Hadronic Transport with the GiBUU model

Janus Weil

Frankfurt Institute for Advanced Studies, Germany

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FIAS Frankfurt Institute for Advanced Studies

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Outline

- the GiBUU model
  - basic features and ingredients
- ω photoproduction and ω in medium
- em. formfactors
  - in particular $\omega, \phi \to \pi^0 e^+ e^-$

The GiBUU transport model

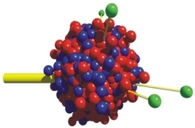
- GiBUU: "The Giessen BUU transport model"
- coupled-channel hadronic transport model, based on the Boltzmann-Uehling-Uhlenbeck equation (BUU)
- microscopic, non-equilibrium description of nuclear reactions
- unified framework for various types of reactions
  - electroweak: γA, eA, νA
  - hadronic: pA, πA, KA
  - heavy-ion collisions: AA
- wide energy range: $\sqrt{s} \approx 100$ MeV to 40 GeV
- implementation: large Fortran code ($\sim$ 100k lines of code)
- publicly available (open source) via svn or git
- current release: GiBUU 2016
- website: http://gibuu.hepforge.org
- contributors: Mosel, Gallmeister, J.W., Gaitanos, Larionov, ...
- similar models: UrQMD, HSD, JAM, ...

The BUU equation

- BUU equ.: space-time evolution of phase-space density F (from gradient expansion of Kadanoff-Baym eq.)

$$\frac{\partial(p_0 - H)}{\partial p_\mu}\frac{\partial F(x,p)}{\partial x^\mu} - \frac{\partial(p_0 - H)}{\partial x_\mu}\frac{\partial F(x,p)}{\partial p^\mu} = C(x,p)$$

- Hamiltonian H:
  - hadronic mean fields, Coulomb, "off-shell potential"
- collision term $C(x,p)$:
  - decays and scattering processes (2- and 3-body)
  - low energy: resonance model, high energy: string fragment.
- test-particle method: $F = \sum_i \delta(\vec{r} - \vec{r}_i)\delta(p - p_i)$
- review paper: O. Buss et al., Phys. Rep. 512 (2012)



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Degrees of Freedom

- included hadronic states:
  - 61 baryons
    - non-strange: N, Δ, 16 N^*, 13 Δ^* states
    - single-strange: Λ, Σ, 12 Λ^*, 7 Σ^* states
    - multi-strange/charmed: Ξ, Ω, Λ_c, Σ_c, Ξ_c, Ω_c
  - 22 mesons
    - non-strange pseudo-scalars: π, σ, f_2, η, η', η_c
    - non-strange vectors: ρ, ω, ϕ, J/Ψ
    - strange: K, K^*
    - charmed: D, D^*, D_s, D_s^*
- each of those is an isospin multiplet (we assume isospin sym.)
- plus antiparticles
- spectral functions of resonance in Breit-Wigner approximation (with mass-dependent width)

$$\mathcal{A}(m) = \frac{1}{\pi} \frac{m\Gamma(m)}{(m^2 - m_0^2)^2 + m^2\Gamma^2(m)}$$

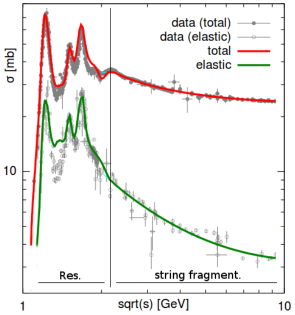
COLLISION TERM

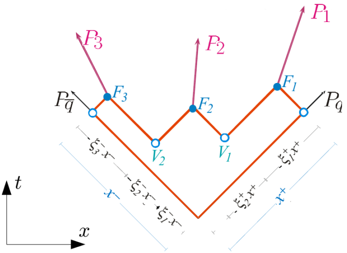
low energies: resonance model

- $\sqrt{s} \lesssim 3 GeV$
- assumption: cross sections dominated by resonance formation
- all res. parameters taken from Manley/Saleski PWA (Phys.Rev.D45,1992)

high energies: Lund string model

- PYTHIA 6.4 (or FRITIOF)
- hard pQCD interactions plus string fragmentation





POTENTIALS & PROPAGATION

- hadronic mean fields:
  - usually: Skyrme-like potentials

$$U_0(x,\vec{p}) = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma} + \frac{2C}{\rho_0}\sum_{i=p,n}\int \frac{g d^3p'}{(2\pi)^3}\frac{f_i(x,\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2}$$
$$+ d_{symm}\frac{\rho_p(x)-\rho_n(x)}{\rho_0}\tau_i$$

  - or: relativistic mean fields (RMF)
- Coulomb potential
- "off-shell potential" (for density-dependent spectral functions)
- mean-field propagation with dynamical density evolution (according to test particle distribution)

Photoproduction

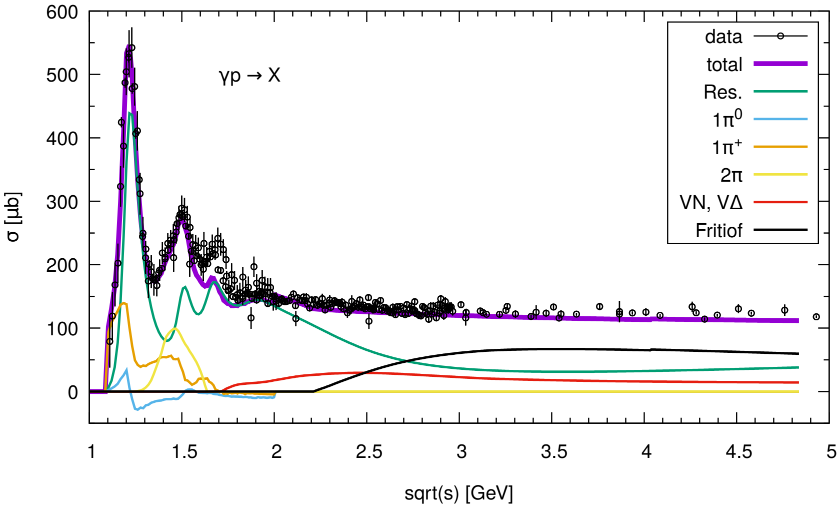
various production channels $\gamma N \to X$:

- at low energies mainly resonance production (couplings from MAID)
- supplemented with non-res. 1π and 2π backgrounds
- vector-meson production (VN and $V\Delta$ with $V = \rho, \omega, \phi$)

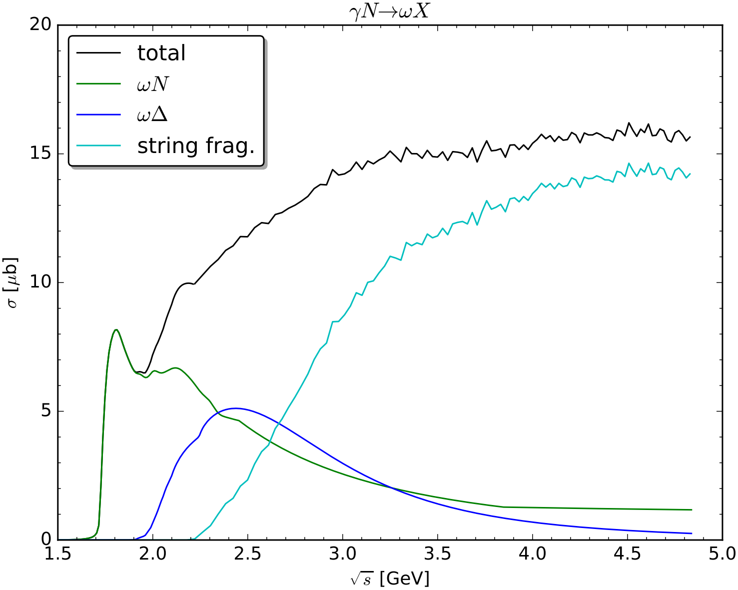
$$\sigma_{\gamma N \to VN} = \frac{1}{p_i s} \int_0^{\mu_{max}} \mathrm{d}\mu^2 \left|\mathcal{M}_V(\sqrt{s})\right|^2 p_f \mathcal{A}_V(\mu),$$

  - ωN: matrix element fitted to SAPHIR data
  - $\omega\Delta$: assume constant matrix element
- at higher energies: string fragmentation (via FRITIOF)

Photoproduction



ω PHOTOPRODUCTION



GiBUU as event generator

- GiBUU can provide a full list of produced particles (hadronic & em.)
- complete with four-momenta etc
- in different formats (Les Houches, Oscar, ...)
- in principle particles can be tracked through the whole collision history
- source code & documentation available

- $\Rightarrow$ feasible to use as an event generator (for background studies etc)

- effects included: Fermi motion, Pauli blocking, production and absorption cross sections, rescattering
- limitations: interference and polarization effects are hard to handle

in-medium physics

Probing in-medium spectral functions

- direct access to in-medium spectral function (via 'line-shape analysis) is only feasible with dileptons
- hadronic decay modes suffer from FSI
  $\Rightarrow$ in-medium info will not survive
- easier to study short-lived particles
- $\rho \to e^+e^-$ and $\rho \to \mu^+\mu^-$ are the ideal cases

- other analyses (e.g. transparency meaurements) can be done with hadronic final states, but cannot provide full access to SF

Dilepton decays

- $V \to e^+e^-$ (with $V = \rho, \omega, \phi$) via strict VMD: $\Gamma(\mu) \propto \mu^{-3}$
- $P \to \gamma e^+e^-$ (with $P = \pi^0, \eta, \eta'$) [Landsberg, Phys.Rep.128, 1985]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{4\alpha}{3\pi}\frac{\Gamma_{P\to\gamma\gamma}}{\mu}\left(1 - \frac{\mu^2}{m_P^2}\right)^3 |F_P(\mu)|^2,$$

- $\omega \to \pi^0 e^+e^-$ [Landsberg]:

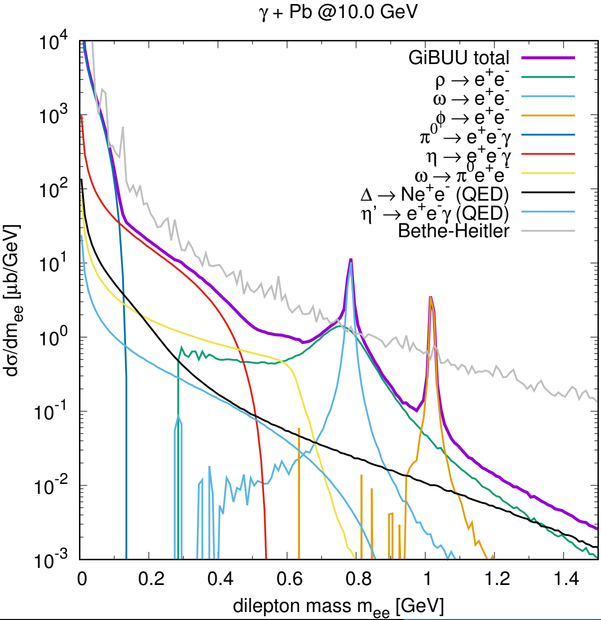
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{2\alpha}{3\pi}\frac{\Gamma_{\omega\to\pi^0\gamma}}{\mu}\left[\left(1 + \frac{\mu^2}{\mu_\omega^2 - m_\pi^2}\right)^2 - \frac{4\mu_\omega^2\mu^2}{(\mu_\omega^2 - m_\pi^2)^2}\right]^{3/2} |F_\omega(\mu)|^2$$

- $\Delta \to Ne^+e^-$ [Krivoruchenko, Phys.Rev.D65, 2002]:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mu} = \frac{2\alpha}{3\pi\mu}\frac{\alpha}{16}\frac{(m_\Delta + m_N)^2}{m_\Delta^3 m_N^2}\sqrt{(m_\Delta + m_N)^2 - \mu^2}\left[(m_\Delta - m_N)^2 - \mu^2\right]^{3/2} |F_\Delta(\mu)|^2$$

- important: form factors well restricted for π^0, η and ω, but completely unknown for Δ! (often neglected)
- Bethe-Heitler process

DILEPTON SPECTRUM AT $E_\gamma = 10$ GeV



Off-Shell Transport

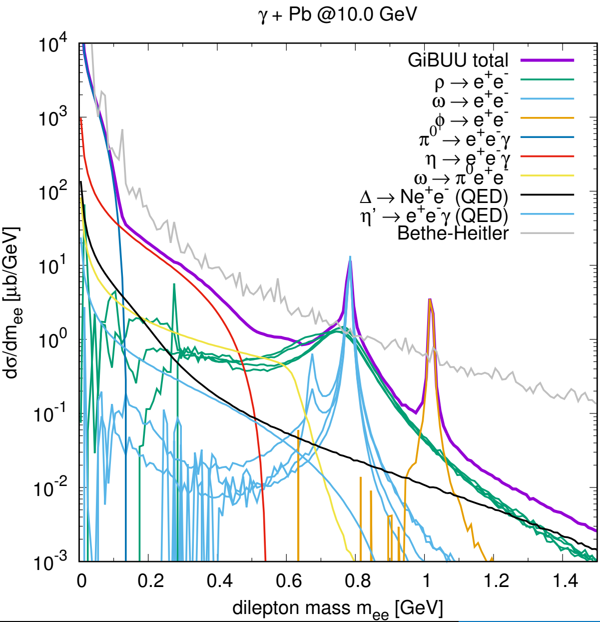
off-shell EOM for test particles:

[Cassing/Juchem (NPA 665, 2000), Leupold (NPA 672, 2000)]:

$$
\begin{aligned}
\dot{\vec{r}}_i &= \frac{1}{1-C_i}\frac{1}{2E_i}\left[2\vec{p}_i + \frac{\partial}{\partial \vec{p}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{p}_i}\right], \\
\dot{\vec{p}}_i &= -\frac{1}{1-C_i}\frac{1}{2E_i}\left[\frac{\partial}{\partial \vec{r}_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial \vec{r}_i}\right], \\
C_i &= \frac{1}{2E_i}\left[\frac{\partial}{\partial E_i} Re(\Sigma_i) + \chi_i \frac{\partial \Gamma_i}{\partial E_i}\right], \\
\chi_i &= \frac{m_i^2 - M^2}{\Gamma_i}, \quad \frac{d\chi_i}{dt} = 0
\end{aligned}
$$

- needed to incorporate density-dependent spectral functions (self energy Σ_i, width $\Gamma_i \sim Im(\Sigma_i)$)
- test particles dynamically change their masses
- but: some approximations required
  - neglecting momentum dependence
  - only works 'close to mass shell'

IN-MEDIUM MODIFICATIONS



assume

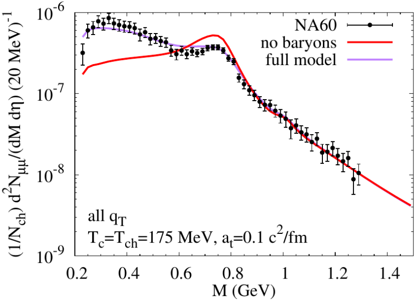
$\Gamma_{coll} = 150\,\mathrm{MeV} \cdot \frac{\rho}{rho_0}$,

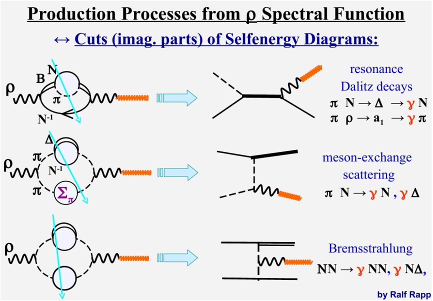
$m^* = m \cdot (1 - 0.16\frac{\rho}{rho_0})$

timelike em. formfactors

NA60: DILEPTONS IN HIC

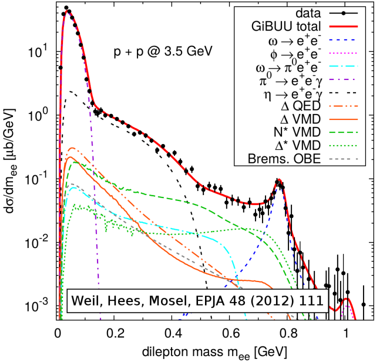
- important dimuon experiment at CERN-SPS, $\sqrt{s} \approx 17\,\mathrm{GeV}$
- NA60 data showed: ρ^0 spectral function substantially broadened in medium (but essentially no mass shift)
- shown by Rapp/Hees: mainly driven by baryonic effects (coupling to N^* resonances)
- H. van Hees, R. Rapp, NPA 806 (2008) 339

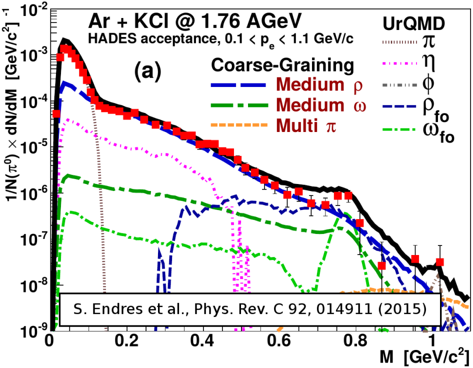


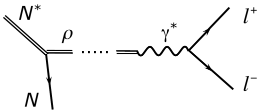


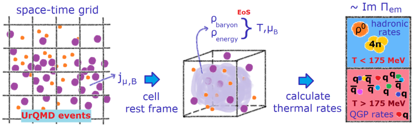
HADES

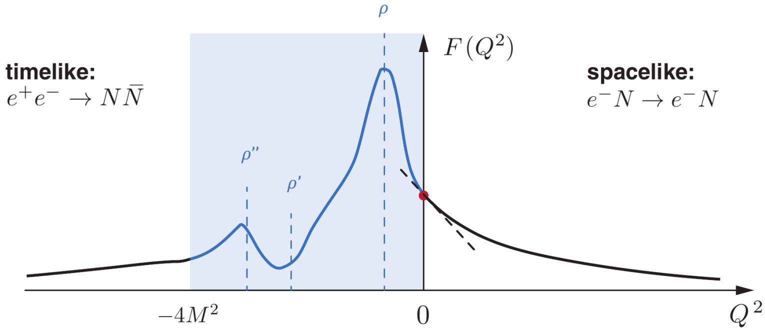
- dielectrons, lower energies (GSI), $\sqrt{s} \approx 2 - 3\,\mathrm{GeV}$
- baryon resonances even more important (even in vacuum)



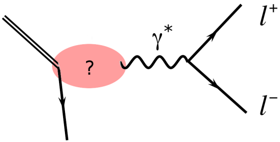




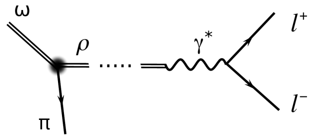




- em. form factors occur in different physical processes
- vector-meson region only accessible via dilepton decays



- VMD hypothesis handled well in transport via 2-step decay

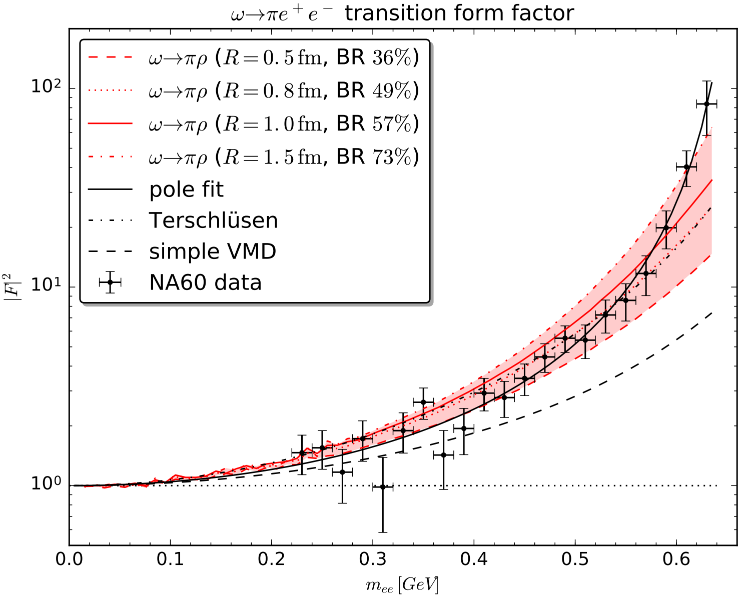


- decay width of $\omega \to \pi\rho$ given by spectral function, phase space and Blatt-Weisskopf factor

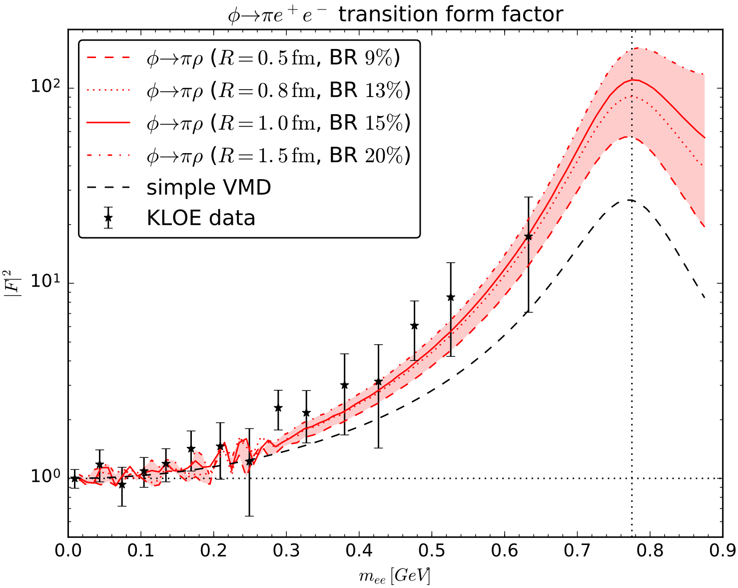
$$\frac{d\Gamma_{\omega\to\pi\rho}}{dm_\rho} \propto \mathcal{A}_\rho(m_\rho) \cdot p_F(m_\omega, m_\rho, m_\pi) \cdot B_L^2(p_F R)$$

- B_L includes phase-space factors (depending on L) and hadronic FF on ω-π-ρ vertex (finite size $R \approx 1$ fm)
- this hadronic FF is the only difference to 'simple VMD'
- J.W. et al., arXiv:1604.07028

ω FORMFACTOR



ϕ FORMFACTOR



more FFs

- even more interesting: em. form factors of baryons
- e.g. $\Delta \to Ne^+e^-$ or $N^*(1520) \to Ne^+e^-$
- experimentally completely unknown in time-like region
- $N^*(1520)$ is being measured by HADES with pion beam
- strict VMD is not expected to work well for $N^*(1520)$

- in general: many FFs not measured at all (in particular time-like), or data quality is limited
- apart from em. FFs, also tests of VMD in hadronic channels are interesting ($\omega, \phi \to 3\pi$ etc)

Summary / Conclusions

- transport models are an important tool to understand and interpret exp. results

- GiBUU includes a wide range of physics
- in particular useful for in-medium studies

- em. FFs are an interesting observable
- they can be generated dynamically in a transport approach

Backup

ω ABSORPTION CROSS SECTION