Electromagnetic Probes in Heavy-Ion Collisions

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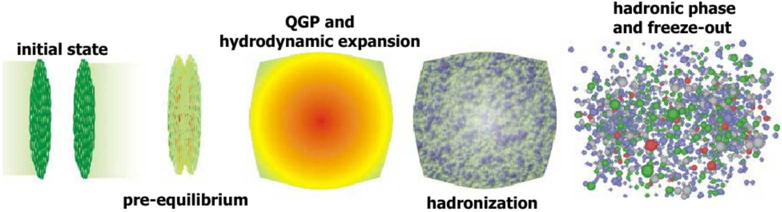
Outline

Heavy-Ion collisions in a Nutshell

- theory of strong interactions: Quantum Chromo Dynamics, QCD
- at high densities/temperatures: hadrons dissolve into a QGP
- create QGP in Heavy-Ion Collisions at RHIC (and LHC)
- GSI SIS: pp, dp, pA, AA collisions at low energies ($E_{\text{kin}} = 1.25\text{-}3.5$ GeV)
  Dielectrons from HADES
- CERN SPS: AA collisions with $E_{\text{kin}} = 158$ GeV per nucleon on a fixed target (center-mass energy: $\sqrt{s_{NN}} = 17.3$ GeV)
  dileptons (particularly $\mu^+\mu^-$ in In-In collisions from NA60)
- BNL RHIC: Au Au collisions with center-mass energy of $\sqrt{s_{NN}} = 200$ GeV; "beam-energy scan" $\sqrt{s_{NN}} = 7.7\text{-}39$ GeV
  dileptons from STAR and PHENIX; direct photons from PHENIX
- CERN LHC: Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV per nucleon
  direct photons from ALICE



QCD and ("accidental") symmetries

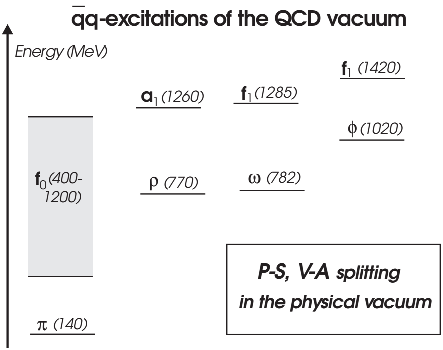
- fundamental theory of strong interactions: QCD

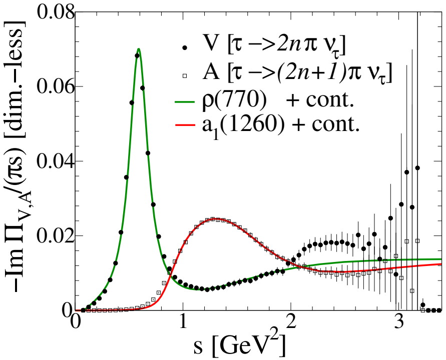
$$\mathscr{L}_{\text{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a + \bar{\psi}(\mathrm{i}\not{D} - \hat{M})\psi$$

- particle content:
  - ψ: Quarks, including flavor- and color degrees of freedom, $\hat{M} = \text{diag}(m_u, m_d, m_s, \ldots) =$ current quark masses
  - A_μ^a: gluons, gauge bosons of $\text{SU}(3)_{\text{color}}$
- symmetries
  - fundamental building block: local $\text{SU}(3)_{\text{color}}$ symmetry
  - in light-quark sector: approximate chiral symmetry
  - chiral symmetry ⇒ connection between QCD and effective hadronic models

Phenomenology and Chiral symmetry

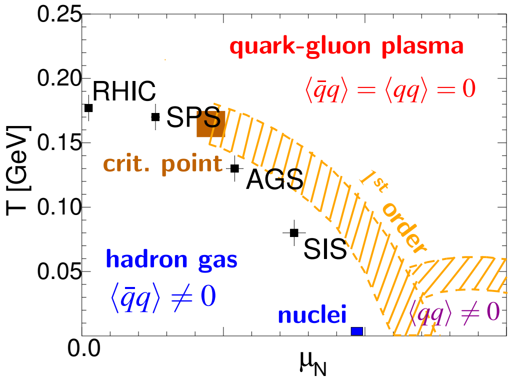
- in vacuum: Spontaneous breaking of chiral symmetry
- ⇒ mass splitting of chiral partners





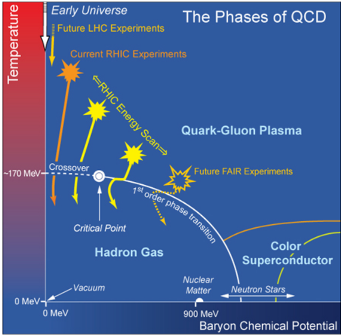
The QCD-phase diagram

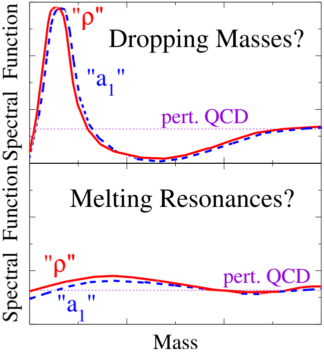
- hot and dense matter: quarks and gluons close together
- highly energetic collisions ⇒ "deconfinement"
- quarks and gluons relevant degrees of freedom ⇒ quark-gluon plasma
- still strongly interacting ⇒ fast thermalization!



The QCD-phase diagram

- at high temperature/density: restoration of chiral symmetry
- lattice QCD: $T_c^{\chi} \simeq T_c^{\text{deconf}}$

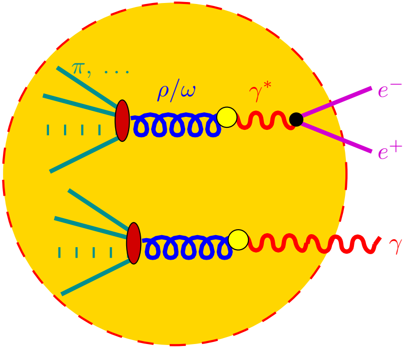




- mechanism of chiral restoration?
- two main theoretical ideas
  - "dropping masses": $m_{\text{had}} \propto \langle \overline{\psi} \psi \rangle$
  - "melting resonances": broadening of spectra through medium effects
  - More theoretical question: realization of chiral symmetry in nature?

Electromagnetic probes in heavy-ion collisions

- $\gamma, \ell^{\pm}$: no strong interactions
- reflect whole "history" of collision:
  - from pre-equilibrium phase
  - from thermalized medium
    QGP and hot hadron gas
  - from VM decays after thermal freezeout



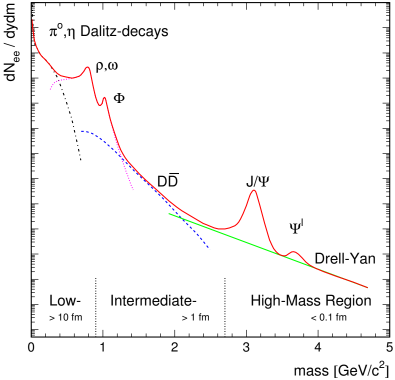


Fig. by A. Drees

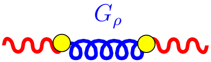
Electromagnetic probes from thermal source

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \overline{\psi_f} \gamma_\mu \psi_f$)
- McLerran-Toimela formula [MT85, GK91]

$$q_0 \frac{\mathrm{d}N_\gamma}{\mathrm{d}^4x\mathrm{d}^3\vec{q}} = -\frac{\alpha_{\text{em}}}{2\pi^2} g^{\mu\nu} \, \mathrm{Im}\, \Pi^{(\text{ret})}_{\mu\nu}(q,u)\Big|_{q_0=|\vec{q}|} f_B(q\cdot u)$$

$$\frac{\mathrm{d}N_{e^+e^-}}{\mathrm{d}^4x\mathrm{d}^4k} = -g^{\mu\nu} \frac{\alpha^2}{3q^2\pi^3} \, \mathrm{Im}\, \Pi^{(\text{ret})}_{\mu\nu}(q,u)\Big|_{q^2=M^2_{e^+e^-}} f_B(q\cdot u)$$

- manifestly Lorentz covariant (dependent on four-velocity of fluid cell, u)
- $q \cdot u = E_{\text{cm}}$: Doppler blue shift of q_T spectra!
- to lowest order in α: $4\pi\alpha\Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

$\Sigma^{\gamma}_{\mu\nu} =$ 

- $\ell^+\ell^-$-inv.-mass spectra $\Rightarrow$ in-med. spectral functions of vector mesons (ρ, ω, ϕ)!

Radiation from thermal QGP: $q\bar{q}$ annihilation

- General: McLerran-Toimela formula

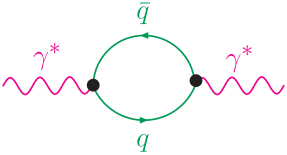
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{l^+l^-}}{\mathrm{d}^4x\mathrm{d}^4q} = -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2} g_{\mu\nu} \mathrm{Im} \sum_i \Pi^{\mu\nu}_{\mathrm{em},i}(M,\vec{q}) f_B(q\cdot u)$$

- i enumerates partonic/hadronic sources of em. currents
- in-medium em. current-current correlation function

$$\Pi^{\mu\nu}_{\mathrm{em},i} = \mathrm{i}\int \mathrm{d}^4x\, \exp(\mathrm{i}qx)\Theta(x^0)\left\langle \left[j^{\mu}_{\mathrm{em},i}(x), j^{\nu}_{\mathrm{em},i}(0)\right]\right\rangle$$

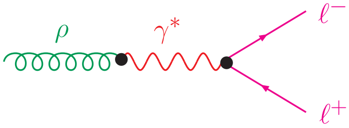
- in QGP phase: $q\bar{q}$ annihilation
- hard-thermal-loop improved electromagnetic current-current correlator

$$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$$



Radiation from thermal sources: ρ decays

- model assumption: vector-meson dominance

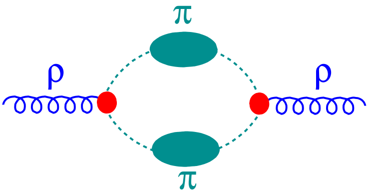


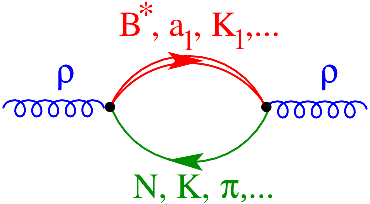
$$\frac{\mathrm{d}N^{(\mathrm{MT})}_{\rho\to l^+l^-}}{\mathrm{d}^4x\mathrm{d}^4q} = \frac{M}{q^0}\Gamma_{\rho\to l^+l^-}(M)\frac{\mathrm{d}N_\rho}{\mathrm{d}^3\vec{x}\mathrm{d}^4q}$$
$$= -\frac{\alpha^2}{3\pi^3}\frac{L(M^2)}{M^2}\frac{m_\rho^4}{g_\rho^2}g_{\mu\nu}\,\mathrm{Im}\,D_\rho^{\mu\nu}(M,\vec{q})f_B\left(\frac{q\cdot u-2\mu_\pi(t)}{T(t)}\right)$$

- special case of McLerran-Toimela (MT) formula
- $M^2=q^2$: invariant mass, M, of dilepton pair
- $L(M^2)=(1+2m_l^2/M^2)\sqrt{1-4m_l^2/M^2}$: dilepton phase-space factor
- $D_\rho^{\mu\nu}(M,\vec{q})$: (four-transverse part of) in-medium ρ propagator at given $T(t)$, $\mu_{\mathrm{meson/baryon}}(t)$
- analogous for ω and ϕ

Hadronic many-body theory

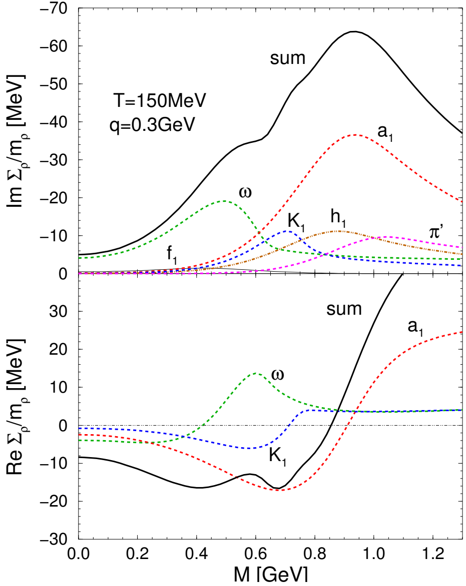
- hadronic many-body theory (HMBT) for vector mesons
  [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- $\pi\pi$ interactions and baryonic excitations
- effective hadronic models, implementing symmetries
- parameters fixed from phenomenology
  (photon absorption at nucleons and nuclei, $\pi N \to \rho N$)
- evaluated at finite temperature and density
- self-energies $\Rightarrow$ mass shift and broadening of particle/resonance in the medium





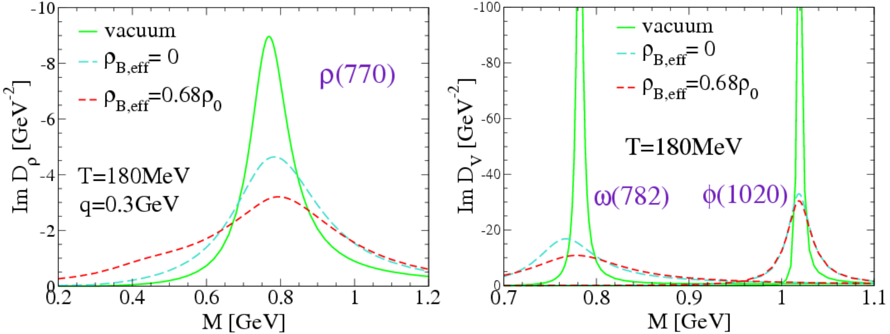
- Baryon (resonances) important, even at low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

Meson contributions



[RG99]

In-medium spectral functions and baryon effects



[RW99]

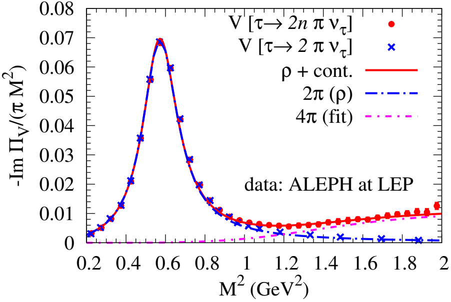
- baryon effects important
  - large contribution to broadening of the peak
  - responsible for most of the strength at small M

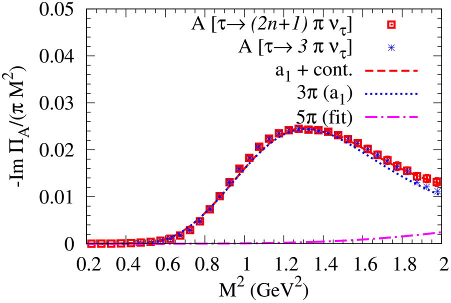
Radiation from thermal sources: multi-π processes

- use vector/axial-vector correlators from τ-decay data
- Dey-Eletsky-Ioffe mixing: $\hat{\varepsilon} = 1/2\varepsilon(T,\mu_\pi)/\varepsilon(T_c,0)$

$$\Pi_V = (1-\hat{\varepsilon}) z_\pi^4 \Pi_{V,4\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2} z_\pi^3 \Pi_{A,3\pi}^{\text{vac}} + \frac{\hat{\varepsilon}}{2}(z_\pi^4 + z_\pi^5)\Pi_{A,5\pi}^{\text{vac}}$$

- avoid double counting: leave out two-pion piece and $a_1 \rightarrow \rho + \pi$ (already contained in ρ spectral function)





Data: [R. Barate et al (ALEPH Collaboration) 98]

Non-thermal sources

- Drell-Yan: $q+\bar{q} \to \ell^+ \ell^-$ in early hard collisions

$$\left.\frac{\mathrm{d}N_{\mathrm{DY}}^{AA}}{\mathrm{d}M\mathrm{d}y}\right|_{b=0} = \frac{3}{4\pi R_0^2} A^{4/3} \frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{DY}}^{NN}}{\mathrm{d}M\mathrm{d}y} = K \frac{8\pi\alpha}{9sM} \sum_{q=u,d,s} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

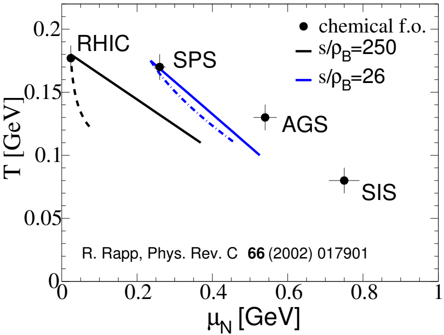
  - parton distribution functions: GRV94LO
  - higher-order effects
    - K factor
    - non-zero pair q_T: for IMR and HMR fitted by Gaussian spectrum (NA50 procedure)
  - extrapolation to LMR: constrained by photon point $M \to 0$
- ρ decays after thermal freeze-out: Cooper-Frye formula

$$\frac{\mathrm{d}N_{\rho\to l^+l^-}^{(\mathrm{fo})}}{\mathrm{d}^3\vec{x}\mathrm{d}^4q} = \frac{\Gamma_{l^+l^-}}{\Gamma_\rho^{\mathrm{tot}}} \frac{\mathrm{d}N_i}{\mathrm{d}^3\vec{x}\mathrm{d}q} = \frac{q_0}{M} \frac{1}{\Gamma_\rho^{\mathrm{tot}}} \left[\frac{\mathrm{d}N_{\rho\to l^+l^-}^{(\mathrm{MT})}}{\mathrm{d}^4x\mathrm{d}^4q}\right]_{t=t_{\mathrm{fo}}}$$

  - additional Lorentz-γ factor q_0/M: life-time dilation of moving ρ!

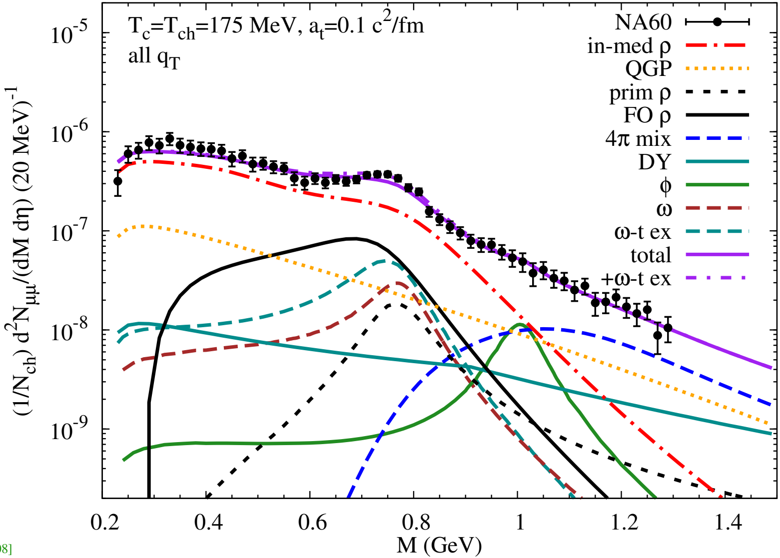
Bulk Evolution: Fireball and Thermodynamics

- cylindrical fireball model: $V_{\text{FB}} = \pi(z_0 + v_{z0}t + \frac{a_z}{2}t^2)\left(\frac{a_\perp}{2}t^2 + r_0\right)^2$
- thermodynamics:
  - isentropic expansion; S_{tot} fixed by N_{ch}; $T_c = T_{\text{chem}} = 175$ MeV
  - $T > T_c$: massless gas for QGP with $N_f^{\text{eff}} = 2.3$
  - mixed phase: $f_{\text{HG}}(t) = [s_c^{\text{QGP}} - s(t)]/[s_c^{\text{QGP}} - s_c^{\text{HG}}]$
  - $T < T_c$: hadron-resonance gas
- $\Rightarrow T(t), \mu_{\text{baryon,meson}}(t)$
- chemical freezeout:
  - $\mu_N^{\text{chem}} = 232$ MeV
  - hadron ratios fixed $\Rightarrow \mu_N, \mu_\pi, \mu_K, \mu_\eta$ at fixed $s/\rho_B = 27$
- thermal freezeout: $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV



M spectra (in p_T slices)

- NA60 experiment: dimuon measurement (In-In collisions at top SPS energy)



[HR06, HR08]

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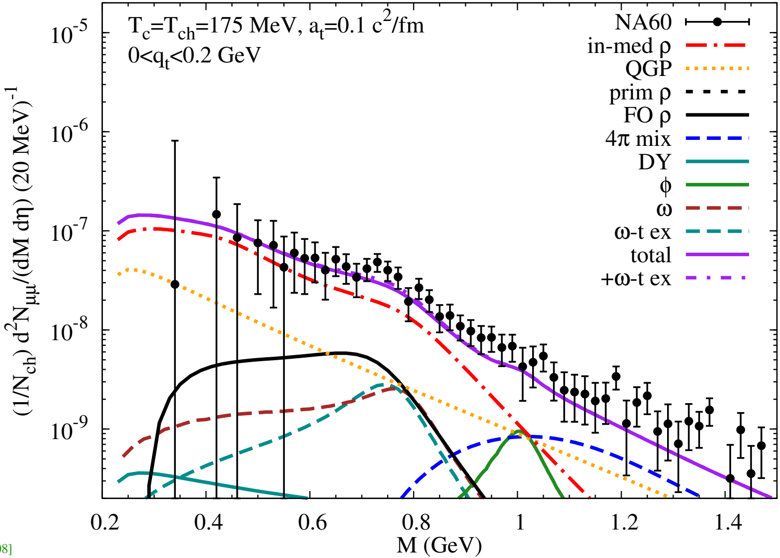

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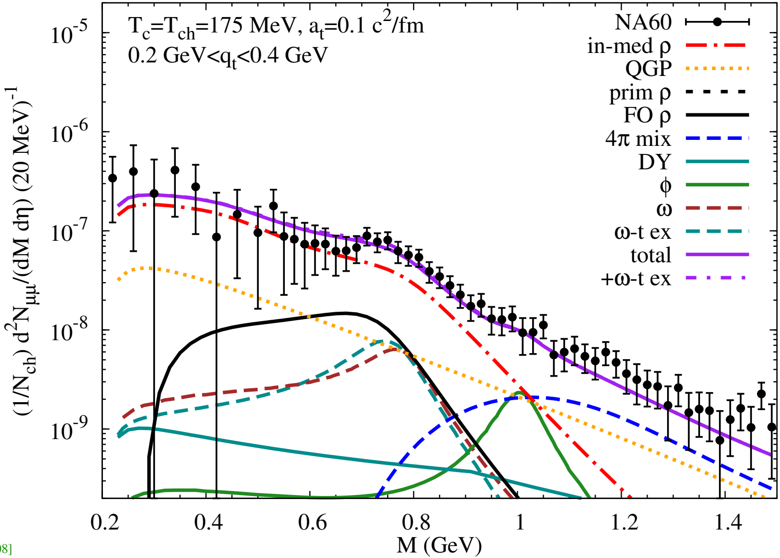

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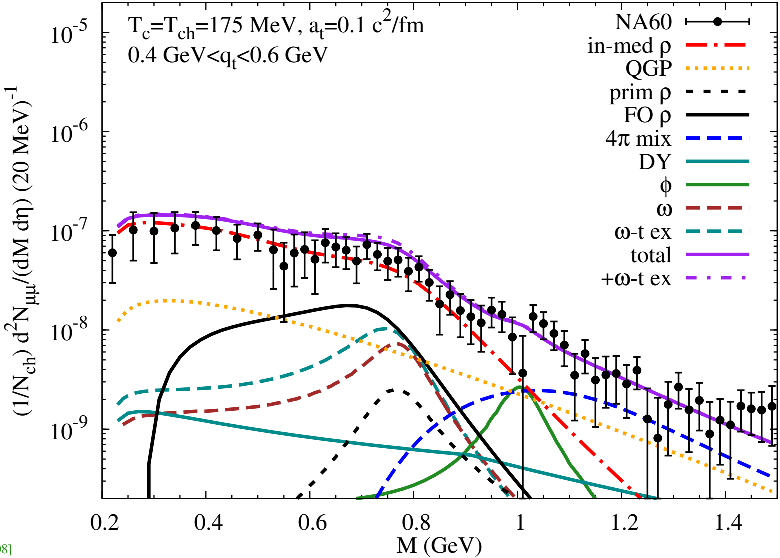

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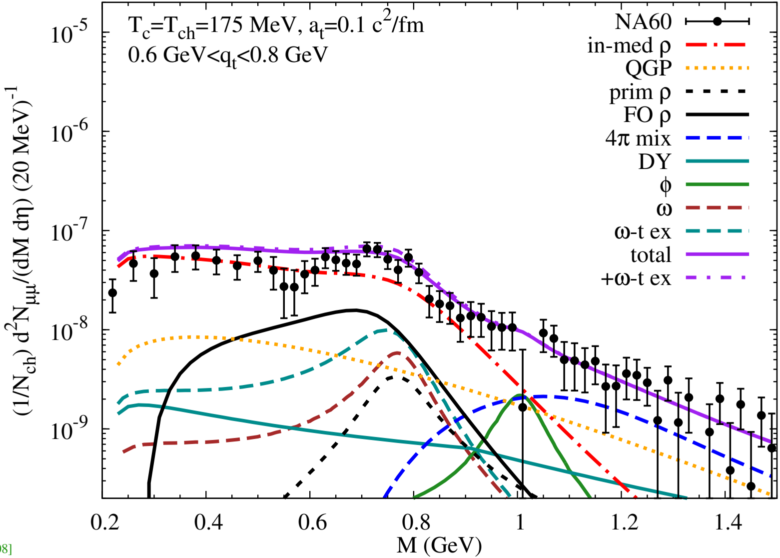

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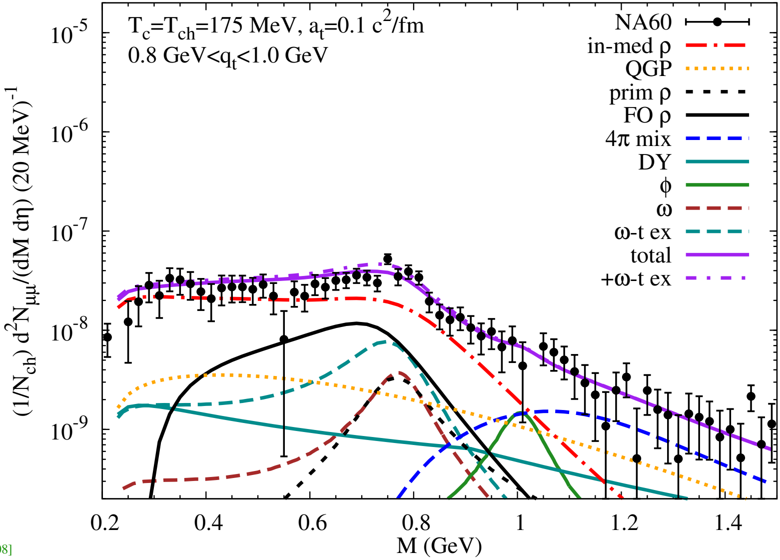

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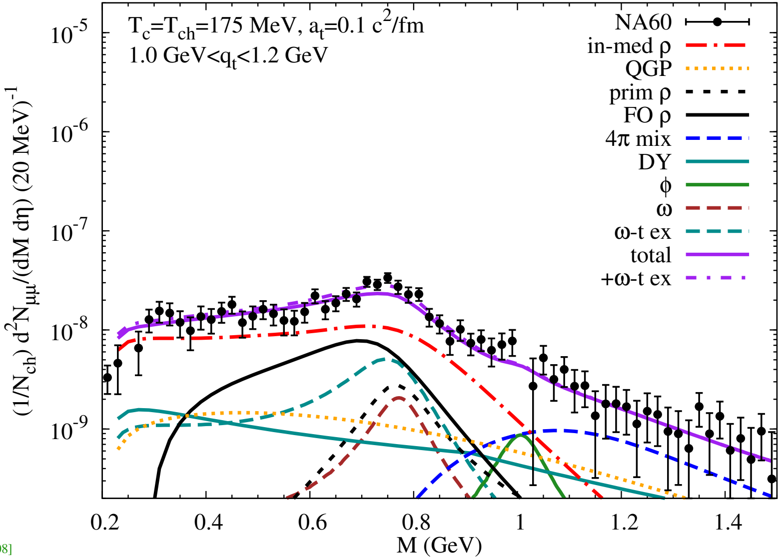

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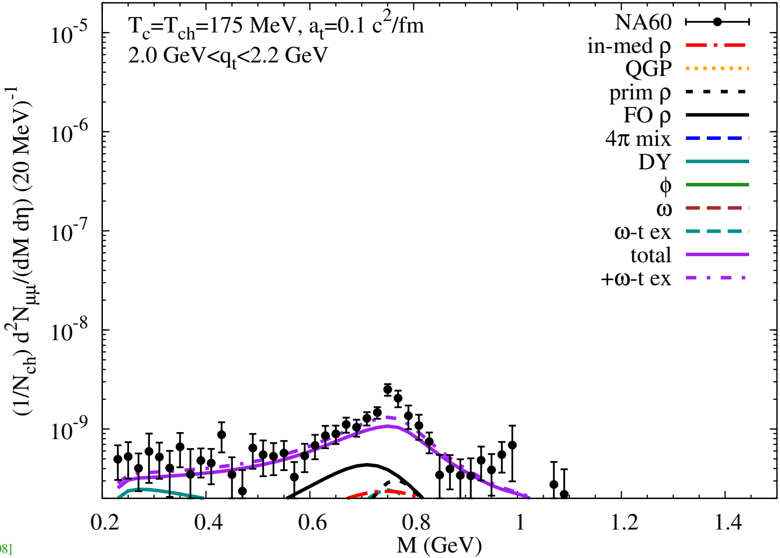

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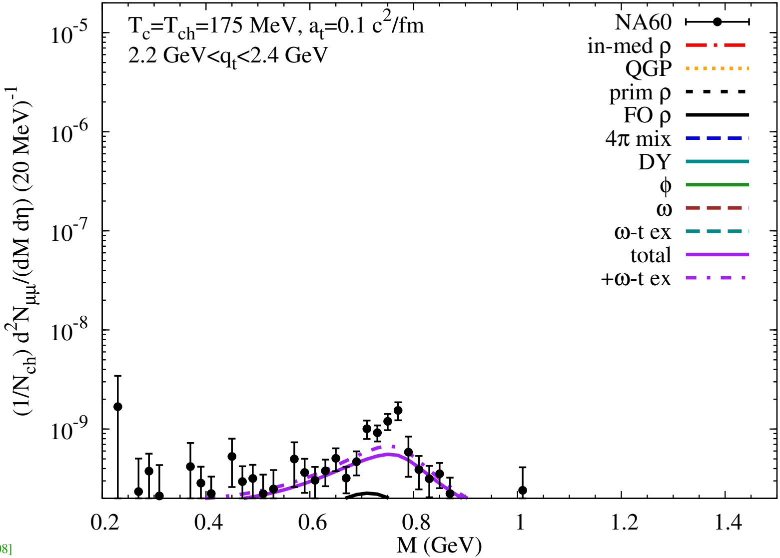
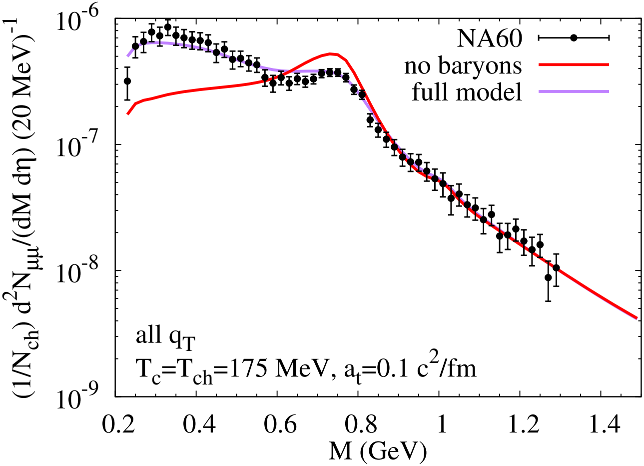


[HR06, HR08]

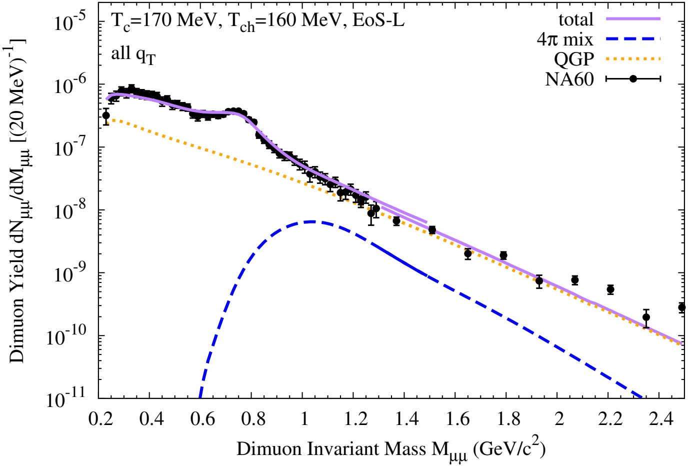
Importance of baryon effects

- baryonic interactions important!
- in-medium broadening
- low-mass tail!

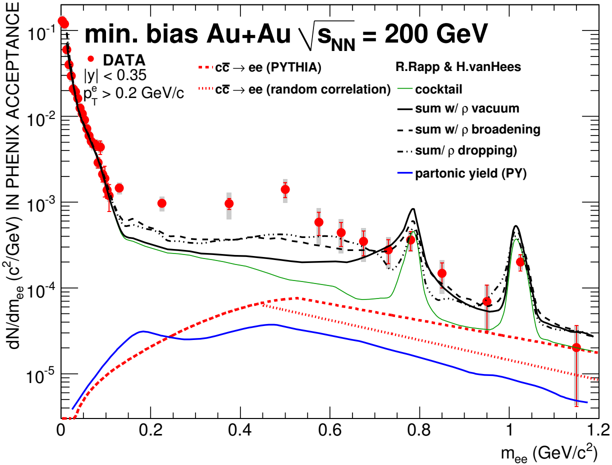


Update: Using lattice equation of state

- use equation of state from lattice calculations (cross over!)
- use QGP rates adapted to recent lattice results
- IMR slope: true (average) temperature of source (no blue shift as in q_T spectra!): $T \simeq$ 205-230 MeV (above $T_c \simeq$ 160 MeV!)



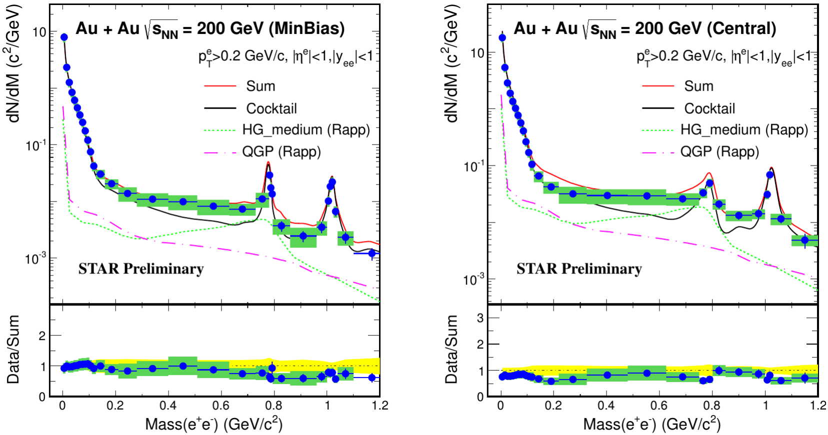
Dileptons@RHIC: PHENIX (2007)



model: Rapp, HvH [A+10]

- huge enhancement in the LMR unexplained yet!
- maybe new result from PHENIX hadron-blind run at QM14!

Dileptons@RHIC: STAR (QM 2012)

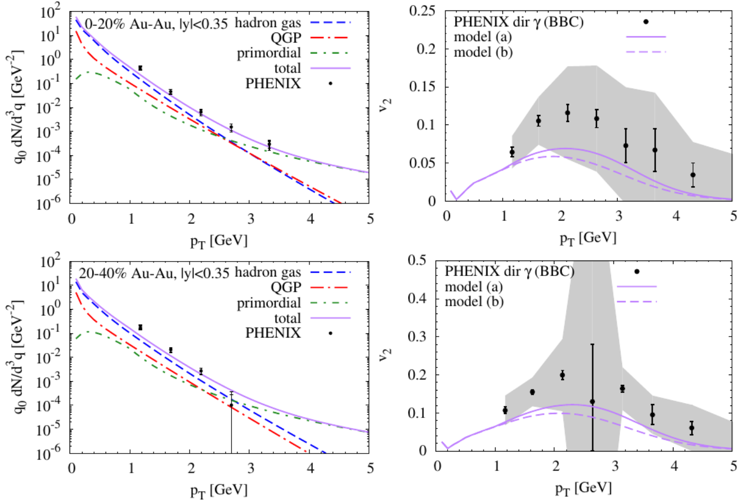


[Rap13], data from [Zha11]

- compatible with medium modifications in model calculation
- a new puzzle at RHIC?

Direct Photons at RHIC

- same model [TRG04, HGR11, HHR14] for rates as for dileptons
- photons inherit v_2 from hadronic sources



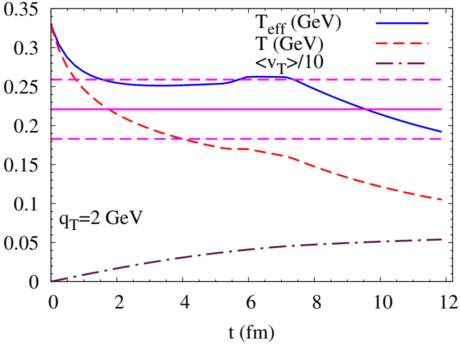
[HGR11, HHR14]

- Parallel talk on Monday 1:20pm: Ralf Rapp

Effective slopes vs. temperatures

- effective slopes of photon p_T spectra are NOT temperatures!
- emission from a flowing medium ⇒ Doppler effect

$$T_{\text{eff}} \simeq \sqrt{\frac{1+\langle v_T \rangle}{1-\langle v_T \rangle}} T$$



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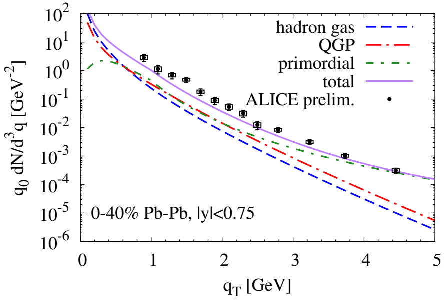
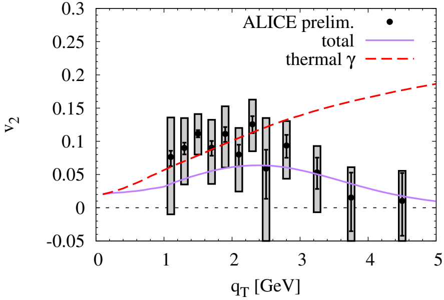
Direct Photons at the LHC

same model, fireball adapted to hadron data from ALICE [HHR14]





- large direct-photon v_2
- early buildup of v_2; here developed already at end of QGP phase
- emission mostly around T_c (dual rates!) $\Rightarrow$
- $\Rightarrow$ source has already developed radial flow and v_2
- large effective slopes include blueshift from radial flow!
- still additional (hadronic?) sources (bremsstrahlung?) missing?!?
- Parallel talk on Monday 1:20pm: Ralf Rapp

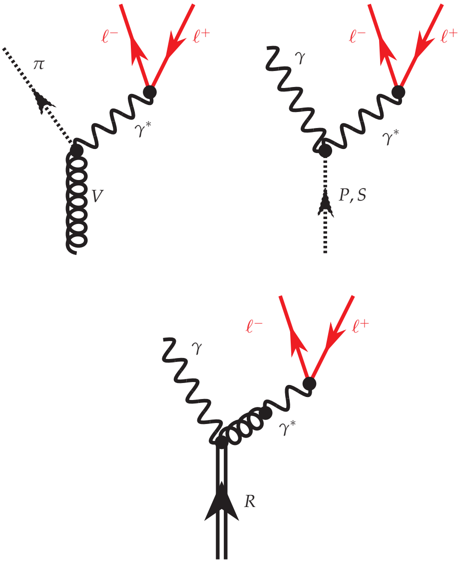
The GiBUU Model

GiBUU

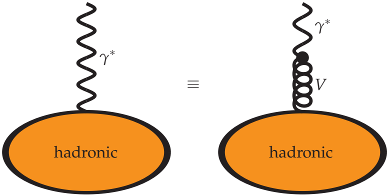
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Boltzmann-Uehling-Uhlenbeck (BUU) framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion (SVN)
- publicly available realeases: https://gibuu.hepforge.org
- Review on hadronic transport (GiBUU): [BGG+12]
- all calculations for dileptons: Janus Weil [Weil:2012ji,Weil:2012yg]

Dalitz decays

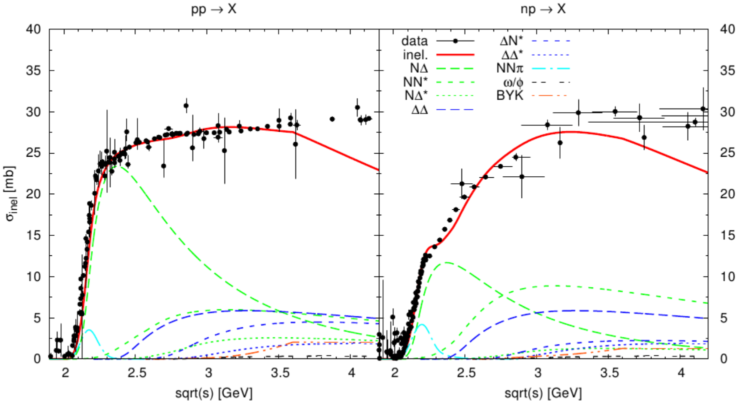


- Dalitz decay:
  1 particle → 3 particles
- V: $\omega \to \pi + \gamma^* \to \pi + \ell^+ + \ell^-$
- P, S: $\pi, \eta \to \gamma + \gamma^* \to \gamma + \ell^+ + \ell^-$
- R: Baryon resonances
  $\Delta, N^* \to N + V \to N + \gamma^* \to N + \ell^+ + \ell^-$
- vector-meson dominance



GiBUU at HADES energies

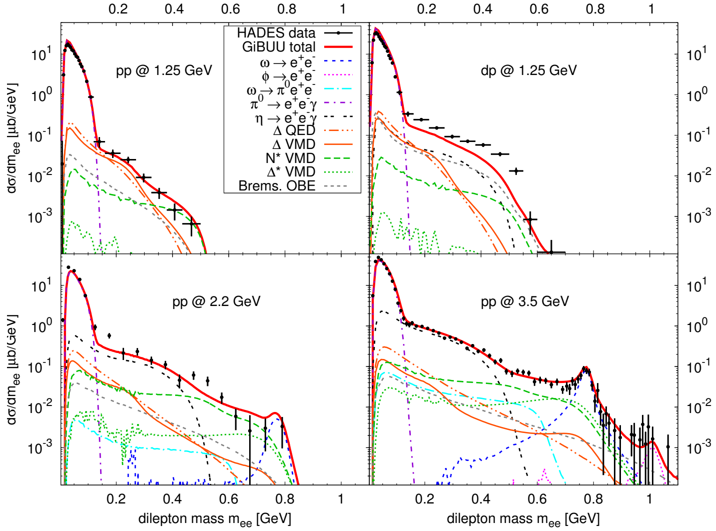
- good description of total pp, pn (inelastic) cross section



- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+ \ell^-$; $\omega \to \pi^0 \ell^+ \ell^-$, $\Delta \to N \ell^+ \ell^-$
  - $\rho, \omega, \phi \to \ell^+ \ell^-$: dilepton invariant-mass spectra $\Rightarrow$ spectral properties of vector mesons
  - for details, see [WHM12]

GiBUU: Dileptons in elementary reactions

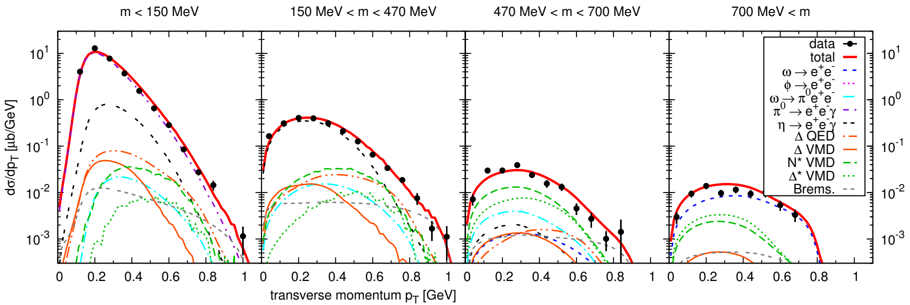
- all baryon resonances decay via VMD mechanism: $R \to N + \rho \to N + \ell^+ \ell^-$
- provides model for electromagnetic transition form factor!



- poster session on Tuesday: poster by Janus Weil

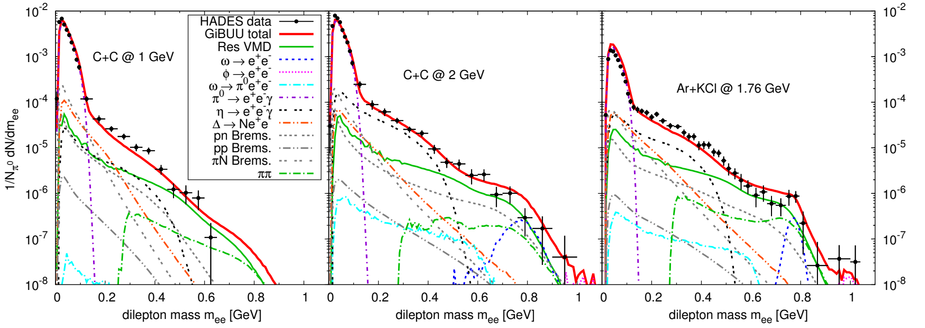
GiBUU: Dileptons in elementary reactions

- 3.5 AGeV pp collisions



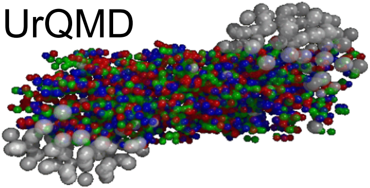
- "VMD form factor" ⇒ consistent description of M and p_T spectra!
- poster session on Tuesday: poster by Janus Weil

GiBUU: AA at HADES



- no medium effects in spectral functions (yet)
- medium effects from transport sufficient
  - "Fermi motion" of nucleons in nucleus; Pauli blocking in collisions
  - particle production from secondary collisions
  - hadronic final-state interactions
- in CC also experimentally well described by "cocktail"
- poster session on Tuesday: poster by Janus Weil

UrQMD transport model



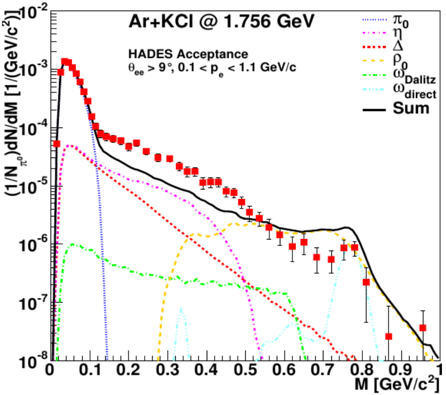
- UrQMD: Ultrarelativistic Quantum Molecular Dynamics
  - contains hadrons with masses up to 2.2 GeV
  - particle production via string excitation and fragmentation
  - solves quasi-classical many-body Hamilton equations of motion
  - “microcanonical” realization of transport equation

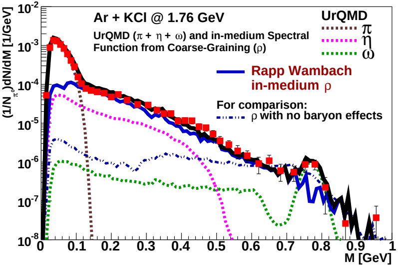
[BBB+98]

“Coarse-grained transport”

- problem in transport models:
  how to implement medium modifications of hadrons?
- how to use detailed calculations from equilibrium many-body QFT?
- Coarse-grained transport
  - define grid of fluid cells in space-time
  - ensemble of UrQMD runs
  - determine $T(t,\vec{x})$, $\mu_B(t,\vec{x})$ from averaged net-baryon current using equation of state
  - now can use dilepton rates from many-body QFT
  - problem: consistency between particle content in UrQMD, QFT model, and EoS
- Rapp-Wambach model [RW99, GR99, RW00, RWH09]
  - as discussed before
  - all dilepton calculations: Stephan Endres [EHB13, EHWB13]

UrQMD: Ar KCl at HADES

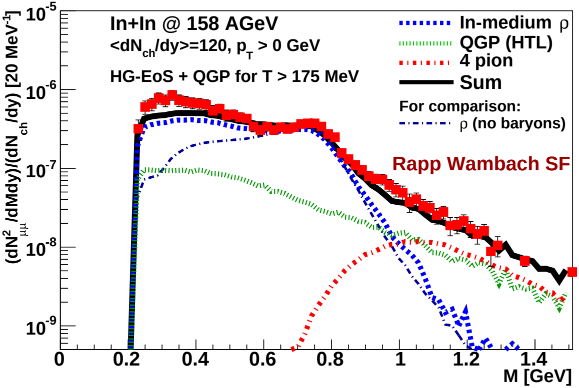




- significant improvement with use of medium modified ρ
- comparison between GiBUU and UrQMD:
  need better constraints for hadronic models for conclusive interpretation
- a lot to do for both experimentalists and theorists!
- poster session on Tuesday: Poster by Stephan Endres

UrQMD: SPS (dimuons from NA60 in In-In collisions)

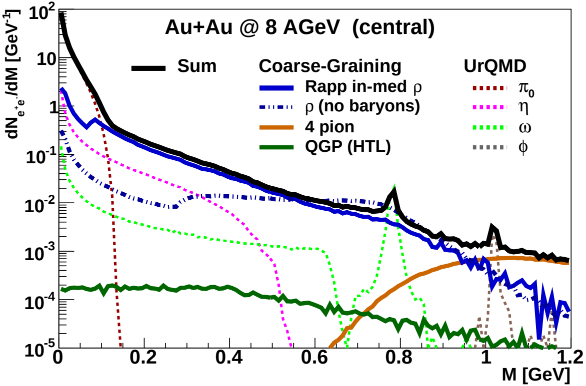
- same rates as in calculations with fireball
- provides more realistic model for medium evolution
- good check of coarse-graining approach



- poster session on Tuesday: Poster by Stephan Endres

UrQMD: Predictions for FAIR (CBM experiment)

- Au+Au at $E_{\text{lab}} = 8$ AGeV



- poster session on Tuesday: Poster by Stephan Endres

Summary

- em. probes, $\ell^+\ell^-$ and γ: neglible final-state interactions
- probe in-medium electromagnetic current-current correlator over entire history of fireball evolution
- provide insight into fundamental properties of QCD matter
- needs models for em. radiation from QGP and hadron gas
- medium effects on vector mesons in hot and dense matter
- hint at chiral-symmetry restoration
  $\Rightarrow$ melting resonances rather than dropping mass
- a lot not covered in this lecture
- for more details, see website of the HQM Lecture Week spring 2014
  http://fias.uni-frankfurt.de/~hees/hqm-lectweek14/index.html
- Electromagnetic probes at QM14
  - plenary talks on em. probes: Fri. 2:30pm-4:00pm
  - parallel talks on em. probes: Mo. 11:00am-6:30pm

Bibliography I

[A^+10] A. Adare, et al., Detailed measurement of the e^+e^- pair continuum in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV and implications for direct photon production, Phys. Rev. C **81** (2010) 034911. http://dx.doi.org/10.1103/PhysRevC.81.034911

[BBB^+98] S. Bass, et al., Microscopic models for ultrarelativistic heavy ion collisions, Prog. Part. Nucl. Phys. **41** (1998) 255. http://dx.doi.org/10.1016/S0146-6410(98)00058-1

[BGG^+12] O. Buss, et al., Transport-theoretical Description of Nuclear Reactions, Phys. Rept. **512** (2012) 1. http://dx.doi.org/10.1016/j.physrep.2011.12.001

[EHB13] S. Endres, H. van Hees, M. Bleicher, Studies of Dilepton Production in Coarse-Grained Transport Dynamics, PoS **CPOD2013** (2013) 052.

Bibliography II

[EHWB13] S. Endres, H. van Hees, J. Weil, M. Bleicher, Dilepton Production in Transport Calculations and Coarse-Grained Dynamics, J. Phys. Conf. Ser. **503** (2013) 012039.
`http://dx.doi.org/10.1088/1742-6596/503/1/012039`

[GK91] C. Gale, J. I. Kapusta, Vector Dominance Model at Finite Temperature, Nucl. Phys. B **357** (1991) 65.
`http://dx.doi.org/10.1016/0550-3213(91)90459-B`

[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`

[HGR11] H. van Hees, C. Gale, R. Rapp, Thermal Photons and Collective Flow at the Relativistic Heavy-Ion Collider, Phys. Rev. C **84** (2011) 054906.
`http://dx.doi.org/10.1103/PhysRevC.84.054906`

[HHR14] H. van Hees, M. He, R. Rapp, Pseudo-Critical Enhancement of Thermal Photons in Relativistic Heavy-Ion Collisions (2014).

Bibliography III

[HR06] H. van Hees, R. Rapp, Comprehensive interpretation of thermal dileptons at the SPS, Phys. Rev. Lett. **97** (2006) 102301.
http://link.aps.org/abstract/PRL/V97/E102301

[HR08] H. van Hees, R. Rapp, Dilepton Radiation at the CERN Super Proton Synchrotron, Nucl. Phys. A **806** (2008) 339.
http://dx.doi.org/10.1016/j.nuclphysa.2008.03.009

[MT85] L. D. McLerran, T. Toimela, Photon and dilepton emission from the quark-gluon plasma: some general considerations, Phys. Rev. D **31** (1985) 545.
http://link.aps.org/abstract/PRD/V31/P545

[Rap13] R. Rapp, Dilepton Spectroscopy of QCD Matter at Collider Energies, Adv. High Energy Phys. **2013** (2013) 148253.
http://dx.doi.org/10.1155/2013/148253

Bibliography IV

[RG99] R. Rapp, C. Gale, ρ Properties in a Hot Meson Gas, Phys. Rev. C **60** (1999) 024903.
http://arxiv.org/abs/hep-ph/9902268

[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

[RWH09] R. Rapp, J. Wambach, H. van Hees, The Chiral Restoration Transition of QCD and Low Mass Dileptons, Landolt-Börnstein **I/23** (2009) 4.
http://arxiv.org/abs/0901.3289

[TRG04] S. Turbide, R. Rapp, C. Gale, Hadronic production of thermal photons, Phys. Rev. C **69** (2004) 014903.
http://dx.doi.org/10.1103/PhysRevC.69.014903

Bibliography V

[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

[Zha11] J. Zhao, Dielectron continuum production from $\sqrt{s_{NN}} = 200$ GeV p+p and Au+Au collisions at STAR, J. Phys. G **38** (2011) 124134.
http://dx.doi.org/10.1088/0954-3899/38/12/124134