Physics at A Fixed Target ExpeRiment (AFTER) using the LHC beams
ECT*, Trento - Feb. 4 - 13, 2013

$S \cdot (P \times P_h)$

- an experimental perspective -

ikerbasque
Basque Foundation for Science

Gunar.Schnell @ EHU.es

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Early years of transverse spin

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- largely neglected

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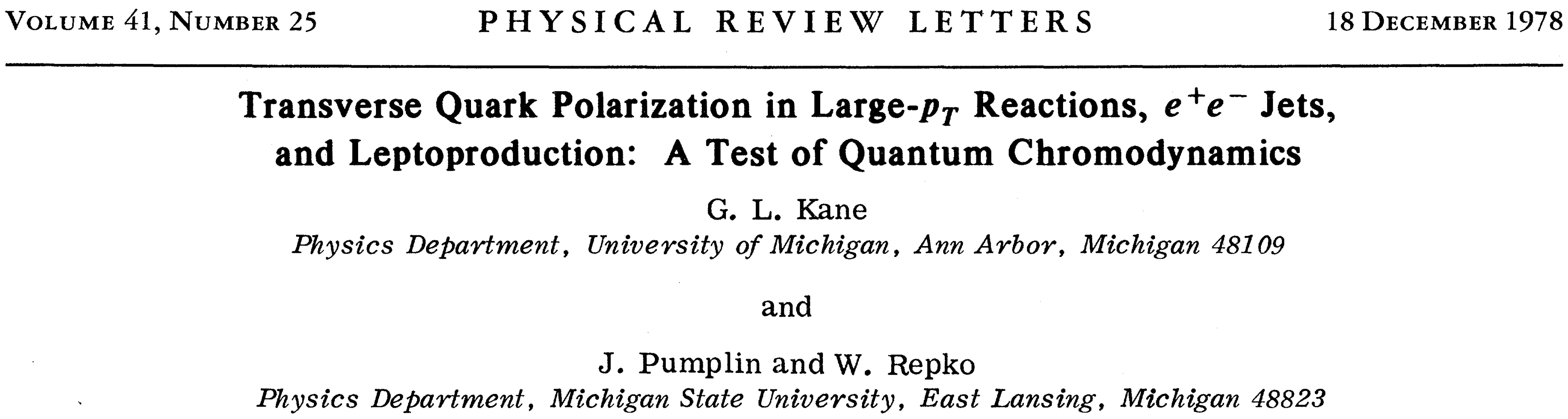

VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

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Physics Department, University of Michigan, Ann Arbor, Michigan 48109

and

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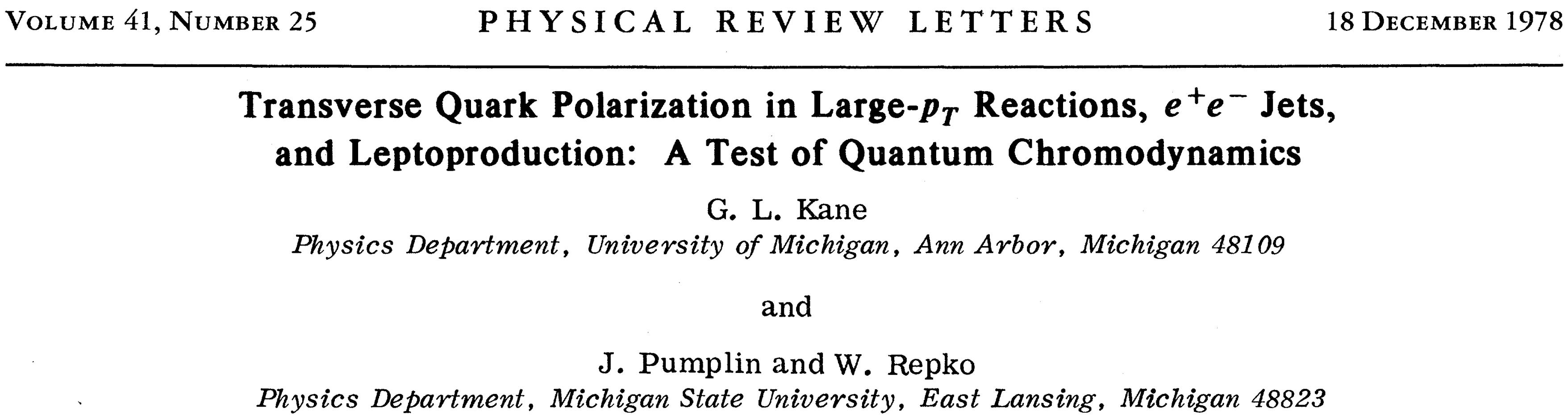
quark mass

energy scale



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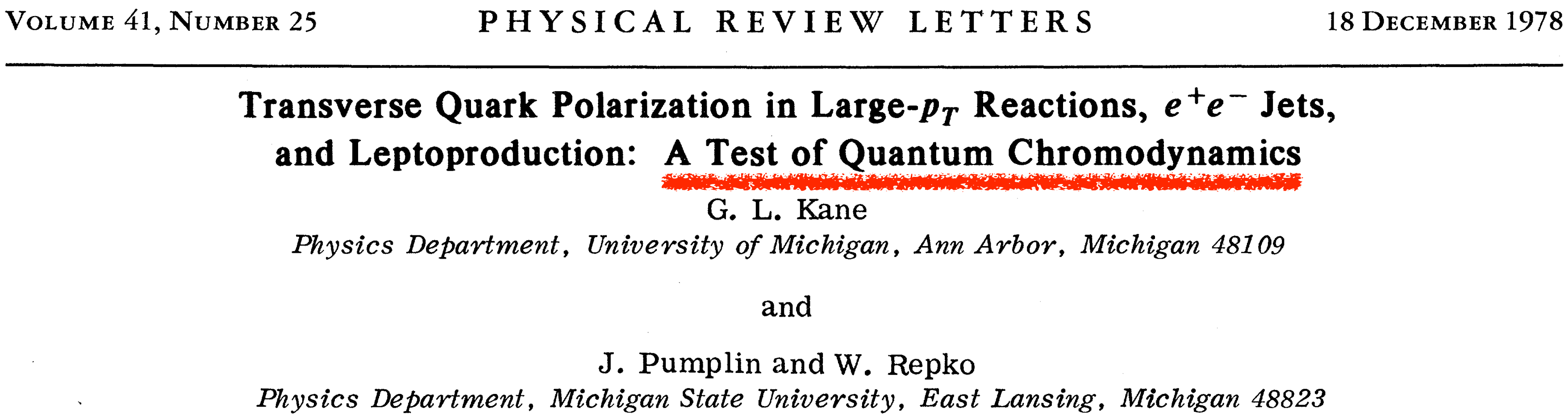

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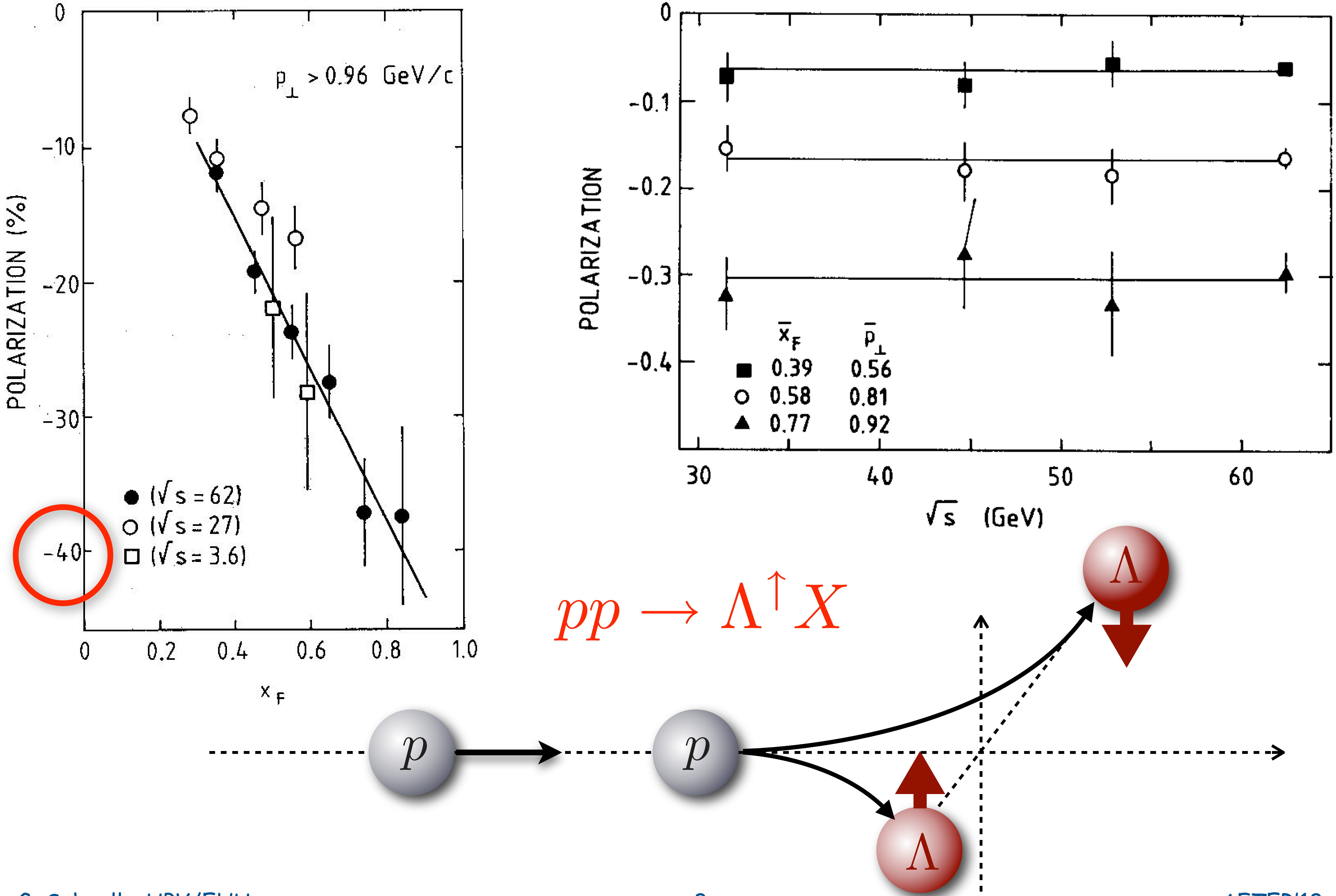
Nature does not seem to cooperate

Comprehensive review of data by A.D. Panagiotou (Int. J. Mod. Phys. A5 (1990) 1197)



$pp \rightarrow \Lambda^{\uparrow} X$

… also not for pion production …

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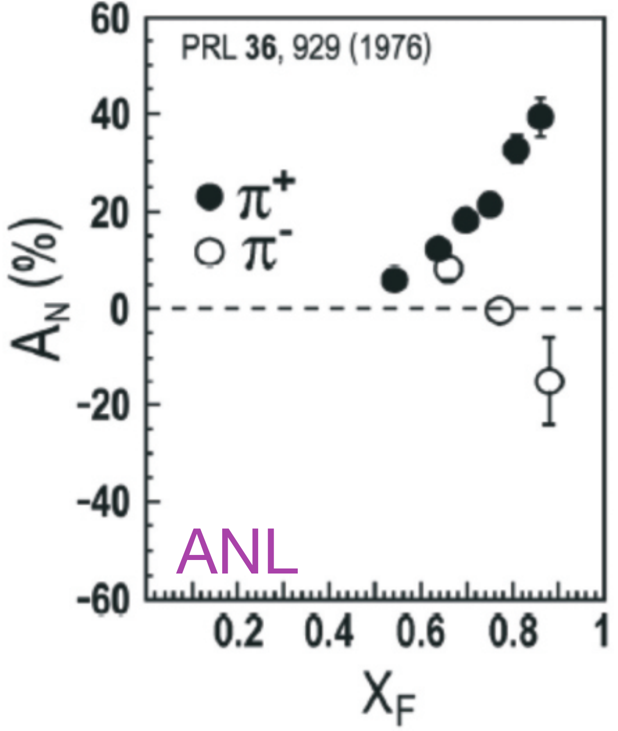
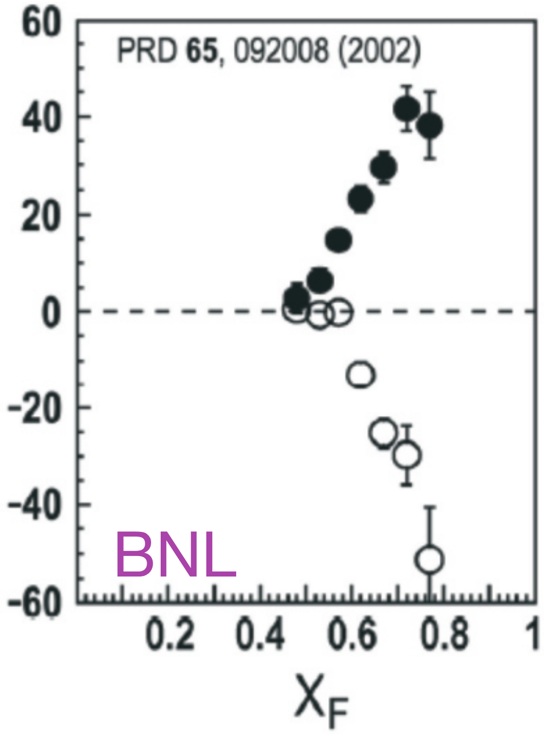
$\sqrt{s} = 4.9$ GeV



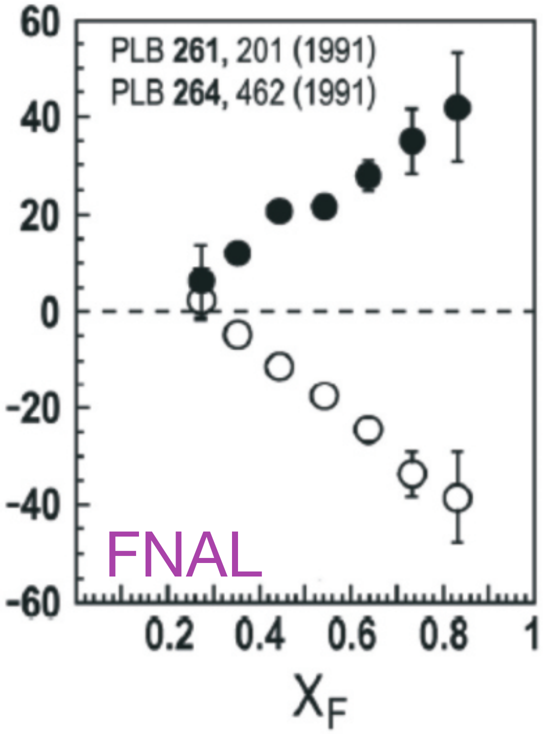
1976

6.6 GeV



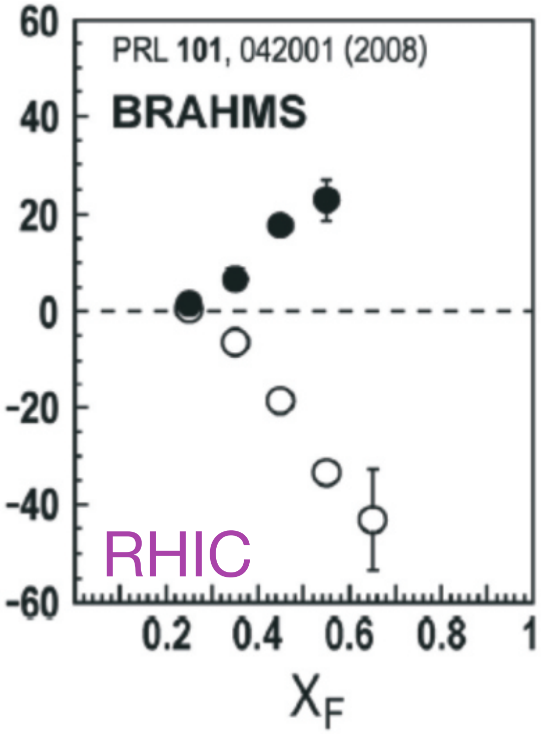
2002

19.4 GeV

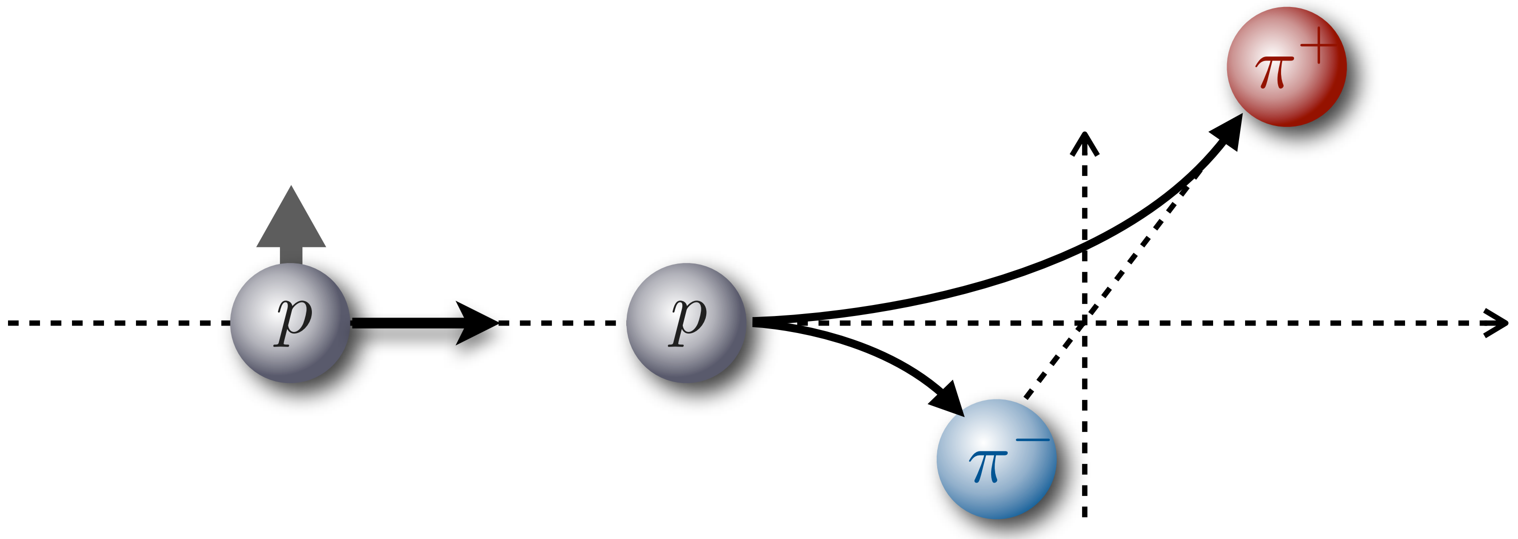


1991

62.4 GeV



2008



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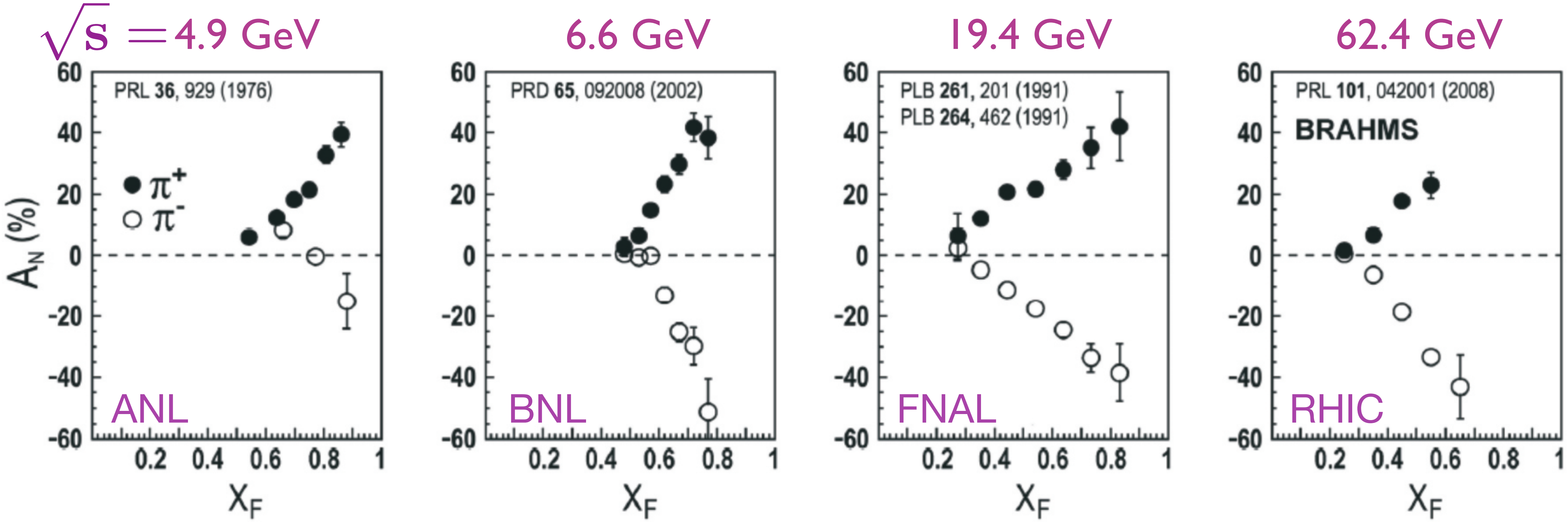
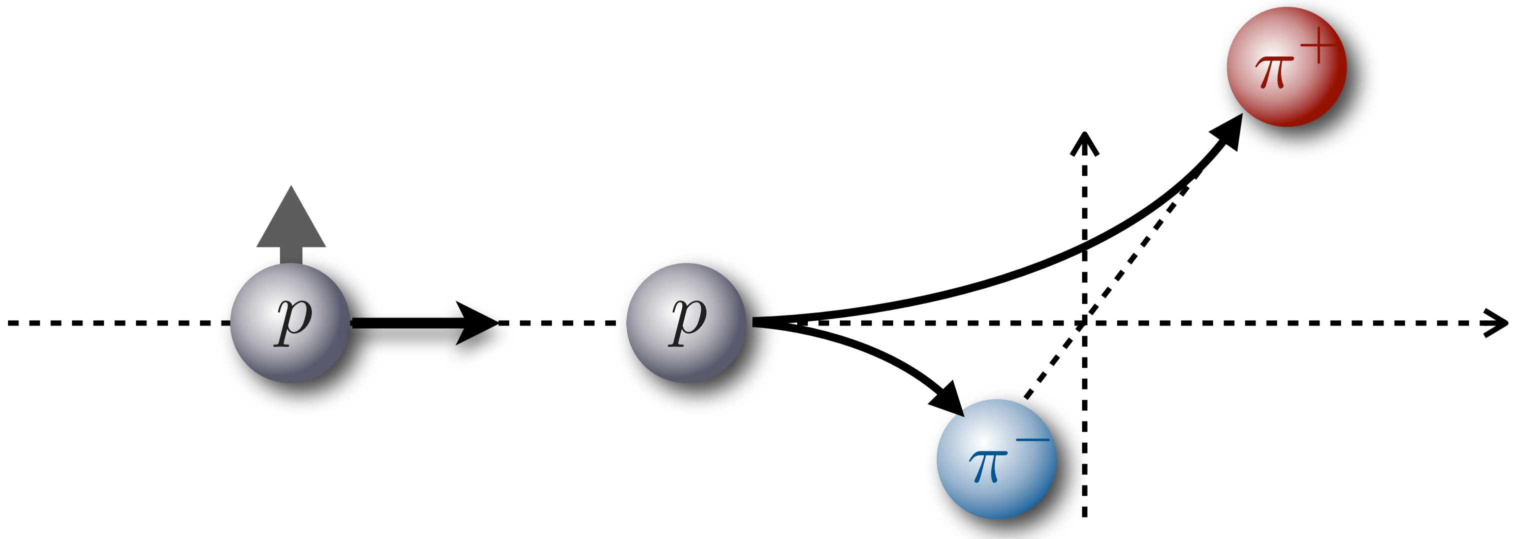


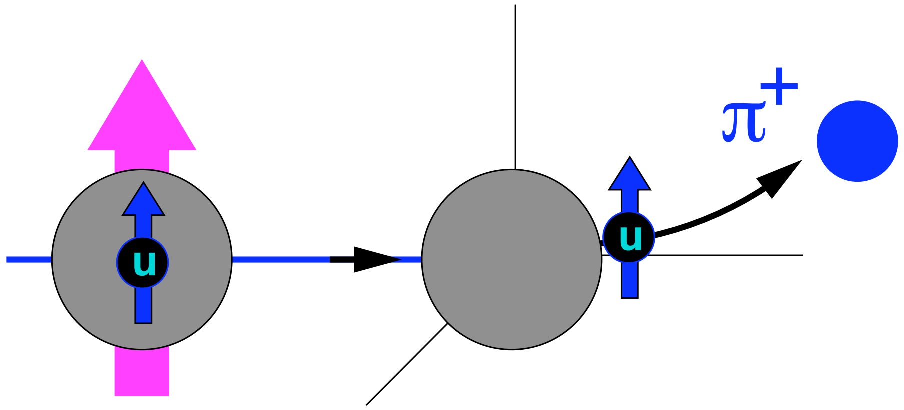
1976 2002 1991 2008



- large left-right asymmetries persist even to RHIC energies

what's the origin of these SSA?

- fragmentation effect?



[J.C. Collins, NPB 396 (1993) 161]

- correlating transverse quark spin with transverse momentum

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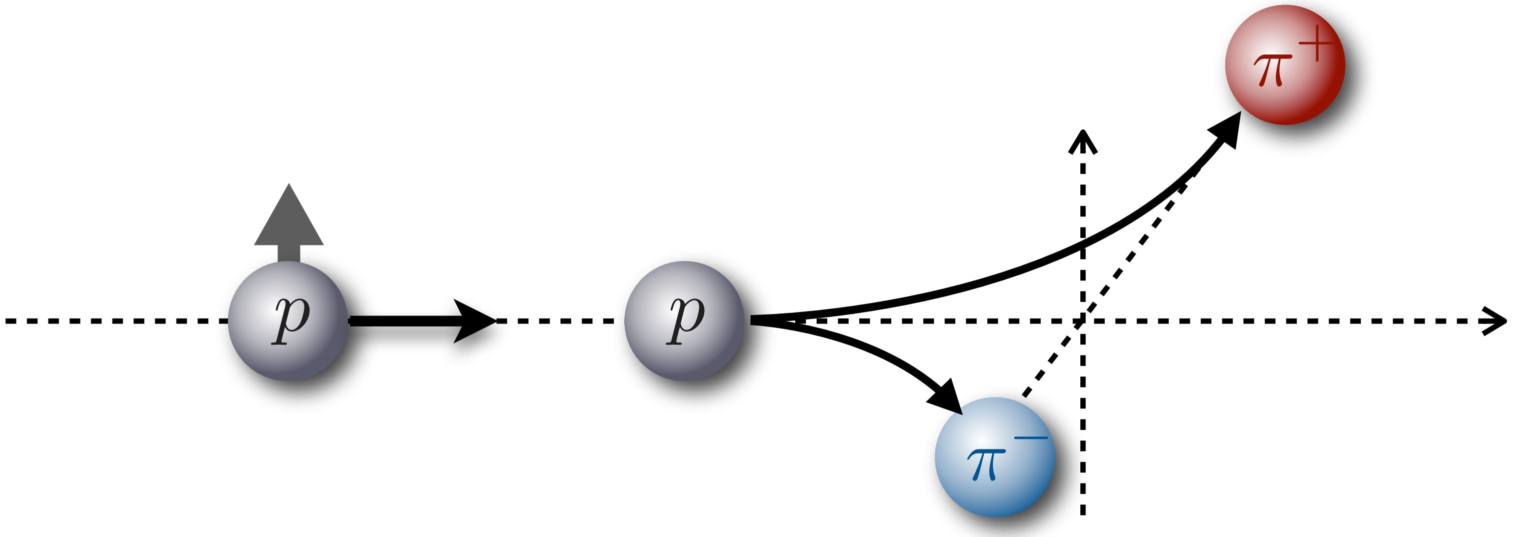

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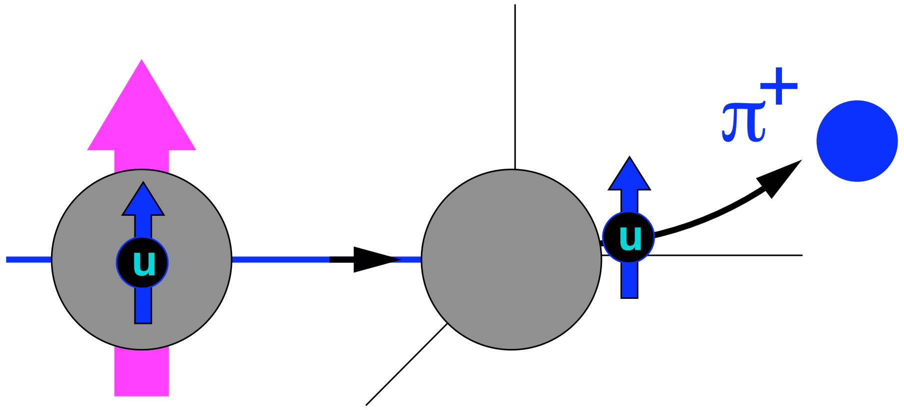

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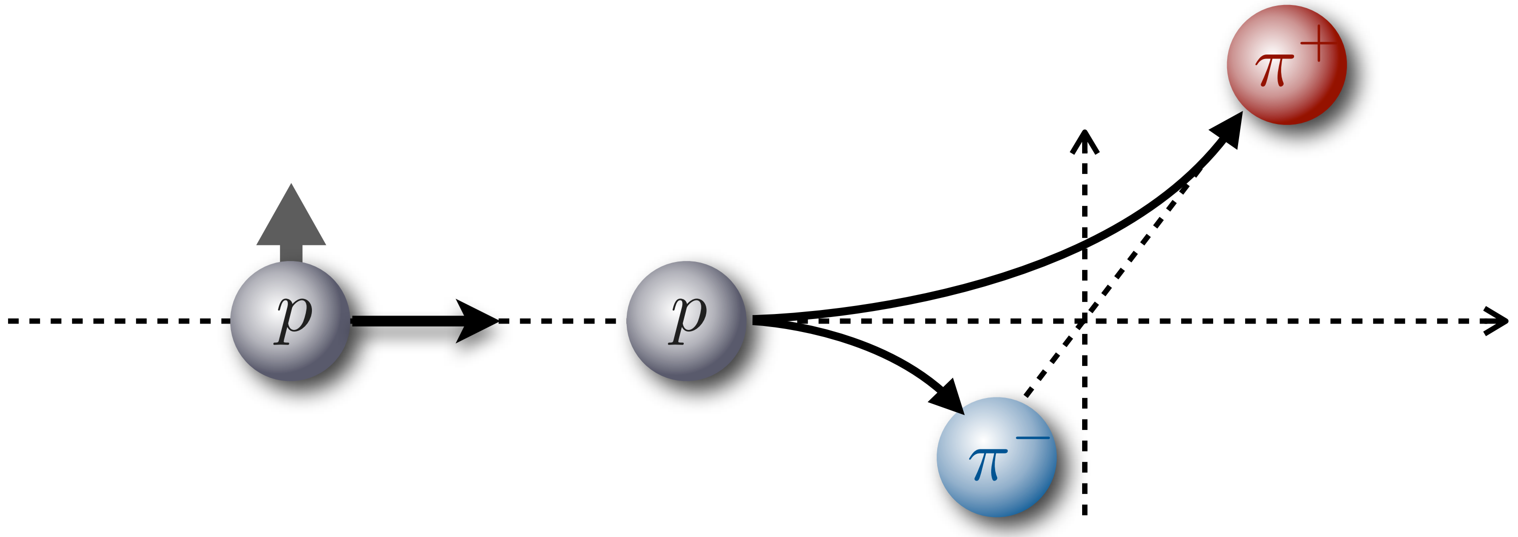

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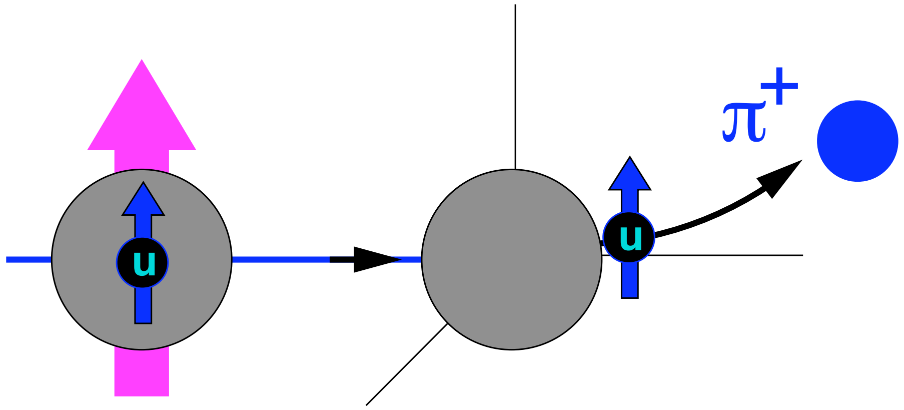

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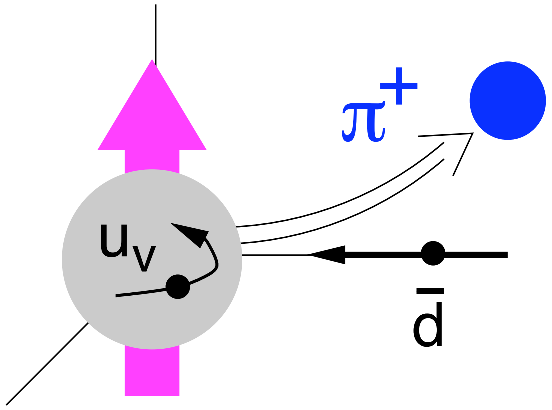
- correlating transverse quark spin with transverse momentum

- quark-distribution effect?



[D.W. Sivers, PRD 41 (1990) 83]

- correlating transverse quark momentum with transverse spin of nucleon

Transverse spin

$$|\uparrow\downarrow\rangle = \frac{1}{2}\left(|+\rangle \pm |-\rangle\right)$$

$$\langle\uparrow|\,\hat{O}\,|\uparrow\rangle - \langle\downarrow|\,\hat{O}\,|\downarrow\rangle \propto \langle+|\,\hat{O}\,|-\rangle - \langle-|\,\hat{O}\,|+\rangle$$

transverse-spin involves **helicity flip**

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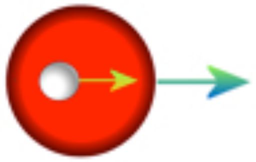
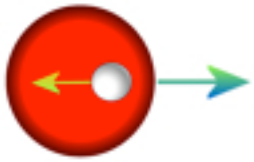
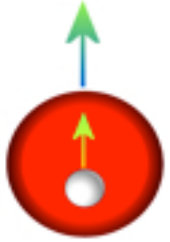
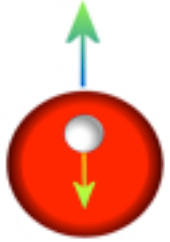
PDFs: $f_1^q =$  $g_1^q =$  −  $h_1^q =$  − 

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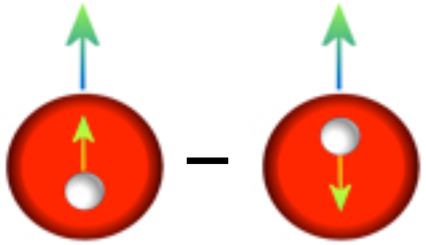

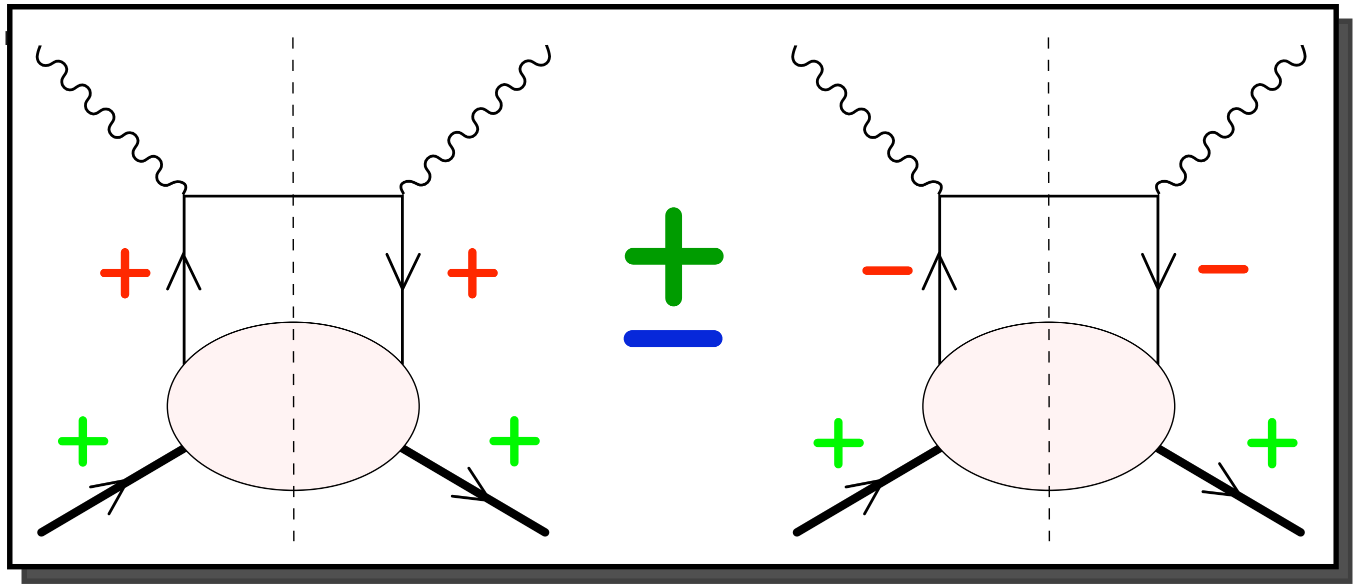

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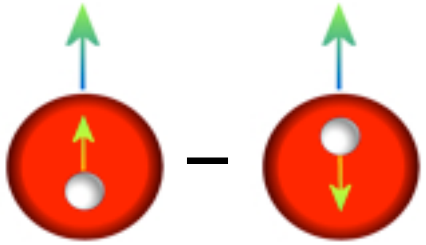
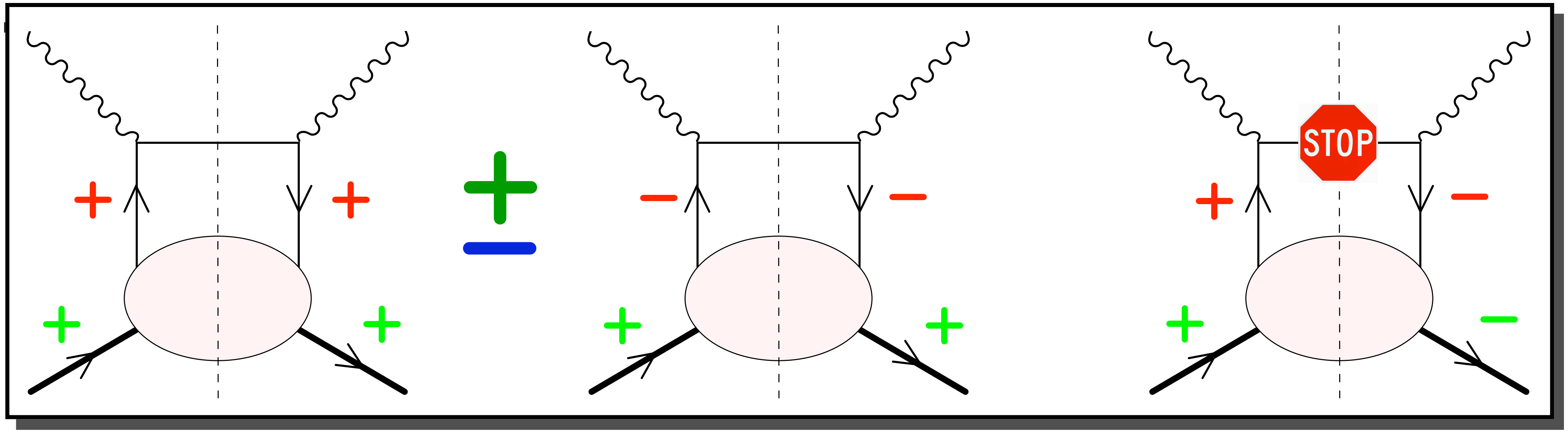
PDFs: f_1^q=  g_1^q=  h_1^q= 



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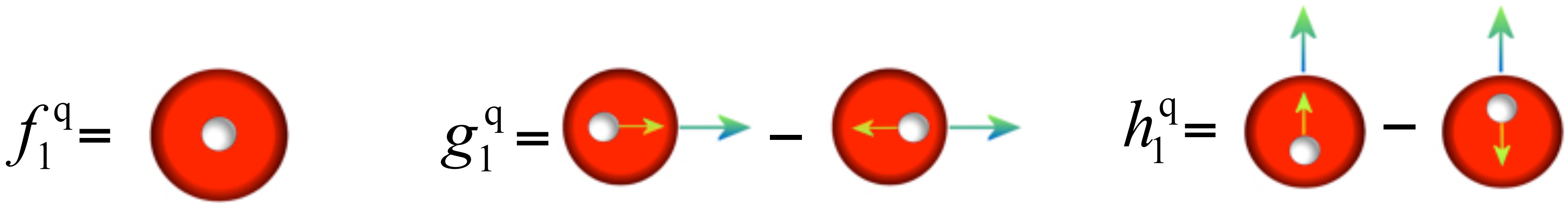
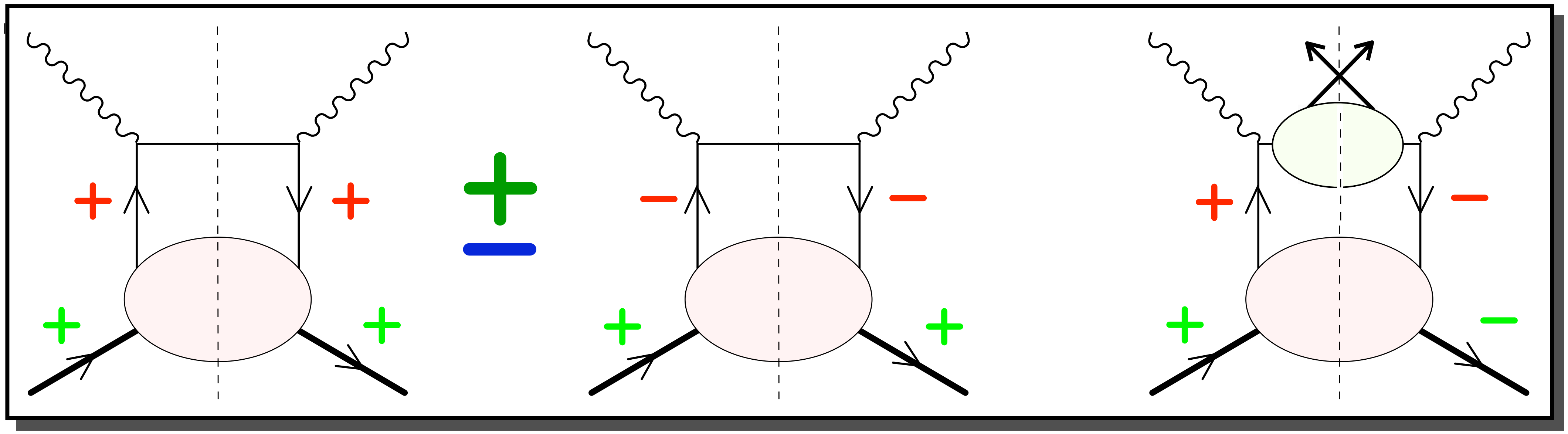
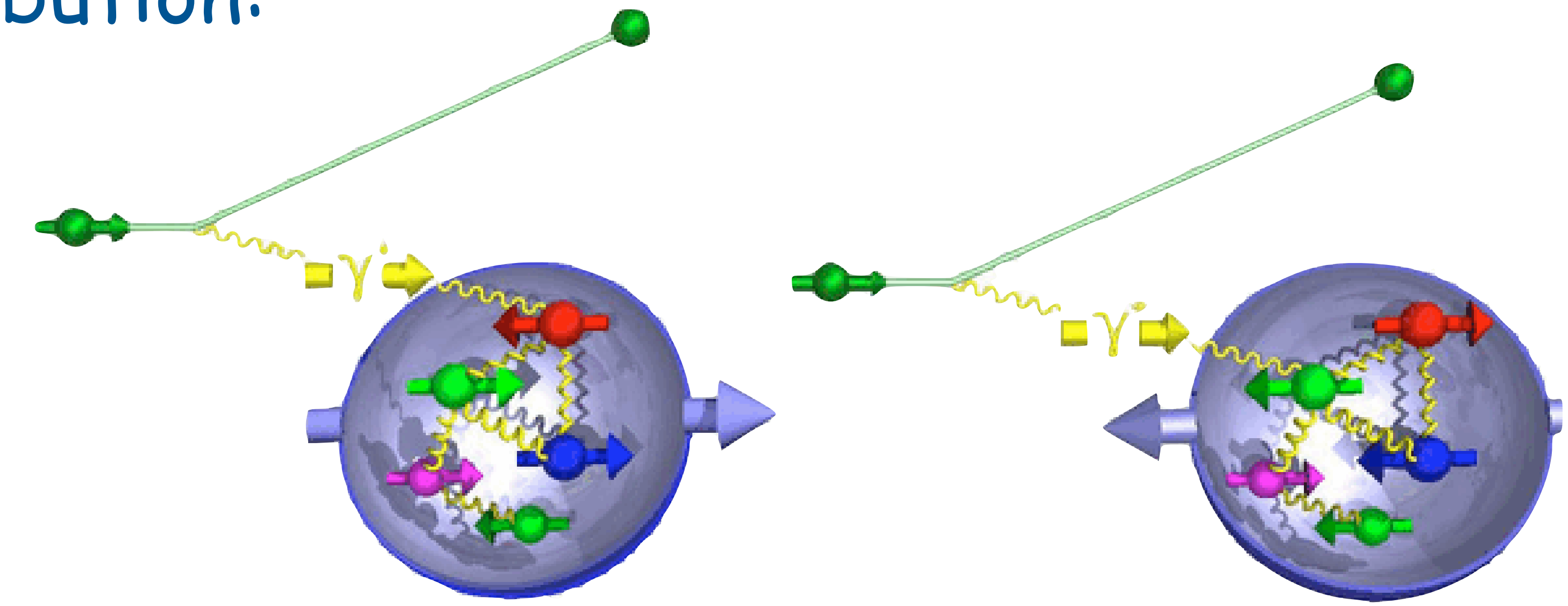




need to couple to chiral-odd fragmentation function, i.e., dependent on transverse quark-spin

quark polarimetry

- helicity distribution:



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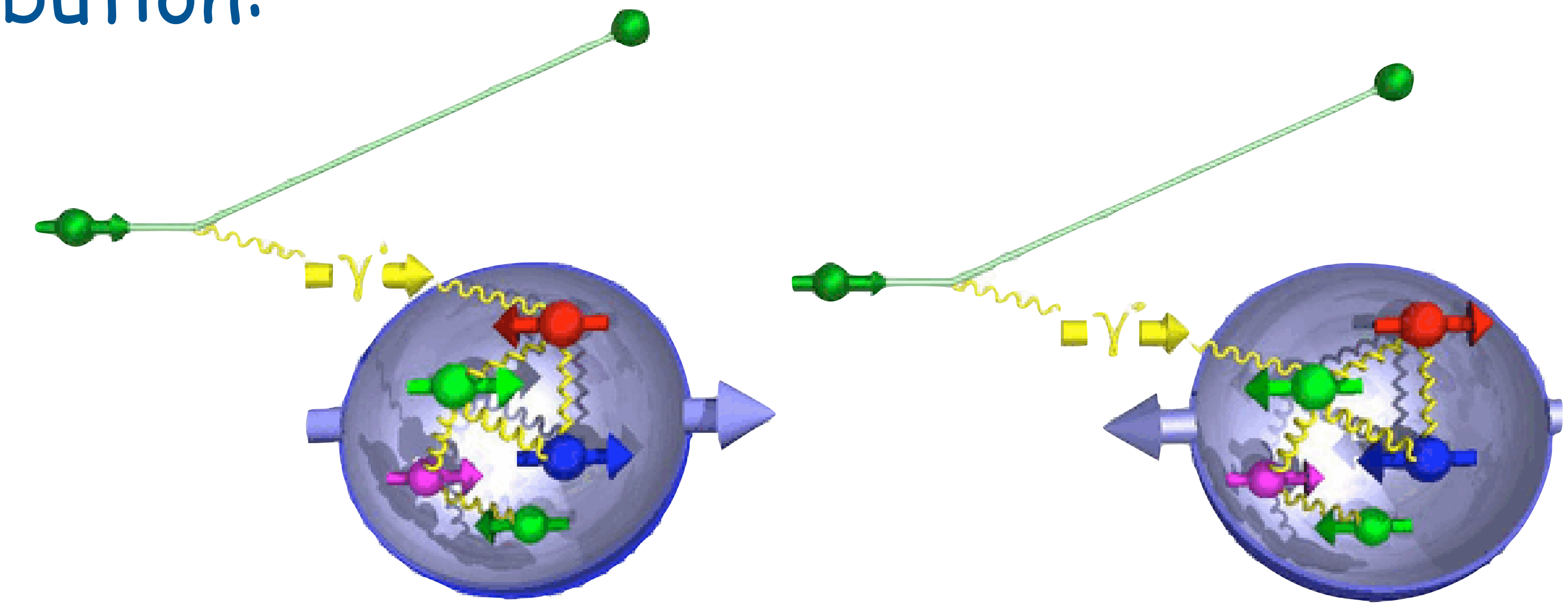
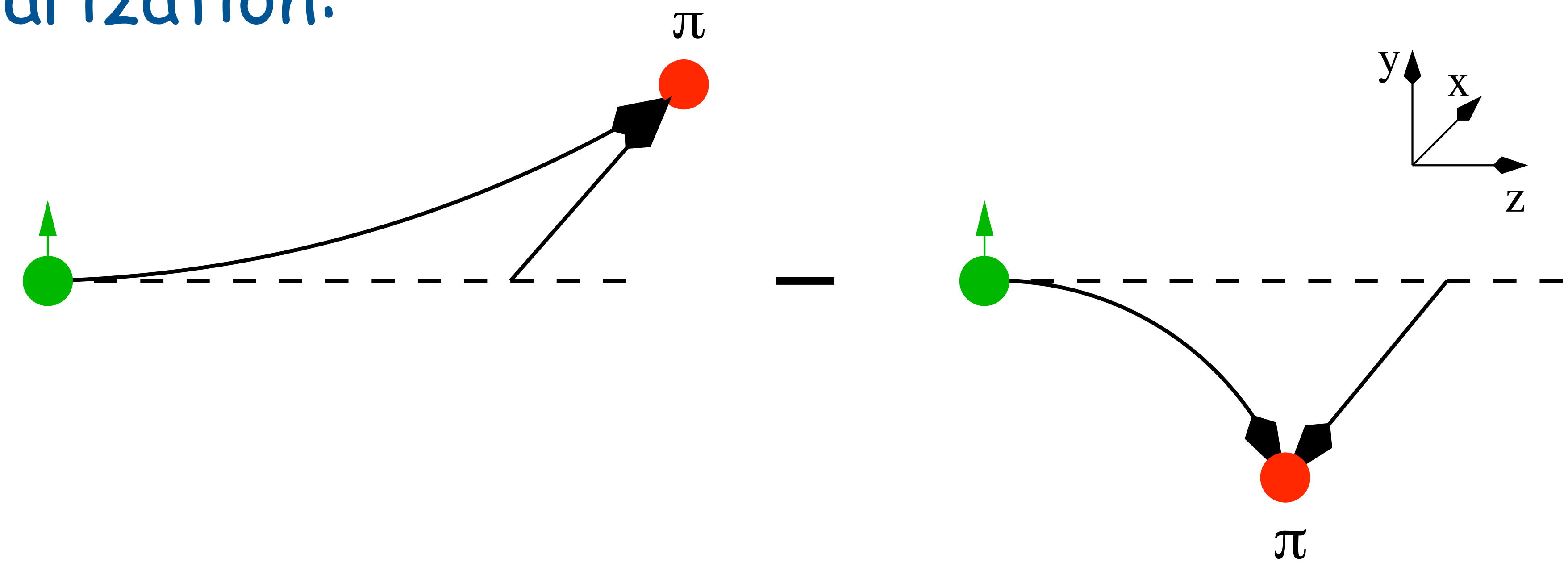
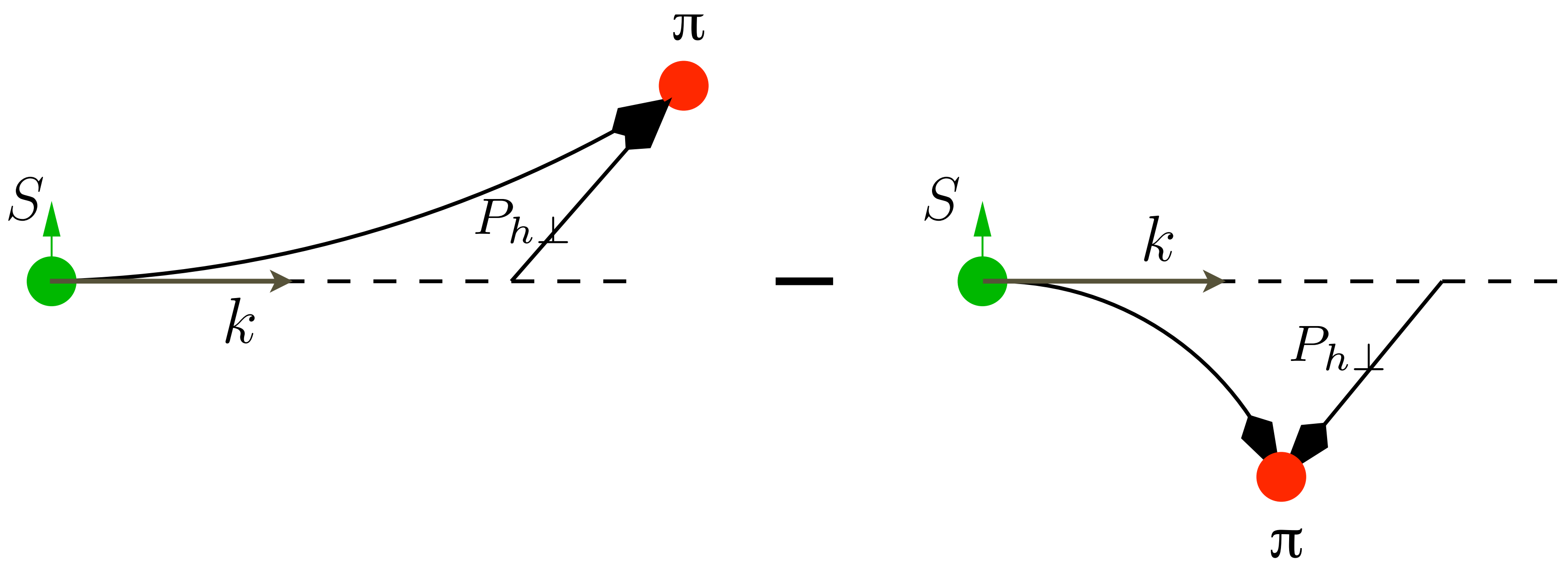


- transverse polarization:



➠ need additional "polarimeter" for transversely polarized quarks

Transverse SSA and time reversal



- time reversal: spin & momentum directions change sign
- if $\sigma \sim S \cdot (k \times P_{h\perp})$
  then (time-reversal invariance): $\sigma \sim -S \cdot (k \times P_{h\perp})$
- $\sigma \overset{?}{\equiv} 0$ ➠ SSA require interference effects!

Transverse SSA and time reversal

- non-vanishing $S \cdot (k \times P_{h\perp})$ structure requires interference of amplitudes (initial- of final-state interactions) with different imaginary parts

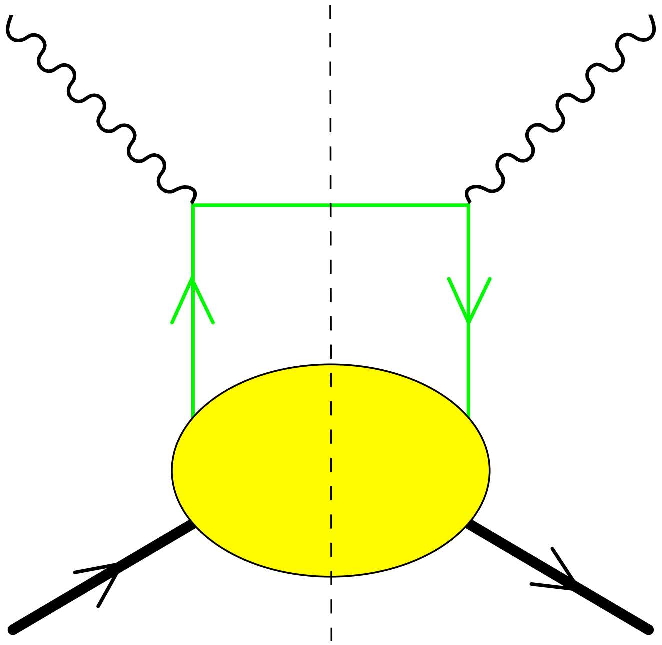
- fragmentation functions involve interference of many amplitudes/channels:

➡ can those interfere constructively and produce such large effects?
(especially at high energies, when many particles can be produced)

- what about leading-twist parton distribution functions?

Quark distributions

- distribution function in handbag representation:



- No interference ➠ no T-odd DF possible!?

Quark distributions

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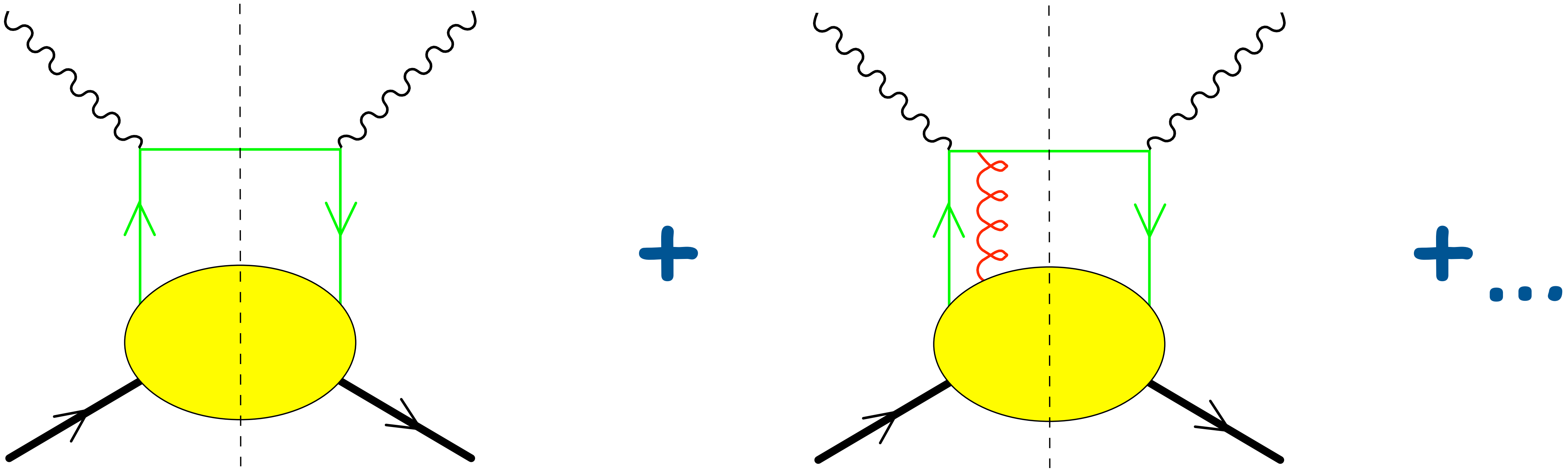
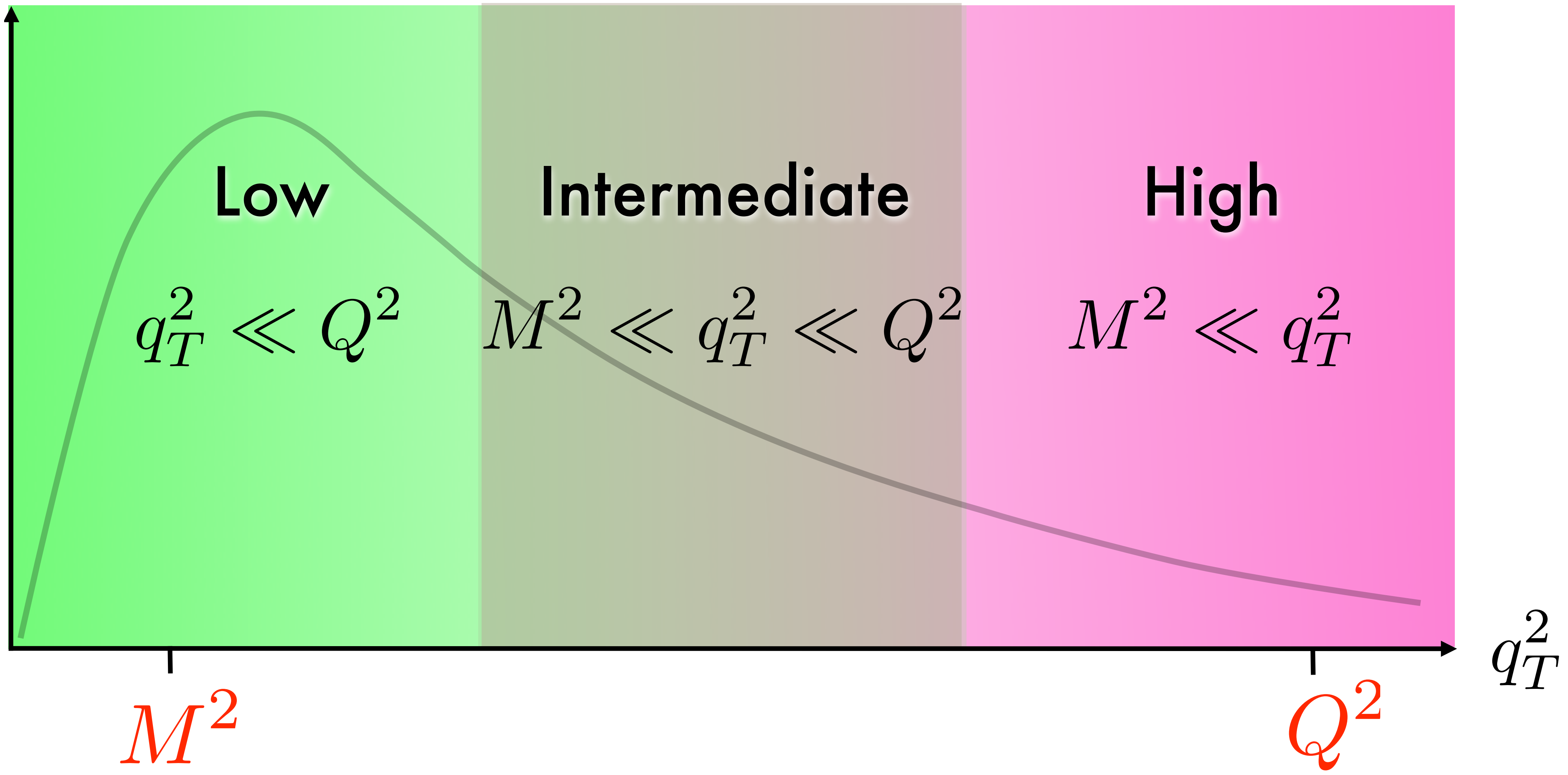


[S. Brodsky et al., Phys. Lett. B530, 99 (2002)]

- interference of amplitudes with different numbers of soft-gluon exchanges possible (not 1/Q suppressed!)
- gluons needed for color gauge invariance
- represent color field of remnant seen by outgoing quark
- involves transverse momentum -> going beyond collinear fact.

SSA: beyond leading-twist collinear approach



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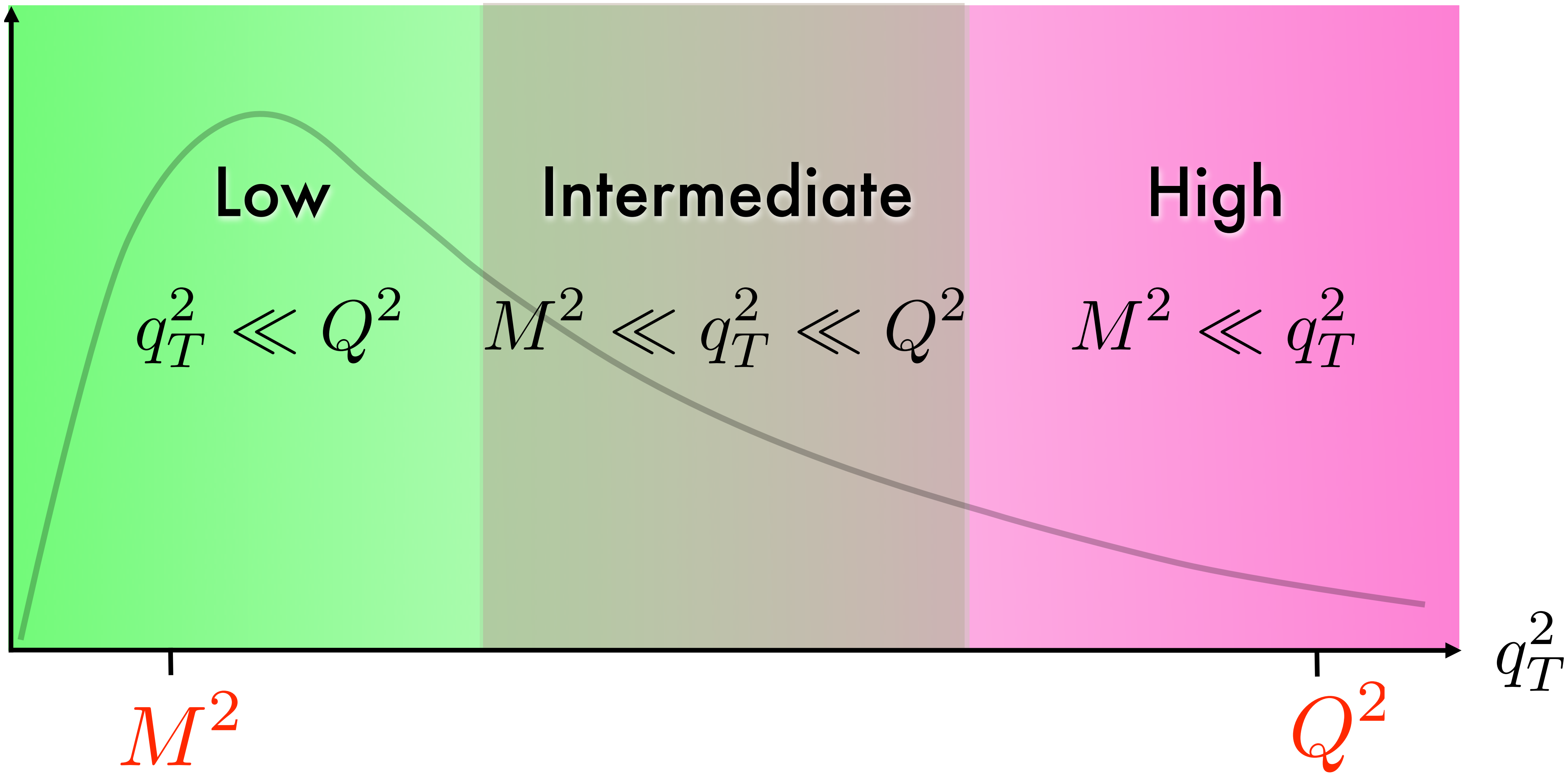
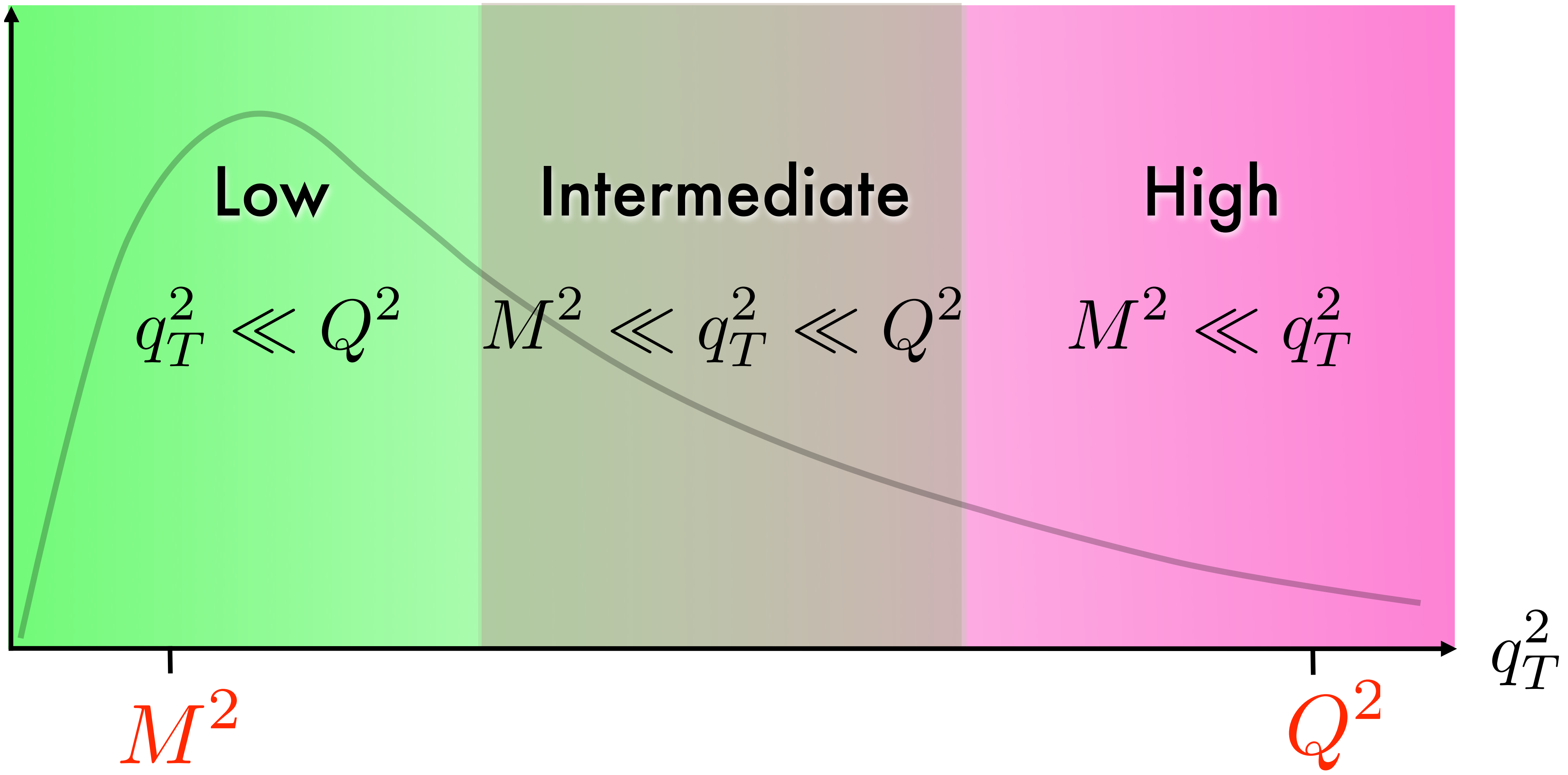


TMD
factorization

TMD: transverse-momentum-dependent distributions

SSA: beyond leading-twist collinear approach



TMD
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twist-3 collinear
factorization

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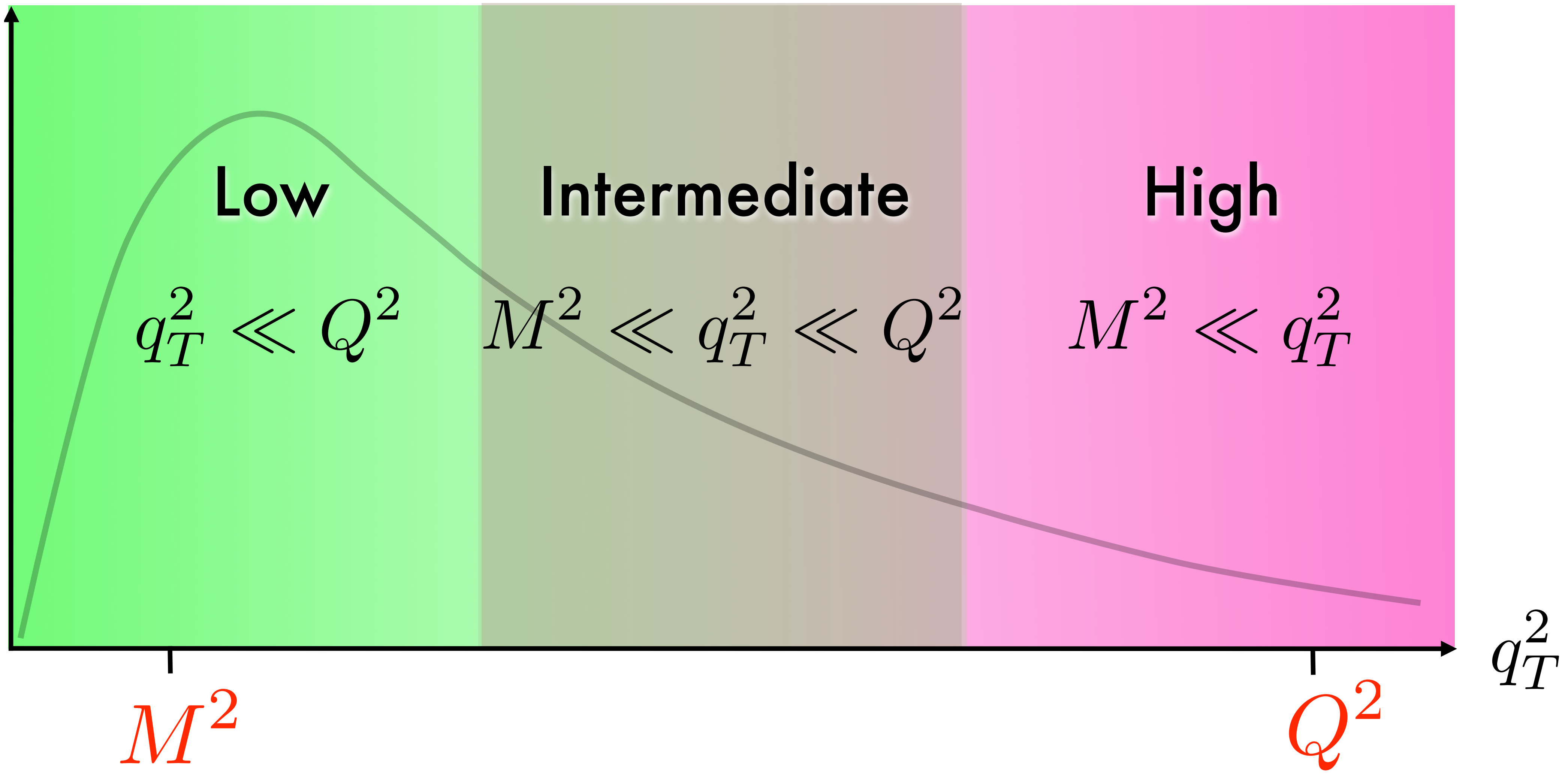

TMD factorization

overlap region

twist-3 collinear factorization

TMD: transverse-momentum-dependent distributions

Spin-Momentum Structure of the Nucleon

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

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

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

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

- each TMD describes a particular spin-momentum correlation
- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

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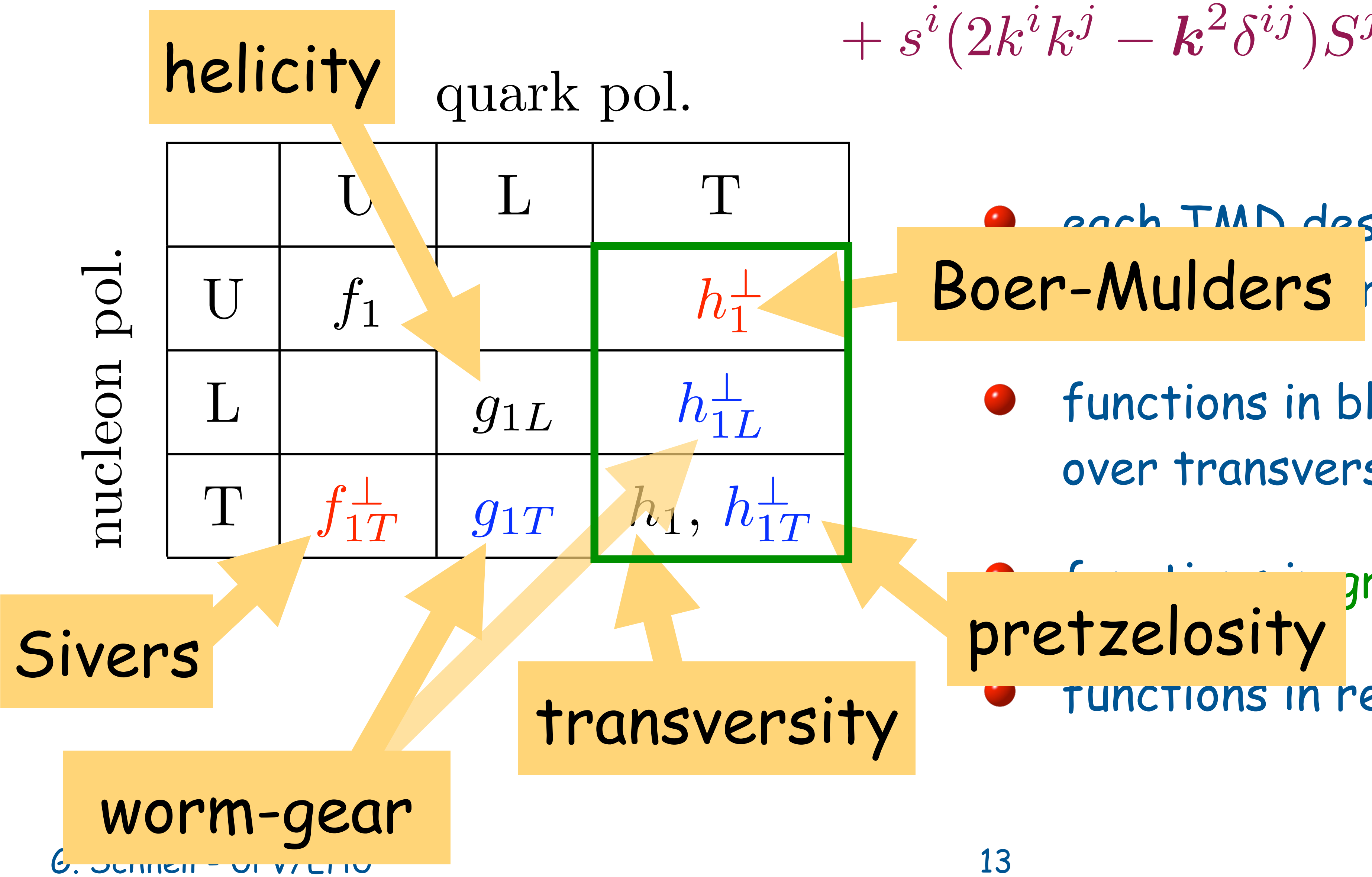

quark pol. / nucleon pol.

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

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TMD fragmentation functions

- similarly characterize hadronization process:

quark pol.

hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

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hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_1	$H_{1L}^\perp$
T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☚ relevant for unpolarized final state

TMD fragmentation functions

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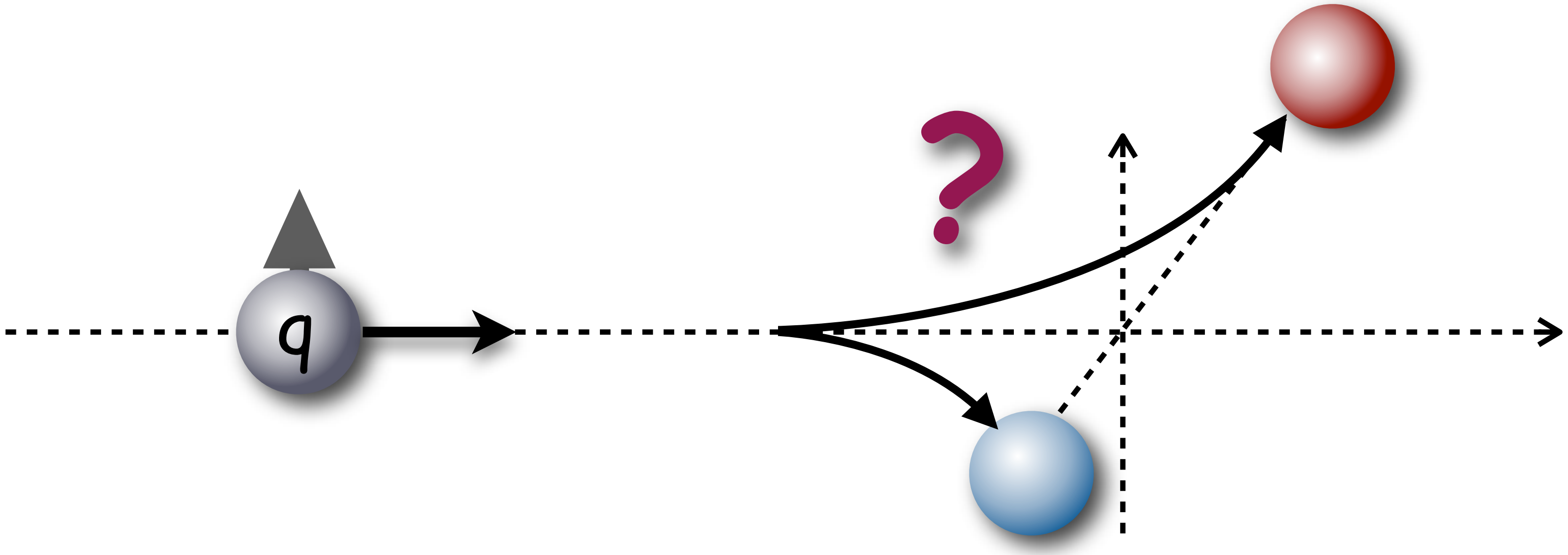
		quark pol.		
		U	L	T
hadron pol.	U	D_1		$H_1^\perp$
	L		G_1	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	$G_{1T}^\perp$	H_1 $H_{1T}^\perp$

☚ relevant for unpolarized final state

Collins FF: $H_1^{\perp,q\to h}$

ordinary FF: $D_1^{q\to h}$

Collins fctn. - chiral-odd fragmentation



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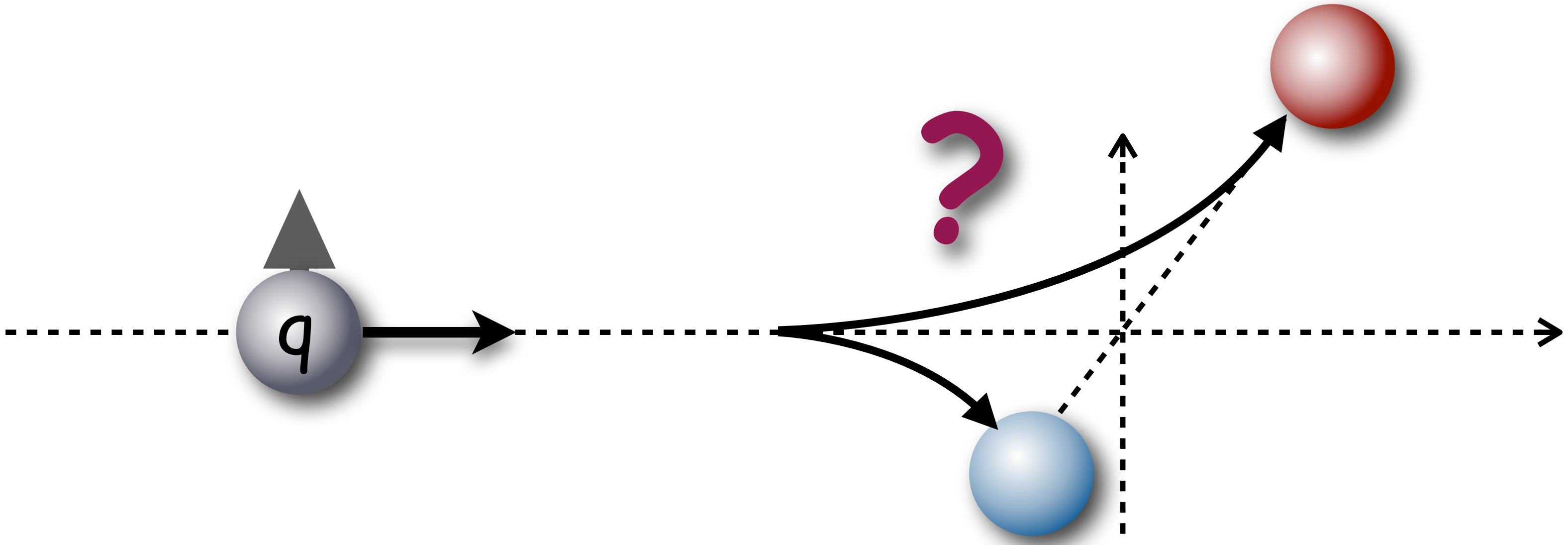

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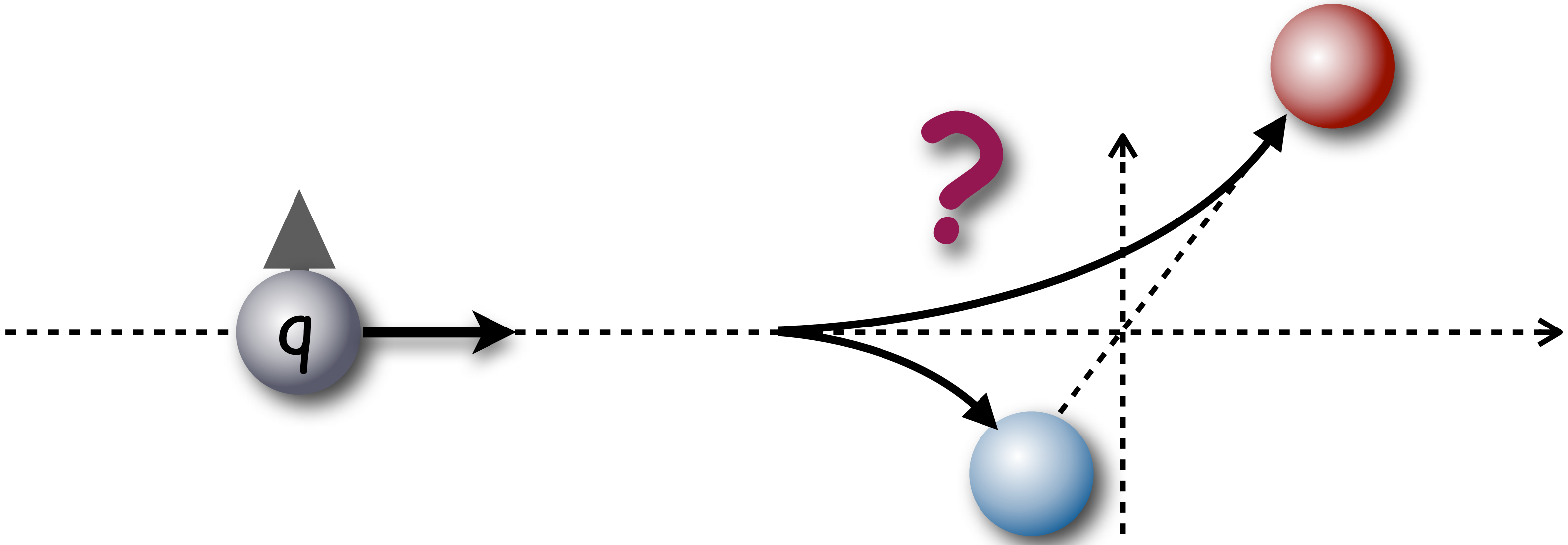

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- left-right asymmetry in hadron direction transverse to both quark spin and momentum

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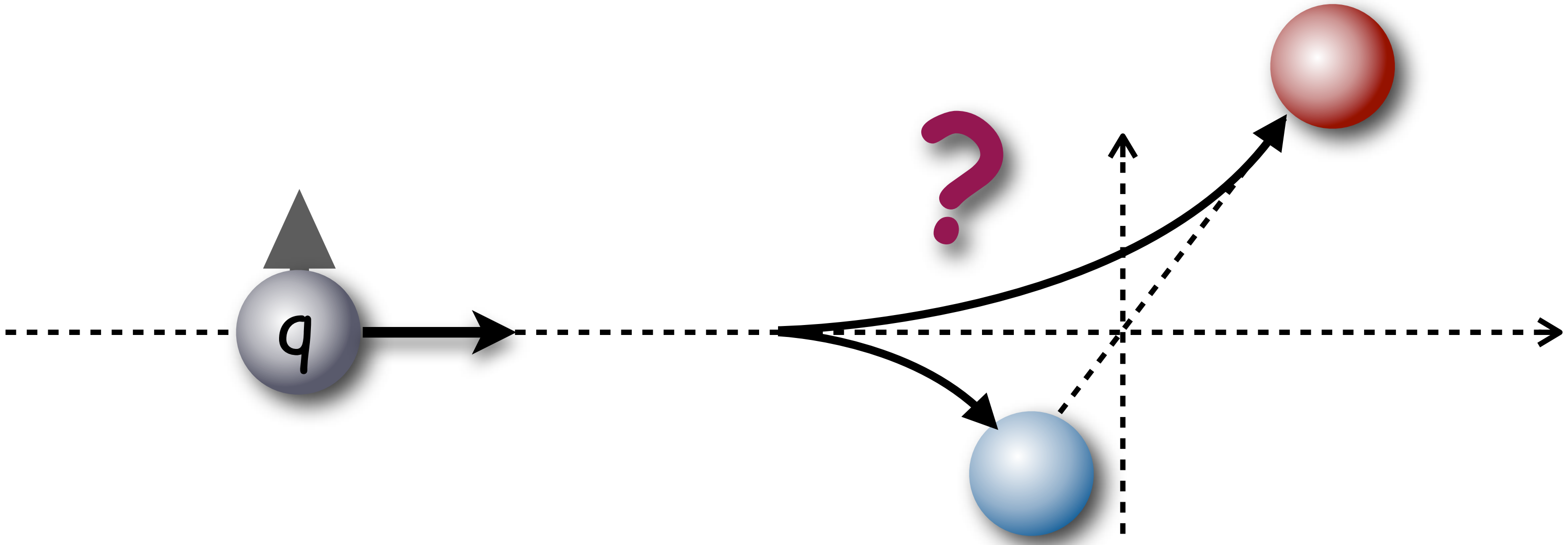

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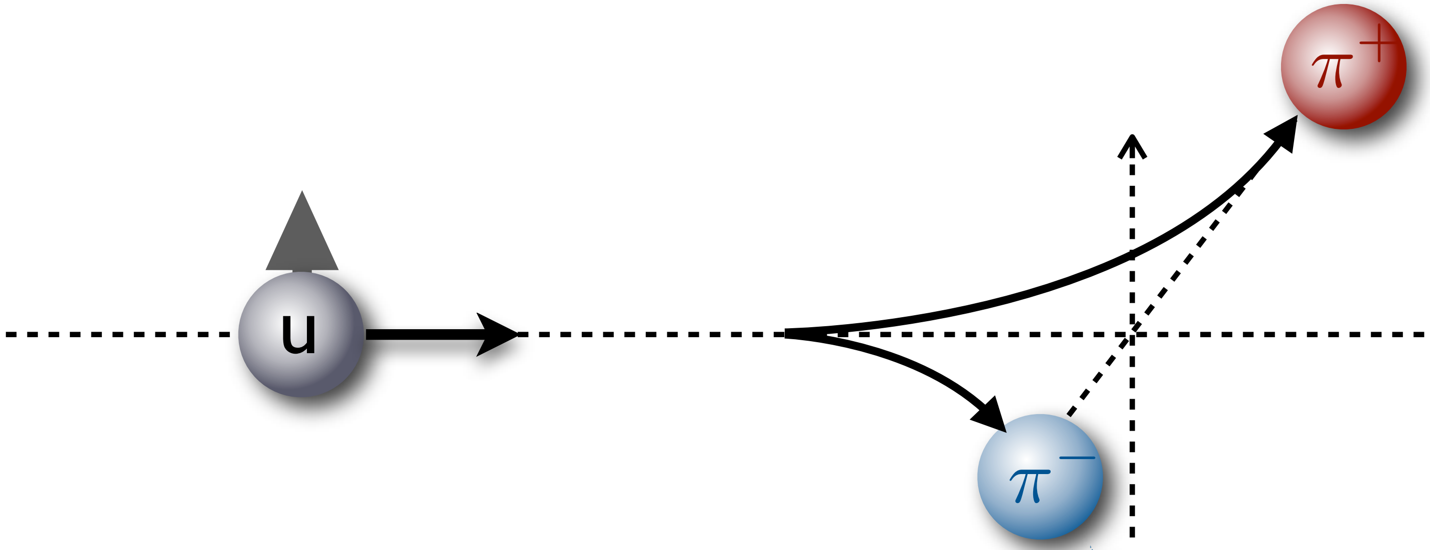

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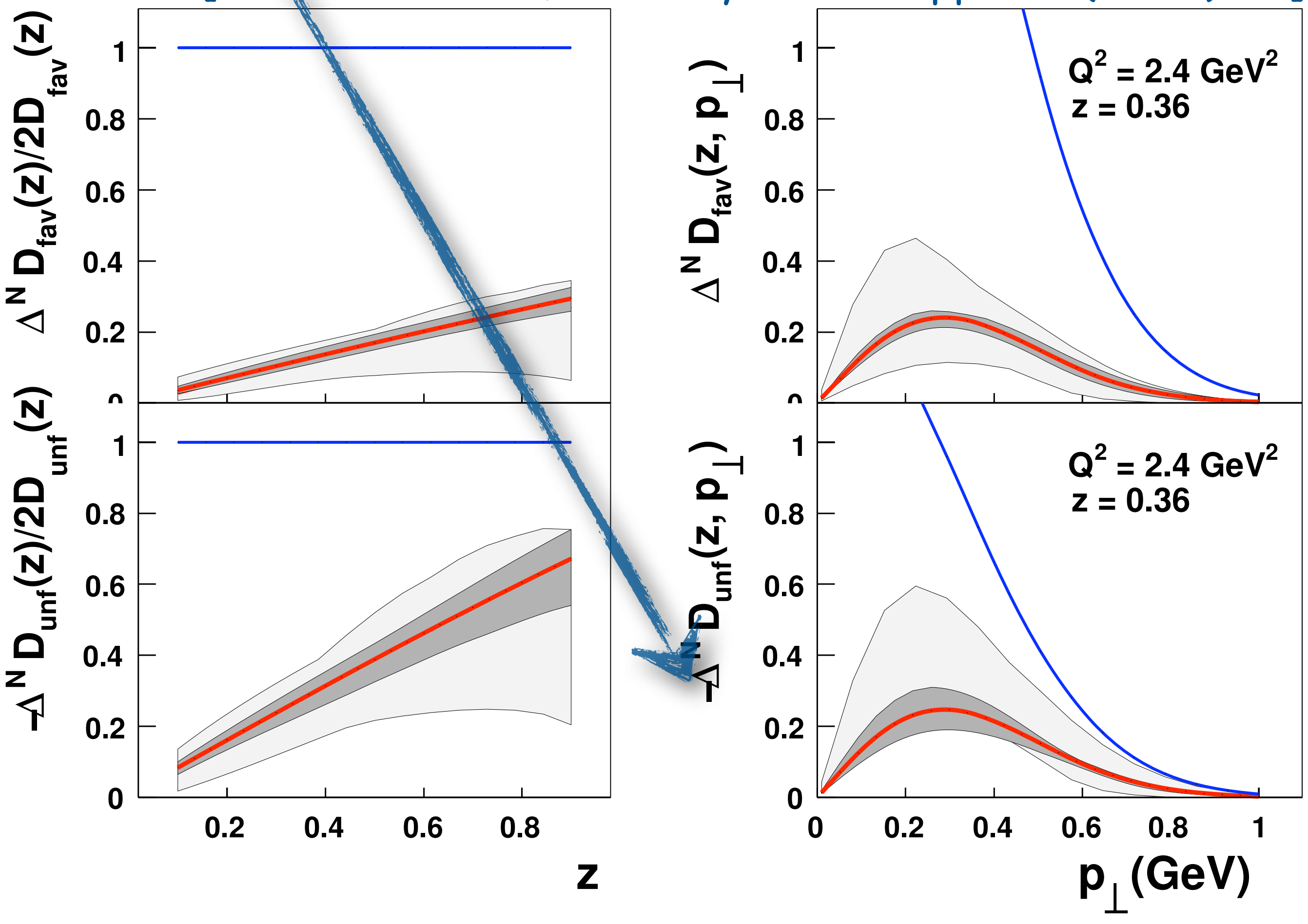
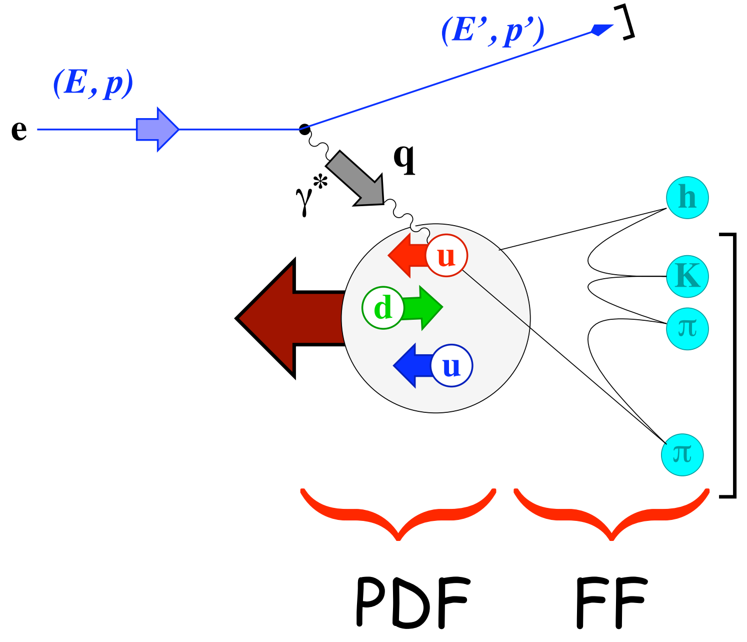
- extracted from SIDIS and e^+e^- annihilation data

[Anselmino et al., Nucl.Phys.Proc.Suppl.191 (2009) 98]



Probing TMDs in semi-inclusive DIS



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, $h_{1T}^\perp$

in SIDIS*) couple PDFs to:

*) semi-inclusive DIS with unpolarized final state

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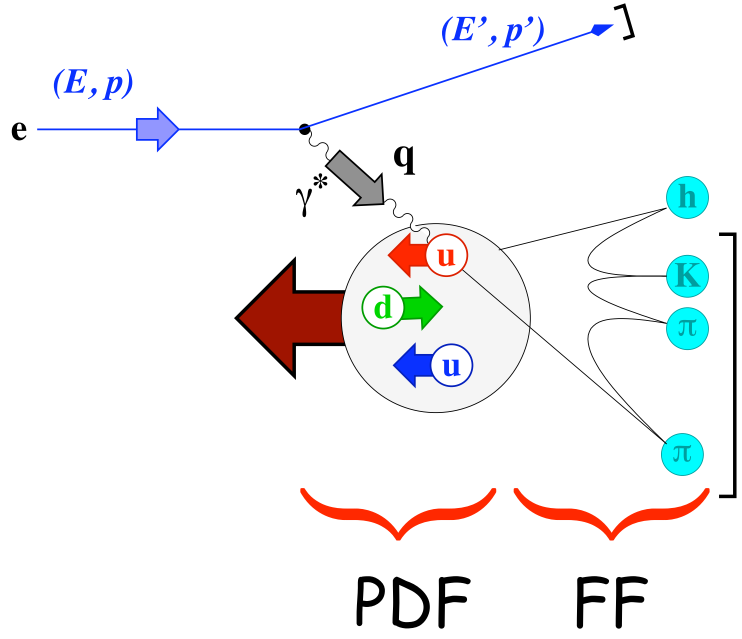

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Collins FF: $H_1^{\perp,q\rightarrow h}$

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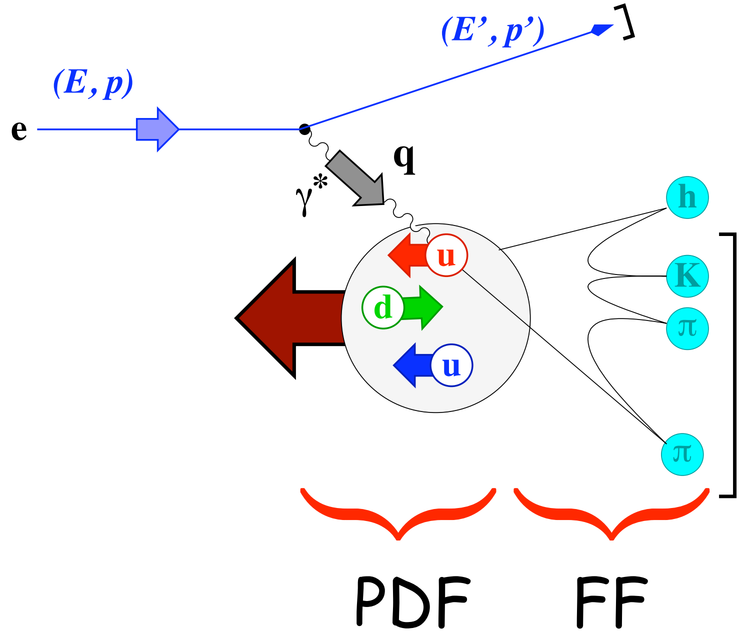

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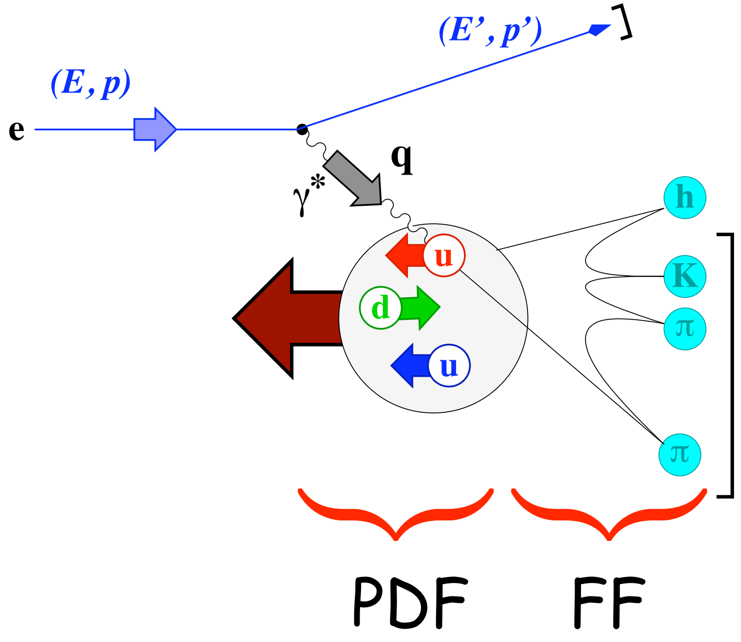
Probing TMDs in semi-inclusive DIS



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in SIDIS*) couple PDFs to:

Collins FF: $H_1^{\perp,q\to h}$

ordinary FF: $D_1^{q\to h}$

➡ gives rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

1-Hadron production (ep→ehX)

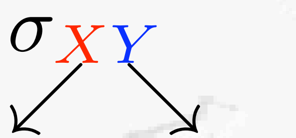
$$d\sigma = d\sigma^0_{UU} + \cos 2\phi\, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^3_{LU}$$

$$+S_L \left\{ \sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL} \right] \right\}$$

$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \right.$$

$$+\frac{1}{Q}\left(\sin(2\phi - \phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)$$

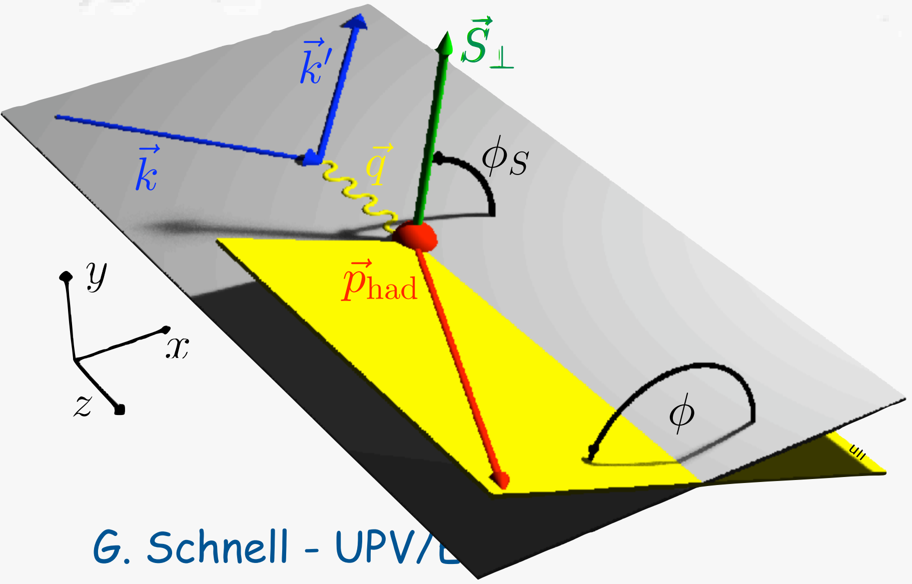
$$\left. +\lambda_e \left[\cos(\phi - \phi_S)\, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S\, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S)\, d\sigma^{15}_{LT}\right) \right] \right\}$$



σ_{XY}

Beam **Target**

Polarization



Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

1-Hadron production (ep→ehX)

$$
\begin{aligned}
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& + S_T \Bigg\{ \boxed{\sin(\phi - \phi_S) \, d\sigma^8_{UT}} + \boxed{\sin(\phi + \phi_S) \, d\sigma^9_{UT}} + \boxed{\sin(3\phi - \phi_S) \, d\sigma^{10}_{UT}} \\
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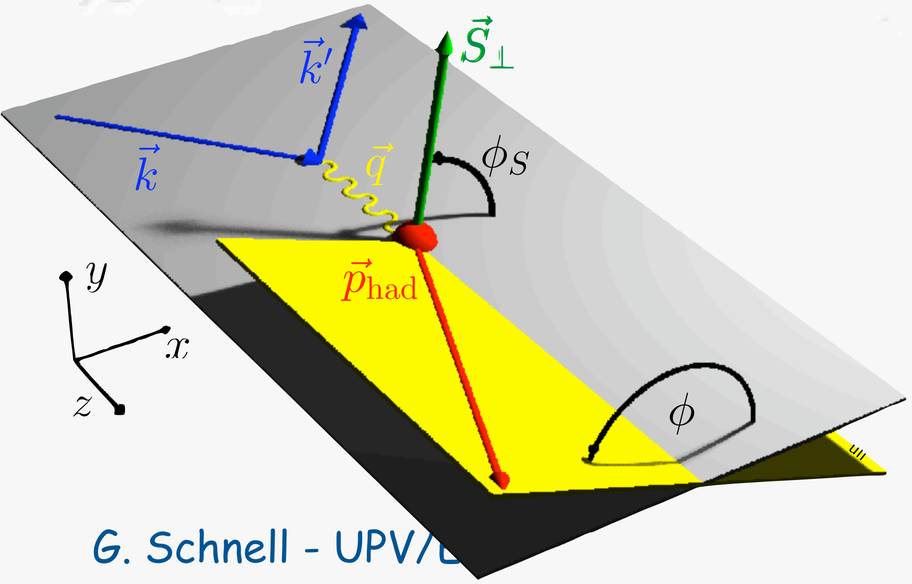
$$

σ_{XY}

↙ ↘

Beam **Target**

Polarization



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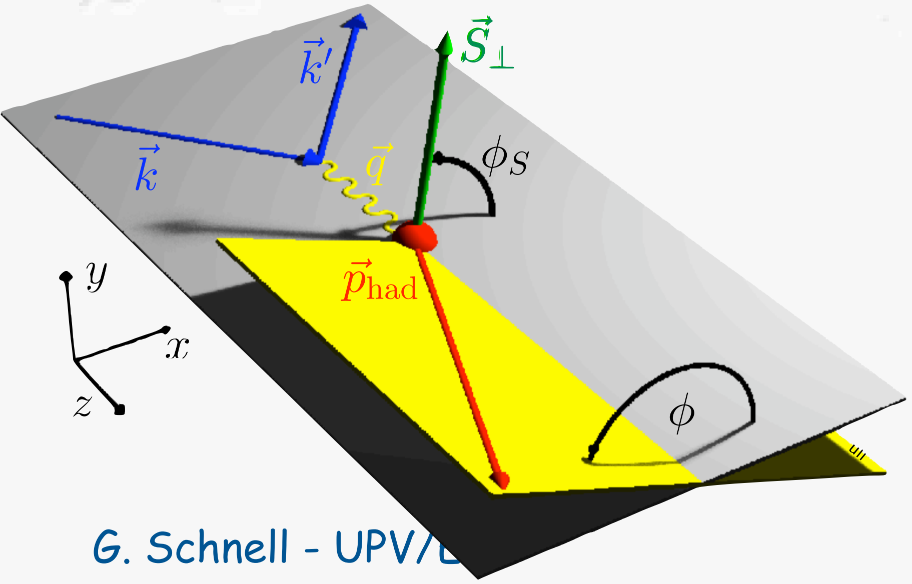
Polarization



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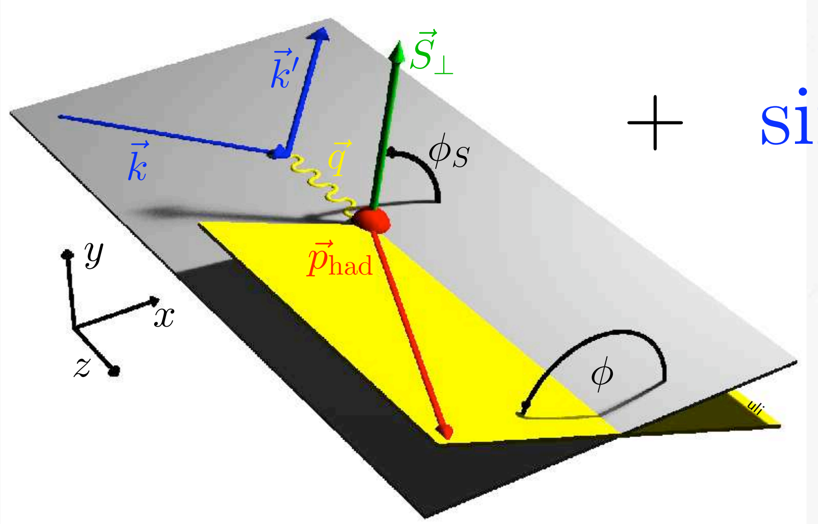
Azimuthal spin asymmetries

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^\uparrow(\phi,\phi_S)-N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S)+N_h^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M_h}h_1^q(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{p_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M}f_{1T}^{\perp,q}(x,p_T^2)D_1^q(z,k_T^2)\right]$$

$$+ \quad \cdots$$



$\mathcal{I}[\ldots]$: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

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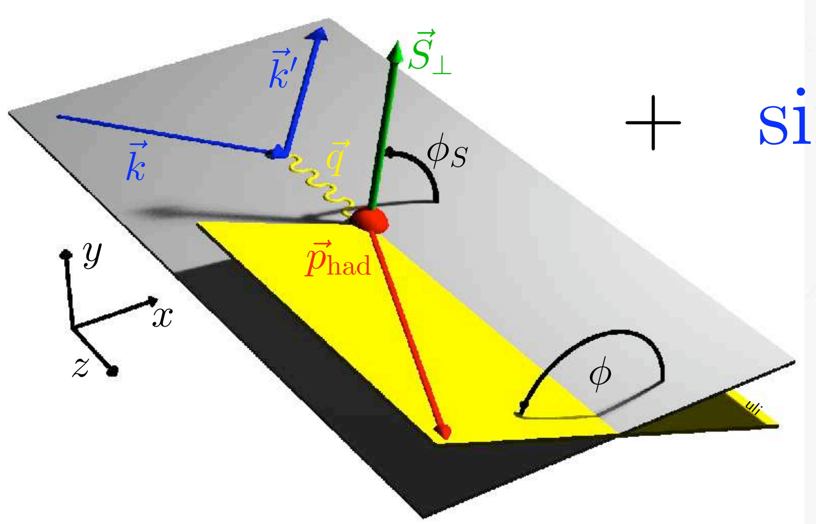
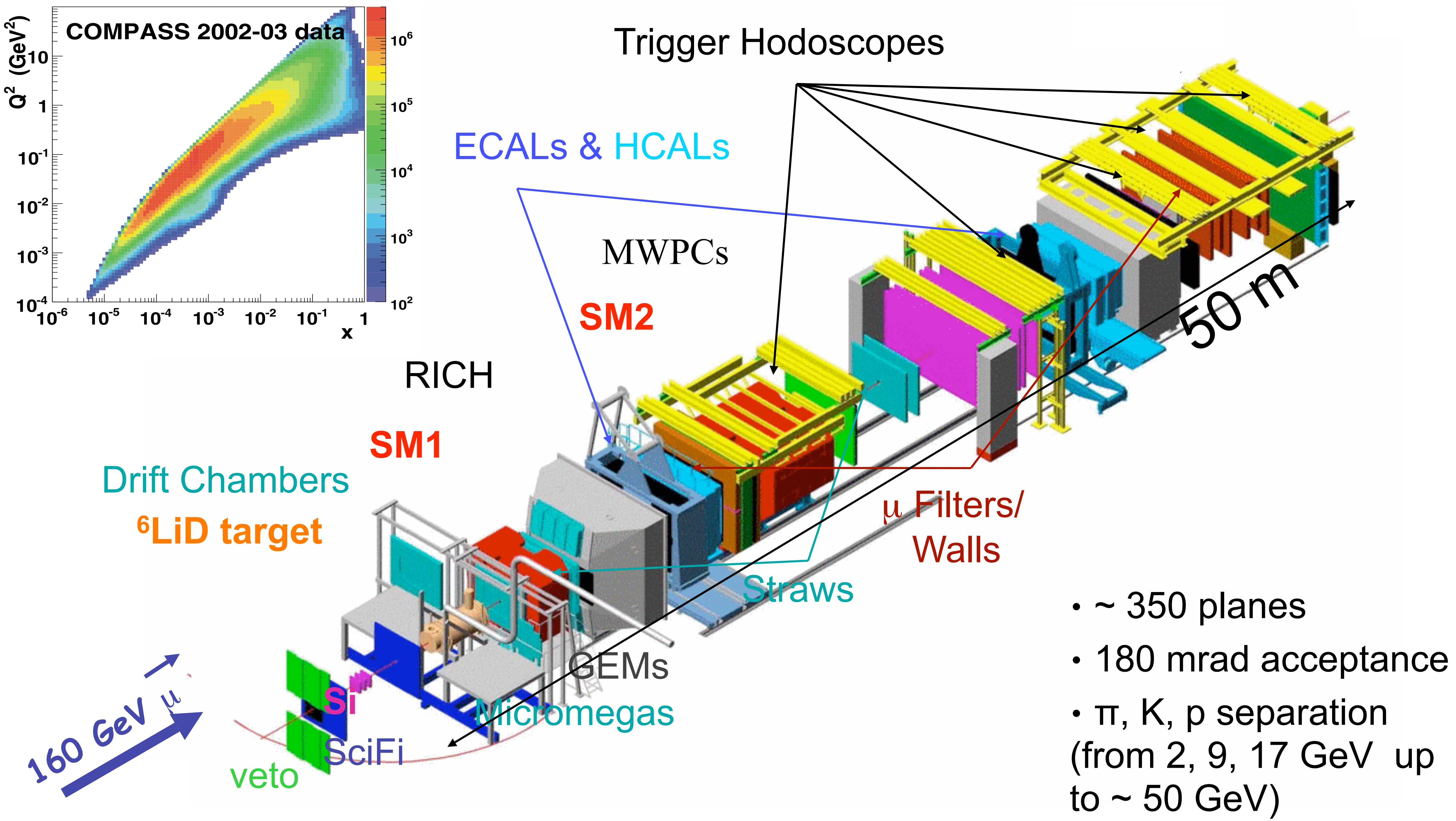


$\mathcal{I}[\ldots]$: convolution integral over initial (p_T) and final (k_T) quark transverse momenta

Fit azimuthal modulations, e.g., using Max.Likelihood:

$$\boxed{PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\sin(\phi\pm\phi_s)+\ldots)\}}$$

The COMPASS experiment @ CERN



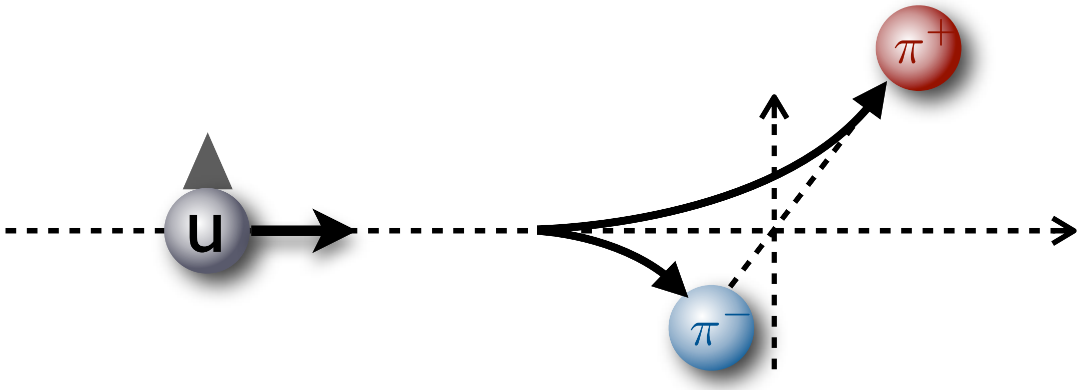
- ~ 350 planes
- 180 mrad acceptance
- π, K, p separation (from 2, 9, 17 GeV up to ~ 50 GeV)

The quest for transversely polarized quarks

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

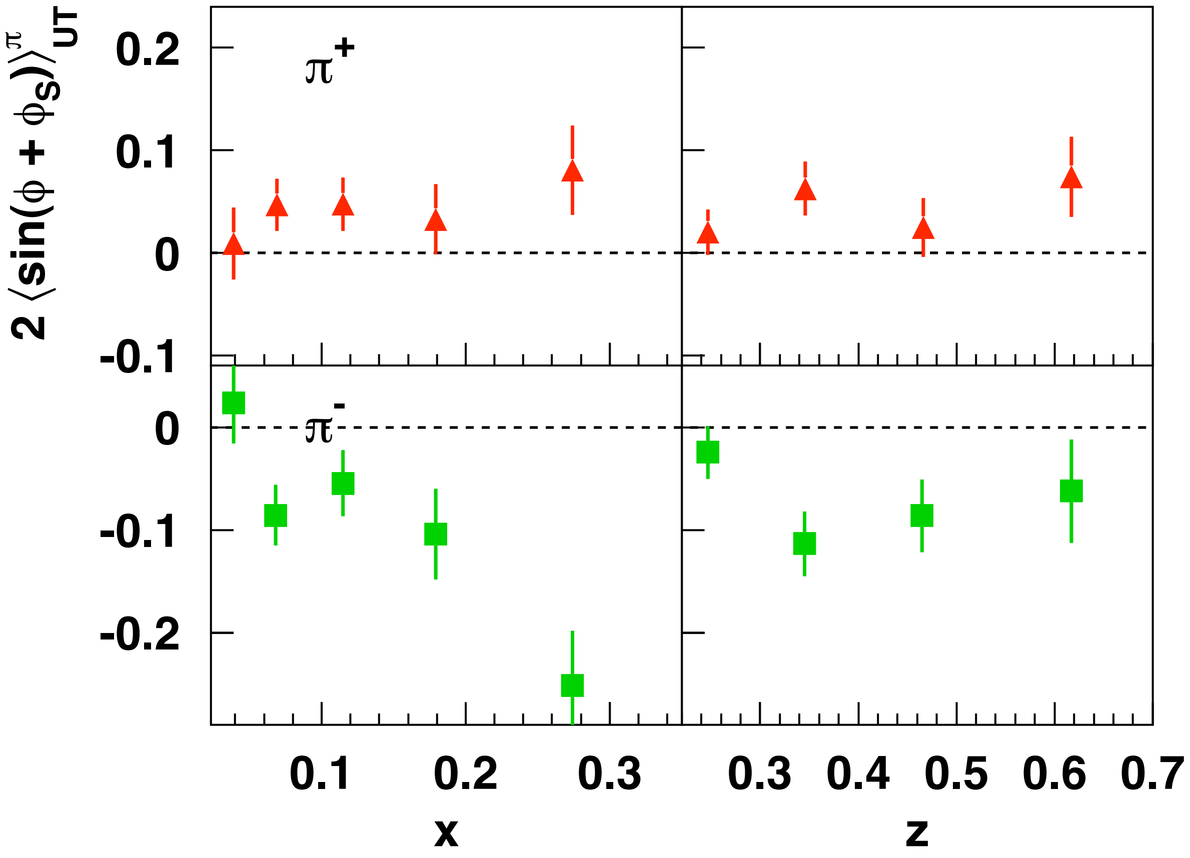
transversity distribution (Collins fragmentation)

- 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]



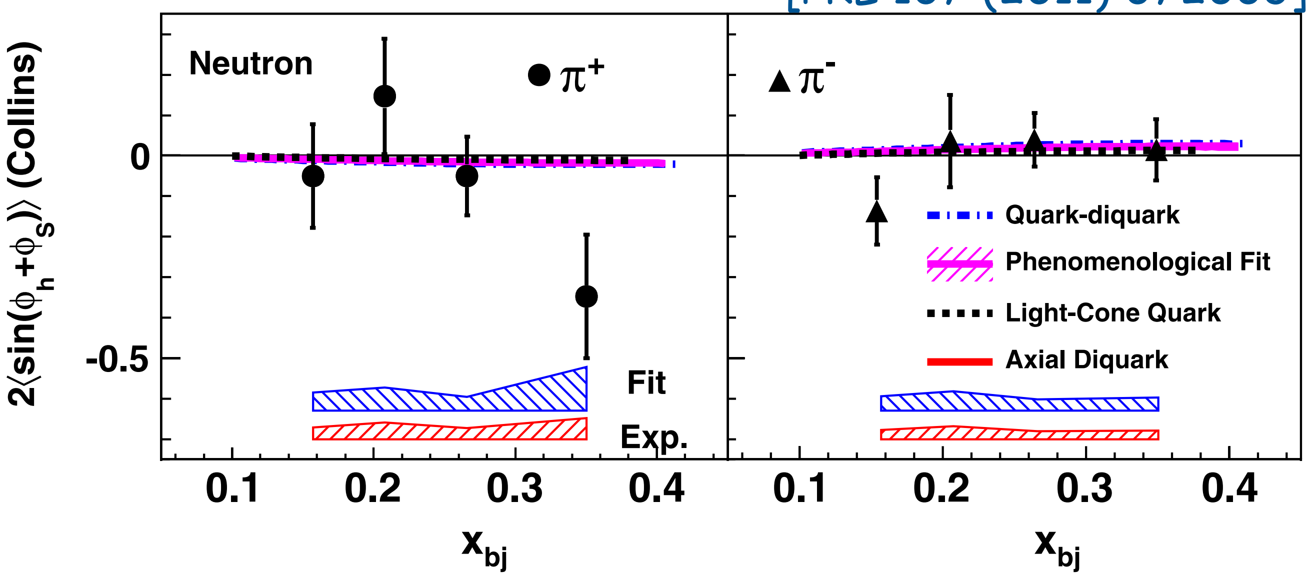
2005: First evidence from HERMES
SIDIS on proton

Non-zero transversity
Non-zero Collins function

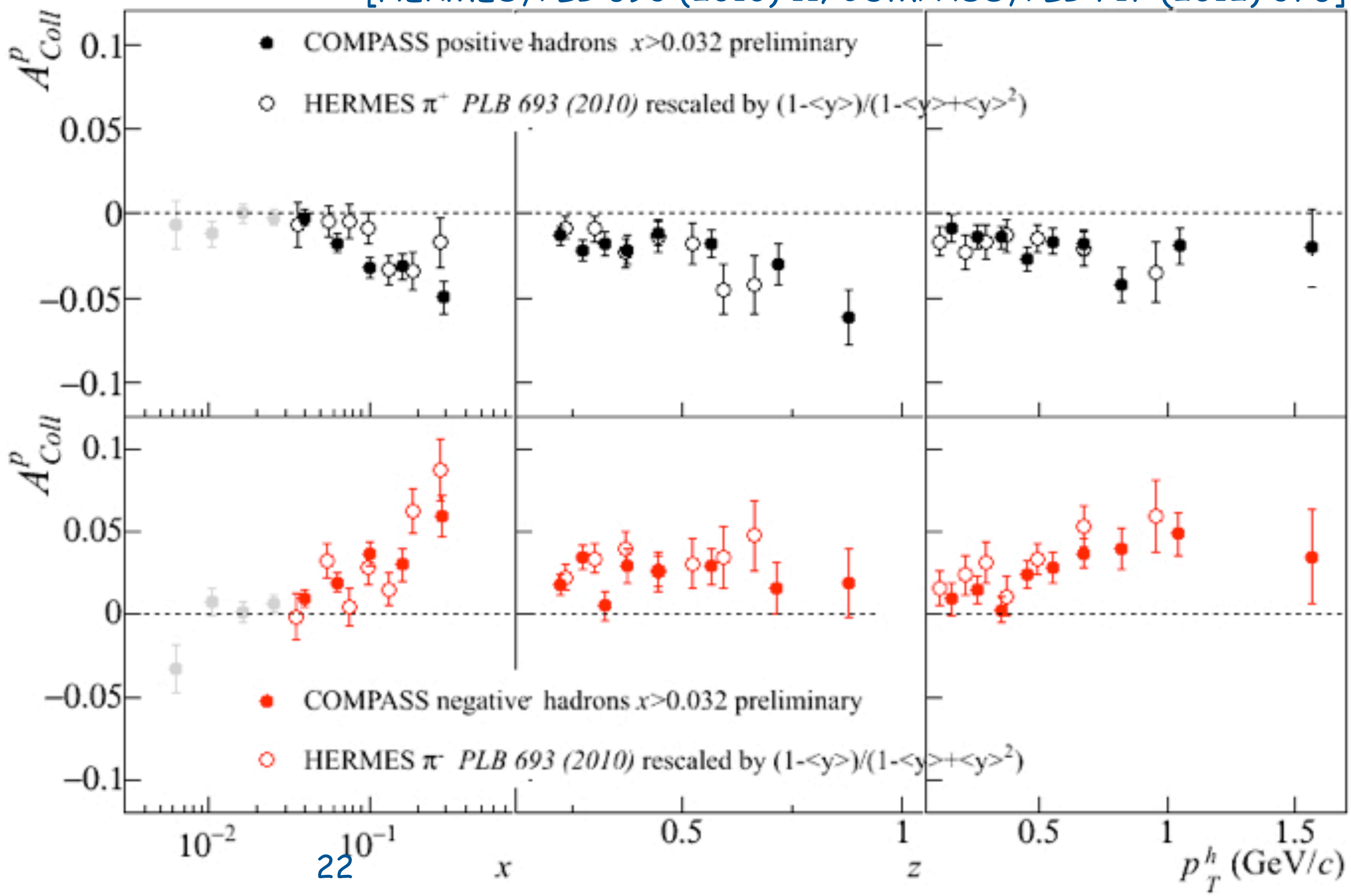
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Collins amplitudes

[PRL 107 (2011) 072003]



[HERMES, PLB 693 (2010) 11; COMPASS, PLB 717 (2012) 376]



- wealth of new results available and/or analyses ongoing
  - **Jefferson Lab** [PRL 107 (2011) 072003]
  - **COMPASS** [PLB 692 (2010) 240, PLB 717 (2012) 376]
  - **HERMES** [PLB 693 (2010) 11]
  - **BELLE**
  - **BaBar**

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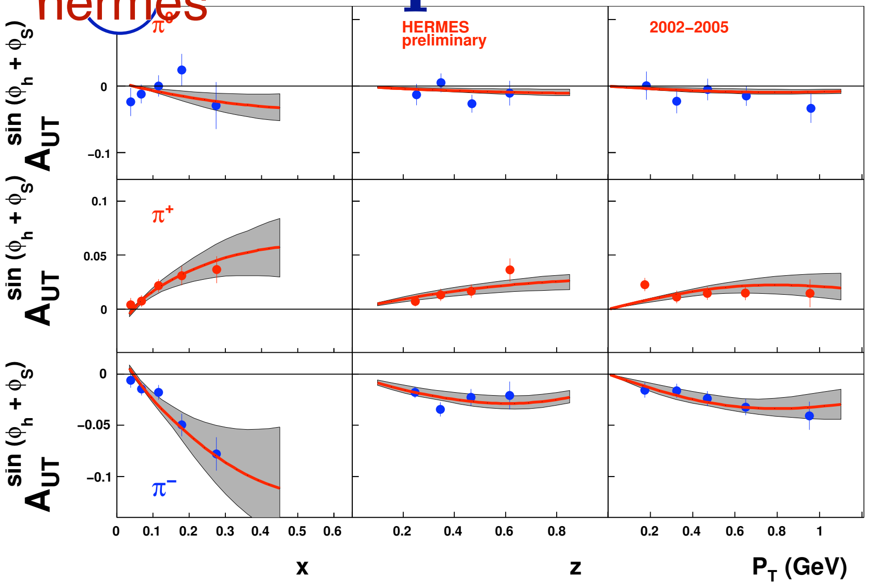
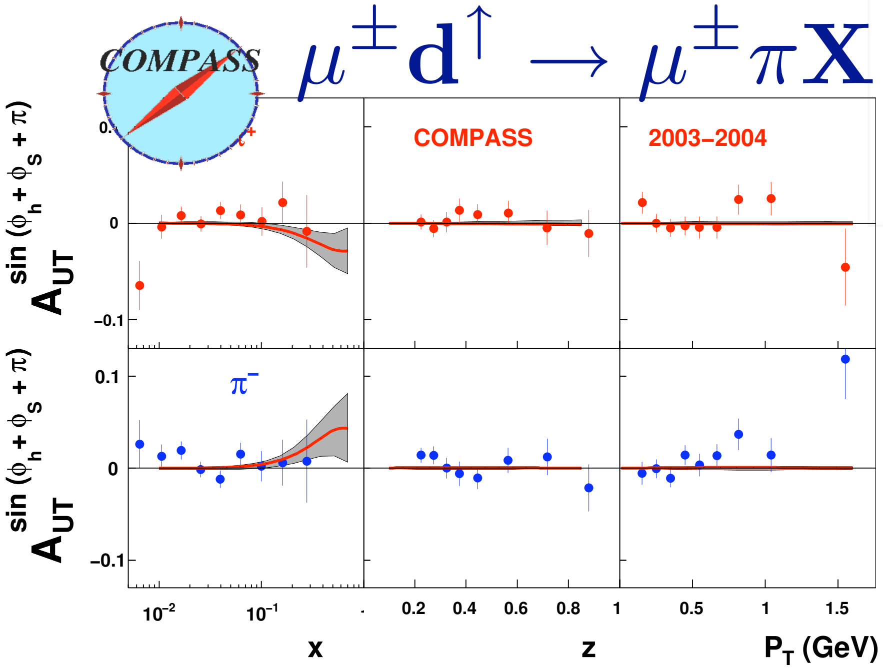
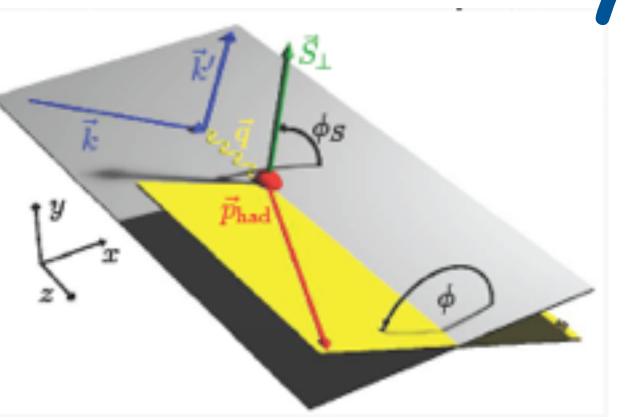
Collins FF and transversity fit

$\mathbf{e}^\pm\mathbf{p}^\uparrow \longrightarrow \mathbf{e}^\pm\pi\mathbf{X}$



$\mu^\pm\mathbf{d}^\uparrow \longrightarrow \mu^\pm\pi\mathbf{X}$





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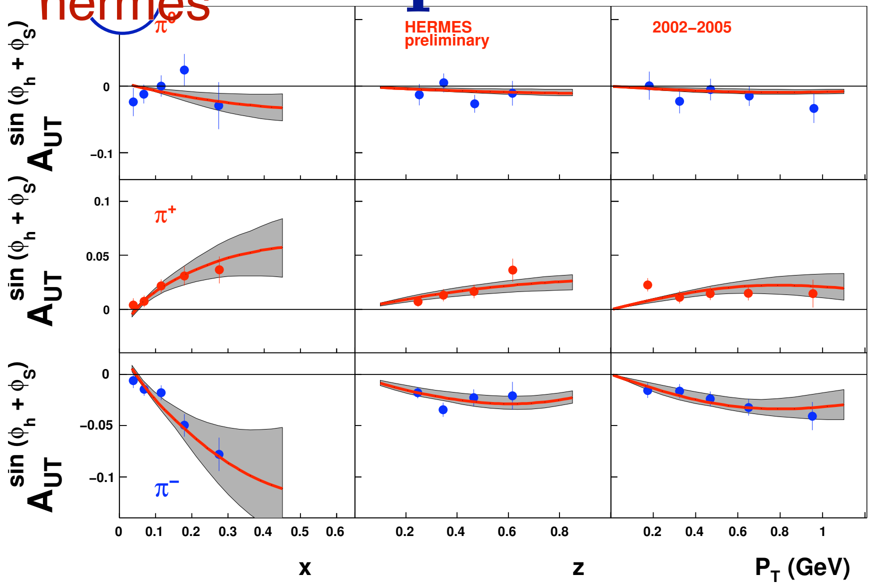

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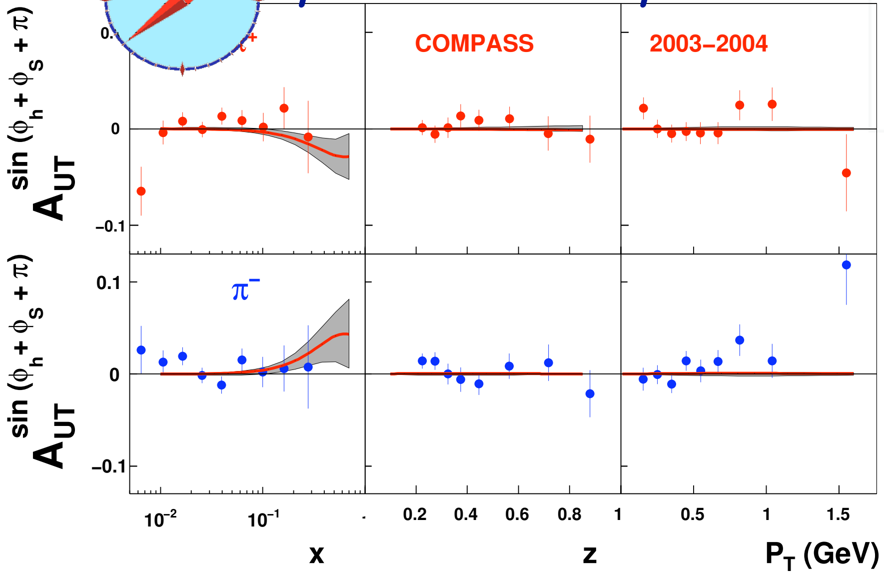
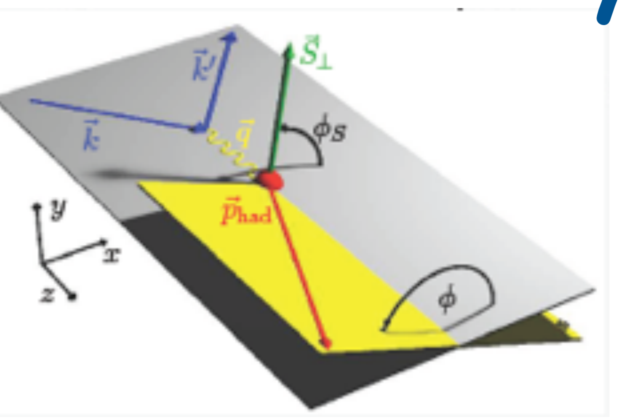
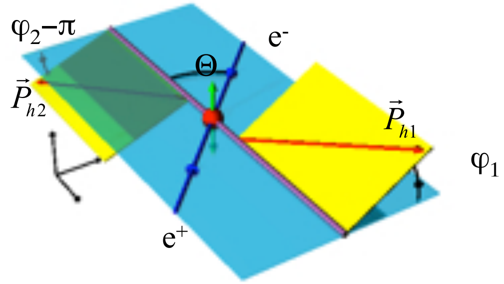
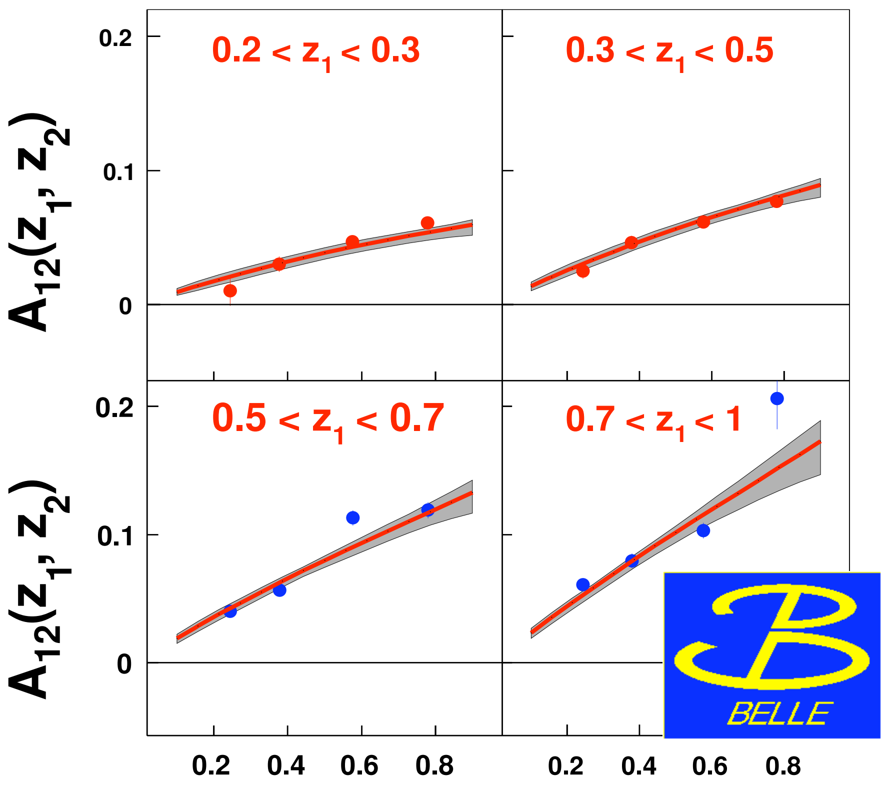






$e^{+}e^{-} \rightarrow \pi\pi X$



	U	L	T
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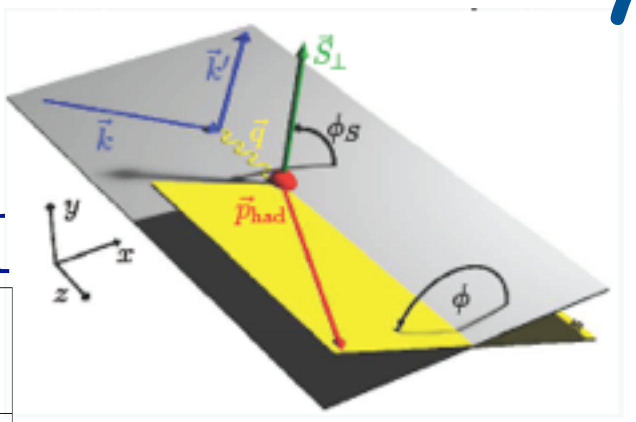
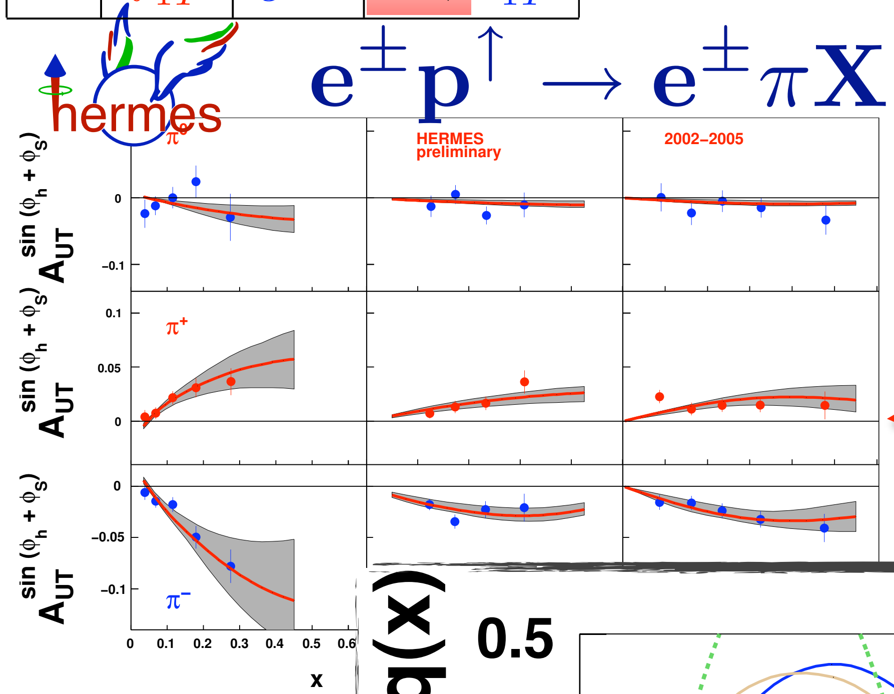
Collins FF and transversity fit



$e^\pm p^\uparrow \to e^\pm \pi X$



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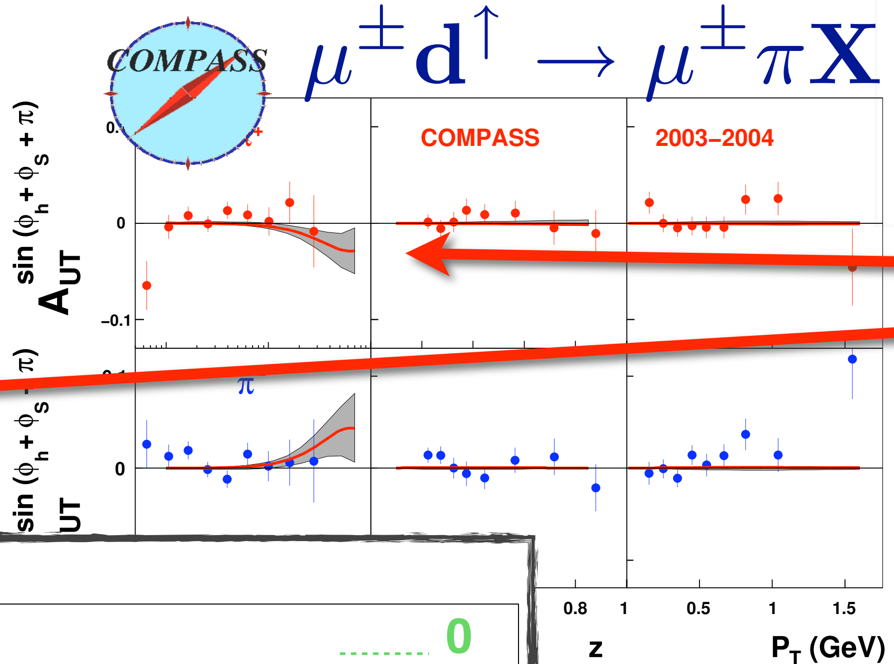
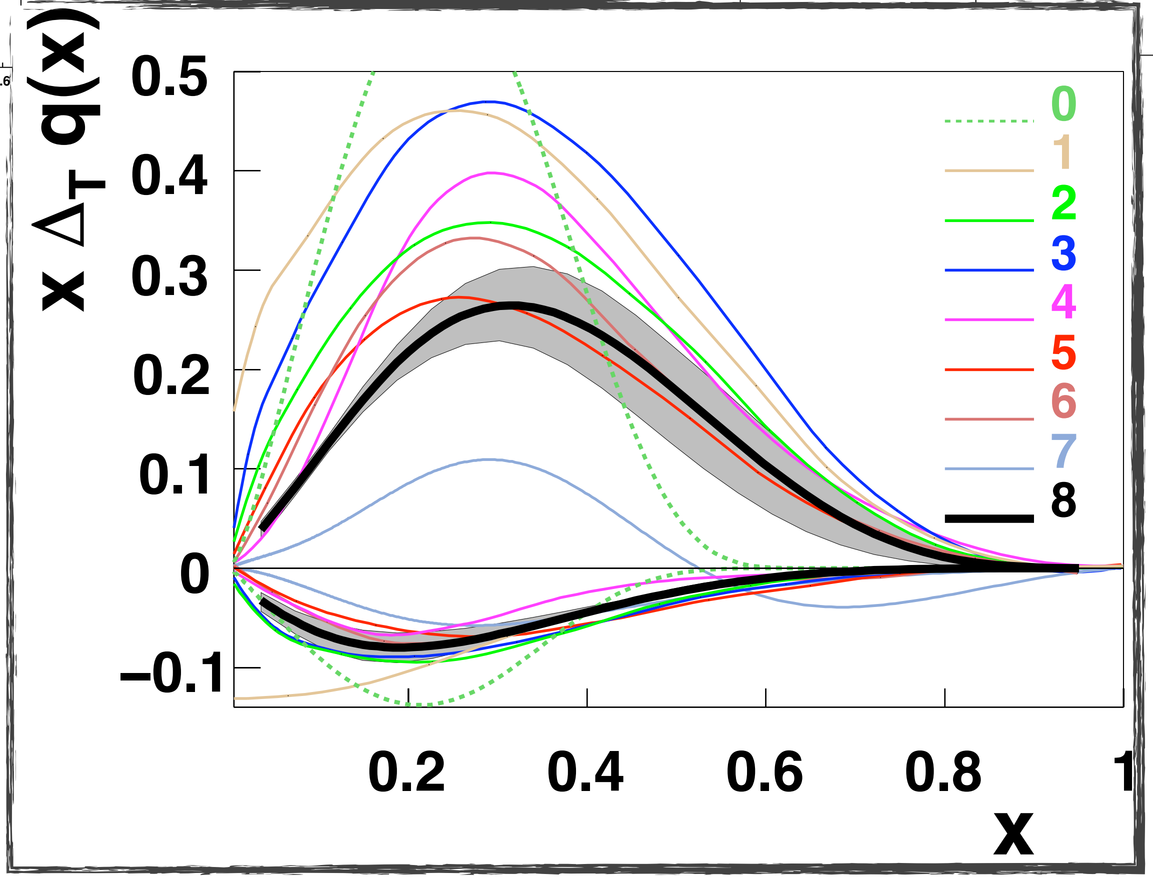
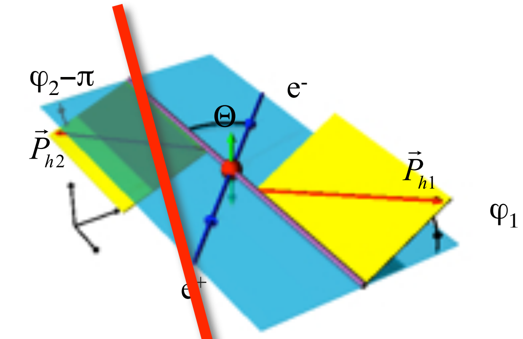
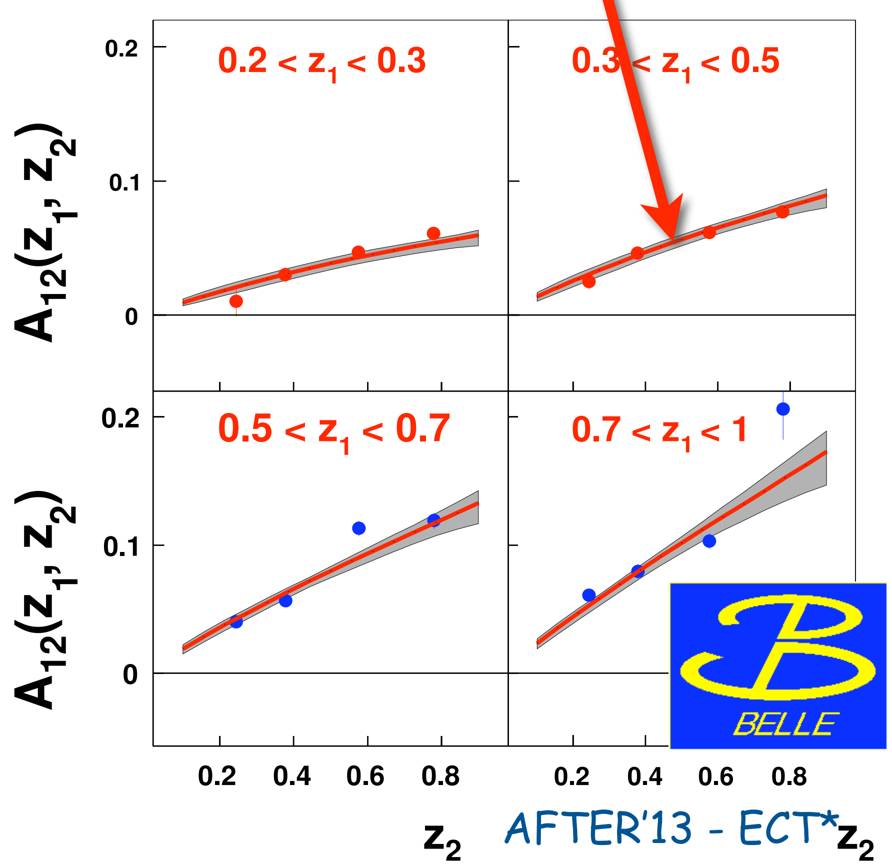


fit to data





$e^+e^- \to \pi\pi X$



details ☛ S. Melis

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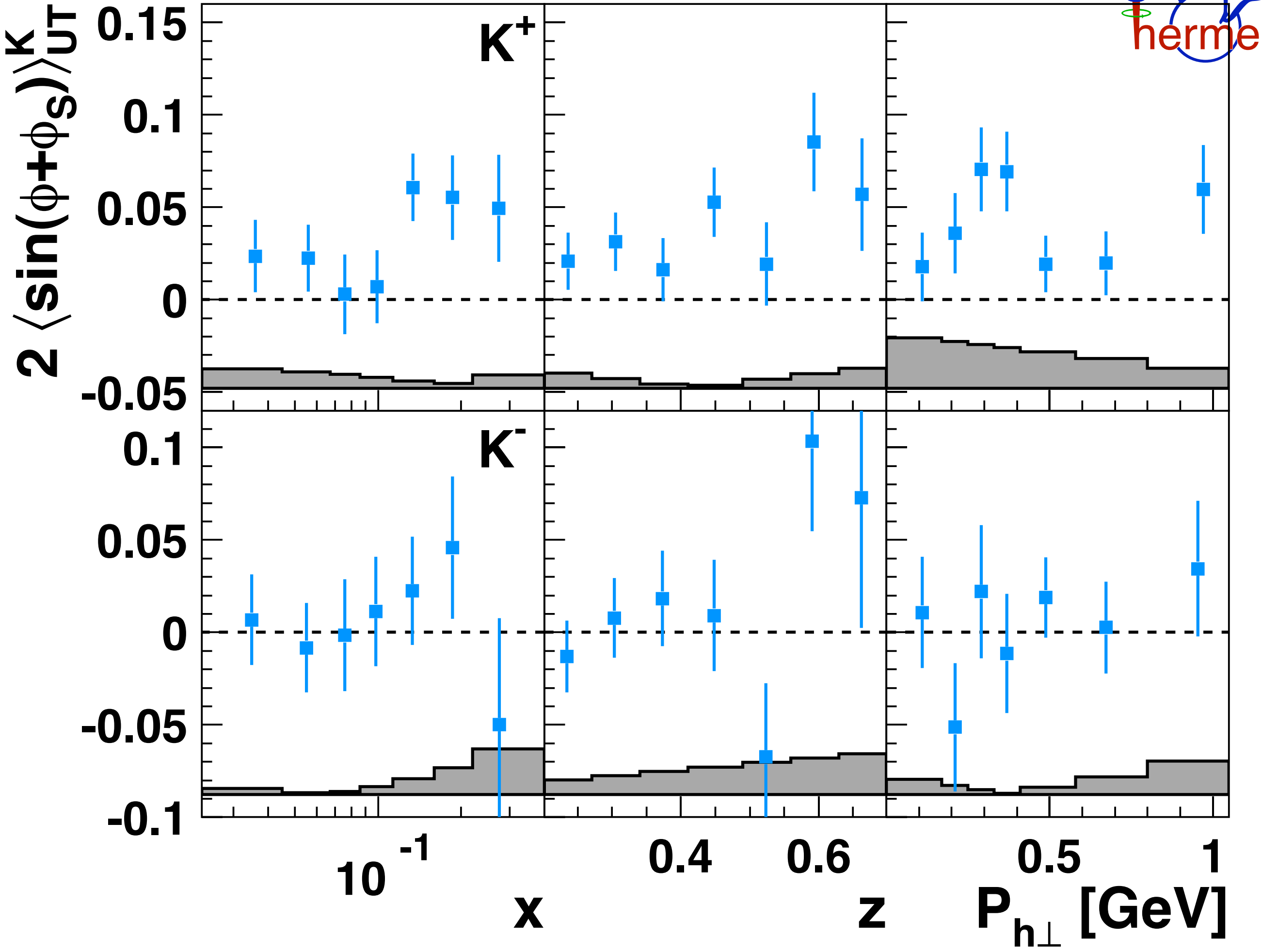
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

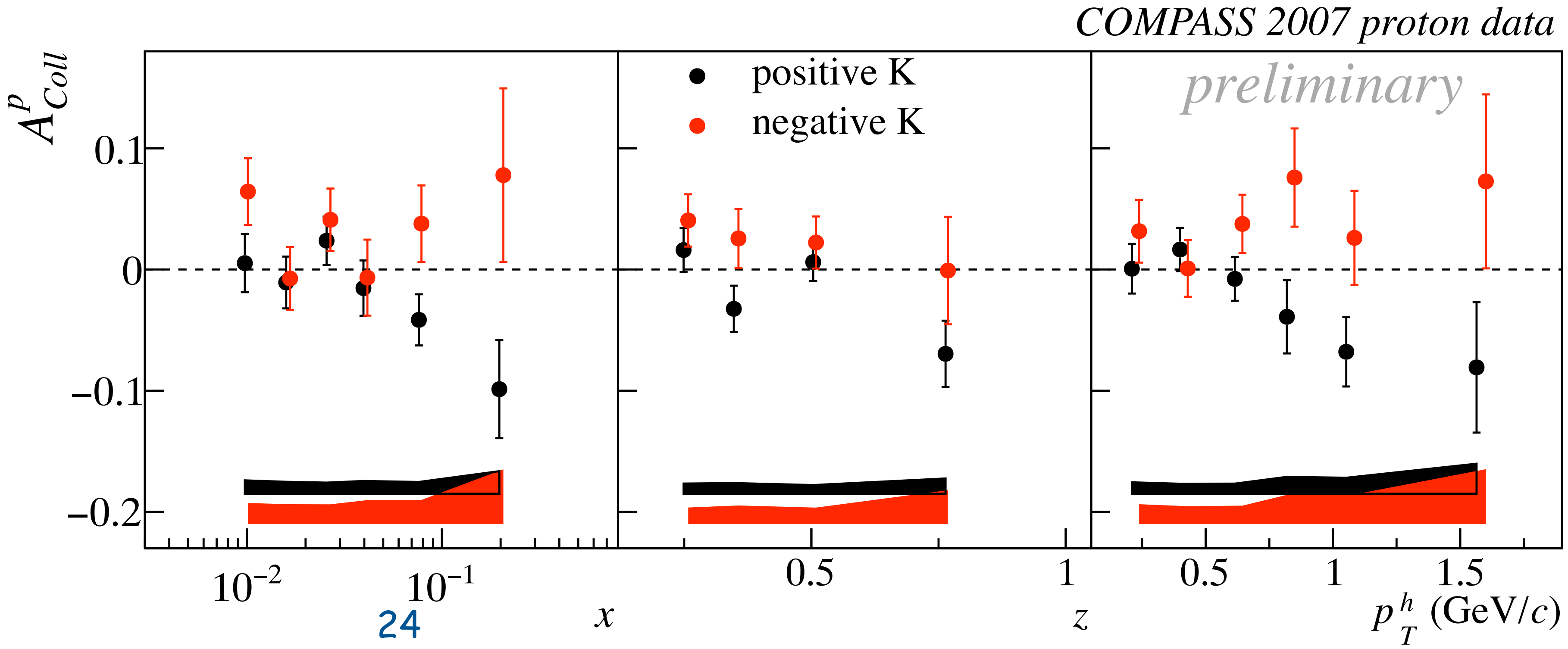
kaon Collins amplitudes

[A. Airapetian et al, PLB 693 (2010) 11]



- similar behavior for pions
- similar behavior for K^+
- different trend for K^-

(opposite sign conventions!)



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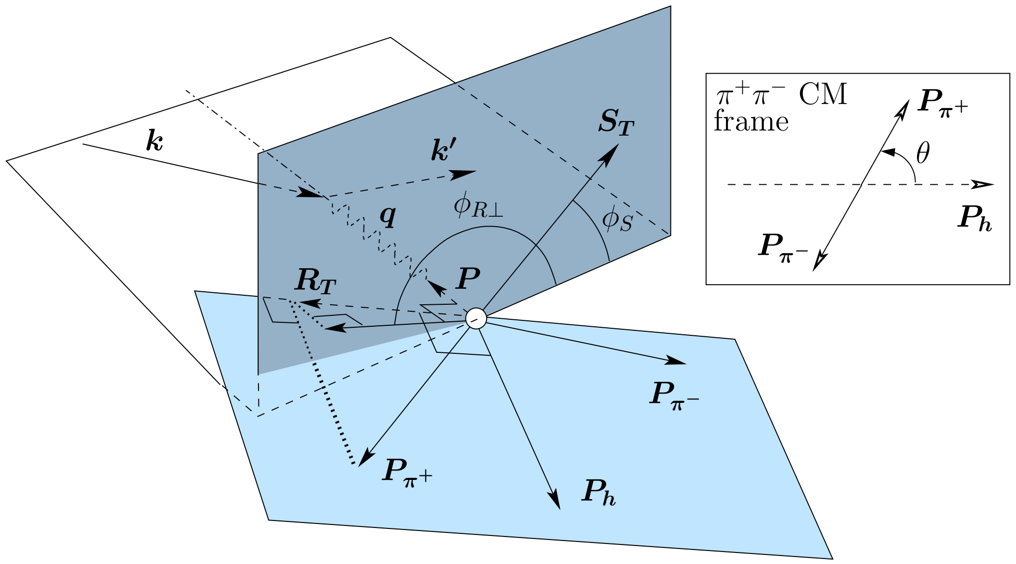
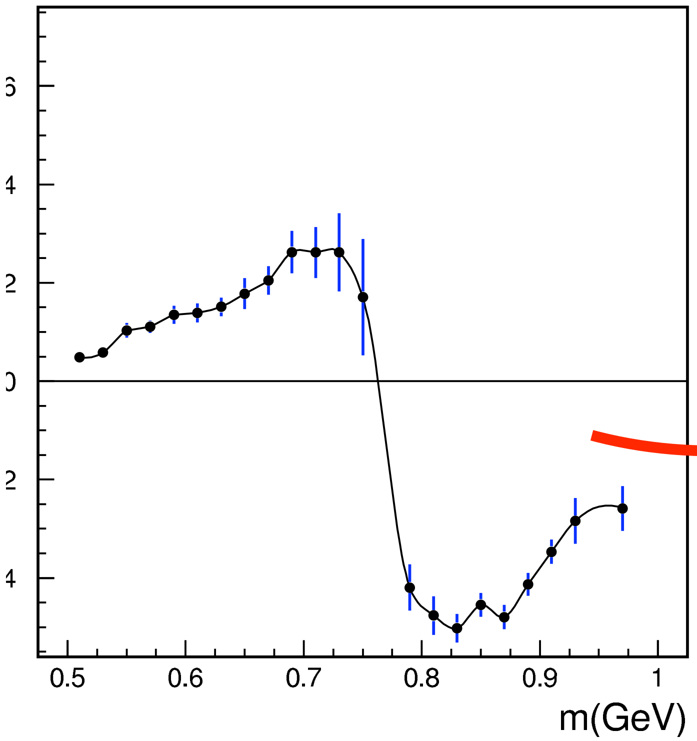
transversity distribution (2-hadron fragmentation)



$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\sin\theta h_1 H_1^{\sphericalangle}$$



Jaffe et al. [**hep-ph/9709322**]:

$$H_1^{\sphericalangle,sp}(z, M^2_{\pi\pi}) = \underline{\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)} H_1^{\sphericalangle,sp'}(z)$$

δ_0 (δ_1) → S(P)-wave phase shifts

$$= \mathcal{P}(M^2_{\pi\pi}) H_1^{\sphericalangle,sp'}(z)$$

$\Rightarrow$ A_{UT} might depend strongly on $M_{\pi\pi}$

	U	L	T
U	f_1		$h_1^\perp$
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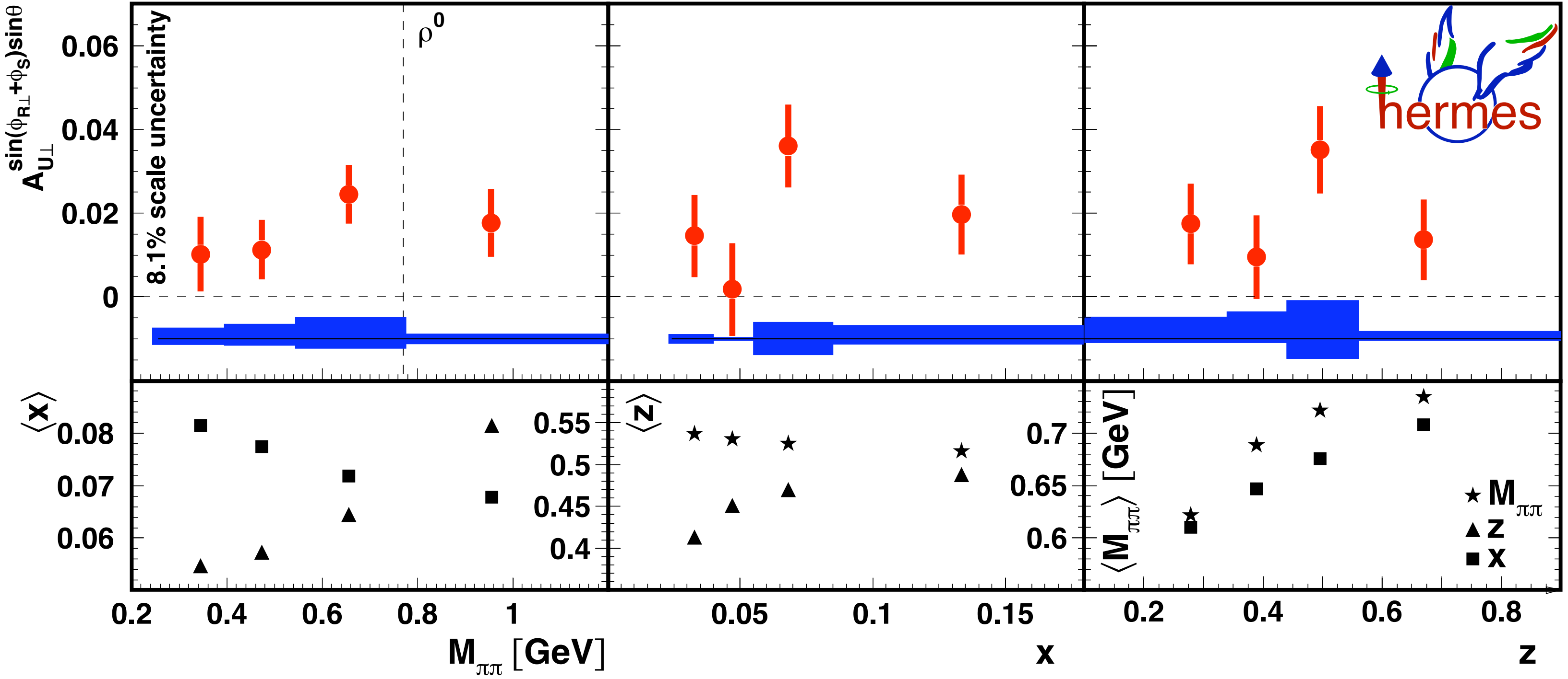
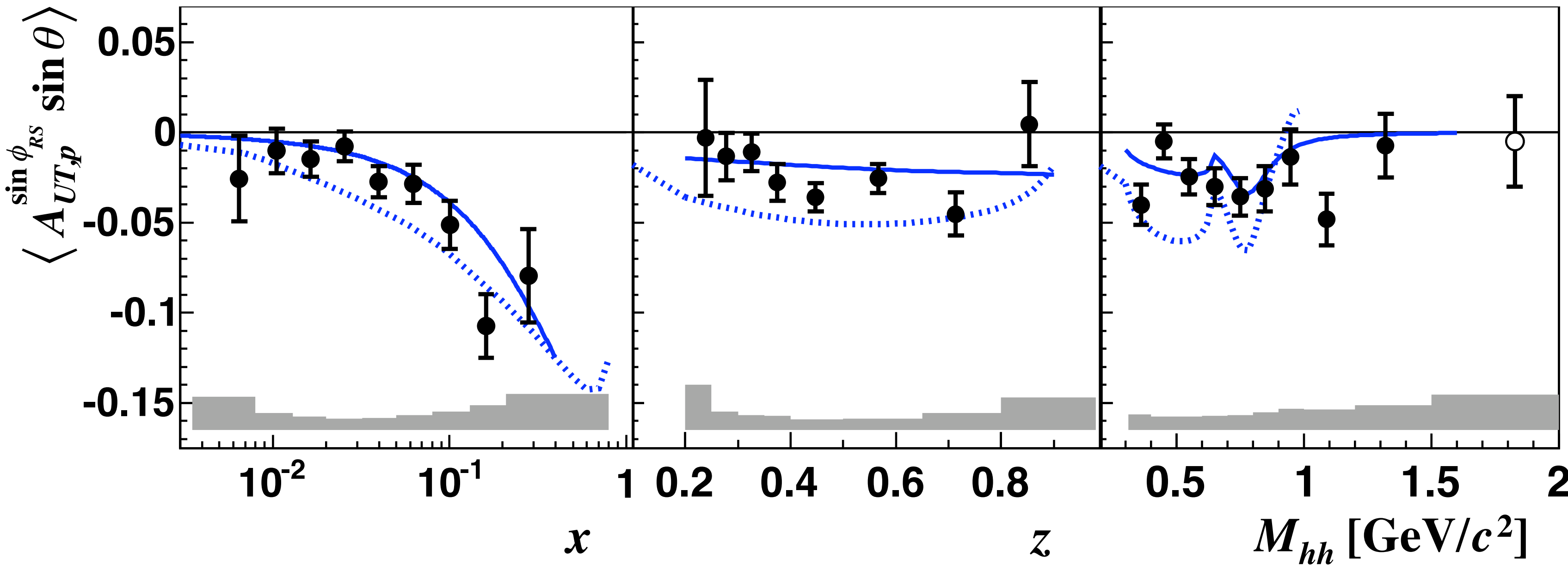
transversity distribution (2-hadron fragmentation)

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



[C. Adolph et al., PLB 713 (2012) 10]



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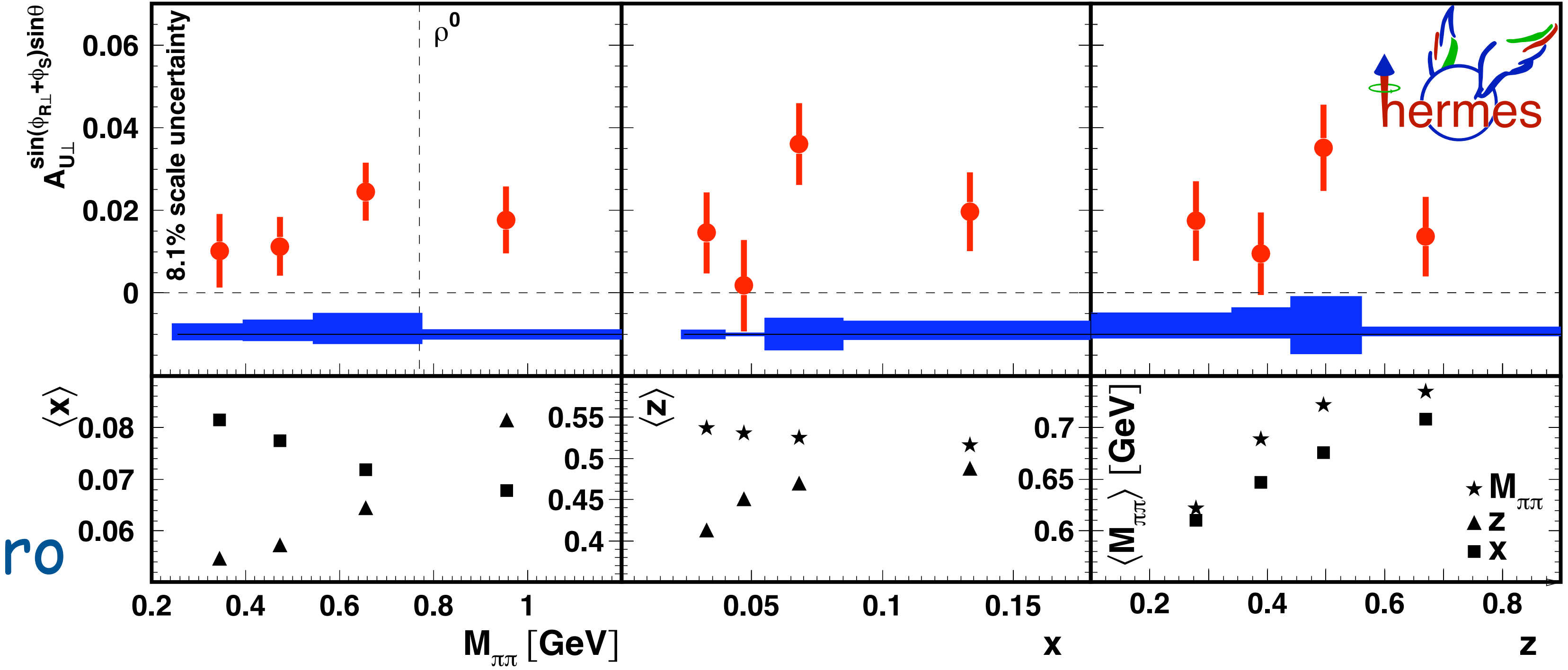
transversity distribution (2-hadron fragmentation)

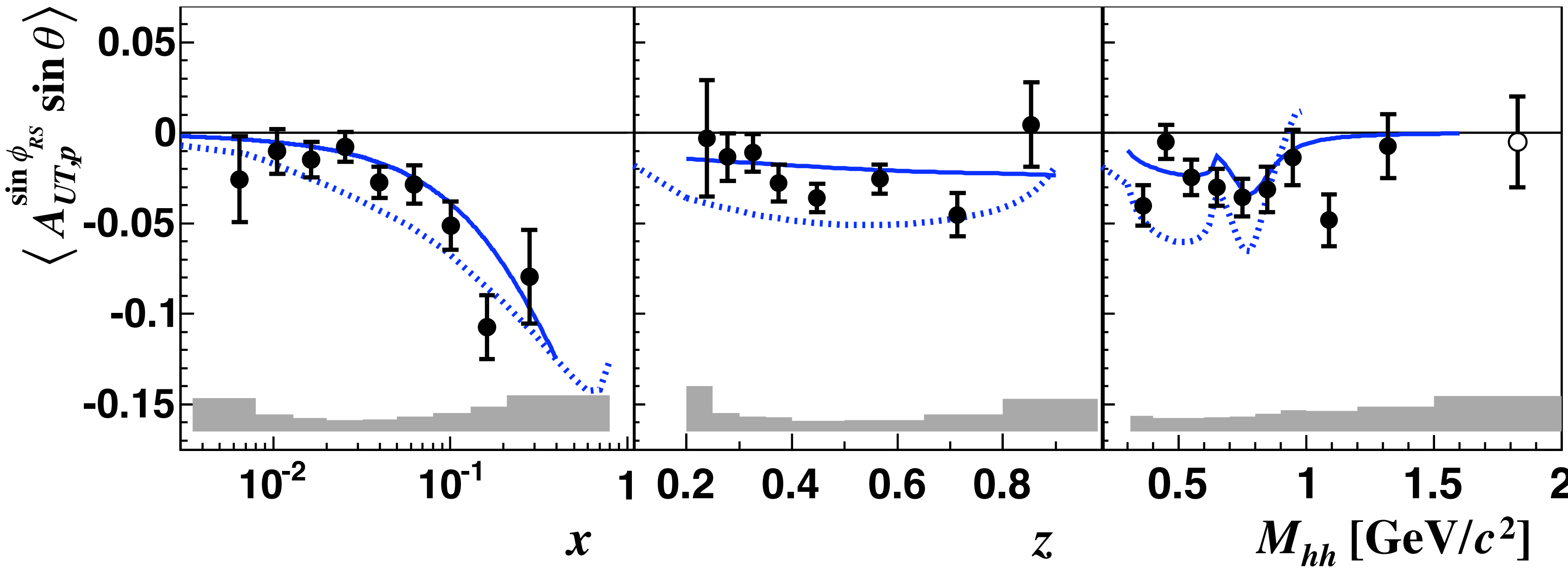
- HERMES: pion pairs
  COMPASS: hadron pairs

  (for comparison need to correct for depolarization factor and sign change)
- ^{2}H results consistent with zero

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



[C. Adolph et al., PLB 713 (2012) 10]



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

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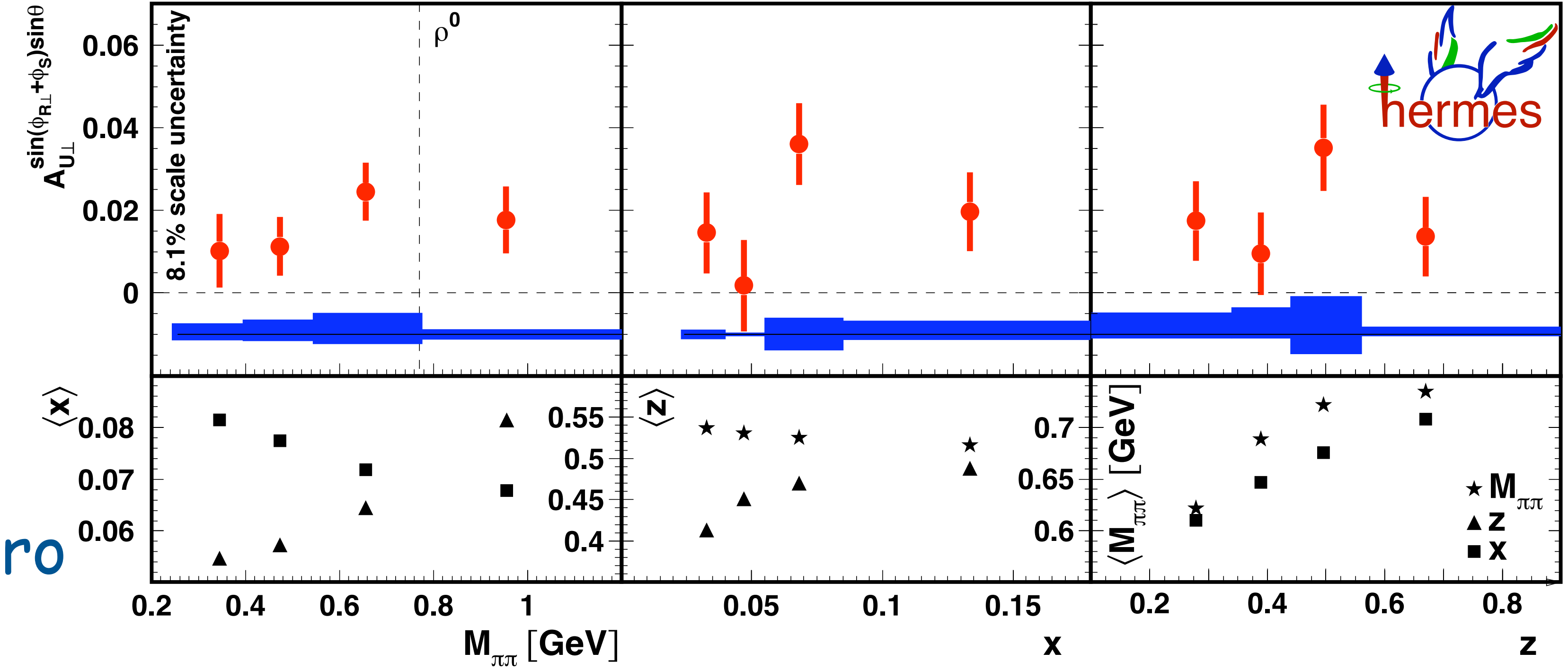

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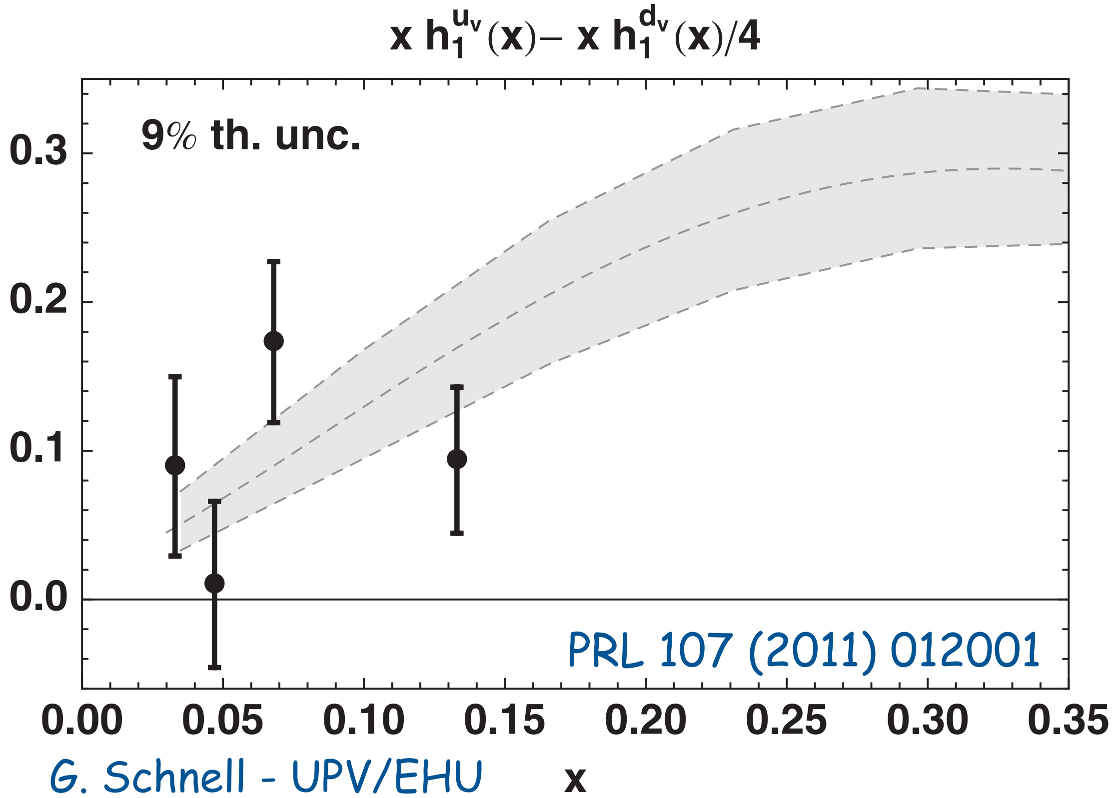
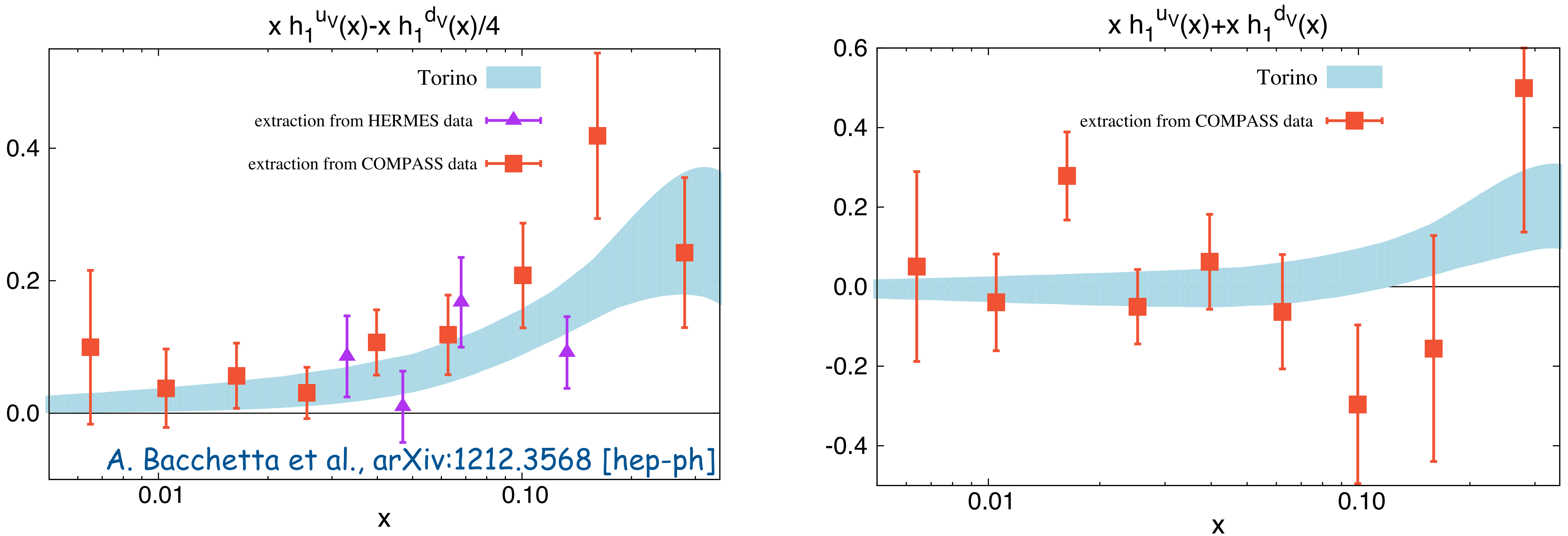


- results from e$^+$e$^-$ by BELLE allow **first (collinear) extraction of transversity** (compared to Anselmino et al.)

transversity extraction

- combining SIDIS (COMPASS & HERMES) and e^+e^- data (BELLE):



- promising agreement between collinear and TMD extraction of transversity
- no obvious sign of difference in TMD (Collins) from collinear (dihadron) FF evolution

	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

- chiral-odd ➥ needs Collins FF (or similar)
- leads to $\sin(3\phi - \phi_s)$ modulation in A_{UT}
- proton and deuteron data consistent with zero
- cancelations? pretzelosity=zero?
  or just the additional suppression by two powers of $P_{h\perp}$

	U	L	T
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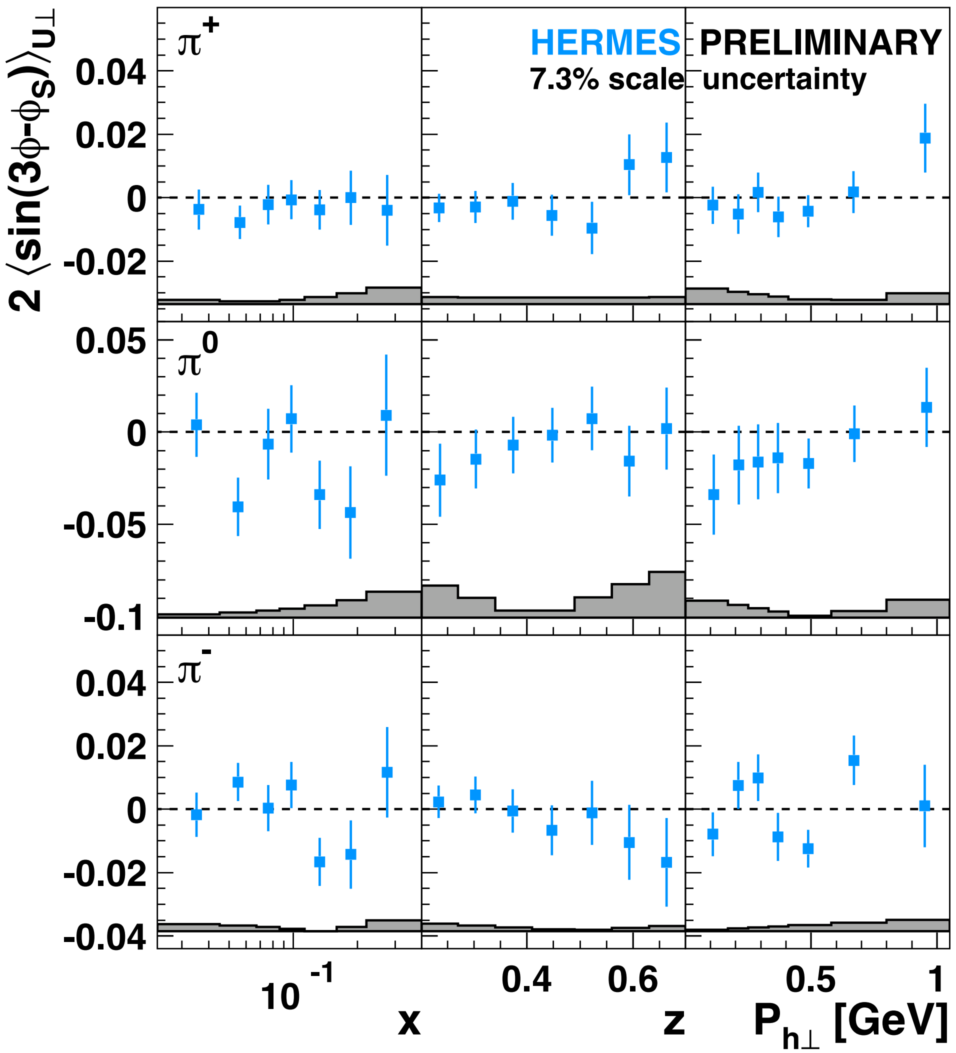

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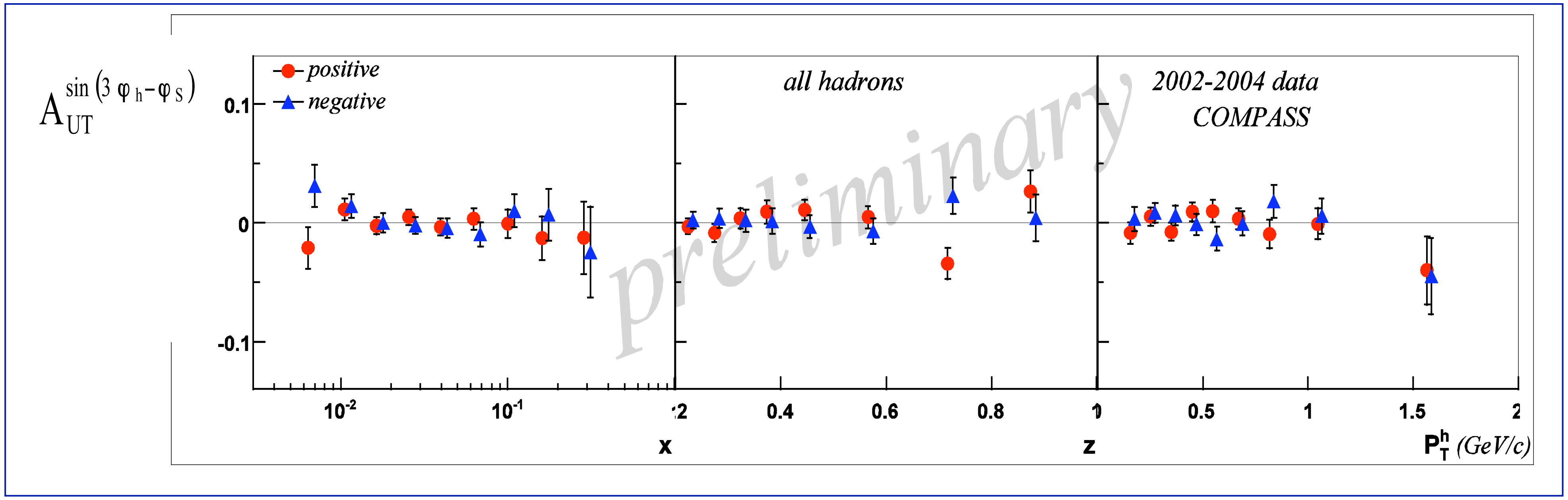
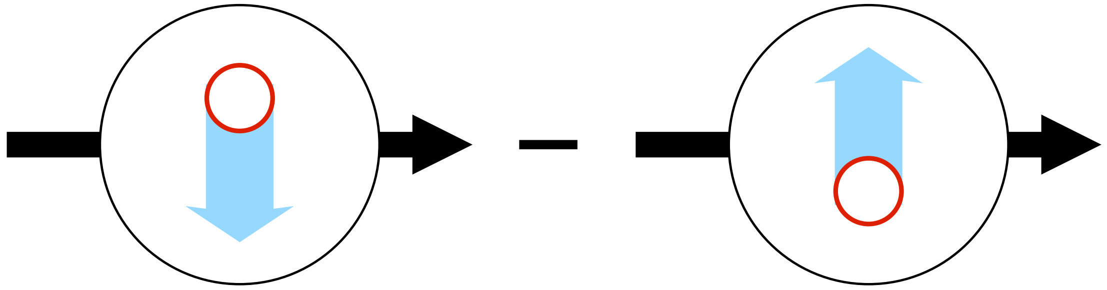
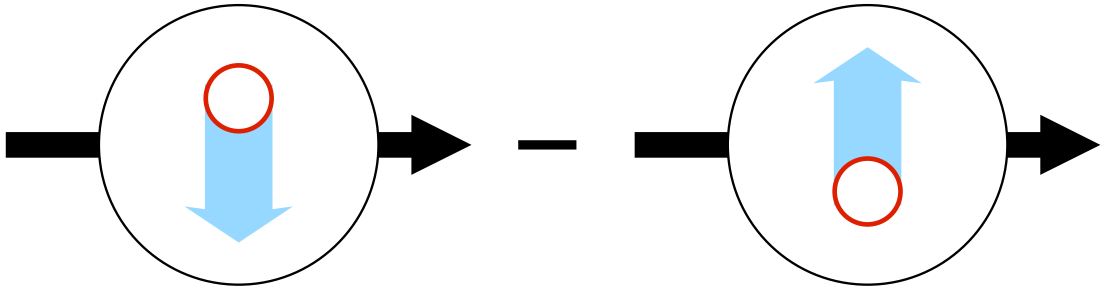




Sivers effect

naively T-odd distributions

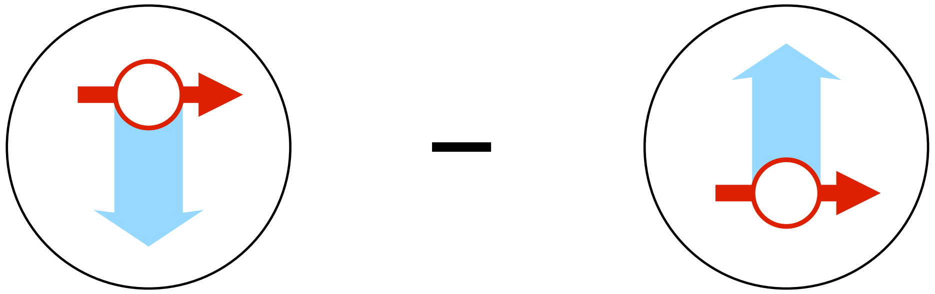
"Wilson-line physics"



Sivers effect

naively T-odd distributions
“Wilson-line physics“

Boer-Mulders effect



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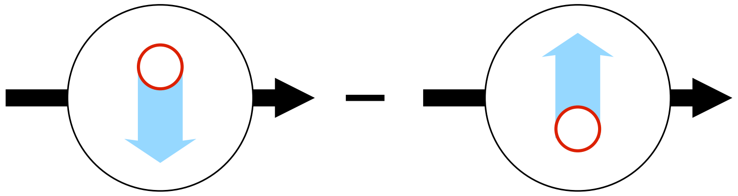
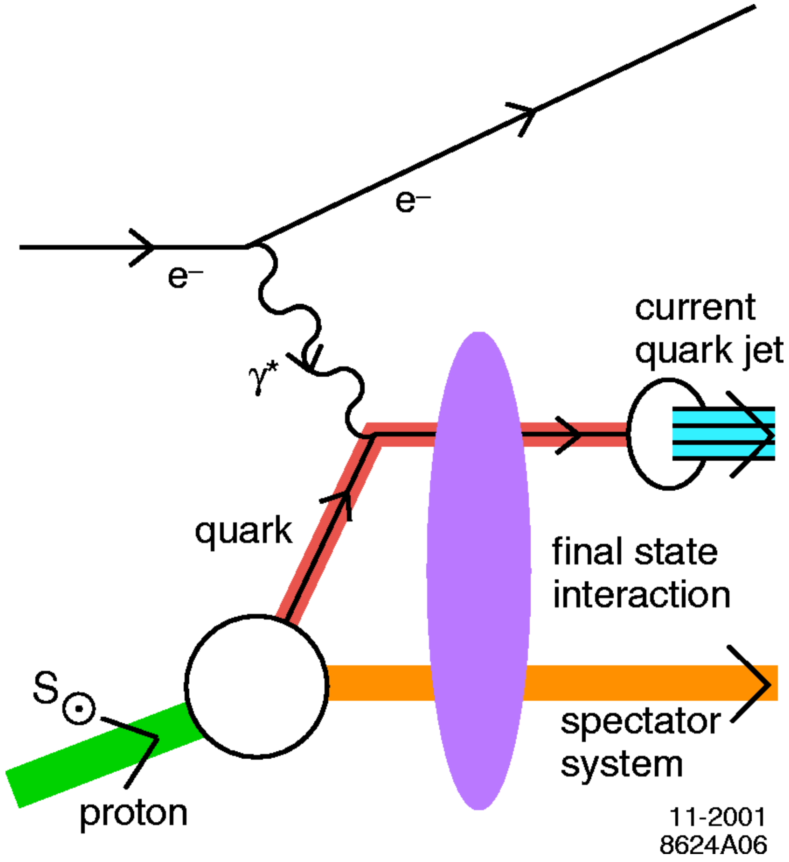


Sivers function

- naive T-odd
- requires FSI via non-perturbative gluon exchange(s) (“Wilson line”)
- leads to opposite sign in DIS and Drell-Yan (firm QCD prediction!)
- relation to GPD E + FSI yields opposite signs of Sivers fct. for up and down quarks



[S. Brodsky et al., Phys. Lett. B530, 99 (2002)]

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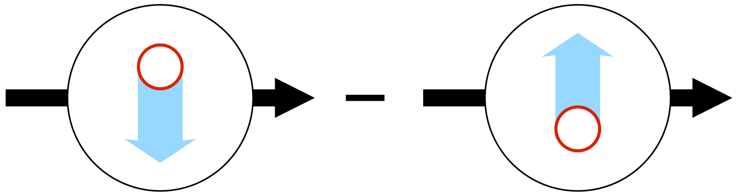

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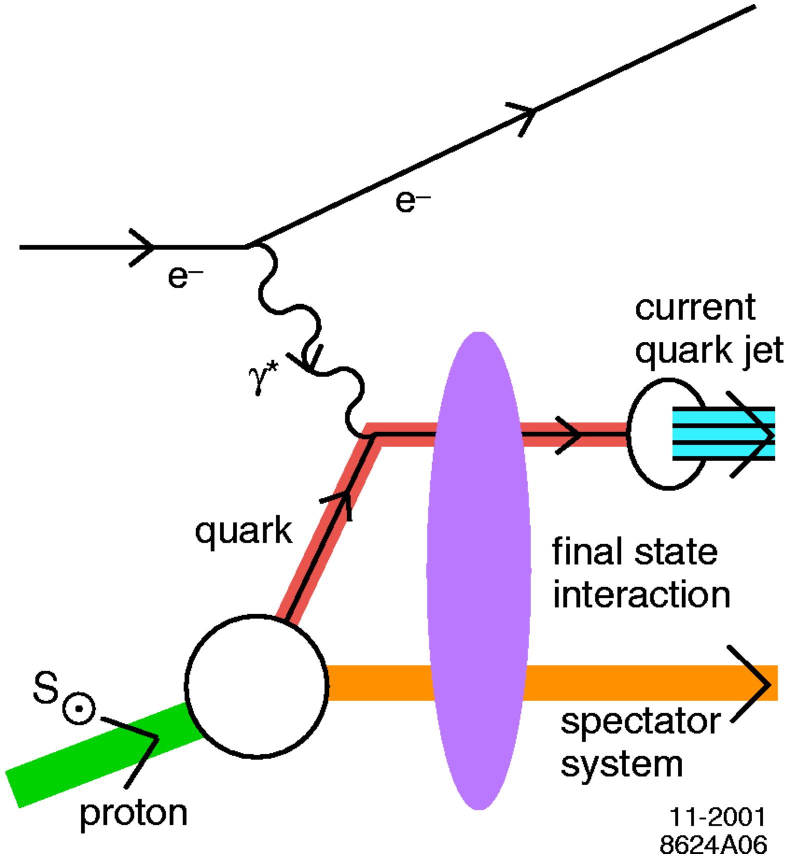

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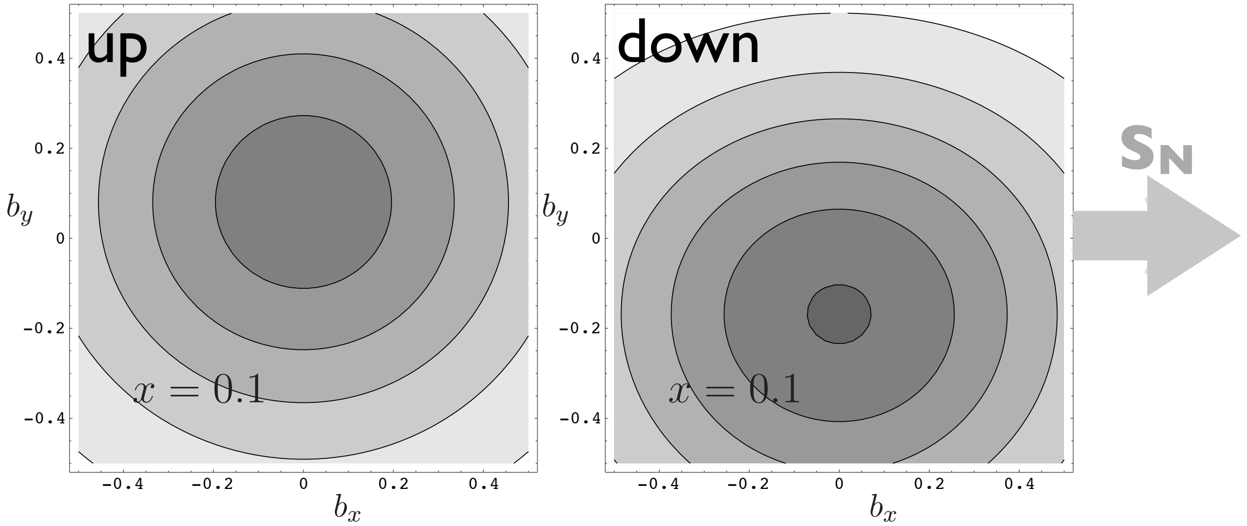

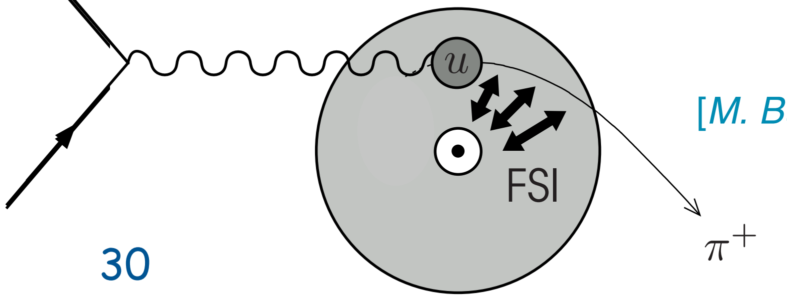

[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]

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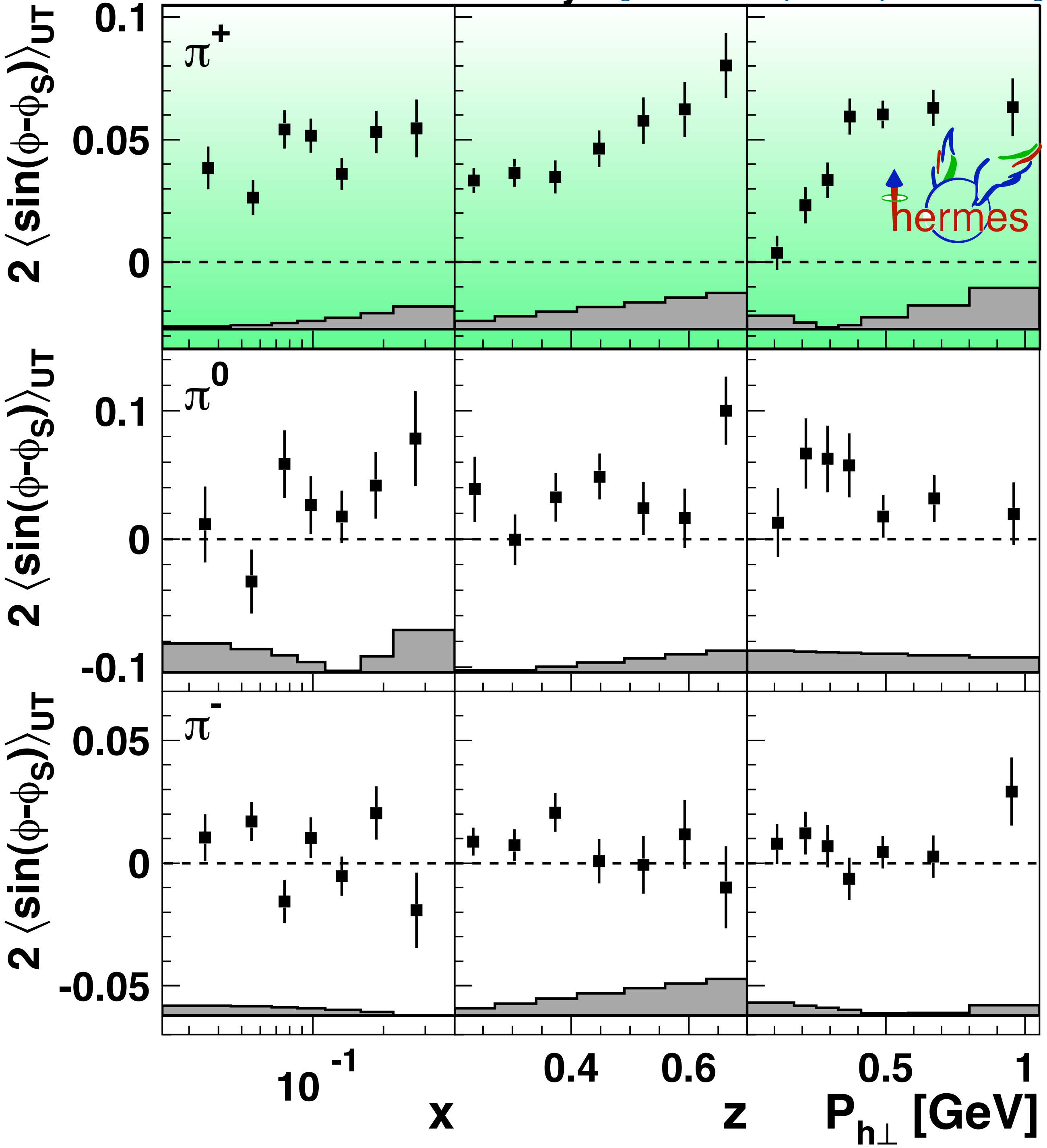
Sivers amplitudes for pions

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

7.3% scale uncertainty

[PRL 103 (2009) 152002]



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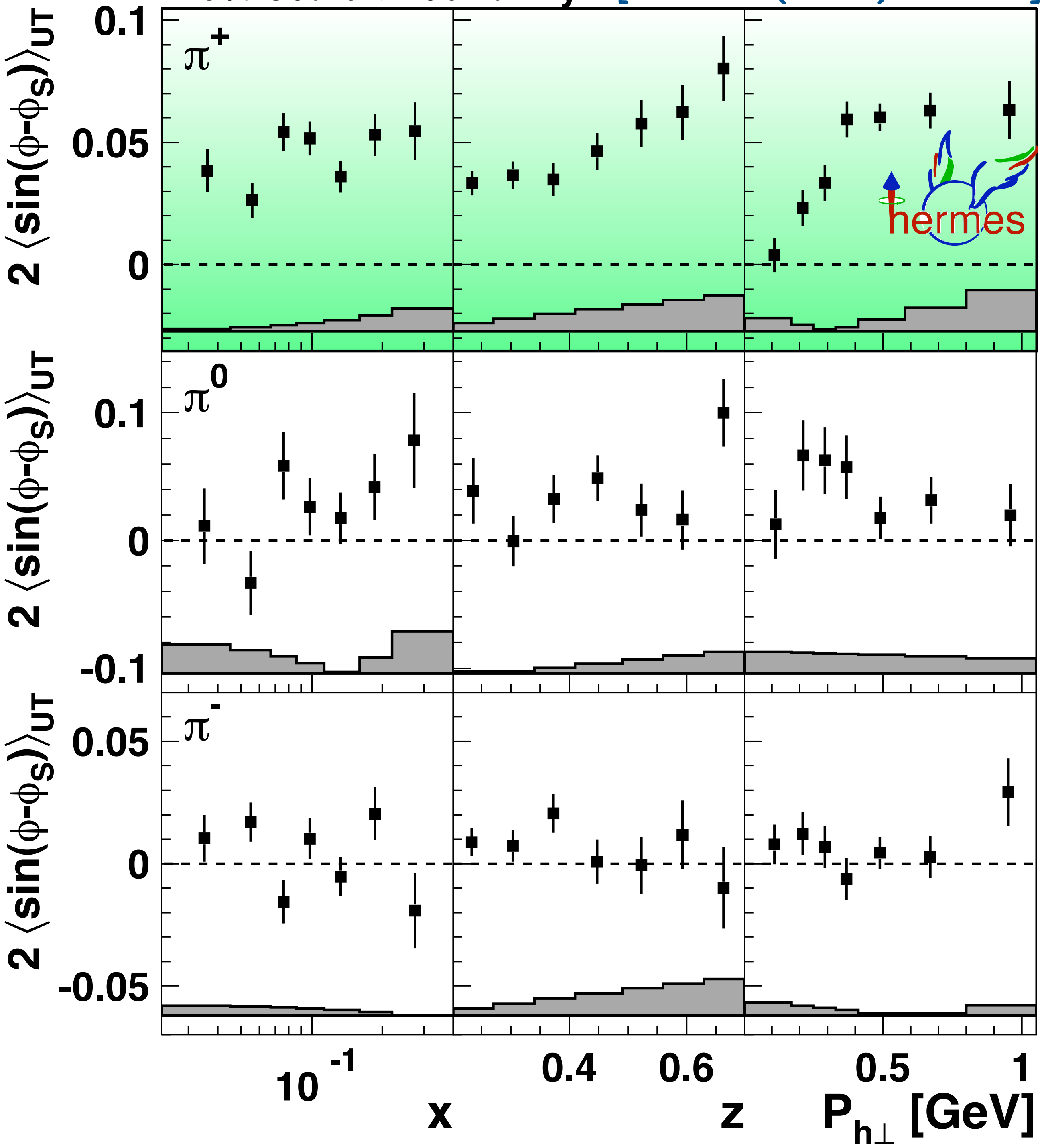

π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

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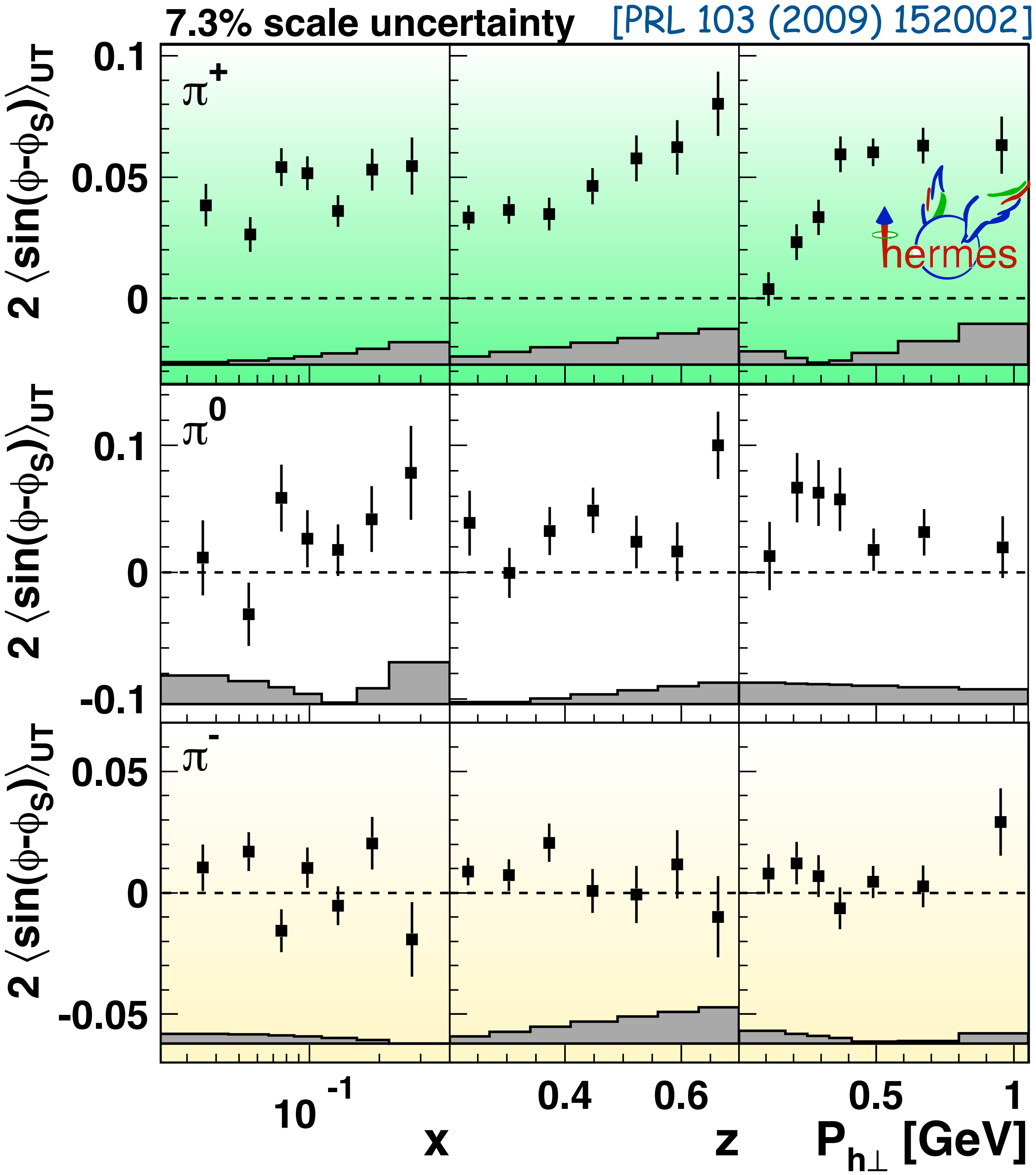
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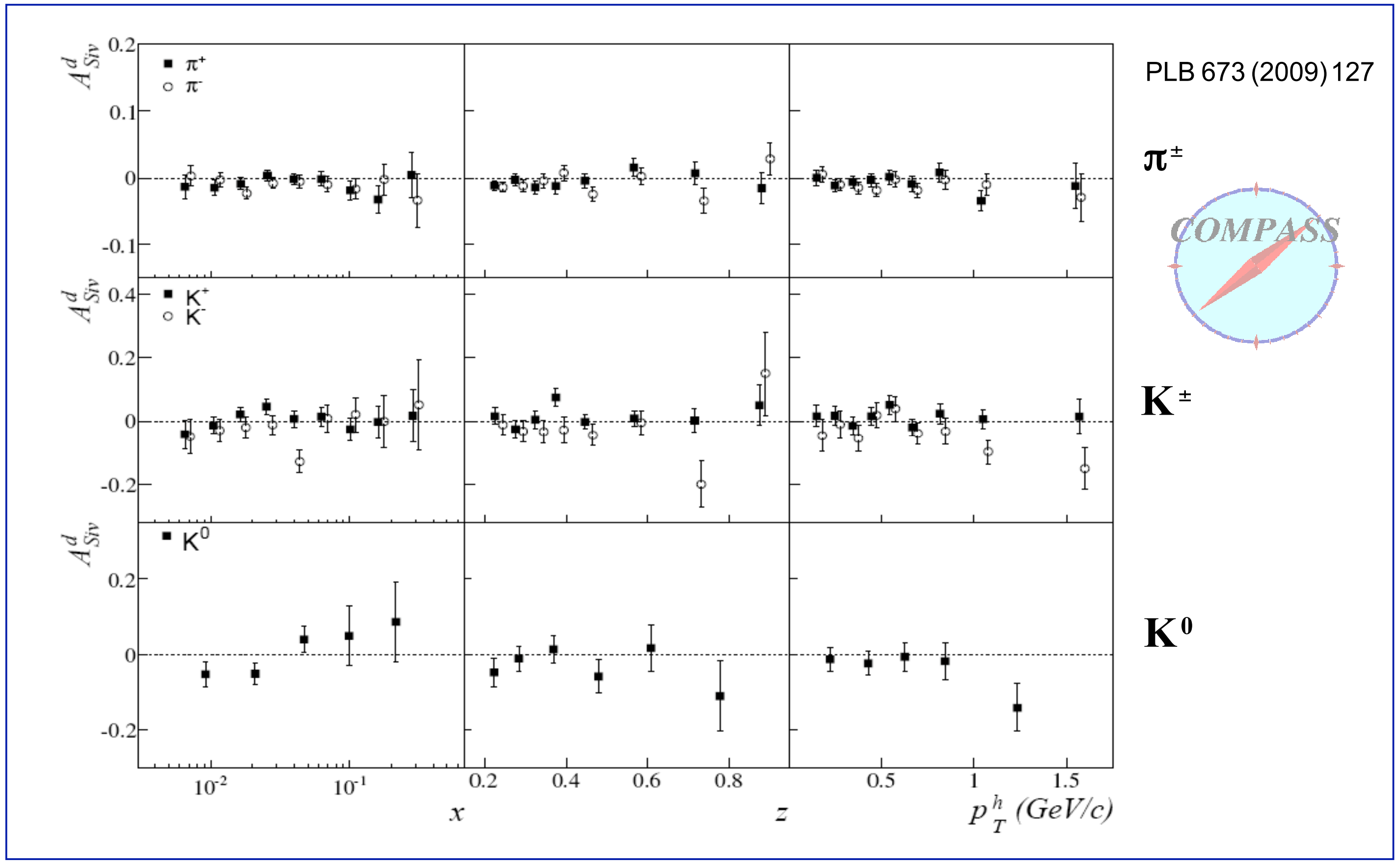
- ☛ u-quark Sivers DF < 0

- ☛ 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 function

- cancelation for D target supports opposite signs of up and down Sivers



PLB 673 (2009) 127

	U	L	T
U	f_1		$h_1^\perp$
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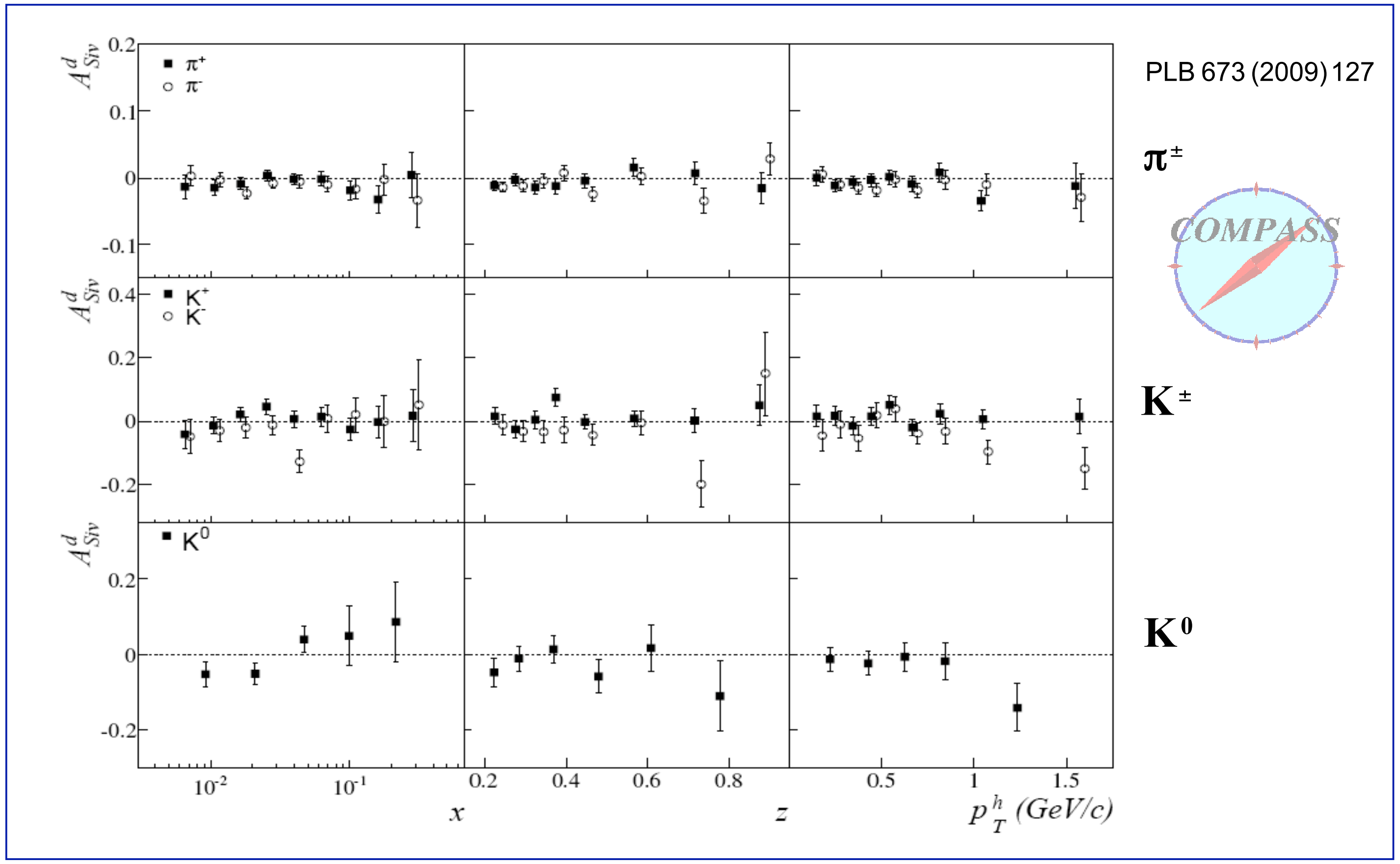

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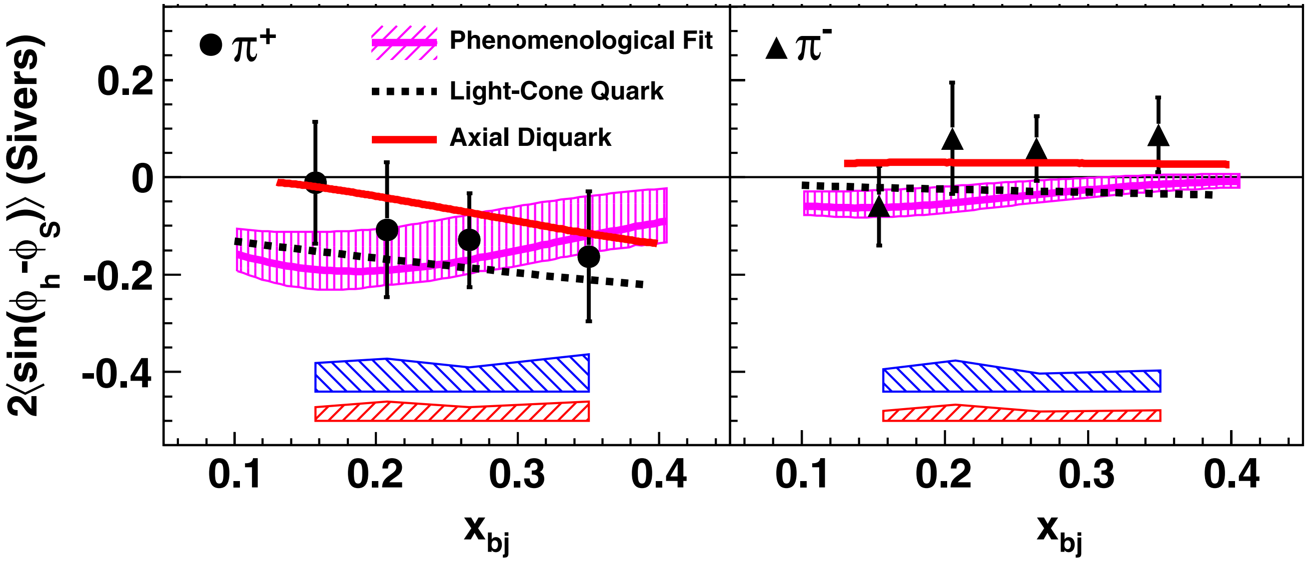
- new results from JLab using ^{3}He target and from COMPASS for proton target

[PRL 107 (2011) 072003]



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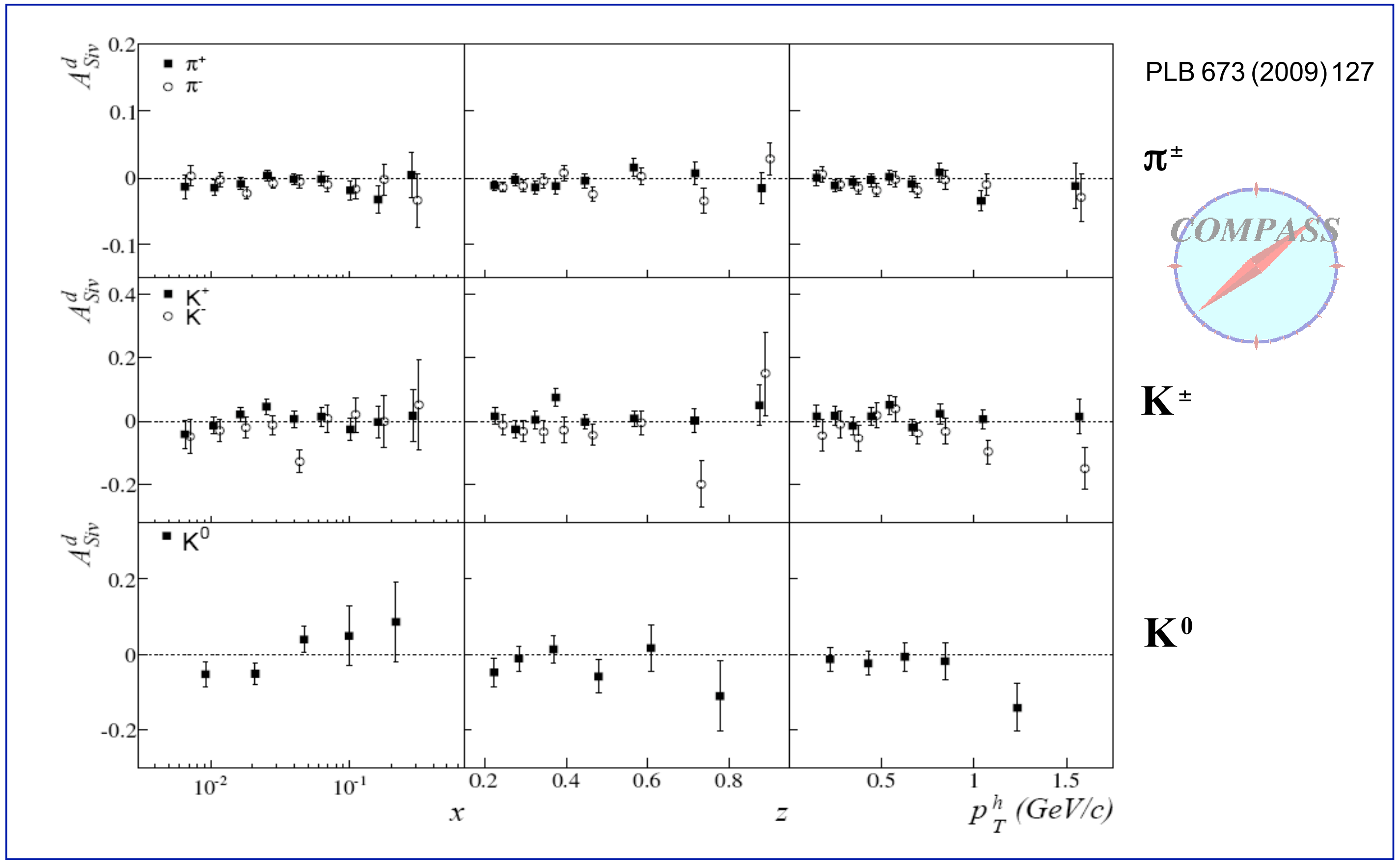
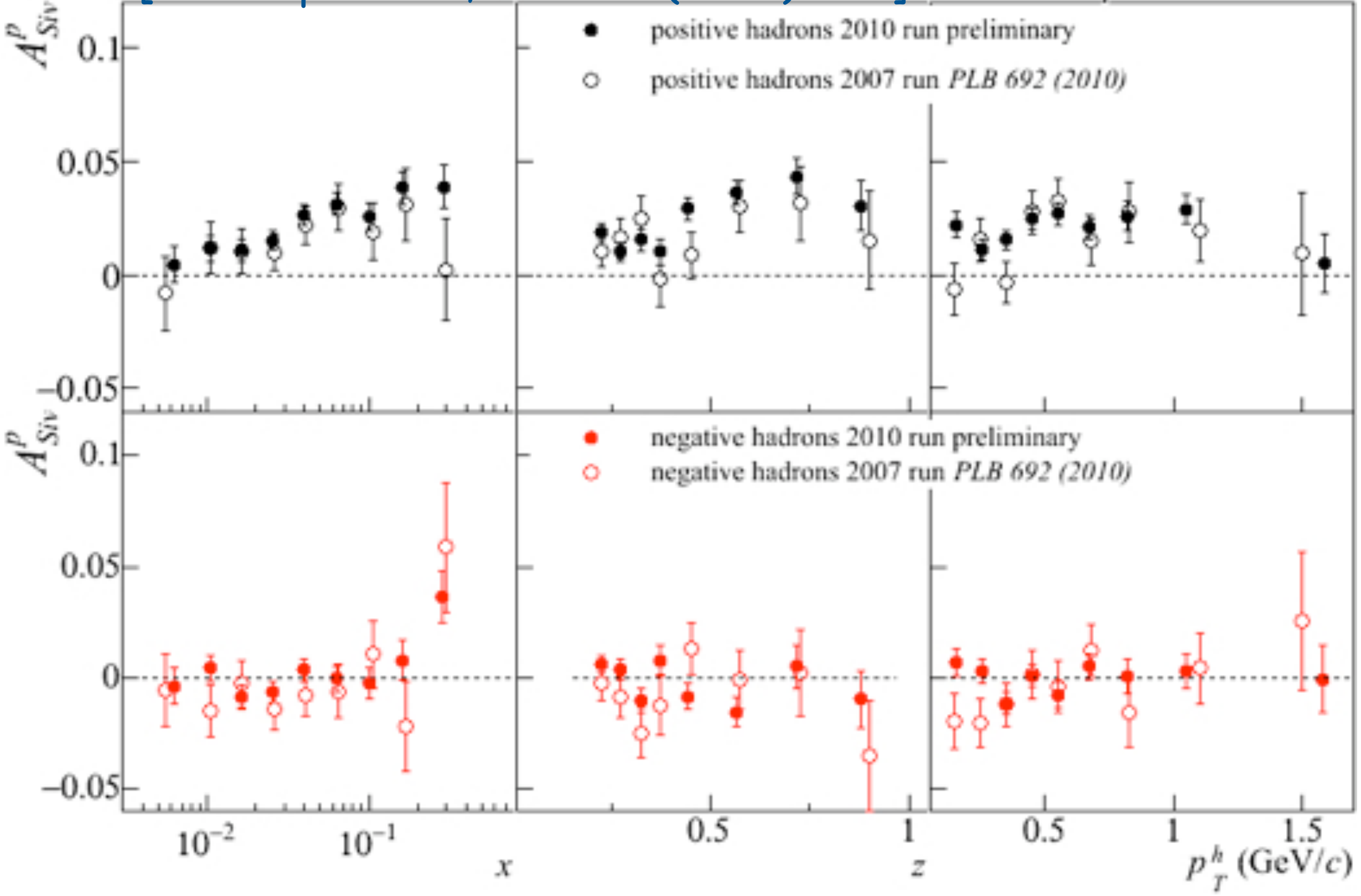


[C. Adolph et al., PLB 717 (2012) 383]



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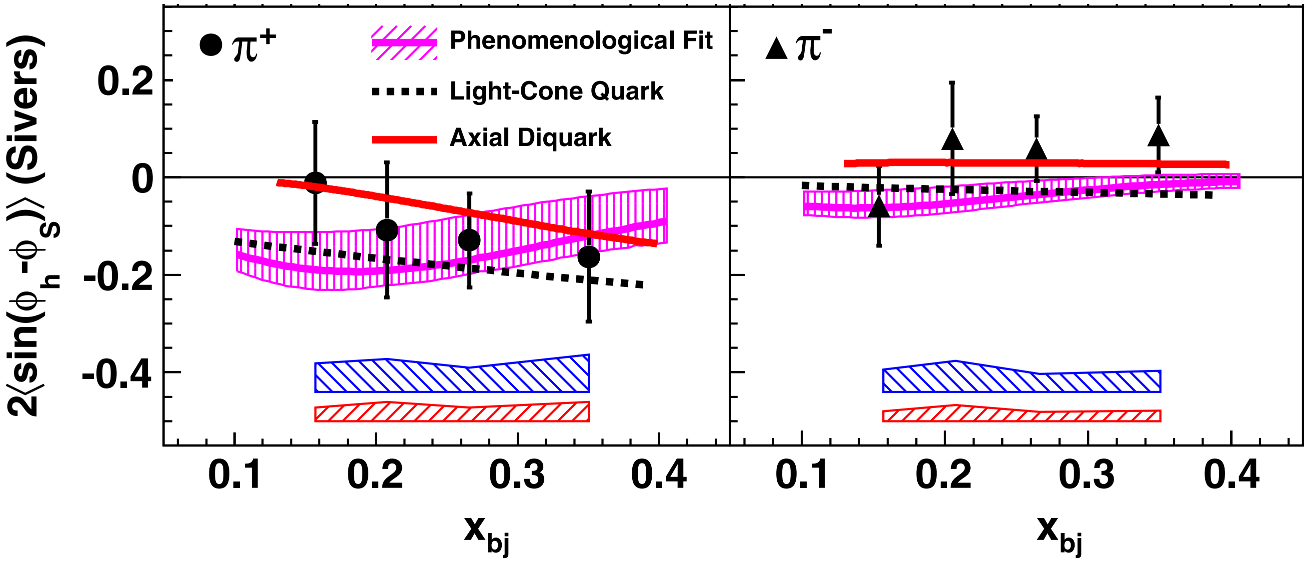

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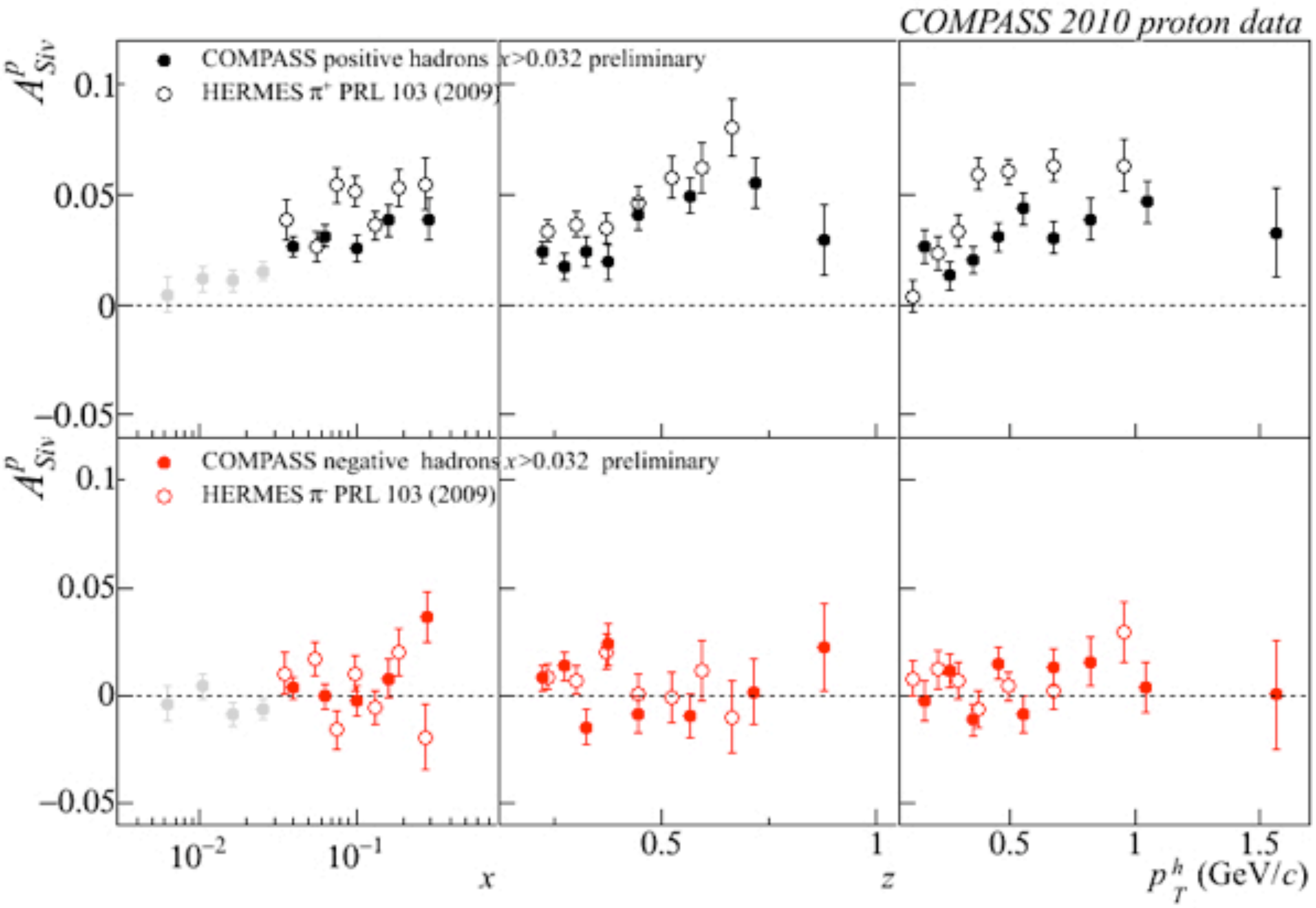
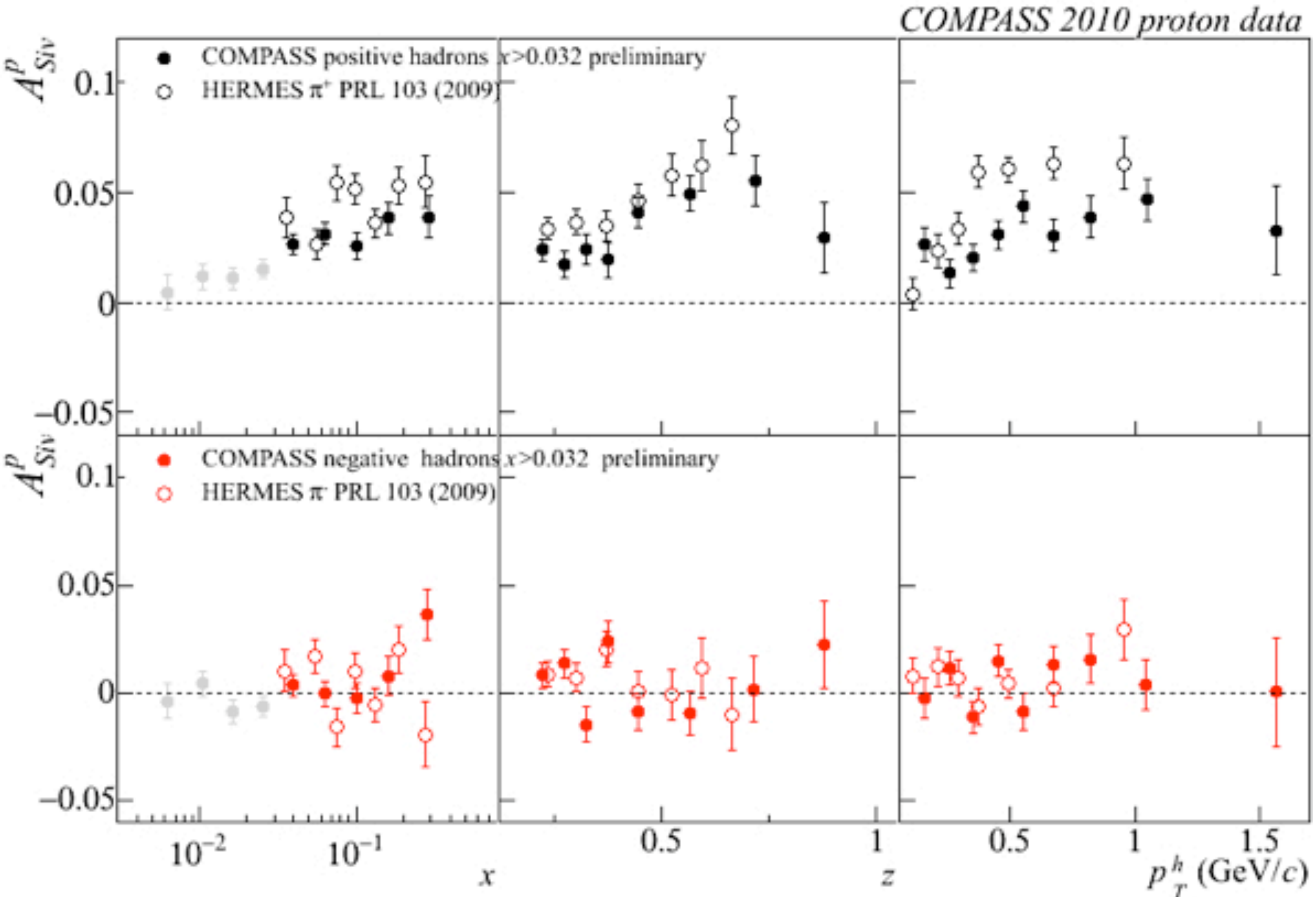
Sivers amplitudes



smaller h^+ amplitudes seen by COMPASS

	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



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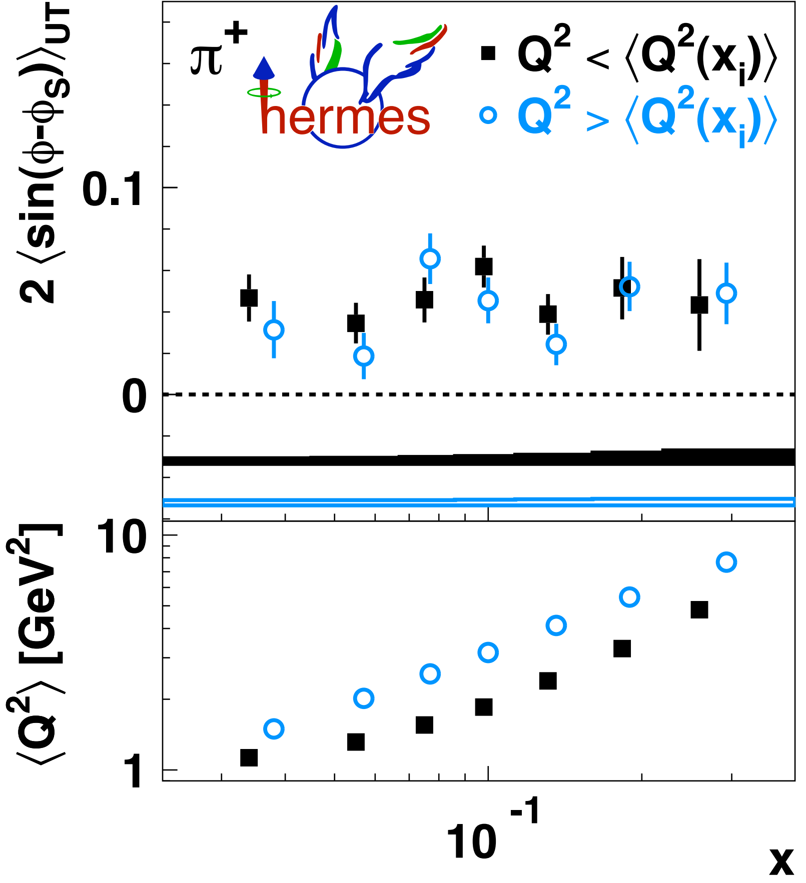

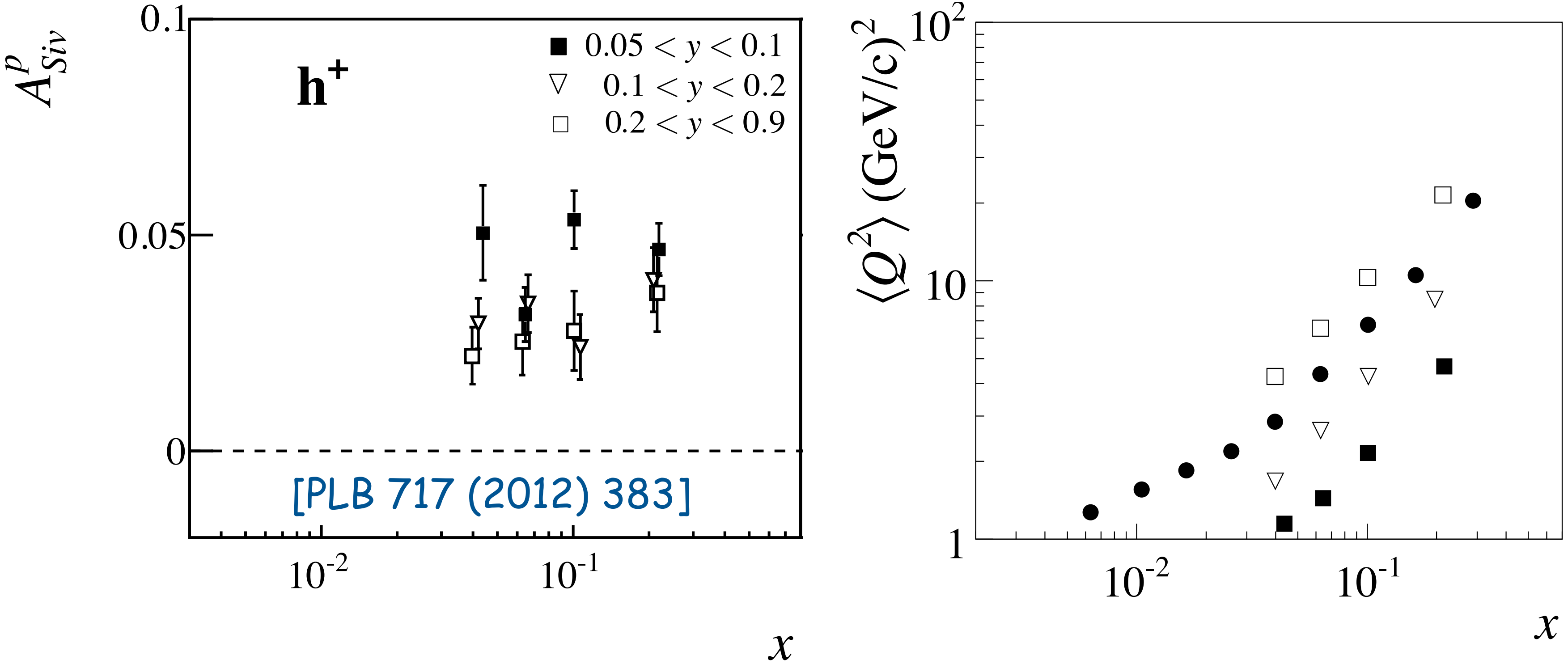

[PLB 717 (2012) 383]

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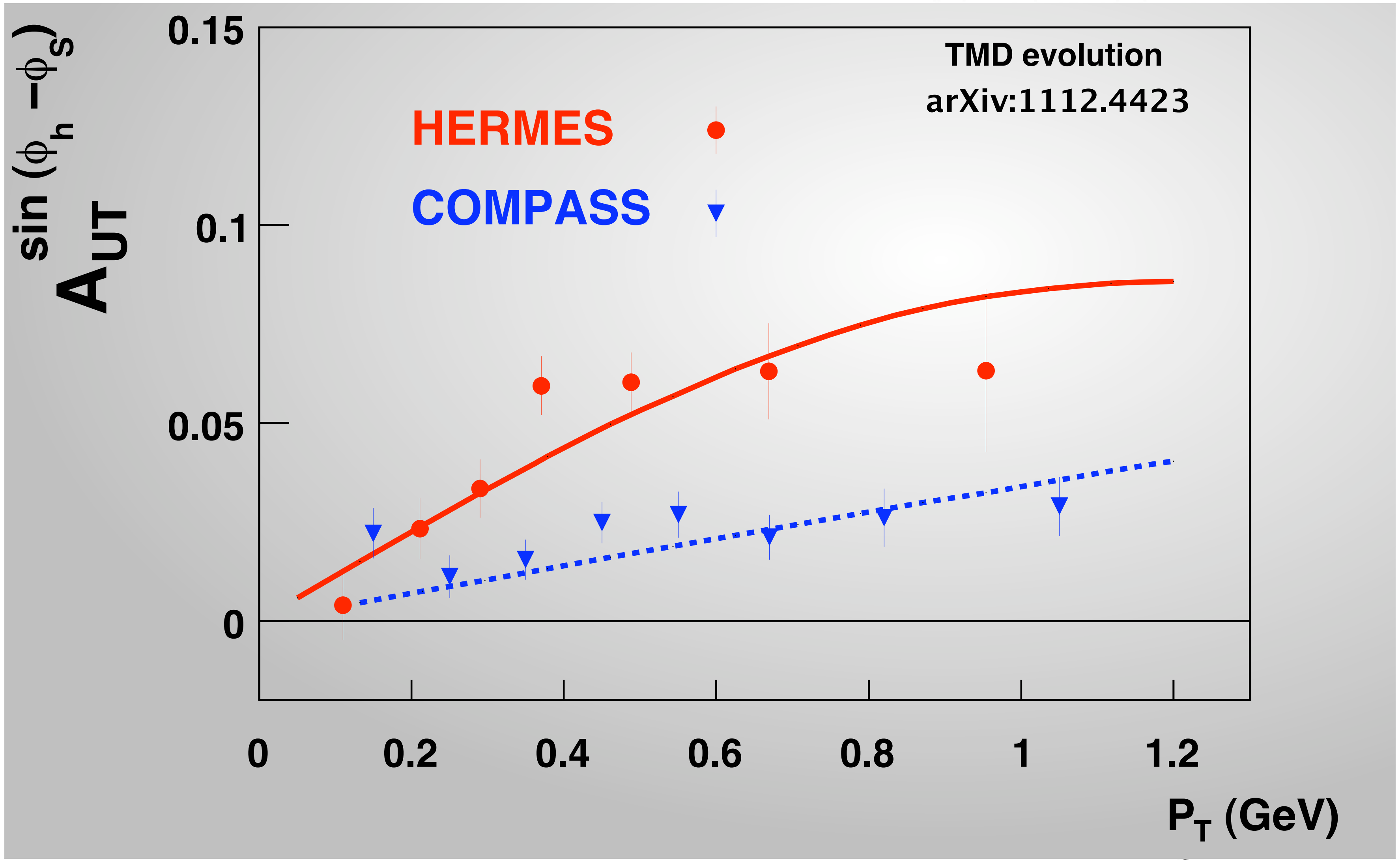
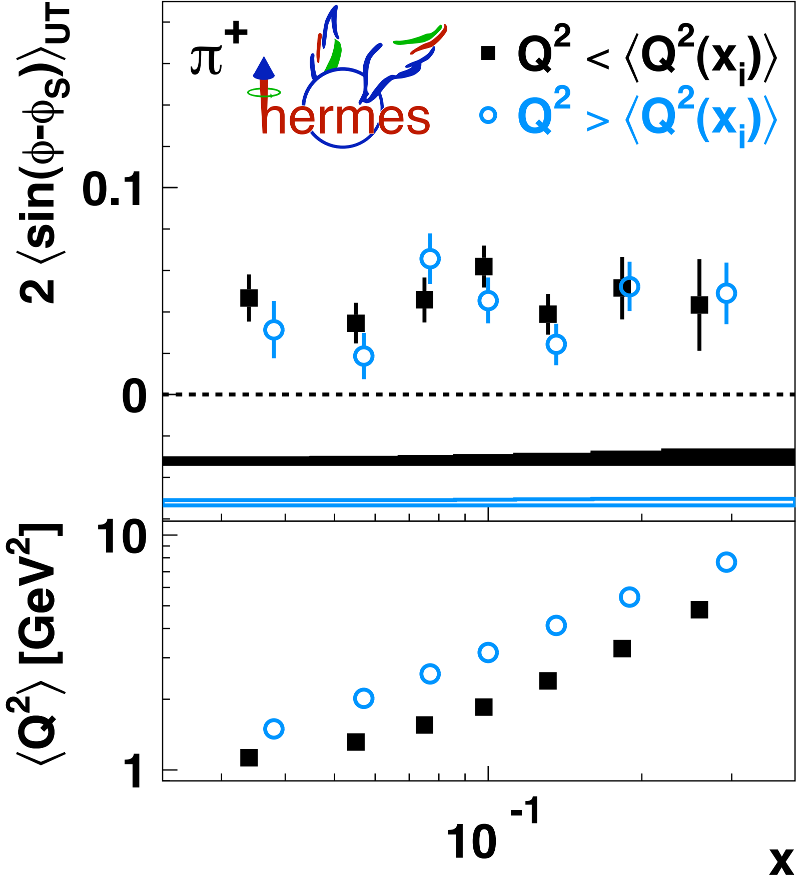
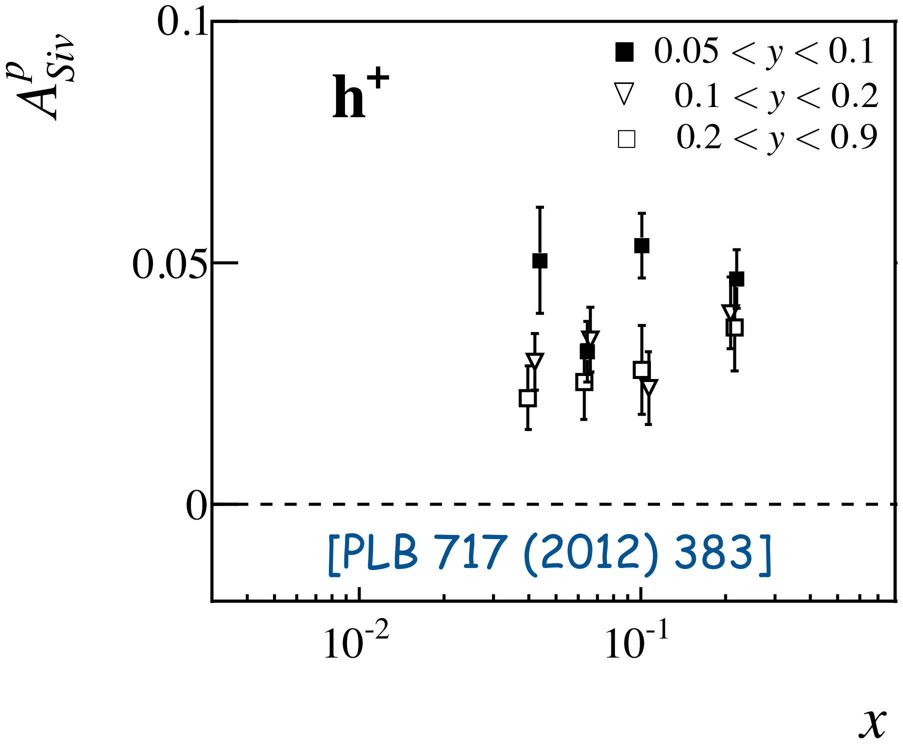


TMD evolution arXiv:1112.4423

difference from evolution?

[PRL 103 (2009) 152002]





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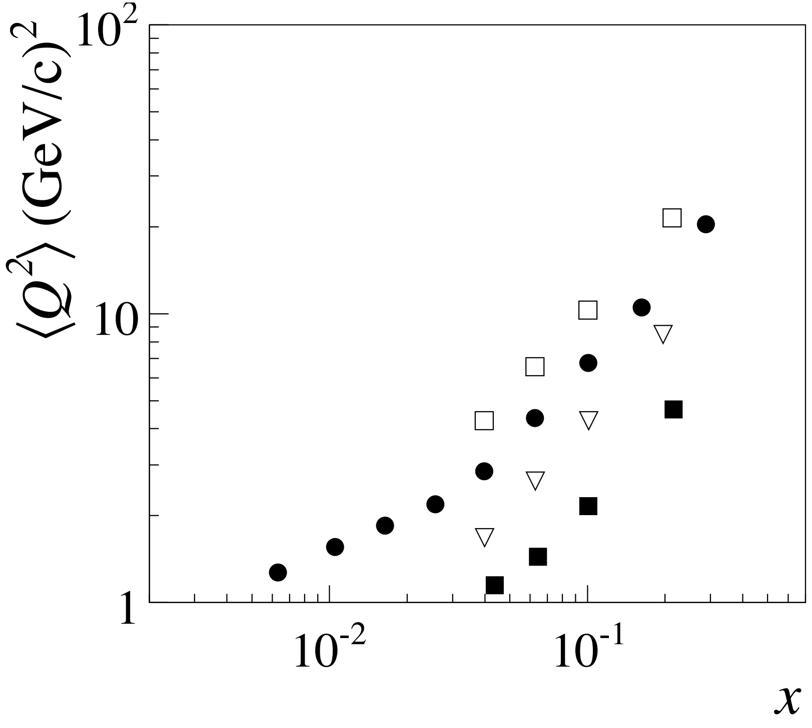
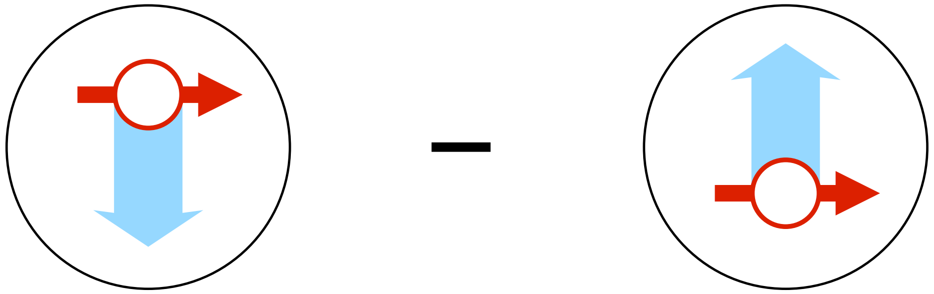


Boer-Mulders

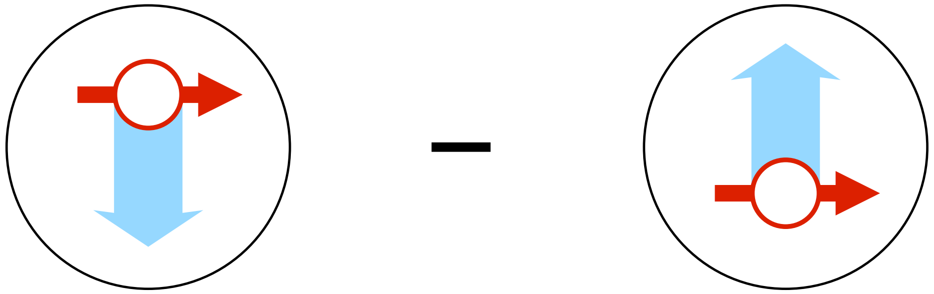
the other naive-T-odd distribution



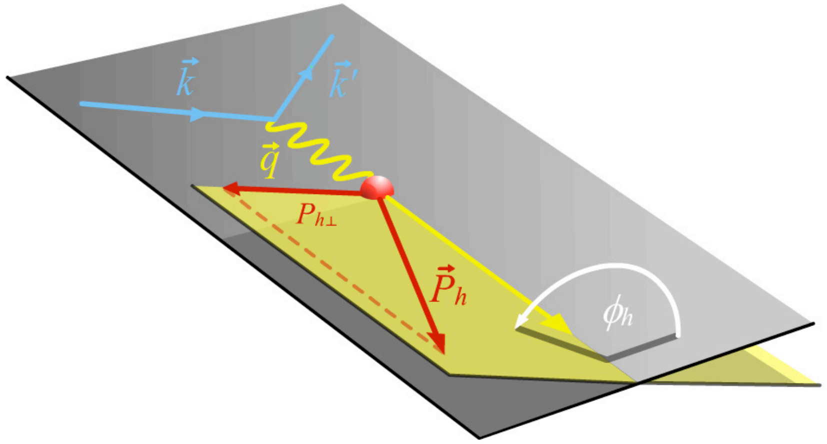
spin effects in unpolarized reactions

Boer-Mulders

the other naive-T-odd distribution

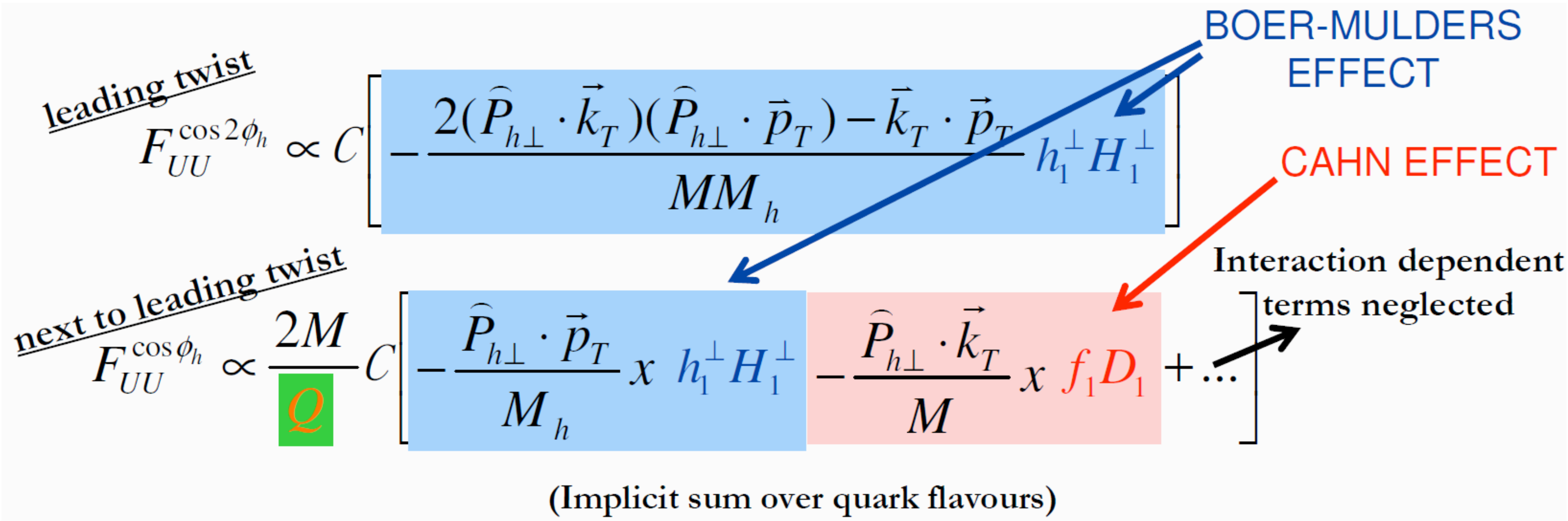


Modulations in spin-independent SIDIS cross section



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

$$+C(y)\cos\phi_h\,F_{\mathrm{UU}}^{\cos\phi_h} + B(y)\cos 2\phi_h\,F_{\mathrm{UU}}^{\cos 2\phi_h}\}$$



leading twist

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

BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

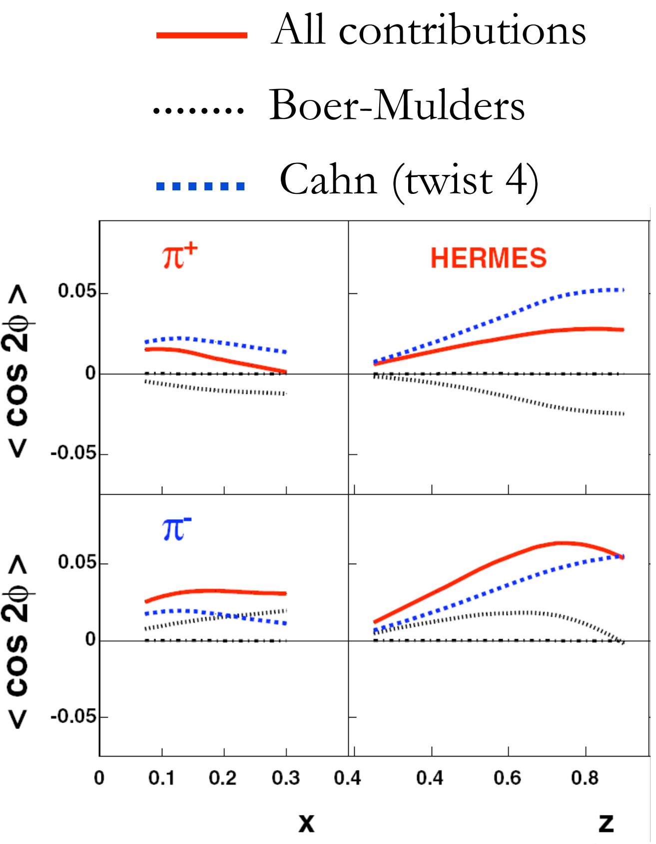
next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}\,C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\,x\;h_1^{\perp}H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\,x\;f_1D_1 + \ldots\right]$$

(Implicit sum over quark flavours)

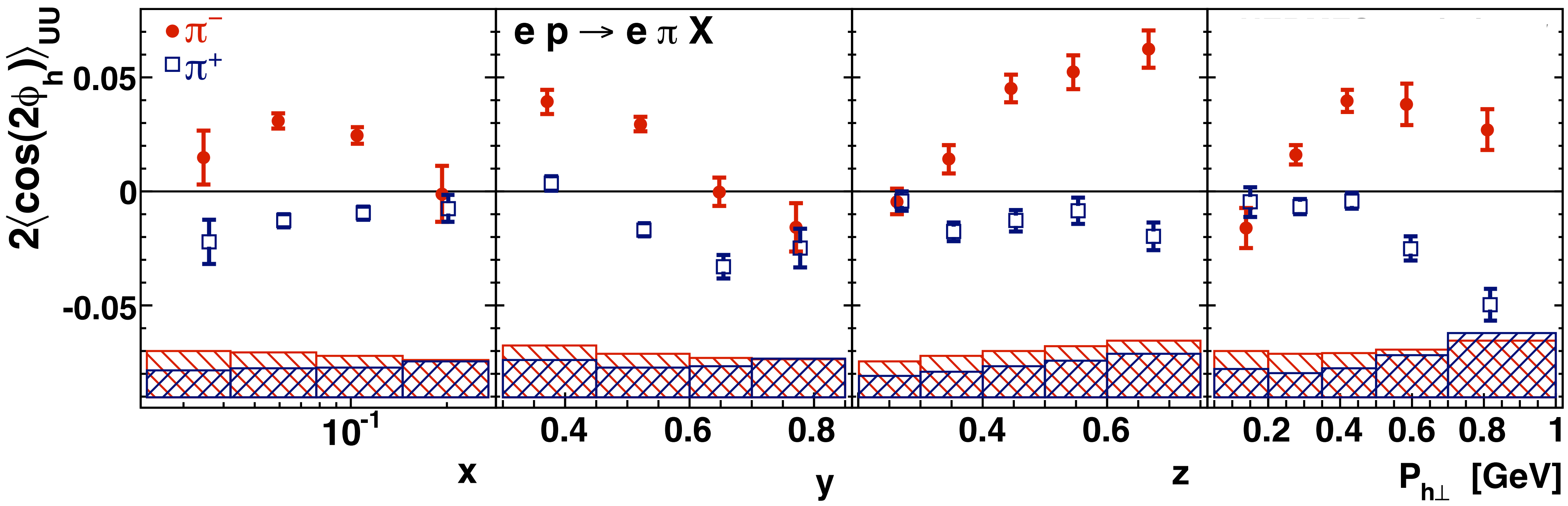
Signs of Boer-Mulders

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



[V. Barone et al., Phys. Rev.D78 (2008) 045022]

[Airapetian et al., PRD 87 (2013) 012010]



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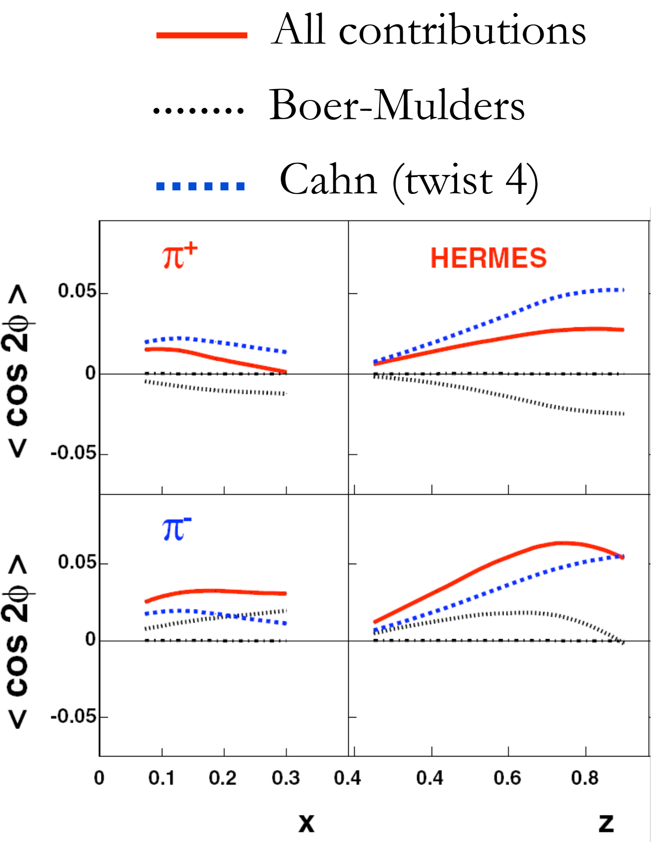
Signs of Boer-Mulders



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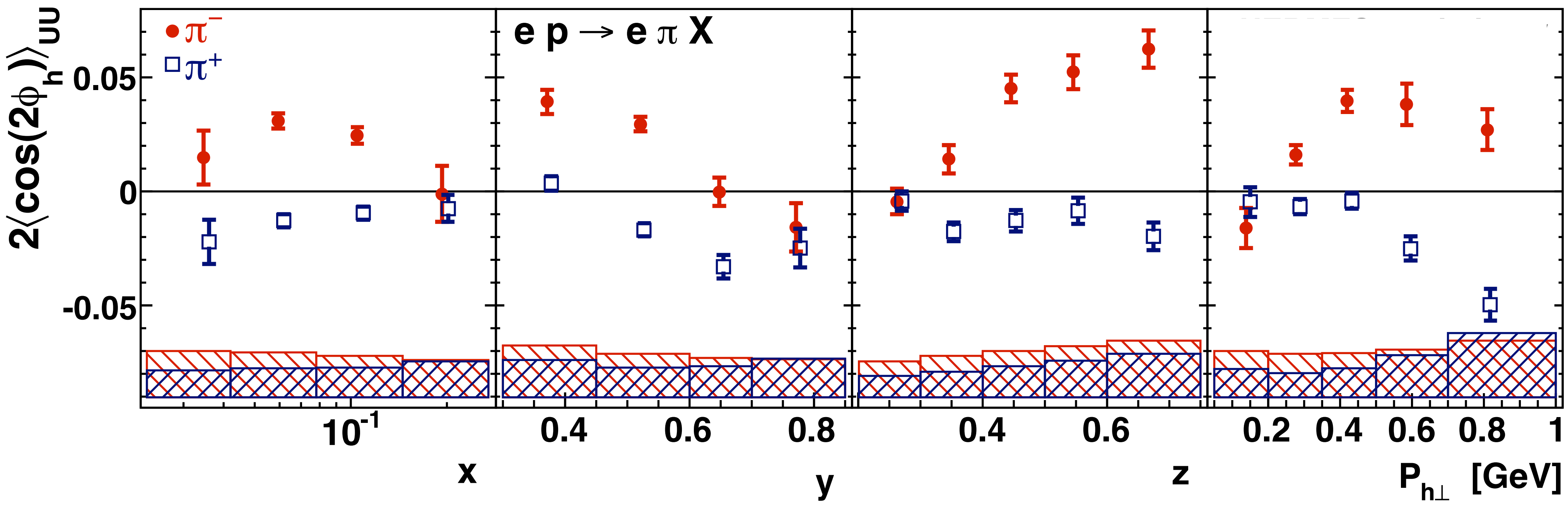

- Cahn effect only does not describe data

Signs of Boer-Mulders

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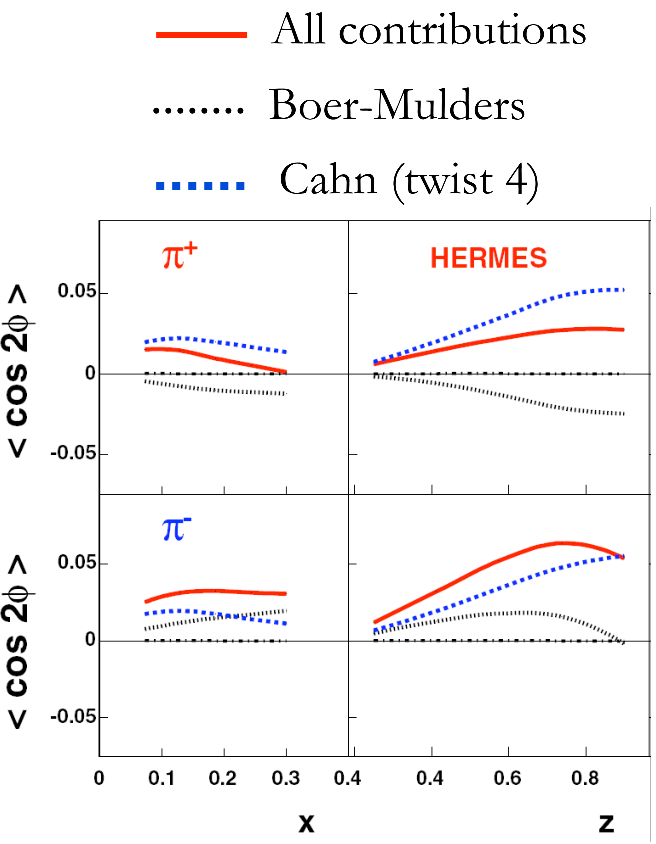

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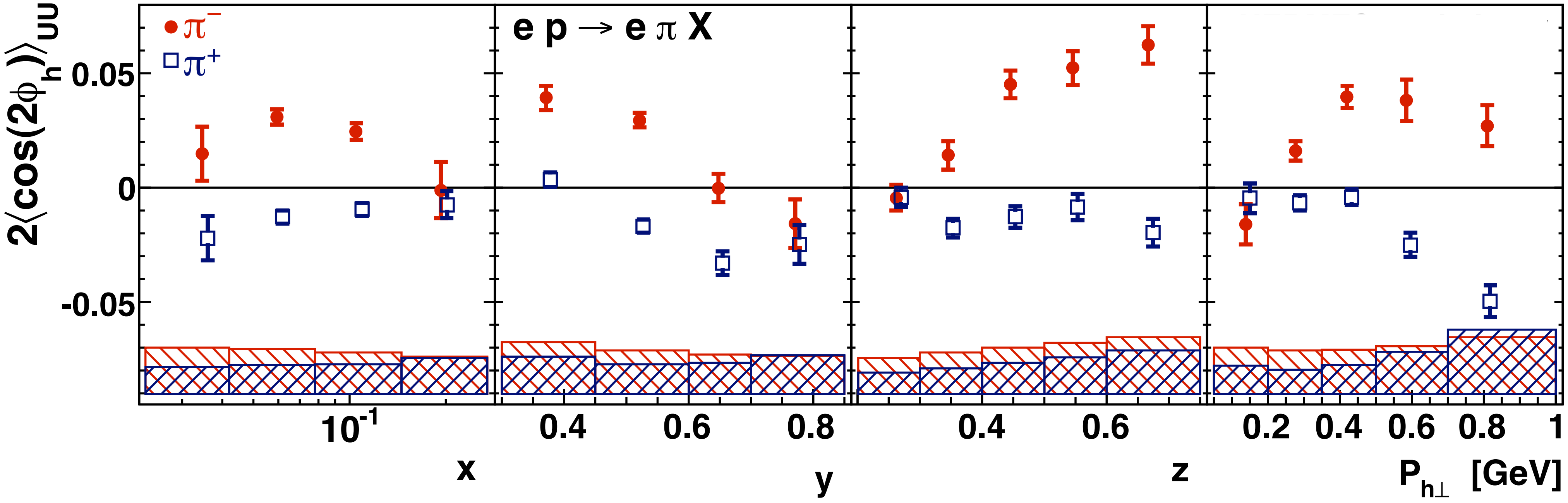
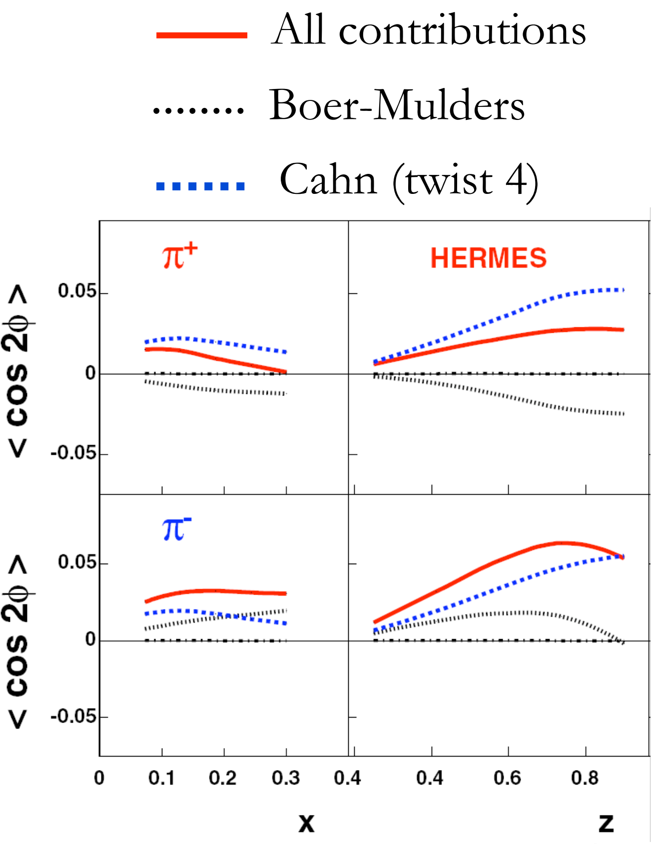


- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for π^- (as expected)
  -> same-sign BM-function for valence quarks

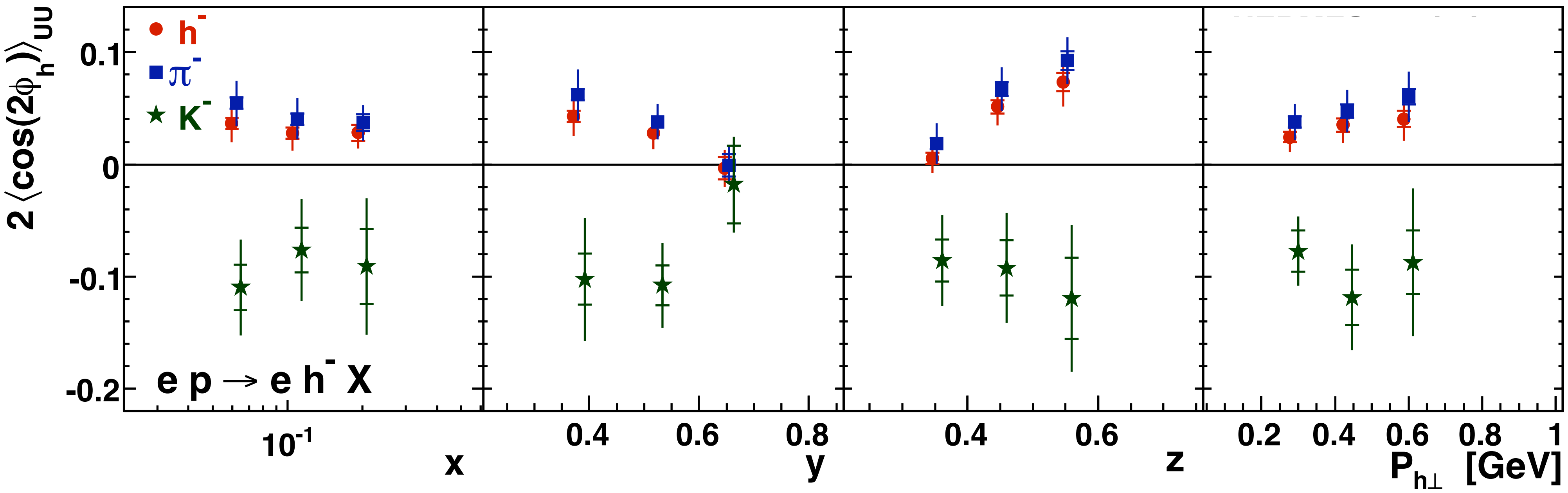
Signs of Boer-Mulders

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



[V. Barone et al., Phys. Rev.D78 (2008) 045022]

[Airapetian et al., PRD 87 (2013) 012010]



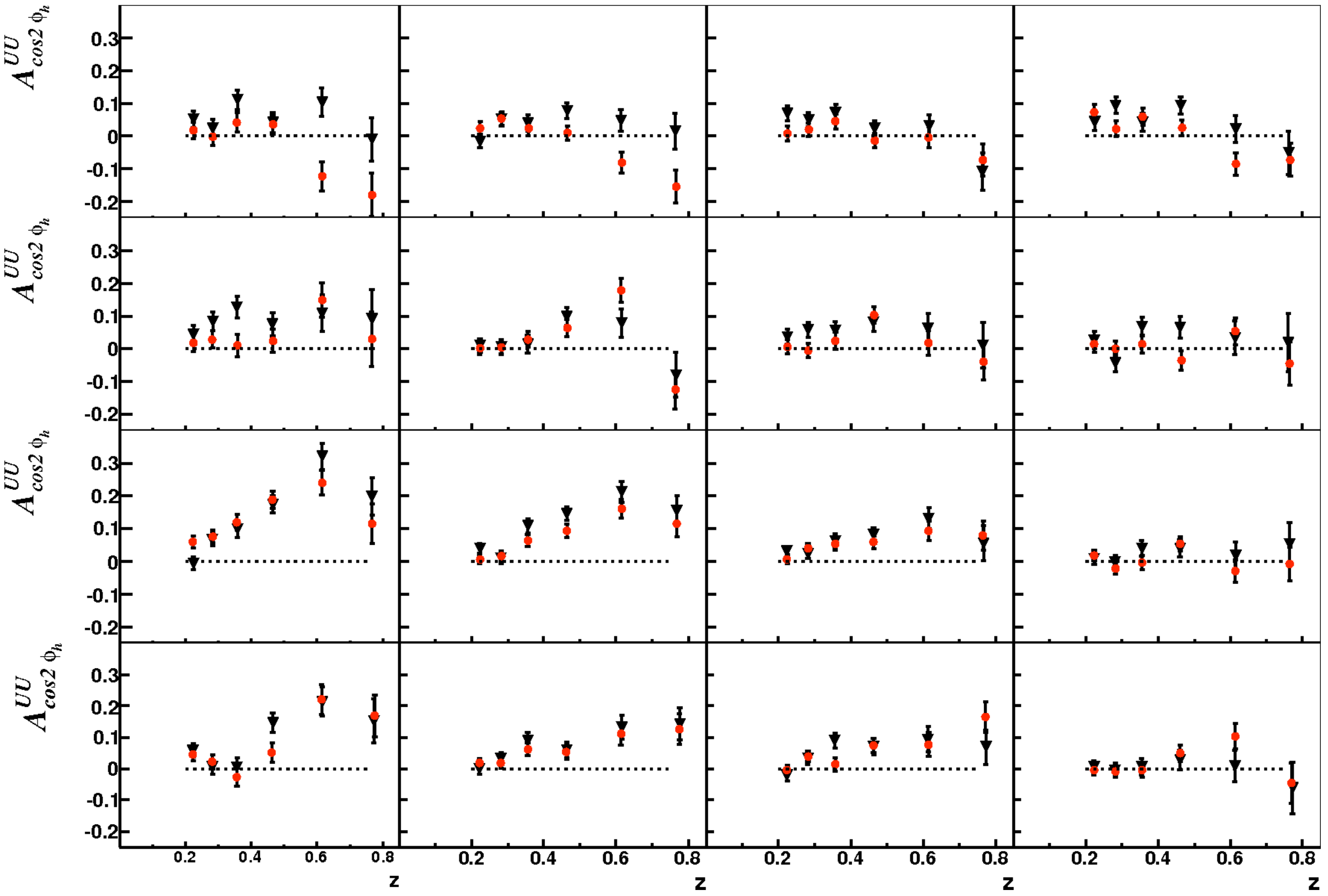
- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for π- (as expected)

  -> same-sign BM-function for valence quarks
- intriguing behavior 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, $h_{1T}^\perp$

Signs of Boer-Mulders

COMPASS ^{6}LiD (25% of 2004 data)



$\uparrow p_T^h; \rightarrow x$

$\sigma_{sys} \approx 2 \cdot \sigma_{stat}$

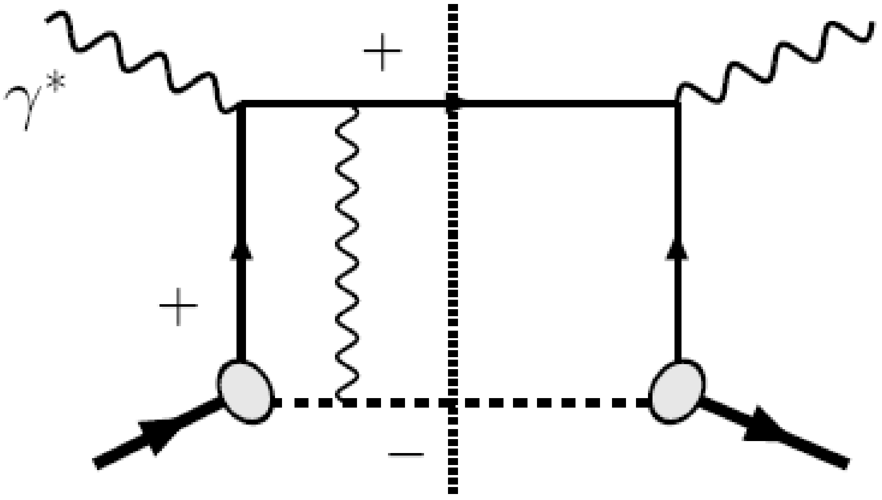
[G. Sbrizzai @ SPIN'12]

preliminary results by COMPASS confirm non-vanishing cosine modulations

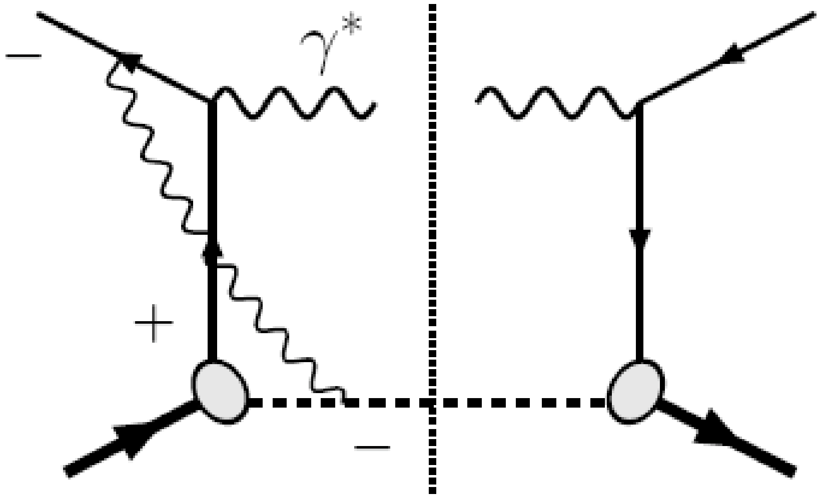
transverse spin in hadron collisions

process dependence of T-odd TMDs

simple QED
example



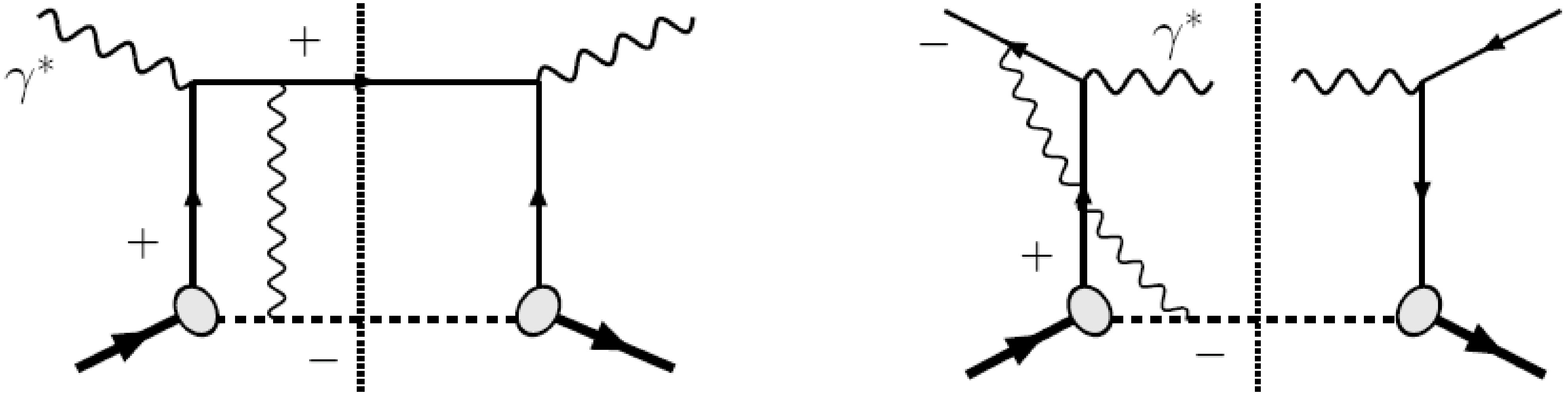
DIS: attractive



Drell-Yan: repulsive

process dependence of T-odd TMDs

simple QED example

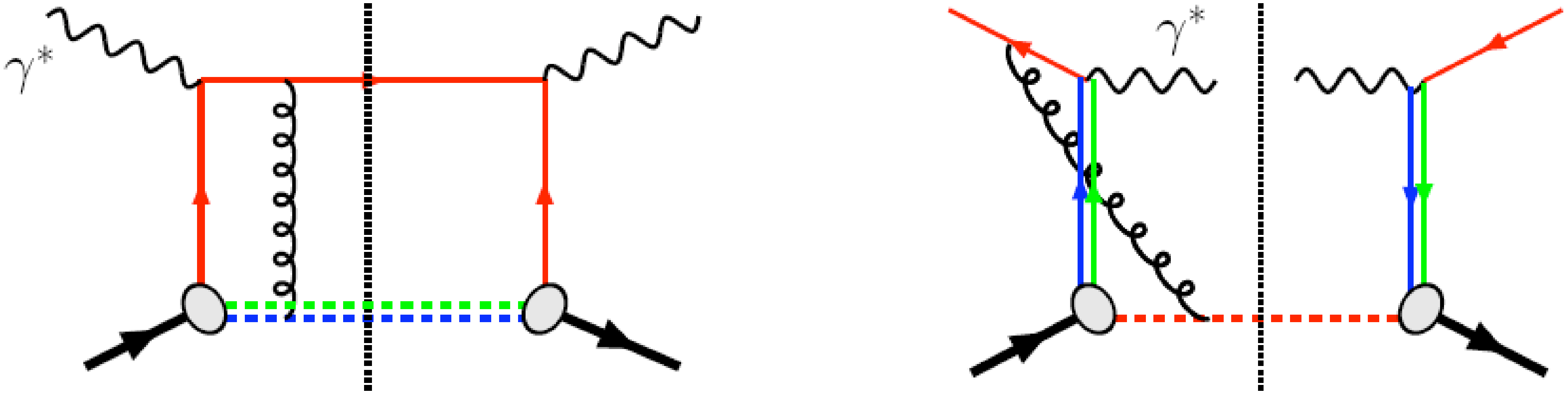


DIS: attractive

Drell-Yan: repulsive

add color:

QCD



result: Sivers$|_{\text{DIS}}$ = - Sivers$|_{\text{DY}}$

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simple QED
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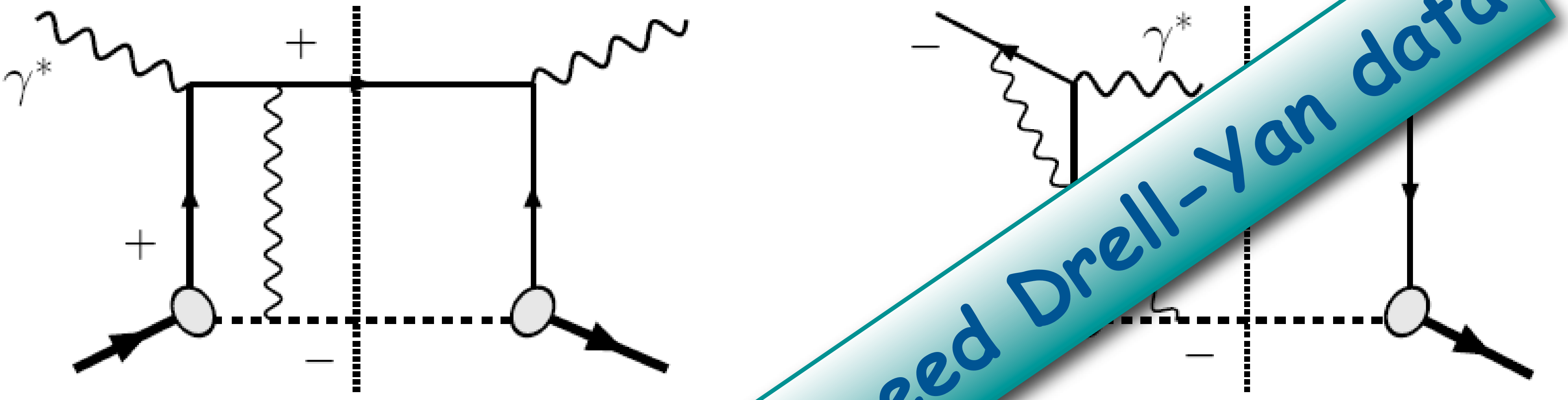

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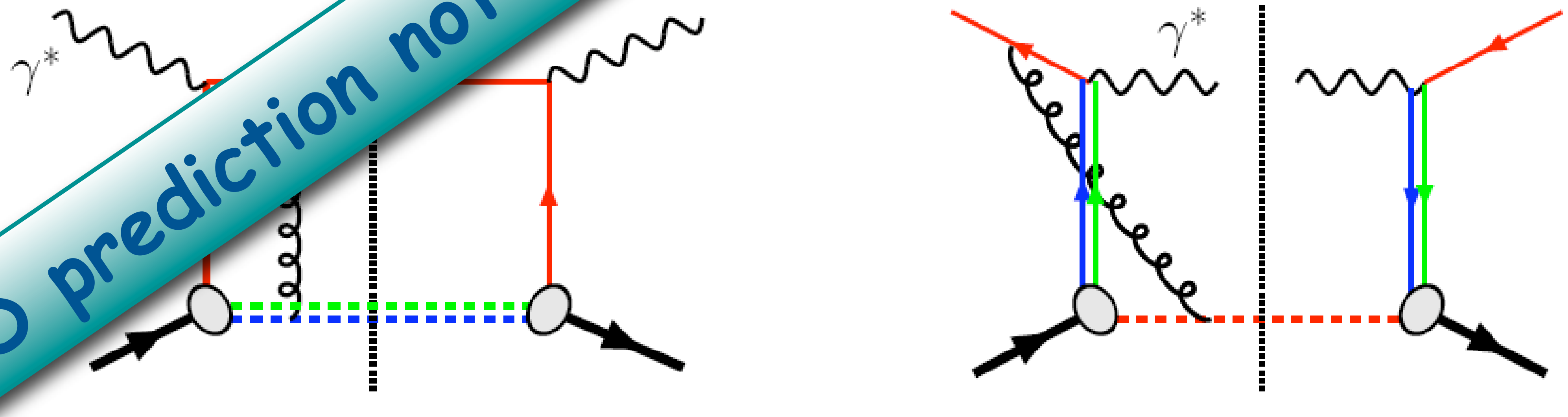
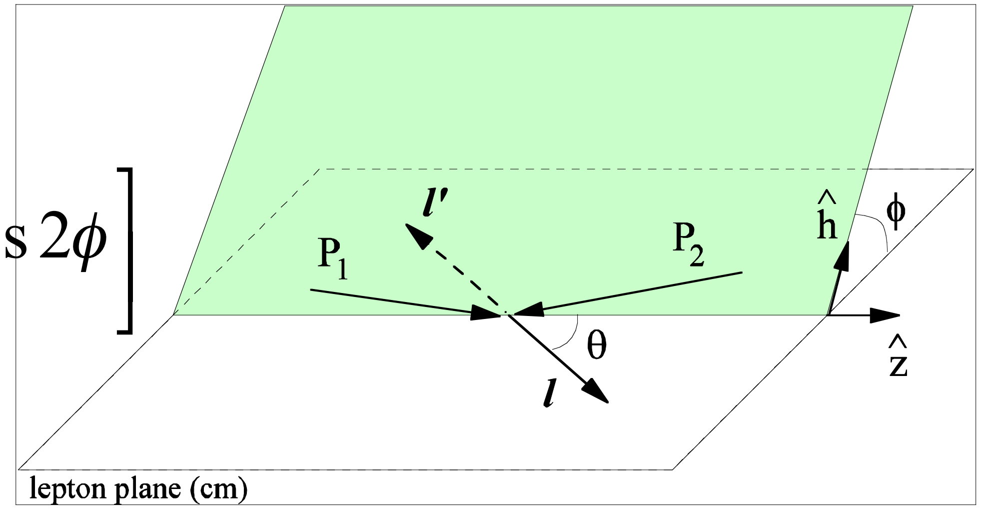


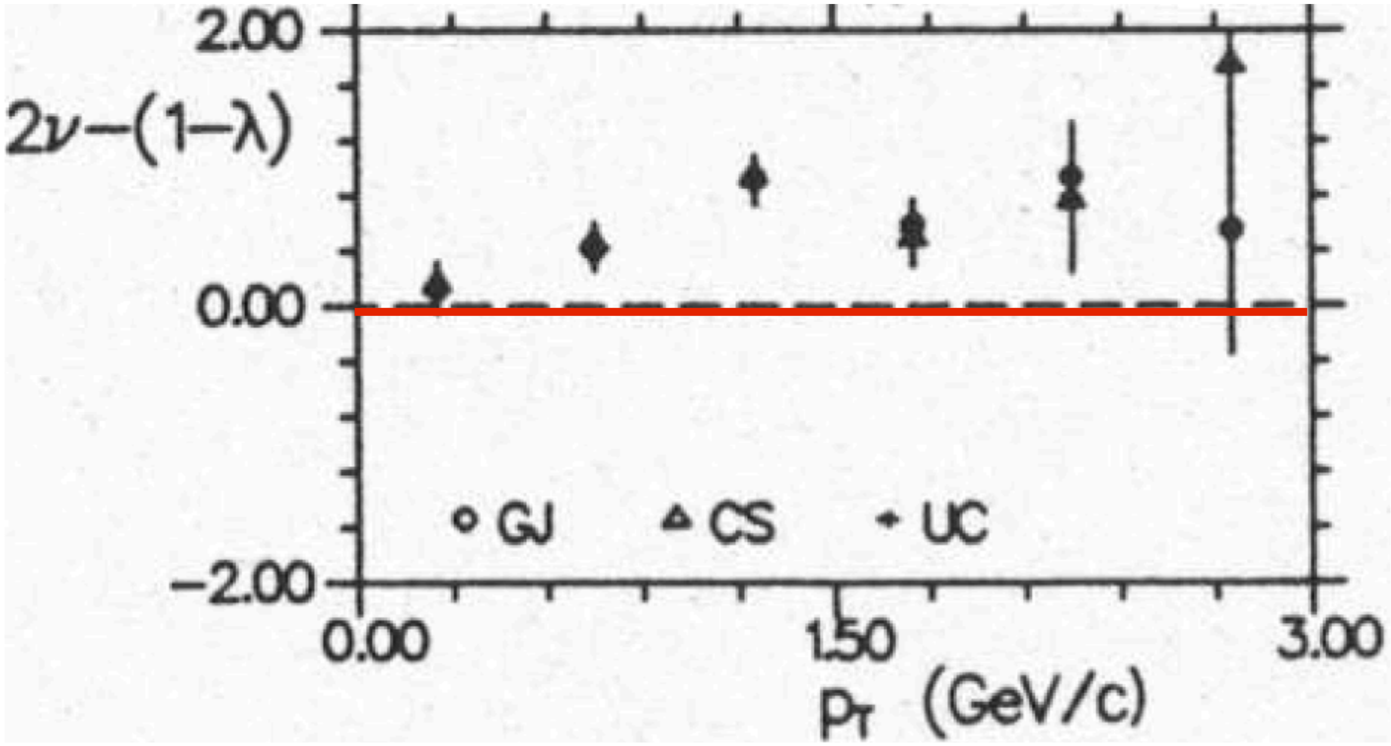
result: $\text{Sivers}|_{\text{DIS}} = - \text{Sivers}|_{\text{DY}}$

rigorous QCD prediction not tested!! - need Drell-Yan data

Unpolarized Drell-Yan

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





$$\boxed{1 - \lambda - 2\nu = 0}$$

Large deviations from Lam-Tung relation observed in pion-induced DY
[NA10 ('86/'88) & E615 ('89)]

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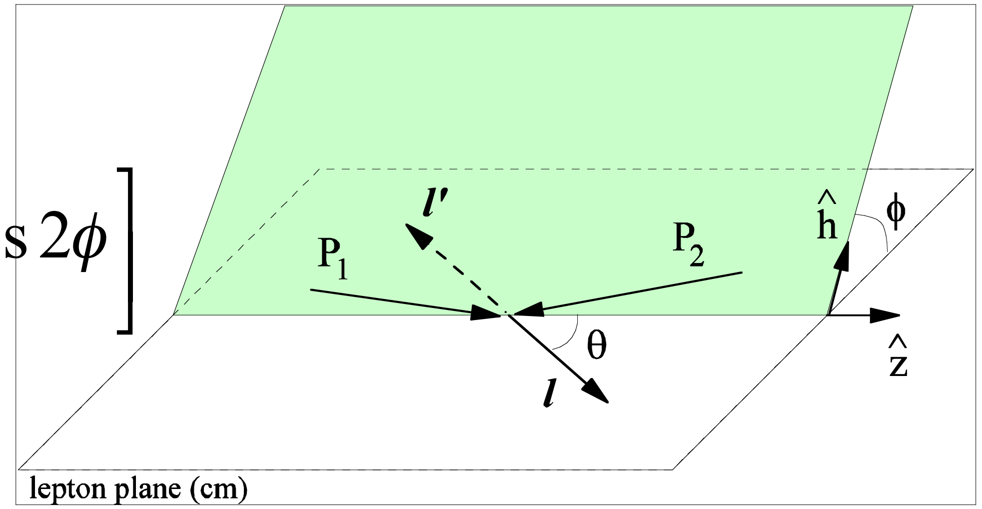

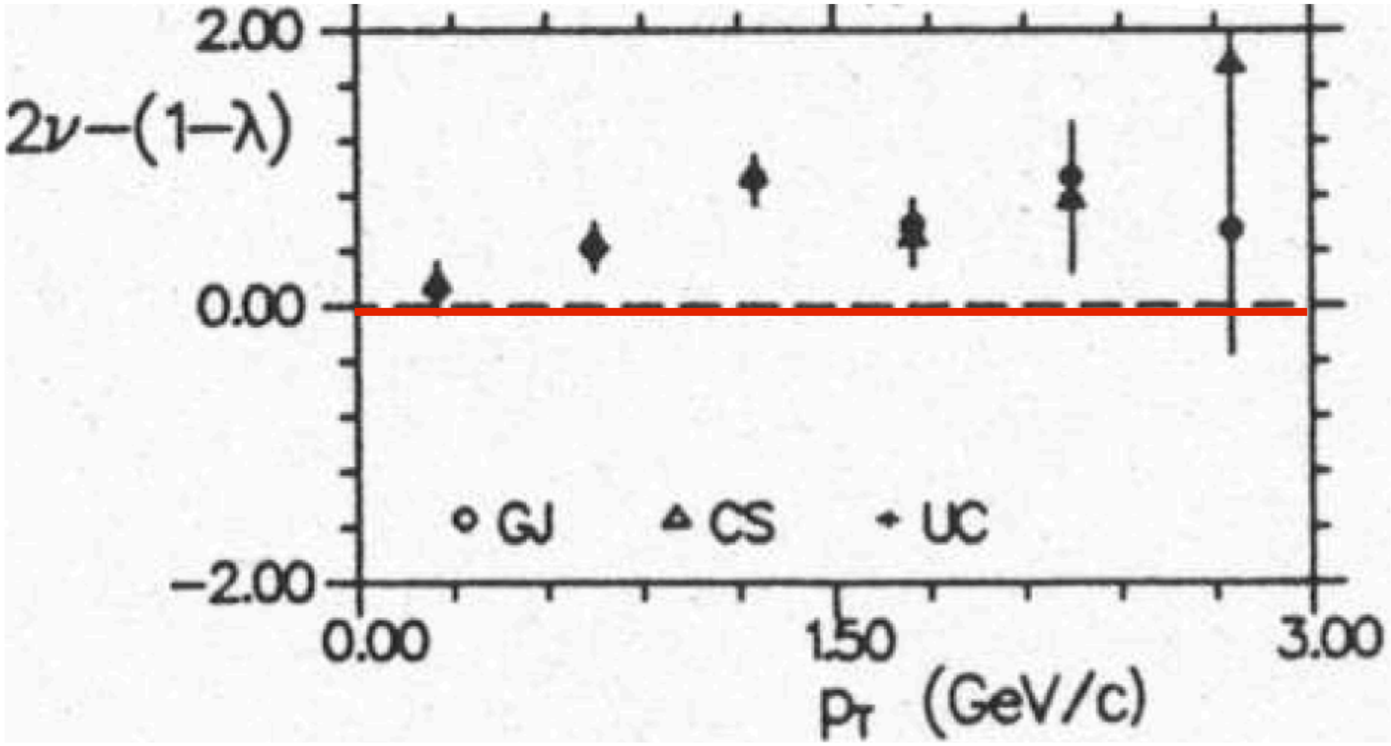

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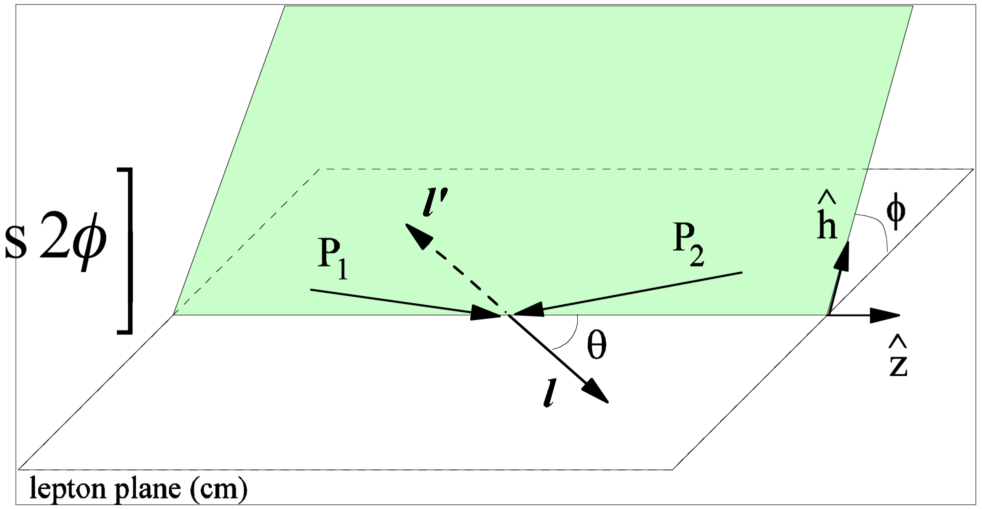

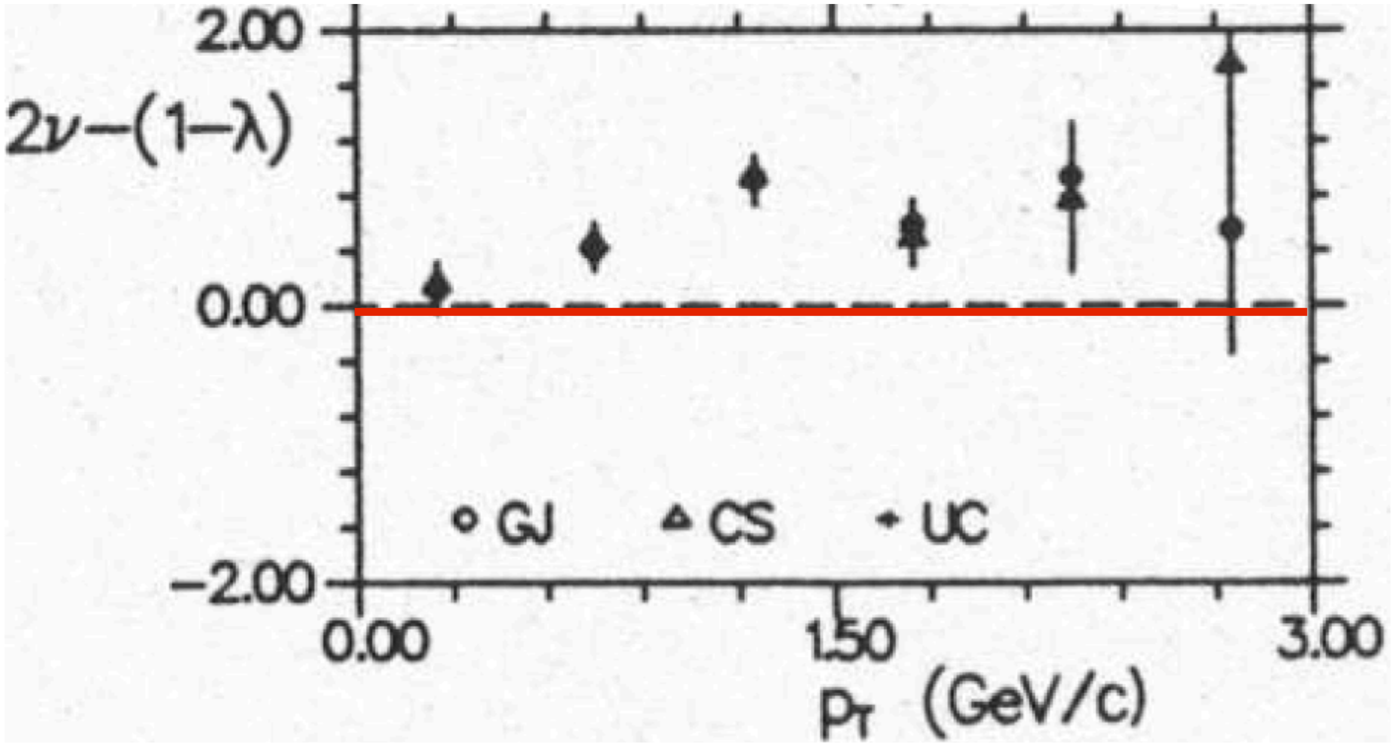

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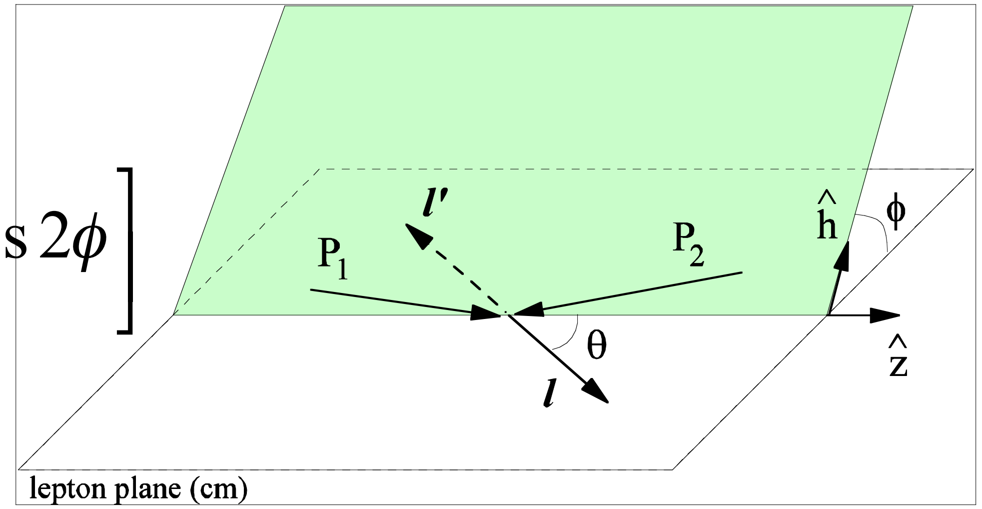

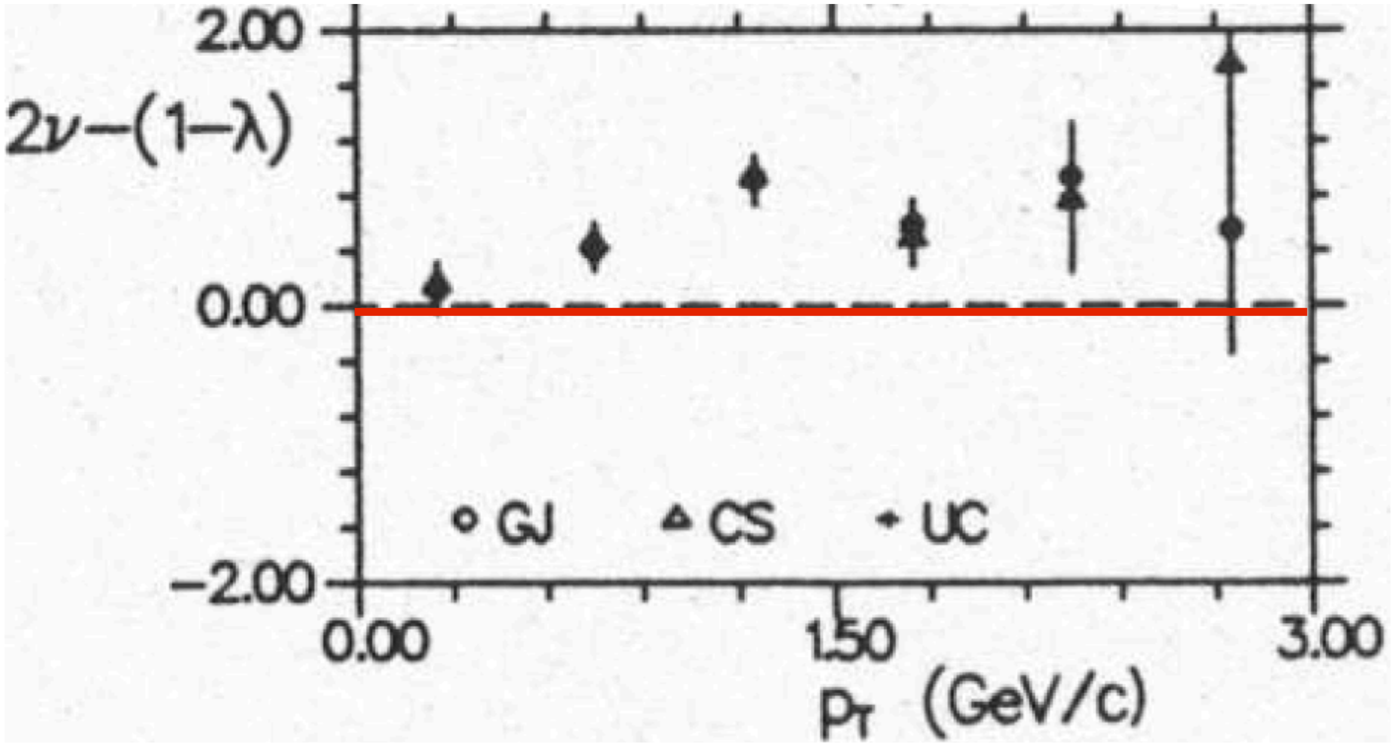

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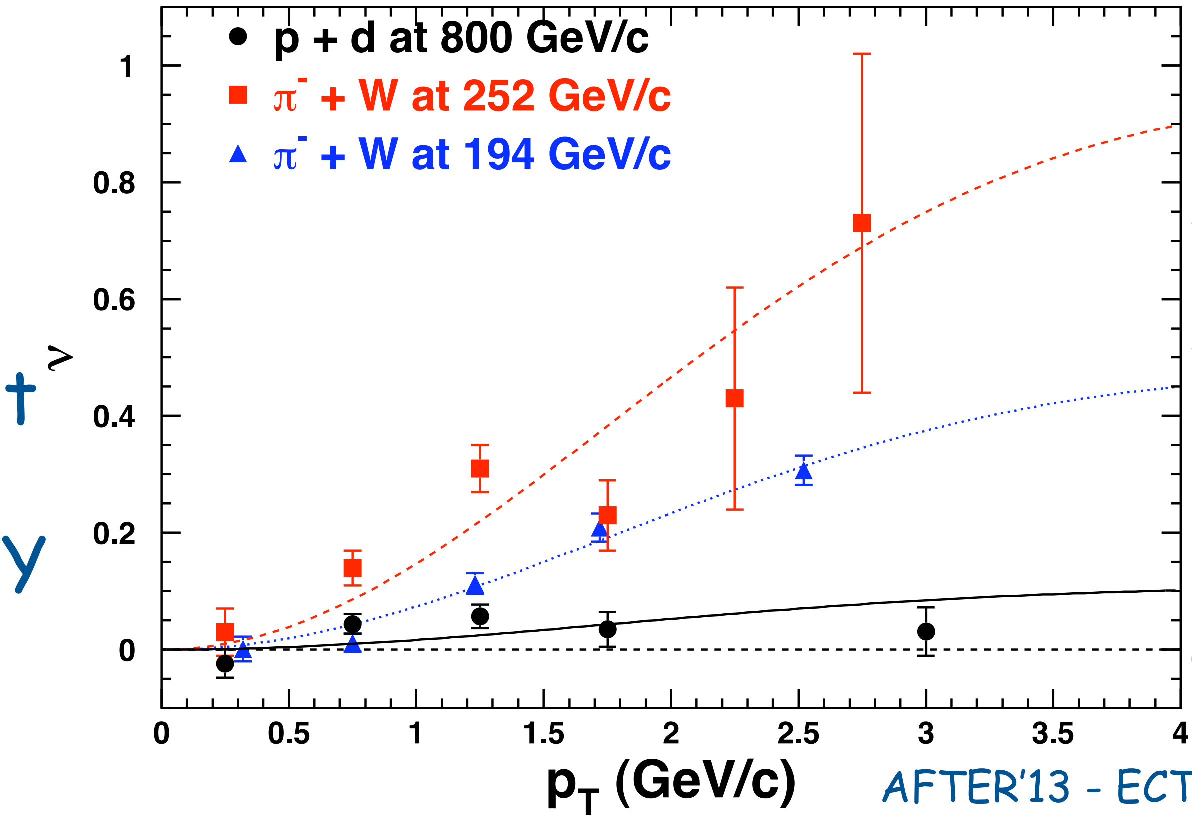
Large deviations from Lam-Tung relation observed in pion-induced DY

[NA10 ('86/'88) & E615 ('89)]

- not explainable using collinear pQCD
- possible source: Boer-Mulders effect
- much smaller effect for pp and pd DY
  ➡valence BM effect?



[E866, PRL 99 (2007) 082301]

pp → hX

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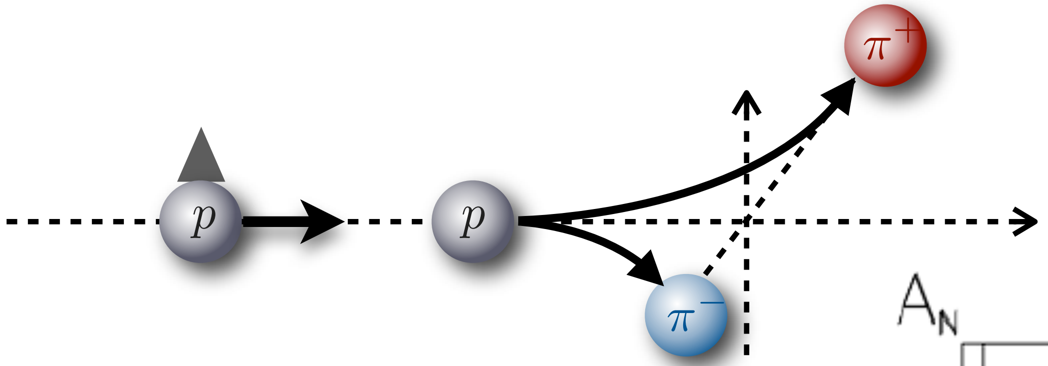
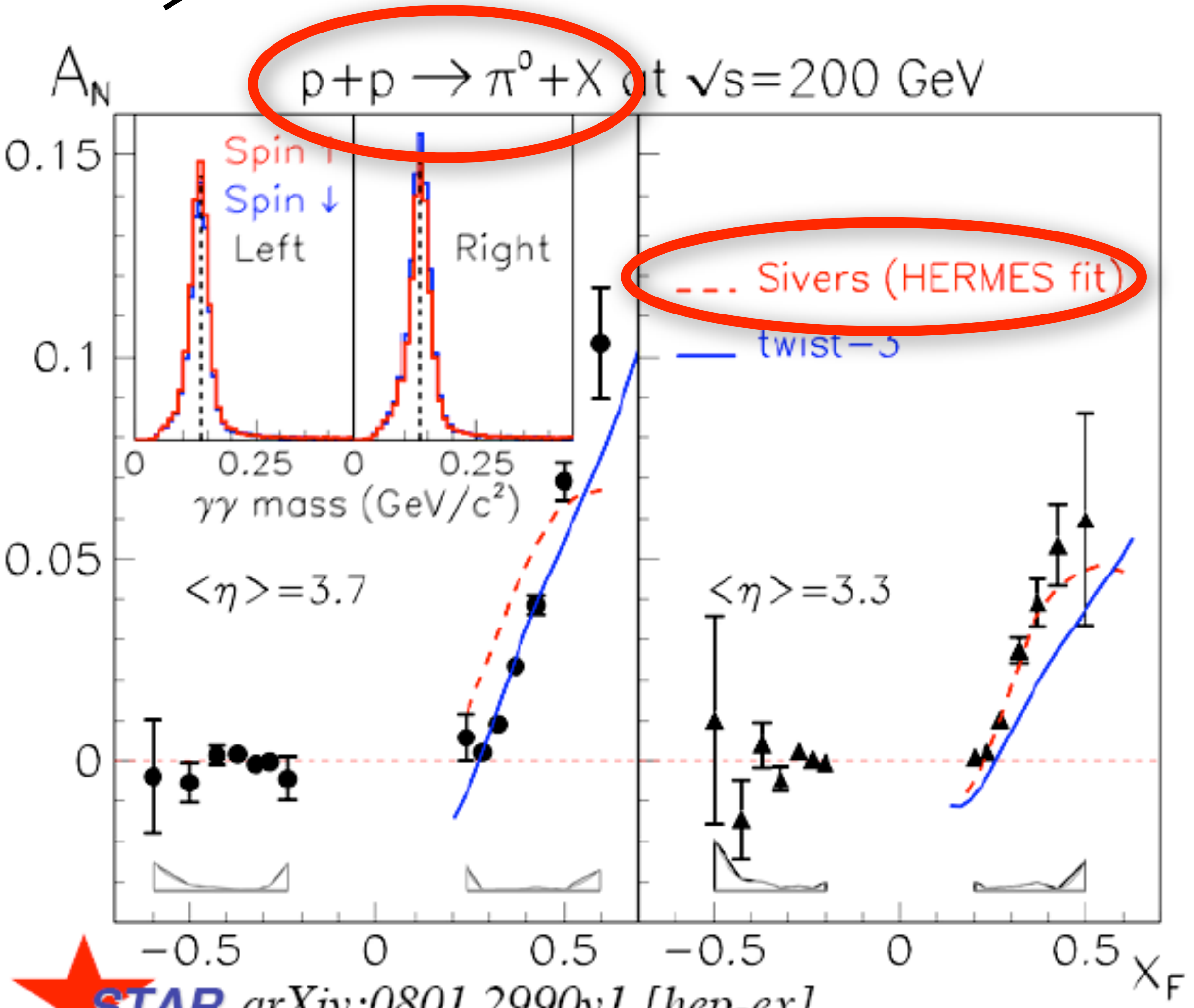
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect or twist-3 effects
- only sizable in forward direction



STAR *arXiv:0801.2990v1 [hep-ex]*

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

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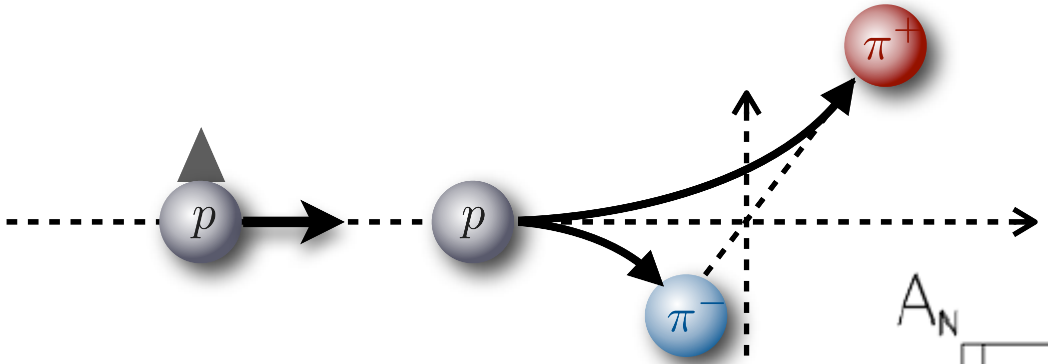
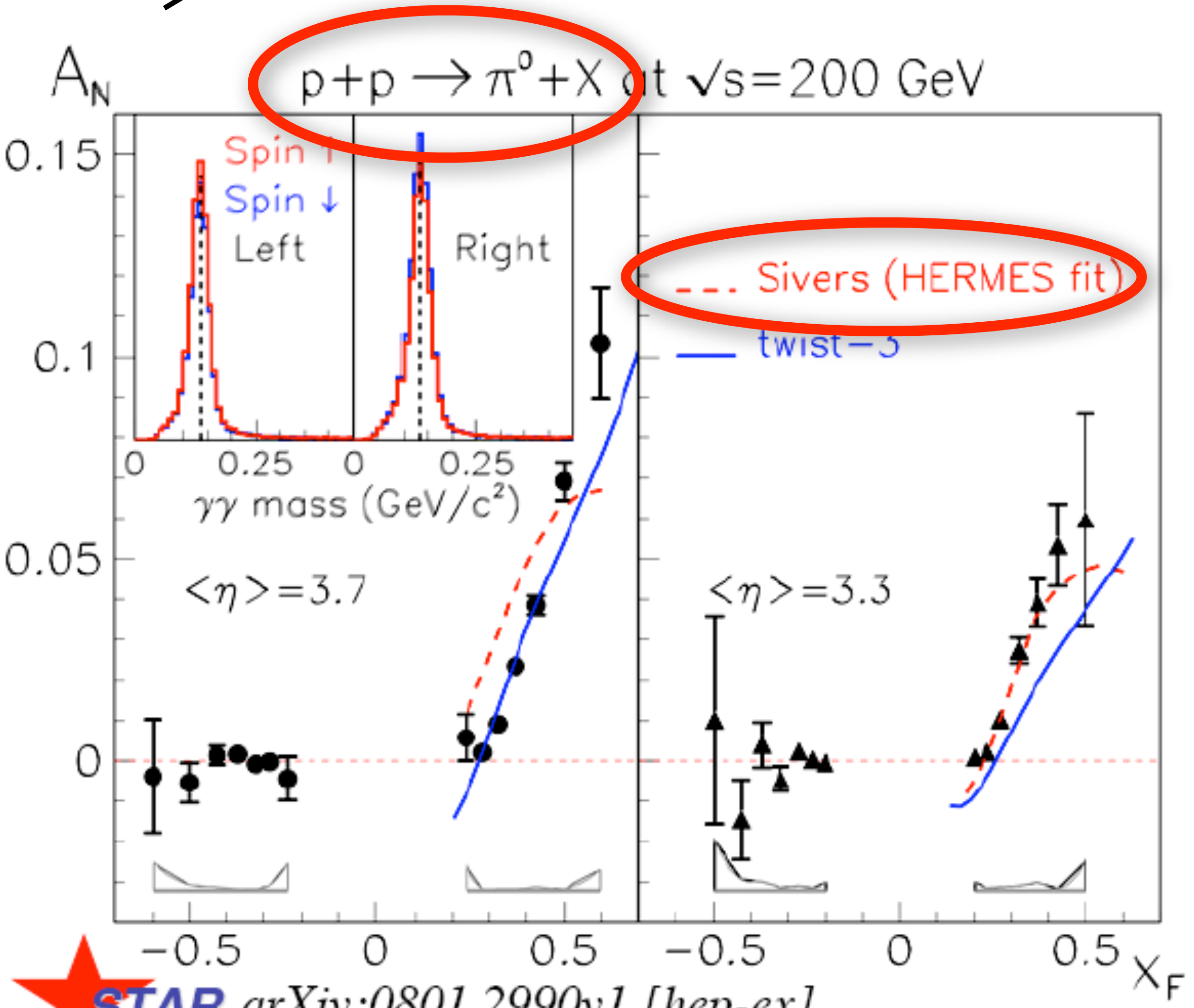


pp → hX

- Sivers fit to HERMES data nicely describes A_N in pp
- may also originate from Collins effect or twist-3 effects
- only sizable in forward direction
- after early success of linking twist-3 with Sivers, sign mismatch discovered:

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)\,|_{\mathrm{SIDIS}}$$



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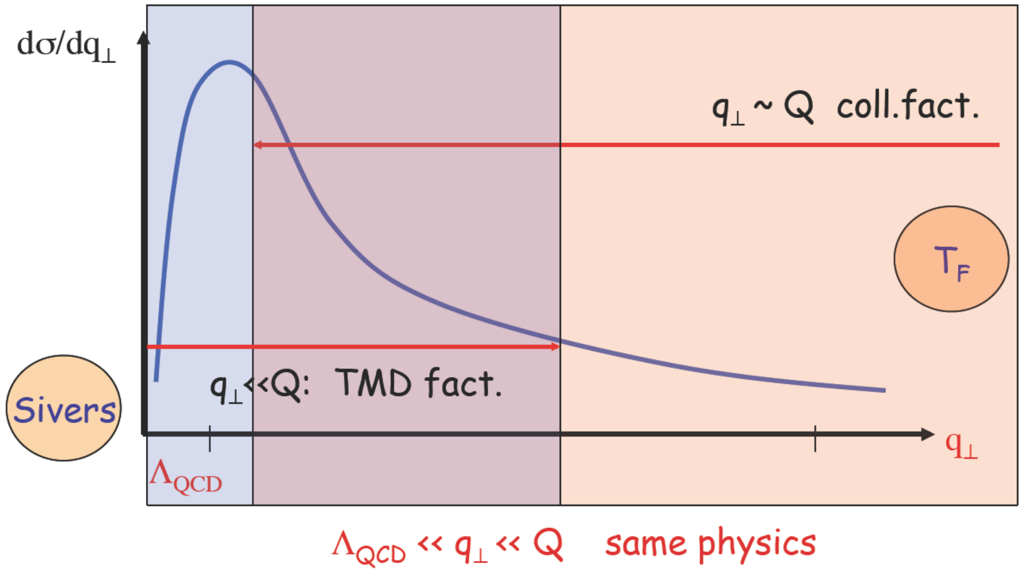
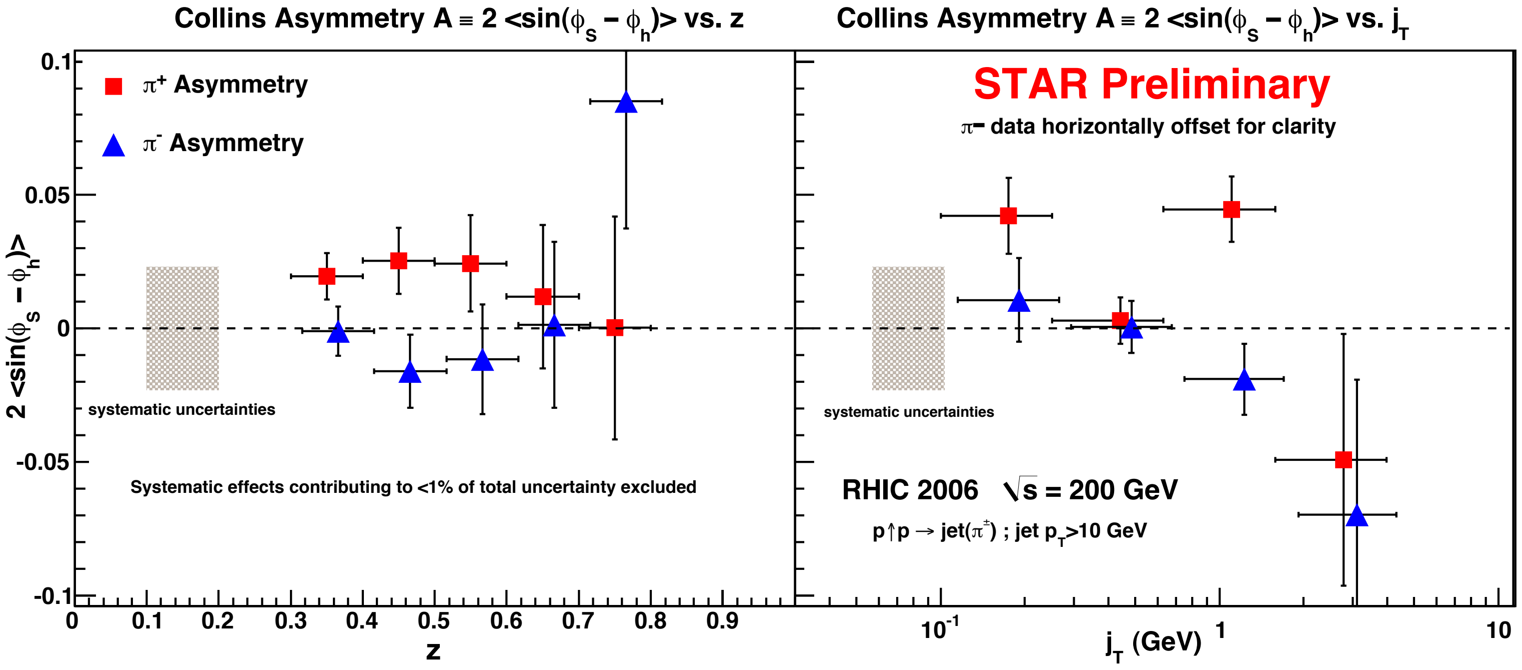


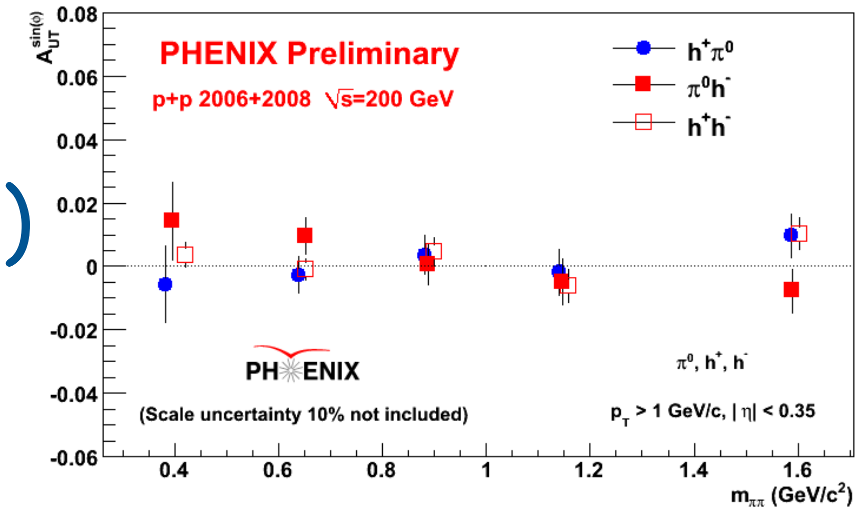
pieces in the A_N puzzle

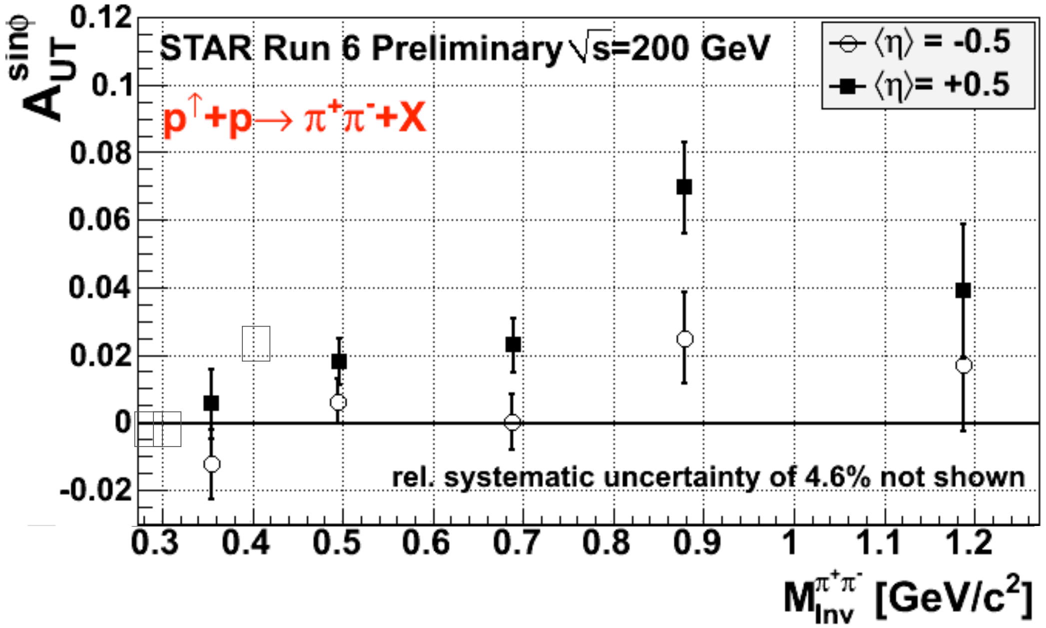
- go from purely inclusive to analyzing angular correlations

➡ Collins effect:

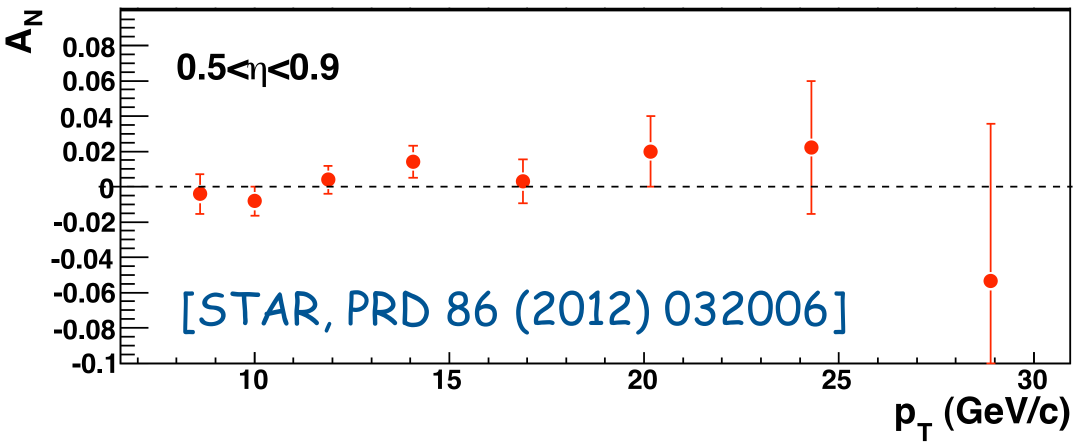


➡ dihadron FF:
(2 hadrons in jet)





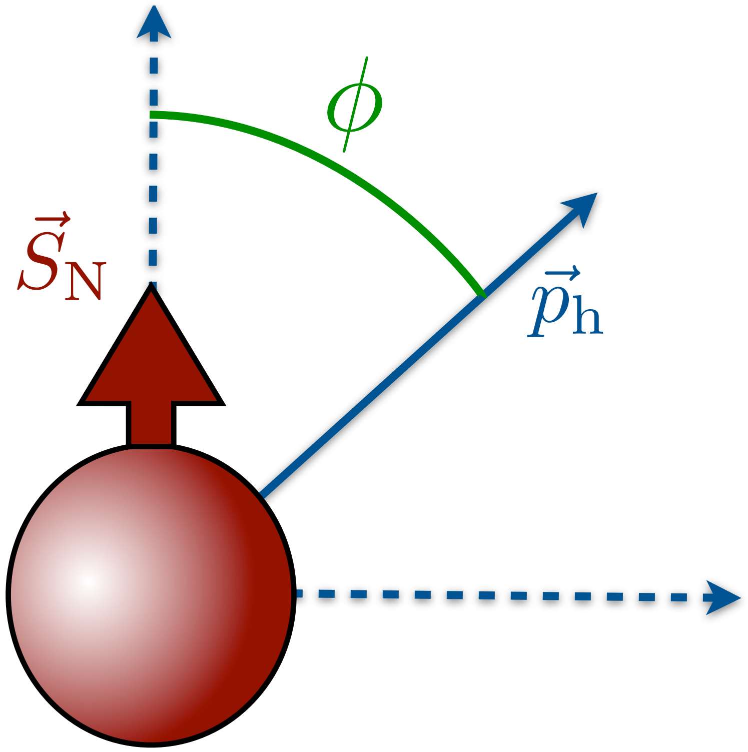
➡ Sivers effect:
(jet A_N, di-jets)



[STAR, PRD 86 (2012) 032006]

Inclusive hadron electro-production

$$ep^{\uparrow} \rightarrow hX$$



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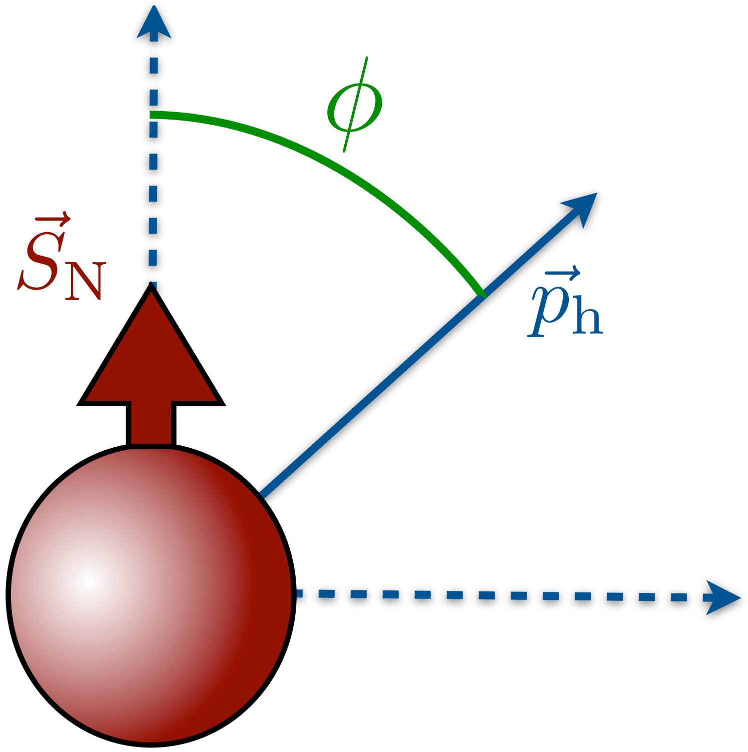

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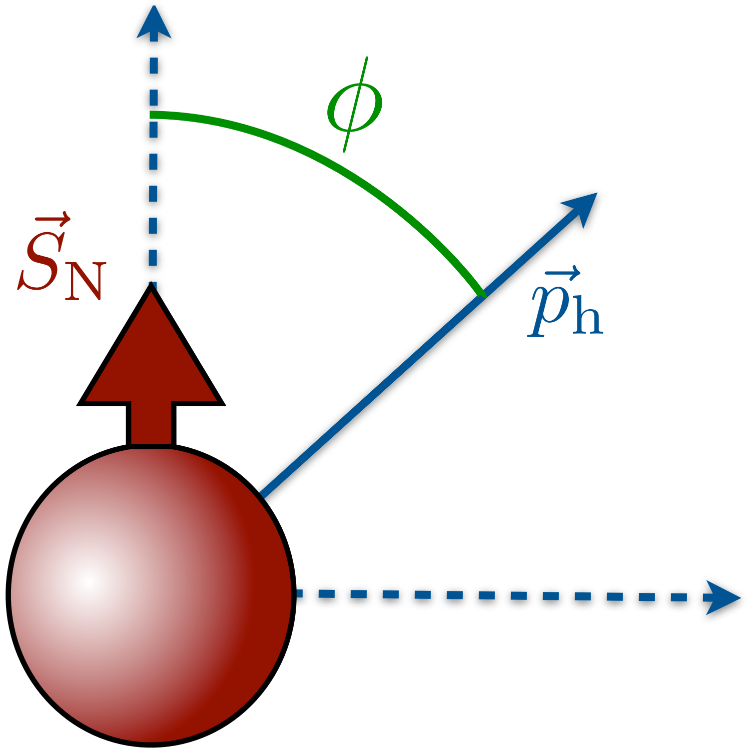

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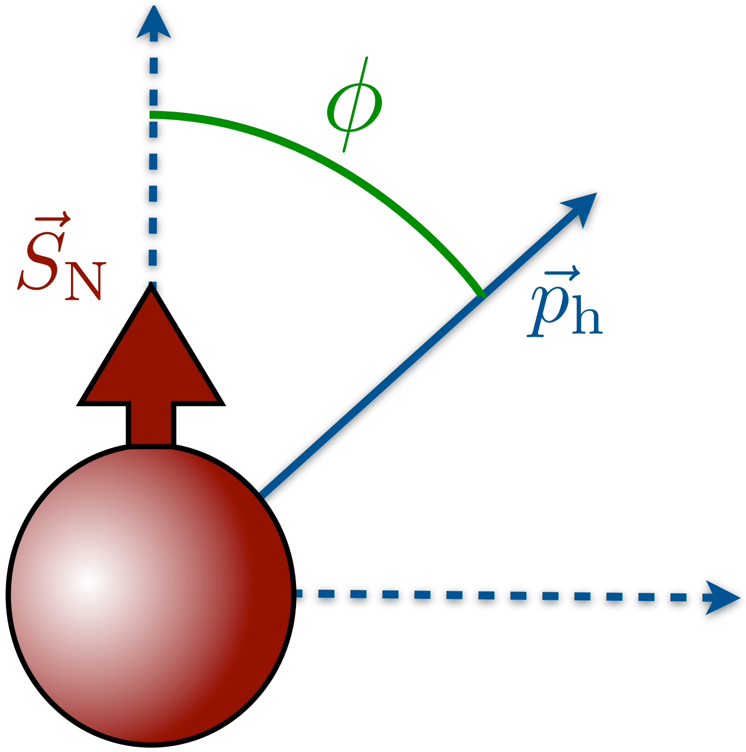

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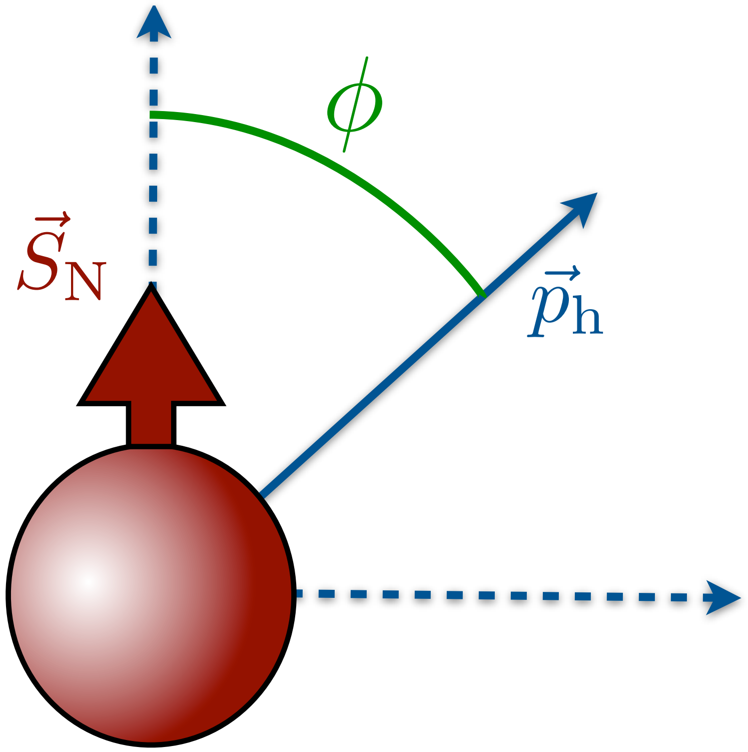
$$A_{UT}(p_T, x_F, \phi) =$$

$$A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$



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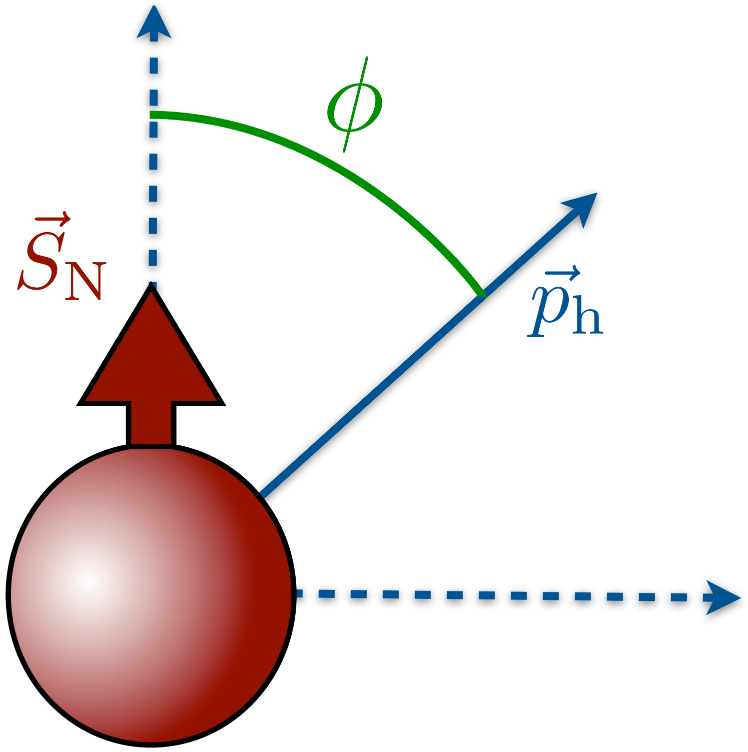


$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

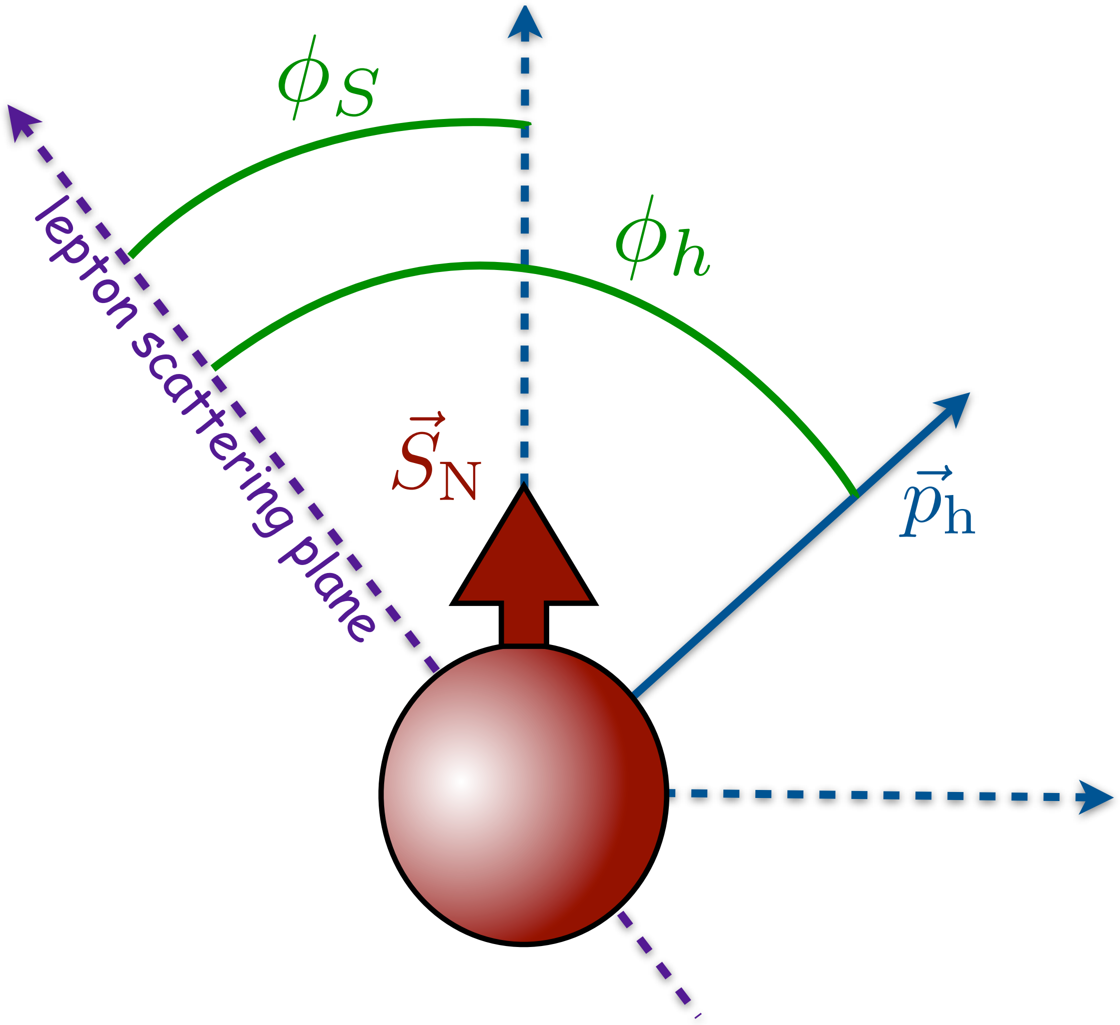
$$A_{\mathrm{N}} \equiv \frac{\int_{\pi}^{2\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UT}} \sin\phi - \int_{0}^{\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UT}} \sin\phi}{\int_{0}^{2\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UU}}}$$

$$= -\frac{2}{\pi} A_{\mathrm{UT}}^{\sin\phi}$$

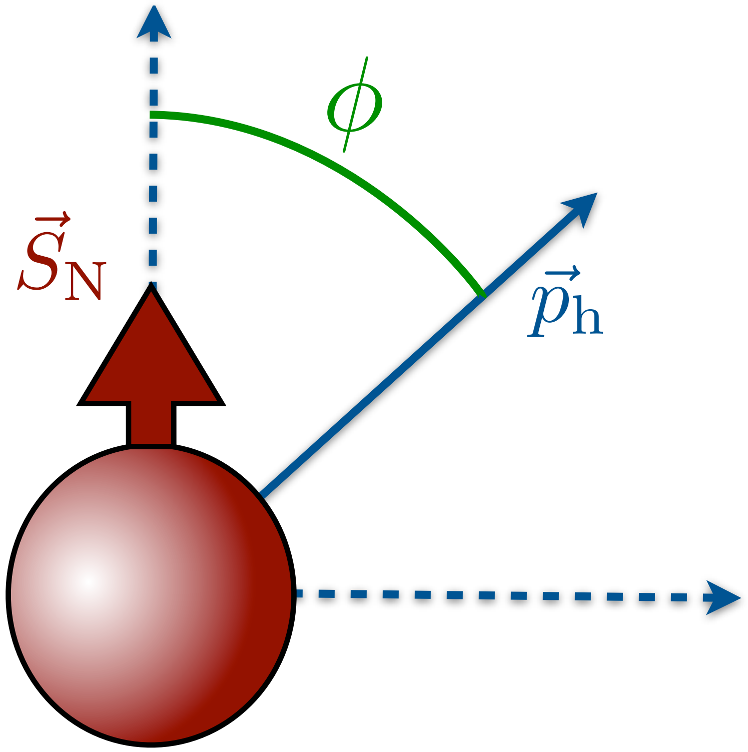
Inclusive hadron electro-production

$$ep^{\uparrow} \rightarrow ehX$$

$$ep^{\uparrow} \rightarrow hX$$



virtual photon going into the page



lepton beam going into the page

$$\phi \simeq \phi_h - \phi_S$$

➠ "Sivers angle"

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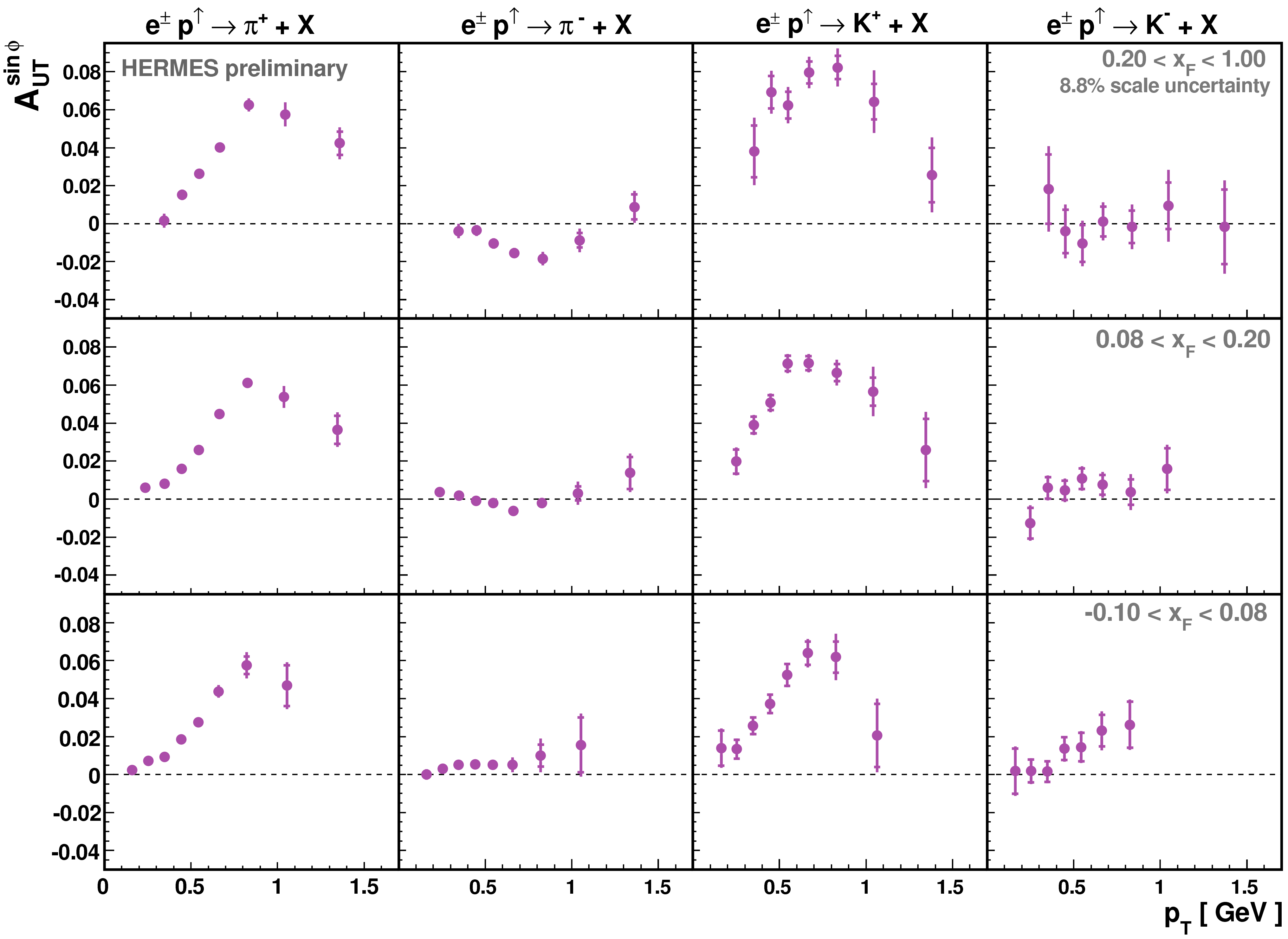
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Inclusive hadrons in ep



	U	L	T
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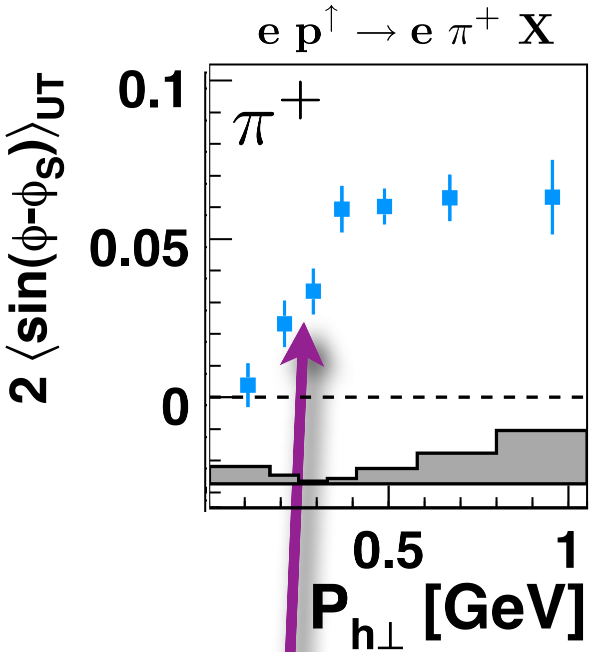
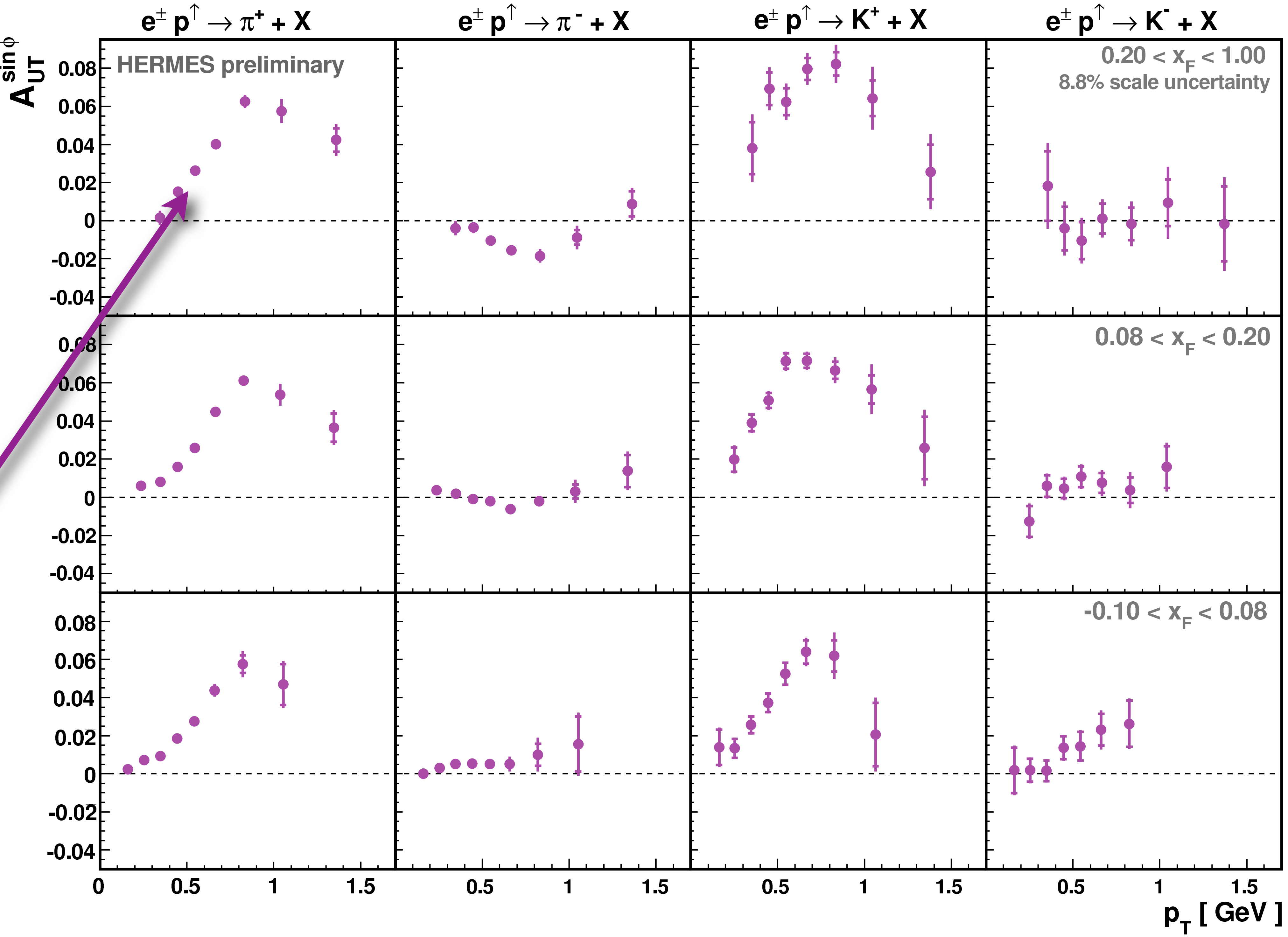
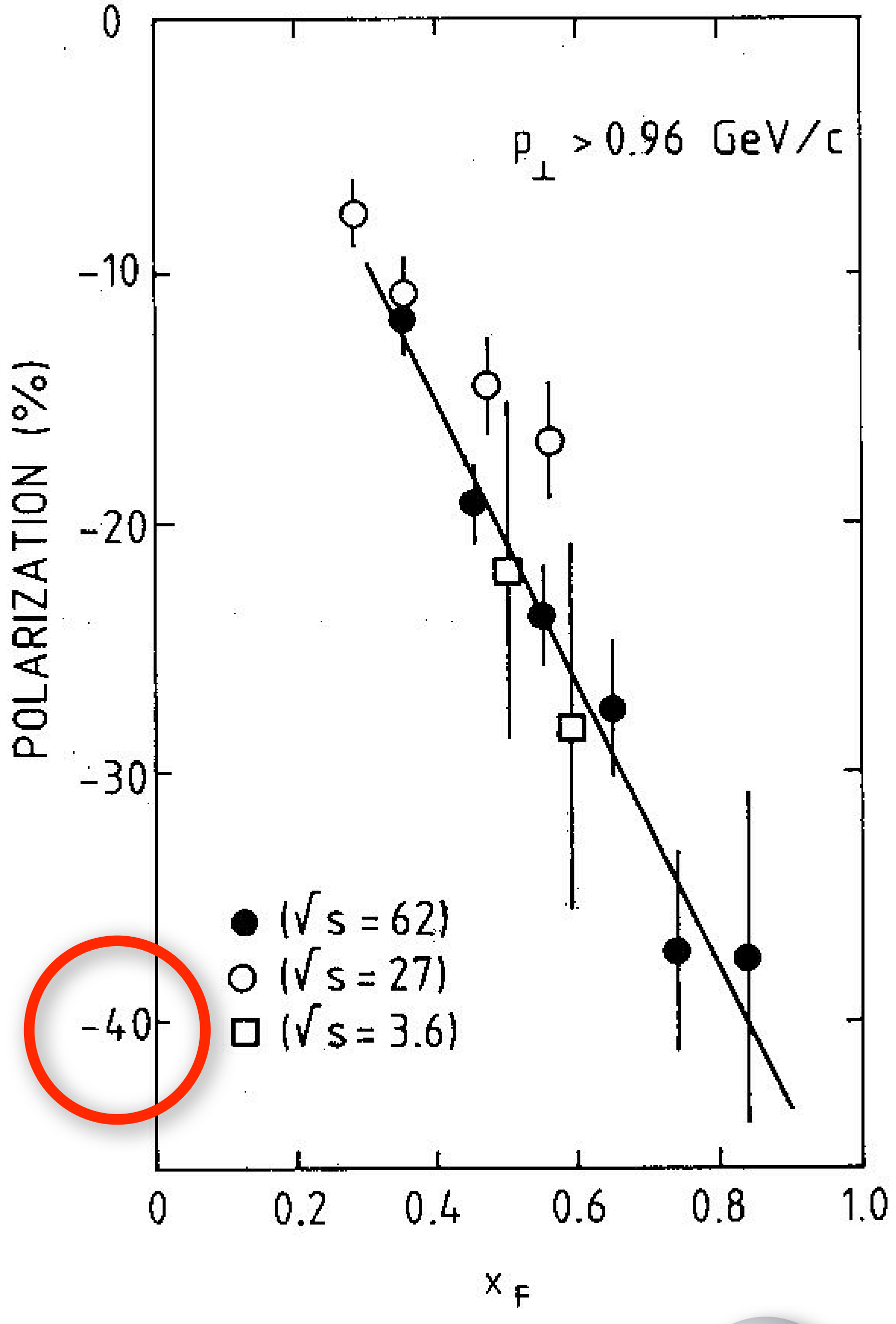


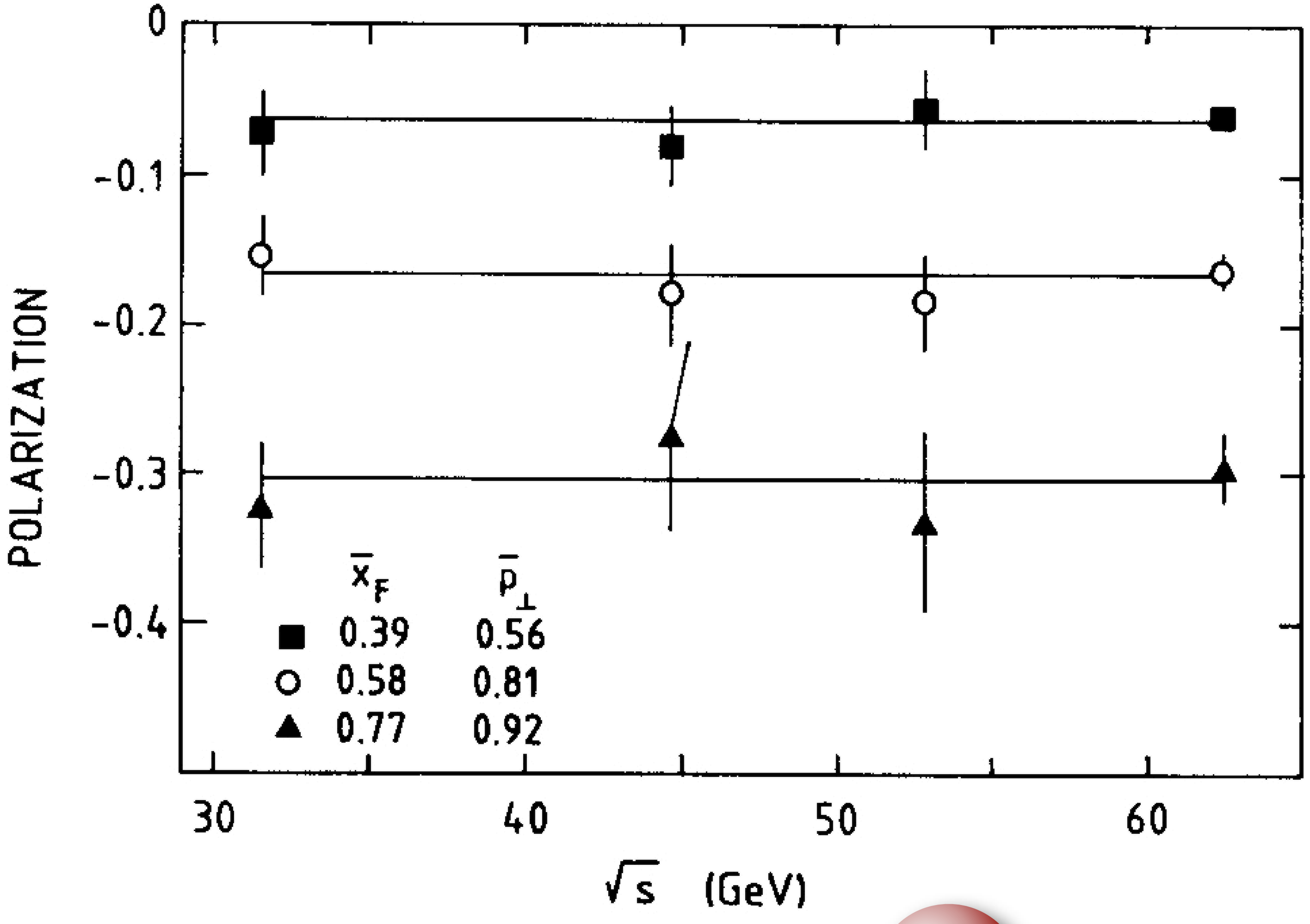


behavior and size similar to SIDIS Sivers

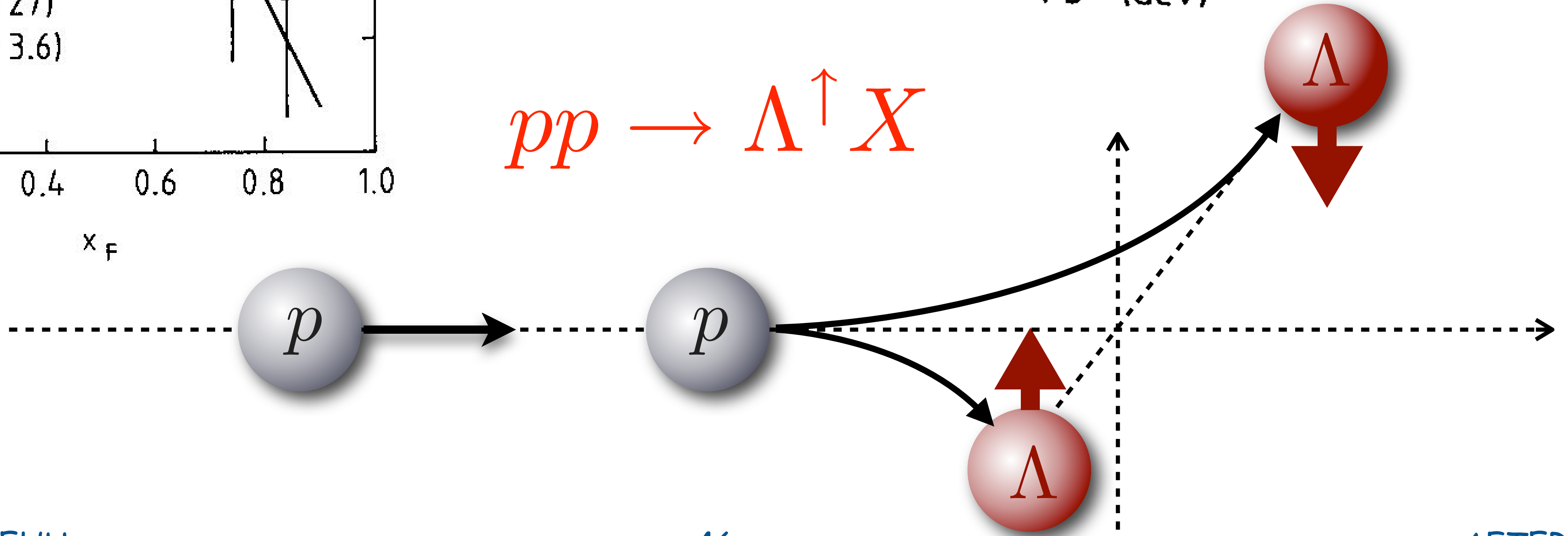
Don't forget these hyperons?

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

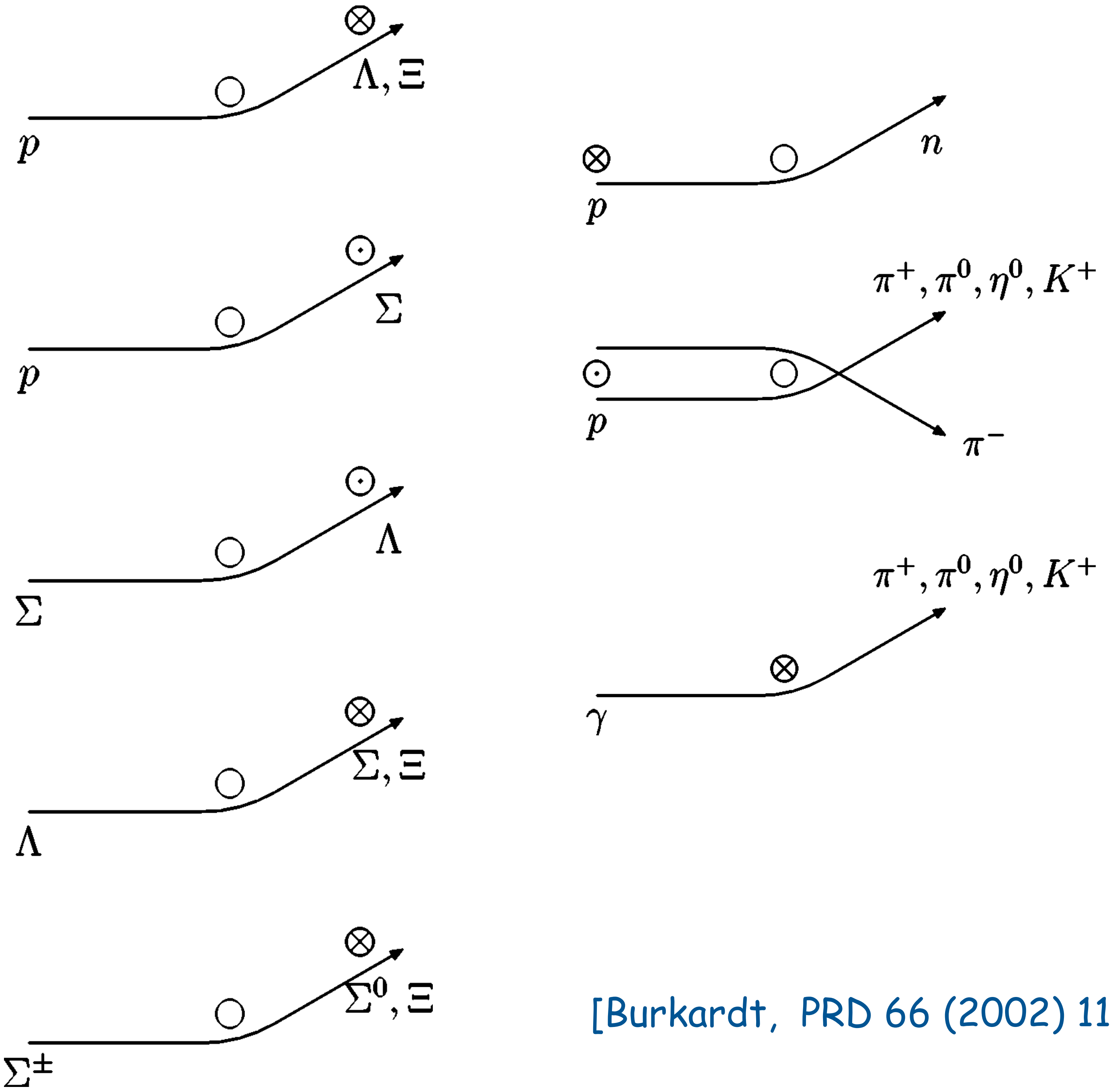




$pp \to \Lambda^\uparrow X$



combining all these data



[Burkardt, PRD 66 (2002) 114005]

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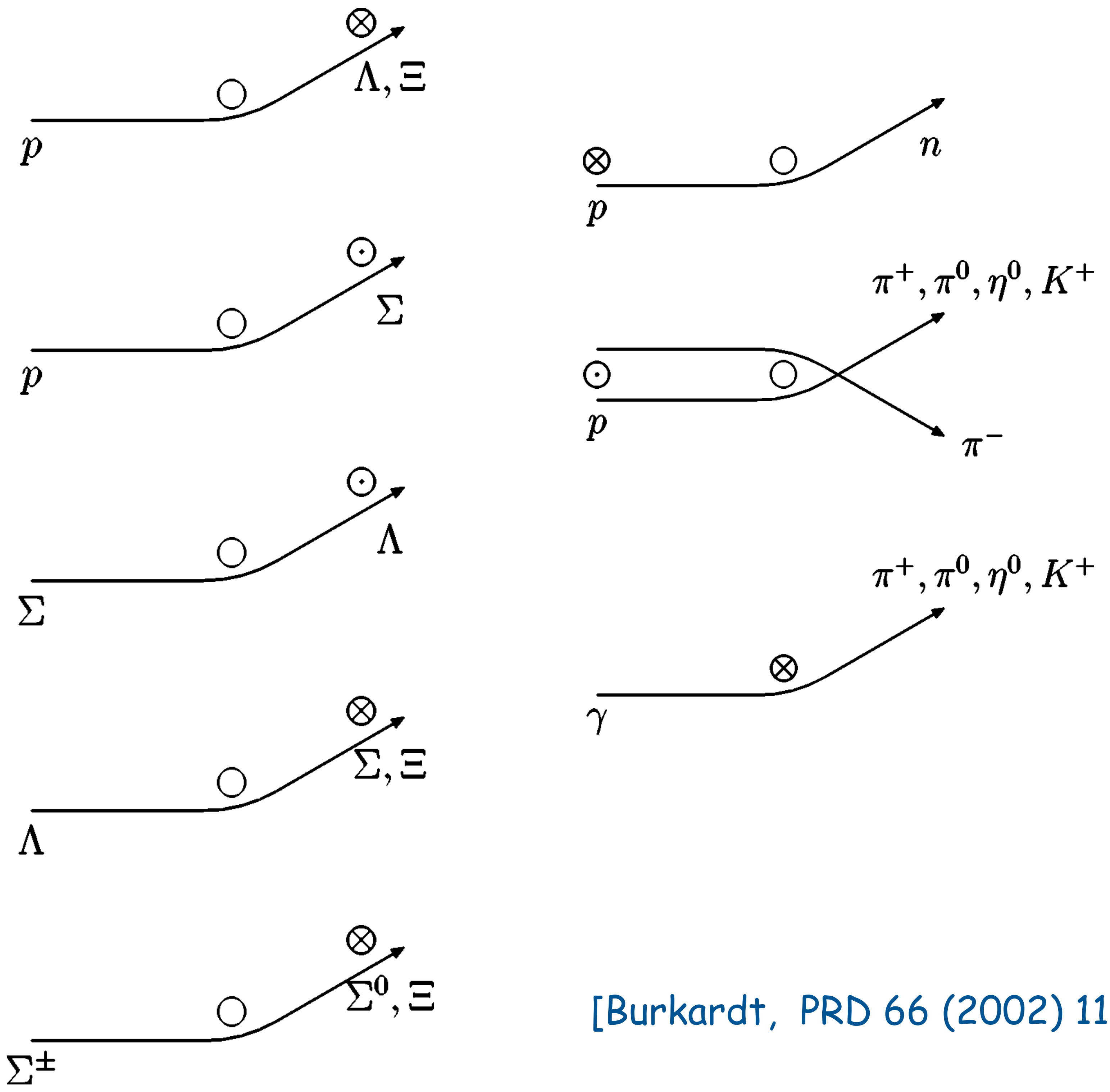

- interpretation using impact-parameter dependent PDFs qualitatively describe many experimental findings

[Burkardt, PRD 66 (2002) 114005]

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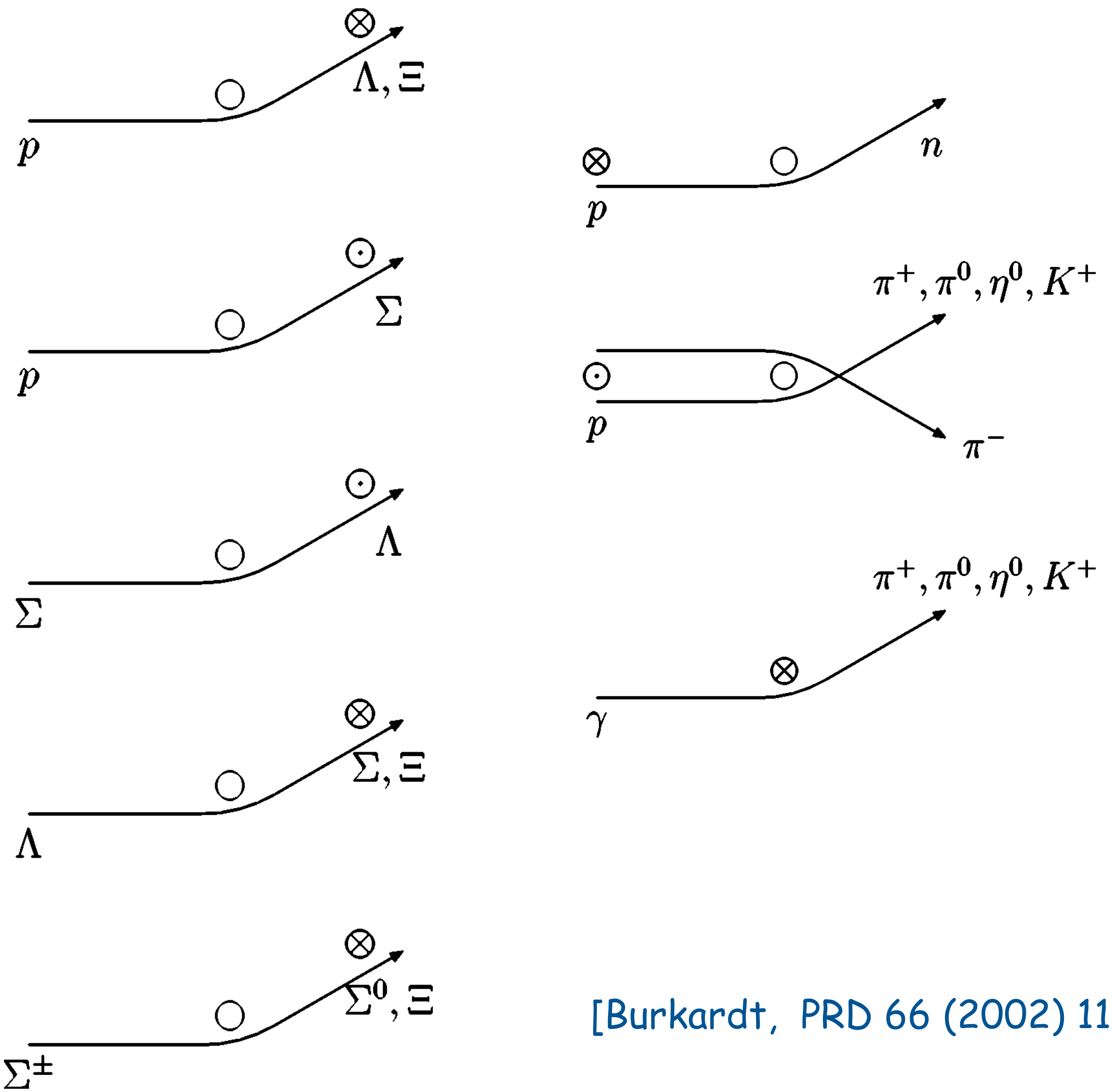
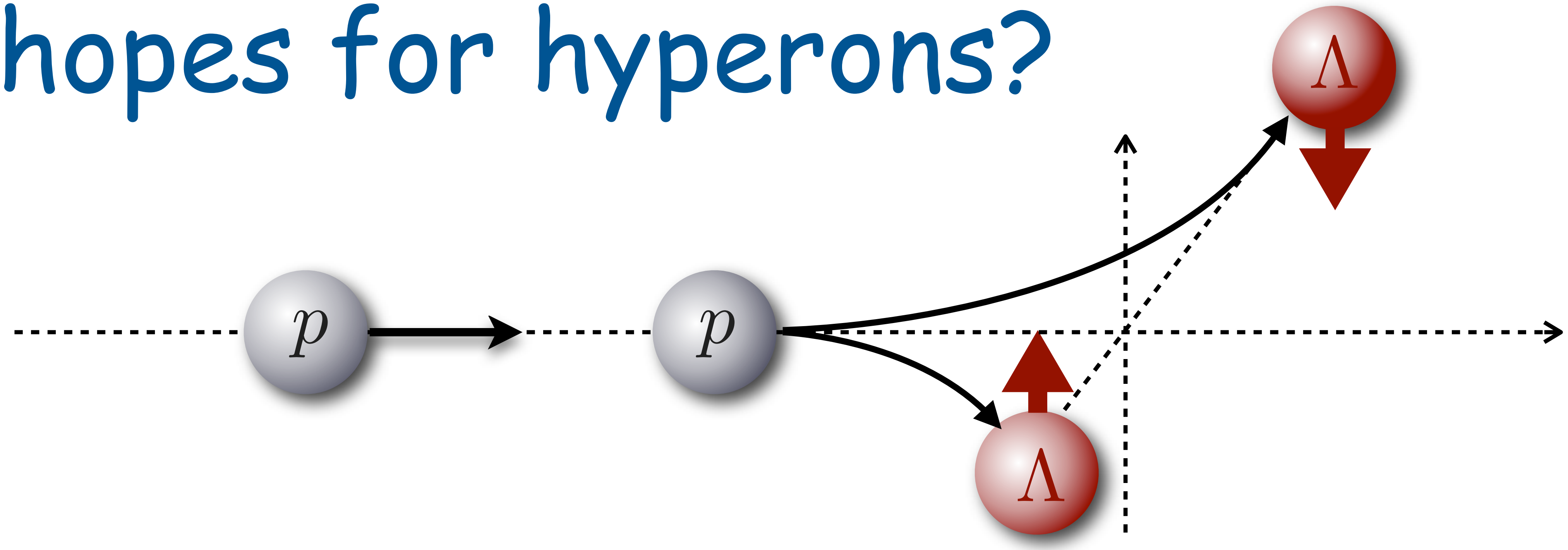


- interpretation using impact-parameter dependent PDFs qualitatively describe many experimental findings
- requires quantitative treatment

[Burkardt, PRD 66 (2002) 114005]

more hopes for hyperons?



- when TMD approach to pp better understood try polarizing FF:

quark pol.

hadron pol.

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- but first check with e^+e^- people: can measure FF much better

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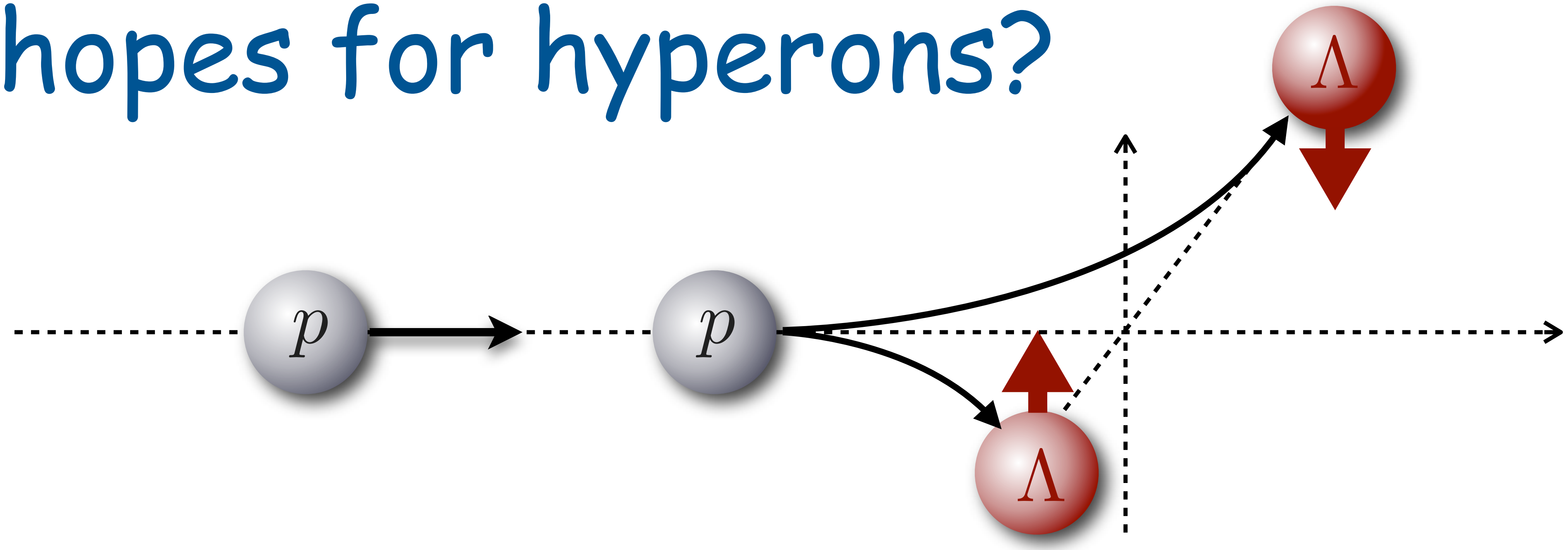

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	L		G_1	$H_{1L}^{\perp}$
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  - **dihadron** fragmention as tool to measure transversity
  - rich phenomenology details ☛ S. Melis
- hadron production in pp: details ☛ M. Anselmino
  - no clear interpretation of A_N (sign mismatch between Sivers and twist-3, large asymmetries even at high pT, ...)
  - signals of Collins and dihadron fragmentation

Conclusion

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  - non-zero transversity, and correlation between transverse hadron momentum and transverse spin of fragm. quark (**Collins effect**)
  - **dihadron** fragmention as tool to measure transversity
  - rich phenomenology   details ☛ S. Melis
- hadron production in pp: details ☛ M. Anselmino
  - no clear interpretation of A_N (sign mismatch between Sivers and twist-3, large asymmetries even at high p_T, ...)
  - signals of Collins and dihadron fragmentation
- hint of a non-zero **valence Boer-Mulders** function from DY