Heavy Ion Collisions in the QCD phase diagram

June 27-July 8, 2022 Subatech, Nantes (France)

HADRONS IN MEDIUM

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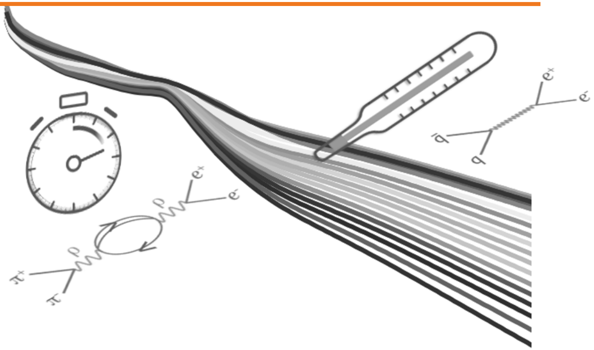
05 July, 2022

Lecture 2

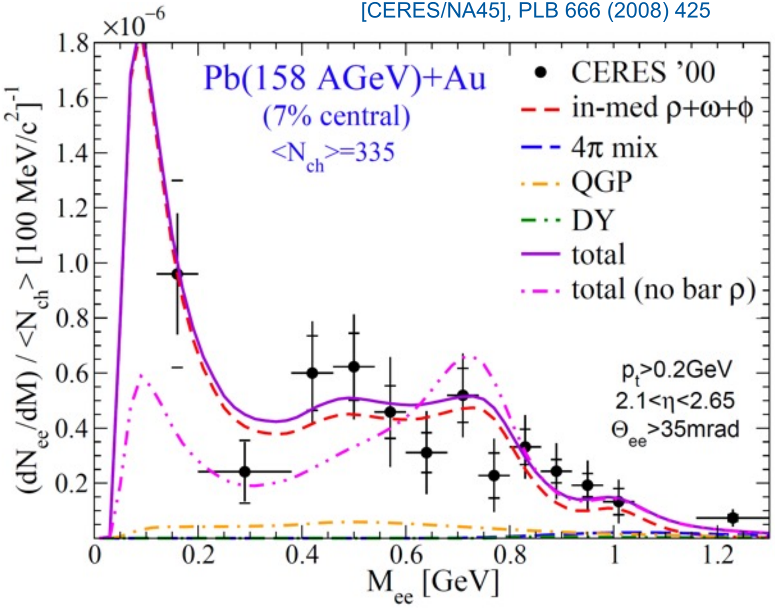


Dileptons as

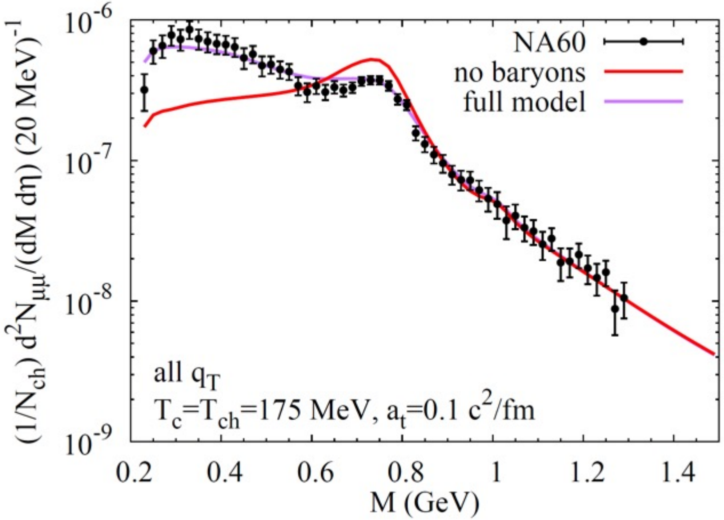
SPECTROMETER

Measured excess dilepton invariant-mass spectra

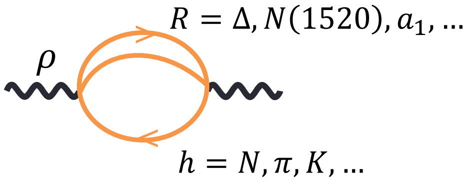
[CERES/NA45], PLB 666 (2008) 425



[NA60], EPJC 61(2009) 711

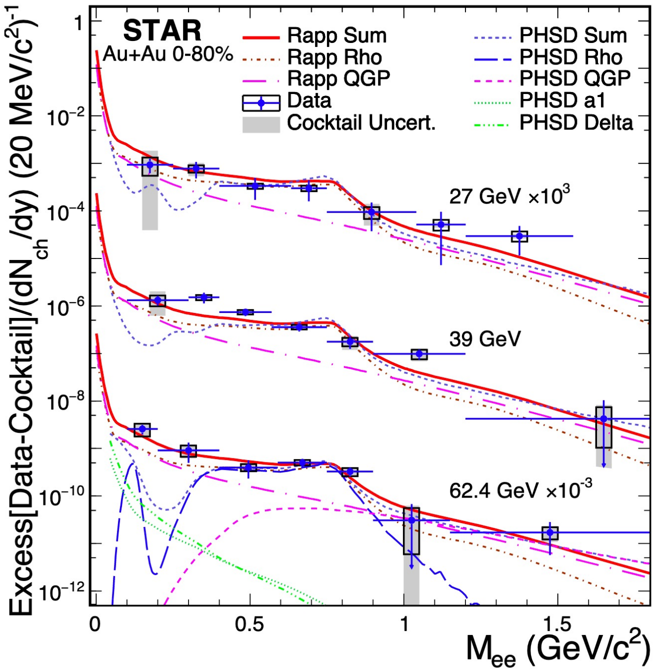


Data strongly support melting of ρ,
in particular due to baryon-induced effects



Rapp, Wambach, EPJ A6 (1999) 415-420 (1999)
Rapp, Wambach, van Hees, Landolt-Bornstein 23 (2010) 134

Dilepton excitation function: SPS – RHIC



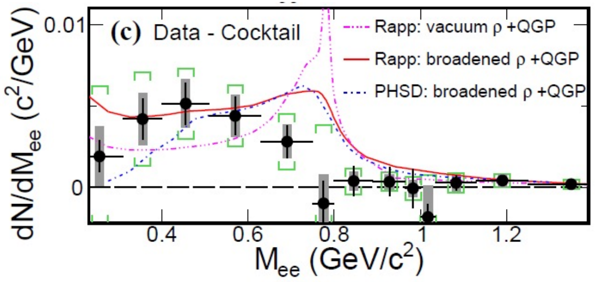
[STAR], Phys. Rev., C92 (2015) 2, 024912
[STAR], Phys.Lett. B750 (2015) 64–71
[STAR], arXiv:1810.10159, 2018
➡ BES 62.4 – 19.6 GeV

- No apparent change of the excess emission source
- Suggests “universal” medium effect around T_{pc}

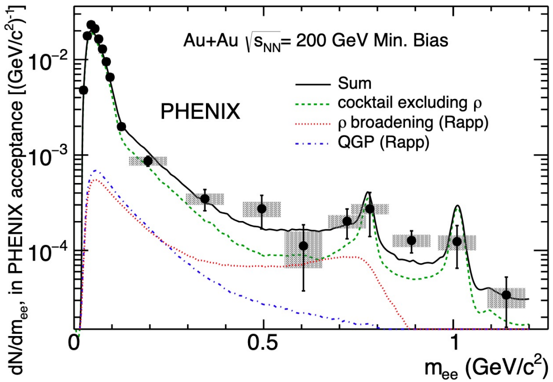
	SPS (Pb+Pb)	RHIC (Au+Au)
dN(p̄)/dy	6.2	20.1
produced baryons (p, p̄, n, n̄)	24.8	80.4
p - p̄	33.5	8.6
particpating nucleons (p - p̄)A/Z	85	21.4
total baryon number	110	102

- Although the **NET-**baryon density is different at SPS, RHIC and LHC, baryon density is practically the same!
- Baryon effects important even at $\rho_{B_{tot}} = 0$! sensitive to $\rho_{B_{tot}} = \rho_B + \rho_B$ (ρN and $\rho\overline{N}$ interactions identical)

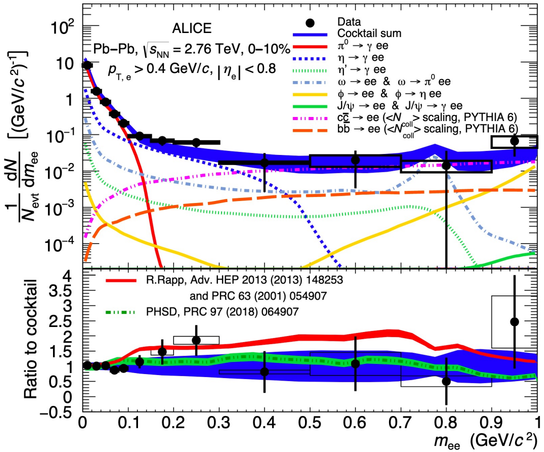
Dilepton excitation function: RHIC - LHC



[STAR], Phys. Rev. Lett.113 (2014) 2, 022301



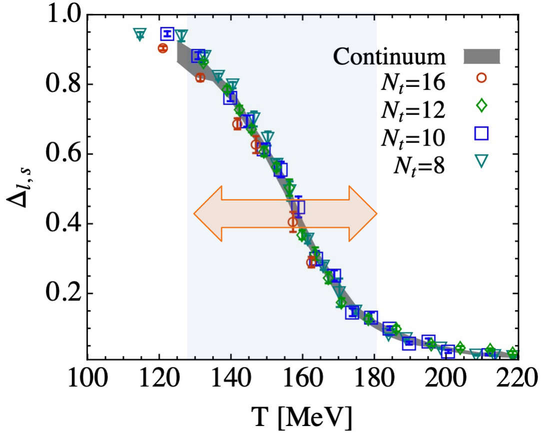
[PHENIX] Phys.Rev. C93 (2016) 1, 014904



[ALICE] Phys.Rev.C 99 (2019) 2, 024002

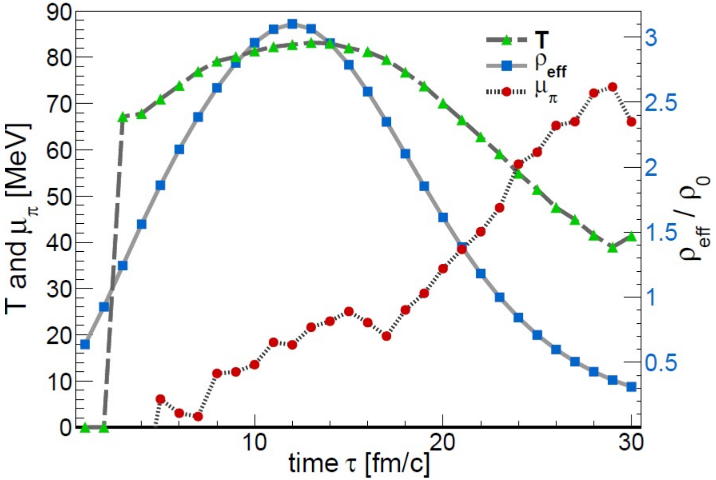
- RHIC, LHC: higher initial temperature,
  open charm (beauty) contribution becomes very significant

- $\mu_B \ll T$: lattice QCD computations are most powerful
- Low-mass spectral shape in chiral restoration window:
  ~60% of thermal low-mass yield in “chiral transition region” (T=125-180 MeV)
- Measure ρ spectral function and “calibrate” EM rates



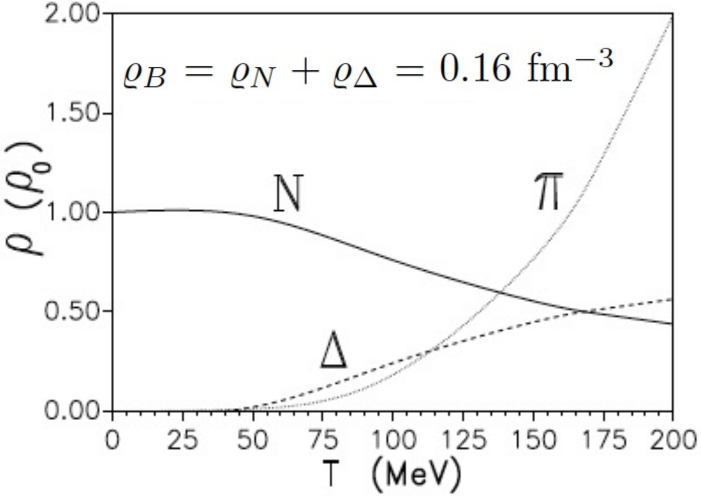
Baryonic matter at few gev beam energy

Central cell (3x3x3 fm3) thermodynamic properties from coarse graining UrQMD



TG, Seck *et al.*, Eur. Phys. J. A 52 (2016) 131

Composition of a hot πΔN gas



Rapp, Wambach, Adv.Nucl.Phys. 25 (2000)

- Long interpenetration times
- Comparatively long lifetime of the dense "fireball" ($\varrho_{max} \approx 3\varrho_0$)

- Moderate temperatures: $T < 90\,MeV$
- Baryon-dominated system throughout the evolution ($N_\pi/A_{part} \approx 10\%$)

Towards few GeV energies

Challenges

- Implementation of in-medium effects in microscopic transport simulations
- justification of thermalization in hydrodynamical simulations

Coarse-grained transport approach

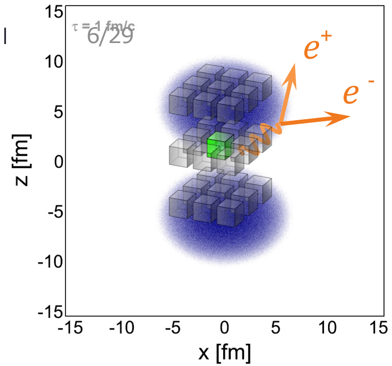
➡ bulk evolution from microscopic transport

➡ apply equilibrium rates locally

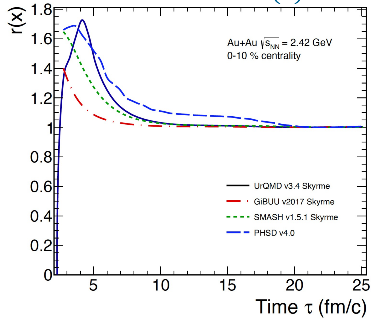
- Simulate many events
  ⇝ ensemble average to obtain smooth space-time distributions
- Average hadron distributions in suitable space-time
- Determine for each cell the bulk properties like $T, \rho_B, \mu_\pi, \beta$
- Use in-medium spectral functions to compute EM emission rates

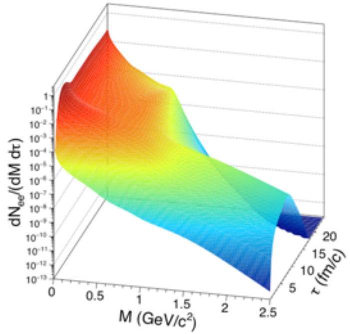
Rapp and Wambach, Adv.Nucl.Phys. (2000) 25
Jung, Rennecke, Tripolt, at al., PRD95 (2017) 036020
Sasaki, Phys.Lett. B801 (2020) 135172

Huovinen et al., PRC 66 (2002) 014903
CG FRA Endres et al.: PRC 92 (2015) 014911
CG GSI-Texas A&M TG et al.: Eur.Phys.J. A52 (2016) no.5, 131
CG SMASH: Phys.Rev.C 98 (2018) 5, 054908



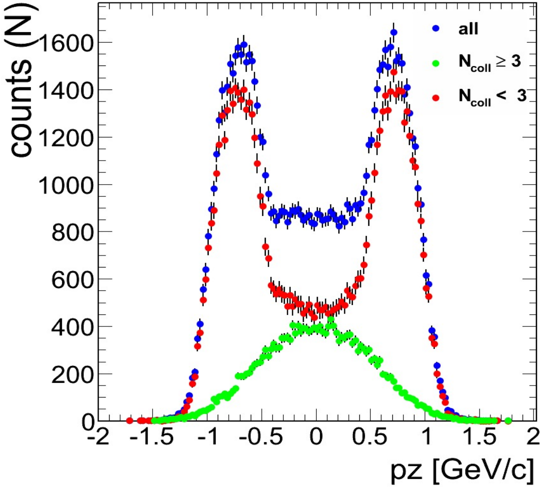
Relaxation function $r(x)$



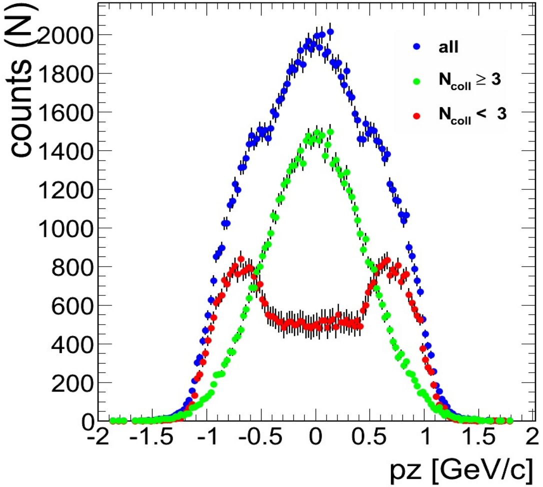


Momentum distributions of nucleons, Au+Au $\sqrt{s_{NN}} = 2.4$ GeV, central cell

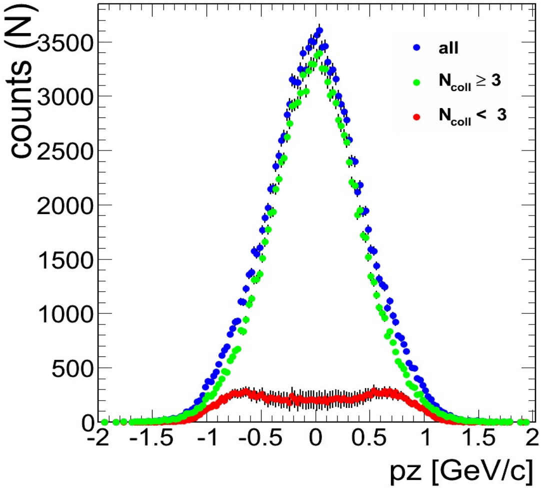
τ = 2 fm/c



τ = 3 fm/c



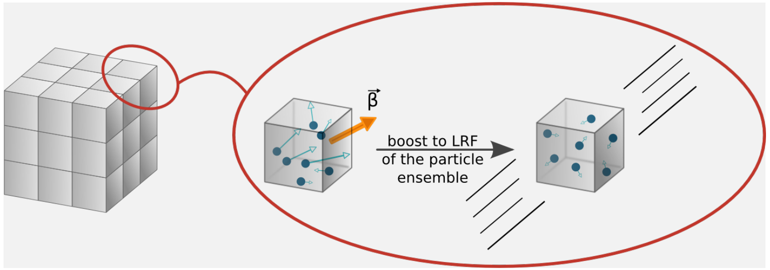
τ = 5 fm/c



- Gaussian shaped p_z distribution builds up for nucleons with $n_{coll} \geq 3$
- m_T spectra have exponential shape
- Check for every cell → deviations are kept in space-time evolution

Determination of bulk properties

- Baryon density via 4-current
- Lorentz-boost to local rest frame (LRF) where the baryon current vanishes



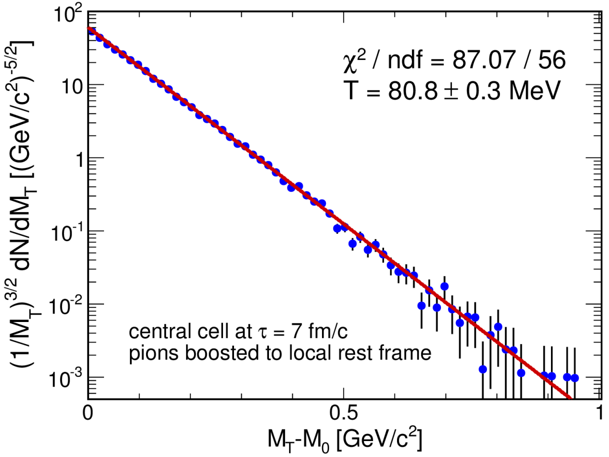
- In Boltzmann approximation

$$\frac{d^3N}{d\vec{p}} = \frac{d^3N}{dp_z\, p_t\, dp_t\, d\theta} \propto \exp(-E/T)$$

$$\Downarrow$$

$$\frac{1}{m_t^{3/2}} \frac{dN}{dm_t} \propto \exp(-m_t/T).$$

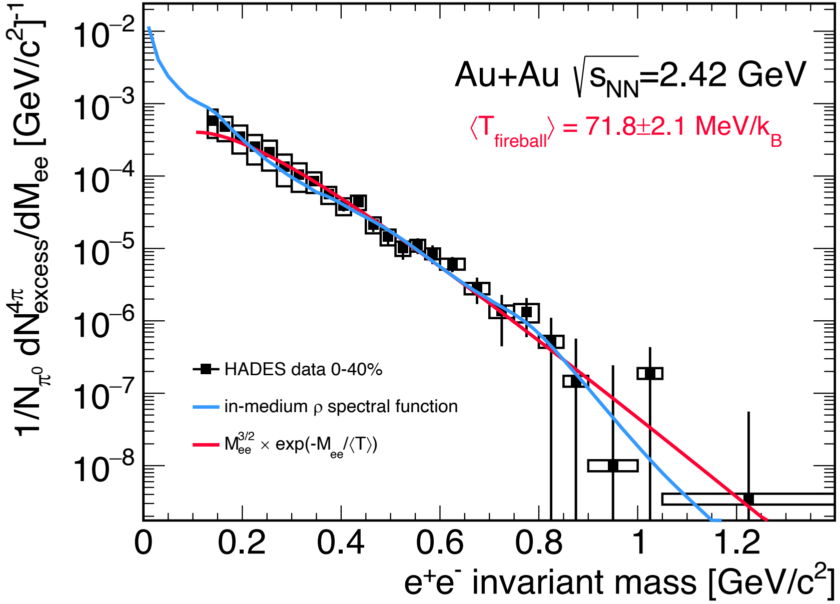
- Fill m_T spectra with particle momenta in LRF (mean flow v_{coll} vanishes)
- Fit exponential function to extract T (species of choice: pions)



Thermal dileptons at SIS energy regime

There is no mission impossible

HADES, Nature Phys. 15(2019) 1040

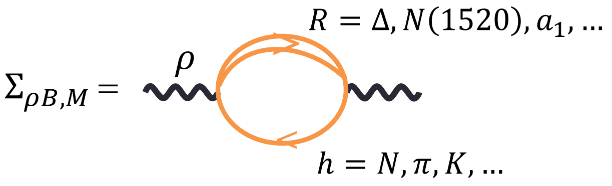


- Thermal rates folded with coarse-grained medium evolution from transport works at low energies

- ρ-meson peak undergoes a strong broadening in medium
- in-medium spectral function from many-body theory consistently describes SIS18, SPS, RHIC, LHC energies

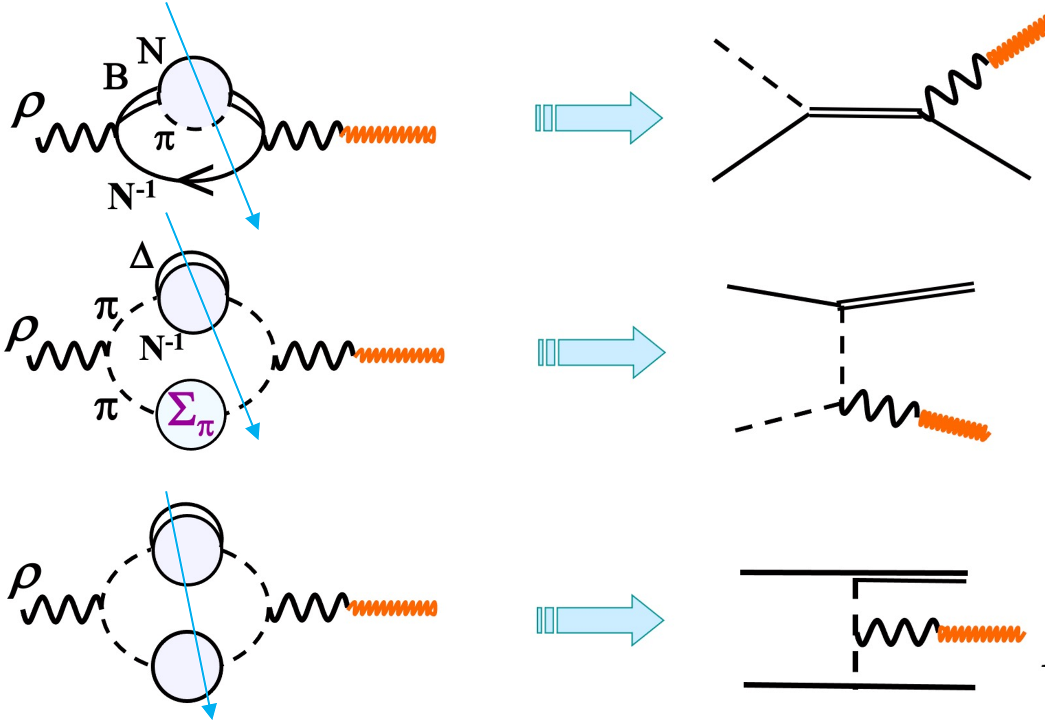
- Baryonic effects are crucial

Rapp and Wambach, Adv.Nucl.Phys. (2000) 25



Production processes from ρ spectral function

↔ cuts (imaginary parts) of selfenergy diagrams:



resonance Dalitz decays

$\pi\, N \rightarrow \Delta \rightarrow \gamma\, N$

$\pi\, \rho \rightarrow a_1 \rightarrow \gamma\, \pi$

meson-exchange scattering

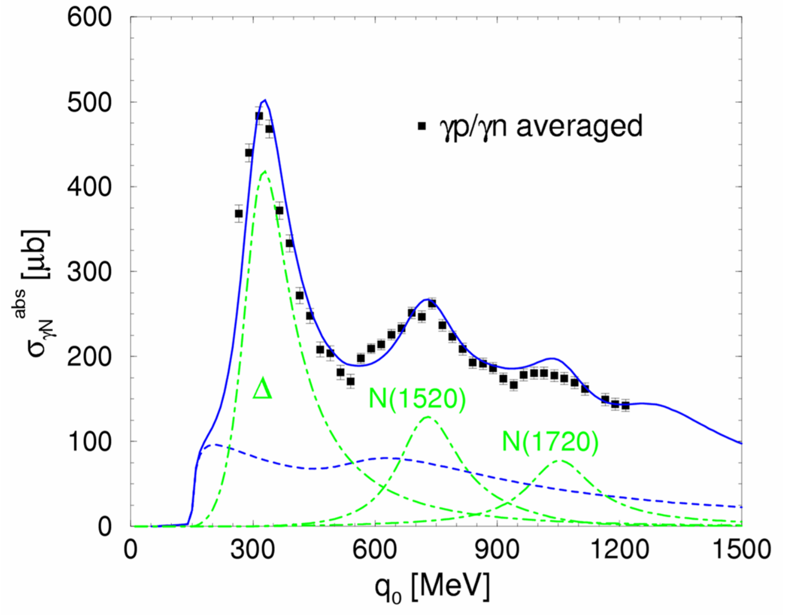
$\pi\, N \rightarrow \gamma\, N\, ,\, \gamma\, \Delta$

Bremsstrahlung

$NN \rightarrow \gamma\, NN,\, \gamma\, N\Delta,\, \gamma\, \Delta\Delta$

"Light-like" ρ-spectral function, $D_\rho(q_0 = q)$ and nuclear photo-absorption

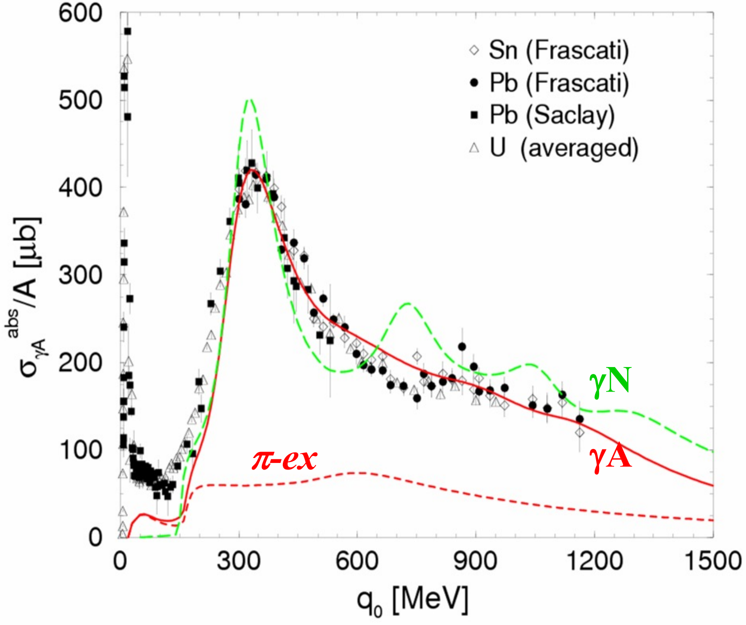
On the Nucleon



- Fixes coupling constants and formfactor cutoffs for ρNB

[Urban,Buballa,RR+Wambach '98]

On Nuclei

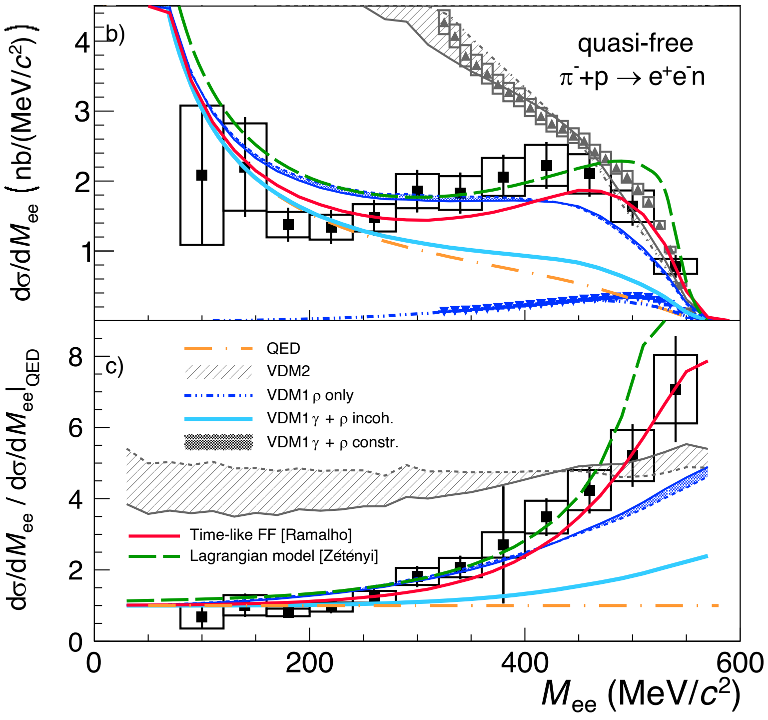


- 2nd + 3rd resonance melt (parameter) (selfconsistent N(1520) → Nρ)

[Post,Mosel et al '98]

First measurement of massive γ^* emission from N^* baryon resonances

HADES, arXiv:2205.15914 [nucl-ex]



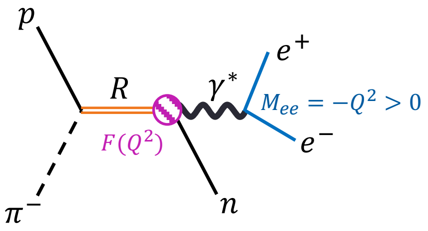
- $\pi^- p \rightarrow n + \pi^- + \pi^+$
  - included in PWA (Bonn-Gatchina) to provide partial wave decomposition

HADES, PRC 102 (2020) 2, 024001
HADES, PRC 95 (2017) 065205

4 first entries ($N\rho$)
4 additional entries

- $\pi^- p \rightarrow n + e^- + e^+$
  - probe baryon resonance – nucleon transition

- Dominance of the $N^*(1520)$ resonance at $\sqrt{s_{NN}} = 1.49$ GeV
  - ρ meson as "excitation" of the meson cloud
  - **Vector Meson Dominance - basis of emissivity calculations for QCD matter**

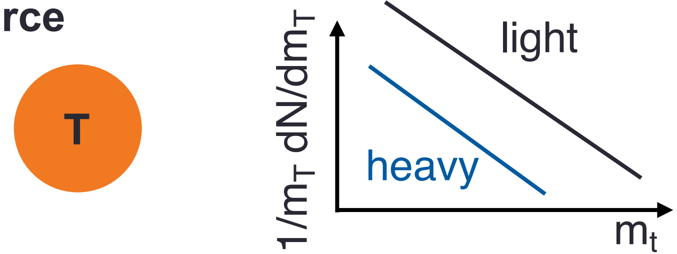


Dileptons as

BAROMETER

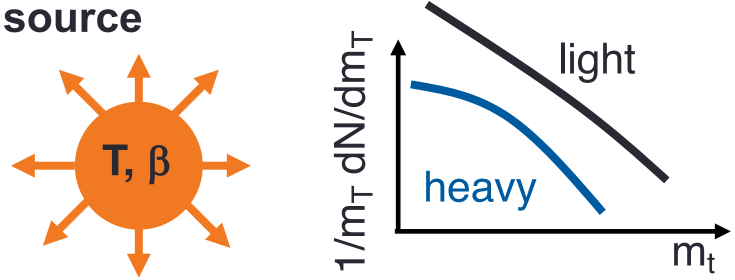
Radial flow

Purely thermal source



- Particles radiated from the “thermal” source → m_t spectra of all particles have the same form

Explosive source



- Additional radial (collective) expansion
  - Form of the m_t spectra for heavier particles differs
  - Important parameter: radial expansion velocity β

Thermal spectra and radial flow

- Radial flow has been defined for central collisions

- The idea: $\langle E \rangle = \frac{1}{2} m\beta^2 + \frac{3}{2} T$ while the thermal energy is independent of mass, the collective flow contribution is proportional to particle mass → from the spectra of particles with different masses extract both the thermal and the collective component

$$T_{eff} = \begin{cases} T_{th} \times \sqrt{\dfrac{1+\langle\beta\rangle}{1-\langle\beta\rangle}} & for \quad p_t \gg m \\ T_{th} + \dfrac{1}{2} m \langle\beta\rangle^2 & for \quad p_t \leq m \end{cases}$$

“Thermal” spectra and radial flow

“blast wave”: based on hydrodynamics

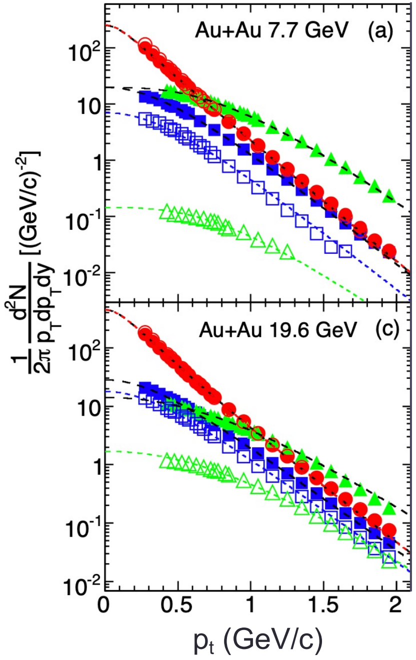
Schnedermann, Sollfrank, and Heinz, Phys. Rev. C46

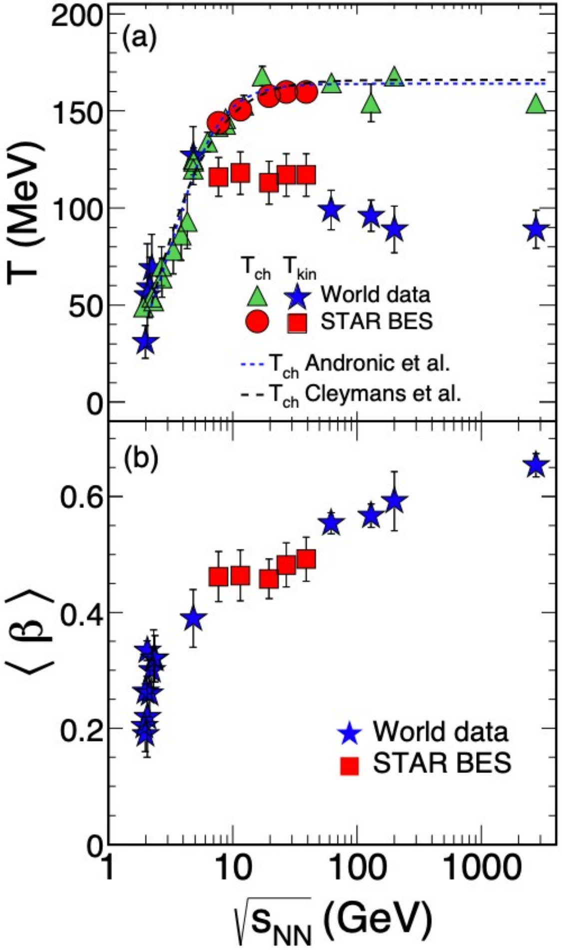
spectrum of the longitudinally and radially expanding thermal source:

$$\frac{dN}{p_t\,dp_t} \propto \int_0^R r\,dr\,m_t\,K_1\left(\frac{m_t \cosh\rho(r)}{T_{kin}}\right)\times I_0\left(\frac{p_t \sinh\rho(r)}{T_{kin}}\right)$$

boost-rapidity: $\rho(r) = \tanh^{-1}\beta$

radial flow velocity profile: $\beta = \beta_s (r/R)^n$

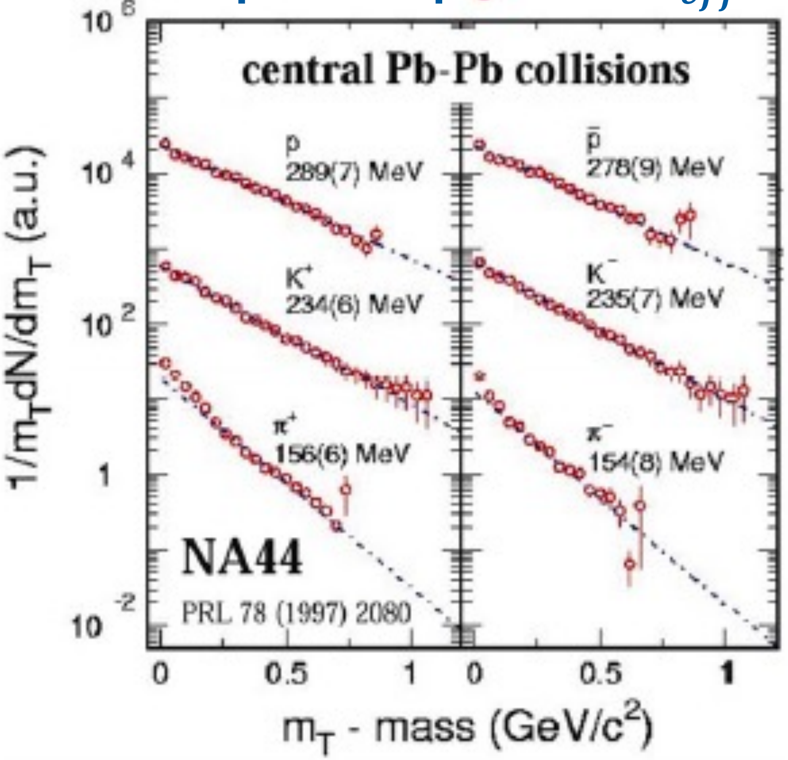




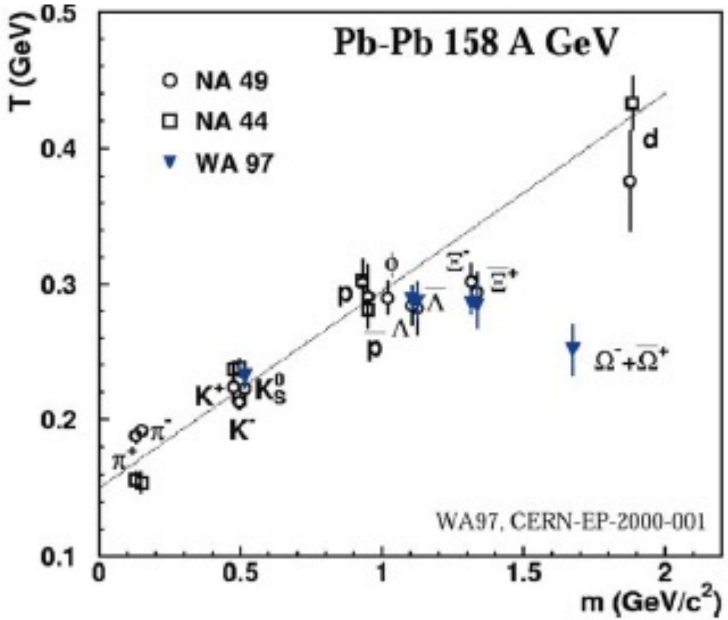
STAR, Phys.Rev.C96 4 (2017) 044904

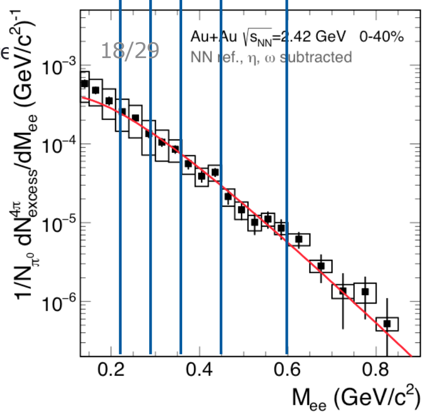
Thermal spectra and radial flow

Step 1: Fit spectra → T_{eff}



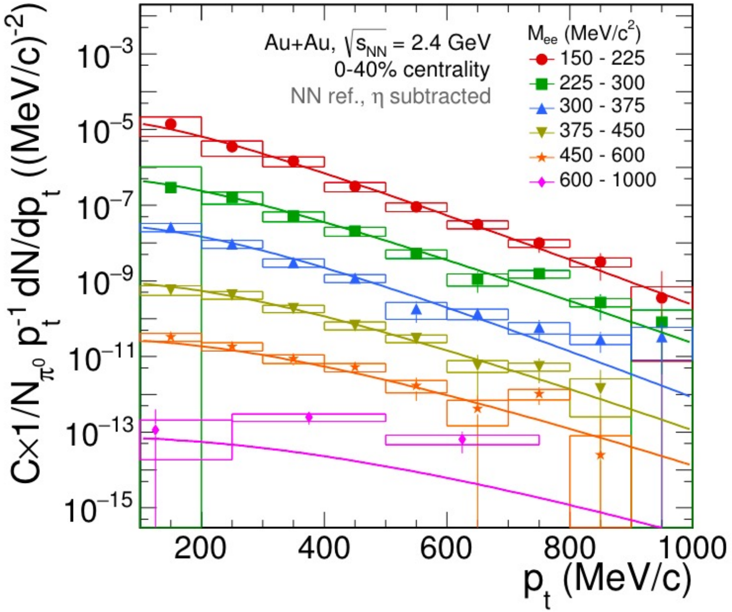
Step 2: Plot T_{eff} vs mass → $T_{th,}\ \beta$





Transverse mass distributions of excess

for each bin of e^+e^- project transverse momentum spectrum



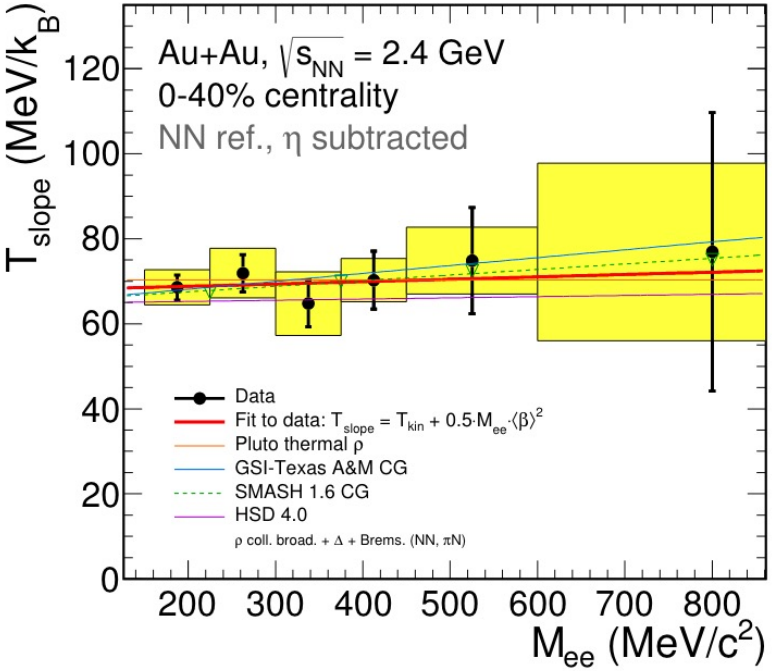
HADES, in preparation

assuming pure Boltzmann nature of the radiating source

$$\frac{d^3N}{dp} \propto exp\left(-\frac{E}{k_BT}\right)$$

$$\frac{1}{p_t}\frac{dN}{dp_t} \propto m_t K_1\left(\frac{m_tc^2}{k_BT}\right)$$

How the collectivity develops



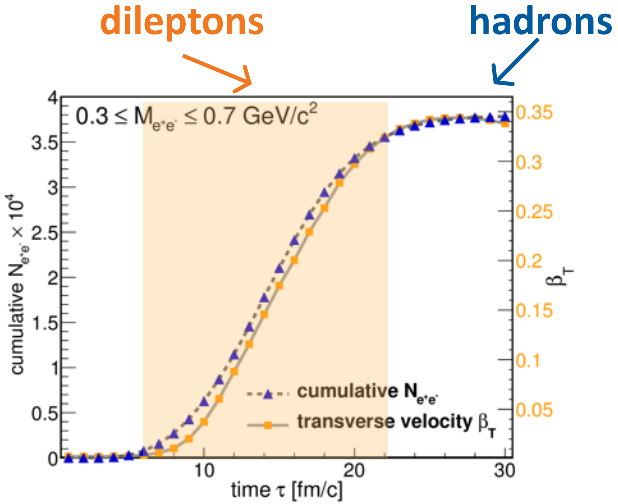
HADES, in preparation

fit to model calculations:

- ☐ CG: $T_{kin} = 65\ MeV, \langle\beta_{ee}\rangle = 0.19$
- ☐ HSD: $T_{kin} = 74\ MeV, \langle\beta_{ee}\rangle = 0.05$

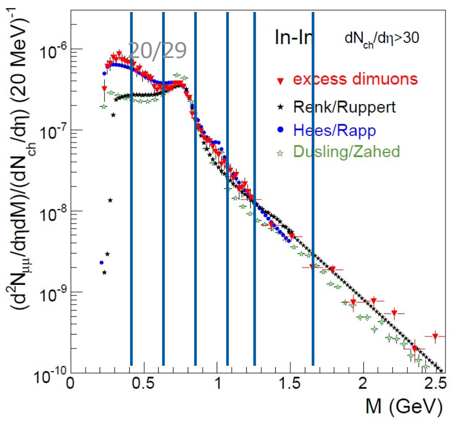
from hadron spectra at kinetic freeze-out

- ☐ $T_{kin} = 62 \pm 8\ MeV, \langle\beta_{had}\rangle = 0.34 \pm 0.04$


dileptons

hadrons

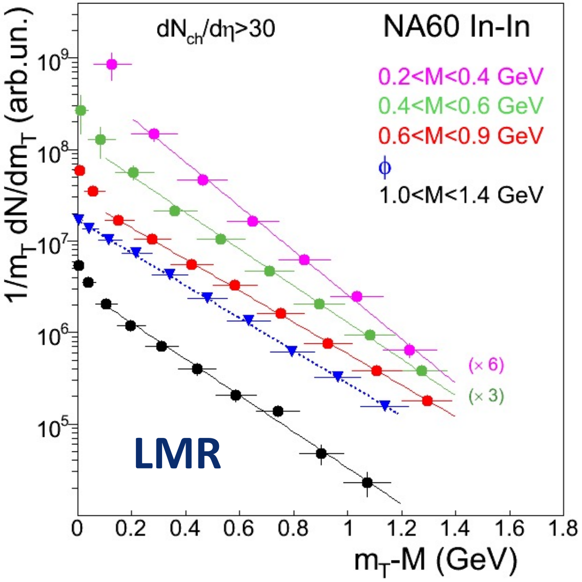
TG, F. Seck, et al., Eur.Phys.J. A52 (2016) no.5, 131



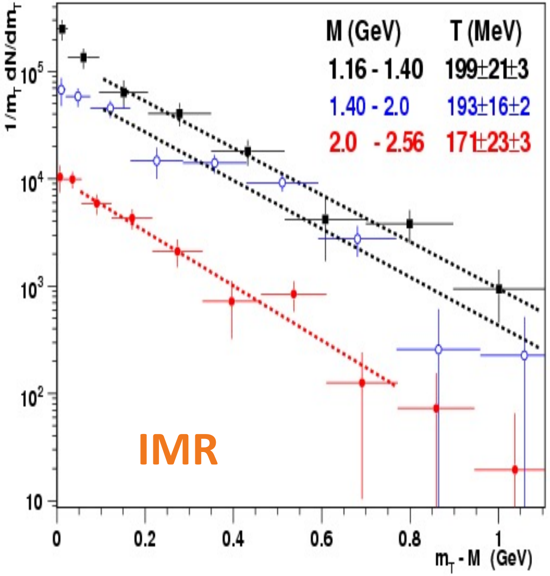
Transverse mass distributions of excess

for each bin of $\mu^+\mu^-$ project transverse mass spectrum: $m_T = \sqrt{p_T^2 + M^2}$

NA60, Phys. Rev. Lett. 100 (2008) 022302

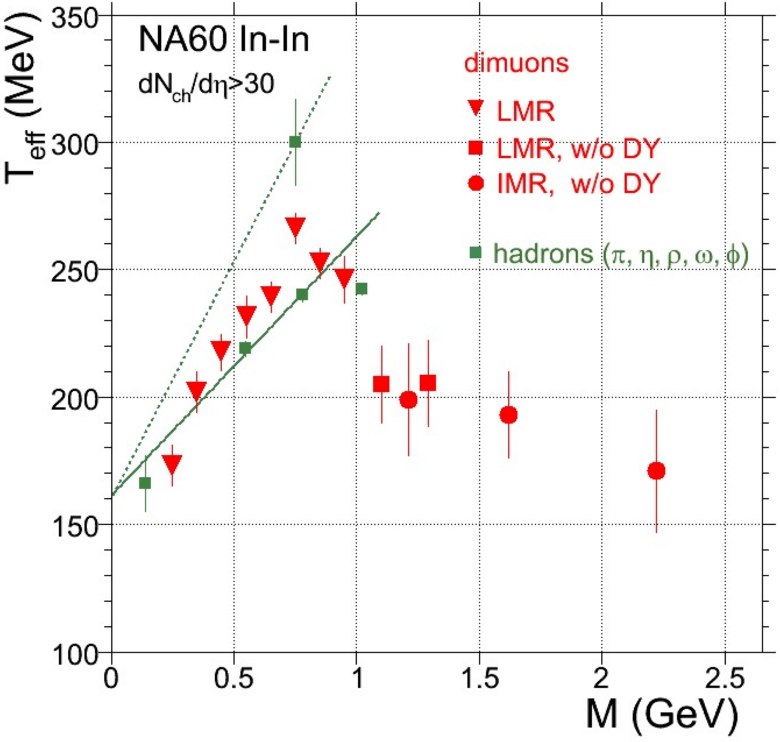


NA60, Eur. Phys. J. C 59 (2009) 607



- ☐ m_T spectra exponential for $m_T - M > 0.1\ GeV\ (< 0.1\ GeV??)$
- ☐ Fit with $\frac{1}{m_T}\frac{dN}{dm_T} \sim \exp\left(-\frac{m_T}{T_{eff}}\right)$
- ☐ Extract T_{eff} and plot vs M

The rise and fall of T_{eff} of thermal dimuons



NA60, PRL 100 (2008) 022302

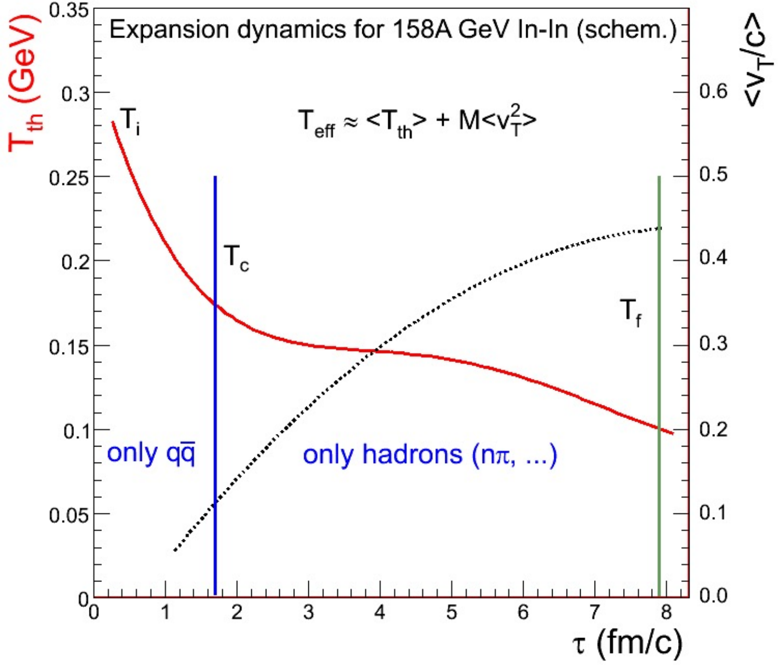
- ☐ $M < 1\ GeV$
  - ☐ strong, almost linear rise of T_{eff} with dimuon mass
  - ☐ follows trend set by hadrons
- ☐ $M > 1\ GeV$
  - ☐ drop of T_{eff} by $\sim 50\ MeV$
  - ☐ followed by an almost flat plateau

What can we learn from m_T spectra?

⇝ radial flow

⇝ origin of dileptons

Interpretation of the dilepton m_T (p_T) spectra



- ☐ Hadron p_T spectra: determined at $T_{kin.f.o.}$ (restricted information)
- ☐ Dilepton p_T spectra: superposition from all fireball stages
  - ☐ early emission → high T_{th}, low v_T
  - ☐ late emission → low T_{th}, high v_T
- ☐ Final spectra from space-time folding over T_{th} & v_T history from $T_{initial} \longrightarrow T_{kin.f.o.}$ note: small flow in the QGP phase

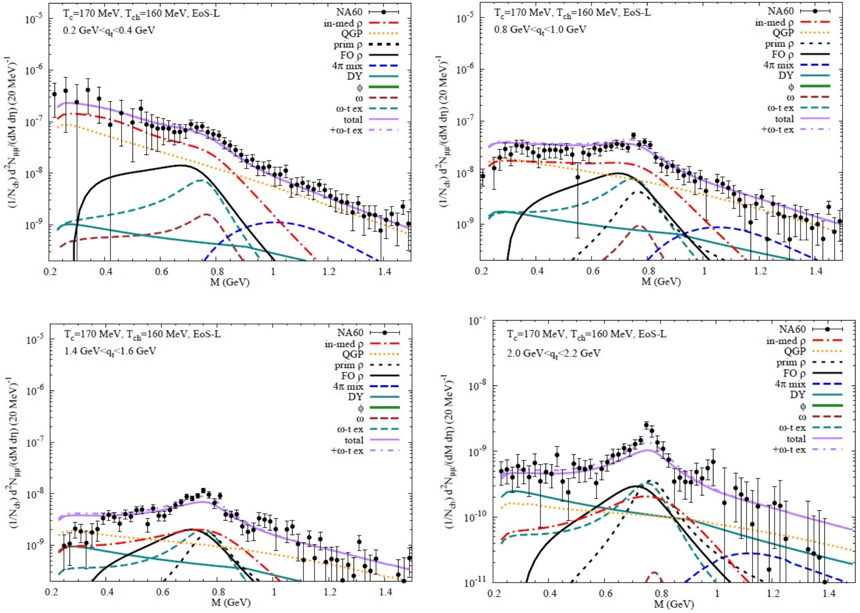
for $M > 1\ GeV$:
$\rightsquigarrow$ T_{eff} independent of M, negligible flow
$\rightsquigarrow$ $\langle T_{th} \rangle \sim 200\ MeV$ > T_{pc}
→ early emission, dominance of partons

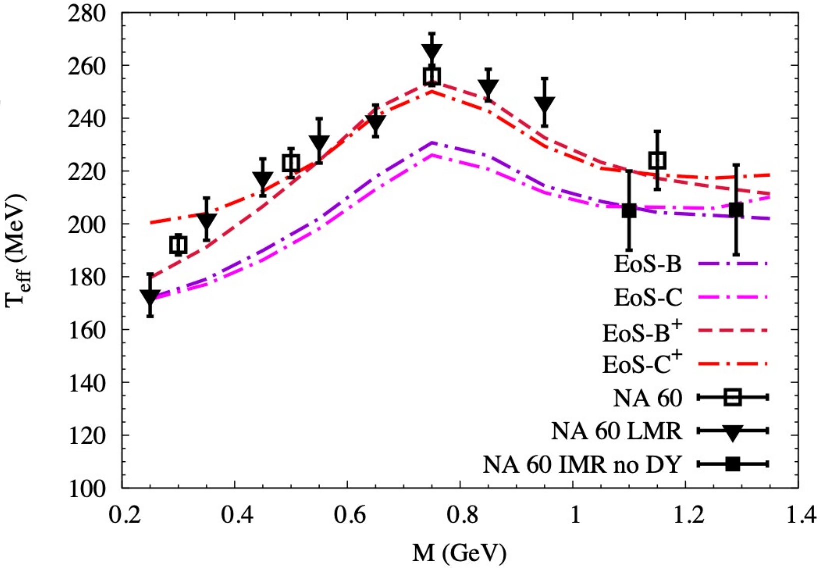
T effective in theory, SPS

- Theoretical slopes originally too soft → increase fireball acceleration from $a_\perp = 0.085\,\frac{c^2}{fm}$ to $0.1\,\frac{c^2}{fm}$
- Effective at all stages of fireball evolution

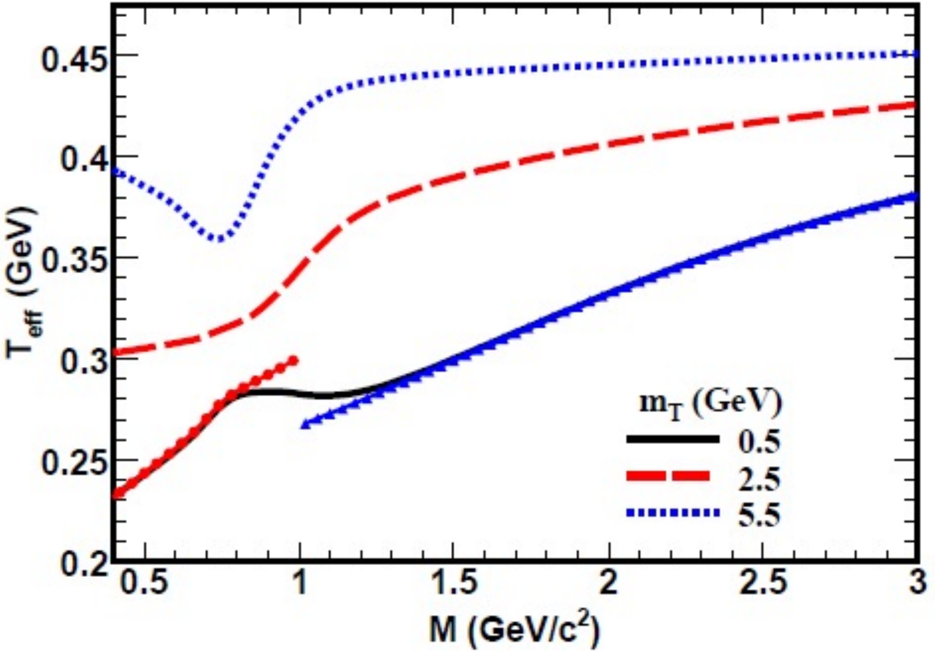
- Spectral shape as function of pair-p_T
- Entangled with transverse flow (barometer)

p_T -sliced mass spectra





T effective at RHIC



Theory:

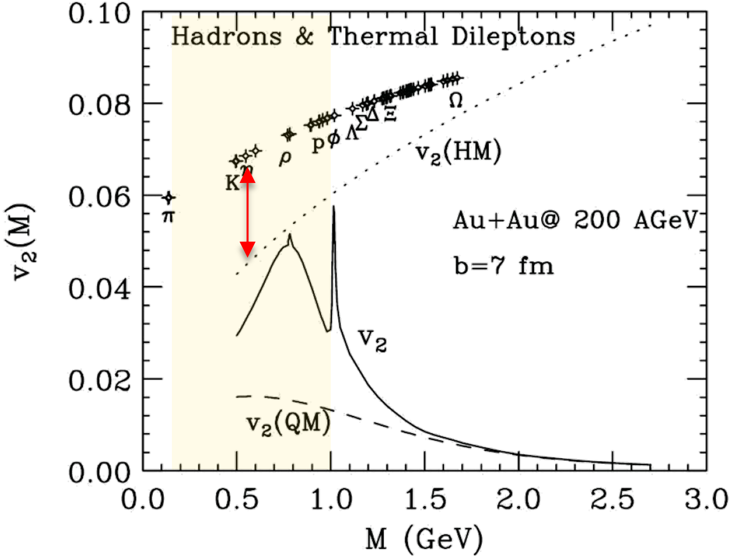
- Qualitative change from SPS to RHIC: flowing QGP
- True temperature “shines” at large m_T

Experiment:

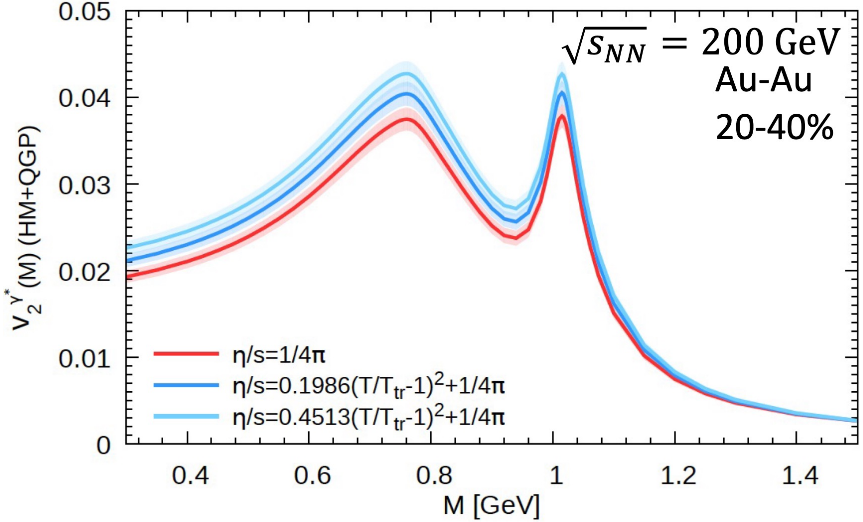
- Large contribution from $c\bar{c}, b\bar{b}$ and QGP
- Negligible $\mathcal{D}$rell-Υan

Azimuthal anisotropy of virtual photons

Chatterjee *et al.*, PRC 75 (2007), 054909



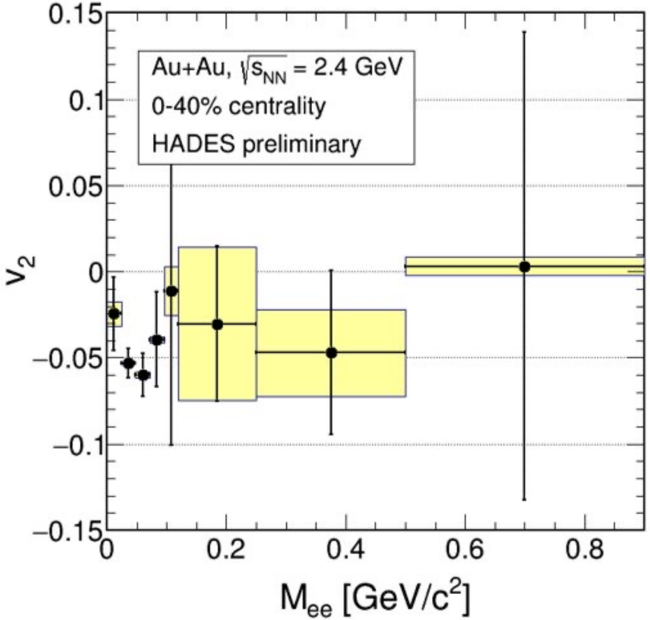
Vujanovic et al., Phys. Rev. C 98, 014902 (2018)

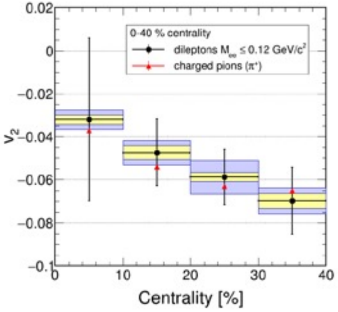


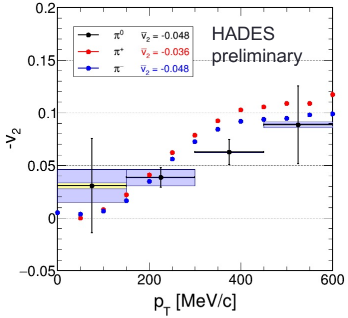
- ☐ Very cleans tool to diagnose the collective expansion dynamics, i.e. origin of the electromagnetic emission source
- ☐ Challenging v_2 vs M analysis
  - ☐ Early emission (partonic matter) → small v_2
  - ☐ Late emission (hadronic matter) → large v_2

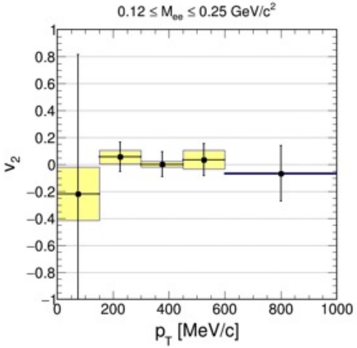
Azimuthal anisotropy of thermal photons in HADES

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV





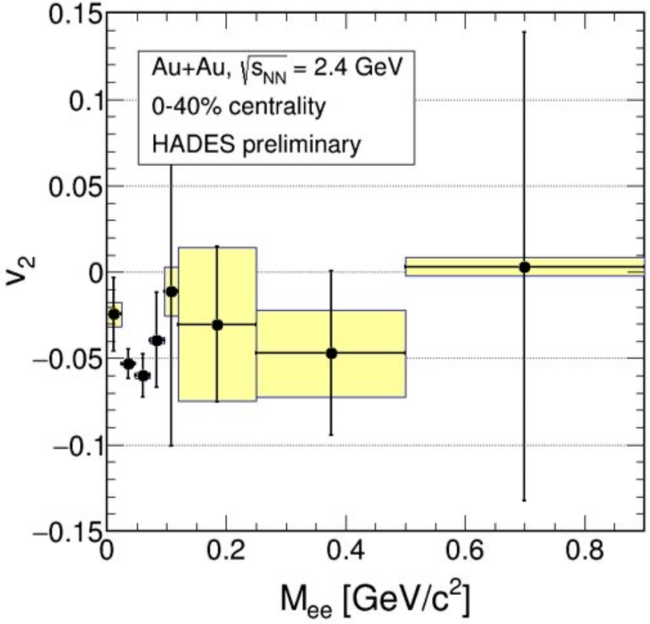




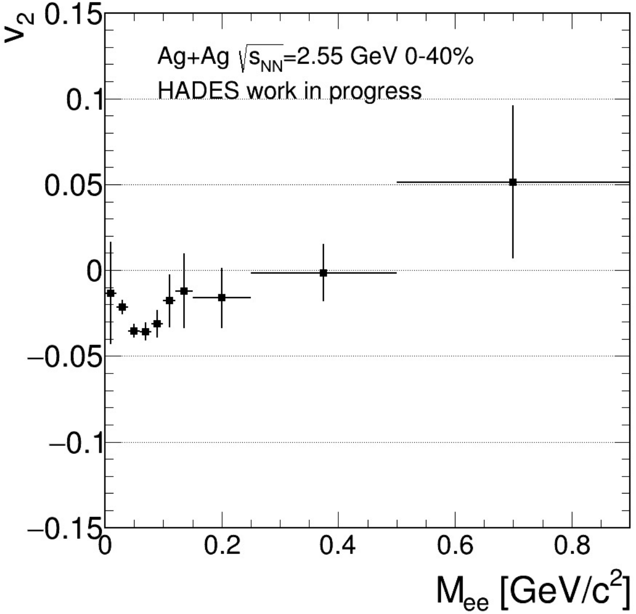
- ☐ v_2 in π^0 Dalitz range:
  - ☐ stronger in peripheral collisions
  - ☐ consistent with v_2 of charged pions
- ☐ v_2 consistent with zero for $M_{ee} > 0.12\ MeV/c^2$

Azimuthal anisotropy of thermal photons in HADES

Au+Au at $\sqrt{s_{NN}} = 2.42$ GeV



Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV



- ☐ v_2 consistent with zero for $M_{ee} > 0.12\ MeV/c^2$
  - ☐ confirms dileptons as penetrating probes of hot and dense medium

Thank you for your attention!