

# MUCH physics case

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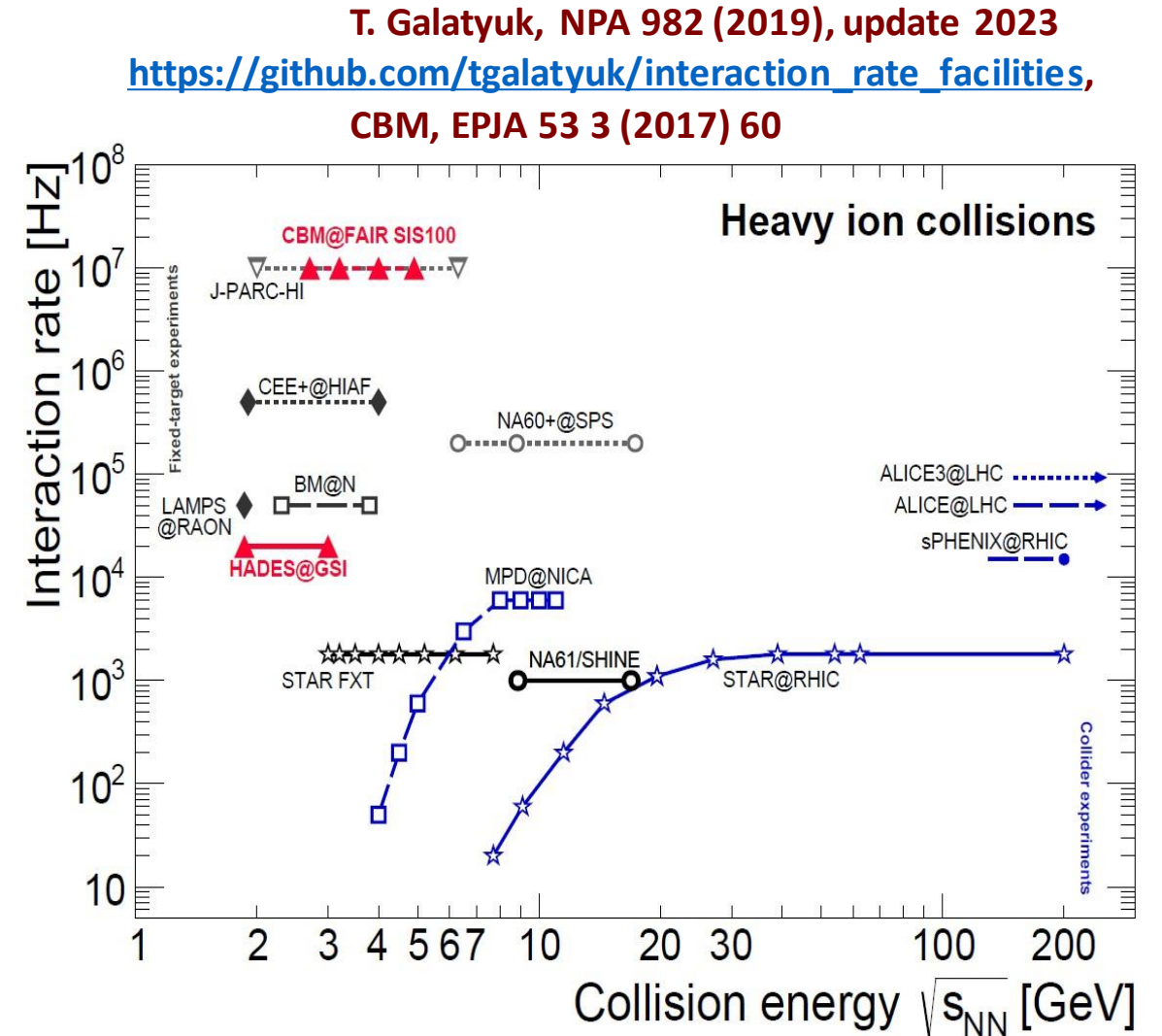


MUST Kick-off meeting  
16 June. 2026

# CBM Objective

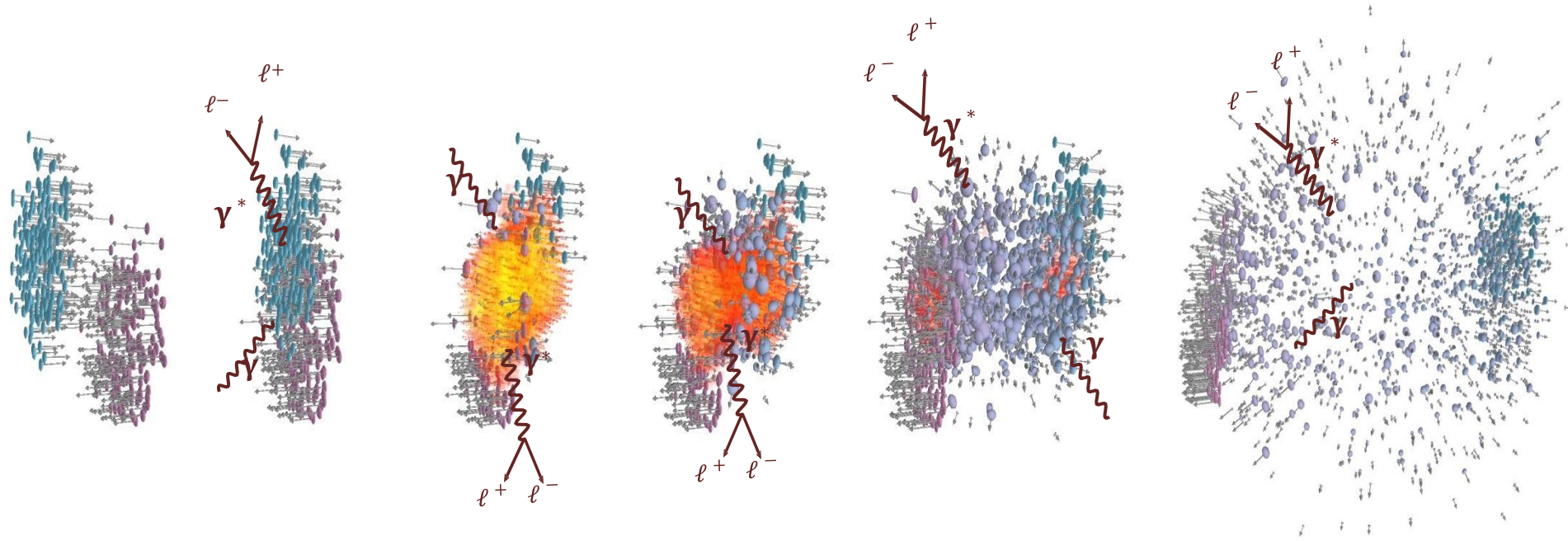
*Explore the phase properties and microscopic structure of strong-interaction matter at high(est) net-baryon densities*

- QCD matter EoS at large baryon densities, signals of phase transition its order and CEP:
  - Hadron yields, collective flow, correlations, fluctuations
  - (Multi-)strange hyperons ( $K$ ,  $\Lambda$ ,  $\Sigma$ ,  $\Xi$ ,  $\Omega$ )
  - production at (sub)threshold energies
- Chiral symmetry at large baryon densities
  - In-medium modifications of light vector mesons
  - $\rho$ ,  $\omega$ ,  $\phi \rightarrow e^+e^-$  ( $\mu^+\mu^-$ ) via dilepton measurements
- Hyper-nuclei production
- Charm production and propagation in baryon rich matter
  - Excitation function in p+A collisions ( $J/\psi$ ,  $D^0$ ,  $D^+$ )
  - Charmonium suppression in cold nuclear matter



- Key observables are rare: precision and sensitive measurements require high statistics
- CBM will measure rarest signals with highest interaction rates of  $10^5 - 10^7$  Au+Au collisions/sec

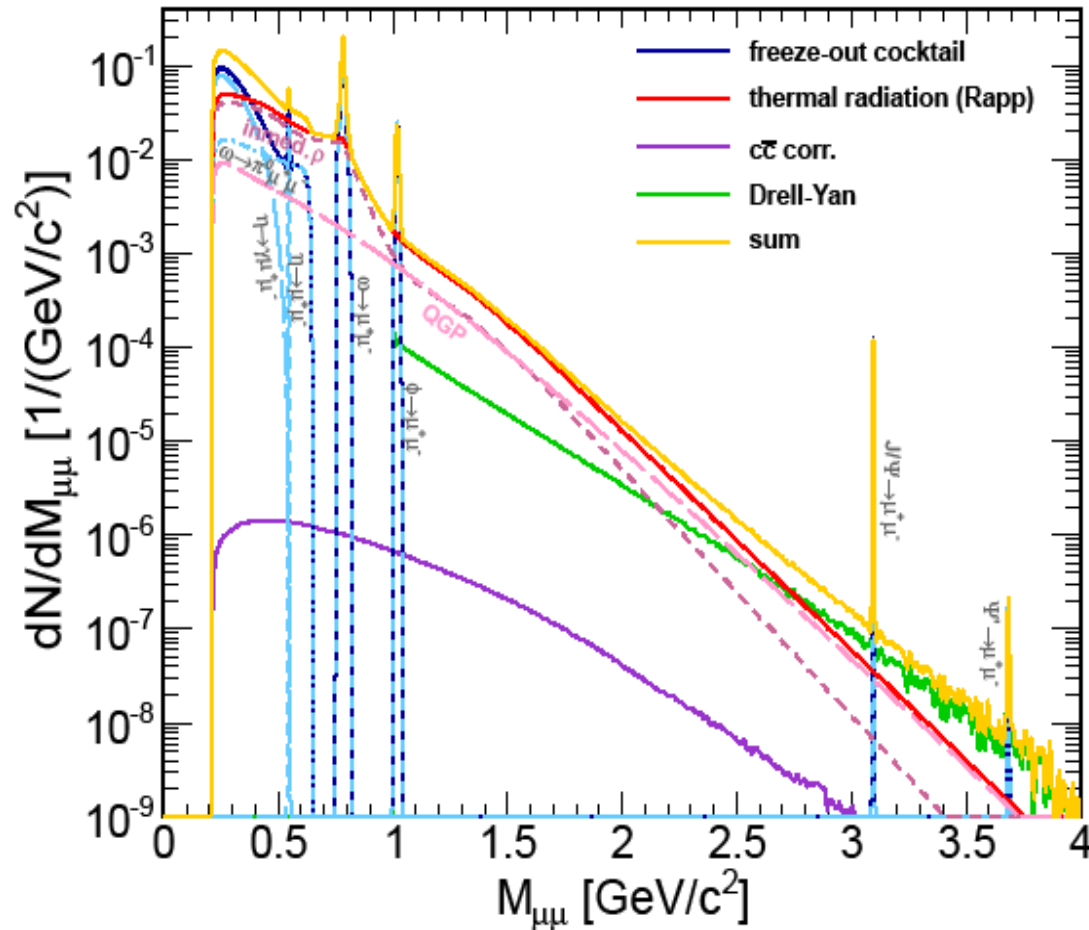
# Electromagnetic signals of relativistic heavy-ion collisions



- Electromagnetic radiation ( $\gamma$ ,  $\gamma^*$ ) emitted from different stages of the fireball: tracks the entire history of the collision
- No strong interaction at the final state, leave the reaction volume undistorted: penetrating probes of dense matter
- Real  $\gamma$  characterized by transverse momentum: one variable  $p_T$
- Virtual  $\gamma^*$  ( $e^+e^-/\mu^+\mu^-$ ) has added information of invariant mass: two variables  $p_T$ ,  $M_{inv}$
- Dileptons carry invaluable information in terms of their 4-momentum

# Di-muon invariant mass spectrum

(0-5) % Au+Au collisions  $\sqrt{s_{NN}} = 4.9$  GeV



Constructed by combining oppositely charged muon track

Falling continuum decorated with multiple peaks

Superposition of multiple physics processes:

- Direct decay of vector bosons ( $\rho, \omega, \phi \rightarrow \mu^+ \mu^-$ )
- Dalitz decay of vector bosons ( $\omega \rightarrow \mu^+ \mu^- \gamma$ )
- Drell-Yan & correlated open charm decay
  - Hadronic decay cocktail, present in p+p, p+A & A+A

Charmonia ( $J/\psi, \psi'$ ) in high mass region

In nuclear collisions additional to this dileptons due to

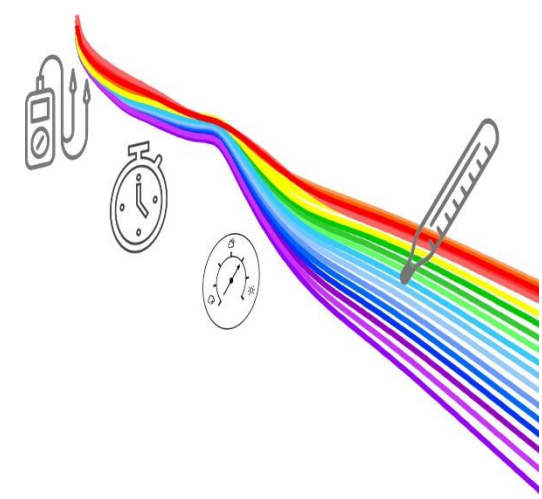
- Thermal radiation from the fireball
- Emitted from both hadronic and partonic phases
- Different regions of collision can be separated based on mass window
- First measured by SPS-NA60 in In+In collisions @  $\sqrt{s_{NN}} = 17.3$  GeV

$$M_{\mu\mu}^2 = (P_{\mu^+} + P_{\mu^-})^2 \text{ where } P_{\mu} = (E, \mathbf{p}) :$$

In low energy collisions ( $\sqrt{s_{NN}} = 2 - 4.9$  GeV) @ CBM:

- Bottomonia ( $M > 9$  GeV) production is kinematically forbidden
- Small contribution from Drell-Yan & open charm decay: useful to extract thermal dileptons

# Dilepton as probe of QCD matter



Depending on the suitable pair mass window thermal dileptons serve as:

## Chronometer:

- LMR yield (0.3 – 0.5 GeV/c<sup>2</sup>) : sensitive to fireball lifetime

## Thermometer:

- Slope of IMR (1.5 – 2.5 GeV/c<sup>2</sup>) mass spectra: emitting source temperature (true T, no blue shift)

## Barometer:

- LMR +IMR inverse slope analysis of transverse spectra : fireball acceleration, dilepton  $v_2$

## Spectrometer:

- $\rho$  mass shape and  $\rho$ -a1 chiral mixing: restoration of chiral symmetry

## Polarimeter:

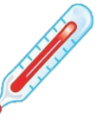
- Angular distributions of Dilepton : extraction of polarization parameter

Charmonia ( $J/\psi$ ,  $\psi'$ ) production in p+A & A+A through high mass  $e^+e^-/\mu^+\mu^-$

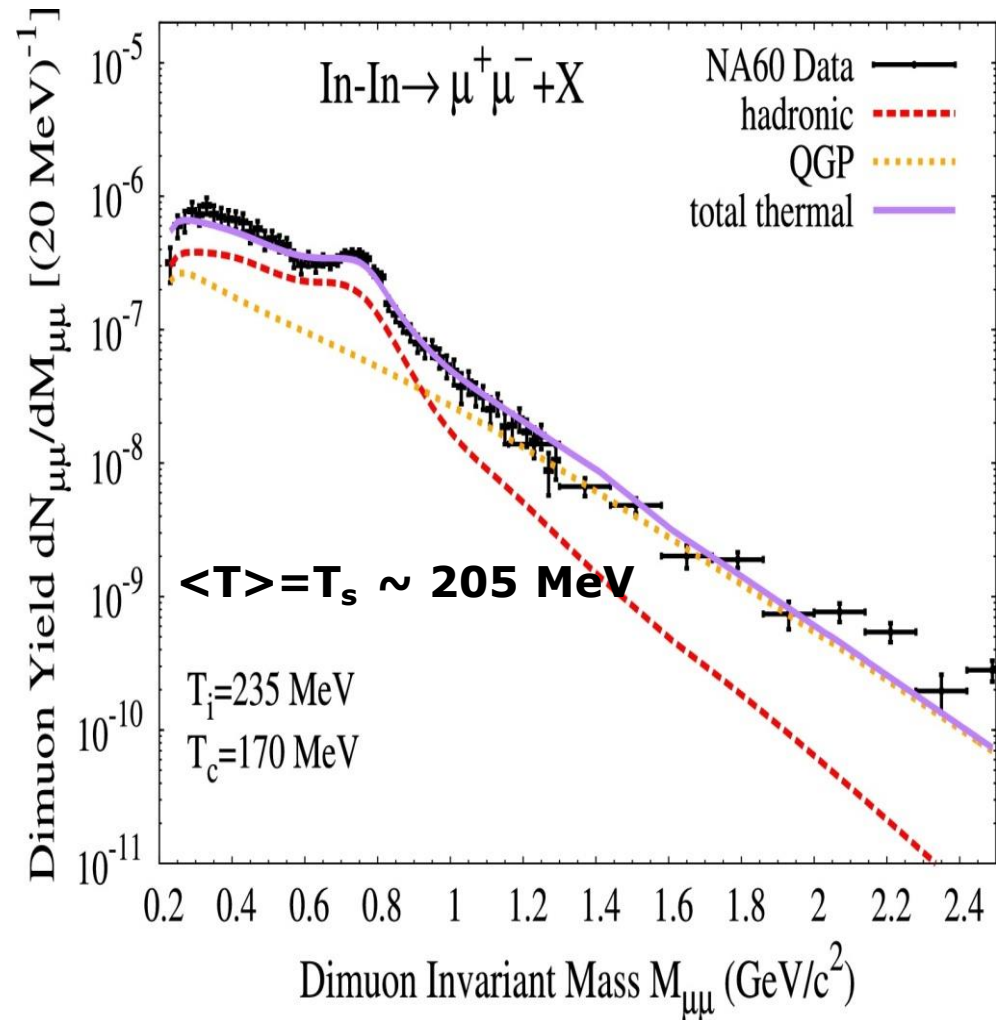
***One observable can address multiple physics issues ...***

- No di-lepton measurements available between  $E_{lab} = 3 A - 40 A$  GeV ( $\sqrt{s_{NN}} = 2.5 - 9$  GeV)!
- CBM will measure both  $e^+e^-$  and  $\mu^+\mu^-$  within same kinematical coverage: robust results

# Di-lepton as thermometer



Measure temperature of the radiating source

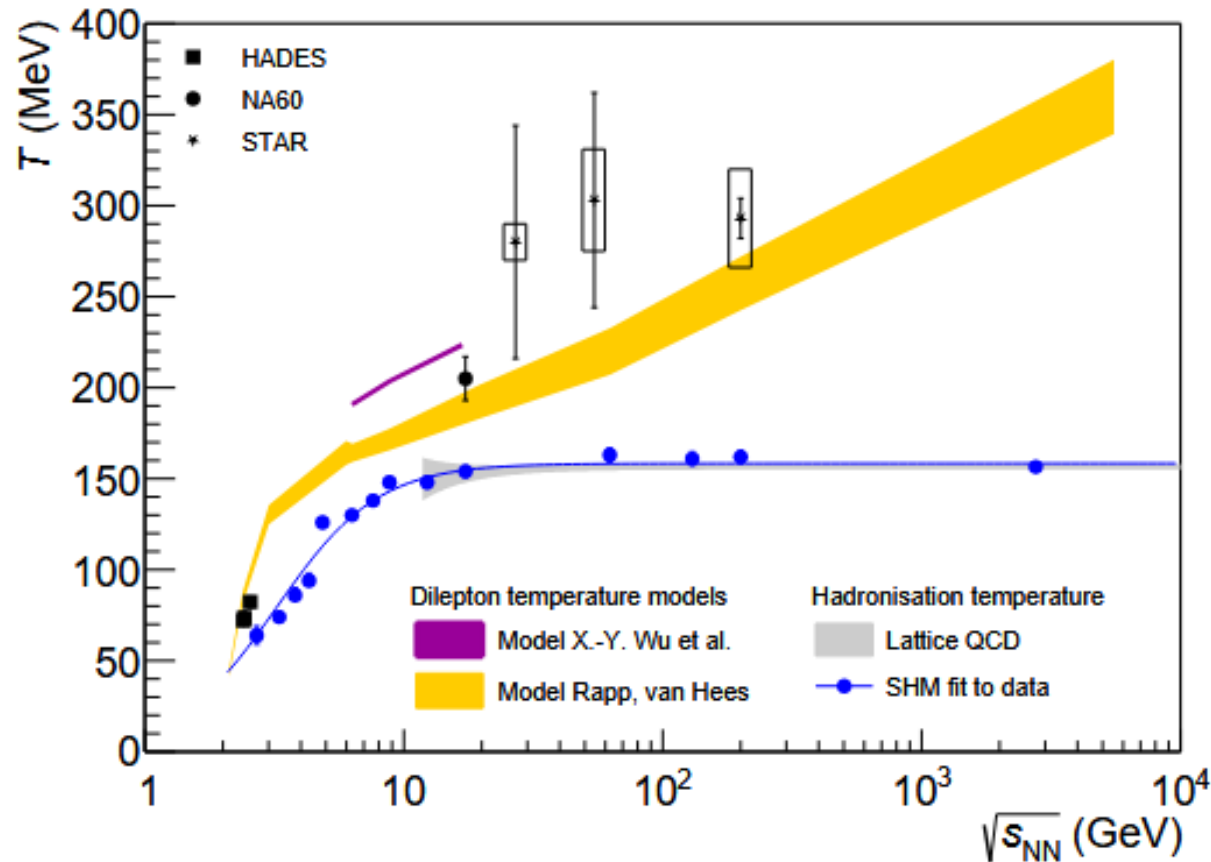


- Di-muon excess in the IMR :  $1.5 < M_{\text{inv}} < 2.5 \text{ GeV}/c^2$
- Dominant emission from QGP phase
- Medium effects are small on spectral function ( $\sim T^2/M^2 \ll 1$ )
- Temperature determination : Stable thermometer
- Exponential falling spectra :  $dN/dM \sim (MT)^{3/2} \exp(-M/T)$
- Contribution from pre-equilibrium and primordial contributions are not of exponential shape
- Contamination can be judged by fit quality of exponential ansatz
- Independent of medium collectivity: no blue shift effects

Model: R. Rapp, H. van Hees, PLB 753 (2016) 586

$$T_s > T_{pc} (\sim 155 \text{ MeV})$$

# Measurement of caloric curve of QCD matter



[https://github.com/tgalatyuk/QCD\\_caloric\\_curve](https://github.com/tgalatyuk/QCD_caloric_curve)

Inverse slope parameter ( $T_s$ ) extracted from mass spectra at different  $\sqrt{s_{NN}}$

Measure the emitting source temperature (true no blue shift)

Existing measurements:

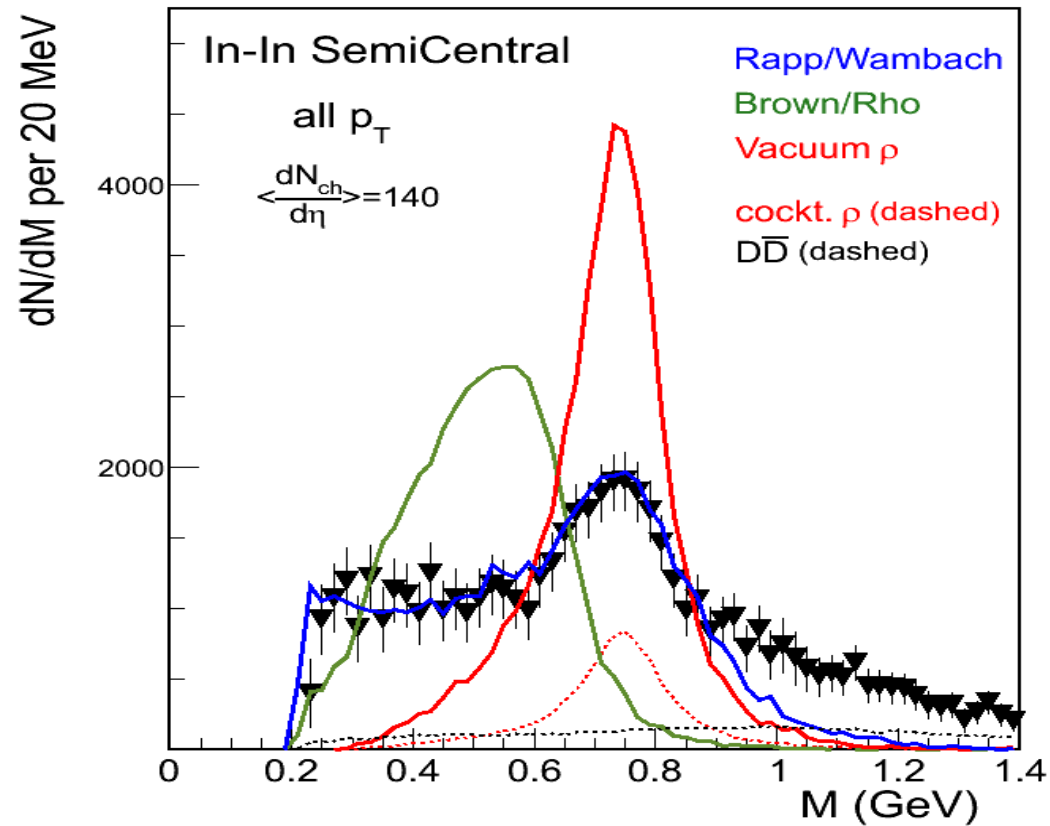
- *HADES (SIS) Au+Au @  $\sqrt{s_{NN}} = 2.42$  GeV:  $T_s \sim 72$  MeV*
- *NA60 (SPS) In+In @  $\sqrt{s_{NN}} = 17.3$  GeV:  $T_s \sim 205$  MeV*
- *STAR Au+Au @  $\sqrt{s_{NN}} = 200$  GeV:  $T_s \sim 300$  MeV*
- *Also from RHIC-BES*

Precision study of the region  $\sqrt{s_{NN}} \sim 3-20$  GeV (**caloric curve**)

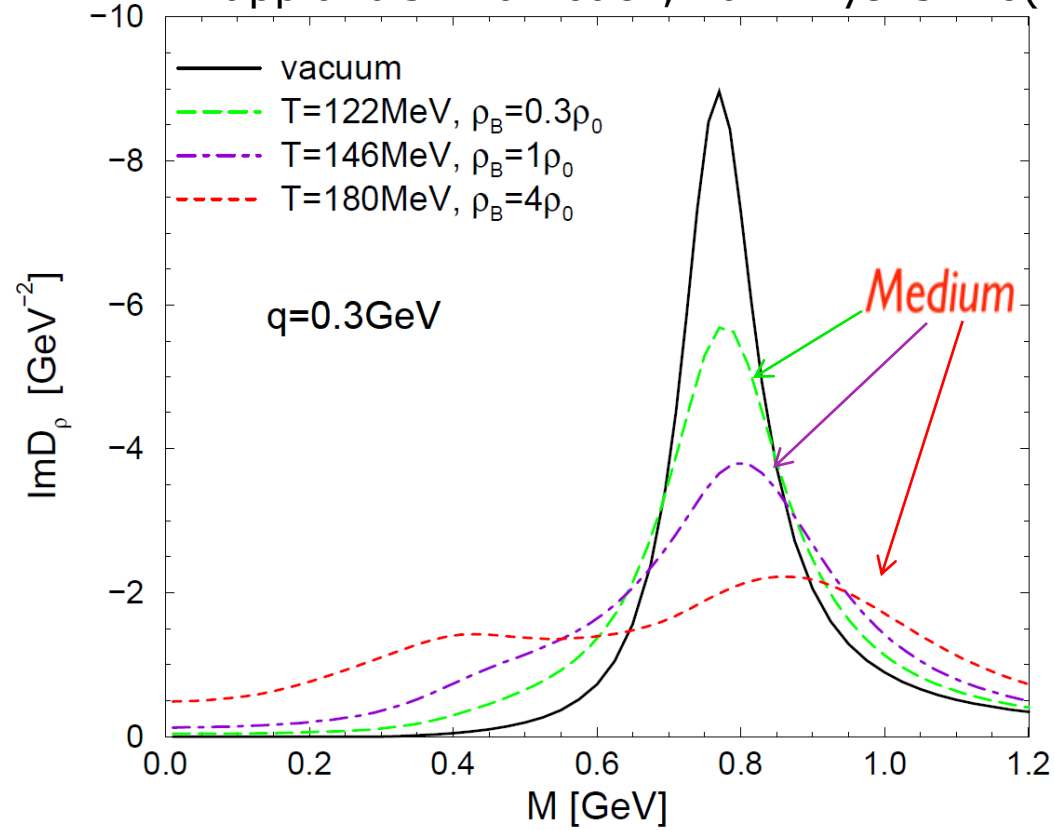
May provide evidence for a flattening related to the occurrence of a first order phase transition: latent heat

Strong motivation for measurement of a caloric curve ( $T_s$  vs  $\sqrt{s_{NN}}$ ) with high precision

# In-medium modification: $\rho$ meson spectral function



R. Rapp and J. Wambach, Eur. Phys. J A 6(1999)



$\rho$  meson : short vacuum life time & regeneration in a much long-lived fireball: probe in-medium hadron modification via  $l^+l^-$  decay

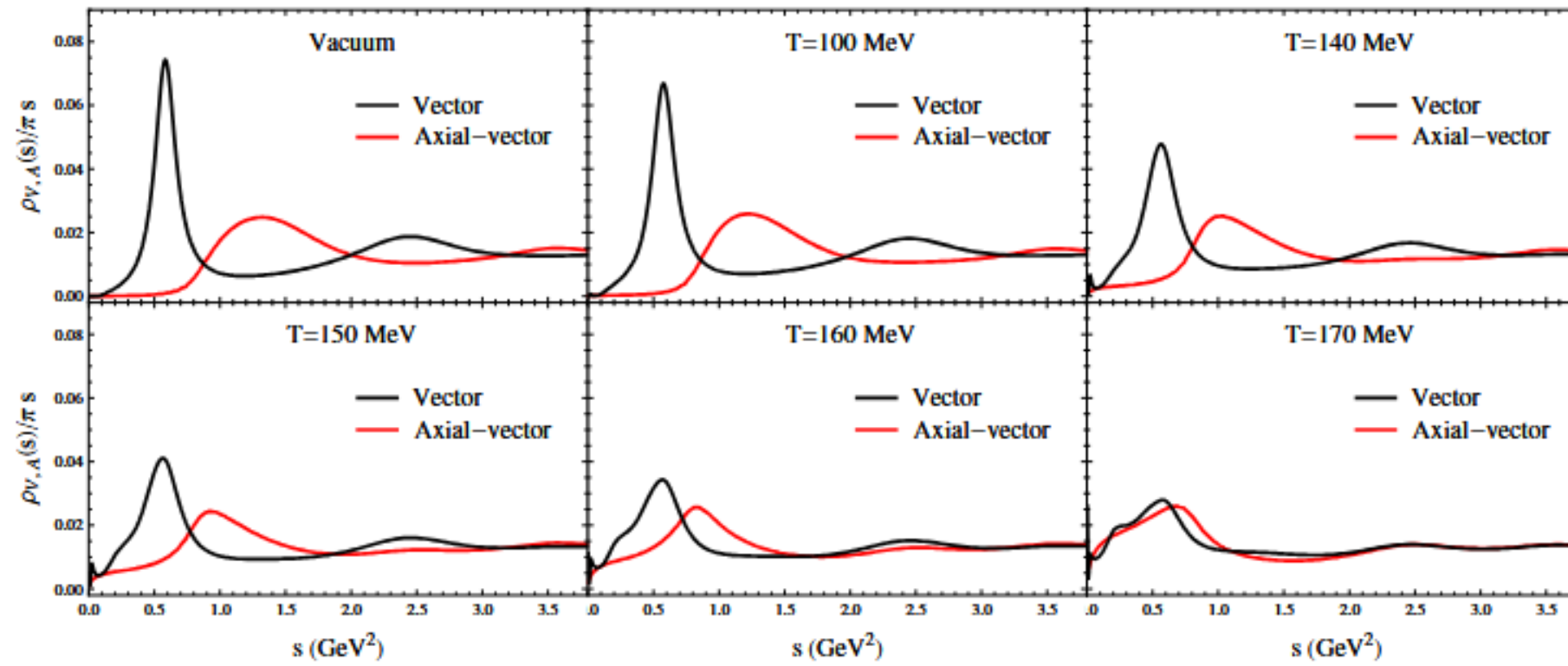
In In+In collisions @ NA60:

- No observable shift of the pole mass; strong in-medium broadening
- Disfavors dropping mass scenario
- Can be connected to **chiral symmetry restoration**

Strong broadening of the in-medium spectral function due to coupling with baryons: can be accessed through high precision di-muon data to be collected @ CBM SIS100

# $\rho$ - $a_1$ chiral mixing and restoration of chiral symmetry

Rapp and Hohler: Phys. Lett. B731 (2014) 103-109



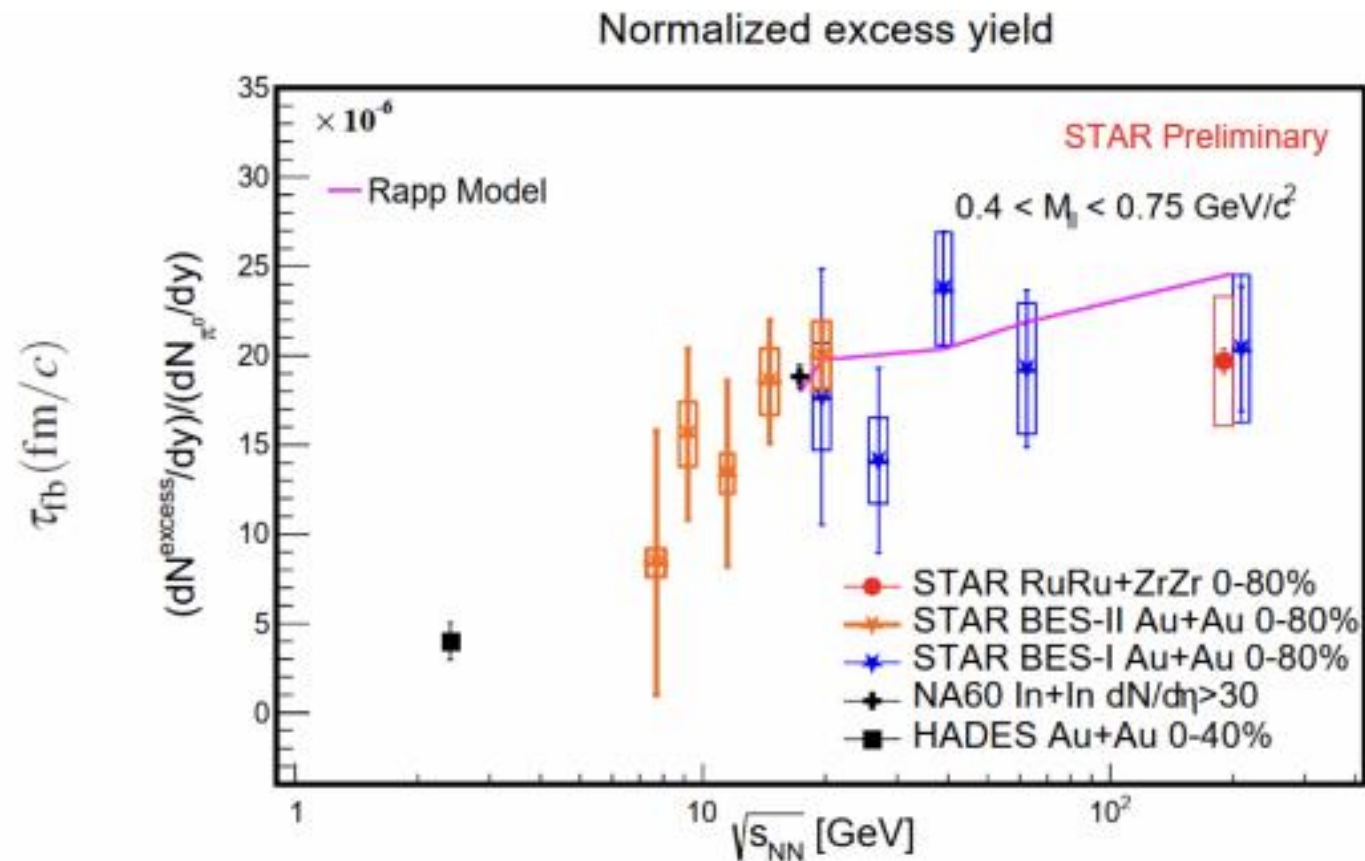
- Chiral transition demands vector( $\rho$ ) axial-vector ( $a_1$ ) degeneracy via  $a_1$  broadening and mass dropping towards  $\rho$
- Direct measurement of  $a_1$  spectral function unfeasible:  $\rho$ - $a_1$  chiral mixing as indirect probe
- Dip in the vacuum dilepton spectrum around  $a_1$  mass region
- In medium pion mediated mixing through  $\pi+a_1$  annihilation : as  $T \rightarrow T_{pc}$  dip fills and vector spectral function flattens signals CHSR
- Probe chiral mixing effect via precision dilepton measurement in  $0.9 < m_{ll} < 1.4 \text{ GeV}/c^2$
- Full mixing enhances thermal dilepton yield by 20 – 30 % : demands precise experimental sensitivity in measuring thermal dileptons
- Study evolution of dip in small bins of  $\sqrt{s}$ : track transition from non-chirally restored medium to chirally restored one
- Strategy: precision study of mass spectrum  $0.9 < M < 1.4 \text{ GeV}$  correlate with  $T$  measurement above 1.5 GeV

# Di-lepton as chronometer

Relate fireball lifetime and thermal di-lepton yields



Model: R. Rapp, H. van Hees, PLB 753 (2016) 586

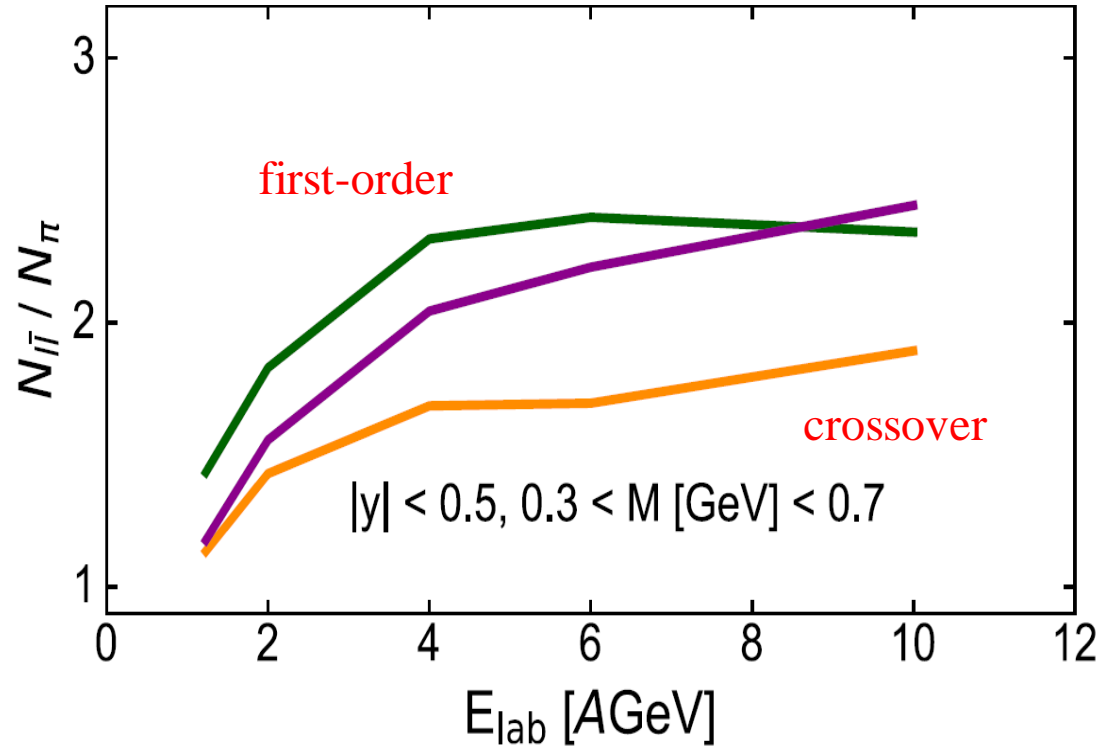


- Integrated “excess” yield in the region below free  $\rho/\omega$  mass  $0.3 < M_{\text{inv}} < 0.7$
- Tracks the total fireball lifetime remarkably well
- Low mass excess radiation yield (over the vacuum cocktail) is proportional to the fireball life time
- Less sensitive ( $< 10\%$ ) to the model input parameters for fireball expansion
- Promising tool to determine source life
- NA60 In+In collisions at  $\sqrt{s}=17.3 \text{ GeV}$ :  $\tau_{fb} = 7 \pm 1 \text{ fm}$

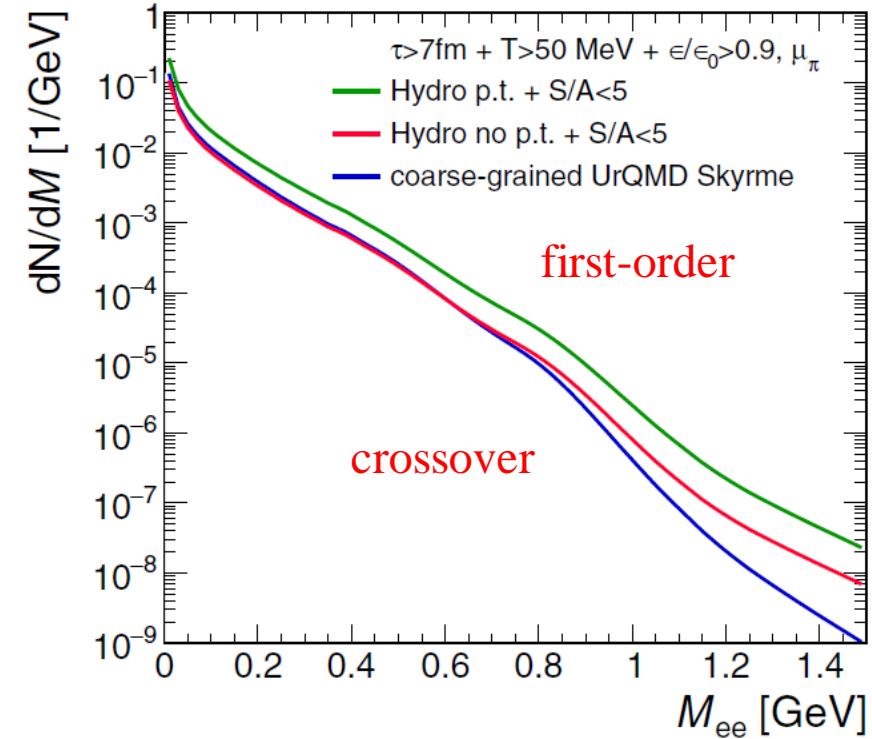
- Anomalous variation may be triggered by 1<sup>st</sup> order phase transition: presence of mixed phase
- Needs good control over the in-medium spectral shape
- Precision data in the low mass region

# Di-lepton signature of first order phase transition

O. Savchuk, et. al., *J. Phys. G: Nucl. Part. Phys.* 50, 125104 (2023)

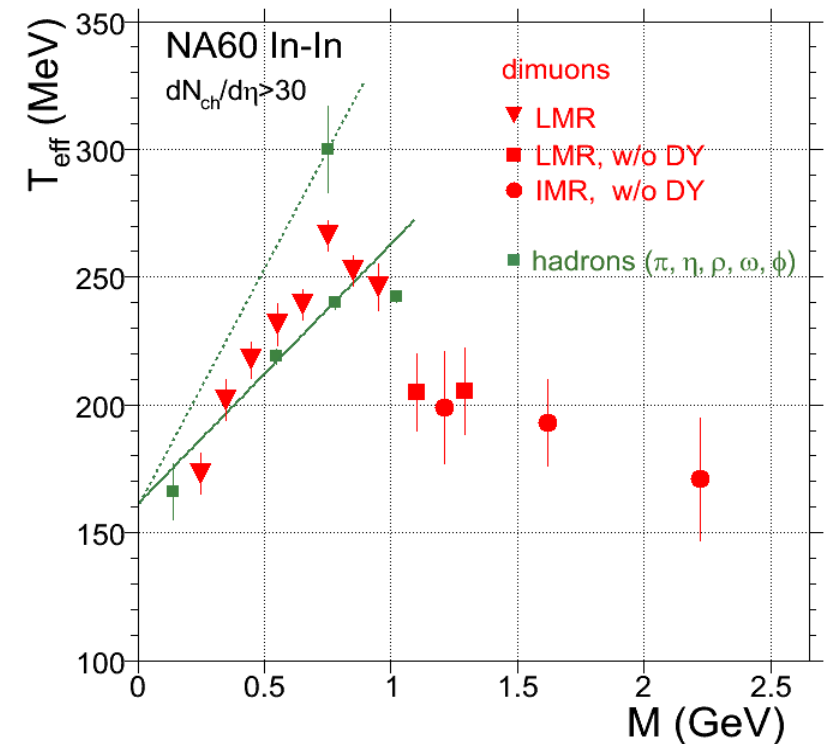
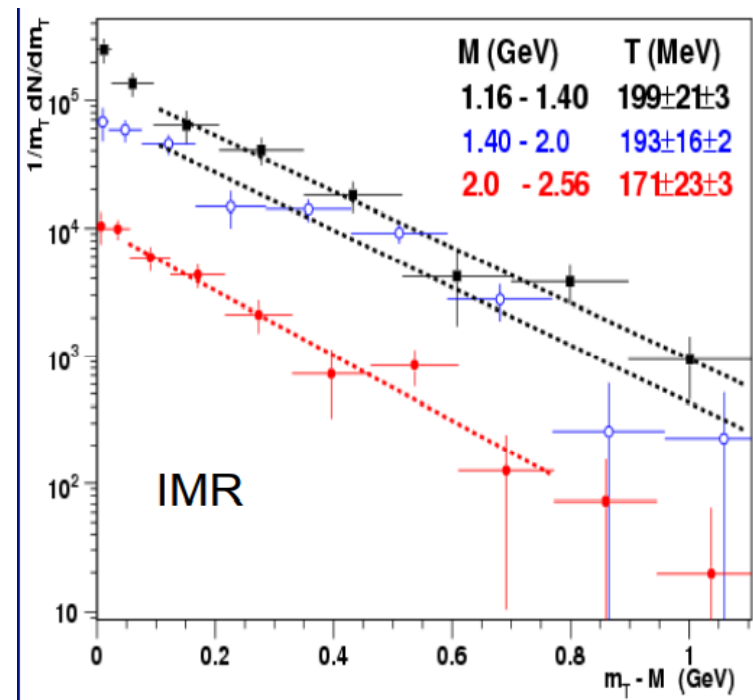
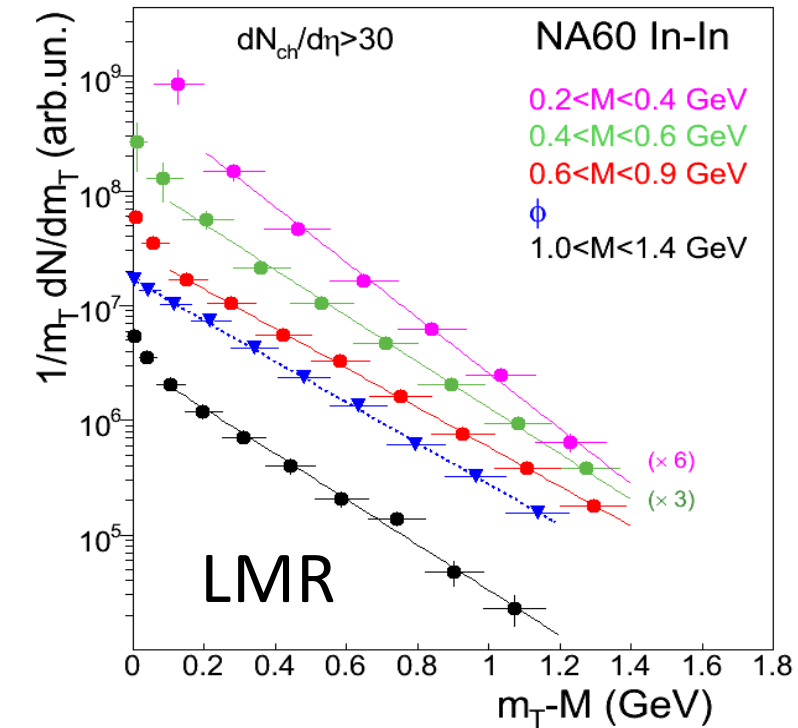


F. Seck et. al., *Phys. Rev. C* 106, 014904 (2022)



- Dilepton yield sensitive to the medium evolution dynamics
- Two different EoS: 1<sup>st</sup> order transition (discontinuous) and cross-over transition (continuous)
- First order transition leads to a substantial increase in low mass thermal dilepton yield compared to a cross over scenario: two times larger in the LMR
- Prolonged lifetime due to mixed phase formation since fireball expansion slows down while crossing mixed phase
- Dileptons being continuously emitted and not affected by final state interactions, extended lifetime significantly increase their total yield
- Entropy production and reheating could boost di-lepton production further

# Di-muon transverse spectra: barometer of the fireball

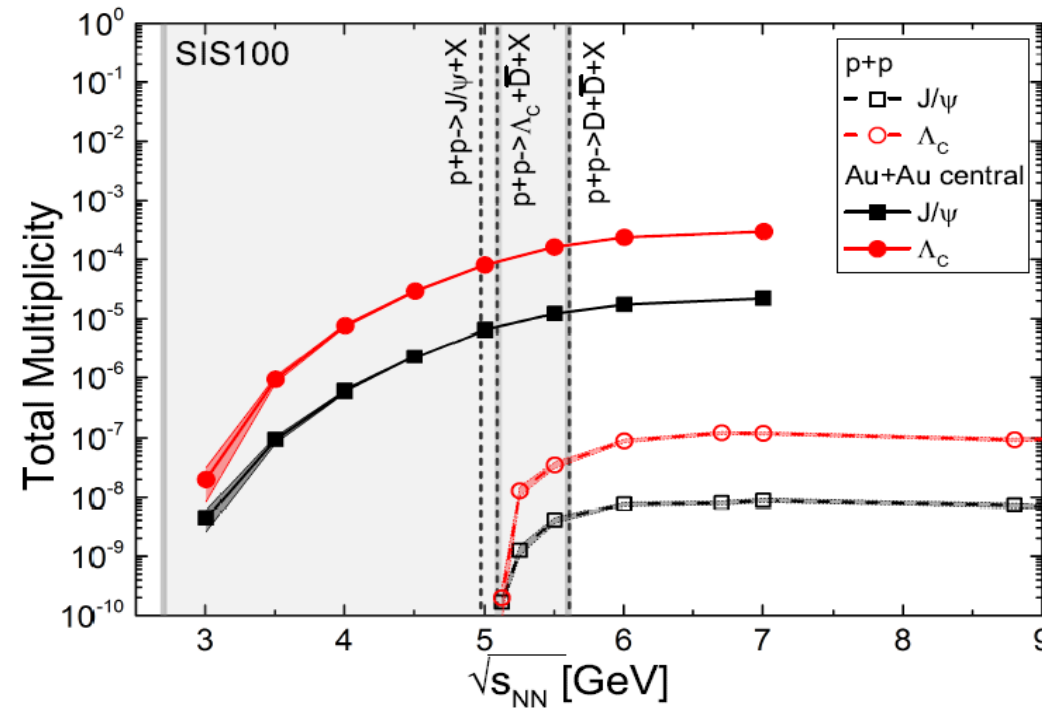


$$1/m_T dN/dm_T \propto \exp(-m_T/T_{\text{eff}}) \quad : \quad T_{\text{eff}} = T + m \langle v_r^2 \rangle$$

- Exponential fit to  $m_T$  spectra & extract  $T_{\text{eff}}$
- Initial rise of  $T_{\text{eff}}$  with  $M$  up to 1 GeV: consistent with emission from radially expanding late hadronic phase
- Drop at  $M > 1$  GeV indicates emission from early (partonic) phase ( $\langle v_r \rangle \longrightarrow 0$ )
- $M > 1$  GeV: parton dominated matter:  $T_{\text{eff}}$  indept of mass within errors
- Consistent value of source temperature from mass spectra ( $205 \pm 12$  MeV) and  $m_T$  spectra ( $192 \pm 21$  MeV)

# J/ψ production in the sub-threshold domain

J. Steinheimer, A. Botvina, and M. Botvina, Phys. Rev. C 95, 014911 (2017)



Kinematic threshold for J/ψ production:  $N + N \longrightarrow N + N + J/\psi$ : threshold energy:  $E_{lab} = 12.5 A \text{ GeV}$  ( $\sqrt{s_{NN}} \sim 5 \text{ GeV}$ )

Below  $\sqrt{s_{NN}}$  J/ψ production will be kinematically impossible

In dense baryonic matter, model calculations predict:

- J/ψ production in 8 - 10 A GeV Au + Au collisions
- via sequential multiple collisions and subsequent decay of heavy baryonic resonances ( $N^* \rightarrow N + J/\psi$ );
- If detected will open up new mechanisms of charm production

# Latest MUCH geometry (v26b)

(revival of TDR absorbers: used in physics performance)

Detectors ( $5.7^\circ - 25^\circ$ ):  $1.44 < \eta < 3$

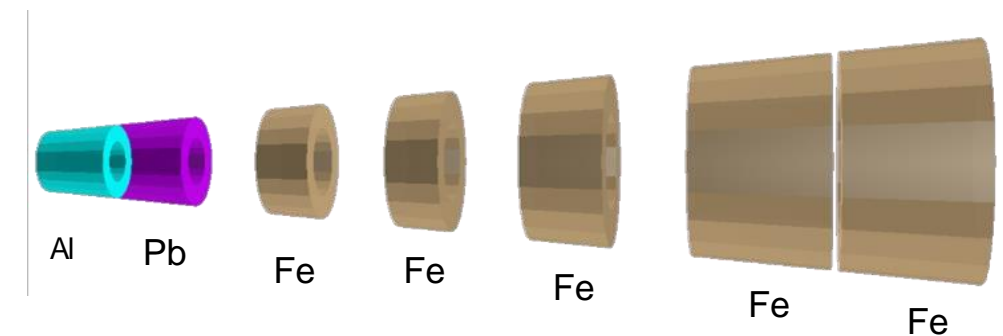
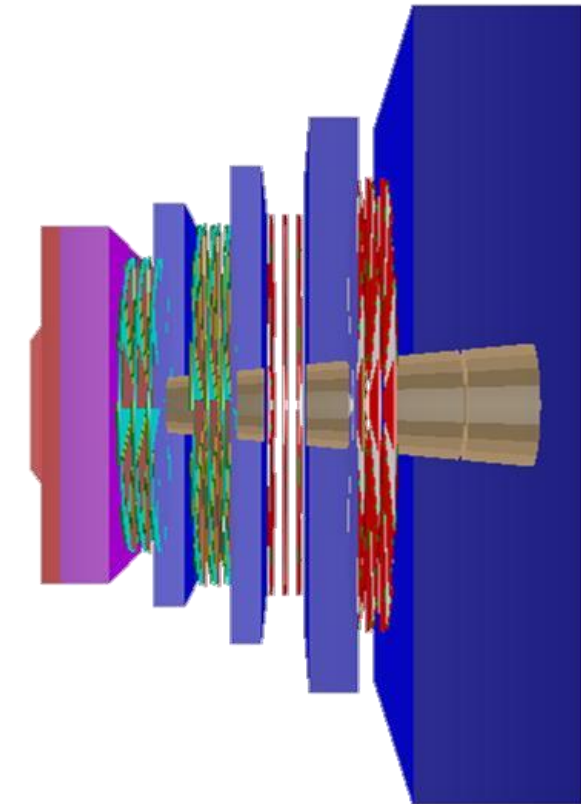
- 2 GEM + 2 RPC stations (to be replaced with straw tube trackers)

Absorbers ( $5.7^\circ - 25^\circ$ ):

- 60 cm C (absorber 1) (16 cm trapezoid + 44 cm box):  $\rho_C = 2.3 \text{ gm/cm}^3$
- (20+20+30+100) cm Fe (absorbers: 2 -5):  $\rho_{Fe} = 7.87 \text{ gm/cm}^3$

Shields inside absorbers ( $2.9^\circ - 5.7^\circ$ ):

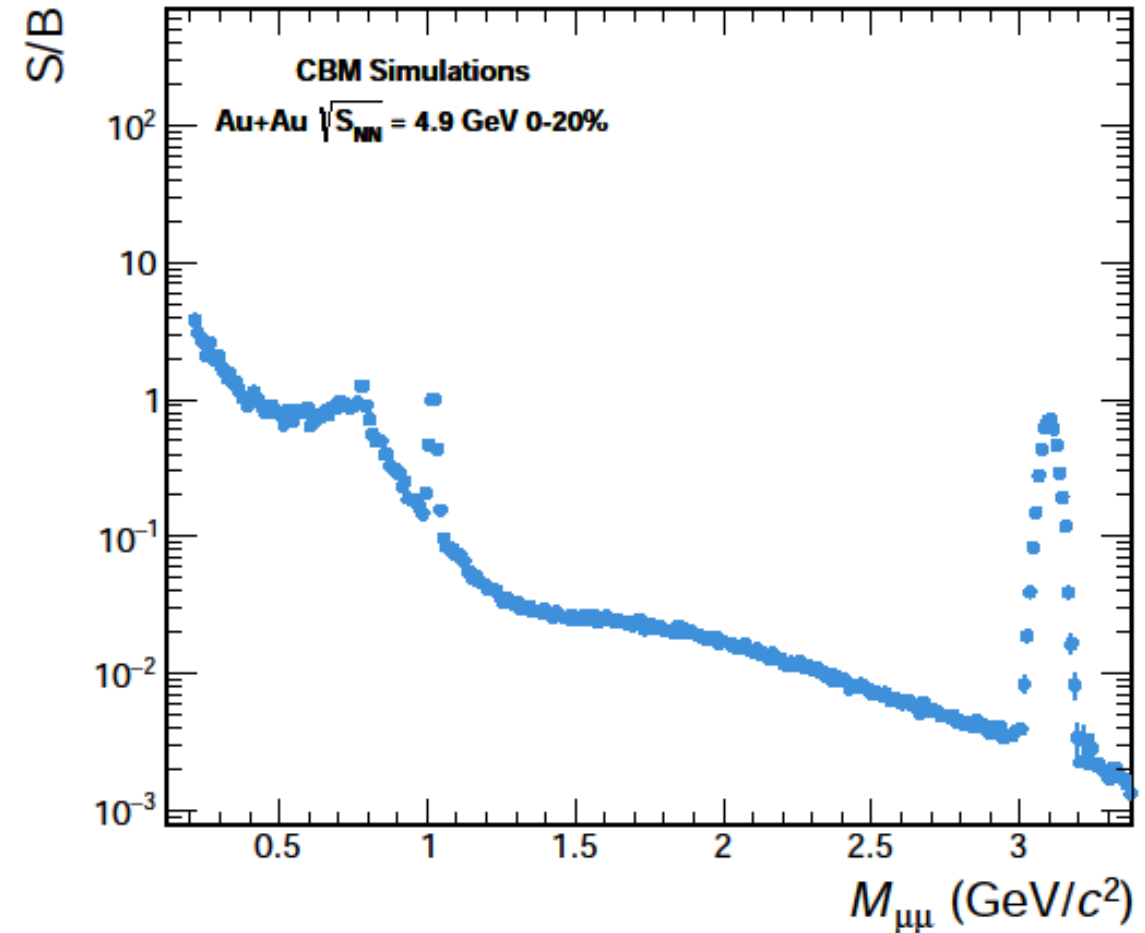
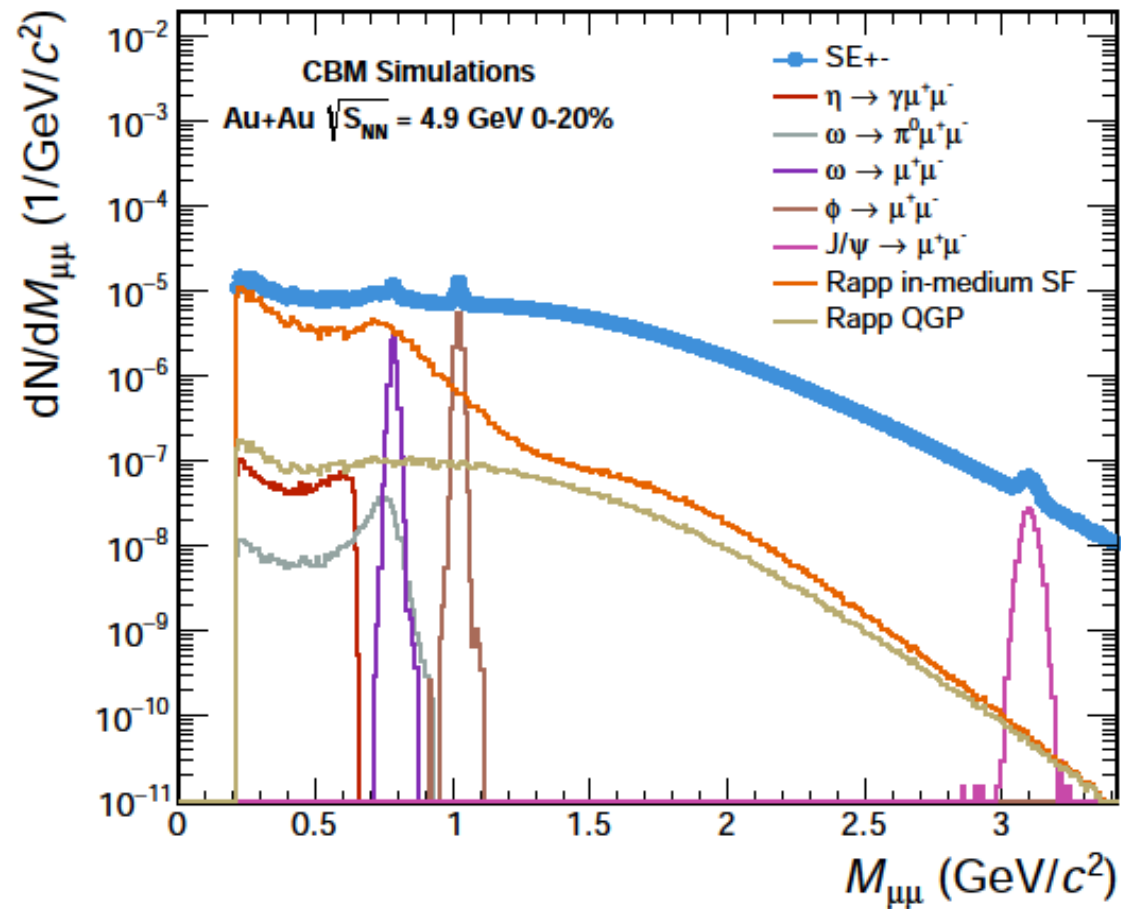
- 30 cm Al + 30 cm Pb – first absorber
- (20+20+30+100) cm Fe – other absorbers
- Shield inside last absorber divided into two pieces (50 cm + 50 cm)
- 3 cm gap in between
- Minimum angle increased from  $2.9^\circ$  to  $3.4^\circ$  for the last 50 cm shield
- No overlap with the beam pipe (v26h)



# Di-muon reconstruction performance

arXiv:2606.16395 (nucl-ex)

*Details: CBM Physics Forum (May 29, 2026) talk by Anna Senger*



Selection of Long muon candidate tracks: reconstructed global tracks with associated:

- STS hits  $>6$  + MUCH hits  $> 10$  + TRD hits  $> 2$  +  $2 \sigma_{TOF} + d_{TOF} < 10$  +  $\chi^2/NDF$  (Vertex)  $< 2$  +  $\chi^2/NDF$  (STS)  $< 2$  +  $\chi^2/NDF$  (MUCH)  $< 3$

Results to appear in CBM overview paper “CBM physics program and recent experimental developments”

## Take home (instead of a summary)

CBM @ FAIR SIS100 aims to study the QCD phase diagram in high  $\mu_B$  region

- Most promising observables are rare and statistics hungry
- Fixed target experiment with highest heavy-ion beam luminosities leading to max.  $R_{int} = 10$  MHz
- Measurement of high precision multi-differential observables

Di-muons identified as multi-messenger signal: on suitably chosen mass window can serve as

- chronometer, thermometer, spectrometer, polarimeter, presence of 1<sup>st</sup> order transition
- charm-nucleon interaction and undiscovered mechanisms of charm(onium) production

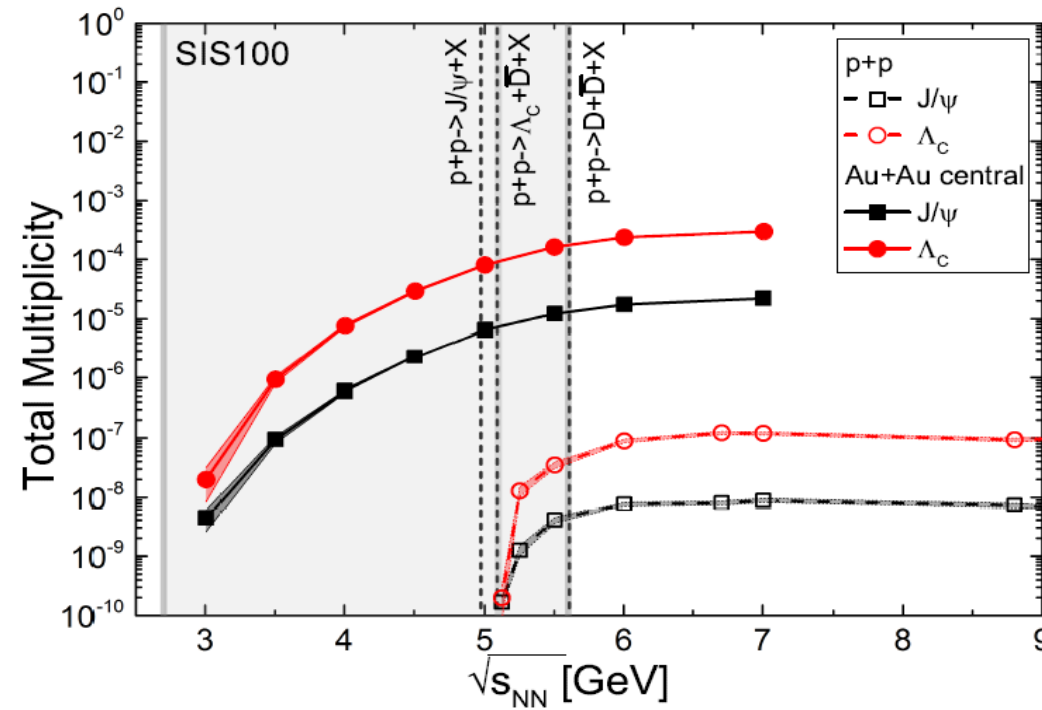
Muon chamber (MuCh) + Muon Straw (MuSt) has a wide physics reach

- GEM detectors in first two stations:
  - ongoing mass production of station 1 modules
  - final prototype testing of station 2 modules
- Straw Tubes in stations 3 & 4
  - ready built modules
  - available for the first data taking period (later could be upgrade to new MPGD technology)
- Need to initiate the physics performance studies with MuCh + MuSt configuration!

# Back ups

# J/ψ production in the sub-threshold domain

J. Steinheimer, A. Botvina, and M. Botvina, Phys. Rev. C 95, 014911 (2017)



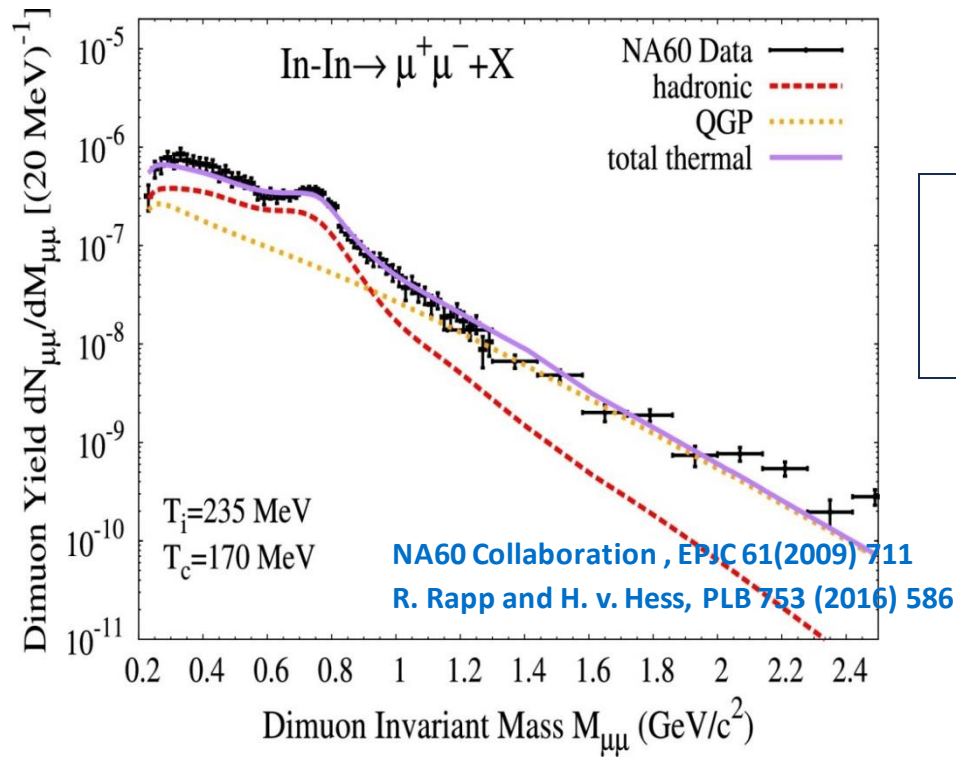
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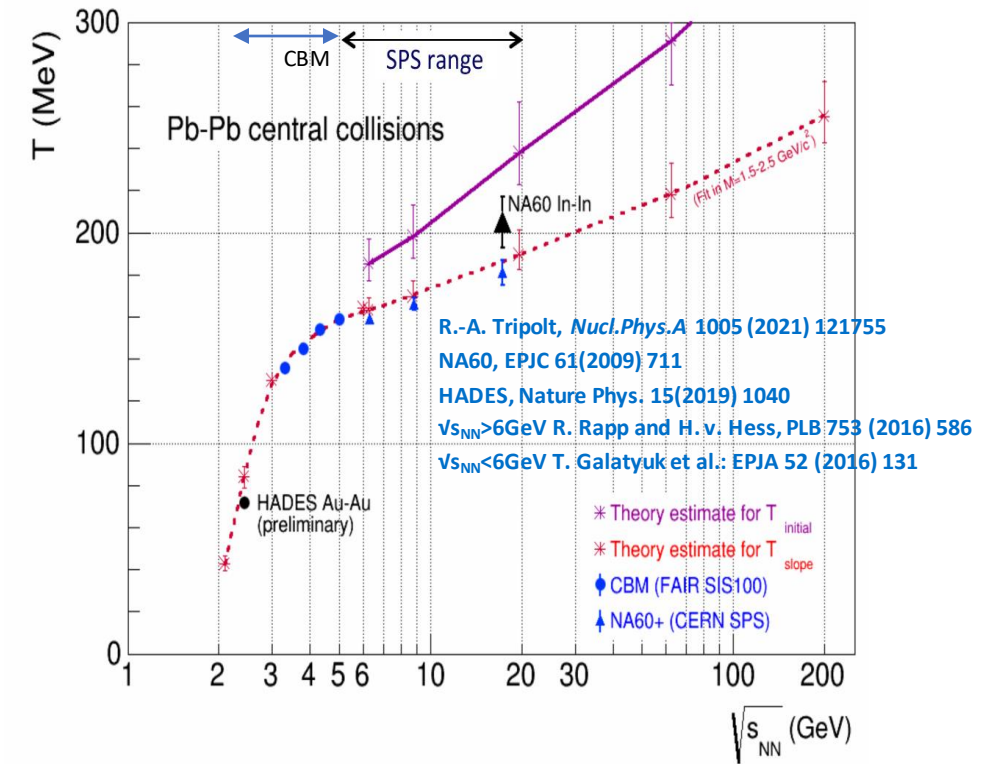
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- J/ψ production in 8 - 10 A GeV Au + Au collisions
- Sequential multiple collisions and subsequent decay of heavy baryonic resonances ( $N^* \rightarrow N + J/\psi$ );
- If detected will open up new mechanisms of charm production

# IMR di-leptons as fireball thermometer: caloric curve of QCD



$$dN/dM \sim (MT)^{3/2} \exp(-M/T)$$

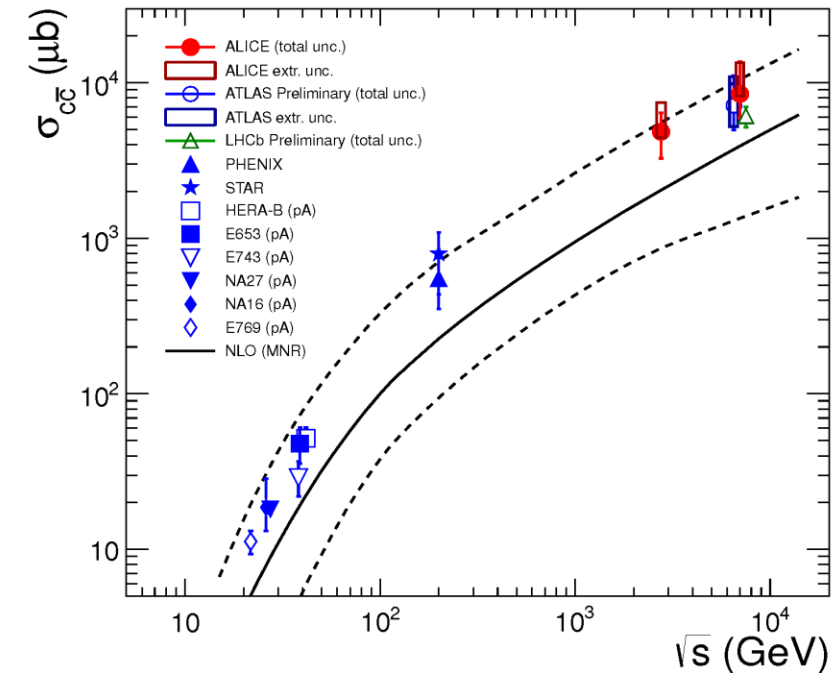
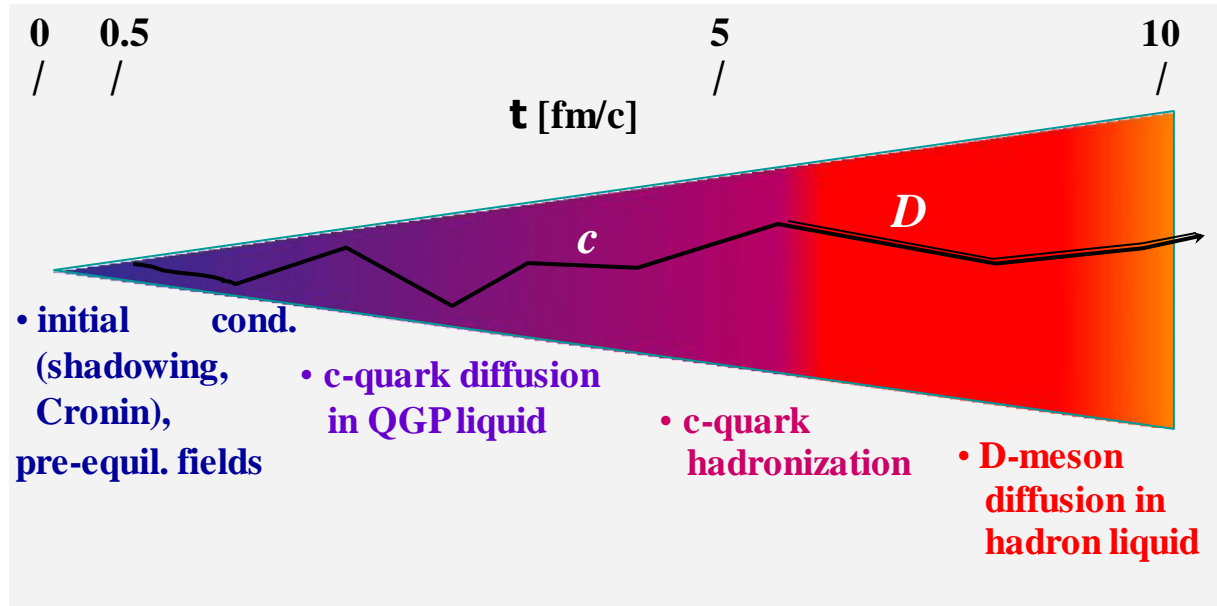


- Di-muons in the mass range:  $1.5 < M_{\text{inv}} < 2.4 \text{ GeV}/c^2$ : dominant contribution from thermal radiation from QGP phase
- Exponential mass shape ( $\exp(-M/T)$ ): can be used to determine the fireball temperature
- Extracted slope parameter not affected by medium expansion: no blue shift: stable thermometer

- HADES at SIS-18 (Au+Au collisions @  $\sqrt{s_{NN}} = 2.4 \text{ GeV}$ ): 72 MeV
- NA60 at CERN-SPS (In+In collisions @  $\sqrt{s_{NN}} = 17.3 \text{ GeV}$ ): 205 MeV

- Aim:
- Precision study of source temperature the region  $\sqrt{s_{NN}} \sim 3\text{-}20 \text{ GeV}$ : caloric curve of QCD matter
- Any plateau in the caloric curve would indicate possible existence of a first order phase transition

# Charm in Heavy-Ion Collisions



Unlike lighter quarks,  $m_c \gg T$

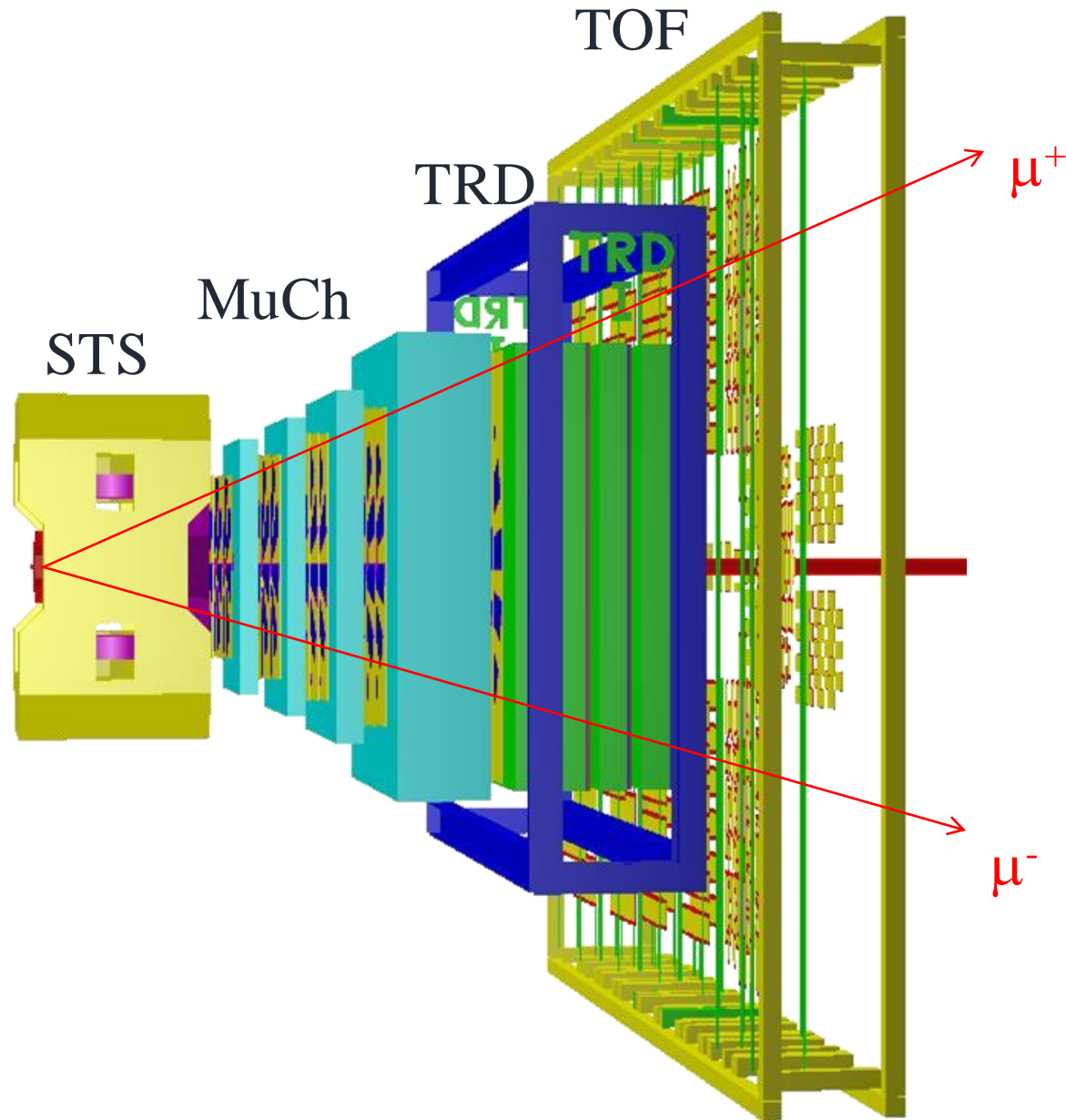
- thermal production of charm negligible
- production of charm in first-chance N-N collisions
- charm probes the produced medium: c quark diffusion in QGP or D meson /  $J/\psi$  propagation in hadronic medium

Total charm production cross section close to threshold is unknown below  $\sqrt{s}=20$  GeV even in elementary reactions (let alone AA collisions)

Perturbative QCD calculations also come with large uncertainties

Large discovery potential for upcoming experiments to measure charm production close to threshold

# The Muon Chamber (MuCh) system for CBM experiment @FAIR-SIS100



STS: Silicon Tracking Station  
MuCh: Muon Chamber (India)  
TRD: Transition Radiation Detector  
TOF: Time of Flight detector

## Design of MuCh detector:

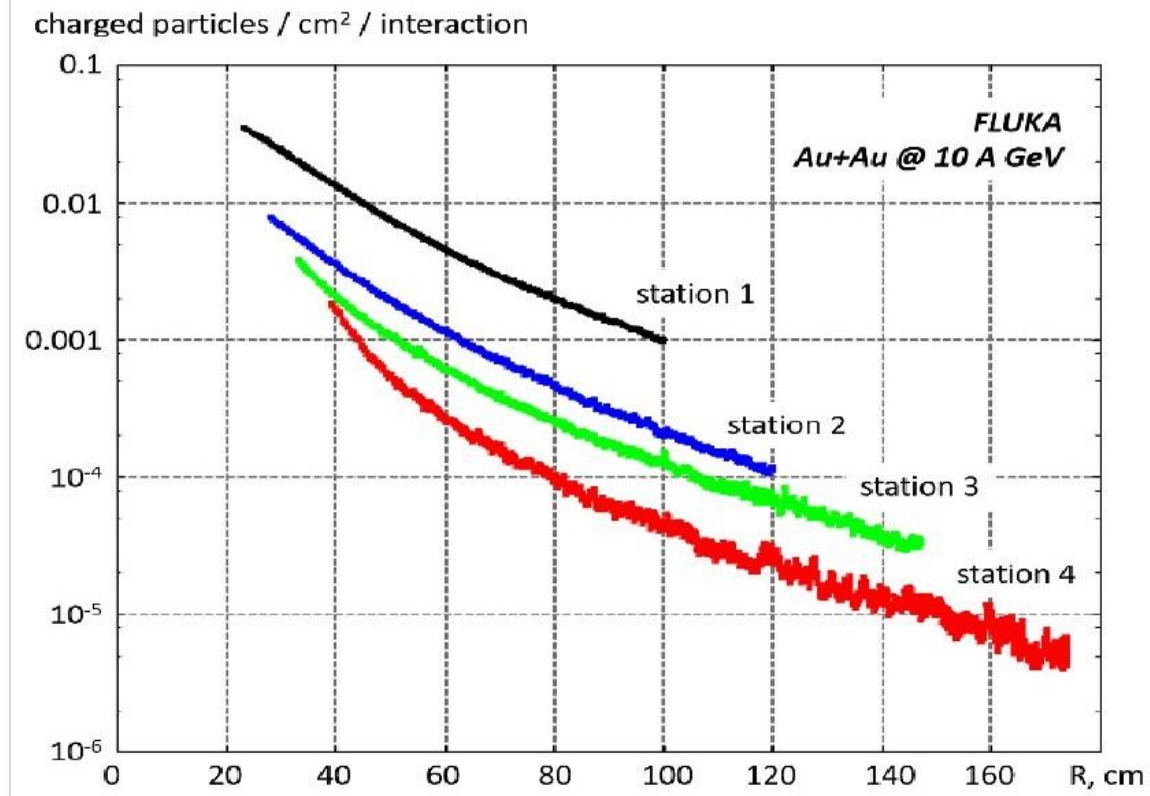
- 4 detector stations: GEM detectors in first two stations
- 5 absorbers: 60 cm C + 20 + 20 + 30 + 100 cm Fe  $\equiv 13.5\lambda_1$
- 1<sup>st</sup> absorber inside the dipole magnet
- Angular acceptance:

$$\theta_{min}=5.7^\circ: \eta_{max}=3 \text{ \& } \theta_{max}=25^\circ: \eta_{min}=1.44$$

## Muon detection strategy:

- Detectors placed between segmented absorbers
- Useful for detection of low mass vector mesons

# Challenges in muon measurements in CBM



High collision rates in heavy-ion collisions (max.  $R_{\text{int}} = 10$  MHz)

Large particle incidence rate on MuCh planes

Different detector technologies for different stations:

- GEM detectors in first two stations due to high rate capability
- Straw tube/RPC technology in other two stations

- Withstand high radiation dose: radiation hard detectors and electronics
- Large Area detector
- Detector should have a modular structure
- Data to be readout in a self triggered mode
- event reconstructed offline by grouping the timestamps of the detector hits.

# Compressed Baryonic Matter (CBM) experimental setup

## Fixed target experiment

- Polar coverage  $2^\circ < \theta_{\text{Lab}} < 25^\circ$ , full  $\phi$  coverage
- Mid-rapidity coverage for all energies, down to low  $p_{\perp}$
- Highest rate for heavy-ion reactions ( $R_{\text{int}} = 10 \text{ MHz}$ )

## Versatile multi-purpose detector systems

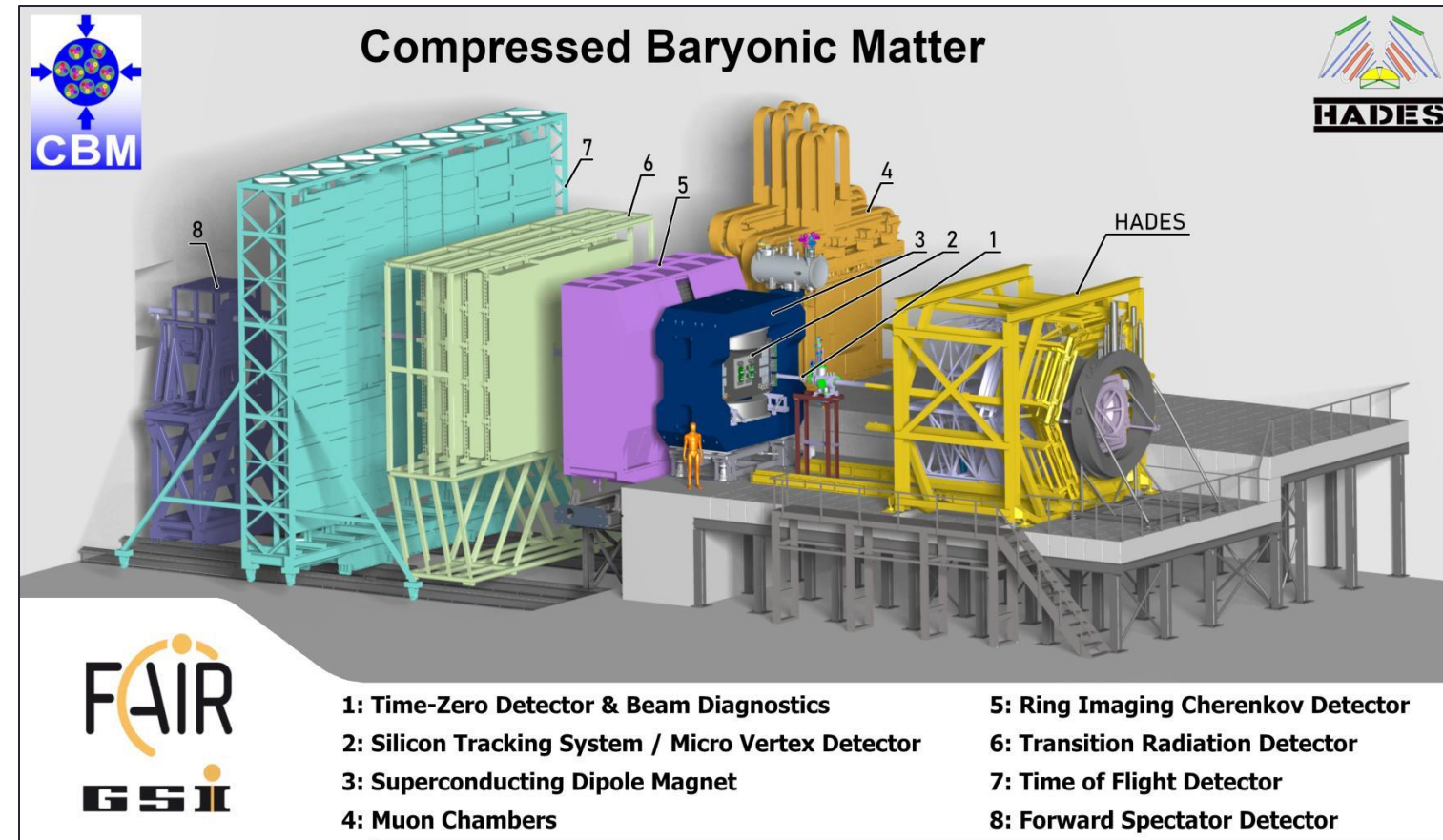
- Capable to measure hadrons, electrons, muons

## Tracking based entirely on silicon

- Fast and precise track reconstruction:  $\Delta p/p \sim 1 \%$

## Optimized for the highest luminosities

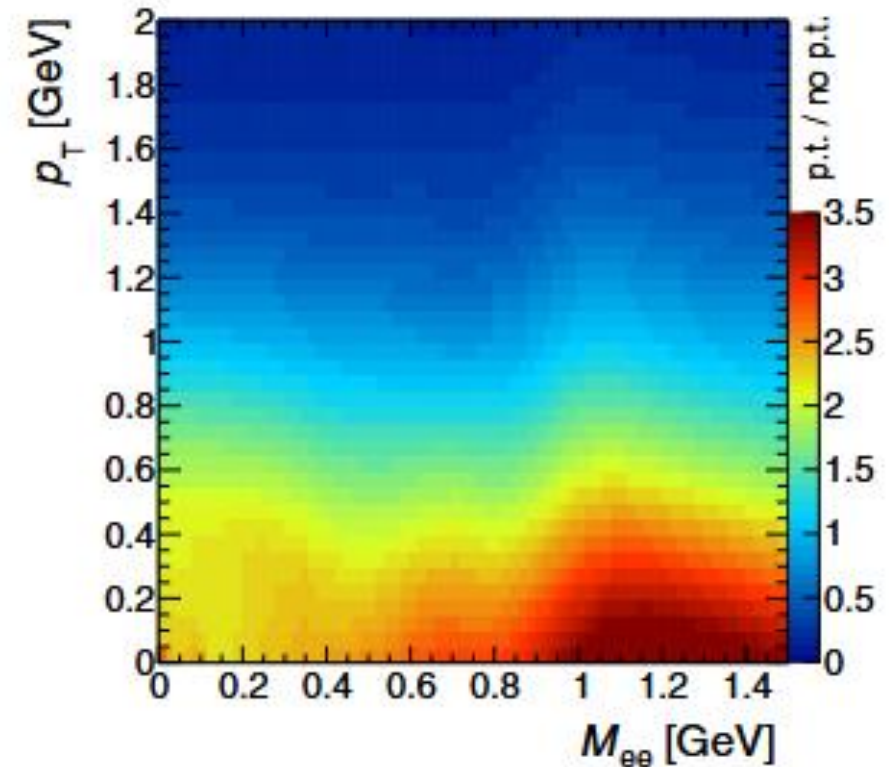
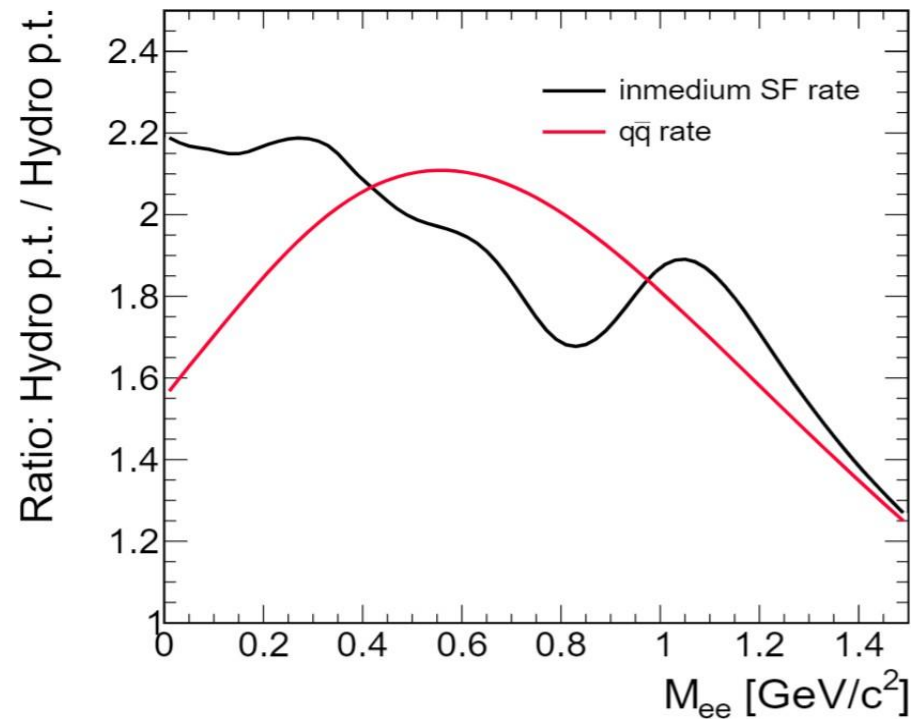
- Free-streaming front-end connectivity up to 10 MHz
- Online trigger and data reduction



- Alternate data taking by muons (MuCh) and electrons (RICH)
- **Muon Chamber (MuCh) detector system: Major Indian contribution**
- Detection of muon pairs ( $\mu^+\mu^-$ ) emitted from the collision zone

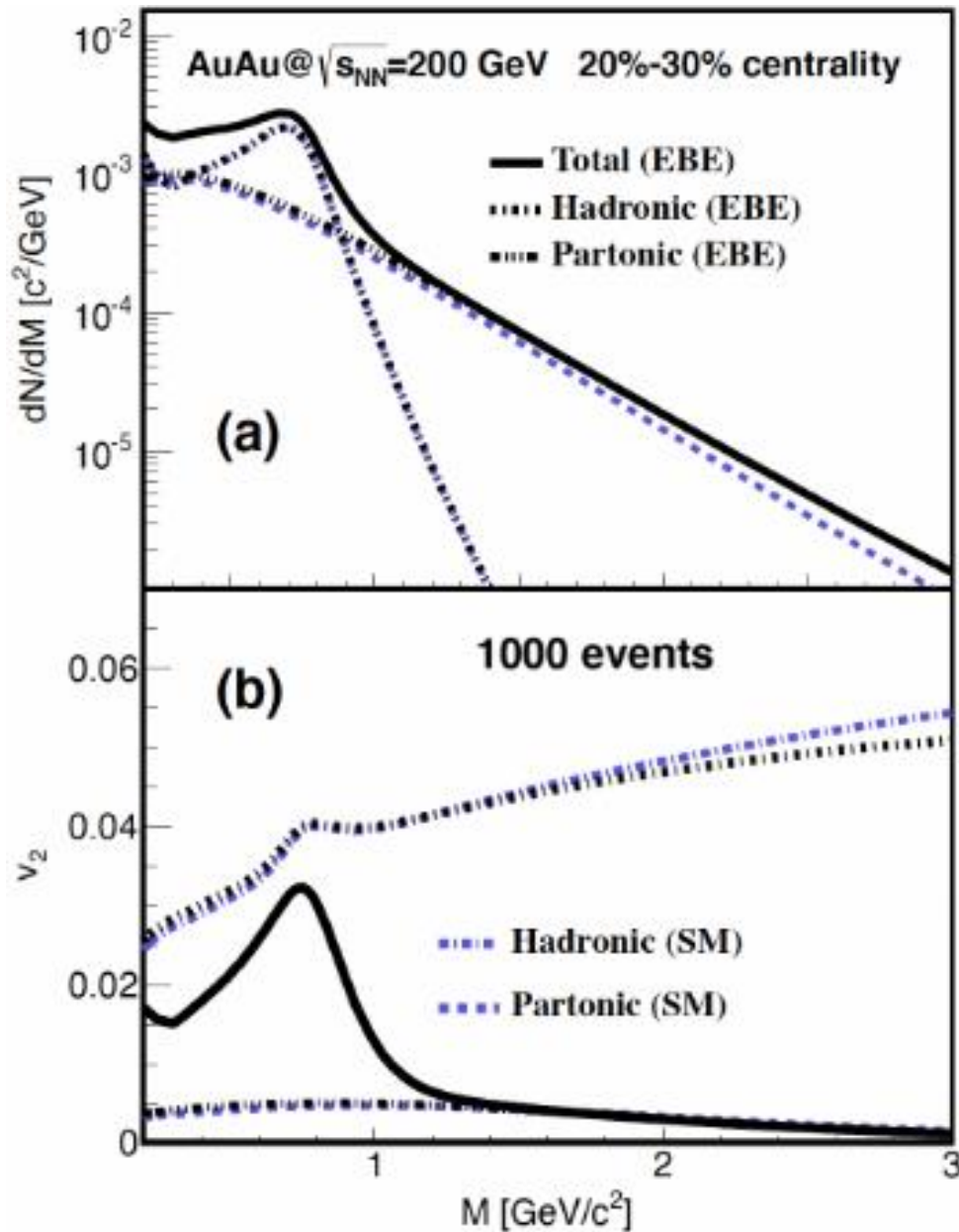
# Di-lepton signature of first order phase transition

F. Seck, *et al.*, PRC 106 (2022) 1, 014904



- Ideal relativistic hydrodynamic simulations for 1 – 2 A GeV Au+Au collisions
- Two different EoS: 1<sup>st</sup> order transition (discontinuous) and cross-over transition (continuous)
- First order transition leads to a substantial increase in low mass thermal dilepton yield compared to a cross over scenario: two times larger in the LMR
- Prolonged lifetime due to mixed phase formation since fireball expansion slows down while crossing mixed phase
- Dileptons being continuously emitted and not affected by final state interactions, extended lifetime significantly increase their total yield
- Entropy production and reheating (latent heat) could boost dilepton production further

# Dilepton anisotropic flow: barometer of the fireball



In non-central collisions initial spatial anisotropy generates stronger pressure gradients along short axis of the overlap volume  
momentum anisotropy

Azimuthally anisotropic emission profile and significant  $v_2$  in the early phase formation of sQGP

Hadron  $v_2$  affected by late stage hadronization and re-scattering effects

Medium properties extracted from hadronic  $v_2$  affected by late stages

Dileptons provide crucial access to time evolution of  $v_2$

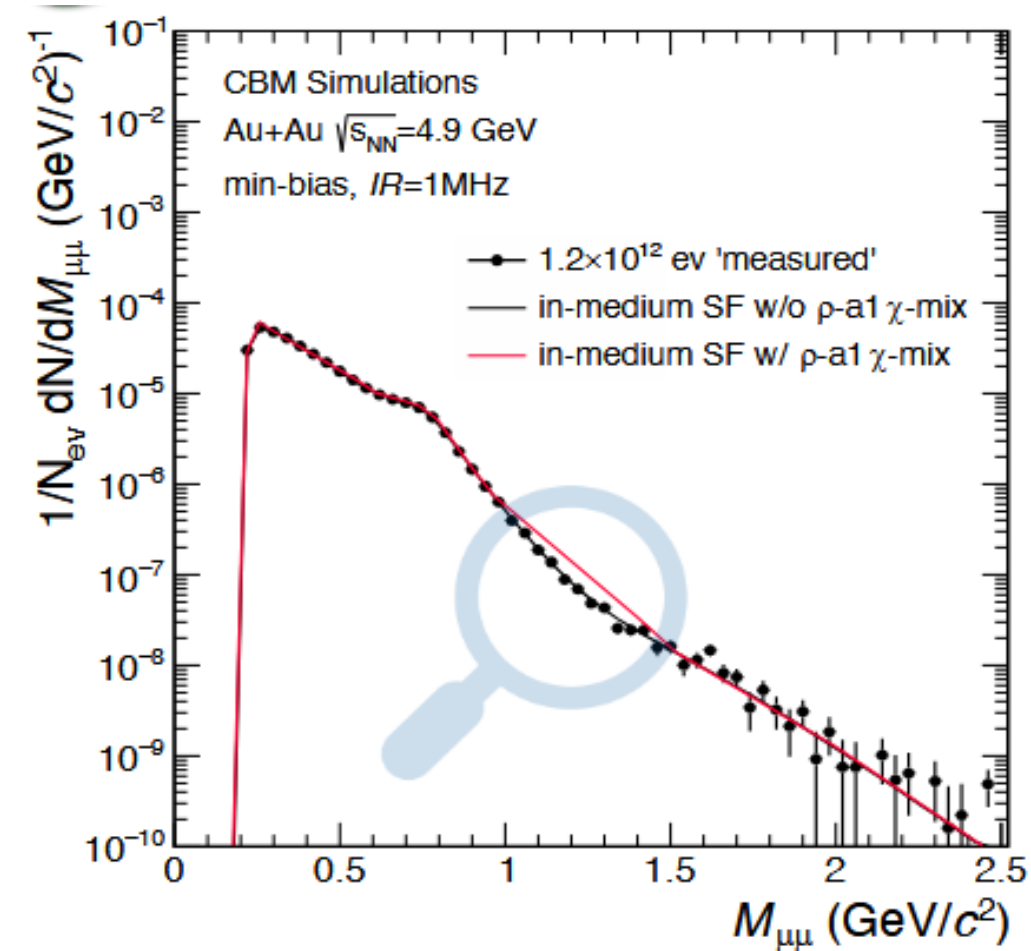
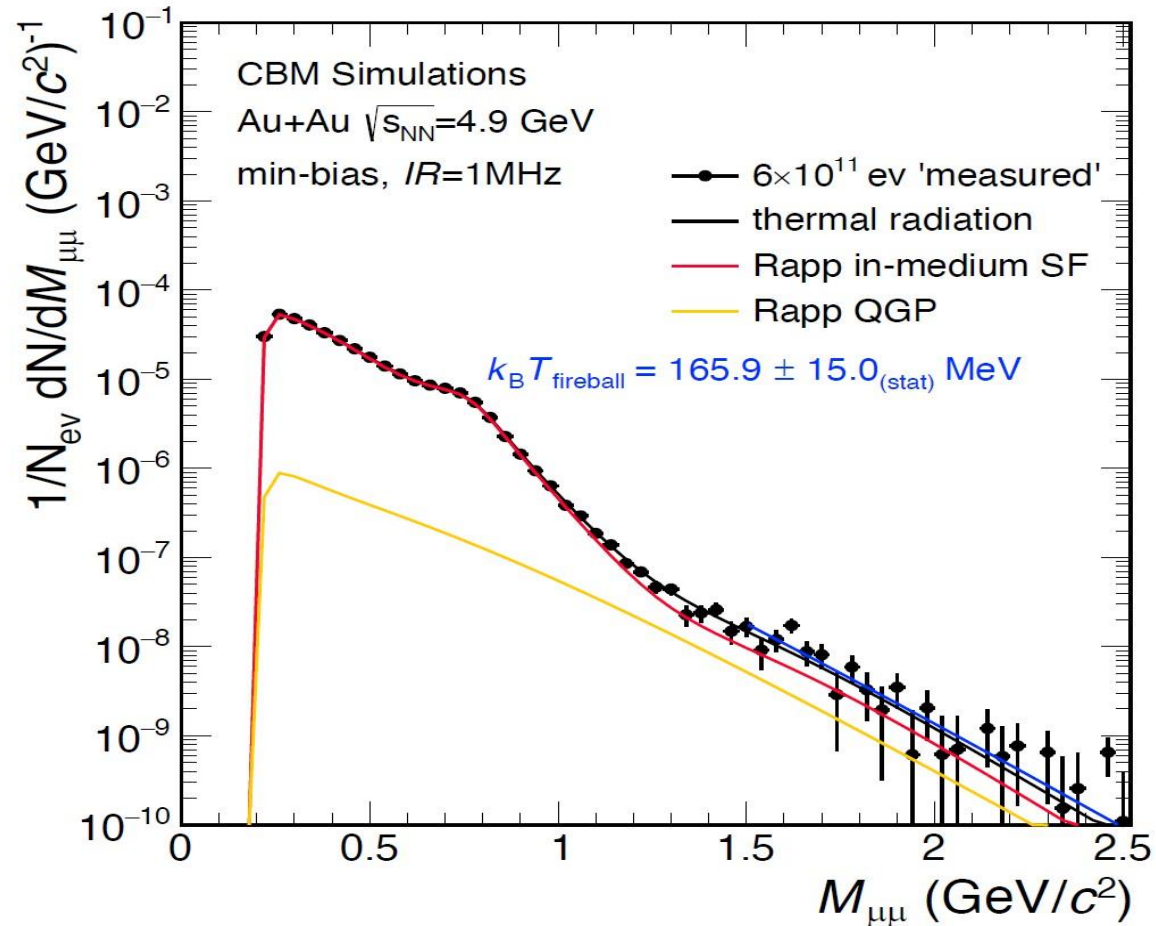
$v_2$  measurement of thermal dileptons presently unachievable by existing experiments due to statistical limitations

$v_2$  in LMR from hadronic phase: rises with  $M$  due to radial flow

$v_2$  in IMR from QGP phase: remains smaller at lower energies

Mass differential dilepton  $v_2$  measurements: insights to early dynamics and QGP to hadron transition

# Thermal di-muons with CBM @ FAIR SIS100



Thermal dileptons after subtraction of combinatorial bkg. and freeze-out cocktail  
 CBM plans an energy scan covering 6 energies.

Expected di-muon performance:

- High statistics runs after first 3 years with  $R_{\text{int}} = 1$  MHz
- Access IMR range with  $<10\%$  errors in  $T_{\text{fireball}}$  & sensitivity to detect chiral mixing