FIAS Frankfurt Institute for Advanced Studies

HFHF

Effective spectral functions via lifetime analysis

Renan Hirayama

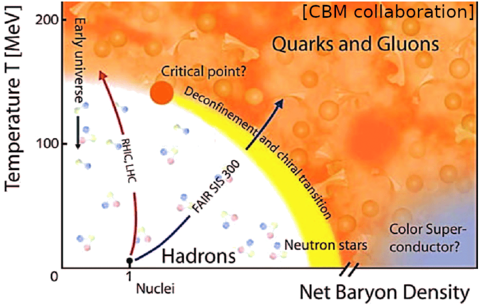
in collaboration with

Jan Staudenmaier, Hannah Elfner

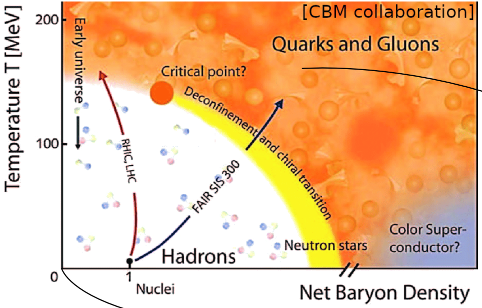
FIAS, Frankfurt am Main, Germany

2022, May 27

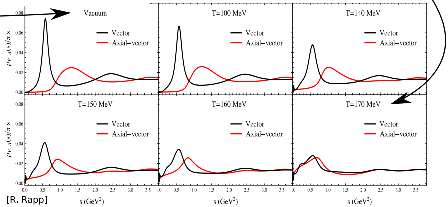
FAIRNESS


[CBM collaboration]
Quarks and Gluons
Critical point?
Deconfinement and chiral transition
Early universe
RHIC, LHC
FAIR SIS 300
Hadrons
Neutron stars
Color Super-
conductor?
Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density

Motivation - Theory

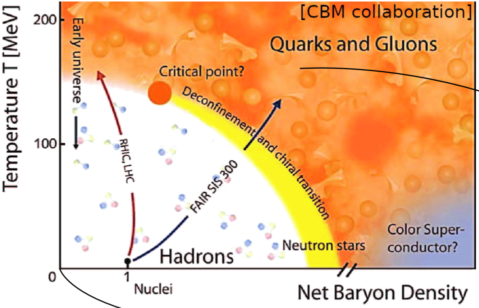


Chiral pairs degenerate



[R. Rapp]

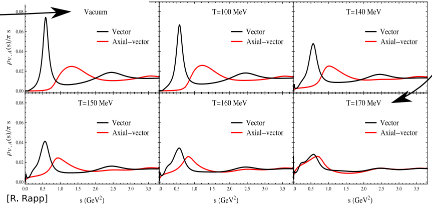
Motivation - Theory



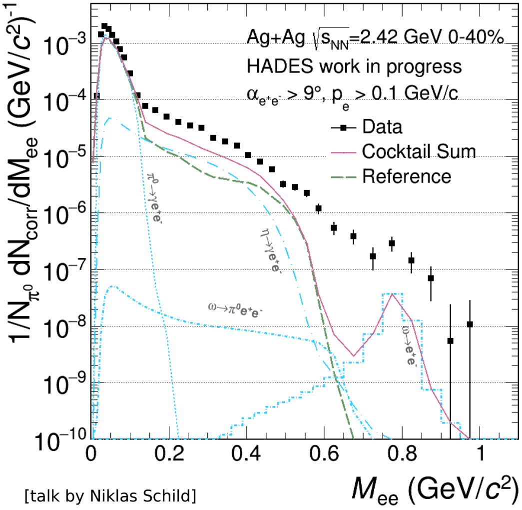
Chiral pairs degenerate

Vector : $\rho(770)$

Axial : $a_1(1260)$

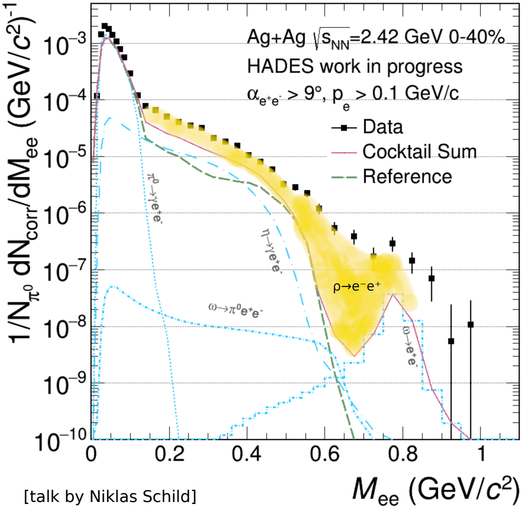


Motivation - Experiment



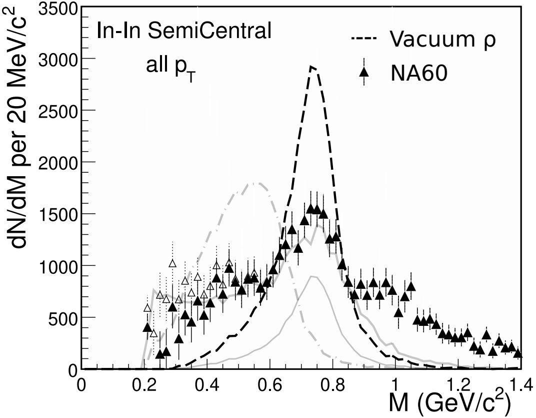
[talk by Niklas Schild]

Motivation - Experiment



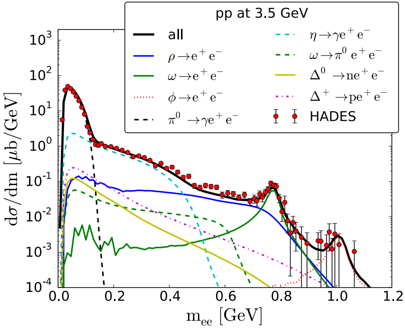
[talk by Niklas Schild]

Motivation - Experiment



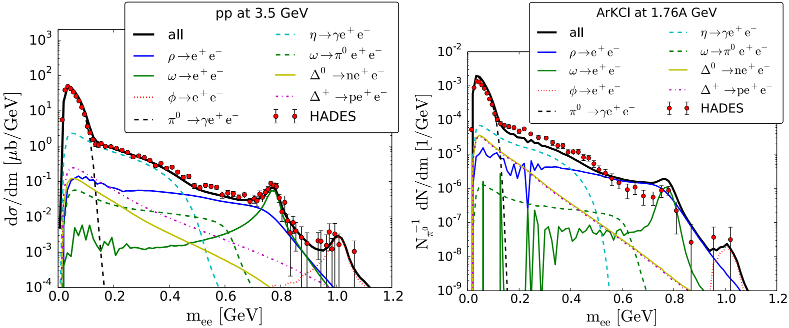
(Not the same experiment, but behavior is similar)

SMASH dileptons



[PRC 98, 054908 (2018)]

SMASH dileptons



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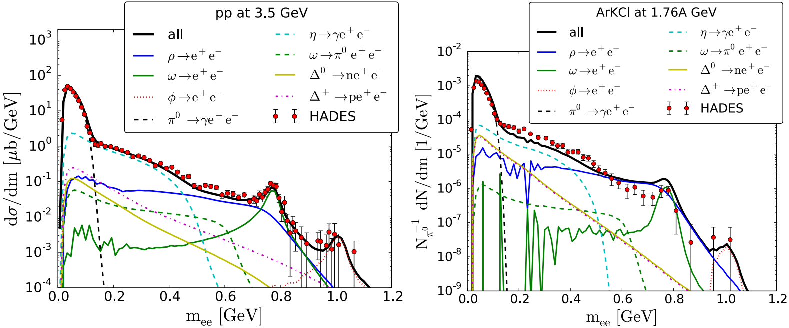
SMASH dileptons



[PRC 98, 054908 (2018)]

Goal: reconstruct the ρ-meson spectral function

Medium modifications

Addition of inelastic interactions where the ρ is absorbed

Vacuum

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

Medium modifications

Addition of inelastic interactions where the ρ is absorbed

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

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

Simulating **M**any **A**ccelerated
Strongly-interacting **H**adrons

Transport approach: the relativistic Boltzmann equation

$$p^{\mu}\partial_{\mu}f_i(x,p) + m_i F^{\alpha}\partial_{\alpha}^{p}f_i(x,p) = C_i^{\mathrm{coll}}$$

Simulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons

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- $f_i(x,p)$ realized as a test-particle (or more)
- F^α from MF potential

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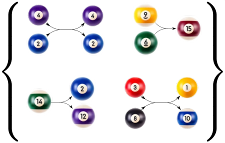
3D billiards
w/ extra steps



On-shell treatment

Resonances are handled with vacuum properties:

- Decay width (=rate of decay)

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

No *a priori* knowledge of medium!

On-shell treatment

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No *a priori* knowledge of medium!

On-shell treatment

Resonances are handled with vacuum properties:

- Decay width (=rate of decay)

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

- 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

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

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Effective width

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$\swarrow$

Collisional width

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

An effective description

From the interaction history:

Effective width

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

$\swarrow$ $\searrow$

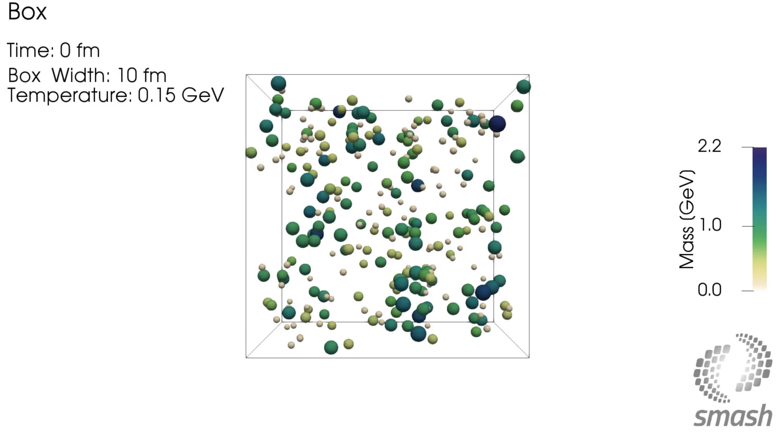
Collisional width

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

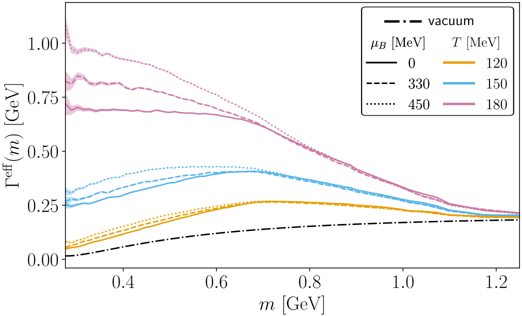
Dynamic spectral function

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

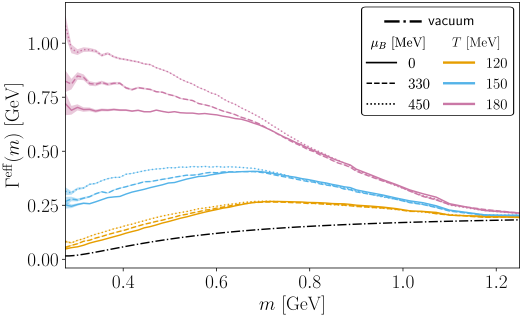
SMASH configuration: box



Thermodynamic behavior

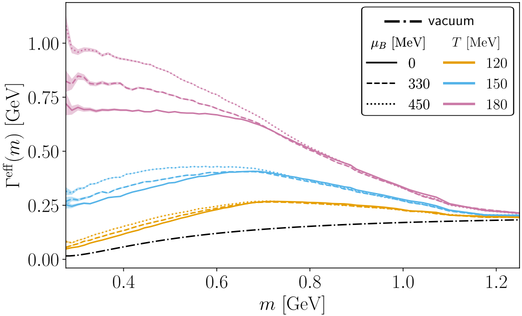


Thermodynamic behavior



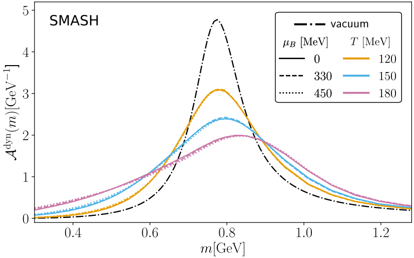
- High-mass ρ suffers little broadening (coupling$\sim 1/m^4$)
- Lower masses are mostly absorbed

Thermodynamic behavior

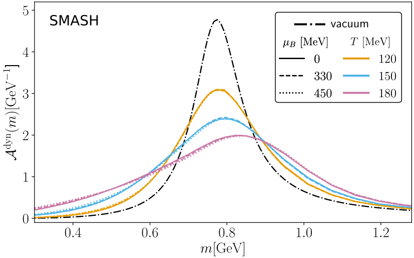


- High-mass ρ suffers little broadening (coupling$\sim 1/m^4$)
- Lower masses are mostly absorbed
- Medium temperature changes whole spectrum
- Baryo-chemical potential affects only $m \leq M_0$ GeV

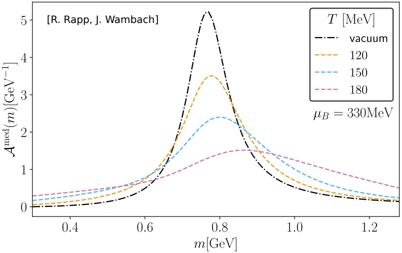
SMASH


SMASH
vacuum
μ_B [MeV]
T [MeV]
0
330
450
120
150
180
$\mathcal{A}^{\rm dyn}(m)[\rm GeV^{-1}]$
m[GeV]
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5

SMASH



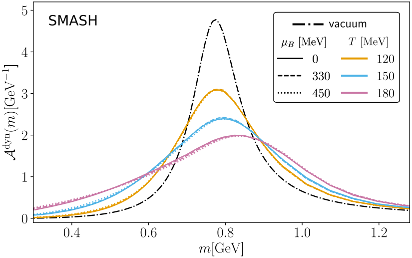
full in-medium model



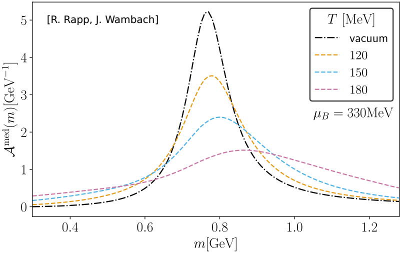
- Melting of ρ ✅
- Positive shift of peak mass ✅

Thermodynamic behavior

SMASH



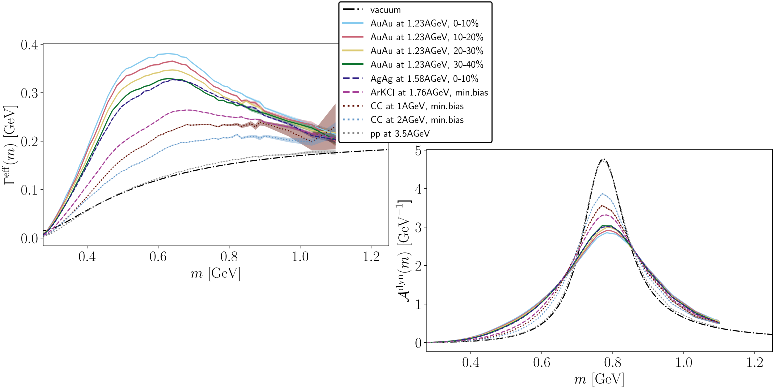
full in-medium model



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

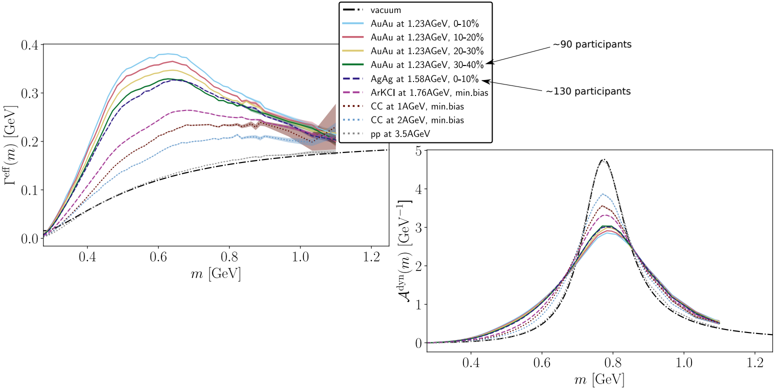
SMASH configuration: collider

Nuclear collisions



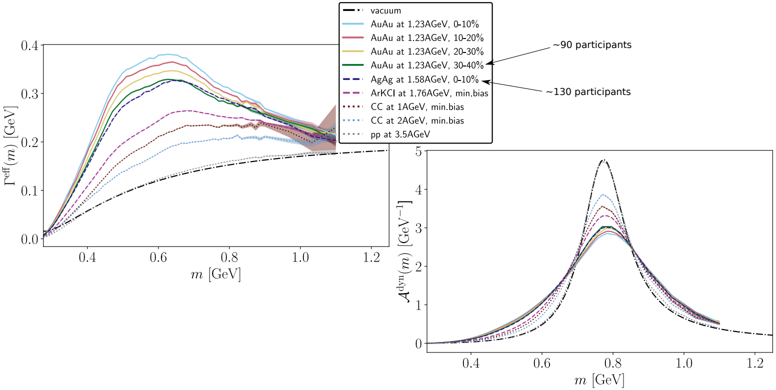
- System size dependence

Nuclear collisions



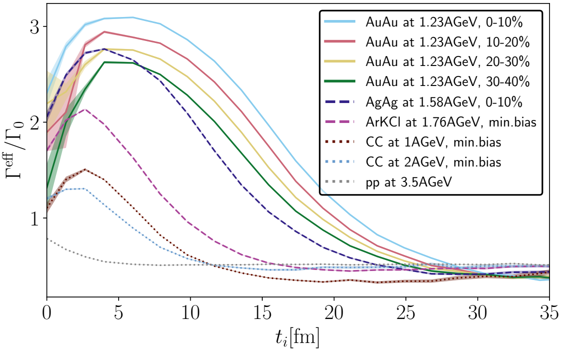
- System size dependence
- Higher energies disperse the medium

Nuclear collisions



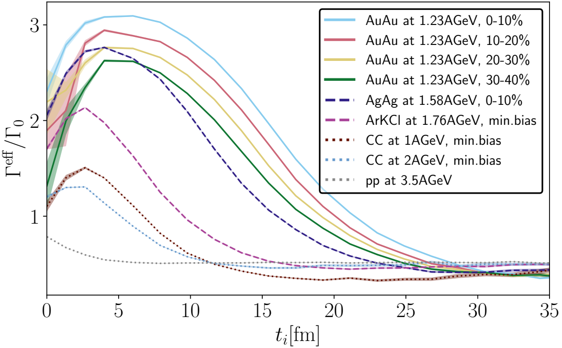
- System size dependence
- Higher energies disperse the medium
- No broadening at hadronic threshold $m = m_{2\pi}$

Nuclear collisions

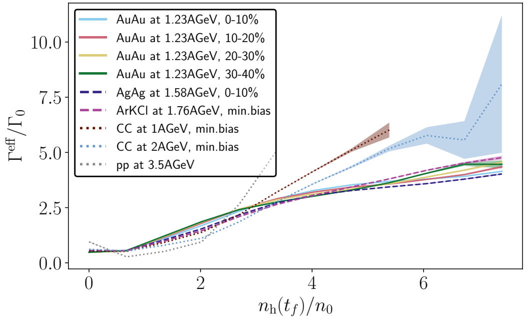


- Cronometer: how long does the medium last?

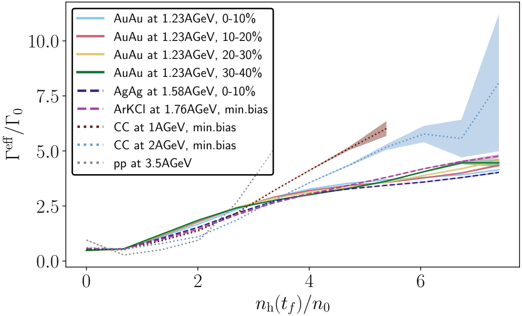
Nuclear collisions



- Cronometer: how long does the medium last?
- Highlights difference between AuAu 1.23AGeV 30-40% and AgAg 1.58AGeV 0-10%

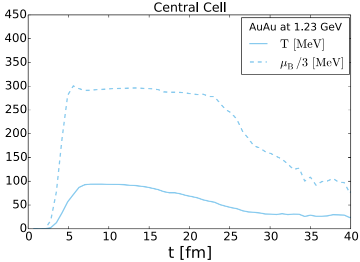


- Near universal dependence on the hadron density n_h
- Off-shell models: $\Gamma^{\mathrm{coll}} = \gamma n_N \left\langle v\sigma^{\mathrm{tot}}_{VN}\right\rangle$ (GiBUU, HSD)

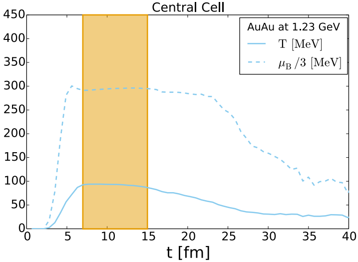


- Near universal dependence on the hadron density n_{h}
- Off-shell models: $\Gamma^{\text{coll}} = \gamma n_N \left\langle v\sigma_{VN}^{\text{tot}} \right\rangle$ (GiBUU, HSD)
- High densities in small systems: numerical artifacts

Non-equilibrium effects

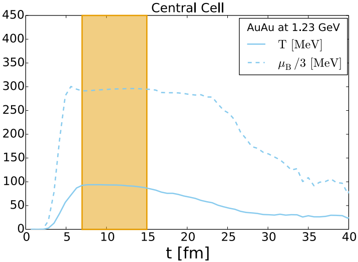


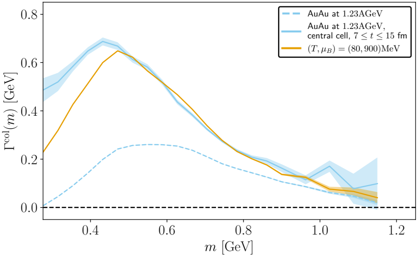
Non-equilibrium effects



- Region of spacetime in a collision where an apparent equilibrium is attained

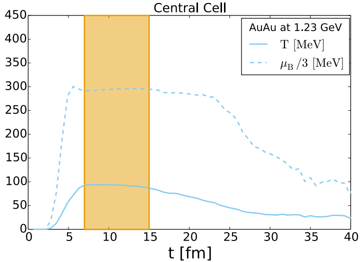
Non-equilibrium effects

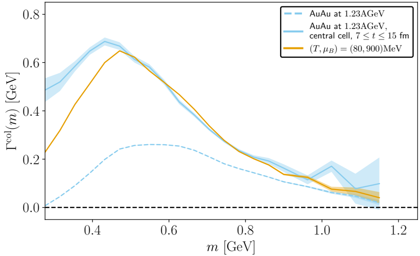




- Region of spacetime in a collision where an apparent equilibrium is attained
- Restriction to this region makes $\Gamma^{\rm col}(m_{2\pi}) \neq 0$

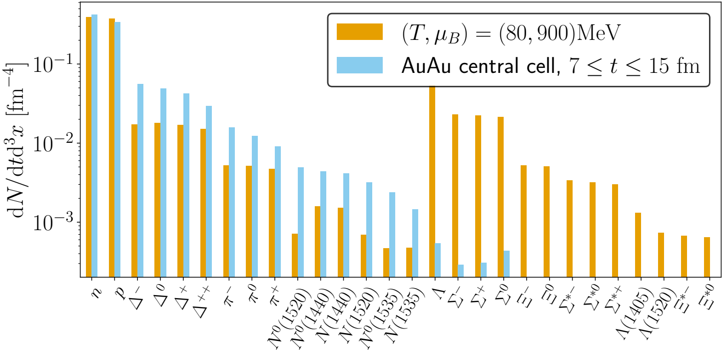
Non-equilibrium effects





- Region of spacetime in a collision where an apparent equilibrium is attained
- Restriction to this region makes $\Gamma^{\text{col}}(m_{2\pi}) \neq 0$
- Similar broadening, excess for small masses

Non-equilibrium effects



- Collision systems are much more baryon-rich $\Rightarrow$ excess in LMR
- Remaining energy in gas is filled by strange hadrons

Summary

- In SMASH: Vacuum properties $\xrightarrow{\text{medium}}$ dynamical 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
- Same $(T, \mu_B) \not\Longrightarrow$ same broadening

T.Hanks

Have a nice lunch!

References

- R. Rapp and J. Wambach, Eur. Phys. J. A6, 415 (1999).
- P. Salabura and J. Stroth, Prog. Part. Nucl. Phys. 120, 103869 (2020).
- H. van Hees and R. Rapp, Nuc. Phys. A, 806 (1-4), 339-387 (2008).
- J. Weil, et al., Phys. Rev. C94 (5), 054905 (2016).
- J. Staudenmaier, et al., Phys. Rev. C98, 054908 (2018).
- D. M. Manley and E. M. Saleski, Phys. Rev. D 45, 4002 (1992).
- H. B. O'Connell, B. C. Pearce, A. W. Thomas, and A. G. Williams, Prog. Part. Nucl. Phys. 39, 201 (1997).

Decay widths

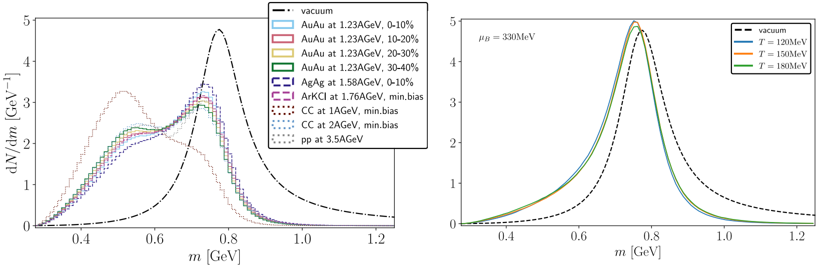
Following Manley et al.,

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

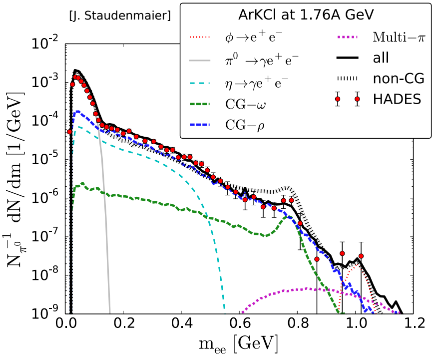
Under the *Vector Meson Dominance* model:

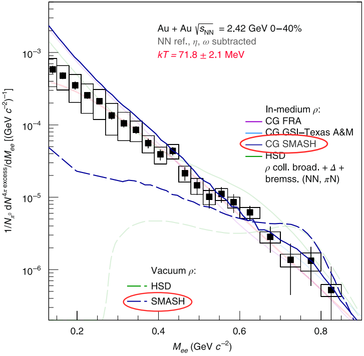
$$\Gamma^{\mathrm{vac}}_{\rho\to ll}(m) = \Gamma^0_{\rho\to ll} \left(\frac{M_0}{m} \right)^3 \left(1 + \frac{2m_l^2}{m^2} \right) \sqrt{1 - \frac{4m_l^2}{m^2}}$$

Produced ρ masses

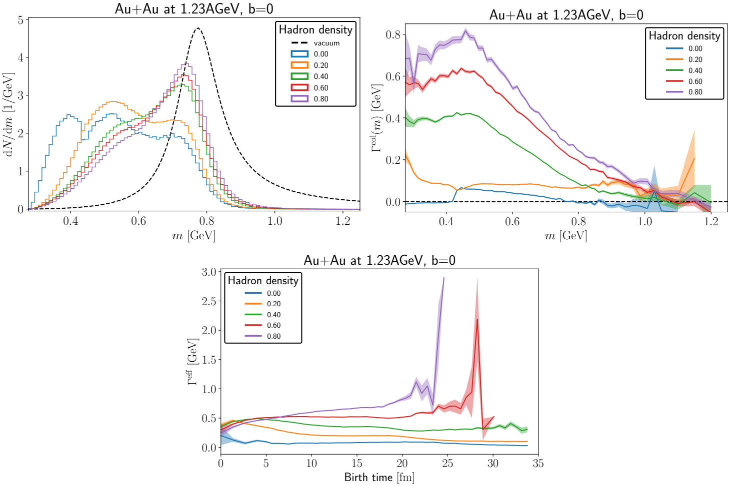


Coarse-Grained SMASH dileptons





Density bins



Late stages of a collision