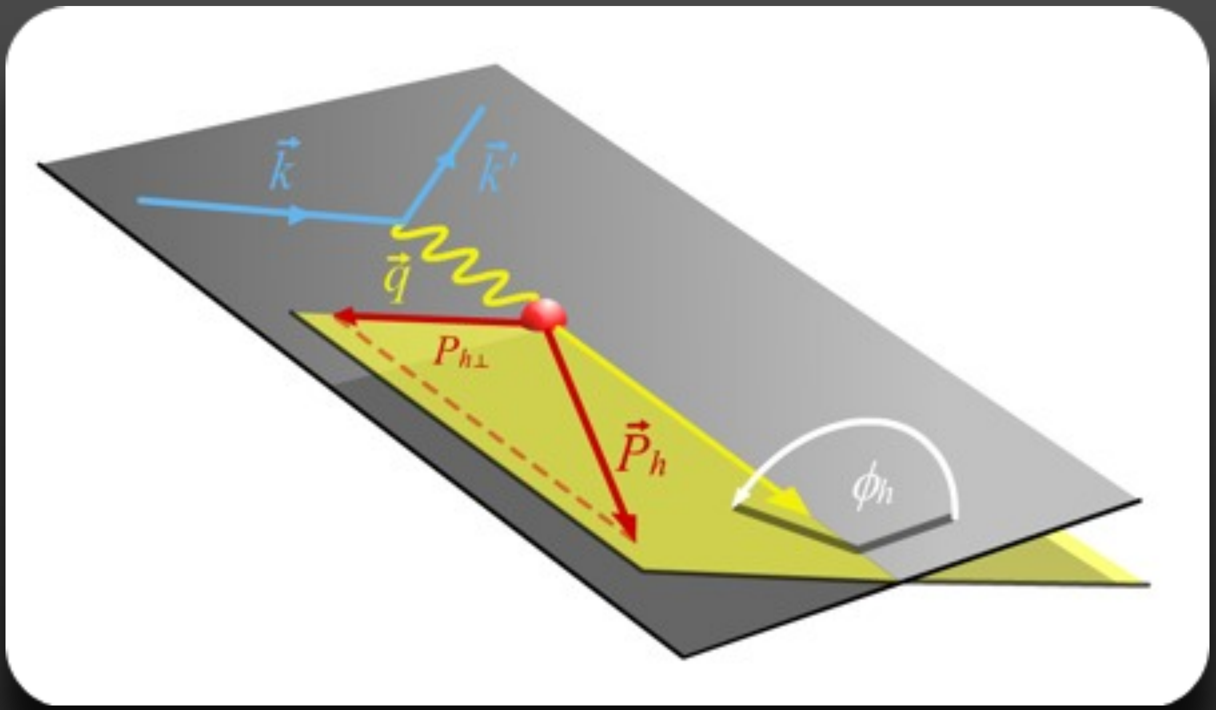
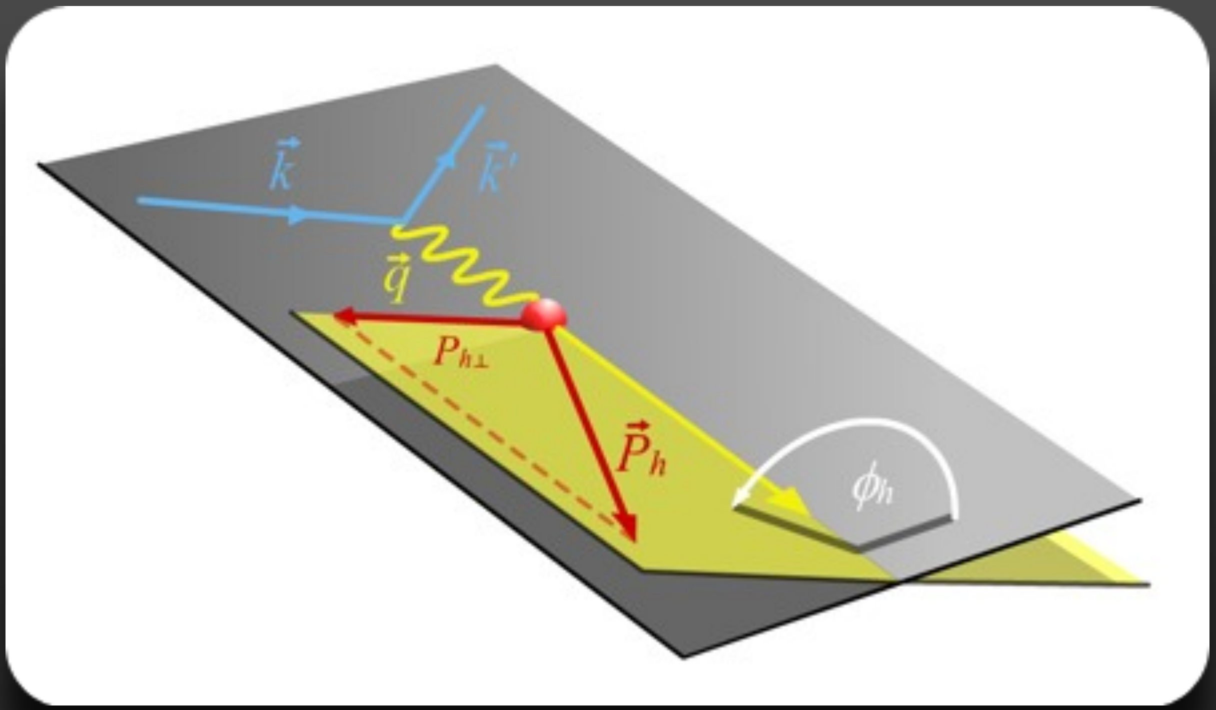
Flavor dependent azimuthal modulations in unpolarized SIDIS cross section @ HERMES

SPIN 2010, Jülich

Francesca Giordano
Rebecca Lamb



Semi-Inclusive DIS



target
polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z)$$

beam
polarization

virtual photon
polarization

Collinear case

$$\frac{d^5\sigma}{dx\,dy\,dz} = \frac{\alpha^2}{xyQ^2}\left(\frac{y^2}{2(1-\epsilon)}\right)\left(1 + \frac{\gamma^2}{2x}\right)\left\{F_{UU,T} + \epsilon F_{UU,L}\right\}$$

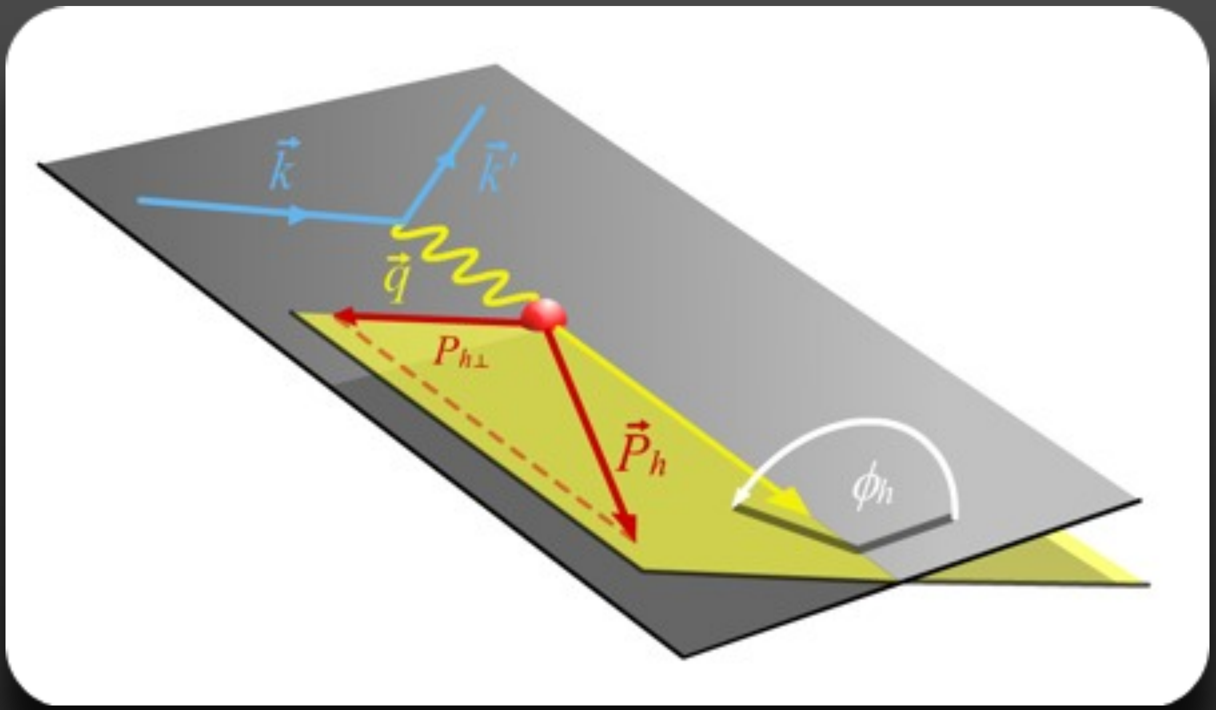
Q^2 **Negative squared 4-momentum transfer to the target**

y **Fractional energy of the virtual photon**

x **Bjorken scaling variable**

z **Fractional energy transfer to the produced hadron**

Semi-Inclusive DIS



target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

beam polarization

virtual photon polarization

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

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

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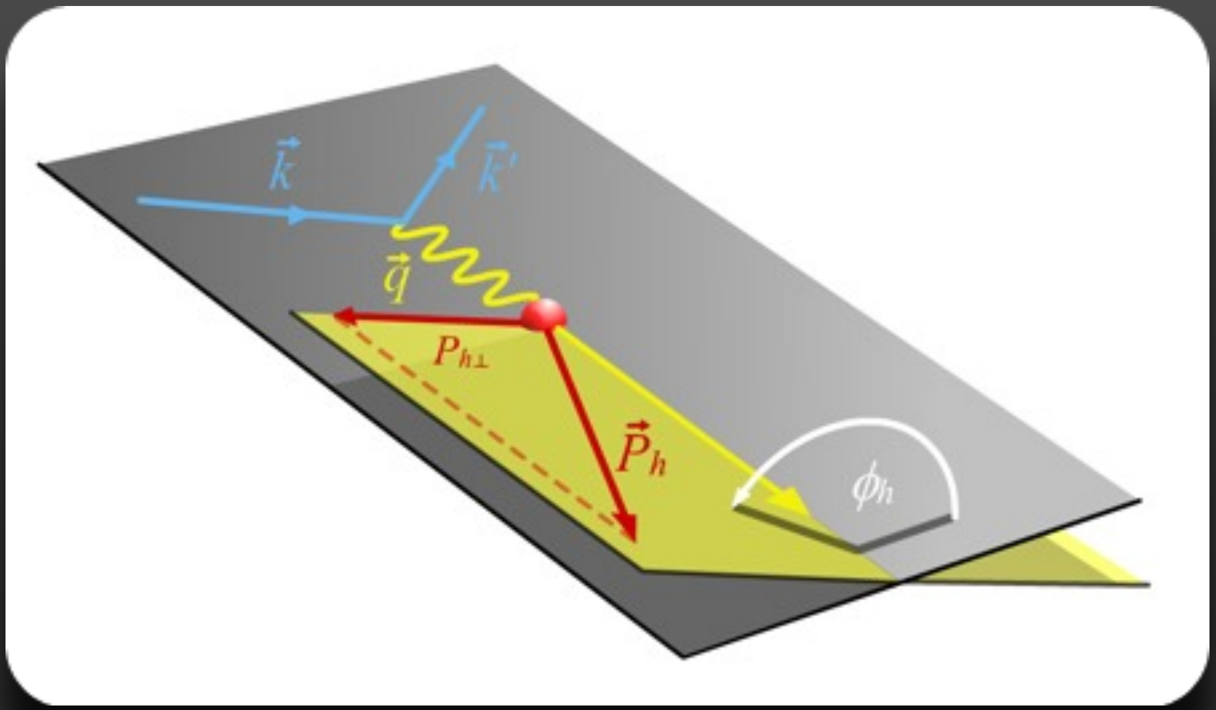

target polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

beam polarization

virtual photon polarization

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

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

Q^2 **Negative squared 4-momentum transfer to the target**

y **Fractional energy of the virtual photon**

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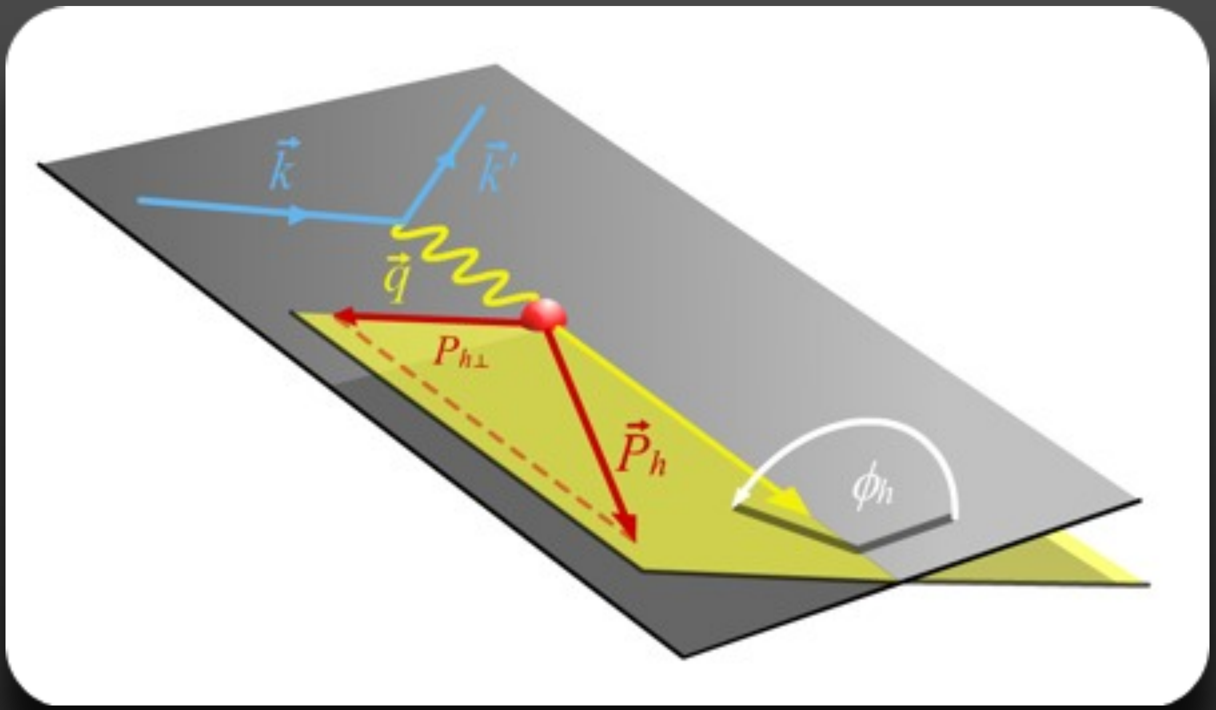
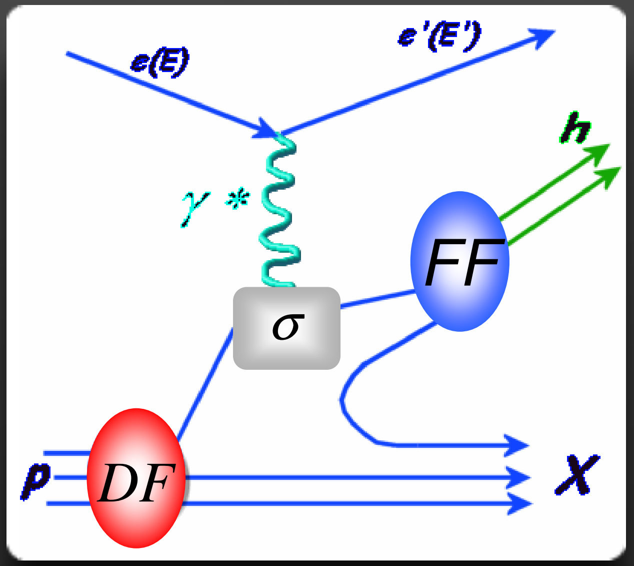
$$\langle\cos n\phi_h\rangle = \frac{\int \cos n\phi_h \frac{d^5\sigma}{x\,dy\,dz\,d\phi_h\,dP_{h\perp}^2}d\phi_h}{\int \frac{d^5\sigma}{x\,dy\,dz\,d\phi_h\,dP_{h\perp}^2}d\phi_h}$$

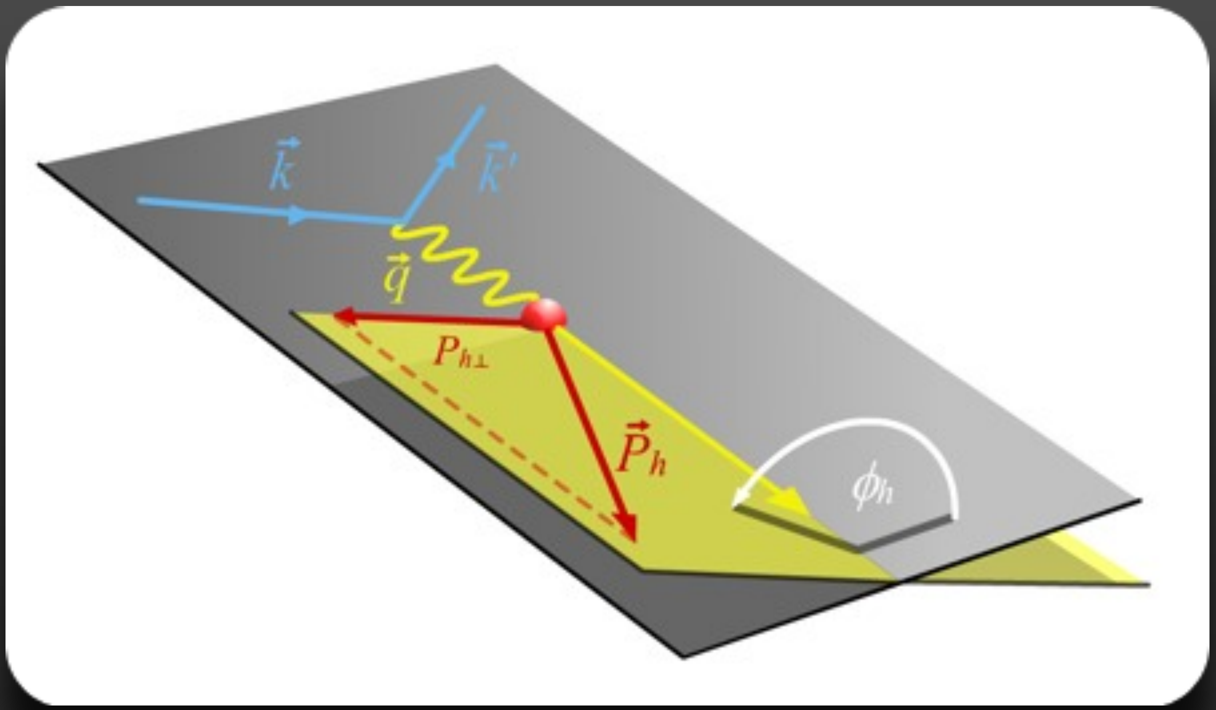
Semi-Inclusive DIS

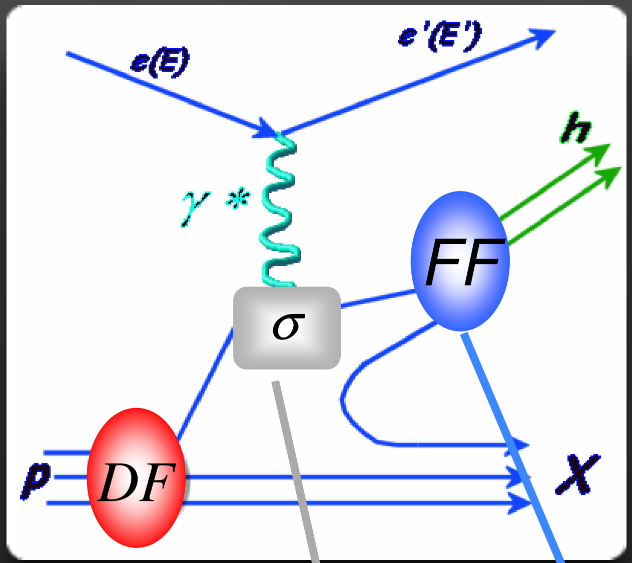


$\vec{k}$
$\vec{k}'$
$\vec{q}$
$P_{h\perp}$
$\vec{P}_h$
ϕ_h

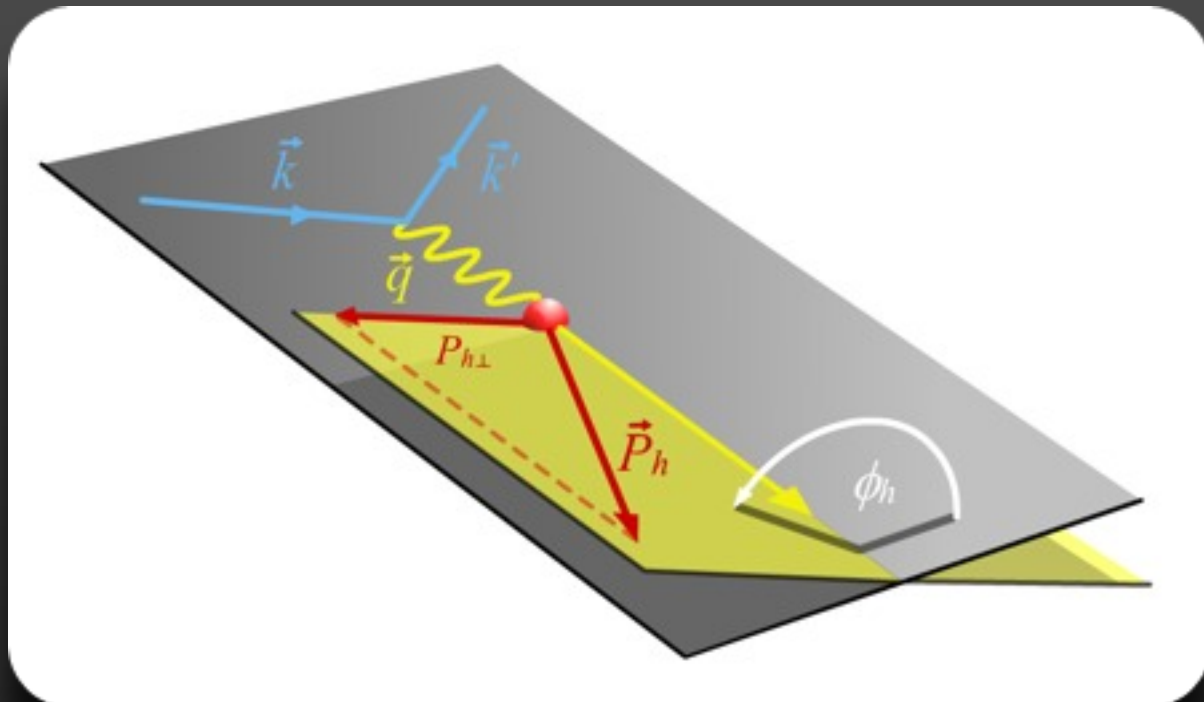


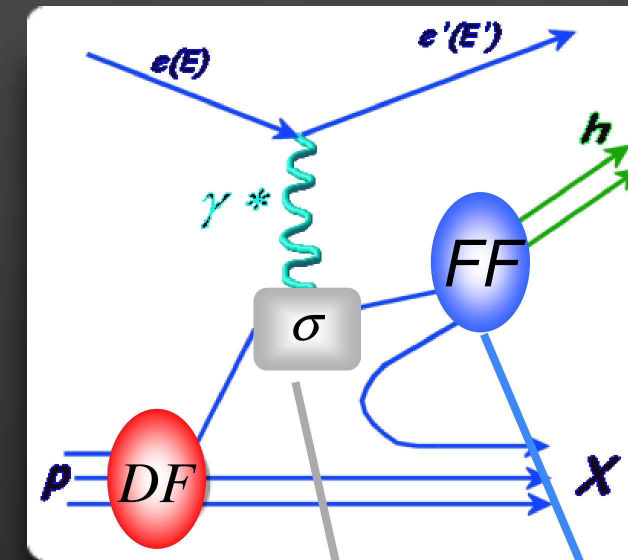
e(E)
e'(E')
h
γ *
FF
σ
DF
p
X





$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

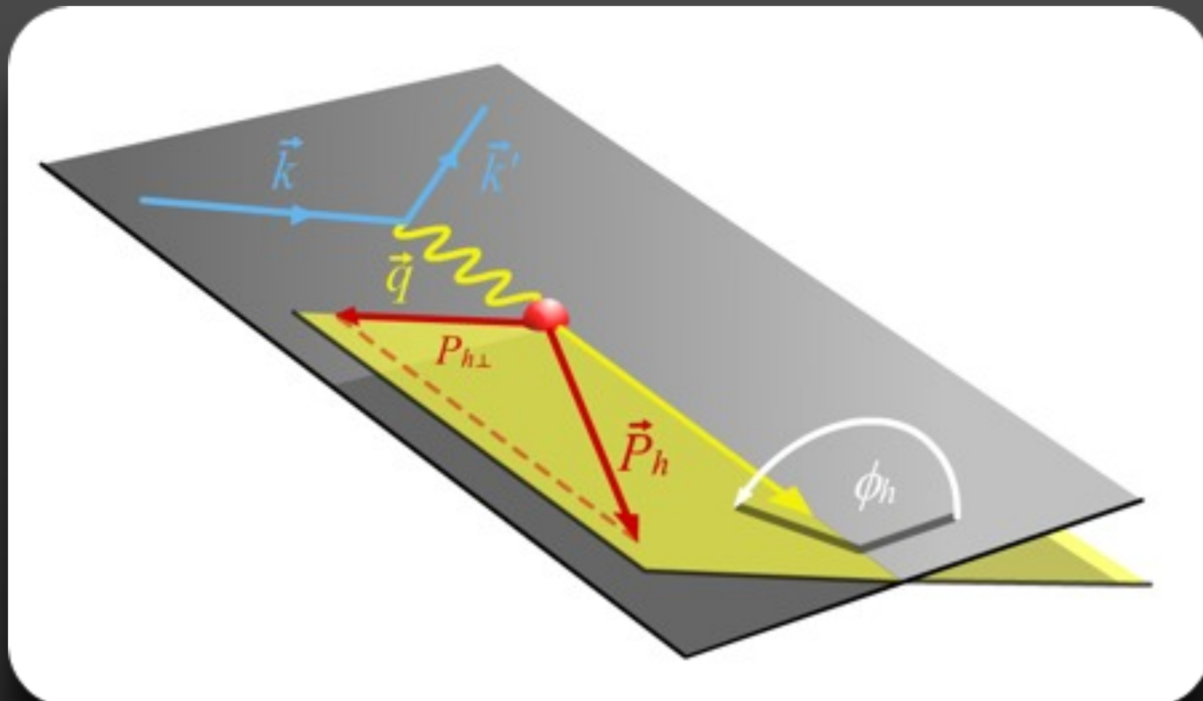


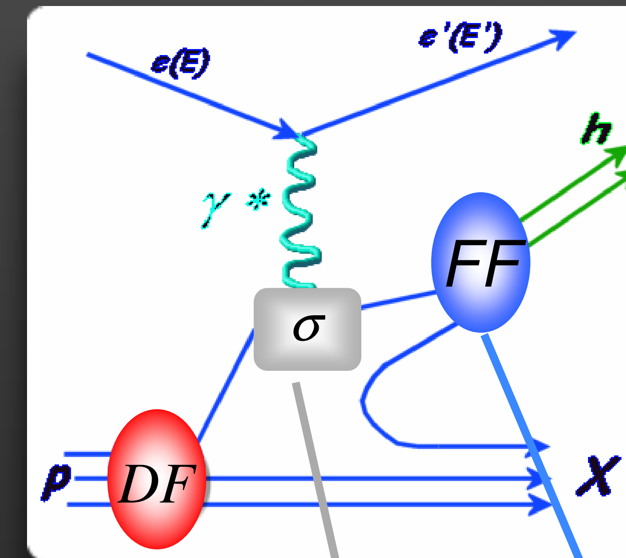


$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

distribution functions

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \quad h_{1T}^\perp$





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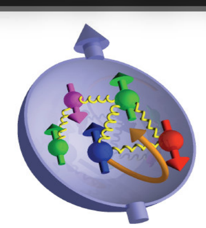		quark		
		U	L	T
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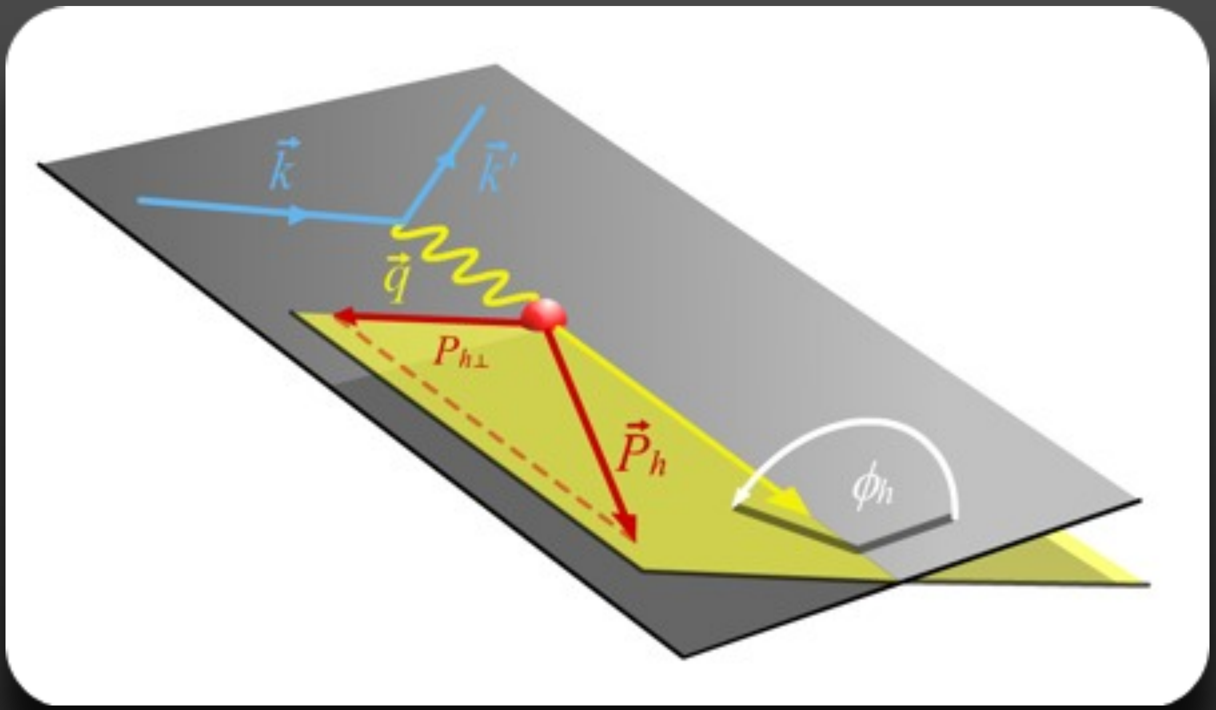
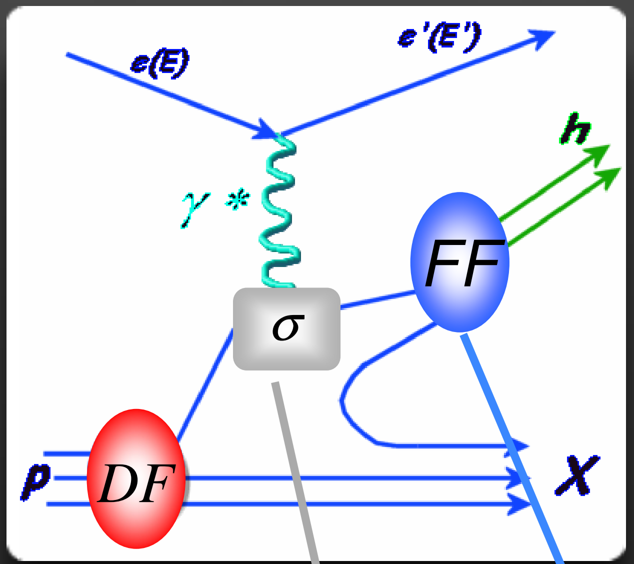
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \quad h_{1T}^\perp$

fragmentation functions

		quark		
		U	L	T
had.	U	D_1		$H_1^\perp$





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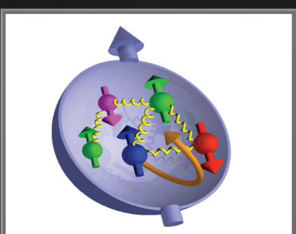		quark		
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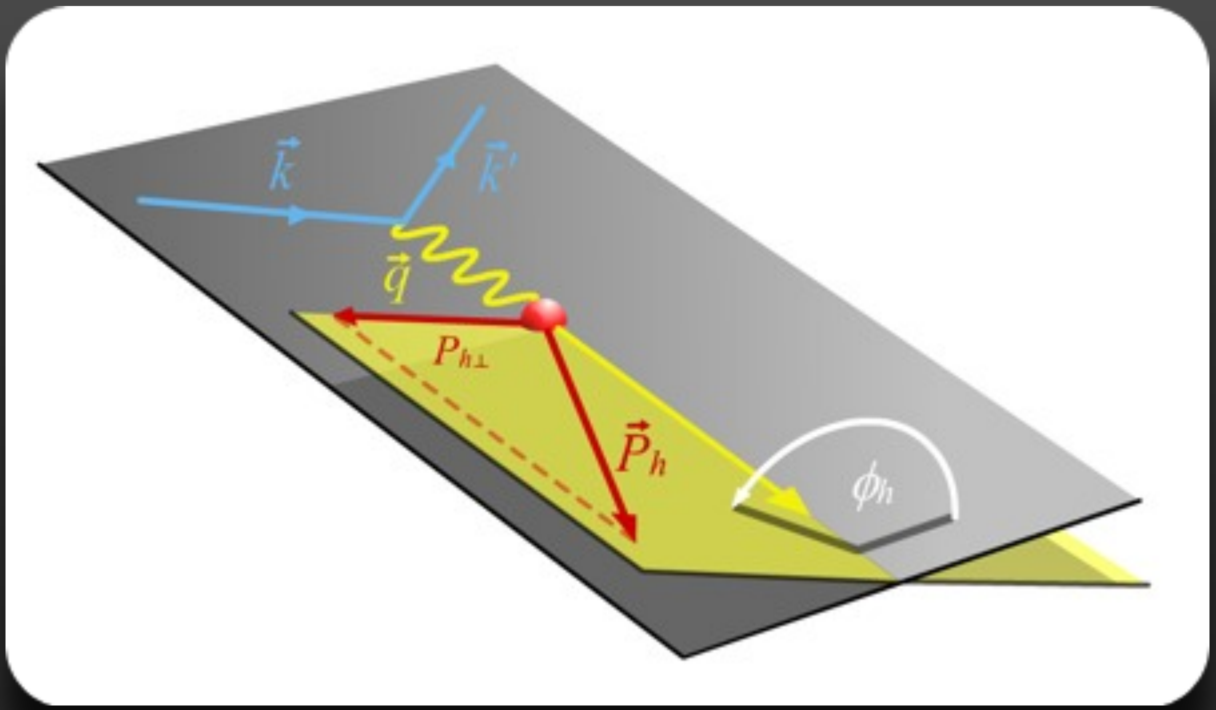

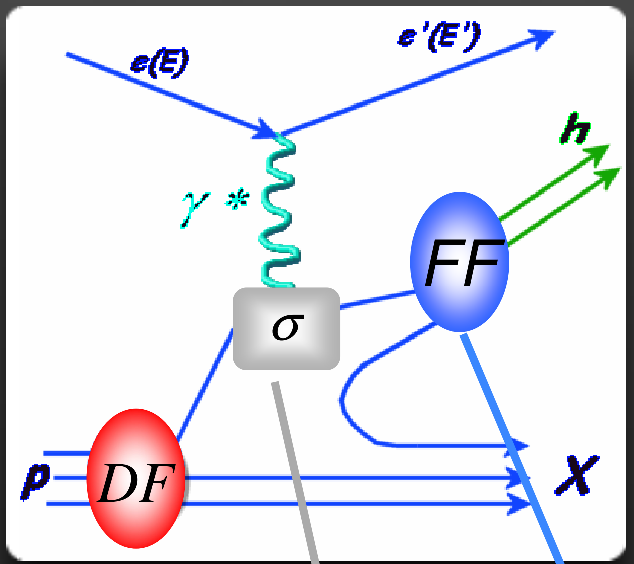

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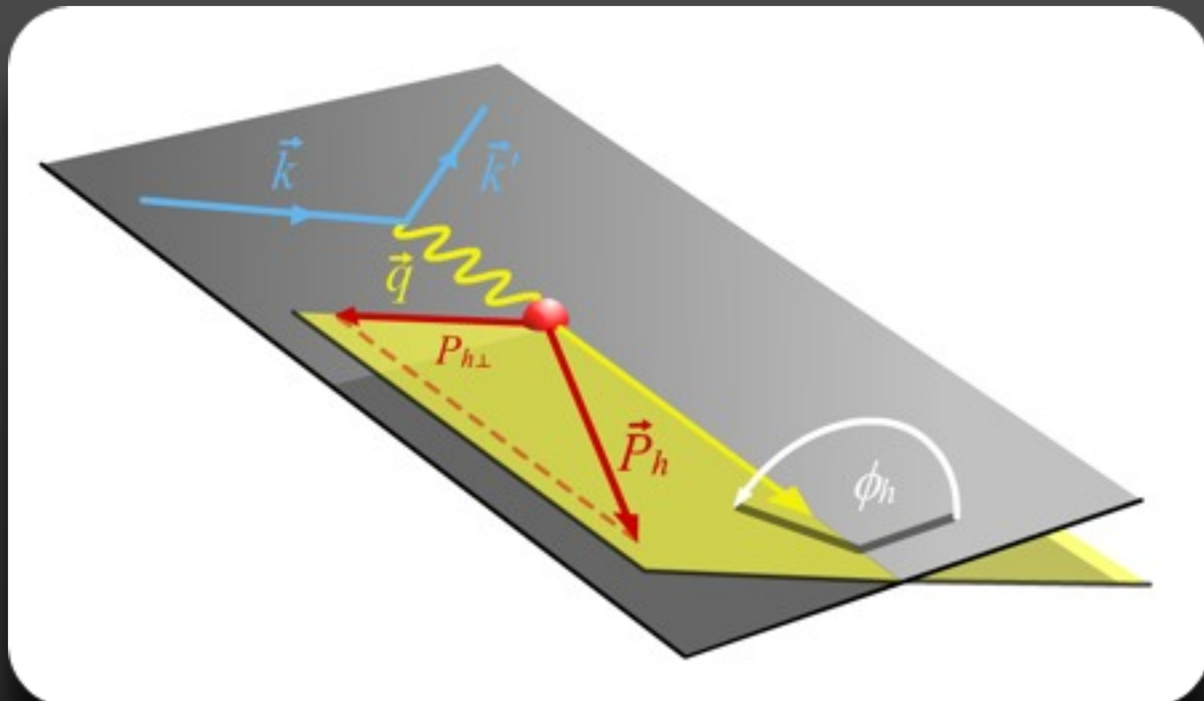
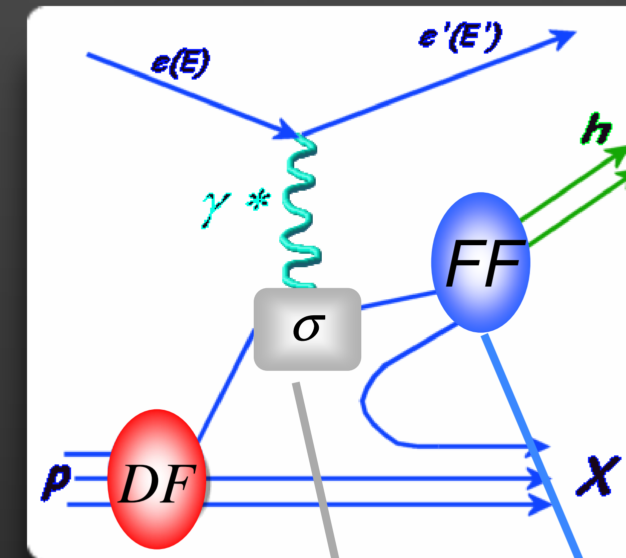
nucleon L		g_1	$h_{1L}^\perp$
nucleon T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 \quad h_{1T}^\perp$

Boer-Mulders DF

fragmentation functions

	quark		
	U	L	T
had. U	D_1		$H_1^\perp$





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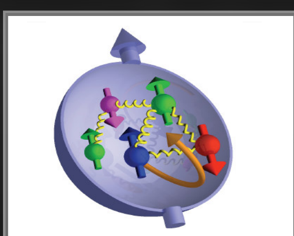
distribution functions

		quark		
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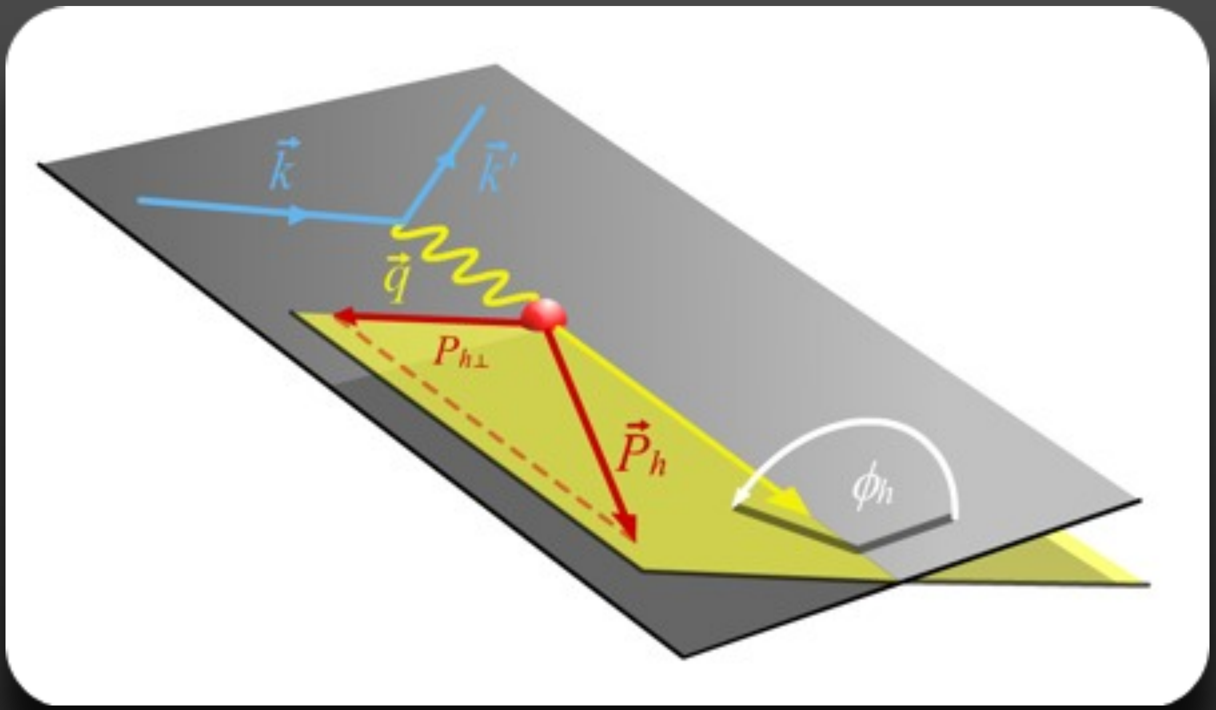
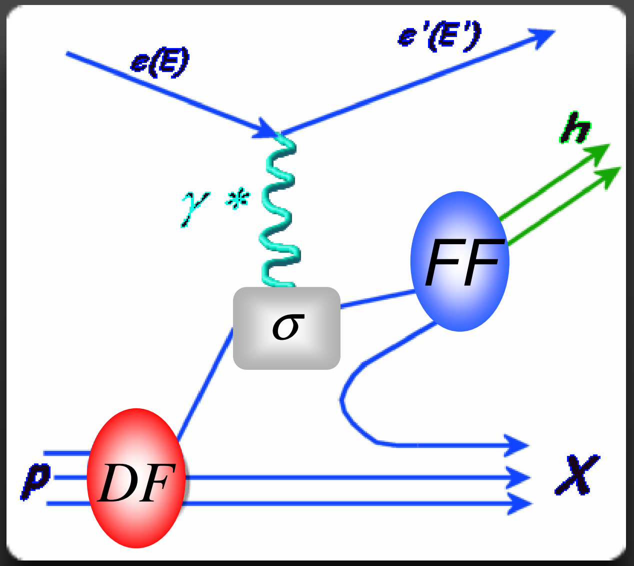
Boer-Mulders DF

Collins FF

fragmentation functions

		quark		
		U	L	T
had.	U	D_1		$H_1^\perp$

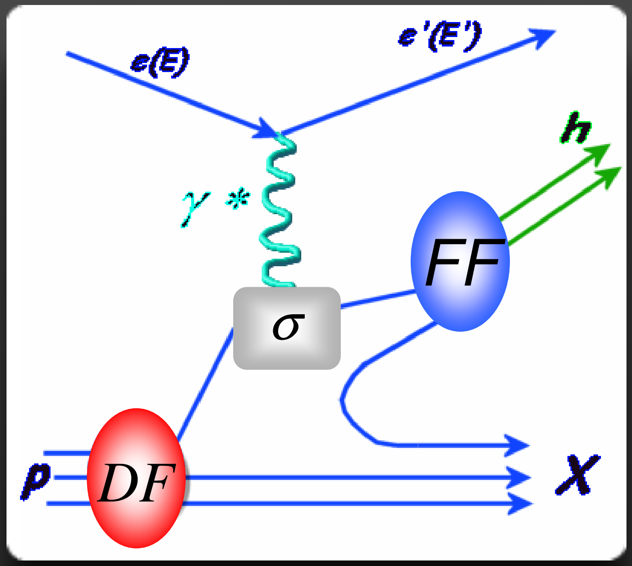




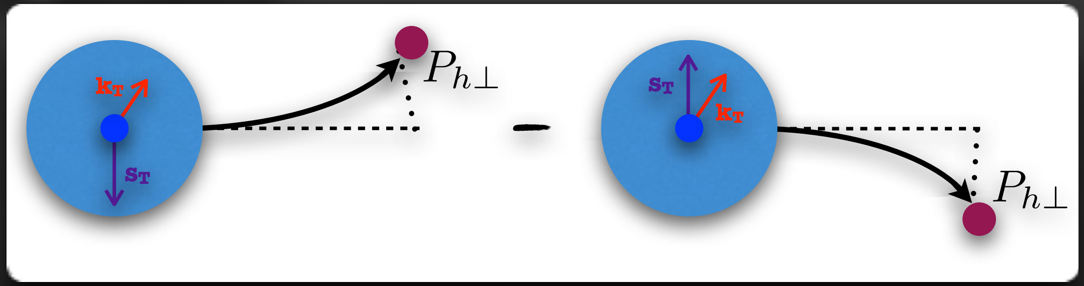
$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\times\vec{\kappa}_T)(\hat{P}_{h\perp}\times\vec{p}_T)-\vec{\kappa}_T\times\vec{p}_T}{MM_h}h_1^{\perp}H_1^{\perp}\right]$$

implicit sum over quark flavors

Leading twist



Boer-Mulders effect



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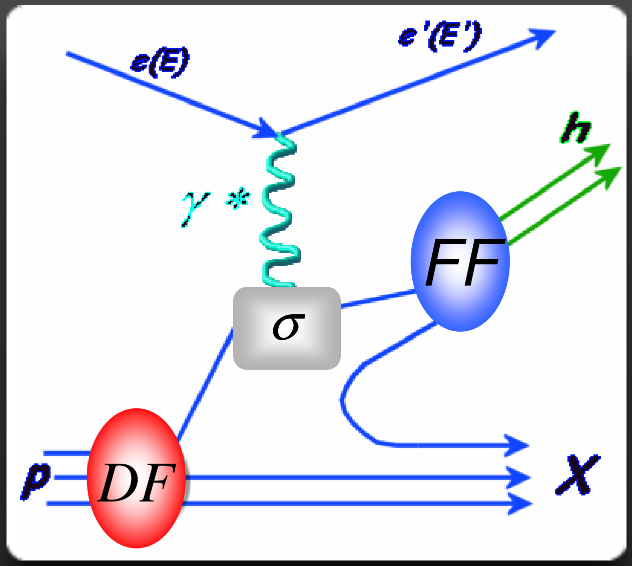

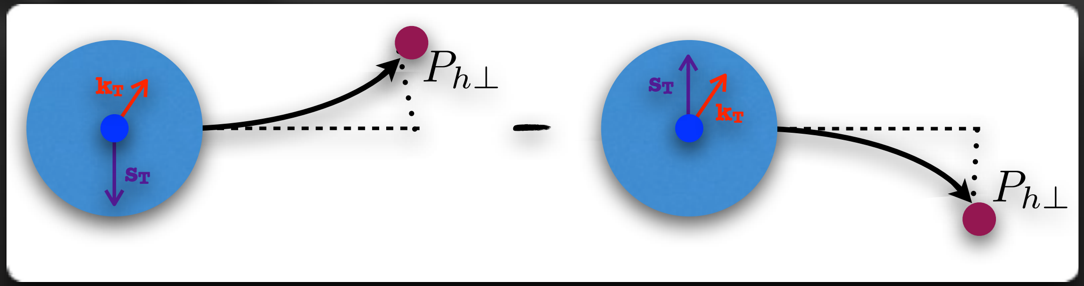

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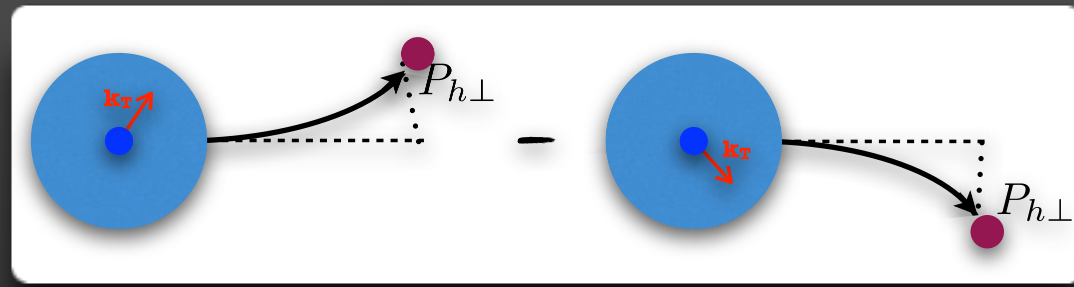
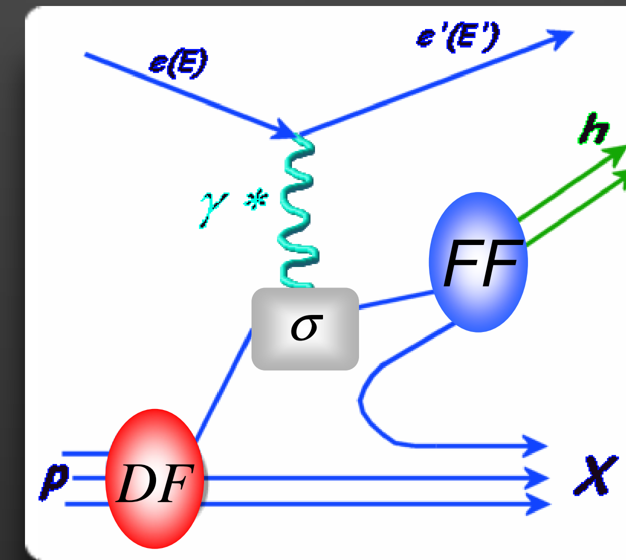
$$F_{UU}^{\cos \phi_h} \propto \frac{2M}{Q} C\left[-\frac{\hat{P}_{h\perp}\times\vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\hat{P}_{h\perp}\times\vec{\kappa}_T}{M} x f_1 D_1 + \ldots\right]$$

implicit sum over quark flavors

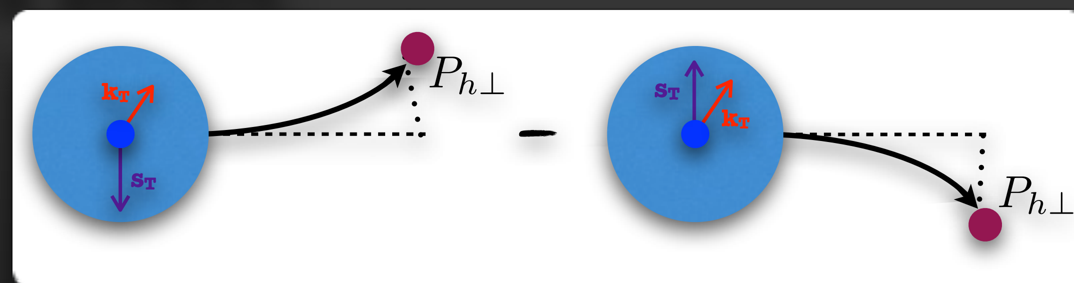
Leading and Next-to Leading twist

Cahn effect





Boer-Mulders effect



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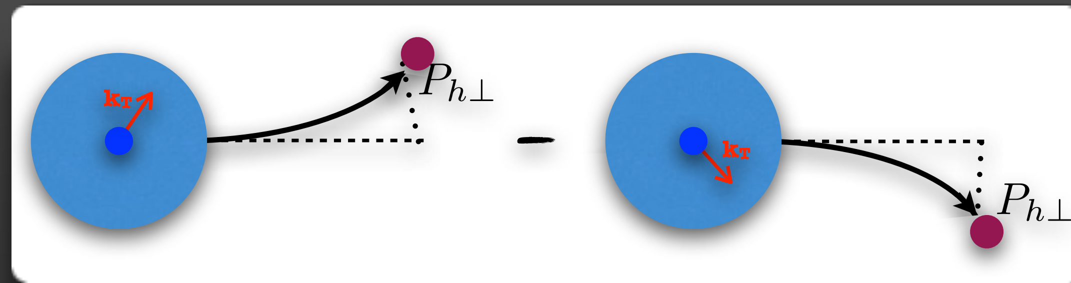
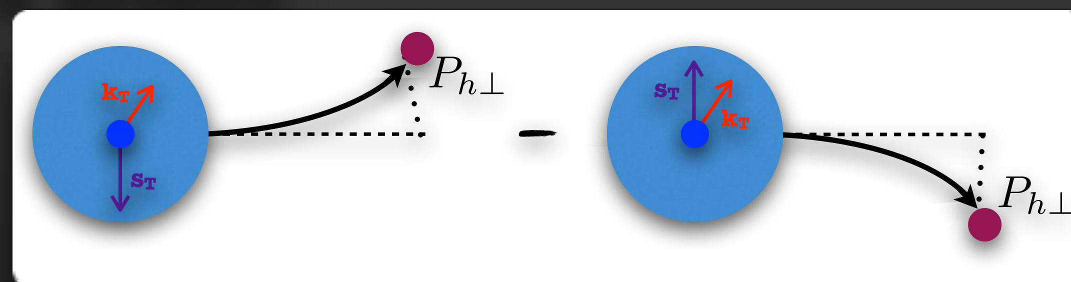
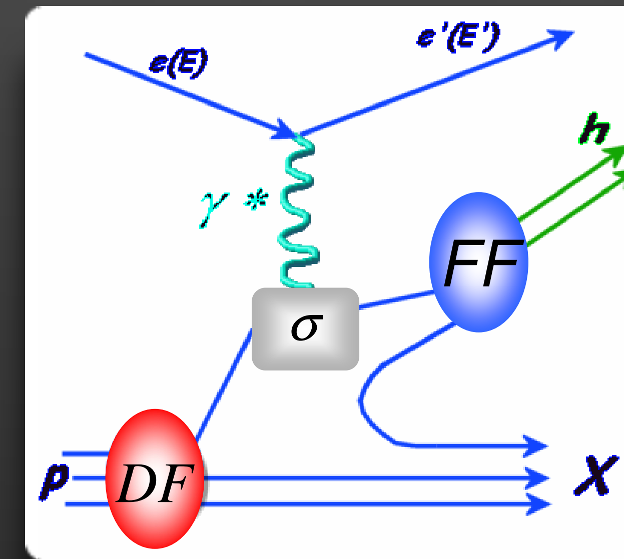


Boer-Mulders effect





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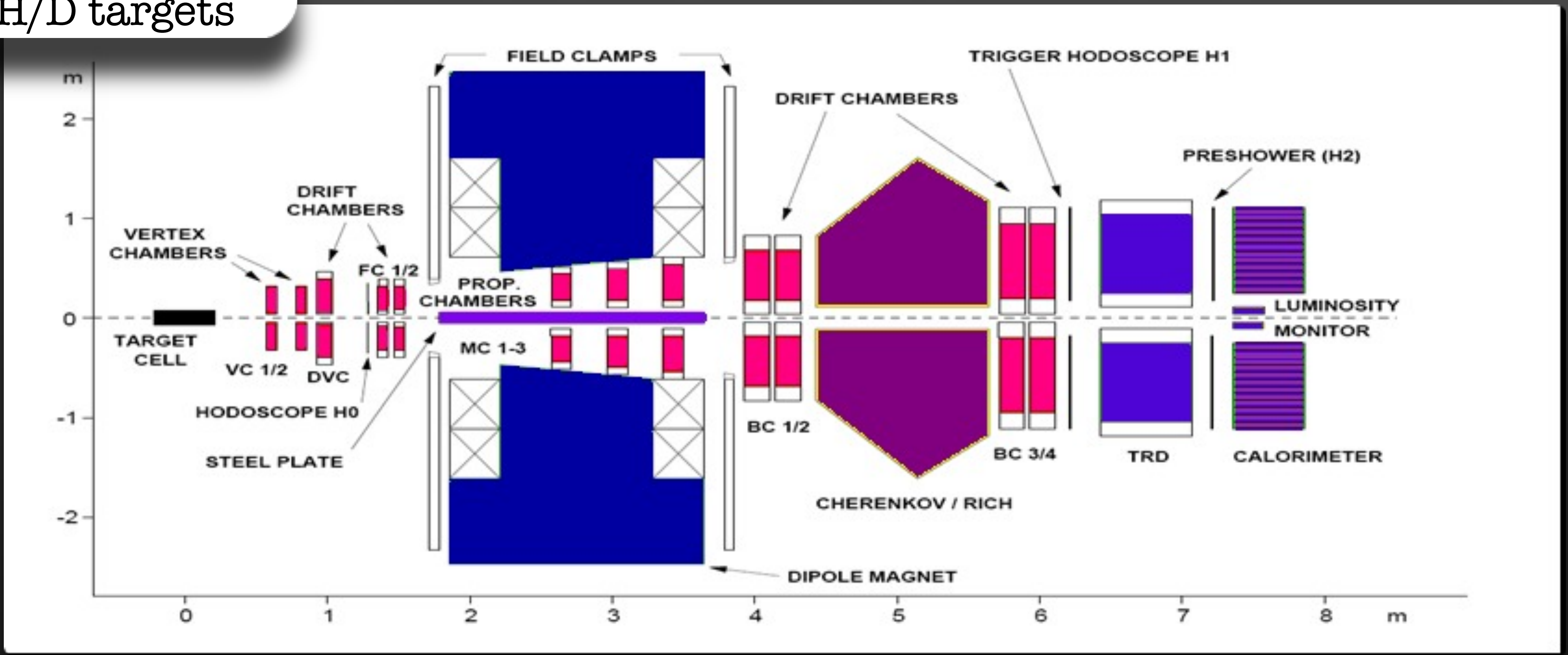
implicit sum over quark flavors

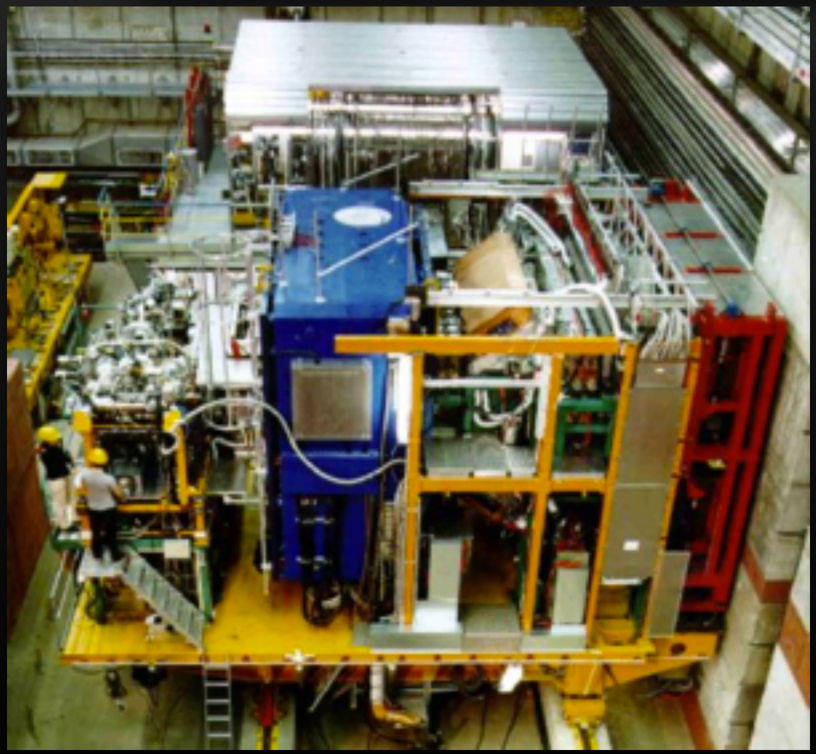
interaction dependent terms neglected

Leading and Next-to Leading twist

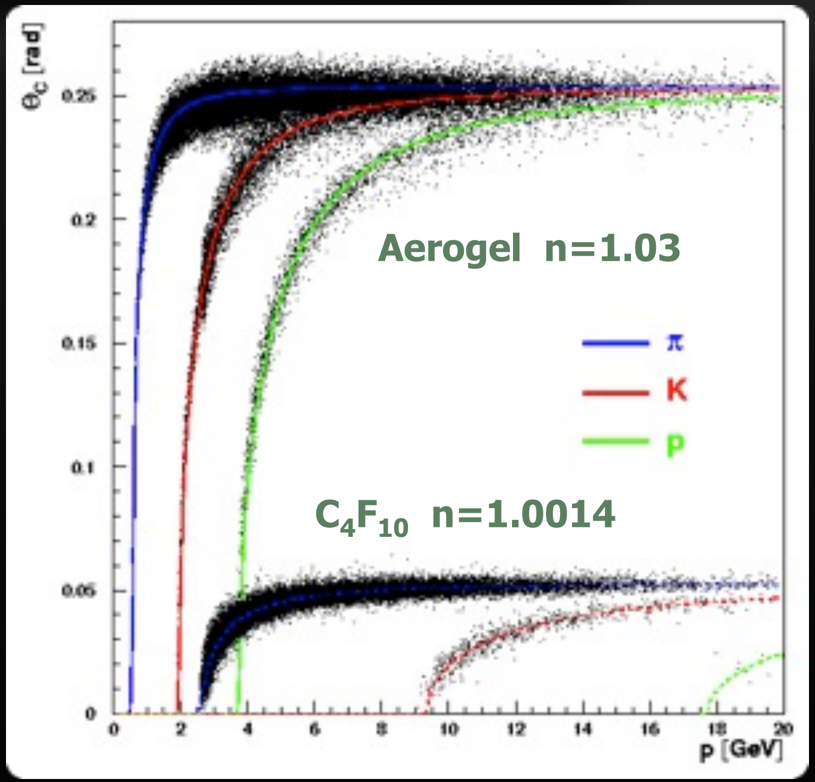
HERMES

Lepton (e+/e-) beam
off H/D targets





HERMES spectrometer



$$n = \int L\sigma^0_w[1 + 2\langle\cos\phi_h\rangle_w \cos\phi_h + 2\langle\cos 2\phi_h\rangle_w \cos 2\phi_h]\epsilon^{acc}_{w,\phi_h}\epsilon^{rad}_{w,\phi_h}dw$$

Experimental extraction

$$w = (x, y, z, P_{h\perp})$$

$$n = \int L\sigma_w^0 [1 + 2\langle\cos\phi_h\rangle_w \cos\phi_h + 2\langle\cos 2\phi_h\rangle_w \cos 2\phi_h]\epsilon_{w,\phi_h}^{acc}\epsilon_{w,\phi_h}^{rad} dw$$

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Multi-dimensional (w)

Binning 900 kinematic bins x ϕ_h-bins								
Variable	Bin limits							#
x	0.023	0.04	0.078	0.145	0.27	0.6		5
y	0.2	0.3	0.45	0.6	0.7	0.85		5
z	0.2	0.3	0.4	0.5	0.6	0.75	1	6
$P_{h\perp}$	0.05	0.2	0.35	0.5	0.7	1	1.3	6

Experimental extraction

$$w = (x, y, z, P_{h\perp})$$

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$$n_{born} = S^{-1}[n - B]$$

Multi-dimensional (w) unfolding

Binning 900 kinematic bins x ϕ_h-bins								
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describes the smearing between adjacent bins

Multi-dimensional (w) unfolding

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describes the smearing between adjacent bins

events smeared in the sample from outside the acceptance

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Experimental extraction

$$w = (x, y, z, P_{h\perp})$$

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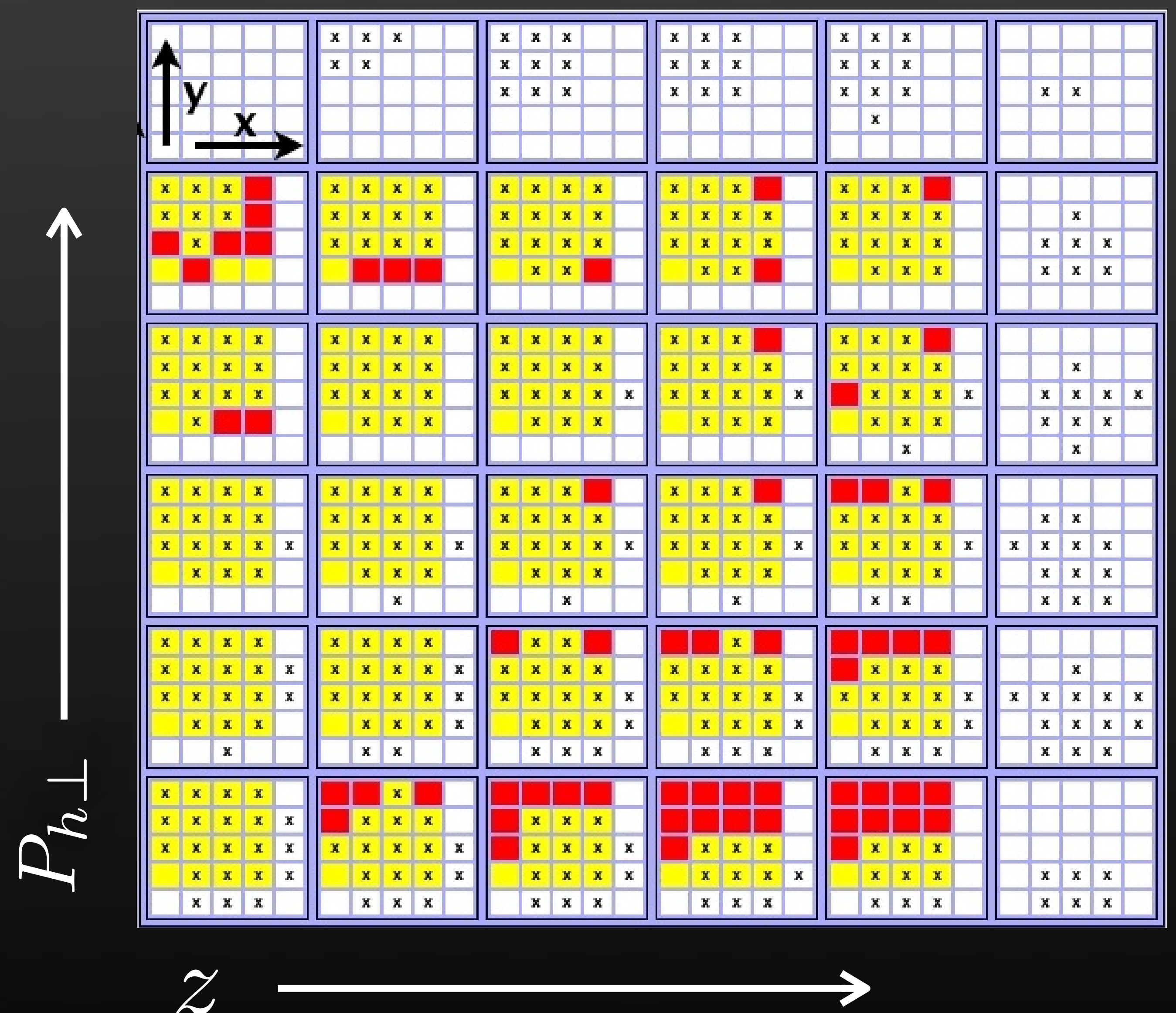

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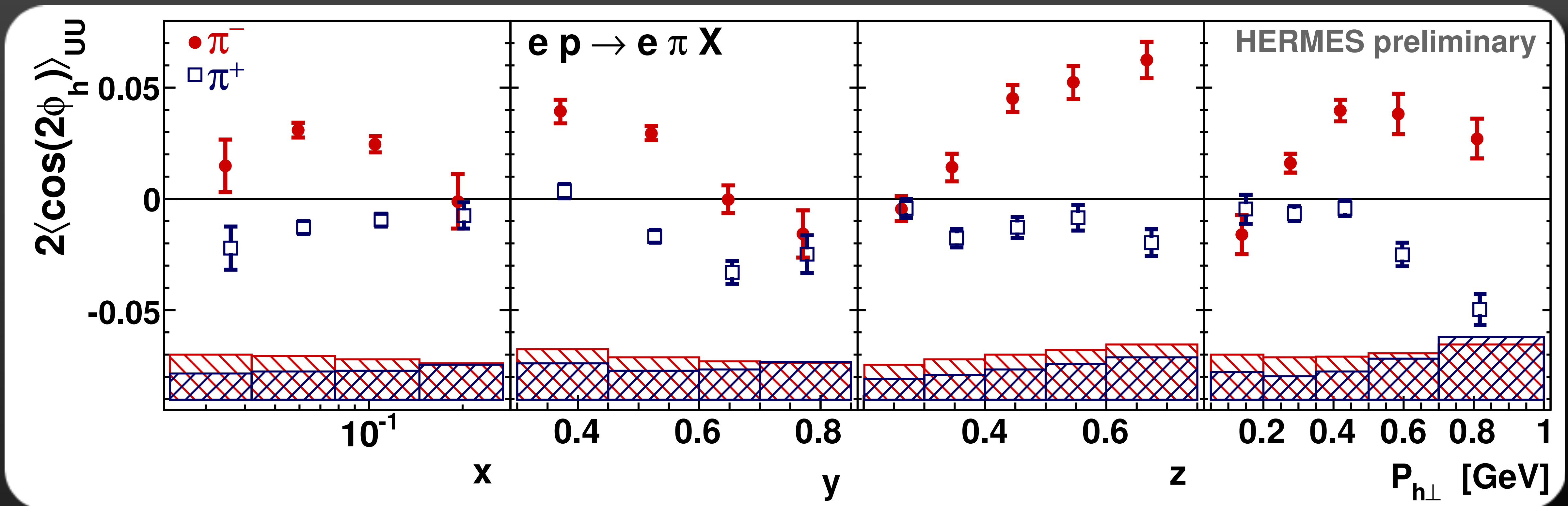
Projection vs. single variable

Pions *Hydrogen data* $\cos 2\phi_h$

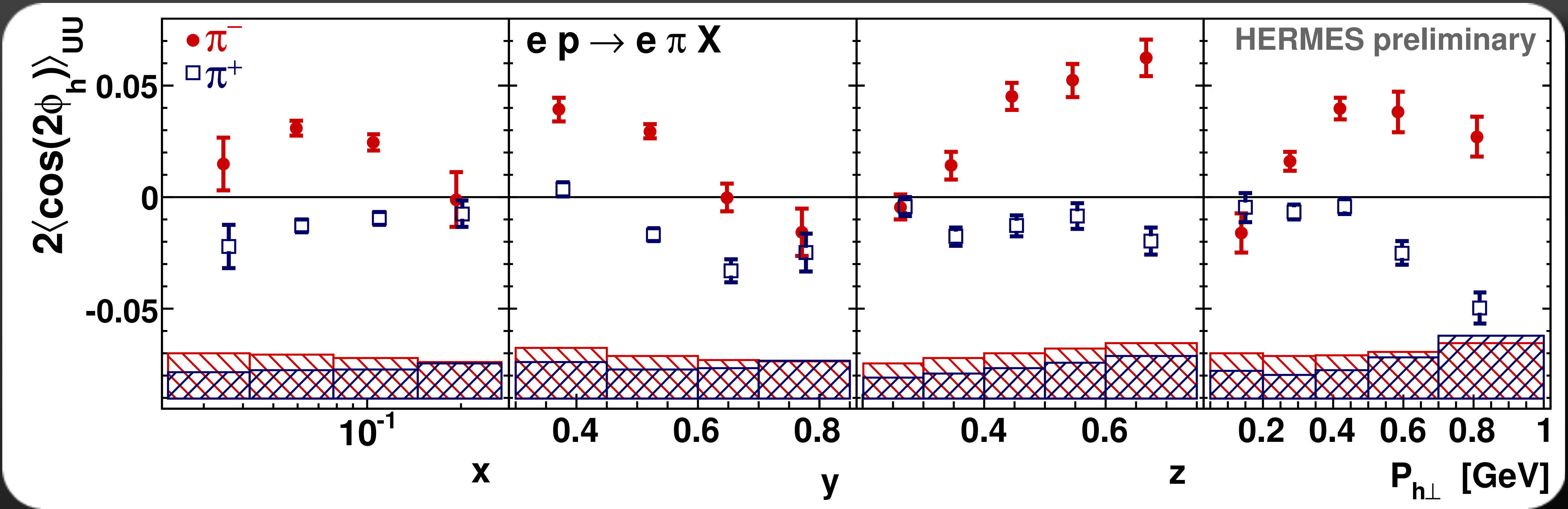


$$F_{UU}^{\cos 2\phi_h} \propto C[-h_1^{\perp} H_1^{\perp}]$$

Pions

Hydrogen data

$\cos 2\phi_h$



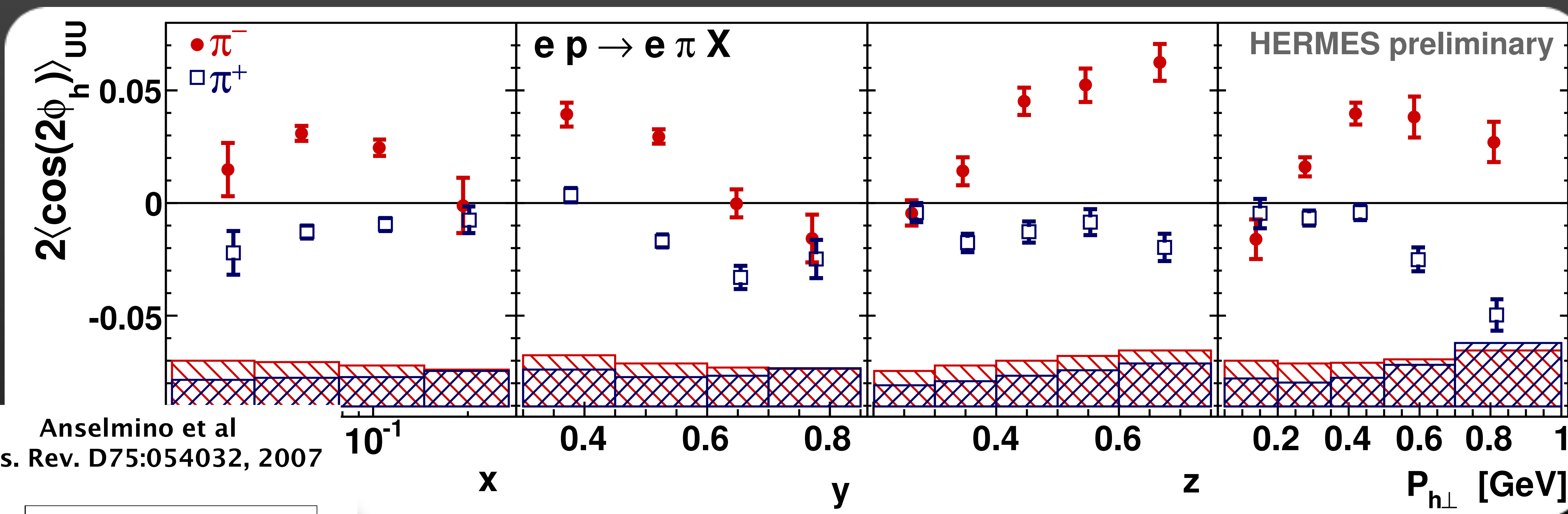
$$F_{UU}^{\cos 2\phi_h} \propto C[-h_1^\perp H_1^\perp]$$

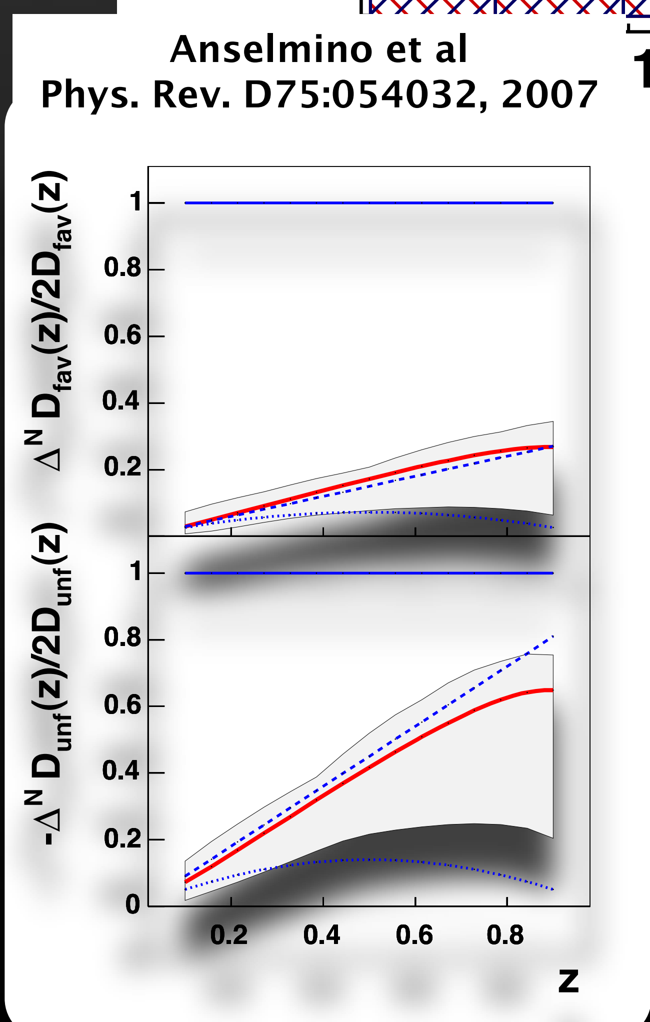
$$H_1^{\perp, u\to\pi^-} \approx -H_1^{\perp, u\to\pi^+}$$

Pions

Hydrogen data

$\cos 2\phi_h$





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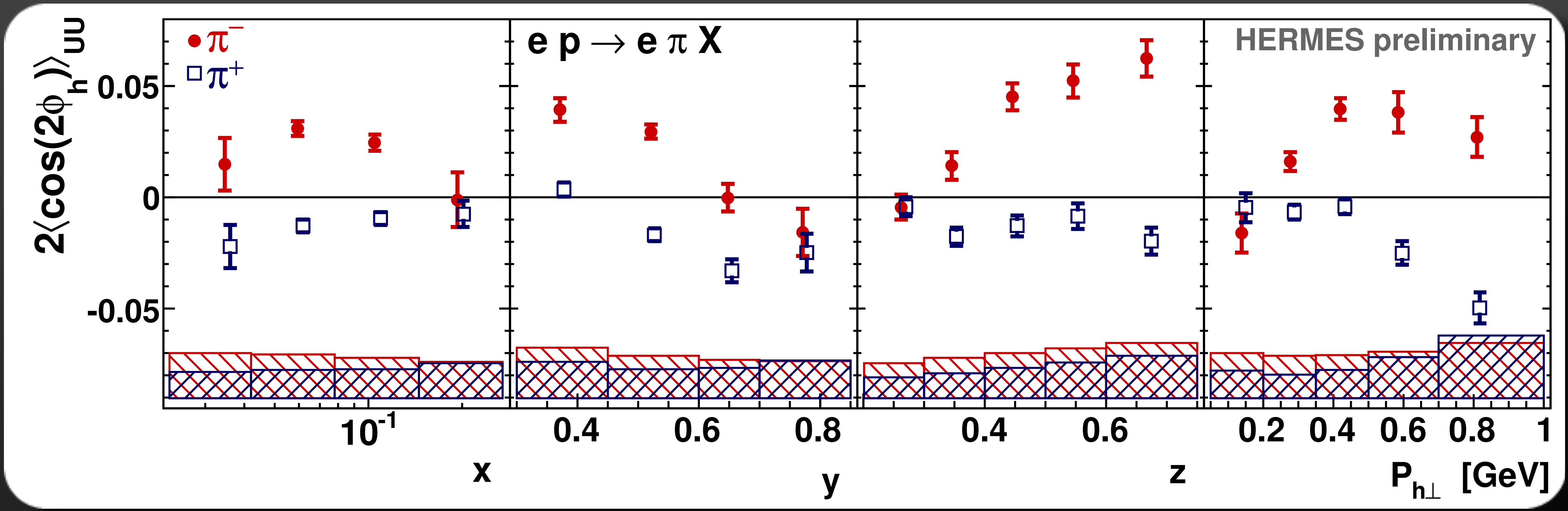

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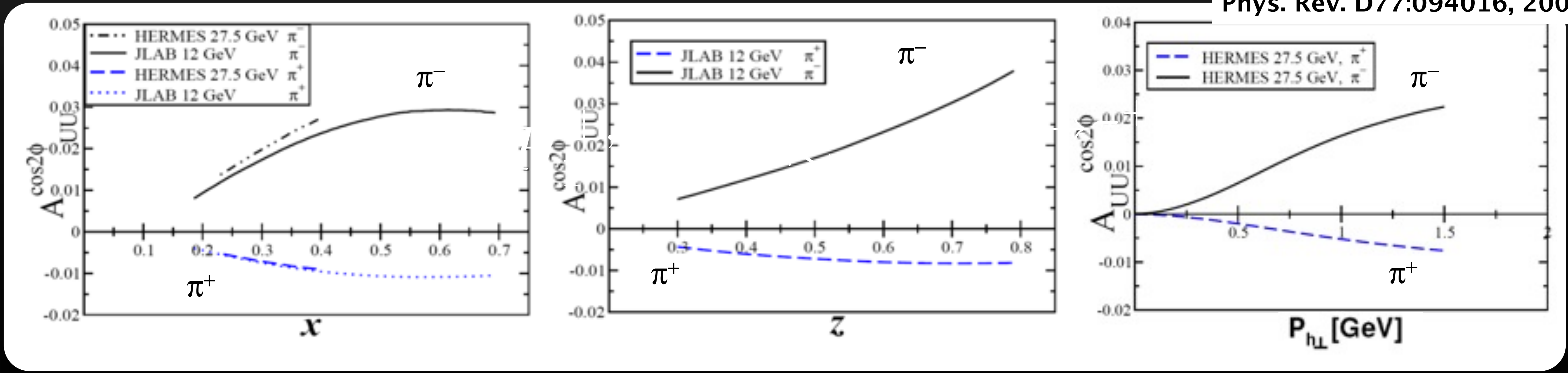
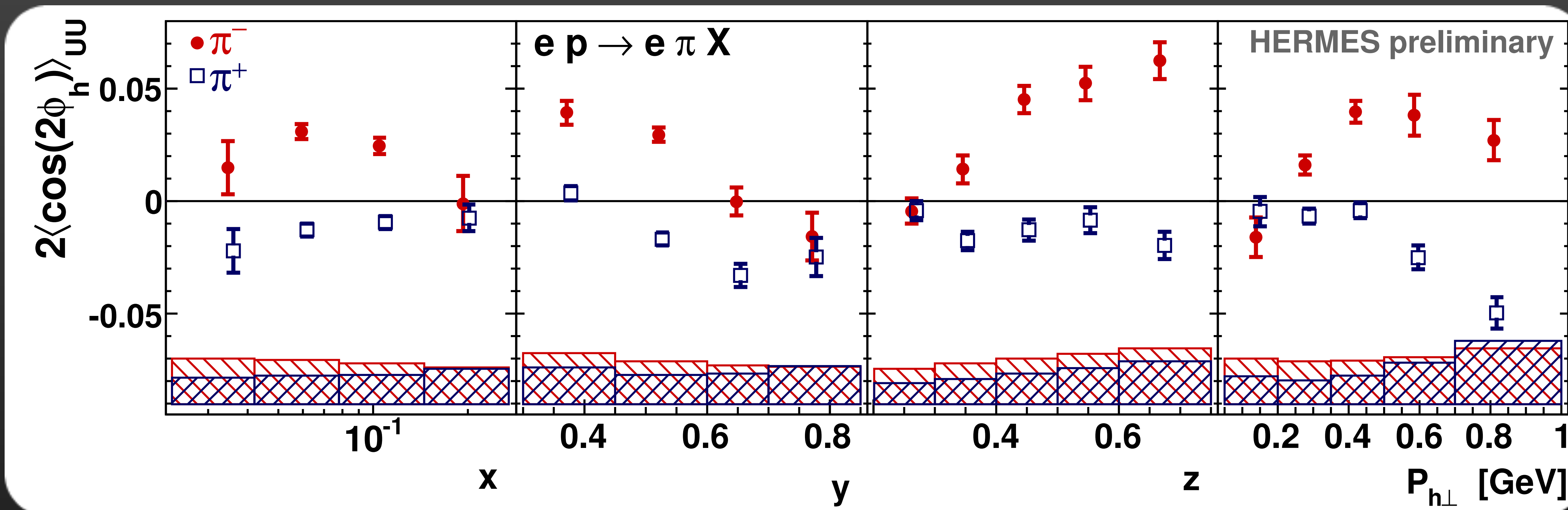
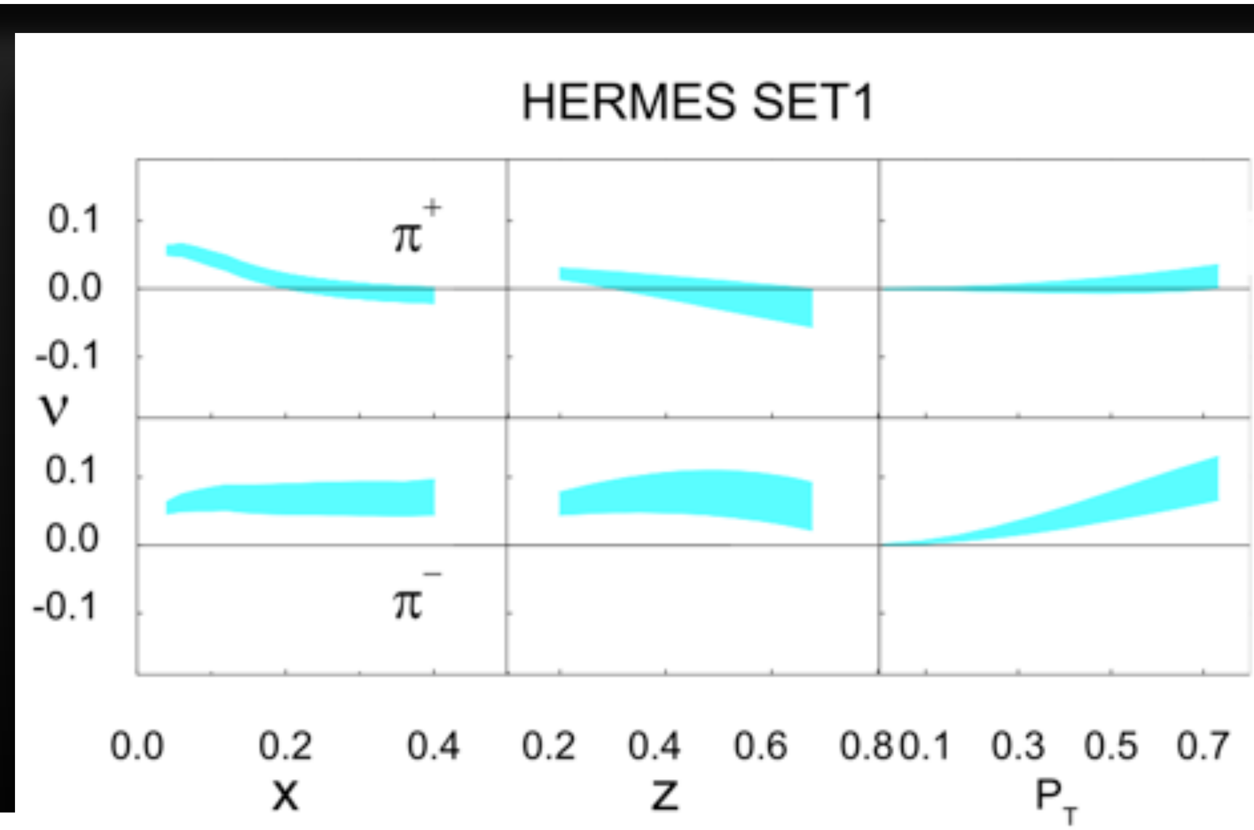
Gamberg, Goldstein
Phys. Rev. D77:094016, 2008



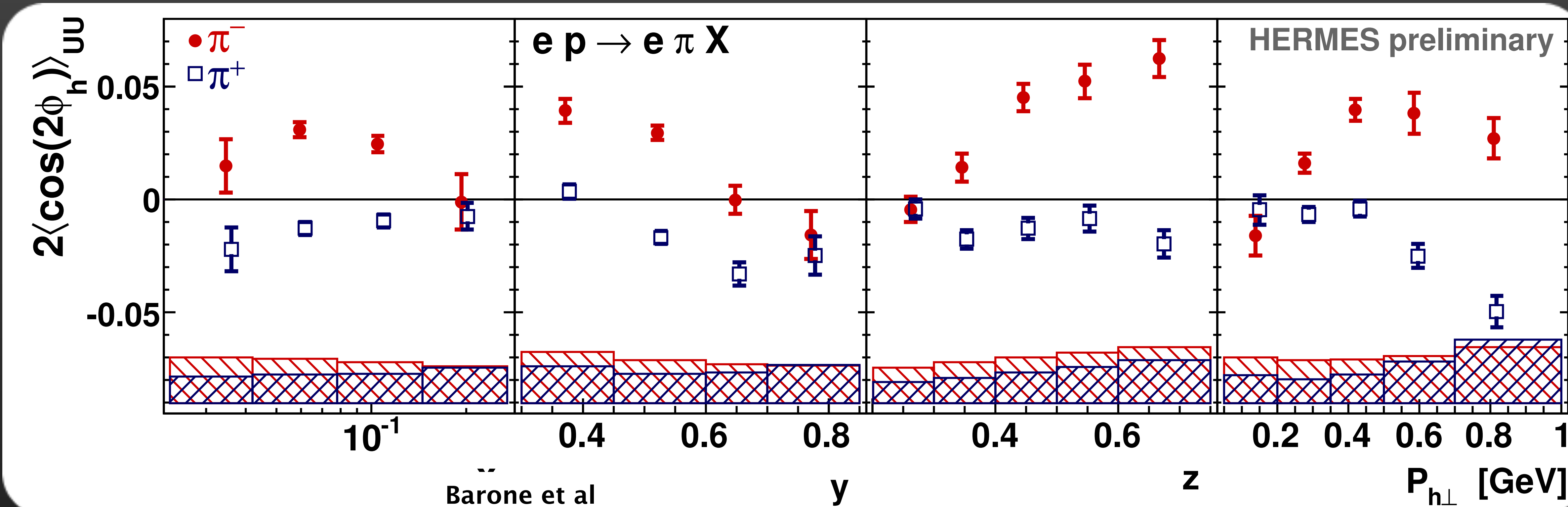
Pions — *Hydrogen data* — $\cos 2\phi_h$



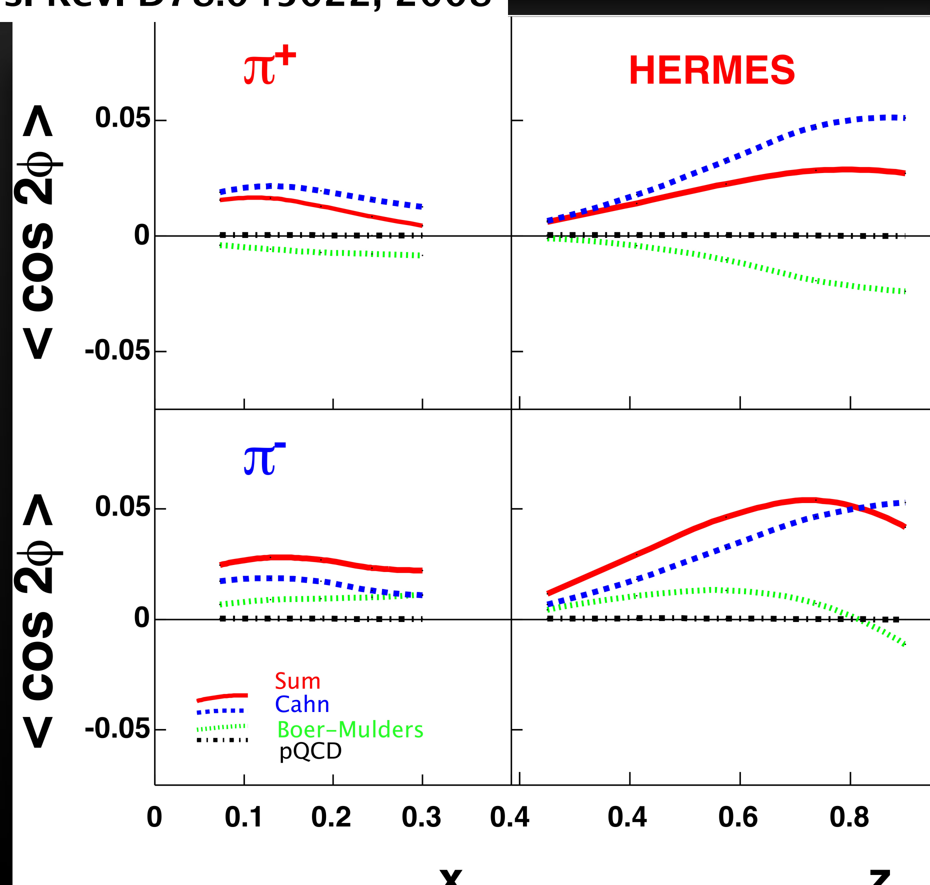


Zhang et al
Phys. Rev. D78:034035, 2008

Pions *Hydrogen data* $\cos 2\phi_h$



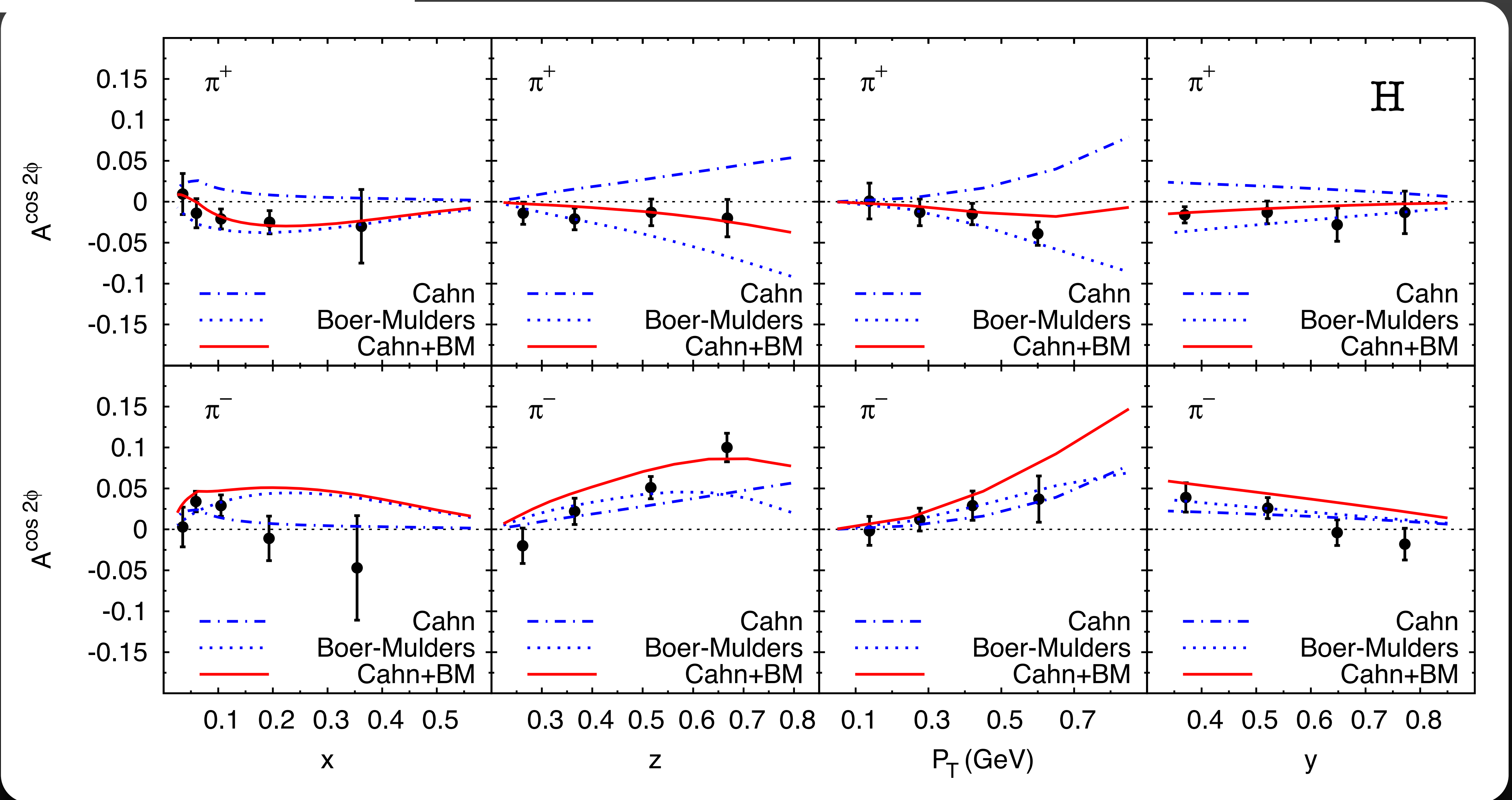
Barone et al
Phys. Rev. D78:045022, 2008



Pions *Hydrogen data* $\cos 2\phi_h$

Barone, Melis, Prokudin
Phys. Rev. D81:114026, 2010

* subsample HERMES data



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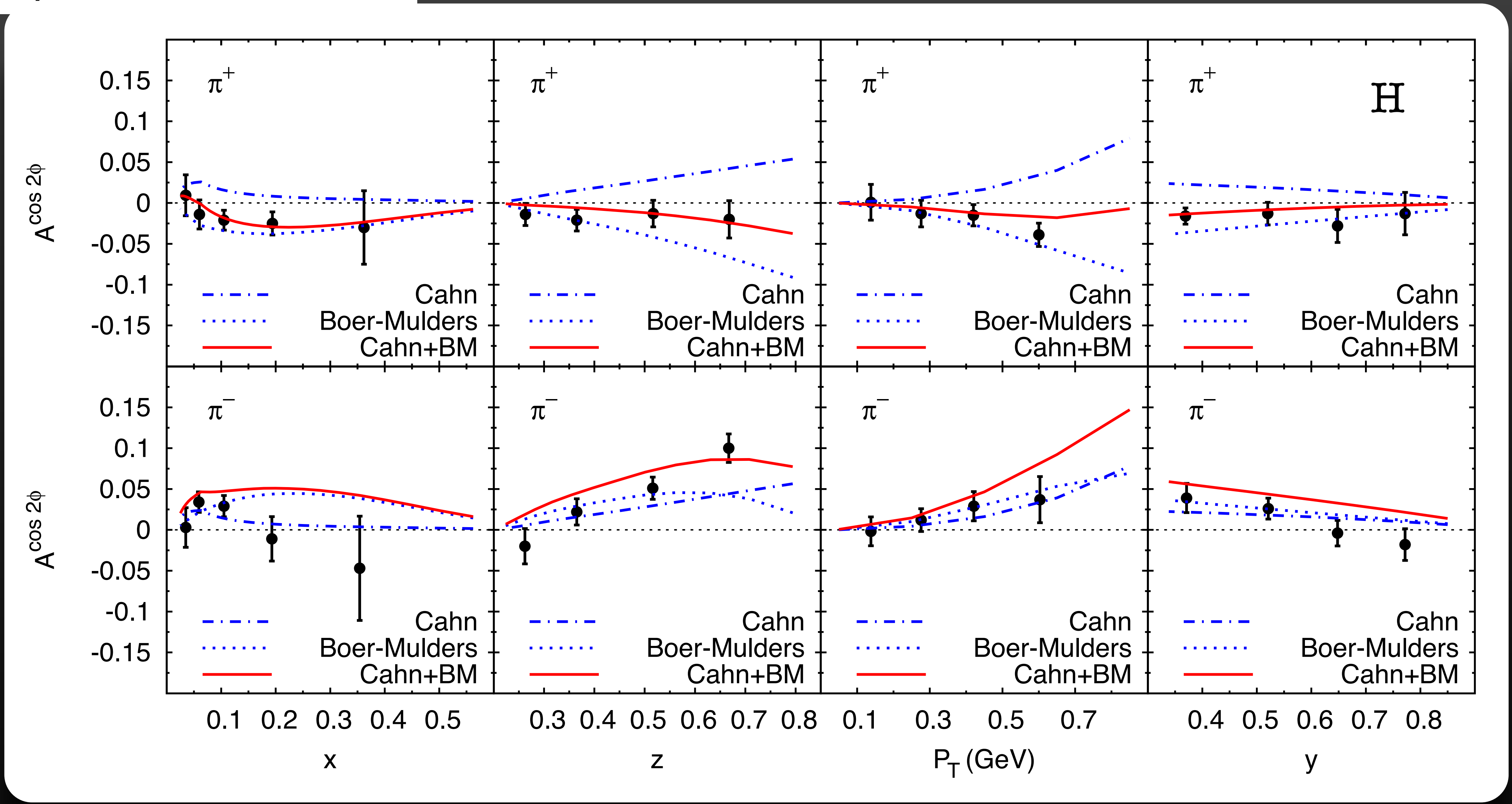

Anselmino et al.,
Phys. Rev. D71:074006, 2005

$$< k_T^2 > = 0.25\, GeV^2 \Longrightarrow$$

Global fit of existing Cahn effect measurements (2005)

Pions

Hydrogen data

$\cos 2\phi_h$

Barone, Melis, Prokudin
Phys. Rev. D81:114026, 2010

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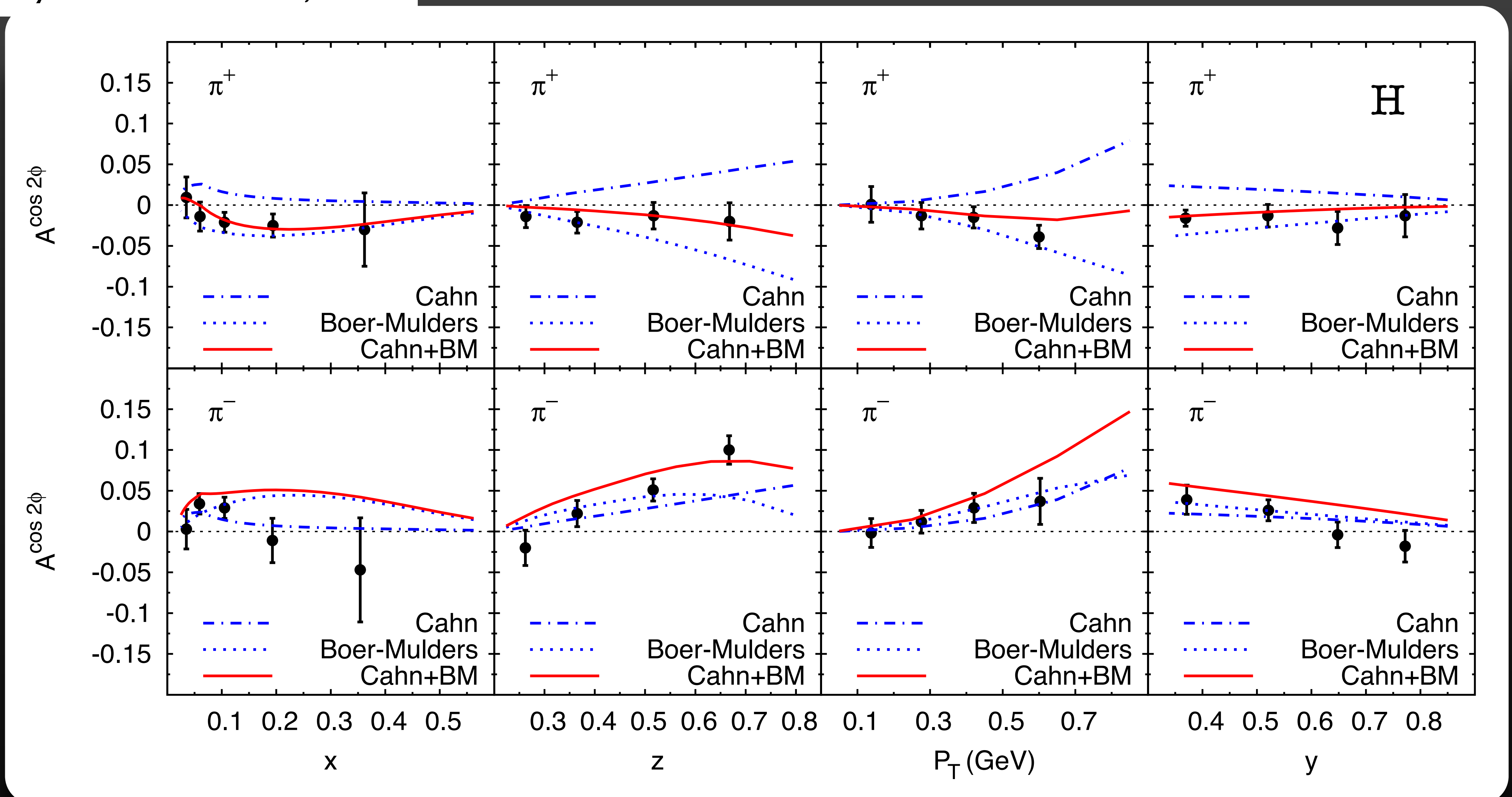


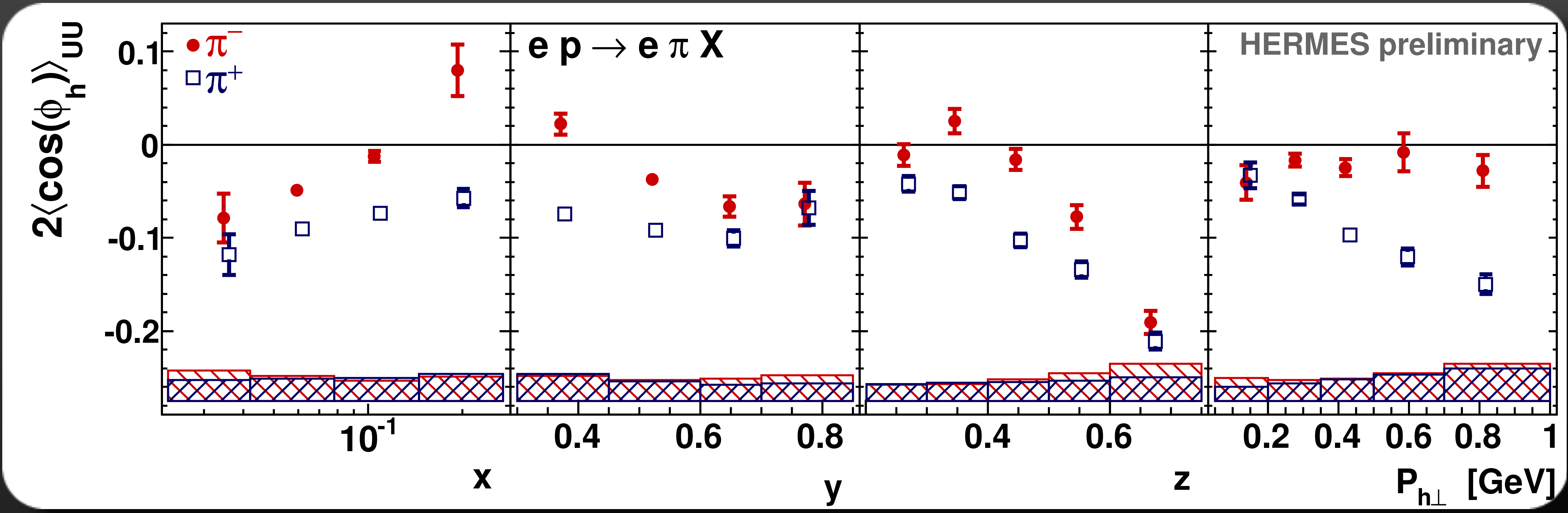
$$< k_T^2 > = 0.18\, GeV^2$$

Extracted from a parametrization of HERMES $P_{h\perp}$ spectrum

$Pions$

$Hydrogen\ data$

$\cos\phi_h$



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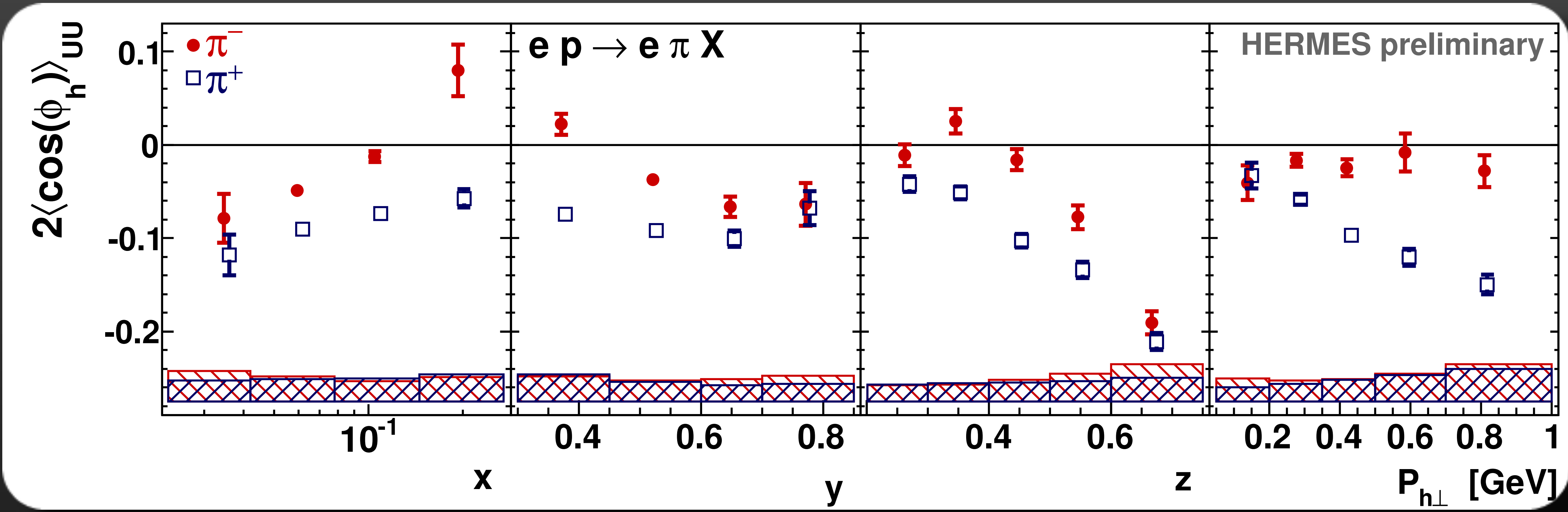

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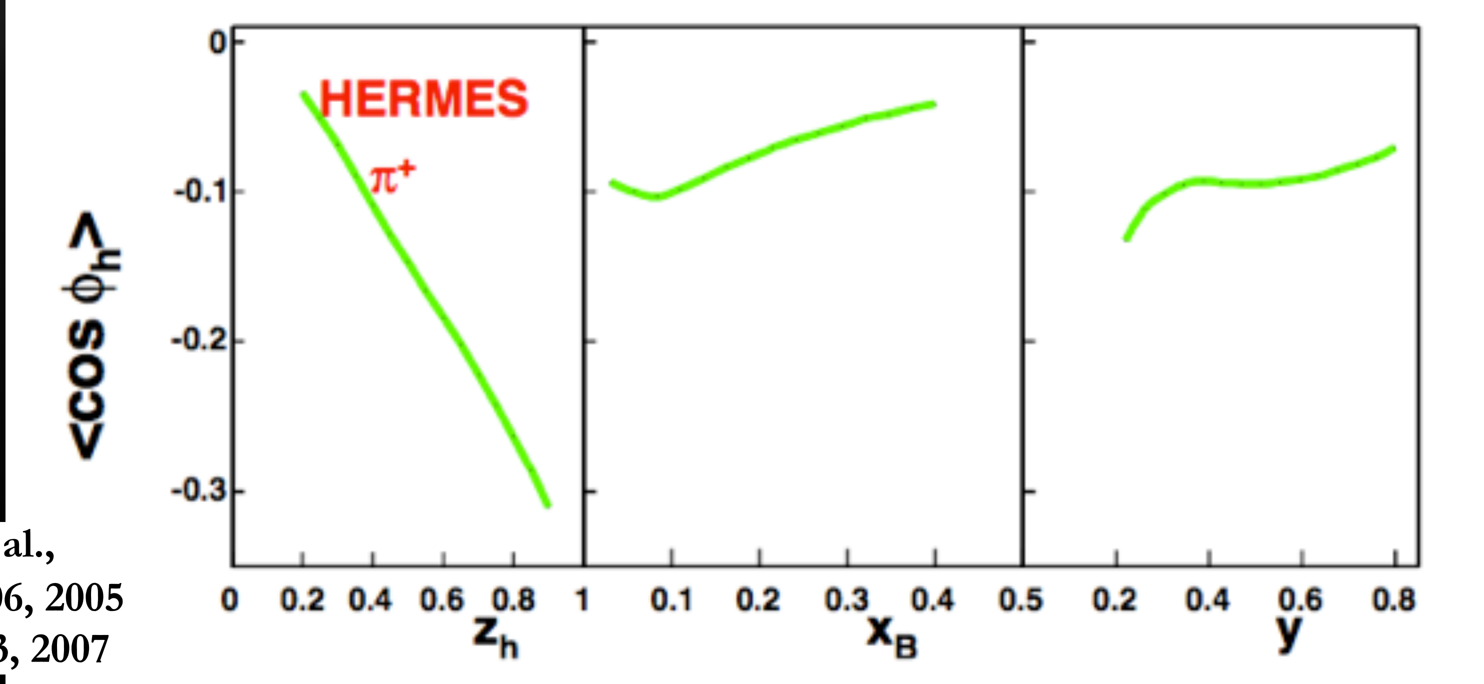
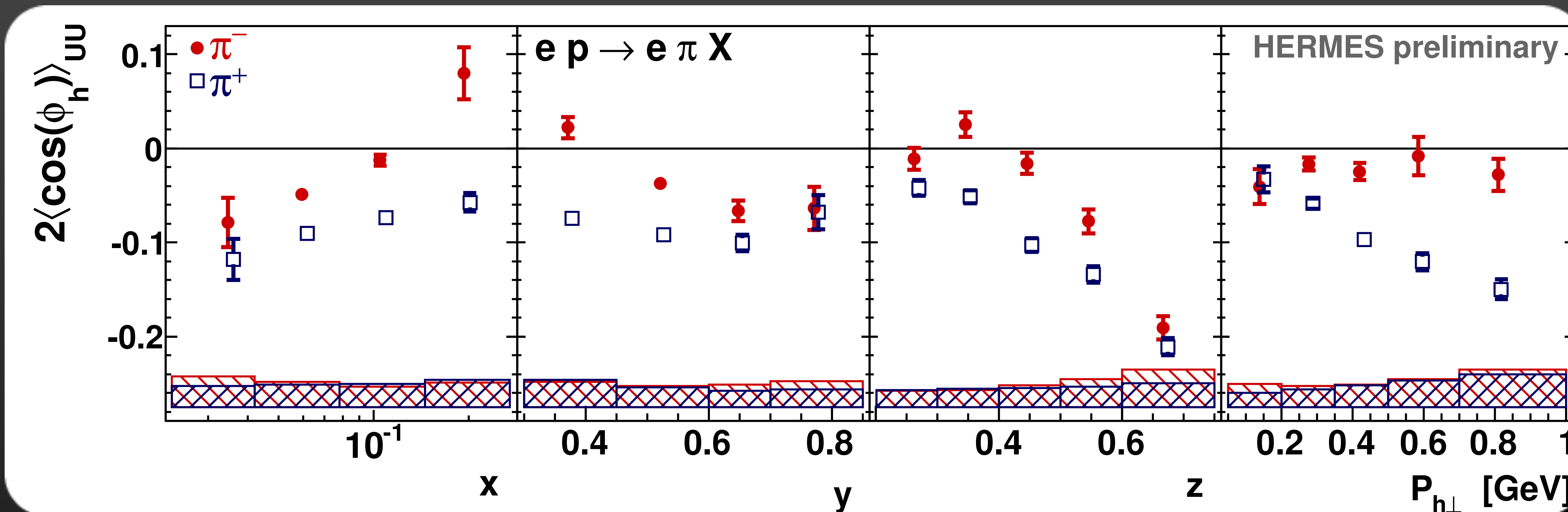


M. Anselmino et al.,
Phys. Rev. D71:074006, 2005
Eur. Phys. J. A31:373, 2007

Pions

Hydrogen data

$\cos\phi_h$



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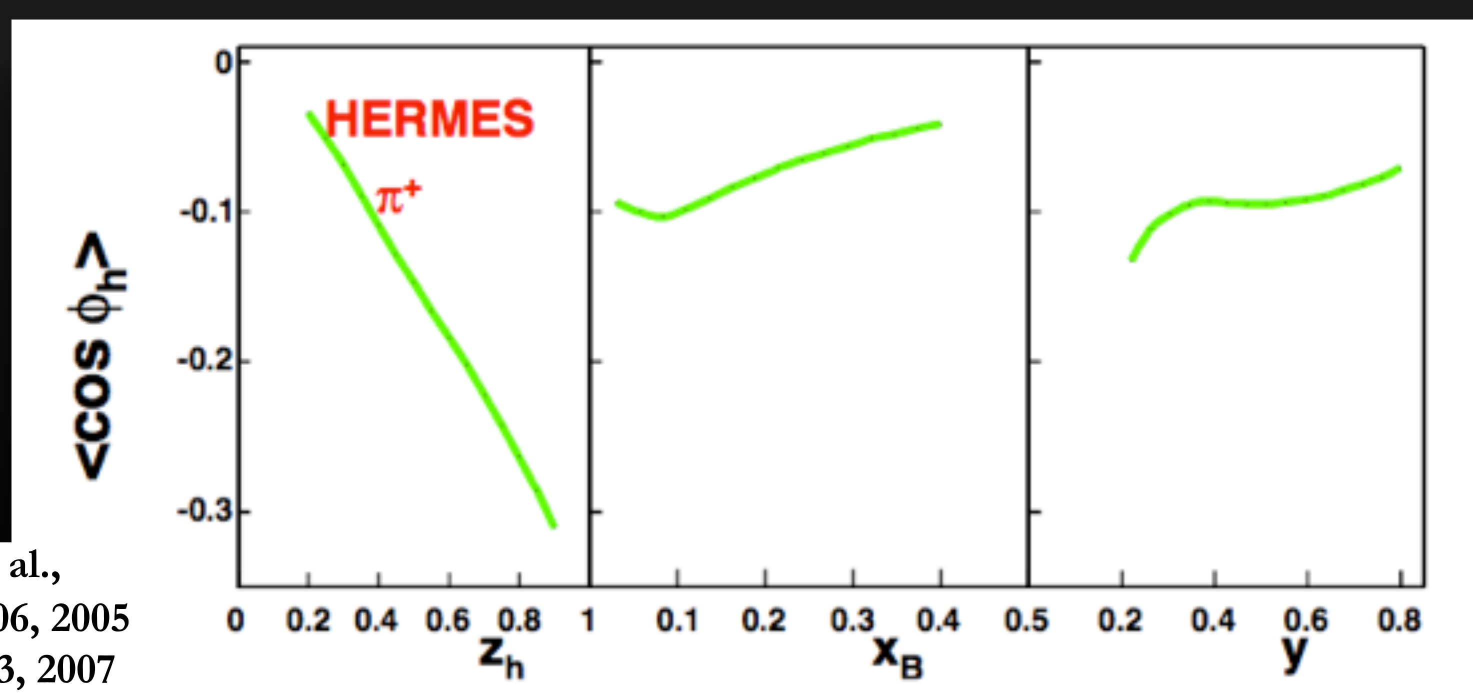

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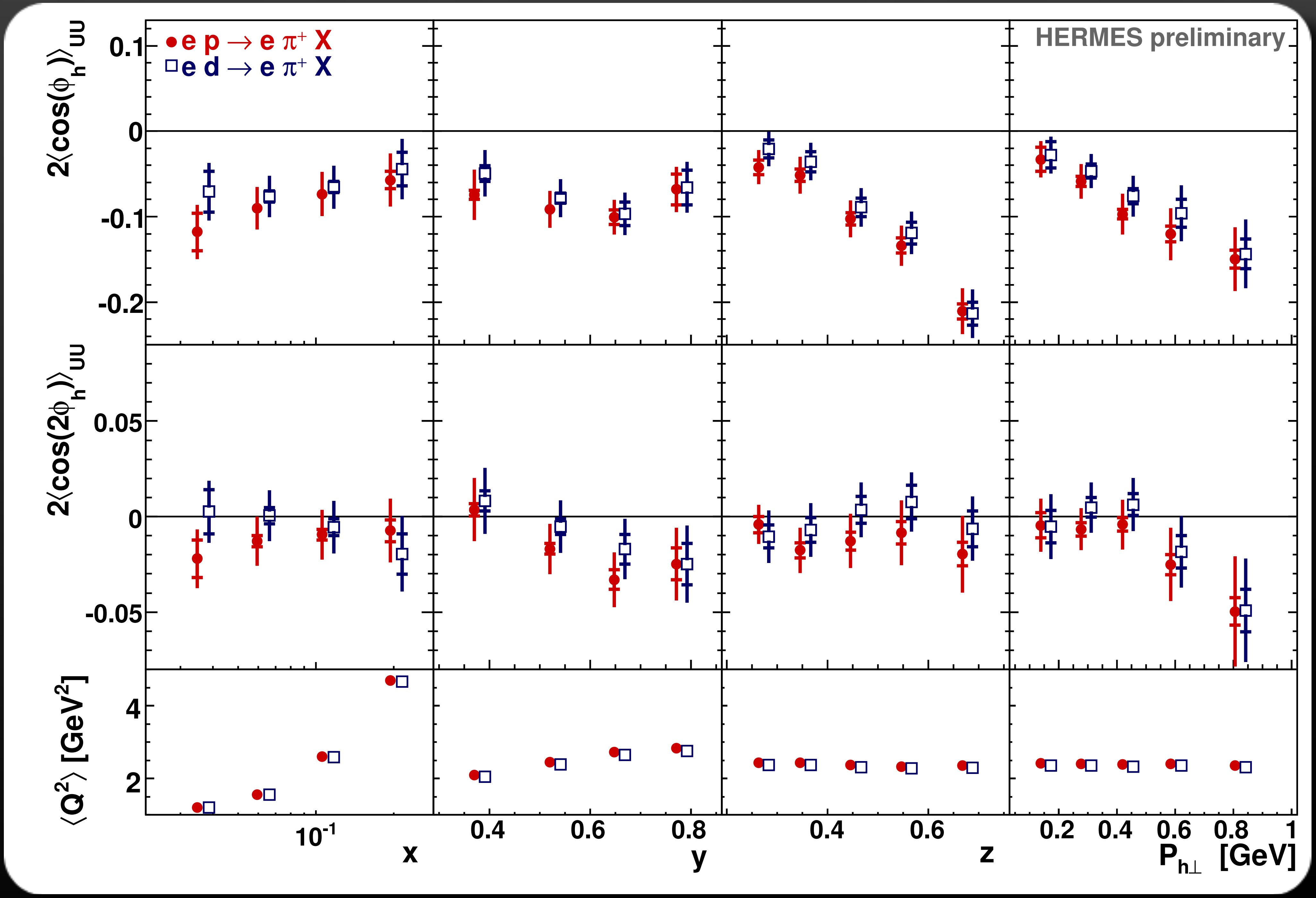
$Hydrogen\ \ vs.\ \ Deuterium$

π^+



Hydrogen vs. Deuterium

$$h_1^{\perp,u} \approx h_1^{\perp,d}$$

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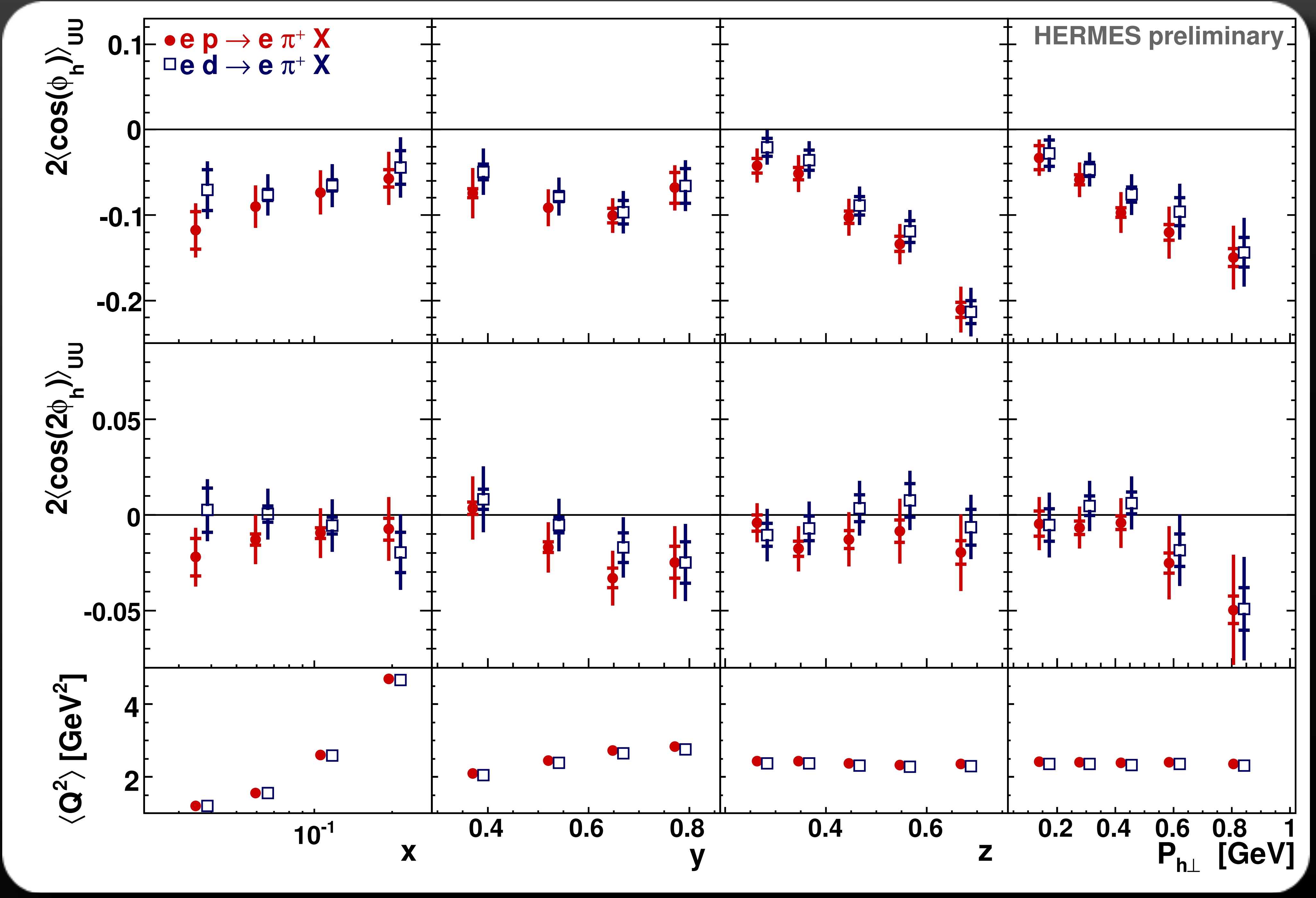

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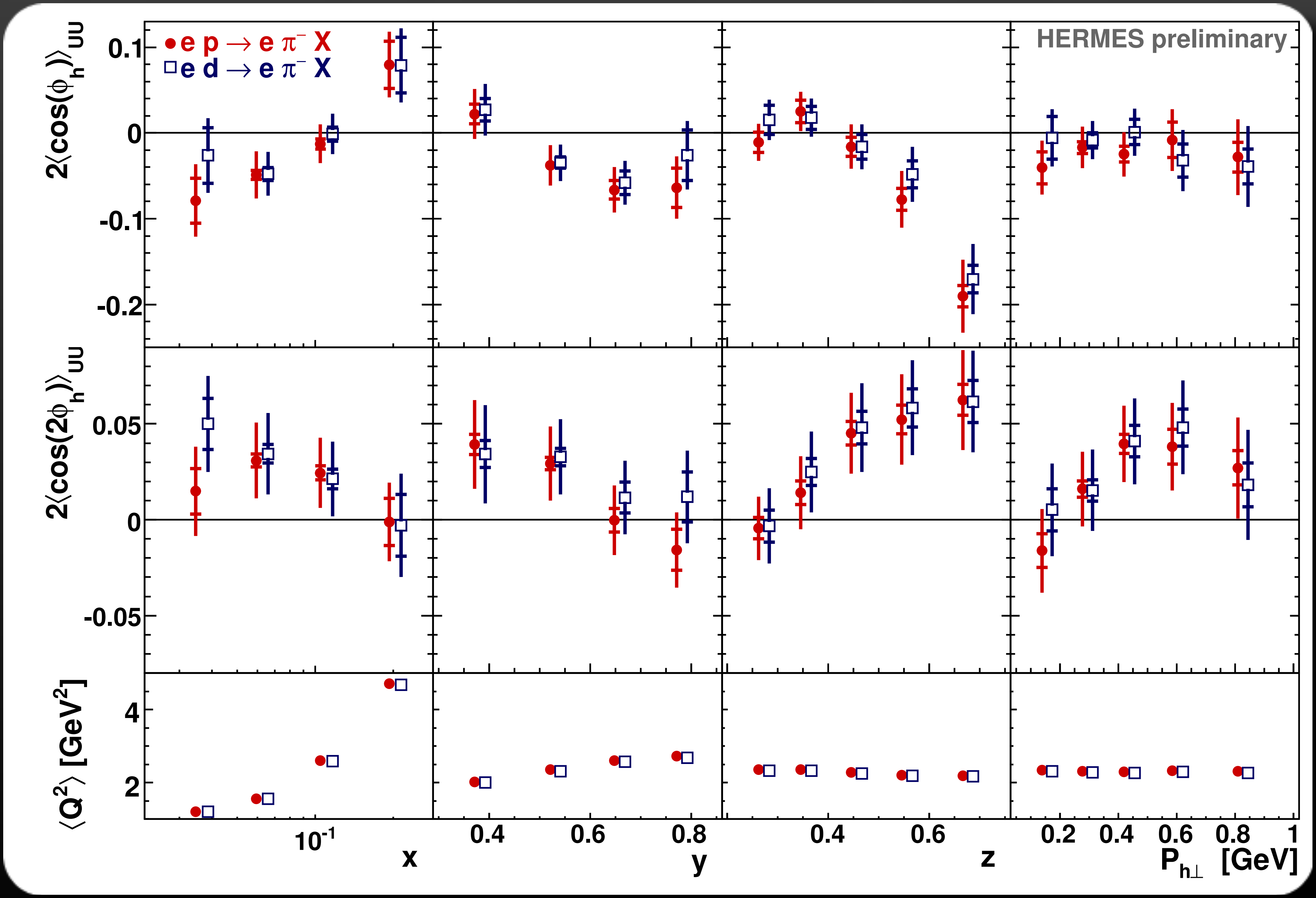
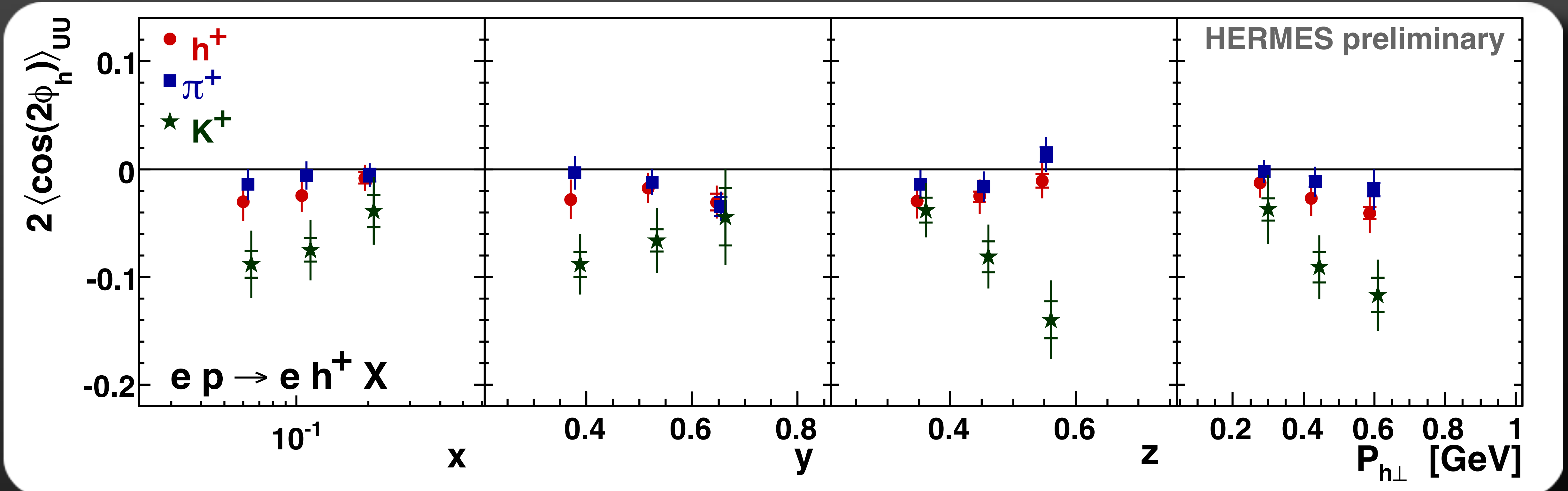
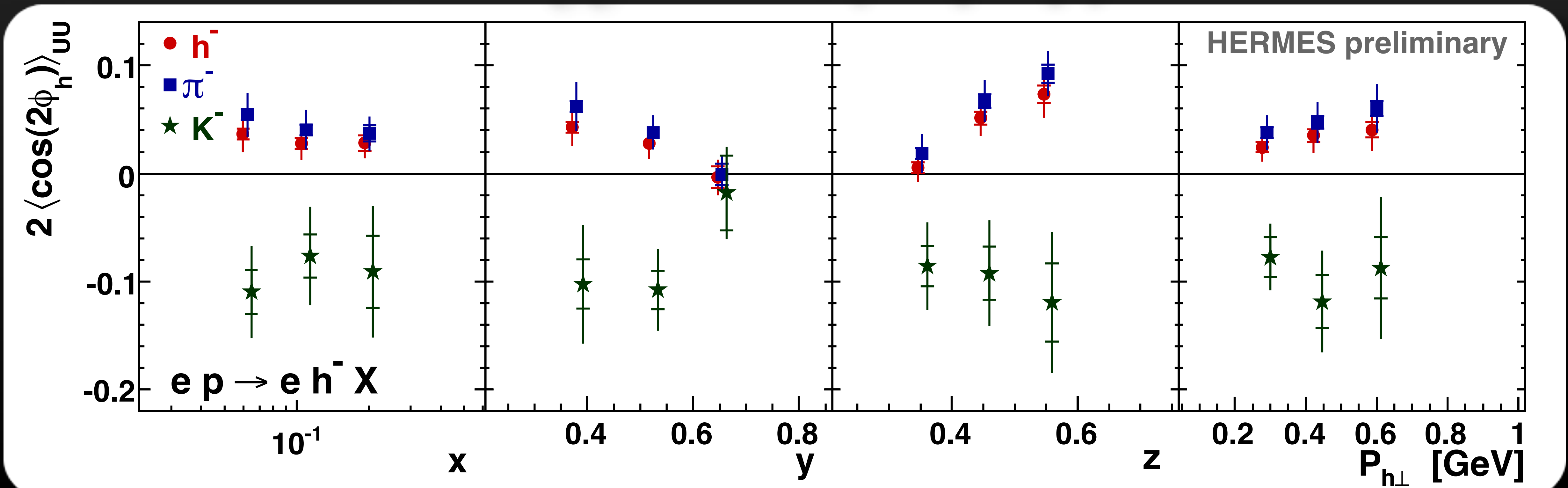


Kaons — *Hydrogen data* — $\cos 2\phi_h$



$$F_{UU}^{\cos 2\phi_h} \propto \mathcal{C}[-h_1^{\perp} H_1^{\perp}]$$



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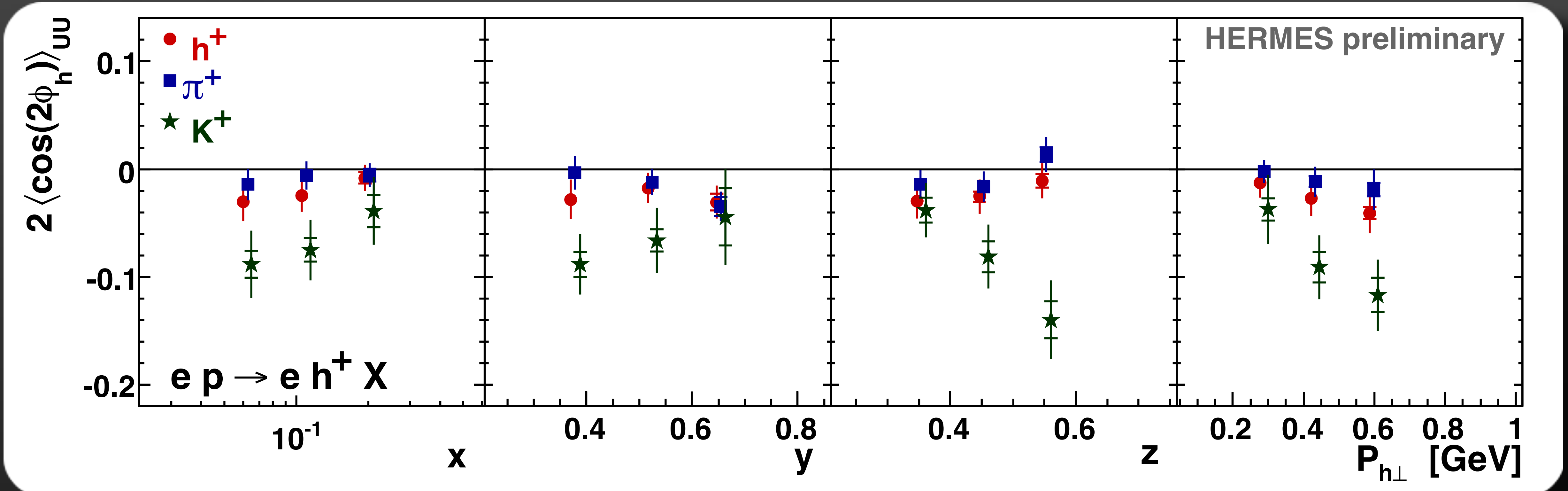
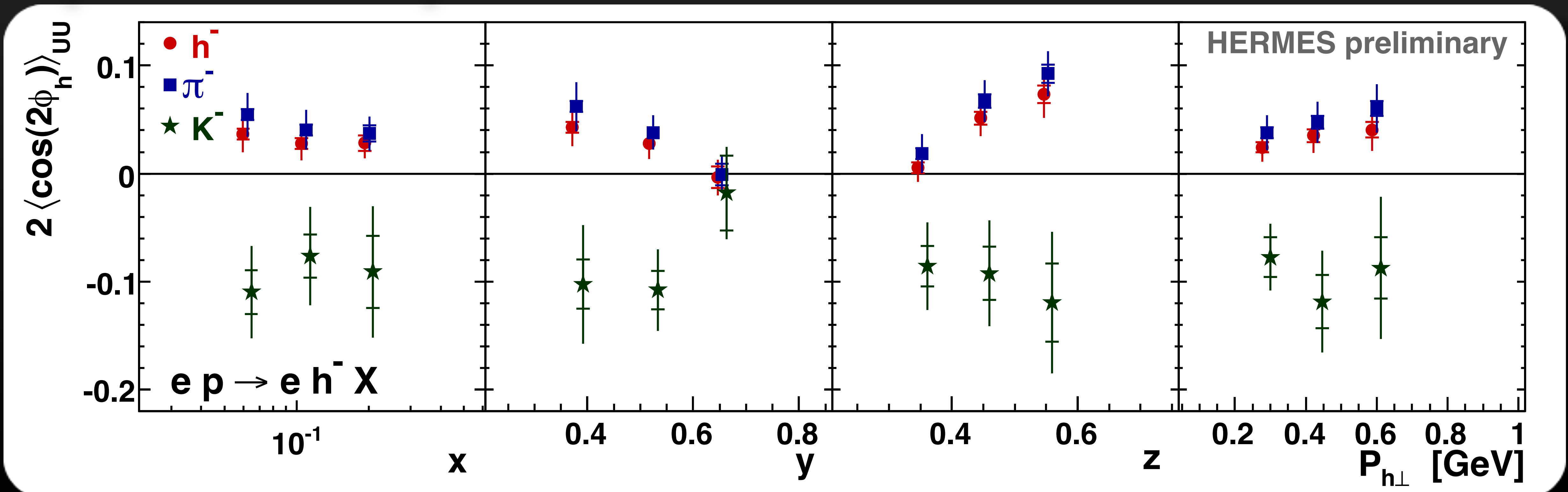
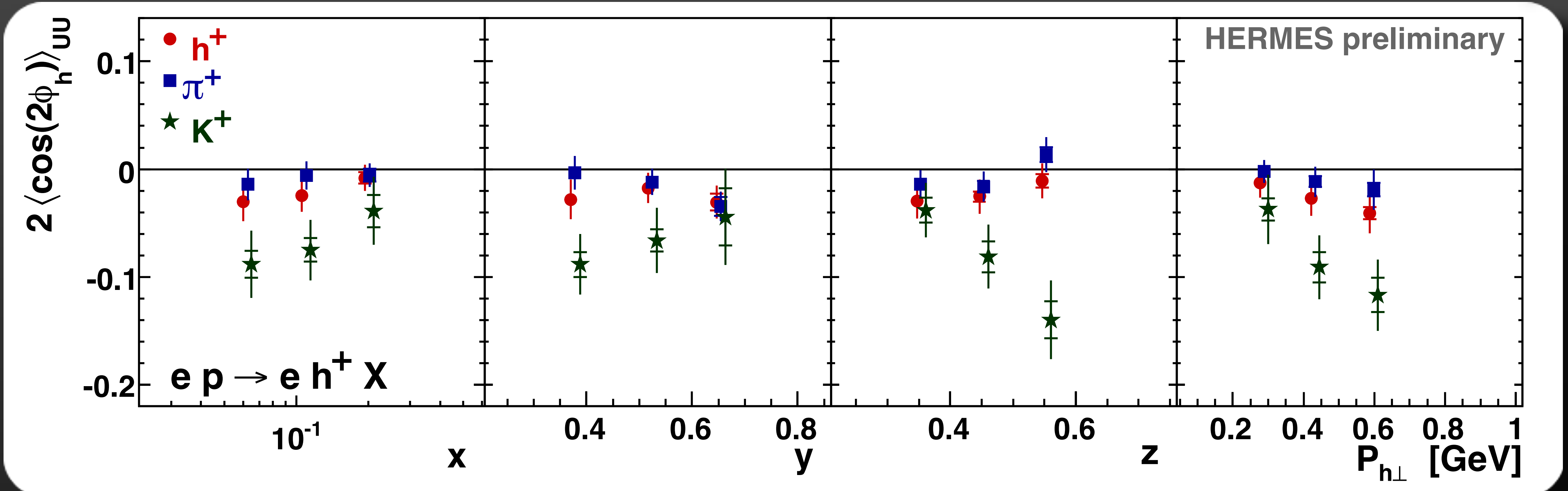


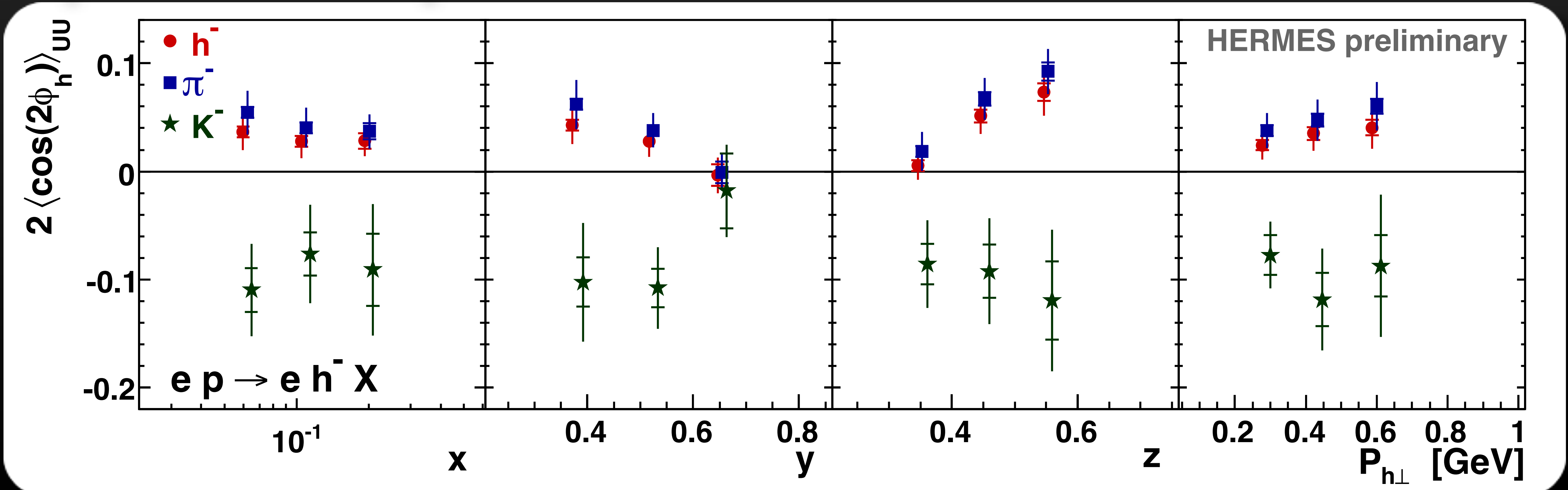
$$H_1^{\perp,u\to\pi^-} \approx -H_1^{\perp,u\to\pi^+}$$



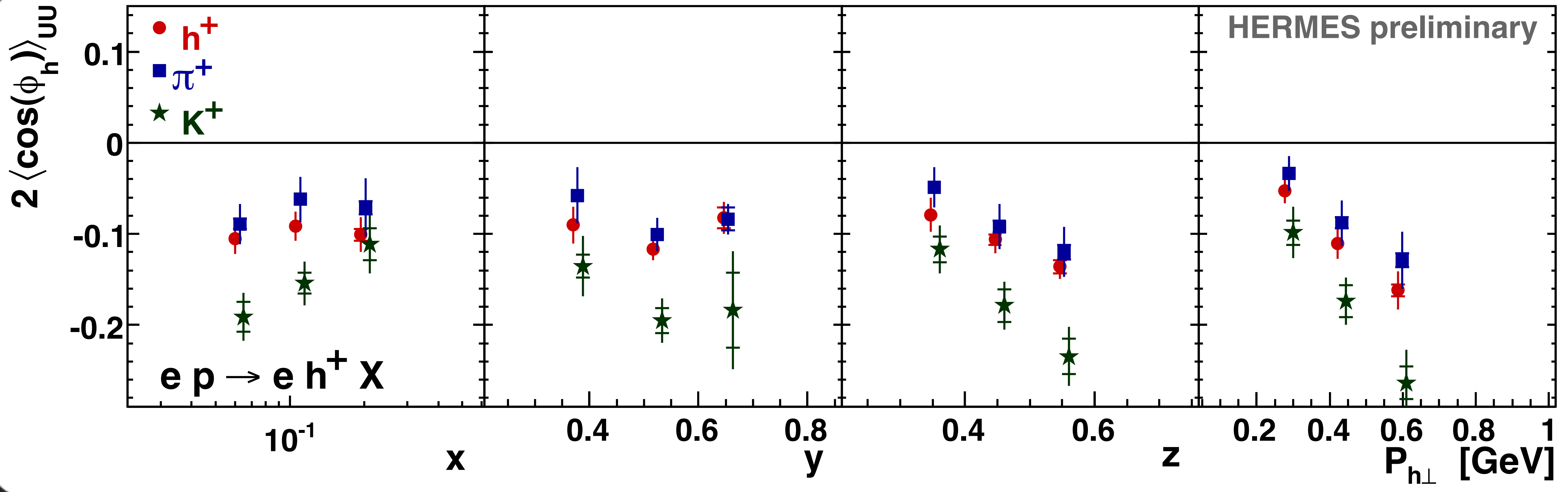
$Kaons$ $Hydrogen\ data$ $\cos 2\phi_h$



$$H_1^{\perp,u\to\pi^-} \approx -H_1^{\perp,u\to\pi^+} \qquad H_1^{\perp,u\to K^-} \overset{?}{\approx} H_1^{\perp,u\to K^+}$$



Kaons *Hydrogen data* $\cos\phi_h$



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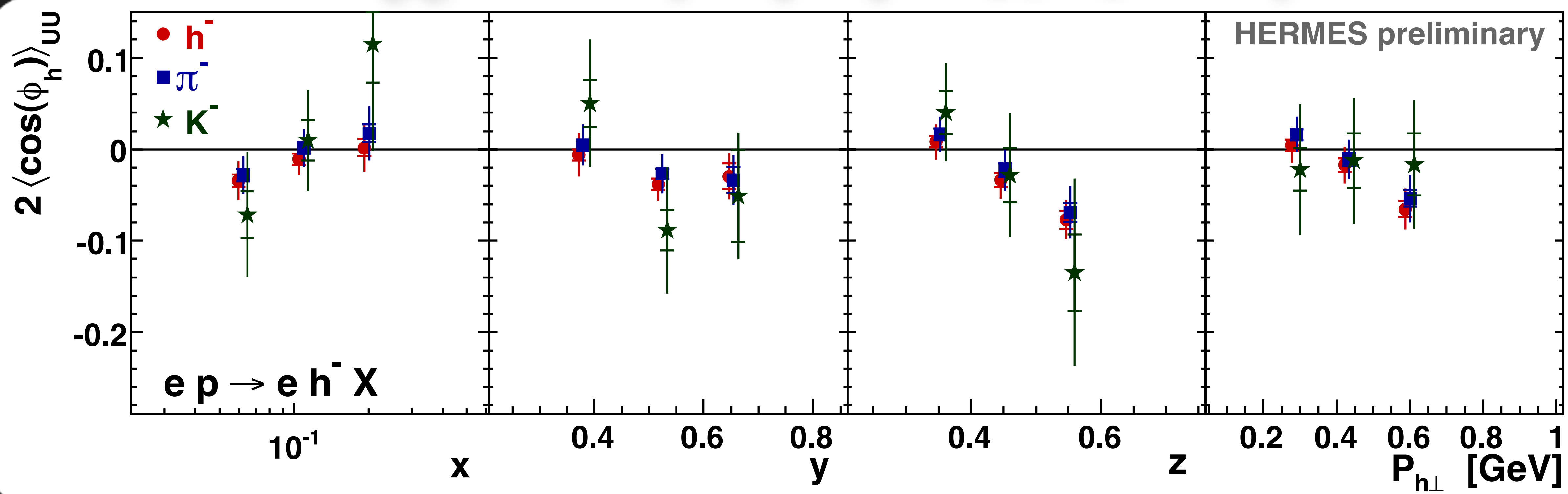
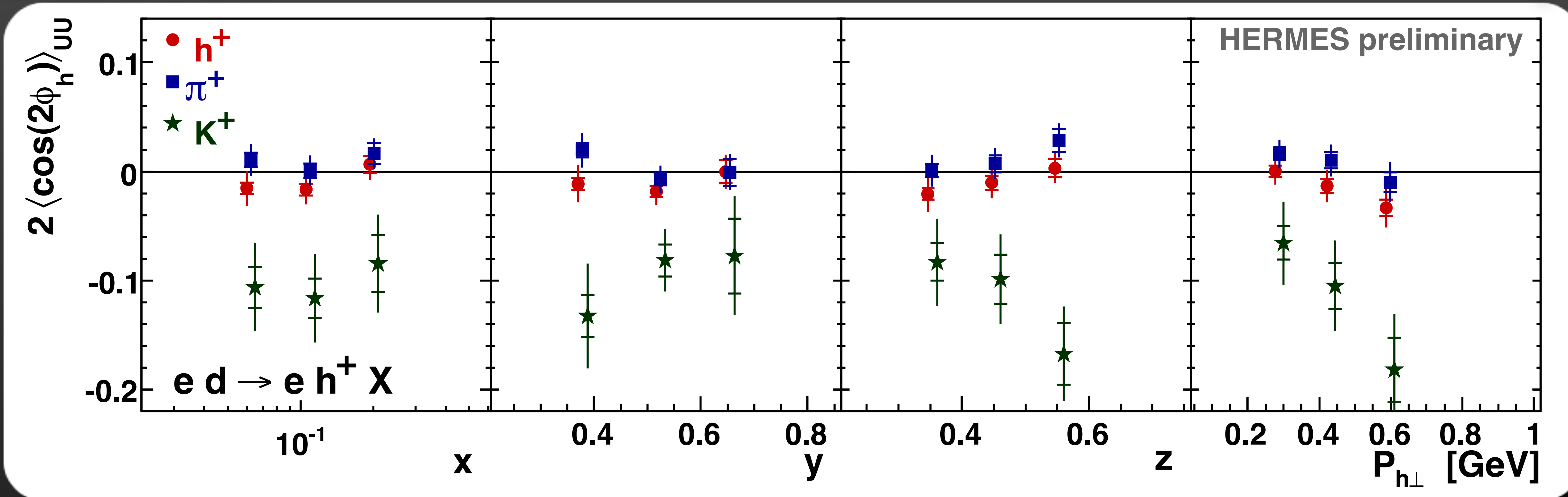


Kaons *Deuterium data* $\cos 2\phi_h$



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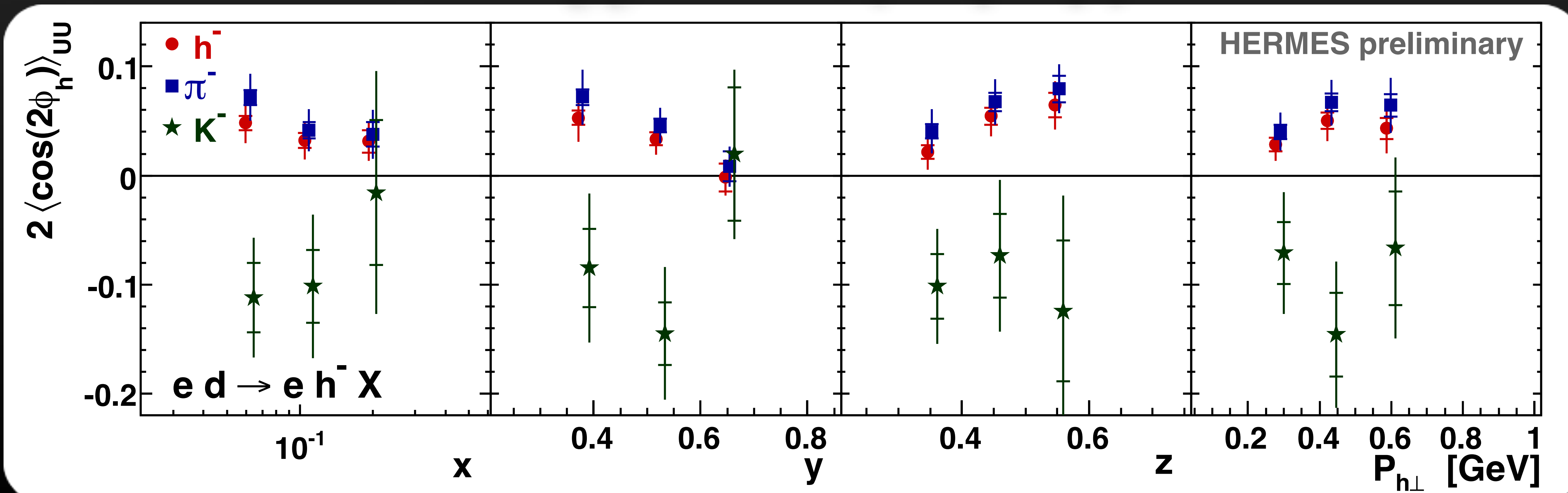
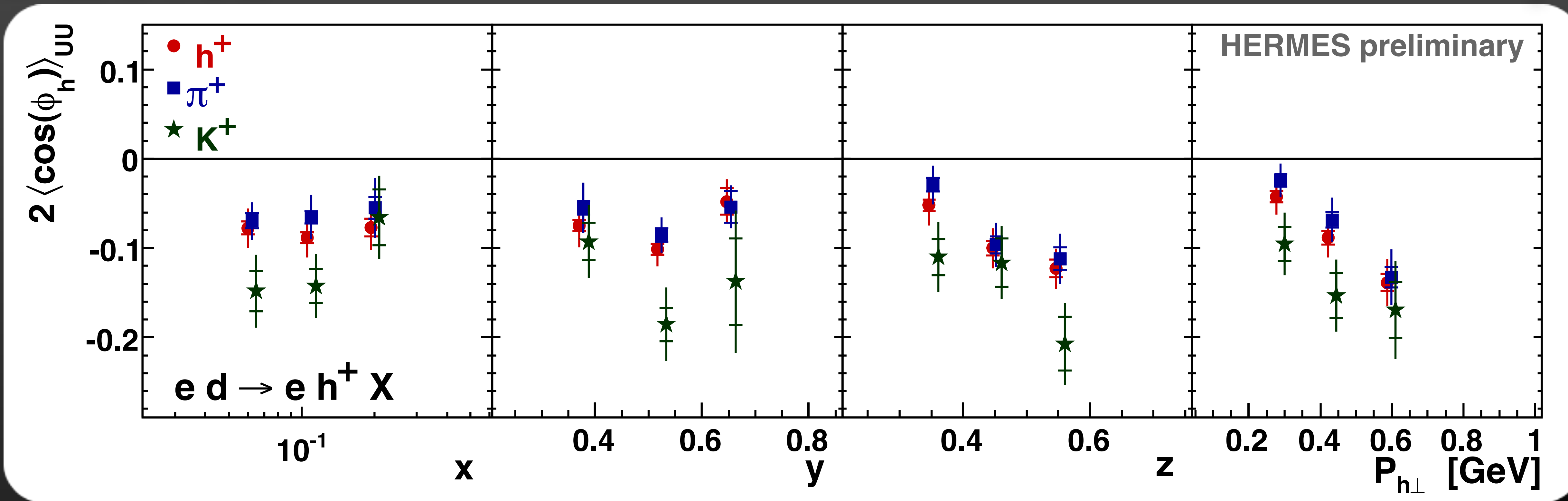


Kaons — *Deuterium data* — $\cos\phi_h$



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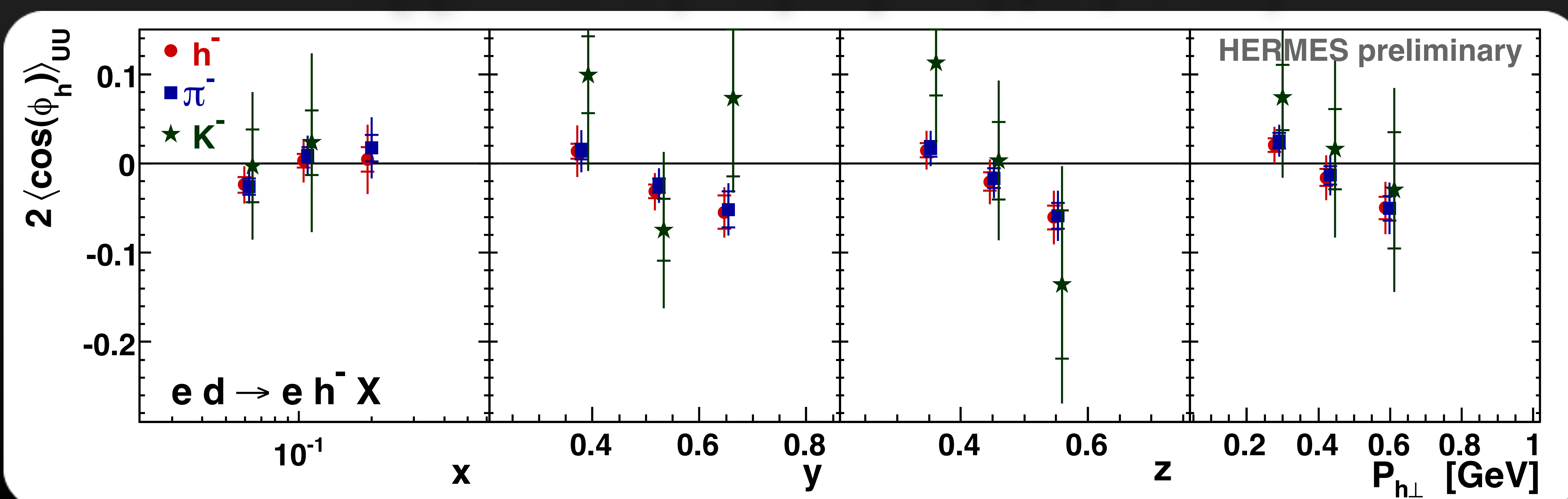

First flavor dependent measurement of cosine amplitudes in DIS reactions !

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- $\cos 2\phi_h$:
  - opposite sign between π^+/π^-
    - evidence of a non-zero Boer-Mulders function
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  - similar results for deuterium & hydrogen data
    - suggest a Boer-Mulders function with same sign for *u* and *d* quarks
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Thank you

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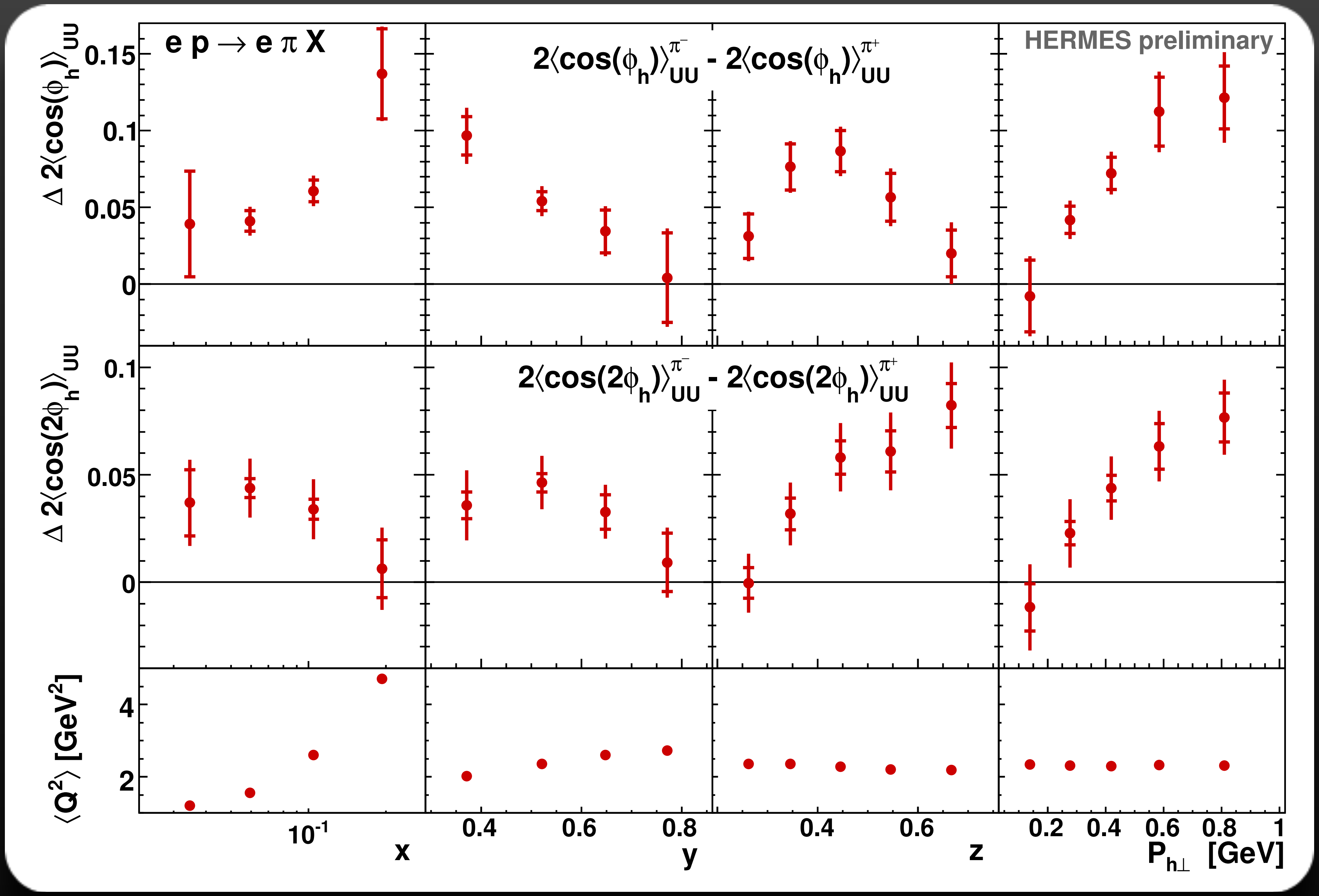
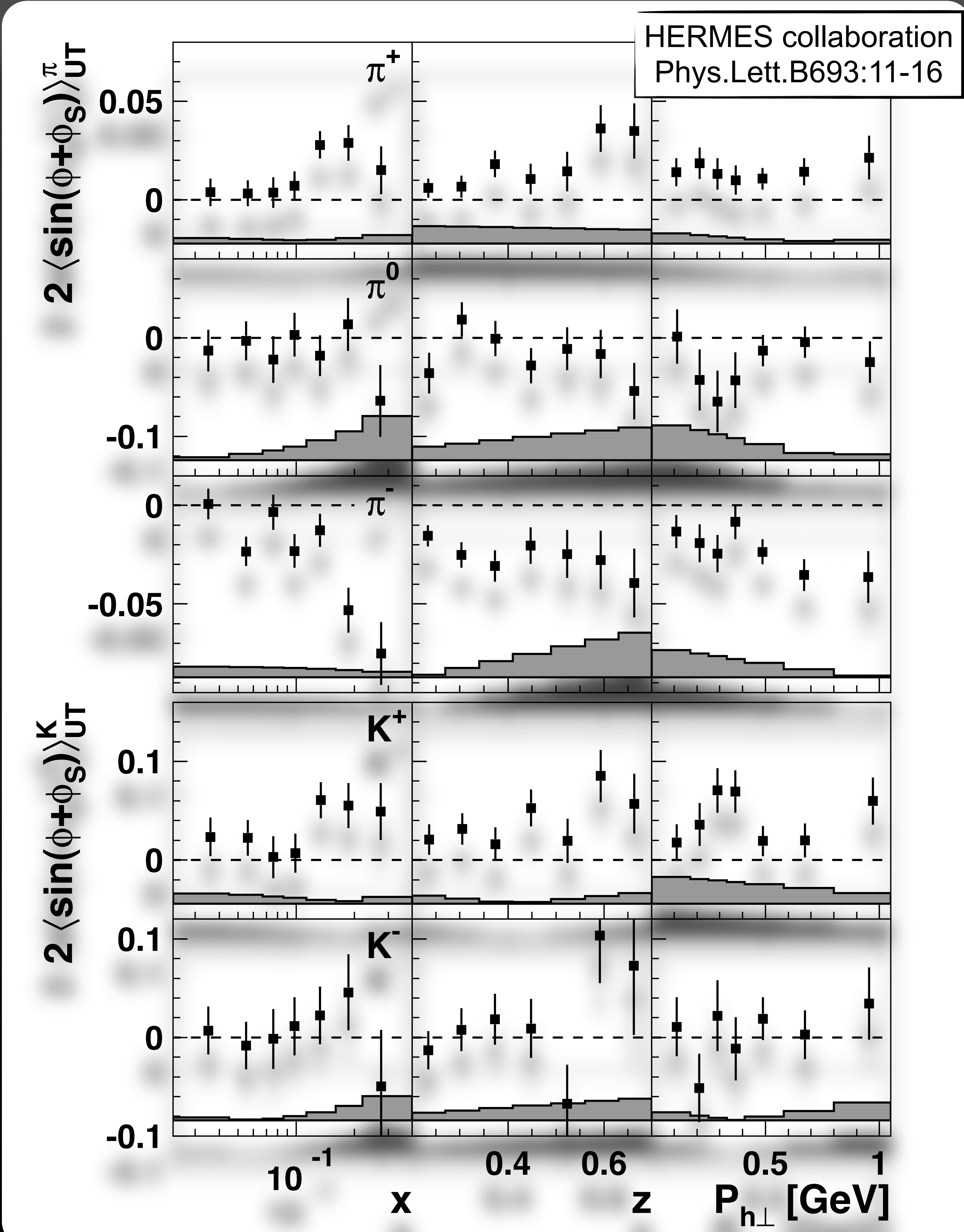
Pions difference





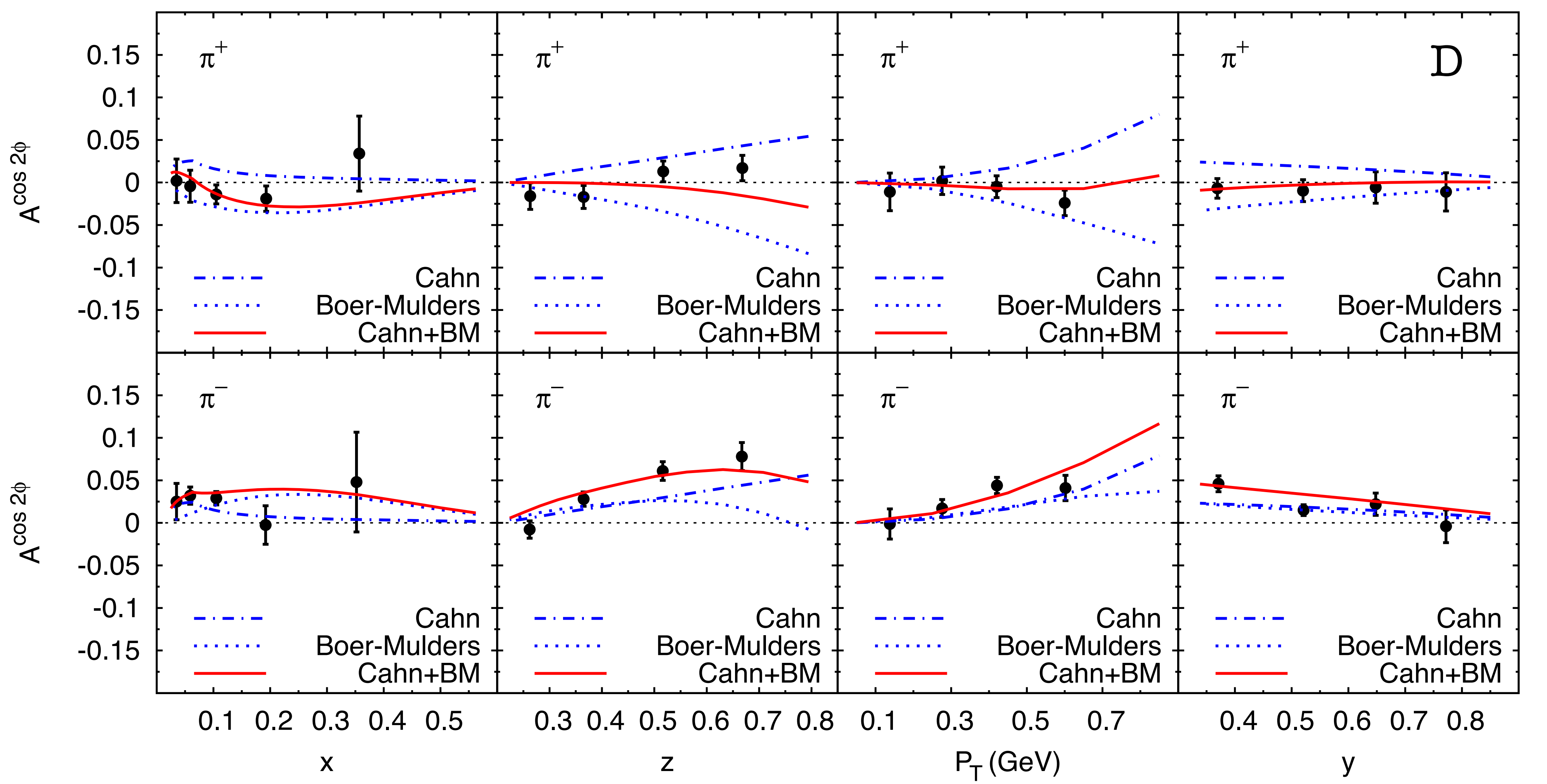
Collins effect

$$\propto C[h_1 H_1^{\perp}]$$

Pions

$\cos 2\phi_h$

Barone, Melis, Prokudin
Phys. Rev. D81:114026,



*

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$Pions$

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COMPASS data