Transport Theoretical Studies of Hadron Attenuation in Nuclear DIS

T. Falter, W. Cassing, K. Gallmeister, U. Mosel

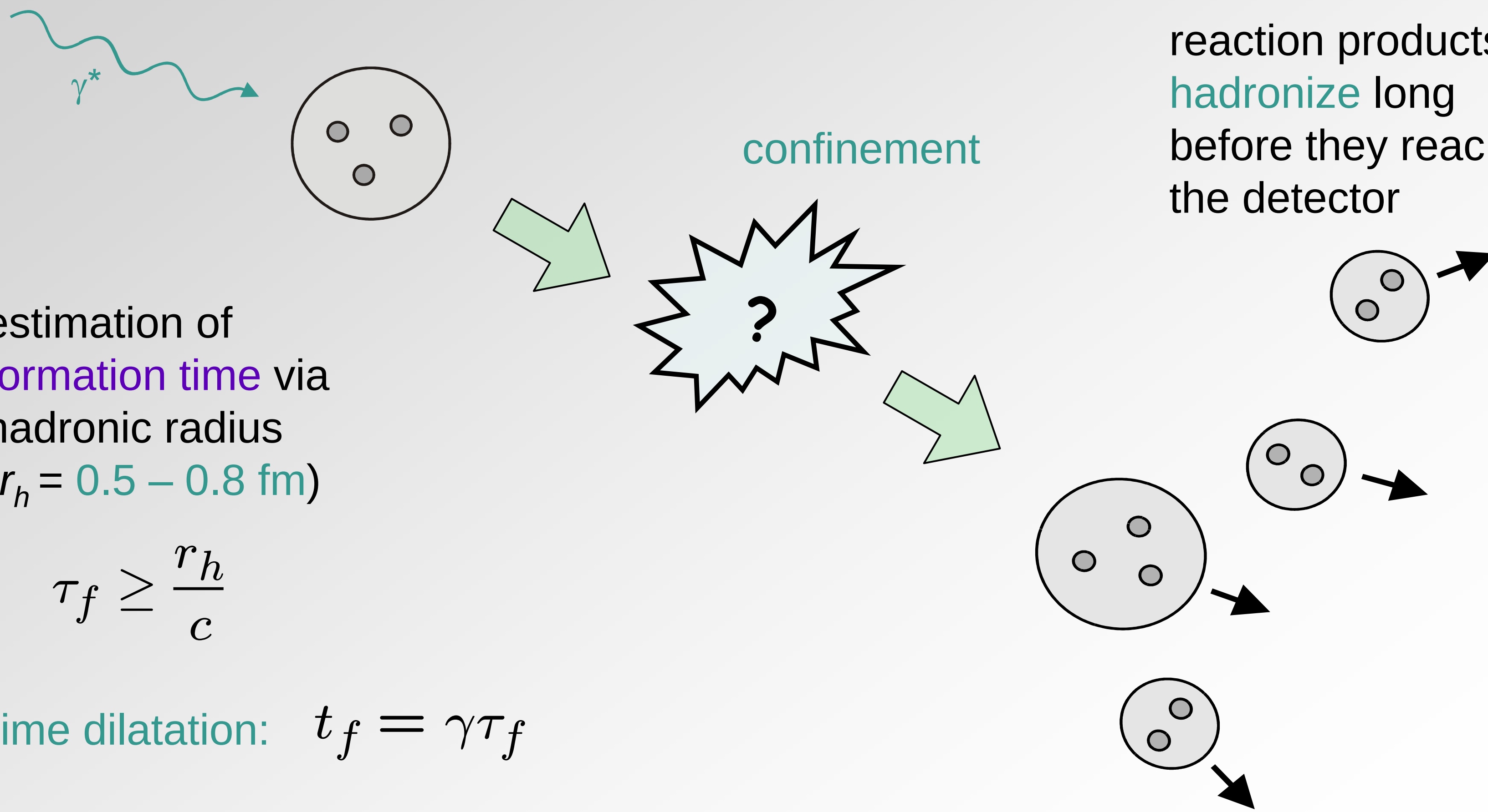
Contents:

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

BROOKHAVEN NATIONAL LABORATORY

Motivation

- elementary *eN* reaction



reaction products hadronize long before they reach the detector

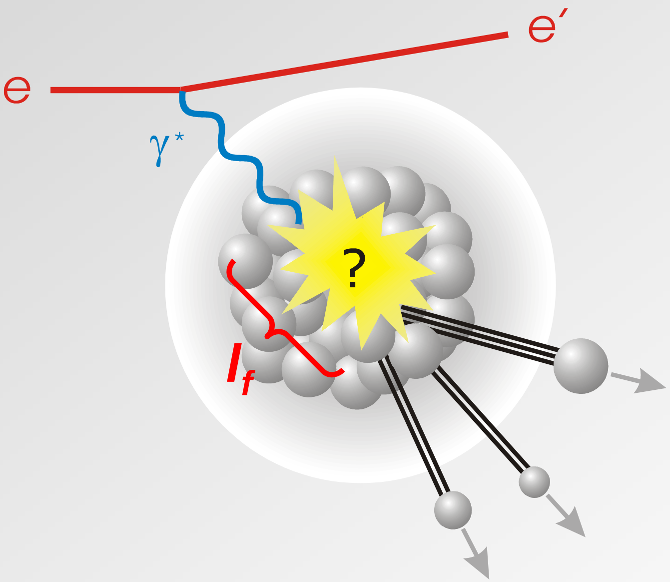
estimation of formation time via hadronic radius (r_h = 0.5 – 0.8 fm)

$$\tau_f \geq \frac{r_h}{c}$$

time dilatation: $t_f = \gamma \tau_f$

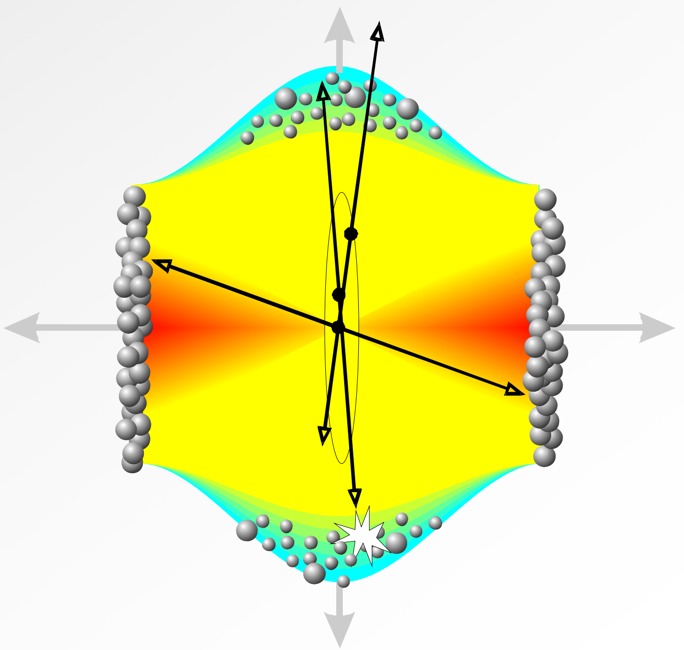
- *eA* reactions at HERMES
  - interactions with (cold) nuclear medium during t_f

→ **space-time picture of hadronization & prehadronic interactions**



- lessons for more complex heavy-ion collisions
  - jet supression at RHIC
    - partonic energy loss in QGP
    - (pre-)hadronic FSI

→ **talk by K. Gallmeister**



Model

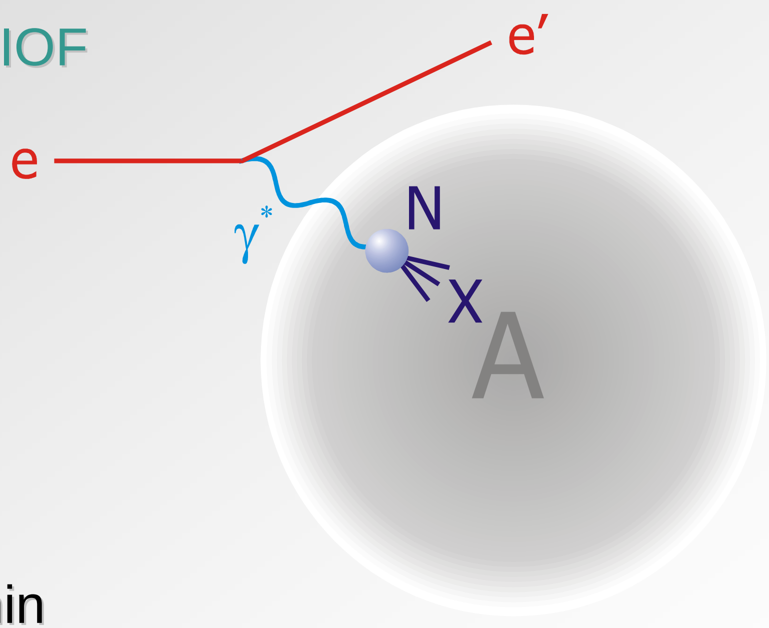
- γA, eA reaction splitted into 2 parts :

  – $\gamma^* N \rightarrow X$ using PYTHIA & FRITIOF

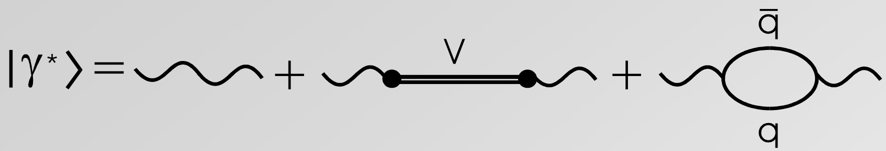
  - additional consideration of
    – binding energies
    – Fermi motion
    – Pauli blocking
    – coherence length effects

  – propagation of final state X within BUU transport model

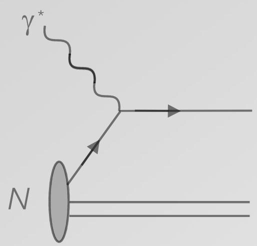
  - consideration of
    – elastic and inelastic scattering (coupled channels)



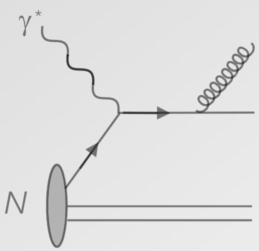
hadronic structure of the photon & event classes



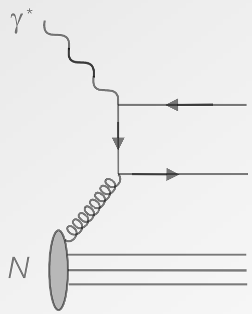
– direct photon interactions:



DIS

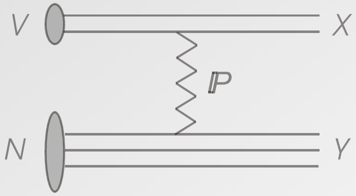


QCD Compton

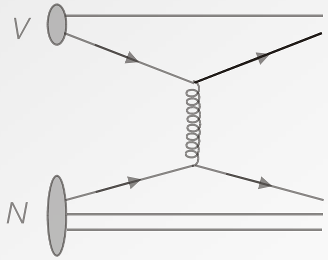


photon-gluon fusion

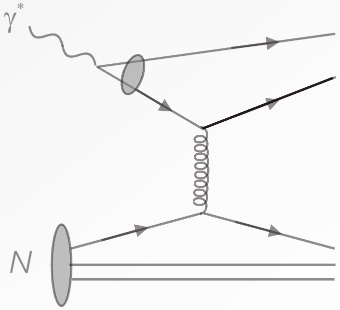
– resolved photon interactions:



diffractive VMD

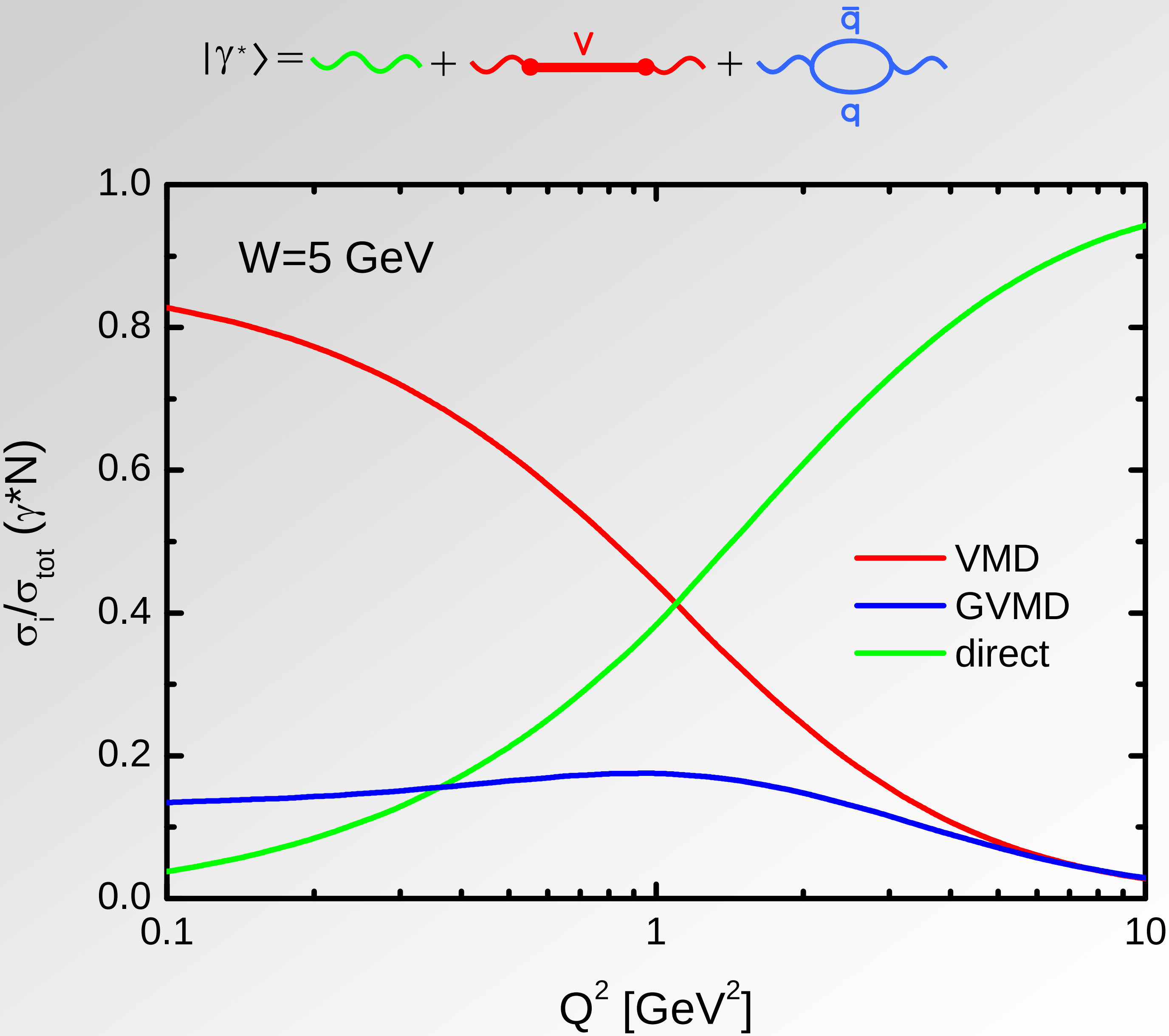


VMD



GVMD

hadronic structure of the photon



shadowing of the vector meson component

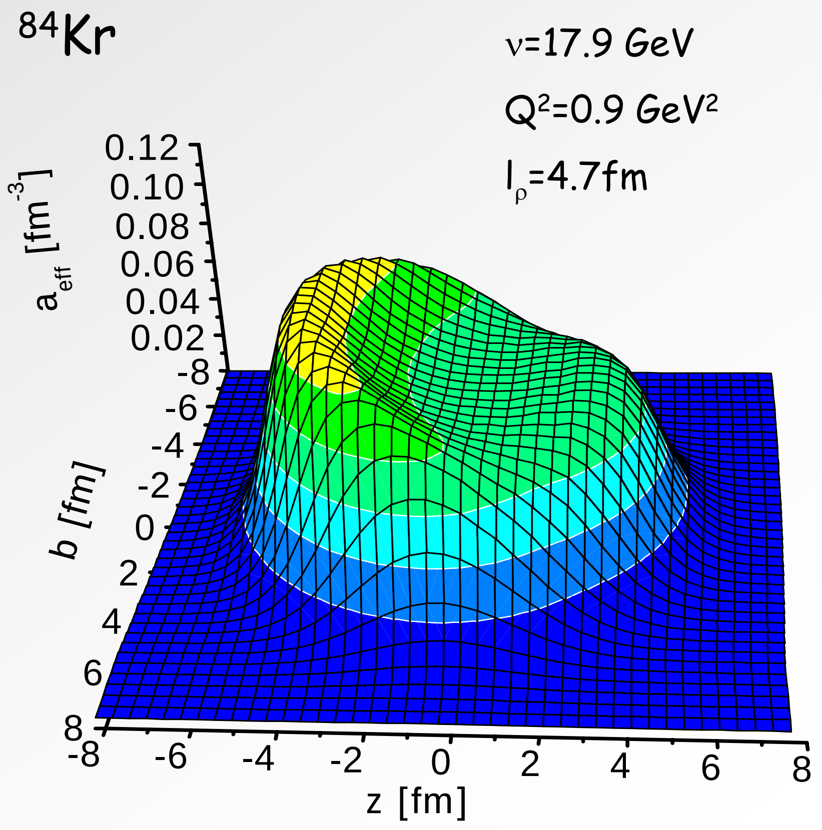
– coherence length:
distance that γ^* travels as a vector meson fluctuation

$$l_V = |k_V - k_\gamma|^{-1} \approx \frac{2\nu}{Q^2 + m_V^2}$$

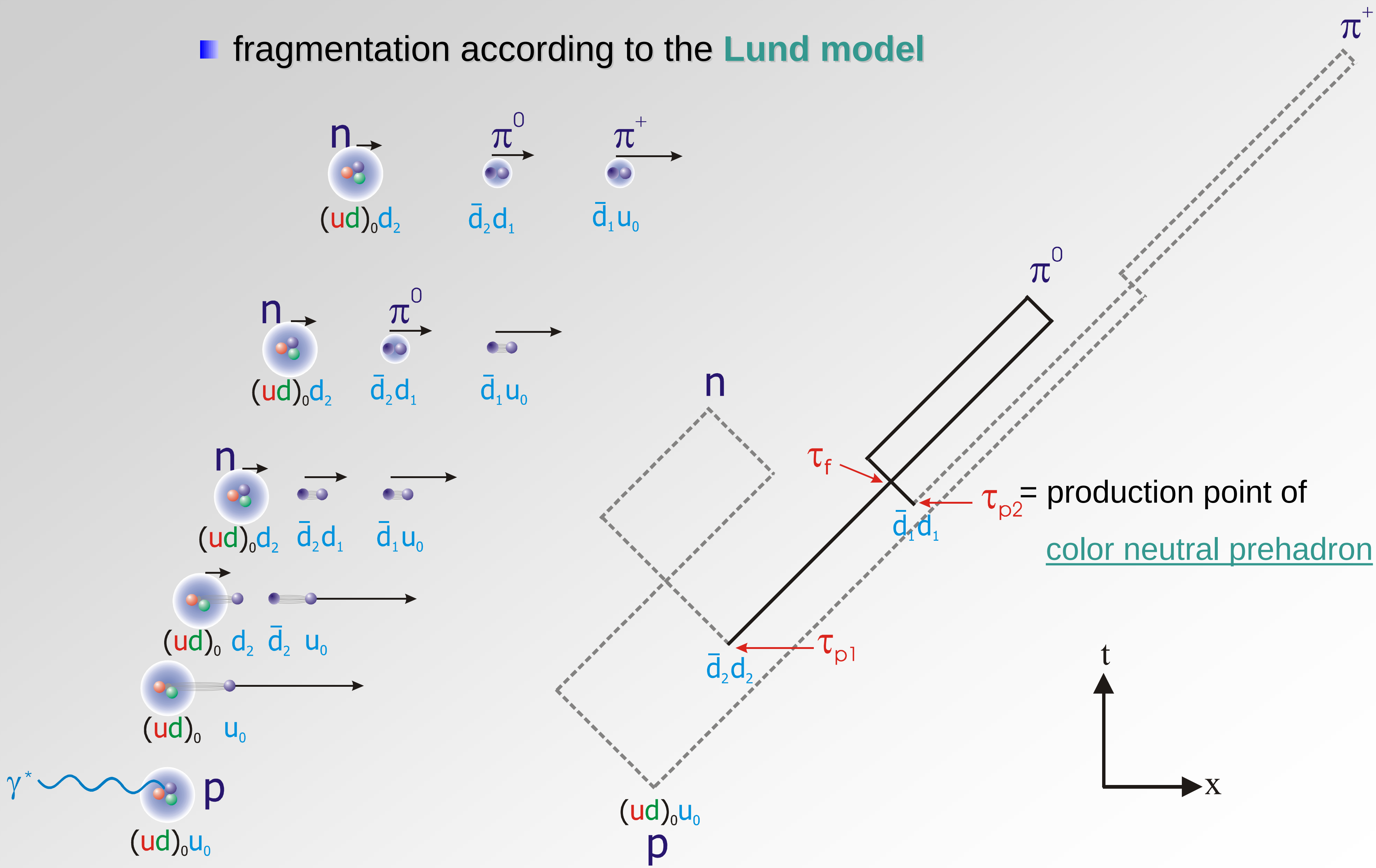
– coherence length > mean free path inside nucleus

- density of nucleons participating in the production process reduced

- influences reactions triggered by the vector meson component (e.g. $\gamma^* N \to \rho^0 N$)



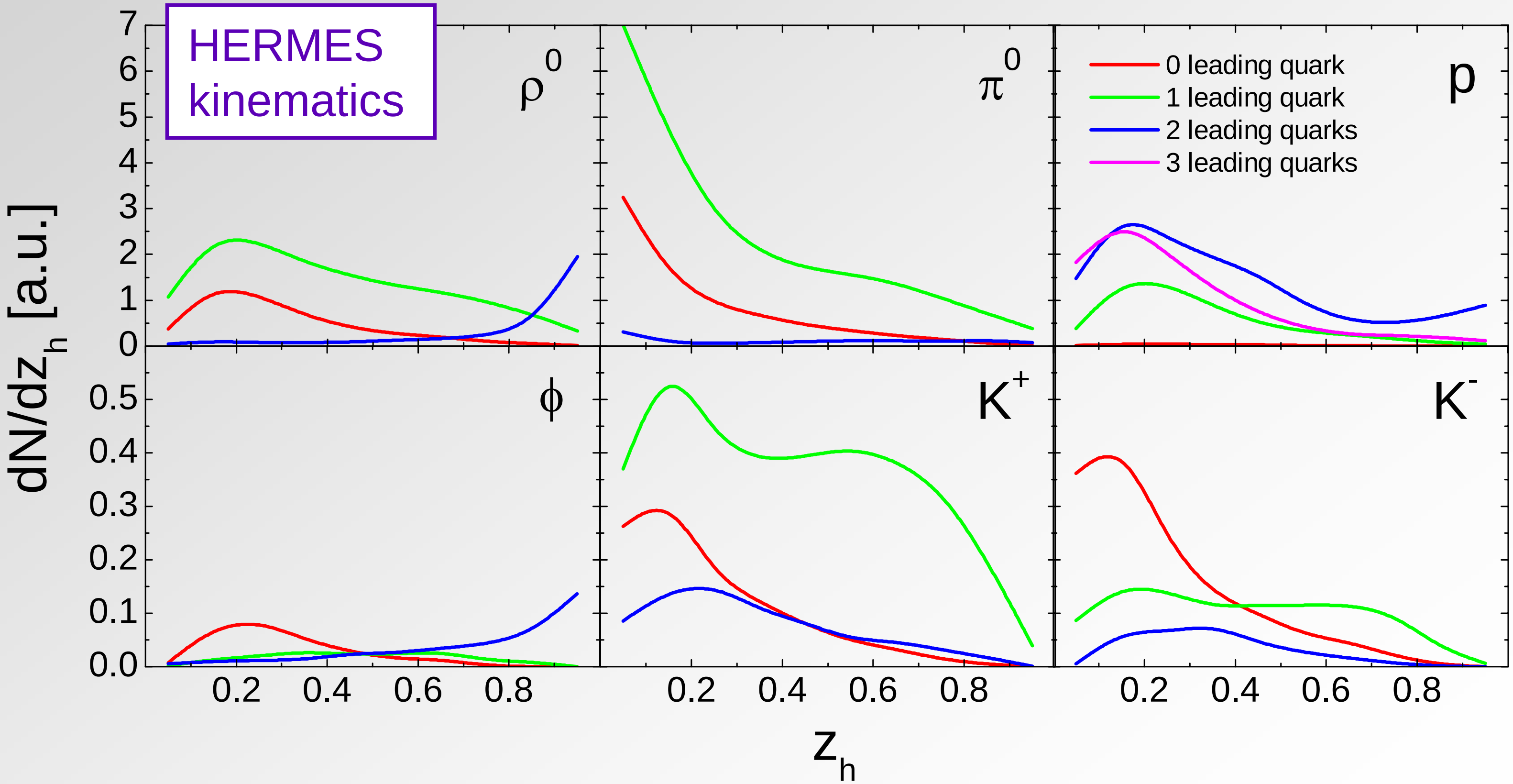
- hard interactions (e.g. direct $\gamma^* N$ reaction)
  - excitation of hadronic strings
  - fragmentation according to the **Lund model**



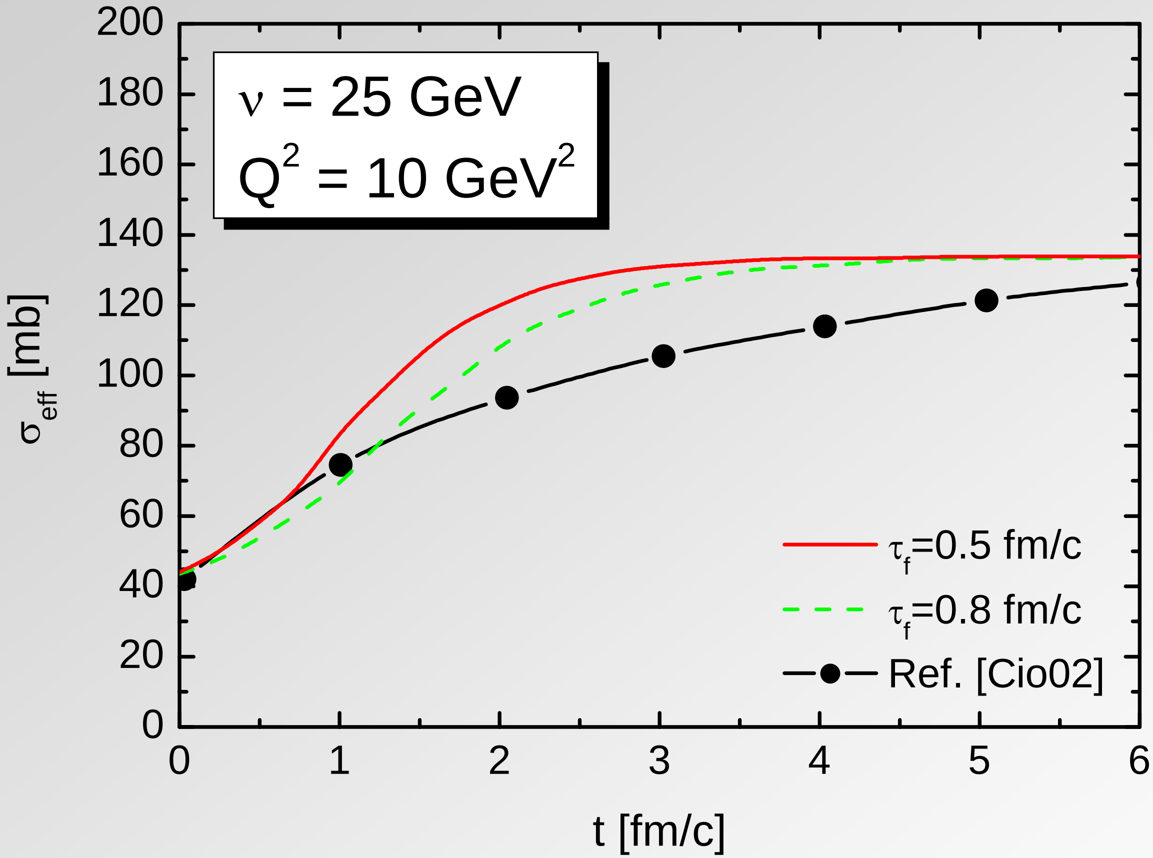
general approach in transport model

- string fragments very fast into
  color-neutral prehadrons $t_p = 0$
- prehadrons need formation time $t_f = \gamma_h \tau_f$
  to build up hadronic wave function
- prehadronic cross section σ^*
  determined by constituent quark model

$$\sigma_b^* = \frac{\# q_{orig}}{3}\sigma_b$$
$$\sigma_m^* = \frac{\# q_{orig}}{2}\sigma_m$$



effective cross section of nucleon debris



comparison with
gluon bremsstrahlung model

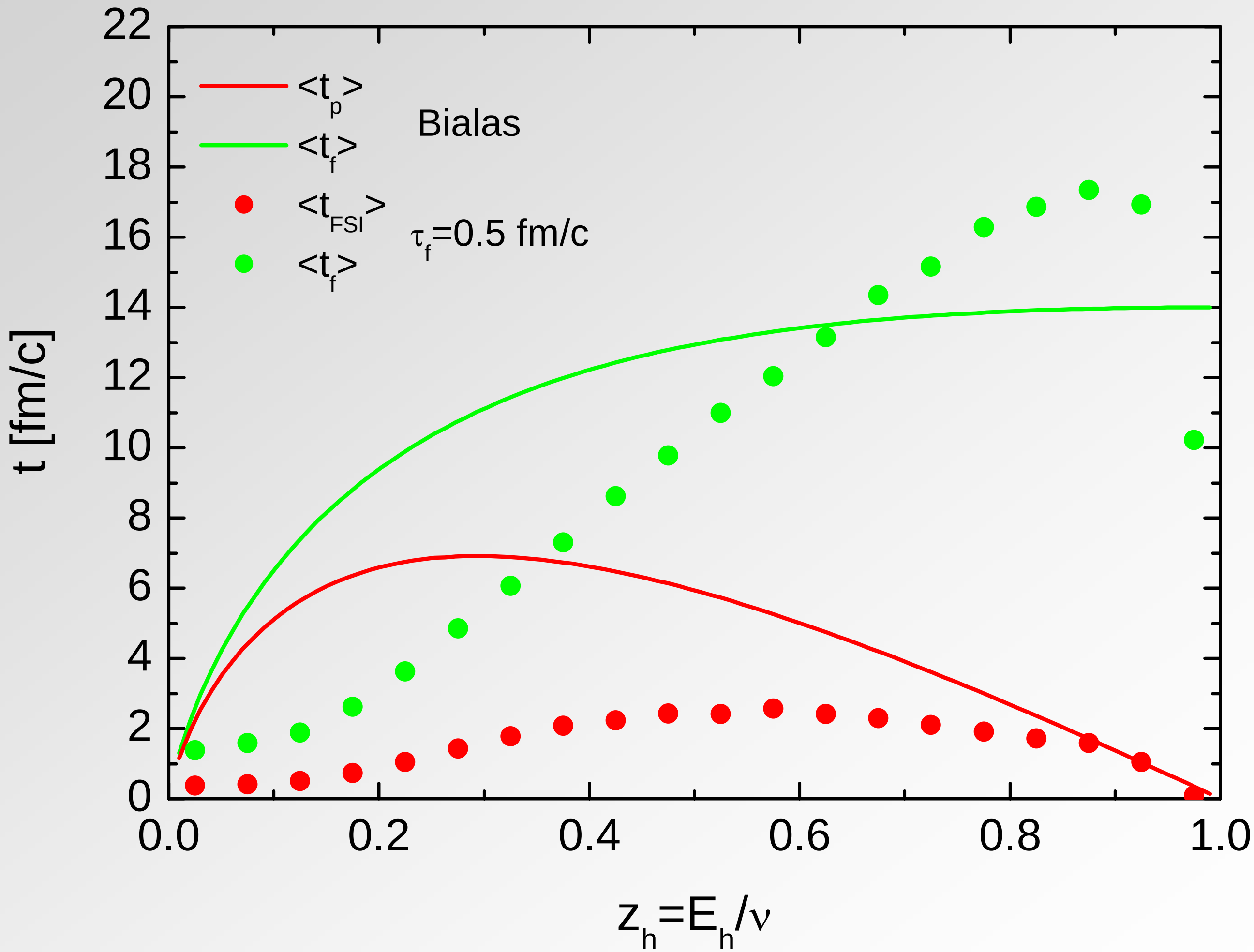
C. Ciofi degli Atti and B. Z. Kopeliovich,

Eur. Phys. J. A **17**, 133 (2003).

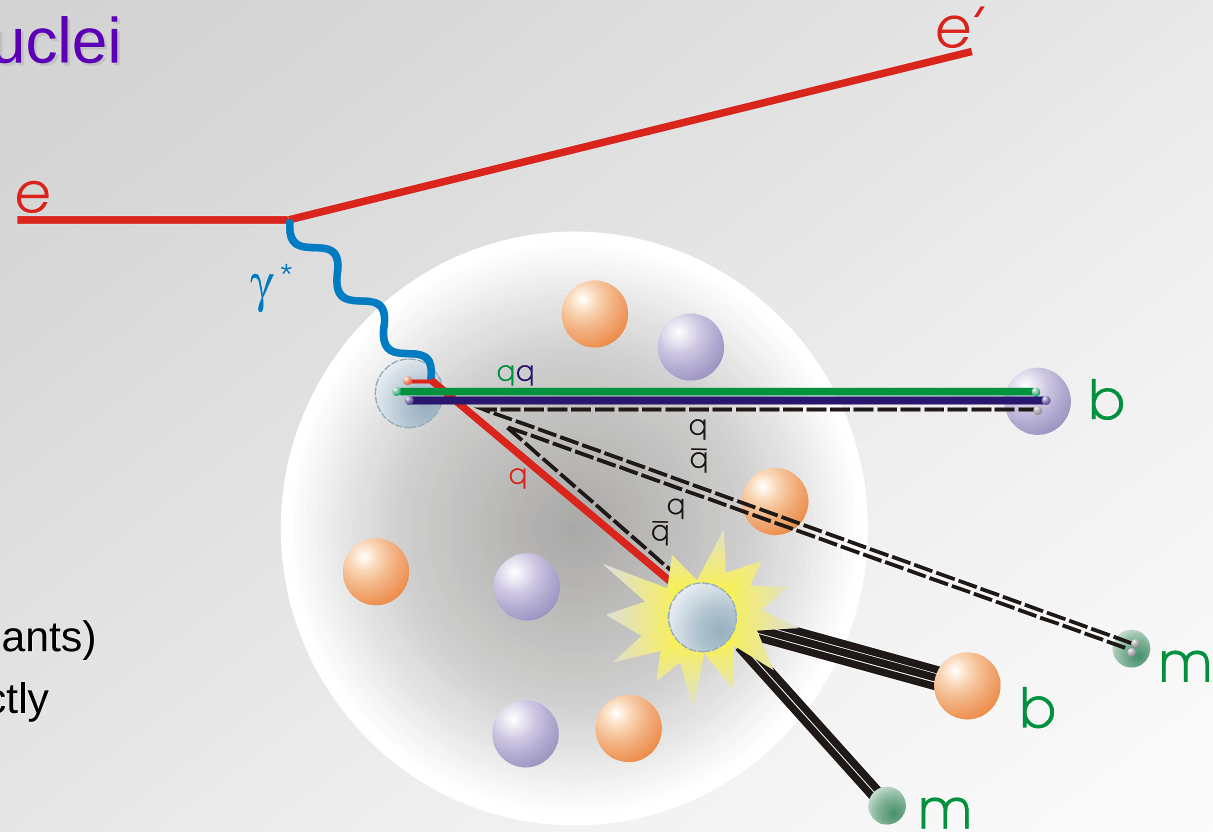
starting time of (pre-)hadronic FSI

- Comparison with Lund estimate

A. Bialas and M.Gyulassy, NPB **291** (1987) 793



DIS of complex nuclei



- "leading" prehadrons
  (= target-, beam remnants)
  can undergo FSI directly
  after $\gamma^{*}N$ interaction

- hadrons that solely contain quarks
  from string fragmentation start to interact after τ_f

FSI ➡

- production of new particles
- redistribution of energy

BUU transport model

- for each particle species i ($i = N, R, Y, \pi, \rho$, K, …) exists a Boltzmann-Uehling-Uhlenbeck equation:

$$\left(\frac{\partial}{\partial t} + (\nabla_{\vec{p}} H)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H)\nabla_{\vec{p}}\right) f_i(\vec{r}, \vec{p}, t) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_M]$$

f_i : phase space density

H : Hamilton function

$$H = \sqrt{(\mu + U_s)^2 + \vec{p}^2}$$

mean field for baryons

collision integral accounts for changes in f_i due to 2 particle collisions: creation, annihilation, elastic scattering (Pauli blocking for fermions)

- set of BUU equations coupled via I_{coll} and mean field

→ products of $\gamma^* A$ reaction need not be created in primary $\gamma^* N$ reaction

Results

- HERMES:

  – look for CT in incoherent ρ^0 electroproduction off ^{14}N

  $$\nu \approx 10 - 20\,\mathrm{GeV}, \quad Q^2 \approx 0.5 - 5\,\mathrm{GeV}^2$$

  – diffractive V production: $\gamma^* N \to \rho^0 N$

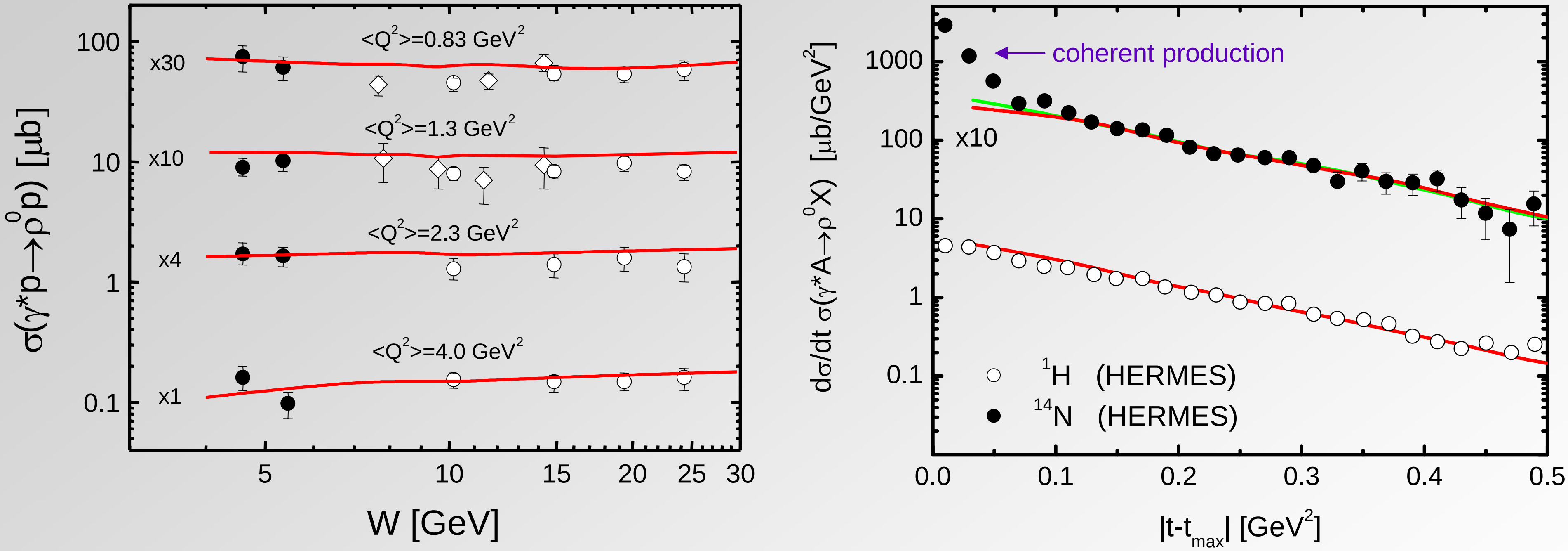
    - size of initially produced $q\bar{q}$ pair is expected to decrease with increasing Q^2
      – early stage of evolution:
      small $q\bar{q}$ pair interacts mainly via its color dipole moment:
      $\sigma_{q\bar{q}} \sim \text{diameter}^2$

    - large energies:
      – $q\bar{q}$ frozen in small sized configuration while passing nucleus

➡ effects nuclear transparency ratio:

$$T_A = \frac{\sigma_{\gamma^* A \to \rho^0 A^*}}{A \sigma_{\gamma^* p \to \rho^0 p}}$$

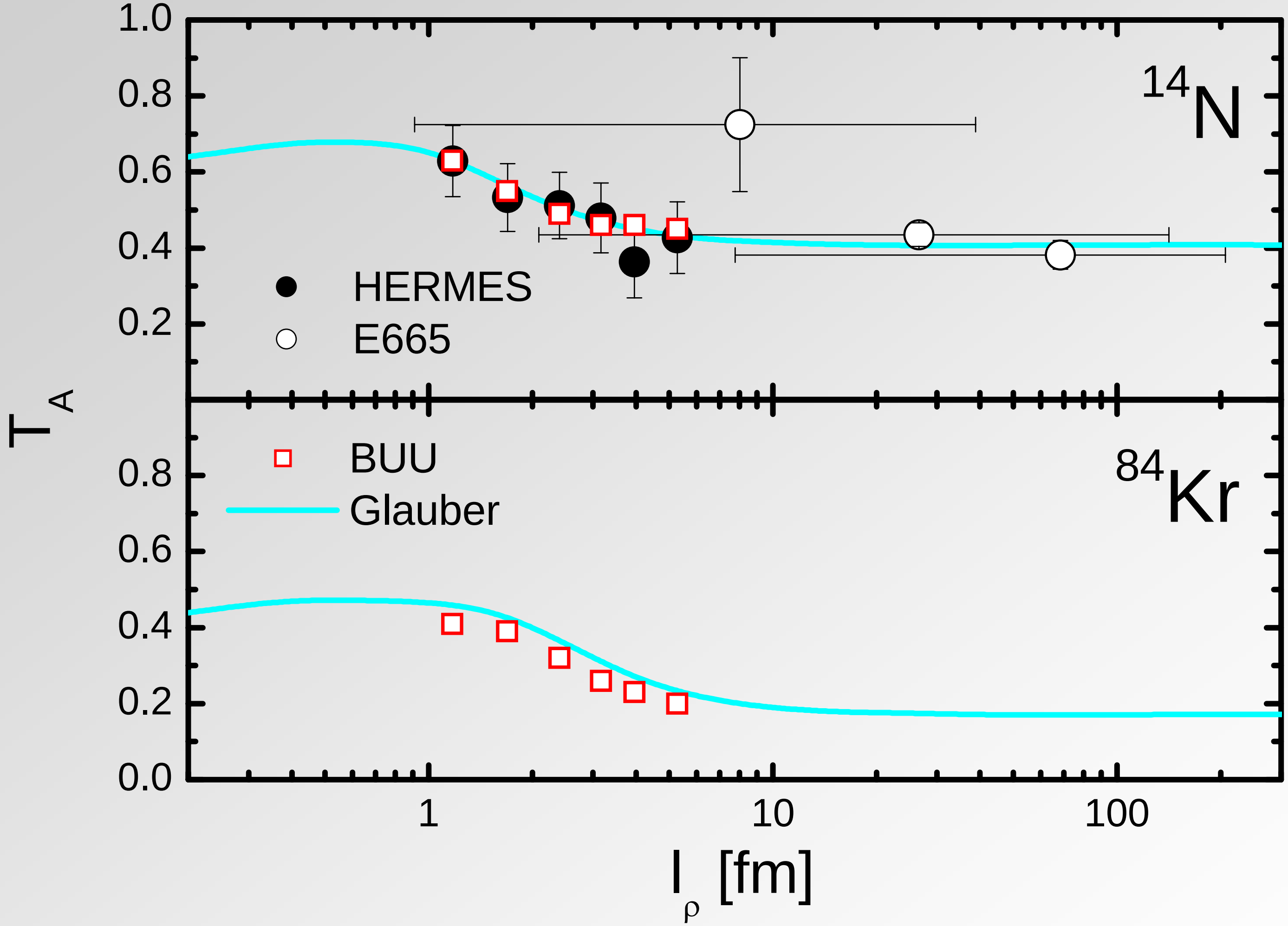
Comparison with Hydrogen data



– experimental *t*-cut: $|t| > 0.09\ \mathrm{GeV}^2$

- to get rid of coherent ρ^0 production: $\gamma^* A \to \rho^0 A$

BUU & Glauber theory agree with experiment



no CT in both calculations
only coherence length effects

hadron attenuation in DIS off nuclei

- multiplicity ratio:

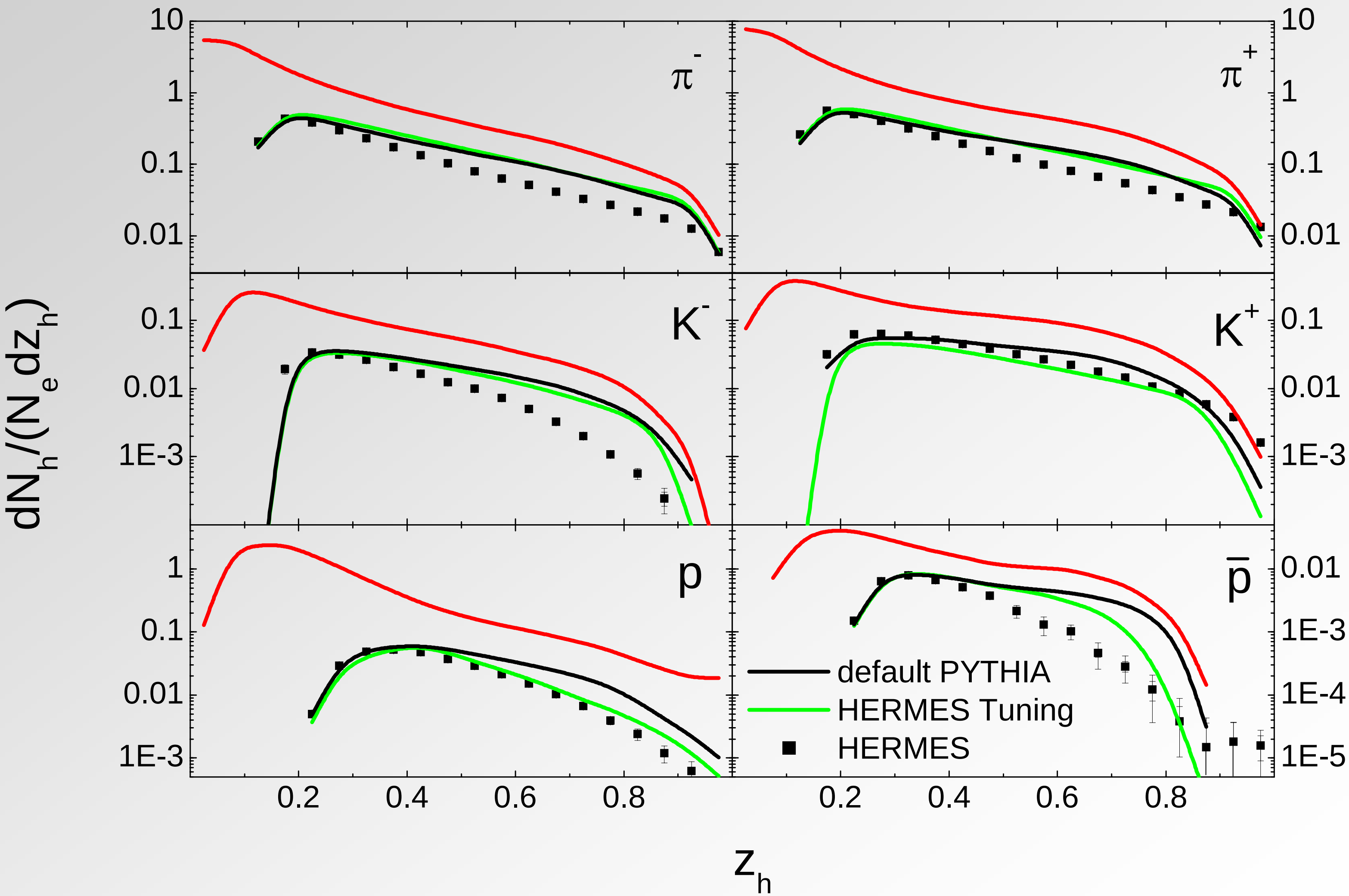
$$R_M^h(z_h, p_T, \nu) = \frac{\left(\frac{N_h(z_h, p_T, \nu)}{N_e(\nu)}\right)_A}{\left(\frac{N_h(z_h, p_T, \nu)}{N_e(\nu)}\right)_D} \qquad z_h = \frac{E_h}{\nu}$$

- Experiments:
  - EMC: 100-200 GeV μ-beam on ^{64}Cu
  - HERMES: 27.6 GeV e^+-beam on ^{14}N, ^{20}Ne, ^{84}Kr
  - Jefferson Lab: 5.4 GeV e^--beam on ^{12}C, ^{56}Fe, ^{208}Pb

- attenuation due to
  - partonic energy loss
    (X.N. Wang et al., F. Arleo)
  - (pre)hadronic absorption
    (A. Accardi et al.) + rescaling of fragmentation function
    (B. Kopeliovich et al., T. Falter et al.)

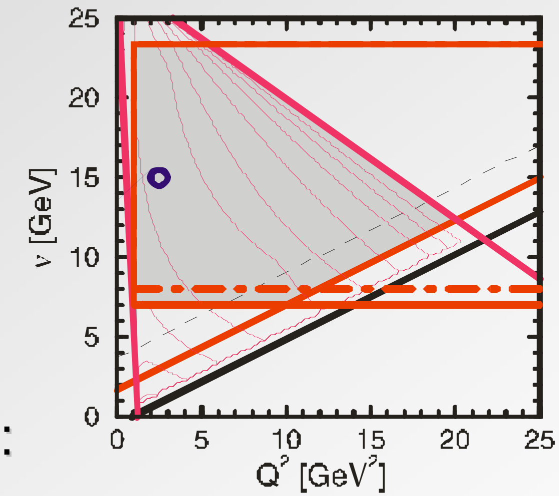
DIS off proton

– HERMES $\nu = 2.5 - 24$ GeV, $Q^2 > 1$ GeV^2, $W > 2$ GeV
– red curves: calculation w/o cuts on hadron kinematics
  and assuming 4π-detector

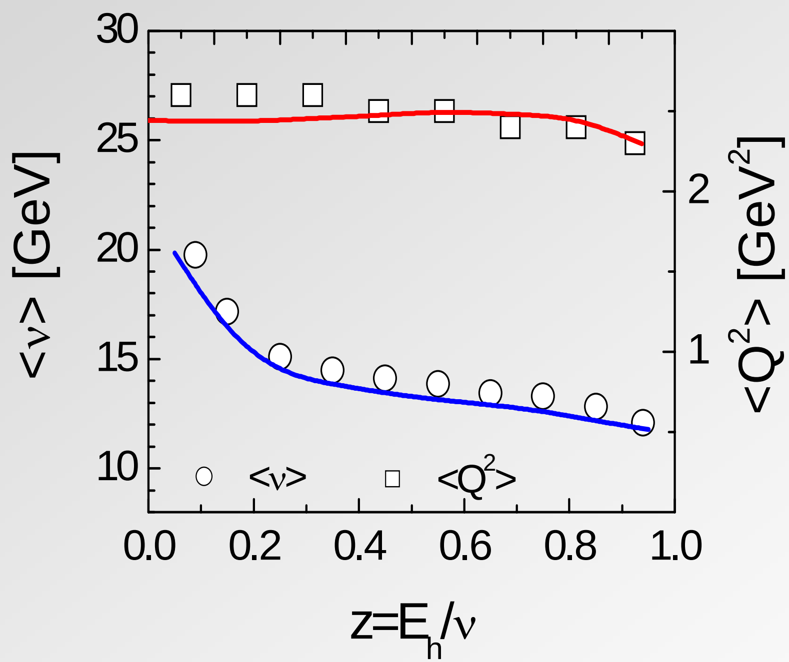


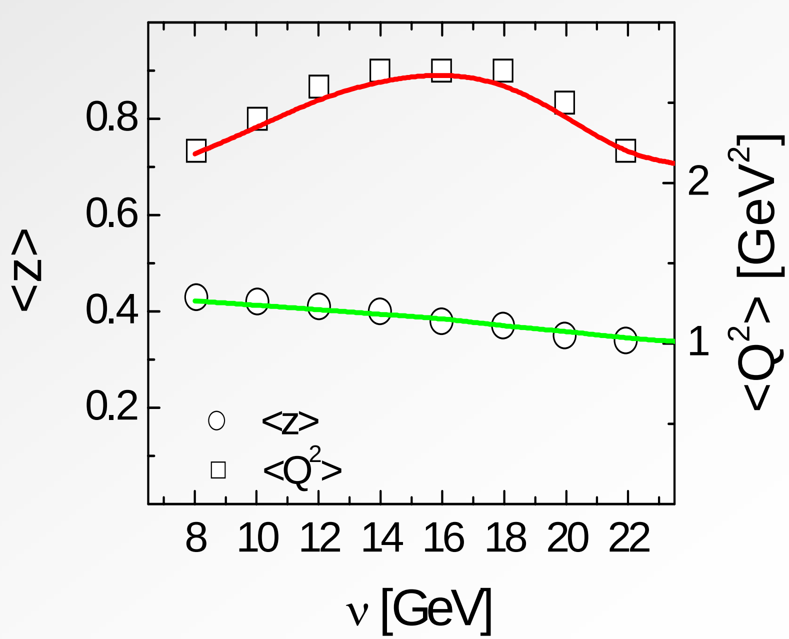
charged hadron production in DIS off ^{84}Kr at HERMES

- including all experimental cuts
- accounting for angular acceptance of HERMES detector

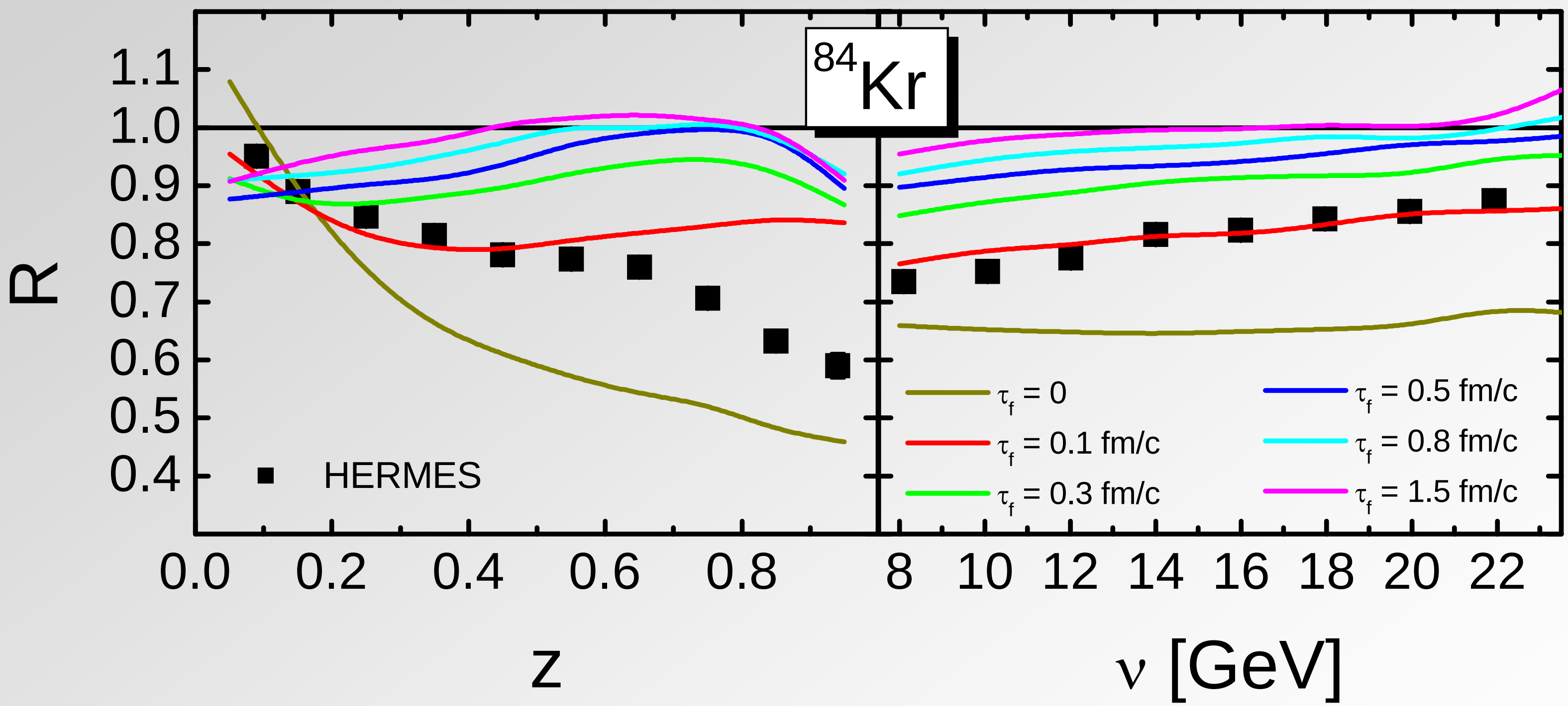


- average kinematic variables from simulation:



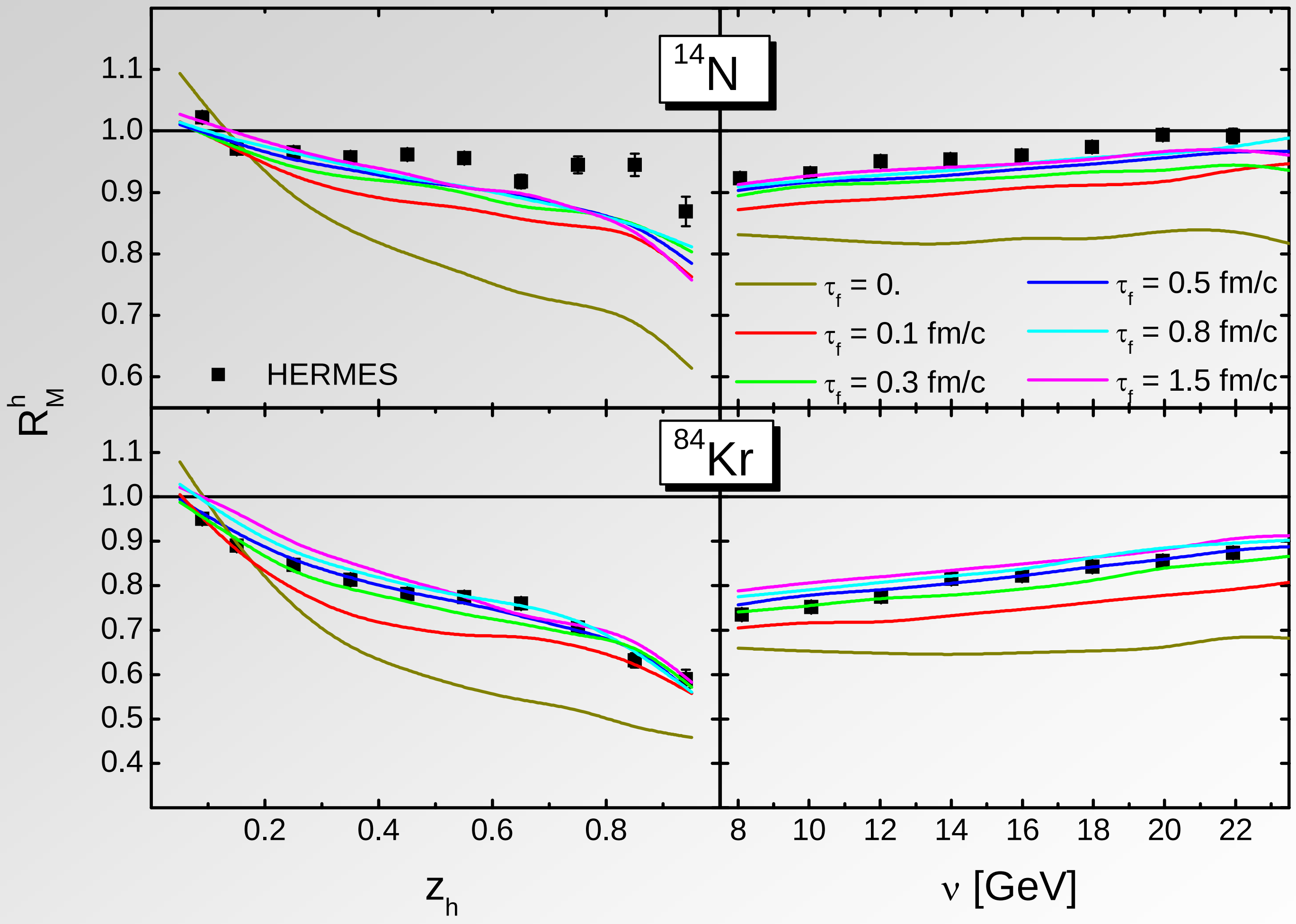


- multiplicity ratio of charged hadrons
  - w/o prehadronic FSI



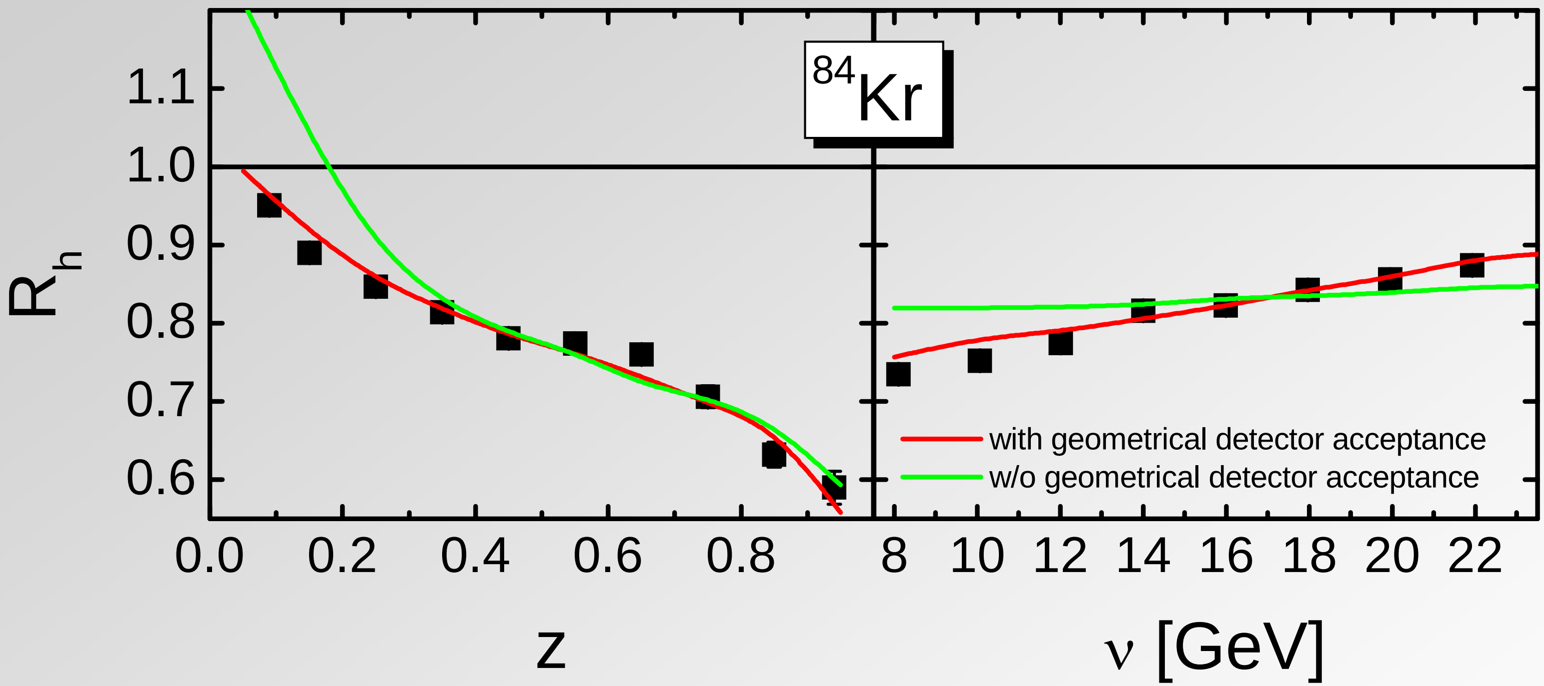
→ prehadronic interactions needed

- charged hadrons
  - with prehadronic interactions



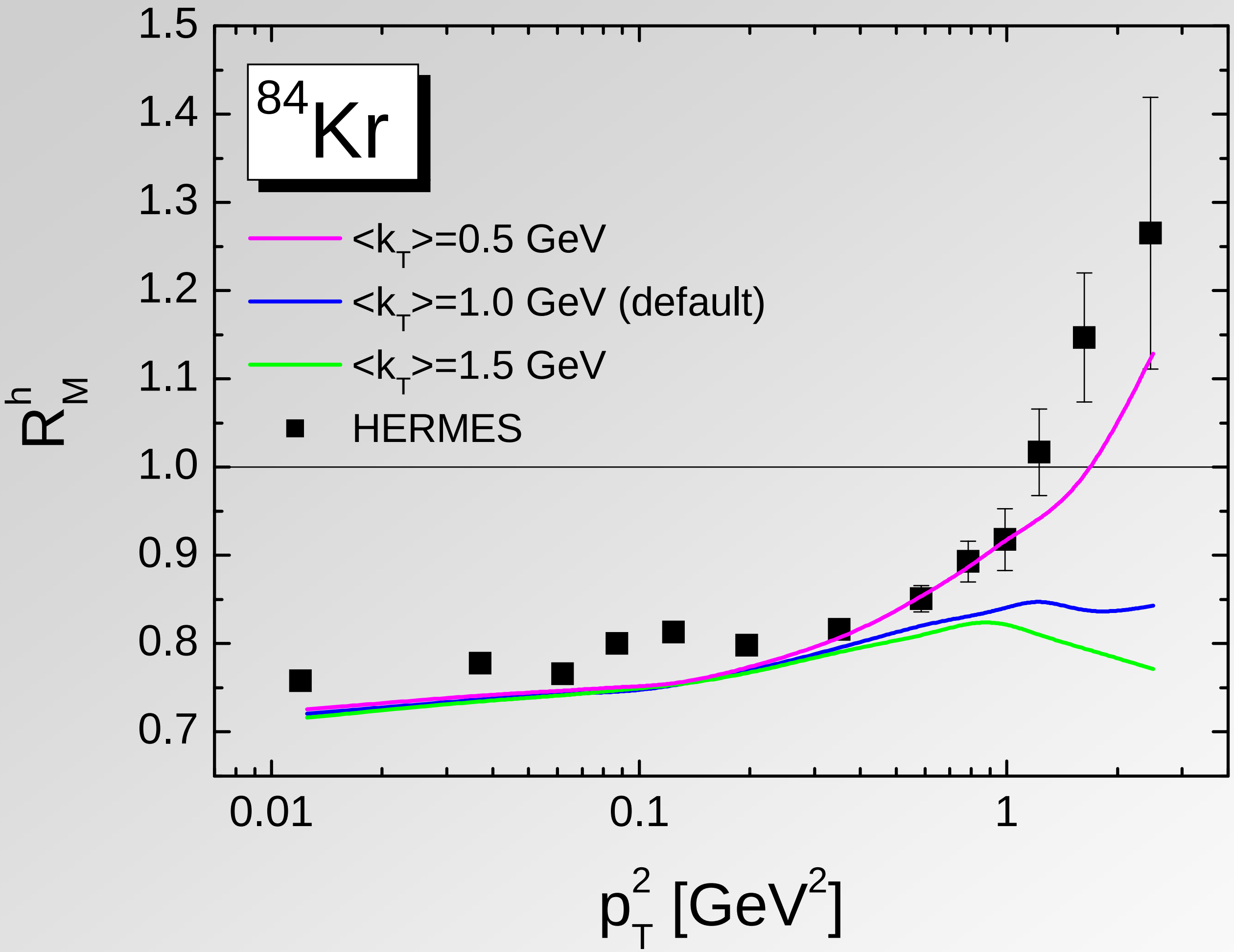
τ_f > 0.5 fm/c compatible with *pA* data at AGS energies

influence of detector geometry (τ_f = 0.5 fm/c)



- needs to be accounted for at $z_h < 0.4$
- important for integrated spectra

p_T-spectrum of charged hadrons ($\tau_f = 0.5$ fm/c)



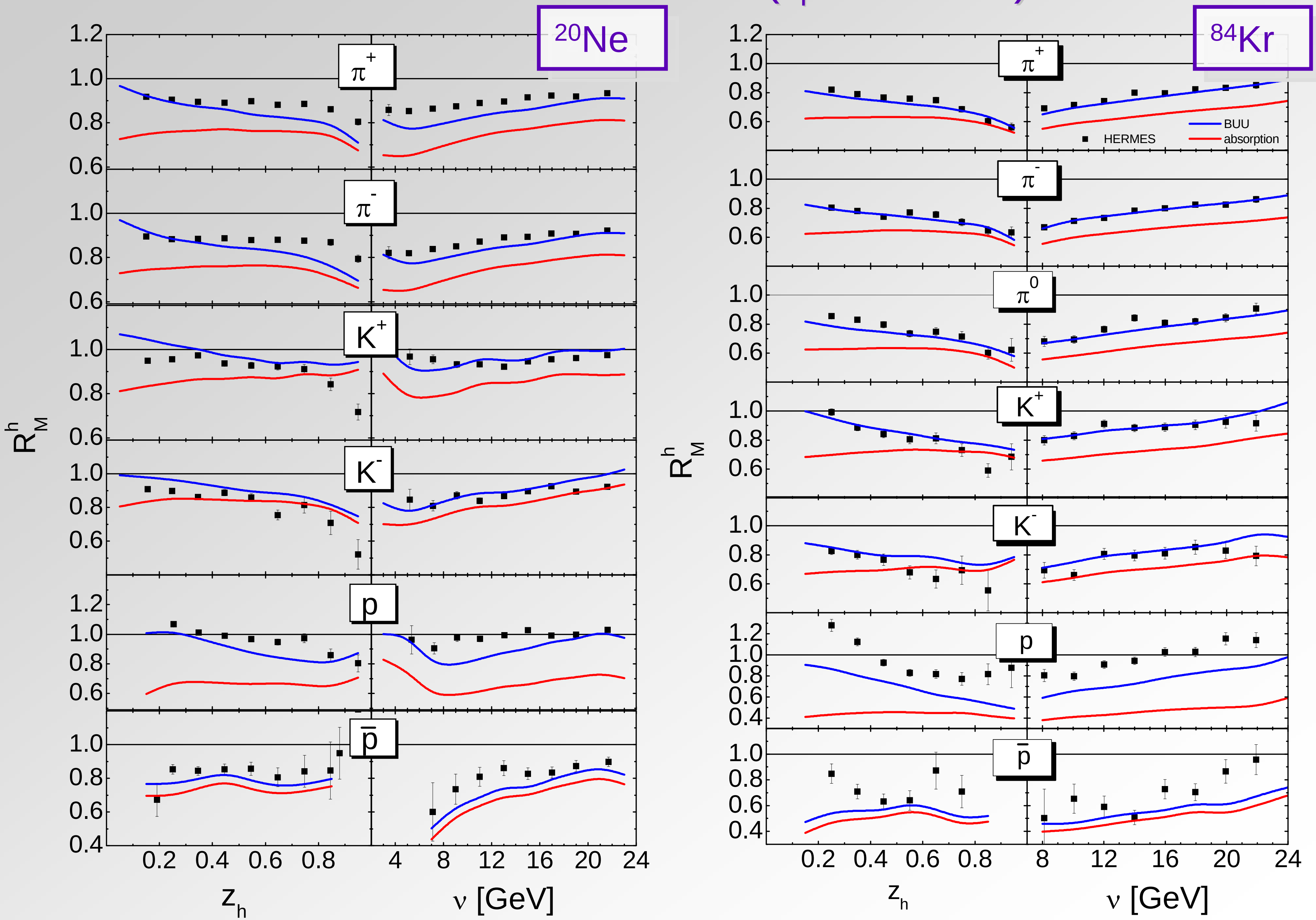
strong increase

at high p_T>1 GeV

Cronin effect ?

from calculations: $<k_T>_A = <k_T>_N$, i.e. not Cronin!

attenuation of identified hadrons ($\tau_f = 0.5$ fm/c)



double-hadron attenuation ($\tau_f = 0.5$ fm/c)

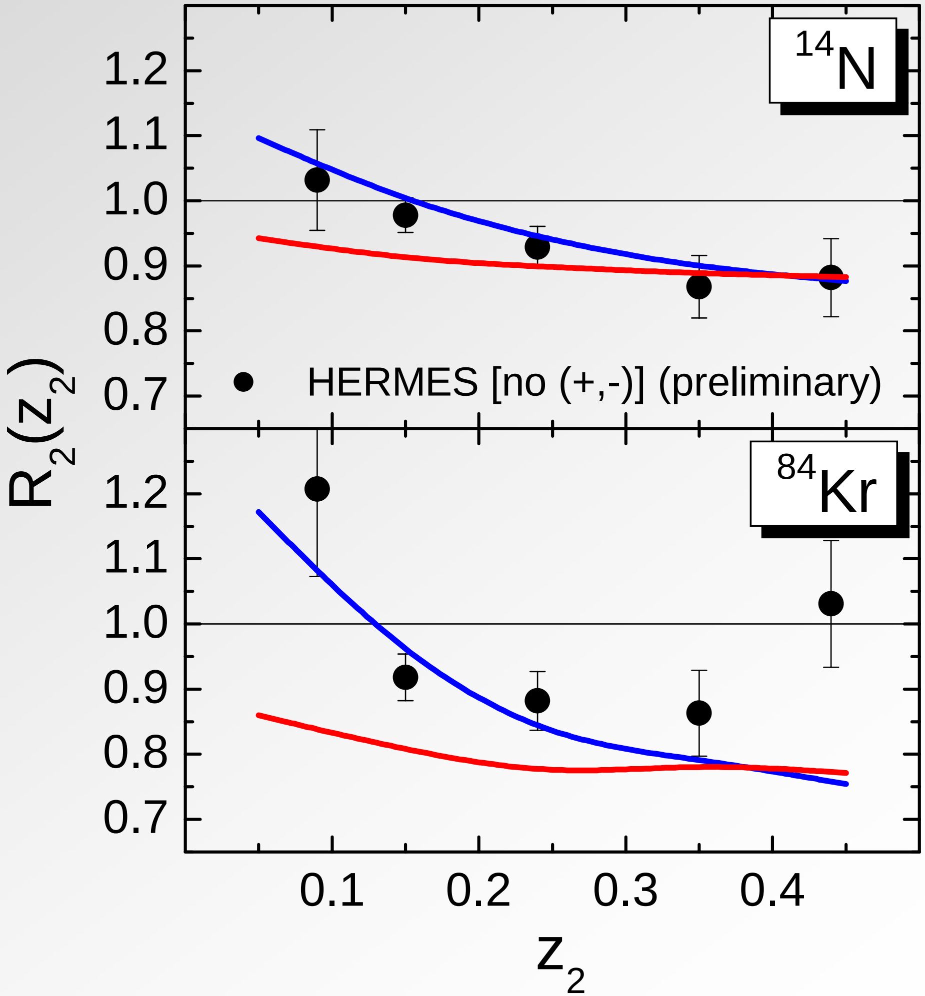
- leading hadron

  $z_1 > 0.5$

- subleading hadron

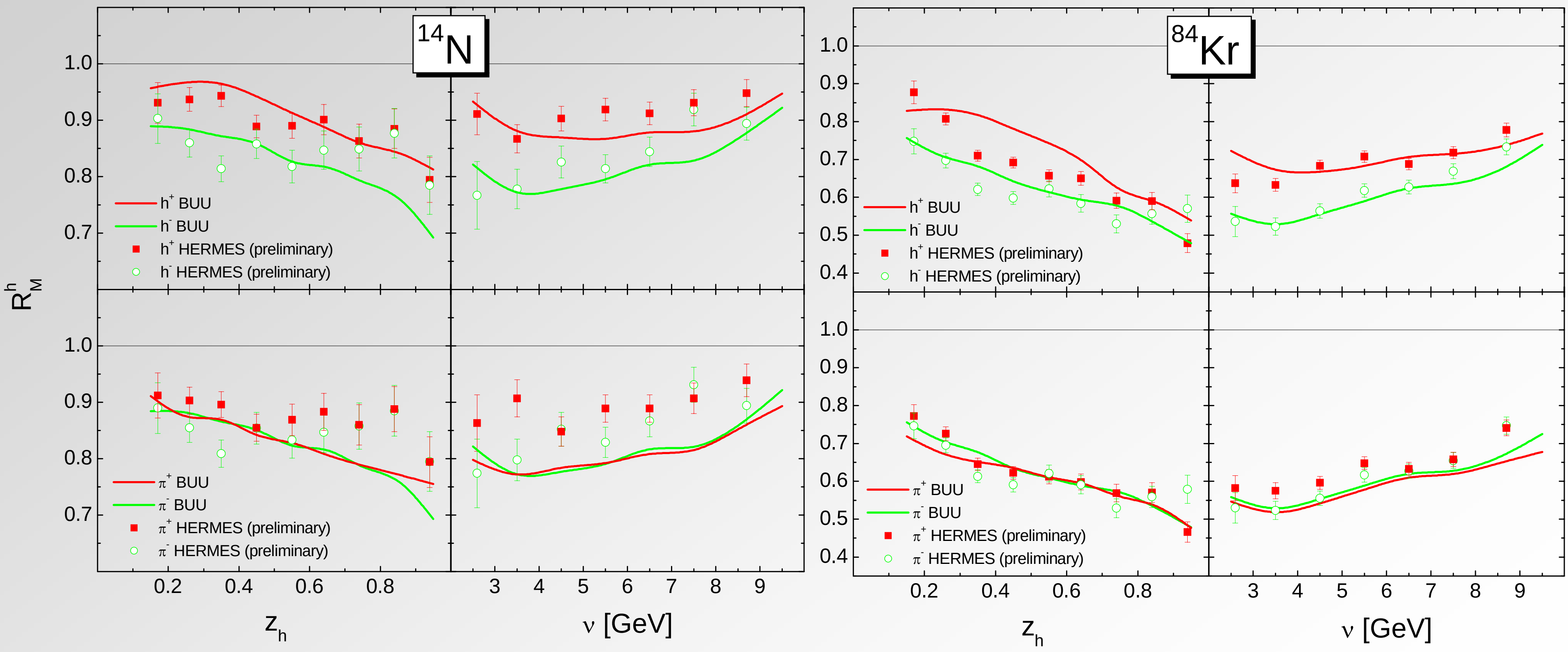
  $z_2 < z_1$

$$R_2(z_2) = \frac{\left(\frac{N_2(z_2)}{N_1}\right)_A}{\left(\frac{N_2(z_2)}{N_1}\right)_D}$$



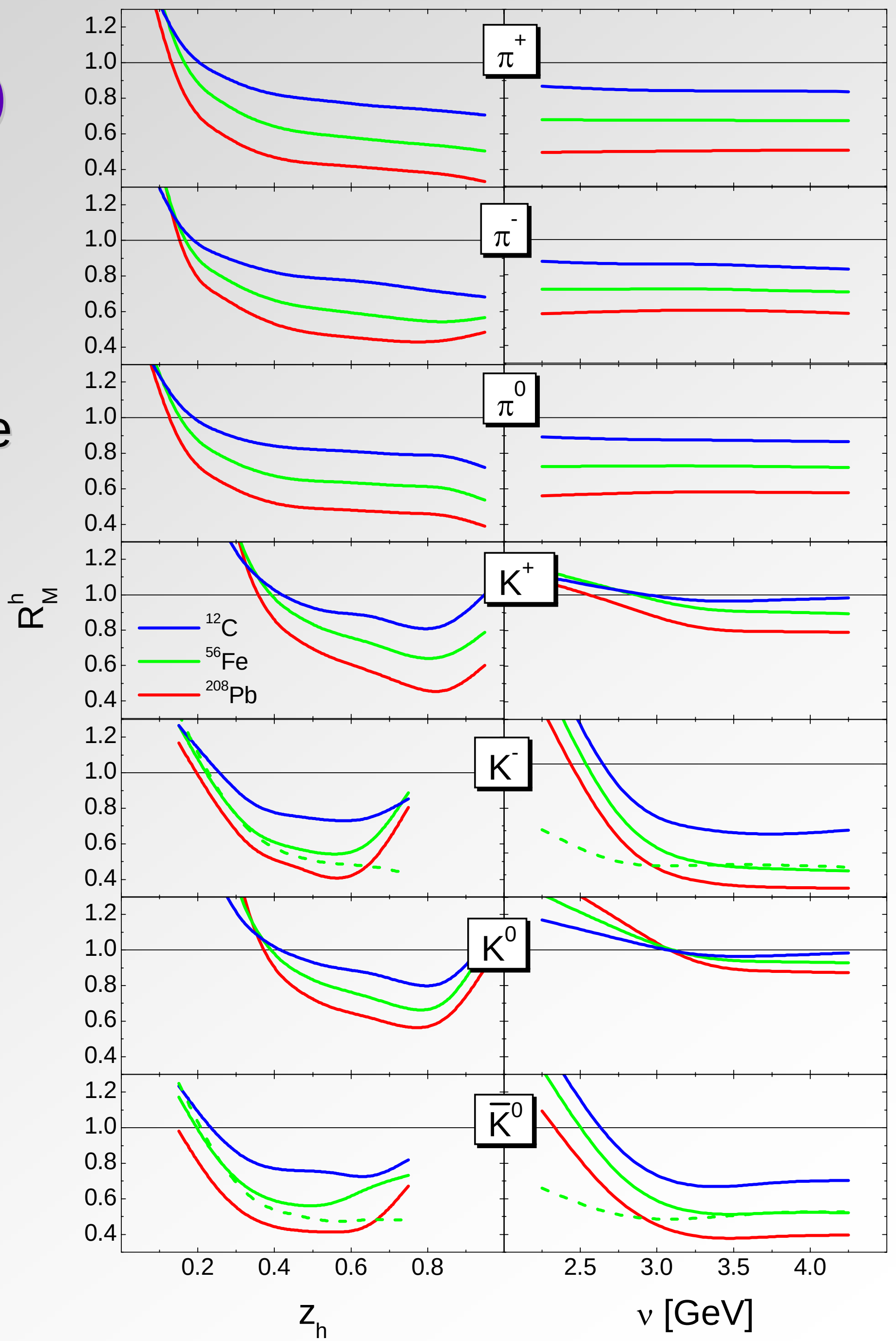
HERMES @ 12 GeV (τ_f = 0.5 fm/c)

– model also works at lower energies



Jefferson Lab (τ_f = 0.5 fm/c)

- CLAS detector
  larger geometrical acceptance
  - detects more secondary particles from FSI
- CEBAF
  lower energy
  - strong effect of Fermi-motion



Summary & Outlook

- model for γ and *e* induced reactions at GeV energies
  - combines:
    - qm coherence in entrance channel
    - sophisticated event generation
    - coupled channel transport description of FSI
  - can decribe
    - coherence length effects in exclusive ρ^0 production
    - most features observed in hadron attenuation

    } at HERMES energies
  - works also for:
    - γ and *e* reactions in resonance region
    - πA, *pA* and *AA* reactions

    } same parameter set

→ **talk by K. Gallmeister**

- future plans:
  - consistent event generation AND space-time picture by PYTHIA ✓
  - analysis of future JLab experiments, ultra-peripheral HIC