Project B.5: Hadrons in Nuclear Matter

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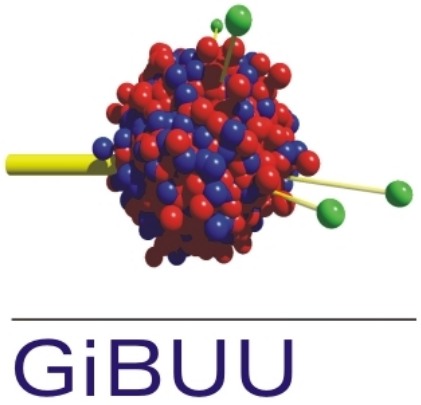
Arbeitstreffen SFB/TR 16
Bochum, 09.09.2010

Outline

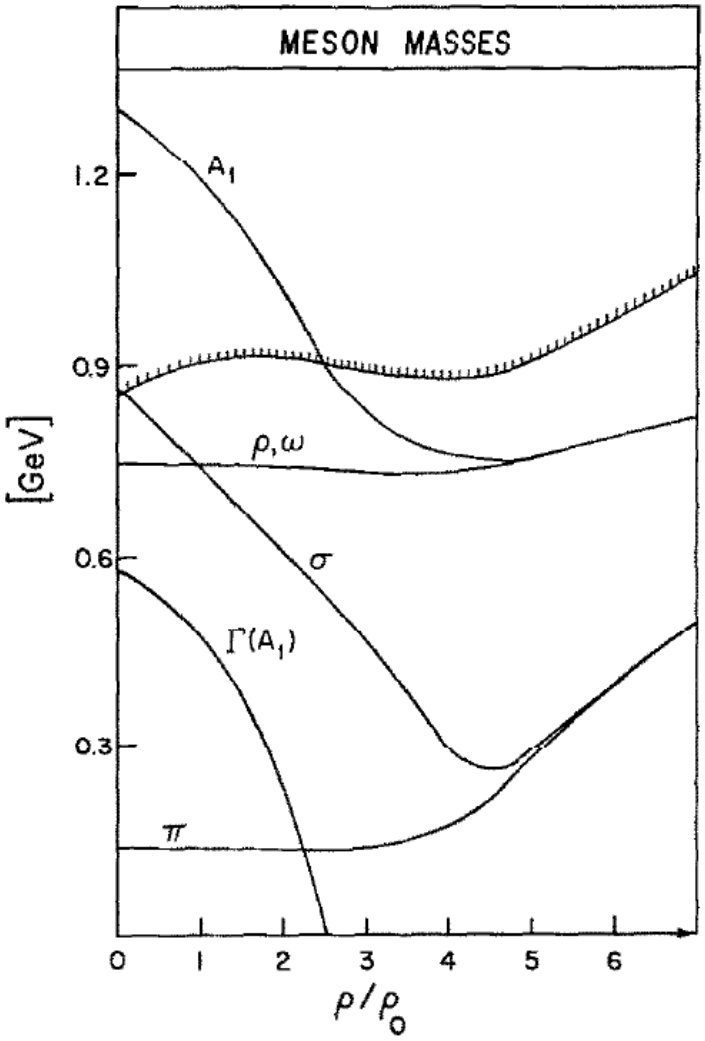
- introduction/motivation
- the GiBUU transport model
- off-shell transport
- photoproduction of omega mesons on nuclei (CB/TAPS)
- dileptons (CLAS/g7, HADES)
- summary



Motivation: Hadrons in Medium

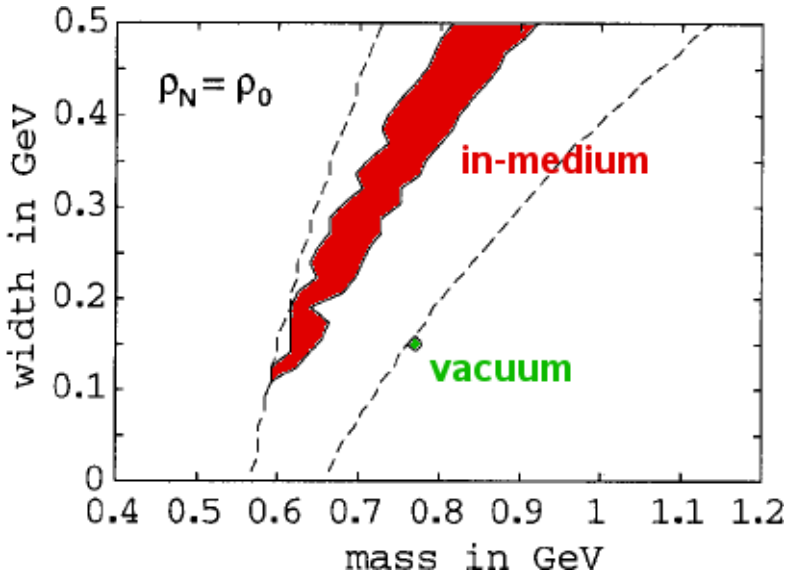
- how do vector mesons behave inside a hadronic medium?
- major prediction: mass shift $\leftrightarrow$ (partial) restoration of chiral symmetry in medium
- Brown/Rho (eff. Lagrang. approach): $m_V^*(\rho_0)/m_V \approx 0.8$
- Hatsuda/Lee (using QCD sum rules, neglecting width): $m_V^*(\rho)/m_V \approx 1 - \alpha(\rho/\rho_0)$, $\alpha \approx 0.16 \pm 0.06$
- mass shift $\Leftrightarrow$ V-N potential $\Leftrightarrow$ bound states?

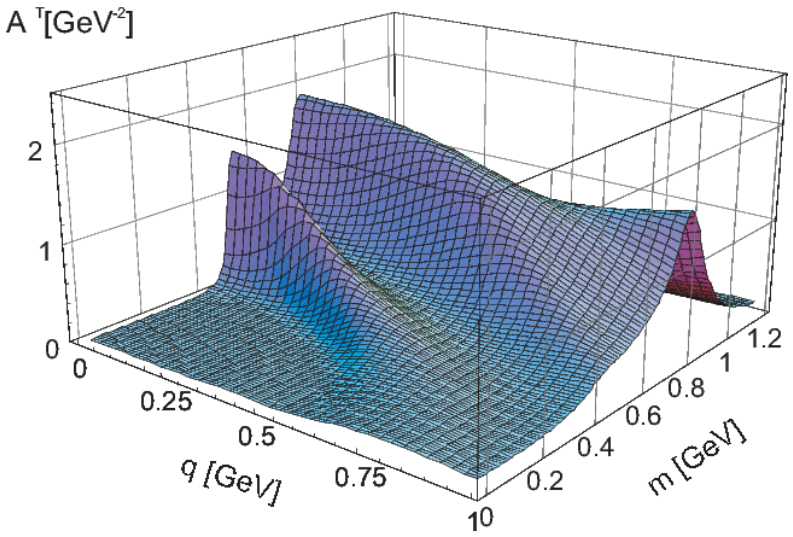
V. Bernard, U.-G. Meissner / Vector and axial-vector mesons



Motivation II

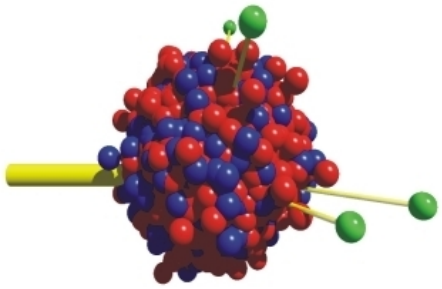
- other effects: collisional broadening, resonance structures, ...
- collisional broadening (LDA): $\Gamma_{coll} = \rho < v_{rel}\sigma_{VN} >$ $\Leftrightarrow$ absorption
- extended sum-rule analysis by Leupold/Peters/Mosel, including finite width (NPA 628, 1998)
- coupling to resonances can introduce additional structures in the spectral function (Post, 2003)





The GiBUU Transport Model

- semi-classical hadronic transport model
- unified framework for various types of reactions (pA, πA, γA, eA, νA, AA) and observables
- modular and well-documented Fortran code
- collaborative effort, SVN-based multi-user environment
- publicly available releases (open source)
- http://gibuu.physik.uni-giessen.de



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

The BUU equation

- BUU equation describes time evolution of phase space density $f_i(\vec{r}, t, \vec{p}, \mu)$ for each particle species i ($i = N, \Delta, \pi, \rho, ...$):

$$\left(\partial_t + (\nabla_{\vec{p}} H_i)\nabla_{\vec{r}} - (\nabla_{\vec{r}} H_i)\nabla_{\vec{p}}\right) f_i(\vec{r}, t, \vec{p}, \mu) = I_{coll}[f_i, f_j, ...]$$

- collision term I_{coll}:
  - depends on all $f_i \Rightarrow$ coupled-channel problem
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model
  - high energy: string model (PYTHIA)
- Hamiltonian H_i:
  - hadronic mean fields and potentials
  - "off-shell potential"
- model includes 61 baryons and 21 mesons
- solve numerically via test-particle method:
  $f = \sum_i \delta(\vec{r} - \vec{r}_i)\delta(p - p_i)$

In-Medium Effects

Mass Shifts

- incorporated as simple scalar potential

Collisional Broadening

- in medium: $\Gamma_{tot} = \Gamma_{vac} + \Gamma_{coll}$
- $\Gamma_{coll} = \rho \langle v_{rel} \sigma_{VN} \rangle$ (low density approx. in lab frame)
- contributing processes: $VN \to \pi N, \pi\pi N, R, ...$
- in practice: use $\Gamma_{coll} = const.$ (from transparency measurements)

Off-Shell Transport

- density-dependent spectral functions need to be handled consistently
- smooth transition from in-medium to vacuum distribution

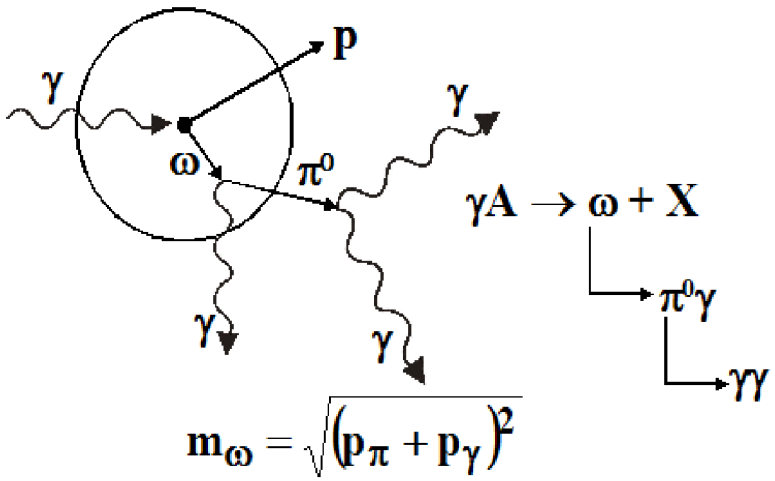
Off-Shell Transport

- off-shell EOM for test particles
  [Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

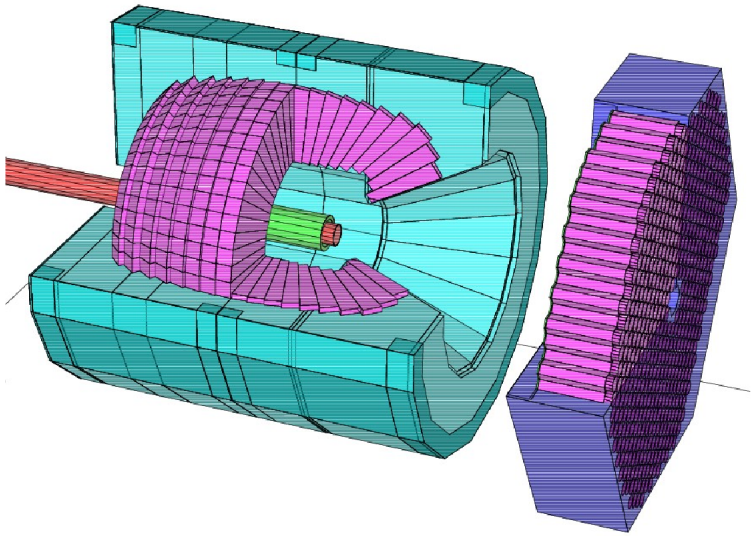
$$
\begin{aligned}
\dot{\vec{r}}_i &= \frac{\vec{p}_i}{E_i} + \frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i}\right] , \\
\dot{\vec{p}}_i &= -\frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{r}_i}\right] , \\
\chi_i &= \frac{m_i^2 - M^2}{\Gamma_i} = const.
\end{aligned}
$$

- incorporate density-dependent self energies Σ_i, $\tilde{\Gamma}_i \sim Im(\Sigma_i)$
- Hamiltonian formulation: $H_i = \sqrt{M^2 + \chi_i \tilde{\Gamma}_i + \vec{p}_i^{\,2} + Re(\Sigma_i)}$
- major difference to BUU model used by Mühlich (which relied on an old 'recipe' by Effenberger)

The CB/TAPS detector



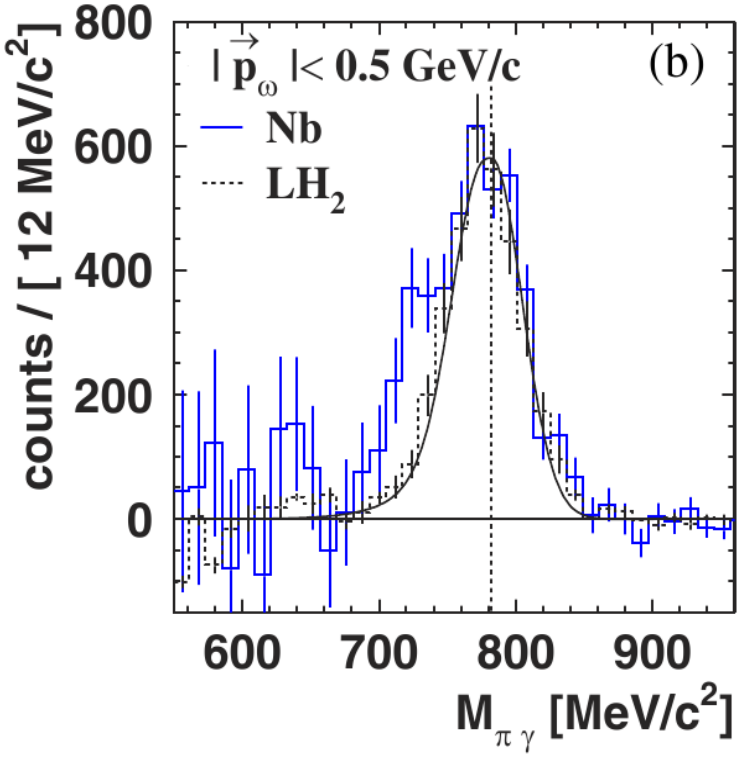
- $\gamma A \rightarrow \omega X \rightarrow \pi^0 \gamma X \rightarrow 3\gamma X$
- Bremsstrahlung photon beam (tagged), $E_\gamma = 0.9 - 2.6 GeV$
- one setup at ELSA (Bonn), one at MAMI (Mainz)
- measure photon triples
  $\rightarrow$ demand that two make up a π^0
  $\rightarrow$ reconstruct ω mass
- mass resolution $\sim 25 MeV$



CB/TAPS: early results

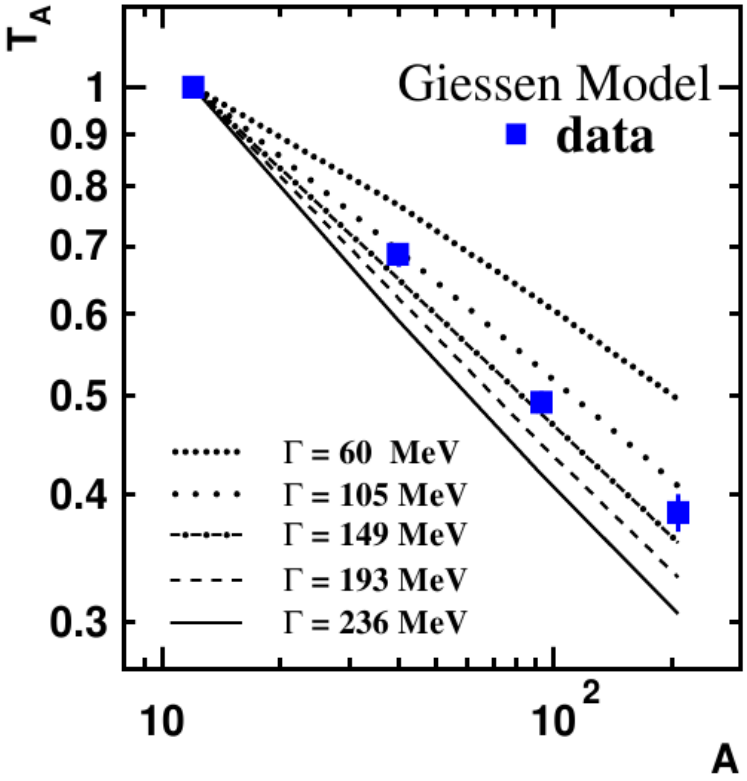
Trnka et al., PRL 94, 2005:

- $m^*_\omega = 722$ MeV
- $\Gamma^*_\omega = 55$ MeV



Kotulla et al., PRL 100, 2008:

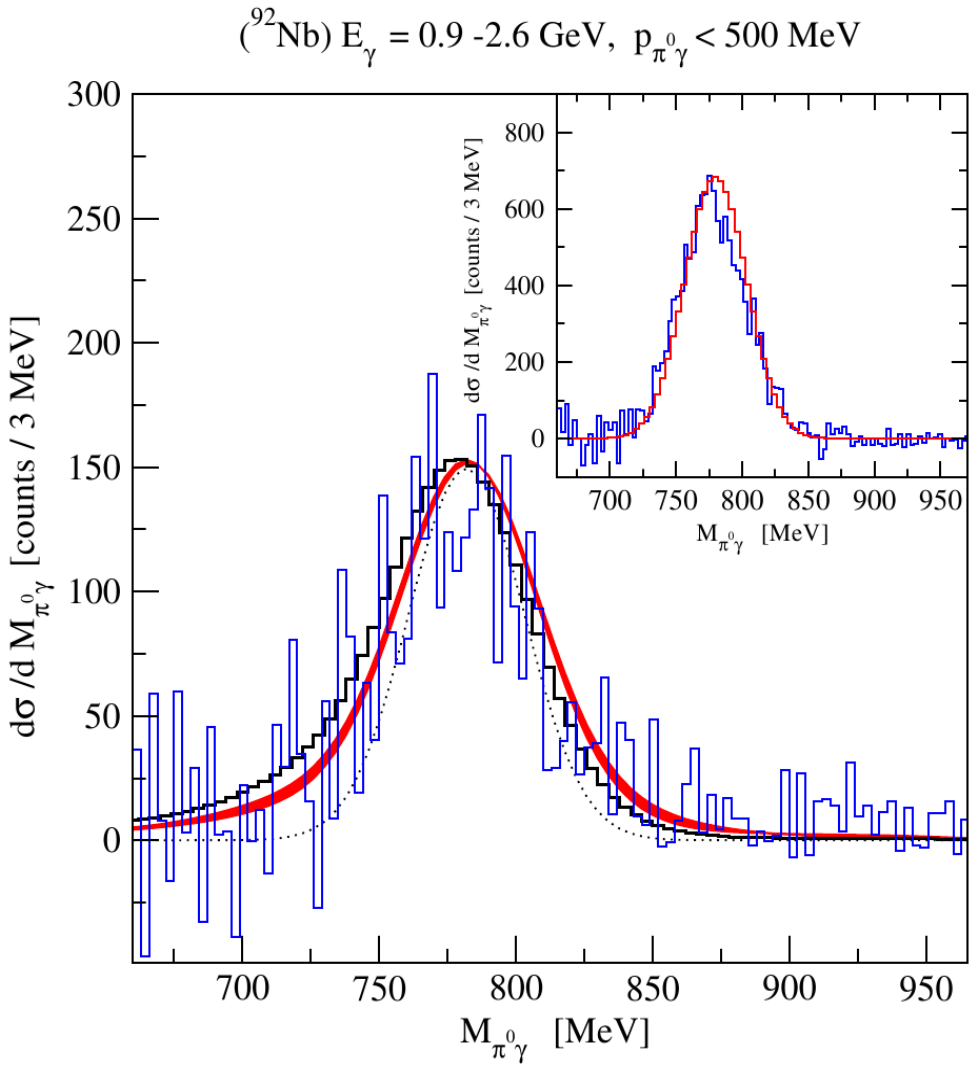
- $T_A = \frac{12 \cdot \sigma(\gamma A \to \omega X)}{A \cdot \sigma(\gamma^{12} C \to \omega X)}$
- $\Gamma_{coll.} = 130 - 150$ MeV



MC simulation results

Kaskulov/Oset, EPJ A31 (2007):

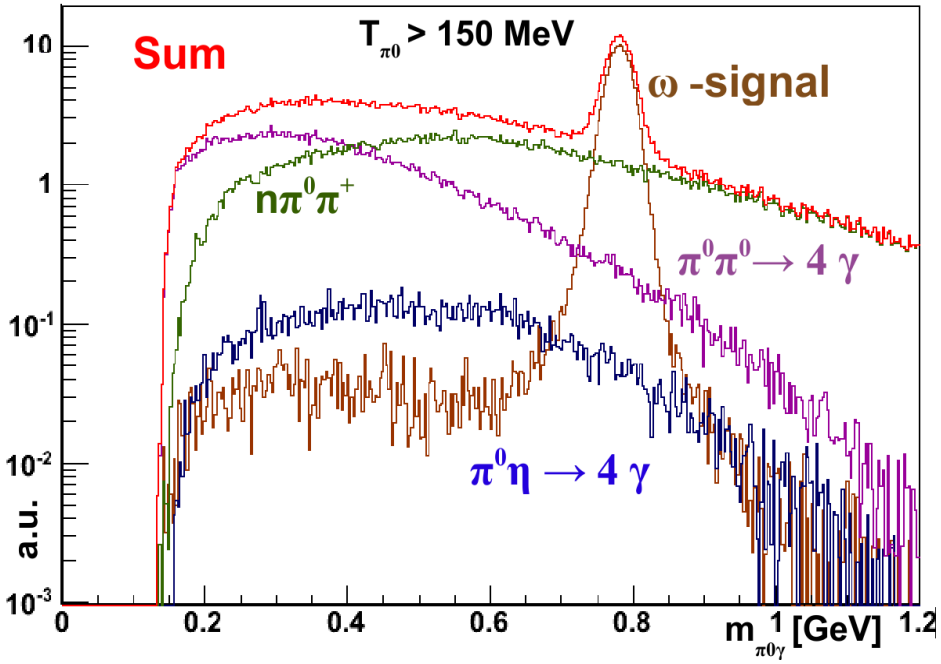
- CB/TAPS only weakly sensitive to in-medium effects (at full energy range of 0.9 - 2.6 GeV)
- but: rather sensitive to background subtraction



CB/TAPS: background channels

main brackground channels:

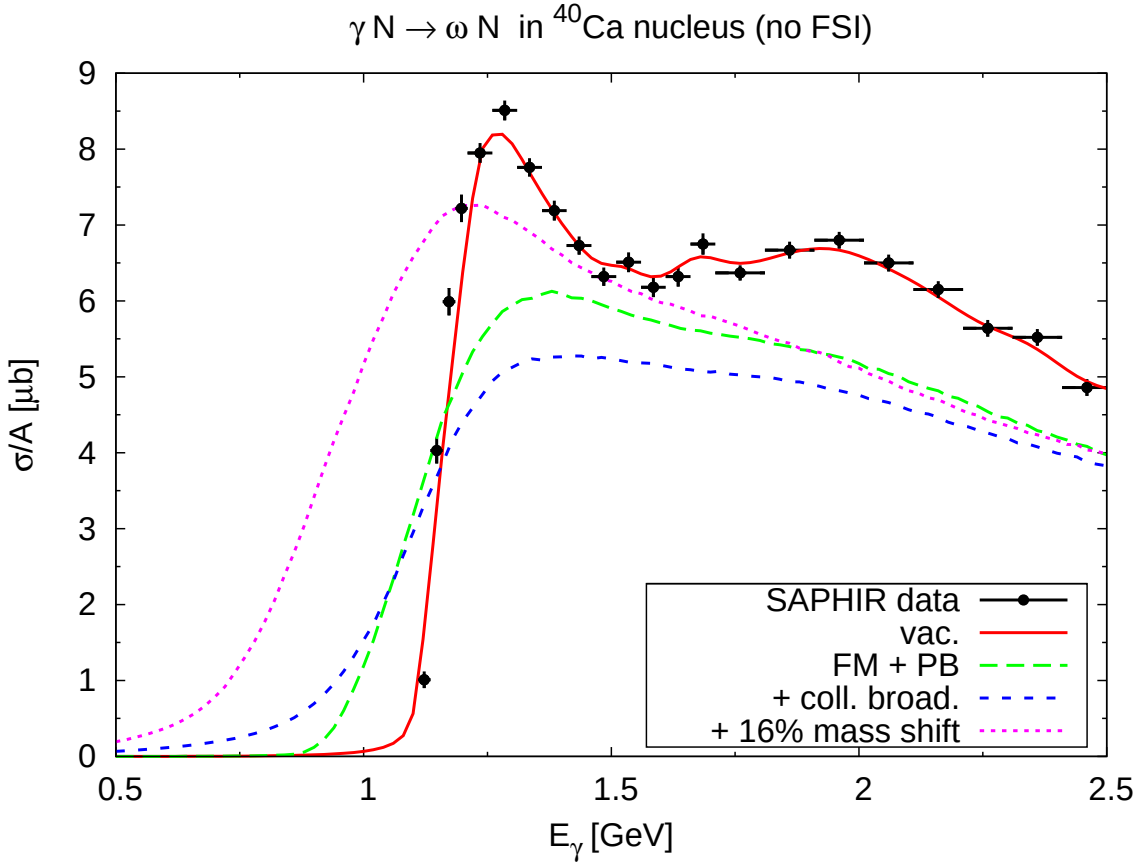
- $\pi^0\pi^0 \rightarrow 4\gamma$ (missing 1 γ)
- $\pi^0\eta \rightarrow 4\gamma$ (missing 1 γ)
- $n\pi^0\pi^+$ misidentified as $3\gamma + p$



- S. Friedrich: describe background via GiBUU simulation
- take complete GiBUU output, feed through GEANT detector simulation

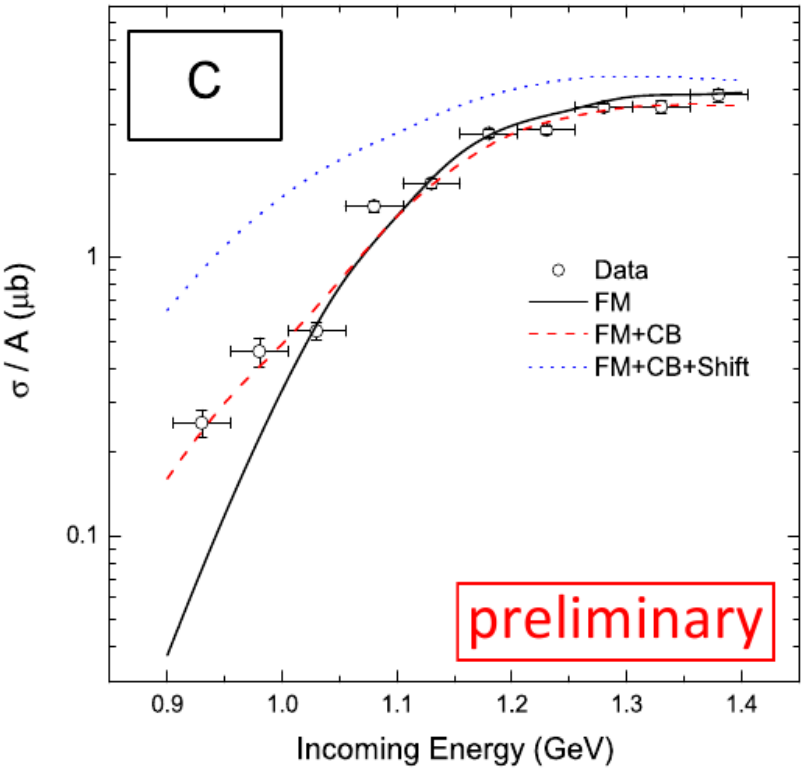
Photoproduction of ω mesons

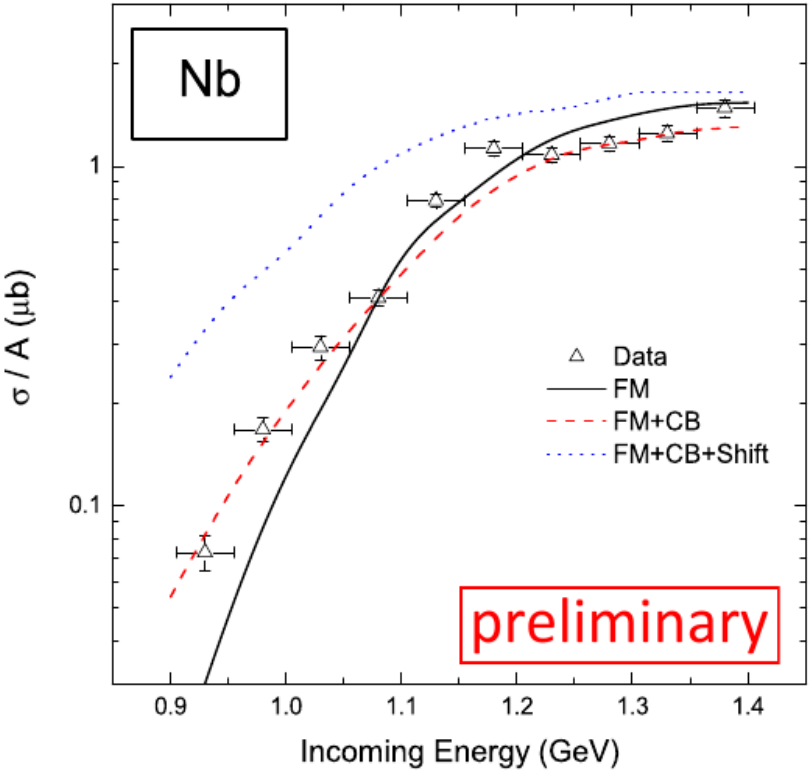
$$\sigma_{\gamma N \to VN} = \frac{1}{16\pi k_{cm} s} \int_{m_\pi}^{\sqrt{s}-m_N} d\mu \left|\mathcal{M}_{\gamma N \to VN}(\sqrt{s})\right|^2 \mathcal{A}_V(\mu,\rho) p_{cm}(\mu)$$



ω Excitation Function

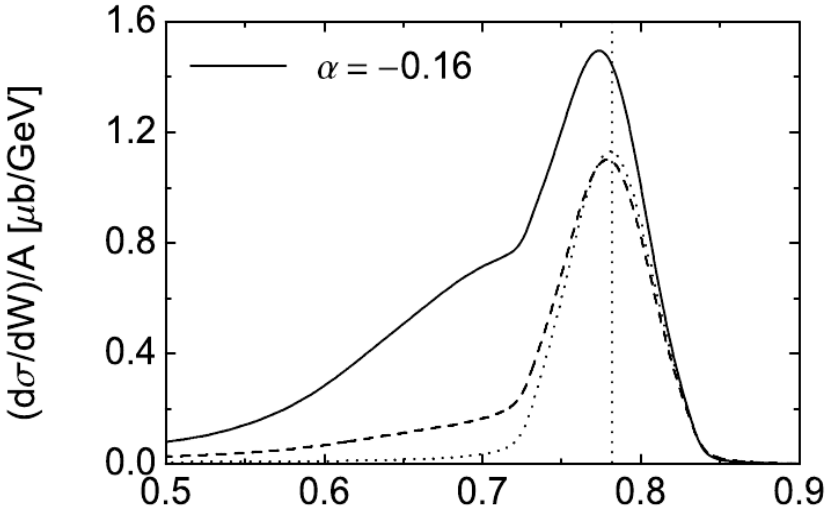
- measure total ω production cross section via $\pi^0\gamma$ final states as a function of E_γ (including FSI/absorption)
- curves: GiBUU simulations, data: B. Lemmer
- data disfavor mass shift scenario



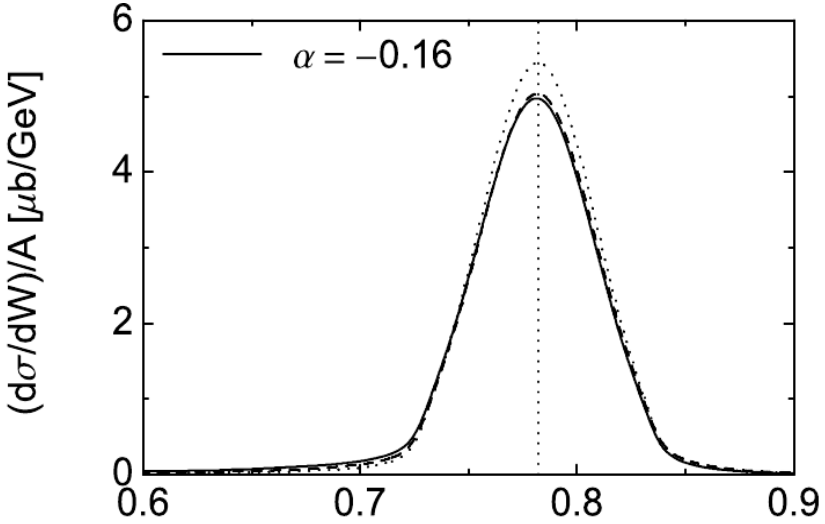


$\pi^0\gamma$ Spectrum: BUU simulations by P. Mühlich

- $\gamma + {}^{40}Ca$, $E_\gamma = 0.9 - 1.2$ GeV
- large low-mass tail

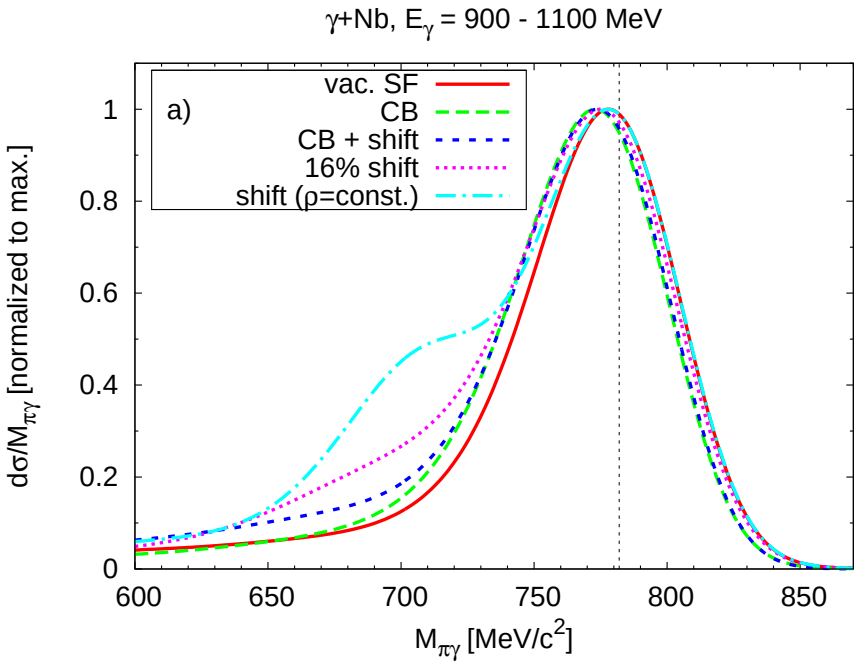


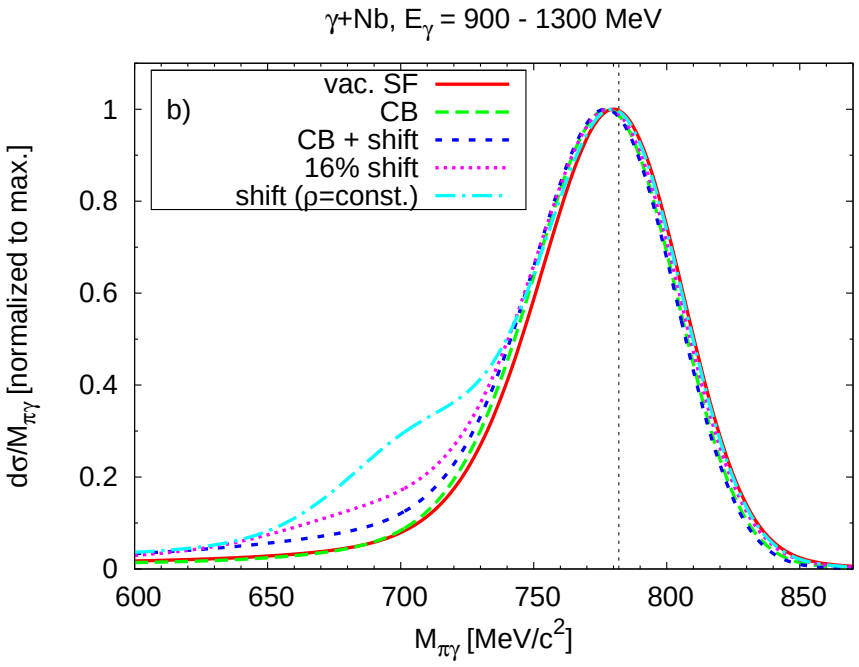
- $\gamma + {}^{40}Ca$, $E_\gamma = 1.5 - 2.2$ GeV
- almost to effects



K. Gallmeister, P. Mühlich et al., Prog. Part. Nucl. Phys. 61 (2008)

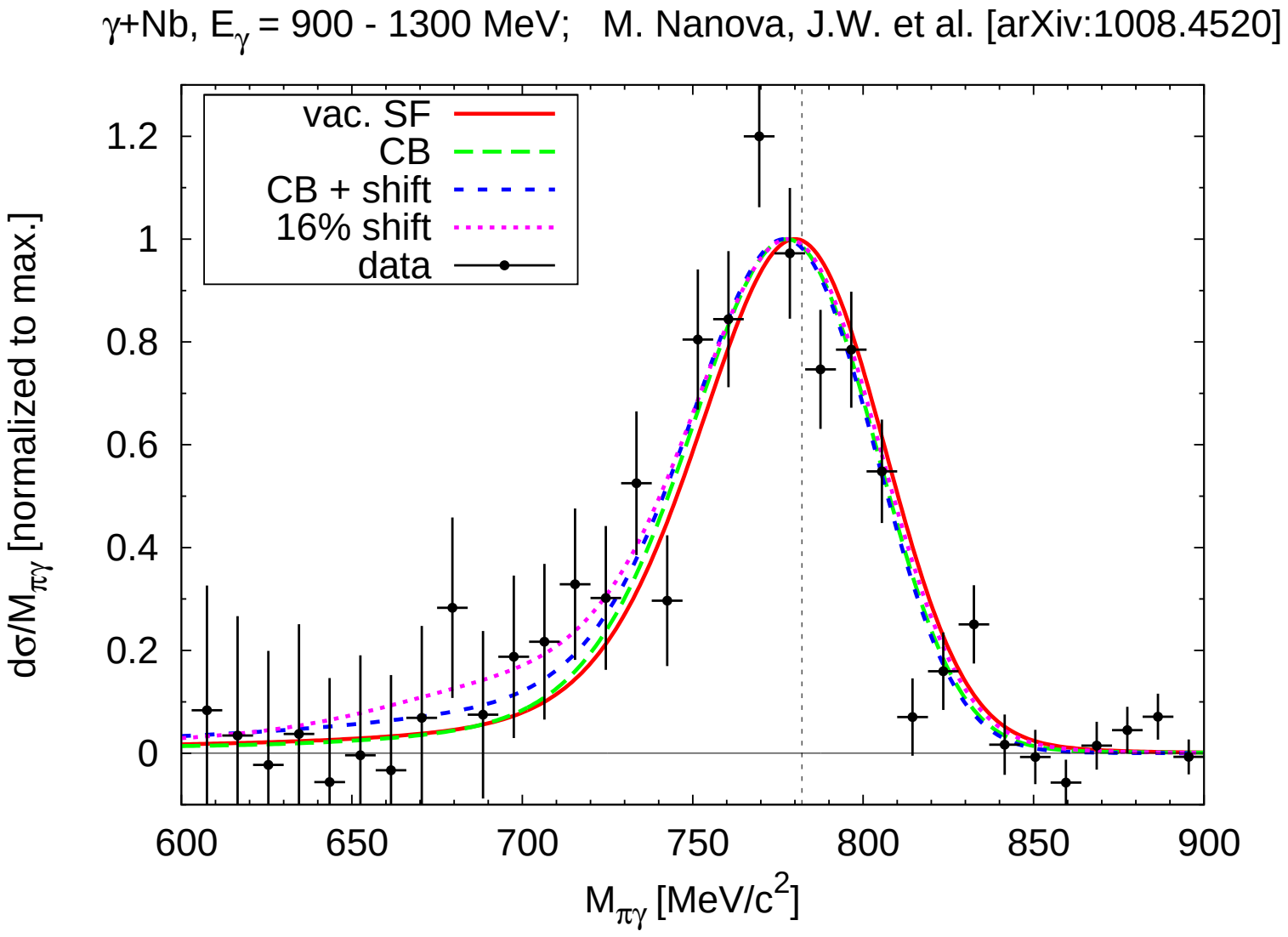
recent simulations with GiBUU





- recent simulations show: effects do increase at threshold
- but: Mühlich tails not reproduced
- soon to be published [arXiv:1008.4520]

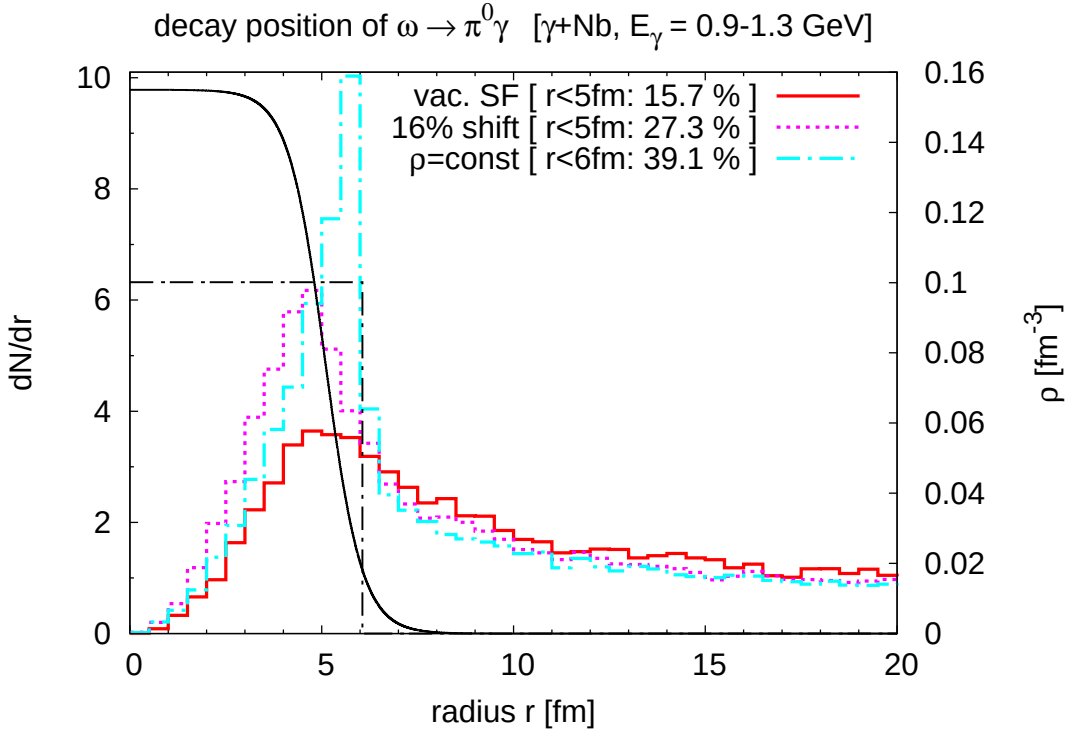
$\pi^0\gamma$ Mass Spectrum: Comparison to Data



$\Rightarrow$ statistics not sufficient to distinguish different scenarios!

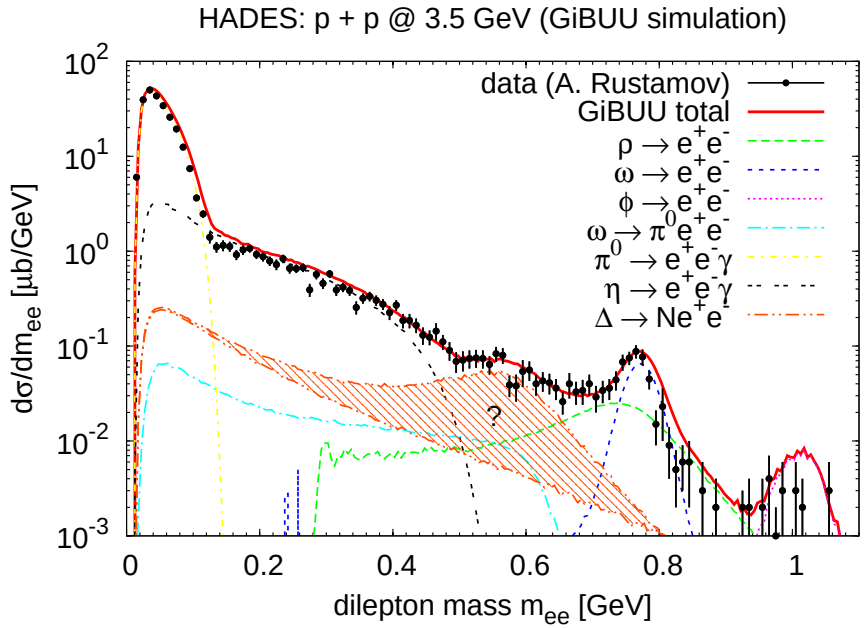
Reasons for weak sensitivity

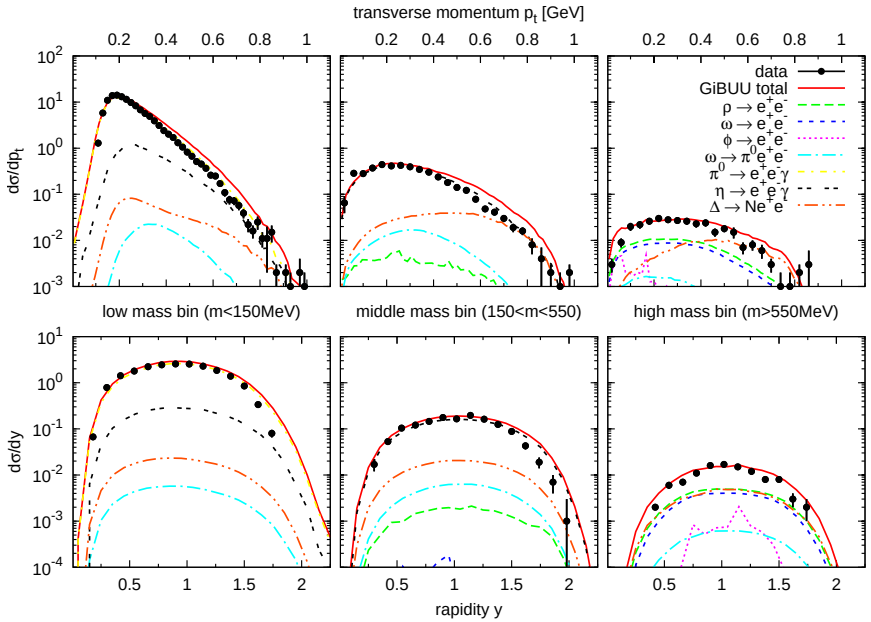
1. long ω decay length [few decays in medium]
2. strong broadening/absorption [smearing of in-medium peak]
3. nuclear density profile [very few decays at full density]



Dileptons from HADES

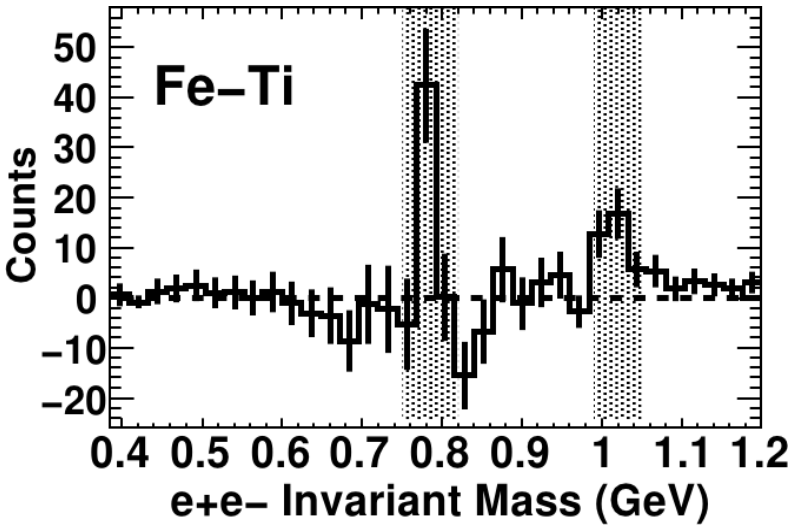
- HADES: in-medium physics with protons and heavy ions
- pp, pA, AA $\rightarrow e^+e^-X$
- e.g. pp@3.5GeV (base line for pNb@3.5GeV)
- open issue: time-like N-Δ transition form factor
- cross checks: dilepton p_T spectra and pion spectra
- medium effects in p+Nb, Ar+KCl?

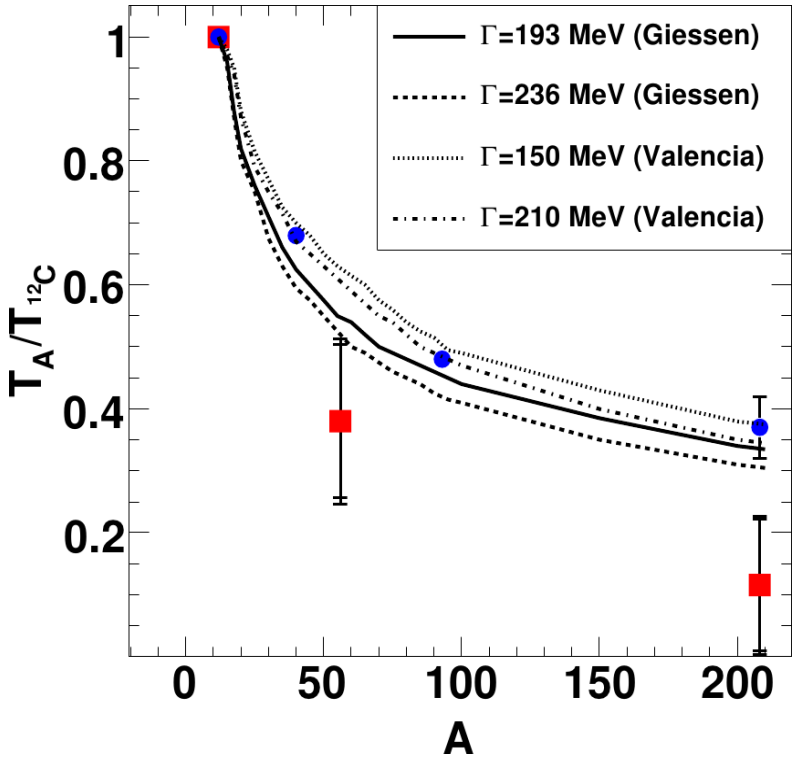




JLab: CLAS/g7

- new results on transparency ratio (preliminary)
- problems with background subtraction (Bethe-Heitler? ρ-ω mixing?)
- to be resolved ...





M. Wood et al. [arXiv:1006.3361]

Summary

1. VM properties in cold nuclear matter: a challenging problem!
2. GiBUU: a valuable tool to study in-medium physics
3. CB/TAPS: present data inconclusive
4. perspectives: improve statistics on $\pi^0\gamma$ line shape, measure *omega* excitation function