Dimuon excess from in-medium ρ decays using QCD sum rules

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arXiv:1309.4135 [hep-ph]

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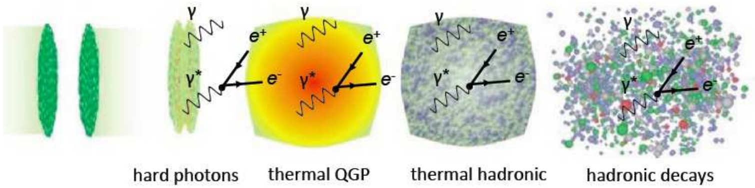
Why study ρ and dilepton spectrum?

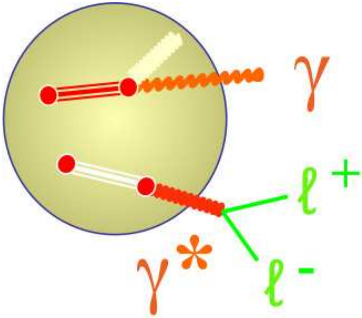
- ✓ ρ has a large coupling to pions and muons $\Longrightarrow$ copiously produced and able to decay and be detected in a heavy-ion collision environment
- ✓ ρ short life-time makes it ideal test particle to sample in-medium changes of hadron properties
- ✓ Changes are linked to chiral symmetry restoration and deconfinement
- ✓ Low-mass dilepton spectrum is great test ground to study basic properties of strong interaction in non-perturbative domain

Electromagnetic probes



- ✓ **Escape after being produced since their mean free path is larger than the system's size**
- ✓ **Reveal entire thermal evolution of the collision**

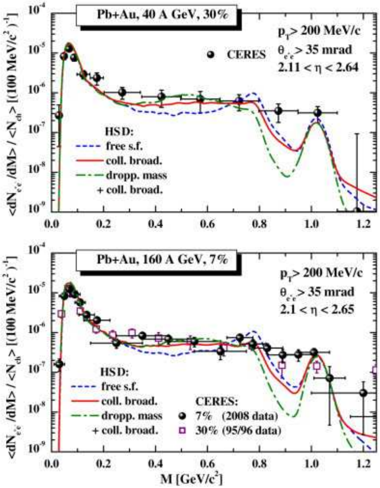
Electromagnetic probes



- ✓ Reveal entire thermal evolution
- ✓ Continuously emitted from early to late collision stages up to freeze out
- ✓ **Low mass dileptons are one of these probes and their invariant-mass spectrum is a direct measurement of the in-medium hadronic spectral function in the vector channel**

Low mass dileptons: Early days, excess below the ρ peak at SPS

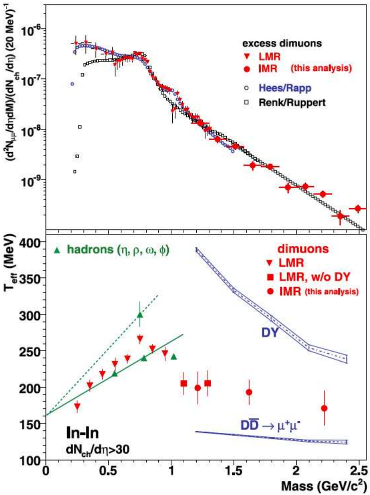
- ρ droping mass (Brown-Rho) vs. broadening (Rapp-Wambach)
- Controversy lasted for more than a decade



Low mass dileptons: Current data, excess due to ρ broadening

- Controversy settled by high-quality NA60 data
- Below 1 GeV, inverse slope parameter T_{eff} rises with mass.
- Above 1 GeV, T_{eff} drops.
- Interpretation: Different sources of dileptons. Below 1 GeV **hadronic source that flows**. Above 1 GeV **partonic source that for SPS energies has not yet build up flow**

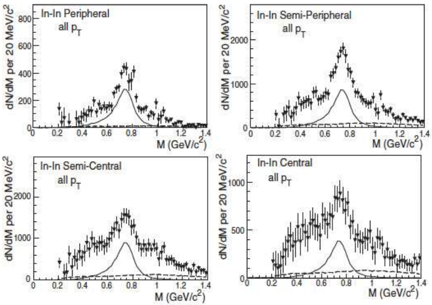
NA60, Eur. Phys. J. C **59**, 607 (2009)



Spectral function

- ✓ Spectral function shows a clear peak at the nominal ρ mass
- ✓ Peak broadens for the most central collisions
- ✓ Total dilepton yield also increases with centrality

NA60, Phys. Rev. Lett. **96**, 162302 (2006)

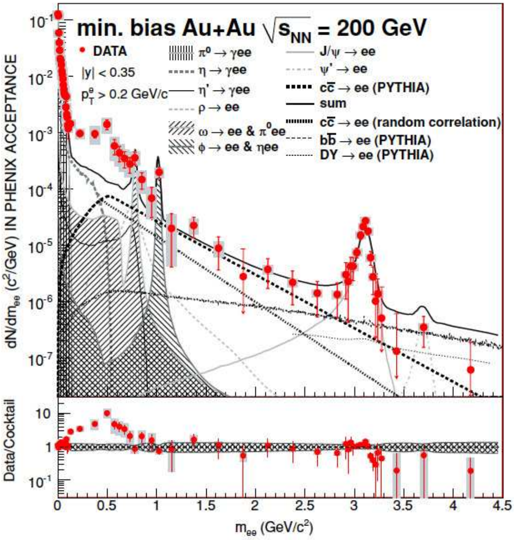


Explanations

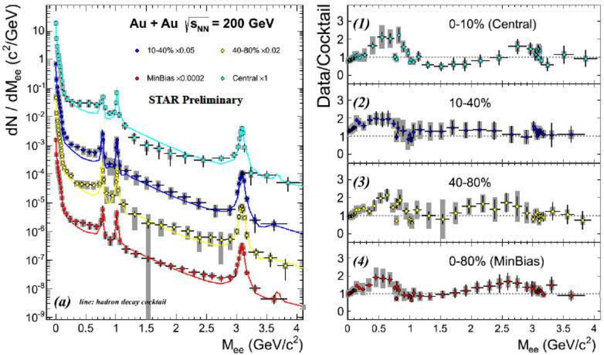
- Many body approach [Rapp & Wambach, Eur. Phys. J. A **6**, 415 (1999); Hess & Rapp, Nucl. Phys. A **806**, 339 (2008)]
- Transport approaches [Bratkosvskaya *et al.*, Phys. Lett. B **670**, 428 (2009); J. Weil *et al.*, PoS BORMIO2011, 053 (2011)]
- In both approaches ρ modified by scattering and melting within a baryon rich environment
- Since average density in SPS and RHIC are similar, these approaches should explain also RHIC data

Low mass dileptons: excess below the ρ peak at RHIC (PHENIX)

PHENIX, Phys. Rev. C **81**, 034911 (2010)

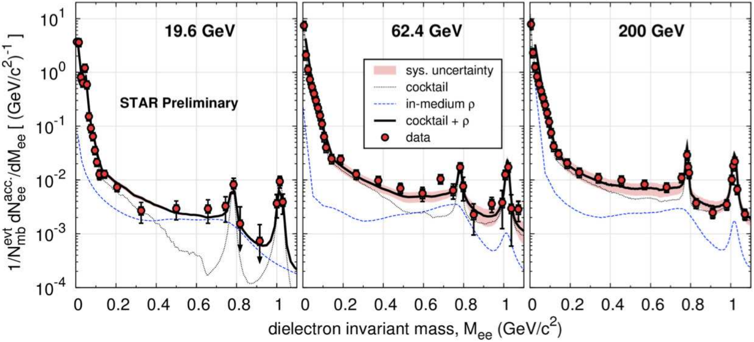


Low mass dileptons: excess below the ρ peak at RHIC (STAR)

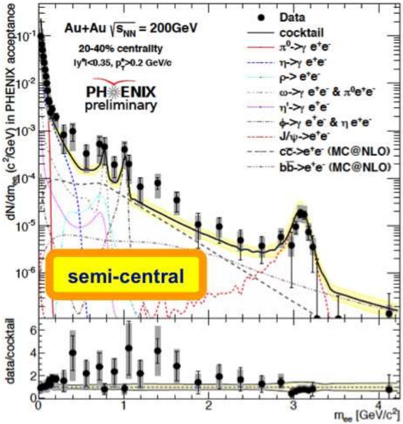


Low mass dileptons: excess below the ρ peak at RHIC (STAR)

Nu Xu's talk



PHENIX Low mas dielectrons semicentral QM2012



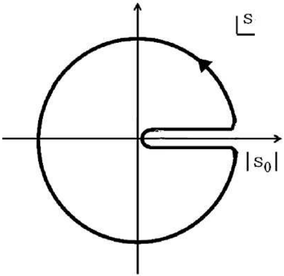
Better S/B seems to have brought PHENIX to closer agreement with STAR

Explanations

- Many body approach [Rapp & Wambach, Eur. Phys. J. A **6**, 415 (1999); Hess & Rapp, Nucl. Phys. A **806**, 339 (2008)]
- Transport approaches [Bratkosvskaya *et al.*, Phys. Lett. B **670**, 428 (2009); J. Weil *et al.*, PoS BORMIO2011, 053 (2011)]
- In both approaches ρ modified by scattering and melting within a baryon rich environment
- Since average density in SPS and RHIC are similar, these approaches should explain also RHIC data
- Is there alternative approach that emphasizes QCD role for chiral symmetry restoration/deconfinement at finite temperature/baryon density?

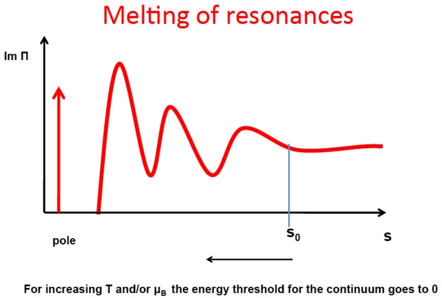
Finite Energy QCD Sum Rules

- ✓ Quantum field theory based on OPE of current-current correlators and Cauchy's theorem on complex energy squared-plane
- ✓ Relates hadron spectral function to QCD condensates and fundamental degrees of freedom (quark-hadron duality)
- ✓ Finite Energy refers to finite radius of integration s_0 called the energy squared-threshold for the continuum



Melting of resonances

- ✓ Hadron spectral function made out of resonances plus a continuum
- ✓ At finite temperature/density, s_0 decreases. Resonances melt
- ✓ FESR allow exploring how the resonance parameters change with temperature/density



Finite Energy QCD Sum Rules

- Vector-current correlator at finite temperature

$$\begin{aligned}\Pi_{\mu\nu}(q_0^2,\mathbf{q}^2) &= i\int d^4x e^{iq\cdot x}\langle \mathcal{T}[V_\mu(x)V_\nu^\dagger(0)]\rangle \\ &= -q^2\left[\Pi_0(q_0^2,\mathbf{q}^2)P_{\mu\nu}^T+\Pi_1(q_0^2,\mathbf{q}^2)P_{\mu\nu}^L\right]\end{aligned}$$

- Work in the limit $\mathbf{q}\to 0$ where $\Pi_{\mu\nu}$ contains only spatial components
- Integrating the function $\frac{s^N}{\pi}\Pi_0(s\equiv q_0^2)$ in the complex s–plane along a contour with a fixed radius $|s|=s_0$

$$\frac{1}{2\pi i}\oint_{C(|s_0|)} ds\ s^N\Pi_0(s) = -\frac{1}{\pi}\int_0^{s_0} ds\ s^N \mathrm{Im}\Pi_0(s).$$

Finite Energy QCD Sum Rules

- The integrand on the right-hand side can be written entirely in terms of hadronic degrees of freedom. Model by ρ saturation

$$\frac{1}{\pi}\mathrm{Im}\Pi_0^{\mathrm{had}}(s) = \frac{1}{\pi}\frac{1}{f_\rho^2}\frac{M_\rho^3\Gamma_\rho}{(s-M_\rho^2)^2+M_\rho^2\Gamma_\rho^2},$$

- The integrand on the left-hand side can be written entirely in terms of QCD degrees of freedom, using the OPE, as

$$\Pi^{\mathrm{QCD}}(s) = \sum_{M=0}\frac{C_{2M}\langle O_{2M}\rangle}{(-s)^M}.$$

- The term with $M=0$ corresponds to the perturbative (pQCD) contribution. The FESR are

$$\begin{aligned}(-1)^{N+1}C_{2N}\langle O_{2N}\rangle &= 8\pi^2\left[\frac{1}{\pi}\int_0^{s_0} ds s^{N-1}\mathrm{Im}\Pi_0^{\mathrm{had}}(s)\right.\\ &- \left.\frac{1}{\pi}\int_0^{s_0} ds s^{N-1}\mathrm{Im}\Pi_0^{\mathrm{pQCD}}(s)\right]\end{aligned}$$

Finite Energy QCD Sum Rules: Finite Temperature

- **Three** leading FESR, **six** unknowns
- Strategy: provide espected behavior of three unknowns based on experience from other channels
- Choose $\Gamma_\rho(T)$, $M_\rho(T)$ and $C_6\langle O_6\rangle(T)$ as inputs

$$\begin{aligned}
\Gamma_\rho(T) &= \Gamma_\rho(0)\left[1-(T/T_c)^3\right]^{-1}, \\
C_6\langle O_6\rangle(T) &= C_6\langle O_6\rangle(0)\left[1-(T/T_q^*)^8\right], \\
M_\rho(T) &= M_\rho(0)\left[1-(T/T_M^*)^{10}\right],
\end{aligned}$$

$\Gamma_\rho(0) = 0.145$ MeV, $C_6\langle O_6\rangle(0) = -0.951667$ GeV^6 and $M_\rho(0) = 0.776$ GeV, $T_c = 0.197$ GeV, $T_q^* = 0.187$ GeV and $T_M^* = 0.222$ GeV

- Solve for $f_\rho(T)$, $s_0(T)$ and $C_4\langle O_4\rangle(T)$

A.A., C.A. Dominguez, M. Loewe, Y. Zhang, Phys. Rev. D **86**, 114036 (2012)

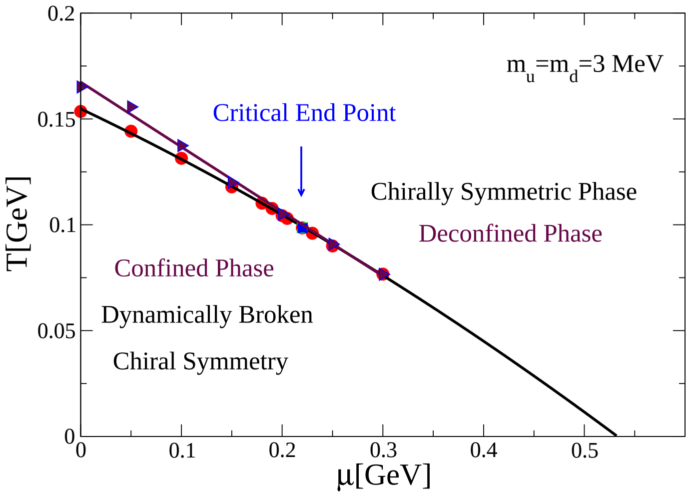
Finite Energy QCD Sum Rules: Finite Temperature & chemical potential

- First include this quantity in the quark loop in the FESR. This modifies the Fermi-Dirac distribution, splitting it into particle–antiparticle contributions.
- Second, include the μ dependence of T_c. Use parametrization for the crossover transition line between chiral symmetry restored and broken phases

E. Gutierrez, A. Ahmad, A.A., A. Bashir, A. Raya, arXiv:1304.8065 [hep-ph]

$$T_c(\mu) = T_c(\mu = 0) - 0.218\mu - 0.139\mu^2$$

Transition line



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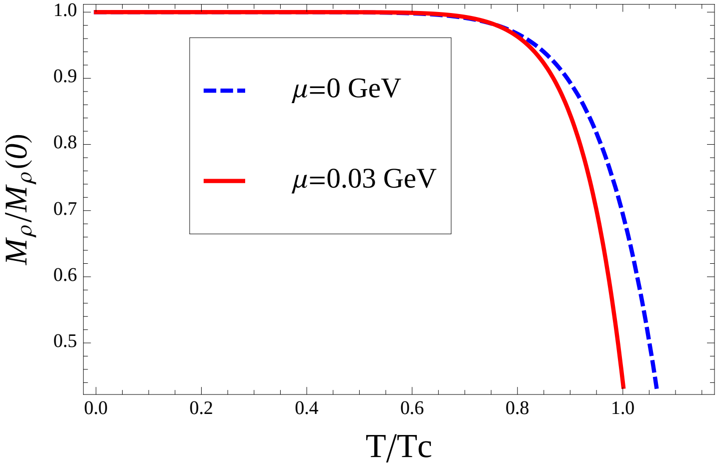
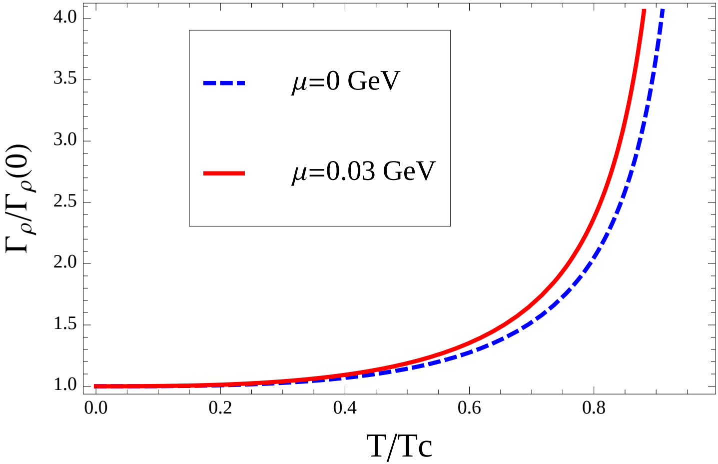
$$T_c(\mu) = T_c(\mu = 0) - 0.218\mu - 0.139\mu^2$$

- **Choose** $s_0(T,\mu)$**,** $f_\rho(T,\mu)$ **and** $C_4\langle O_4\rangle(T,\mu)$ **as inputs**
- **Solve for** $M\rho(T)$**,** $\Gamma(T)$ **and** $C_6\langle O_6\rangle(T)$

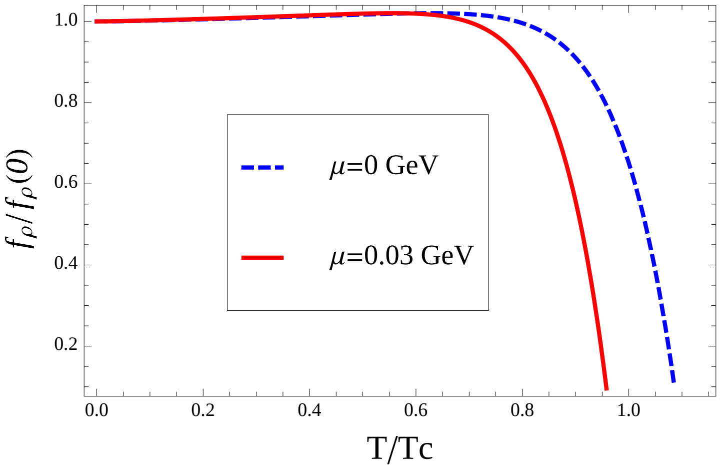
$M_\rho(T, \mu)$



$\Gamma_\rho(T, \mu)$

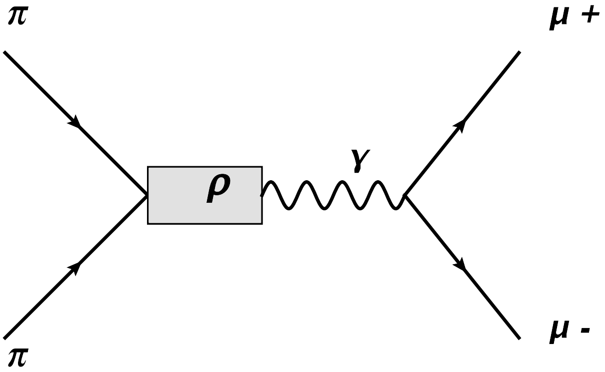


$f_\rho(T, \mu)$



Dilepton rate

- Consider processes where pions anhilate into ρ's which in turn decay into dimuons by vector dominance



Dilepton rate

- The number of muon pairs per unit of infinitesimal space-time and energy-momentum volume is

$$
\begin{aligned}
\frac{dN}{d^4x d^4K} &= \frac{\alpha^2}{48\pi^4}\left(1+\frac{2m^2}{M^2}\right)\left(1-\frac{4m_\pi^2}{M^2}\right)\sqrt{1-\frac{4m^2}{M^2}} \\
&\times \; e^{-K_0/T}\mathcal{R}(K,T)\mathrm{Im}\Pi_0^{\mathrm{had}}(M^2), \\
\mathcal{R}(K,T) &= \frac{T/K}{1-e^{-K_0/T}} \\
&\times \; \ln\left[\left(\frac{e^{-E_{\mathrm{max}}/T}-1}{e^{-E_{\mathrm{min}}/T}-1}\right)\left(\frac{e^{E_{\mathrm{min}}/T}-e^{-K_0/T}}{e^{E_{\mathrm{max}}/T}-e^{-K_0/T}}\right)\right],
\end{aligned}
$$

with

$$
\begin{aligned}
E_{\mathrm{max}} &= \frac{1}{2}\left[K_0+K\sqrt{1-\frac{4m_\pi^2}{M^2}}\right] \\
E_{\mathrm{min}} &= \frac{1}{2}\left[K_0-K\sqrt{1-\frac{4m_\pi^2}{M^2}}\right].
\end{aligned}
$$

Space-time evolution

- To compute the thermal rate as a function of the invariant mass, we need to integrate over the appropriate phase space variables

$$\begin{aligned} d^4K &= \frac{1}{2} dM^2 d^2K_\perp dy \\ d^4x &= \tau d\tau d\eta d^2x_\perp, \end{aligned}$$

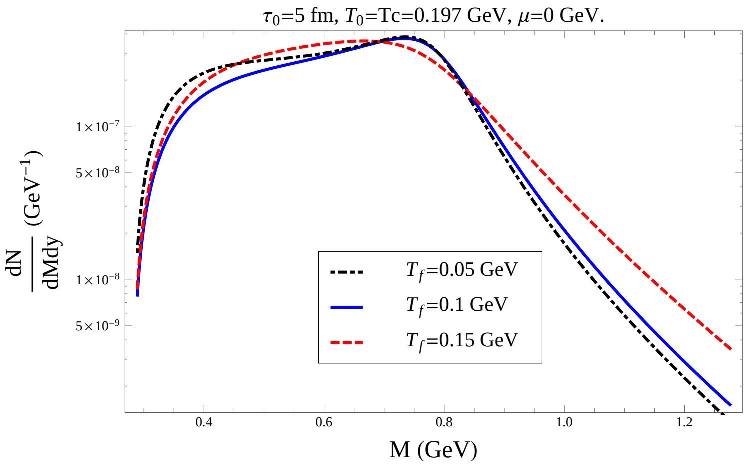
- The main expansion takes place along the longitudinal direction and thus take as the cooling law

$$T = T_0 \left(\frac{\tau_0}{\tau}\right)^{v_s^2},$$

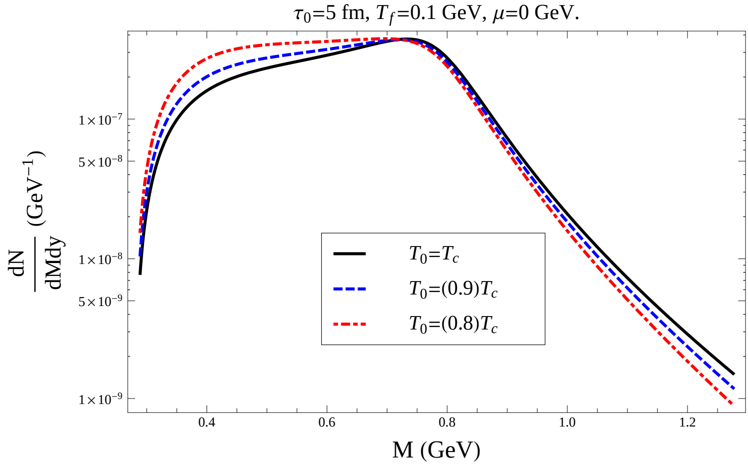
- The invariant mass distribution is given by

$$\frac{dN}{dMdy} = \Delta y M \int_{\tau_0}^{\tau_f} \tau d\tau \int d^2K_\perp \int d^2x_\perp \frac{dN}{d^4x d^4K}.$$

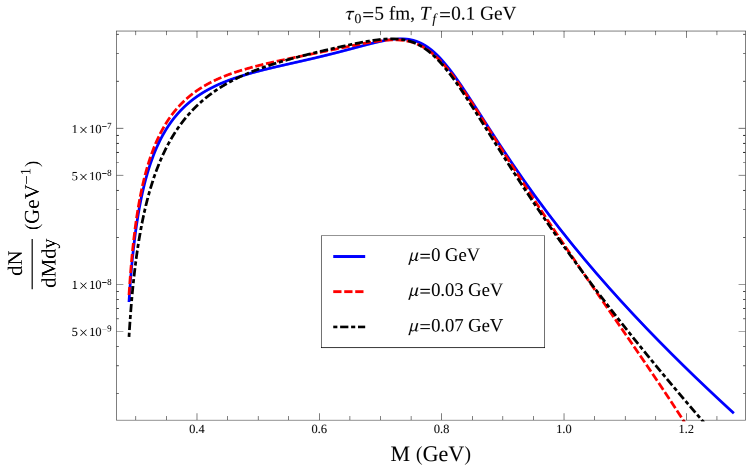
$dN/dM_{\mu^+\mu^-}$, different T_f



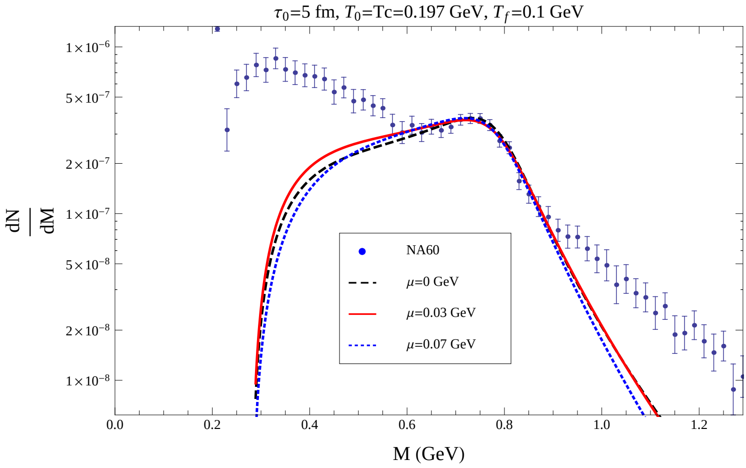
$dN/dM_{\mu^+\mu^-}$, different T_0



$dN/dM_{\mu^+\mu^-}$, different μ



Comparison with NA60 data



CONCLUSIONS

- ✓ FESR powerful tool to compute ρ parameters at finite T and μ
- ✓ $\Gamma(T,\mu)$ drops faster than $M(T,\mu)$ near (μ-dependent) T_c
- ✓ Calculation of dilepton spectrum from ρ decays in evolving medium in good agreement with NA60 data around the ρ peak
- ✓ Other effects around the ρ peak: Transverse expansion velocity, equation of state
- ✓ For lower invariant masses, consider scattering of off mass-shell ρ's with pions also at finite T and μ

¡Feliz Cumpleaños Profesor Kodama!