Electromagnetic probes: Messengers from the hot and dense fireball

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Outline

Em. current correlator in-medium approaches $\ell^+\ell^-$ and γ rates

Em. current correlation function and electromagnetic Probes

- photon and dilepton thermal emission rates given by same electromagnetic-current-correlation function ($J_\mu = \sum_f Q_f \bar{\psi}_f \gamma_\mu \psi_f$)

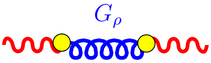
  [MT85, Wel90, GK91]

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 f_B(q \cdot u) \operatorname{Im} \Pi^{(\text{ret})}_{\mu\nu}(q)$$

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

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

- u: four-velocity of the fluid cell; $p \cdot u = p_0^{\text{hb}}$ energy in “heat-bath frame”
- to lowest order in α: $e^2 \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- vector-meson dominance model:

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

1. initial hard processes: Drell Yan
2. "core" ⇔ emission from thermal source

$$\frac{1}{q_T}\frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}M\mathrm{d}q_T} = \int \mathrm{d}^4x \int \mathrm{d}y \int M\mathrm{d}\varphi \frac{\mathrm{d}N^{(\text{thermal})}}{\mathrm{d}^4x\mathrm{d}^4q}$$

3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons

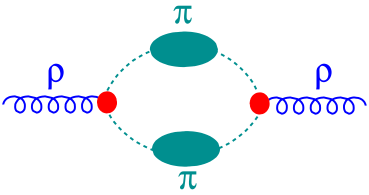
[CF74]

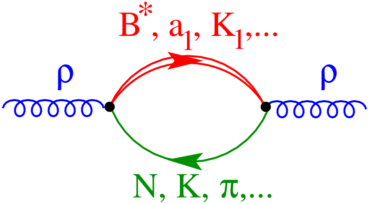
$$N^{(\text{fo})} = \int \frac{\mathrm{d}^3q}{q_0} \int q_\mu \mathrm{d}\sigma^\mu f_B(u_\mu q^\mu/T) \frac{\Gamma_{\text{meson}\to\ell^+\ell^-}}{\Gamma_{\text{meson}}}$$

[HR08, HR06]

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





- +corresponding vertex corrections $\Leftrightarrow$ gauge invariance
- 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)

Rapp-Wambach model

- pion cloud: dressing with baryon resonance excitations [RW00]
- direct ρ-N/Δ interactions $\Rightarrow$ [RW00]

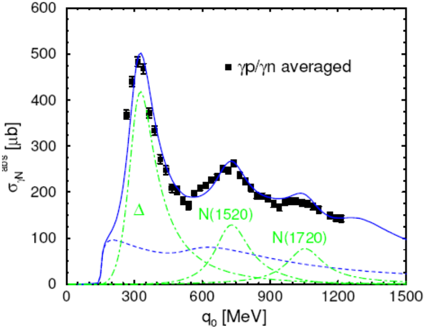
B	$l_{\rho N}$	$SI(\rho BN^{-1})$	$\Gamma^0_{\rho N}$ [MeV]	$\Gamma^{0,fit}_{\rho N}$ [MeV]	$\left(\frac{f^2_{\rho BN}}{4\pi}\right)$	$\Lambda_{\rho BN}$	Γ^{med} [MeV]
N(939)	P	4	–	–	6.0	1500	0
Δ(1232)	P	16/9	–	–	16.2	700	25
N(1440)	P	4	<28	0.5	1.1	600	200
N(1520)	S	8/3	24	23.5	6.8	600	300
Δ(1620)	S	8/3	24	36	1.5	700	200
Δ(1700)	S	16/9	128	111	2.5	1000	200
N(1720)	P	8/3	115	100	8.5	600	100
Δ(1905)	P	4/5	>210	315	14.5	1200	50
N(2000)	P	6/5	~300	75	1.0	1500	50

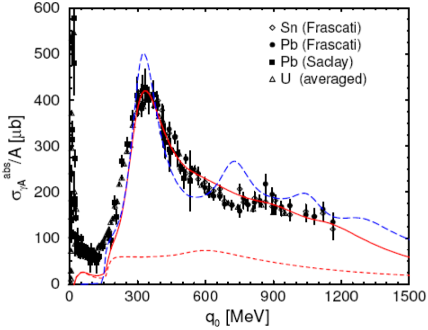
- direct ρ-heavy-meson interactions [GR99]

R	$I^G J^P$	Γ_{tot} [MeV]	ρh decay	$\Gamma^0_{\rho h}$ [MeV]	$\Gamma^0_{\gamma h}$ [MeV]
$\omega(782)$	0^-1^-	8.43	$\rho\pi$	~ 5	0.72
$h_1(1170)$	0^-1^+	~ 360	$\rho\pi$	seen	?
$a_1(1260)$	1^-1^+	~ 400	$\rho\pi$	dominant	0.64
$K_1(1270)$	$\frac{1}{2}1^+$	~ 90	ρK	~ 60	?
$f_1(1285)$	0^+1^+	25	$\rho\rho$	$\leqslant 8$	1.65
$\pi'(1300)$	1^-0^-	~ 400	$\rho\pi$	seen	?

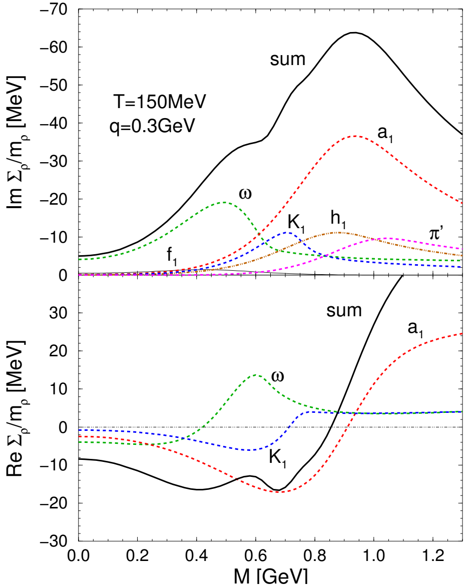
Photoabsorption on nucleons and nuclei

- important: fit of model parameters to data
- particle-data book: decay widths, branching rations,...
- photo-absorption on nucleons and nuclei [RW00]



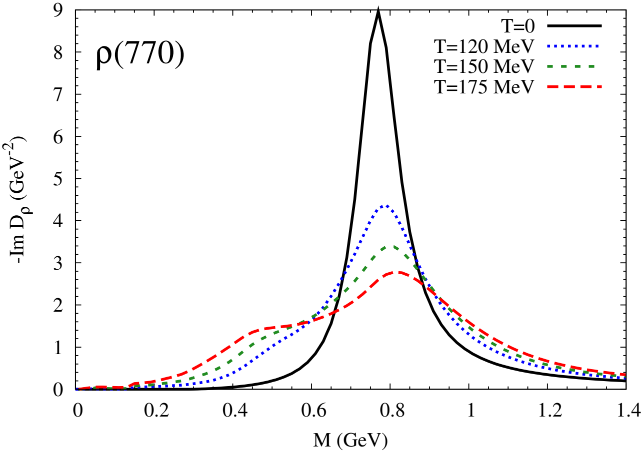


Meson contributions to ρ-selfenergy



[GR99, RW00]

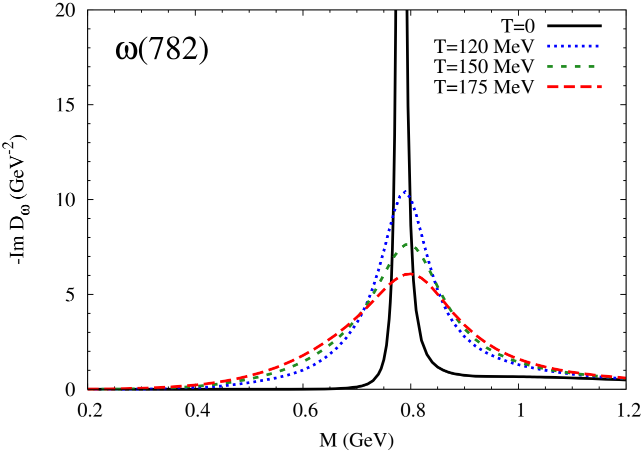
In-medium spectral functions and baryon effects



[GR99, RW00]

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

In-medium spectral functions and baryon effects



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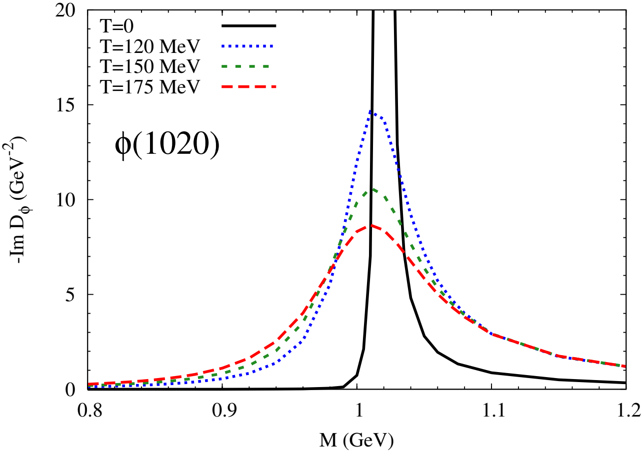

[GR99, RW00]

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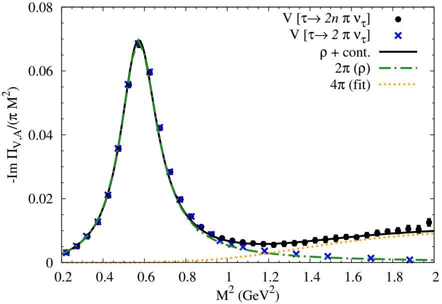
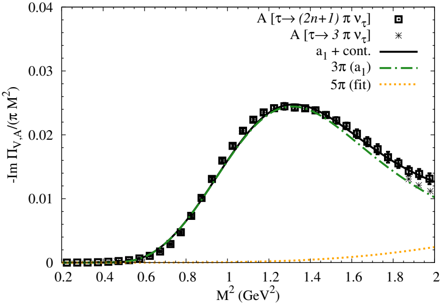
Intermediate masses: hadronic “4π contributions”

- e.m. current-current correlator $\Leftrightarrow$ $\tau \rightarrow 2n\pi$





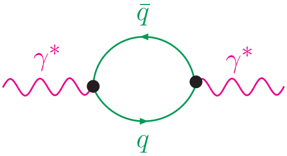
- “4π contributions”: $\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$
- leading-order virial expansion for “four-pion piece”
- additional strength through “chiral mixing”

[HR08, HR06]

Dileptons from thermal QGP

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

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

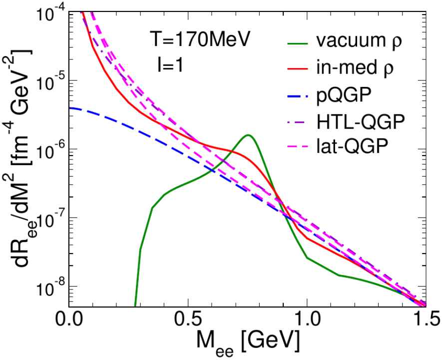


- or em. current correlator from the lattice [DFK+11] (extrapolated to finite q)
- "quark-hadron duality" around T_c

[Rap13]

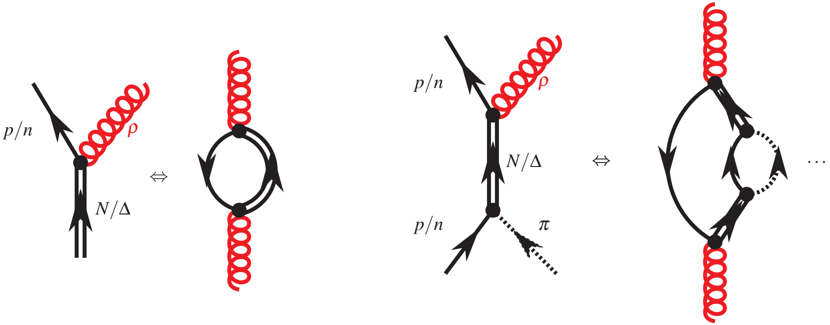
Dilepton rates: Hadron gas ↔ QGP

- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



[Rap13]

- cross sections in collision terms: same physics as in QFT approaches
- Fermi's golden rule: S-matrix amplitudes $\Leftrightarrow |\mathscr{M}_{ji}^2| \Leftrightarrow$ self-energy diagrams
- other way around: cut self-energy diagrams $\Leftrightarrow$ S-matrix amplitudes

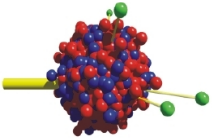


[FHK+11]

Dileptons in pp, pn, pA, AA

pure transport: GiBUU (with Janus Weil)

The GiBUU Model



GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

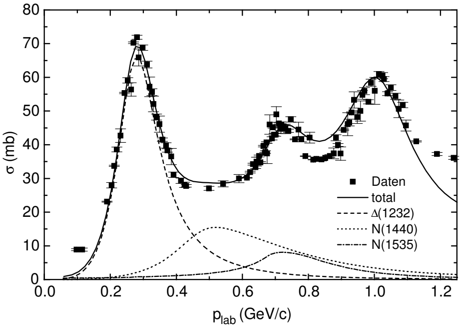
- Boltzmann-Uehling-Uhlenbeck (BUU) framework for hadronic transport
- reaction types: pA, πA, γA, eA, νA, AA
- open-source modular Fortran 95/2003 code
- version control via Subversion
- publicly available realeases: `https://gibuu.hepforge.org`
- Review on hadronic transport (GiBUU): [BGG+12]
- all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

Resonance Model

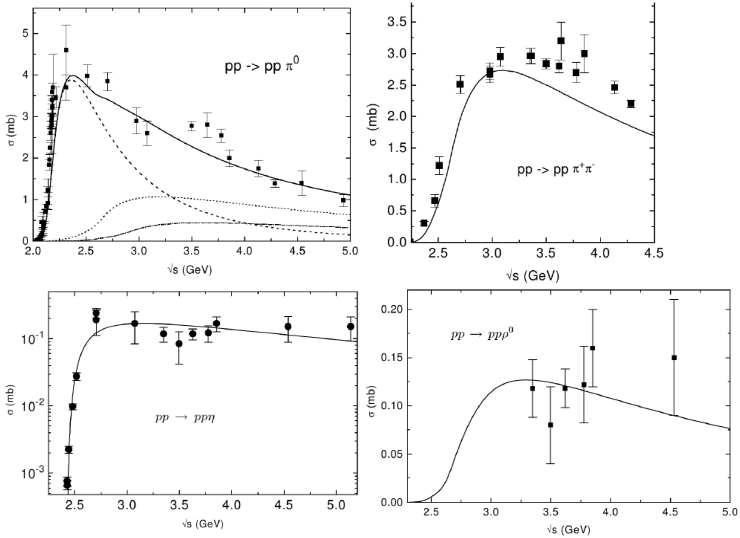
- reactions dominated by resonance scattering: $ab \to R \to cd$
- Breit-Wigner cross-section formula

$$\sigma_{ab \to R \to cd} = \frac{2s_R+1}{(2s_a+1)(2s_b+1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab \to R}\Gamma_{R \to cd}}{(s-m_R^2)^2+s\Gamma_{\text{tot}}^2}$$

- applicable for low-energy nuclear reactions $E_{\text{kin}} \lesssim 1.1$ GeV
- example: $\sigma_{\pi^- p \to \pi^- p}$ [Teis (PhD thesis 1996), data: Baldini et al, Landolt-Börnstein **12** (1987)]



- further cross sections



GiBUU: Extension to HADES energies

- [WHM12, WM13]
- keep same resonances (parameters from Manley analysis)

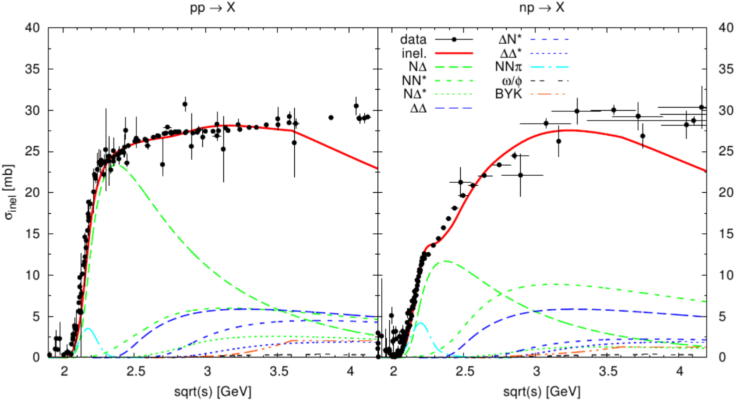
		M_0	Γ_0	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2]		branching ratio in %						
	rating	[MeV]	[MeV]	NR	ΔR	πN	ηN	$\pi\Delta$	ρN	σN	$\pi N^*(1440)$	$\sigma\Delta$
$P_{11}(1440)$	****	1462	391	70	—	69	—	22_P	—	9	—	—
$S_{11}(1535)$	***	1534	151	8	60	51	43	—	$2_S + 1_D$	1	2	—
$S_{11}(1650)$	****	1659	173	4	12	89	3	2_D	3_D	2	1	—
$D_{13}(1520)$	****	1524	124	4	12	59	—	$5_S + 15_D$	21_S	—	—	—
$D_{15}(1675)$	****	1676	159	17	—	47	—	53_D	—	—	—	—
$P_{13}(1720)$	*	1717	383	4	12	13	—	—	87_P	—	—	—
$F_{15}(1680)$	****	1684	139	4	12	70	—	$10_P + 1_F$	$5_P + 2_F$	12	—	—
$P_{33}(1232)$	****	1232	118	OBE	210	100	—	—	—	—	—	—
$S_{31}(1620)$	**	1672	154	7	21	9	—	62_D	$25_S + 4_D$	—	—	—
$D_{33}(1700)$	*	1762	599	7	21	14	—	$74_S + 4_D$	8_S	—	—	—
$P_{31}(1910)$	****	1882	239	14	—	23	—	—	—	—	67	10_P
$P_{33}(1600)$	***	1706	430	14	—	12	—	68_P	—	—	20	—
$F_{35}(1905)$	***	1881	327	7	21	12	—	1_P	87_P	—	—	—
$F_{37}(1950)$	****	1945	300	14	—	38	—	18_F	—	—	—	44_F

- production channels in Teis: $NN \to N\Delta$, $NN \to NN^*, N\Delta^*$, $NN \to \Delta\Delta$
- extension to $NN \to \Delta N^*, \Delta\Delta^*$, $NN \to NN\pi$, $NN \to NN\rho, NN\omega, NN\pi\omega, NN\phi$, $NN \to BYK$ $(B = N, \Delta,\ Y = \Lambda, \Sigma)$

[WHM12, WM13]

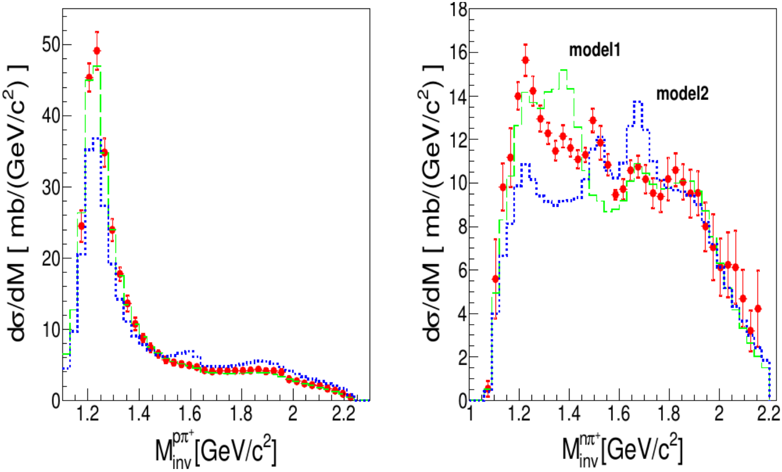
GiBUU Extension to HADES energies

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



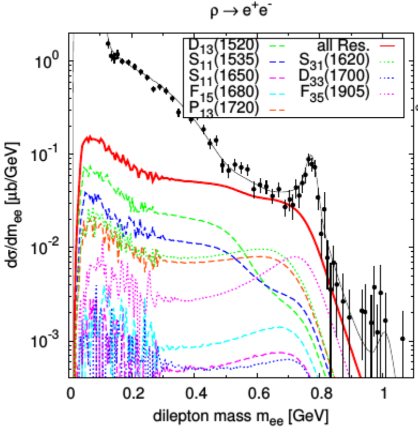
- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+\ell^-$; $\omega \to \pi^0 \ell^+\ell^-$, $\Delta \to N \ell^+\ell^-$
  - $\rho, \omega, \phi \to \ell^+\ell^-$: invariant mass $\ell^+\ell^-$ spectra $\Rightarrow$ spectral properties of vector mesons
  - for details, see [WHM12]

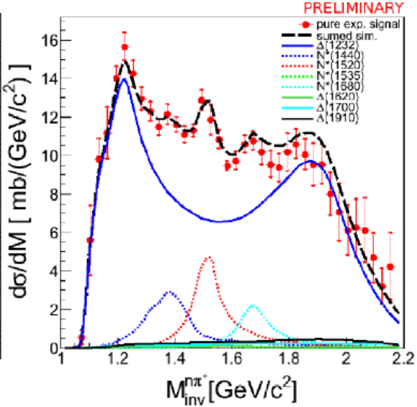
Exclusive pion production: p+p (3.5 GeV) (SIS/HADES)



- exclusive $\mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{n} + \pi^+$
- left: $M_{p\pi^+}$ spectrum; right: $M_{n\pi^+}$ spectrum
- model 1: GiBUU; model 2: UrQMD
- chance to refine resonance models further!

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

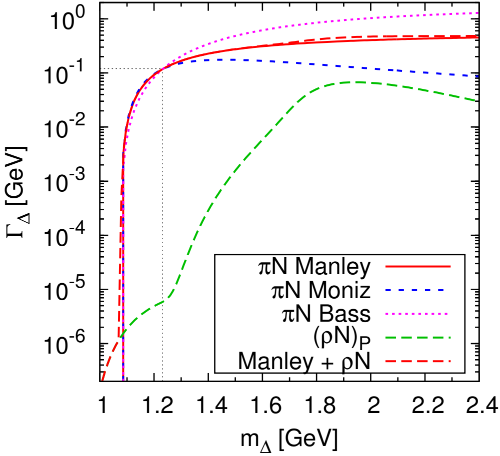




- "ρ"-line shape "modified" already in elementary hadronic reactions
- due to production mechanism via resonances

GiBUU: Δ meson in VMD model

- so far: Δ-Dalitz decay treated separately from other resonances
- now: treating Δ as all other resonances via VMD model
- model for em. transition form factor



[WEH+14]

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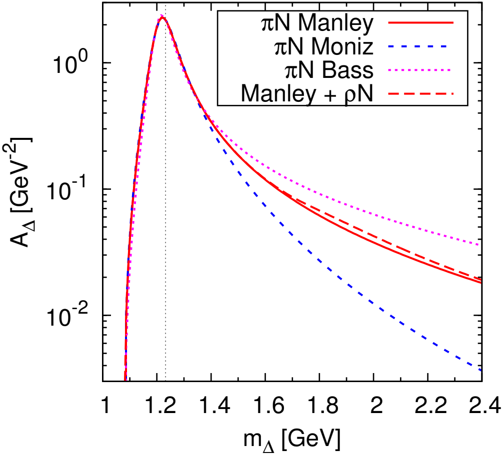

[WEH+ 14]

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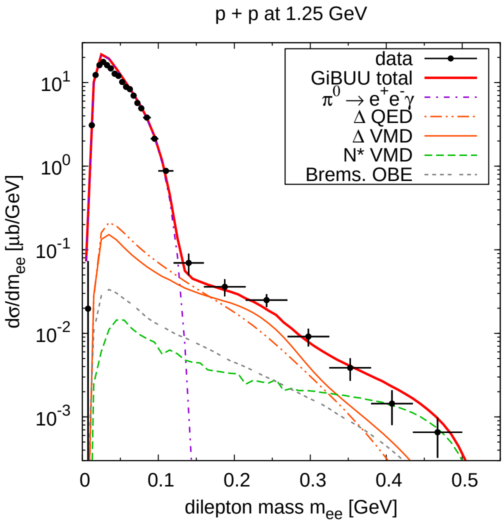

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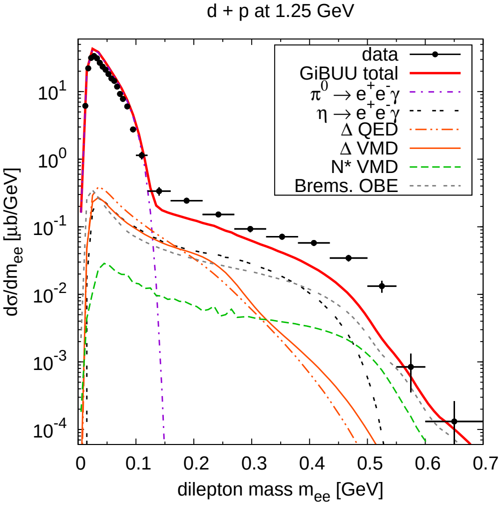

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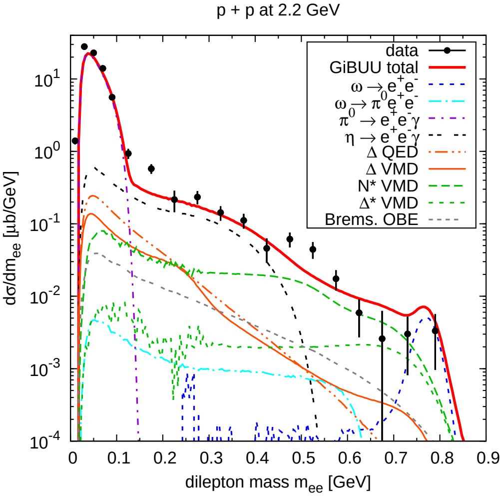

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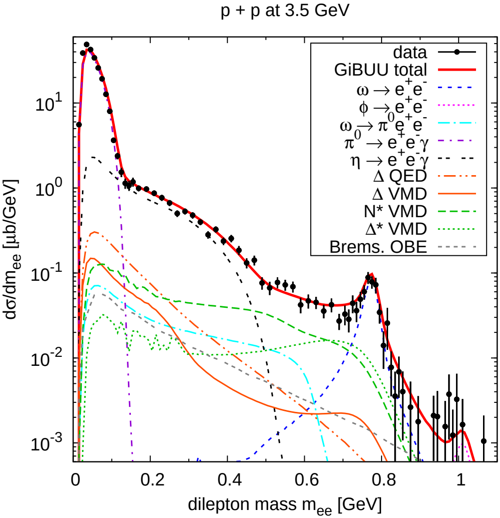
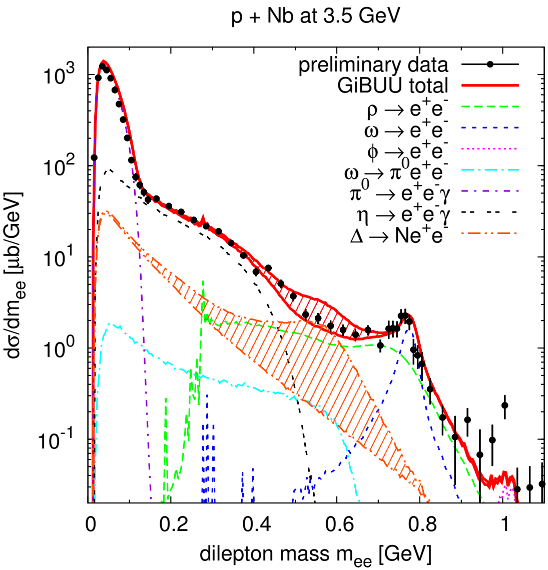


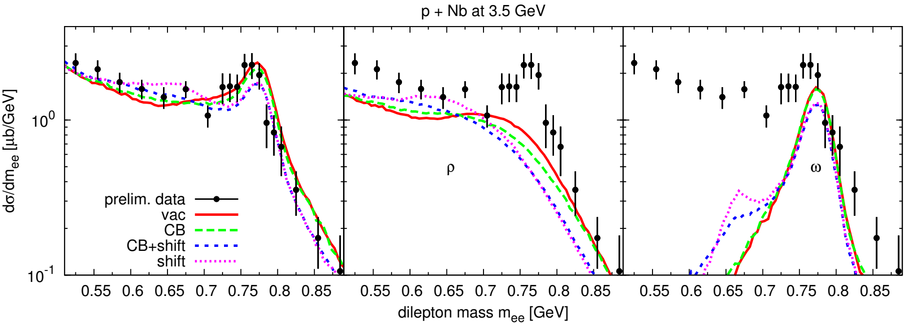
GiBUU: p+Nb (3.5 GeV) (SIS/HADES)

- with vacuum spectral functions:



GiBUU: p+Nb (3.5 GeV) (SIS/HADES)

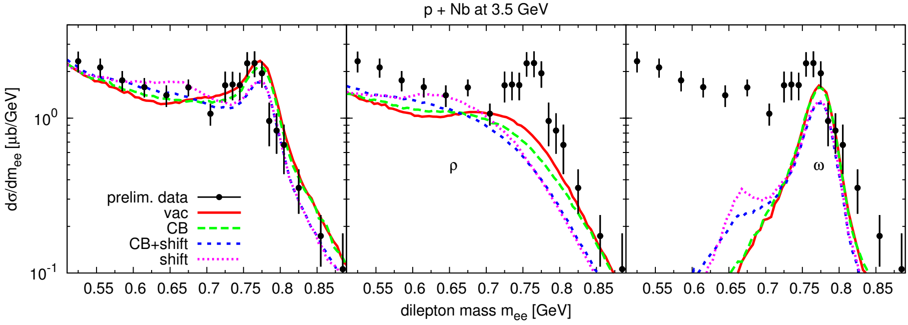
- with medium modified spectral functions:

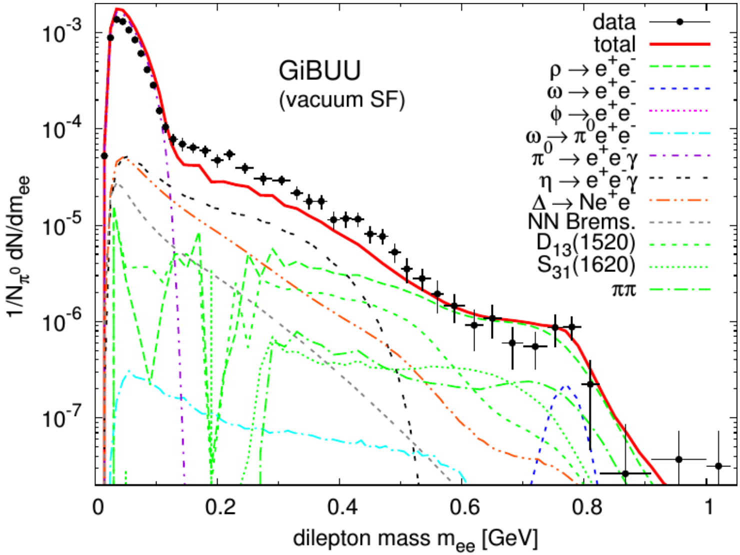


- no definite hint for medium modifications in p Nb

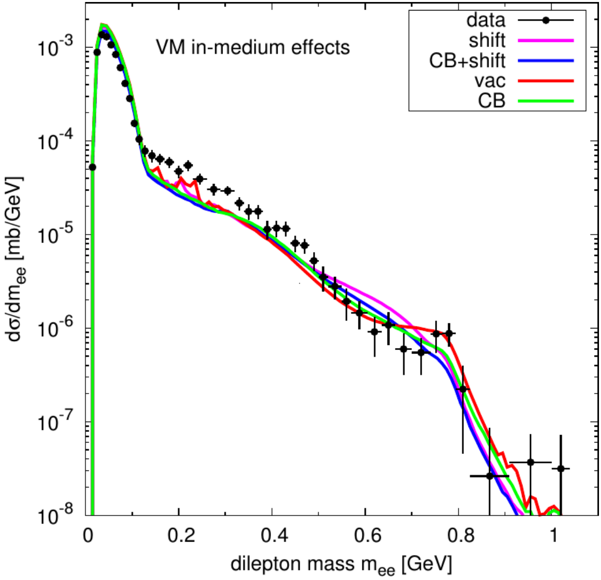
GiBUU: p+Nb (3.5 GeV) (SIS/HADES)

- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity on medium effects of vector-meson spectral functions?

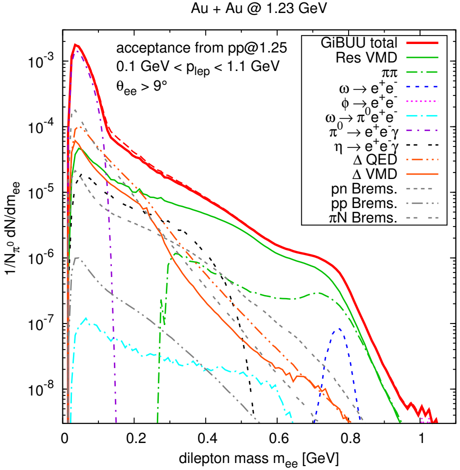



GiBUU
(vacuum SF)
data
total
$\rho \to e^+e^-$
$\omega \to e^+e^-$
$\phi \to e^+e^-$
$\omega \to \pi^0 e^+e^-$
$\pi^0 \to e^+e^-\gamma$
$\eta \to e^+e^-\gamma$
$\Delta \to Ne^+e^-$
NN Brems.
$D_{13}(1520)$
$S_{31}(1620)$
$\pi\pi$
$1/N_{\pi^0}\, dN/dm_{ee}$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
0.2
0.4
0.6
0.8
1
dilepton mass m_{ee} [GeV]

GiBUU: Ar+KCl (1.76 AGeV) (SIS/HADES)

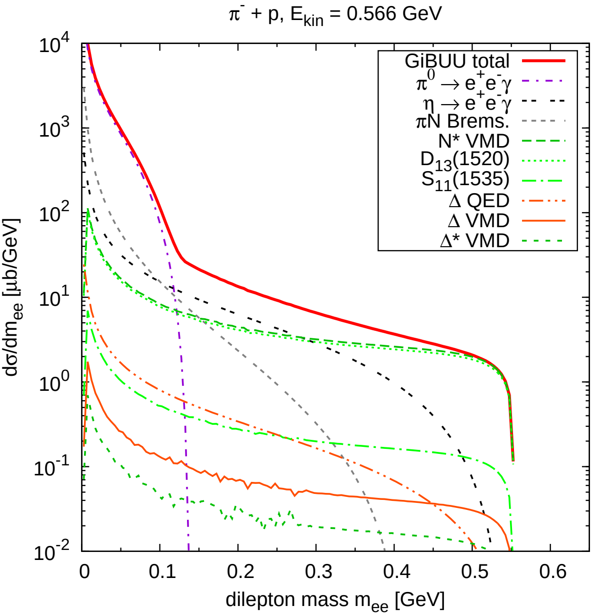


GiBUU (NEW!): Au+Au (1.23 *A*GeV) (SIS/HADES)



- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- comparison to preliminary HADES data [Gal14] ⇒ room for medium modifications (data points not shown here on request of the HADES collaboration)

GiBUU (NEW!): π+p (566 MeV) (SIS/HADES)



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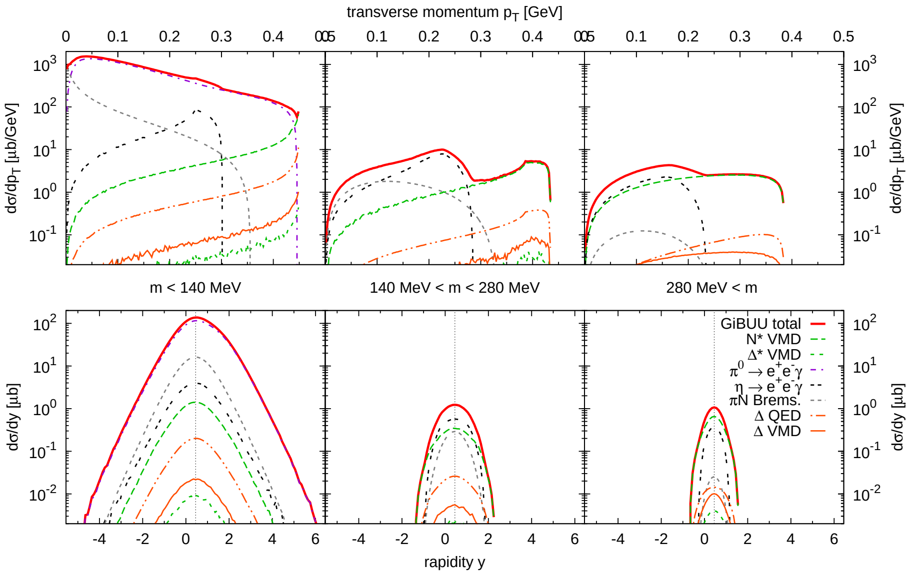
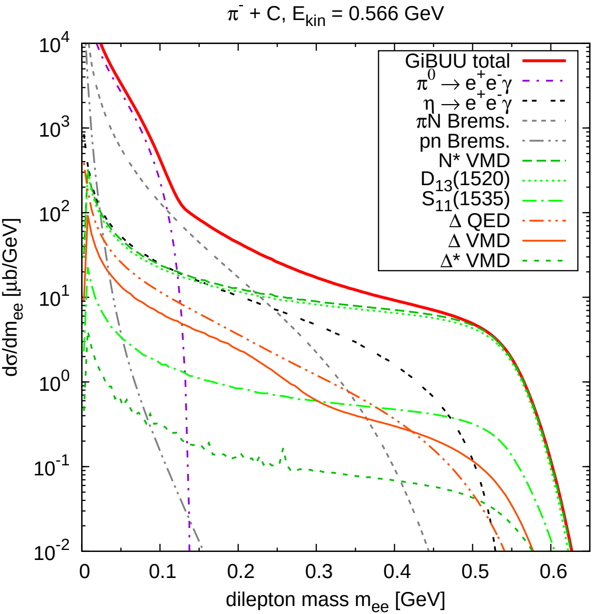
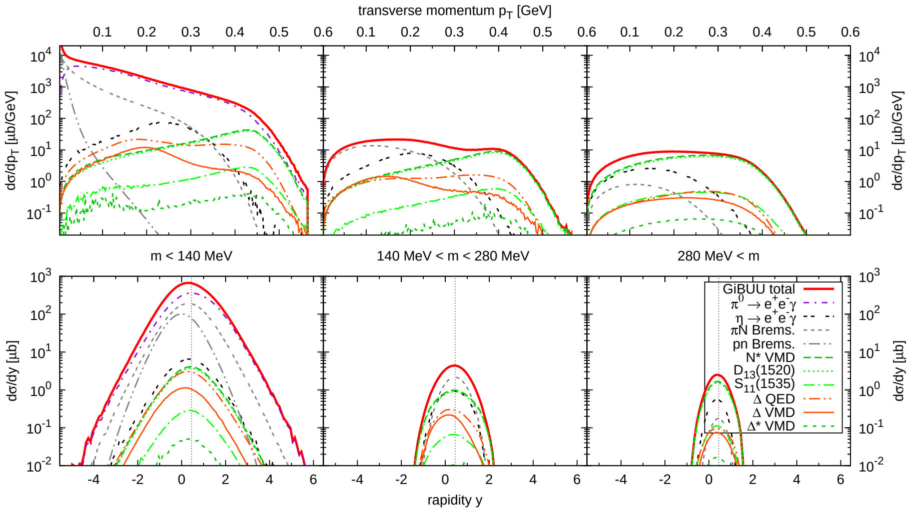


GiBUU (NEW!): π+C (566 MeV) (SIS/HADES)



GiBUU (NEW!): π+C (566 MeV) at (SIS/HADES)

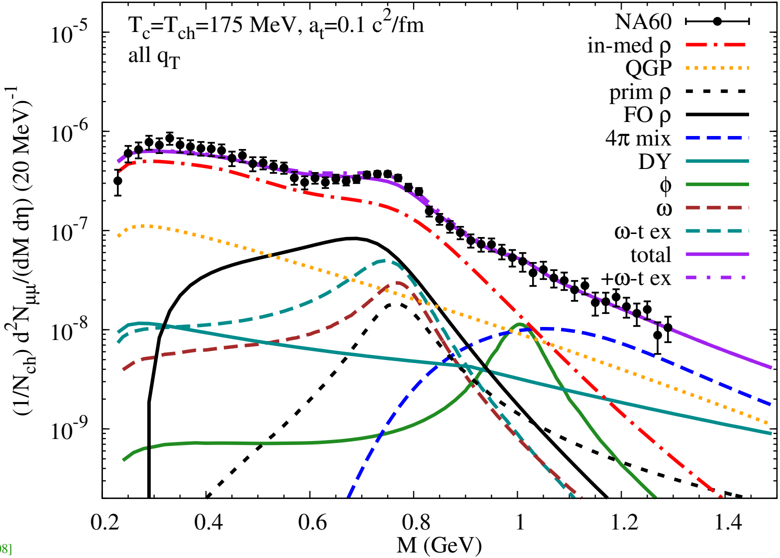


Dileptons at SPS and RHIC

thermal fireball model (with Ralf Rapp)

M spectra (in p_T slices)

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



[HR06, HR08]

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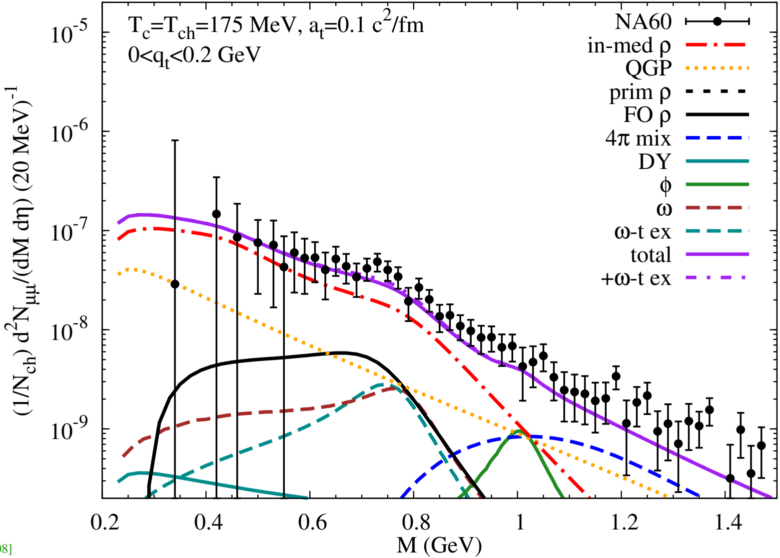

[HR06, HR08]

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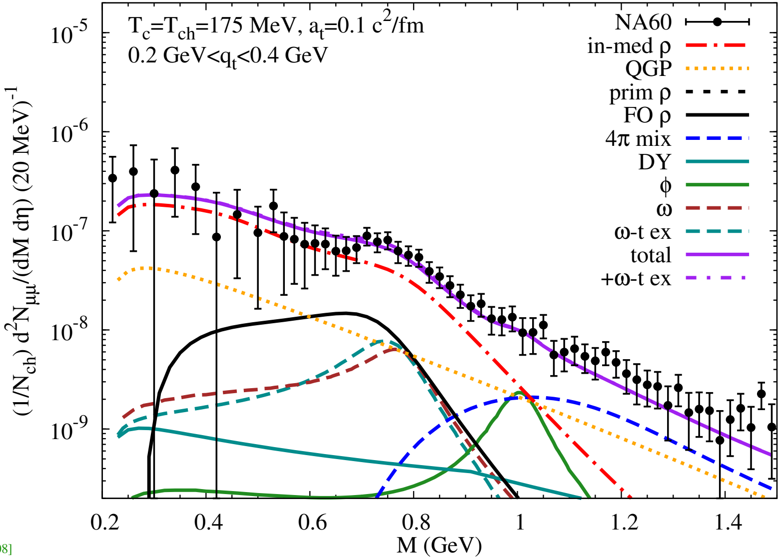

[HR06, HR08]

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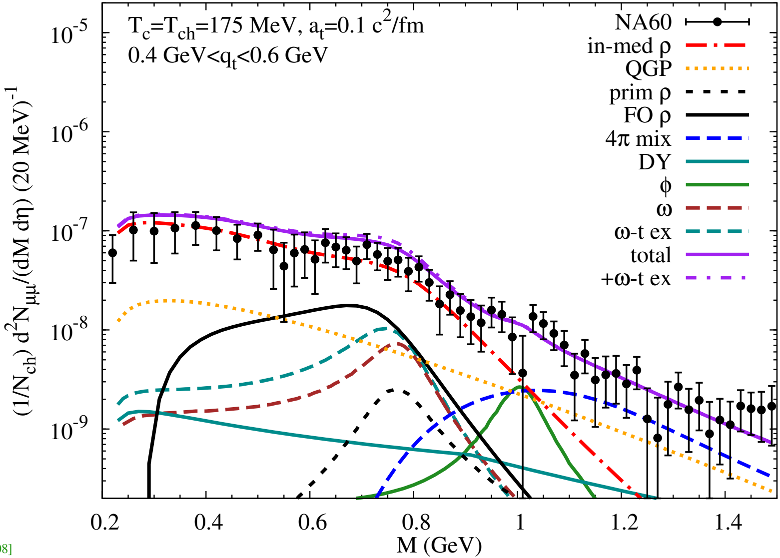

[HR06, HR08]

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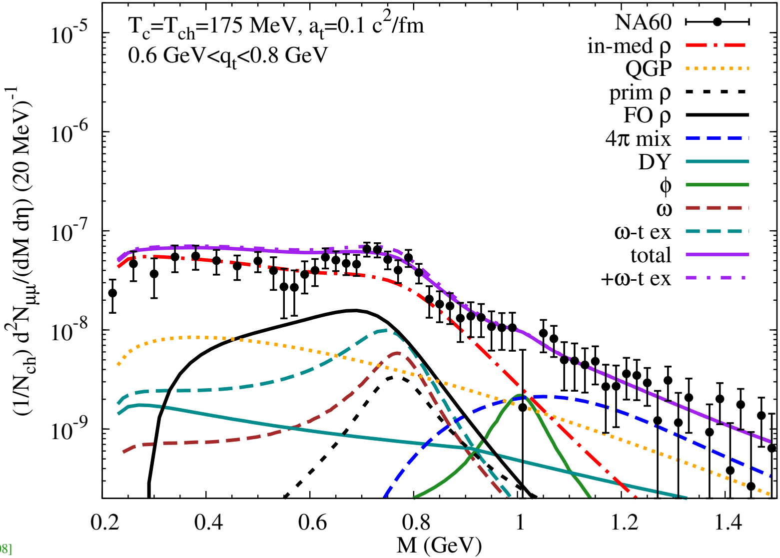

[HR06, HR08]

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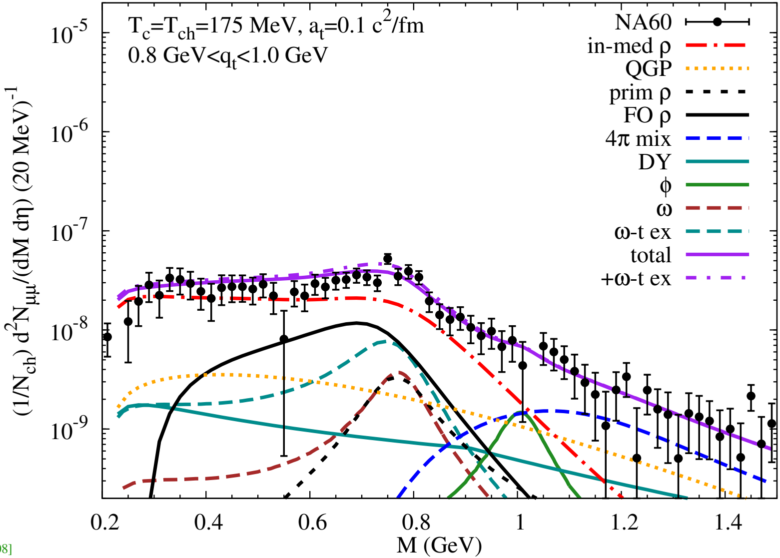

[HR06, HR08]

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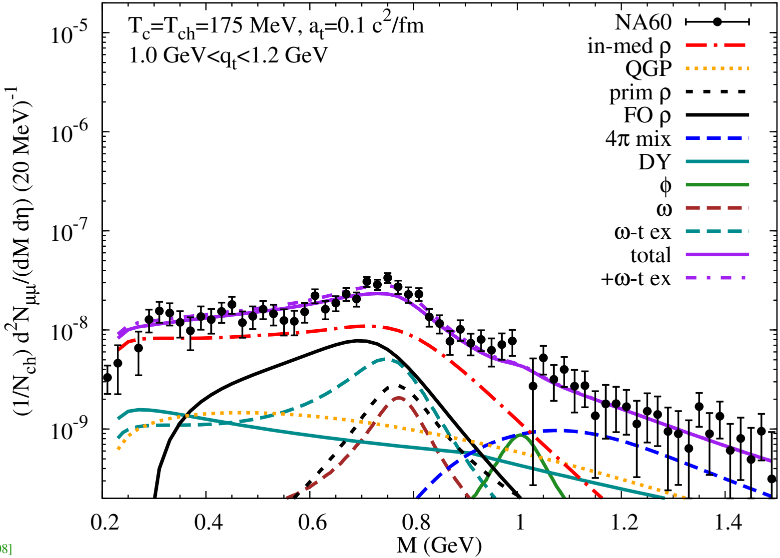

[HR06, HR08]

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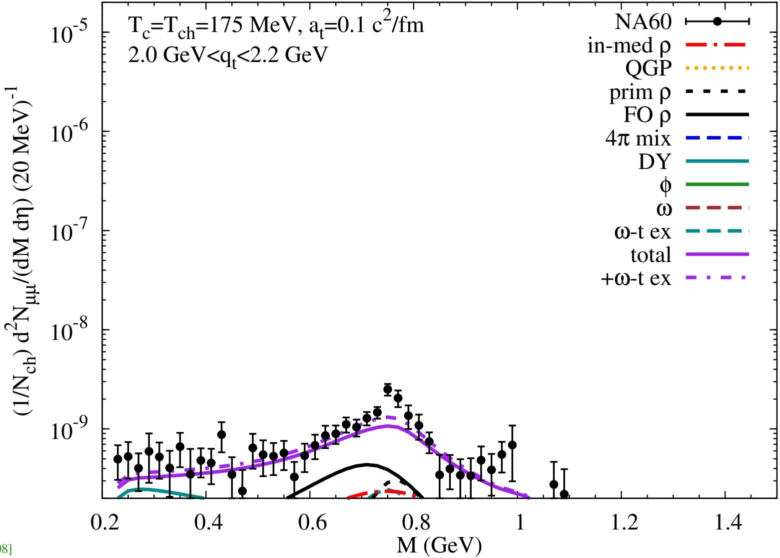

[HR06, HR08]

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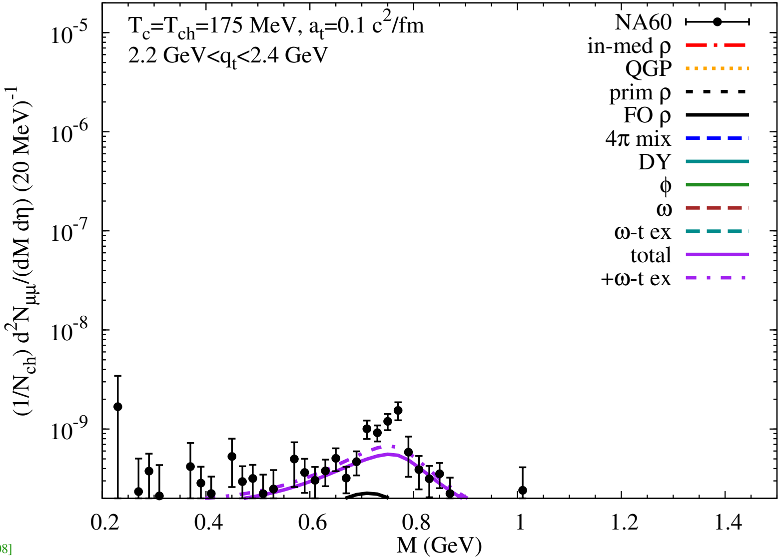
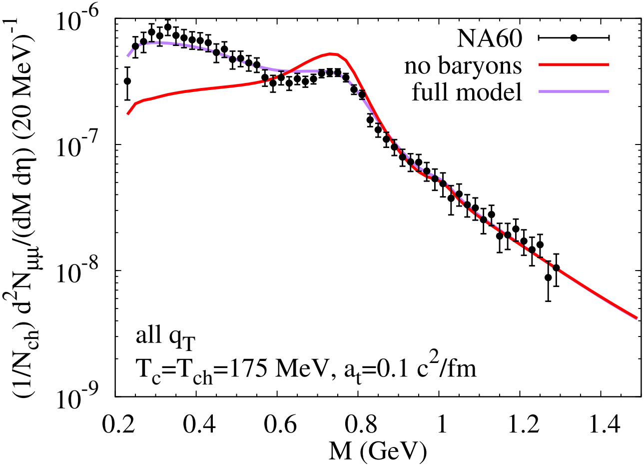


[HR06, HR08]

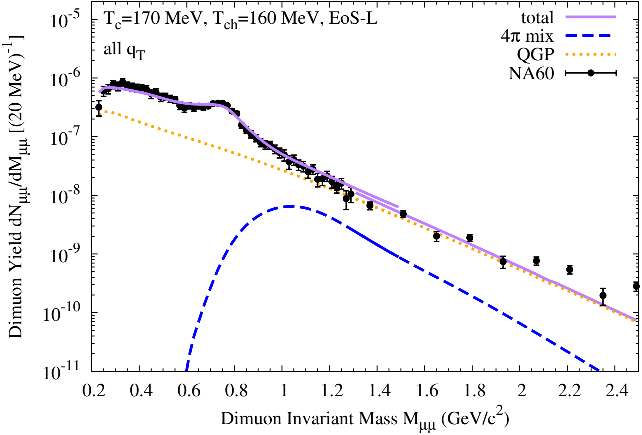
Importance of baryon effects

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



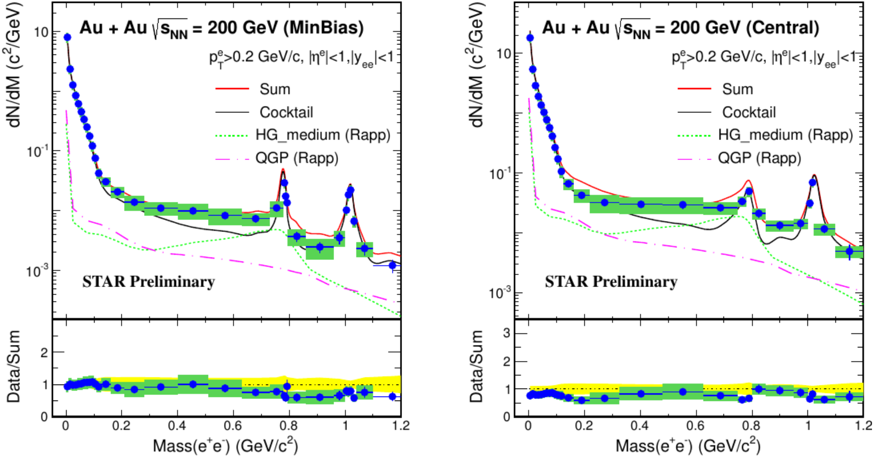
Update: Using lattice equation of state

- 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!)



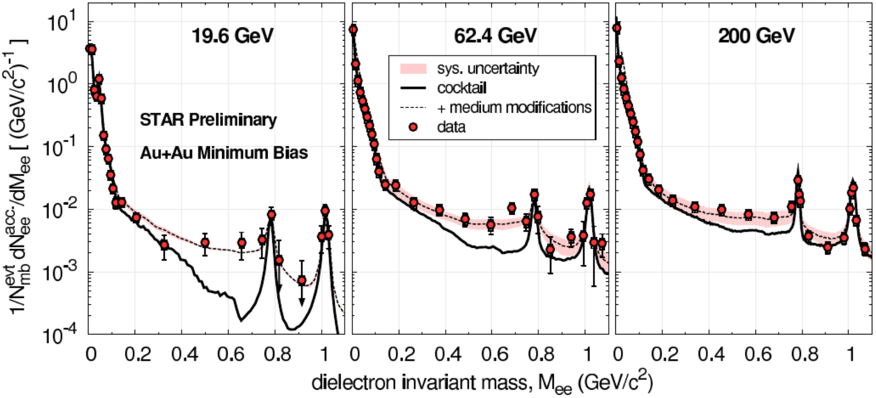
- compatible with coarse-grained UrQMD calculation (see Stephan Endres's talk!)

- dielectron spectra Au+Au collisions ($\sqrt{s_{NN}} = 200$ GeV) at RHIC/STAR
- same model as before successful over wide range of beam energies [Rap13]
- NB: together with CG UrQMD also at SIS energies! (see S. Endres's talk)

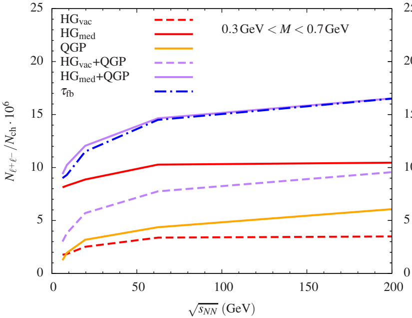


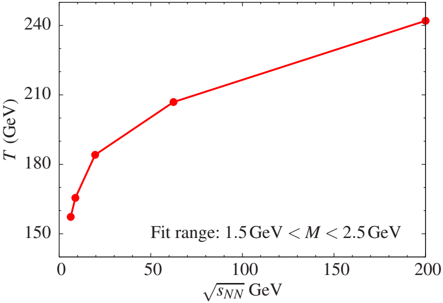
RHIC beam-energy scan (STAR)

- dielectron spectra Au+Au collisions at RHIC
- same model as before successful over wide range of beam energies [Rap13]
- NB: together with CG UrQMD also at SIS energies! (see S. Endres's talk)



- fireball model $\Rightarrow$ lifetime, dilepton excess, temperature as fct. of $\sqrt{s_{NN}}$
- indications of phase transition???





Conclusions

- General ideas
  - em. probes $\Leftrightarrow$ in-medium em. current-correlation function
  - effective QFT models for hadronic interactions and $\ell^+\ell^-$ (and γ!) production
  - HTL improved or lattice QGP $\ell^+\ell^-$ (and γ) rates
  - dual rates around T_c (compatible with χ symmetry restoration)
  - medium modifications of ρ, ω, ϕ
  - importance of hadron-resonance interactions
  - baryon resonances prevalent for medium effects
  - reliable input on resonance physics in elementary reactions crucial!
  - need to fix masses, couplings, form factors (including em. transition FFs)
- Application to dileptons in HICs
  - thermal fireball, (ideal) hydrodynamics, (coarse-grained) transport, hybrid...
  - equation of state $\Leftrightarrow$ compatibility with QFT/transport models!?!
  - use of thermal-QFT spectral VM functions
  - successful description at HADES, SPS, and RHIC (STAR)
  - consistent description of M and m_T spectra!
  - not too sensitive to details of medium evolution
  - beam-energy scan at RHIC and FAIR $\Rightarrow$ signature of phase transition?
  - sensitivity to equation of state?
  - signature of cross-over vs. 1st order (or even critical endpoint)?
  - effective slope of M spectra in higher IMR ($1.5\ \text{GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$

Bibliography I

[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`

[CF74] F. Cooper, G. Frye, Single-particle distribution in the hydrodynamic and statistical thermodynamics models of multiparticle production, Phys. Rev. D **10** (1974) 186.
`http://dx.doi.org/10.1103/PhysRevD.10.186`

[DFK+11] H.-T. Ding, et al., Thermal dilepton rate and electrical conductivity: An analysis of vector current correlation functions in quenched lattice QCD, Phys. Rev. D **83** (2011) 034504.

[FHK+11] B. Friman, et al. (eds.), The CBM Physics Book, vol. 814 of *Lecture Notes in Physics*, Springer-Verlag, Berlin, Heidelberg (2011).
`http://www.gsi.de/forschung/fair_experiments/CBM/PhysicsBook.html`

Bibliography II

[Gal14] T. Galatyuk, HADES overview, Nucl. Phys. A (2014), published online; DOI:10.1016/j.nuclphysa.2014.10.044.
`http://dx.doi.org/10.1016/j.nuclphysa.2014.10.044`

[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`

[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`

Bibliography III

[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

[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

[WEH+14] J. Weil, S. Endres, H. van Hees, M. Bleicher, U. Mosel, Dilepton Production in Transport-based Approaches (2014).

[Wel90] H. A. Weldon, Reformulation of finite temperature dilepton production, Phys. Rev. D **42** (1990) 2384.
http://link.aps.org/abstract/PRD/V42/P2384

Bibliography IV

[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.
http://dx.doi.org/10.1088/1742-6596/426/1/012035