Dynamical broadening of vector-meson spectral functions

Renan Hirayama*, Jan Staudenmaier, Hannah Elfner

QUARK MATTER
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Introduction

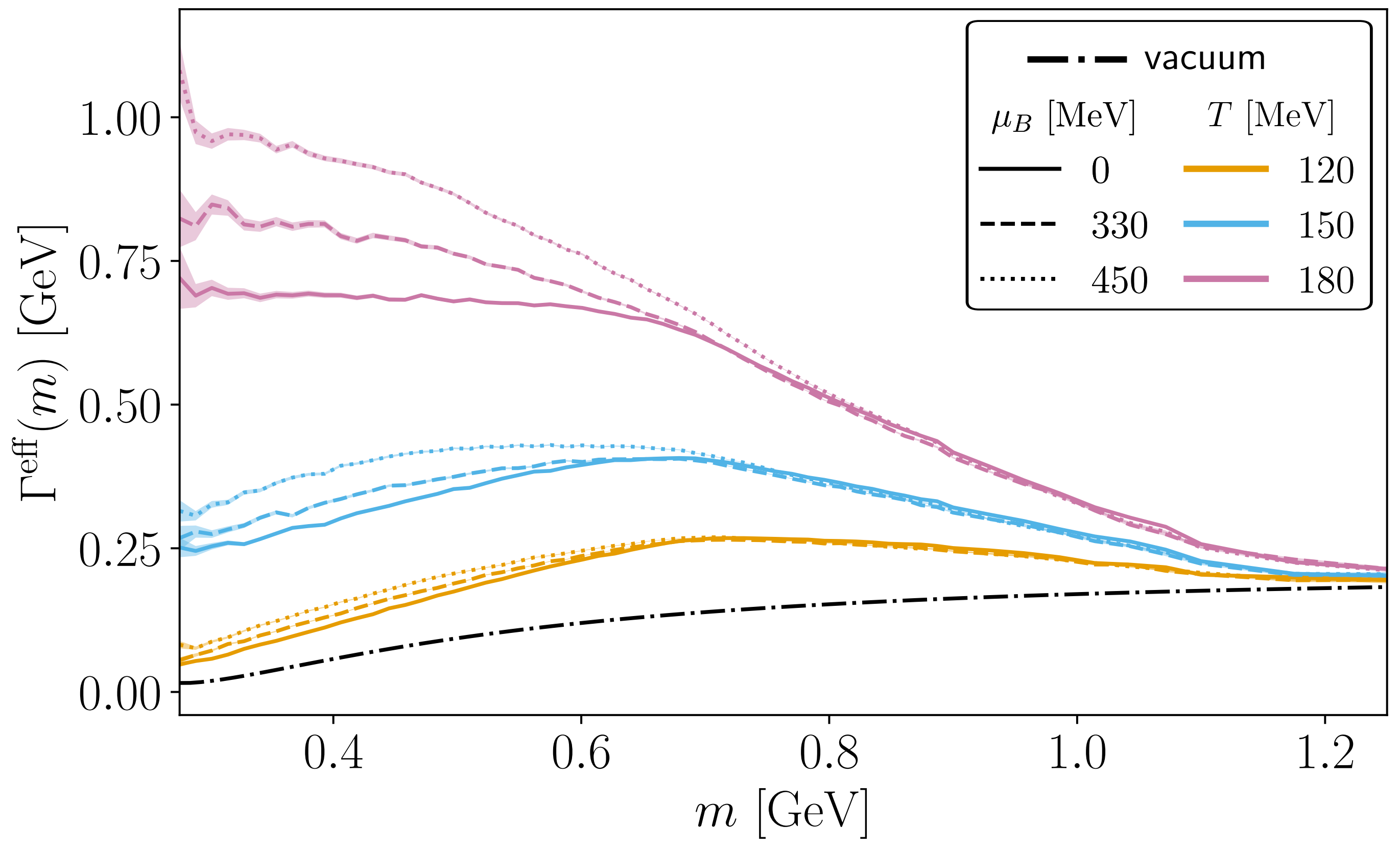
- Chiral symmetry partially restored under extreme conditions
- $\mathcal{A}_\rho(m) \overset{\text{medium}}{\approx} \mathcal{A}_{a_1}(m)$
- SMASH particles assumed in a vacuum a priori
- Invariant mass spectra of dileptons modified in HIC
- Inelastic collision channels that absorb ρ-mesons:

Vacuum	Medium
$\rho \to \pi\pi$	$\rho N \to N^*, \Delta, \ldots$
$\rho^0 \to l^+ l^-$	$\rho\pi \to \omega, a_1, \phi, \ldots$

Collisional broadening: *Shortening of resonance lifetimes due to medium absorptions*

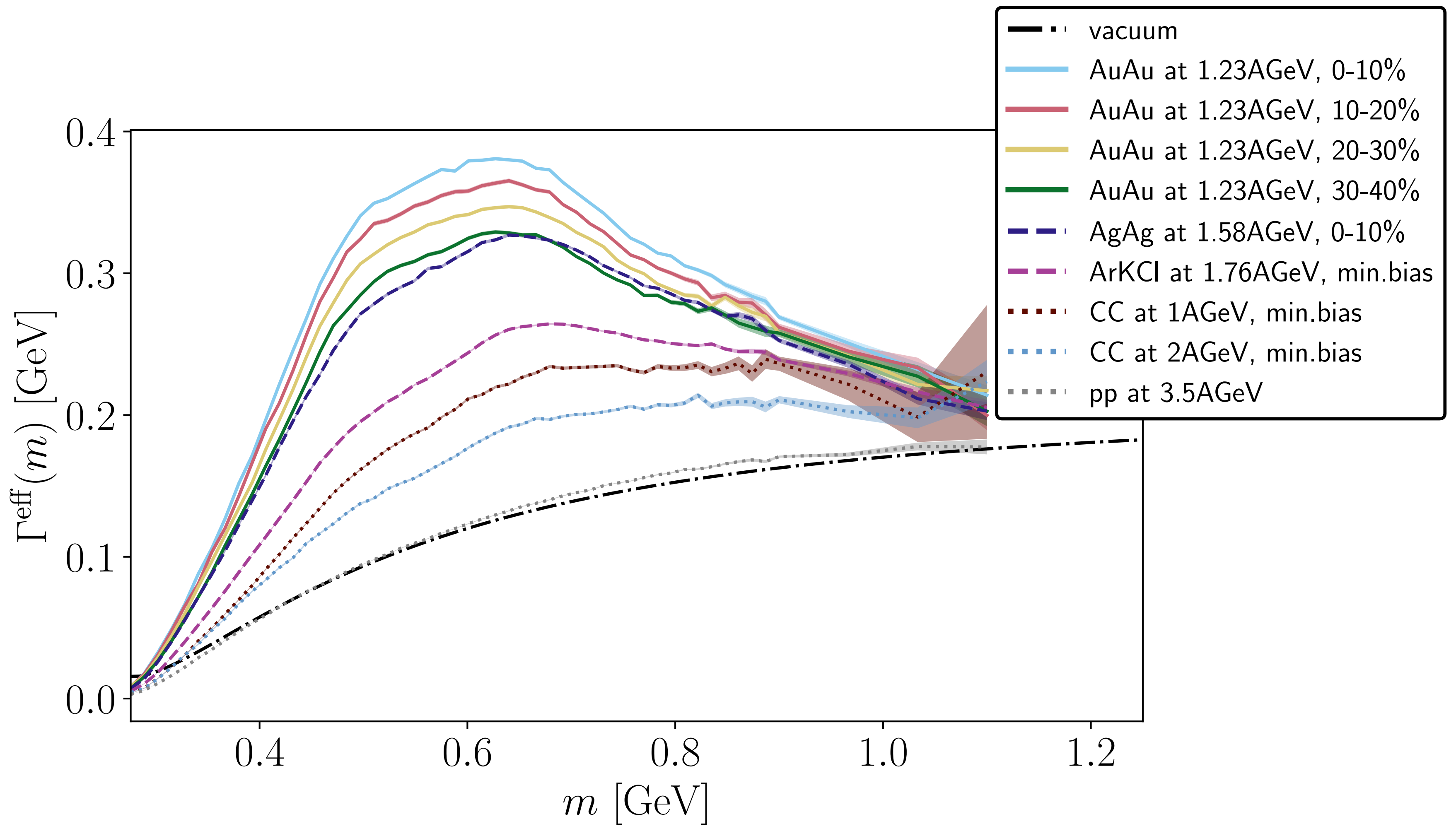
$$\Gamma^{\text{eff}} = \frac{1}{\langle\tau\rangle} = \left\langle \frac{\gamma}{t_f - t_i} \right\rangle = \Gamma^{\text{vac}} + \Gamma^{\text{col}}$$

Thermalized hadron gas



- High masses display little to no broadening, while low masses easily absorbed by the medium
- Increasing μ_B affects low mass range $m \leq M_0 = 0.776$ GeV

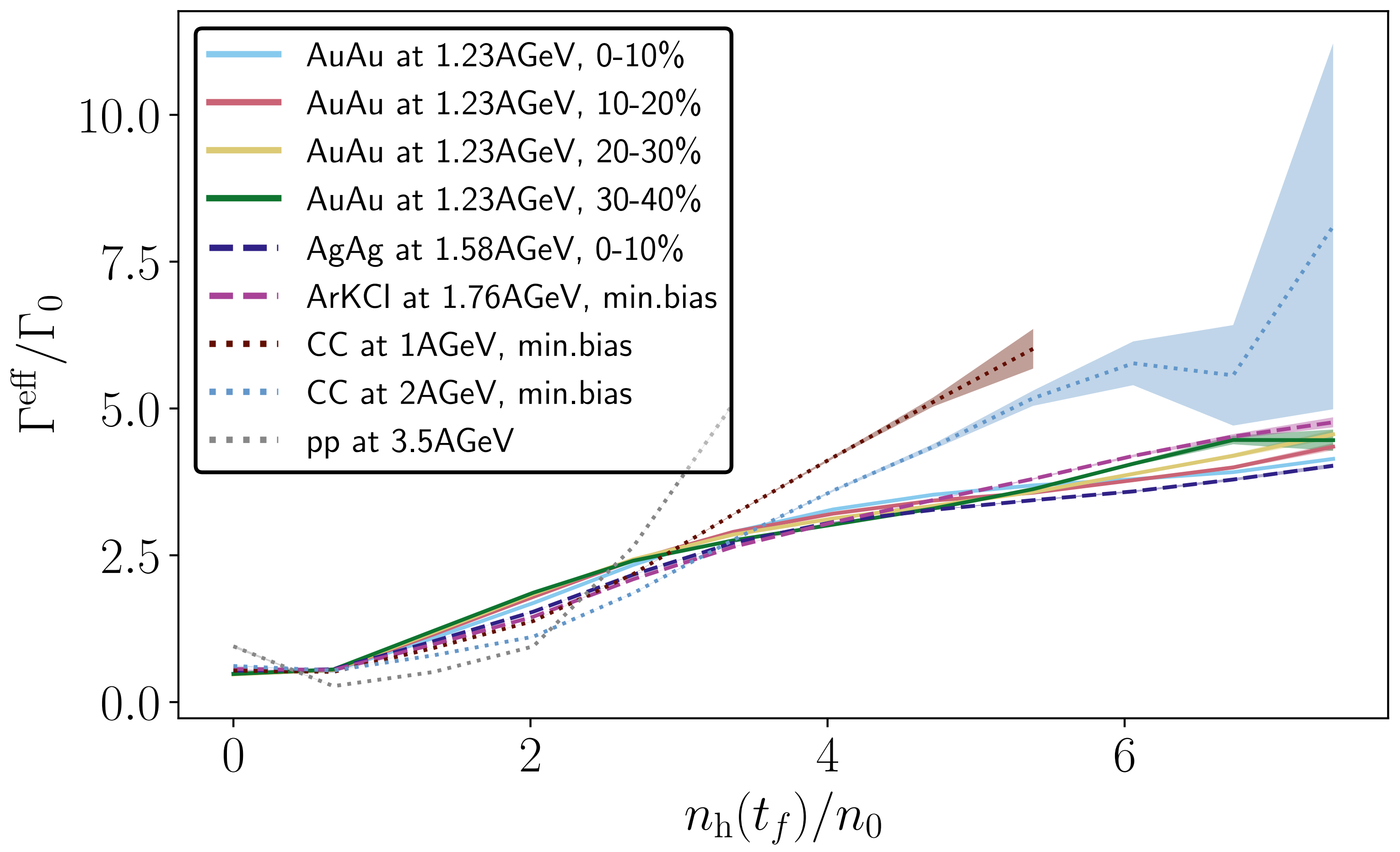
Nuclear collisions



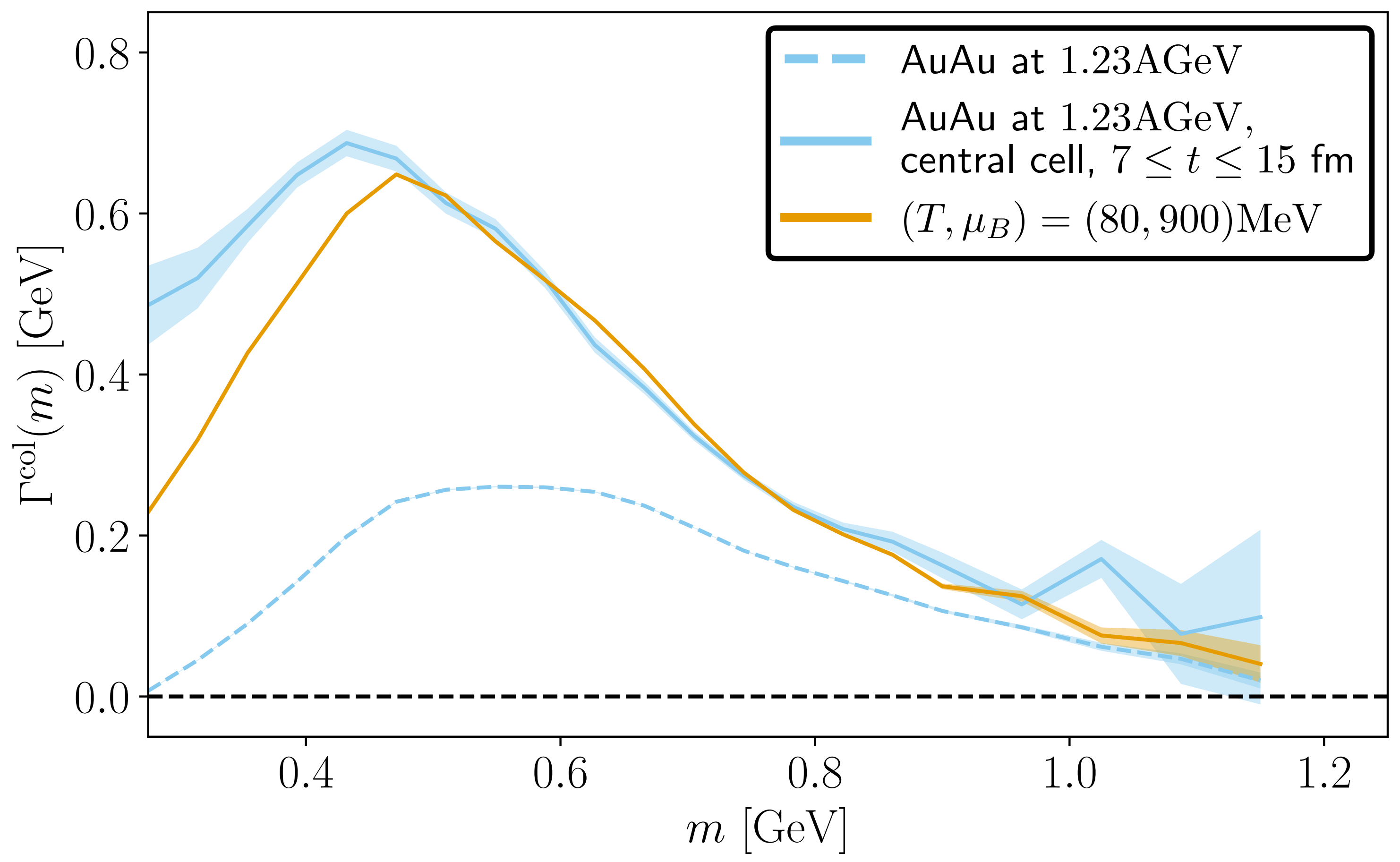
- No broadening at hadronic threshhold $m = m_{2\pi}$ (time-dependence)
- Large system ⇒ larger width
- High beam energy ⇒ short-lived medium ⇒ smaller width

⇓

Universal dependence on hadron density



Non-equilibrium effects



- Spacetime region of a HIC in apparent thermal equilibrium
- $\Gamma^{\text{eff}}_{\text{Au+Au}}(T, \mu_B) \neq \Gamma^{\text{eff}}_{\text{gas}}(T, \mu_B)$
- Collision is baryon-rich ⇒ excess width in $m \leq 0.5$ GeV

Summary

- Quantified emergent collisional broadening in SMASH
- Similar qualitative behavior to full in-medium calculations
- Heavy-ion systems follow universal density curve
- Baryonic interactions enhance broadening in low mass range

HFHF
CRC-TR 211 Strong-interaction matter under extreme conditions
smash
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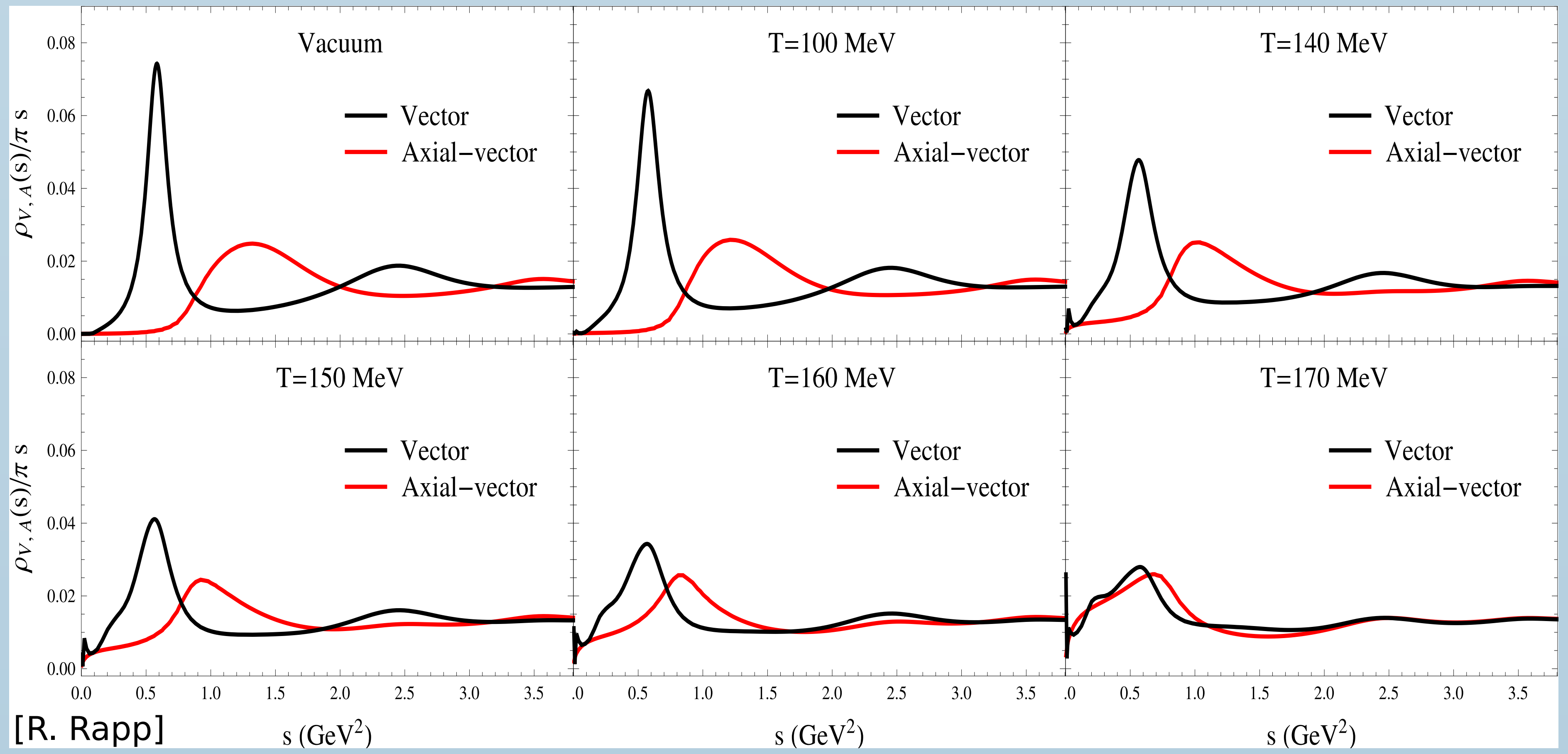
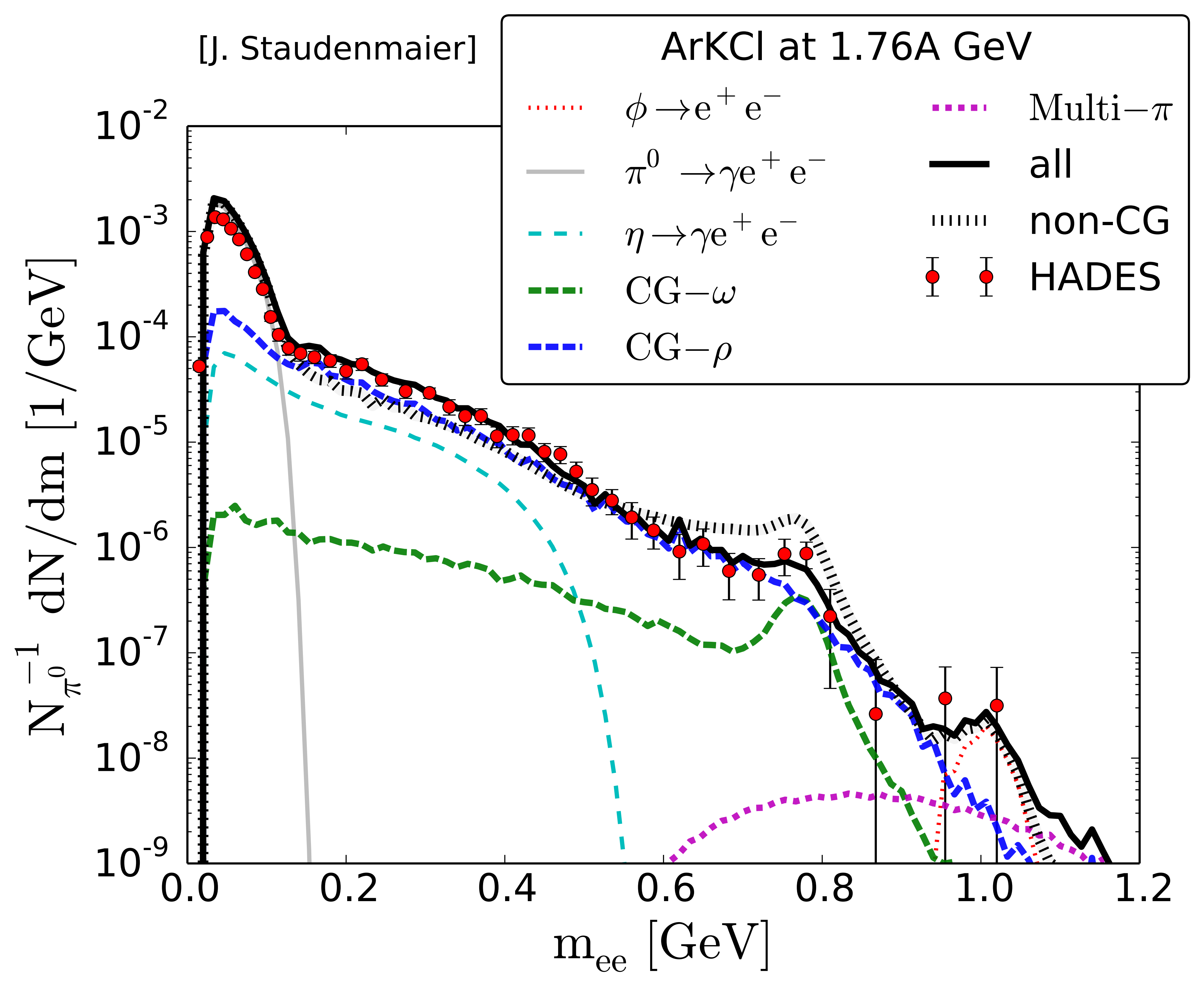
- In a hot or dense medium, the spectral functions of chiral partners are expected to become degenerate. This signals a partial **restoration of chiral symmetry**.
- Such *in-medium* modification are reflected in the invariant mass distribution of the resonance decay products. Particularly, the **dileptons** in heavy-ion collisions are useful probes as they do not interact strongly with the medium after emission.
- Within SMASH, the resonances follow **vacuum properties** a priori:

$$\Gamma^{\text{vac}}(m) = \Gamma_{\rho\to\pi\pi}(m) + \Gamma_{\rho\to l^+l^-}(m)$$

$$\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi}\frac{m^2\Gamma^{\text{vac}}(m)}{(m^2-M_0^2)^2+m^2\Gamma^{\text{vac}}(m)^2}$$



[R. Rapp]



[J. Staudenmaier]

- The relevant consequence of surrounding the ρ-meson in a hot/dense medium is the addition of inelastic collisions where it is **absorbed before decaying**. This shortens its lifetime and hence increases its effective width, which is known as **collisional broadening**.
- The **effective width** in SMASH is defined as

$$\Gamma^{\text{eff}} = \frac{1}{\langle\tau\rangle} = \left\langle\frac{\gamma}{t_f - t_i}\right\rangle,$$

which can be computed differentially in bins of mass, density and so on.

- The collisional broadening is quantified by the collisional width $\Gamma^{\text{col}} = \Gamma^{\text{eff}} - \Gamma^{\text{vac}}$.
- The **dynamic** spectral function correspondent to these collisional modifications is given in the fashion as the vacuum one:

$$\mathcal{A}^{\text{dyn}}(m) = \frac{2\mathcal{N}'}{\pi}\frac{m^2\Gamma^{\text{eff}}(m)}{(m^2-M_0^2)^2+m^2\Gamma^{\text{eff}}(m)^2}$$

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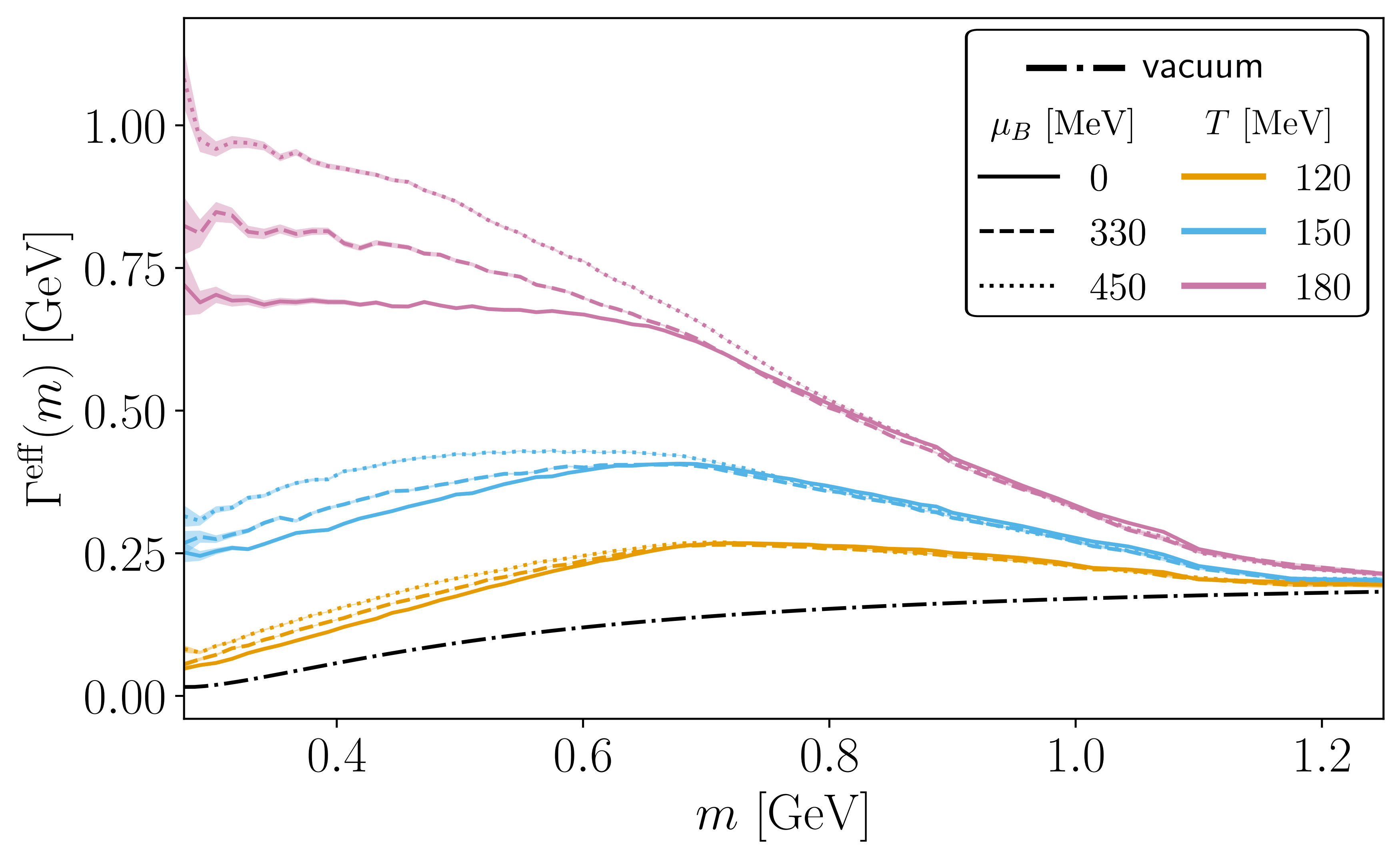
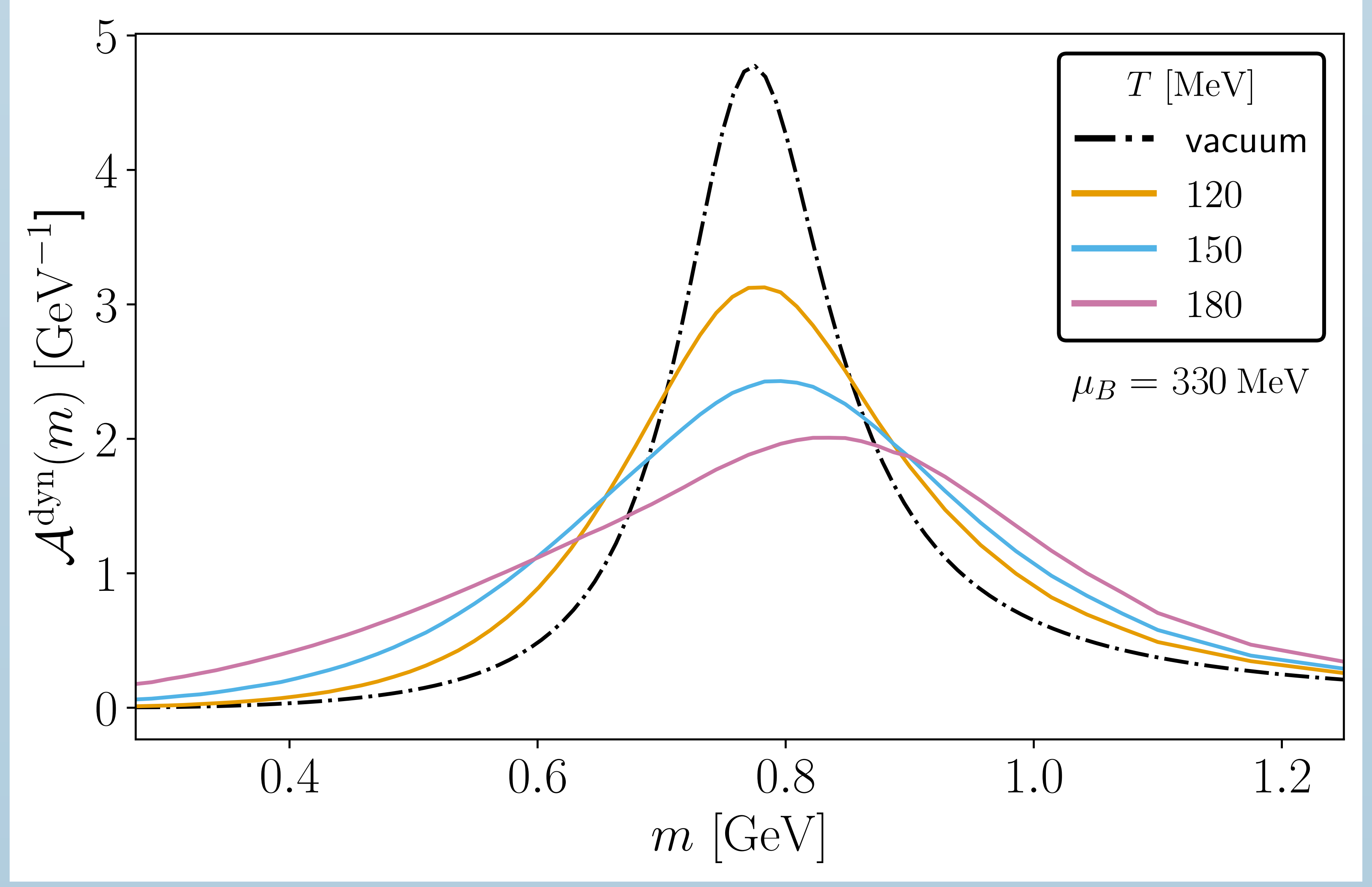
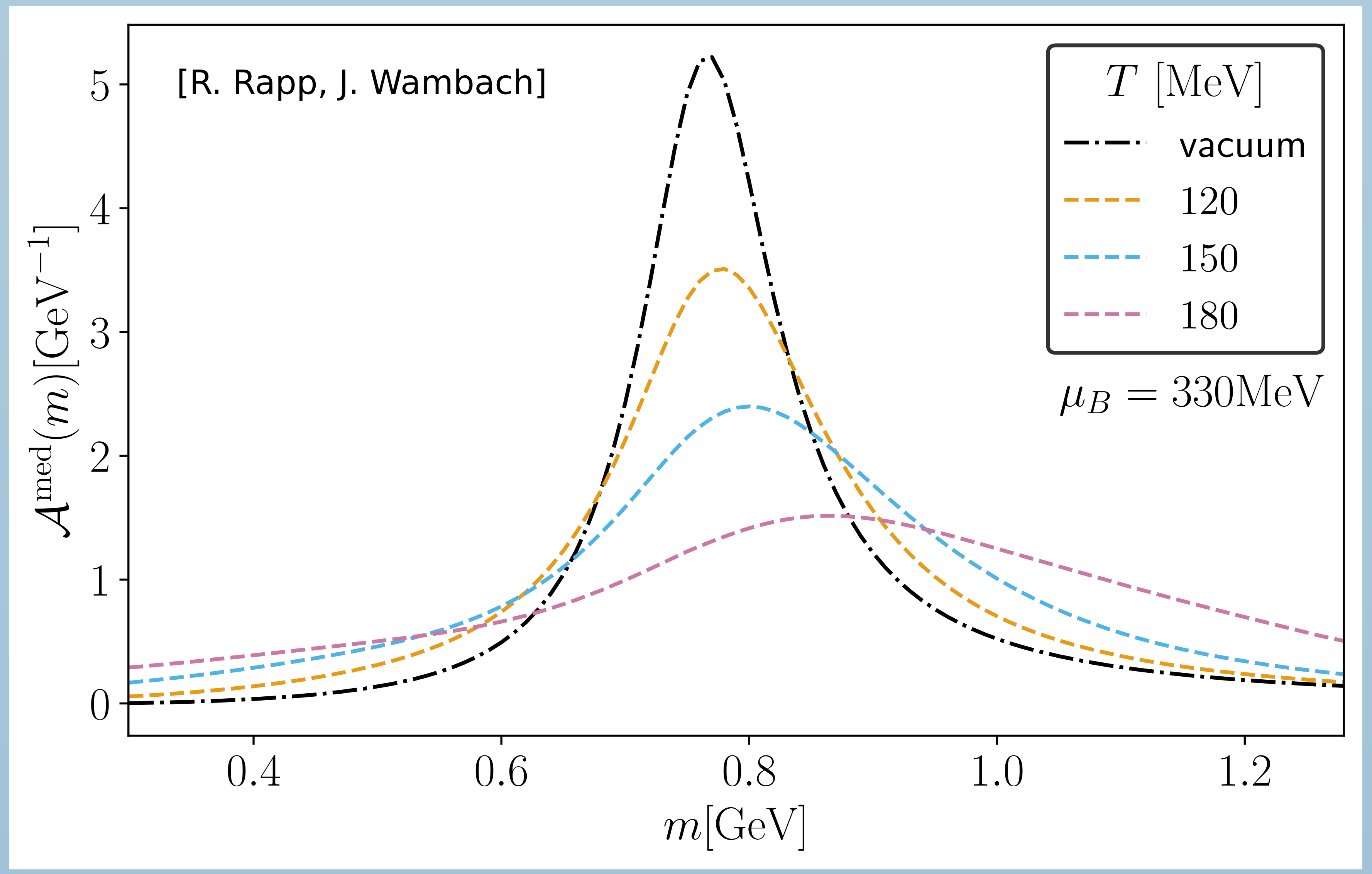


- High masses display little to no broadening, while low masses easily absorbed by the medium.
- Changes in T affect whole mass range, but increasing μ_B only broadens the LMR $m \leq M_0 = 0.776\ \mathrm{GeV}$.

SMASH



full in-medium model



- **Qualitatively**, the collisional broadening gives a similar spectral function to full in-medium calculations: the distribution melts and a slight increase in the peak mass happens at larger temperatures.
- Differences come from the *a priori* vacuum handling of hadrons, for which the cross-sections are tuned. However, the basic collisional broadening does not take into account the medium effects to **non-tree-level interactions**.
- Another difference is in the treatment of the intermediate ρ, implemented as the mediator between quasi-elastic channels like $\pi\pi \to \rho \to \pi\pi$ and Dalitz decays such as $N^*(1520) \to \rho N \to e^+e^-N$.

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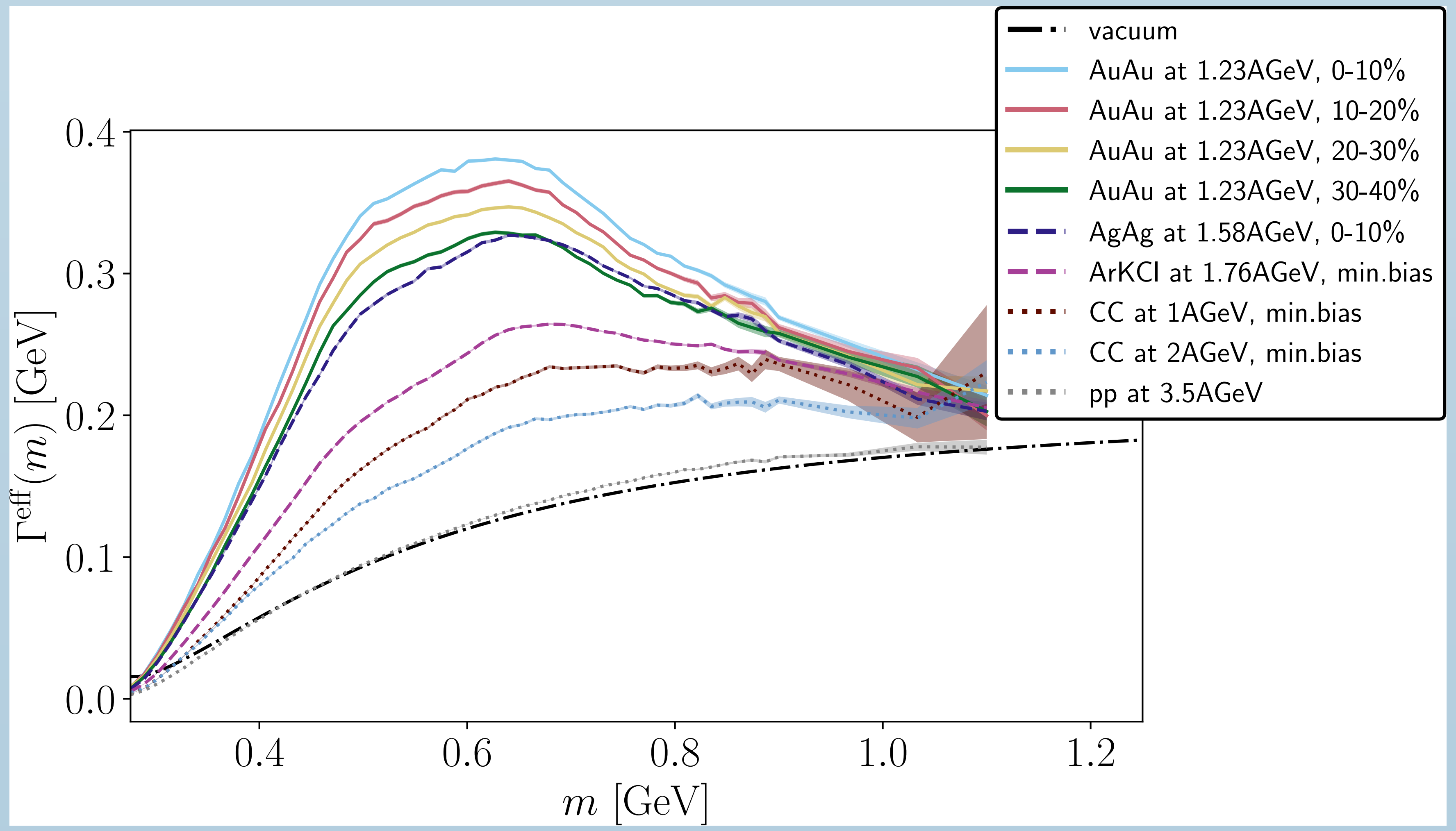
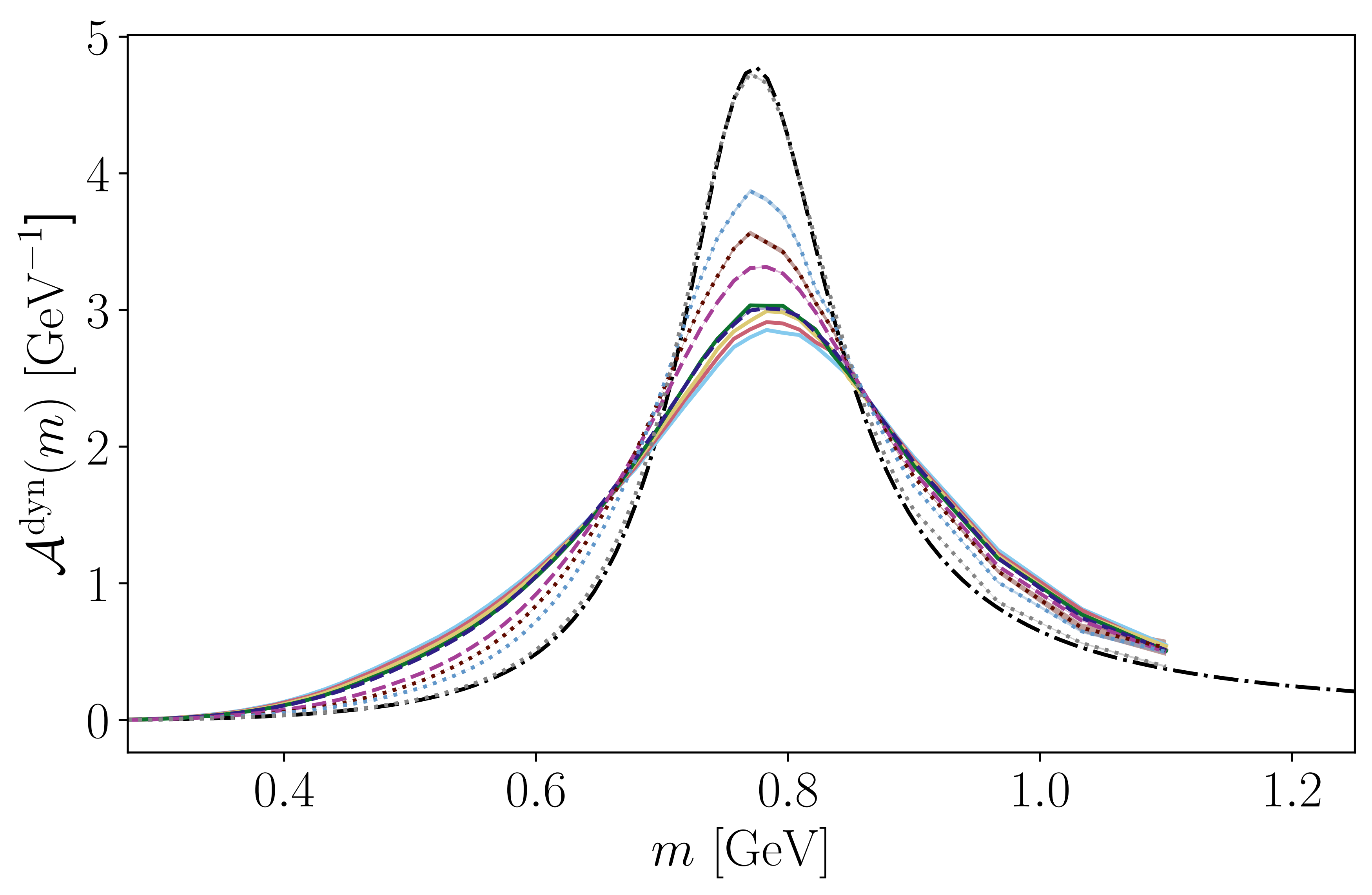




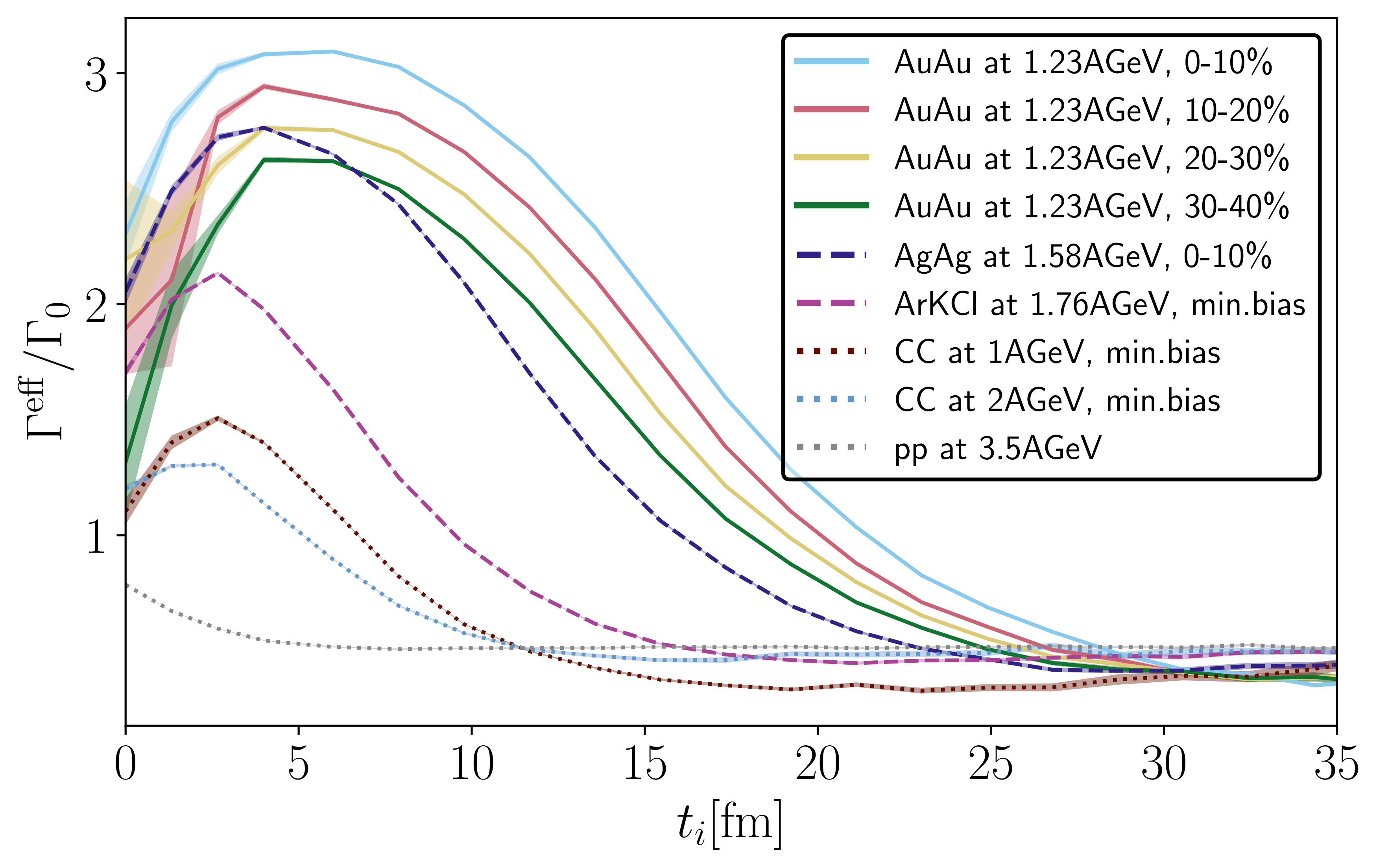
- **Time dependence:** Lower masses are mostly produced in the later stages of the collision as the energy available is low. At that point, the system is already **dilute** and hence no broadening emerges.

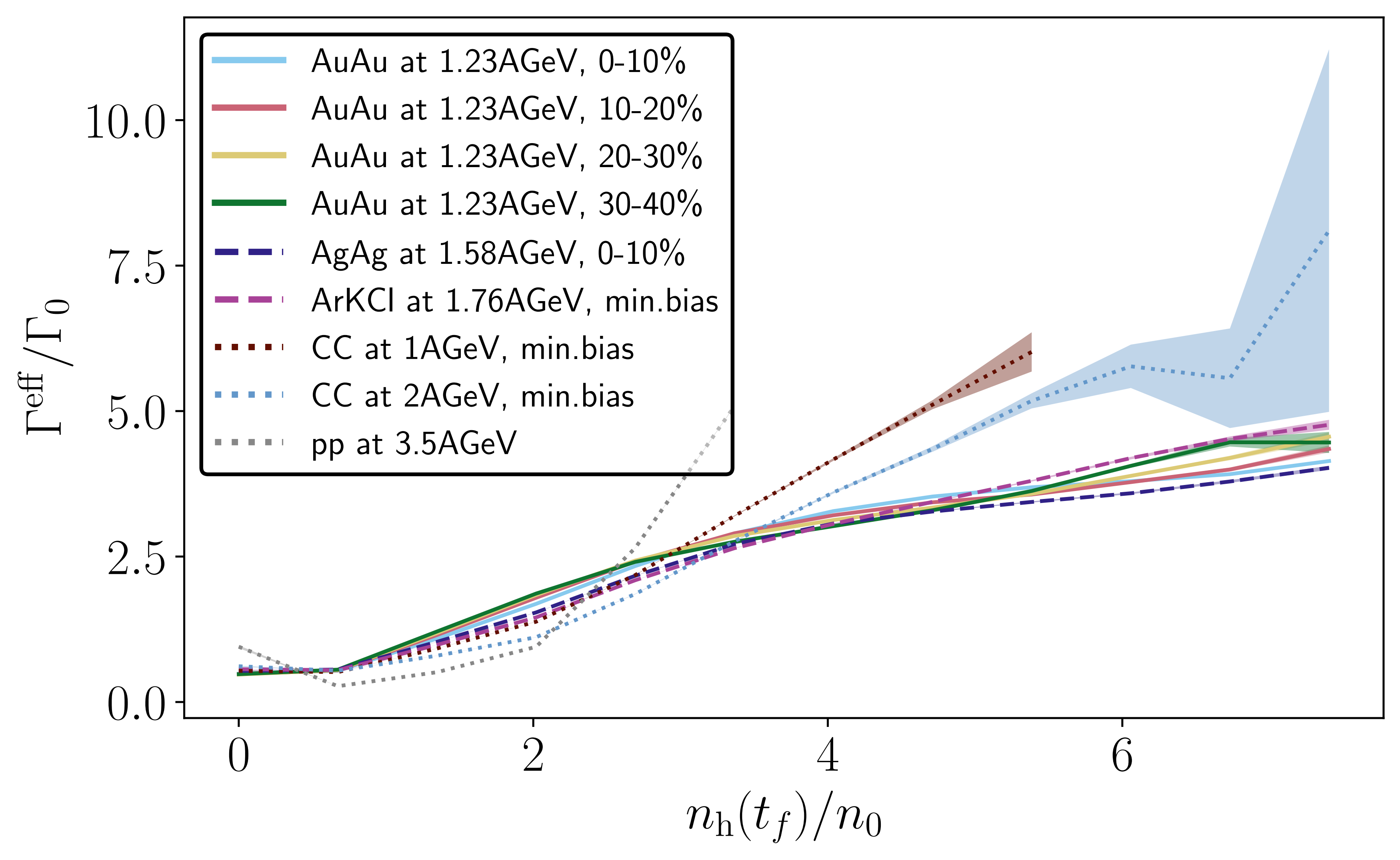
- **System size dependence:** pp collisions have no medium, so $\Gamma^{\rm eff}_{\rm pp} \sim \Gamma^{\rm vac}_{\rm pp}$, and AuAu collisions have a large width that diminishes towards peripheral events.

- **Beam energy dependence:** CC at $1\ \mathrm{GeV}$ is broader than at $2\ \mathrm{GeV}$, because the higher beam energy spreads more the same nuclei, leaving behind a shorter-lived medium to absorb ρ-mesons.

- There is an interplay between size and beam energy in the systems 30-40% AuAu at $1.23\ \mathrm{GeV}$ and 0-10% AgAg at $1.58\ \mathrm{GeV}$. They have a similar broadening, even though the numbers of participants are 90 and 130, respectively, but the medium dies faster in the latter.

- Previous points explained by the **universal density dependence** in HICs, reminiscent of $\Gamma^{\rm coll} \sim \gamma n \langle v\sigma^{\rm tot}_{NN}\rangle$. Deviations from this curve follow from numerical artifacts in determinating densities in small systems.





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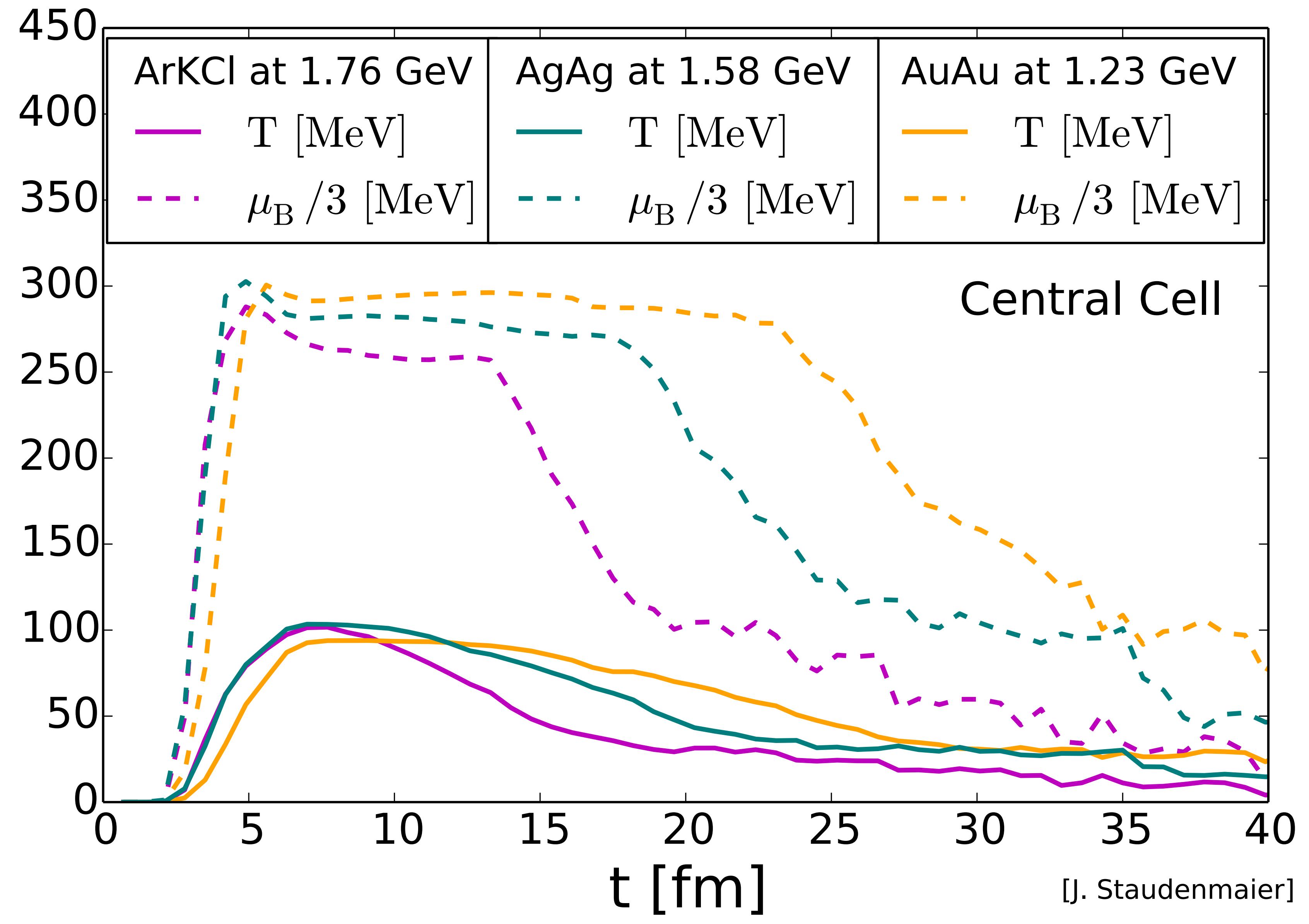

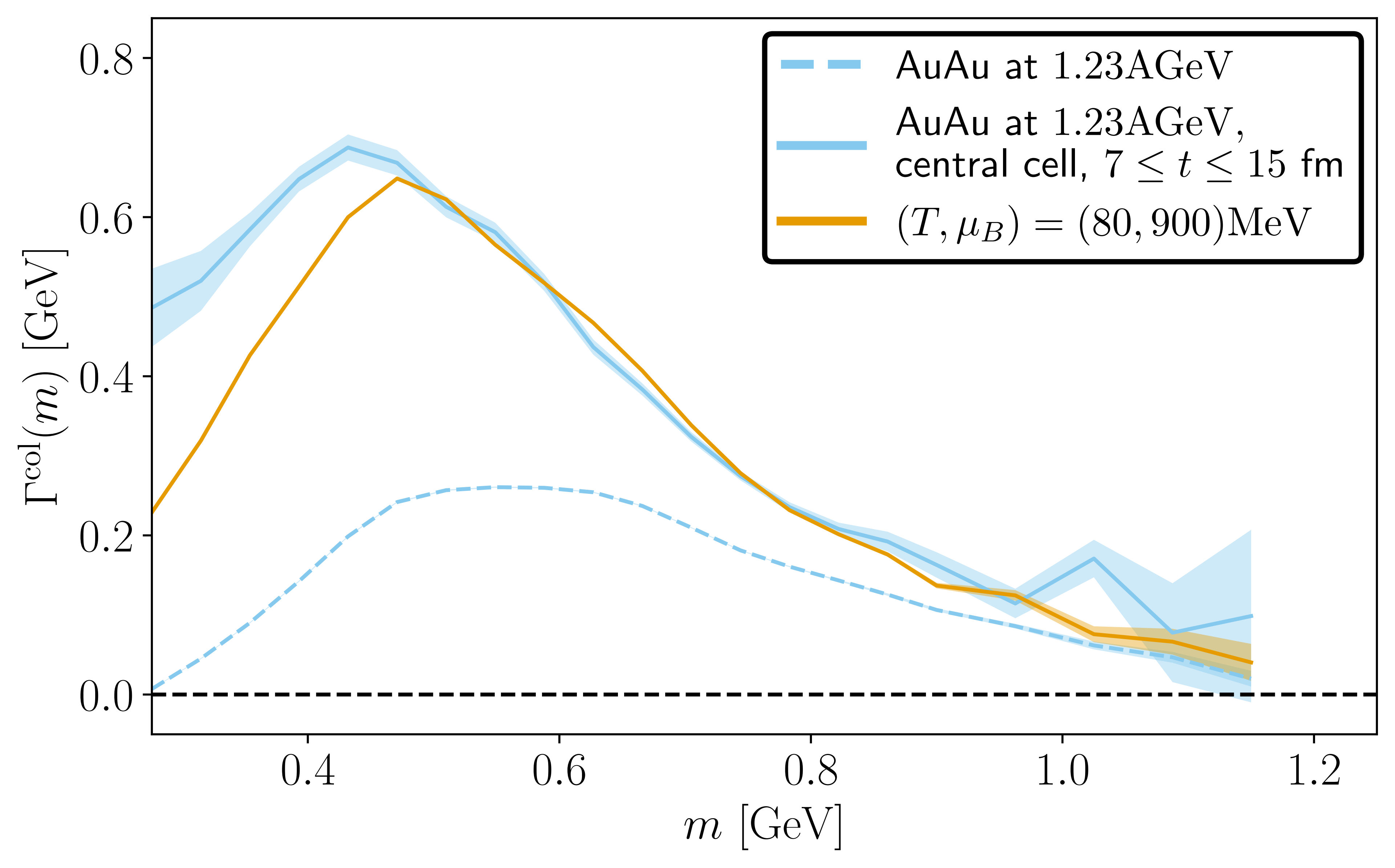

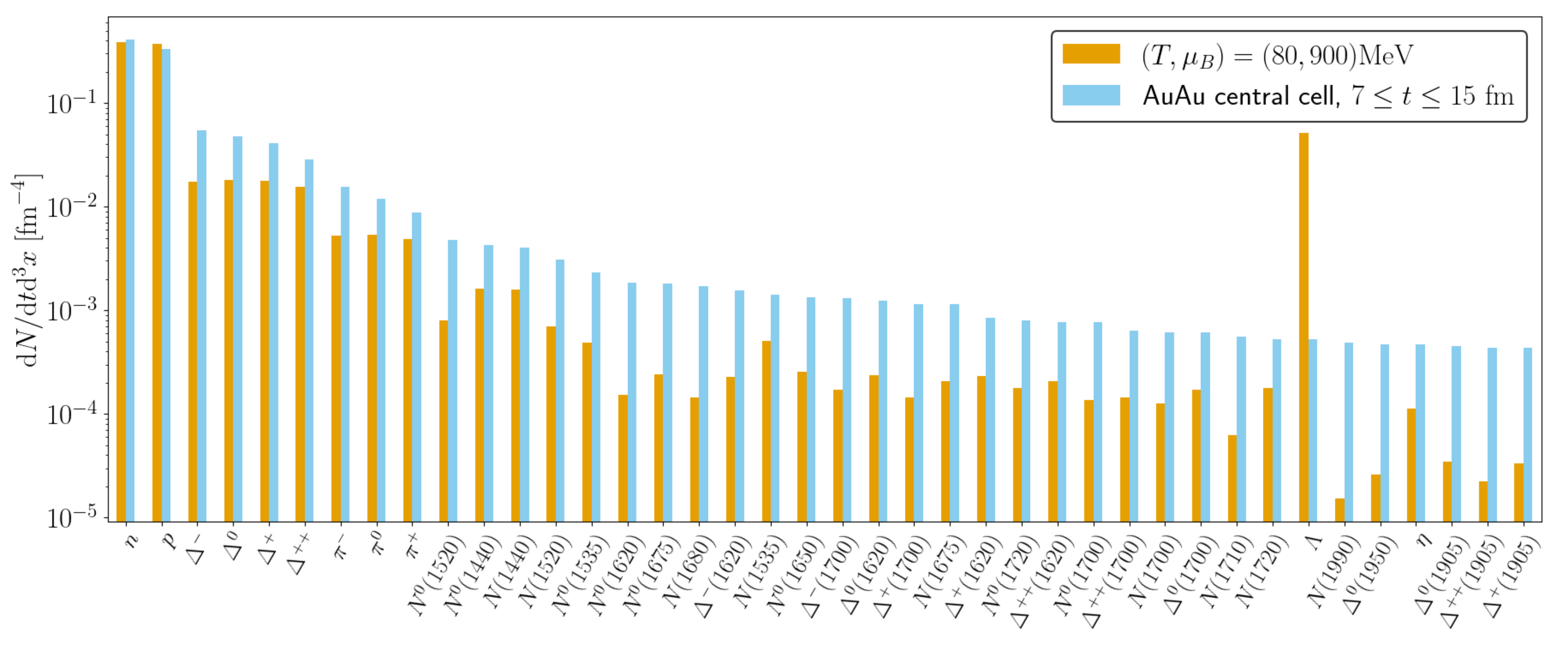

- In the central cell of a AuAu collision at $E_{\mathrm{kin}} = 1.23\mathrm{GeV}$, there is a time interval in which the temperature and chemical potential are **constant**.
- The broadening in this region is much higher than the full phase-space average.
- Compared to a hadron gas with the same (T, μ_B), the width in this region is higher for $m \lesssim 0.5$ GeV.
- This is due to the different **chemical composition** of the systems: a nuclear collision is much more baryon-rich, and baryons predominate in the low-mass range interactions.