FIAS Frankfurt Institute for Advanced Studies

CRC–TR 211 Strong-interaction matter under extreme conditions

Effective spectral functions via lifetime analysis

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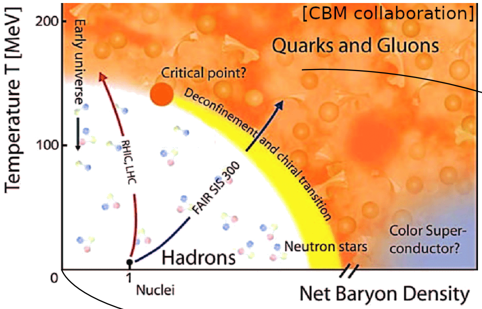
in collaboration with

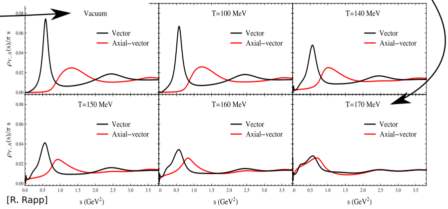
Jan Staudenmaier, Hannah Elfner

HFHF Retreat 2022, Castiglione della Pescaia

HFHF Helmholtz Forschungsakademie Hessen für FAIR

Motivation - Theory



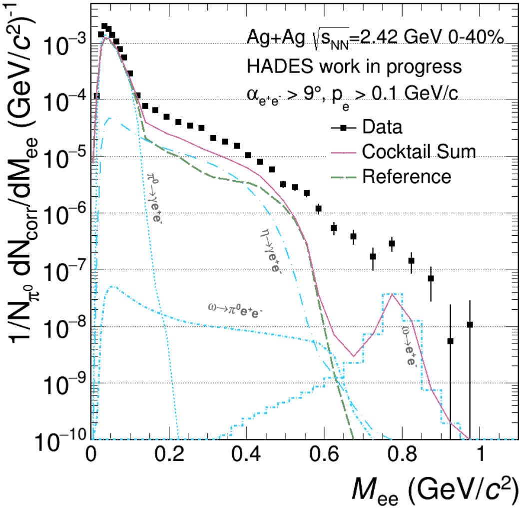


Chiral pairs degenerate

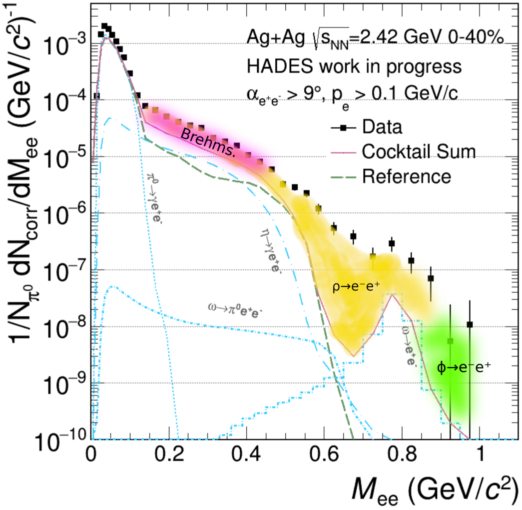
Vector : $\rho(770)$

Axial : $a_1(1260)$

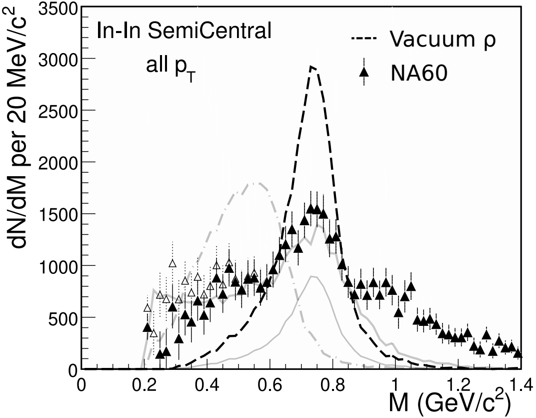
Motivation - Experiment



Motivation - Experiment



Motivation - Experiment



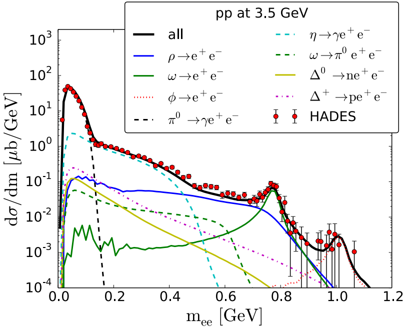
(Not the same experiment, but behavior is similar)

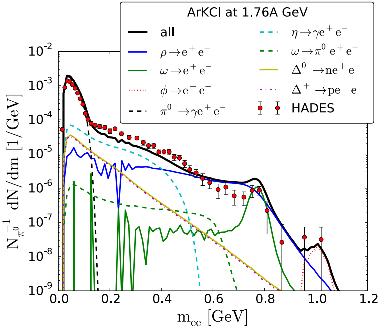
Medium modifications

Different approaches:

1. Vacuum spectral functions with *dynamic* broadening: UrQMD [S. Endres et al.: PRC 92.1 (2015)] and SMASH cascades [J. Weil et al.: PRC 94 (2016)]
2. Transport with *collisional* broadening dependent on local density: GiBUU [A.B. Larionov et al.: PRC 102.6 (2020)] and (P)HSD [E.L. Bratkovskaya et al.: Nuc. Phys. A 807 (2008)]
3. Full in-medium modifications: Rapp-Wambach model [H. van Hees and R. Rapp: Eur. Phys. J. A6, 415–420 (1999)] and FRG [R.A. Tripolt et al.: PRD 104 (2021)];

SMASH dileptons

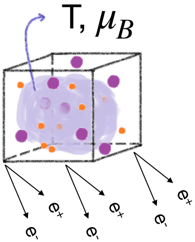




[J. Staudenmaier et al.: PRC 98 (2018)]

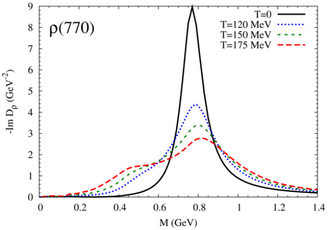
Dynamical broadening insufficient!

SMASH dileptons



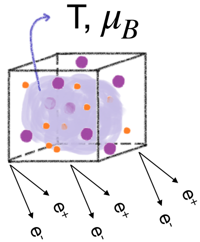
[by S.Endres]

$\Longrightarrow$



[Nuc.Phys. A 806 (2008)]

SMASH dileptons



[by S.Endres]

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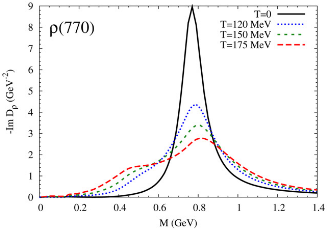
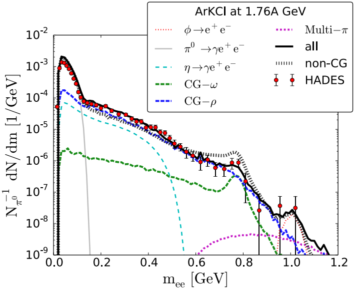


[Nuc.Phys. A 806 (2008)]



Goal

Quantify dynamic collisional broadening of ρ mesons

[2206.15166]

Medium modifications

Addition of inelastic interactions where the ρ is absorbed

Vacuum

$$\rho^{\pm} \to \pi^0 \pi^{\mp}$$
$$\rho^0 \to \pi^+ \pi^-$$
$$\rho^0 \to l^+ l^-$$

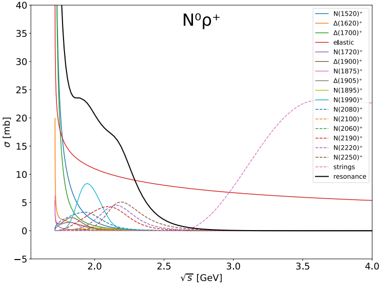
Medium modifications

Addition of inelastic interactions where the ρ is absorbed

Vacuum	Medium
$\rho^{\pm} \to \pi^0\pi^{\mp}$	$\rho N \to N^*, \Delta, \ldots$
$\rho^0 \to \pi^+\pi^-$	$\rho K \to K^*$
$\rho^0 \to l^+l^-$	$\rho\pi \to \omega, \phi, f_1, a_1, \ldots$

Medium modifications

Addition of inelastic interactions where the ρ is absorbed



Medium

$$\rho N \to N^*, \Delta, \ldots$$
$$\rho K \to K^*$$
$$\rho\pi \to \omega, \phi, f_1, a_1, \ldots$$

Medium modifications

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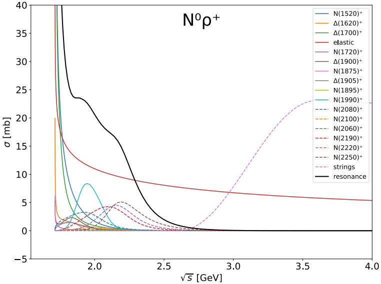


Medium

$$\rho N \to N^*, \Delta, \ldots$$
$$\rho K \to K^*$$
$$\rho \pi \to \omega, \phi, f_1, a_1, \ldots$$

Collisional broadening: *Shortening the average lifetime of resonances due to absorptions by a medium*

On-shell treatment

Resonances are handled with vacuum properties:

- Decay width

$$\Gamma^{\mathrm{vac}}(m) = \Gamma_{\rho\to\pi\pi}(m) + \Gamma_{\rho\to ll}(m)$$

- Breit-Wigner for mass sampling

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

No *a priori* knowledge of medium!

On-shell treatment

Resonances are handled with vacuum properties:

- Decay width

$$\Gamma^{\text{vac}}(m) = \Gamma_{\rho\to\pi\pi}(m) + \cancel{\Gamma_{\rho\to ll}(m)} \xrightarrow{} m \geq m_{2\pi}$$

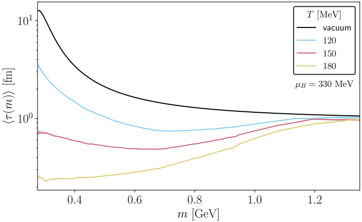
- Breit-Wigner for mass sampling

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

No *a priori* knowledge of medium!

An effective description

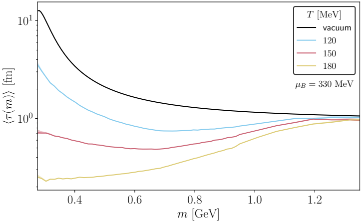
From the interaction history:



Effective width

$$\Gamma^{\mathrm{eff}}(x) = \frac{1}{\langle \tau \rangle_x} = \left\langle \frac{\gamma}{t_f - t_i} \right\rangle_x$$

An effective description



From the interaction history:

<u>Effective width</u>

$$\Gamma^{\text{eff}}(x) = \frac{1}{\langle\tau\rangle_x} = \left\langle \frac{\gamma}{t_f - t_i} \right\rangle_x$$

$\swarrow$ $\searrow$

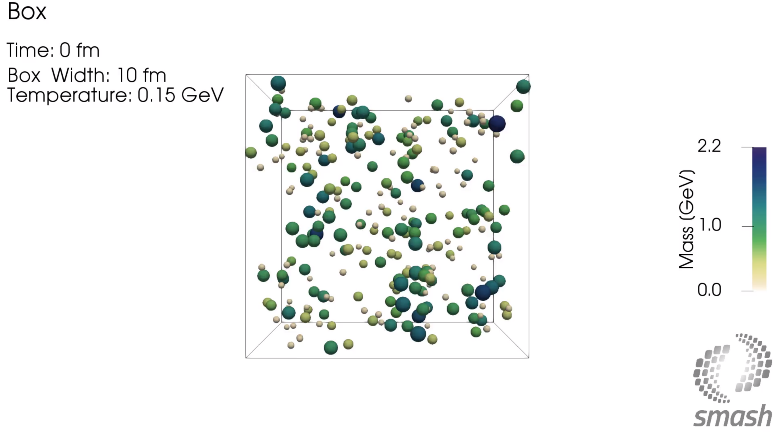
<u>Collisional width</u>

$$\Gamma^{\text{col}} = \Gamma^{\text{eff}} - \Gamma^{\text{vac}}$$

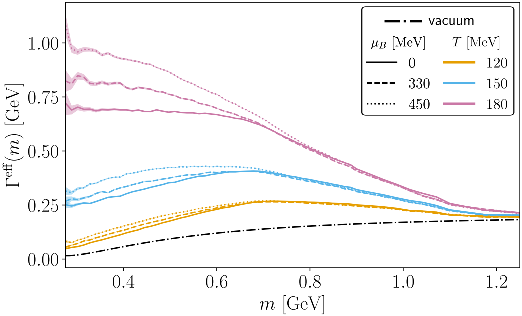
<u>Dynamic spectral function</u>

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

Thermodynamic behavior

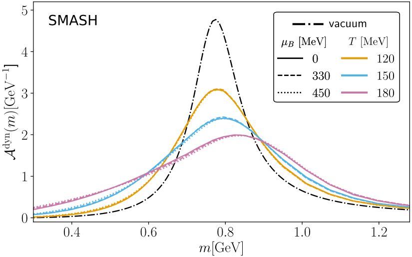


Thermodynamic behavior

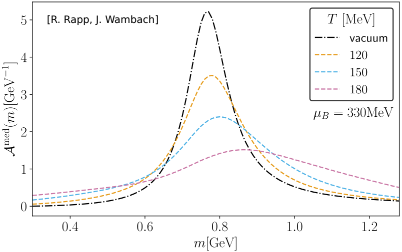


- High-mass ρ suffers little broadening ($\sigma_{2\to1} \sim 1/M^4$)
- Lower masses are mostly absorbed
- Medium temperature changes whole spectrum
- Baryochemical potential affects only $m \leq M_0$ GeV

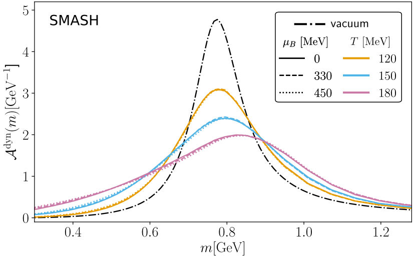
SMASH



full in-medium model



SMASH



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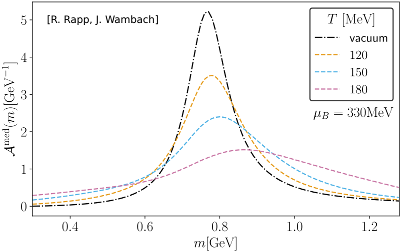
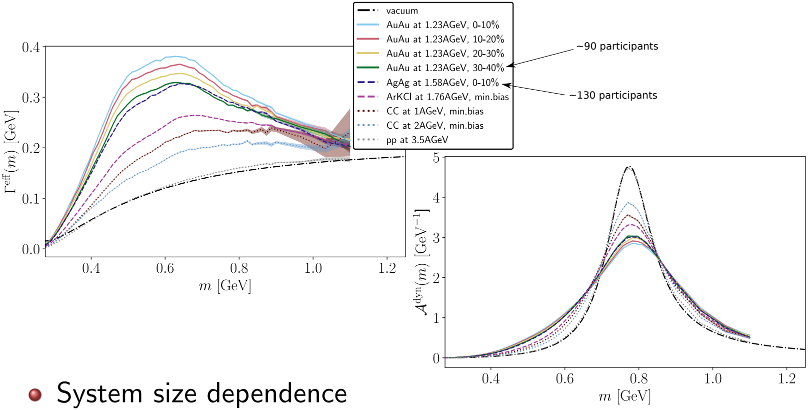


- Melting of ρ ✅
- Positive shift of peak mass ✅
- Differences: distinct processes present in SMASH ❌ (intermediate resonances, no self-energy, ...)

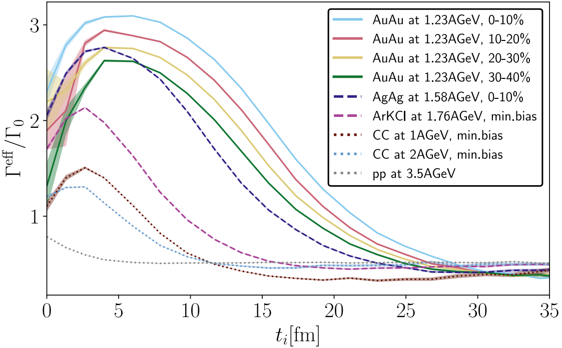
Nuclear collisions

Nuclear collisions



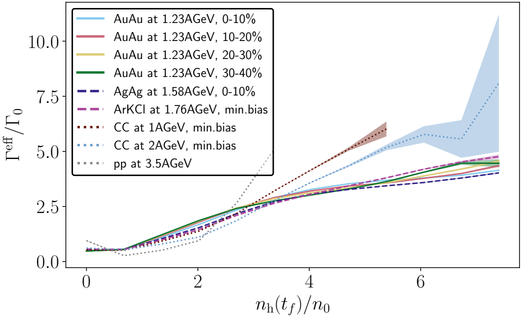
- System size dependence
- Higher energies disperse the medium
- No broadening at hadronic threshold $m = m_{2\pi}$

Nuclear collisions



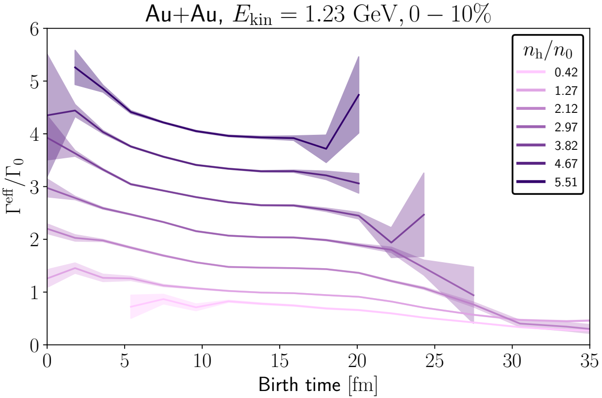
- "Cronometer" for the medium
- Highlights difference between AuAu 1.23AGeV 30-40% and AgAg 1.58AGeV 0-10%

Nuclear collisions



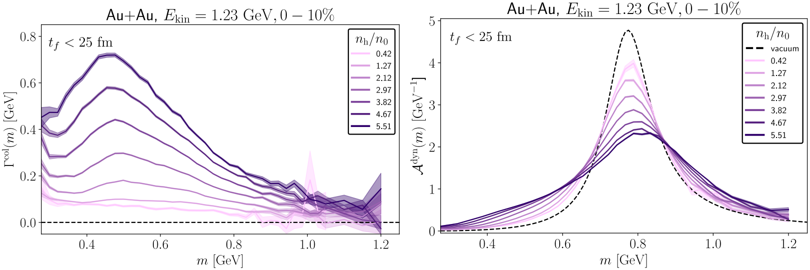
- Near universal dependence on the hadron density $n_{\rm h}$
- Deviations for high densities in small systems
- Off-shell models: $\Gamma^{\rm coll} = \gamma n_N \left\langle v\sigma_{VN}^{\rm tot}\right\rangle$ (GiBUU, HSD)

Nuclear collisions



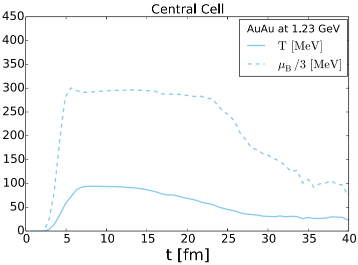
- No dense regions after $t \approx 25$ fm
- Almost constant (chemical composition changes)

Nuclear collisions

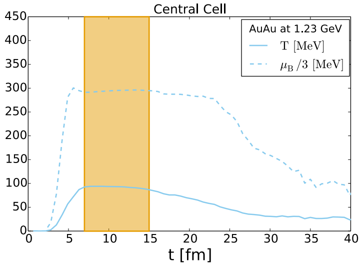


- Peak in $m \approx 0.5$ GeV appears at high densities
- $\mathcal{A}^{\rm dyn}$ resembles equilibrated gas

Non-equilibrium effects

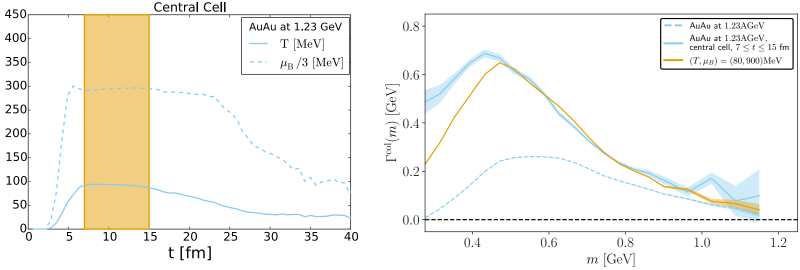


Non-equilibrium effects



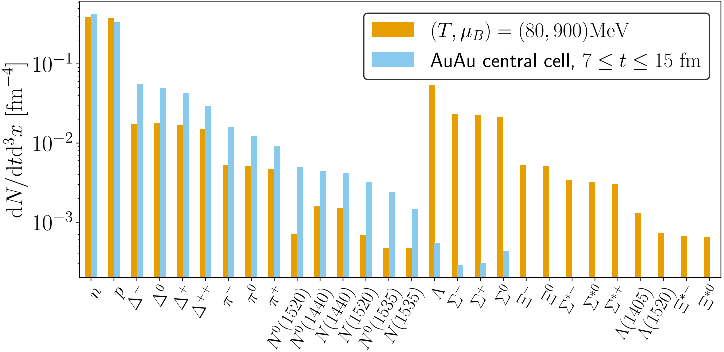
- Spacetime region of a collision where equilibrium is apparent
- Run a box w/ same thermodynamic conditions

Non-equilibrium effects



- Spacetime region of a collision where equilibrium is apparent
- Run a box w/ same thermodynamic conditions
- Restriction to this region makes $\Gamma^{\text{col}}(m_{2\pi}) \neq 0$
- Similar broadening, excess for small masses

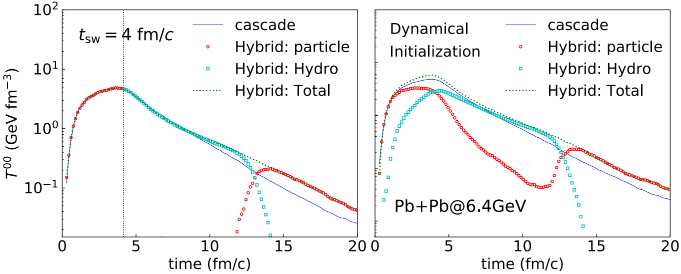
Non-equilibrium effects



- Equilibrium populated also by strange particles ($N \propto e^{-m/T}$)
- Collision system has more particles that can absorb a ρ-meson

Future projects

- Dynamic initialization of SMASH+vHLLE hybrid: intermediate beam energies
- Direct connection to full in-medium models (no CG)
- Electromagnetic signals of 1st order PT



[Akamatsu et al.: PRC 98.2 (2018)]

Summary

- In SMASH: Vacuum properties $\xrightarrow{\text{medium}}$ collisional broadening
- Equilibrium $\mathcal{A}^{\text{dyn}}$ similar to full in-medium calculations
- Collision systems: clear setup dependence (mass number, centrality, beam energy), universality in density
- Effective width works as a cronometer for medium duration
- Out-of-equilibrium may increase collisional broadening

Summary

- In SMASH: Vacuum properties $\xrightarrow{\text{medium}}$ collisional broadening
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- Collision systems: clear setup dependence (mass number, centrality, beam energy), universality in density
- Effective width works as a cronometer for medium duration
- Out-of-equilibrium may increase collisional broadening

T.Hanks for the attention!

BACKUP SLIDES

Decay widths

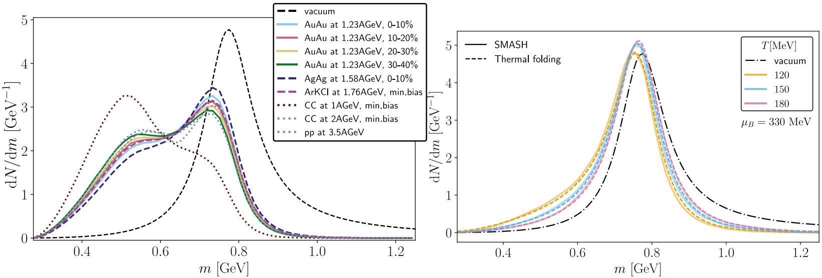
Following Manley et al.,

$$\Gamma^{\text{vac}}_{\rho\to\pi\pi}(m) = \Gamma^0 \frac{M_0}{m} \left(\frac{\frac{1}{4}m^2 - m_\pi^2}{\frac{1}{4}M_0^2 - m_\pi^2} \right)^{3/2} \left(\frac{\frac{1}{4}M_0^2 - m_\pi^2 + \Lambda^2}{\frac{1}{4}M_0^2 - m_\pi^2 + \Lambda^2} \right)$$

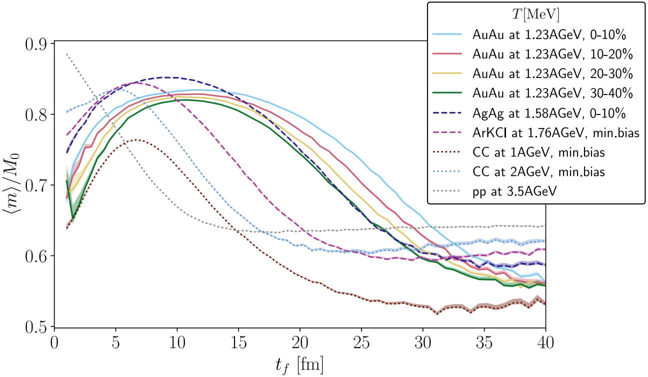
Under the *Vector Meson Dominance* model:

$$\Gamma^{\text{vac}}_{\rho\to ll}(m) = \Gamma^0_{\rho\to ll} \left(\frac{M_0}{m} \right)^3 \left(1 + \frac{2m_l^2}{m^2} \right) \sqrt{1 - \frac{4m_l^2}{m^2}}$$

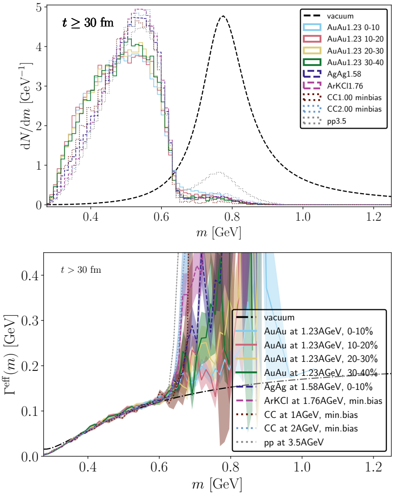
Produced ρ masses



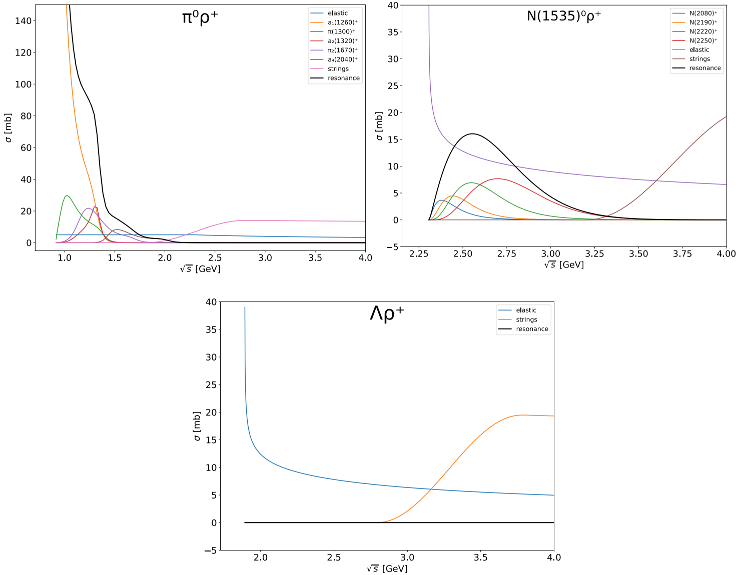
Evolution of average mass



Late stages of a collision



ρ-meson interactions



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