Thermal dilepton production in heavy-ion collisions at Beam Energy Scan (BES) energies

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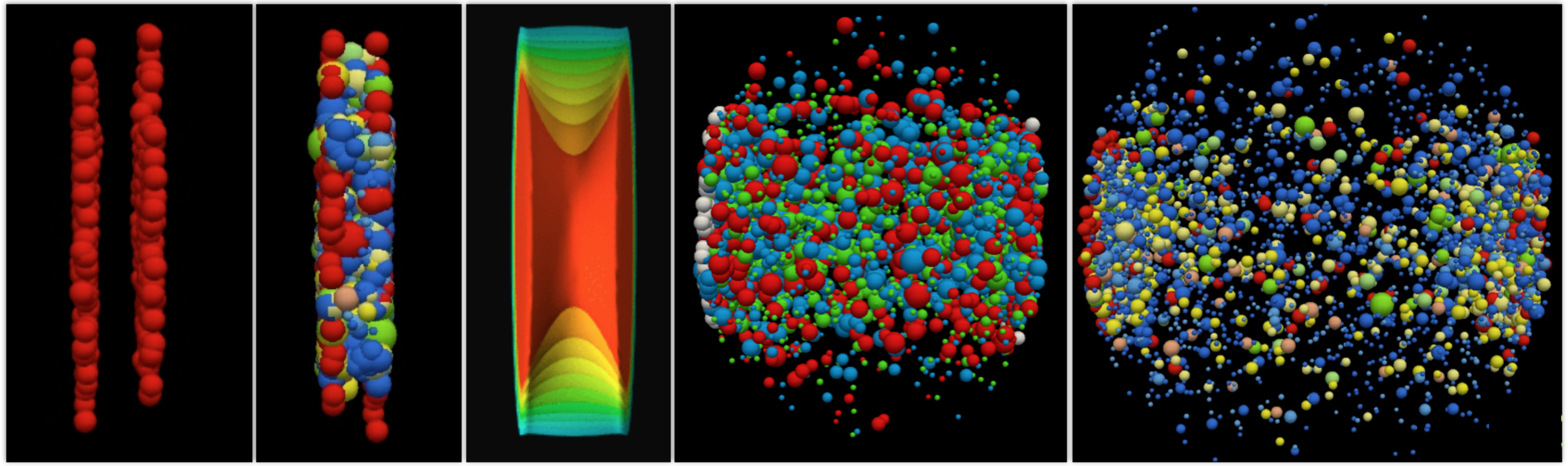
DIRECT PHOTONS AND HIC MODELLING

- Unlike hadrons, photons(*) are emitted throughout the entire space-time history of the HIC



pQCD photons
"primordial" photons

"Pre-eq. photons"

"Plasma photons"

"Hadronic medium photons"

Late stage reactions
Decay photons

(*) Real & virtual

Info Carried by the thermal radiation

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)\langle f|J_\mu|i\rangle\langle i|J_\nu|f\rangle$$

Thermal ensemble average of the current-current correlator

Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(photons)} \quad \left(=\frac{i}{2(2\pi)^3}(\Pi^\gamma_{12})^\mu_\mu\right)$$

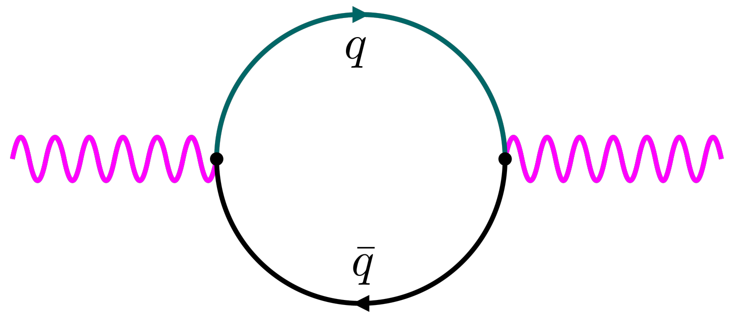
$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(dileptons)}$$

Feinberg (76); McLerran, Toimela (85); Weldon (90); Gale, Kapusta (91)

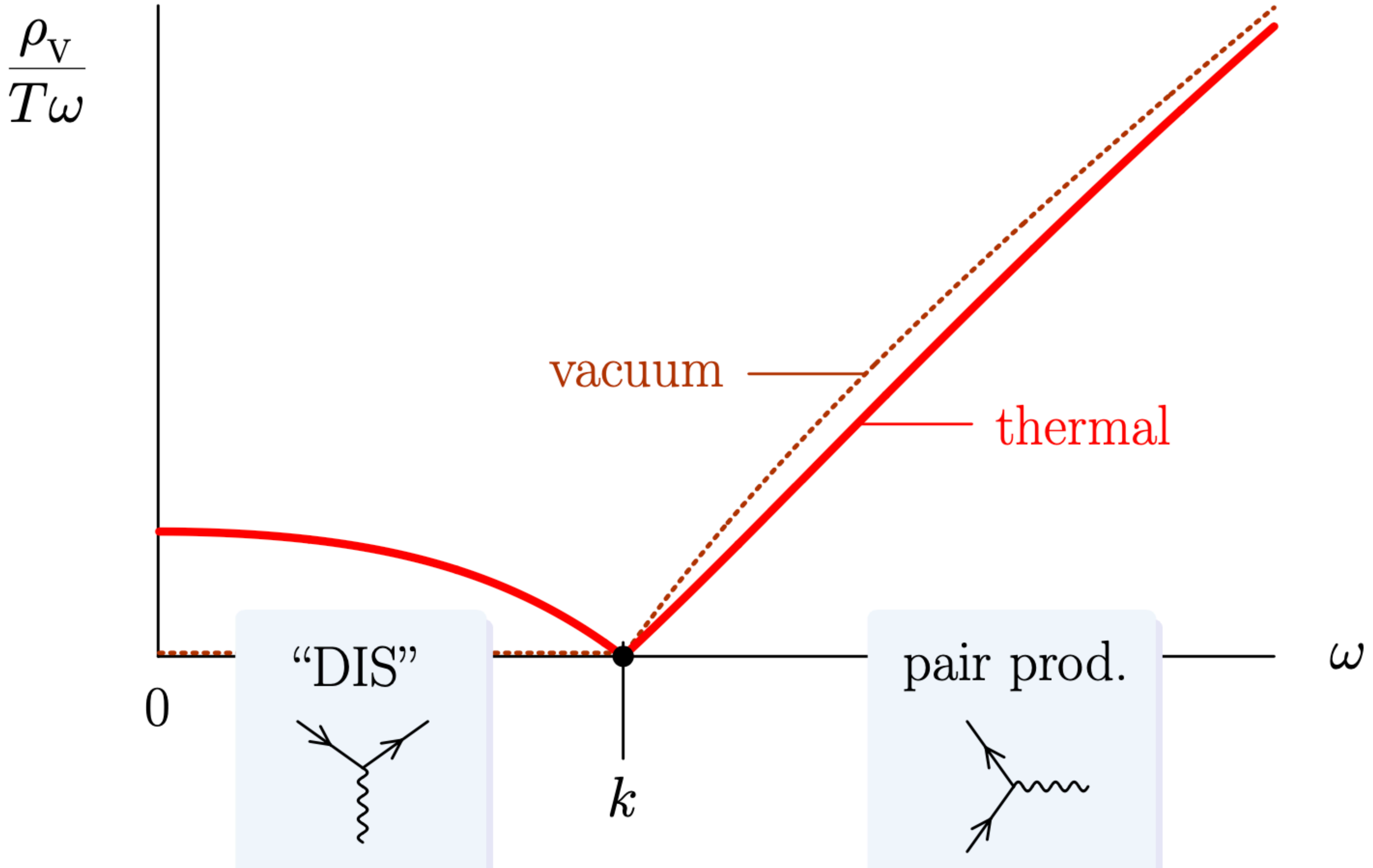
$$\mathrm{Im}\,\Pi_{\mu\nu} = \rho_{\mu\nu} = \mathbb{P}^{\mathrm{T}}_{\mu\nu}\,\rho_{\mathrm{T}} + \mathbb{P}^{\mathrm{L}}_{\mu\nu}\,\rho_{\mathrm{L}}$$

$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} \sim \rho_V = \rho^{\mu}_{\mu} = 2\,\rho_{\mathrm{T}}(\omega,\mathbf{k}) + \rho_{\mathrm{L}}(\omega,\mathbf{k})$$

LO:

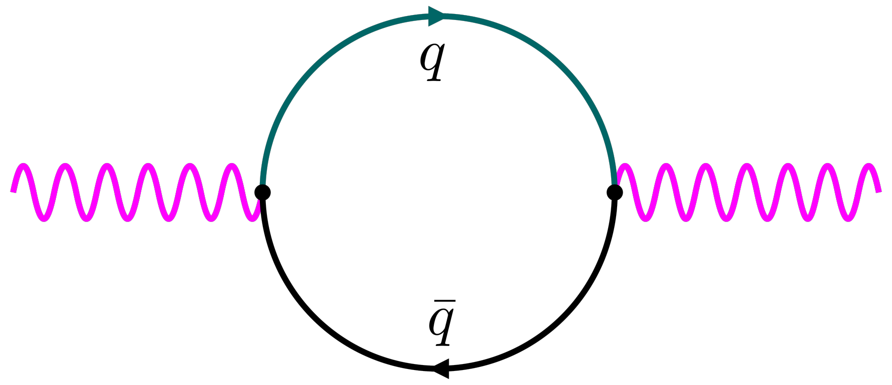


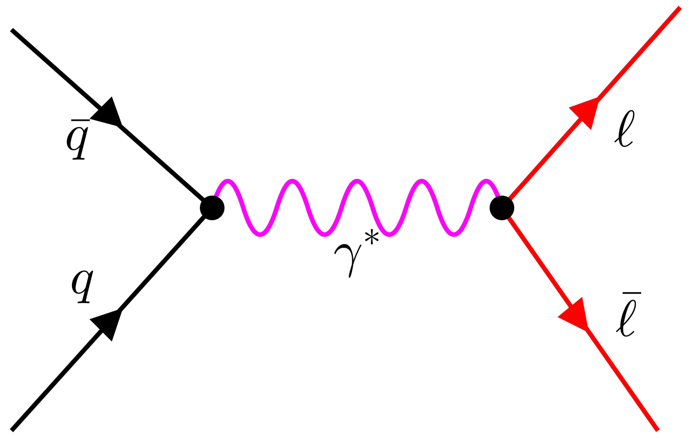
$$\rho_V = \frac{N_c M^2}{4\pi}\left\{\frac{2T}{k}\ln\left[\frac{1+e^{-(\omega+k)/2T}}{1+e^{-|\omega-k|/2T}}\right] + \Theta(M^2)\right\}$$

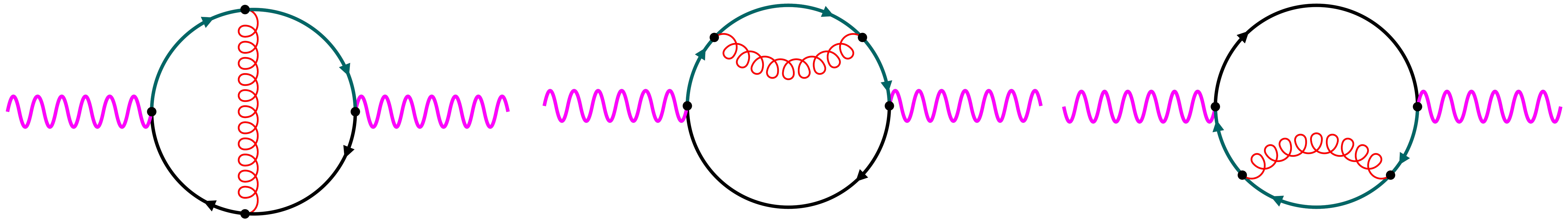


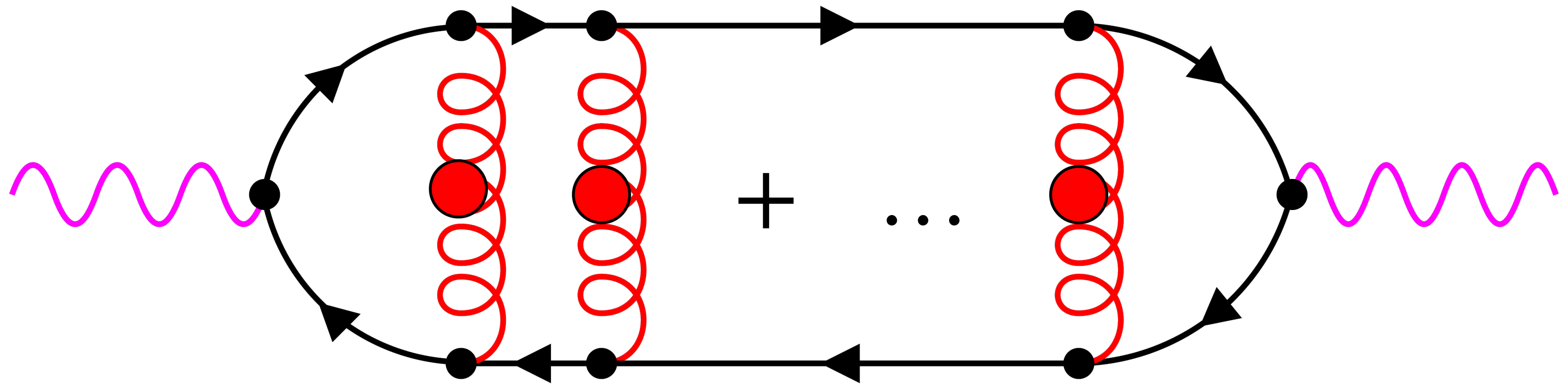
G. Jackson

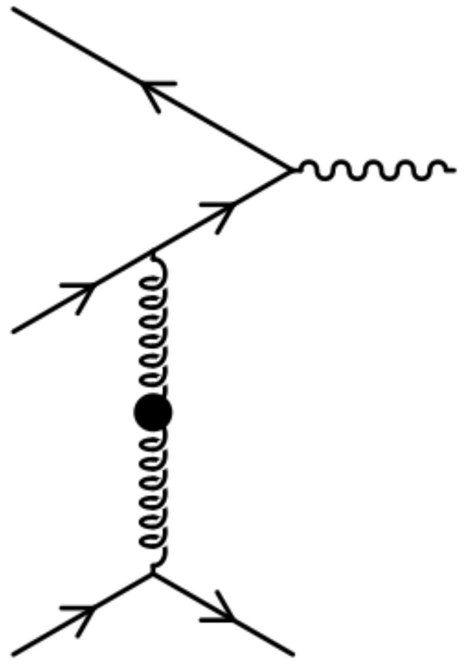
Going from LO to NLO

LO: Im 

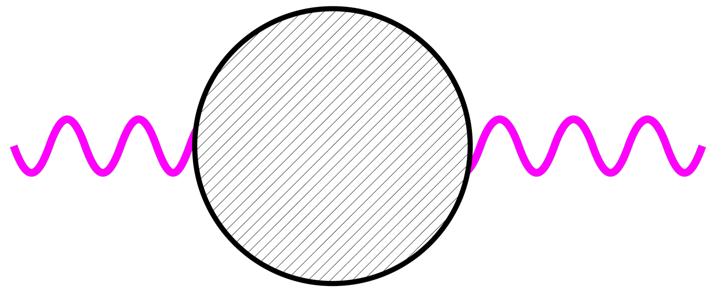


NLO: Im 

LPM: 



Arnold, Moore, Yaffe JHEP (2001);
Aurenche, Gélis, Moore, Zaraket JHEP (2002)

$\mathrm{Im}\,\Pi_{\mu\nu} \to$  $\sim \mathcal{O}(\alpha_s)^n$

QGP dilepton rates @ NLO in FTFT , in a variety of limits:

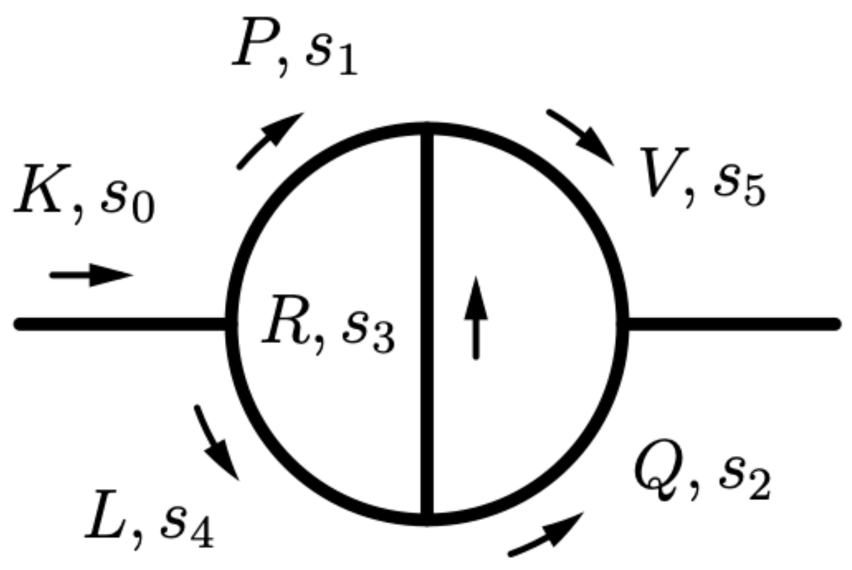
$M \sim \pi T,\ k = 0$ Altherr, Aurenche, Z. Phys. C (1989)

$M \sim gT,\ k = 0$ Braaten, Pisarski, Yuan, PRL (1990)

$M \sim gT, k \gtrsim gT$ Aurenche, Gélis, Moore, Zaraket, JHEP (2002) [LPM]

$M \sim \pi T,\ k \sim \pi T$ Ghiglieri, Moore, JHEP (2014)

@ 2 loops, a set of master integrals for general kinematics:



M. Laine, JHEP (2013)
G. Jackson, PRD (2019)

To interpolate between small and large M:

$$\rho\,|_{\mathrm{NLO}} = \rho_{1-\mathrm{loop}} + \rho_{2-\mathrm{loops}} + \left(\rho^{\mathrm{full}}_{\mathrm{LPM}} - \rho^{\mathrm{expanded}}_{\mathrm{LPM}}\right)$$

Ghisoiu and Laine, JHEP (2014)

- On the lattice — Ding et al., PRD (2011); Ghiglieri, Kaczmarek, Laine, Meyer, PRD (2016)
- Hadronic rates — Rapp, Wambach, Adv. Nucl. Phys (2000); C. Gale, Landolt-Bornstein (2010); . . .

What do we know at NLO and $\mu_B \neq 0$?

Dumitru et al., PRL (1993) [LO]
Traxler, Vija, Thoma, PLB (1995)
Gervais, Jeon, PRC (2012)
C. Shen et al., 2307.08498

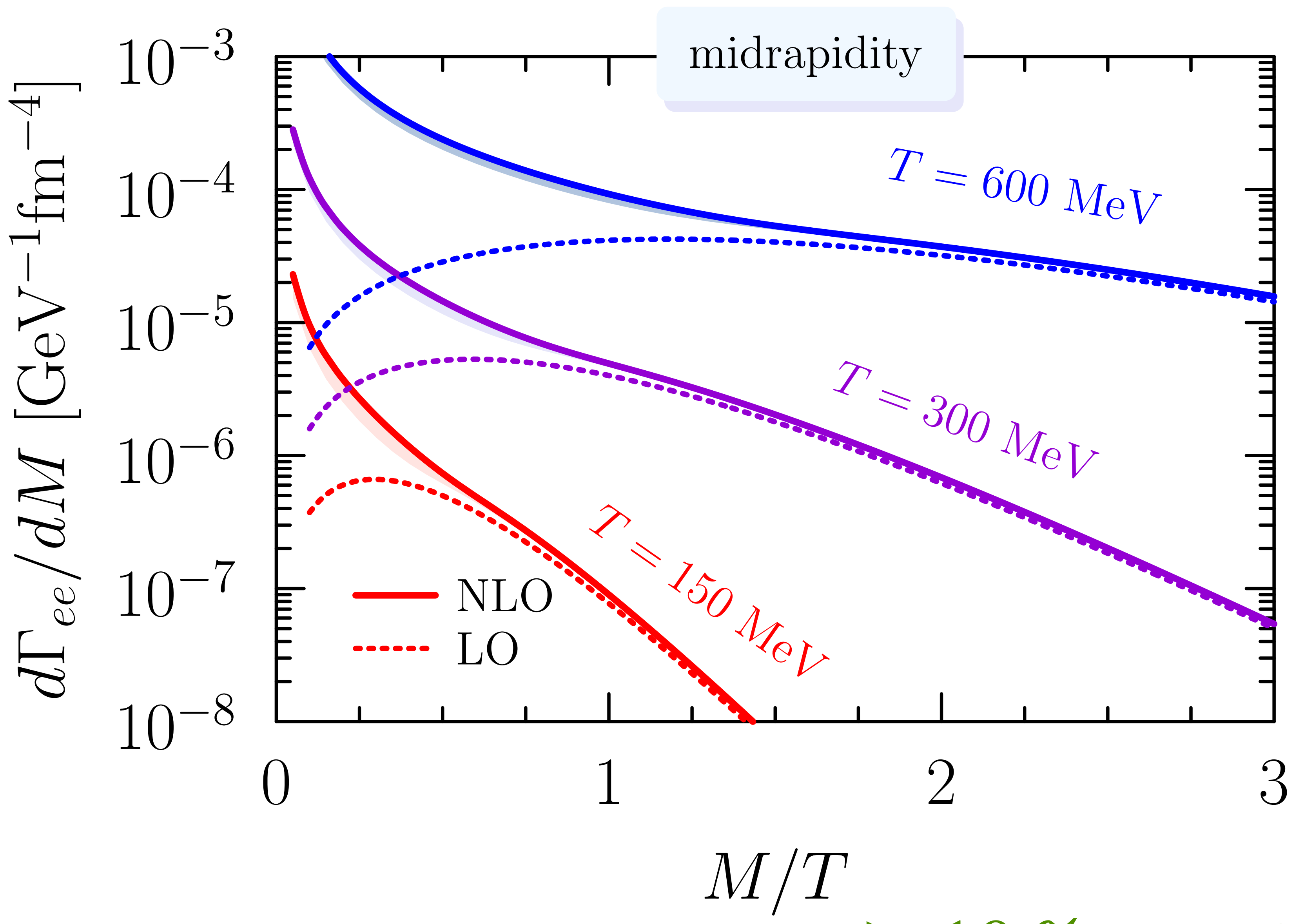
$\Big\}\,\gamma$

$\mu_B \neq 0$

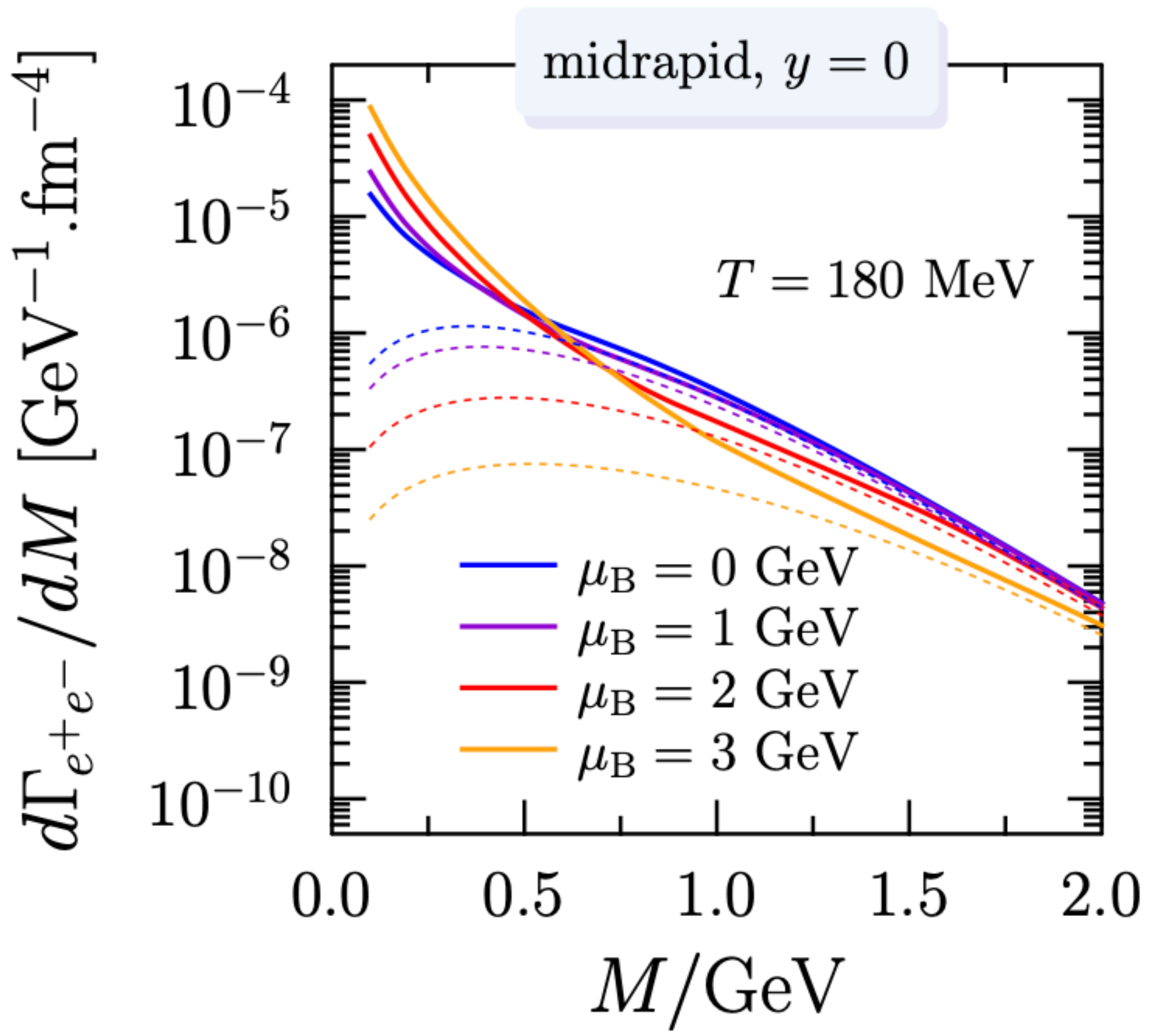
$$m_D^2 \equiv g^2\left[\left(\frac{1}{2}n_f + N_c\right)\frac{T^2}{3} + n_f\frac{\mu^2}{2\pi^2}\right],\ m_\infty^2 \equiv g^2\frac{C_F}{4}\left(T^2 + \frac{\mu^2}{\pi^2}\right)$$

Churchill, Du, Forster, Jackson, Gale, Gao, Jeon, (2023)

$\boxed{\mu_B = 0}$



NLO correction gives $\gtrsim 10\,\%$ even for 1 GeV < M < 3 GeV



$\boxed{\mu_B \neq 0}$

Growing μ_B: enhancement at low M, suppression at intermediate M

Large NLO correction at low M

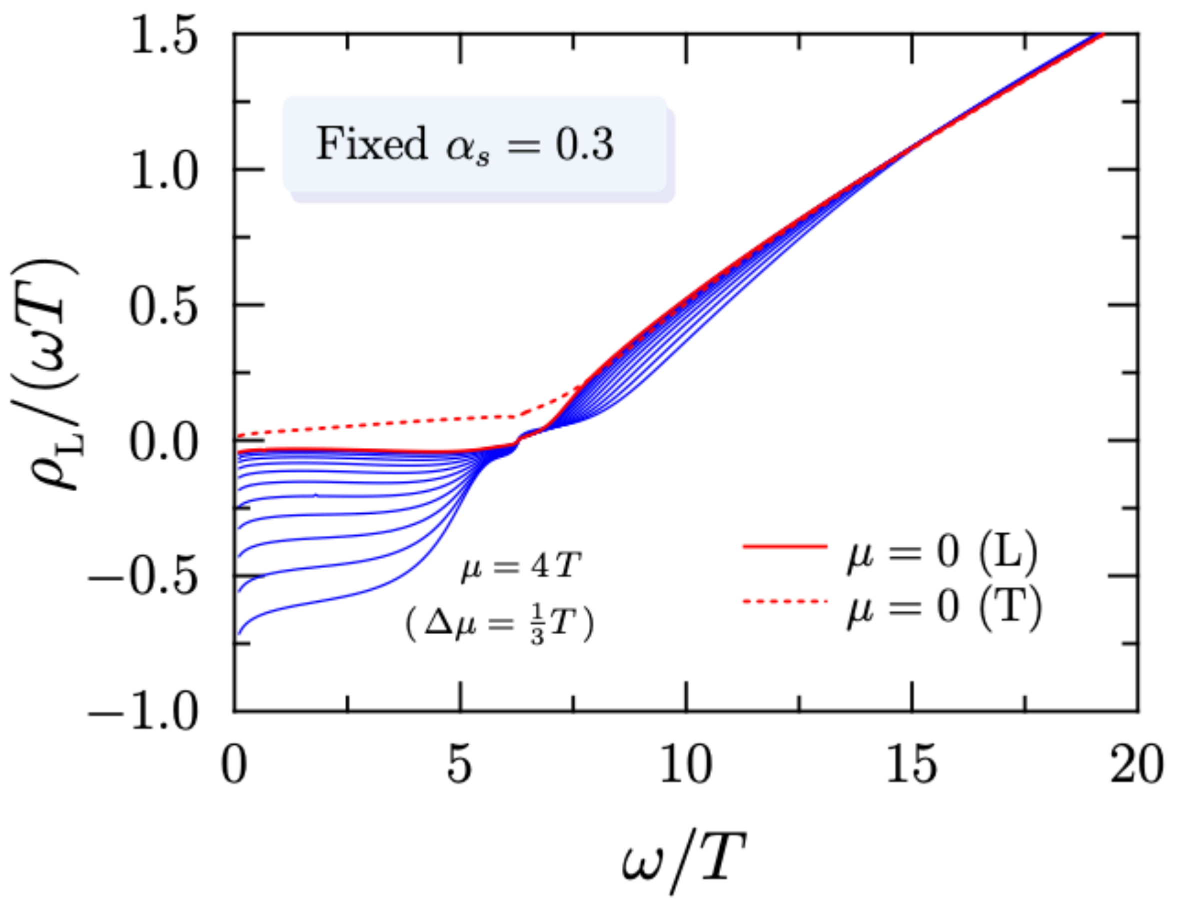
Some interesting features seen in the spectral densities (more on this later)

$$\mathrm{Im}\,\Pi_{\mu\nu} = \rho_{\mu\nu} = \mathbb{P}^{\mathrm{T}}_{\mu\nu}\,\rho_{\mathrm{T}} + \mathbb{P}^{\mathrm{L}}_{\mu\nu}\,\rho_{\mathrm{L}}$$

Weldon. PRD (1990); Gale, Kapusta Nucl. Phys. B (1991)

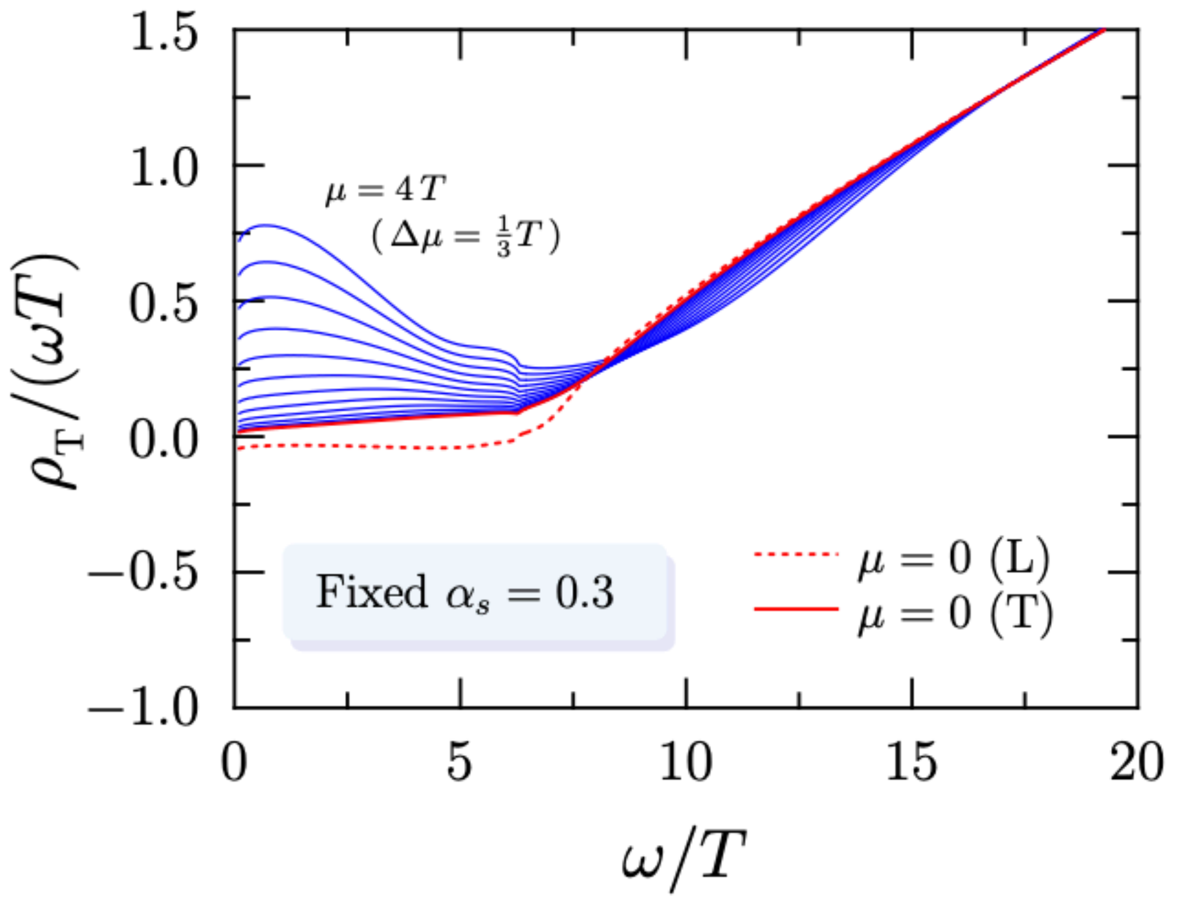
$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} \sim \rho_V = \rho^{\mu}_{\mu} = 2\,\rho_{\mathrm{T}}(\omega,\mathbf{k}) + \rho_{\mathrm{L}}(\omega,\mathbf{k})$$

$$\rho_L = -\frac{M^2}{k^2}\rho_{00}$$



$(k/T = 2\pi)$

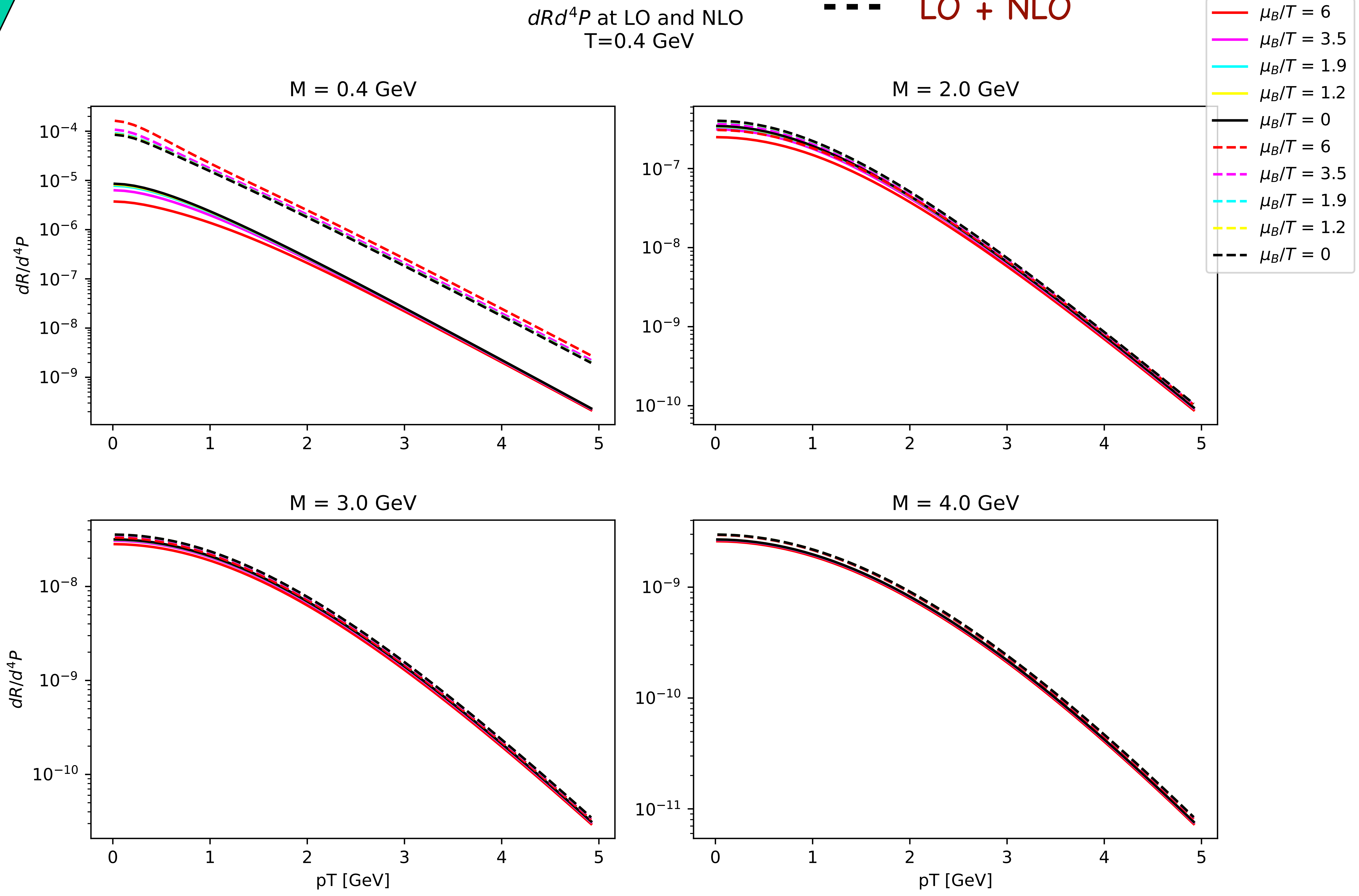
$$\rho_T = \frac{1}{2}\left(\rho^{\mu}_{\mu} + \frac{M^2}{k^2}\rho_{00}\right)$$



... but net μ_B effect on spectra not large

LO

LO + NLO



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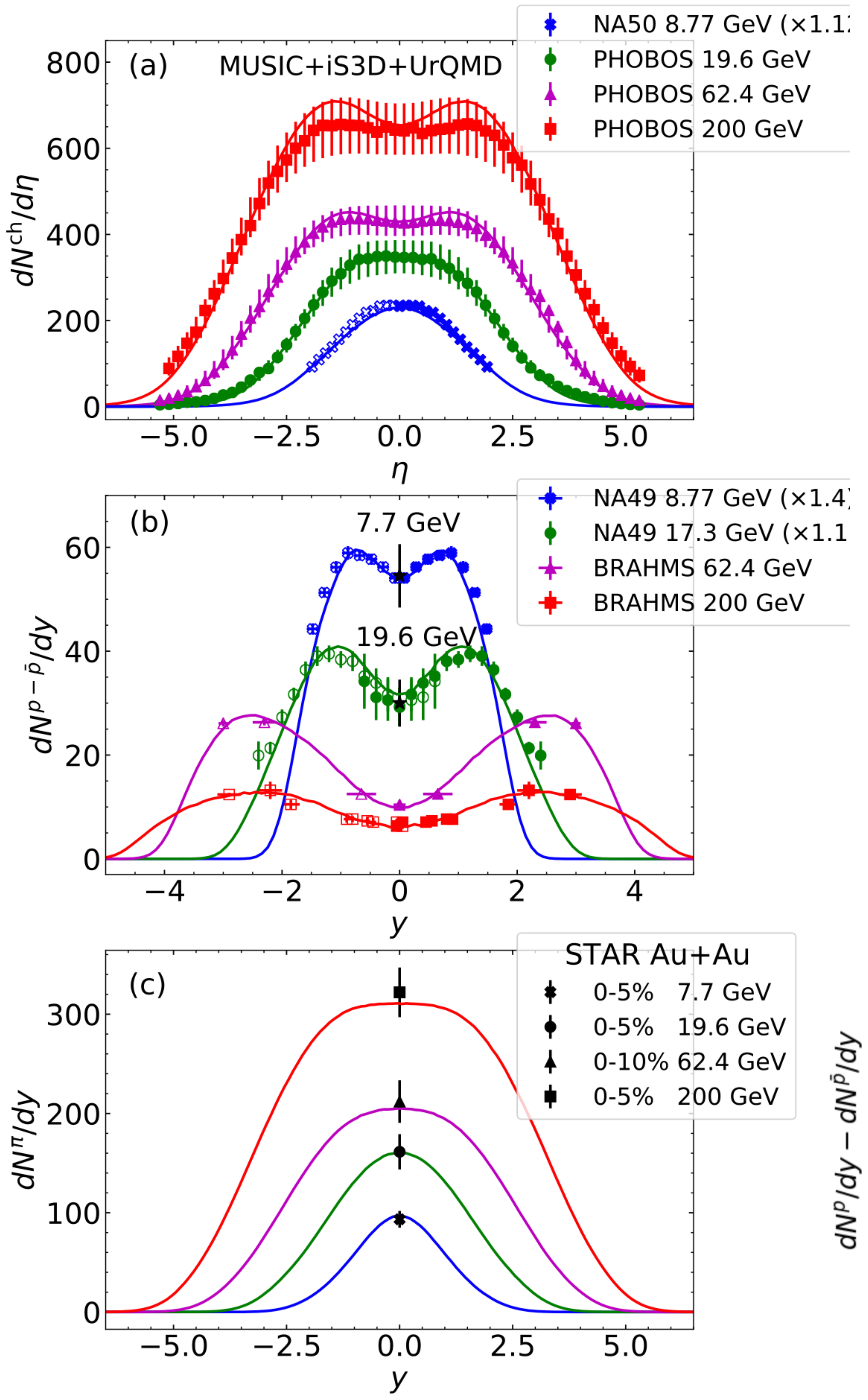
Integrating the rates with a realistic hydro

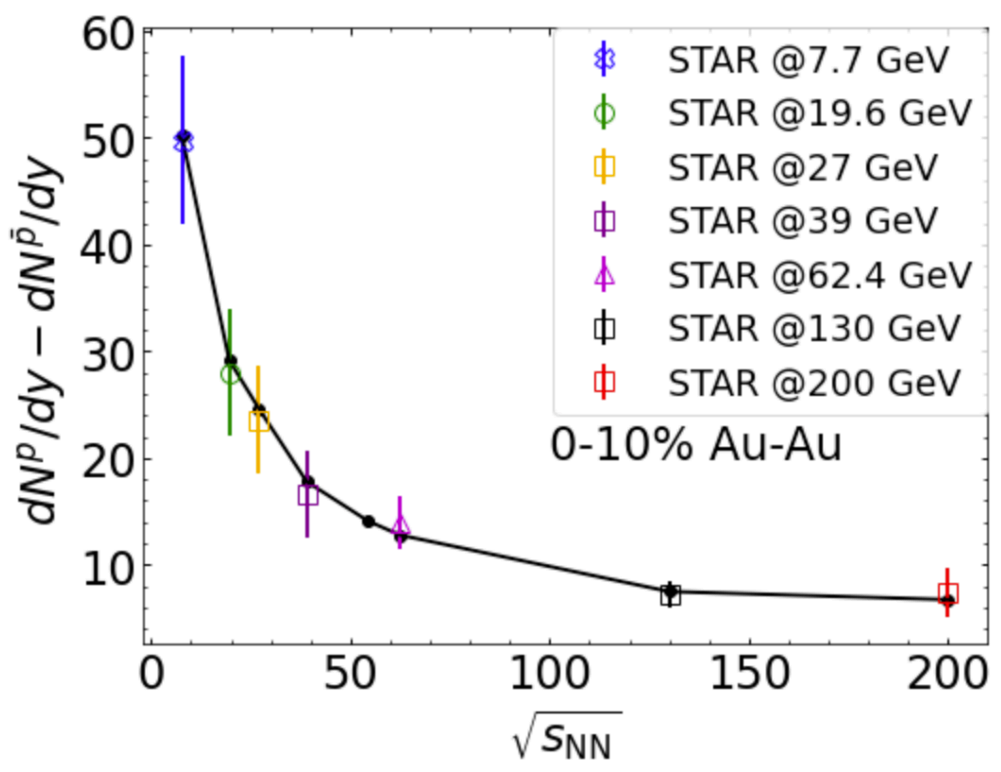
MUSIC+iS3D+UrQMD

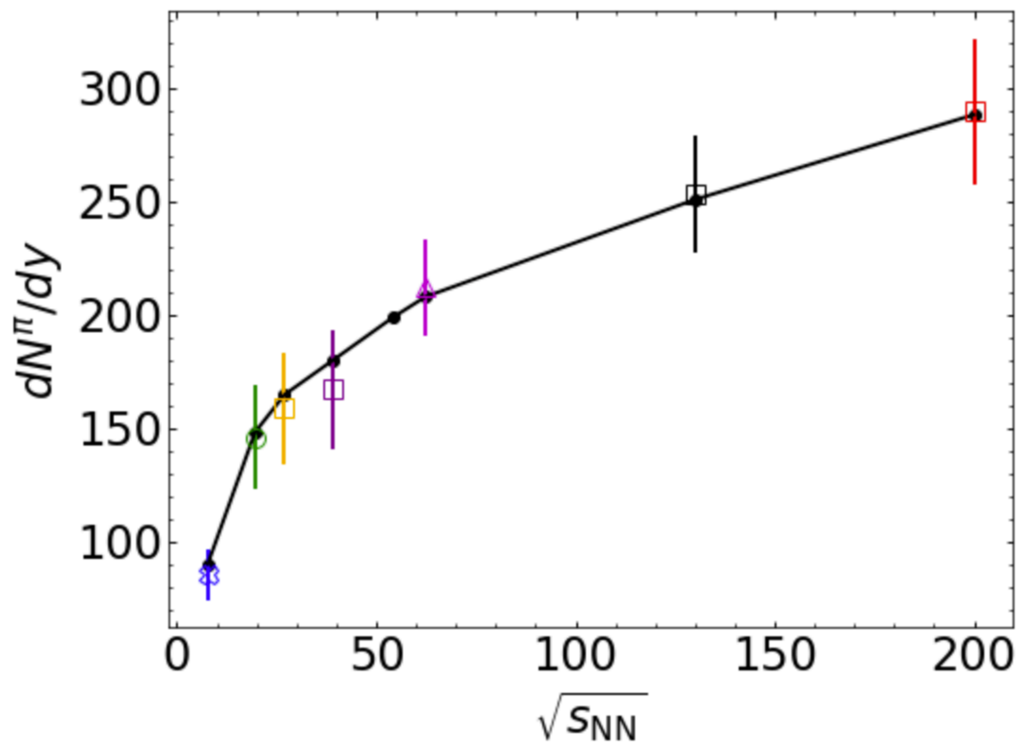


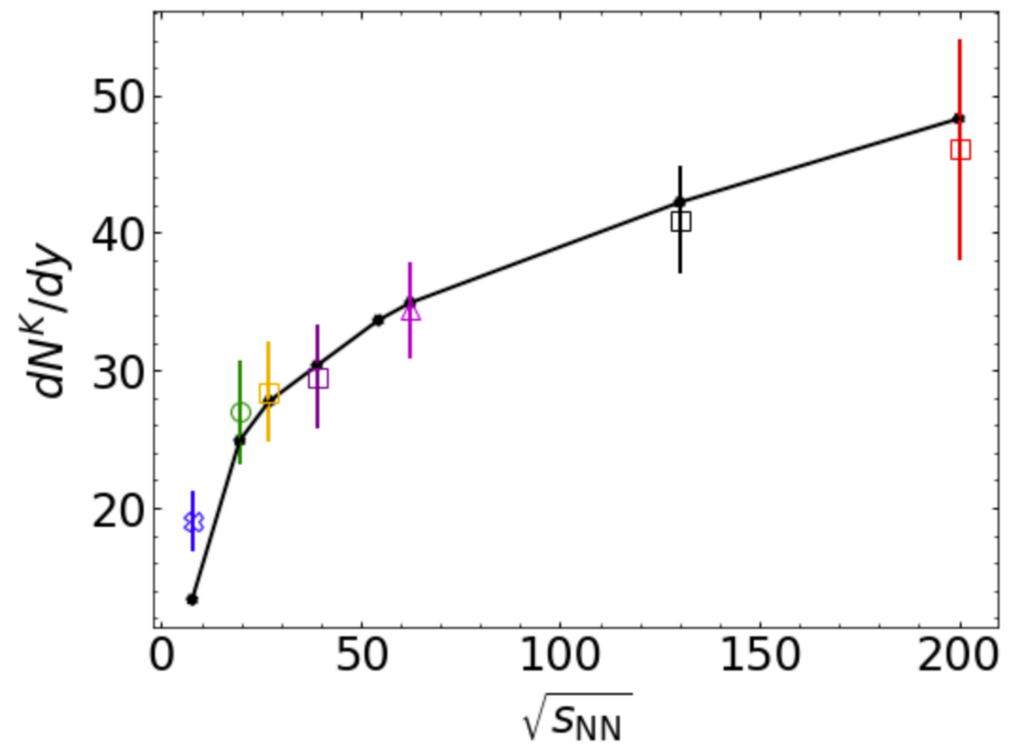
Initial state (pre-hydro) profile adjusted to data

Denicol, Gale, Jeon, Monnai, Schenke, Shen, PRC (2018)
Shen, Alzhrani, PRC (2020)
Du, Gao, Jeon, Gale, 2302.13852

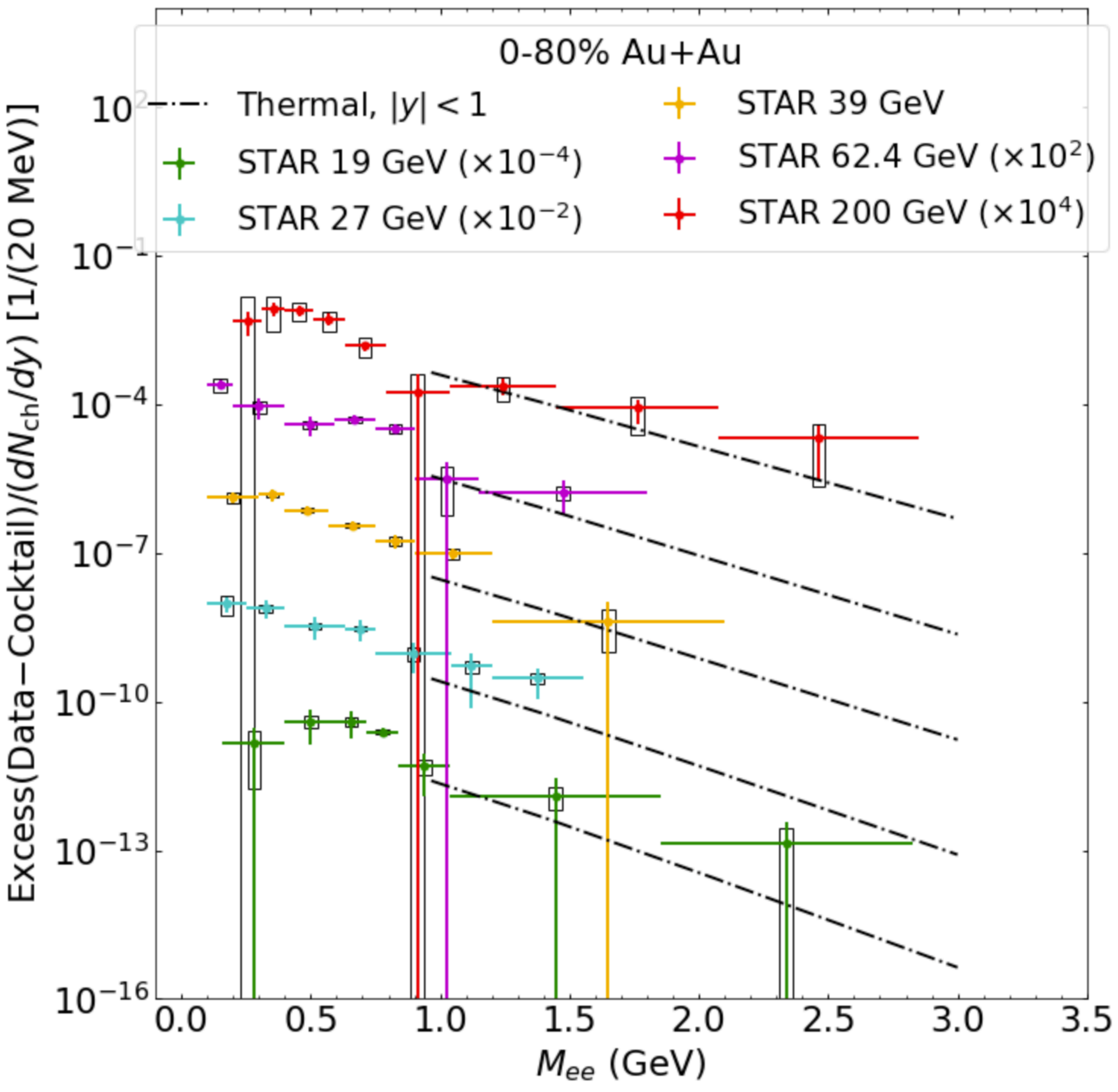
Hydro performance with hadronic observables is good







Now comparing with dilepton data from the reduced energy runs



Data: Abhdulhamid et al. (STAR), PRC (2023)

What is plotted is "Excess"= (Data - cocktail)/$(dN_{\rm ch}/dy)$

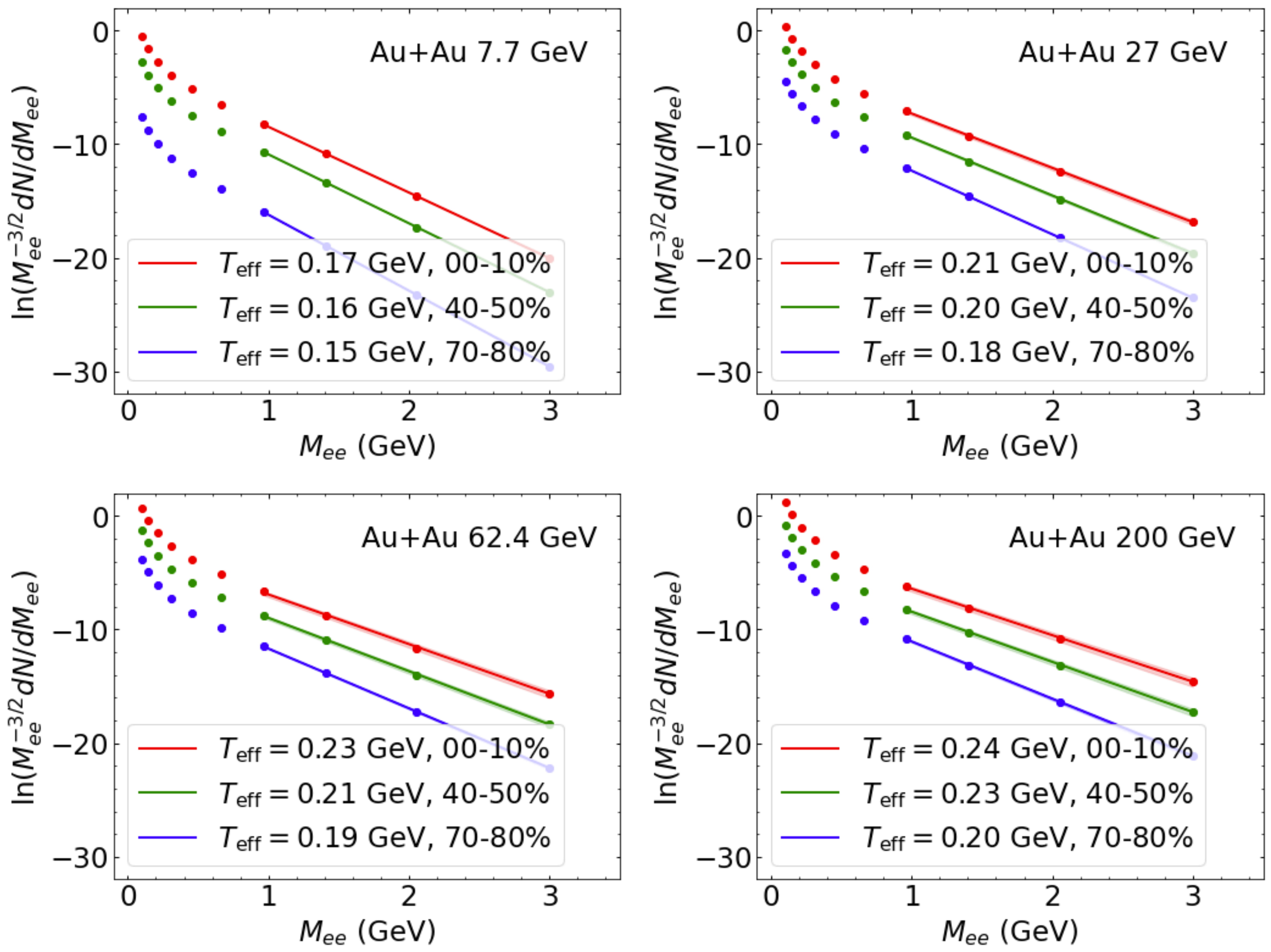
(Cocktail = radiative decays + $c\bar{c}$+ DY)

- In most cases, within data uncertainty limits
- Next step: calculate the cocktail and add to thermal contribution
- Data at low M is dominated by hadronic contributions not included here
- First estimate of NLO dilepton emission with finite μ_B, using hydrodynamics

Putting EM probes to work

- Real photon spectrum is sensitive to local T and to blue shift: informs the modelling
- Virtual photon spectrum is invariant, but "T" depends on some details

Those two are complementary



The y-axis is $\ln\left\{dN/dM \times M^{-3/2}\right\}$
The effective T is extracted from slope, considering $1 \text{ GeV} < M < 3 \text{ GeV}$

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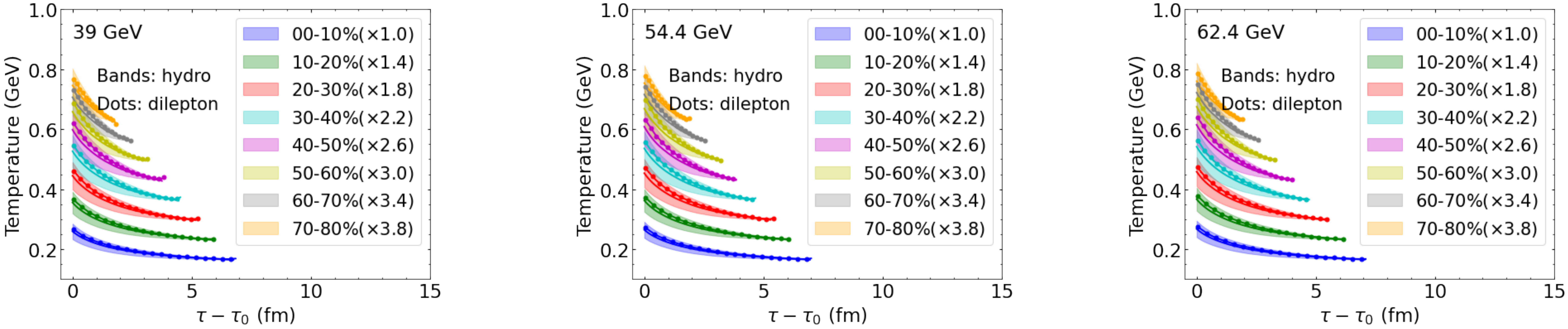
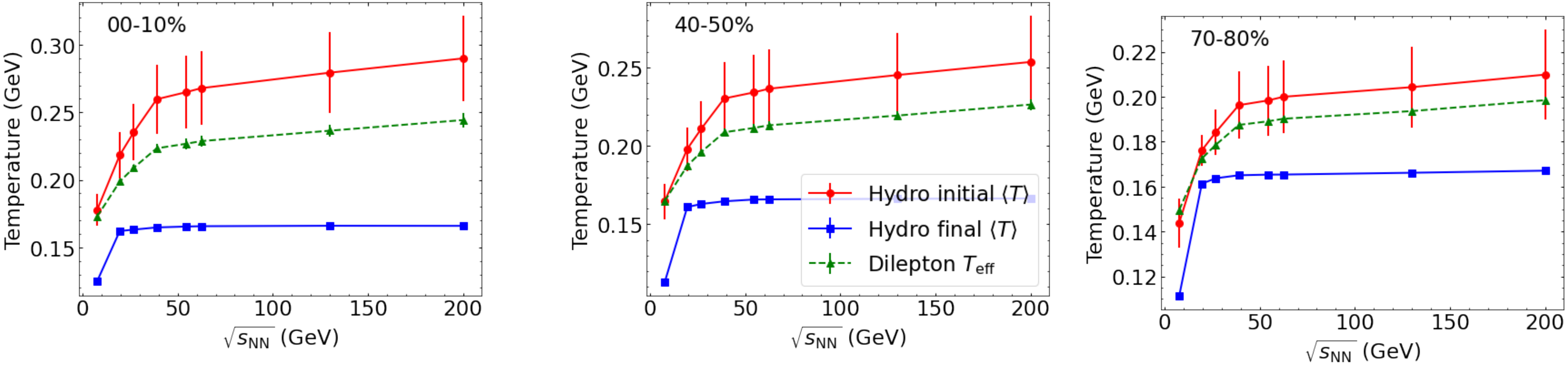
Evaluating the efficacy of the dilepton thermometer

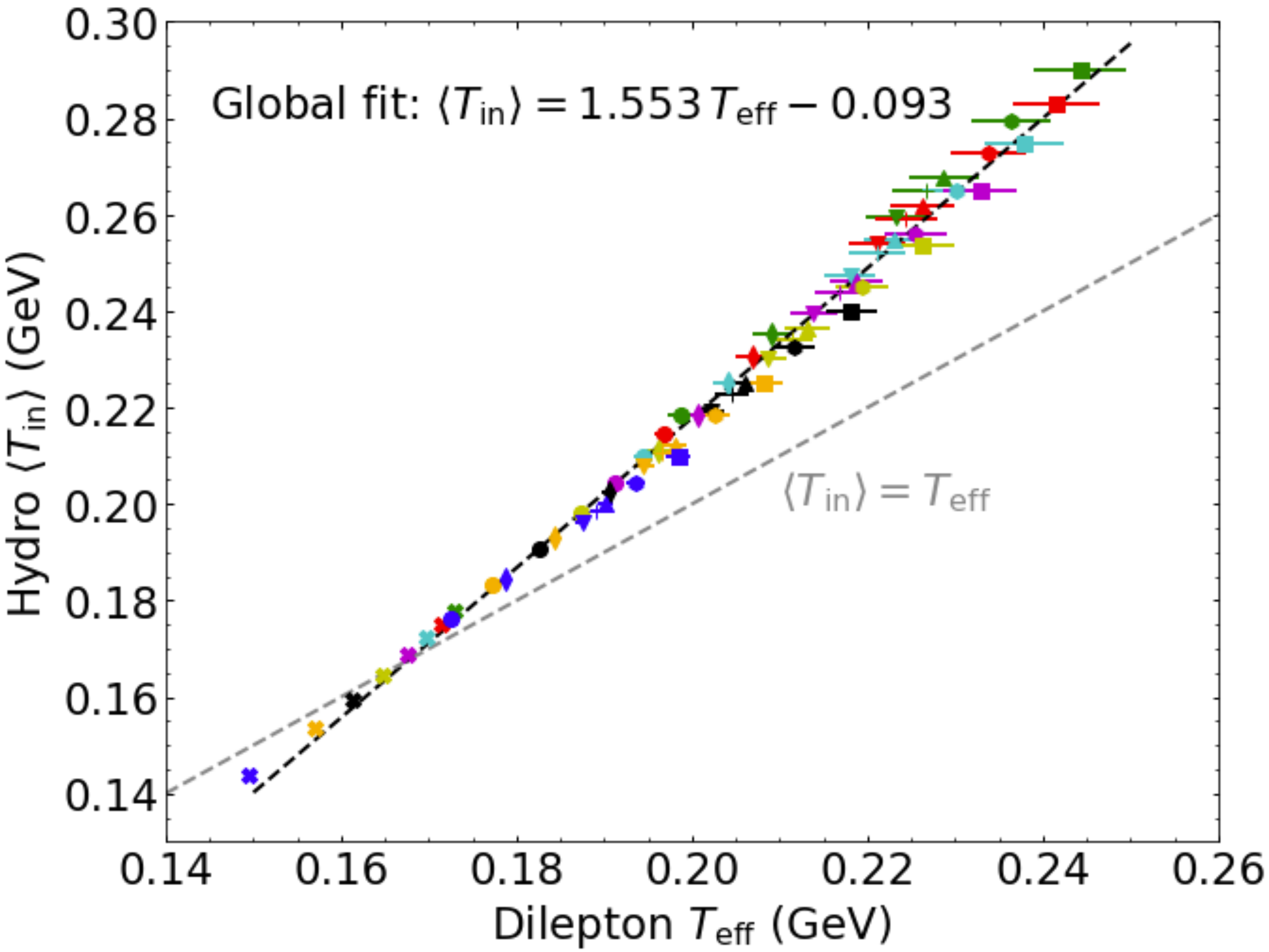


- Bands represent the temperature spread in hydro cells
- Dots are effective T read off the dilepton spectrum



- Dilepton T_{eff} increases with colliding energy
- We see that $T_{\text{final}} < T_{\text{eff}} < T_{\text{initial}}$

Putting all of this together



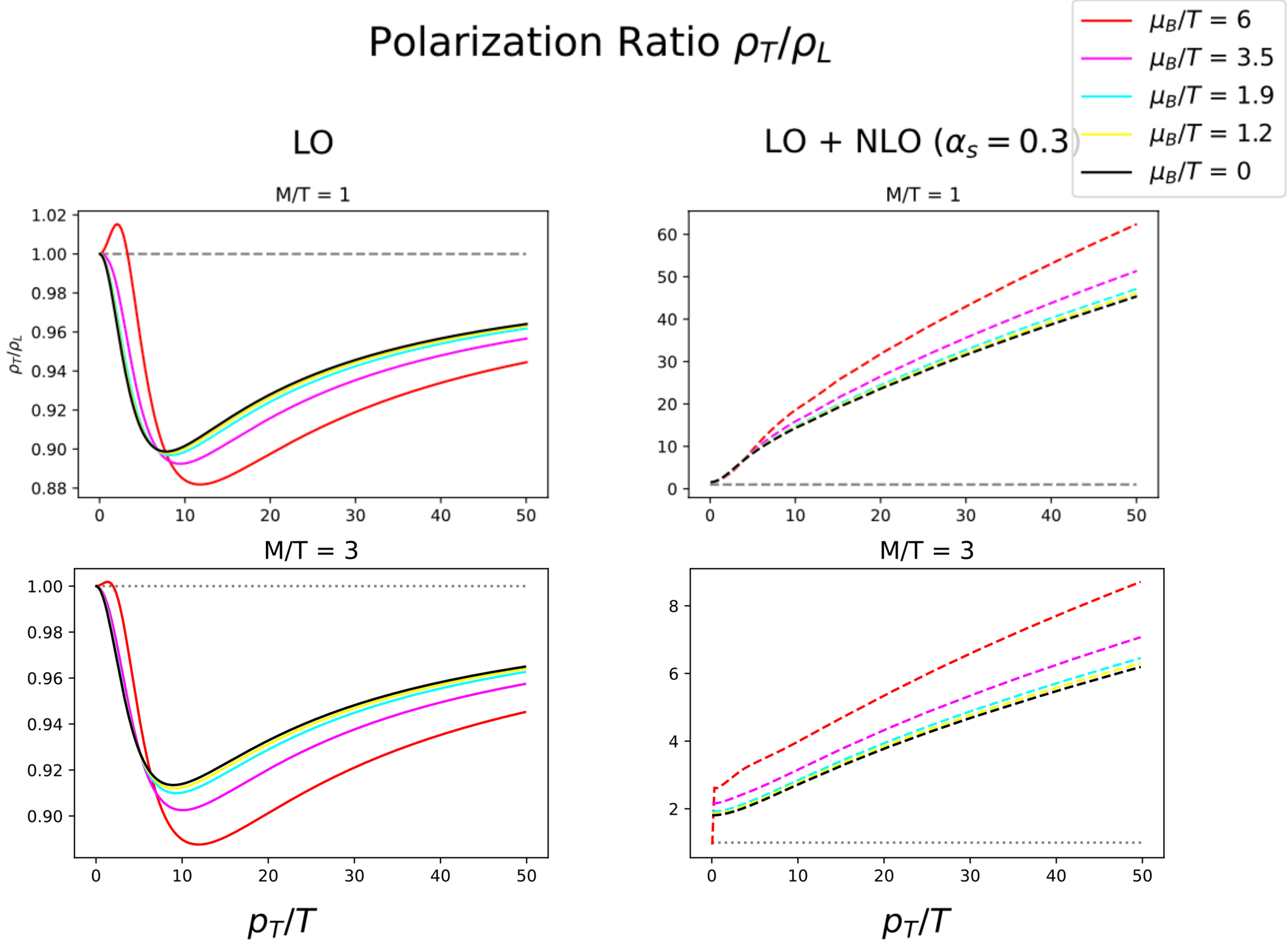
Combining all energies and centralities, the initial temperature in the fluid dynamical model correlates well with the effective temperature extracted from the dilepton spectrum

Dileptons: very good for temperature extraction, less so for baryon number?

Return to the emission rate

$$\mathrm{Im}\,\Pi_{\mu\nu} = \rho_{\mu\nu} = \mathbb{P}^{\mathrm{T}}_{\mu\nu}\,\rho_{\mathrm{T}} + \mathbb{P}^{\mathrm{L}}_{\mu\nu}\,\rho_{\mathrm{L}}$$

$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} \sim \rho_V = \rho^{\mu}_{\mu} = 2\,\rho_{\mathrm{T}}(\omega,\mathbf{k}) + \rho_{\mathrm{L}}(\omega,\mathbf{k})$$



- The "double-differential" spectral densities are rich in features
- Large quantitative difference in polarizations, going from LO to NLO
- Up to a 10-20% difference between values of μ_B

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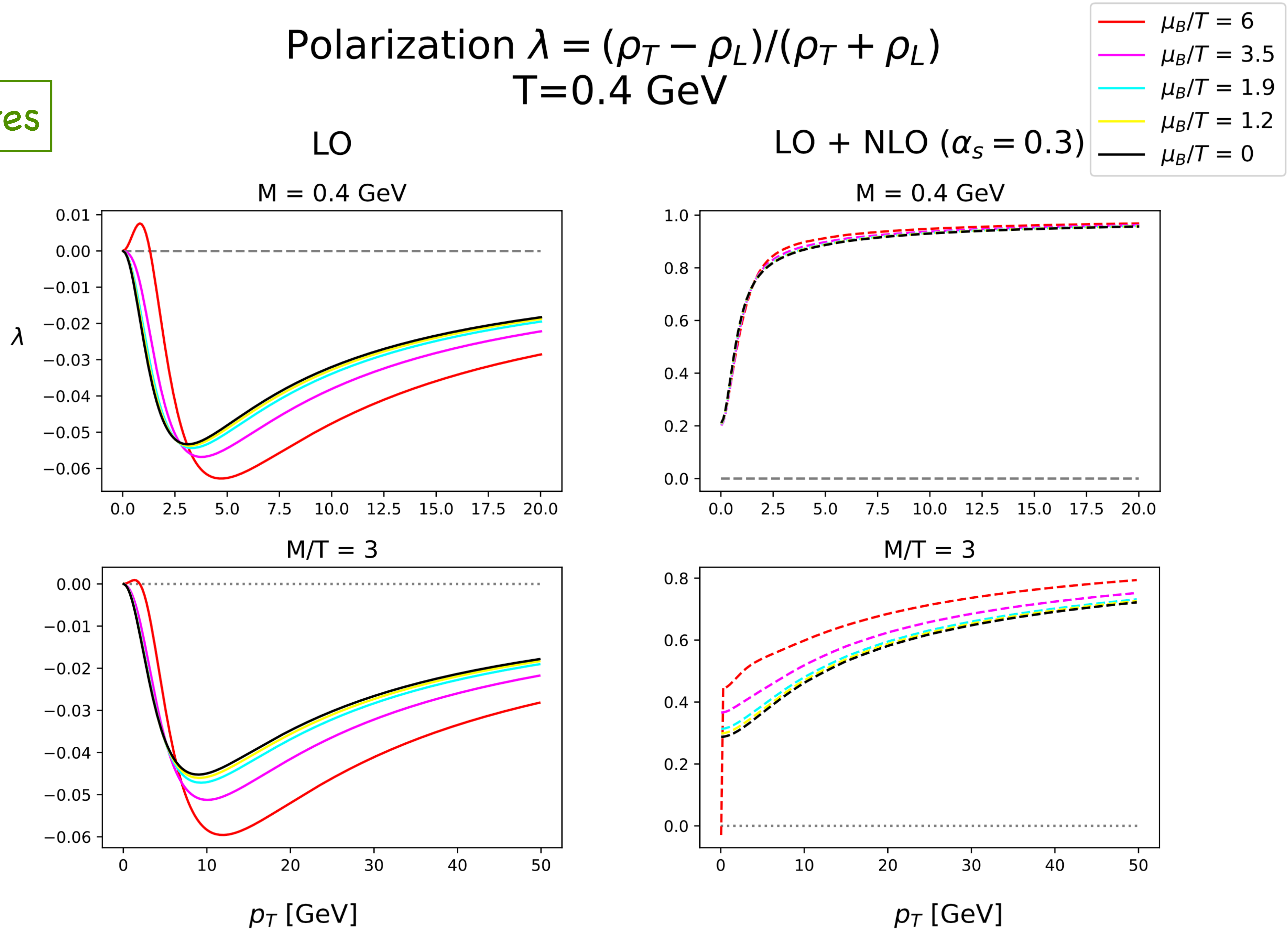
Polarization $\lambda = (\rho_T - \rho_L)/(\rho_T + \rho_L)$
T=0.4 GeV

Rates



Polarization contains lot of info that is difficult to obtain otherwise

Conclusions

- First results for dilepton emission rates at NLO with $\mu_B \neq 0$
- Implemented these in a hydrodynamical model at BES energies and above
- Combined with realistic dynamical modelling, measurements of dilepton spectra constitute a clean probe of early temperatures
- Dilepton polarization: promising and discriminating observable
- To do:
  - Pre-equilibrium emission (work on the initial state)
  - Rates with transport-coefficients corrections (η and ζ)

    G. Vujanovic et al. PRC (2018); S. Hauksson PRC (2018)
  - Combine with late-stage dilepton emission calculation

    A. Elfner et al., HP2023; A. Schäfer et al., PRC (2022)
  - Include dilepton flow evaluation (i.e. v_n)