TRANSVERSITY 2011
Third International Workshop on
TRANSVERSE POLARIZATION PHENOMENA IN HARD SCATTERING
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Veli Lošinj, Croatia

ECSAC
European Centre for Science Arts and Culture

TMDs in semi-inclusive DIS off unpolarized targets

--the hermes perspective--

ikerbasque
Basque Foundation for Science

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eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Leading-twist TMDs

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

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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helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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  - non-collinear kinematics lead to cosine modulations in semi-inclusive DIS cross section ("Cahn effect")

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  - belongs to special class of **naive-T-odd** PDFs -> sign reversal from DIS to DY
  - violation of Lam-Tung relation in Drell-Yan already hints at non-vanishing Boer-Mulders function

Cross section without polarization

target polarization

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

beam polarization

virtual-photon polarization

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right)\left\{\boxed{F_{UU,T} + \epsilon F_{UU,L}}\right\}$$

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093

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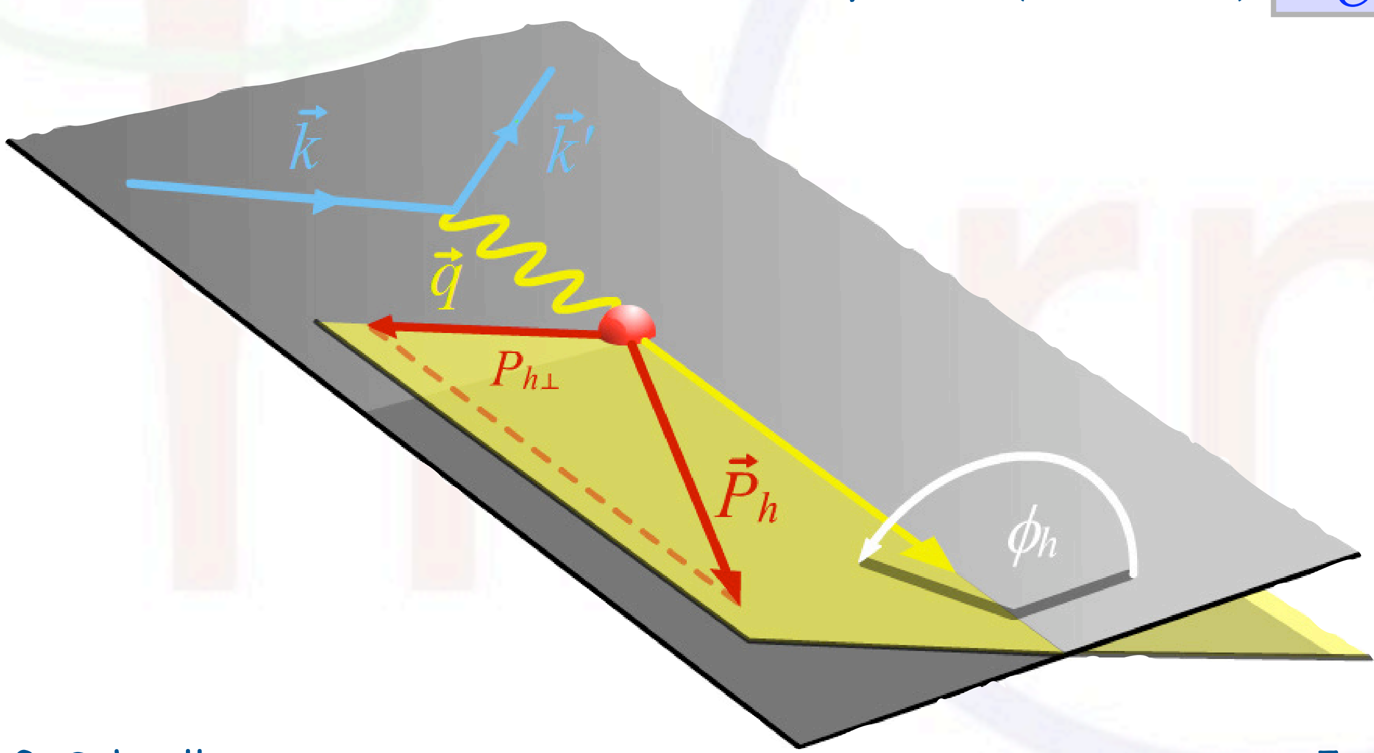

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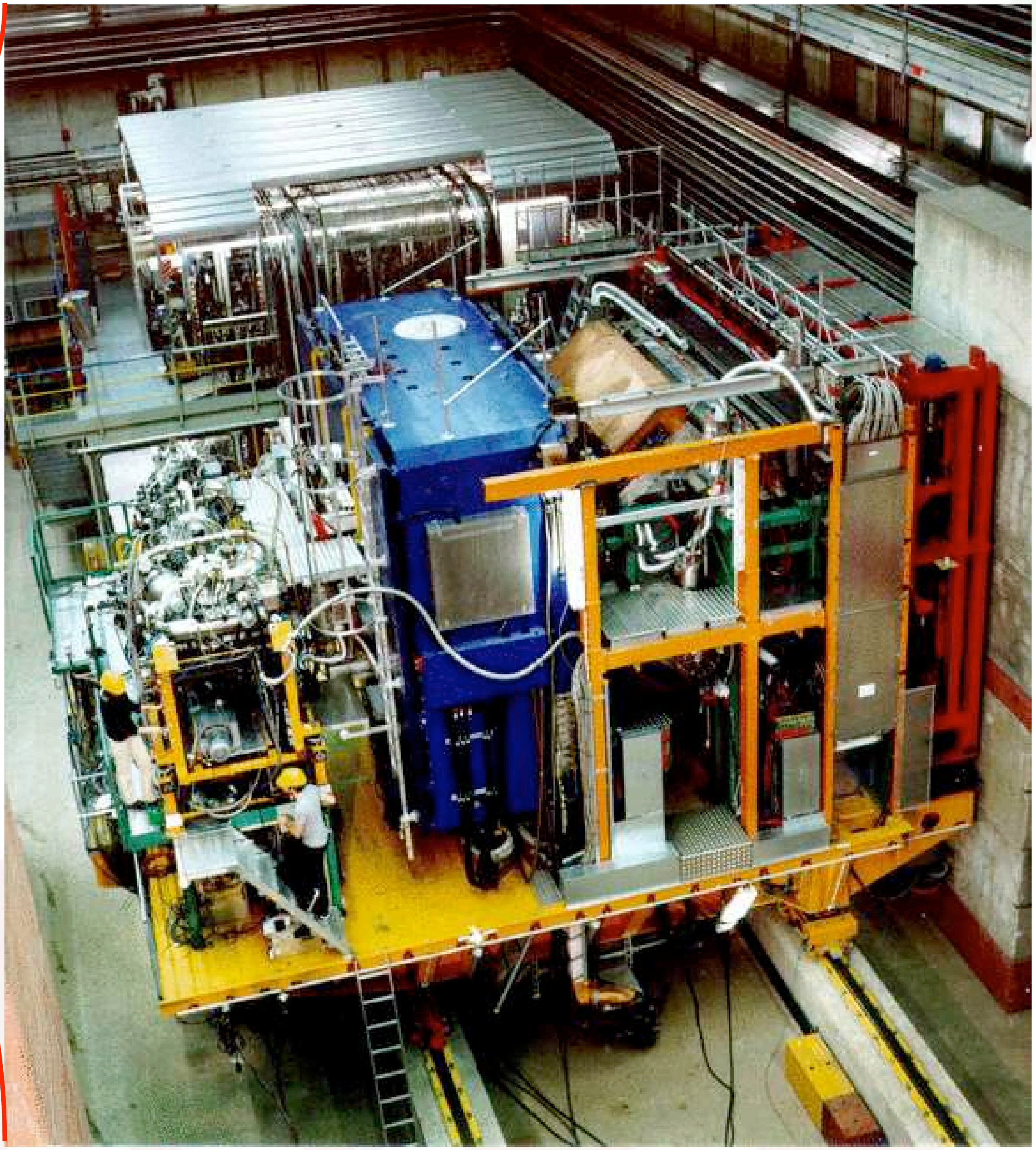
Some **experimental** challenges ...

- pure targets
- large acceptance
- excellent particle identification
- no spin asymmetry -> few systematics cancel
  - efficiencies
  - absolute luminosity
  - acceptance
  - smearing

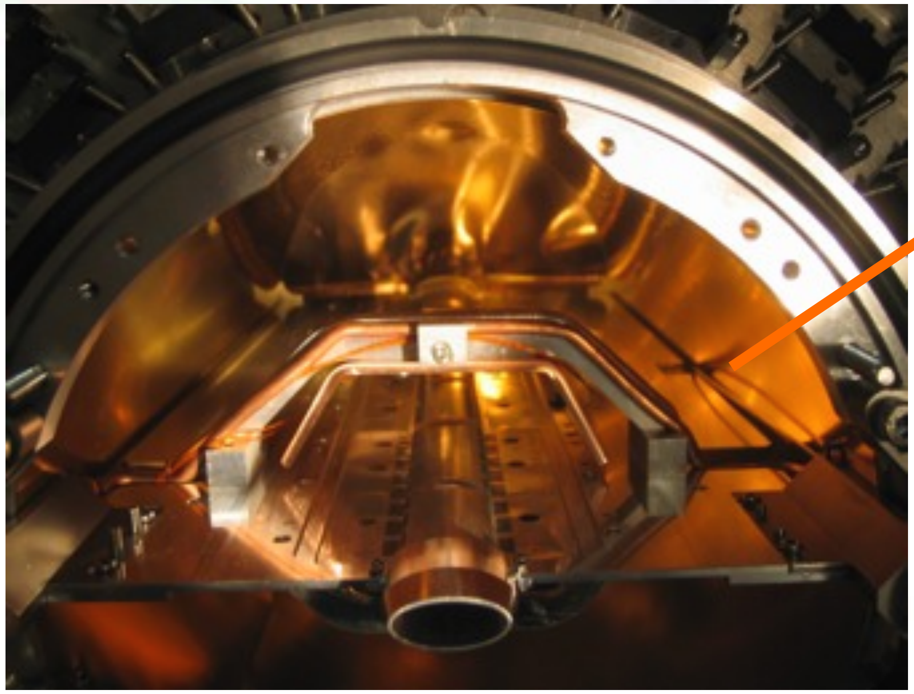
The HERMES Experiment

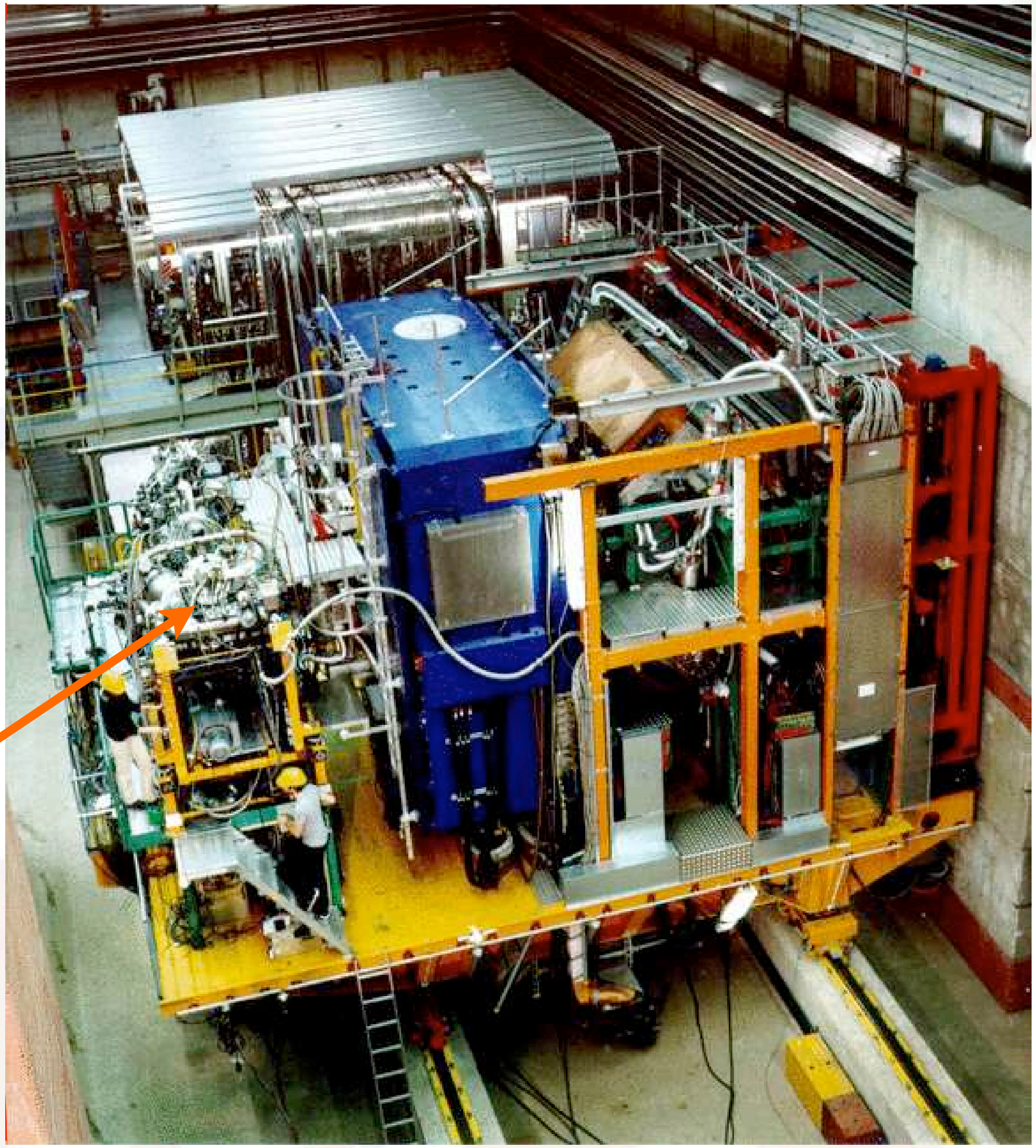
27.5 GeV e^+/e^- beam of HERA



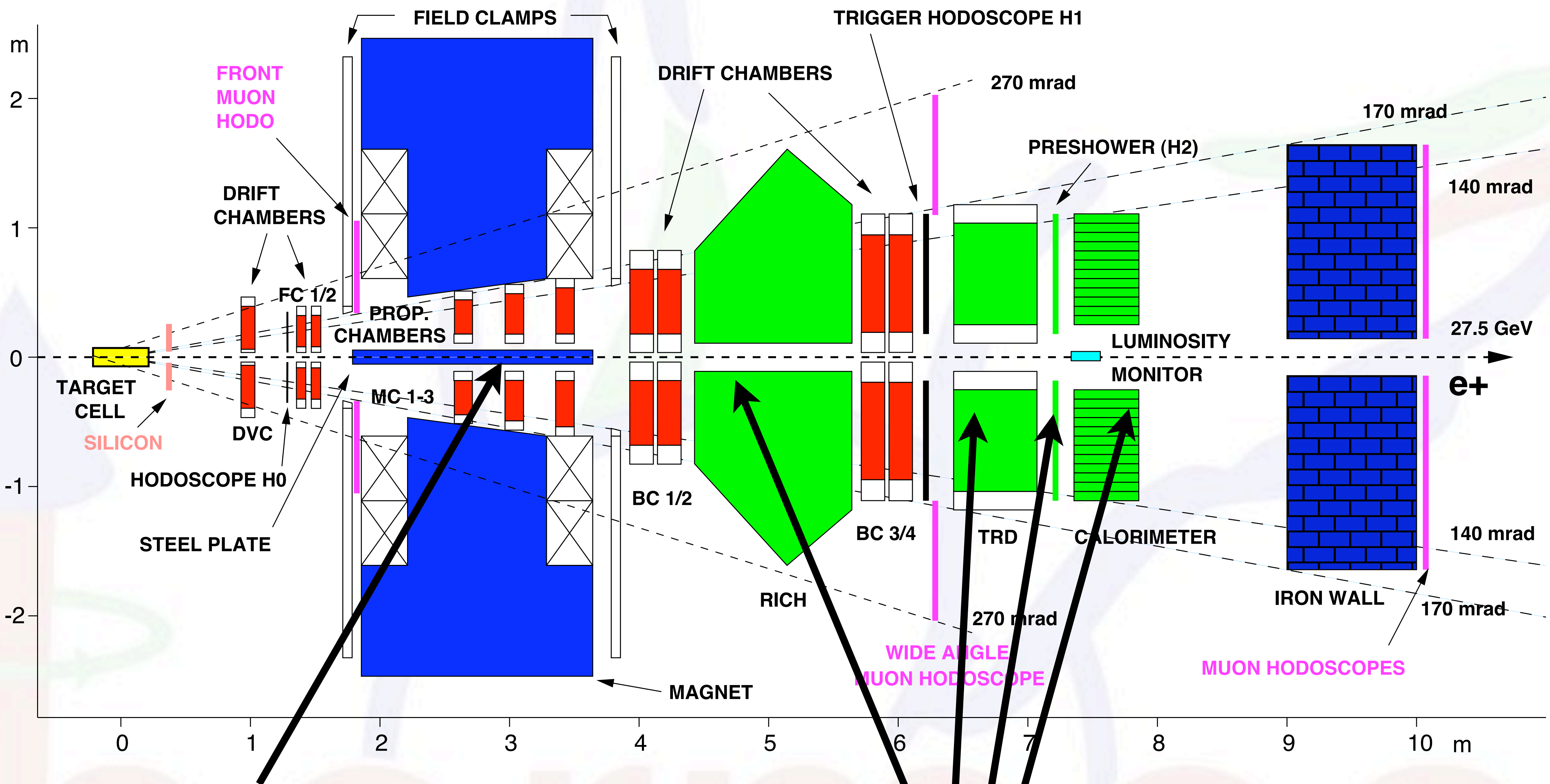
The HERMES Experiment

- pure gas targets
- internal to lepton ring
- unpolarized (^{1}H … Xe)
- longitudinal polarized: ^{1}H, ^{2}H
- transversely polarized: ^{1}H





… and solutions



two (mirror-symmetric) halves
-> no homogenous azimuthal coverage

Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

… and solutions …

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

… and solutions …

hadron multiplicity:
normalize to inclusive DIS cross section

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$$\frac{d^2\sigma^{\mathrm{incl.DIS}}}{dx\,dy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dx\,dy\,dz\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon F_{UU,L}}{F_T+\epsilon F_L}$$

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$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

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$$2\langle\cos 2\phi\rangle_{UU} \equiv 2\frac{\int d\phi_h \cos 2\phi\, d\sigma}{\int d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

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$$\boxed{\approx \epsilon\frac{\sum_q e_q^2\; h_1^{\perp,q}(x,p_T^2)\otimes_{\mathrm{BM}} H_1^{\perp,q\to h}(z,K_T^2)}{\sum_q e_q^2\; f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}}$$

moments:
normalize to azimuth-independent cross-section

… geometric acceptance …

extract acceptance from Monte Carlo simulation:

$$\epsilon(\phi, \Omega) = \frac{\epsilon(\phi, \Omega)\sigma_{UU}(\phi, \Omega)}{\sigma_{UU}(\phi, \Omega)} \qquad \Omega = x, y, z, ..$$

simulated acceptance

simulated cross section

… geometric acceptance …

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$$\epsilon(\phi,\Omega) = \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} \neq \frac{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)}$$

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"Aus Differenzen und Summen kürzen nur die Dummen."

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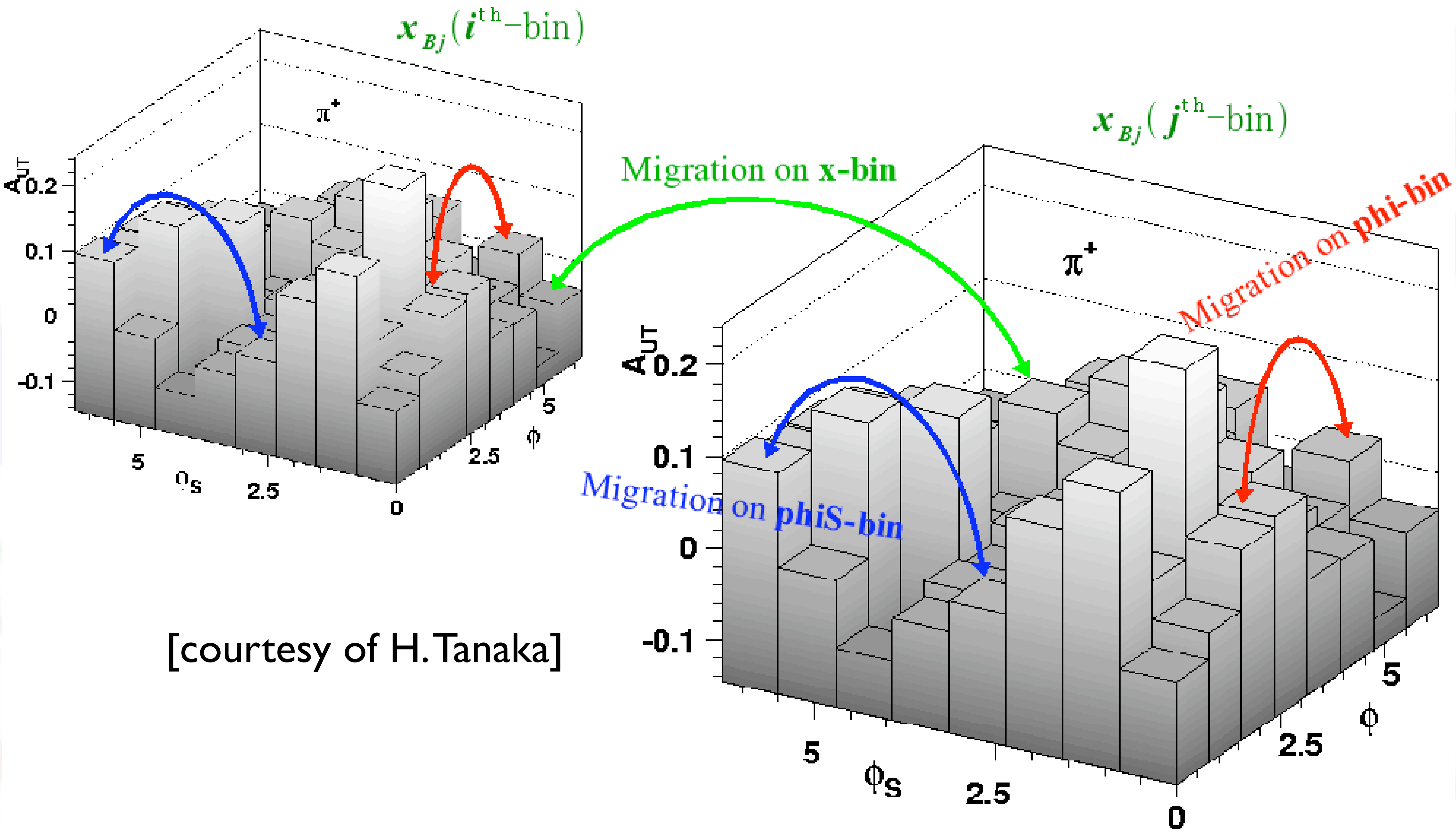
$$\neq \int \mathrm{d}\Omega\, \epsilon(\phi,\Omega) \equiv \epsilon(\phi)$$

$$\Omega = x, y, z, \ldots$$

"Aus Differenzen und Summen kürzen nur die Dummen."

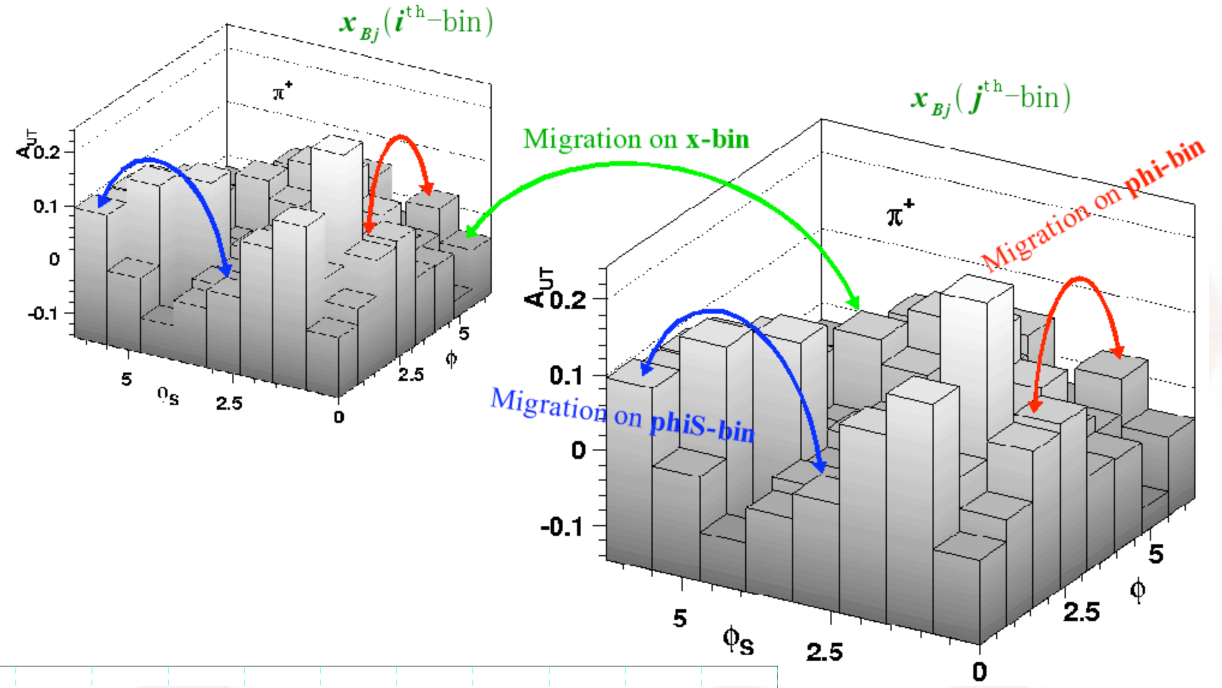
Cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!

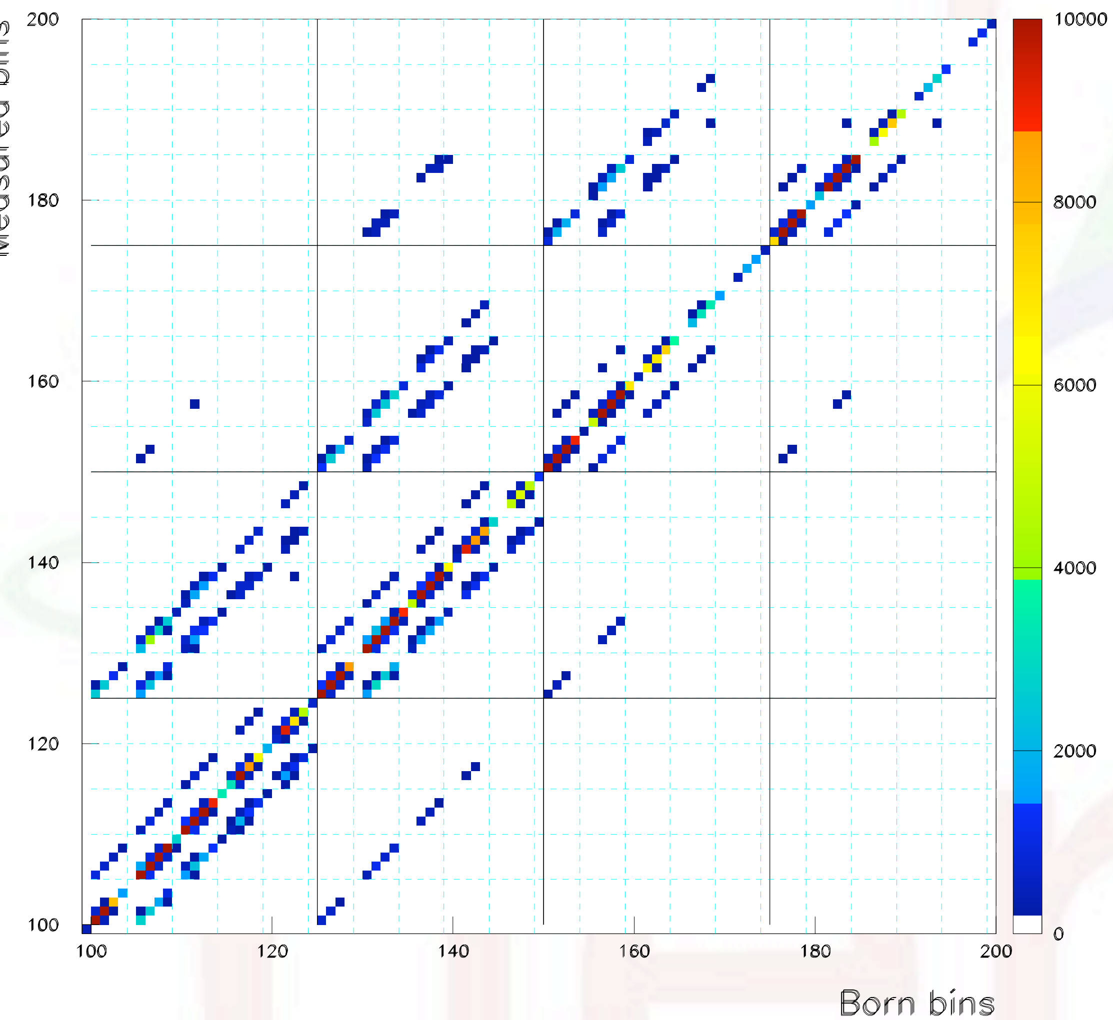
… event migration …

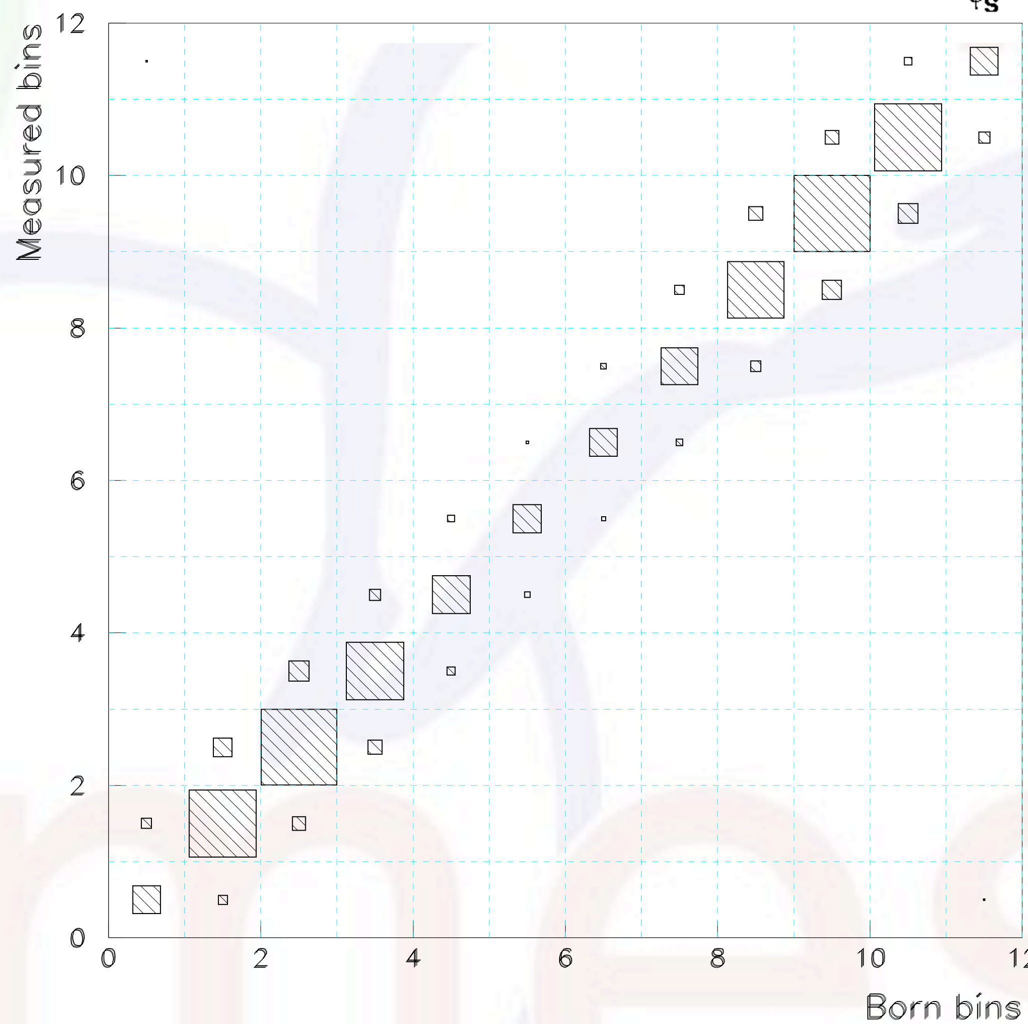


[courtesy of H. Tanaka]

… event migration …







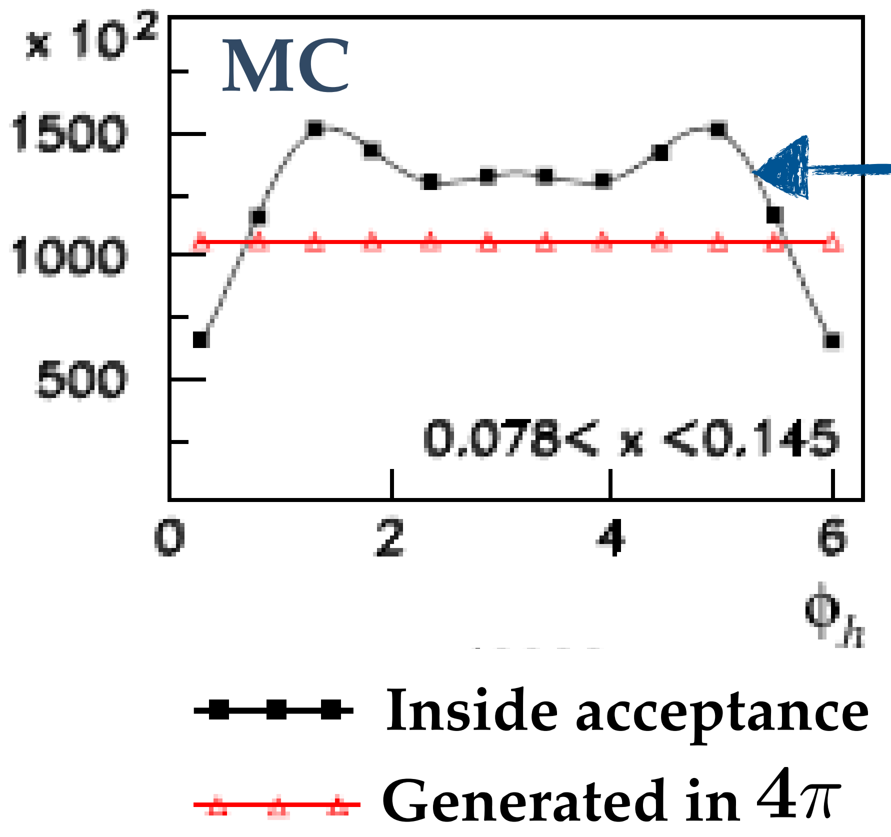
- migration correlates yields in different bins
- can't be corrected in bin-by-bin approach

… event migration -> unfolding

$$\mathcal{Y}^{\rm exp}(\Omega_i) \propto \sum_{j=1}^{N} S_{ij} \int_j d\Omega\, d\sigma(\Omega) + \mathcal{B}(\Omega_i)$$

- experimental yield in i^{th} bin depends on all Born bins j
- and on BG entering kinematic range from outside region
- smearing matrix S_{ij} determined from MC - independent of physics model in limit of infinitesimally small bins
- inversion gives Born cross section from measured yields
- in real life: dependence on BG and physics model due to finite bin sizes -> effects studied and found to be small @HERMES

Multi-D vs. 1D unfolding at work



simulated yield with clear cosine modulations from migration and acceptance

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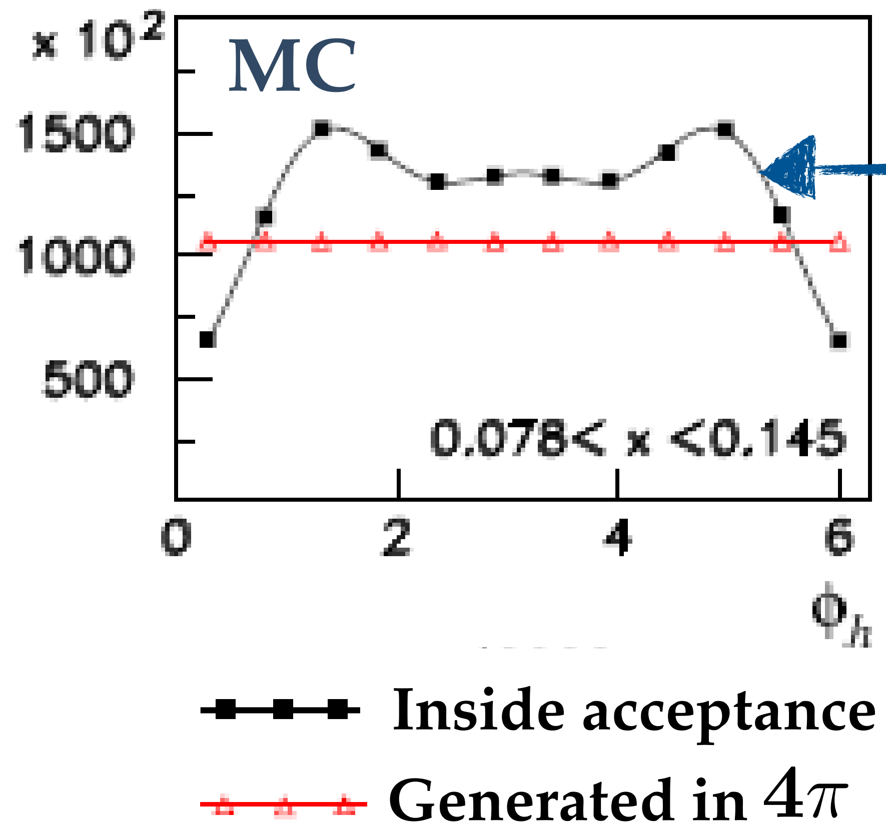

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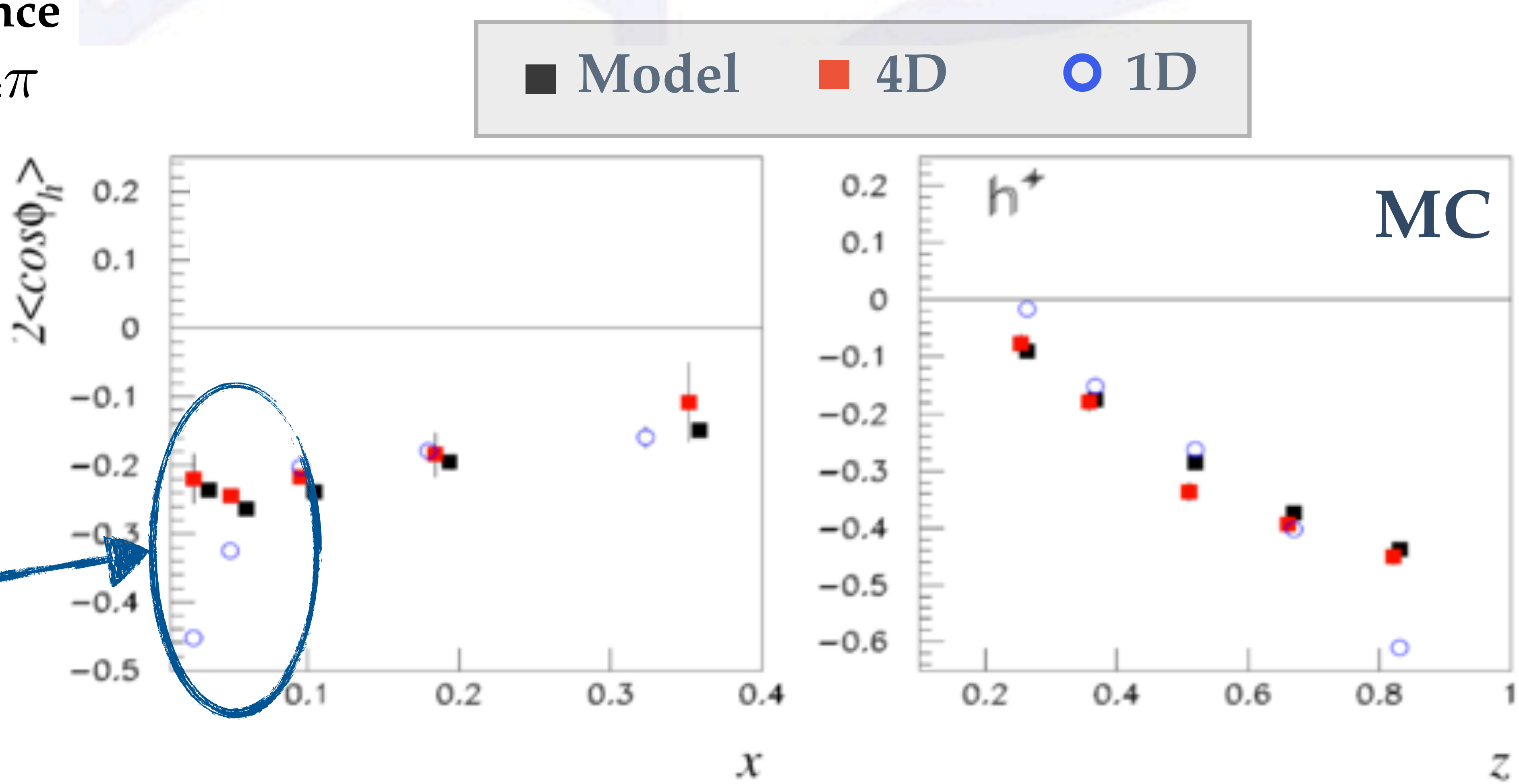

1D clearly not sufficient

Results

Influence from exclusive VM

$$ep \to ep\,\rho^0 \to ep\,\pi^+\pi^-$$

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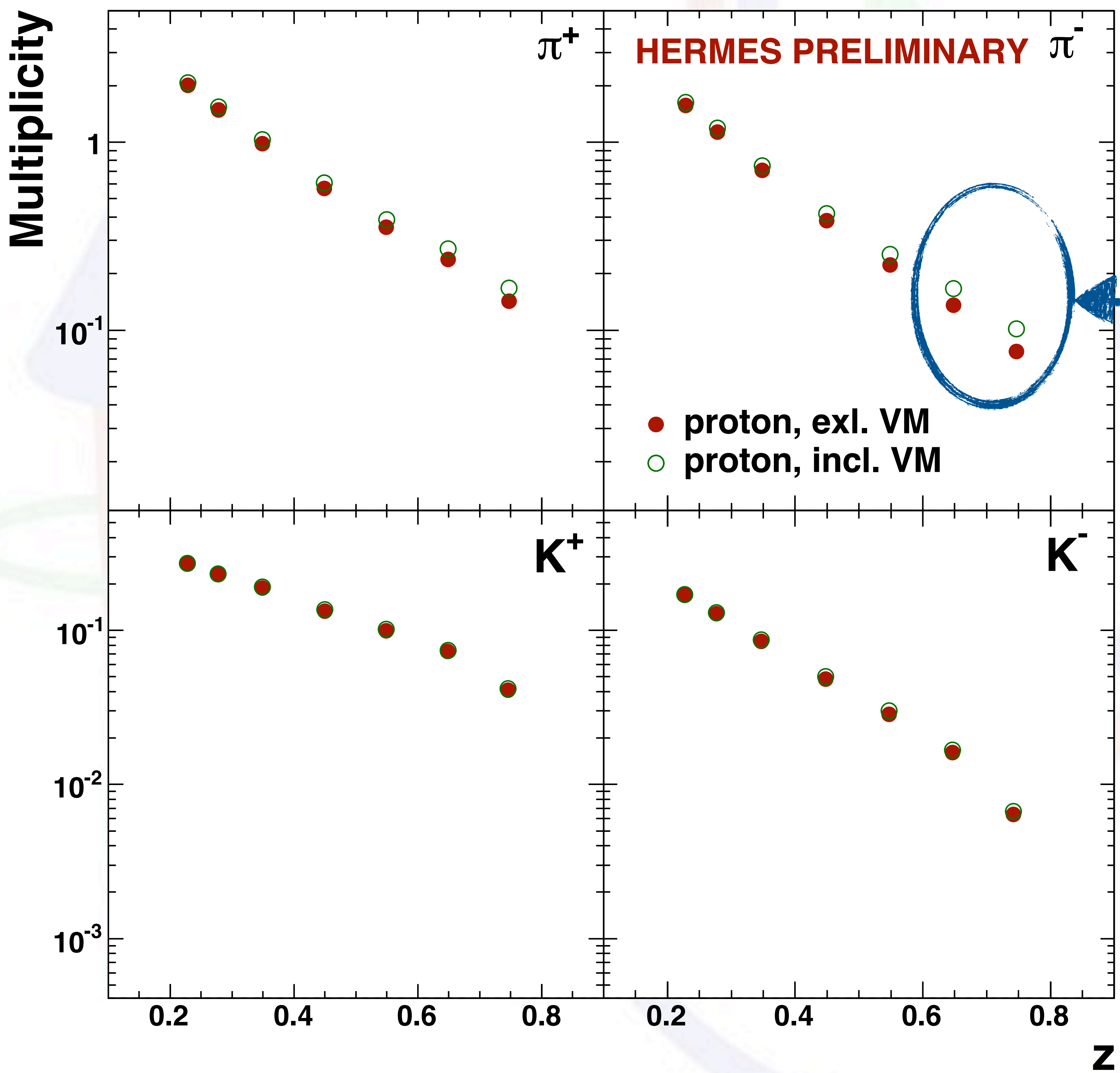
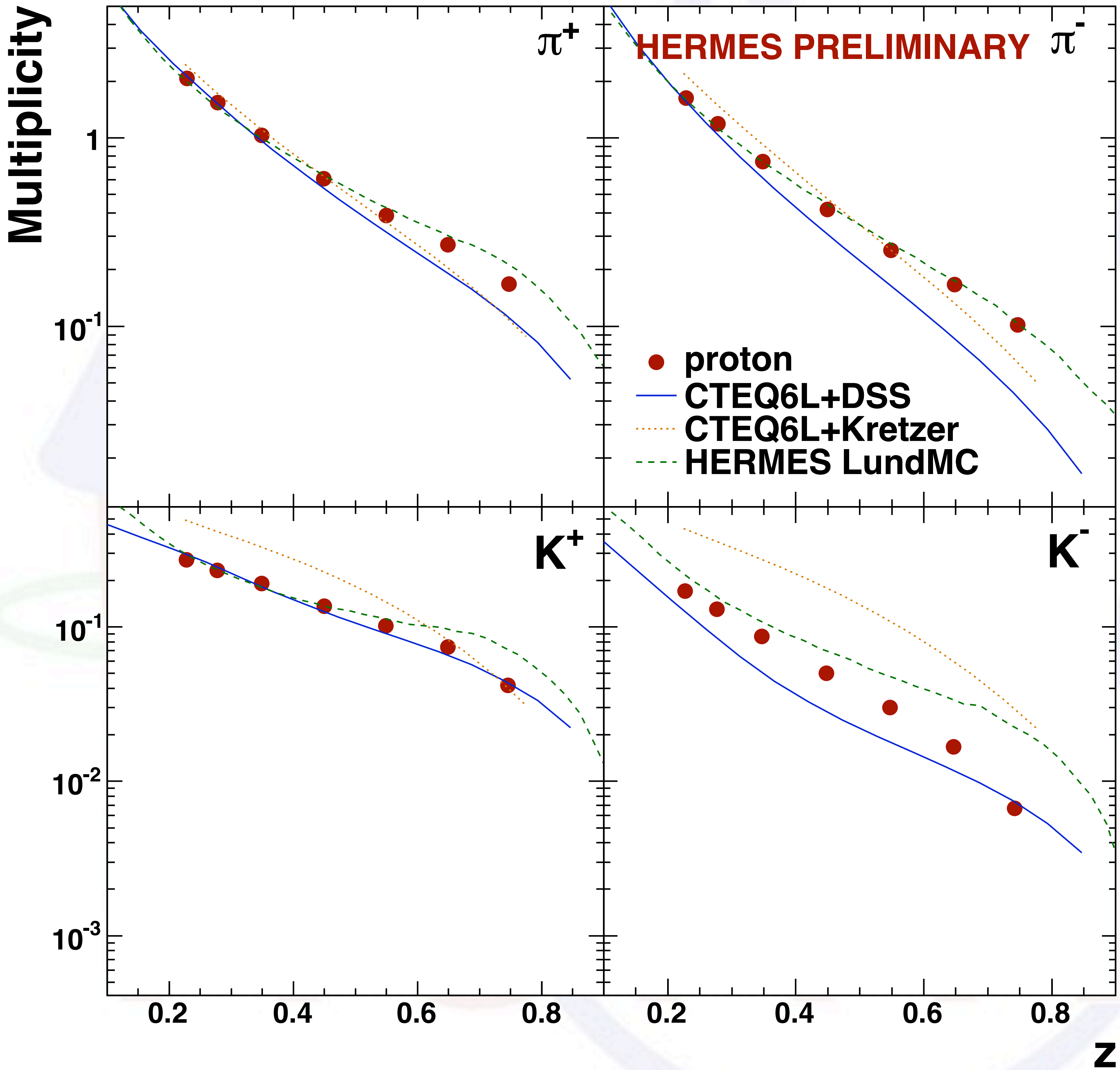


multiplicities before and after correction for contribution from exclusively produced VMs

(strategy under discussion -> next slides without subtraction)

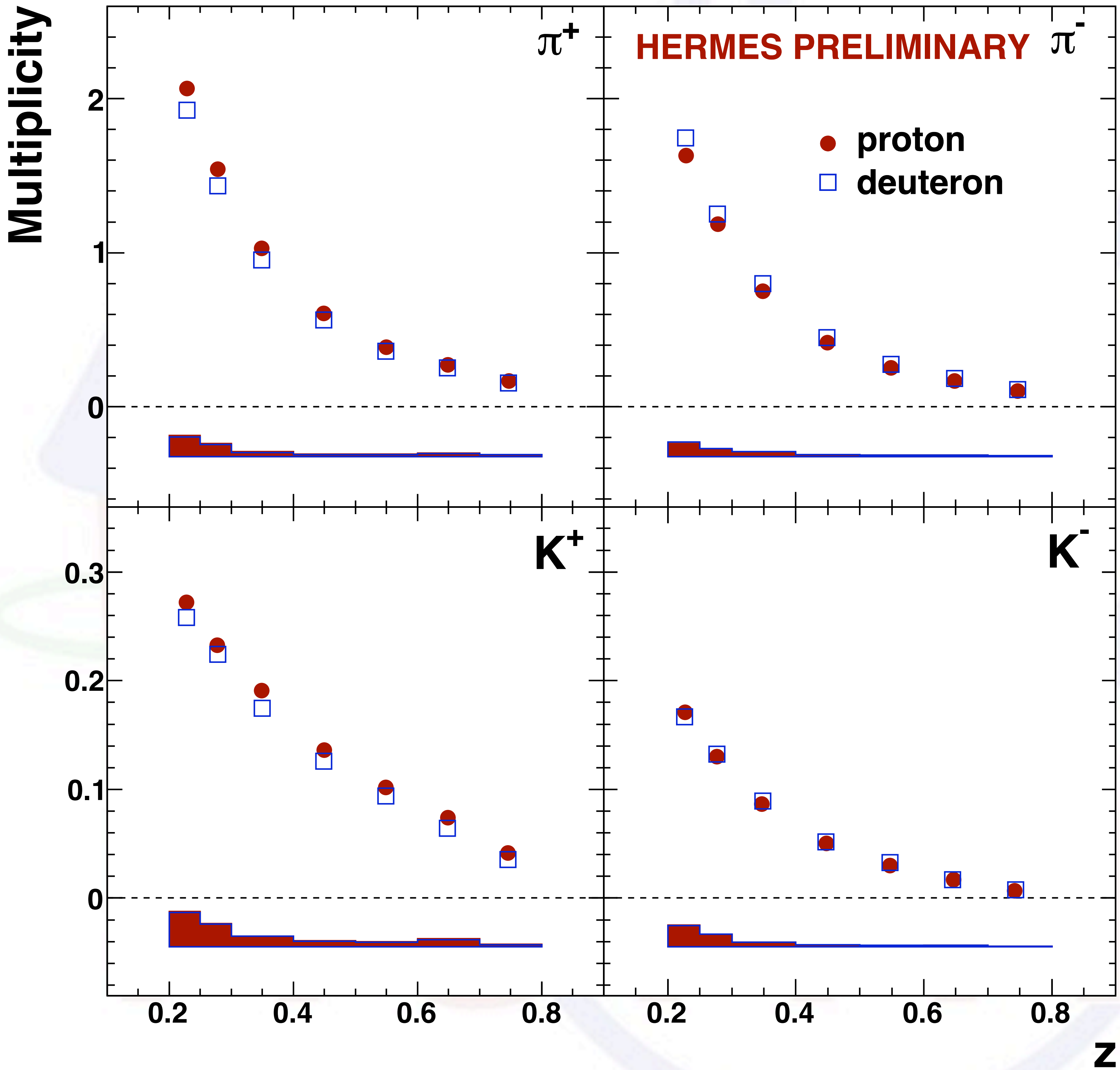
Charged-meson multiplicities



pions best described by HERMES Jetset tune surprisingly, only fair agreement with DSS

kaons best described by DSS FF set, though problems with K^-

Charged-meson multiplicities

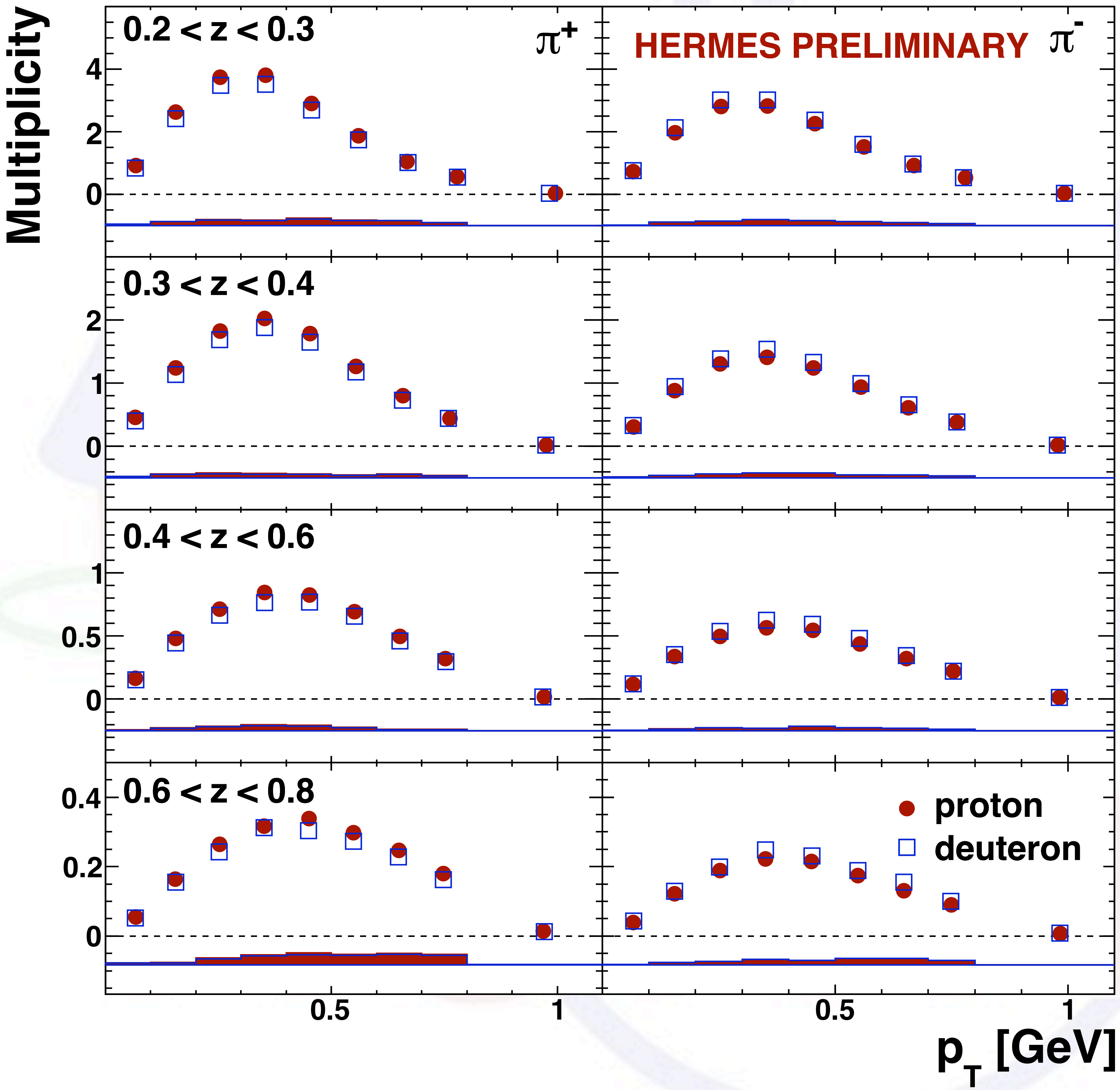


slight differences between proton and deuteron targets

most exhaustive data set on (p_T-integrated) electro-production of charged mesons on nucleons

valuable input for future FF fits, especially quark/anti-quark separation

2-D multiplicities - p_T dependence



only data on multi-D dependences in electro-production of mesons on p and d!

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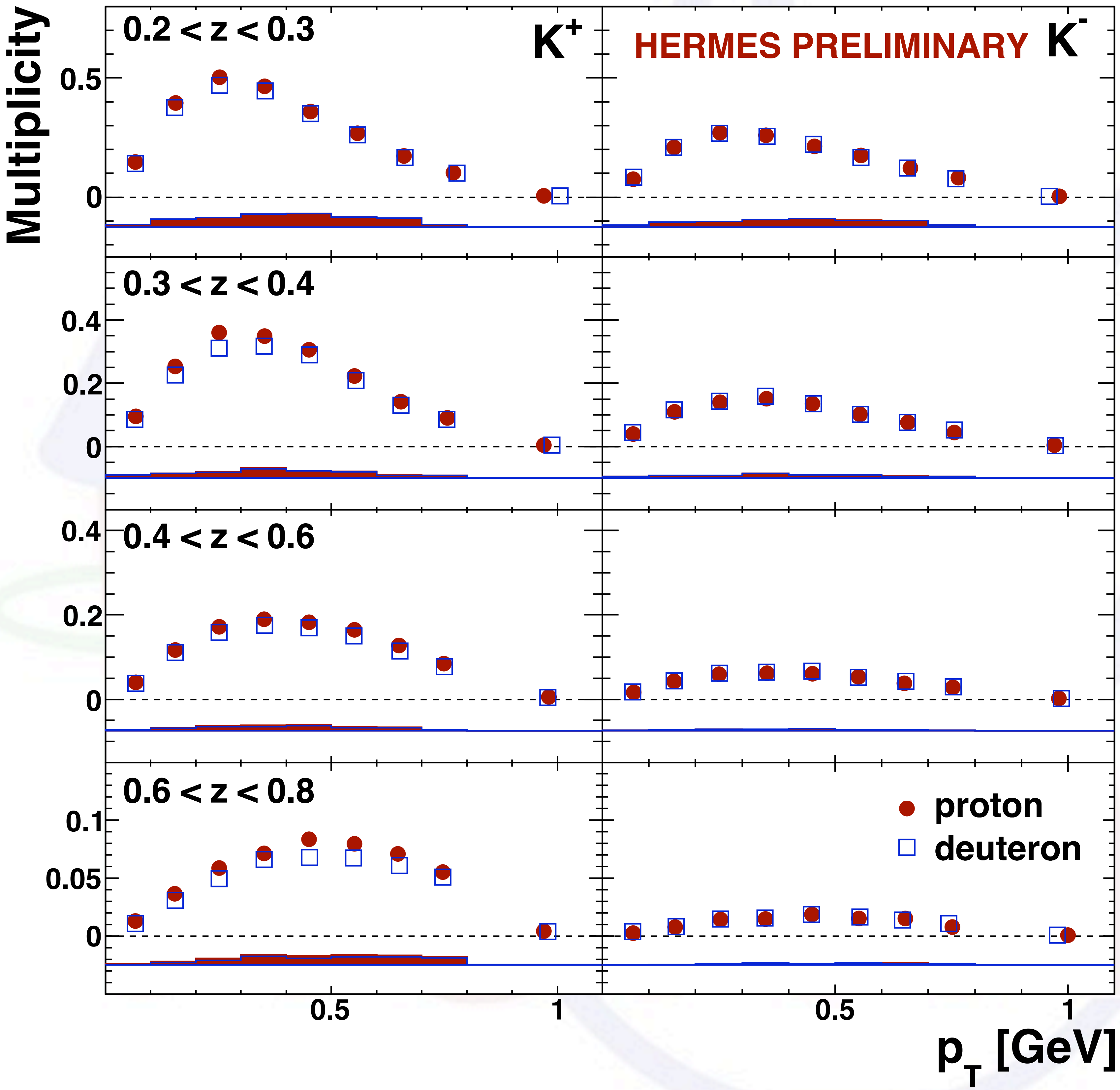

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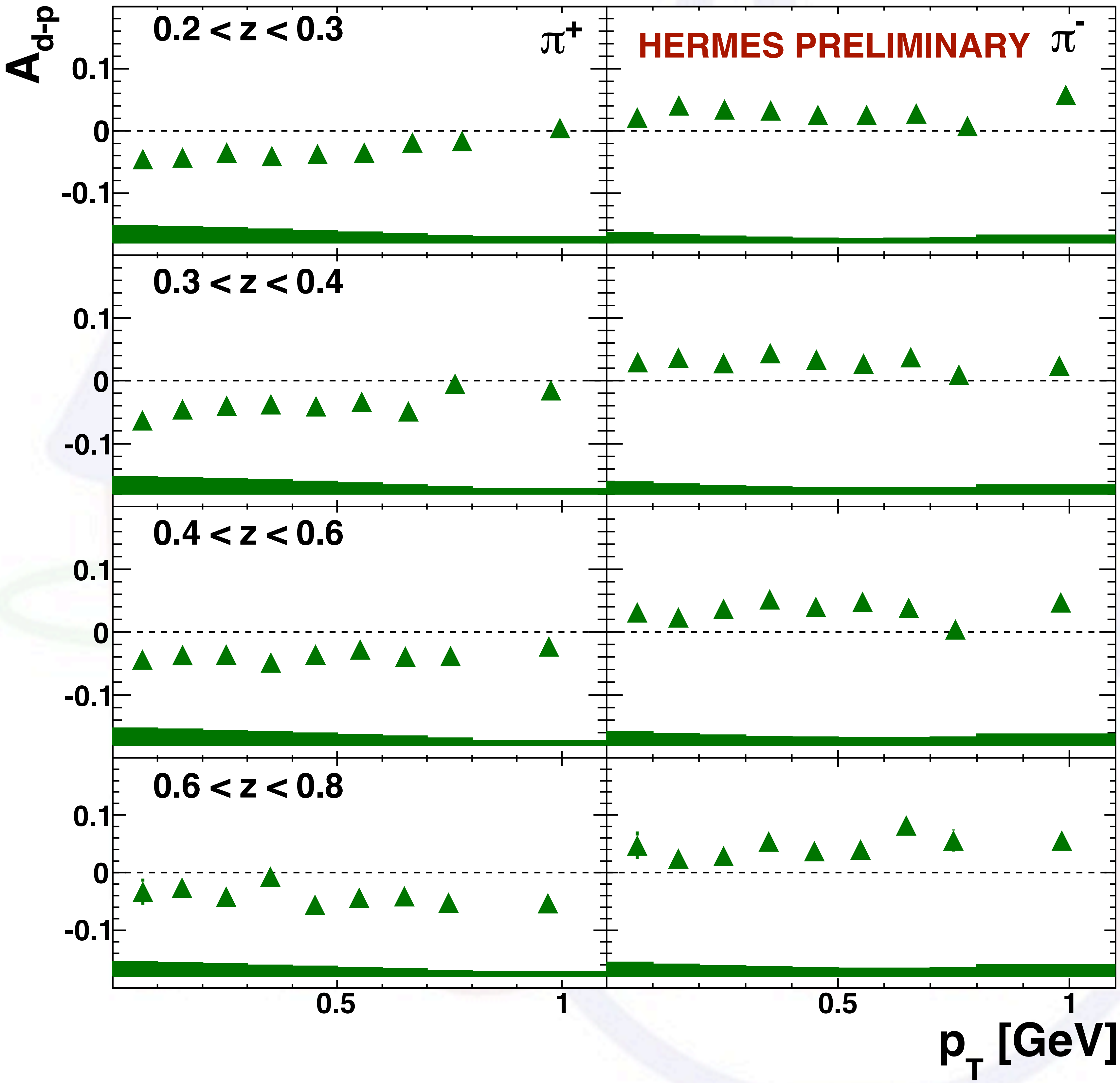
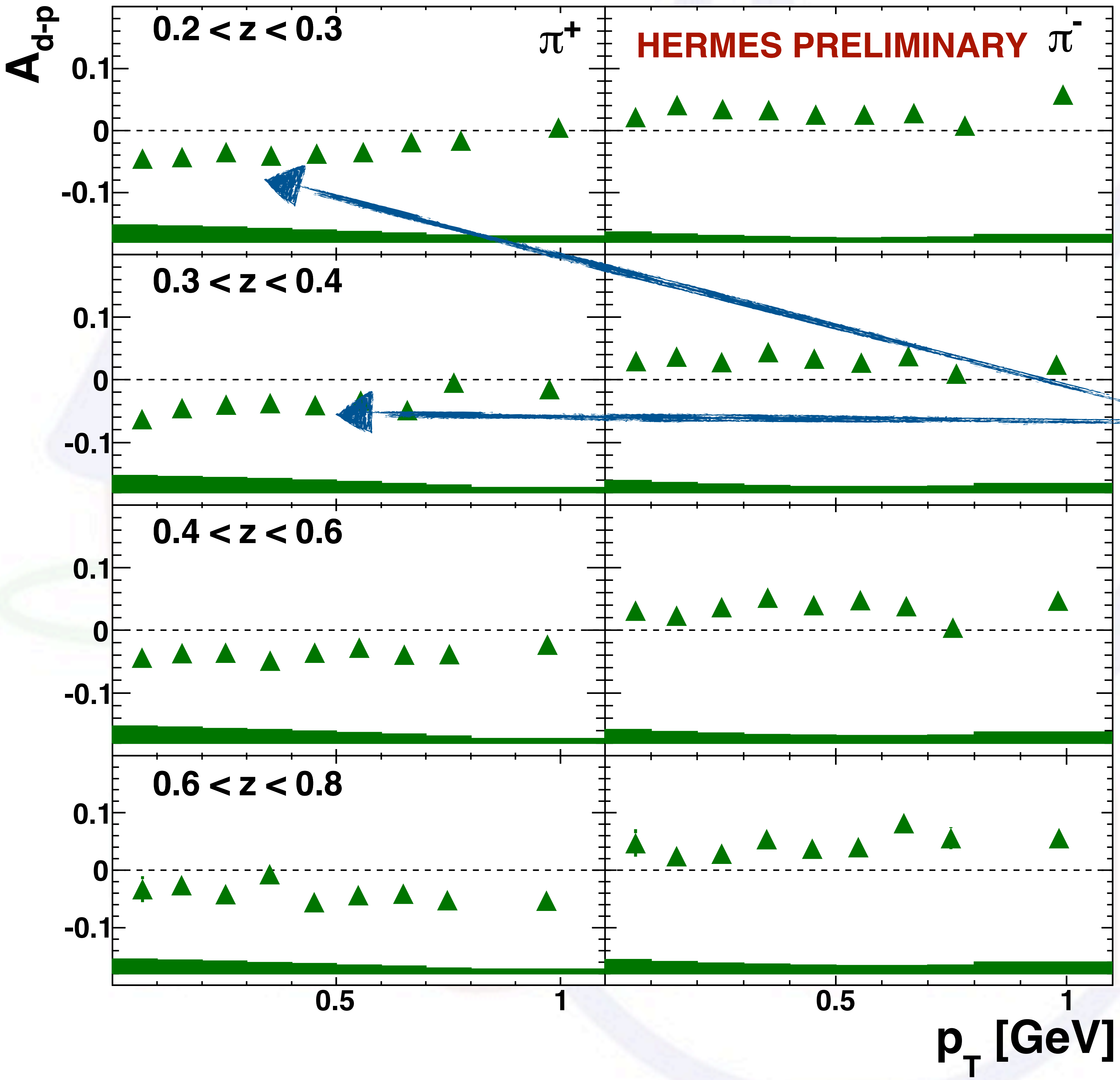
also available for kaons

Proton-deuteron asymmetry



$$A_{d-p} \equiv \frac{\mathcal{M}_d^h - \mathcal{M}_p^h}{\mathcal{M}_d^h + \mathcal{M}_p^h}$$

Proton-deuteron asymmetry



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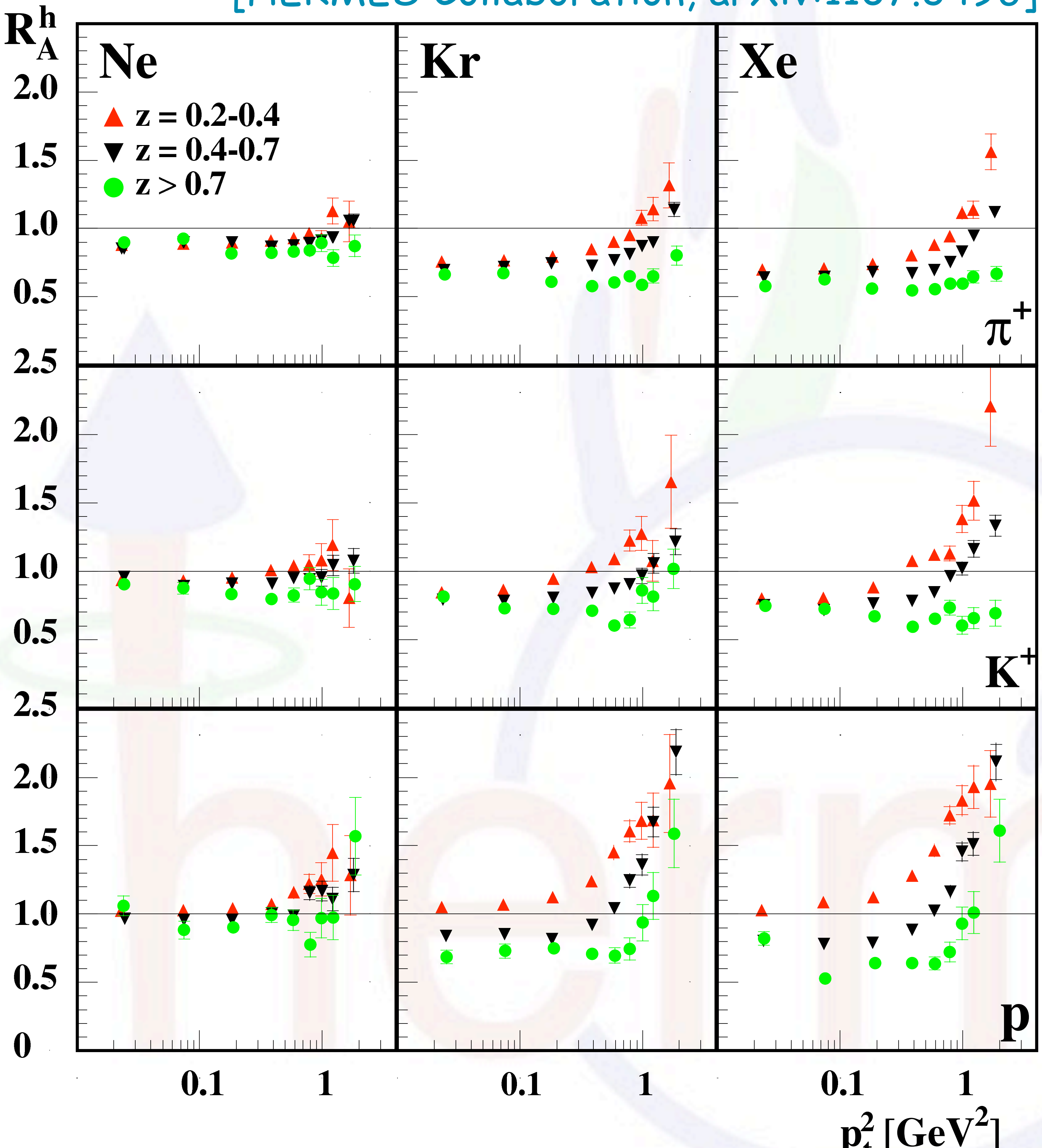
indication of flavor-dependence of transverse momentum

cf. results from Hall C [talk by M. Aghasyan]

Multiplicity ratios

[HERMES Collaboration, arXiv:1107.3496]

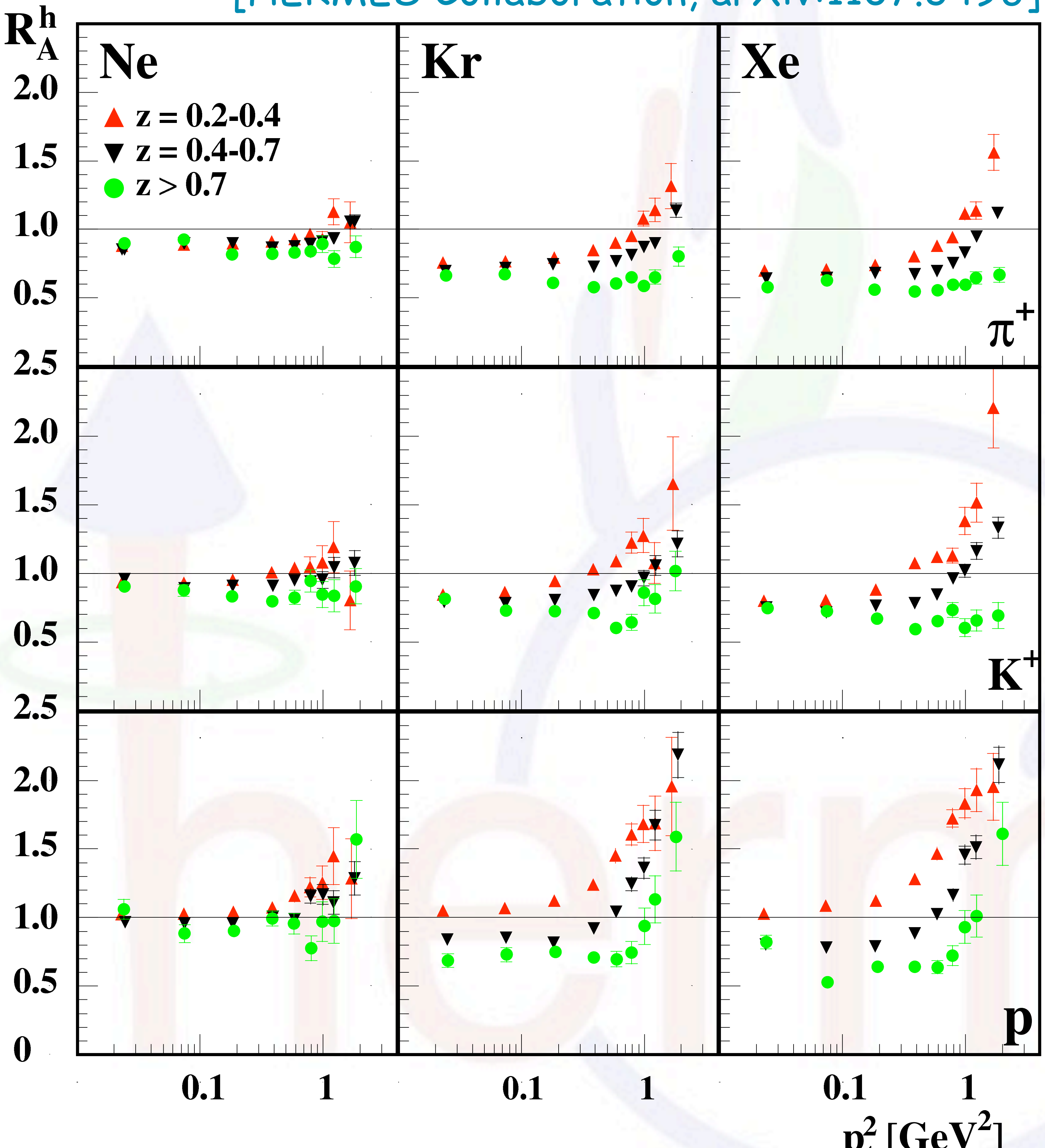


$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

Multiplicity ratios

[HERMES Collaboration, arXiv:1107.3496]



$$R_A^h = \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

needs to be considered when interpreting TMD effects off nuclear targets

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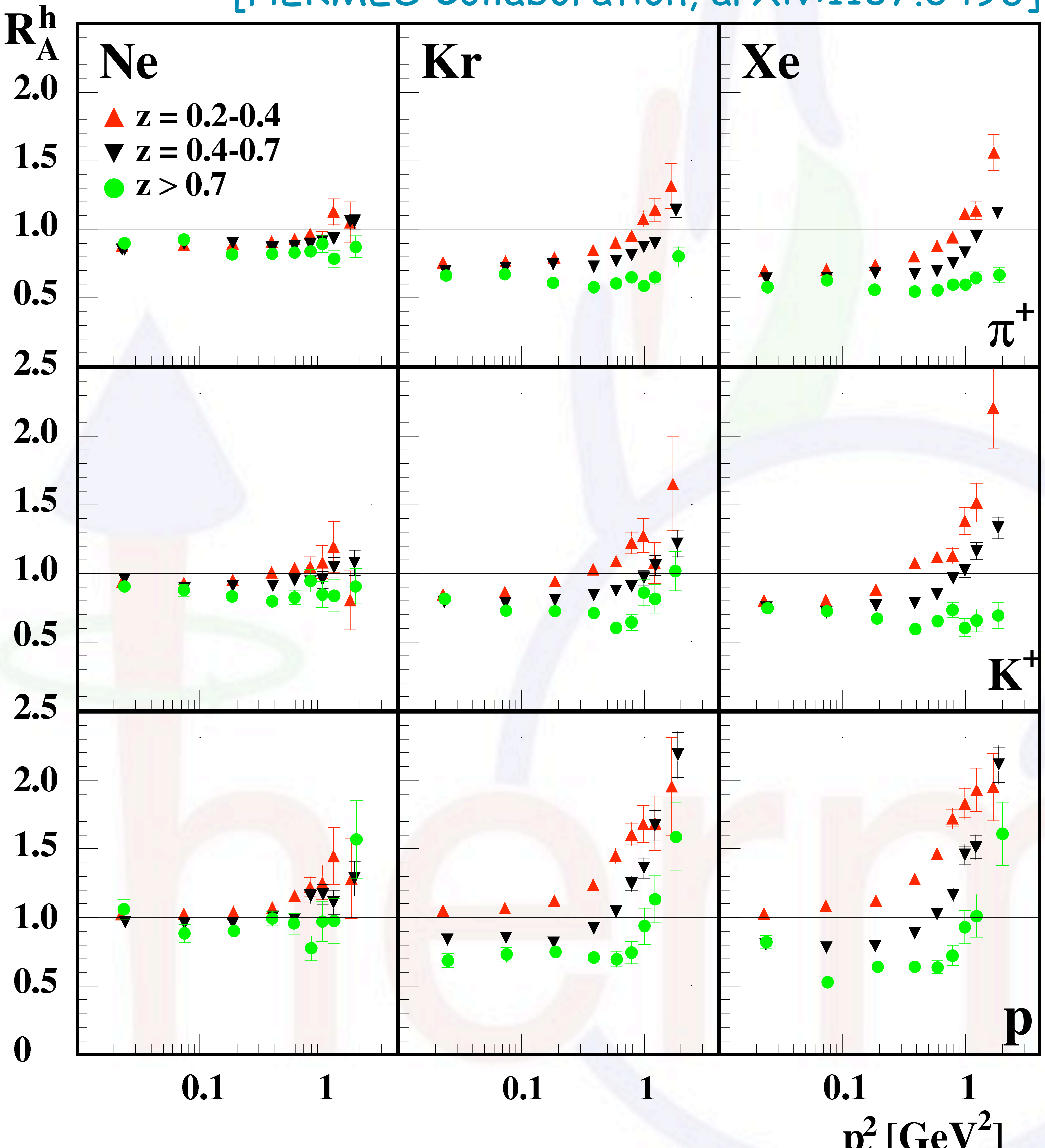

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(other 2D dependences available)

Azimuthal modulations

Azimuthal modulations

<u>leading twist</u>

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

BOER-MULDERS EFFECT

CAHN EFFECT

<u>next to leading twist</u>

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

Interaction dependent terms neglected

(Implicit sum over quark flavours)

[courtesy of F. Giordano]

Analysis of azimuthal moments

- correction for finite acceptance, QED radiation, kinematic smearing, detector resolution via **unfolding**

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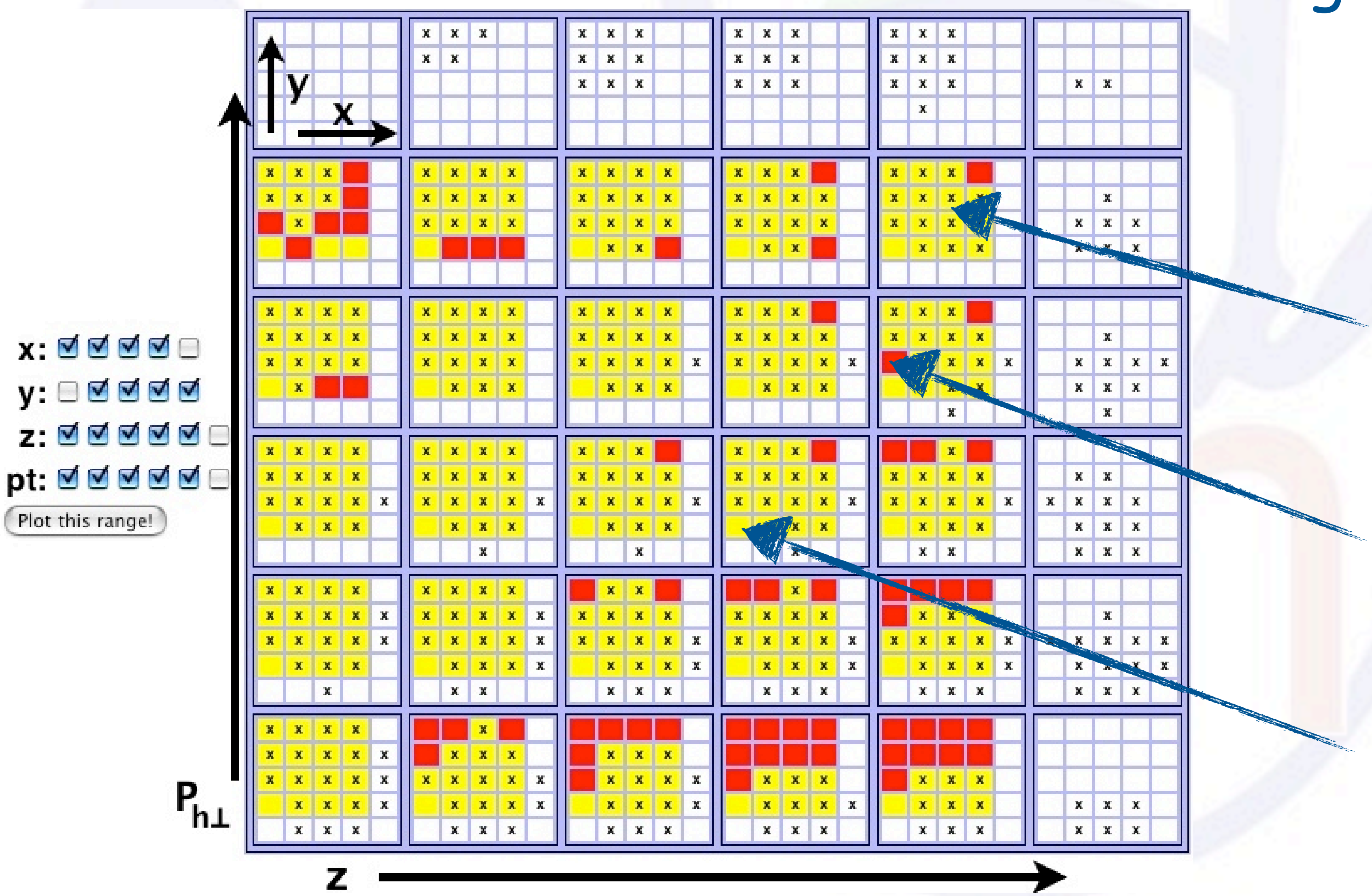
- **fully differential** analysis in 900 $(x,y,z,P_{h\perp})$ bins
- for visualization select kinematic ranges via "cherry picking":



- good measurement available

- no meaningful results

- cross section negligible

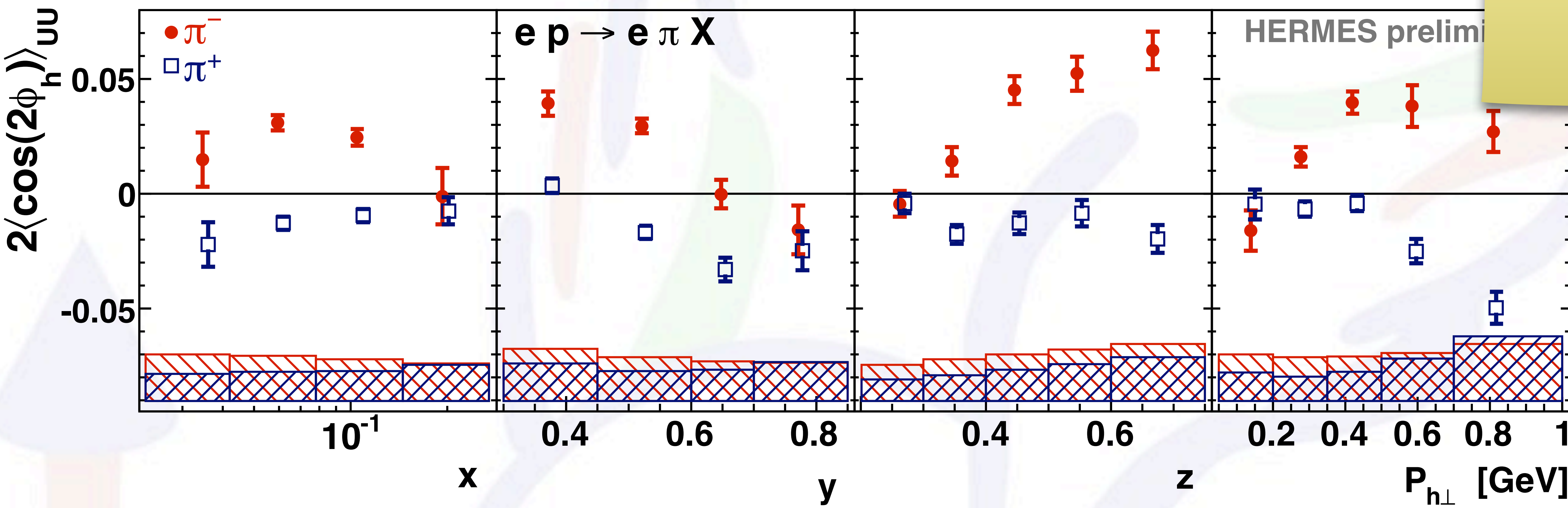
Analysis of azimuthal moments

- correction for finite acceptance, QED radiation, kinematic smearing, detector resolution via **unfolding**
- **fully differential** analysis in 900 (x,y,z,$P_{h\perp}$) bins
- for visualization select kinematic ranges via "cherry picking":
  - all hadron types in comparison must have enough events in each of the bins included, e.g.:

Binning 900 kinematic bins x 12 ϕ_h -bins								
Variable	Bin limits							#
x	0.023	0.042	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

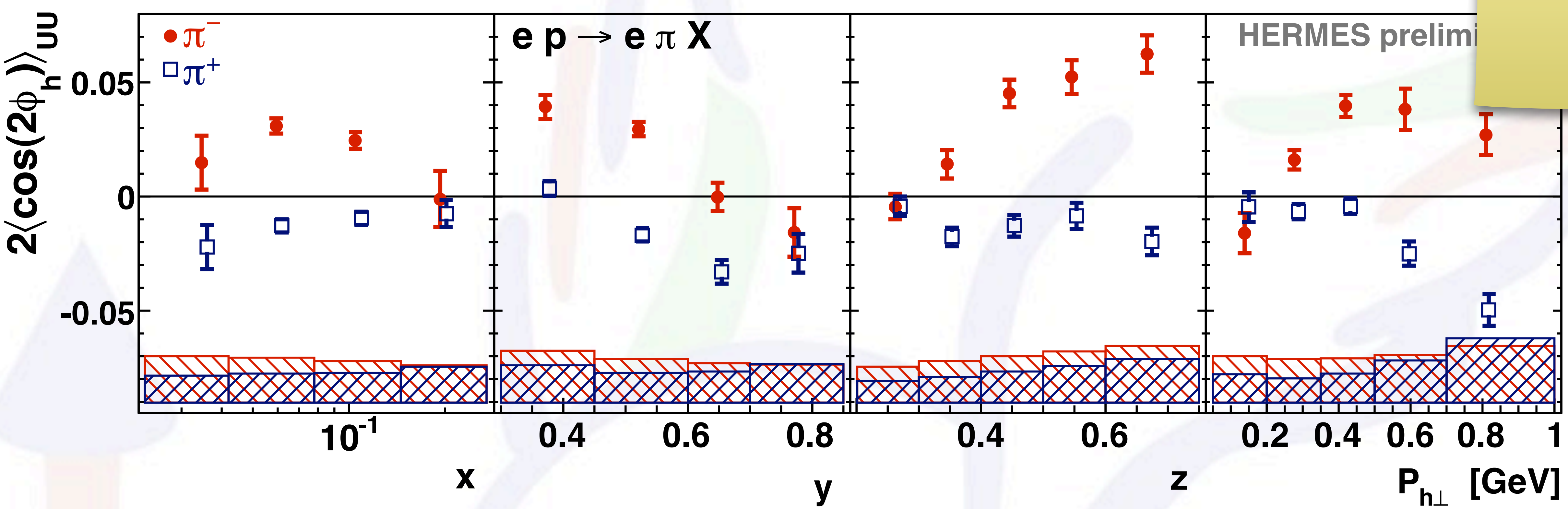
"Boer-Mulders modulation" (pions)

add discussion of r



“Boer-Mulders modulation“ (pions)

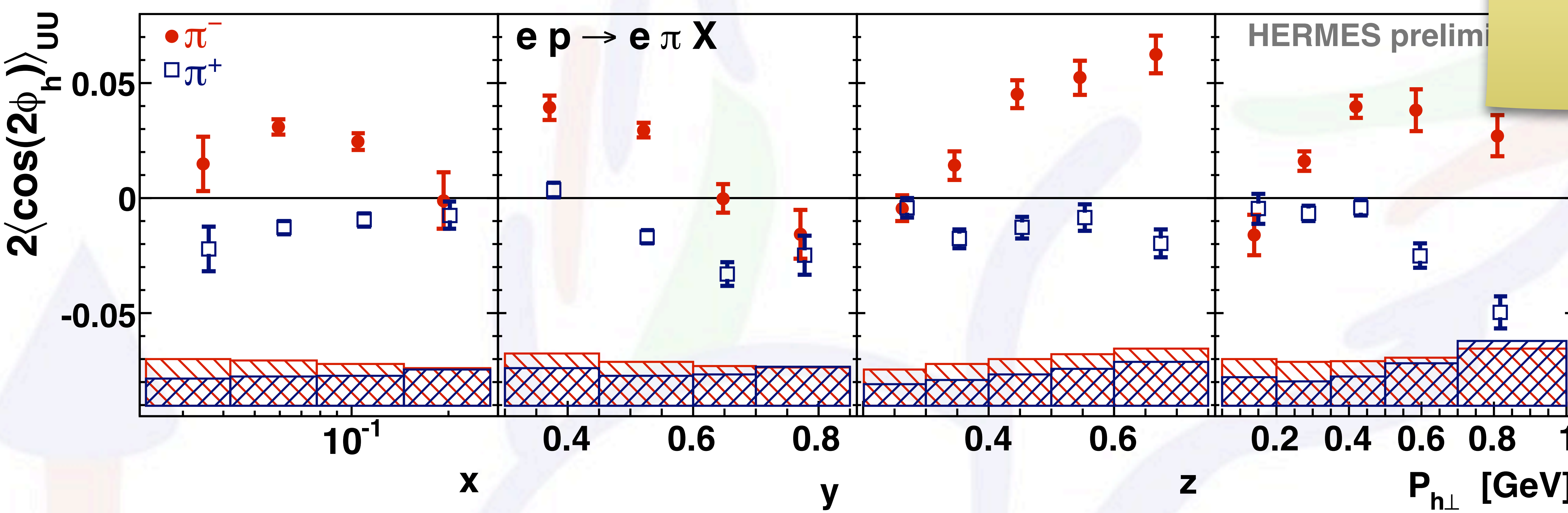
add discussion of r



- Cahn effect (twist-4) supposedly flavor blind

"Boer-Mulders modulation" (pions)

add discussion of r



- Cahn effect (twist-4) supposedly flavor blind
- large flavor dependence points at significant leading-twist BM effect

“Boer-Mulders modulation“ (pions)

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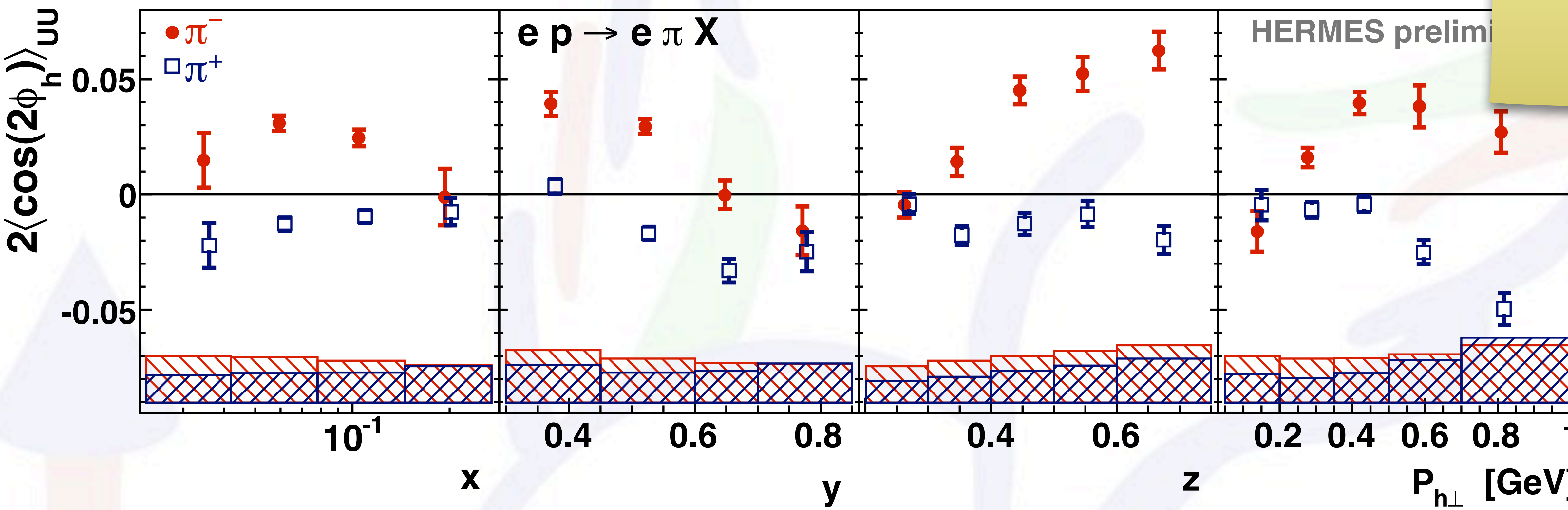
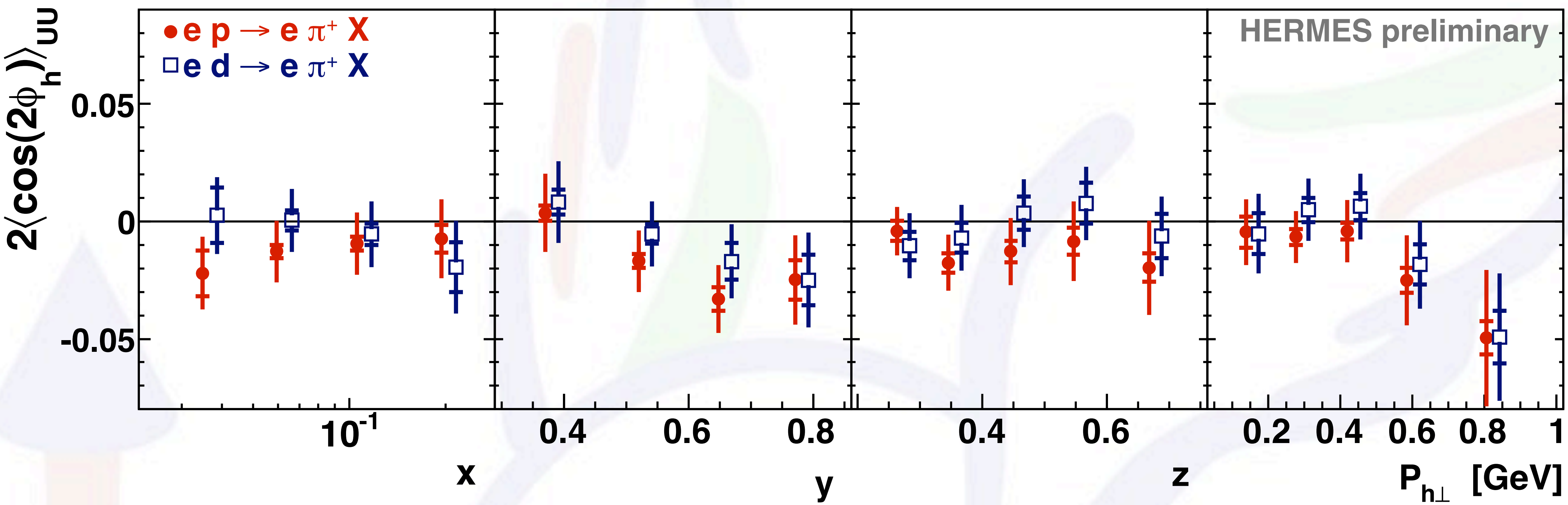


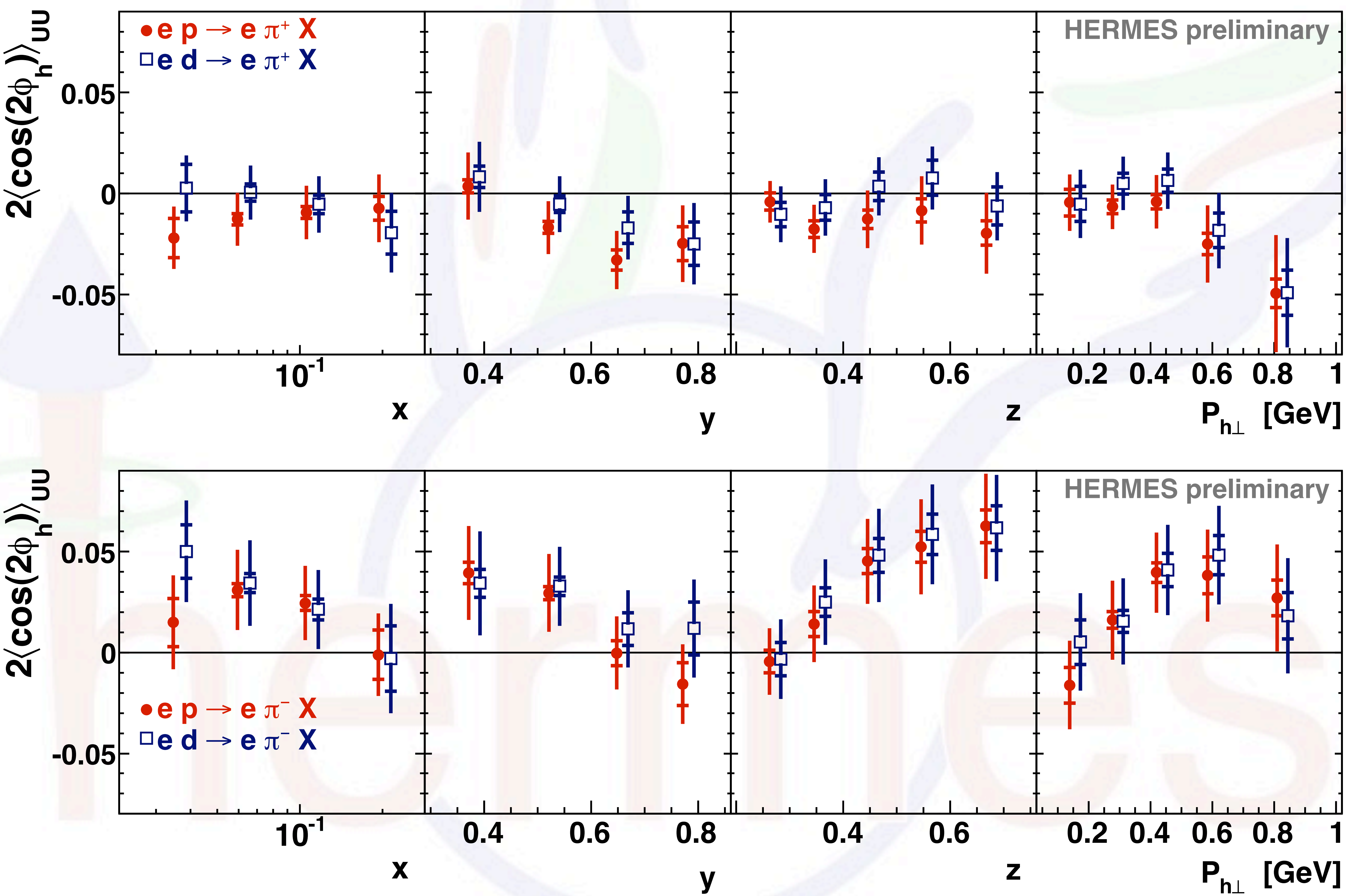
- Cahn effect (twist-4) supposedly flavor blind
- large flavor dependence points at significant leading-twist BM effect
- opposite sign for opposite pion charge can be expected from same-sign BM functions for up and down quarks

"Boer-Mulders modulation" (pions)

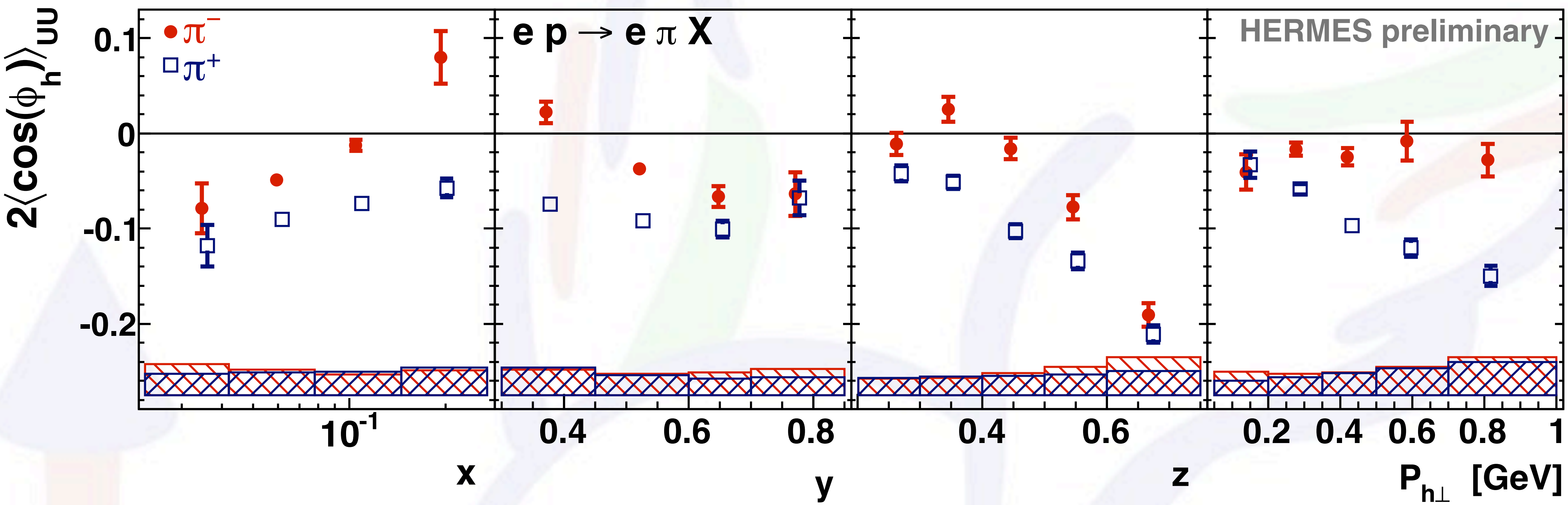


- hardly any dependence on target!
- consistent with same-sign up/down BM of similar size

“Boer-Mulders modulation“ (pions)



"Cahn modulation"



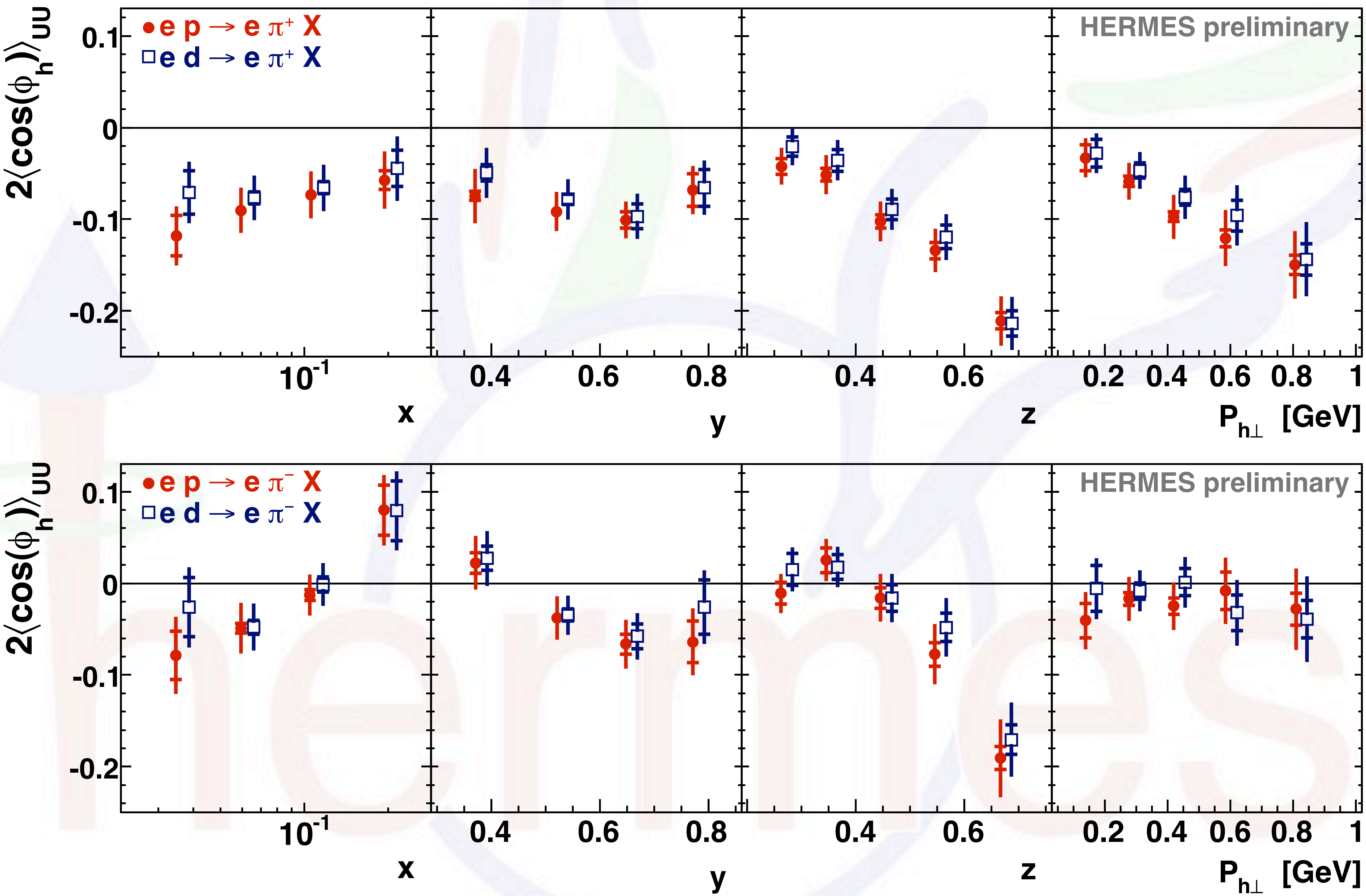
- no dependence on hadron charge expected for Cahn effect

➡ flavor dependence of transverse momentum

➡ sign of Boer-Mulders in cosϕ modulation
(indeed, overall pattern resembles B-M modulations)

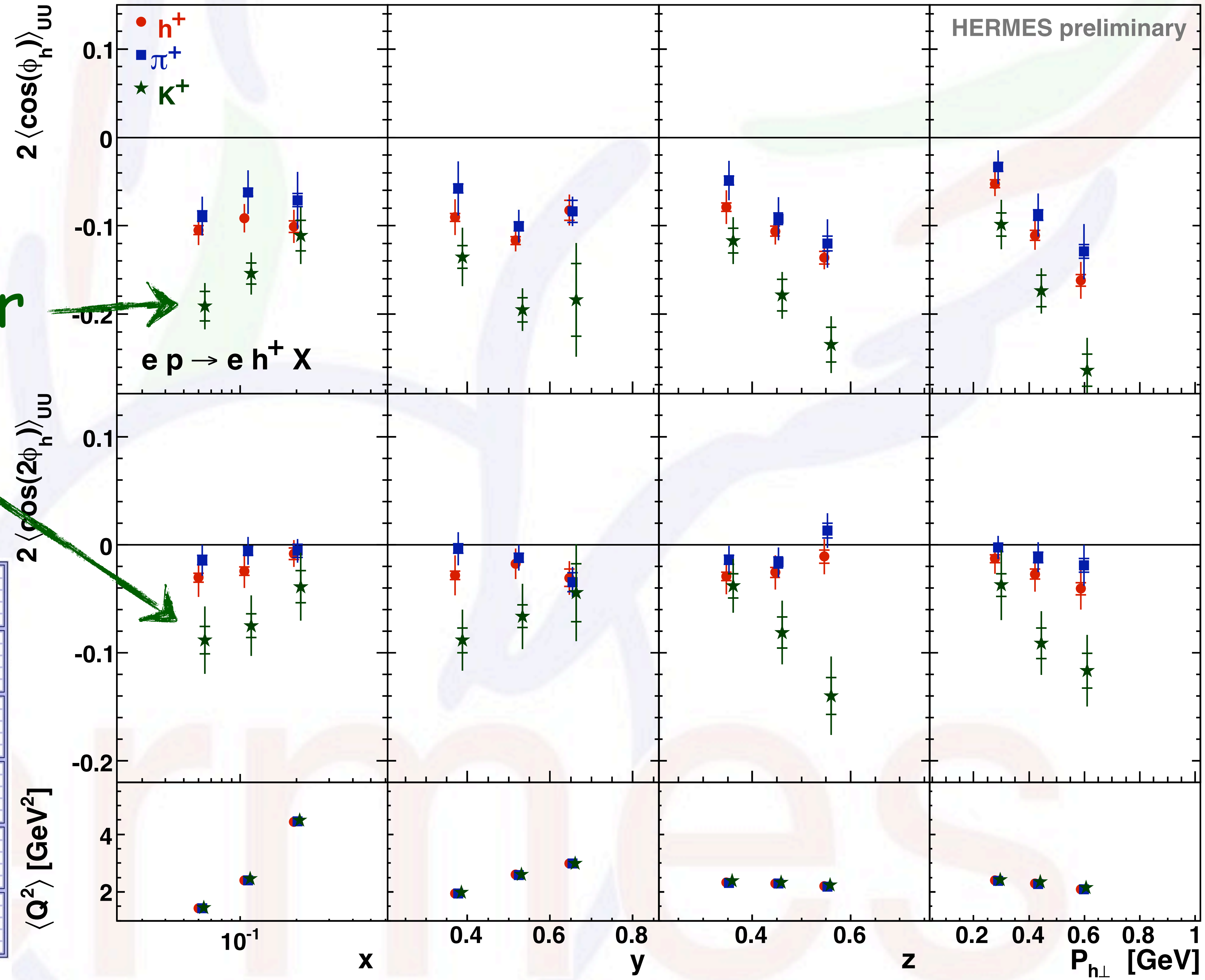
➡ "genuine" twist-3?

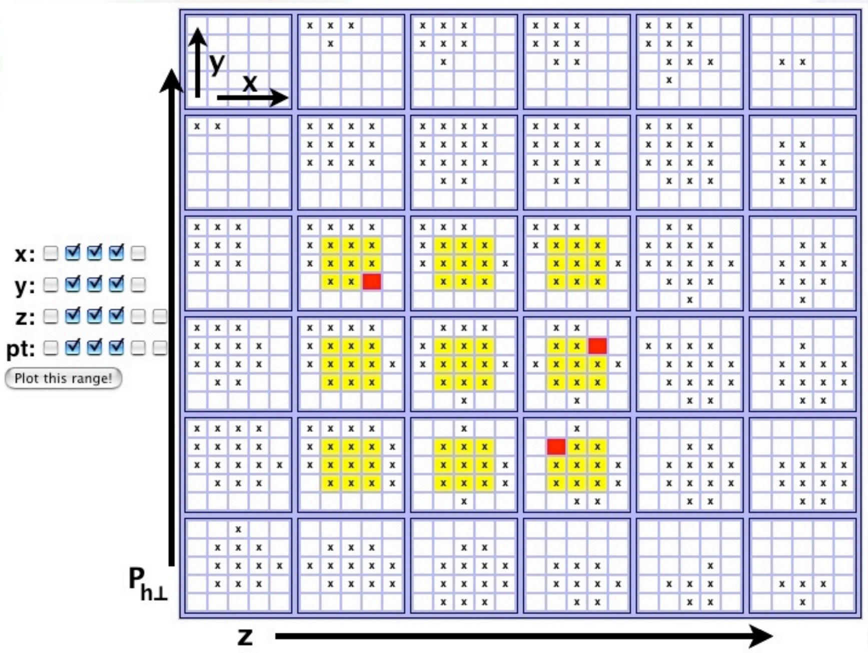
"Cahn modulation" - proton vs. deuteron



strange results

intriguing behavior for kaons





strange results

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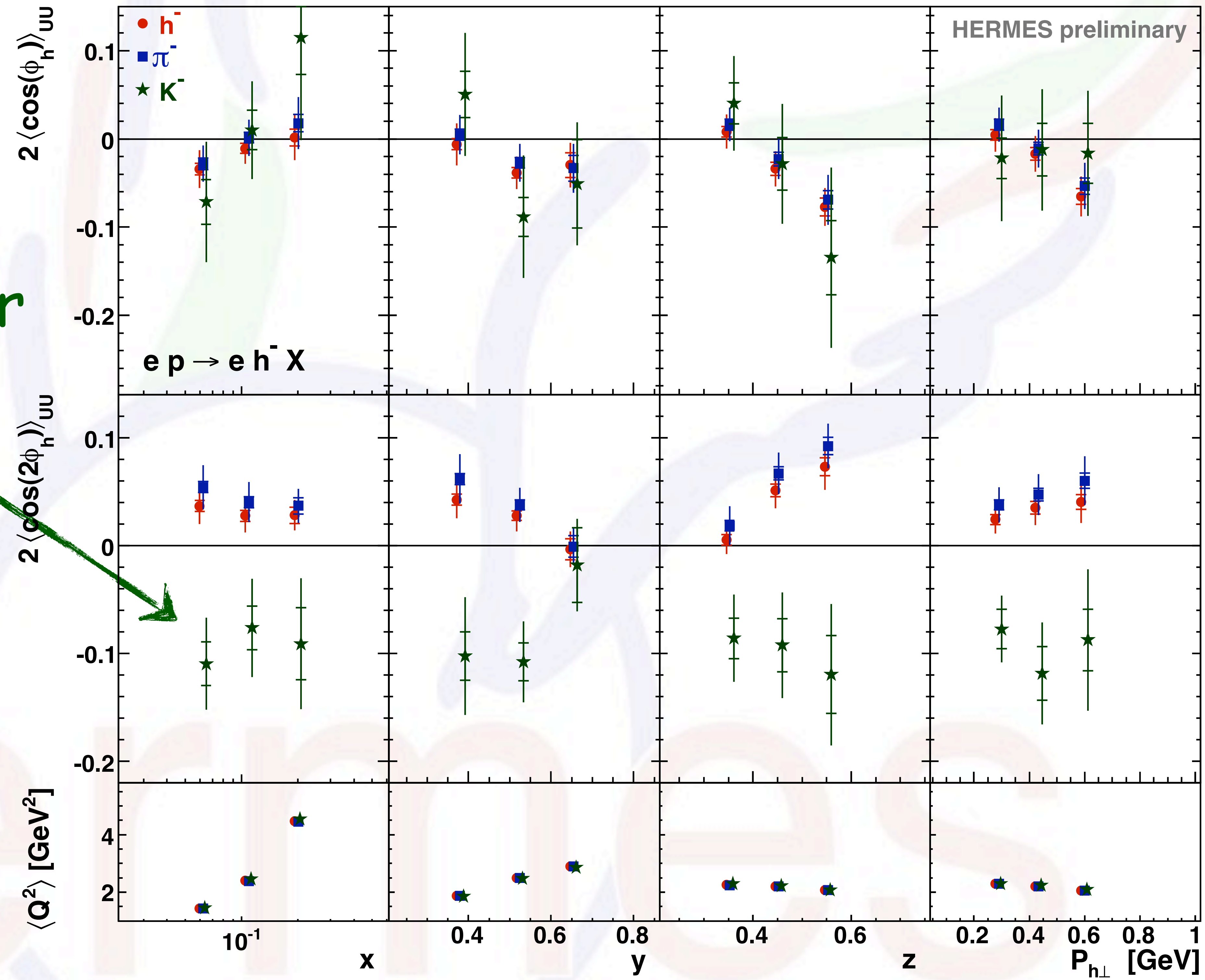
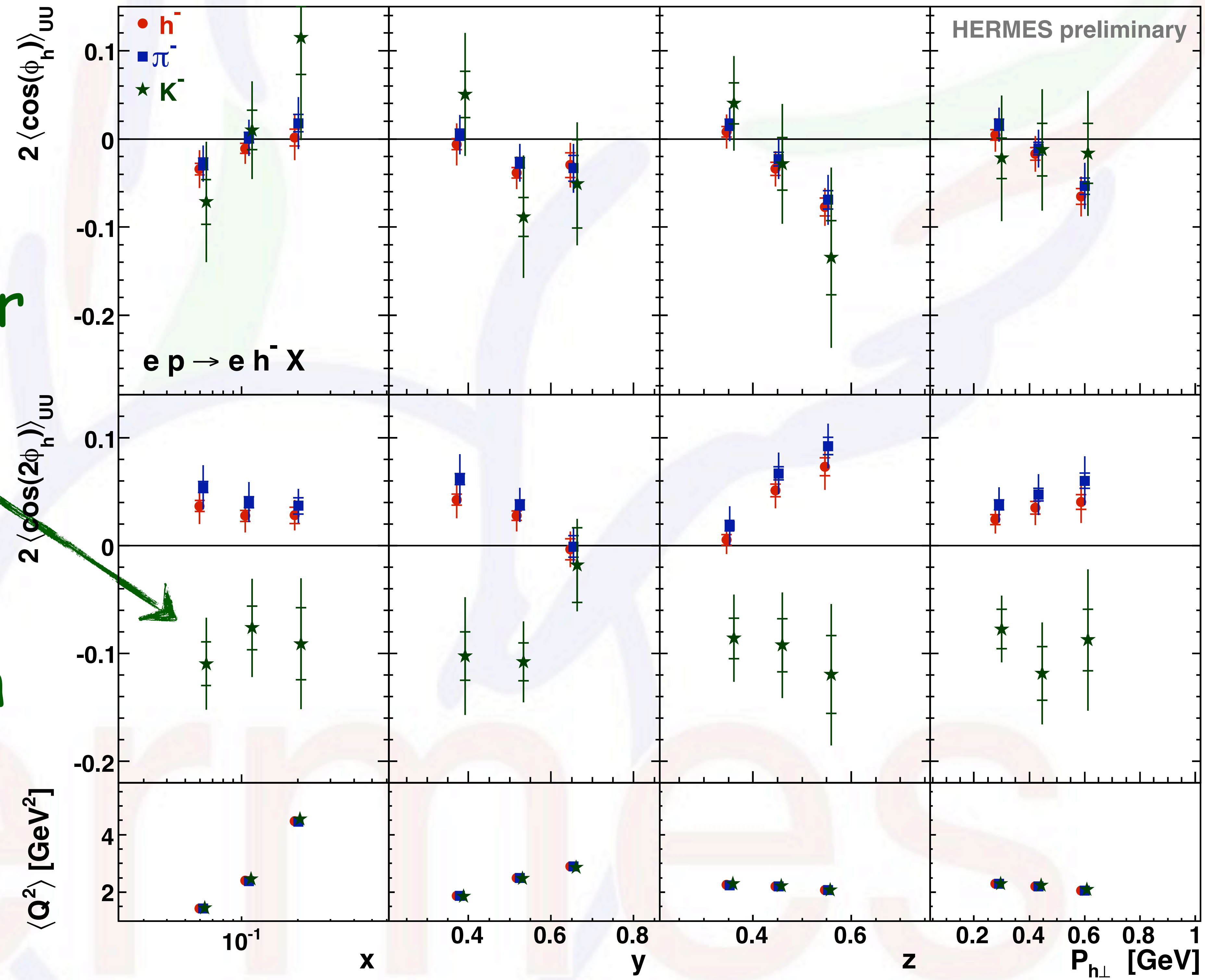


strange results

intriguing behavior for kaons

different pattern for kaon Collins function?
(cf. BRAHMS A_N and SIDIS Collins)



Conclusions

- HERMES managed step from spin-asymmetry experiment to unpolarized-target experiment
- largest data set on charged-meson lepto-production
- multi-dimensional analysis and various targets allow study of correlations and flavor dependences
- large azimuthal modulations, different for positive and negative pions, point at important role of Boer-Mulders fctn.
- Cahn effect maybe suppressed at HERMES kinematics
- kaons remain strange (Collins, sea quarks, or both?)
- nuclear environment can play significant role in TMD effects
- don't forget longitudinal photons