Dilepton Production with SMASH – a new transport model

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FAIRNESS
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FIAS Frankfurt Institute for Advanced Studies
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Outline

- what's so interesting about dileptons?
- some important results
  - NA60
  - HADES
- the SMASH model
  - basic features
  - first dilepton results
  - in particular: focus on ω meson

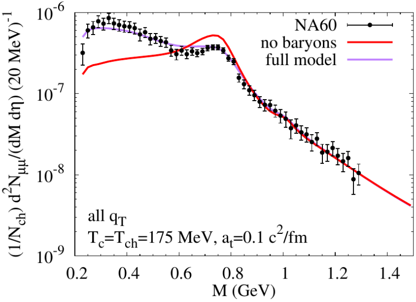
Intro & Motivation

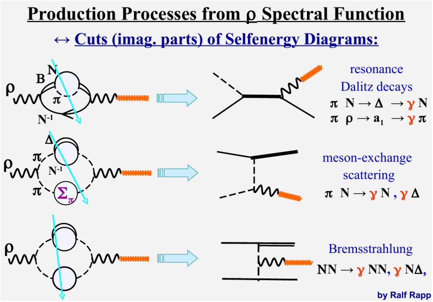
- dileptons (e^+e^-, $\mu^+\mu^-$) are an important probe of physics at high densities and temperatures
- only em. interaction, traverse hadronic medium
- "electromagnetic probe for studying QCD physics"

- 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

NA60

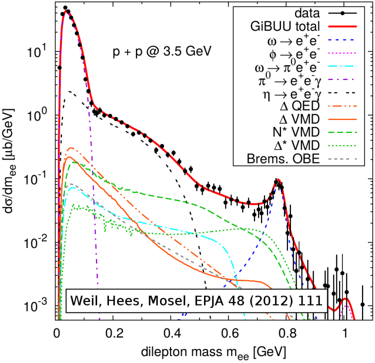
- important dimuon experiment at CERN-SPS, $\sqrt{s} \approx 17\,\mathrm{GeV}$
- NA60 data showed: ρ^0 spectral function substantially broadened in medium (but essentially no mass shift)
- shown by Rapp/Hees: mainly driven by baryonic effects (coupling to N^* resonances)
- H. van Hees, R. Rapp, NPA 806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

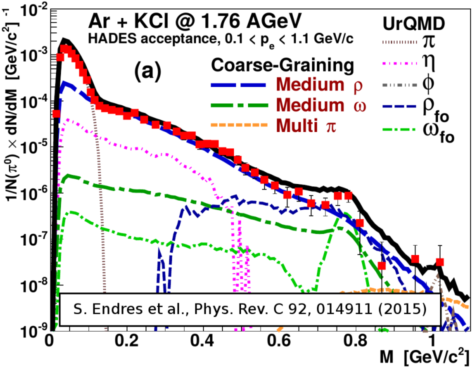


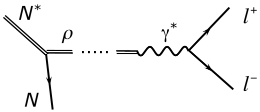


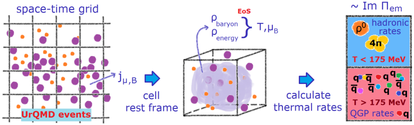
HADES

- dielectrons, lower energies (SIS18), $\sqrt{s} \approx 2 - 3\,\mathrm{GeV}$
- baryon resonances even more important (even in vacuum)









SMASH

- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- 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)

DEGREES OF FREEDOM

hadrons included in the SMASH model:

- mesons:
  - π, ρ, η, ω, ϕ, σ, f_2
  - K, $K^*(892)$, $K^*(1410)$
- baryons:
  - N + 16 N^* states
  - Δ + 7 Δ^* states
  - Λ + 7 Λ^* states
  - Σ + 4 Σ^* states
  - Ξ, Ω
- plus antiparticles
- assuming isospin symmetry

SMASH: resonance implementation

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

- ω meson:
  - dominantly decays into 3π ($\sim 90\%$)
  - $\omega \to 3\pi$ emulated by decay chain $\omega \to \rho\pi \to 3\pi$ in Smash

$2 \to 1$ resonance production (Breit-Wigner):

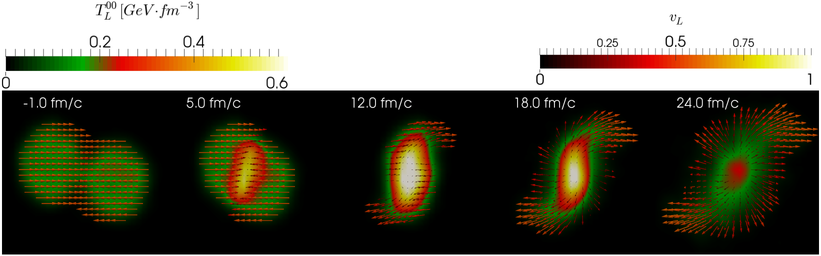
$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)} \mathcal{S}_{ab} \frac{4\pi}{p_{cm}^2} \frac{s\Gamma_{ab\to R}(s)\Gamma_R(s)}{(s-M_0^2)^2 + s\Gamma_R(s)^2}$$

$2 \to 2$ (e.g. $NN \to N\Delta$):

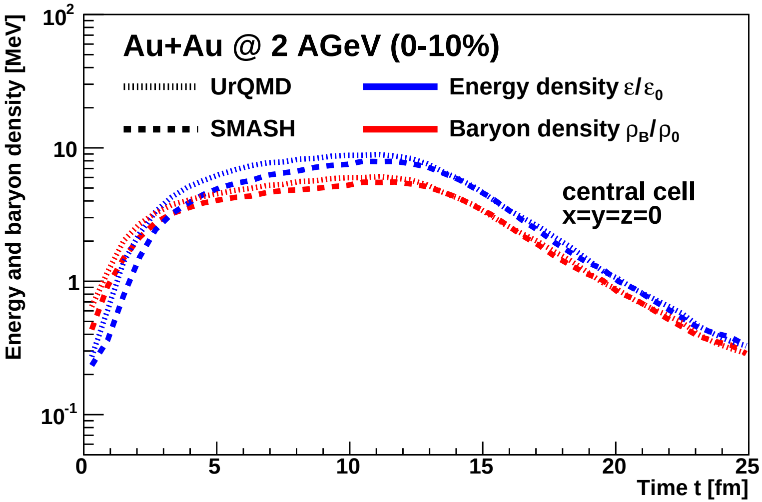
$$\sigma_{ab\to Rc}(s) = C_I^2 \frac{|M|^2_{ab\to Rc}}{64\pi^2 s} \frac{4\pi}{p_{cm}^i} \int dm^2 \mathcal{A}(m^2) p_{cm}^f$$

with the spectral function $\mathcal{A}(m) = \frac{1}{\pi} \frac{m\Gamma(m)}{(m^2-M_0^2)^2 + m^2\Gamma(m)^2}$

TIME EVOLUTION OF THE ENERGY DENSITY

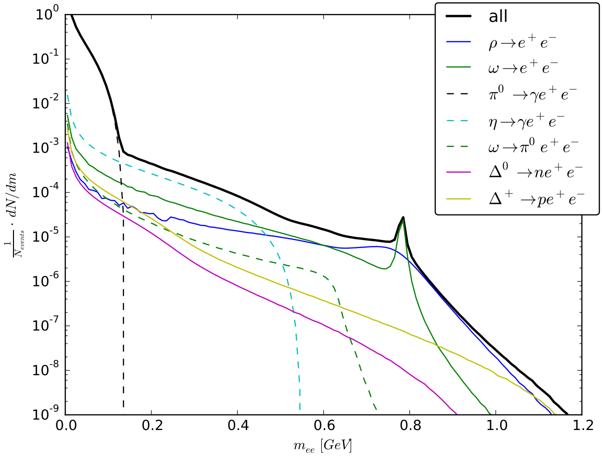


- $Au + Au$ at $E_{Kin} = 0.8$ GeV with $b = 3$ fm
- Landau rest frame energy density T_L^{00} (background color)
- velocity of Landau frame (arrows), both for baryons



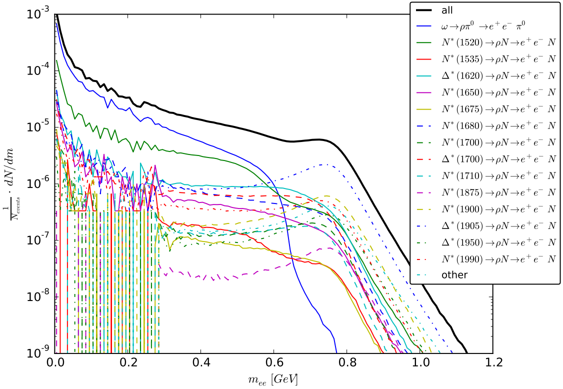
time evolution of density at center of collision compared to UrQMD

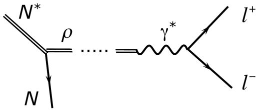
DILEPTON SPECTRUM: P+P @ 3.5 GeV



- most channels as expected (std Dalitz decays etc)
- ρ includes Dalitz-like contributions from N^* decays
- most surprising: ω

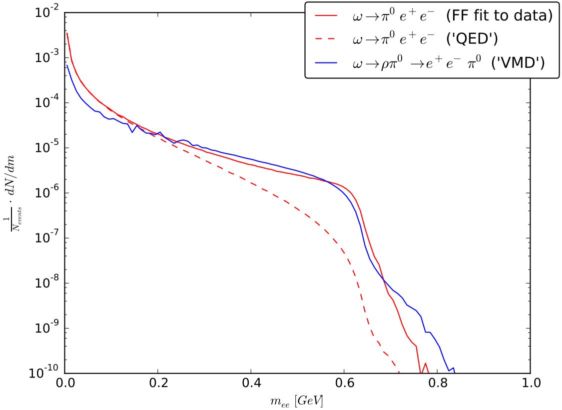
ρ-like contributions (B^* Dalitz decays)

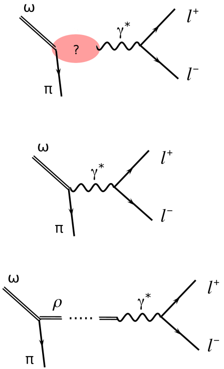




- whole cocktail of N^* and Δ^* decays
- different shapes (mostly determined by res. mass)
- plus: "feed-down" from ω (aka ω Dalitz decay)

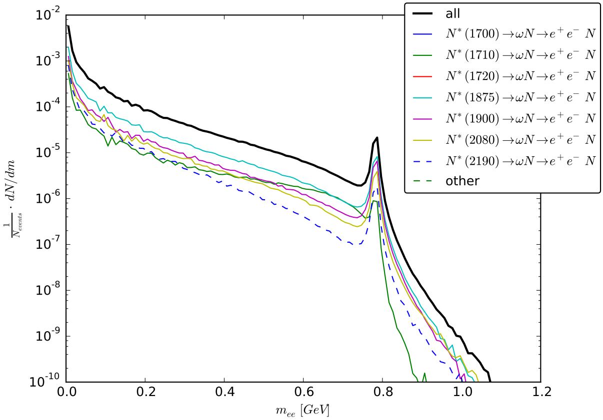
ω Dalitz decay

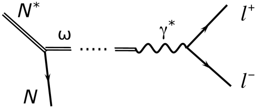




- red: Dalitz decay with FF (fit to data)
- blue: 2-step decay via ρ
- both are reasonably similar, but do not agree fully
- to do: compare to NA60 data for ω FF

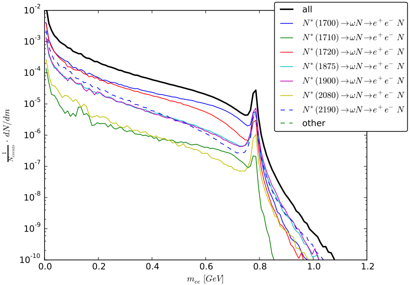
ω-like contributions (N^* Dalitz decays)

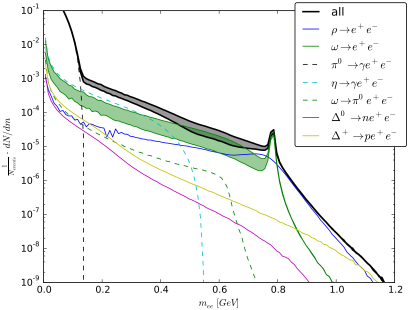




- again: contributions from several N^* resonances
- structure: peak at ω pole mass, plus Dalitz-like tail
- branching ratios from PDG 2014

ω FROM BONN-GATCHINA

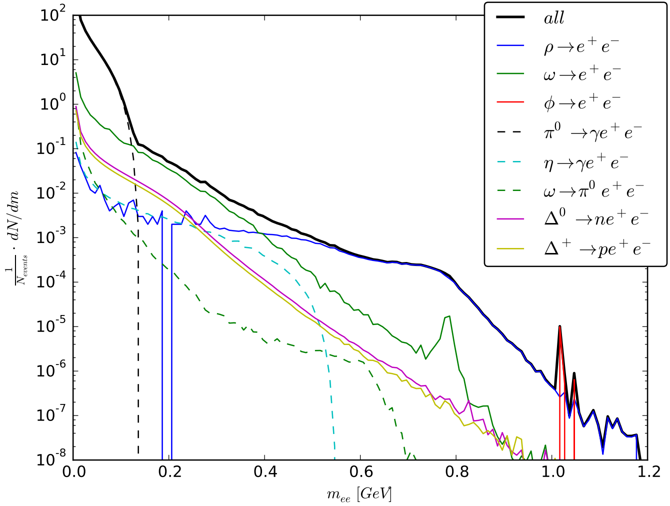




- new $N^* \to N\omega$ branching ratios
- from recent PWA of photoproduction data by Bonn-Gatchina group (arXiv:1601.0609)
- $\Rightarrow$ even stronger ω production (at least in low-mass tail)

Resonance	B.R.	$\delta(\chi^2)$	Resonance	B.R.	$\delta(\chi^2)$
$N(1700)3/2^-$	22 ± 12	100	$N(1900)3/2^+$	15 ± 8 13 ± 9	70
$N(1710)1/2^+$	2 ± 2 8 ± 5	26	$N(2000)5/2^+$	18 ± 8 1 ± 1	42
$N(1720)3/2^+$	26 ± 14	105	$N(2060)5/2^-$	4 ± 3	37
$N(1875)3/2^-$	13 ± 7 20 ± 4	98	$N(2100)1/2^+$	15 ± 10	78
$N(1880)1/2^+$	20 ± 8	33	$N(2150)3/2^-$	12 ± 8	99
$N(1895)1/2^-$	28 ± 12	100	$N(2190)7/2^-$	14 ± 6	131

Au+Au @ 1.25 GeV



- fully dominated by baryonic Dalitz decays via ρ and ω
- preliminary! further checks required ...

Summary / Conclusions / Outlook

- the SMASH model shows some interesting first results for dilepton production at SIS energies...
- 2-step VMD approach yields good estimate of ω Dalitz FF
- em. Dalitz decays of N^* resonances are quite important
- they can not only go through ρ, but also through ω 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

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

$$U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau + 2S_{pot}\frac{\rho_p - \rho_n}{\rho_0} \cdot \frac{I_3}{I}$$

$$H_i = \sqrt{\mathbf{p_i}^2 + m_i^2} + U(\mathbf{r_i})$$

parameters:

$a = -209.2$ MeV, $b = 156.4$ MeV, $\tau = 1.53$, $S_{pot} = 18$ MeV

[Shanghai WS 2014]

$\Rightarrow$ rather soft EOS: $K = 240$ MeV

equations of motion:

$$\frac{d\mathbf{r_i}}{dt} = \frac{\partial H_i}{\partial \mathbf{p_i}} = \frac{\mathbf{p_i}}{\sqrt{\mathbf{p_i}^2 + m_i^2}}$$

$$\frac{d\mathbf{p_i}}{dt} = -\frac{\partial H_i}{\partial \mathbf{r_i}} = -\frac{\partial U}{\partial \mathbf{r_i}}$$

DECAY WIDTHS

use Manley/Saleski ansatz:

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

$$\rho_{ab}(m) = \int dm_a^2 dm_b^2 \mathcal{A}_a(m_a^2)\mathcal{A}_b(m_b^2)\frac{p_f}{m}B_L^2(p_f R)\mathcal{F}_{ab}^2(m)$$

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

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