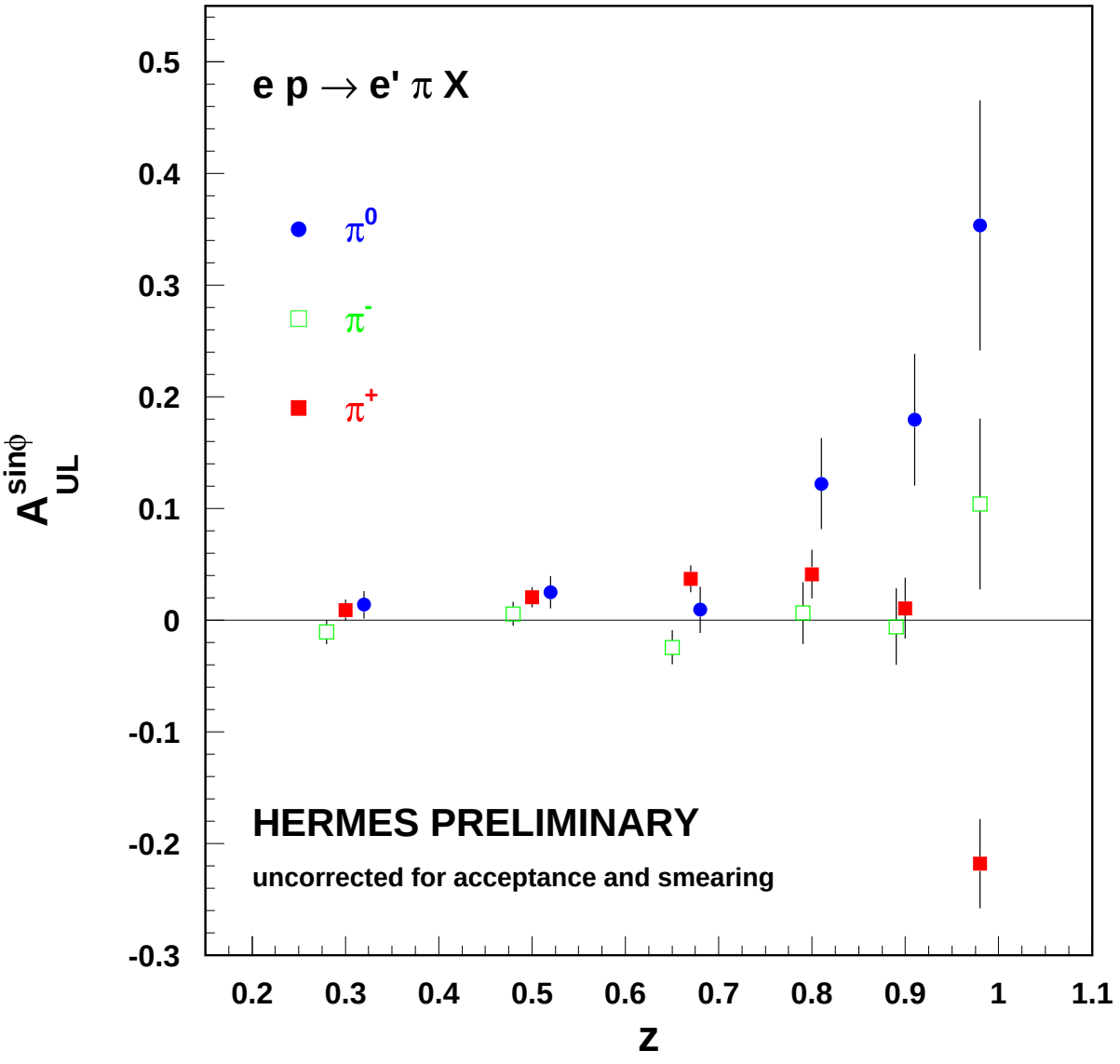
- $\sim$ 1.7 k exclusive π^+ for 96+97 data.
- Agreement between data and MC.
- Missing mass resolution $\approx$ 0.25 GeV.

t-distribution



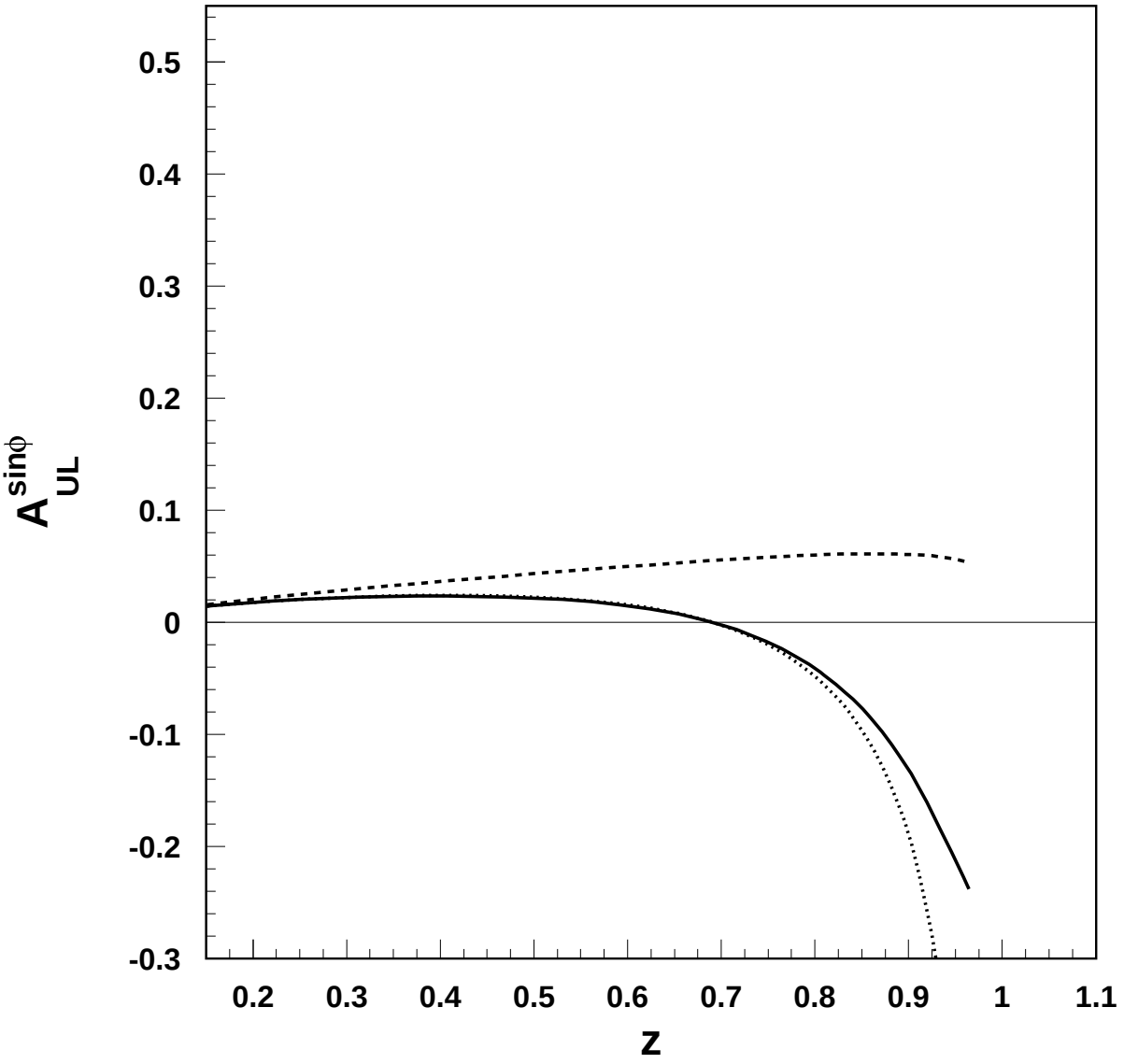
- Rough agreement between data and exclusive MC
  - ▷ MC studies: Q^2 , ν dependence.

Spin Asymmetries from HERMES



Model Estimates of Spin Asymmetries

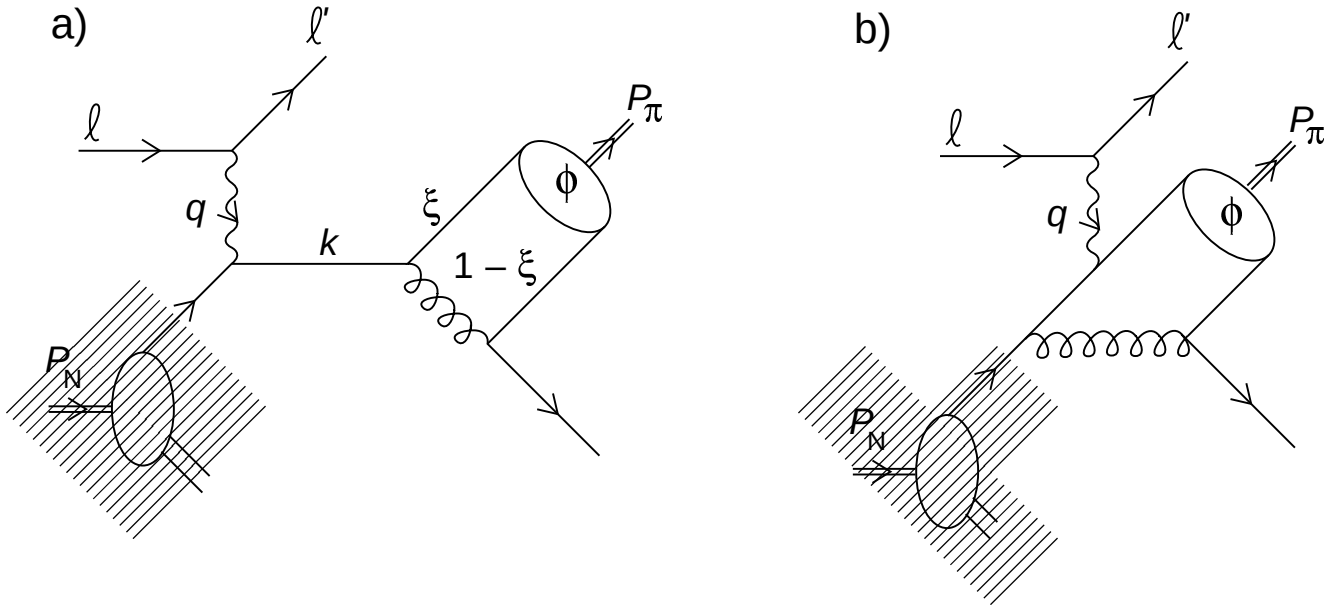
$A_{UL}^{\sin\phi}$ for π^+.



- Upper curve: includes only the $H_1^{\perp(1)}$ contribution,
- Lower curve: $\tilde{H}$ term added.
- Middle curve: same but $D(z) \to D(z) + \frac{2}{9}\frac{\langle P_\perp^2 \rangle}{Q^2}$

Semi-exclusive electroproduction

Berger 1980, Brandenburg 1994



Dominant contribution to *semi-exclusive pion* production ($u + e^- \rightarrow e^- + \pi^+ + d$)

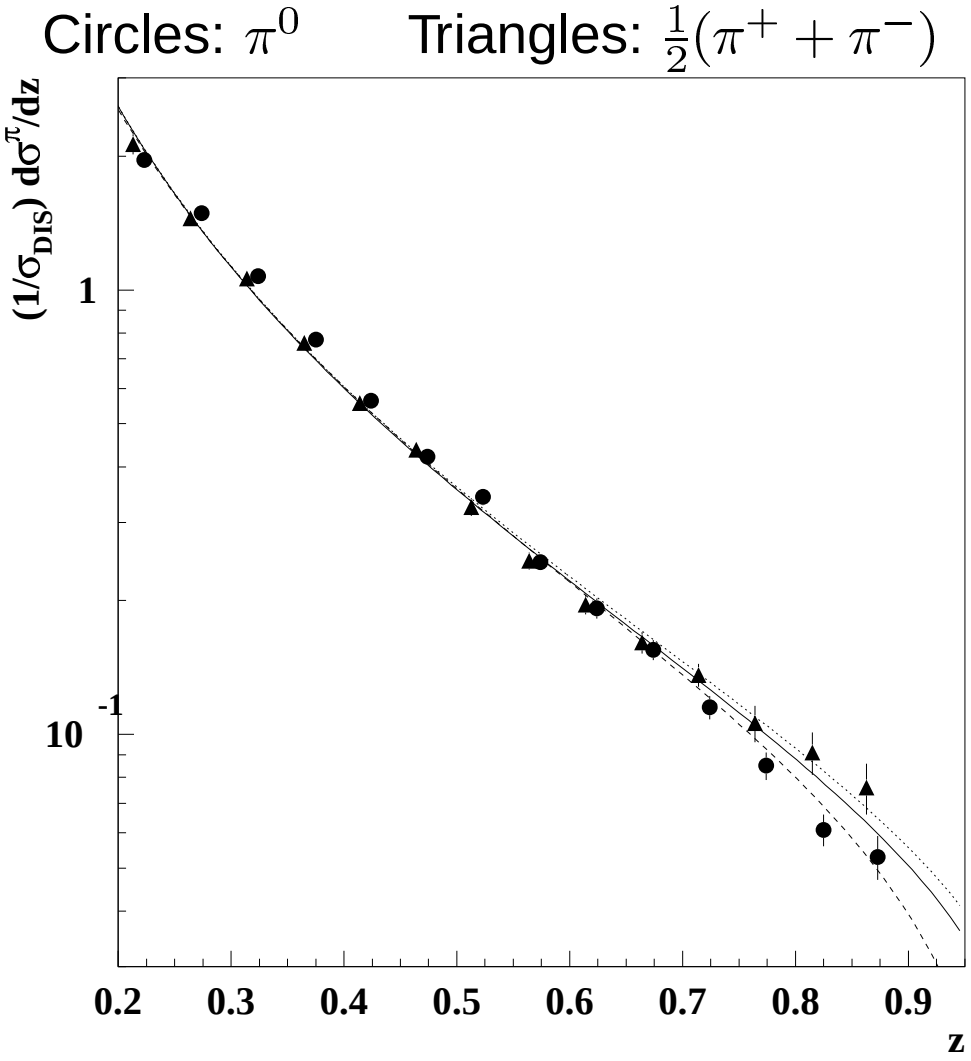
At large z, struck quark becomes far off shell (time-like): $k^2 = \frac{P_\perp^2}{z(1-z)}$

$\Rightarrow$ Dominant contribution to meson wave function is perturbative one-gluon exchange

$\Rightarrow$ $D_{\pi/q}(z, Q^2)$ acquires at large z an extra non-scaling term Berger-Z.Phys. C 4,289 (1980)

$$D_{\pi/q}(z, Q^2) \propto D_{\pi/q}(z) + \frac{2}{9}\frac{\langle P_\perp^2 \rangle}{Q^2}$$

DIS Pion Multiplicities from HERMES



- Dashed (bottom) curve is BKK fit to $\frac{1}{2}(\pi^+ + \pi^-)$
- Upper curves with Berger term included $\langle Q^2 \rangle = 2.5$ GeV^2, and $\langle P_\perp^2 \rangle = 0.25$ or $\langle P_\perp^2 \rangle = 0.18$

Summary

- Target-related spin-azimuthal asymmetries measured in semi-inclusive DIS agree with expectations based on data from FNAL and LEP

- The Collins fragmentation function is indicated to be substantial, and suitable for future measurements of transversity.

- As $z \rightarrow 1$ (exclusive region), *longitudinal* target-related spin-azimuthal asymmetries increase dramatically, but not as suggested by model predictions for *transverse* target polarization.

- Measured $A_{UL}^{\sin\phi}$ for π^+ changes sign as $z \rightarrow 1$, in conflict with 'expectations'.

- Measured $A_{UL}^{\sin\phi}$ for π^0 as $z \rightarrow 1$ is as large as for π^+, in conflict with 'expectations'.

- A twist-3 fragmentation function might cause the observed sign reversal for π^+.