Electromagnetic probes
Clarification on similarities and differences of models

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Outline

General scheme of models

- there are several “layers” of models for dilepton production in heavy-ion collisions:
- microscopic models for dilepton production
  - roughly speaking we deal with QED of strongly interacting particles
  - need models for strong interactions + QED
  - QCD + electromagnetic standard model
  - effective hadronic models + coupling of the photons
  - need empirical input (cross sections, electromagnetic (transition) form factors, branching ratios of hadron resonances,...
  - $\Rightarrow$ importance of elementary hadron-collision data
  - need to be evaluated in the medium
- Bulk-medium evolution
  - need evolution of the fireball over its entire history, including “chemistry” and “continuum-mechanical evolution”
  - consistency with microscopic models

Theory toolbox

- various "combinations" of bulk-medium evolution models
  + Microscopic models
  - thermal fireball models (blastwave)
    + equibrium thermal many-body QFT
  - ideal or viscous hydro
    + equibrium thermal many-body QFT
  - transport models (onshell/offshell)
    + cross sections from QFT models
  - coarse grained transport
    +equibrium thermal many-body QFT
- Approximations necessary for *all* schemes
- no fully self-consistent off-equibrium scheme available
- not even in principle!

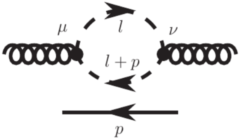
What's a "ρ meson"?

- key player for QED of hadrons: light vector mesons, particularly the "ρ meson"
- it's a resonance!!!
- it's *not* an asymptotic state
- some model dependence!
- puristic view: only reaction rates from "asymptotic free into asymptotic free out states" observable
  (S-matrix elements, cross sections, decay rates)
- observed resonance shape depends on production **and** decay channel!

The PDG "ρ meson"

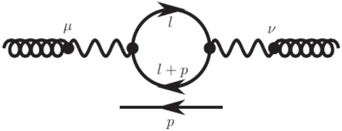
- in the PDG review of particle physics: "ρ meson" is strong resonance in isospin-1 channel of $e^+ + e^- \rightarrow \pi^+ + \pi^-$ (nearly exclusive)
- minimal model: (Extended) Vector Meson Dominance [Sak60, GS68, KLZ67]
- minimal evaluation: one-loop "ρ" self-energy $\Rightarrow$ "ρ" propagator $\Rightarrow$ "ρ" spectral function
- calculate "ρ" selfenegy (transversality from gauge invariance)

$i\Pi^{\mu\nu}_{\rho\pi\pi}(p) =$



$= is\Pi_{\rho\pi\pi}(s)\Theta^{\mu\nu}(p), \quad s = p^2$

$i\Pi^{\mu\nu}_{\rho ee}(p) =$



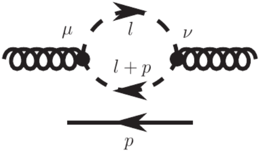
$= is\Pi_{\rho ee}(s)\Theta^{\mu\nu}(p), \quad s = p^2$

- NB: threshold at $2m_e$ ($\text{Im}\,\Pi_\rho(s) \propto \Theta(s - 2m_e)$)
- suppressed by factor $\mathcal{O}(\alpha^2) \simeq \mathcal{O}(1/137^2)$

VMD model (ρ-self-energy and dressed $\gamma\pi\pi$ vertex)

- calculate ρ-self-energy (transversality from gauge invariance)

$i\Pi^{\mu\nu}_{\rho\pi\pi}(p) =$



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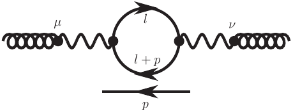


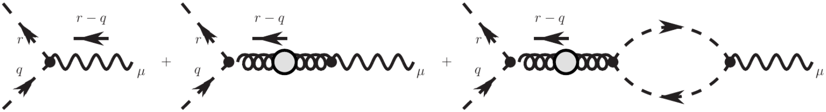
$= is\Pi_{\rho ee}(s)\Theta^{\mu\nu}(p), \quad s = p^2$

- Dressed Green's function

$$G^{\mu\nu}_{\rho}(p) = -\frac{\Theta^{\mu\nu}(p)}{p^2 - M^2 - p^2\Pi_{\rho\pi\pi}(p^2)} - \frac{\Lambda^{\mu\nu}(p)}{p^2 - M^2 + i0^+}$$

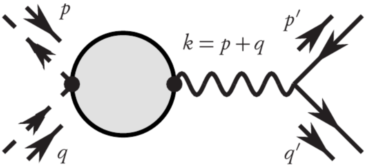
- dressed $\gamma\pi\pi$ vertex to $\mathscr{O}(e)$

$i\Gamma^{\mu}_{\gamma\pi\pi} =$

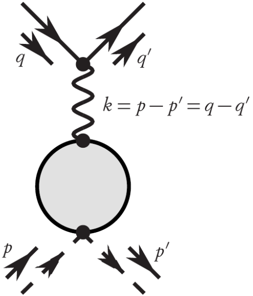


VMD model (em. form factor of the π)

- $\pi^+ + \pi^- \rightarrow e^+ + e^-$ ("time-like form factor")

$i\mathcal{M}_{fi} =$ 

- $\Rightarrow |F(s)|^2$ with Mandelstam $s = (p+q)^2$
- physical region $s > 4m_\pi^2$
- $\pi^+ + e^- \rightarrow \pi^+ + e^-$ ("space-like form factor")

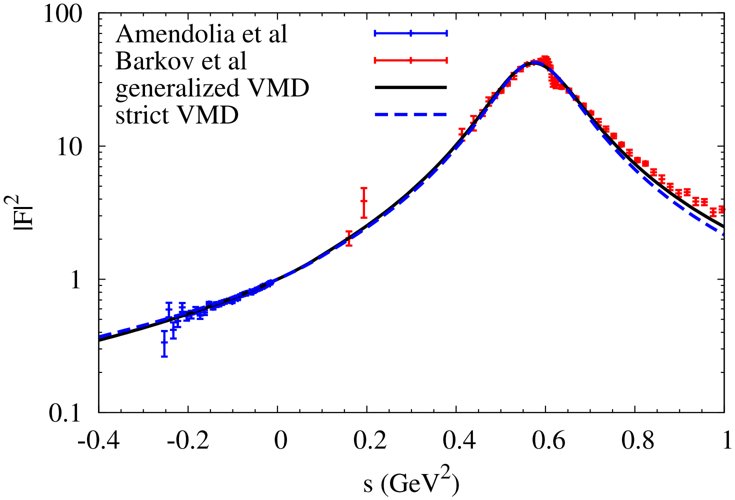
$i\mathcal{M}_{fi} =$ 

- $\Rightarrow |F(t)|^2$ with Mandelstam $t = (p-p')^2$
- physical region $t < 0$

VMD model: (fit of parameters)

- best fit to form-factor data: $g = 5.461$, $g' = 5.233$, $m_\rho = 763.1\ \mathrm{MeV}/c^2$

  strict VMD: $g \stackrel{!}{=} g' = 5.328$, $m_\rho = 763.1\ \mathrm{MeV}/c^2$



data from [A+86, BCE+85]

VMD model: (fit of parameters)

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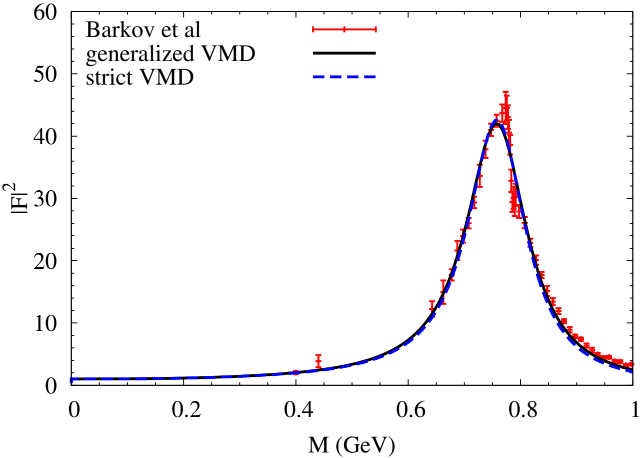


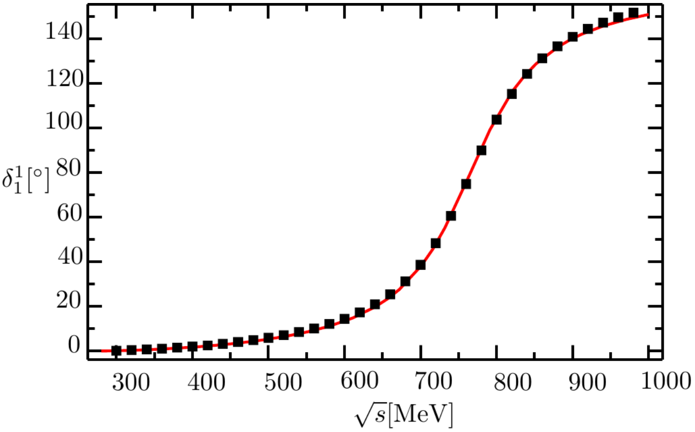
data from [BCE+85]

- small discrepancies around ρ peak: contribution from $\omega(782)$ meson!

VMD (elastic $\pi\pi$ phase shift)

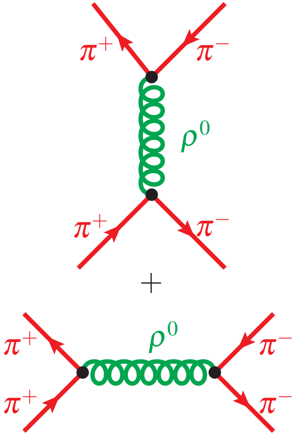
- $\pi\pi \to \pi\pi$ phase shift in $I = 1$ channel

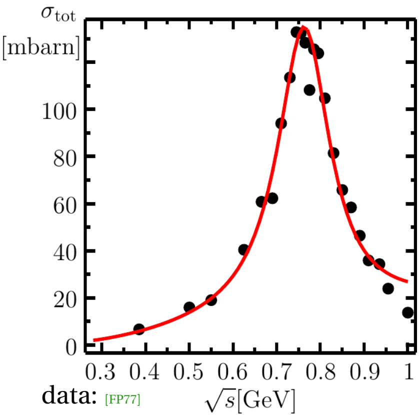
$$\delta_1^1 = \arccos \frac{\mathrm{Re}\, G_\rho}{|G_\rho|}$$



data: [FP77]

- $\pi\pi \to \pi\pi$ total cross section

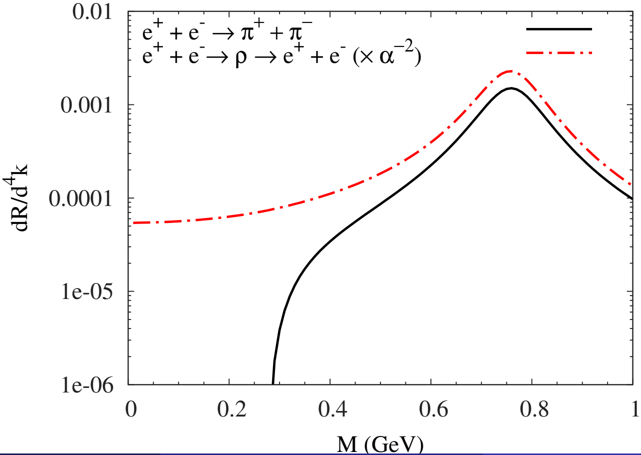




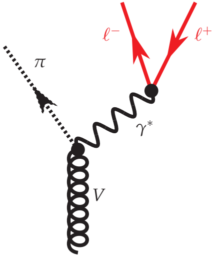
data: [FP77]

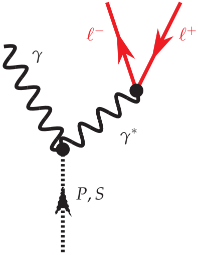
“ρ” shape: dependence on processes looked at

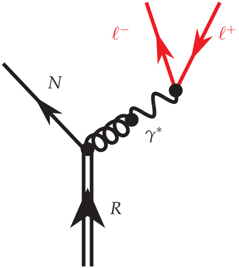
- look at “transition rates” $\sum_i' \sum_f |\mathcal{M}_{fi}|^2$ (averaged over i/summed over f)
- for $e^+ + e^- \rightarrow \pi^+\pi^-$ (“PDG definition”)
- for $e^+ + e^- \rightarrow \rho \rightarrow \mathrm{e}^+ + e^-$ (s channel)
  (annihilation part to Bhabba scattering via the ρ scaled by $\alpha^{-2} \simeq 137^2$)
- plot vs. $M = \sqrt{s}$



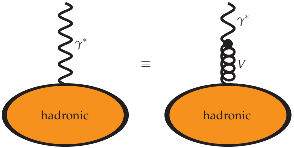
The GiBUU dileptons and “ρ mesons”





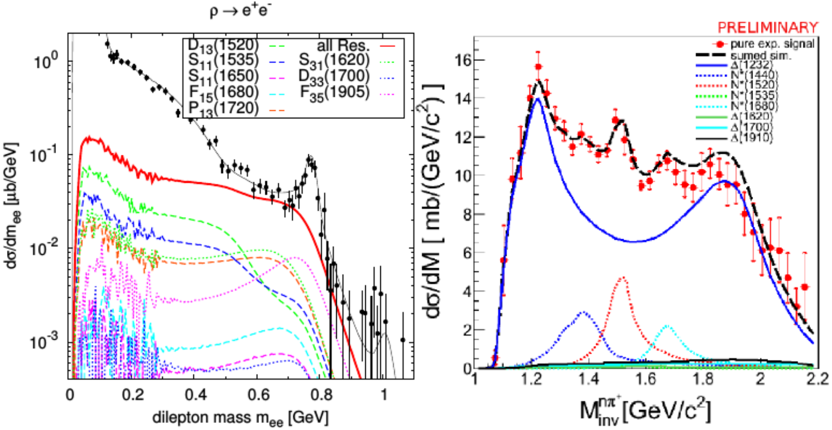


- vector mesons have “vacuum spectral shapes”
- propagated as “on-shell particles” of finite lifetime and variable mass
- Dalitz decay:
  1 particle $\rightarrow$ 3 particles
- V: $\omega \rightarrow \pi + \gamma^* \rightarrow \pi + \ell^+ + \ell^-$
- P, S: $\pi, \eta \rightarrow \gamma + \gamma^* \rightarrow \gamma + \ell^+ + \ell^-$
- R: Baryon resonances
  $\Delta, N^* \rightarrow N + V \rightarrow N + \gamma^* \rightarrow N + \ell^+ + \ell^-$
- vector-meson dominance
- model for baryon em. trans. FF



GiBUU: “ρ meson” in pp

- production through hadron resonances
  $NN \to NR \to NN\rho,\ NN \to N\Delta \to NN\pi\rho$



- plots: J. Weil et al [WHM12, ABB+14]
- VMD model ⟺ em. transition form factors of baryon resonances!
- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

GiBUU: resonances & mass distributions

- $2 \to 1$ resonance production (Breit-Wigner), e.g. $\pi\pi \to \rho$, $\pi N \to N^*$:

$$\sigma_{ab\to R}(s) = \frac{2J_R+1}{(2J_a+1)(2J_b+1)} \mathscr{S}_{ab} \frac{2\pi^2}{p_{cm}^2} \Gamma_{ab\to R}(s) \mathscr{A}_R(\sqrt{s})$$

- $1 \to 2$ res. decay (Manley), with another res. in final state, e.g. $N^* \to \rho N$:

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

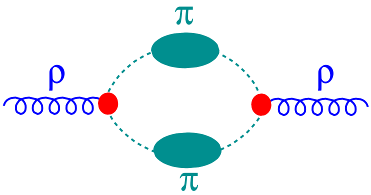
$$\rho_{ab}(m) = \int_{m_a^{min}}^{m-m_b} dm_a \mathscr{A}_a(m_a) \frac{p_f}{m} B_L^2(p_f R) \cdot \mathscr{F}_{ab}^2(m)$$

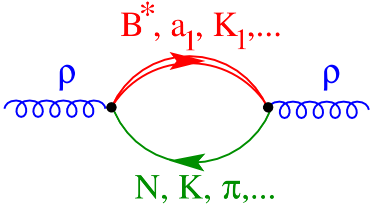
- for $\mathscr{A}$, we always use the vacuum spectral function (of ρ or N^*)
- but: effective mass distribution of produced ρ is nontrivial (**not** simply determined by vacuum SF)

$$\frac{\partial \Gamma_{R\to ab}}{\partial m_a} \propto \mathscr{A}_a(m_a) \cdot p_f \cdot B_L^2(p_f R)$$

The "Rapp-Wambach ρ"

- Phenomenological HMBT [RW99, GR99, RW00] for vector mesons
- $\pi\pi$ interactions and baryonic excitations





- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)
- underlying microscopic processes ⇔ cut the self-energy diagrams
- em. gauge invariance ⇔ vertex corrections
- ⇒ ρ production
  - via $\pi\pi$ as in vacuo
  - direct decay of hadron resonances
- very similar to Giessen model (modulo details in particle spectrum)
- well constrained by elementary scattering data!

Kinetic theory versus thermal QFT

- common microscopic starting point for in-medium calculations
  - effective hadronic theory
  - constrained by symmetries and elementary crosss sections
    $\Leftrightarrow$ very similar interactions/particle content
  - vector-meson dominance
- Kinetic theory
  - solves the Boltzmann(-Uehling-Uhlenbeck) transport equation
  - classical particle picture (usually "on the mass shell")
  - resonances: vacuum spectral function as "mass-distribution function"
  - propagated as a particle with fixed mass determined at production and finite lifetime
  - cross sections in collision term: incoherent summation over all possible processes
- Equilibrium many-body qft
  - calculate self-energies (semi-)selfconsistently with dressed propagators
  - similar to collision term in BUU simulations
  - but fully coherent summation (quantum interference!)
  - describes continuous creation-annihilation/decay processes
    ("regeneration" of resonances over lifetime of medium)
  - restricted to medium in equilibrium

Dilepton emission in HICs I

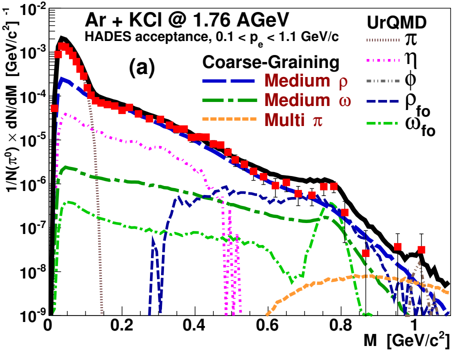
- Equilibrium bulk-medium models
  - medium as fluid in/close to local thermal equilibrium
  - different levels of sophistication: blastwave-like fireball parametrizations, ideal hydro, viscous hydro
  - equilibrium QFT dilepton rates directly usable
  - for viscous hydro partially even with off-equilibrium corrections of rates
  - approximation: medium always in/close to thermal equilibrium
- Transport simulation
  - hadrons simulated with BUU code
  - resonance decays to dileptons during entire lifetime of the medium ("shining formalism")
  - needs electromagnetic transition form factors (in GiBUU implemented via VMD aproach)
  - on-shell approach, incoherent summation over processes, medium effects implemented only partially
  - realized with GiBUU [WM13, WHM12]

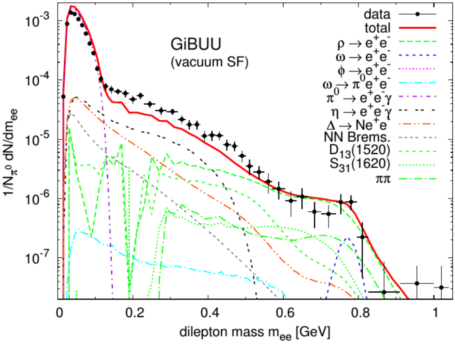
Dilepton emission in HICs II

- Transport-hydro-hybrid approach
  - initial conditions for hydro via transport (includes initial-state fluctuations)
  - (test) particles mapped to energy-momentum tensor, conserved-charge currents on a grid ("Gaussian smearing")
  - use hydro (involves equation of state!)
  - some "particlization" like Cooper-Frye
  - transport afterburner
  - dileptons via equilibrium QFT rate in hydro part
  - shining in transport-afterburner part
  - challenge: consistency of particle content in transport model, EoS of the hydro, and in QFT dilepton rate
  - realized with UrQMD [PSB+08, SSV+09, SSBS11]
- Coarse-grained transport
  - simulate the entire bulk evolution with transport
  - realize in many simulation runs
  - $T^{\mu\nu}$, j_{B}^{μ} via ensemble average on space-time grid
  - use EoS to map each fluid-grid cell to local thermal equilibrium (T, μ_{B}, μ_{π},...)
  - use equilibrium-QFT dilepton rates
  - shining afterburner for "frozen-out" fluid cells
  - realized with UrQMD [EHWB15a, EHWB15b]

Ar+KCl (1.76 *A*GeV) (SIS/HADES)

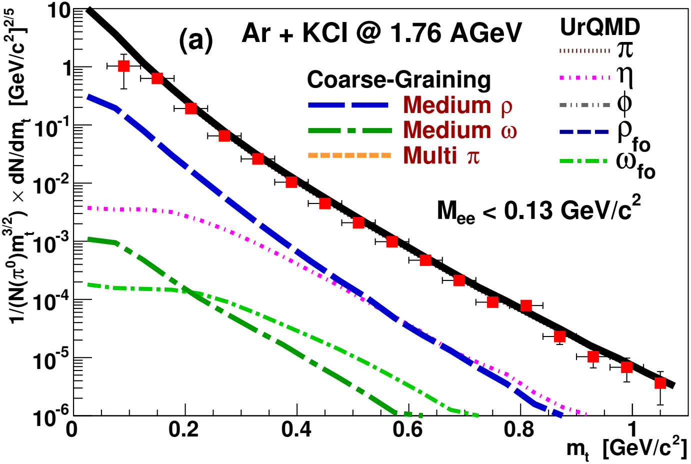
- CG UrQMD with RW in-medium rates [EHWB15b] (left) works at low energies!
- pure GiBUU transport lacks medium effects [WM13]



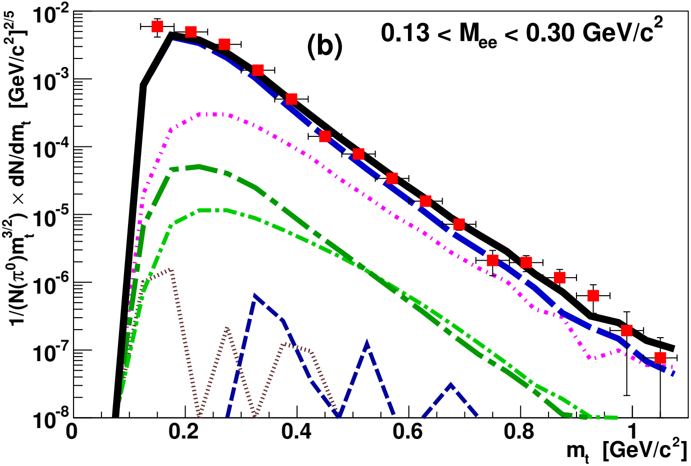


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

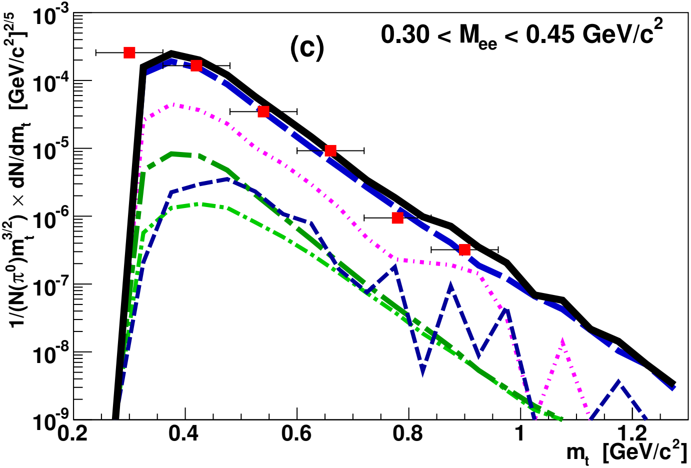
- dielectron spectra from Ar + KCl(1.76 *A*GeV) → e^+e^- (SIS/HADES)
- m_t spectra [EHWB15b]
- $M_{ee} < 0.13$ GeV



- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $0.13\ \mathrm{GeV} M_{\mathrm{ee}} < 0.3\ \mathrm{GeV}$

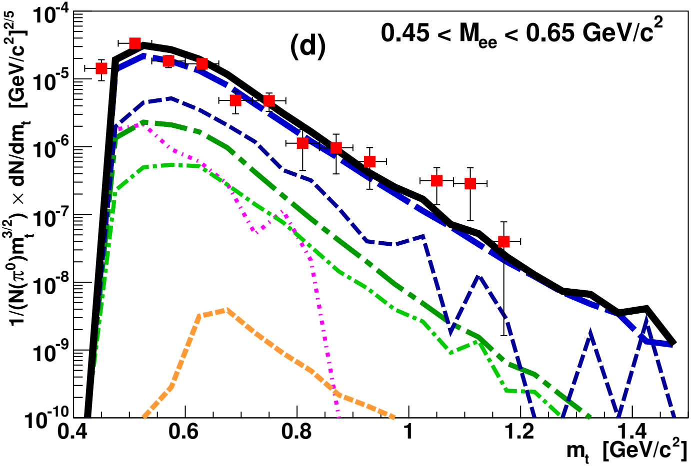


- dielectron spectra from Ar + KCl(1.76 *A*GeV) → e^+e^- (SIS/HADES)
- m_t spectra [EHWB15b]
- 0.3 GeV M_{ee} < 0.45 GeV



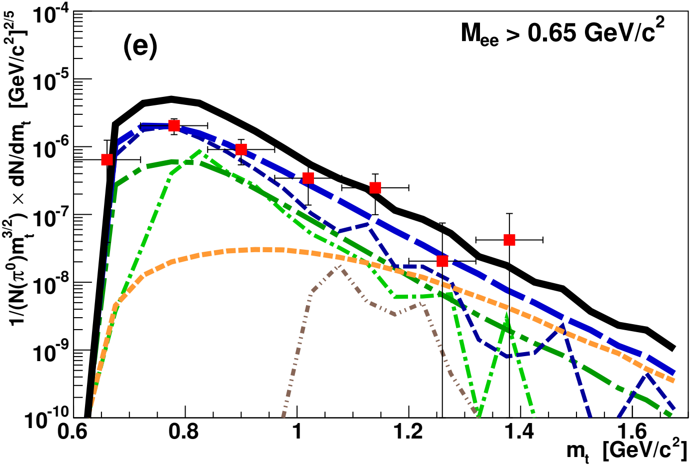
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $0.45\,\mathrm{GeV} M_{\mathrm{ee}} < 0.65\,\mathrm{GeV}$



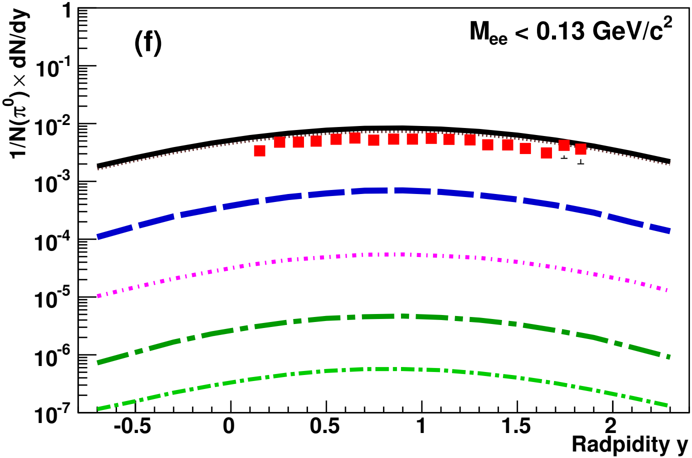
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76\,A\mathrm{GeV}) \rightarrow e^+e^-$ (SIS/HADES)
- m_t spectra [EHWB15b]
- $M_{ee} > 0.65$ GeV

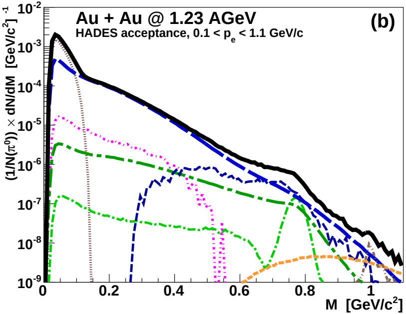


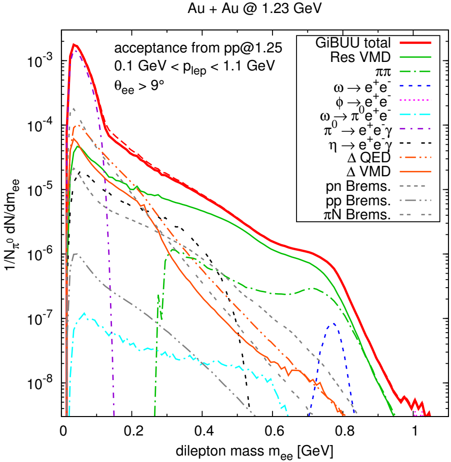
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from Ar + KCl(1.76 *A*GeV) → e^+e^- (SIS/HADES)
- rapidity spectrum ($M_{ee} < 0.13$ GeV)



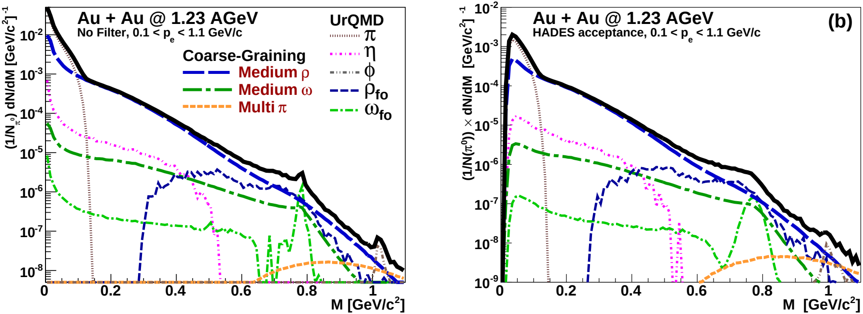
Au+Au (1.23 *A*GeV) (SIS/HADES)





- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data (data points not shown here on request of the HADES collaboration)

Au+Au (1.23 *A*GeV) (HADES acceptence)



- left: CG UrQMD without HADES acceptance filter
- right: with pp/np acceptance filter

Bibliography I

[A+86] S. Amendolia, et al., A Measurement of the Space-Like Pion Electromagnetic Form-Factor, Nucl. Phys. B **277** (1986) 168.
http://dx.doi.org/10.1016/0550-3213(86)90437-2

[ABB+14] G. Agakishiev, et al., Baryon resonance production and dielectron decays in proton-proton collisions at 3.5 GeV, Eur. Phys. J. A **50** (2014) 82.
http://dx.doi.org/10.1140/epja/i2014-14082-1

[BCE+85] L. Barkov, et al., Electromagnetic Pion Form-Factor in the Timelike Region, Nucl. Phys. B **256** (1985) 365.
http://dx.doi.org/10.1016/0550-3213(85)90399-2

[EHWB15a] S. Endres, H. van Hees, J. Weil, M. Bleicher, Coarse-graining approach for dilepton production at energies available at the CERN Super Proton Synchrotron, Phys. Rev. C **91** (2015) 054911.
http://dx.doi.org/10.1103/PhysRevC.91.054911

Bibliography II

[EHWB15b] S. Endres, H. van Hees, J. Weil, M. Bleicher, Dilepton production and reaction dynamics in heavy-ion collisions at SIS energies from coarse-grained transport simulations, Phys. Rev. C **92** (2015) 014911. `http://dx.doi.org/10.1103/PhysRevC.92.014911`

[FP77] C. D. Frogatt, J. L. Petersen, Phase-Shift Analysis of $\pi^+\pi^-$ Scattering between 1.0 and 1.8 GeV Based on Fixed Transfer Analyticity (II), Nucl. Phys. B **129** (1977) 89.

[GR99] C. Gale, R. Rapp, Rho Properties in a hot Gas: Dynamics of Meson-Resonances, Phys. Rev. C **60** (1999) 024903. `http://publish.aps.org/abstract/PRC/v60/e024903`

[GS68] G. J. Gounaris, J. J. Sakurai, Finite-Width Corrections to the Vector-Meson-Dominance Prediction for $\rho \rightarrow$ e^{+} e^{-}, Phys. Rev. Lett. **21** (1968) 244. `http://link.aps.org/doi/10.1103/PhysRevLett.21.244`

Bibliography III

[KLZ67] N. M. Kroll, T. D. Lee, B. Zumino, Neutral Vector Mesons and the Hadronic Electromagnetic Current, Phys. Rev. **157** (1967) 1376. http://link.aps.org/abstract/PR/v157/i5/p1376

[PSB+08] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher, H. Stöcker, A Fully Integrated Transport Approach to Heavy Ion Reactions with an Intermediate Hydrodynamic Stage, Phys. Rev. C **78** (2008) 044901. http://dx.doi.org/10.1103/PhysRevC.78.044901

[RW99] R. Rapp, J. Wambach, Low mass dileptons at the CERN-SPS: Evidence for chiral restoration?, Eur. Phys. J. A **6** (1999) 415. http://dx.doi.org/10.1007/s100500050364

[RW00] R. Rapp, J. Wambach, Chiral symmetry restoration and dileptons in relativistic heavy-ion collisions, Adv. Nucl. Phys. **25** (2000) 1. http://arxiv.org/abs/hep-ph/9909229

[Sak60] J. J. Sakurai, Theory of strong interactions, Ann. Phys. (NY) **11** (1960) 1. http://dx.doi.org/10.1016/0003-4916(60)90126-3

Bibliography IV

[SSBS11] E. Santini, J. Steinheimer, M. Bleicher, S. Schramm, Dimuon radiation at the CERN SPS within a (3+1)d hydrodynamic+cascade model, Phys. Rev. C **84** (2011) 014901.
http://dx.doi.org/10.1103/PhysRevC.84.014901

[SSV+09] K. Schmidt, et al., Production and evolution path of dileptons at energies accessible to the HADES detector, Phys. Rev. C **79** (2009) 064908.
http://dx.doi.org/10.1103/PhysRevC.79.064908

[WHM12] J. Weil, H. van Hees, U. Mosel, Dilepton production in proton-induced reactions at SIS energies with the GiBUU transport model, Eur. Phys. J. A **48** (2012) 111.
http://dx.doi.org/10.1140/epja/i2012-12111-9,10.1140/epja/i2012-12150-2

[WM13] J. Weil, U. Mosel, Dilepton production at SIS energies with the GiBUU transport model, J. Phys. Conf. Ser. **426** (2013) 012035.