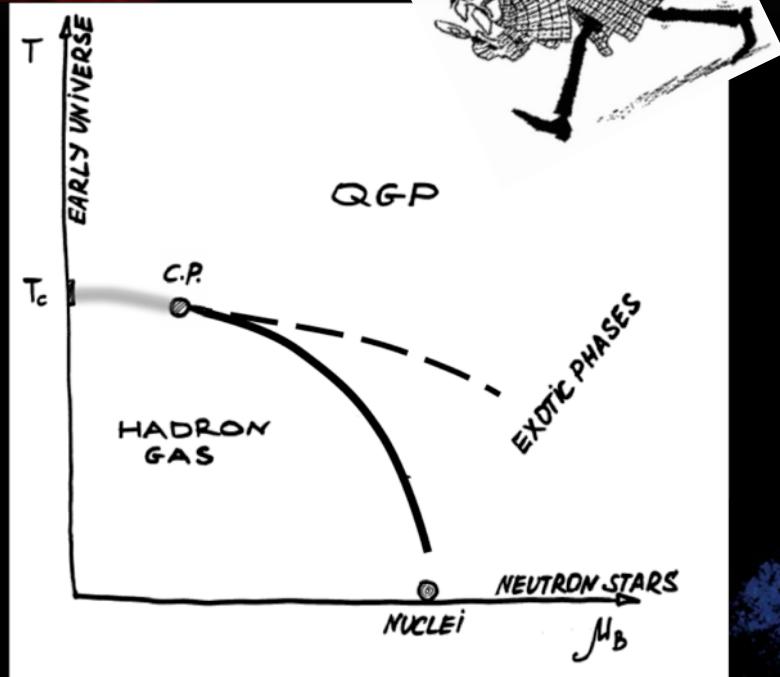


# Exploring QCD phase diagram with dileptons

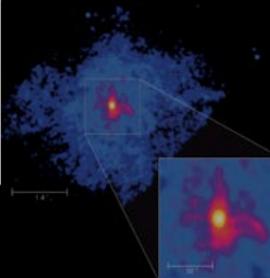
Tetyana Galatyuk  
for the HADES, STAR and CBM Collaborations

Technische Universität Darmstadt / GSI

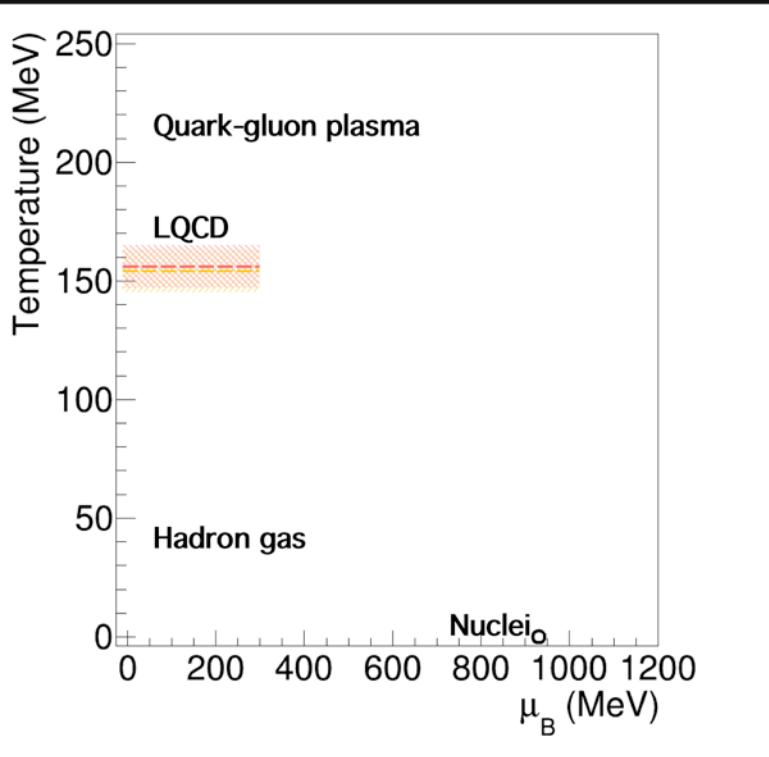
# Exploring the phase diagram of QCD matter



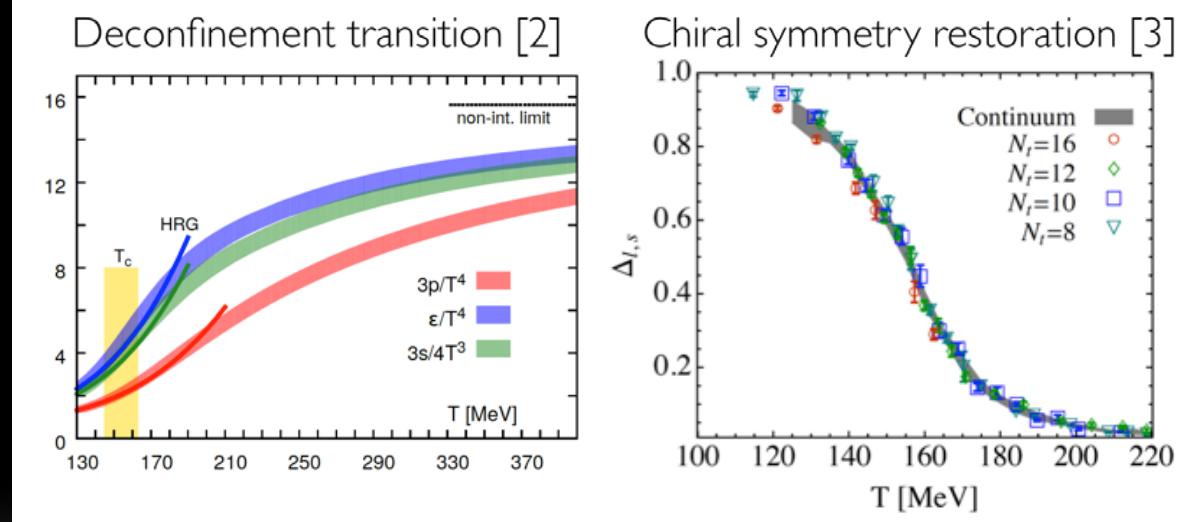
- What are the properties of matter under extreme temperatures and densities?
- Where are the phase boundaries located?
- Is there a critical point?
- Where are the limits of hadronic existence?



# Theoretical guidance



- Vanishing  $\mu_B$ , high T (Lattice QCD)
  - Crossover transition
  - $\epsilon_c \sim 1 \text{ GeV/fm}^3, T_c \sim 155 \text{ MeV}$

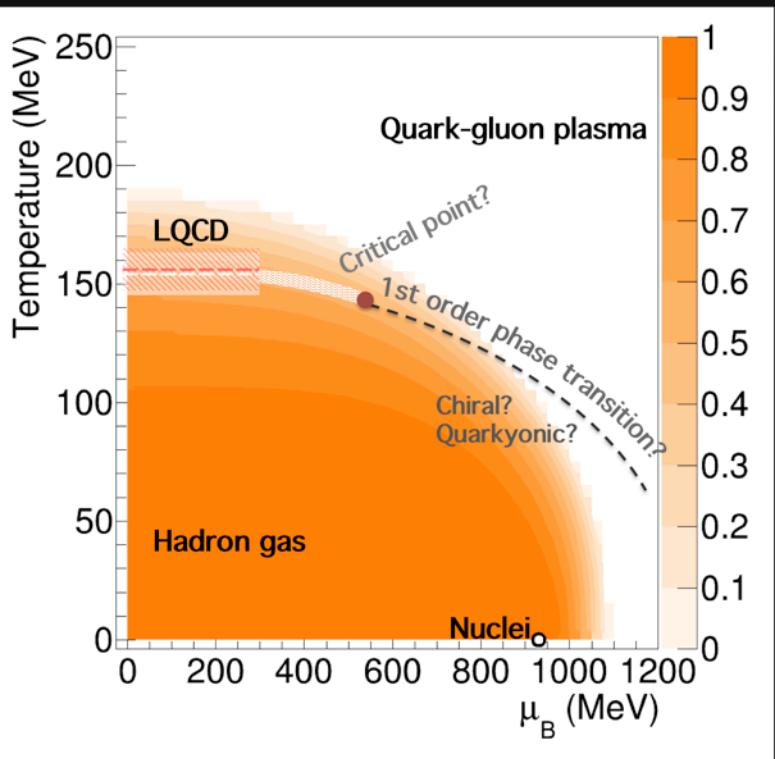


[1] O. Kaczmarek et al., PRD 83 (2011) 014504

[2] S. Borsanyi et al. [Wuppertal-Budapest Coll.], JHEP 1009 (2010) 073

[3] A. Bazavov et al. [Hot QCD Coll.], PRD90 (2014) 094503

# Theoretical guidance

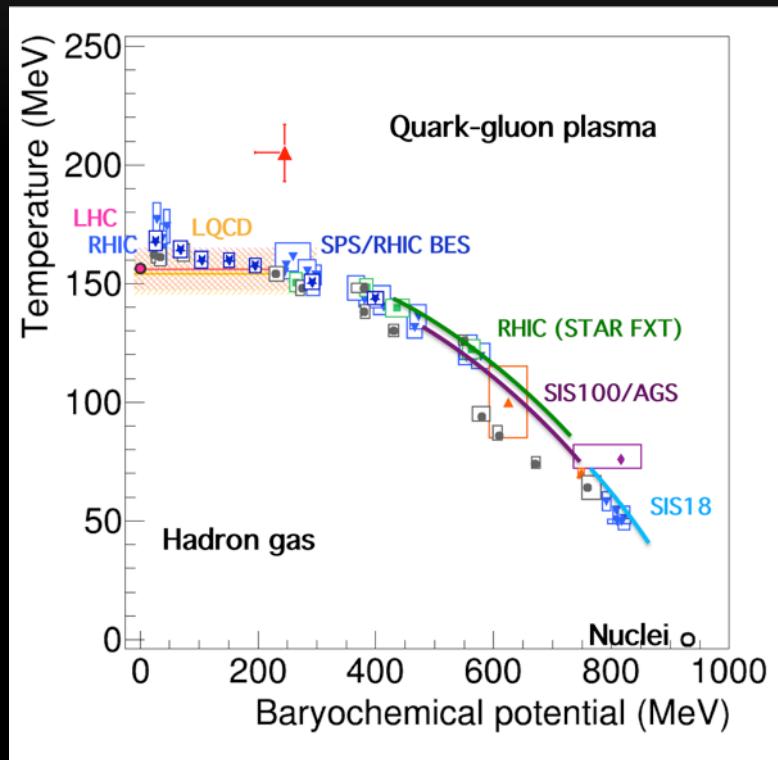


- Vanishing  $\mu_B$ , high T (Lattice QCD)
  - Crossover transition
  - $\epsilon_c \sim 1 \text{ GeV/fm}^3, T_c \sim 155 \text{ MeV}$
  
- Large  $\mu_B$ , moderate T (effective, Lattice QCD inspired models)
  - 1<sup>st</sup> order transition
  - QCD critical point
  - Melting of the condensate (order parameter  $\langle 0 | \bar{q} q | 0 \rangle = \langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \neq 0$ )

$$\frac{\langle \bar{q} q \rangle_{T, \mu_B}}{\langle \bar{q} q \rangle_{T=0, \mu_B=0}}$$

B.-J. Schaefer and J. Wambach

# Searching for landmarks of the QCD matter phase diagram



Nucl. Phys. A 931 (2014)

## □ Experimental approach:

- Recreate the conditions of the deconfinement transition in the lab.
- Probe with highest precision different regions of the QCD matter phase diagram

## □ Observables:

- Flavor production (multi-strange, charm)
- Emissivity of matter (dileptons)
- Higher moments of e-b-e multiplicities (B, S, Q)

[ALICE](#)



[CMS](#)



[ATLAS](#)



[LHCb](#)



[STAR](#)



[PHENIX](#)



[NA-61](#)

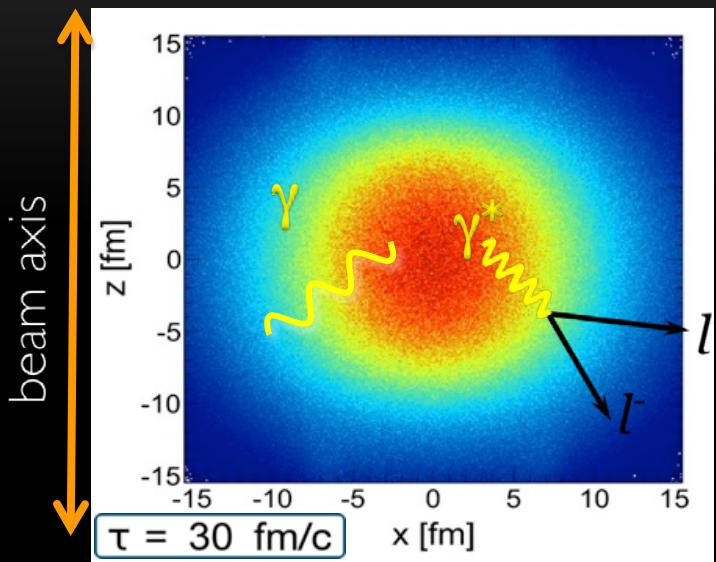


[HADES](#)

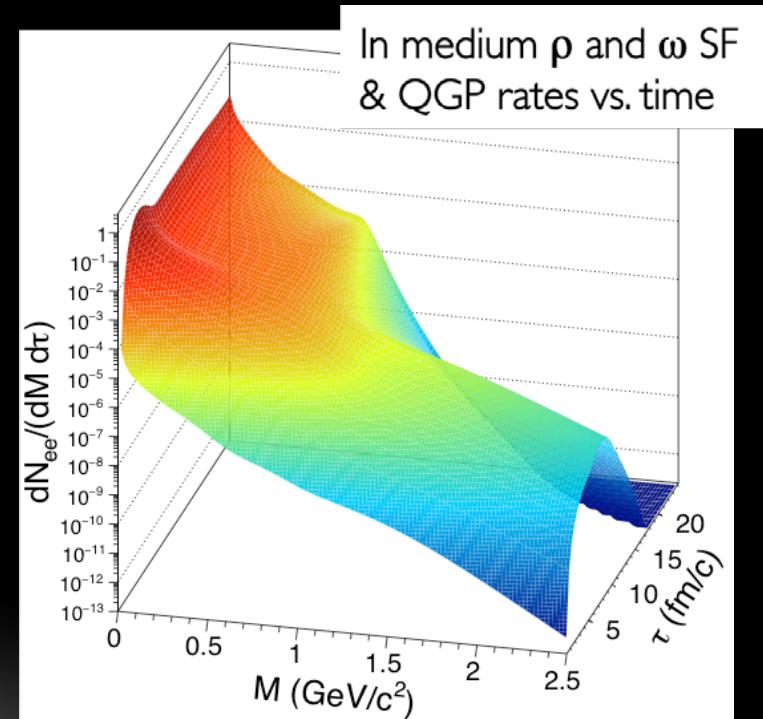


# Electromagnetic radiation

Photons and lepton pairs probe the interior of fireballs – “PET” of the fireball



- The dilepton signal contains contributions from throughout the collision
- No strong final state interactions → leave reaction volume undisturbed
- Encodes information on collisions ( $T$ ,  $\mu_B$ ,  $\tau_{coll}$ )



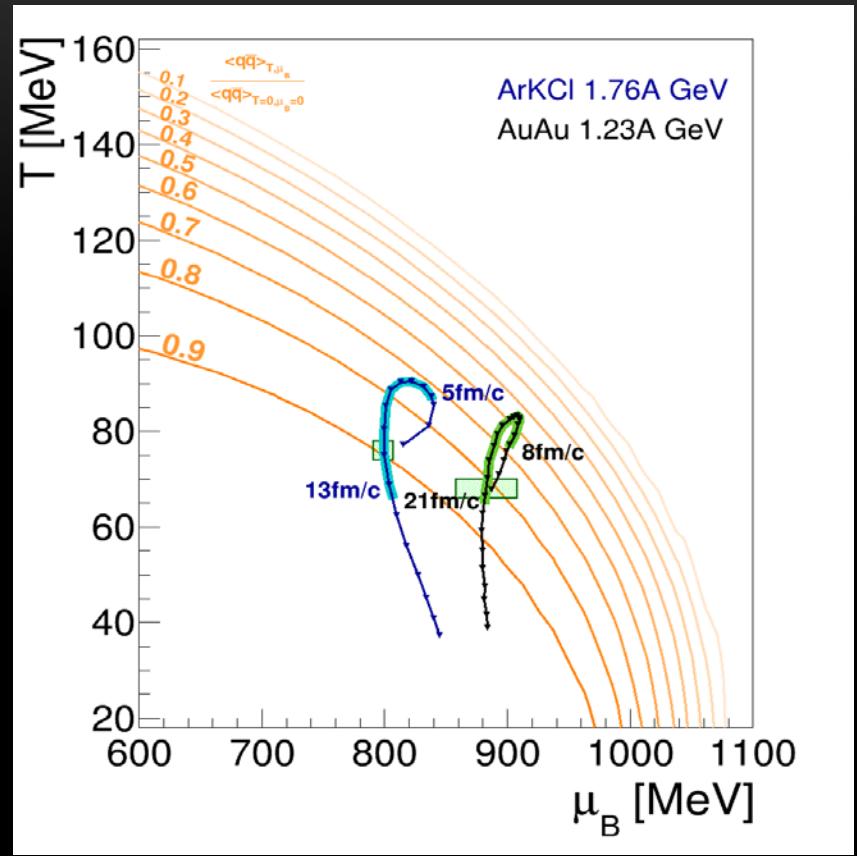
The vector correlator is directly accessible in HIC:

$$\frac{dN_{ll}}{d^4x d^4q} = \frac{-\alpha_{EM}^2}{\pi^3 M^2} f^B(q_0; T) \text{Im} \Pi_{EM}^{\mu\nu}(M, q; \mu_B, T)$$

→ Unique direct access to in-medium spectral function

# Two different perspectives

- If we know the in-medium vector spectral function we can  
⇒ study the fireball evolution
- If we know the fireball evolution we can  
⇒ measure the in-medium spectral function



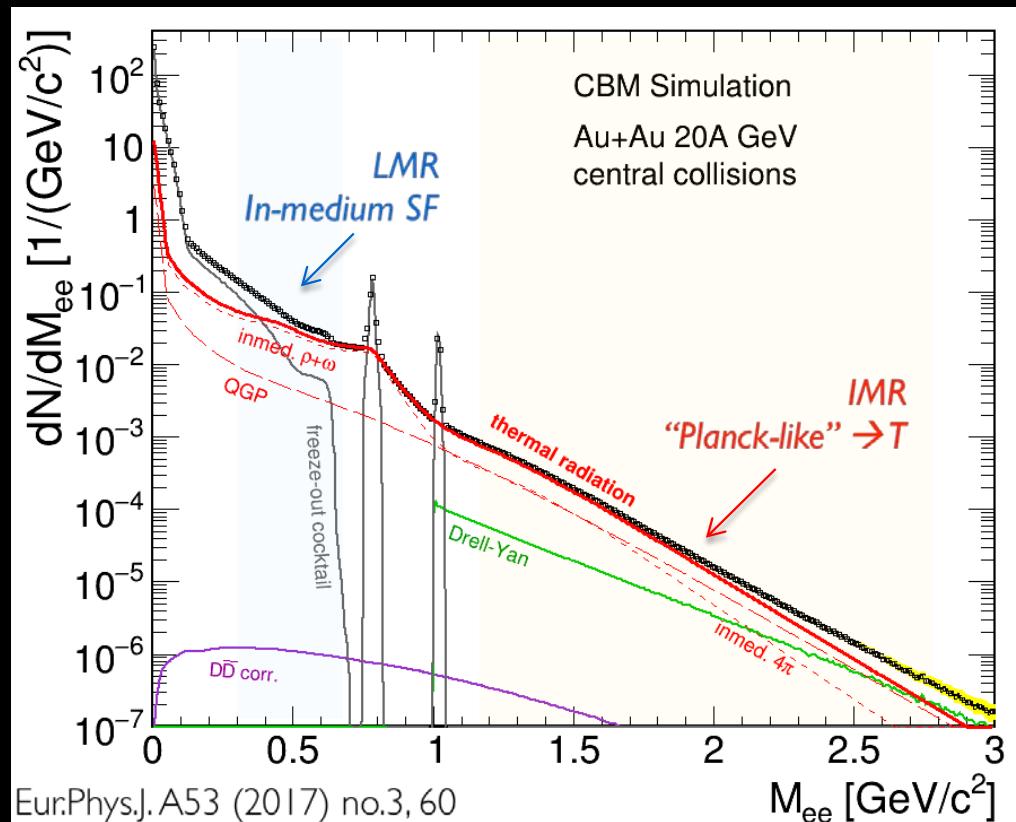
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→ Unique direct access to in-medium spectral function

# Characteristic features of dilepton invariant mass spectra

- Dilepton spectra represent the space-time integral of EM radiation
- Mass dependence allows separation of collision stages



Low-mass dileptons (LMR)  $M < 1.1$  GeV/ $c^2$

Intermediate-mass dileptons (IMR)  $M < 1.1$  GeV/ $c^2$

- Drell-Yan ( $NN \rightarrow l^+l^-X$ )
- Heavy-flavor:  $c\bar{c} \rightarrow l^+l^-$
- Medium radiation (R. Rapp):
  - QGP:  $\bar{q}q \rightarrow l^+l^-$
  - In-medium  $\rho, \omega \rightarrow l^+l^-$
  - "4 $\pi$  annihilation":  $\pi a_1 \rightarrow l^+l^-$
- Final state decays (hadron cocktail):  
 $\pi^0, \eta \rightarrow \gamma e^+e^-$

# The experimental challenge ...



*There is no such thing as a free lunch*

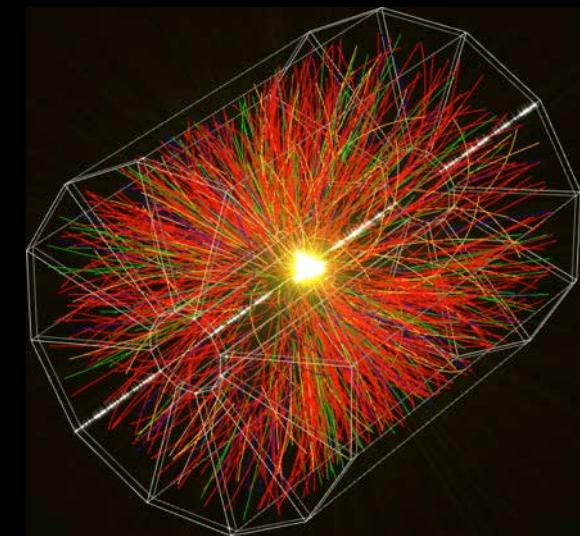
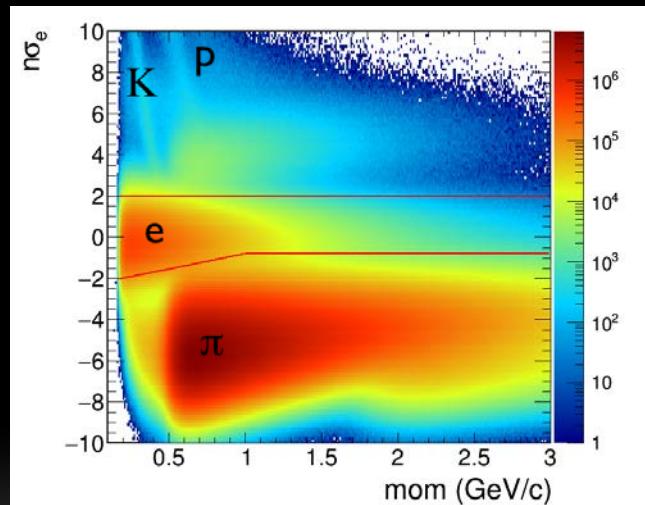
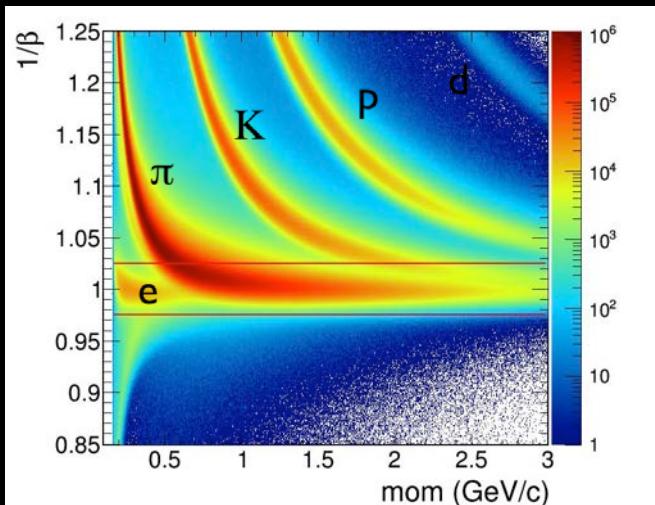
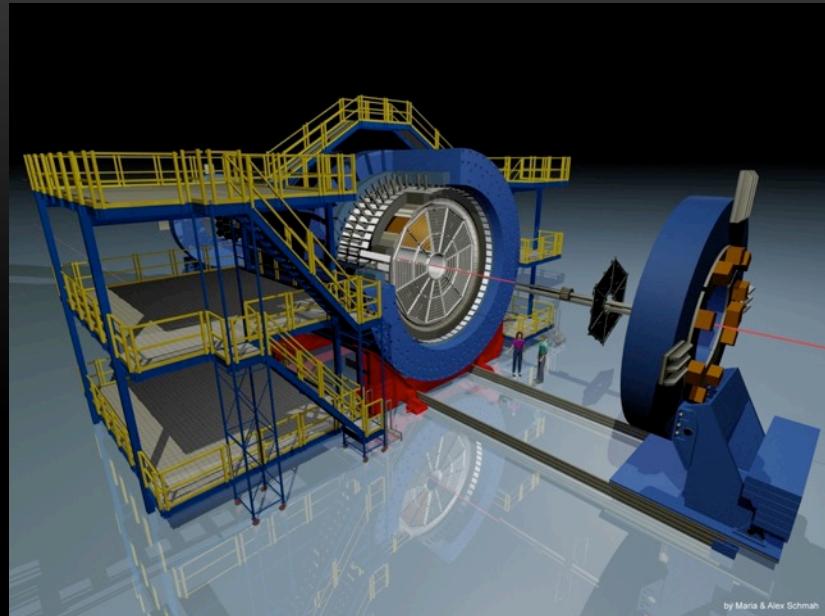
- Lepton pairs are rare probes ( $\text{BR} < 10^{-4}$ )
- at SIS energies sub-threshold vector meson production  
→  $M_r \times \Gamma_{ee}/\Gamma_{\text{tot}}$  decay per 10 mio events
- Large combinatorial background
  - in  $e^+e^-$  from Dalitz decays ( $\pi^0 \rightarrow e^+e^-\gamma$ ) and conversion pairs ( $e^+e^-$ )
  - in  $\mu^+\mu^-$ : weak  $\pi$ , K decays
- Isolate the contribution to the spectrum from the dense stage
- Low-momentum coverage!

## DATA QUALITY

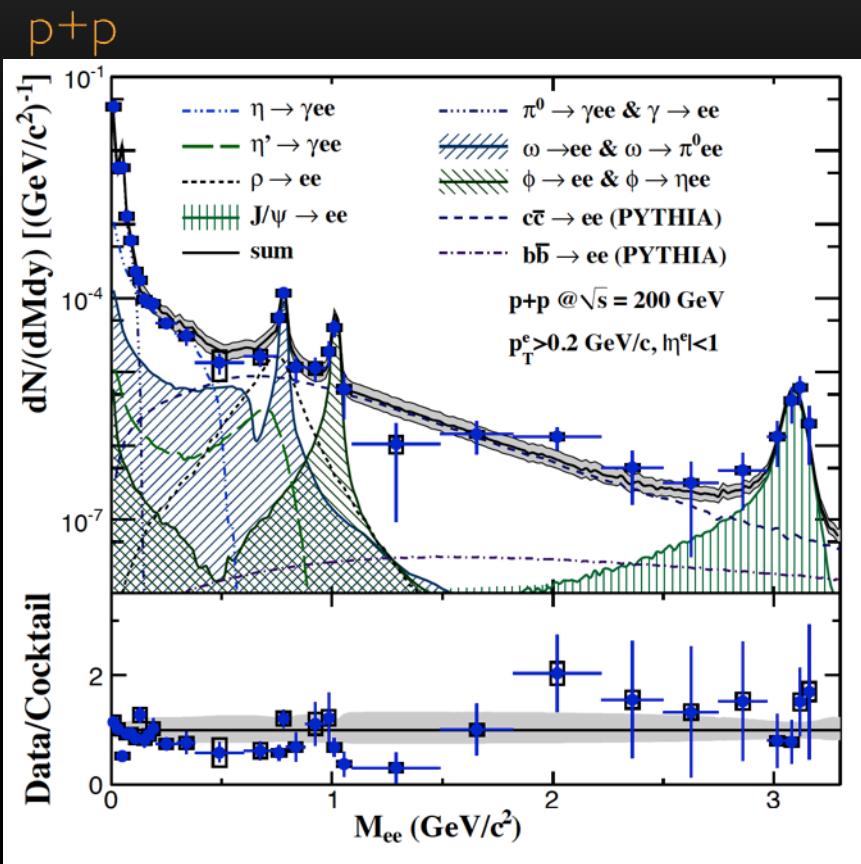
- The decisive parameters: Number of Interactions and Signal/Background
  - Range of B/S: 20 - 100 →  $B/S \gg 1$ ;
    - Effective sample size:  $S_{\text{eff}} \sim 1 \times S/B$  reduction by factors of 20-100
    - Systematics:  $\delta S_{\text{eff}}/S_{\text{eff}} = \delta B/B \times B/S$   $\delta B/B = 2 \dots 5 \times 10^{-2}$

# The STAR detector at BNL

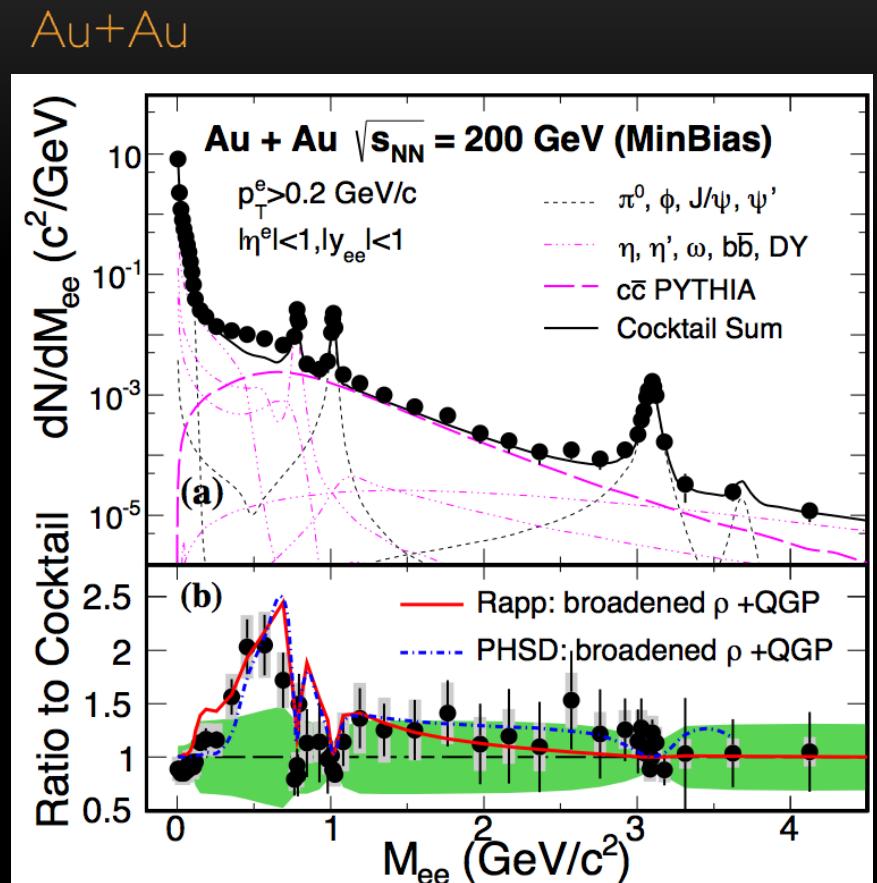
- Large acceptance hadron and electron ID
- Time Projection Chamber
  - $0 < \phi < 2\pi, |\eta| < 1$
  - Tracking,  $dE/dx$
- Time-of-Flight detector
  - $0 < \phi < 2\pi, |\eta| < 1$
  - Time resolution  $< 100$  ps



# Dielectron mass spectra at $\sqrt{s_{NN}} = 200$ GeV



Phys. Rev. C86 (2012) 024906



Phys. Rev. Lett. 113 (2014) 22301

- Comparison to the simulated  $e^+e^-$  cocktail accounting for decays of mesons, is consistent with data

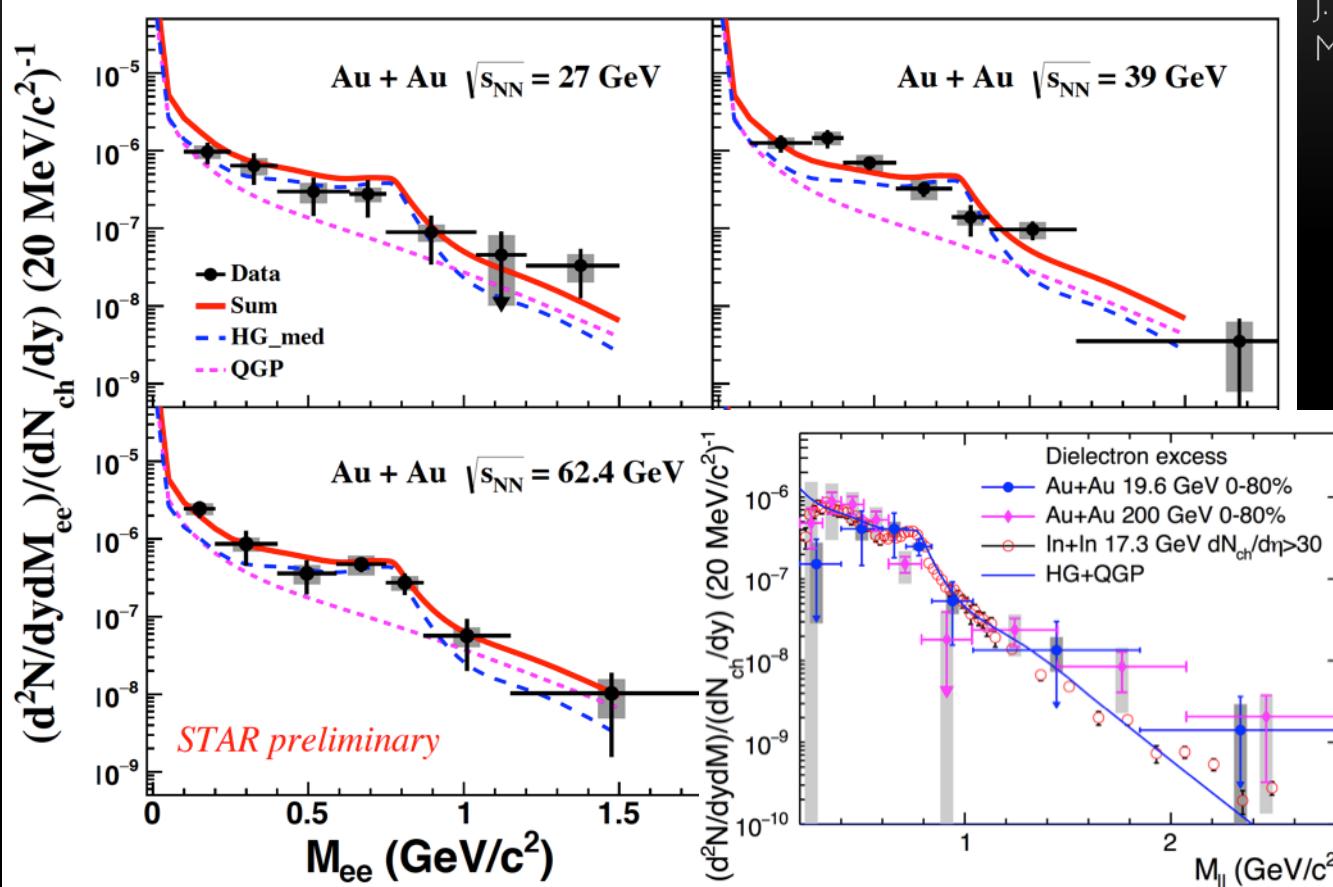
- Significant excess  $0.3 < M_{ee} < 0.8 \text{ GeV}/c^2$   
→ true in-medium effect

# Dielectron mass spectra from Beam Energy Scan I

Phys.Lett. B750 (2015) 64-71

J. Butterworth et al., arXiv:1612.05484 [nucl-ex]

Model: Rapp/Wambach/Hees



- Isolation of the excess by subtracting the measured decay cocktail
- Acceptance corrected spectra

- In-medium **broadened  $\rho$**  spectral function consistently describes the low-mass electron-positron excess **for all the energies 19.6-200 GeV**
- Strong change of net baryon density, but **total baryon density** ( $\sim 110$ ) same at the SPS and at RHIC

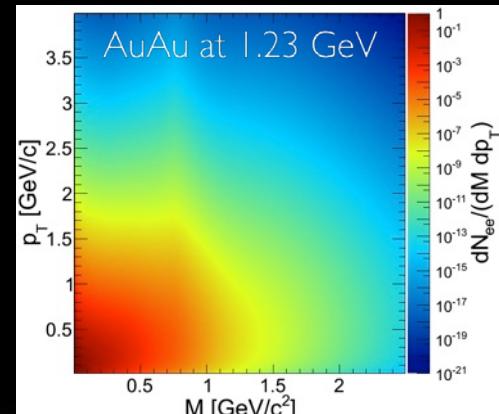
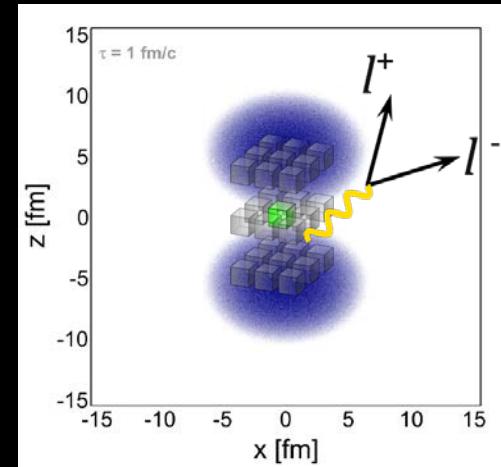
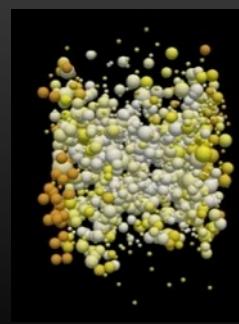
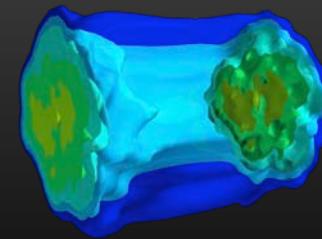
# Coarse-grained transport approach

- “Combine” the advantages of two descriptions: hydrodynamics & transport
- Simulate events with a transport model
  - ensemble average to obtain smooth space-time distributions
- Divide space-time evolution into 4-dimensional cells
  - $21 \times 21 \times 21$  space cells ( $1\text{fm}^3$ ), 30 time steps →  $\sim 280\text{k}$  cells
- Determine for each cell the bulk properties like  $T$ ,  $\mu_B$ ,  $\mu_\pi$ , collective velocity
- Apply in-medium  $\rho$  &  $\omega$  spectral functions to compute EM emission rates
  - parameterization of RW in-medium spectral function
- Sum up contributions of all cells

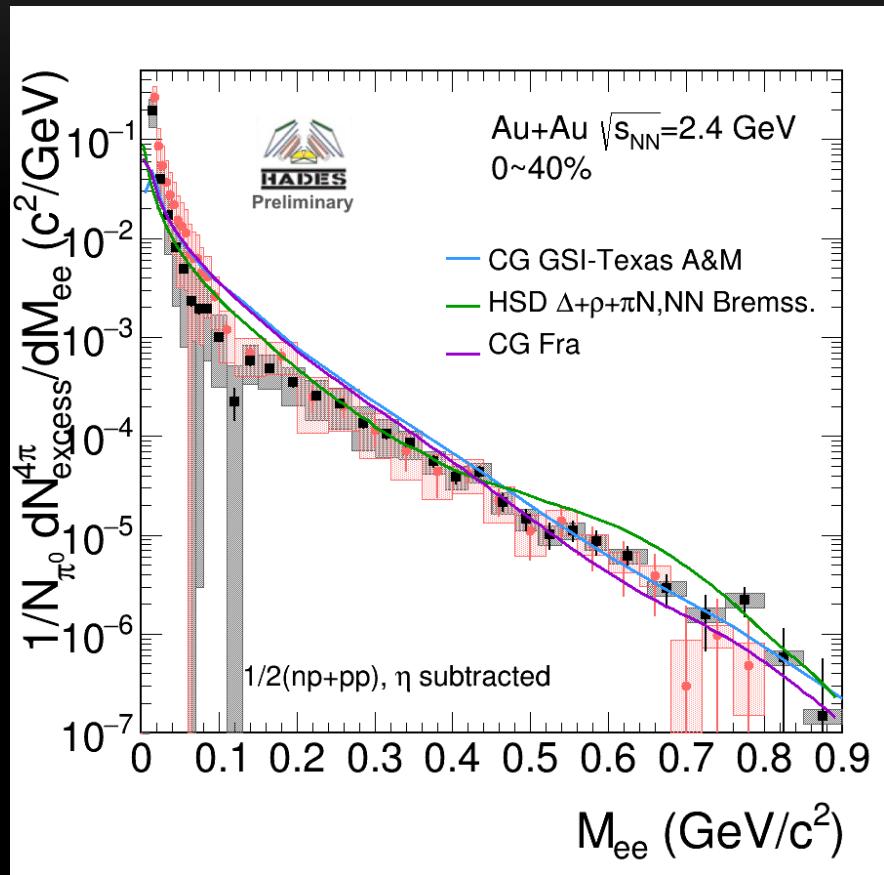
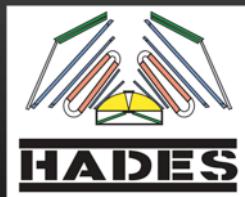
Huovinen et al., PRC 66 (2002) 014903

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

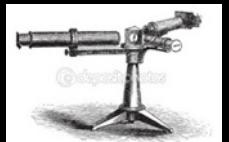


# Dielectron mass spectra at $\sqrt{s_{NN}} = 2.42$ GeV

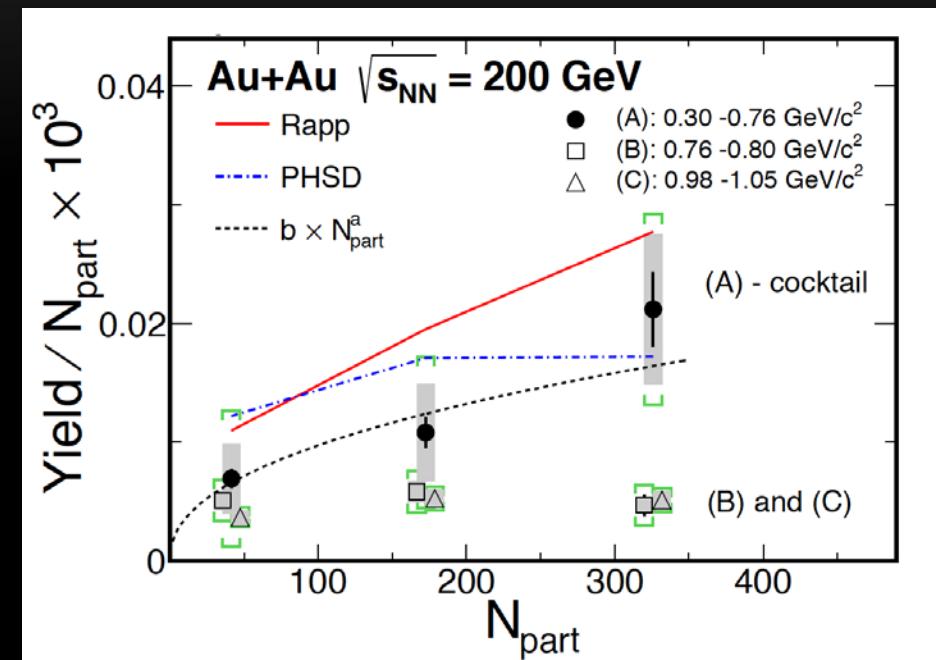
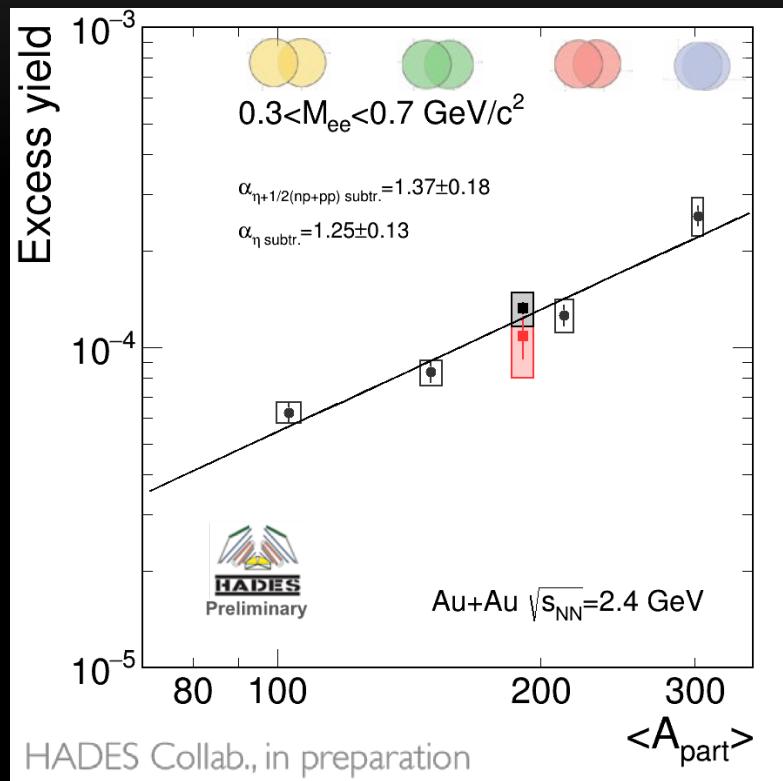


- Inclusive excess mass spectrum
  - All known sources subtracted
  - Fully corrected for acceptance
- Almost exponential spectrum up to vector meson region!

- Coarse-graining method works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!
- Robust understanding across QCD phase diagram



# Centrality dependence of the excess yield



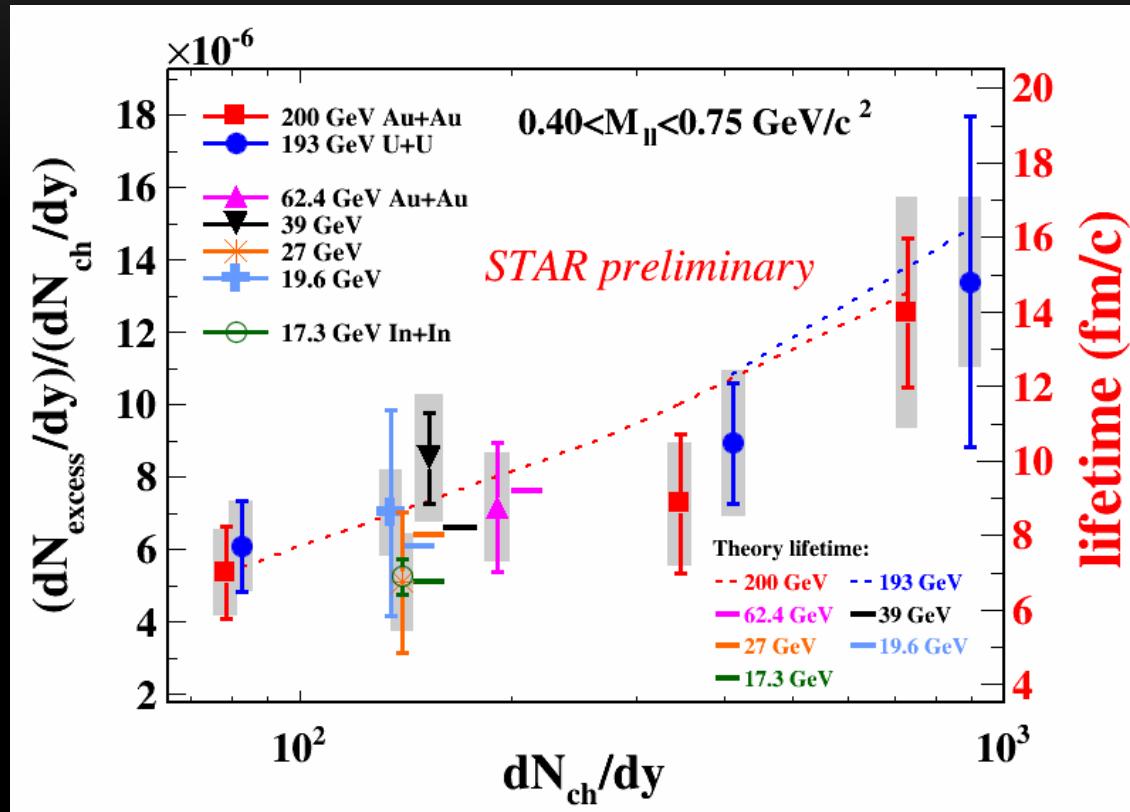
STAR Collab., Phys. Rev. Lett. 113 (2014) 22301

- Excess yield scales stronger than linear with mean number of participants
- Note the very similar  $A_{\text{part}}$  scaling independently of  $\sqrt{s_{\text{NN}}}$
- $\sim A_{\text{part}}^{1.3}$ , interplay  $V \otimes \tau_{\text{coll}}$

# Dileptons as chronometer



STAR data: arXiv:1612.05484 [nucl-ex]  
Model: R. Rapp, H. van Hees, PLB 753 (2016) 586



- Normalized **excess yields** for the mass region  $0.3 < M < 0.7 \text{ GeV}/c^2$  is proportional to the **lifetime** of the interacting fireball

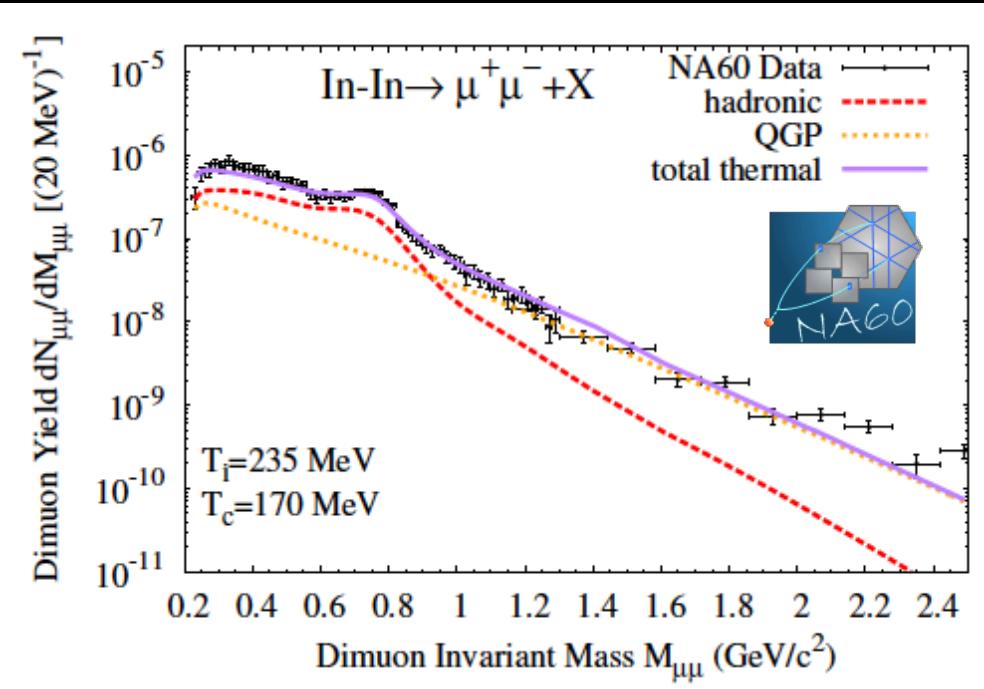
# Dileptons as thermometer

Measurement of radiating source temperature



NA60: H.J. Specht, AIP Conf. Proc. 1322 (2010) 1

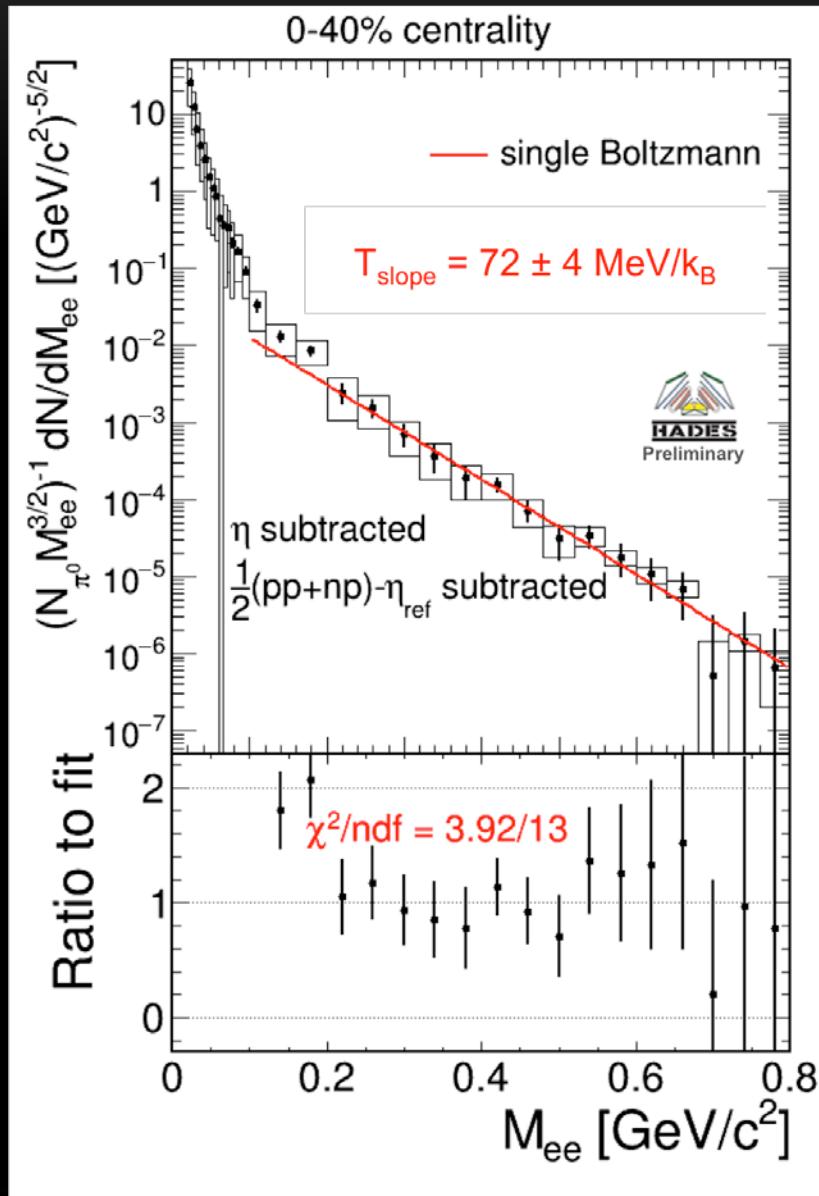
Model: R. Rapp, H. van Hees, PLB 753 (2016) 586



- $M_{\mu\mu} > 1 \text{ GeV}c^2 \sim \text{exponential fall-off}$   
→ 'Planck-like'
- fit  $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$  to range  $M=1.1-2 \text{ GeV}$
- $T=205 \pm 12 \text{ MeV}$
- ✓ Agrees with Rapp/Wambach SF:  
partonic emission dominant

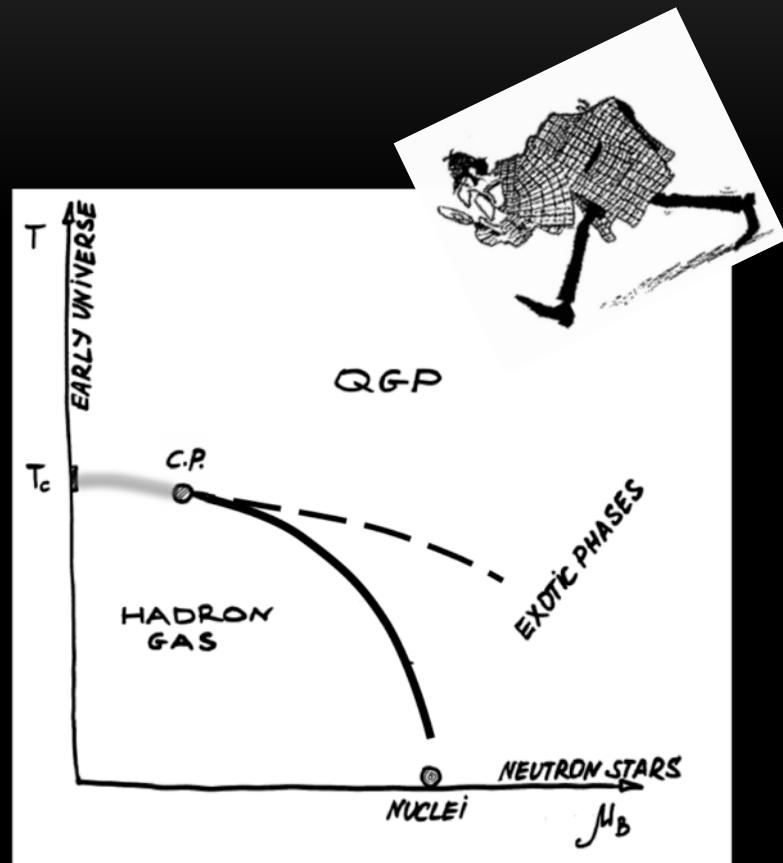
# Dileptons as thermometer

Measurement of radiating source temperature



- $M_{ee} < 1 \text{ GeV}/c^2 \sim \text{exponential fall-off}$   
→ 'Planck-like'
- fit  $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$  to range  $M=0.1-0.8 \text{ GeV}$
- $T=72 \pm 4 \text{ MeV}$
- ✓ Agrees with coarse-grained approach

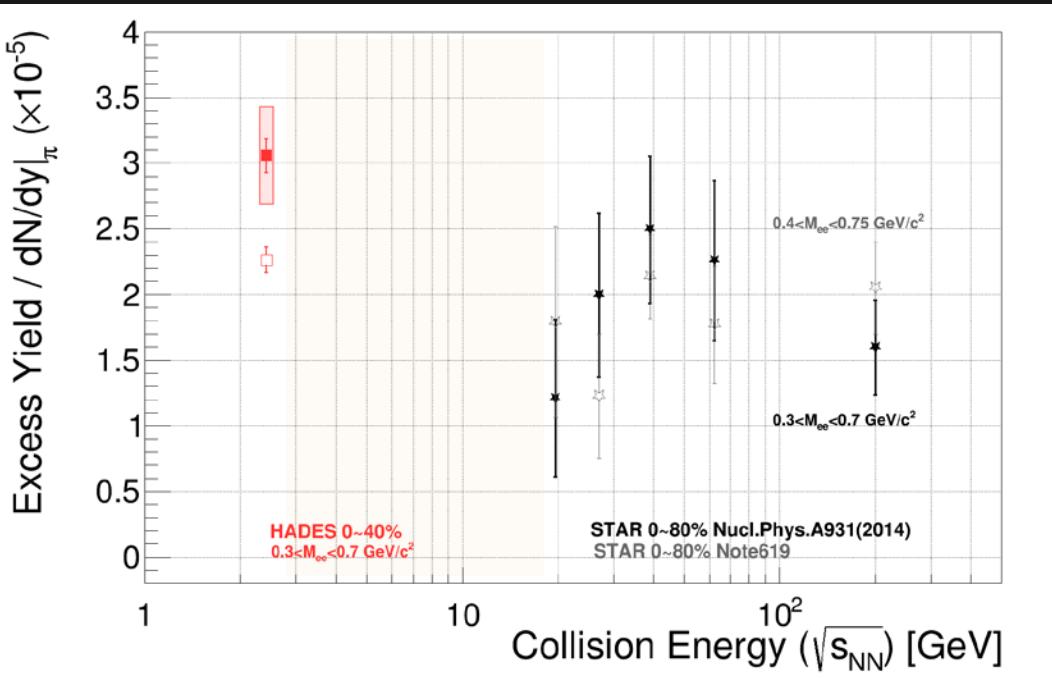
# Dileptons and QCD phase diagram of matter



Excitation functions

- Fireball lifetime
- Emitting source temperature

# Energy dependence of low-mass excess

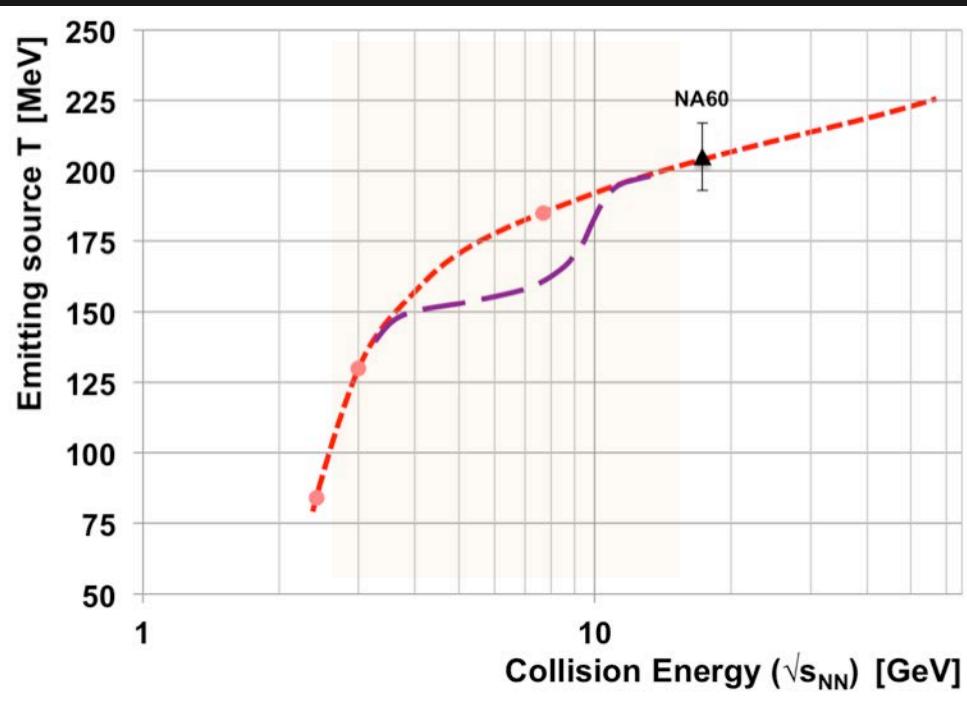


- Yield in low-mass window tracks fireball lifetime
- Search for anomalous fireball lifetime around phase transition & critical point
  - 2019 - STAR at RHIC BES II
  - 2024 - CBM at FAIR

- Quite moderate energy dependence
- Dilepton yield determined by interplay between temperature and  $V \otimes \tau_{\text{coll}}$



# Energy dependence of intermediate mass slope



Dashed violet curve corresponds to a speculated shape with phase transition

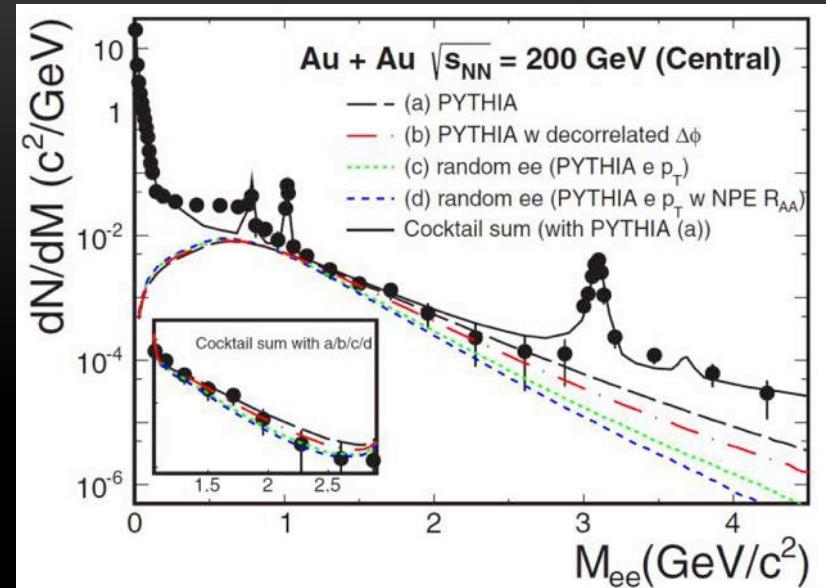
- Measures the emitting source temperature (true, no blue shift)
  - Measure  $T_s$  (note,  $T_s < T_{initial}$ ) "caloric curve"
  - Plateau around onset of deconfinement?  
[see e.g. M. D'Agostino et al. NPA 749 (2005) 5533]
- Precision measurements are the key
  - 2024 - CBM at FAIR

# STAR dielectrons

## ongoing analysis

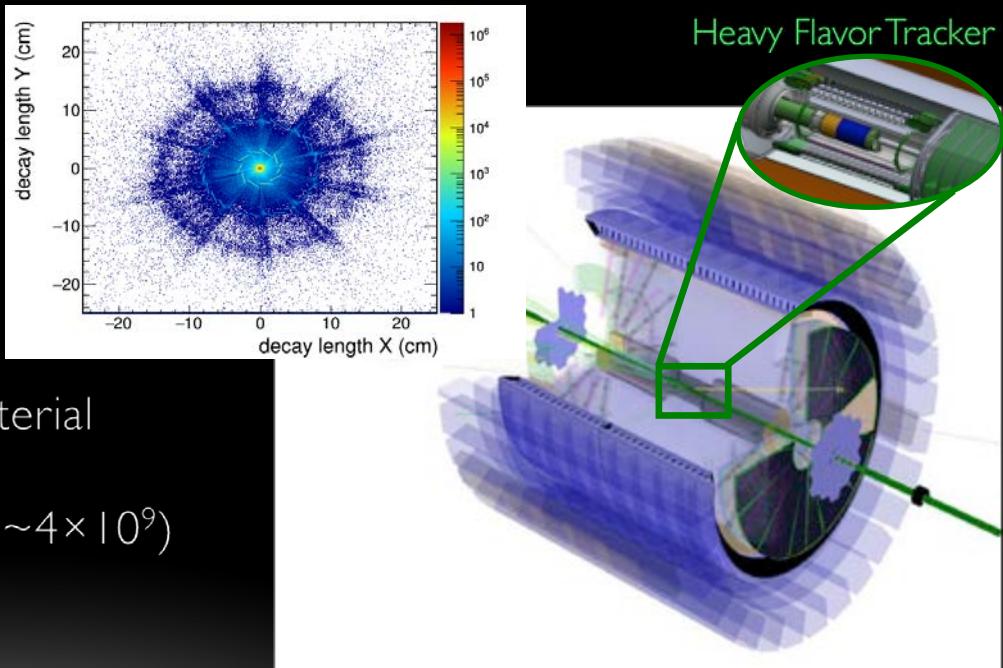
Au+Au  $\sqrt{s_{NN}} = 200$  GeV

- $\mu_B \ll T$ , i.e. vanishing net-baryon density
- Lattice QCD computations are most powerful
- Measure  $\rho$  spectral function and “calibrate” EM rates
- Extract fireball temperature (IMR)



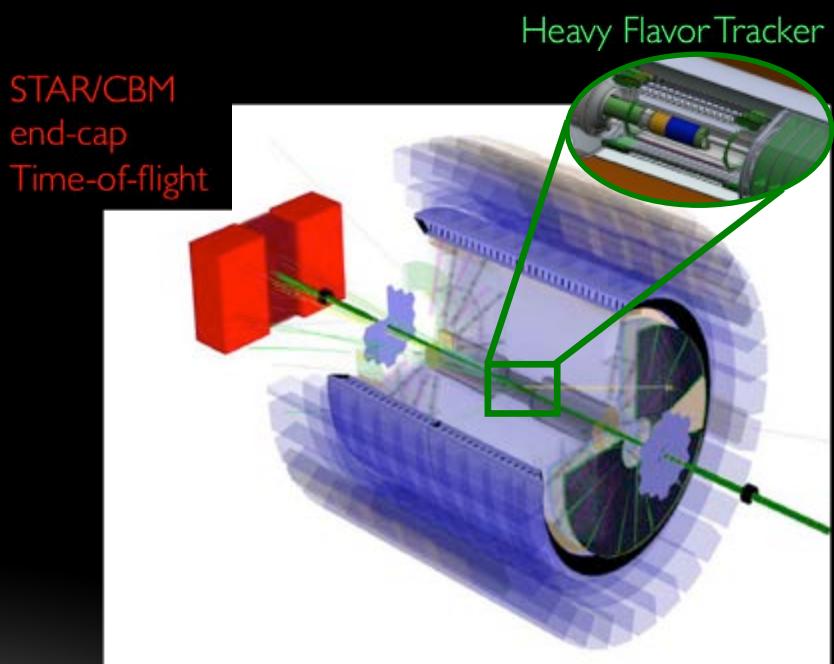
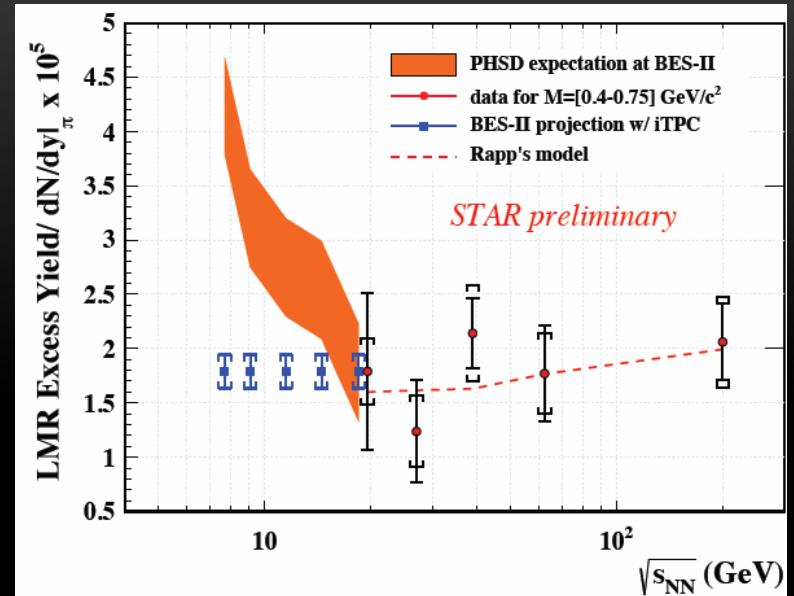
### Dielectron reconstruction with HFT

- Reduce uncertainties on charm contribution
- Challenge:  $\gamma$  conversion in HFT detector material  
→ use excellent vertexing to reject it  
(looks promising, statistics Runs 10,11,14,16  $\sim 4 \times 10^9$ )

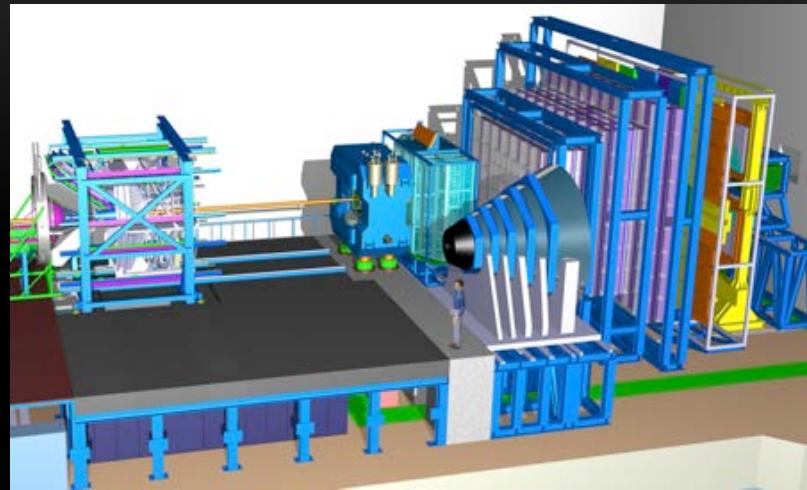
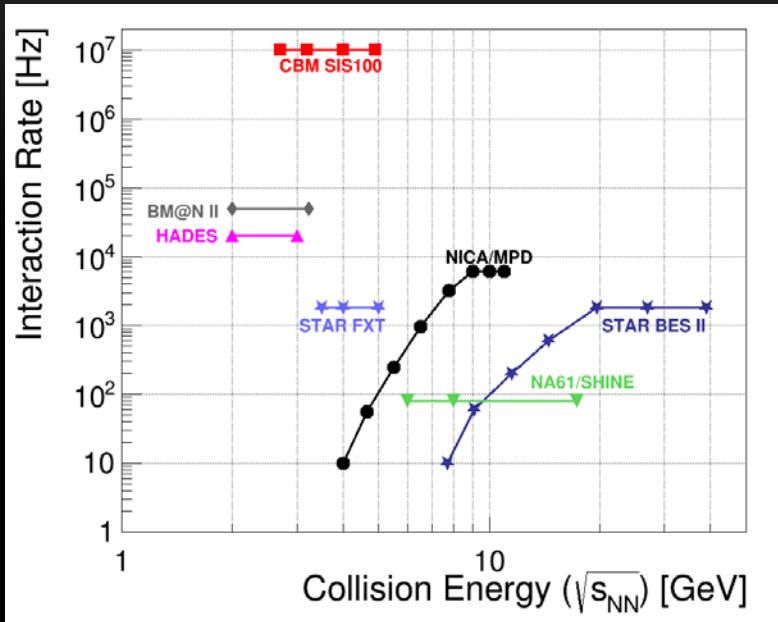


# STAR dielectrons Beam Energy Scan II 2019 - 2020

- Improve statistics for existing low energy samples
  - Quantify lifetime and baryon density dependence of the  $\rho$  spectral function
  - Disentangle various model calculations
- 
- Inner TPC upgrade
  - Installation of eToF (CBM Phase-0)
  - Collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV

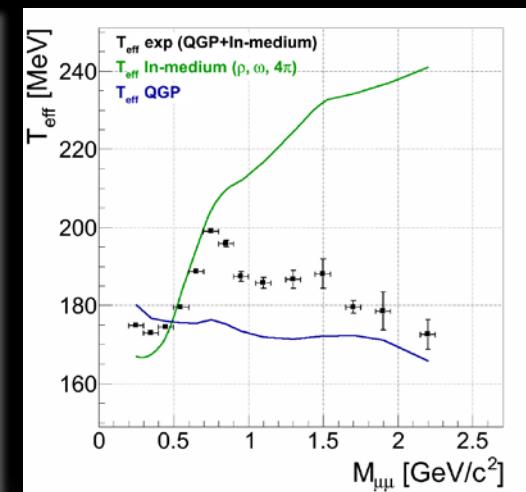
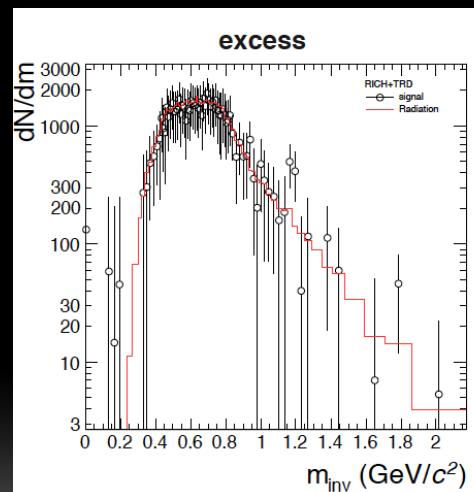


# Compressed Baryonic Matter experiment at FAIR



CBM Collab., EPJA, 53 3 (2017) 60

CBM will play a unique role in the exploration of the QCD phase diagram in the region of high net-baryon densities



"If you are out to describe the truth,  
leave elegance to the tailor" (A. Einstein)



## Proposal for experiments at SIS18 during FAIR Phase-0

The HADES Collaboration



Properties of hadron resonances  
and baryon rich matter

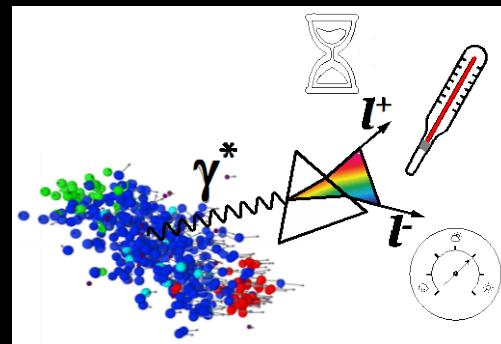
- High statistics  $\pi+p$ ,  $\pi+A$ ,  $p+A$ ,  $A+A$
- Results in elementary collisions provide an important baseline for current and future explorations in HIC

# Résumé and prospects

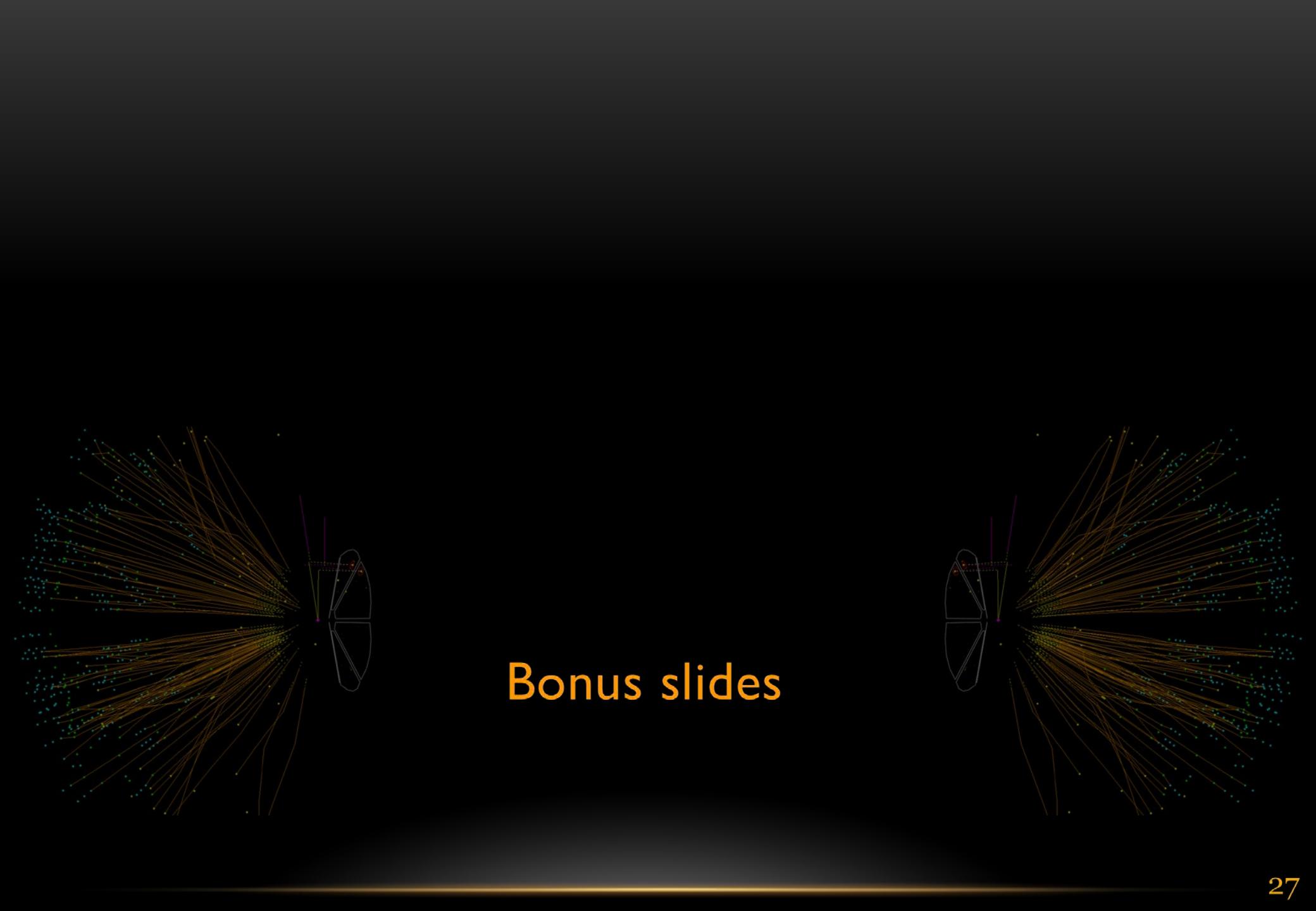


*There is no mission impossible*

- Unique possibility of characterizing properties of hot and dense QCD matter with dileptons
- Robust understanding of low-mass dilepton excess radiation by  $\rho$ -baryon coupling (at top RHIC, RHIC BES, SPS and SIS18 energies)
- Enable unique measurements
  - Degrees of freedom of the medium
  - Restoration of chiral symmetry
  - Fireball lifetime
  - Emitting source temperature



Thank you  
for your attention!



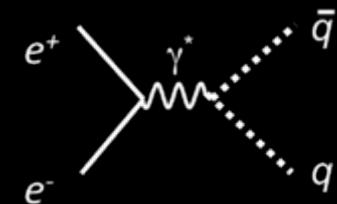
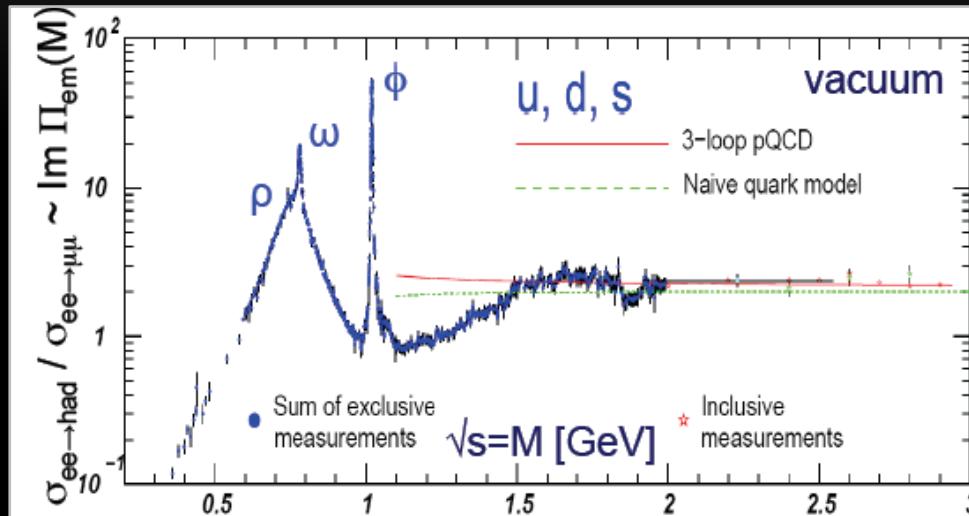
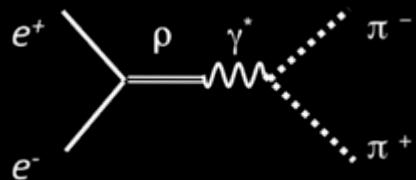
## Bonus slides

# Electromagnetic radiation to probe fireball

Thermal dilepton production rates:

$$\frac{dN_{ll}}{d^4x d^4q} = -\frac{\alpha_{EM}^2}{\pi^3} \frac{L(M)}{M^2} f^B(q_0; T) \text{Im } \Pi_{EM}^{\mu\nu}(M, q, \mu_B, T)$$

Photon self-energy



Hadrons:  $\text{Im } D_{\rho, \omega, \phi}$

- Change in degrees of freedom
- Restoration of chiral symmetry

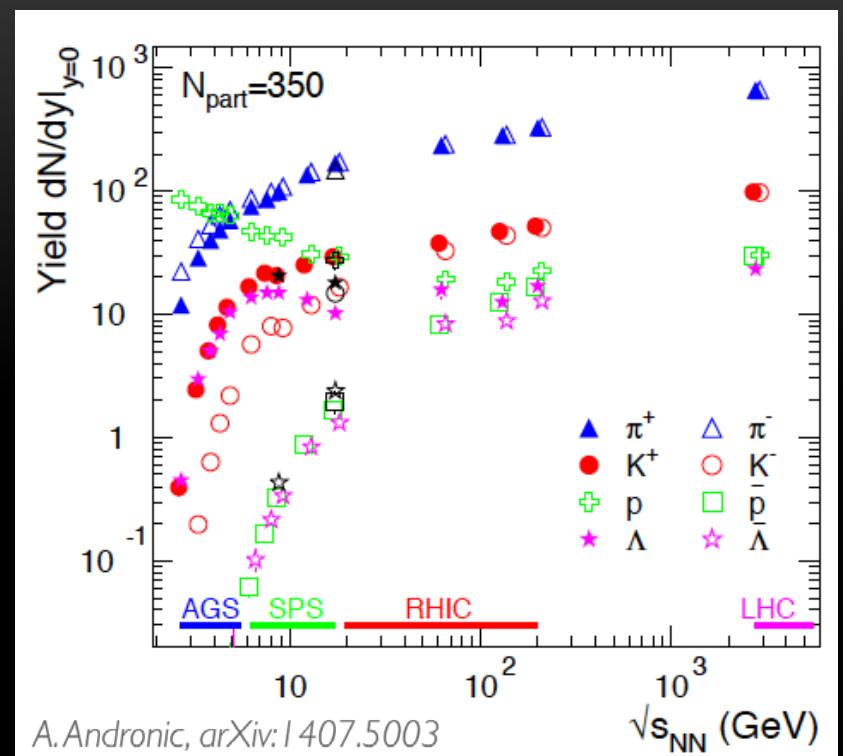
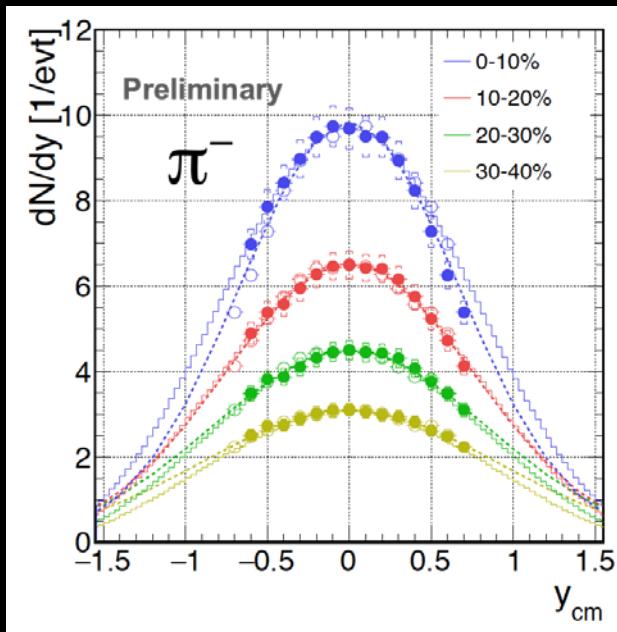
$\bar{q}q$  continuum

- Emitting source temperature

- Transport coefficient (charge)
- Total yield  $\longleftrightarrow$  fireball lifetime

# Spectra normalization

- Normalization to number of neutral pions
  - Fireball dominated by incoming nucleons at lower energies
  - Number of charged particles  $N_{ch}$  not a good proxy for thermal excitation energy



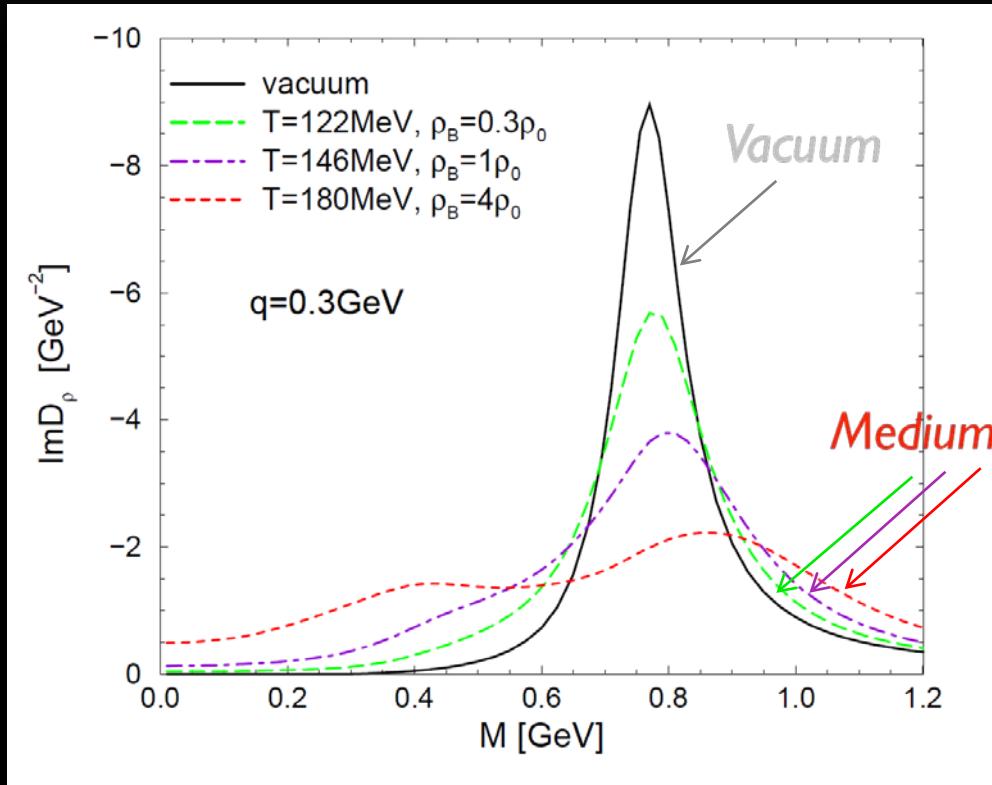
Centrality class	$\langle N_{\pi^-} \rangle$ per event	$\langle N_{\pi^+} \rangle$ per event	$\langle N_{\pi^0} \rangle$ per event
0-10%	17.05	9.75	13.40
10-20%	12.20	6.75	9.48
20-30%	8.85	4.80	6.83
30-40%	6.35	3.45	4.90
0-40%	<b>11.10</b>	<b>6.20</b>	<b>8.65</b>

# $\rho$ meson in hot and dense medium...

... interacts with hadrons from heat bath →

additional contributions to the  $\rho$ -meson self-energy in the medium

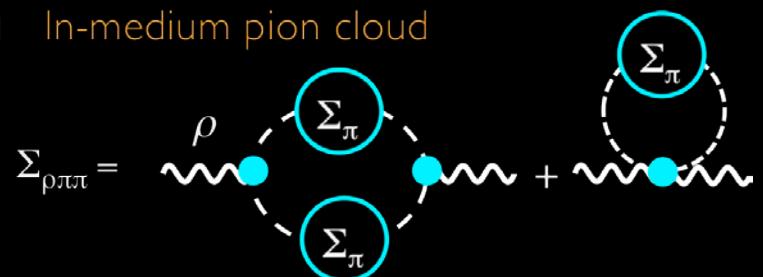
R. Rapp and J. Wambach, Eur.Phys.J.A6 (1999)



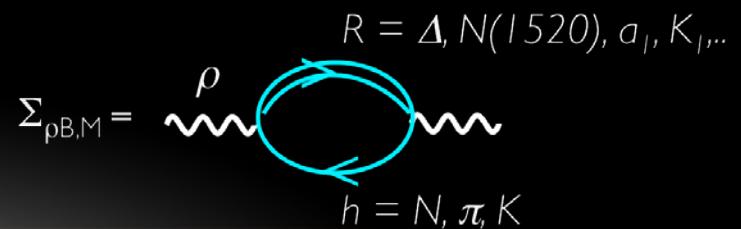
The  $\rho$  spectral function strongly broadens in the medium because the  $\rho$  couples to baryons!

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

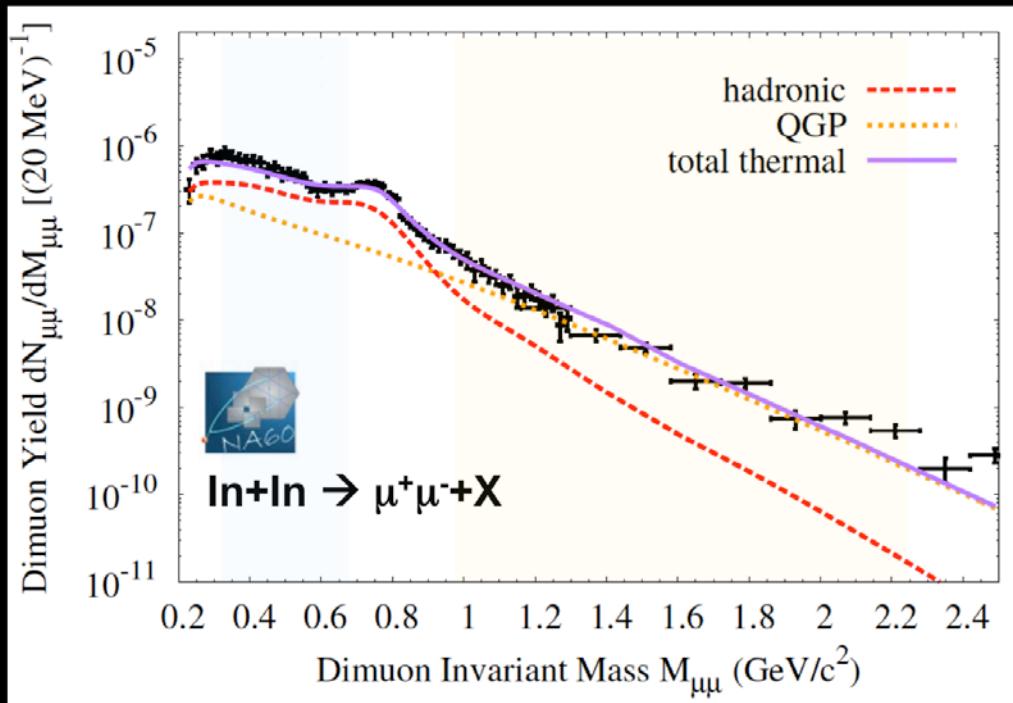
□ In-medium pion cloud



□ Direct  $\rho$ -hadron scattering



# Characteristic features of excess radiation



NA60: H.J. Specht, AIP Conf.Proc. 1322 (2010) 1  
Model: R. Rapp, H. van Hees, PLB 753 (2016) 586

## Spectrometer

- Shape and yield  
→ restoration of chiral symmetry



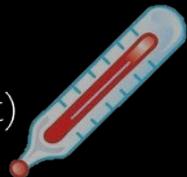
## Chronometer

- LMR dilepton yield  
→ fireball lifetime



## Thermometer

- IMR slope → emitting source temperature (true T, no blue shift)



## Barometer

- Inverse-slope analysis,  $v_2$   
→ fireball acceleration

