What semi-inclusive DIS has taught us about TMDs

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One of the cornerstones of modern hadronic physics is the recognition of the important role of partonic transverse momentum and spin-orbit correlations in the description of the nucleon structure. In semi-inclusive deep-inelastic scattering (DIS) these effects lead to sizable modulations in the azimuthal distribution of hadrons about the virtual-photon direction, which are parameterized in terms of several semi-inclusive structure functions. At leading order in an expansion in M_N/Q, the structure functions are described by transverse-momentum-dependent parton distribution and fragmentation functions (TMDs).

Evidence for TMDs in semi-inclusive DIS were found in the seminal measurement by the Hermes collaboration of pion production off longitudinally polarized protons. All interpretations of these data were hampered by the variety of TMD contributions to this measurement. Two major branches were followed: the interpretation in terms of the Collins fragmentation function and the interpretation as a signal for the naive-T-odd Sivers function. It took a few more years to shed additional light on the true origin of the observed single-spin asymmetries: measurements of similar asymmetries but on transversely polarized protons made it clear that both the Collins function and the Sivers function are non-zero; but the observed asymmetries off longitudinally polarized protons are caused by twist-3 effects.

In the meantime, a wealth of data on TMDs have emerged. Recently the Hermes collaboration completed its analysis of the Sivers modulation using the entire available data set with transversely polarized protons. A manifest signal of non-zero Sivers functions for valence quarks was found, with strong indications that the Sivers distributions for up and down quarks are opposite in sign. This observation is supported by vanishing Sivers modulations measured by the Compass collaboration. A surprisingly large signal for positive kaons was found by both collaborations, larger than the one for pions, implying a non-trivial role of sea quarks and/or of the underlying transverse-momentum dependences of the distributions and fragmentation functions.

Besides the Sivers modulation, the Hermes and Compass collaborations have data on the Collins effect with tantalizing large signals for π^-. In combination with the results for π^+, which are of opposite sign and smaller in size, it is conjectured that the disfavored Collins fragmentation, i.e., up quarks into π^-, is opposite in sign to and as large as the favored Collins fragmentation, i.e., up quarks into π^+. This can also be concluded when analyzing these data together with data from e^+e^- collision and from semi-inclusive DIS off transversely polarized deuterons.

Sivers, Collins, and transversity are not the only TMDs found to be non-zero. Up to date there are in addition signs for a non-vanishing distribution of longitudinally polarized quarks in transversely polarized nucleons from Hermes and JLab, for the Boer–Mulders distribution, as well as for several subleading-twist distributions.

Spin-Momentum Structure of the Nucleon

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\Big] \;=\; \frac{1}{2}\left[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^\perp + \lambda\Lambda\,g_1 + \lambda\,S^ik^i\,\frac{1}{m}\,g_{1T}\right]$$

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] \;=\; \frac{1}{2}\Bigg[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^\perp + s^iS^i h_1$$

$$+\, s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Bigg]$$

quark pol. / nucleon pol.

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

Twist-2 TMDs

helicity

Sivers

worm-gear

transversity

Boer-Mulders

Mulders-Tangerman*

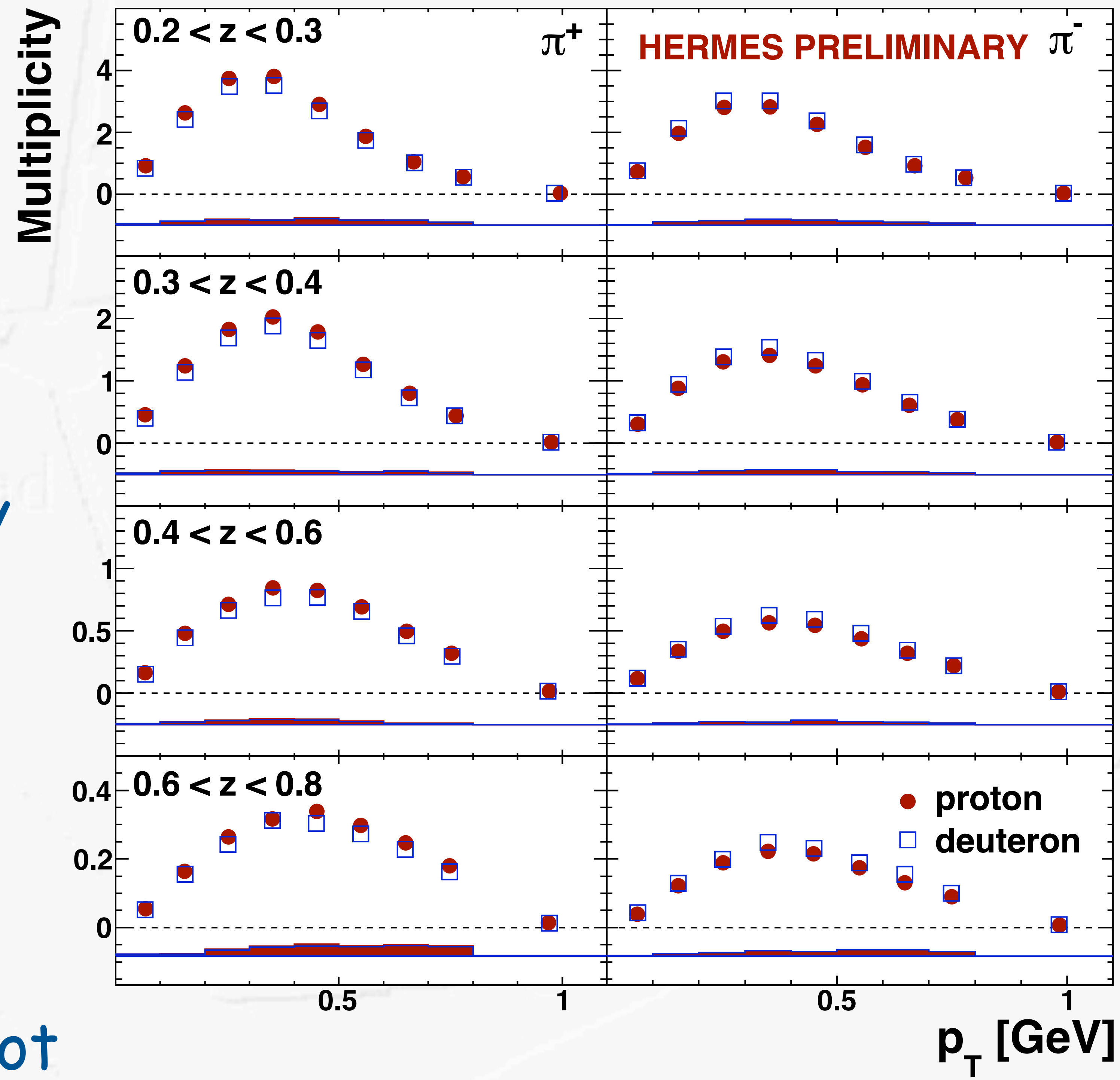
- functions in black survive integration … se momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

*aka Pretzelosity

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

Momentum density

- plenty of data available
- but only for integrated version of f_1
- some efforts to get unintegrated gluon density
- spin asymmetries involve unintegrated f_1 in denominator
- need multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$

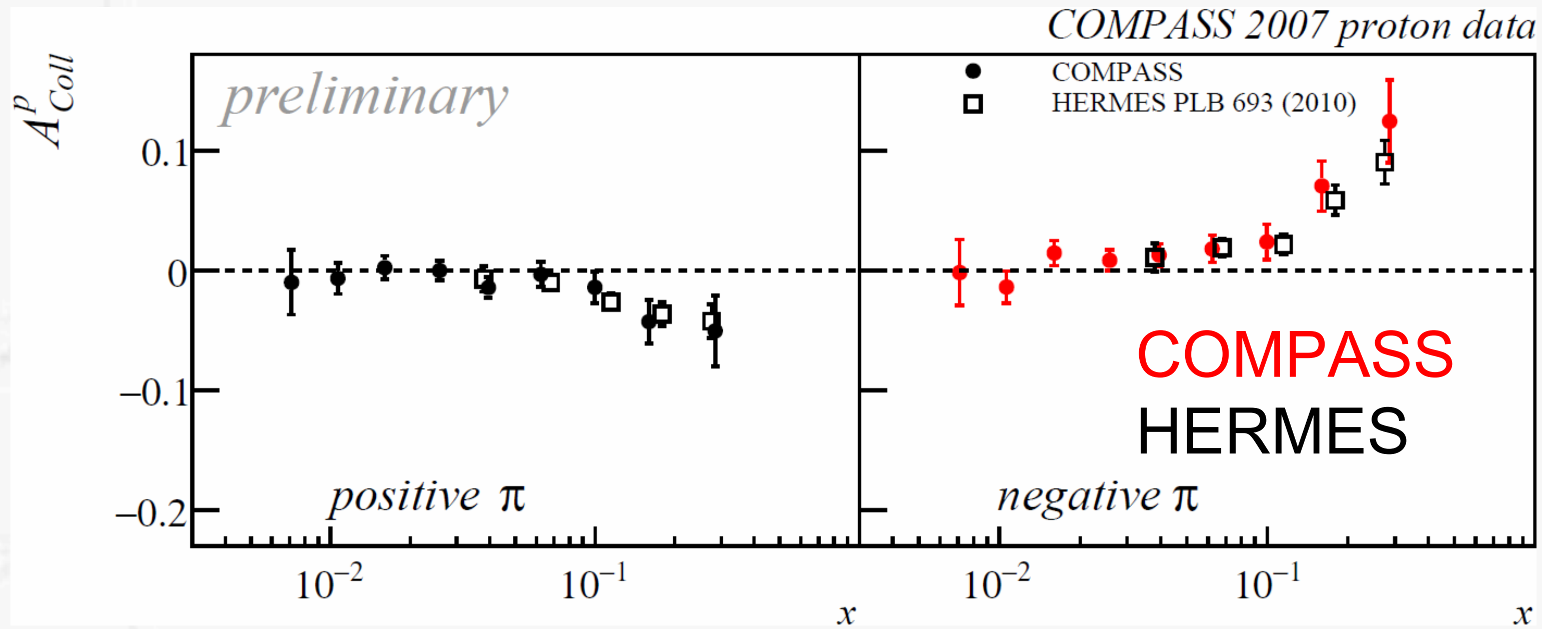


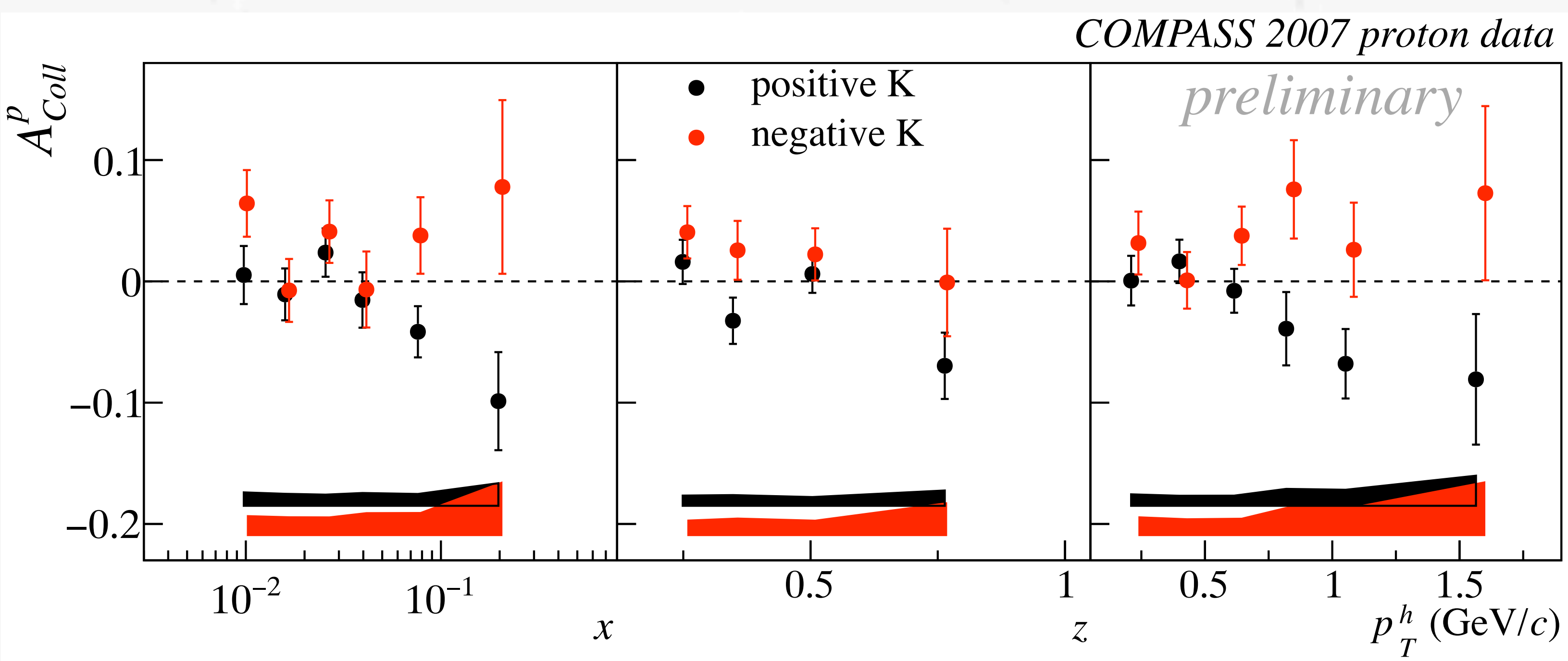
also available for kaons

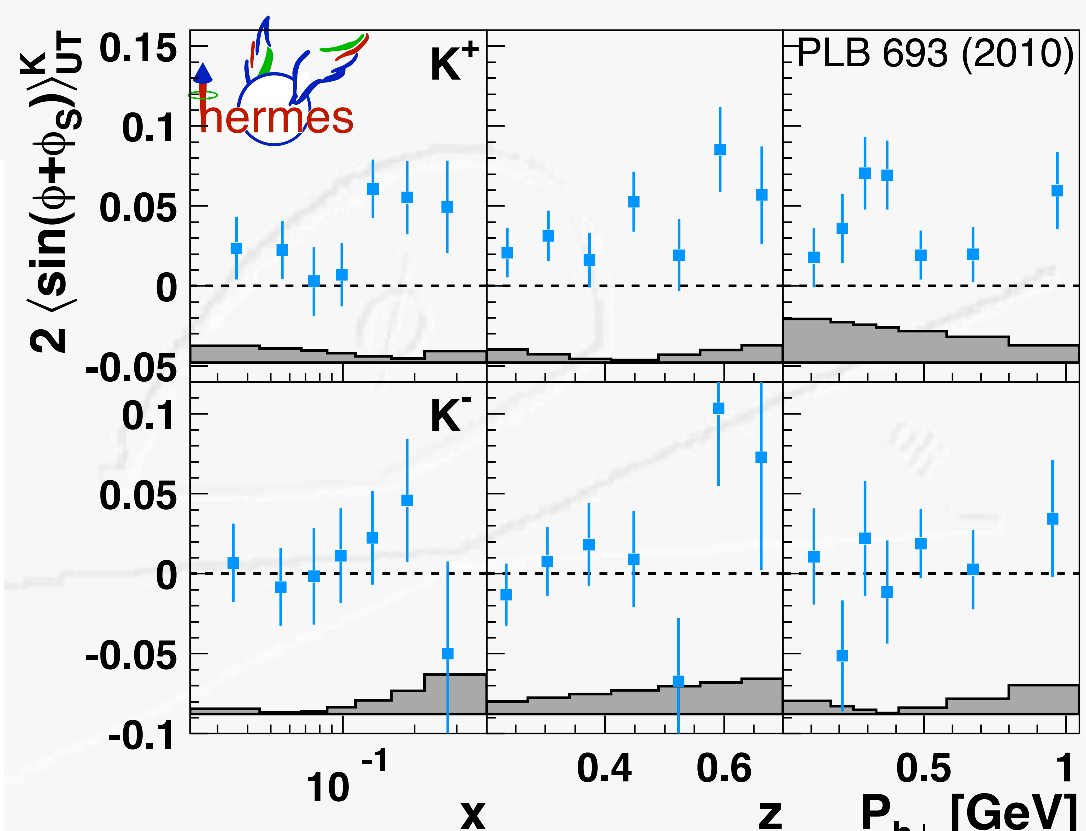
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins amplitudes COMPASS & HERMES

- similar behavior for pions
- similar behavior for K^+
- different trend for K^-
- opposite sign conventions!



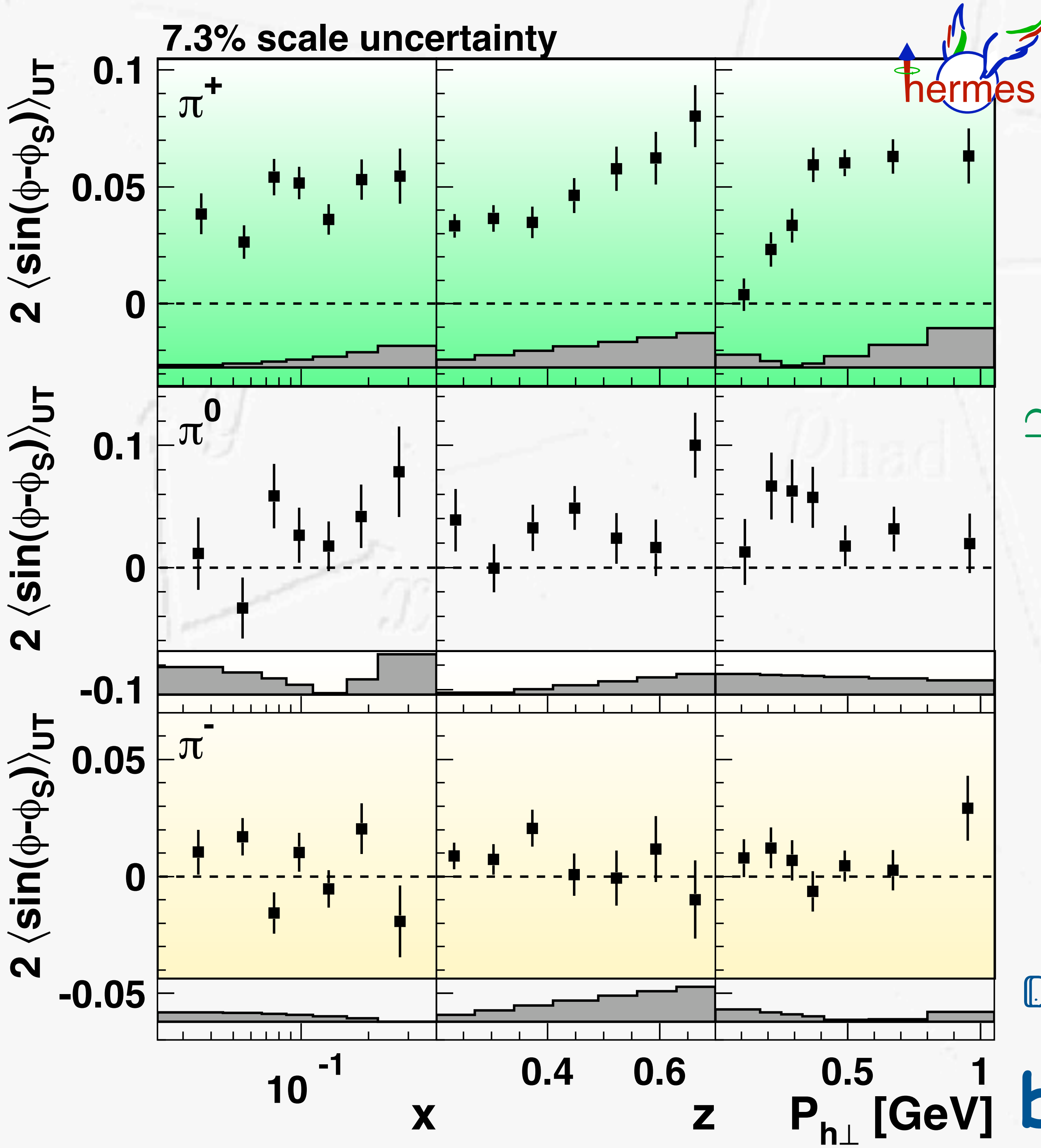




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_S)\rangle_{\rm UT} = -\frac{\sum_q e_q^2 f_{1\rm T}^{\perp,q}(x,p_T^2)\otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



π^+ dominated by u-quark scattering:

$$\simeq -\frac{f_{1\rm T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

- u-quark Sivers DF < 0
- d-quark Sivers DF > 0 (cancelation for π^-)
- u-d cancelation supported by COMPASS D data

Summary

- TMDs provide rich field for studying nucleon structure
- transversity is non-zero and quite sizable
  - can be measured, e.g., via Collins effect or s-p interference in 2-hadron fragmentation
- Sivers and Boer-Mulders effects are also non-zero
  - direct probe of “physics of the QCD gauge links”
- so far no sign of a non-zero Mulders-Tangerman (aka Pretzelosity) distribution
- but first evidence for non-vanishing worm-gear functions
- **great opportunities for measurements in Drell-Yan especially for naive-T-odd TMDs**