Thermal dileptons from coarse-grained transport as probes of hot and dense QCD matter

Lunch Club Seminar, Universität Gießen

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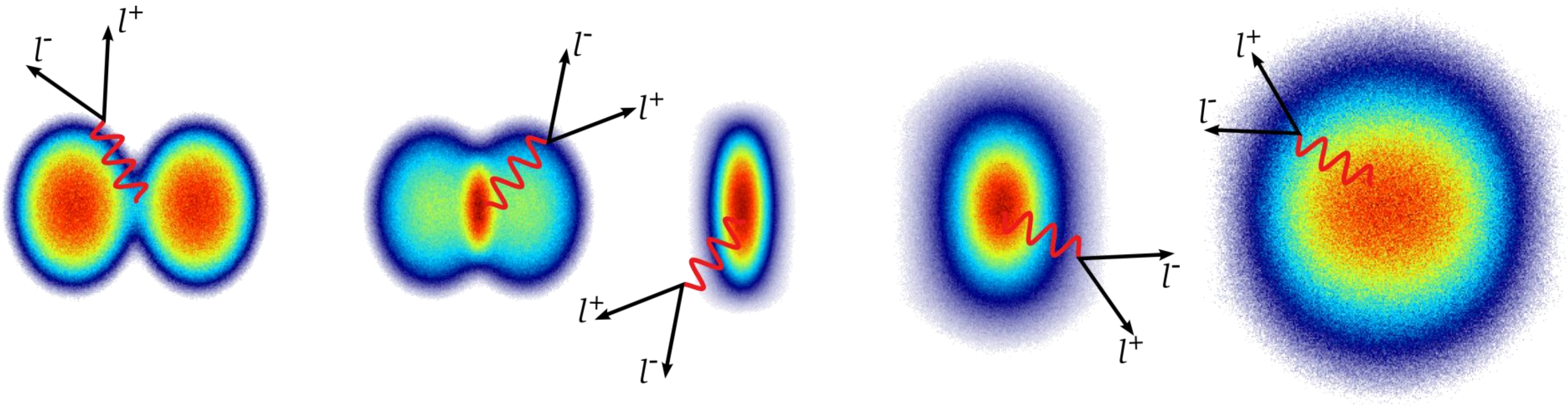
in collaboration with T. Galatyuk, R. Rapp & J. Stroth



Electromagnetic probes in heavy-ion collisions

Experiments across the QCD phase diagram

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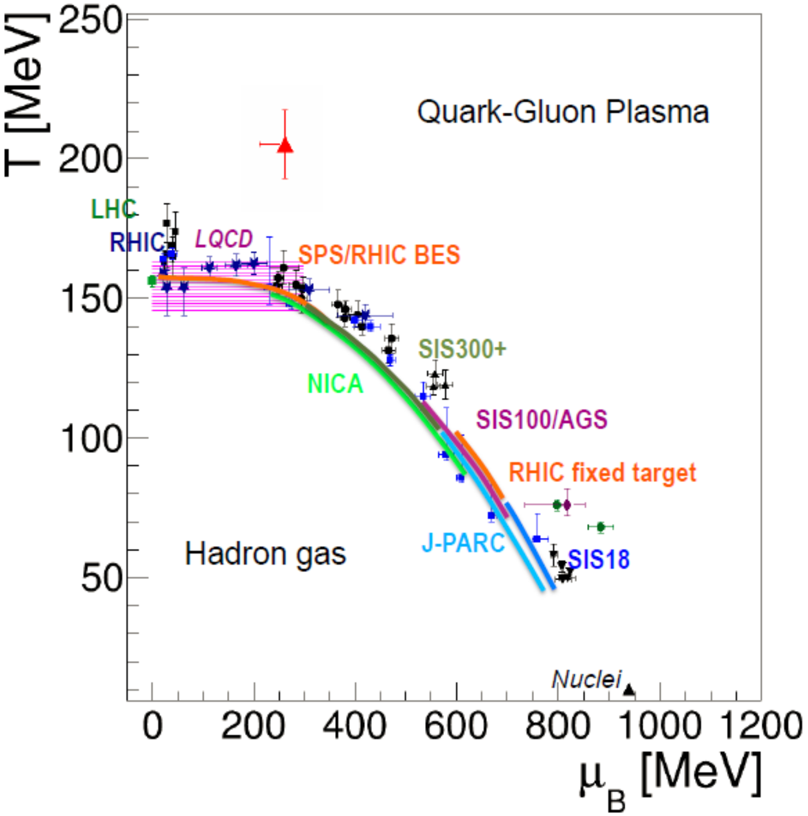

- Search for
  - phase boundary(ies)
    - → fluctuations of conserved quantum numbers
    - → flavor production (multi-strange, charm)
  - change in microscopic degrees of freedom
  - restoration of chiral symmetry
  - emitting source temperature
    - → electromagnetic probes leave collision zone undistorted
    - → real γ characterized by transverse momentum
    - → dileptons carry extra information: invariant mass

▲ NA60 (μ+μ-) : H.J.Specht: AIP Conf. Proc. 1322 (2010)

Electromagnetic probes in heavy-ion collisions

CBM cocktail – invariant mass of dielectrons

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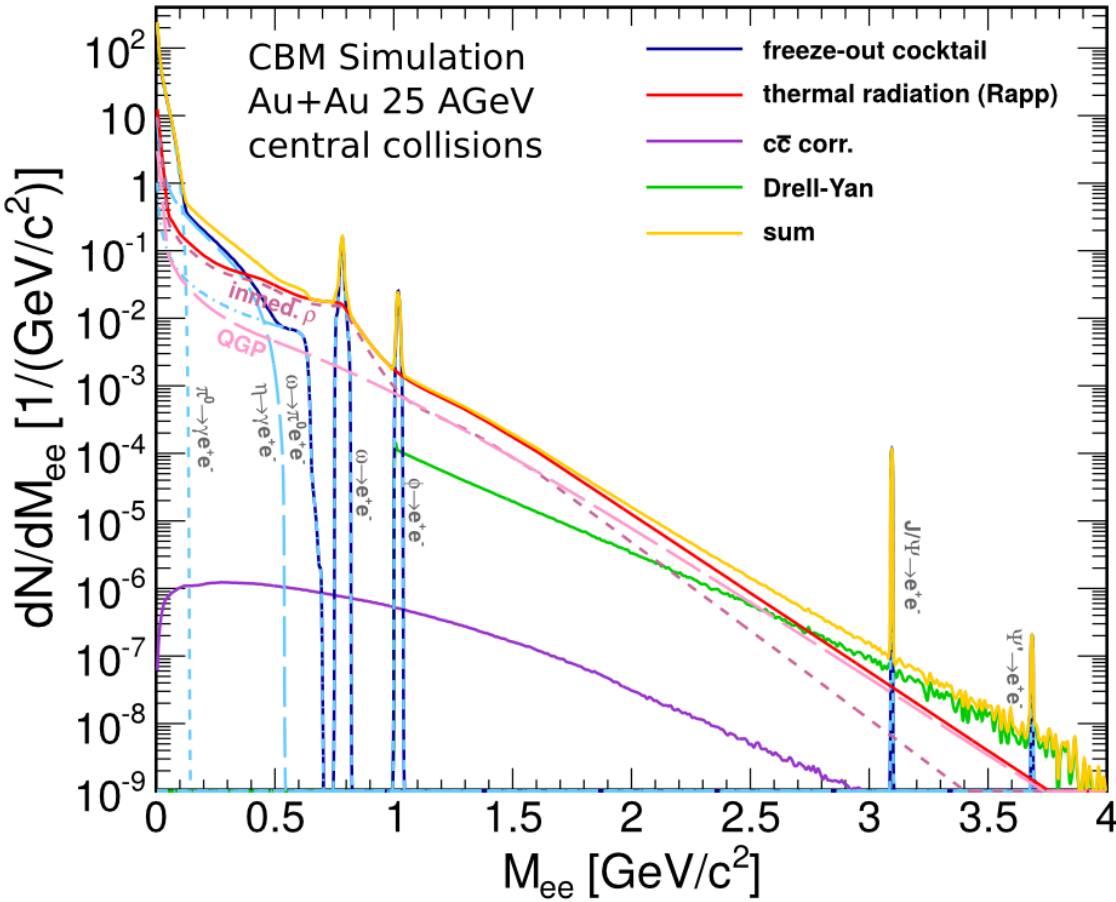
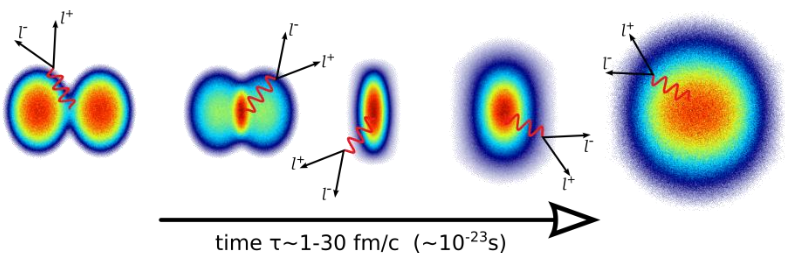


dilepton spectra reflect the whole history of a collision



➡ necessary ingredients:

- realistic emission rates
- accurate description of fireball evolution

Electromagnetic probes in heavy-ion collisions

Insights from theory

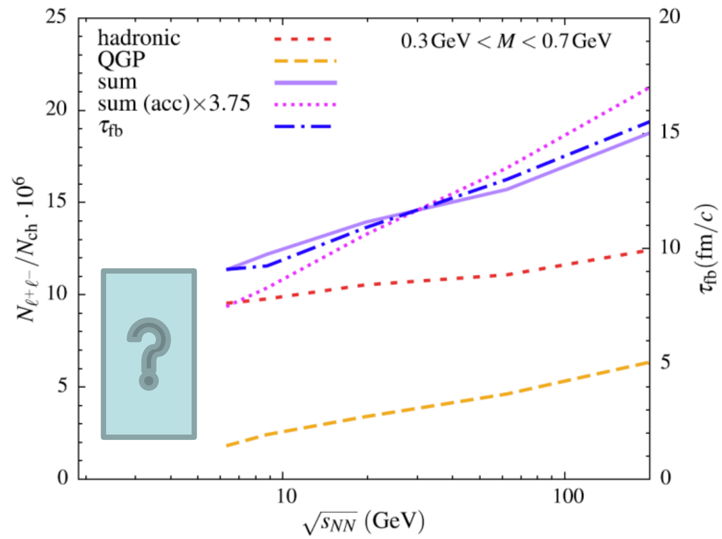
- integrated yield of thermal radiation in the mass range 0.3-0.7 GeV/c² is sensitive to the lifetime of the fireball

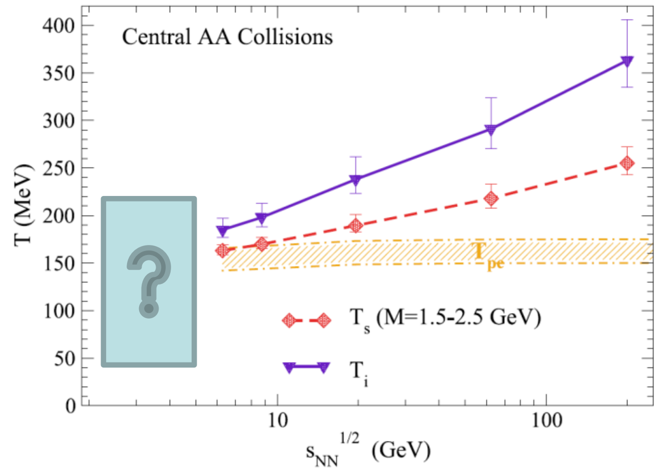
  R. Rapp, H. van Hees: Phys. Lett. B **753** (2016) 586

- dilepton yield determined by interplay between temperature and fireball volume

- slope of dileptons in the intermediate-mass range constitutes a blue-shift free fireball thermometer

- **What happens at low energies?**



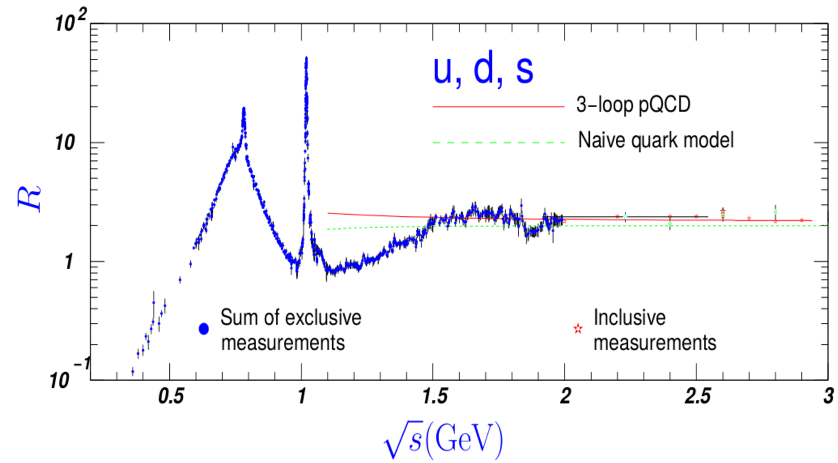


Realistic dilepton emission rates

8-differential thermal production rate

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2}{\pi^3 M^2} f^B(q\cdot u;T)\, \mathrm{Im}\Pi_{EM}(M,q;\mu_B,T)$$

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{\mathrm{Im}\Pi_{EM}^{vac}}{M^2}$$

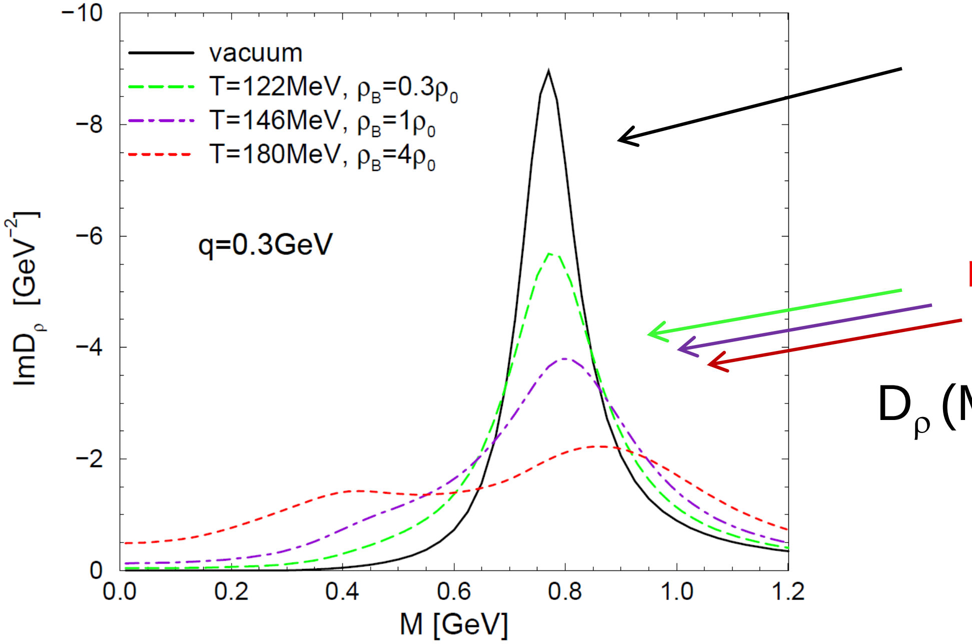


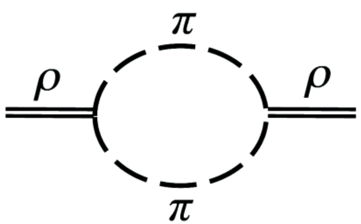
$$\mathrm{Im}\Pi_{EM}^{vac}(M) = \begin{cases} \sum_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 \mathrm{Im}D_v^{vac}(M)\,, & M < M_{dual}^{vac} \simeq 1.5\,\mathrm{GeV/c}^2 \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right) N_c \sum_{q=u,d,s} (e_q)^2\,, & M > M_{dual}^{vac} \end{cases}$$

Realistic dilepton emission rates

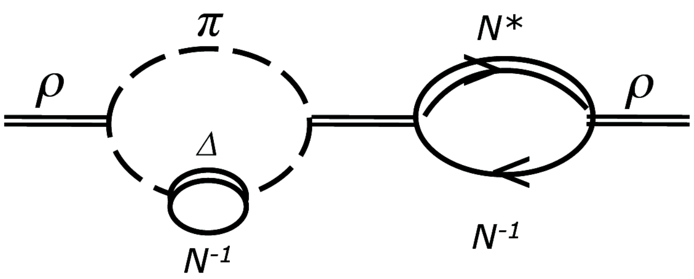
The ρ meson in nuclear matter

R. Rapp, J. Wambach: Eur. Phys. J. A **6** (1999) 415





$$D_\rho(M,q;\mu_B,T) = [M^2 - m_\rho^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]^{-1}$$



The ρ spectral function strongly broadens in the medium as the ρ meson couples to baryons !

additional contributions to the ρ meson self-energy in the medium

Realistic dilepton emission rates

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Hadronic matter

- parameterization of Rapp-Wambach in-medium ρ spectral function

  R. Rapp, J. Wambach: Eur. Phys. J. A **6** (1999) 415

  depends on

  - temperature T
  - effective baryon density ρ_{eff}
  - pion chemical potential μ_π

$$\varrho_{\text{eff}} = \varrho_{\text{N}} + \varrho_{\bar{\text{N}}} + \frac{1}{2}\left(\varrho_{\text{R}} + \varrho_{\bar{\text{R}}}\right)$$

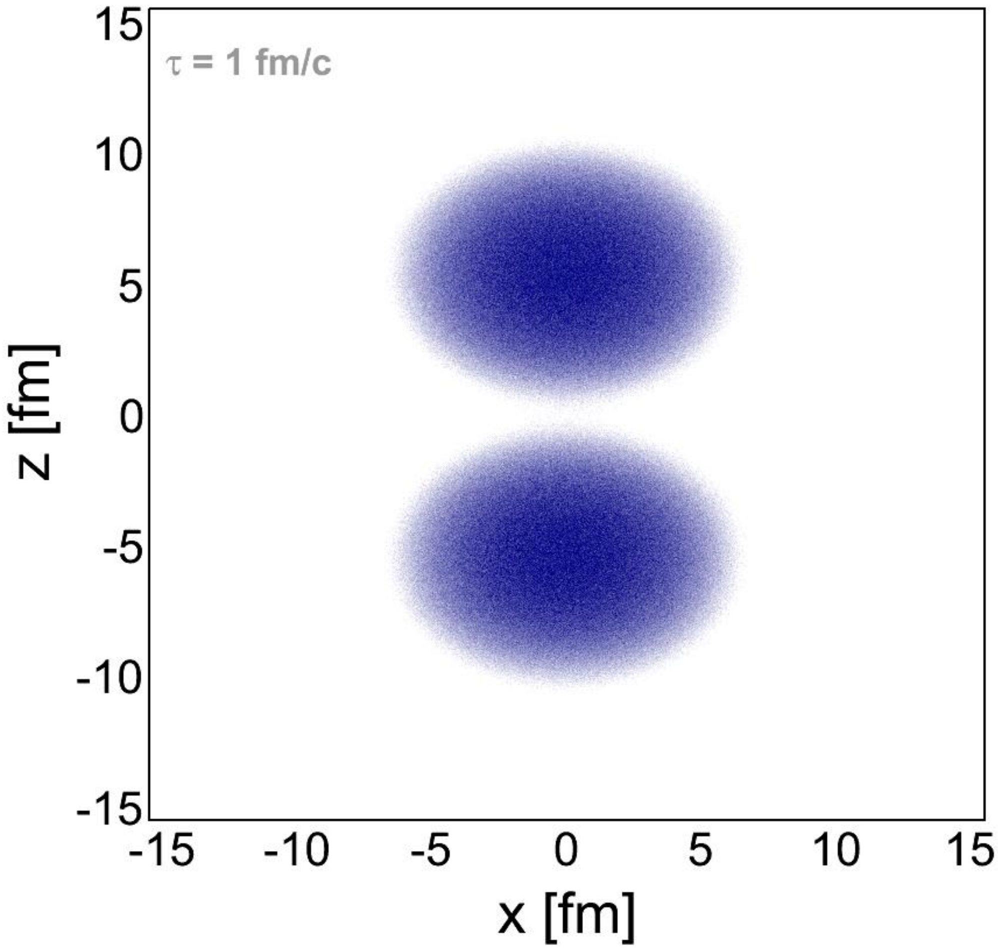
- reproduces excess in experimental data
  - CERES
  - NA60
  - STAR (including BES)
  - PHENIX with HBD

- at higher masses: include hadronic continuum radiation

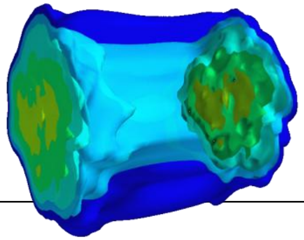
  E. V. Shuryak: Rev. Mod. Phys. **69** (1993) 1

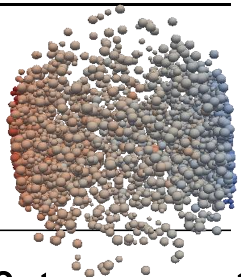
Space-time evolution of a heavy-ion collision

Au+Au at 1.23 AGeV ($\sqrt{s_{NN}}$ = 2.4 GeV) ⇨ HADES energy regime



Description of the fireball evolution





Coarse-graining of hadronic transport

- “combine” the advantages of both descriptions: hydrodynamics & transport
- simulate events with a transport model

  ⟶ ensemble average to obtain smooth space-time distributions

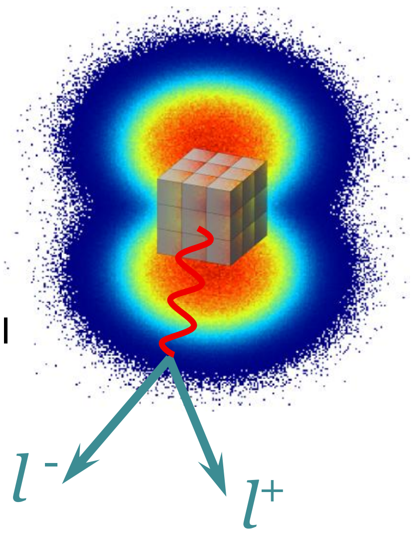
- divide space-time evolution into 4-dimesional cells

  21 x 21 x 21 space cells (1fm^3), 30 time steps ⟶ ~ 280 k cells

- determine for each cell the bulk properties like T, ρ_B & v_{coll}
- calculate dilepton rates based on these inputs

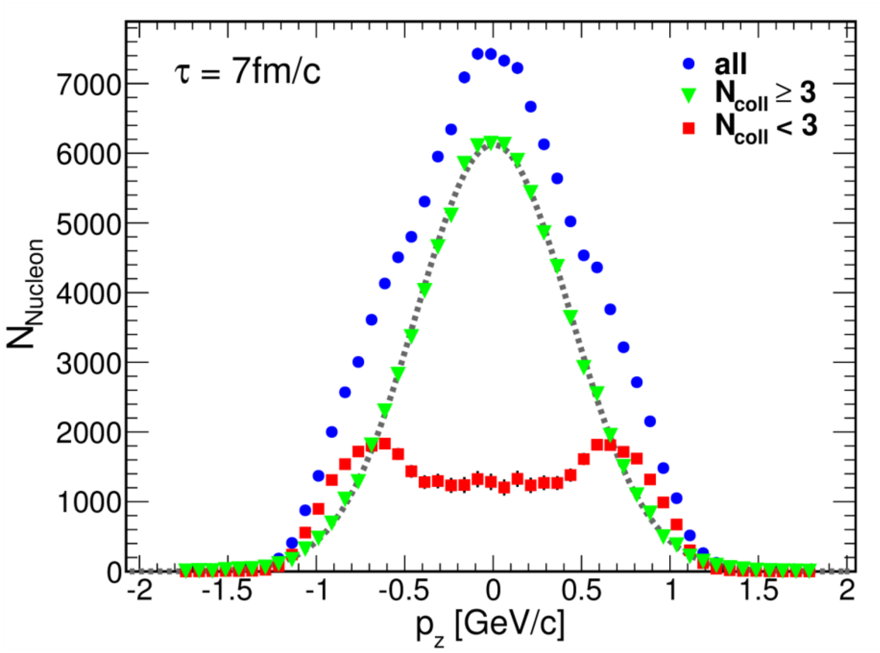
  ⟶ parameterization of RW in-medium spectral function

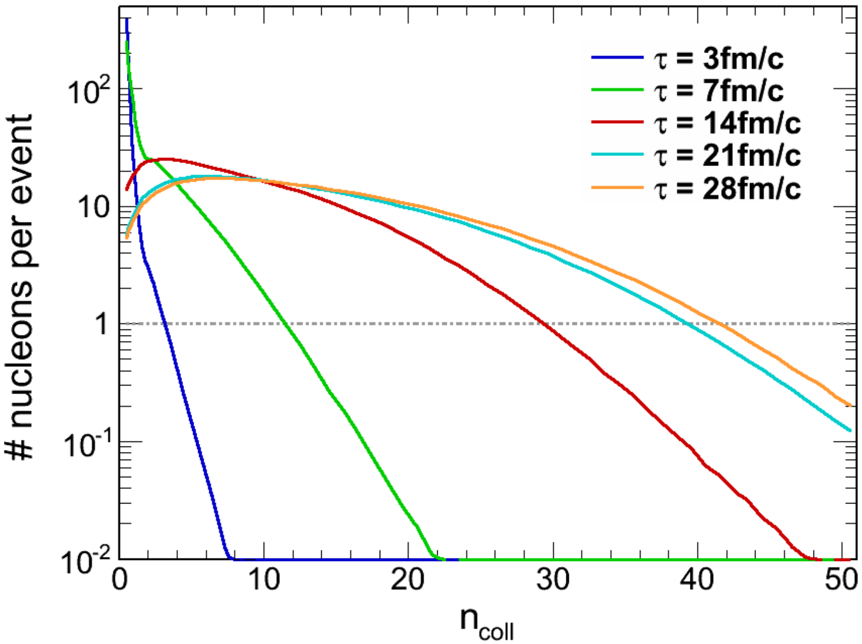
- sum up the contributions of all cells
- similar approaches by
  - Huovinen *et al.*: PRC **66** (2002) 014903
  - Endres *et al.*: PRC **91** (2015) 054911, PRC **92** (2015) 014911, PRC **93** (2016) 054901, PRC **94** (2016) 024912



Local thermalization

Momentum distributions of nucleons ($n_{coll} \geq 3$) & evolution of n_{coll}



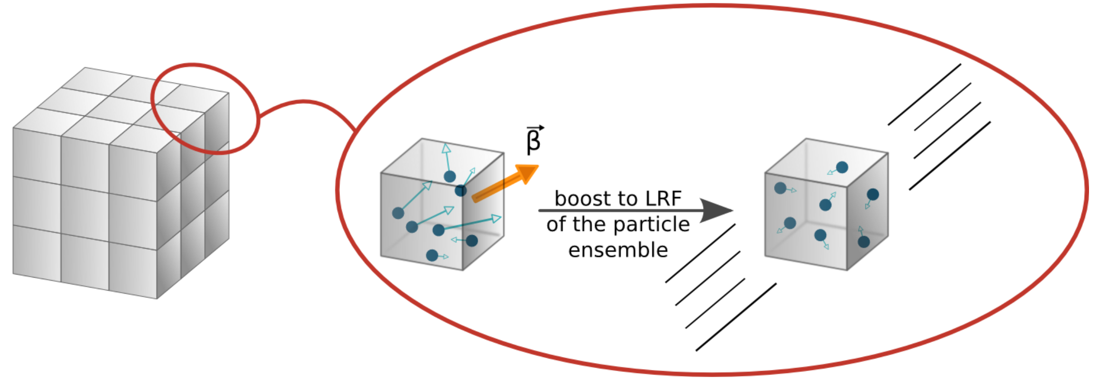


- Gaussian shaped p_z distribution builds up for nucleons with $n_{coll} \geq 3$
- m_t spectra have exponential shape
- check for every cell ⟶ deviations are kept in space-time evolution

Determination of bulk properties

(Baryon) density, collective flow velocity & temperature

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



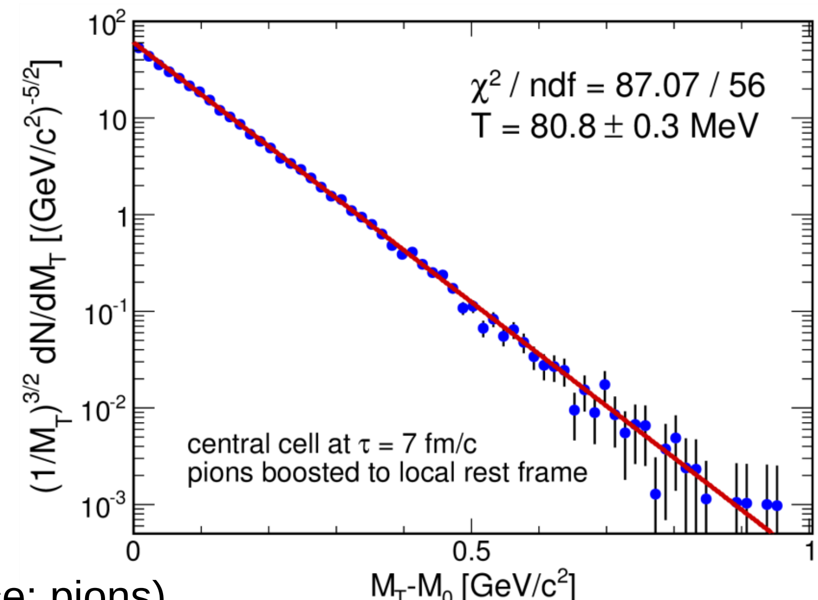
- in Boltzmann approximation

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

$$\Downarrow$$

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

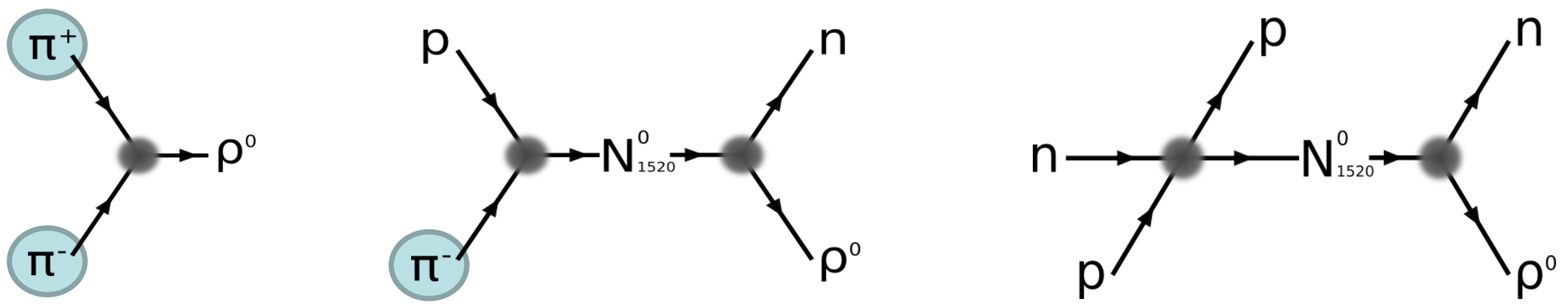
- fill m_t spectra with particle momenta in LRF (mean flow v_{coll} vanishes)
- fit exponential function to extract T (species of choice: pions)



Out of chemical equilibrium?

Build-up of effective chemical potentials

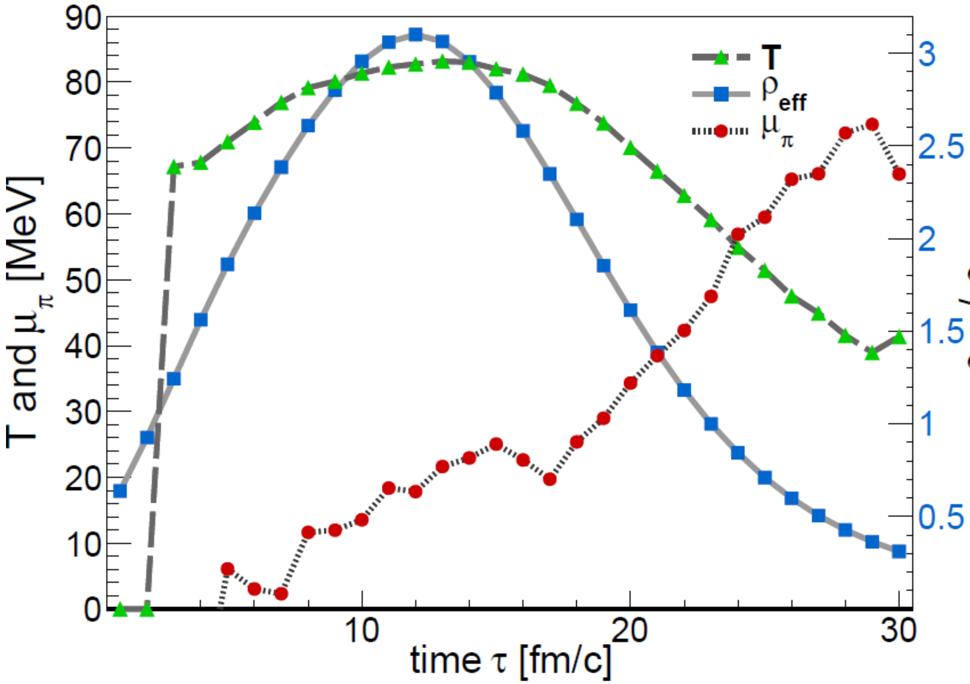
- thermal emission rates assume chemical equilibrium
- chemical non-equilibrium possible, e.g. after chemical freeze-out
  - no more inelastic interactions → pion number conserved
  - system in thermal equilibrium cools down further → over-population of pions
  - build-up of an effective chemical potential μ_π
- induces a factor $(z_\pi)^\kappa$ in the dilepton rates with the fugacity $z = \exp\left(\frac{\mu_\pi}{T}\right)$
  - exponent κ reflects the main production mechanism of ρ mesons
  - at HADES energies UrQMD suggests κ = 1.12

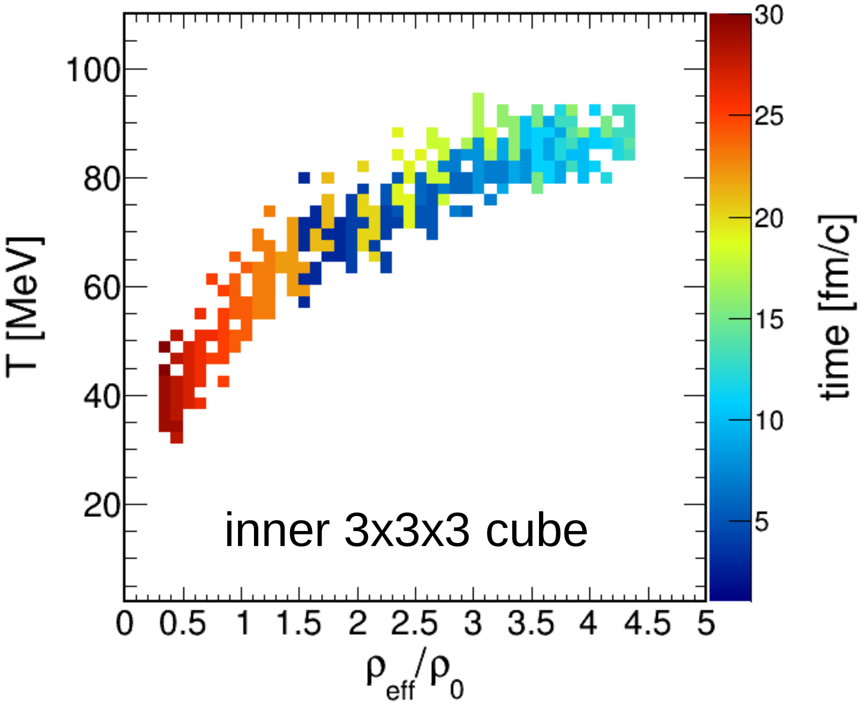


Time-evolution

Au+Au at 1.23 AGeV

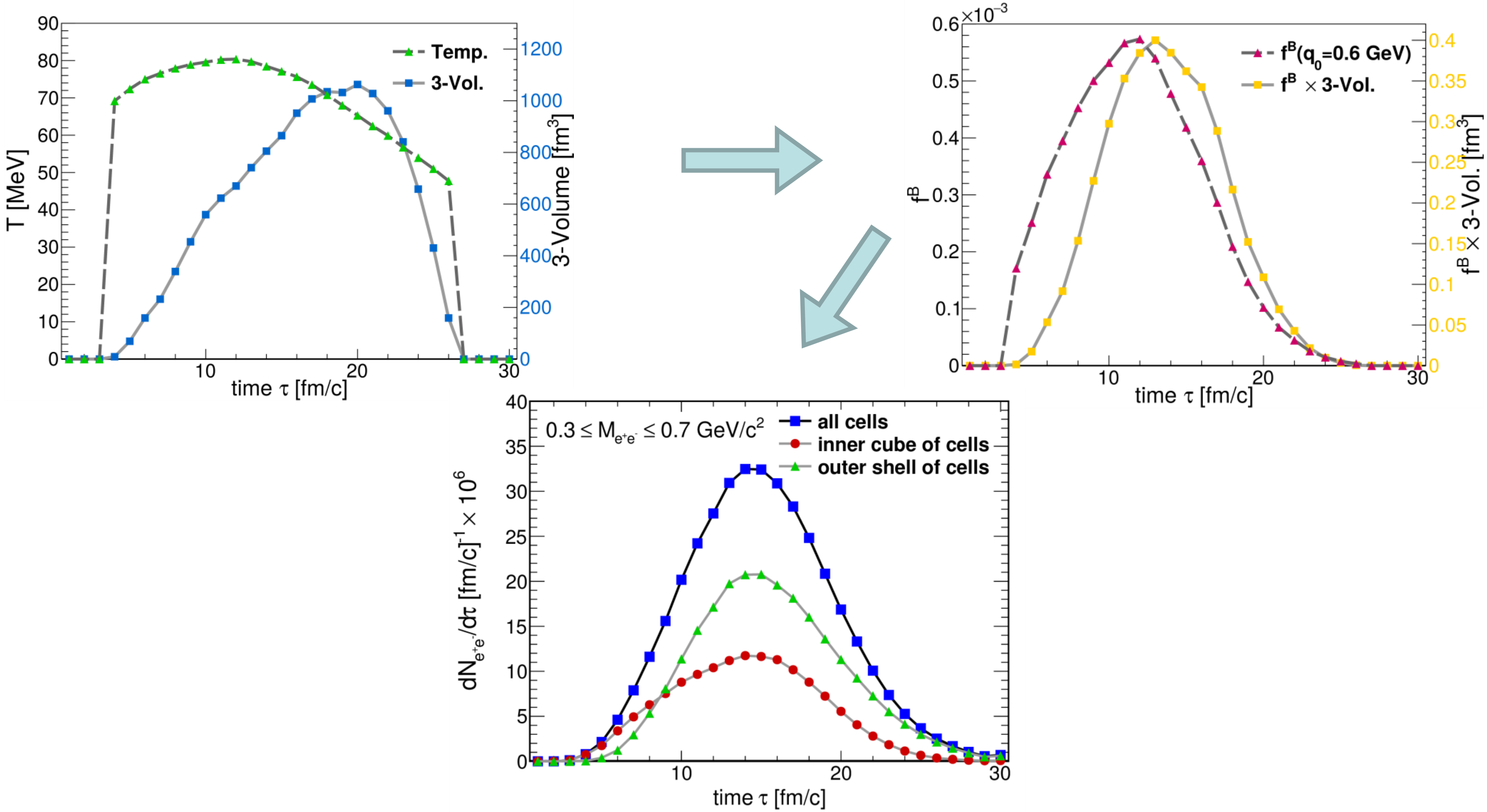
- evolution of T, ρ_{eff} and μ_π in the central cube of 7x7x7 cells
- trajectories of the cells in the temperature-density plane





Interplay temperature – fireball volume

Au+Au at 1.23 AGeV



Dileptons as fireball probes

Au+Au at 1.23 AGeV

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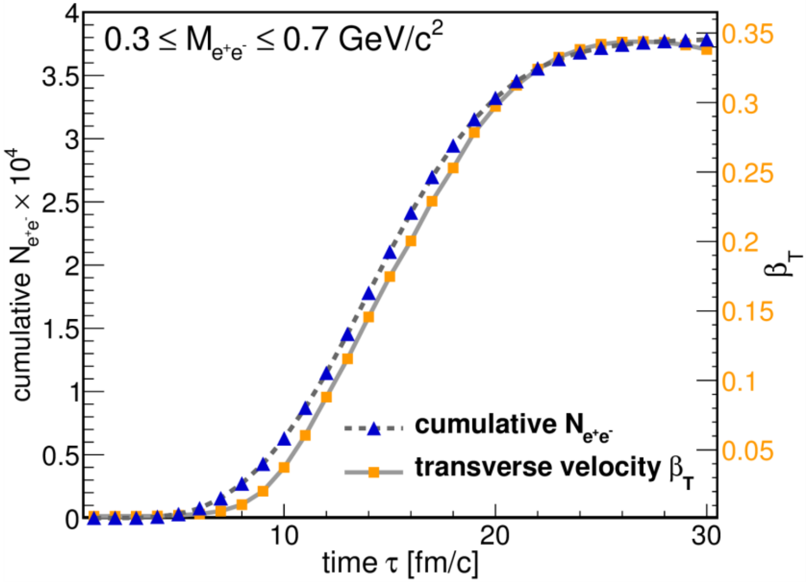
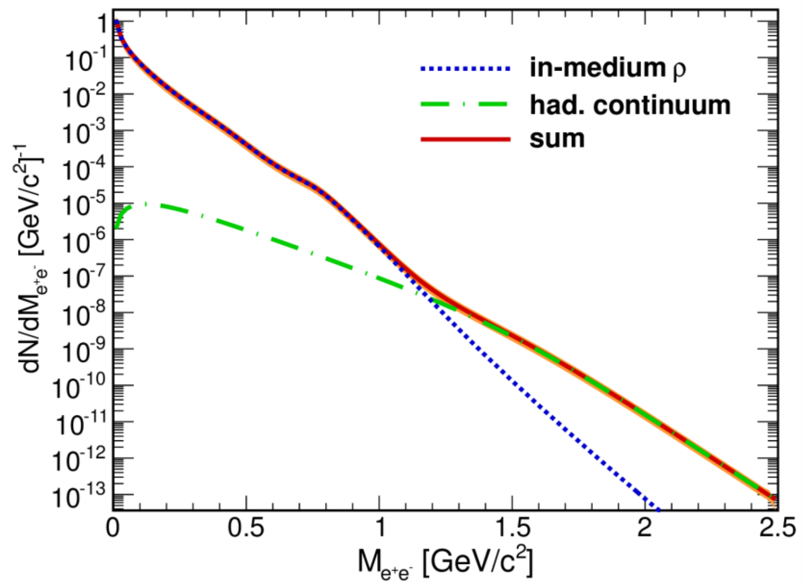
- time evolution of cumulative dilepton yield in mass window M = 0.3-0.7 GeV/c^2
- active radiation window ~13 fm/c follows build-up of collective medium flow ⇨ fireball lifetime
- strong medium effects on ρ-meson ⇨ remarkably structure-less low-mass spectrum
- $\mathrm{d}R_{ll}/\mathrm{d}M \propto (MT)^{3/2} \exp(-M/T)$
- inverse slope parameter: T_S = 88 ± 5 MeV in IMR, T_S = 64 ± 5 MeV in LMR



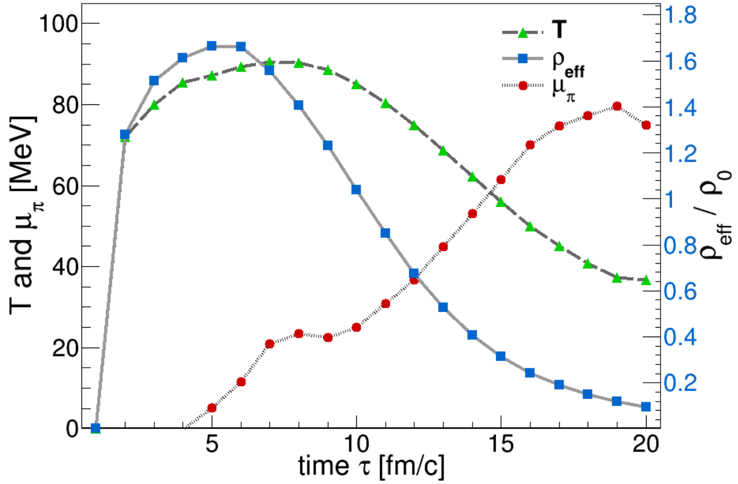


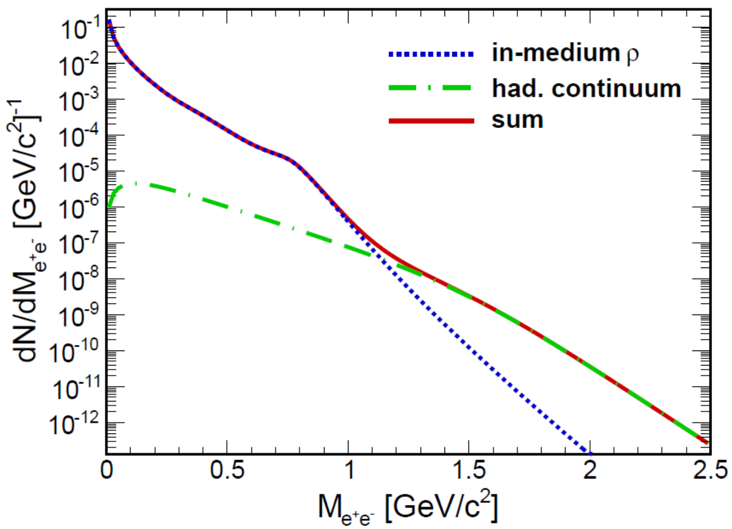
T. Galatyuk *et al.*: Eur. Phys. J. A **52** (2016) 131

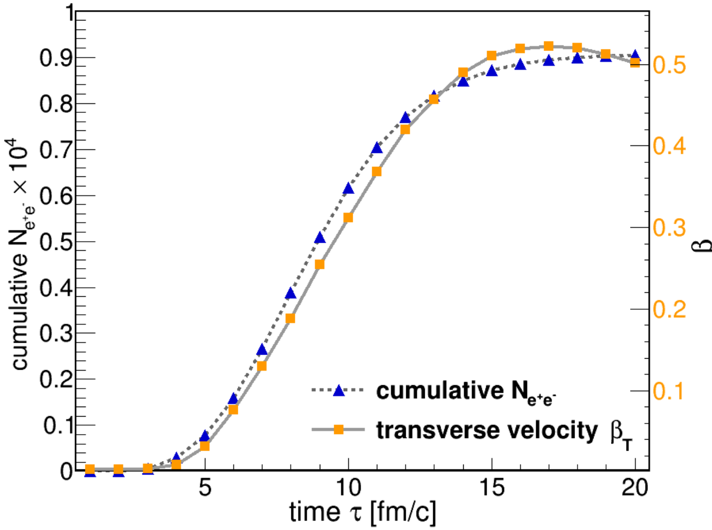
Dileptons as fireball probes

Ar+KCl at 1.76 AGeV ($\sqrt{s_{NN}}$ = 2.6 GeV)

- evolution of T, ρ_{eff} and μ_π in the inner cube of 5x5x5 cells
- invariant mass spectrum for the thermal radiation
- window for dilepton radiation & build-up of collectivity ~ 8fm/c







FS *et al.*, CPOD2016 proceedings

Excitation function of dilepton production

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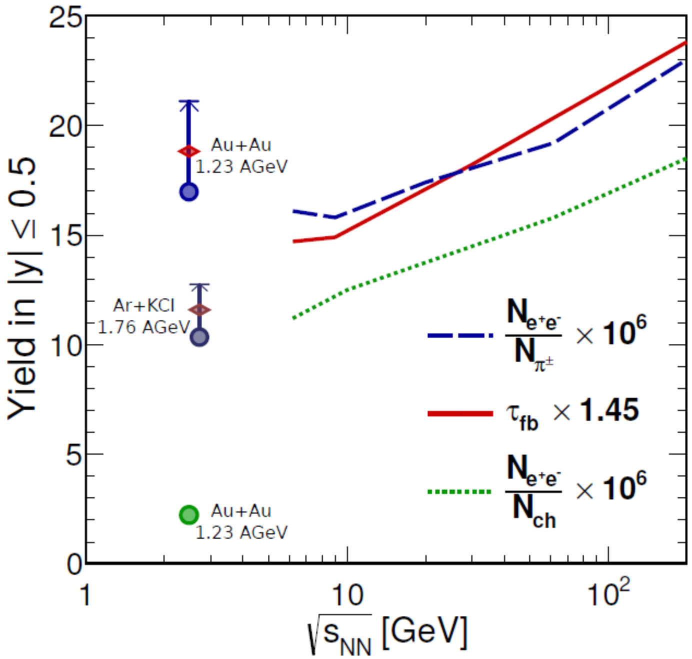
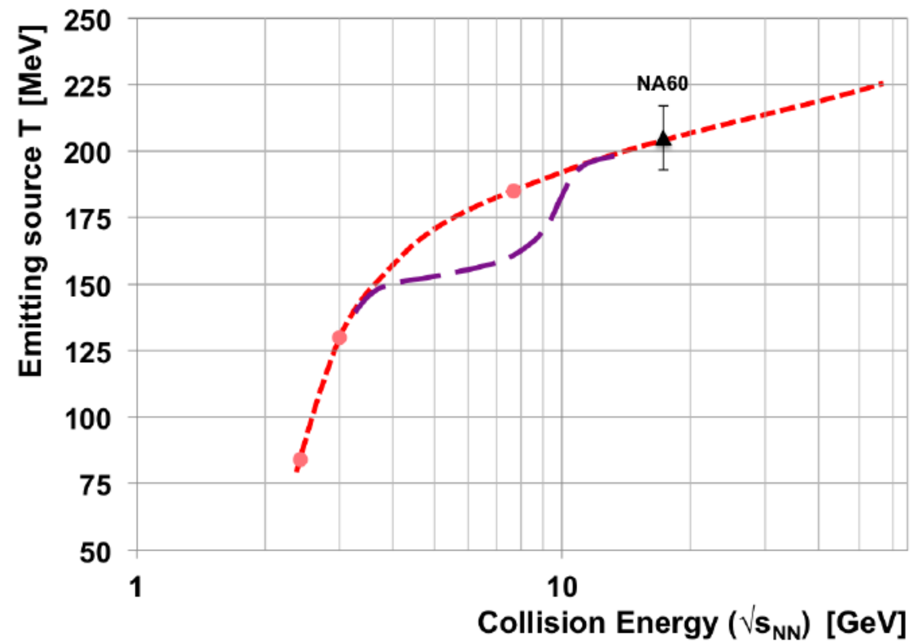
Yield in low-mass window tracks fireball lifetime



FS *et al.*, CPOD2016 proceedings

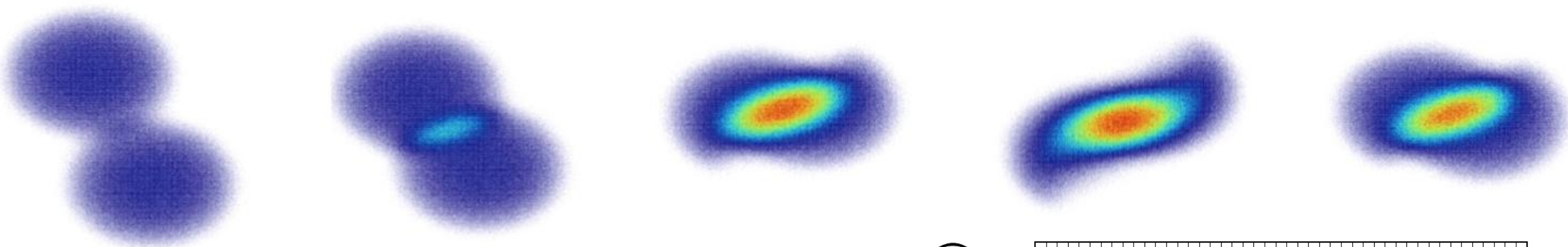


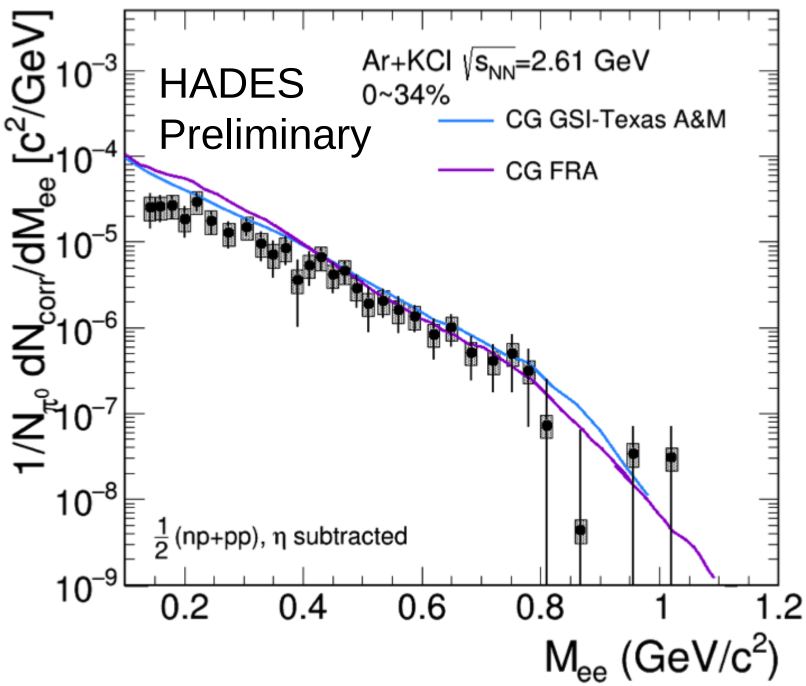
CBM coll., Eur. Phys. J. A **53** (2017) 60

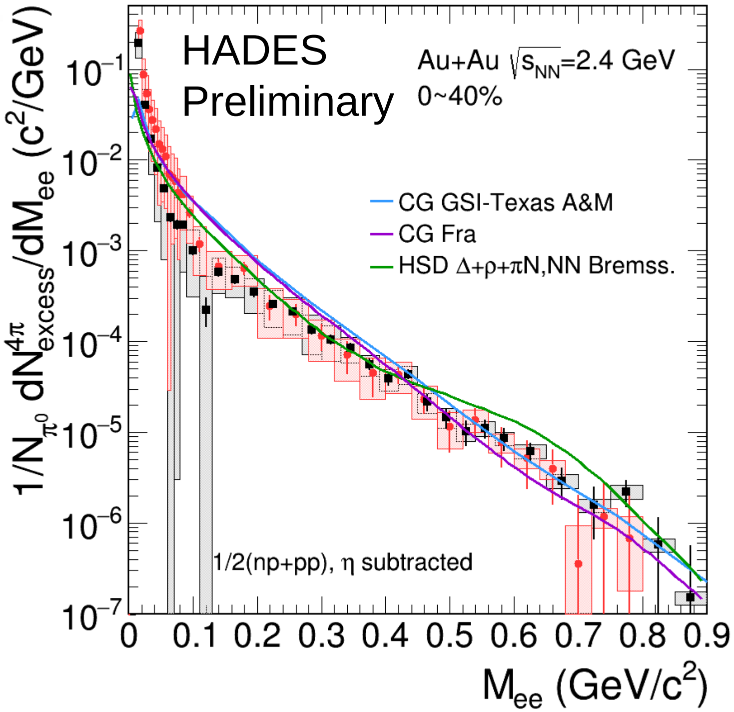
- fireball dominated by incoming nucleons at lower energies
- number of charged particles N_{ch} not a good proxy for thermal excitation energy
- normalization to number of charged pions N_π
- lifetime from dilepton yield in mass window 0.3-0.7 GeV/c²: $\frac{N_{l^+l^-}}{N_{\pi^\pm}} \cdot 10^6 \simeq 1.45 \cdot \tau_{\text{fb}}$

Comparison to experimental excess spectra

Ar+KCl at 1.76 AGeV & Au+Au at 1.23 AGeV (min. bias)

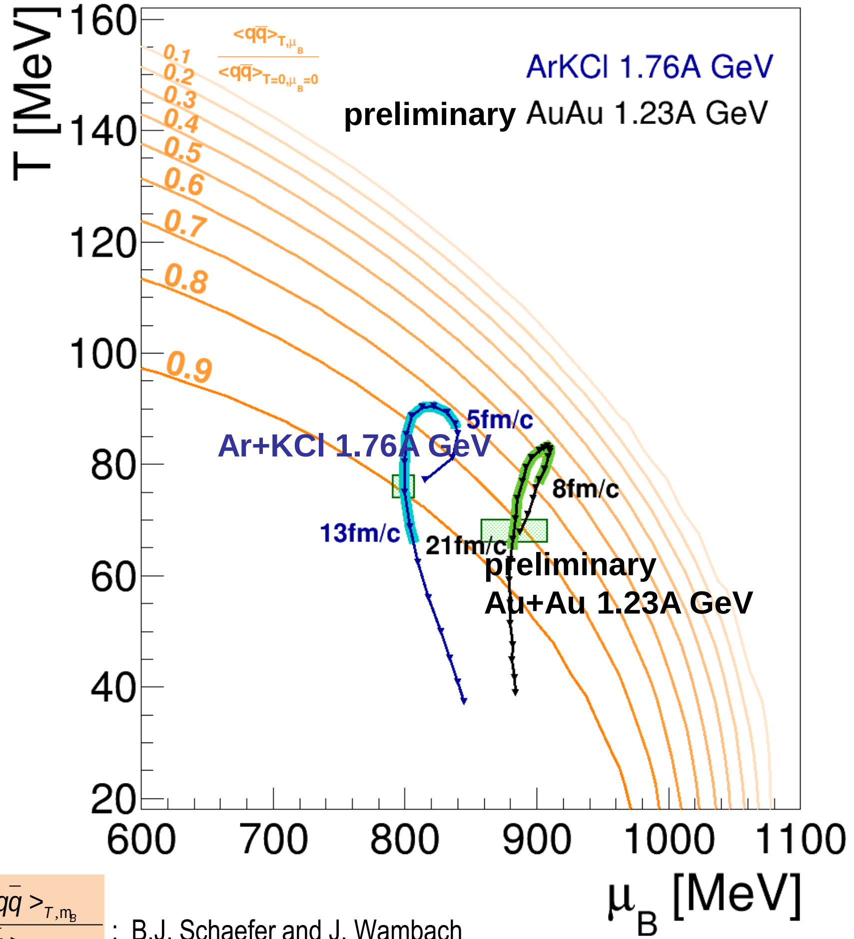






Exploring the QCD phase diagram –

– with dileptons



$\frac{<q\bar{q}>_{T,\mu_B}}{<q\bar{q}>_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

- chemical freeze-out from measured particle yields analyzed with SHM THERMUS 2.3
- trajectories extracted from inner cube of cells with coarse-grained UrQMD
- time-window of dilepton emission
  - radiation stops shortly after chemical freeze-out
  - access to hot and dense stage of the heavy-ion collision

Exploring the QCD phase diagram –

– with dileptons

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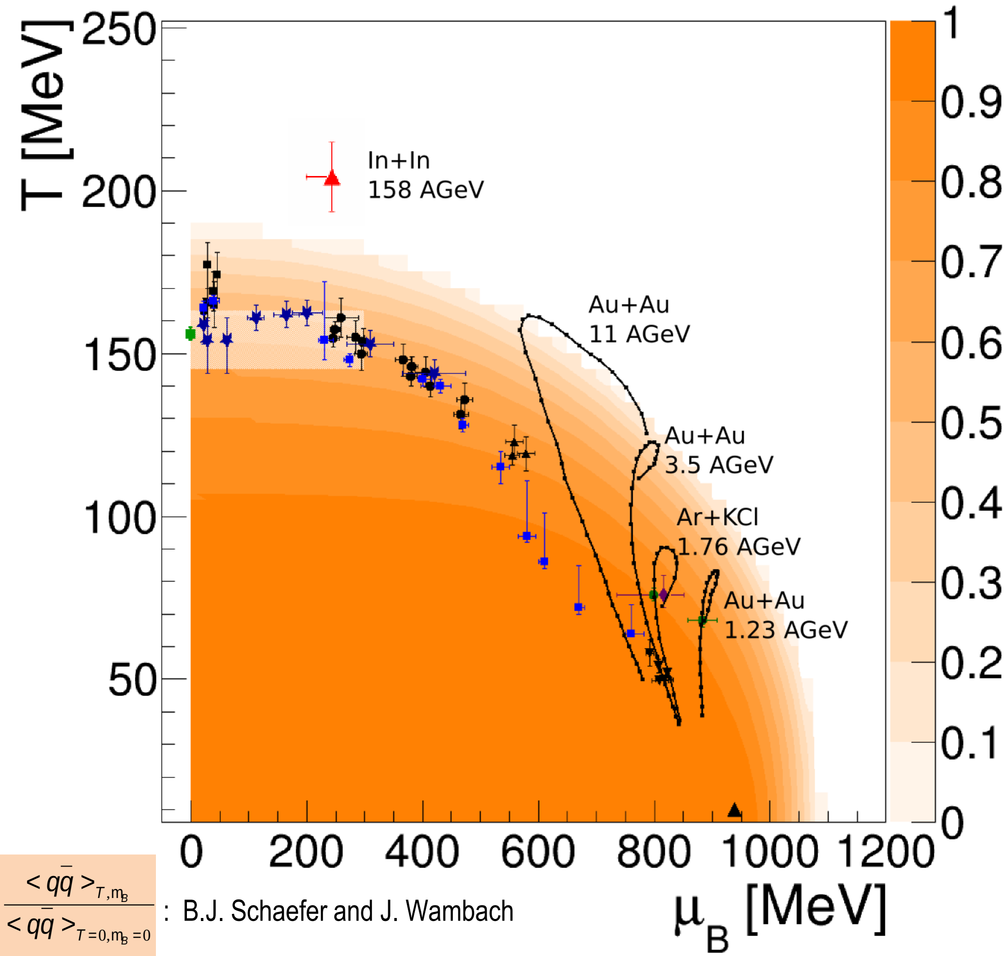


$\frac{< q\bar{q} >_{T,m_B}}{< q\bar{q} >_{T=0,m_B=0}}$: B.J. Schaefer and J. Wambach

▲ NA60 (μ+μ-) : H.J.Specht: AIP Conf. Proc. 1322 (2010)

- NA60 intermediate mass $\mu^+\mu^-$
- trajectories at SIS18
- trajectories at SIS100

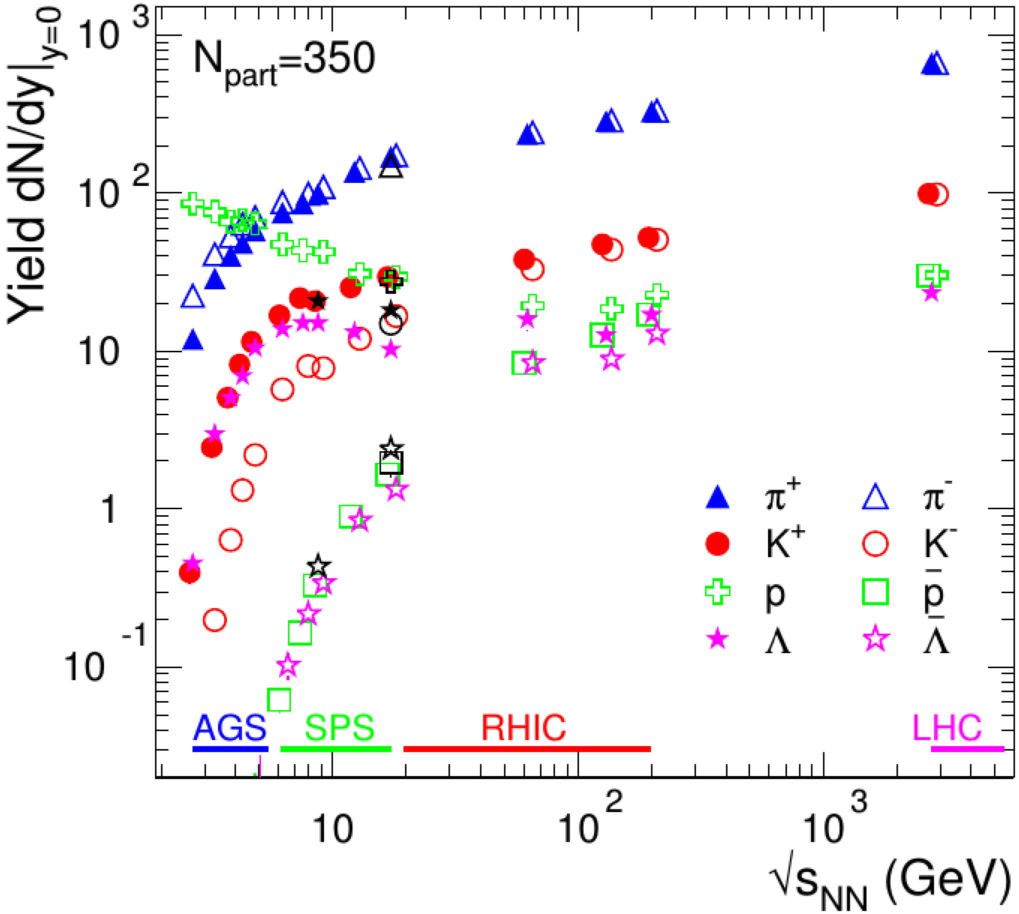
Summary

THANK YOU FOR YOUR ATTENTION !

- dileptons are excellent fireball probes
  - thermometer & chronometer
  - new insights into the matter created under extreme conditions
- thermal dilepton spectra from highest to lowest energies
  - realistic thermal dilepton emission rates
  - accurate description of fireball evolution in terms of T, ρ_{eff}, v_{coll} and μ_{π}
  - coarse-graining of hadronic transport at SIS energies
- baseline for future experimental explorations
  - any significant deviation can indicate new physics!

Backup slides

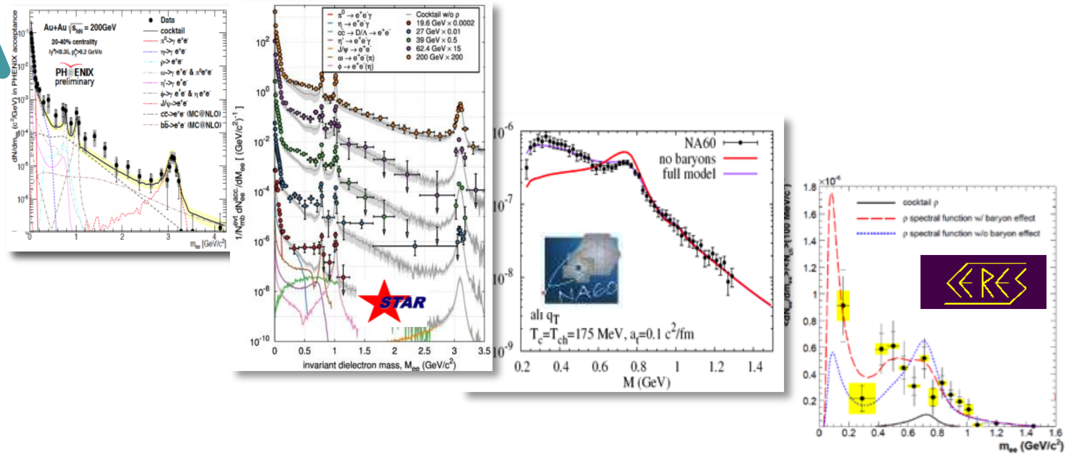
Excitation function of hadron yields



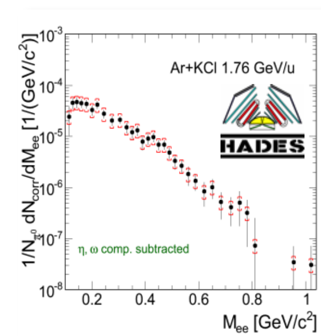
A. Andronic, arXiv:1407.5003

Virtual photon radiation from hot and dense QCD matter

T



Model: Ralf Rapp
STAR: QM2014,
NA60: EPJC 59 (2009) 607,
CERES: Phys. Lett. B 666 (2006) 425,
HADES: Phys.Rev.C84 (2011) 014902

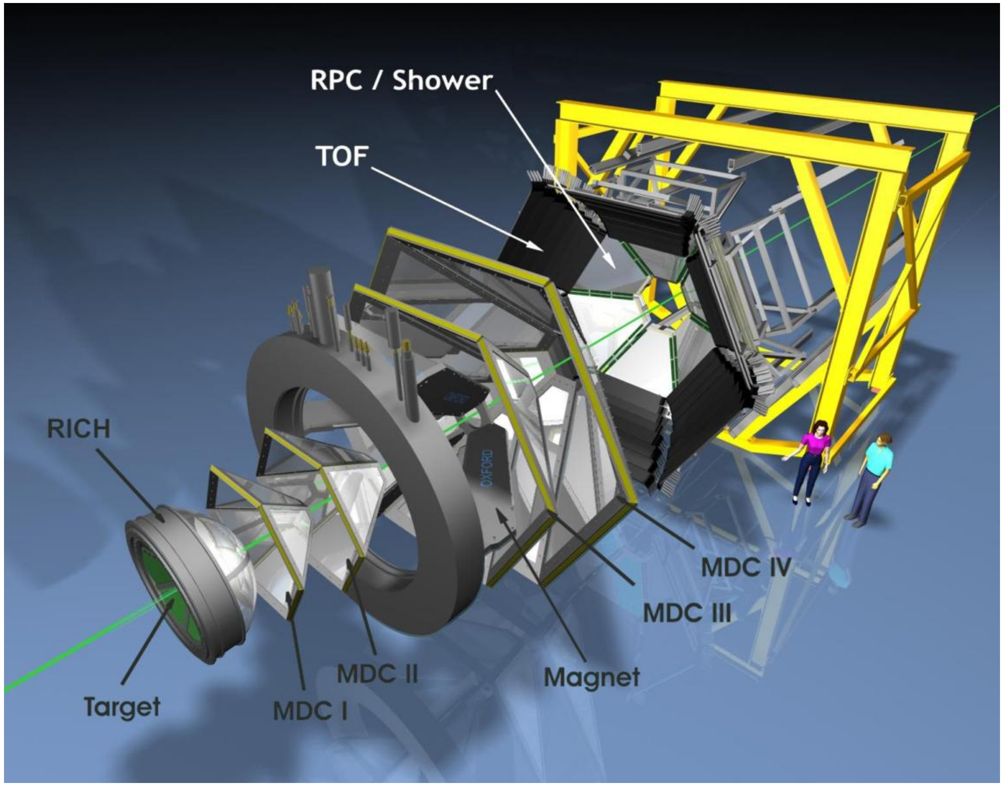


highly interesting results from RHIC, SPS, SIS18
→ lepton pairs as true messengers
of the dense phase

μ_B

HADES at GSI, Darmstadt

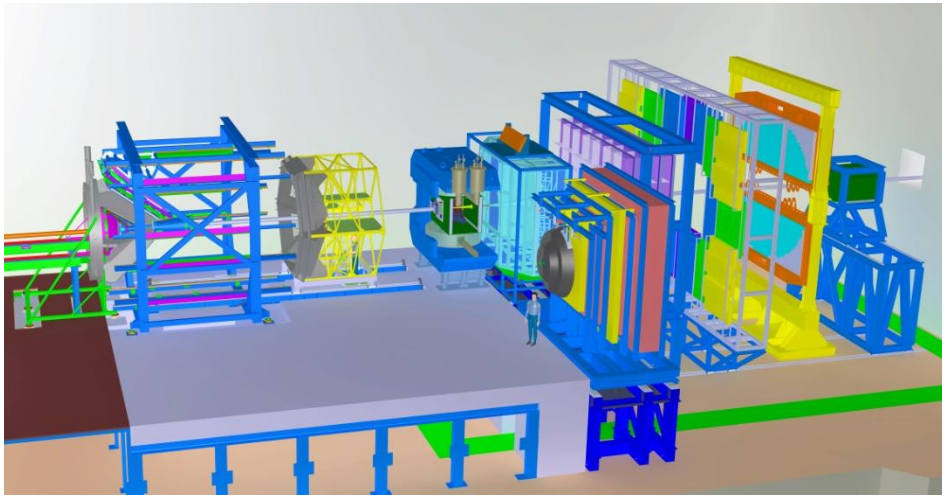
- Fixed target
- 50 kHz event rate (400 Mbyte/s peak data rate)
- Full azimuthal coverage, 18° to 85° in polar angle
- Hadron and lepton identification:
  - Tracking with 4x6 Multiwire Drift Chambers and superconducting magnet
  - Time of flight measurement with ToF and RPC Walls
  - Specific energy loss in MDC and ToF
  - RICH and shower detectors to identify leptons



CBM at the future FAIR facility, Darmstadt

- QCD matter equation of state at neutron star core densities studied in heavy-ion collisions
  - Observable: collective phenomena in charged particle phase space distributions
- restoration of chiral symmetry (ρ-a_1 mixing) observed in heavy-ion collisions
  - Observable: yield of intermediate mass lepton pairs
- evidence for a first order phase transition in QCD matter

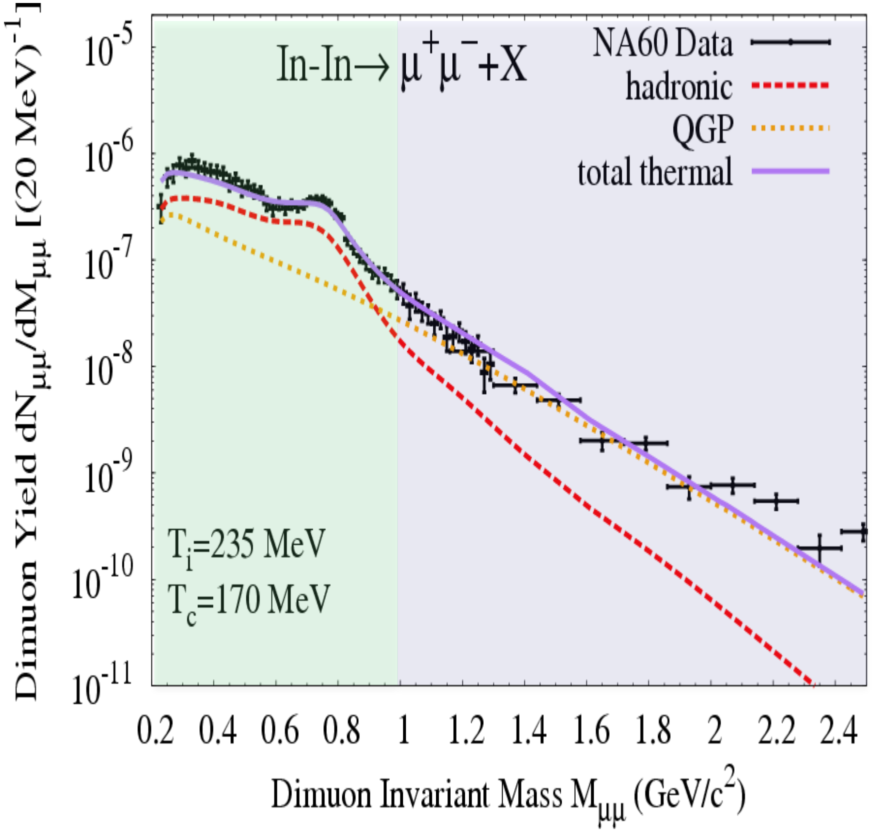
  Observables:
  - excitation function of temperatures measured with intermediate mass dileptons
  - excitation function of the yield of multi-antistrange hyperons
- extension of the nuclear chart into the strange sector



Dileptons

Invariant-mass spectrum

Invariant-mass excess spectrum



NA60 ($\mu+\mu$-) : H.J.Specht: AIP Conf.Proc. 1322 (2010)
Model: van Hees + Rapp, 2013

LMR:

broadening of ρ-spectral function

- larger excess in support of the decisive role of baryon interactions, will get maximal at low energies (HADES)
- linked to the chiral symmetry restoration (yet in model dependent way!)

measure excitation function of ρ-spectral function

- critical point?
- first order phase transition?

IMR:

- ρ-a_1 chiral mixing → signal for χ-symmetry restoration
- onset of QGP radiation

measure:

- $\pi a_1 \rightarrow e^+e^-(\mu^+\mu^-)$ dominant source at SIS 100 energies (correlated charm, Drell-Yan and QGP contributions decrease with lower the beam energy)
  → direct access to ρ-a_1 chiral mixing
- decrease of T for lower beam energies (R.Rapp, arXiv:1411.4612v1 [hep-ph])
  → plateau around onset of deconfinement?

Determination of bulk properties

Temperature

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

changing from p_t to m_t and from p_z to y & integrating over the angles yields

$$\frac{d^2N}{dy\, dm_t} \propto 2\pi\, m_t\, E\, \exp(-E/T)$$

integrating over rapidity yields

$$\frac{dN}{dm_t} \propto 2\pi\, m_t^2 \cdot 2\, K_1\left(\frac{m_t}{T}\right)$$

approximating the Bessel function for large arguments

$$\frac{dN}{dm_t} \propto 2\pi\, m_t^2 \cdot 2\left(\frac{T}{m_t}\right)^{1/2} \exp(-m_t/T)$$

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

- subtract mean flow of the cells from particle motion
- fill m_t spectra & fit exponential function to extract T
- use different fit ranges to get the systematics

Out of chemical equilibrium ?

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Derivation of the effective chemical potentials

- particle density in Boltzmann approximation

$$n = \frac{g}{(2\pi)^3} \int_{\mathbb{R}^3} d^3\vec{p}\ \exp(-\beta\ (E-\mu))$$

- moving fugacity z in front of the integral & integrating over the angles

$$n = \frac{4\pi\ g}{(2\pi)^3}\ z \int_0^\infty dp\ p^2\ \exp(-\beta\ \sqrt{p^2+m^2})$$

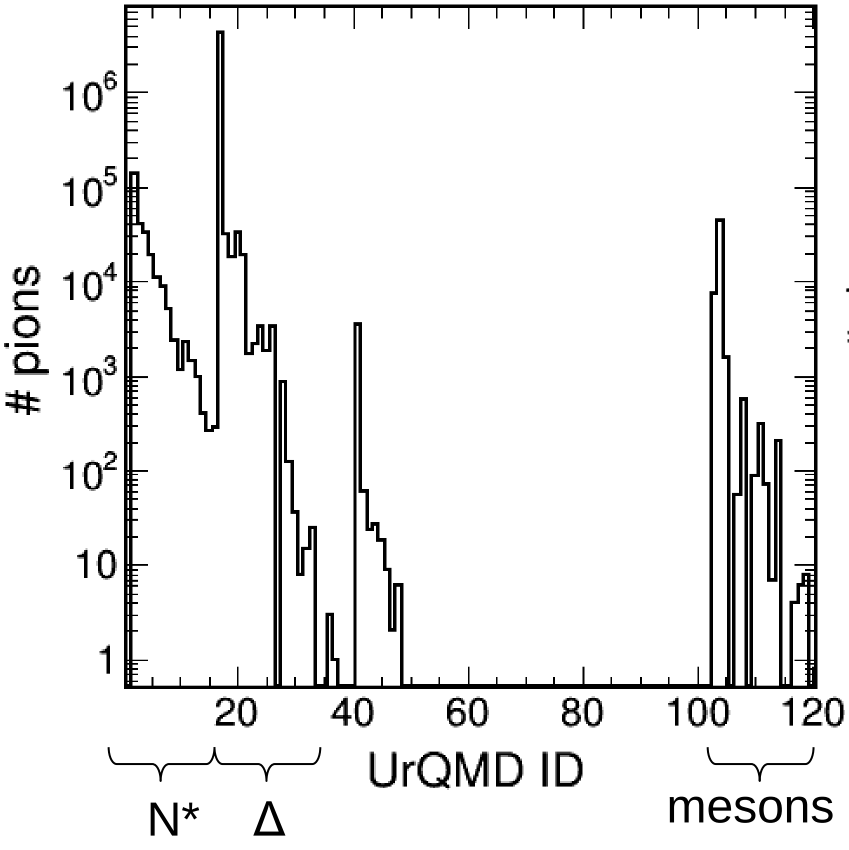
- carrying out the momentum integral yields $n = \frac{4\pi\ g\ m^3}{(2\pi)^3}\ z\ \frac{1}{\beta\ m} K_2(\beta m)$

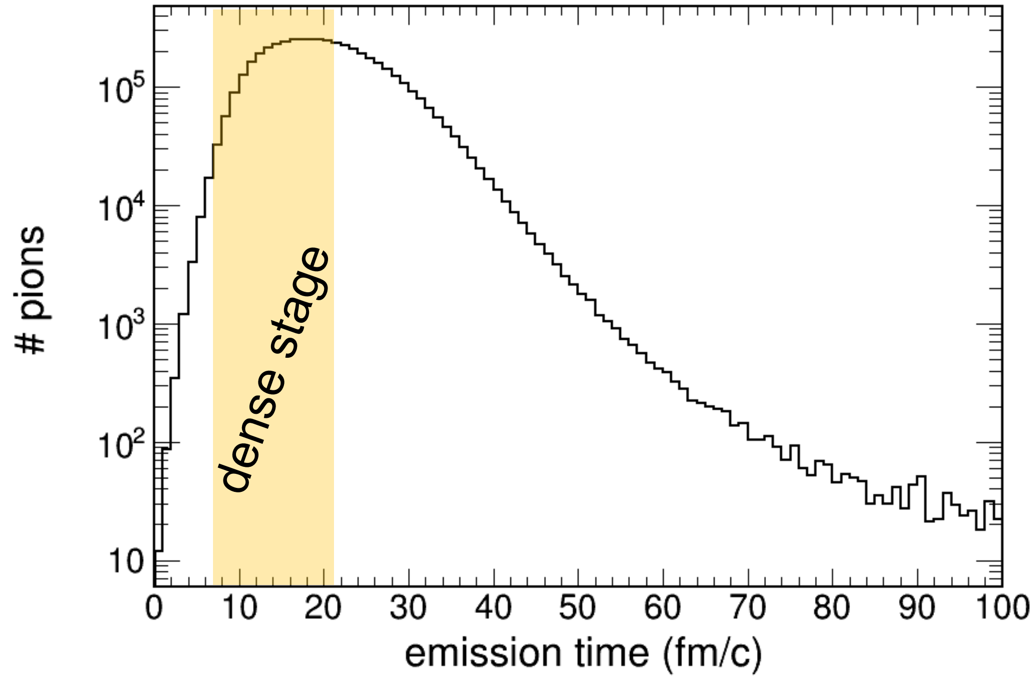
- solving for the chemical potential results in

$$\mu = T\ \ln\left(\frac{2\pi^2\ n\ (\hbar c)^3}{g\ T\ m^2\ K_2\left(\frac{m}{T}\right)}\right)$$

Final-state pion cocktail

PID of mother particle

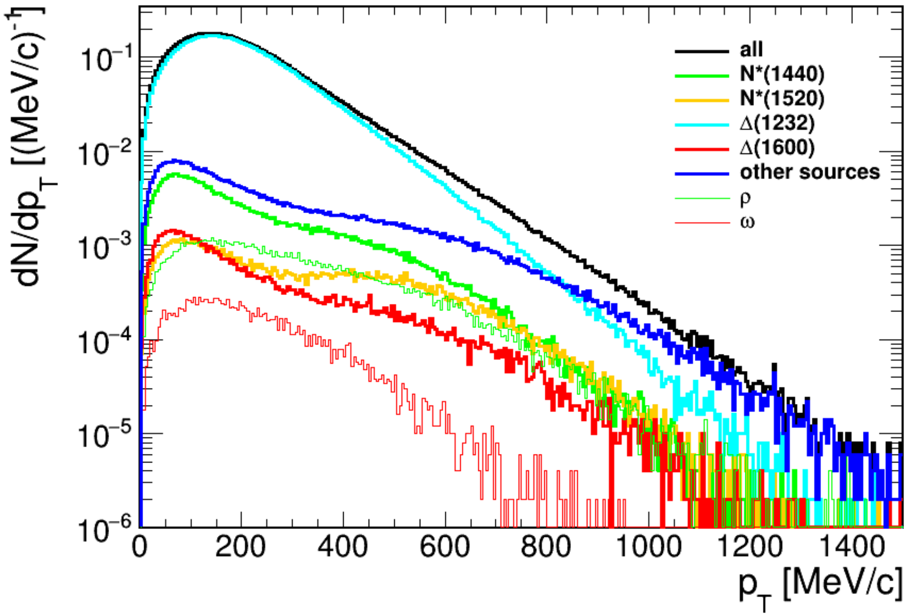


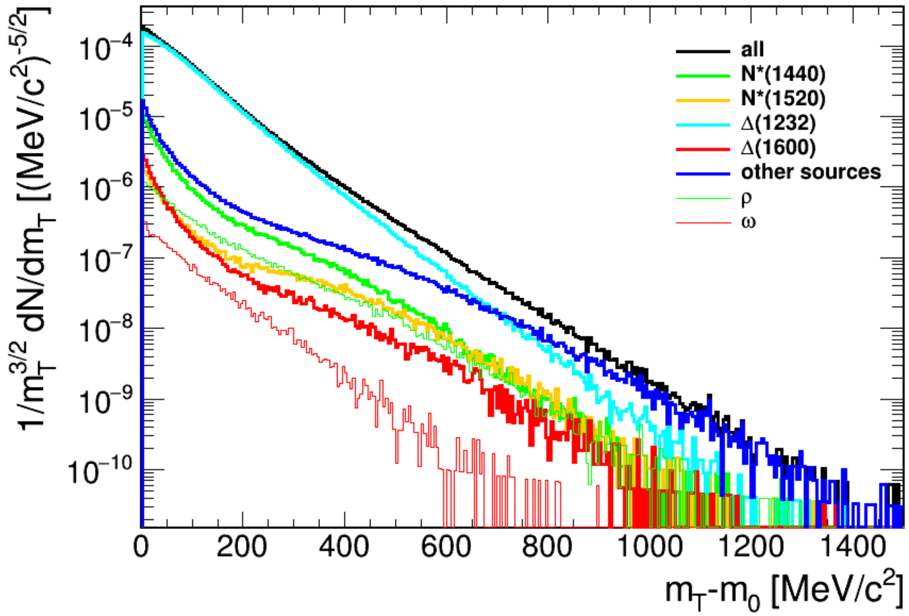


- 90% (95%) of pions are emitted before 30 (40) fm/c

Final-state pion spectra

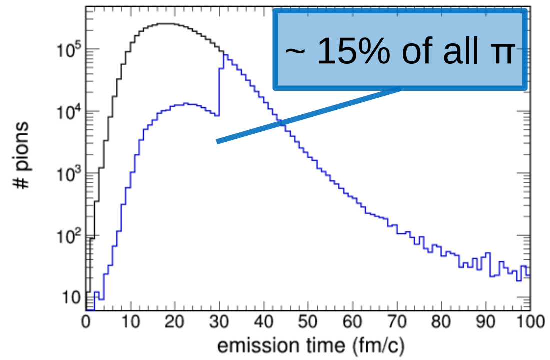
- Dominant contribution: Δ(1232) decays (cyan)
- Many more resonances contribute especially at higher p_T

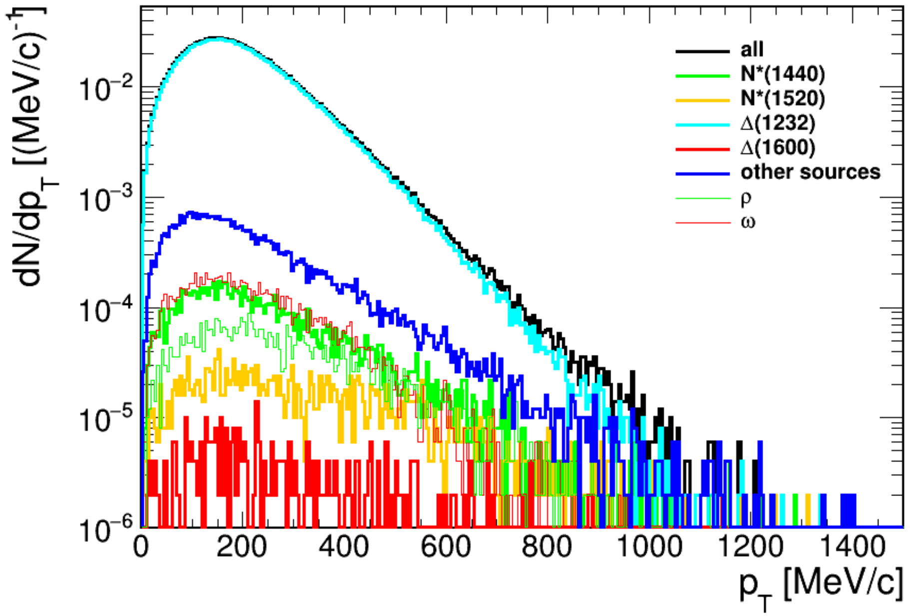


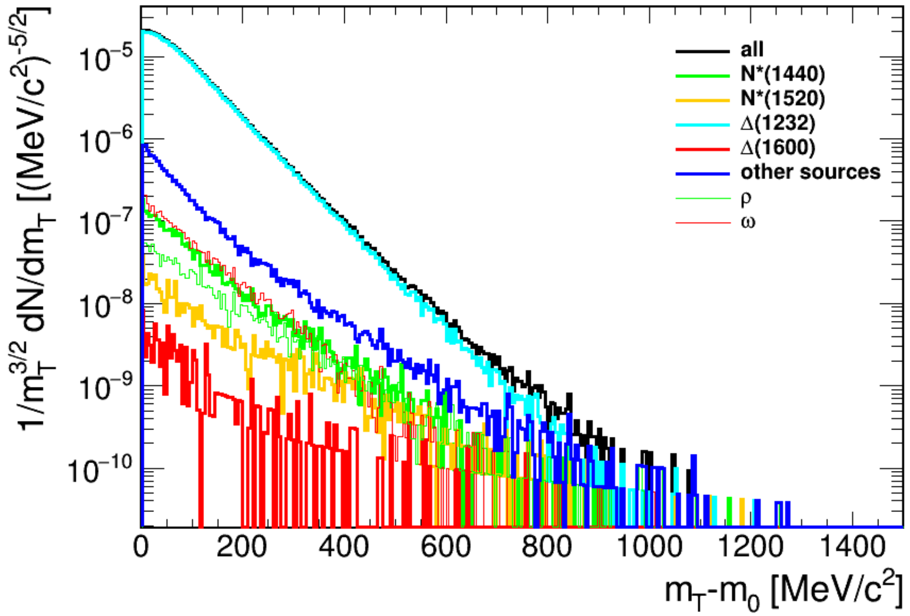


Final-state pion spectra: density dependent

$\rho/\rho_0 < 0.1$ at emission or $t_{emission} > 30fm/c$

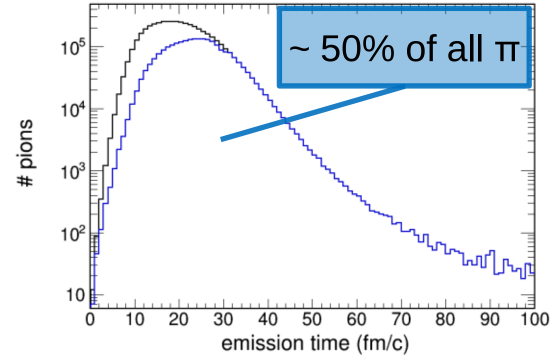


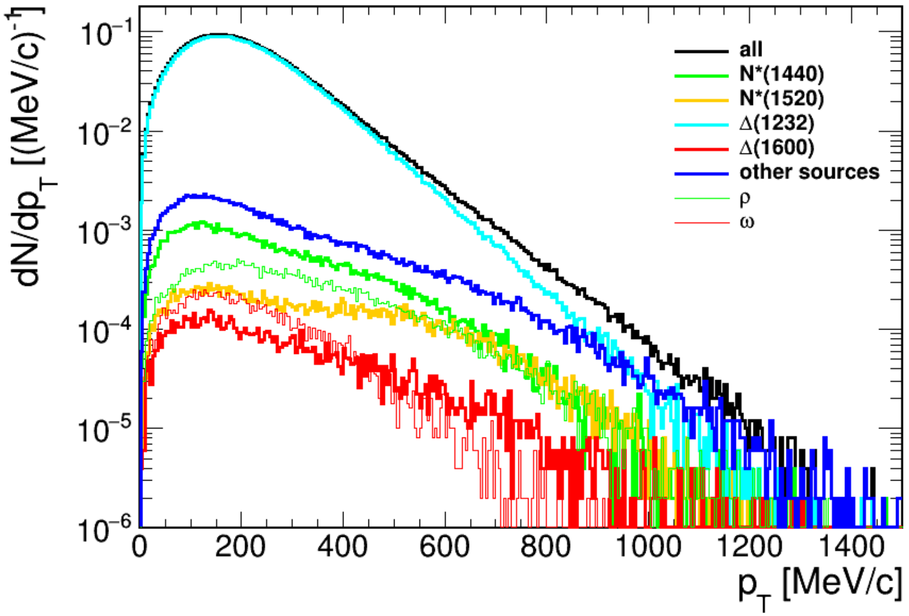


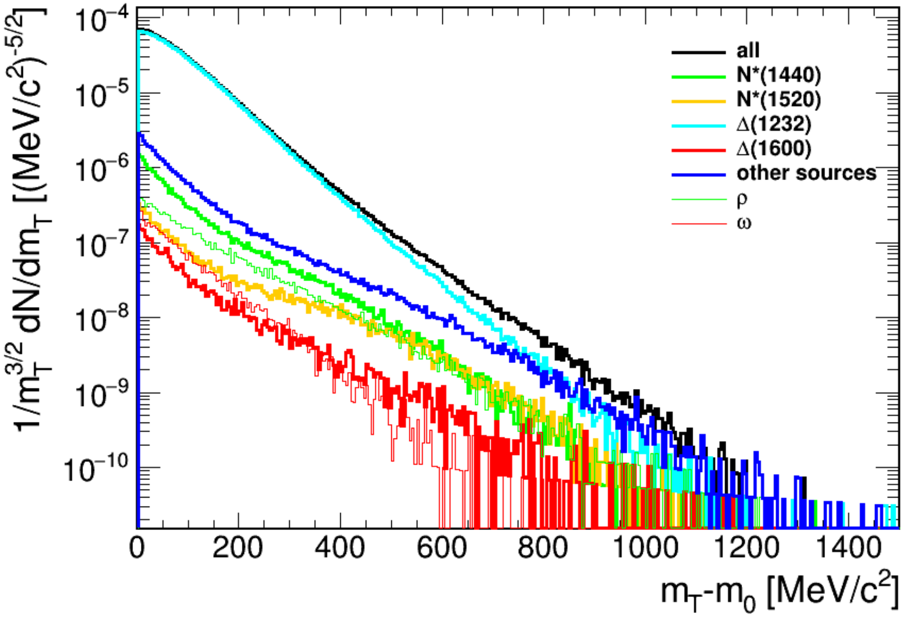


Final-state pion spectra: density dependent

$\rho/\rho_0 < 0.5$ at emission or $t_{emission} > 30$fm/c







Final-state pion spectra: density dependent

$\rho/\rho_0 > 1$ at emission