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Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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In-medium Hadrons Properties, Interaction and Formation

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In-medium Hadrons
Properties, Interaction and Formation

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Why study in-medium hadrons?

- In-medium properties may signal exotic states of nuclear matter (e.g.: QGP, chirally restored phase)

→ need baseline effects in normal nuclear matter

- Mesons in medium can give infos on meson-nucleon interactions through selfenergies

- Nucleus as a ‚microdetector':
  - access to production- and formation-times in quark-fragmentation, color transparency

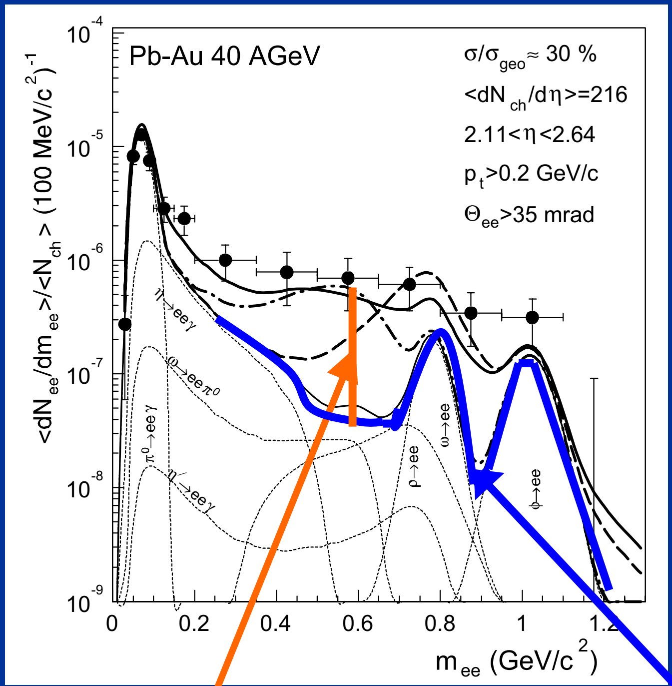
Experiments

- Observe outgoing nucleons, mesons, photons, dileptons, ...
- A + A: GSI, AGS, SPS, RHIC, LHC
- p + A : COSY
- π + A : GSI (HADES)
- $\gamma^{(*)}$+ A : MAMI, ELSA, JLAB, HERMES
  incoherent photo- and electroproduction of hadrons on nuclei from 100 MeV (MAMI, ELSA) over few GeV (JLAB) to ~20 GeV (HERMES)
- ν + A in LBL neutrino experiments
- Need to understand connection between in-medium property and final observable!

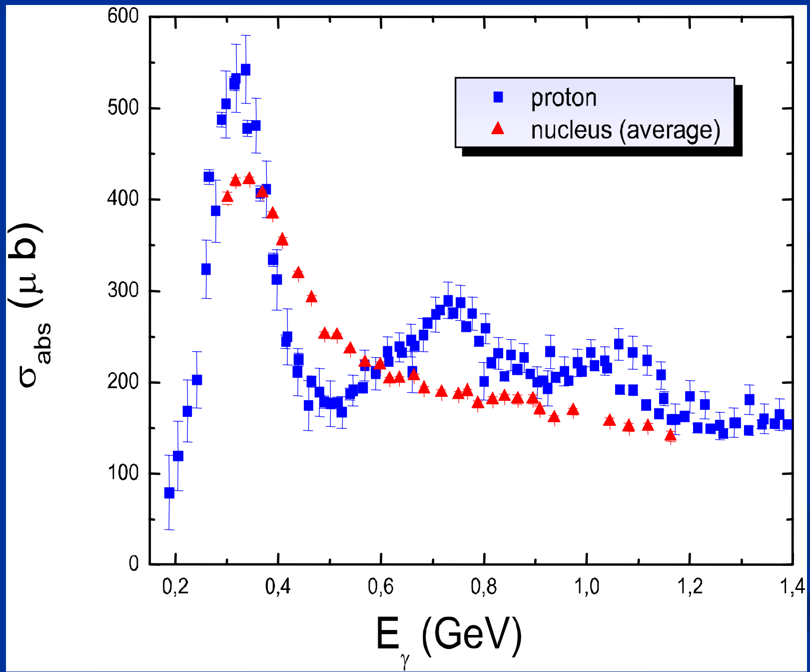
In-medium changes: experiment 2000

explained by spectral change of ρ meson in dense, (hot) matter

Evidence for QGP at CERN
Invariant (e+e-) mass spectrum



Total photoabsorption cross section



CERES effect

Cocktail plot of free sources

Hadron Properties in Medium: Theory

1. QCD Sum Rules for Vector Mesons
2. Hadronic Models
3. Connection with Experiment

   through universal transport method for low and high energies

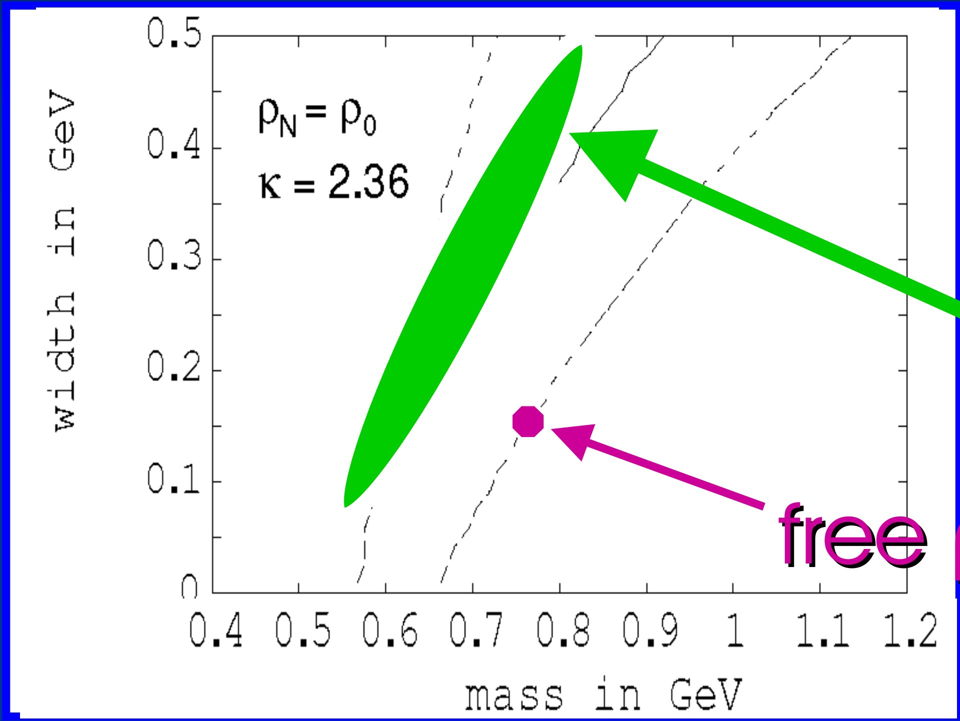
QCD Sum Rule

Compare spectral function in time-like region with OPE of current-correlator for space-like distances

$$\frac{Q^2}{\pi}\int_0^\infty ds\,\frac{\Im\Pi(s)}{s\left(s+Q^2\right)} = -\frac{1}{8\pi^2}\left(1+\frac{\alpha_s}{\pi}\right)\ln\frac{Q^2}{\Lambda^2} + \frac{m_q\langle\bar{q}q\rangle}{Q^4} + \frac{1}{24}\frac{\langle\frac{\alpha_s}{\pi}G^2\rangle}{Q^4} + \frac{\langle(\bar{q}q)^2\rangle}{Q^6} + \ldots$$

- Lhs dominated by soft scale ~ m_ρ
- Rhs separates hard scale ~ Q^2 from soft scale (condensates)

ϱ spectral function in medium



QCDSR-allowed (Γ,m) at saturation density

free ρ meson

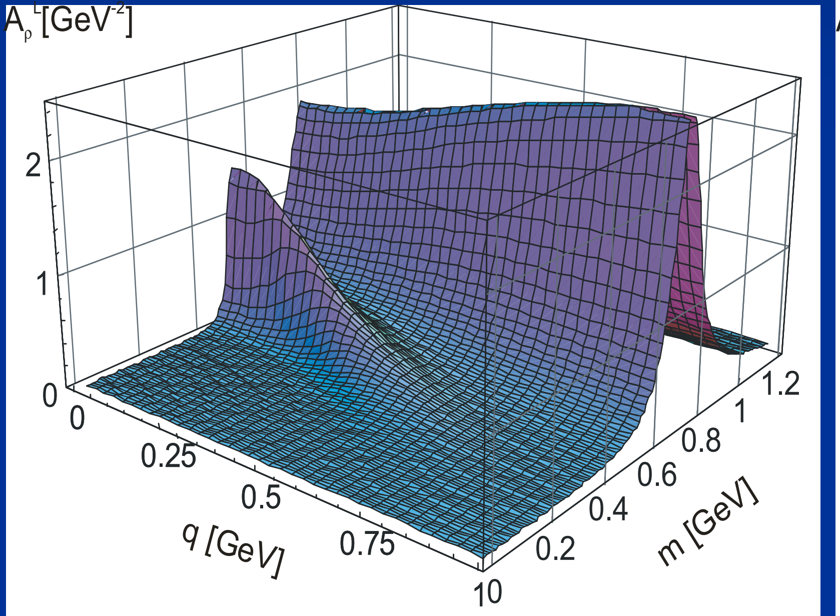
Leupold et al, Phys.Rev.C58:2939-2957,1998

QCD Sum Rules provide constraints, but do not fix in-medium hadron props

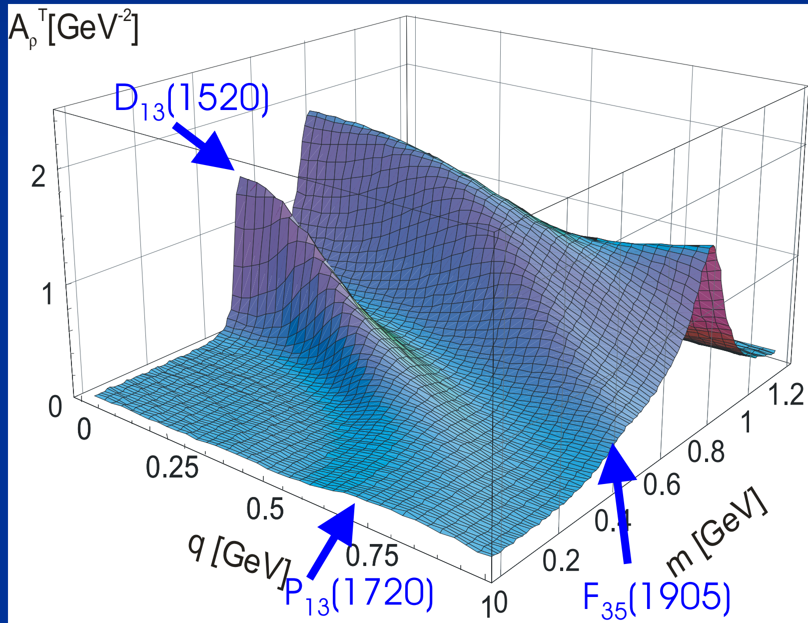
Need hadronic model

Rho meson in matter: Resonance-hole model

- Longitudinal



- Transverse



Post et al., 2004

$D_{13}(1520)$ and ρ (2π) strongly mixed

Observables: Theoretical Method

1. Calculate hadronic properties in equilibrium nuclear matter
2. Calculate elementary production cross section, in vacuo and in matter, formation times determined by resonance lifetimes or string-fragmentation times
3. Propagate produced particles out from production to detector, including all FSI and CC effects.

Theoretical Method for FSI (and ISI):

BUU CC Transport Model

Off-shell CCBUU Equation for ‚spectral phase space density‘

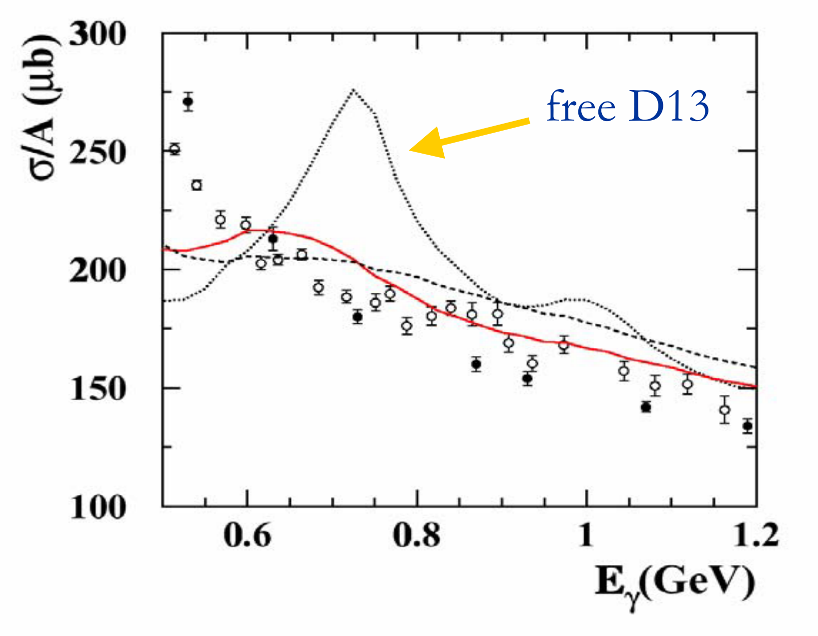
$$\left(\frac{\partial}{\partial t} + \left(\vec{\nabla}_{\vec{p}} H\right) \cdot \vec{\nabla}_{\vec{r}} - \left(\vec{\nabla}_{\vec{r}} H\right) \cdot \vec{\nabla}_{\vec{p}}\right) f_i(\vec{r}, \vec{p}, \mu, t) = I_{\text{coll}}[f_1, \ldots, f_n]$$

with $H = \sqrt{(\mu_{\text{vac}} + U_s + U_{\text{off}})^2 + \vec{p}^{\,2}}$

1. In-medium changes can be modelled in *H* (selfenergies) and in I_{coll} (reaction rates, form. times, prehadron cross sections)
2. Experimental acceptance can be simulated event by event

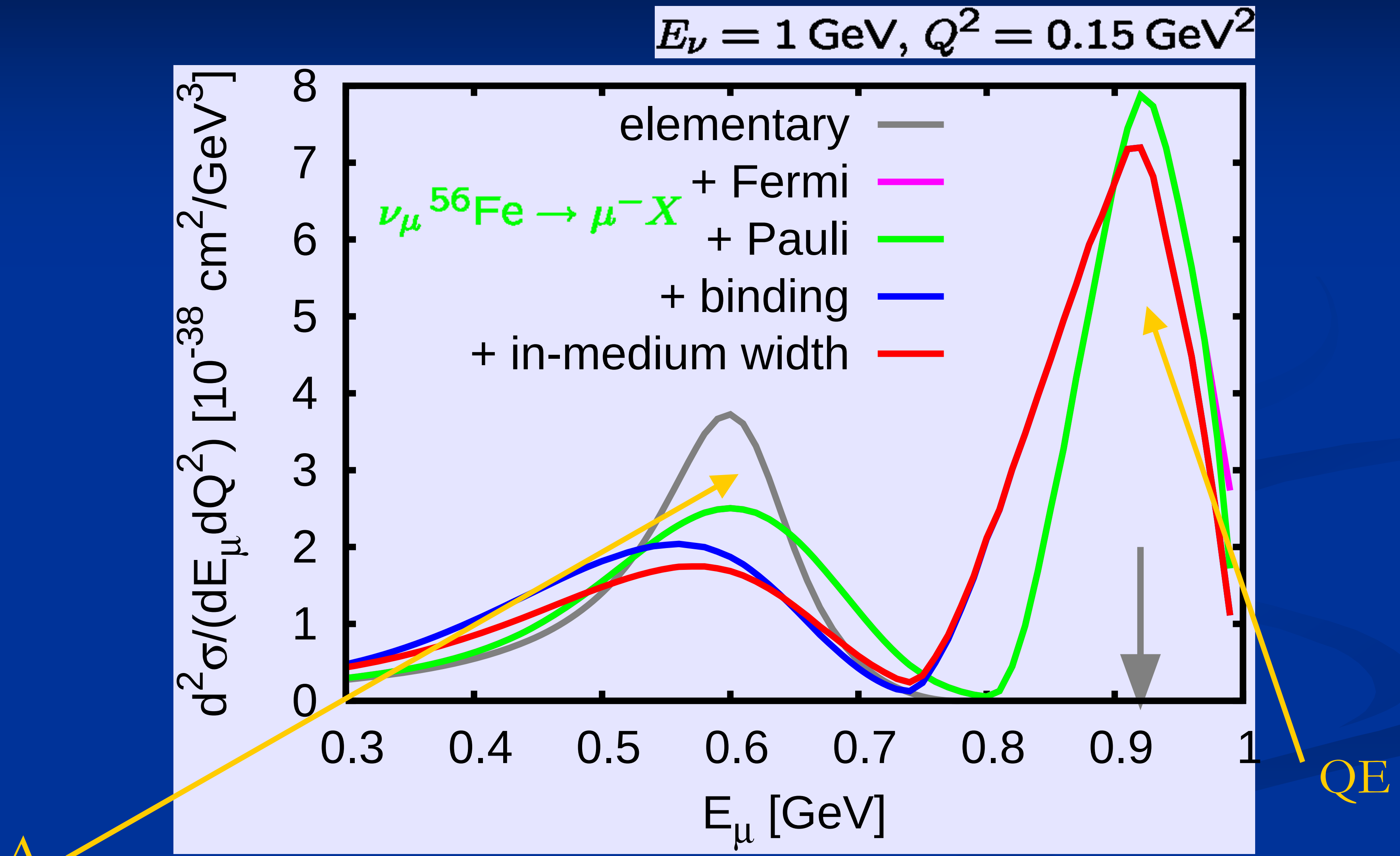
Consequences of in-medium change

- Broad ρ spectral function explains:
  - Absence of nucleon resonances in total photoabsorption cross sections on nuclei
  - D13(1520) couples to ρ, ρ broad with strength at low masses → opens phase-space for decay of D13

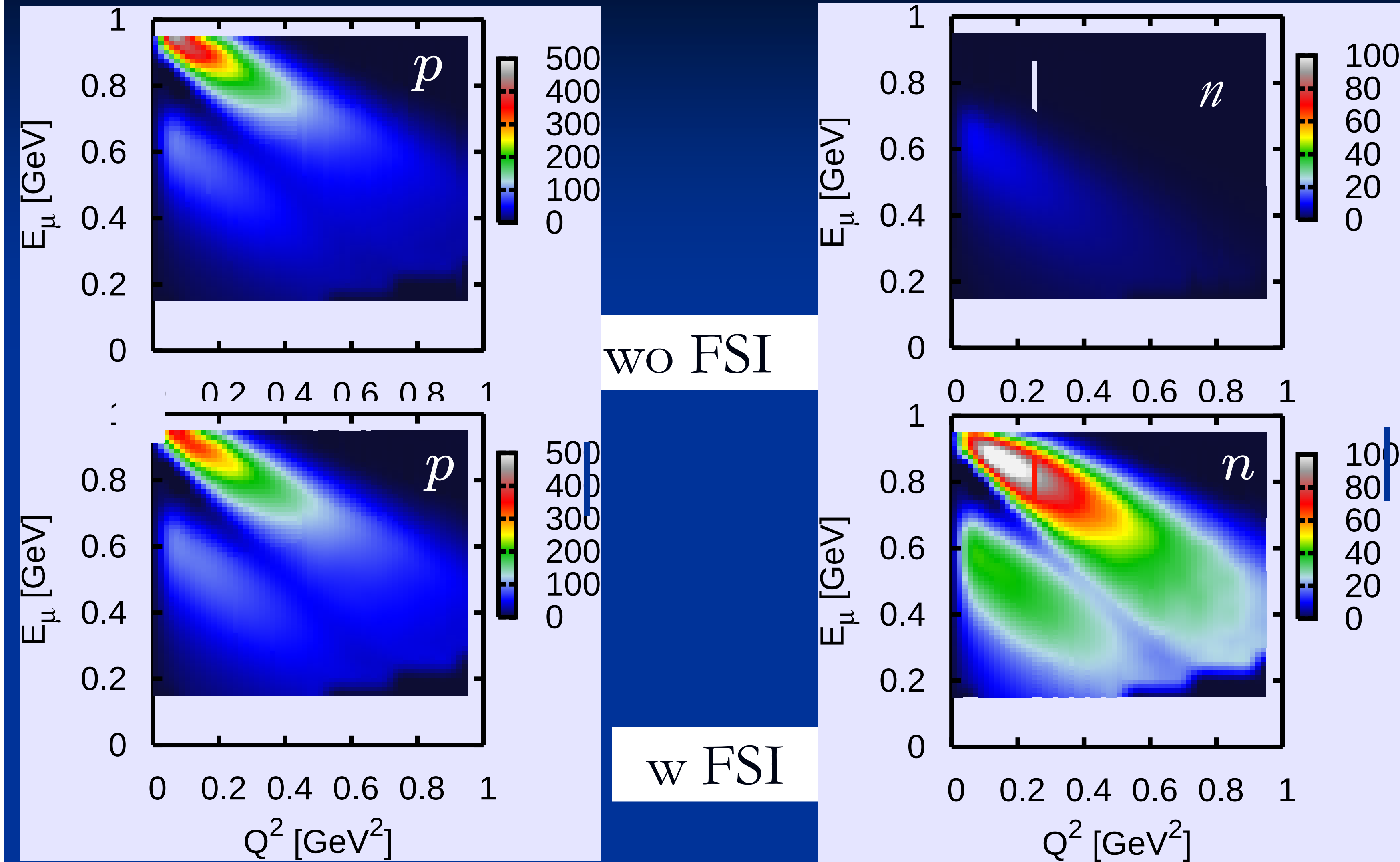


  - Dilepton spectra in URHICs

In-medium effects



Nucleon Knockout at $E_\nu = 1$ GeV $\nu_\mu\,{}^{56}\mathrm{Fe} \to \mu^- N X$

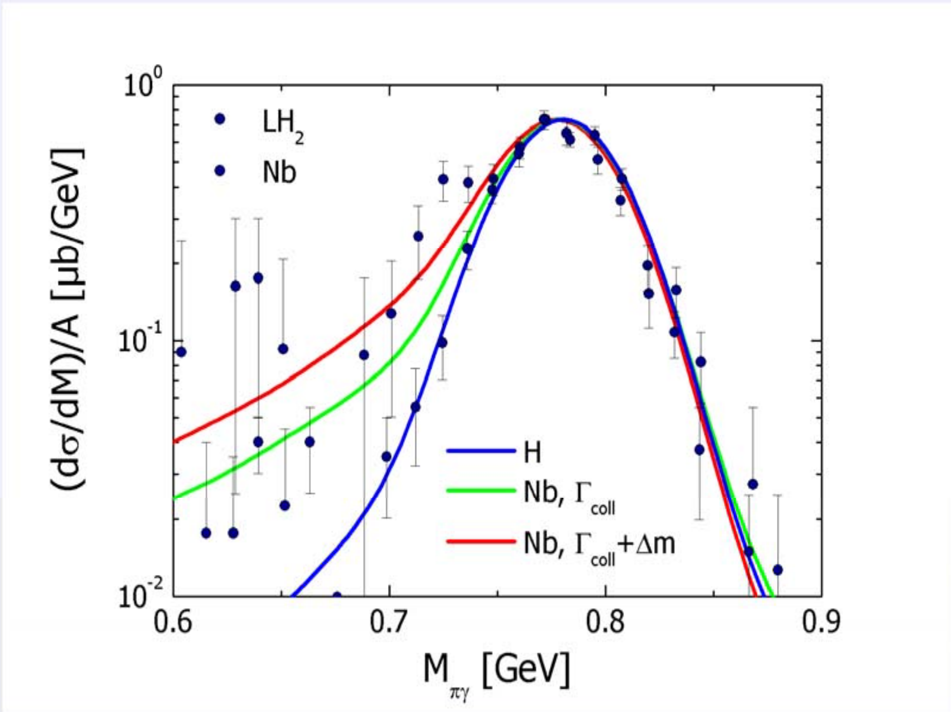


Absorption alone not sufficent, Need coupling between channels

ω in Medium

$A(\gamma, \omega \rightarrow \pi^0 \gamma')$

D. Trnka et al., PRL 94 (2005) 192303



Theory: P. Muehlich et al

Δ m = -0.15 ρ/ρ_0

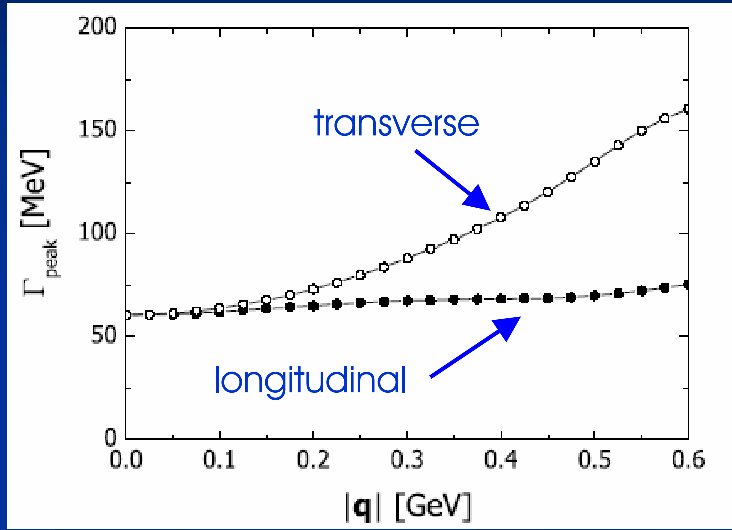
put in by hand

ω in Medium

Very little mass change from hadronic resonance-hole models

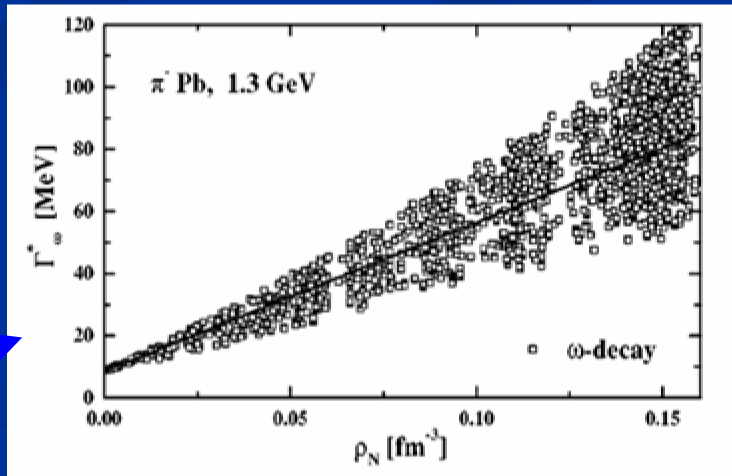
Collisional broadening ≈ 60-70 MeV

from $t\rho$ approx
with K-matrix parameters

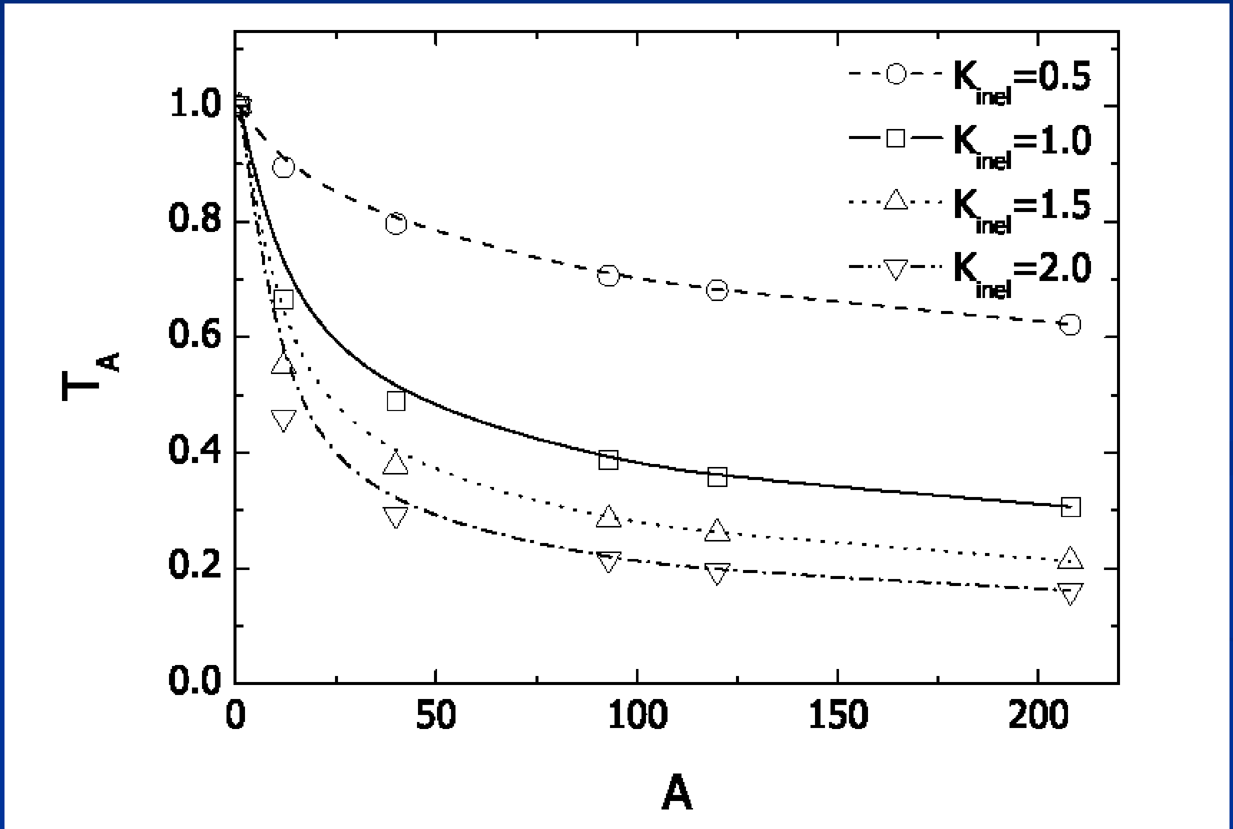


Inelastic width → transparency

also from Γ = ρ σ v
(Weidmann et al, 1999)



Nuclear Transparency for ω



Depends crucially on inelastic σ
Method to measure σ_inel

P. Muehlich, U. Mosel
Nucl. Phys. A (2006)
In press.
E_γ = 1.5 GeV

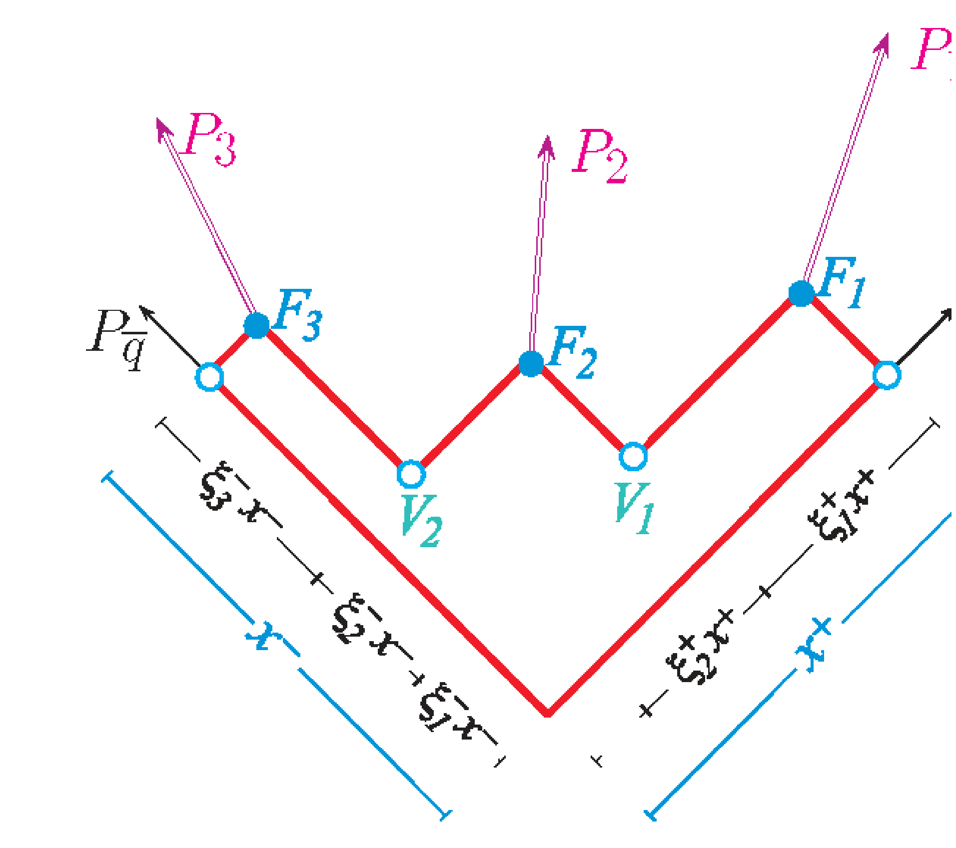
Crucial Input: inelastic omega-N cross section

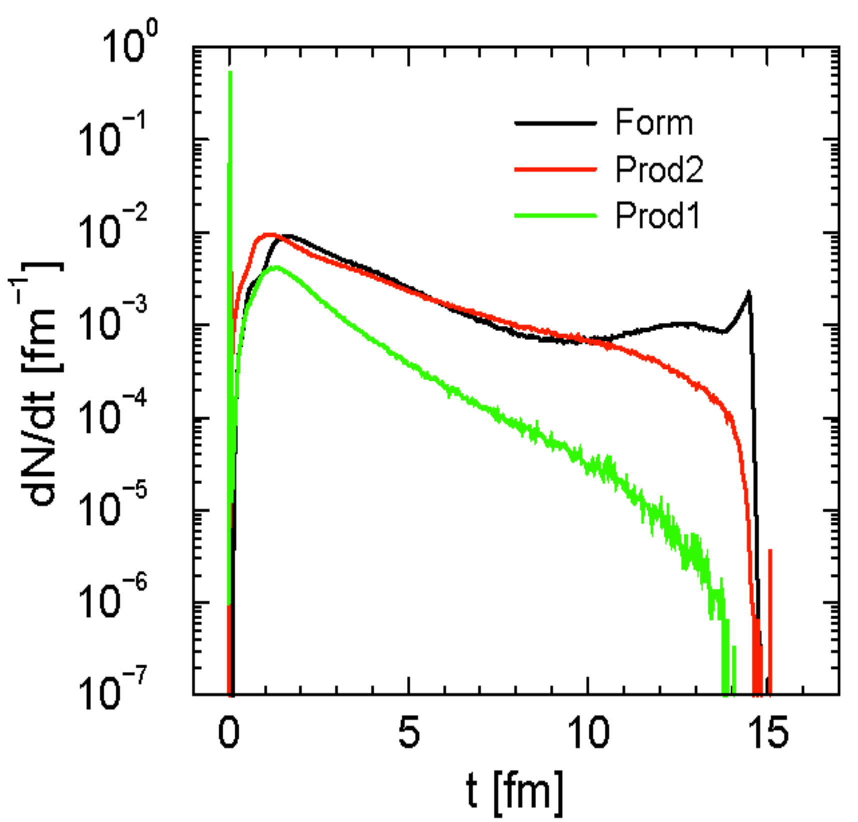
Formation times

- At low energies, resonance regime:
  t_f = lifetime of resonance → N + hadron

- At high energies, QCD regime,
  t_f from string-fragmentation

Transparency at high energies determined by quark fragmentation

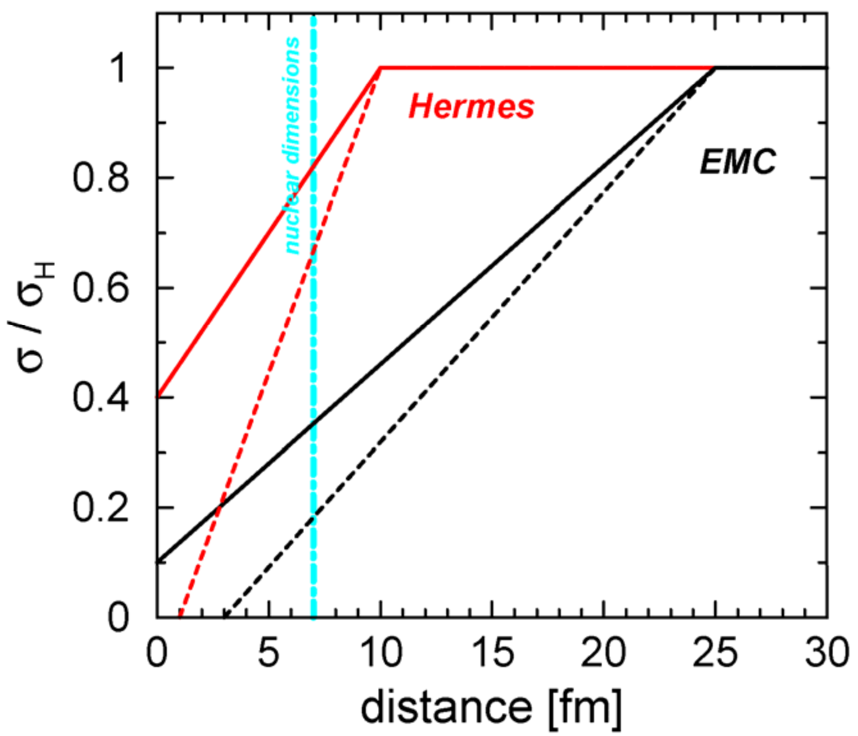




Hermes condition

ν = 14 GeV, Q^2 = 2.5 GeV^2

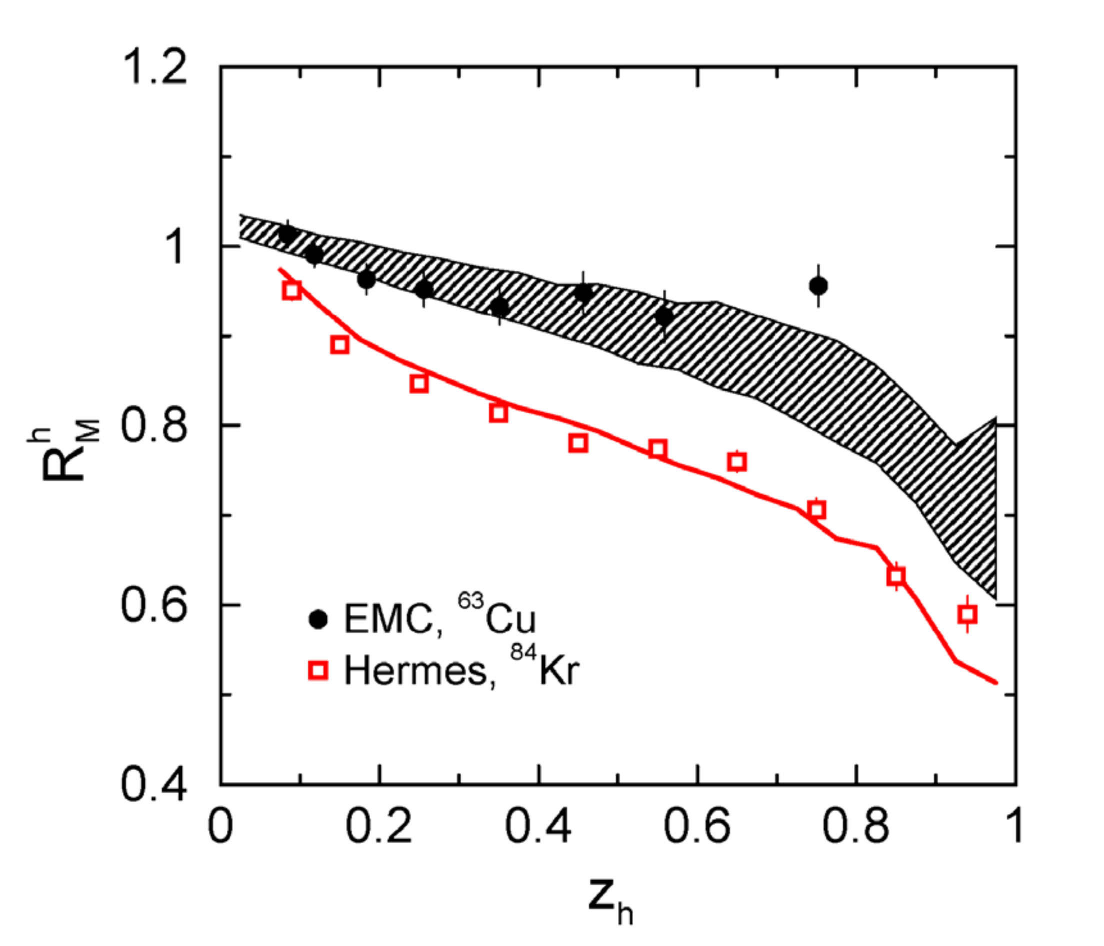
Prehadron cross sections



$$\frac{\sigma}{\sigma_H} = \# \frac{n_q}{Q^2}\left(1 - \frac{t - t_p}{t_f - t_p}\right) + \frac{t - t_p}{t_f - t_p}$$

After: Farrar, Liu, Frankfurt, Strikman

EMC and Hermes Transparency



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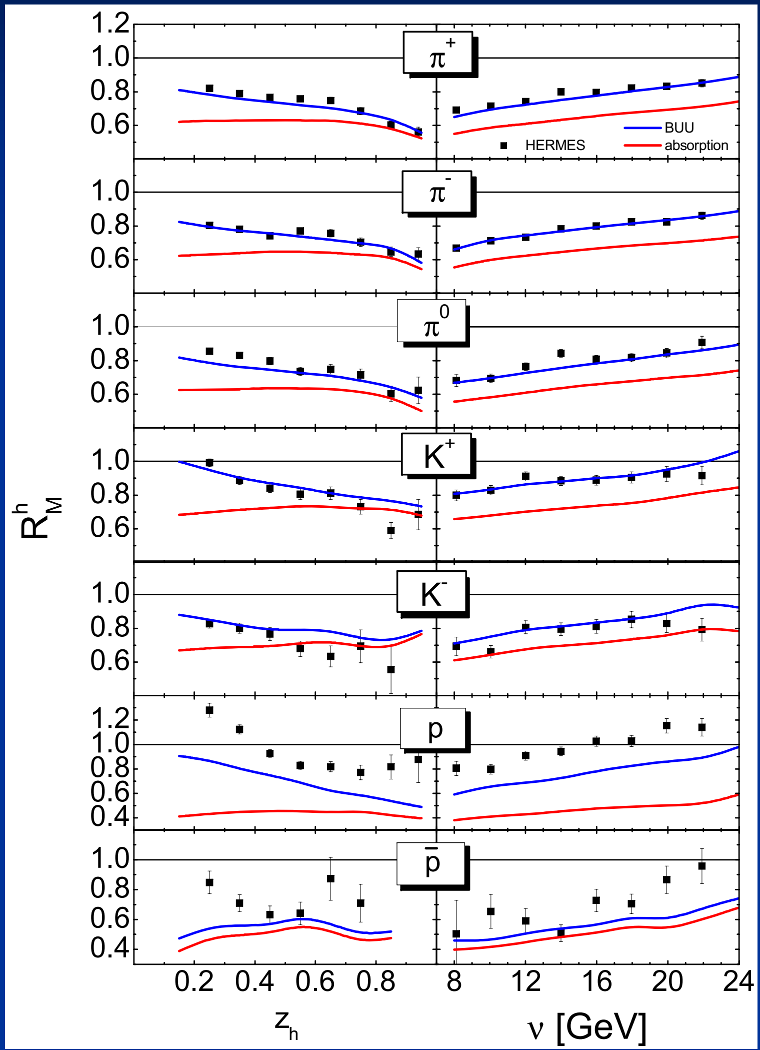
After: Farrar, Liu, Frankfurt, Strikman

Attenuation of Identified Hadrons



^{84}Kr

Red: absorption only
Blue: with CC and rescattering

Essential to know what happens to hadrons after attenuation
→distinguish between energy-loss and absorption

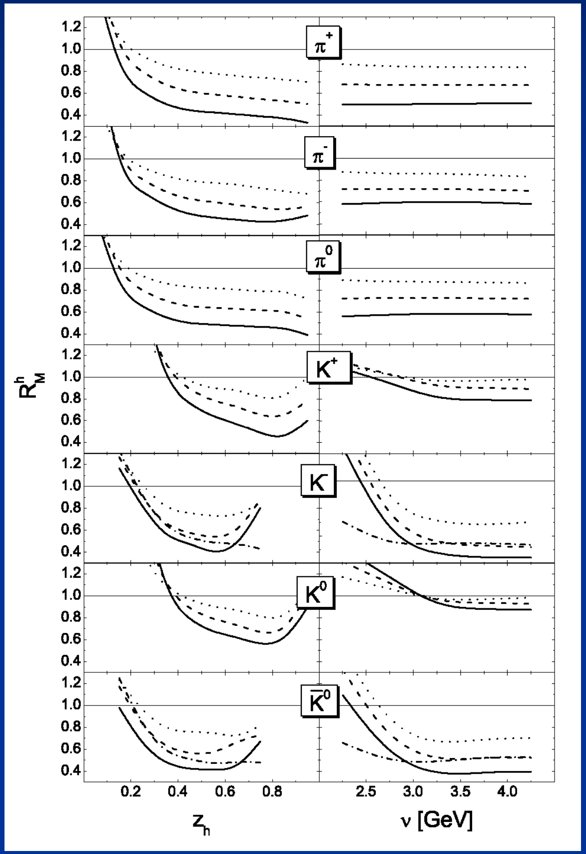
T. Falter et al., PRC

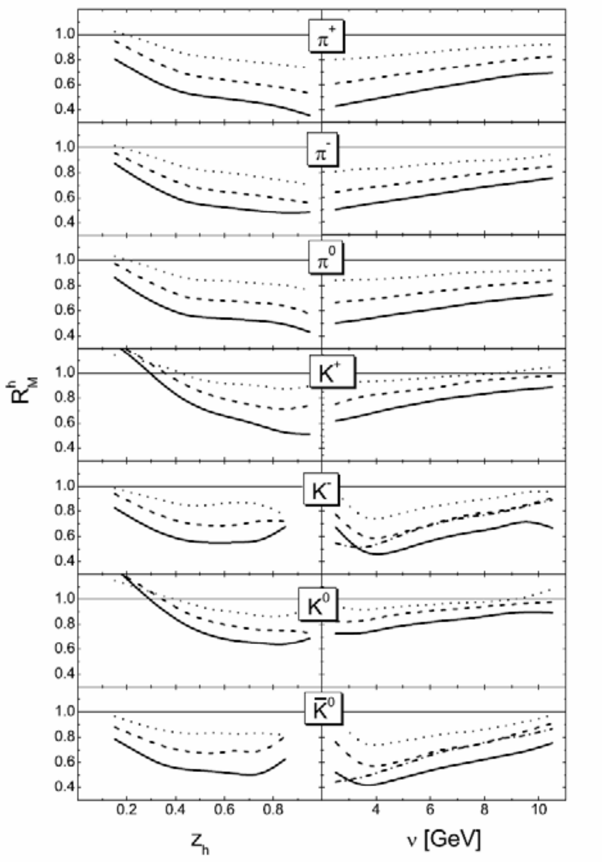
JLAB

5 GeV

12 GeV

CLAS
acceptance
corrected
Prediction 2004





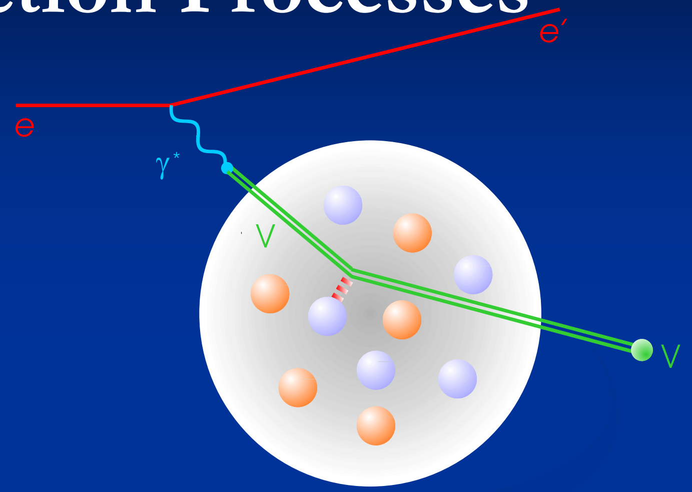
C
Fe
Pb

Strong nuclear effects: Fermi motion, stronger overpopulation of low z

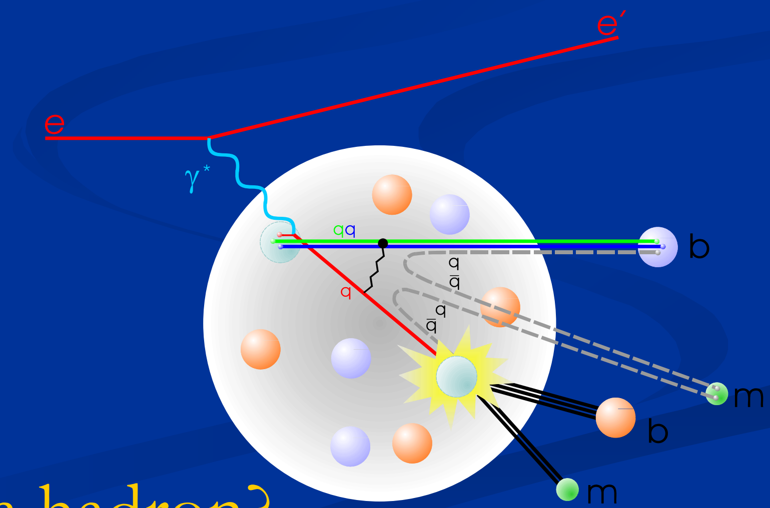
Summary - Conclusions

- Essential problem: link of in-medium props to observables → FSI must be part of theory
- Models of attenuation have to describe not only that leading hadrons disappear, but also where they go → separate energy loss from absorption
- In-medium changes seem to be established:
  CERES, NA60, TAPS/CB, Photoabs., hadron attenuation
- Transport is now reliable for a wide class of reactions

Nucleus as Microdetector
High Energy γ Production Processes



- Diffractive VMD-Event
  - Main contribution to exclusive ϱ^0-production



- Deep inleastic scattering, Jets

How long does it take to form a hadron?

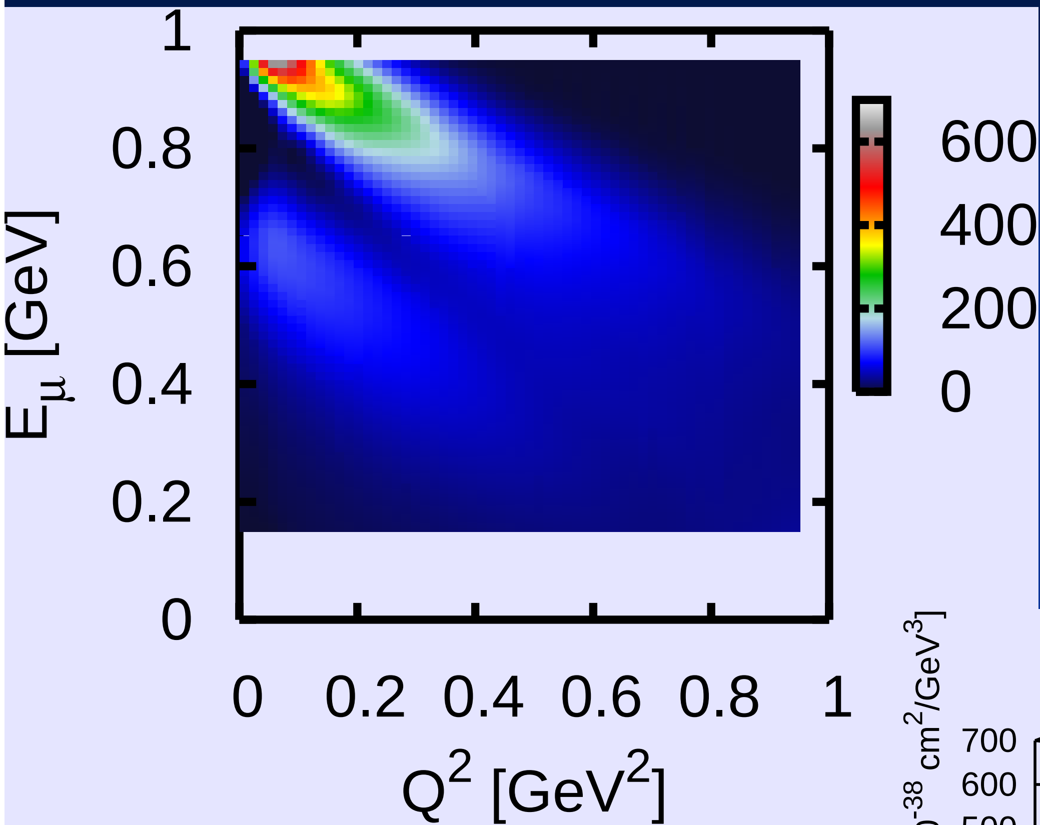
Introduction

Neutrino nucleus interactions are relevant for:

- Oscillation experiments: systematic uncertainties
  - neutrino fluxes
  - backgrounds
  - detector responses
- Hadron structure:
  - nucleon axial form factor
  - N-R axial transitions
  - strangeness in the nucleon spin
- In-medium modifications:
  - form factors
  - spectral functions
  - nuclear correlations

Understanding nuclear effects is essential for the interpretation of the data and represents both a challenge and an opportunity

Inclusive cross section



$\nu_\mu\,^{56}\text{Fe} \rightarrow \mu^- X$

$E_\nu = 1$ GeV