Correlations in Partonic and Hadronic Interactions 2018
Yerevan, September 24-28, 2018

Transverse-momentum distributions in electro-production and e^+e^- annihilation

selected results from
HERMES as well as BaBar, Belle and BESIII

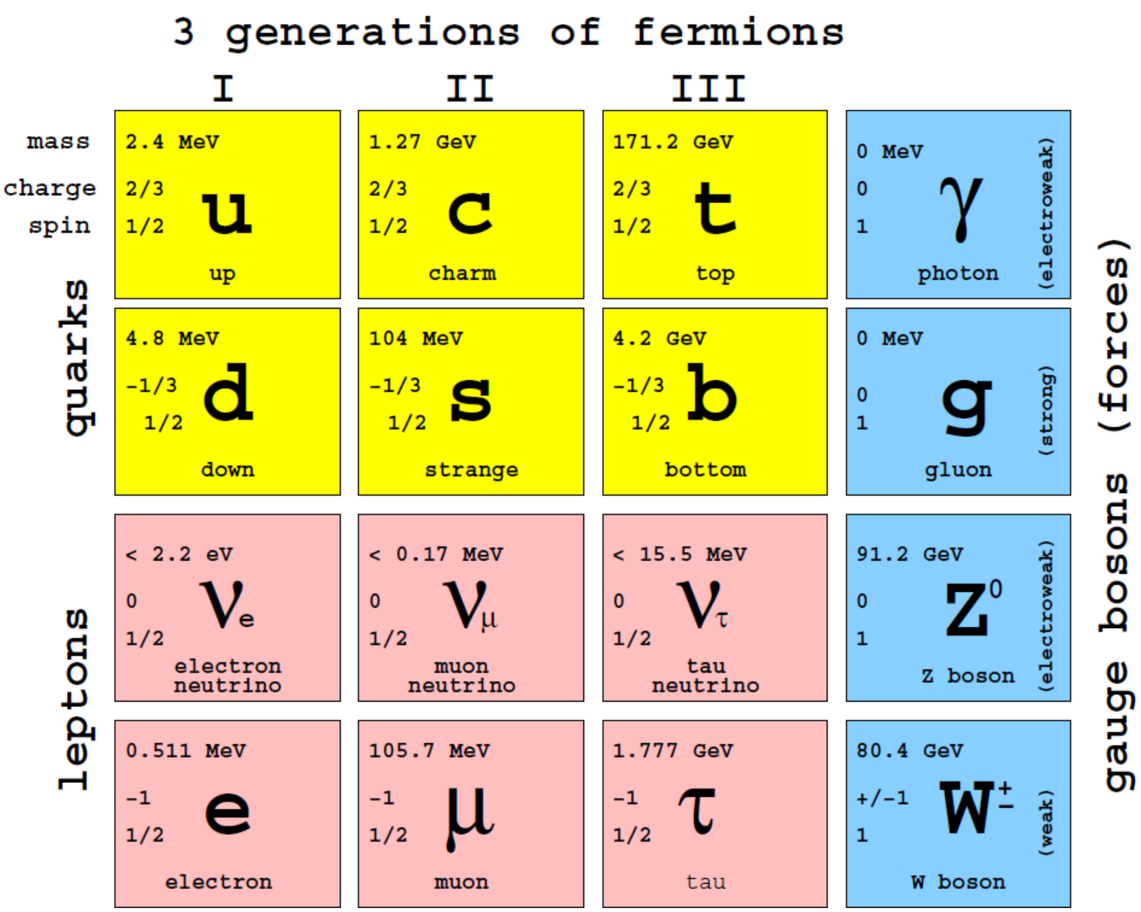
ikerbasque
Basque Foundation for Science

Gunar.Schnell @ DESY.de

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

what makes the visible universe

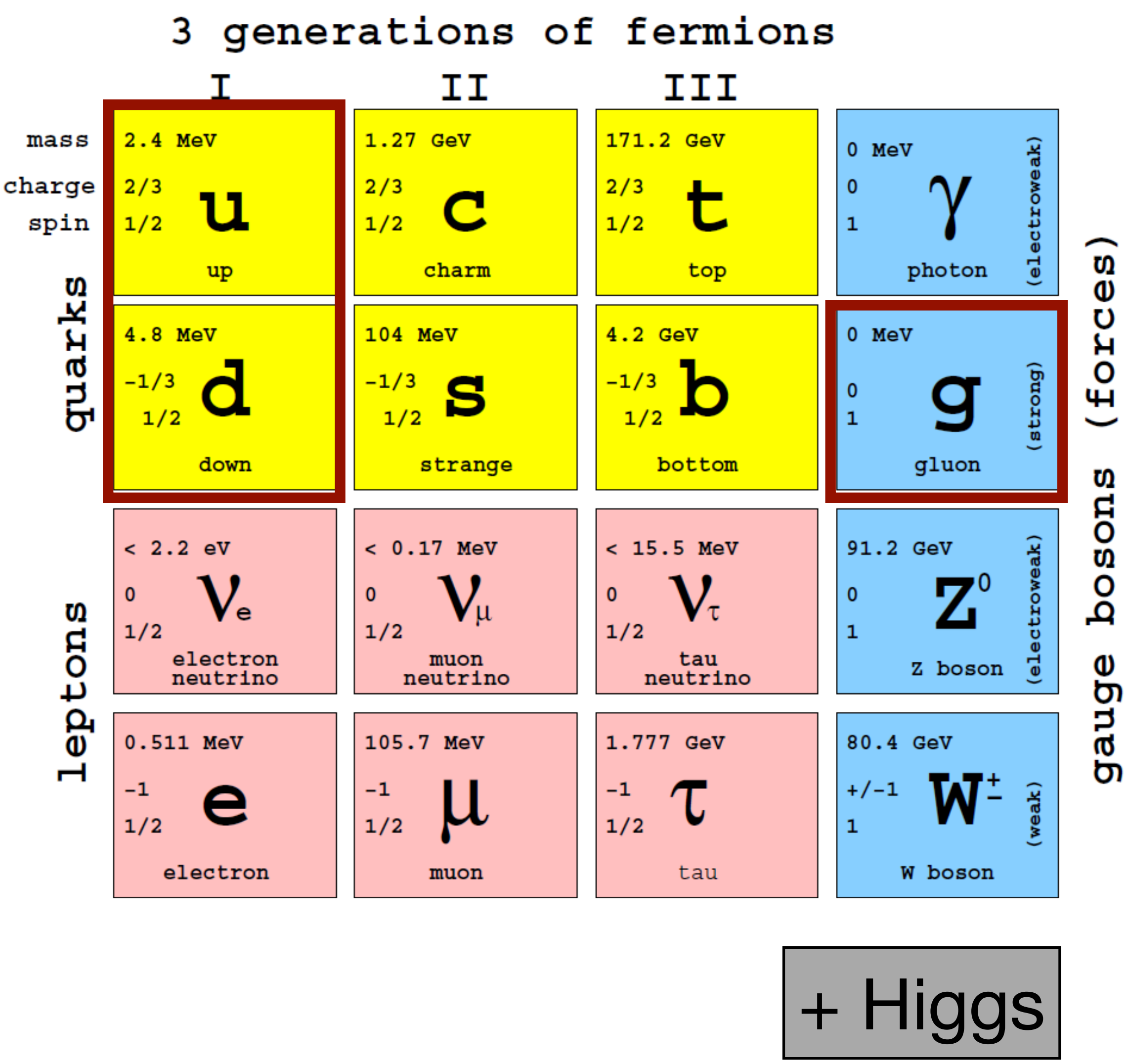
standard model



+ Higgs

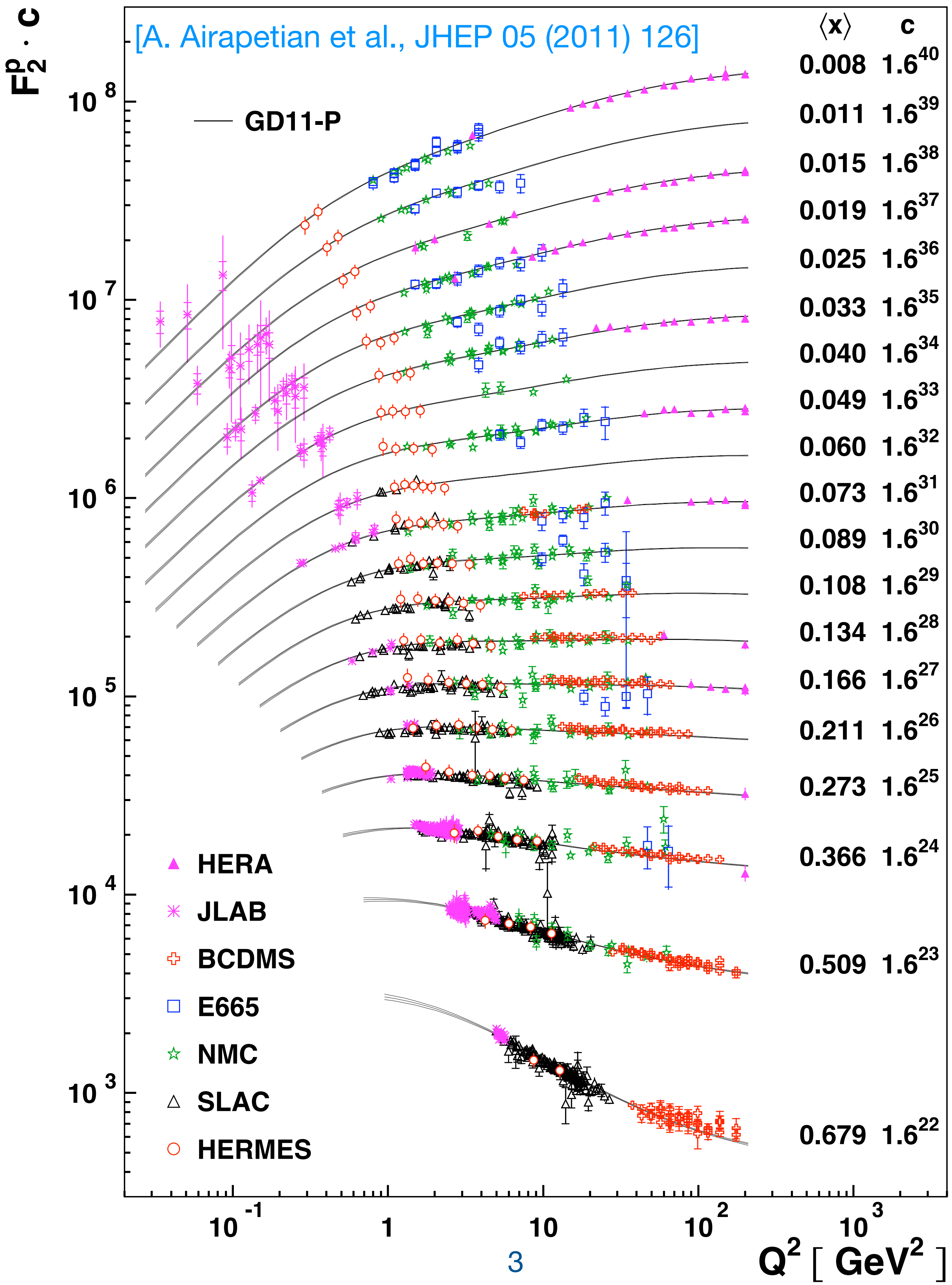
what makes the visible universe

standard model



- not Higgs but non-abelian quantum chromodynamics (QCD) responsible for mass in every-day life
- 40+ years success story of (p)QCD
- but non-perturbative part (**hadron structure and formation**) still a vast, partly unexplored field

4+ decades of QCD - a success story



4+ decades of QCD - a success story?

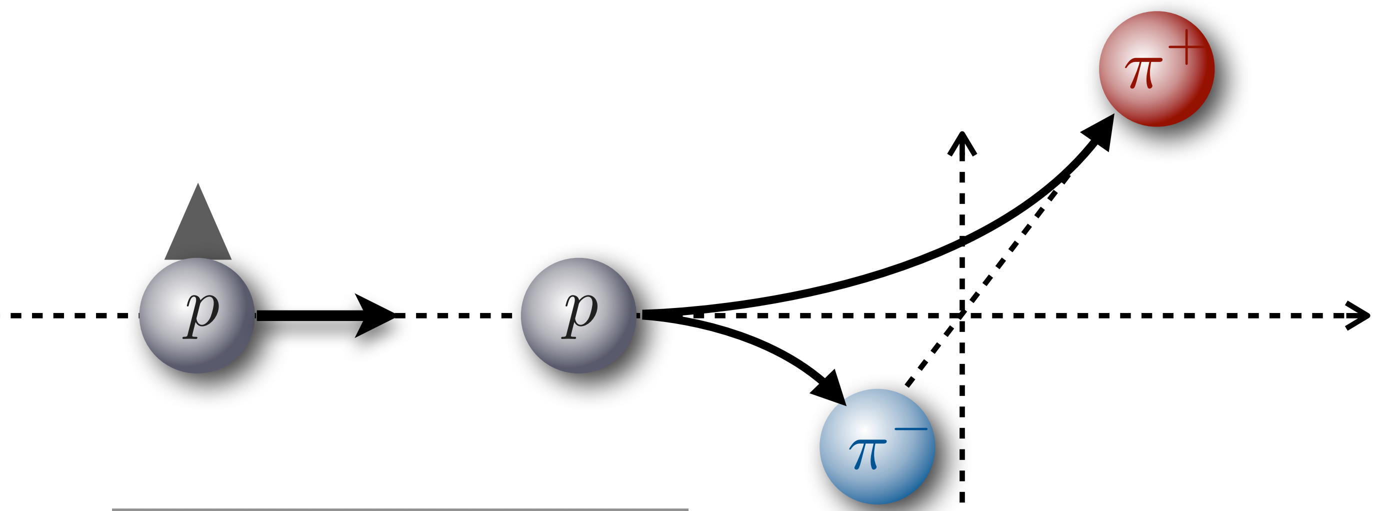
$\frac{1}{2} = \frac{1}{2} \Delta\Sigma$ ⟵ quark spin ≈ ½ **1/3**

$+ \Delta G$ ⟵ gluon spin ≈ 0 / small

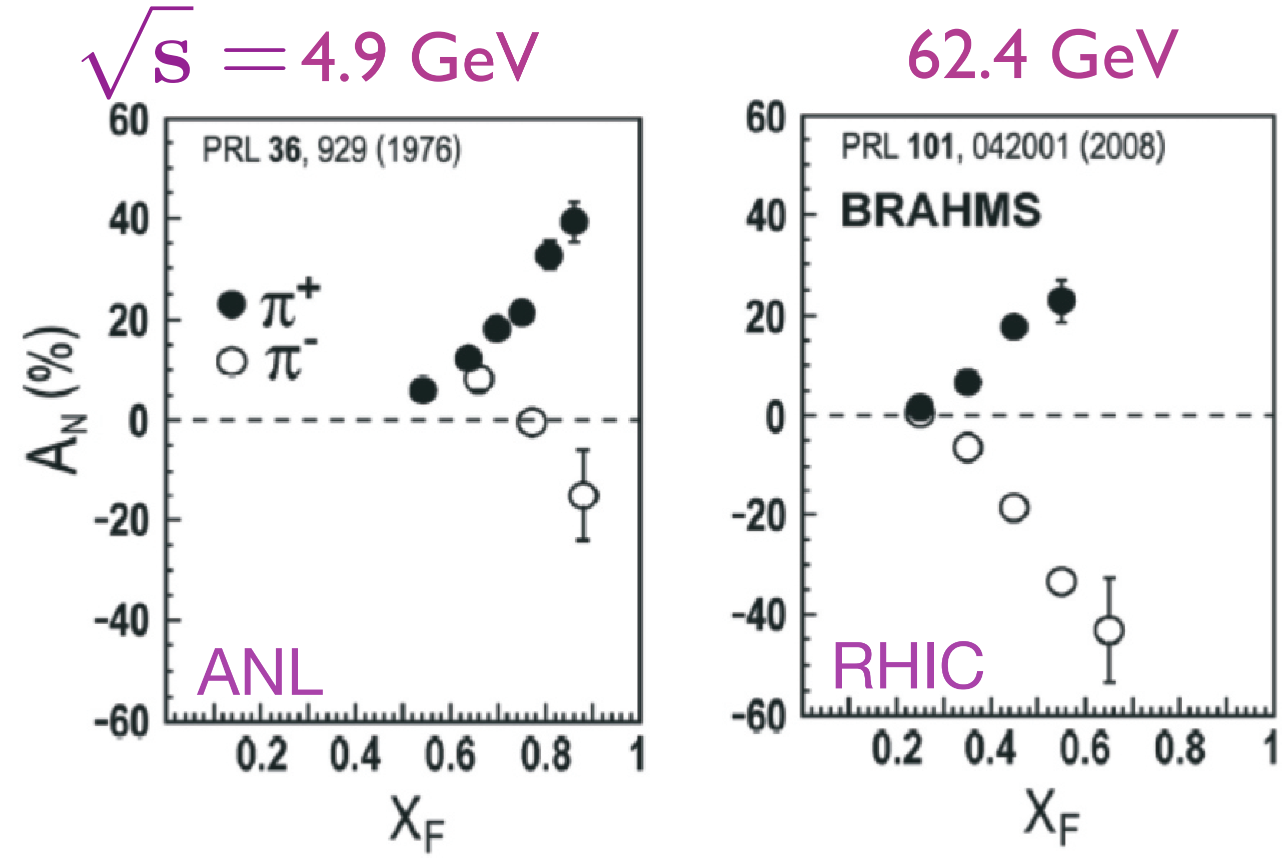
$+ L_{\mathbf{q}} + L_{\mathbf{g}}$ ⟵ orbital angular momentum ≈ **?**

- spin of the nucleon

4+ decades of QCD - a success story?



$$\boxed{A_N \propto \alpha_S \frac{m_q}{Q^2}}$$

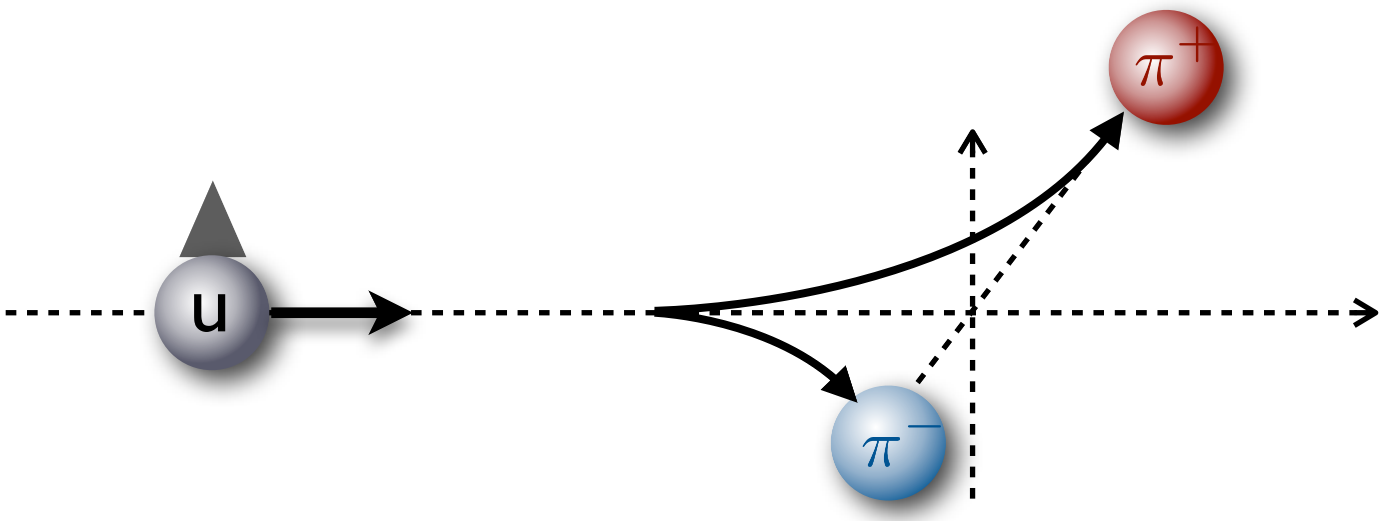


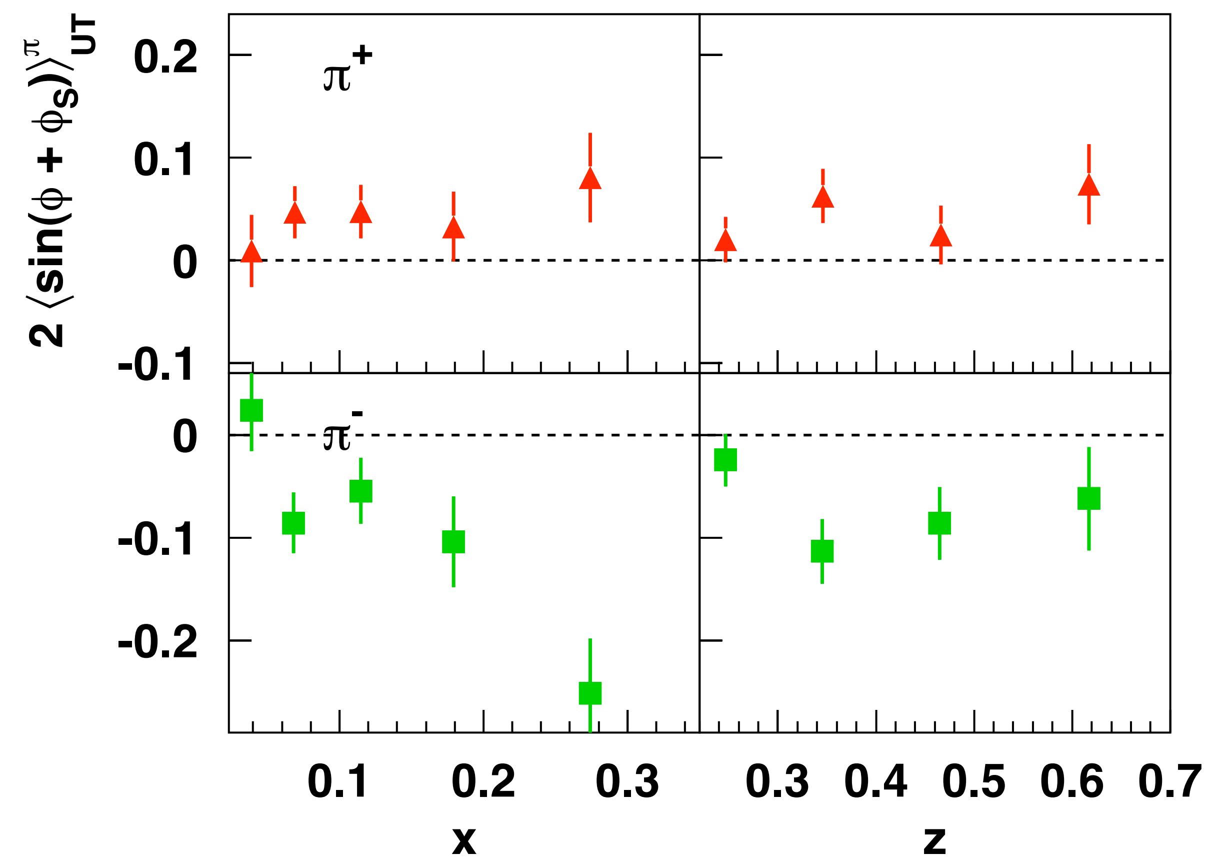
1976

2008

- spin of the nucleon
- transverse single-spin asymmetries in pp collision

4+ decades of QCD - a success story?



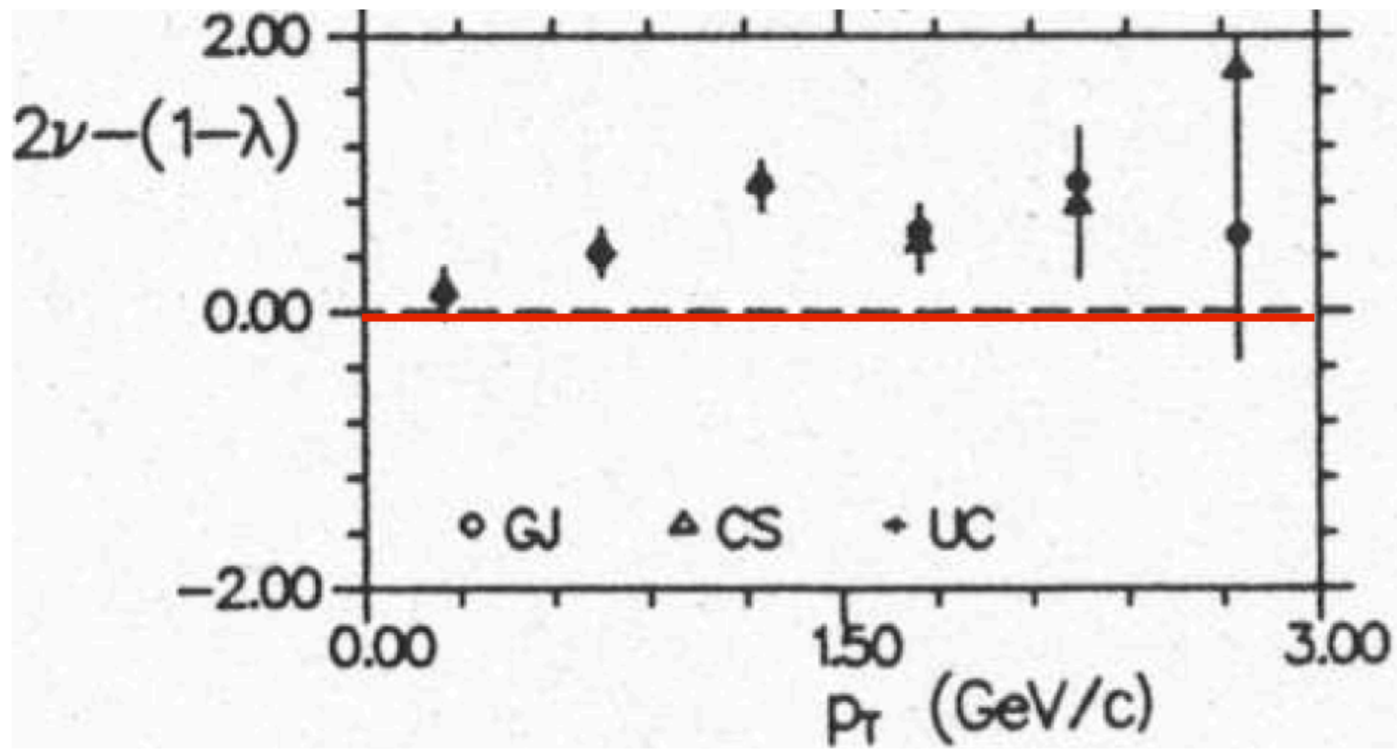


- spin of the nucleon
- transverse single-spin asymmetries in pp collision
- hadron-momentum preference in hadronization of pol. quarks

4+ decades of QCD - a success story?

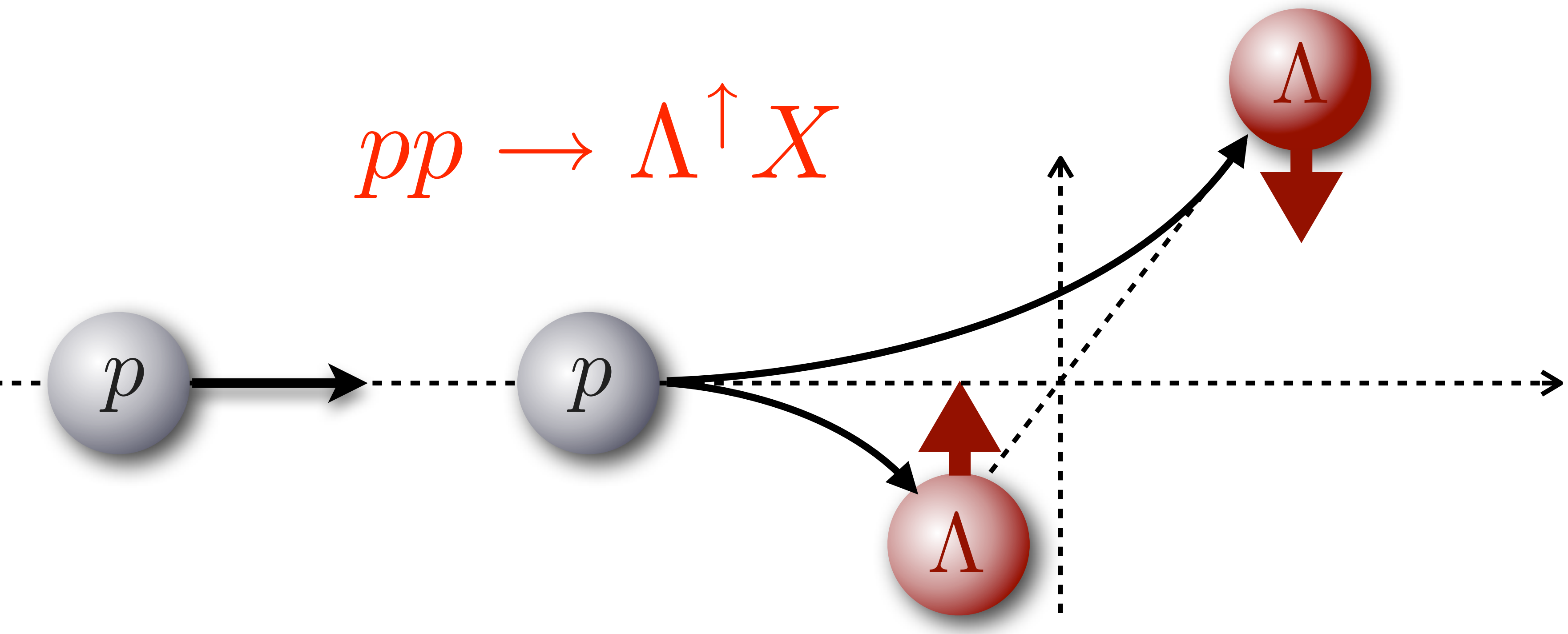
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

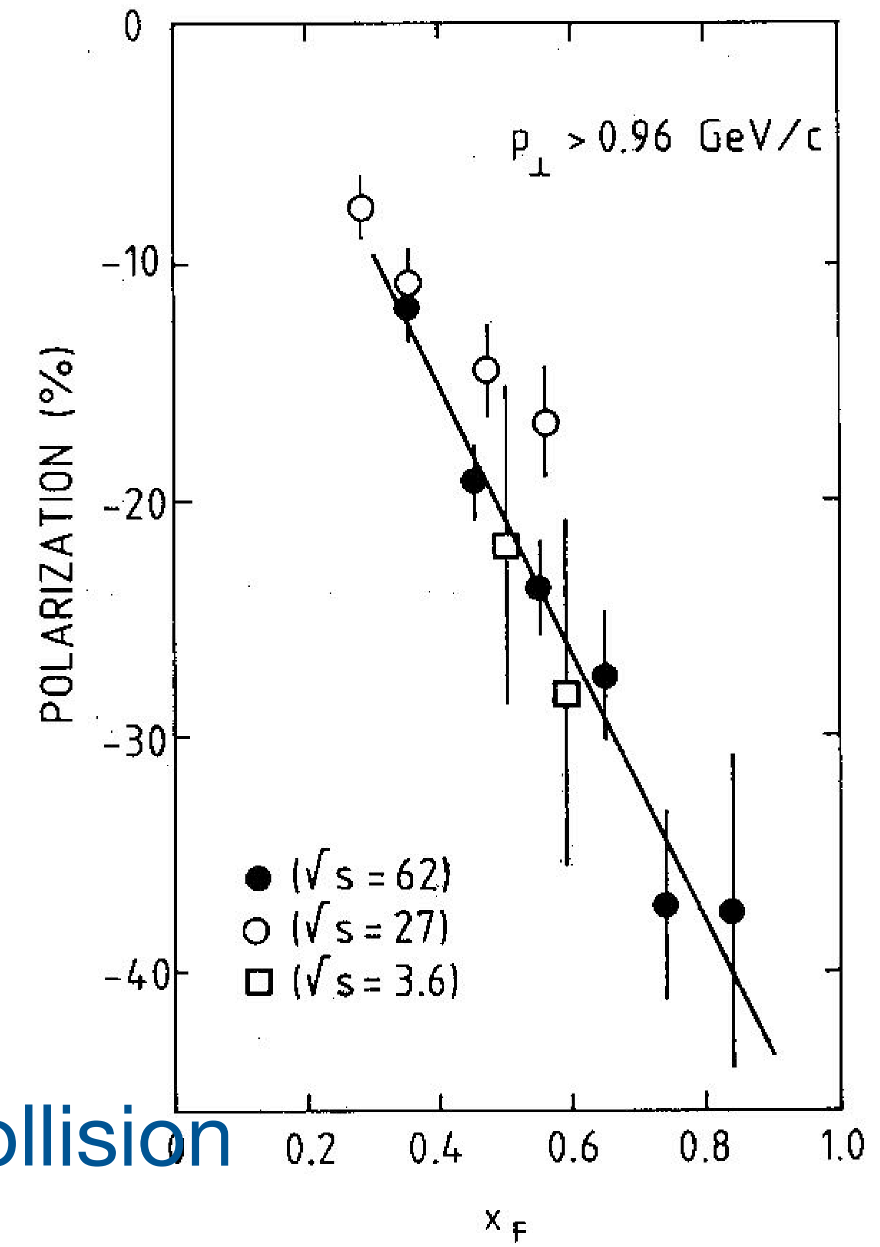
$$\boxed{1-\lambda-2\nu=0}$$



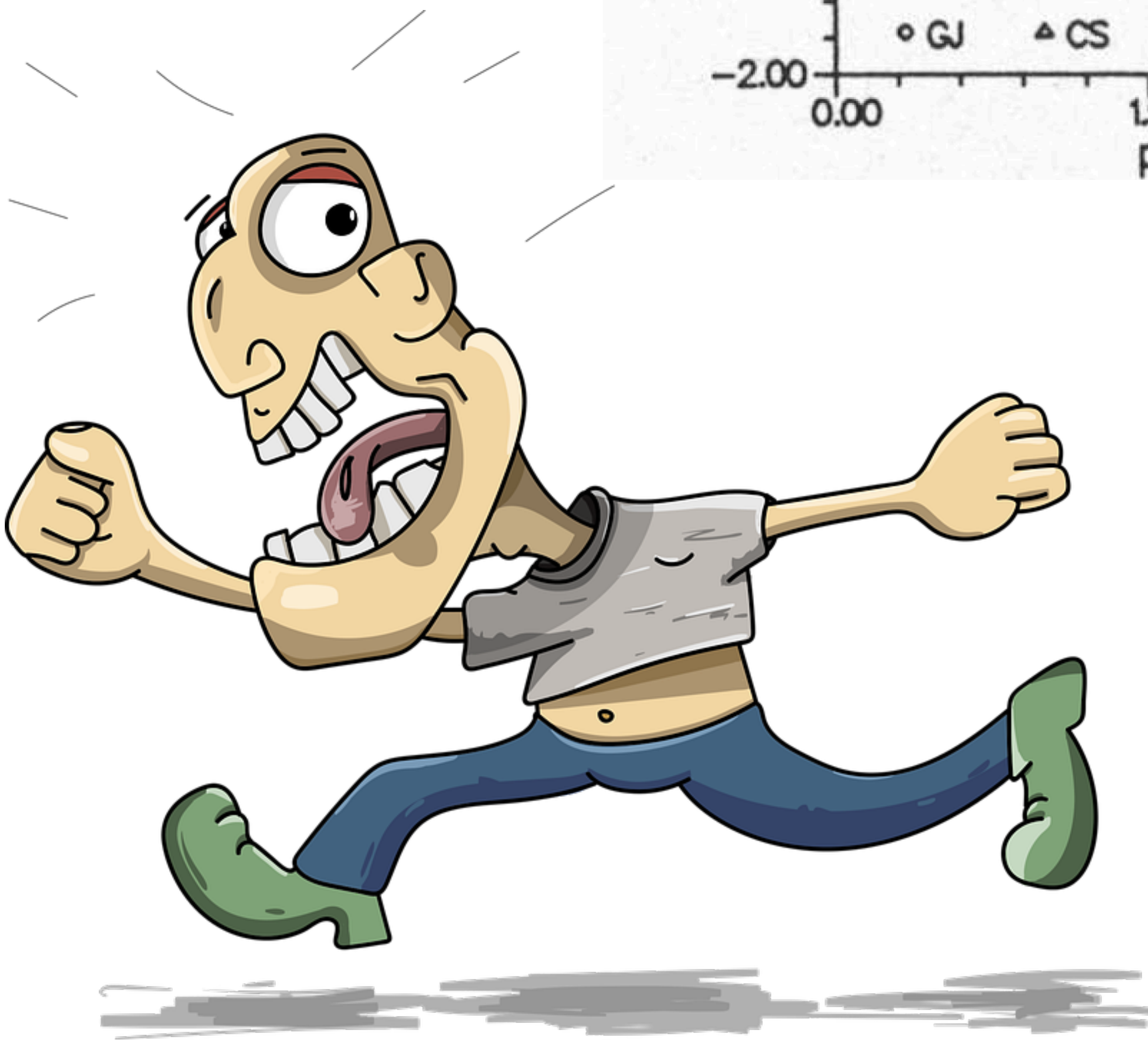
- spin of the nucleon
- transverse single-spin asymmetries in pp collision
- hadron-momentum preference in hadronization of pol. quarks
- violation of Lam-Tung relation in Drell-Yan

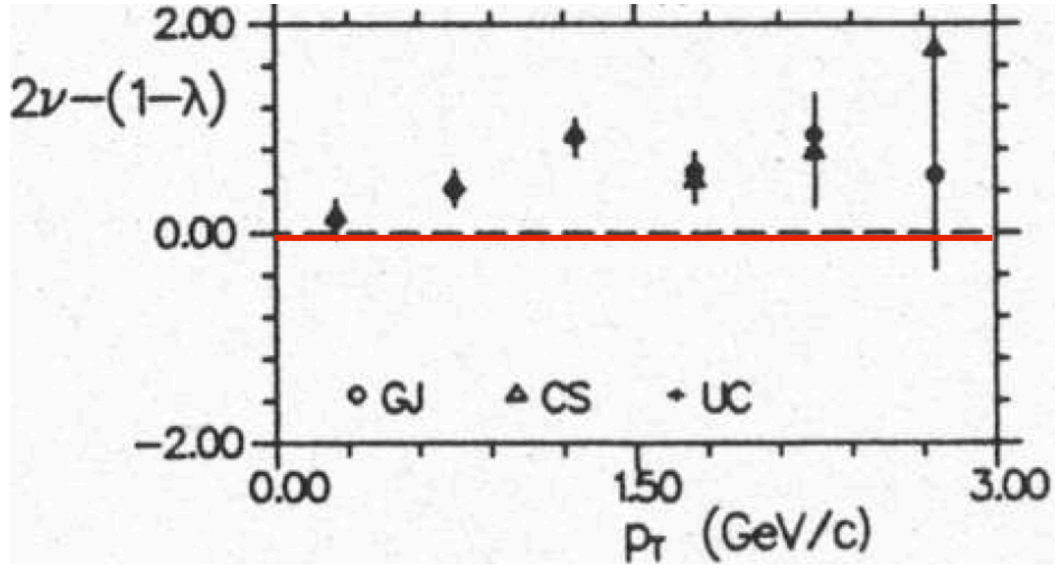
4+ decades of QCD - a success story?

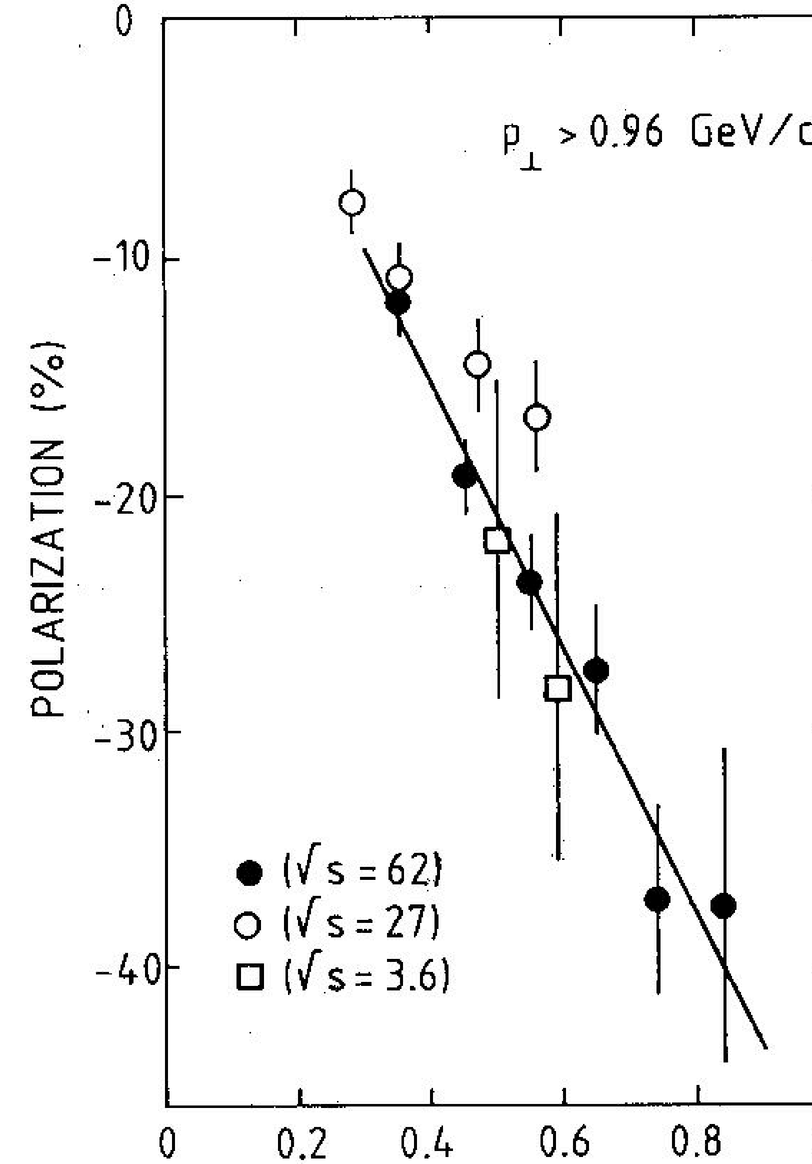




- spin of the nucleon
- transverse single-spin asymmetries in pp collision
- hadron-momentum preference in hadronization of pol. quarks
- violation of Lam-Tung relation in Drell-Yan
- large hyperon polarization in unpolarized proton collisions

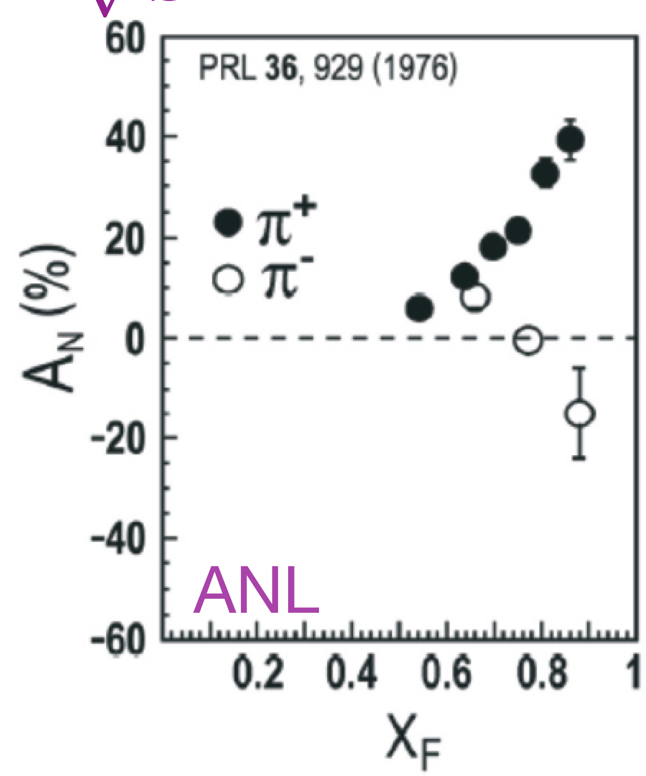


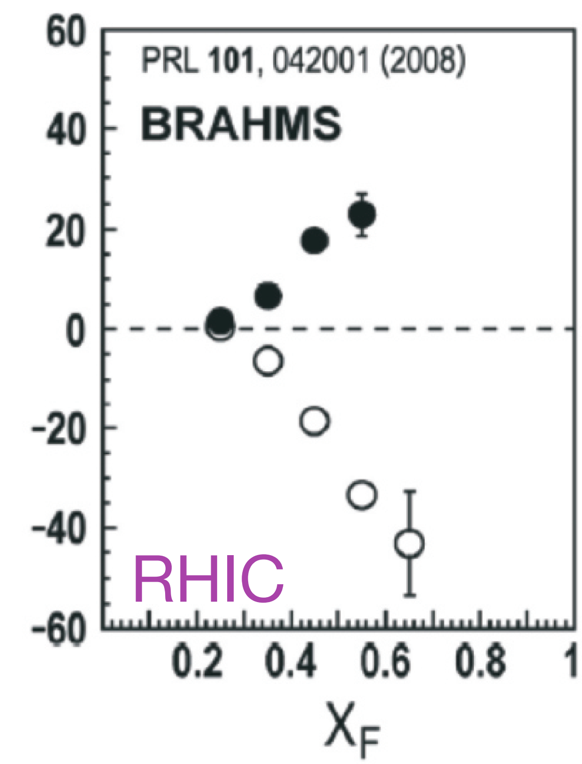


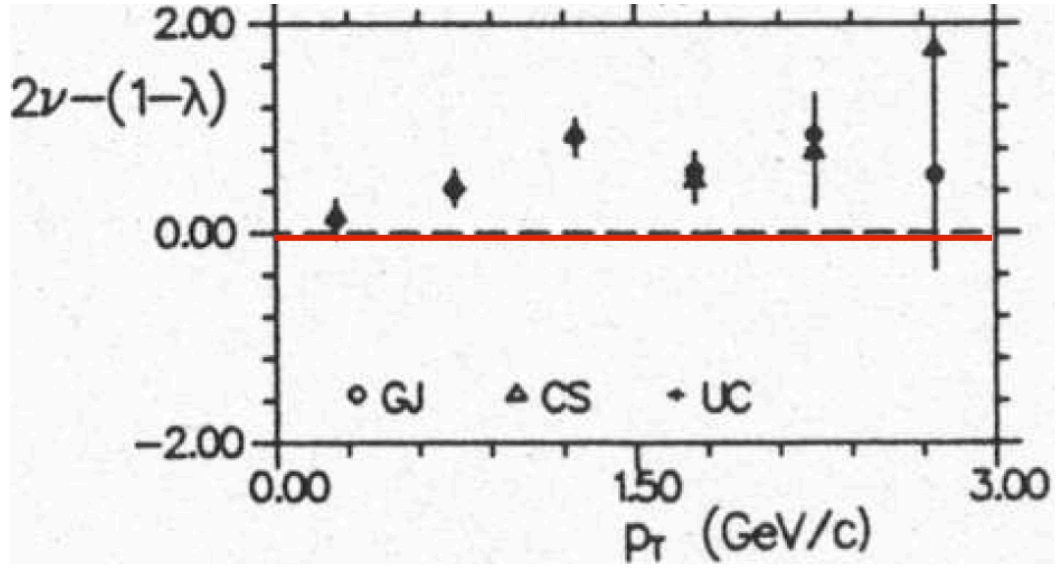


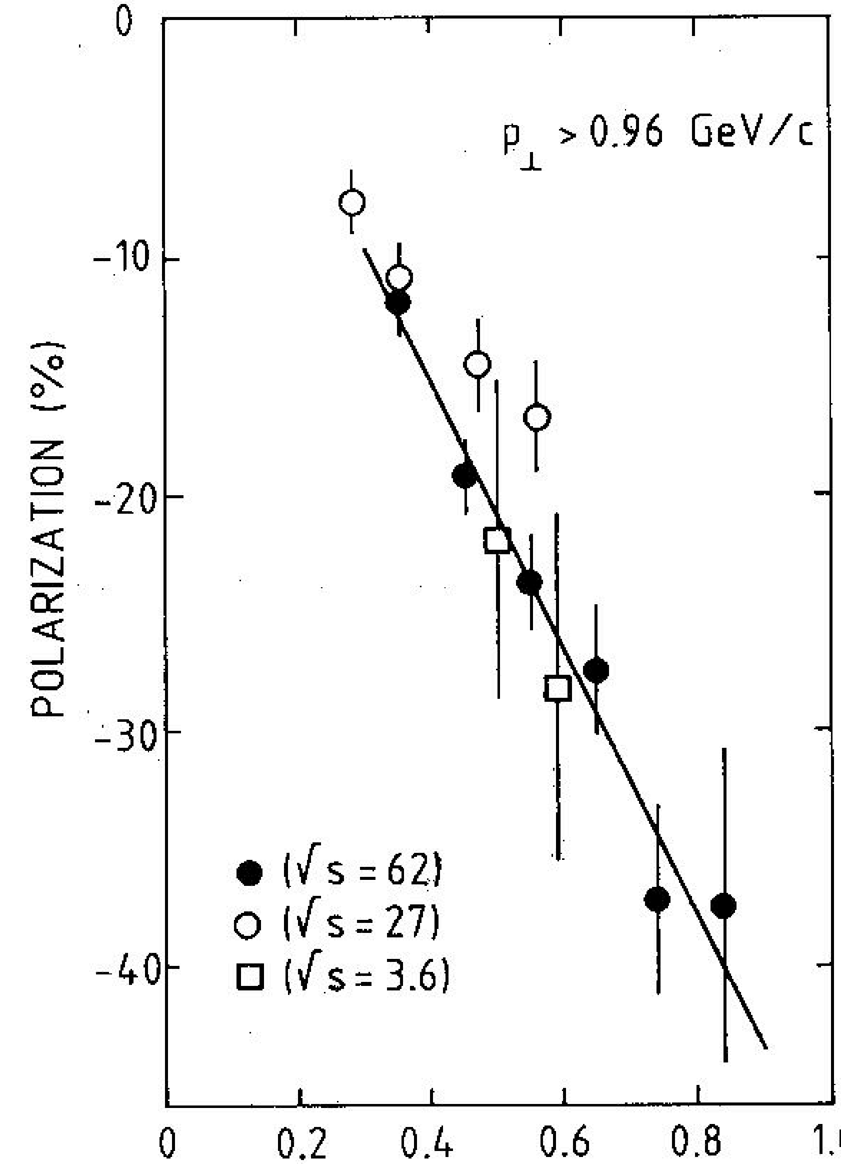
$\sqrt{s} = 4.9$ GeV

62.4 GeV









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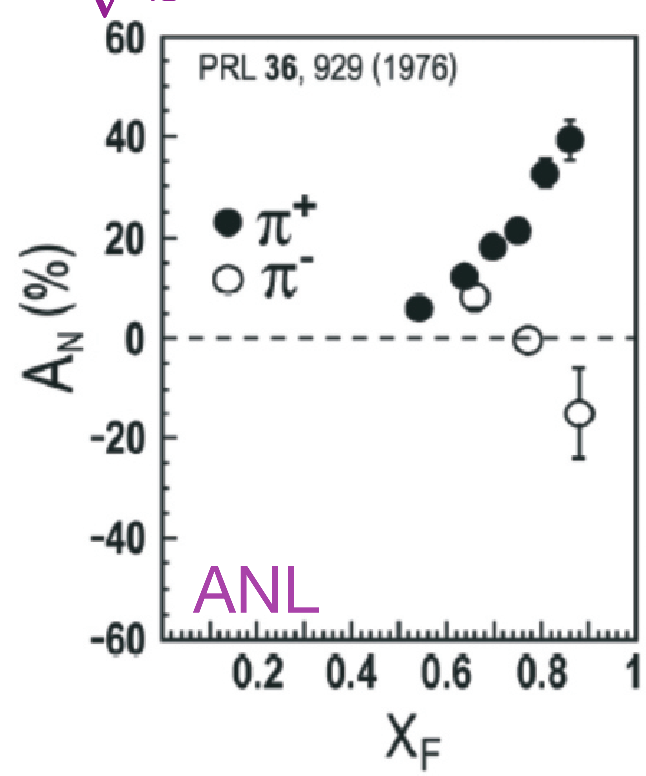
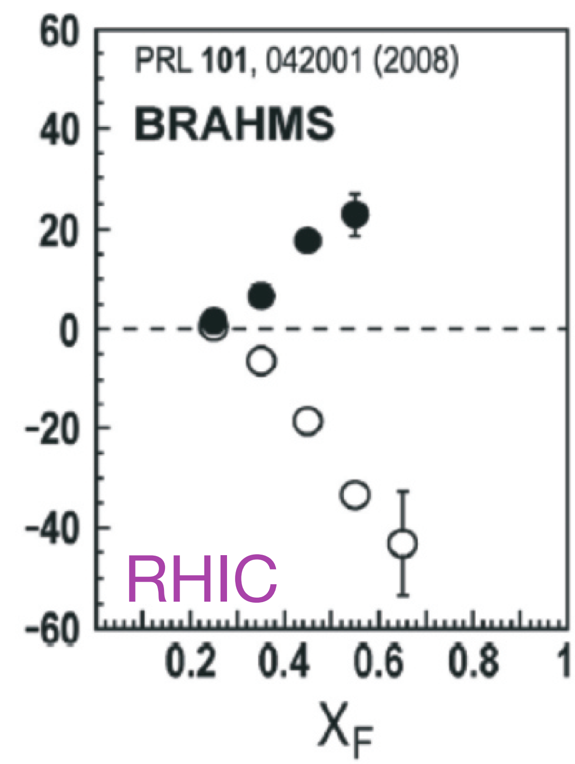
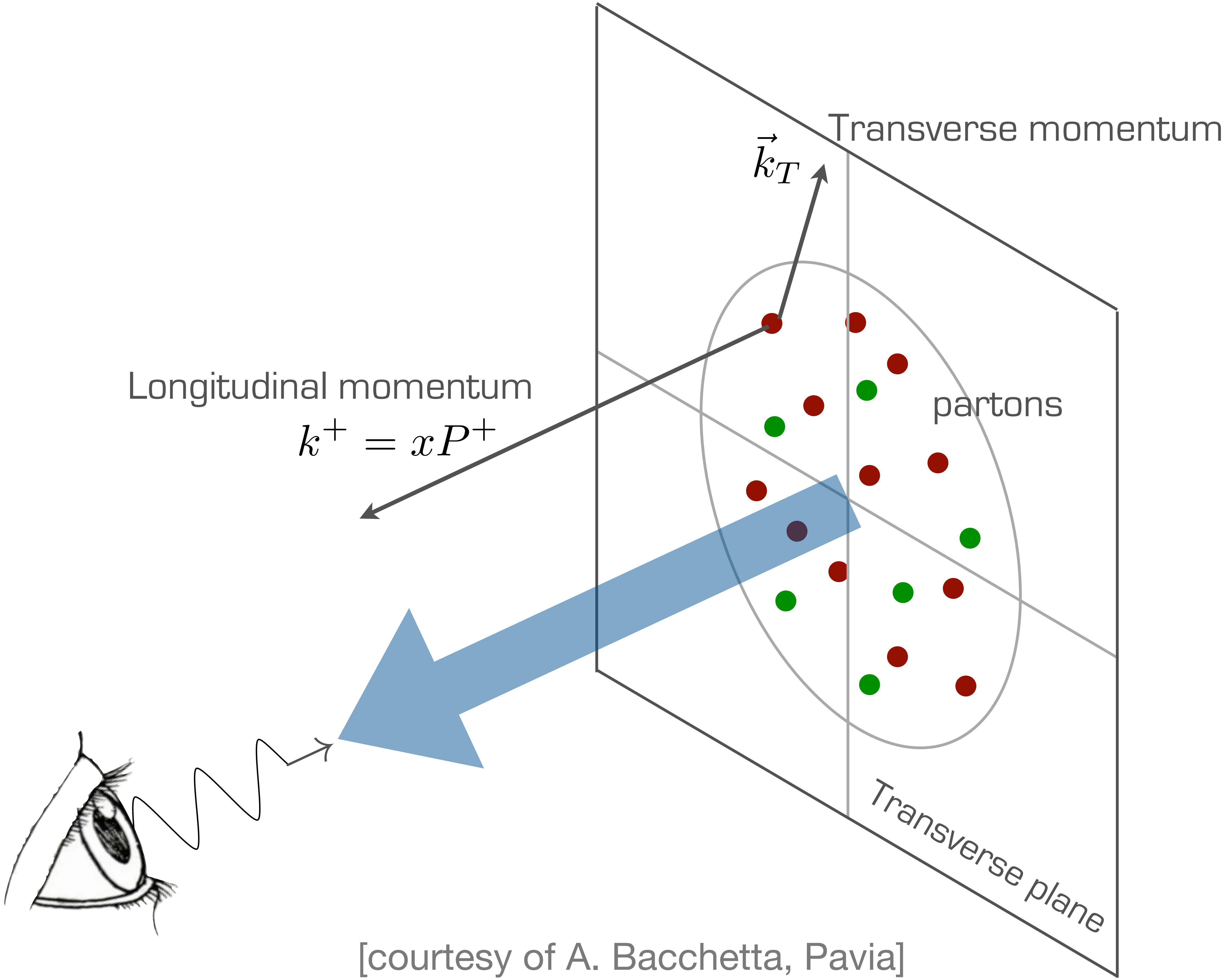




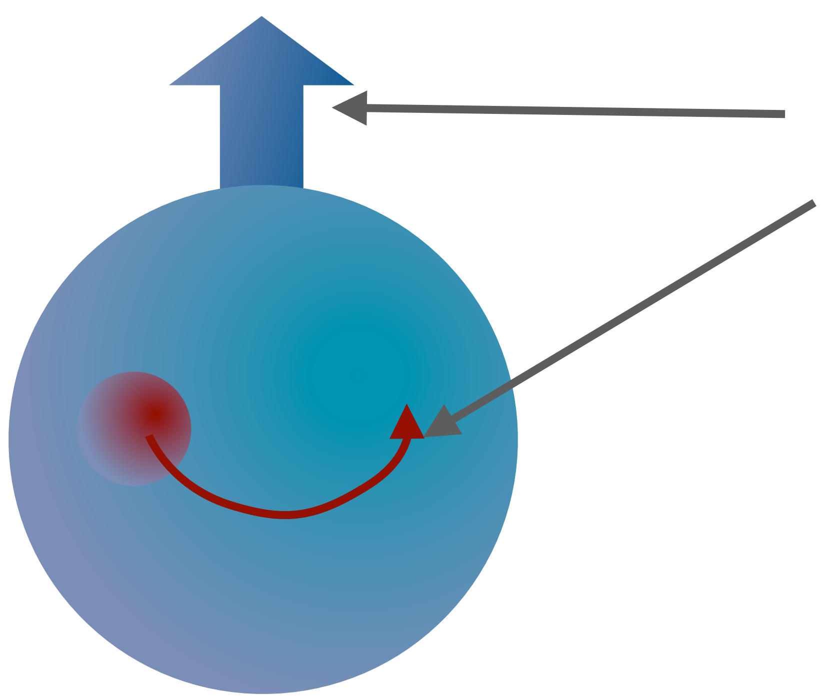
transverse-momentum distributions



[courtesy of A. Bacchetta, Pavia]

transverse-momentum distributions

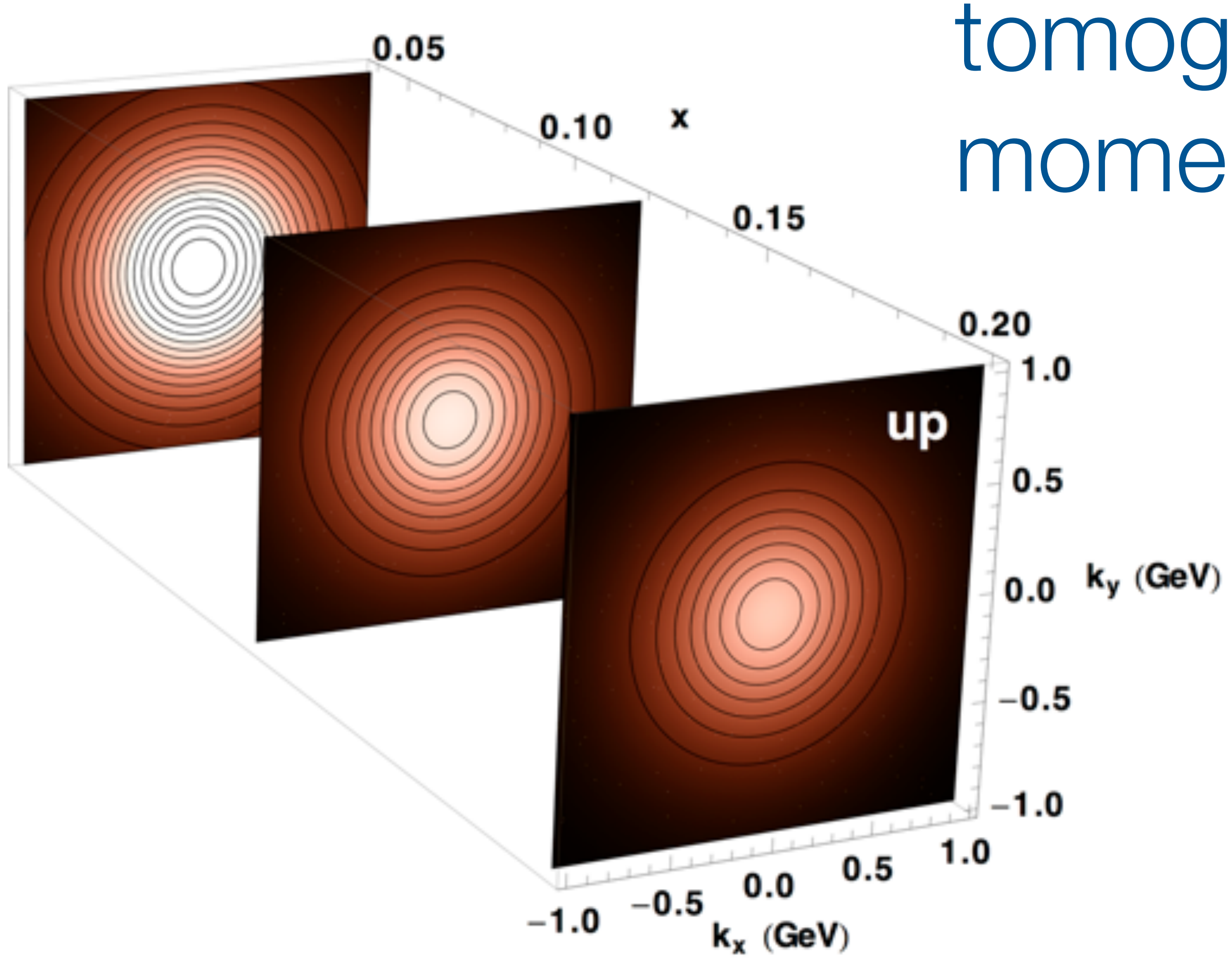
- go beyond collinear description of original quark-parton model
- explore correlations between spins and transverse momenta
- new insights into workings of QCD



- **e.g., Sivers effect:**
  - correlation between nucleon (transverse) polarization and quark transverse momentum
  - linked to orbital angular momentum
  - **rigorous QCD prediction:** breaking of universality of parton distributions by **change of sign going from deep-inelastic scattering to Drell-Yan**

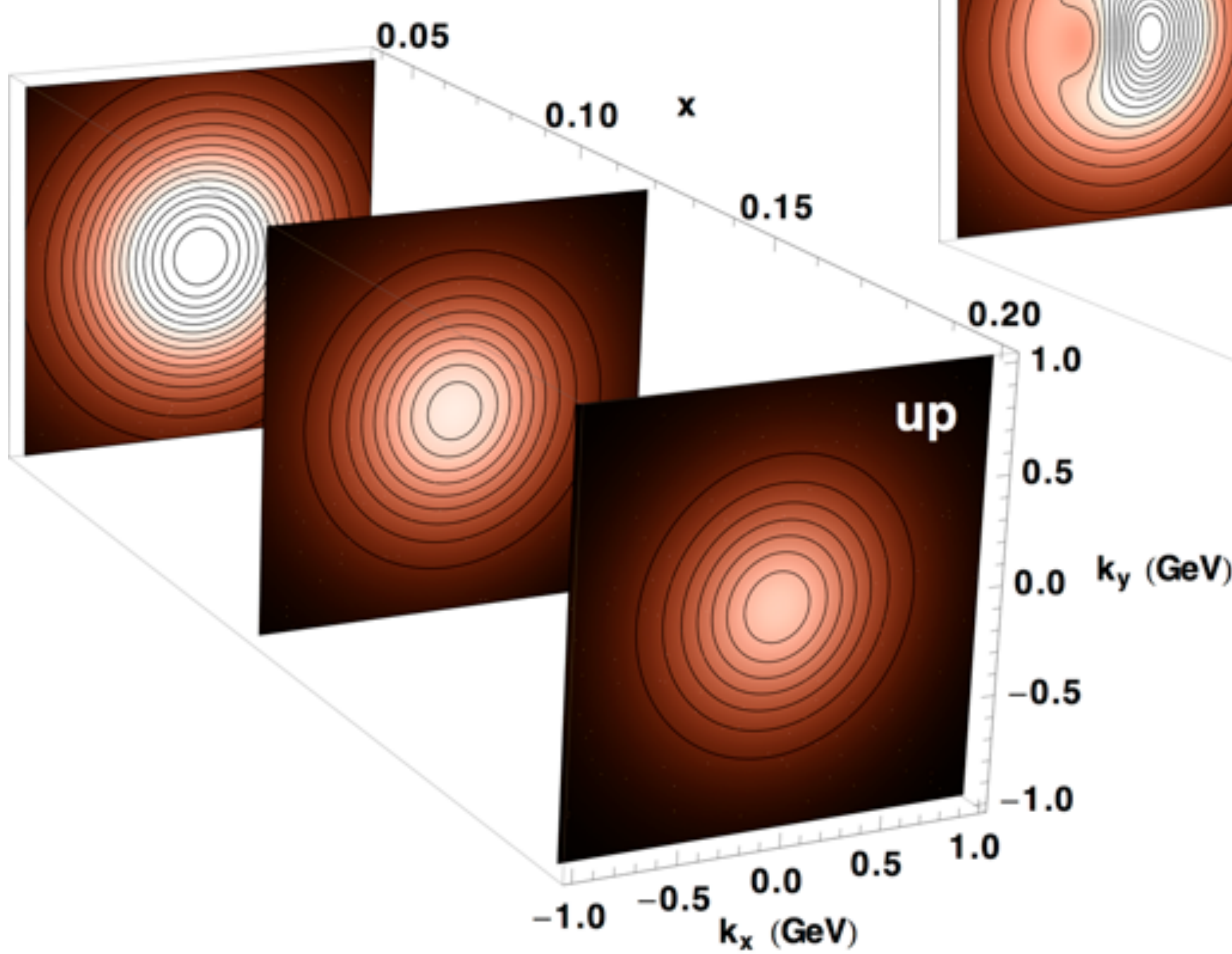
transverse-momentum distributions

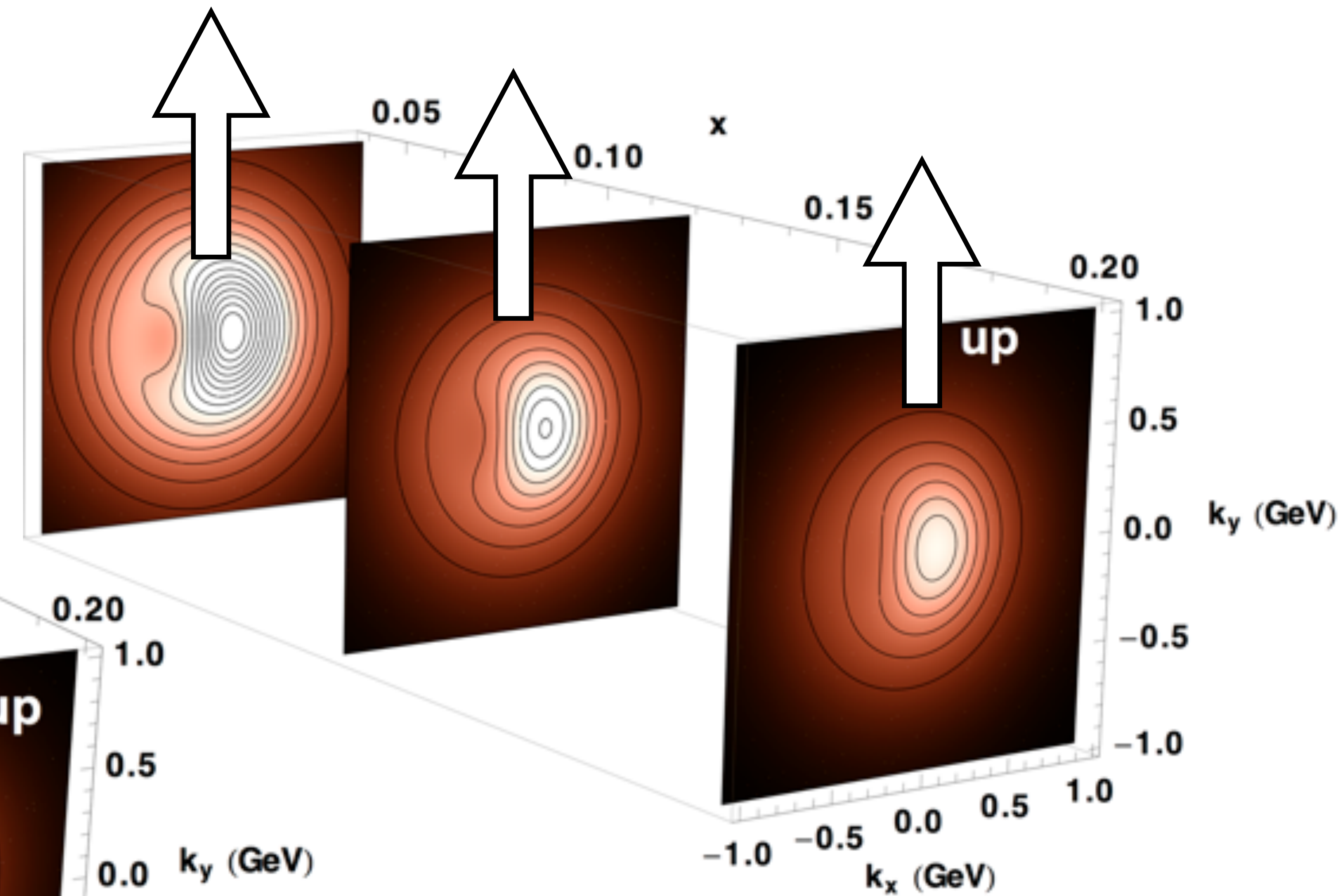
$f_1(x, k_T^2)$



flavor-dependent tomographic maps in momentum space

transverse-momentum distributions

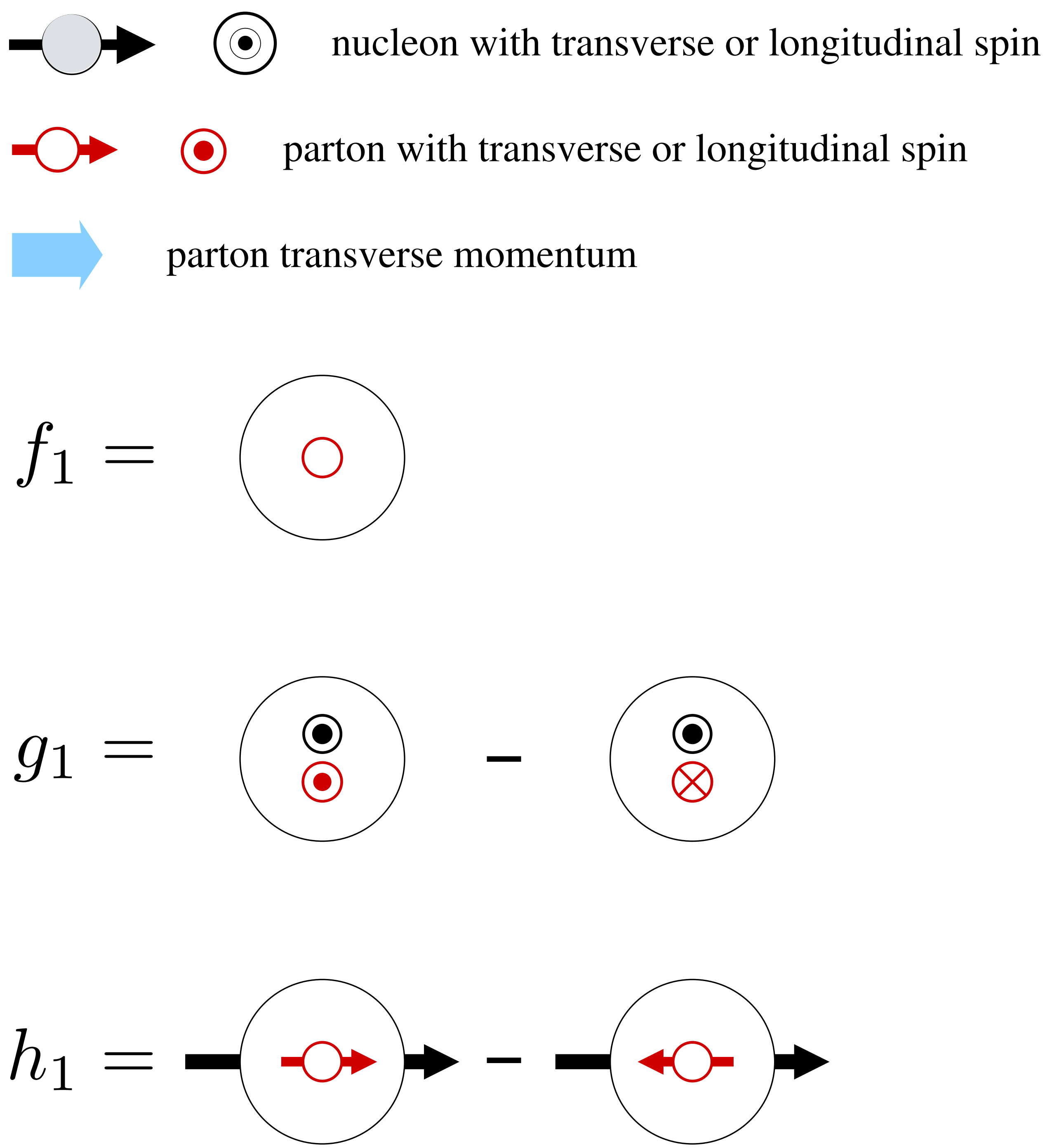


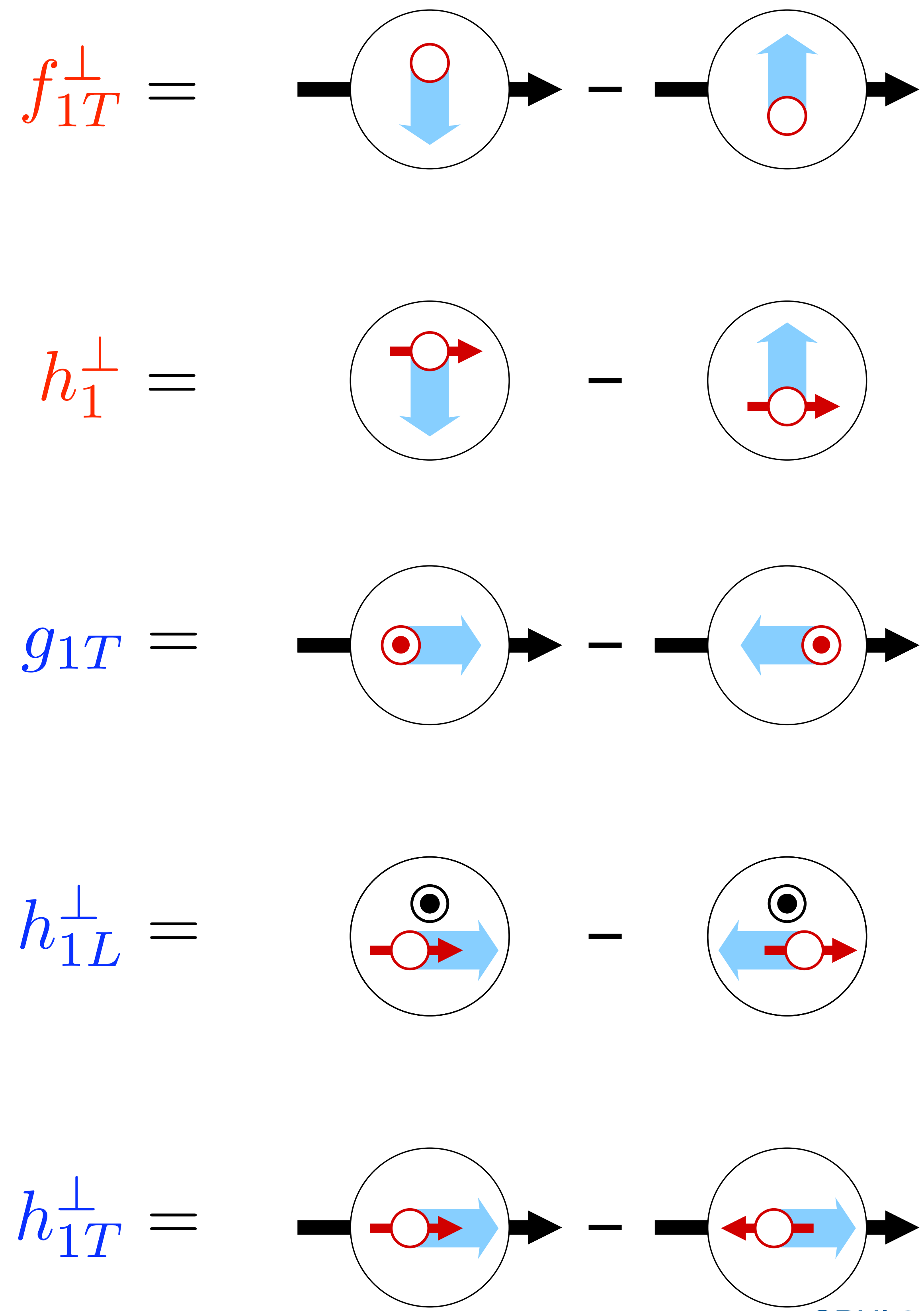


with spin:
many possible
configurations

TMDs - probabilistic interpretation

proton goes out of the screen / photon goes into the screen





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TMDs - probabilistic interpretation

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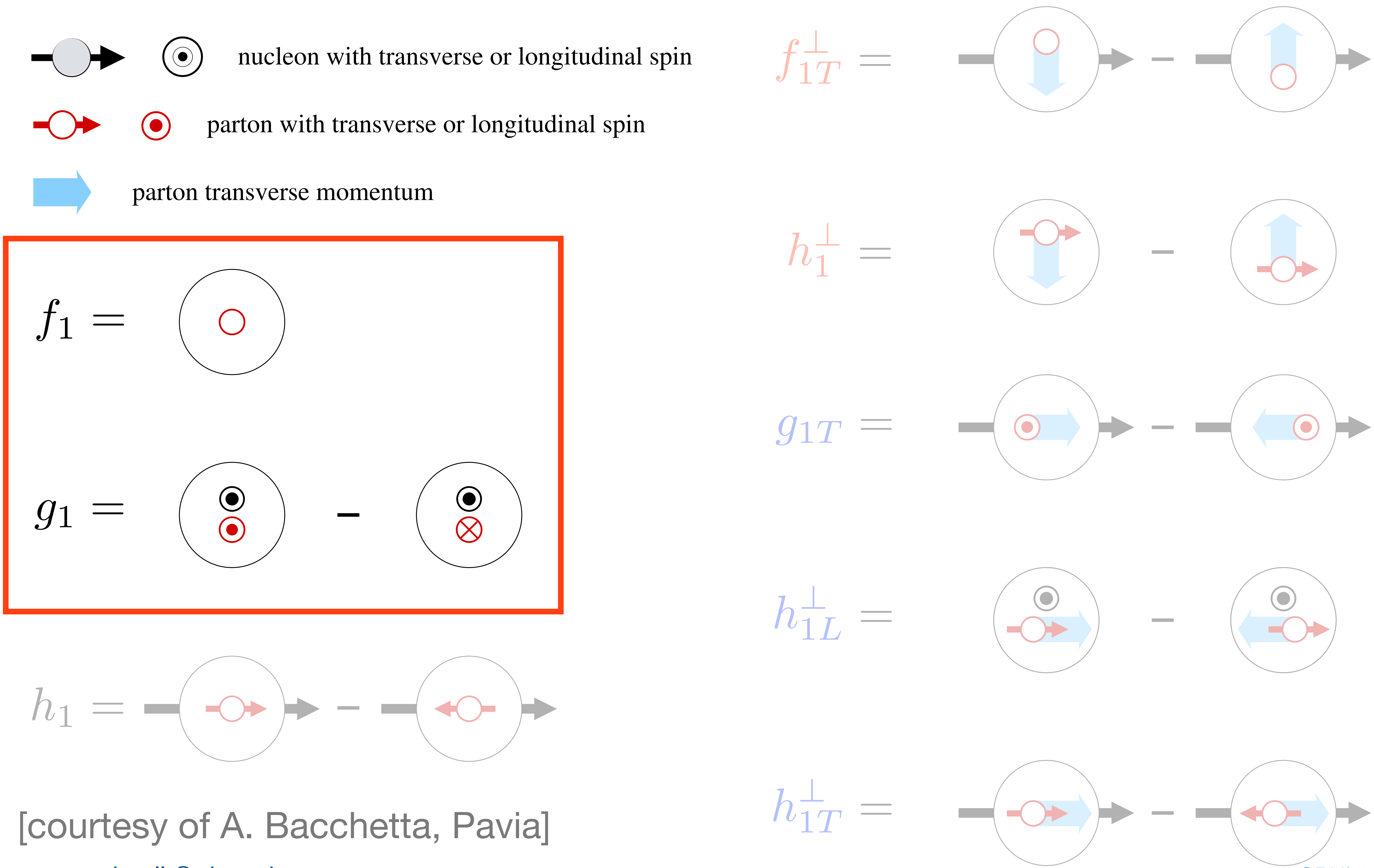
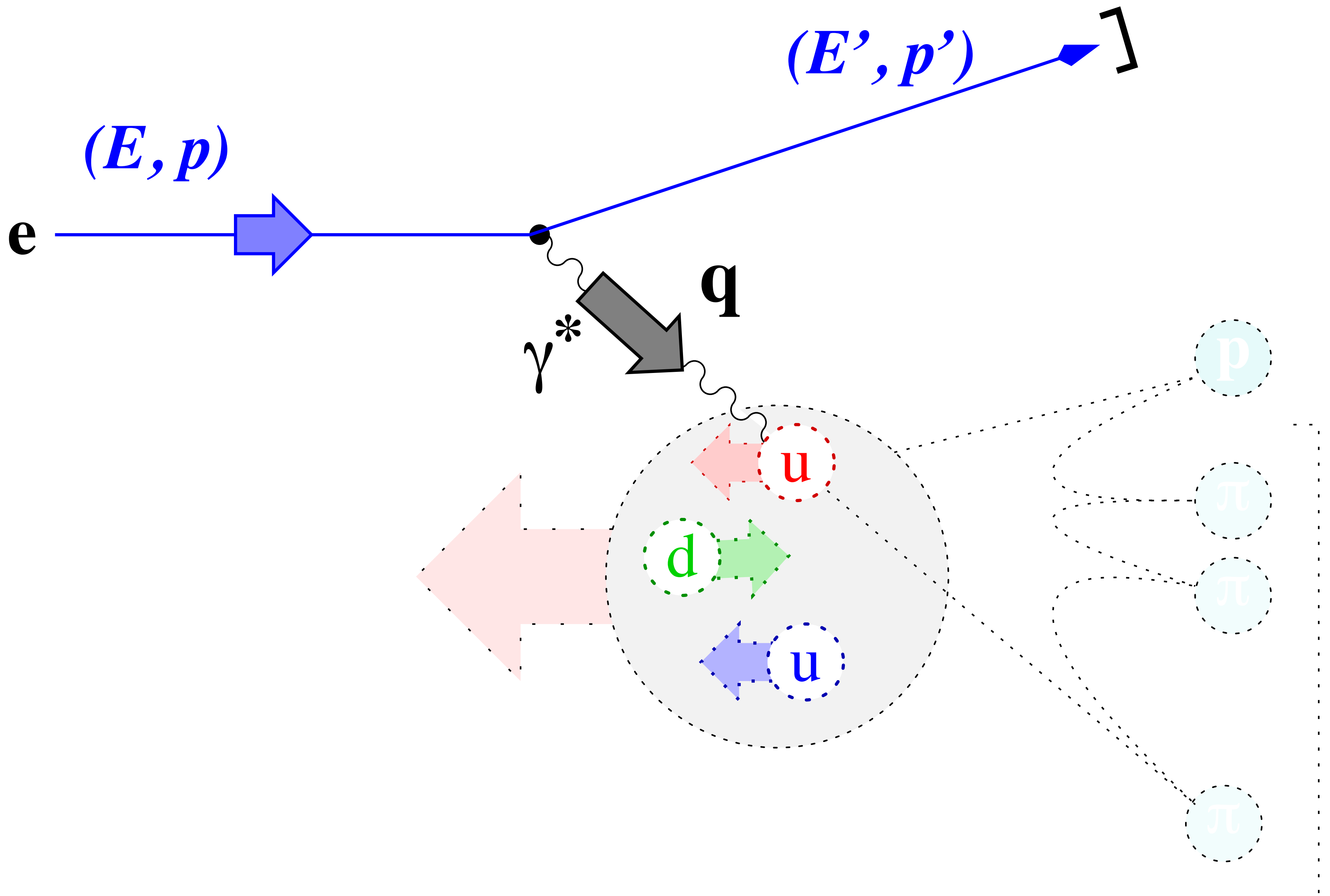


[courtesy of A. Bacchetta, Pavia]

inclusive DIS (one-photon exchange)



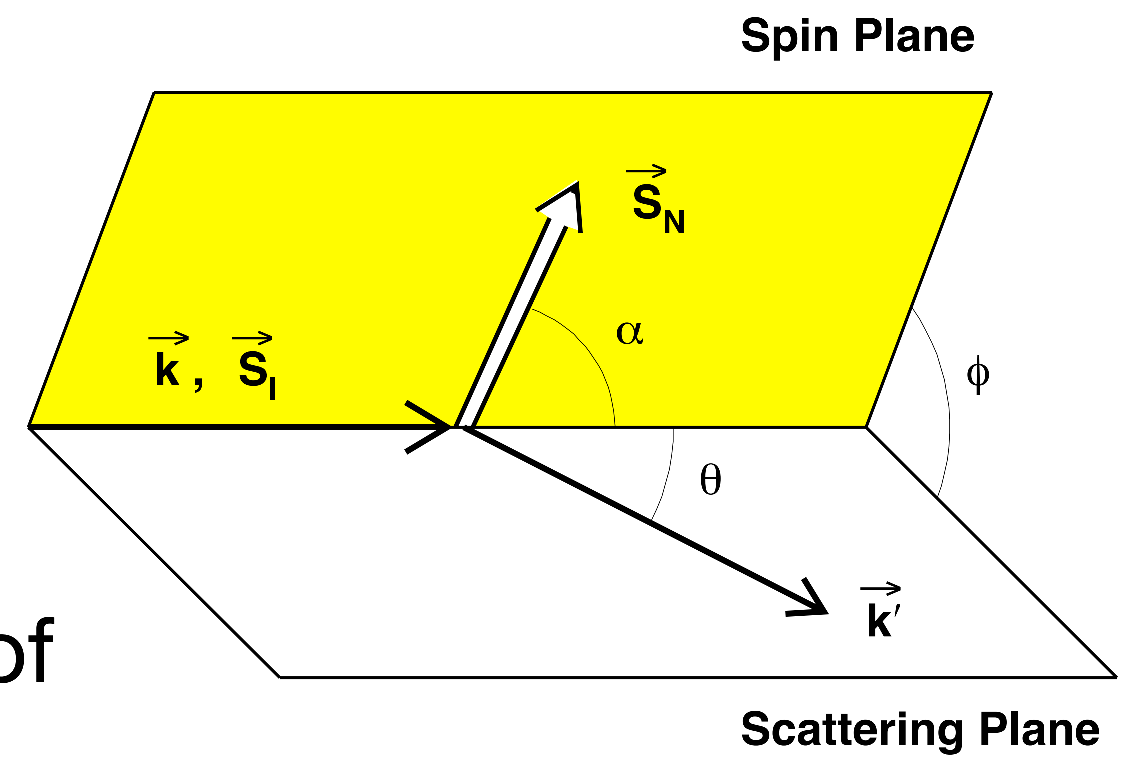
DIS … deep-inelastic scattering

inclusive DIS (one-photon exchange)

$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

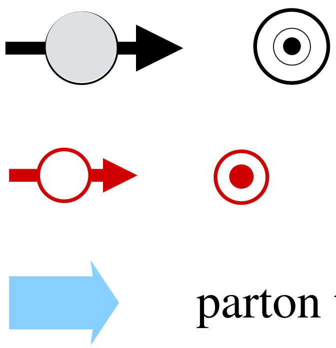
Hadron Tensor
parametrized in terms of
Structure Functions



$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$
$$-S_l S_N \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2) - \frac{\gamma^2 y}{2}g_2(x,Q^2)\right]$$
$$+S_l S_N \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

TMDs - probabilistic interpretation

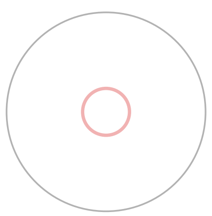
proton goes out of the screen / photon goes into the screen



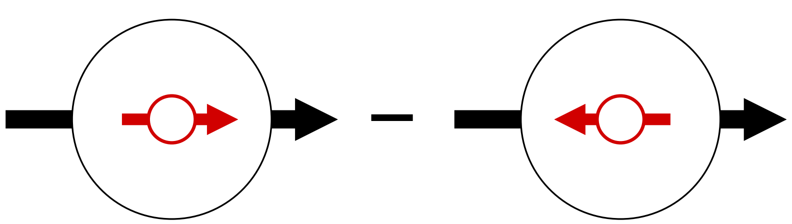
nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

$f_1 =$ 

$g_1 =$ 

$h_1 =$ 

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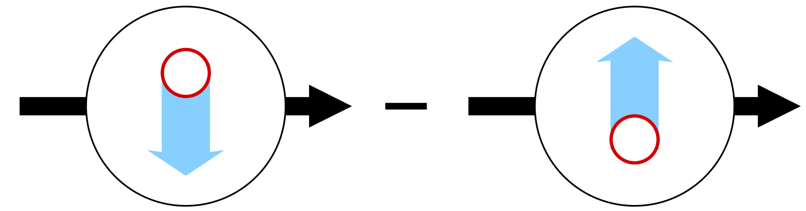
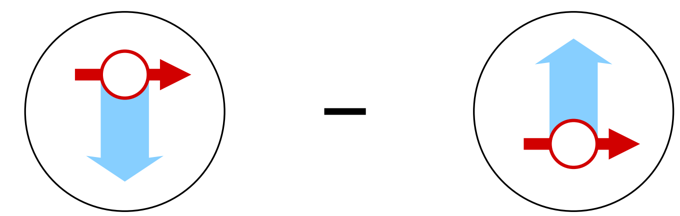
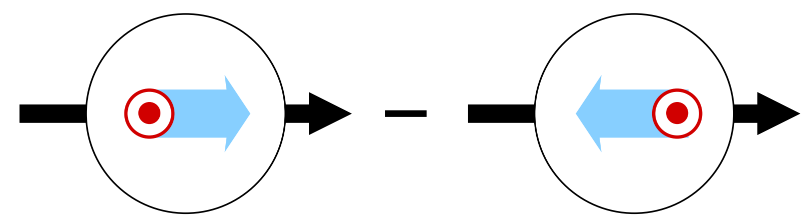
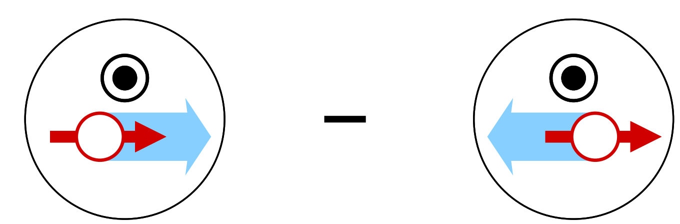
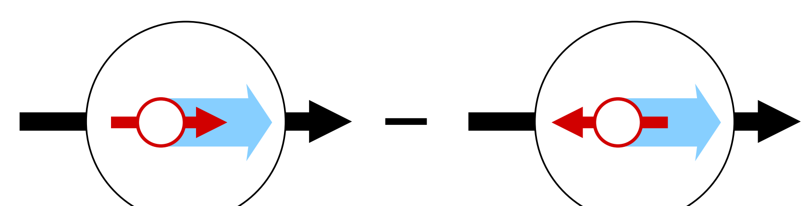
$f_{1T}^{\perp} =$ 

$h_1^{\perp} =$ 

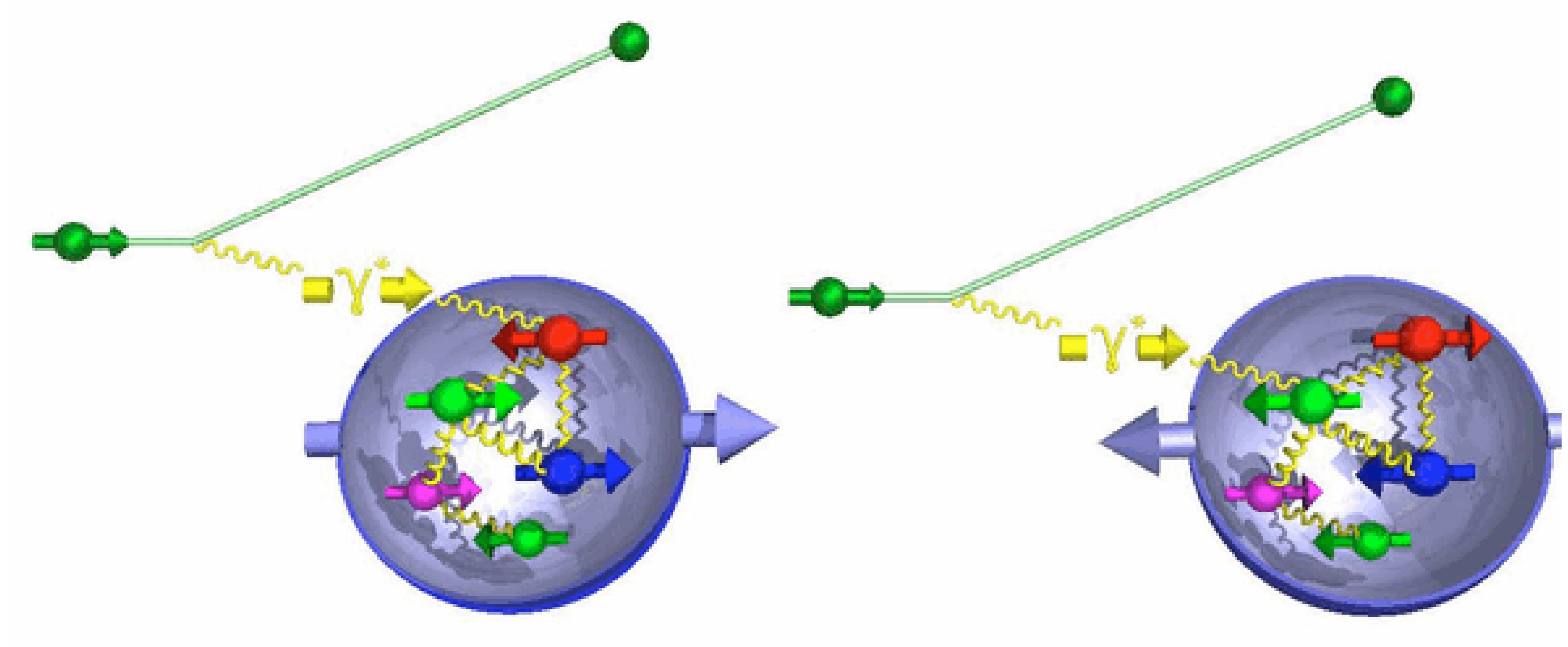
$g_{1T} =$ 

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

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

quark polarimetry

- unpolarized quarks: easy - “just” hit them
- longitudinally polarized quarks: use polarized beam



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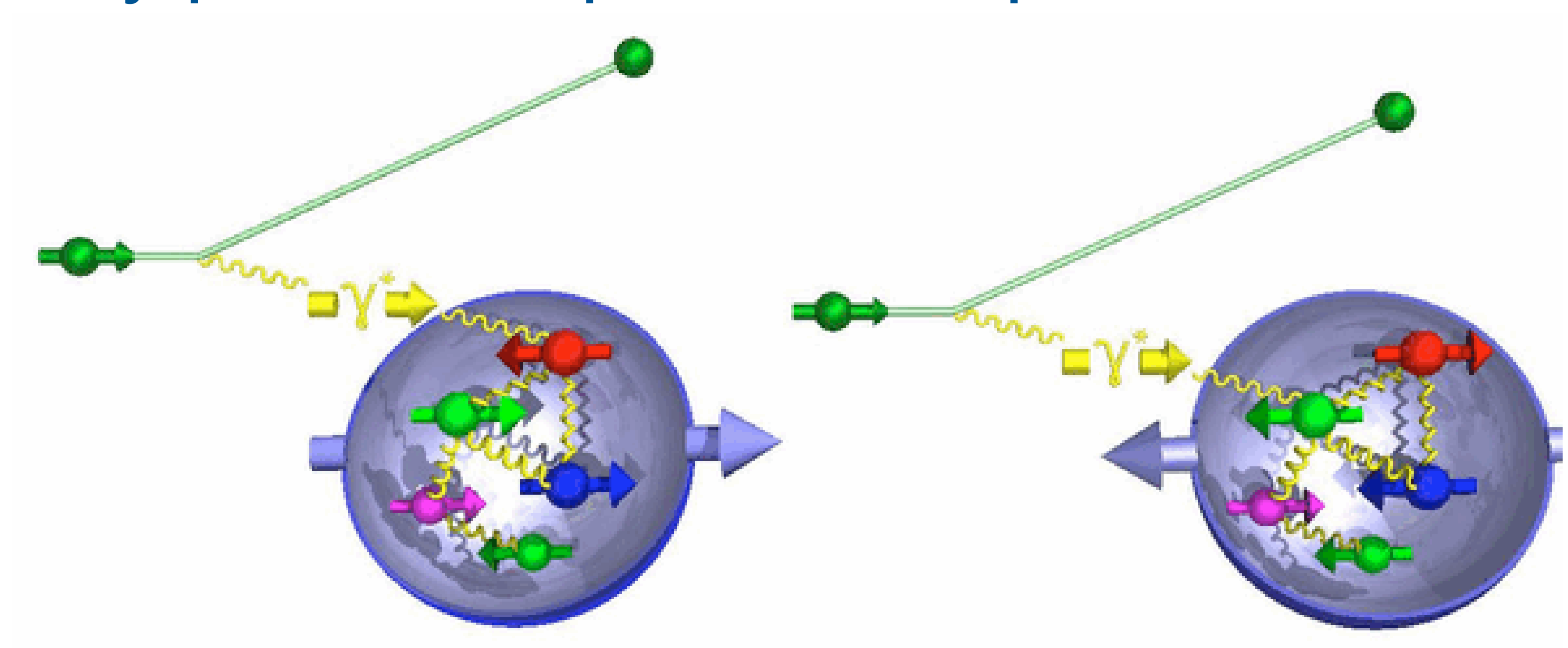
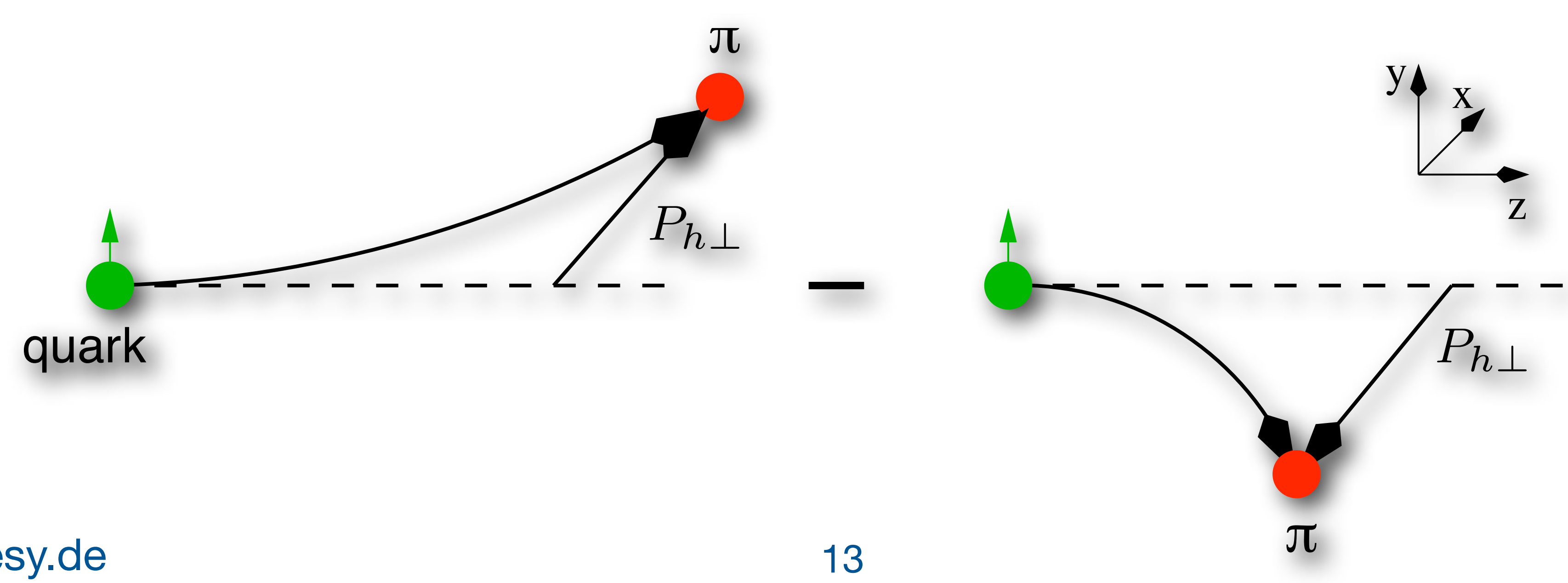
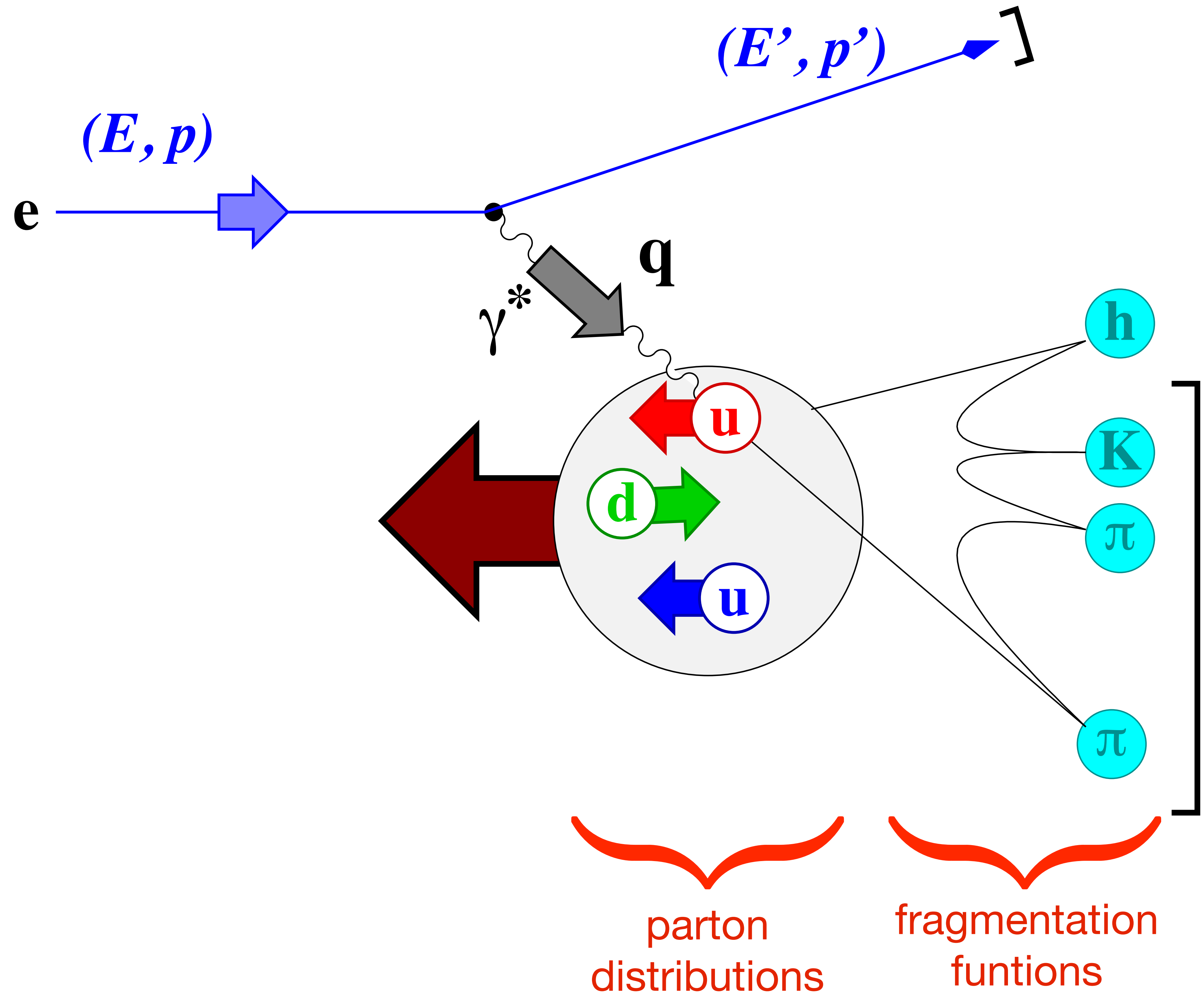


- transversely polarized quarks: need final-state polarimetry, e.g.



semi-inclusive DIS

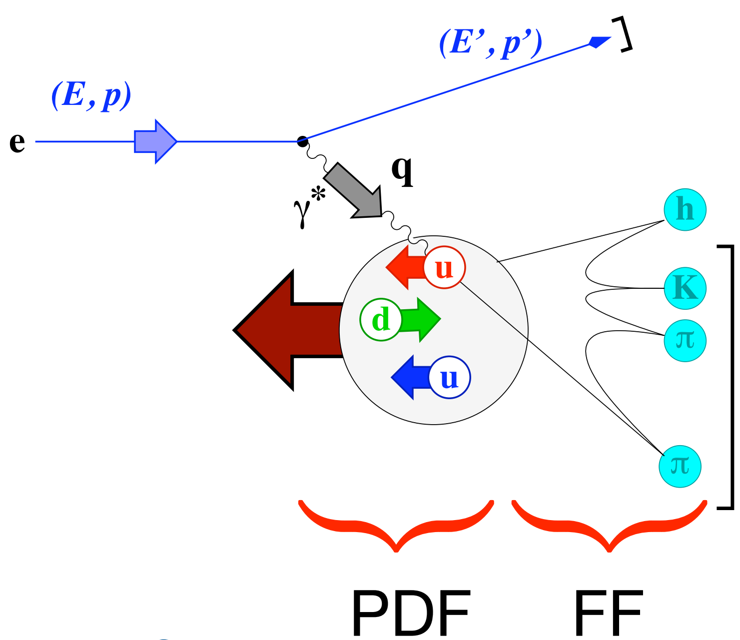


probing TMDs in semi-inclusive DIS

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

probing TMDs in semi-inclusive DIS

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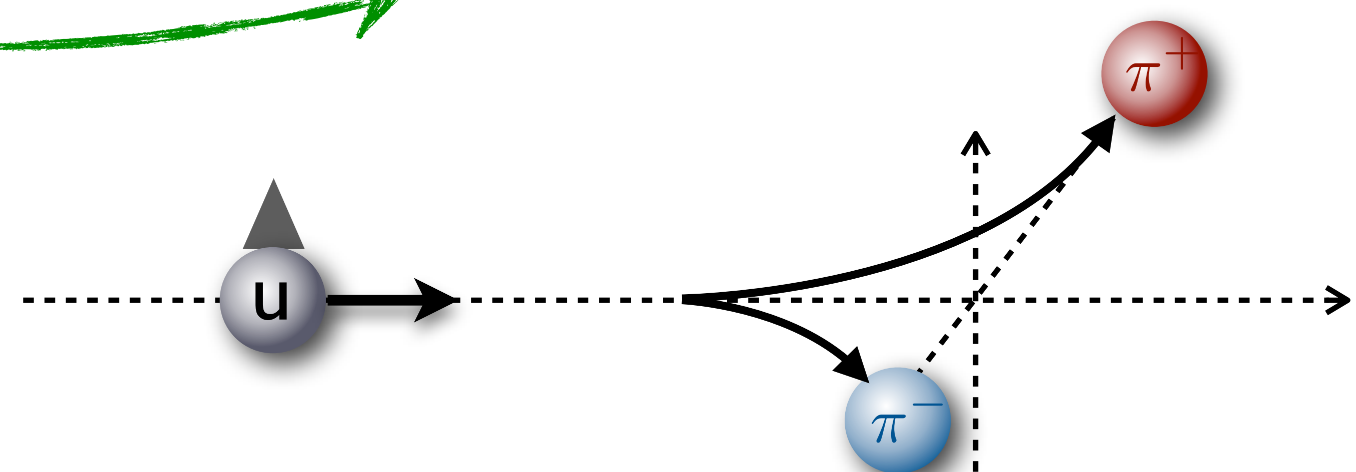
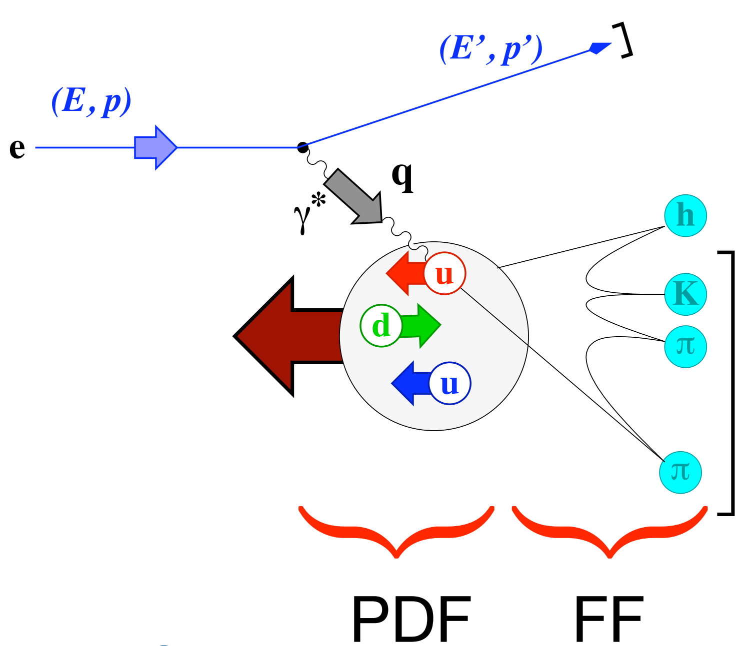
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

in SIDIS*) couple PDFs to:

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





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probing TMDs in semi-inclusive DIS

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		U	L	T
nucleon pol.	U	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
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in SIDIS*) couple PDFs to:

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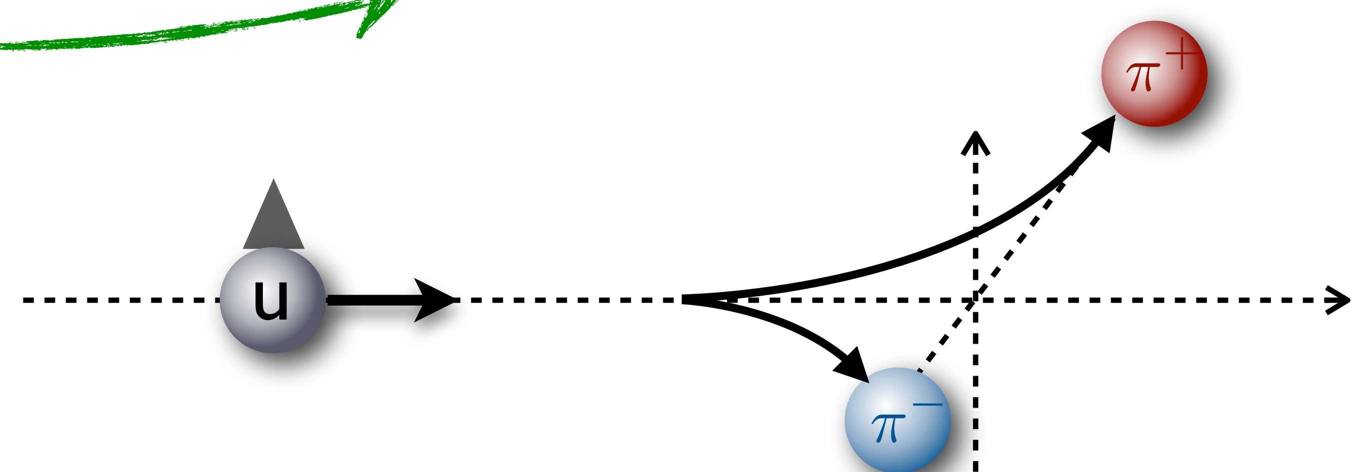

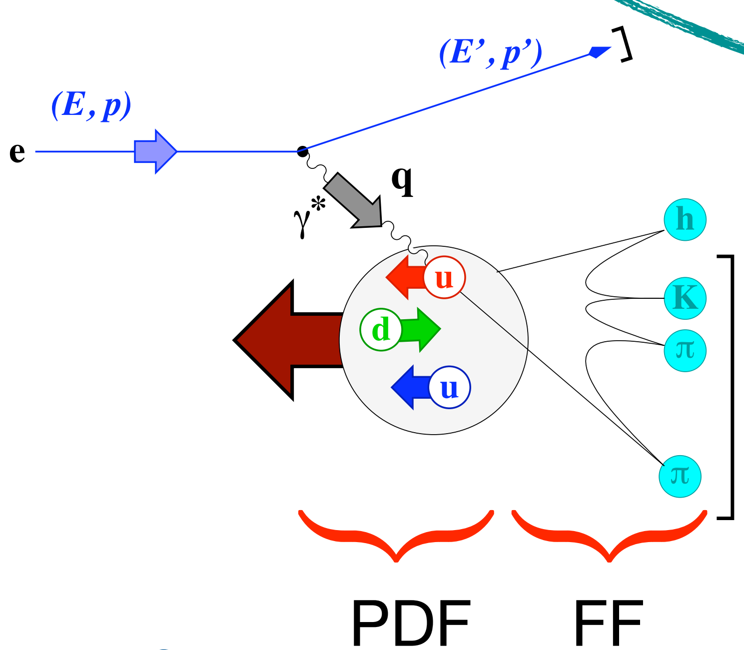

ordinary FF: $D_1^{q\to h}$

*) semi-inclusive DIS with unpolarized final state

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:

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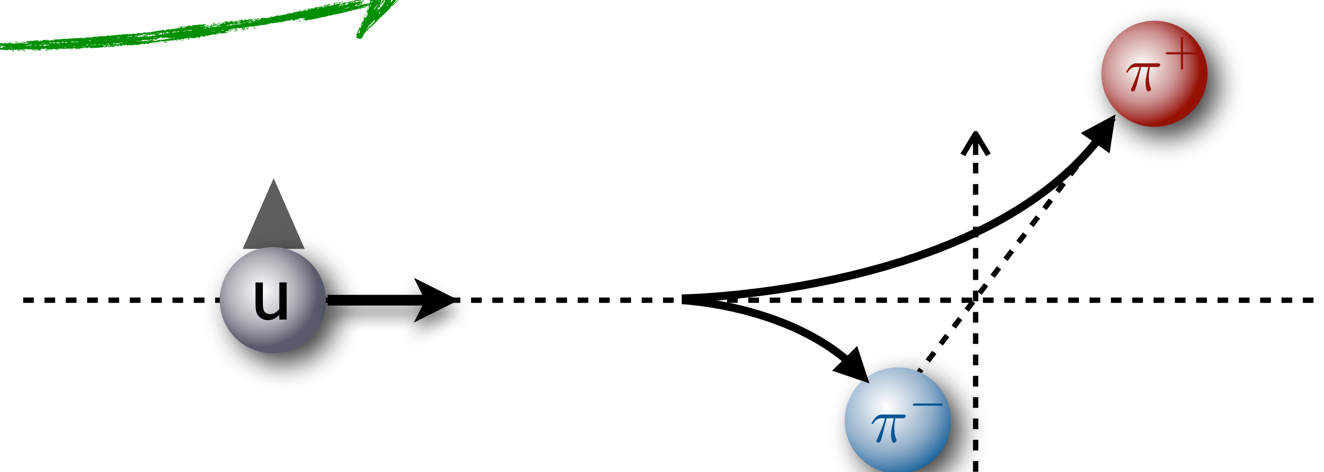


ordinary FF: $D_1^{q\to h}$

gives rise to characteristic azimuthal dependences

*) semi-inclusive DIS with unpolarized final state

single-hadron electroproduction (ep→ehX)

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

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

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

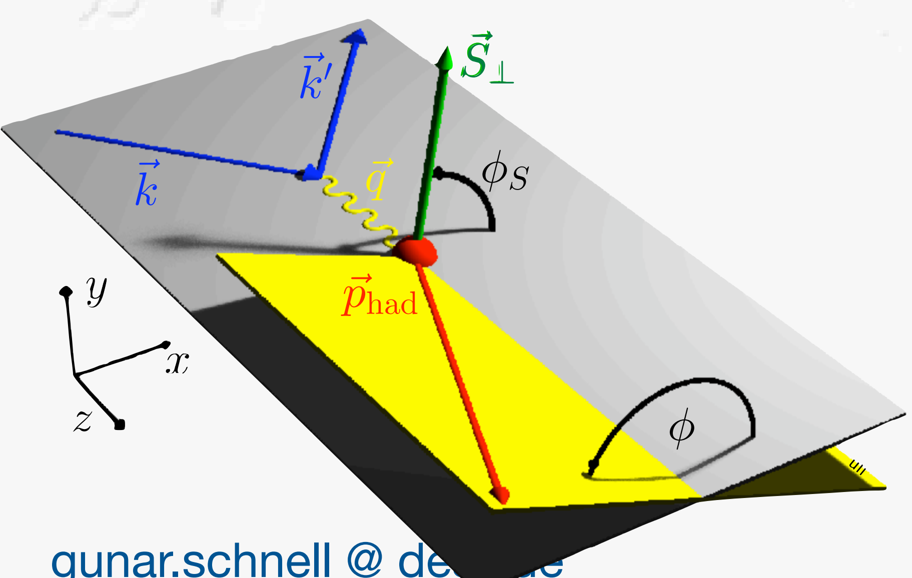
$$+ \frac{1}{Q} \left(\sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin\phi_S \, d\sigma_{UT}^{12} \right)$$

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

σ_{XY}

Beam Target

Polarization



Mulders and Tangerman, 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

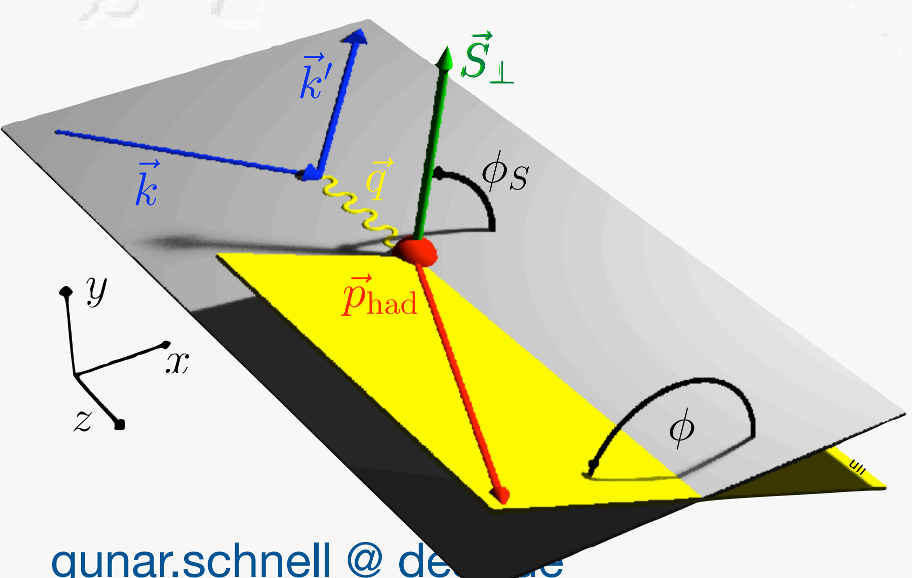
single-hadron electroproduction (ep→ehX)

$$
\begin{aligned}
d\sigma = \; & d\sigma^{0}_{UU} + \boxed{\cos 2\phi \, d\sigma^{1}_{UU}} + \frac{1}{Q}\cos\phi \, d\sigma^{2}_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^{3}_{LU} \\
& + S_L \left\{ \boxed{\sin 2\phi \, d\sigma^{4}_{UL}} + \frac{1}{Q}\sin\phi \, d\sigma^{5}_{UL} + \lambda_e \left[d\sigma^{6}_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^{7}_{LL} \right] \right\} \\
& + S_T \left\{ \boxed{\sin(\phi - \phi_S) \, d\sigma^{8}_{UT}} + \boxed{\sin(\phi + \phi_S) \, d\sigma^{9}_{UT}} + \boxed{\sin(3\phi - \phi_S) \, d\sigma^{10}_{UT}} \frac{1}{Q} \right. \\
& \qquad + \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \qquad \left. + \lambda_e \left[\boxed{\cos(\phi - \phi_S) \, d\sigma^{13}_{LT}} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

σ_{XY}

Beam **Target**

Polarization



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

Bacchetta et al., JHEP 0702 (2007) 093

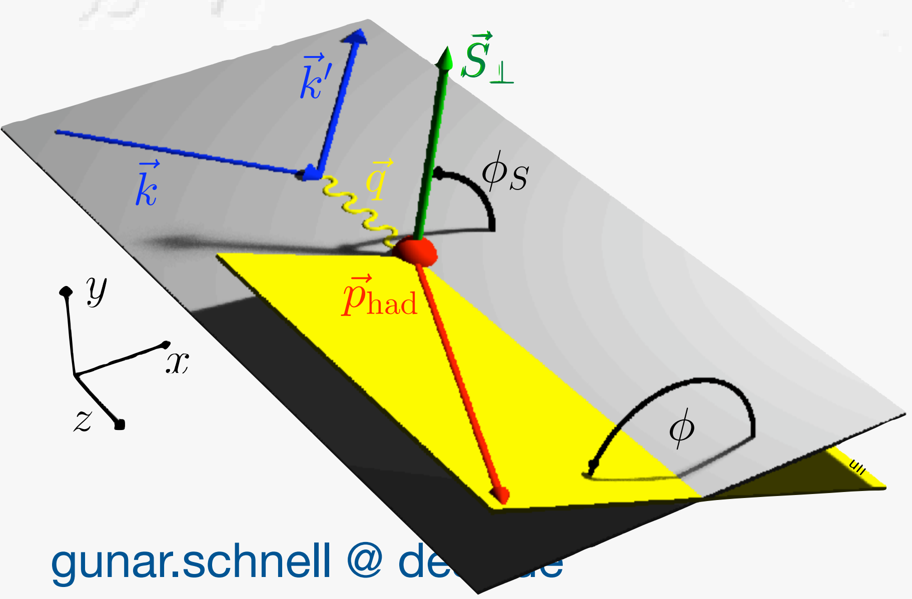
“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

single-hadron electroproduction (ep→ehX)

$$
\begin{aligned}
d\sigma = {} & d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin\phi \, d\sigma^3_{LU} \\
& + S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q} \sin\phi \, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^7_{LL} \right] \right\} \\
& + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \right. \\
& \quad + \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
& \quad \left. + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \right\}
\end{aligned}
$$

σ_{XY}

Beam **Target**
Polarization



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the rich world of fragmentation

		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 $H_{1T}^\perp$

the rich world of fragmentation

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

- unpolarized/spin-less hadrons

the rich world of fragmentation

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 $H_{1T}^\perp$

- unpolarized/spin-less hadrons
- polarized hadrons

- 6 out of 8 require final-state polarimetry
- most accessible: hyperons (parity-violating decay), but
  - lower production rate
  - spin structure often dominated by strange quarks
- more involved: dihadron fragmentation functions
- clean process: e^+e^- annihilation into hadron(s)

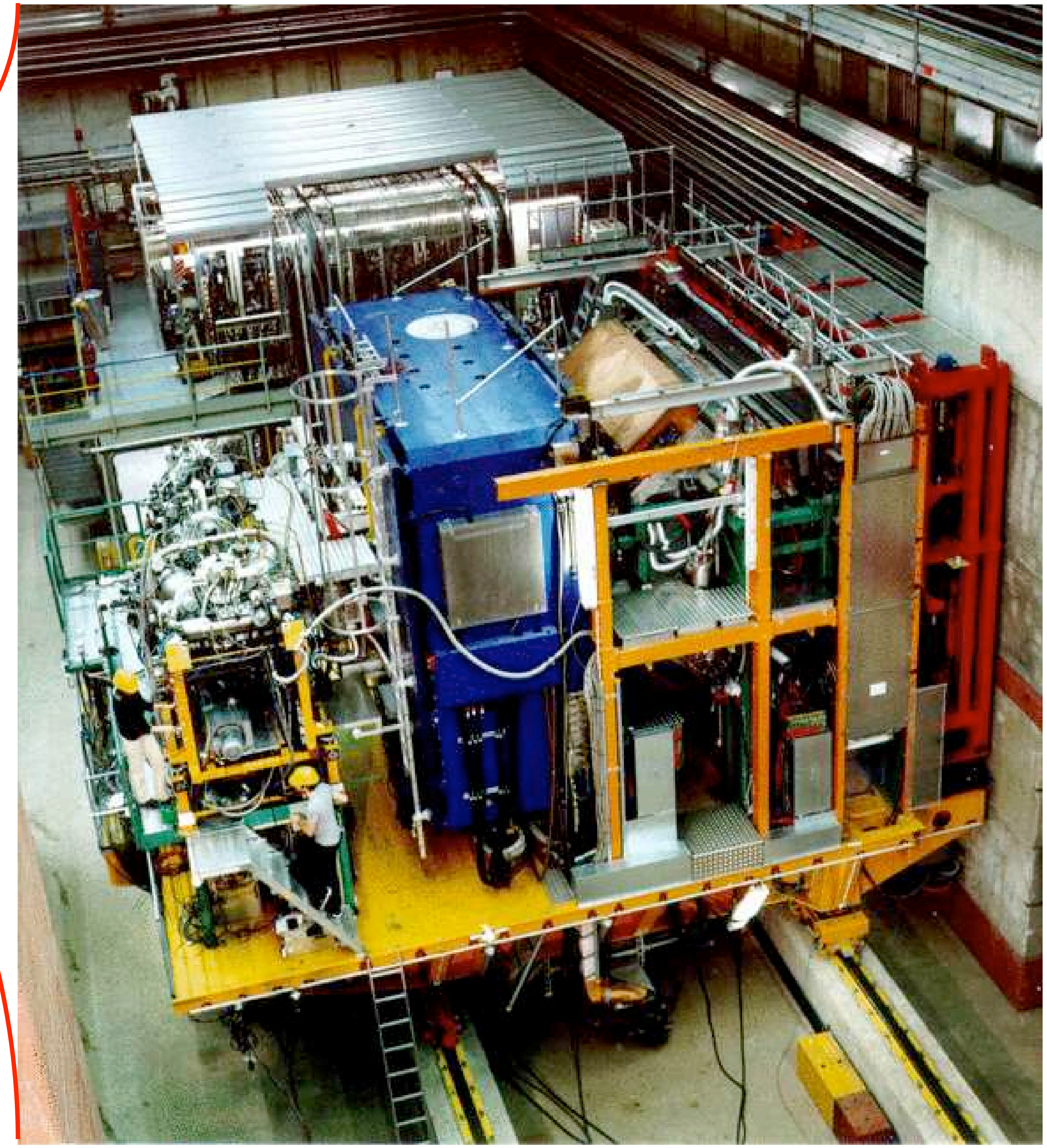
experimental data

The HERMES experiment (1995-2007)

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

… transversely polarized through Sokolov-Ternov effect

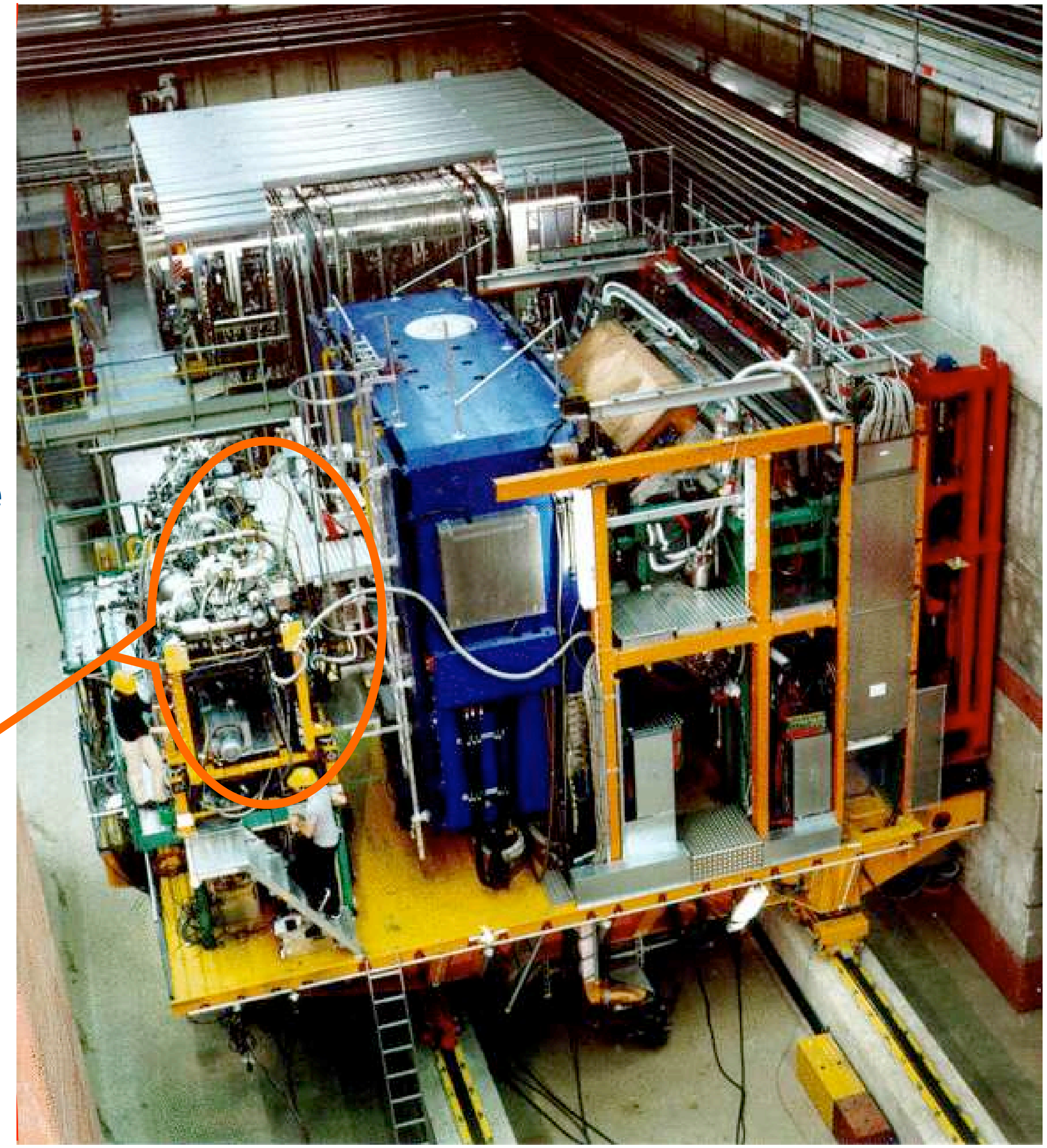
=> longitudinal polarization at HERMES by means of spin rotators

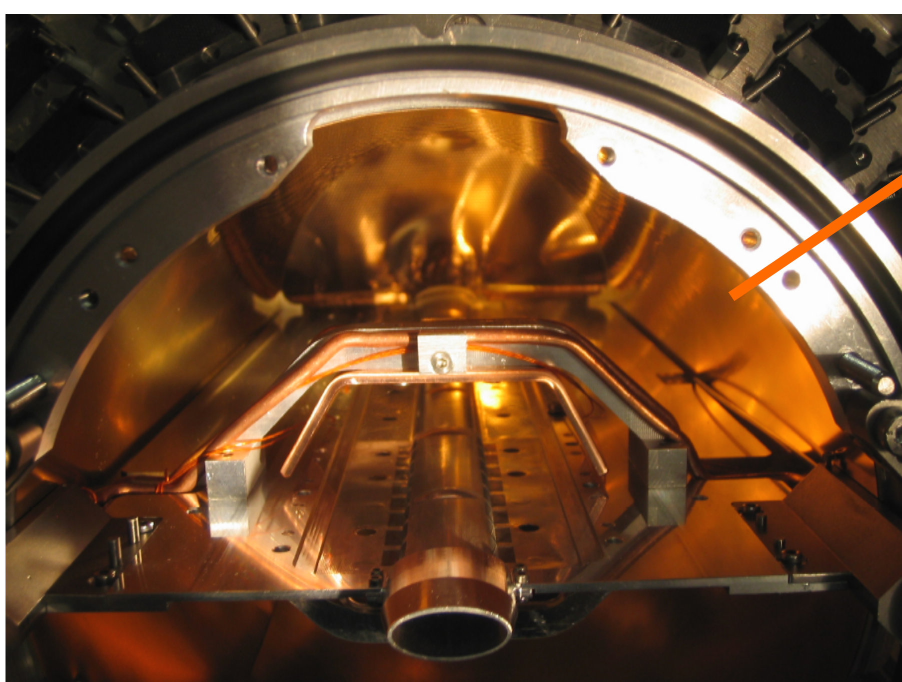


The HERMES experiment (1995-2007)

novel (pure) gas target:

- internal to HERA 27.6 GeV $e^{\pm}$ ring
- unpolarized (^{1}H … Xe)
- longitudinally polarized: ^{1}H, ^{2}H, ^{3}He
- transversely polarized: ^{1}H

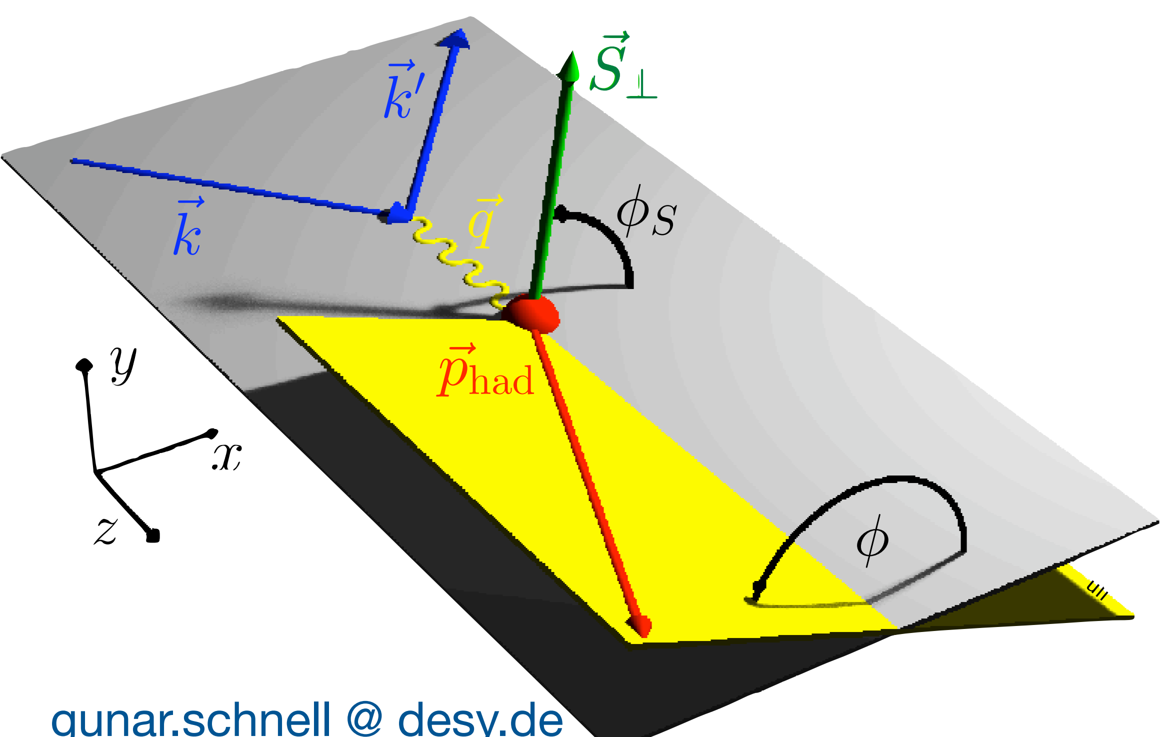




	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

transversely polarized quarks?

- look at characteristic azimuthal dependence of single-hadron lepto-production cross section



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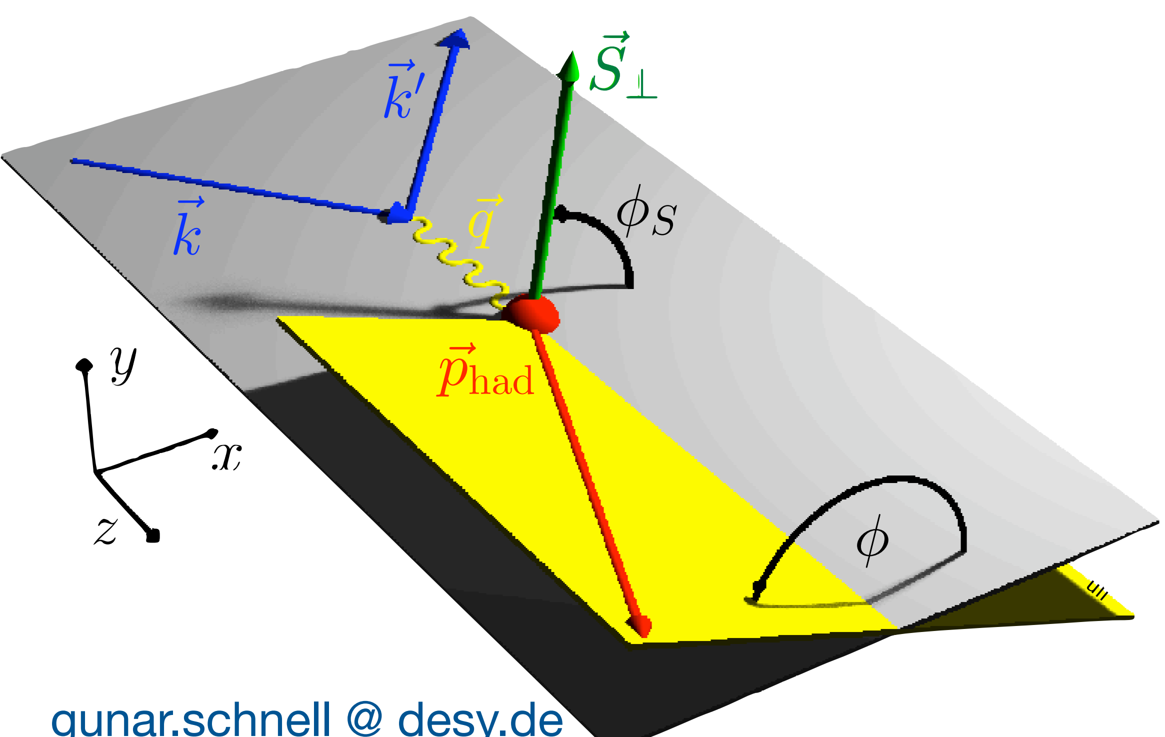
- in practice, reverse nucleon-polarization orientation and form spin asymmetries



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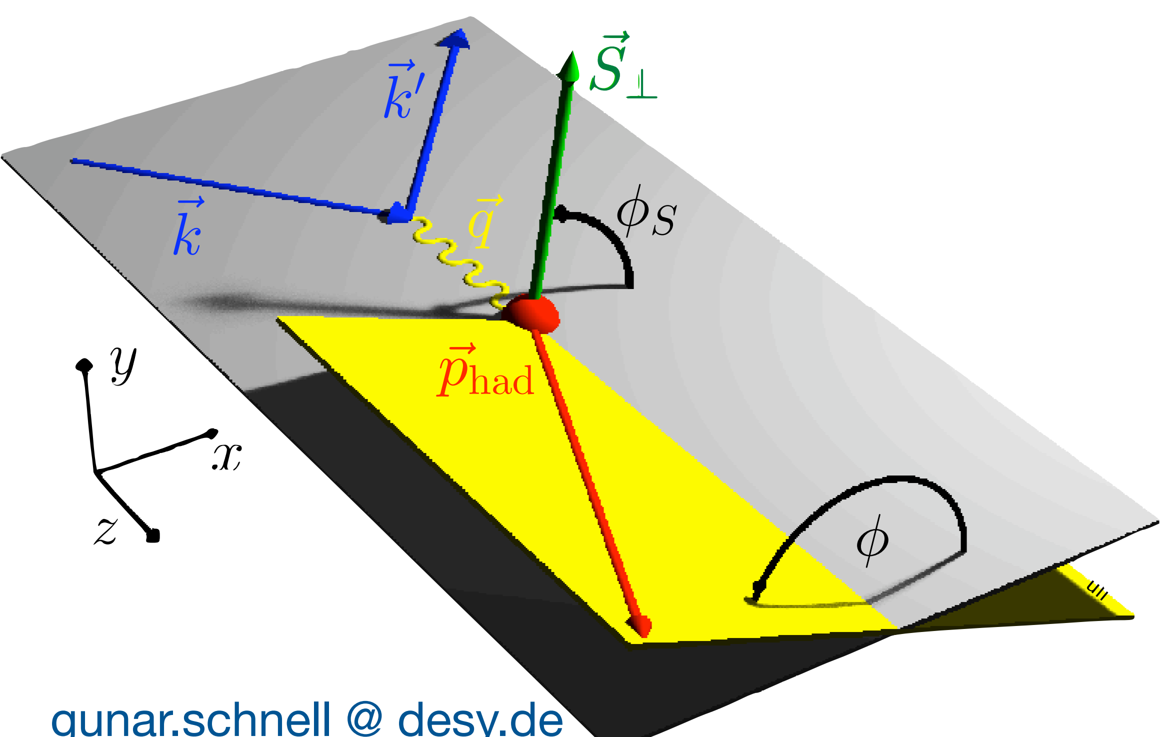
transversely polarized quarks?

- look at characteristic azimuthal dependence of single-hadron lepto-production cross section
- in practice, reverse nucleon-polarization orientation and form spin asymmetries
  - many of the systematics of polarization-averaged observables cancel (e.g., luminosity)



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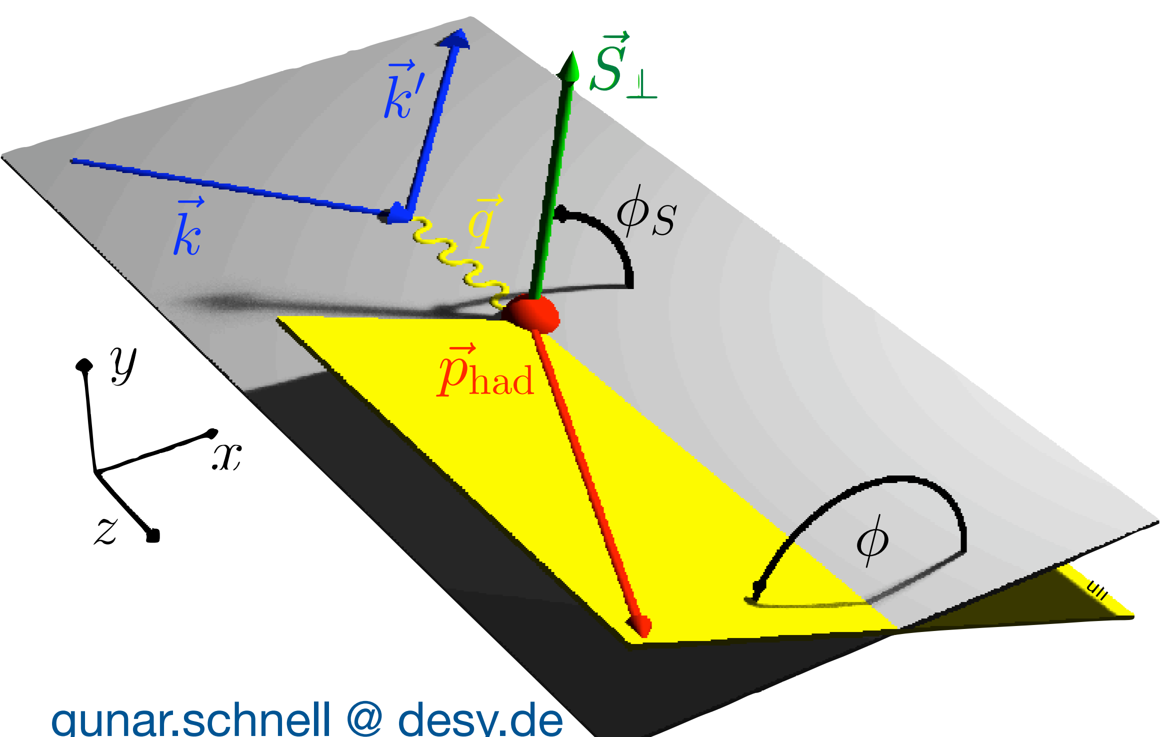

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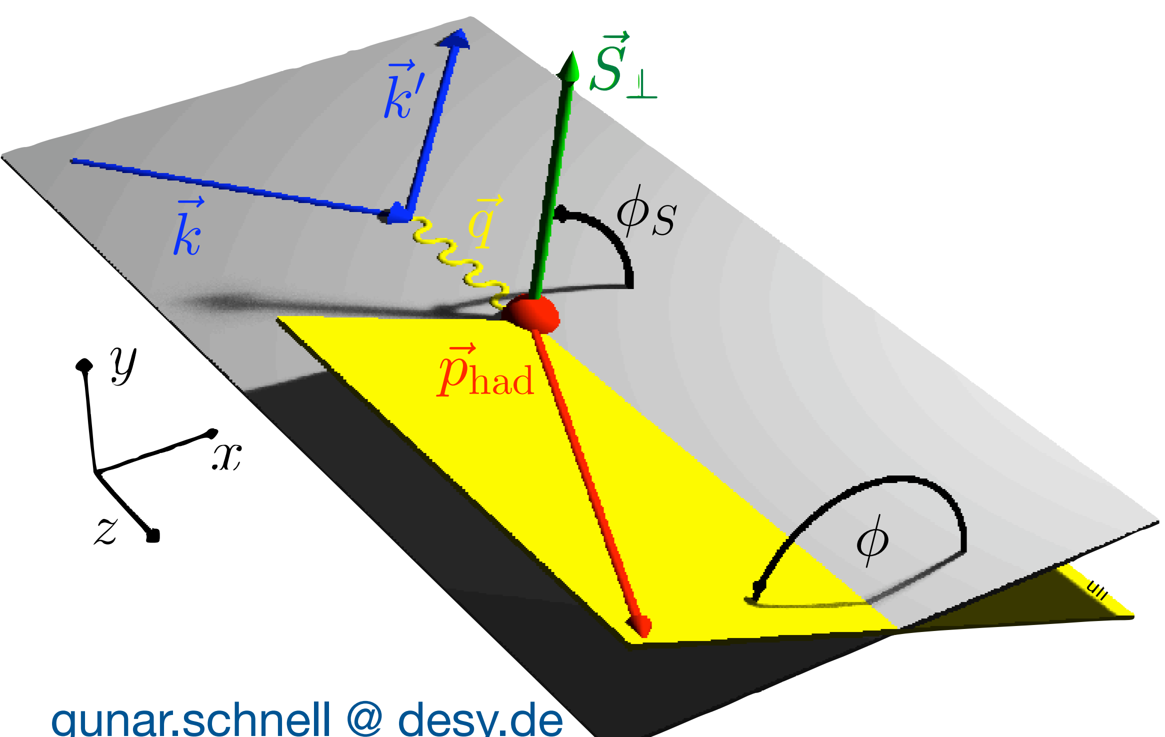
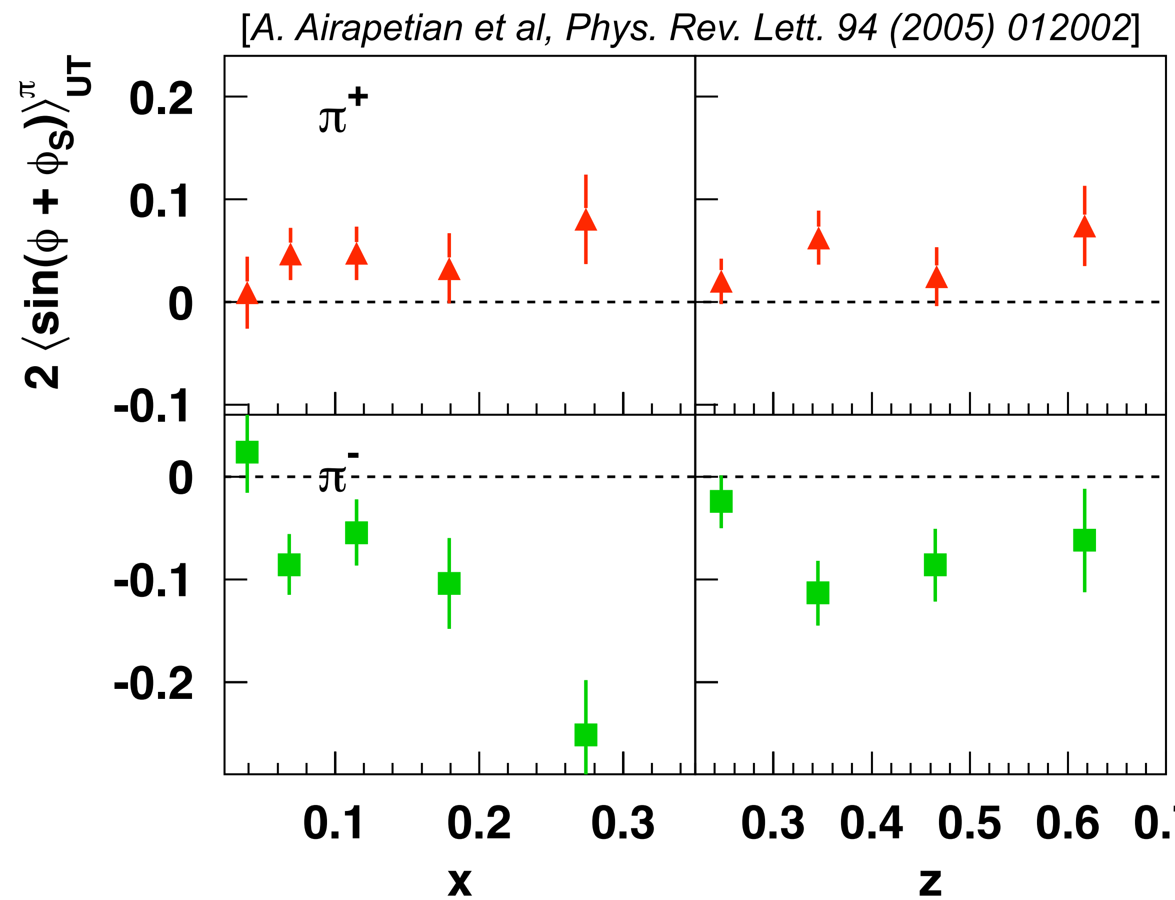
transversely polarized quarks?

- transverse polarization of quarks leads to large effects!





2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

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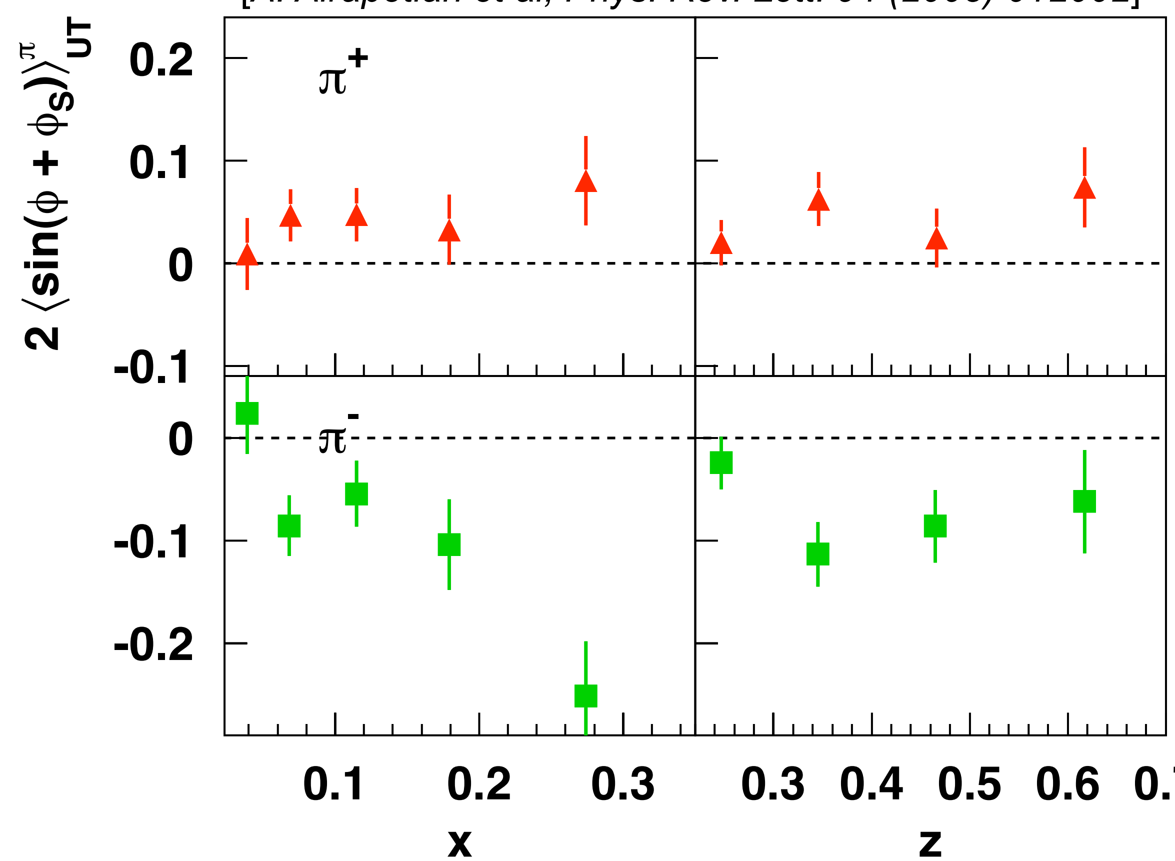
- opposite in sign for charged pions

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



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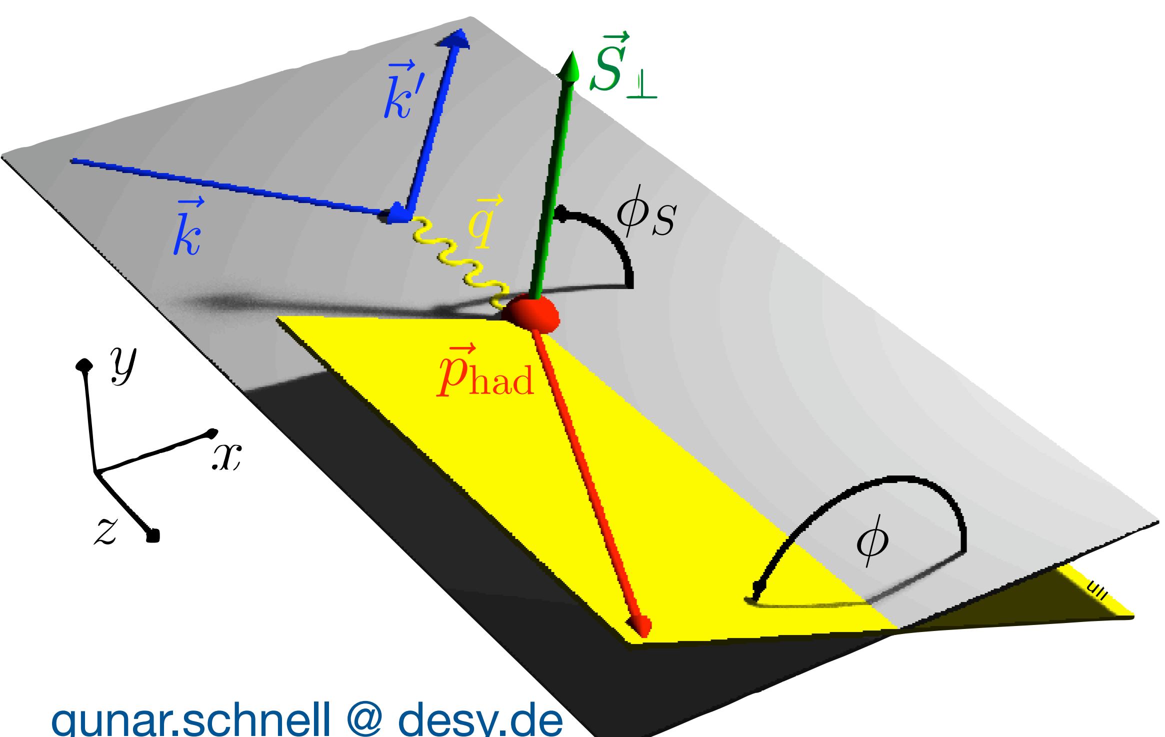

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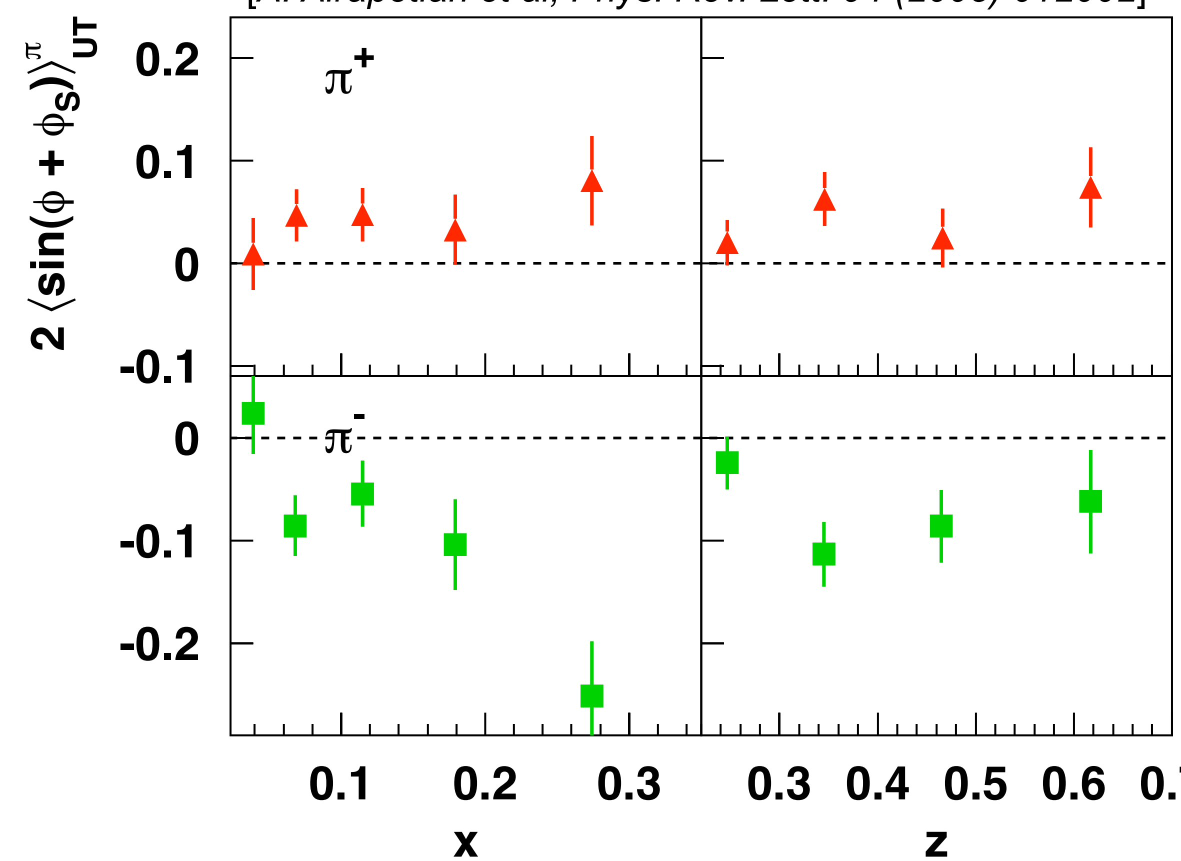

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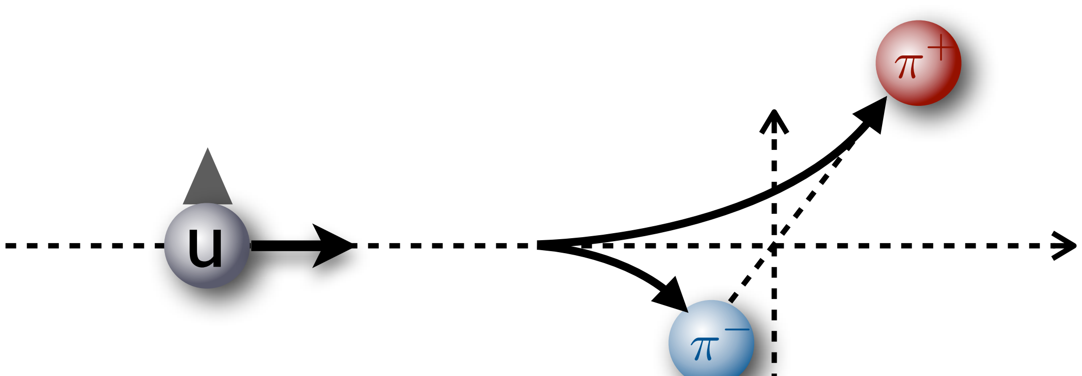

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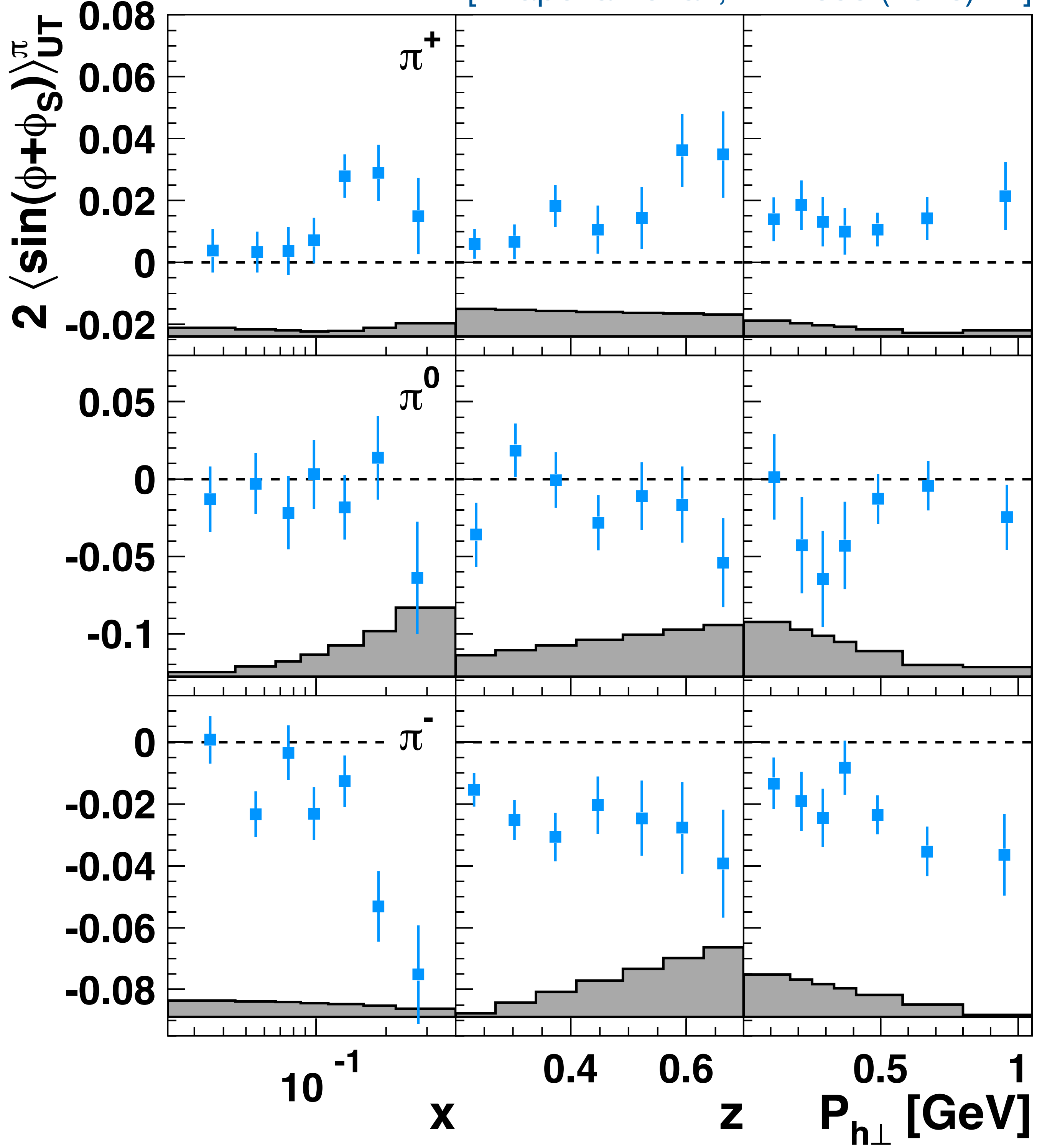
transversely polarized quarks?

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



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- opposite in sign for charged pions
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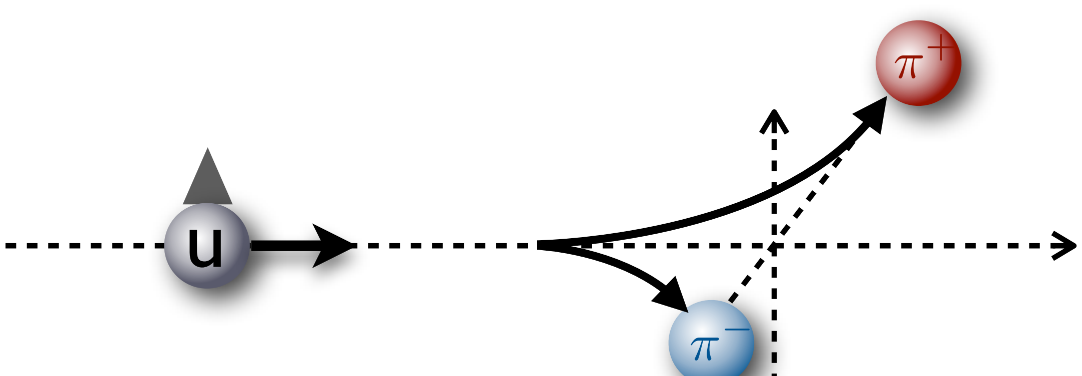

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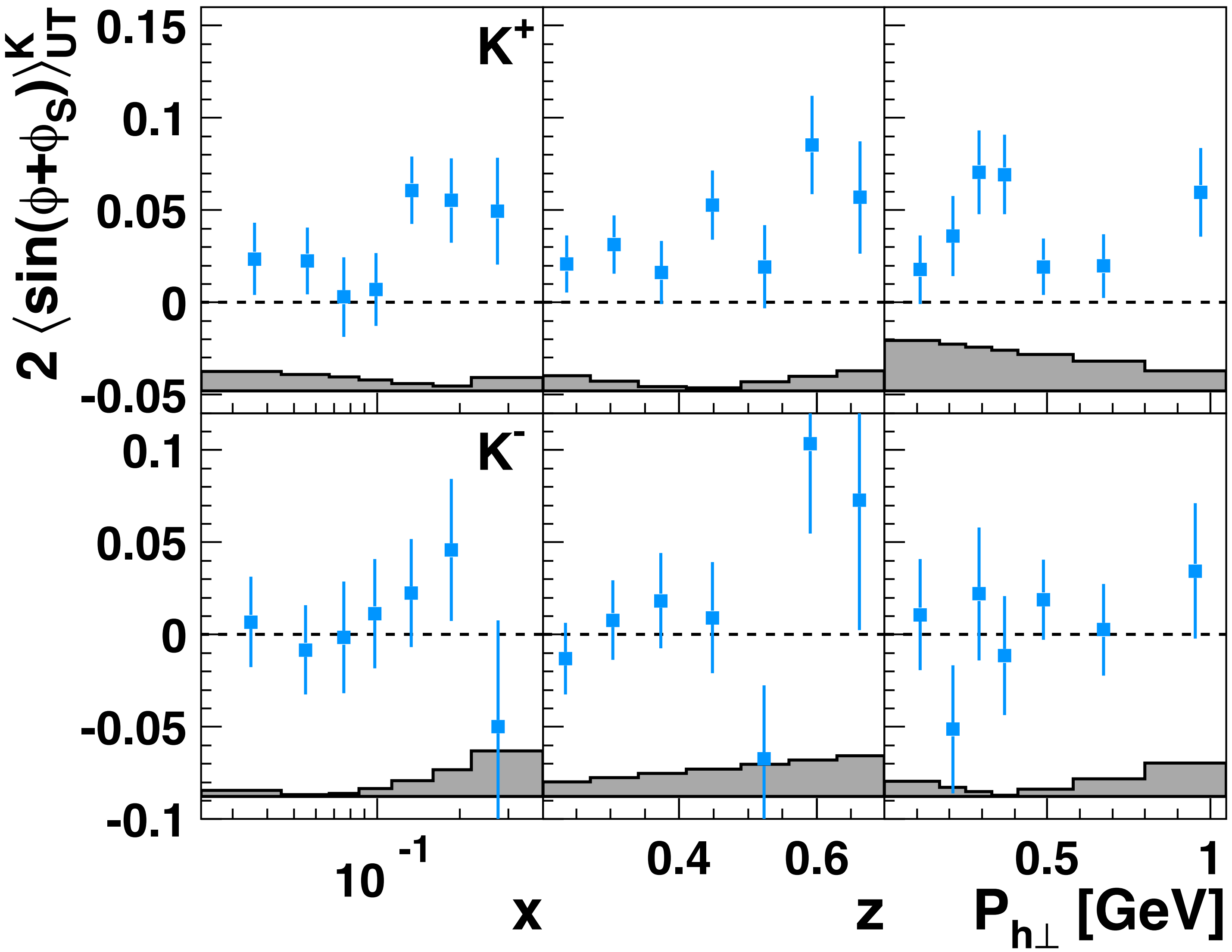
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Collins effect for kaons and (anti) protons

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



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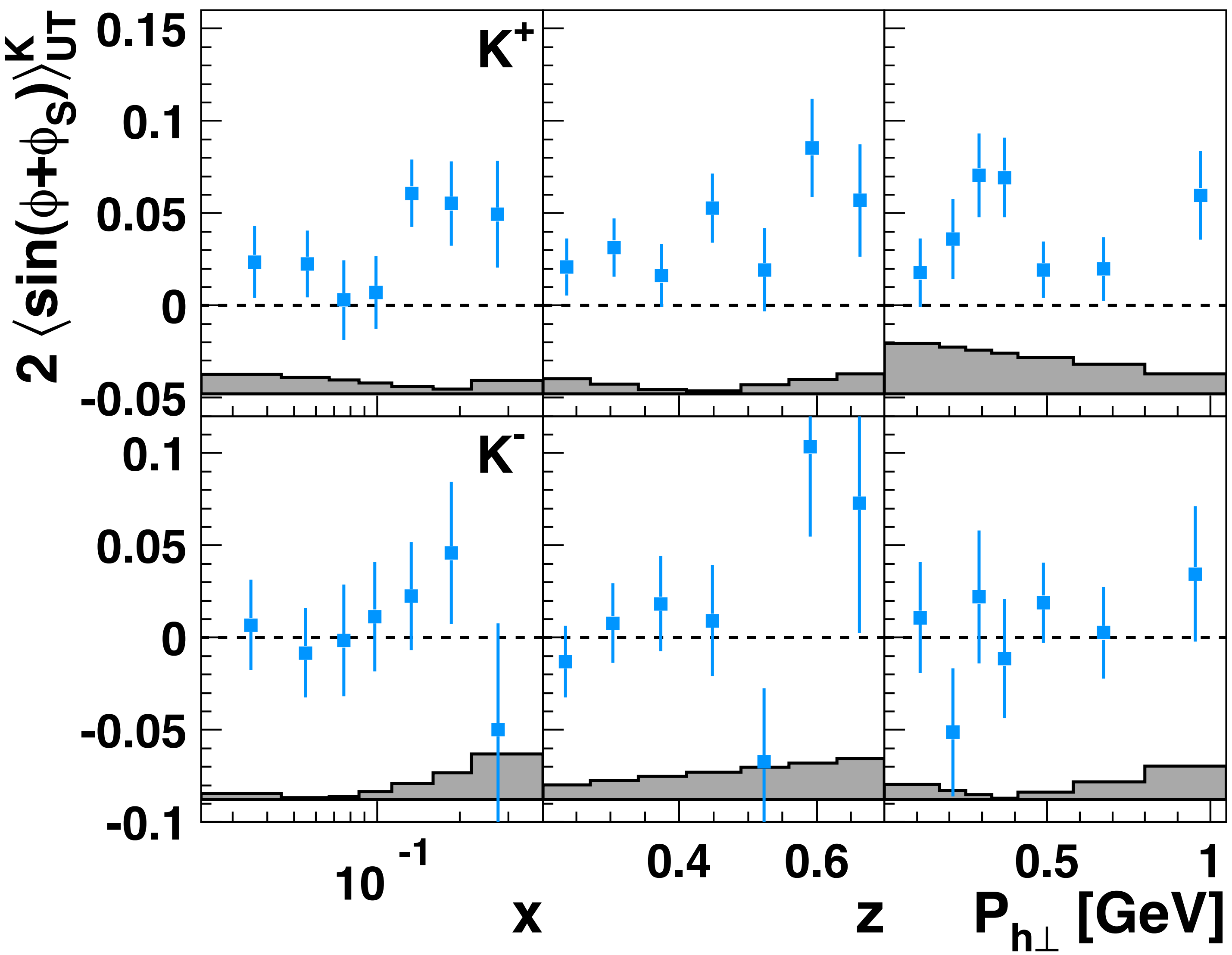

- positive Collins SSA amplitude for positive kaons (u-dominance)

	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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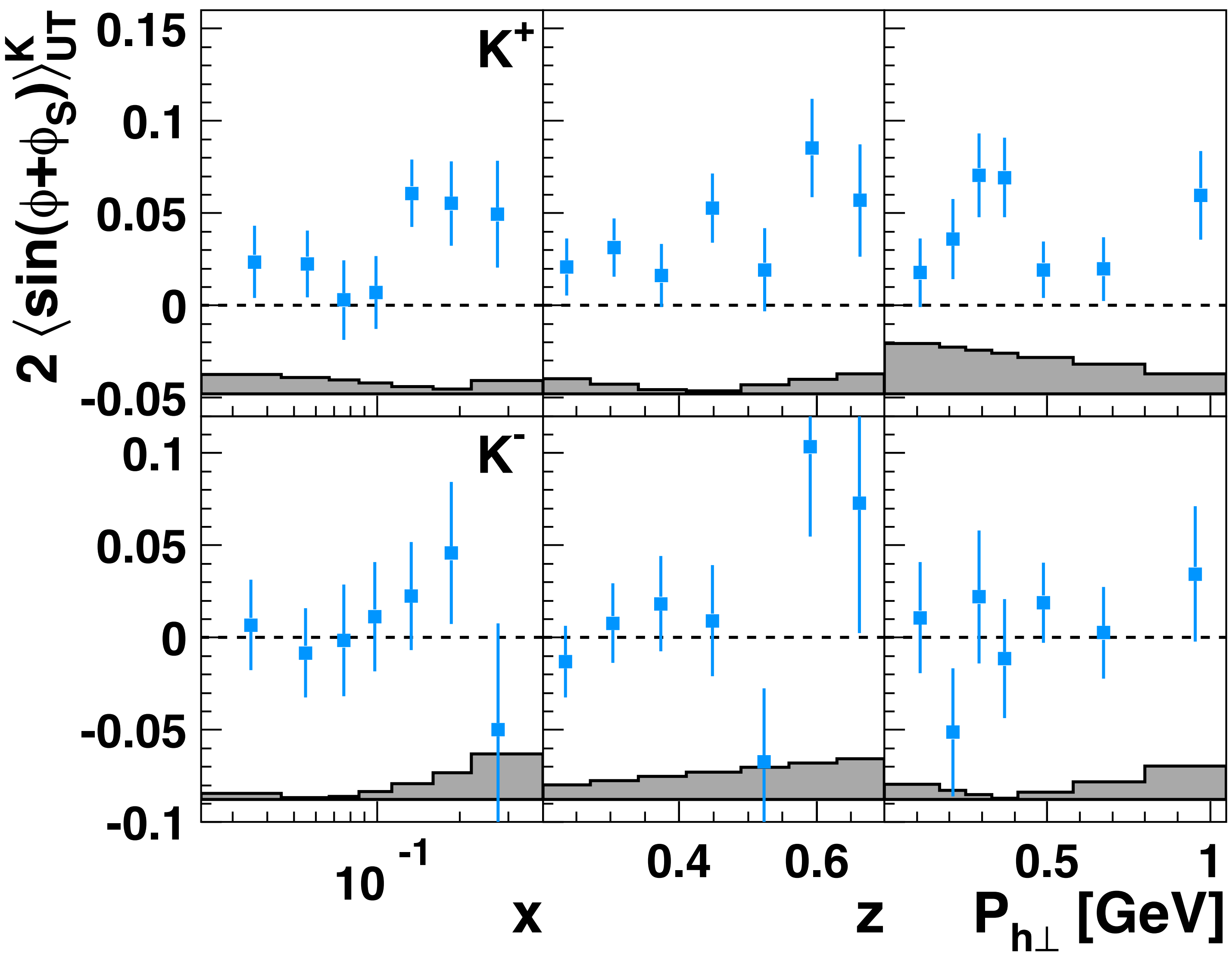
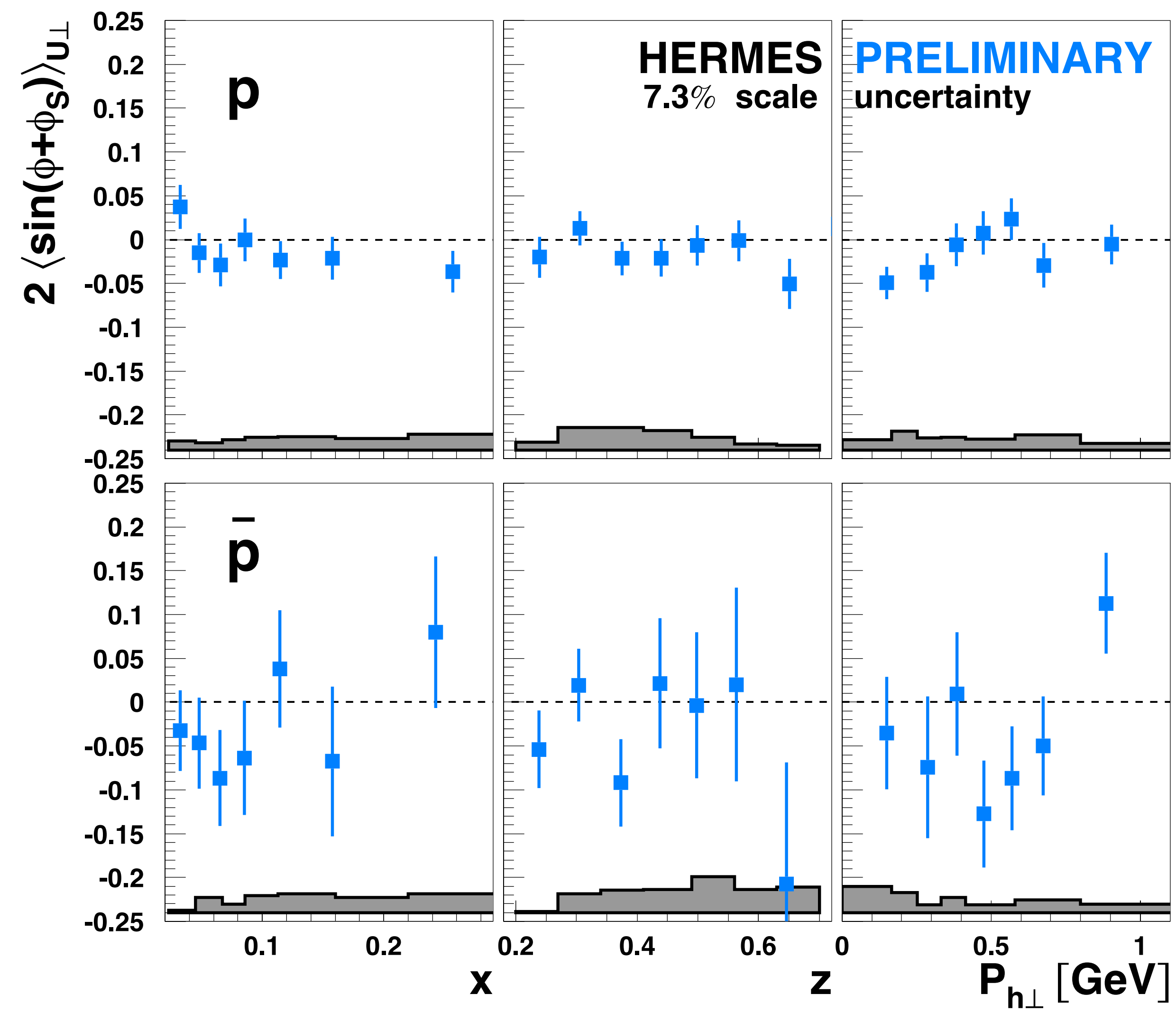


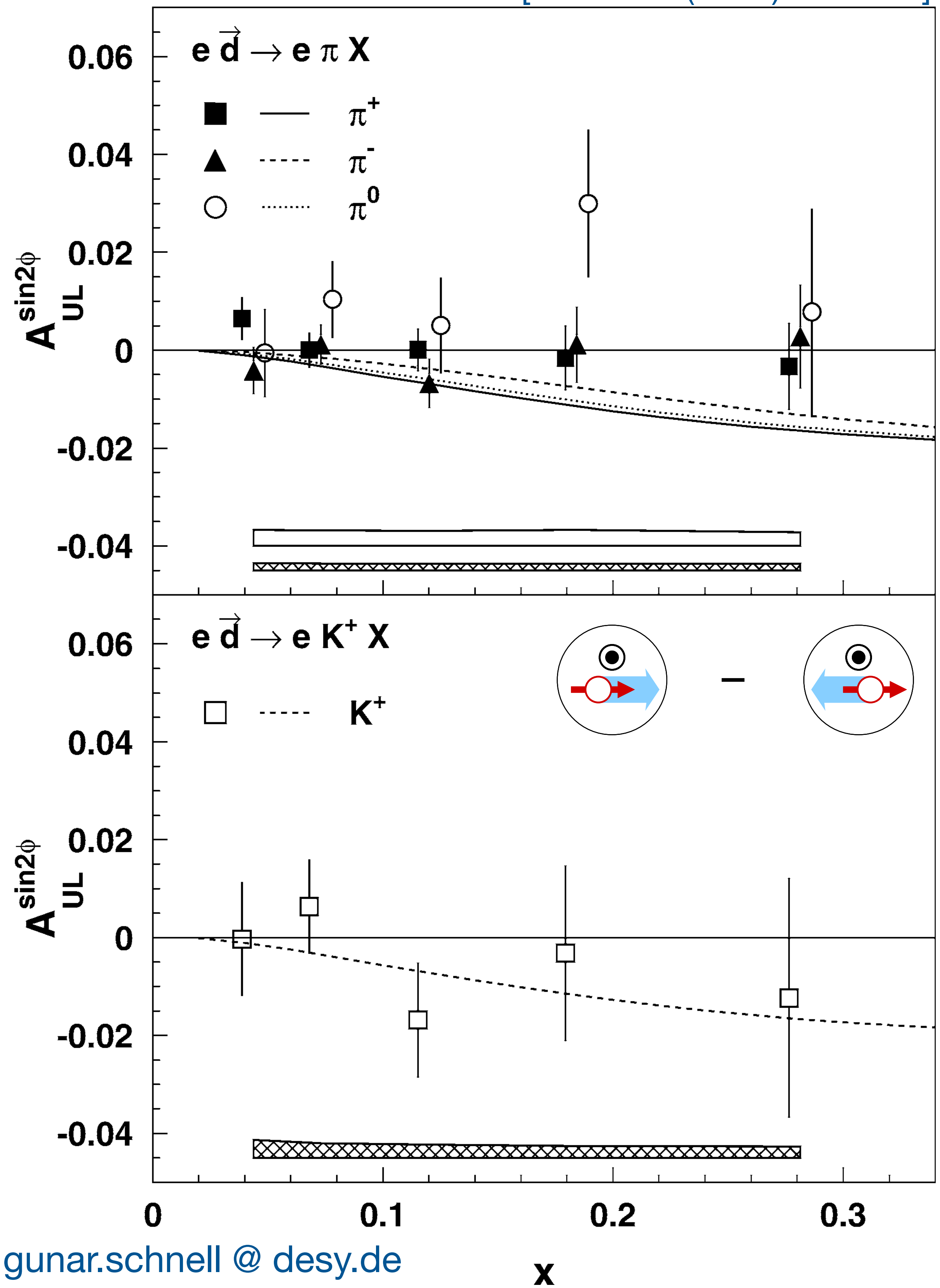


- positive Collins SSA amplitude for positive kaons (u-dominance)
- consistent with zero for negative kaons and (anti)protons
  ➡ vanishing sea-quark transversity and baryon Collins effect?

Worm-Gear? Pretzelosity?

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

[PLB 562 (2003) 182-192]



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L		g_{1L}	$h_{1L}^\perp$
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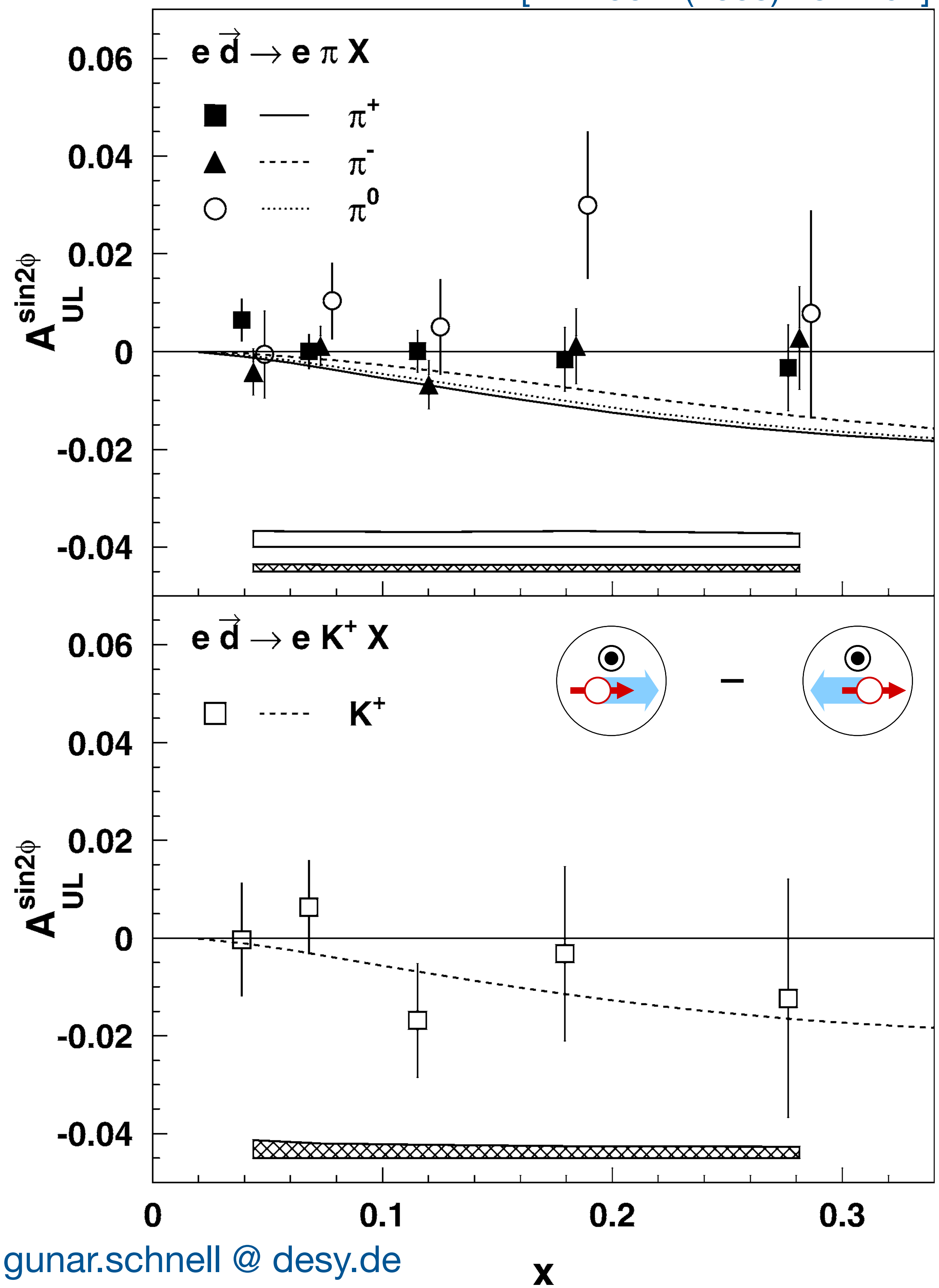
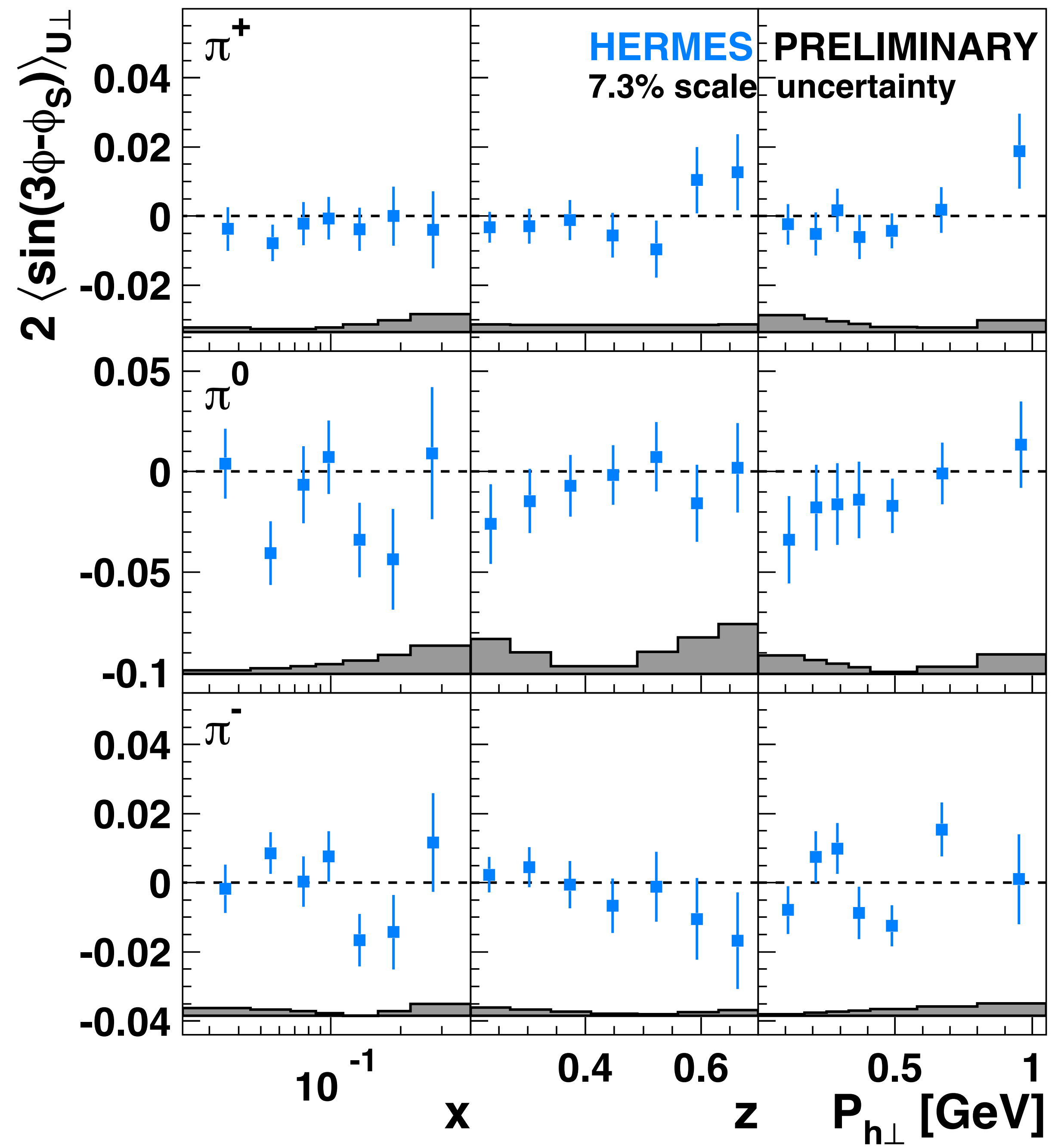
Worm-Gear? Pretzelosity?

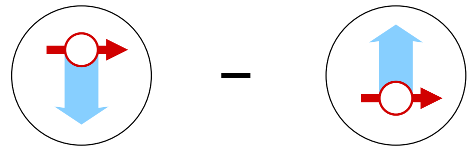
[PLB 562 (2003) 182-192]





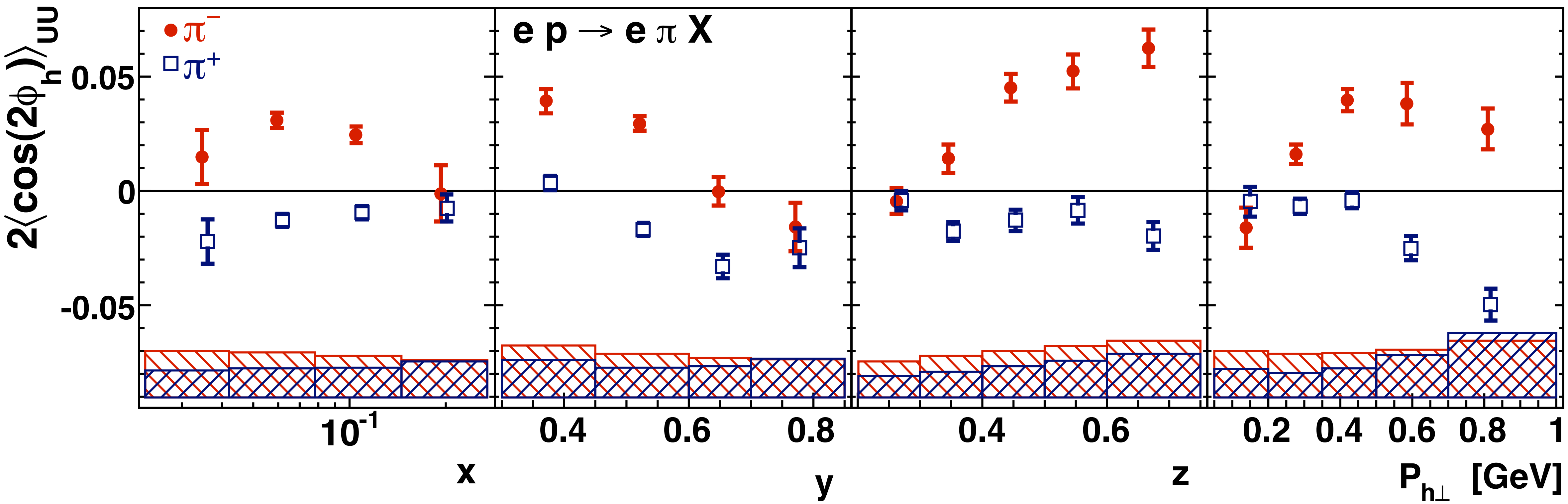
- both consistent with zero
- but suppressed by one (two) power(s) of $P_{h\perp}$ (compared to, e.g., transversity⊗Collins)

	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

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



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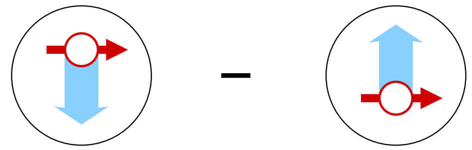

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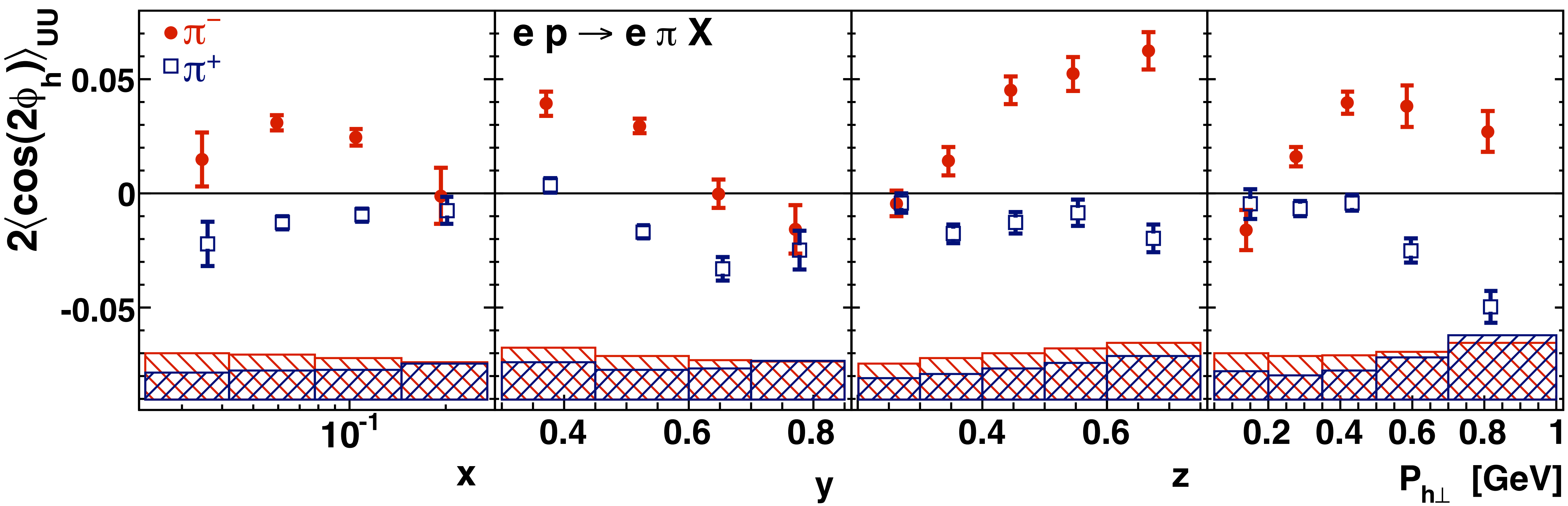

- none-zero modulations!

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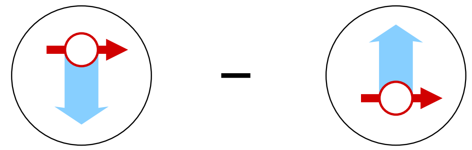
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$



signs of Boer-Mulders

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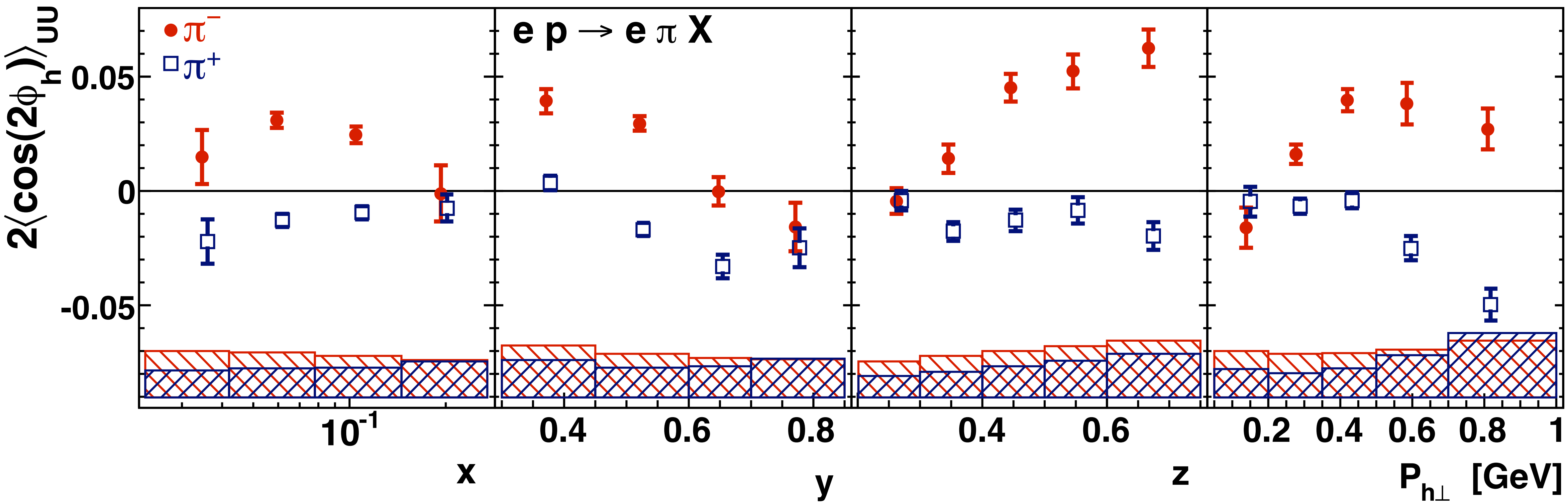

- none-zero modulations!
- opposite sign for charged pions with larger magnitude for π^-

	U	L	T
U	f_1		$h_1^\perp$
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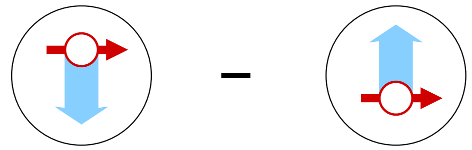
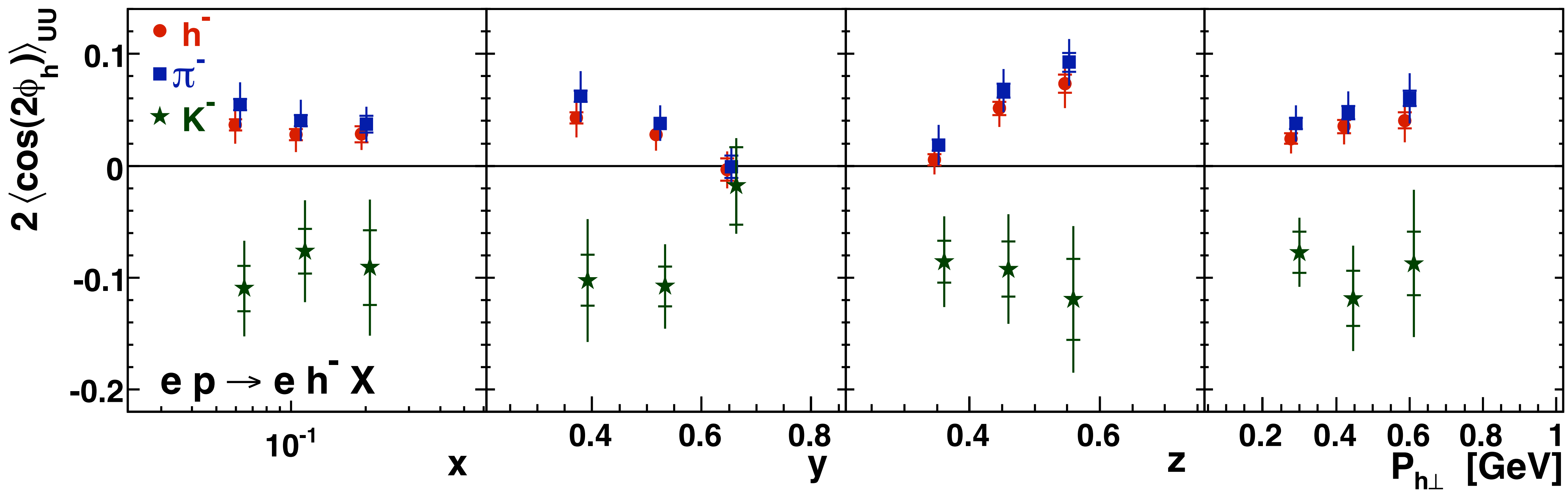


signs of Boer-Mulders

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



- none-zero modulations!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons

	U	L	T
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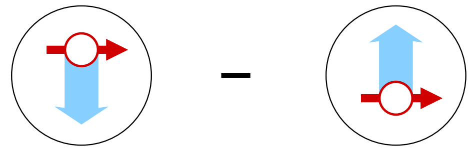

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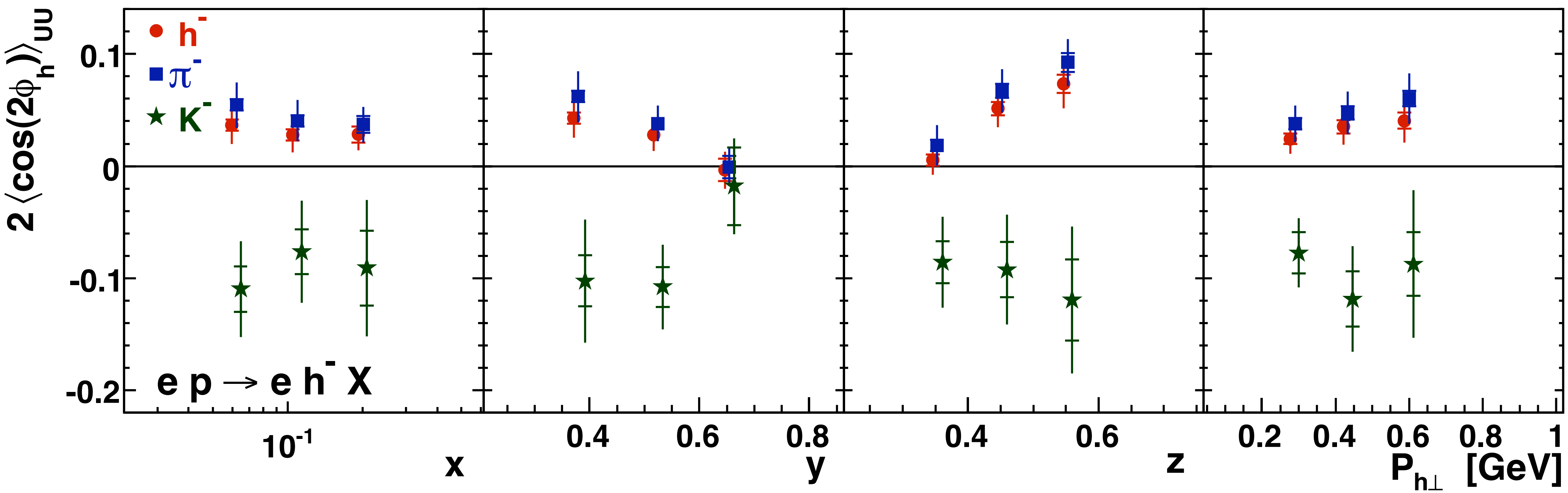
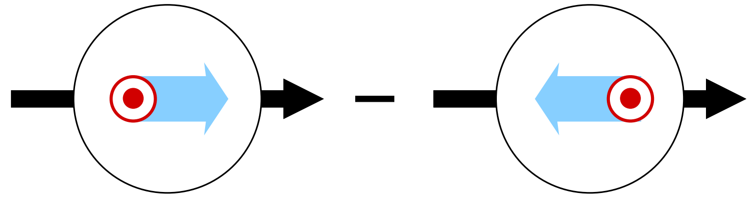


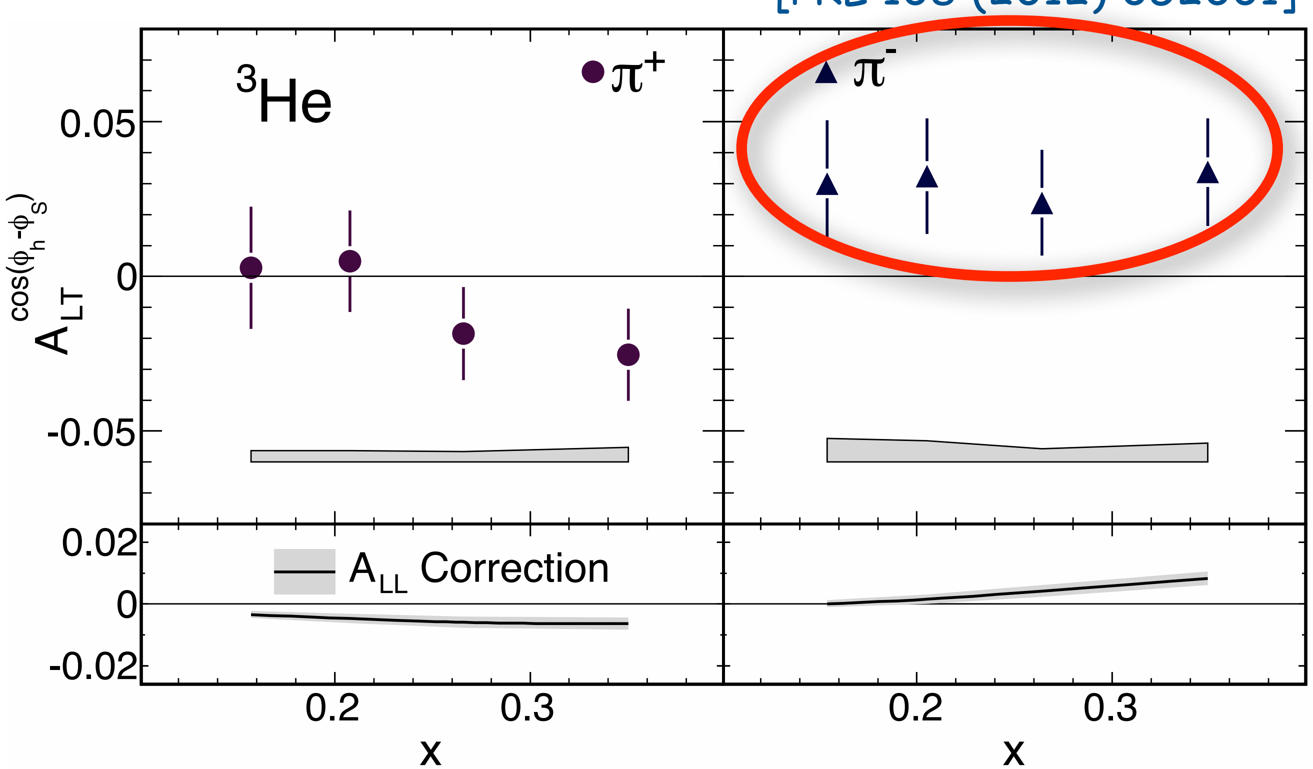
- none-zero modulations!
- opposite sign for charged pions with larger magnitude for π^-
- intriguing behavior for kaons
- available also in fully differential binning, e.g., before projecting

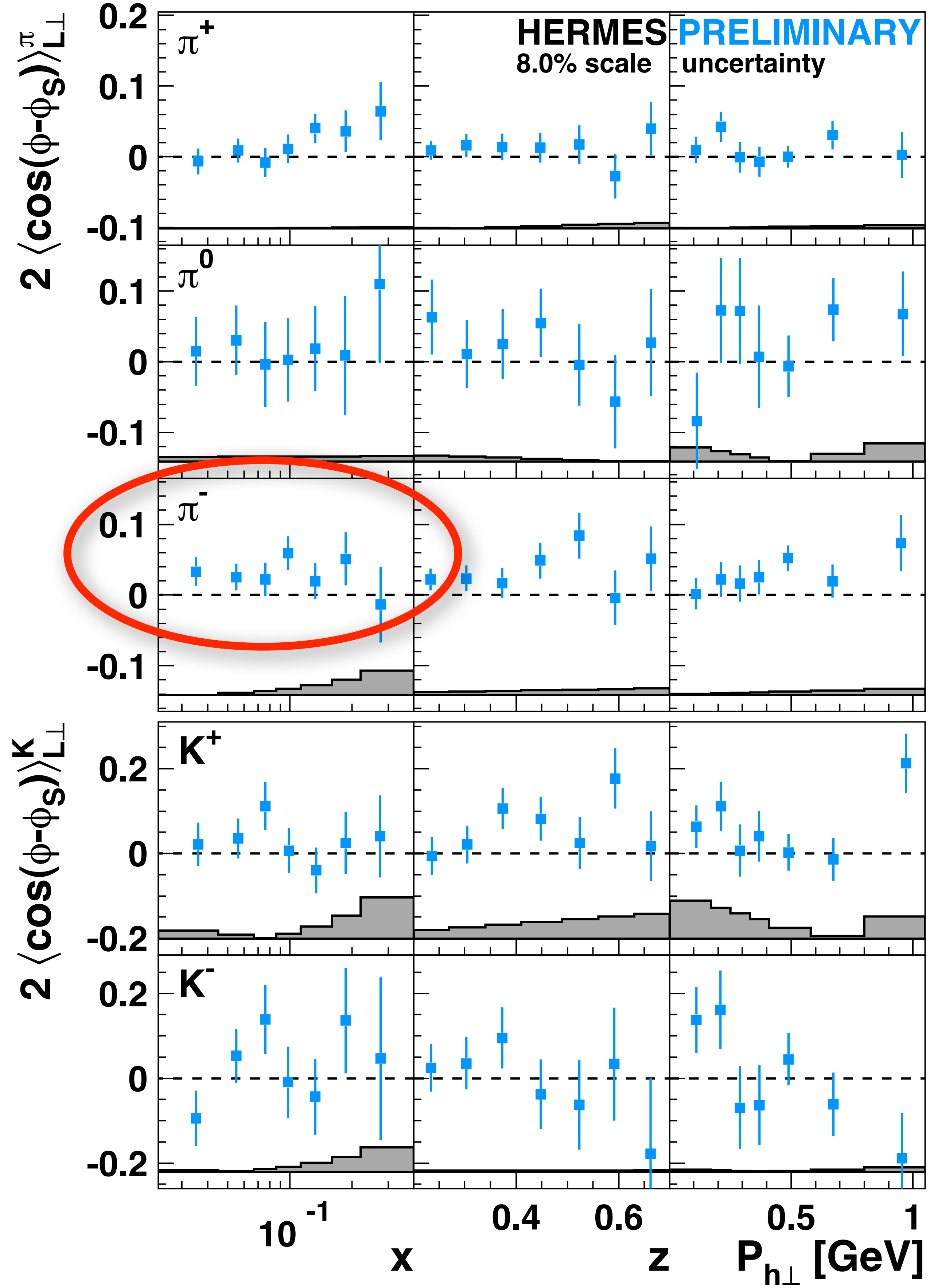
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$



Worm-Gear

- chiral even
- first direct evidence for worm-gear g_{1T} on
  - ^{3}**He** target at JLab
  - **H** target at HERMES





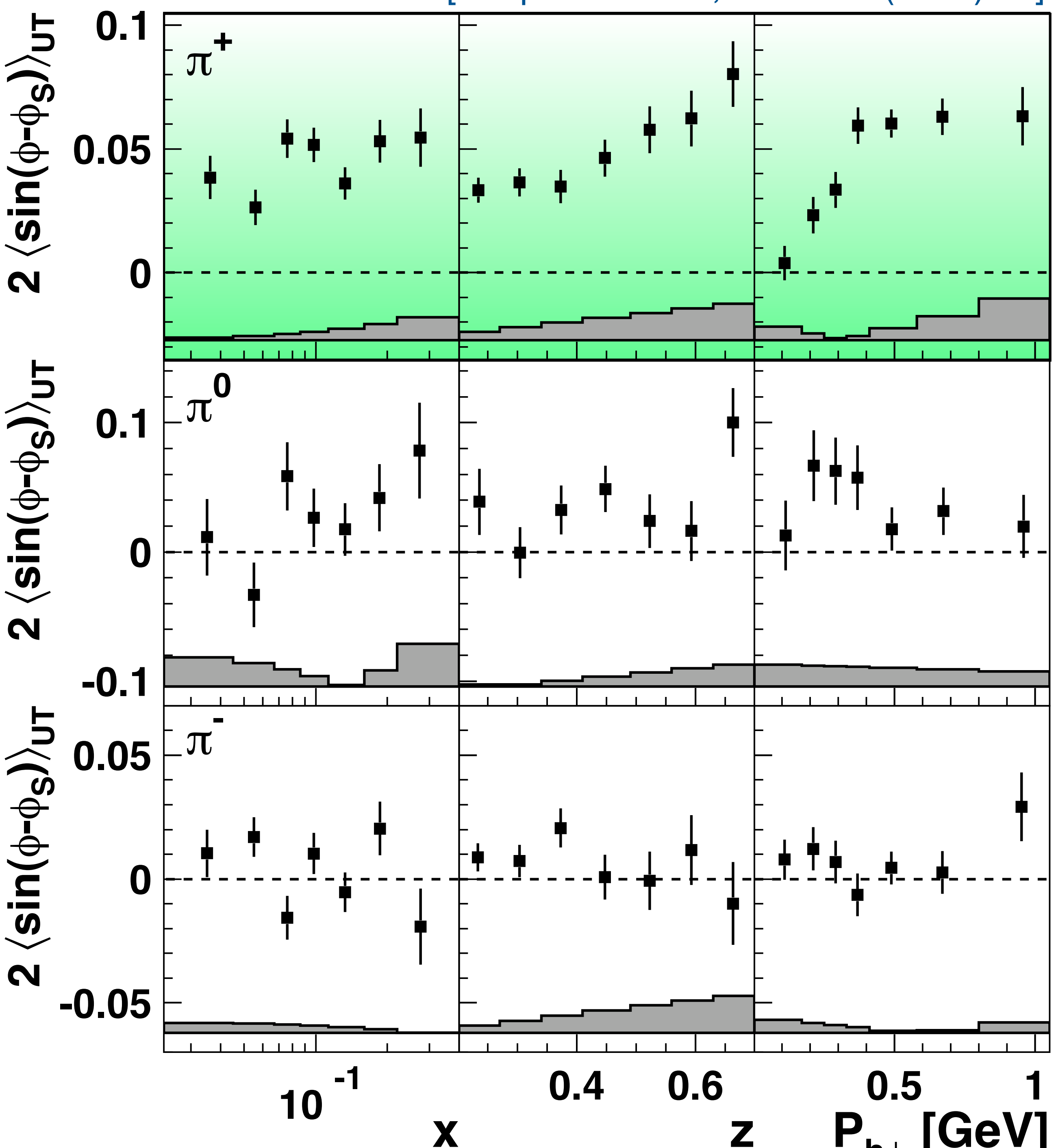
CPHI 2018

	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

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

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



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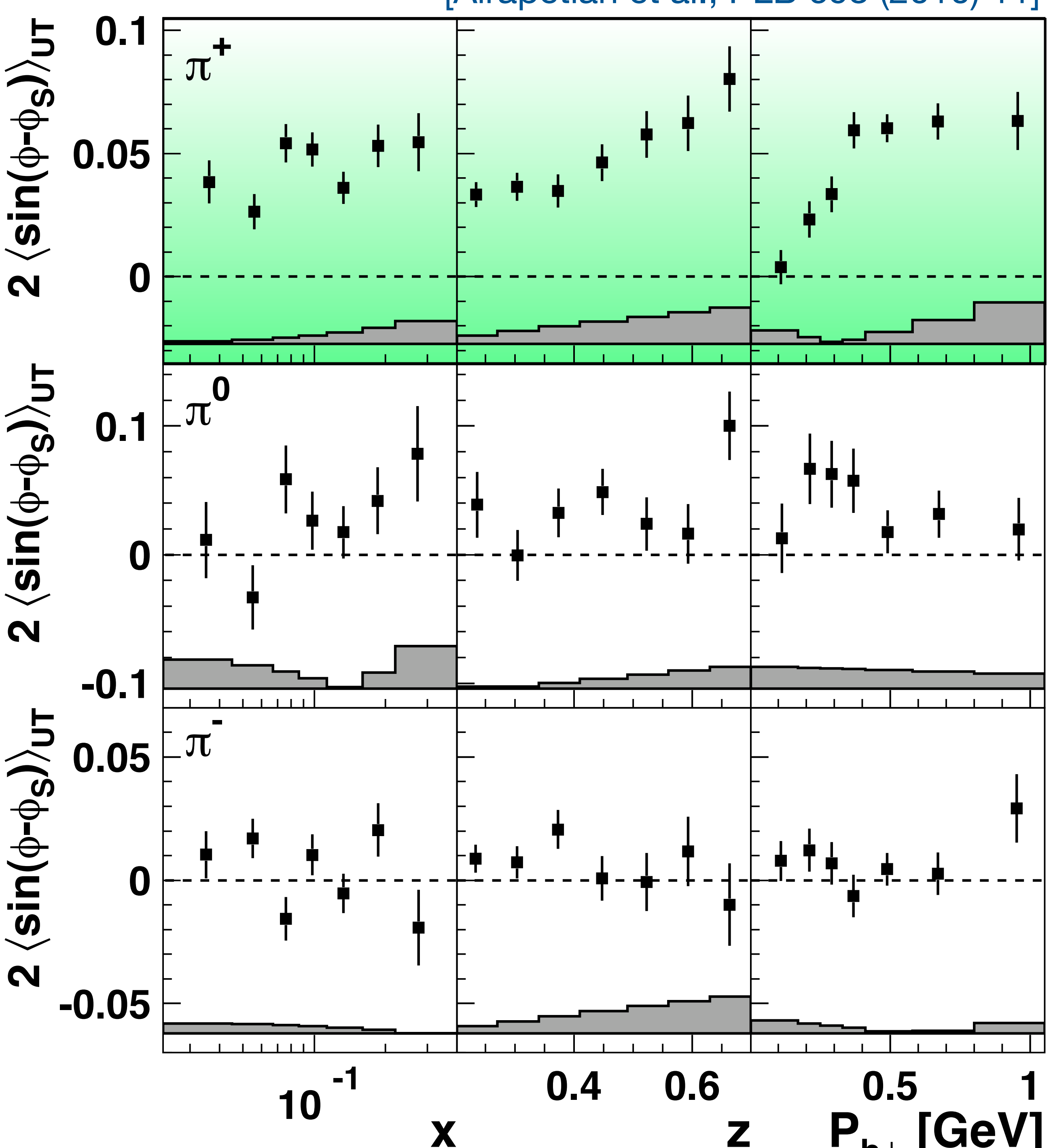

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

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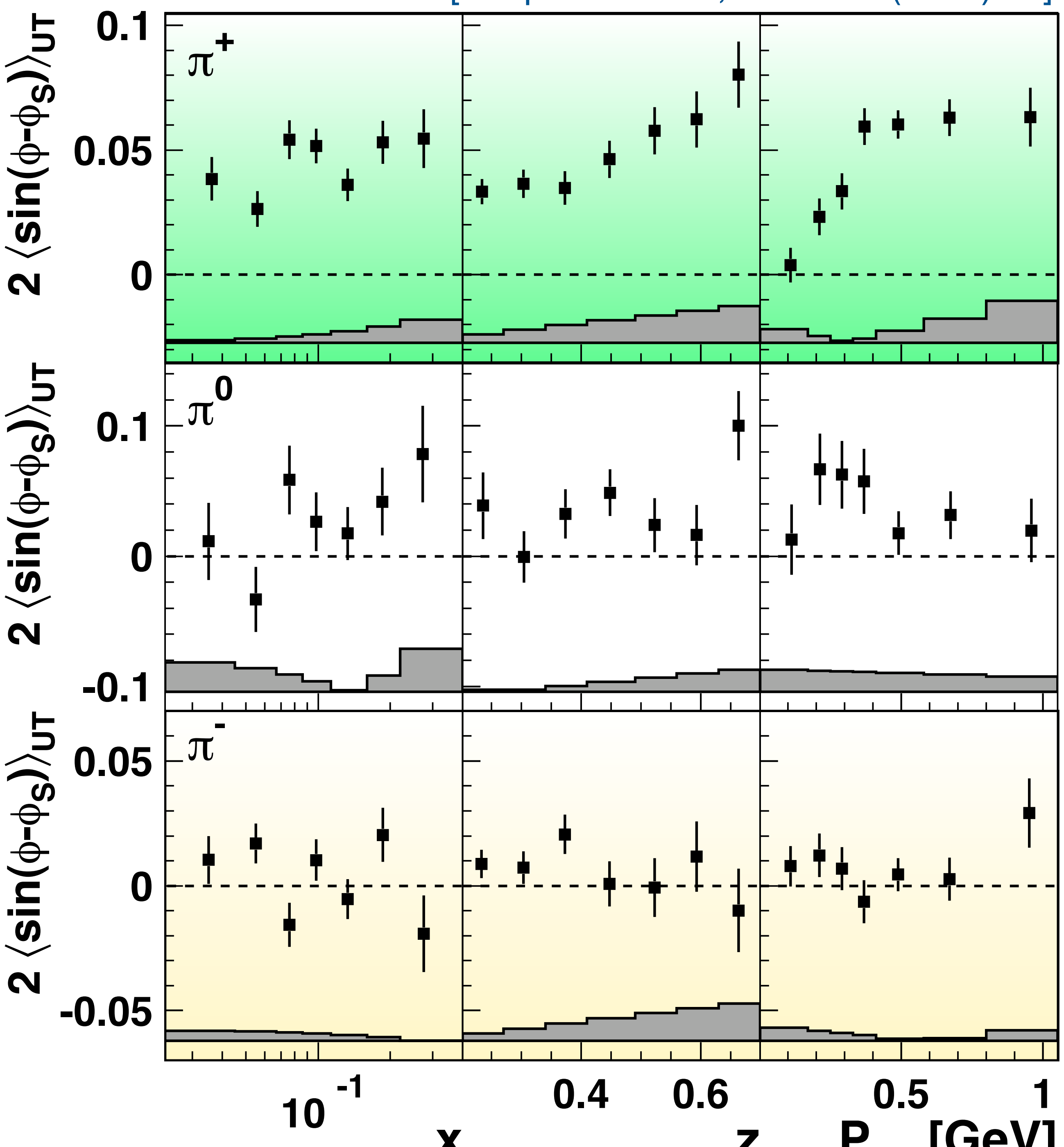
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

Sivers amplitudes for pions

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

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



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**

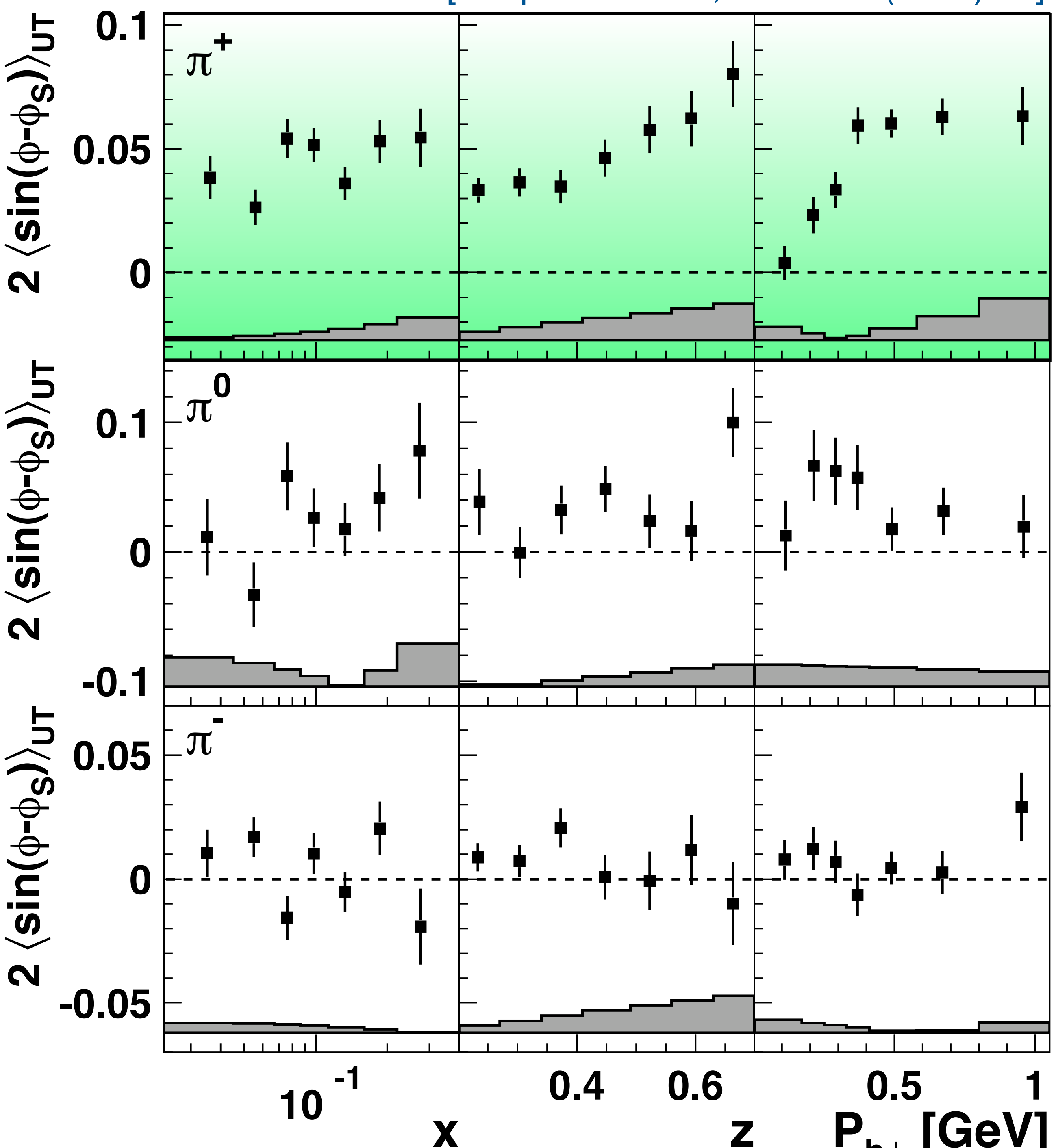
(cancelation for π^-)

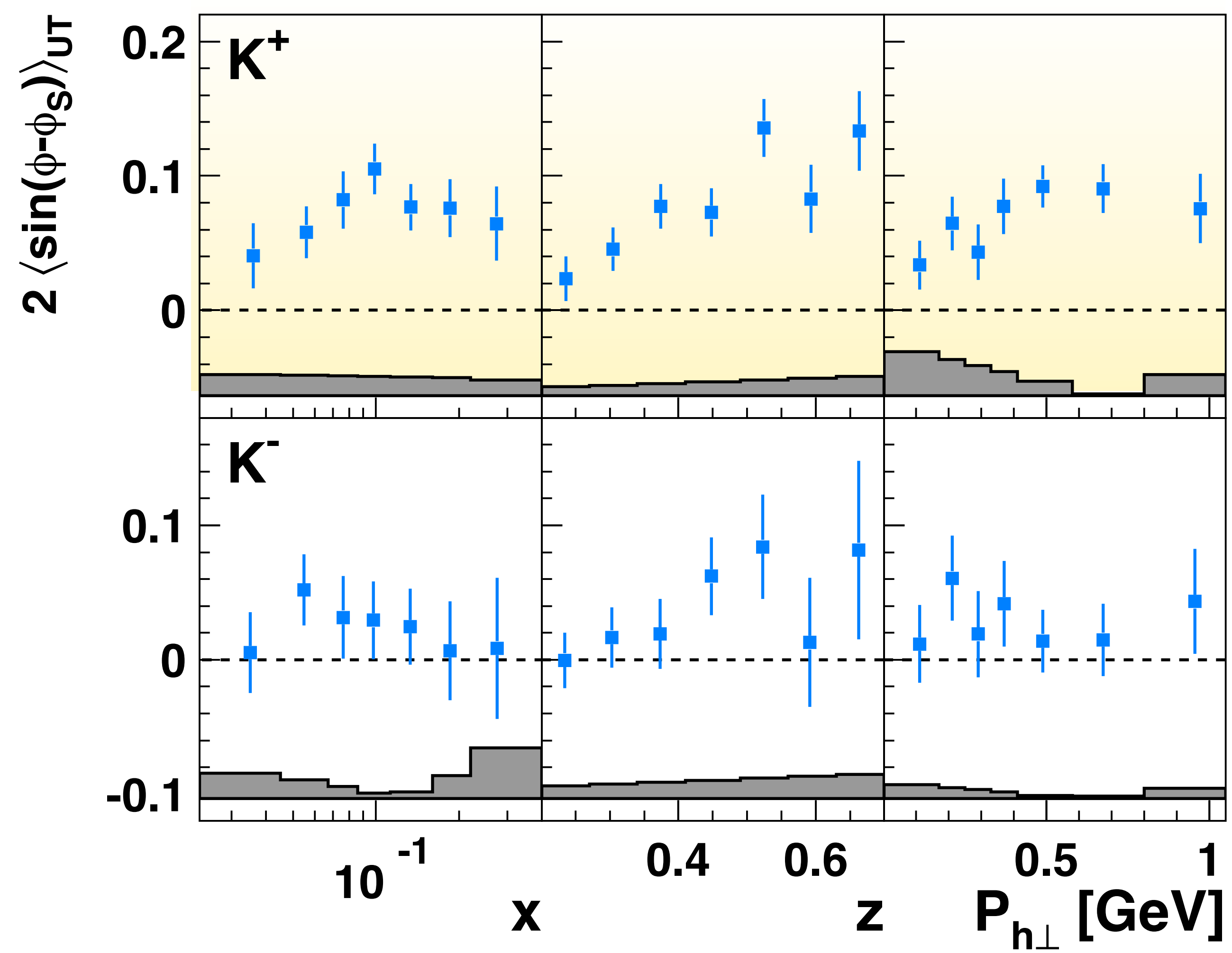
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Sivers amplitudes for mesons

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

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





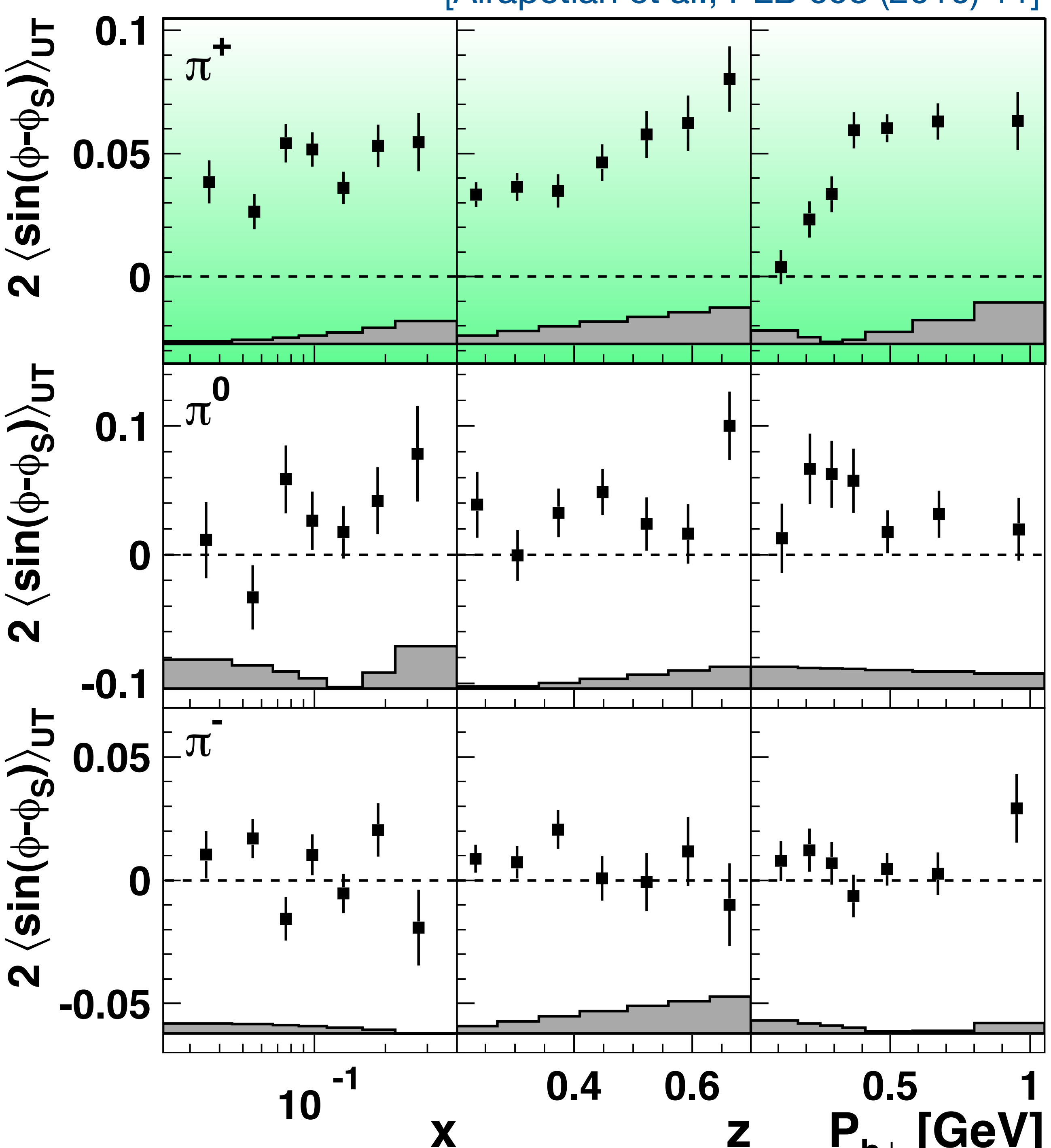
☛ larger amplitudes for positive kaons vs. pions

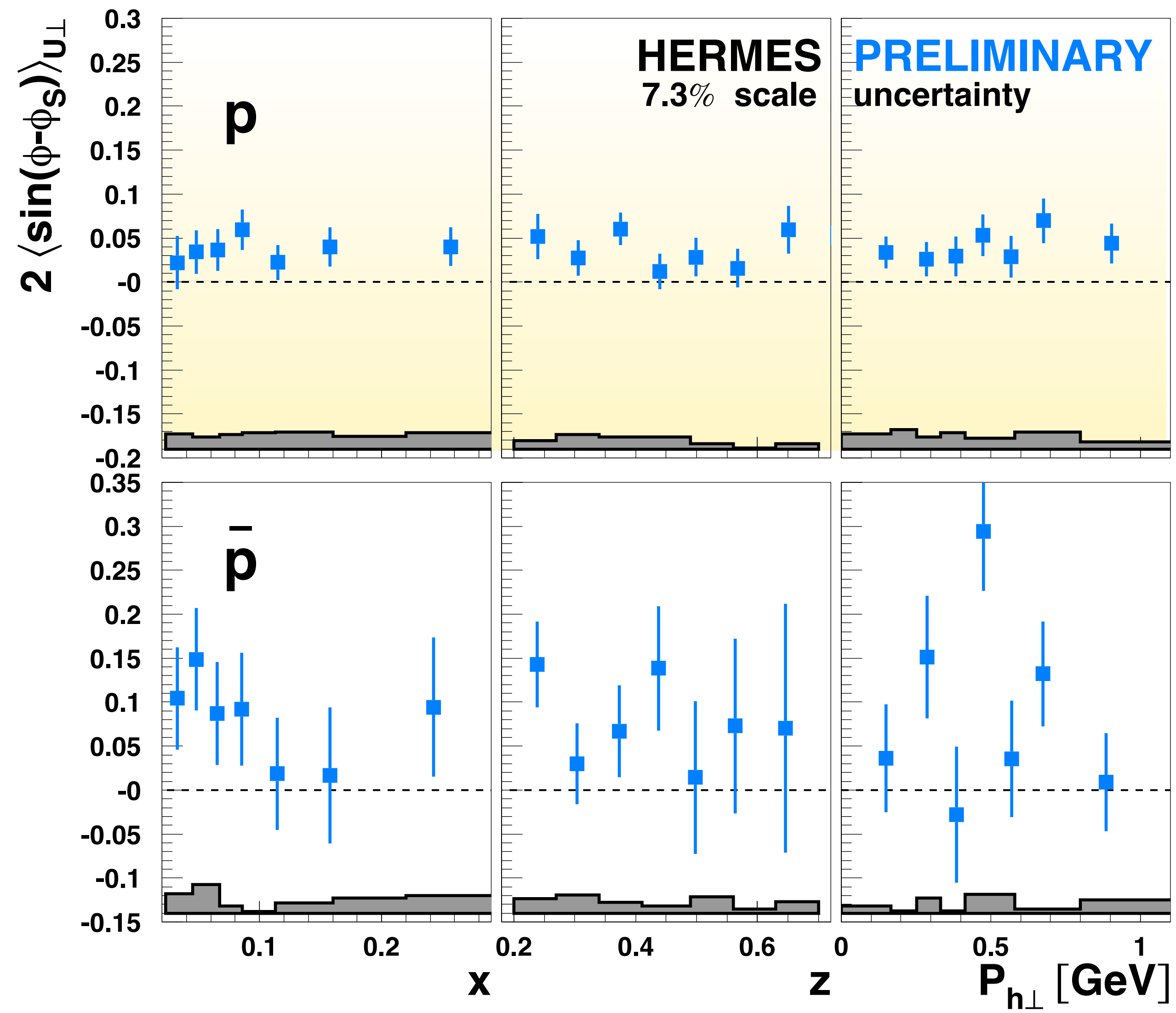
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Sivers amplitudes for baryons

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

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

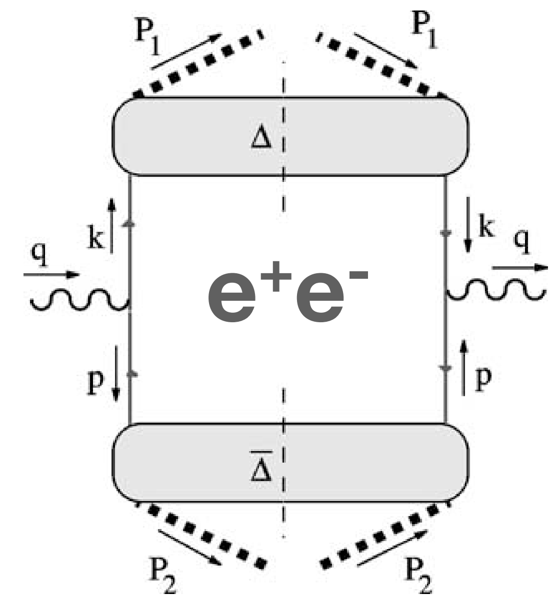




similar amplitudes for positive pions and protons ☛ u-quark dominance

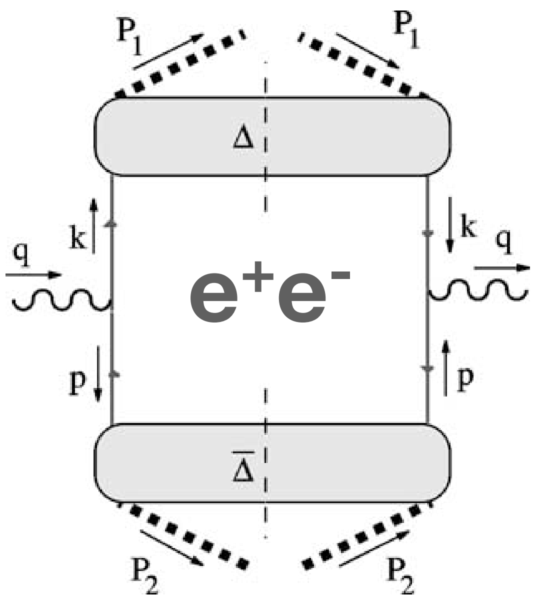
e^+e^- annihilation

fragmentation in e^+e^- annihilation



fragmentation in e^+e^- annihilation

- single-inclusive hadron production,
  $e^+e^- \rightarrow hX$
  - D_1 fragmentation fctn.
  - $D_{1T}^{\perp}$ spontaneous transv. pol.

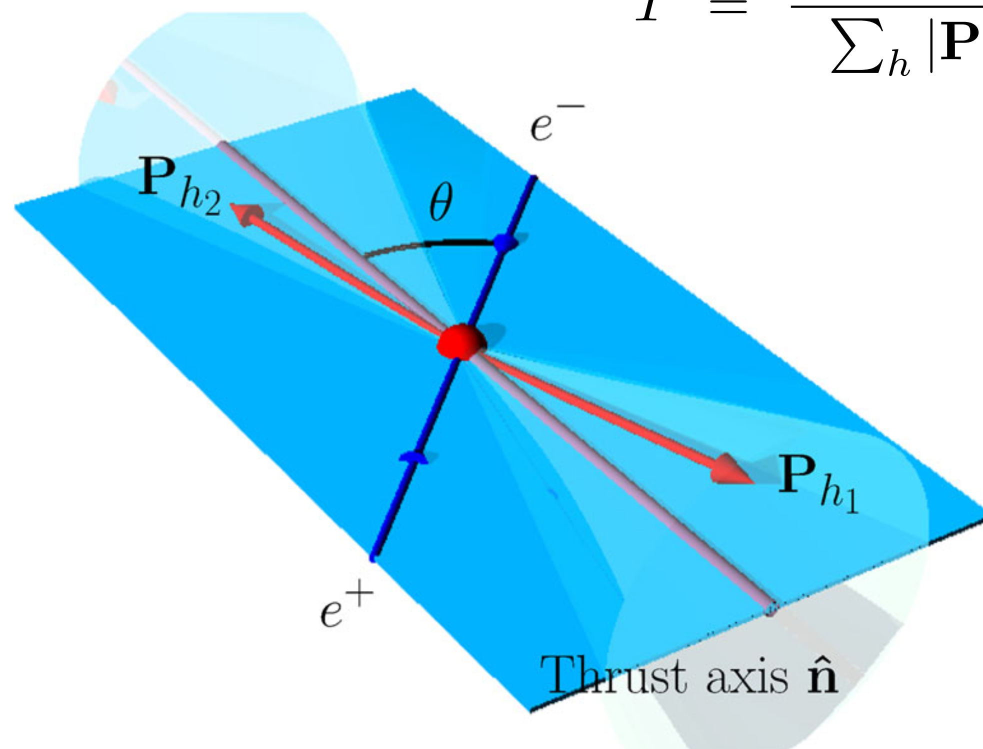


fragmentation in e^+e^- annihilation

- single-inclusive hadron production, **$e^+e^- \rightarrow hX$**
  - D_1 fragmentation fctn.
  - $D_{1T}^{\perp}$ spontaneous transv. pol.
- inclusive “back-to-back” hadron pairs, **$e^+e^- \rightarrow h_1h_2X$**
  - product of FFs
  - flavor, transverse-momentum, and/or polarization tagging

Thrust (axis):

$$T \stackrel{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

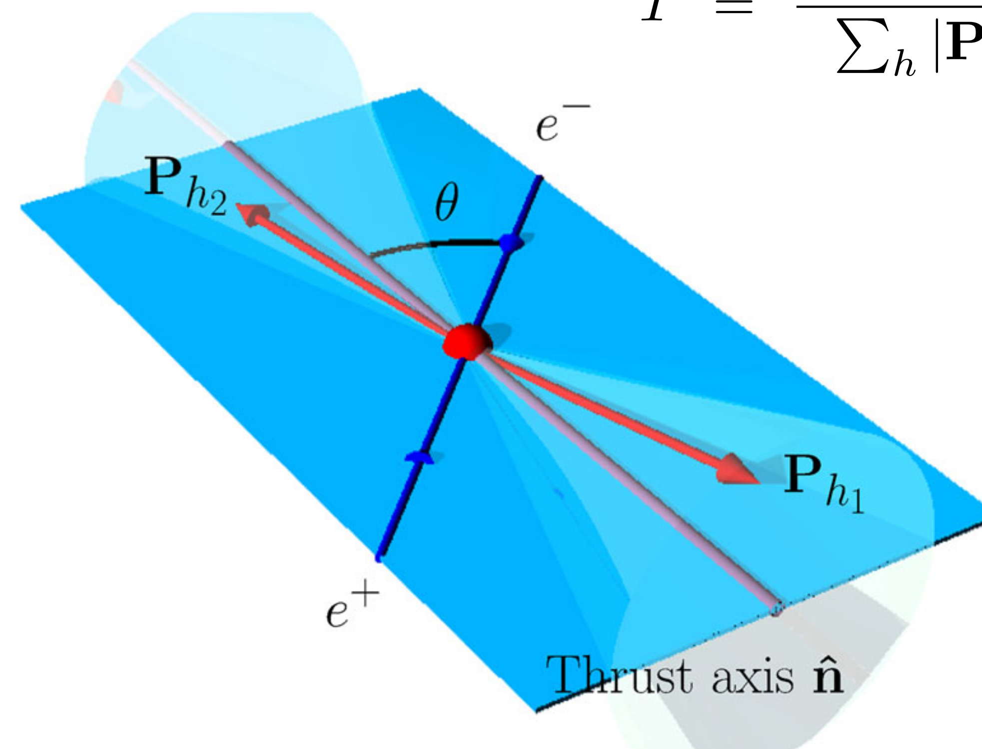


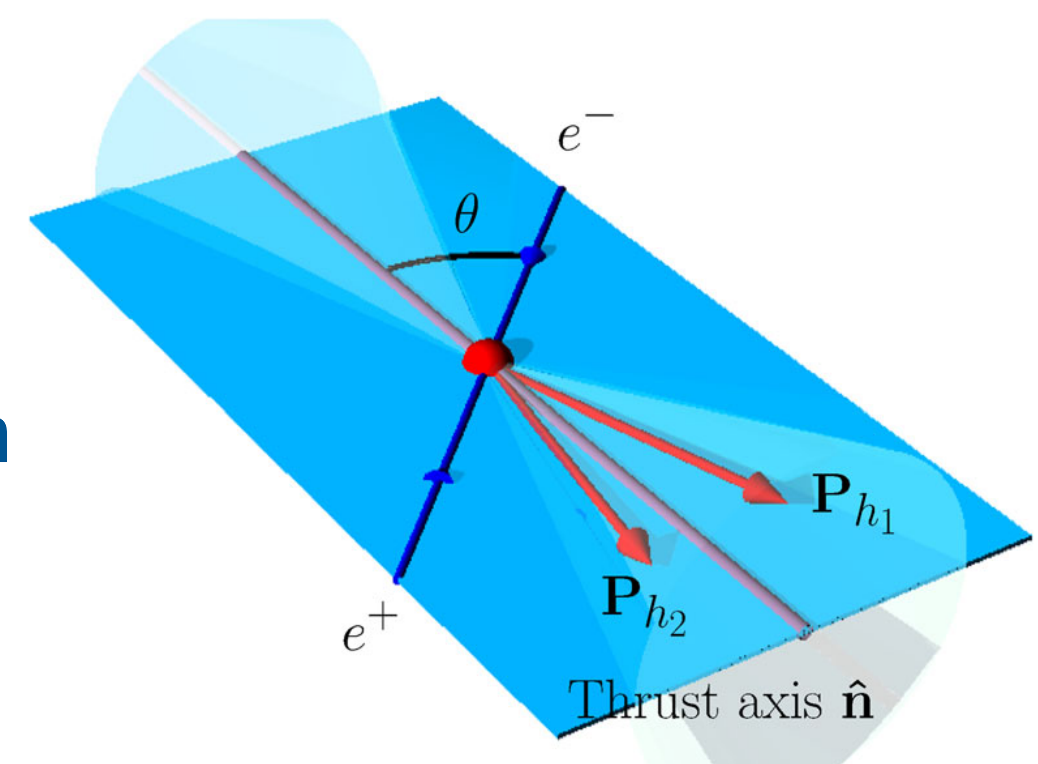
fragmentation in e$^+$e$^-$ annihilation

- single-inclusive hadron production, **e$^+$e$^-$ → hX**
    - D_1 fragmentation fctn.
    - $D_{1T}^{\perp}$ spontaneous transv. pol.
- inclusive “back-to-back” hadron pairs, **e$^+$e$^-$ → h$_1$h$_2$X**
    - product of FFs
    - flavor, transverse-momentum, and/or polarization tagging
- inclusive same-hemisphere hadron pairs, **e$^+$e$^-$ → h$_1$h$_2$X**
    - dihadron fragmentation

Thrust (axis):

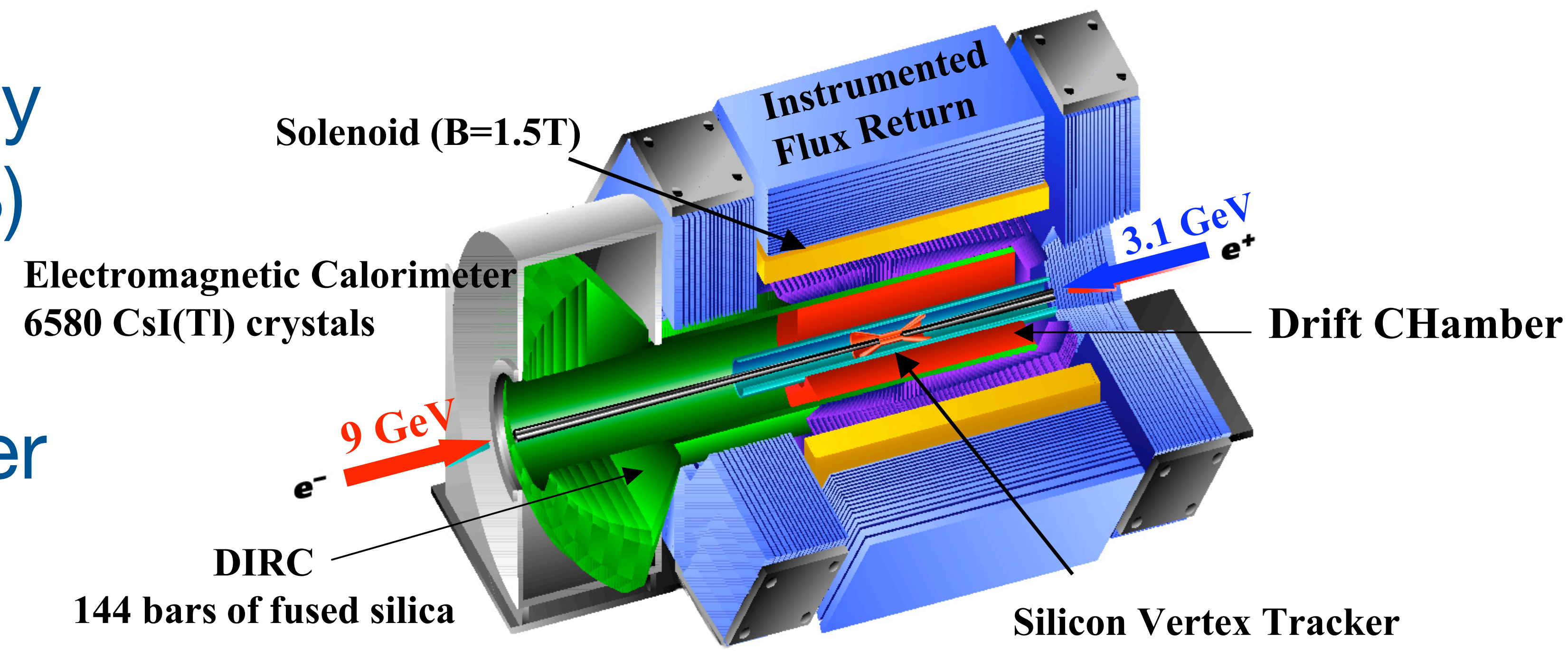
$$T \stackrel{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

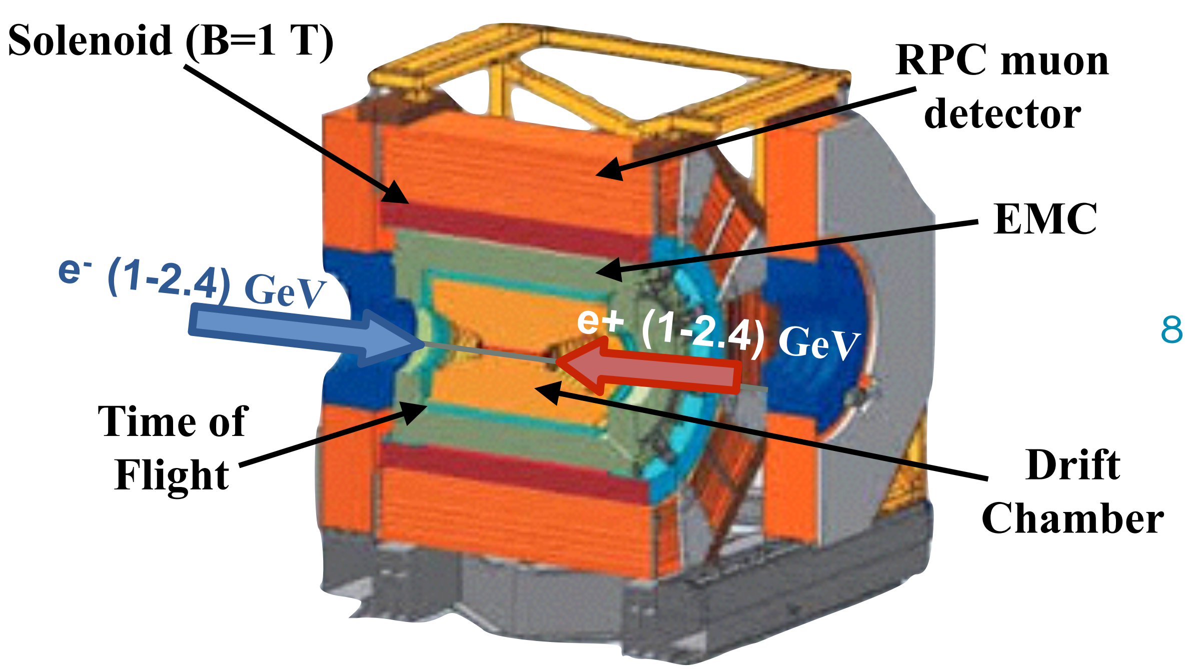


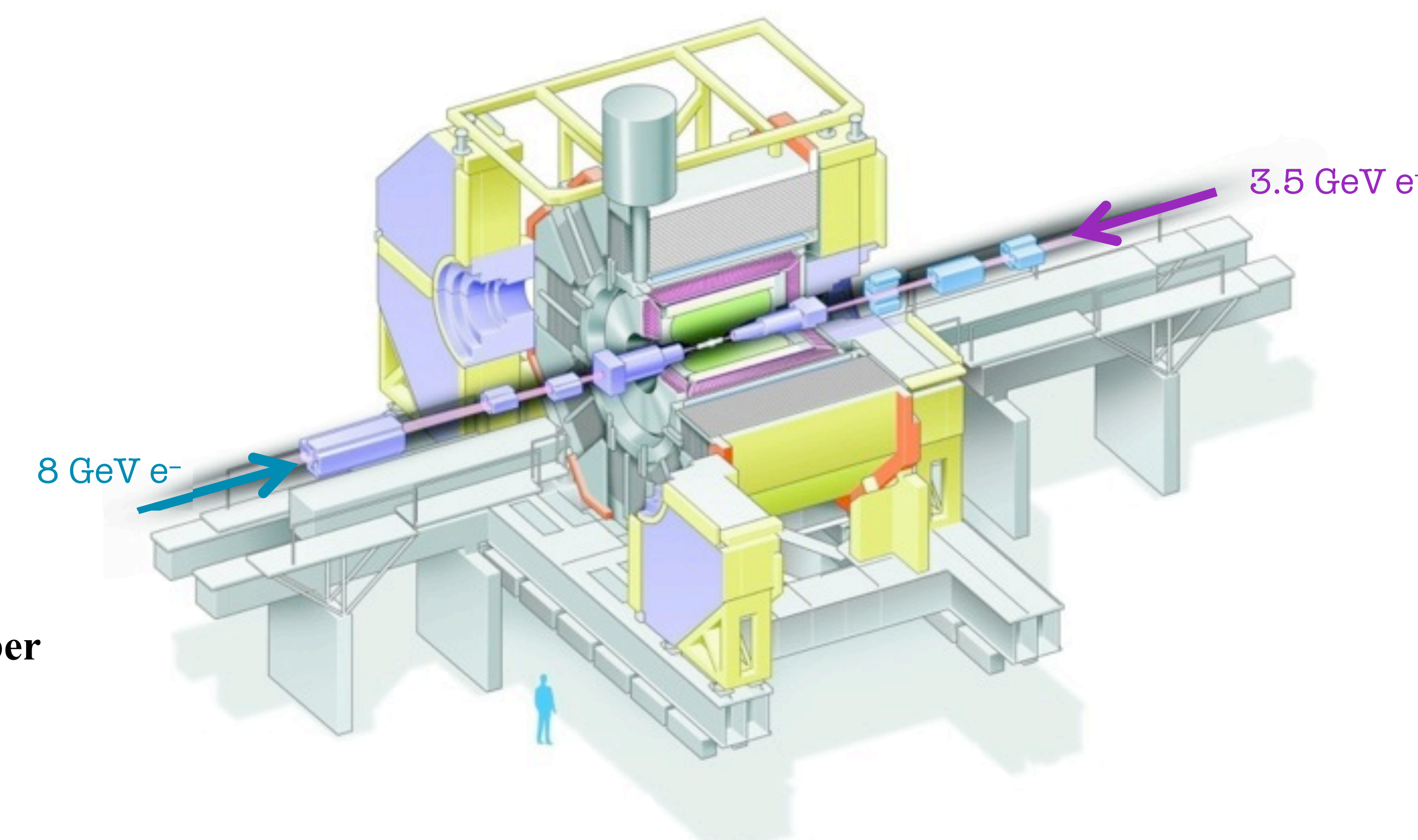


e^+e^- annihilation at BESIII, BaBar & Belle

- BaBar & Belle: asymmetric beam-energy e^+e^- collider near/at $\Upsilon(4S)$ resonance (10.58 GeV)
- BESIII: symmetric collider with E_e=1...2.4 GeV

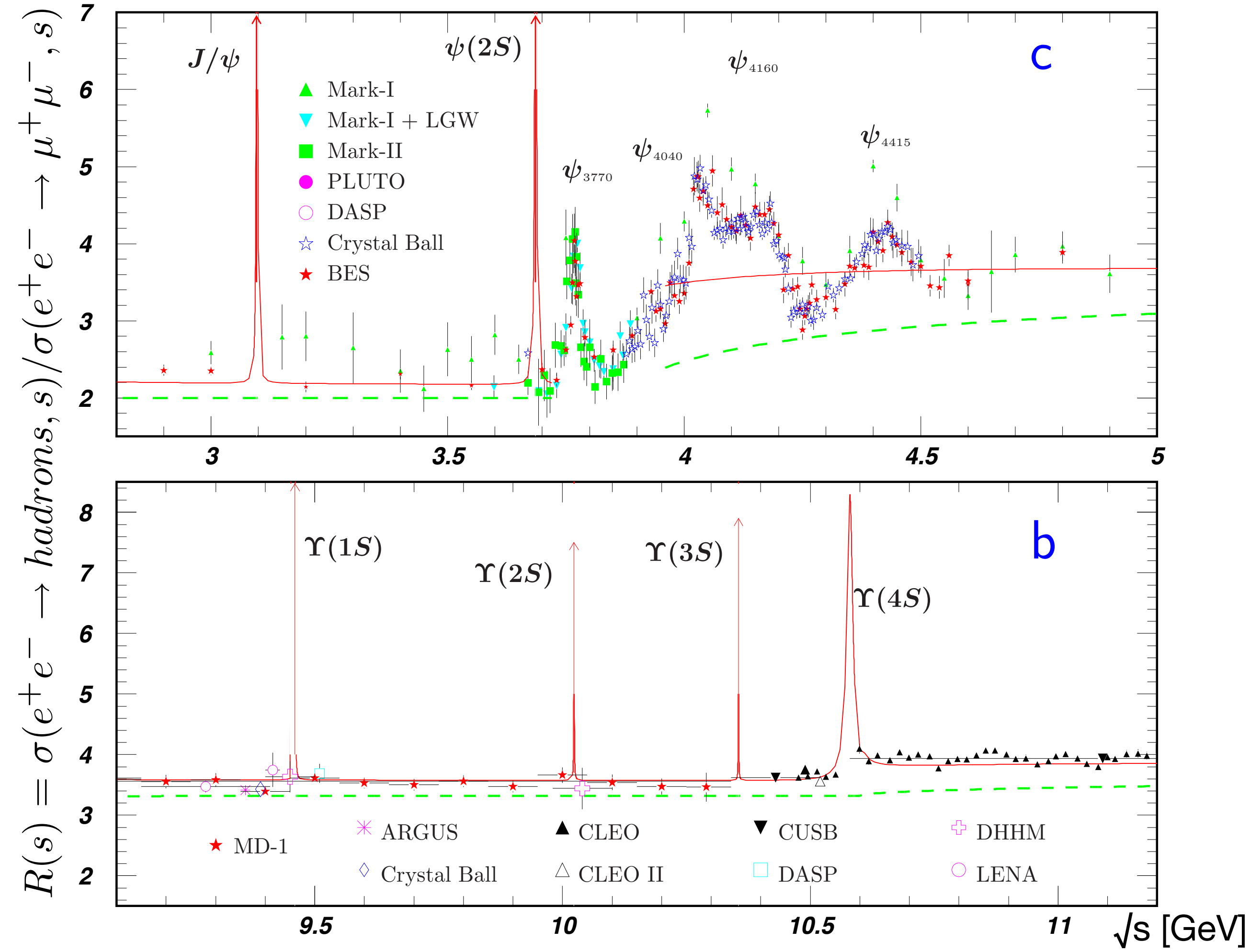






e^+e^- annihilation at BESIII, BaBar & Belle

- BaBar & Belle: asymmetric beam-energy e^+e^- collider near/at Υ(4S) resonance (10.58 GeV)
- BESIII: symmetric collider with E_e=1...2.4 GeV
- integrated luminosities:

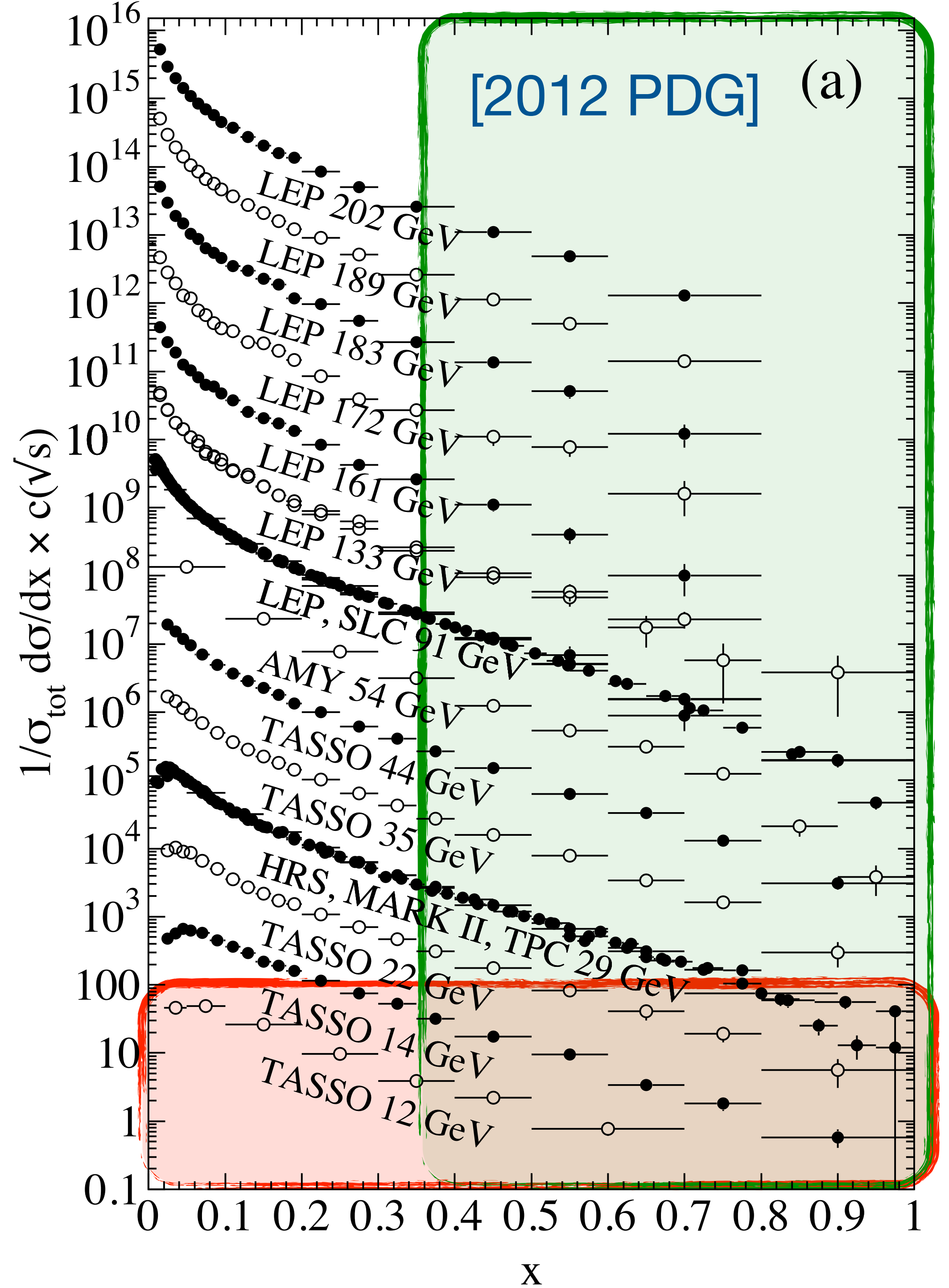


	Υ(4S) on resonance	Υ(4S) off resonance	other
BaBar	424.2 fb^{-1}	43.9 fb^{-1}	
Belle	(140+571) fb^{-1}	(15.6+73.8) fb^{-1}	
BESIII			~62 pb^{-1} @3.65 GeV *)

*) used for the Collins analysis presented here

single-hadron production

- before 2013: lack of precision data at (moderately) high z and at low $\sqrt{s}$
  - limits analysis of evolution and gluon fragmentation
  - limited information in kinematic region often used in semi-inclusive DIS



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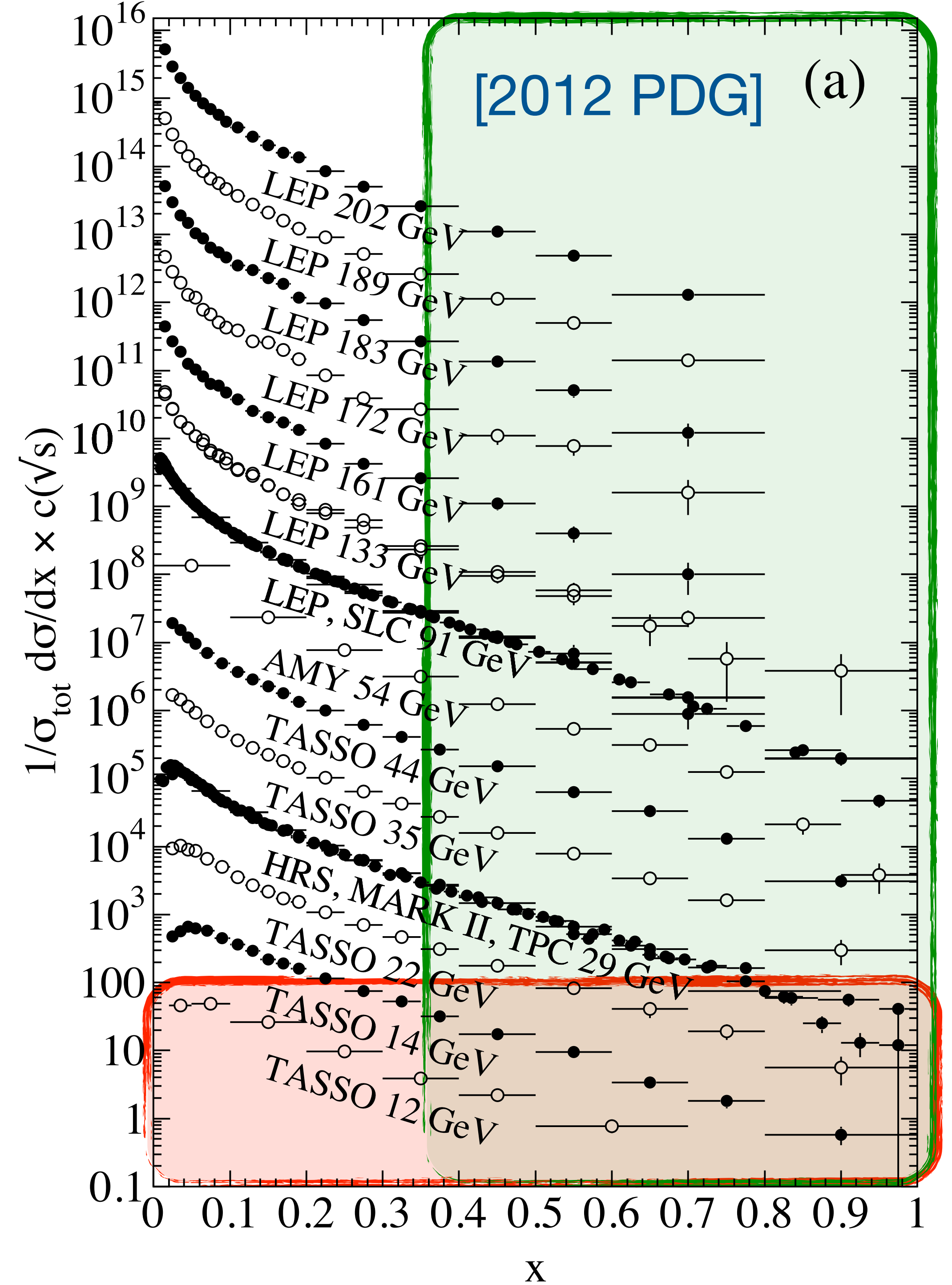
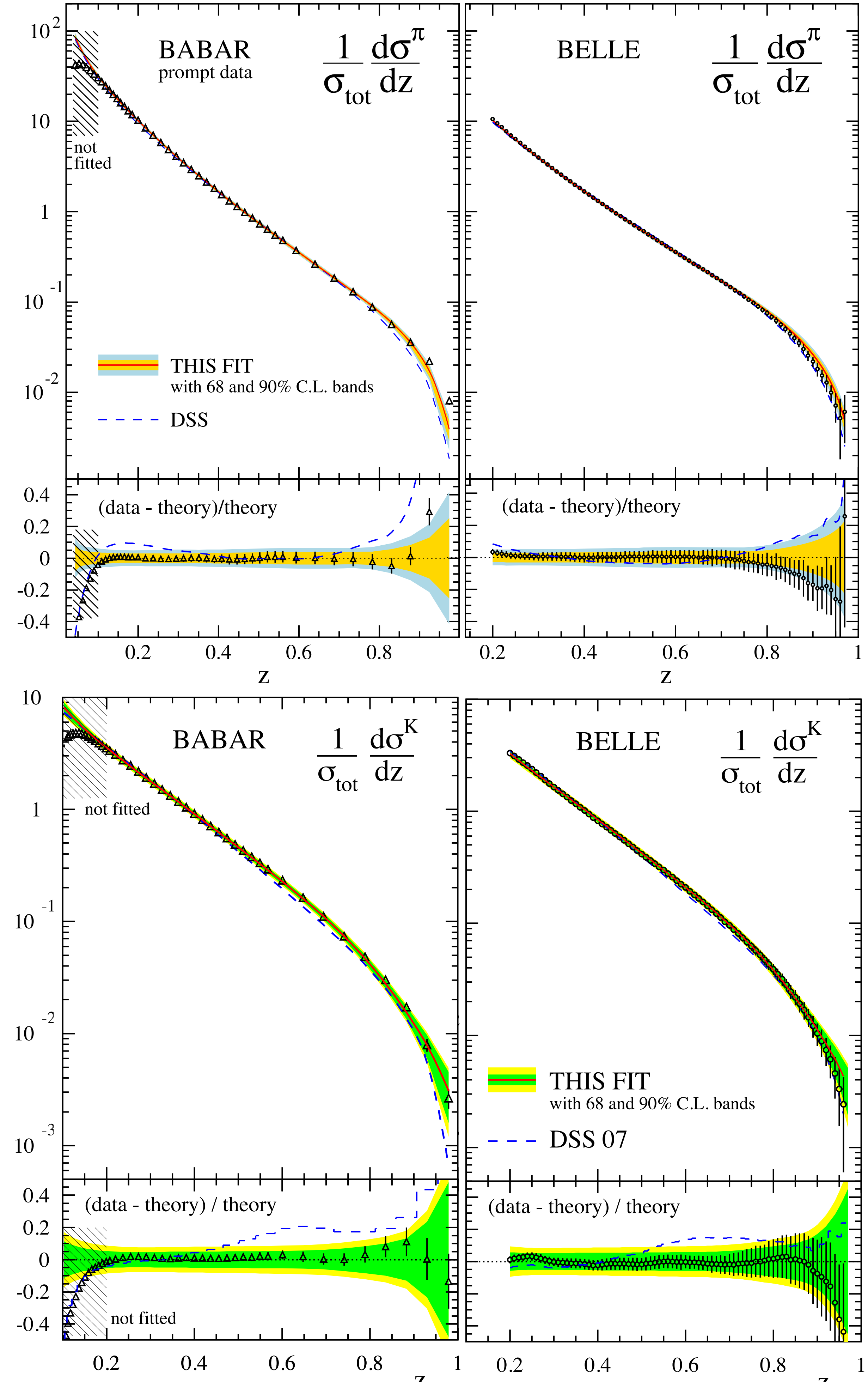


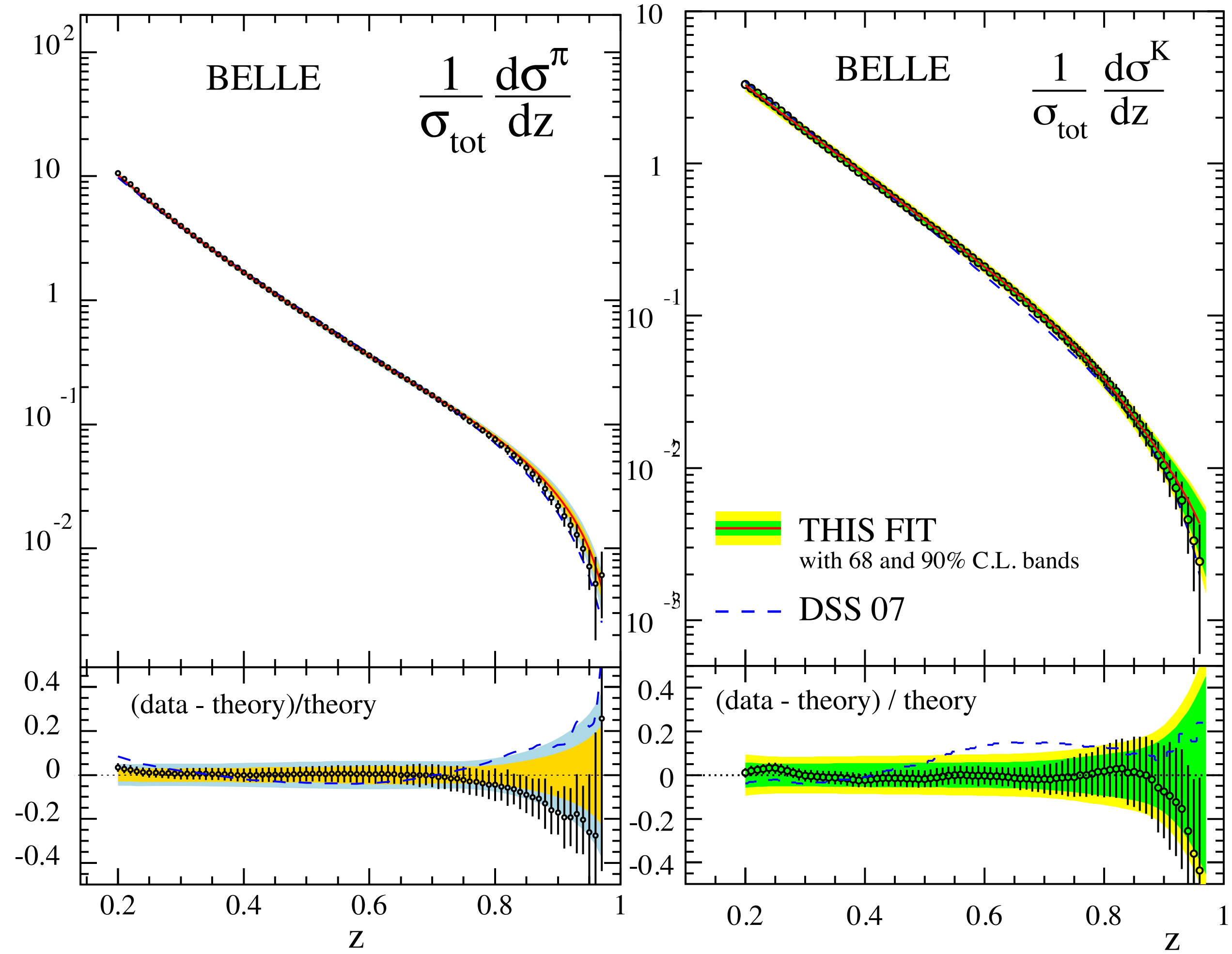
- now, results available from BaBar and Belle:
  - BaBar Collaboration, Phys. Rev. D88 (2013) 032011: **$\pi^\pm$, $K^\pm$, p+p**
  - Belle Collaboration, Phys. Rev. Lett. 111 (2013) 062002: **$\pi^\pm$, $K^\pm$**
  - Belle Collaboration, Phys. Rev. D92 (2015) 092007: **$\pi^\pm$, $K^\pm$, p+p**

single-hadron production

- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- included in recent DEHSS fits
    - slight tension at low-z for BaBar and high-z for Belle



single-hadron production



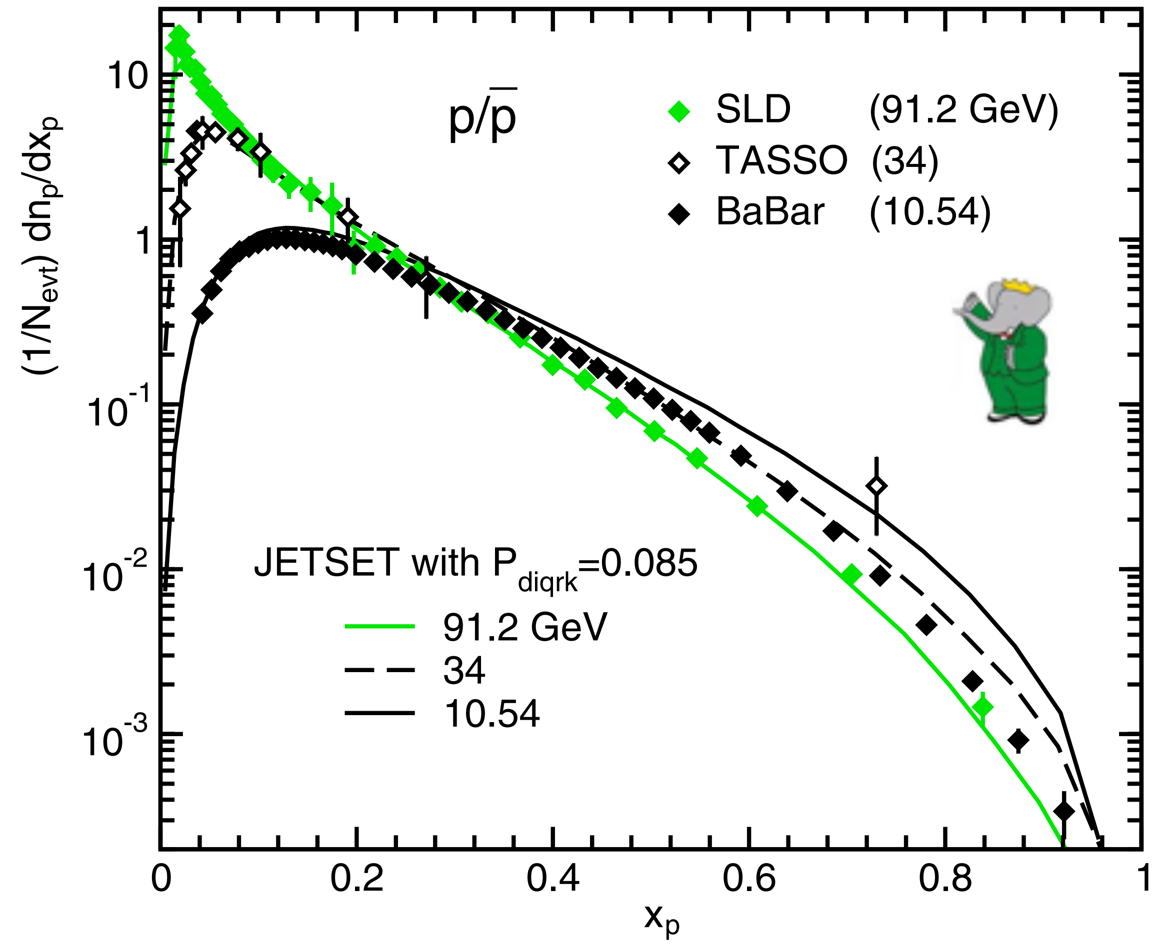
- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections **undone** in FF fits

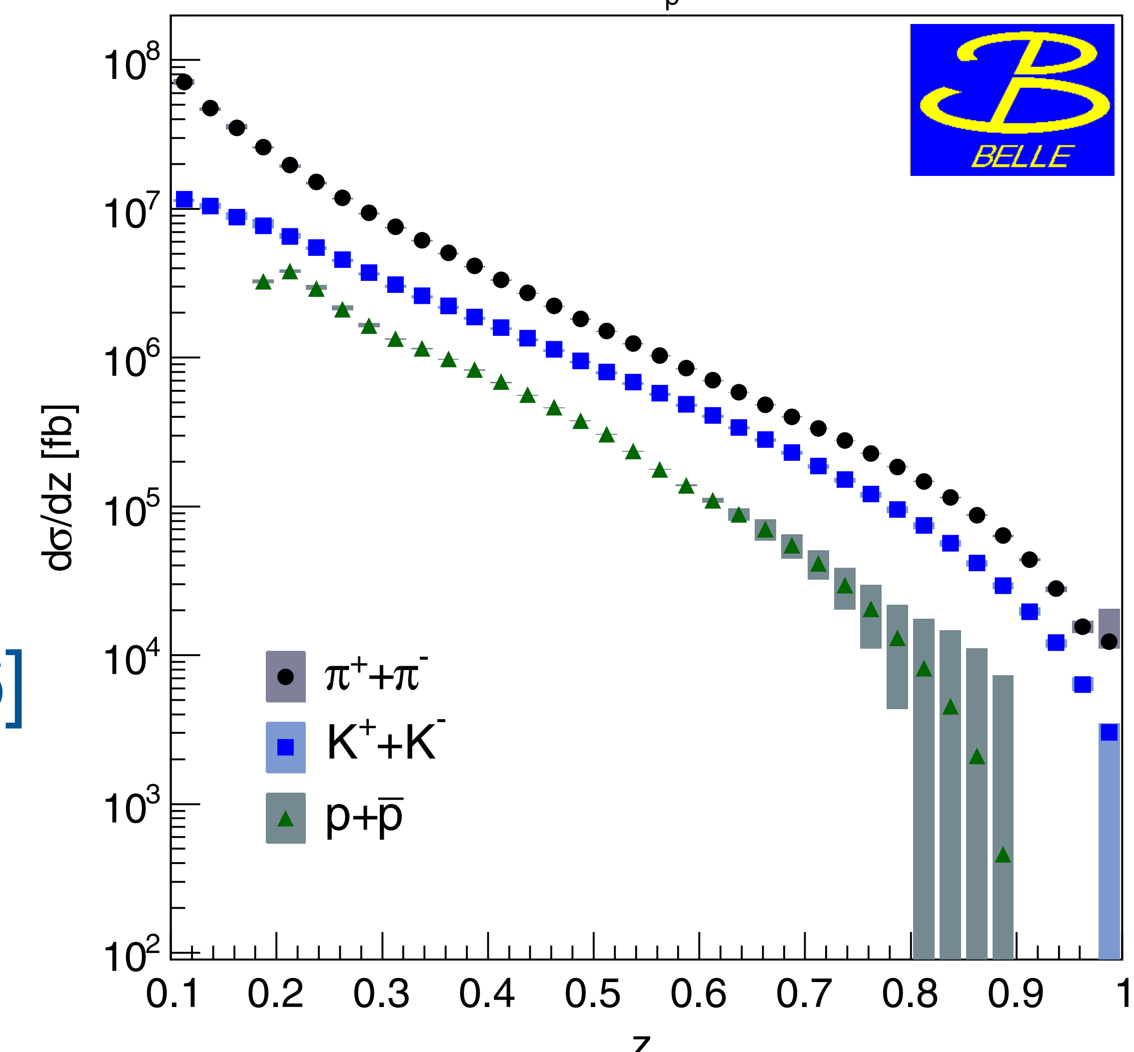
[EPJC 77 (2017) 516, NNFF1.0]

In the case of the BELLE experiment we multiply all data points by a factor $1/c$, with $c = 0.65$ for charged pions and kaons [69] and with c a function of z for protons/antiprotons [53]. This correction is required in order to treat the BELLE data consistently with all the other SIA measurements included in NNFF1.0. The reason is that a kinematic cut on radiative photon events was applied to the BELLE data sample in the original analysis instead of unfolding the radiative QED effects. Specifically, the energy scales

single-hadron production

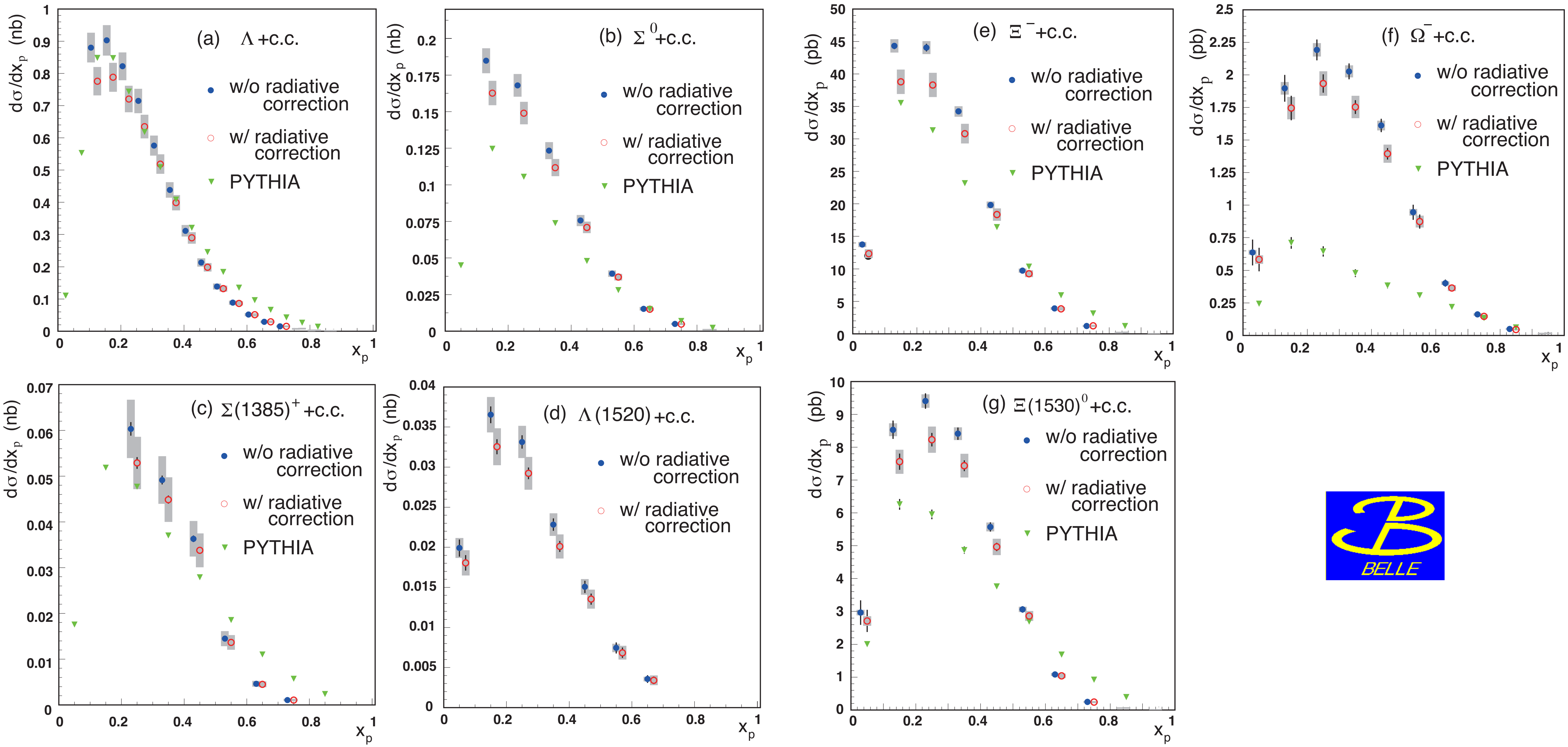
- very precise data for charged pions and kaons
- Belle data available up to very large z (z<0.98)
- included in recent DEHSS fits [e.g. PRD 91, 014035 (2015)]
- Belle radiative corrections **undone** in FF fits
- data for protons & anti-protons
  - not (yet) included in DEHSS, but in NNFF 1.0 [EPJC 77 (2017) 516]
  - similar z dependence as pions
  - about ~⅕ of pion cross sections





inclusive hyperon production

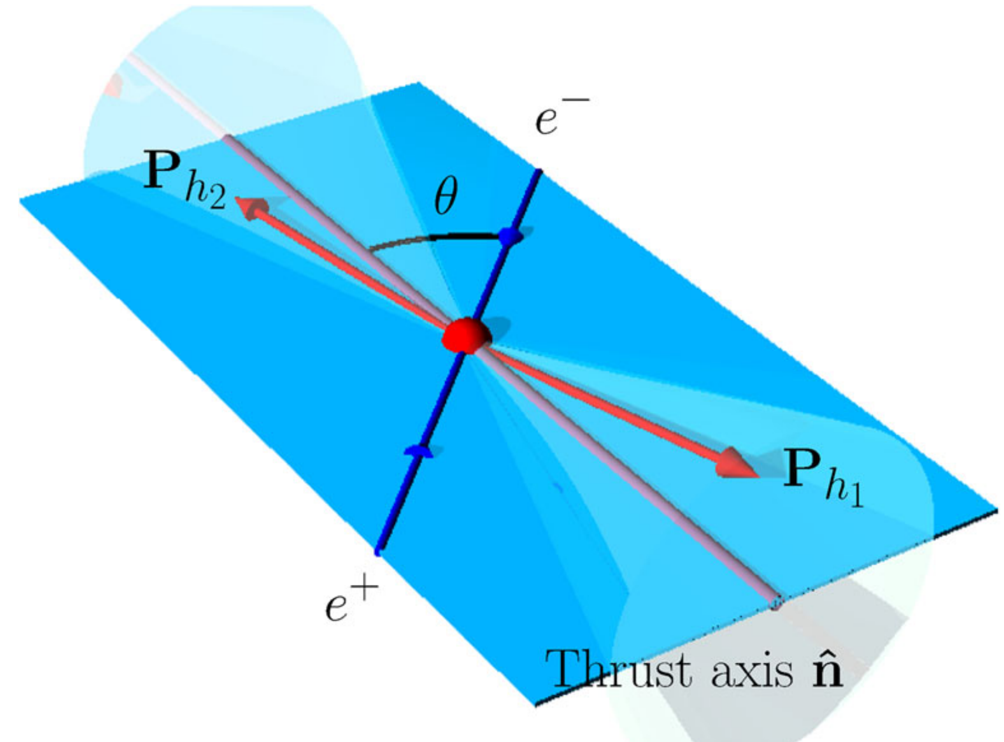
[M. Niiyama et al., PRD 97 (2018) 072005]

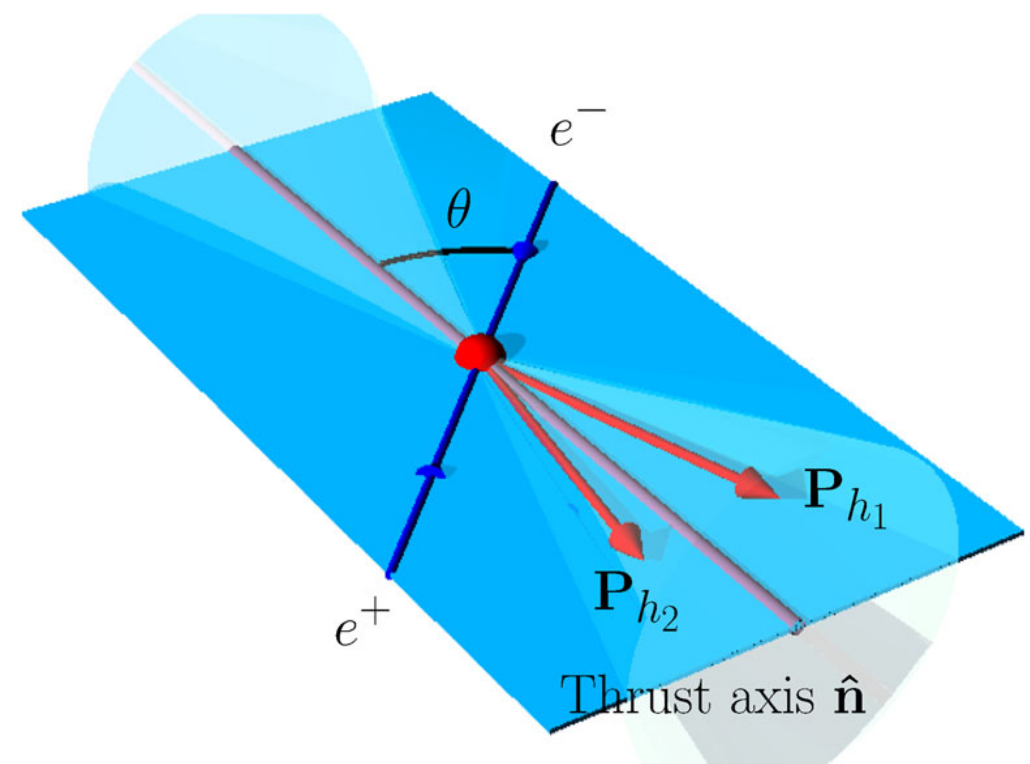


- Λ production reasonably well described by Pythia
- less satisfactory for heavier hyperons
- fails to describe Ω^- production

hadron-pair production

- single-hadron production has low discriminating power for parton flavor
- can use 2nd hadron in **opposite hemisphere** to “tag” flavor
  - mainly sensitive to product of single-hadron FFs
- if hadrons in same hemisphere: **dihadron fragmentation**
  - a la de Florian & Vanni [Phys. Lett. B 578 (2004) 139]
  - a la Collins, Heppelmann & Ladinsky [Nucl. Phys. B 420 (1994) 565]; Boer, Jacobs & Radici [Phys. Rev. D 67 (2003) 094003]
- opens the question of **defining hemispheres**

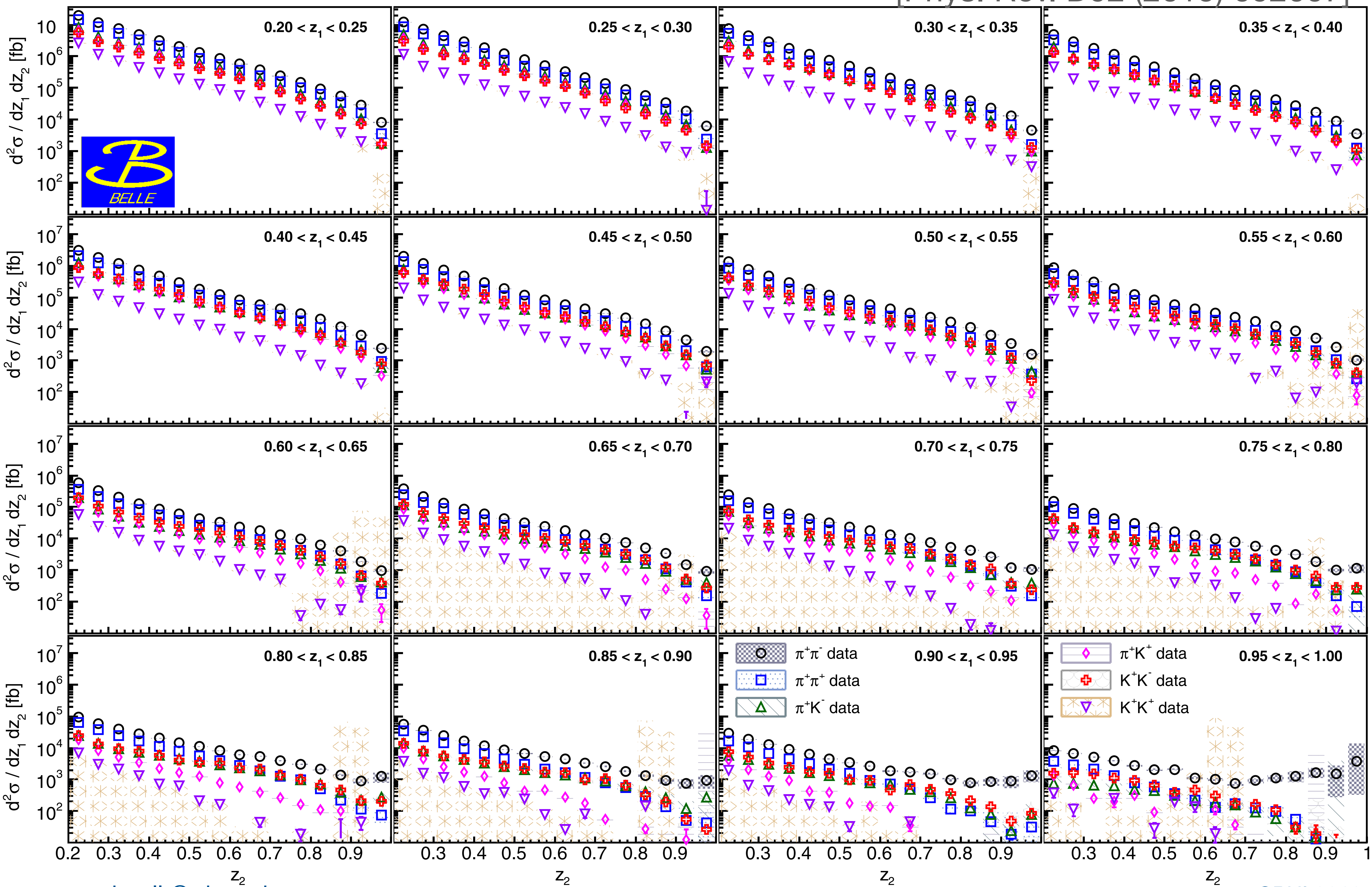




no hemisphere selection

hadron-pair production

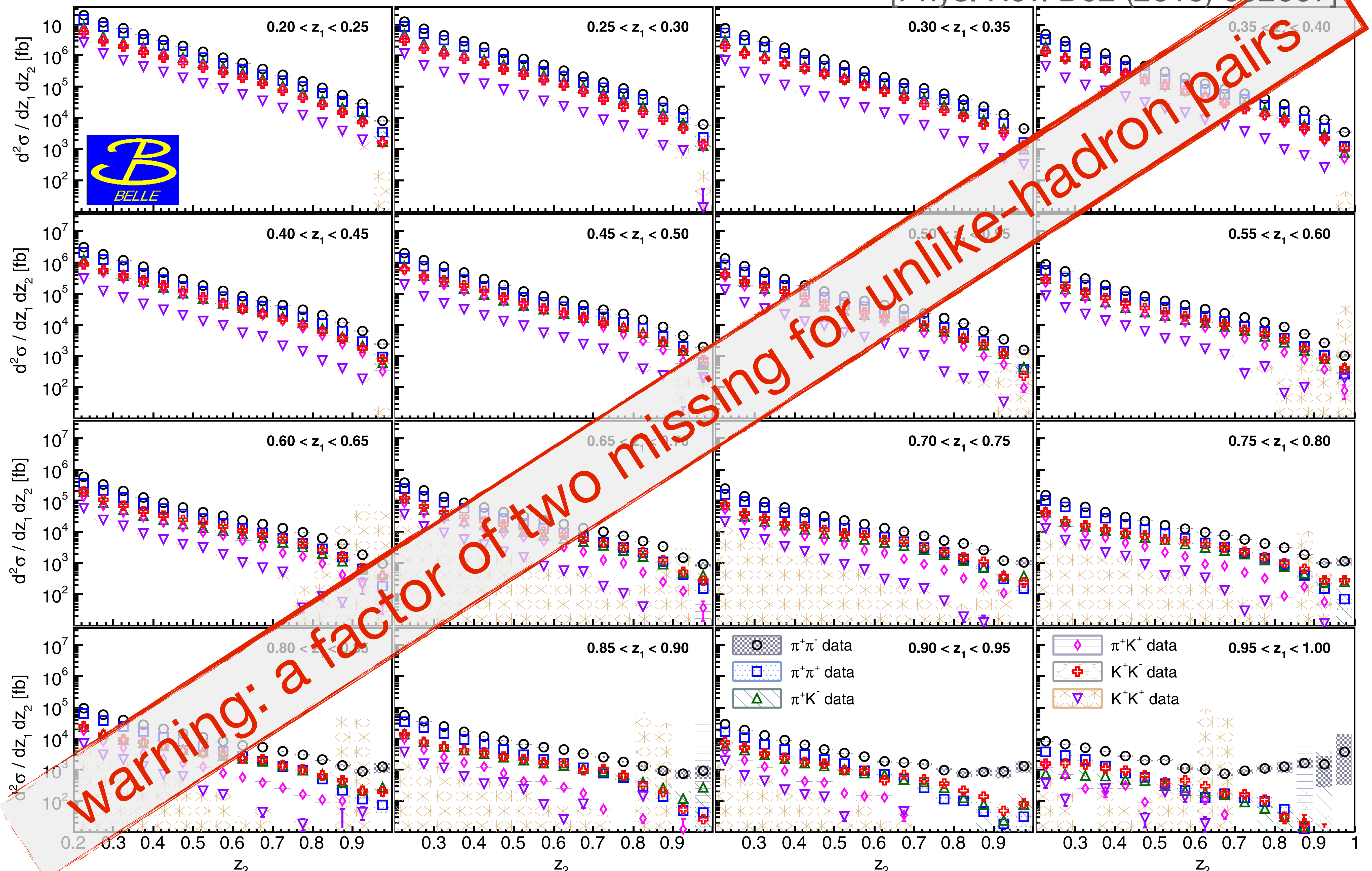
[Phys. Rev. D92 (2015) 092007]



hadron-pair production

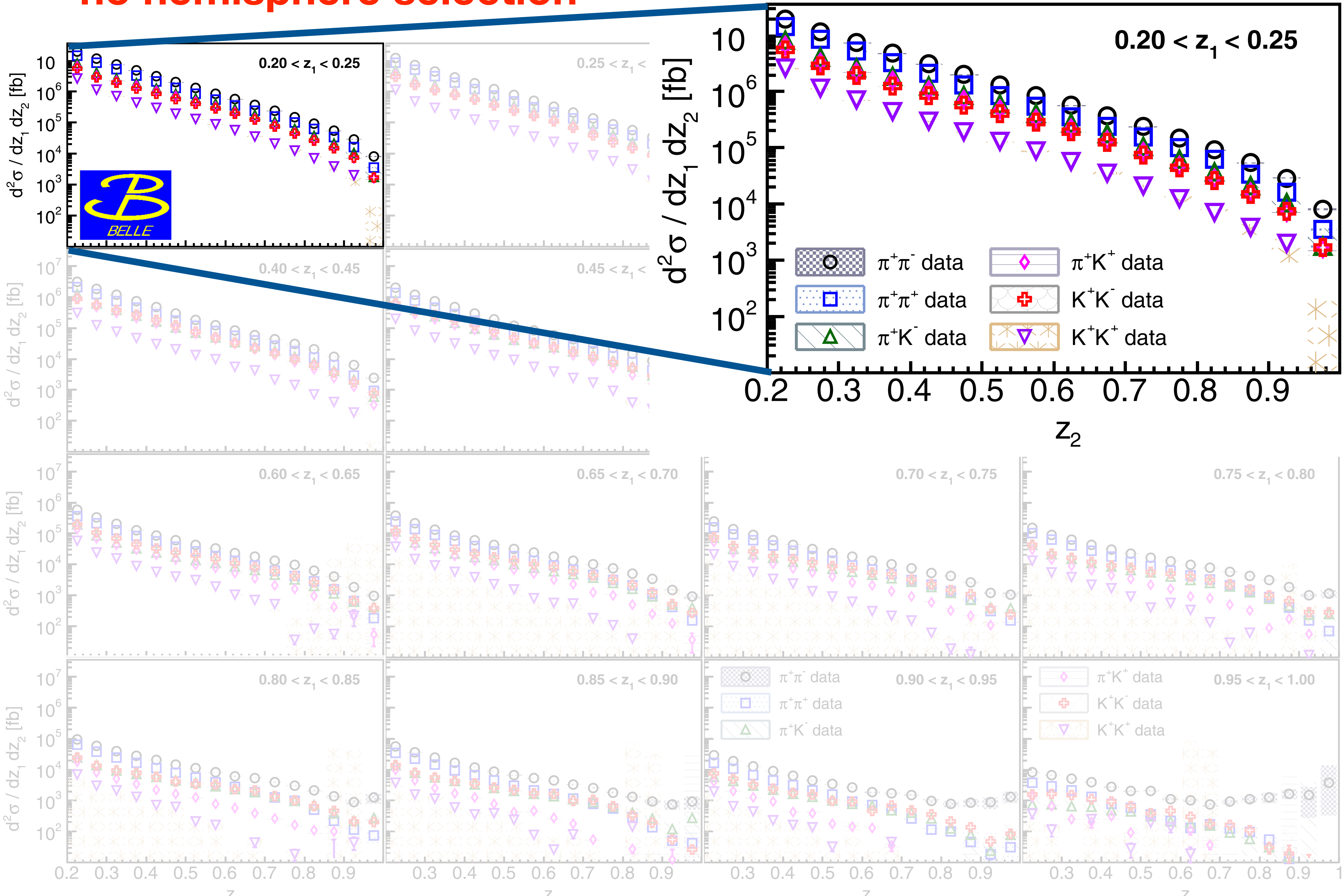
no hemisphere selection

[Phys. Rev. D92 (2015) 092007]



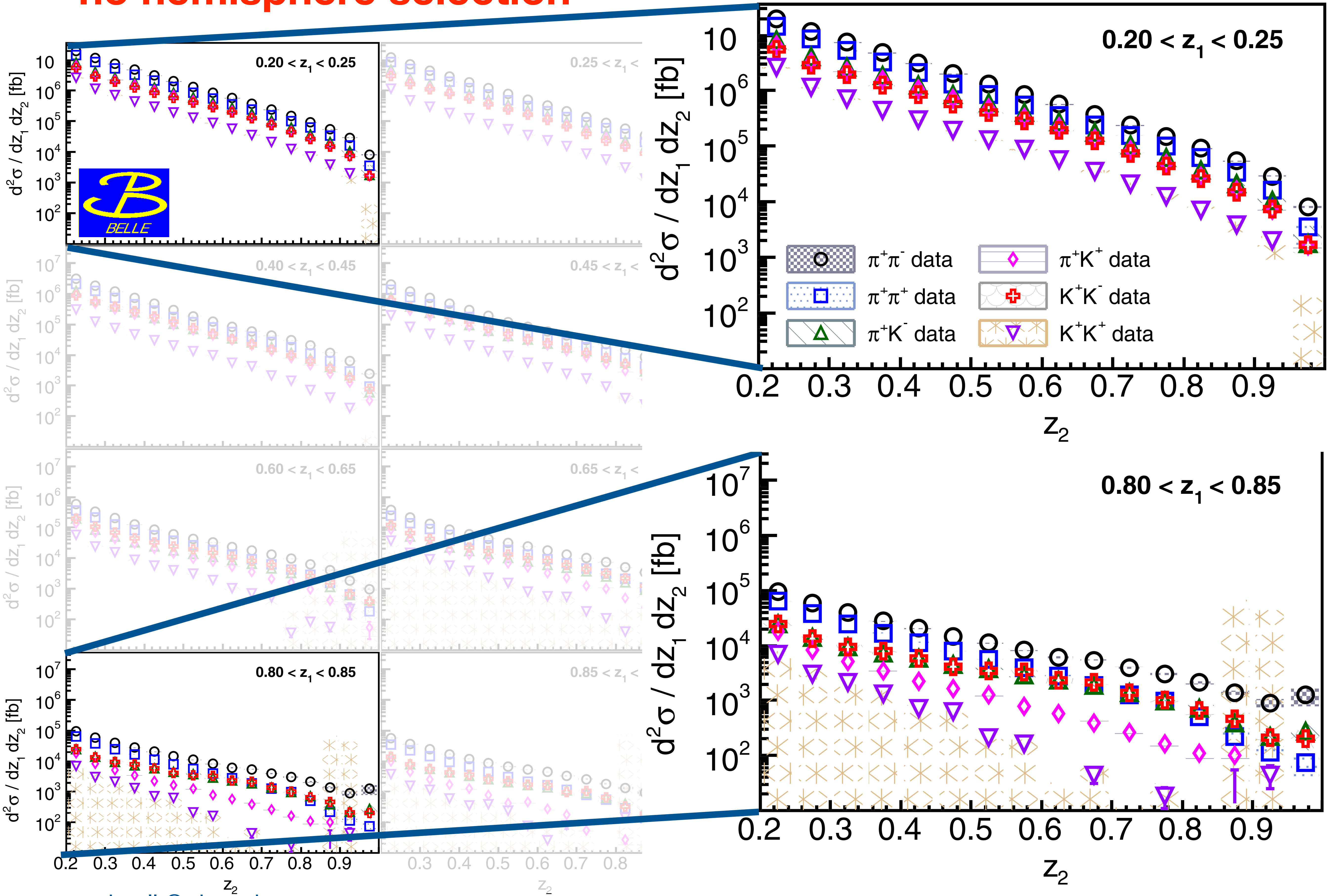
hadron-pair production

no hemisphere selection



hadron-pair production

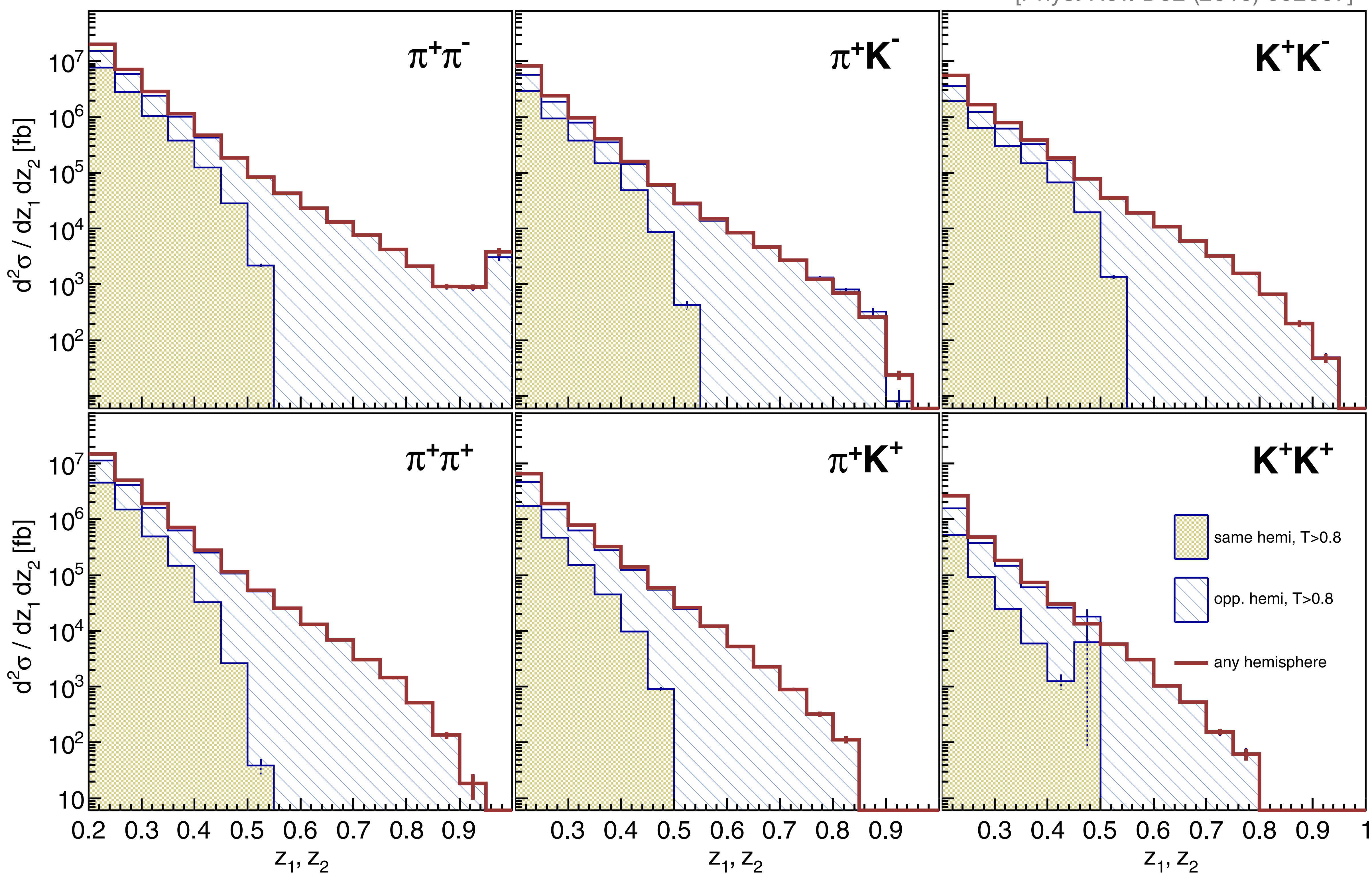
no hemisphere selection



hadron-pairs: topology comparison

- any hemisphere vs. opposite- & same-hemisphere pairs
  - same-hemisphere pairs with kinematic limit at z_1=z_2=0.5

[Phys. Rev. D92 (2015) 092007]

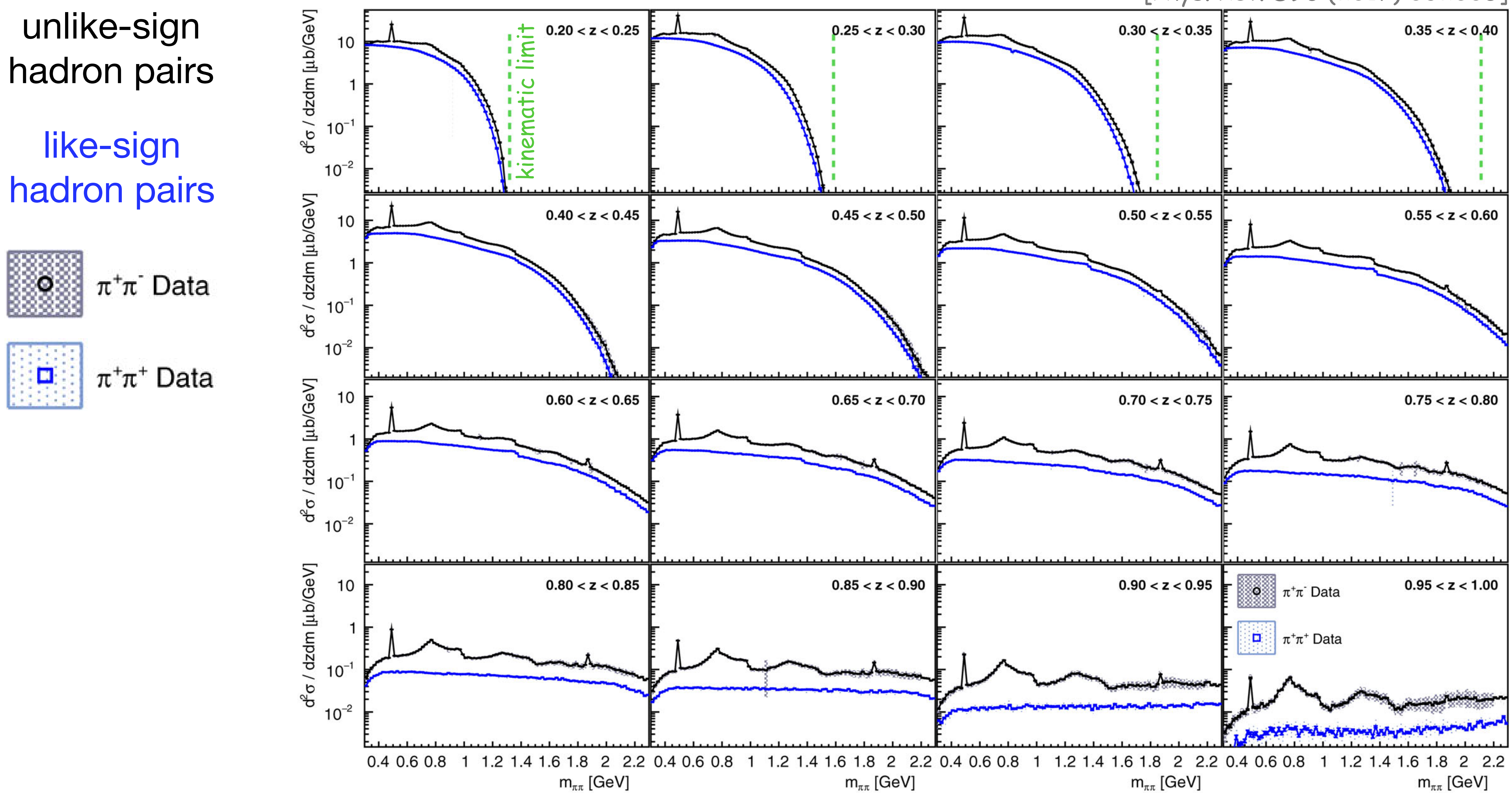


same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign
hadron pairs

like-sign
hadron pairs

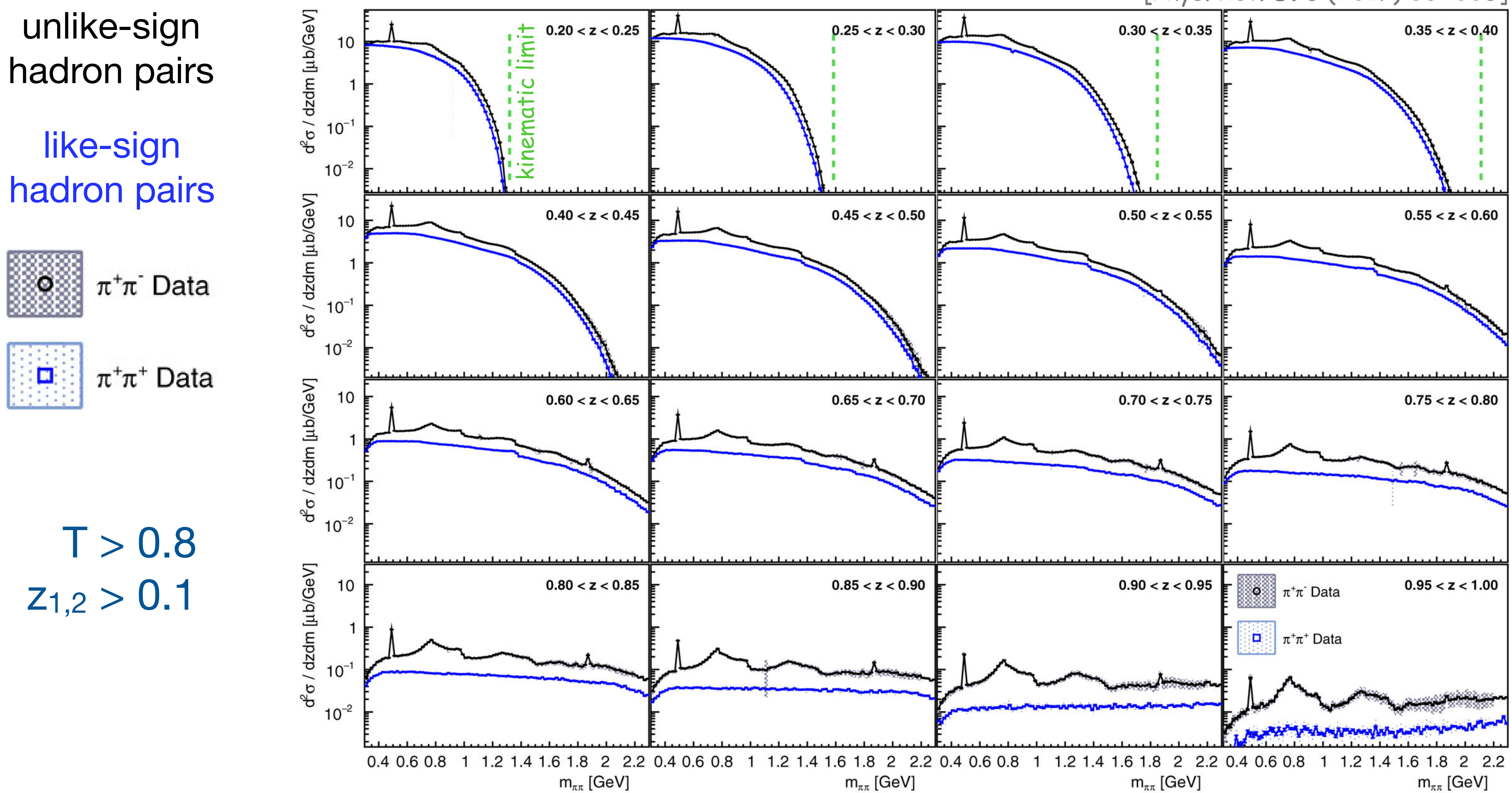


same-hemisphere data: M_{h1h2} dependence

[Phys. Rev. D96 (2017) 032005]

unlike-sign hadron pairs

like-sign hadron pairs



$T > 0.8$

$z_{1,2} > 0.1$

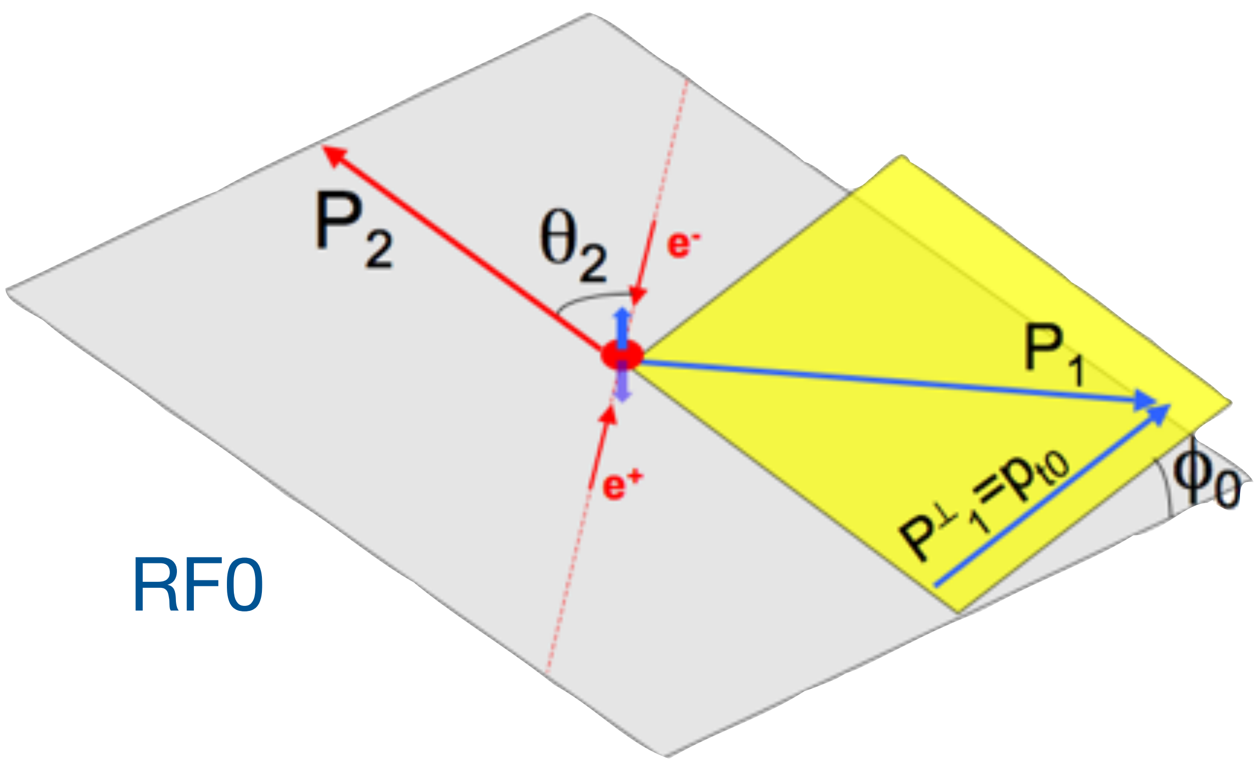
- unlike-sign pairs with clear decay and resonance structure: K_s, ρ^0 …
- like-sign pairs with much smoother and smaller cross sections

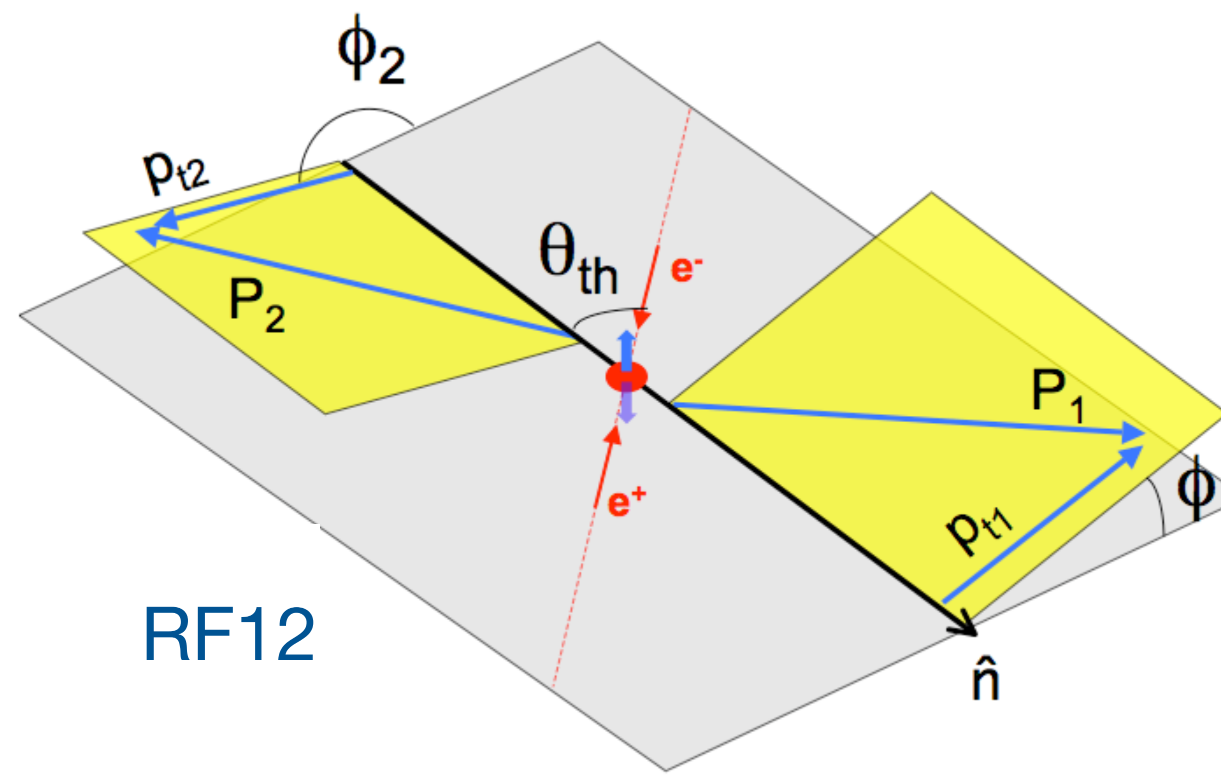
polarization

hadron pairs: angular correlations

- **angular correlations** between nearly back-to-back hadrons used to **tag** transverse quark **polarization** -> Collins fragmentation fct.

  - RF0: one hadron as reference axis -> $\cos(2\phi_0)$ modulation
  - RF12: thrust (or similar) axis -> $\cos(\phi_1+\phi_2)$ modulation



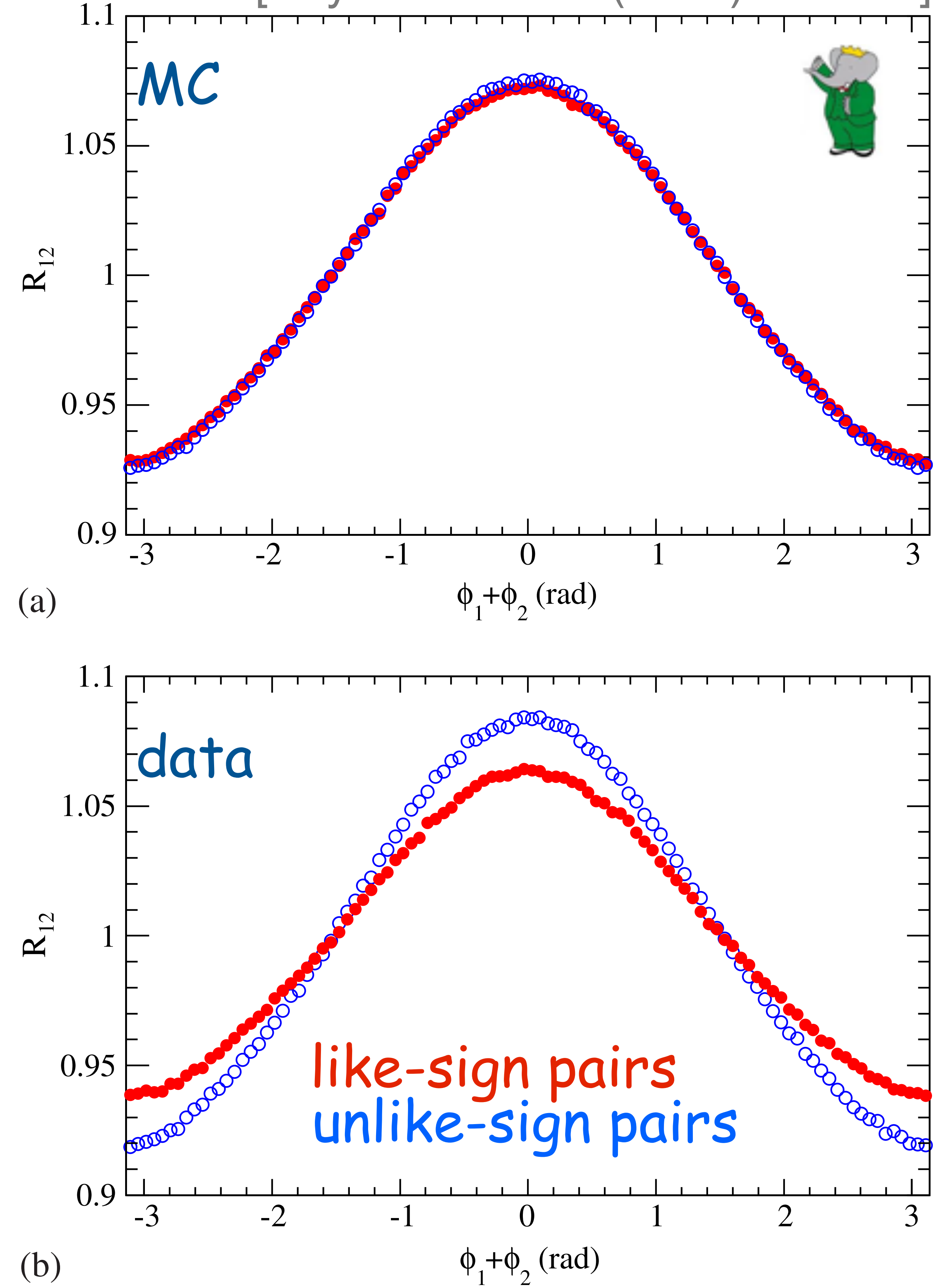


- RF0 and RF12: different convolutions over transverse momenta
- debatable: MC used to “correct” thrust axis to $q\bar{q}$ axis

hadron pairs: angular correlations

- challenge: large modulations even without Collins effect (e.g., MC)

[Phys. Rev. D90 (2014) 052003]



hadron pairs: angular correlations

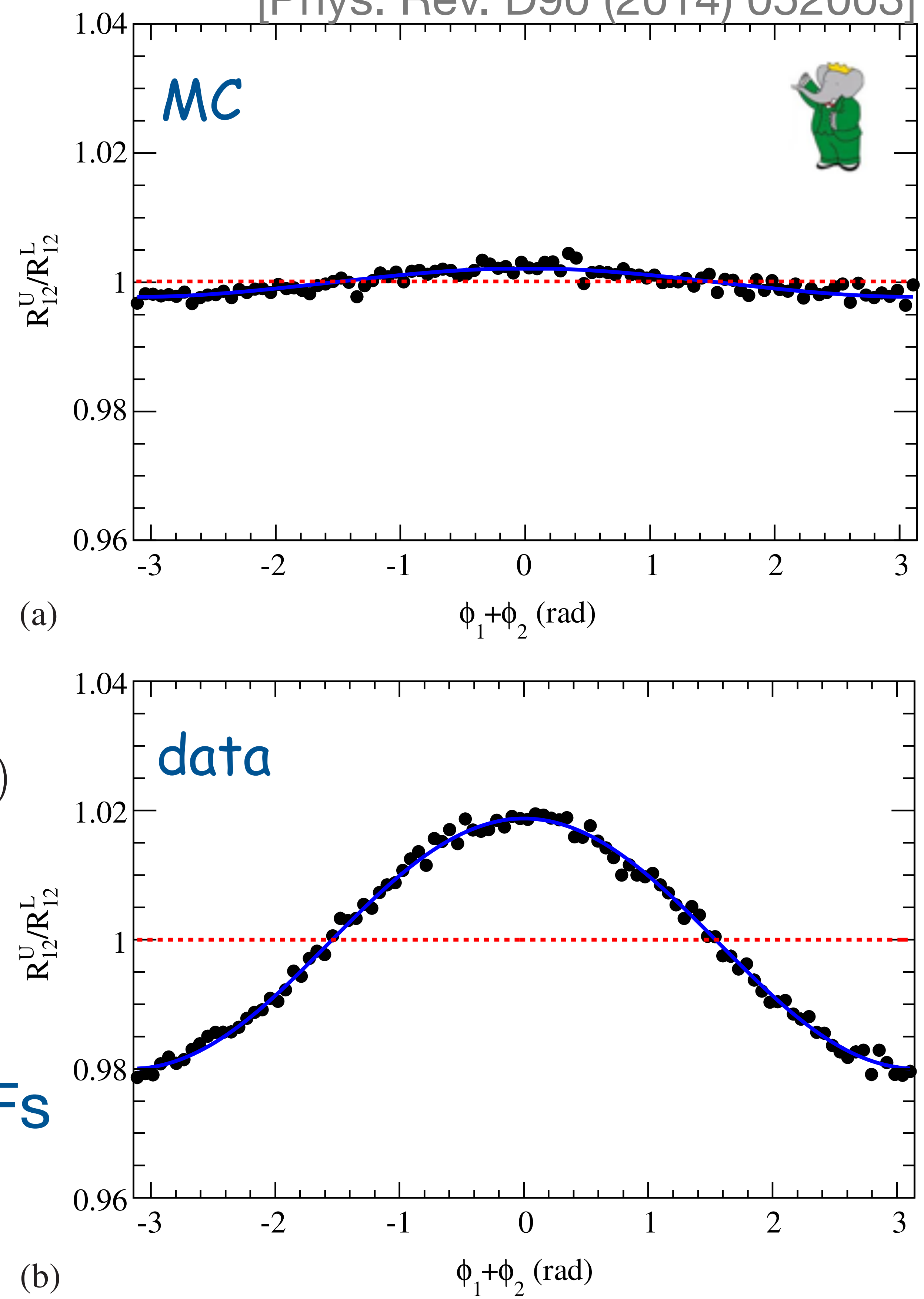
[Phys. Rev. D90 (2014) 052003]

- challenge: large modulations even without Collins effect (e.g., MC)
- construct double ratio of normalized-yield distributions R_{12}, e.g. unlike-/like-sign:

$$\frac{R_{12}^U}{R_{12}^L} \simeq \frac{1 + \langle\frac{\sin^2\theta_{\text{th}}}{1+\cos^2\theta_{\text{th}}}\rangle G^U \cos(\phi_1+\phi_2)}{1 + \langle\frac{\sin^2\theta_{\text{th}}}{1+\cos^2\theta_{\text{th}}}\rangle G^L \cos(\phi_1+\phi_2)}$$

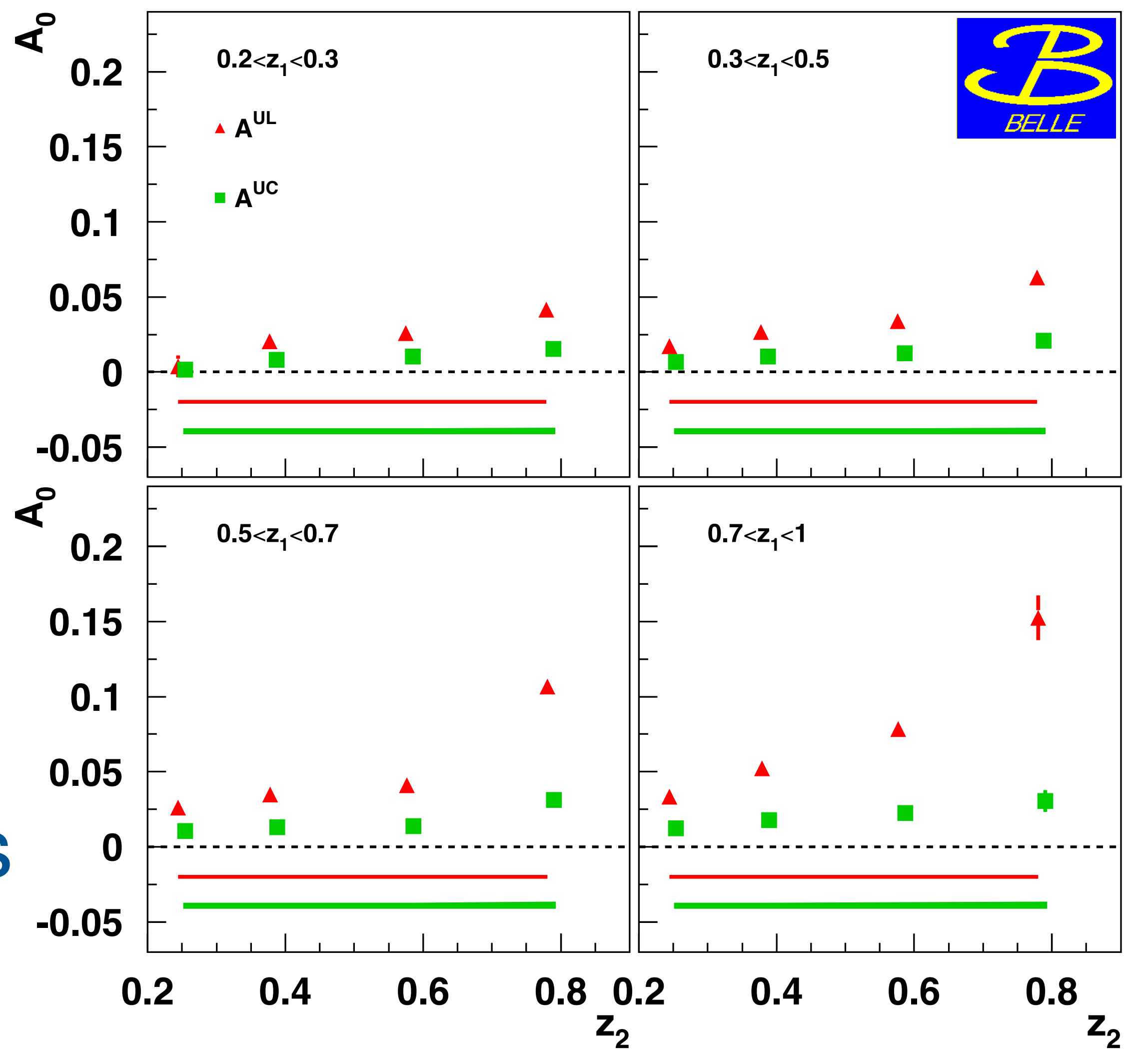
$$\simeq 1 + \left\langle \frac{\sin^2\theta_{\text{th}}}{1+\cos^2\theta_{\text{th}}} \right\rangle \{G^U - G^L\} \cos(\phi_1+\phi_2)$$

  - suppresses flavor-independent sources of modulations
  - $G^{U/L}$ specific combinations of FFs
  - remaining MC asymmetries: -> systematics



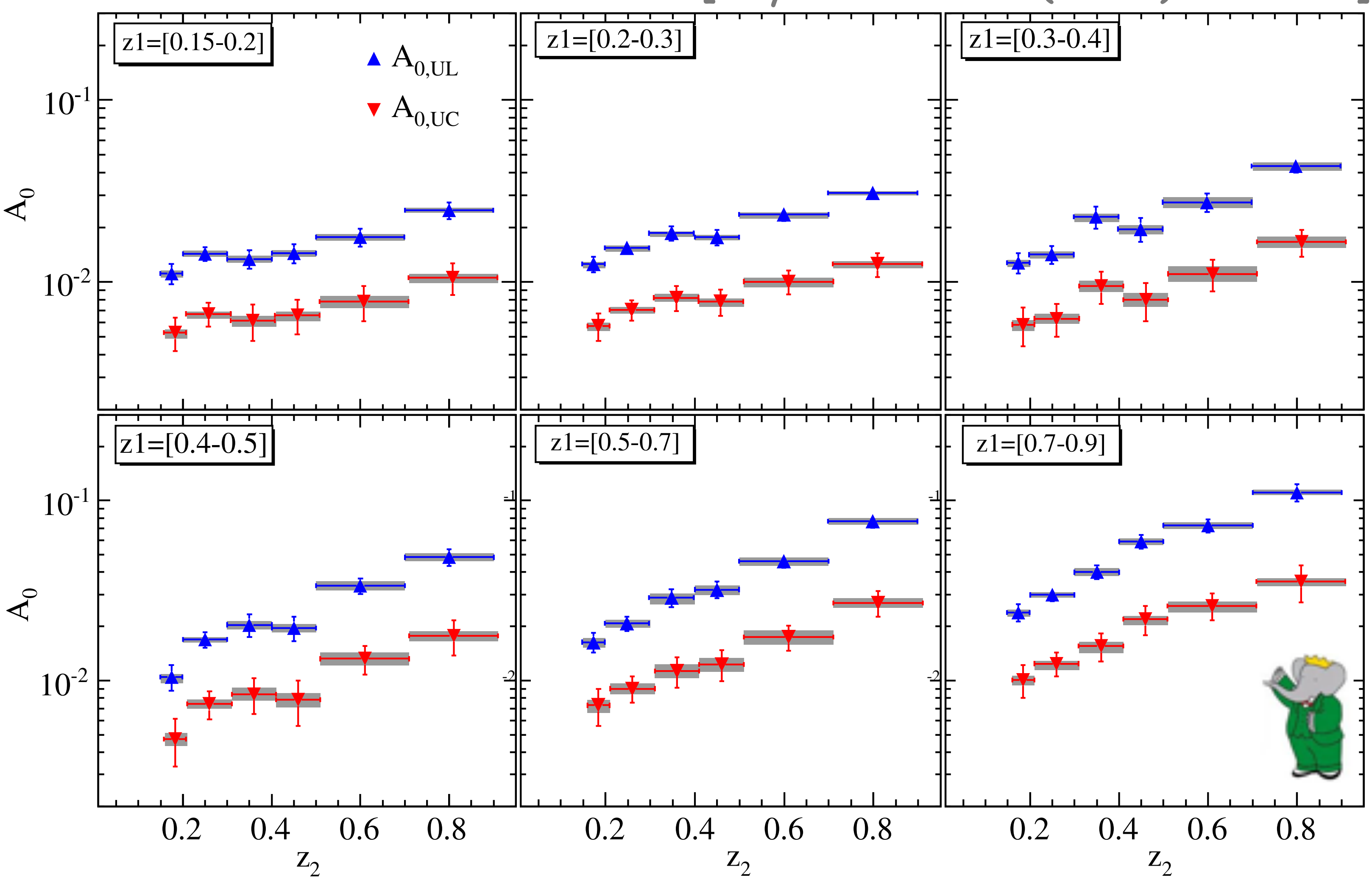
Collins asymmetries (RF0)

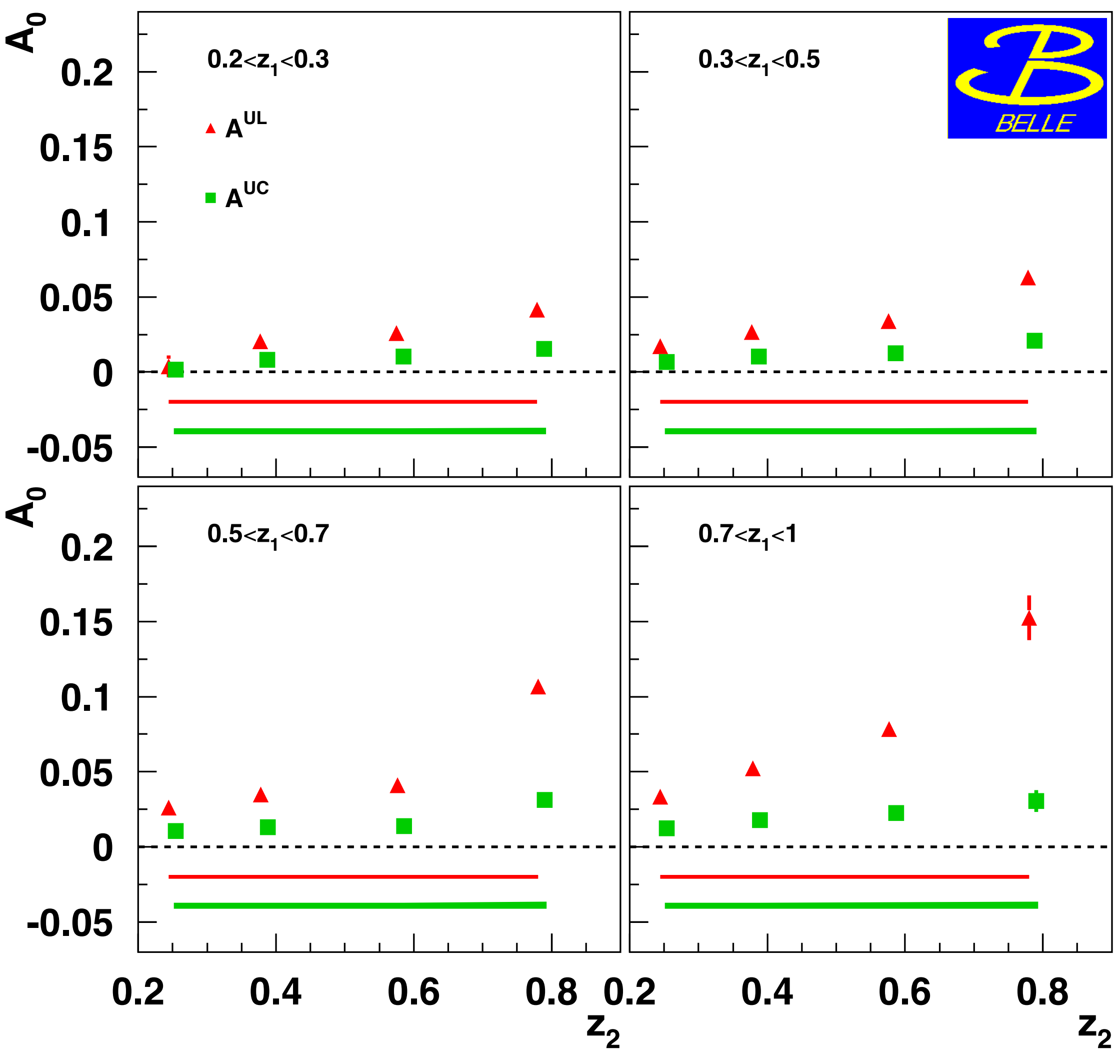
- first measurement of Collins asymmetries by Belle [PRL 96 (2006) 232002, PRD 78 (2008) 032011, PRD 86 (2012) 039905(E)]
  - significant asymmetries rising with z
  - used for first transversity and Collins FF extractions



Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

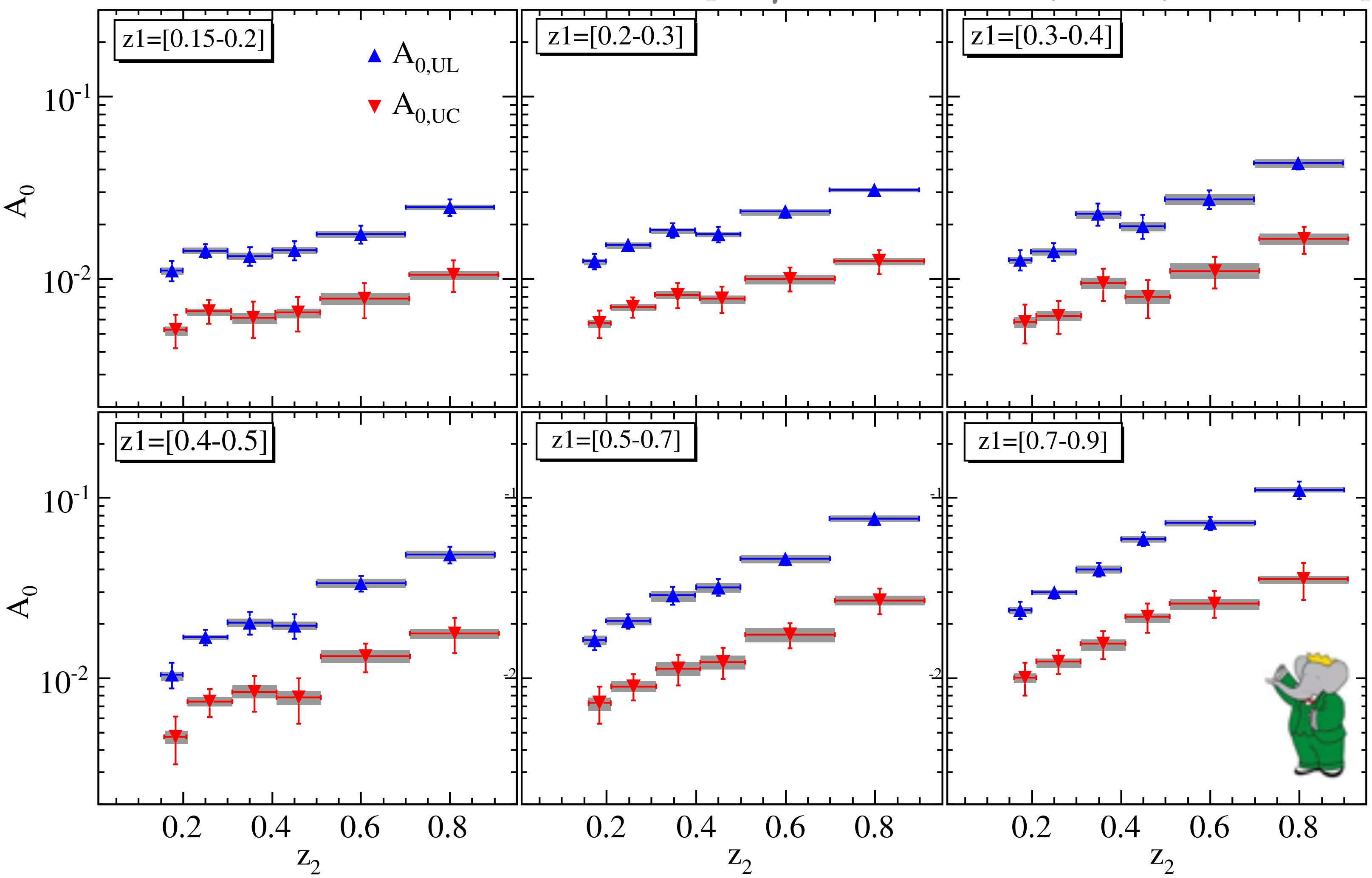


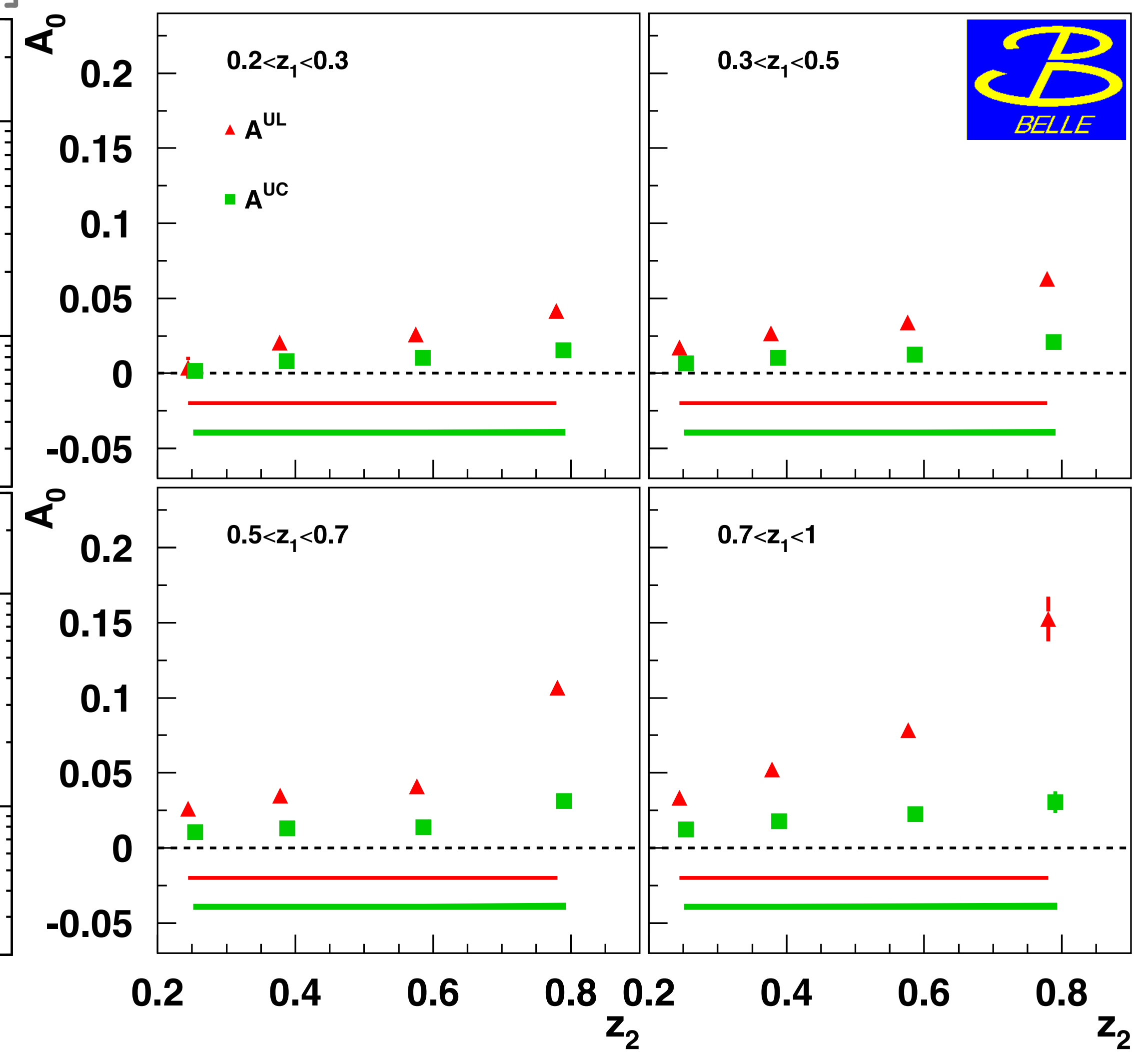


- BaBar results [PRD 90 (2014) 052003] consistent with Belle

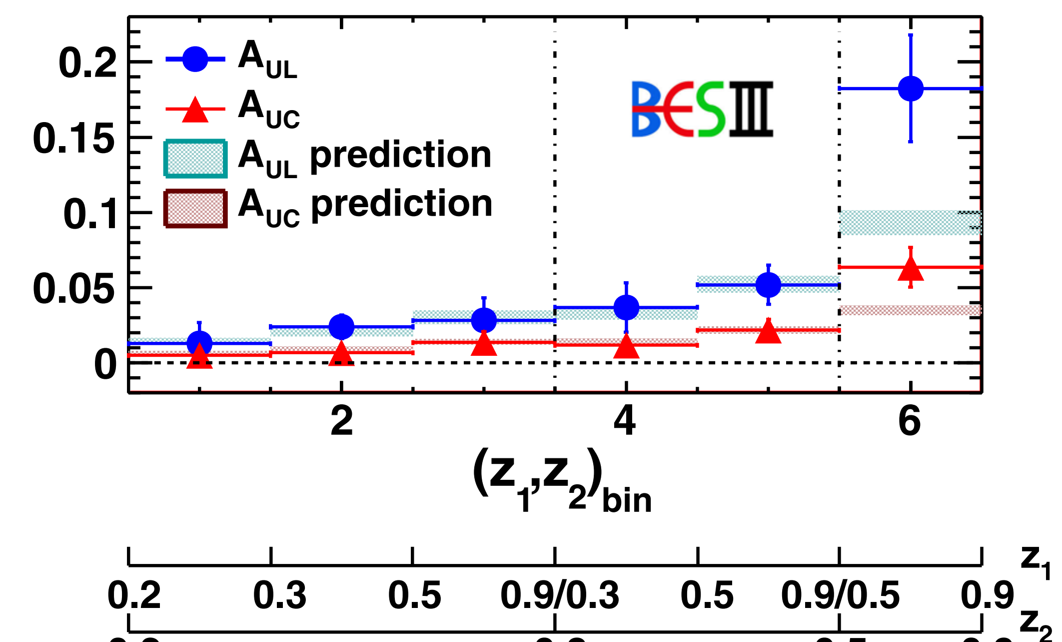
Collins asymmetries (RF0)

[Phys. Rev. D90 (2014) 052003]

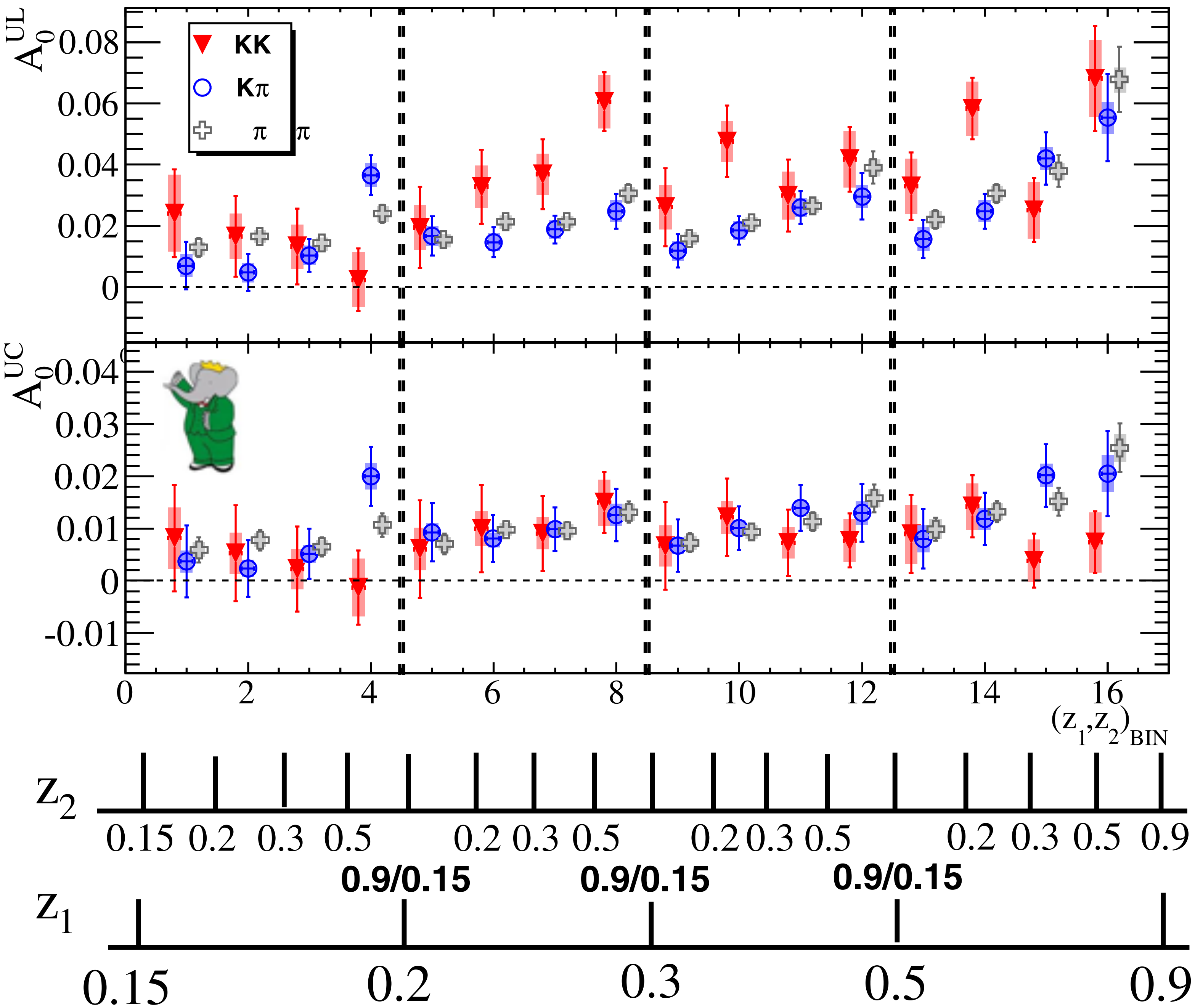




- BaBar results [PRD 90 (2014) 052003] consistent with Belle
- BESIII [PRL 116 (2016) 042001] (at smaller s) consistent with TMD evolution [Z.-B. Kang et al., PRD 93 (2016) 014009]

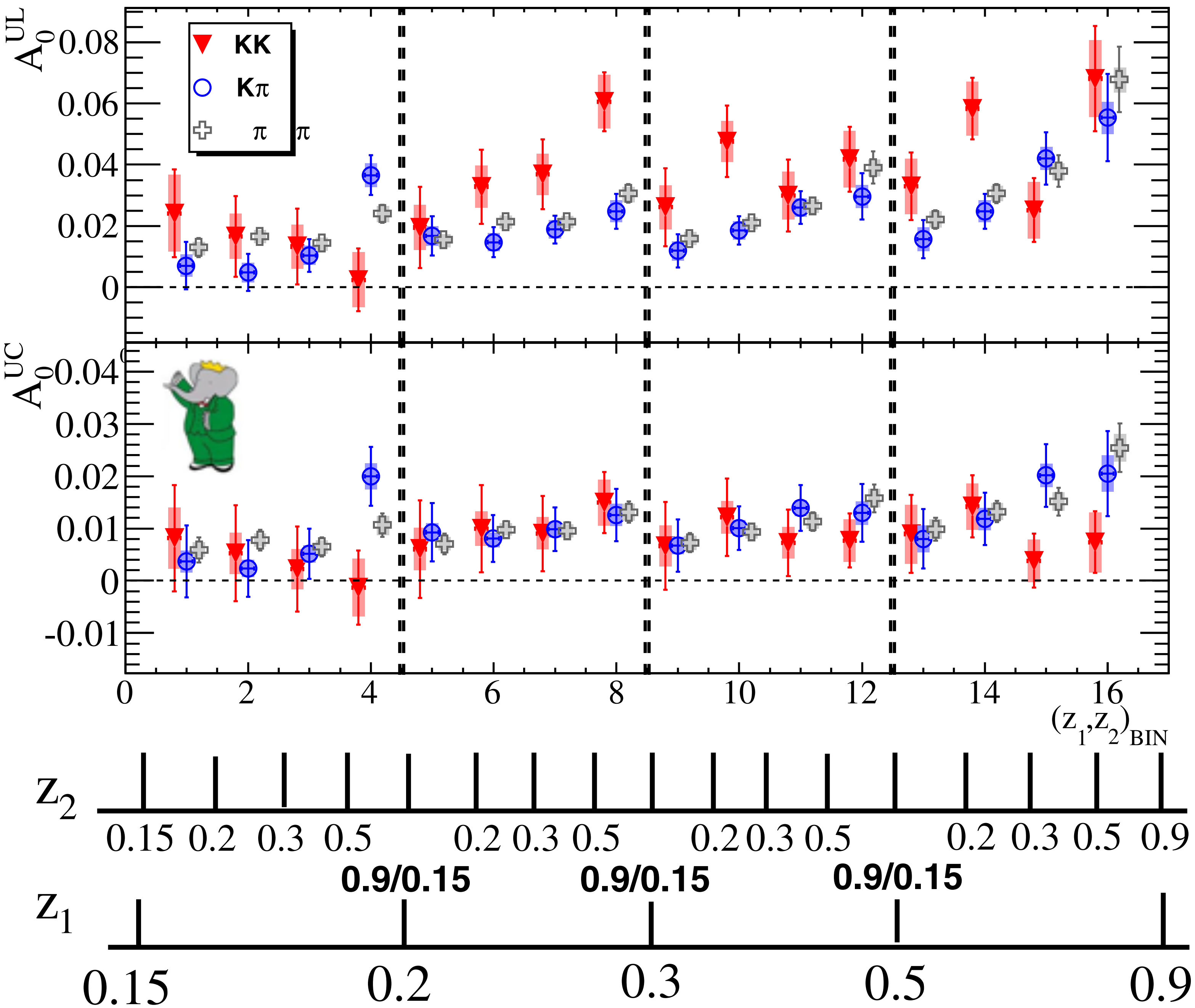


Collins asymmetries - going further

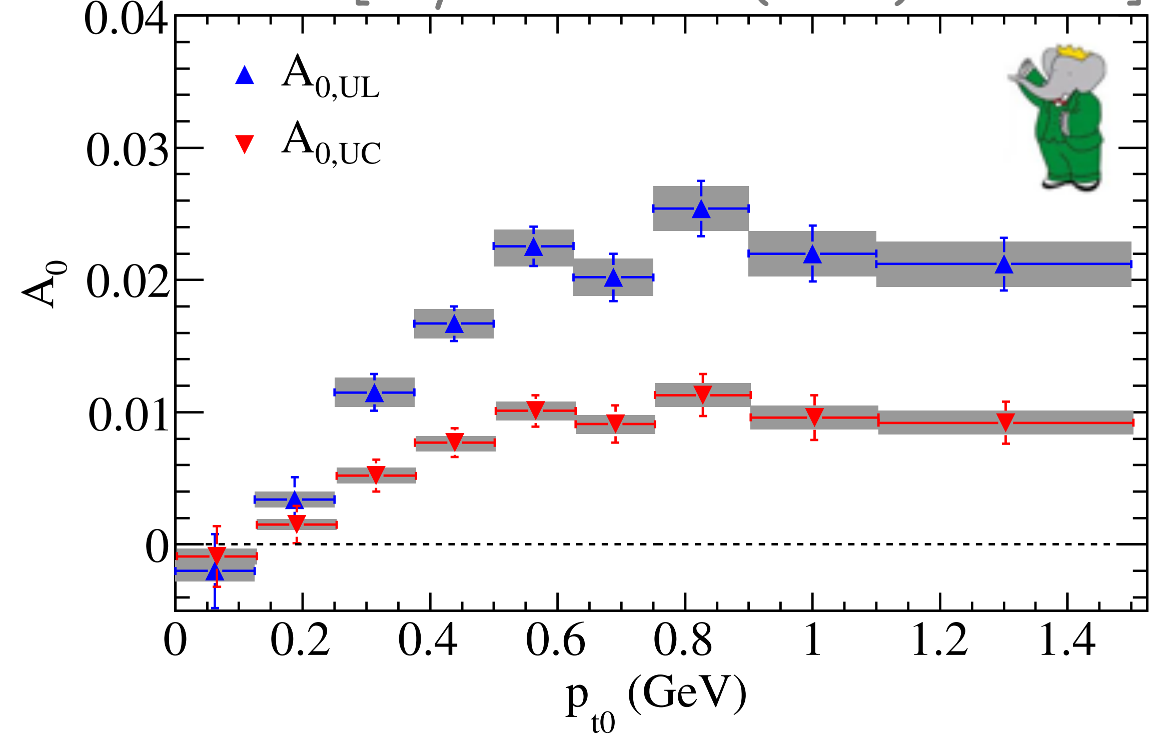


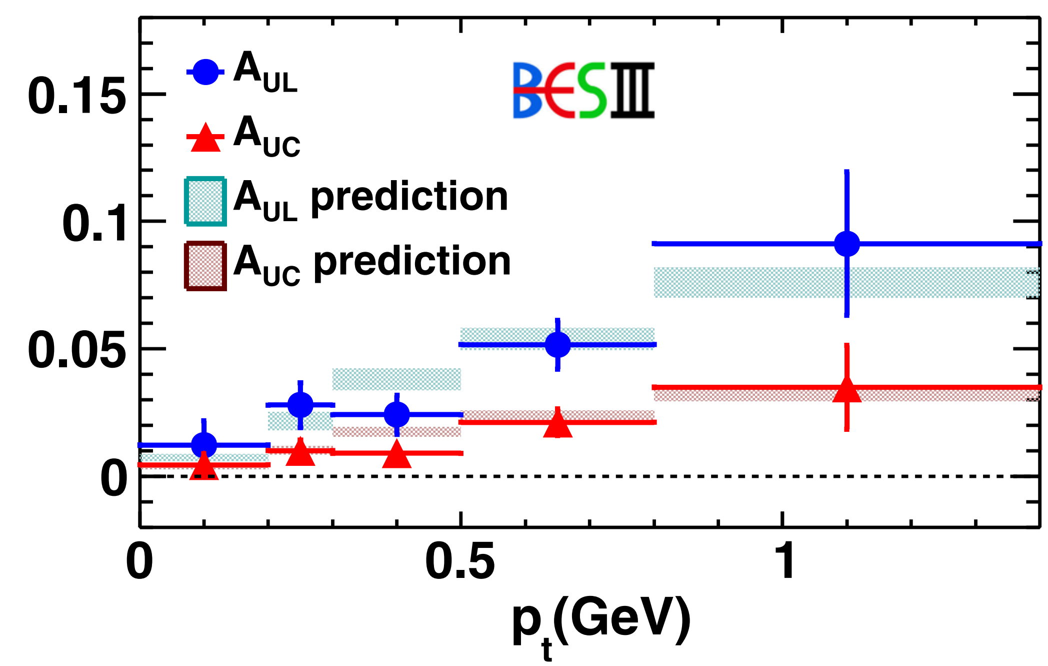
- even larger effects seen for kaon pairs

Collins asymmetries - going further



[Phys. Rev. D90 (2014) 052003]



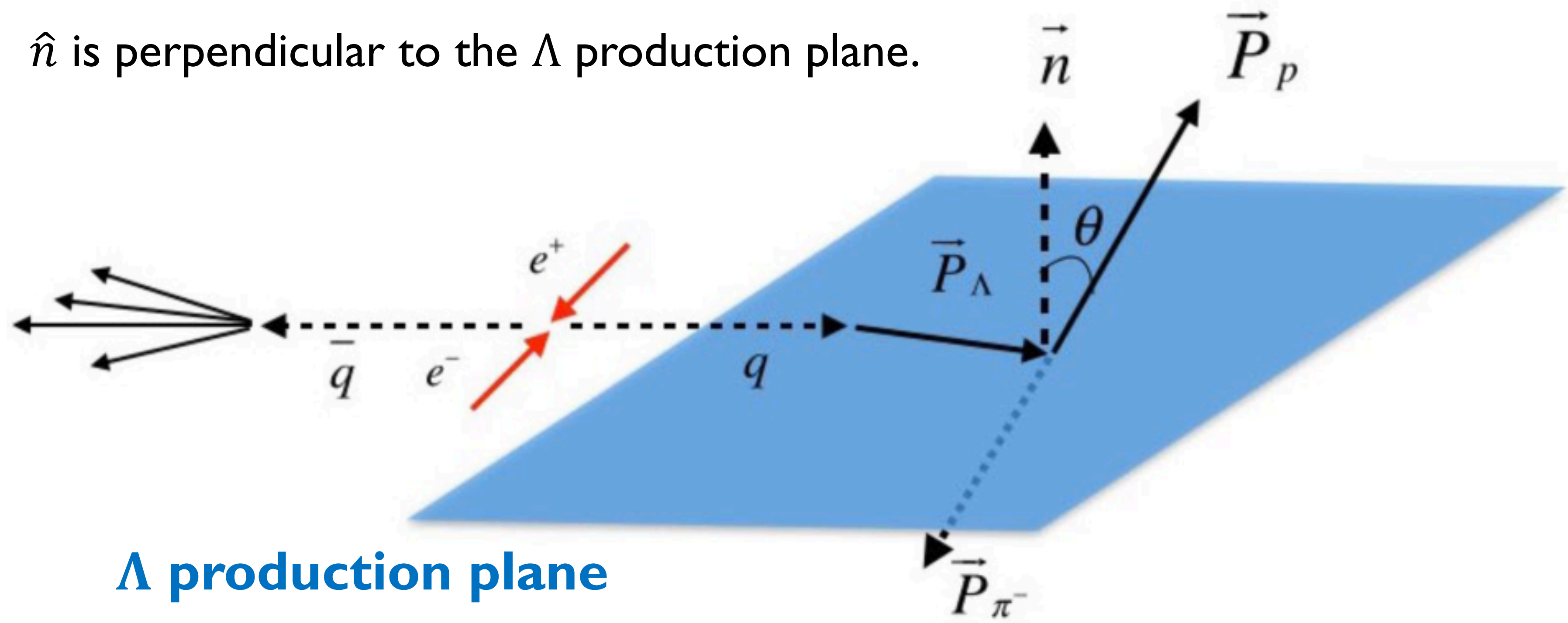


[PRL 116 (2016) 042001]

- even larger effects seen for kaon pairs
- p_T dependence for pions

polarizing fragmentation function

- polarization normal to production plane, i.e $\propto$ ("q" $\times$ P_Λ)
  [note that the sign got reversed in the drawing]

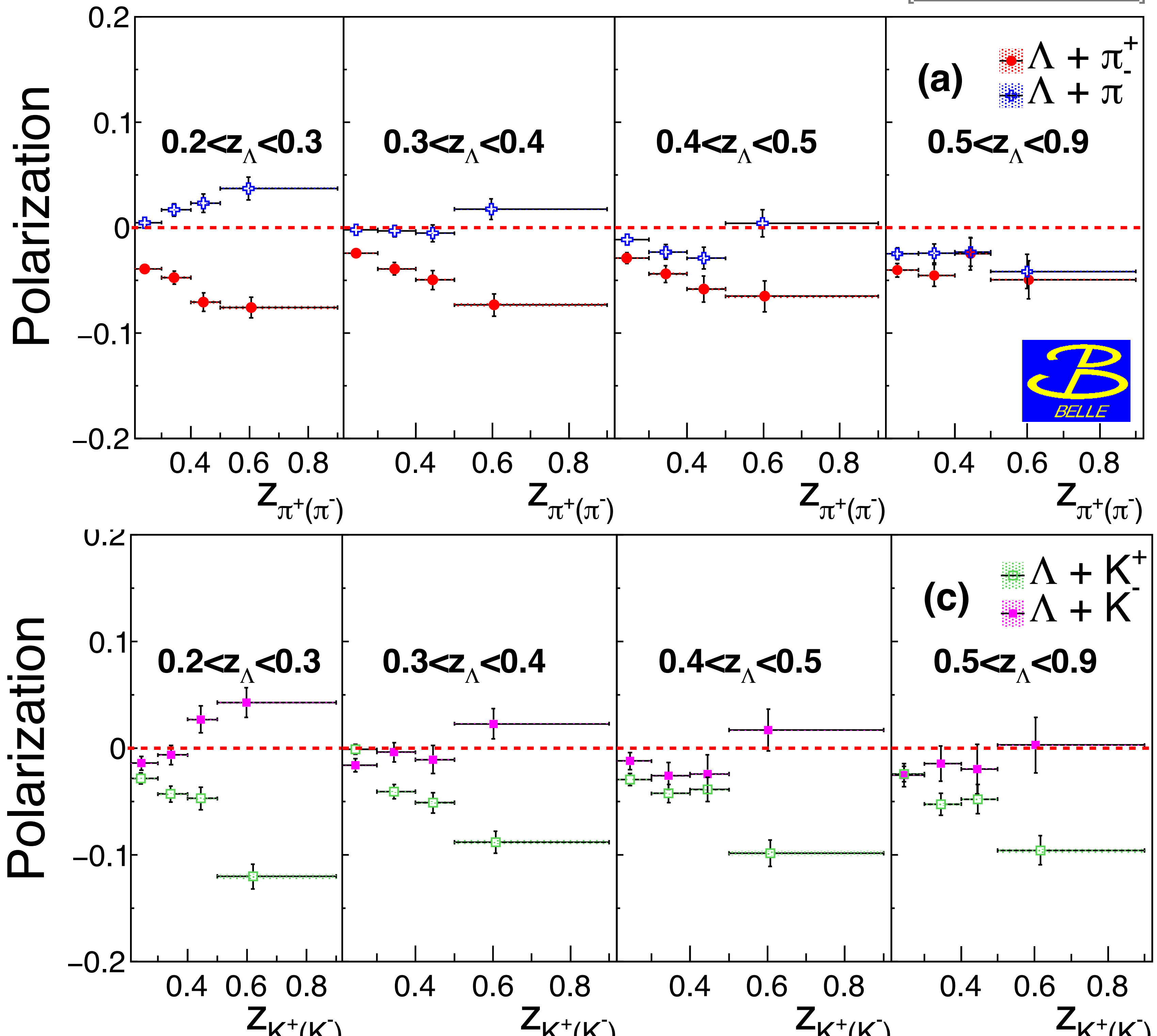


- reference axis to define transverse momentum:
  - "thrust frame" - use thrust axis
  - "hadron frame" - use momentum direction of "back-to-back" hadron

polarizing fragmentation function

- flavor tagging through hadrons in opposite hemisphere:

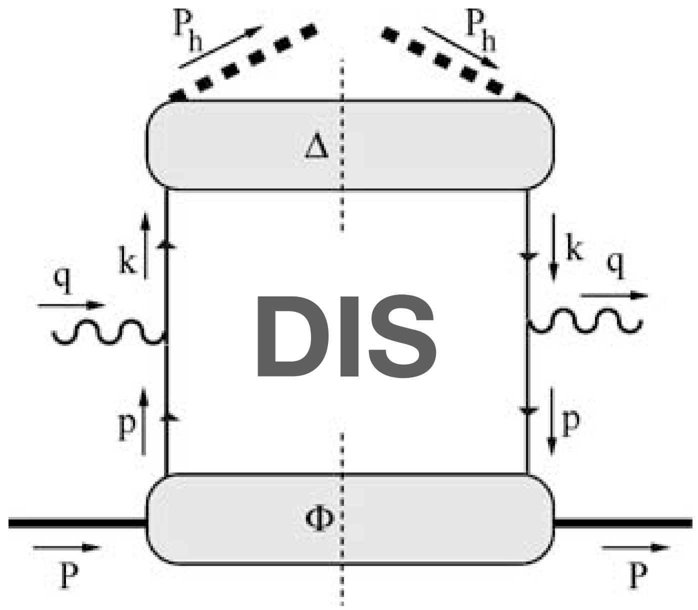
[arXiv:1808.05000]

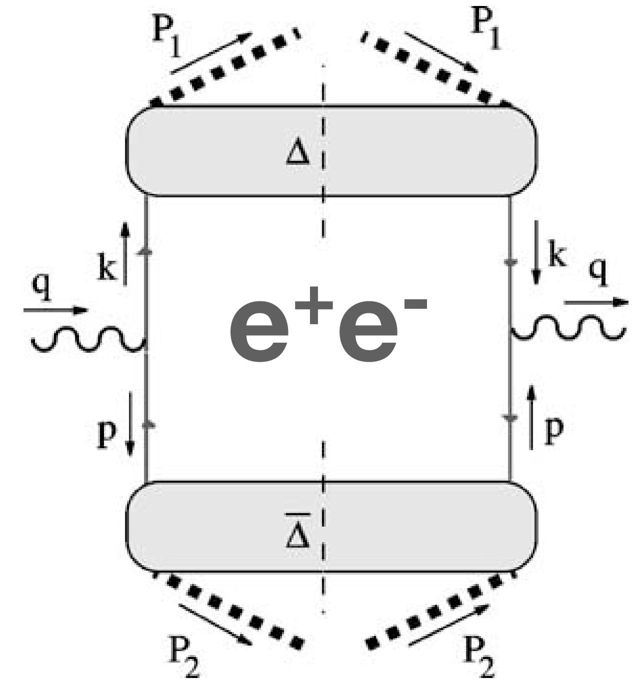


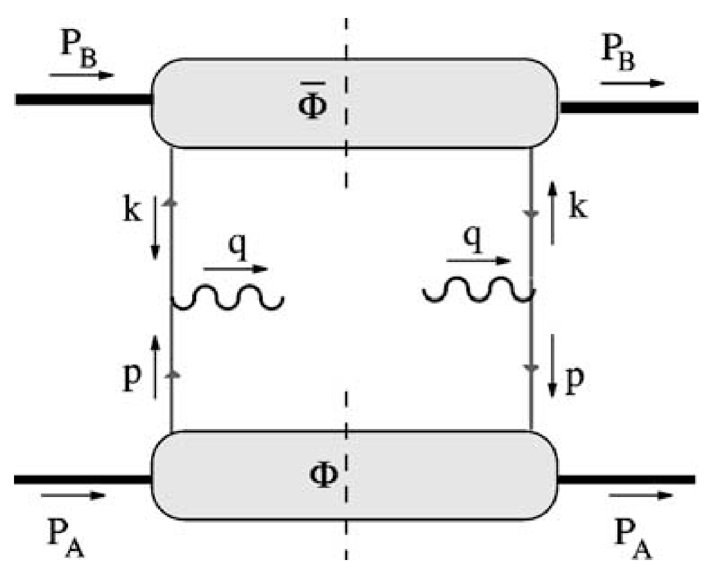
- large-z_h hadrons tag quark flavor more efficiently

➡ enlarges differences between oppositely charged hadrons instead of summarizing results ...

a QCD laboratory

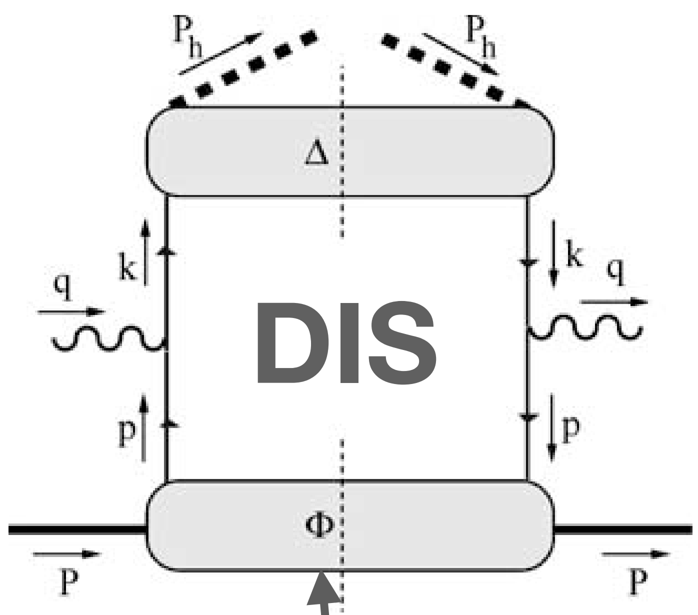


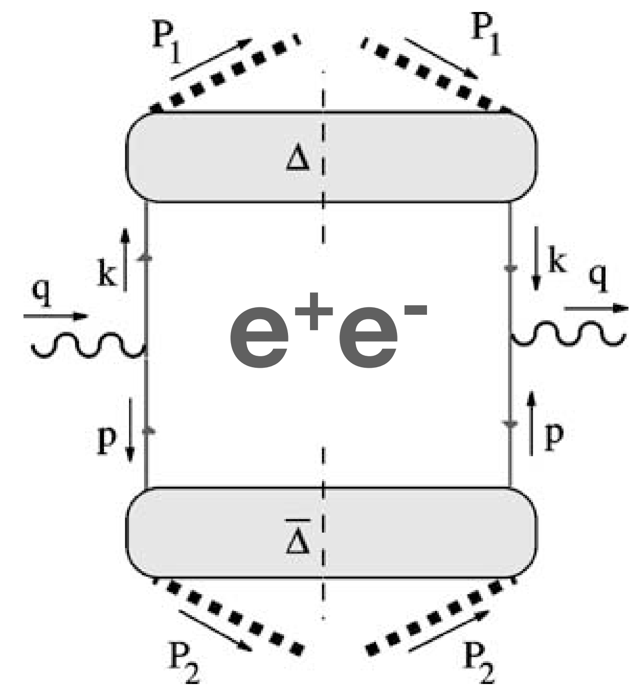




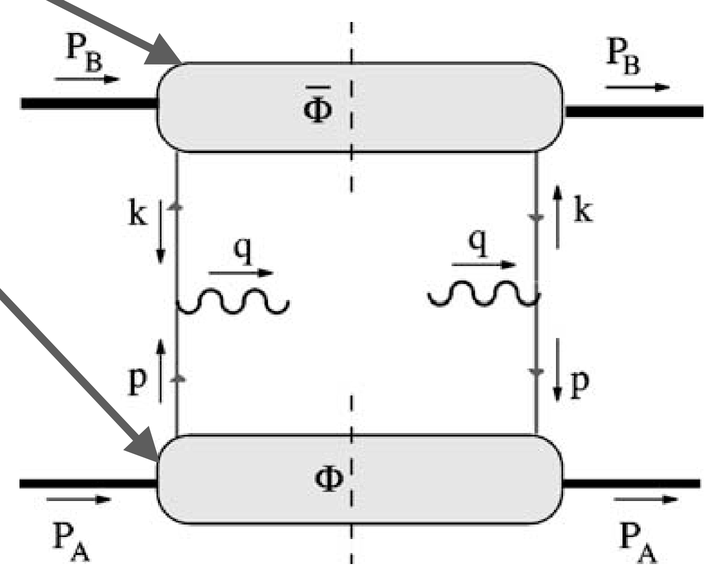
Drell-Yan

a QCD laboratory



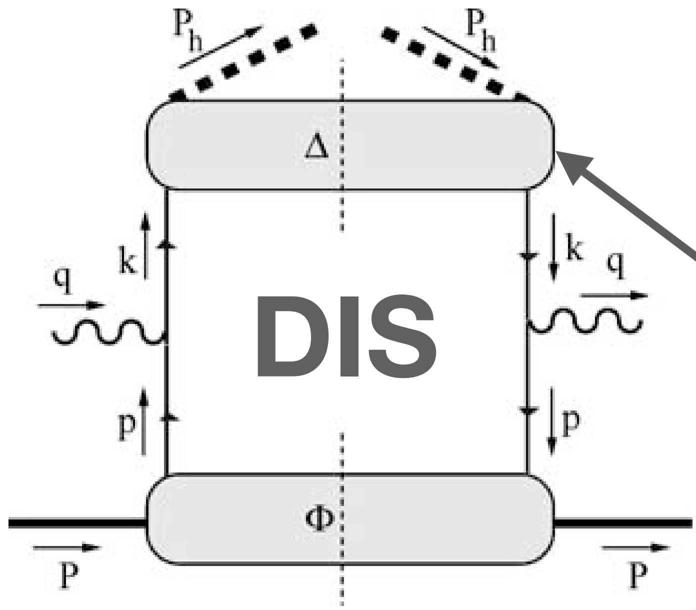


hadron structure
(distribution functions)

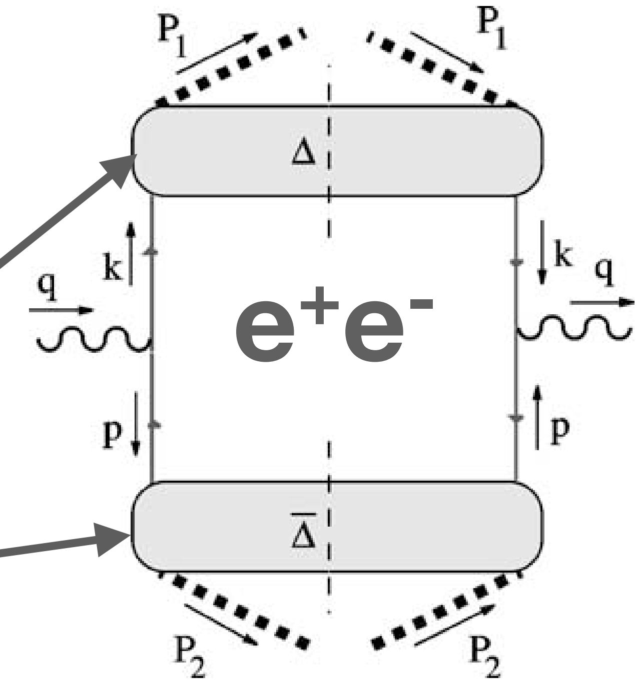


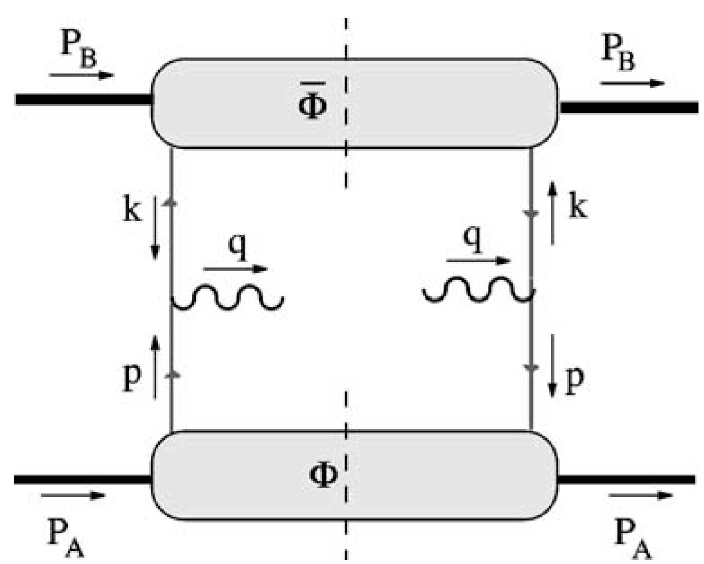
Drell-Yan

a QCD laboratory



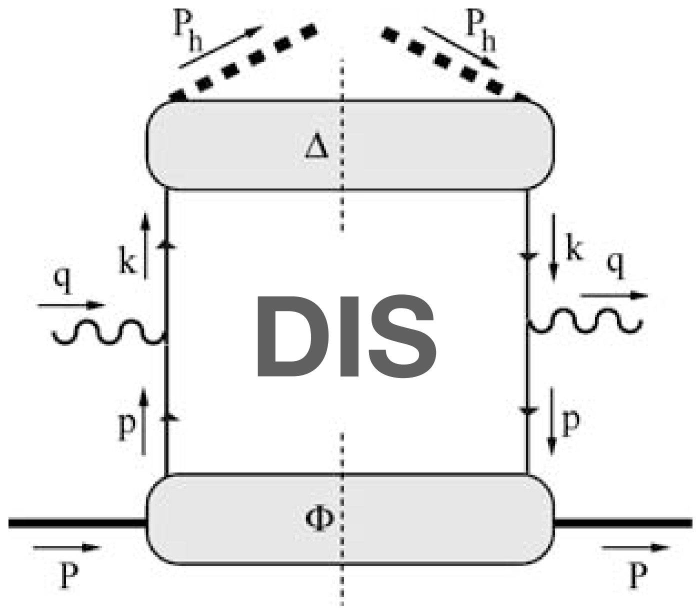
hadronization
(fragmentation functions)

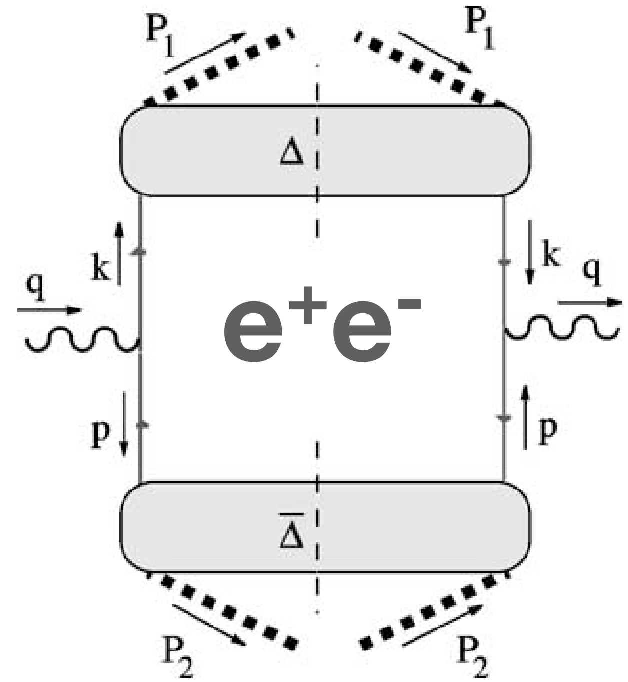




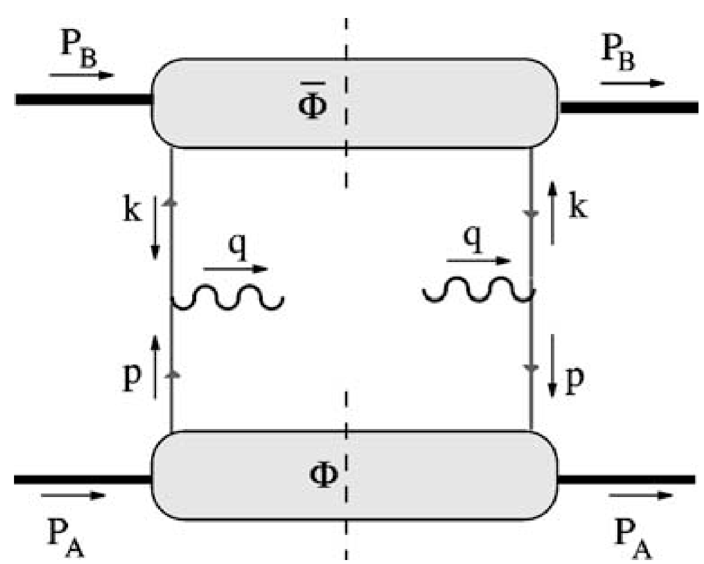
Drell-Yan

a QCD laboratory



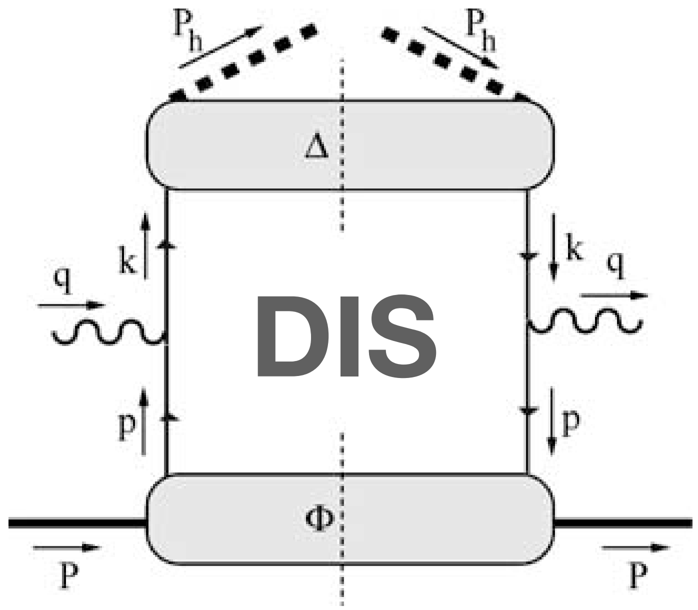


- **data from HERMES,** JLab and COMPASS; planned for future EIC
- convolutes parton distribution (Φ) and fragmentation (Δ) functions $\Phi\otimes\Delta$
- **need fragmentation function to extract distribution functions**



Drell-Yan

a QCD laboratory



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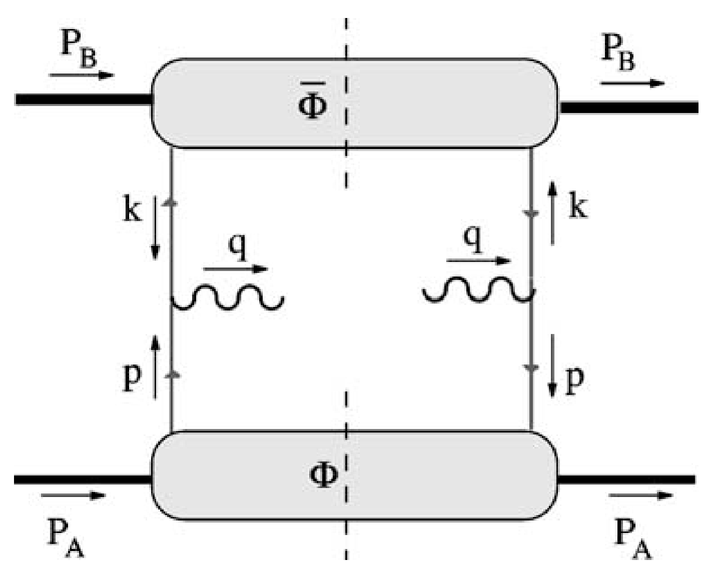
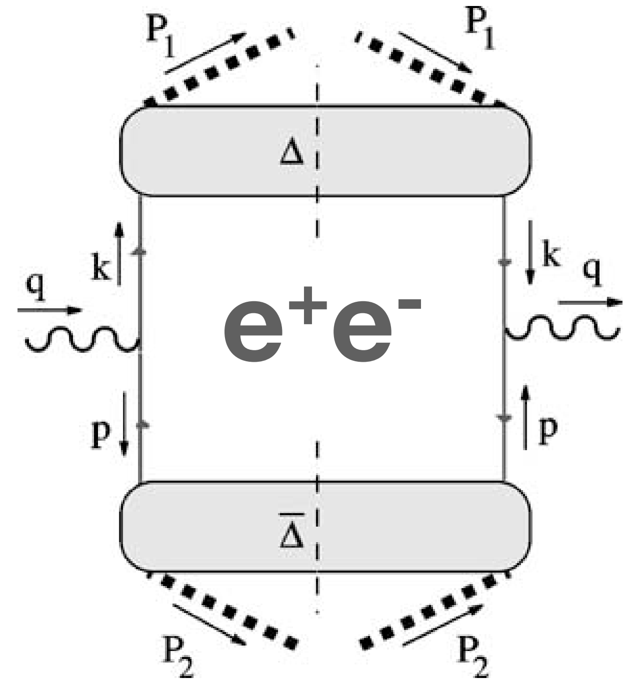
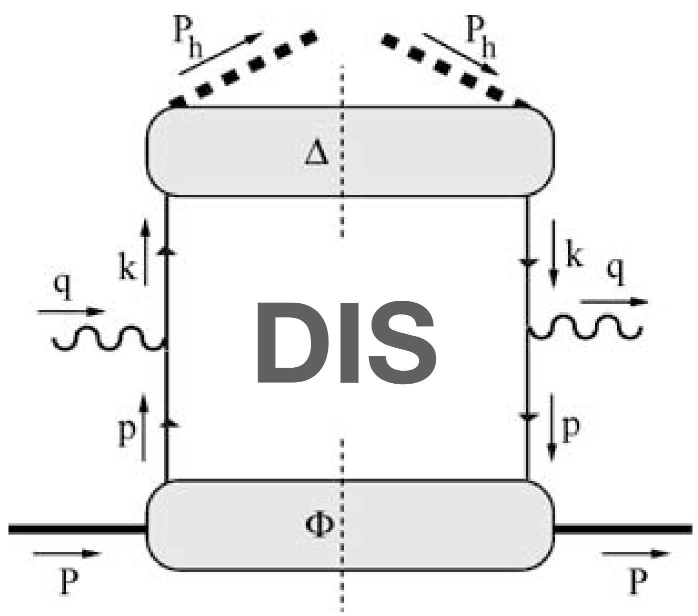


Drell-Yan



- **ideal place to study hadronization**
- convolutes parton fragmentation functions $\Delta \otimes \Delta$
- **wealth of existing data** from **BELLE/ BaBar & BESIII** and more to come (especially Belle2)

a QCD laboratory



- **data from HERMES,** JLab and COMPASS; planned for future EIC
- convolutes parton distribution (Φ) and fragmentation (Δ) functions $\Phi \otimes \Delta$
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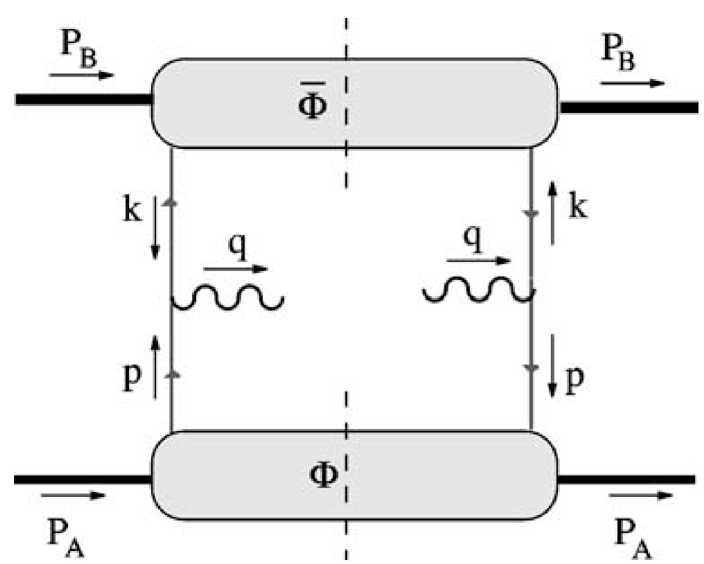
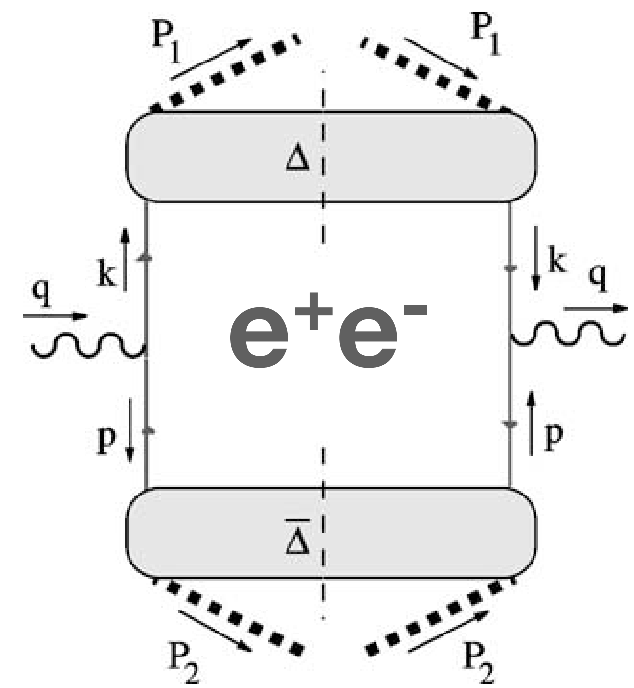
- **testing ground for universality of TMDs**
- convolutes parton distribution functions $\Phi \otimes \Phi$
- **measurable at COMPASS, RHIC, Fermilab and LHC**



Drell-Yan



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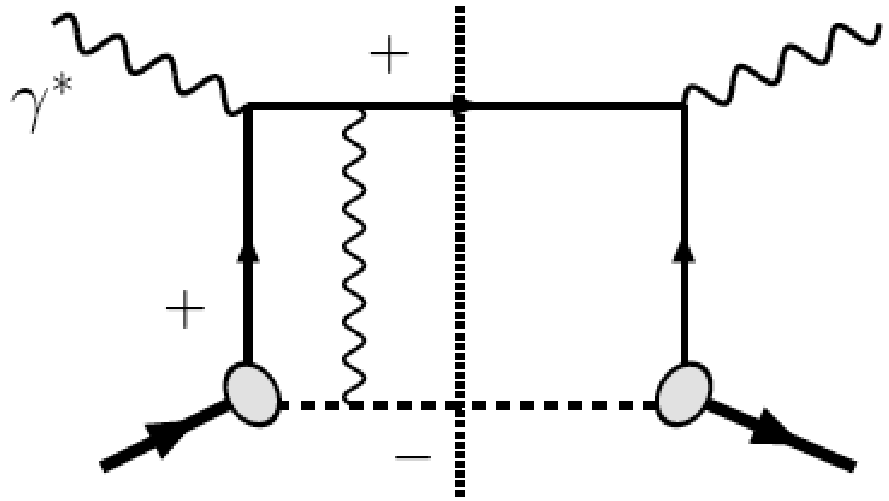
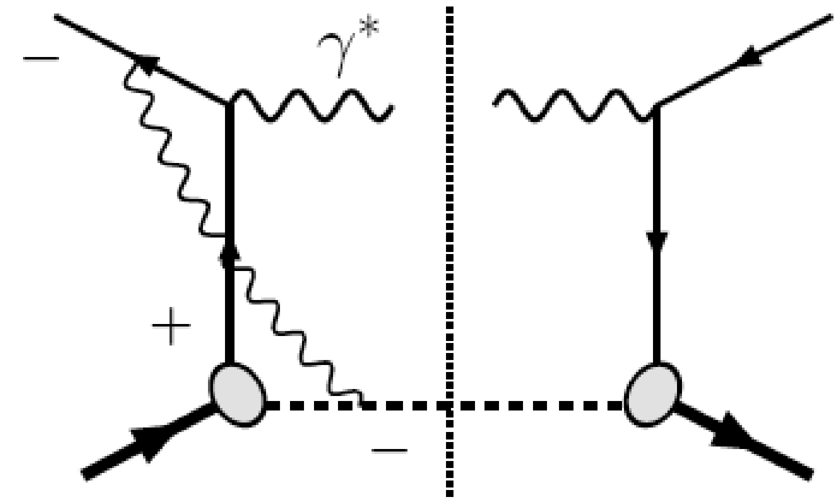
backup

Process dependence

simple QED example



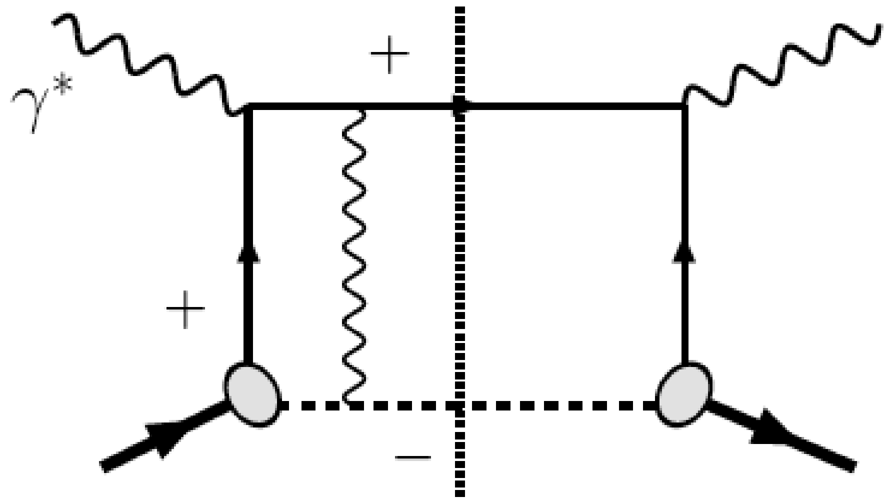


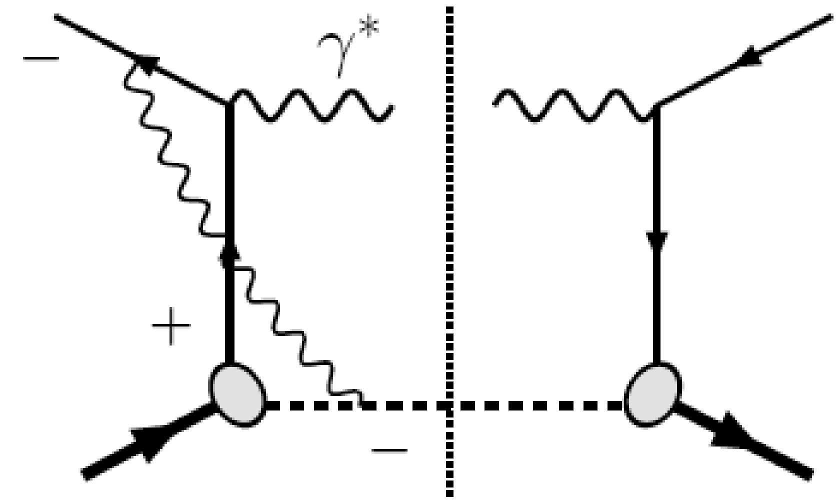
DIS: attractive

Drell-Yan: repulsive

Process dependence

simple QED example

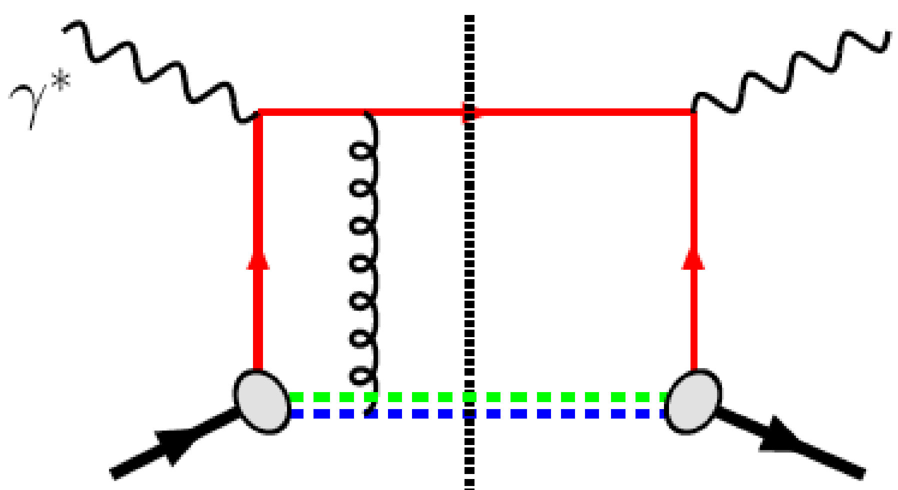


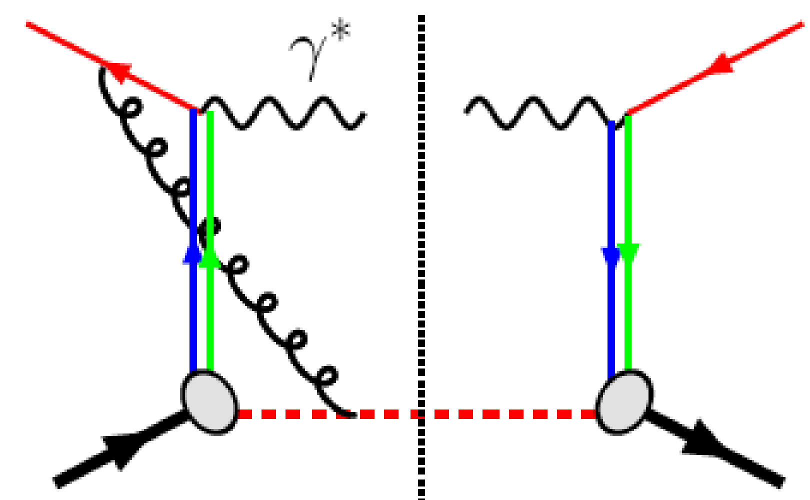


DIS: attractive

Drell-Yan: repulsive

add color: QCD

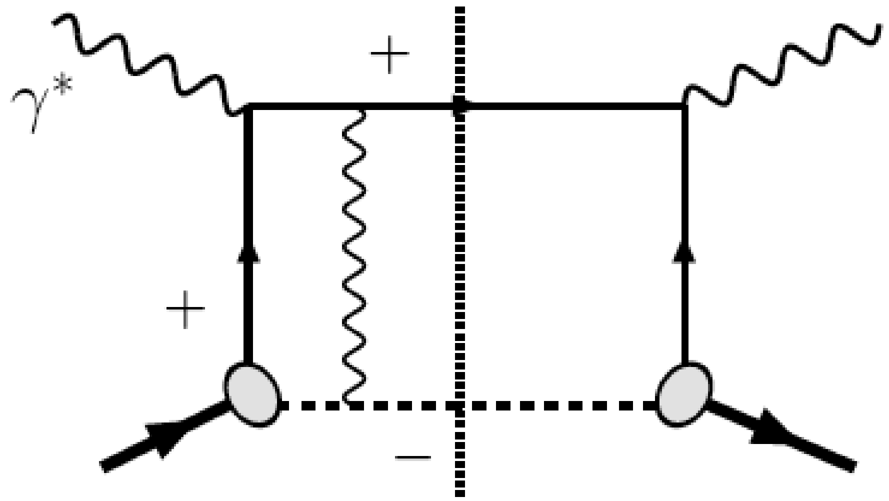


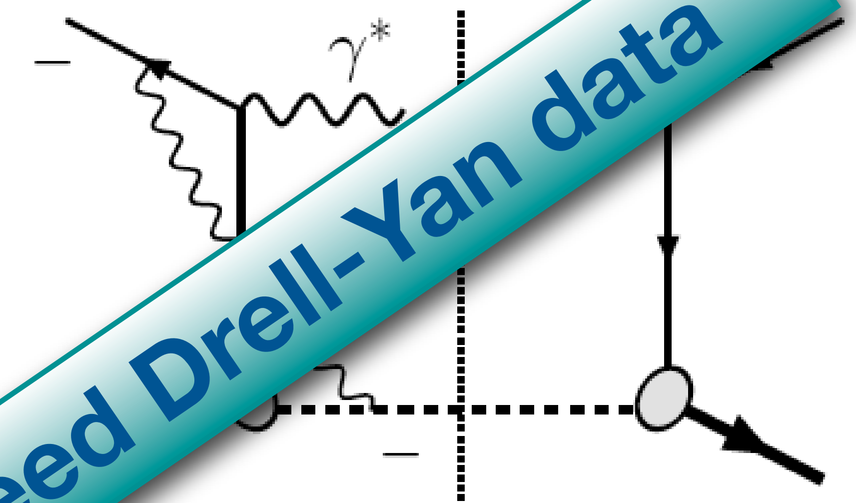


result: Sivers$|_{\mathrm{DIS}}$ = - Sivers$|_{\mathrm{DY}}$

Process dependence

simple QED example





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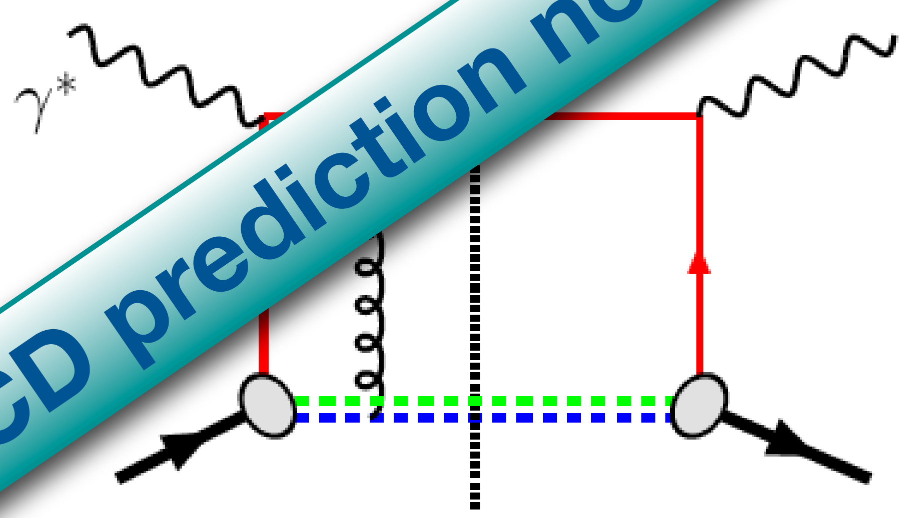

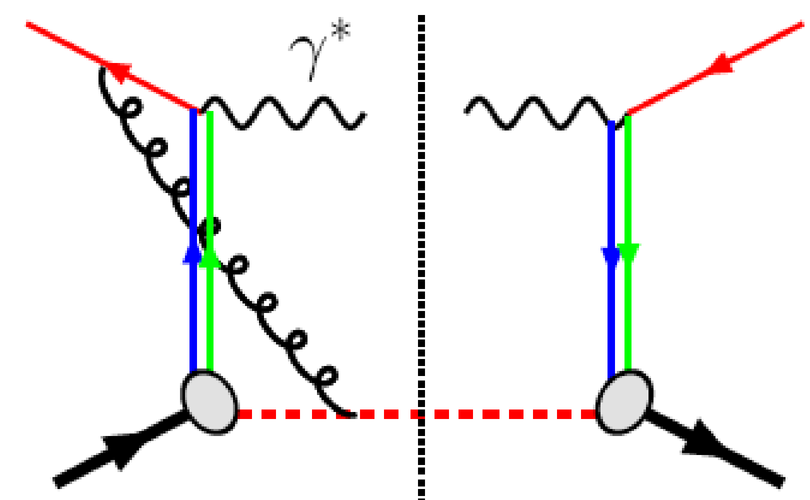

result: Sivers|$_{DIS}$ = - Sivers|$_{DY}$

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