Formation Times

from high (200 GeV) to low (<1 GeV) energies

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- Hadron Production
  - High energies → Formation times
  - Low energies → In med spectral functions
- Comparison with experiment
- Summary

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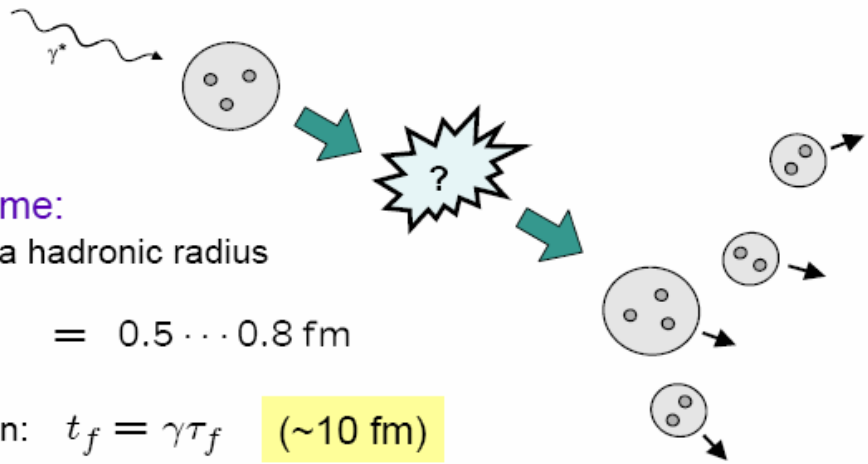
High Energies (DIS, W > 2 GeV

- elementary reactions (eN, γN) on nucleon:



formation time:
estimation via hadronic radius

$$\tau_f \geq \frac{r_h}{c} = 0.5 \cdots 0.8 \text{ fm}$$

time dilatation: $t_f = \gamma \tau_f$ (~10 fm)

reaction products hadronize long before they reach the detector

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

interactions with nuclear medium during t_f

→ space-time picture of hadronization

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

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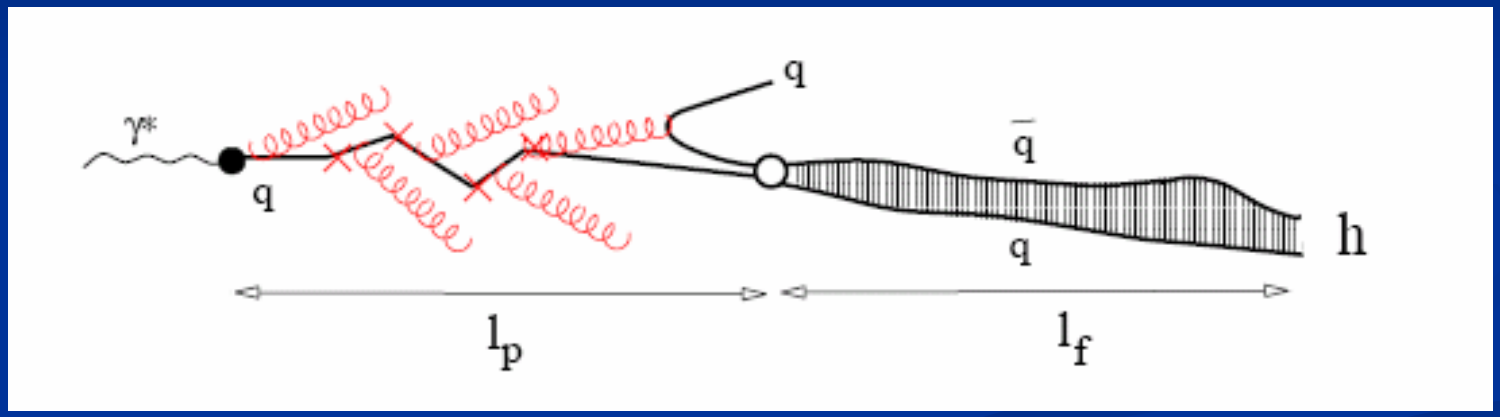
Formation Times

- 2 relevant Times:
  - Production Time: Time needed to produce a new quark (parton) from the sea, after first interaction
  - Formation Time: Time needed to produce a hadron in its physical groundstate
    $\tau_f \approx 1/(M^* - M_0) \approx 0.5$ fm/c
    for an excitation of a few hundred MeV

Production and Formation Times



From: Kopeliovich et al

- 2 Problems:
  - What are these times?
  - What are the interactions in these time-spans?
- Measure for interactions: Nuclear attenuation

Observables, Experiments

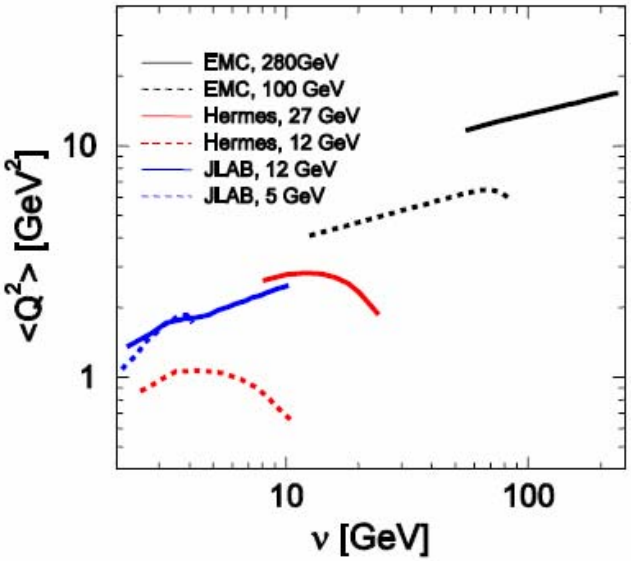
- multiplicity ratio

$$R_M^h(z_h,\ldots) = \frac{\left(\frac{N_h(z_h,\ldots)}{N_e(\ldots)}\right)_A}{\left(\frac{N_h(z_h,\ldots)}{N_e(\ldots)}\right)_D}$$

- hadronic: $z_h = \frac{E_h}{\nu}$, $p_\perp$, $\ldots$
- photonic: ν, Q^2, W, $x_B, \ldots$

- Experiments

	E_{lepton} =
EMC	100…280 GeV
Hermes	27 GeV
Hermes	12 GeV
CLAS	12 GeV
CLAS	5 GeV



…multiple combinations of targets

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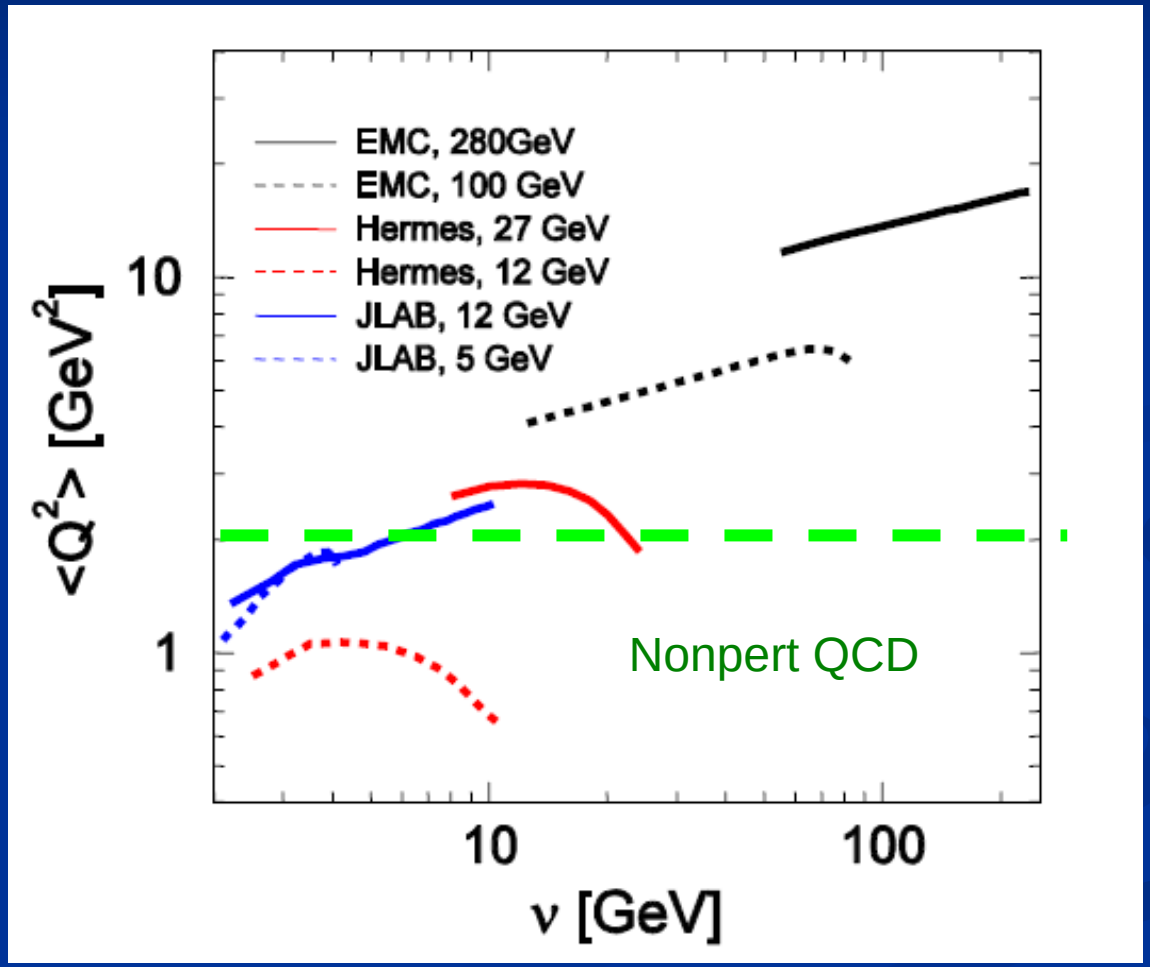
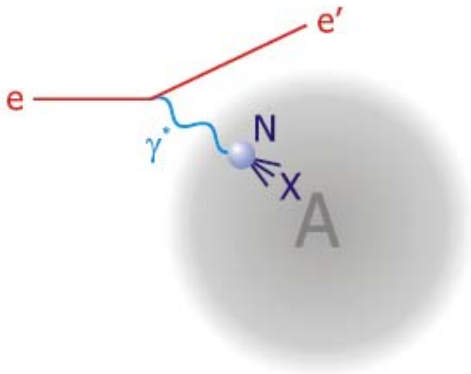
Kinematical regimes



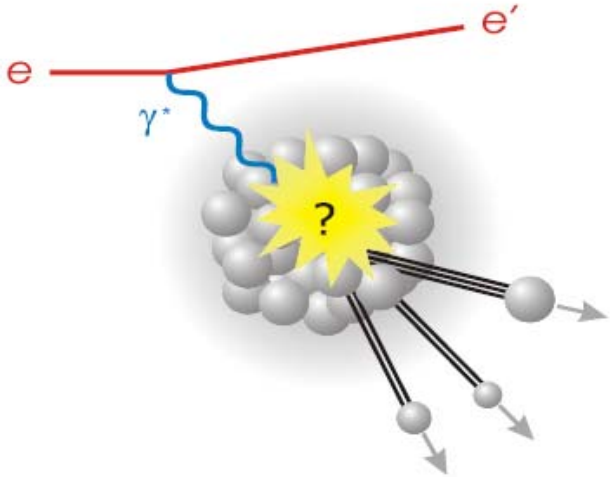
Model

- $\gamma^* N \rightarrow X$ using PYTHIA

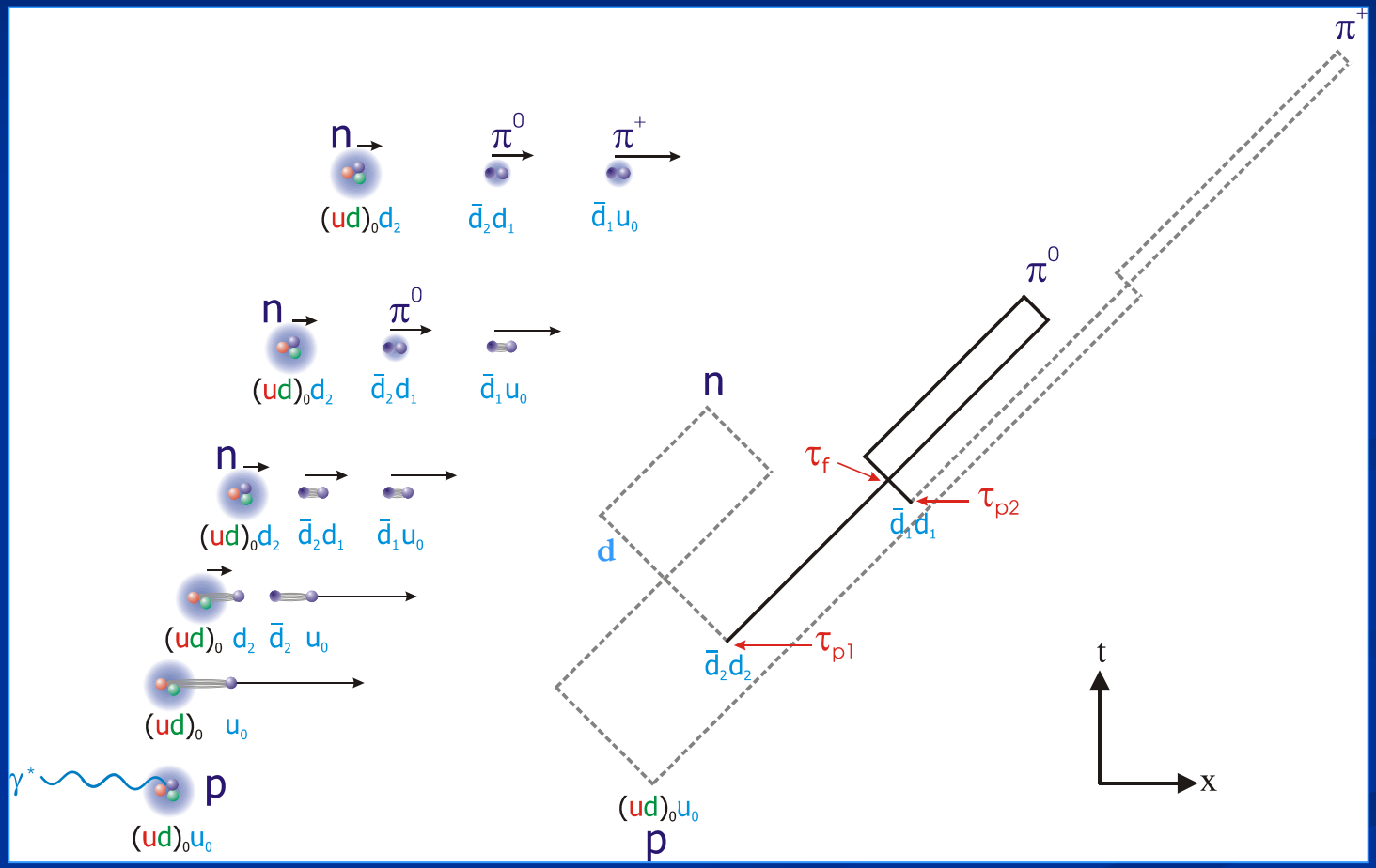
  additional:
  - binding energies
  - Fermi motion
  - Pauli blocking
  - coherence length effects



- propagation of final state X within GiBUU transport model
  - elastic/inelastic scatterings (coupled channels)
  - experimental acceptance

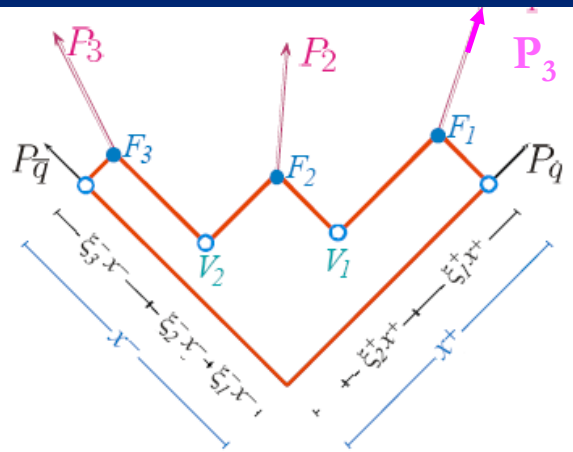


Dynamics of Hadron Production: Pion Production



Formation Times 29.10.07

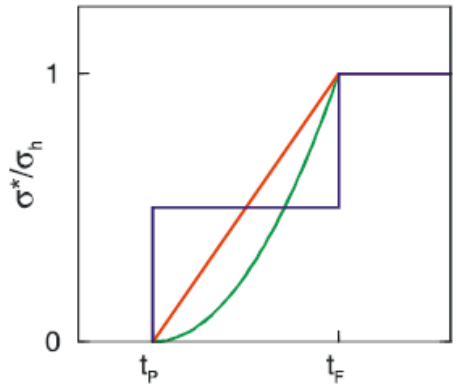
Hadronization Model (PYTHIA)

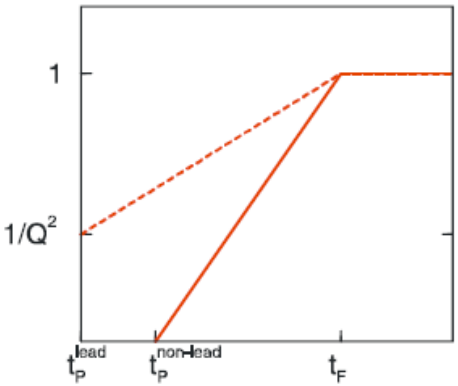


- 3 times/points per particle:
  - „Production 1“ String-Break
  - „Production 2“ String-Break
  - „Formation“ Line Meeting
- leading vs. non-leading

CT

- XS evolution scenarios:





Frankfurt, Strikman, Miller

Production and Formation Times

- Leading Hadrons:
  have at least one parton line connected with the interaction point
  → Production Time of at least one constituent is zero
  → fsi from the initial interaction on

- Non-leading Hadrons:
  produced entirely from the sea
  → interactions set in later

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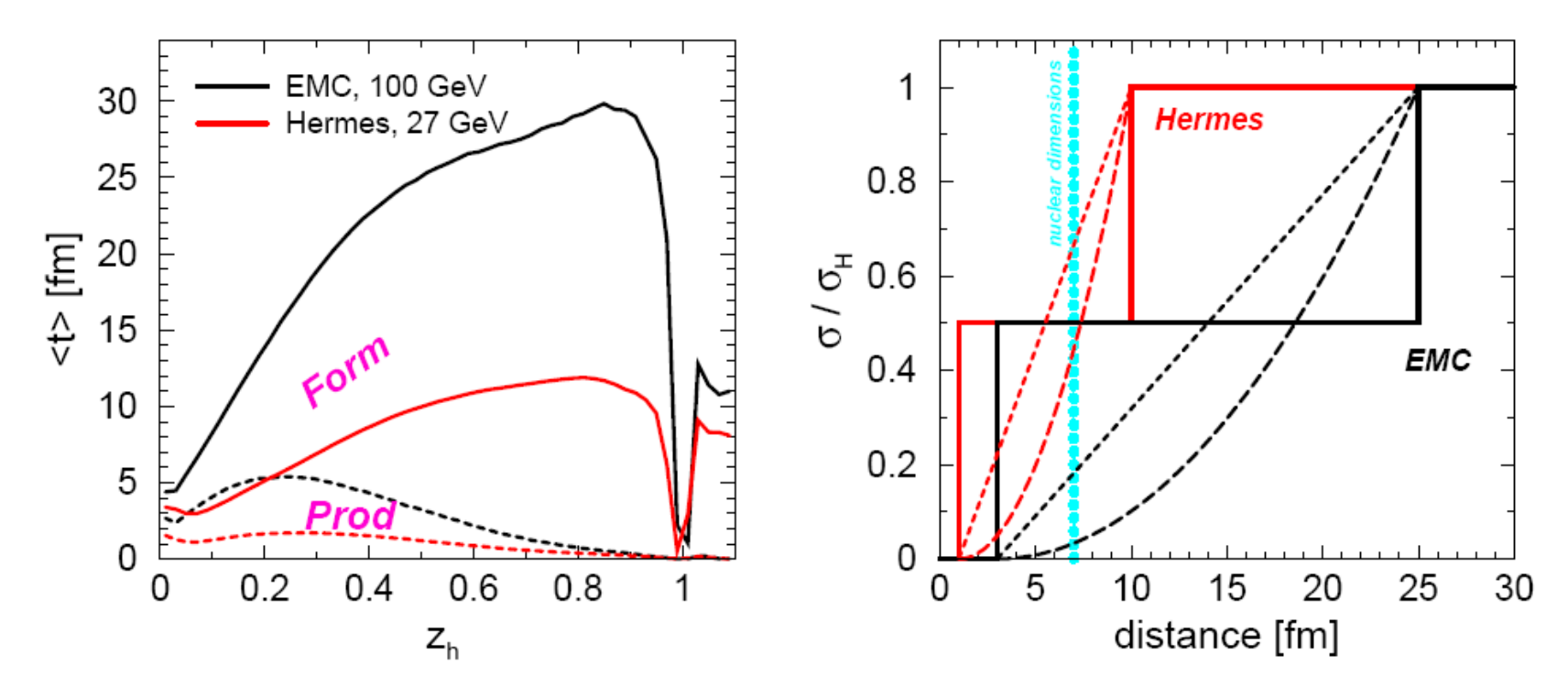
Production and Formation Times from PYTHIA

$z_h = E_h/\nu$



All times in lab (nucleus) frame, from **Falter & Gallmeister**, **Phys.Lett.B630:40-48,2005**

FSI: GiBUU transport

- what is GiBUU?
  semiclassical coupled channels transport model

- general information:
  http://theorie.physik.uni-giessen.de/GiBUU/
- GiBUU describes (within the same unified theory and code)
  - heavy ion reactions
  - pion induced reactions
  - low and high energy photon and electron induced reactions
  - neutrino induced reactions

……..using the same physics input! And the same code!

GiBUU transport model

- time evolution of spectral phase space density (for $i = N, \Delta, \pi, \rho, \ldots$) given by BUU equation

$$\frac{df_i}{dt} = \left(\partial_t + (\nabla_{\vec{p}} H)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H)\nabla_{\vec{p}}\right) f_i(\vec{r}, \vec{p}, \mu, t) = I_{coll}\left[f_i, f_N, f_\pi, f_\Delta, \ldots\right]$$

$f_i(\vec{r}, \vec{p}, \mu, t)$ ← one-particle spectral phase space density for particle species i

$$H = \sqrt{(m_i + U_s)^2 + \vec{p}^{\,2}}$$ ← Hamiltonian

- one eq. for each particle species (61 baryons, 21 mesons)
- coupled through potentials U_s and collision integral I_{coll}
- For W > 2 GeV interactions by PYTHIA, below by resonance physics

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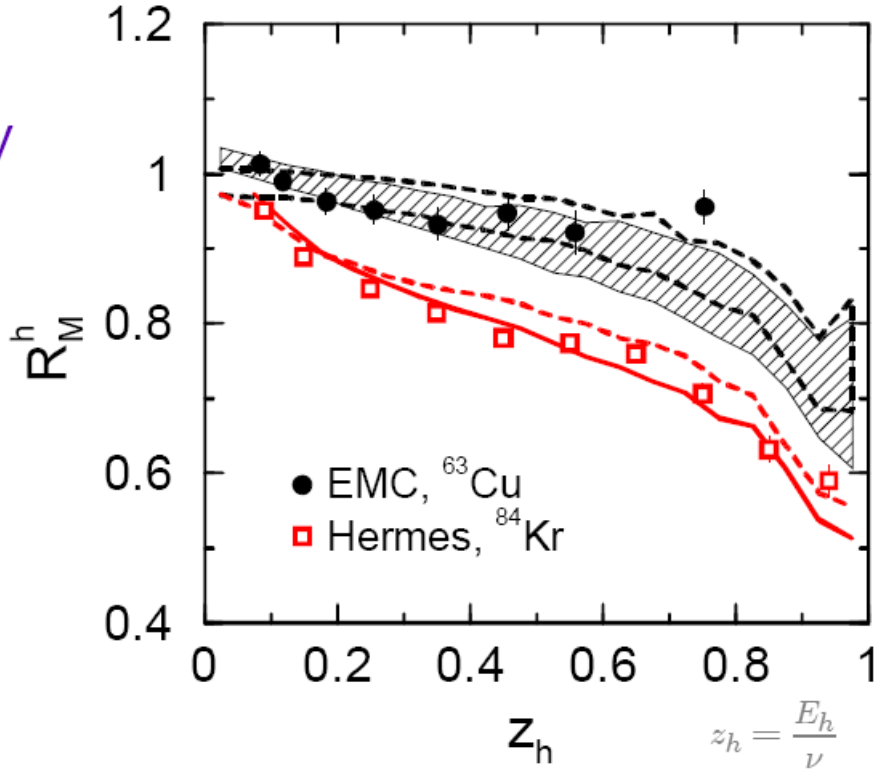
Attenuation: EMC and HERMES

$$\frac{\sigma^*}{\sigma_h} = \frac{r_{\text{lead}}}{Q^2} + \left(1 - \frac{r_{\text{lead}}}{Q^2}\right)\left(\frac{t - t_{P_1}}{t_F - t_{P_1}}\right)$$

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

!

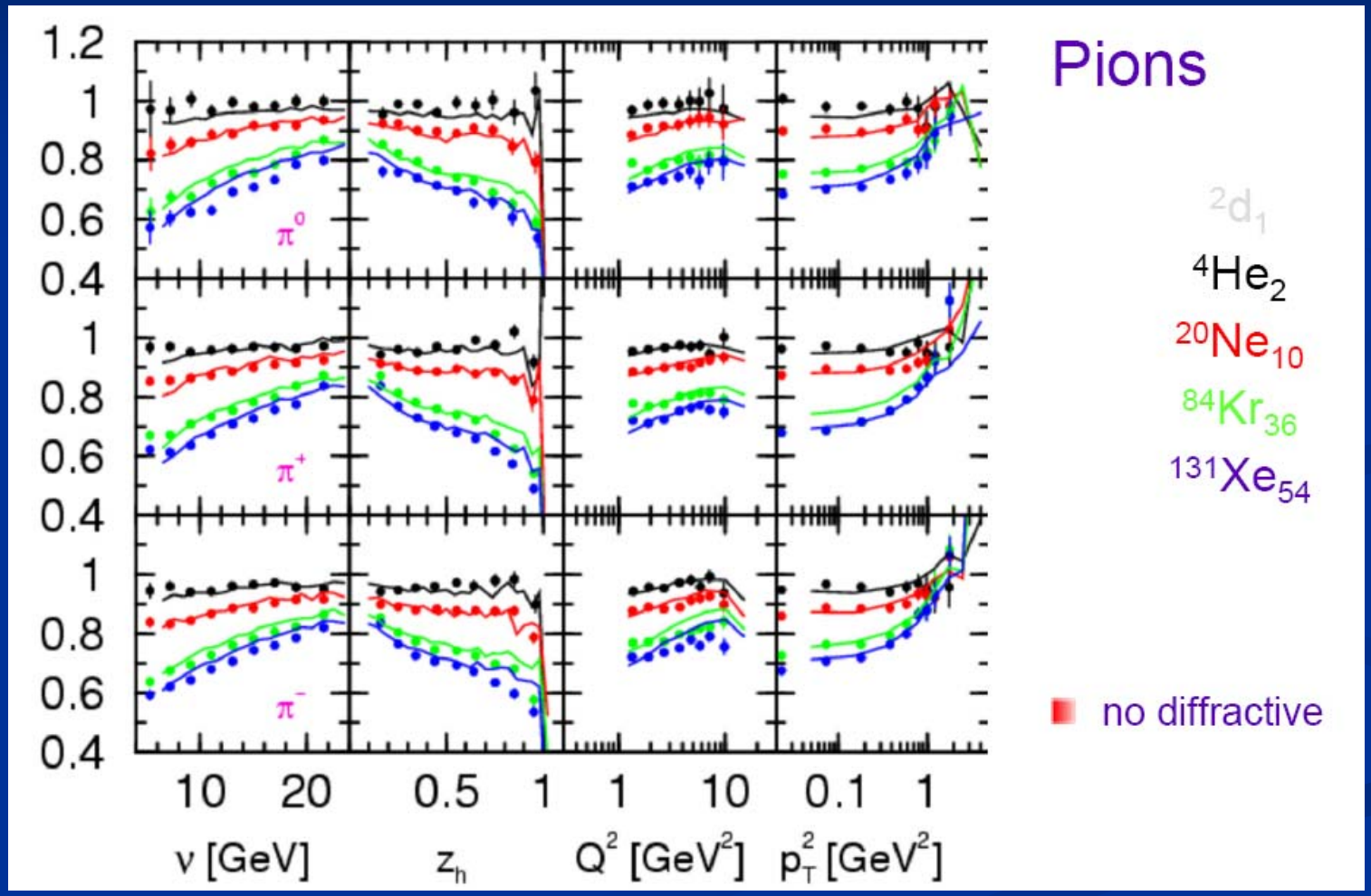
Color transparency?
…small effect!



$z_h = \frac{E_h}{\nu}$

HERMES@27 GeV

Airapetian et al.



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JLAB

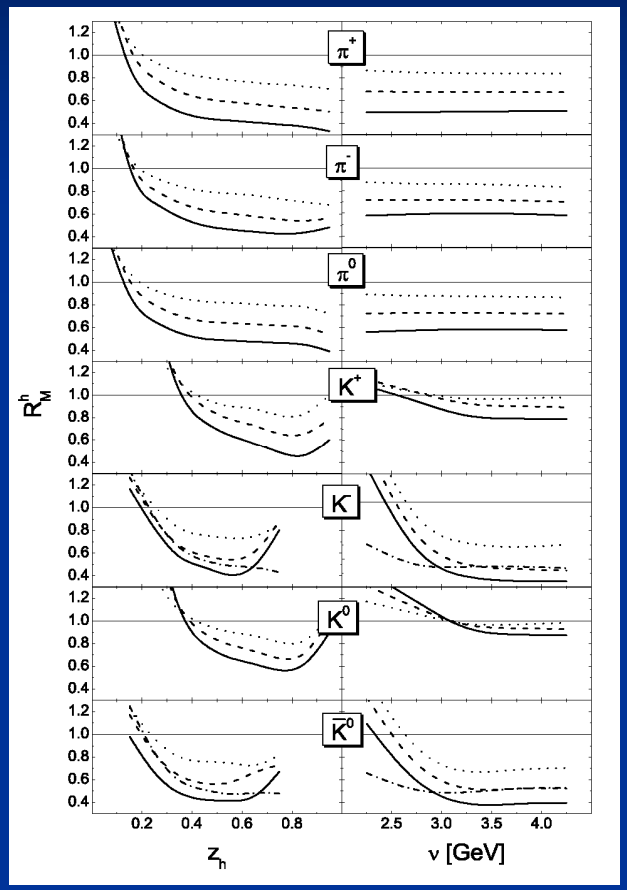
5 GeV

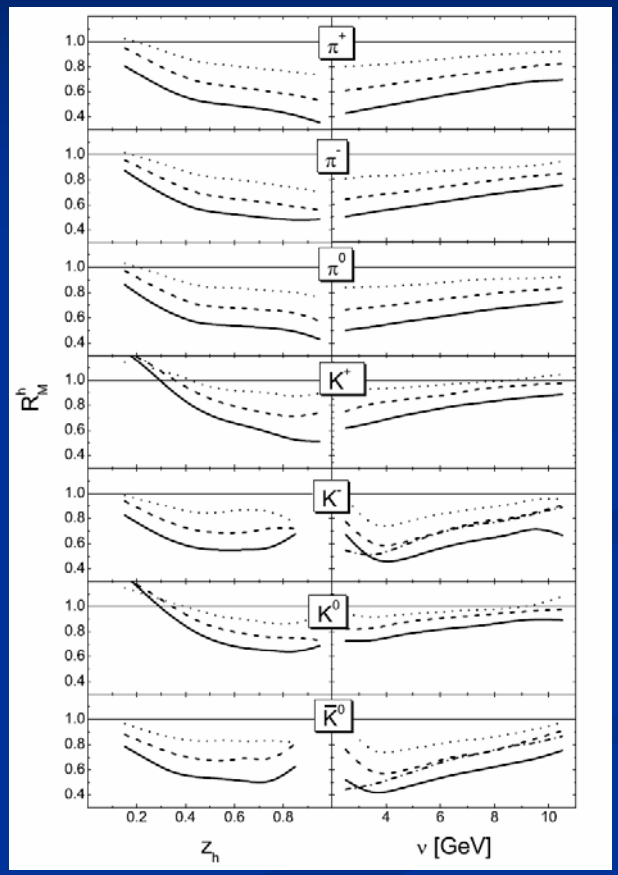
12 GeV

CLAS acceptance corrected

Prediction 2004

prelim data: Brooks et al, Hafidi et al





C
Fe
Pb

Strong nuclear effects: Fermi motion, overpopulation of low z

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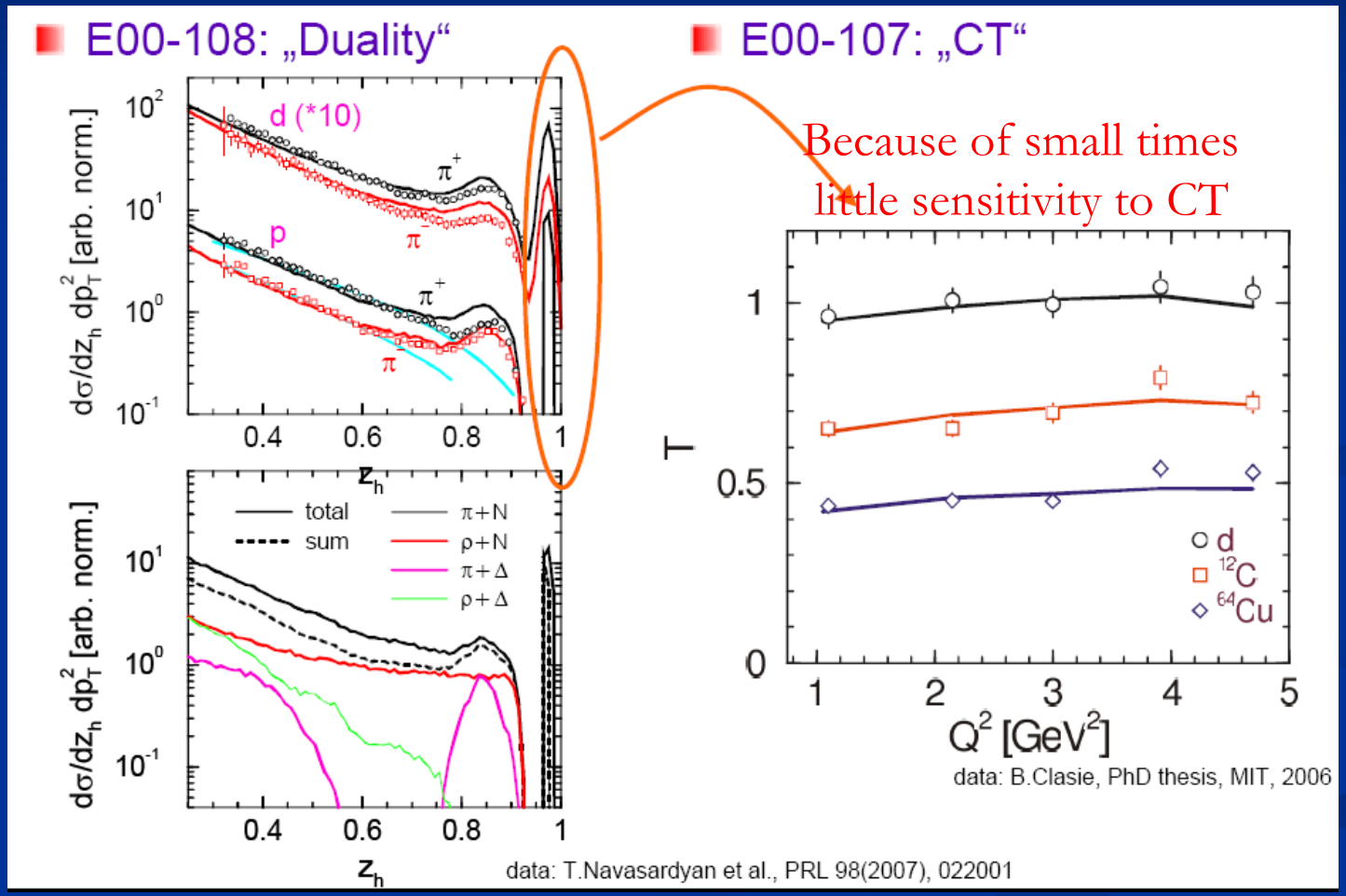
JLAB@5 GeV



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High Energy Summary

- model for γ and e induced reactions at GeV energies
  - combines:
    - QM coherence in entrance channel
    - coupled channel transport description of FSI
    - 4D production/formation points per every particle
  - GiBUU is multi purpose transport code
  - can describe:
    - coherence length effects in exclusive ρ^0 production
    - hadron attenuation
    - *…much more…*

    } **EMC** **HERMES** JLAB
- pre-hadronic cross section increases linear in time
- tiny hints towards color transparency

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Times at low (< 1 GeV) energies

- Physics dominated by isolated nucleon resonances, e.g.:

  $(e, \nu) + N \rightarrow \Delta \rightarrow \pi + N$

- Lifetime of Δ determines production time of pion, formation time is zero (because hadrons,are produced in their gs, due to phase-space limitation)

Times at Low Energies

- Naive guess for production time:

$$\tau_p = 1/\Gamma_0 \qquad (\Gamma_0 = \text{free resonance width})$$

- Educated guess:

$$\tau_p = 1/(\Gamma_0 + \Gamma_{coll}) \text{ with } \Gamma_{coll} \approx \rho\, v\, \sigma$$

- Production Times change in Medium

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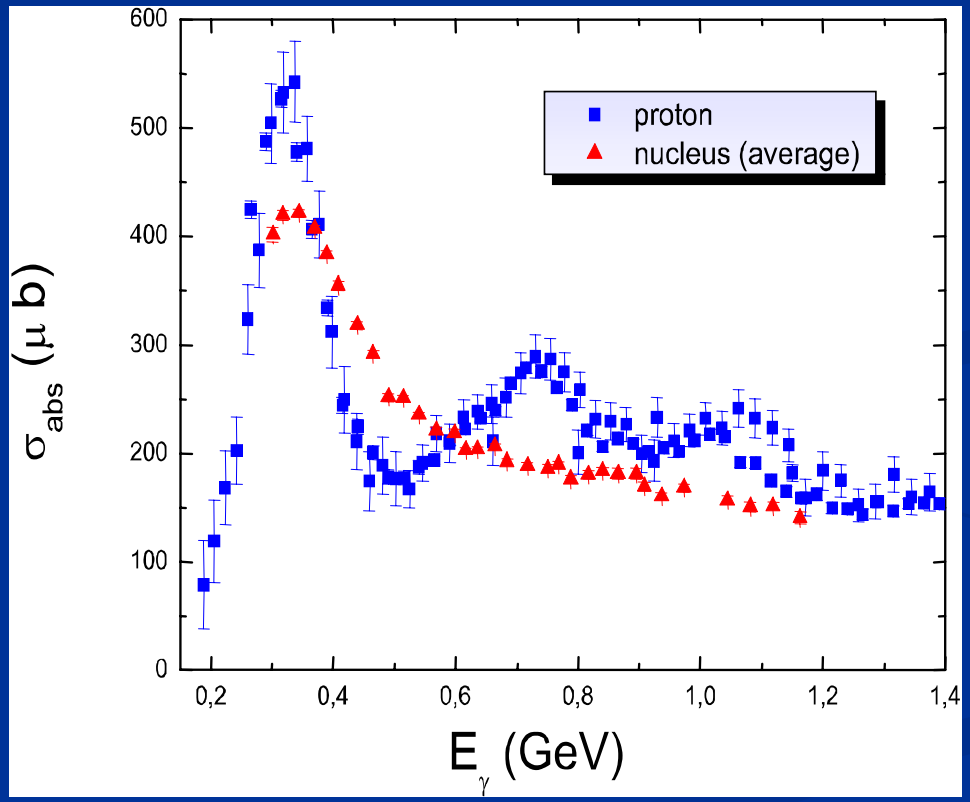
Times at Low Energies

- Times handled correctly in GiBUU
  - Formation times shortened by collisions (collisional width)
  - Interactions of resonance *R* during formation handled by including:
    - $R + N \rightarrow R + N$ (elastic)
    - $R + N \rightarrow R' + N$ (inelastic, R' other resonance or resonance R at different mass)
    - $R + N \rightarrow N + N$ (absorptive)

In-medium width and observables

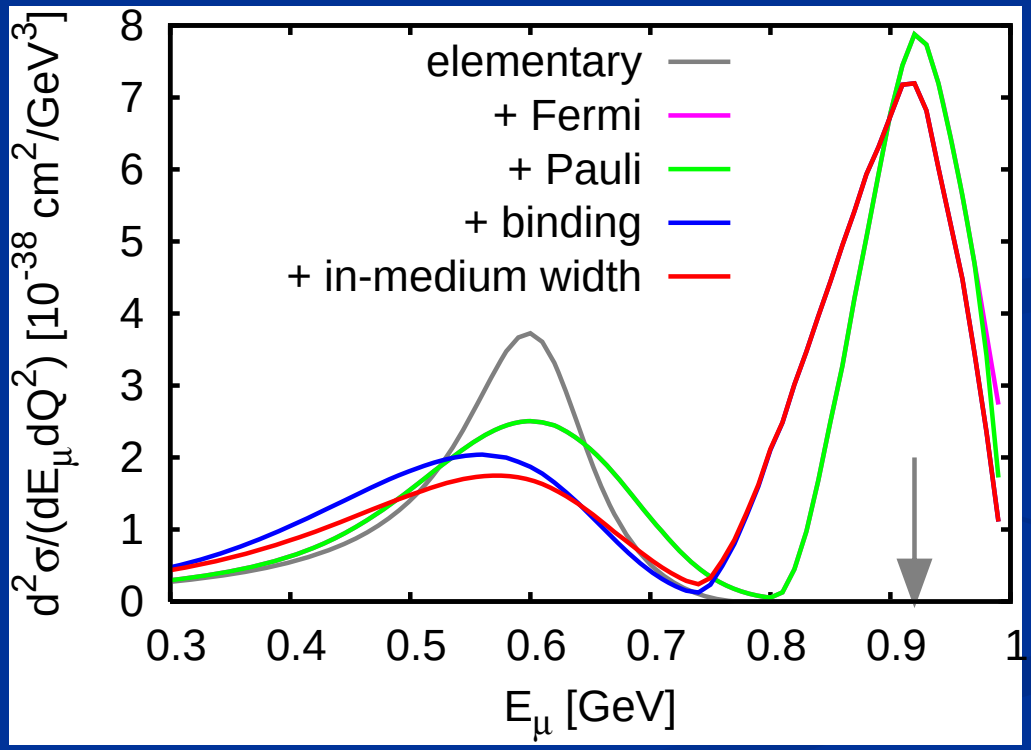
- Inclusive Photoabsorption



σ_{abs} on nucleus normalized by number of nucleons, higher resonances disappear

In-medium width and observables

- $\nu + {}^{56}Fe$ inclusive



$Q^2 = 0.15$ GeV^2
$\nu = 1$ GeV

Summary

- Times
  - At low energies, resonance regime:

    t_f = lifetime of resonance → N + hadron
  - At high energies, QCD regime,

    t_f from string-fragmentation
- Interactions
  - At low energies: collisional broadening of resonances
  - At high energies: nuclear attenuation

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Literature

- K. Gallmeister and U. Mosel:
  „Time Dependent Hadronization via HERMES and EMC Data Consistency", nucl-th/0701064
- K. Gallmeister and T. Falter:
  „Space-time picture of fragmentation in PYTHIA/JETSET for HERMES and RHIC"
- O. Buss et al.,
  „ The Influence of the nuclear medium on inclusive electron and neutrino scattering off nuclei", Phys.Rev. C76:035502,2007
- T. Leitner et al.,
  „ Neutral current neutrino-nucleus interactions at intermediate energies", Phys.Rev. C74:065502,2006;
  „Charged current neutrino-nucleus interactions at intermediate energies", Phys.Rev. C73:065502,2006

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