Electromagnetic probes in the GiBUU Transport Model

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Outline

1. Motivation for transport models
2. The GiBUU model
   - The Boltzmann-Uehling-Uhlenbeck Equation
   - Off-shell transport: kinetics of broad resonances
3. Dileptons
   - pp collisions (HADES)
   - $p\mathrm{Nb}$ (HADES)
4. ω production in γA collisions

Motivation for Transport Models

- description of various nuclear reactions within one framework
  - pA, γA, eA, νA, AA
- time evolution of system $\Rightarrow$ need dynamical approach
- transport models well suited for Monte-Carlo simulations (test-particle approach)
- strongly interacting many-body system: "medium modifications" of hadrons
- challenging task: description of broad resonance-like excitations
  - off-shell transport with consistent dynamical evolution of spectral properties
  - conservation laws
  - thermodynamic consistency
- in this talk: GiBUU model
  - dileptons in pp and pNb collisions (HADES)
  - ω production in γA (CBELSA/TAPS)

The GiBUU Model

GiBUU

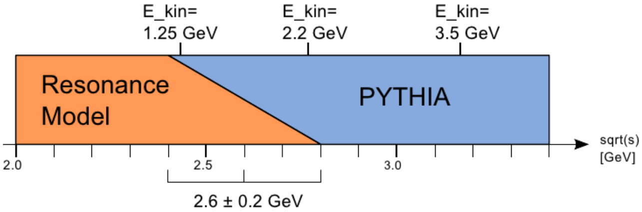
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- BUU framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion
- publicly available realeases:
  http://gibuu.physik.uni-giessen.de

- time evolution of phase-space distribution functions

$$[\partial_t + (\vec{\nabla}_p H_i) \cdot \vec{\nabla}_x - (\vec{\nabla}_x H_i) \cdot \vec{\nabla}_p] f_i(t, \vec{x}, \vec{p}) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_j]$$

- Hamiltonian H_i
  - selfconsistent hadronic mean fields, Coulomb potential, "off-shell potential"
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - at low reaction energies: resonance model
  - at high reaction energies: (modified) PYTHIA



Transport model for broad resonances

- resonances described with relativistic Breit-Wigner distribution

$$\mathcal{A}(x,p) = -\frac{1}{\pi} \frac{\operatorname{Im}\Pi}{(p^2 - M^2 - \operatorname{Re}\Pi)^2 + (\operatorname{Im}\Pi)^2}; \quad \operatorname{Im}\Pi = -\sqrt{p^2}\Gamma$$

- full off-shell equation from quantum-transport approach [Botermans, Malfliet,...] hard to solve due to "back-reaction term"
- way out: off-shell potential ansatz [Effenberger, Mosel; Leupold; Cassing, Juchem; Buss]
- in test-particle ansatz: off-shell potential, $\Delta\mu_i^2$,

$$p_i^2 = M^2 + \operatorname{Re}\Pi + \Delta\mu_i^2, \quad \chi_i = \frac{\Delta\mu_i^2}{\Gamma_i}$$

- off-shell equations of motion

$$\dot{\vec{r}}_i = \frac{1}{1-C_i} \frac{1}{2E_i} \left[2\vec{p}_i + \vec{\nabla}_{p_i}(\operatorname{Re}\Pi_i + \chi_i \Gamma_i)\right]$$

$$\dot{\vec{p}}_i = -\frac{1}{1-C_i} \frac{1}{2E_i} \vec{\nabla}_r(\operatorname{Re}\Pi_i + \chi_i \Gamma_i)$$

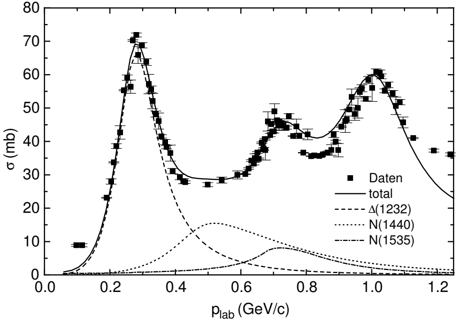
$$C_i = \frac{1}{2E_i} \frac{\partial}{\partial E_i}(\operatorname{Re}\Pi_i + \chi_i \Gamma_i), \quad \dot{\chi}_i = 0$$

Resonance Model

- reactions dominated by resonance scattering: $ab \to R \to cd$
- Breit-Wigner cross-section formula

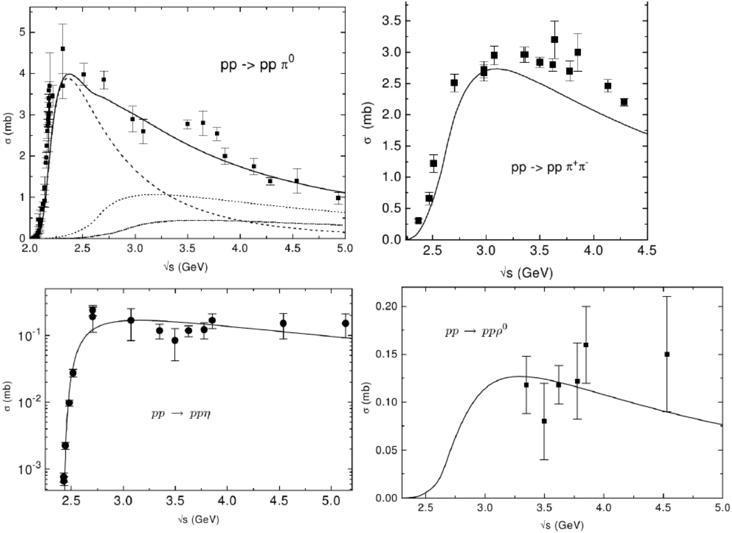
$$\sigma_{ab\to R\to cd} = \frac{2s_R+1}{(2s_a+1)(2s_b+1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab\to R}\Gamma_{R\to cd}}{(s-m_R^2)^2+s\Gamma_{\text{tot}}^2}$$

- applicable for low-energy nuclear reactions $E_{\text{kin}} \lesssim 1.1\ \text{GeV}$
- example: $\sigma_{\pi^- p\to\pi^- p}$ [Teis (PhD thesis 1996)]



Resonance Model

- further cross sections

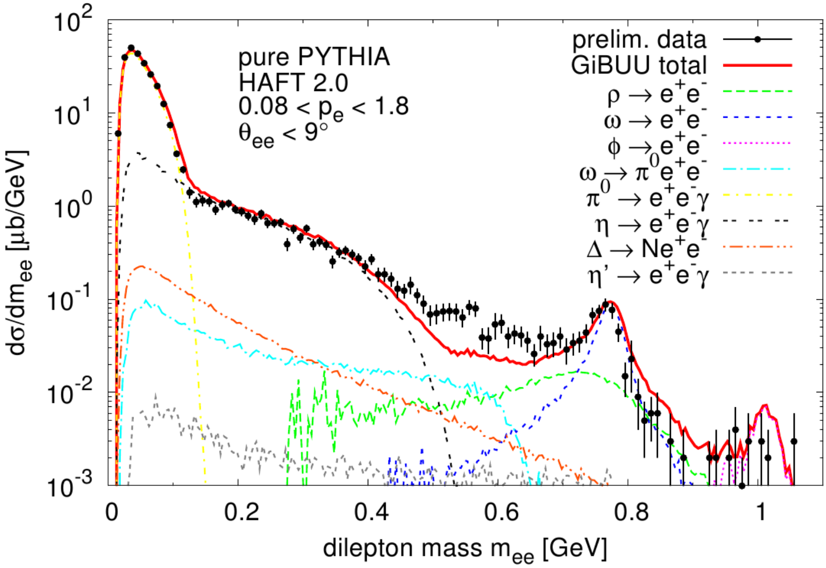


The Dilepton Probe

- dileptons valuable probe for in-medium properties of vector mesons
- main sources
  - Dalitz decays: $\pi^0, \eta \rightarrow \gamma \ell^+ \ell^-$; $\omega \rightarrow \pi^0 \ell^+ \ell^-$, $\Delta \rightarrow N \ell^+ \ell^-$
  - $\rho, \omega, \phi \rightarrow \ell^+ \ell^-$: invariant mass $\ell^+ \ell^-$ spectra $\Rightarrow$ spectral properties of vector mesons
- provides direct access to in-medium properties of vector mesons, if they decay inside the medium!
- in GiBUU: strict vector-dominance model $J_{\text{em}}^{\text{had}} \propto V^\mu$

Comparison to HADES data

pp@3.5 GeV



Comparison to HADES data

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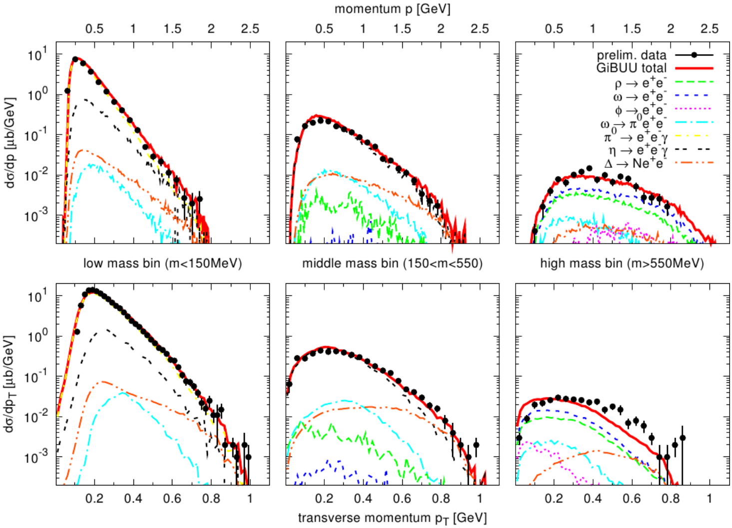
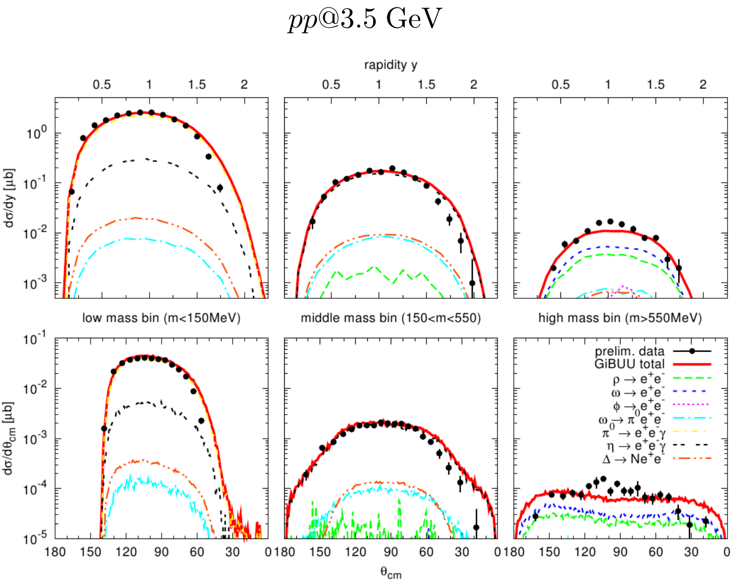
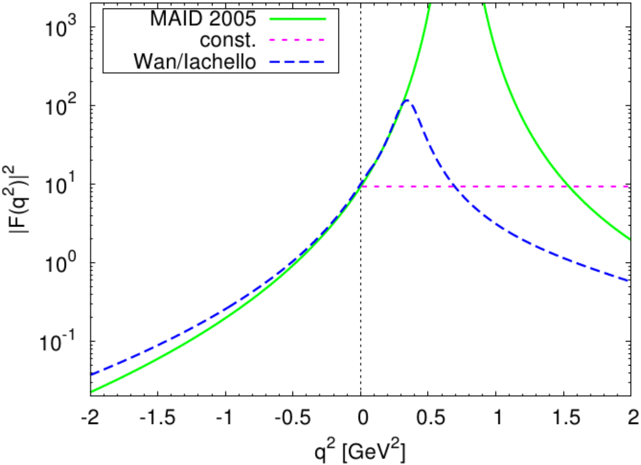


Comparison to HADES data

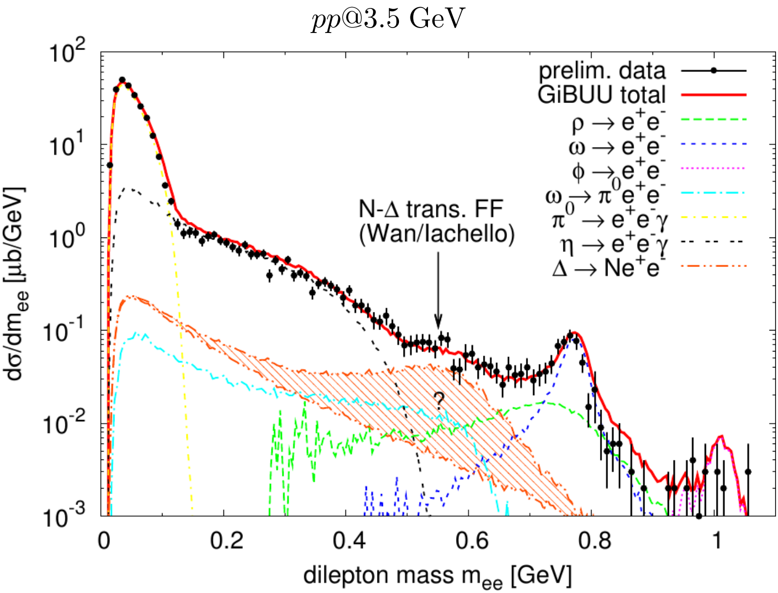


Δ-Dalitz Decay

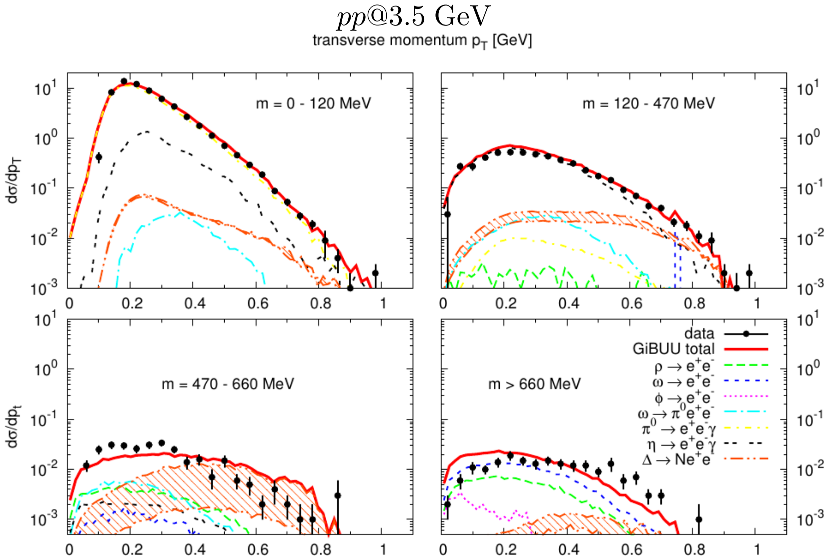
- transition-form factor $\Delta \to N\gamma^*$
- unknown in time-like region
- two-component quark model [Wan, Iachello, IJP A **20** (2005)]



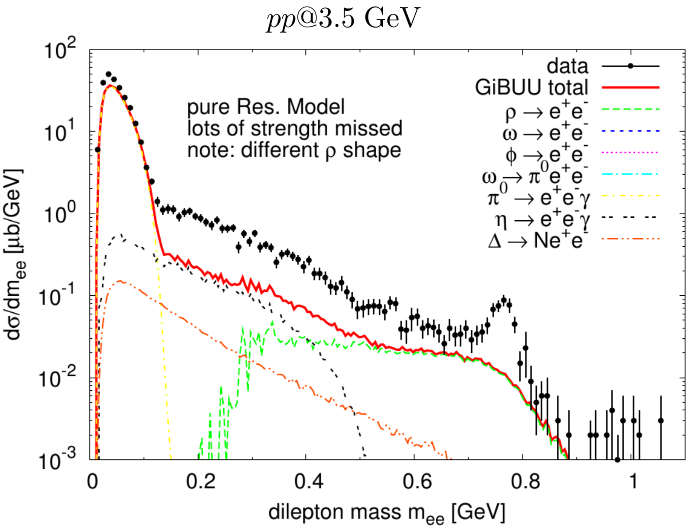
Comparison to HADES data with Δ form factor



Comparison to HADES data with Δ form factor



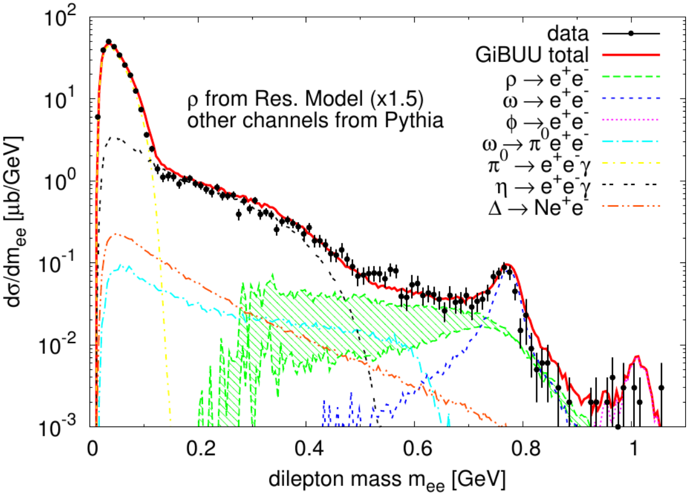
Comparison to HADES data with resonance model



- need higher resonances at this energy
- ρ shape changes

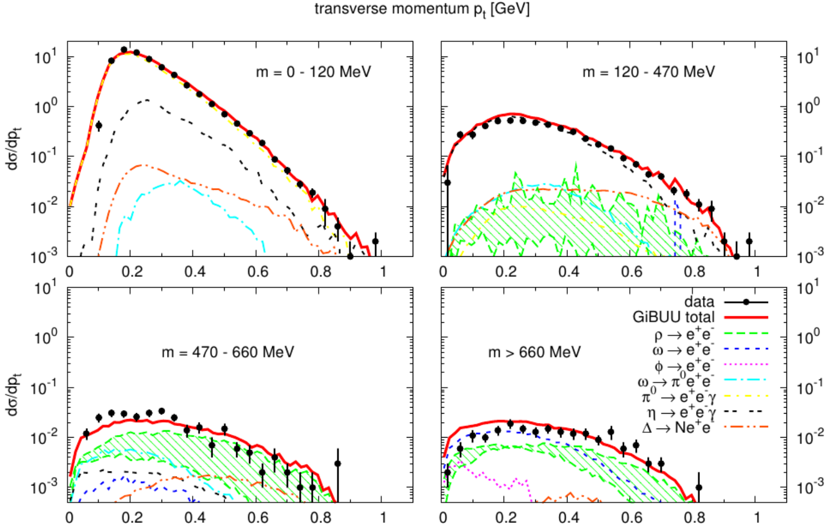
Comparison to HADES data with resonance model+PYTHIA

- use ρ shape from resonance model (rescaled by factor 1.5!)
- use PYTHIA for all other channels as before



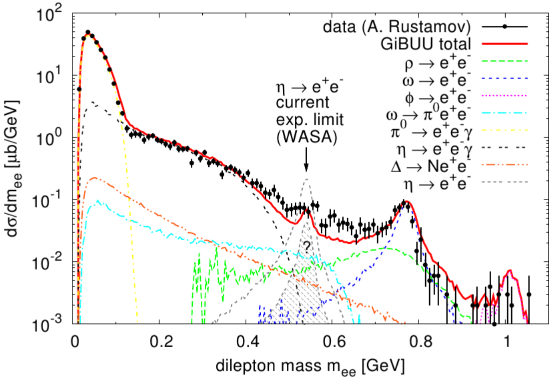
Comparison to HADES data with Δ form factor

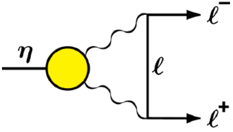
pp@3.5 GeV



Improved experimental upper limit for $\eta \to e^+e^-$?

- upper limit from [Berlowski et al [WAFA Collab.], PRD **77** (2008)]: $\mathrm{BR}(\eta \to e^+e^-) < 2.7 \cdot 10^{-5}$
- theoretical prediction [Browder et al, PRD **56** (1997)]: $\mathrm{BR}(\eta \to e^+e^-) \simeq 10^{-9}$

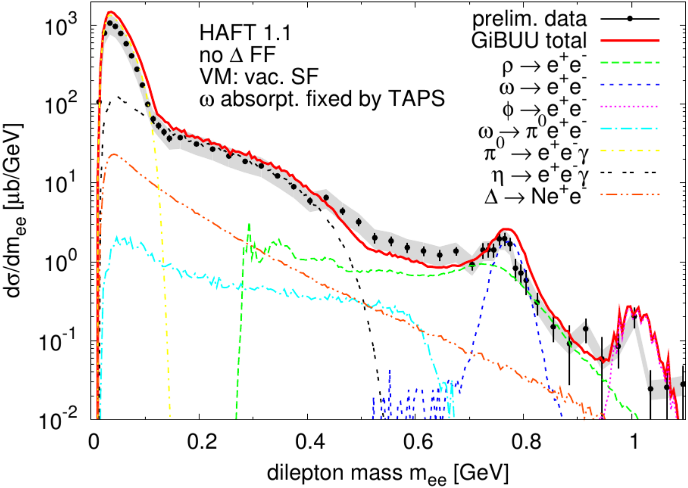




pNb@HADES (3.5 GeV)

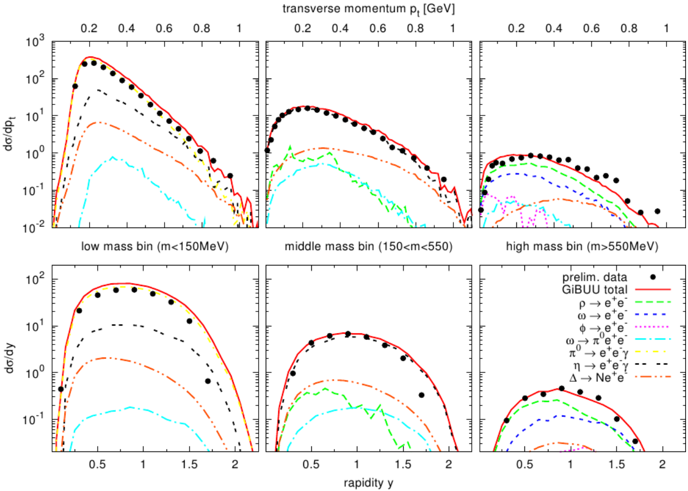
- pp baseline as input (including the discussed uncertainties!) cross sections, branching ratios, form factors, etc.
- medium effects built in transport model
  - final-state interactions
  - production from secondary collisions
- additional impact from vector-meson spectral functions?

pNb@HADES (3.5 GeV)



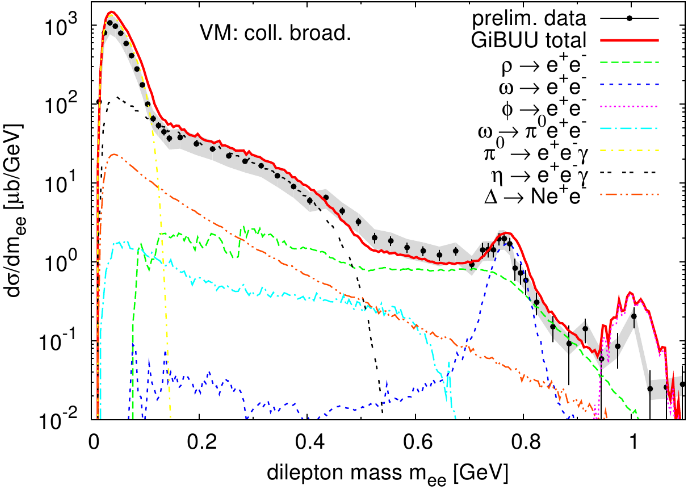
- discrepancy in normalization (π_0 Dalitz?)
- acceptance issue?

pNb@HADES (3.5 GeV)



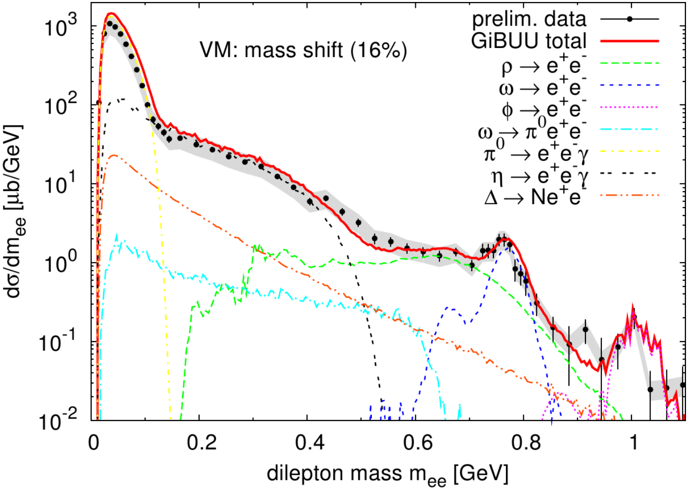
pNb@HADES (3.5 GeV)

- medium modifications of vector-meson spectral functions?
- collisional broadening



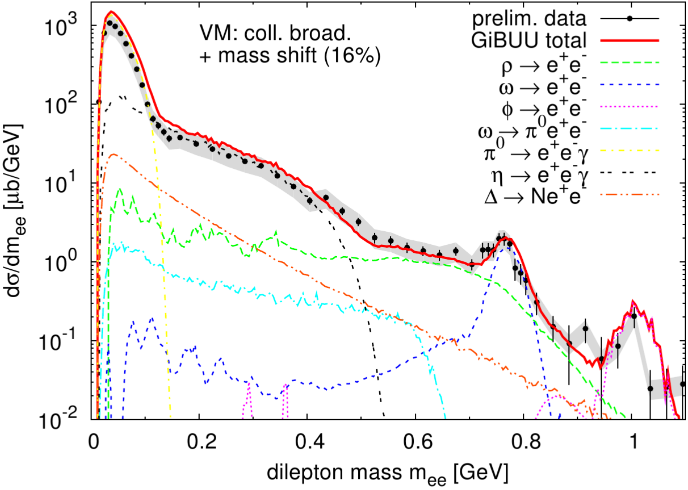
pNb@HADES (3.5 GeV)

- medium modifications of vector-meson spectral functions?
- dropping mass (16% at nuclear-matter density)



pNb@HADES (3.5 GeV)

- medium modifications of vector-meson spectral functions?
- dropping mass + collisional broadening

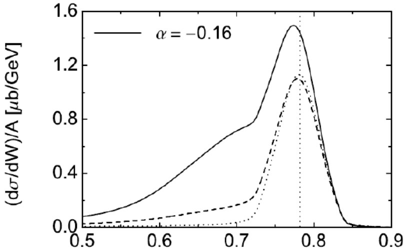


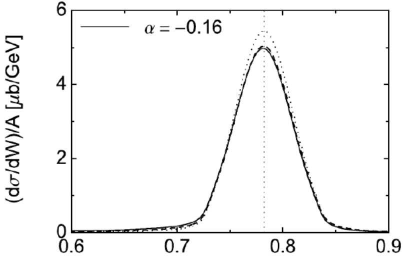
ω production in γA collsions

- main motivation: medium effects on ω spectral function
- earlier GiBUU simulations by Mühlich

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

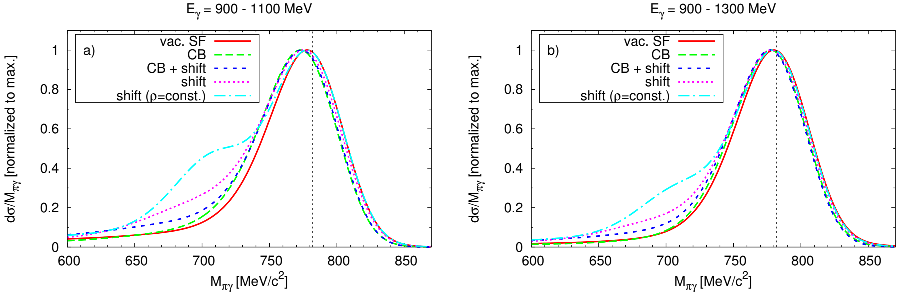
- $\gamma\,^{40}$Ca, $E_\gamma = 1.5\text{-}2.2$ GeV
- nearly no effect



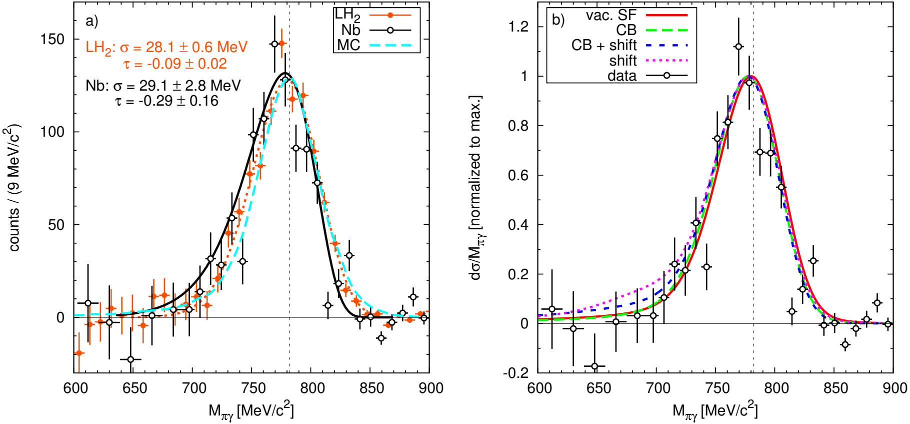


[Gallmeister, Kaskulov, Mosel, Prog. Part. Nucl. Phys. **61**, 283 (2008)]

- improved implementation of off-shell transport
- spectral functions relax properly to vacuum shape!



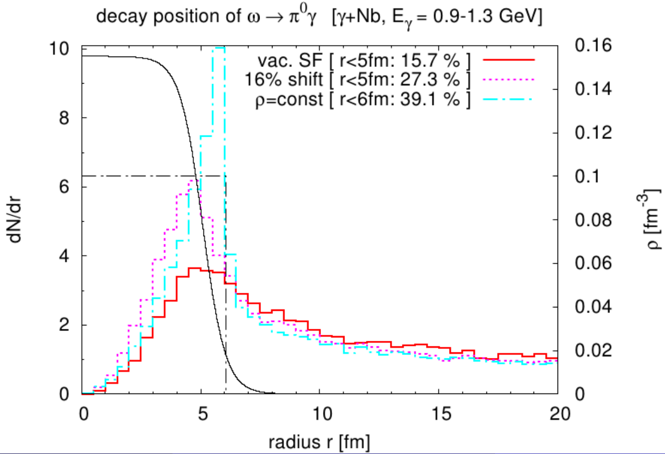
- improved implementation of off-shell transport
- spectral functions relax properly to vacuum shape!
- $E_\gamma = 0.9\text{-}1.3\ \text{GeV}$



[Nanova, Weil et al, Eur. Phys. J. A **47**, 16 (2011)]

Position of decaying ω's

- not so much sensitivity to in-medium effects
  - few ω's decay inside the nucleus
  - strong in-medium broadening
  - density profile of nucleus
- correct implementation of off-shell transport crucial!



Conclusions

- GiBUU transport model
  - comprehensive model for pA, πA, γA, eA, νA, AA collisions
  - dynamically consistent transport of broad resonances via "off-shell potential"
  - open-source releases available (Fortran 95/2003)
  - http://gibuu.physik.uni-giessen.de
- Dilepton probes@HADES
  - resonance model for VM production ($E_{\text{kin}} \lesssim 1.1 \text{ GeV}$)
  - vector-meson dominance model for dileptons
  - modified PYTHIA at higher energies
  - pp baseline: still uncertainties in VM region (form factors)
  - pA: within uncertainties no clear indication of medium effects (also in normalization/acceptance)
  - AA: work in progress
- photoproduction of ω mesons on nuclei
  - mass spectra inconclusive wrt. medium effects
  - consistent off-shell transport crucial!
  - transparency ratio: large broadening of ω ($\Gamma_\omega \simeq 140 \text{ MeV}$)