Vector mesons in cold nuclear matter

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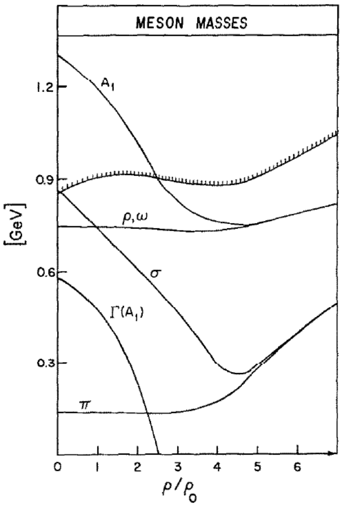
Outline

- introduction/motivation
- the GiBUU transport model
- photoproduction of omega mesons on nuclei (CB/TAPS)
- dileptons from HADES:
  p + p @ 3.5 GeV
  p + Nb @ 3.5 GeV
- summary

Motivation: Hadrons in Medium

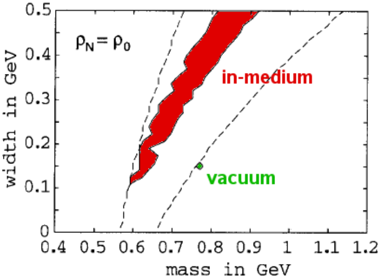
- how do vector mesons behave inside a hadronic medium?
- major prediction: mass shift $\leftrightarrow$ (partial) restoration of chiral symmetry in medium
- Brown/Rho (eff. Lagrang. approach): $m_V^*(\rho_0)/m_V \approx 0.8$
- Hatsuda/Lee (using QCD sum rules, neglecting width): $m_V^*(\rho)/m_V \approx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

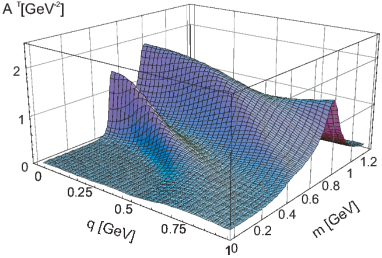
V. Bernard, U.-G. Meissner / Vector and axial-vector mesons



Motivation II

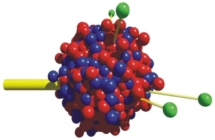
- other effects: collisional broadening, resonance structures, ...
- collisional broadening (LDA):
  $\Gamma_{coll} = \rho < v_{rel}\sigma_{VN} >$
  $\Leftrightarrow$ absorption
- extended sum-rule analysis by Leupold/Peters/Mosel, including finite width (NPA 628, 1998)
- coupling to resonances can introduce 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 $\Gamma_{coll}(\rho)$ [no momentum dependence]

Off-Shell Transport

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

Off-Shell Transport

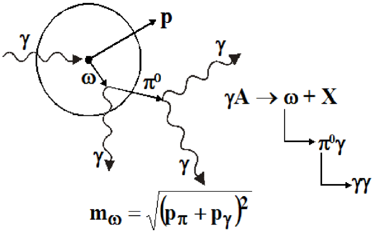
- off-shell EOM for test particles
  [Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

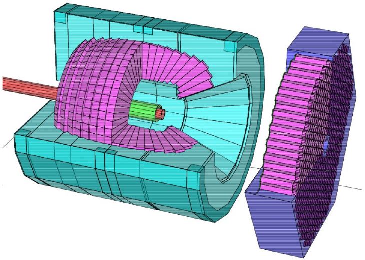
$$
\begin{aligned}
\dot{\vec{r}}_i &= \frac{1}{1-C_i}\frac{1}{2E_i}\left[2\vec{p}_i + \frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i}\right] , \\
\dot{\vec{p}}_i &= -\frac{1}{1-C_i}\frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i)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

- incorporate density-dependent self energies Σ_i, $\Gamma_i \sim Im(\Sigma_i)$
- major difference to BUU model used by Mühlich
  (which relied on an old 'recipe' by Effenberger)

The CB/TAPS detector

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

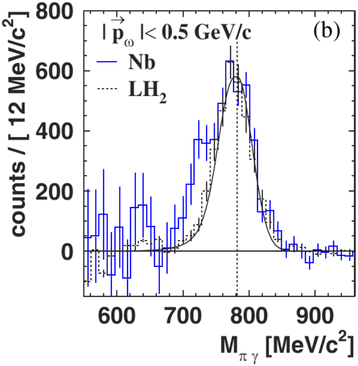




CB/TAPS: early results

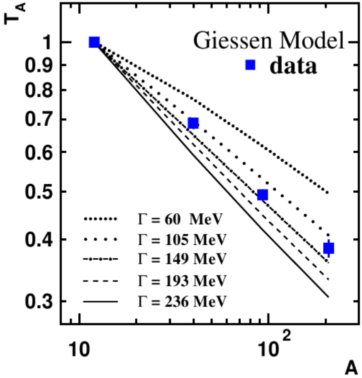
Trnka et al., PRL 94, 2005:

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



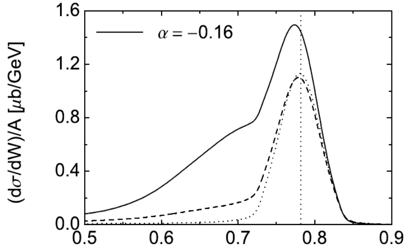
Kotulla et al., PRL 100, 2008:

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

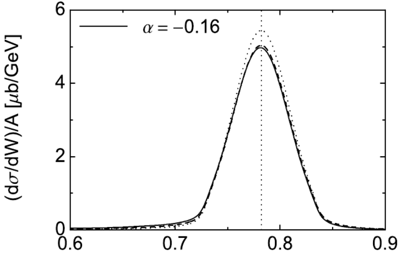


$\pi^0\gamma$ Spectrum: BUU simulations by P. Mühlich

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

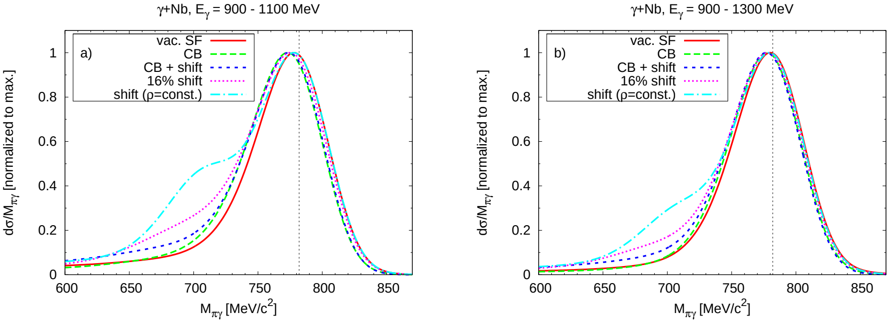


- $\gamma + {}^{40}Ca$,
  $E_\gamma = 1.5 - 2.2$ GeV
- almost to effects



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

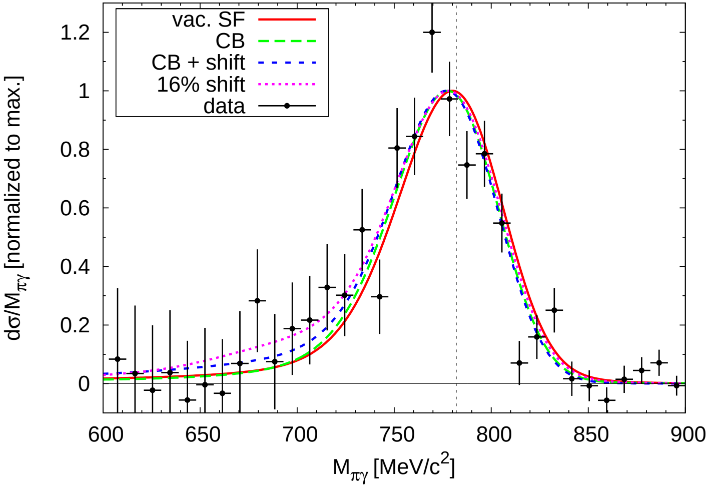
recent simulations with GiBUU



- 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

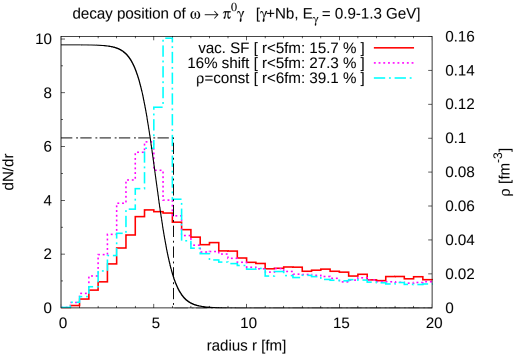
γ+Nb, E_γ = 900 - 1300 MeV; M. Nanova, J.W. et al. [arXiv:1008.4520]



⇒ statistics not sufficient to distinguish different scenarios!

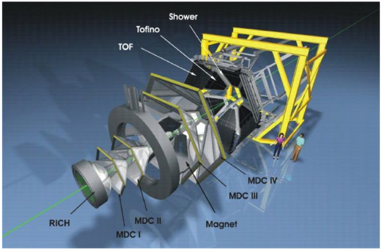
Reasons for weak sensitivity

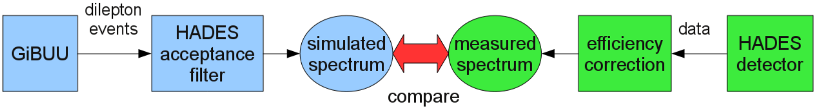
1. long ω decay length [few decays in medium]
2. strong broadening/absorption [smearing of in-medium peak]
3. nuclear density profile [very few decays at full density]



The HADES detector at GSI

- "High Acceptance Di-Electron Spectrometer"
- pp, pA, AA $\rightarrow e^+e^-X$
  $\Rightarrow$ p+p@3.5GeV
  $\Rightarrow$ p+Nb@3.5GeV
- mass resolution: $\sim$ 15 MeV
- polar angle: $15^\circ < \theta < 85^\circ$
- opening angle cut: $\theta_{ee} > 9^\circ$





The Dilepton Cocktail

decay channels contributing to the dilepton spectrum:

direct decays:

- $\rho^0 \to e^+e^-$
- $\omega \to e^+e^-$
- $\phi \to e^+e^-$
- $(\eta \to e^+e^-)$

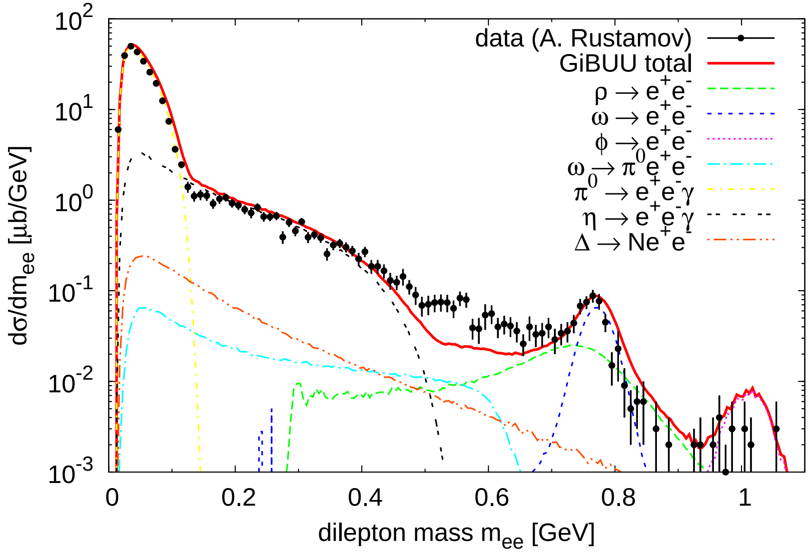
Dalitz decays:

- $\pi^0 \to e^+e^-\gamma$
- $\eta \to e^+e^-\gamma$
- $\omega \to \pi^0 e^+e^-$
- $\Delta \to Ne^+e^-$

other contributions:

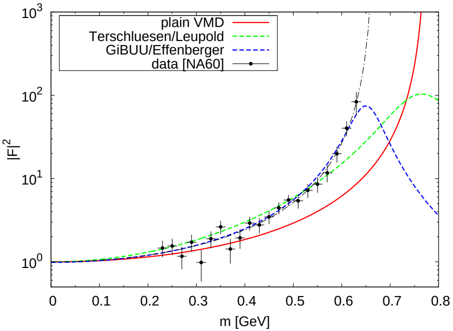
- NN-Bremsstrahlung: $NN \to NNe^+e^-$
- higher resonances?
- Bethe-Heitler process: $\gamma N \to Ne^+e^-$ (only in photoproduction)

p+p @ 3.5 GeV, mass spectrum

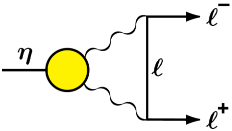


ω Dalitz decay: $\omega \to \pi^0 e^+ e^-$

- inclusive ω production cross section fixed by $\omega \to e^+e^-$, BR($\omega \to e^+e^-$) well known ($7.2 \cdot 10^{-5}$)
- ω Dalitz branching also well known
- form factor fixed by NA60 data (Arnaldi et al., PLB 677)

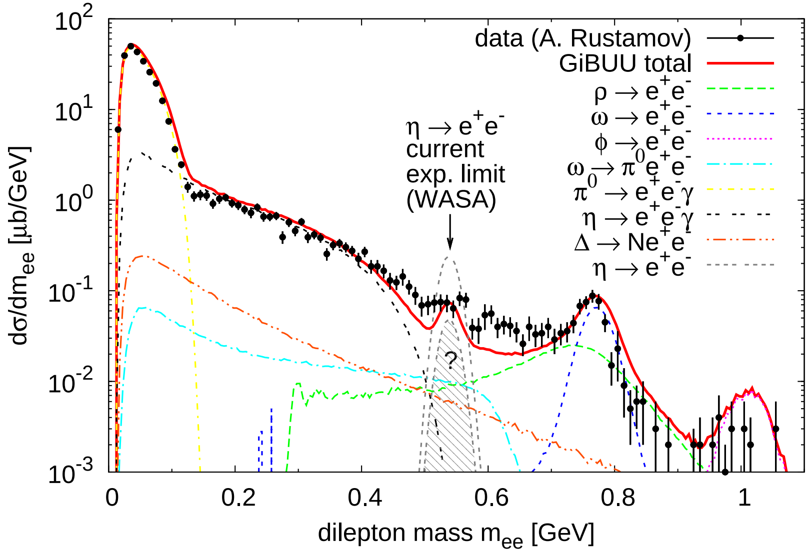


DIRECT η DECAY: $\eta \to e^+e^-$

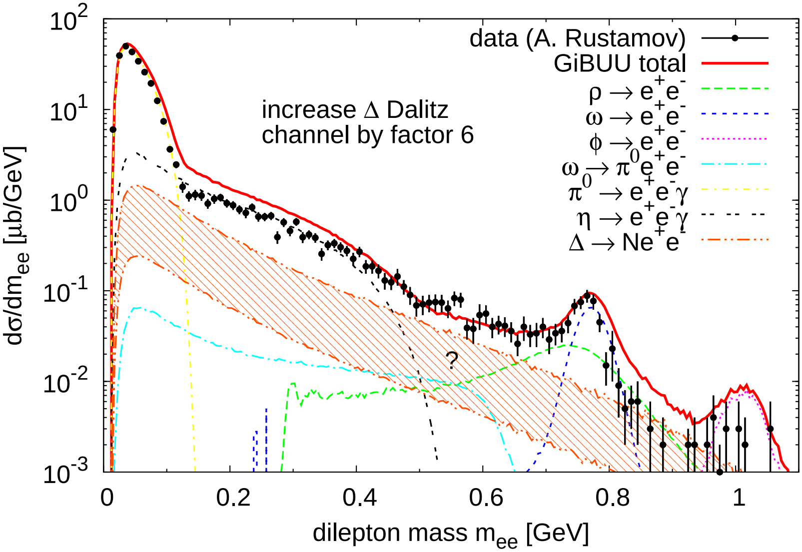


- exp. upper limit (WASA, Berlowski et al., PRD 77, 2008): BR($\eta \to e^+e^-$) $< 2.7 \cdot 10^{-5}$
- HADES might be able to push down this limit ...
- theor. prediction (Browder et al., PRD 56, 1997): BR($\eta \to e^+e^-$) $\approx 10^{-9}$

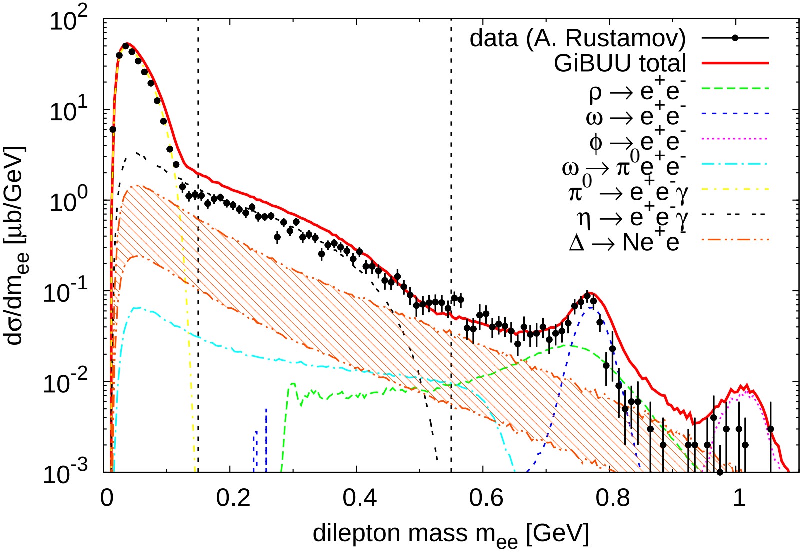
p+p @ 3.5 GeV, mass spectrum



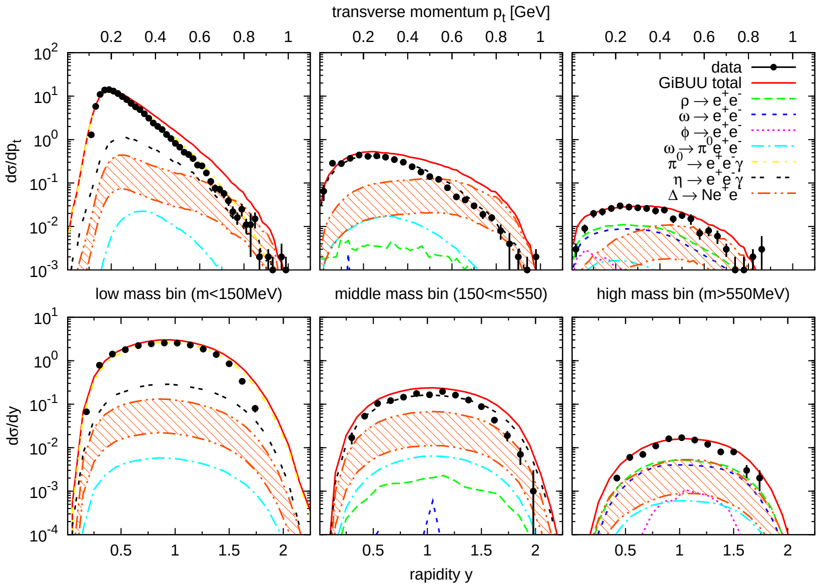
p+p @ 3.5 GeV, mass spectrum



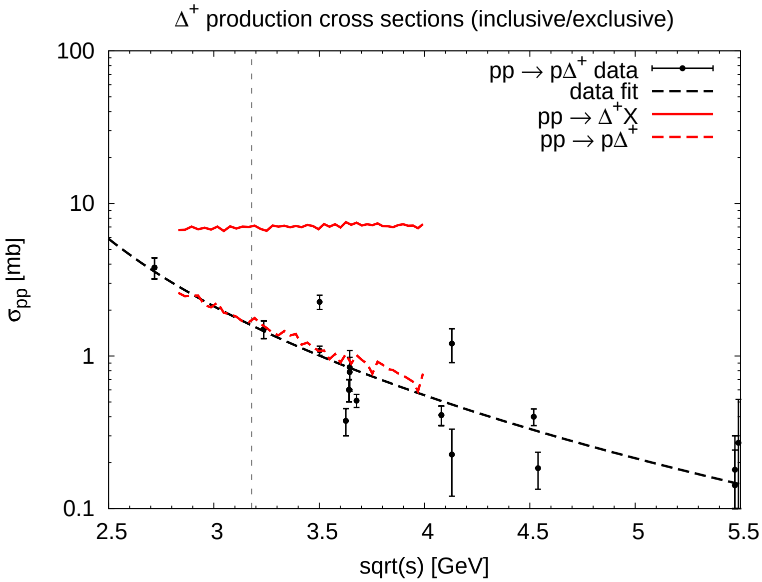
p+p @ 3.5 GeV, mass spectrum



p+p @ 3.5 GeV, p_T and rap. spectra

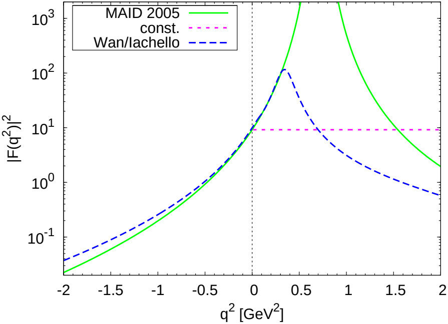


Δ production cross sections

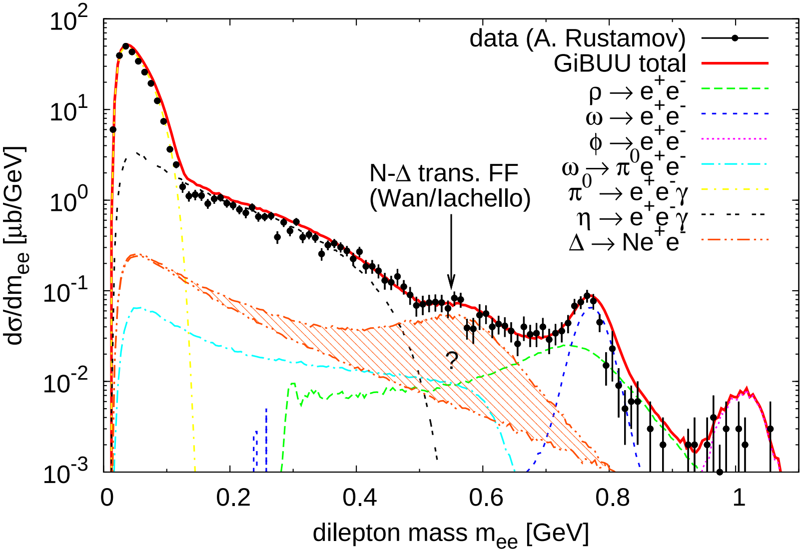


Δ Dalitz decay

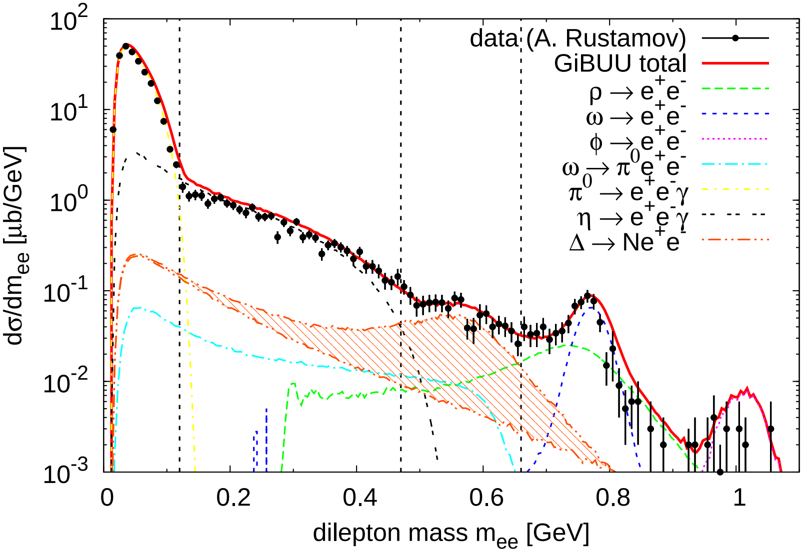
- transition form factors $\Delta \rightarrow N\gamma^*$
  - basically unknown in time-like region (no data)
  - space-like region: data from electroproduction
- best available guess for time-like region:
  two-component quark model (Wan/Iachello, IJMP A20, 2005)
  $F \sim (1-\gamma e^{i\theta} q^2)^{-2} \cdot F_\rho(q^2)$



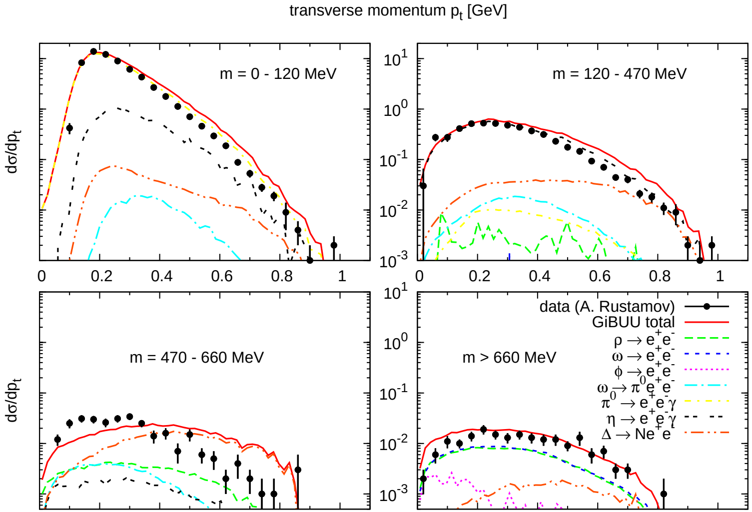
p+p @ 3.5 GeV, mass spectrum



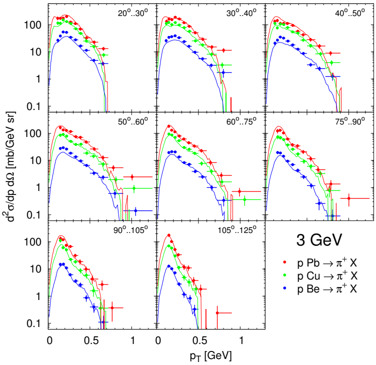
p+p @ 3.5 GeV, mass spectrum

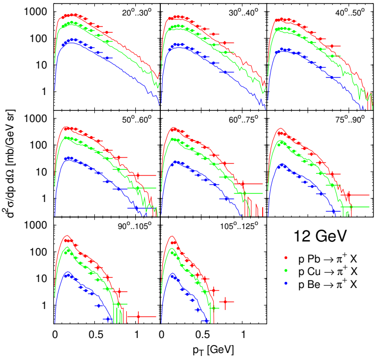


p+p @ 3.5 GeV, p_T spectra



- pions are important for normalization
- can serve as a cross check for dilepton spectra
- GiBUU nicely describes inclusive pion data by HARP (Gallmeister, NPA 826, 2009)

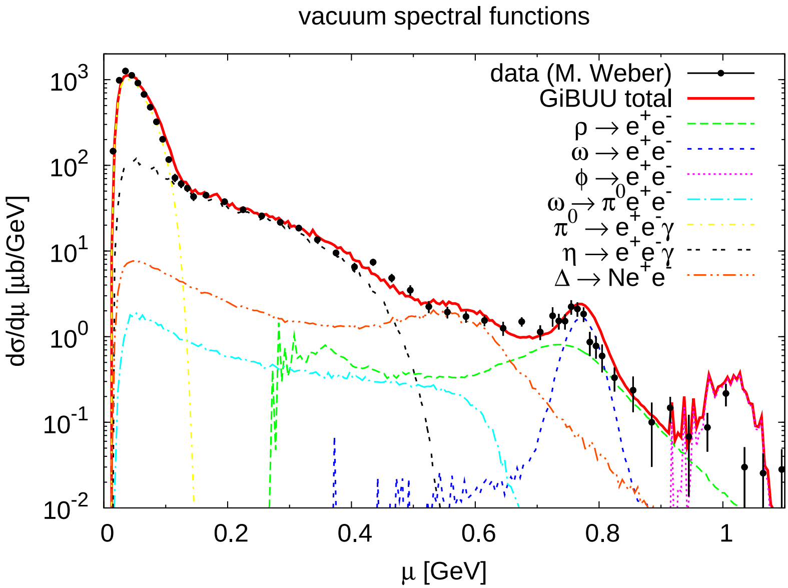




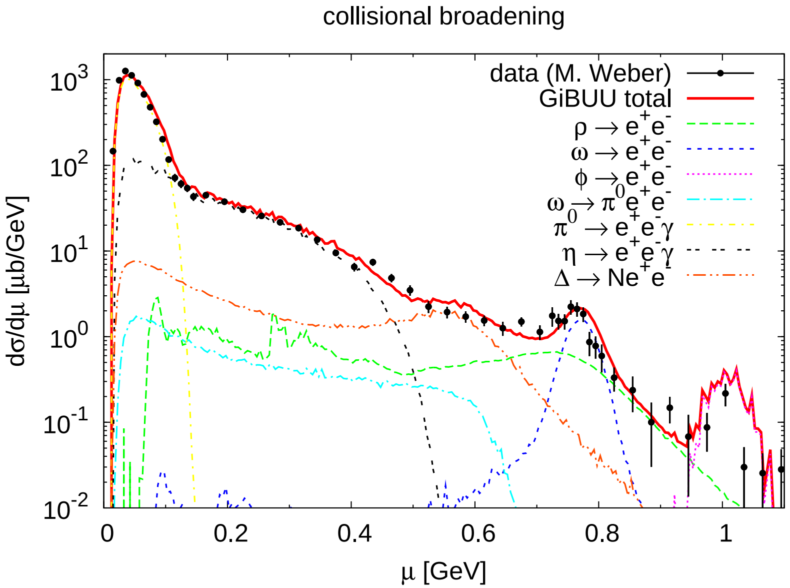
Next Step: p+Nb@3.5 GeV

- once we can reasonably describe p+p@3.5GeV: use p+p as a base line
- look for medium effects in p+Nb (at same incident energy)
- option #1: direct modification of mass spectrum (ρ?)
- option #2: transparency ratio / absorption (ω/ϕ?)
- warning: p+p not described perfectly yet
- therefore: no hard conclusions on p+Nb possible at this point

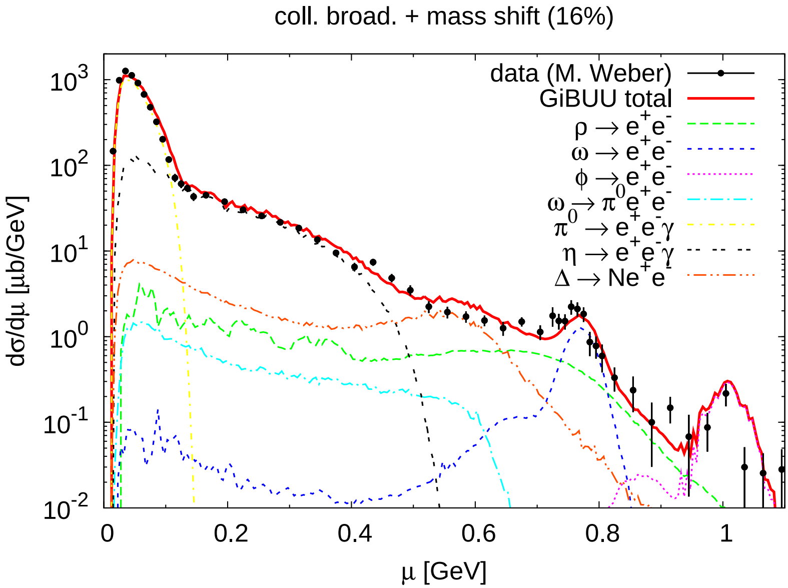
p+Nb@3.5 GeV, mass spectrum



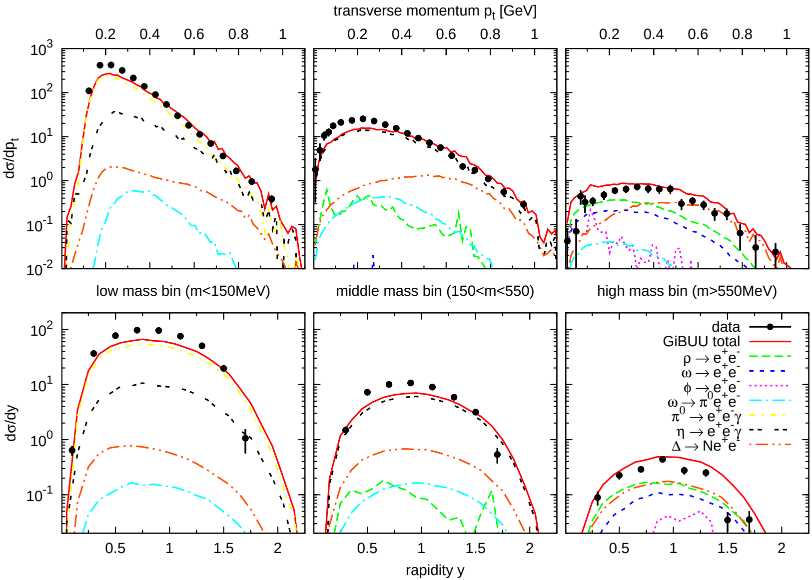
p+Nb@3.5 GeV, mass spectrum



p+Nb@3.5 GeV, mass spectrum



p+Nb@3.5 GeV, p_T and y spectra



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,
   more statistics needed (MAMI!)
4. HADES: we need to understand elementary reactions
   before we can make conclusions on p+A and A+A