Selected HERMES results on semi-inclusive meson production

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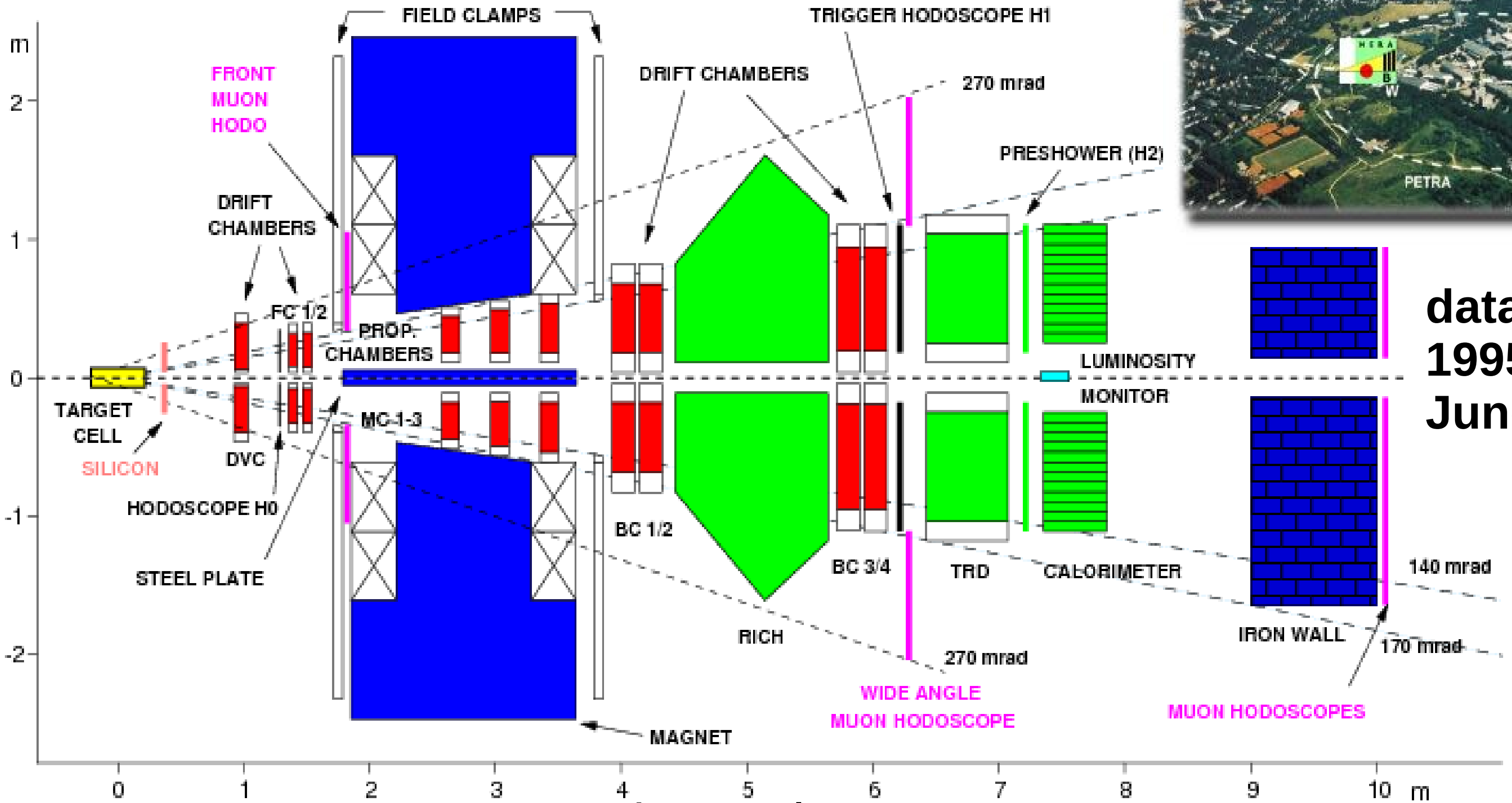
Outline

- the HERMES experiment
- $\pi^{\pm}$ and $K^{\pm}$ multiplicities on hydrogen and deuterium
- hadronization in nuclei
- single-spin asymmetries in SIDIS off transversely polarized protons

  - Sivers effect

  - transversity and Collins
- spin-independent non-collinear cross section

HERMES: HERA MEasurement of Spin



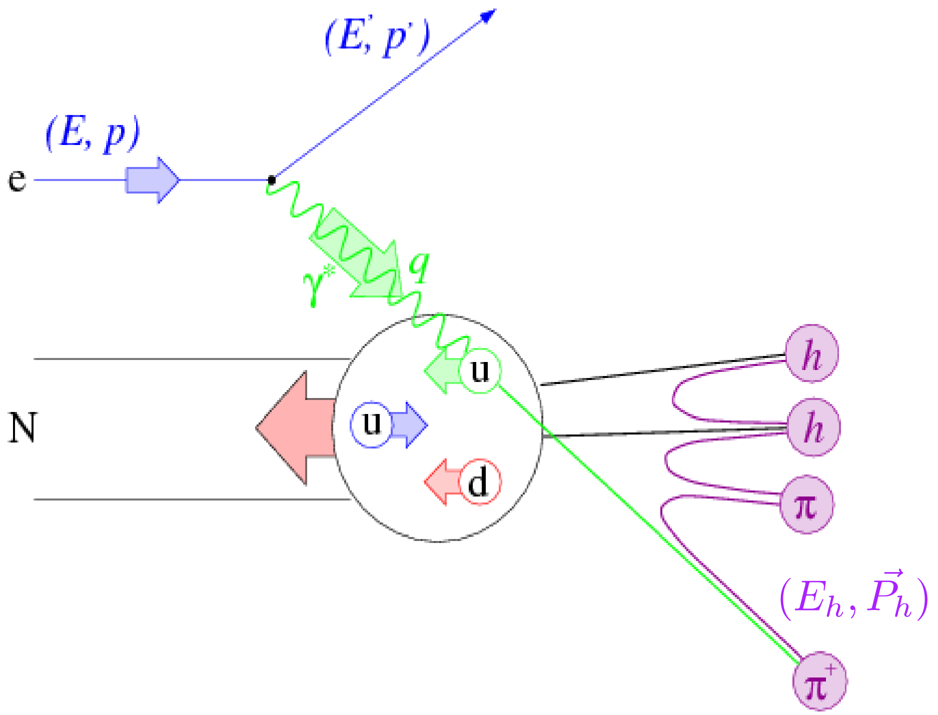
data taking from 1995 until June, 30 2007

<u>Beam</u>
longitudinally pol.
e^+ & e^-
E= 27.6 GeV

<u>Gaseous internal target</u>
transversely pol. H (~75%)
unpol. H,D,He,Ne,Kr,Xe
longitudinally pol. H,D,He (~85%)

- **lepton-hadron PID: high efficiency (>98%) & low contamination (<1%)**
- **hadron PID: RICH 2-15 GeV**

Semi-inclusive deep-inelastic scattering



$$Q^2 = -q^2$$

$$\nu \overset{lab}{=} E - E'$$

$$W^2 = M_N^2 + 2M_N\nu - Q^2$$

$$y \overset{lab}{=} \frac{\nu}{E}$$

$$x_B \overset{lab}{=} \frac{Q^2}{2M_N\nu}$$

$$z \overset{lab}{=} \frac{E_h}{\nu} \qquad P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

$$\sigma^{ep\to eh} = \sum_q DF^{p\to q}(x_B, p_T^2, Q^2) \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}(z, k_T^2, Q^2)$$

Distribution Function (DF): distribution of quarks in nucleon

Fragmentation Function (FF): fragmentation of struck quark into final-state hadron

p_T / k_T: transverse momentum of struck/fragmenting quark

Hadron multiplicities

$$\mathrm{M}_n^h(x_B, Q^2, z, P_{h\perp}) = \frac{1}{d^2\,N^{DIS}(x_B,Q^2)}\frac{d^4\,N^h(x_B,Q^2,z,P_{h\perp})}{dzdP_{h\perp}}$$

$$= \frac{\sum_q e_q^2\, f_1^q(x_B, p_T^2, Q^2) \otimes \mathcal{W}\, D_1^q(z, k_T^2, Q^2)}{\sum_q e_q^2\, f_1^q(x_B, Q^2)}$$

collinear

QPM, leading twist, LO

$$M_n^h(x_B, Q^2, z) = \frac{\sum_q e_q^2\, f_1^q(x_B, Q^2)\, D_1^q(z, Q^2)}{\sum_q e_q^2\, f_1^q(x_B, Q^2)}$$

Extraction of Born multiplicities

$$M^h_{Born}(j) = \frac{1}{n^{DIS}_{Born}(j)} \sum_i \left[S_h^{-1}\right](j,i) \left[M^h_{meas}(i)\, N^{DIS}_{meas}(i) - n^h(i,0)\right]$$

smearing matrix from LEPTO+JETSET Monte-Carlo simulation

$$S_h(i,j) = \frac{n^h(i,j)}{n^h_{Born}(j)}$$

→ reconstructed (i)
→ generated (Born) (j)

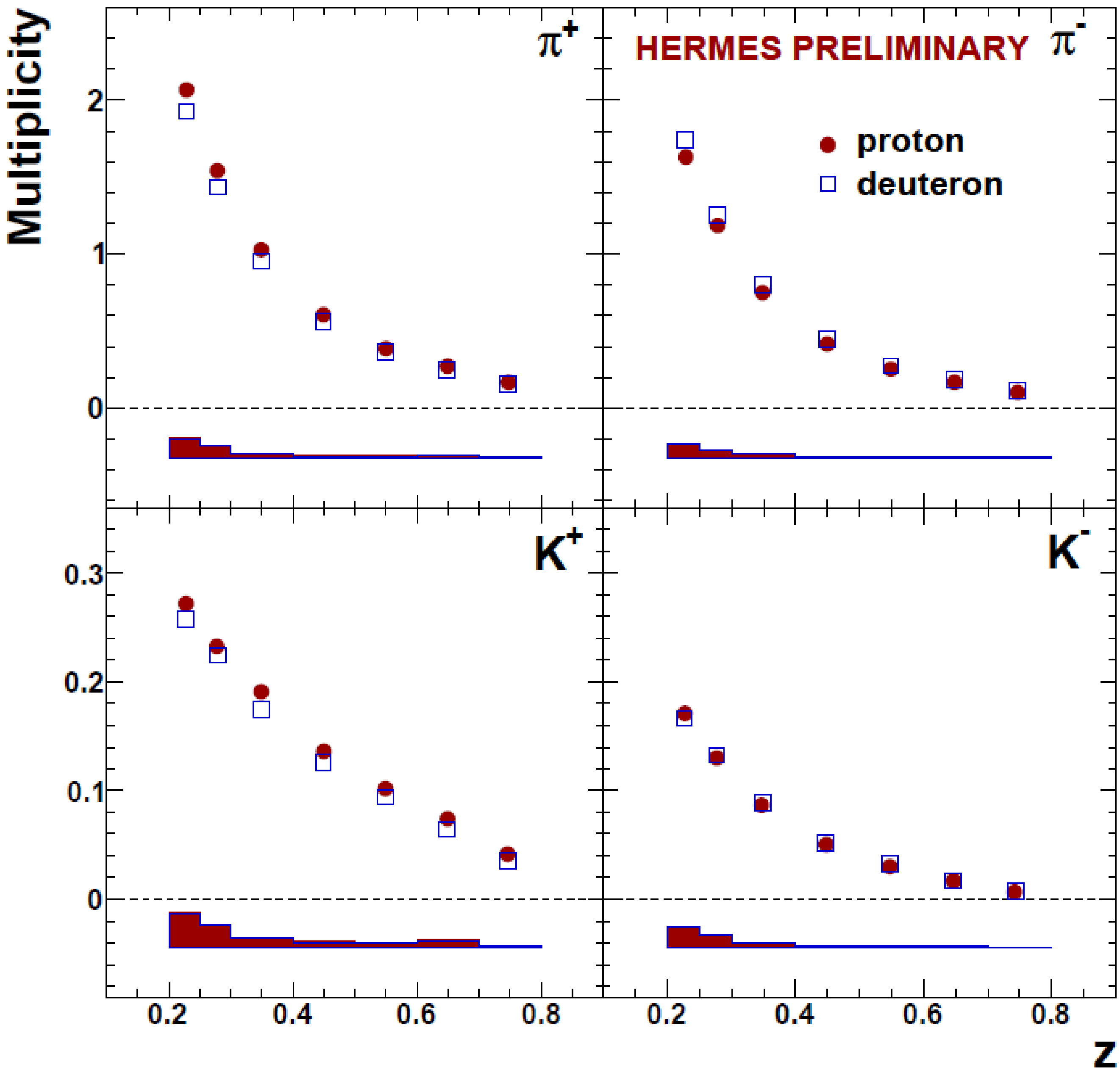
accounts for

- QED radiative effects (RADGEN)
- limited geometric and kinematic acceptance of spectrometer
- detector resolution

$n^h(i,0)$ migration of events outside acceptance into acceptance

extraction in 3D: binning in $(x_B, z, P_{h\perp})$ and $(Q^2, z, P_{h\perp})$

Results projected in z



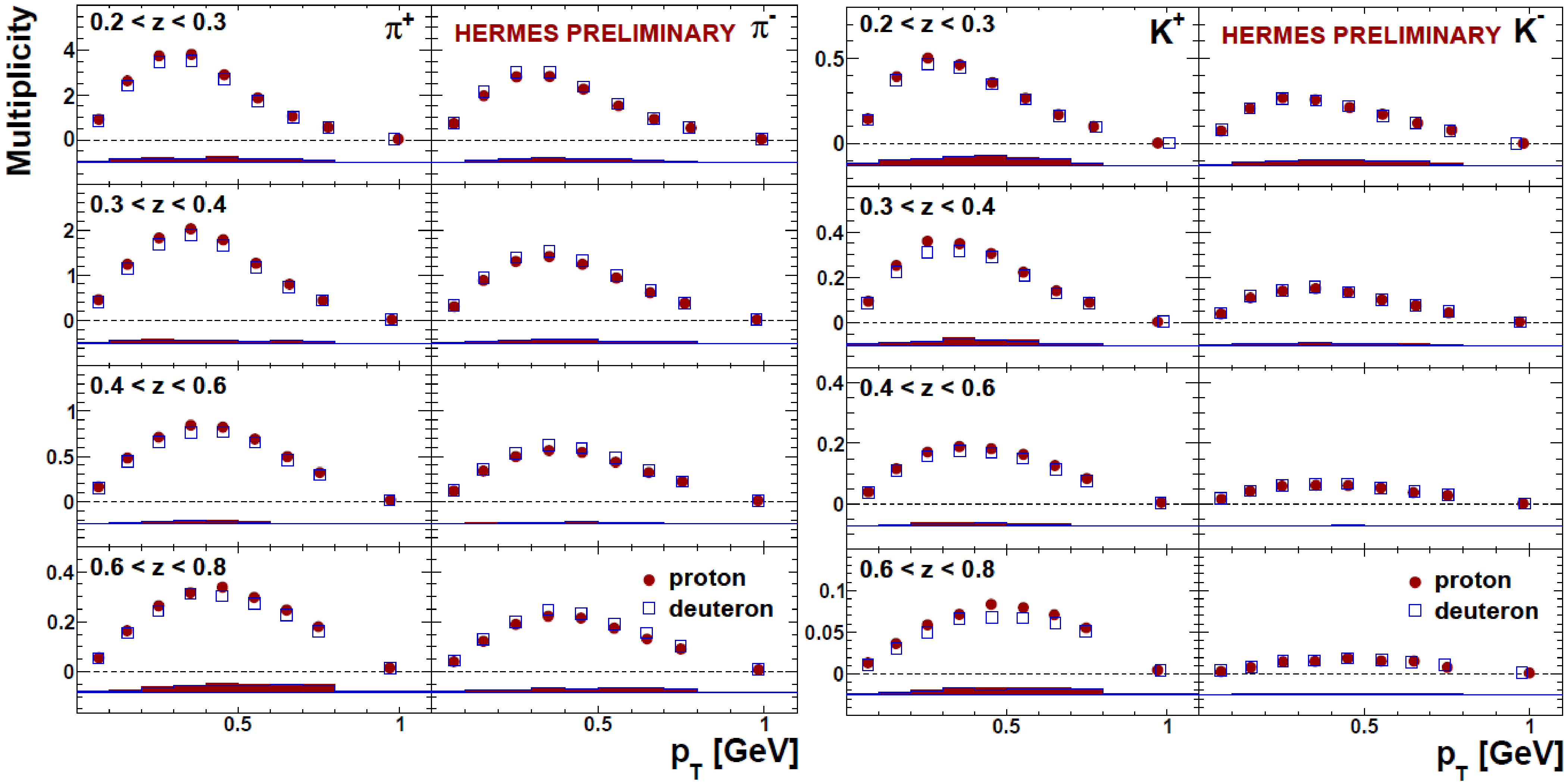
$$\frac{M^{\pi^+}_{p(d)}}{M^{\pi^-}_{p(d)}} = 1.2 - 2.6\,(1.1 - 1.8)$$

$$\frac{M^{K^+}_{p(d)}}{M^{K^-}_{p(d)}} = 1.5 - 5.7\,(1.3 - 4.6)$$

multiplicities reflect

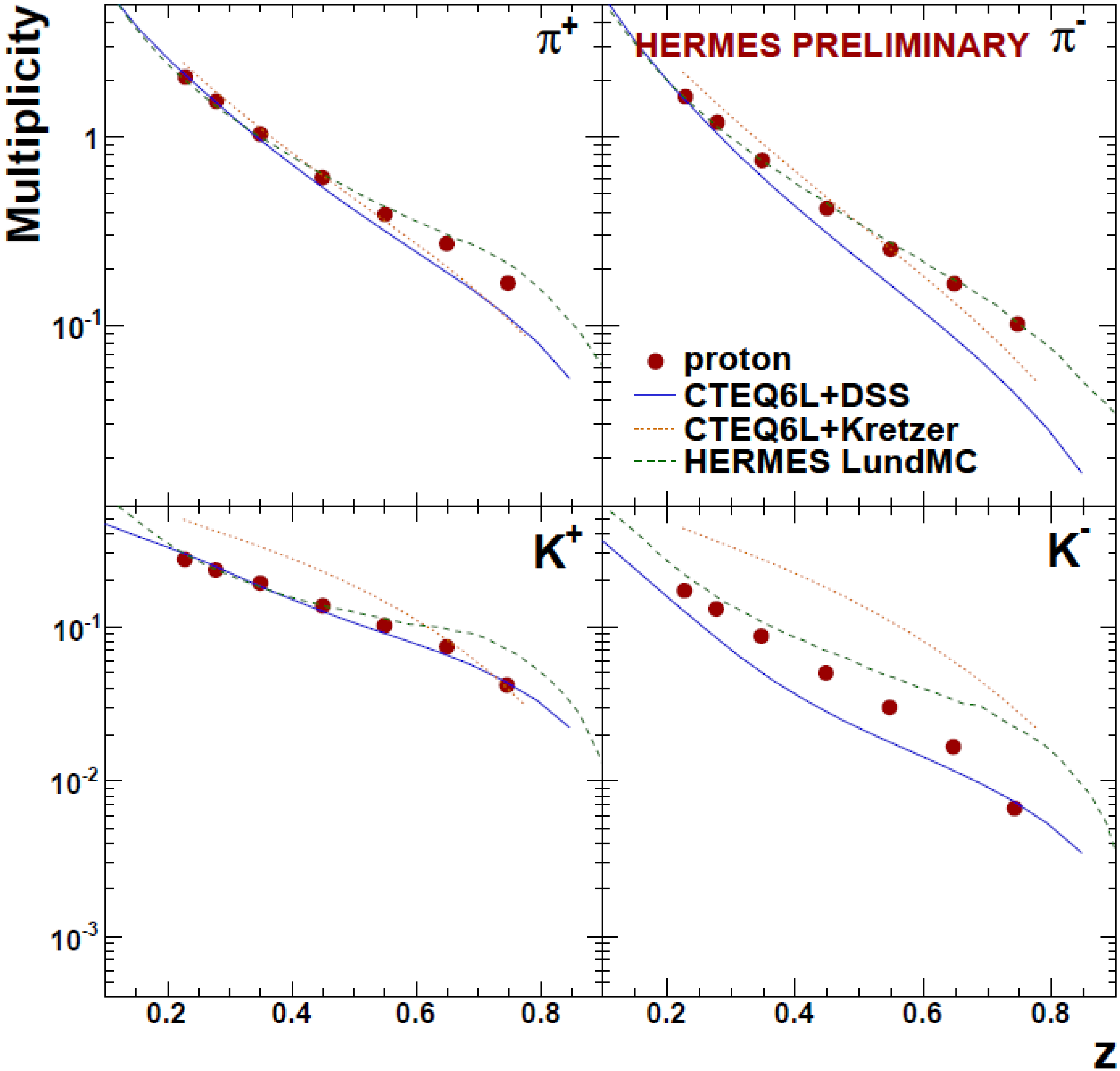
- nucleon valence-quark content (u-dominance)
- favored $\leftrightarrow$ unfavored fragmentation

Results projected in z and $P_{h\perp}$



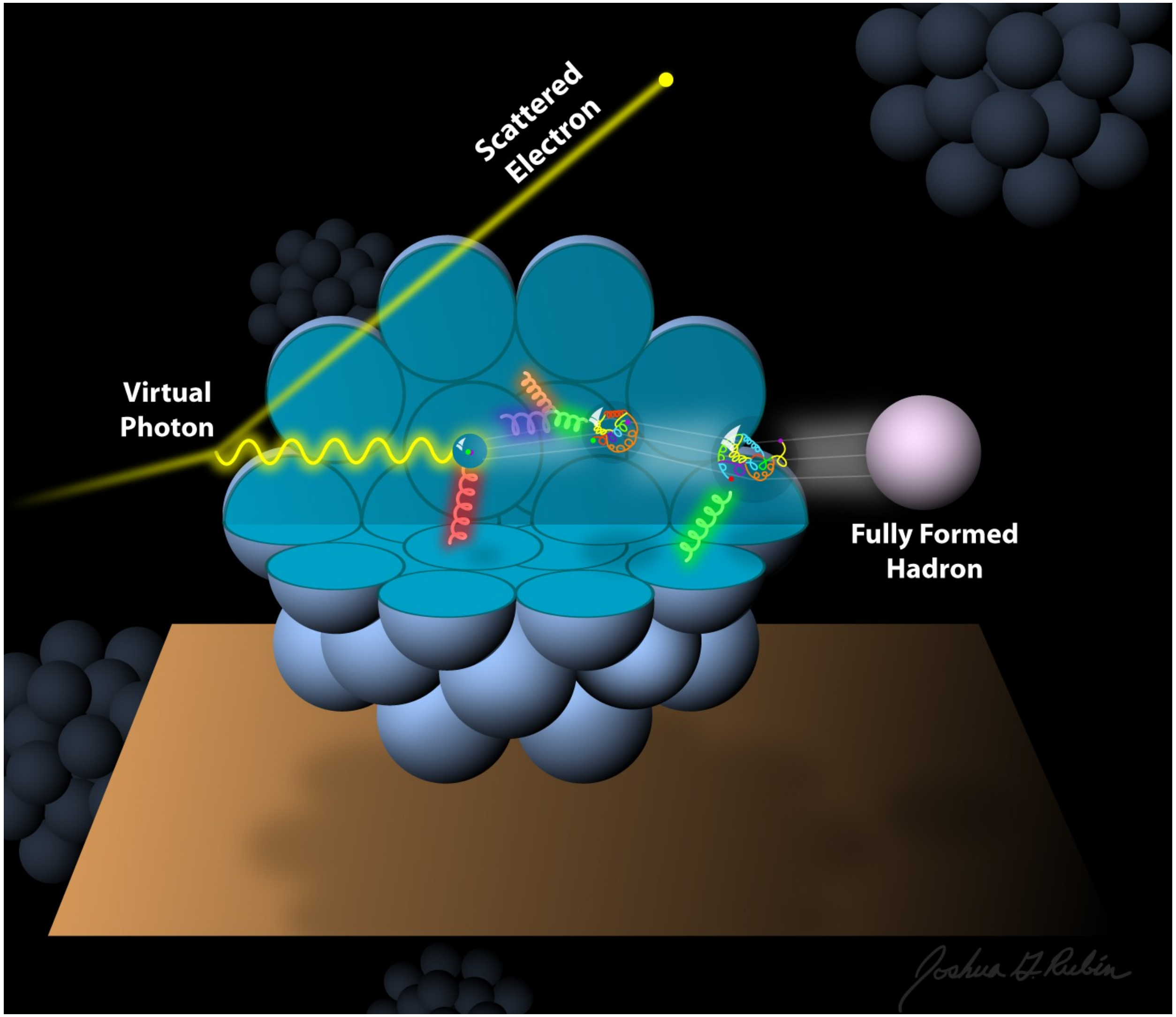
- $P_{h\perp}$ (=p_T on figures): - transverse intrinsic struck-quark momentum
  - transverse momentum from fragmentation process
- K^-: broader distribution

Comparison with models



- LO in α_S
- CTEQ6L PDFs
  JHEP **0602** (2006) 032
- DSS FFs
  Phys. Rev. D**75** (2007) 114010
- Kretzer FFs
  Phys. Rev. D**62** (2000) 054001

Probing space-time evolution of hadronization



parton and nuclear medium:

- PDFs modified by nuclear medium
- gluon radiation and rescattering

(pre-)hadron and nuclear medium:

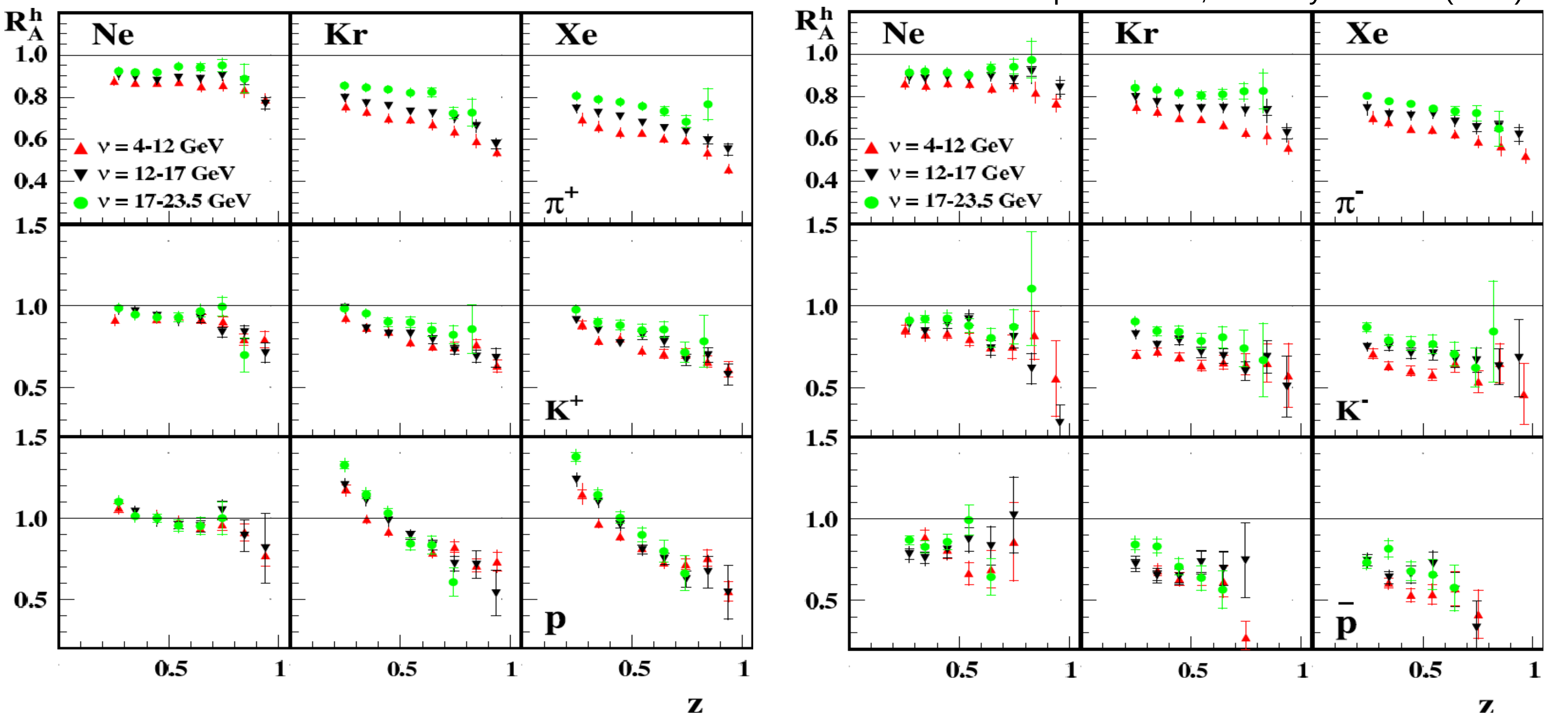
- rescattering
- absorption

- differences predicted for partonic and (pre-)hadronic interactions

hadron multiplicity ratios from heavier targets and deuterium
→ space-time evolution of hadron formation

Results in z for slices of ν

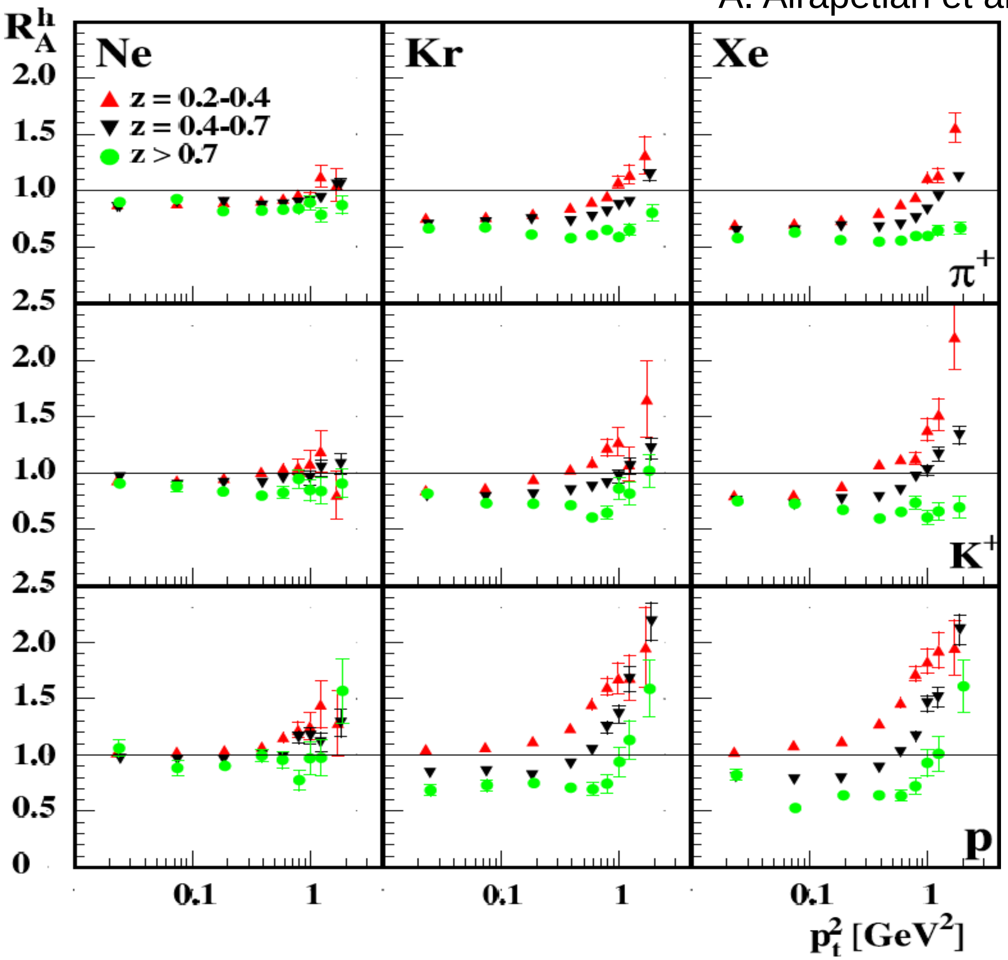
A. Airapetian et al., Eur. Phys. J. **A**47 (2011) 113



- R_A^h decreases with increasing z
- effect increases with increasing A
- p: $R_A^h > 1$ at low z
- K^+: $R_A^h \simeq 1$ at low z

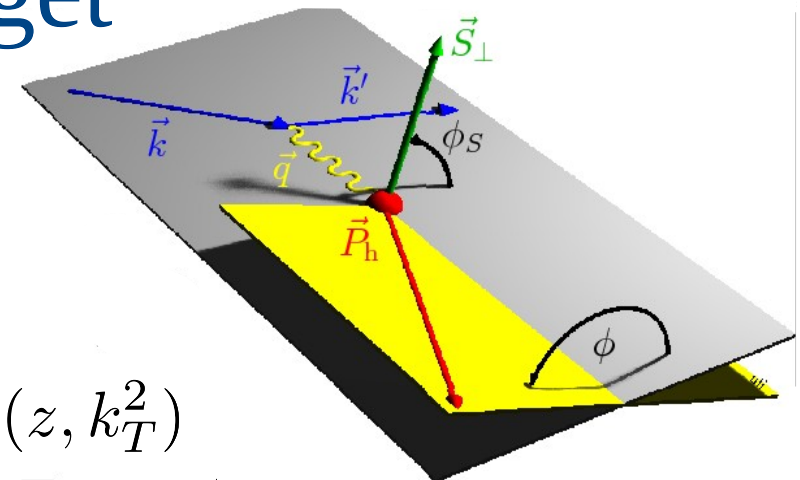
Results in $P^2_{h\perp}$ for slices of z

A. Airapetian et al., Eur. Phys. J. **A**47 (2011) 113



- R^h_A increases strongly with increasing $P^2_{h\perp}$ (Cronin effect)
- except at large z for π^+ and K^+

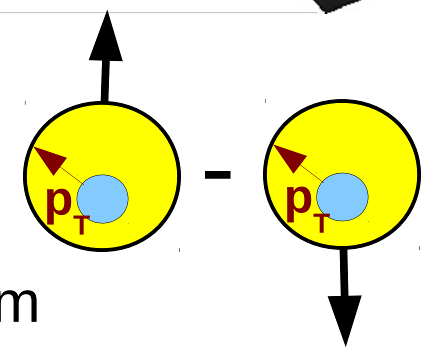
Single-spin asymmetry on transversely polarized target



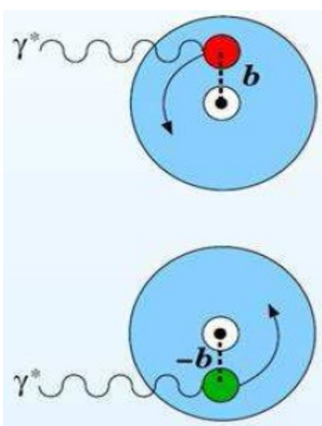
$$A_{UT} = \frac{1}{\langle |S_T| \rangle} \frac{N^\uparrow(\phi,\phi_S) - N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$

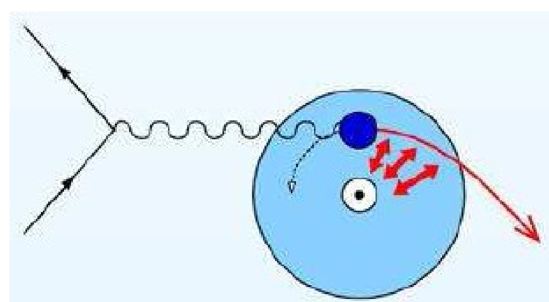
$$\sim \sin(\phi - \phi_S) \sum_q e_q \frac{\vec{p}_T . \hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x, p_T^2) \otimes D_1^q(z, k_T^2)$$

$f_{1T}^{\perp,q}(x, p_T^2)$: Sivers distribution function



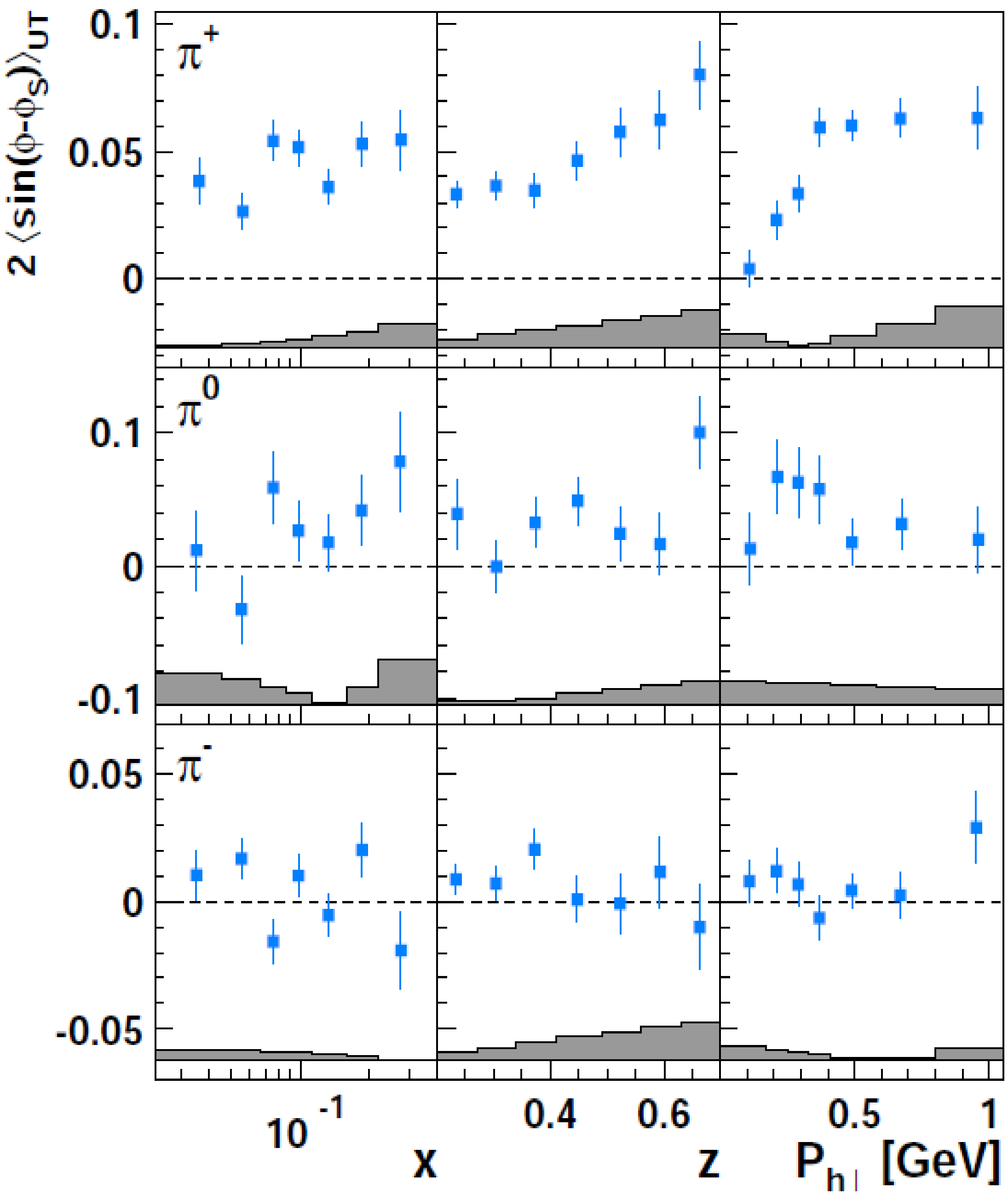
- requires non-zero quark orbital angular momentum
- naïve-T-odd
- FSI ⟶ left-right (azimuthal) asymmetry in direction of outgoing hadron





Sivers amplitudes for pions

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



- π^+
  - significantly positive → non-zero orbital angular momentum!
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - amplitude dominated by u-quark scattering:

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

→ $f_{1T}^{\perp,u}(x,p_T^2) < 0$

- π^-
  - consistent with zero
  - u- and d- quark cancellation
  - $f_{1T}^{\perp,d}(x,p_T^2) > 0$
- π^0
  - slightly positive
  - isospin symmetry fulfilled

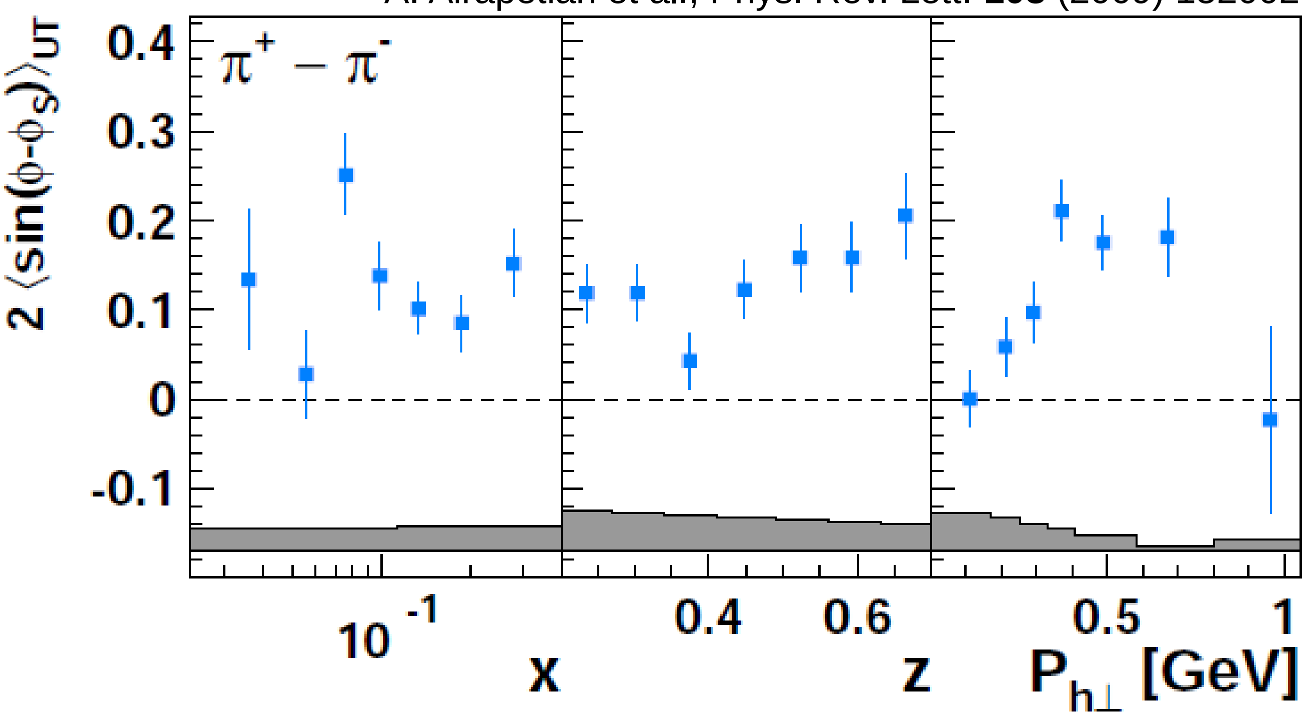
Sivers distribution for valence quarks

$$A_{UT}^{\pi^+-\pi^-} = \frac{1}{\langle|S_T|\rangle} \frac{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+} - \sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+} - \sigma_{U\downarrow}^{\pi^-})}$$

→ suppressed exclusive VM (ρ^0) contribution

→ $$\langle\sin(\phi - \phi_S)\rangle_{UT}^{\pi^+-\pi^-} \approx -\frac{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002



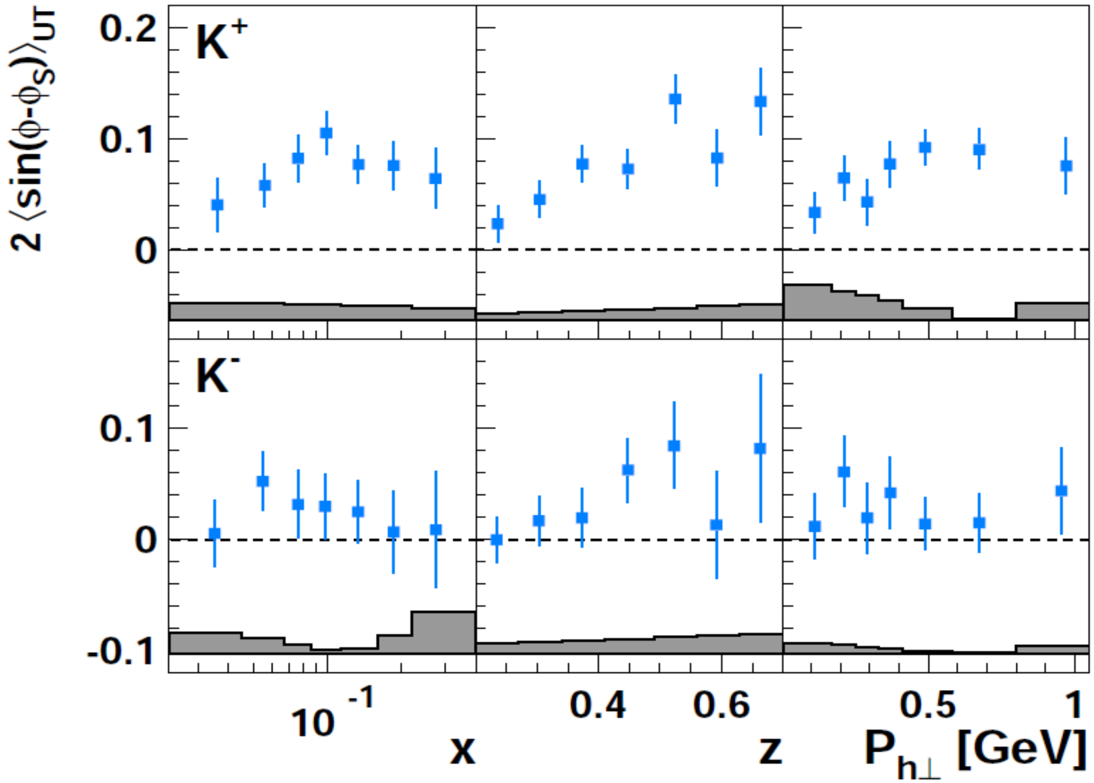
- Sivers distribution for d-valence >> u-valence

  or

- Sivers distribution for u-valence is large & <0 (more likely)

Sivers amplitudes for kaons

A. Airapetian et al., Phys. Rev. Lett. **103** (2009) 152002

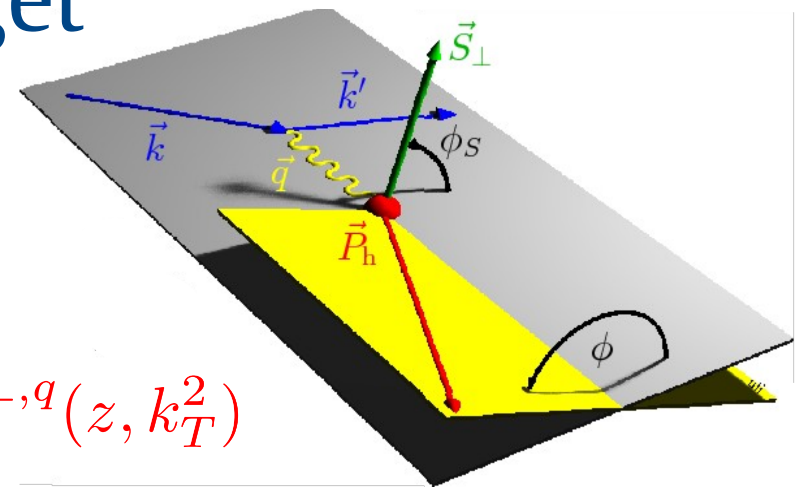


- K^+
  - significantly positive
  - clear rise with z
  - rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
  - larger than π^+

non-trivial role of sea quarks?

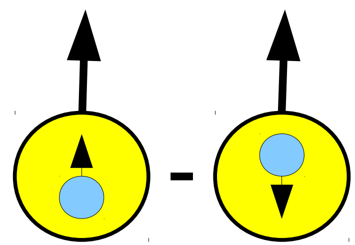
- K^-
  - slightly positive

Single-spin asymmetry on transversely polarize target



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

$$\sim \sin(\phi+\phi_S) \sum_q e_q^2 \frac{\vec{k}_T . \hat{P}_{h\perp}}{M_h} h_{1T}^q(x,p_T^2) \otimes H_1^{\perp,q}(z,k_T^2)$$

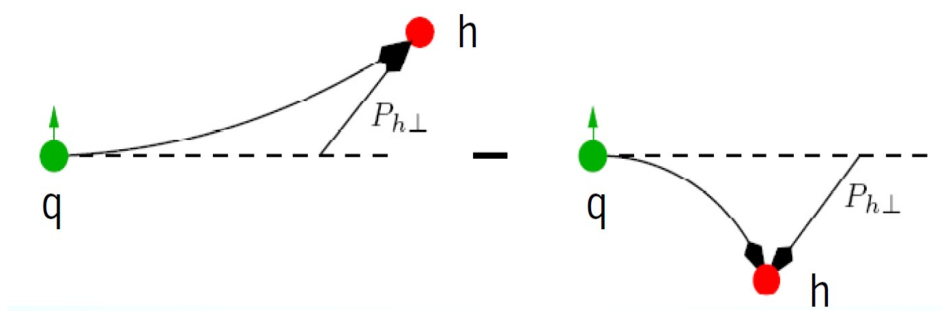


$h_{1T}^q(x,p_T^2)$: transversity

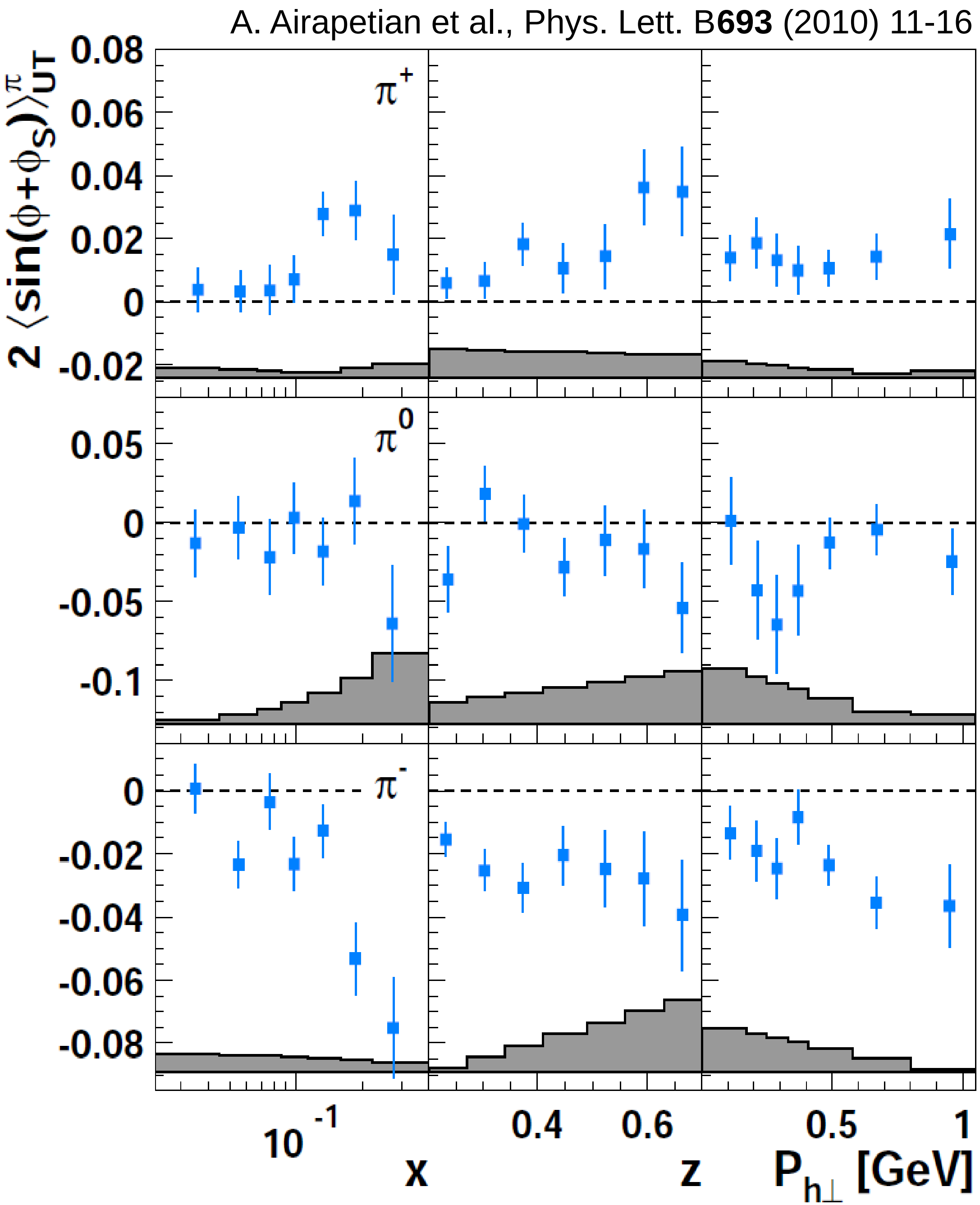
- chiral odd

$H_1^{\perp,q}(z,k_T^2)$: Collins fragmentation function

- chiral odd
- naïve-T-odd



Collins amplitudes for pions



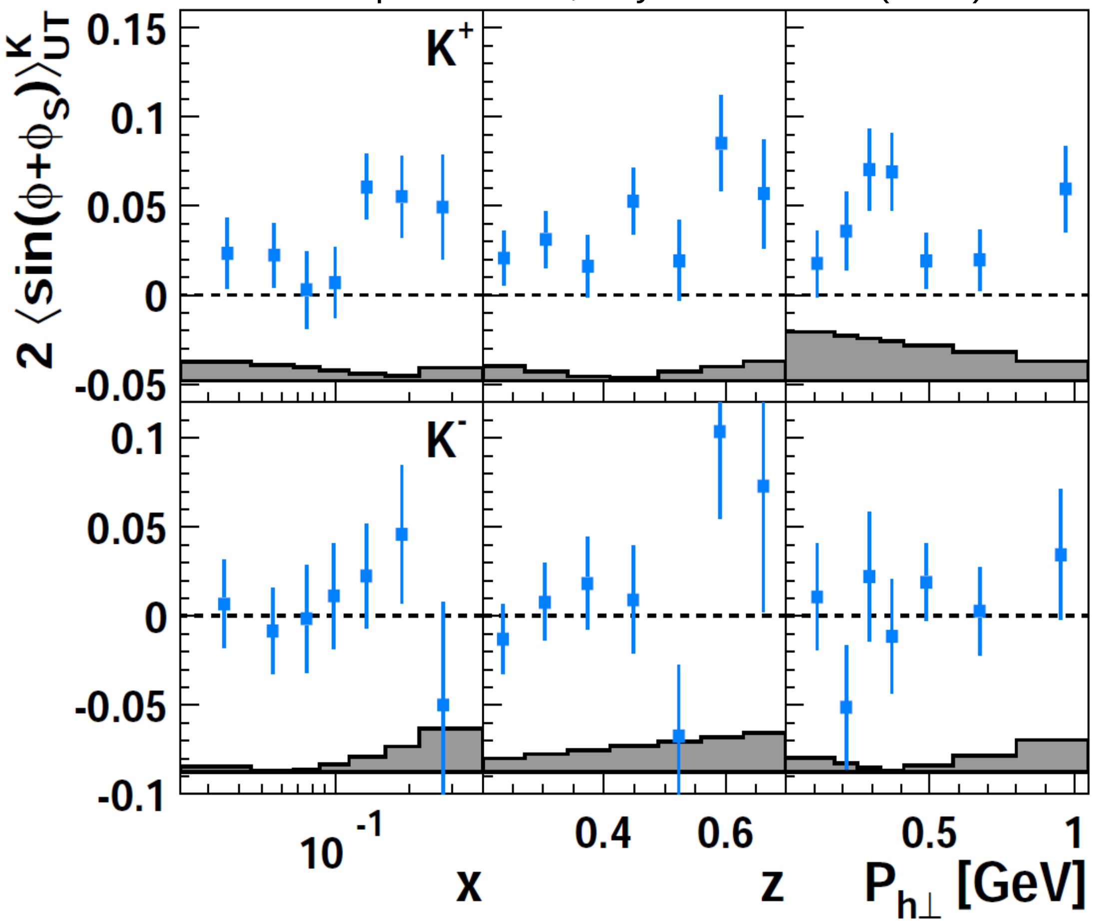
- $\pi^{\pm}$ increasing with z and x_B
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled

Collins amplitudes for kaons

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

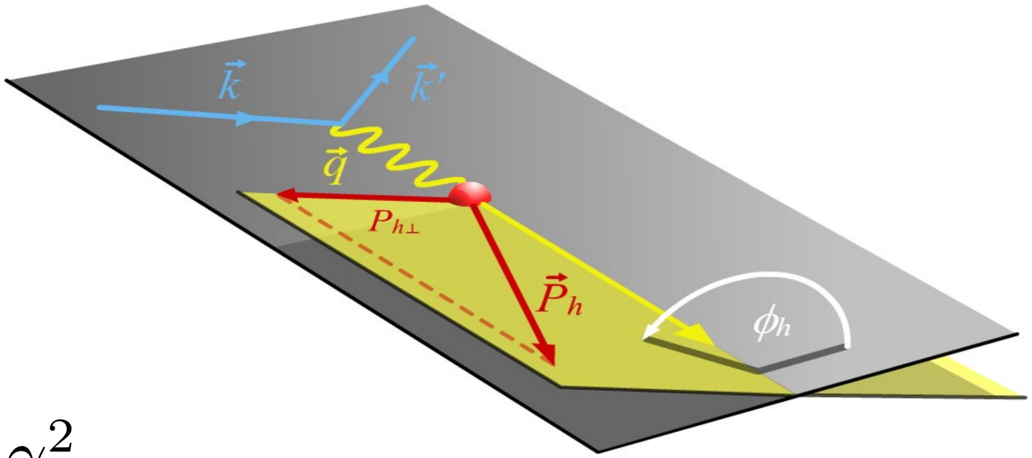


- K^+: increasing with z and x_B
- positive for K^+ & larger than for π^+
  - role of s-quark
  - u-dominance ?

$$H_1^{\perp,u\to K^+} > H_1^{\perp,u\to\pi^+}$$

- $K^- \approx 0$, $\neq$ from π^-
  K^- is pure sea object:
  sea-quark transversity expected to be small

Spin-independent semi-inclusive DIS cross section



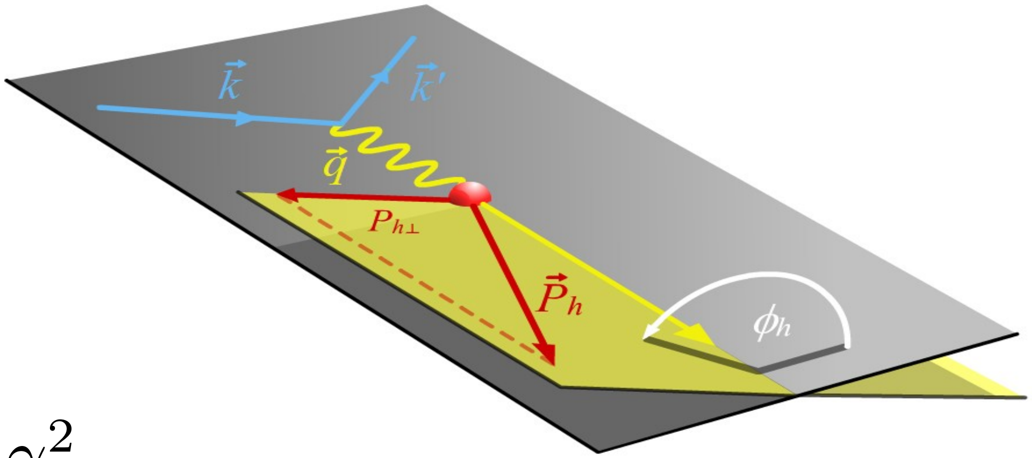
non-collinear cross section

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

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

$$\gamma = \frac{2Mx}{Q}, \; F = F(x, Q, z, \vec{P_{h\perp}})$$

Spin-independent semi-inclusive DIS cross section



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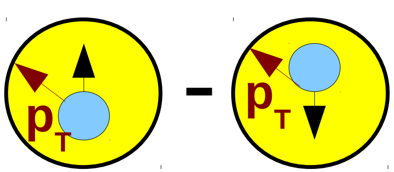
leading twist

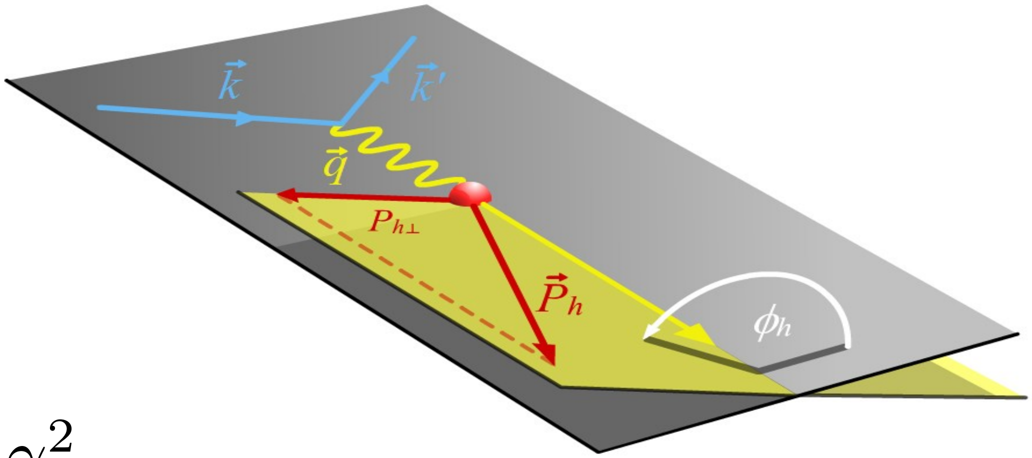
$$F_{UU}^{\cos 2\phi_h} = \mathcal{I}\left[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T) - \vec{p}_T.\vec{k}_T}{M_h M} h_1^\perp H_1^\perp\right]$$



Boer-Mulders DF
- chiral odd
- naïve-T-odd

Collins FF
- chiral odd
- naïve-T-odd

Spin-independent semi-inclusive DIS cross section



non-collinear cross section

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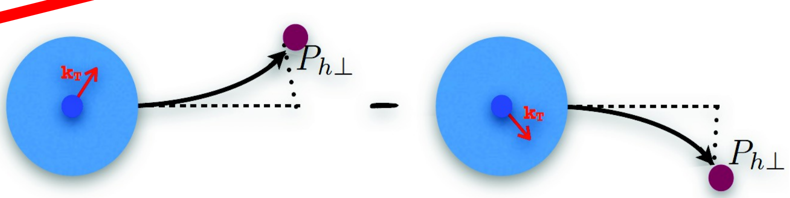
$$+C(y)\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}$$

$$\gamma = \frac{2Mx}{Q}, \quad F = F(x, Q, z, \vec{P_{h\perp}})$$

sub-leading twist

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{I}\left[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp + \ldots\right]$$

Cahn effect



quark-gluon-quark correlations

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \stackrel{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

$$\updownarrow$$

$$\langle \cos(n\phi_h) \rangle \stackrel{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}$$

extraction is challenging!
azimuthal modulations also possible due to
- detector geometrical acceptance
- higher-order QED effects

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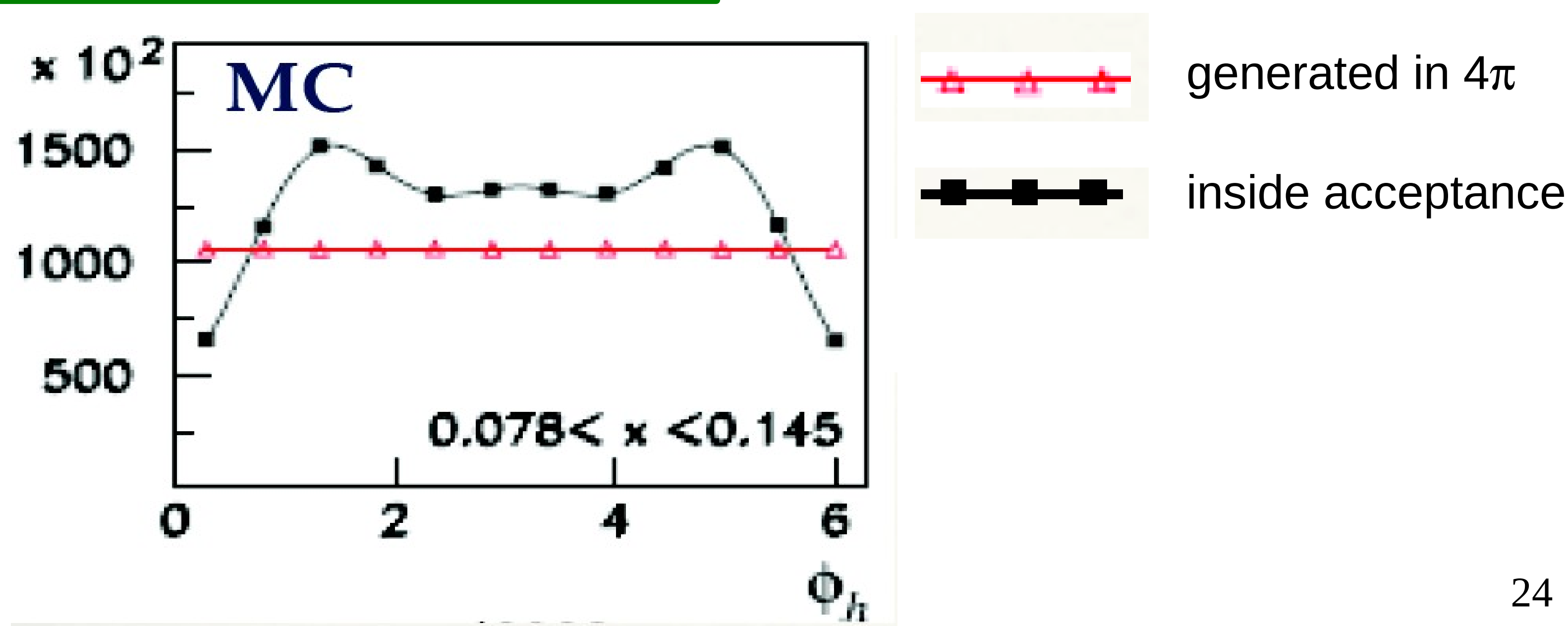

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extraction is challenging!

azimuthal modulations also possible due to

- detector geometrical acceptance
- higher-order QED effects

fully differential analysis needed

unfolding procedure with 400 x 12 bins

BINNING 400 kinematic bins x 12 ϕ-bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

Extraction of the cosine moments

$$\langle \cos(n\phi_h) \rangle \overset{th.}{=} \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)}$$

$$\omega = (x, y, z, P_{h\perp}^2)$$

$$\langle \cos(n\phi_h) \rangle \overset{exp.}{=} \frac{\int d\phi_h \cos(n\phi_h) \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \epsilon_{acc}(\omega, \phi_h) \epsilon_{rad}(\omega, \phi_h) \sigma_{UU}(\omega, \phi_h)}$$

extraction is challenging!
azimuthal modulations also possible due to
- detector geometrical acceptance
- higher-order QED effects

unfolding

$$\langle \cos(n\phi_h) \rangle \Big|_{\text{bin i}} \approx \frac{\int d\phi_h \cos(n\phi_h) \sigma_{UU}(\omega, \phi_h)}{\int d\phi_h \sigma_{UU}(\omega, \phi_h)} \Bigg|_{\text{bin i}}$$

fully differential analysis needed
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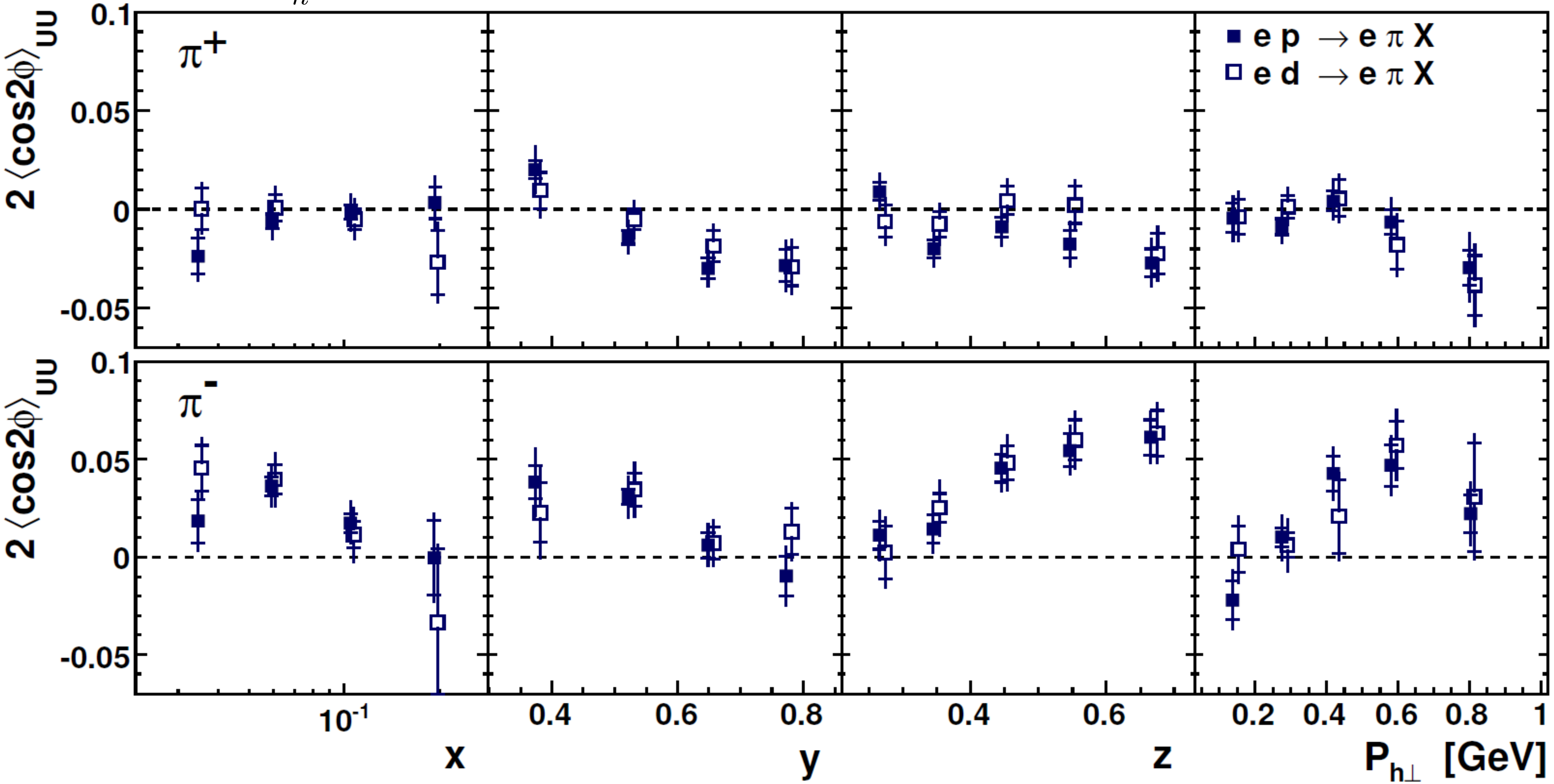
P_{hT}	0.05	0.2	0.35	0.5	0.75		4

Results for <cos 2ϕ_h>: pions

$$\mathcal{I}[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T) - \vec{p}_T.\vec{k}_T}{M_h M} h_1^{\perp} H_1^{\perp}]$$

A. Airapetian et al., arXiv:1204.4161

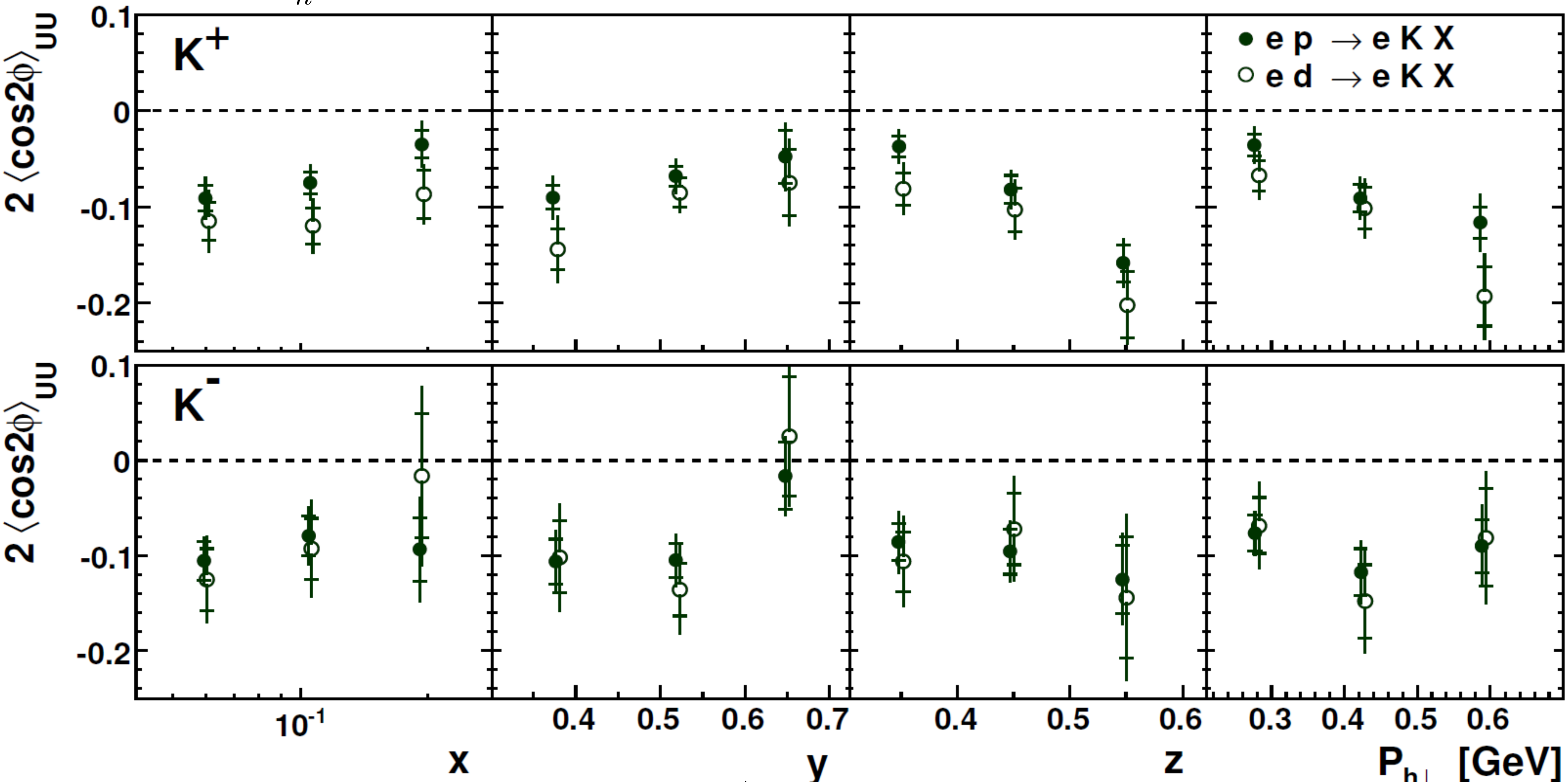


- H-D comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- $\pi^- > 0$ ◄──► $\pi^+ \leqslant 0$: $H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$

Results for <cos 2ϕ$_h$>: kaons

$$\mathcal{I}[-\frac{2(\hat{P}_{h\perp}.\vec{p}_T)(\hat{P}_{h\perp}.\vec{k}_T)-\vec{p}_T.\vec{k}_T}{M_h M} h_1^\perp H_1^\perp]$$

A. Airapetian et al., arXiv:1204.4161

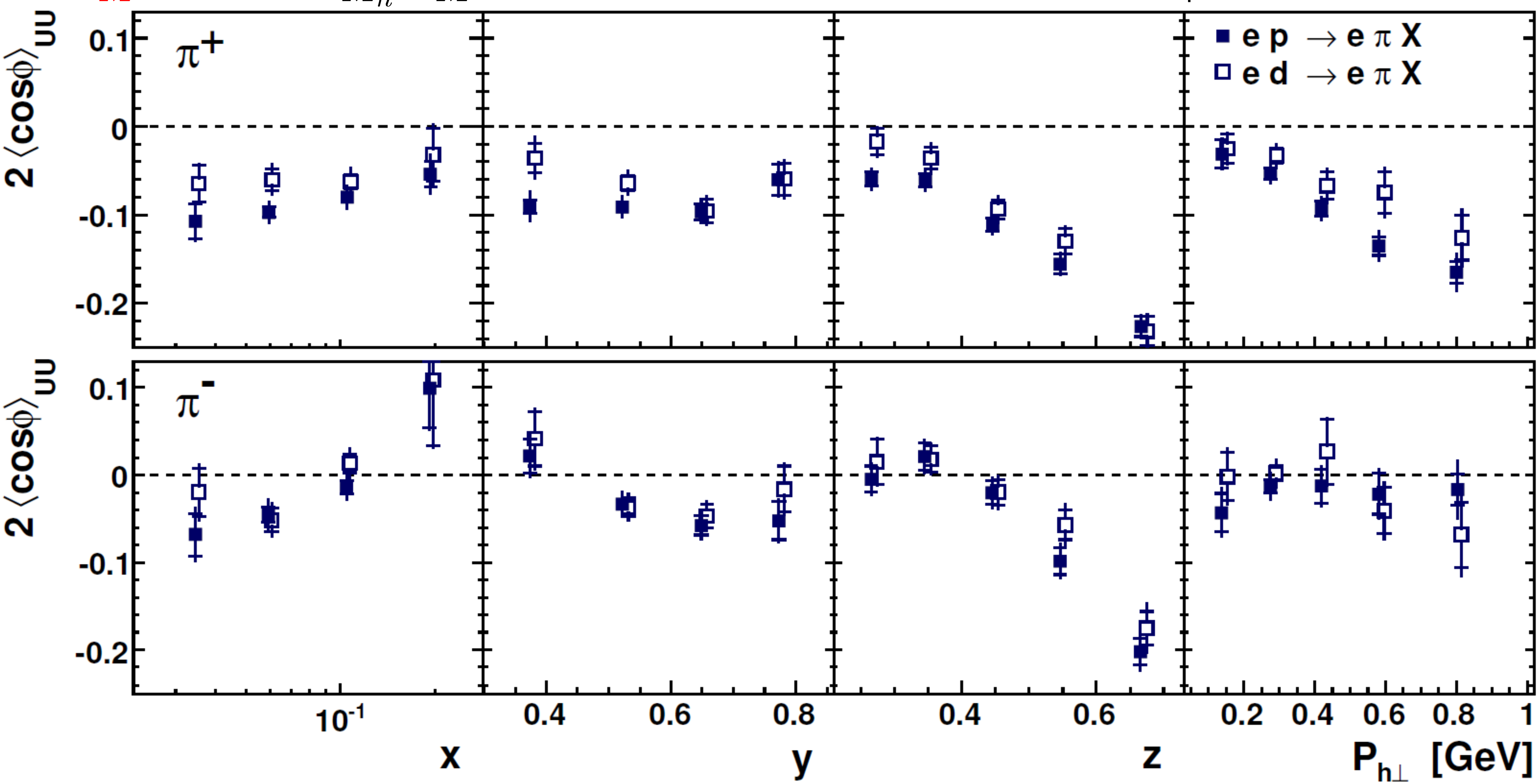


- $K^+<0$: - Artru model: sign $H_1^{\perp,u\to K^+}$ = sign $H_1^{\perp,u\to\pi^+}$
- $K^- \simeq K^+$: - u-dominance $\xrightarrow{?}$ $H_1^{\perp,u\to K^+} \approx H_1^{\perp,u\to K^-}$
  - role of sea-quarks

Results for <cos ϕ_h>: pions

$$\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp + ...]$$

A. Airapetian et al., arXiv:1204.4161

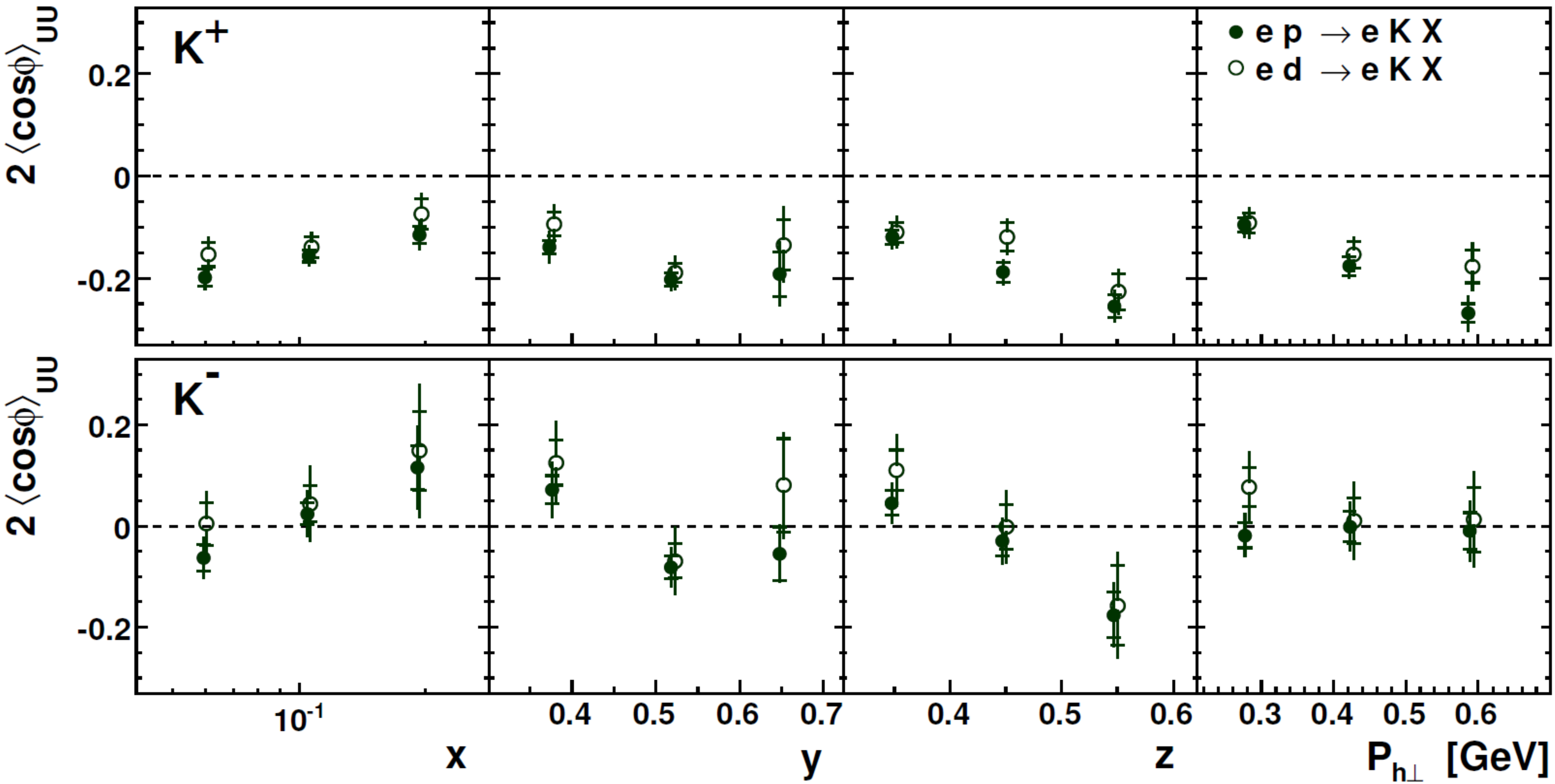


- H-D comparison: weak flavor dependence
- magnitude increases with z
- π^+: magnitude increases with $P_{h\perp}$

Results for <cos ϕ_h>: kaons

$$\mathcal{I}[-\frac{\hat{P}_{h\perp}.\vec{p}_T}{M} f_1 D_1 - \frac{\hat{P}_{h\perp}.\vec{k}_T}{M_h}\frac{p_T^2}{M^2} h_1^\perp H_1^\perp + ...]$$

A. Airapetian et al., arXiv:1204.4161



- $K^+<0$, larger in magnitude than π^+
- $K^-\simeq 0$

Summary

- $p^{\pm}$ and $K^{\pm}$ multiplicities on hydrogen and deuterium:

  - 3-dimensional extraction

  - support notion of favored fragmentation

- hadronization in nuclei:

  - 2-dimensional extraction

  - contribute to increased understanding of fragmentation process

- significant Sivers amplitudes for π^{+} and K^{+} (role of sea quarks)

  non-zero orbital angular momentum

- significant Collins amplitudes for $\pi^{\pm}$ and K^{+}

  access to transversity and Collins fragmentation function

- Spin-independent non-collinear cross section:

  evidence for non-zero Boer-Mulders distribution function and Collins fragmentation function

  through Cahn effect constraint on quark intrinsic momentum and spin-independent transverse-momentum fragmentation functions

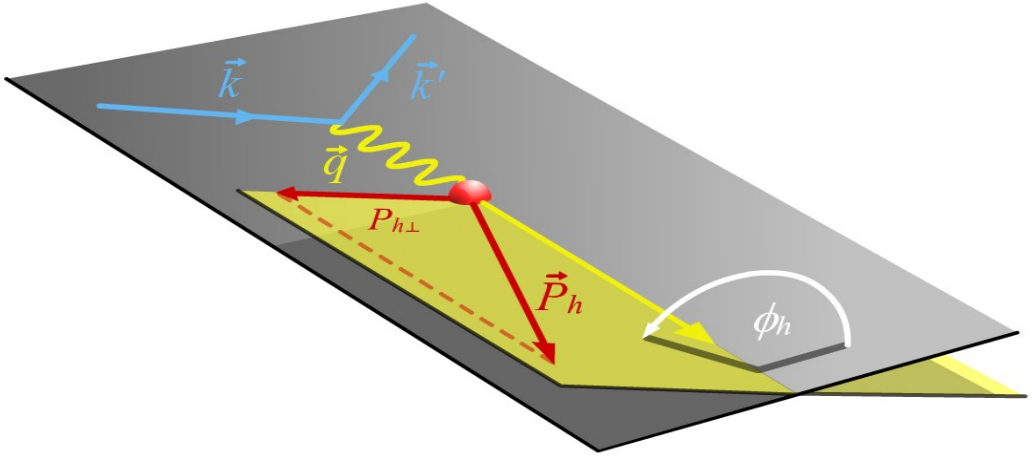
Backup

Extraction of multiplicities

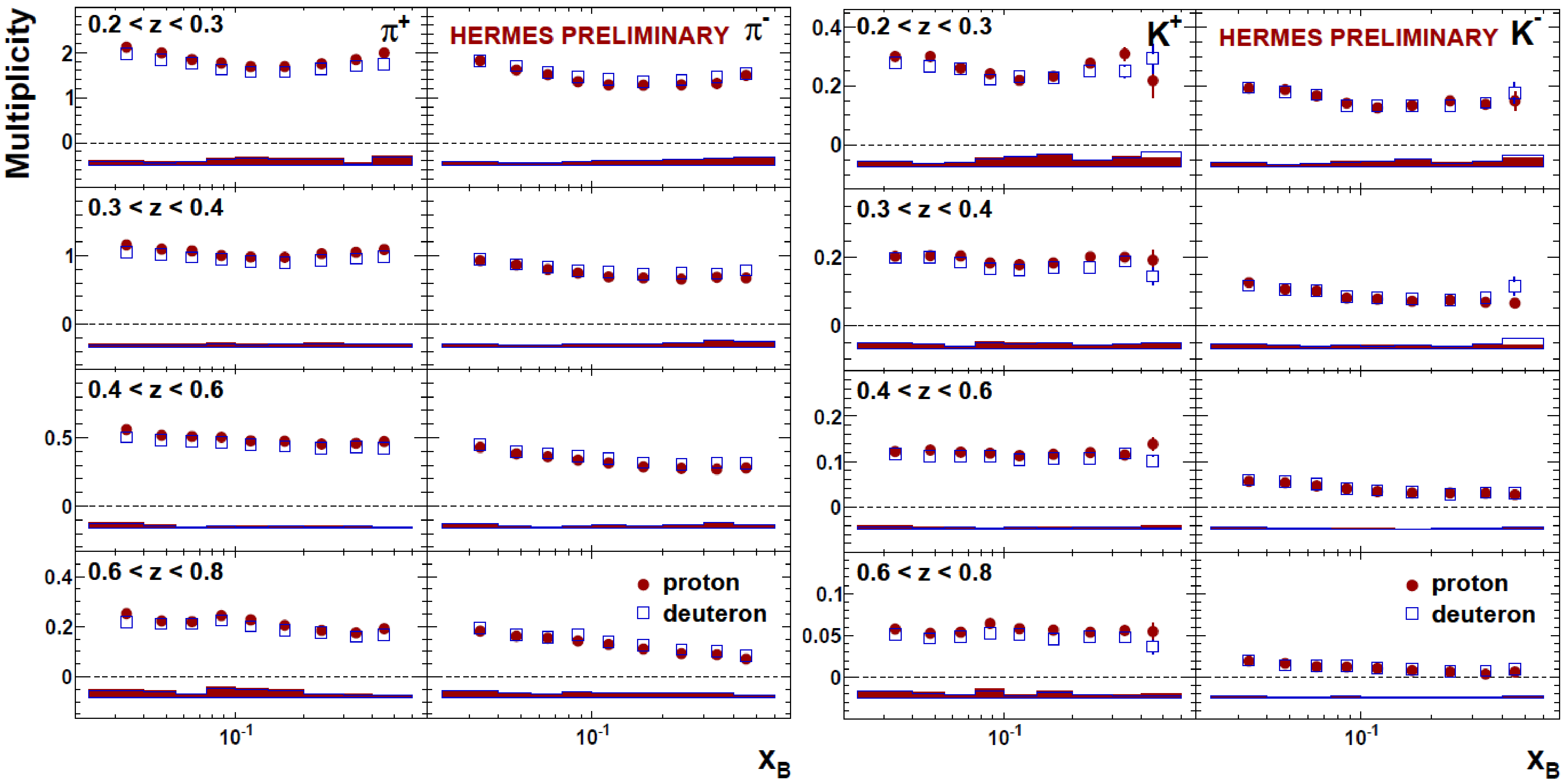
- charged pion and kaon multiplicities
- hydrogen and deuterium targets
- kinematic requirements:

$$Q^2 > 1\ \mathrm{GeV}^2 \qquad 0.1 < y < 0.85$$
$$W^2 > 10\ \mathrm{GeV}^2 \qquad 2\ \mathrm{GeV} < P_h < 15\ \mathrm{GeV}$$
$$0.2 < z < 0.8$$

- 3D binning: $(x_B, z, P_{h\perp})$ and $(Q^2, z, P_{h\perp})$

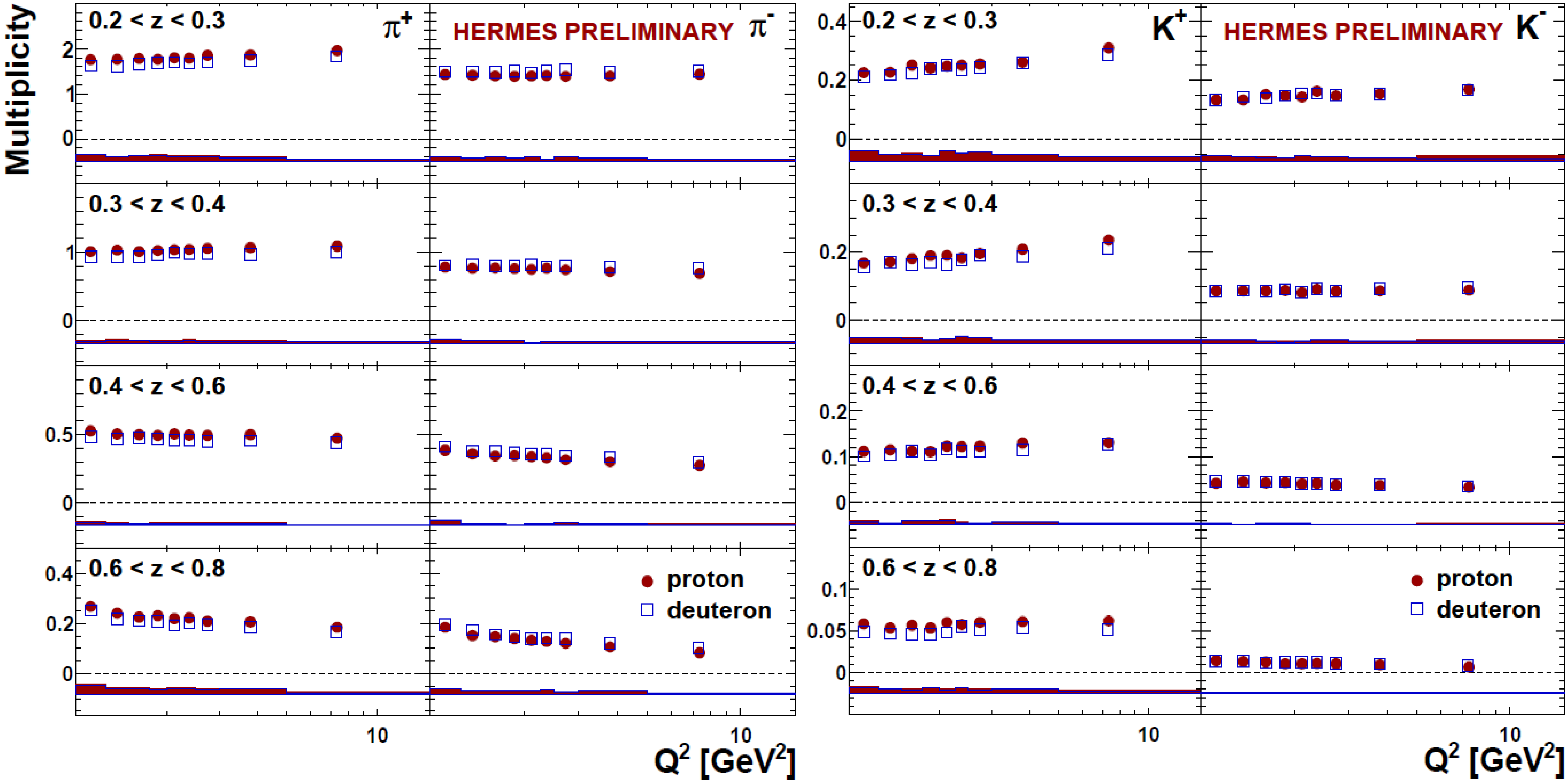


Multiplicities: results projected in z_B and x



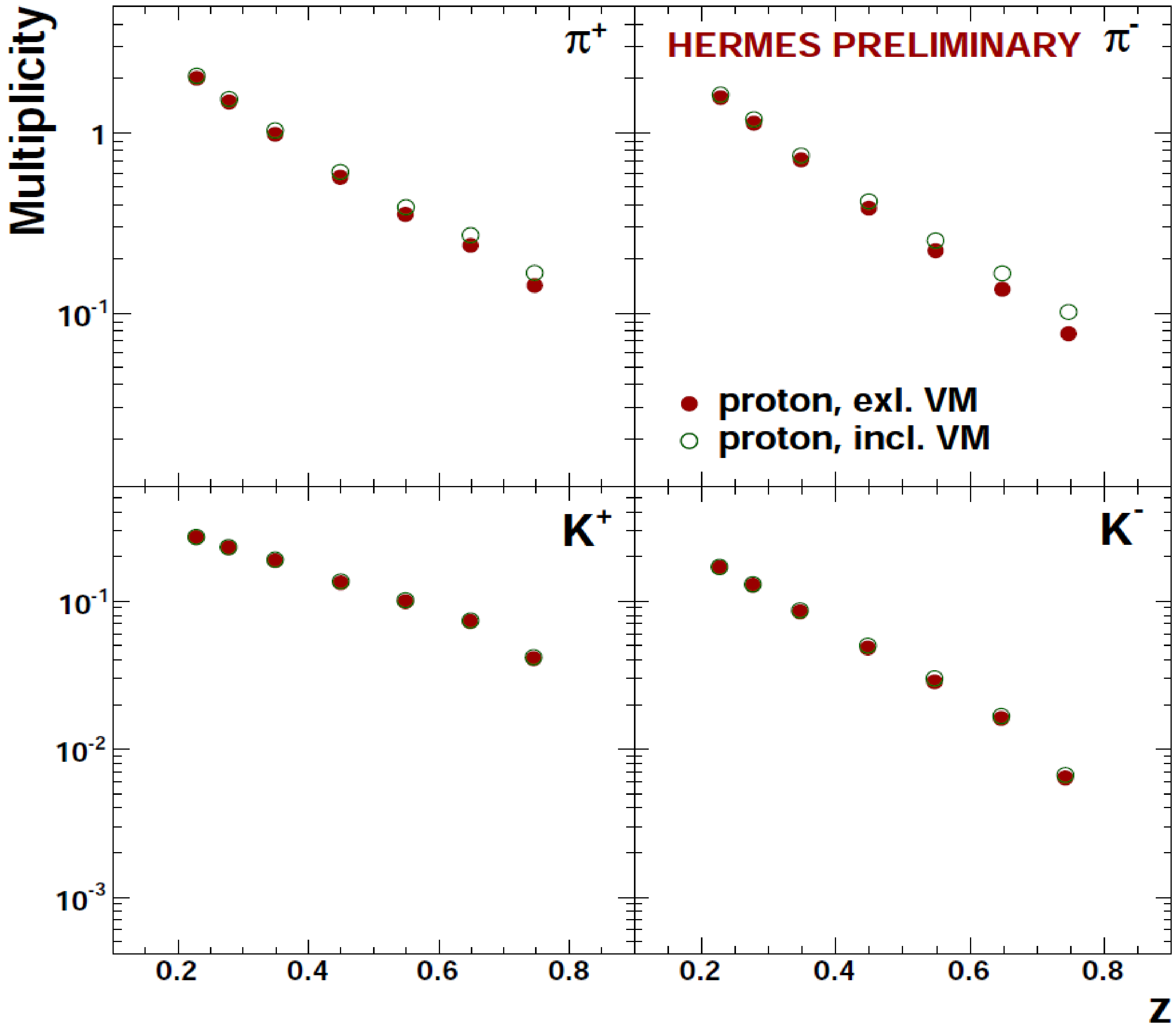
- no strong dependence on x_B

Multiplicities: results projected in z and Q^2

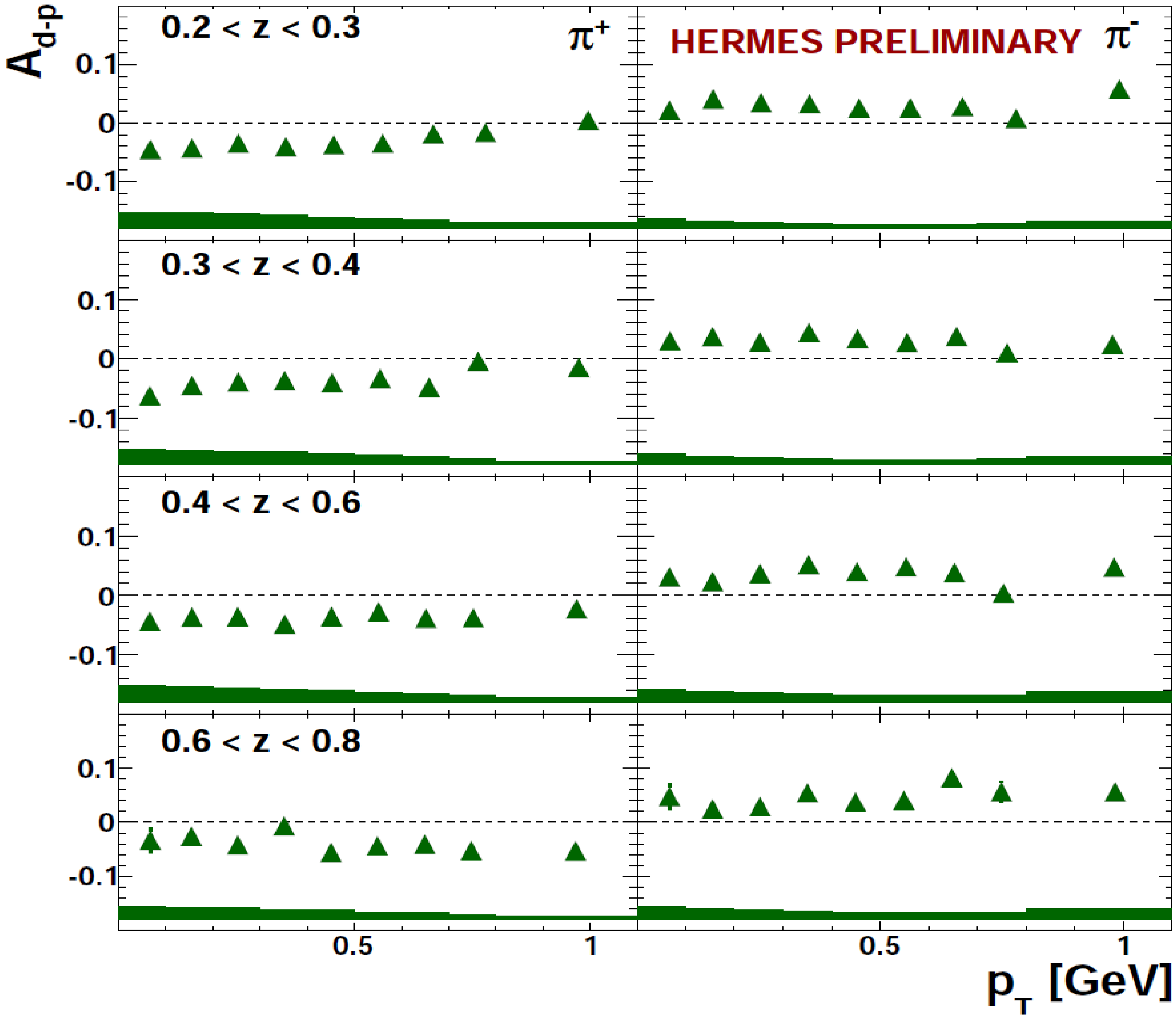


- strong correlation x_B and Q^2

Multiplicities projected in z: VM contribution

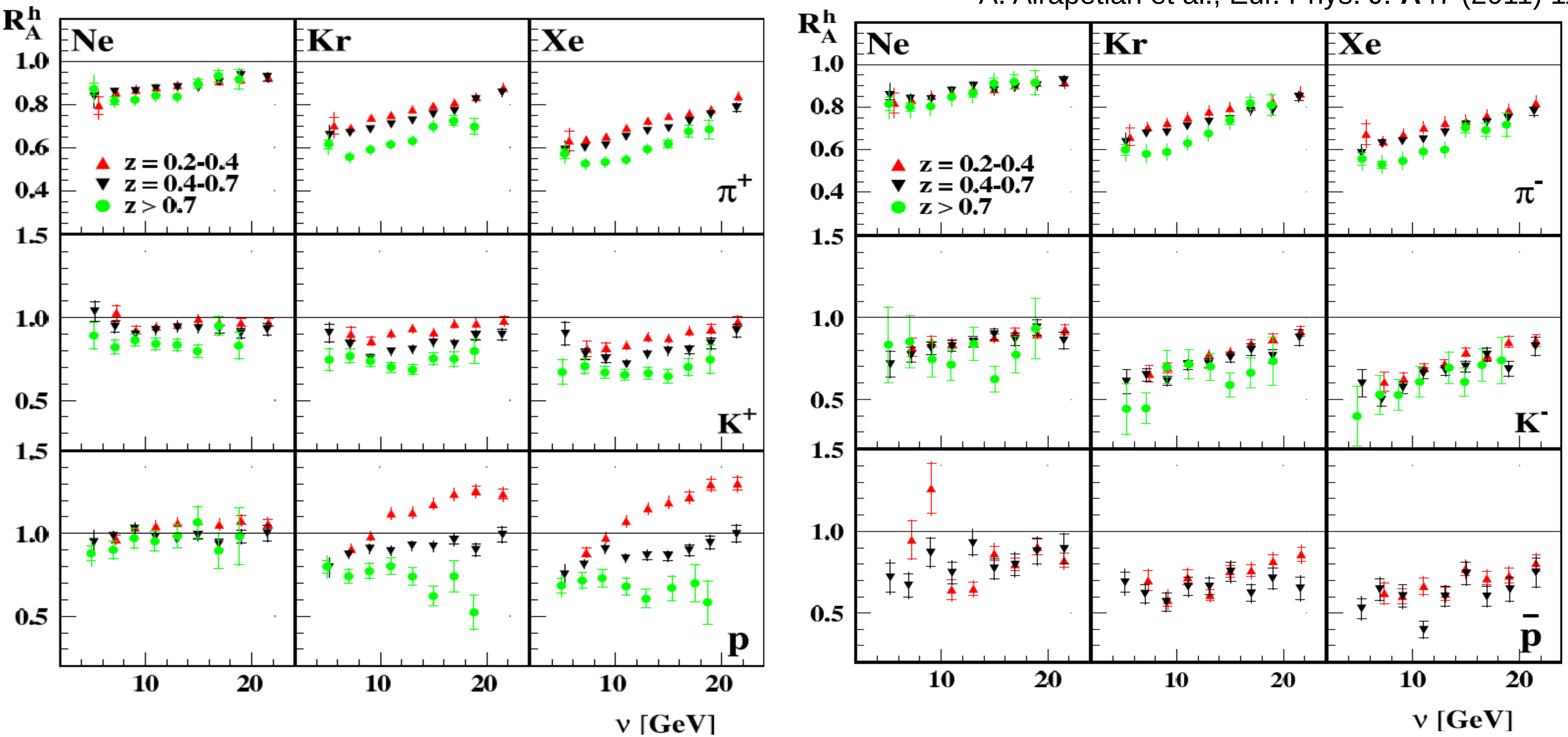


Mulitplicities d-p: results projected in z and $P_{h\perp}$



Multiplicity ratios: results in ν for slices of z

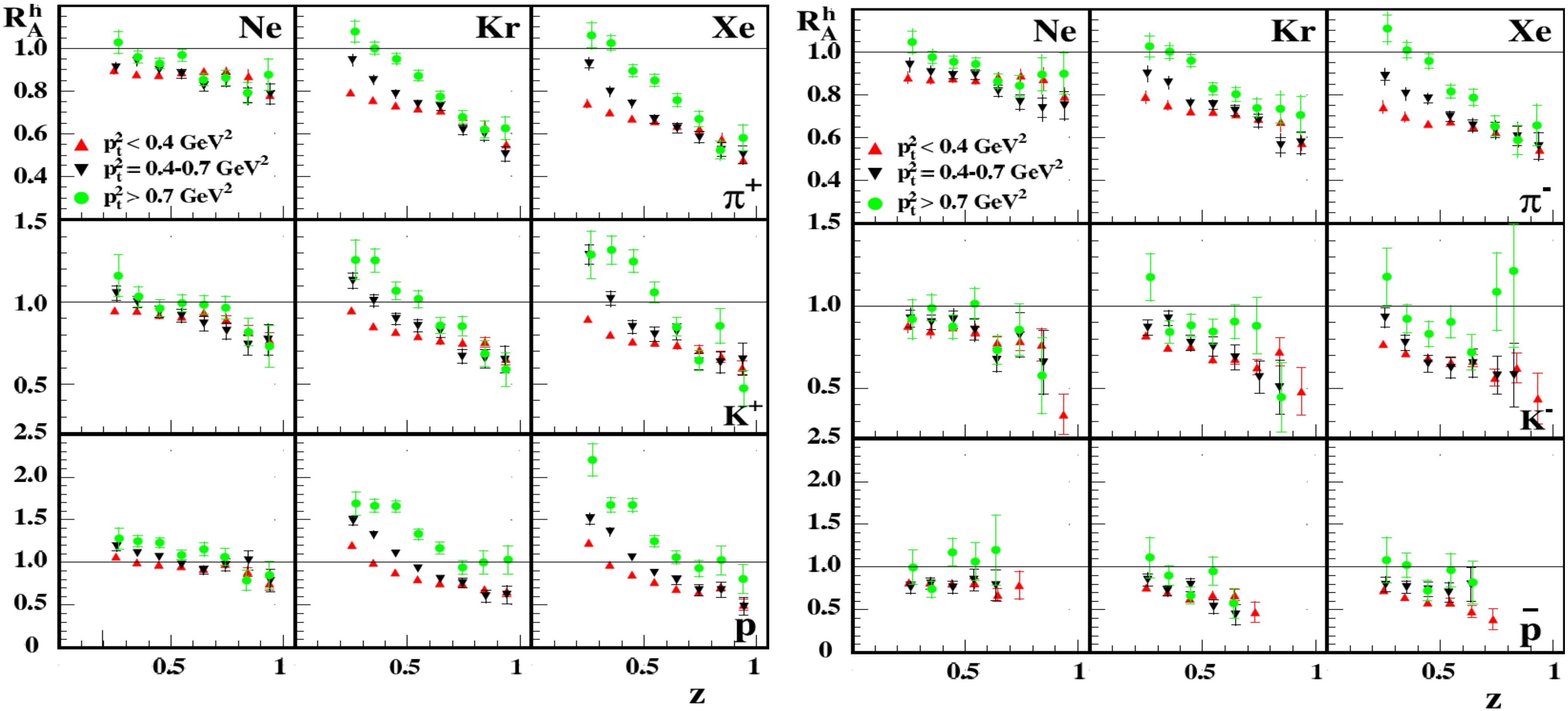
A. Airapetian et al., Eur. Phys. J. **A**47 (2011) 113



- R_A^h decreases with increasing A (except for protons)
- $\pi^\pm$ & K^-: R_A^h increases with increasing ν
- K^+: R_A^h increases with increasing ν, but different behavior
- p: $R_A^h > 1$ at low z

Results in z for slices of $P^2_{h\perp}$

A. Airapetian et al., Eur. Phys. J. **A**47 (2011) 113

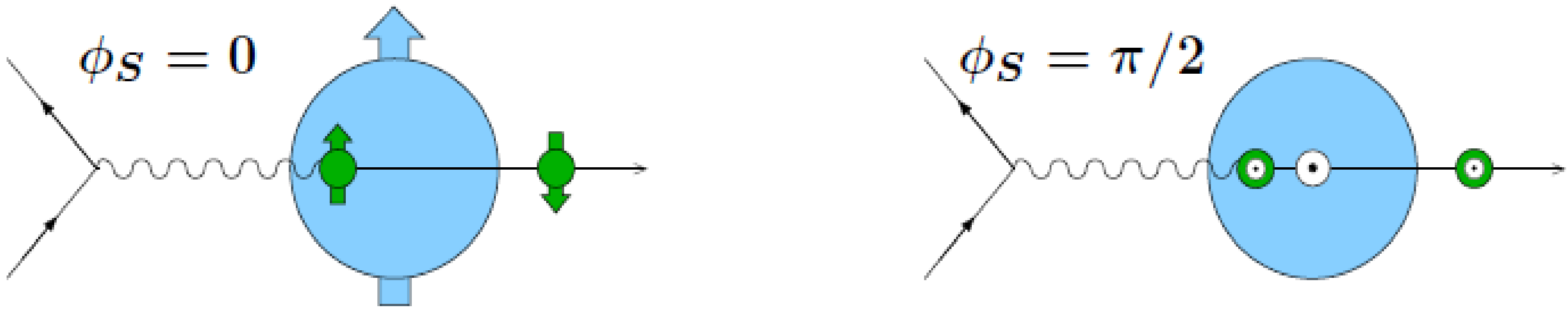


- decrease of R^h_A with increasing z stronger at large $P^2_{h\perp}$ and A
- no Cronin effect at large z
- p: R^h_A at low z larger for large $P^2_{h\perp}$

Collins fragmentation function: Artru model

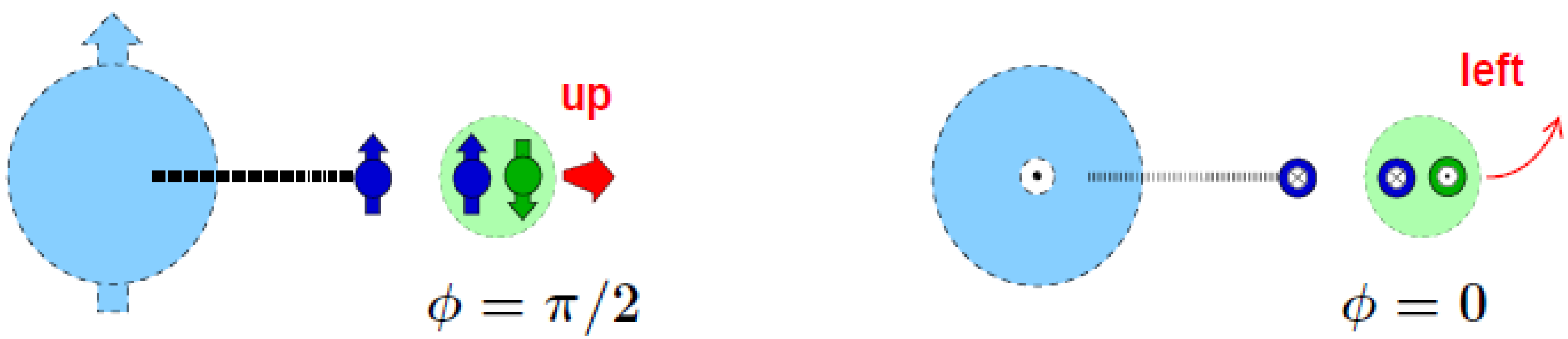
X. Artru et al. , Z. Phys. C**73** (1997) 527

polarisation component in lepton scattering plane reversed by photoabsorption:



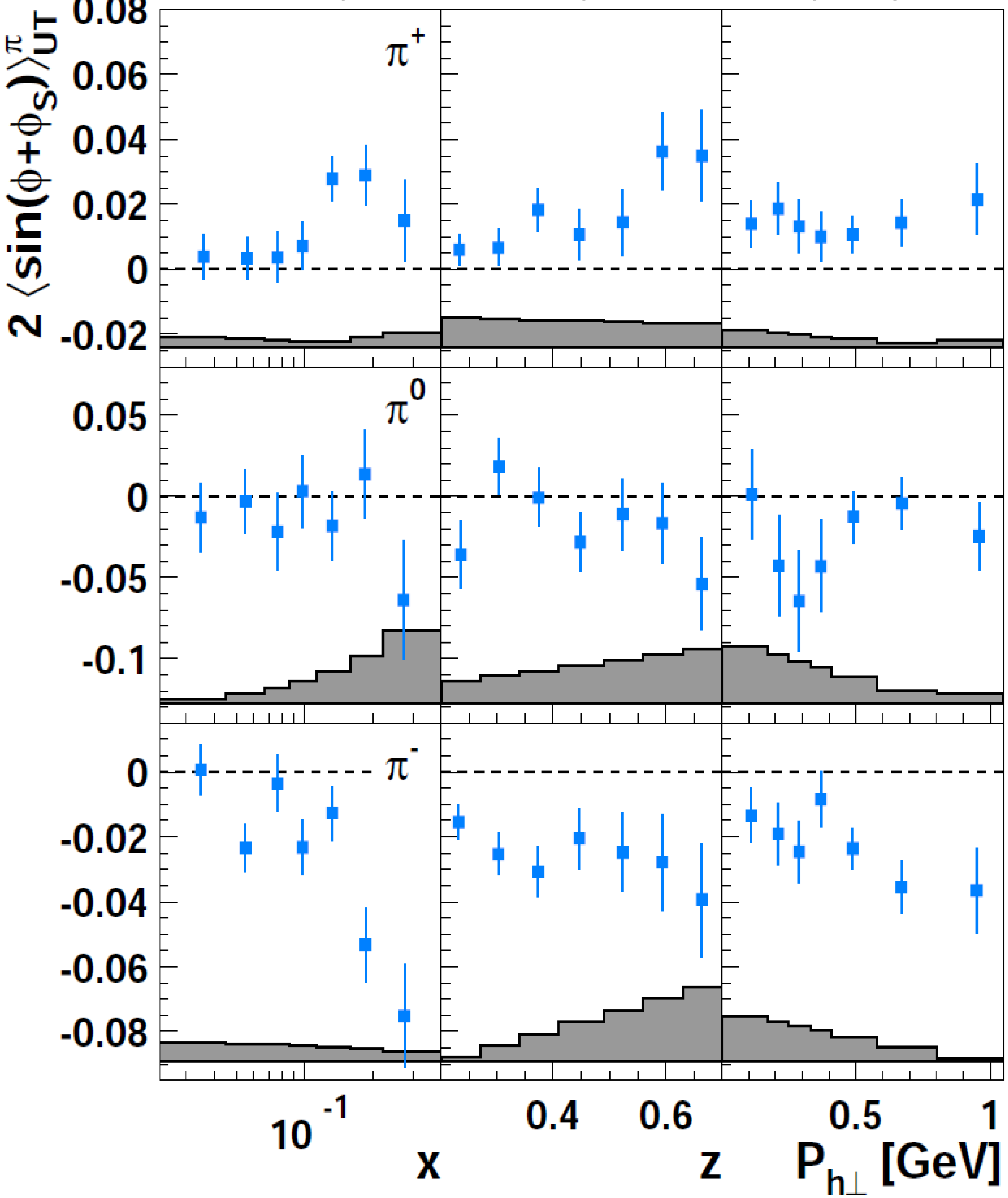
string break, quark-antiquark pair with vacuum numbers:

orbital angular momentum creates transverse momentum:



Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

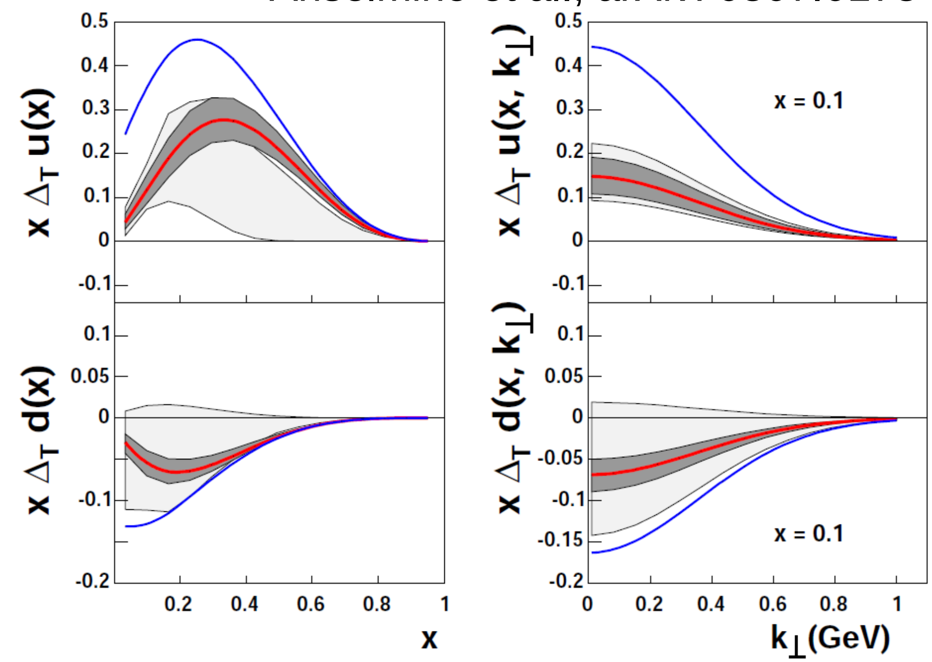


- $\pi^{\pm}$ increasing with z
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

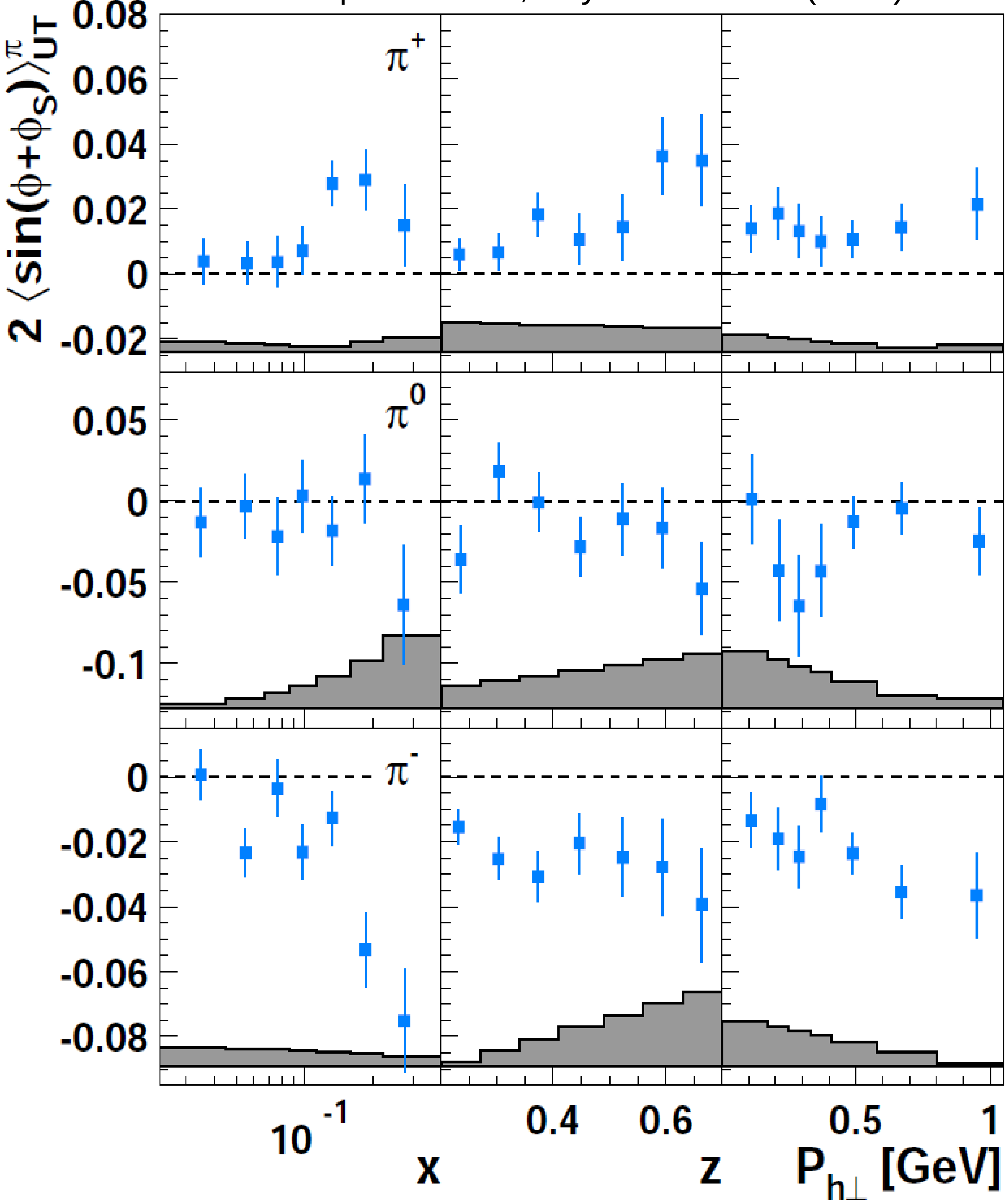
- isospin symmetry fulfilled
- data from BELLE, COMPASS & HERMES ⟶ extraction of h^q_{1T}

Anselmino et al., arXiv: 0807.0173



Collins amplitudes for pions

A. Airapetian et al., Phys. Lett. B**693** (2010) 11-16

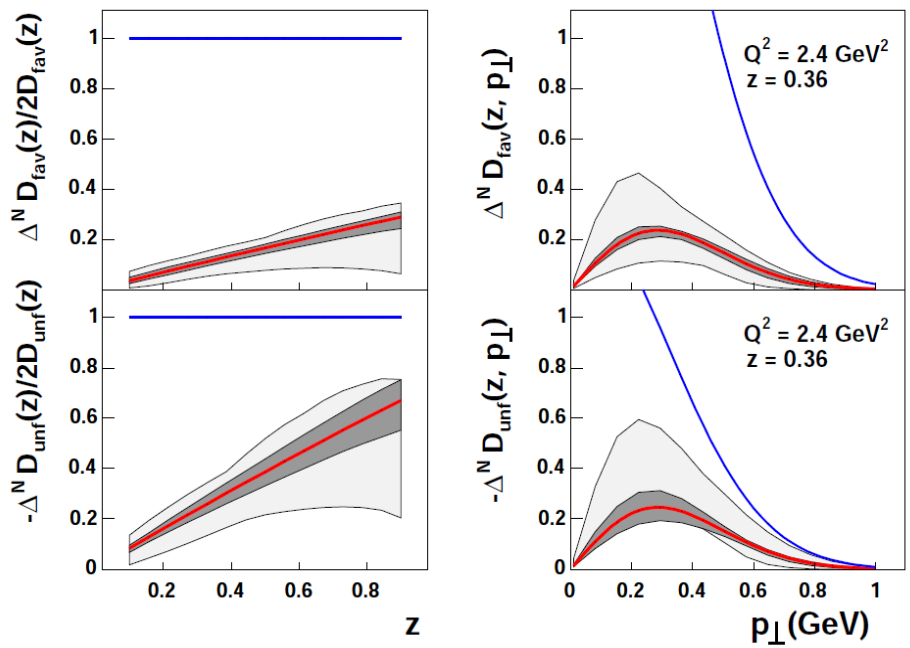


- $\pi^{\pm}$ increasing with z
- positive for π^+
- large & negative for π^-

$$H_1^{\perp,fav} \approx -H_1^{\perp,unfav}$$

- isospin symmetry fulfilled
- data from BELLE, COMPASS & HERMES $\longrightarrow$ extraction of $H_1^{\perp}$

Anselmino et al., arXiv: 0807.0173



Cahn effect

R. N. Cahn, Phys. Lett. B78:269, 1978
Phys. Rev. D40: 3107, 1989

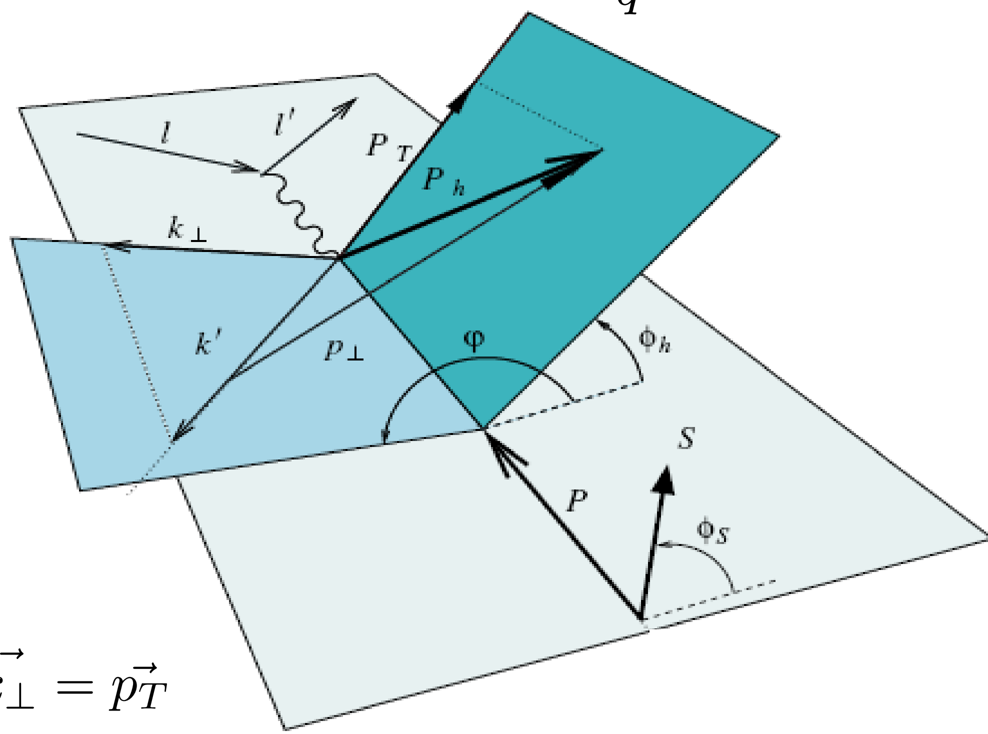
M. Anselmino et al., Phys. Rev. D71:074006, 2005

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}^2} \sim \sum_q \int d^2p_T\, f_1^q(x, p_T)\, \frac{d\hat{\sigma}^{lq\to lq}}{dQ^2}\, D_1^q(z, p_\perp)\ldots.$$

$$\frac{2\pi\alpha^2}{x^2s^2}\,\frac{\hat{s}^2+\hat{u}^2}{Q^4} \sim \vec{l}.\vec{p}_T \sim \cos\varphi$$

and

$$\vec{P}_{h\perp} \simeq z\vec{p}_T + \vec{k}_T$$



$$\vec{k_\perp} = \vec{p_T}$$

after integration over p_T azimuthal dependence remains, reflected in $\cos\phi_h$