

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

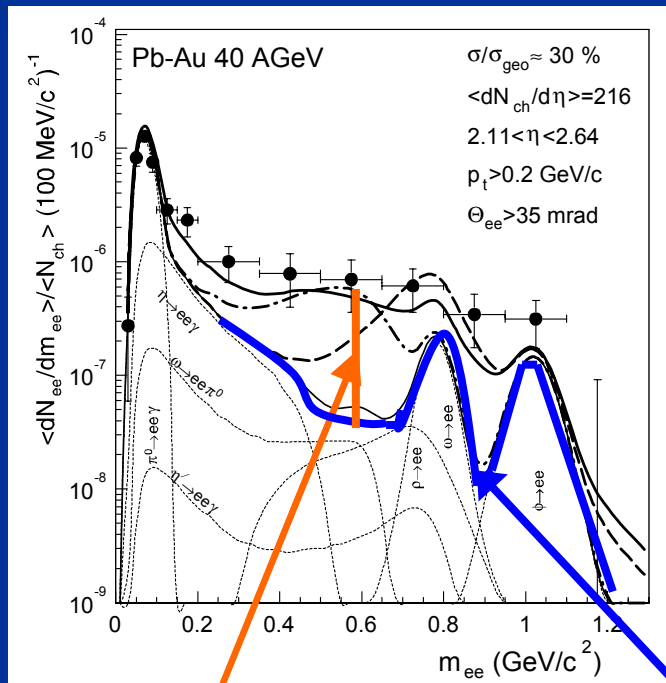
- Observe outgoing nucleons, mesons, photons, dileptons, ...
- $A + A$: GSI, AGS, SPS, RHIC, LHC
- $p + A$: COSY
- $\pi + A$: GSI (HADES)
- $\gamma^{(*)} + A$: MAMI, ELSA, JLAB, HERMES
incoherent photo- and electroproduction of hadrons on nuclei from 100 MeV (MAMI, ELSA) over few GeV (JLAB) to ~ 20 GeV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



In-medium changes: experiment 2000

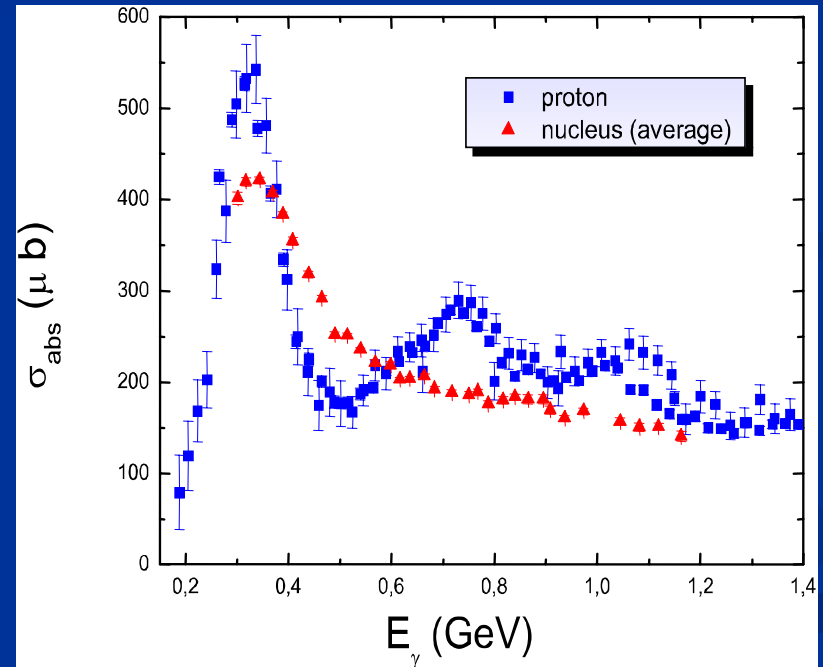
explained by spectral change of ρ meson in dense, (hot) matter

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



CERES effect

Total photoabsorption cross section



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

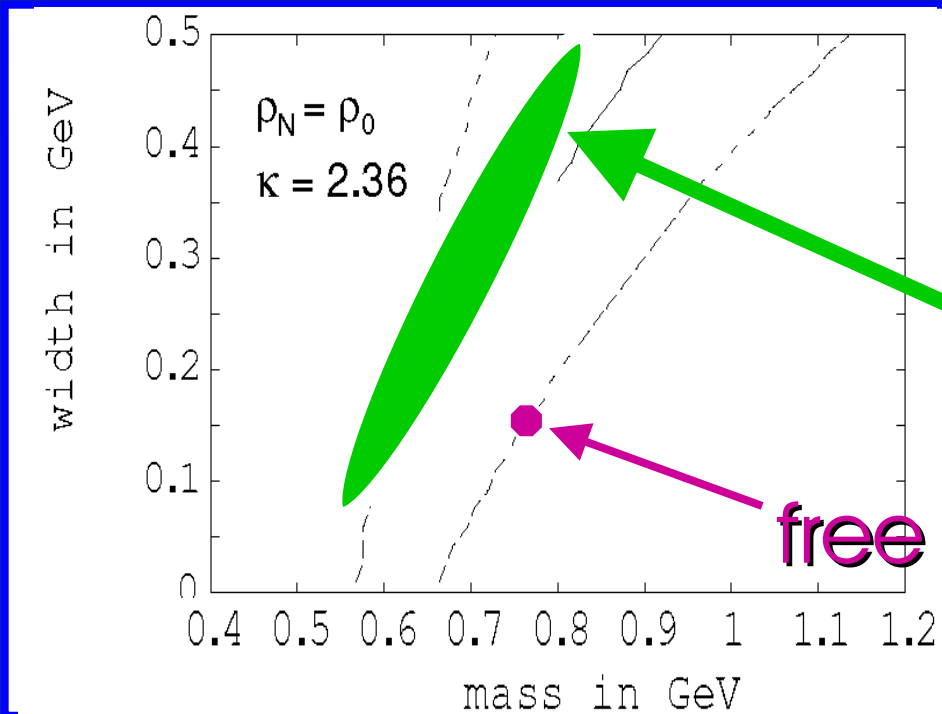
Compare spectral function in time-like region with OPE of **current-correlator** for space-like distances

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

- Lhs dominated by soft scale $\sim m_\rho$
- Rhs separates hard scale $\sim Q^2$ from soft scale (condensates)



ρ spectral function in medium



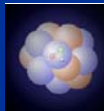
QCDSR-allowed (Γ, m)
at saturation density

free ρ meson

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

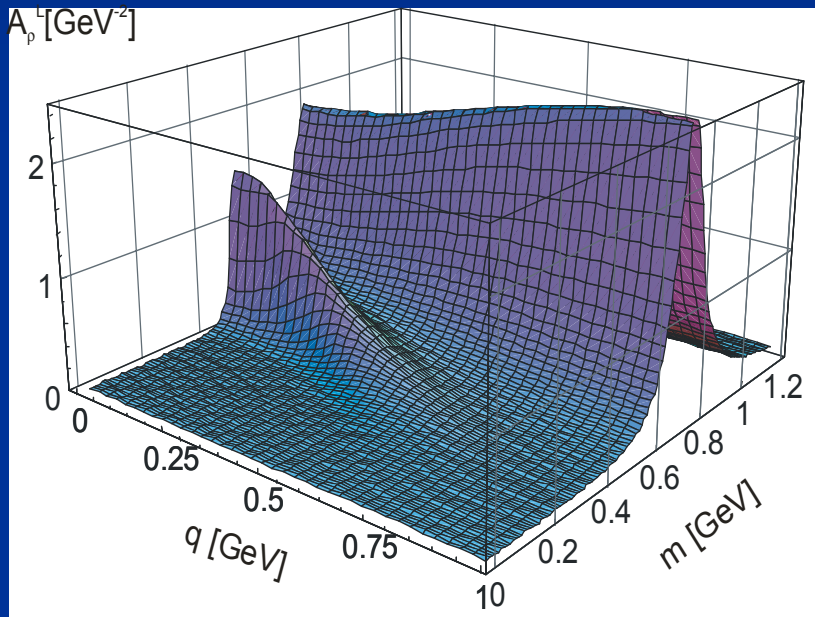
Leupold et al, Phys.Rev.C58:2939-2957,1998

Need hadronic model

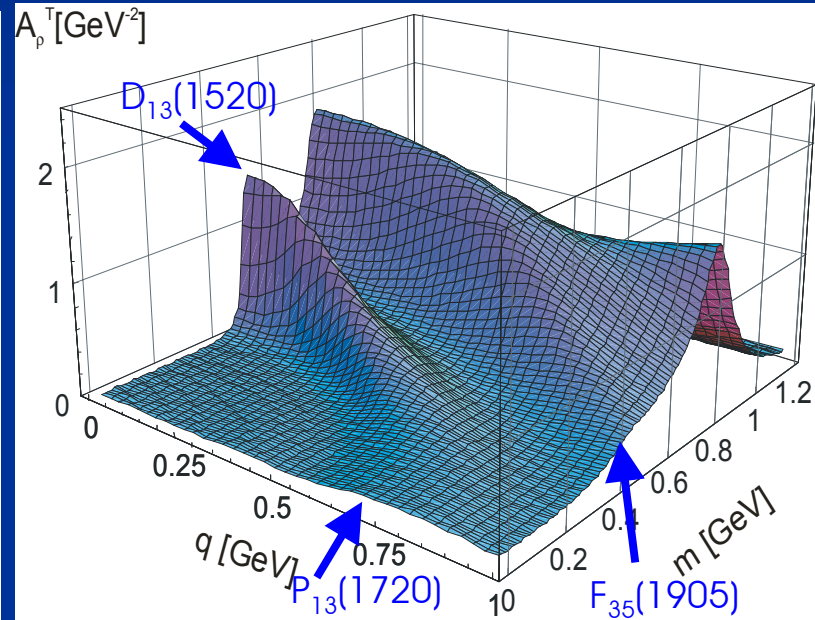


Rho meson in matter: Resonance-hole model

■ Longitudinal



■ Transverse



Post et al., 2004

$D_{13}(1520)$ and $\rho(2\pi)$ 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‘

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

with

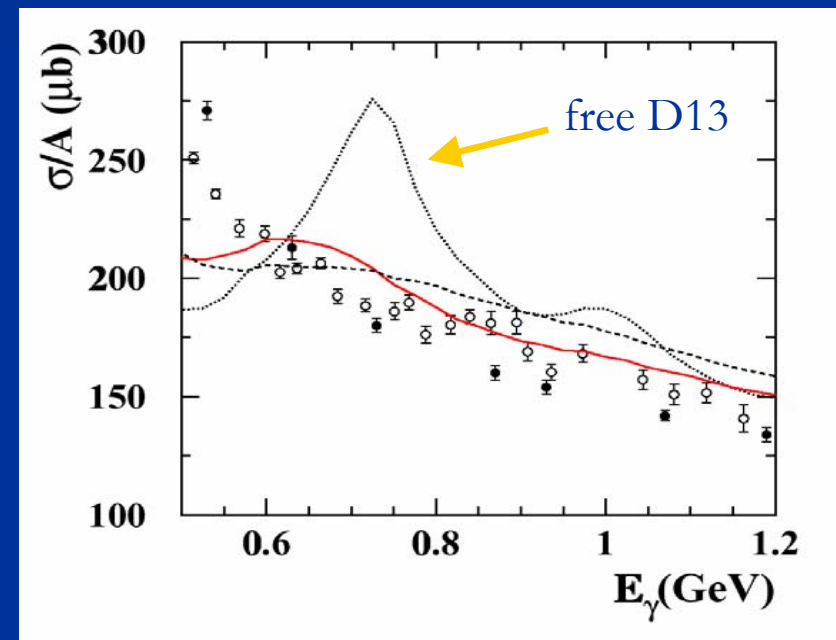
$$H = \sqrt{(\mu_{\text{vac}} + U_s + U_{\text{off}})^2 + \vec{p}^2}$$

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



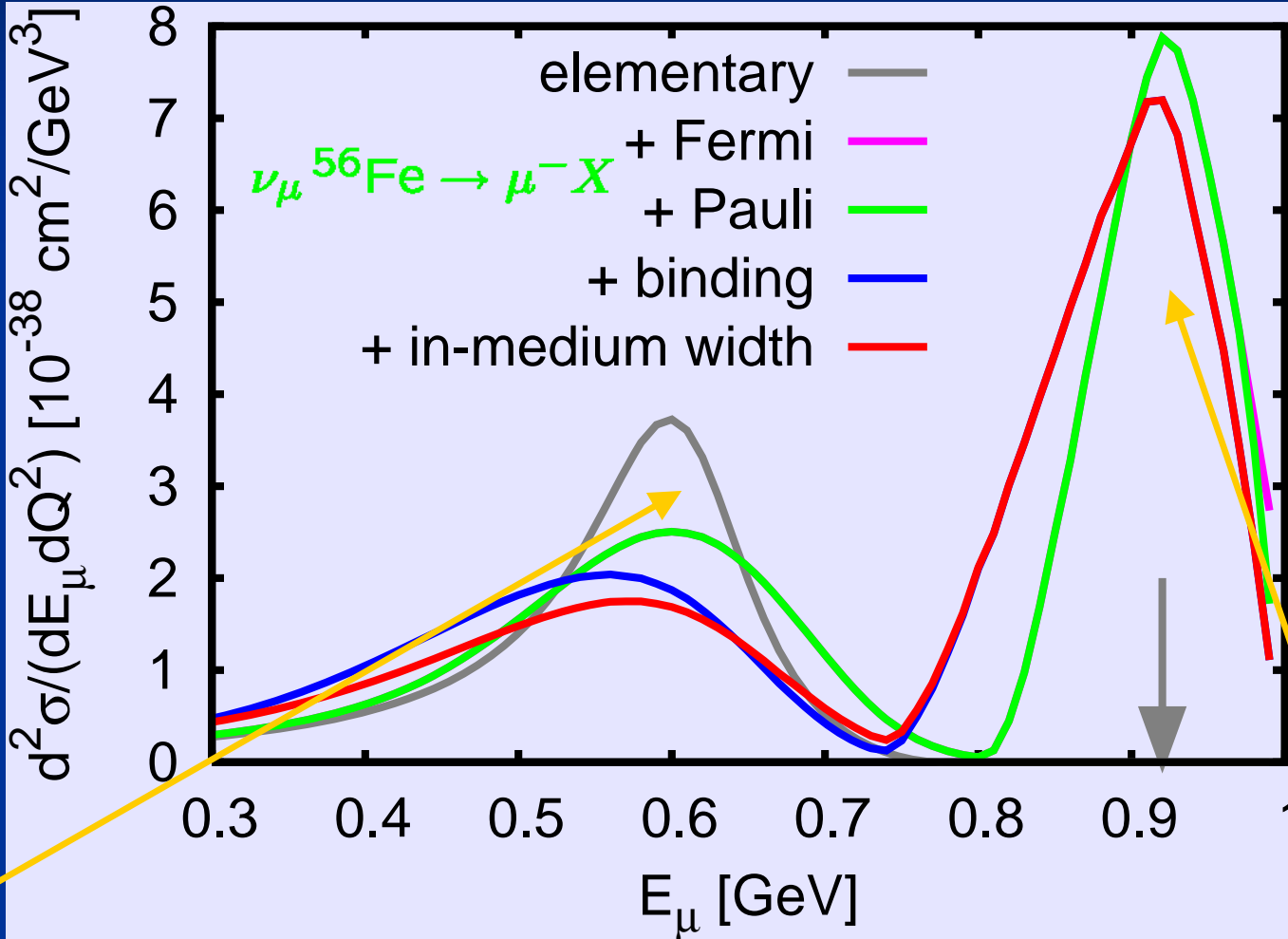
Consequences of in-medium change

- 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 \rightarrow opens phase-space for decay of D13
 - Dilepton spectra in URHICs



In-medium effects

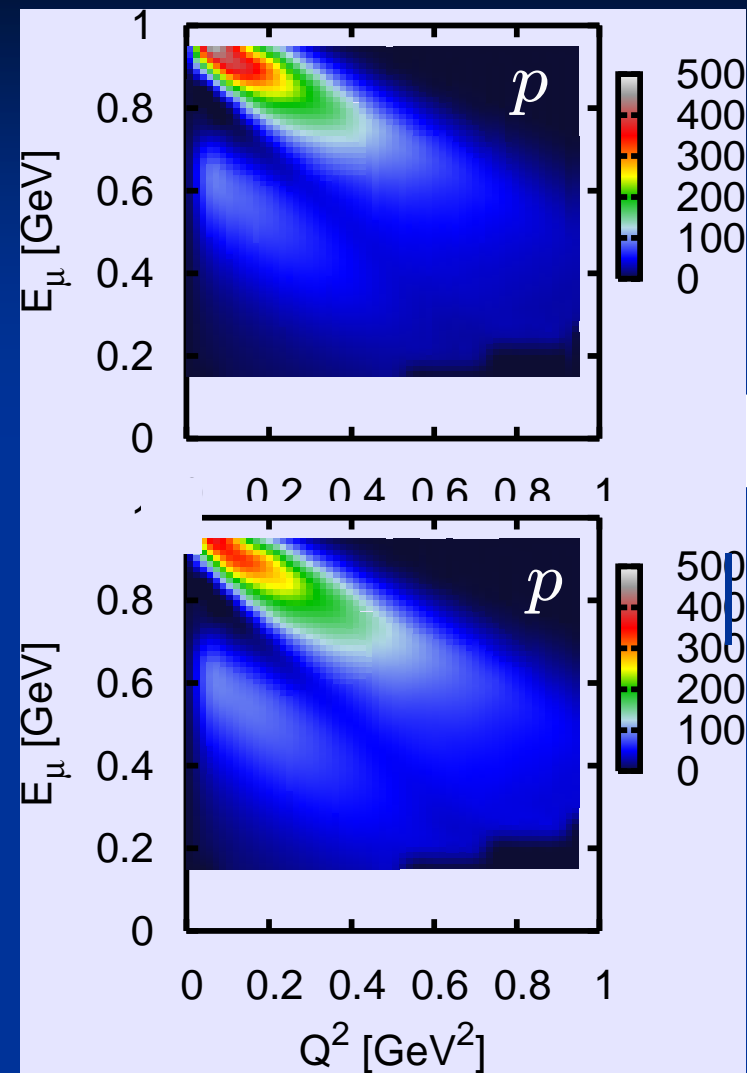
$$E_\nu = 1 \text{ GeV}, Q^2 = 0.15 \text{ GeV}^2$$



QE

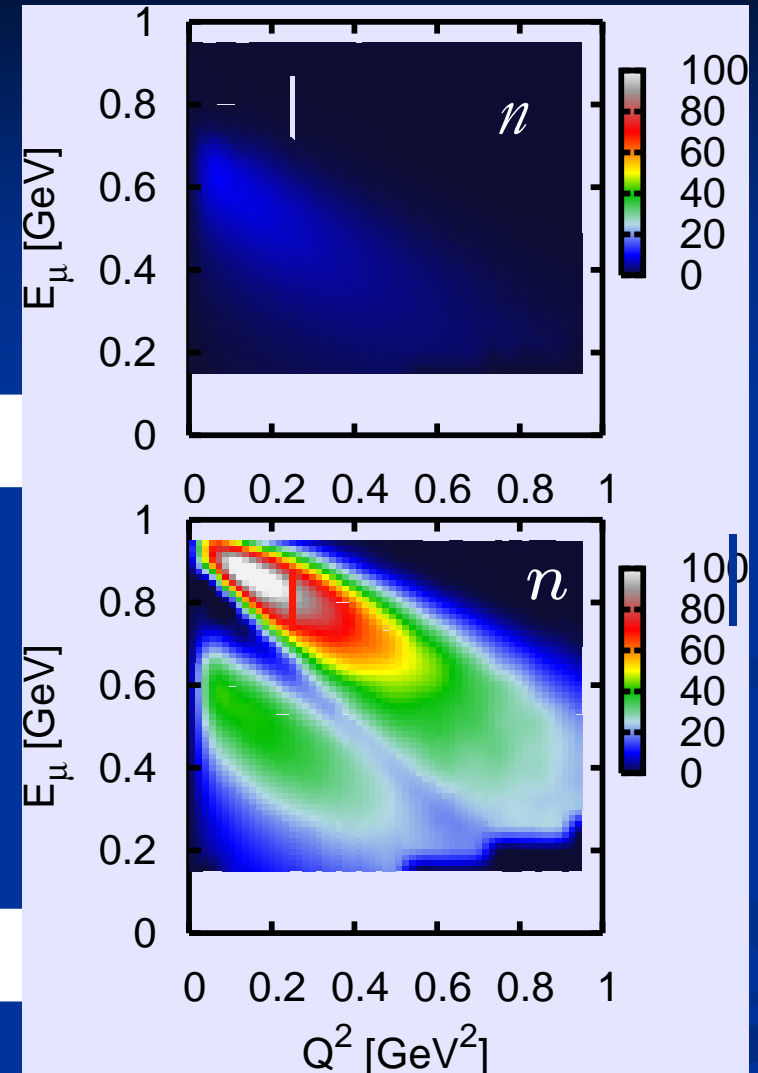


Nucleon Knockout at $E_\nu = 1 \text{ GeV}$ $\nu_\mu {}^{56}\text{Fe} \rightarrow \mu^- N X$



wo FSI

w FSI



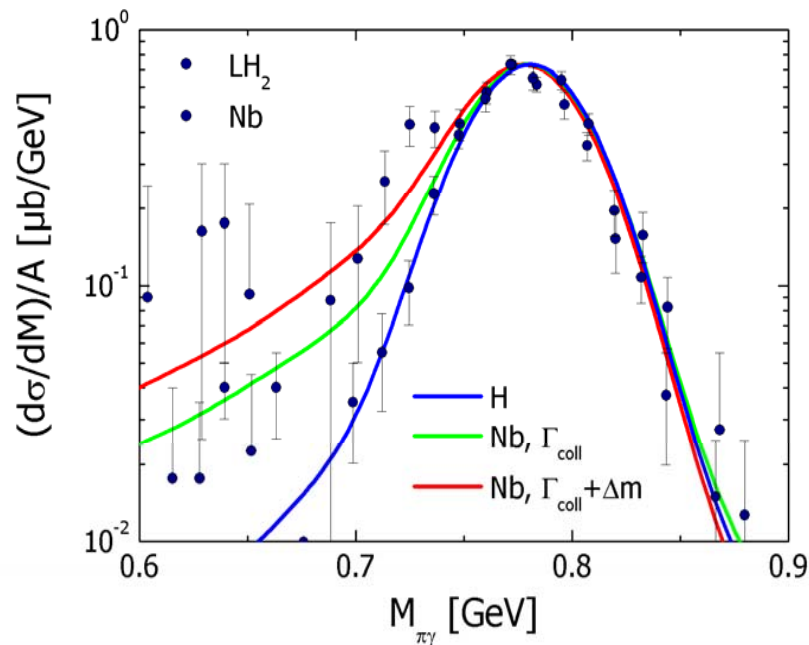
Absorption alone not sufficient, Need coupling between channels



ω in Medium

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

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



Theory: P. Muehlich et al

$\Delta m = -0.15 \rho / \rho_0$
put in by hand



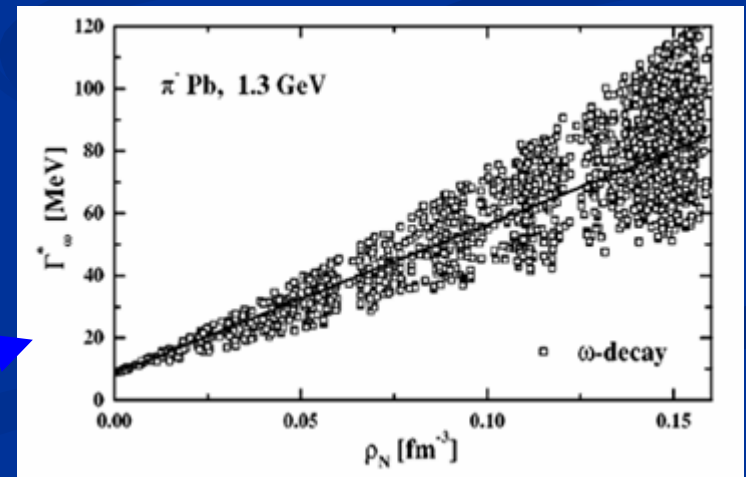
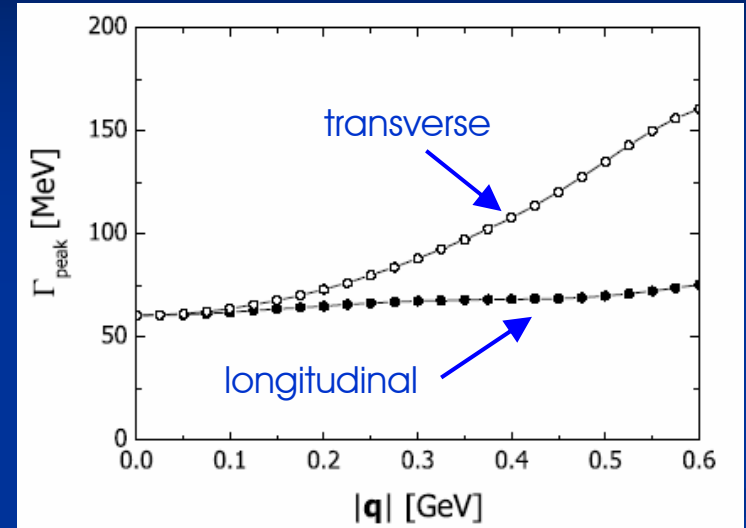
ω in Medium

Very little mass change from hadronic resonance-hole models
 Collisional broadening $\approx 60-70$ MeV

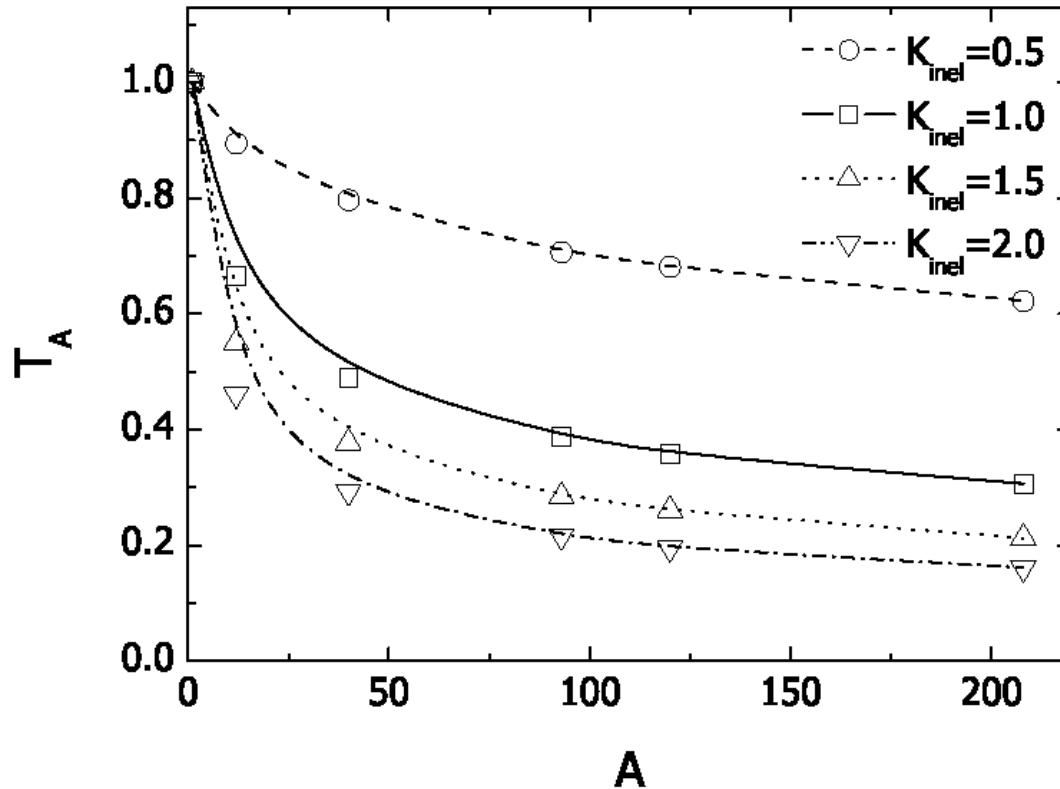
from $t\rho$ approx
 with K -matrix parameters

Inelastic width \rightarrow transparency

also from $\Gamma = \rho \sigma v$
 (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.
 $E_\gamma = 1.5 \text{ GeV}$

Crucial Input: inelastic ω -N cross section

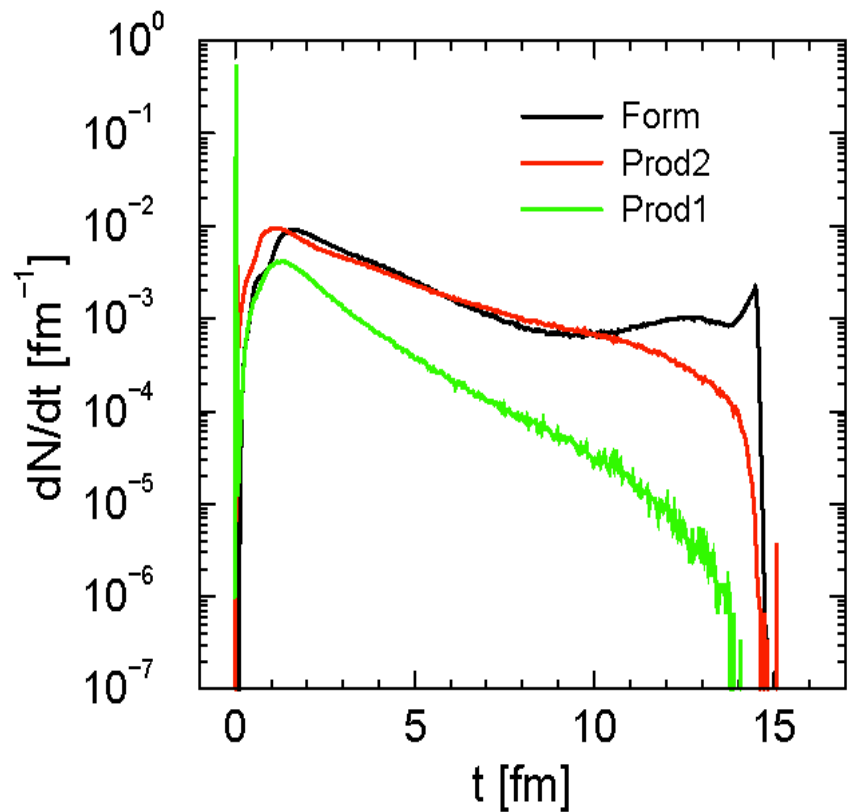
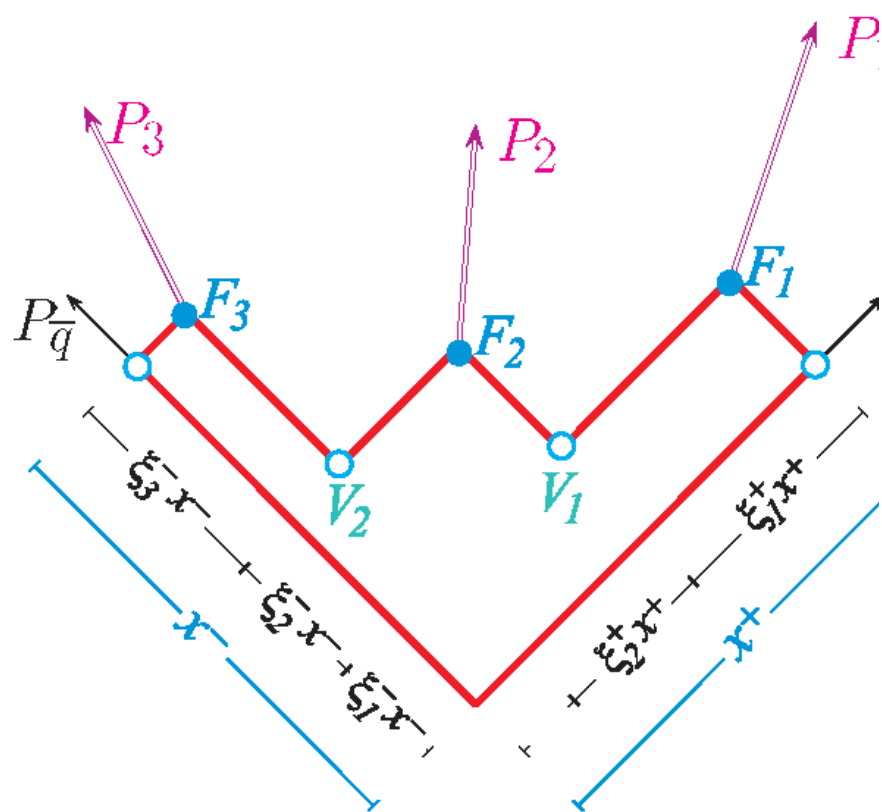


Formation times

- At low energies, resonance regime:
 $t_f = \text{lifetime of resonance} \rightarrow N + \text{hadron}$
- At high energies, QCD regime,
 t_f from string-fragmentation



Transparency at high energies determined by quark fragmentation

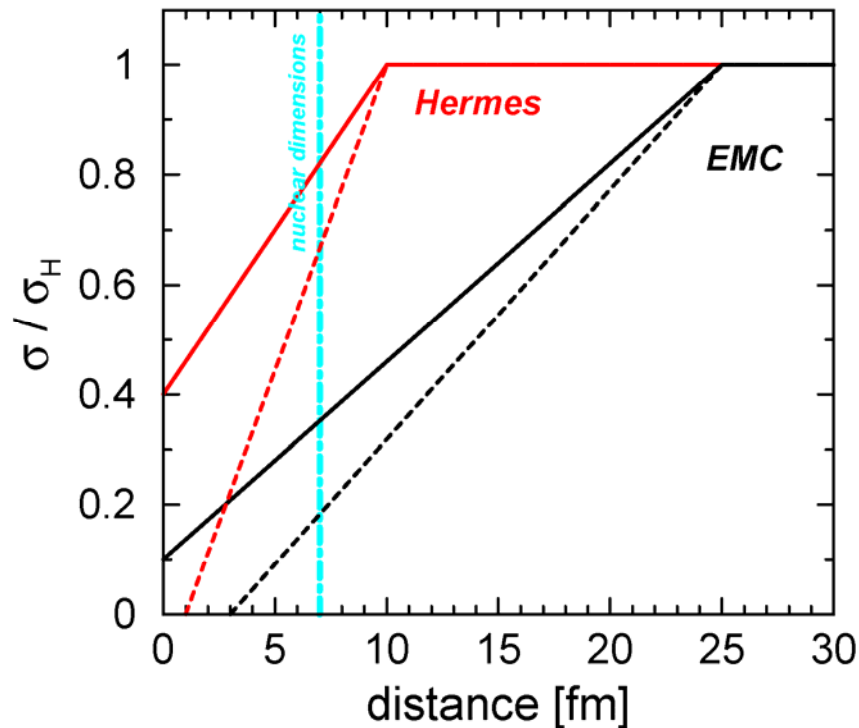


Hermes condition

$\nu = 14 \text{ GeV}, Q^2 = 2.5 \text{ GeV}^2$



Prehadron cross sections

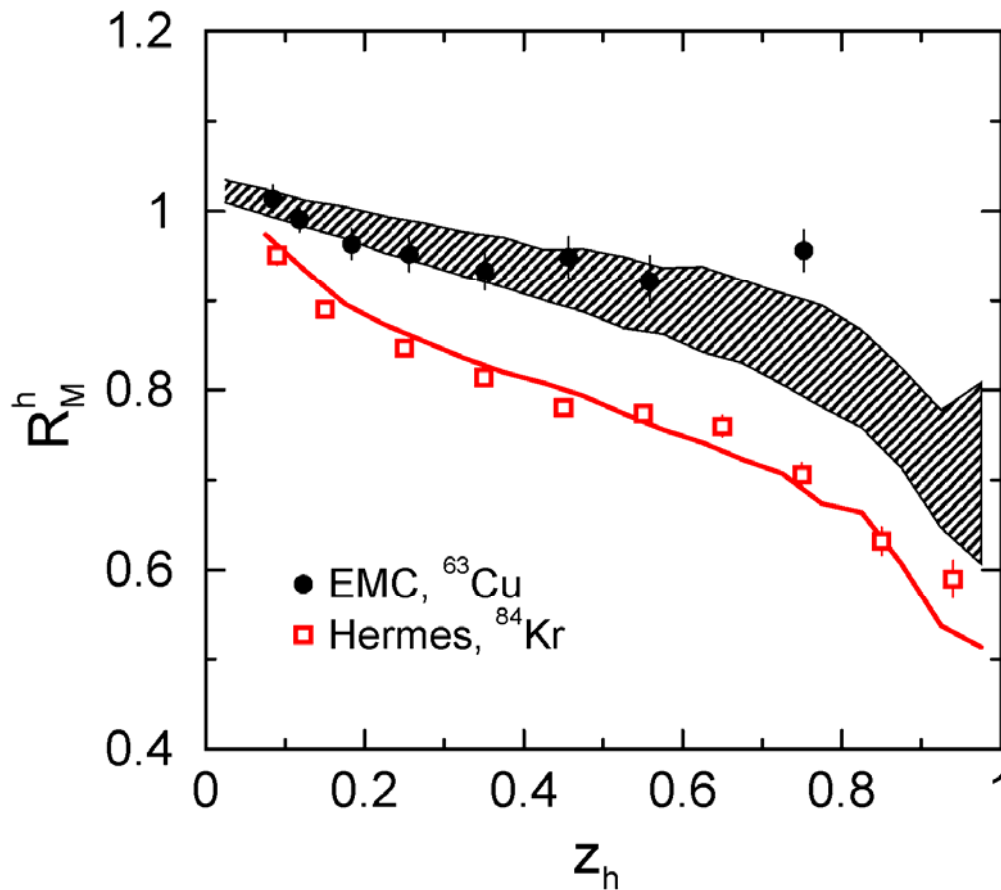


$$\frac{\sigma}{\sigma_H} = \# \frac{n_q}{Q^2} \left(1 - \frac{t - t_p}{t_f - t_p} \right) + \frac{t - t_p}{t_f - t_p}$$

After: Farrar, Liu,
Frankfurt,
Strikman

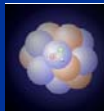


EMC and Hermes Transparency

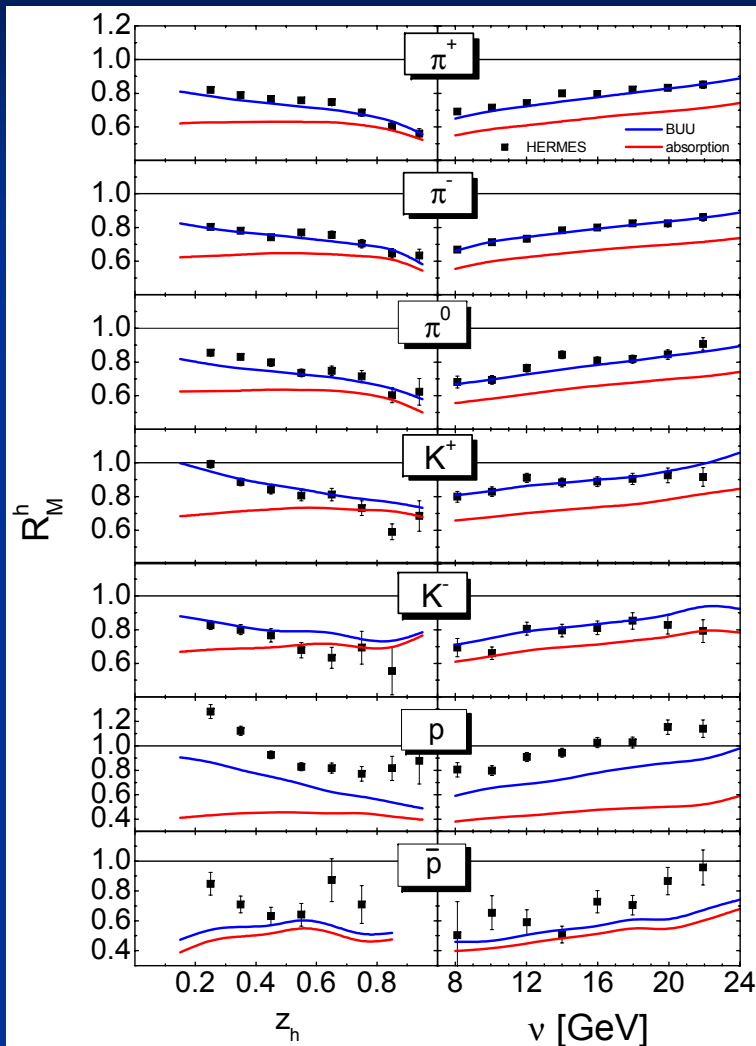


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After: Farrar, Liu,
Frankfurt, Strikman



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

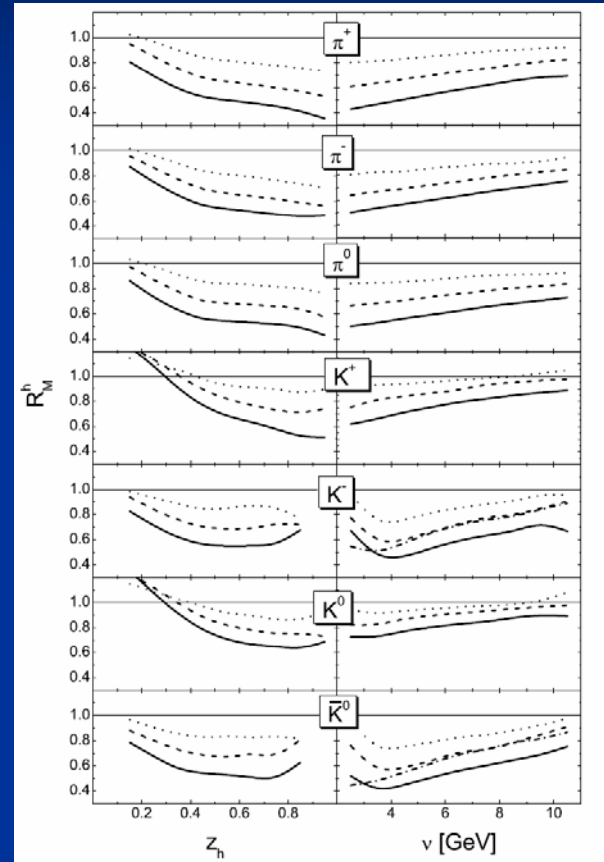
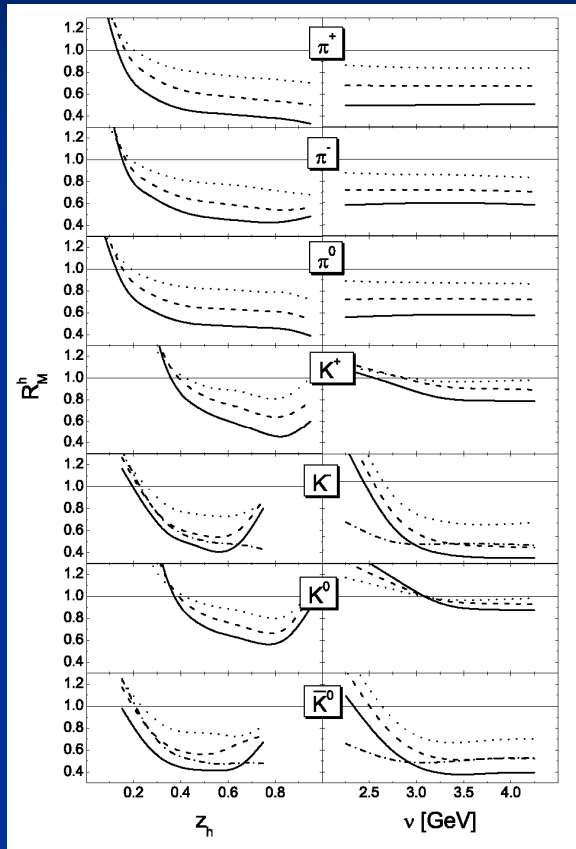


JLAB

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



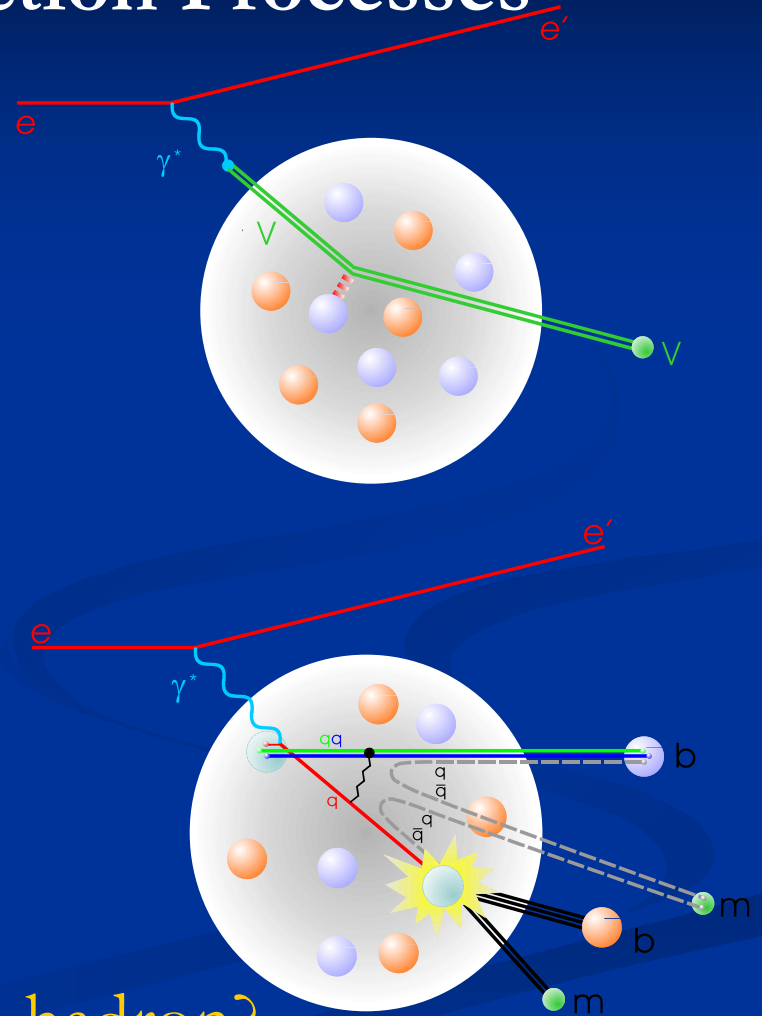
Nucleus as Microdetector

High Energy γ Production Processes

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

- Deep inelastic scattering, Jets

How long does it take to form a hadron?



Introduction

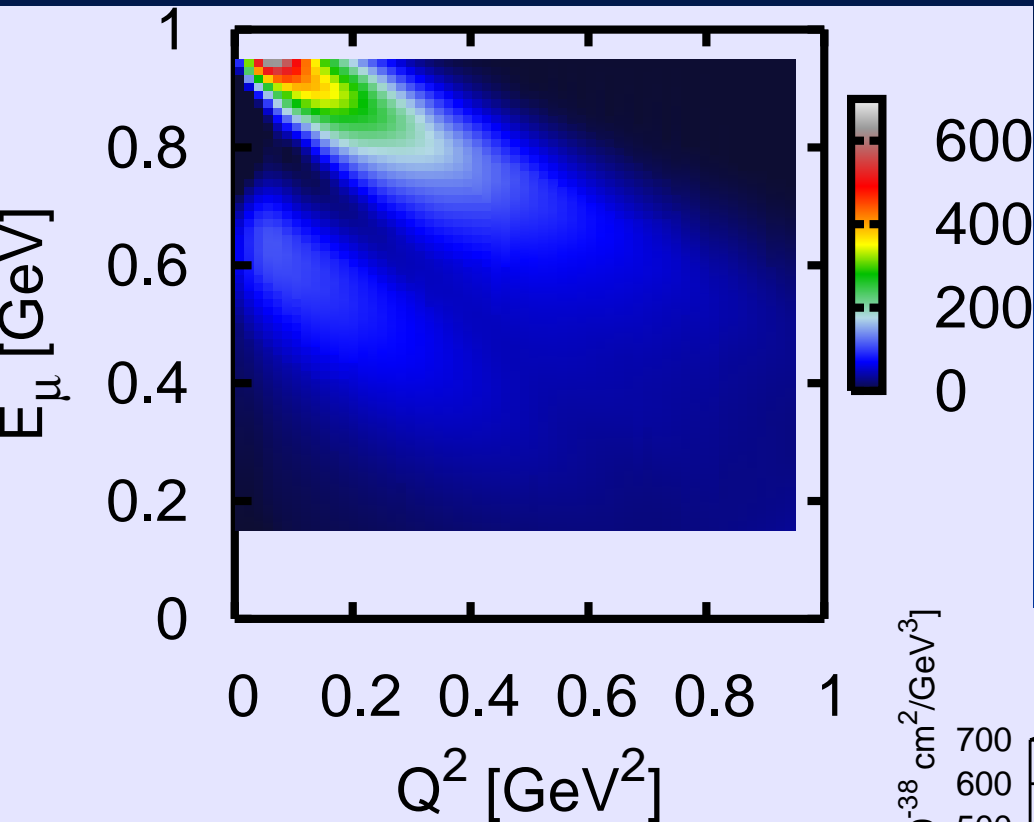
Neutrino nucleus interactions are relevant for:

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



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

$E_\nu = 1 \text{ GeV}$

