GiBUU-Physics of e-A Interactions

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for the GiBUU collab, based on a talk by

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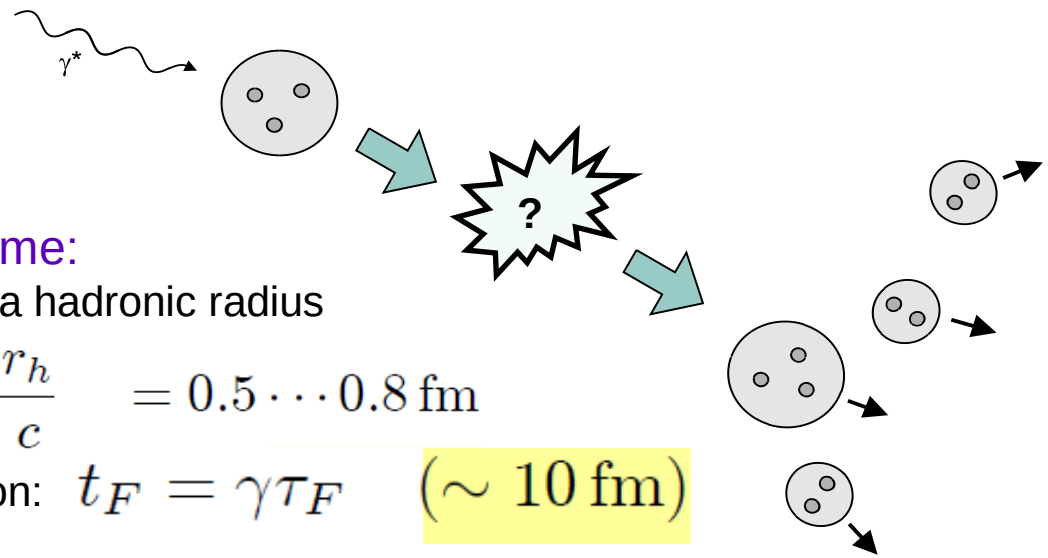
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Motivation

- elementary reactions (eN, γN) on nucleon:



formation time:
estimation via hadronic radius

$$\tau_F \geq \frac{r_h}{c} \quad = 0.5 \cdots 0.8\,\mathrm{fm}$$

time dilatation: $t_F = \gamma \tau_F \quad (\sim 10\,\mathrm{fm})$

reaction products hadronize long before they reach the detector

- nuclear reactions (eA, γA @ GeV energies) :

interactions with nuclear medium during formation ??

→ space-time picture of hadronization

$$\sigma^* / \sigma_H \sim t^{0,1,2,\ldots}$$??

Relevant Publications

1. T. Falter and U. Mosel:
   „Hadron formation in high-energy photonuclear reactions“,
   Phys. Rev. C66, 024608 (2002)

2. T. Falter, W. Cassing, K. Gallmeister and U. Mosel:
   „Hadron attenuation in deep inelastic lepton-nucleus scattering“,
   Phys. Rev. C70, 054609 (2004)

3. T. Falter,
   „Nuclear reactions of high energy protons, photons, and leptons“,
   PhD thesis, Giessen 2004, report GSI-2017-01185

1. K. Gallmeister and T. Falter:
   „Space-time picture of fragmentation in PYTHIA/JETSET for HERMES and RHIC“,
   Phys. Lett. B630, 40 (2005)

2. T. Falter, W. Cassing, K. Gallmeister and U. Mosel:
   „Hadron attenuation at HERMES and Jefferson Lab“,
   Acta Phys.Hung. A27, 71 (2006)

3. K. Gallmeister and U. Mosel:
   „Time Dependent Hadronization via HERMES and EMC“,
   Nucl. Phys. A 801, 68 (2008)

- GiBUU describes (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

  using the same physics input! And the same code!

- Specifically:
  GiBUU can describe both the current fragmentation region (my talk) and the target fragmentation region (following talk by Alexei Larionov)

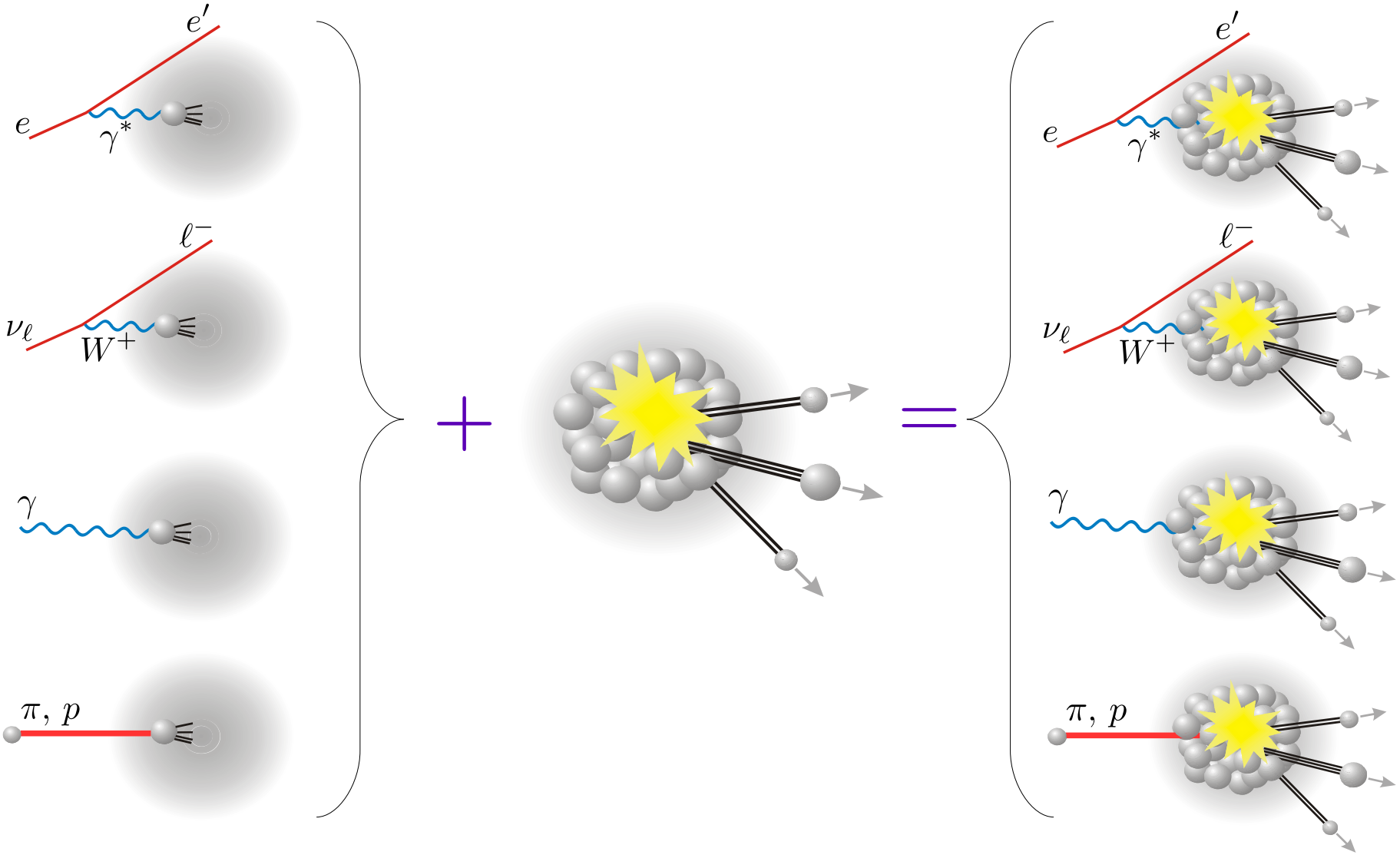
Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from **gibuu.hepforge.org**,

GiBUU = ISI + FSI



- init + FSI = full event

Applications of GiBUU

- A + A

FOPI, HADES experiments at GSI (~ 1 A GeV), AGS (~ 20 A GeV)

- p + A, π + A

HARP at CERN (~ 10 GeV), BGO at LAMPF, LADS at SIN (few 100 MeV)

- γ + A

TAPS at MAMI, CBELSA/TAPS at ELSA (up to ~2 GeV)

- γ^* + A

JLAB, SLAC (up to ~ 5 GeV), HERMES (12 and 30 GeV), EMC (~250 GeV)

- ν + A

T2K at Tokai (~ 700 MeV), BNB at Fermilab (~ 700 MeV),
MINERvA at FNAL (~ 3 – 10 GeV), NOvA at FNAL (~ 2 GeV), DUNE (planned at FNAL, Sanford Lab, ~ 3 GeV)

FSI are severely constrained
by all these different reaction analyses

Quantum-kinetic Transport Theory
Kadanoff-Baym equations

On-shell drift term

Off-shell transport term

Collision term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p) \ .$$

Cross sections go here

For each particle species one such equation, all coupled by the collision term *C*

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

8D-Wigner-distribution of the one-body density matrix
= spectral phase-space distribution
= phase-space distribution times spectral function

The BUU equation for quasiparticles

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r}, t, \vec{p}) = C\left[f_i, f_j, \ldots\right]$$

$$i = N, \Delta, \pi, \rho, \ldots$$

- describes space-time evolution of single particle densities
- index *i* represents particle species
  → one equation for each species

- Hamiltonian H
  - hadronic mean fields (Skyrme/Welke or RMF)
  - Coulomb
  - „off-shell-potential“

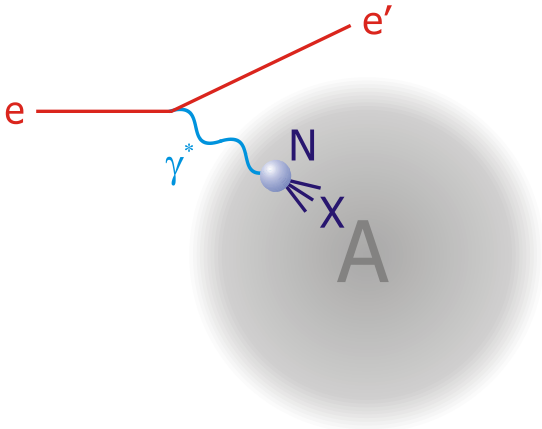
- collision term C
  - decay and scattering processes: 1-, 2- and 3-body
  - (low energy: resonance model, high energy: string model)
  - contains Pauli-blocking

- equations coupled via mean fields and via collision term

Model

- $\gamma^* N \rightarrow X$
  using explicit N* resonances
  or PYTHIA (for W > 2 GeV)

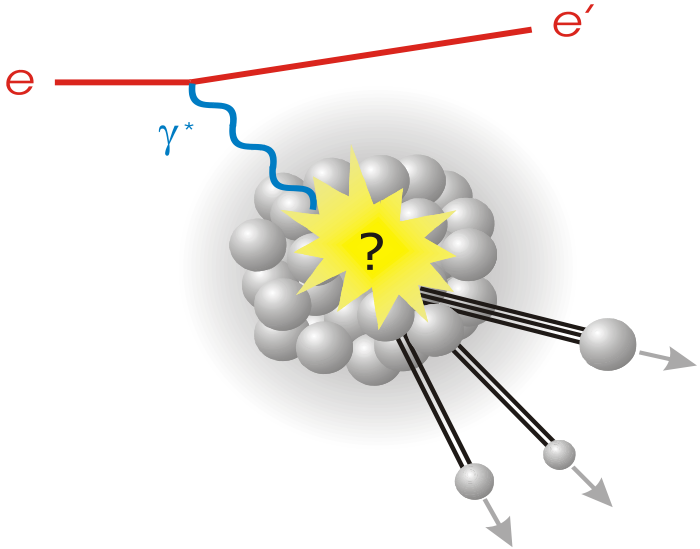
  additional:
  - binding energies
  - Fermi motion
  - Pauli blocking
  - coherence length effects



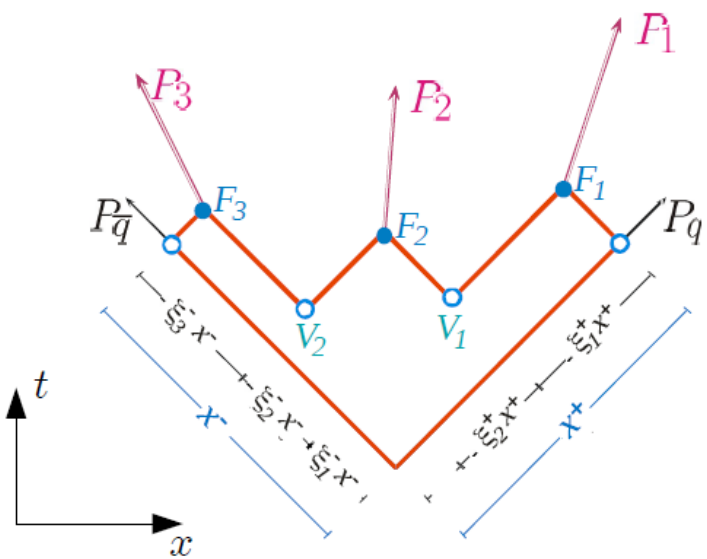
- propagation of final state X
  within GiBUU transport model

  - elastic/inelastic scatterings, particle production (coupled channels)

  - experimental acceptance, since complete final state is available: four-vectors of all particles

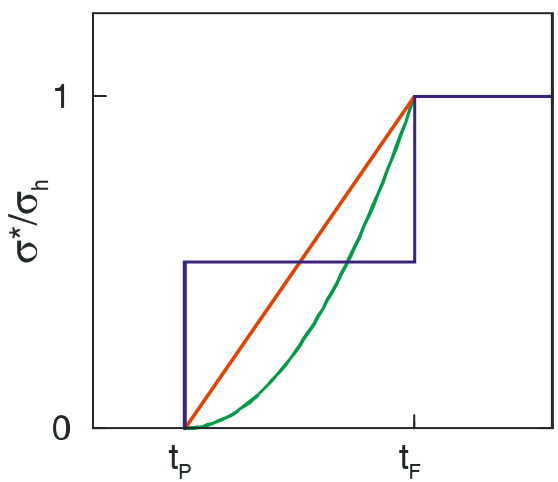


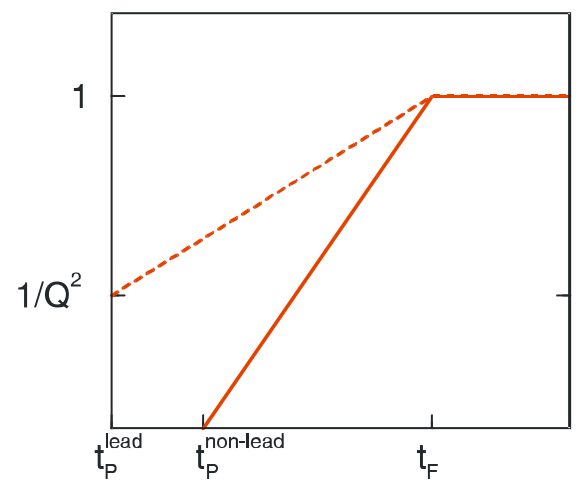
Model: Hadronization in String Model (PYTHIA/JETSET)



- 3 times/points per particle:
  - „production 1“ *string-breaking*
  - „production 2“ *string-breaking*
  - „formation“ *line-meeting*
- leading vs. non-leading
  - connection to interaction vertex

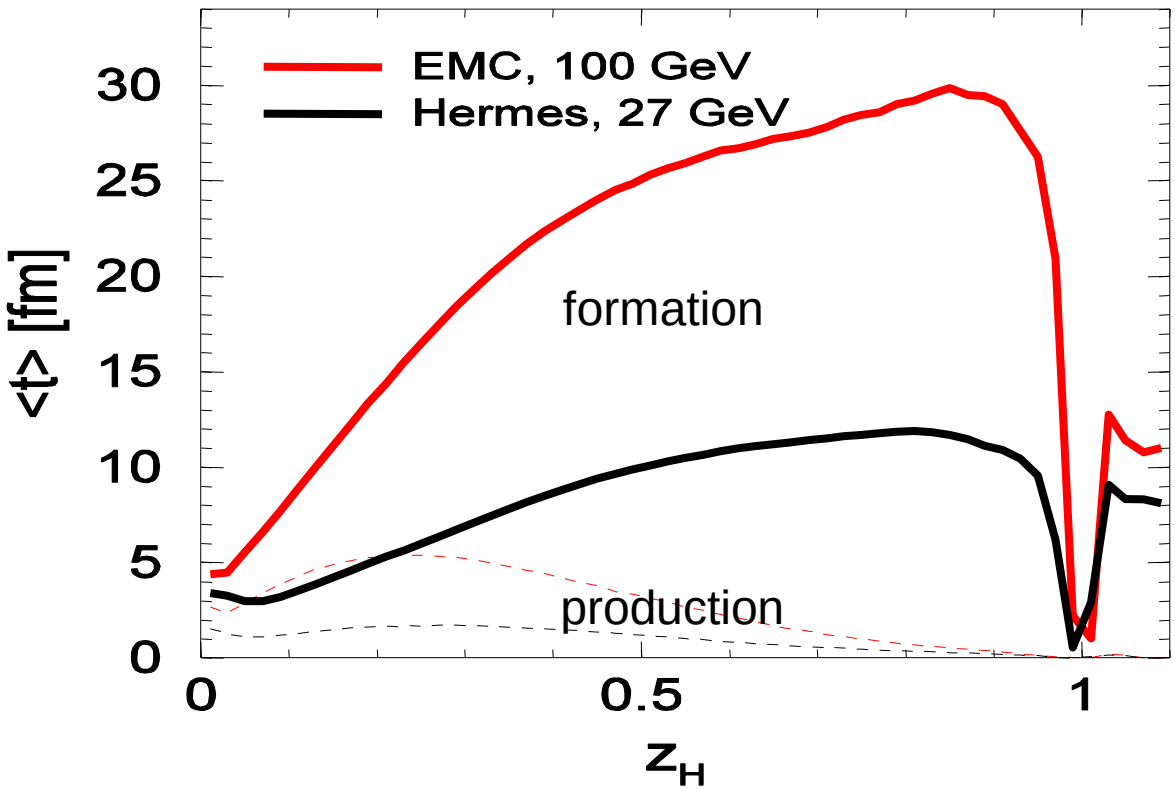
- possible cross section evolution scenarios (prehadronic interactions):





CT

Times



here: averaged times
in code: individual times
All in lab system

Interactions during production and formation times determine both:

1. Spectra of forward-moving, fast particles (jets)
2. Excitation of target remnants

What are these interactions? (0 as in BeAGLE or something else?)

•Jet-like Observables, Experiments

- $$R^h(z_h,\dots) = \frac{\left.\frac{N_h(z_h,\dots)}{N_e(\dots)}\right|_A}{\left.\frac{N_h(z_h,\dots)}{N_e(\dots)}\right|_D}$$

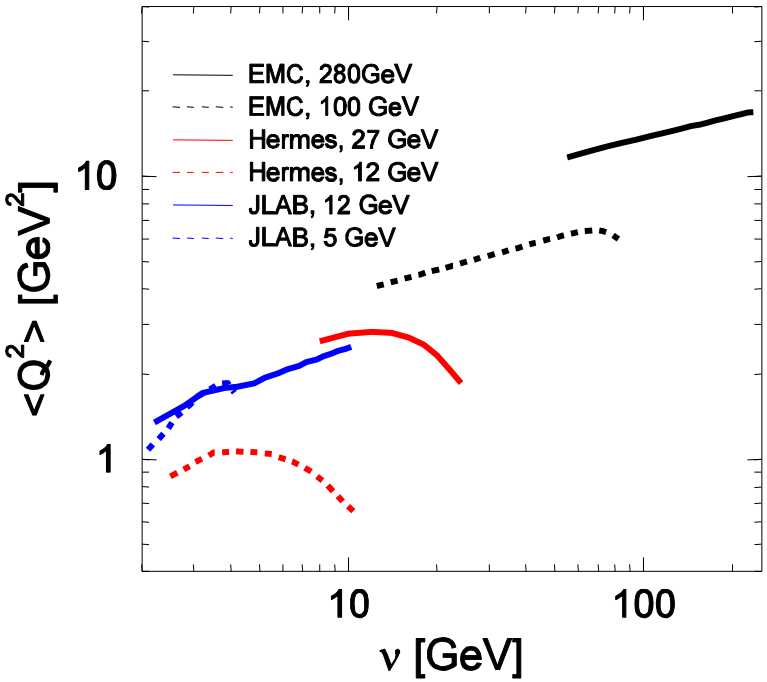
- $$\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$

- hadronic: $z_h = \frac{E_h}{\nu}\,, \quad p_T\,, \cdots$
- photonic: $\nu\,,\ Q^2\,,\ W\,,\ x_B\,, \dots$

- Experiments

	E_{lepton} =
EMC	**100…280 GeV**
Hermes	**27 GeV**
	12 GeV
CLAS	12 GeV (upgrade)
	5 GeV
EIC	e.g. 5+50 GeV

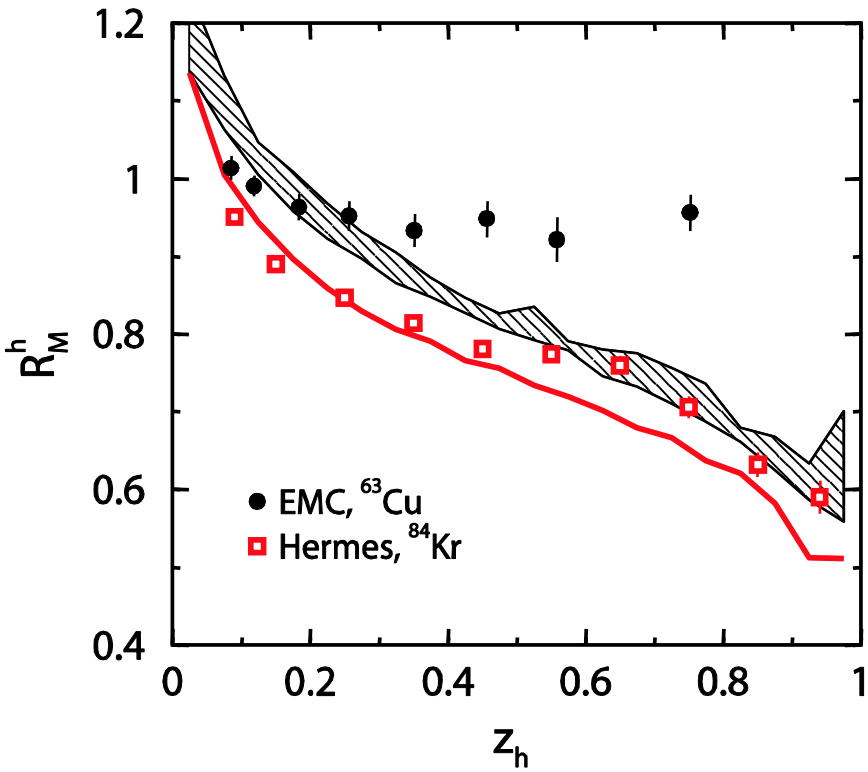
…multiple combinations of targets



Results: EMC & Hermes

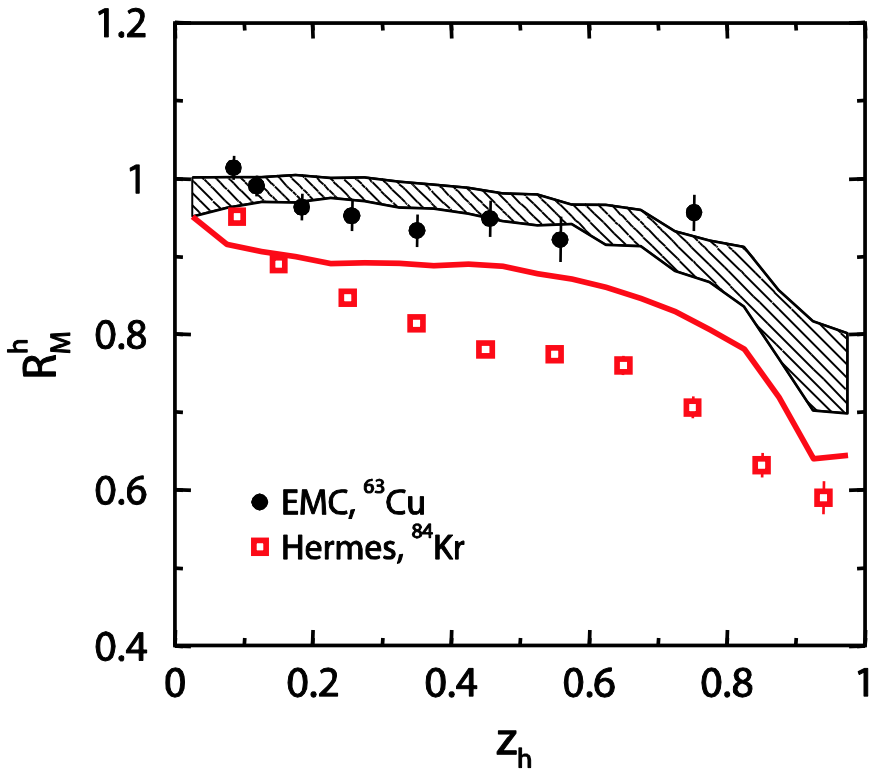
- constant cross section

$$t = t_{\mathrm{P}} \cdots t_{\mathrm{F}} : \quad \sigma^* = 0.5\,\sigma_H$$



- quadratic increase

$$\sigma^* = \left(\frac{t - t_{\mathrm{P}}}{t_{\mathrm{F}} - t_{\mathrm{P}}}\right)^2 \sigma_H$$



Results: EMC & Hermes

$$\frac{\sigma^*}{\sigma_H} = \frac{r_{\rm lead}}{Q^2} + \left(1 - \frac{r_{\rm lead}}{Q^2}\right)\left(\frac{t - t_{\rm P}}{t_{\rm F} - t_{\rm P}}\right)$$

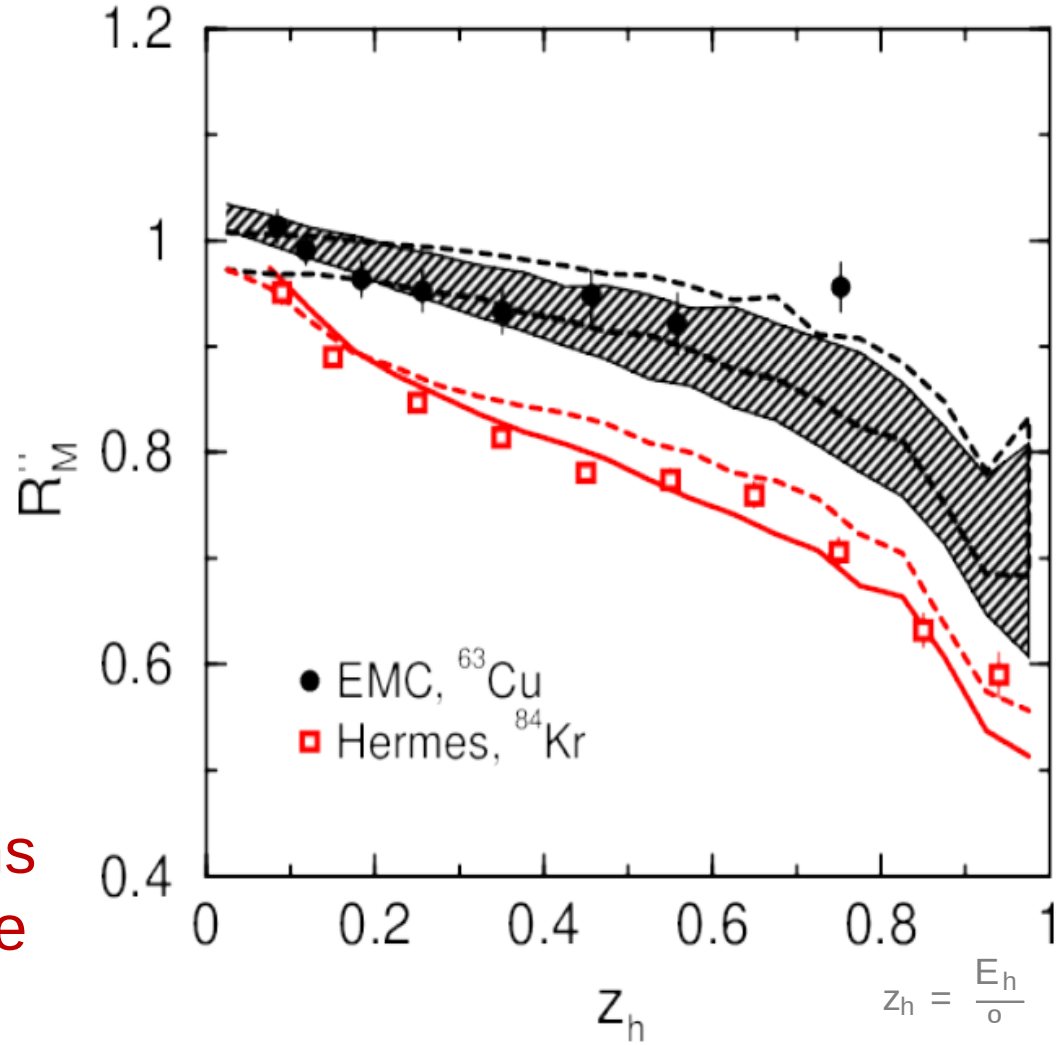
Farrar, Strikman

EMC@100...280 GeV
and
Hermes@27 GeV described
simultanously

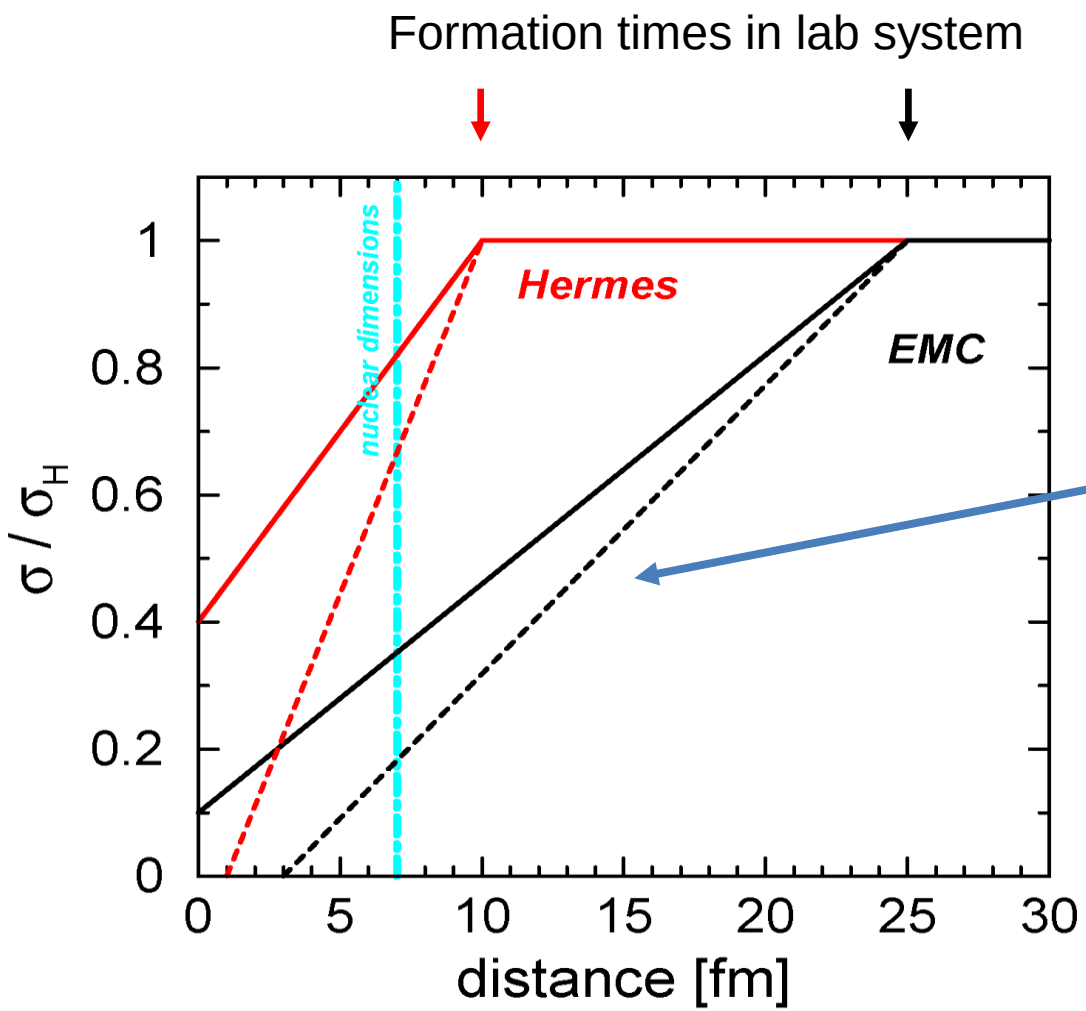
!

$1/Q^2$ pedestal value?
…small effect!

Prehadronic cross sections
increase linearly with time



Time-development of cross sections

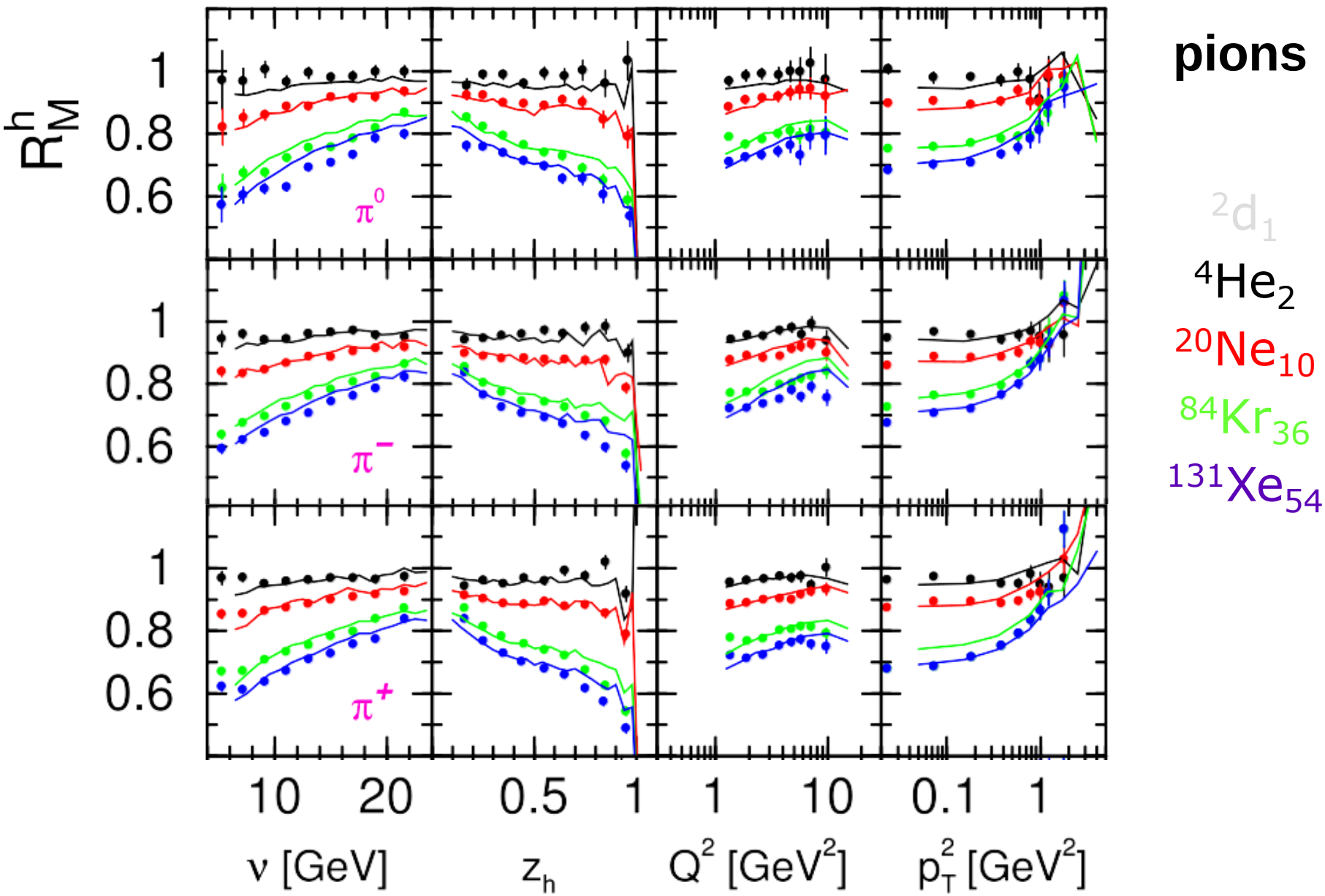


prehadronic cross sections

At EMC a large part of the formation time is spent outside the nucleus

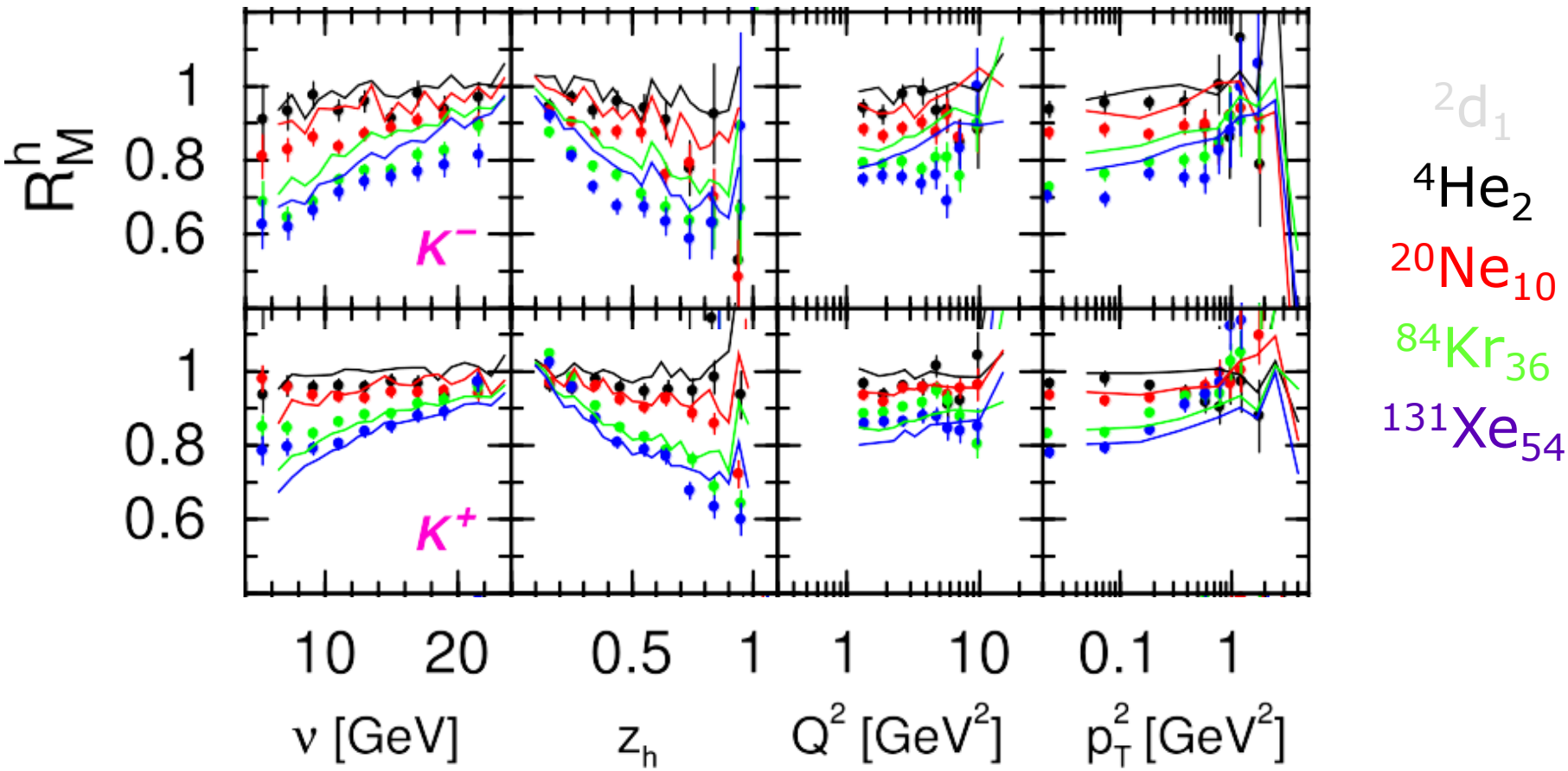
Effects of FSI dependent on prehadronic cross sections

Hermes@27: A.Airapetian et al., NPB780(2007)1



Hermes@27: A.Airapetian et al., NPB780(2007)1

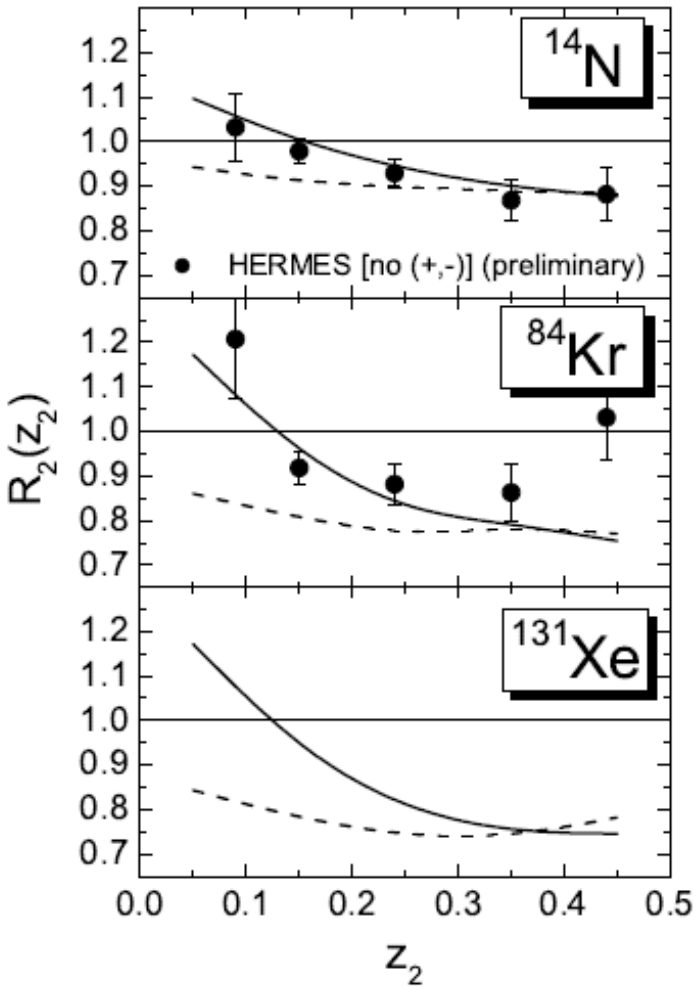
kaons



Attenuation of subleading hadron

Double hadron attenuation:

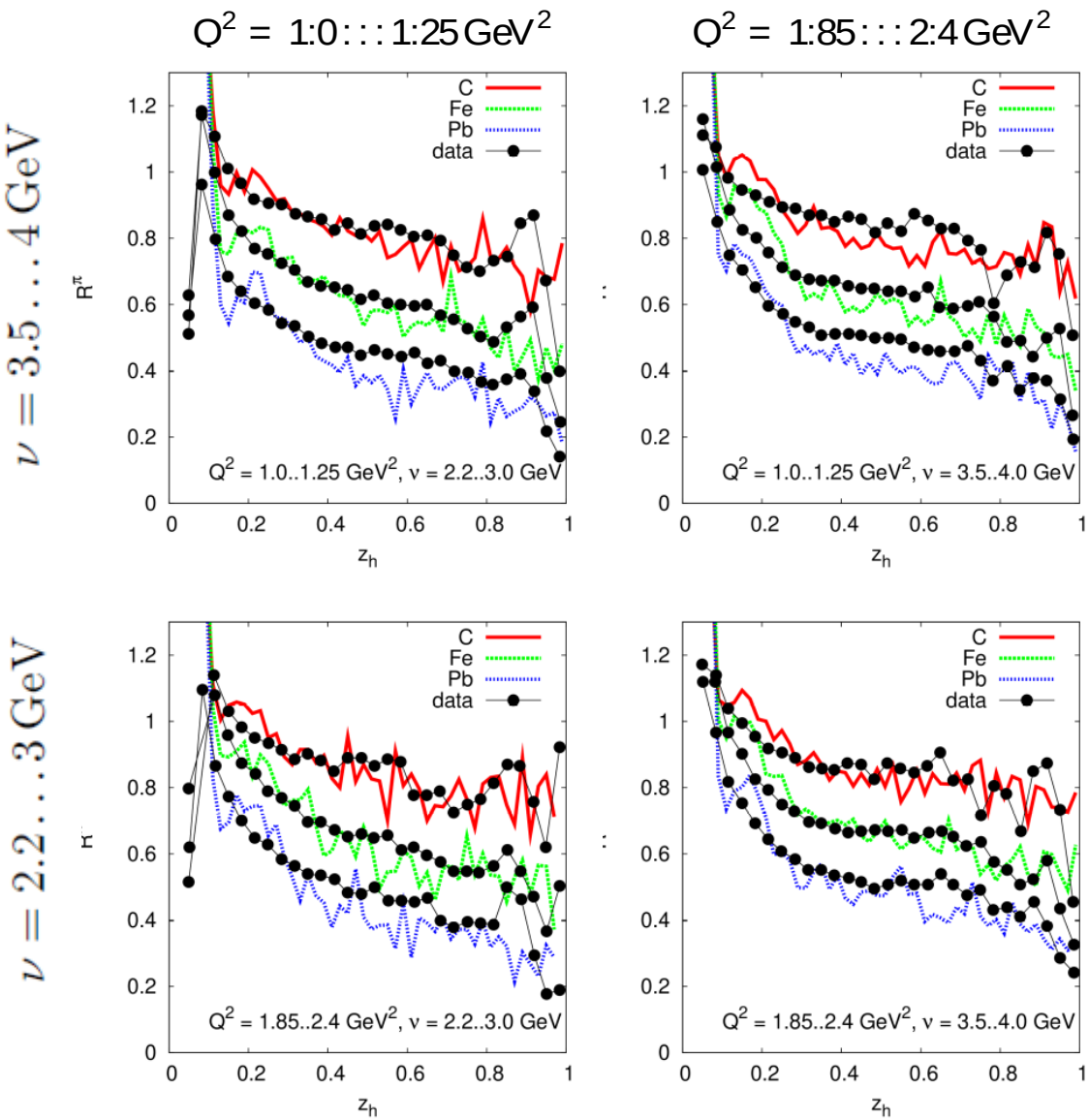
$z_1 > 0.5$, $z_2 < z_1$



Dashed:
Purely absorptive FSI

Data show „avalanche effect“

CLAS@5, π^+ : selected (ν,Q^2) bins



Data:

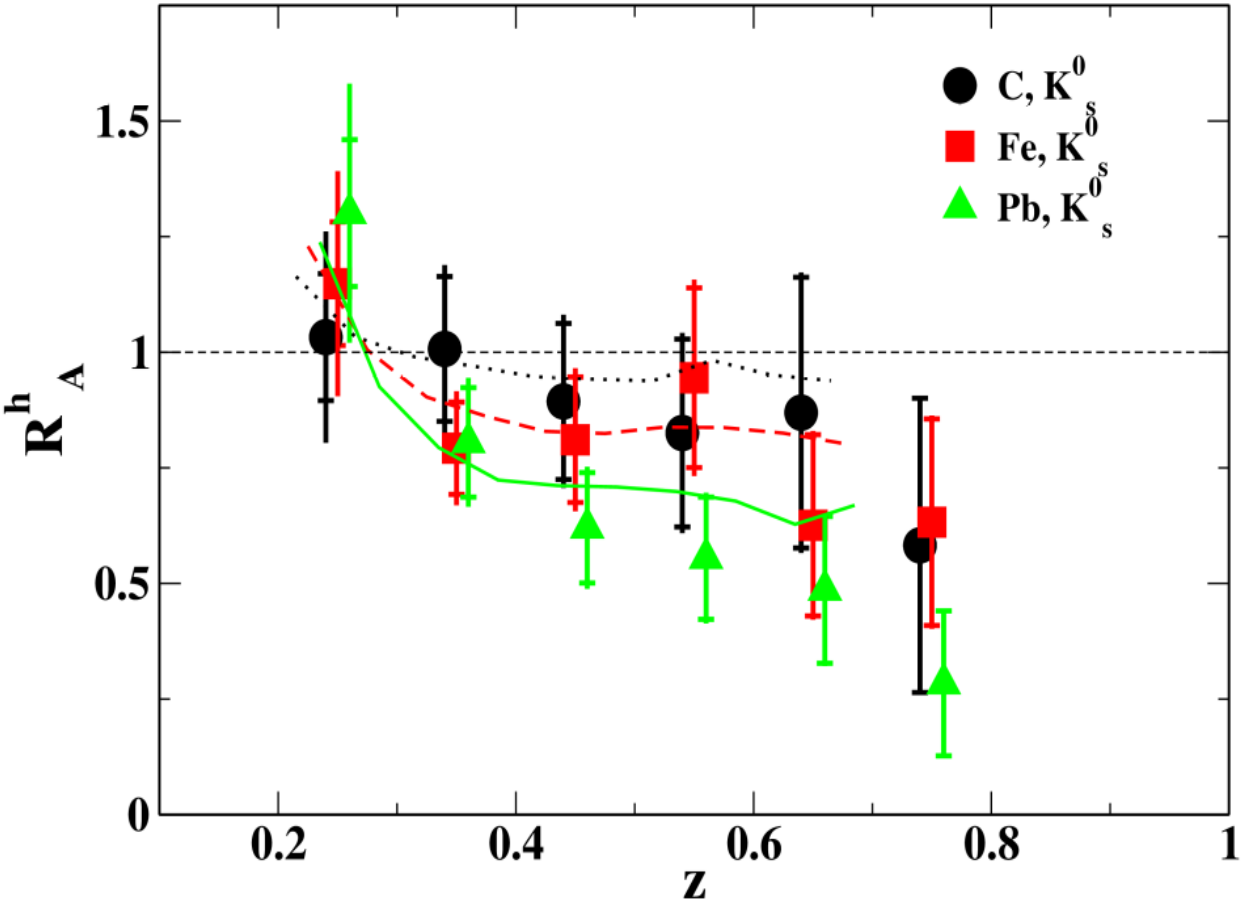
- CLAS preliminary (W. Brooks et al)
- no error bars shown

Calculations:

- not tuned !!!
- no Fermi Motion (W<2 GeV possible)
- no potentials

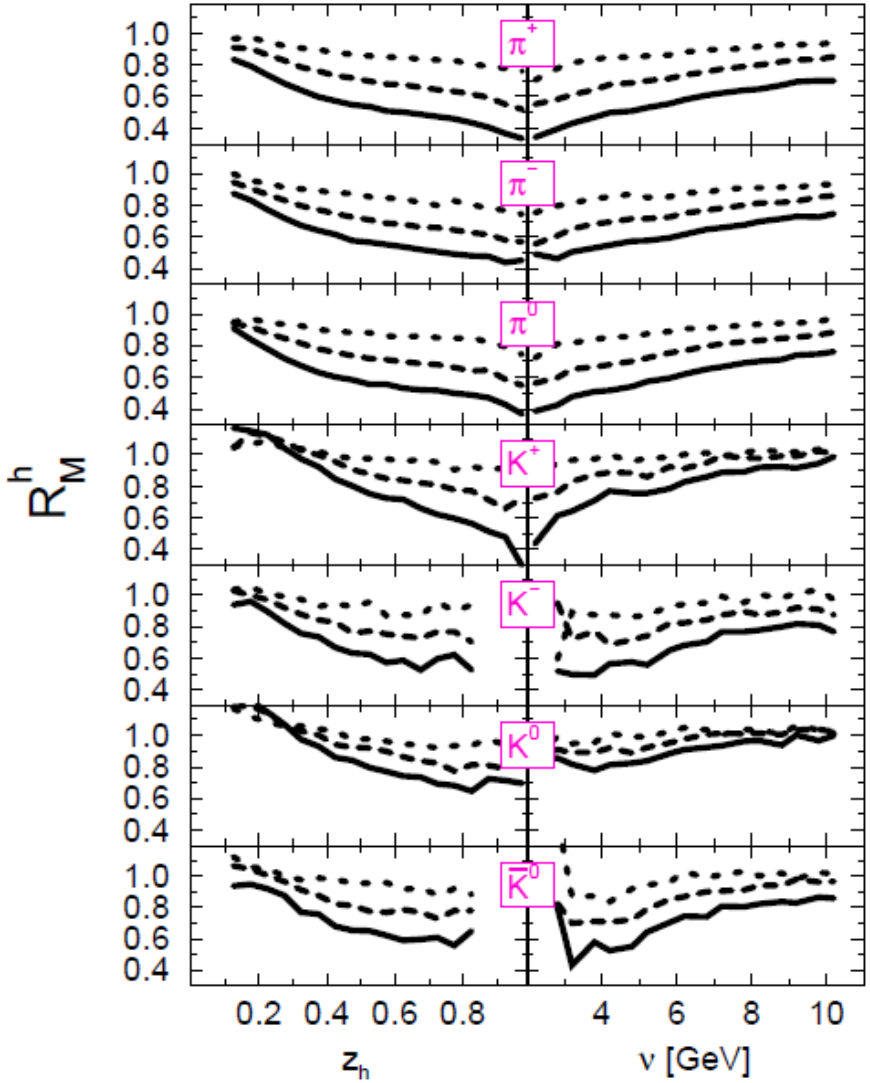
As good as at higher energies !

CLAS@5, K : A.Daniel et al., PLB 706(2011) 26



Predictions:
Kai Gallmeister, U.M., NPA801(2008)68

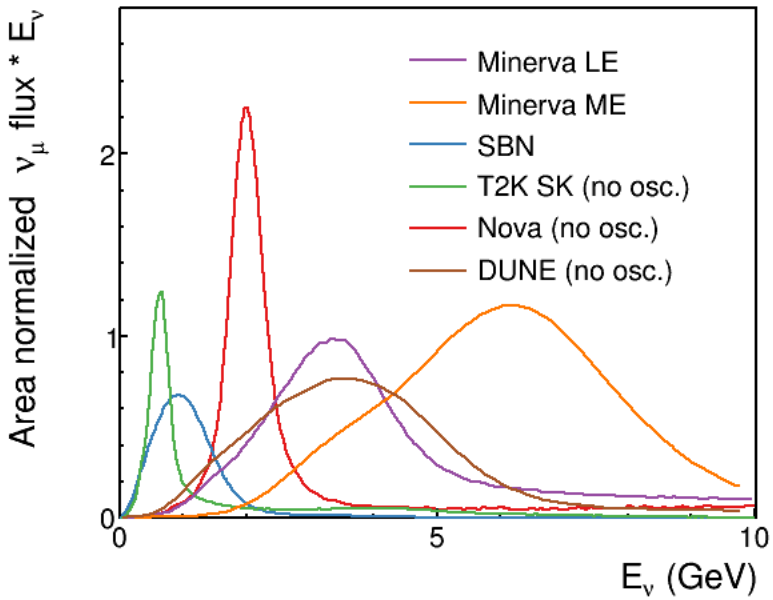
Hadron Attenuation at 12 GeV

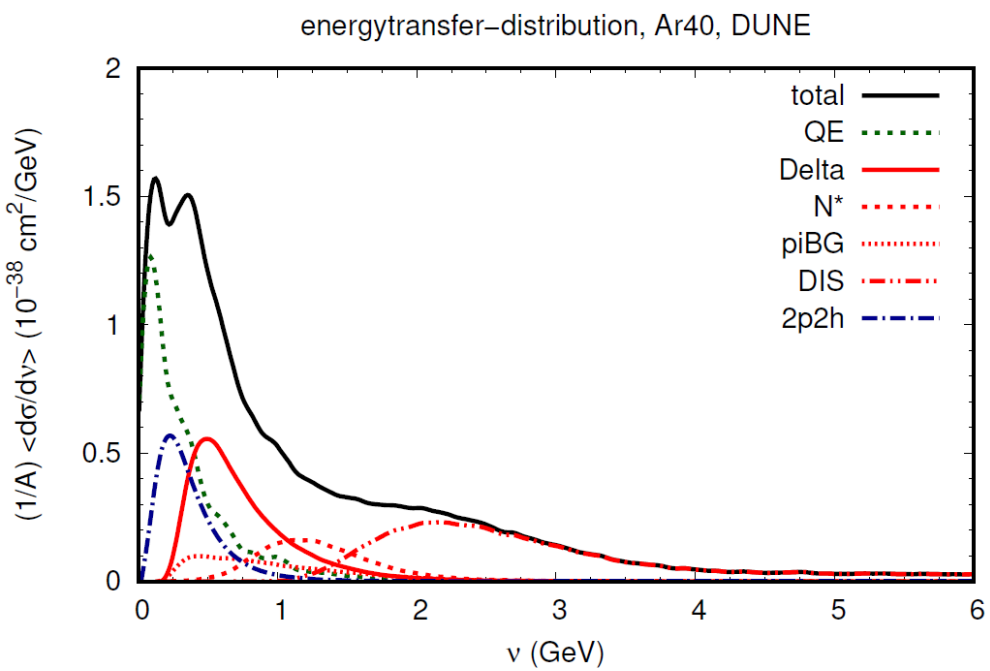


C
Fe
Pb

Prediction in
K. Gallmeister, U. Mosel,
Nucl.Phys.A 801 (2008) 68-79

Relevance for Neutrino Experiments





For DUNE the energy transfers are fairly low (~ 2 -3 GeV DIS), hadronic (not prehadronic) FSI prevail

Conclusions

- GiBUU handles a wide range of nuclear reactions, from A + A to e + A and ν + A, tested on all these reaction types → FSI are constrained
- GiBUU delivers the complete final state of reactions, i.e. four-momenta of all final hadrons and their positions. It gives single particle phase-space-distributions
- For fragments GiBUU needs afterburner,
  - either by coalescence models: particles close to each other in phase-space are lumped together
  - or by statistical models (following talk by A.L.)
- Prehadronic final state interactions affect both jet-like particles AND fragment excitation:
  consistent theory must describe both