Indiana-Illinois Workshop on Fragmentation Functions

Bloomington, IN,
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# Semi-inclusive DIS off unpolarized targets

--the hermes perspective--


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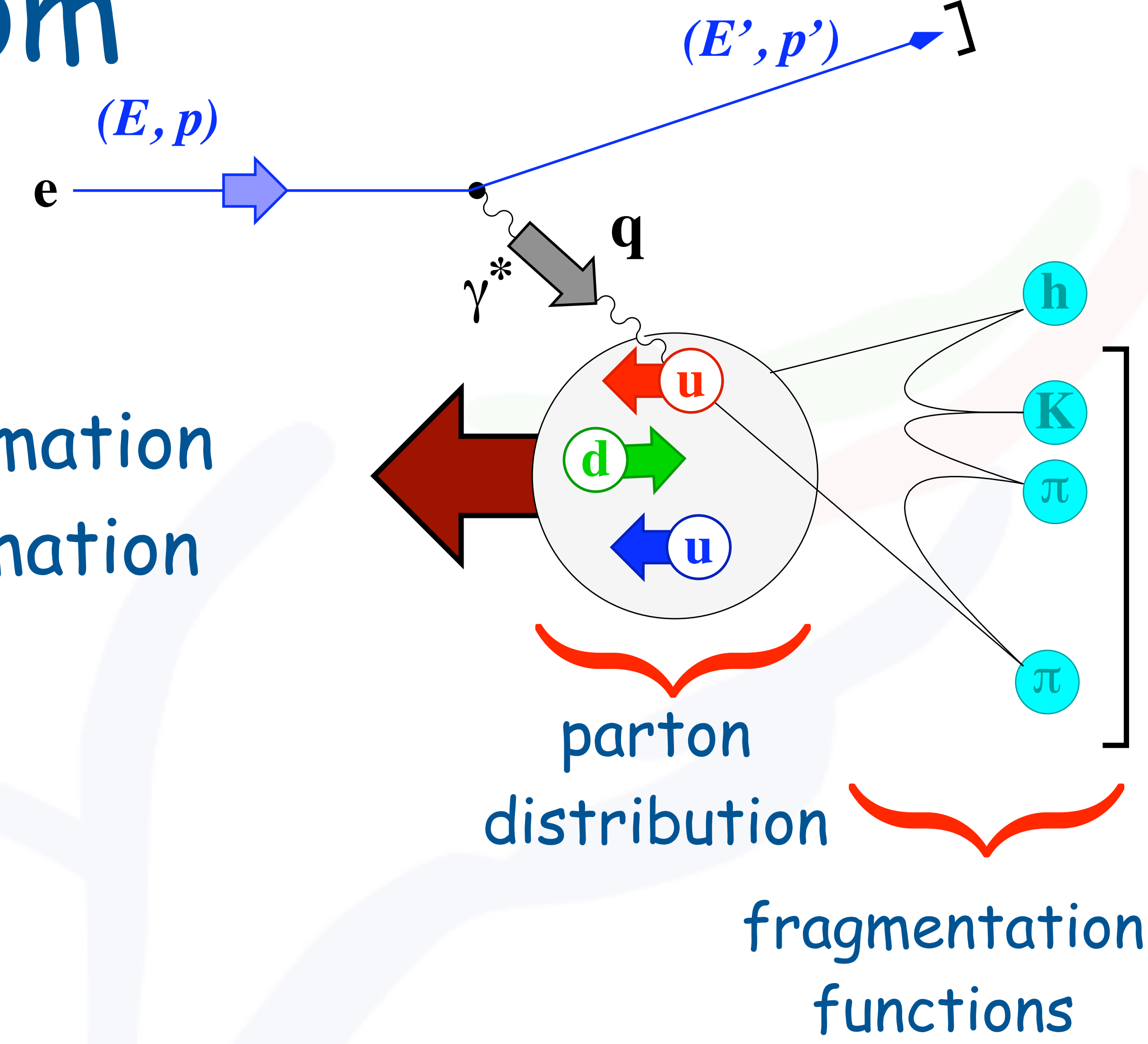
# Why study SIDIS from unpolarized targets?

- Semi-inclusive DIS provides information on both hadron structure and formation



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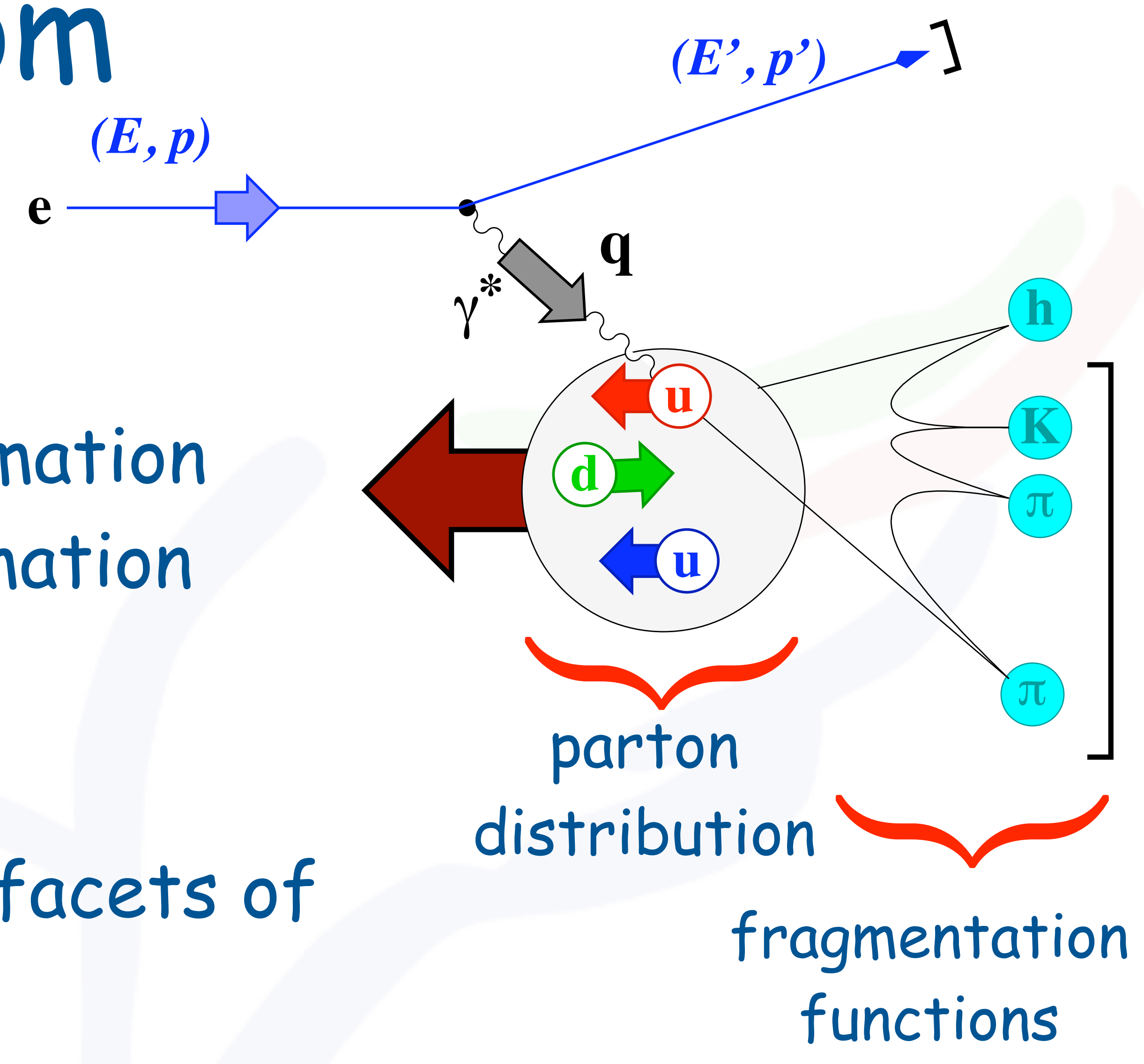


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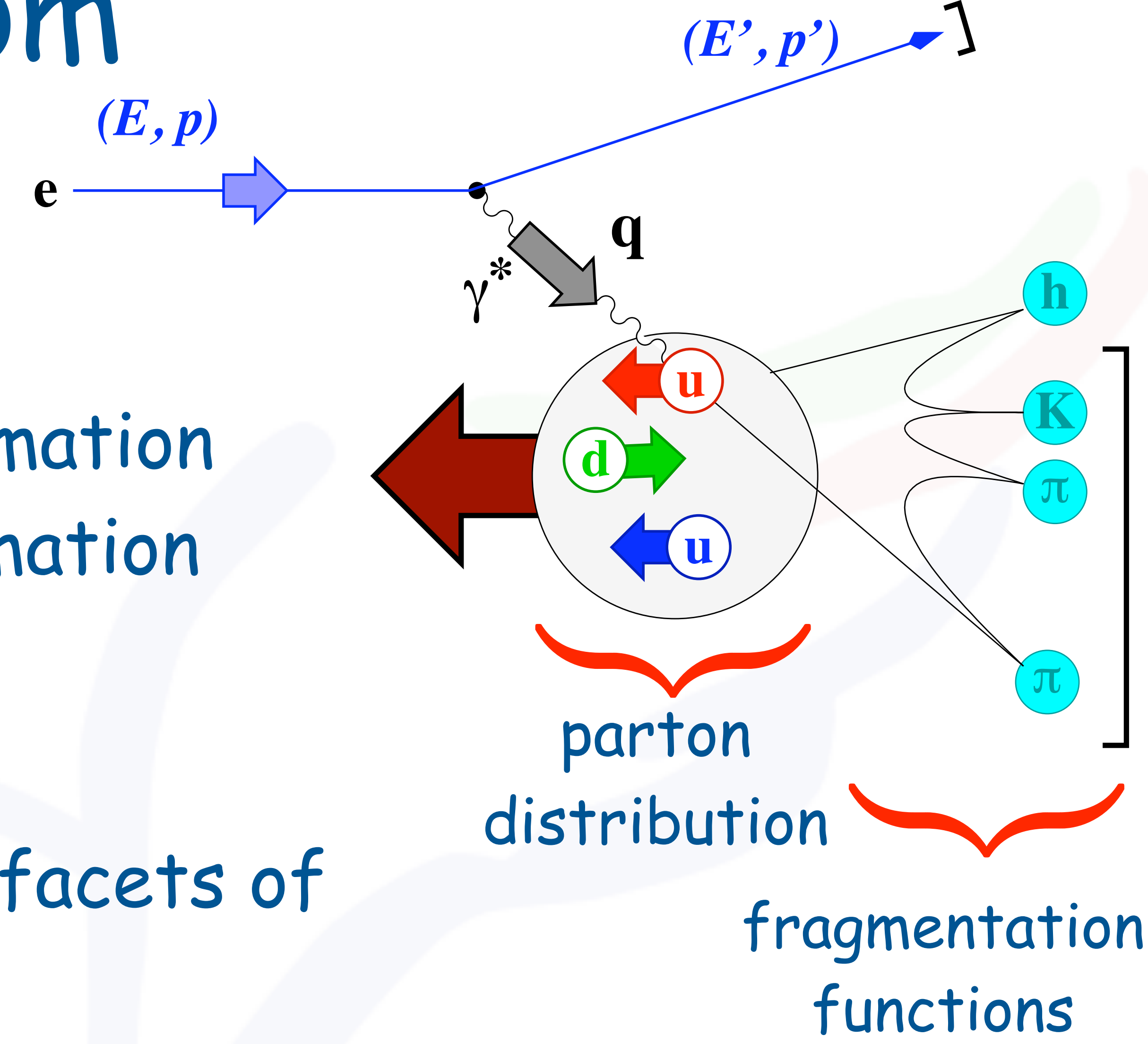


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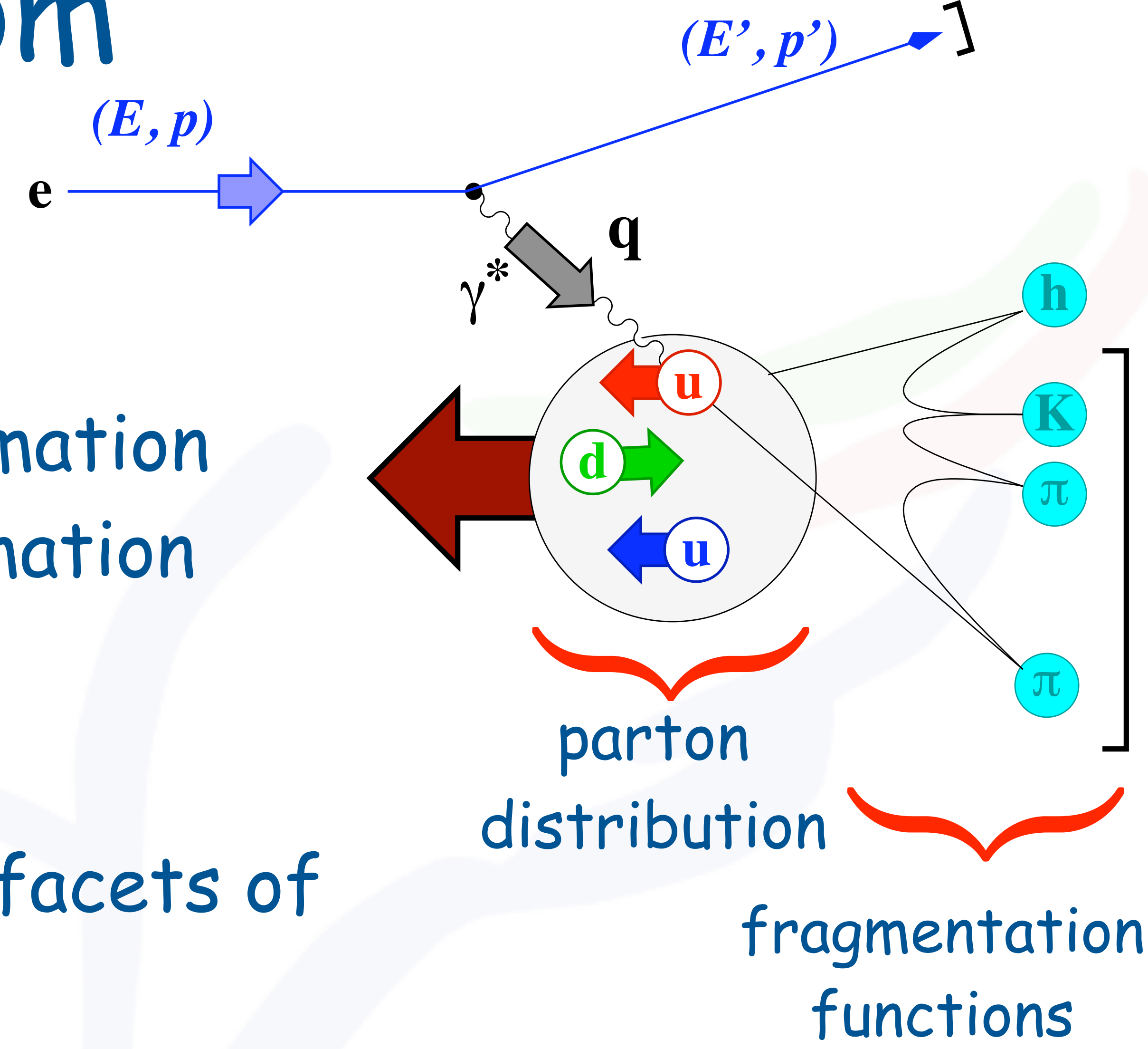


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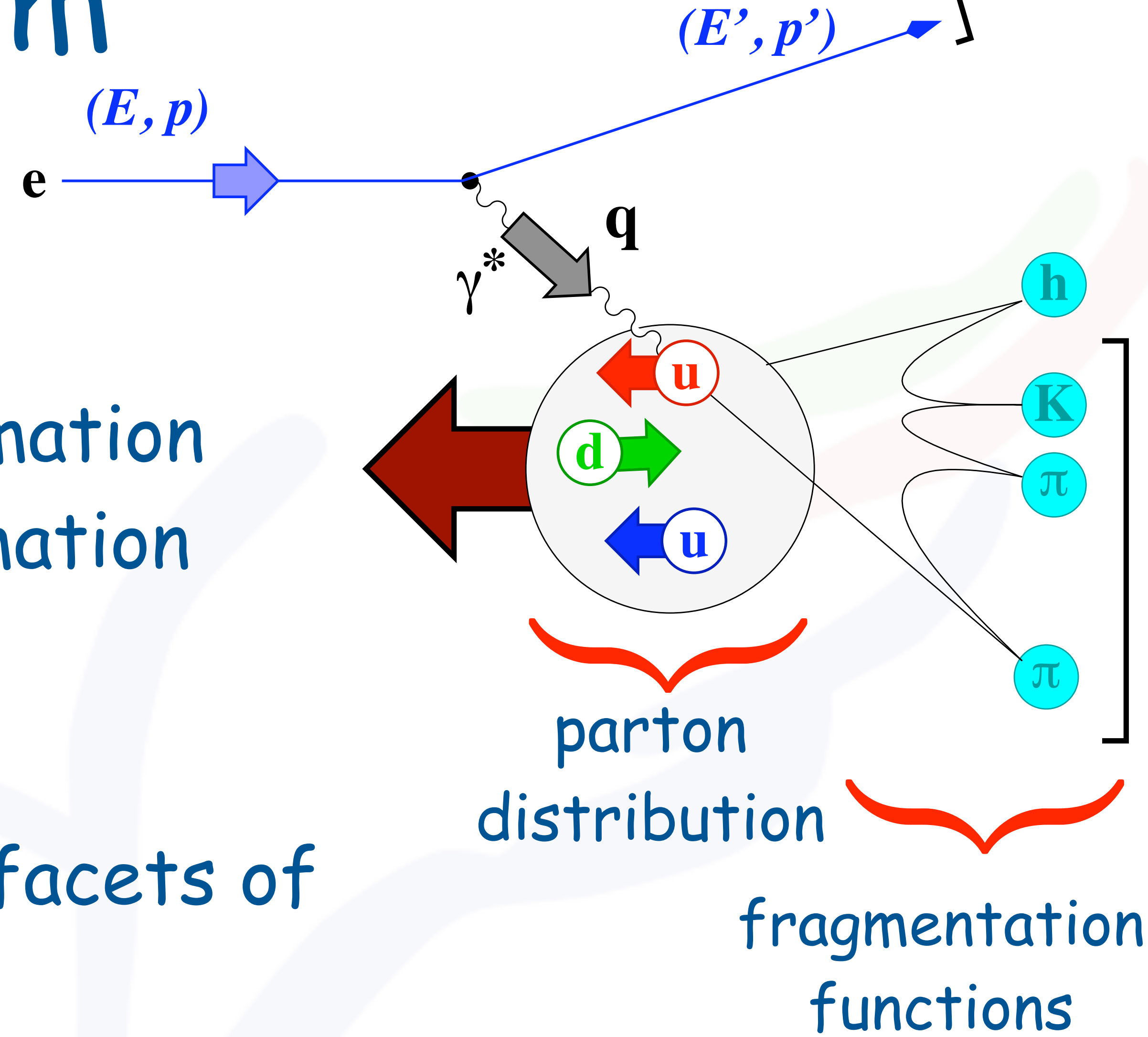


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- complimentary info on FFs to $e^+e^-$ (e.g., charge separation)
- nuclear targets provide laboratory for hadronization studies

# Polarization-averaged cross section

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

target polarization

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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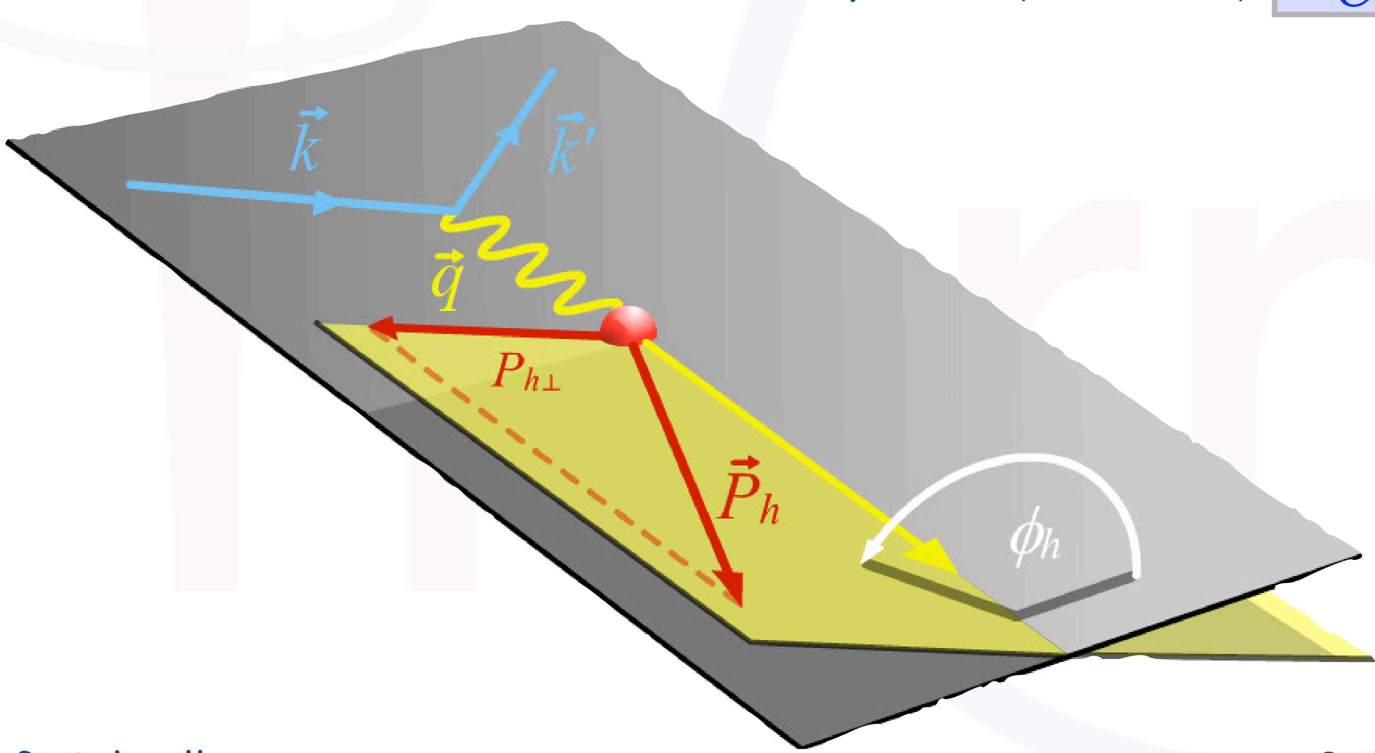


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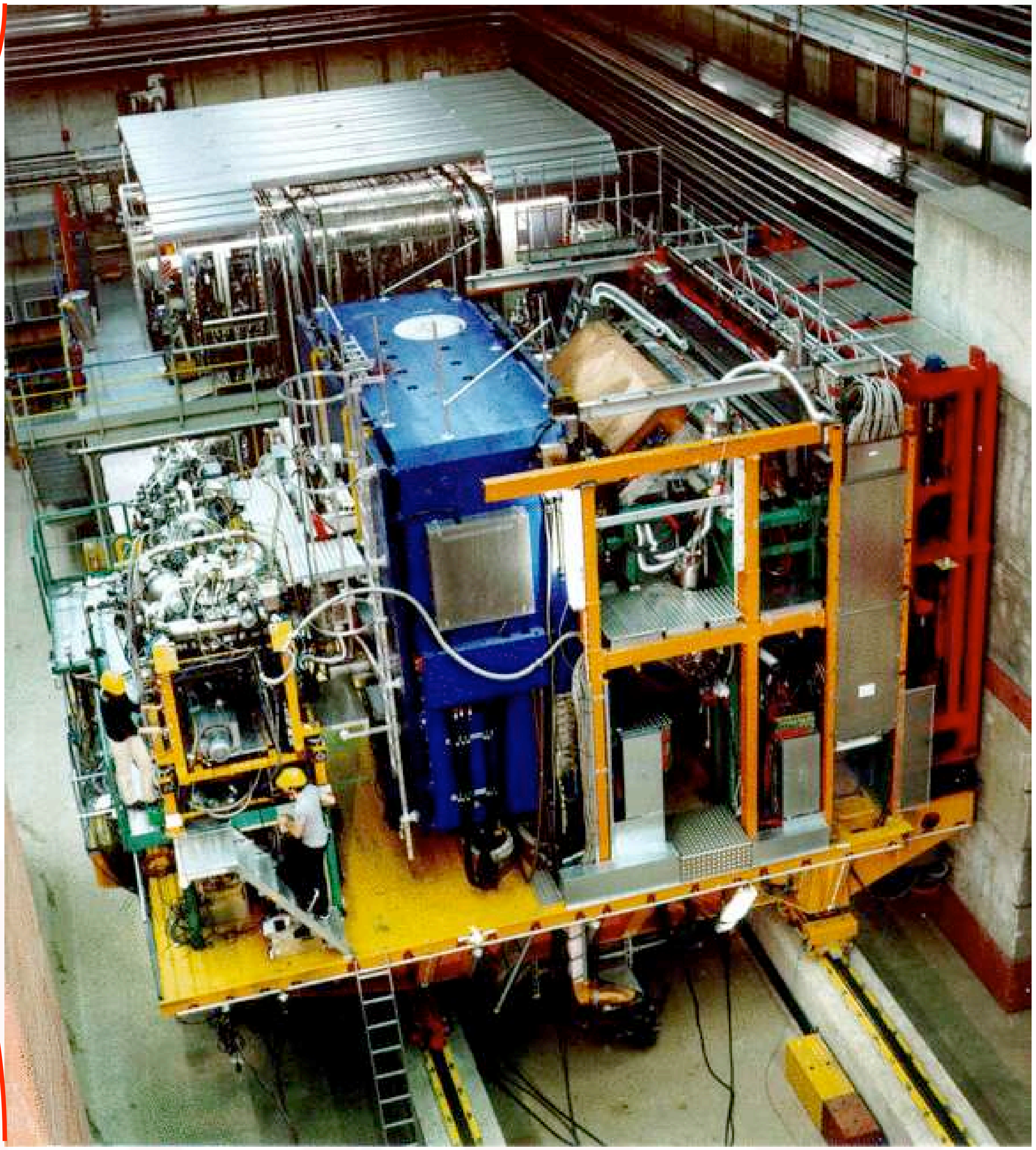
# Some **experimental** challenges ...

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

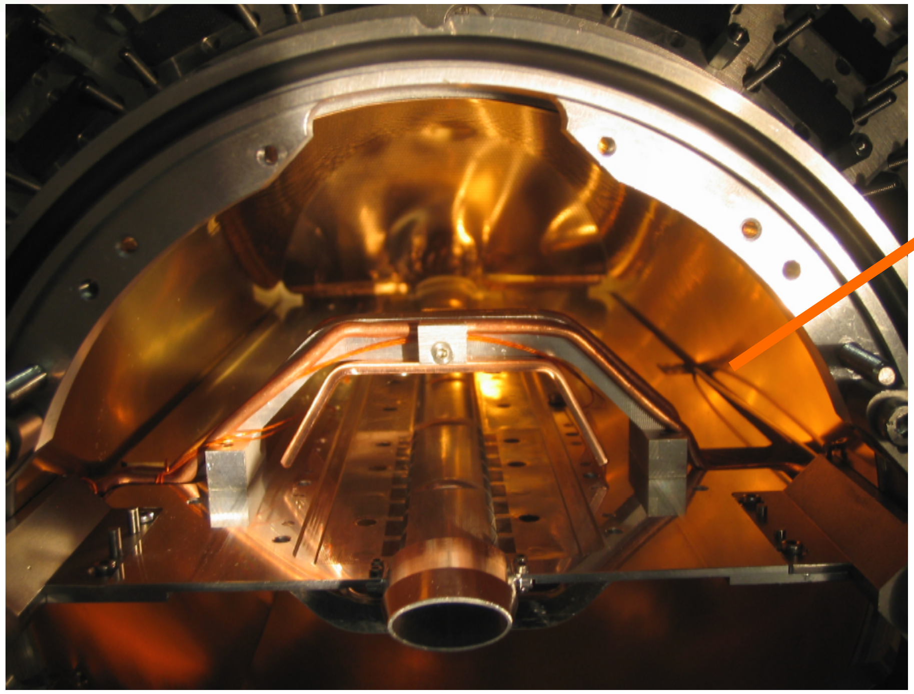
# The HERMES Experiment

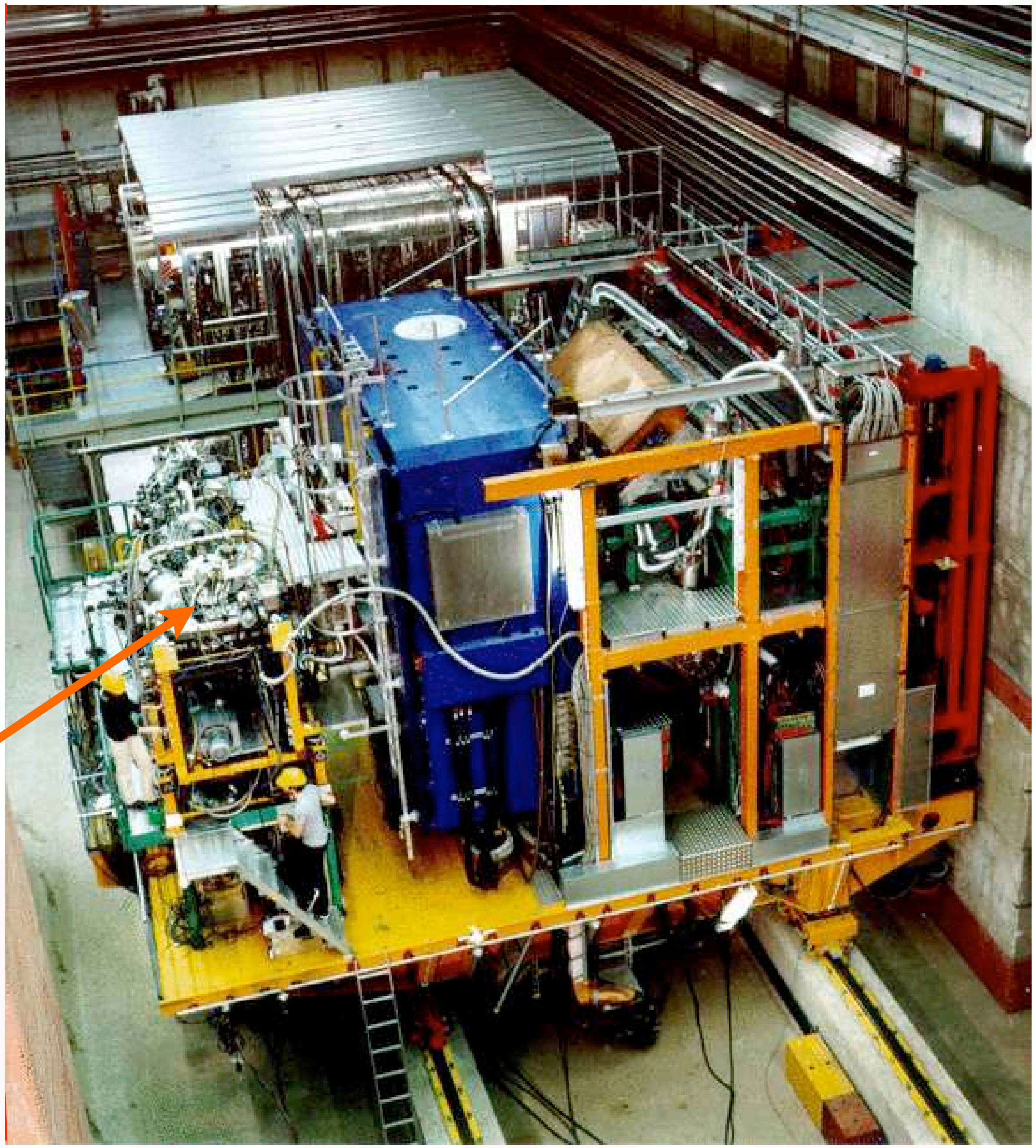
27.5 GeV $e^+/e^-$ beam of HERA

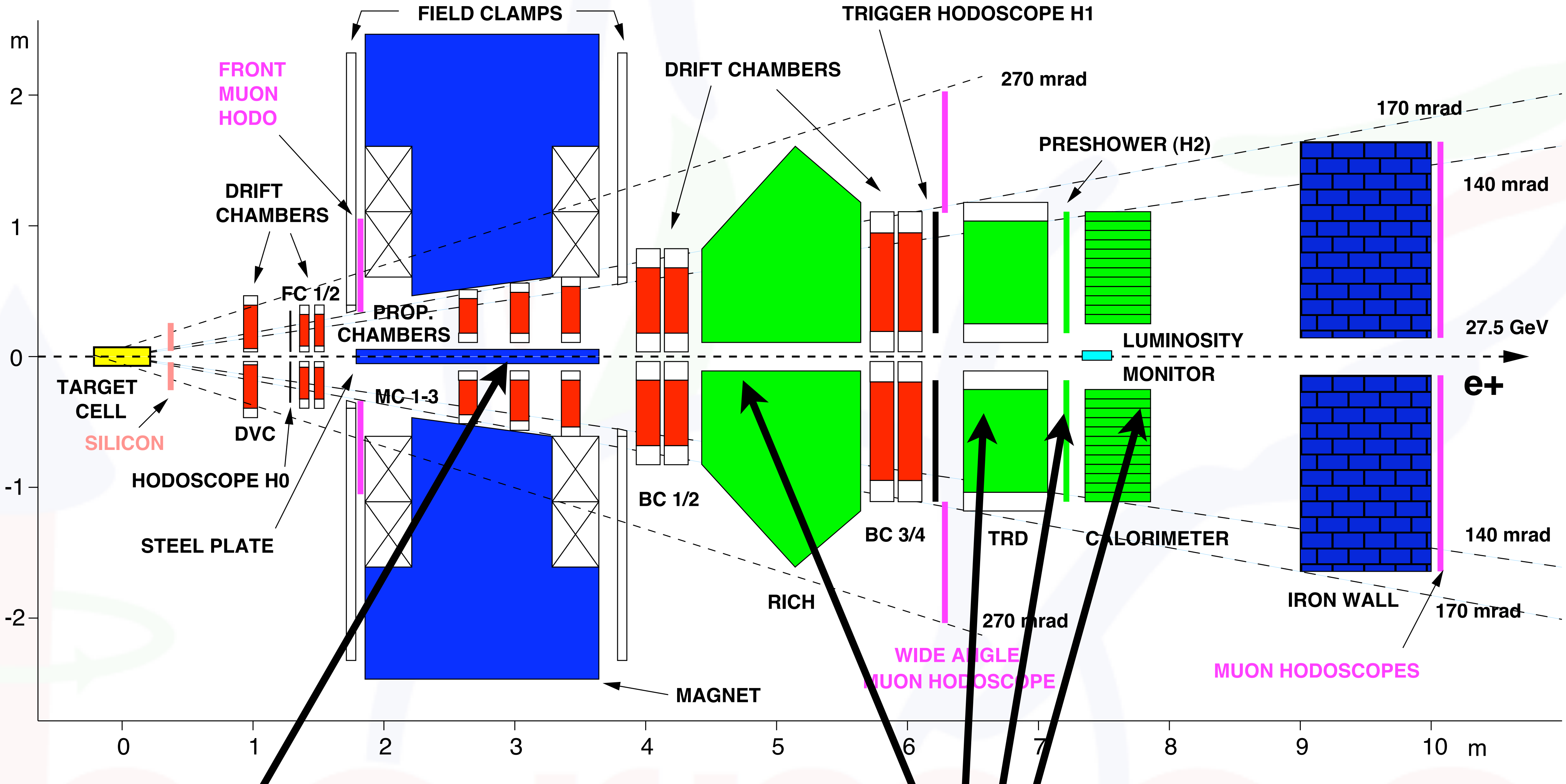
# The HERMES Experiment

- pure gas targets
- internal to lepton ring
- unpolarized ($^1$H … Xe)
- long. polarized: $^1$H, $^2$H, $^3$He
- 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 ...

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

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

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**hadron multiplicity:**
**normalize to inclusive DIS cross section**

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☛ this talk

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☛ S. Gliske (Saturday)

# … 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

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"Aus Differenzen und Summen kürzen nur die Dummen."

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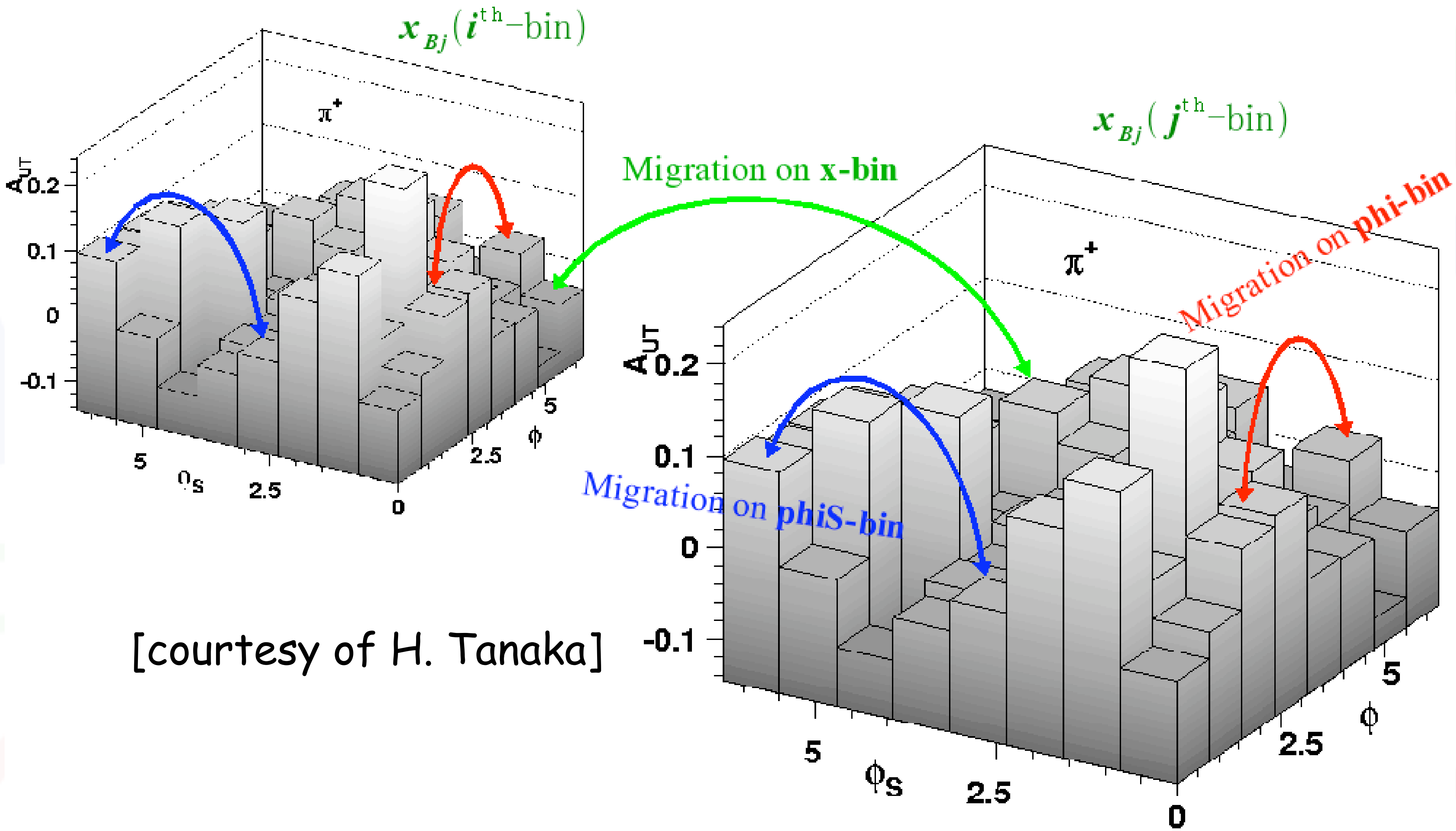
**Cross-section model does NOT CANCEL in general when integrating numerator and denominator over (large) ranges in kinematic variables!**

# … event migration …




[courtesy of H. Tanaka]

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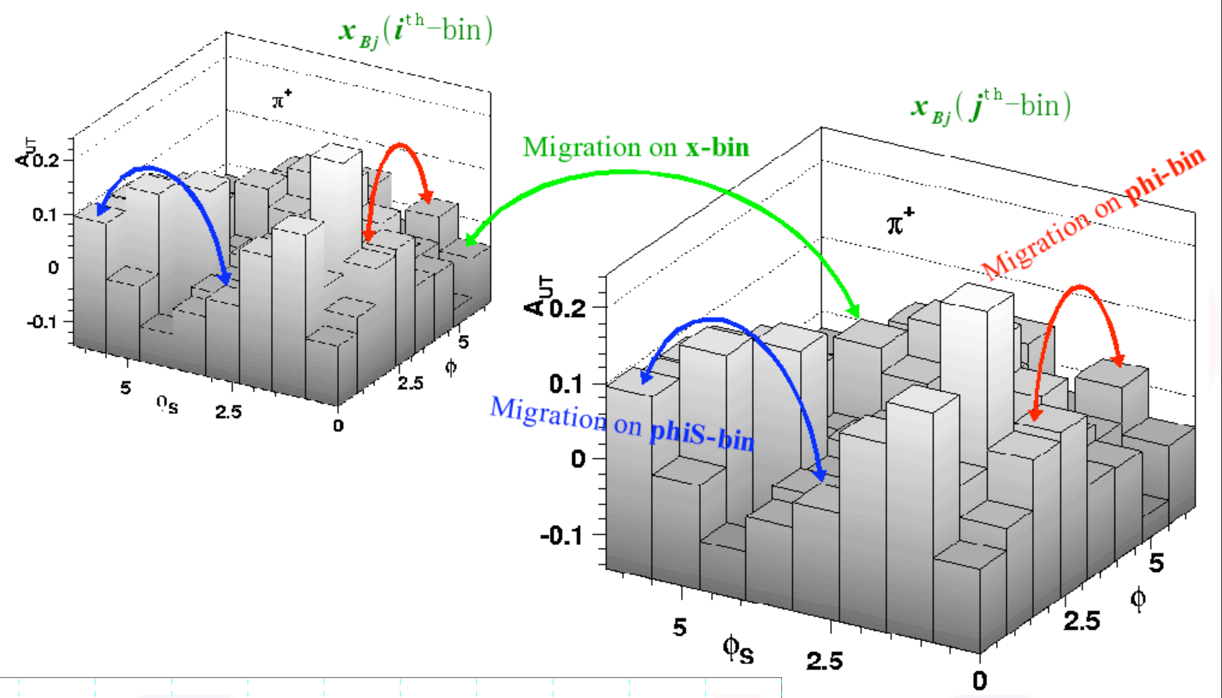


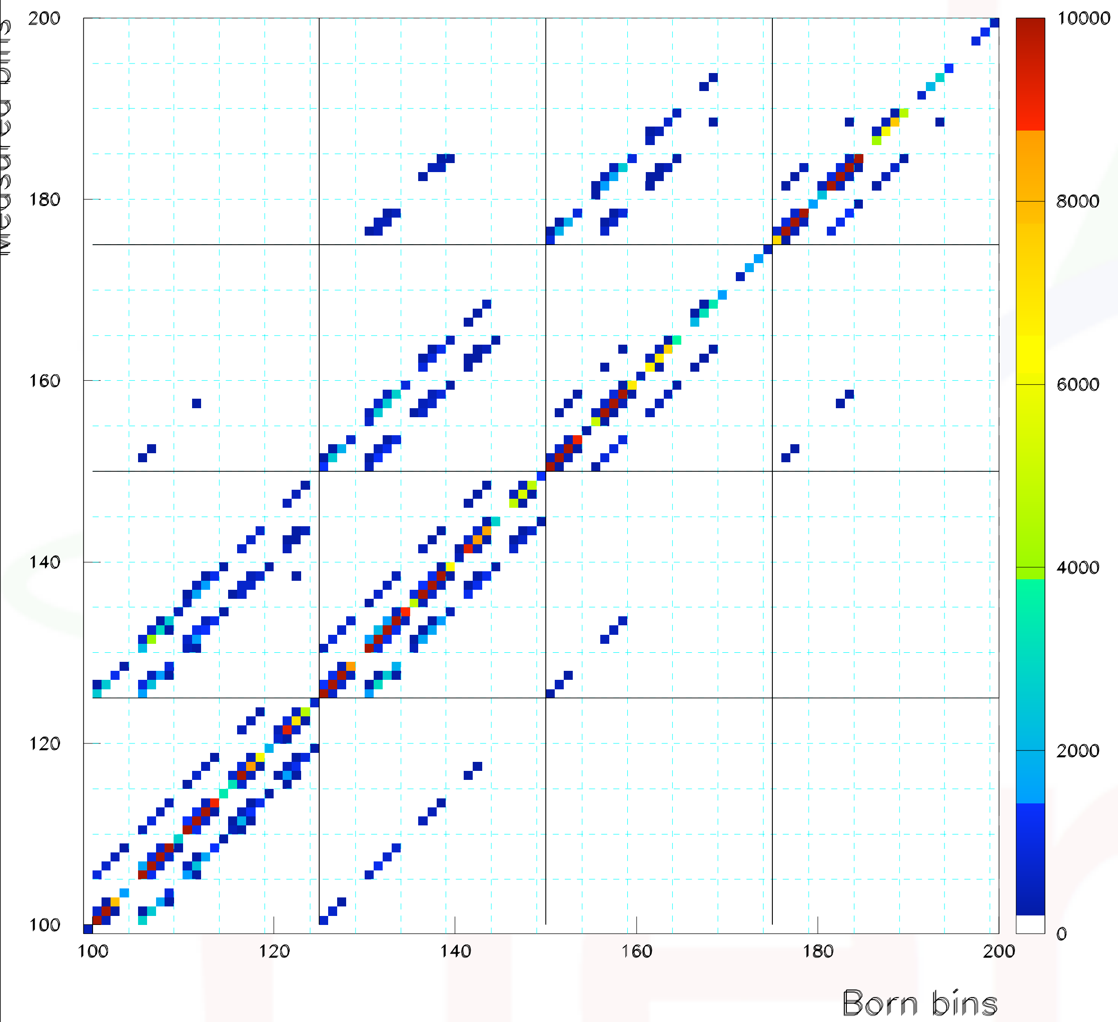


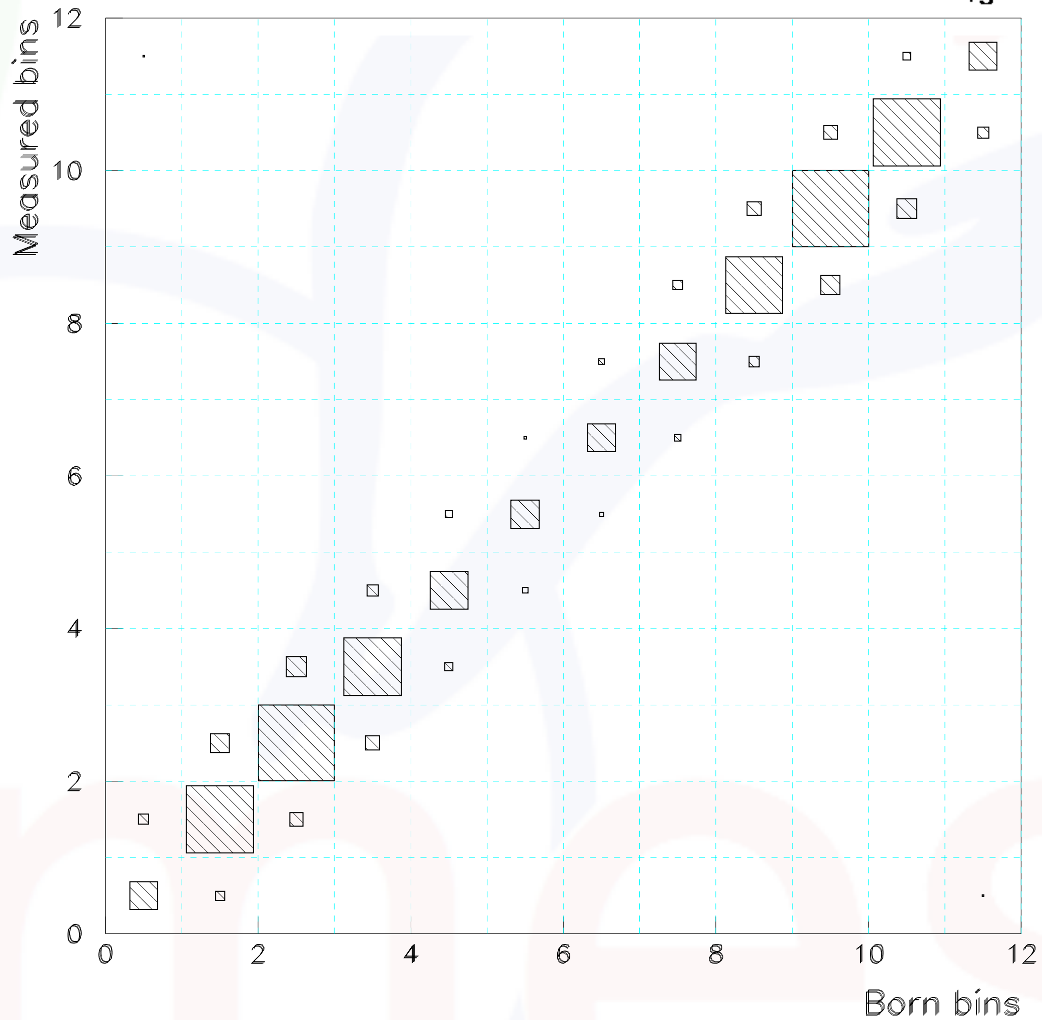


- migration correlates yields in different bins
- can't be corrected properly in bin-by-bin approach

# … event migration -> unfolding

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

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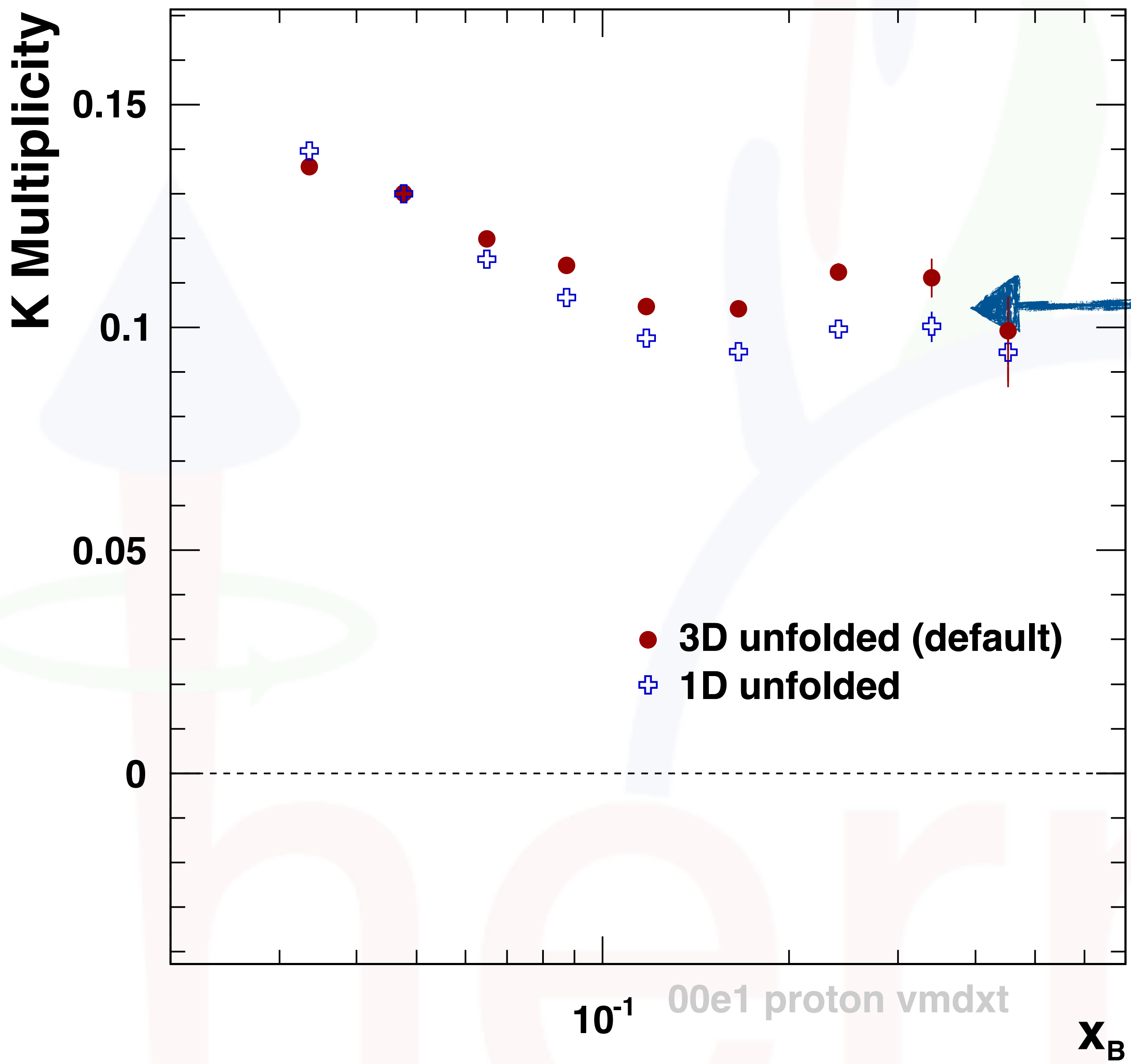
  - in real life: dependence on BG and physics model due to finite bin sizes
- inversion of relation gives Born cross section from measured yields

# Multi-D vs. 1D unfolding at work

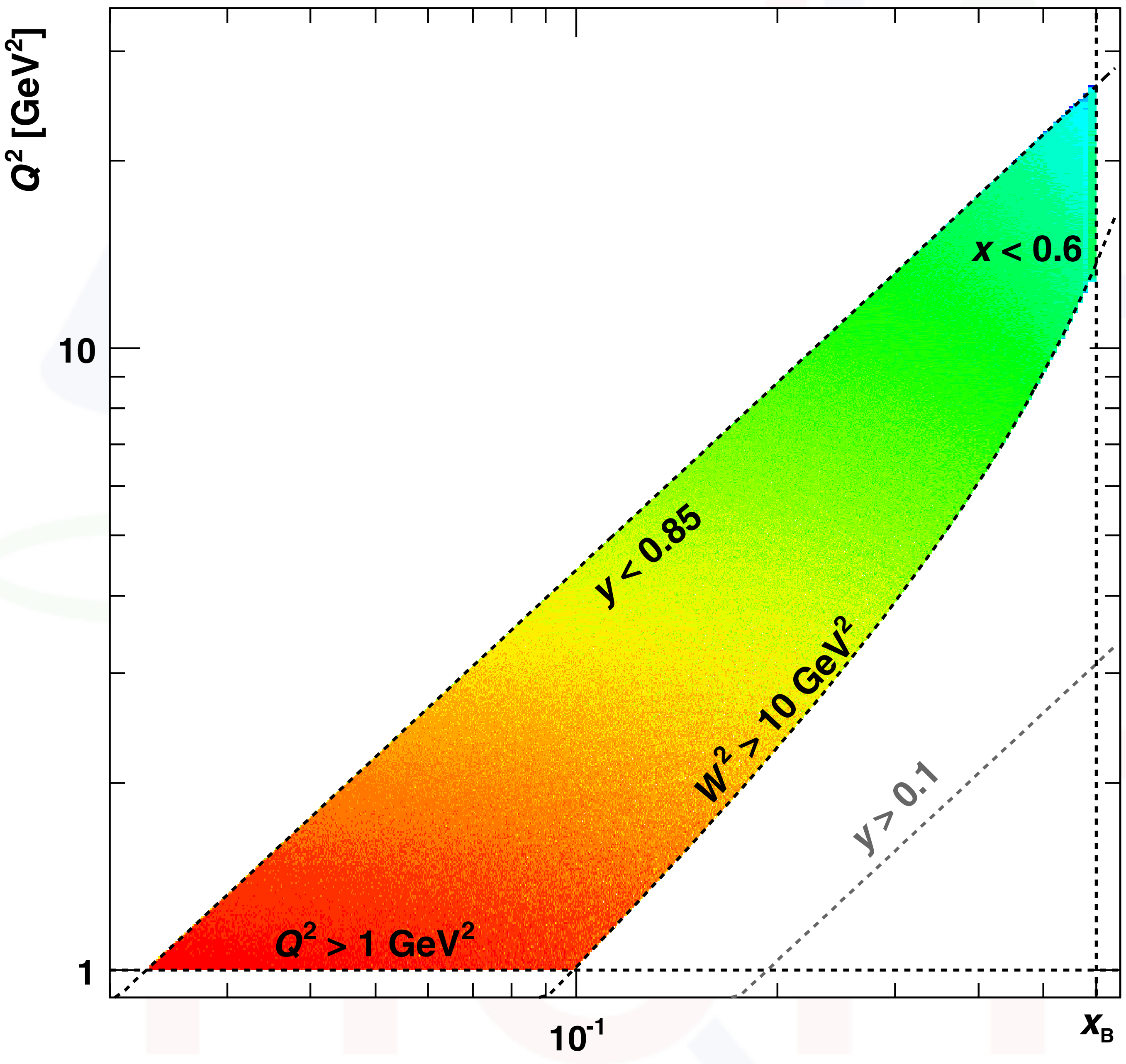
[S.J. Joosten, PhD thesis UIUC (2013)]




Neglecting to unfold in z changes x dependence dramatically

➡ 1D unfolding clearly insufficient

# Kinematic range at HERMES




- $0.023 < x < 0.6$
- $0.1 < y < 0.85$
- $0.2 < z < 0.8$
- $W^2 > 10$ GeV$^2$
- $Q^2 > 1$ GeV$^2$

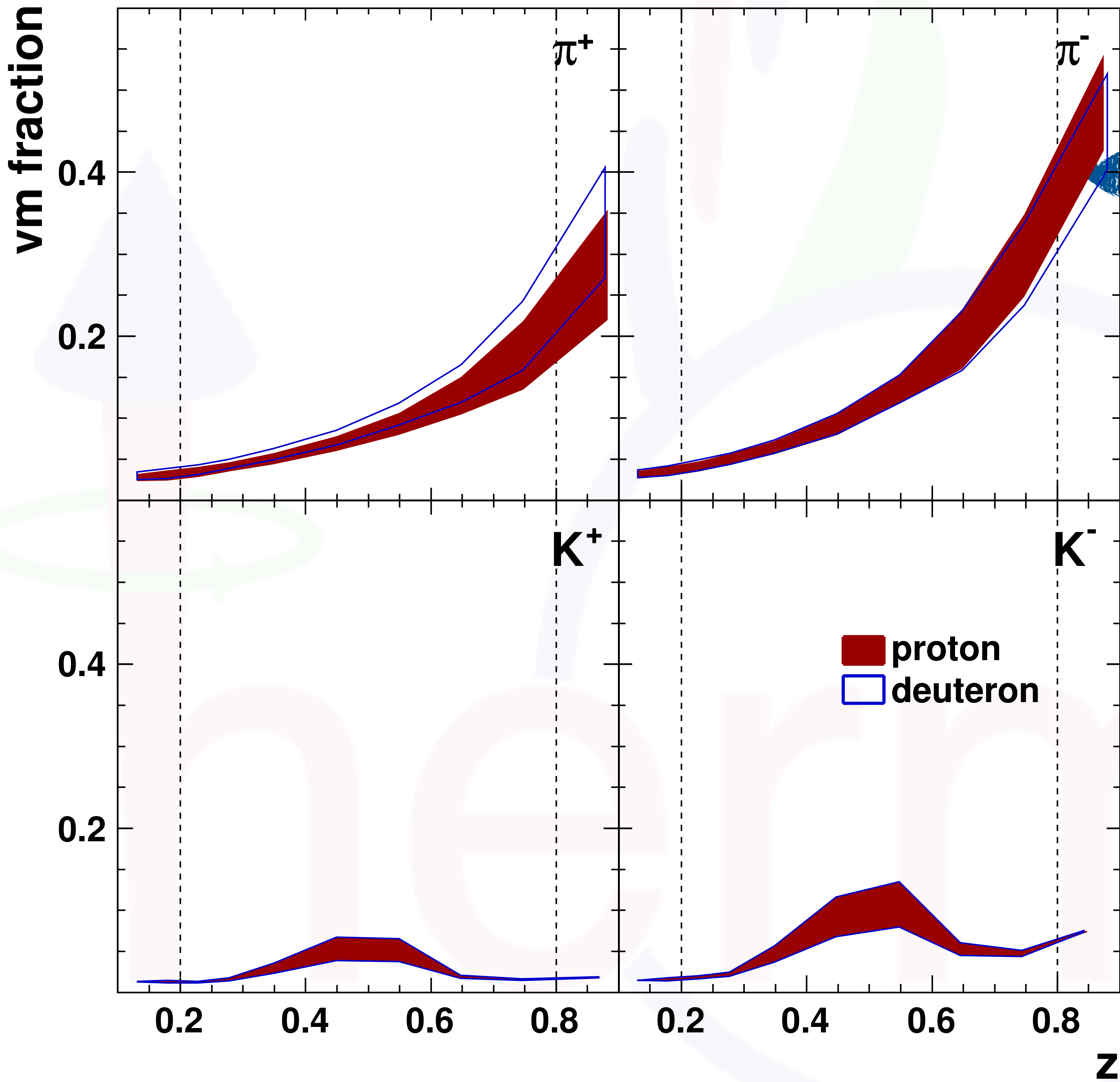
# Results I:
## charged pions and kaons from proton and deuteron targets

A. Airapetian et al., Phys. Rev. D87 (2013) 074029
http://www-hermes.desy.de/multiplicities

# Influence from exclusive VM

for instance: $ep \rightarrow ep\,\rho^0 \rightarrow ep\,\pi^+\pi^-$

[Airapetian et al., PRD 87 (2013) 074029]




partially large contribution from exclusive VM production, in particular at high z

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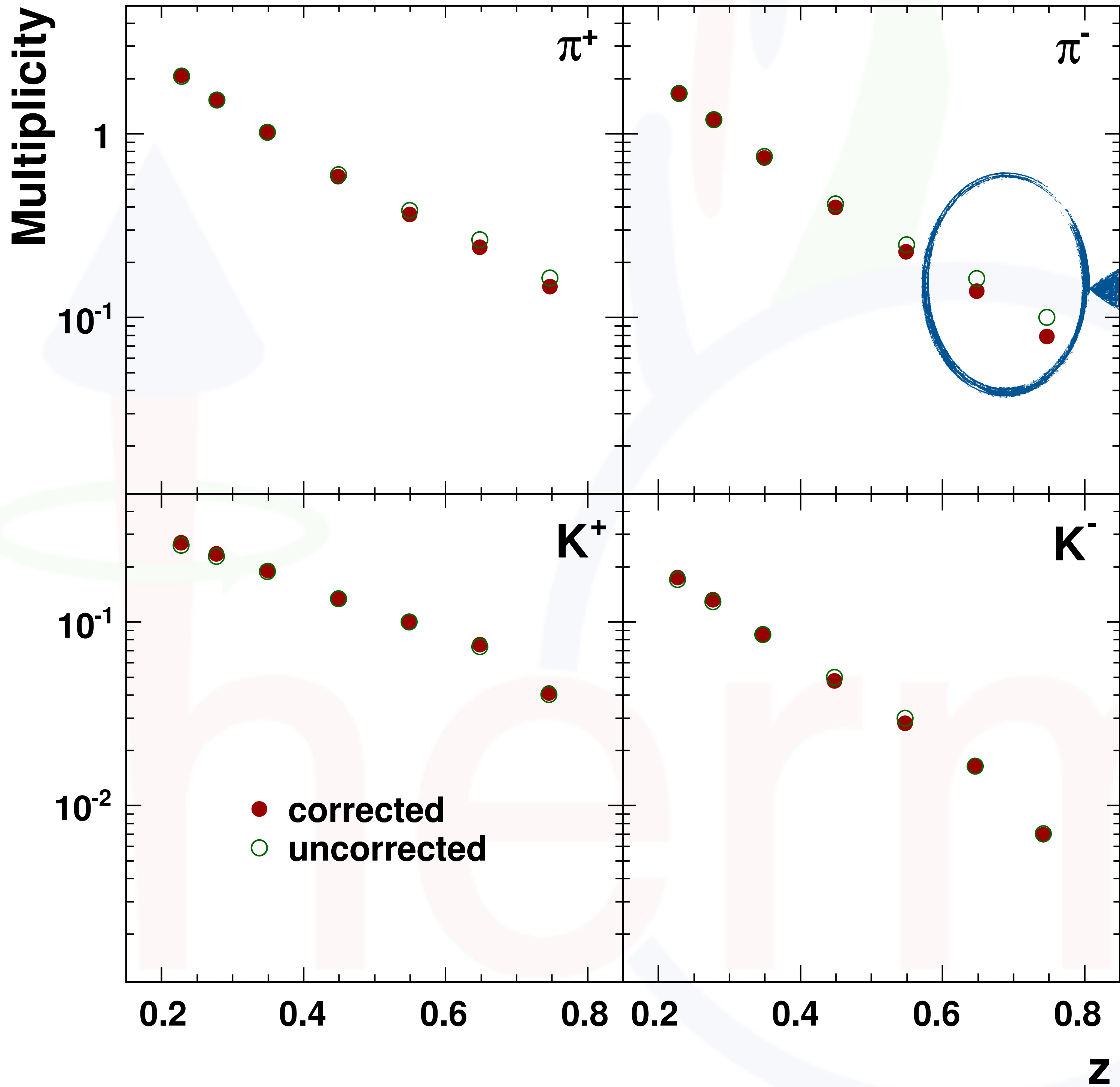
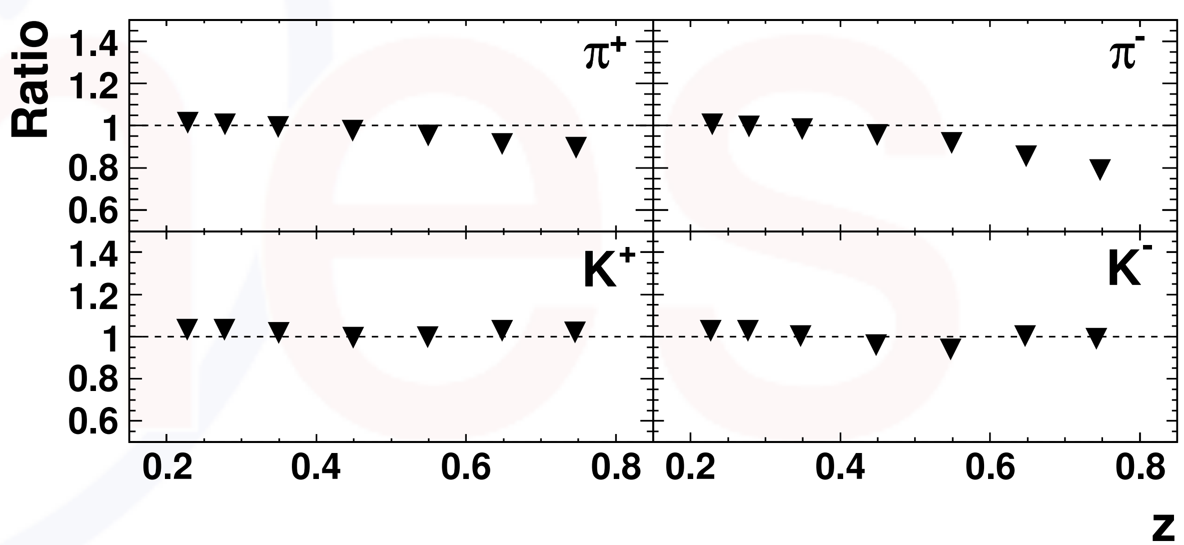


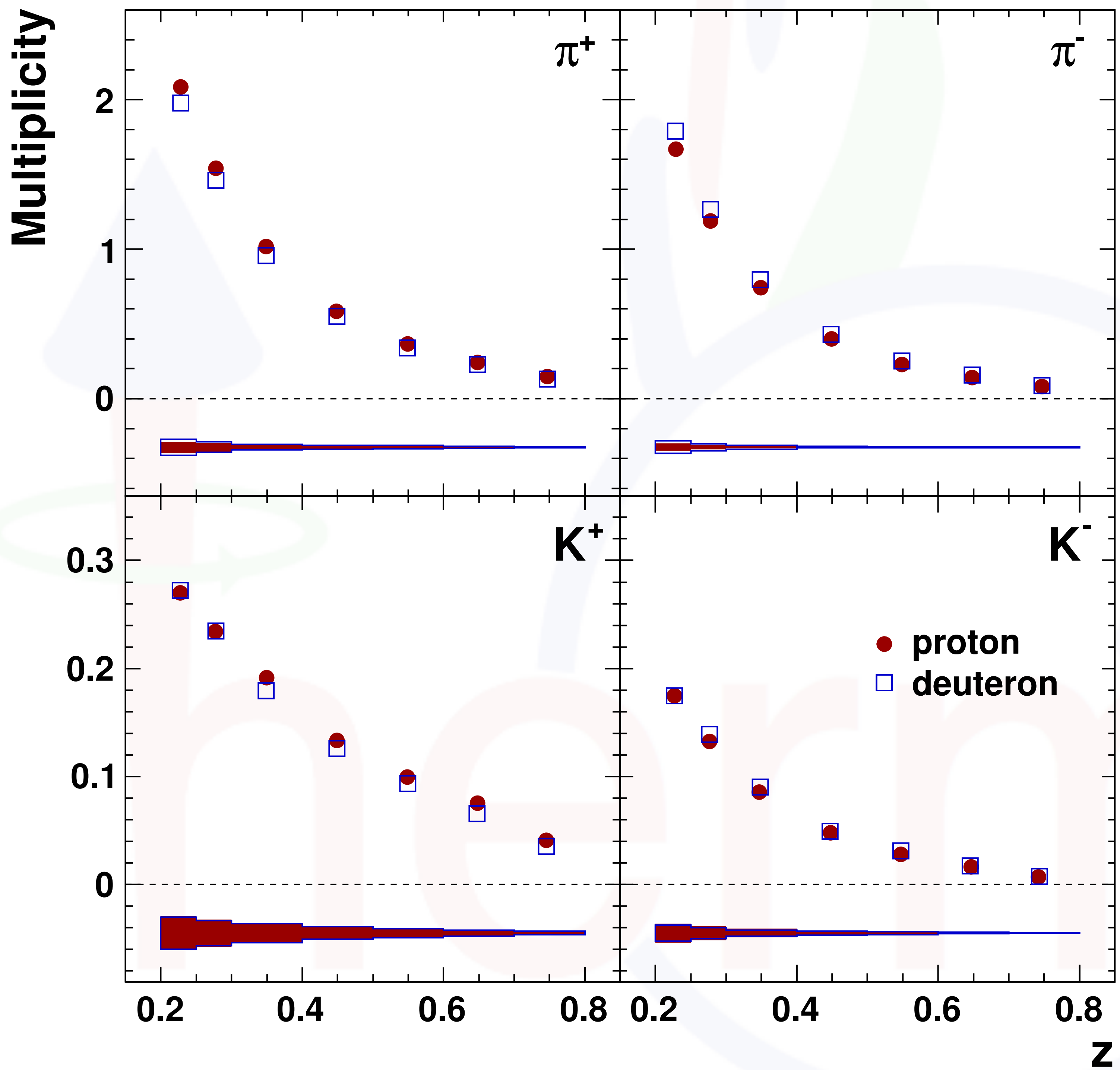

multiplicities before and after subtraction of contributions from exclusively produced VMs



# Multiplicities: z projection

most exhaustive data set on ($P_{h\perp}$-integrated) electro-production of charged identified mesons on nucleons

[Airapetian et al., PRD 87 (2013) 074029]




➡ slight differences between proton and deuteron targets: reflection of valence structure of target and produced meson, e.g.

$u/d \rightarrow \pi^+ / \pi^-$

$p = |uud\rangle$ and $n = |udd\rangle$

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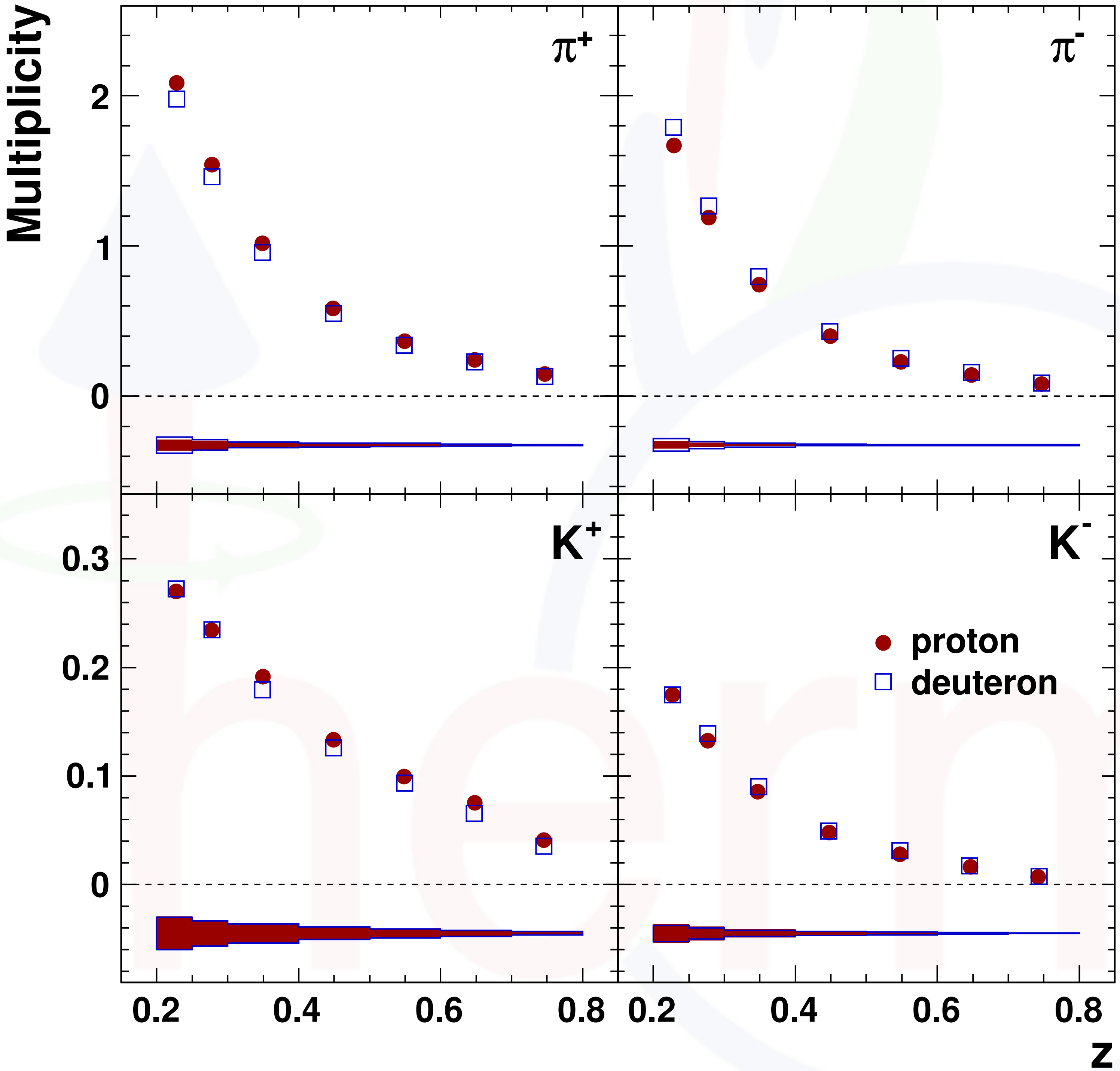
[Airapetian et al., PRD 87 (2013) 074029]




➡ slight differences between proton and deuteron targets: reflection of valence structure of target and produced meson, e.g.

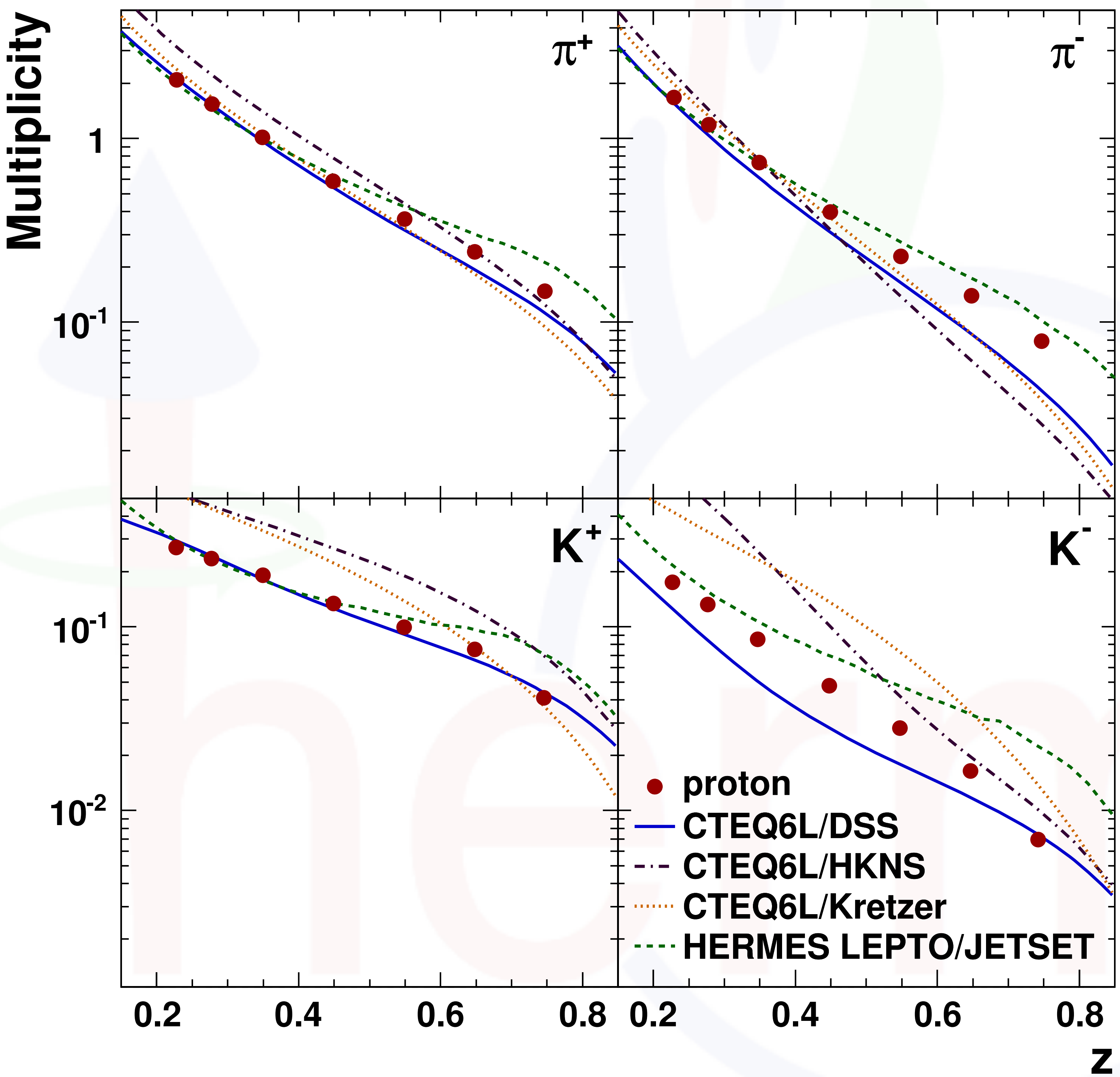
u/d -> $\pi^+$ / $\pi^-$

p = |uud> and n = |udd>

➡ $K^-$ pure "sea object" hence suppressed and hardly any difference for proton and deuteron

# Multiplicities: z projection

[Airapetian et al., PRD 87 (2013) 074029]




**proton target:**
(deuteron similar)

positive hadrons in general better described than negative ones

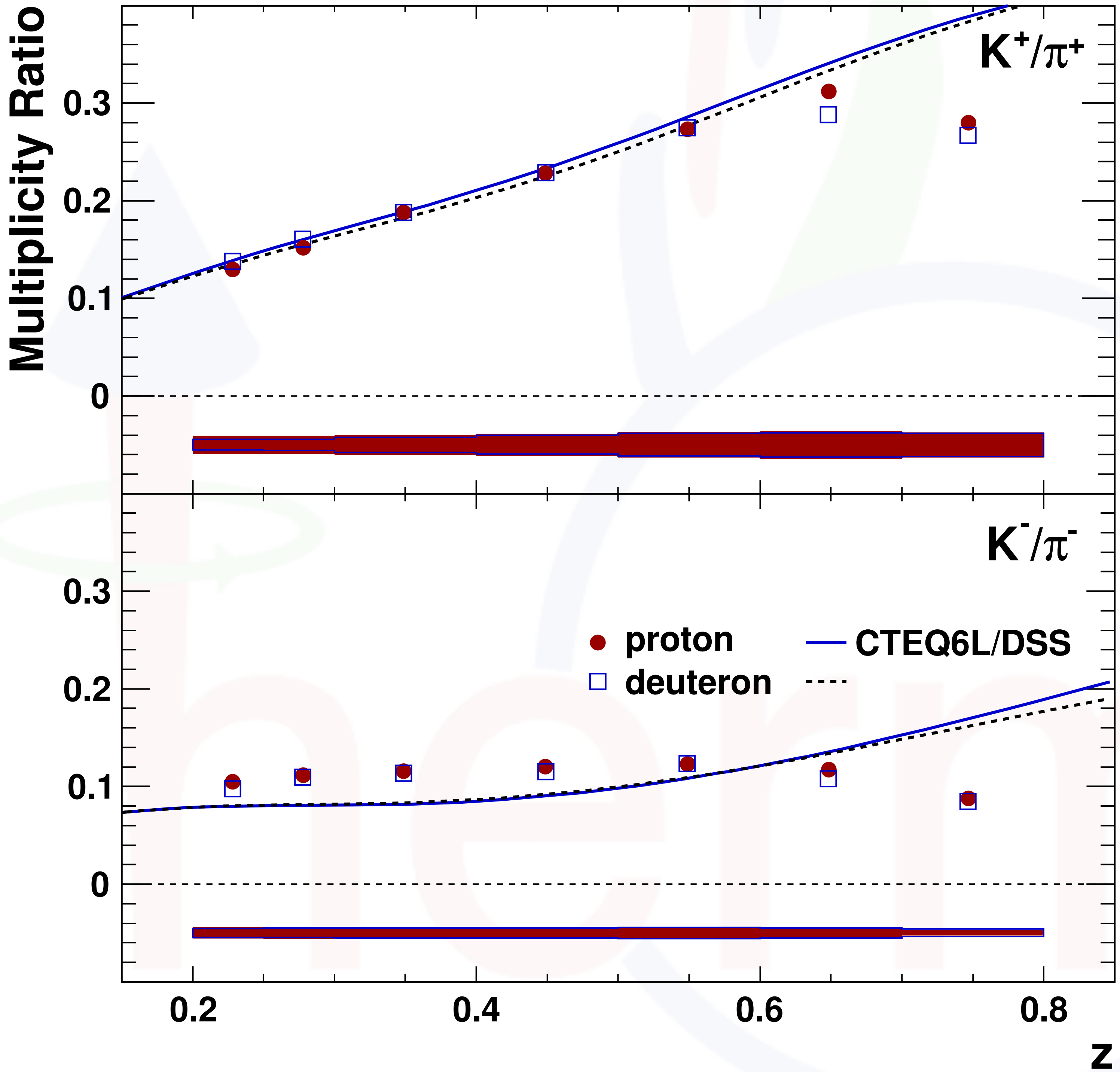
➡ better understanding of favored fragmentation?

➡ best described by HERMES Jetset tune and DSS FF set

kaons best described by DSS FF set, though all with problems in describing $K^-$

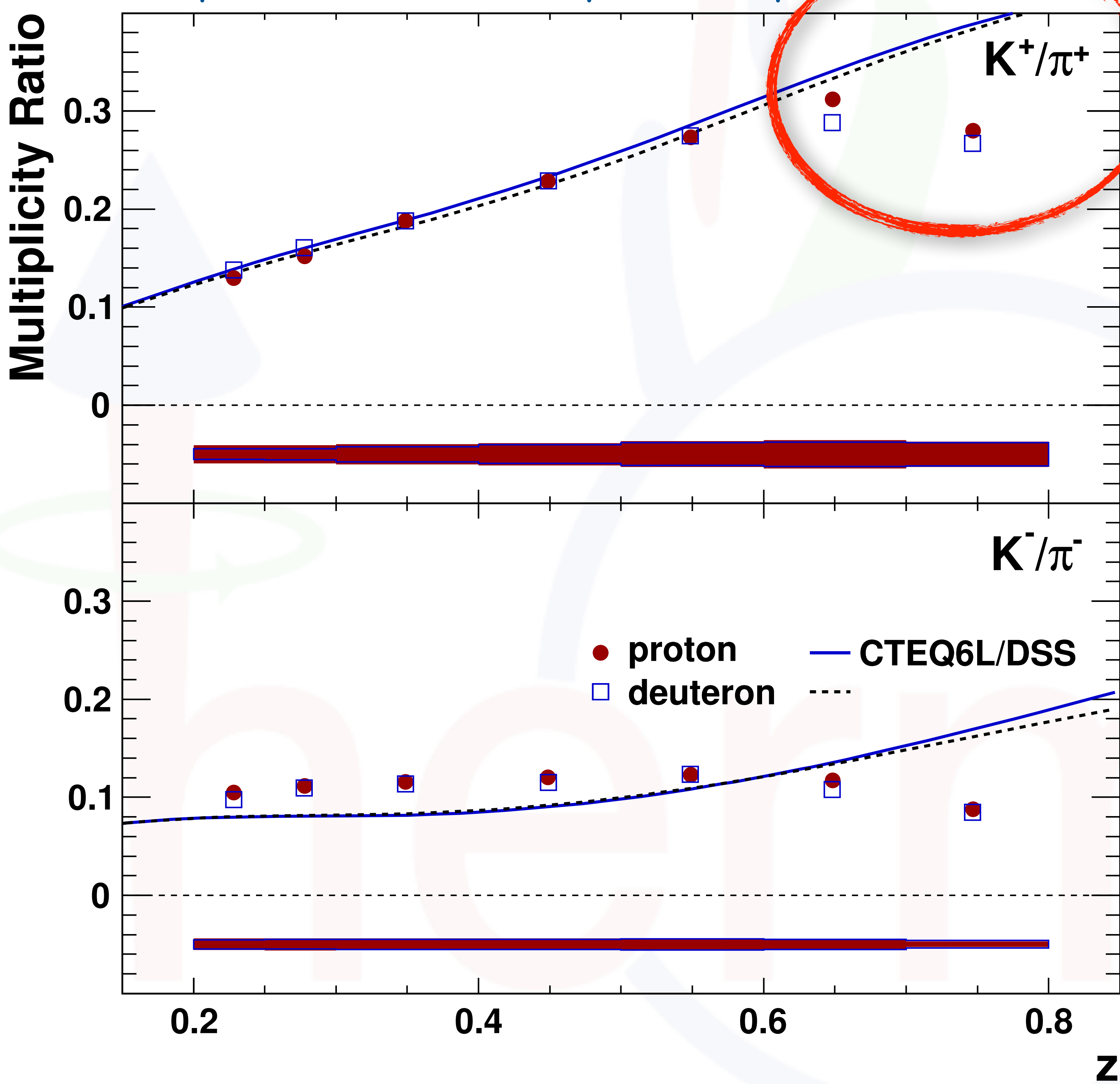
# Multiplicity ratio: z projection

[http://www-hermes.desy.de/multiplicities]



# Multiplicity ratio: z projection

[http://www-hermes.desy.de/multiplicities]




at large z mainly favored fragmentation:

➡ dominated by up quarks

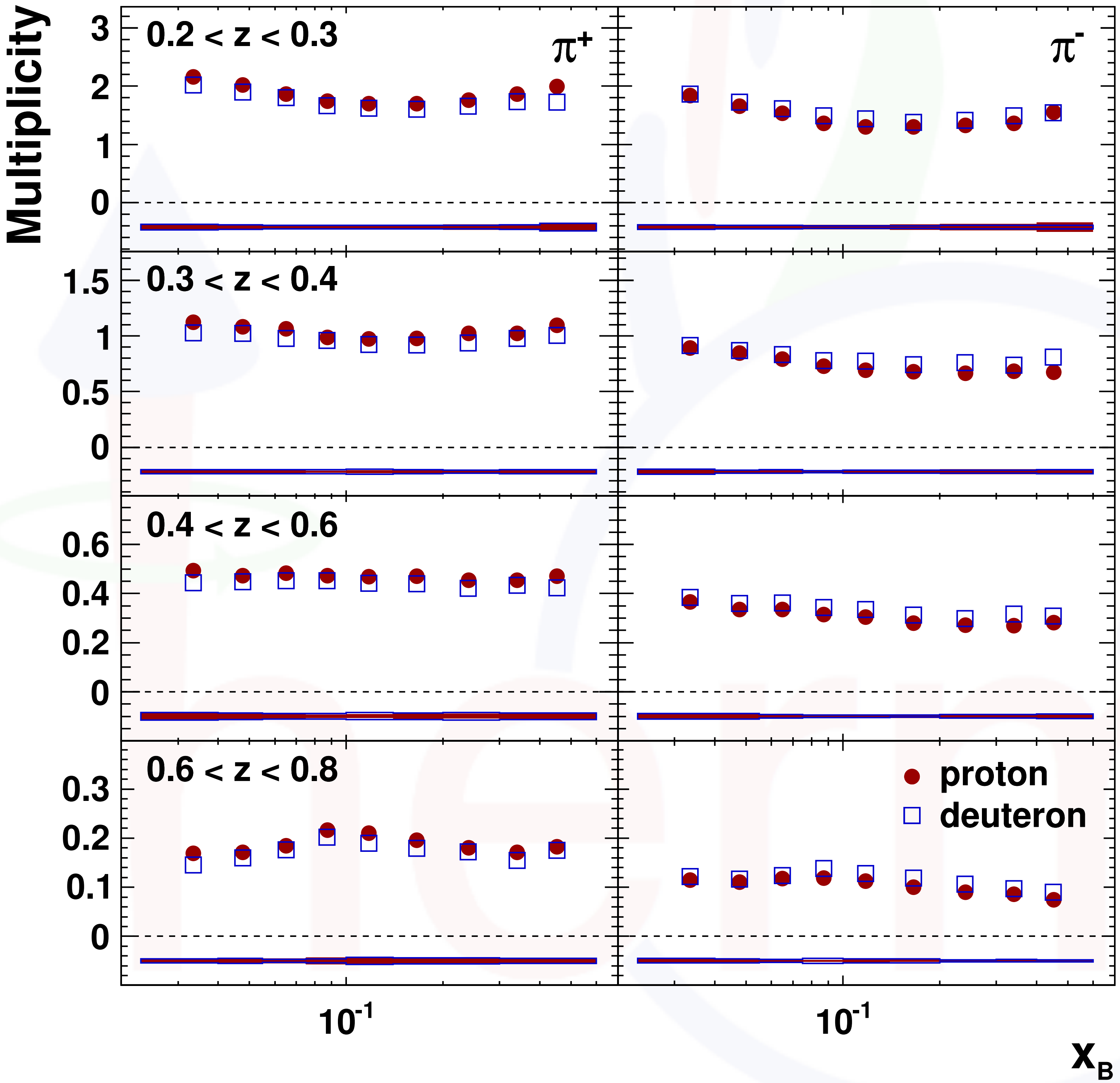
➡ kaon requires strangeness production

➡ strangeness suppression of about 0.3 (apparently stronger than modeled in DSS FF set)

➡ in rough agreement with typical ansatz of 1/3

# Multiplicities: x-z projection

[Airapetian et al., PRD 87 (2013) 074029]

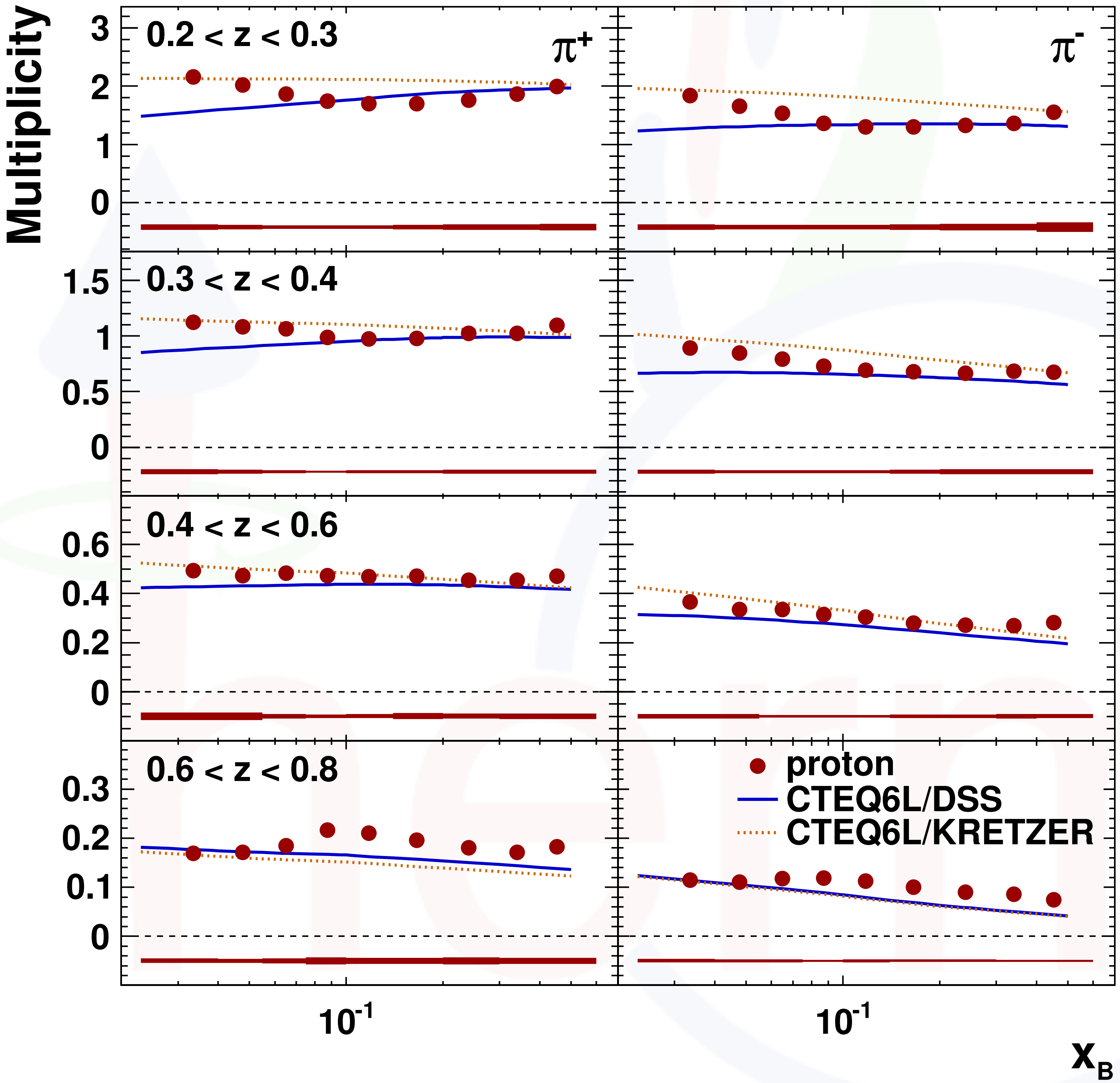



➡ weaker dependence on x

$$\sum_q \frac{e_q^2 f_1^q(x)}{\sum_{q'} e_{q'}^2 f_1^{q'}(x)} D_1^{q\to\pi}(z)$$

# Multiplicities: x-z projection

[Airapetian et al., PRD 87 (2013) 074029]




➡ weaker dependence on x

➡ remaining dependence from $f_1$ - $D_1$ convolution over quark flavors

$$\sum_q \frac{e_q^2 f_1^q(x)}{\sum_{q'} e_{q'}^2 f_1^{q'}(x)} D_1^{q\to\pi}(z)$$

# Strange-quark distribution

- use isoscalar probe and target to extract strange-quark distribution
- only need $K^{+}+K^{-}$ multiplicities on deuteron

$$\boxed{S(x)}\int \mathcal{D}_S^K(z)\,\mathrm{d}z \simeq Q(x)\left[5\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{\mathrm{DIS}}(x)} - \int \mathcal{D}_Q^K(z)\,\mathrm{d}z\right]$$

$$\mathbf{S(x) = s(x) + \bar{s}(x)}$$

$$\mathbf{Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)}$$

$$\mathcal{D}_{\mathbf{S}}^{\mathbf{K}} = \mathbf{D_1^{s\to K^+} + D_1^{\bar{s}\to K^+} + D_1^{s\to K^-} + D_1^{\bar{s}\to K^-}}$$

$$\mathcal{D}_{\mathbf{Q}}^{\mathbf{K}} = \mathbf{4D_1^{u\to K^+} + 4D_1^{\bar{u}\to K^+} + D_1^{d\to K^+} + D_1^{\bar{d}\to K^+}} + \ldots$$

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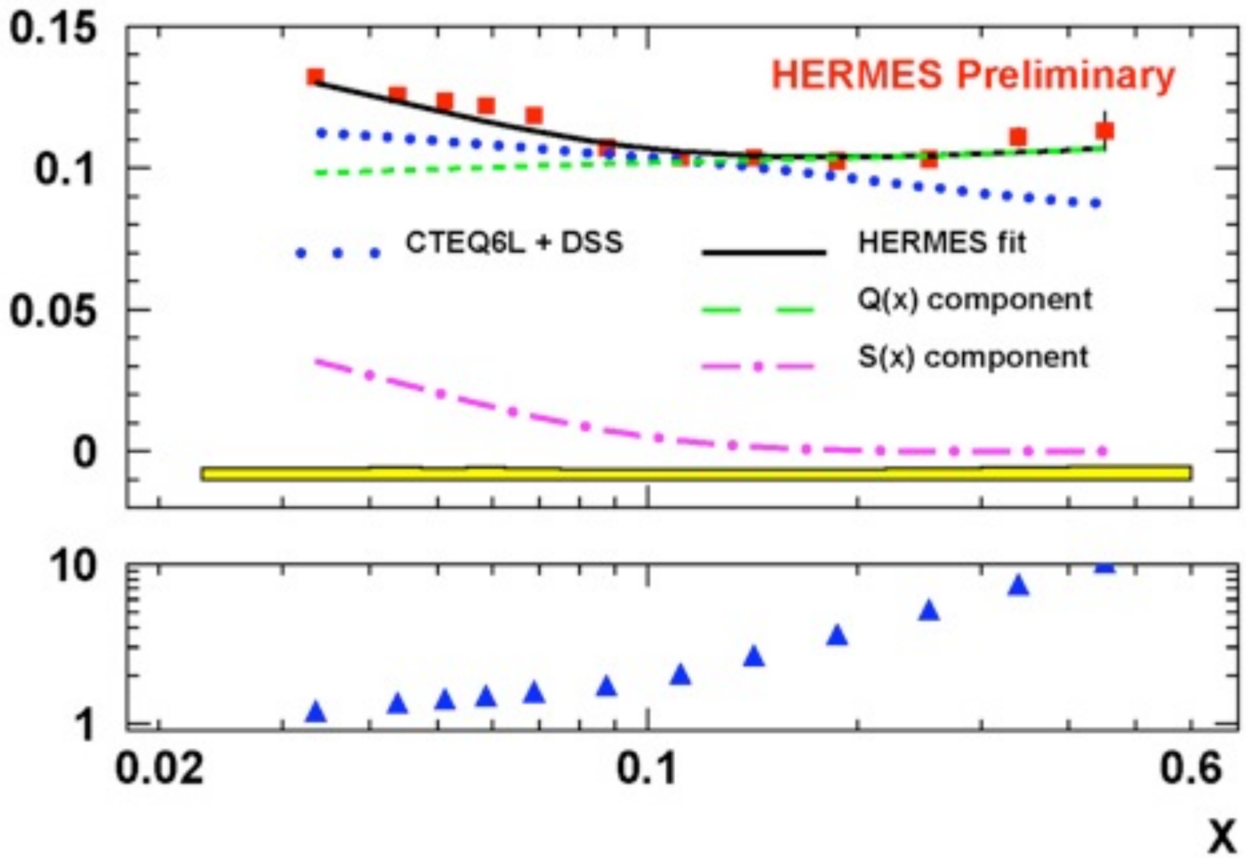
- assume vanishing strangeness **at high x** to **extract non-strange fragmentation**




$$\mathbf{S(x) = s(x) + \bar{s}(x)}$$
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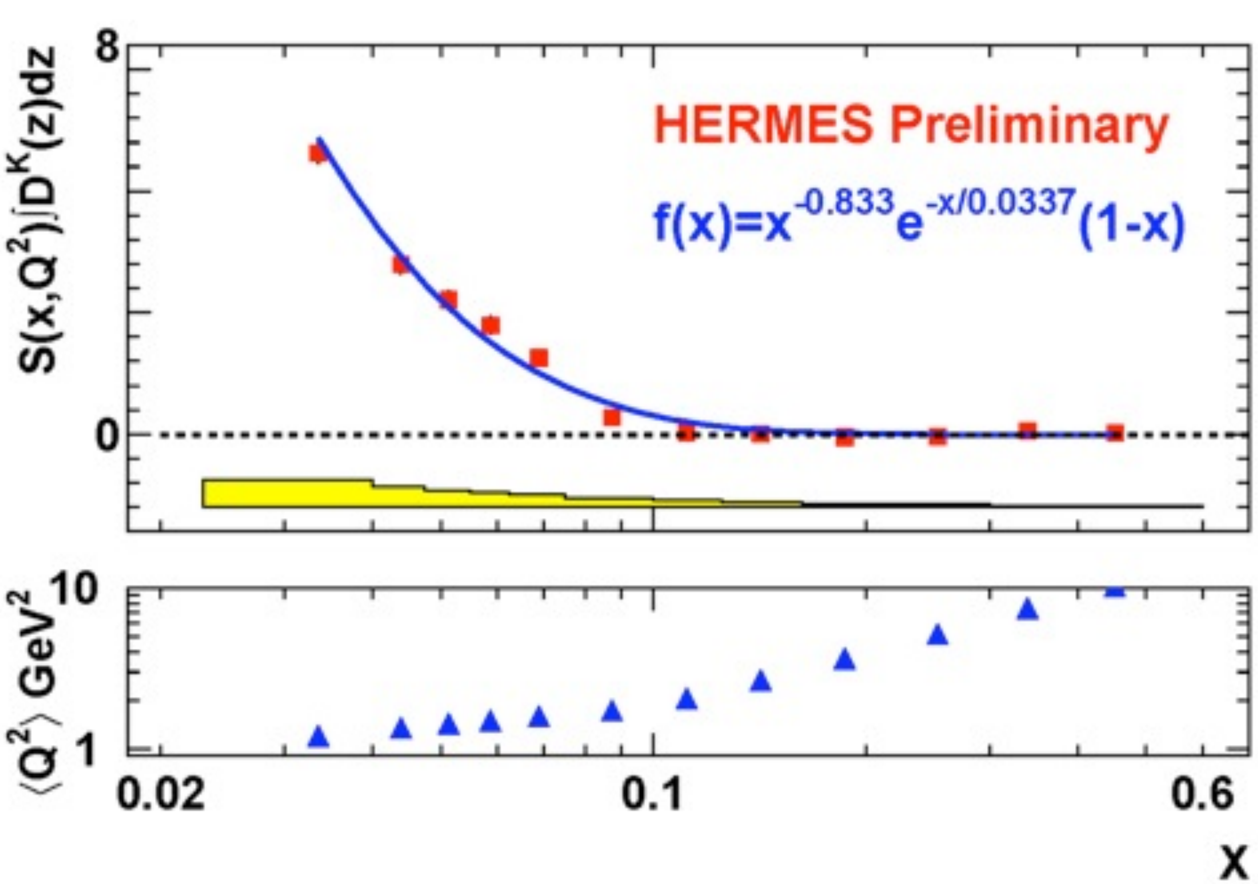
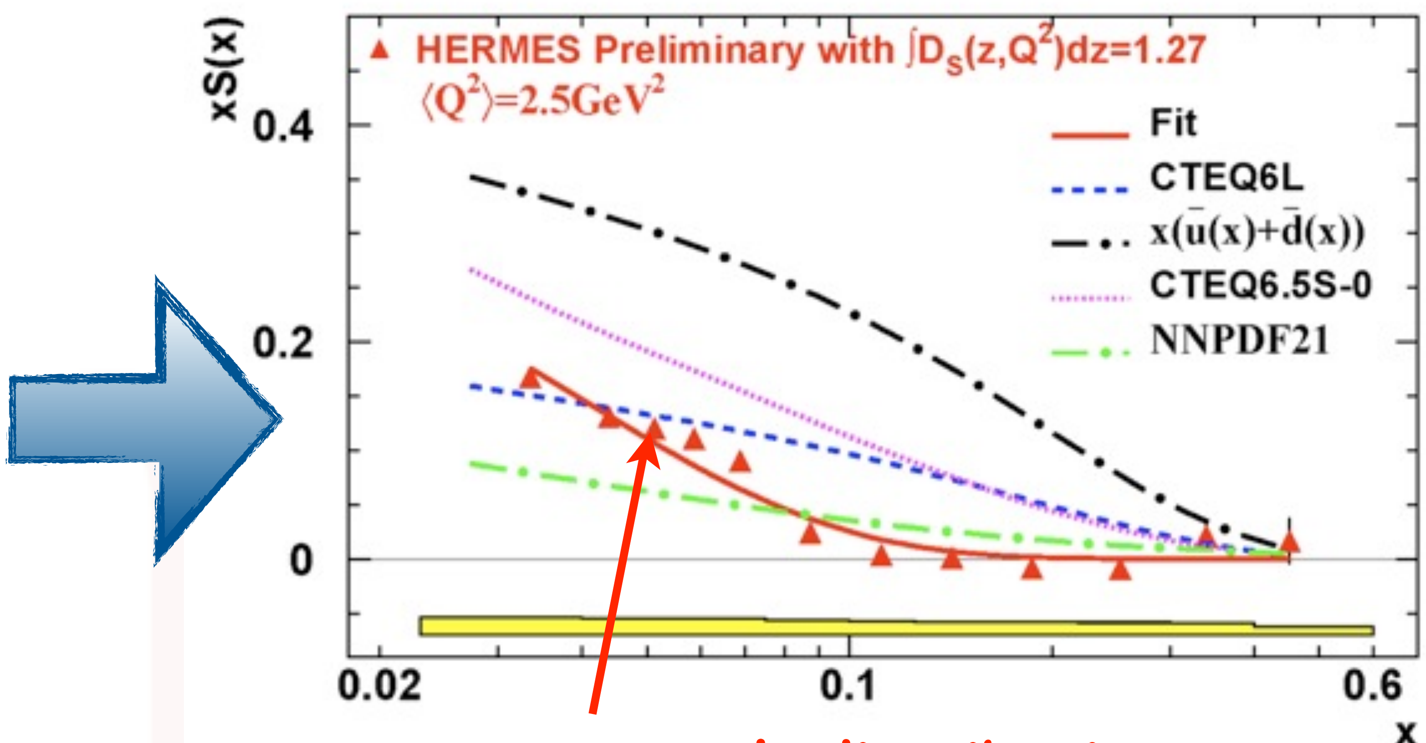


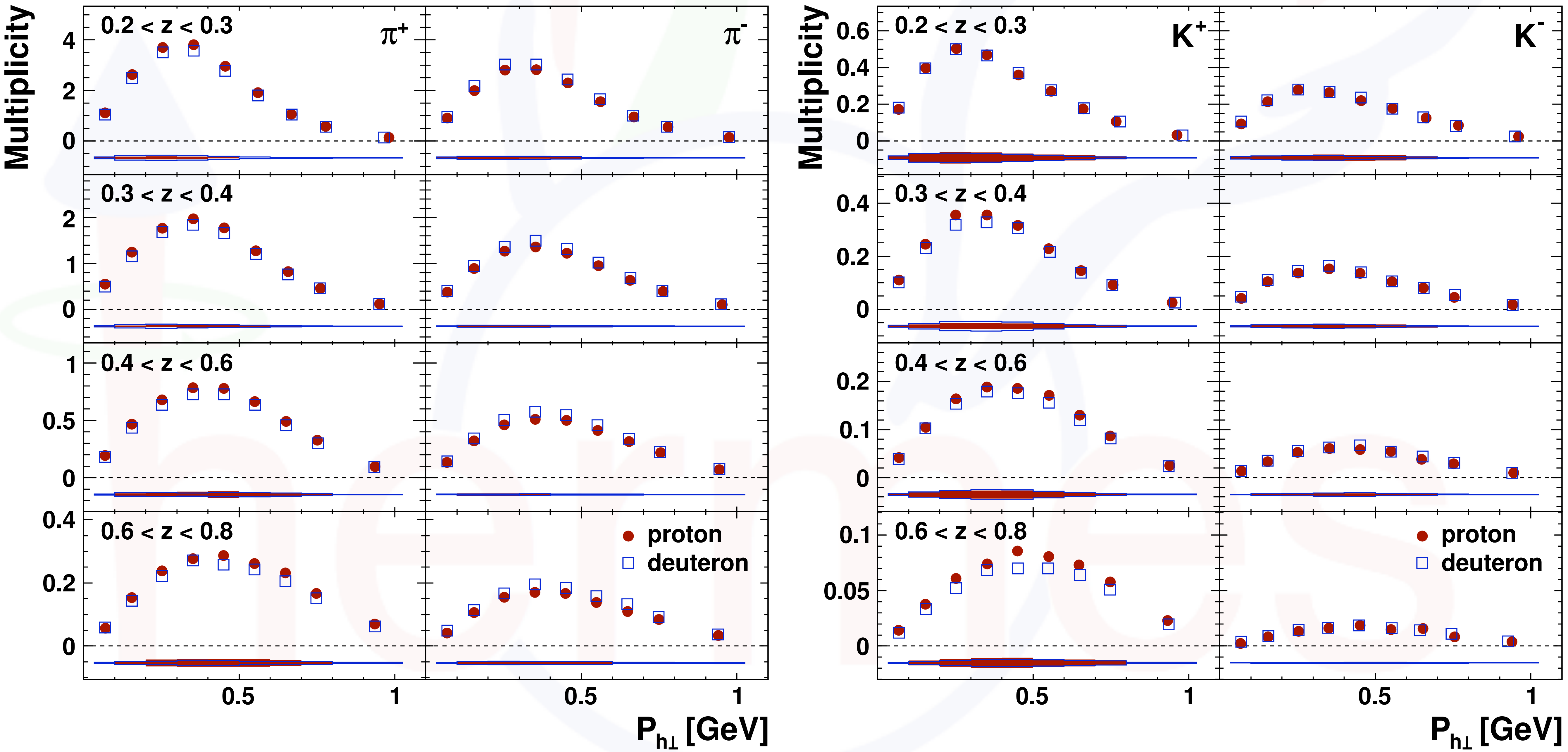

strange-quark distribution

softer than (maybe) expected

# Transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID

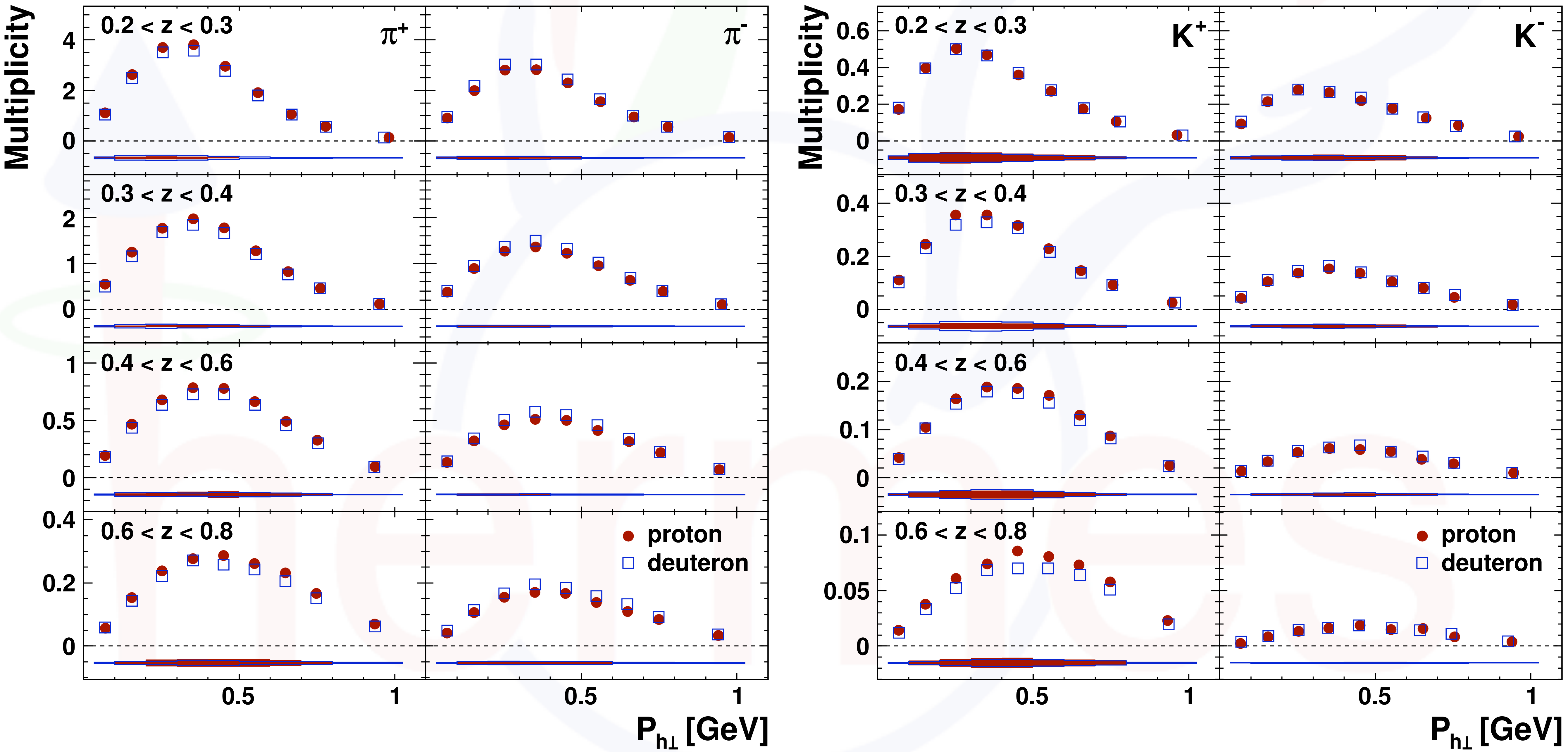
[Airapetian et al., PRD 87 (2013) 074029]



# Transverse momentum dependence

- multi-dimensional analysis allows going beyond collinear factorization
- flavor information on transverse momenta via target variation and hadron ID ☛ A. Signori (Friday)

[Airapetian et al., PRD 87 (2013) 074029]



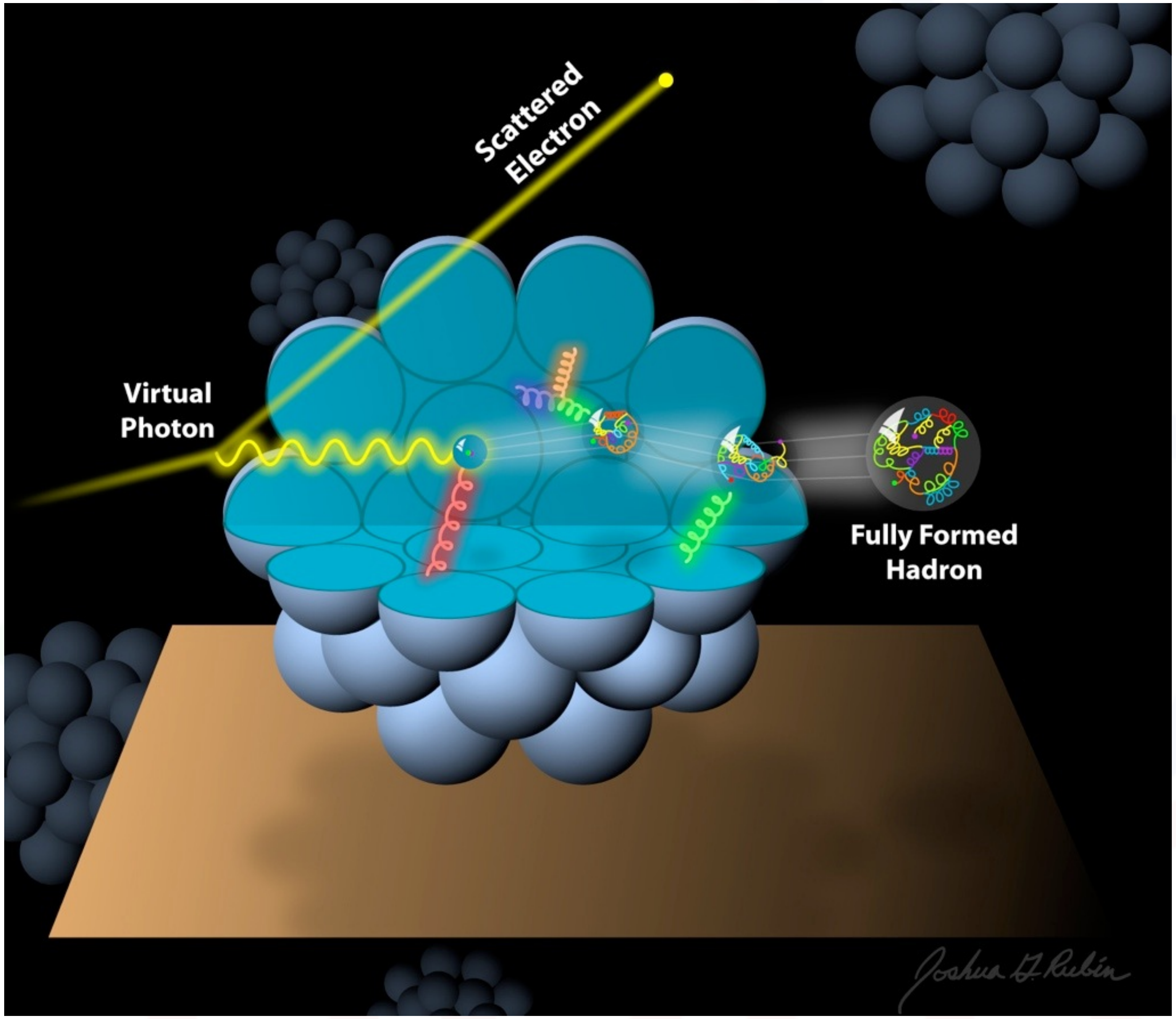
# Results II:
# multiplicity ratios - nuclear attenuation

A. Airapetian et al., Nucl. Phys. B 780 (2007) 1-27

A. Airapetian et al., EPJ A 47 (2011) 113

http://inspirebeta.net/record/918944/

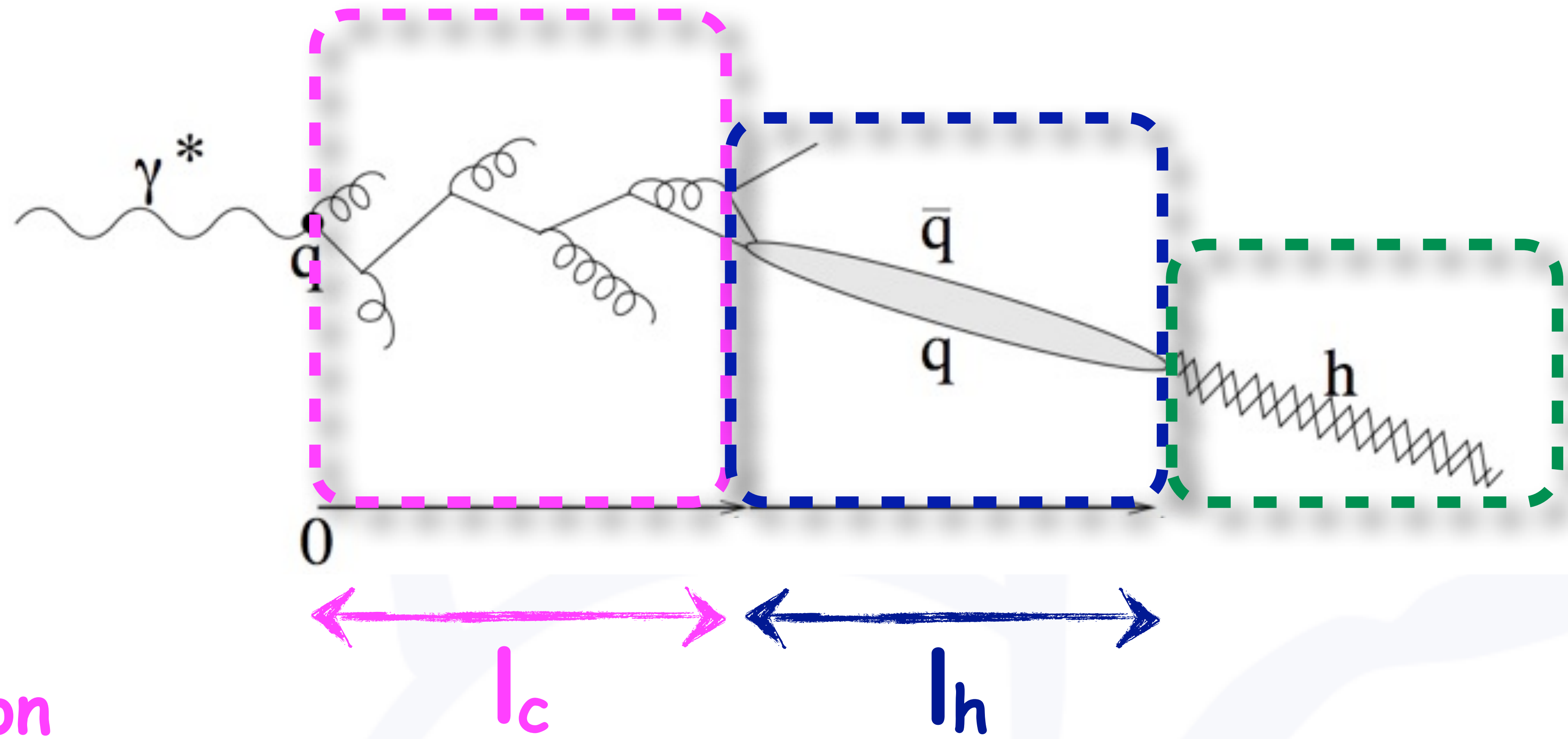
# Nuclei: a hadronization laboratory




[J. Rubin]

- partons in nuclear medium:
  - PDFs modified (e.g, EMC effect)
  - gluon radiation and rescattering effects
- (pre)hadron in nuclear medium:
  - rescattering
  - absorption

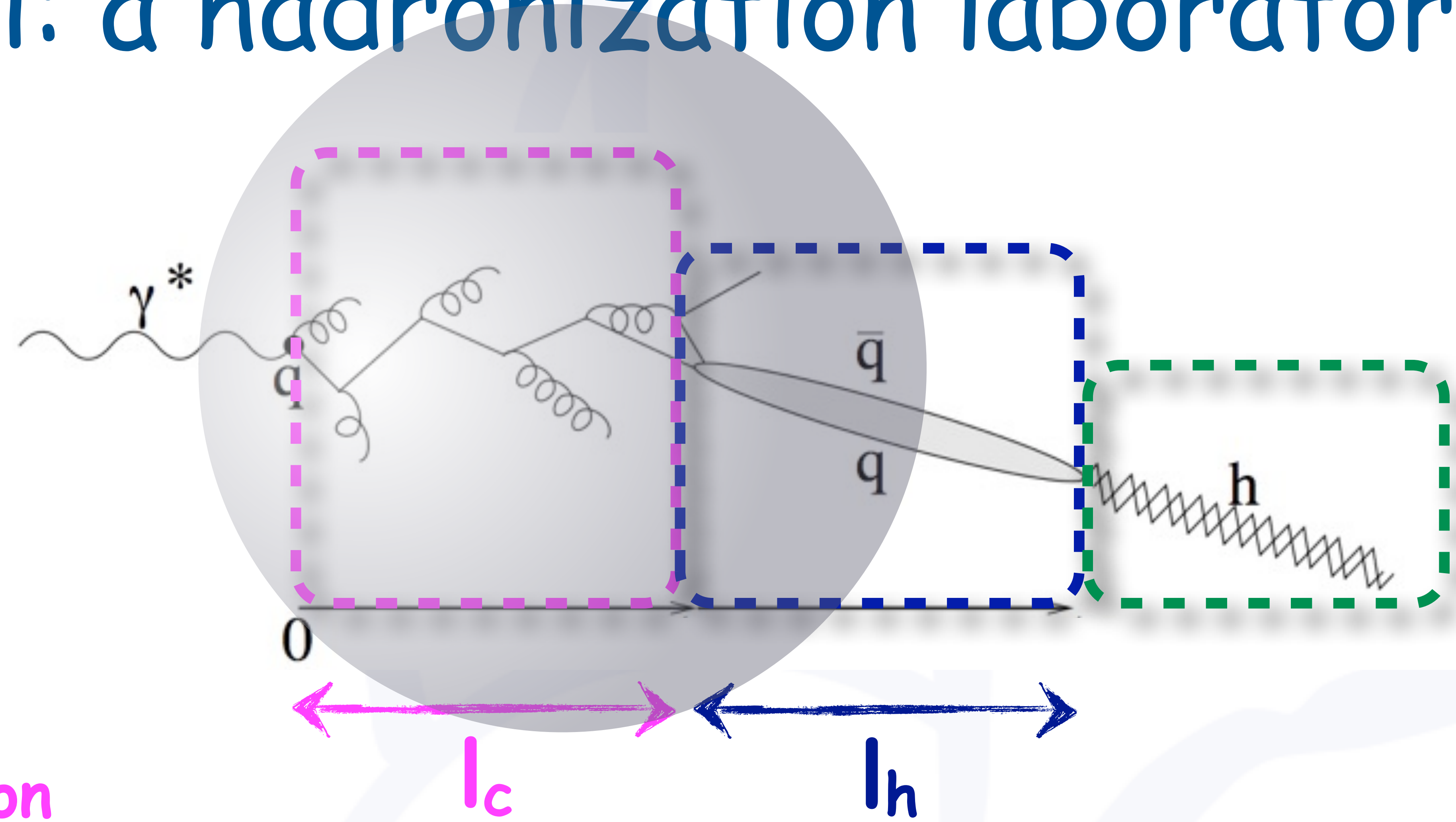
# Nuclei: a hadronization laboratory




- **parton**
- **pre-hadron**
  - colorless
  - quantum numbers of final hadron
- **final state hadron**

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

# Nuclei: a hadronization laboratory




- parton
- pre-hadron
  - colorless
  - quantum numbers of final hadron
- final state hadron

- differences predicted for partonic and (pre-)hadronic interactions
- depends on formation lengths (1-10fm) = O(nucleus size)

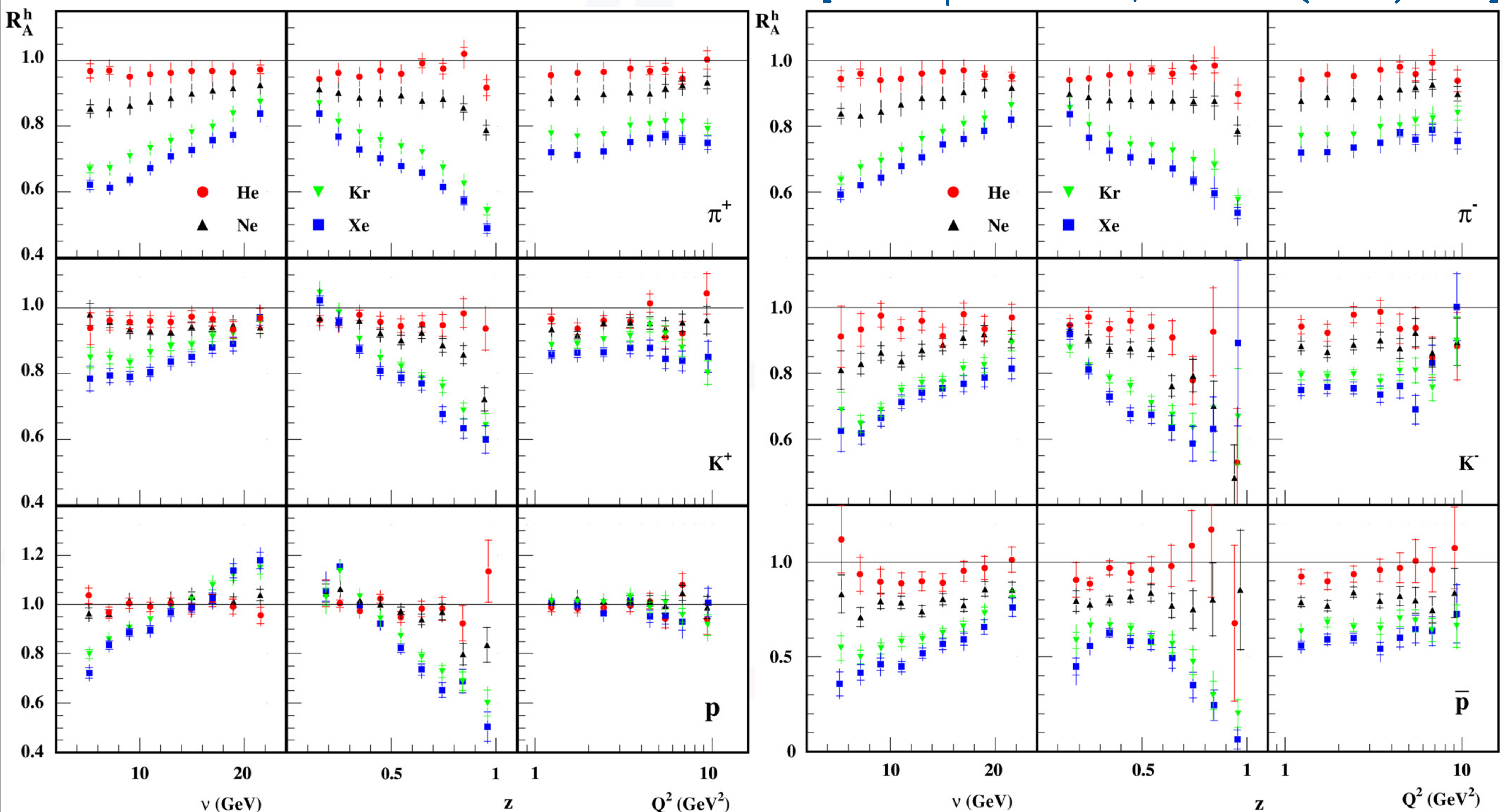
# Multiplicity ratios

$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu,Q^2,z,p_t^2)}{N^e(\nu,Q^2)}\right)_A}{\left(\frac{N^h(\nu,Q^2,z,p_t)}{N^e(\nu,Q^2)}\right)_D}$$

- nuclear targets: (He,) Ne, Kr, Xe compared to D
- ratio ➠ approximate cancellation of:
  - QED radiative effects (RADGEN)
  - limited geometric and kinematic acceptance of spectrometer
  - detector resolution
- multi-dimensional extraction

# Nuclear attenuation

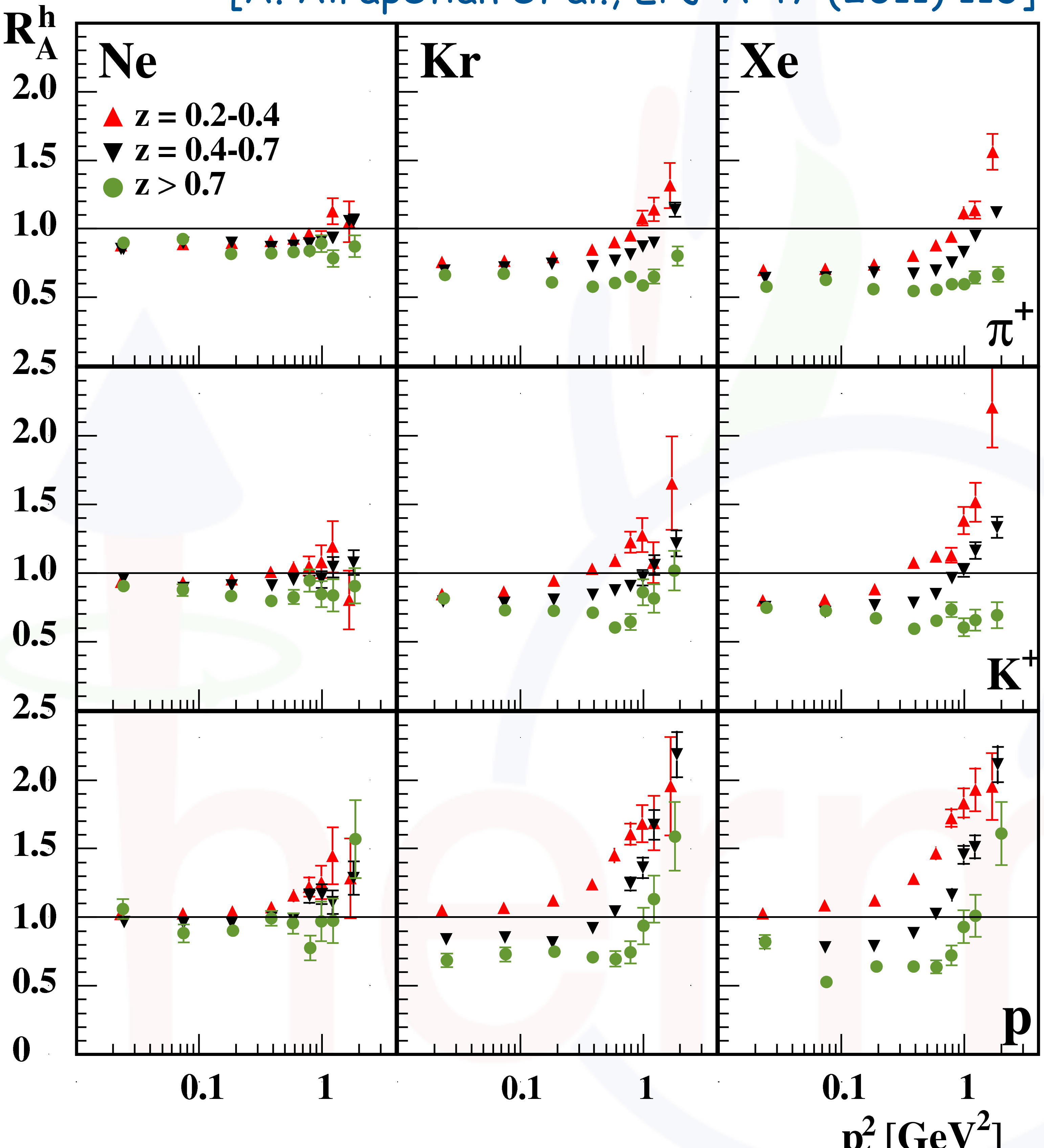
[A. Airapetian et al., NPB 780 (2007) 1–27]




- strong mass dependence: attenuation mainly increases with A
- quite different behavior for protons

# Nuclear attenuation

[A. Airapetian et al., EPJ A 47 (2011) 113]



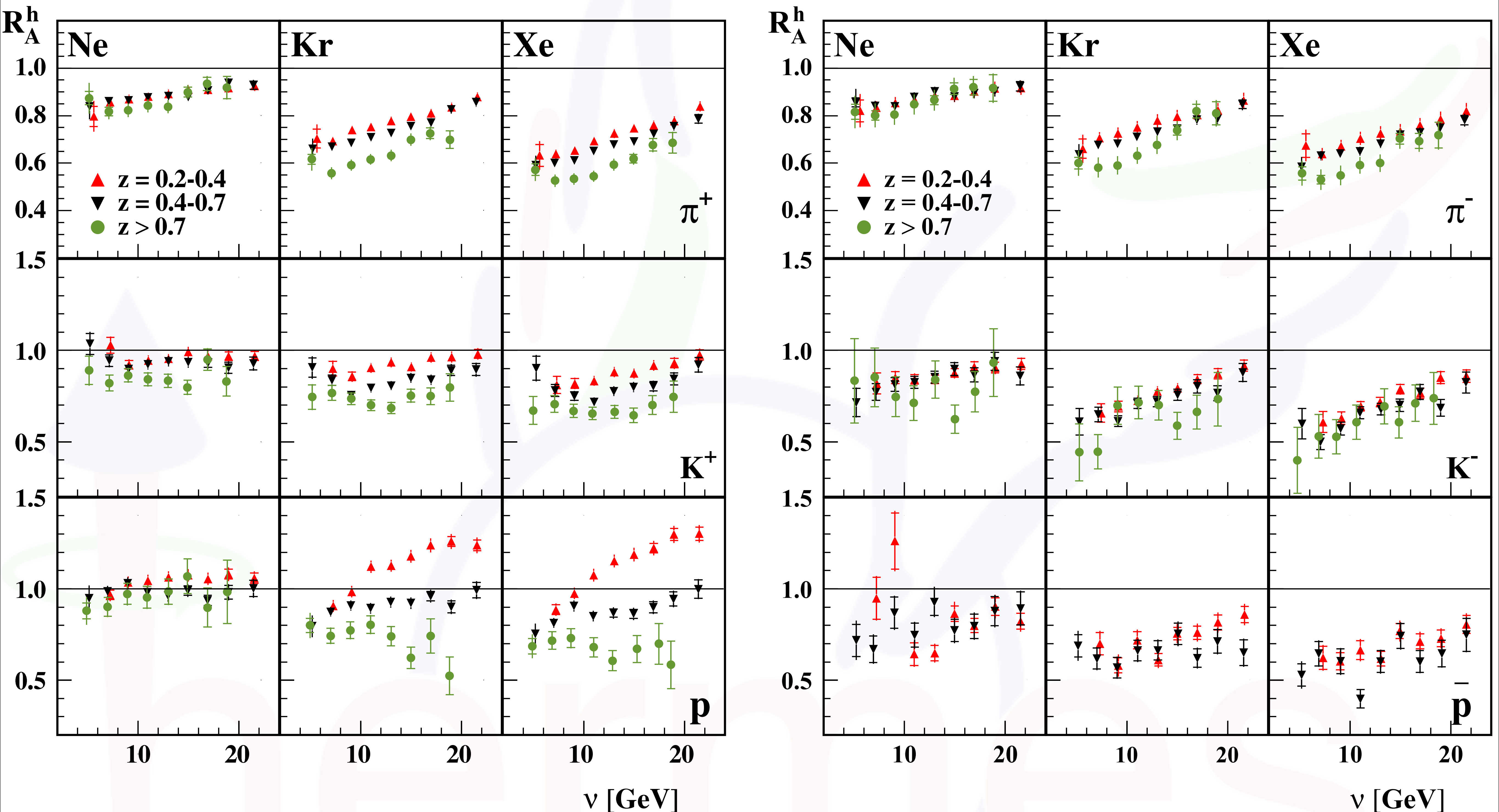

$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong $p_T$ dependence of nuclear attenuation (e.g., Cronin effect - enhancement at large $p_T$)

except maybe at large z for pions and kaons (little energy loss dictates few interactions)

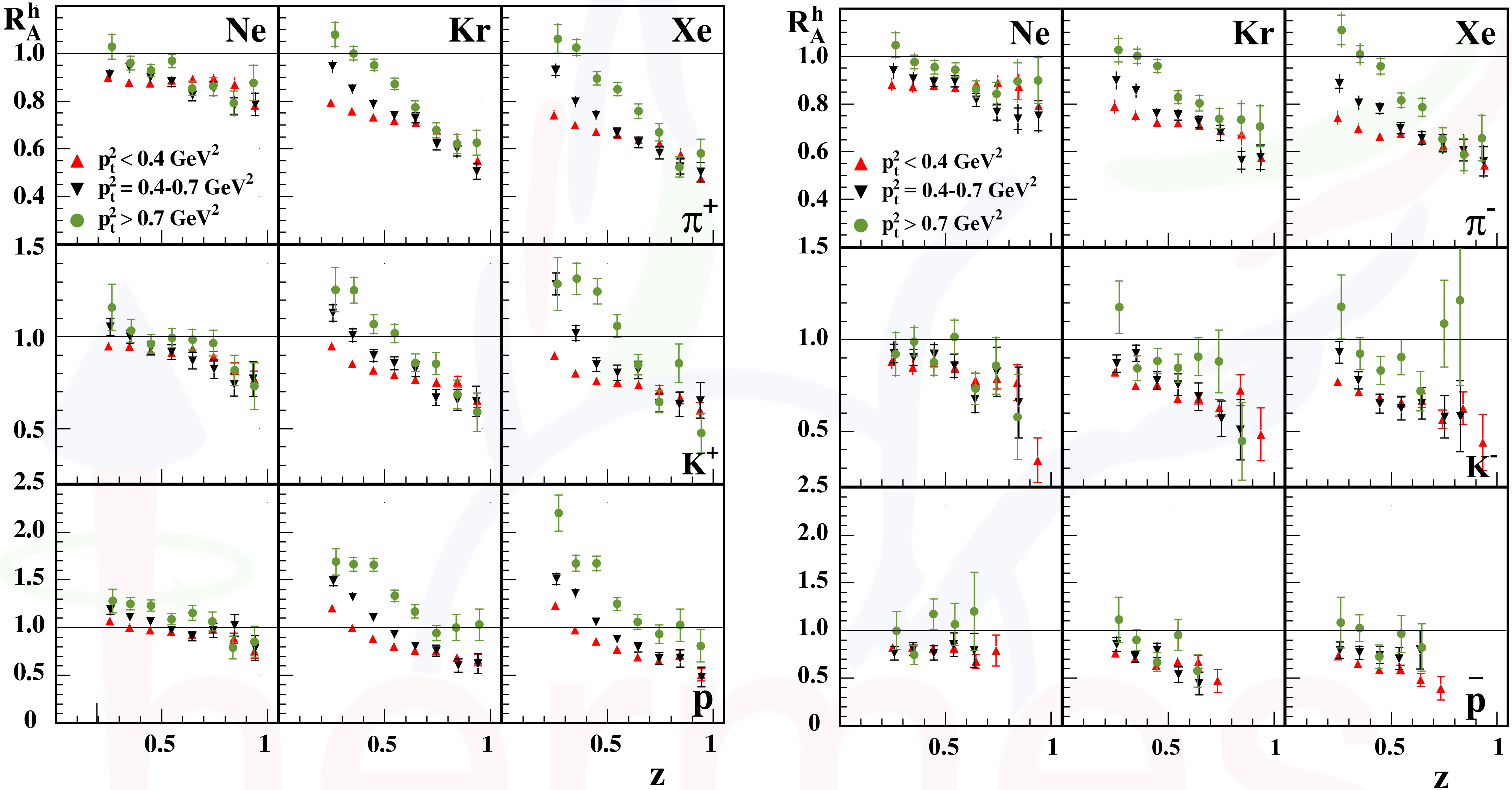
larger effect for protons

# Nuclear attenuation




- mostly decrease of attenuation with increasing $\nu$
- enhancement of proton multiplicities at low z and high $\nu$

# Nuclear attenuation




- strong **z** dependence of attenuation
- amplified by transverse momentum and target mass (i.e., size)

# Conclusions

- HERMES managed step from spin-asymmetry experiment to unpolarized-target experiment
- largest data set on charged-separated identified meson lepto-production
- multi-dimensional analysis and various targets allow study of correlations and flavor dependences
- large attenuation effects at HERMES energies, mainly increasing with nucleus size (except protons) with correlated kinematic dependences
- nuclear environment can play significant role in TMD effects
- don't forget longitudinal photons