# In-medium Hadrons
## Properties and Interactions

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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

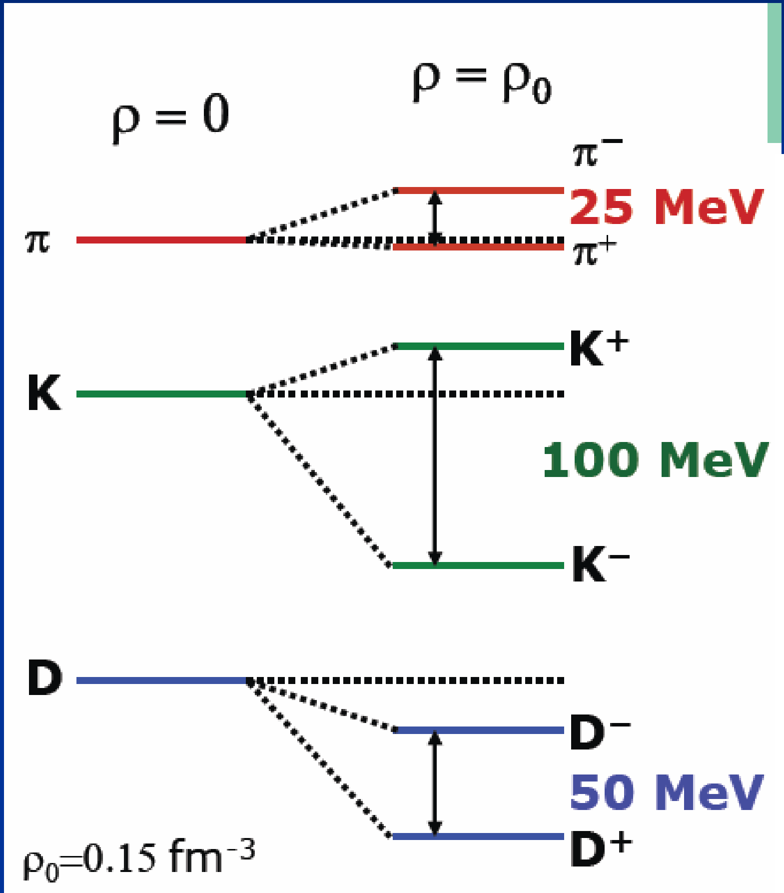
- Mesons in medium can give infos on meson-nucleon interactions through selfenergies

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

# Many possible 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
- pbar + A (PANDA)
- Same Physics in very different scenarios! Common to all of them: Need to understand connection between in-medium property and final observable!

# In-medium Masses,
# from light to heavy quarks



$\pi^\pm$
deeply bound pionic states
(N/Z ≈ 1.5)

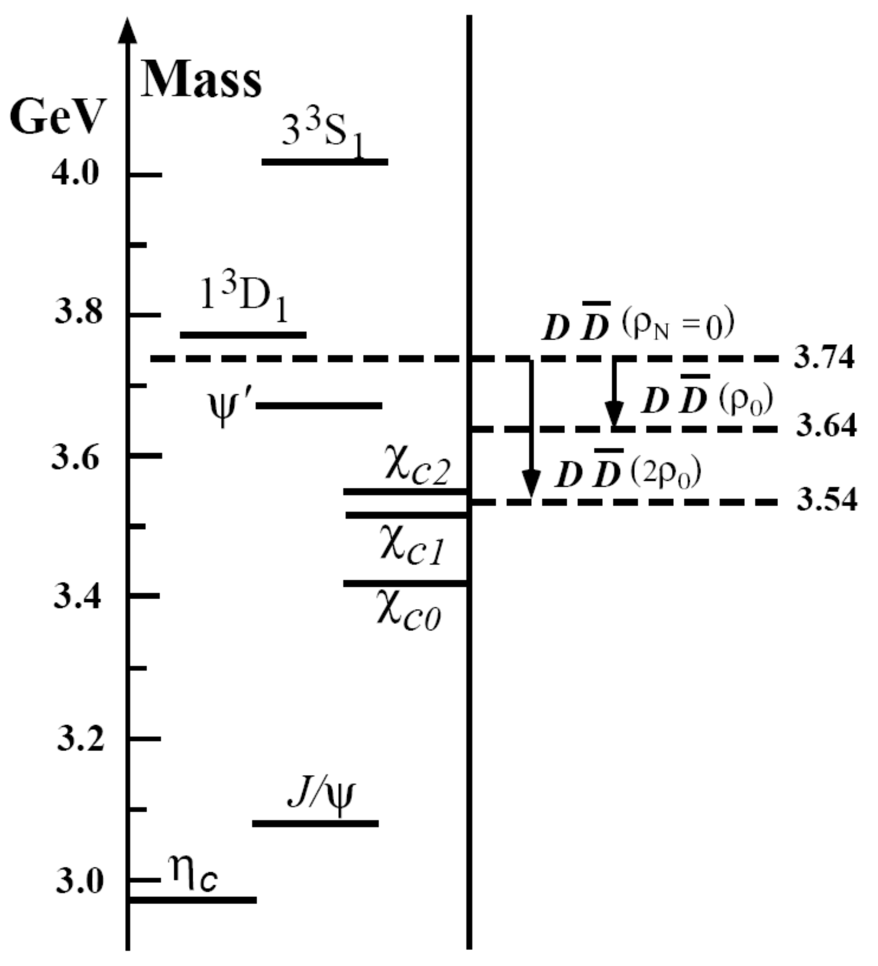
$K^+$
momentum shift in p+A
$K^-$
discussed controversially

?

$D^\pm$
unknown so far

Olaf Hartmann, Meson2006

# In medium open charm mesons: observable consequences?



Hayashigaki, 1998:

Lowering of D, Dbar, from QCDSR

Is it still true?

# 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: light quarks

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

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

Rhs dominated by quark condensates:

$$\langle\bar{q}q\rangle \quad \text{and} \quad \langle(\bar{q}q)^2\rangle$$

# QCD Sum Rule

- In vacuum: know lhs (=(Π)), get condensates on rhs

- In medium: model density dependence of condensates $\langle \bar{q}q \rangle \sim \rho$ $\langle (\bar{q}q)^2 \rangle = \kappa \langle \bar{q}q \rangle^2$
→ get lhs (integral over =(Π))

# QCD Sum Rule: heavy quarks

Assume small width:

$$m_Q \langle \bar{Q}Q \rangle = -\frac{1}{12}\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle - \frac{\langle g_s^3 G^3 \rangle}{1440\pi^2 m_Q^2} - \frac{1}{30 m_Q^2}\left\langle \frac{\alpha_s}{\pi}(D^\mu G^a_{\alpha\mu})(D_\nu G_a^{\alpha\nu}) \right\rangle + \dots$$

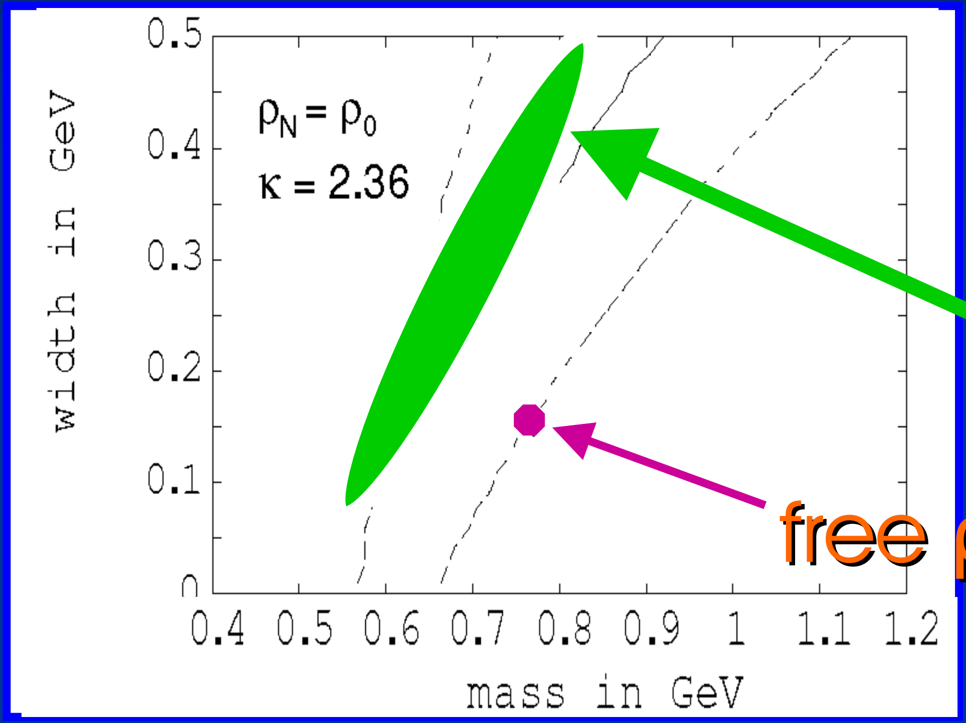
Rhs dominated by glue condensates:

$$\langle GG \rangle \quad \text{and} \quad \langle DG\,DG \rangle$$

Glue condensates rather insensitve to nuclear density

→ Small in-medium changes for heavy-quark mesons expected

# $\varrho$ spectral function in medium



QCDSR-allowed ($\Gamma$,m) at saturation density

free $\rho$ meson

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

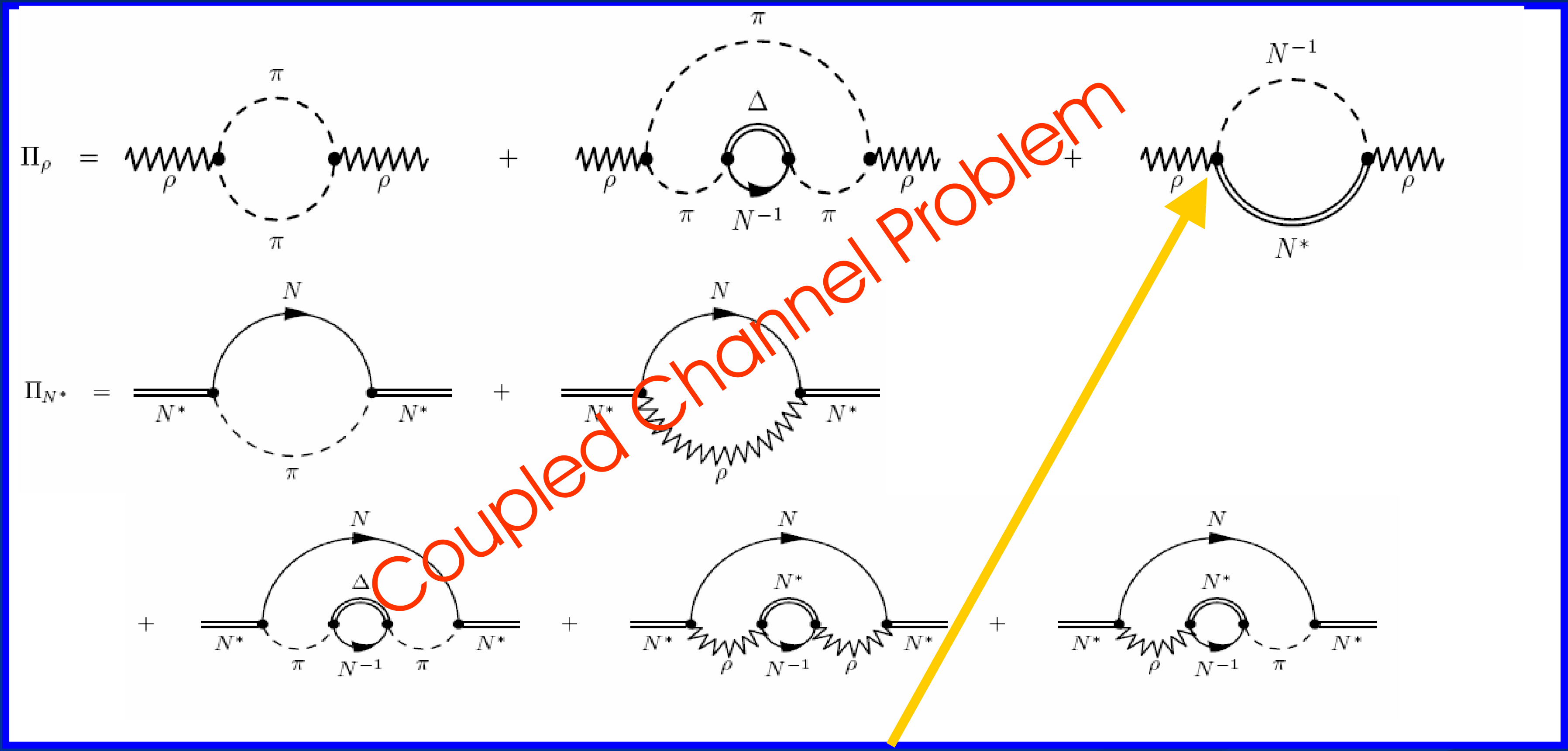
QCD Sum Rules provide constraints, but do not fix in-medium hadron props

**Need hadronic model**

# Observables: Theoretical Method

1. Calculate hadronic properties in equilibrium nuclear matter
2. Use local density approximation to embed hadrons in finite nuclei
3. Propagate produced particles out from production to detector, including all FSI and CC effects.

# ϱ and N* selfenergy in medium



Coupled Channel Problem

Resonance-hole model

Crucial $N^*$ →N ρ coupling

# Selfenergy in Medium

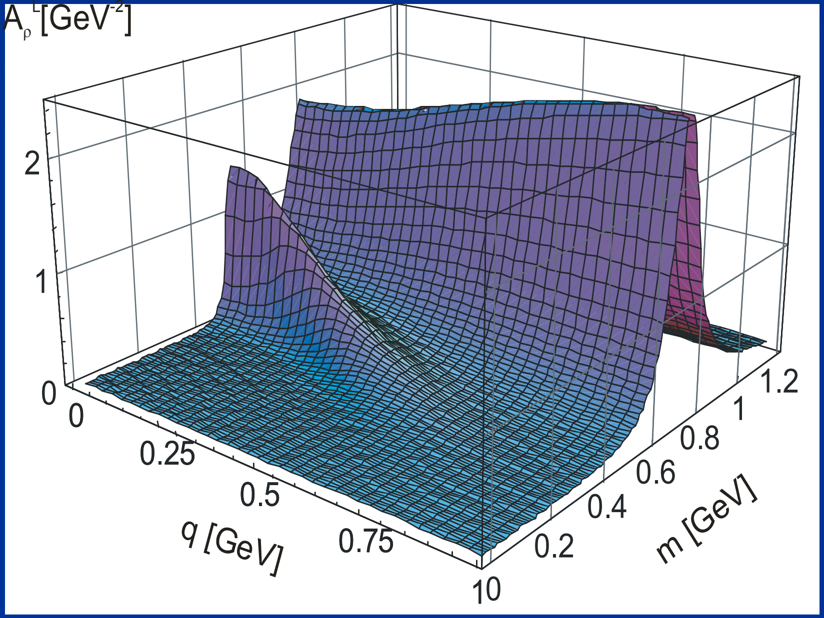
$$D(\omega,\vec{q}) = \frac{1}{q^2 - m^2 - \Pi_{\mathrm{vac}} - \Pi_{\mathrm{med}}}$$

With density- and momentum-dependent Π:

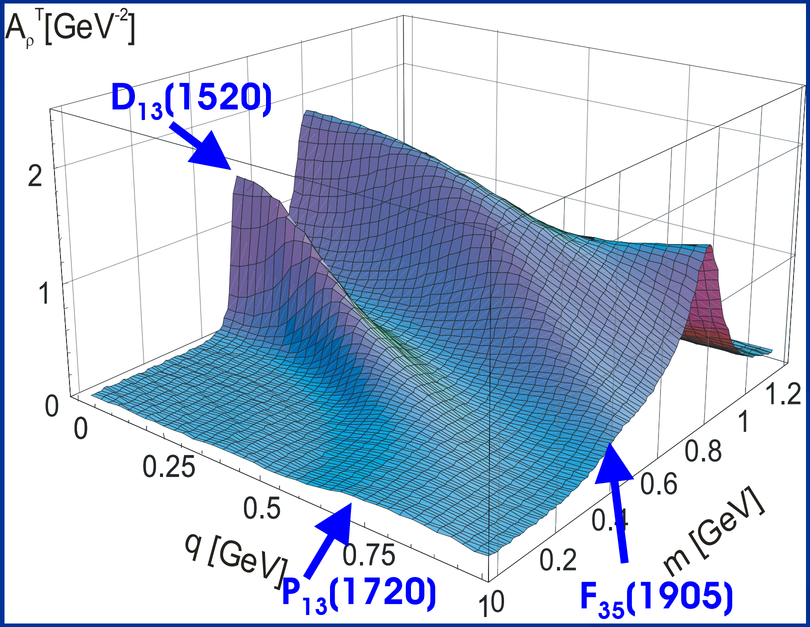
$$\Pi = \Pi(\rho, \vec{p})$$

# Rho meson in matter: Resonance-hole model

- Longitudinal



- Transverse

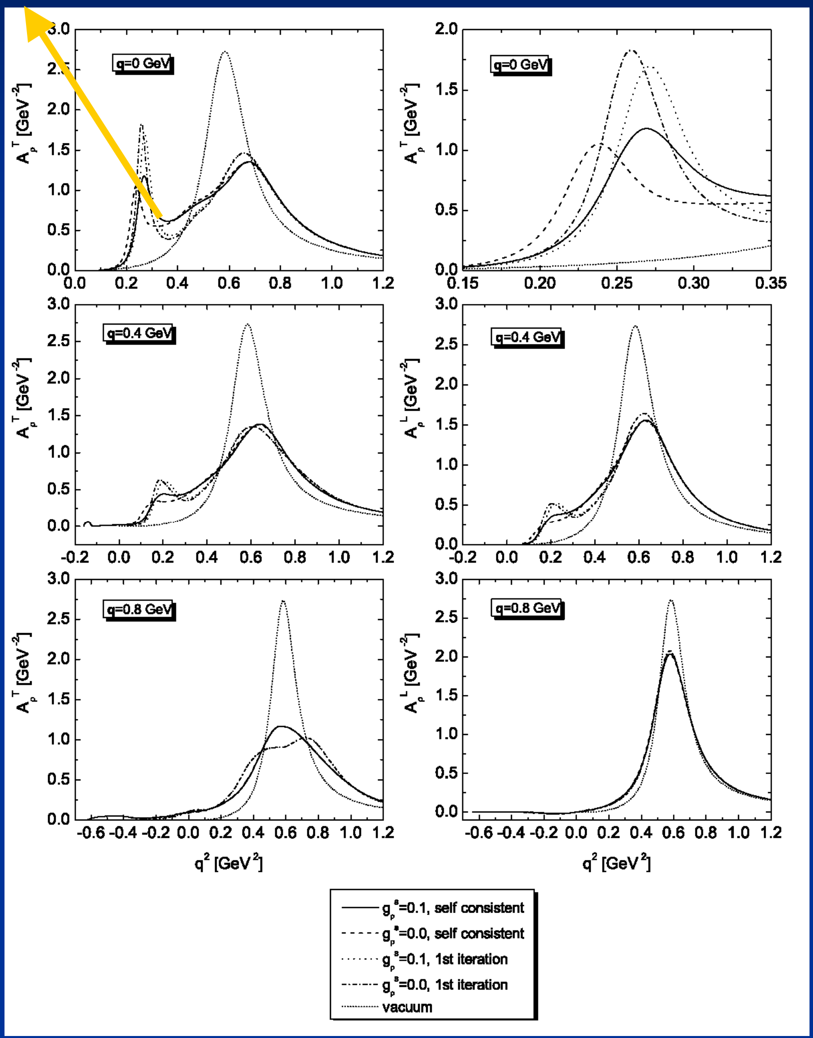


Post et al., 2004

$D_{13}(1520)$ and $\rho$ $(2\pi)$ strongly mixed

# ρ Spectral Function: Momentum Dependence

Resonance-hole component



ρ spectral function strongly Momentum dependent!

In-medium changes largest at small p where also lifetime in nucleus is largest

# Observables: Theoretical Method

1. Calculate hadronic properties in equilibrium nuclear matter
2. Use local density approximation to embed hadrons in finite nuclei
3. Propagate produced particles out from production to detector, including all FSI and CC effects.

# Local Density Approximation

- Selfenergy in LDA

$$\Pi = \Pi(\rho(x,t),\vec{p})$$

- Problem:
  Effects of Density Gradients missing, time delay for reaction to medium?

# Observables: Theoretical Method

1. Calculate hadronic properties in equilibrium nuclear matter
2. Use local density approximation to embed hadrons in finite nuclei
3. Propagate produced particles out from production to detector, including all FSI and CC effects.

# Theoretical Method for FSI (and ISI):

## **GiBUU** CC Transport Model

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

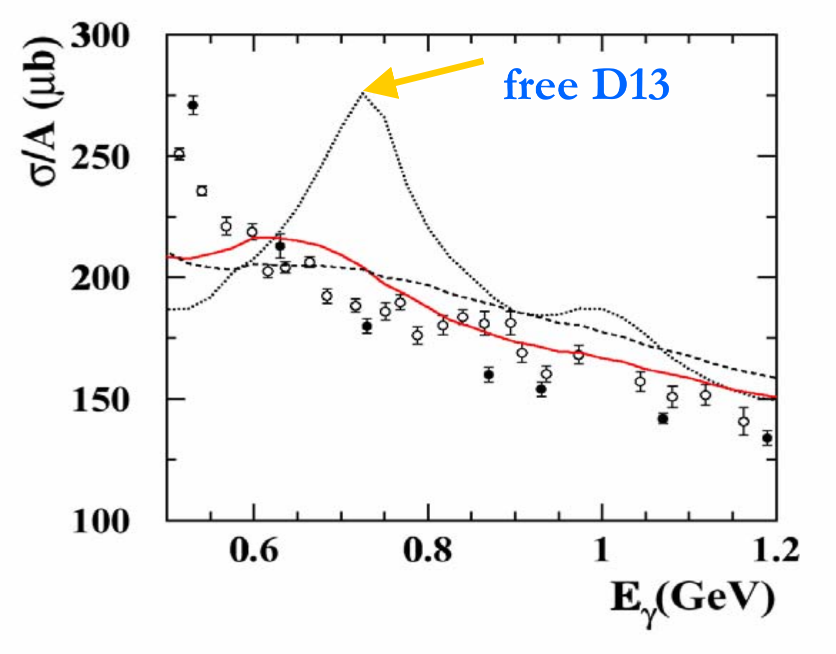
$$\left(\frac{\partial}{\partial t} + \left(\vec{\nabla}_{\vec{p}} H\right) \cdot \vec{\nabla}_{\vec{r}} - \left(\vec{\nabla}_{\vec{r}} H\right) \cdot \vec{\nabla}_{\vec{p}}\right) f_i\left(\vec{r}, \vec{p}, \mu, t\right) = I_{\text{coll}}[f_1, \ldots, f_n]$$

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

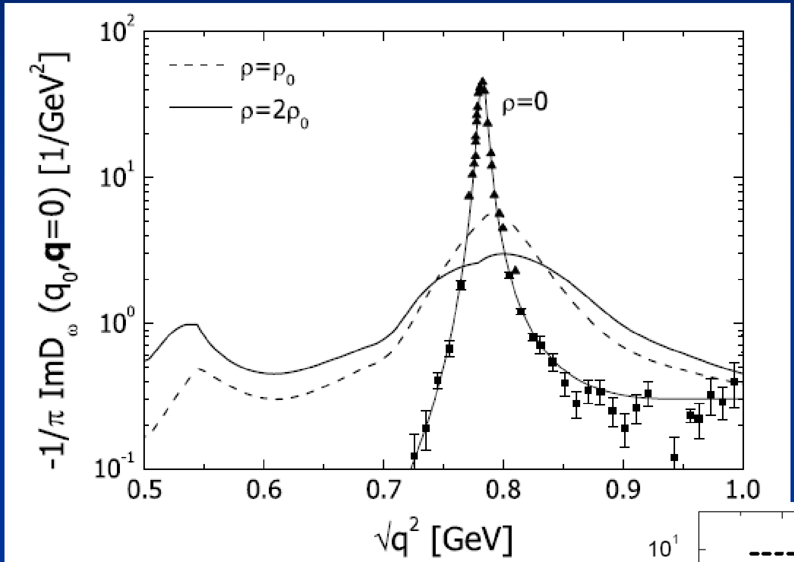
1. In-medium changes can be modelled in *H* (selfenergies) and in $I_{\text{coll}}$ (reaction rates, form. times, prehadron cross sections)
2. Experimental acceptance can be simulated event by event

# Consequences of in-medium change: ρ

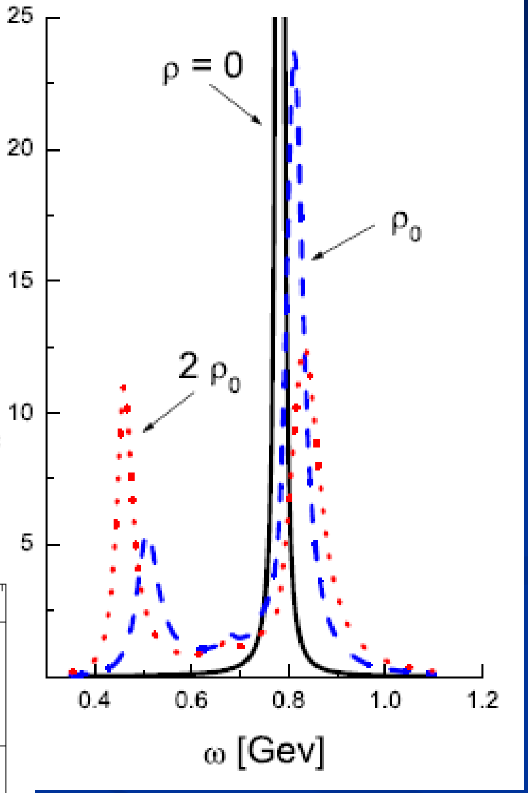
- Broad ρ spectral function explains:
  - Absence of nucleon resonances in total photoabsorption cross sections on nuclei
  - D13(1520) couples to ρ,
    ρ broad with strength at low
    masses → opens phase-space
    for decay of D13
  - Dilepton spectra in URHICs: CERES, NA60



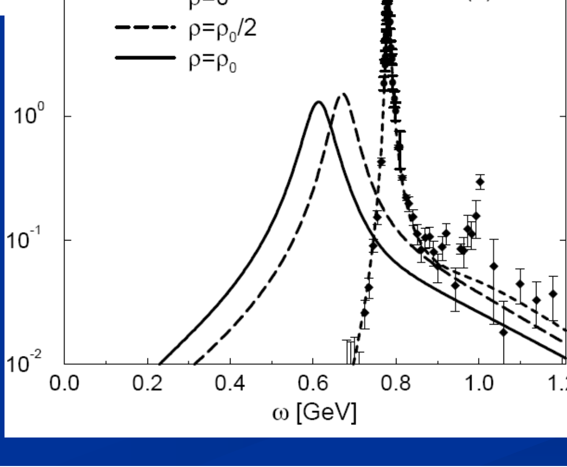
# ω in Medium: Theory



Muehlich et al



Lutz et al

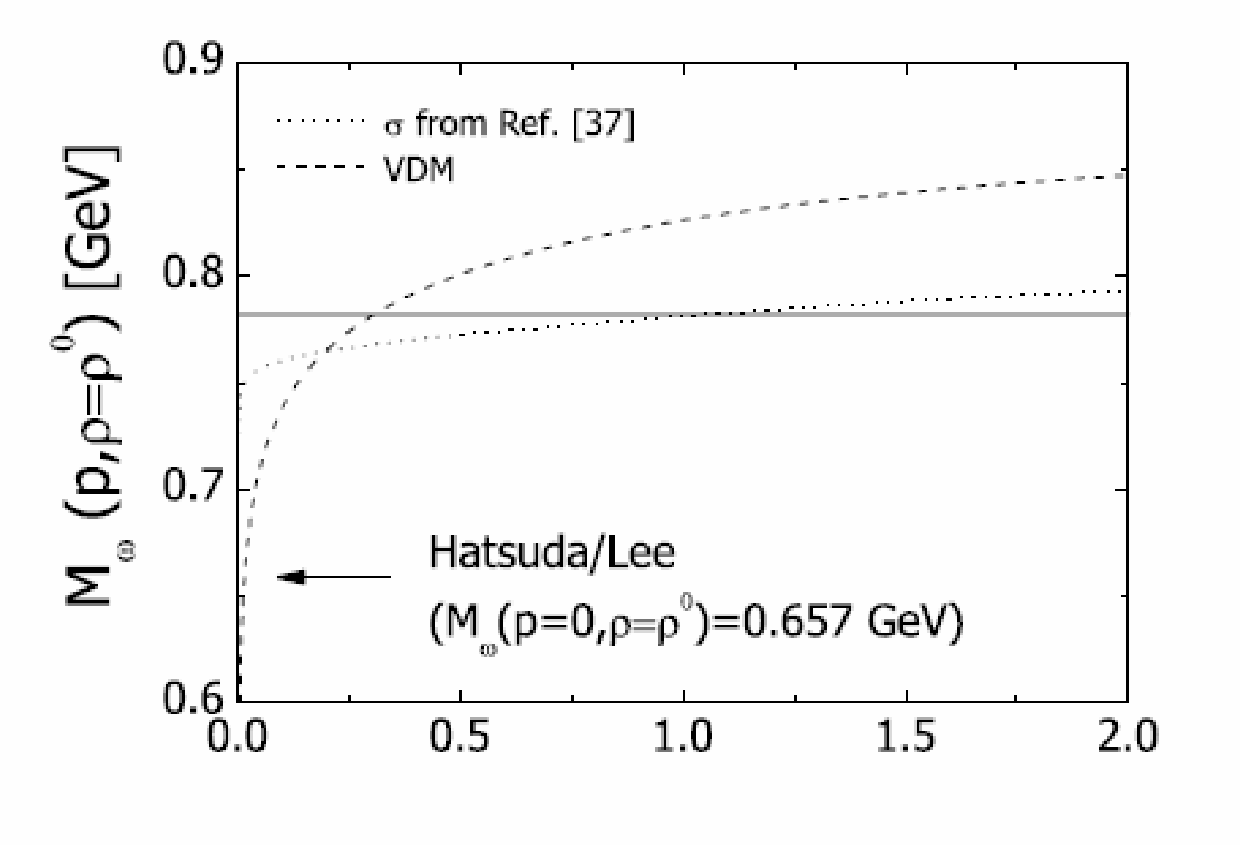


Klingl, Weise

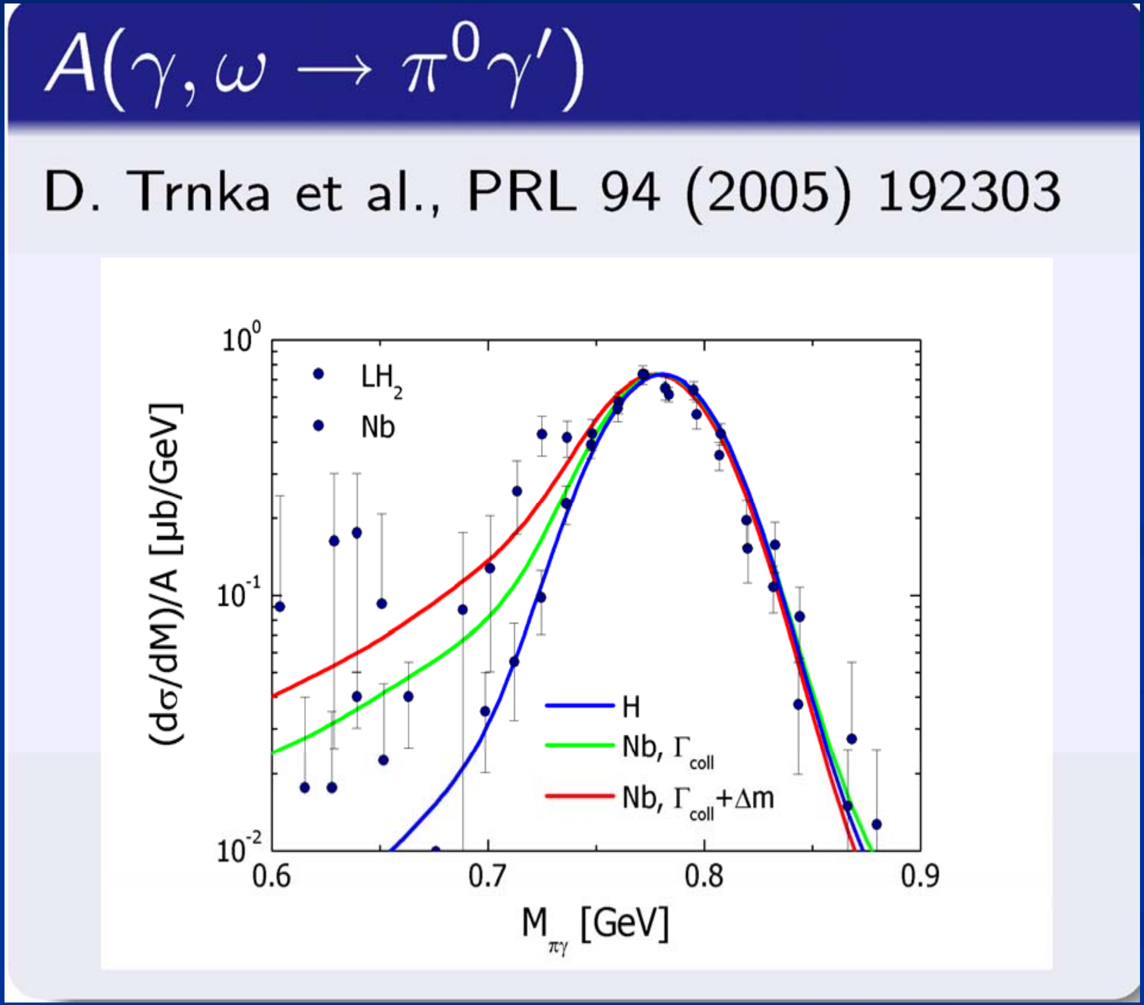
All at **zero** momentum

# ω selfenergy: p-dependence

From dispersion relation:



# ω in Medium: Experiment



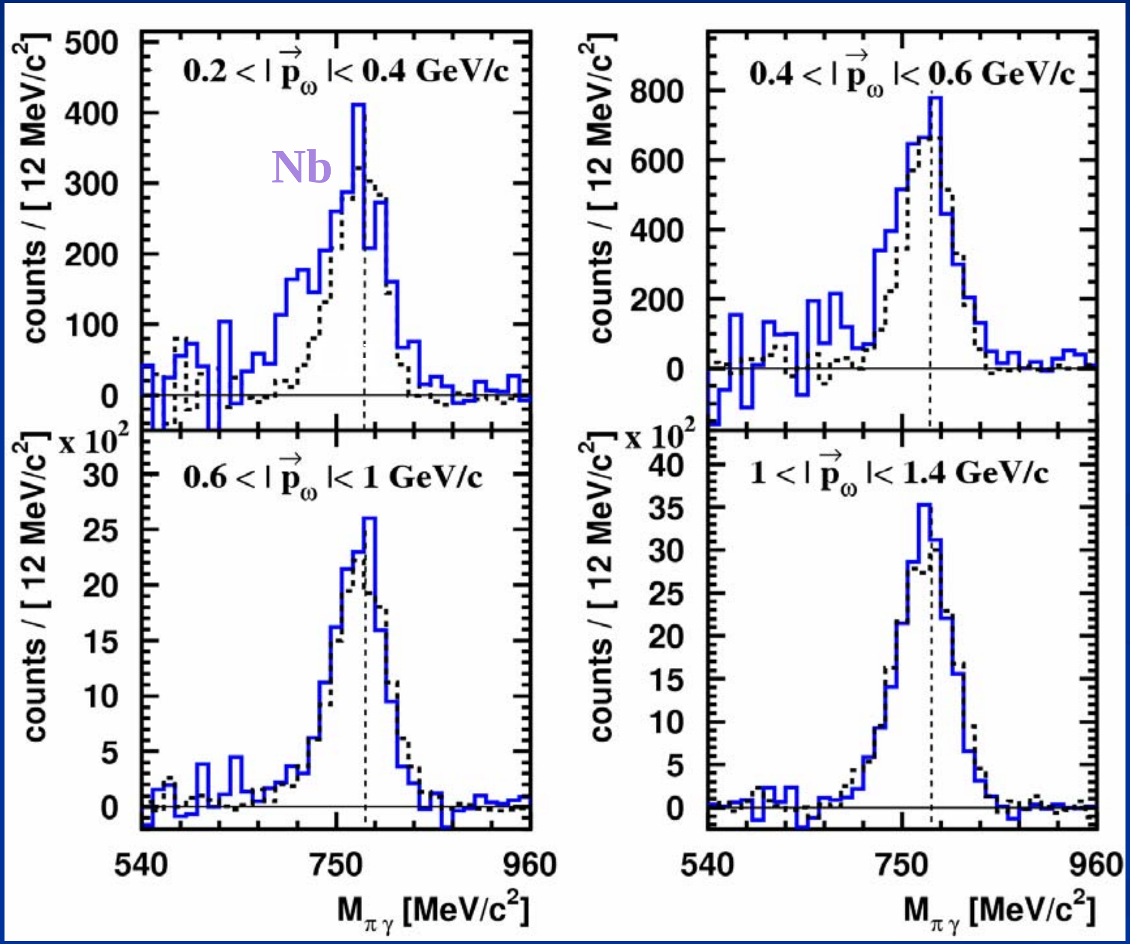
$A(\gamma, \omega \to \pi^0 \gamma')$

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

Theory: P. Muehlich et al

$\Delta$ m = -0.15 $\rho/\rho_0$
put in by hand, theory tends to shift ω up

# Omega in medium: Experiment



Momentum dependence seen, BUT:
Hard to distinguish between momentum dependence of selfenergy and volume effects

Trnka et al, TAPS

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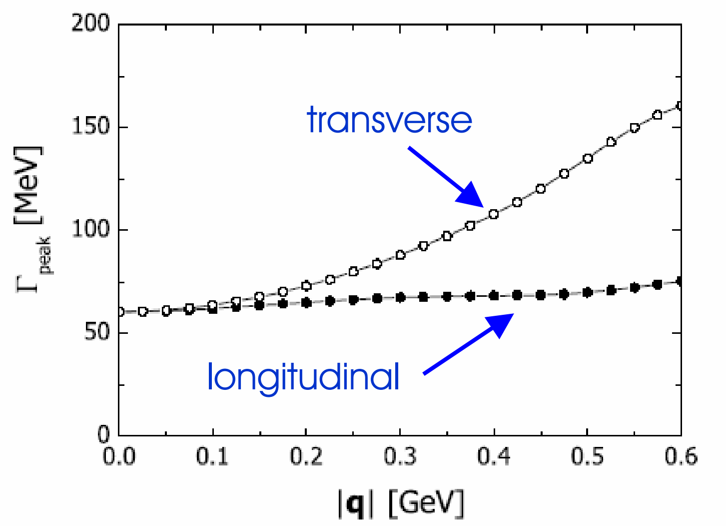
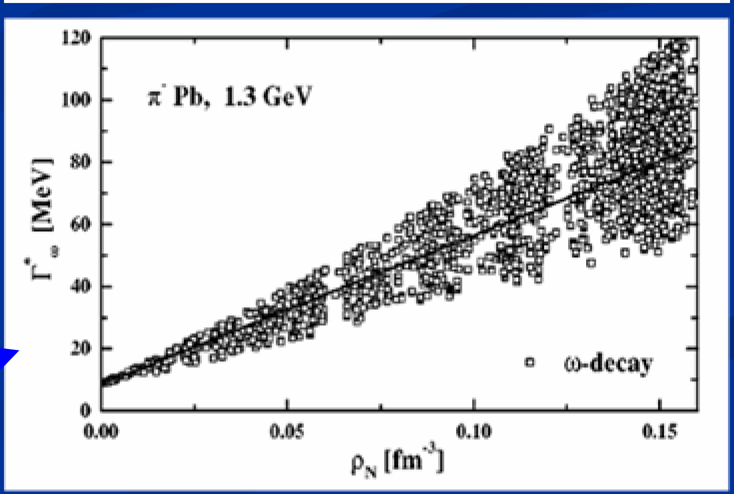
# ω in Medium: Theory

Collisional broadening ~ 60-70 MeV from *tρ*-approx with *K*-matrix parameters

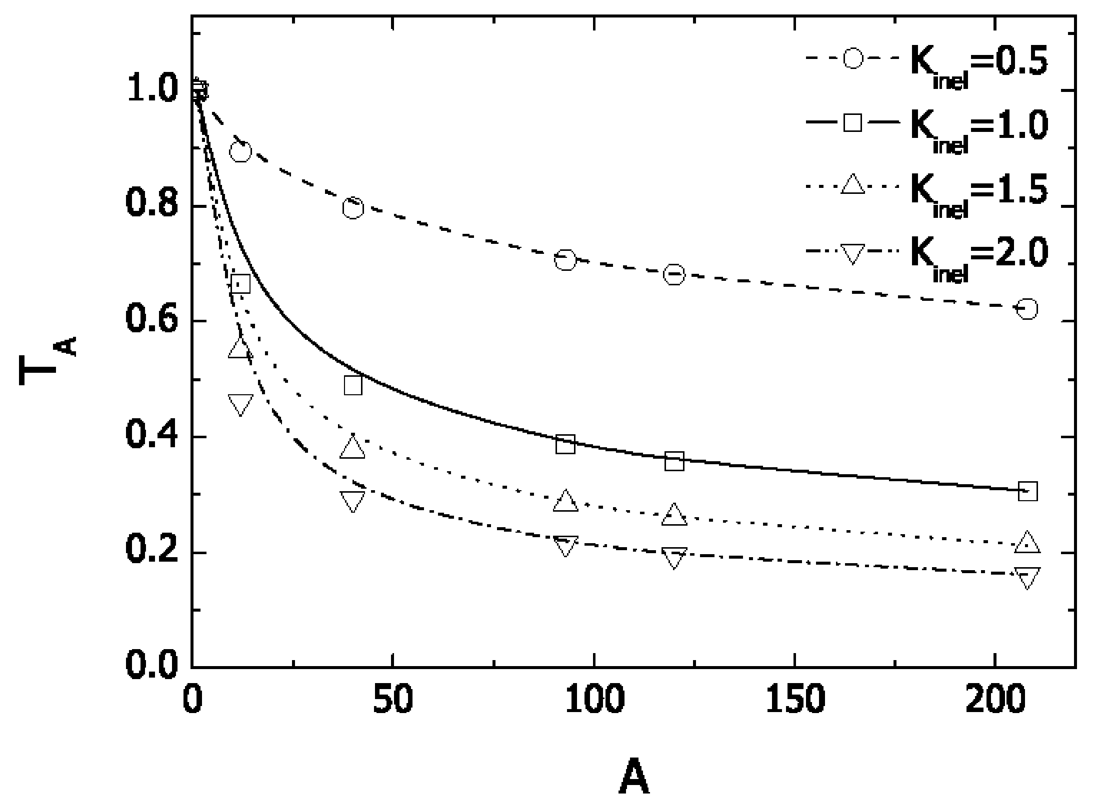


Inelastic width → transparency



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.
$E_\gamma = 1.5$ GeV

Crucial Input: inelastic omega-N cross section

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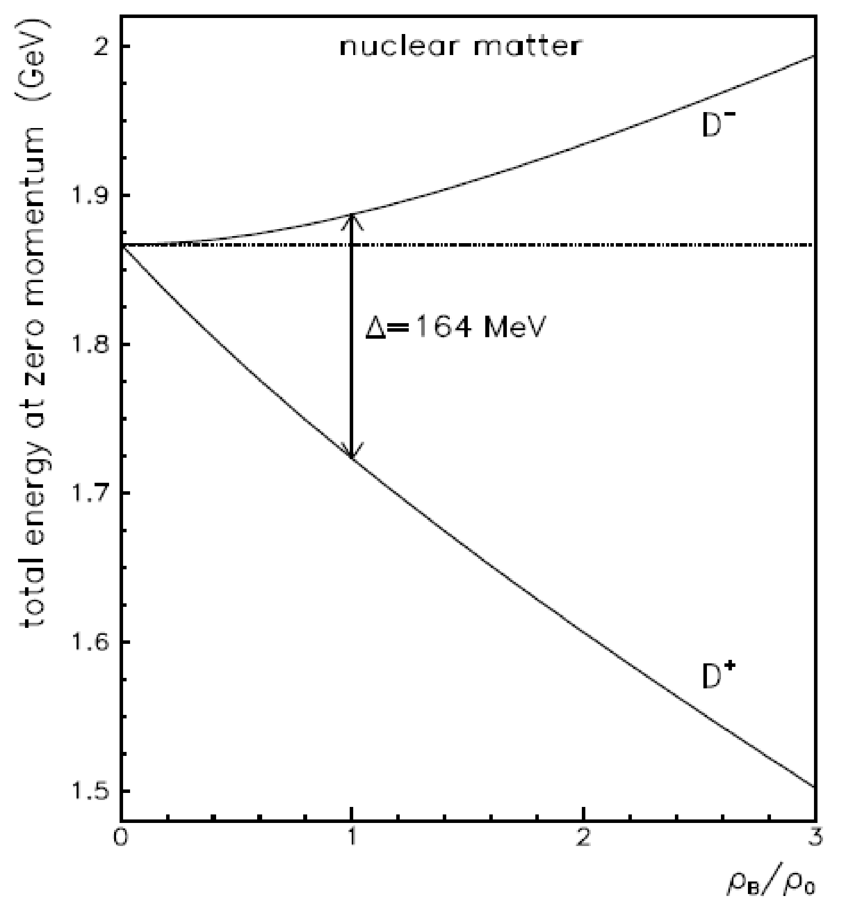
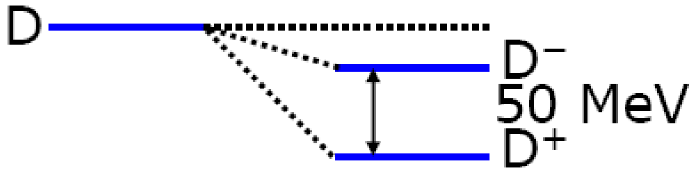
# In medium open charm mesons



Sibirtsev et al., 1999

# In medium open charm mesons

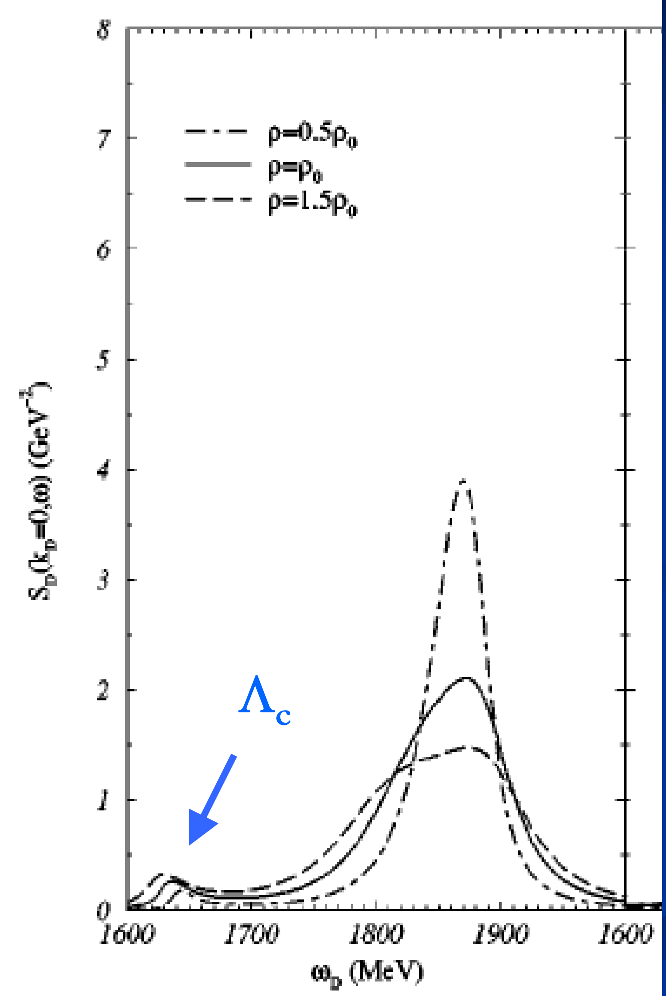


attractive mass shift
for $D^+$ and $D^-$

*Hayashigaki, PLB 487(2000)96*
*Morath, Lee, Weise, priv. comm.*

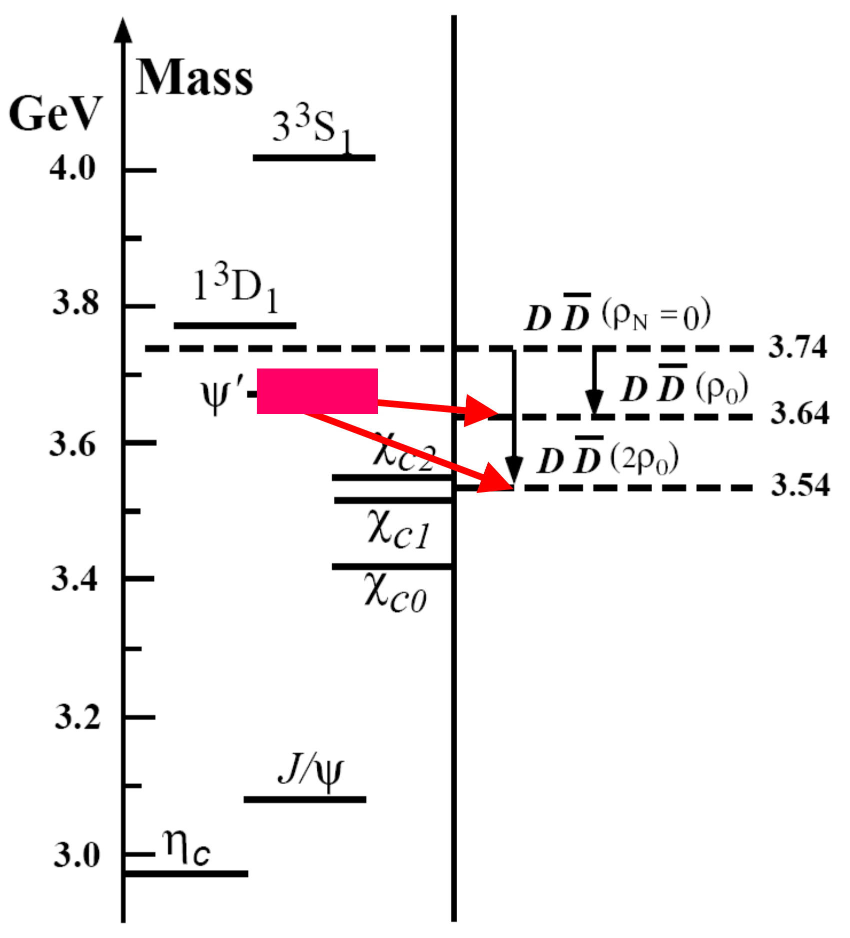
O. Hartmann, Meson2006

Mesons at rest, $p = 0$



Tolos, Schaffner-Bielich,Mishra

# In medium open charm mesons



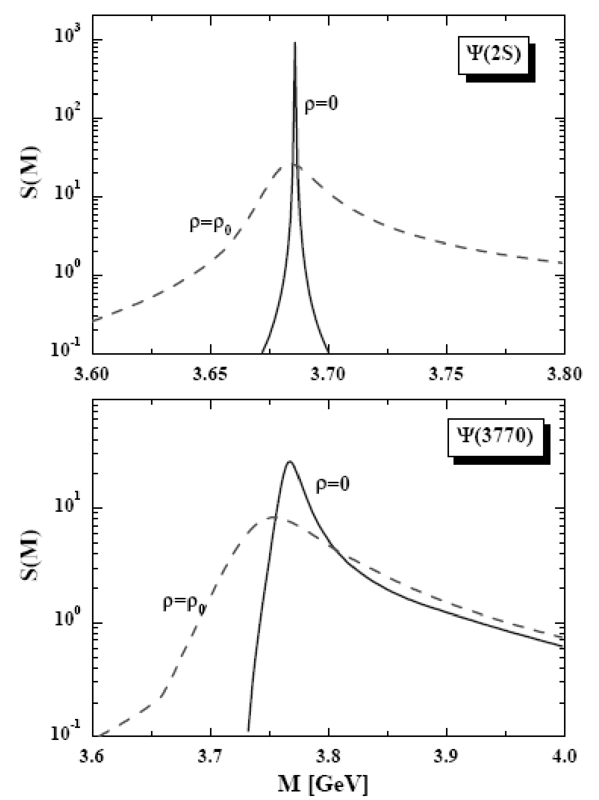
- Hayashigaki, 1998:
  Lowering of D, Dbar, from QCDSR because of light quark content
  → Broadening of ψ´

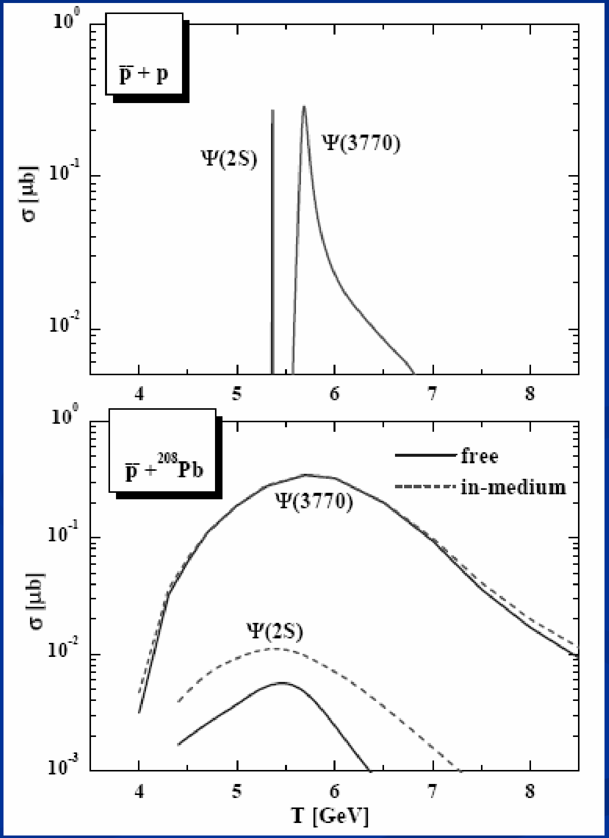
- Lee, 2003:
  Very small change of J/Psi: Δ m ~ – 8 MeV, because dominated by glue content, stable with density, but Δ m(ψ´) ~ - 100 MeV

# In medium open charm mesons

Mesons at rest, p = 0

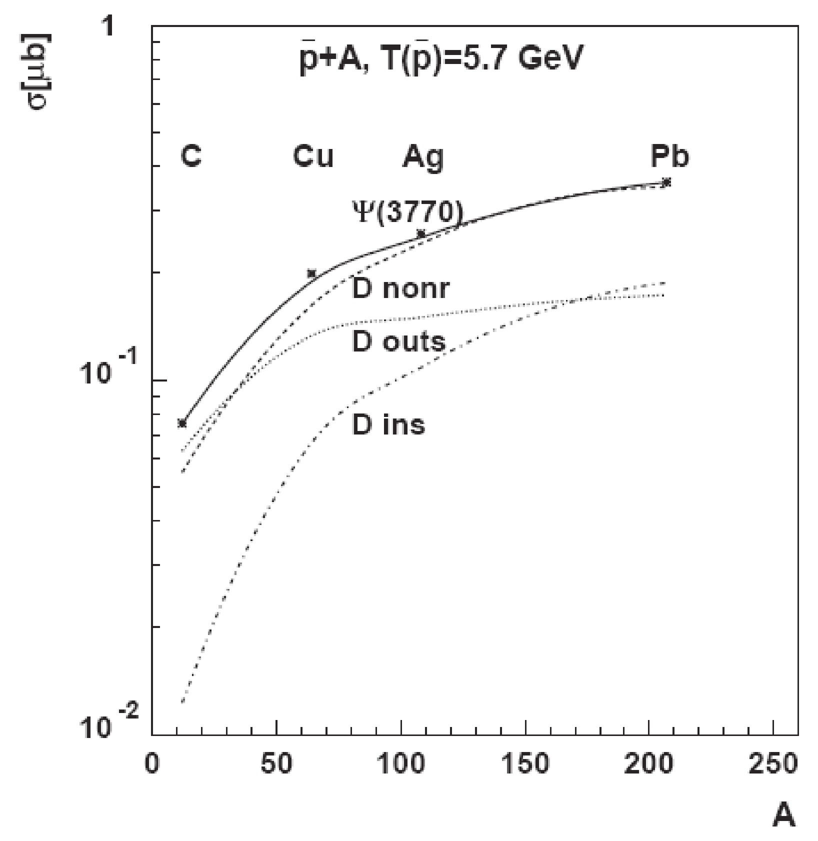
Influence on production X-sections

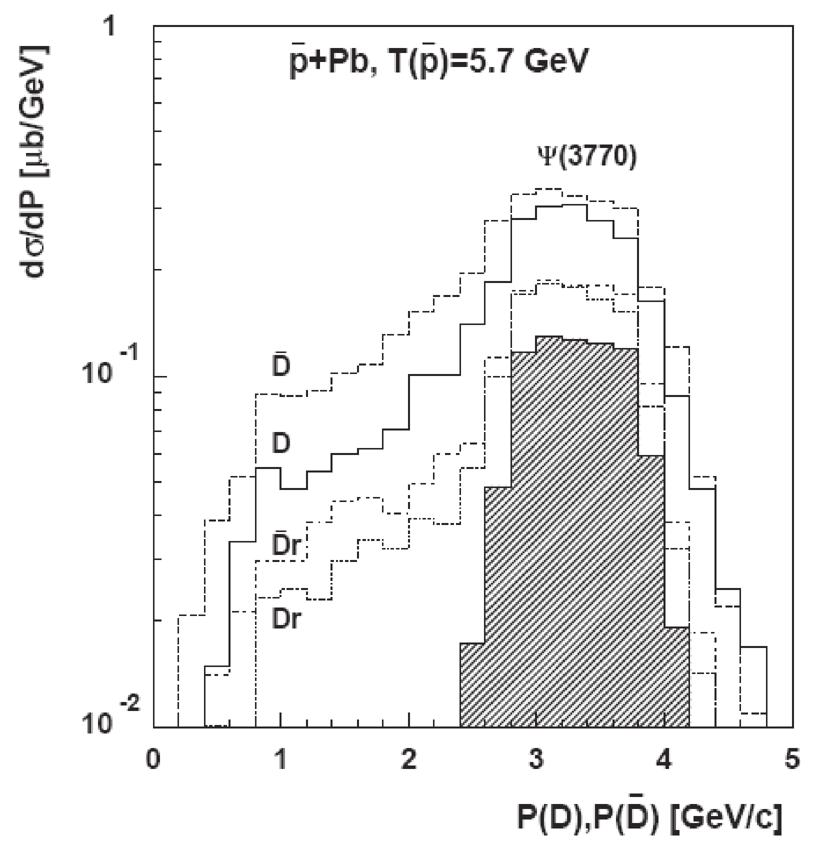




From: Golubeva, Cassing, et al., 2002

# In medium open charm mesons



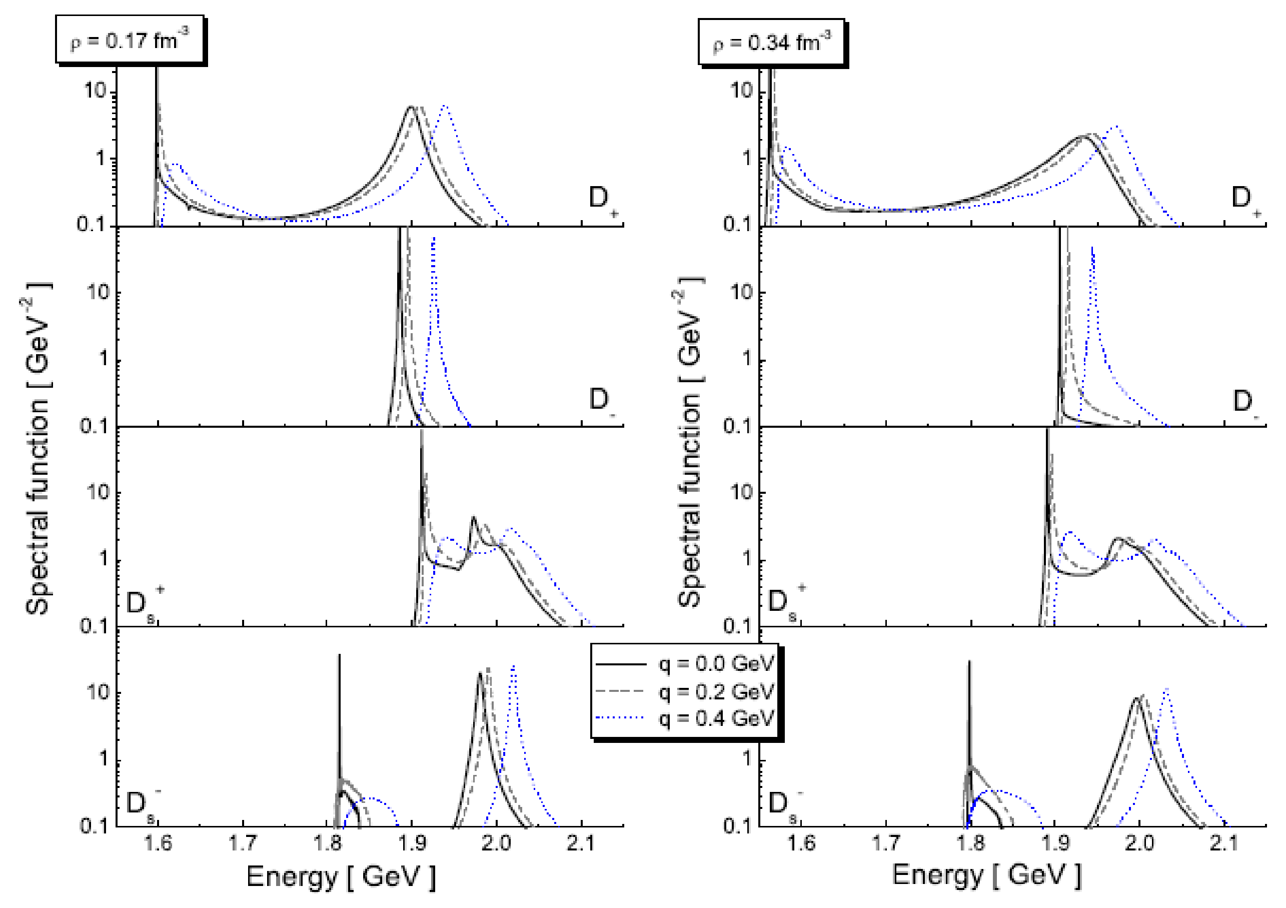


Golubeva et al

Nonresonant decays win in most nuclei
→ no chance to see broadening of ψ‘

High momenta produced

# Charmed mesons with momenta: the latest word



Lutz, Korpa,
2006
**Δ m = + 30 MeV**

# Summary - Conclusions

- In-medium changes seem to be established in light quark sector:

CERES, NA60, TAPS/CB, Photoabs., hadronattenuation

- One common feature in all cases: influence of resonance-hole excitations, detailed spectral function not seen!
- In heavy-quark sector main problems are:
  - Smallness of predicted effects,
  - Production mechanism that leads to large p
  - qualitative disagreement between theories
- Essential problem: link of in-medium props to observables → FSI must be part of theory