In-Medium Properties of Vector Mesons and Dileptons in Heavy-Ion Collisions

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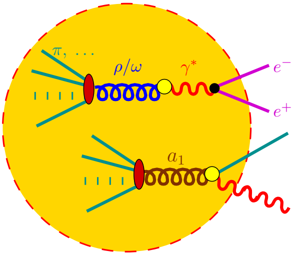
Outline

Motiviation:

Electromagnetic probes and vector in relativistic heavy-ion collisions

Why Electromagnetic Probes?

- $\gamma, \ell^{\pm}$: only e. m. interactions
- whole matter evolution



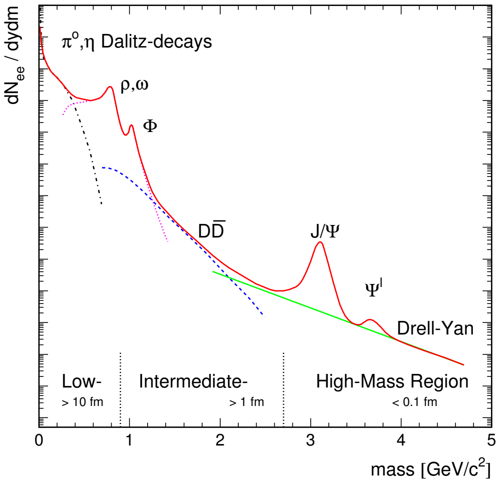


Fig. by A. Drees (from [RW00])

Vector Mesons and electromagnetic Probes

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

$$\Pi^{<}_{\mu\nu}(q) = \int \mathrm{d}^4 x \exp(\mathrm{i} q \cdot x) \left\langle J_\mu(0) J_\nu(x) \right\rangle_T = -2 n_B(q_0) \Pi^{(\mathrm{ret})}_{\mu\nu}(q)$$

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

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

- $u^\mu(x)$ four-velocity field of the fluid
- to lowest order in α: $4\pi\alpha \Pi_{\mu\nu} \simeq \Sigma^{(\gamma)}_{\mu\nu}$
- derivable from underlying thermodynamic potential, Ω!

Vector Mesons and chiral symmetry

- vector and axial-vector mesons $\leftrightarrow$ respective current correlators

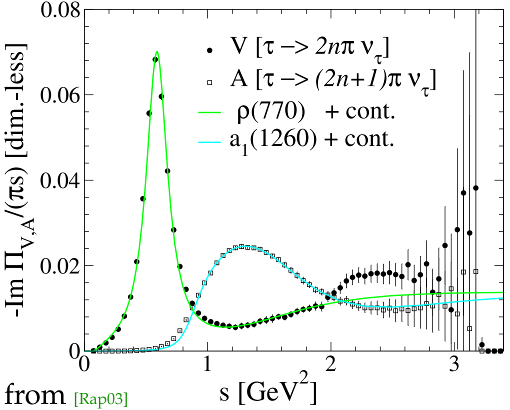
$$\Pi^{\mu\nu}_{V/A}(p) := \int \mathrm{d}^4 x \exp(\mathrm{i} p x) \left\langle J^{\nu}_{V/A}(0) J^{\mu}_{V/A}(x) \right\rangle_{\text{ret}}$$

- Ward-Takahashi Identities of χ symmetry $\Rightarrow$ Weinberg-sum rules

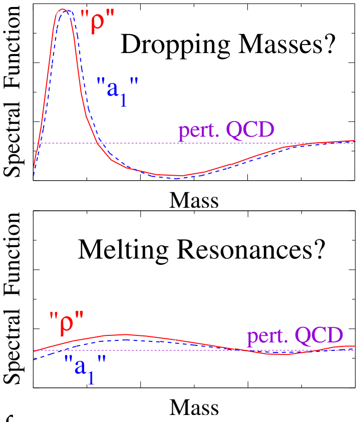
$$f_\pi^2 = -\int_0^\infty \frac{\mathrm{d}p_0^2}{\pi p_0^2} [\mathrm{Im}\,\Pi_V(p_0, 0) - \mathrm{Im}\,\Pi_A(p_0, 0)]$$

- spectral functions of vector (e.g. ρ) and axial vector (e.g. a_1) directly related to order parameter of chiral symmetry!

Vector Mesons and chiral symmetry



from [Rap03]



from [Rap05]

Dileptons in pp np, pA, and AA at SIS energies (HADES)

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: http://gibuu.physik.uni-giessen.de
- Review: [O. Buss et al, Phys. Rept. 512, 1 (2012)]

The Boltzmann-Uehling-Uhlenbeck Equation

- time evolution of phase-space distribution functions

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

- 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

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

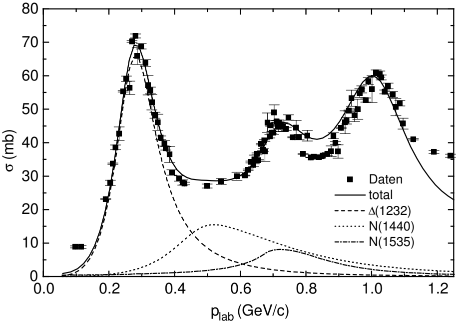
  - off-shell propagation: test particles with off-shell potential

Resonance Model

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

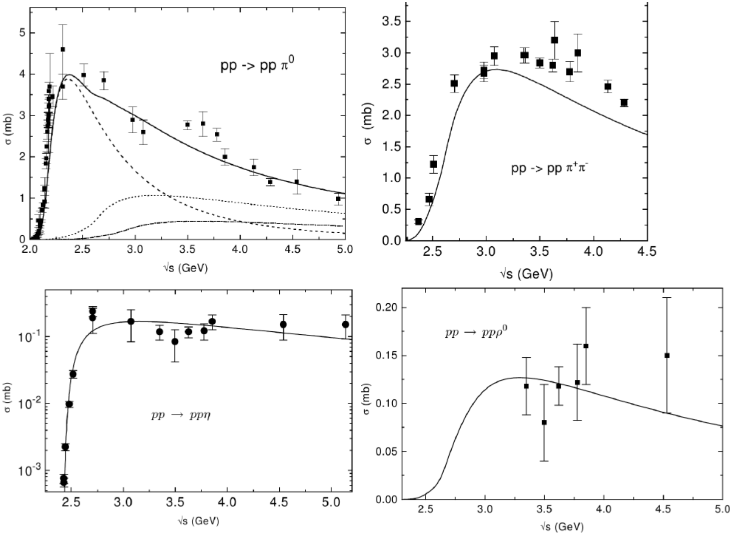
$$\sigma_{ab\to R\to cd} = \frac{2s_R+1}{(2s_a+1)(2s_b+1)} \frac{4\pi}{p_{\text{lab}}^2} \frac{s\Gamma_{ab\to R}\Gamma_{R\to cd}}{(s-m_R^2)^2+s\Gamma_{\text{tot}}^2}$$

- 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)]



Resonance Model

- further cross sections



Extension to HADES energies

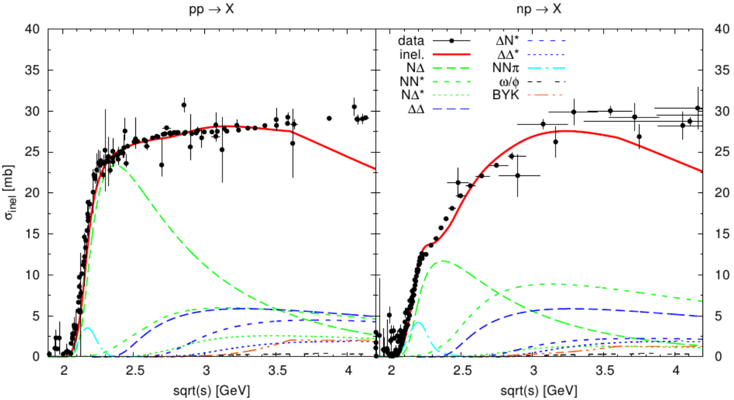
- keep same resonances (parameters from Manley analysis)

	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 $NN \to \Delta N^*, \Delta\Delta^*$, $NN \to NN\pi$, $NN \to NN\rho, NN\omega, NN\pi\omega, NN\phi$, $NN \to BYK$ ($B = N, \Delta$, $Y = \Lambda, \Sigma$)

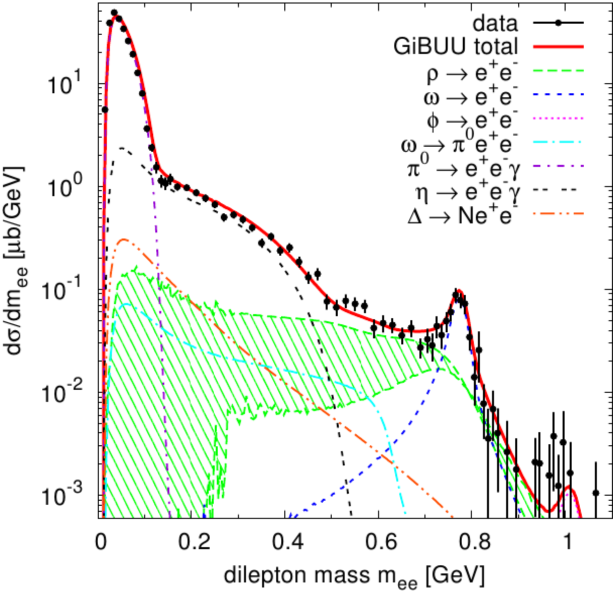
Extension to HADES energies

- 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 ⇒ spectral properties of vector mesons

p p at HADES ($E_{\text{kin}} = 3.5$ GeV)



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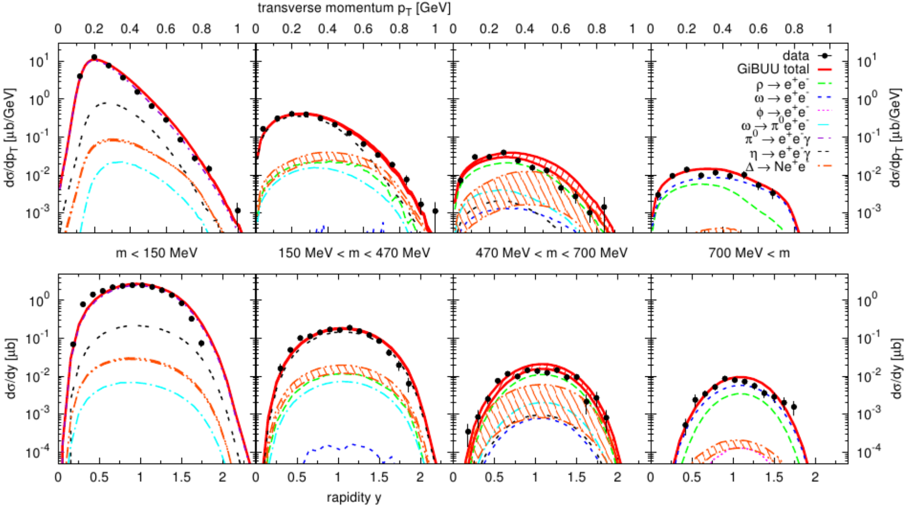
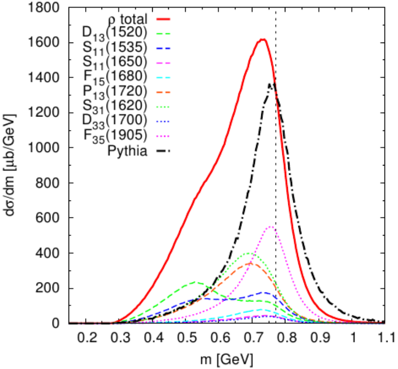
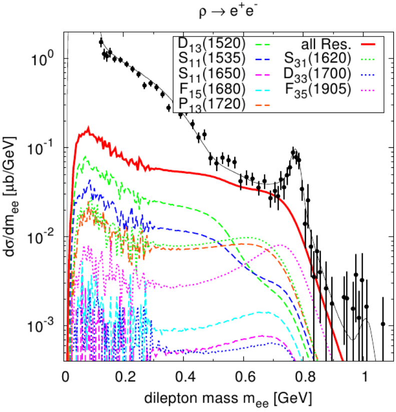


"ρ meson" in pp

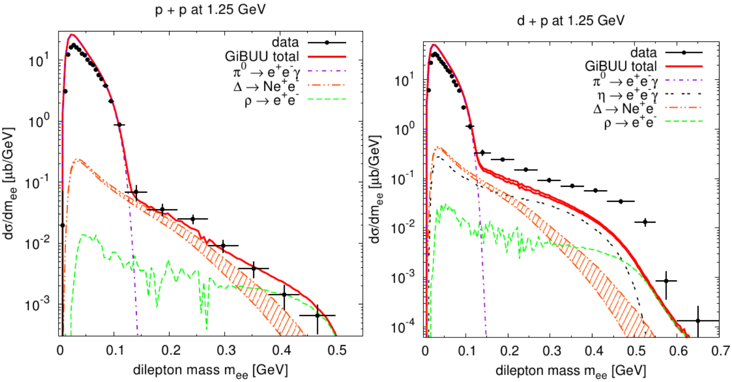
- production through hadron resonances
  $NN \rightarrow NR \rightarrow NN\rho$, $NN \rightarrow N\Delta \rightarrow NN\pi\rho$





- "ρ"-line shape "modified" already in elementary hadronic reactions

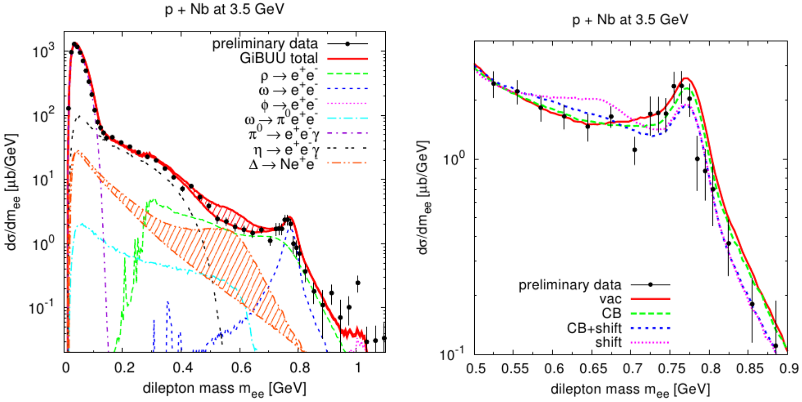
dp at 1.25 GeV



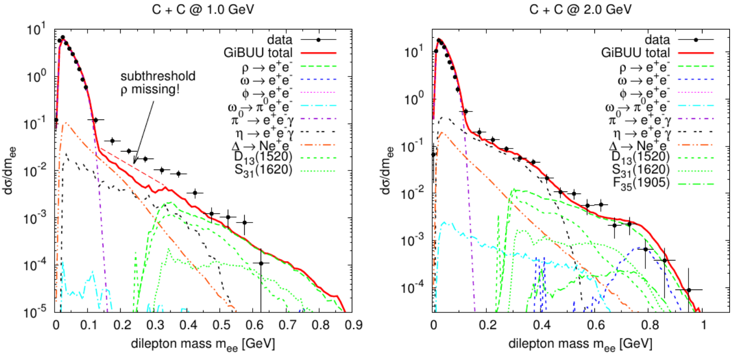
- pp quite well described at low energies
- discrepancies in np (“quasifree dp”)
- isospin effects at low energies? Further modelling/data needed!

p Nb at HADES (3.5 GeV)

- 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?

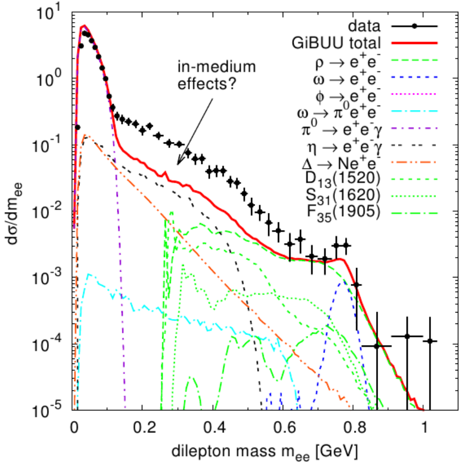


CC at 1.0 GeV and 2.0 GeV



- overall good description without medium effects (small system)
- discrepancy at 1.0 GeV ⇔ uncertainties in pn?

Ar KCl at 1.76 GeV

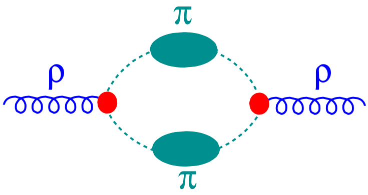


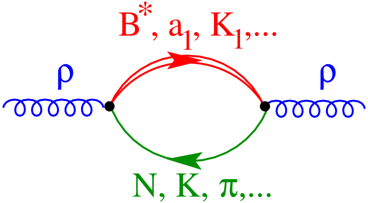
- room for medium effects!

Dileptons in AA collisions at the SPS (CERES/NA45, NA60)

Hadronic many-body theory

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

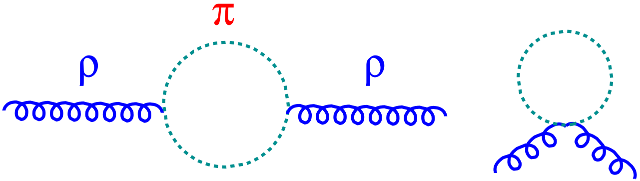


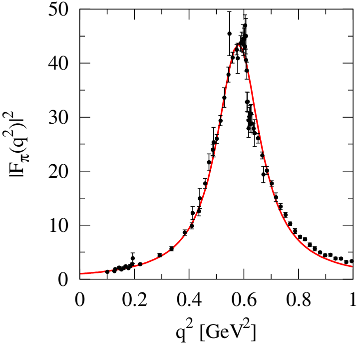


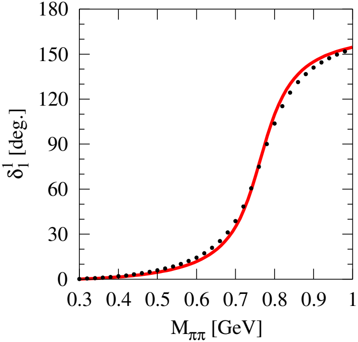
- Baryon (resonances) important, even at RHIC with low **net** baryon density $n_B - n_{\bar{B}}$
- reason: $n_B + n_{\bar{B}}$ relevant (CP inv. of strong interactions)

The meson sector (vacuum)

- most important for ρ-meson: pions

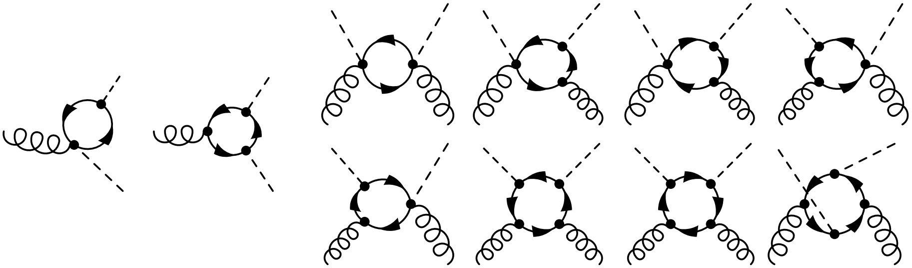




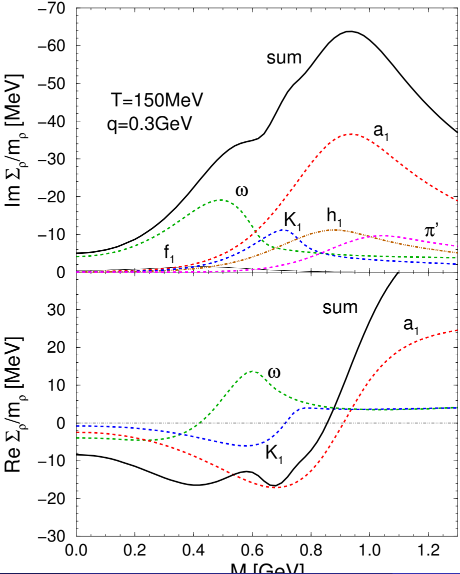


The meson sector (matter)

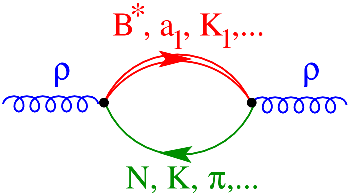
- Pions dressed with N-hole-, Δ-hole bubbles
- Ward-Takahashi ⇒ vertex corrections mandatory!



The meson sector (contributions from higher resonances)

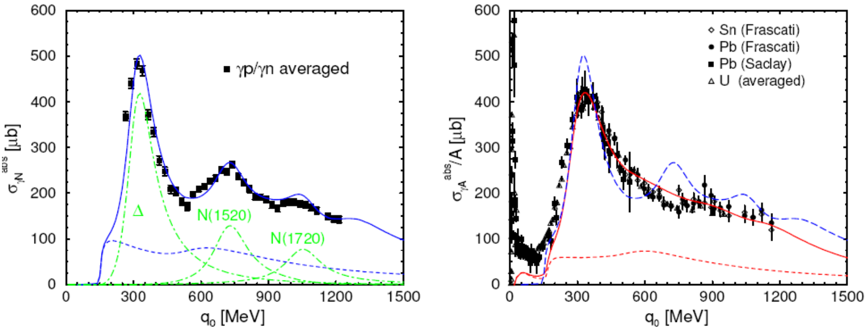


The baryon sector (vacuum)

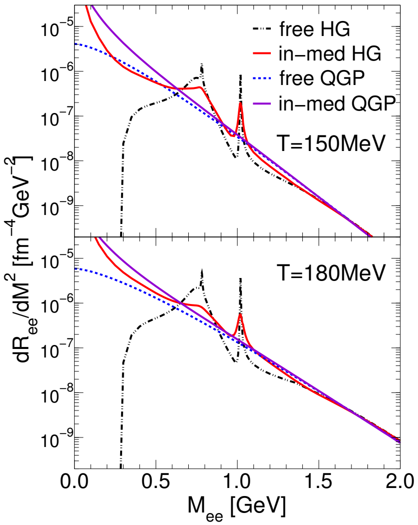


- $P = 1$-baryons: p-wave coupling to ρ:
  N(939), Δ(1232), N(1720), Δ(1905)
- $P = -1$-baryons: s-wave coupling to ρ:
  N(1520), Δ(1620), Δ(1700)

Photoabsorption on nucleons and nuclei



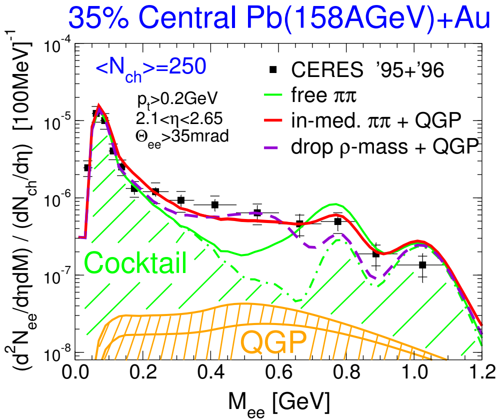
Dilepton rates: Hadron gas ↔ QGP

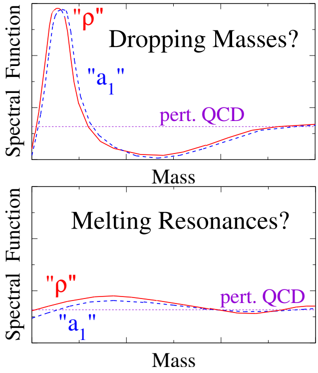


- in-medium hadron gas matches with QGP
- similar results also for γ rates
- "quark-hadron duality"?
- does it work with chiral model?
- hidden local symm.+baryons? [Harada, Yamawaki et al.]

Dilepton rates at SpS

- describe bulk medium with thermal cylindrical fireball
- equation of state: QGP → mixed phas → hadron gas





- how to decide about scenario experimentally?
- need compare (more) precise data to detailed model!

Sources of dilepton emission in heavy-ion collisions

1. "core" ⇔ emission from thermal source [MT85, GK91]

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

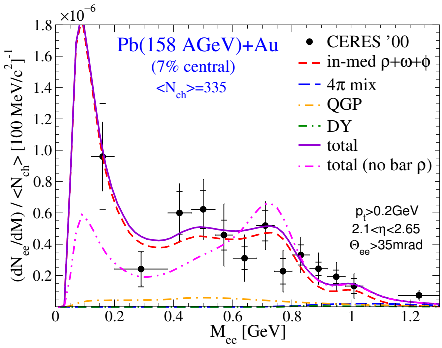
   - QGP: HTL improved $q\bar{q} \to \ell^+\ell^-$
   - ρ,ω,ϕ decays
   - π,ω,a_1 t-channel exchange
2. "corona" ⇔ emission from "primordial" mesons (jet-quenching)
3. after thermal freeze-out ⇔ emission from "freeze-out" mesons

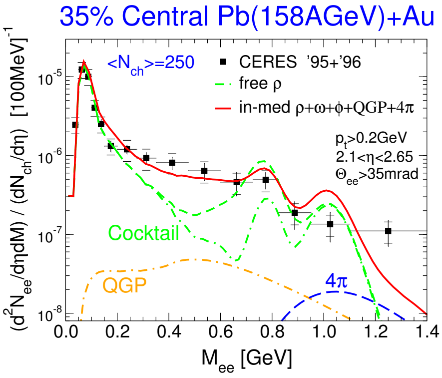
   [Cooper, Frye 1975]

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

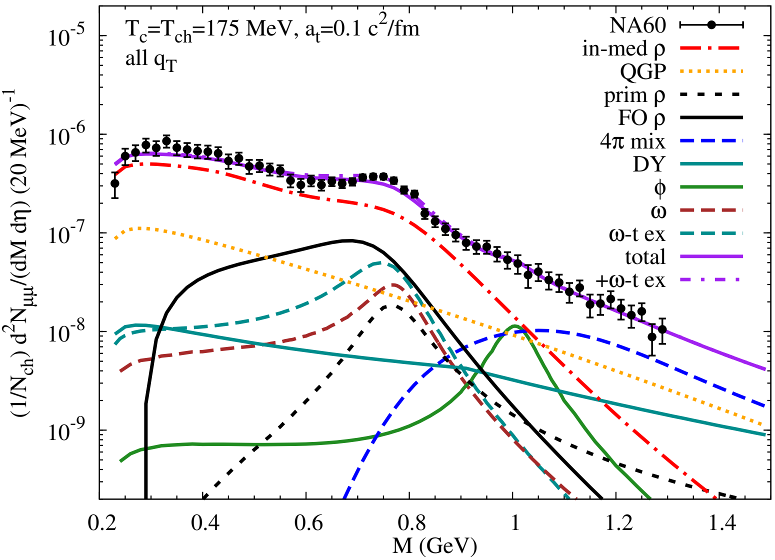
   - additional lifetime-dilation factor $\gamma=q_0/M$ compared to MT formula!
4. initial hard processes: Drell Yan

- good agreement also for dielectron spectra in 158 GeV Pb-Au
- further check of low-mass tail from baryon effects down to $M \to 2m_e$





M spectra (in p_T slices)



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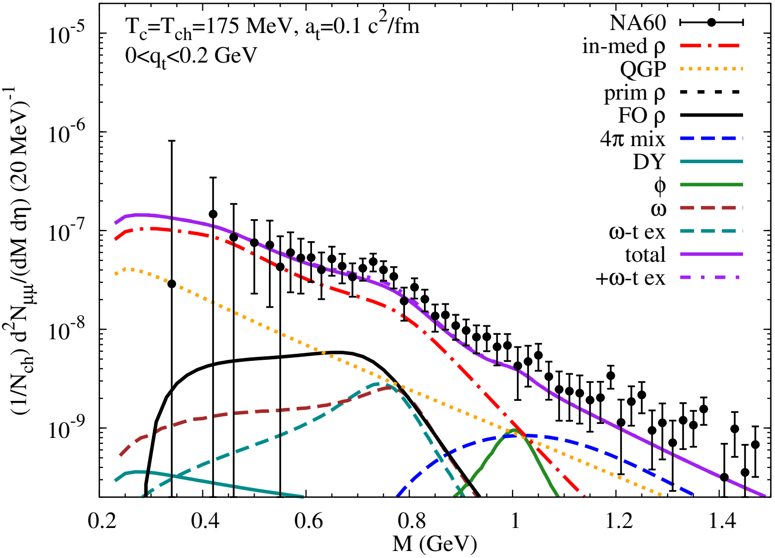

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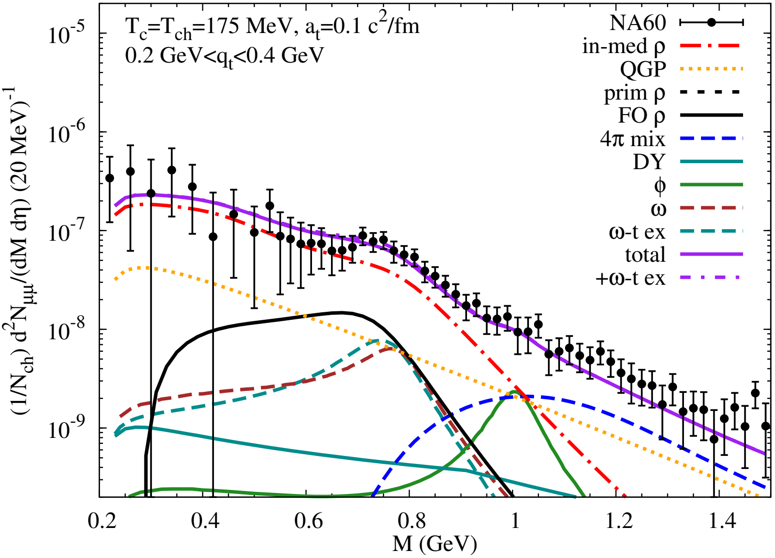

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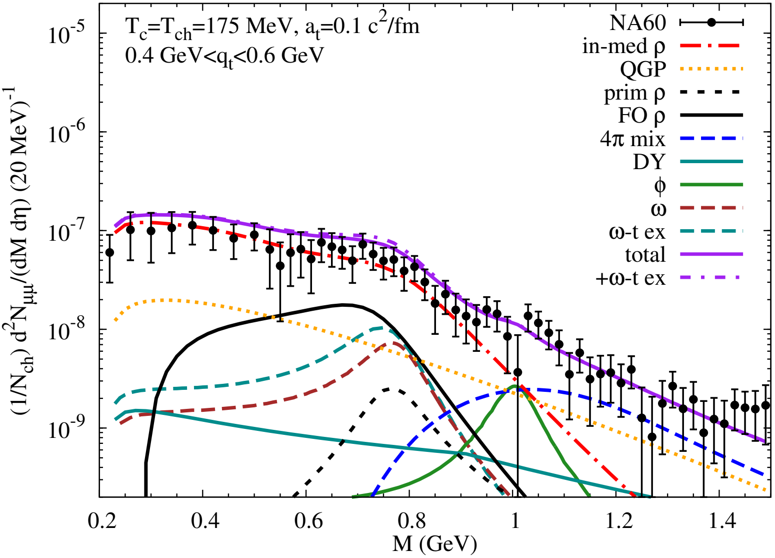
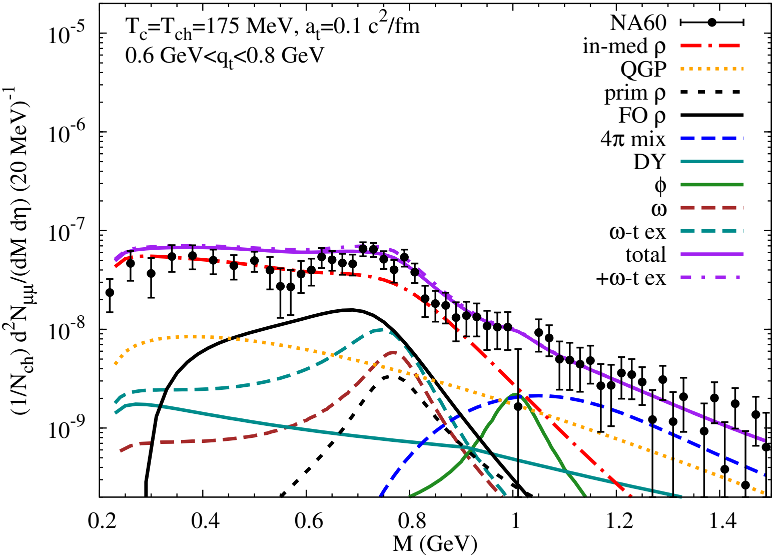


M spectra (in p_T slices)



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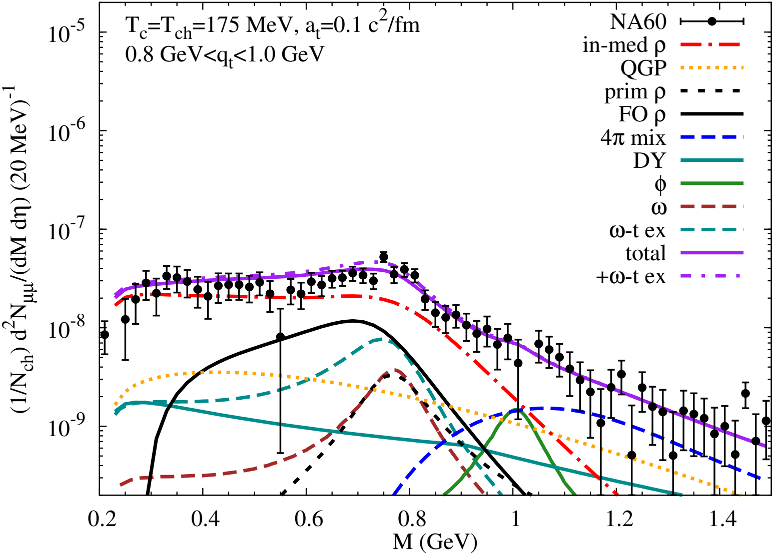

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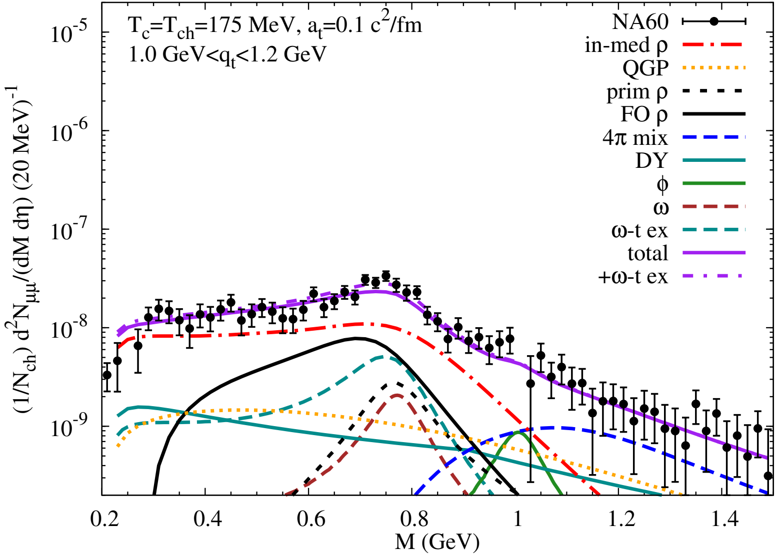

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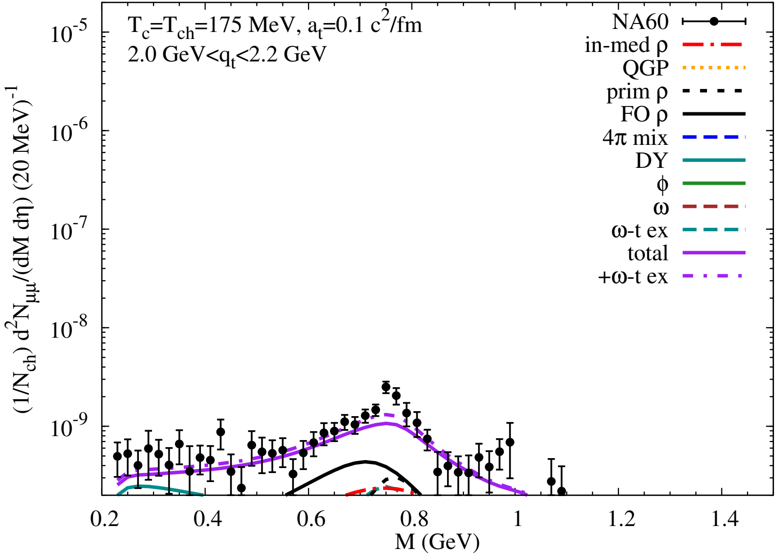
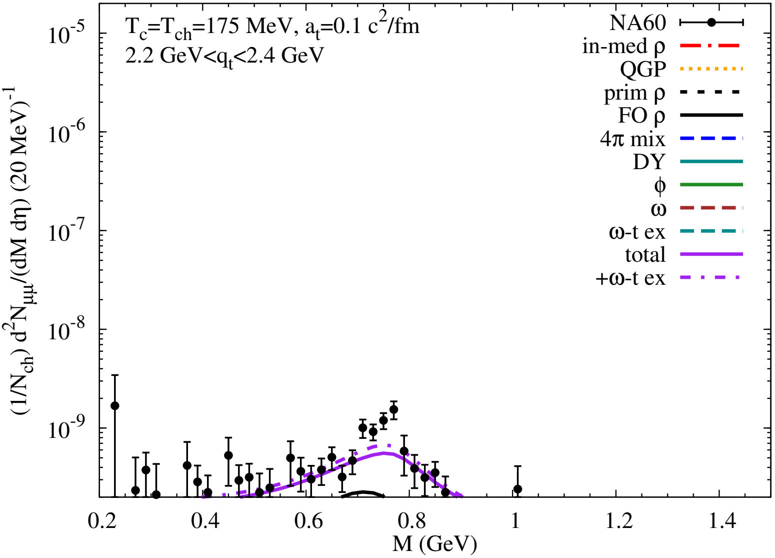
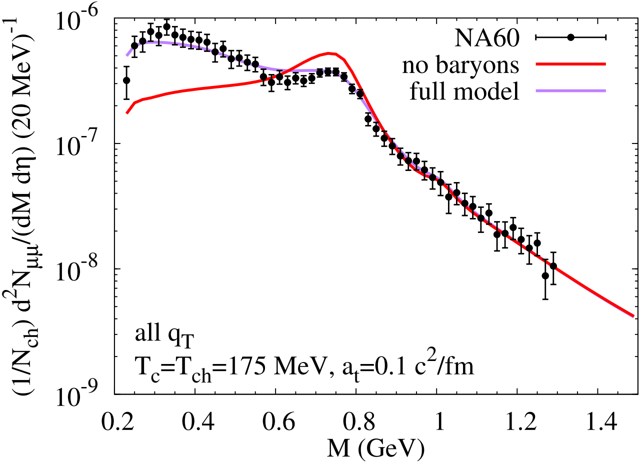


M spectra (in p_T slices)



Importance of baryon effects

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



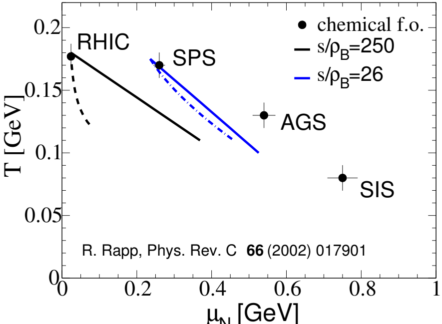
Conclusions and Outlook

- GiBUU with baryon-resonance/VMD model at SIS
  - comprehensive description of $\ell^+\ell^-$ production in pp
  - some discrepancies in np at low energies (isospin effects?)
  - good description of pNb and CC (no medium effects)
  - room for medium effects in Ar KCl (work in progress)
- HMBT at SPS energies
  - QGP + hadronic fireball (thermal medium)
  - HTL improved pQCD: $\bar{q}q \rightarrow \ell^+\ell^-$
  - hadronic many-body theory at finite T, μ_B; (modified) VMD model
  - duality of QGP and hadronic $\ell^+\ell^-$ rates around T_c
  - inclusion of non-thermal sources (DY, primordial ρ)
  - baryon effects important for medium modifications of ρ (ω, ϕ)
- Further developments
  - vector- should be complemented with axial-vector-spectral functions
    (a_1 as chiral partner of ρ)
  - constrained with lQCD via in-medium Weinberg chiral sum rules
  - direct connection to chiral phase transition!
    first results from QCD and Weinberg sum rules, see [HR12]

Backup Slides

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 $s/\varrho_B = 27$
- thermal freezeout: $(T_{\text{fo}}, \mu_\pi^{\text{fo}}) \simeq (120, 80)$ MeV



Flow and particle/resonance distributions

- assume local thermal equilibrium: $T(t)$
- collective radial flow: $u(t,\vec{x}) = 1/\sqrt{1-\vec{v}^2}(1,\vec{v})$
- $\vec{v}(t,\vec{x}) = a_\perp t\, \vec{x}_\perp / R(t)$
- phase-space distribution for hadrons [F. Cooper, G. Frye 74]

$$\frac{\mathrm{d}N_i}{\mathrm{d}^3\vec{p}\mathrm{d}^3\vec{x}} = \frac{g_i}{(2\pi)^3} f_{B/F}\left(\frac{p \cdot u(t,\vec{x}) - \mu_i(t)}{T(t)}\right)$$

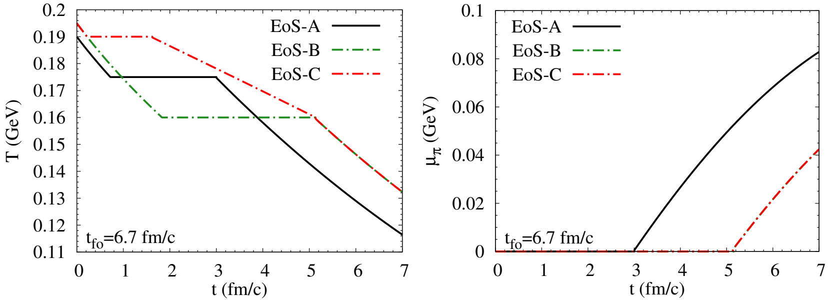
- NB:
  - covariant notation $\mathrm{d}^3\vec{x}\mathrm{d}^3\vec{p} = p_\mu \mathrm{d}\sigma^\mu \mathrm{d}^3\vec{p}/\sqrt{\vec{p}^2+m^2}$
  - $pu(t,\vec{x}) = \overline{p_0}$: energy of particle in rest frame of fluid cell
  - leads to "Doppler shifts" of hadron and dilepton spectra; for radial flow in HICs: blue shift $\Rightarrow$ hardening of p_T spectra
- phase-space distribution for bosonic resonances:

$$\frac{\mathrm{d}N_i}{\mathrm{d}^4p\mathrm{d}^3\vec{x}} = \frac{g_i}{(2\pi)^4} f_B\left(\frac{p \cdot u(t,\vec{x}) - \mu_i}{T(t)}\right)[-2p_0 \mathrm{Im}\, D_i(p)]$$

- $D_i(p)$: propagator of resonance, $A_i(p) = -2\,\mathrm{Im}\, D_i(p)$: spectral function

Sensitivity to T_c and hadro-chemistry

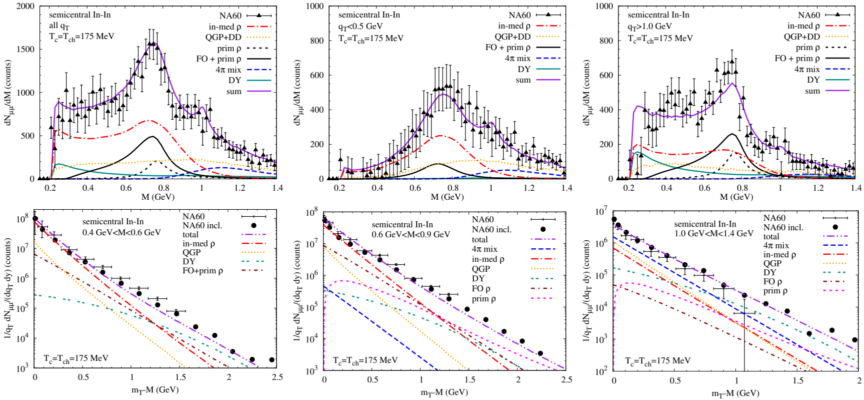
- recent lattice QCD: $T_c \simeq$ 190-200 MeV or $T_c \simeq$ 150-160 MeV?
- thermal-model fits to hadron ratios: $T_{\text{chem}} \simeq$ 150-160 MeV



- EoS-A: $T_c = T_{\text{chem}} = 175$ MeV
- EoS-B: $T_c = T_{\text{chem}} = 160$ MeV
- EoS-C: $T_c = 190$ MeV, $T_{\text{chem}} = 160$ MeV
  - $T_c \geq T \geq T_{\text{chem}}$: hadron gas in chemical equilibrium
- keep fireball parameters the same (including life time)

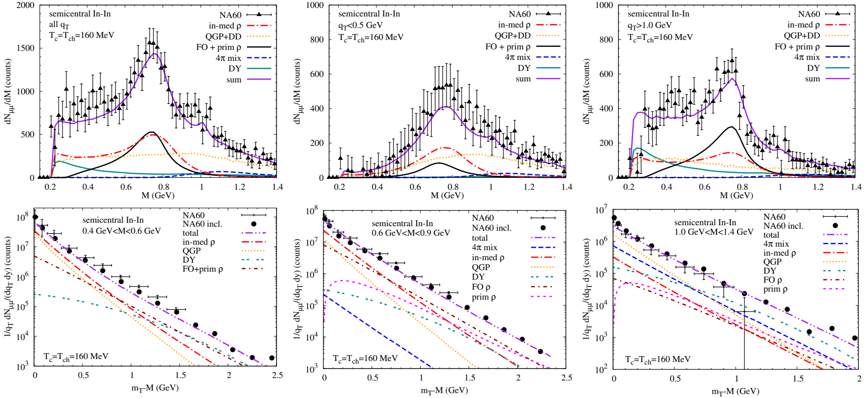
EoS-A

- ρ, ω, ϕ multi-π, QGP, freeze-out+primordial ρ, Drell-Yan



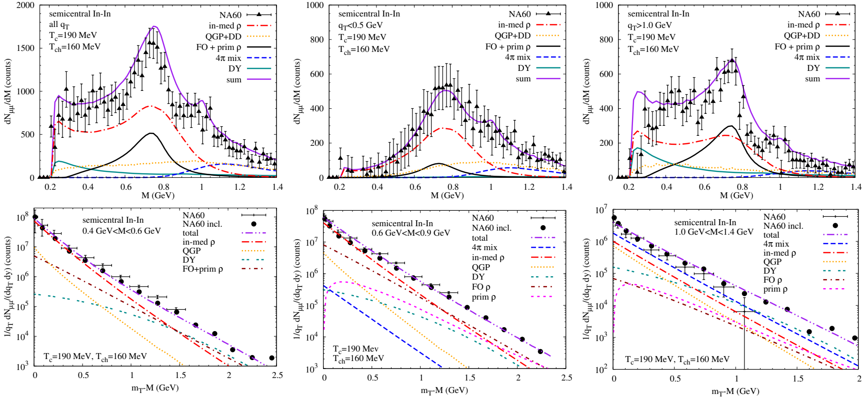
- M spectra [HvH, Rapp 07]
  - consistent with predicted broadening of ρ meson
  - $M <$ 1GeV: thermal ρ; $M >$ 1 GeV: thermal multi-pion processes
- m_t spectra
  - $q_t <$ 1 GeV: thermal radiation
  - $q_t >$ 1 GeV: freeze-out + hard primordial ρ, Drell-Yan

EoS-B



- mass spectra comparable to EoS-A ↔ slight enhancement of fireball lifetime
- in IMR QGP > multi-pion contribution
- higher hadronic temperatures ⇒ slightly harder q_T spectra
- not enough to resolve discrepancy with data

EoS-C



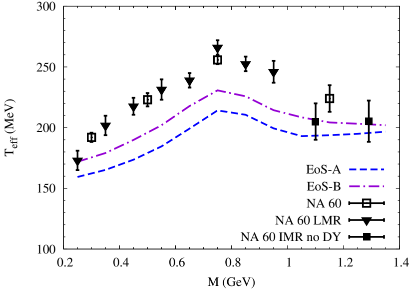
- mass spectra comparable to EoS-A ↔ slight reduction of fireball lifetime
- in IMR multi-pion ≫ QGP contribution
- higher hadronic temperatures + high-density hadronic phase ⇒ harder q_T spectra
- better agreement with data

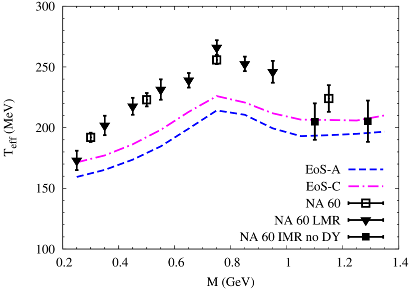
Inverse-slope analysis

- to extract T_{eff} fit to

$$\frac{1}{q_T}\frac{\mathrm{d}N}{\mathrm{d}q_T} = \frac{1}{m_T}\frac{\mathrm{d}N}{\mathrm{d}m_T} = C \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)$$

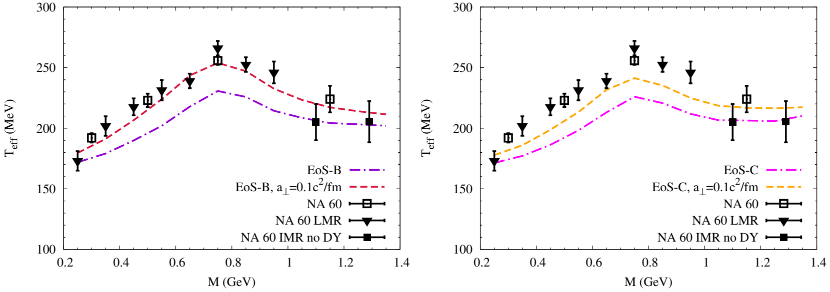
- fit of theoretical q_T spectra: $1\ \text{GeV} < q_T < 1.8\ \text{GeV}$





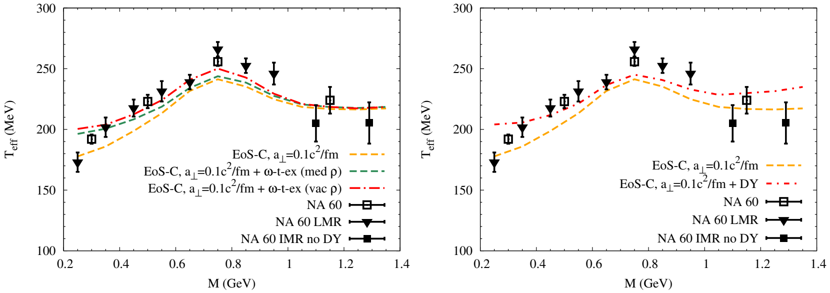
- standard fireball acceleration: too soft q_T spectra
- lower T_c in EoS-B and EoS-C helps (higher hadronic temperatures)
- NB: here, Drell Yan contribution taken out

Inverse-slope analysis



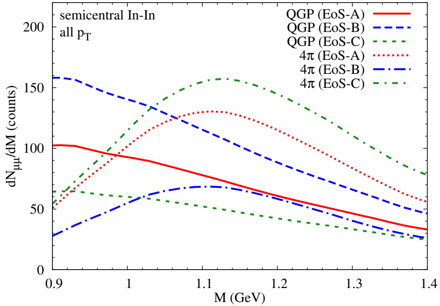
- enhance fireball acceleration to $a_\perp = 0.1c^2/\text{fm}$
- effective at all stages of fireball evolution
- agreement in IMR not spoiled ⇔ dominated from earlier stages
- EoS-B harder ⇔ relative contribution of harder freezeout ρ decays vs. thermal ρ's larger

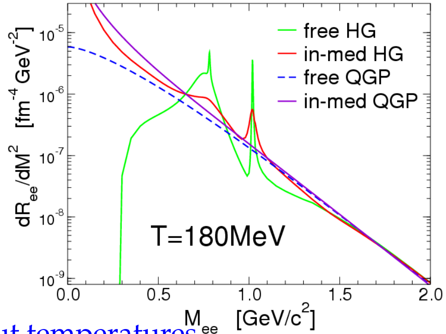
Inverse-slope analysis



- sensitivity to contributions from meson *t*-channel exchange
  - hardens low-mass region
  - using vacuum ρ in *t*-channel contribution: enhances slope in ρ region
- sensitivity to Drell-Yan contribution
  - for IMR: describes effect seen in data (open vs. solid square data point)
  - in LMR: too high around muon threshold ⇔ due to uncertainties in extrapolation to low M?!?

IMR: QGP vs. multi-pion radiation





- different critical and freeze-out temperatures
  $T_c = 160 \ldots 190$ MeV, $T_{\text{chem}} = 160 \ldots 175$ MeV
- M- and p_T spectra comparably well described!
- reason: T vs. volume $\Rightarrow$ maximal l^+l^- emission for
  $T = T_{\max} = M/5.5$
- hadronic and partonic radiation "dual" for $T \sim T_c$
  compatible with chiral-symmetry restoration!
- inconclusive whether hadronic or partonic emission in IMR!

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