Dileptons in heavy-ion collisions with transport models

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FIAS Frankfurt Institute for Advanced Studies

DFG

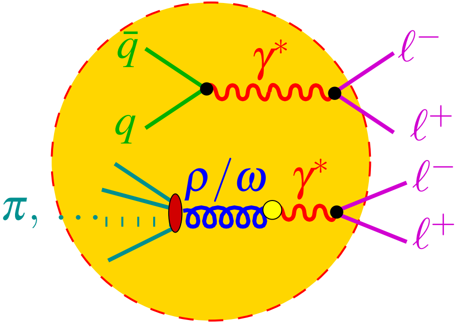
Outline

1. Electromagnetic probes in heavy-ion collisions
   - Em. current correlation function and electromagnetic probes
   - Sources of dilepton emission in heavy-ion collisions
   - Sources of thermal photons in heavy-ion collisions
2. Dileptons in pp, pn, pA, AA in pure transport (GiBUU with J. Weil)
   - GiBUU
   - Dalitz decays of hadron resonances
   - Baryon-resonance model at SIS energies
   - Dielectrons (SIS/HADES)
3. Dileptons in AA in coarse-grained transport (with S. Endres)
   - Models for bulk-medium evolution
   - Dielectrons (SIS/HADES)
   - Dimuons (SPS/NA60)
4. Conclusions and Outlook

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

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



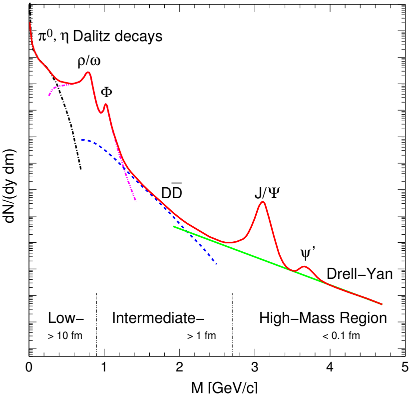


Fig. by A. Drees

Em. current correlation function and electromagnetic Probes

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

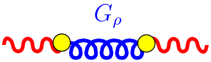
[MT85, Wel90, GK91]

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

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

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

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

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

Sources of dilepton emission in heavy-ion collisions

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

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

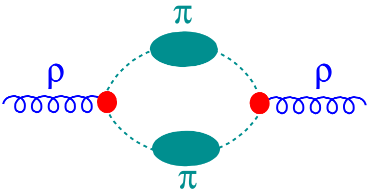
3. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
4. after thermal freeze-out ⇔ emission from "freeze-out" mesons

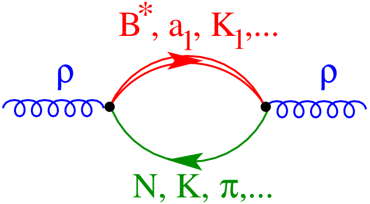
[CF74]

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

Hadronic many-body theory

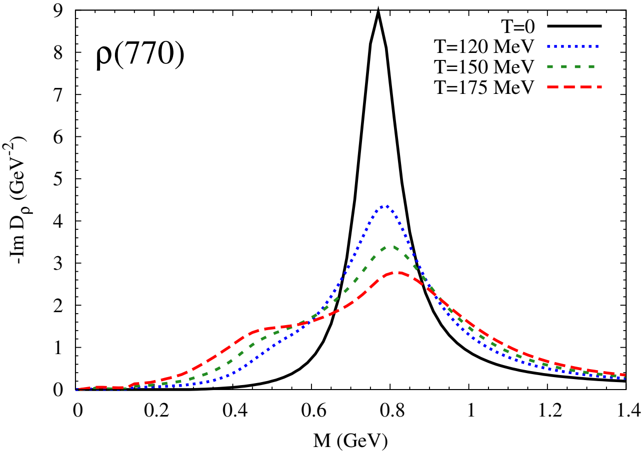
- HMBT for vector mesons [Ko et al, Chanfray et al, Herrmann et al, Rapp et al, ...]
- $\pi\pi$ interactions and baryonic excitations





- +corresponding vertex corrections ⇔ 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)

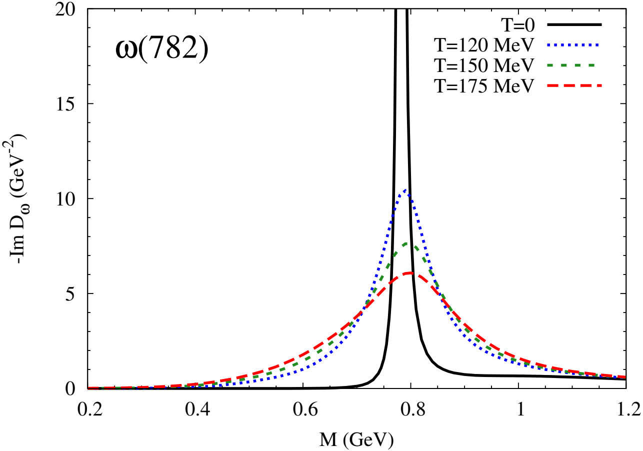
In-medium spectral functions and baryon effects



[R. Rapp, J. Wambach 99]

- 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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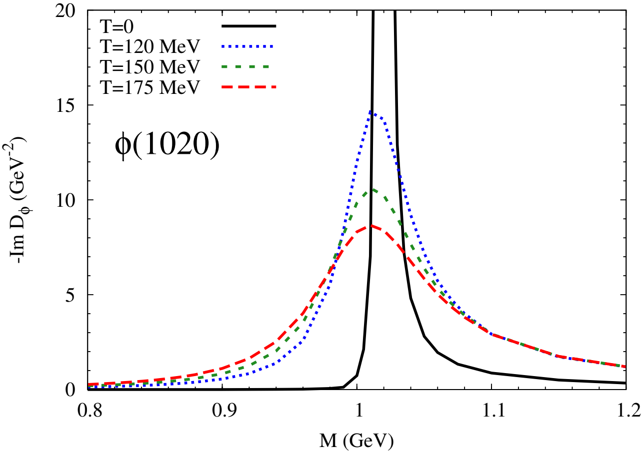

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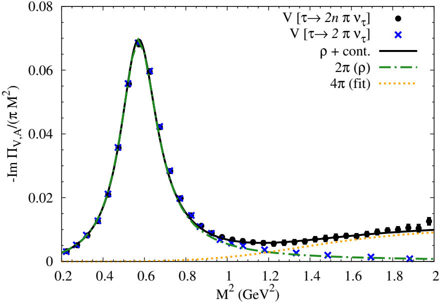
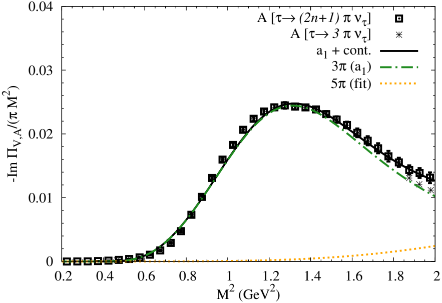
Intermediate masses: hadronic “4π contributions”

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

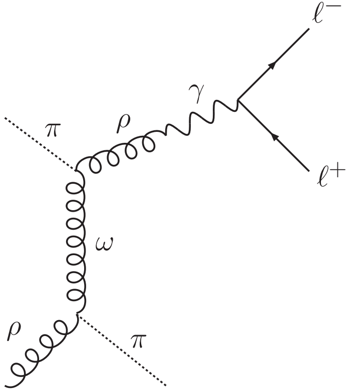




- “4π contributions”: $\pi + \omega, a_1 \rightarrow \mu^+ + \mu^-$
- leading-order virial expansion for “four-pion piece”
- additional strength through “chiral mixing”

Radiation from thermal sources: Meson t-channel exchange

- motivation: q_T spectra too soft compared to NA60 data
- thermal contributions not included in models so far

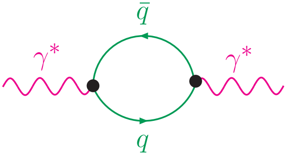


- also for π, a_1

Dileptons from thermal QGP

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

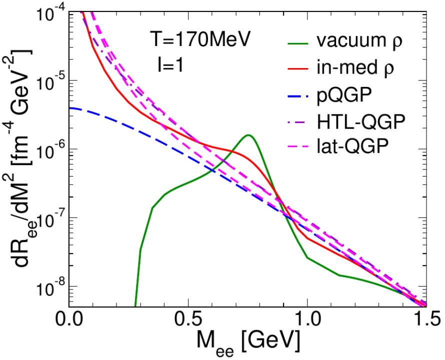
$-\mathrm{i}\Pi_{\mathrm{em,QGP}} =$



- or electromagnetic current correlator from the lattice [H.-T. Ding, A. Francis et al (Bielefeld) 2011] (extrapolated to finite q)
- "quark-hadron duality" around T_c

Dilepton rates: Hadron gas $\leftrightarrow$ QGP

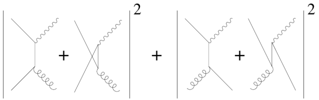
- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?



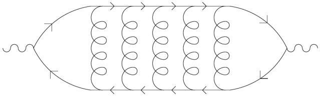
[R. Rapp, arXiv: 1304.2309 [hep-ph]]

Sources of thermal photons in heavy-ion collisions

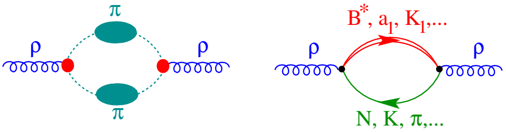
- QGP: rates from [Arnold, Moore, Yaffe, JHEP **12**, 009 (2001)]
  - $q\bar{q} \to \gamma g$, $qg \to \gamma q$



  - resummation of soft-gluon bremsstrahlung contributions
  - Landau-Pomeranchuk-Migdal effect



- hadronic matter from [Turbide, Rapp, Gale, PRC **69**, 014903 (2004); Rapp, Wambach EPJ A **6**, 415 (1999)]
  - pion-cloud dressing + vector meson-baryon/meson interactions

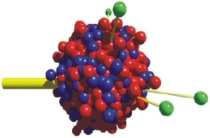


  - $\pi\rho a_1$, ω-t-channel exchange

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

The Boltzmann-Uehling-Uhlenbeck Equation

- time evolution of phase-space distribution functions

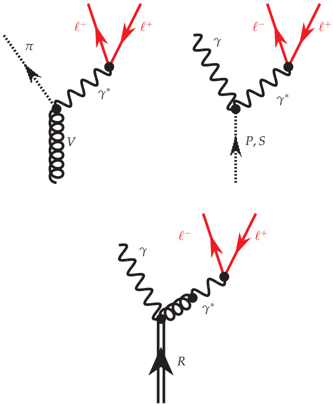
$$[\partial_t + (\vec{\nabla}_p H_i) \cdot \vec{\nabla}_x - (\vec{\nabla}_x H_i) \cdot \vec{\nabla}_p] f_i(t, \vec{x}, \vec{p}) = I_{\text{coll}}[f_1, \ldots, f_i, \ldots, f_j]$$

- use Monte-Carlo simulation for test particles
- transition probability W in collision term used to define stochastic process ("random numbers" on the computer)
- Hamiltonian H_i
  - selfconsistent hadronic mean fields, Coulomb potential, "off-shell potential"
- collision term I_{coll}
  - two- and three-body decays/collisions
  - multiple coupled-channel problem
  - resonances described with relativistic Breit-Wigner distribution

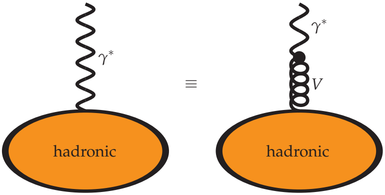
$$\mathscr{A}(x,p) = -\frac{1}{\pi} \frac{\operatorname{Im}\Pi}{(p^2 - M^2 - \operatorname{Re}\Pi)^2 + (\operatorname{Im}\Pi)^2}; \quad \operatorname{Im}\Pi = -\sqrt{p^2}\Gamma$$

  - off-shell propagation: test particles with off-shell potential

Dalitz decays



- 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



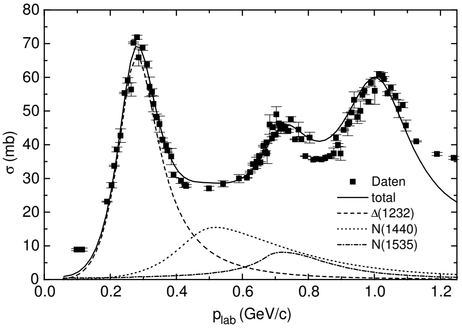
- NB: vector-meson resonances “produced” from stable particles
- Fermi’s golden rule: equivalent to self-energies for vector mesons!
- cutting self-energy diagrams $\Rightarrow$ elementary processes

Resonance Model

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

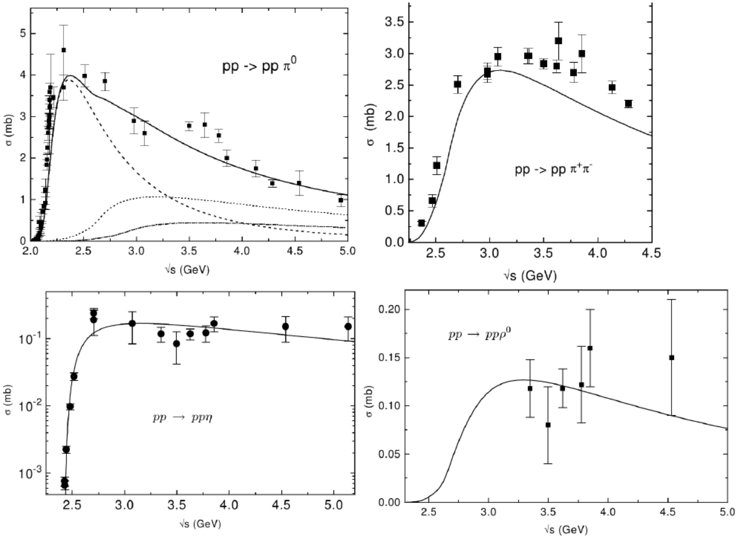
$$\sigma_{ab\to R\to cd} = \frac{2s_R+1}{(2s_a+1)(2s_b+1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab\to R}\Gamma_{R\to cd}}{(s-m_R^2)^2+s\Gamma_{\text{tot}}^2}$$

- 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)]



GiBUU: Resonance Model

- further cross sections



GiBUU: Extension to HADES energies

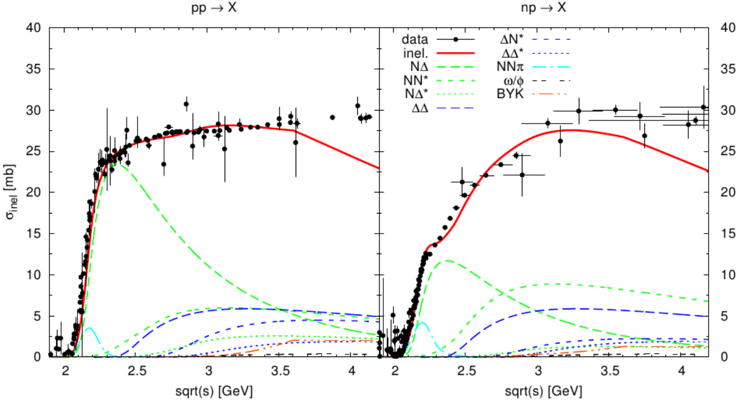
- [WHM12, WM13]
- keep same resonances (parameters from Manley analysis)

	rating	M_0 [MeV]	Γ_0 [MeV]	$\lvert\mathcal{M}^2\rvert/16\pi$ [mb GeV^2] NR	ΔR	branching ratio in % 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 $NN \to \Delta N^*, \Delta\Delta^*$, $NN \to NN\pi$, $NN \to NN\rho, NN\omega, NN\pi\omega, NN\phi$, $NN \to BYK$ ($B = N, \Delta$, $Y = \Lambda, \Sigma$)

GiBUU Extension to HADES energies

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

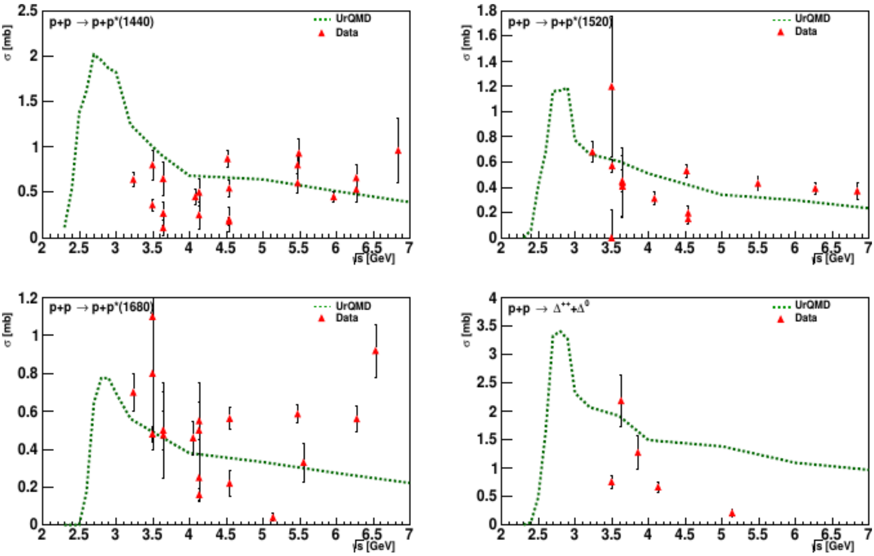


- dilepton sources
  - Dalitz decays: $\pi^0, \eta \to \gamma \ell^+ \ell^-$; $\omega \to \pi^0 \ell^+ \ell^-$, $\Delta \to N \ell^+ \ell^-$
  - $\rho, \omega, \phi \to \ell^+ \ell^-$: invariant mass $\ell^+ \ell^-$ spectra $\Rightarrow$ spectral properties of vector mesons
  - for details, see [WHM12]

UrQMD: Baryon resonances

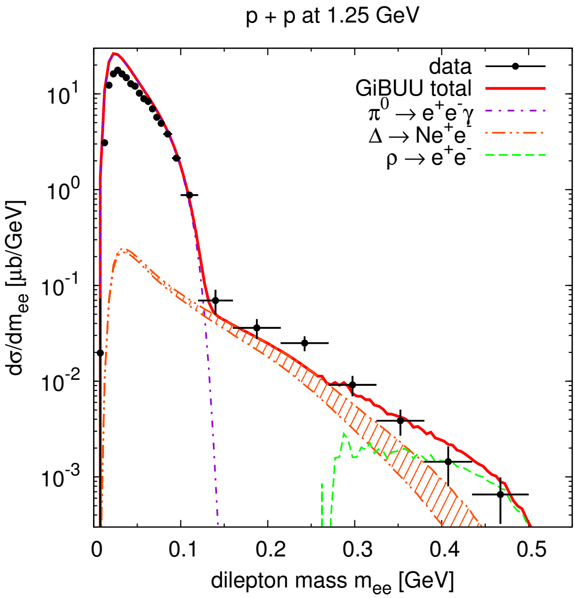
Resonance	Mass	Width	$N\pi$	$N\eta$	$N\omega$	$N\varrho$	$N\pi\pi$	$\Delta_{1232}\pi$	$N^*_{1440}\pi$	ΛK	ΣK	$f_0 N$	$a_0 N$
N^*_{1440}	1.440	350	0.65				0.10	0.25					
N^*_{1520}	1.515	120	0.60			0.15	0.05	0.20					
N^*_{1535}	1.550	140	0.60	0.30			0.05		0.05				
N^*_{1650}	1.645	160	0.60	0.06		0.06	0.04	0.10	0.05	0.07	0.02		
N^*_{1675}	1.675	140	0.40					0.55	0.05				
N^*_{1680}	1.680	140	0.60			0.10	0.10	0.15	0.05				
N^*_{1700}	1.730	150	0.05			0.20	0.30	0.40	0.05				
N^*_{1710}	1.710	500	0.16	0.15		0.05	0.21	0.20	0.10	0.10	0.03		
N^*_{1720}	1.720	550	0.10			0.73	0.05			0.10	0.02		
N^*_{1900}	1.850	350	0.30	0.14	0.39	0.15				0.02			
N^*_{1990}	1.950	500	0.12			0.43	0.19	0.14	0.05	0.03		0.04	
N^*_{2080}	2.000	550	0.42	0.04	0.15	0.12	0.05	0.10		0.12			
N^*_{2190}	2.150	470	0.29			0.24	0.10	0.15	0.05	0.12			
N^*_{2220}	2.220	550	0.29		0.05	0.22	0.17	0.20		0.12			
N^*_{2250}	2.250	470	0.18			0.25	0.20	0.20	0.05	0.12			
Δ_{1232}	1.232	115	1.00										
Δ^*_{1600}	1.700	350	0.10					0.65	0.25				
Δ^*_{1620}	1.675	160	0.15			0.05		0.65	0.15				
Δ^*_{1700}	1.750	350	0.20			0.25		0.55					
Δ^*_{1900}	1.840	260	0.25			0.25		0.25	0.25				
Δ^*_{1905}	1.880	350	0.18			0.80		0.02					
Δ^*_{1910}	1.900	250	0.30			0.10		0.35	0.25				
Δ^*_{1920}	1.920	200	0.27					0.40	0.30	0.03			
Δ^*_{1930}	1.970	350	0.15			0.22		0.20	0.28	0.15			
Δ^*_{1950}	1.990	350	0.38			0.08		0.20	0.18	0.12			0.04

UrQMD: Baryon resonances

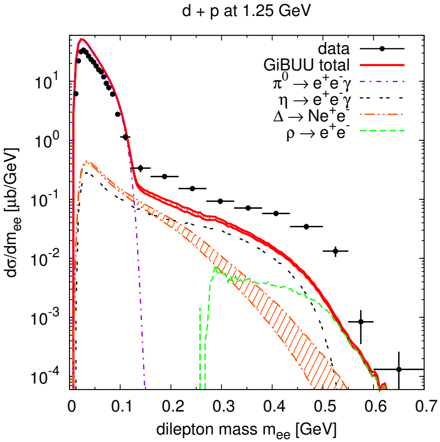


Dileptons in pp, pA, and AA collisions at SIS energies

GiBUU: p+p (1.25 GeV) (SIS/HADES)

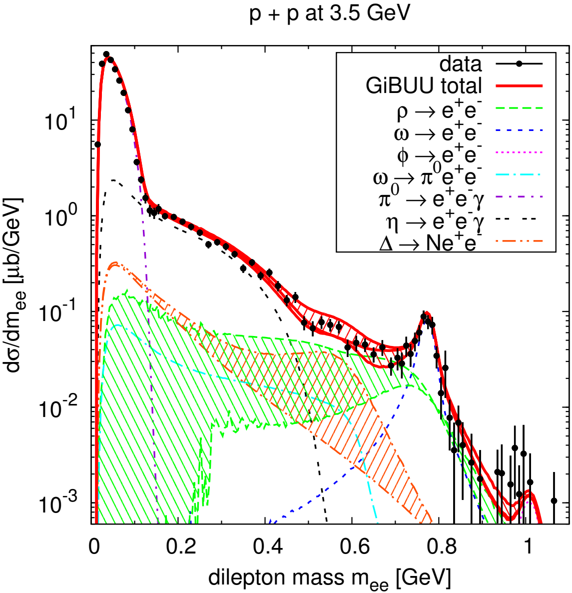


d+p (1.25 GeV) (SIS/HADES)

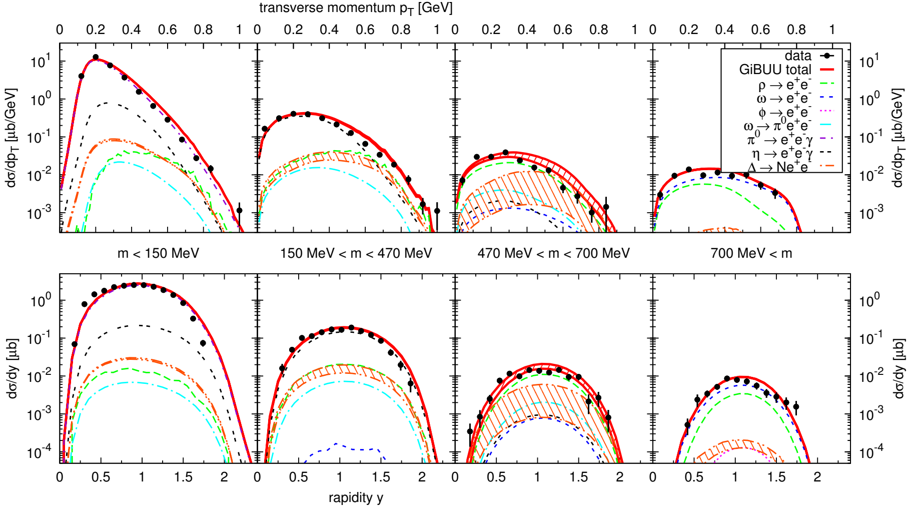


- triggered on forward protons → quasifree np scattering
- model uncertainties:
  - ρ production through $D_{13}(1525)$ (isospin symmetric?)
  - $S_{11}(1535)$ [enhanced in np; (from η production)]
  - d-wave function treatable as quasiclassical "distribution"?
  - bremsstrahlung contributions

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

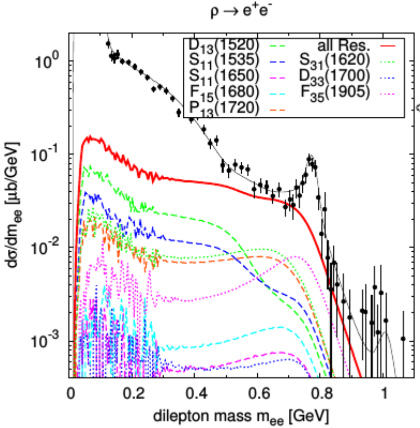


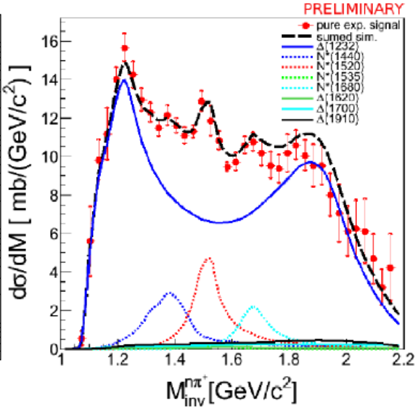
GiBUU: p+p (3.5 GeV) (SIS/HADES)



GiBUU: “ρ meson” in pp

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

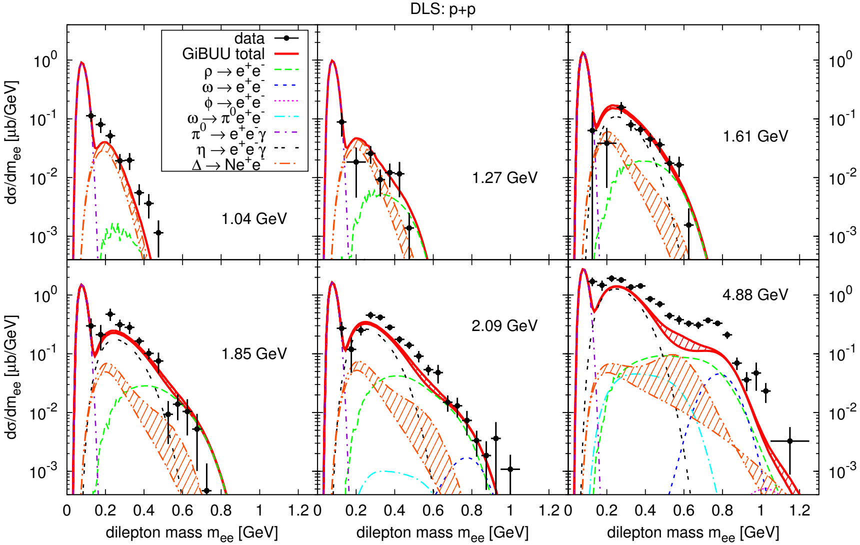




- “ρ”-line shape “modified” already in elementary hadronic reactions
- due to production mechanism via resonances

GiBUU: Comparison to old DLS data (pp)

- HADES data consistent with DLS data
- checked by comparing HADES data within DLS acceptance



GiBUU: Comparison to old DLS data (pd)

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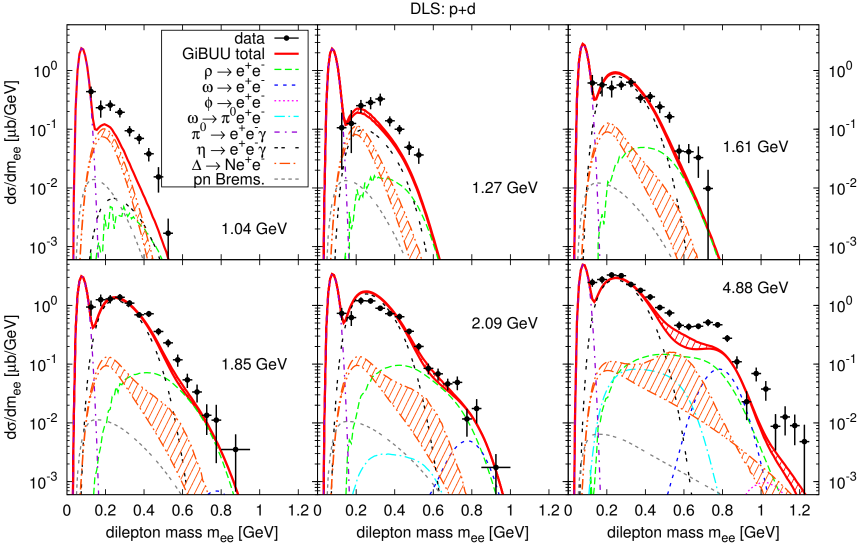
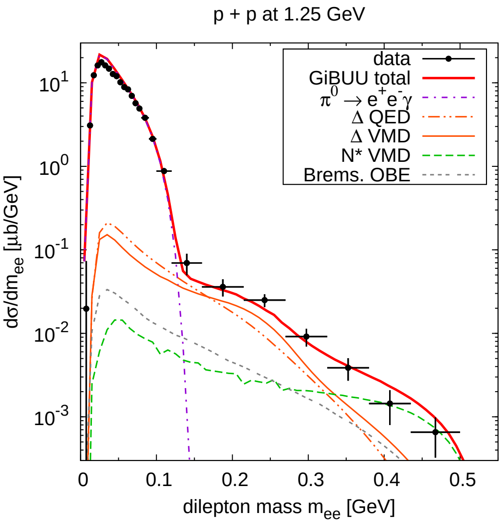
- checked by comparing HADES data within DLS acceptance



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



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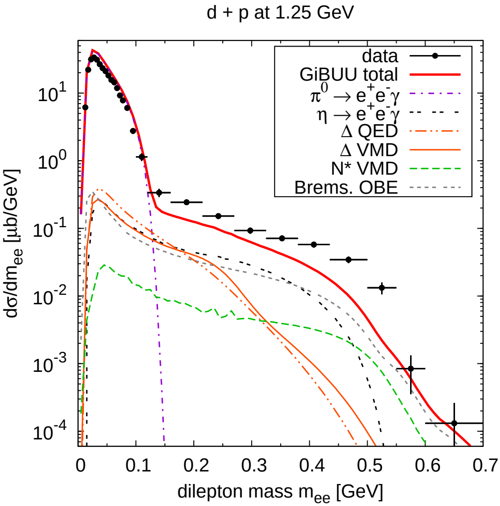

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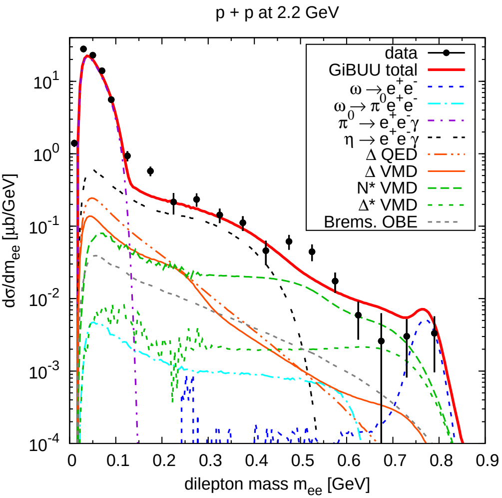

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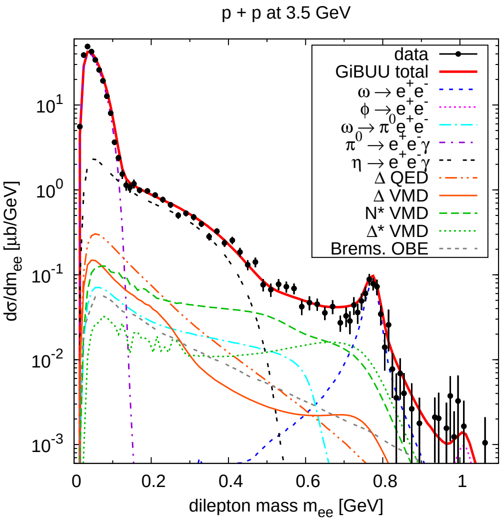


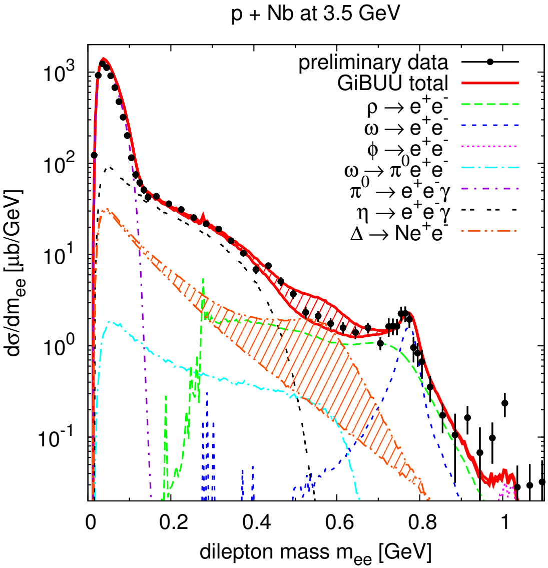
GiBUU: p+Nb (3.5 GeV) (SIS/HADES)

GiBUU:

- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity to additional in-medium modifications of vector mesons?

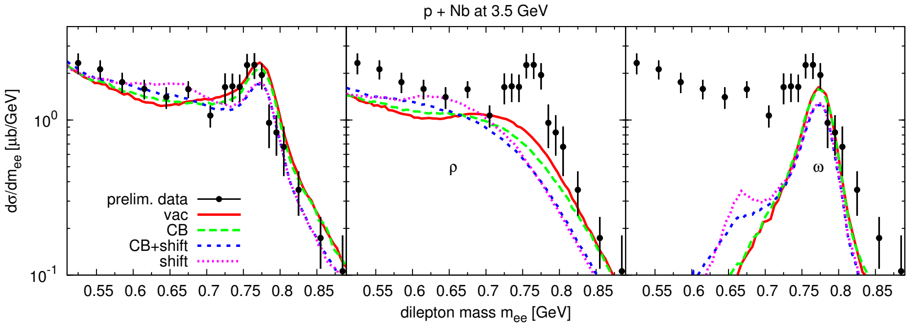
GiBUU: p+Nb (3.5 GeV) (SIS/HADES)

- with vacuum spectral functions:



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

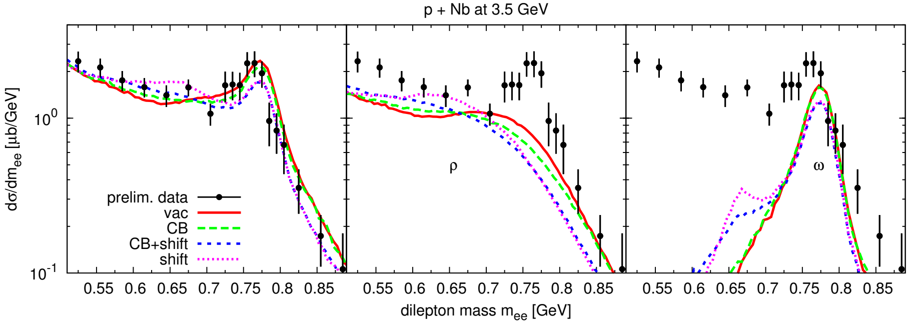
- with medium modified spectral functions:



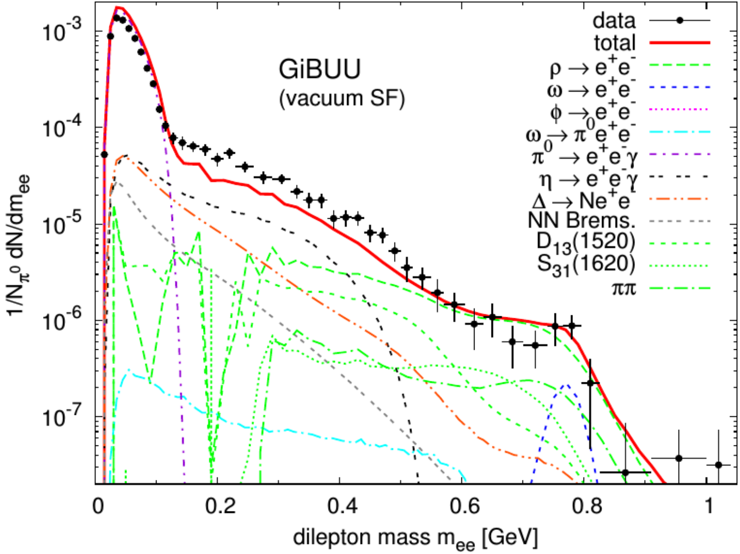
- no definite hint for medium modifications in p Nb

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

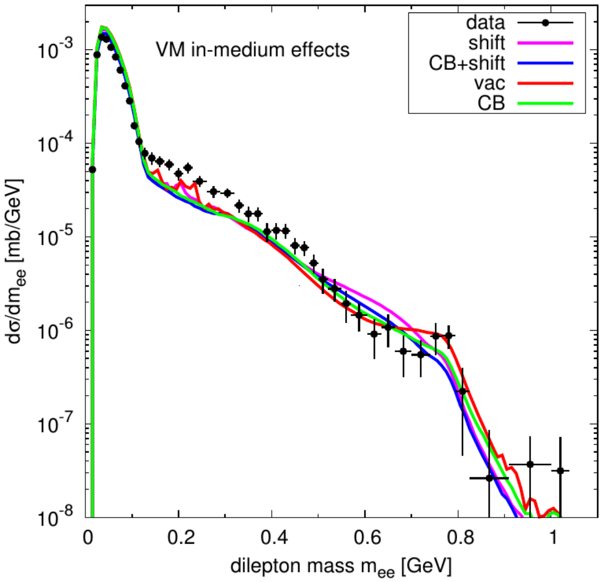
- medium effects built in transport model
  - binding effects, Fermi smearing, Pauli blocking
  - final-state interactions
  - production from secondary collisions
- sensitivity on medium effects of vector-meson spectral functions?



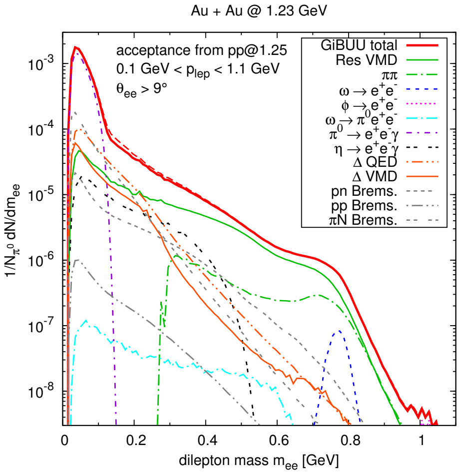
GiBUU: Ar+KCl (1.76AGeV) (SIS/HADES)



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

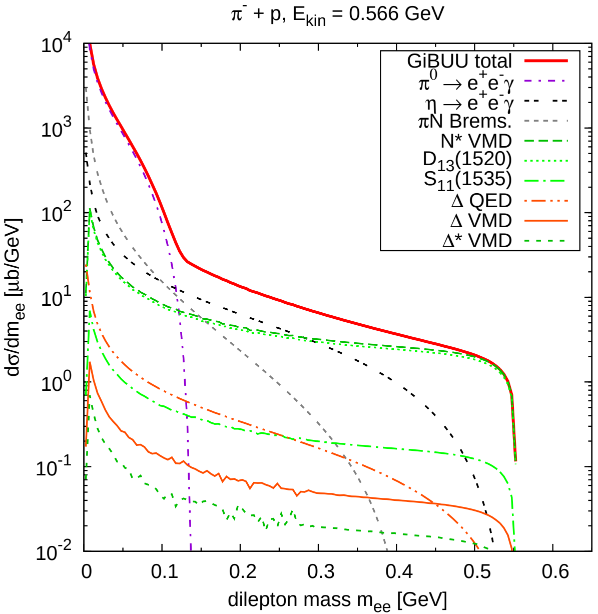


GiBUU (NEW!): Au+Au (1.23 *A*GeV) (SIS/HADES)

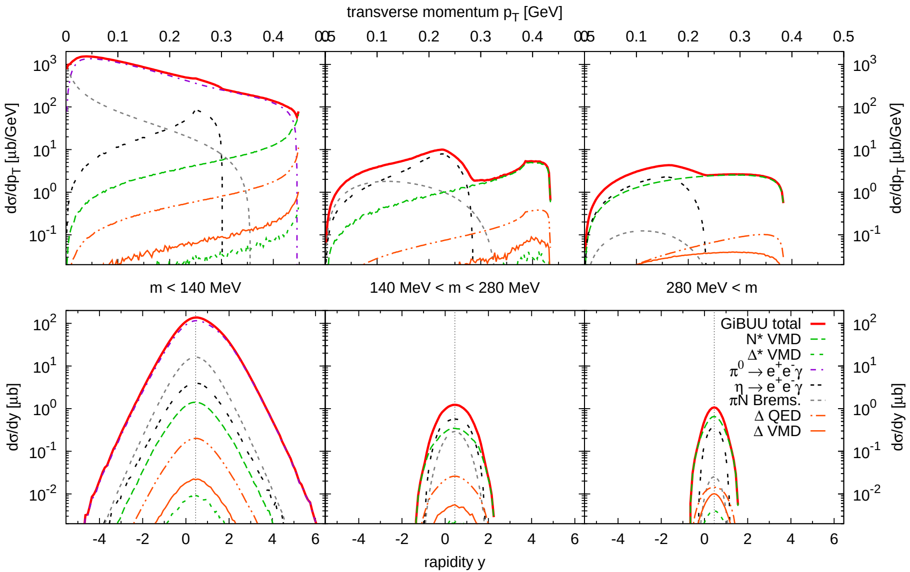


- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- comparison to preliminary HADES data [Gal14] ⇒ room for medium modifications (data points not shown here on request of the HADES collaboration)

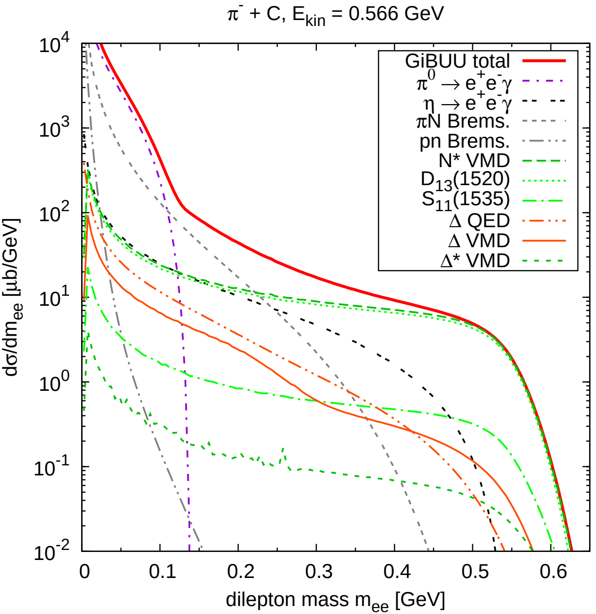
GiBUU (NEW!): π+p (566 MeV) (SIS/HADES)



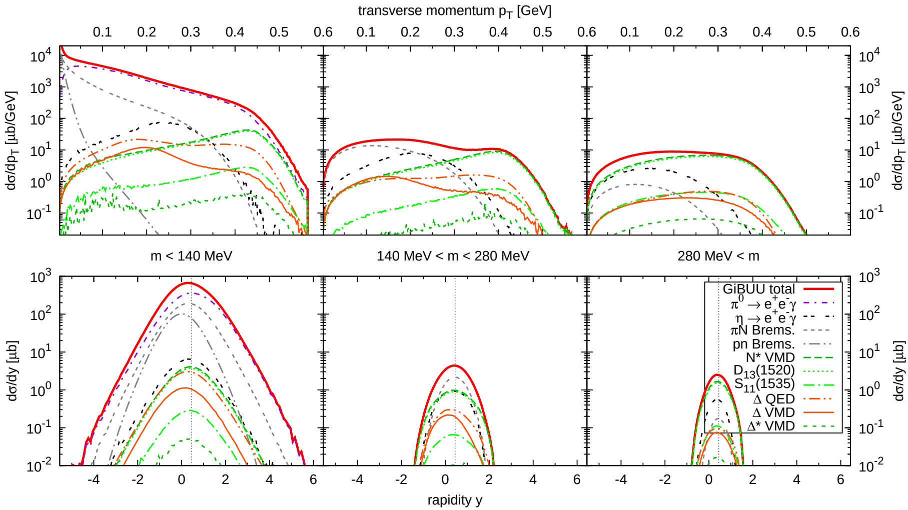
GiBUU (NEW!): π+p (566 MeV) (SIS/HADES)



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



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



Heavy-ion collisions and medium effects

"Coarse grained UrQMD" (with Stephan Endres)

Coarse-grained UrQMD (CGUrQMD)

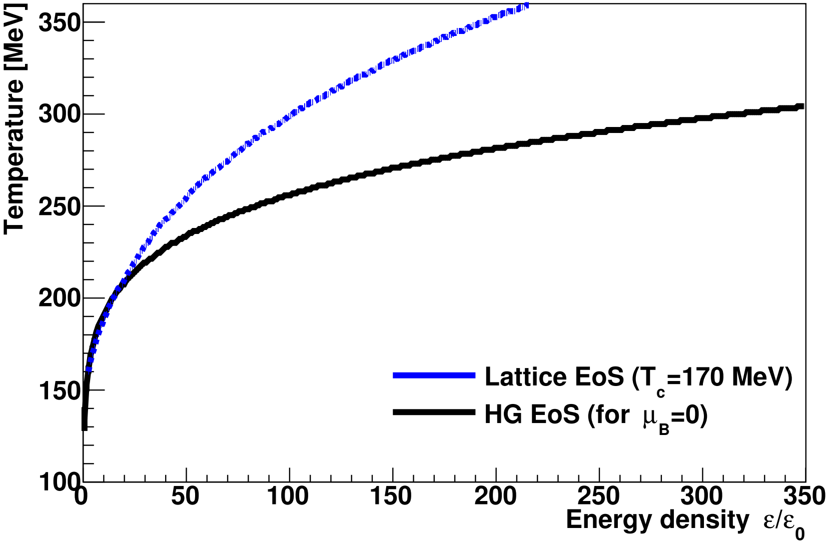
- problem with medium modifications of spectral functions/interactions
- only available in equilibrium many-body QFT models
- implementing "in-medium cross sections" naively: double counting?!?
- way out: map transport to local-equilibrium fluid
- Use ensemble of UrQMD runs with an equation of state
- fit temperature, chemical potentials, flow-velocity field
  from anisotropic energy-momentum tensor [W. Florkowski et al, NPA **904-905**, 803c (2013)]

$$T^{\mu\nu} = (\varepsilon + P_\perp) u^\mu u^\nu - P_\perp g^{\mu\nu} - (P_\parallel - P_\perp) V^\mu V^\nu$$

- thermal rates from partonic/hadronic QFT become applicable
- here: extrapolated lattice QGP and Rapp-Wambach hadronic many-body theory
- caveat: consistency between EoS, matter content of QFT model/UrQMD!

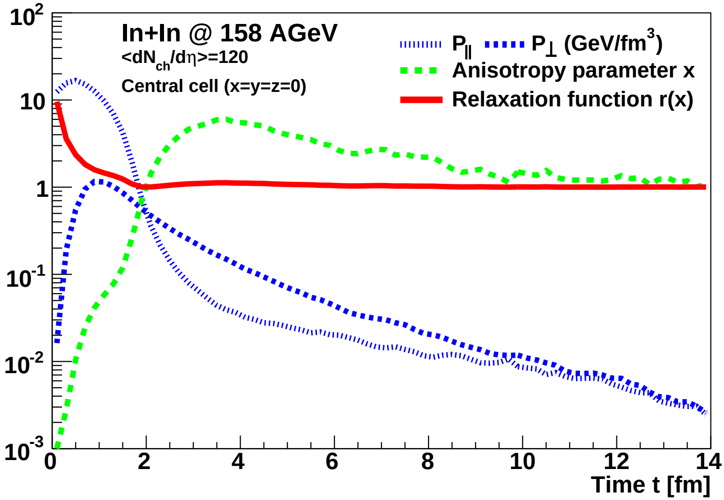
Coarse-grained UrQMD (CGUrQMD)

- $T_c = 170$ MeV; $T > T_c \Rightarrow$ lattice EoS; $T < T_c \Rightarrow$ HRG EoS



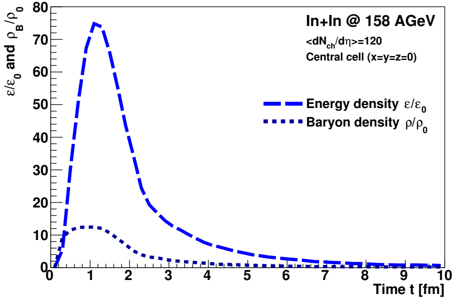
Coarse-grained UrQMD (CGUrQMD)

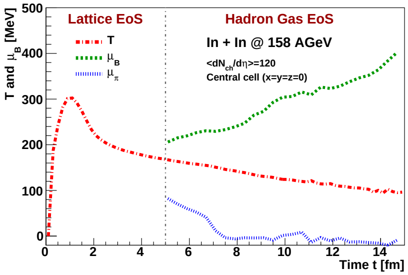
- pressure anisotropy (In-In collisions (NA60) at SIS)



Coarse-grained UrQMD (CGUrQMD)

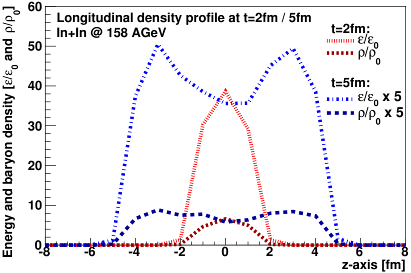
- energy/baryon density ⇒ T, μ_{B} (for In+In @ SPS; NA60)
- central "fluid" cell!

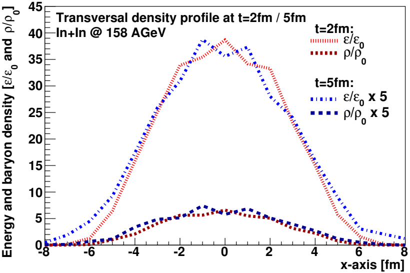




Coarse-grained UrQMD (CGUrQMD)

- temperature/density profiles (for In+In@SPS; NA60)

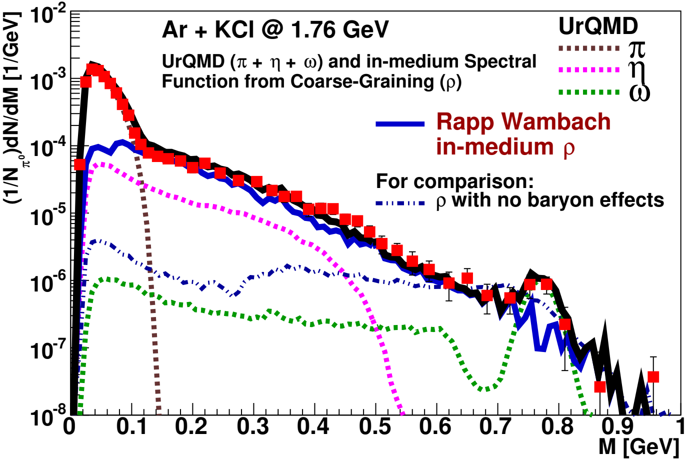




Dielectrons (SIS/HADES)

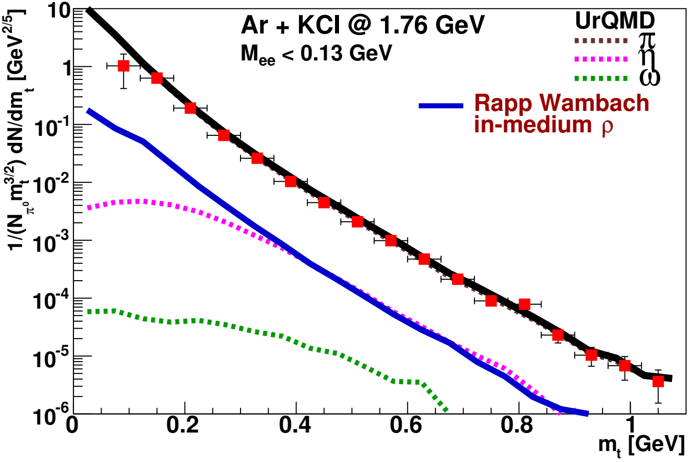
CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- coarse-graining method works at low energies!
- UrQMD-medium evolution + RW-QFT rates

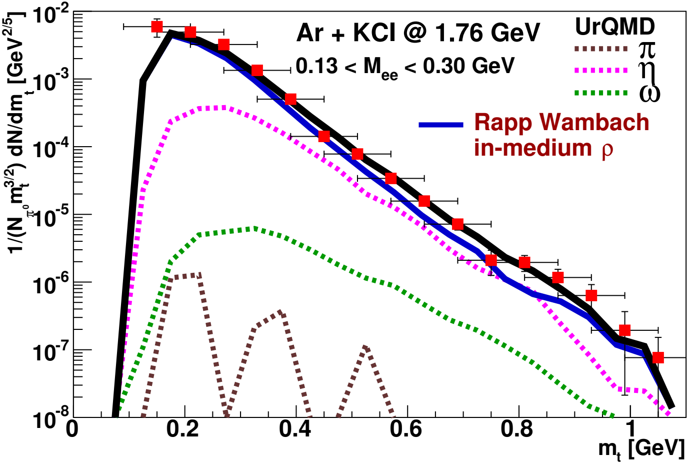


CGUrQMD: Ar+KCl (1.76 *A*GeV) (SIS/HADES)

- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76A\mathrm{GeV}) \rightarrow \mathrm{e}^{+}\mathrm{e}^{-}$ (SIS/HADES)



- dielectron spectra from $\mathrm{Ar}+\mathrm{KCl}(1.76A\mathrm{GeV}) \rightarrow \mathrm{e}^+\mathrm{e}^-$ (SIS/HADES)



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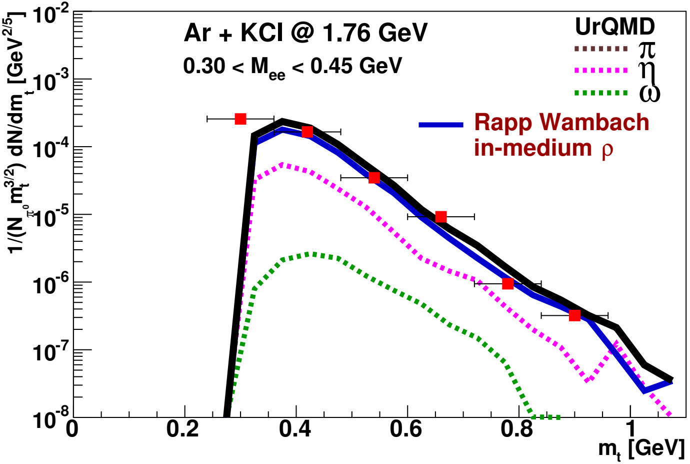

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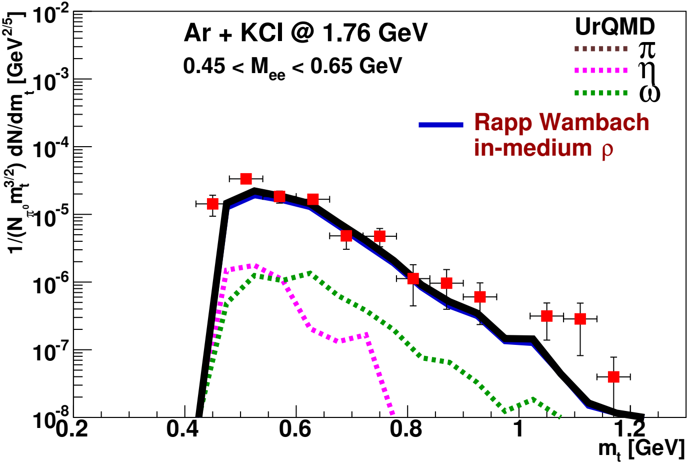

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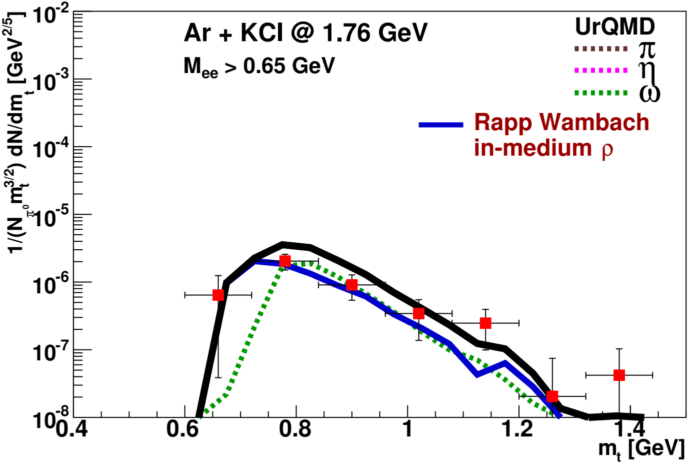
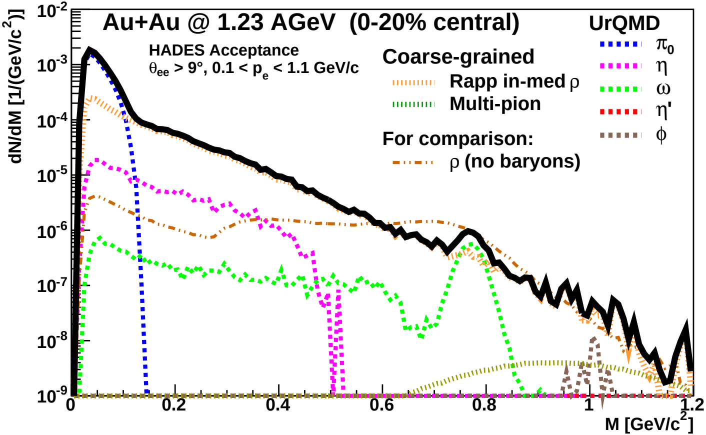


CGUrQMD: (NEW) Au+Au (1.23 *A*GeV) (SIS/HADES)

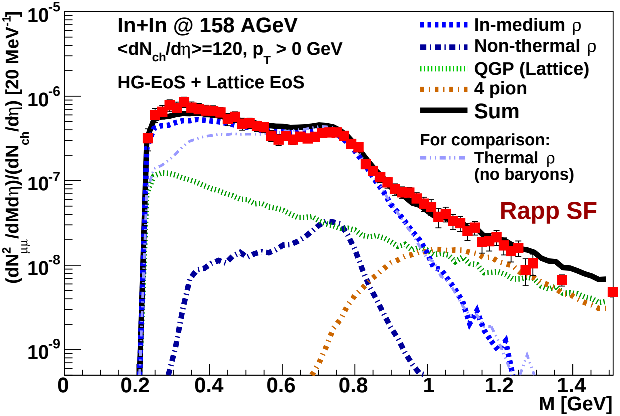


- caveat: pp/np acceptance filter with single-e cut, $p_t < 100$ MeV
- correct filter urgently needed!
- excellent agreement with preliminary HADES data [Gal14]
  (data points not shown here on request of the HADES collaboration)

Dimuons (SPS/NA60)

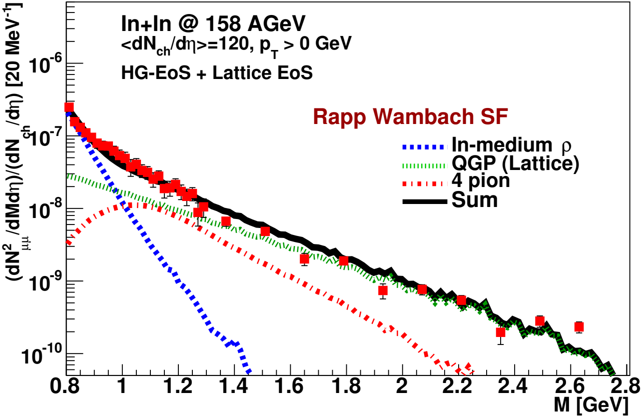
CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$



CGUrQMD: In+In (158 *A*GeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($\text{d}N_{\text{ch}}/\text{d}y = 120$)
- higher IMR: provides averaged true temperature
  (no blueshifts in the invariant-mass spectra!)



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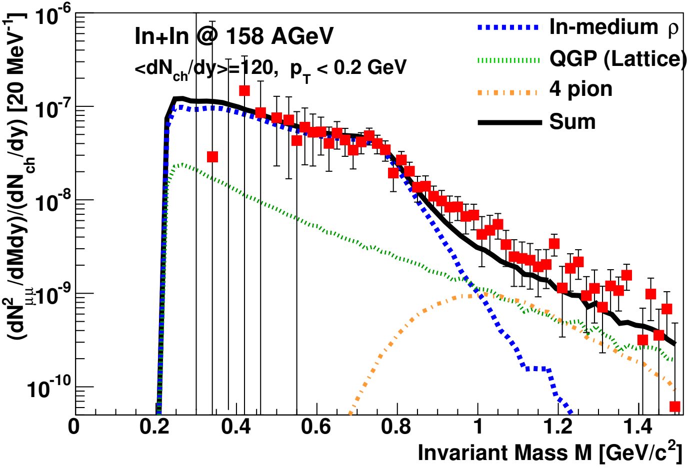

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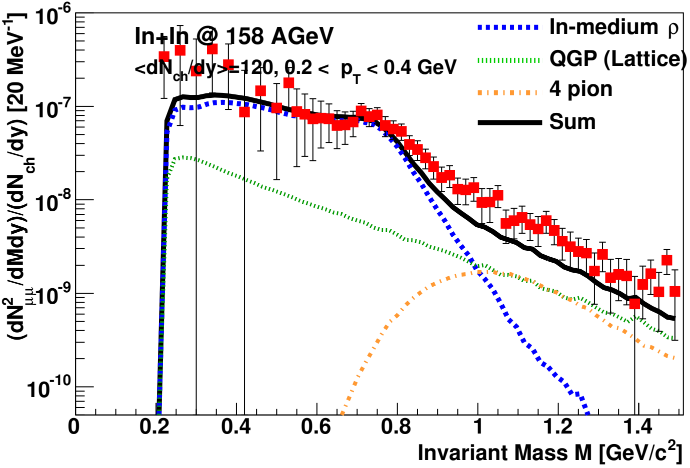

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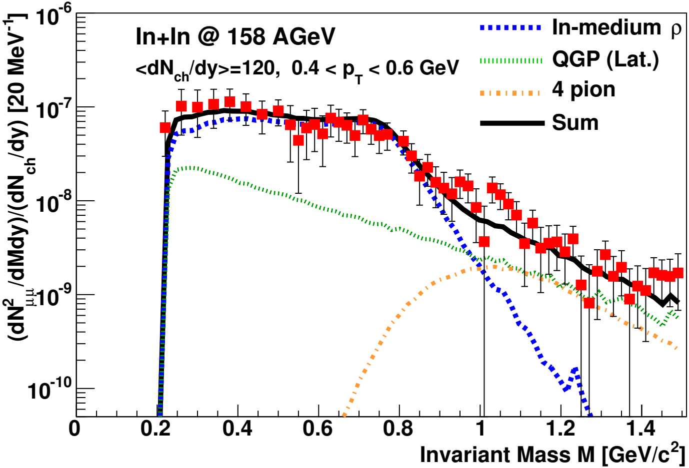

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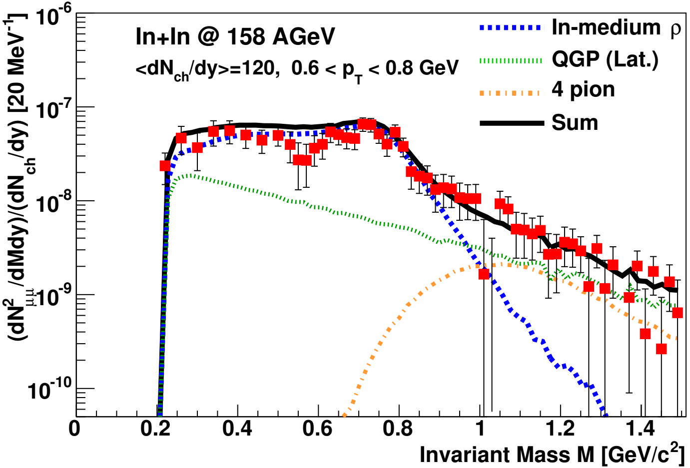

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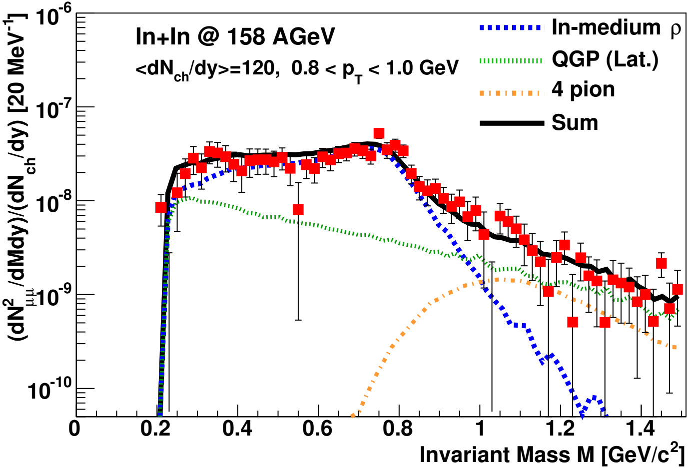
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)



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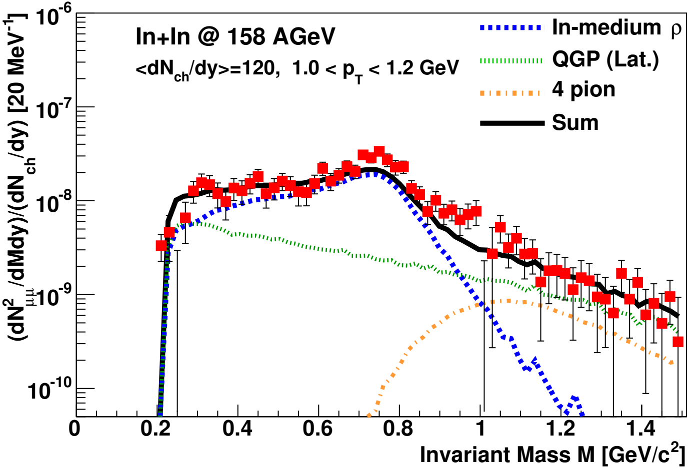

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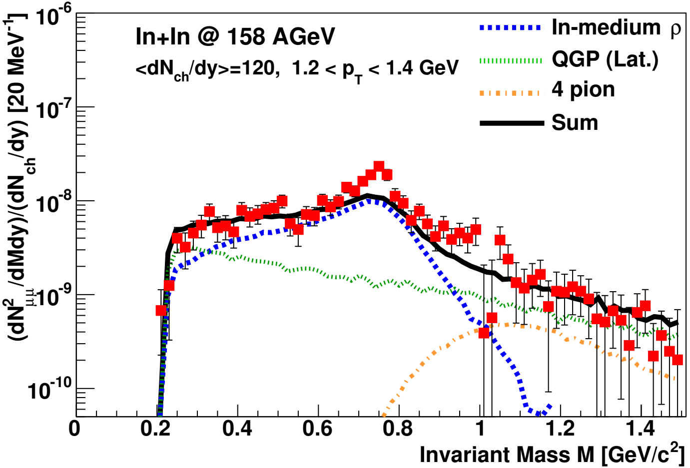

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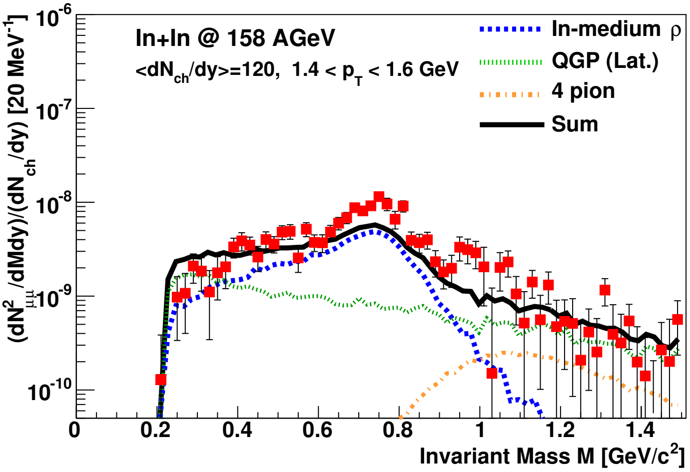
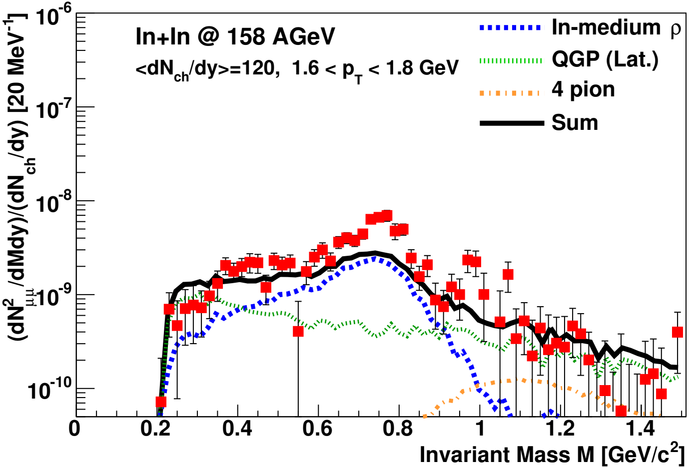


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\text{In} + \text{In}(158\,A\text{GeV}) \rightarrow \mu^{+}\mu^{-}$ (NA60)
- min-bias data ($\mathrm{d}N_{\text{ch}}/\mathrm{d}y = 120$)



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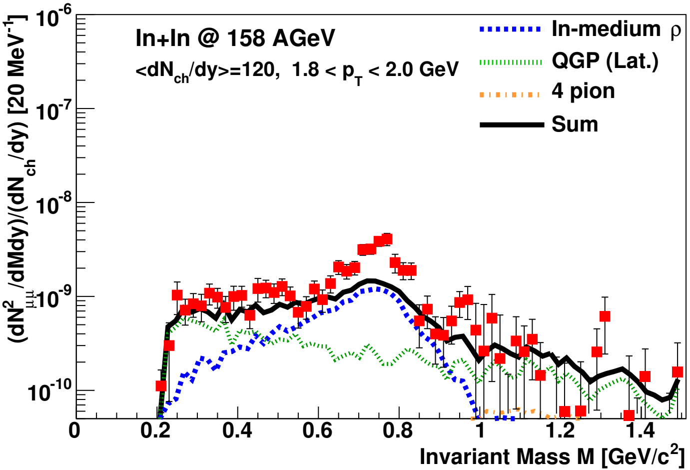

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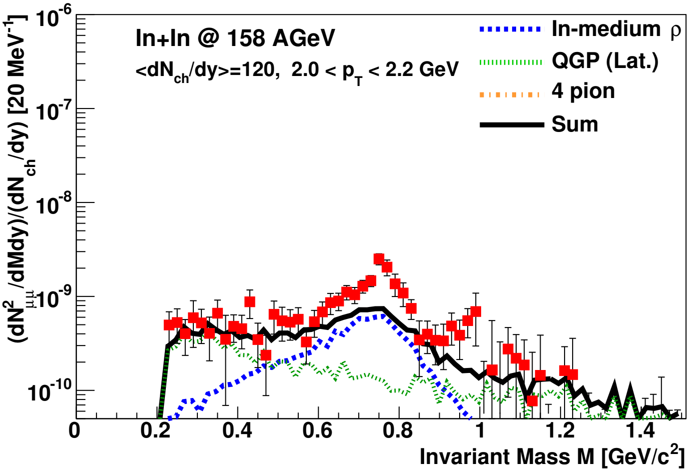

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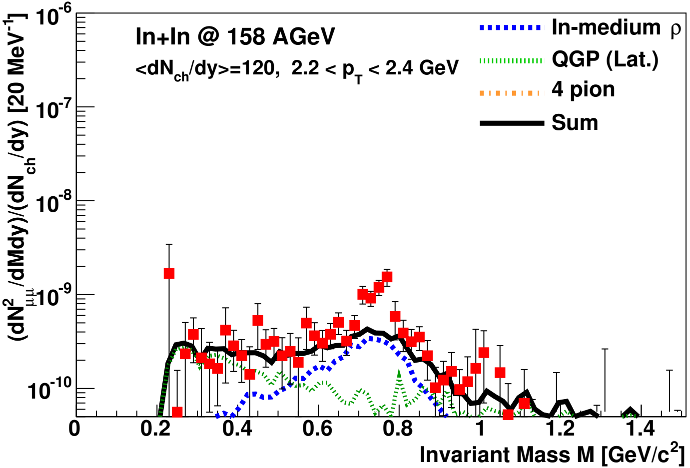
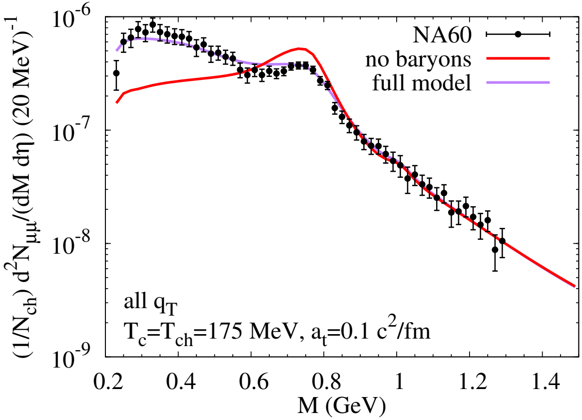


CGUrQMD: In+In (158 AGeV) (SPS/NA60)

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120$)
- influence of baryon interactions in spectral function
- from previous calculation with thermal-fireball parametrization (compatible with course-grained UrQMD)



CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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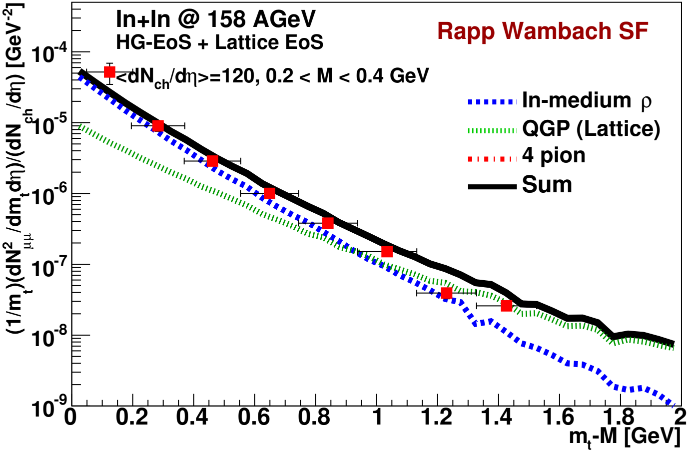

CGUrQMD: In+In (158 AGeV) (SPS/NA60)

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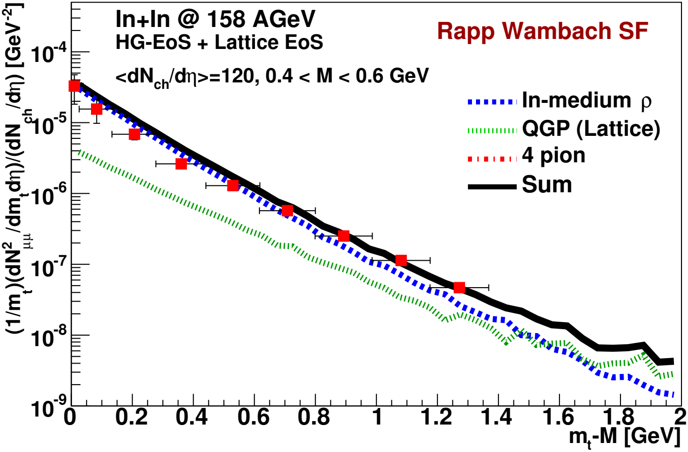

- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
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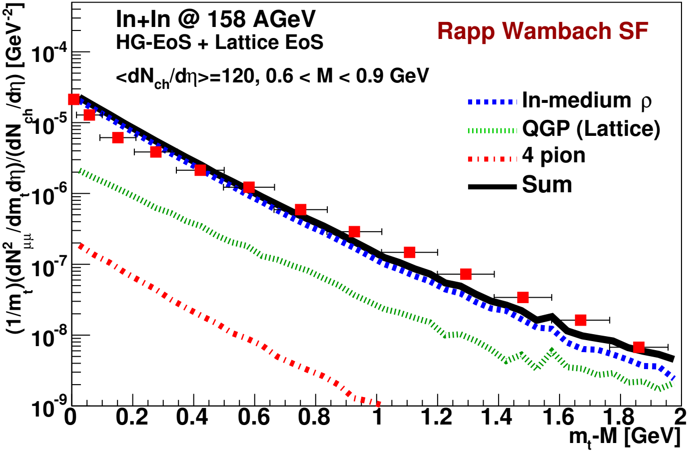

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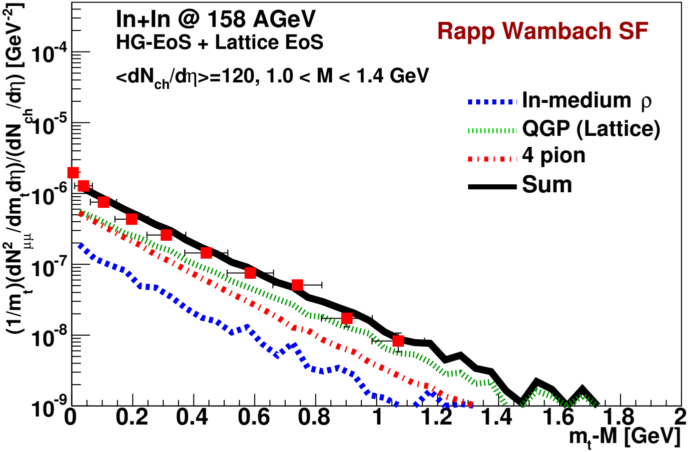
- dimuon spectra from $\mathrm{In}+\mathrm{In}(158\,A\mathrm{GeV}) \rightarrow \mu^+\mu^-$ (NA60)
- min-bias data $(\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 120)$



Conclusions and Outlook

- General ideas
  - em. probes ⇔ in-medium em. current-correlation function
  - dual rates around T_c (compatible with χ symmetry restoration)
  - medium modifications of ρ, ω, ϕ
  - importance of baryon-resonance interactions
- Application to dileptons in HICs
  - need realistic bulk-medium evolution
  - thermal fireball, (ideal) hydrodynamics, transport
  - coarse-grained transport (here: CGUrQMD)
  - allows use of thermal-QFT spectral VM functions
  - applicable also at low collision energies
  - allows use of thermal-QFT models for em. current-correlation functions
  - successful description at HADES, SPS, and RHIC (STAR)
  - consistent description of M and m_T spectra!
- Outlook
  - effective slope of M spectra in higher IMR ($1.5\text{ GeV} < M < M_{J/\psi}$) provides $\langle T \rangle$
  - beam-energy scan at RHIC and FAIR ⇒ signature of phase transition?
  - signature of cross-over vs. 1st order (or even critical endpoint)?

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