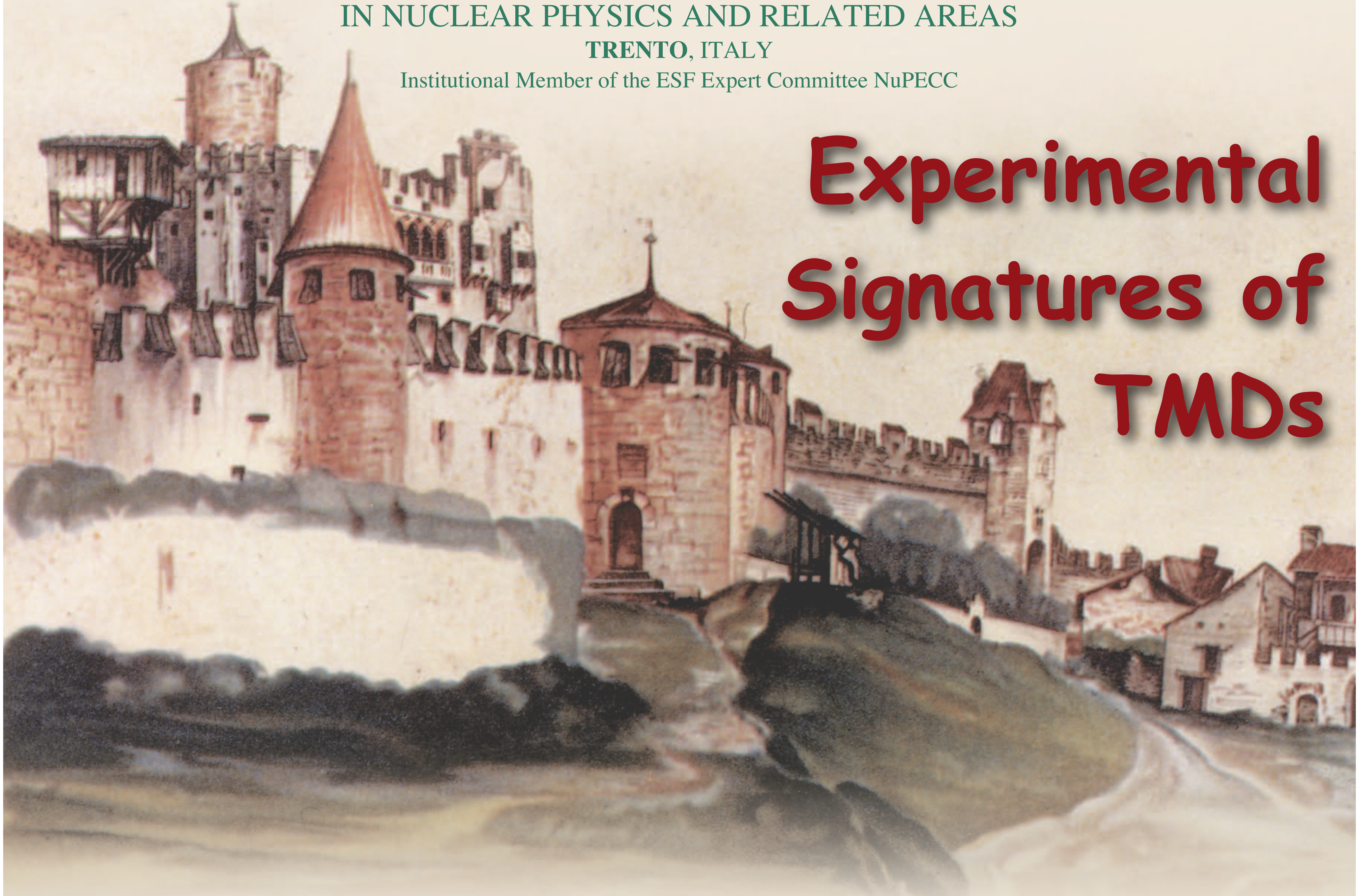
ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

Institutional Member of the ESF Expert Committee NuPECC

Experimental Signatures of TMDs



Castello di Trento (“Trint”). watercolour, 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495)

British Museum, London.

Transverse Momentum Distributions (TMD 2010)

Trento, June 21-25, 2010

Spin-Momentum Structure of the Nucleon

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

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^\perp + s^iS^ih_1$$

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

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

- **functions in black survive integration over transverse momentum**
- **functions in green box are chirally odd**
- **functions in red are naive T-odd**

gunar.schnell @ desy.de

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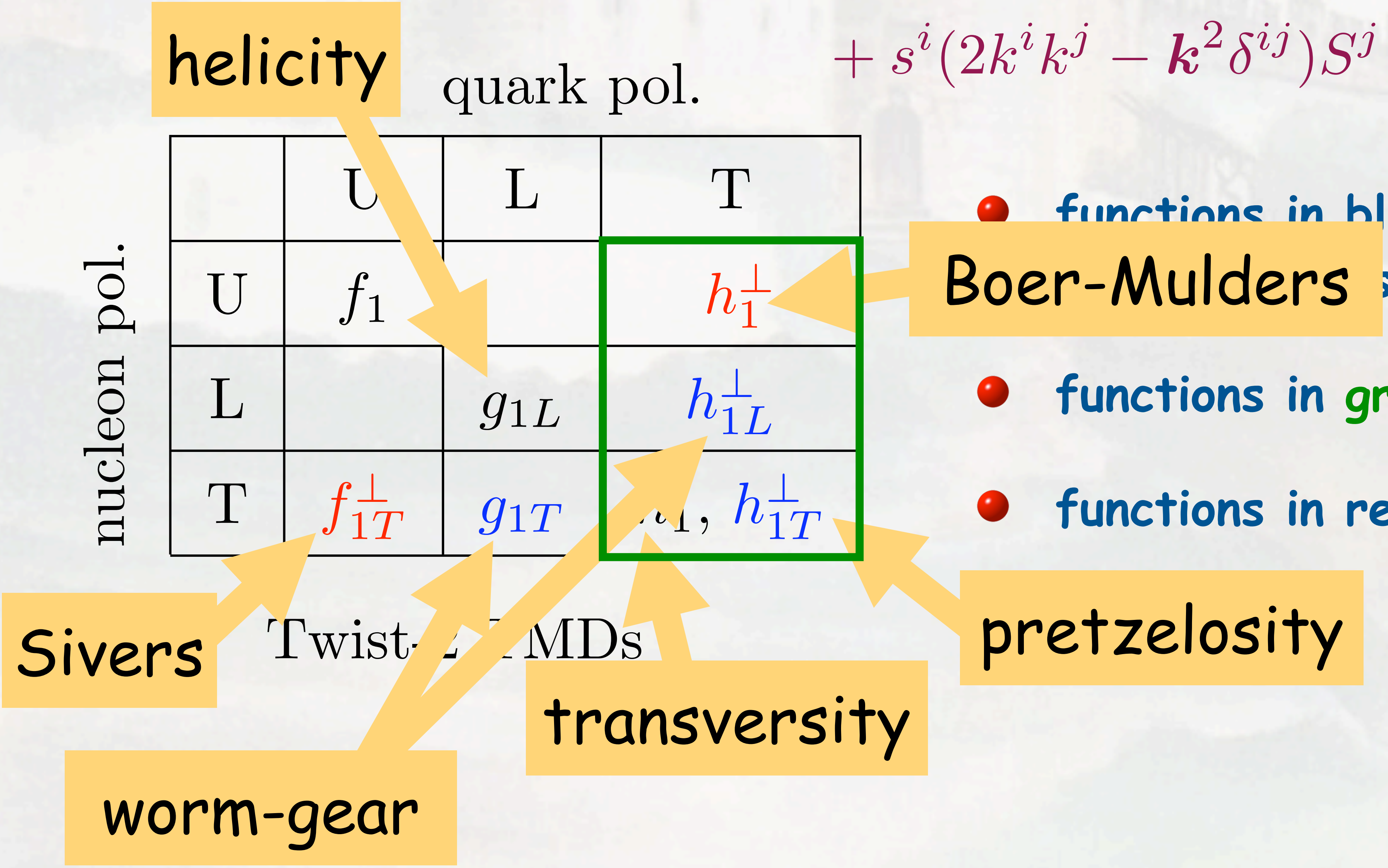

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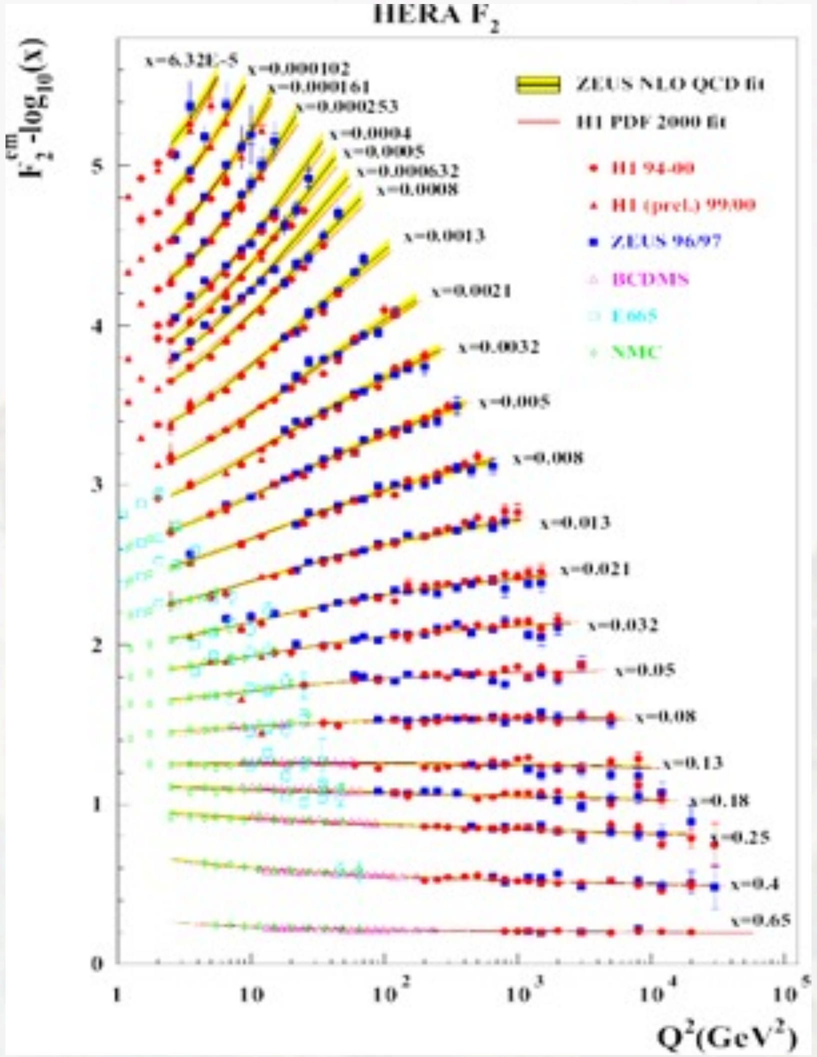
Momentum density

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



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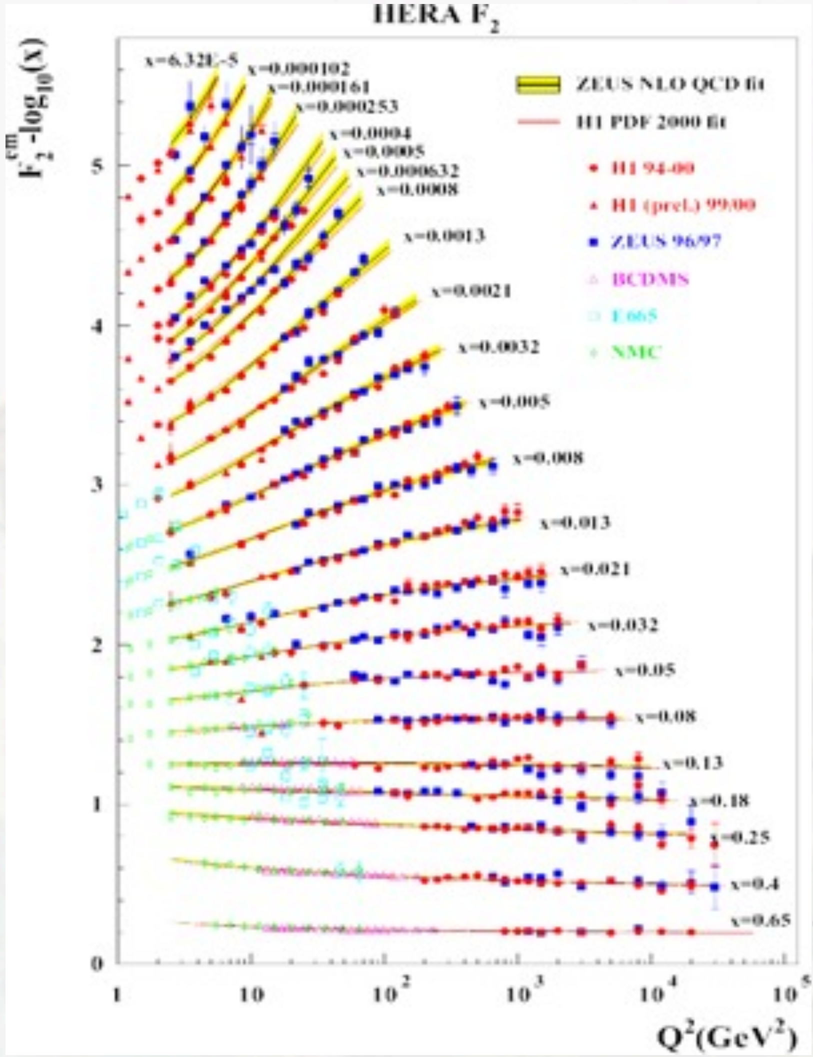

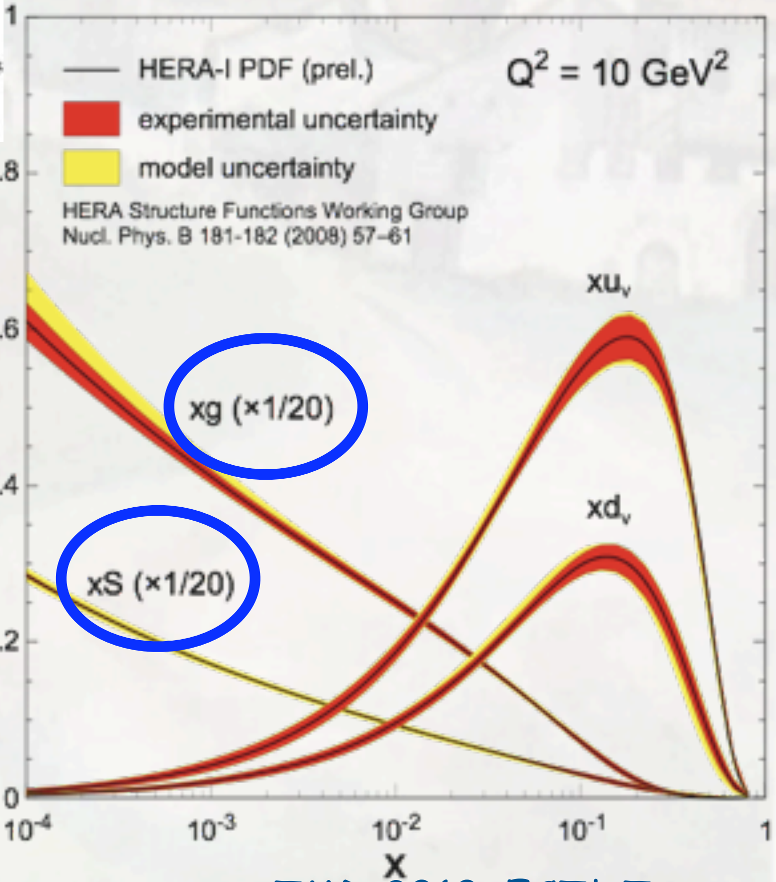

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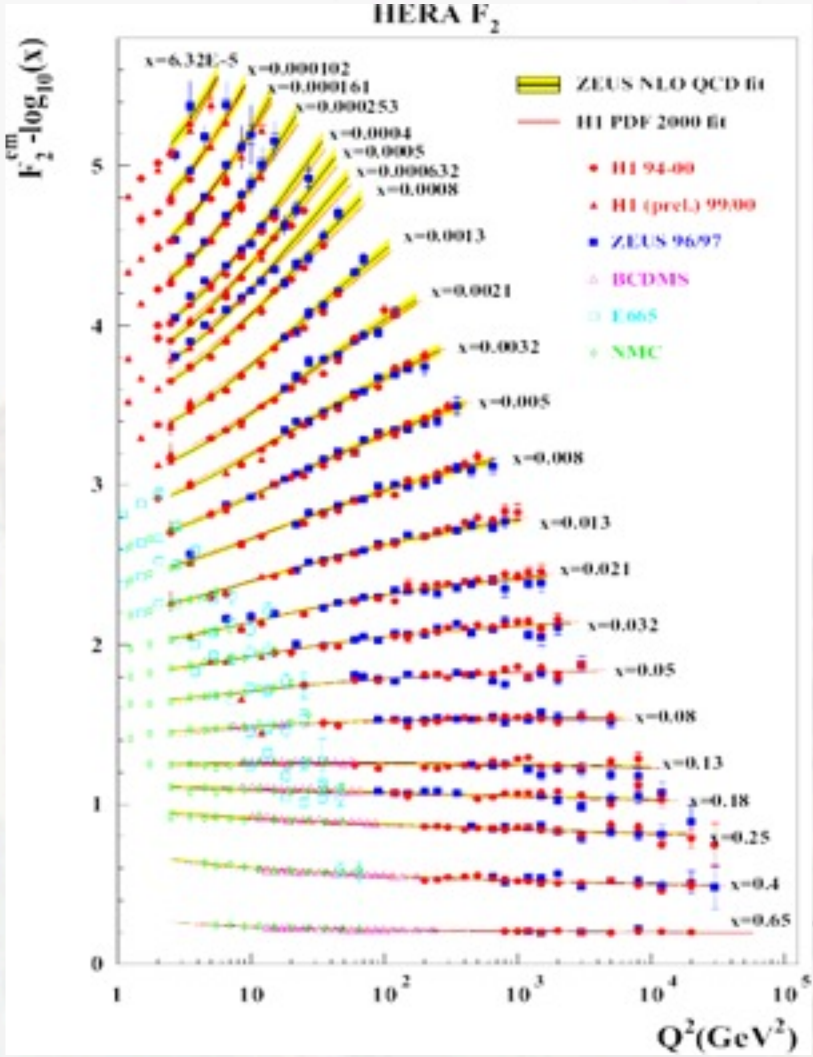

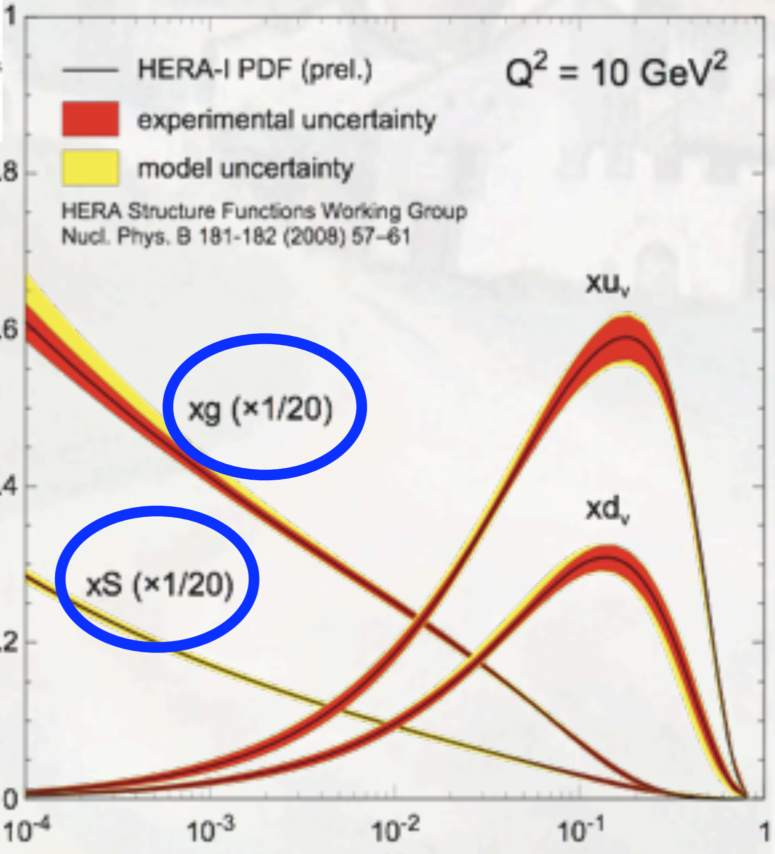

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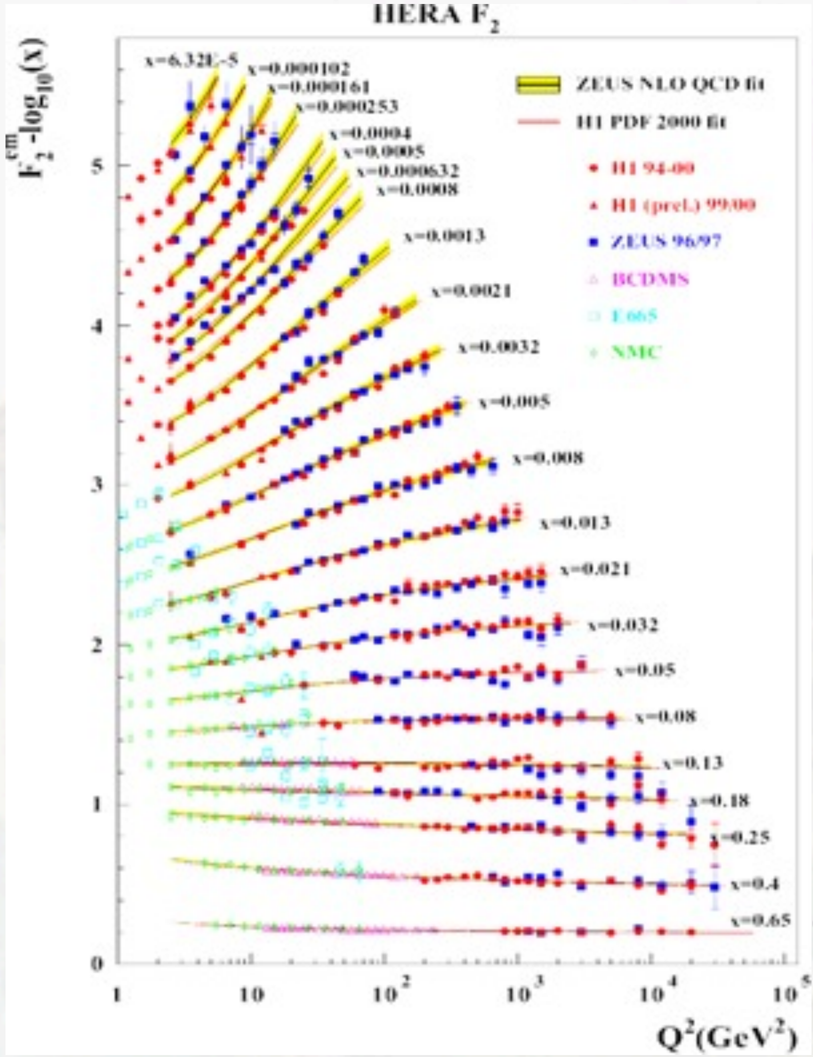

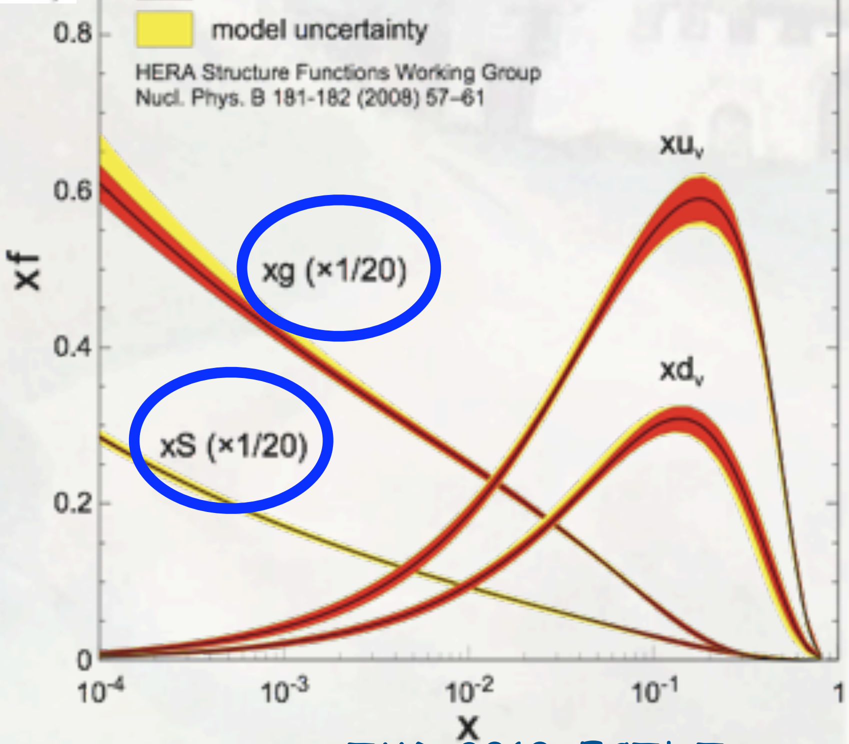

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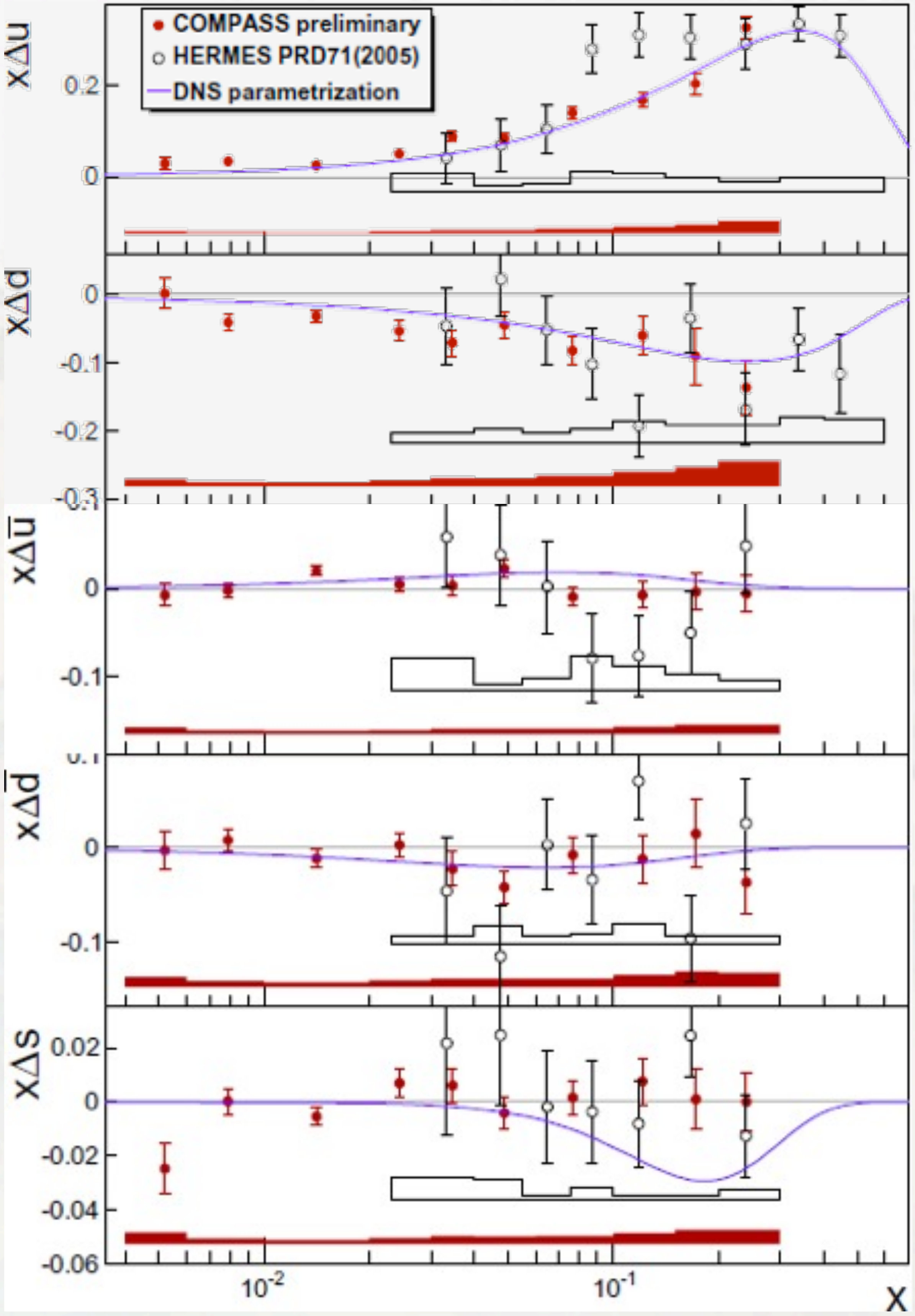
Helicity density

- smaller range in (x,Q^2) than for f_1
- data mainly for integrated version of g_{1L}
- need asymmetries not only binned in x but also in $P_{h\perp}$



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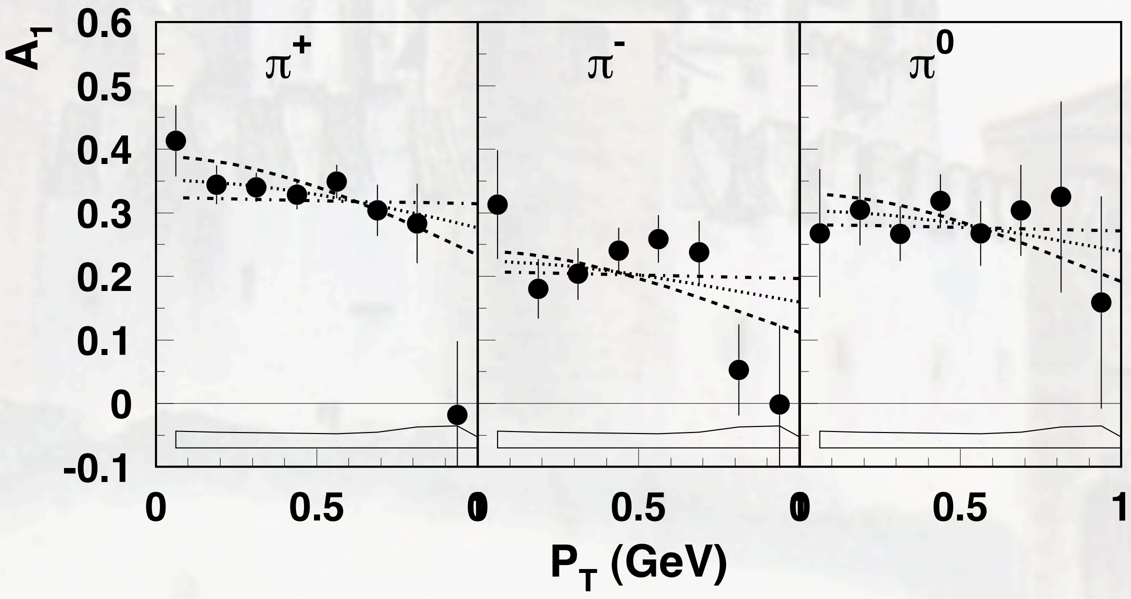
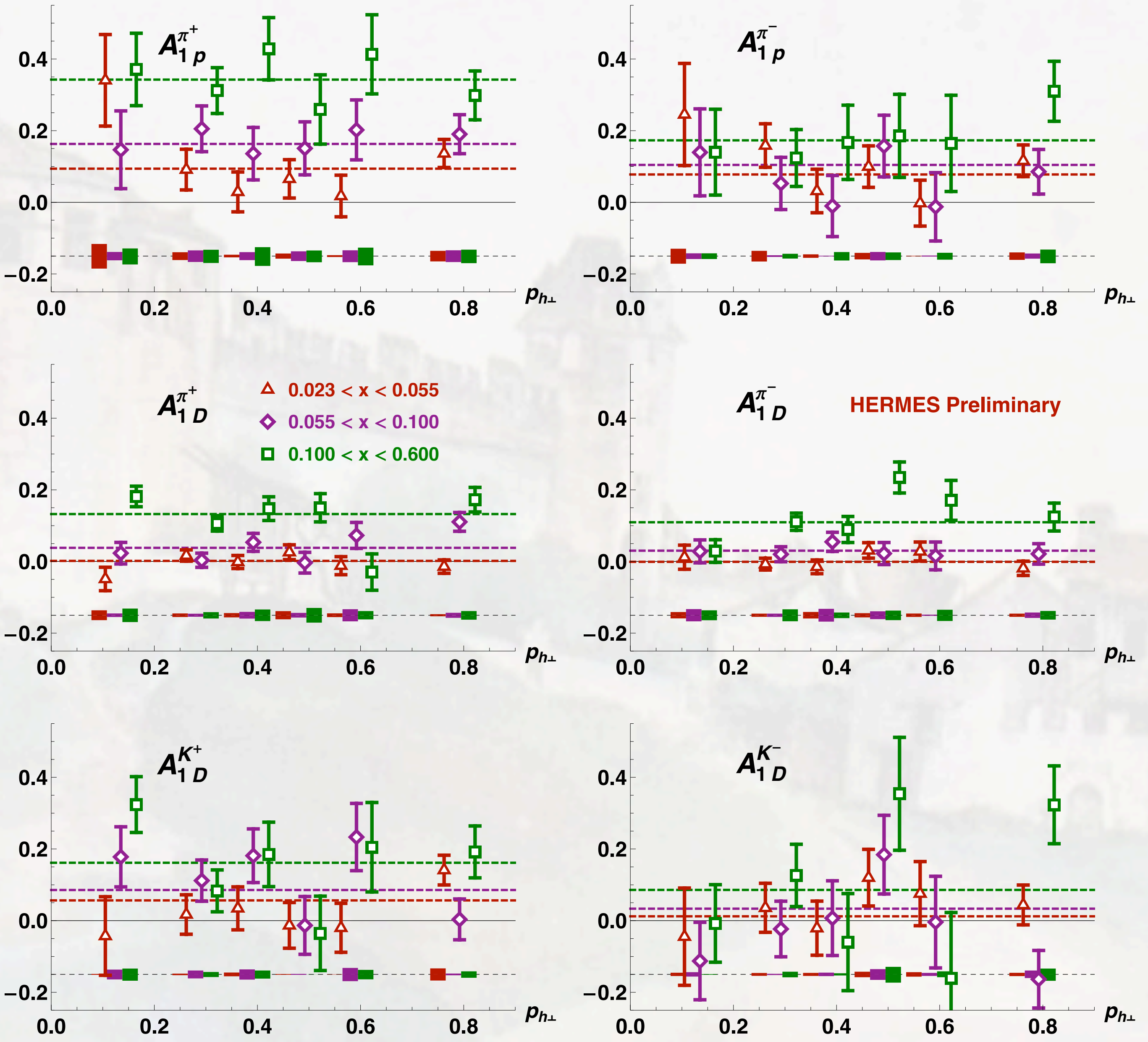
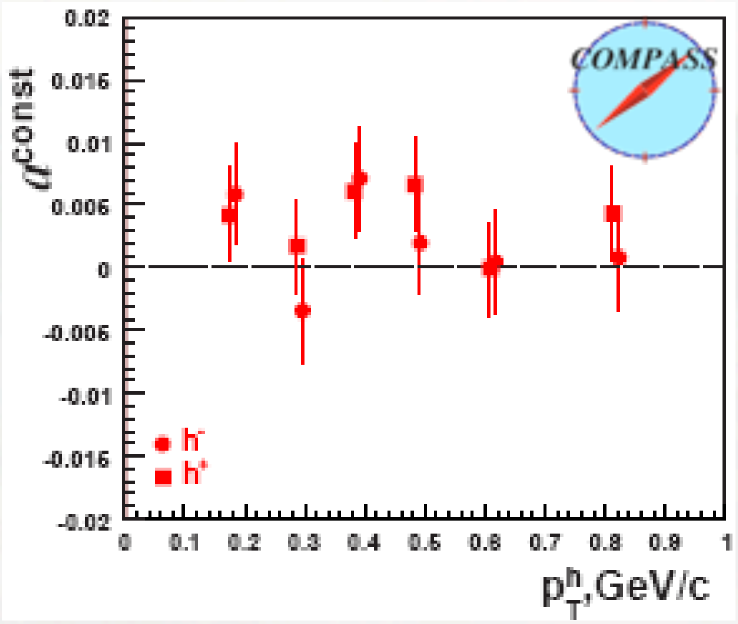
Helicity density (unintegrated)

Avakian et al. [CLAS], arXiv:1003.4549







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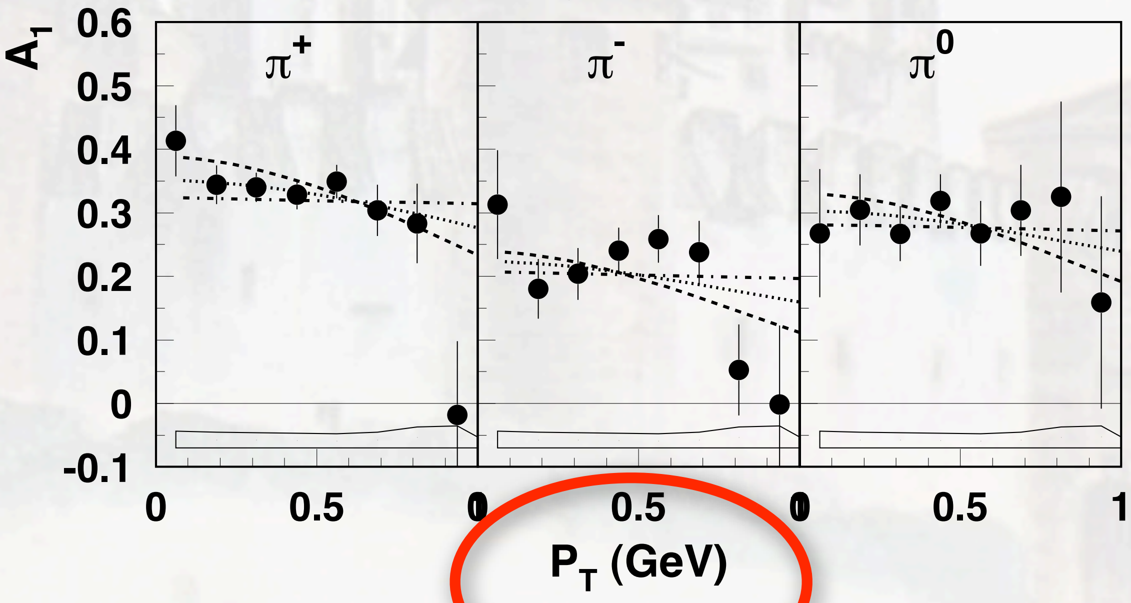

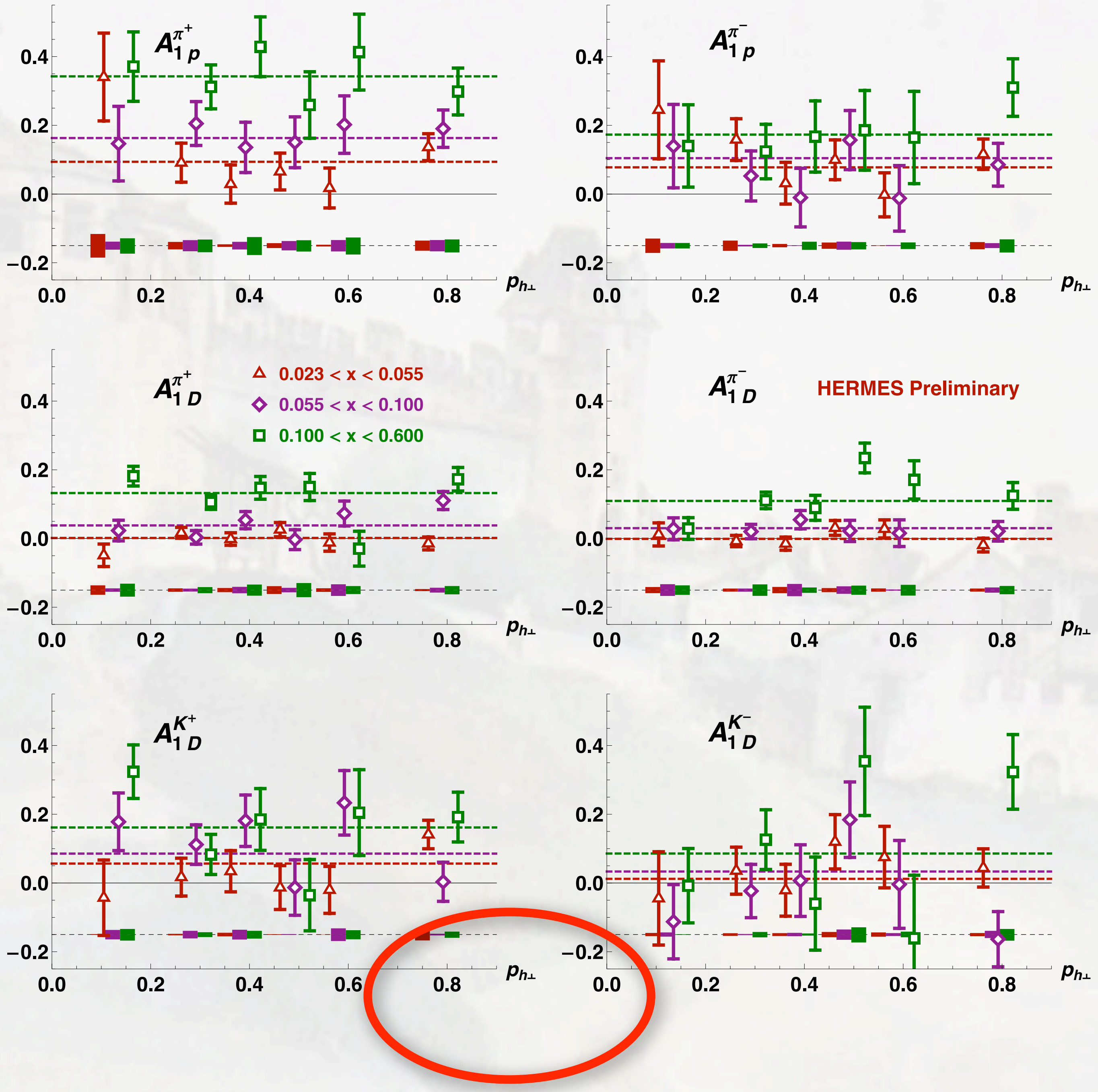

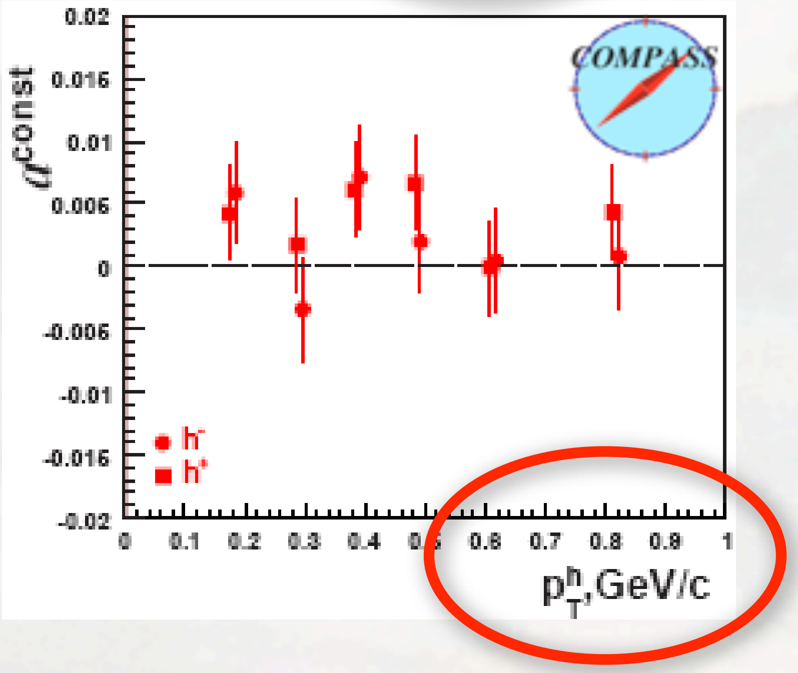

only weak if any dependence on $P_{h\perp}$ seen

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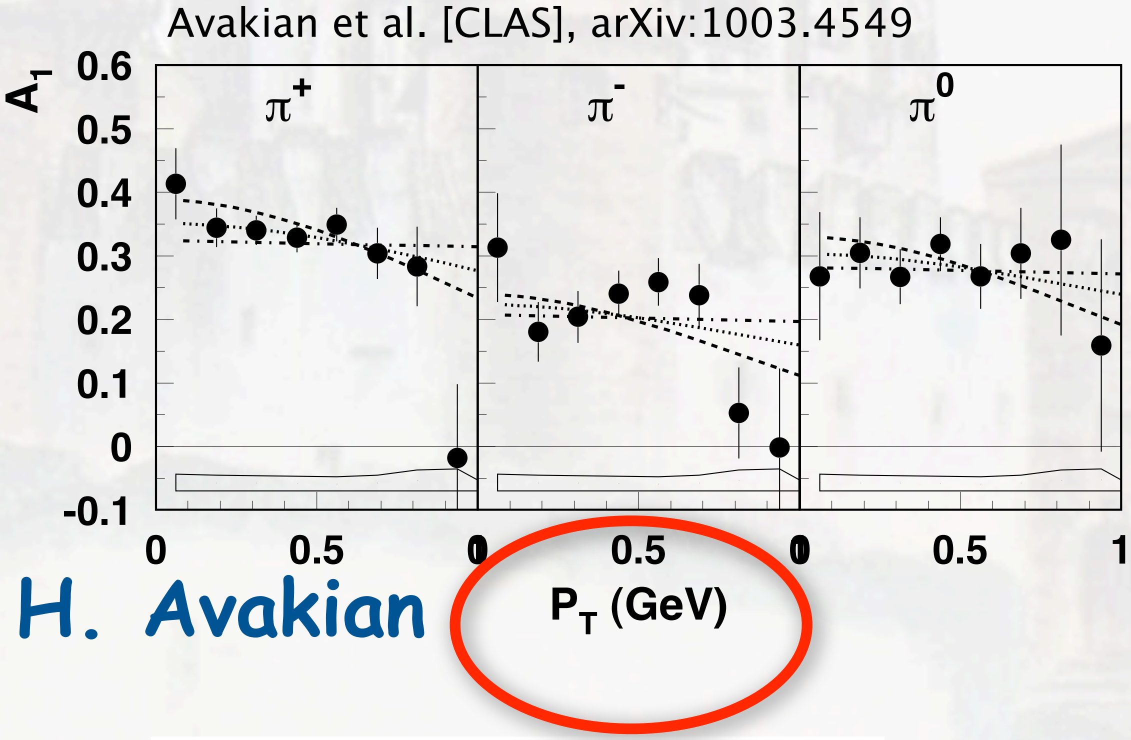
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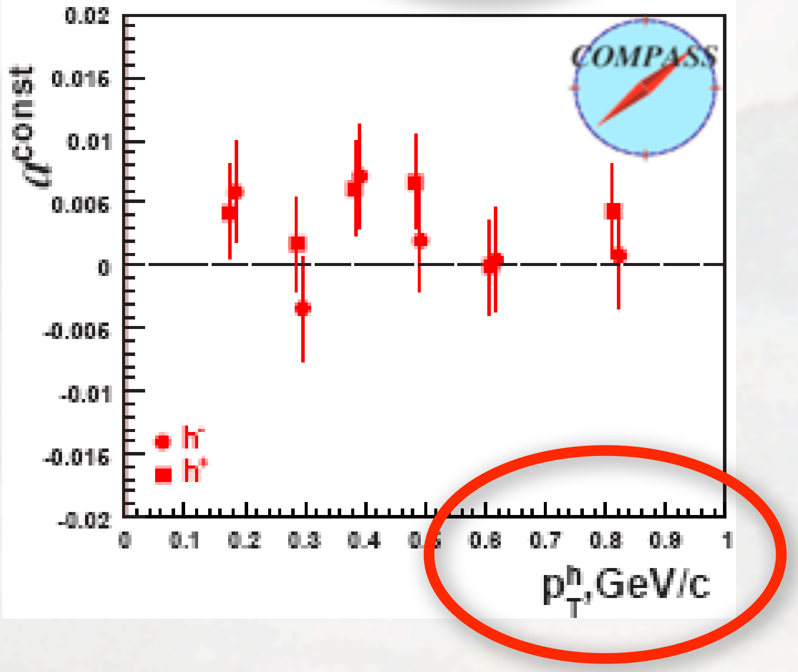
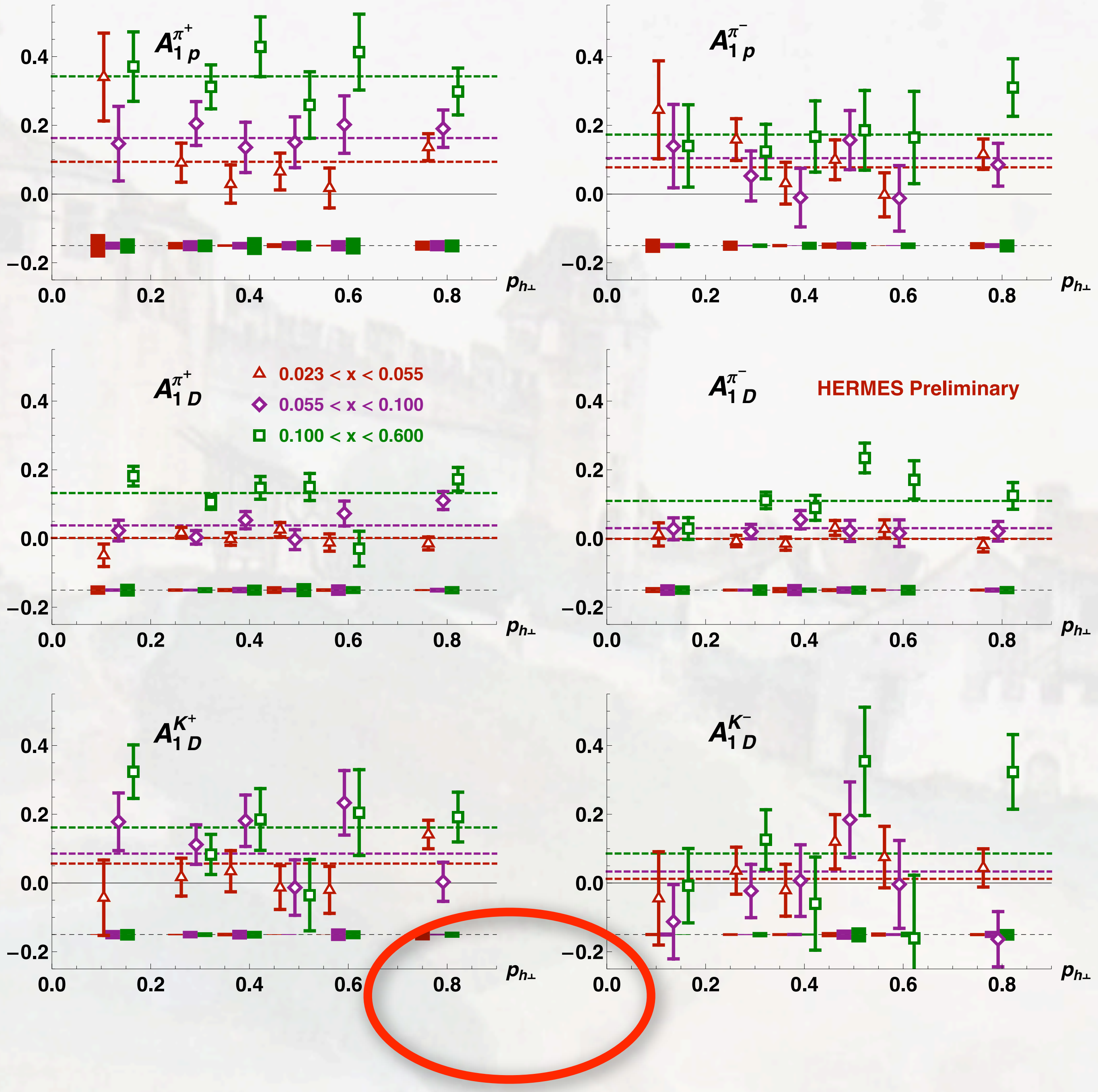
☛ **H. Avakian**





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Transversity distribution

chiral-odd transversity involves quark helicity flip

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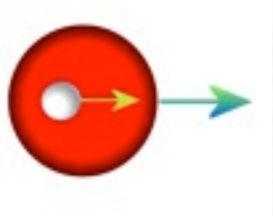
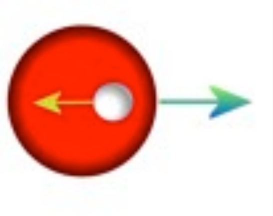
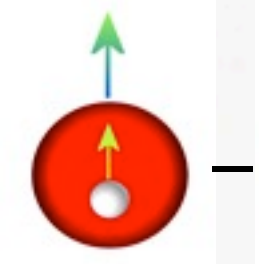
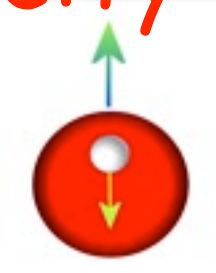
$g_1^q =$  $-$ 

$h_1^q =$  $-$ 

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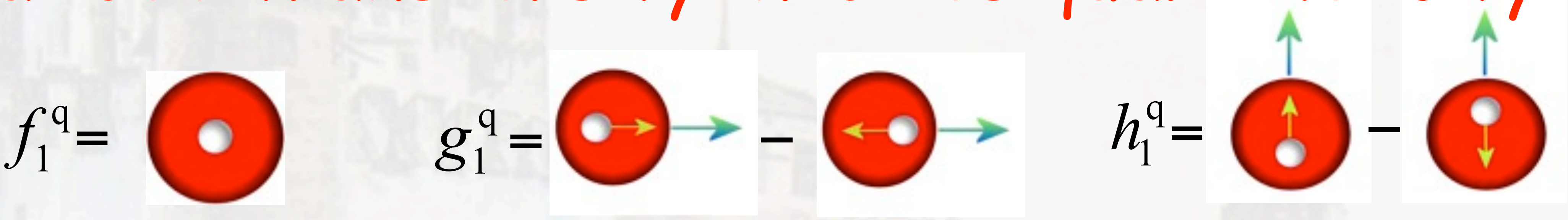
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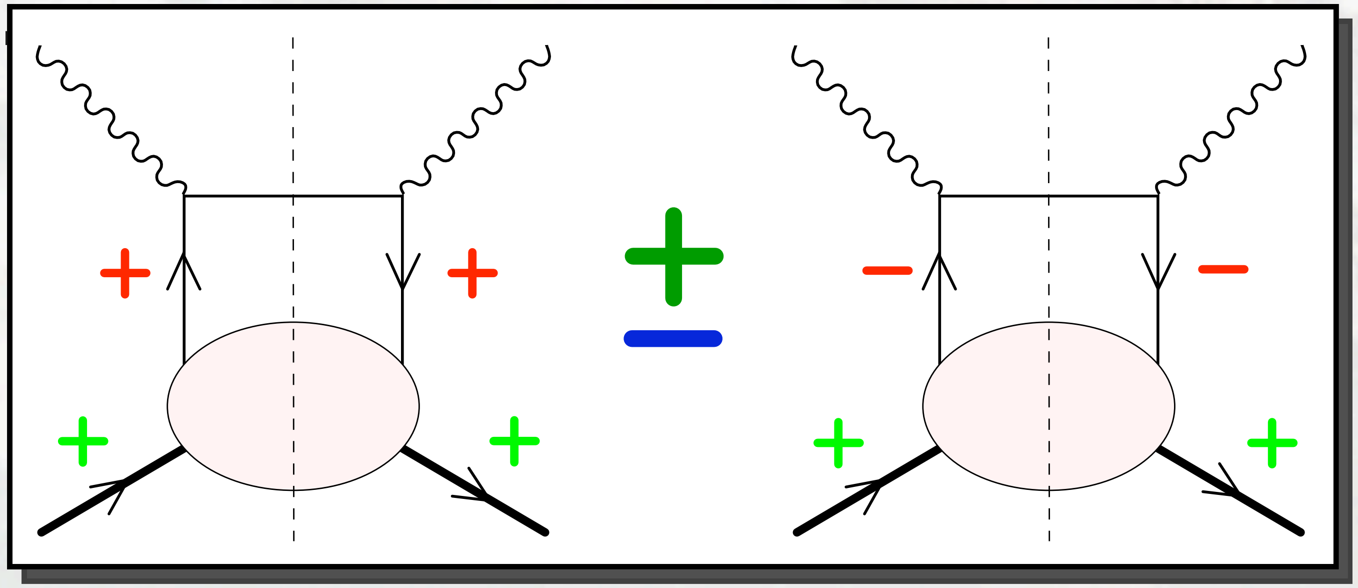

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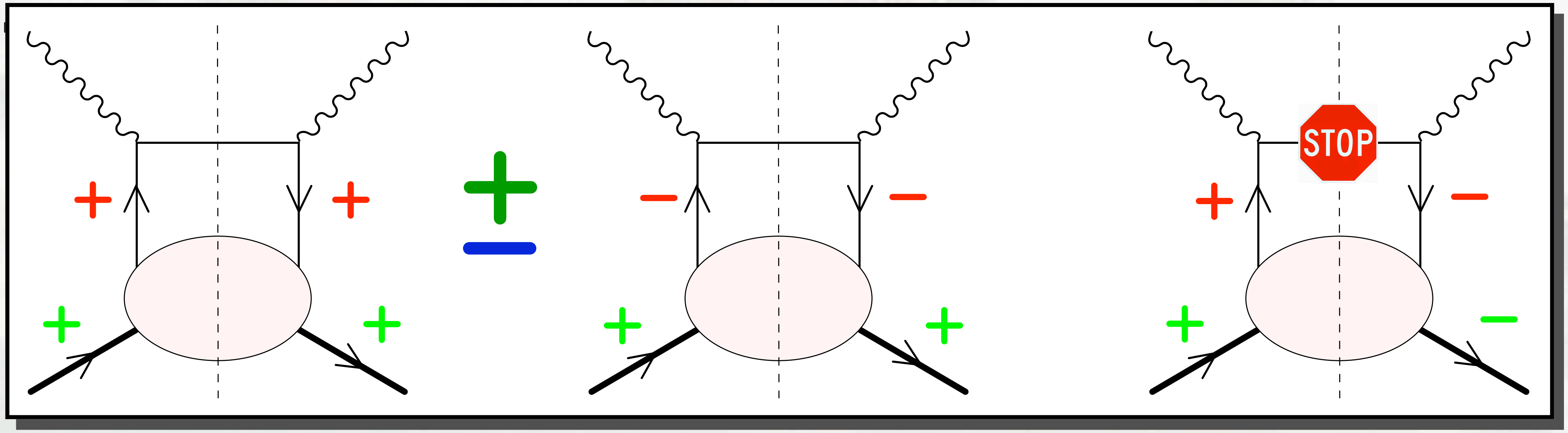

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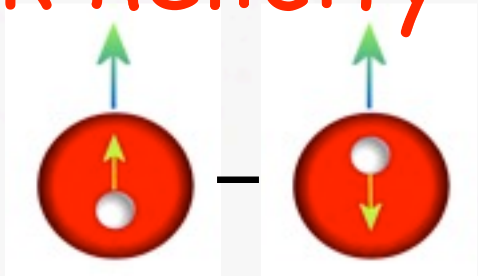
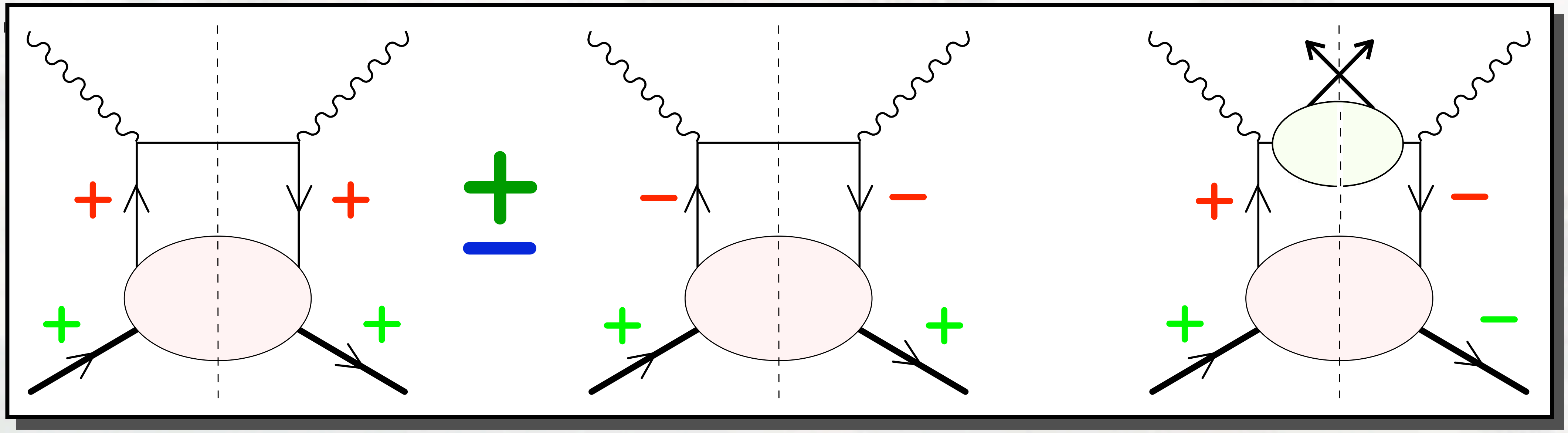
$h_1^q =$ 



need to couple to chiral-odd fragmentation function:

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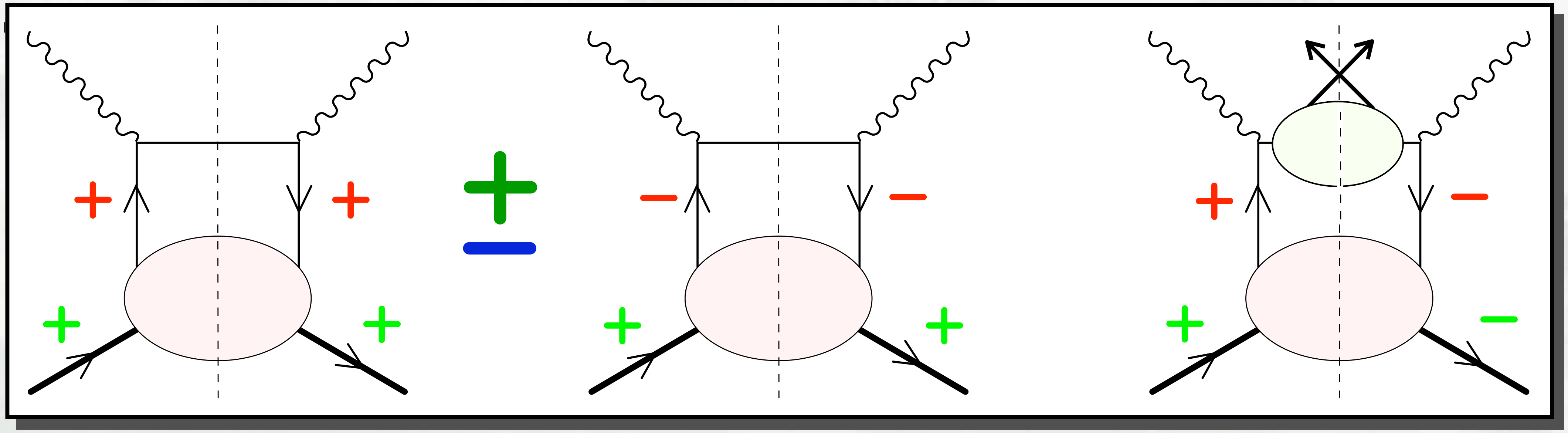

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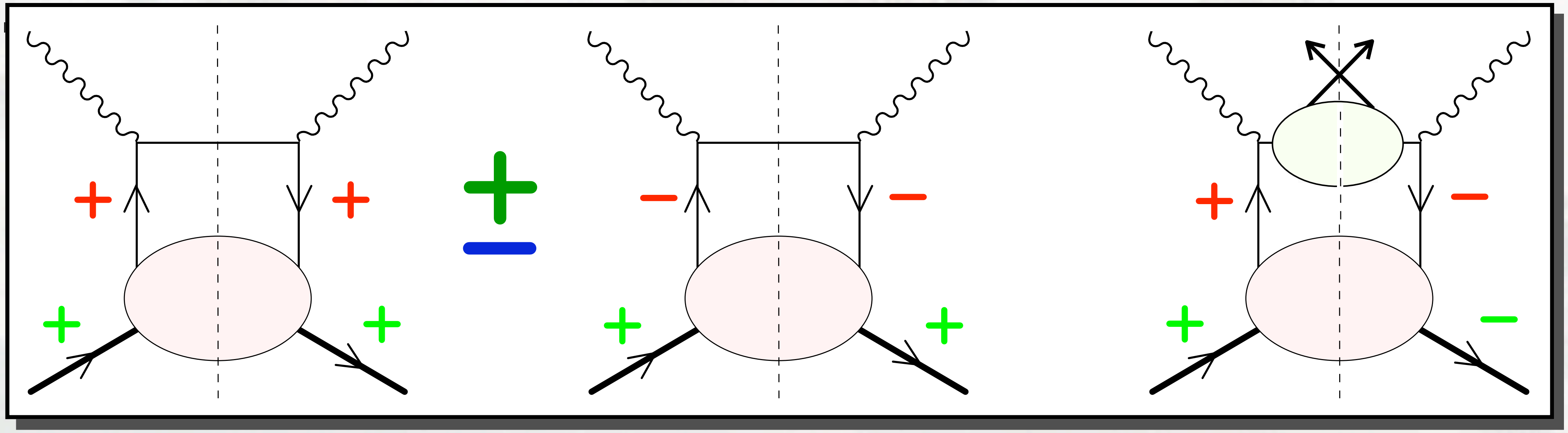

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- **2-hadron fragmentation**

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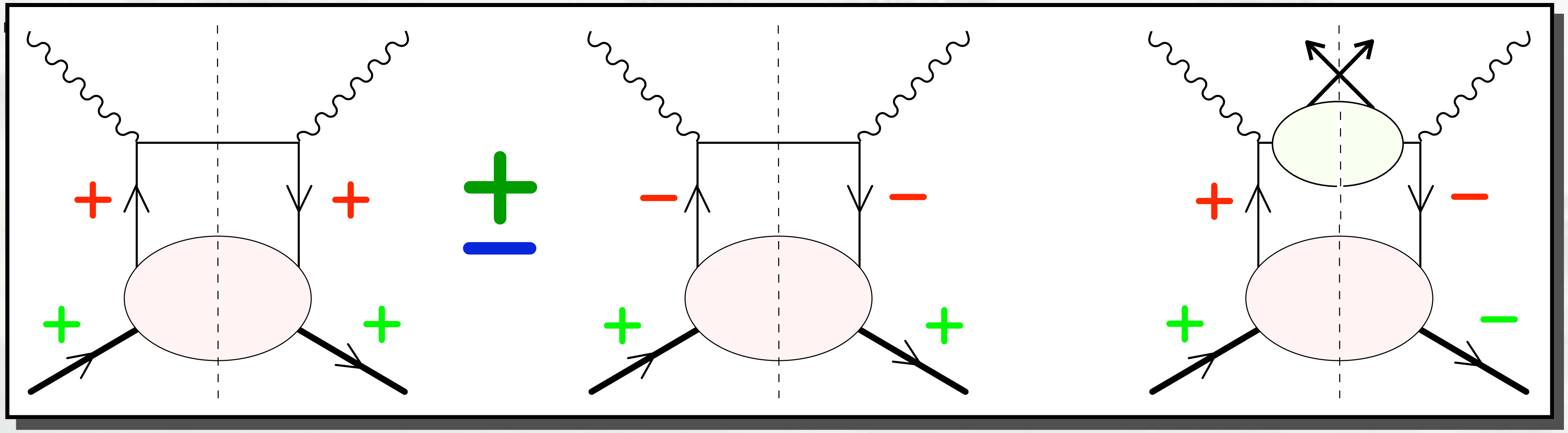

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- **Collins fragmentation**

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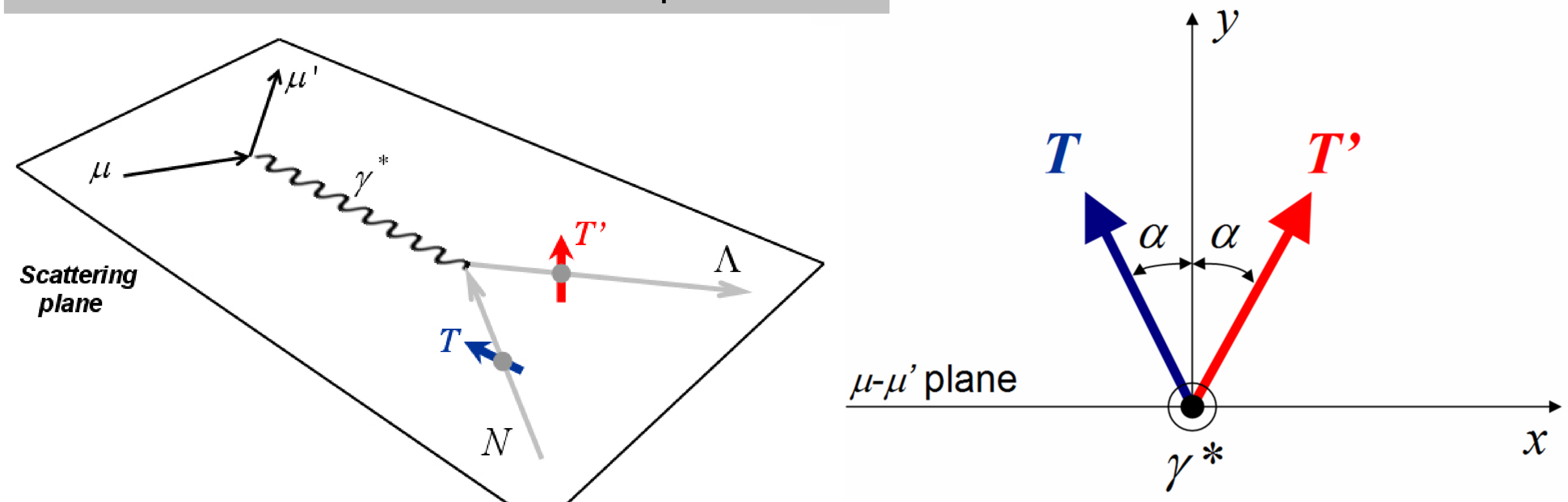
Transversity distribution (transverse-spin transfer)

Quantization axis for transverse Λ polarization



M. Anselmino & F. Murgia,
Physics Letters B 483 (2000) 74-86

T (initial quak spin) : component of target spin perpendicular to γ^*
T' (final quark spin) : symmetric of the ***T*** w.r.t. the normal to the scattering plane

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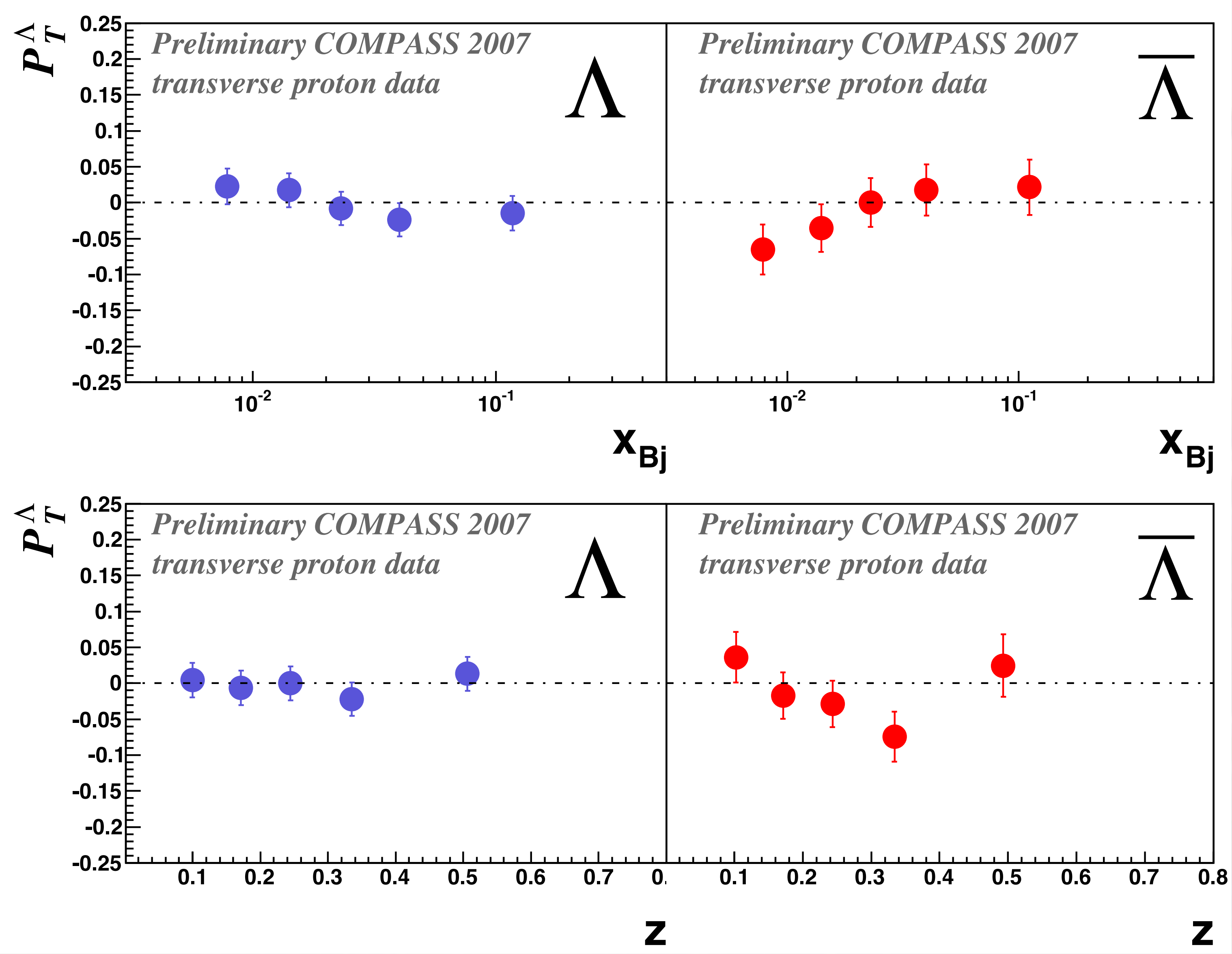

- compatible with zero
- low sensitivity to u & d quark polarization?
- measured at lower x where transversity is expected not to be large
- 2010 data will reduce statistical uncertainty by factor 2
- need to look at other hyperons?

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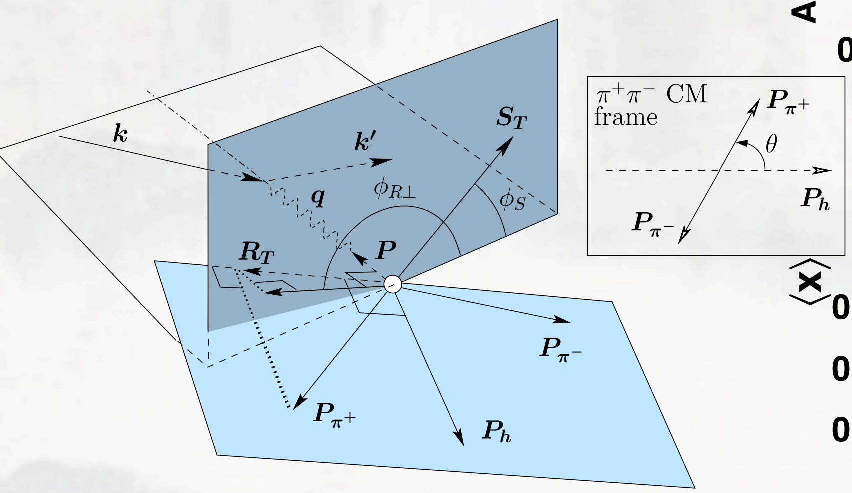
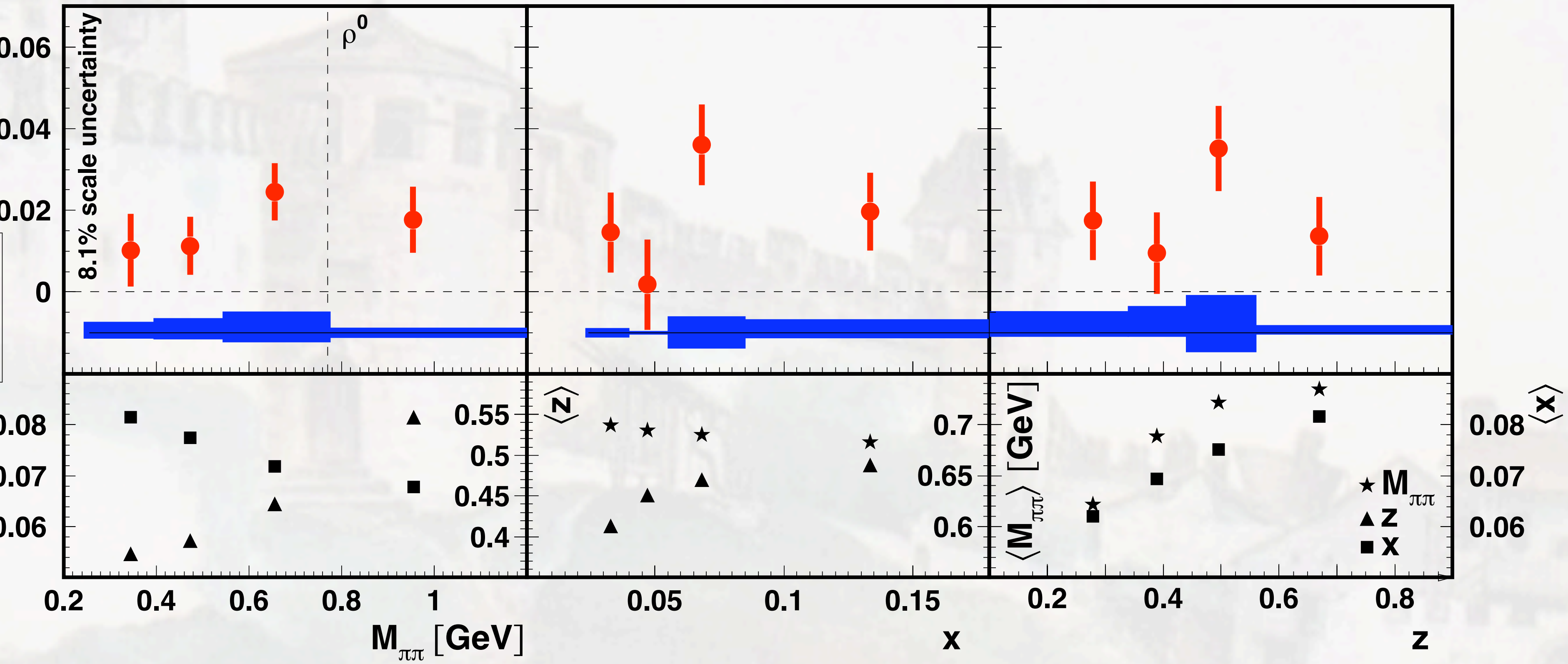


A. Airapetian et al. [HERMES], JHEP 06 (2008) 017



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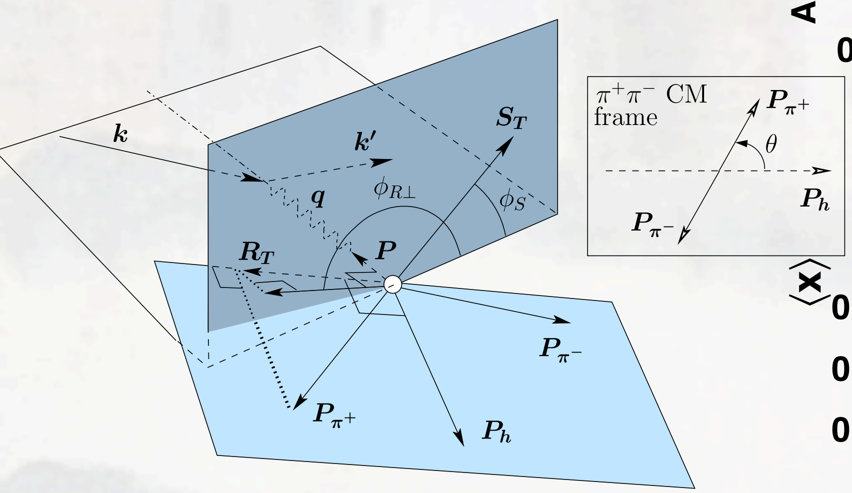

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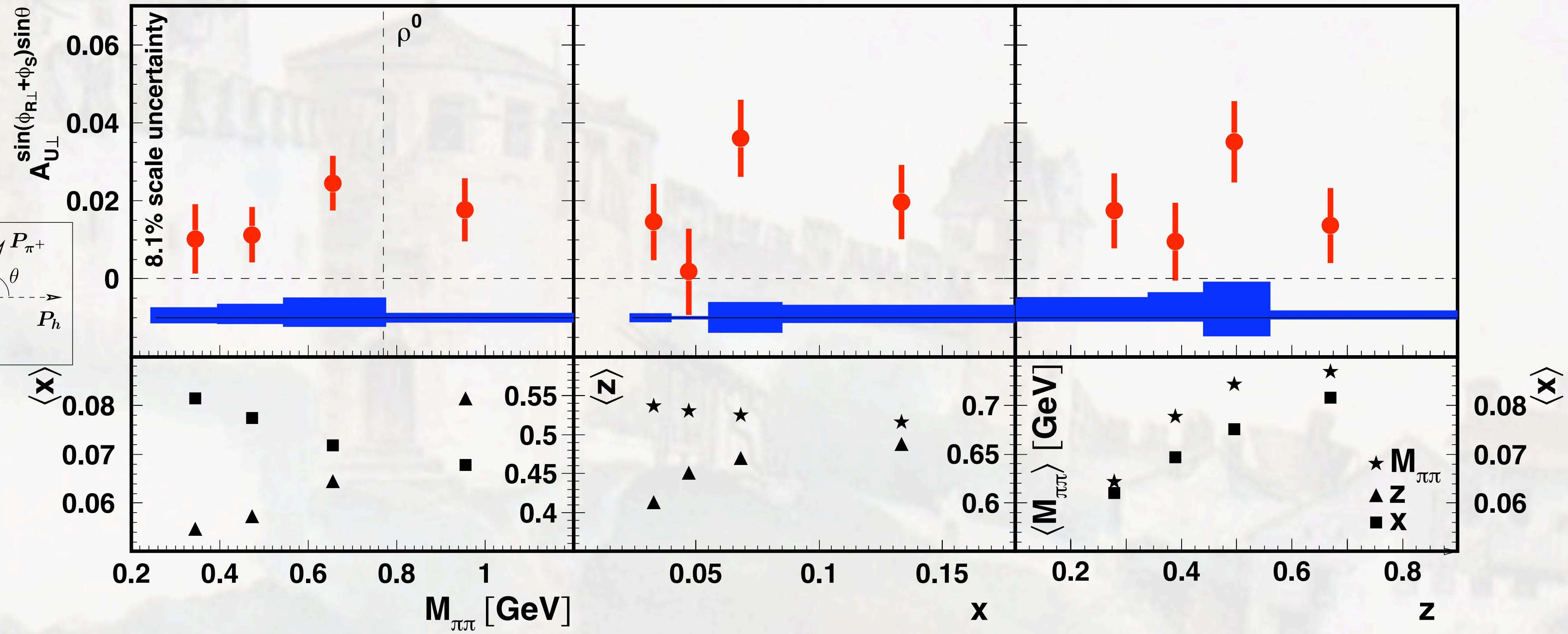

☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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Transversity distribution (2-hadron fragmentation)

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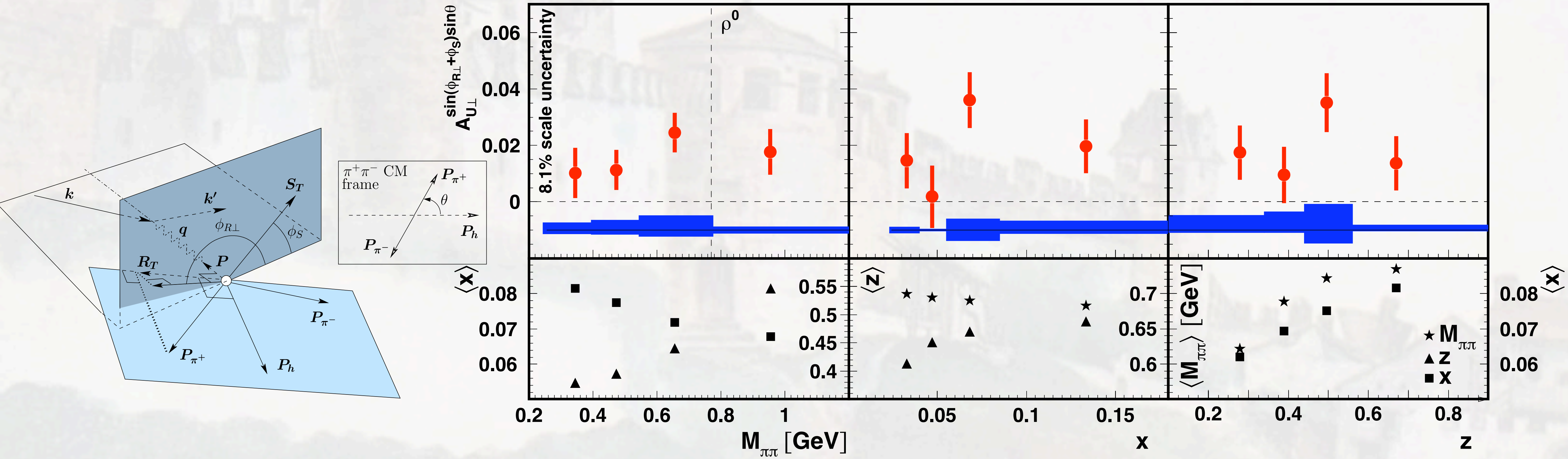

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☑ invariant-mass dependence rules out Jaffe model

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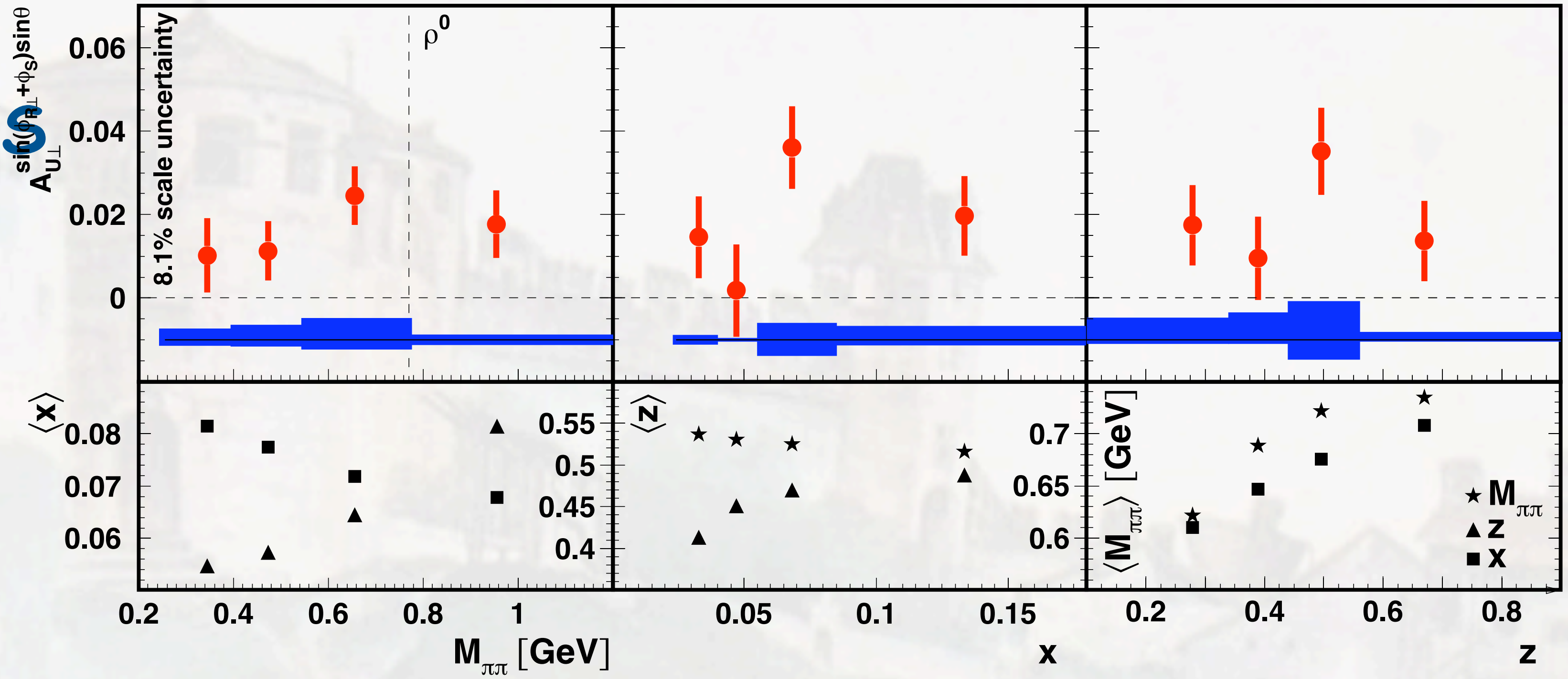
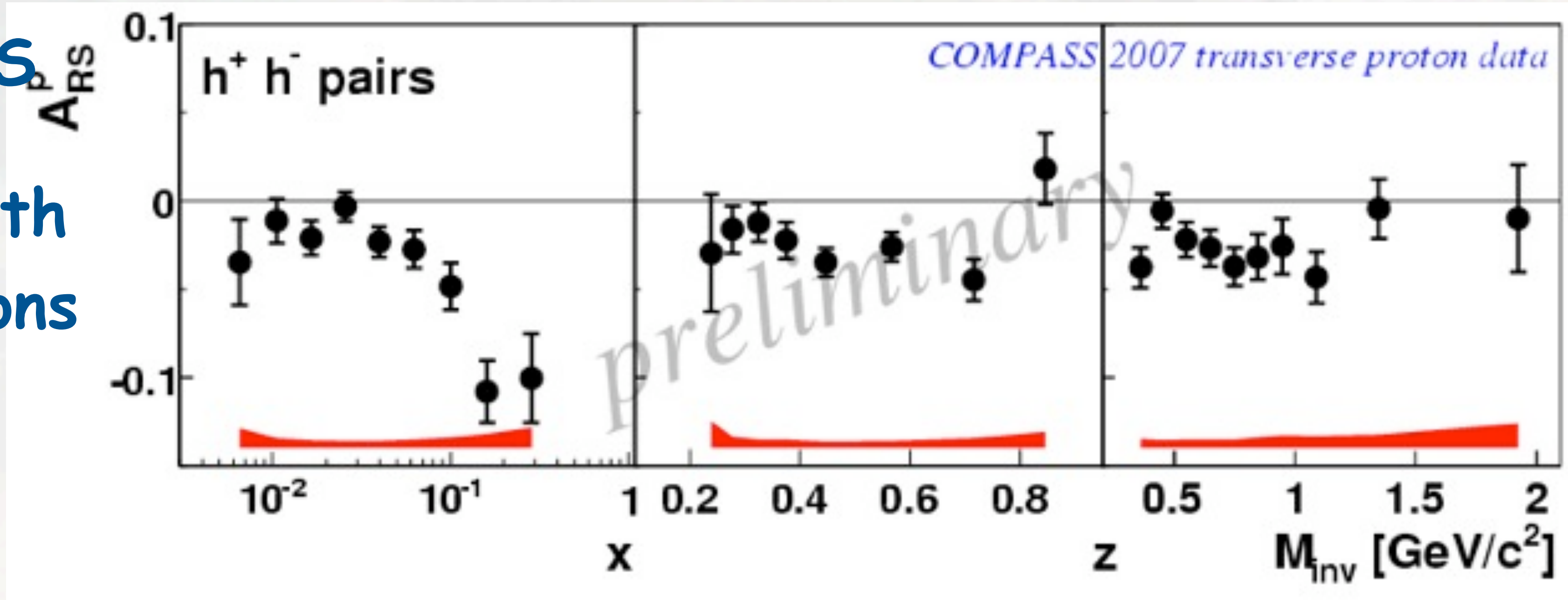
Transversity distribution (2-hadron fragmentation)

- non-zero amplitudes both from COMPASS and HERMES
- similar $M_{\pi\pi}$ dependence
- COMPASS: hadron pairs
  HERMES: pion pairs
- larger amplitudes at COMPASS than at HERMES
- data from pp consistent with zero but dominated by gluons
- first results from e^+e^- by BELLE





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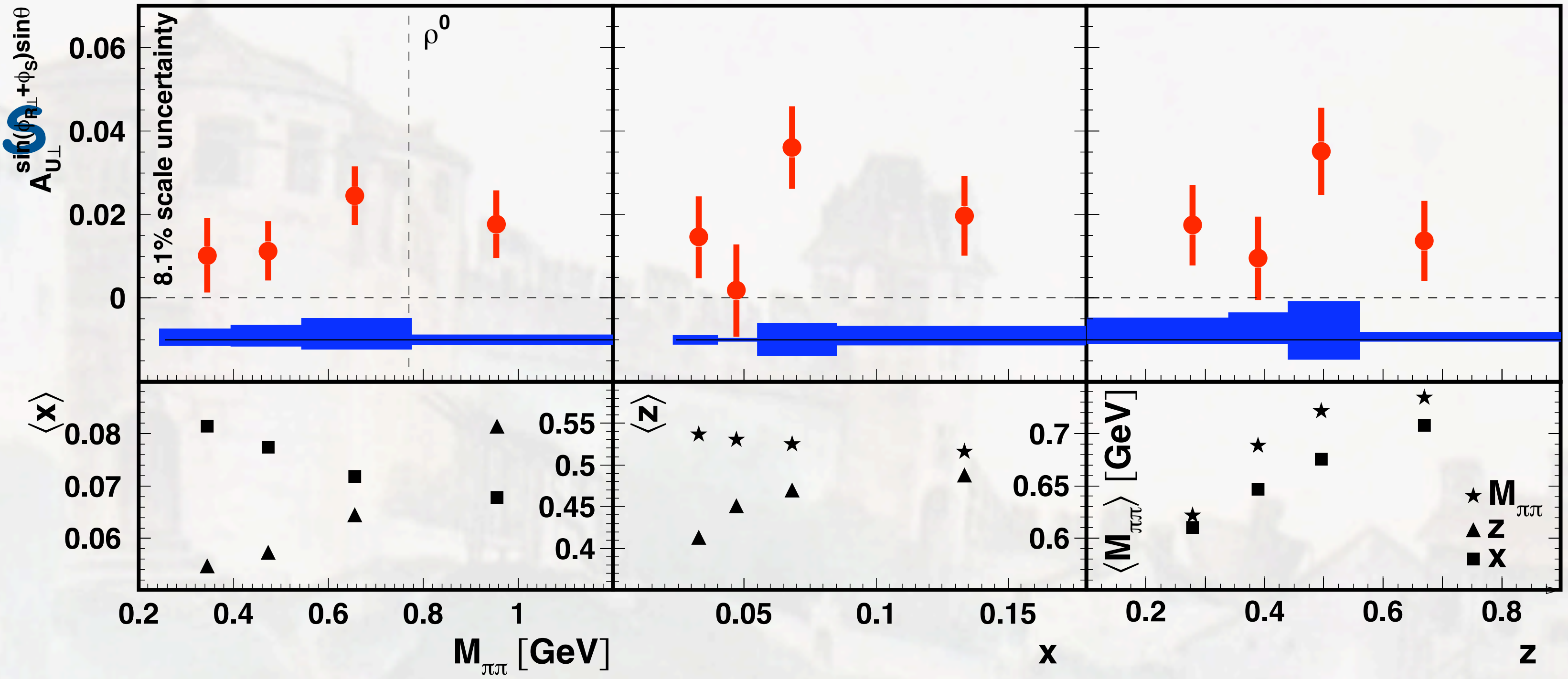
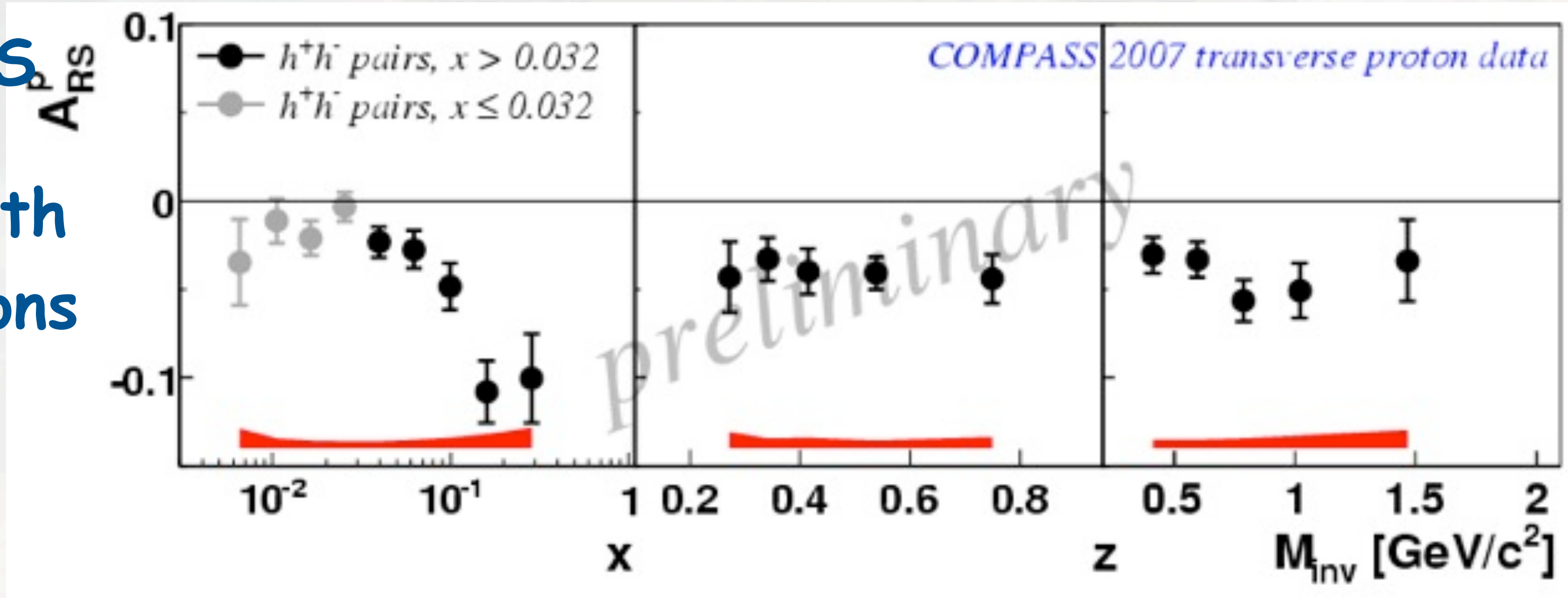
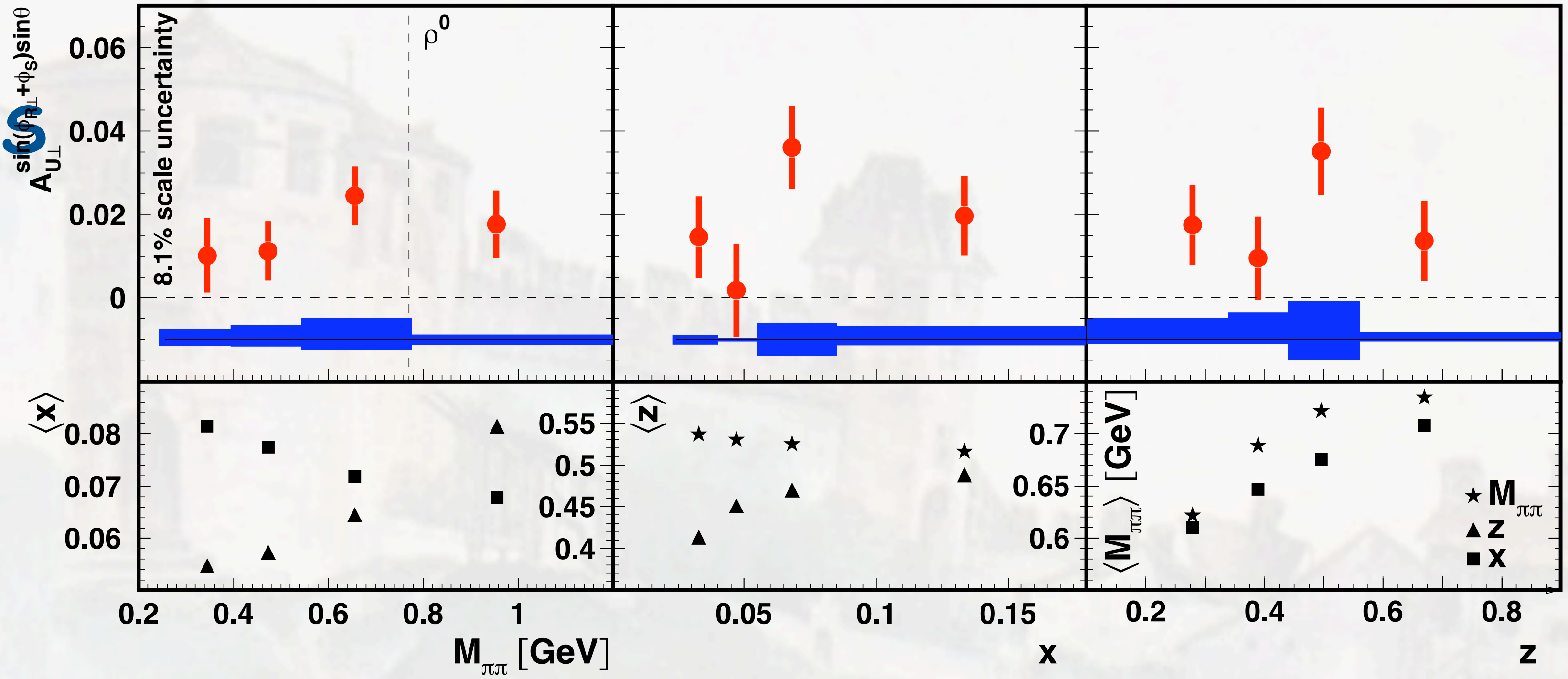


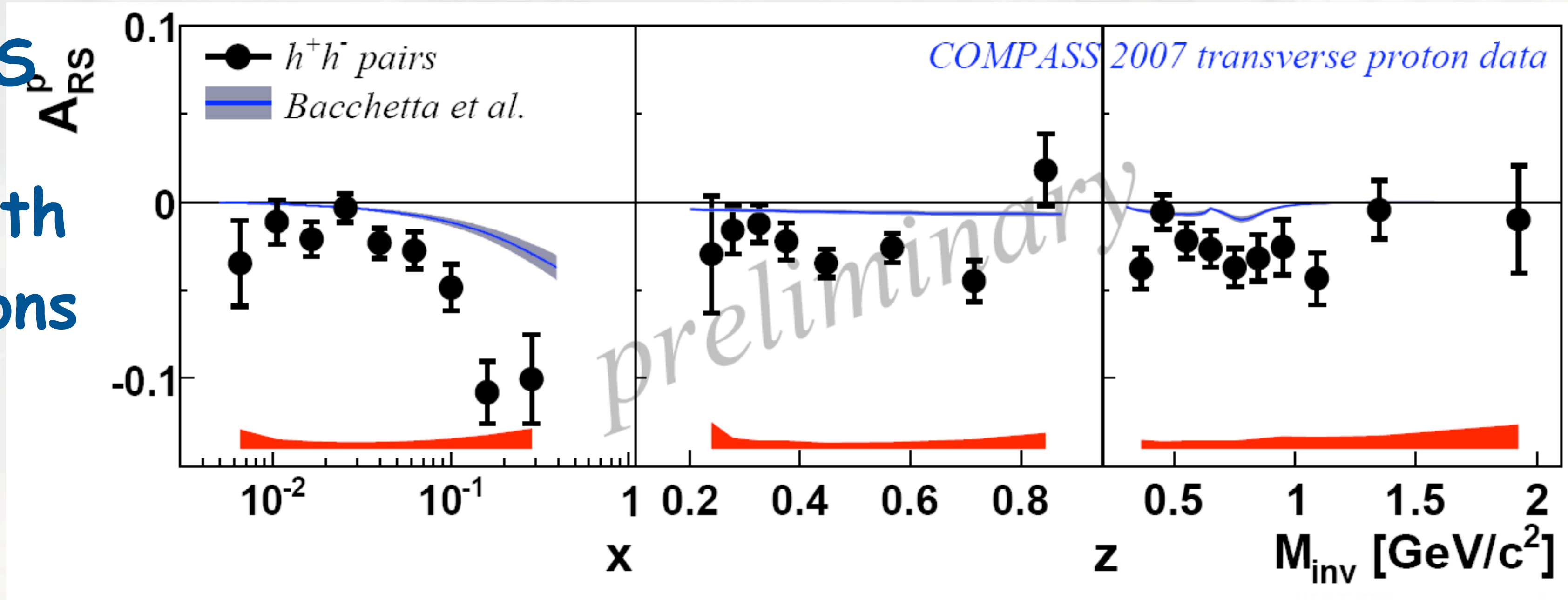


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Transversity distribution (2-hadron fragmentation)

- non-zero amplitudes both from COMPASS and HERMES
- similar $M_{\pi\pi}$ dependence
- COMPASS: hadron pairs
  HERMES: pion pairs
- larger amplitudes at COMPASS than at HERMES
- data from pp consistent with zero but dominated by gluons
- first results from e^+e^- by BELLE





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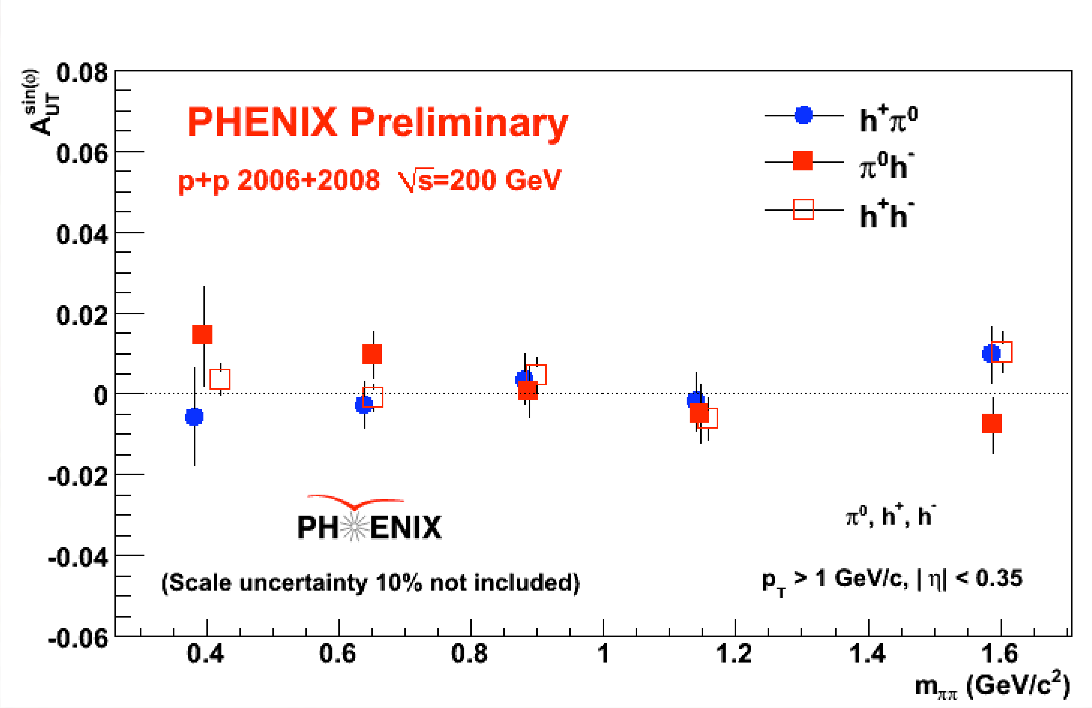

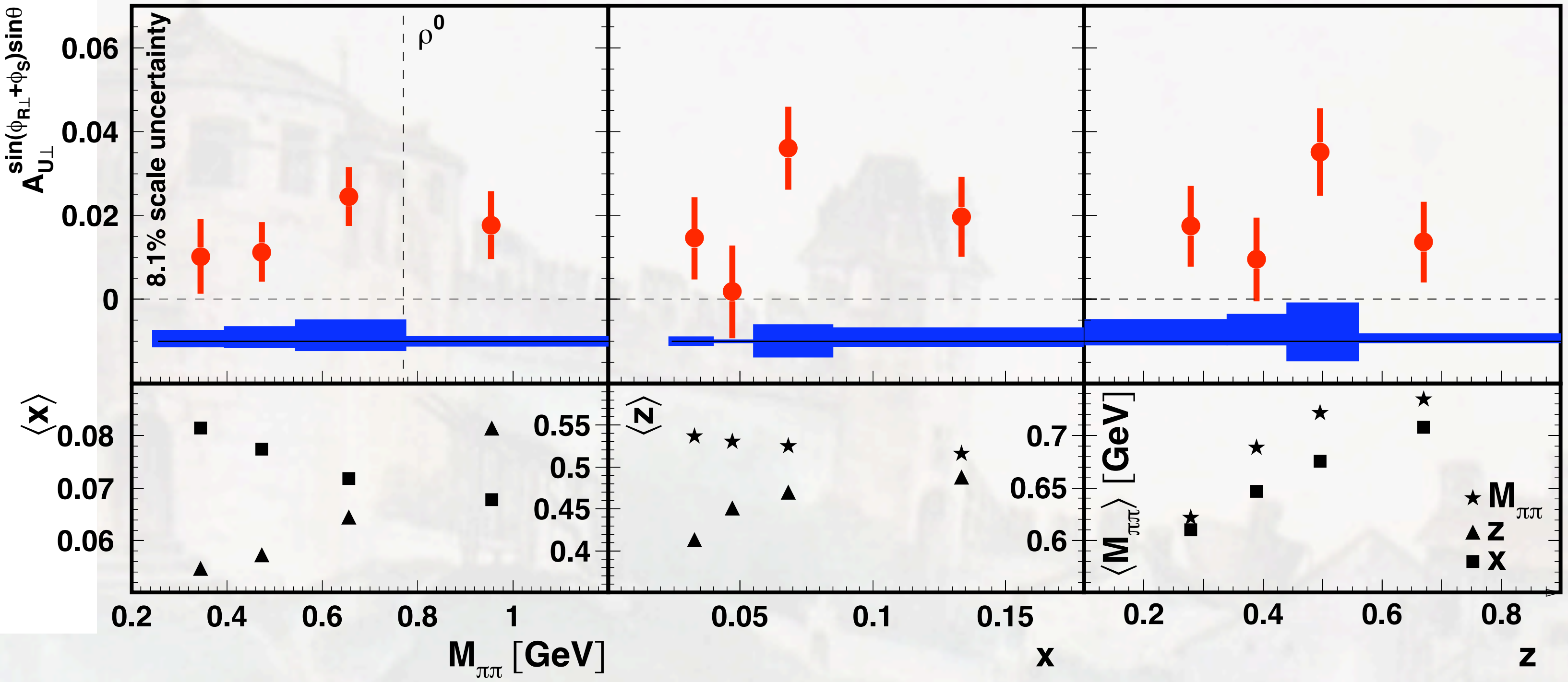

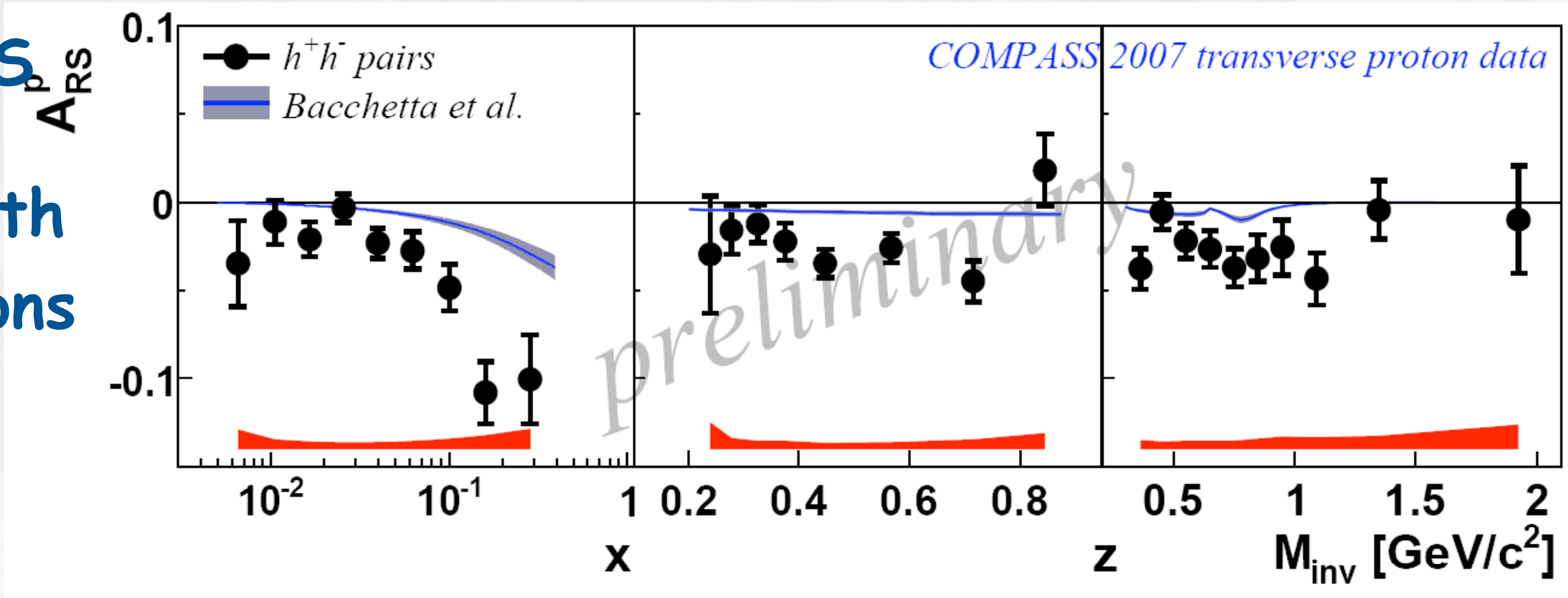

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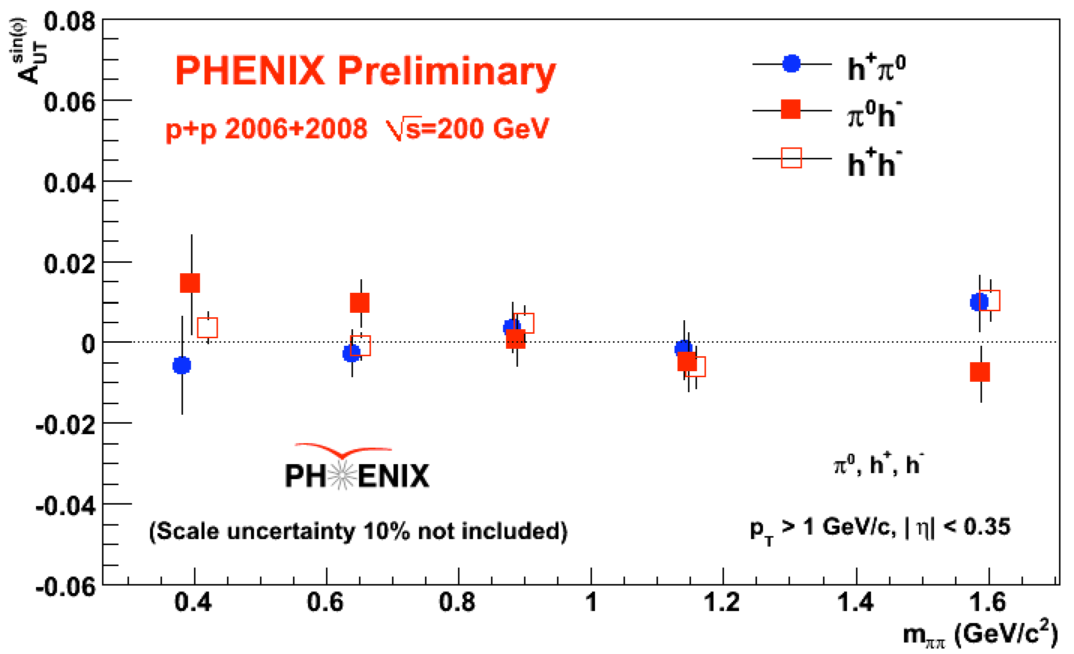

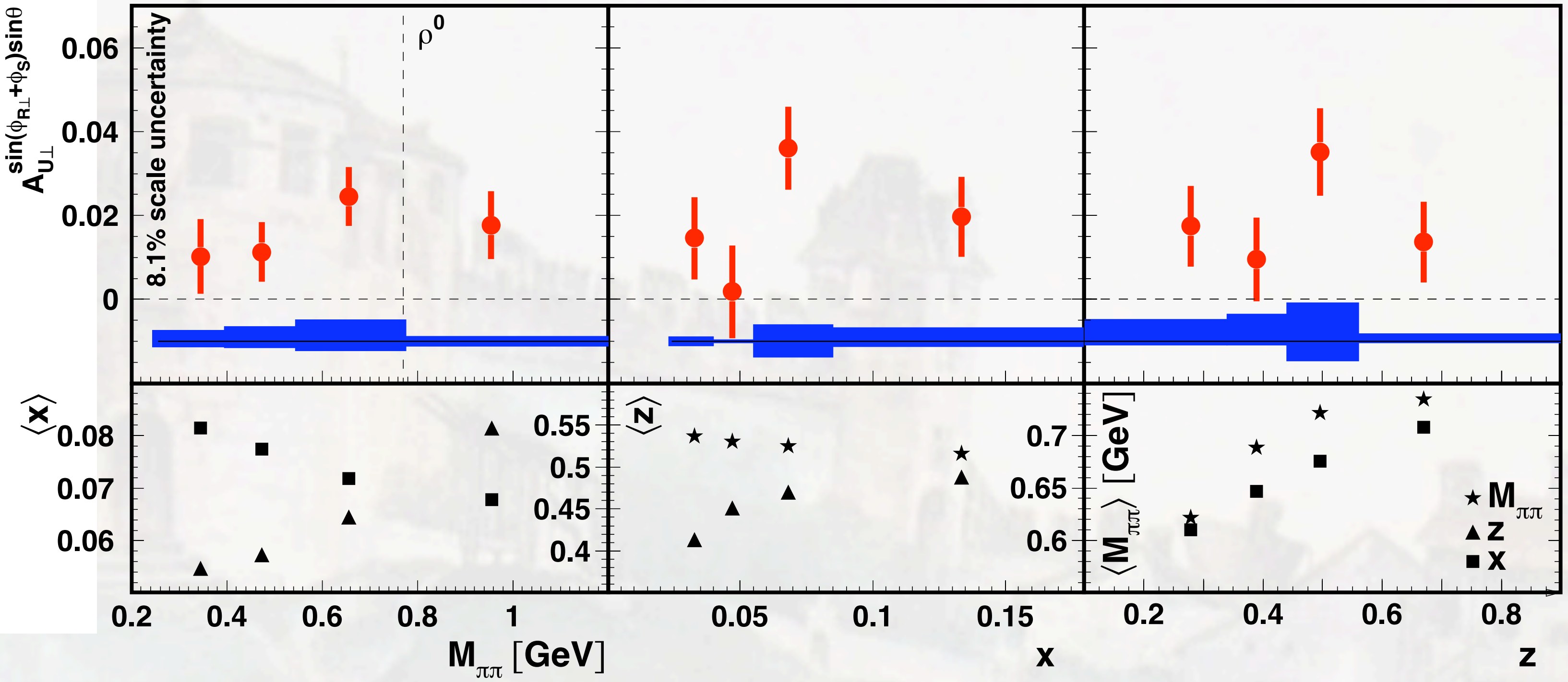

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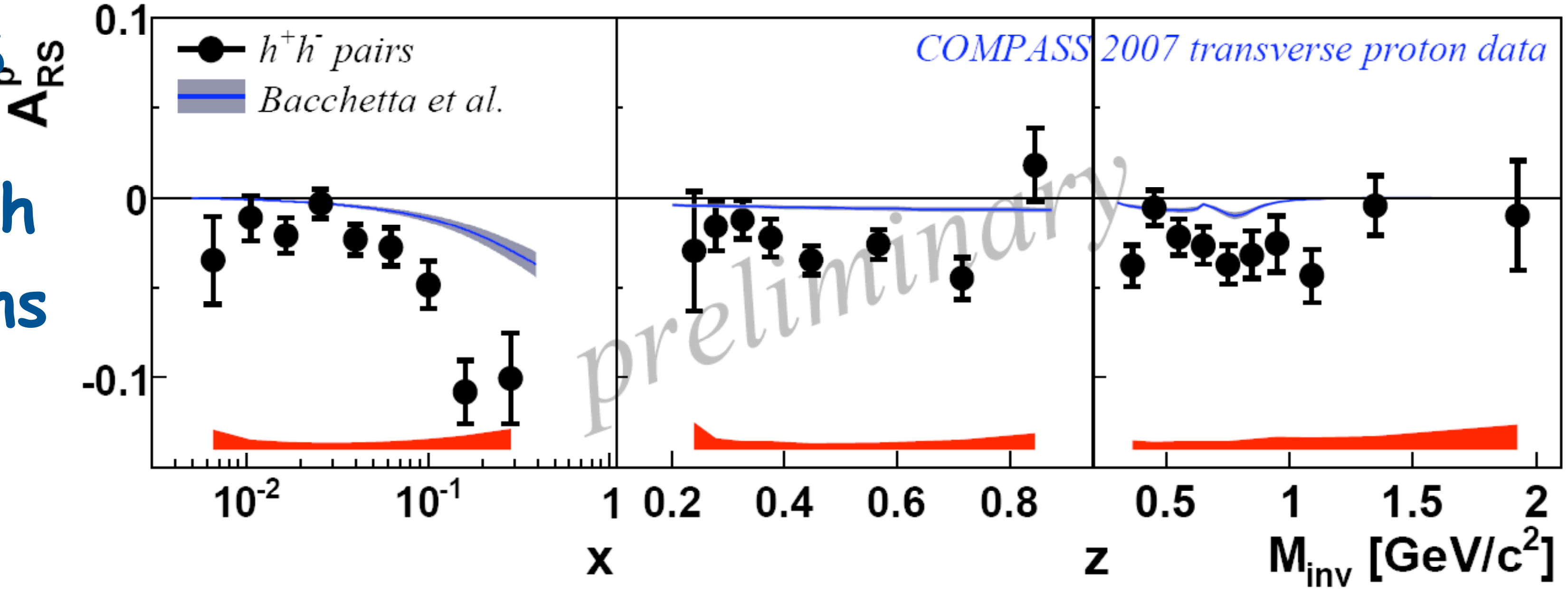

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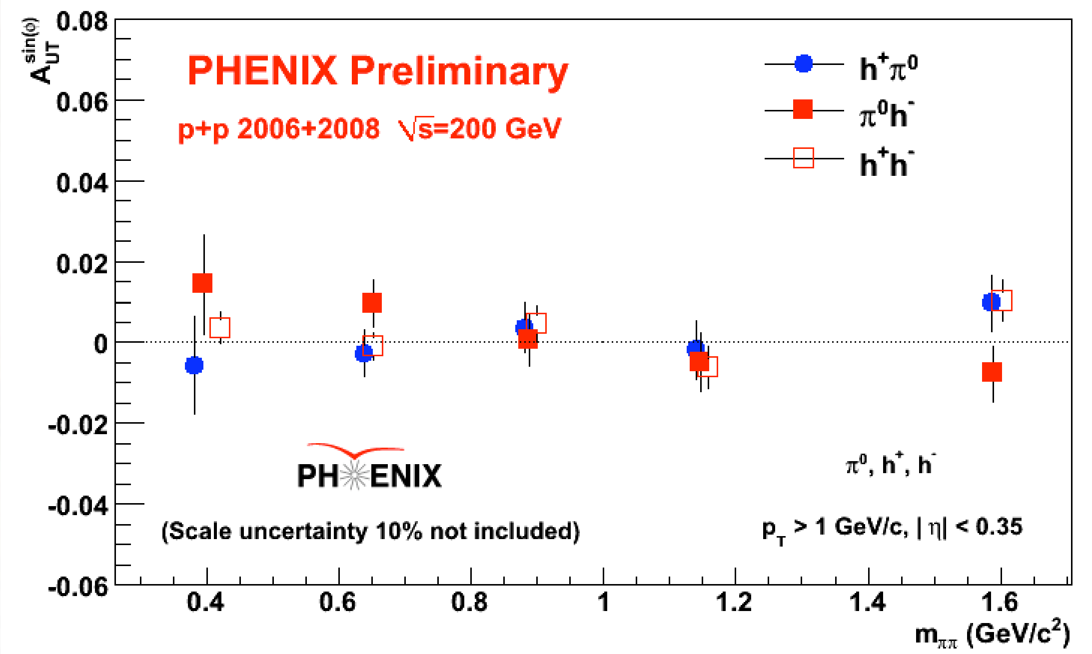

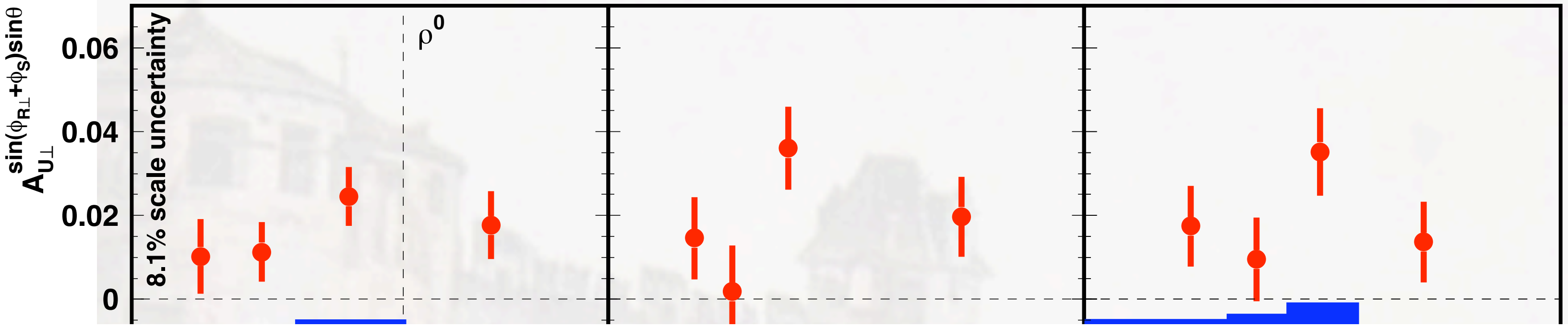

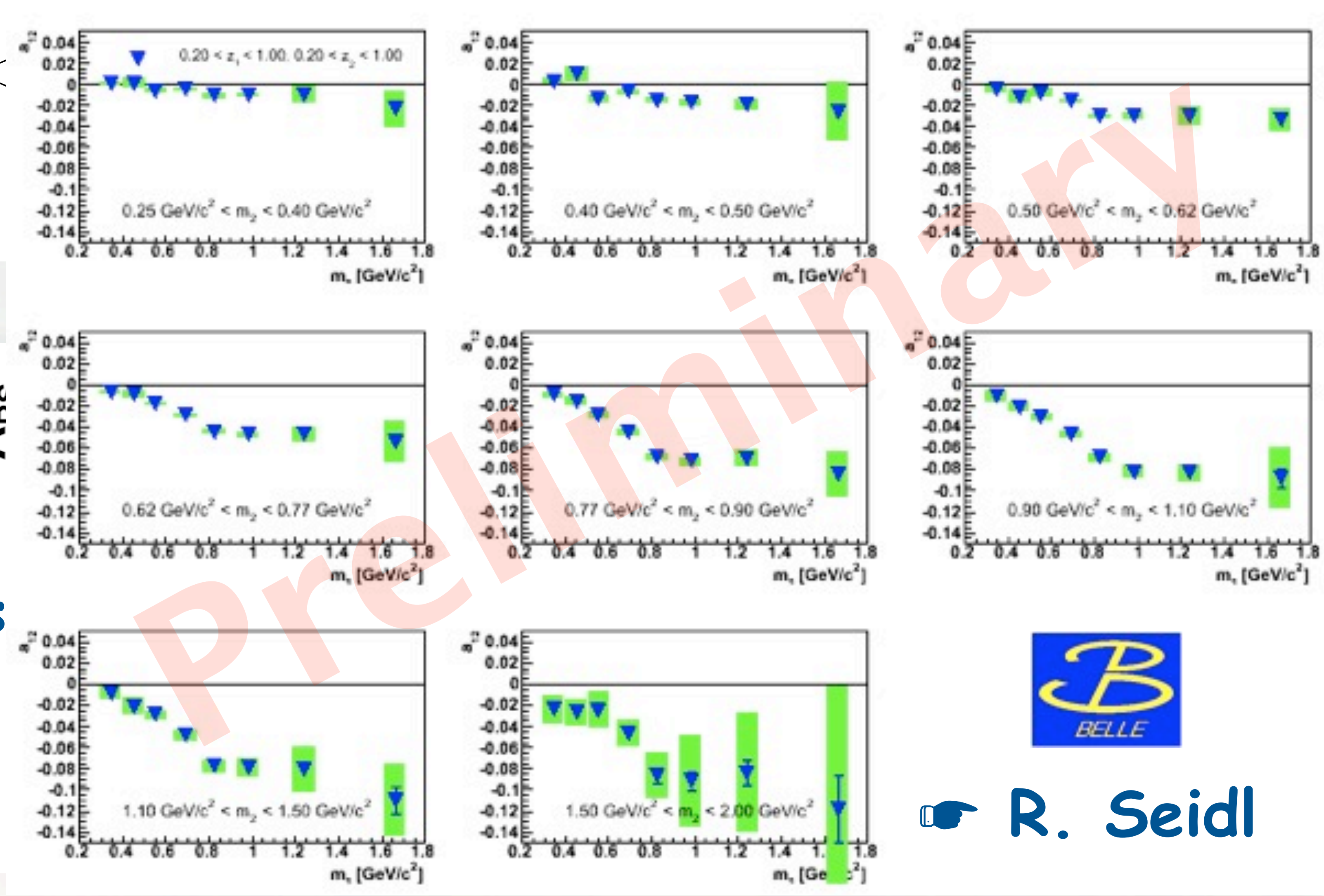

☛ R. Seidl

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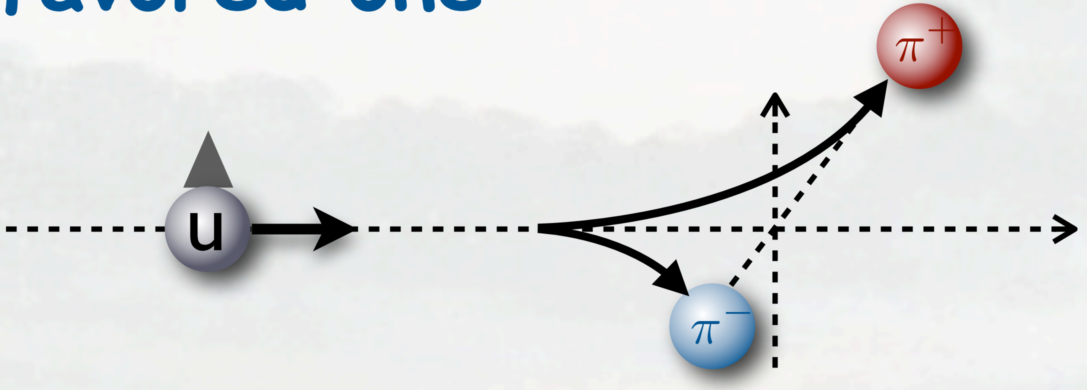
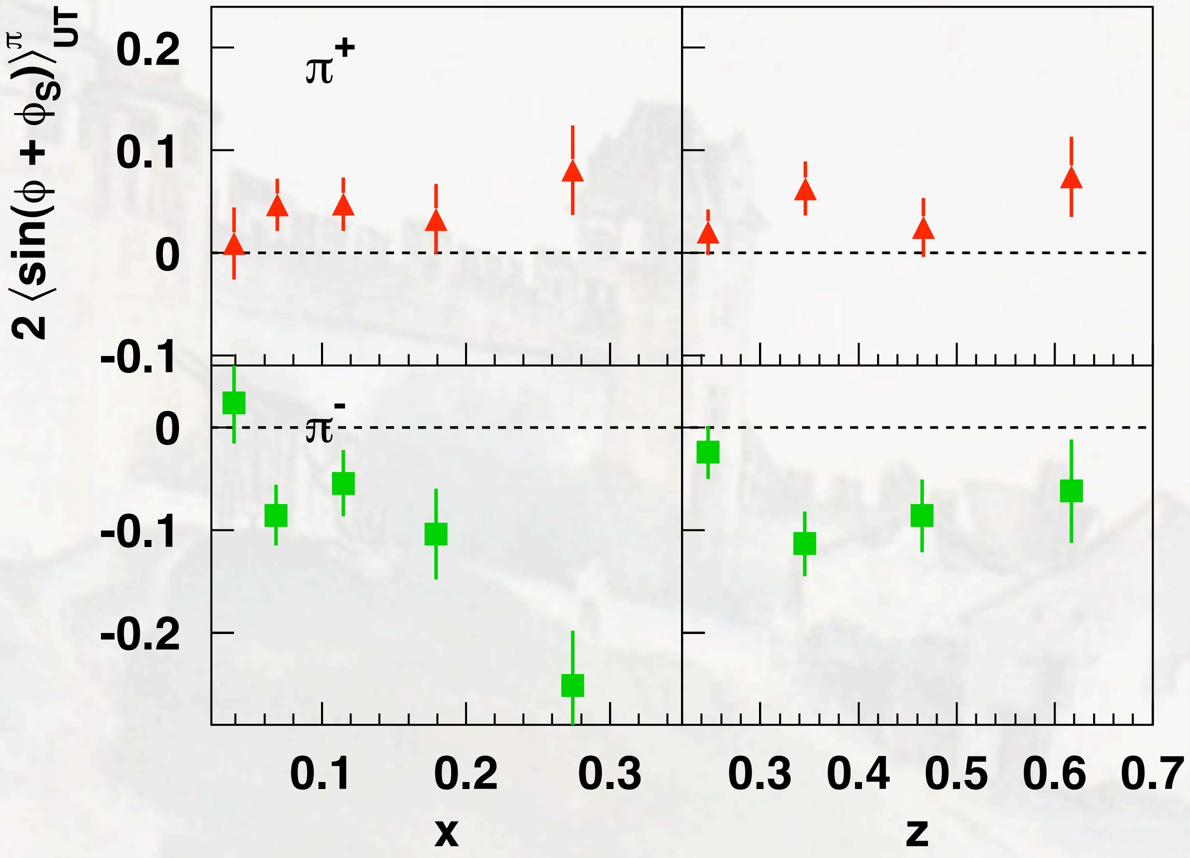
Transversity distribution (Collins fragmentation)

- significant in size and opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one



- leads to various cancellations in SSA observables

[A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]



2005: First evidence from HERMES
SIDIS on proton

Non-zero transversity
Non-zero Collins function

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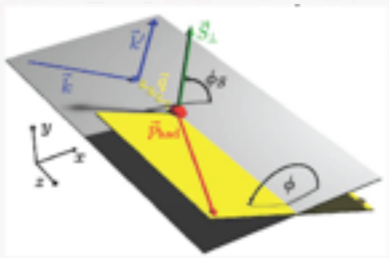
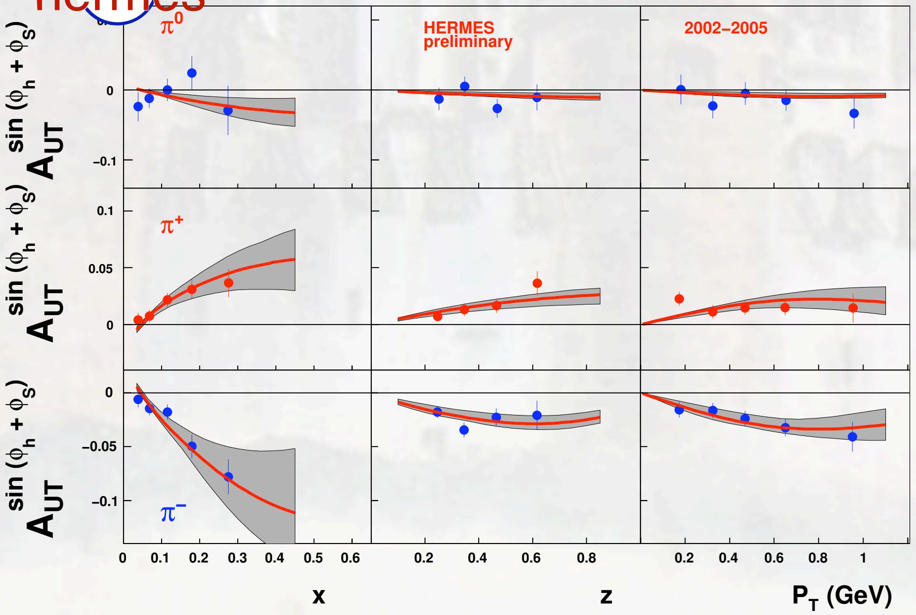
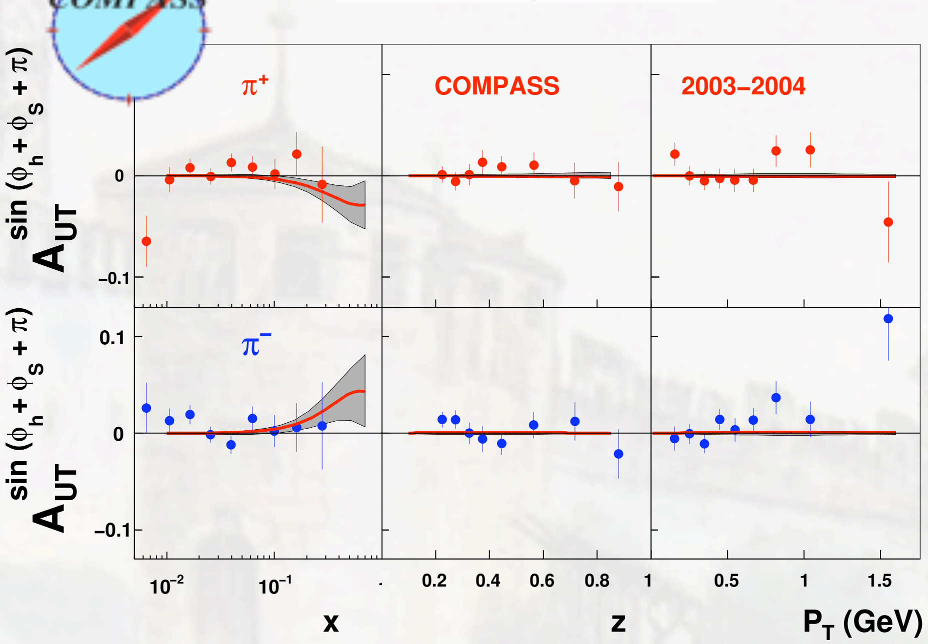
Fit of Collins amplitudes







[left] HERMES data [*Diefenthaler et al. 2007*]

(hydrogen target)

(deuteron target)

[right] COMPASS data [*Alekseev et al. 2008*].

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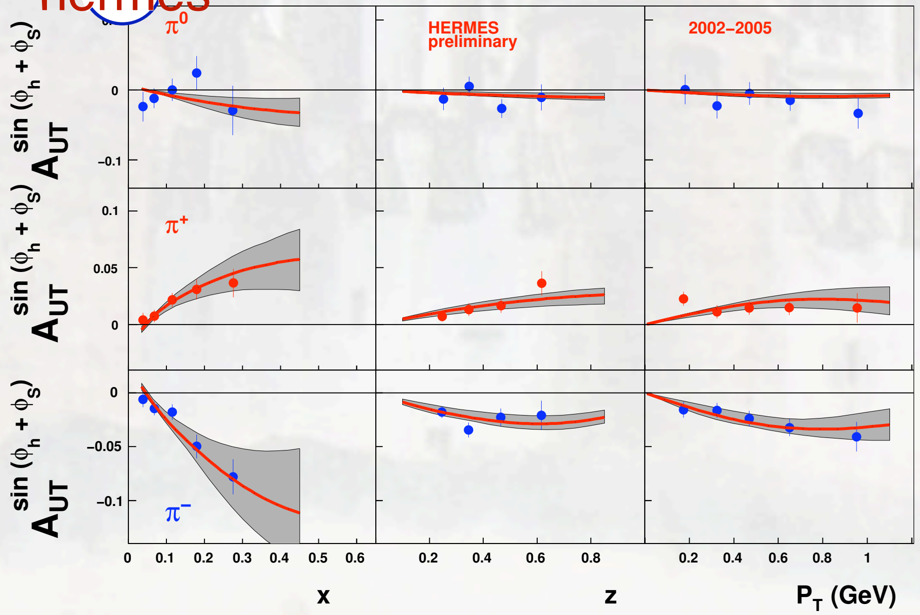

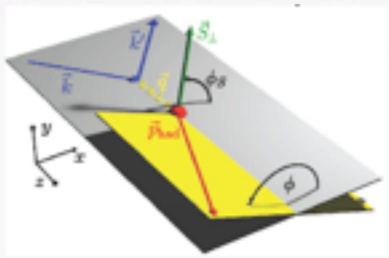

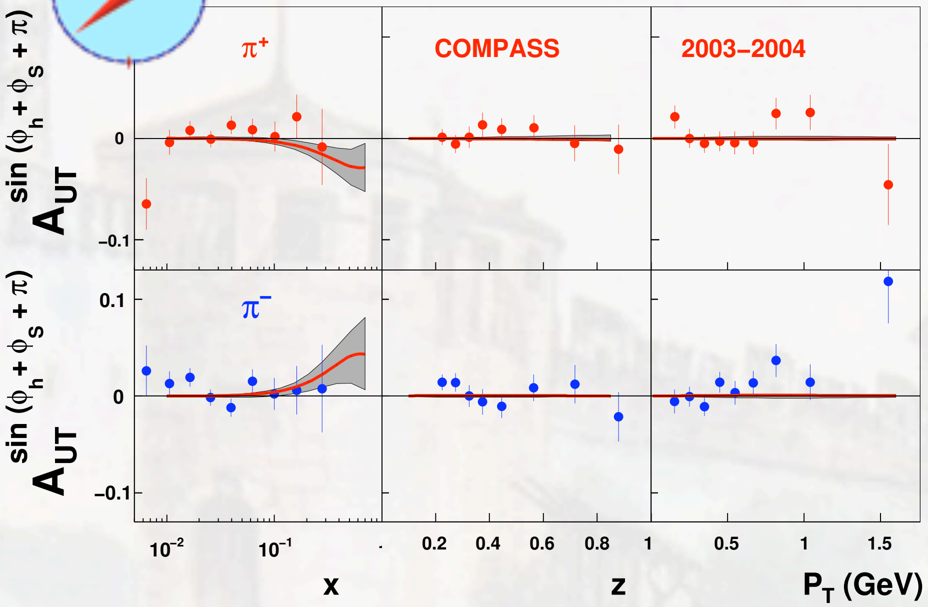

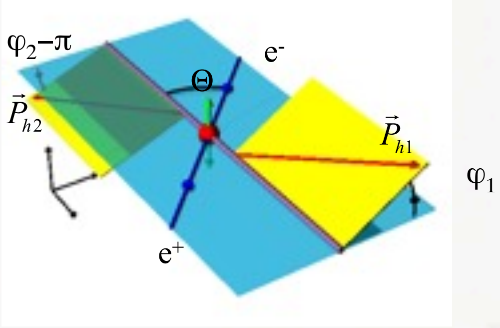

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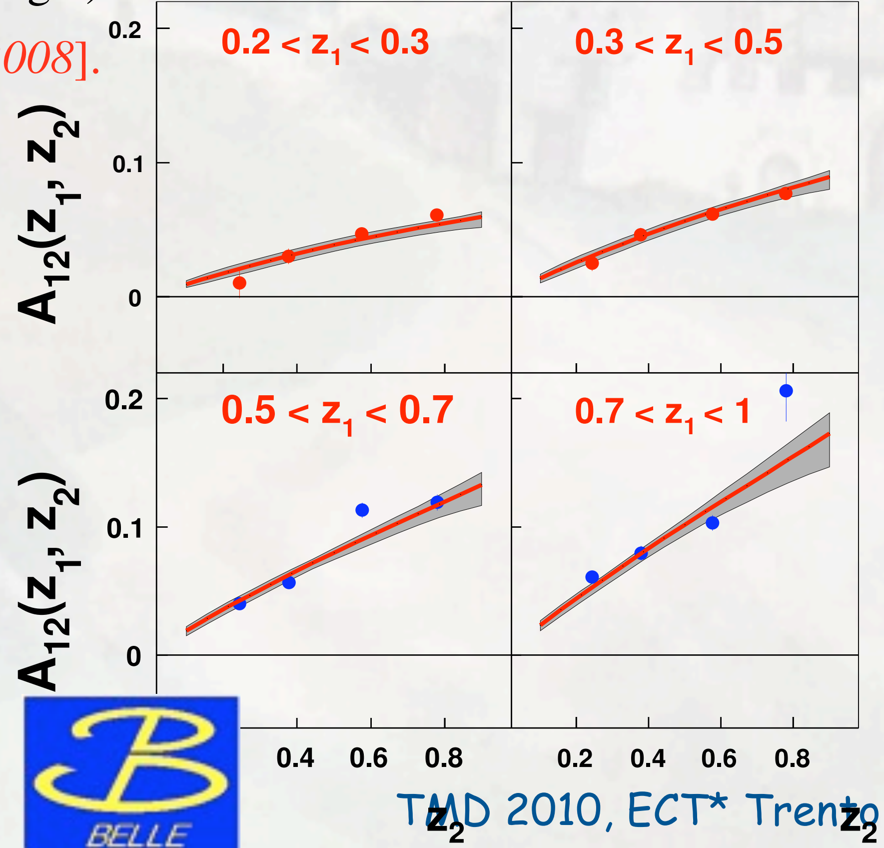

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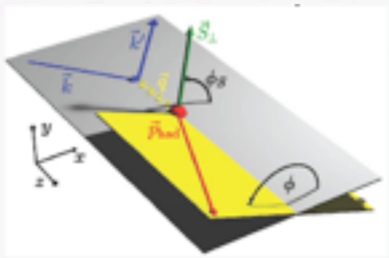
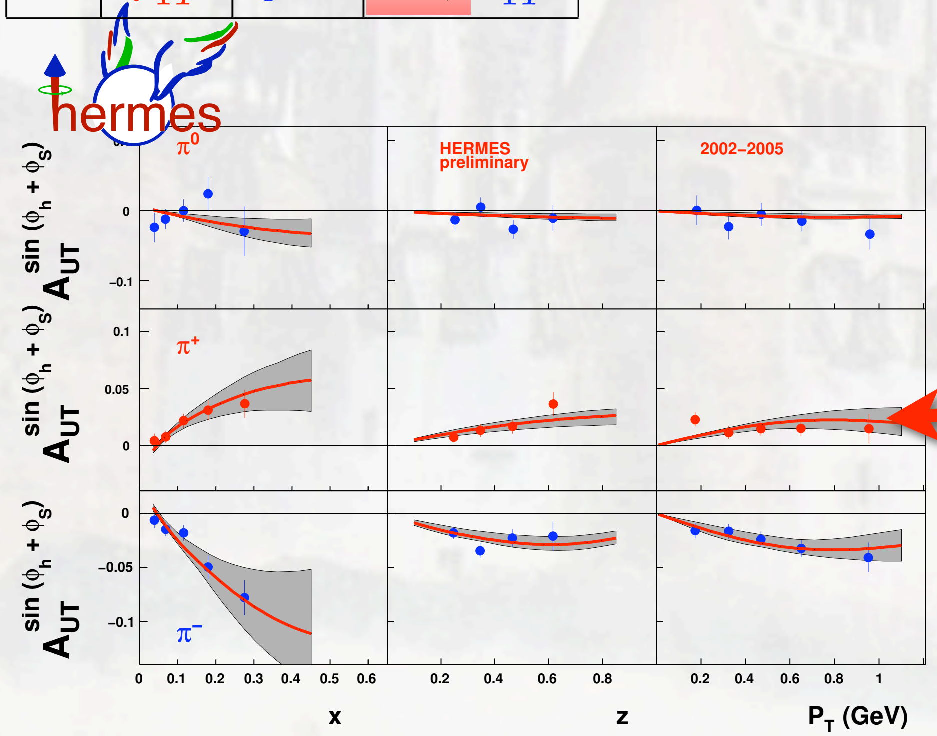
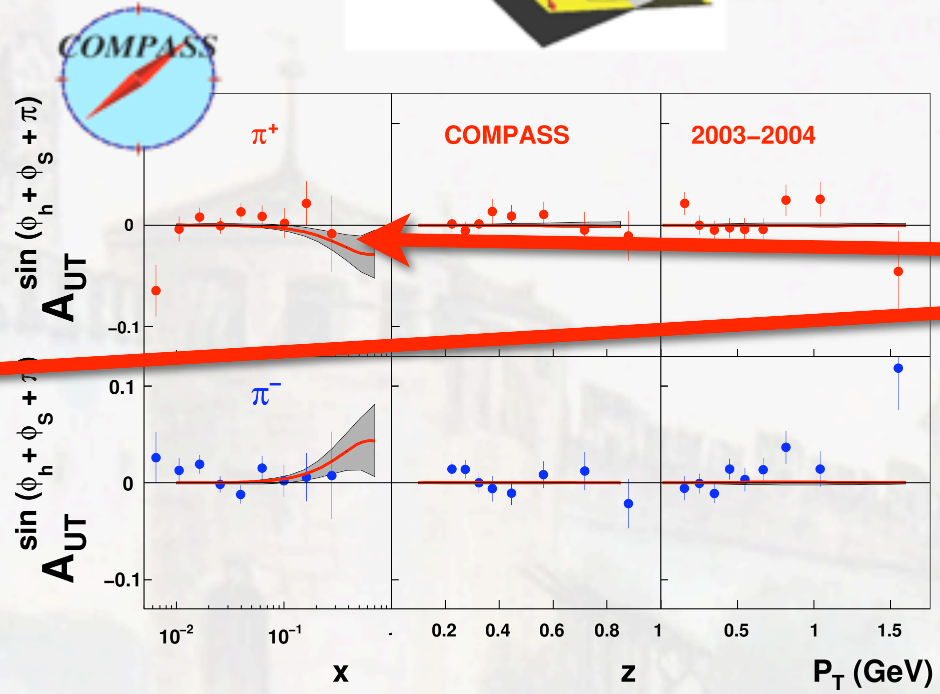
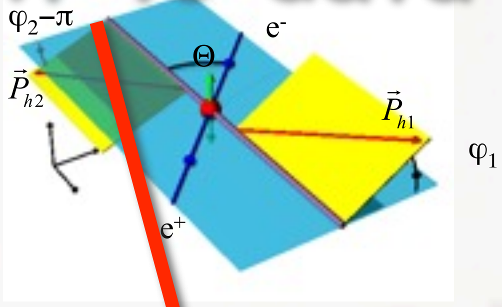






fit to data



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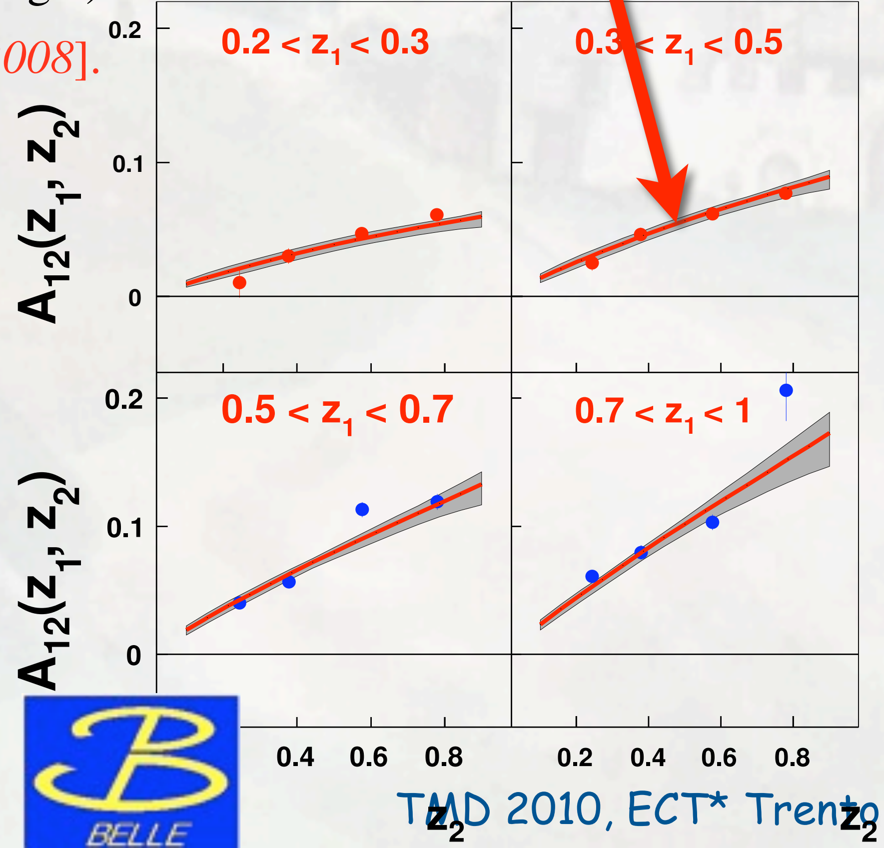

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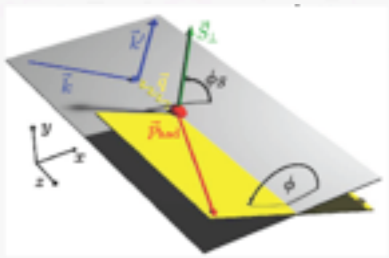

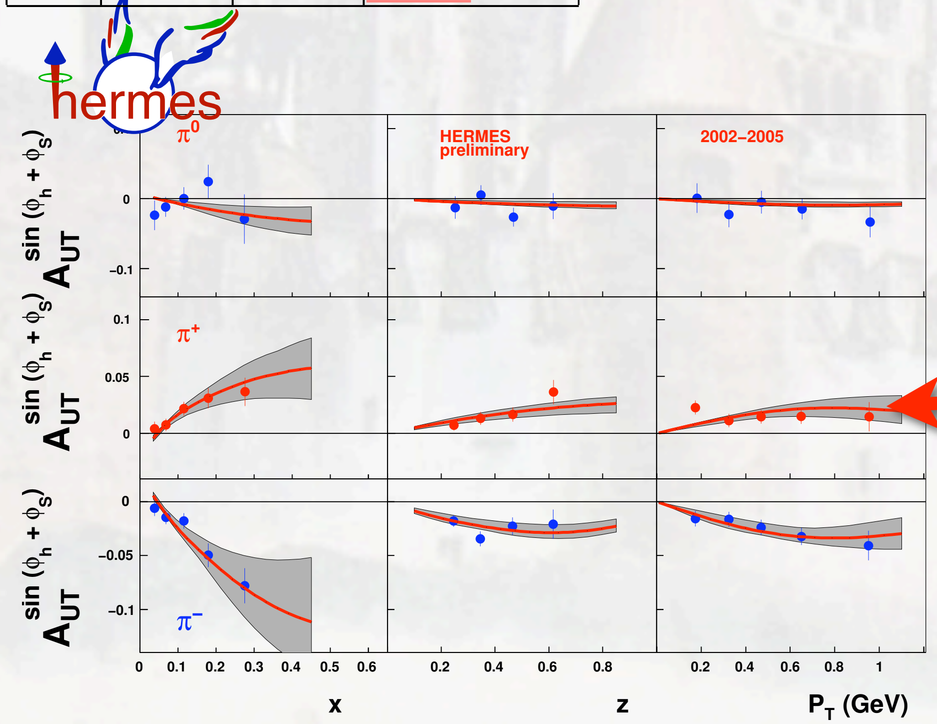

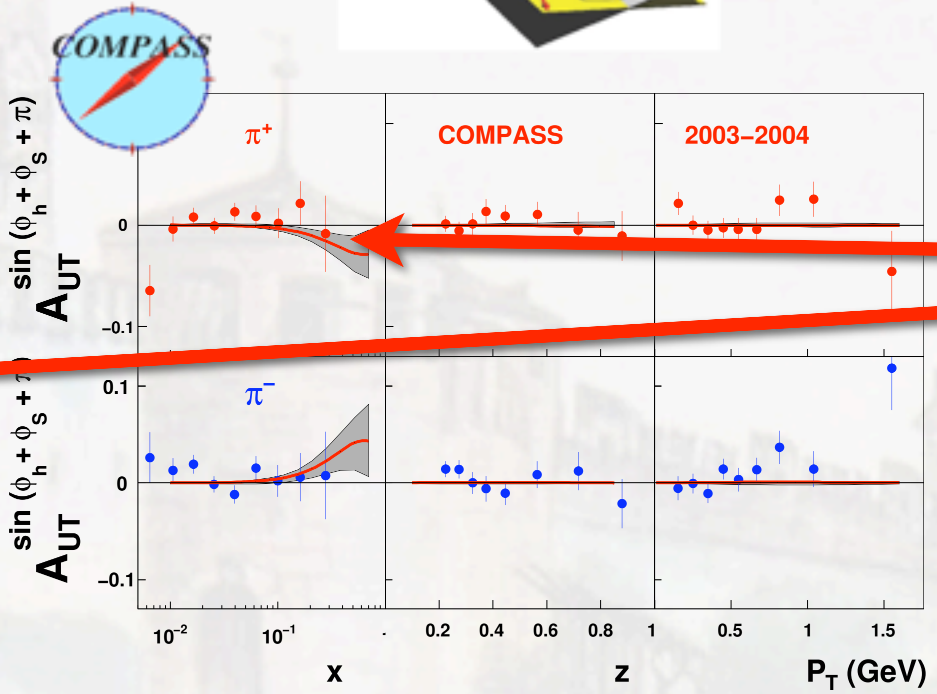

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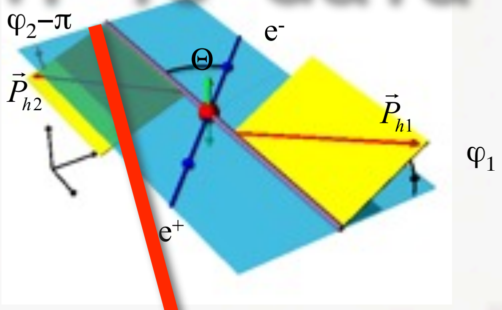

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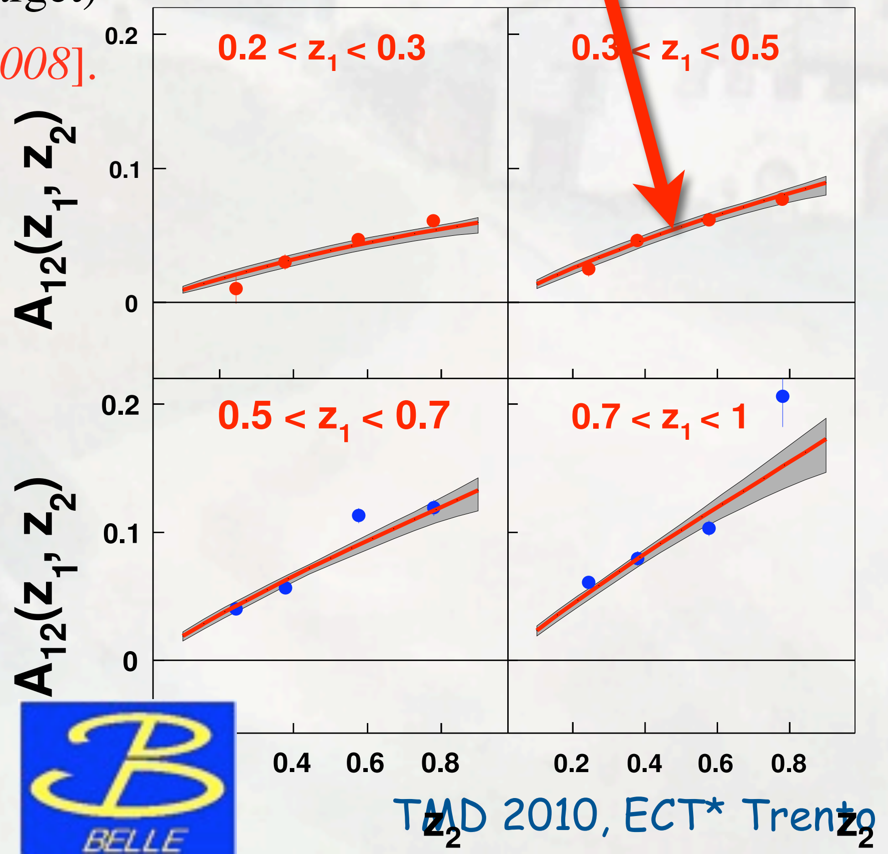

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☛ **M. Anselmino, S. Melis**

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Transversity: models and fits

[1] Soffer et al. PRD 65 (02)
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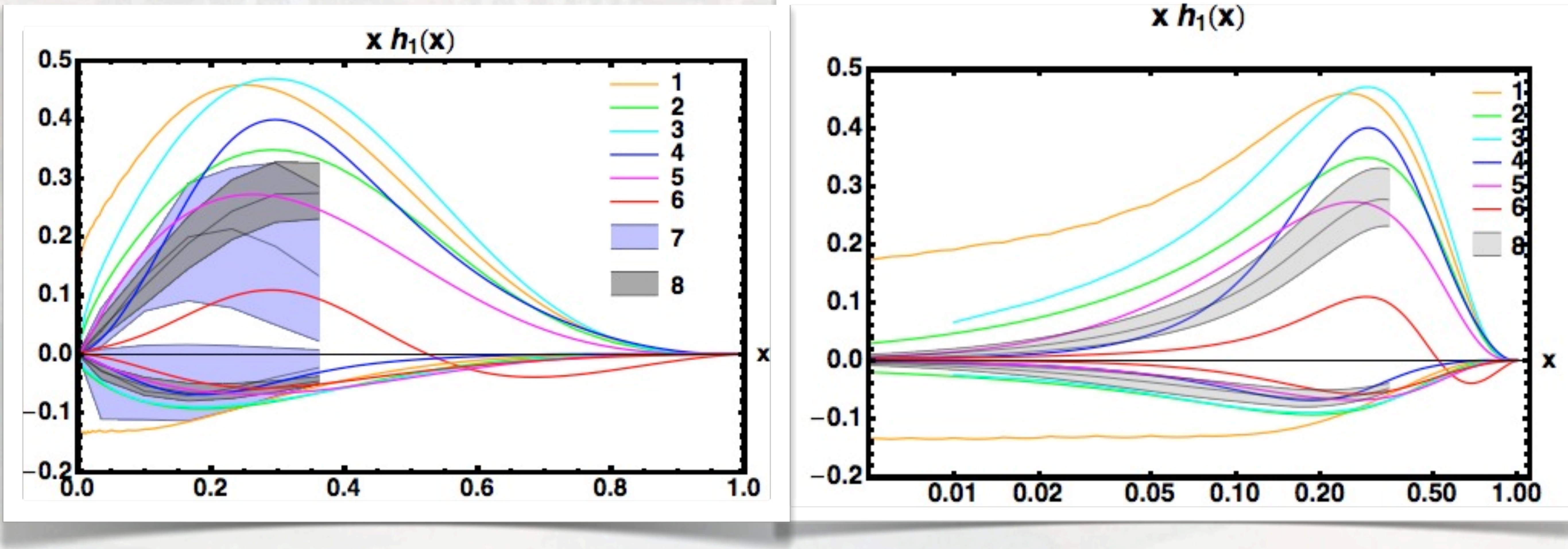

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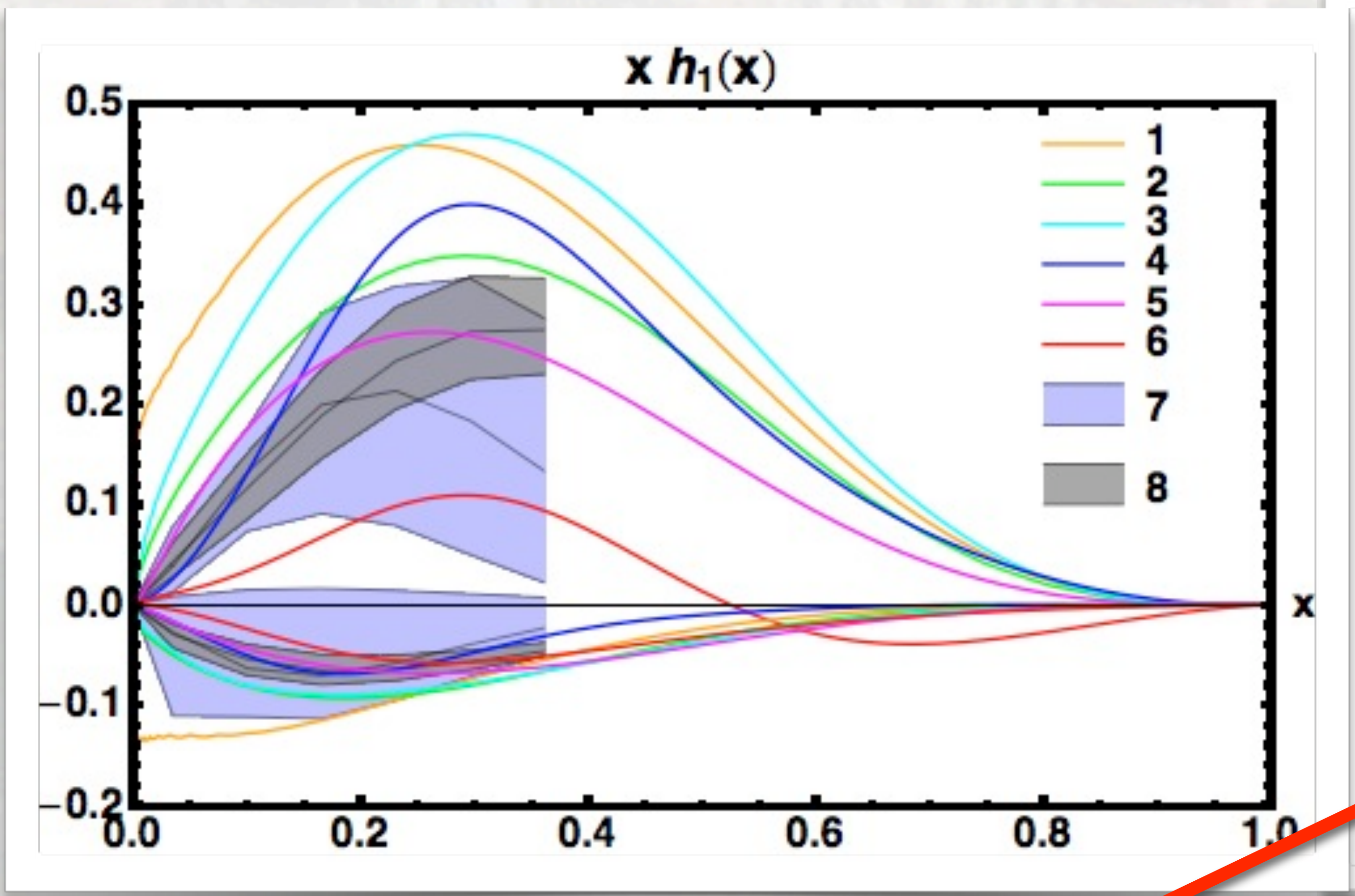

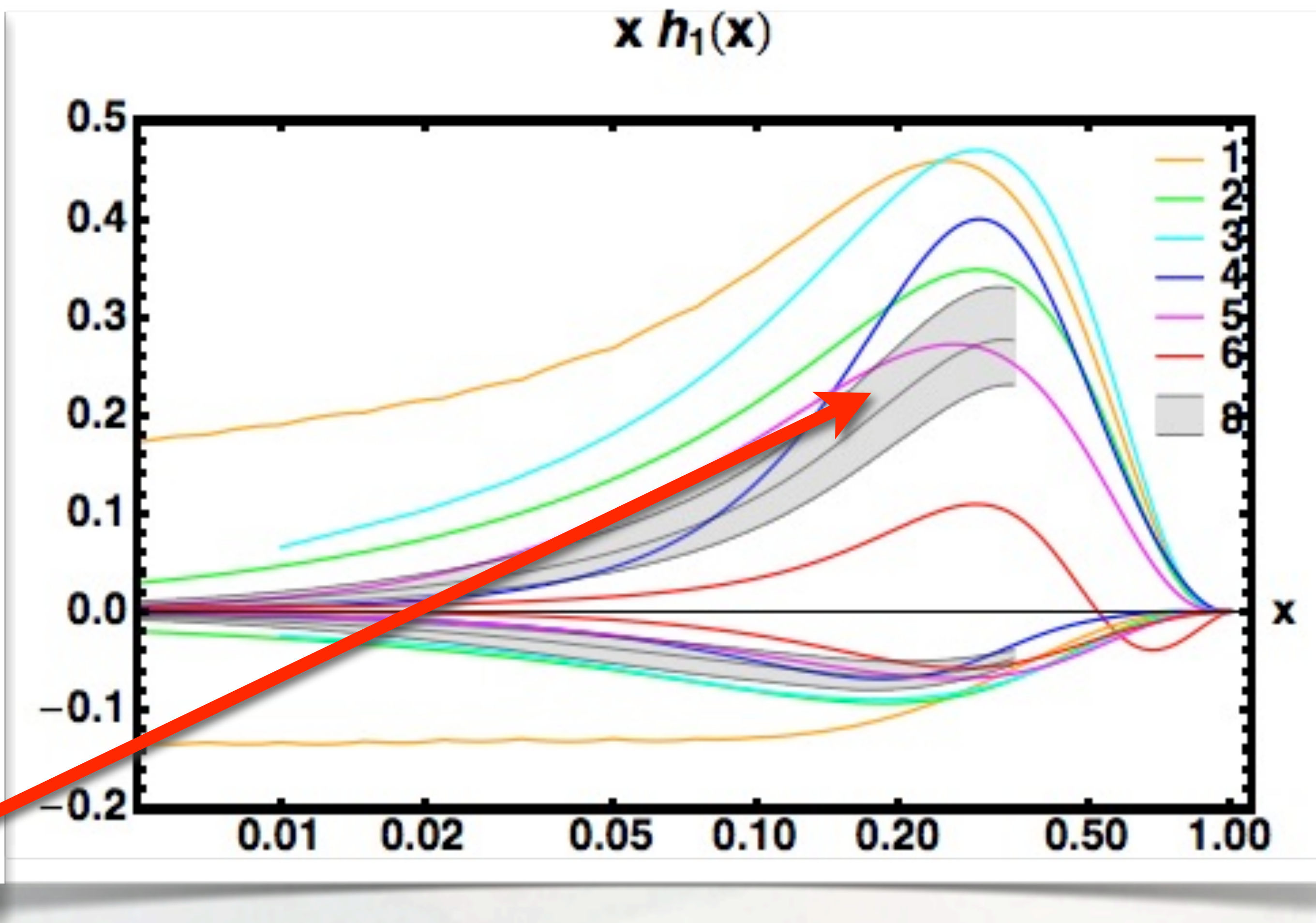

☑ u quark transversity along nucleon spin

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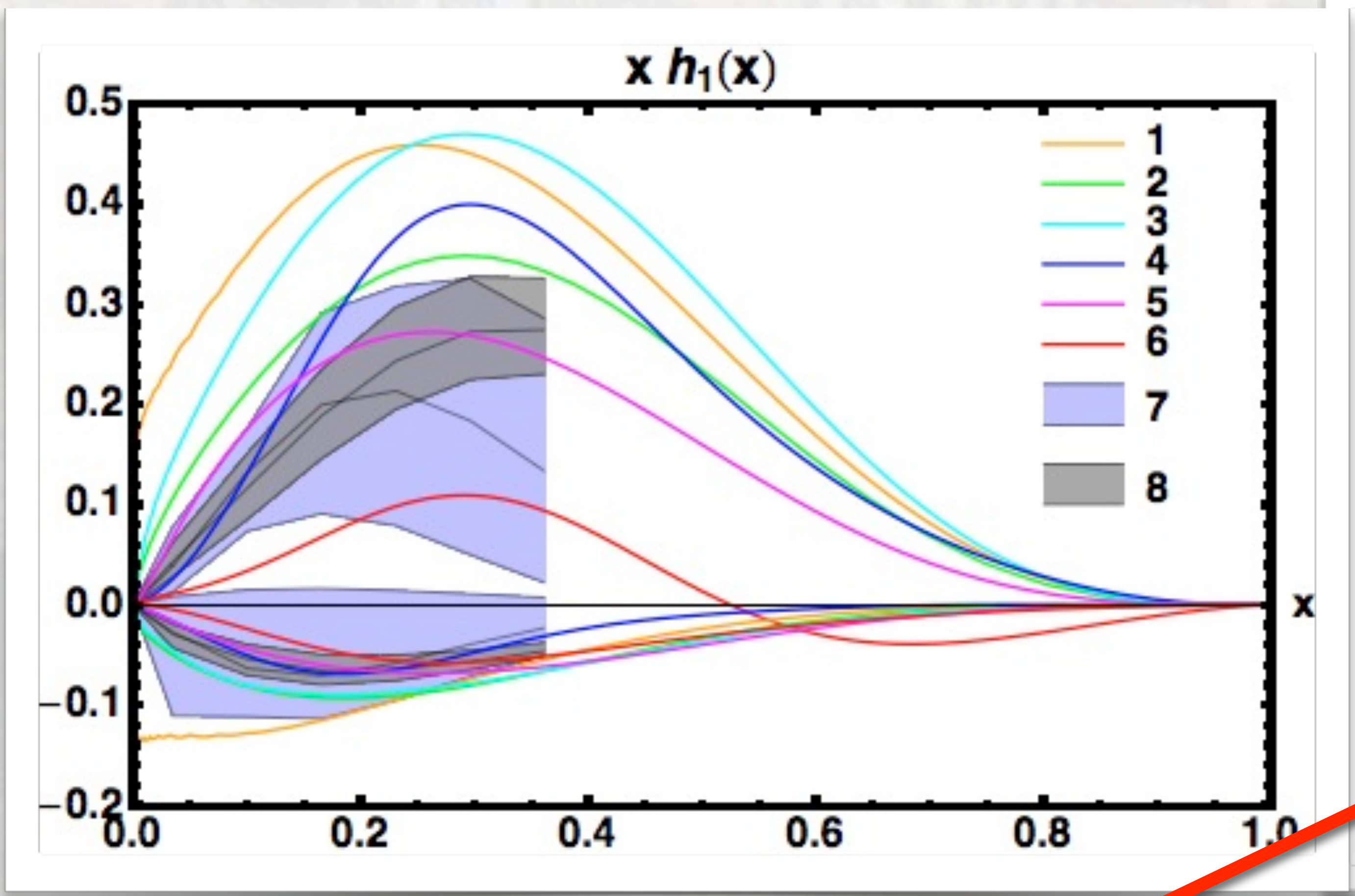

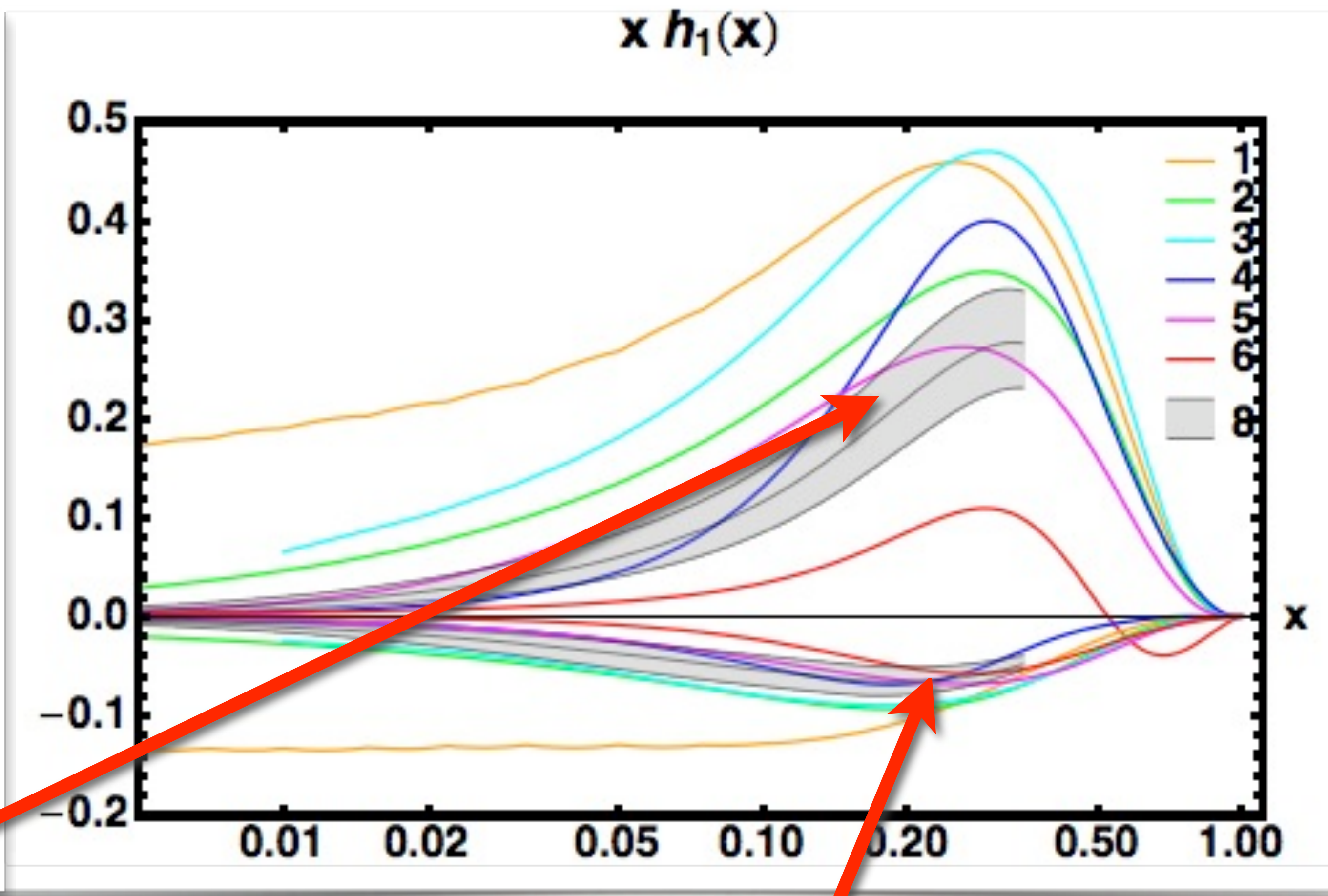

☑ u quark transversity along nucleon spin

☑ d quark transversity anti-parallel to nucleon spin

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Transversity: models and fits

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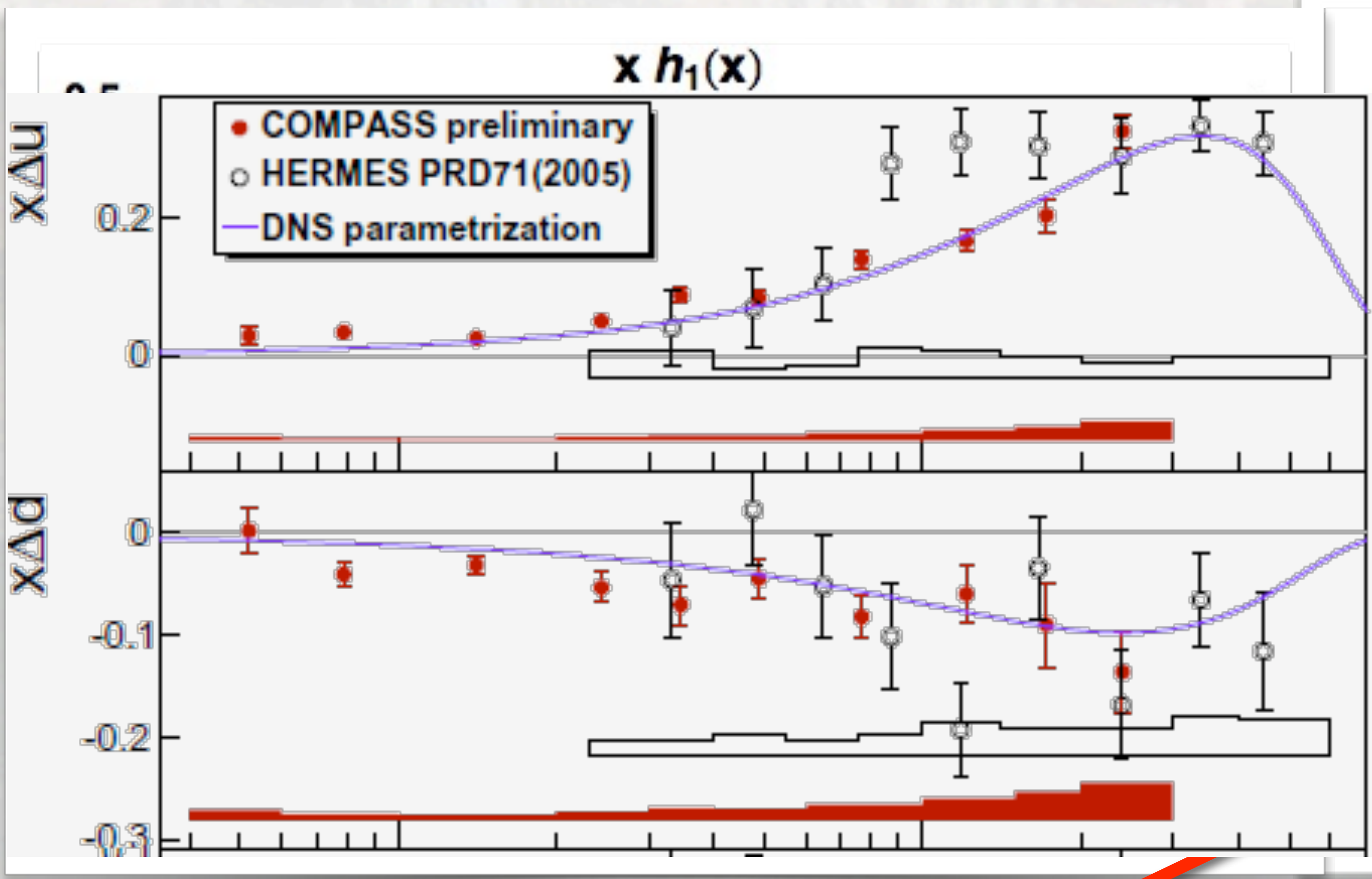

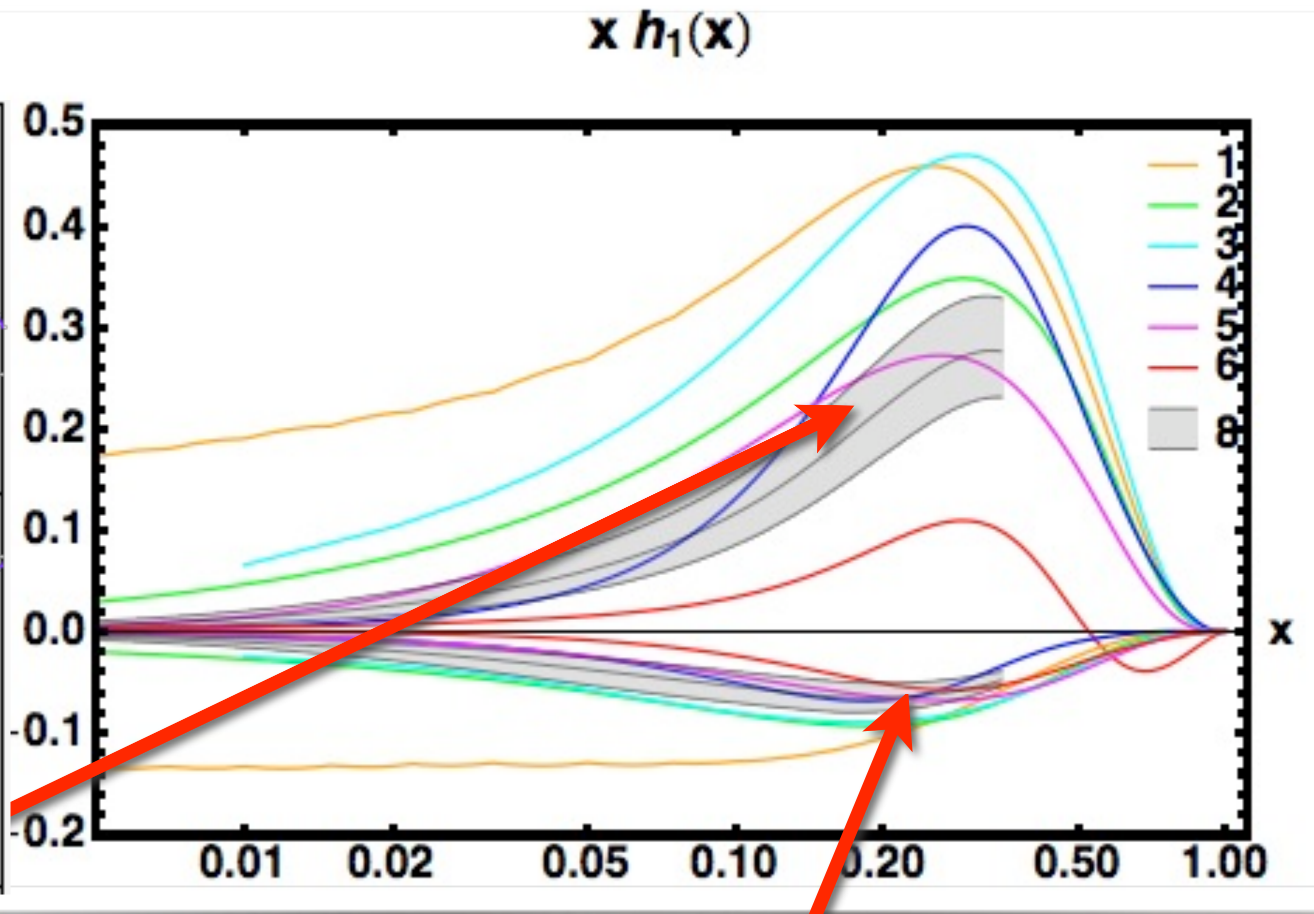

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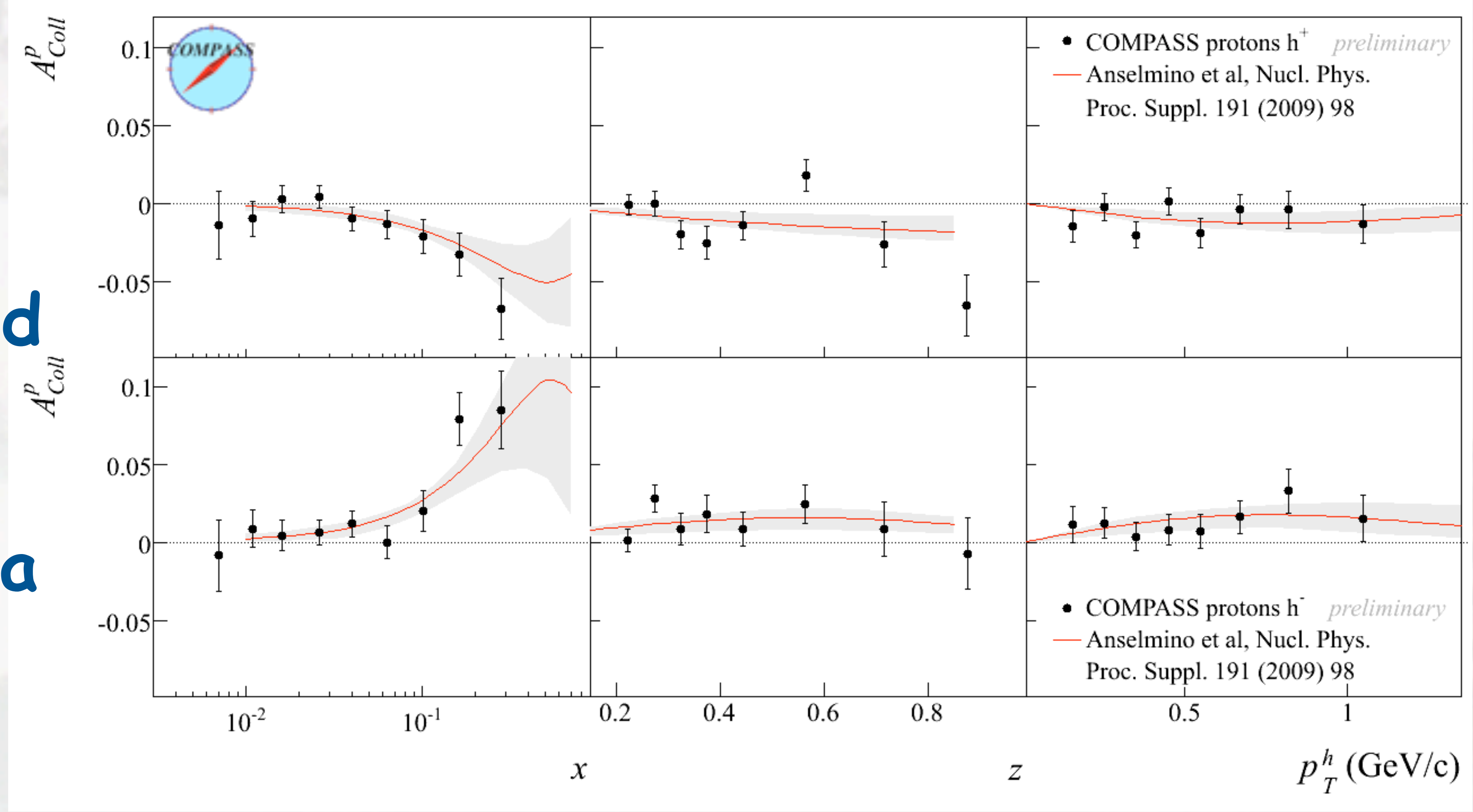
Transversity distribution (Collins fragmentation)



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  - BaBar ☛I. Garzia
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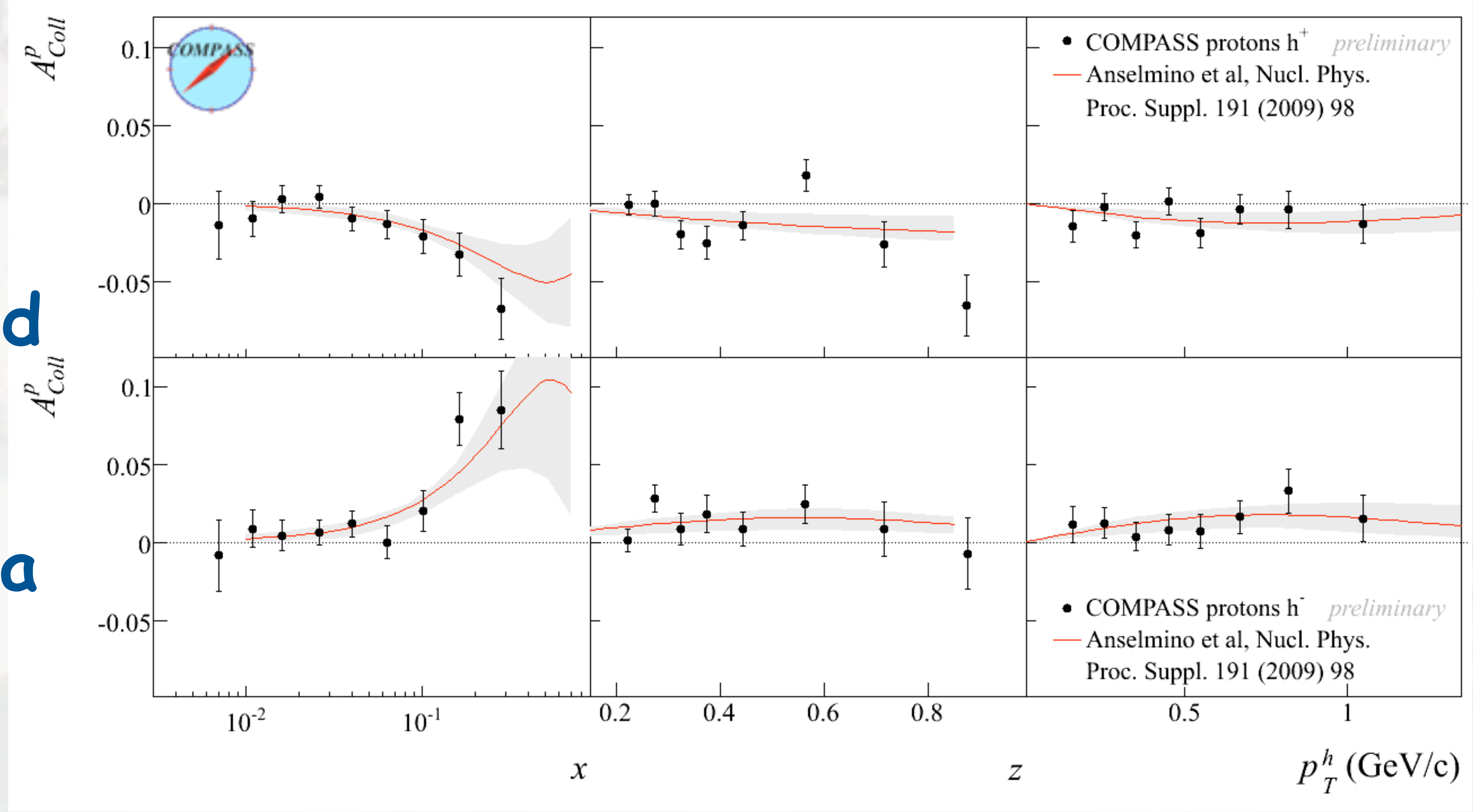

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Pretzelosity

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- chiral-odd ➥ needs Collins FF
  (or similar)
- leads to sin(3 ϕ - ϕ s) modulation in A_{UT}
- proton and deuteron data consistent with zero
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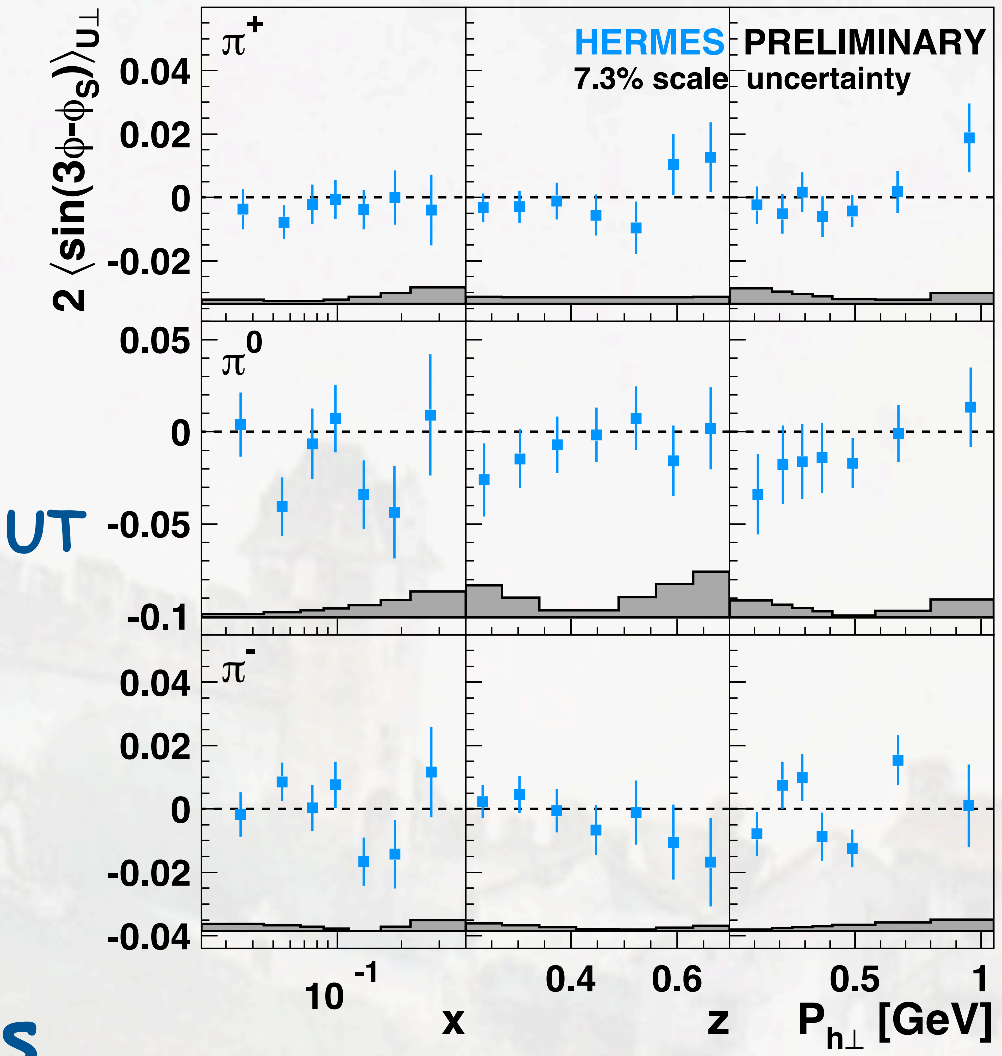

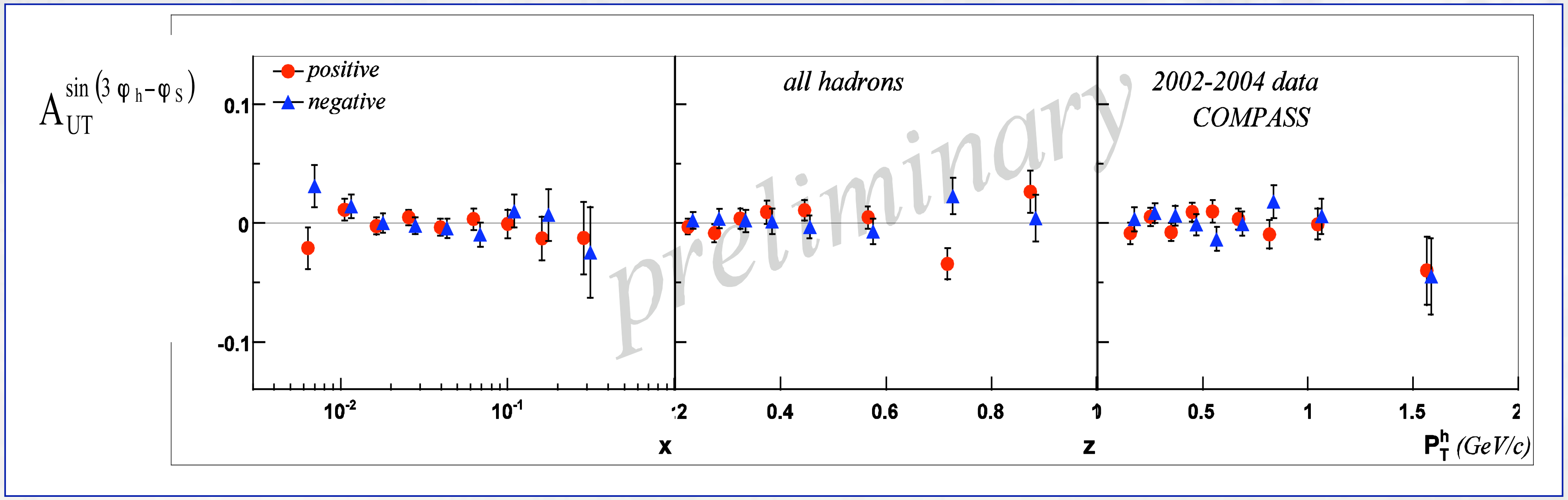

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Pretzelosity

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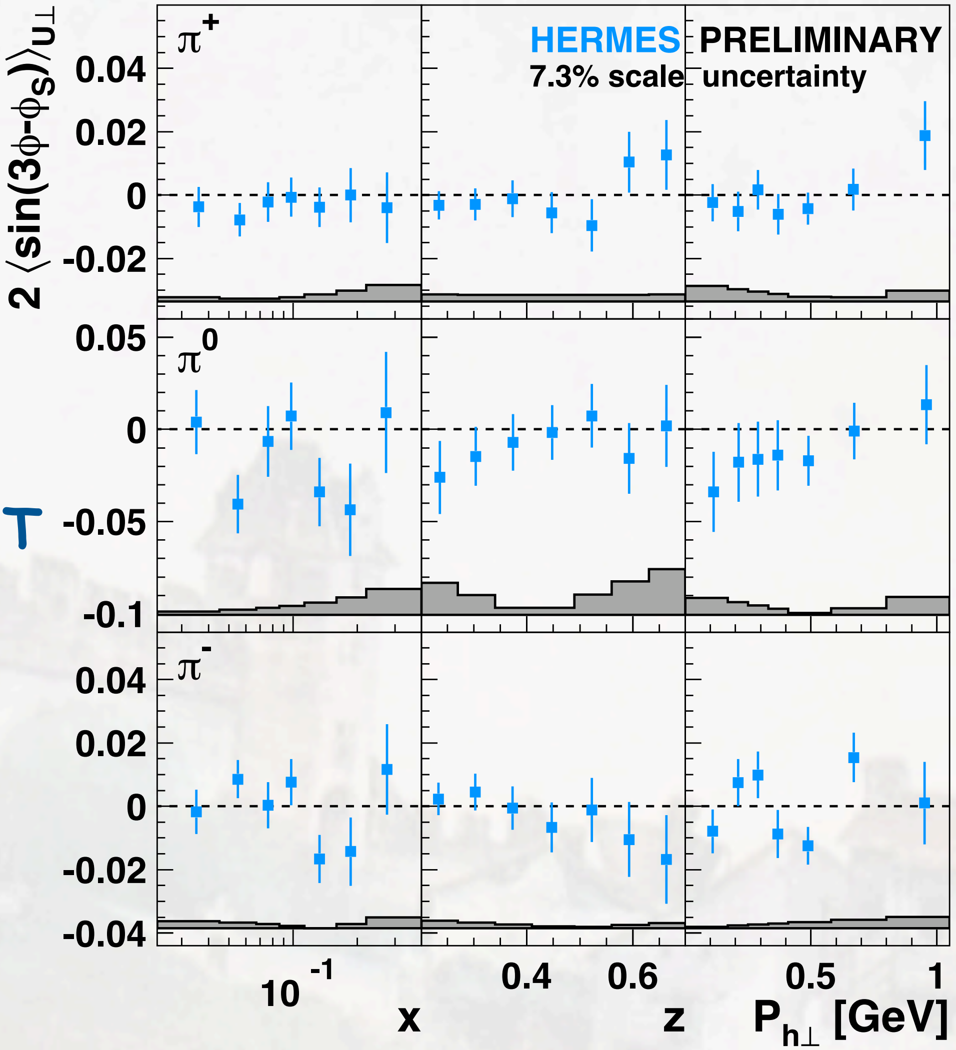
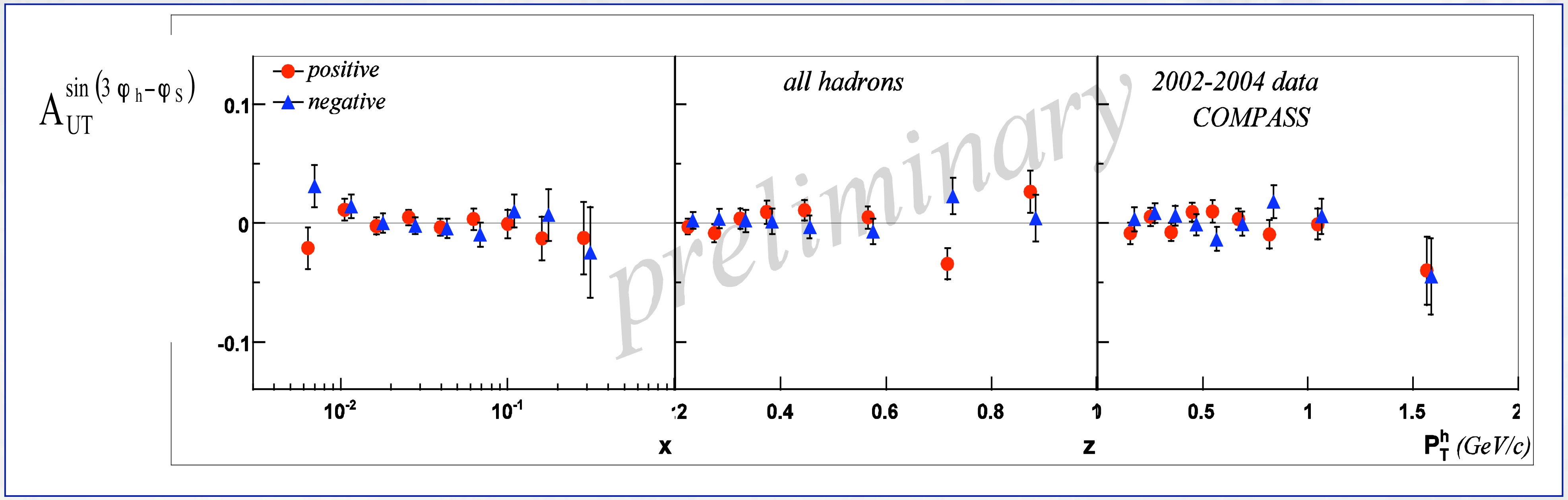
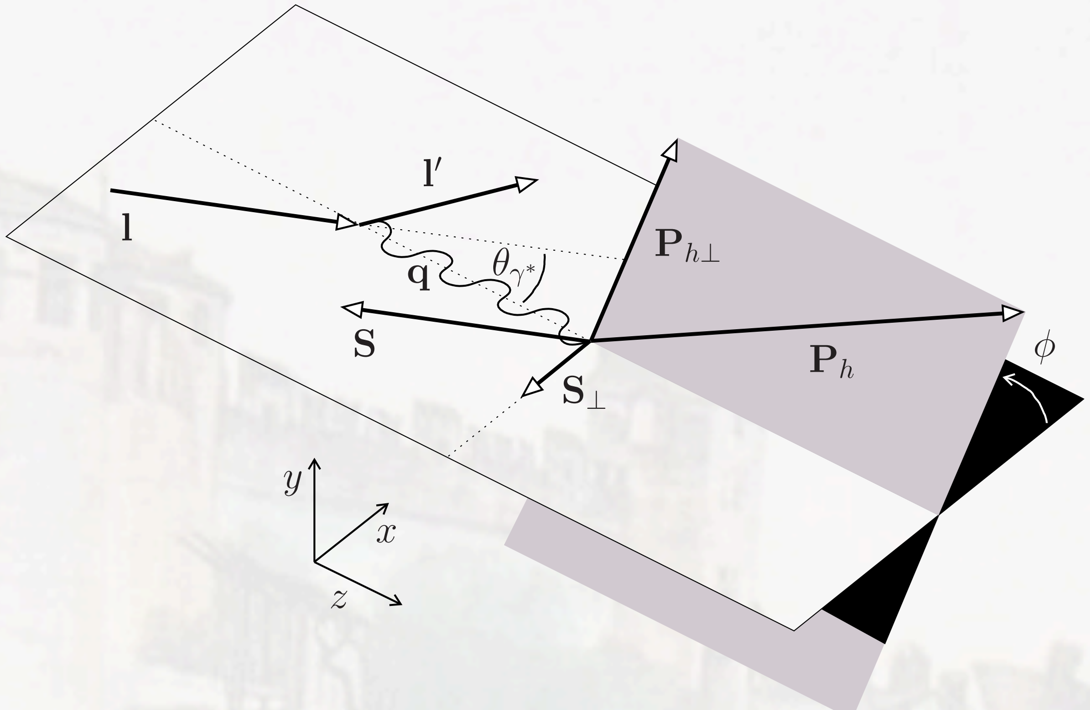


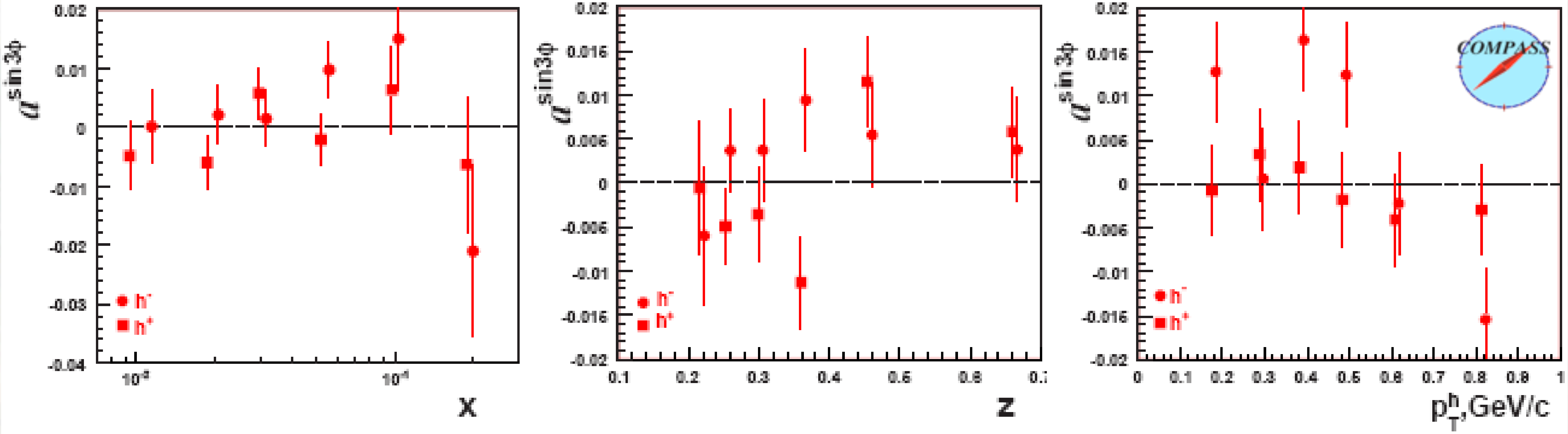


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

Pretzelosity

- can also use longitudinally polarized targets:

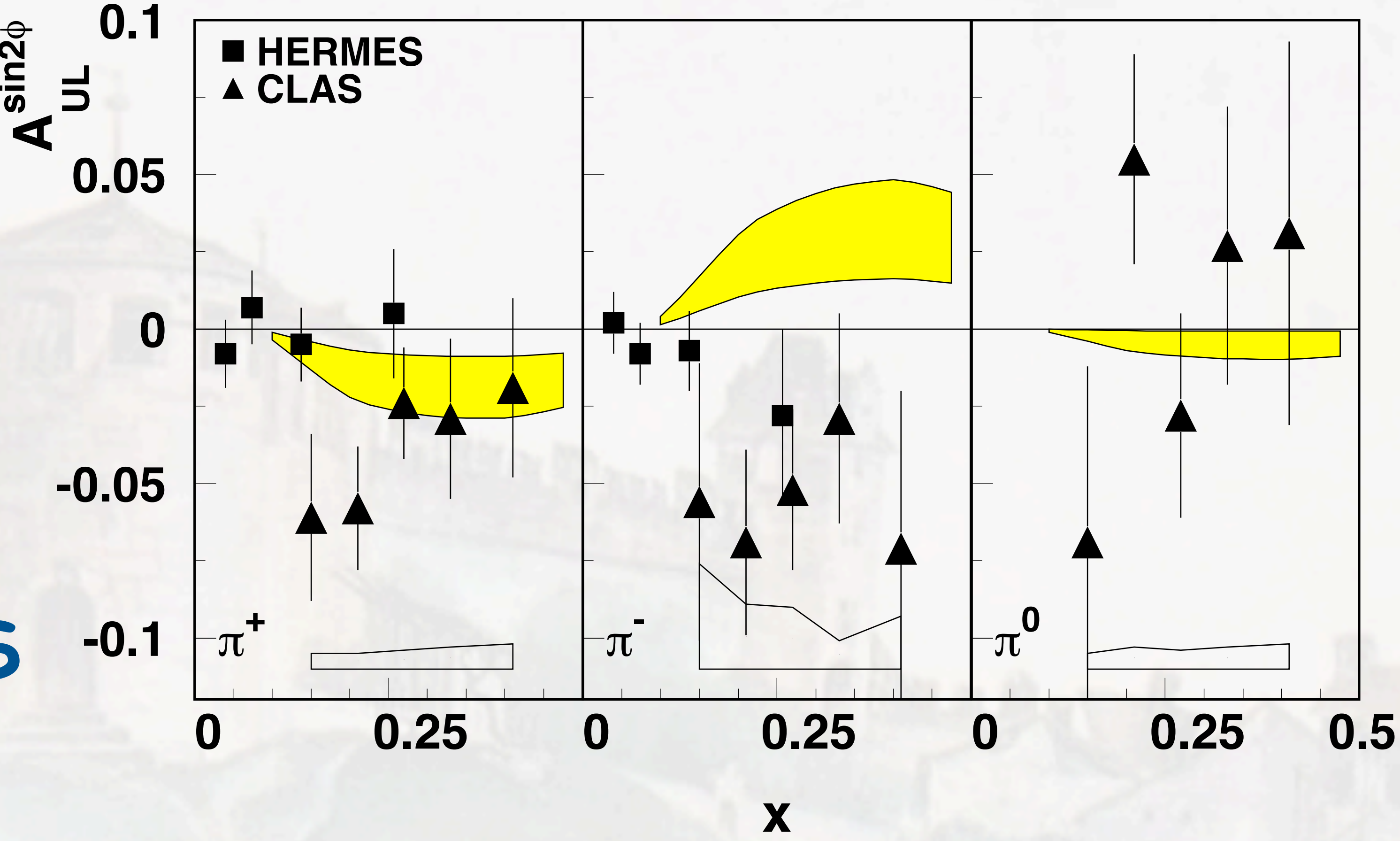


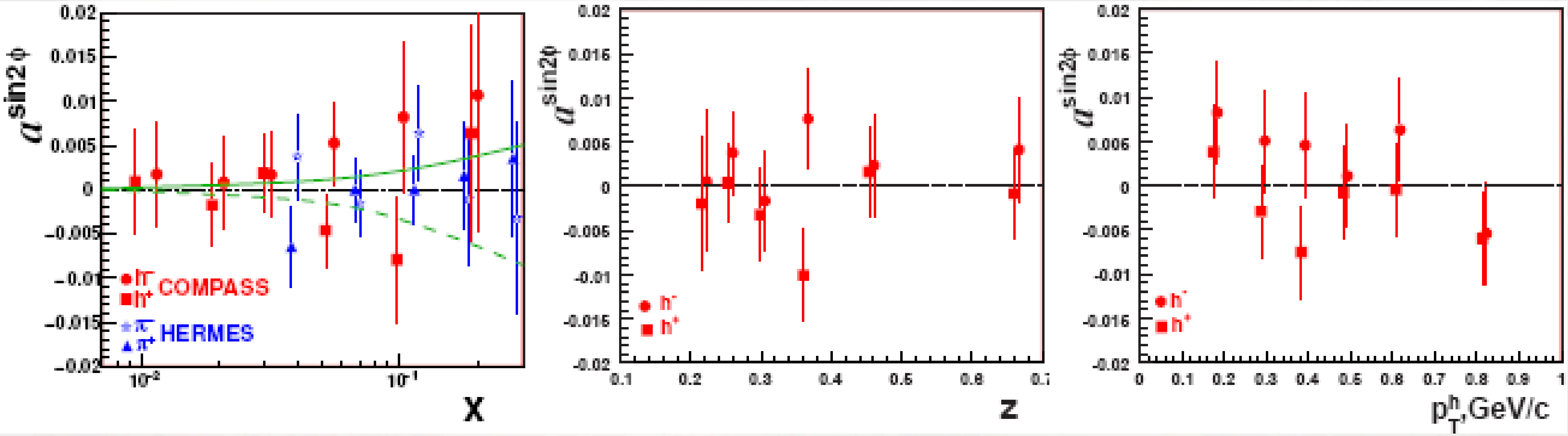


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Worm-Gear I

- chiral-odd
- evidence from CLAS
- consistent with zero at COMPASS and HERMES

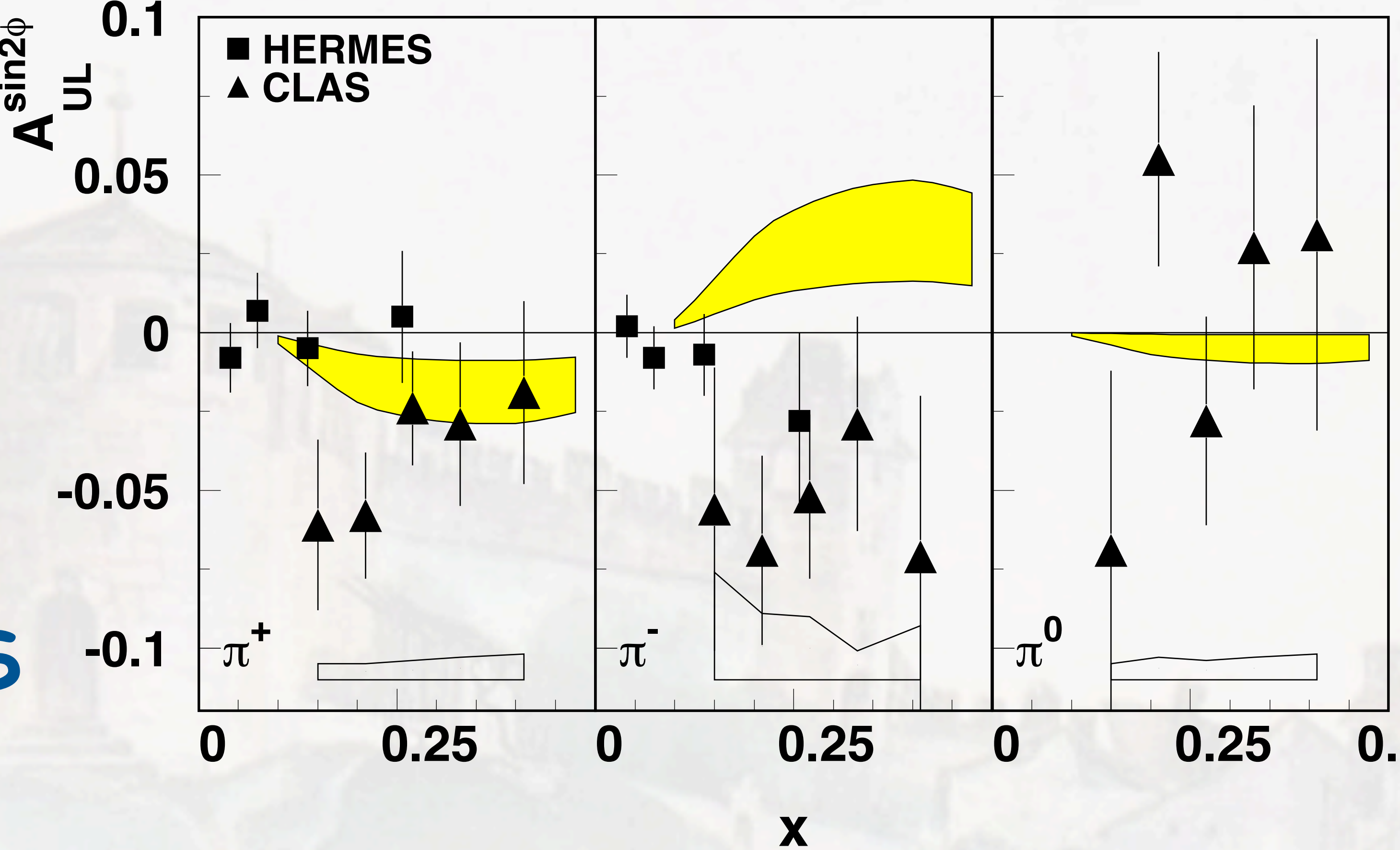




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Worm-Gear I

☛ H. Avakian



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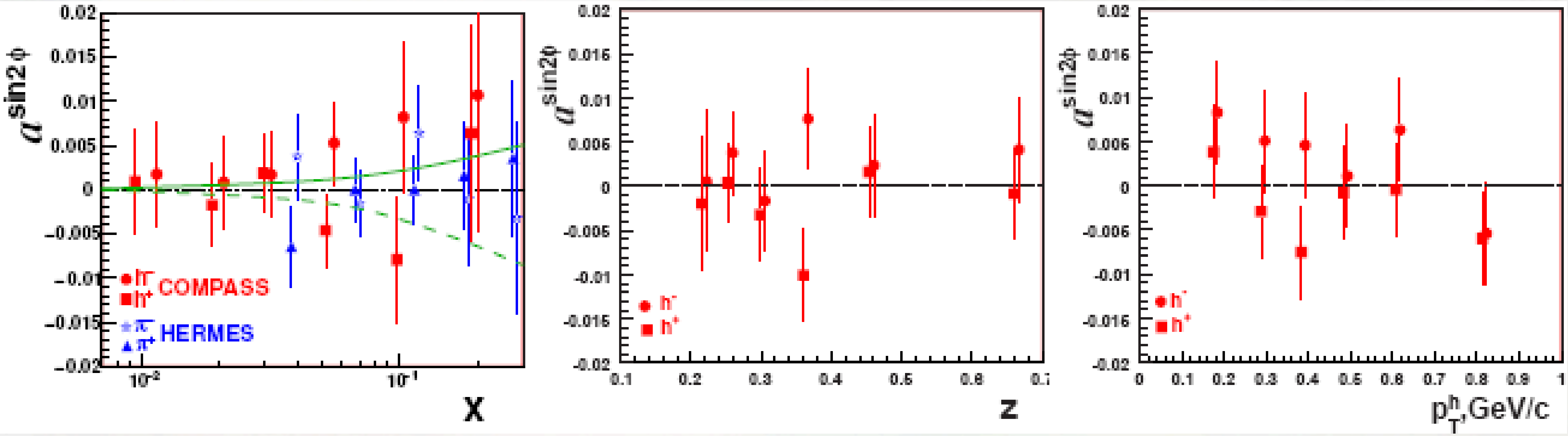

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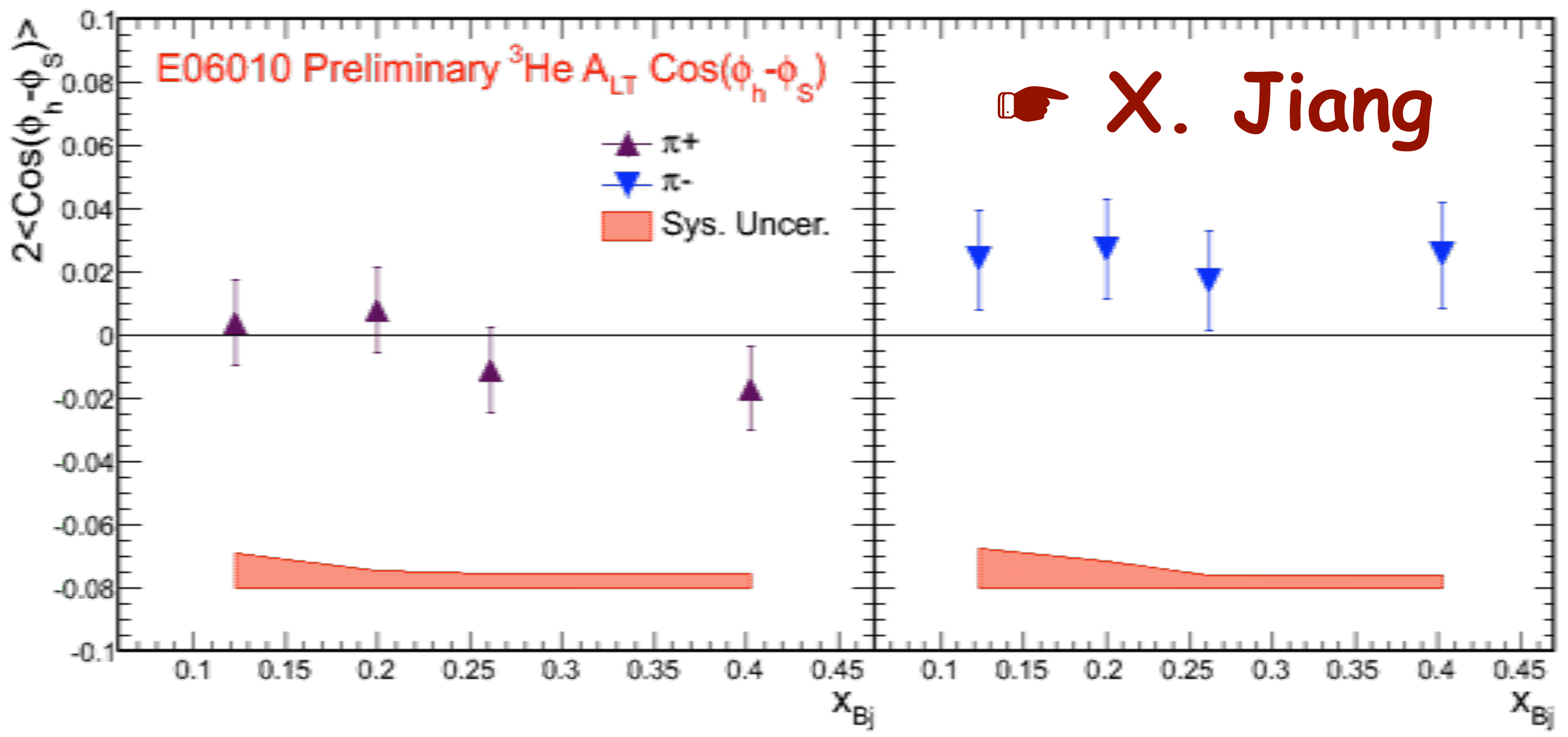
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Worm-Gear II

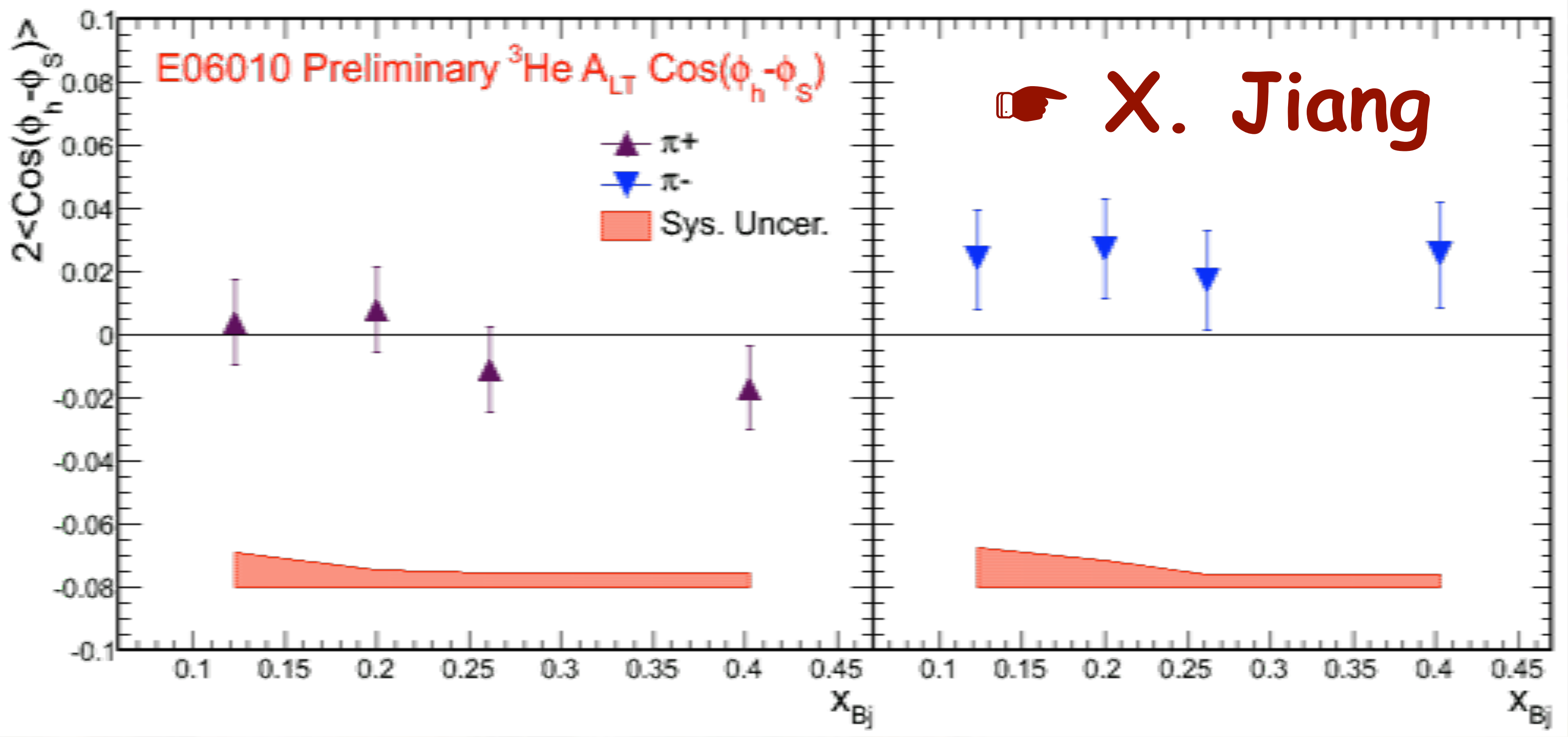
- chiral even
- first direct evidence for worm-gear g_{1T}



☛ X. Jiang

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

Worm-Gear II



☞ X. Jiang

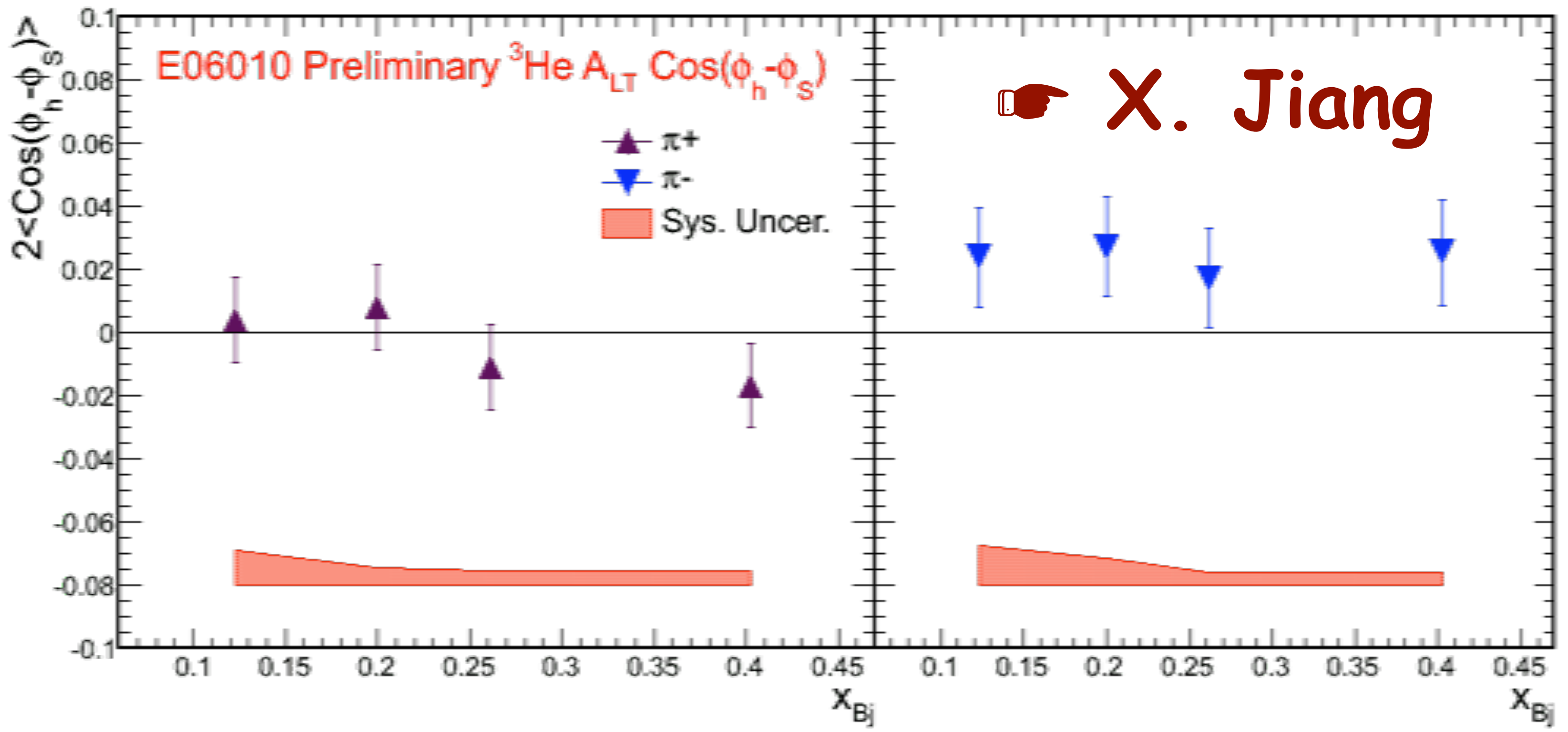
- chiral even
- first direct evidence for worm-gear g_{1T}
- indirect hints from A_{UT}

$$\propto \left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right)$$

$$- \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) - \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{D}^{\perp}}{z} \right) \right]$$

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

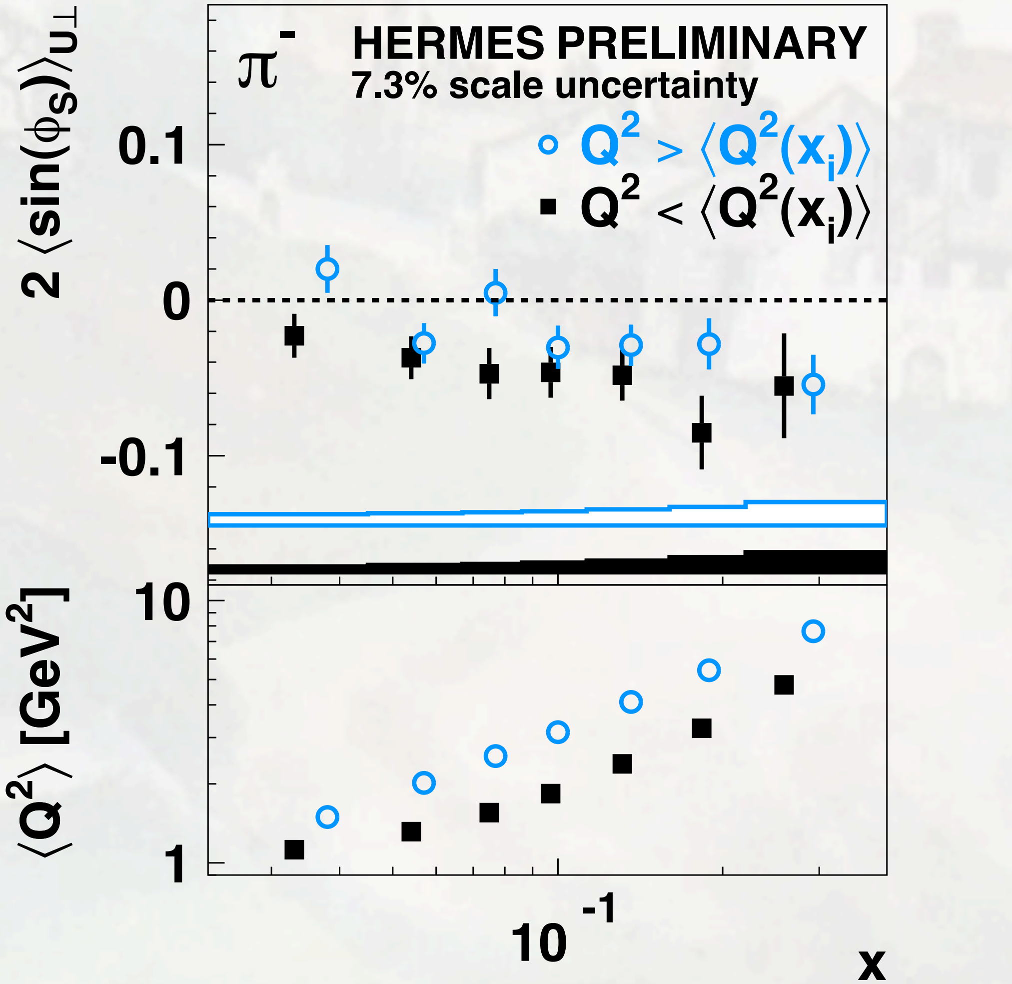
Worm-Gear II



☛ X. Jiang

- chiral even
- first direct evidence for worm-gear g_{1T}
- indirect hints from A_{UT} ☛ A.Rostomyan

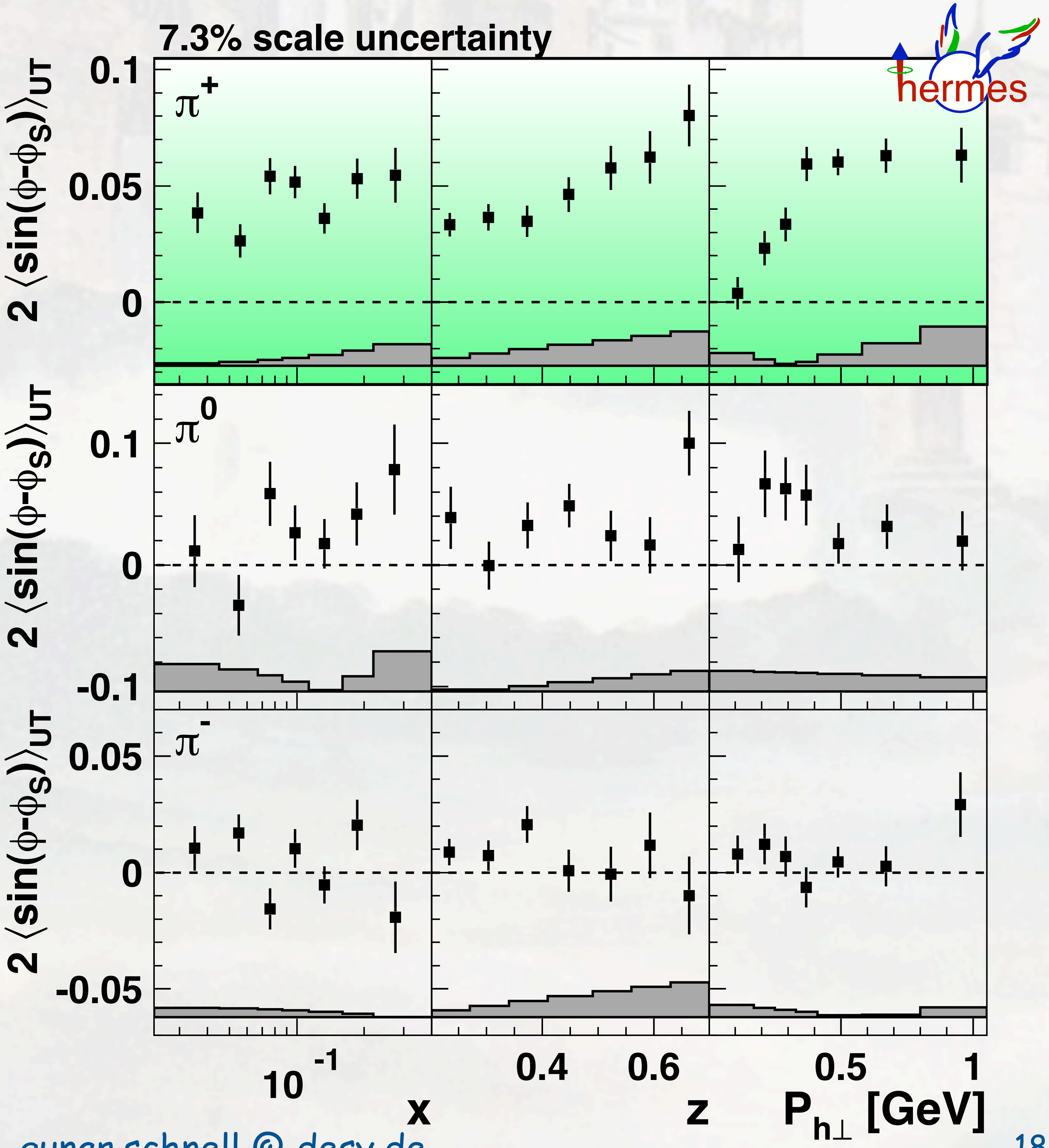
$$\propto \left(x f_{T}^{\perp} D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z} \right) - \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^{\perp}}{z} \right) - \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp} \frac{\tilde{D}^{\perp}}{z} \right) \right]$$



	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

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



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

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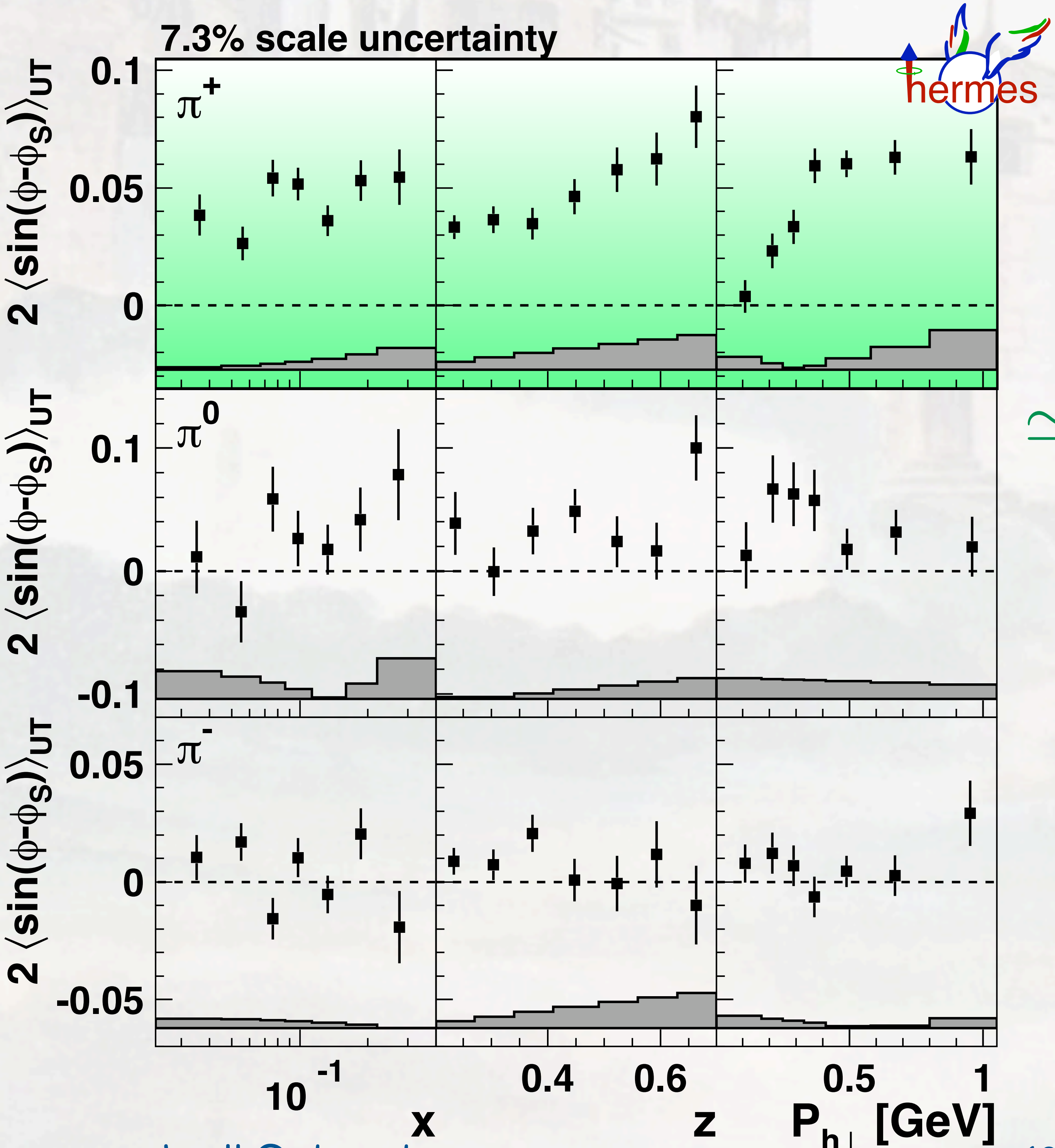


π^+ dominated by u-quark scattering:

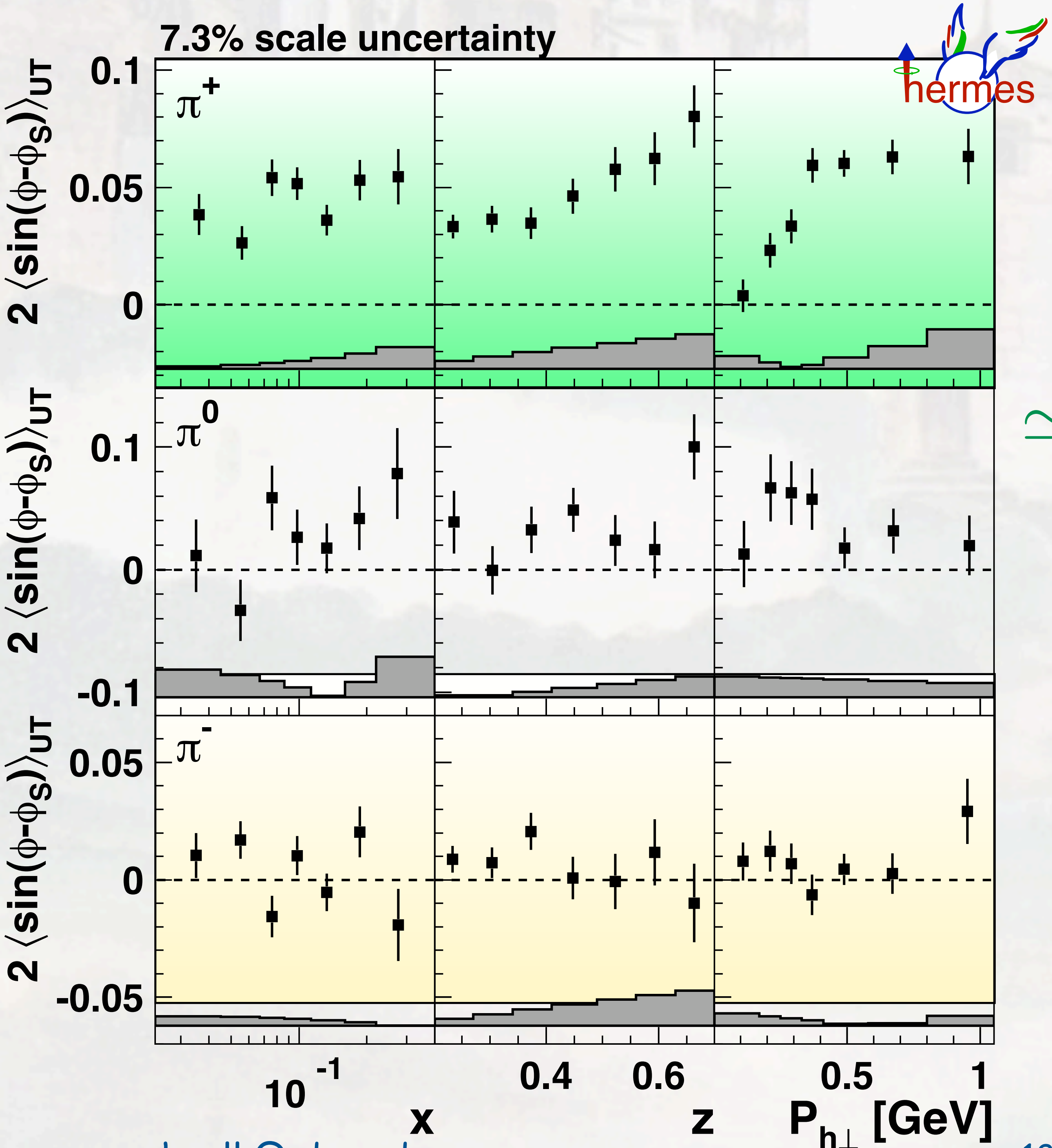
$$\simeq -\frac{f_{1\rm T}^{\perp,u}(x,p_T^2)\otimes\mathcal{W}\, D_1^{u\rightarrow\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\rightarrow\pi^+}(z,k_T^2)}$$

☛ **u-quark Sivers DF < 0**

	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

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



π^+ dominated by u-quark scattering:

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

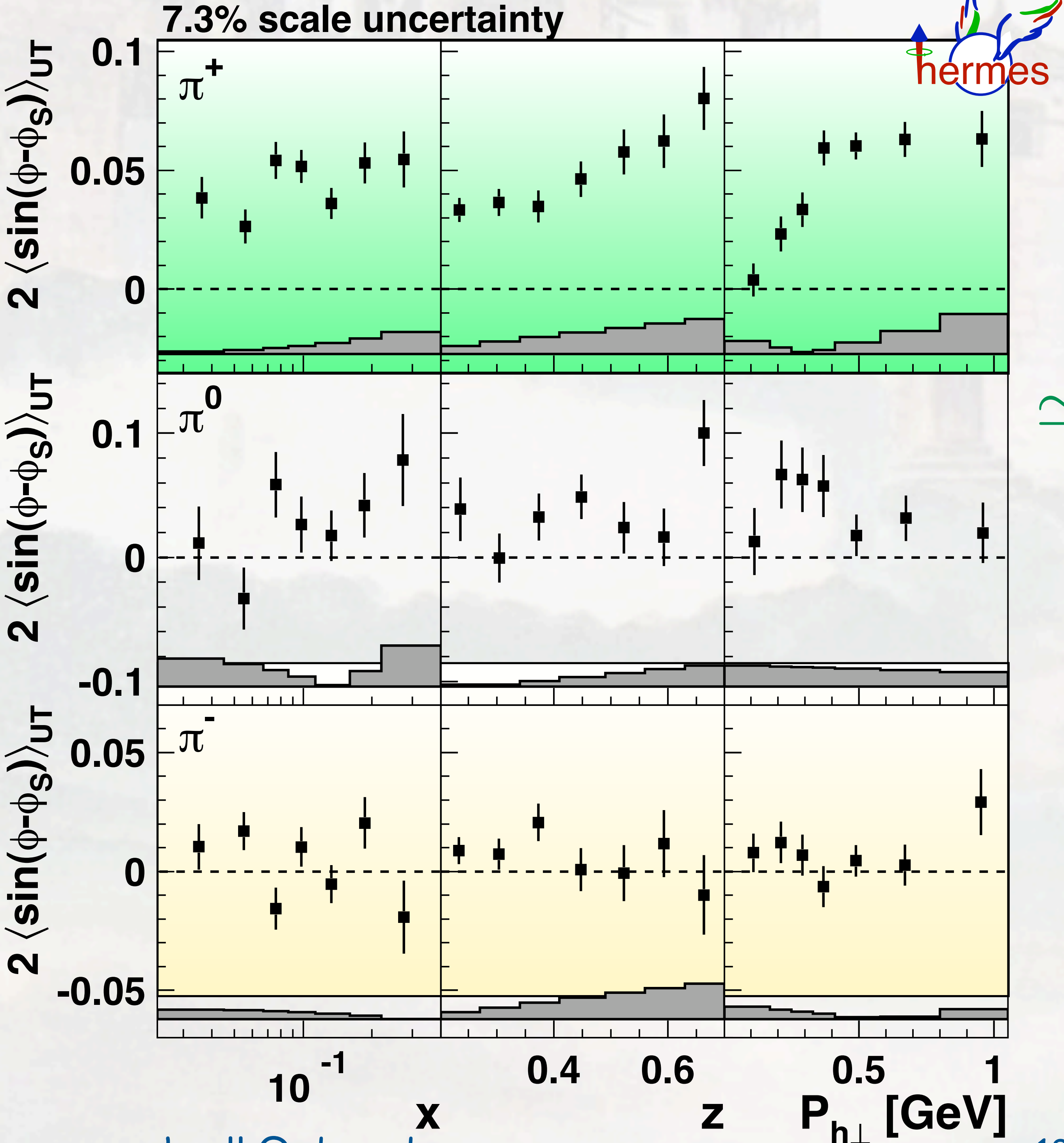
☛ **u-quark Sivers DF < 0**

☛ **d-quark Sivers DF > 0 (cancelation for π^-)**

	U	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

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



π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

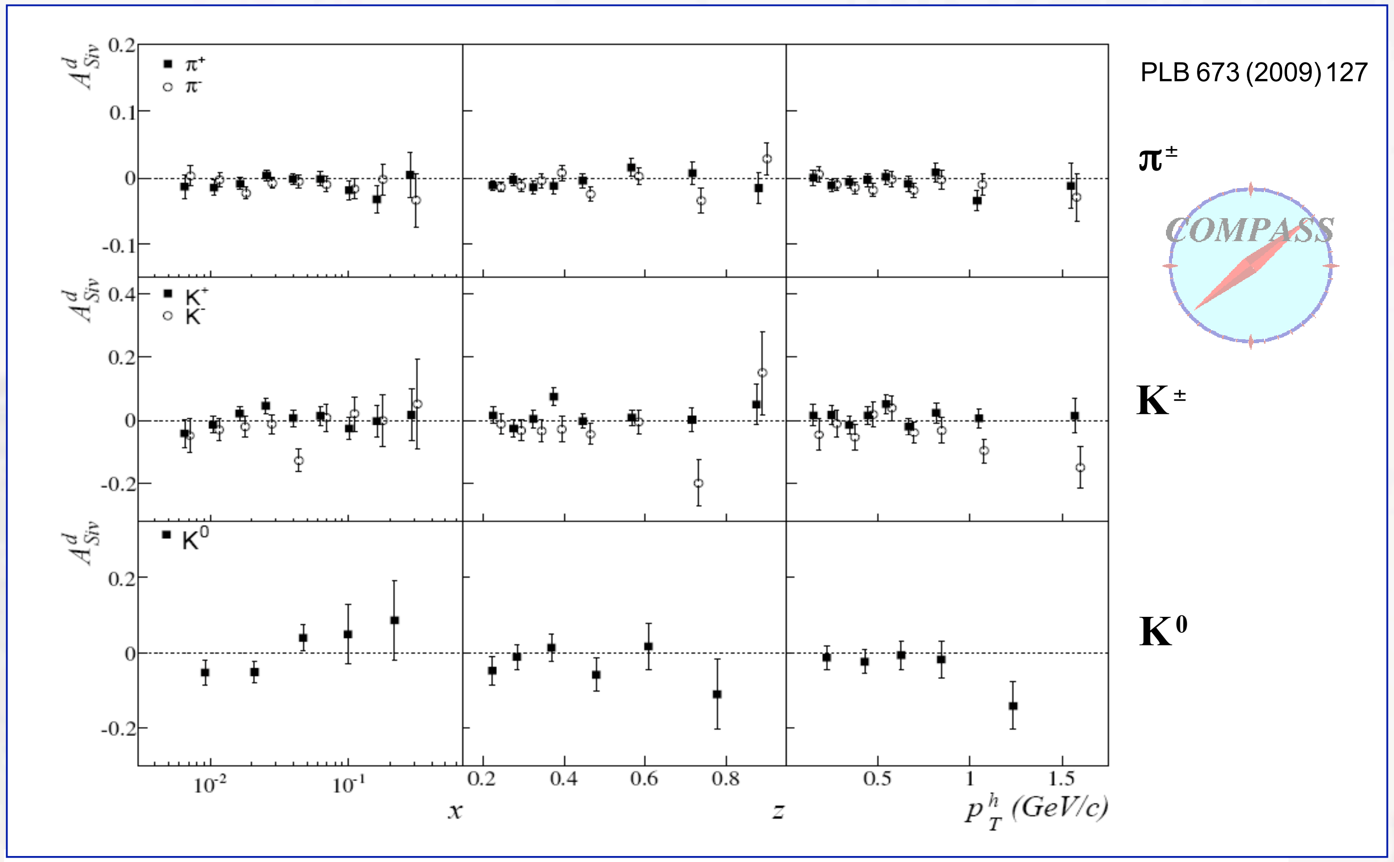
☛ d-quark Sivers DF > 0
(cancelation for π^-)

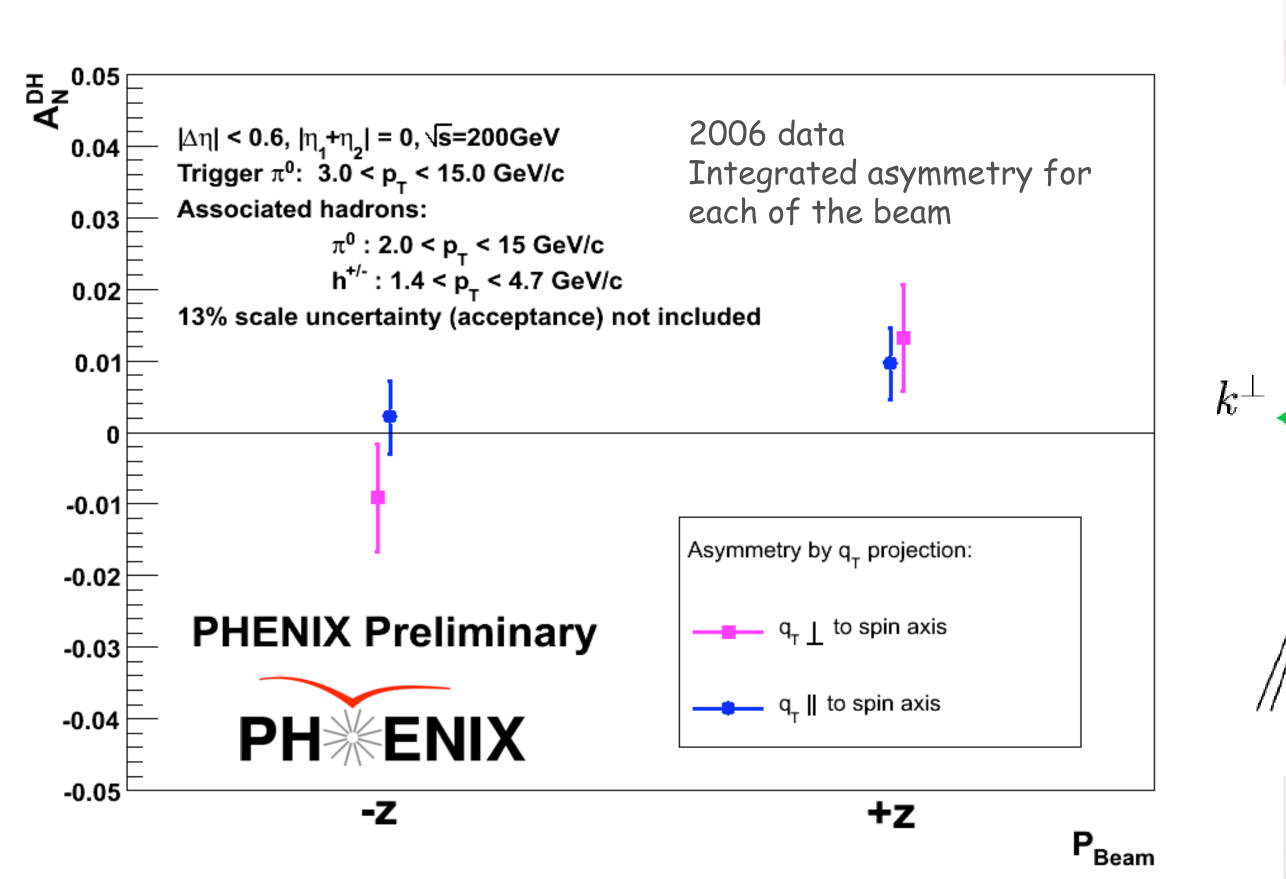
☛ A. Rostomyan

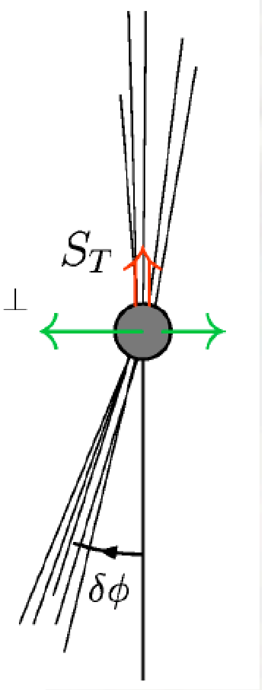
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function

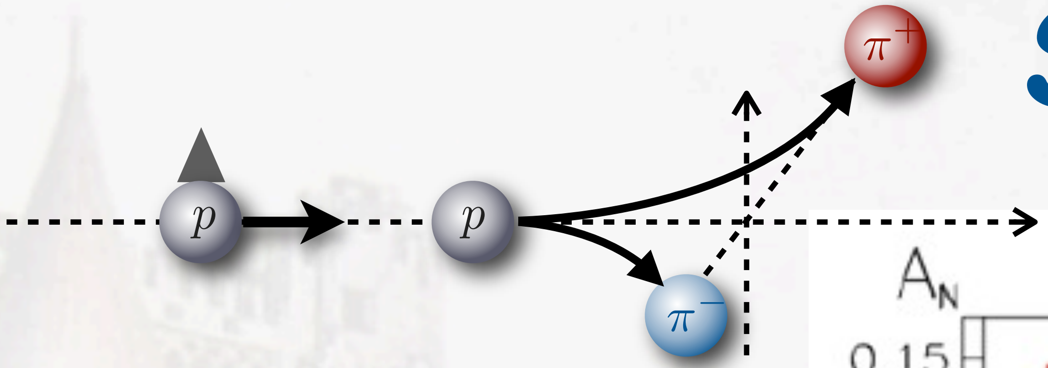
- cancelation for D target supports opposite signs of u and d Sivers
- interpreted also in terms of vanishing gluon Sivers
- small gluon Sivers supported by Phenix
  ☛ A. Ogawa
- new results from JLab using ^{3}He target
  ☛ X. Jiang





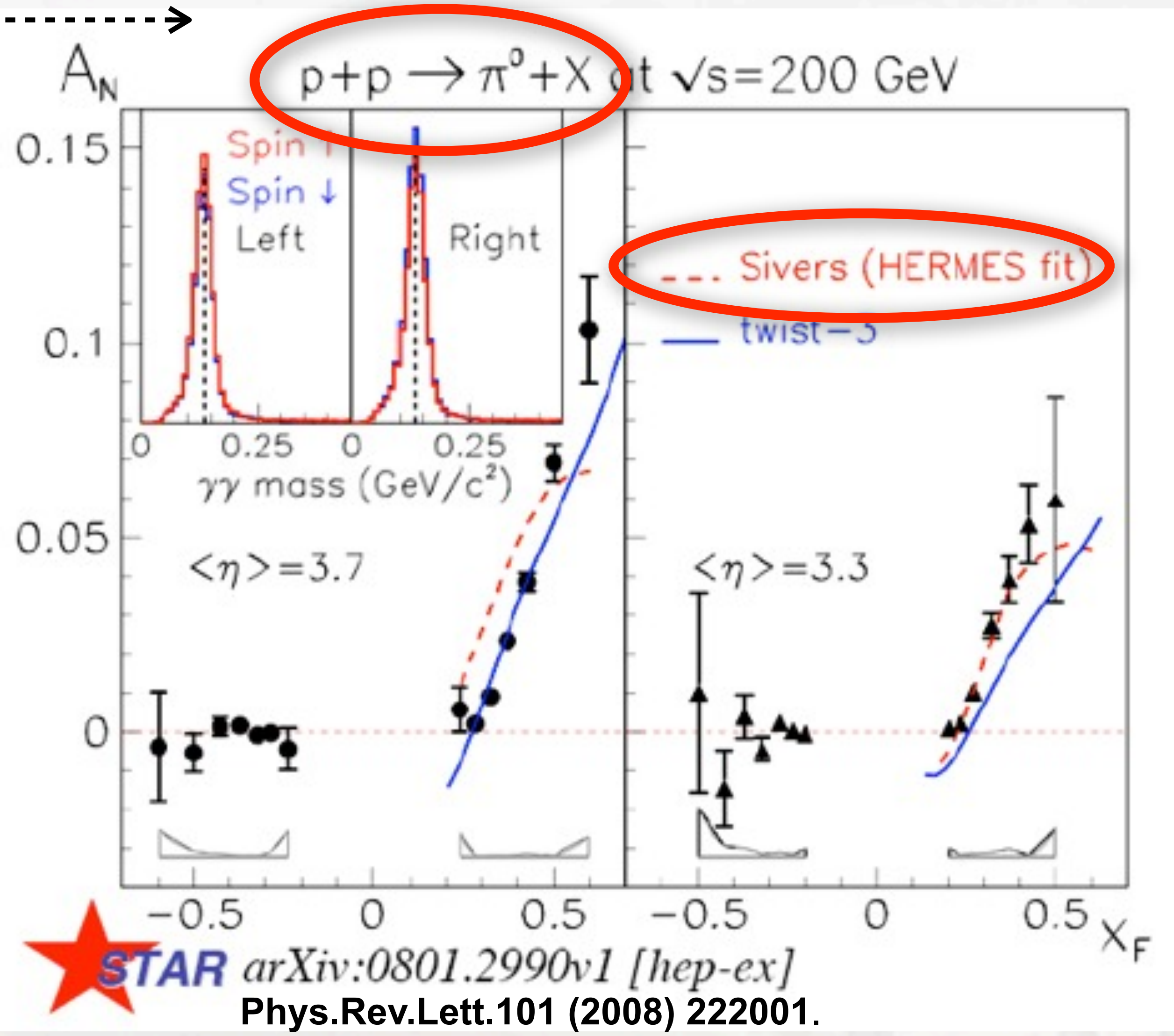


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



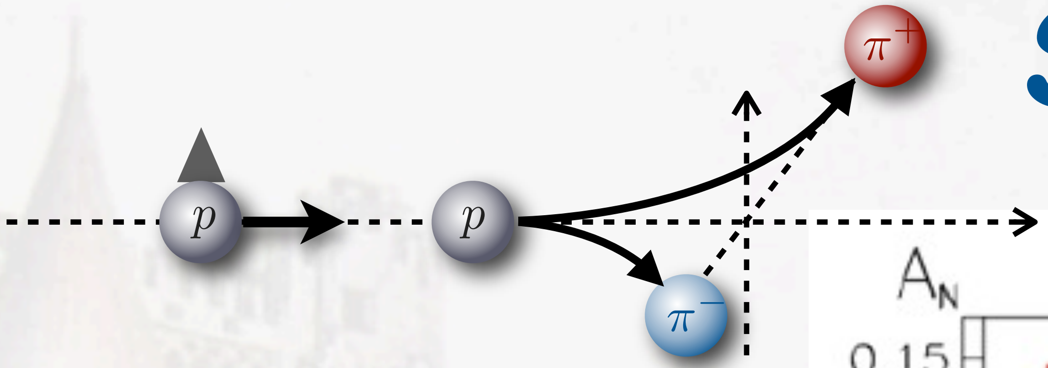
Sivers function

- Sivers fit to HERMES data nicely describes A_N in pp
- only sizable in forward direction

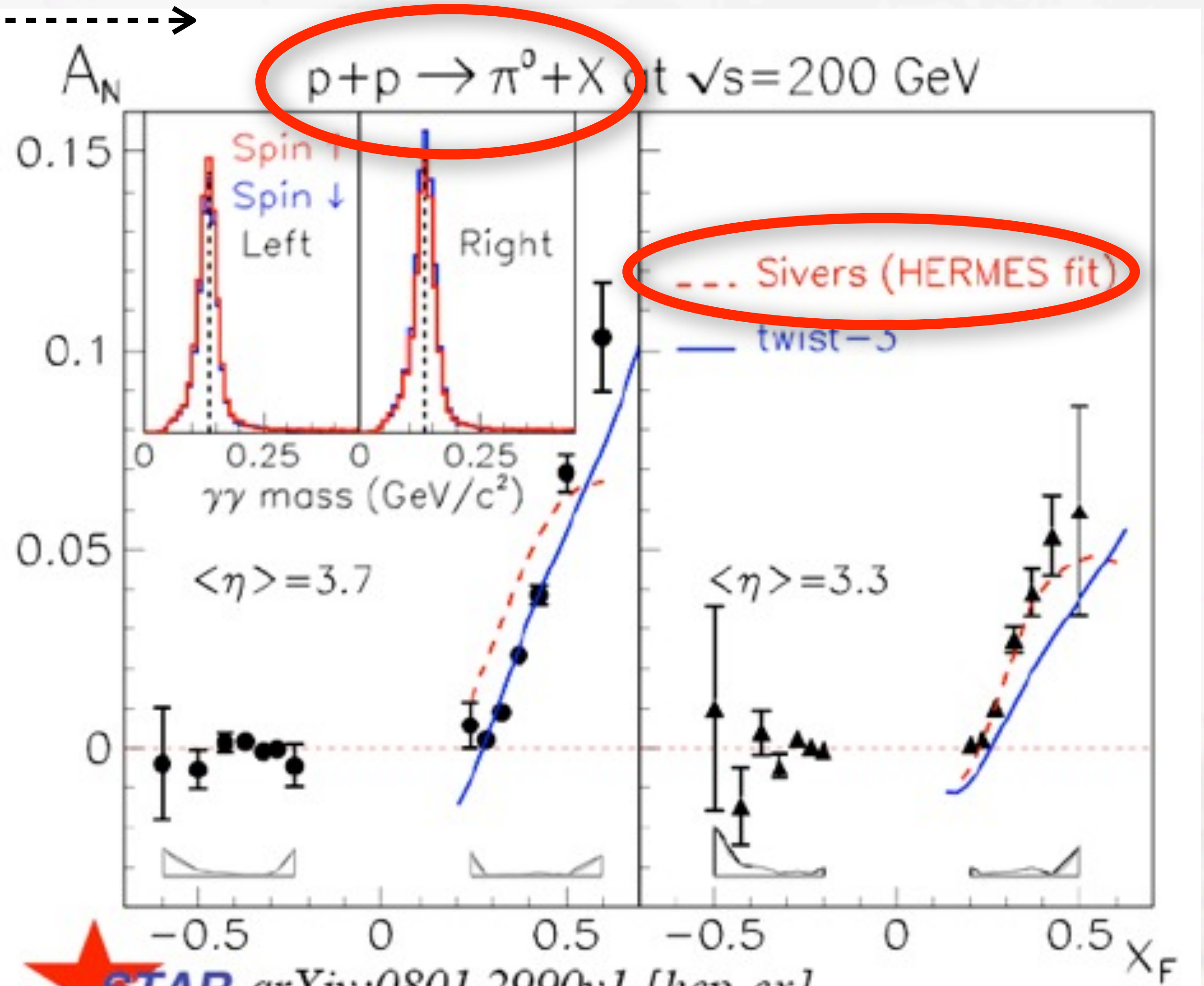


Phys.Rev.Lett.101 (2008) 222001.

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



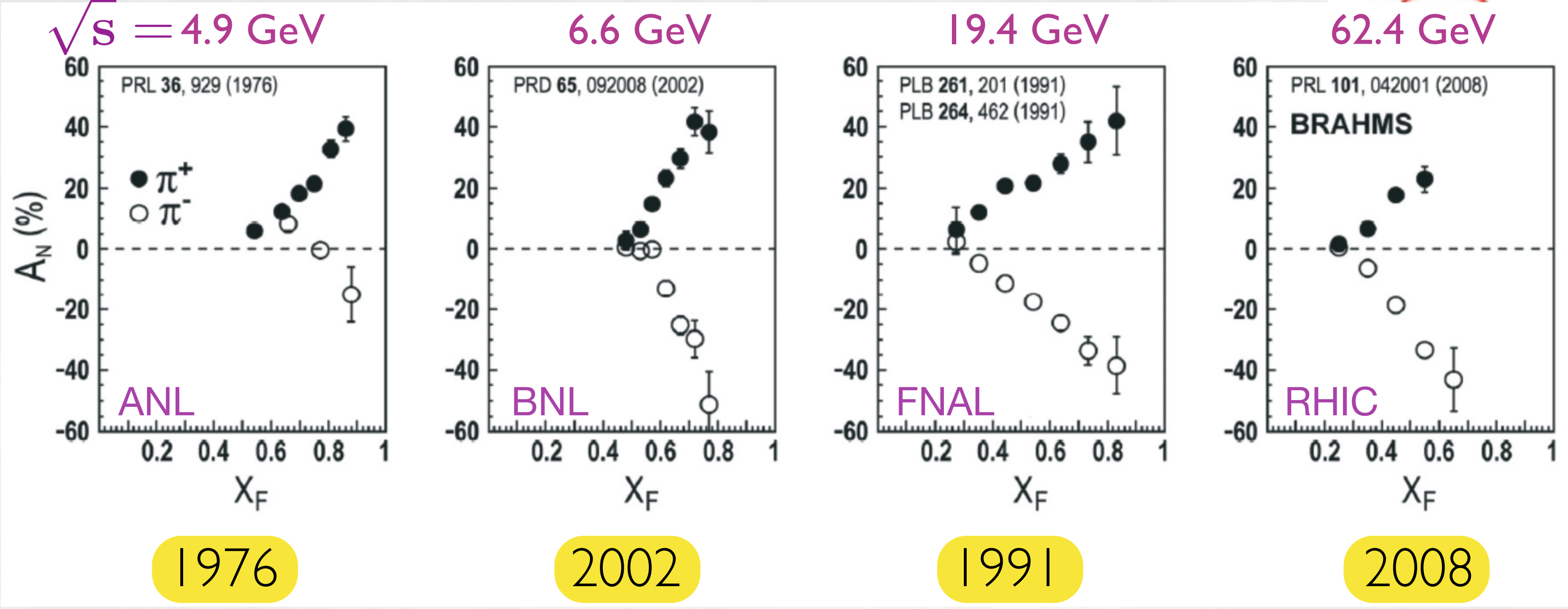
Sivers function



STAR arXiv:0801.2990v1 [hep-ex]

Phys.Rev.Lett.101 (2008) 222001.

- **Sivers fit to HERMES data nicely describes A_N in pp**
- **only sizable in forward direction**
- **A_N in pp persist over wide energy range:**



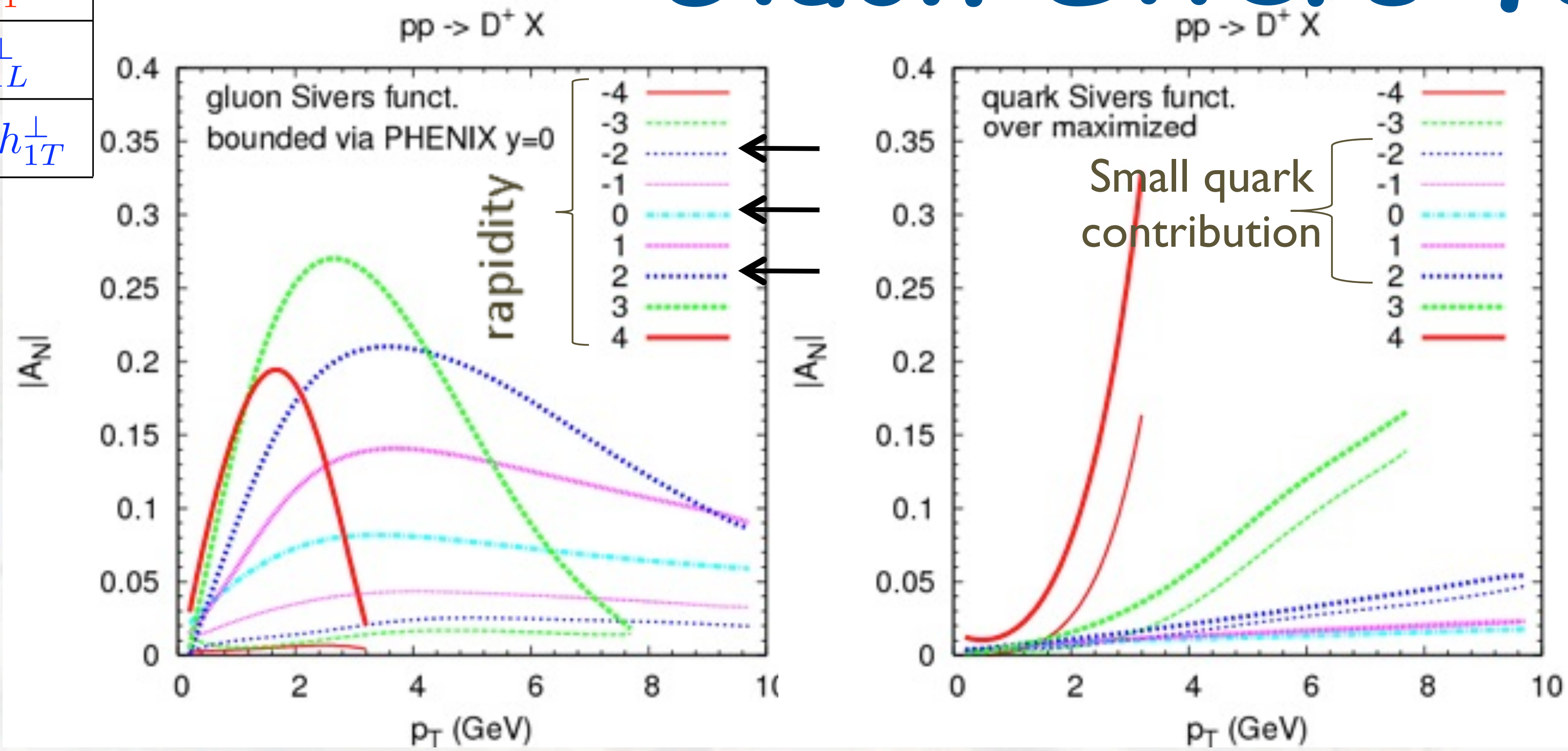
☞ **A. Ogawa**

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

Gluon Sivers function

PRD 70,074025

- Quark Sivers set to zero
- Gluon Sivers set to max



- Quark Sivers set to max
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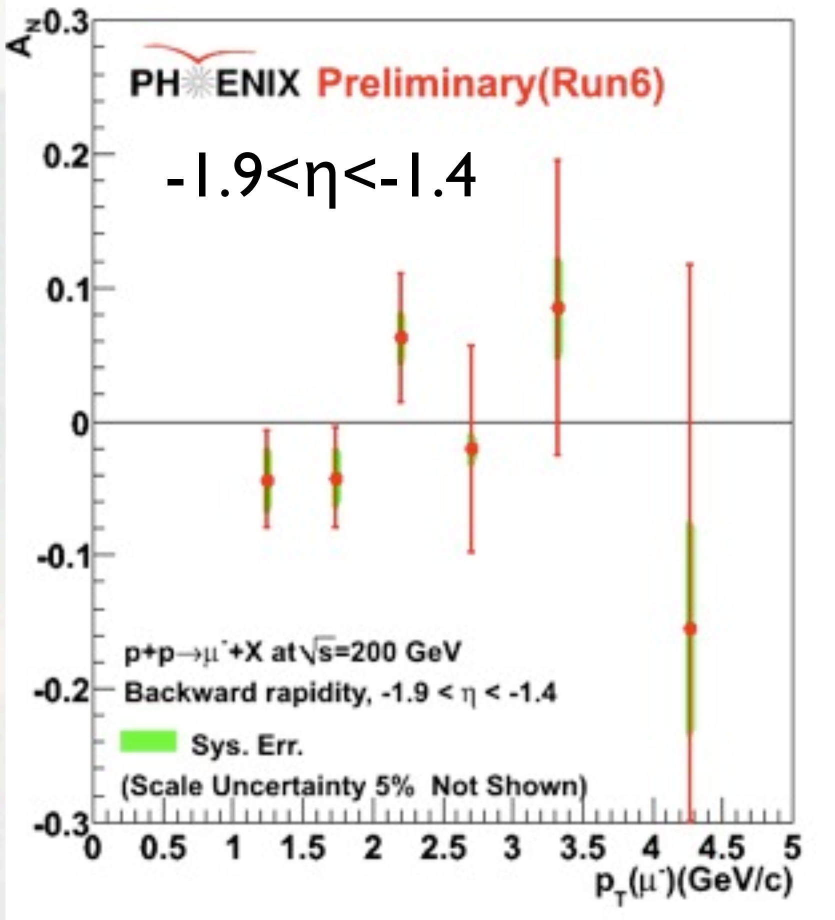
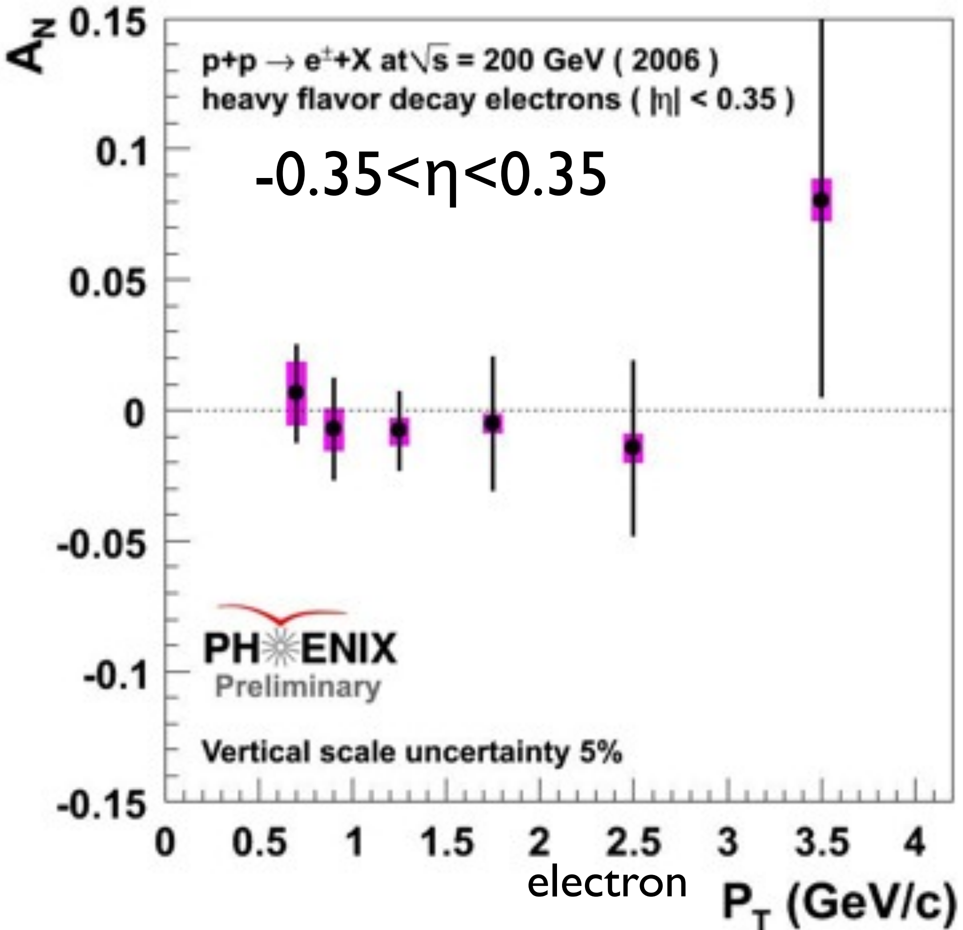
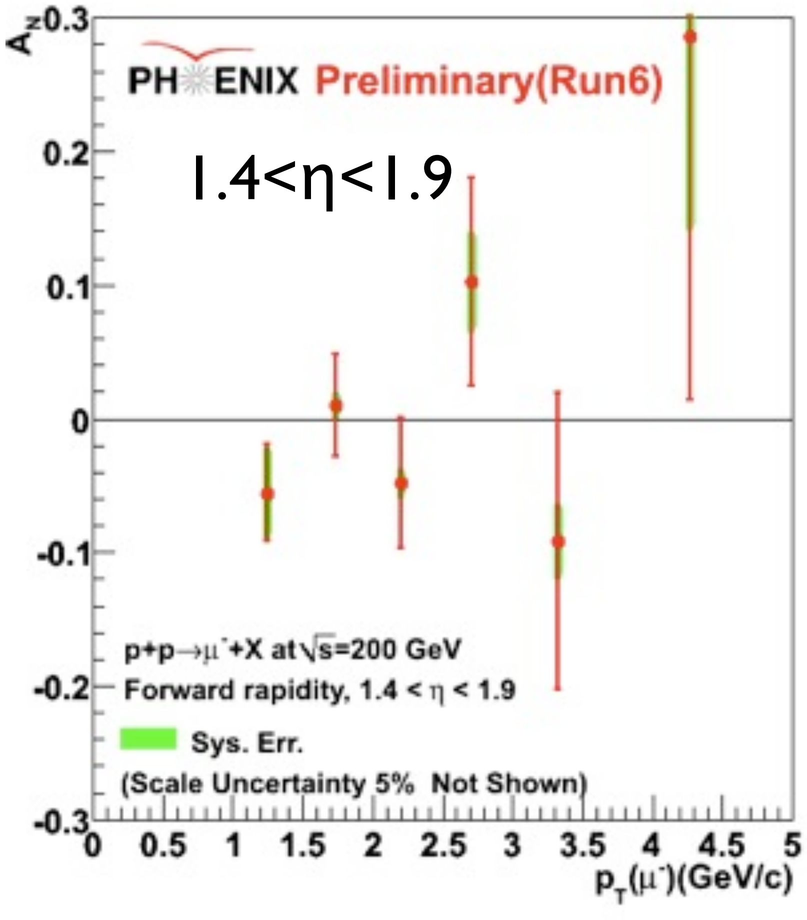
Theory



Theory



Theory



Gluon Sivers function

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

PRD 70,074025

- Quark Sivers set to zero
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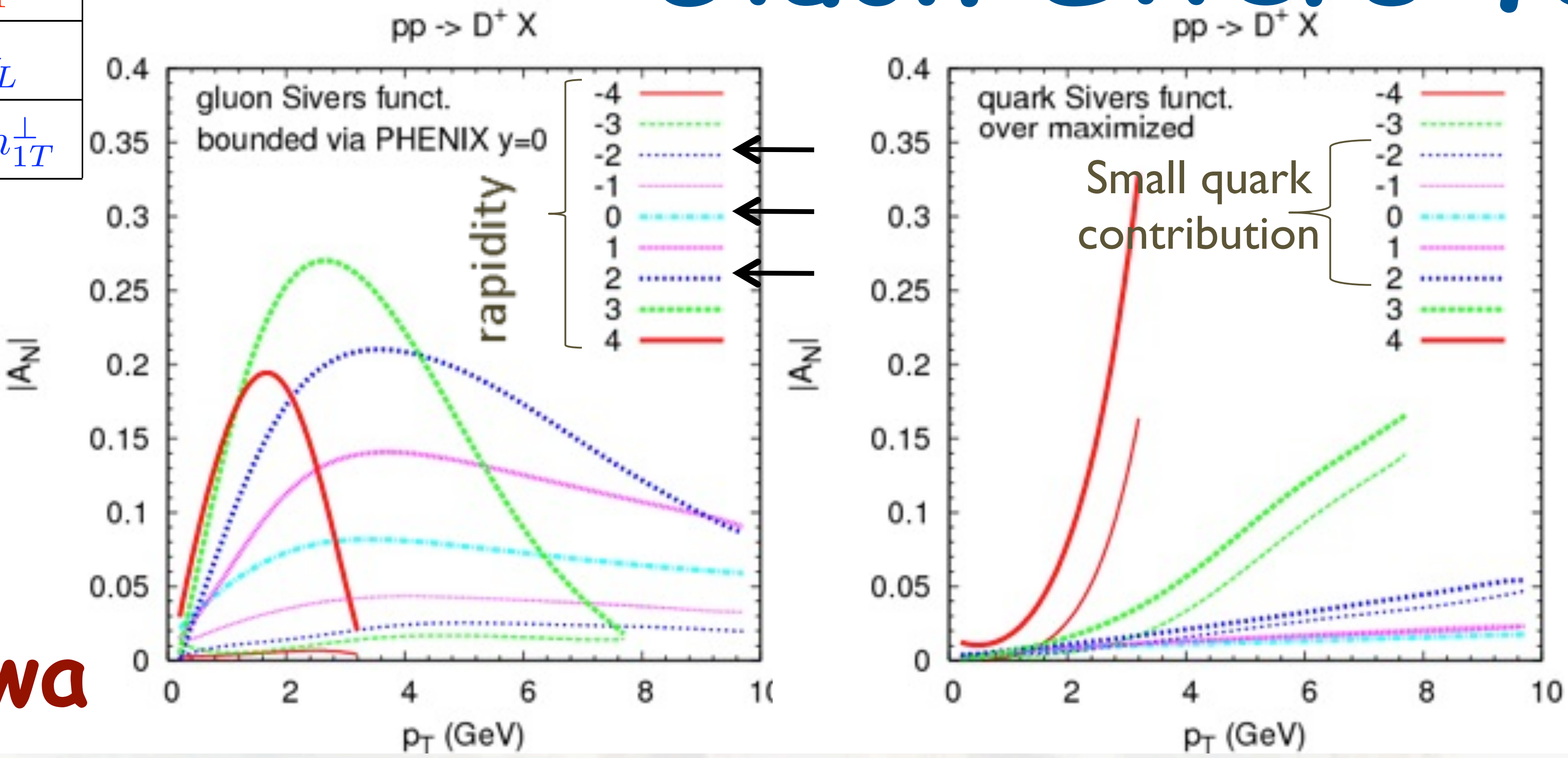
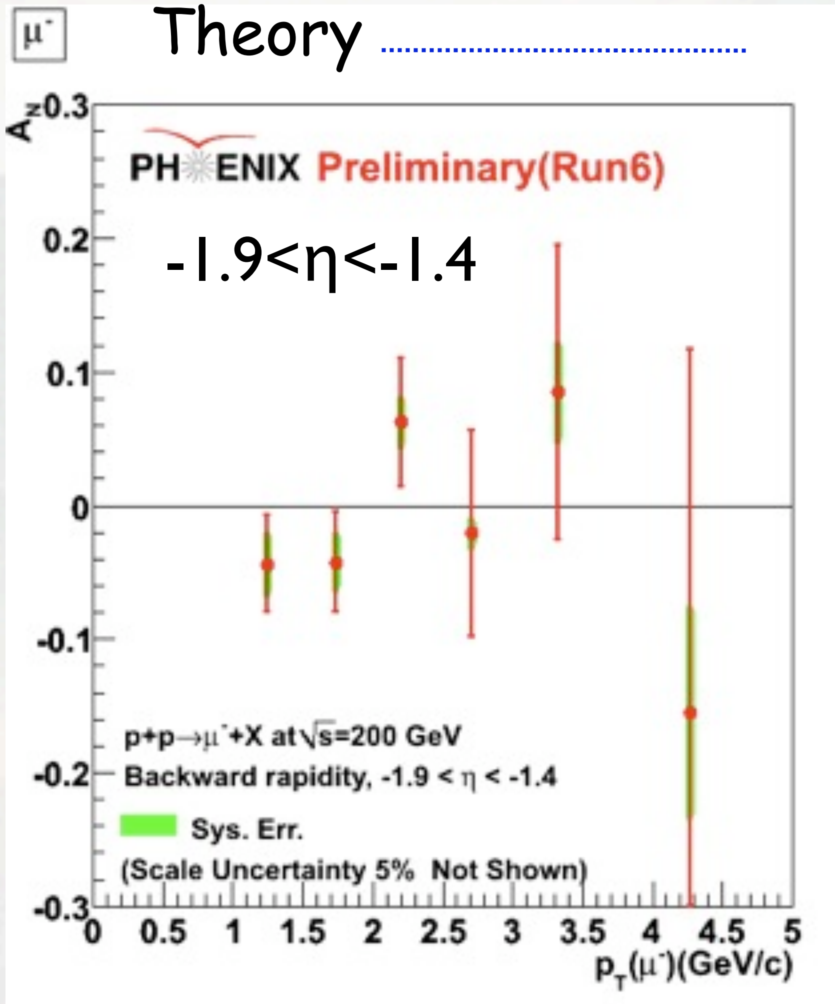


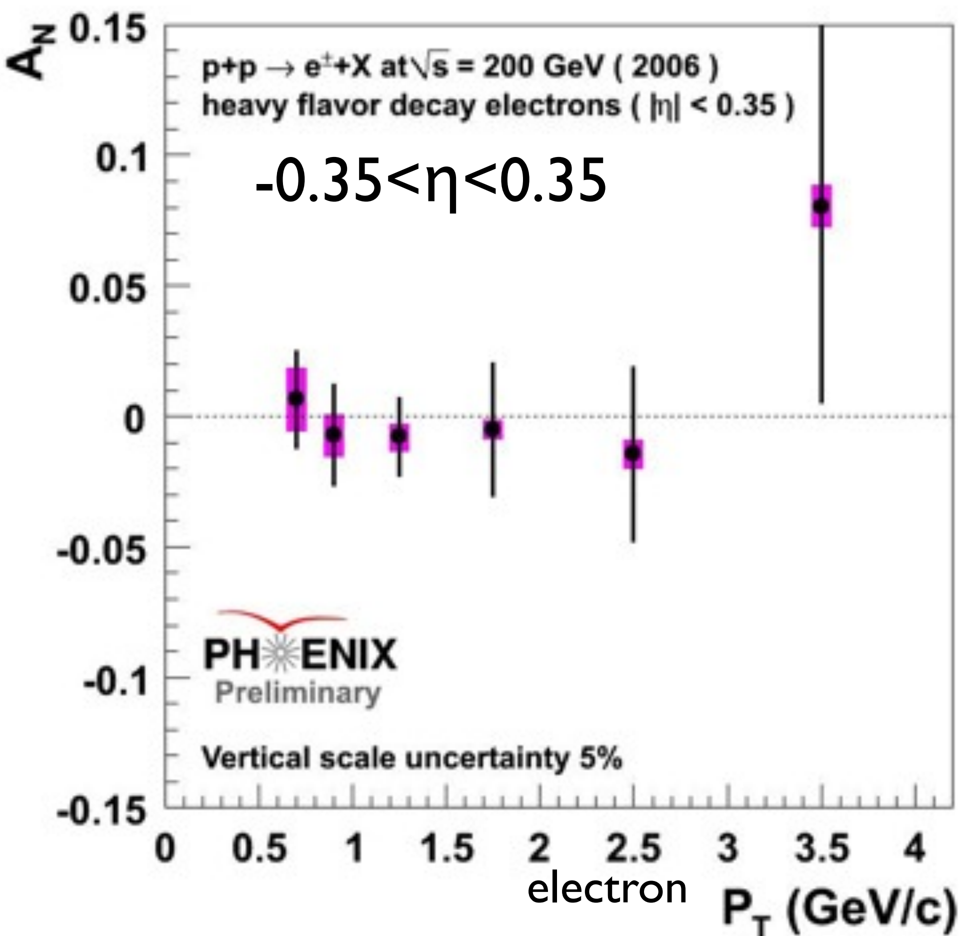
- Quark Sivers set to max
- Gluon Sivers set to zero

☛ **A.Ogawa**

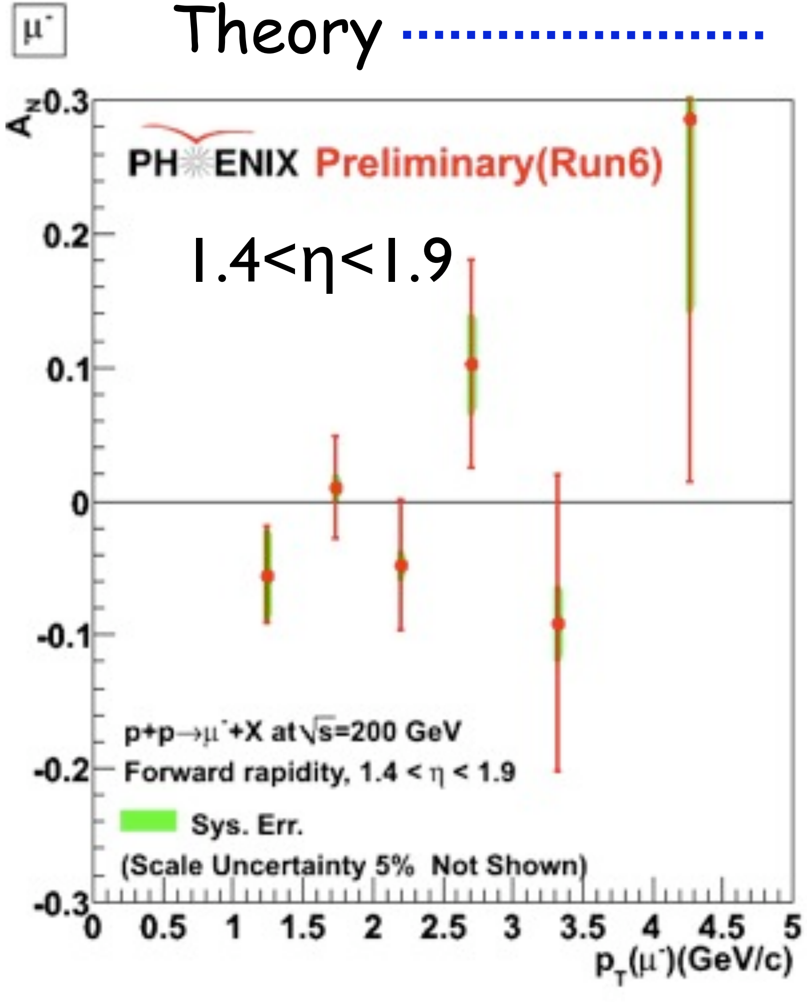
Theory ....



Theory - · - · - · - ·



Theory ....



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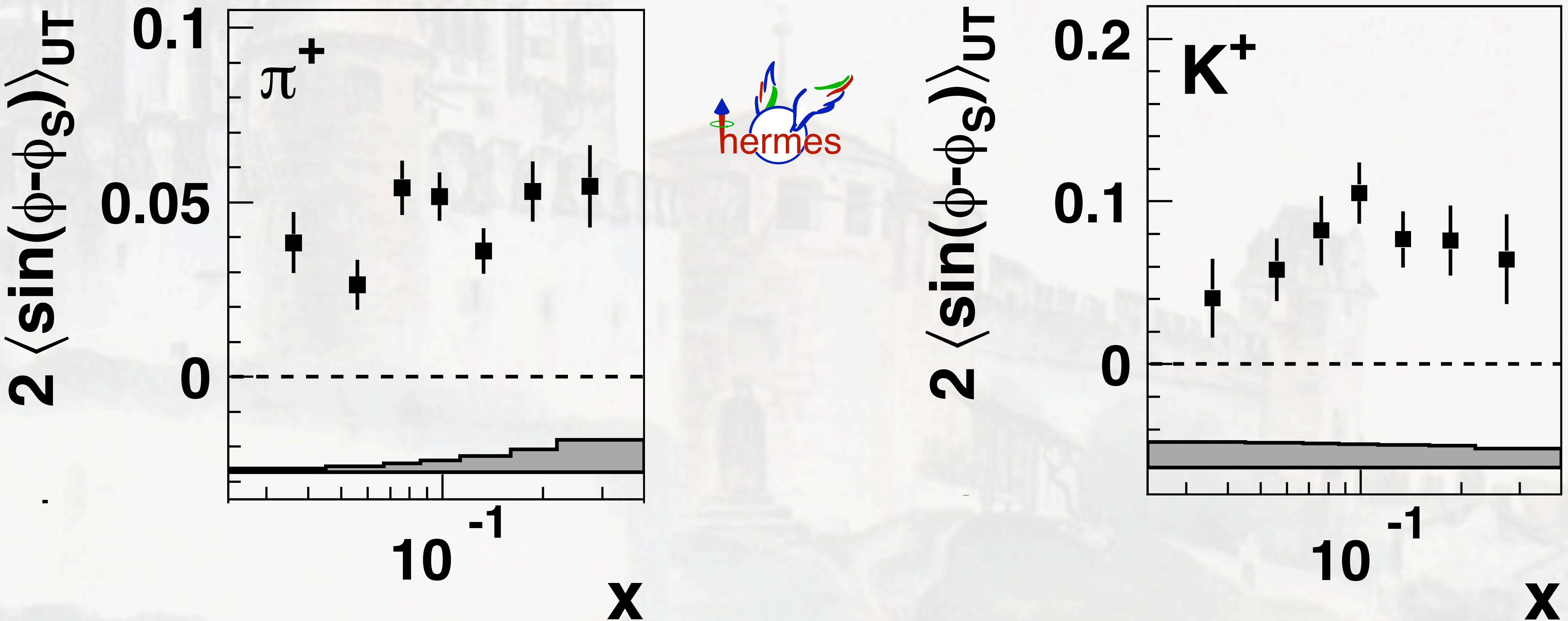
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers function (some surprises)



π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{\mathbf{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}}{\mathbf{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}}$

	U	L	T
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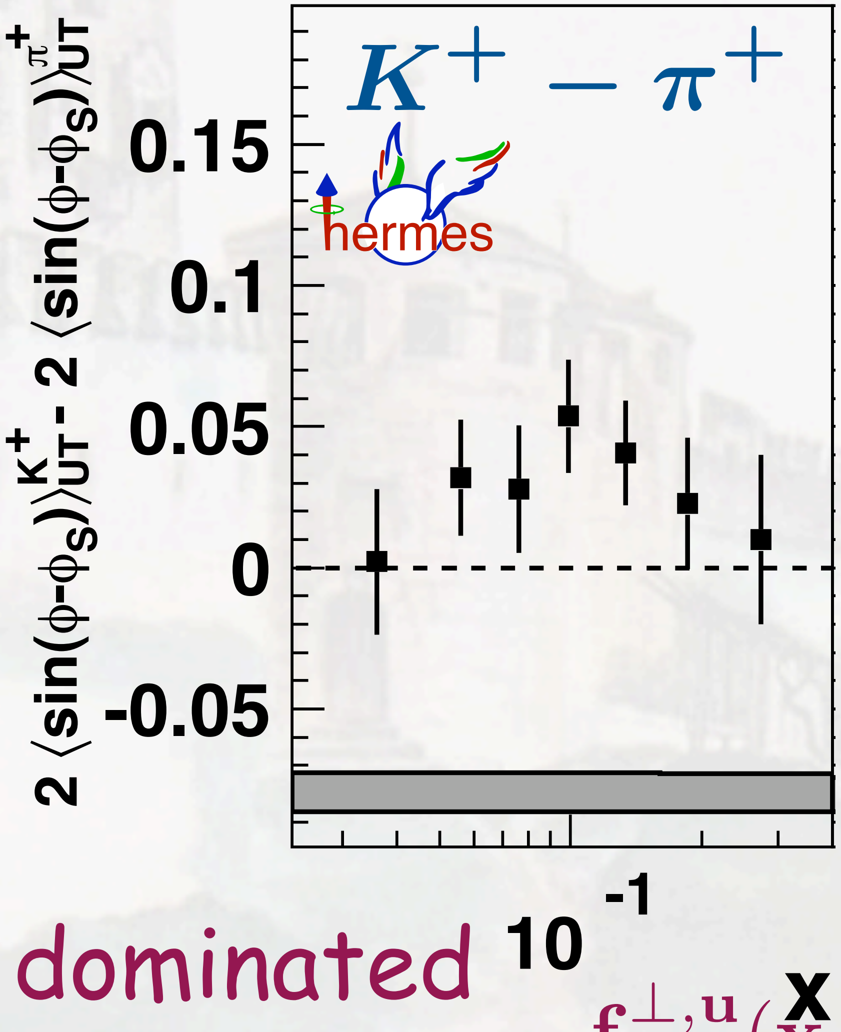

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	U	L	T
U	f_1		$h_1^\perp$
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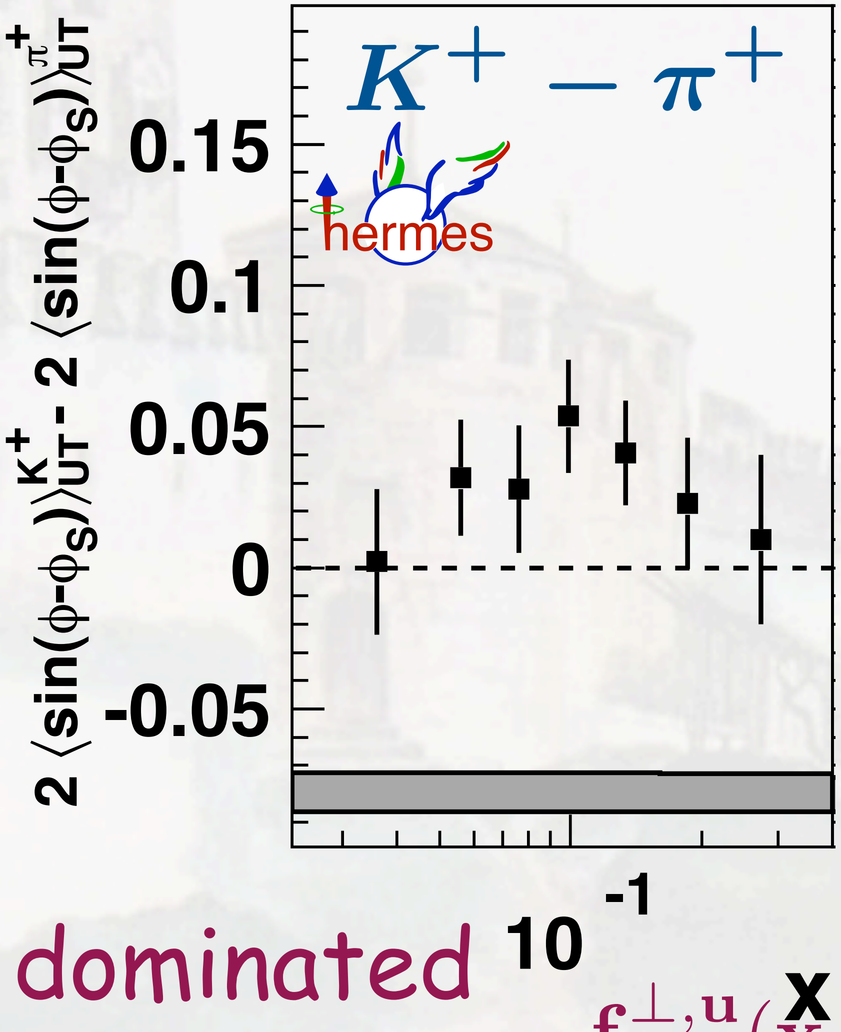

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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks?**

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
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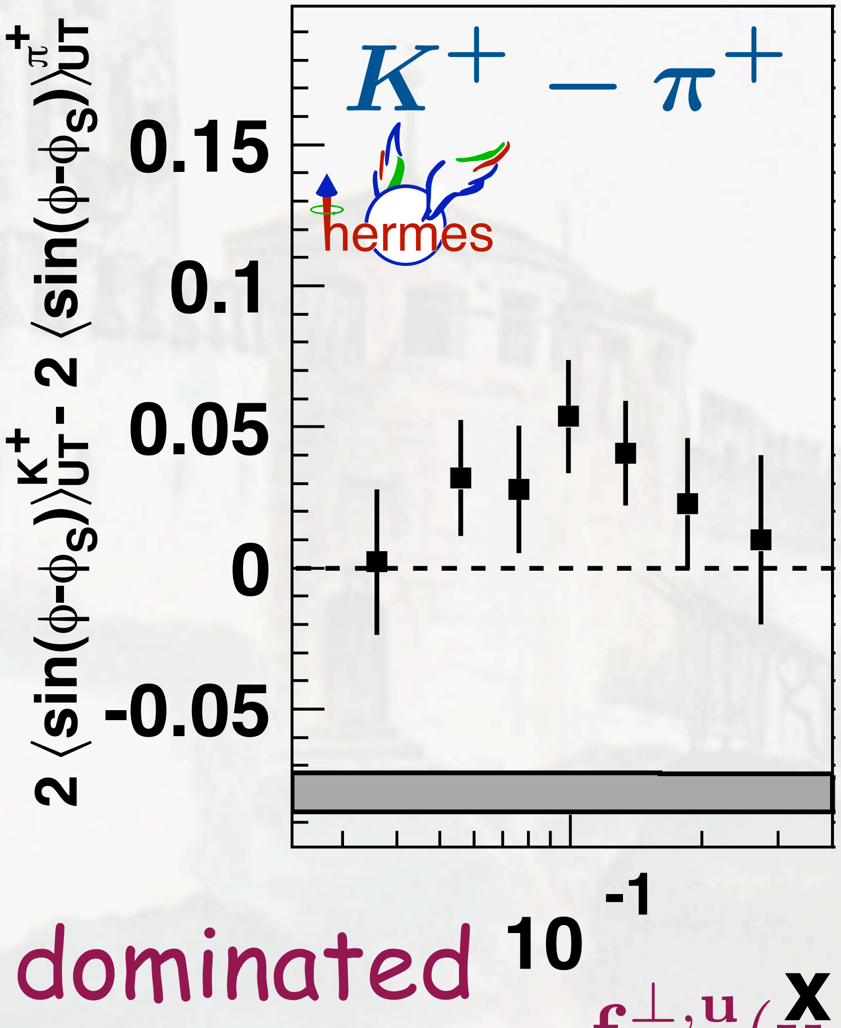
Sivers function (some surprises)



π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$

- ☐ $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- ☐ convolution integrals depend on k_T dependence of fragmentation functions

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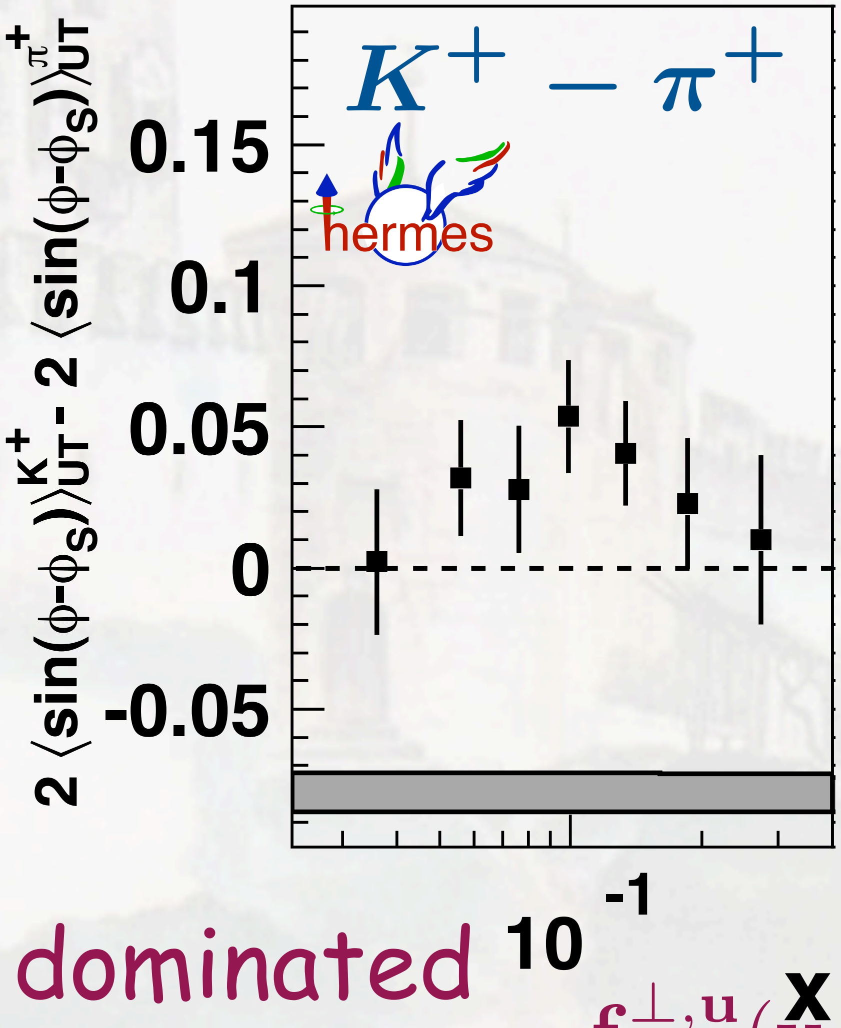
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function (some surprises)

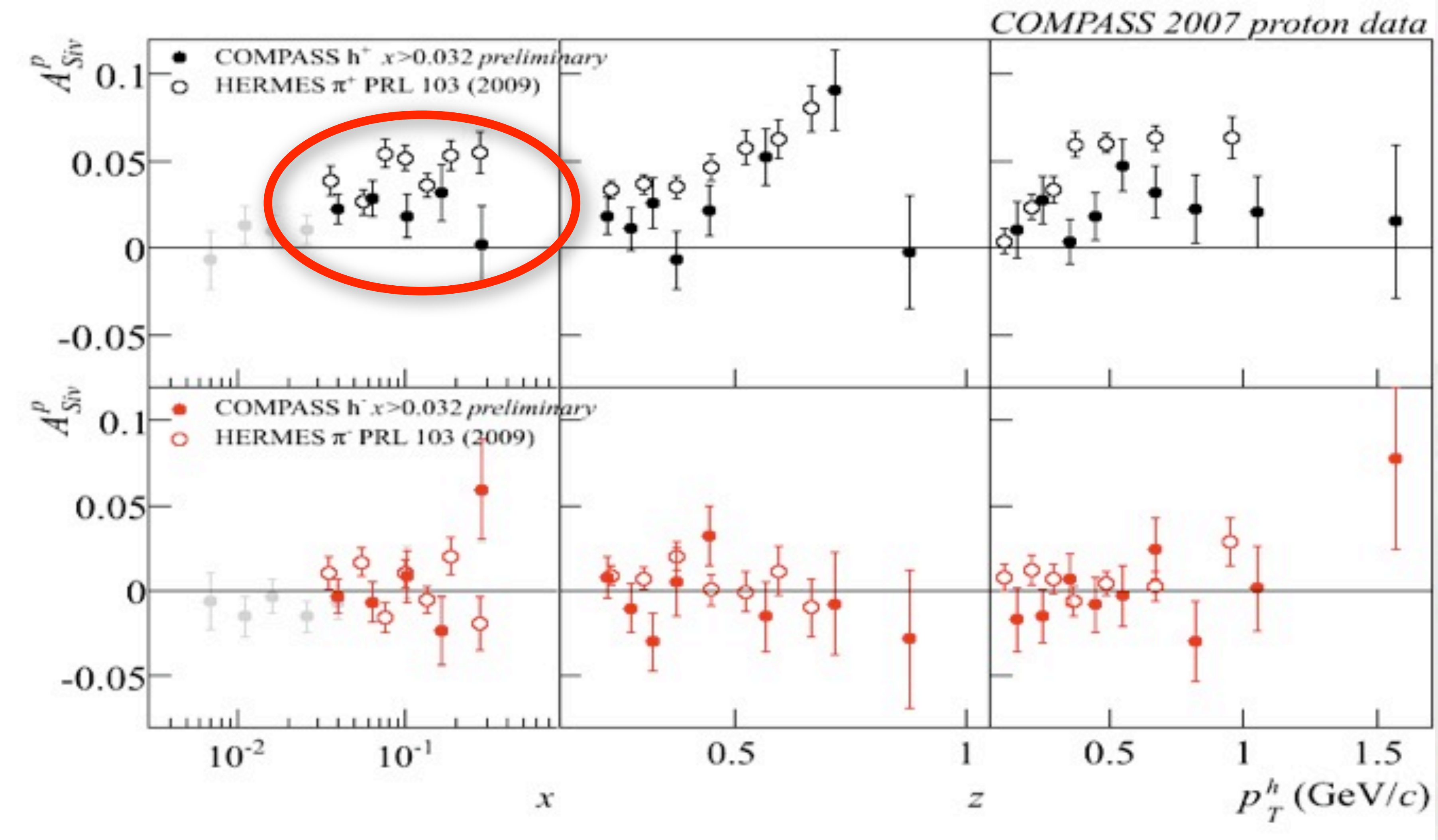


π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{f_{1T}^{\perp,u}(x,p_T^2)\otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2)\ \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$

- ☐ $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➡ non-trivial role of sea quarks?
- ☐ convolution integrals depend on k_T dependence of fragmentation functions
- ☐ possible difference in dependences on the kinematics integrated over

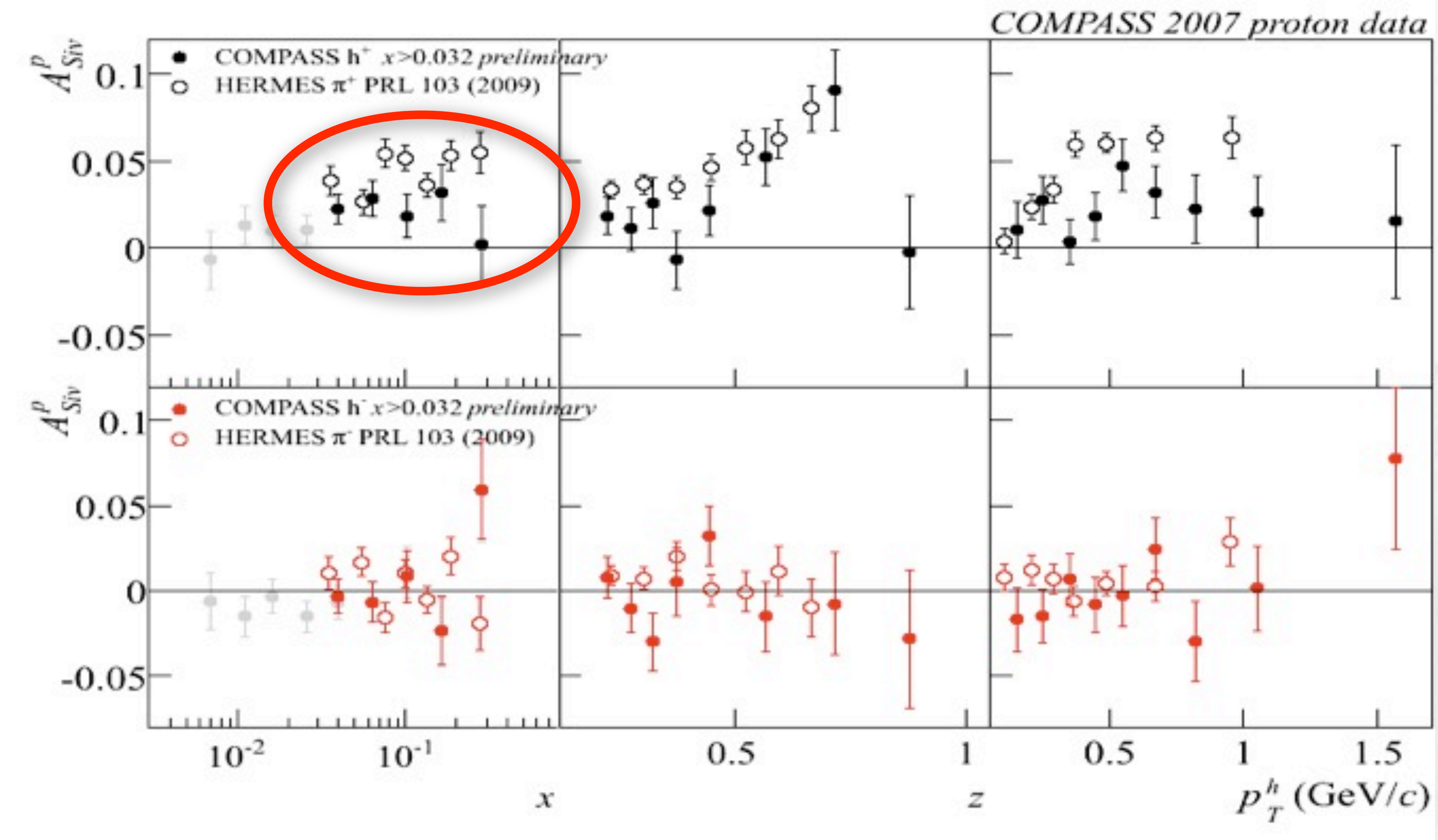
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function (some surprises)



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

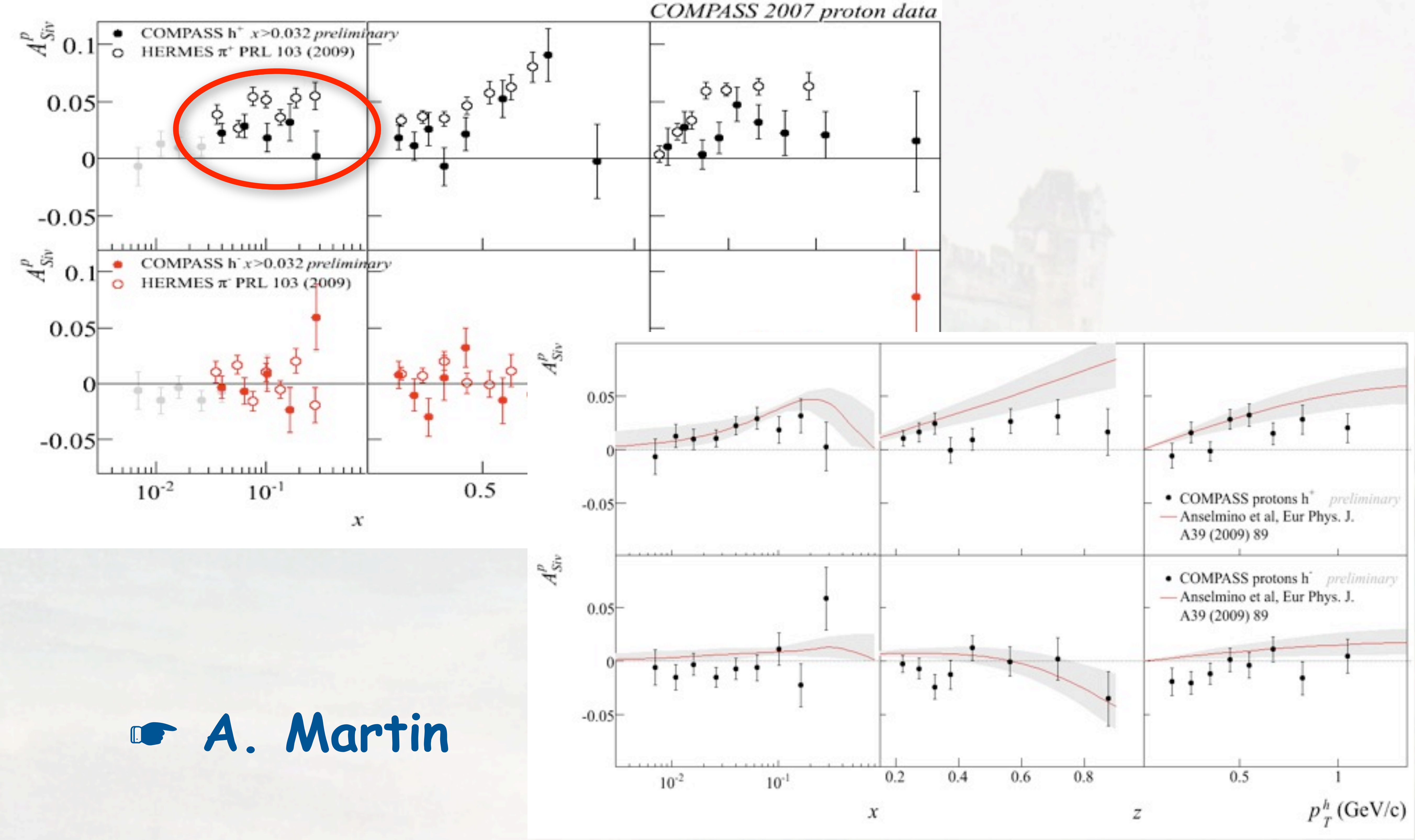
Sivers function (some surprises)



☛ **A. Martin**

	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 function (some surprises)



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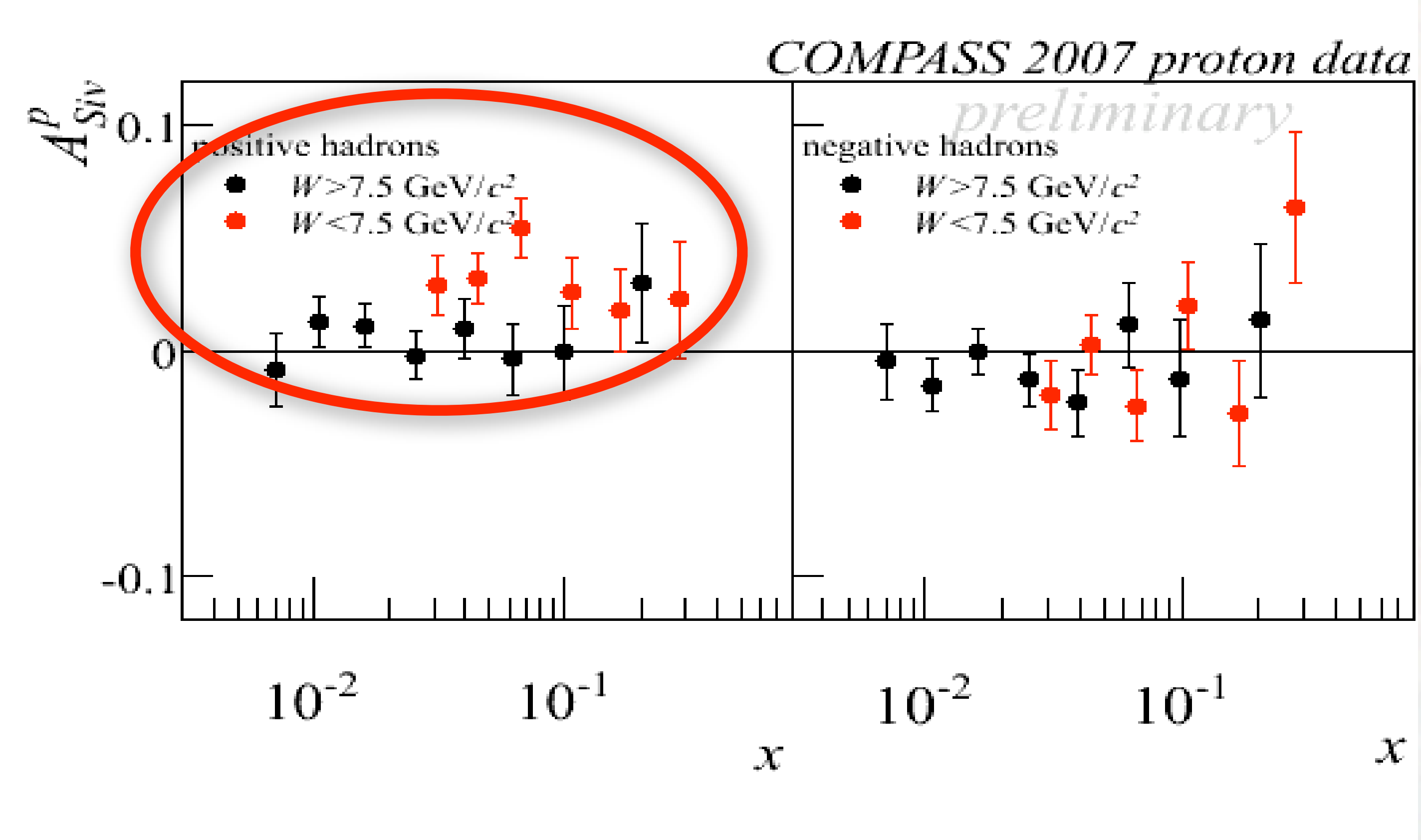
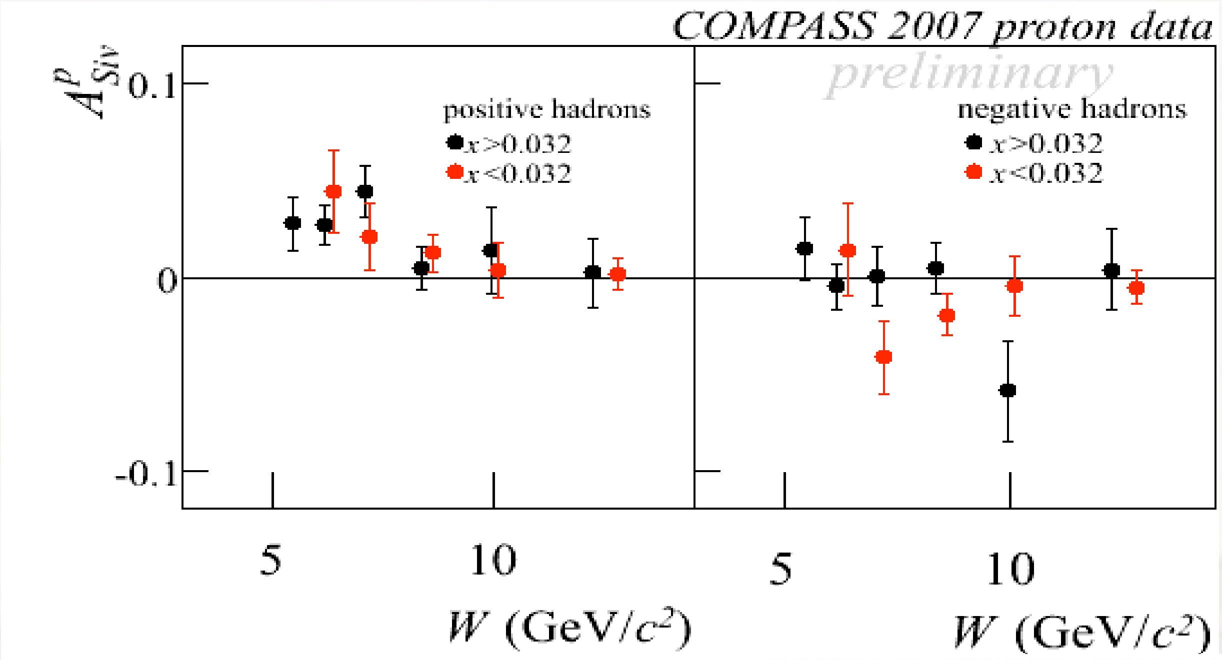
TMD 2010, ECT* Trento

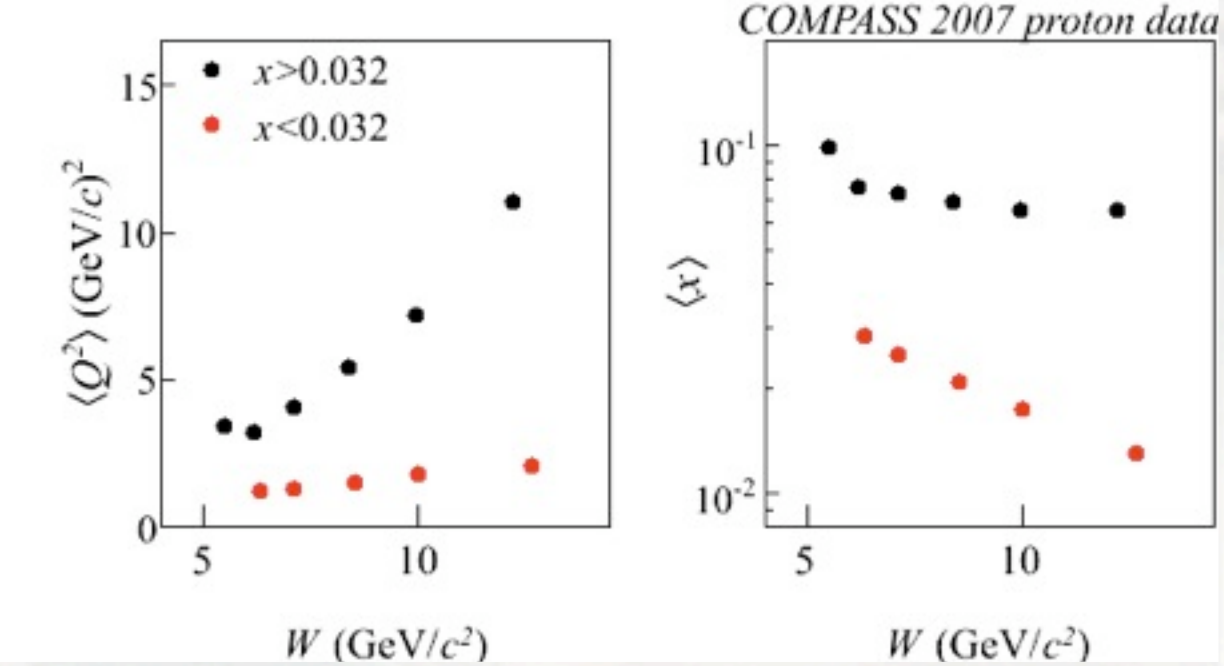
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function (some surprises)

- W^2 dependence?



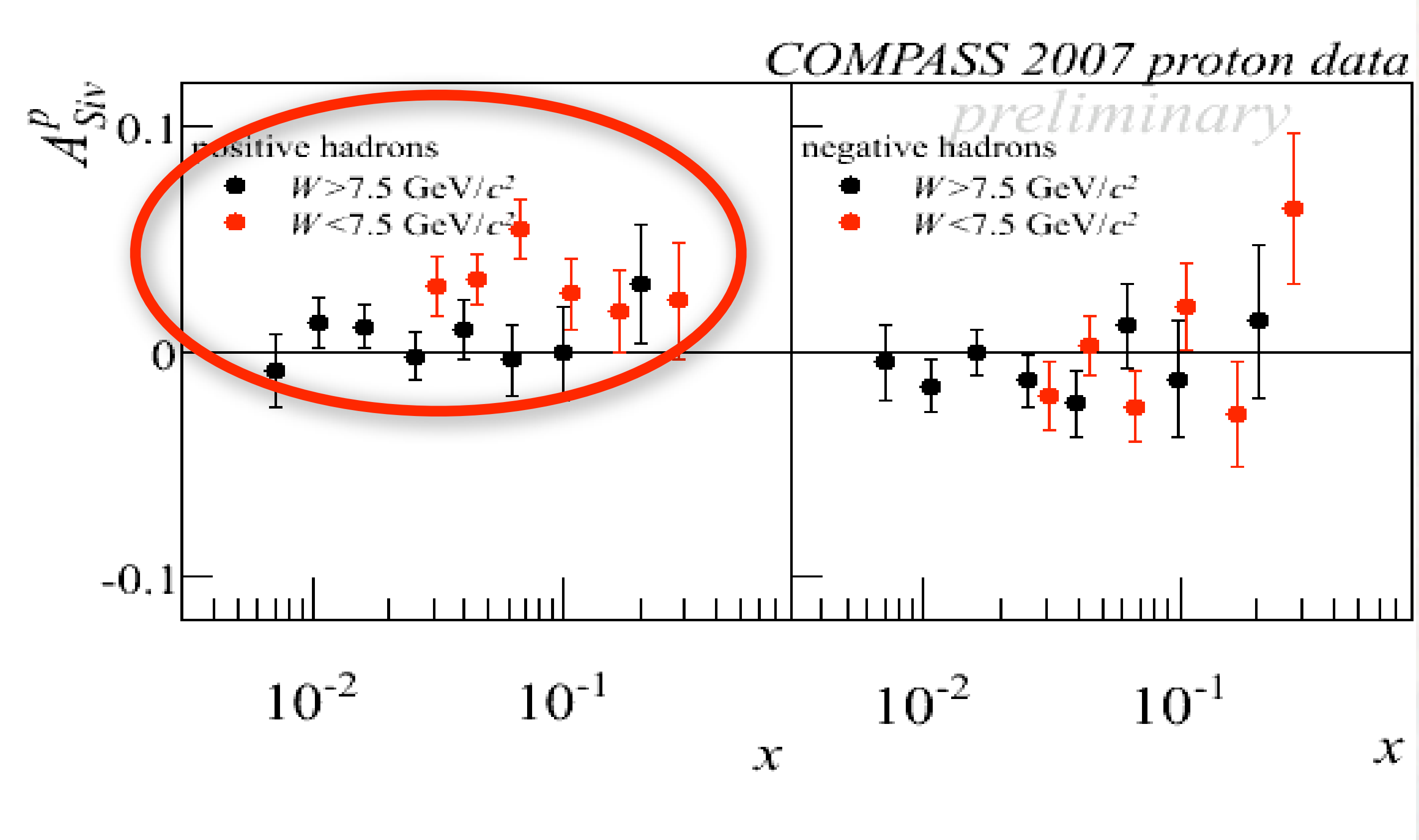


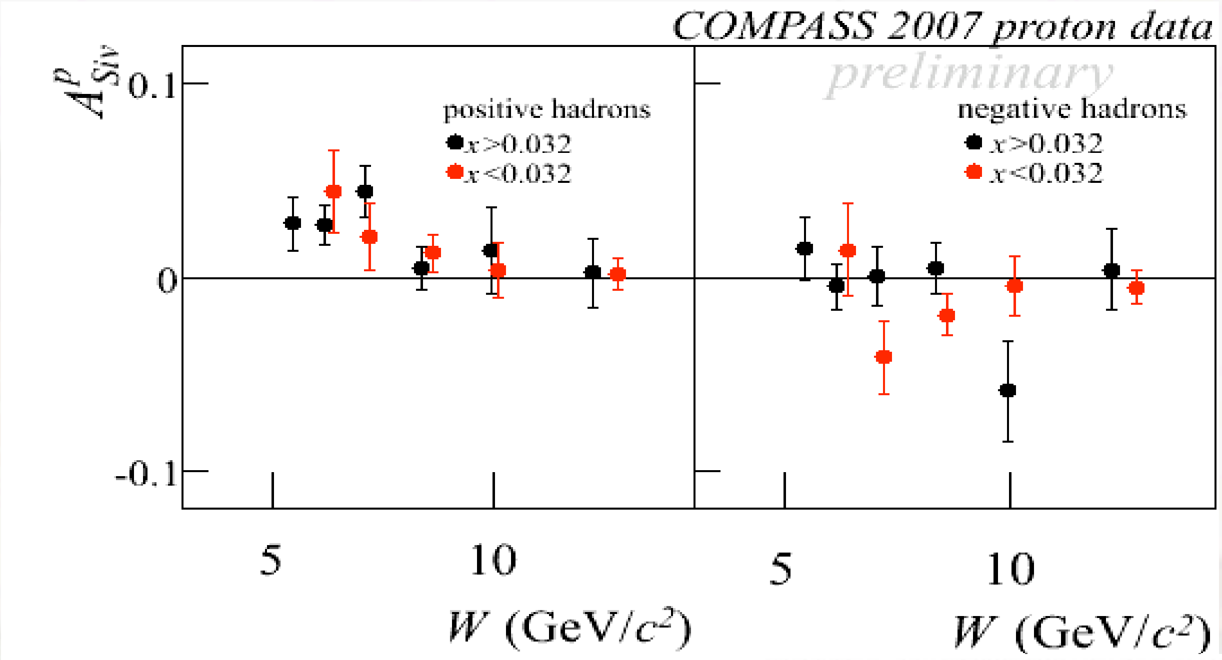


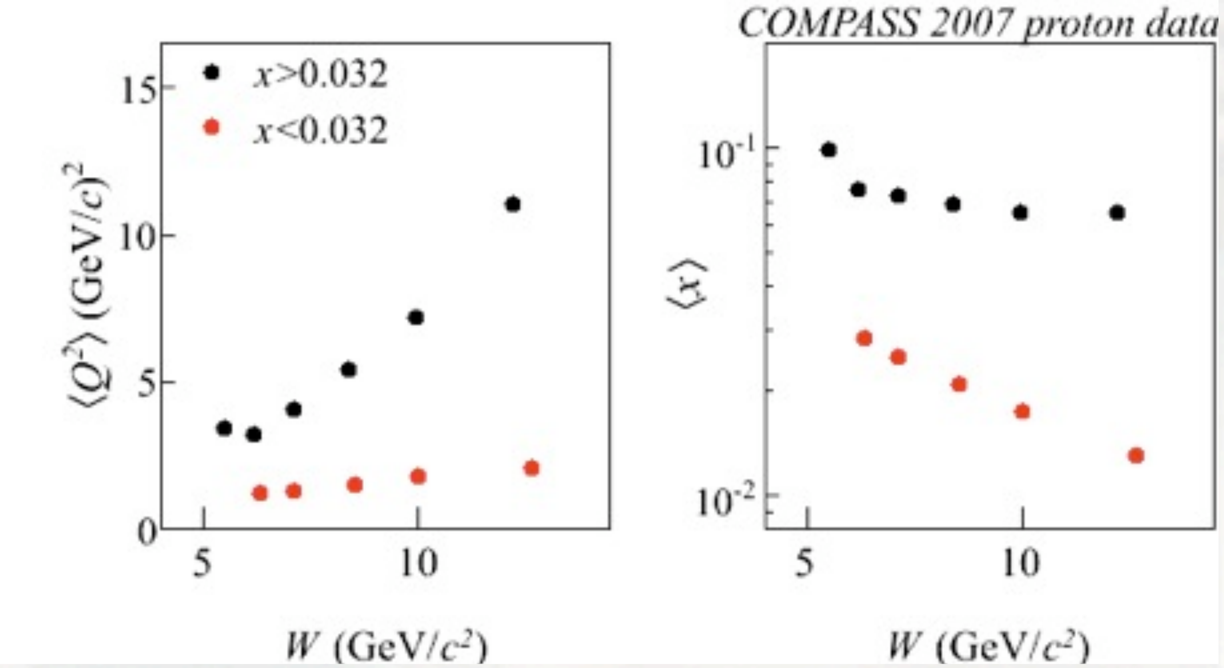
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function (some surprises)

- **W² dependence?**



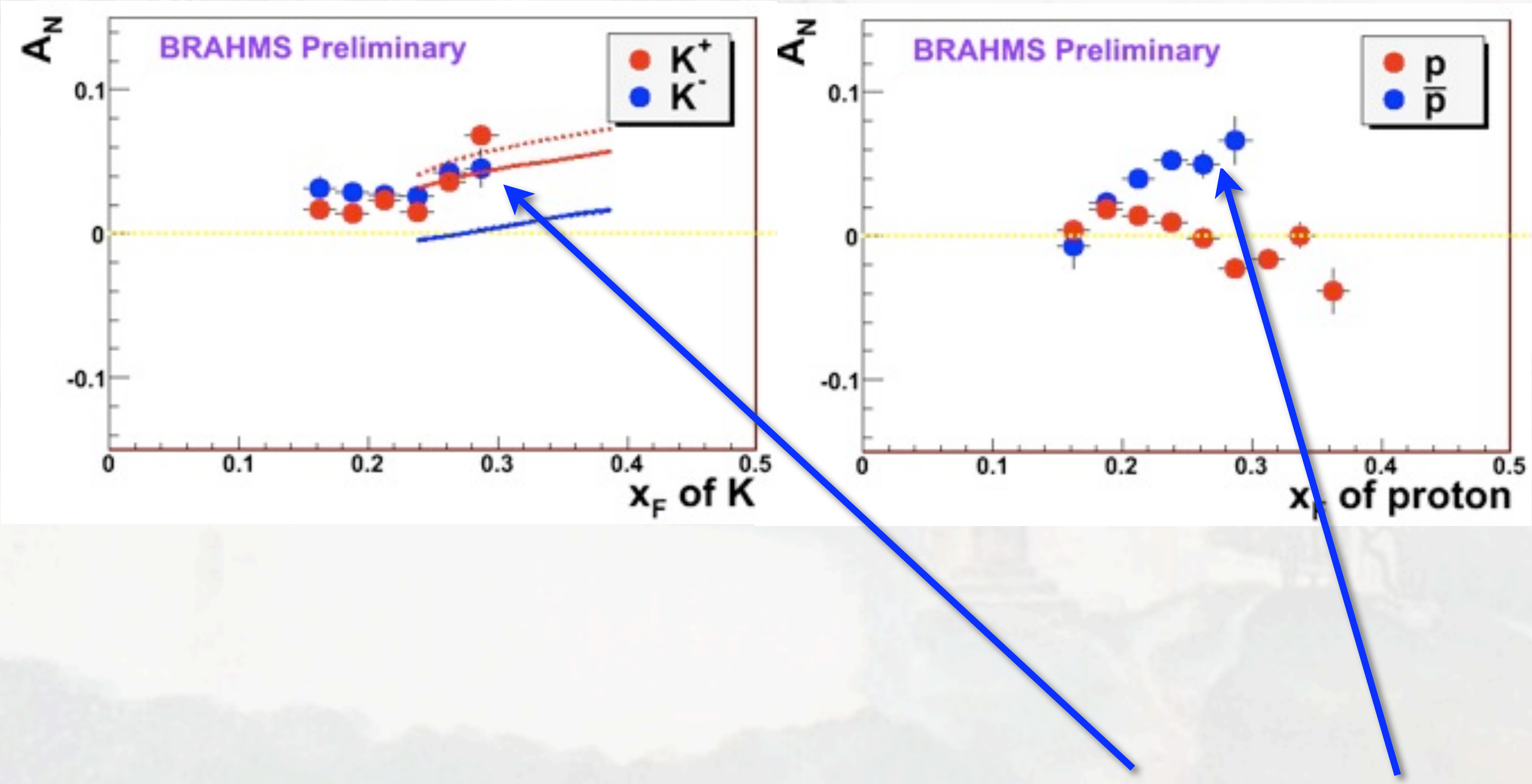




☞ **A. Martin**

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

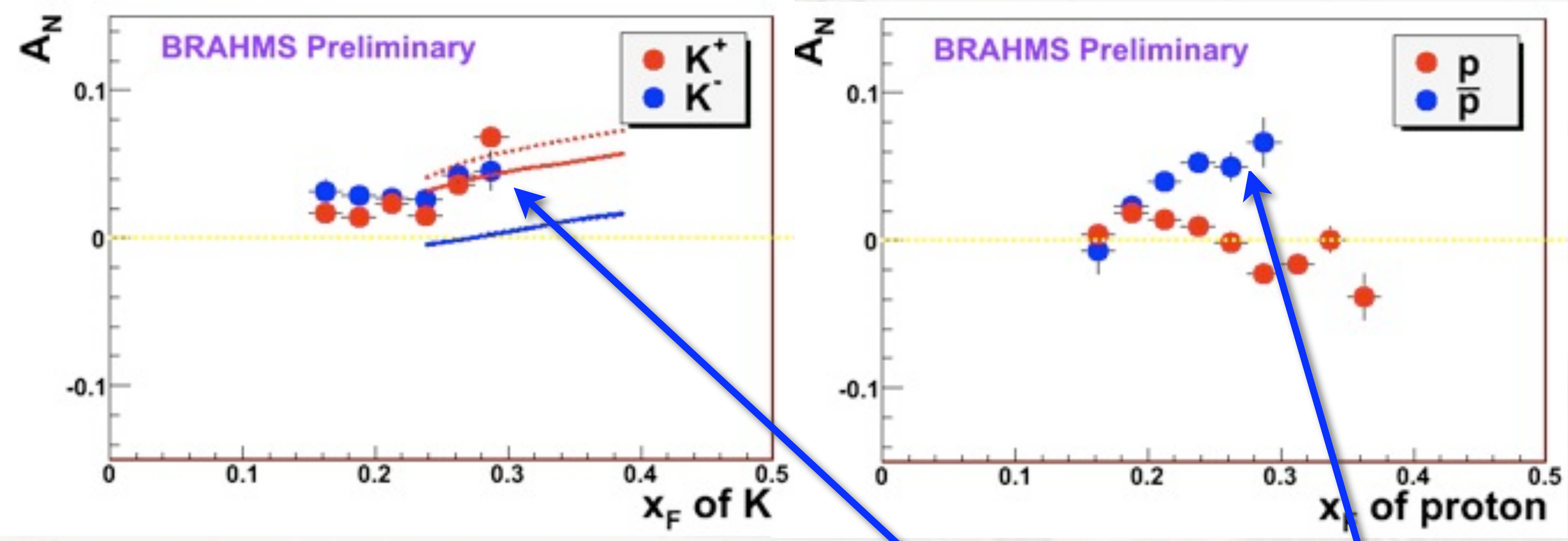
Sivers function (some surprises)

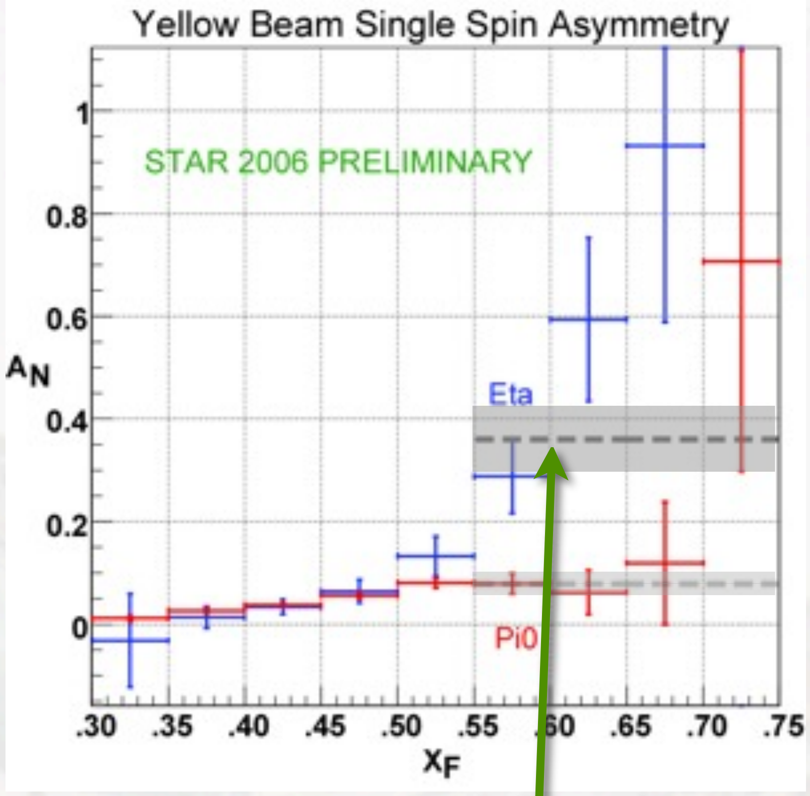


large K$^-$ and anti-proton asymmetries

	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 function (some surprises)



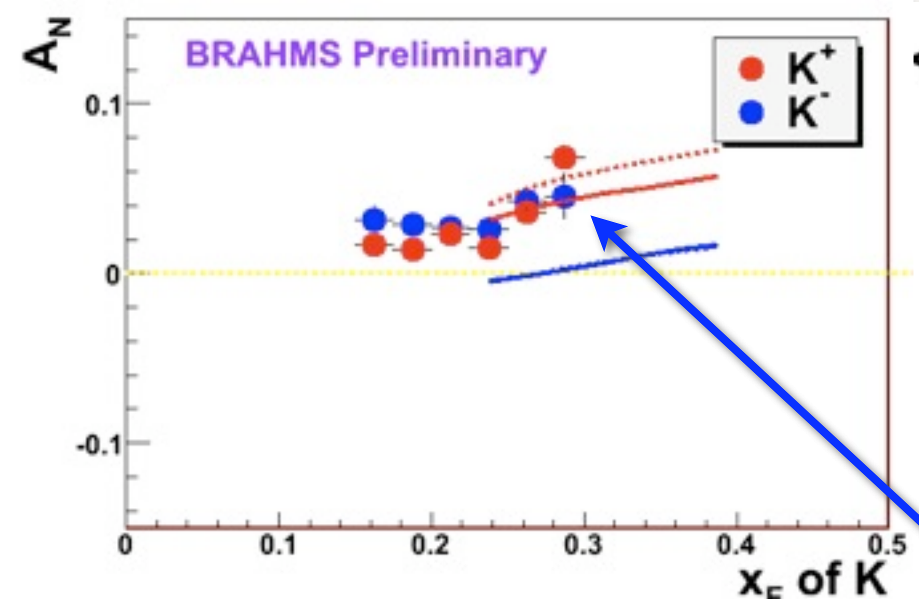


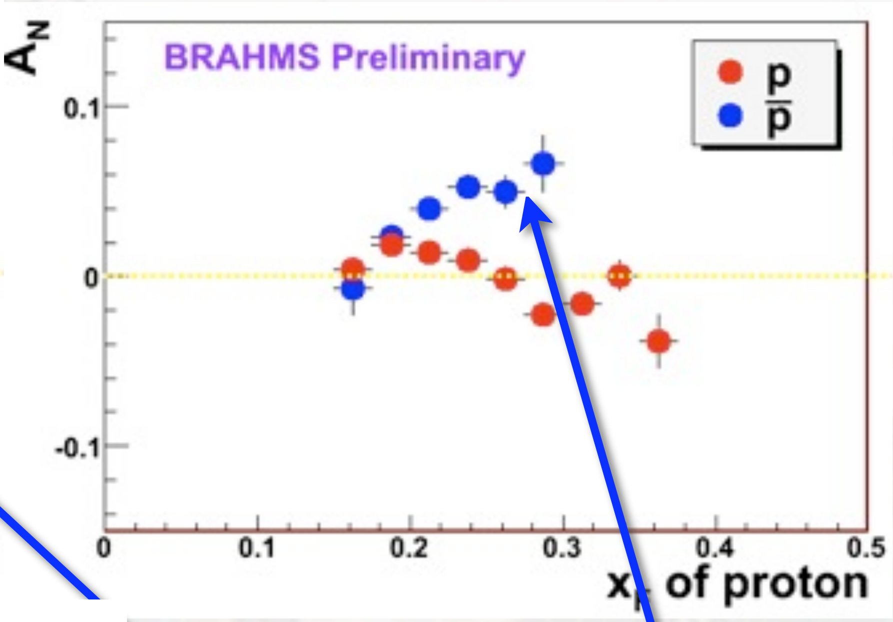
large K$^-$ and anti-proton asymmetries

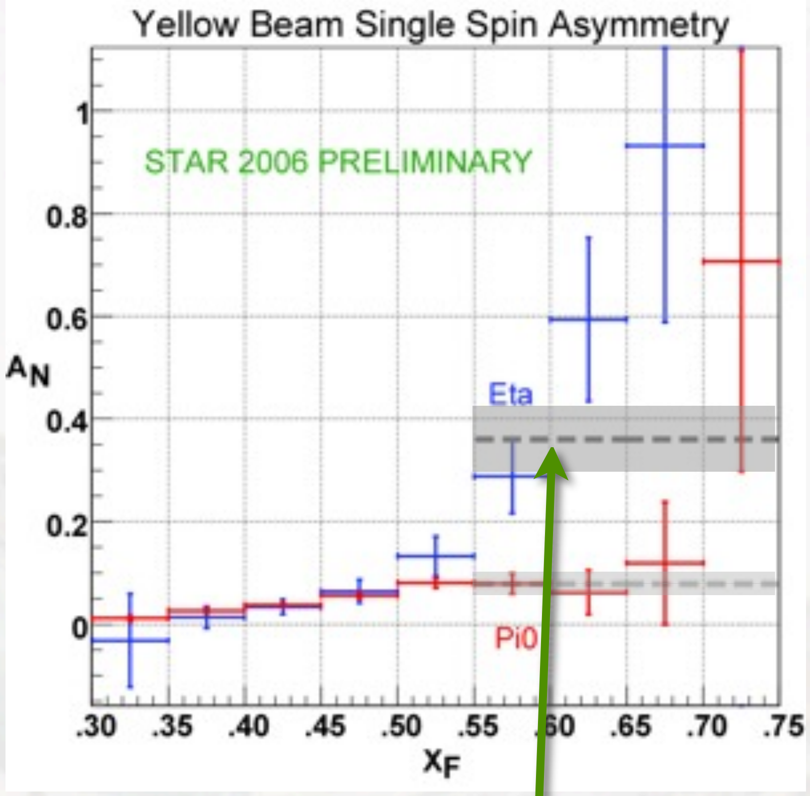
large eta asymmetries

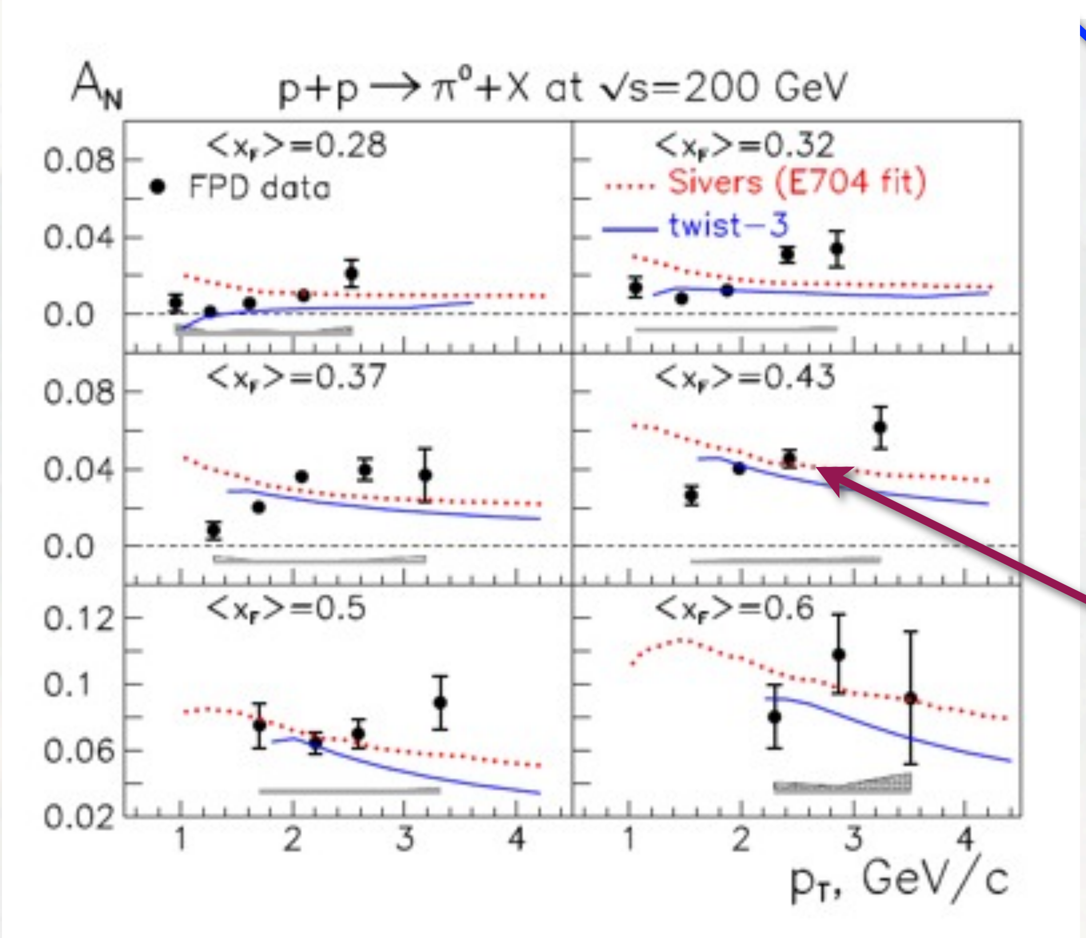
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers function (some surprises)









large K^- and anti-proton asymmetries

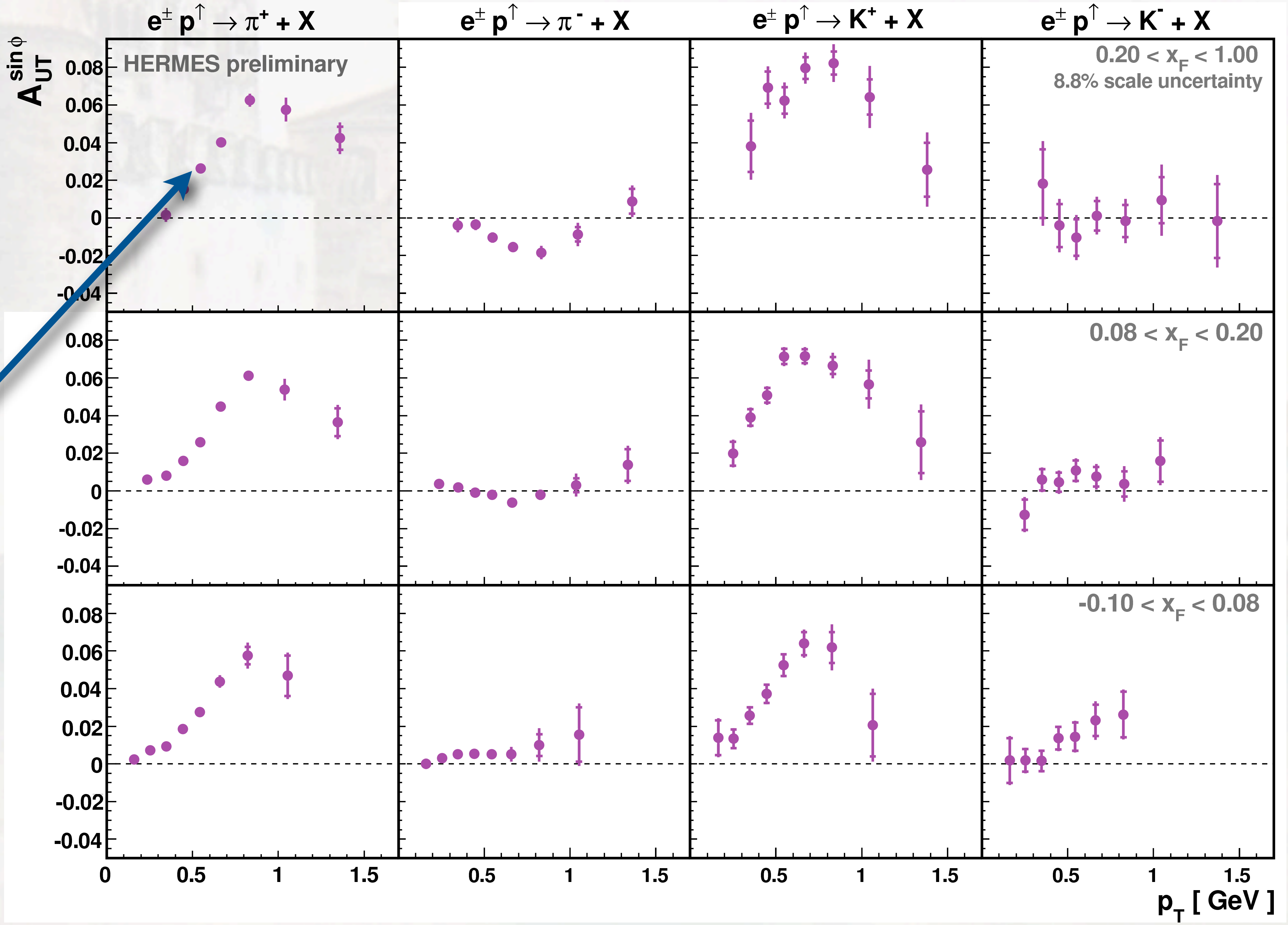
at fixed x_F don't follow expected (perturbative) behavior

large eta asymmetries

☛ A.Ogawa

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

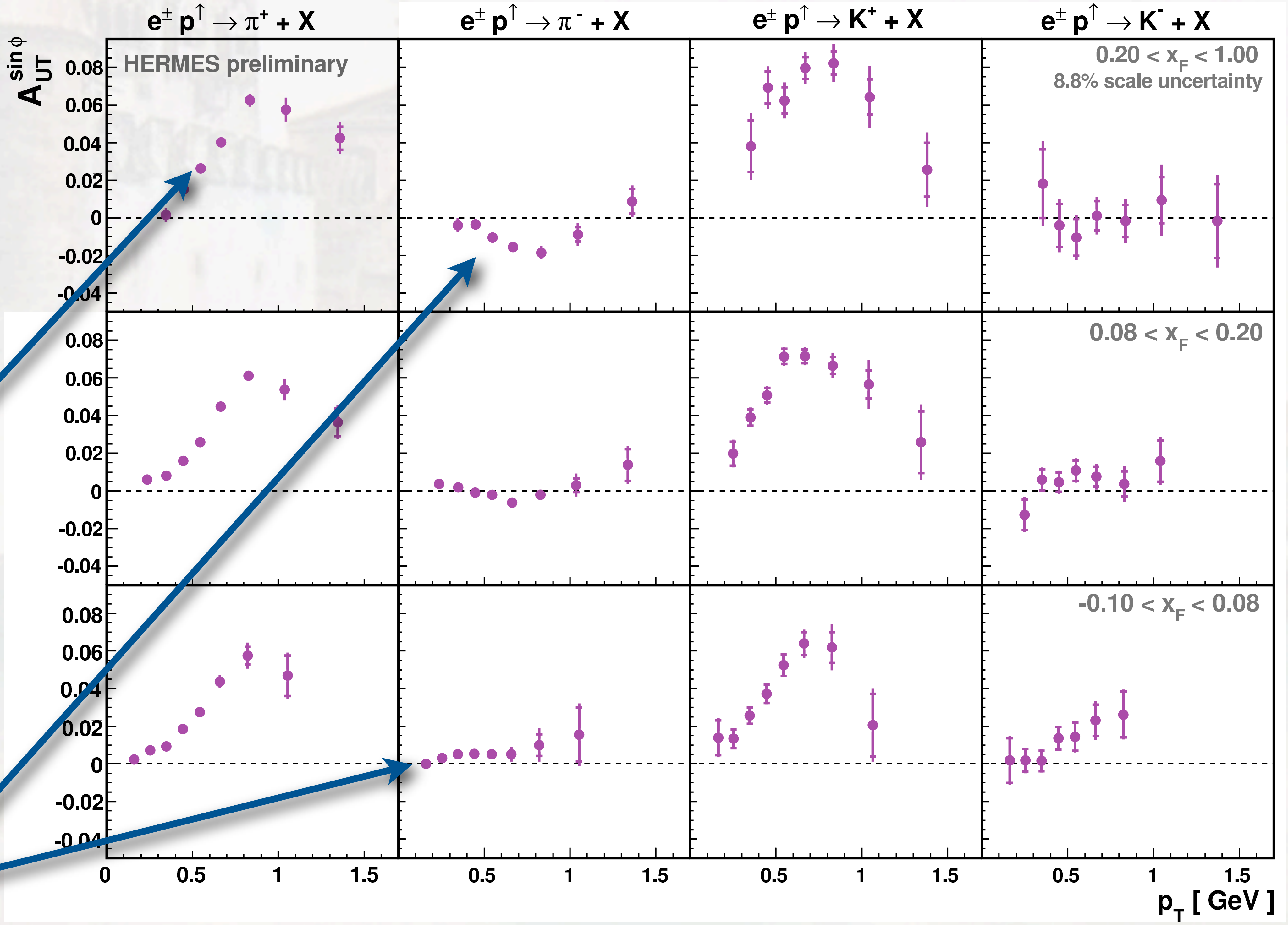
Inclusive hadrons in ep



increasing amplitudes with turnover

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

Inclusive hadrons in ep

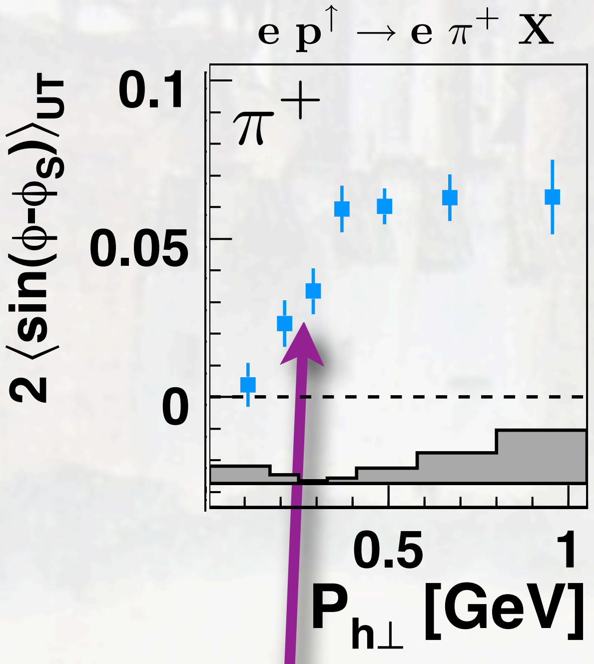


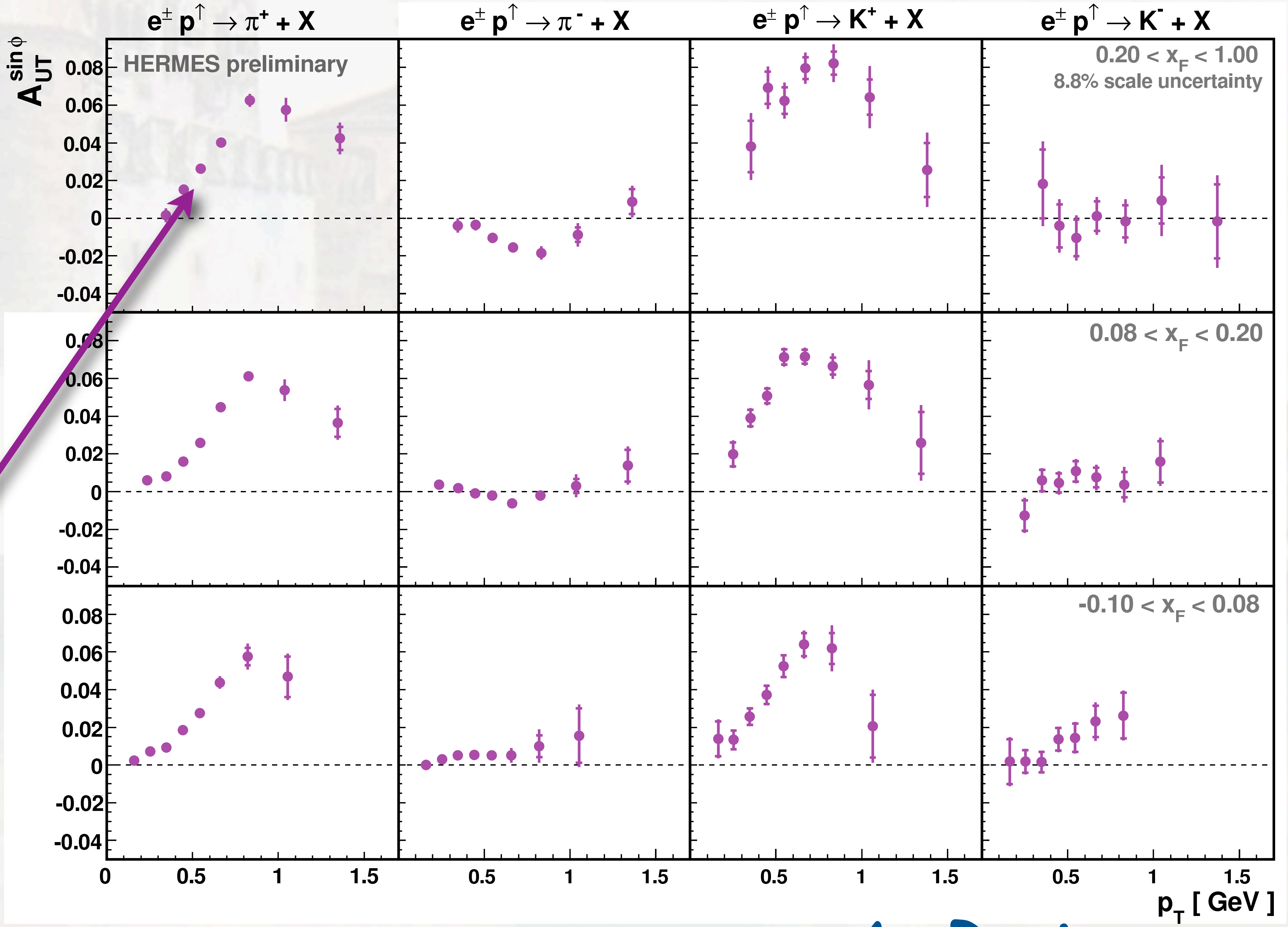
increasing amplitudes with turnover

sign change

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

Inclusive hadrons in ep



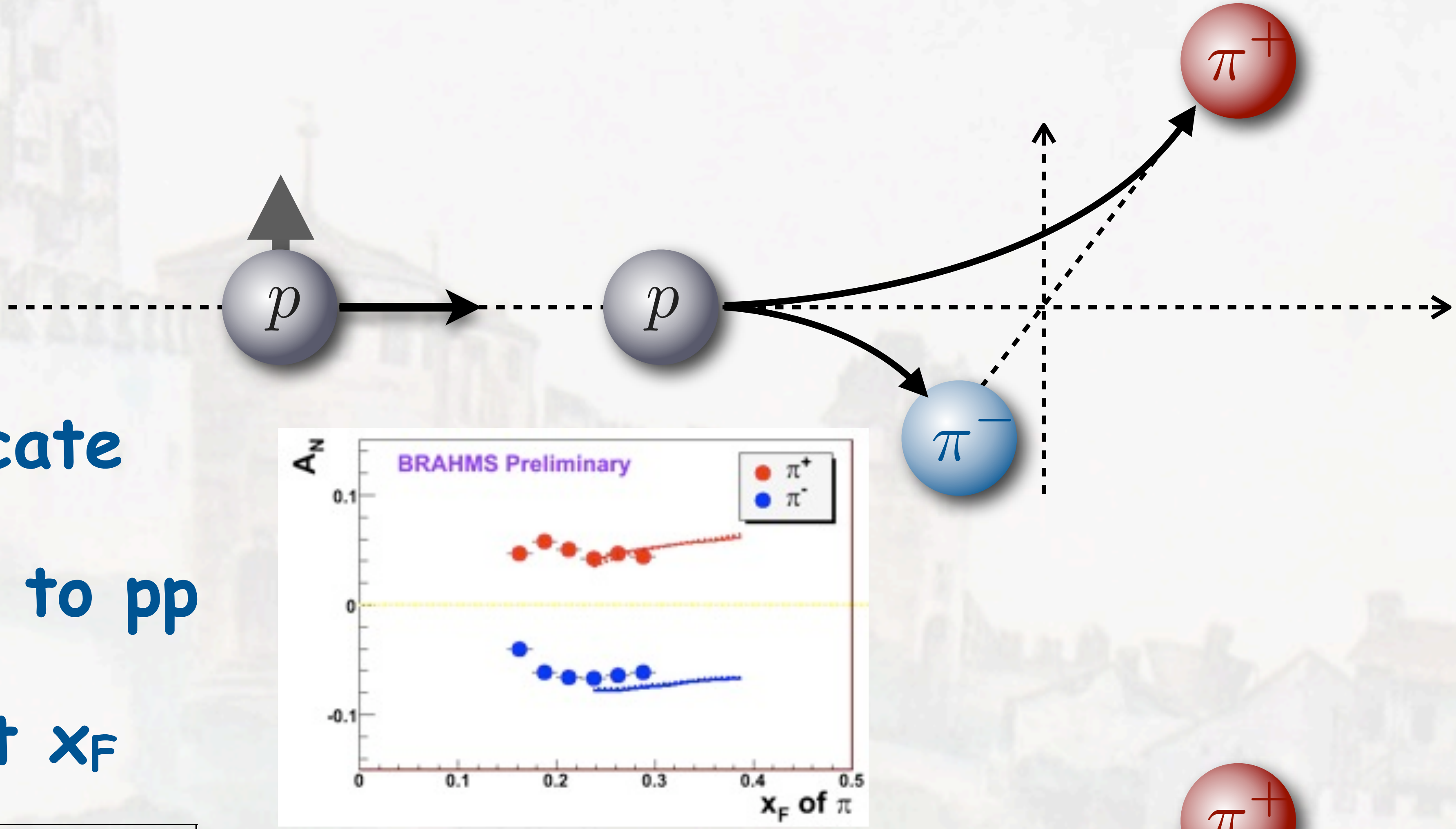


behavior and size similar to SIDIS Sivers

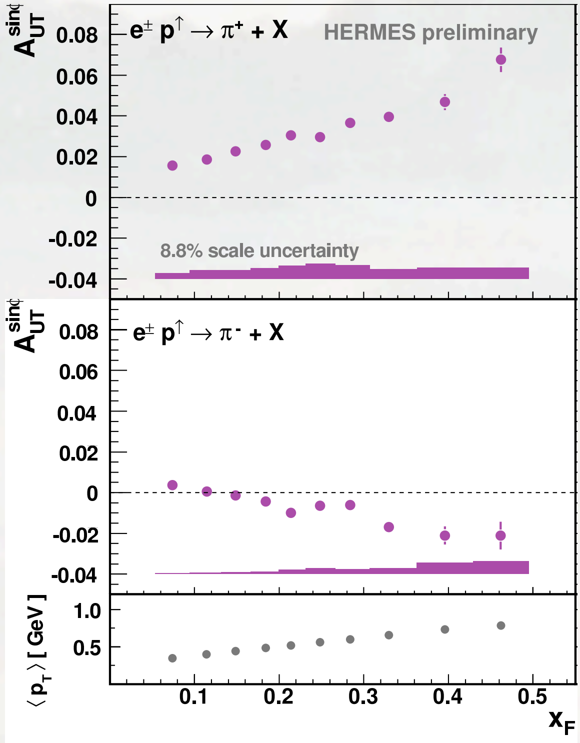
☛ A. Rostomyan

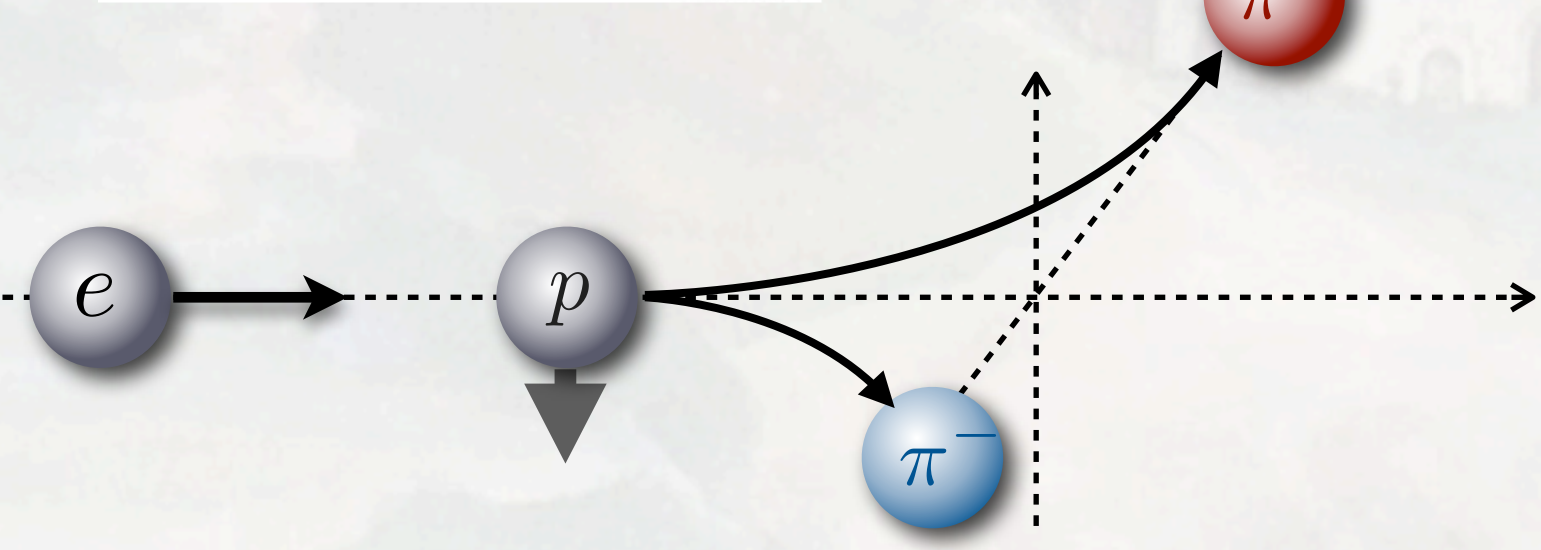
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Inclusive hadrons in pp & ep



- factorization intricate
- sign in ep opposite to pp
- signals in different x_F regions





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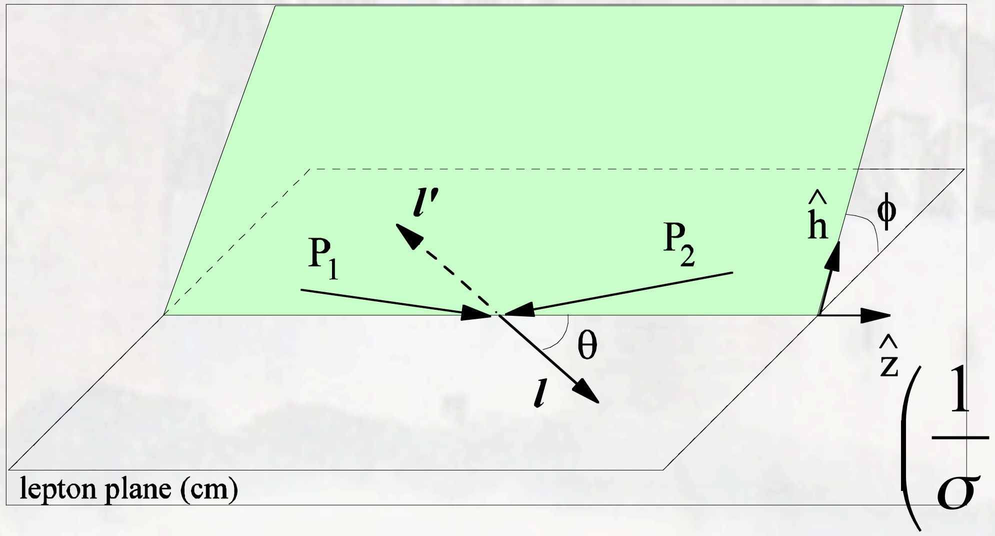
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Boer-Mulders function (Drell-Yan)

☛ J.C. Peng

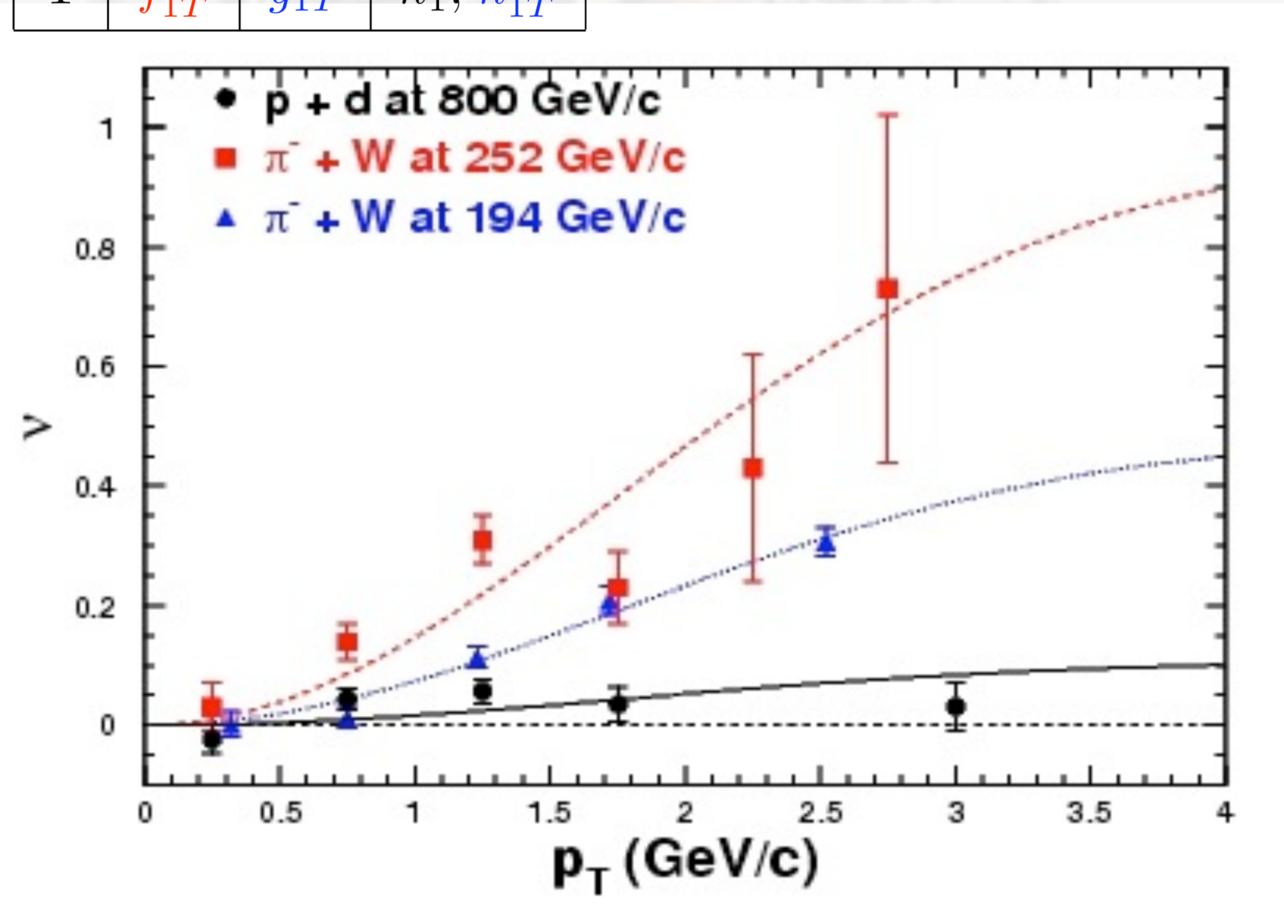


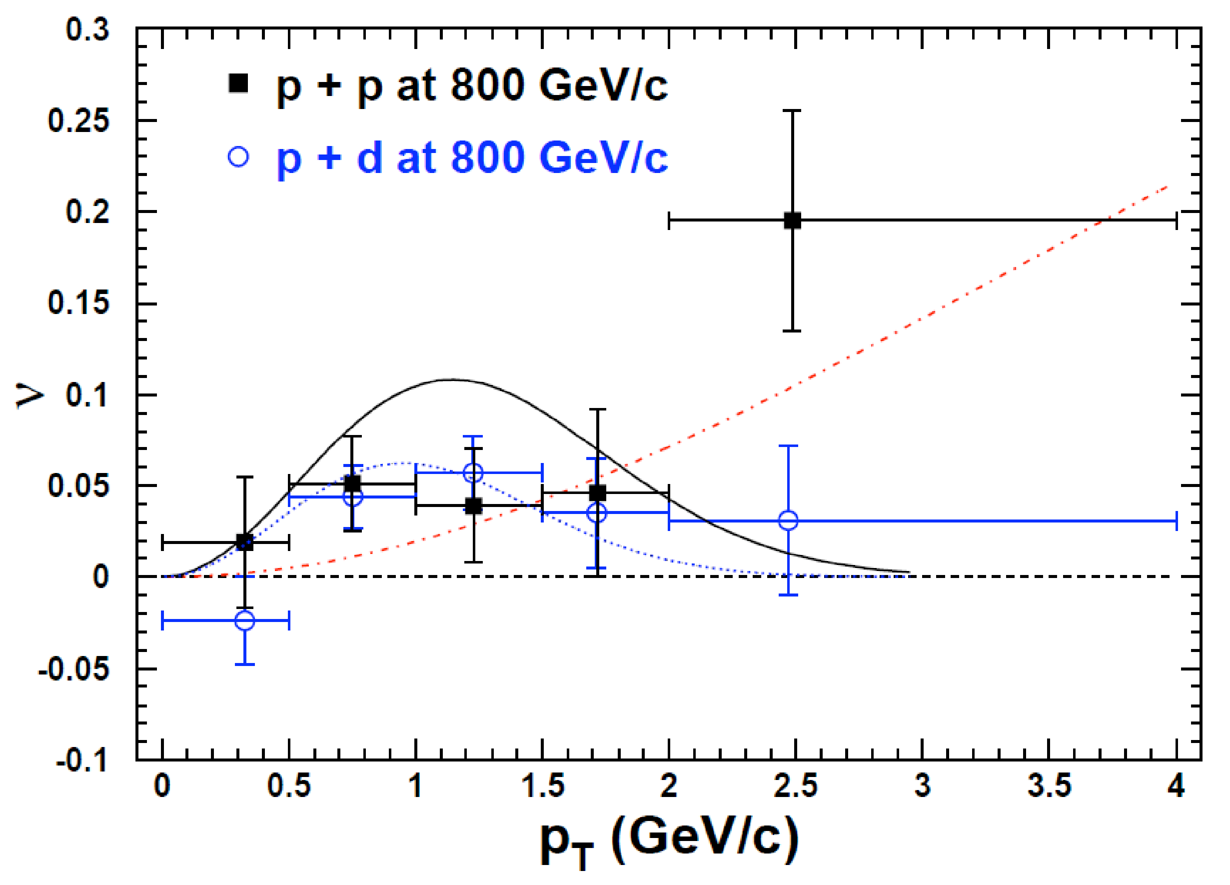
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right) = \left[\frac{3}{4\pi}\right]\left[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

- Lam-Tung relation: $1 - \lambda = 2\nu$
  - insensitive to QCD corrections
  - clear sign for Boer-Mulders effect ($\sim \nu$)
  - violated in pion-induced Drell-Yan

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

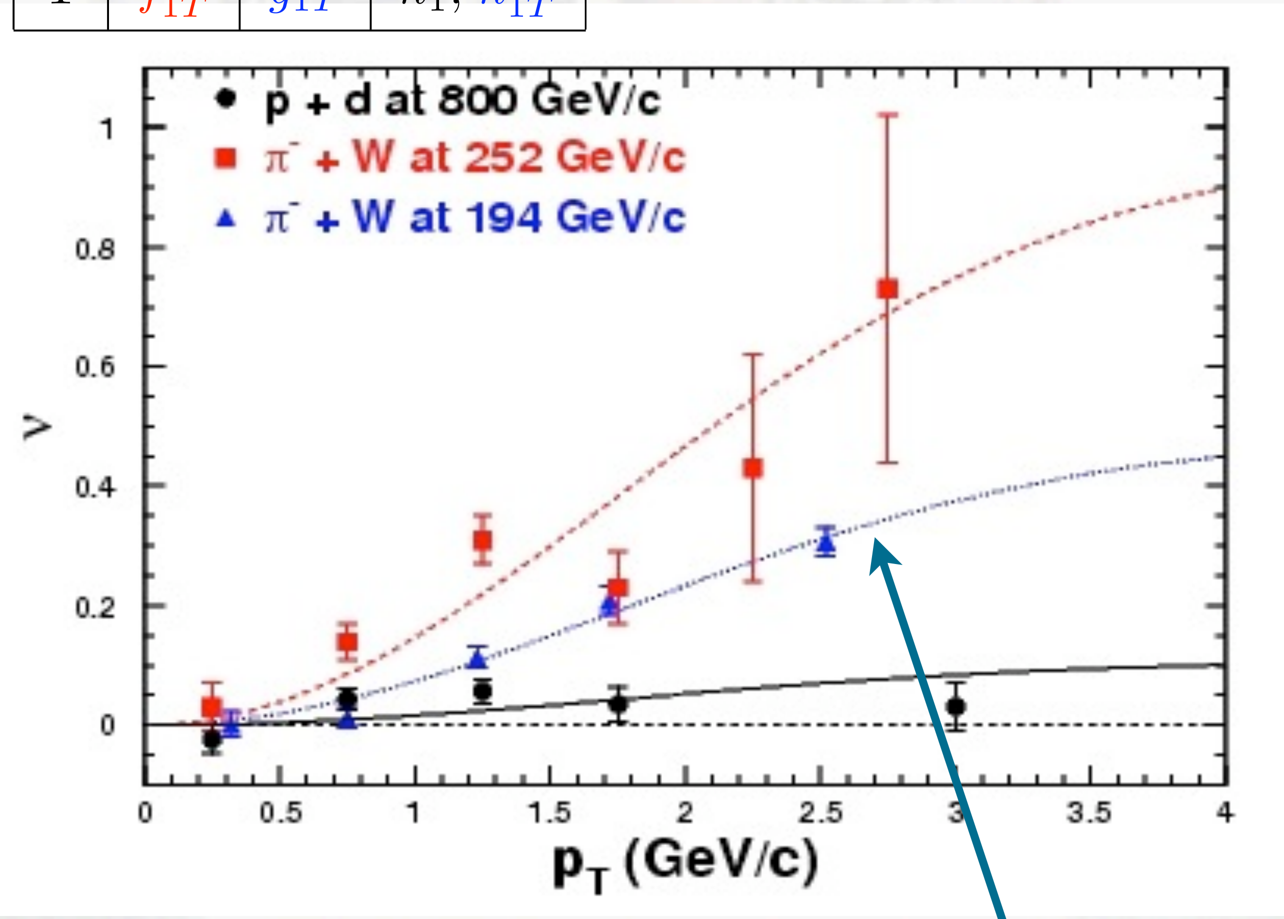
Signs of Boer-Mulders

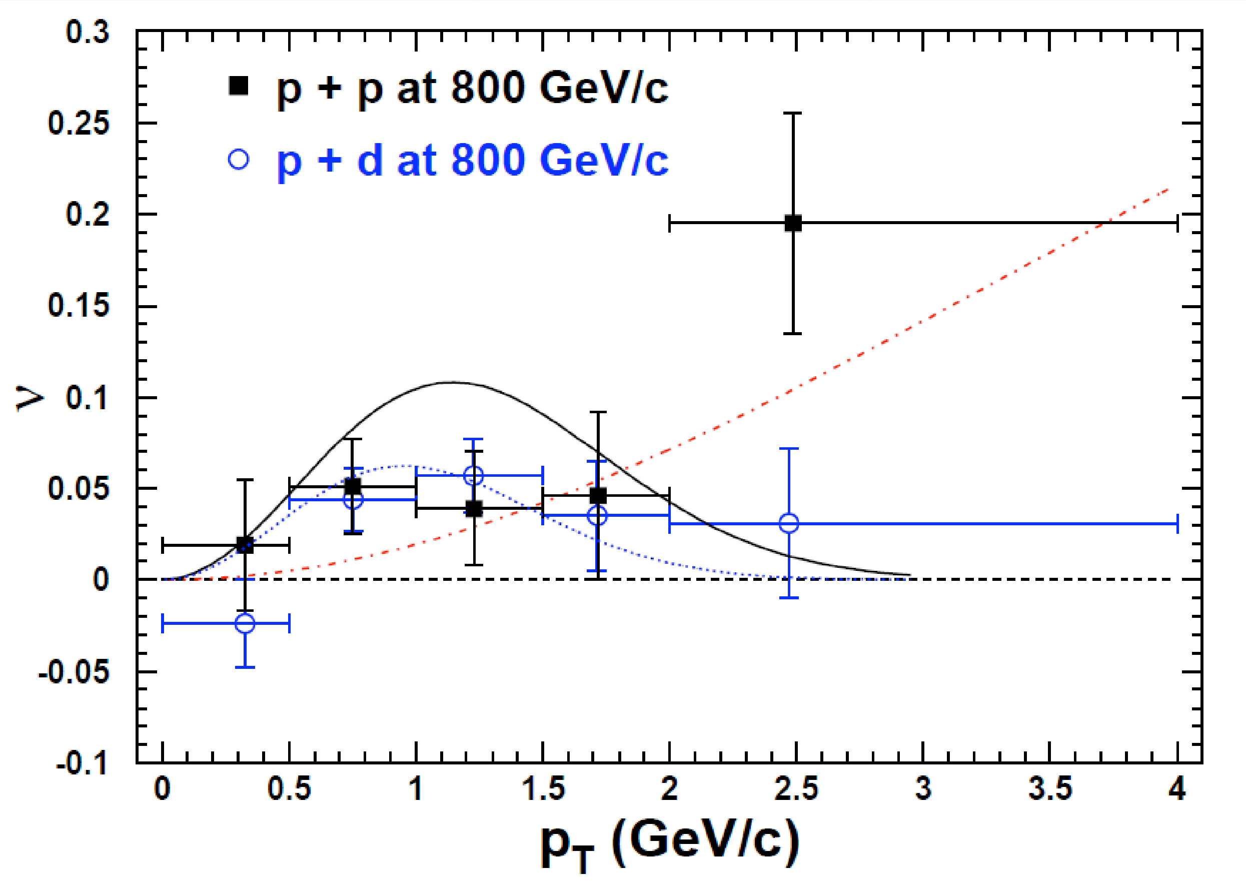




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Signs of Boer-Mulders

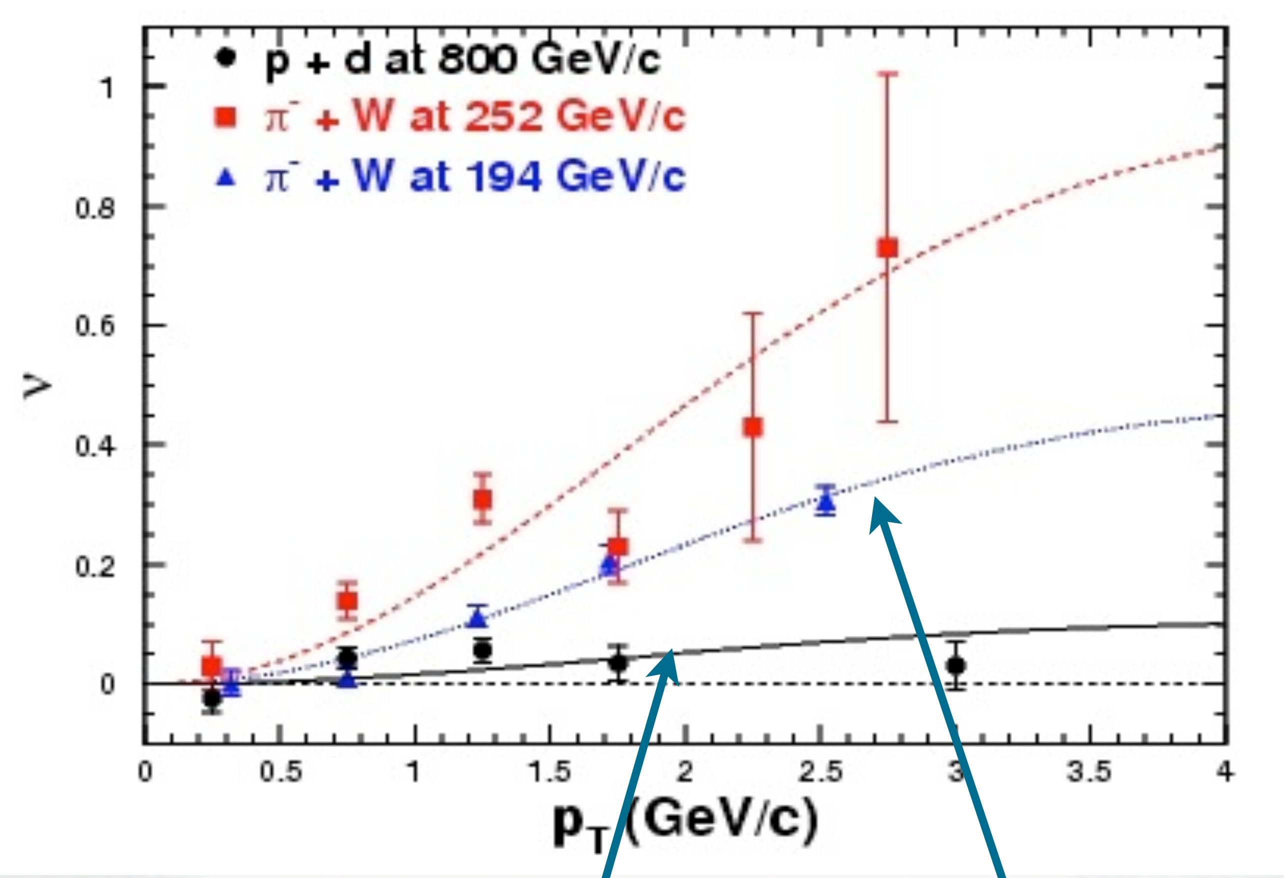


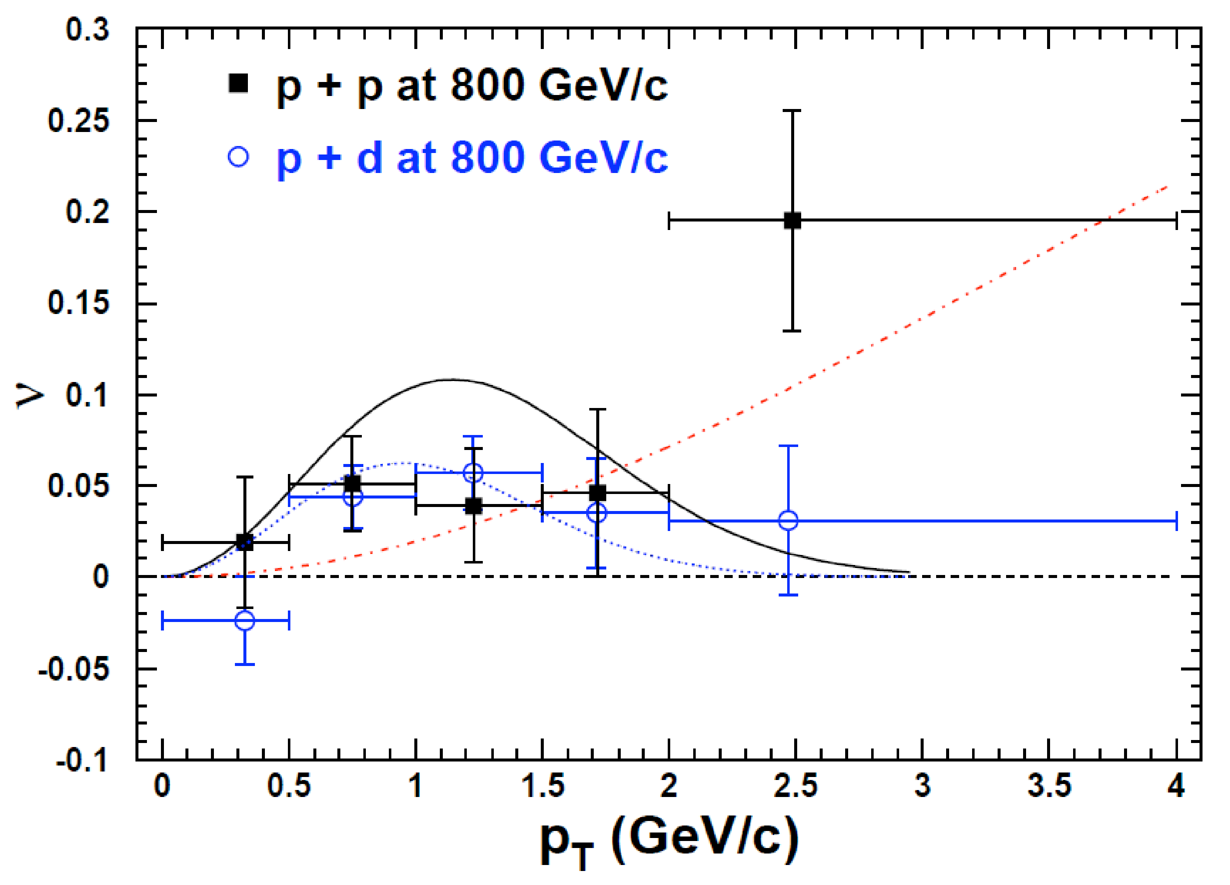


valence BM fctn

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

Signs of Boer-Mulders



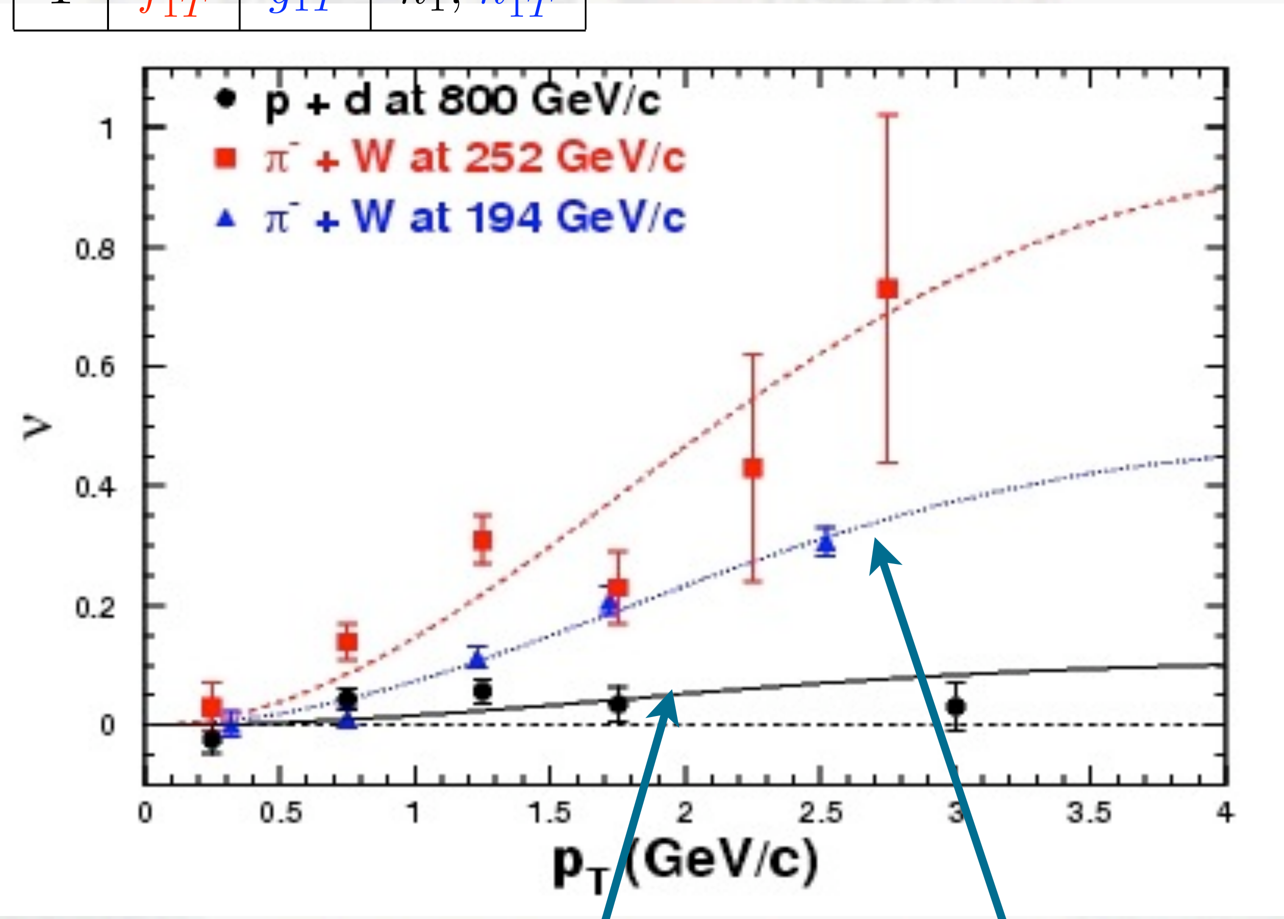


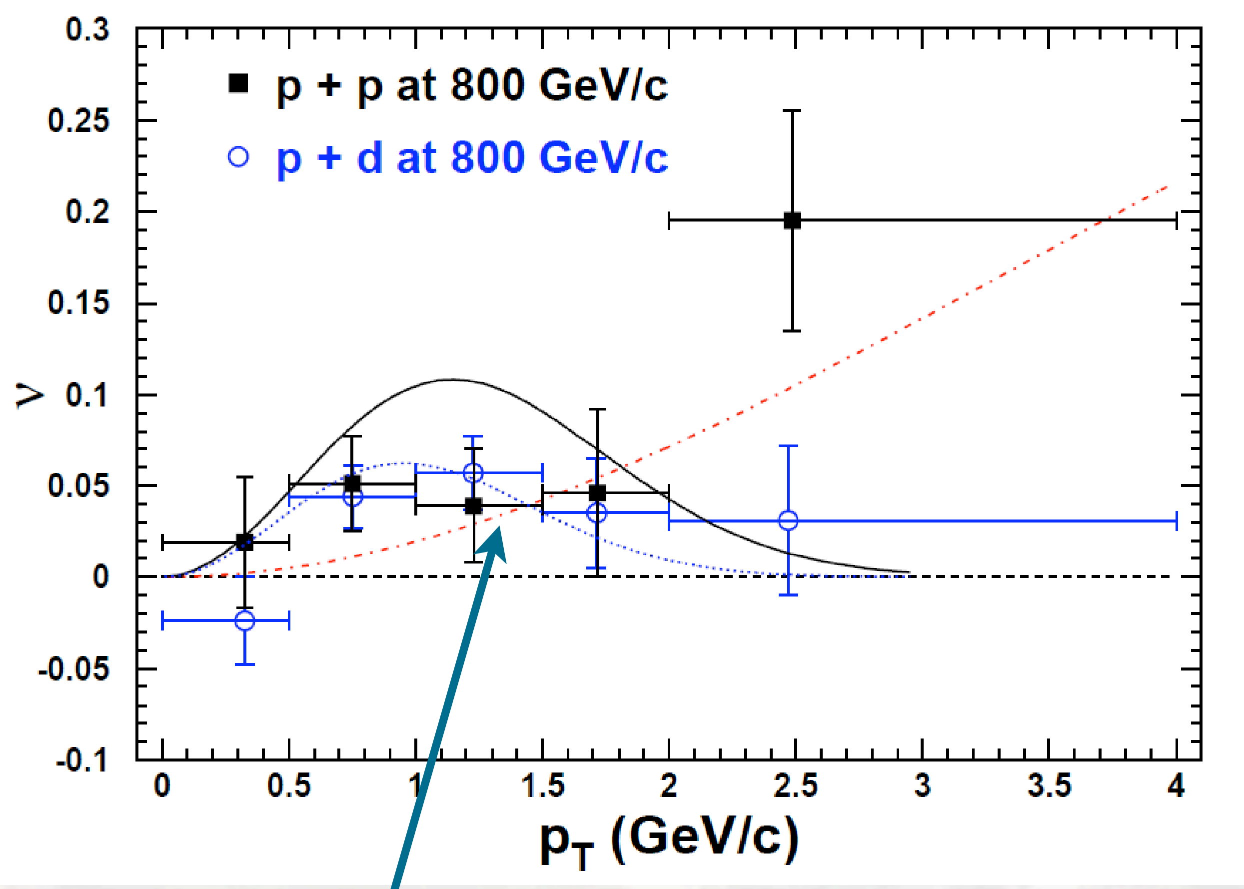
valence and sea BM fctn

valence BM fctn

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

Signs of Boer-Mulders





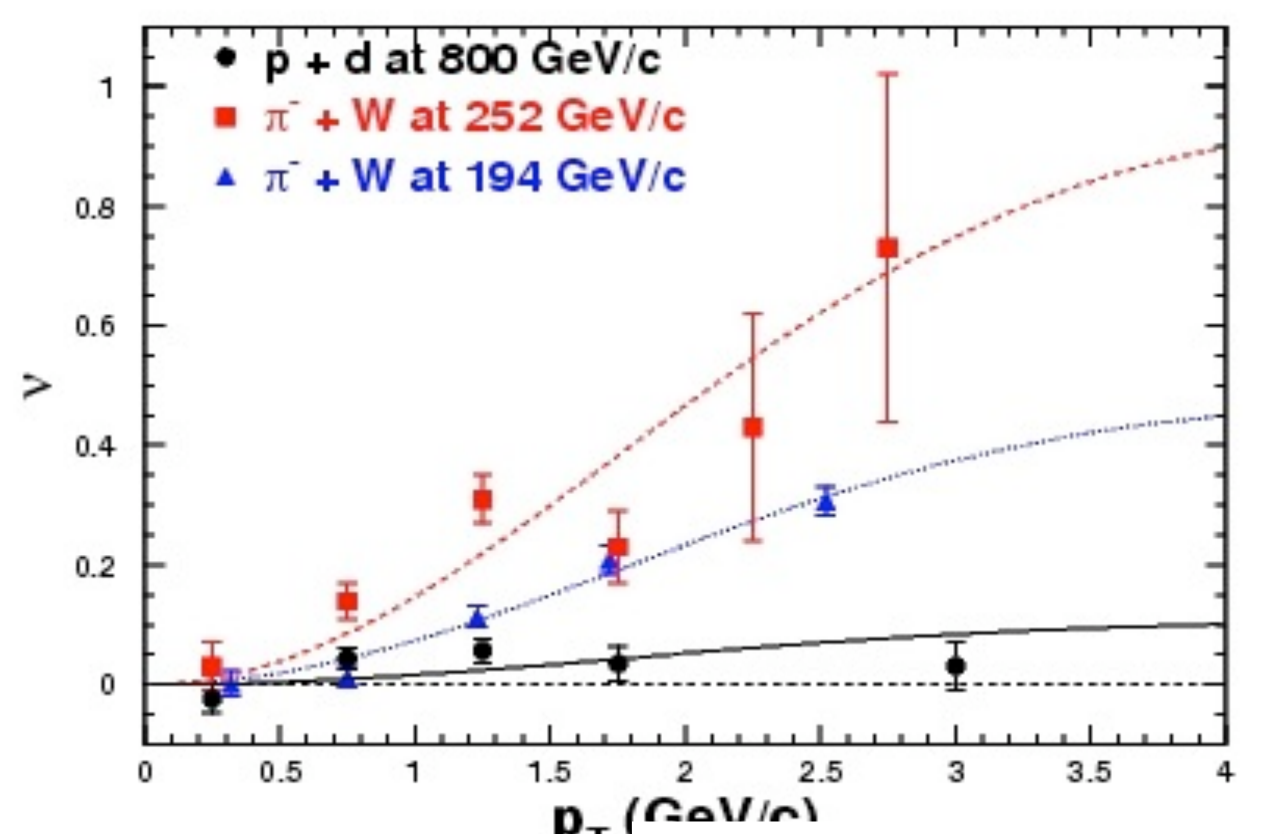
similar BM fctn for up and down quarks?

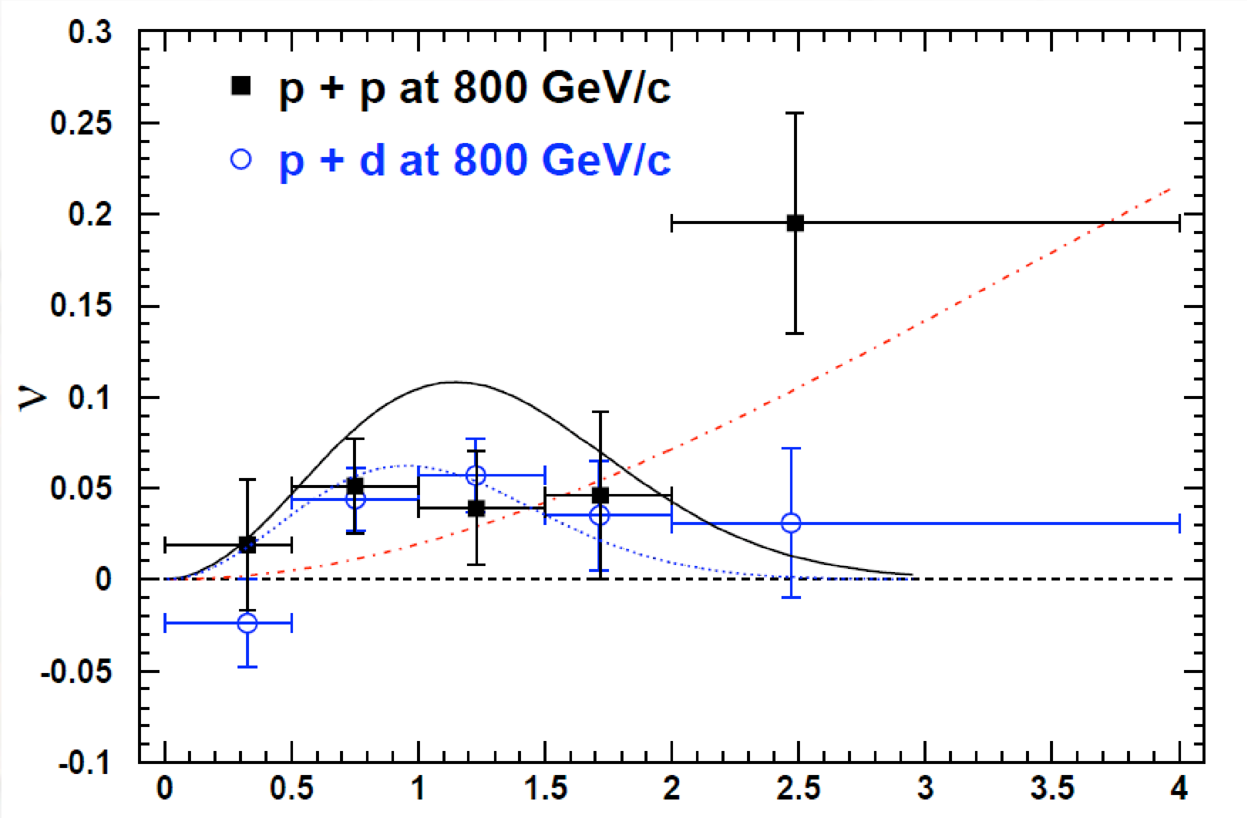
valence and sea BM fctn

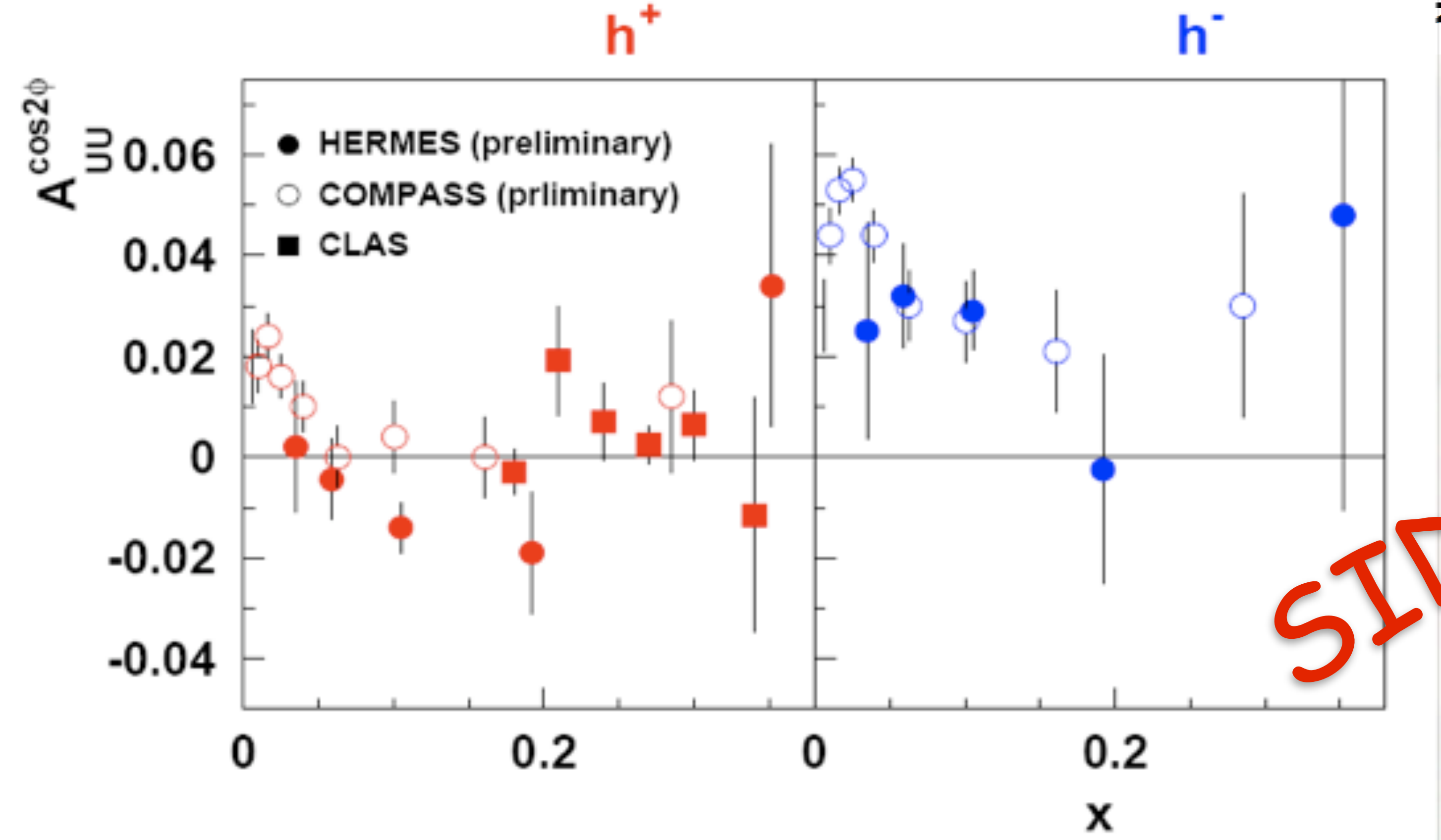
valence BM fctn

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

Signs of Boer-Mulders



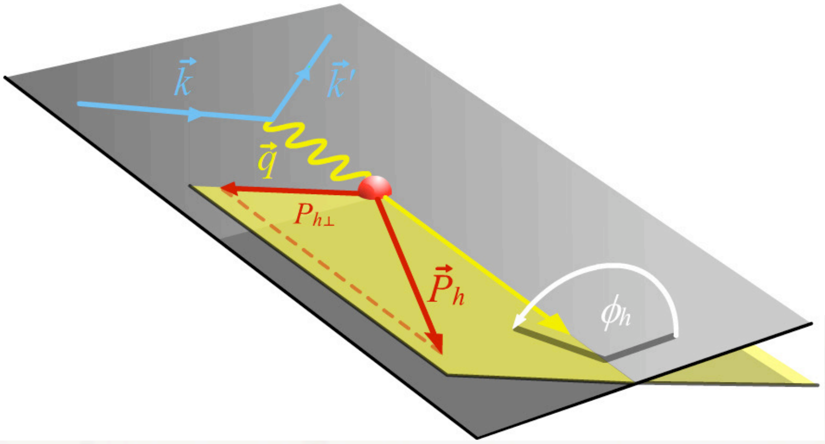


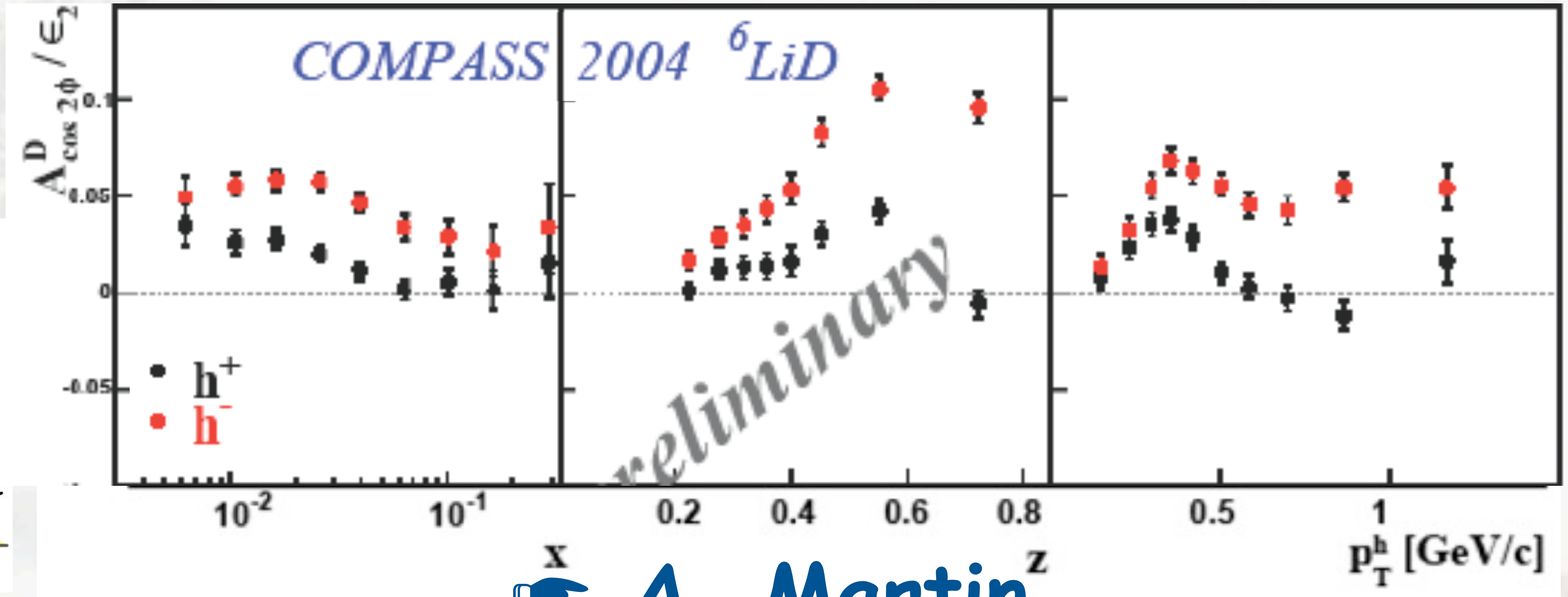


SIDIS

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

Signs of Boer-Mulders





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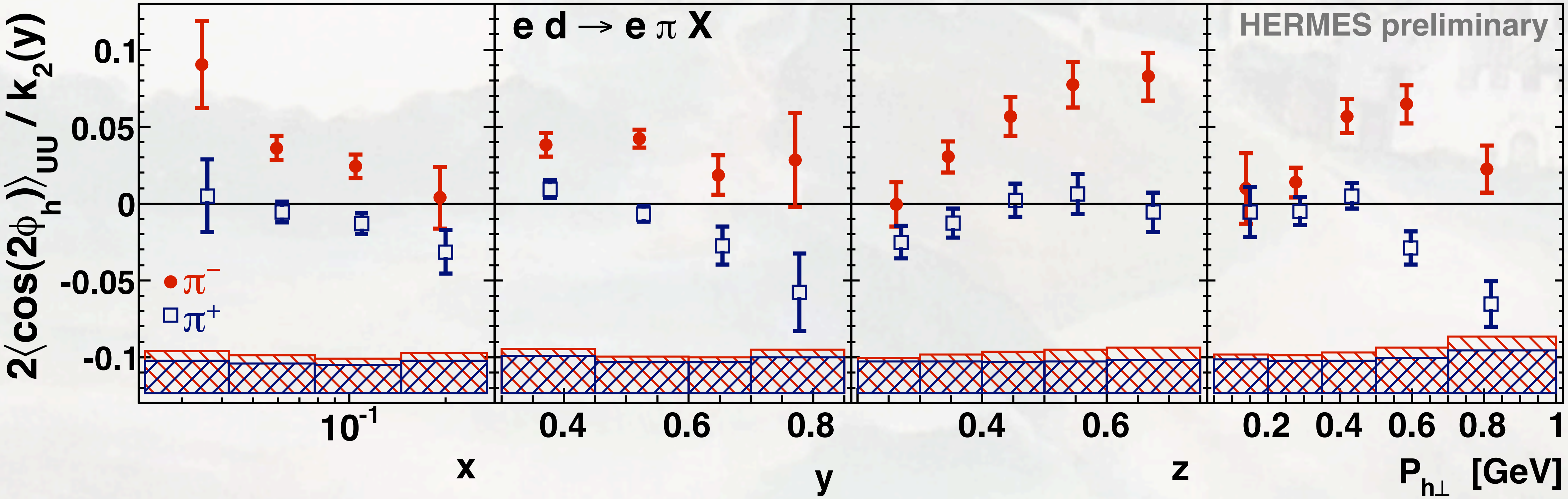
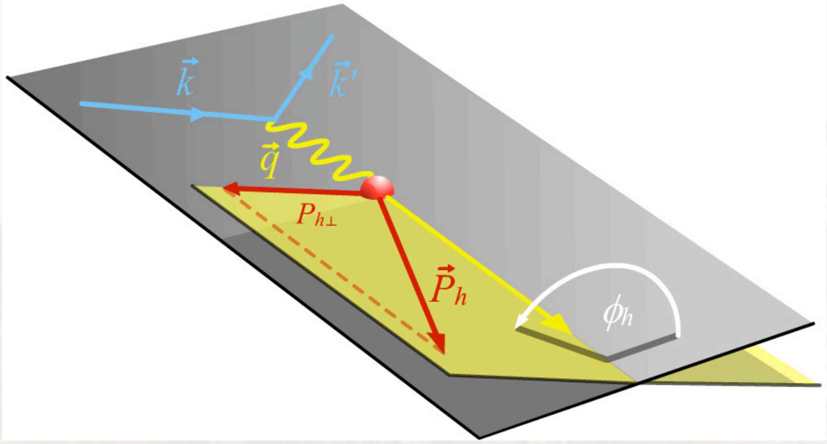
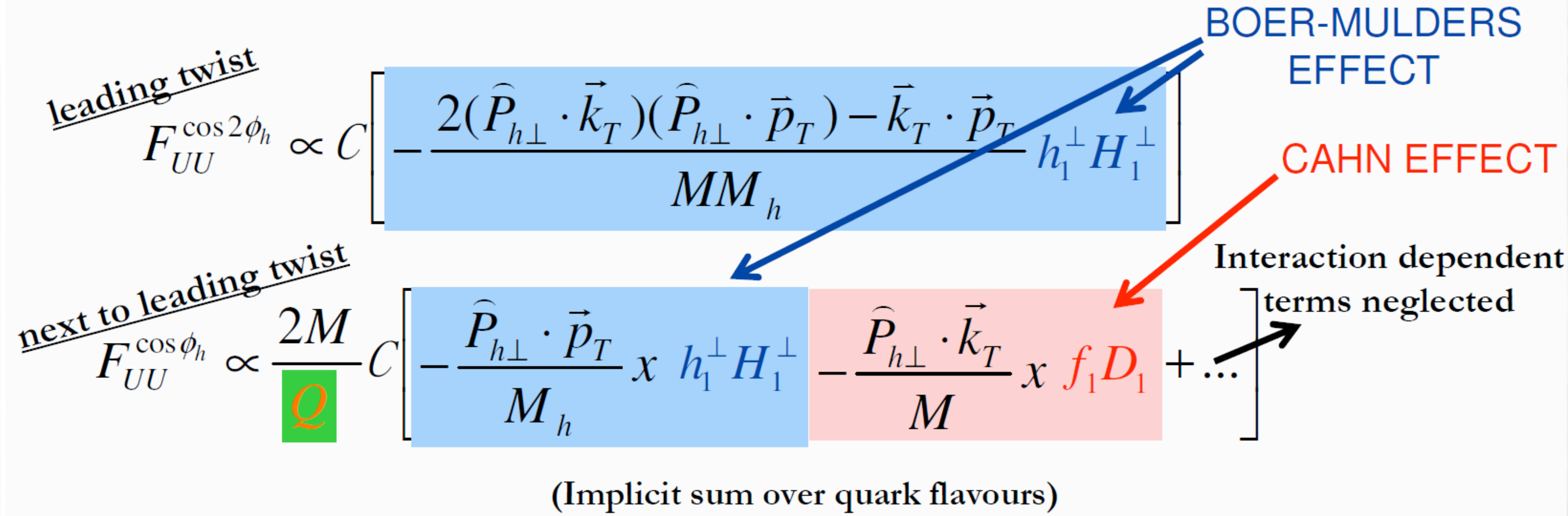


☛ **A. Rostomyan**

Modulations in spin-independent SIDIS cross section



$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_h\,\mathrm{d}P_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)\,F_{\mathrm{UU,T}} + B(y)F_{\mathrm{UU,L}}$$
$$+C(y)\cos\phi_h F_{\mathrm{UU}}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{\mathrm{UU}}^{\cos 2\phi_h}\}$$



BOER-MULDERS EFFECT

CAHN EFFECT

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\widehat{P}_{h\perp}\cdot\vec{k}_T)(\widehat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^\perp H_1^\perp\right]$$

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\widehat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\ h_1^\perp H_1^\perp - \frac{\widehat{P}_{h\perp}\cdot\vec{k}_T}{M}x\ f_1 D_1 + \ldots\right]$$

Interaction dependent terms neglected

(Implicit sum over quark flavours)

Cahn effect?

next to leading twist

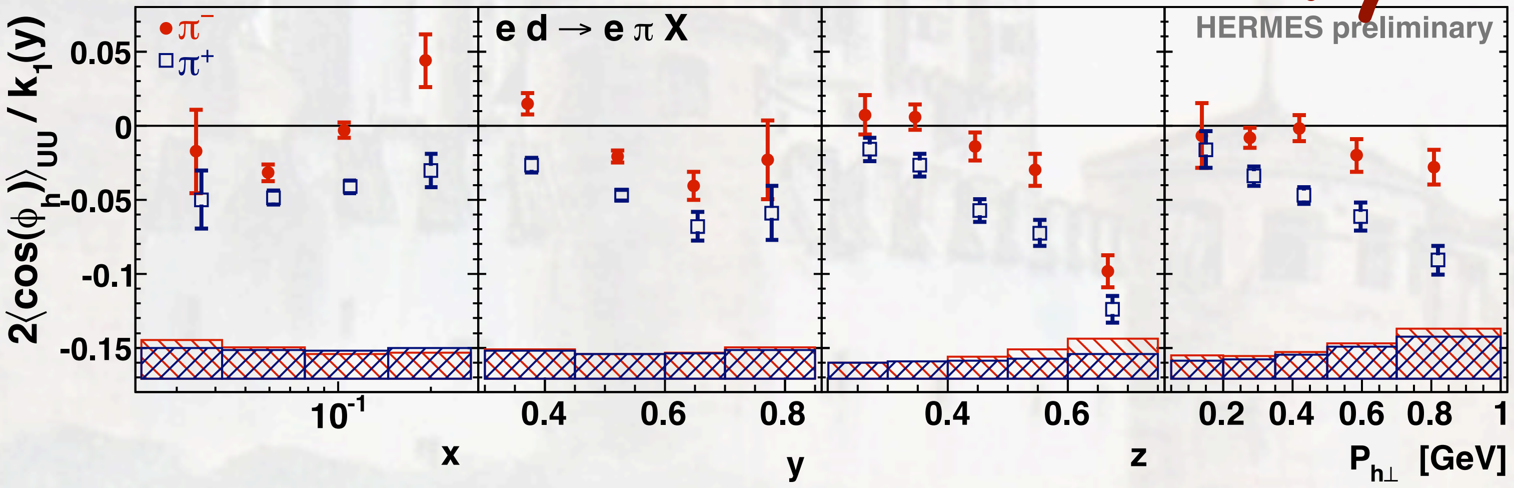
BOER-MULDERS EFFECT

CAHN EFFECT

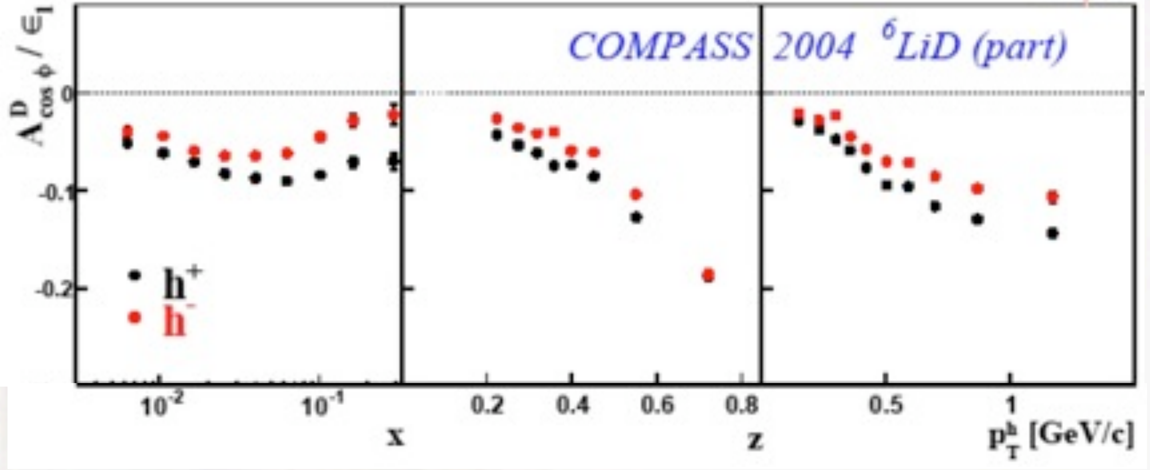
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{\boxed{Q}} C\left[\boxed{-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^\perp H_1^\perp} \boxed{-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1} + \ldots \right]$$

Interaction dependent terms neglected

☛ **A.Rostomyan**



☛ **A.Martin**



- no dependence on hadron charge expected

Cahn effect?

next to leading twist

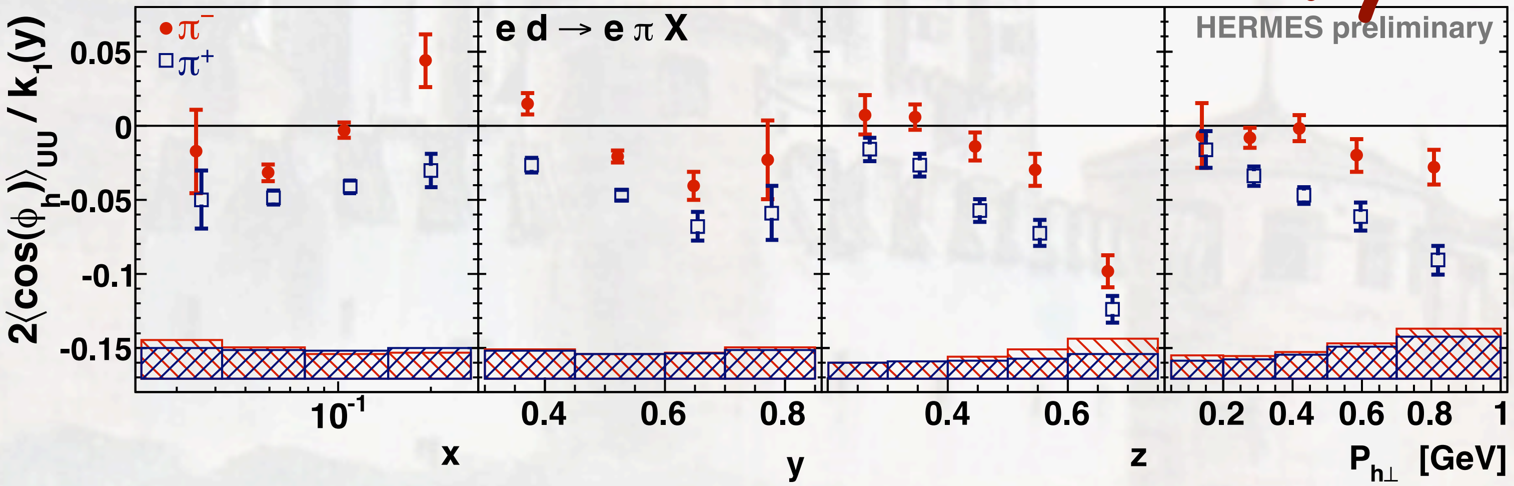
BOER-MULDERS EFFECT

CAHN EFFECT

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\, x\, h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\, x\, f_1 D_1 + \ldots\right]$$

Interaction dependent terms neglected

☛ **A.Rostomyan**



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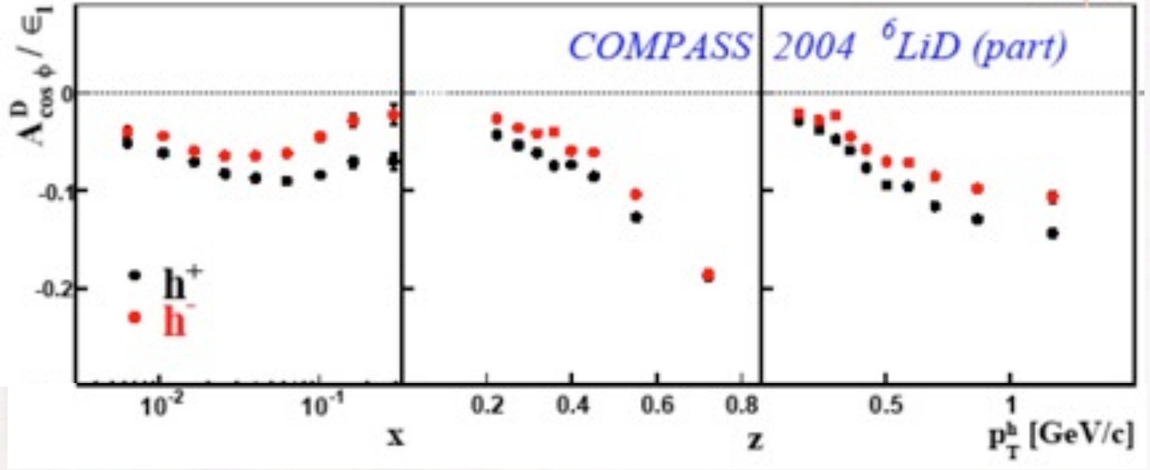
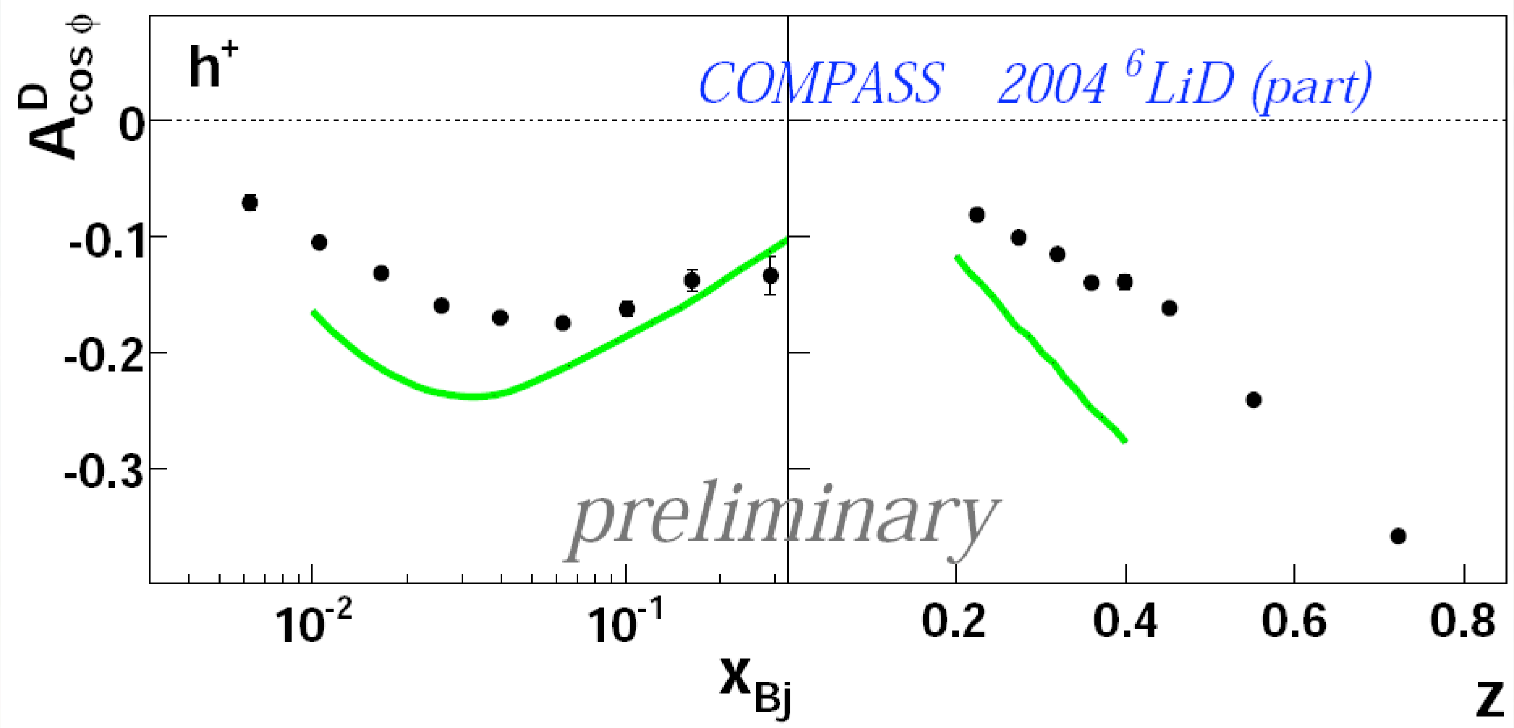
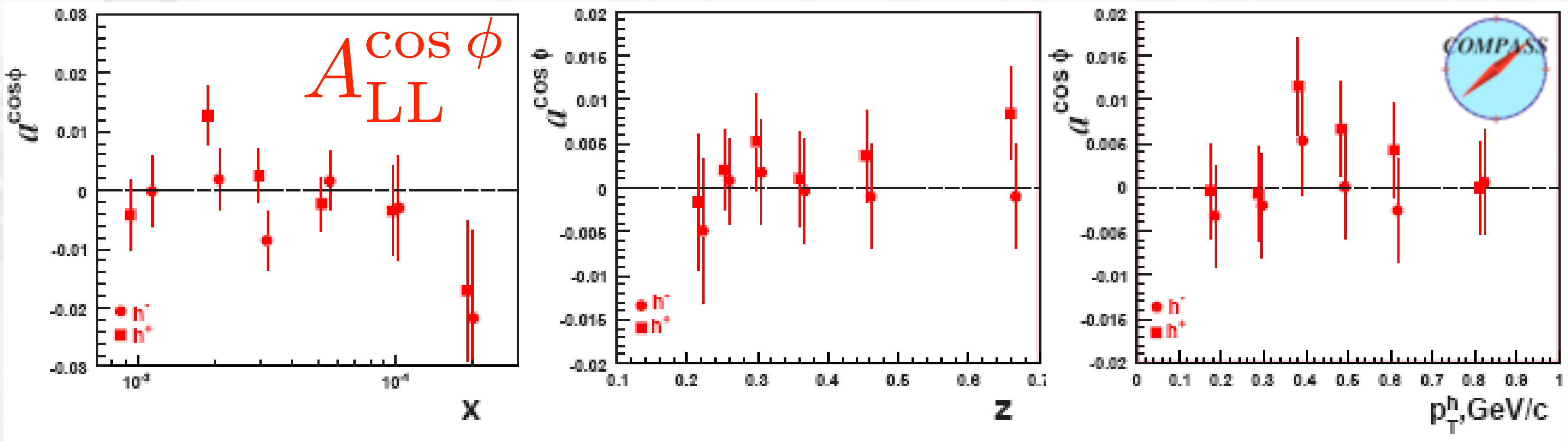


- no dependence on hadron charge expected
- prediction off from data

➡ sign of Boer-Mulders in $\cos\phi$ modulation or “real” twist-3?

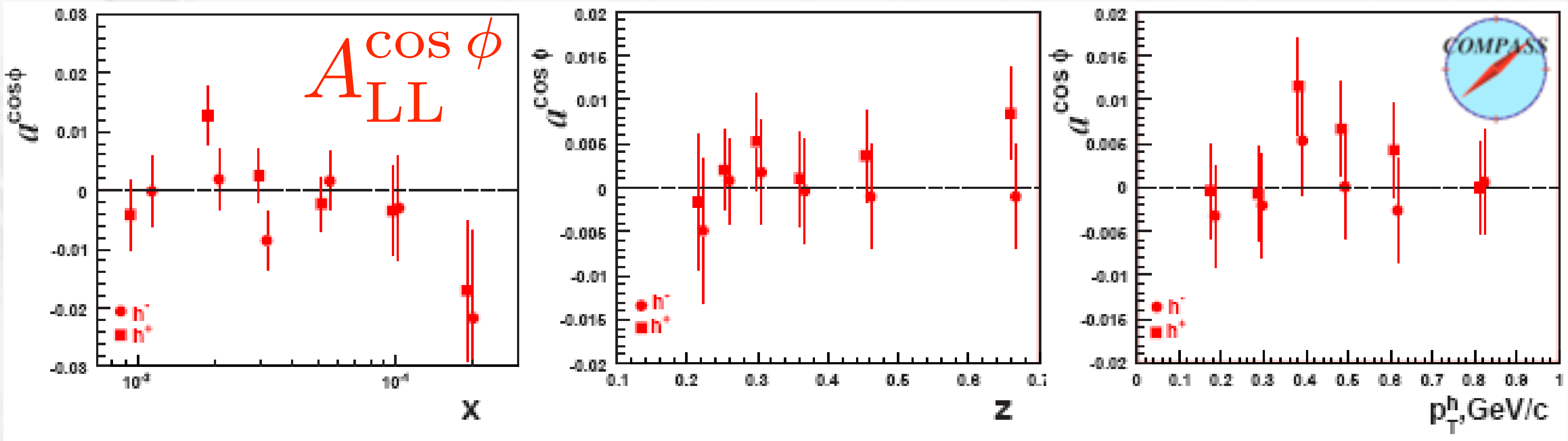


Other (twist-3) TMDs



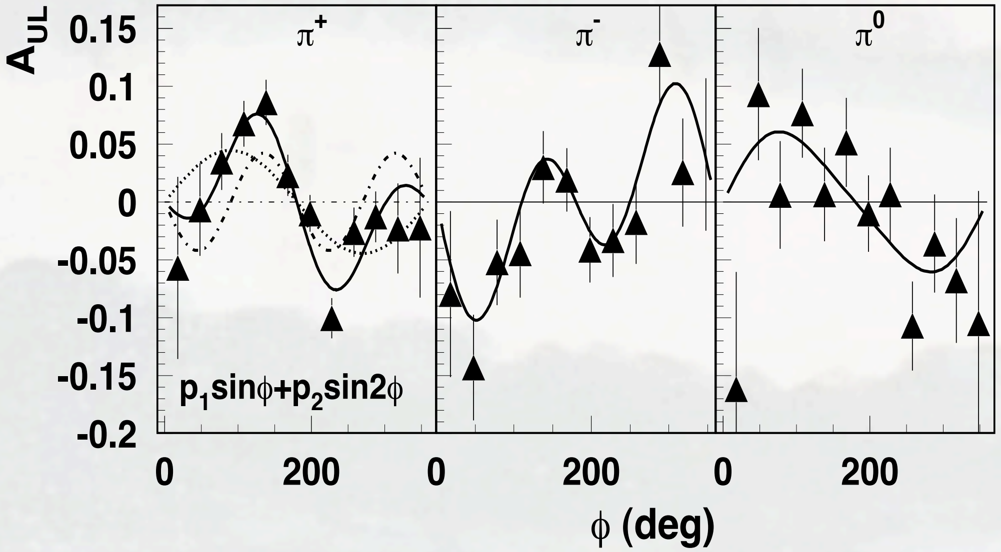
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^{\perp} D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Other (twist-3) TMDs



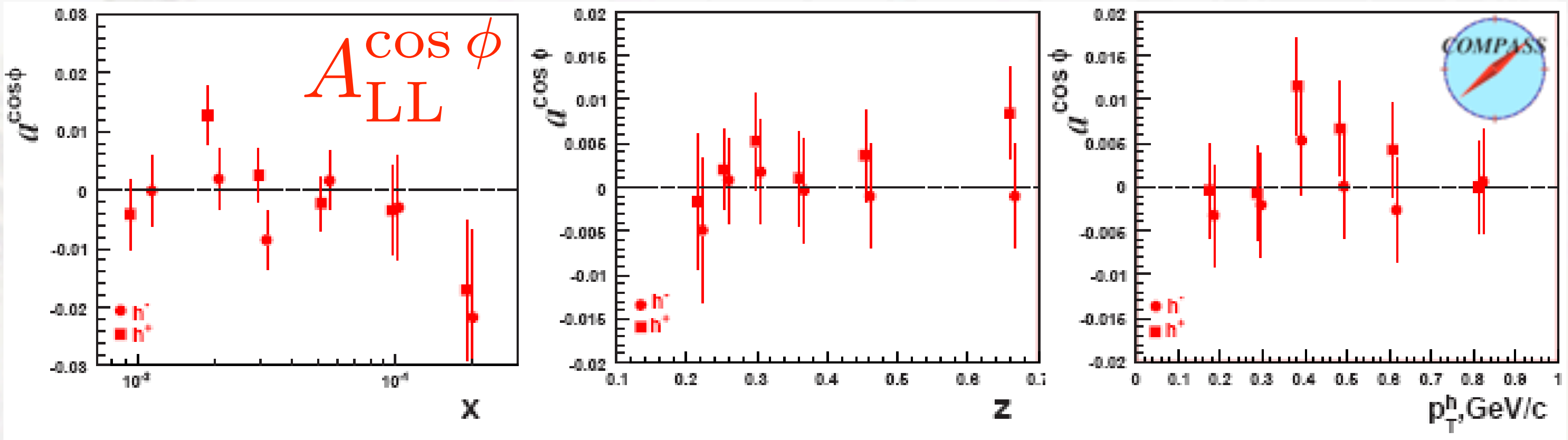
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^{\perp}D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



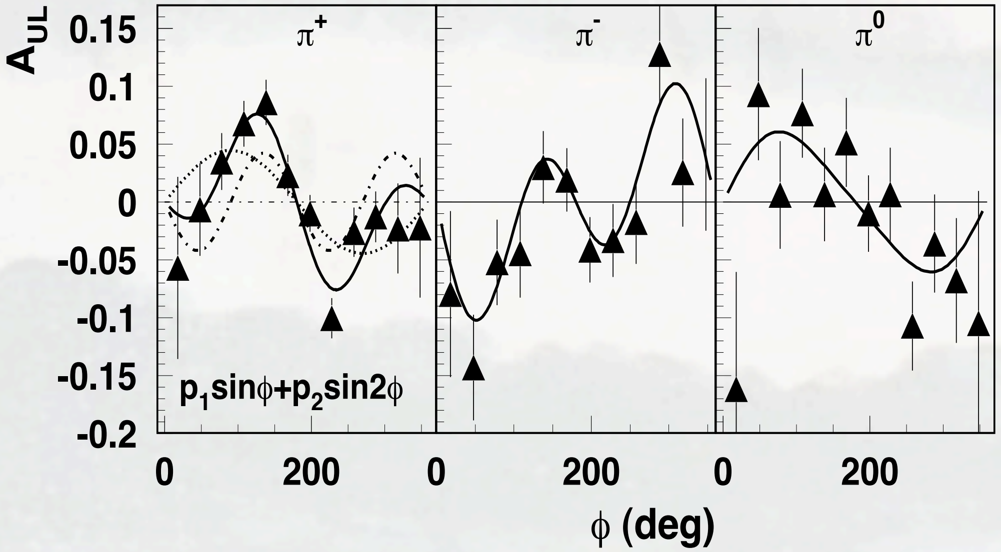
$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L H_1^{\perp} + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^{\perp}D_1 - \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

Other (twist-3) TMDs



$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^\perp - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^\perp D_1 + \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{E}}{z}\right)\right]$$

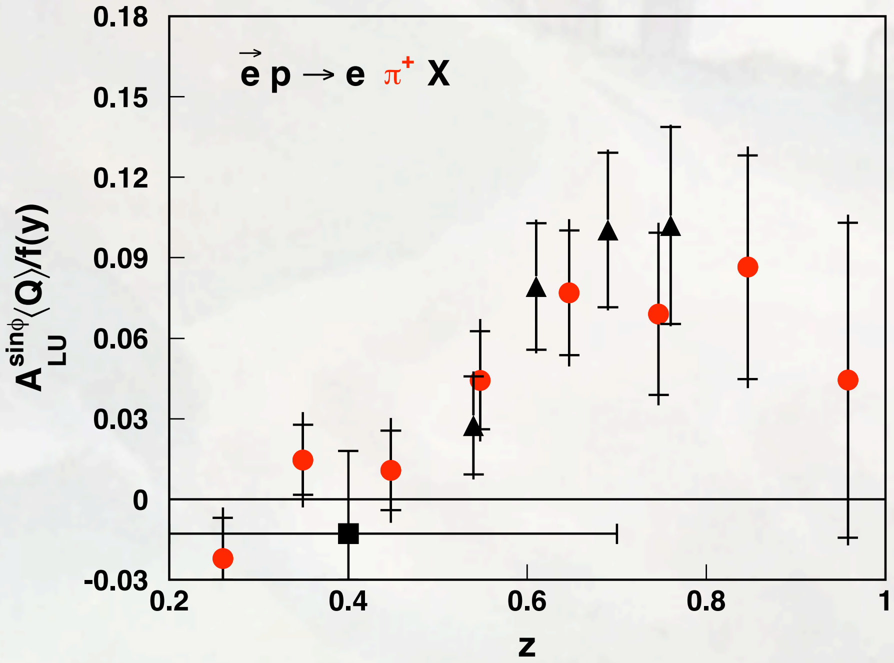
Avakian et al. [CLAS], arXiv:1003.4549



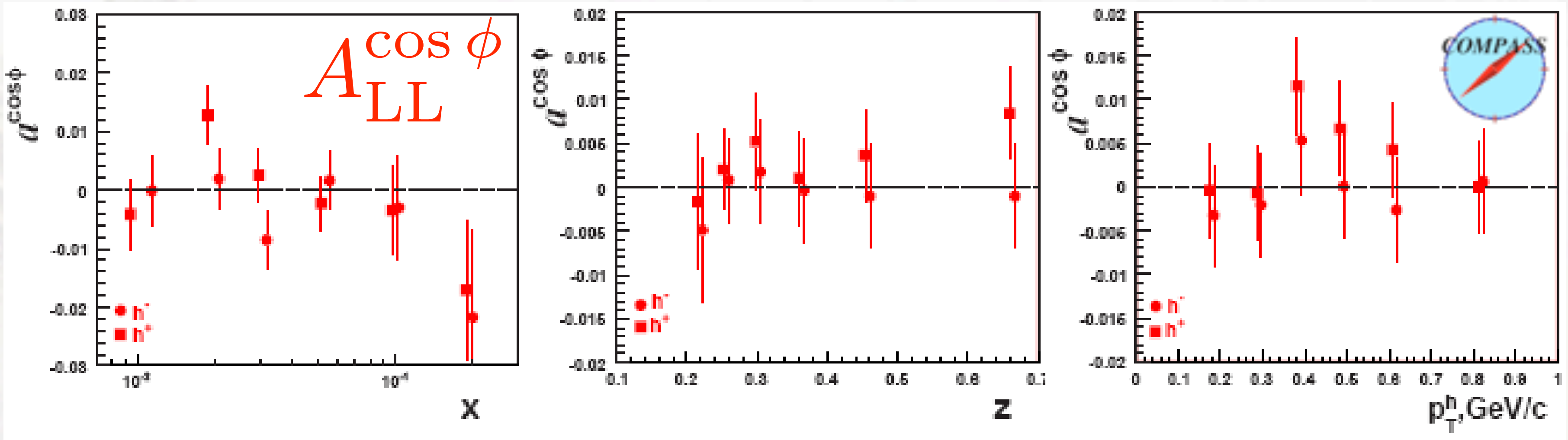
$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L H_1^\perp + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^\perp D_1 - \frac{M_h}{M}\,h_{1L}^\perp\frac{\tilde{H}}{z}\right)\right]$$

☛ **H. Avakian**

$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

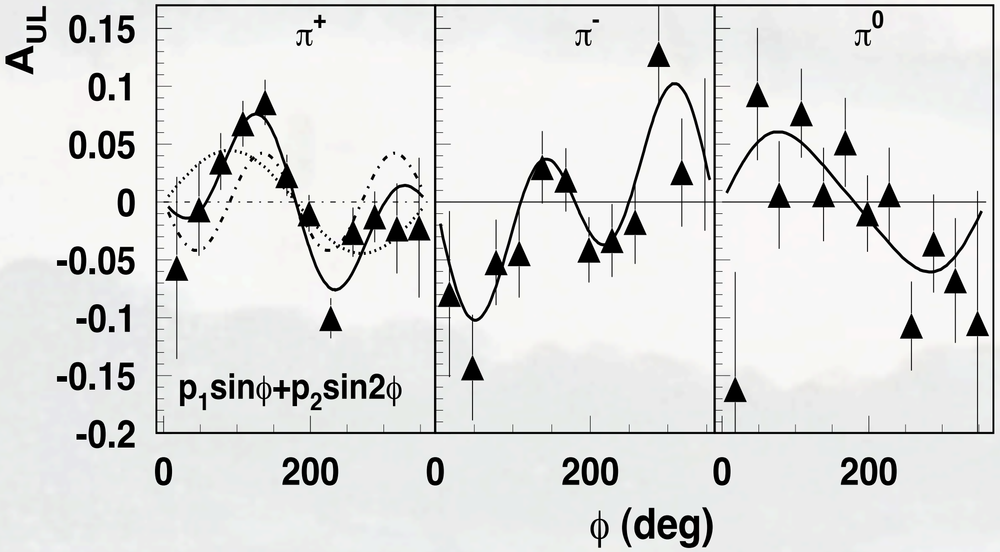


Other (twist-3) TMDs



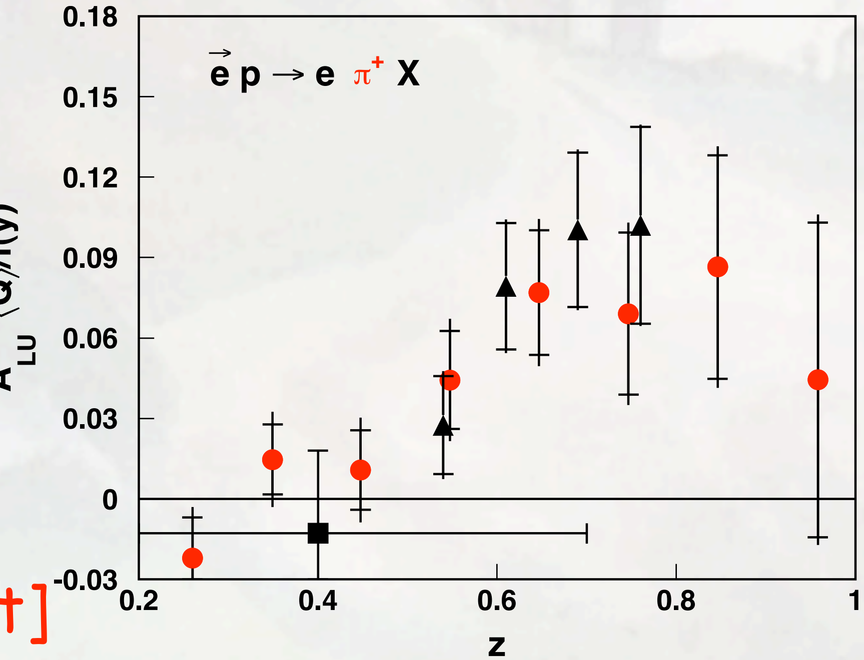
$$= \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol h}\cdot\boldsymbol k_T}{M_h}\left(xe_L H_1^\perp - \frac{M_h}{M}\,g_{1L}\frac{\tilde D^\perp}{z}\right) - \frac{\hat{\boldsymbol h}\cdot\boldsymbol p_T}{M}\left(x g_L^\perp D_1 + \frac{M_h}{M}\,h_{1L}^\perp \frac{\tilde E}{z}\right)\right]$$

Avakian et al. [CLAS], arXiv:1003.4549



$$= \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol h}\cdot\boldsymbol k_T}{M_h}\left(x h_L H_1^\perp + \frac{M_h}{M}\,g_{1L}\frac{\tilde G^\perp}{z}\right) + \frac{\hat{\boldsymbol h}\cdot\boldsymbol p_T}{M}\left(x f_L^\perp D_1 - \frac{M_h}{M}\,h_{1L}^\perp \frac{\tilde H}{z}\right)\right]$$

☛ **H. Avakian**

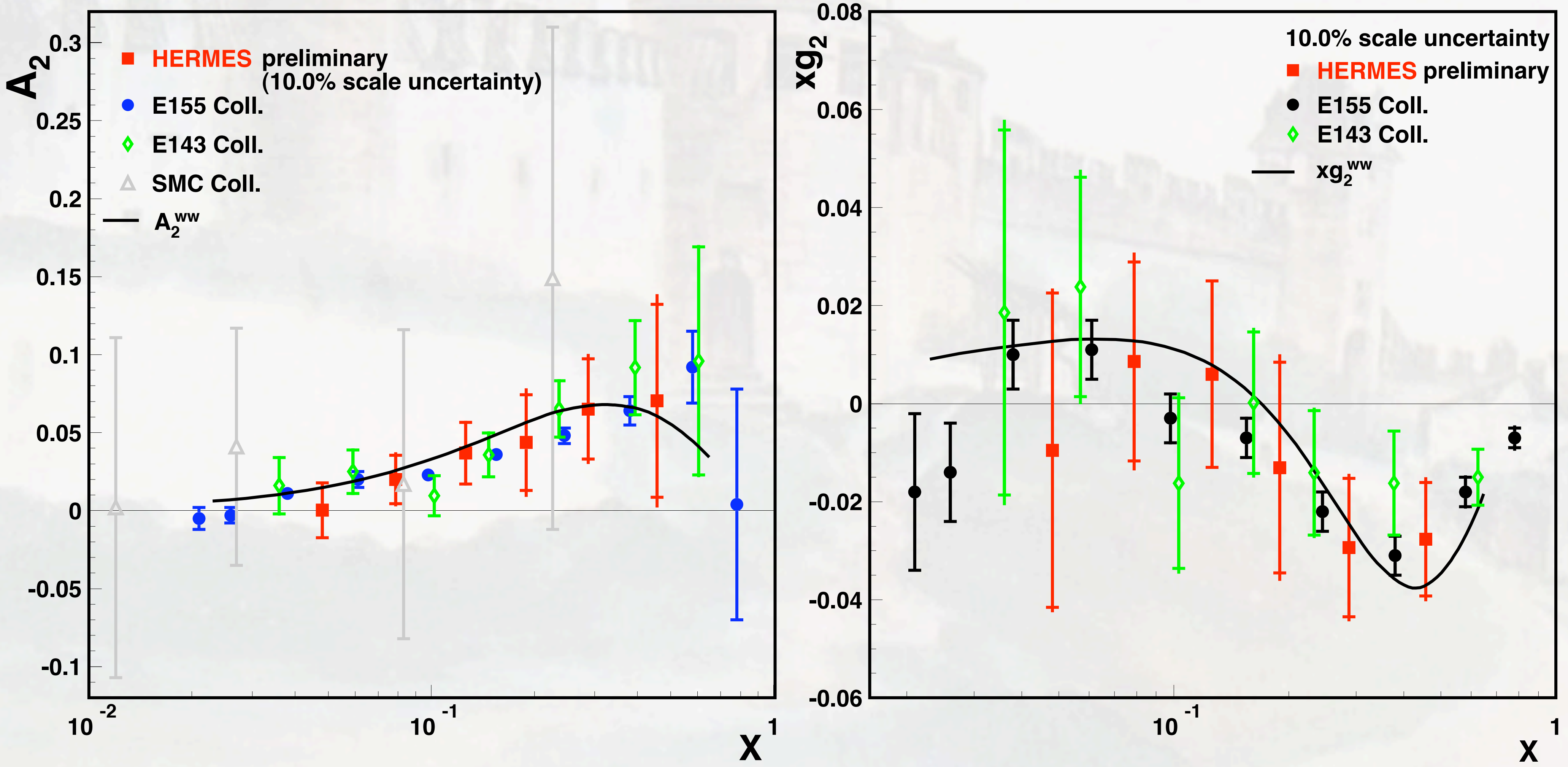


$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol h}\cdot\boldsymbol k_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde G^\perp}{z}\right) + \frac{\hat{\boldsymbol h}\cdot\boldsymbol p_T}{M}\left(x g^\perp D_1 + \frac{M_h}{M}\,h_1^\perp \frac{\tilde E}{z}\right)\right]$$

transverse force on transversely pol. quarks [M. Burkardt]

g_2 structure function

deviation from WW related to transverse force acting on struck quark [M. Burkardt]



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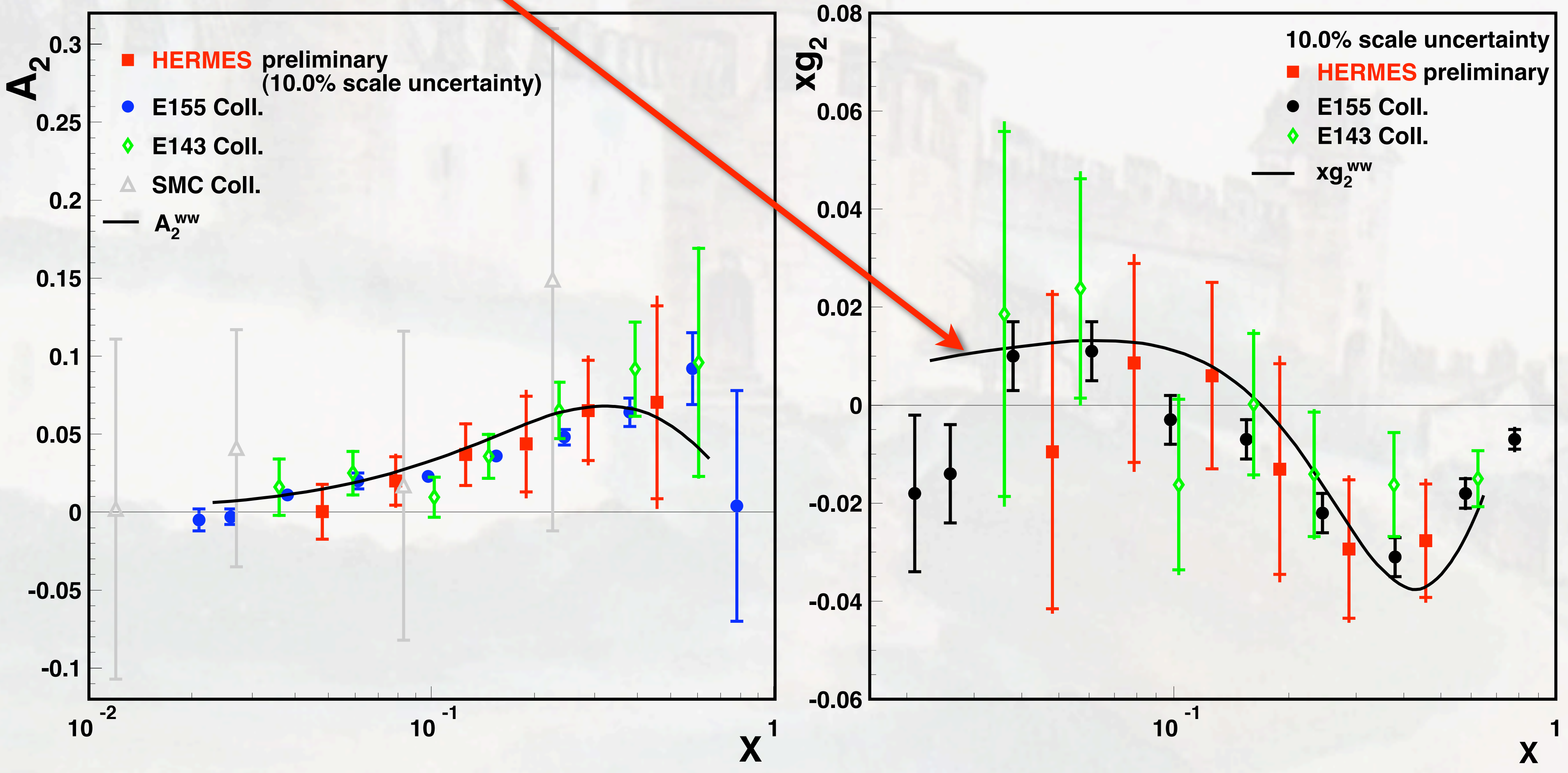
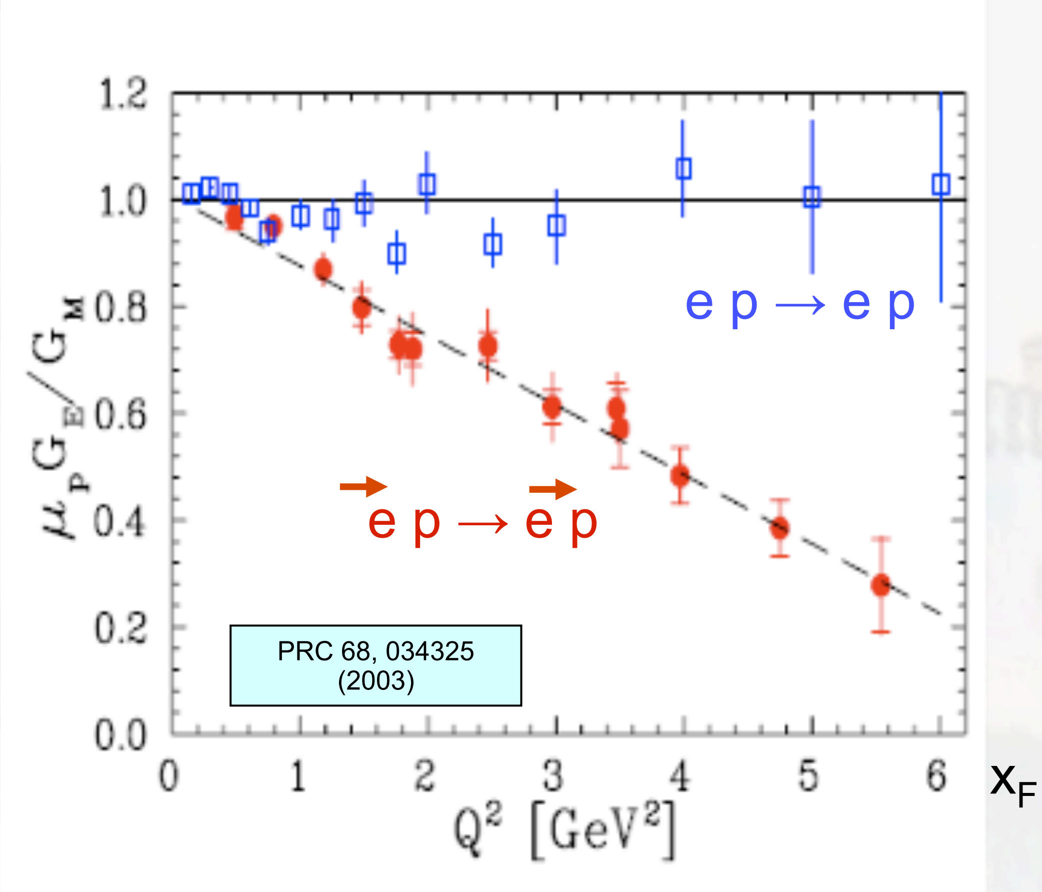


☛ **more data needed!**

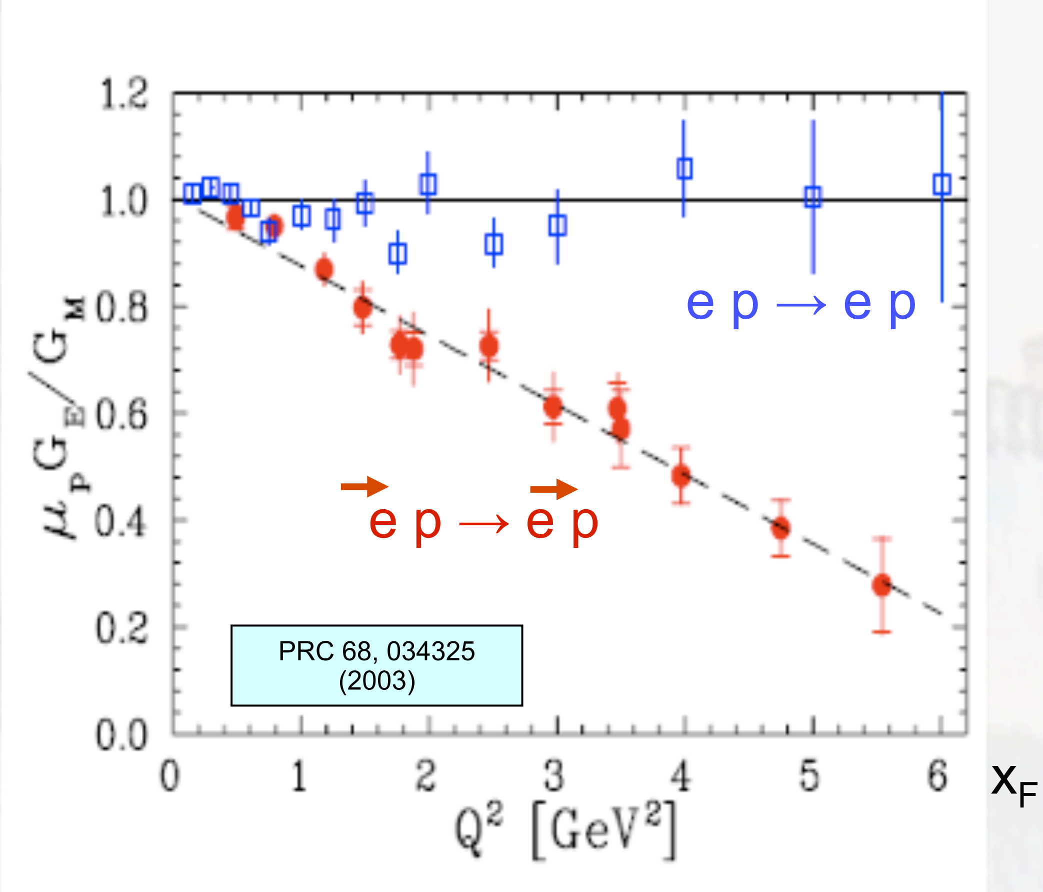
Check the details!

Check the details!

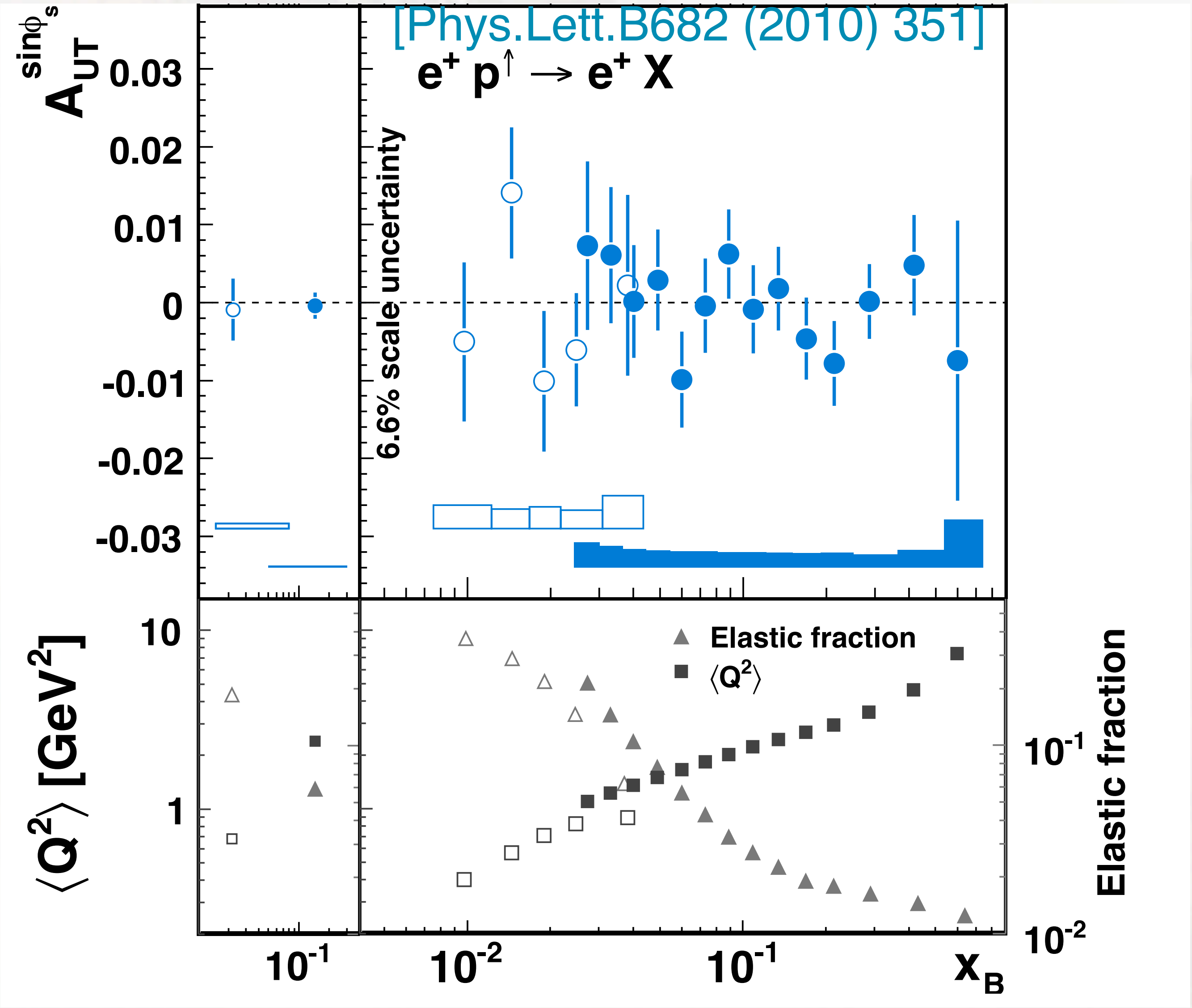


☛ two-photon exchange important?!

Check the details!



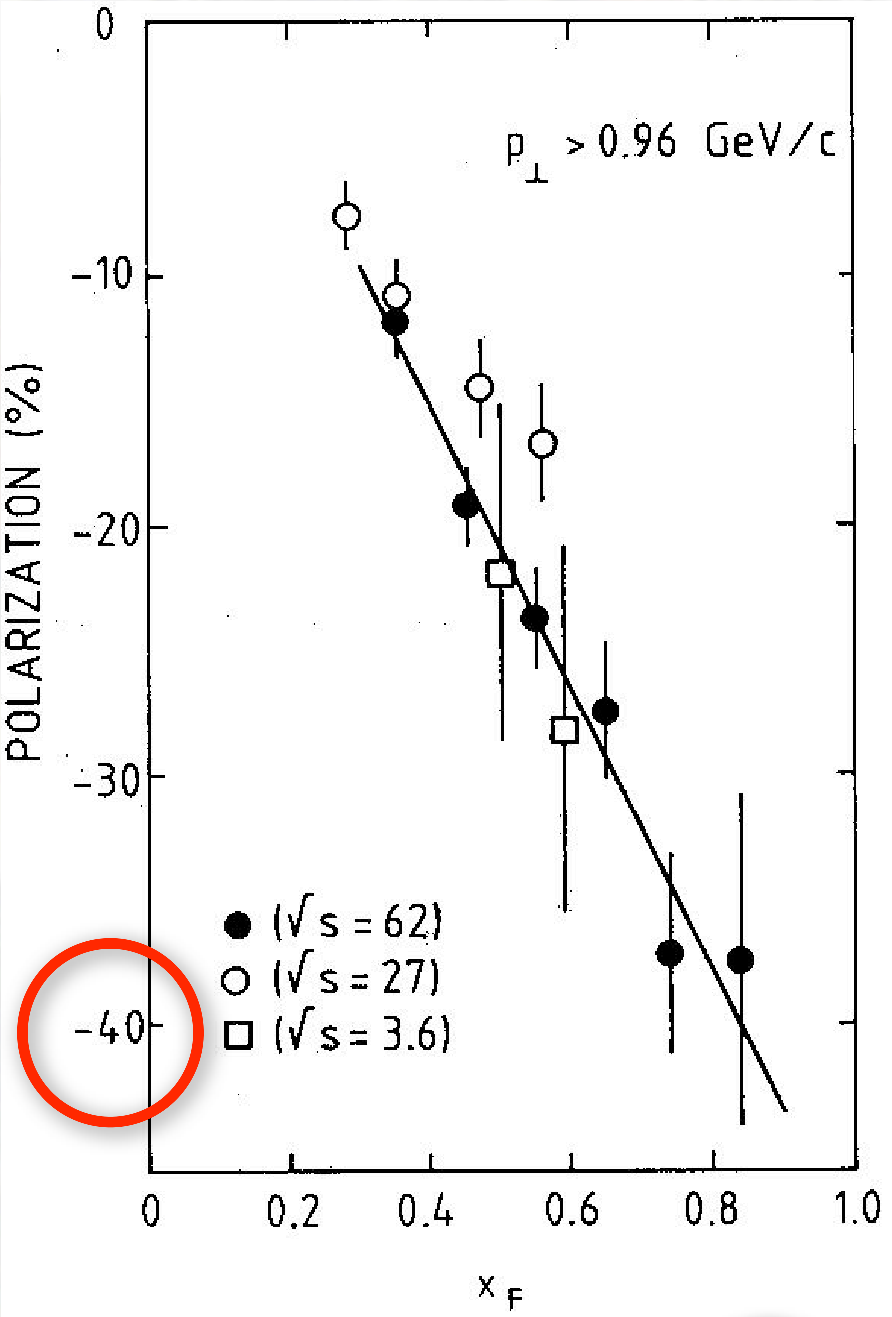
- ☛ two-photon exchange important?!

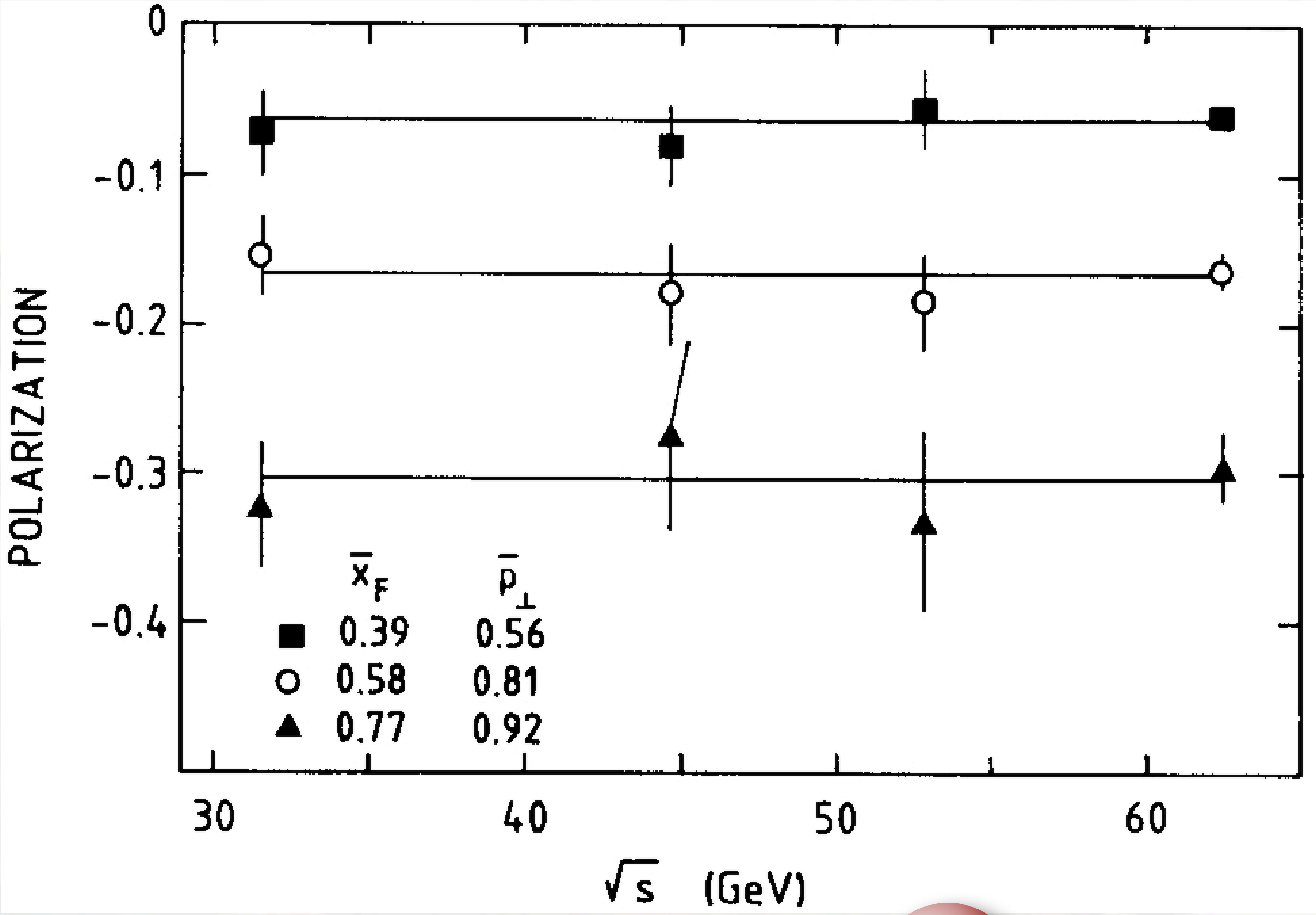


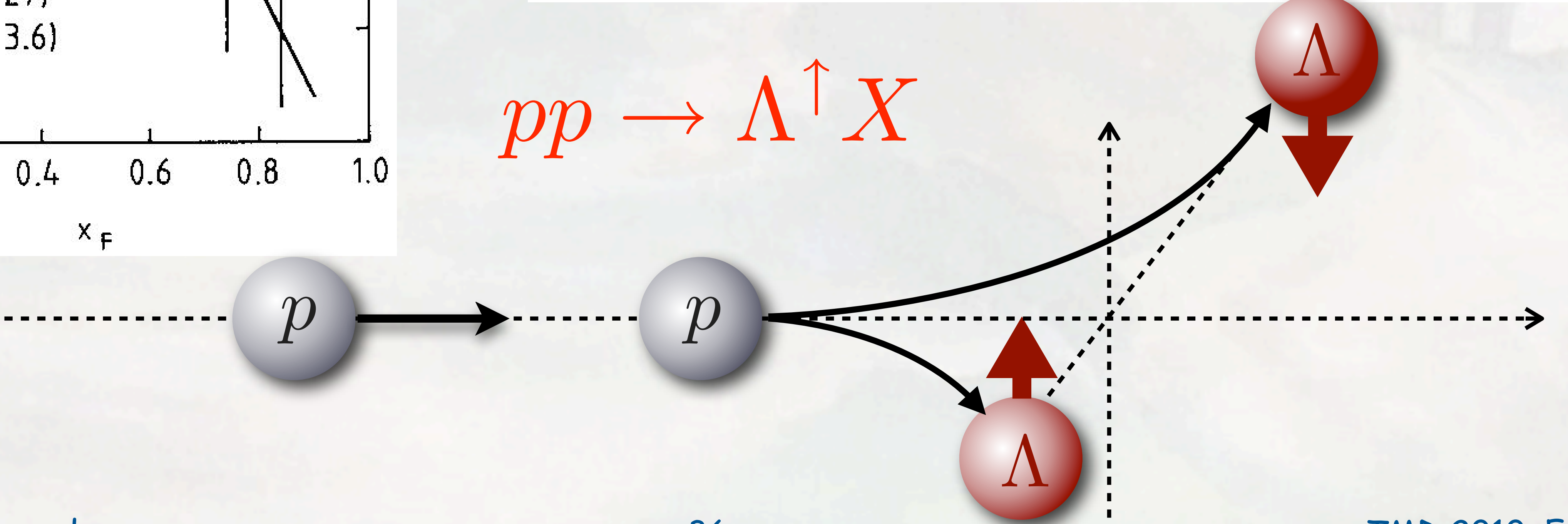
- ☛ not so much for A_{UT} (so it seems)

Don't forget these hyperons?

Comprehensive review of data by A.D. Panagiotou (Int.J.Mod.Phys.A 5 (1990) 1197)





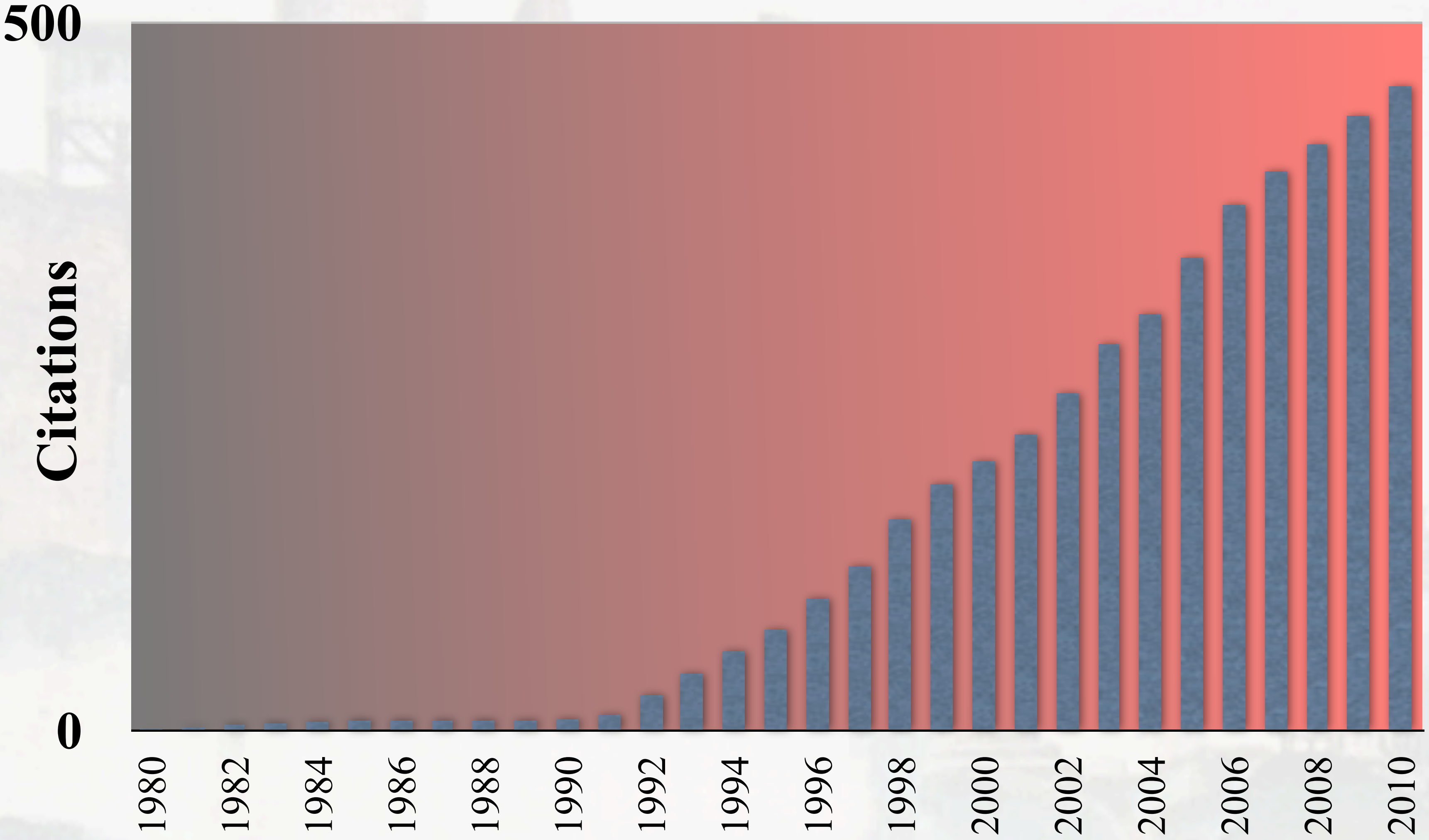


$pp \to \Lambda^\uparrow X$

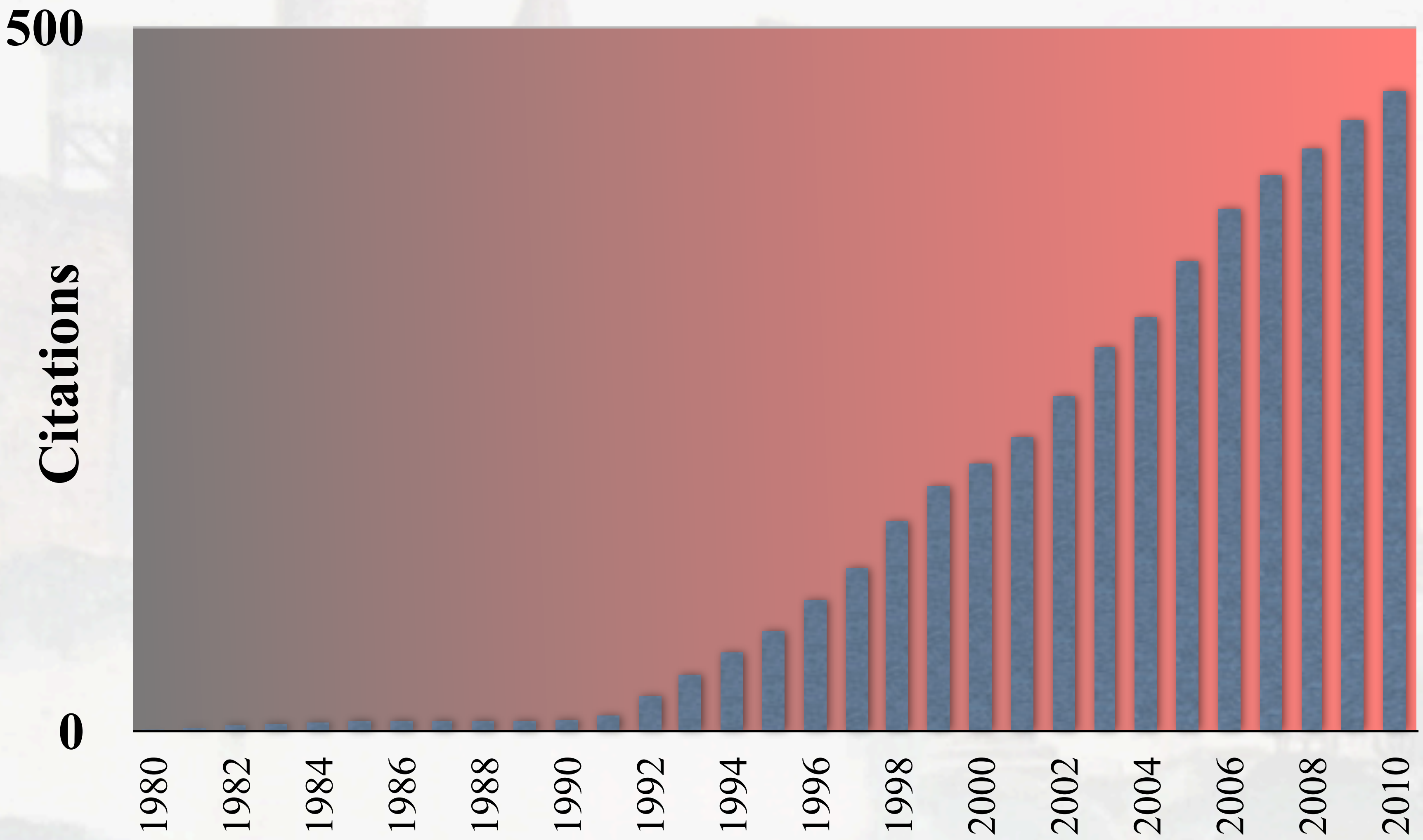
Instead of a summary …

gunar.schnell @ desy.de

Instead of a summary ...



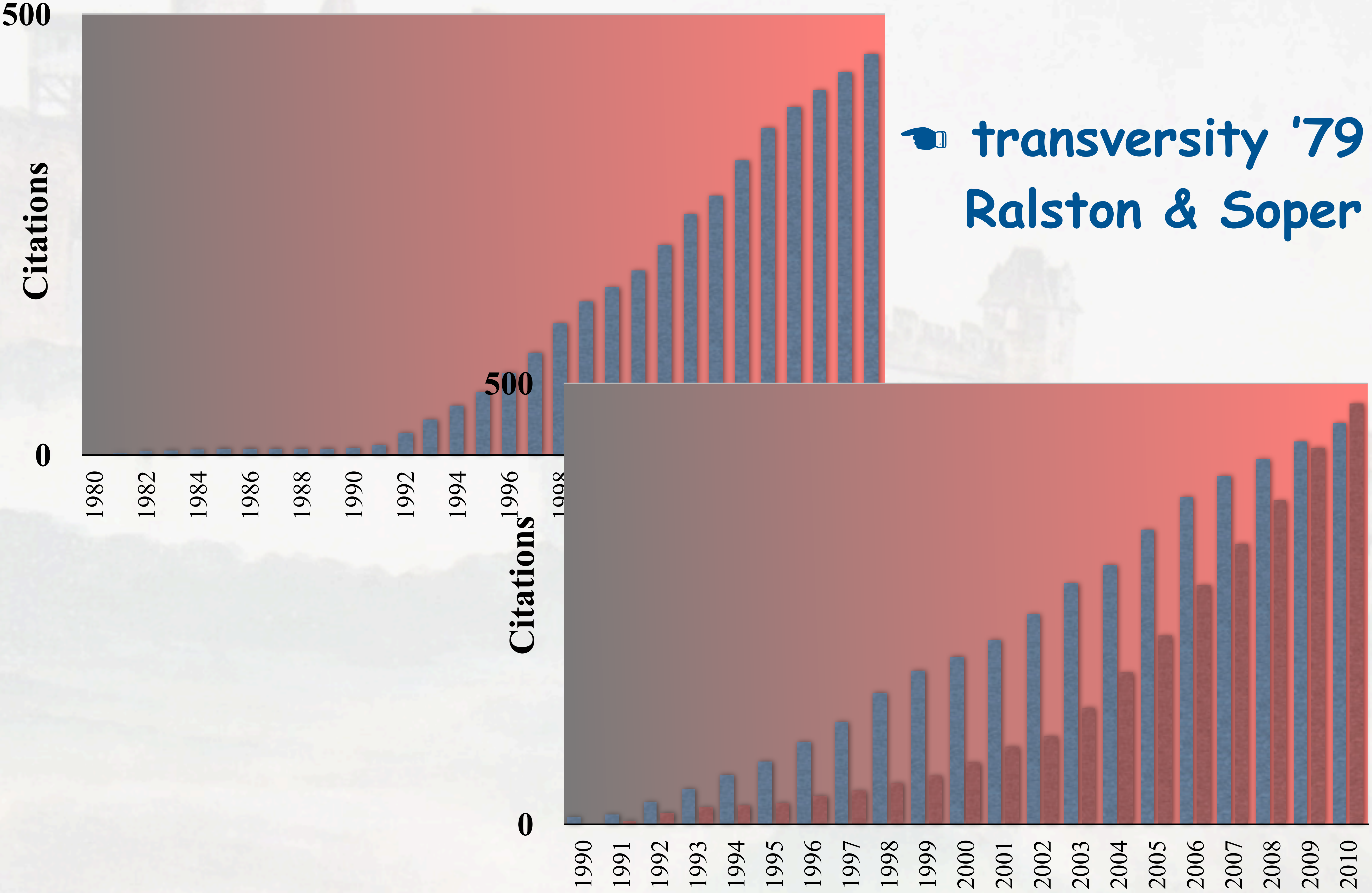
Instead of a summary ...



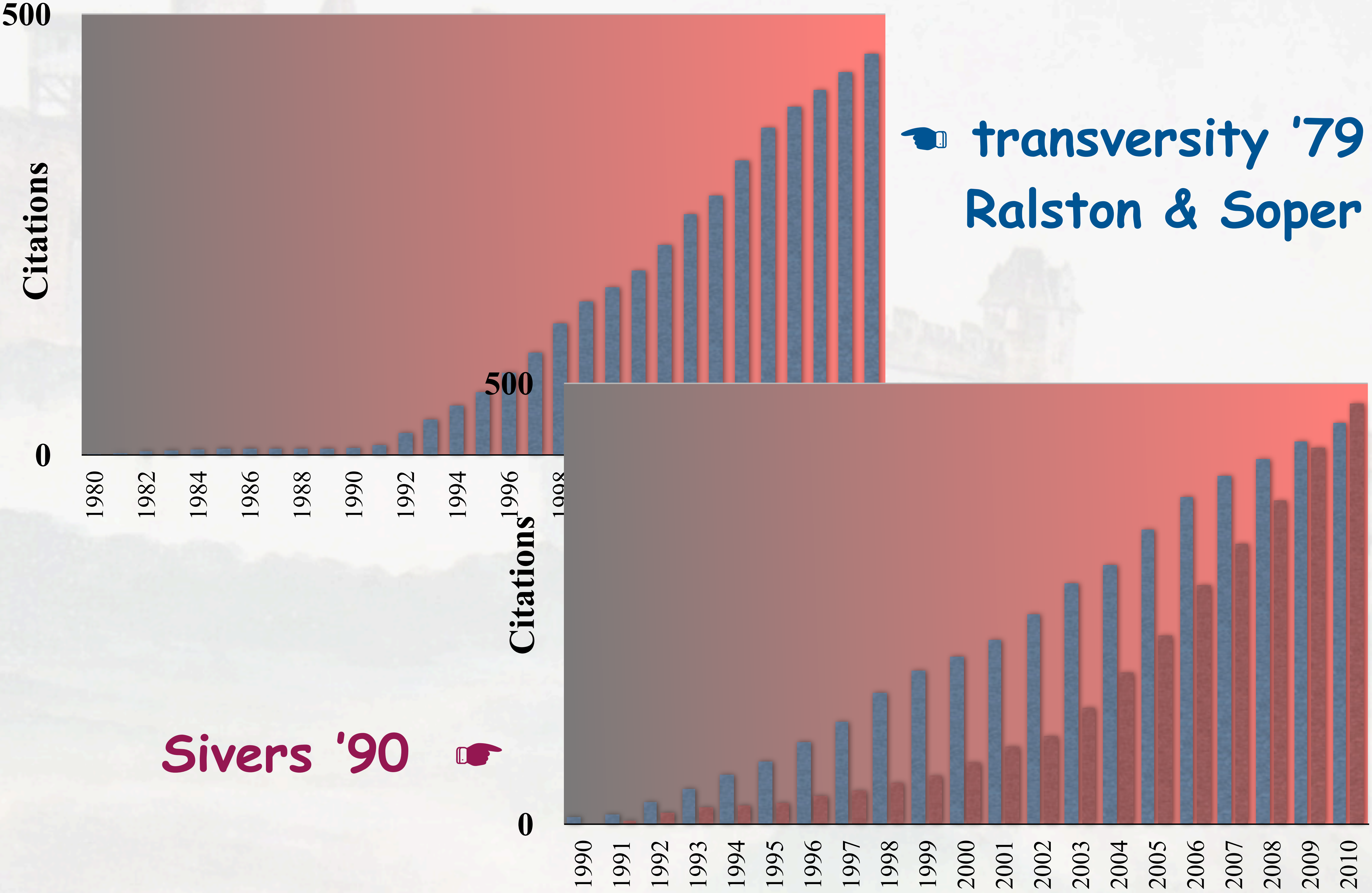
- ☚ transversity '79
  Ralston & Soper

Instead of a summary …

☚ transversity '79
Ralston & Soper



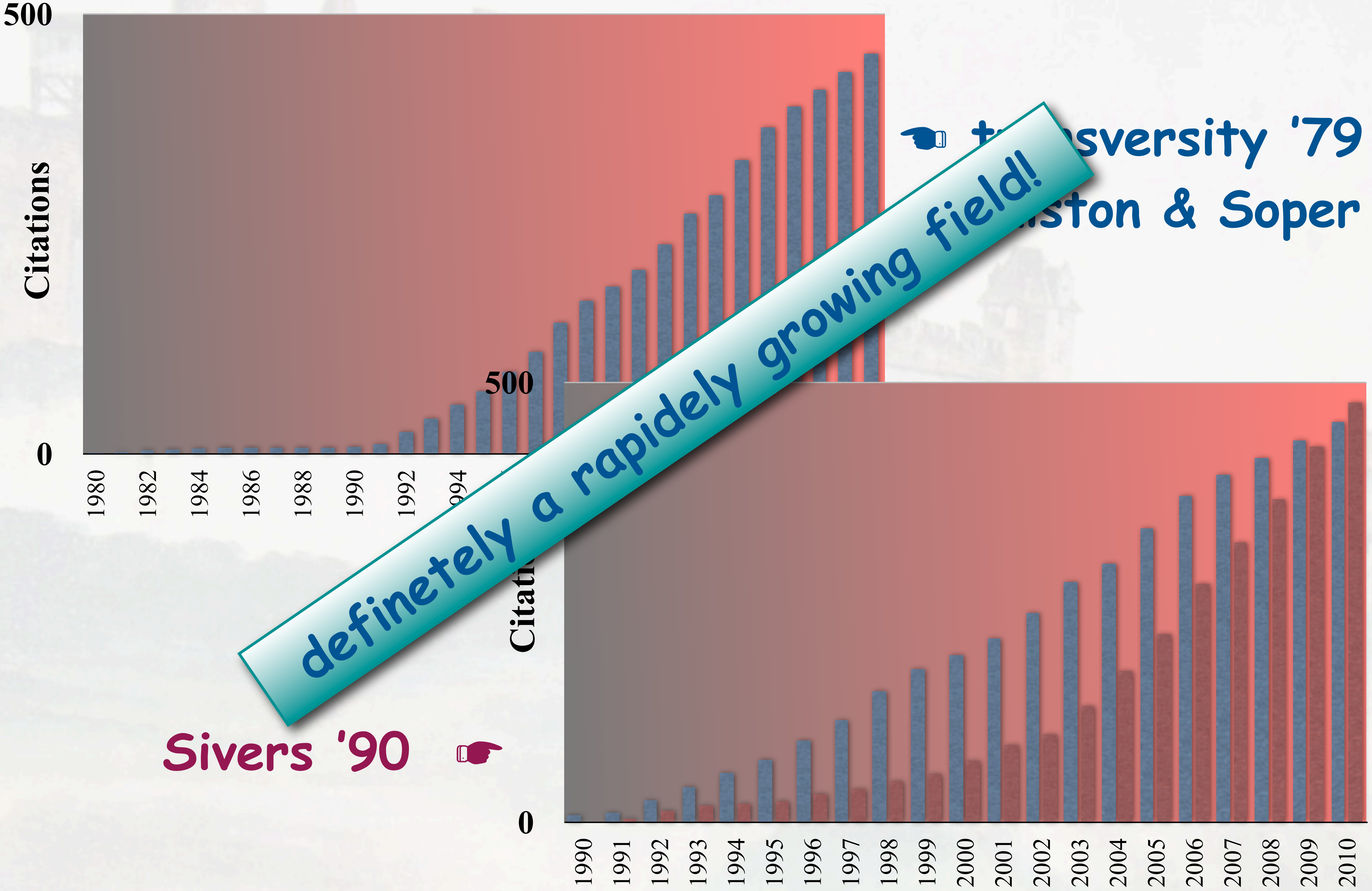
Instead of a summary ...



☚ **transversity '79**
Ralston & Soper

Sivers '90 ☛

Instead of a summary ...



☚ t sversity '79

ston & Soper

definetely a rapidely growing field!

Sivers '90 ☛