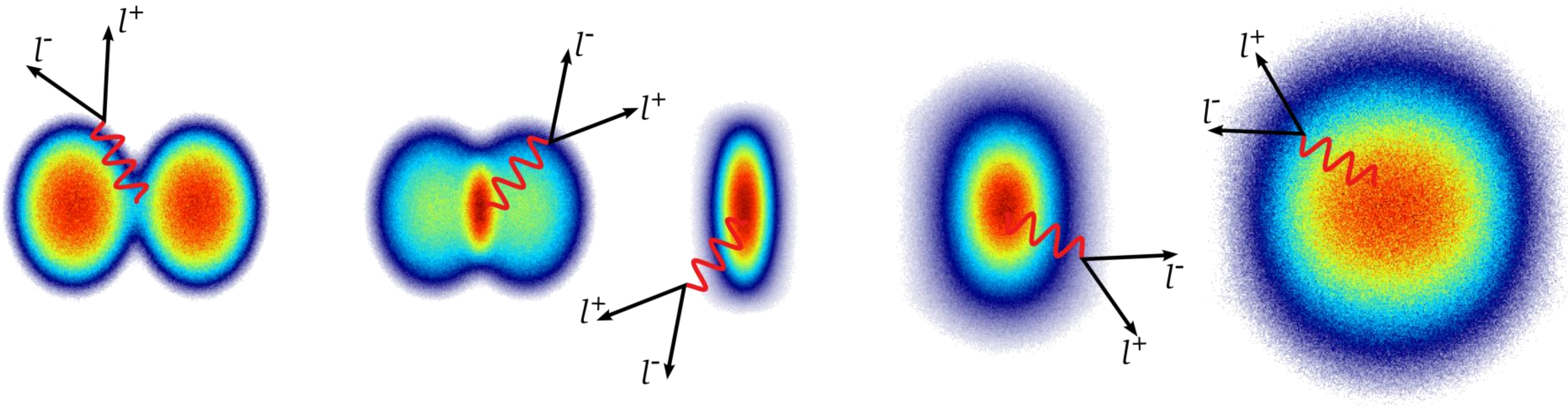
Thermal dileptons as fireball probes at SIS energies

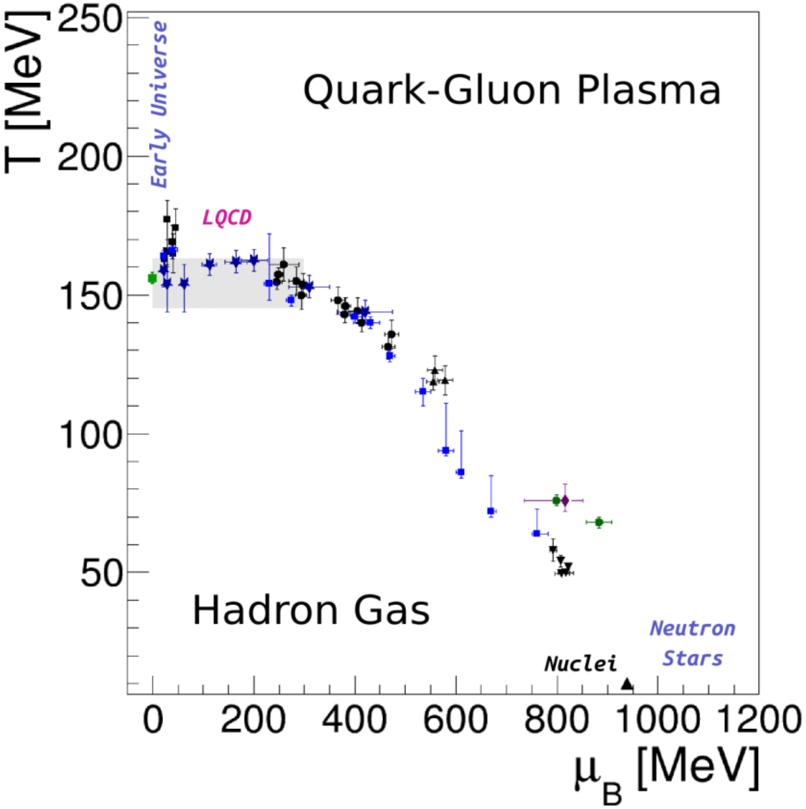
Critical Point and Onset of Deconfinement 2016, Wrocław

Florian Seck – TU Darmstadt

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



Landmarks in the phase diagram of QCD matter



- What do we know?
  - chemical „freeze-out“ from measured particle yields analyzed with Statistical Hadronization Model (SHM)
  - crossover transition at vanishing μ_B (lattice QCD)

SHM : J. Cleymans: PRC 73 (2006) 034905, A. Andronic PLB 673 (2009) 142
ALICE : J. Stachel, arXiv:1311.4662
STAR : PRC 79 (2009) 034909
HADES : NPA 931 (2014)
FOPI : PRC 76 (2007) 052203
Lattice : $T_c(\mu_B) = 154(9)\,[1-0.0006(7)\mu_B^2]$ MeV

Landmarks in the phase diagram of QCD matter

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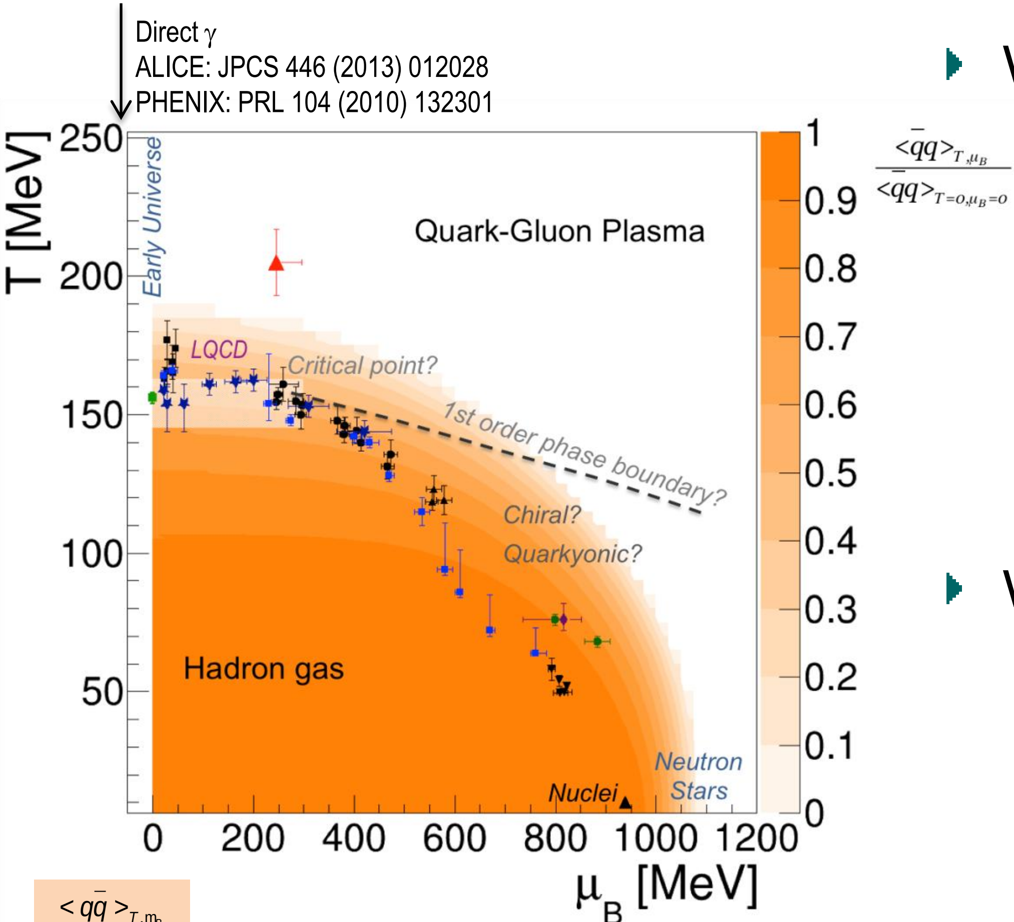


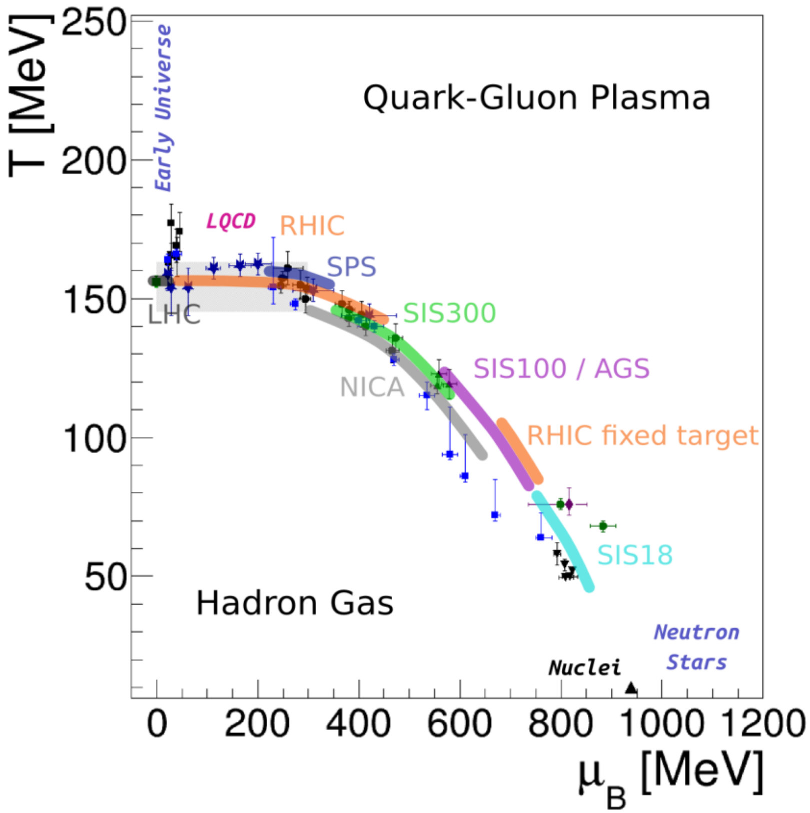
$\frac{<\bar{q}q>_{T,\mu_B}}{<\bar{q}q>_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

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

- What do we know?
  - chemical „freeze-out“ from measured particle yields analyzed with Statistical Hadronization Model (SHM)
  - crossover transition at vanishing μ_B (lattice QCD)
- What is predicted?
  - possible 1st order phase transition and critical point at large μ_B
  - QCD inspired effective models predict melting of the χ condensate

CBM HADES VIP

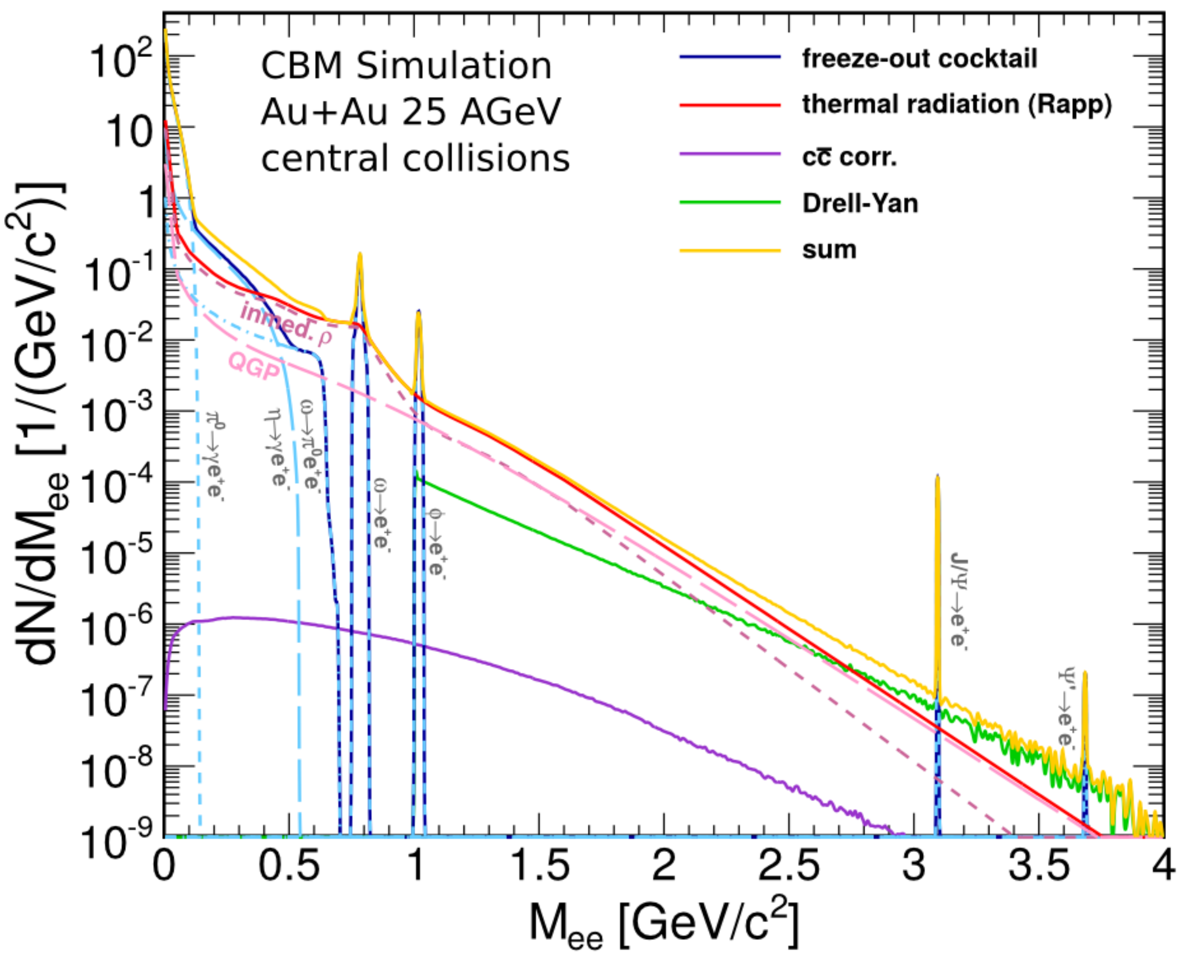
Exploring QCD phase structure with heavy-ion experiments using rare probes



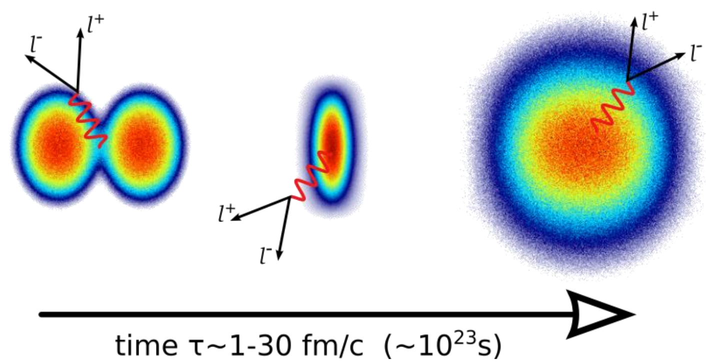
- What could be done?
  - phase boundary(ies)
    - → fluctuations of conserved quantum numbers
    - → flavor production (multi-strange, charm)
  - change in microscopic degrees of freedom
  - restoration of chiral symmetry
  - emitting source temperature
    - → electromagnetic probes leave collision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

Electromagnetic probes in heavy-ion collisions

CBM cocktail – invariant mass of dielectrons



dilepton spectra reflect the whole history of a collision



➡ necessary ingredients:

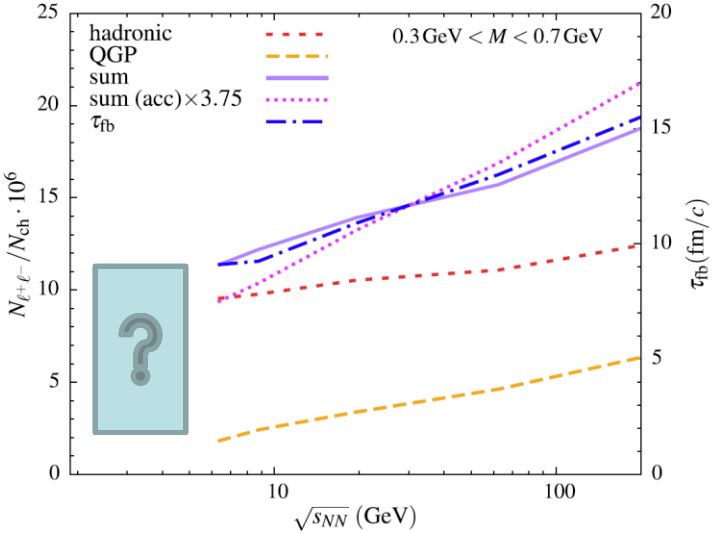
- realistic emission rates
- accurate description of fireball evolution

Electromagnetic probes in heavy-ion collisions

Insights from theory

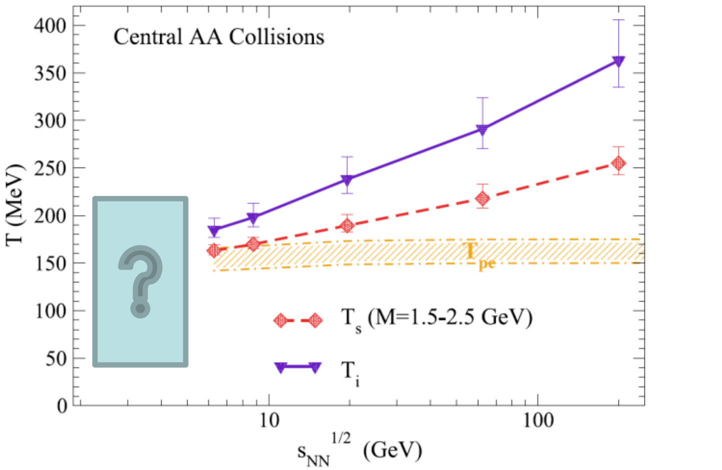
- integrated yield of thermal radiation in the mass range 0.3-0.7 GeV/c² is sensitive to the lifetime of the fireball

  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

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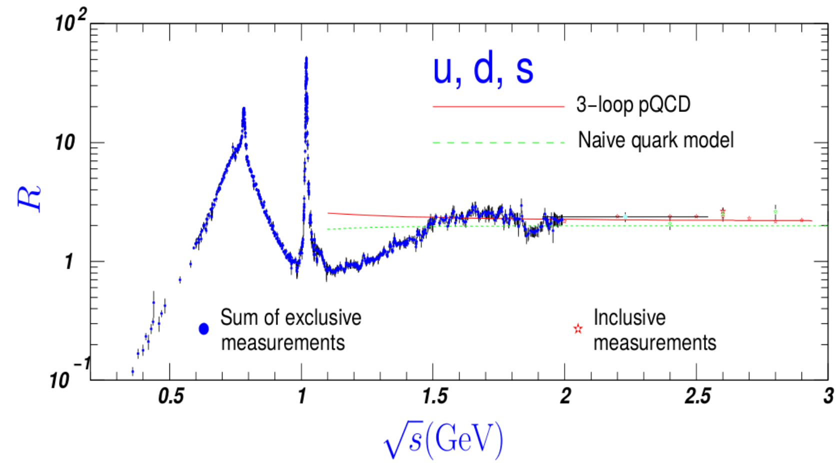
8-differential thermal production rate

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

$$R = \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \propto \frac{{\rm Im}\Pi^{\rm vac}_{\rm EM}}{M^2}$$

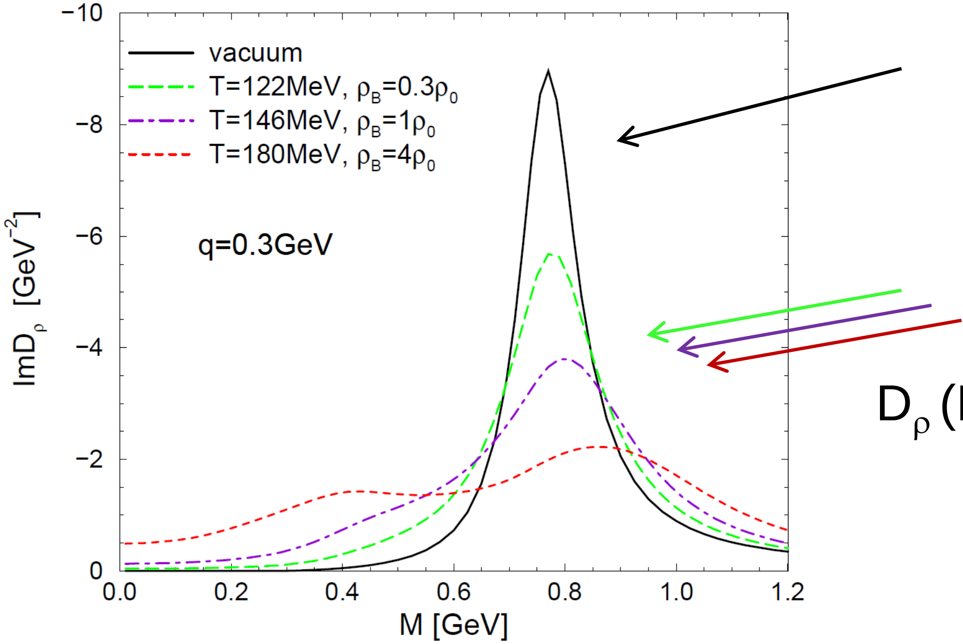


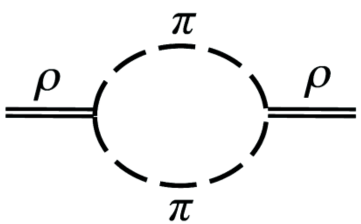
$${\rm Im}\Pi^{\rm vac}_{\rm EM}(M) = \begin{cases} \sum\limits_{v=\rho,\omega,\phi} \left(\frac{m_v^2}{g_v}\right)^2 {\rm Im}D_v^{\rm vac}(M)\,, & M < M^{\rm vac}_{\rm dual} \simeq 1.5\,{\rm GeV/c}^2 \\ -\frac{M^2}{12\pi}\left(1+\frac{\alpha_s(M)}{\pi}+\ldots\right) N_c \sum\limits_{q=u,d,s} (e_q)^2\,,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

Realistic dilepton emission rates

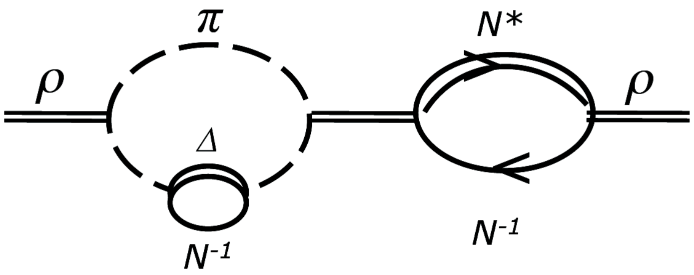
The ρ meson in nuclear matter

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

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

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

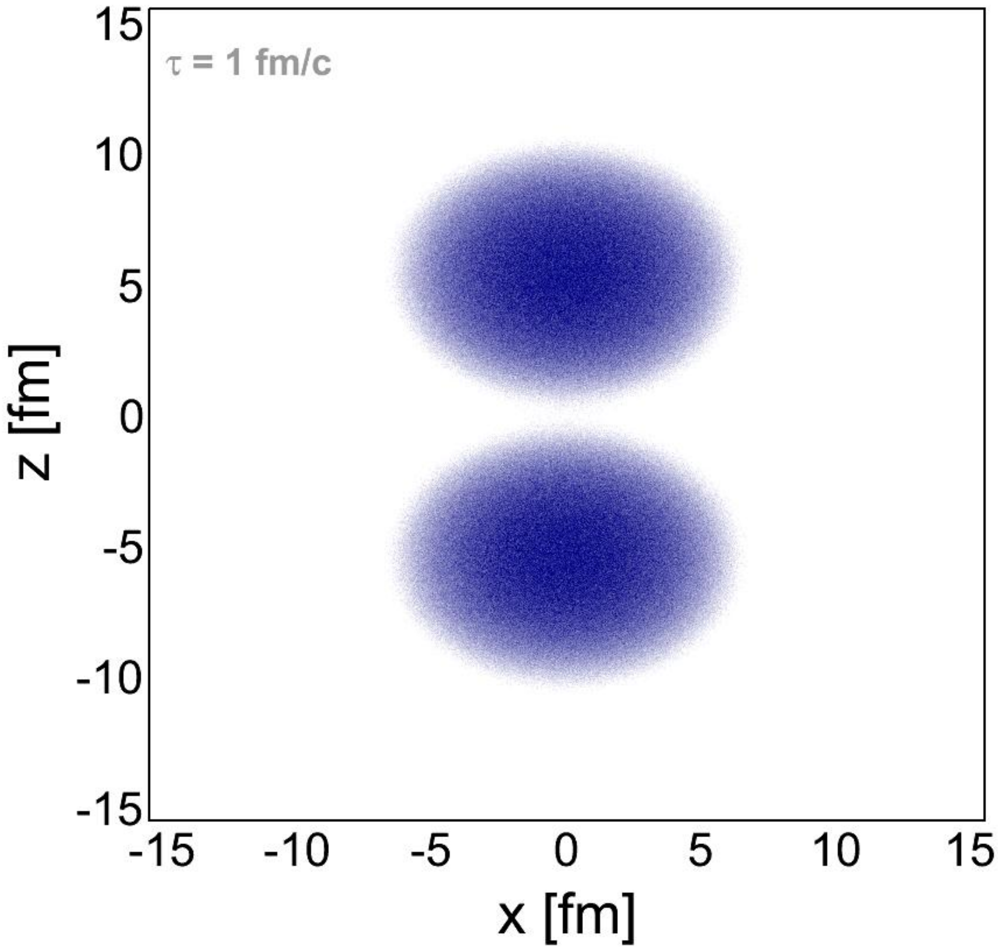
- reproduces excess in experimental data
  - CERES
  - NA60
  - STAR (including BES)
  - PHENIX with HBD

- at higher masses: include hadronic continuum radiation

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

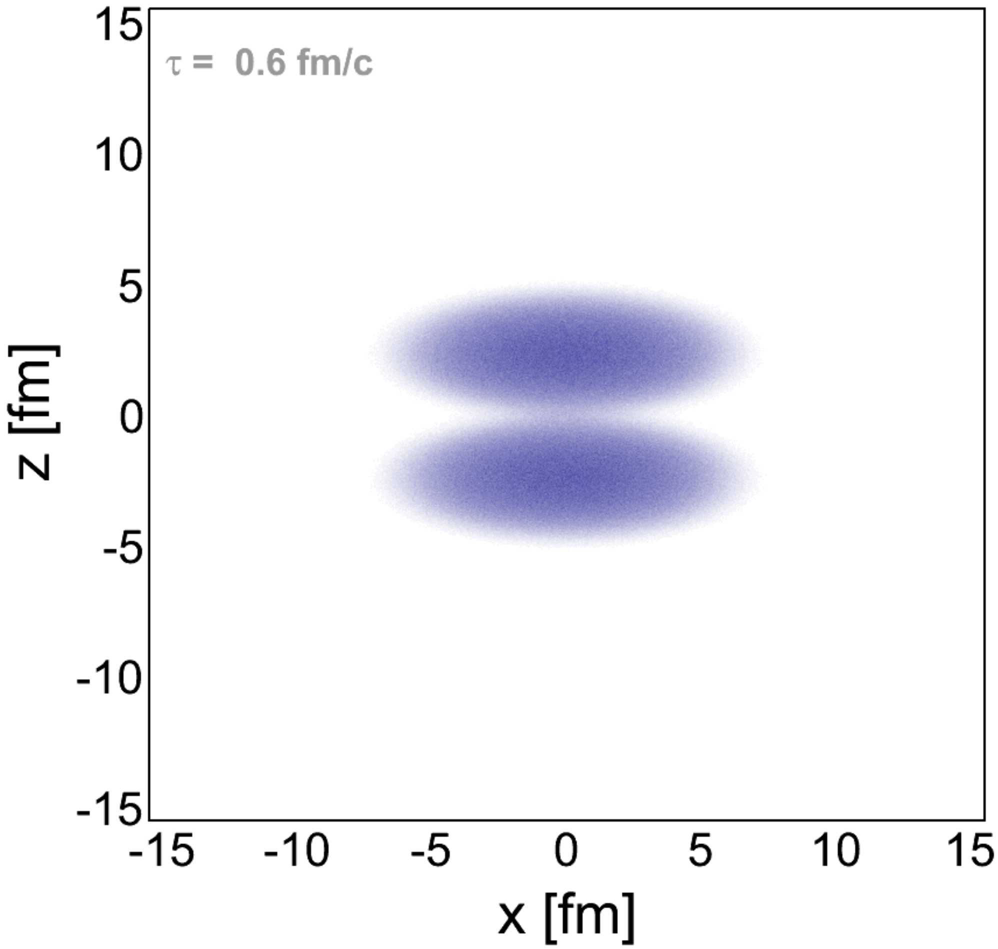
Space-time evolution of a heavy-ion collision

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

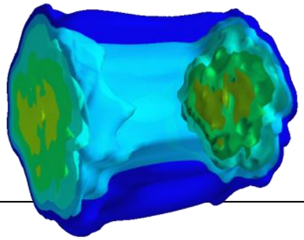


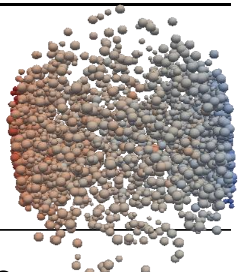
Space-time evolution of a heavy-ion collision

Au+Au at 11 AGeV ($\sqrt{s_{NN}}$ = 4.9 GeV) ⇨ CBM 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

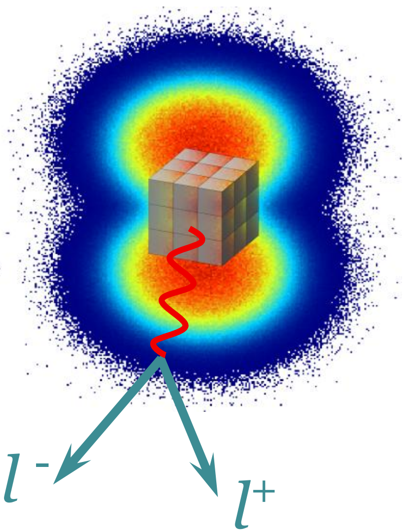
- divide space-time evolution into 4-dimesional cells

  21 x 21 x 21 space cells ($1 fm^3$), 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

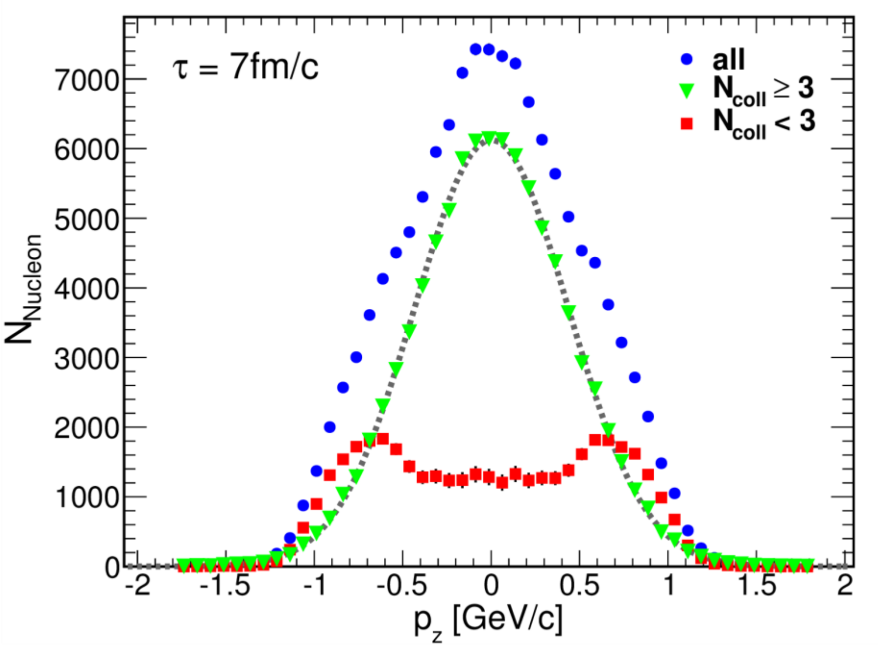
  ⟶ parameterization of RW in-medium spectral function

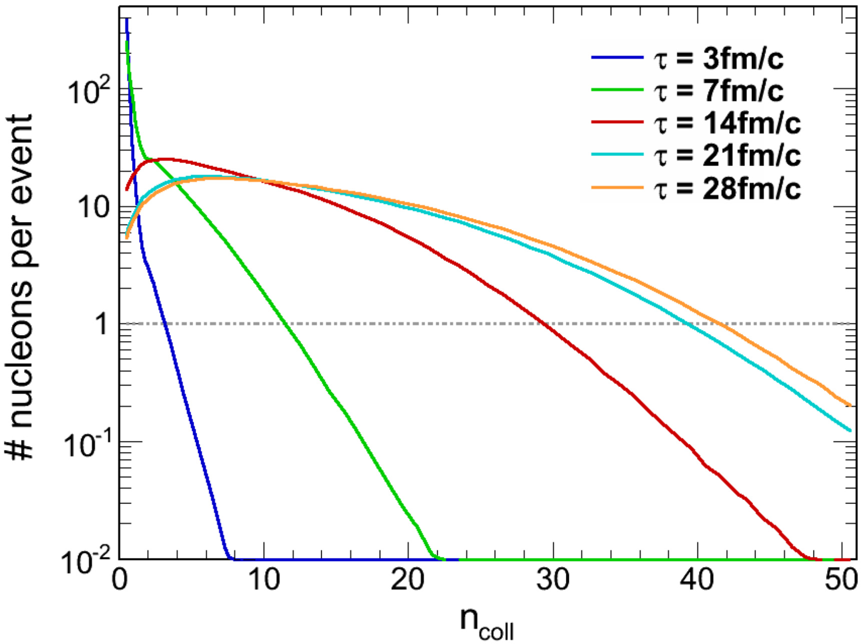
- sum up the contributions of all cells
- similar approaches by
  - Huovinen *et al.*: PRC **66** (2002) 014903
  - Endres *et al.*: PRC **91** (2015) 054911, PRC **92** (2015) 014911, PRC **93** (2016) 054901, arXiv:1604.06414



Local thermalization

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



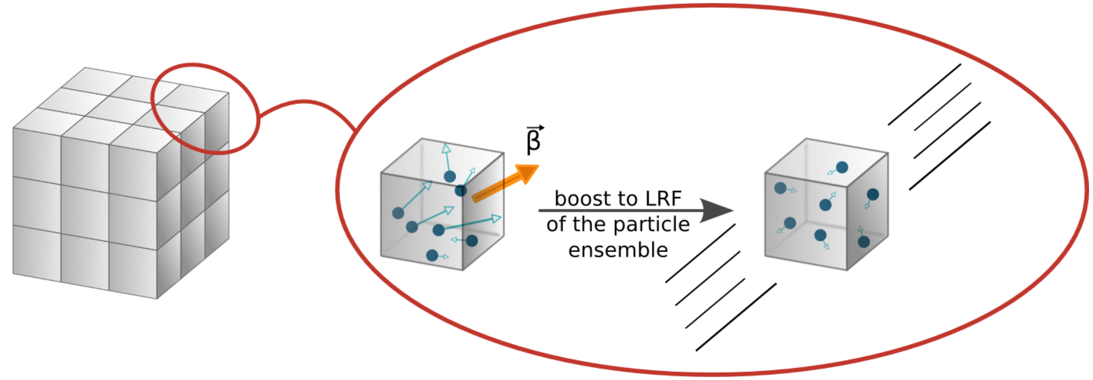


- Gaussian shaped p_z distribution builds up for nucleons with $n_{coll} \geq 3$
- m_t spectra have exponential shape
- check for every cell ⟶ deviations are kept in space-time evolution

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

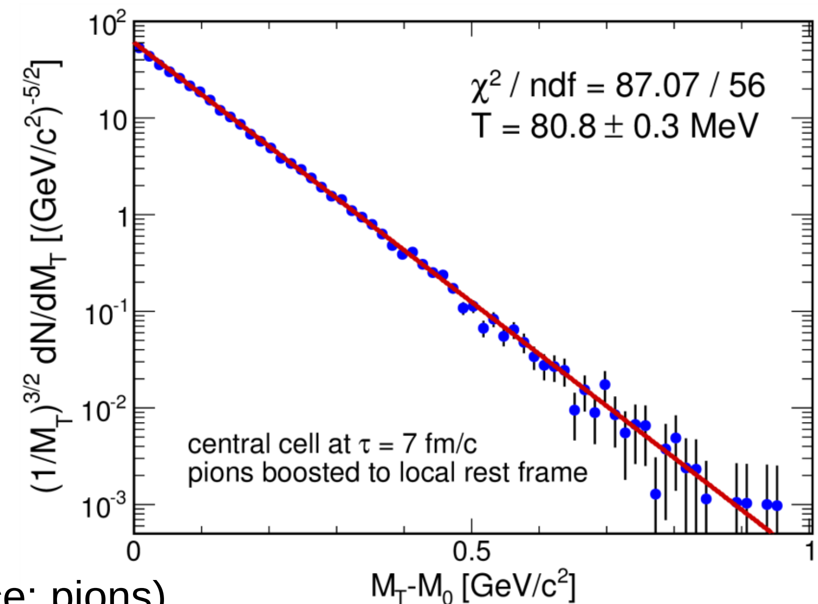


- in Boltzmann approximation

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

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

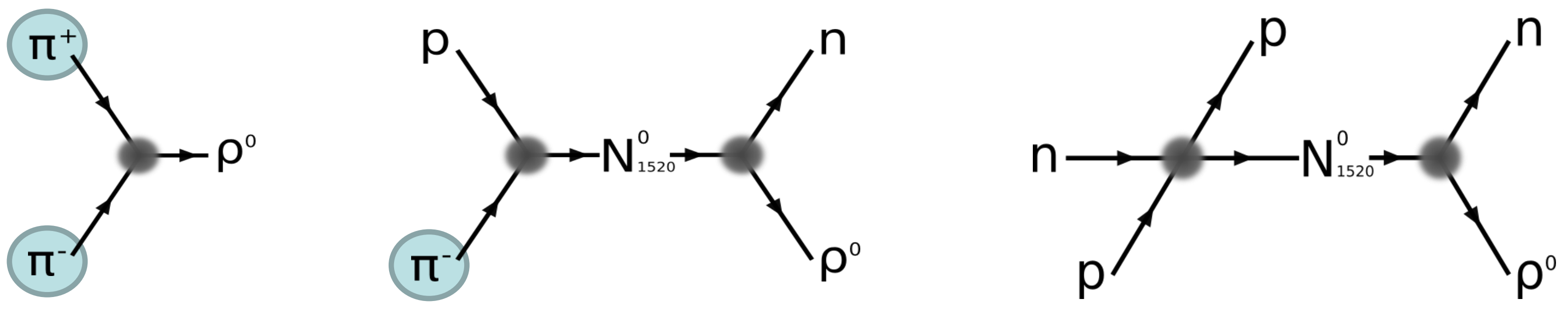
- fill m_t spectra with particle momenta in LRF (mean flow v_{coll} vanishes)
- fit exponential function to extract T (species of choice: pions)



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

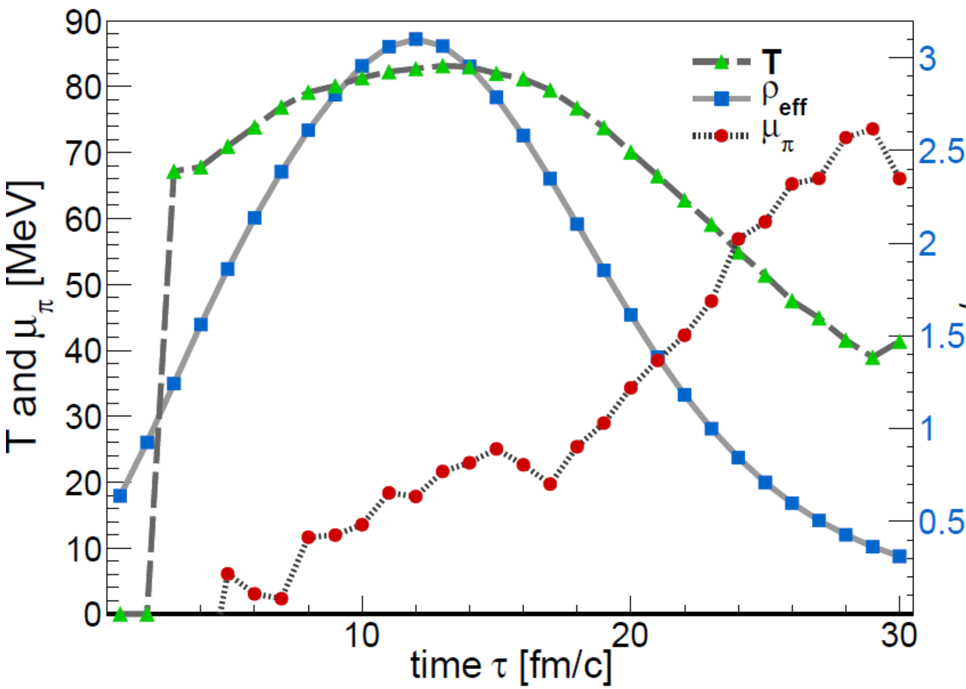


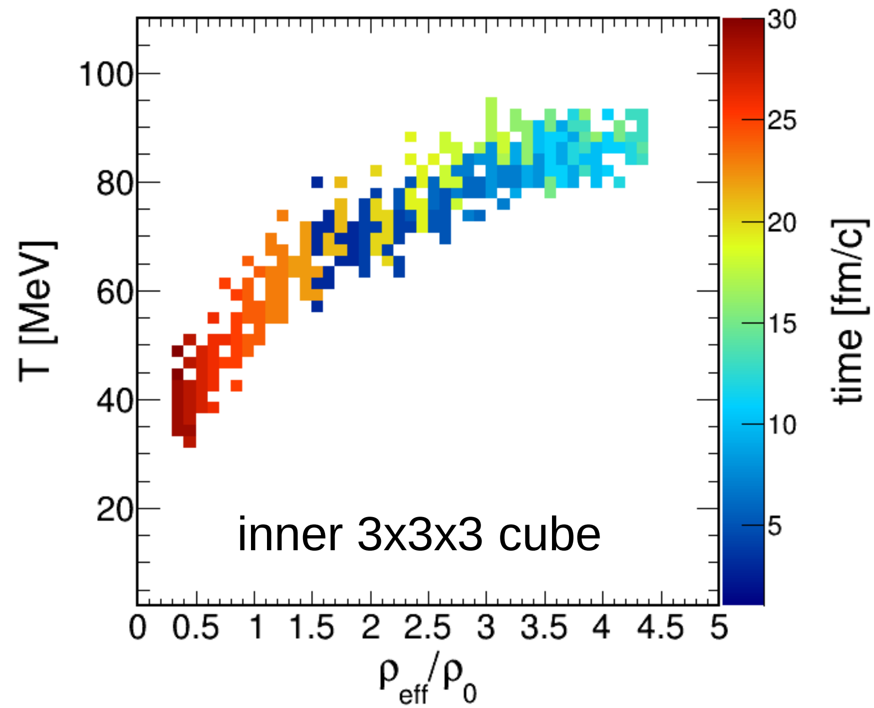
Time-evolution

Au+Au at 1.23 AGeV

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

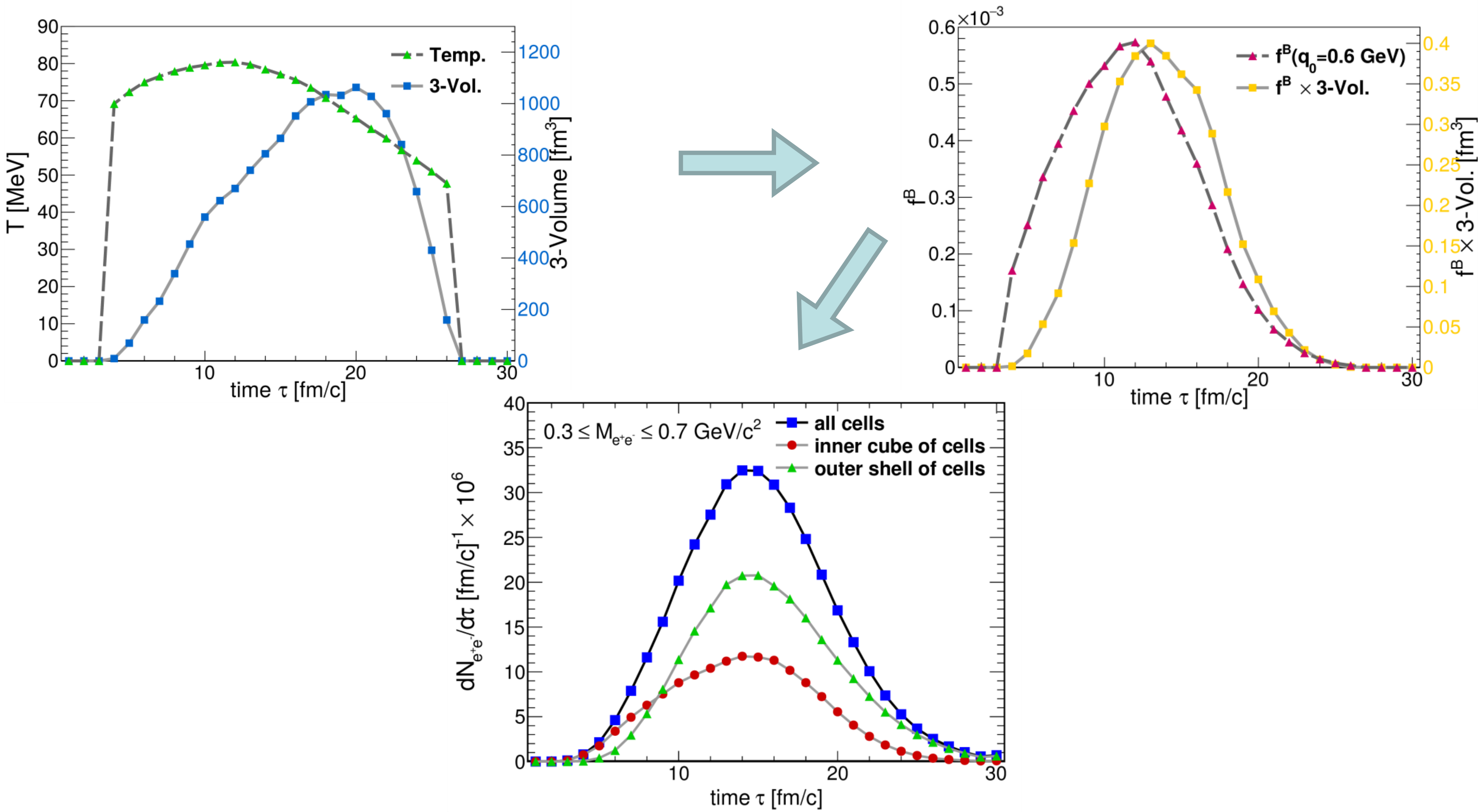
- trajectories of the cells in the temperature-density plane





Interplay temperature – fireball volume

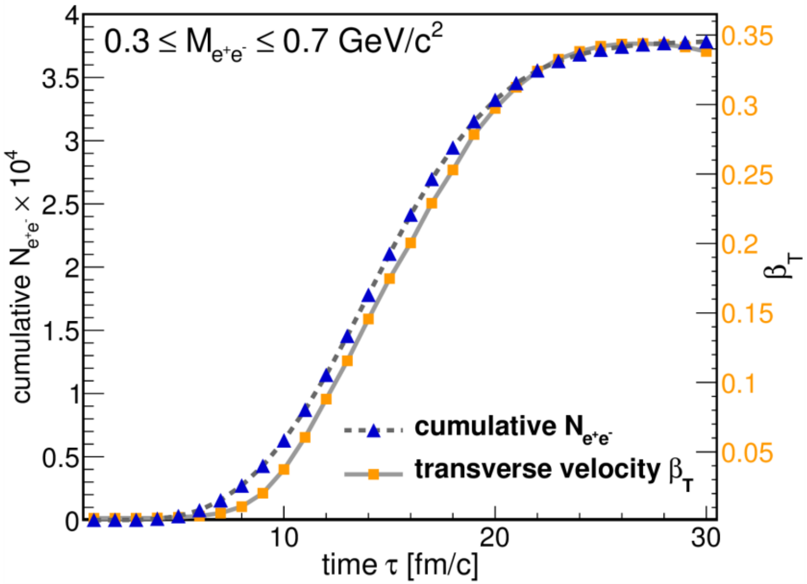
Au+Au at 1.23 AGeV

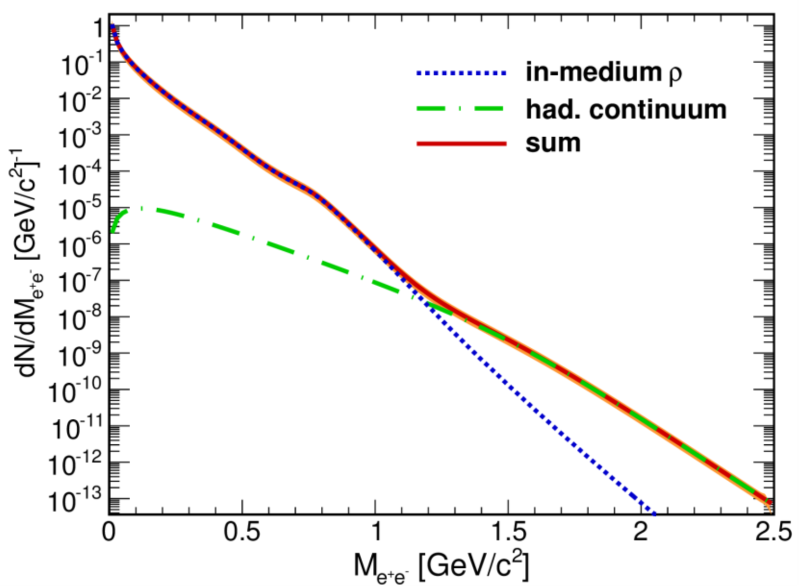


Dileptons as fireball probes

Au+Au at 1.23 AGeV

- 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
- $dR_{ll}/dM \propto (MT)^{3/2} \exp(-M/T)$
- 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)

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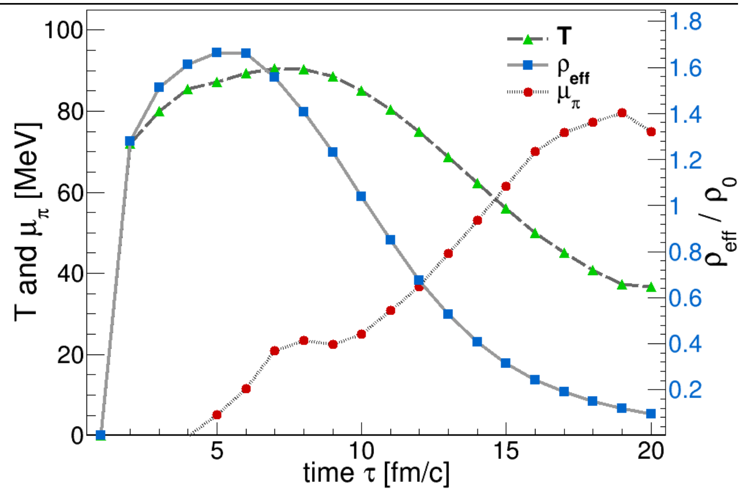
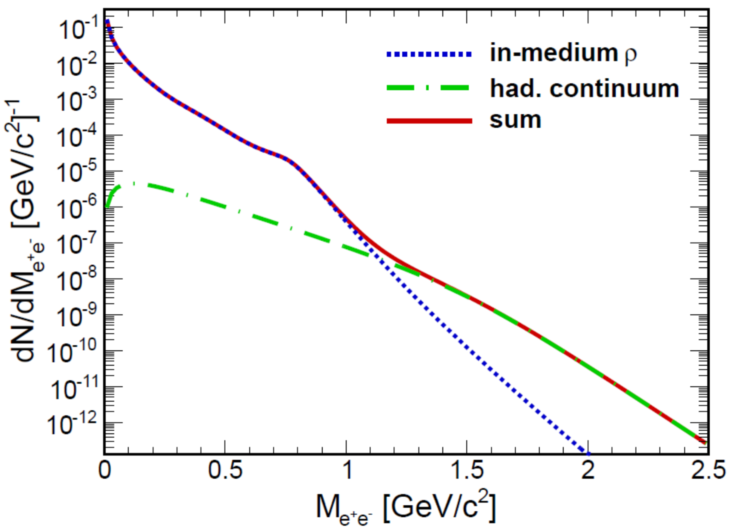
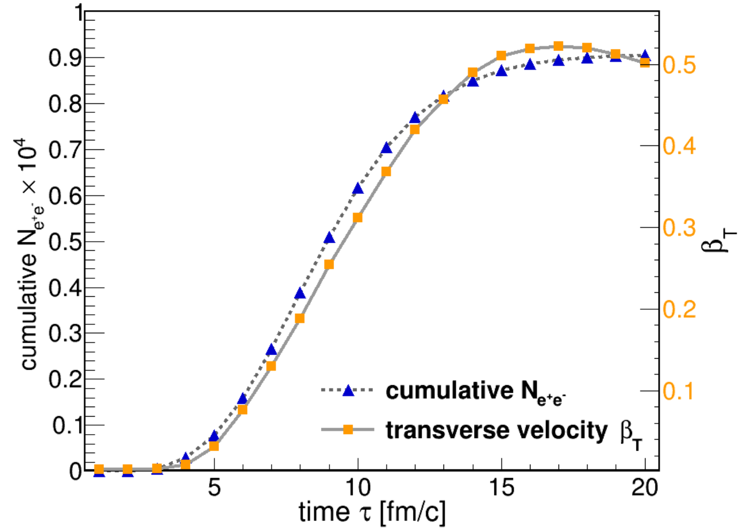
- evolution of T, ρ_{eff} and μ_π in the inner cube of 5x5x5 cells
- invariant mass spectrum for the thermal radiation
- window for dilepton radiation & build-up of collectivity ~ 8fm/c
- integrated yield in mass window divided by N_π suggests lifetime τ ~ 7fm/c







CBM HADES VIP

Excitation function of dilepton production

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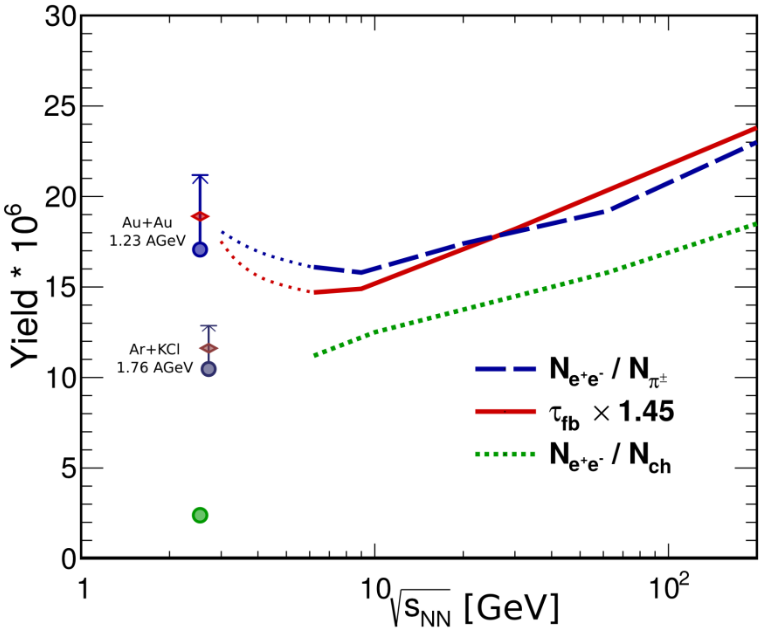
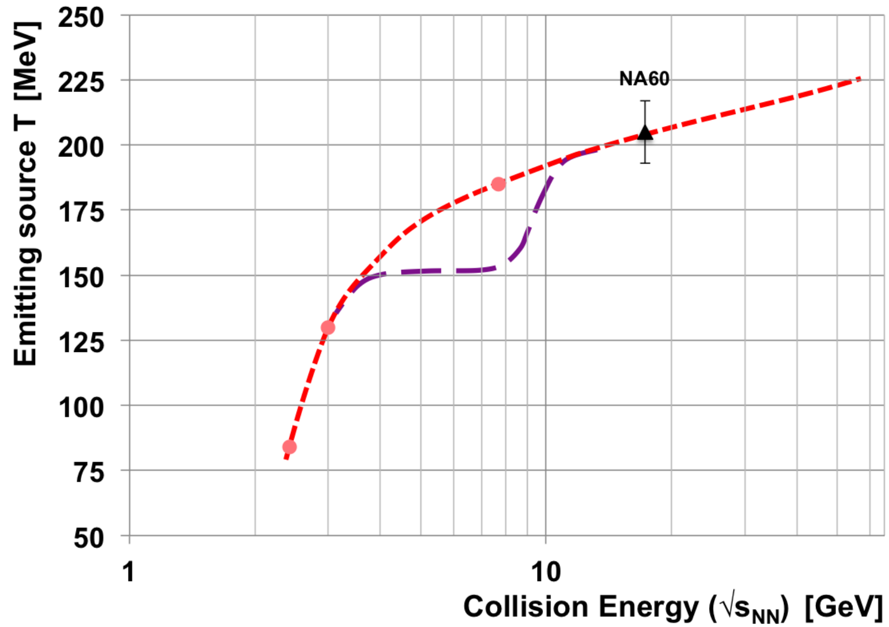
Yield in low-mass window tracks fireball lifetime

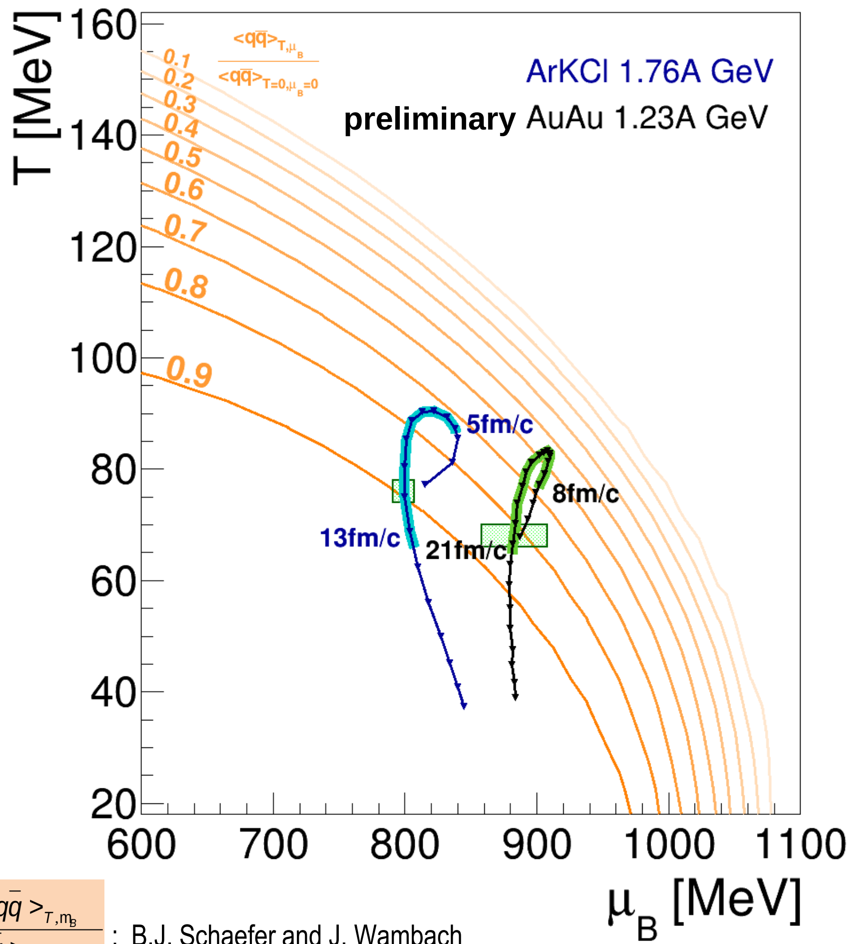




- fireball dominated by incoming nucleons at lower energies
- number of charged particles N_{ch} not a good proxy for thermal excitation energy
- normalization to number of charged pions N_{π}
- lifetime from dilepton yield in mass window 0.3-0.7 GeV/c^2: $\frac{N_{l^+l^-}}{N_{\pi^\pm}} \cdot 10^6 \simeq 1.45 \cdot \tau_{\mathrm{fb}}$

Exploring the QCD phase diagram –

– with dileptons

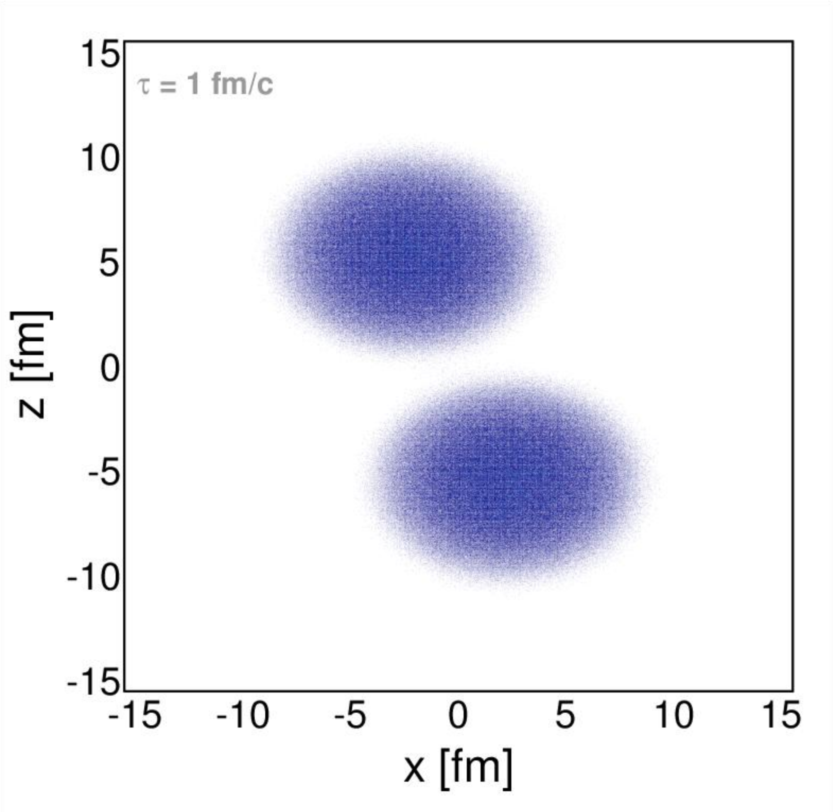


$\frac{<q\bar{q}>_{T,\mu_B}}{<q\bar{q}>_{T=0,\mu_B=0}}$: B.J. Schaefer and J. Wambach

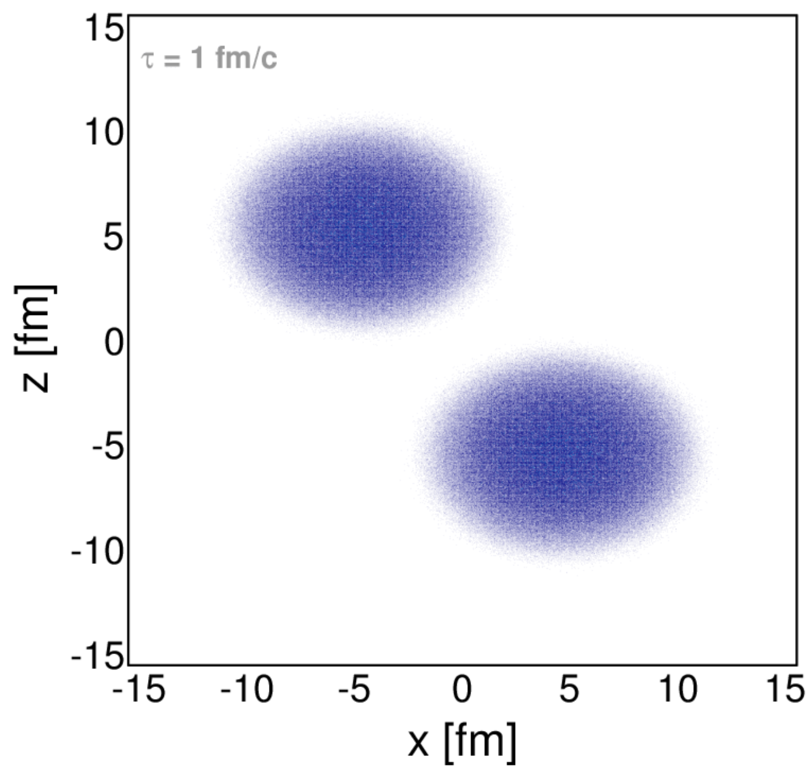
- chemical freeze-out from measured particle yields analyzed with SHM
- trajectories extracted from inner cube of cells with coarse-grained UrQMD
- time-window of dilepton emission
  - radiation stops shortly after chemical freeze-out
  - access to hot and dense stage of the heavy-ion collision

Space-time evolution of a heavy-ion collision

Au+Au at 1.23 AGeV ($\sqrt{s_{NN}}$ = 2.4 GeV) for different impact parameters



b=4.6fm

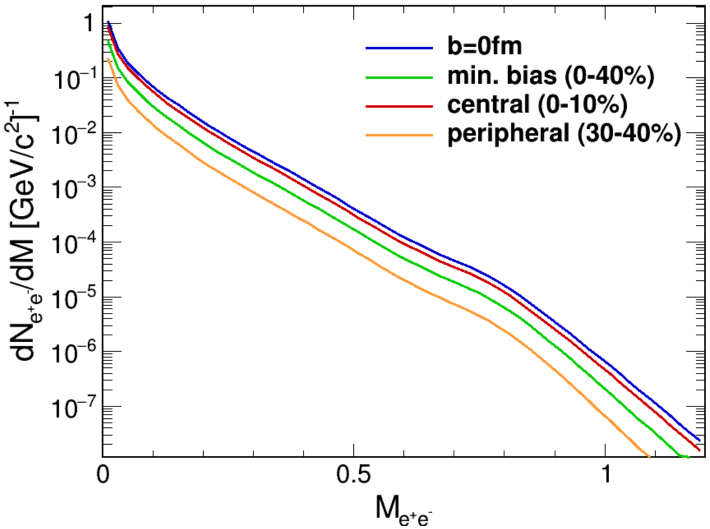


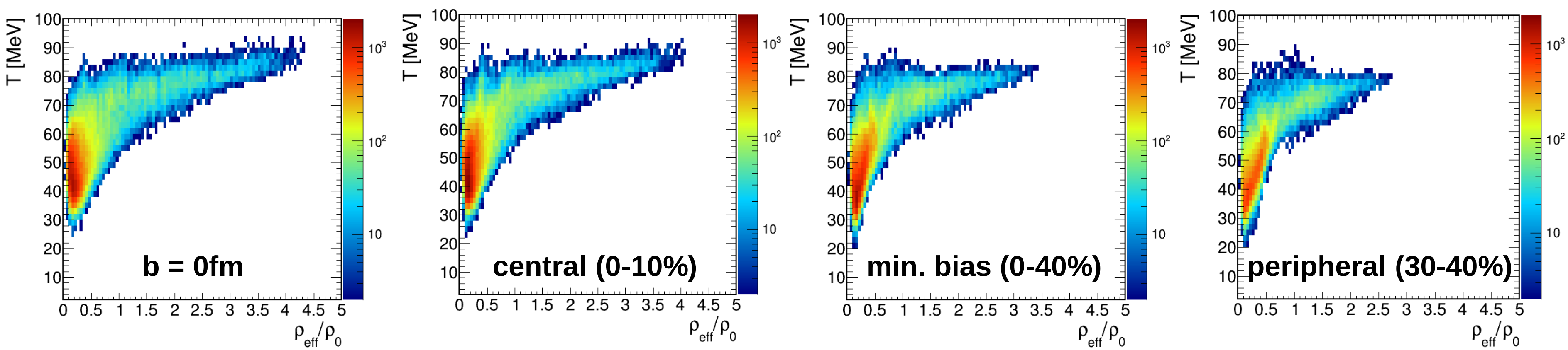
b=9.3fm

Centrality dependent analysis

Au+Au at 1.23 AGeV

- whole framework done for different centralities
- shape of inv. mass spectrum almost unchanged
- thermal excess radiation scales with $(A_{part})^{1.4}$

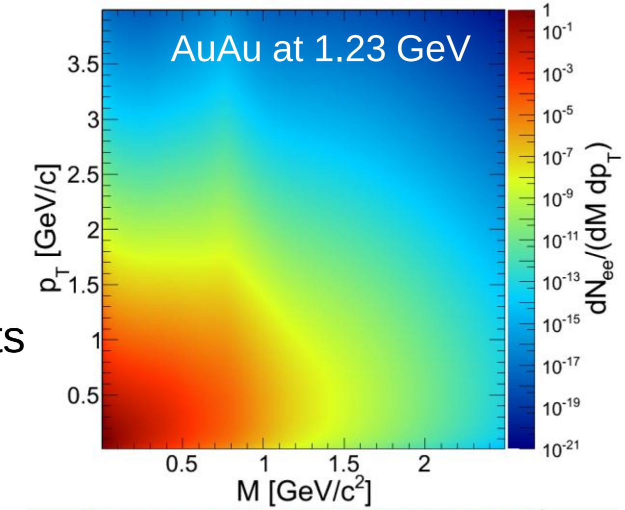




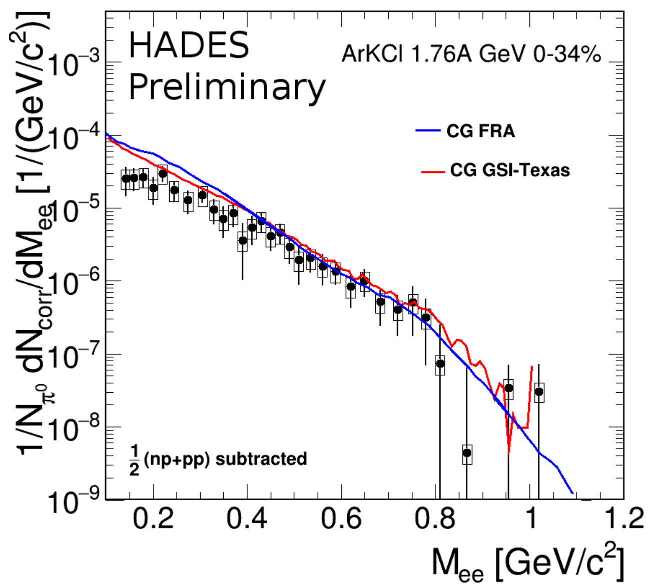
Thermal radiation generated with Pluto

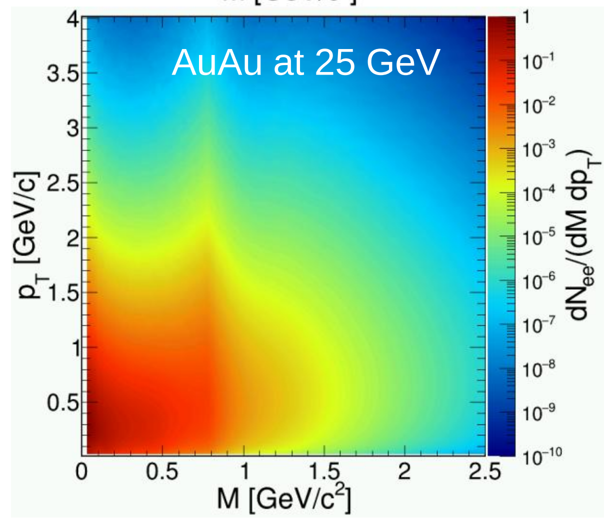
Input for Monte Carlo generator

- differential spectra $\frac{d^3N}{dM\,dp_T\,dy}$ to sample dileptons with Monte Carlo generator Pluto
- input histogram for Au+Au from 1.23 AGeV to 25 AGeV
- filter through experimental acceptance & apply analysis cuts



see talk tomorrow by S. Harabasz





Exploring the QCD phase diagram –

– with dileptons

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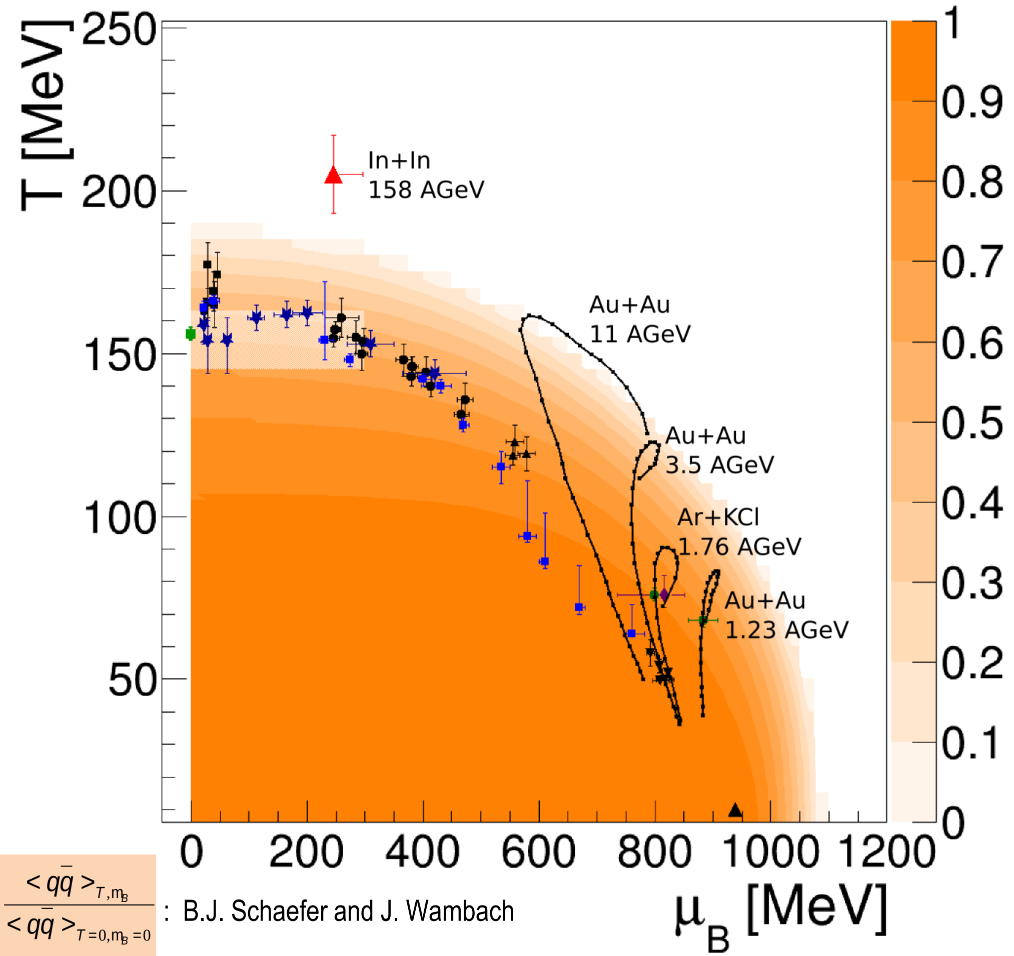


$\frac{<q\bar{q}>_{T,m_B}}{<q\bar{q}>_{T=0,m_B=0}}$: B.J. Schaefer and J. Wambach

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

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

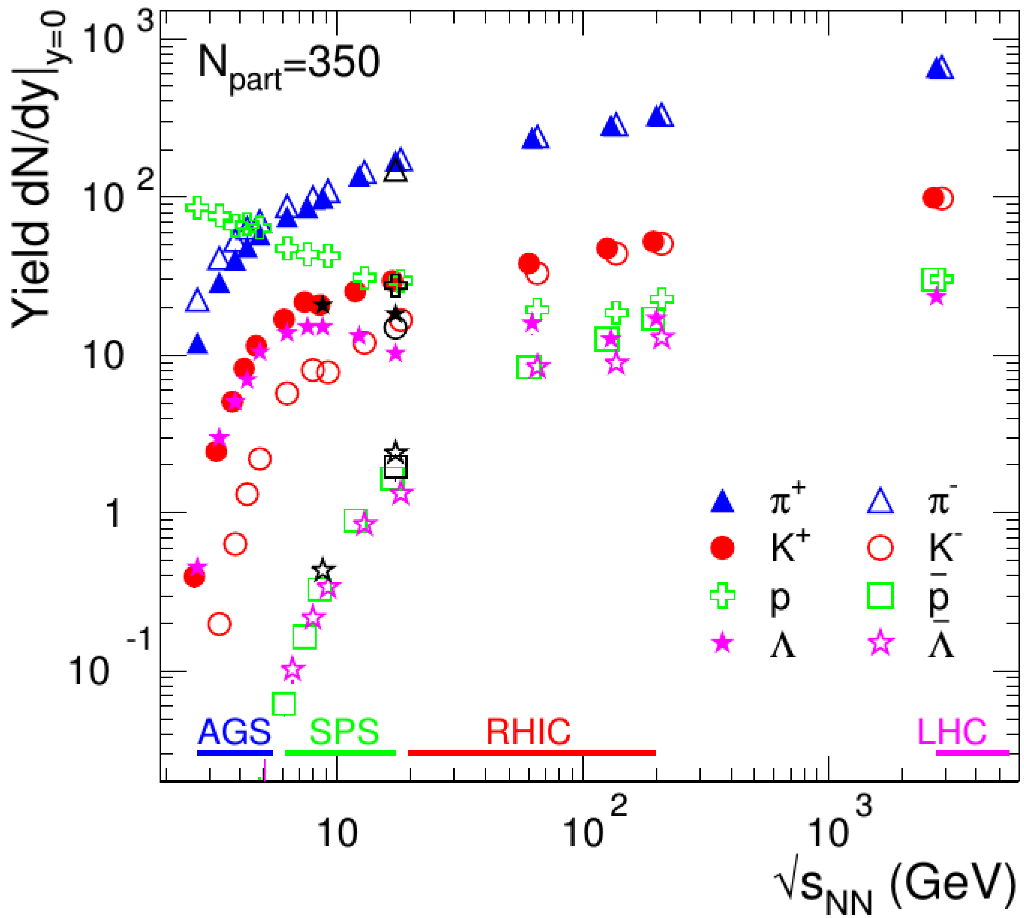
Summary

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 explorations by HADES & CBM
  - any significant deviation can indicate new physics!

Backup slides

Excitation function of hadron yields



A. Andronic, arXiv:1407.5003

Final-state pion spectra: time dependent

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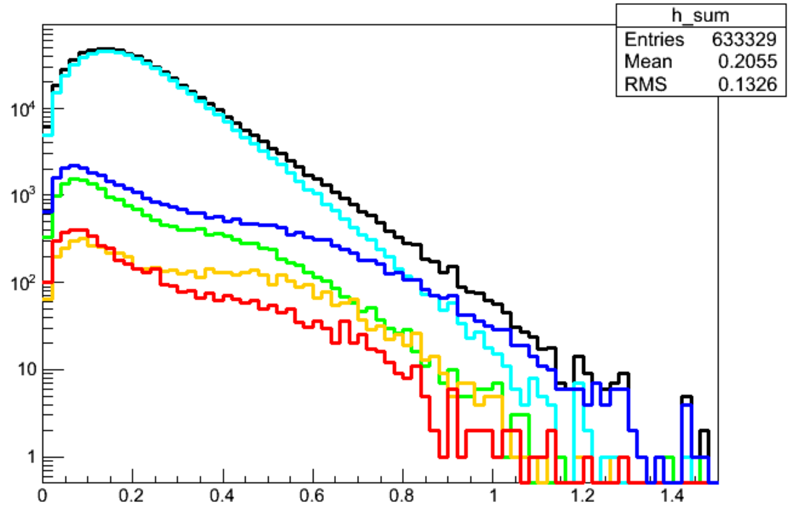
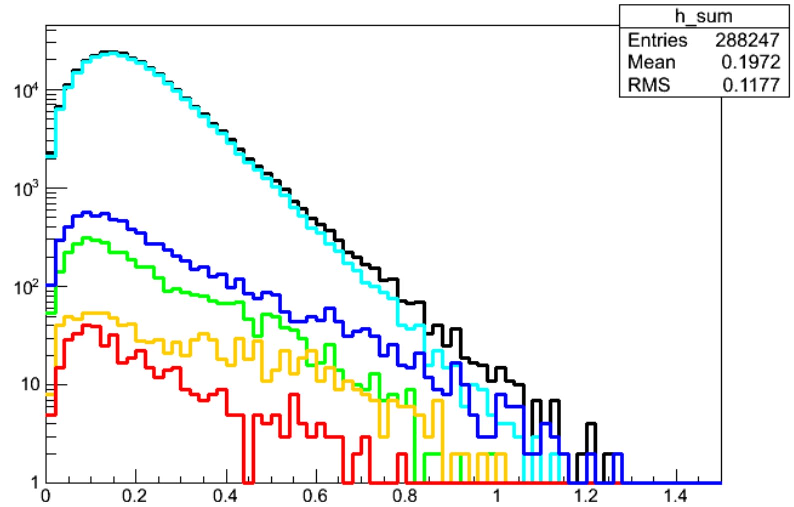
- Black: all
- Cyan: Delta(1232)
- Green: N(1440)
- Yellow: N(1520)
- Red: Delta(1600)
- Blue: all other resonances

all times



p_T

t > 21 fm/c



p_T

CBM HADES VIP

Final-state pion spectra: time dependent

- Black: all
- Cyan: Delta(1232)
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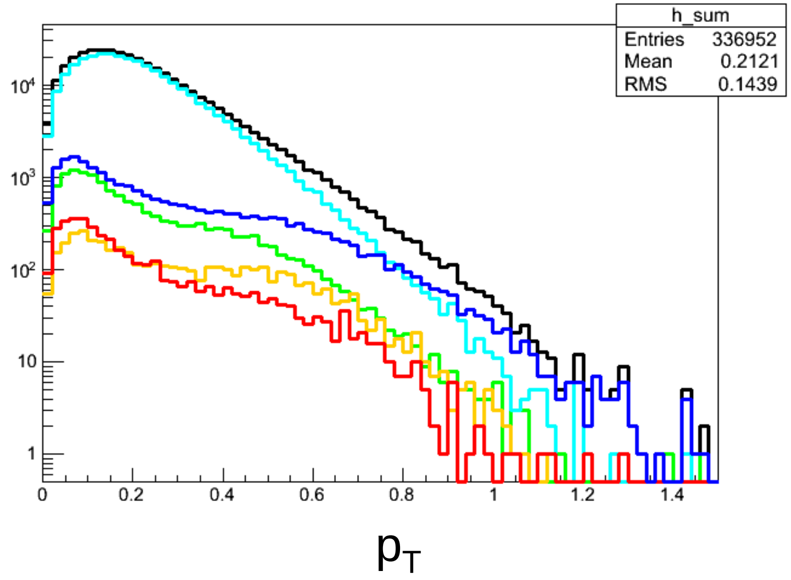
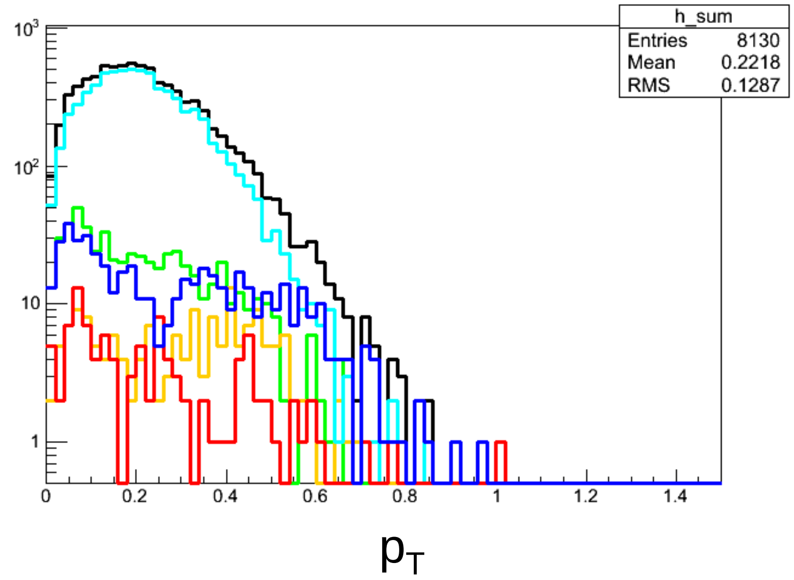
- Blue: all other resonances

8 fm/c < t < 21 fm/c



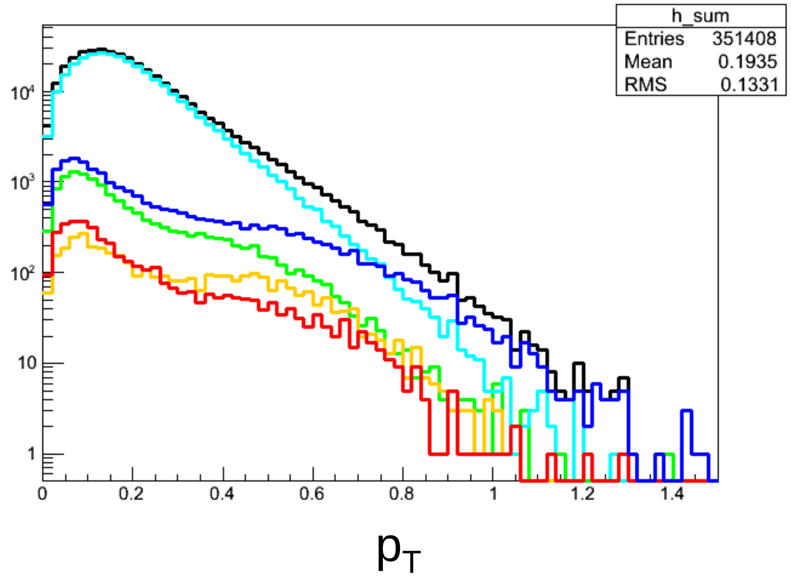
t < 8 fm/c



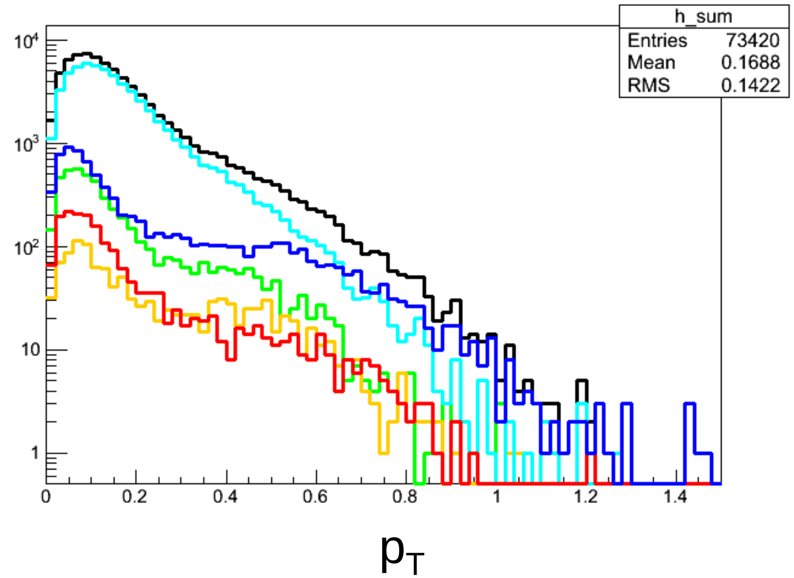
Final-state pion spectra: density dependent

- Black: all
- Cyan: Delta(1232)
- Green: N(1440)
- Yellow: N(1520)
- Red: Delta(1600)
- Blue: all other resonances

ρ < 0.5 + t > 30 fm/c



ρ > 1.5 && 8 fm/c < t < 21 fm/c



Final-state pion spectra: density dependent

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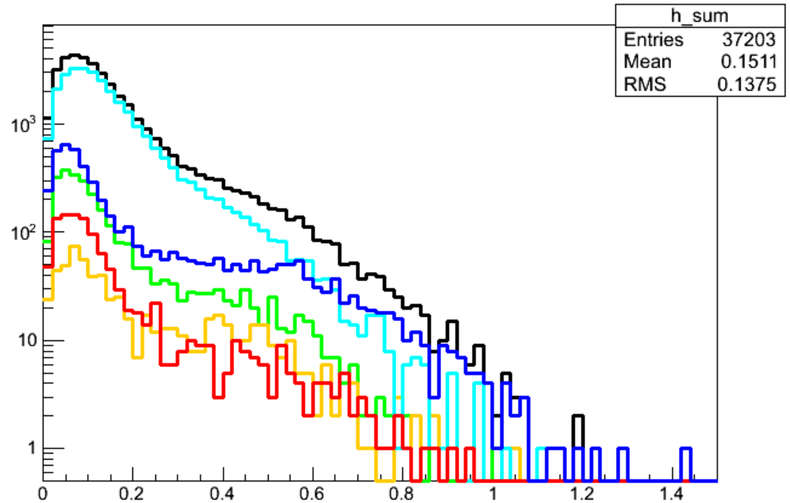
- Black: all
- Cyan: Delta(1232)
- Green: N(1440)
- Yellow: N(1520)
- Red: Delta(1600)
- Blue: all other resonances

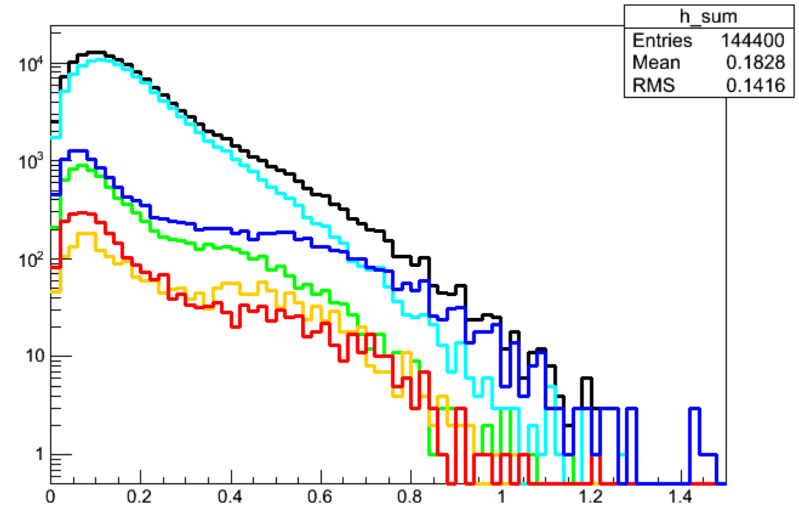
~ 20% of all $\pi^{\pm}$

$\rho > 2$



p_T

$\rho > 1$



p_T