Dilepton Production with SMASH
– A New Transport Model

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FAIRNESS
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what’s so interesting about dileptons?

some important results
- NA60
- HADES

the SMASH model
- basic features
- first dilepton results
- in particular: focus on $\omega$ meson
dileptons ($e^+e^−, \mu^+\mu^−$) are an important probe of physics at high densities and temperatures
- only em. interaction, traverse hadronic medium
- “electromagnetic probe for studying QCD physics”

- vector mesons carry quantum numbers of a ’heavy photon’, can directly convert into a lepton pair
- important application of dileptons: observe in-medium spectral function of vector mesons
- naive expectations: broadening or shift of spectral functions at finite density/temperature
important dimuon experiment at CERN-SPS, $\sqrt{s} \approx 17$ GeV
NA60 data showed: $\rho^0$ 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
- dielectrons, lower energies (SIS18), $\sqrt{s} \approx 2 - 3$ GeV
- baryon resonances even more important (even in vacuum)

**Figure:**

- Graph showing dilepton production with SMASH, comparing data, GIBUU total, and other models.
- Legend includes various decay channels and models such as $\pi$, $\rho$, $\omega$, and others.
- Reference: Weil, Hees, Mosel, EPJA 48 (2012) 111
Simulating Many Accelerated Strongly-interacting Hadrons

new hadronic transport model (written in C++), developed in group of Hannah Petersen at FIAS

solves the relativistic Boltzmann equation for a hadron gas:

\[ p^\mu \partial_\mu f_i(x, p) = I_{coll}[f_i, f_j, ...] \]

optional: Skyrme potential, Pauli blocking etc
use test-particle method to improve sampling of phase space

model is still under development (currently v0.9), but already yields some interesting results
results shown here: so far only qualitative, need to be worked out further (no detector acceptance yet, etc)
hadrons included in the SMASH model:

- **mesons:**
  - $\pi, \rho, \eta, \omega, \phi, \sigma, f_2$
  - $K, K^*(892), K^*(1410)$

- **baryons:**
  - $N + 16 \ N^* \text{ states}$
  - $\Delta + 7 \ \Delta^* \text{ states}$
  - $\Lambda + 7 \ \Lambda^* \text{ states}$
  - $\Sigma + 4 \ \Sigma^* \text{ states}$
  - $\Xi, \Omega$

- plus antiparticles

- assuming isospin symmetry
SMASH: resonance implementation

- primary particle production mechanisms in few-GeV regime:
  - $NN \rightarrow B_1 B_2$
  - $\pi N \rightarrow B$
- with baryons $B = N, N^*, \Delta, \Delta^*$
- essentially all mesons ($m = \pi, \eta, \rho, \omega, \ldots$) produced via $B^*$ decays, $B^* \rightarrow mN$ etc
- model currently only contains $1 \leftrightarrow 2$ and $2 \leftrightarrow 2$ processes (in order to strictly fulfill detailed balance)
- no string fragmentation yet

- $\omega$ meson:
  - dominantly decays into $3\pi$ ($\sim 90\%$)
  - $\omega \rightarrow 3\pi$ emulated by decay chain $\omega \rightarrow \rho \pi \rightarrow 3\pi$ in Smash
2 → 1 resonance production (Breit-Wigner):

\[
\sigma_{ab \rightarrow R}(s) = \frac{2J_R + 1}{(2J_a + 1)(2J_b + 1)} S_{ab} \frac{4\pi}{p_{cm}^2} \frac{s\Gamma_{ab \rightarrow R}(s)\Gamma_R(s)}{(s - M_0^2)^2 + s\Gamma_R(s)^2}
\]

2 → 2 (e.g. \(NN \rightarrow N\Delta\)):

\[
\sigma_{ab \rightarrow Rc}(s) = C_l^2 \frac{|M|_{ab \rightarrow Rc}^2}{64\pi^2 s} \frac{4\pi}{p_{cm}^i} \int dm^2 A(m^2) p_{cm}^f
\]

with the spectral function \(A(m) = \frac{1}{\pi} \frac{m\Gamma(m)}{(m^2-M_0^2)^2 + m^2\Gamma(m)^2}\)
TIME EVOLUTION OF THE ENERGY DENSITY

- $Au + Au$ at $E_{Kin} = 0.8$ GeV with $b = 3$ fm
- Landau rest frame energy density $T^{00}_L$ (background color)
- velocity of Landau frame (arrows), both for baryons
time evolution of density at center of collision compared to UrQMD
most channels as expected (std Dalitz decays etc)
- $\rho$ includes Dalitz-like contributions from $N^*$ decays
- most surprising: $\omega$
whole cocktail of $N^*$ and $\Delta^*$ decays

different shapes (mostly determined by res. mass)

plus: "feed-down" from $\omega$ (aka $\omega$ Dalitz decay)
Dalitz decay

- red: Dalitz decay with FF (fit to data)
- blue: 2-step decay via $\rho$
- both are reasonably similar, but do not agree fully
- to do: compare to NA60 data for $\omega$ FF
ω-like contributions ($N^*$ Dalitz decays)

- again: contributions from several $N^*$ resonances
- structure: peak at $\omega$ pole mass, plus Dalitz-like tail
- branching ratios from PDG 2014
new $N^* \to N\omega$ branching ratios

from recent PWA of photoproduction data by Bonn-Gatchina group (arXiv:1601.0609)

⇒ even stronger $\omega$ production (at least in low-mass tail)
fully dominated by baryonic Dalitz decays via $\rho$ and $\omega$
preliminary! further checks required ...
the SMASH model shows some interesting first results for dilepton production at SIS energies...

2-step VMD approach yields good estimate of $\omega$ Dalitz FF

em. Dalitz decays of $N^*$ resonances are quite important

ey can not only go through $\rho$, but also through $\omega$ meson

to do:

- apply detector acceptance
- compare to pp data
- possibly adjust some res. properties (branching ratios etc)
- look at heavy-ion data
- cross-check with pion beam
Backup Slides
Skyrme potentials

standard Skyrme-type potential (without mom-dep.):

\[ U = a \left( \frac{\rho}{\rho_0} \right) + b \left( \frac{\rho}{\rho_0} \right)^\tau + 2S_{pot} \frac{\rho_p - \rho_n}{\rho_0} \cdot \frac{l_3}{l} \]

\[ H_i = \sqrt{p_i^2 + m_i^2} + U(r_i) \]

parameters:
\[ a = -209.2 \text{ MeV}, \quad b = 156.4 \text{ MeV}, \quad \tau = 1.53, \quad S_{pot} = 18 \text{ MeV} \]

[Shanghai WS 2014]
⇒ rather soft EOS: \( K = 240 \text{ MeV} \)

equations of motion:

\[ \frac{dr_i}{dt} = \frac{\partial H_i}{\partial p_i} = \frac{p_i}{\sqrt{p_i^2 + m_i^2}} \]

\[ \frac{dp_i}{dt} = -\frac{\partial H_i}{\partial r_i} = -\frac{\partial U}{\partial r_i} \]
use Manley/Saleski ansatz:

$$\Gamma_{R \rightarrow ab} = \Gamma_{R \rightarrow ab}^0 \frac{\rho_{ab}(m)}{\rho_{ab}(M_0)}$$

$$\rho_{ab}(m) = \int dm_a dm_b A_a(m_a^2) A_b(m_b^2) \frac{p_f}{m} B_L^2(p_f R) F_{ab}^2(m)$$

example: $L = 1$ decays with stable daughters ($\Delta \rightarrow \pi N, \rho \rightarrow \pi\pi$):

$$\Gamma(m) = \Gamma_0 \frac{m_0}{m} \left( \frac{q}{q_0} \right)^3 \frac{q_0^2 + \Lambda^2}{q^2 + \Lambda^2}$$