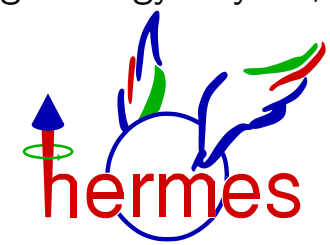
Recent results on TMDs from the HERMES Experiment

V.A. Korotkov
(on behalf of the HERMES Collaboration)

Institute for High Energy Physics, Protvino, Russia

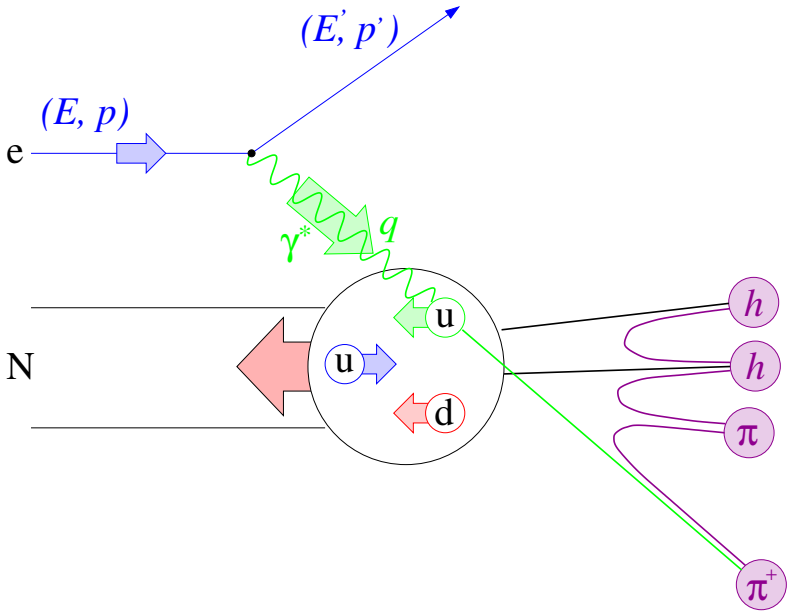


DSPIN-15, Dubna, 08.09.15

Outline

- Introduction
- Experiment HERMES
- Asymmetry A_{LU}
- Asymmetry A_{UT}
- Asymmetry A_{LT}
- Summary

SIDIS



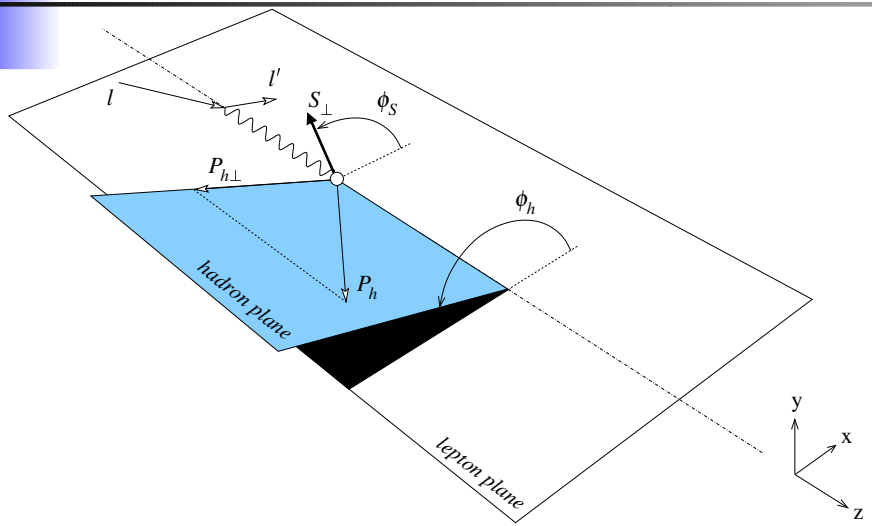
$$Q^2 = -q^2 = -(k - k')^2$$
$$x_B = \frac{Q^2}{2P \cdot q}$$
$$y = \frac{P \cdot q}{P \cdot k}$$
$$W^2 = (P + q)^2$$
$$z = \frac{P \cdot P_h}{P \cdot q}$$

inclusive DIS: detect scattered lepton
semi-inclusive DIS: detect scattered lepton and some fragments

$W^2 > 10$ GeV^2, $0.1 < y < 0.85$, $Q^2 > 1$ GeV^2, $0.2 < z < 0.7$

$< Q^2 >= 2.4$ GeV^2, $< x >= 0.09$, $< y >= 0.54$, $< z >= 0.36$, $P_{h\perp} = 0.41$ GeV^2

Quark Distributions



$$eN \to e'hX$$

A.Kotzinian, Nucl.Phys. B441 (1995) 234.

P.J.Mulders , R.D.Tangerman, Nucl.Phys. B461 (1996) 197; B484 (1997) 538.

A.Bacchetta et al., JHEP02 (2007) 093.

$$\Phi(x,p_T) = \frac{1}{2}\left\{ f_1 \not{n}_+ - f_{1T}^\perp \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} \not{n}_+ + g_{1s}\gamma_5 \not{n}_+ + h_{1T} \frac{[\not{S}_T, \not{n}_+]\gamma_5}{2} + h_{1s}^\perp \frac{[\not{p}_T, \not{n}_+]\gamma_5}{2M} + i\, h_1^\perp \frac{[\not{p}_T, \not{n}_+]}{2M} \right\}$$
$$+ \frac{M}{2P^+}\left\{ e - i\, e_s\, \gamma_5 - e_T^\perp \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} + f^\perp \frac{\not{p}_T}{M} - f_T' \epsilon_T^{\rho\sigma}\gamma_\rho S_{T\sigma} - f_s^\perp \frac{\epsilon_T^{\rho\sigma}\gamma_\rho p_{T\sigma}}{M} + g_T' \gamma_5 \not{S}_T + g_s^\perp \gamma_5 \frac{\not{p}_T}{M} - g^\perp \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho p_{T\sigma}}{M} + h_s \frac{[\not{n}_+, \not{n}_-]\gamma_5}{2} + h_T^\perp \frac{[\not{S}_T, \not{p}_T]\gamma_5}{2M} + i\, h \frac{[\not{n}_+, \not{n}_-]}{2} \right\}. \quad (1)$$

Quark Distributions

$$g_{1s}(x, p_T) = S_L g_{1L}(x, p_T^2) - \frac{p_T \cdot S_T}{M} g_{1T}(x, p_T^2)$$

$$h_{1s}(x, p_T) = S_L h_{1L}(x, p_T^2) - \frac{p_T \cdot S_T}{M} h_{1T}(x, p_T^2)$$

Eight distributions of twist two, and 16 distributions of twist three.

		Quark		
		U	**L**	**T**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

$$f_1(x) = \int d^2\vec{p}_T f_1(x, p_T^2), \quad g_1(x) = \int d^2\vec{p}_T g_1(x, p_T^2), \quad h_1(x) = \int d^2\vec{p}_T \{h_{1T}(x, p_T^2) + \frac{p_T^2}{2M} h_{1T}^\perp(x, p_T^2)\}$$

SIDIS, $eN \to e'hX$

(A.Bacchetta et al., JHEP02 (2007) 093; JHEP08 (2008) 023)

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,Q^2}\,\frac{y}{2\,(1-\varepsilon)}\left\{T_{UU} + \lambda_e\,T_{LU} + S_\parallel\,T_{UL} + S_\parallel\,\lambda_e\,T_{LL} + |\boldsymbol{S}_\perp|\,T_{UT} + |\boldsymbol{S}_\perp|\lambda_e\,T_{LT}\right\}$$

$$T_{UU} = F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$T_{LU} = \sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$T_{UL} = \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}$$

$$T_{LL} = \sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}$$

$$T_{UT} = \sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\times F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}$$

$$T_{LT} = \sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\times F_{LT}^{\cos(2\phi_h-\phi_S)}$$

$F_{XY,Z}$ – X - beam polarization, Y - target polarization, Z - virtual photon poalrization.
$X, Y = U, L, T$, $Z = L, T$.

ε is the ratio of longitudinal and transverse photon flux, $\varepsilon = \dfrac{1-y}{1-y+y^2/2}$.

SIDIS

(A.Bacchetta et al., JHEP02(2007)093; JHEP08(2008)023)

The following notations are introduced:

$$\mathcal{C}\left[w\,f\,D\right] = x\sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\right) w(\boldsymbol{p}_T,\boldsymbol{k}_T)\, f^a(x,p_T^2)\, D^a(z,k_T^2), \tag{2}$$

where $w(\boldsymbol{p}_T,\boldsymbol{k}_T)$ is an arbitrary function and the summation runs over quarks and antiquarks and the unit vector $\hat{\boldsymbol{h}} = \boldsymbol{P}_{h\perp}/|\boldsymbol{P}_{h\perp}|$.

The expressions for the structure functions are:

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

$$F_{UU,L} = 0$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h\, H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{H}}{z}\right)\right]$$

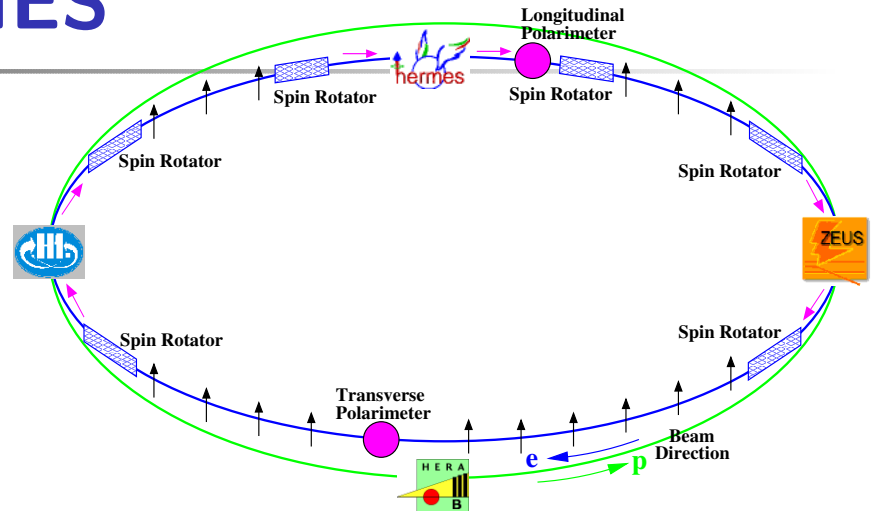
$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^\perp H_1^\perp\right]$$

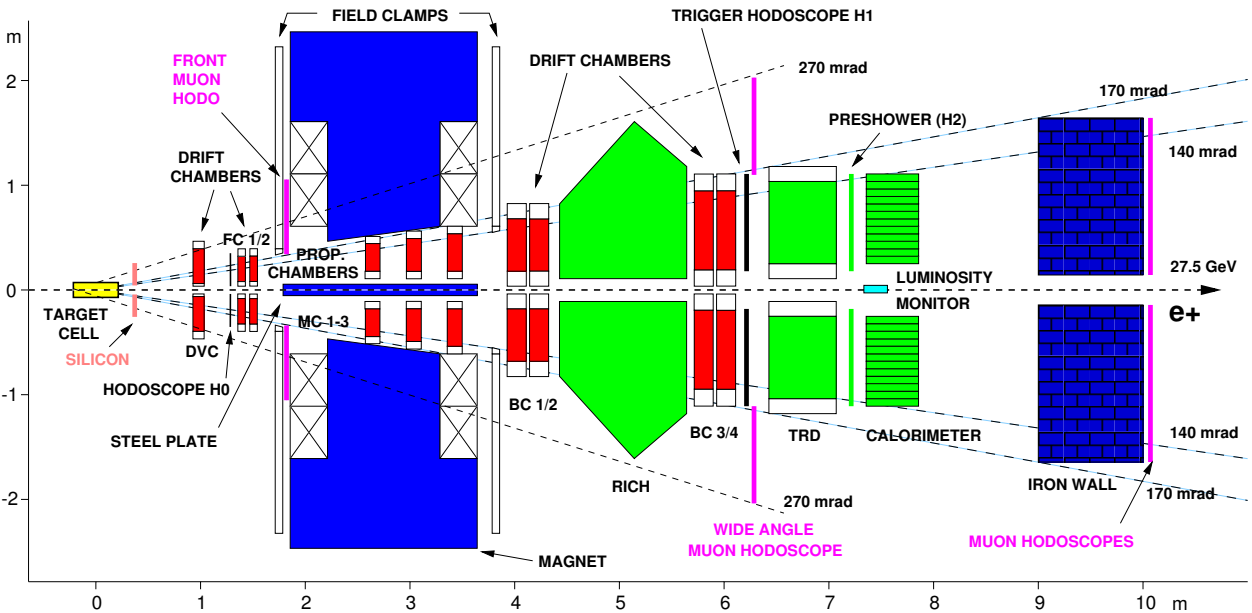
$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e\, H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z}\right)\right]$$

.....

Experiment HERMES

27.5 GeV polarized e^+/e^- beam of HERA





Internal gas Target: polarized - $H^{\uparrow}$

Angular acceptance: $40 < \theta < 220$ mrad

RICH: π / K / p

- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

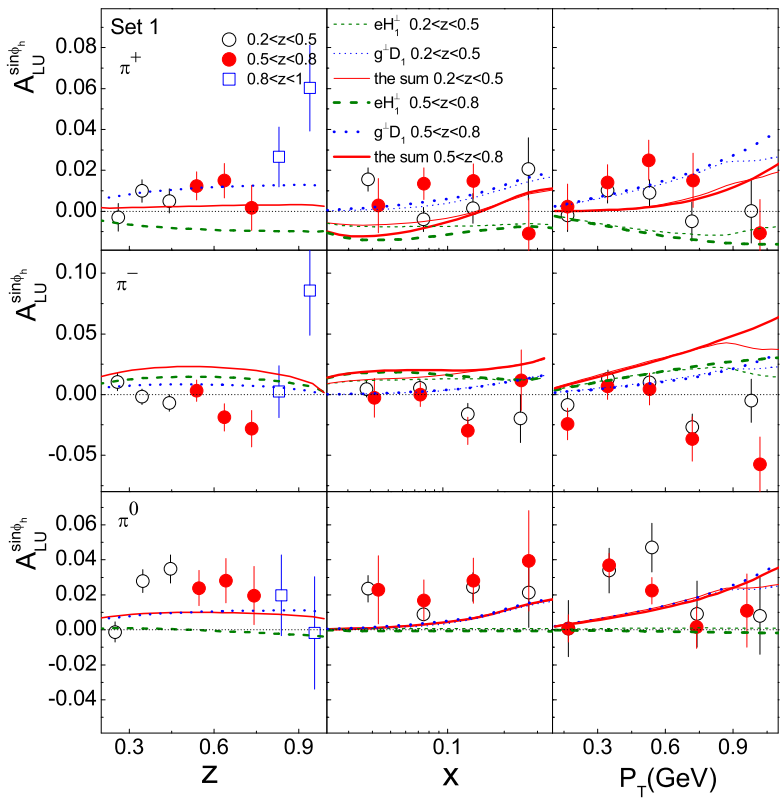
Asymmetry A_{LU}

$$d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + P_L \cdot A_{LU}^{\sin(\phi_h)})$$

$$A_{LU}^{\sin(\phi_h)} \propto F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e\, H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

HERMES A.Airapetian et al., Phys.Lett., B648, 164 (2007)
Data of 1996–1997 years

$eH_1^{\perp}$ A.Efremov, K.Goeke, P.Schweitzer, Ph.Rev. D67, 114014(2003)
$h_1^{\perp}\tilde{E}$ F.Yuan. Ph.Lett. B589, 28(2004)
$g^{\perp}D_1$ A.Metz, M.Schlegel, EPJ A22, 489 (2004)
$g^{\perp}D_1$, $eH_1^{\perp}$ W.Mao, Z.Lu, EPJ C73, 2557 (2013)



Asymmetry A_{LU}

New analysis.

All data sets.

96–97 – threshold Čerenkov detector:
pions $4.5 < P < 13.5$ GeV

97–07 – dual radiator RICH detector:
pions, kaons $2.0 < P < 15.0$ GeV
(anti)protons $4.0 < P < 15.0$ GeV

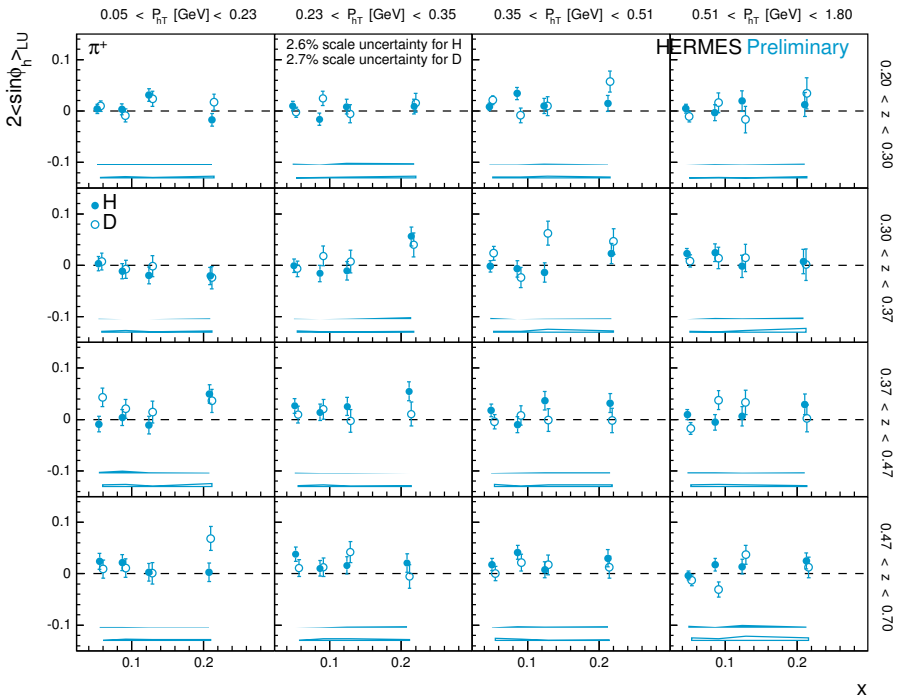
Hydrogen – 53 mln DIS events
Deuterium – 20 mln DIS events

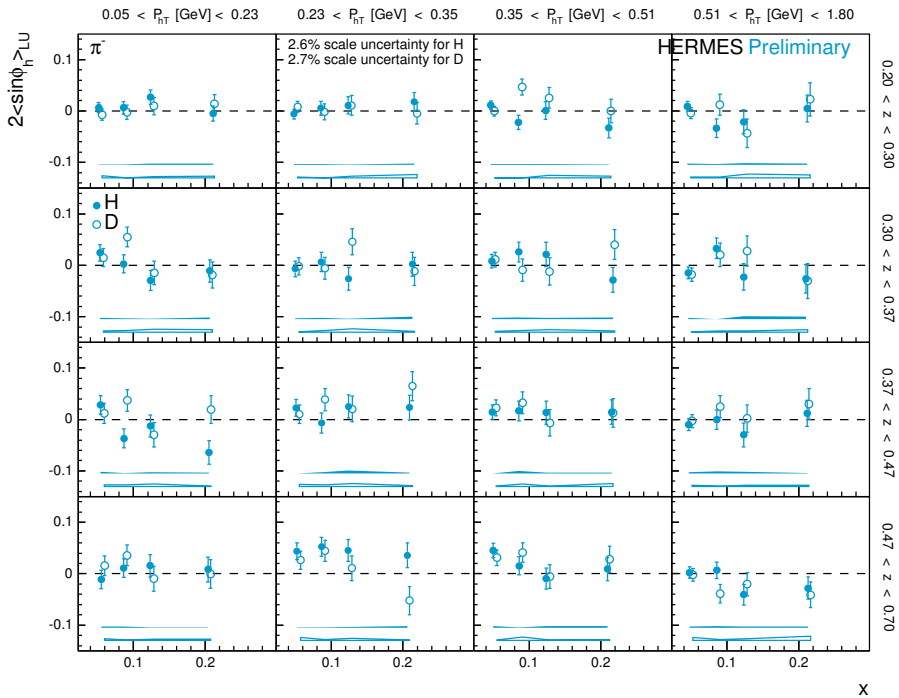
1D and 3D analysis

3D – kinematical range is separated in four x, four z, and four $P_{h\perp}$ bins.

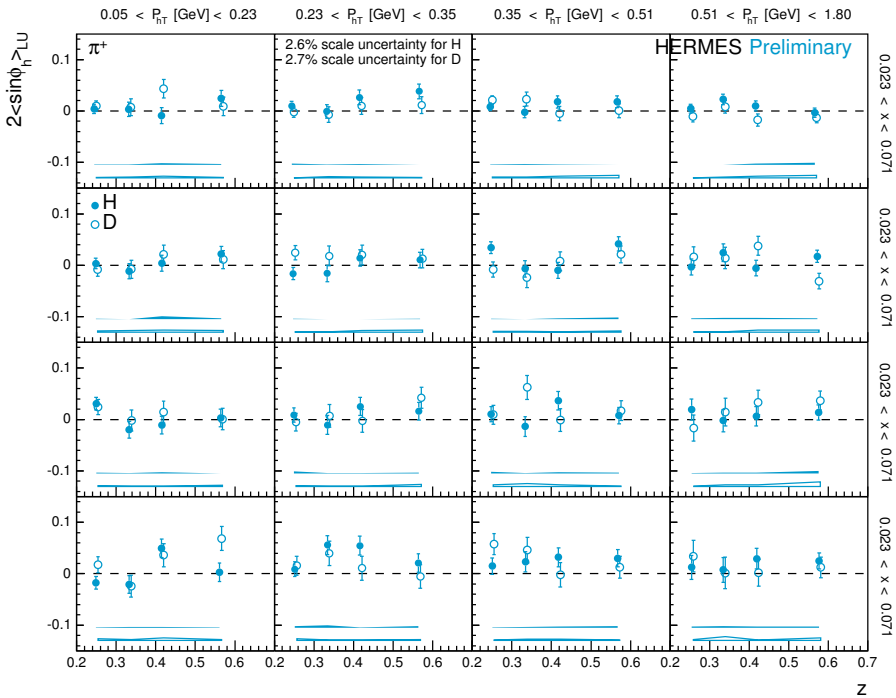
The results are presented in 64 $(x, z, P_{h\perp})$ kinematical bins for each particle type.

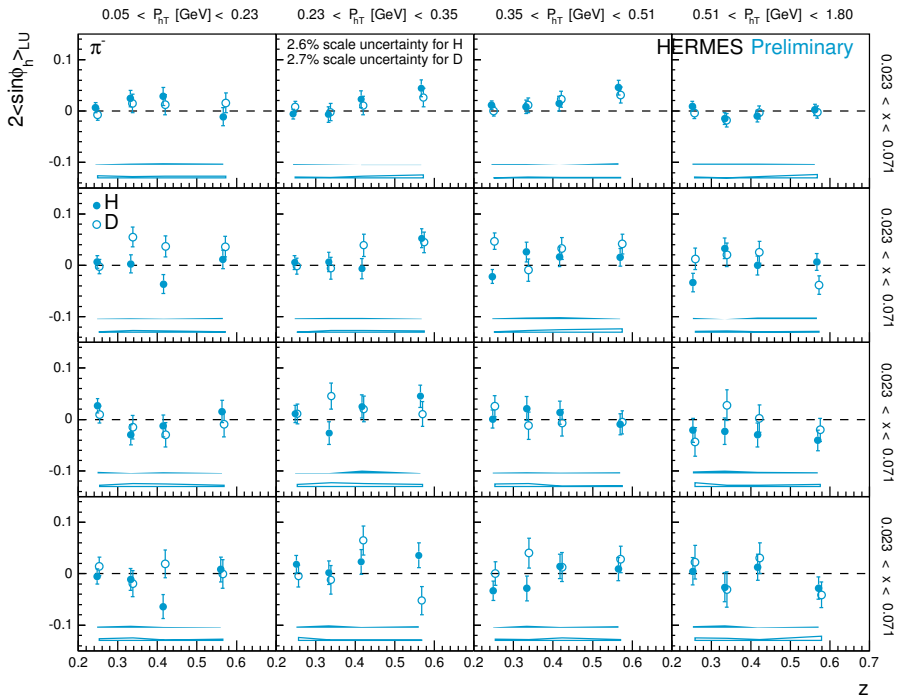
$A_{LU}^{\sin(\phi)}$ vs. x, 3D



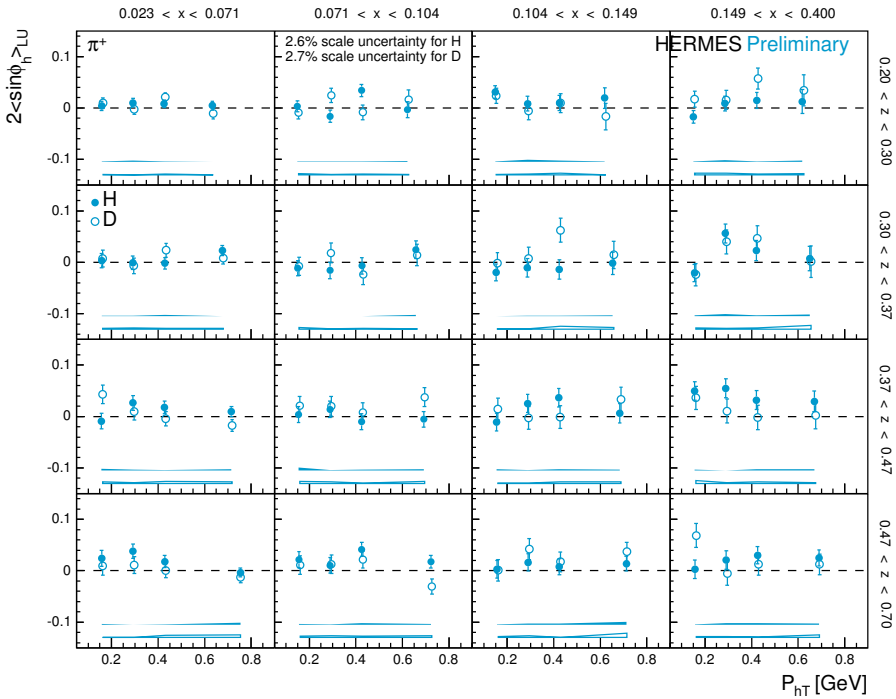


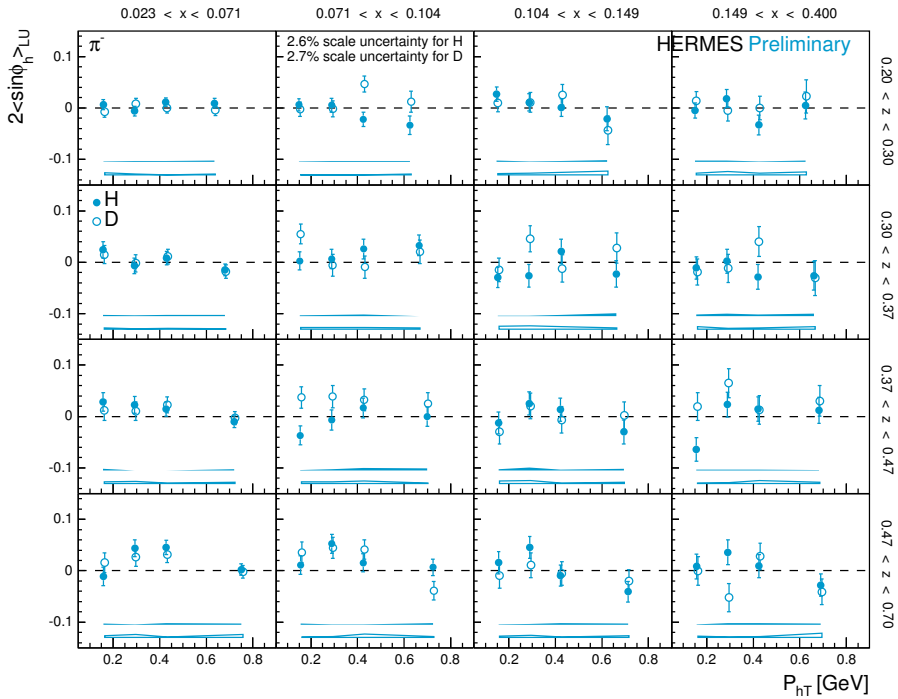
$A_{LU}^{\sin(\phi)}$ vs. z, 3D





$A_{LU}^{\sin(\phi)}$ vs. $P_{h\perp}$, 3D





Asymmetry A_{UT}

$$d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + |\boldsymbol{S}_\perp| \cdot \{A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + A_{UT}^{\sin\phi_S}\sin\phi_S + A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\})$$

$A_{UT}^{\sin(\phi_h-\phi_S)} \propto F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} D_1\right]$ – Sivers asymmetry (PRL 103 (2009) 152002)

$A_{UT}^{\sin(\phi_h+\phi_S)} \propto F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$ – Collins asymmetry (Phys.Lett. B693 (2010) 11)

$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)(\boldsymbol{p}_T\cdot\boldsymbol{k}_T) + \boldsymbol{p}_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T) - 4(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)}{2M^2 M_h} h_{1T}^{\perp} H_1^{\perp}\right]$

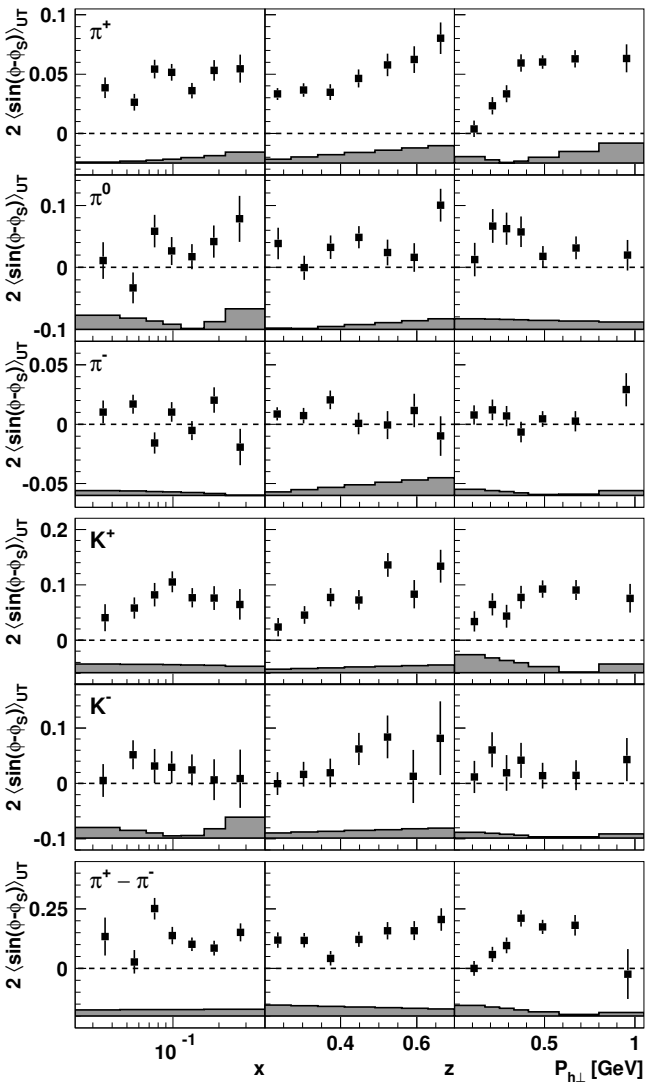
Other asymmetries are twist-3:

$$A_{UT}^{\sin(\phi_S)} \propto F_{UT}^{\sin(\phi_S)} = \frac{2M}{Q}\mathcal{C}\left\{\left(x f_T D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right) - \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]\right\}$$

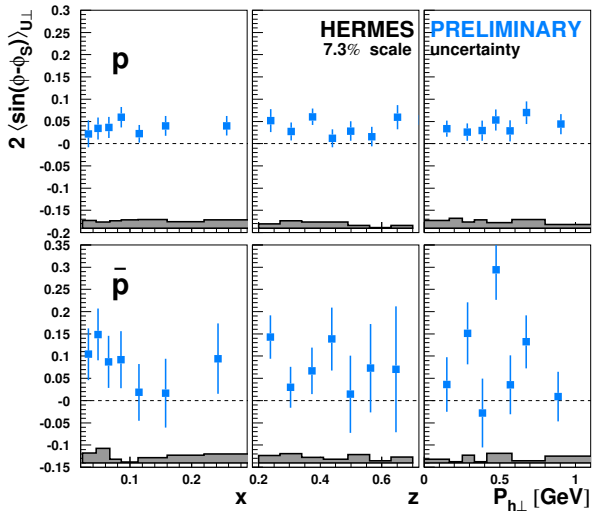
$$F_{UT}^{\sin(2\phi_h-\phi_S)} \propto F_{UT}^{\sin(2\phi_h-\phi_S)} = \frac{2M}{Q}\mathcal{C}\left\{\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2}\left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp}\frac{\tilde{H}}{z}\right) - \frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right) + \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]\right\}$$

Sivers Asymmetry

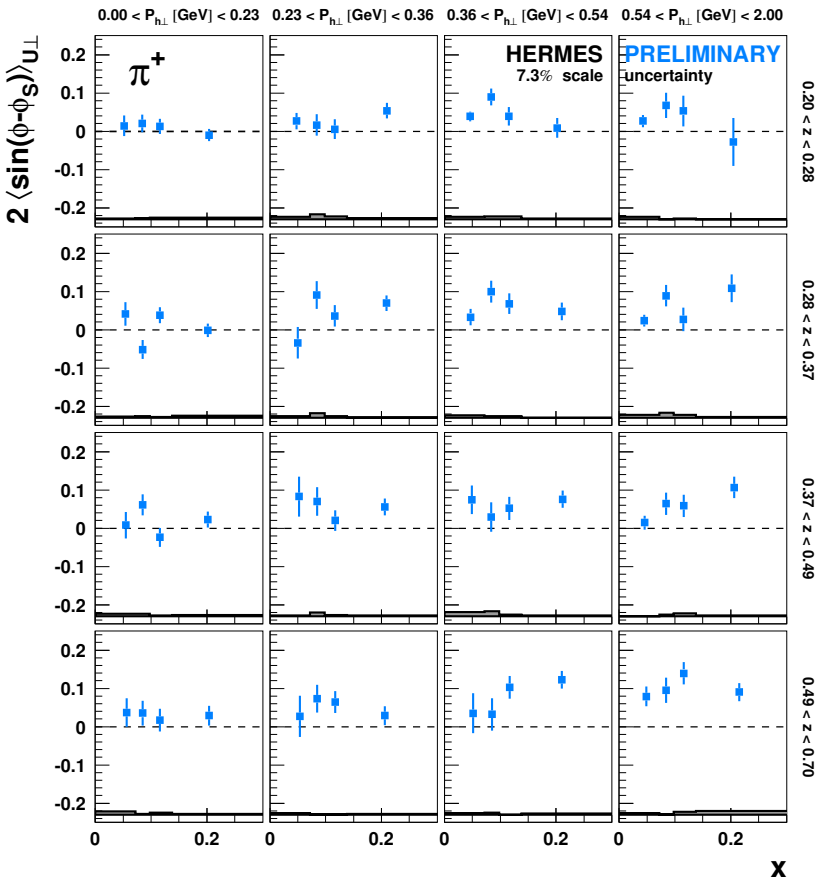
PRL 103 (2009) 152002

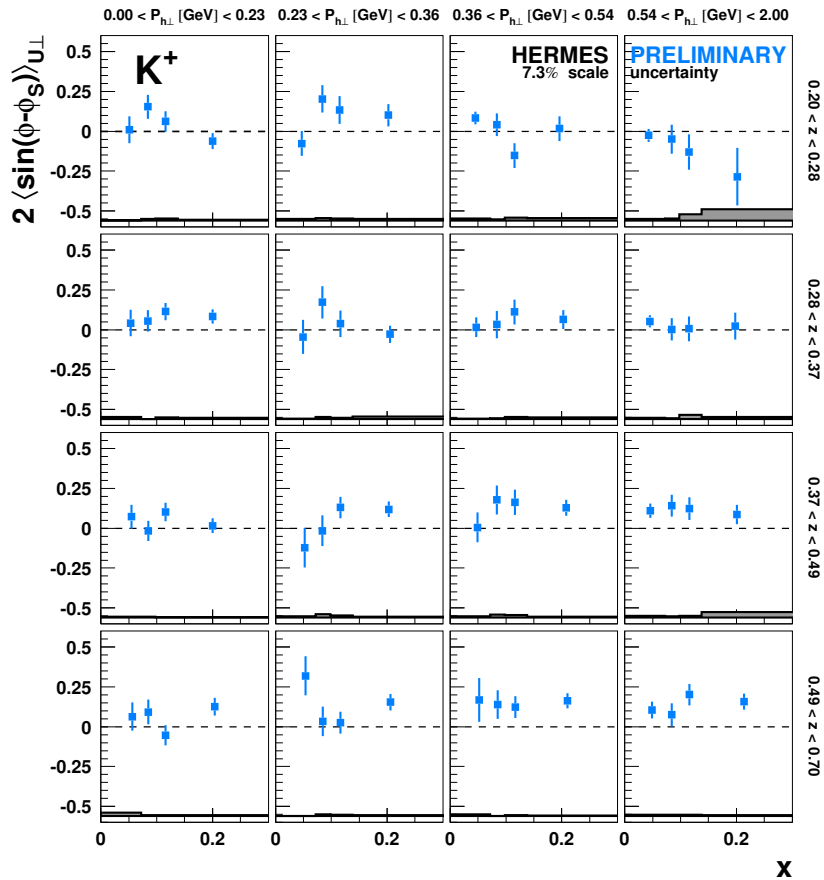


NEW

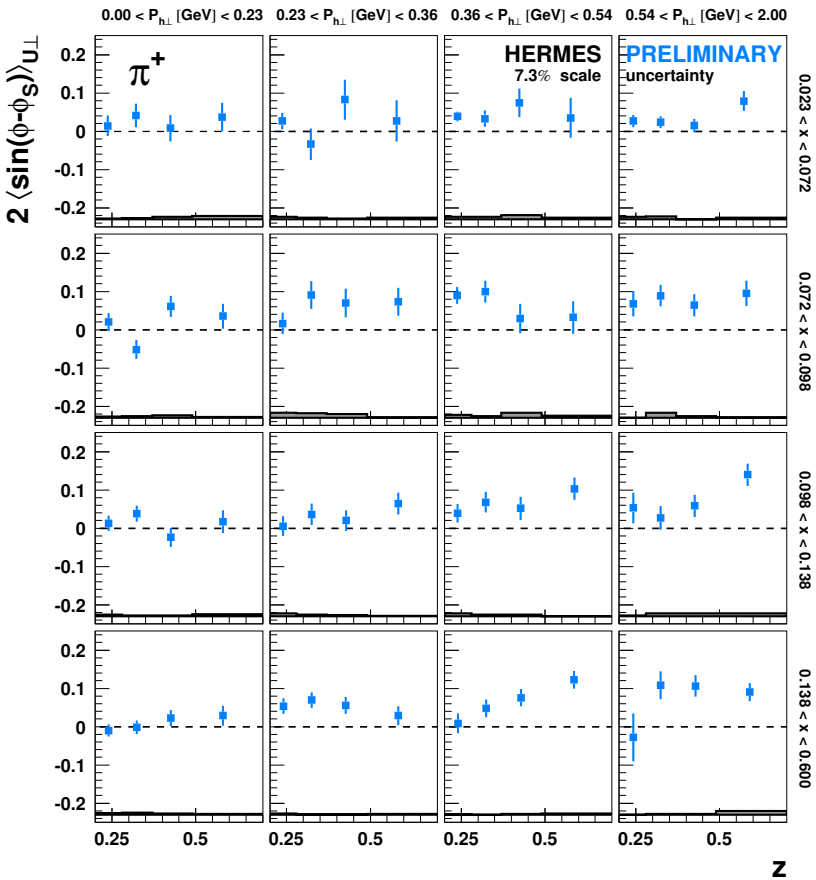


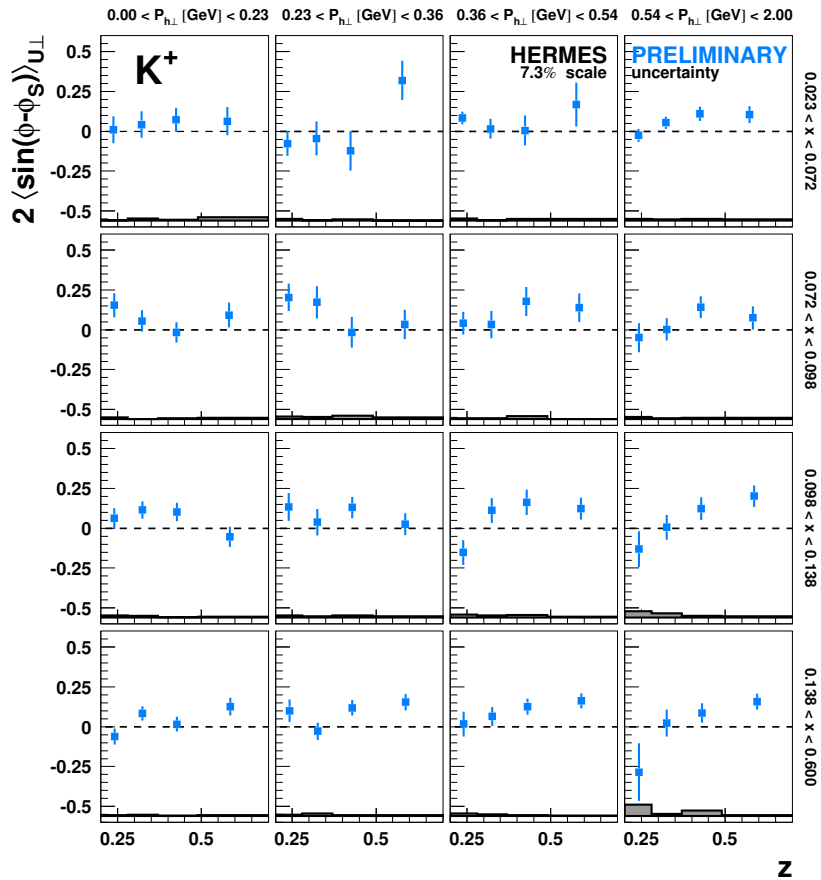
Sivers vs. x, 3D, π^+, K^+



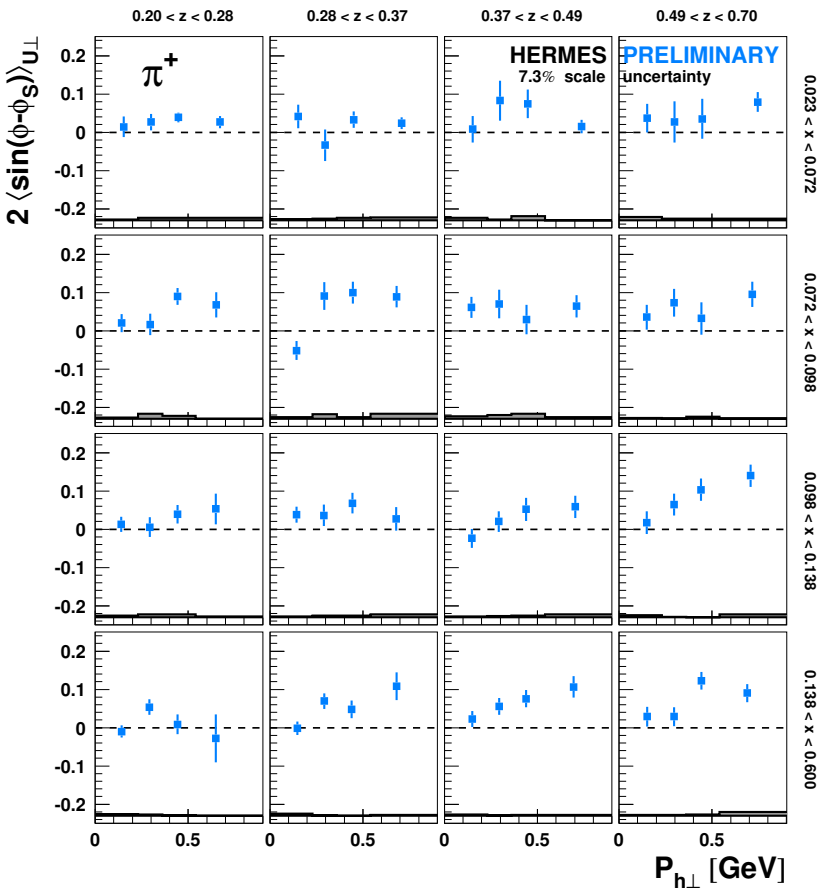


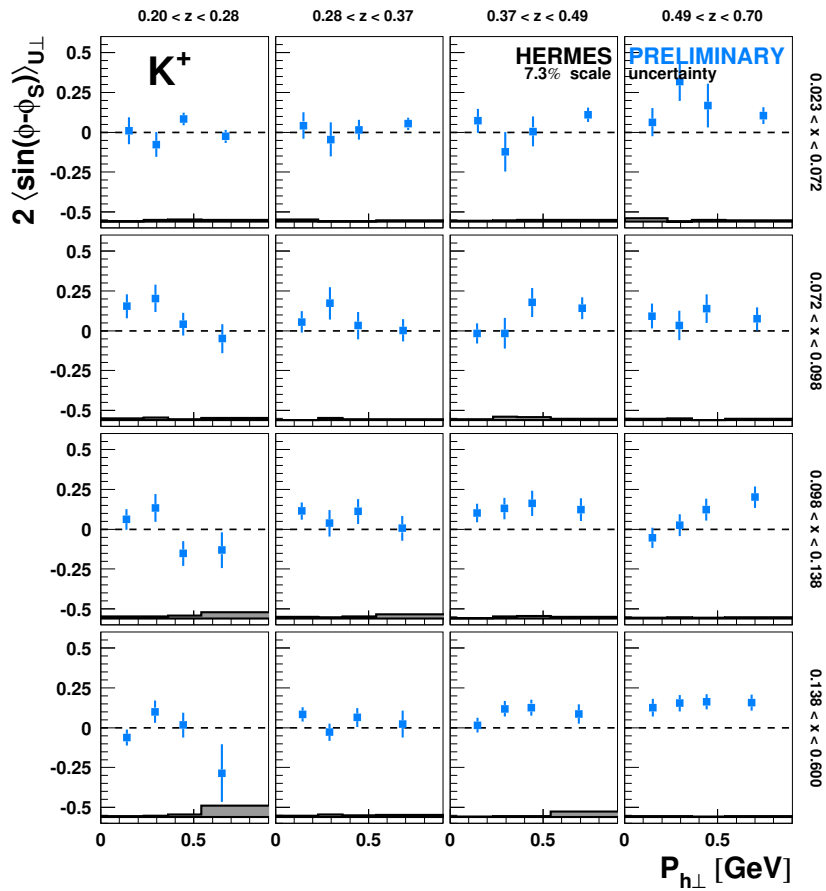
Sivers vs. z, 3D, π^+, K^+





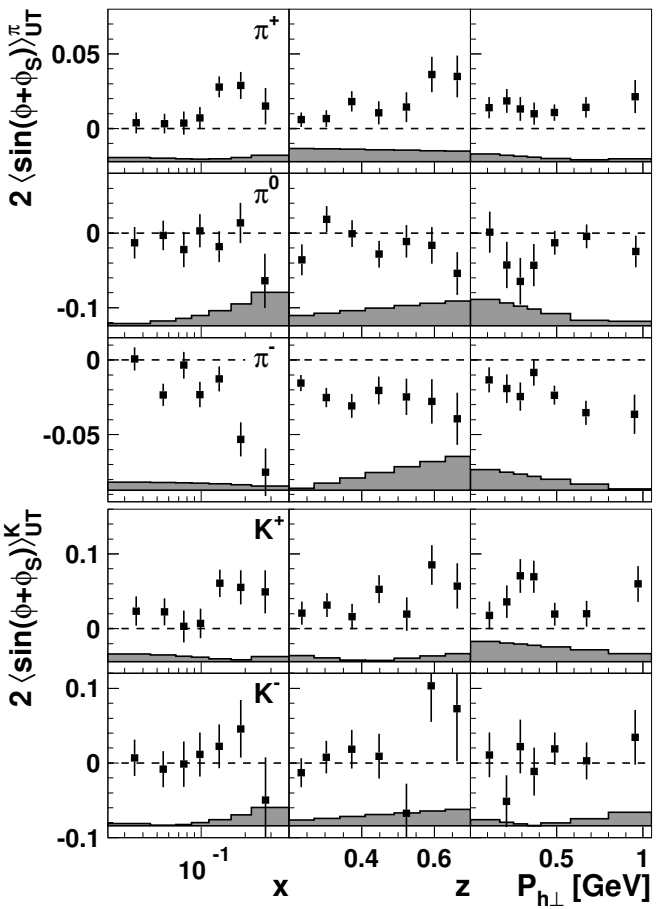
Sivers vs. $P_{h\perp}$, 3D, π^+, K^+



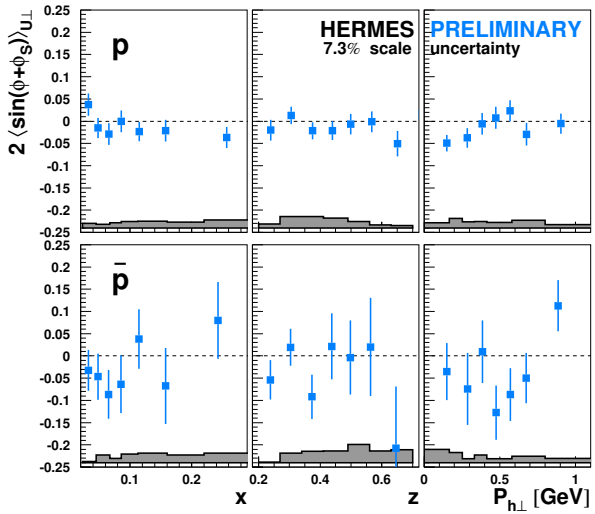


Collins Asymmetry

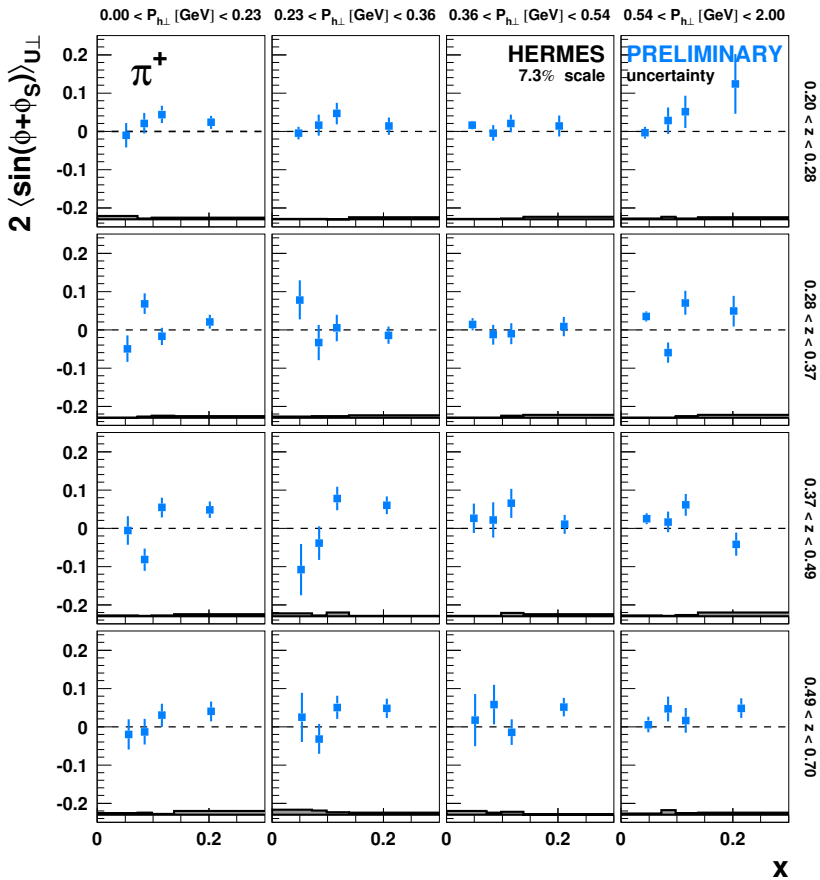
Phys.Lett. B693 (2010) 11

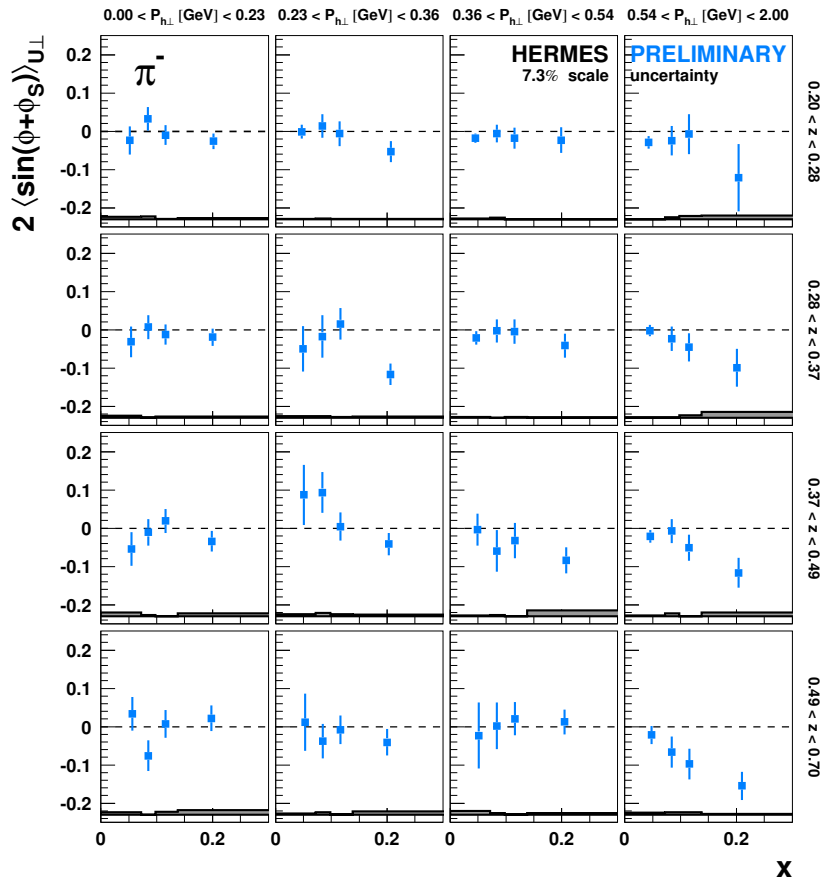


NEW

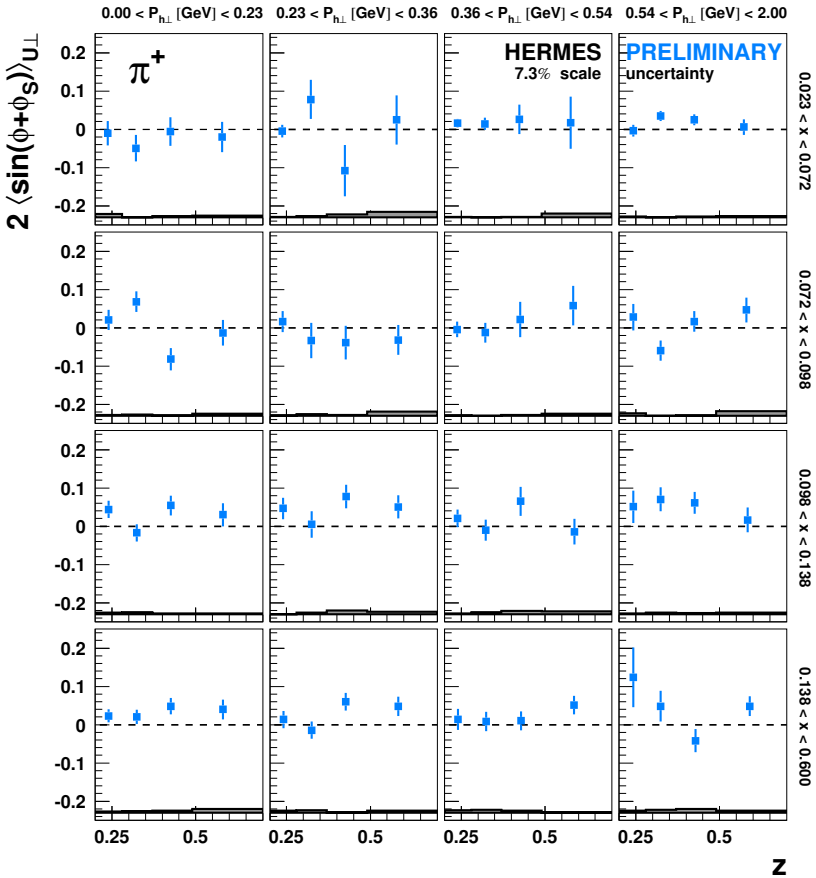


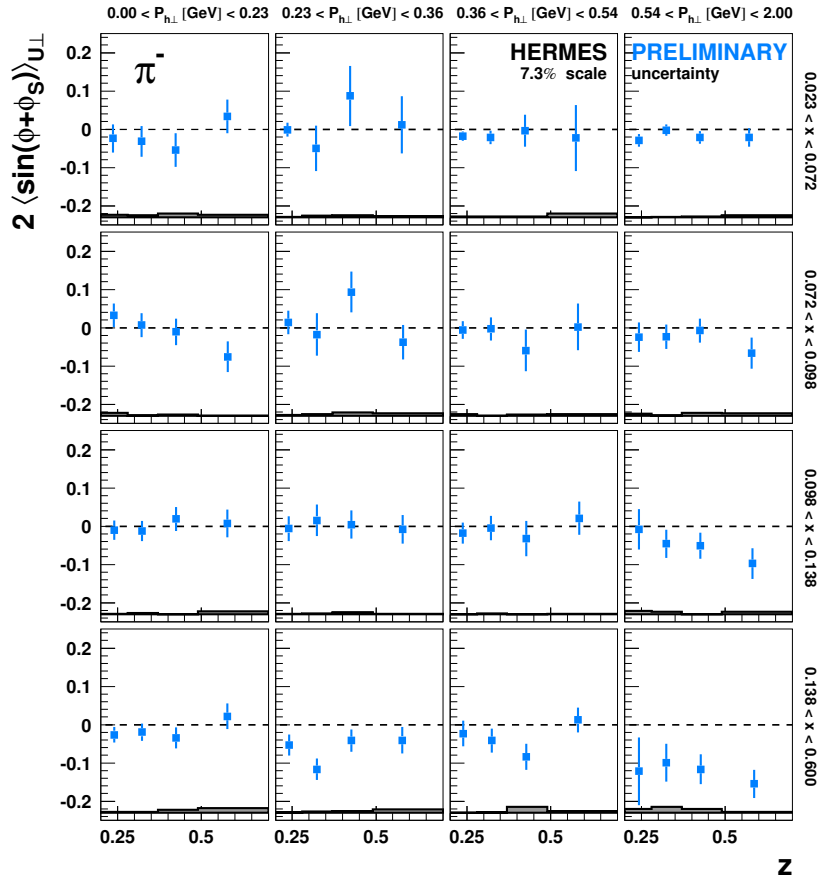
Collins vs. x, 3D, π^+, π^-



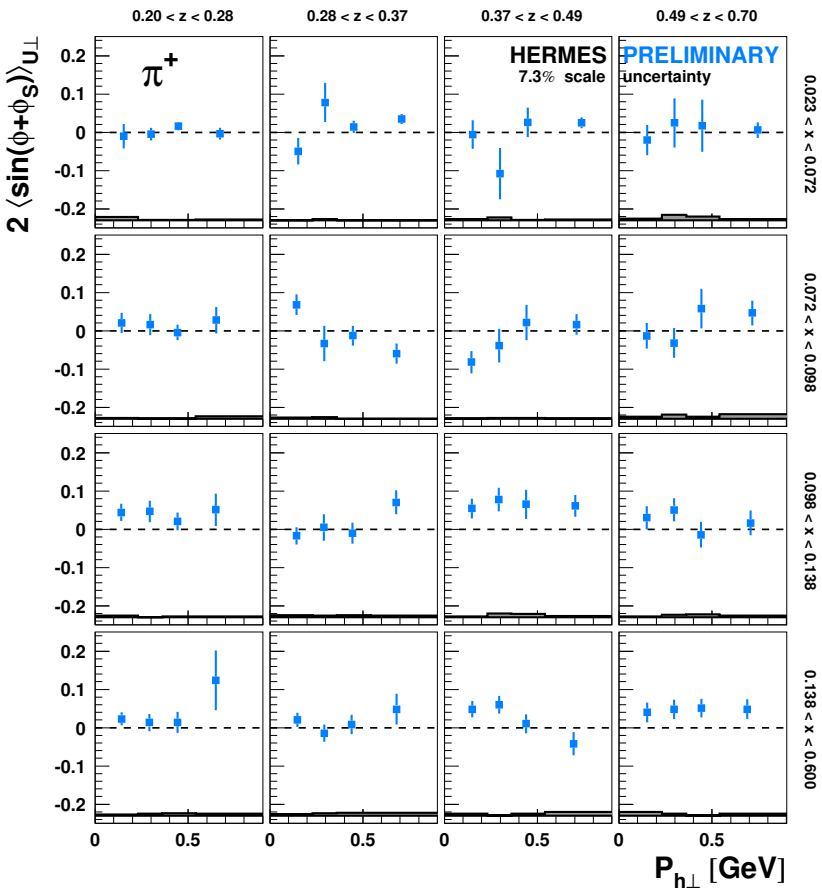


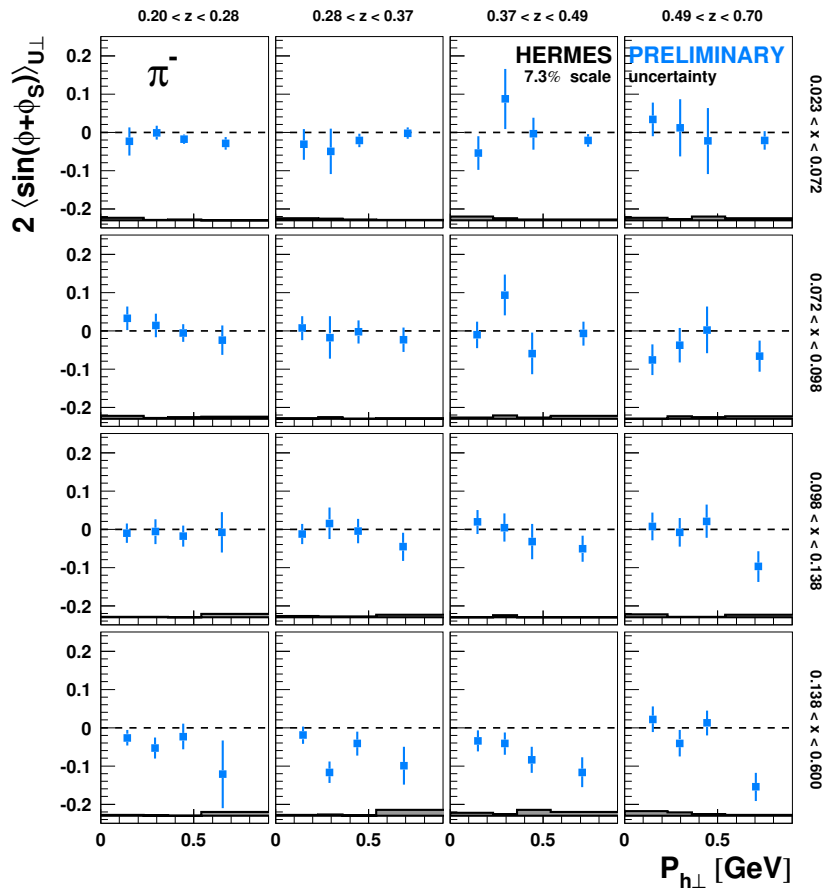
Collins vs. z, 3D, π^+, π^-



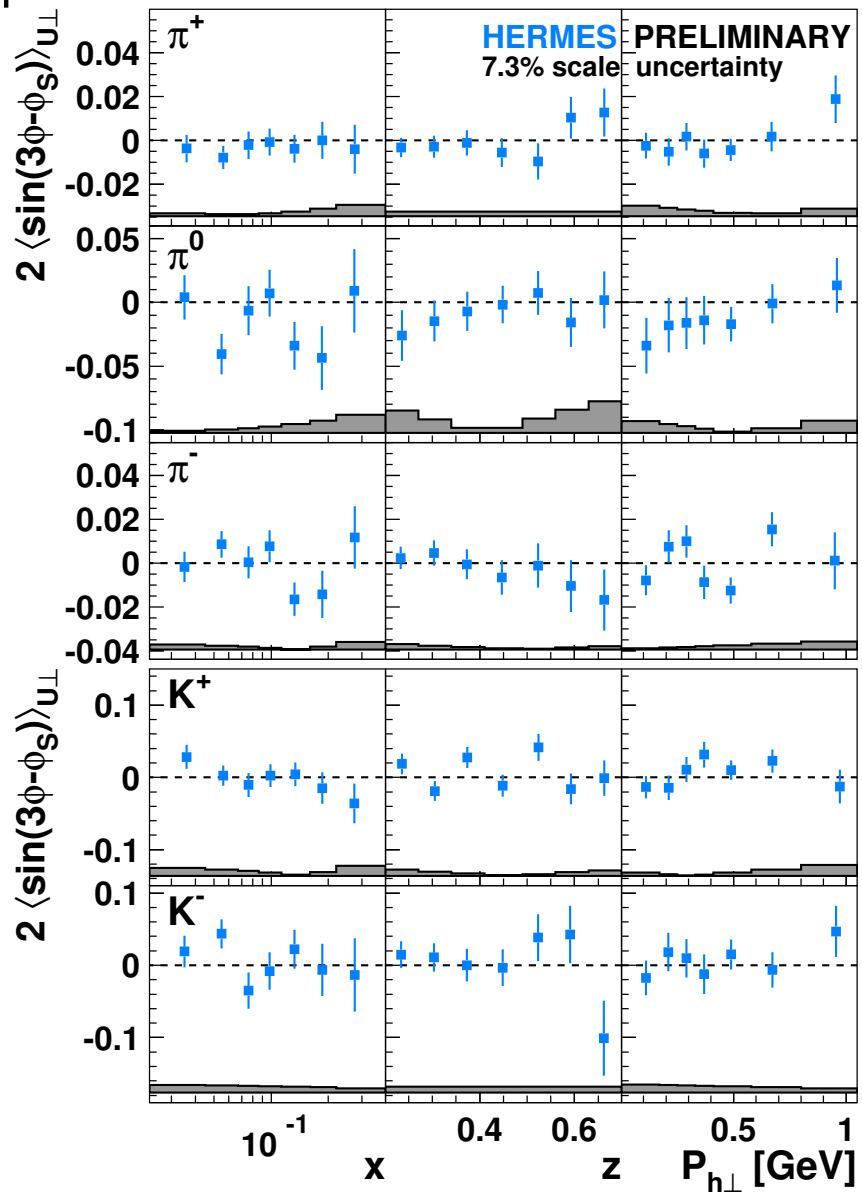


Collins vs. $P_{h\perp}$, 3D, π^+, π^-

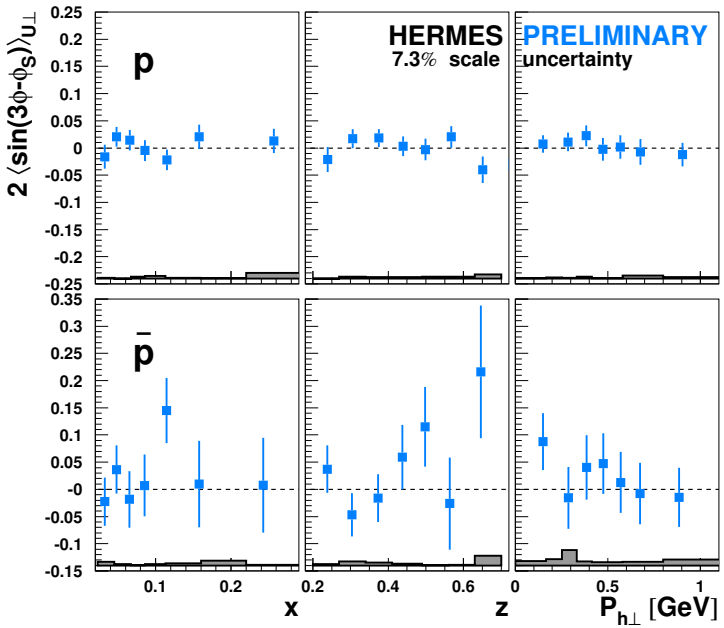




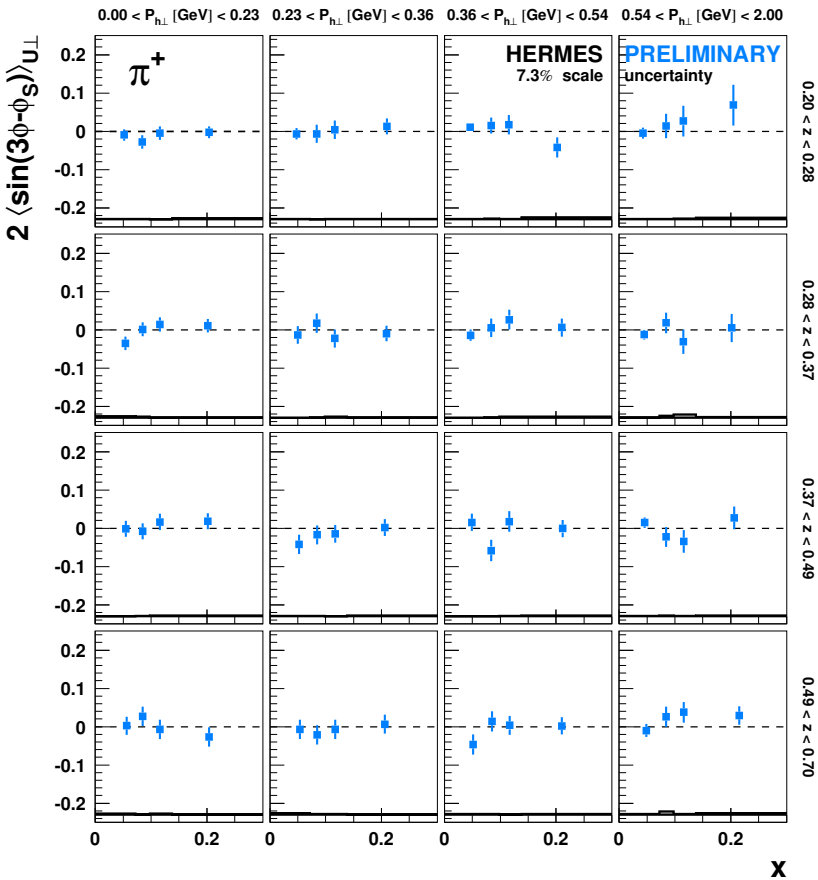
Pretzelosity $A_{UT}^{sin(3\phi-\phi_S)}$

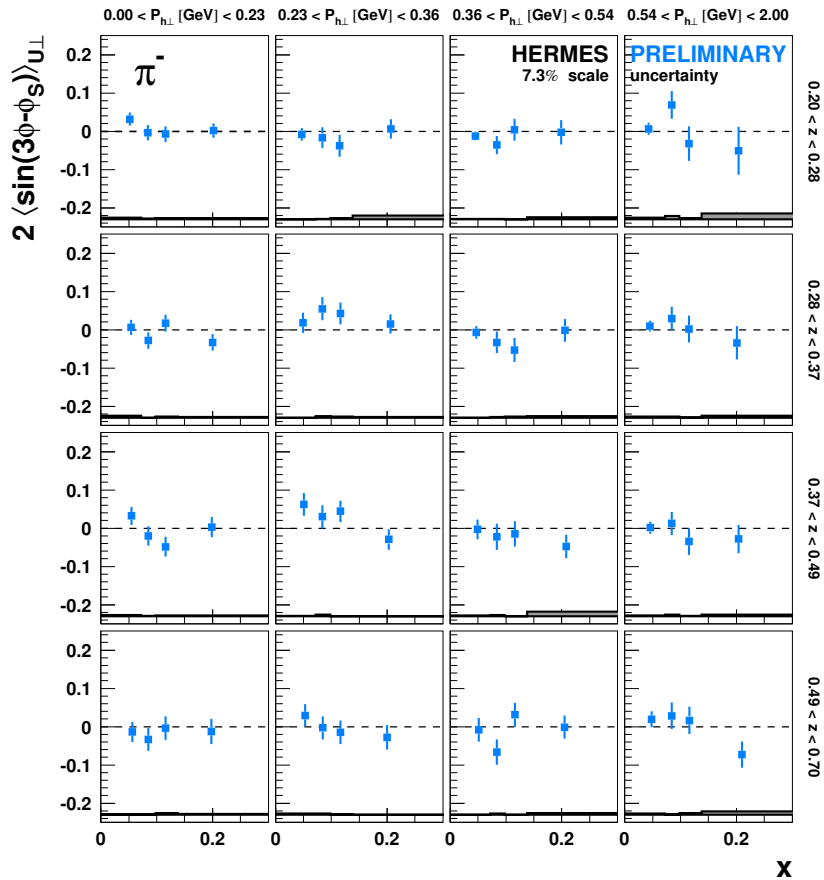


NEW

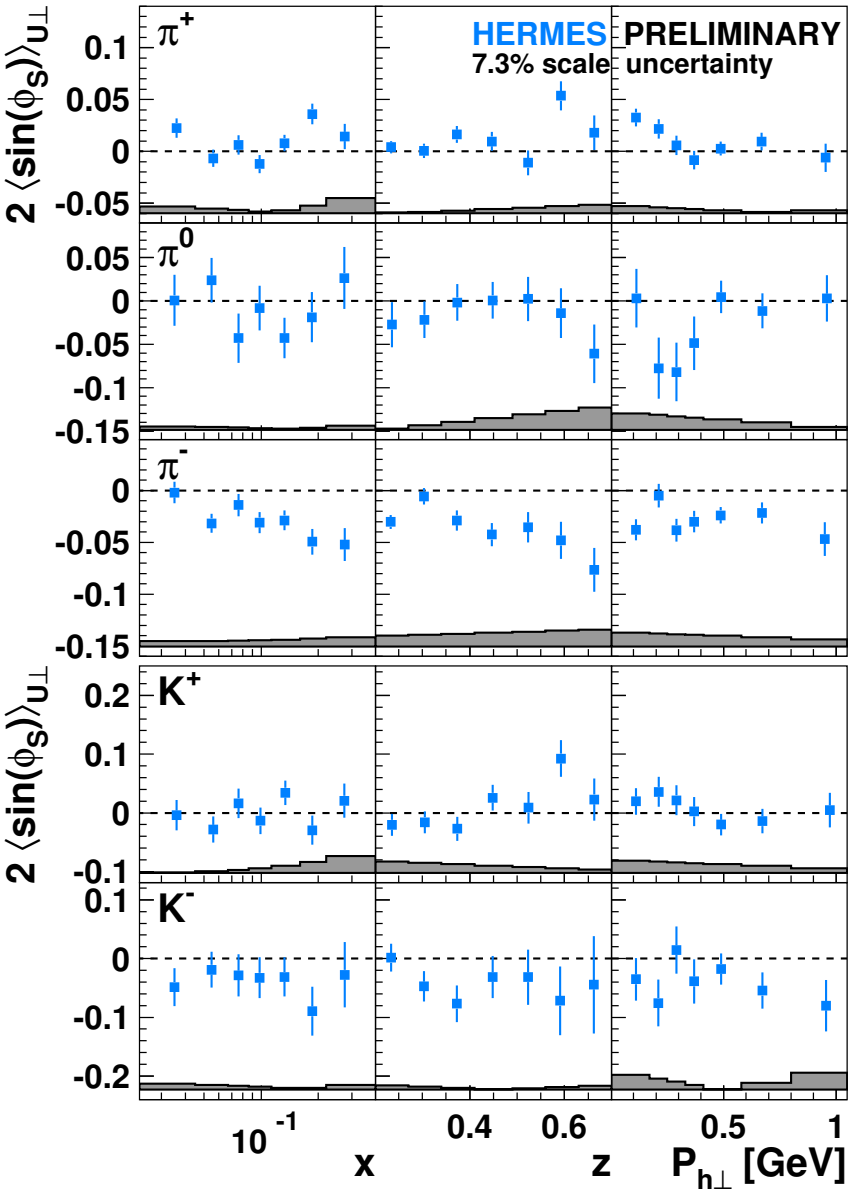


Pretzelosity vs. x, 3D, π^+, π^-

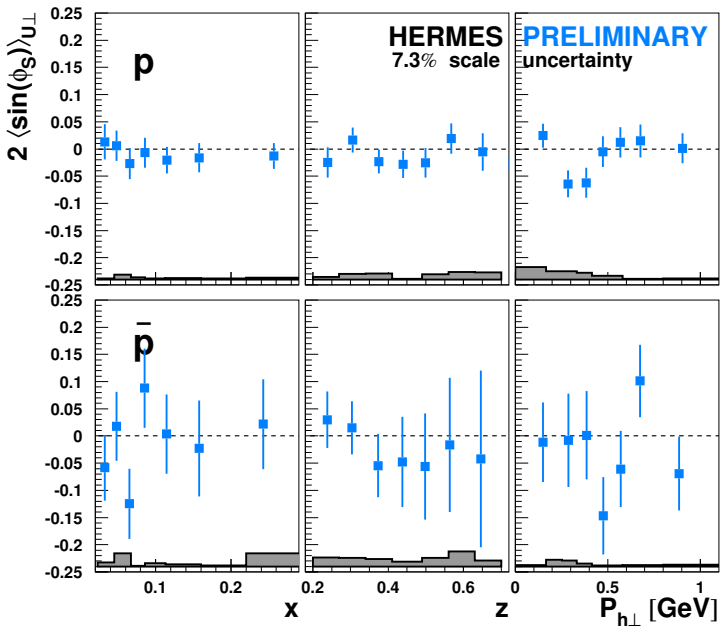




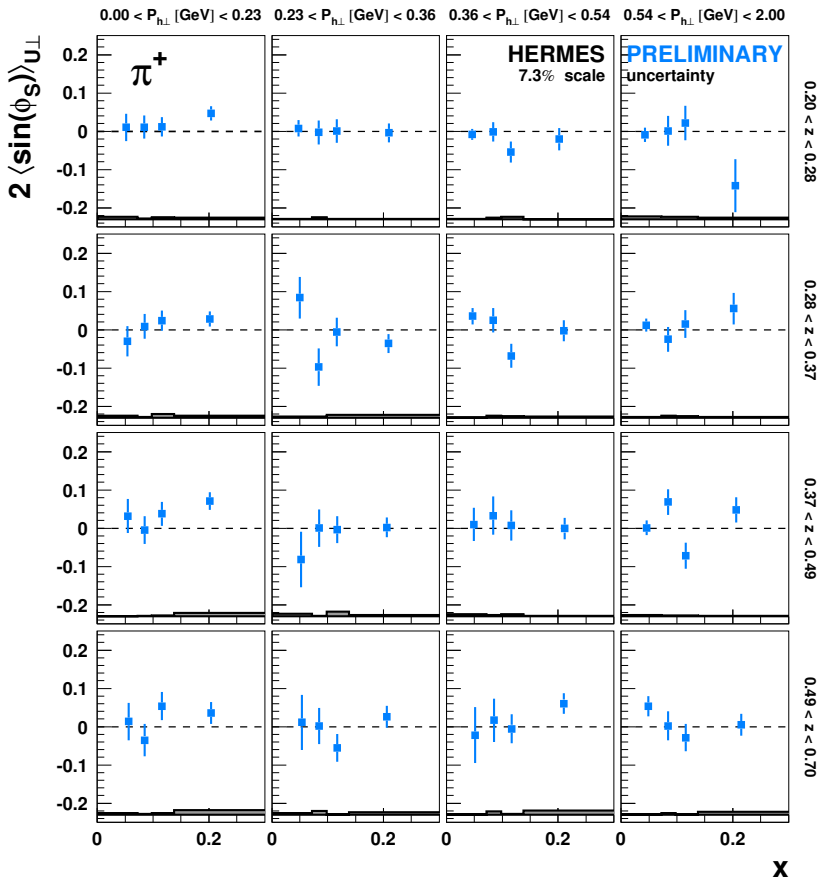
$A_{UT}^{\sin(\phi_S)}$

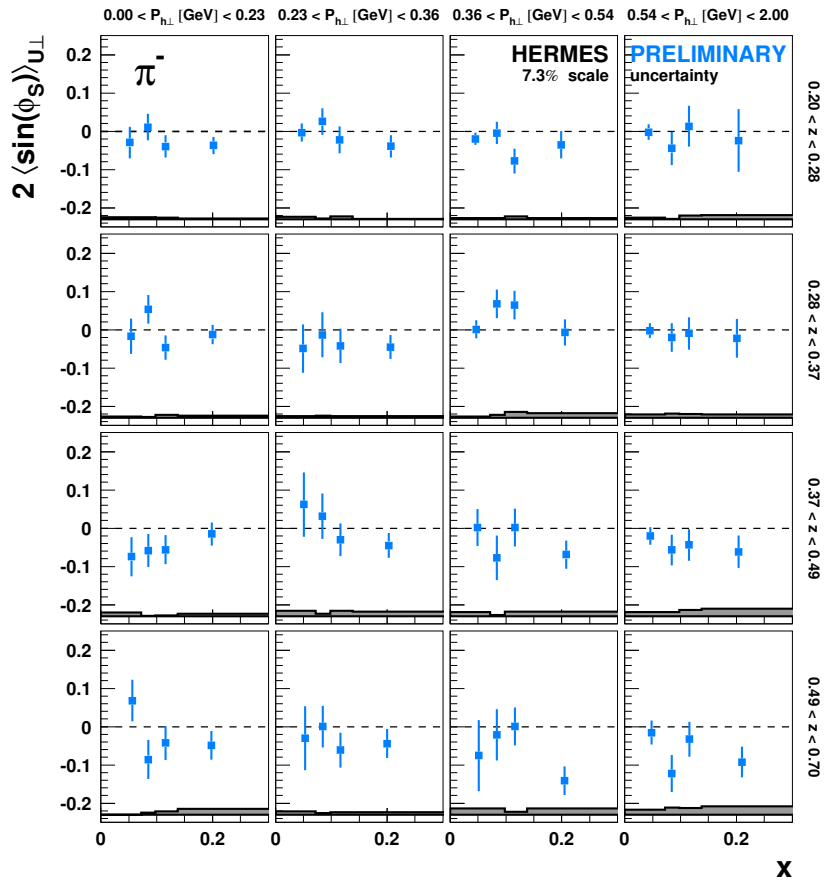


NEW

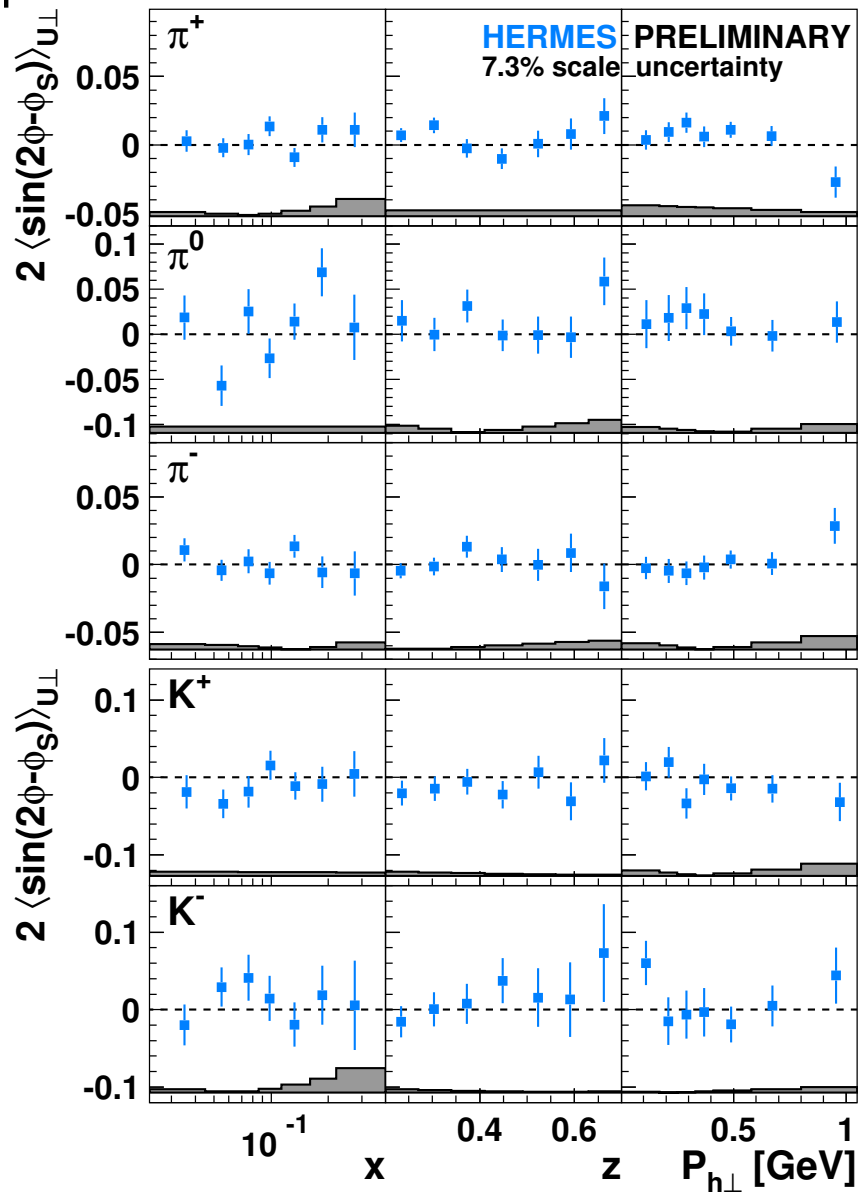


$A_{UT}^{\sin(\phi_S)}$ vs. x, 3D, π^+, π^-

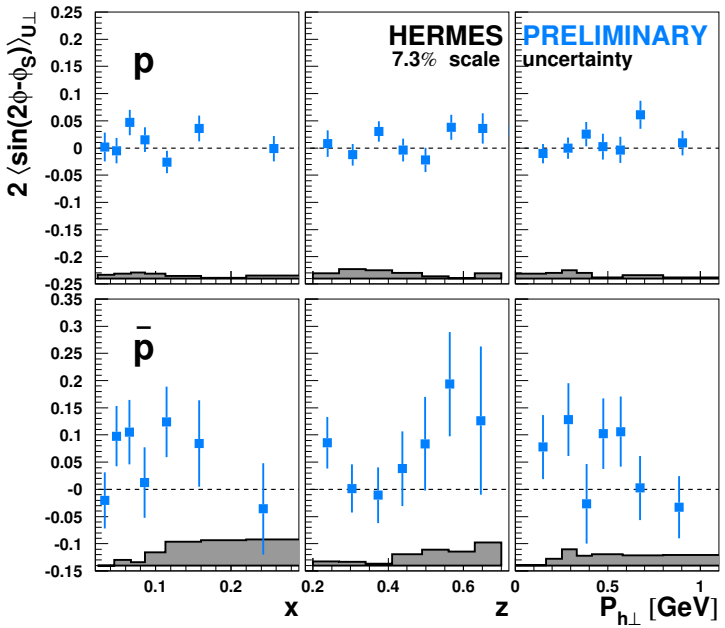




SIDIS: $A_{UT}^{sin(2\phi-\phi_S)}$



NEW



Asymmetry A_{LT}

$$d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e|\boldsymbol{S}_\perp| \cdot \{A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) + A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) + A_{LT}^{\cos(\phi_S)}cos(\phi_S)\})$$

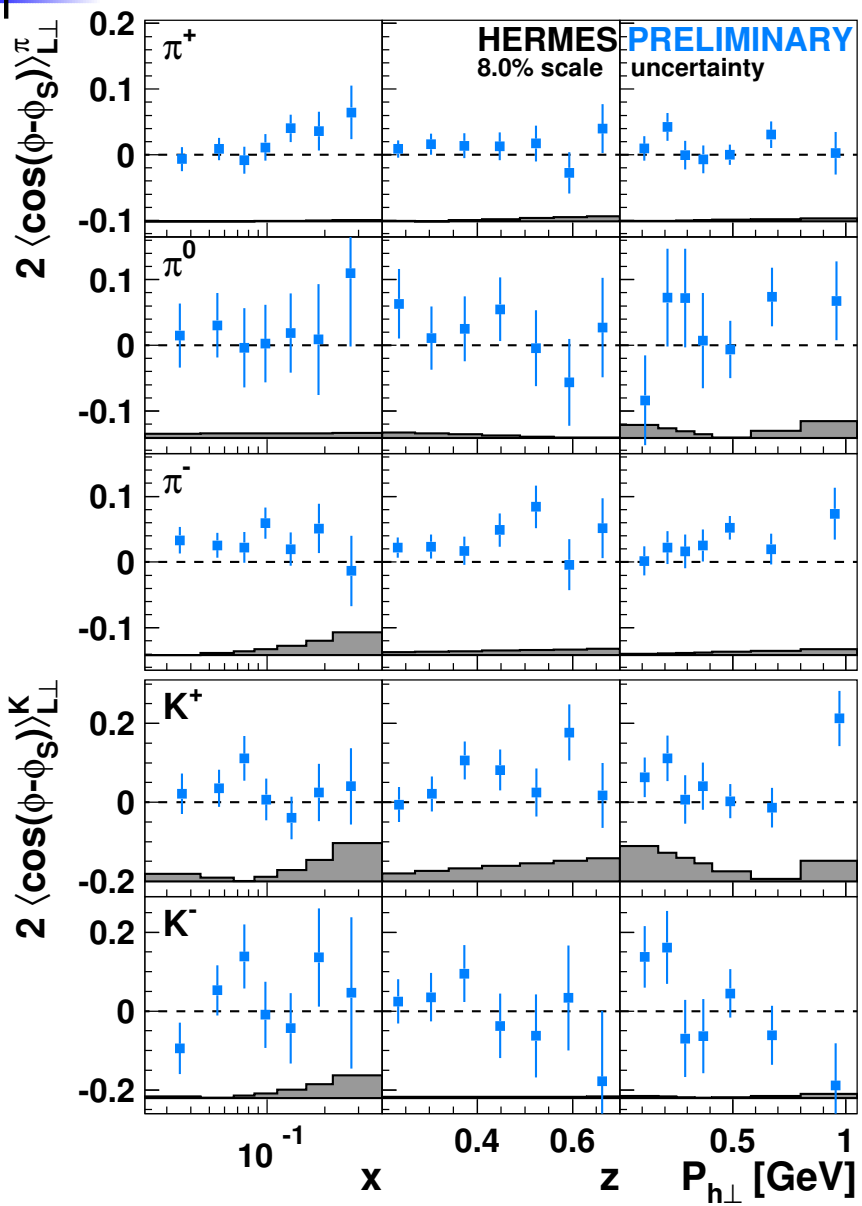
$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} g_{1T} D_1\right]$$

Other asymmetries are twist-3:

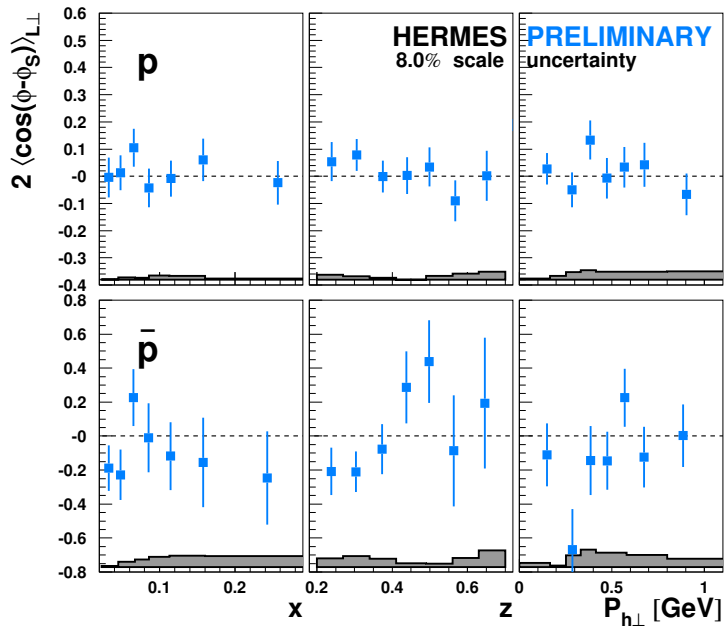
$$A_{LT}^{\cos\phi_S} \propto F_{LT}^{\cos\phi_S} = \frac{2M}{Q}\mathcal{C}\left\{-\left(x g_T D_1 + \frac{M_h}{M} h_1 \frac{\tilde{E}}{z}\right) + \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x e_T H_1^\perp - \frac{M_h}{M} g_{1T}\frac{\tilde{D}^\perp}{z}\right) + \left(x e_T^\perp H_1^\perp + \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{G}^\perp}{z}\right)\right]\right\}$$

$$A_{LT}^{\cos(2\phi_h-\phi_S)} \propto F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2}\left(x g_T^\perp D_1 + \frac{M_h}{M} h_{1T}^\perp \frac{\tilde{E}}{z}\right) + \frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x e_T H_1^\perp - \frac{M_h}{M} g_{1T}\frac{\tilde{D}^\perp}{z}\right) - \left(x e_T^\perp H_1^\perp + \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{G}^\perp}{z}\right)\right]\right\}$$

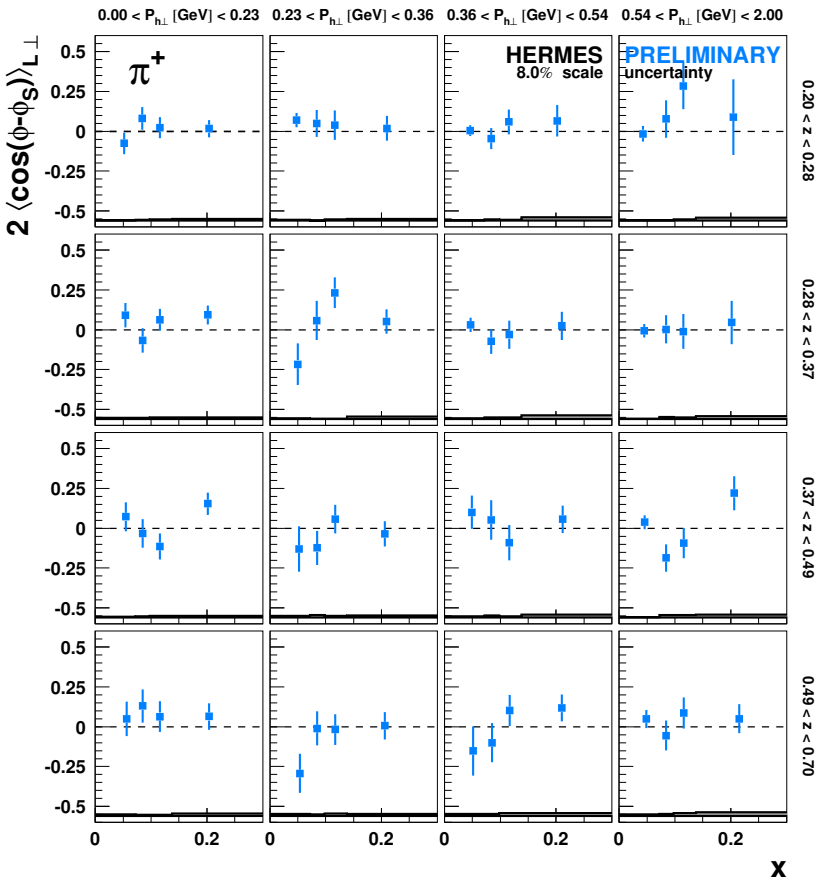
$A_{LT}^{\cos(\phi-\phi_S)}$

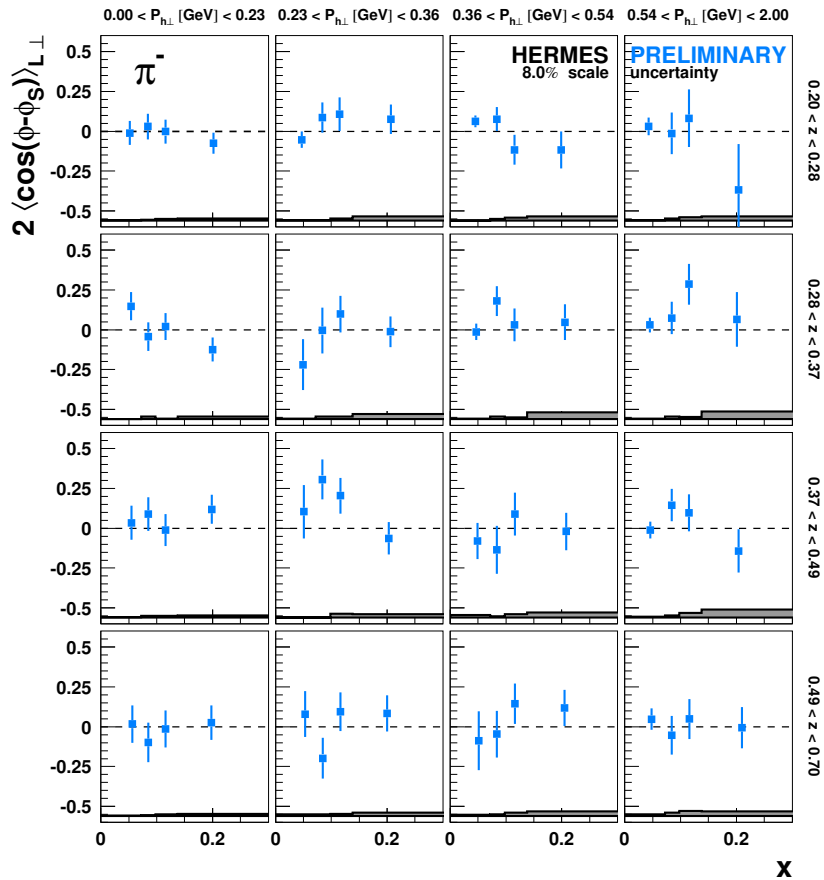


NEW

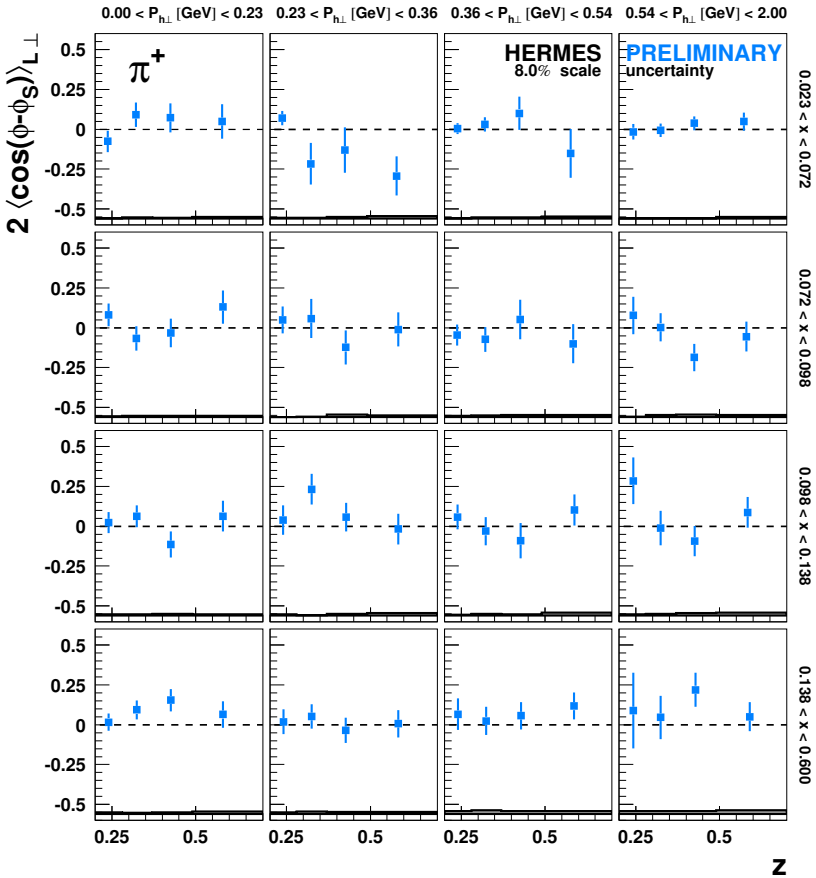


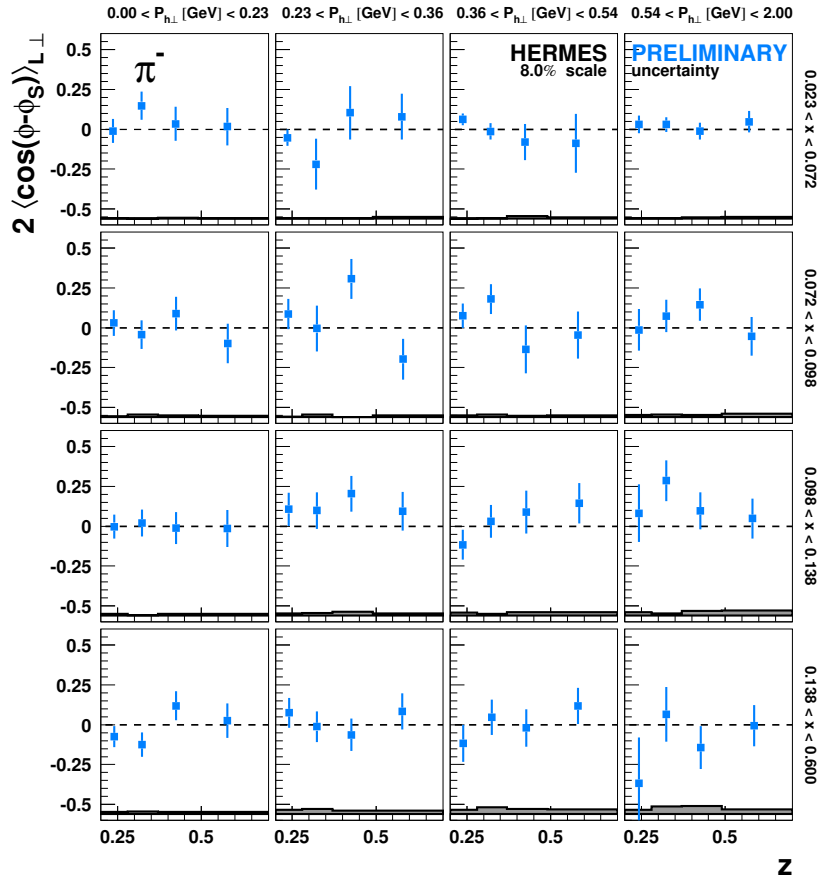
$A_{LT}^{\cos(\phi-\phi_S)}$ vs. x, 3D, π^+, π^-



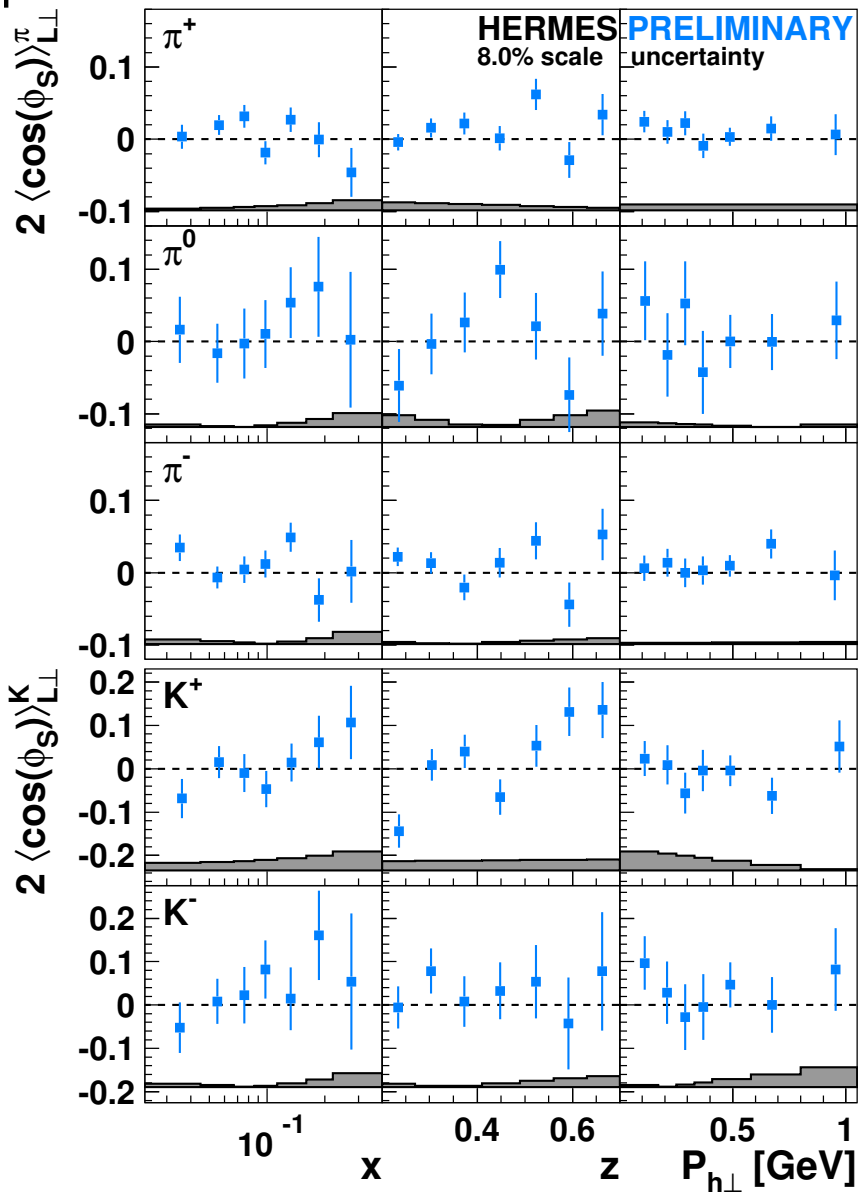


$A_{LT}^{\cos(\phi-\phi_S)}$ vs. z, 3D, π^+, π^-

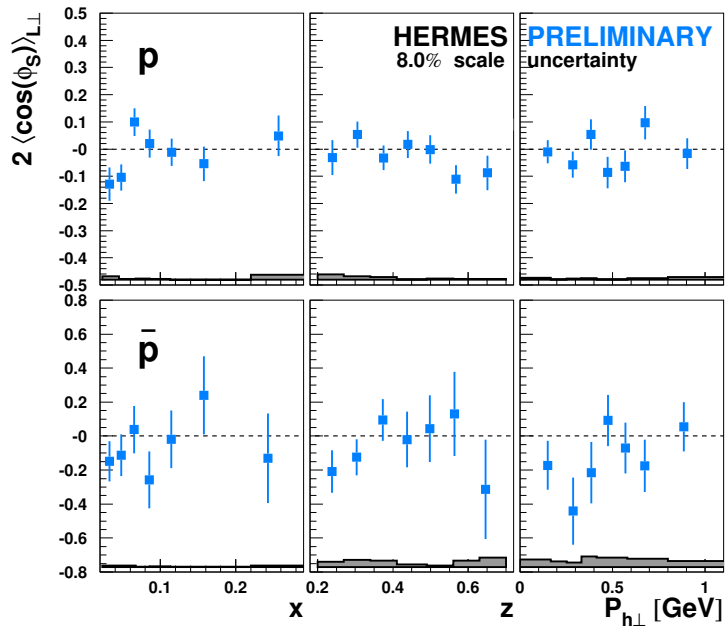




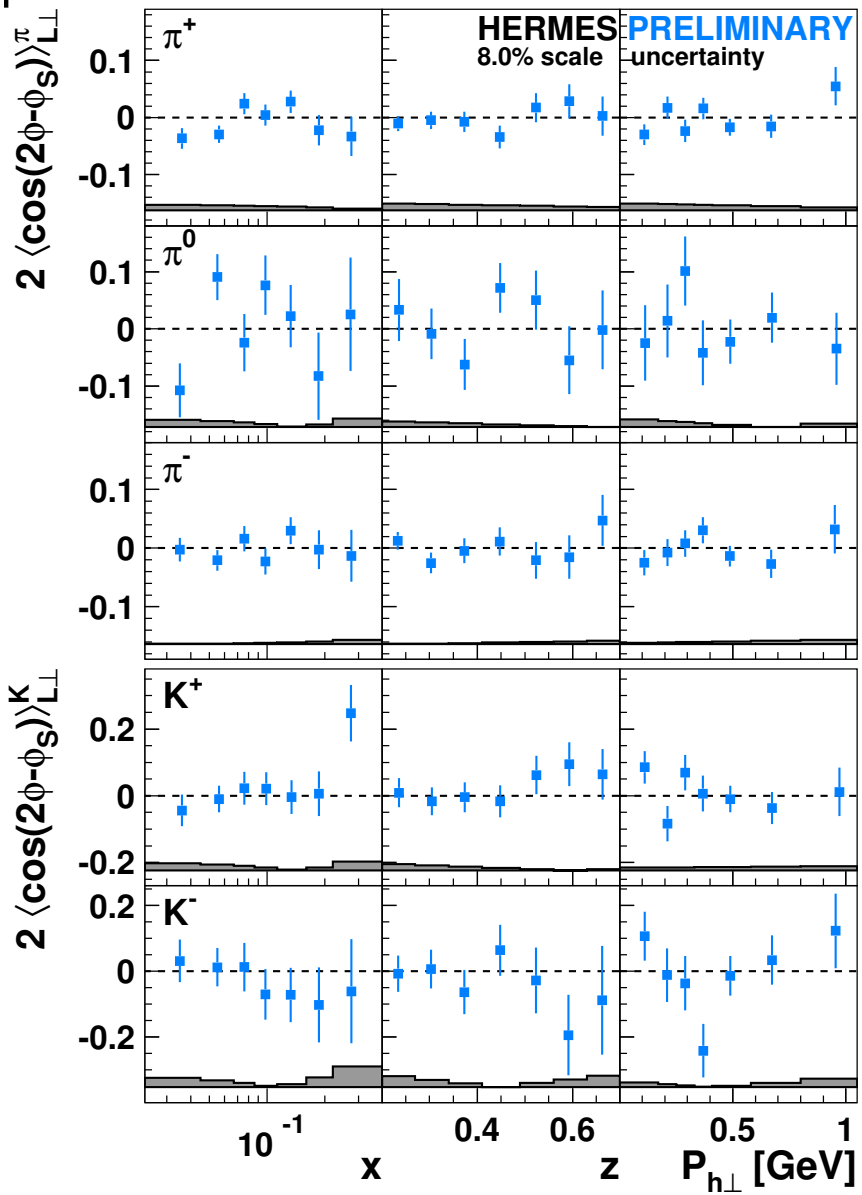
SIDIS: $\sigma_{LT}^{cos(\phi_S)}$



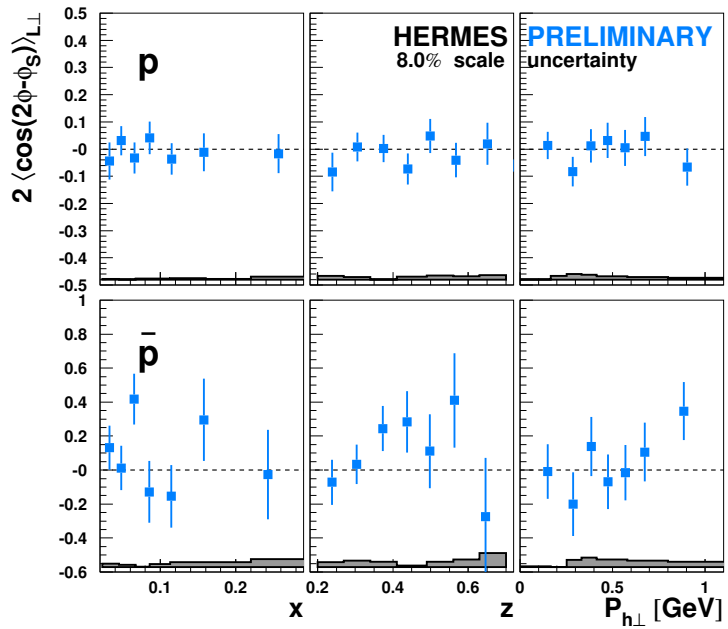
NEW



SIDIS: $\sigma_{LT}^{cos(2\phi-\phi_S)}$



NEW



Summary

- HERMES continues the study of the azimuthal asymmetries in SIDIS.
- Azimuthal asymmetries A_{LU}, A_{UT}, and A_{LT} in SIDIS production of (anti)protons have been evaluated.
- A new, extended, analysis of A_{LU} asymmetries was carried out: high statistics, all types of charged hadrons, deuterium target.
- 3D analysis of the asymmetries in x, z, and $P_{h\perp}$ was carried out.
Each plot contains four x, four z, and four $P_{h\perp}$ bins, i.e. 64 bins in total.
- It is expected that the 3D asymmetries could be much more useful for a phenomenological analysis with a goal to constrain the TMDs. At the moment HERMES is able to present 18 3D plots for A_{LU} asymmetries, 90 3D plots for A_{UT} asymmetries, and 60 3D plots for A_{LT} asymmetries.
- Asymmetries for neutral pions are expected to be soon.