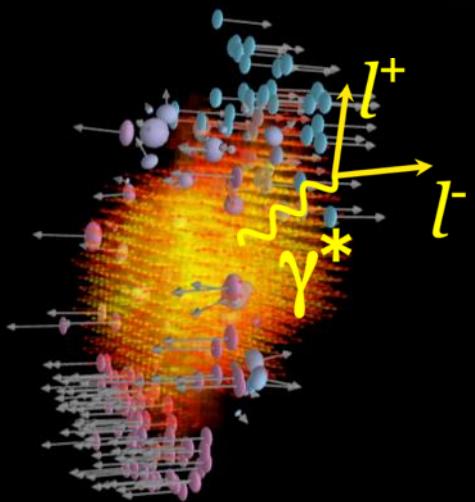




WE-Heraeus Physics School

QCD – Old Challenges and  
New Opportunities

Bad Honnef, Sept 24–30, 2017

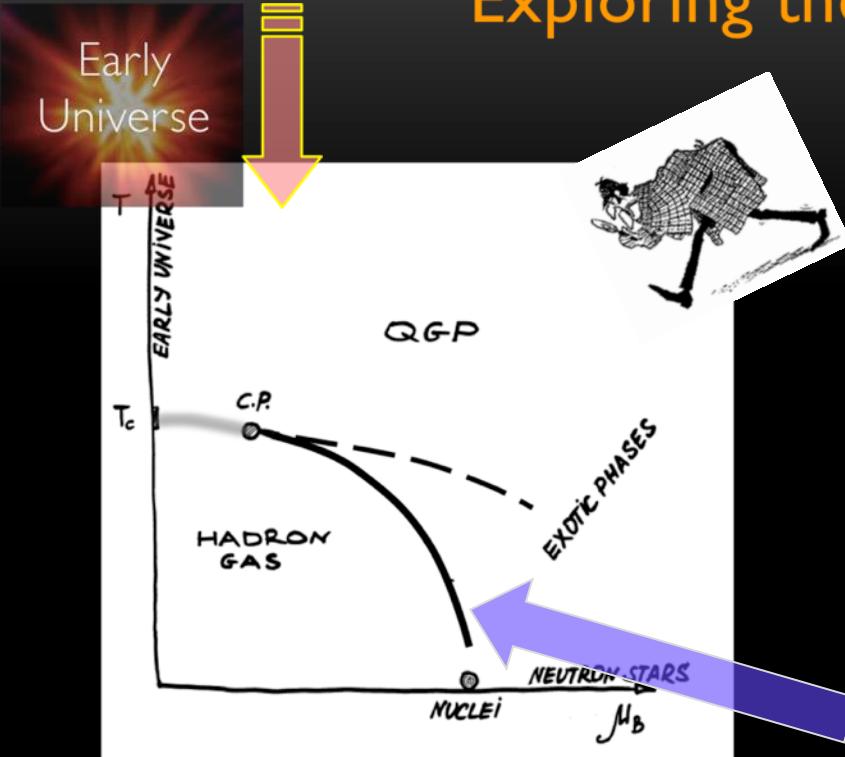


# Experimental search for signals of chiral symmetry restoration in heavy-ion collisions

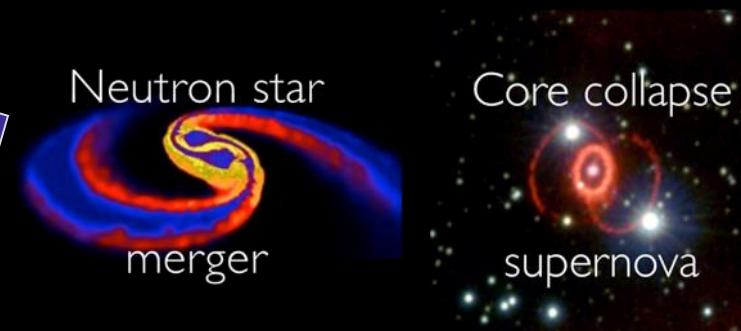
Tetyana Galatyuk

Technische Universität Darmstadt /  
GSI Helmholtzzentrum für Schwerionenforschung

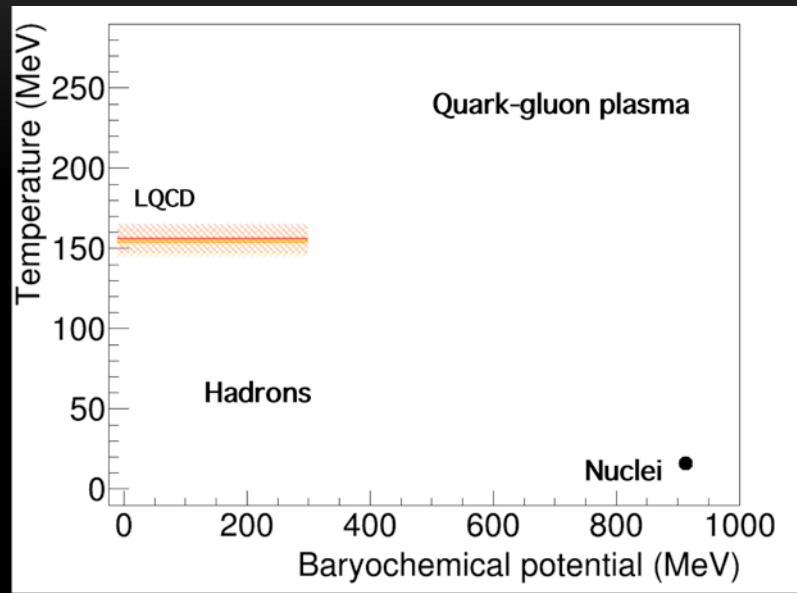
# Exploring the phase diagram of QCD matter



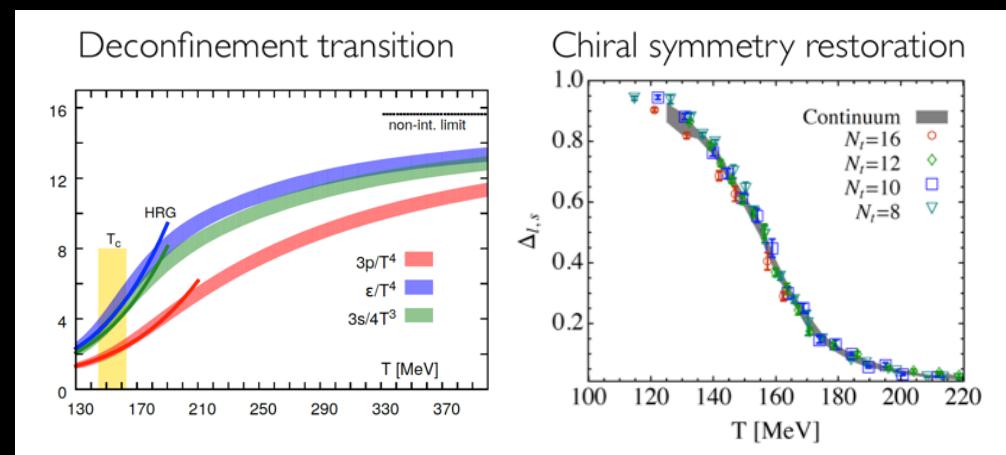
- What are the properties of matter under extreme temperatures and densities?
- Where are the phase boundaries located?
- Is there a critical point?
- Where are the limits of hadronic existence?



# Theoretical guidance



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

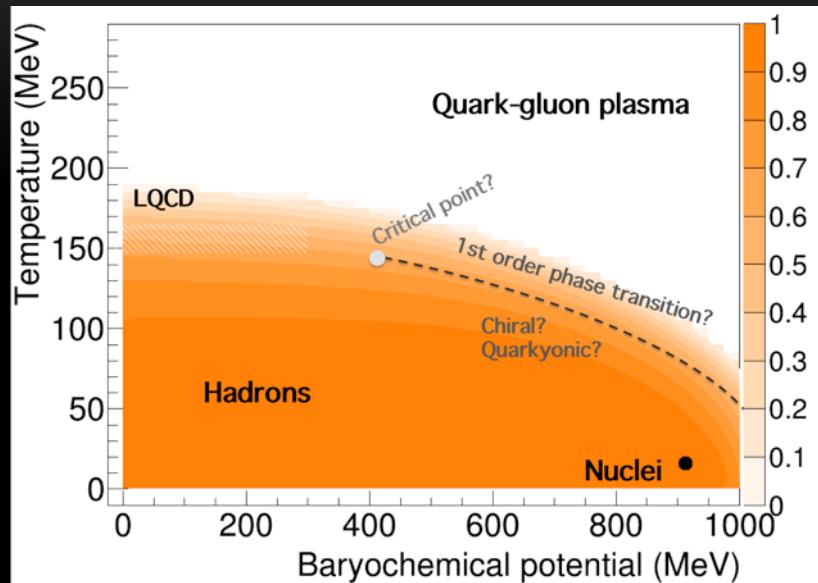


O. Kaczmarek et al., PRD 83 (2011) 014504

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

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

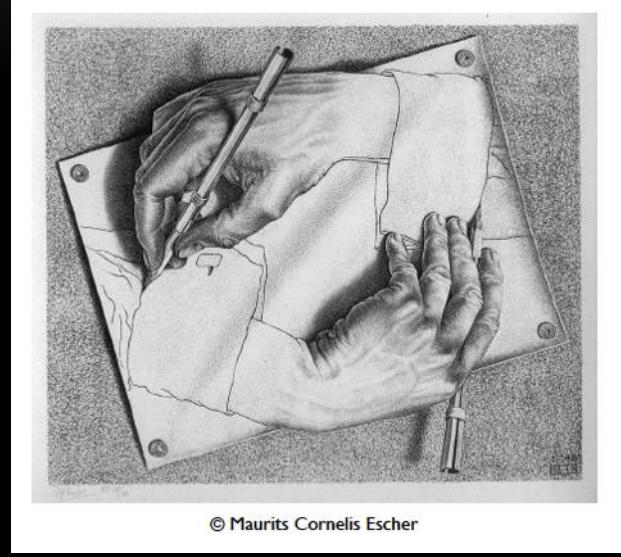
# Theoretical guidance



$$\frac{\langle \bar{q}q \rangle_{T,m_B}}{\langle \bar{q}q \rangle_{T=0,m_B=0}} : B.J. Schaefer and J. Wambach$$

- 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  $\langle 0 | \bar{q}q | 0 \rangle = \langle 0 | \bar{q}_L q_R + \bar{q}_R q_L | 0 \rangle \neq 0$ )

# Chiral symmetry in QCD



© Maurits Cornelis Escher

# Chiral Symmetry in QCD: Vacuum

$$\mathcal{L}_{QCD} = \bar{q} (i\cancel{D} + g\cancel{A} - \hat{m}_q) q - \frac{1}{4} G_{a\mu\nu}^2$$

Current quark masses:  $m_u \approx m_d \approx 5-10 \text{ MeV}$

Chiral  $SU(2)_V \times SU(2)_A$  transformation up to  $\mathcal{O}(m_q)$ ,  $\mathcal{L}_{QCD}$  invariant under

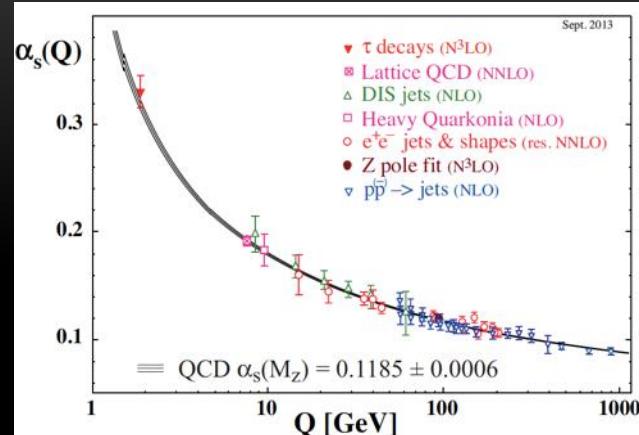
$$q \mapsto R_v(\vec{\alpha}_v) q = \exp(-i\vec{\alpha}_v \cdot \vec{\tau}/2) q$$

$$q \mapsto R_A(\vec{\alpha}_A) q = \exp(-i\gamma_5 \vec{\alpha}_A \cdot \vec{\tau}/2) q$$

Rewrite  $\mathcal{L}_{QCD}$  using  $q_{L,R} = (l \pm \gamma_5)/2 q$ :

$$\mathcal{L}_{QCD} = (\bar{u}_L, \bar{d}_L) i\cancel{D} \begin{pmatrix} u_L \\ d_L \end{pmatrix} + (\bar{u}_R, \bar{d}_R) i\cancel{D} \begin{pmatrix} u_R \\ d_R \end{pmatrix} + \mathcal{O}(m_q) - \frac{1}{4} G_{a\mu\nu}^2$$

$$q_{L,R} \mapsto \exp(-i\vec{\alpha}_{L,R} \cdot \vec{\tau}/2) q_{L,R}$$



Invariance under  
isospin and “handedness”

# Chiral symmetry breaking

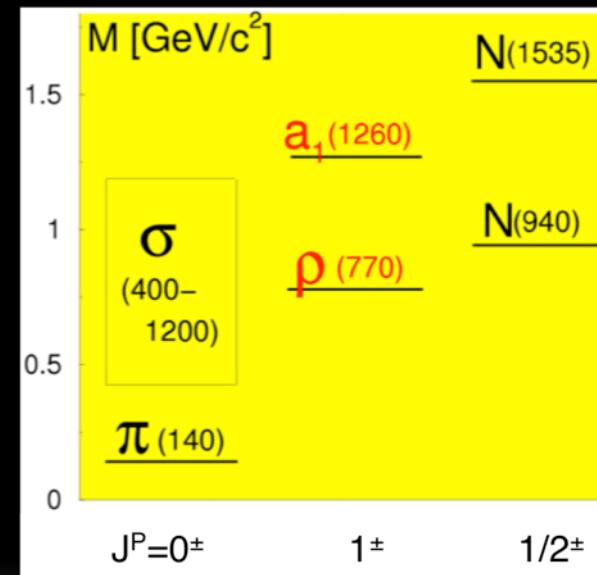
Chiral symmetry is explicitly broken by the finite masses of the current (u, d, s) quarks

On top of this, chiral symmetry is spontaneously broken: strong  $q\bar{q}$  attraction → Chiral Condensate fills QCD vacuum  $\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \approx -[(229 \pm 9) \text{ MeV}]^3$  an order parameter of chiral symmetry

- Mass generation
- $\langle \bar{q}q \rangle$  is not an observable!

But: hadronic excitations reflect spontaneous breaking of chiral symmetry:

- “massless” Goldstone bosons  $\pi^{0,\pm}$   
(explicit breaking:  $f_\pi^2 m_\pi^2 = m_q \langle \bar{q}q \rangle$ )
- “chiral partners” split:  $\Delta M \approx 0.5 \text{ GeV}$



# QCD and Weinberg sum rules

Weinberg Sum Rules...

 Weinberg '67, Das et al '67

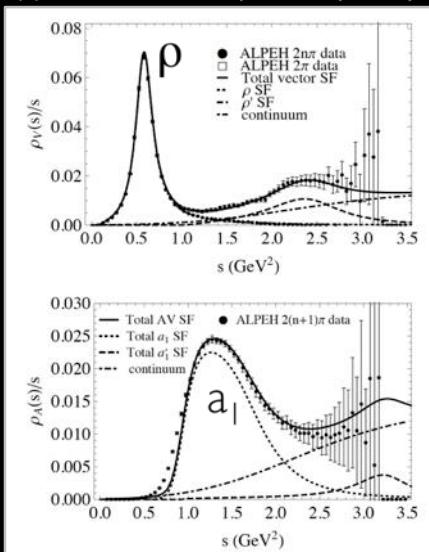
$$\int \frac{ds}{\pi} \frac{1}{s} (\rho_V - \rho_A) = f_\pi^2$$

$$\int \frac{ds}{\pi} (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle$$

$$\int \frac{ds}{\pi} s (\rho_V - \rho_A) = c \alpha_s \langle (\bar{q}q)^2 \rangle$$

... accurately satisfied in vacuum

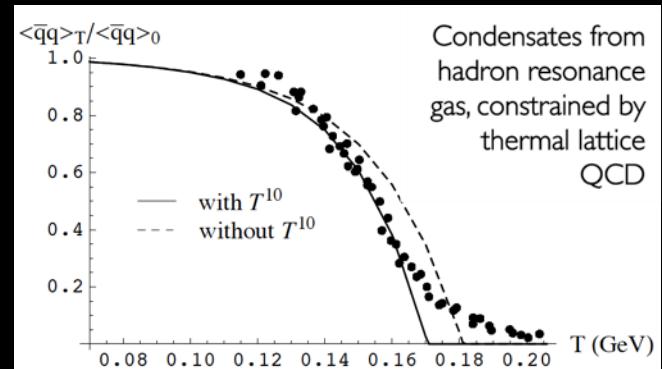
 Rapp et al, Annals Phys. 368 (2016)



$\rho - a_1$  mass splitting due to  
 $\chi_s$  breaking ( $\sim f_\pi \langle \bar{q}q \rangle$ )

... remain valid in medium

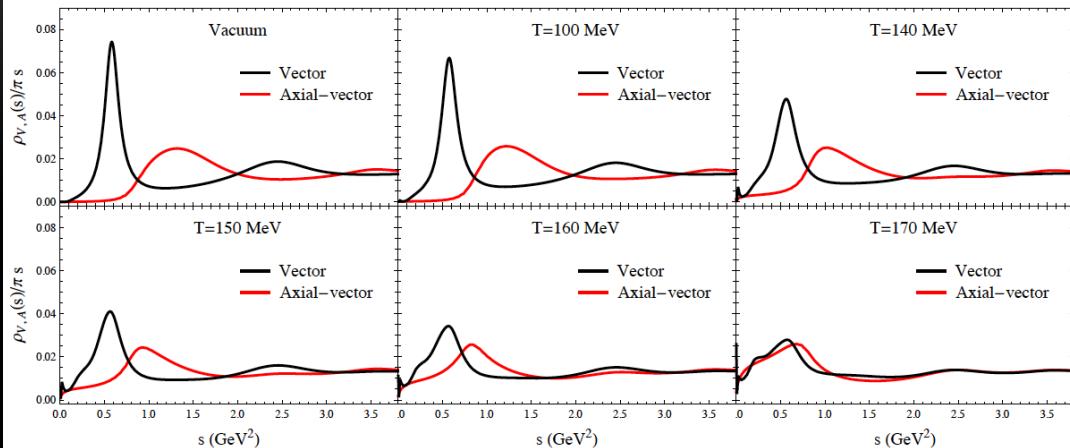
 J. Kapusta, E. Suryak '94



Condensates from hadron resonance gas, constrained by thermal lattice QCD

→ Test in-medium  $\rho - a_1$  spectral function

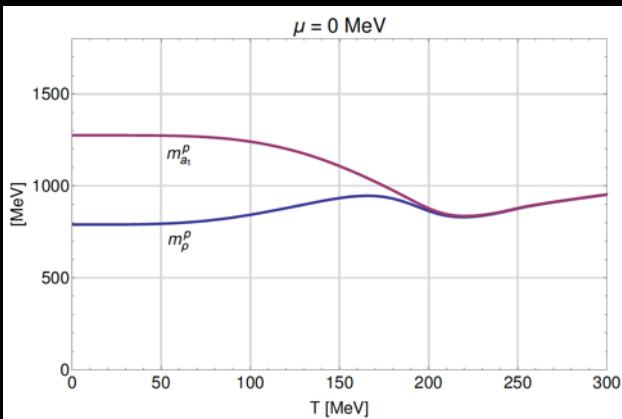
# QCD and Weinberg sum rules in medium



- Finite  $T$  vector and axial-vector spectral functions
- No baryon effects accounted for yet
- Chiral mass splitting “burns off”, resonances melt



Hohler & Rapp, Phys.Lett. B731 (2014)

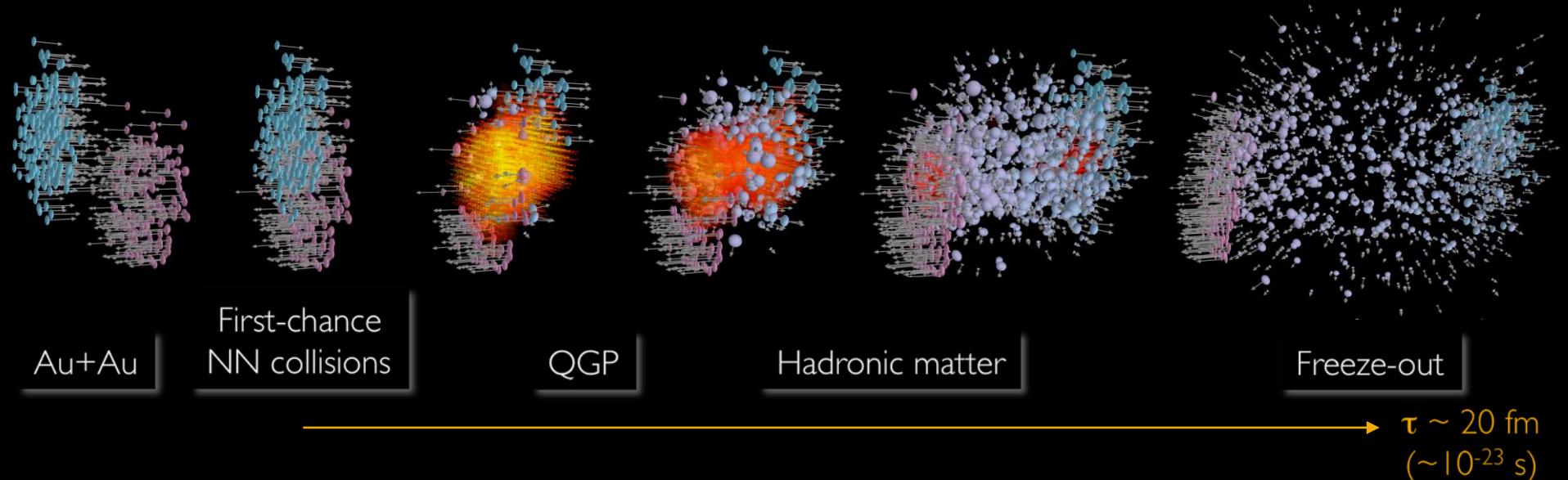


- Degeneracy of hadronic chiral partners at finite  $T$  from Functional Renormalization Group (FRG)



Jung, Tripolt, von Smekal, Wambach, Phys.Rev. D95, 036020 (2017)

# Experimental approach: high energy heavy-ion collisions

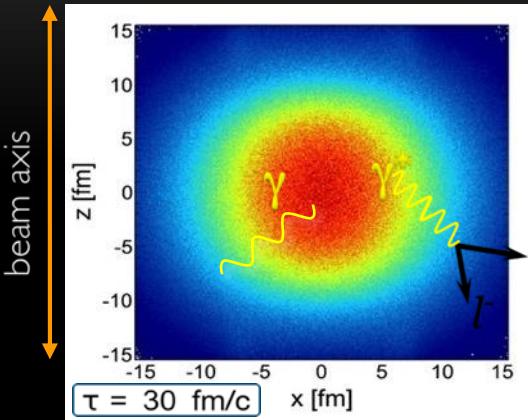


Systematic experimental measurements ( $E_{\text{beam}}$ ,  $A$ )

- Extract numbers that might be related to the QCD phase diagram
- Objective: use dileptons to probe the nature of Strongly Interacting Matter

# Electromagnetic radiation

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

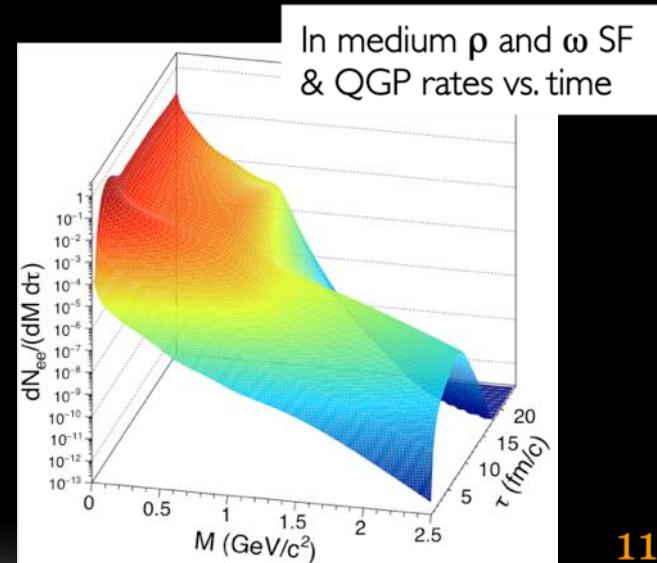


- EM radiation contains contributions from throughout the collision
- EM probes leave collision zone undisturbed
- Real  $\gamma$  characterized by transverse momentum
- Lepton pairs carry extra information: invariant mass

The vector correlator is directly accessible in HIC

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

→ Unique direct access to in-medium spectral function



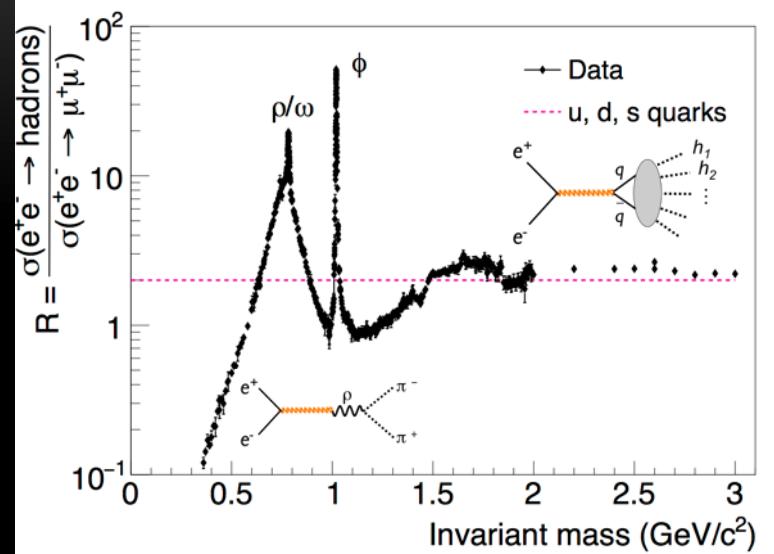
# Electromagnetic correlator in vacuum

McLerran-Toimela formula

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

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

- If  $\frac{\text{Im} \Pi_{EM}^{uv}}{M^2} \sim \text{const.}$  thermal dilepton emission will follow a Bose distribution
- Intermediate mass range as thermometer



$$\text{Im} \Pi_{EM}^{\text{vac}}(M \leq 1.5 \text{ GeV}) = \sum_{v=\rho, \omega, \phi} \left( \frac{m_v^2}{g_v} \right)^2 \text{Im} D_v^{\text{vac}}(M)$$

➡ Vector Meson Dominance:  $J^P = 1^-$  for both  $\gamma^*$  and VM (with  $\rho$  playing a dominant role)

➡ pQCD continuum

$$\text{Im} \Pi_{EM}^{\text{vac}}(M > 1.5 \text{ GeV}) = -\frac{M^2}{12\pi} \left( 1 + \frac{\alpha_s(M)}{\pi} + \dots \right) N_c \sum_{q=u,d,s} (e_q)^2$$

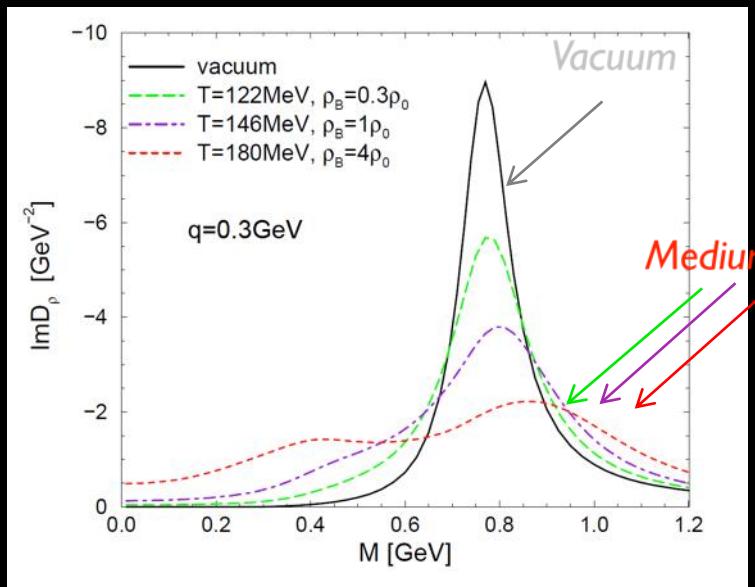
# $\rho$ meson in hot and dense medium

interacts with hadrons from heat bath →

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



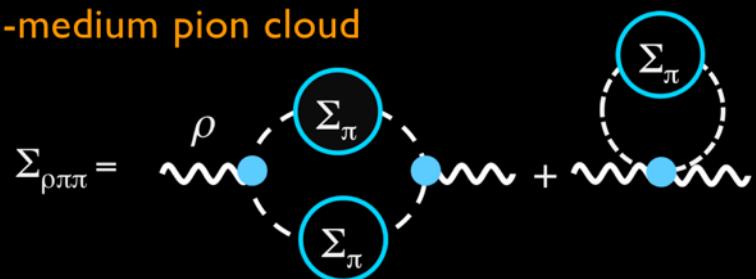
R. Rapp and J. Wambach, Eur.Phys.J.A6 (1999)



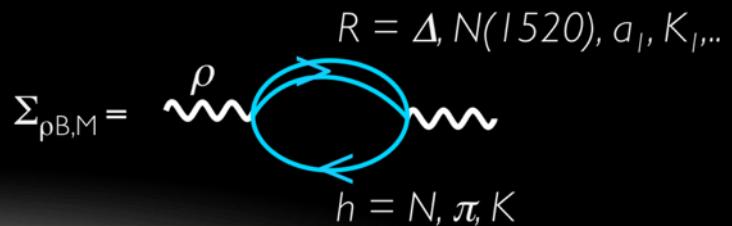
The  $\rho$  spectral function **strongly broadens** in the medium because the  $\rho$  couples to baryons!

$$D_r(M, q; m_B, T) = \frac{I}{[M^2 - m_r^2 - S_{r\pi\pi} - S_{rB} - S_{rM}]} \quad \boxed{I}$$

In-medium pion cloud



Direct  $\rho$ -hadron scattering



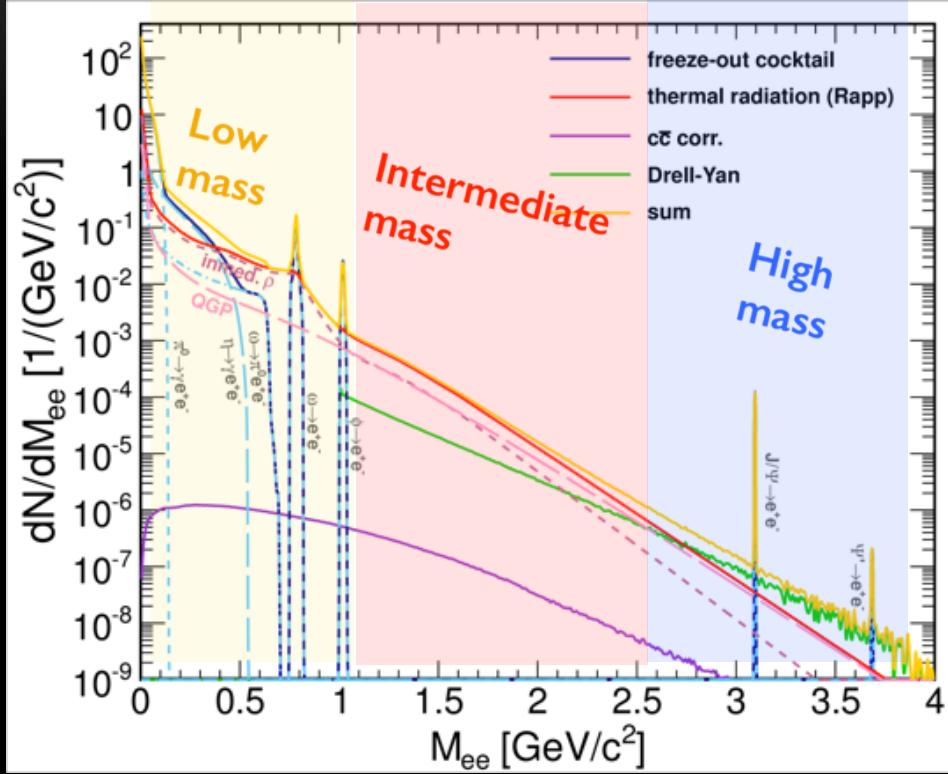
# Components of EM probes

- Degrees of freedom of the medium:
  - Spectral function merges into QGP description  
Direct evidence for transition hadrons → quarks & gluons
  
- Restoration of chiral symmetry
  - Condensates constrained by Lattice-QCD
  - Chiral mass splitting “burns off” → resonances melt
  
- Phenomenological tools → excitation functions
  - Fireball lifetime
  - Emitting source temperature
  
- Transport properties
  - Electric conductivity → probes soft limit of EM SF



$$\sigma_{EM}(T) = -e^2 \lim_{q_0 \rightarrow 0} \left[ \frac{\partial}{\partial q_0} \text{Im}\Pi_{EM}(q_0, q=0; T) \right]$$

# Characteristic regimes in invariant $e^+e^-$ mass



- Drell-Yan: power-low  $\sim M^n$
- Heavy-flavor:  $c\bar{c} \rightarrow l^+l^-$
- Thermal radiation:  $\sim \exp(-M/T)$ 
  - QGP – highest T, no flow
  - "4π annihilation":  $\pi a_1 \rightarrow l^+l^-$
  - In-medium  $\rho$ ,  $\omega$  – moderate T, flow
- Final state decays (hadron cocktail):  $\pi^0, \eta \rightarrow \gamma e^+e^-$

$$M^2 = (P_{e^+} + P_{e^-})^2$$

# The experimental challenge ...

- 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!



*There is no such thing as a free lunch*

## DATA QUALITY

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



Fotolia.de

# Italian Artist Sven Sachsalber looked for a needle in haystack (November 2014)



... but after 2 days, he found it !



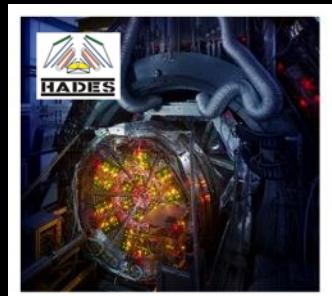
... he has gone through periods of doubt  
and serious discouragement

T



Highly interesting results from  
LHC, RHIC BES, SPS, SIS18

→ Lepton pairs as true messengers of the dense phase

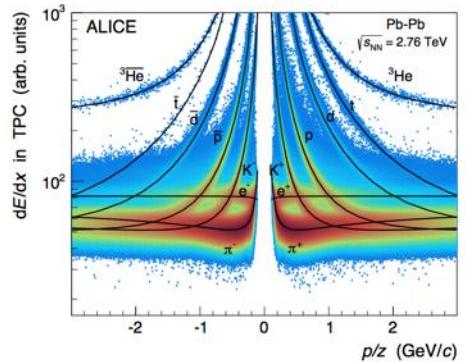


$\mu_B$

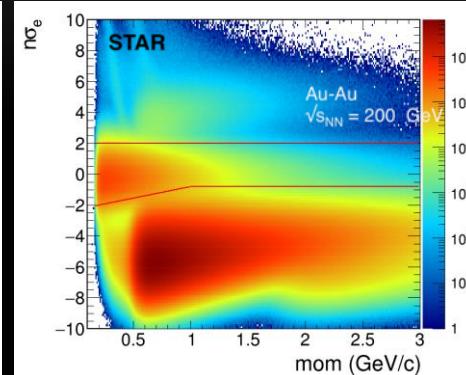
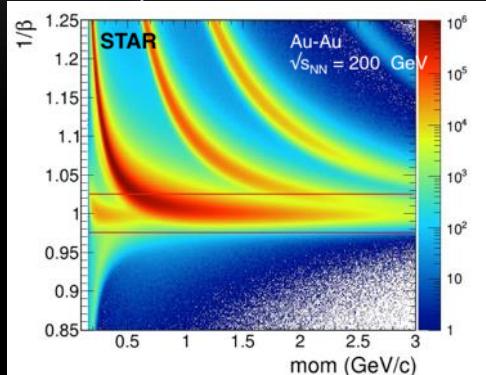
# Particle identification

Electron identification by means of: momentum,  $dE/dx$ , velocity, RICH information

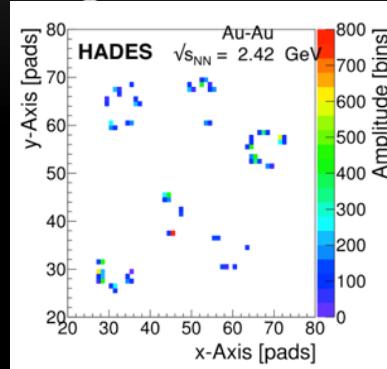
$dE/dx$  in TPC



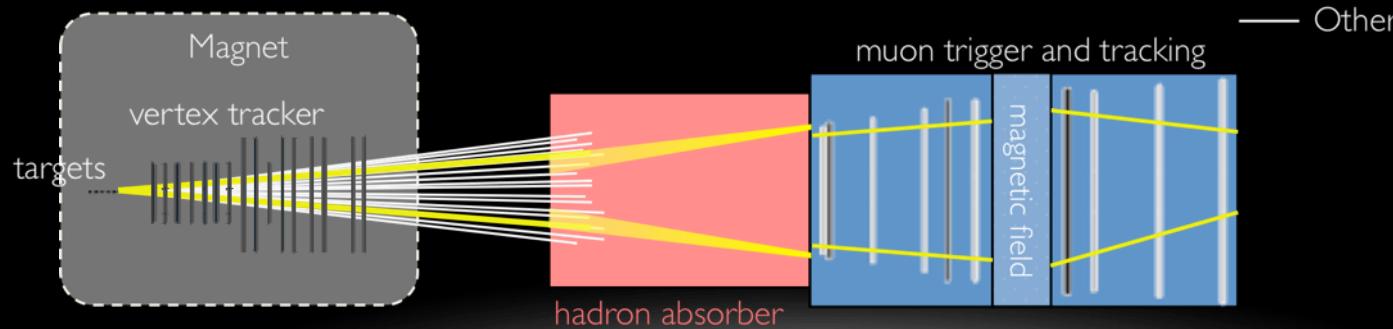
Velocity in ToF



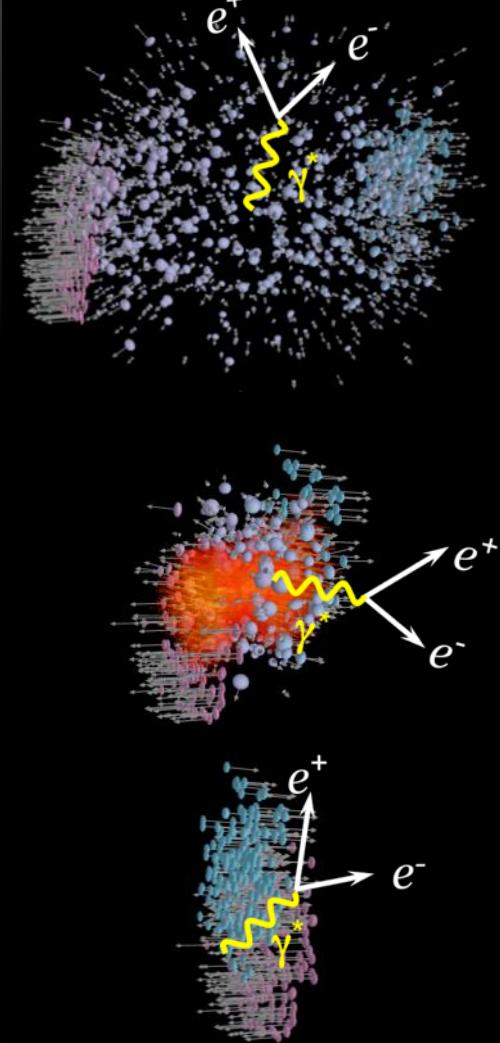
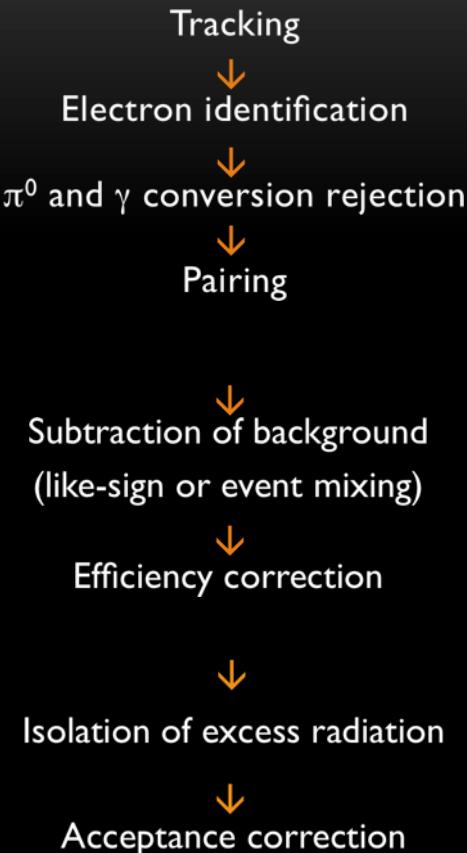
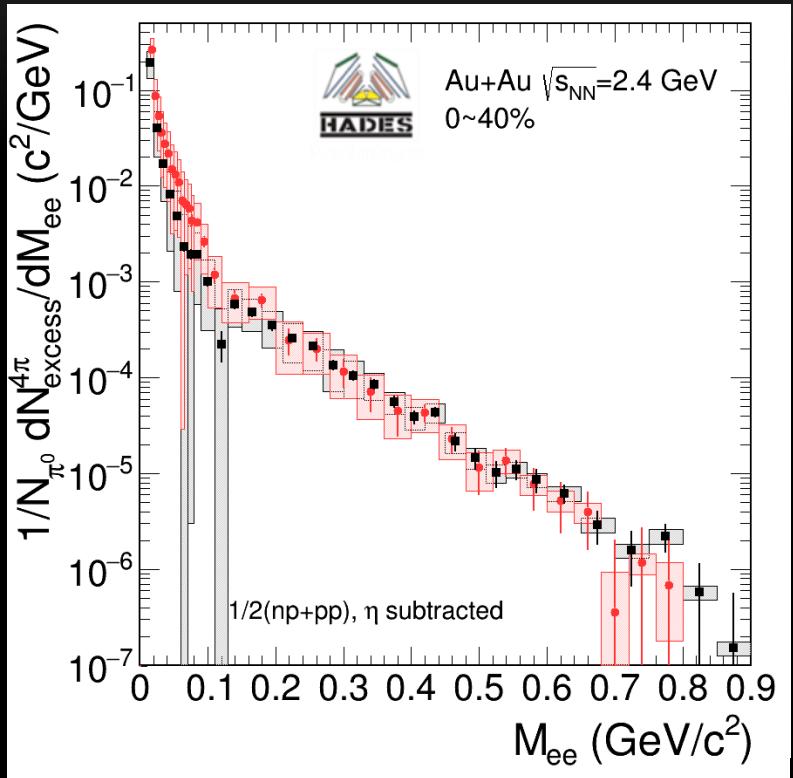
Rings in RICH



Muon identification: absorber technic



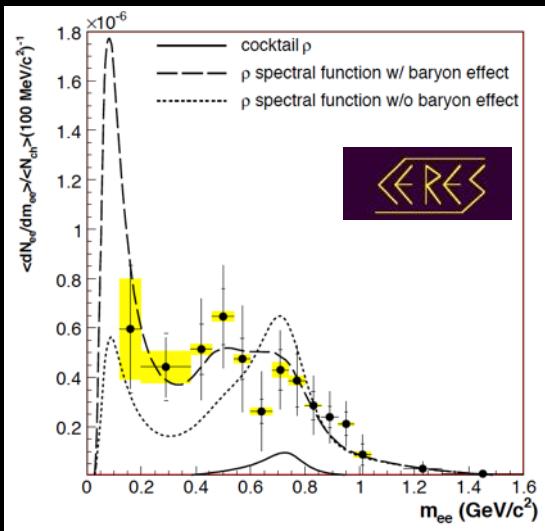
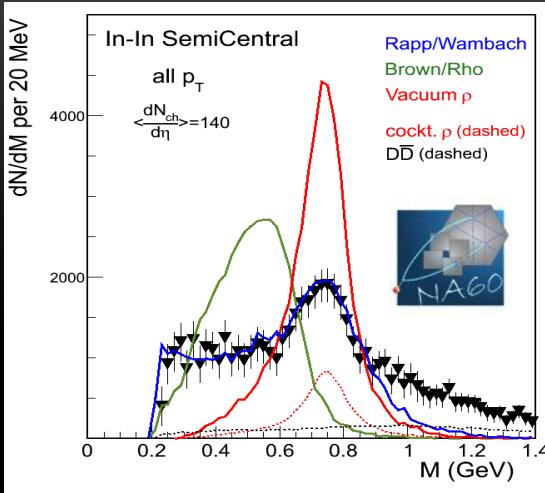
# Just few steps ;)



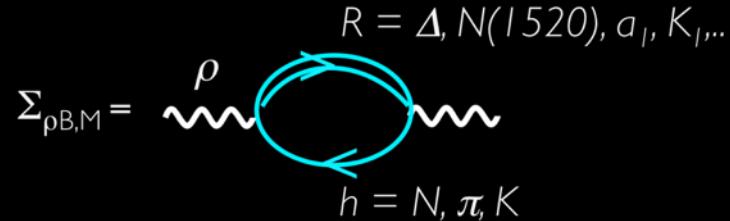
# Dileptons as spectrometer



# Are narrow in-medium vector meson states with substantially shifted pole mass observed?



- Disfavors “dropping mass” scenario:  $m_{had} \sim \langle \bar{q}q \rangle$
- Strongly supports in-medium broadening

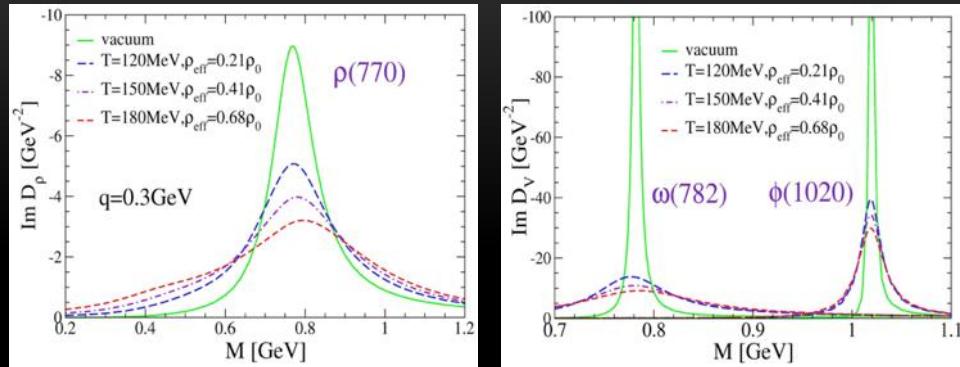
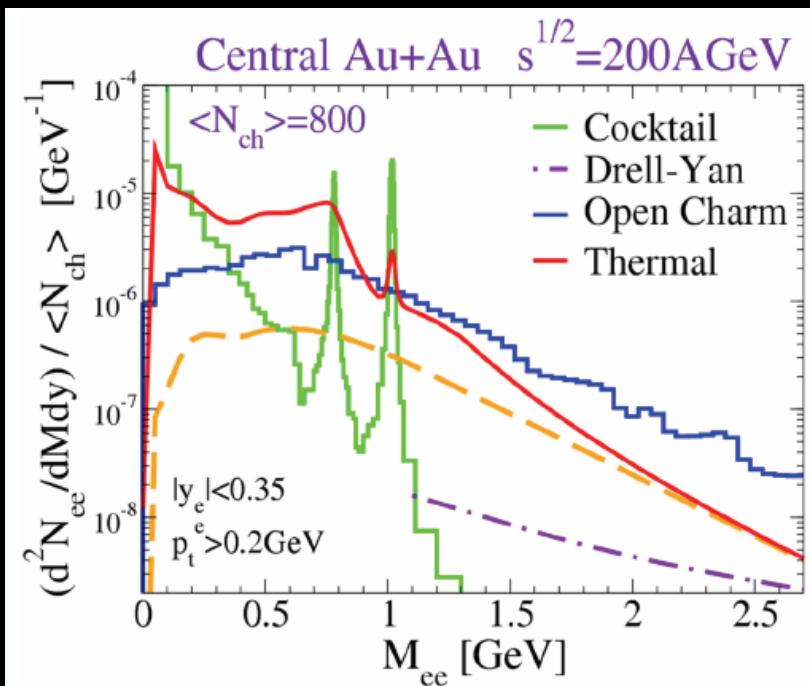


Data NA60: Phys. Rev. Lett. 96 (2006) 162302

Data CERES: Phys. Lett. B666 (2008)

Calculations: R.Rapp and H. van Hees, 2008

# Predictions for RHIC

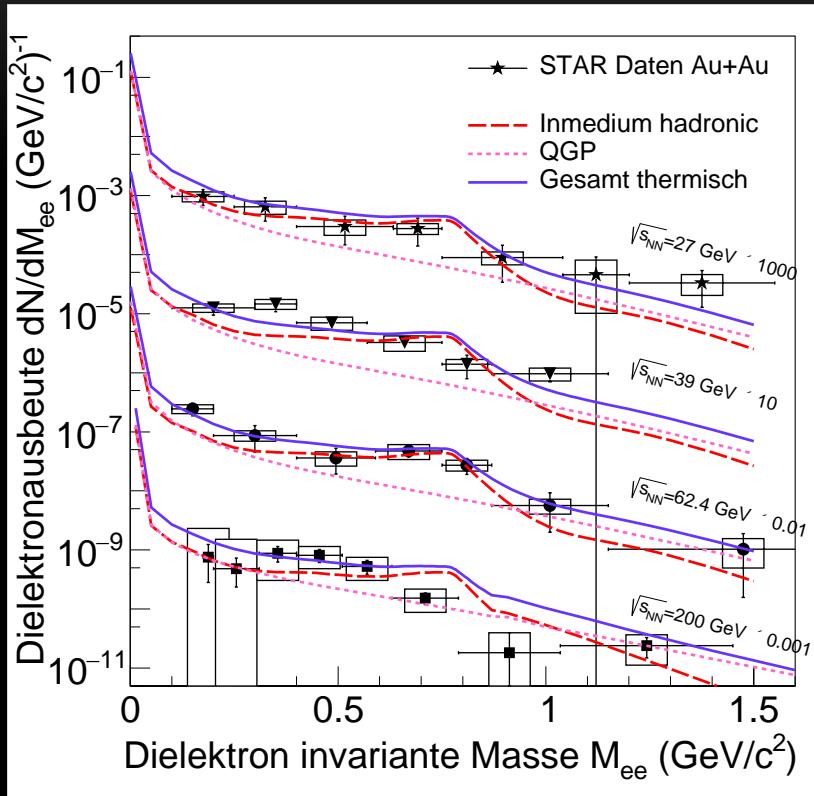


In-medium modifications of vector mesons persists (R. Rapp)

Open charm contribution becomes significant

# Dielectron mass spectra from STAR BES I

Au+Au  $\sqrt{s_{NN}} = 19.6 - 200 \text{ GeV}$



Phys.Lett.B750 (2015) 64-71

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

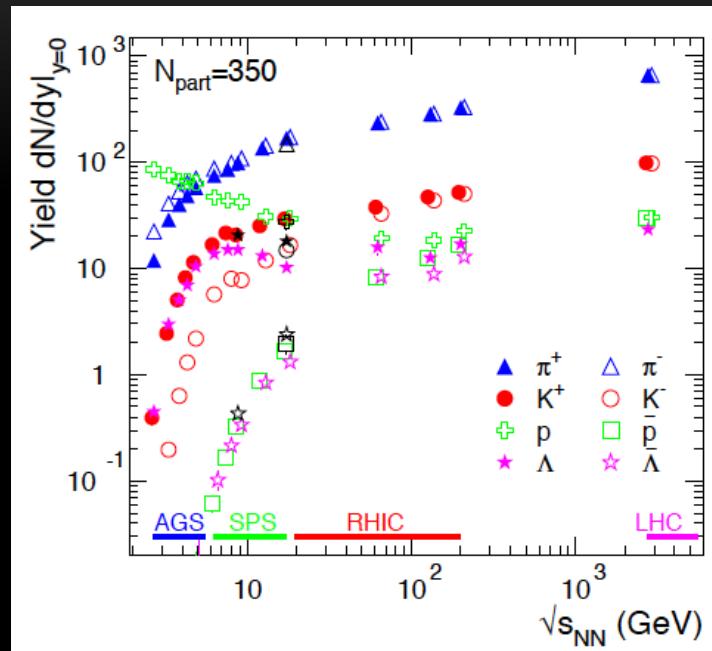
Model: Rapp/Wambach/Hees

- 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

# From SPS to RHIC

|  | SPS (Pb+Pb) | RHIC (Au+Au) |
|--|-------------|--------------|
| $dN(\bar{p})/dy$                                       | 6.2         | 20.1         |
| produced baryons ( $p$ , $\bar{p}$ , $n$ , $\bar{n}$ ) | 24.8        | 80.4         |
| $p - \bar{p}$  | 33.5        | 8.6          |
| participating nucleons ( $p - \bar{p}$ )A/Z            | 85          | 21.4         |
| total baryon number                                    | 110         | 102          |

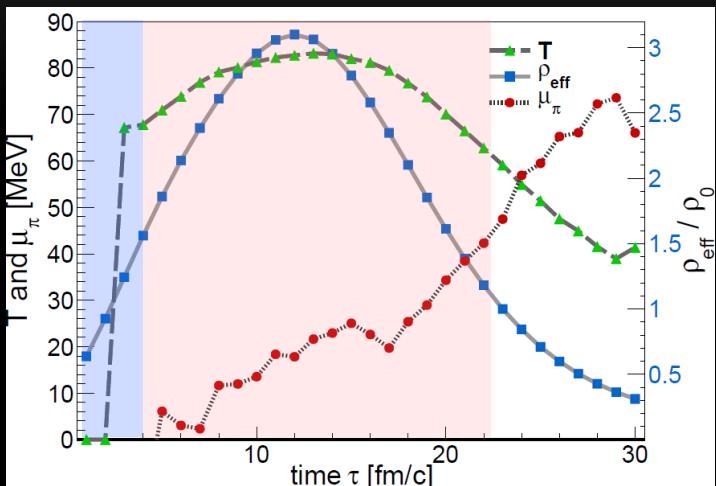
- Although the NET baryon density is different at SPS and RHIC, baryon density is practically the same!
- Baryon effects important even at  $\rho_{B,\text{tot}} = 0$ : sensitive to  $\rho_{B\text{tot}} = \rho_B + \rho_{\bar{B}}$  ( $p$ -N and  $p$ - $\bar{N}$  interactions identical)
- Higher initial temperature at RHIC



A. Andronic, arXiv:1407.5003

# Baryonic matter at few GeV beam energy Au+Au $\sqrt{s_{NN}} = 2.42$ GeV

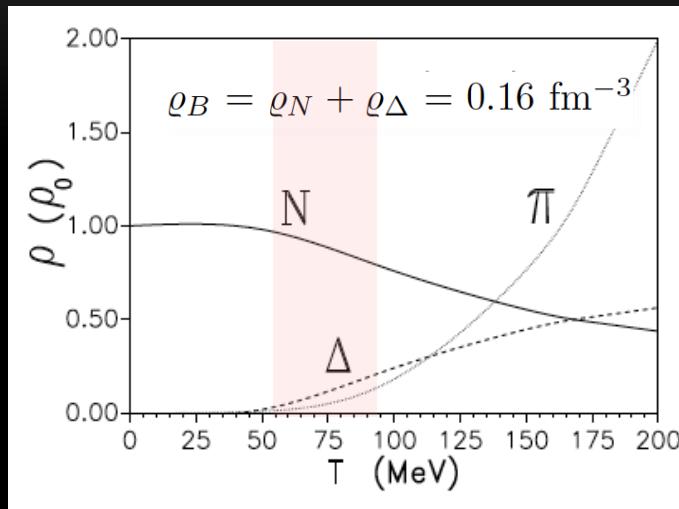
Central cell (3x3x3 fm<sup>3</sup>) thermodynamic properties from coarse graining UrQMD



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

- Long interpenetration times
- Comparatively long lifetime of the dense "fireball" ( $\rho_{\text{max}} \approx 3 \rho_0$ )

Composition of a hot  $\pi\Delta N$  gas

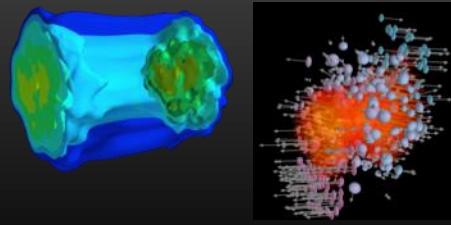


Rapp, Wambach, Adv.Nucl.Phys. 25 (2000)

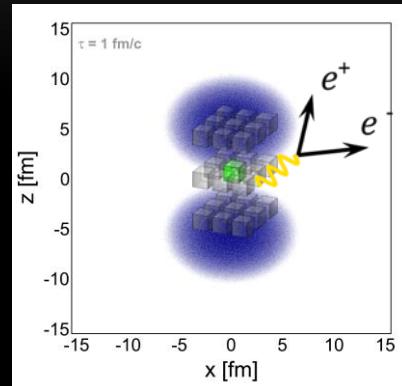
- Moderate temperatures:  $T < 90$  MeV
- Baryon-dominated system throughout the evolution ( $N_\pi / A_{\text{part}} \approx 10\%$ )

# Coarse-grained transport approach

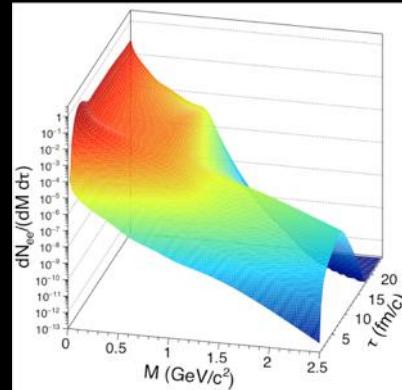
- “Combine” the advantages of two descriptions: hydrodynamics & transport
- Simulate events with a transport model
  - ensemble average to obtain smooth space-time distributions



- 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

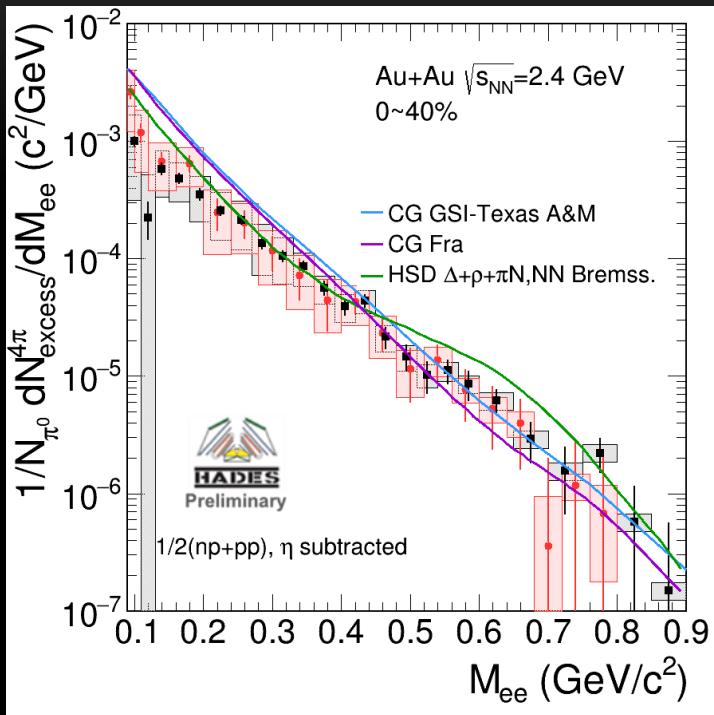


Huovinen et al., PRC 66 (2002) 014903

CG FRA Endres et al.: PRC 92 (2015) 014911

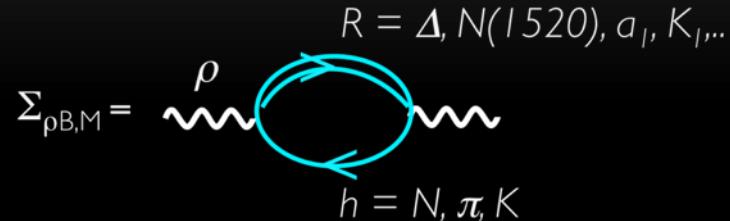
CG GSI-Texas A&M TG et al.: Eur.Phys.J.A52 (2016) no.5, 131

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



HADES, collaboration review

- Strong broadening of the in-medium  $\rho$  due to direct  $\rho$ -hadron scattering



- Thermal rates folded over coarse-grained UrQMD medium evolution works at low energies
- Supports baryon-driven medium effects at UrHIC (SPS and RHIC)!

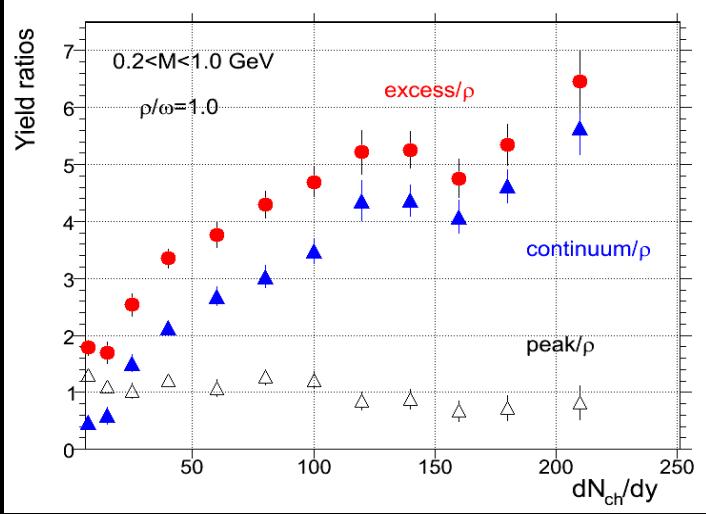
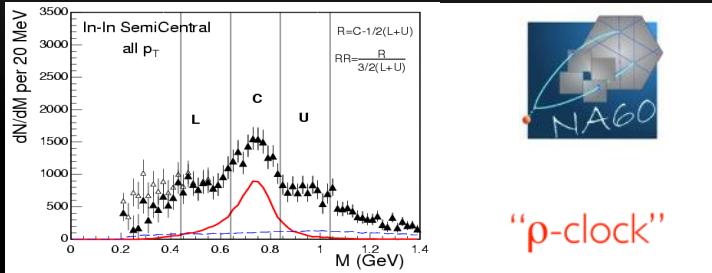
Robust understanding across QCD phase diagram

# Dileptons as chronometer

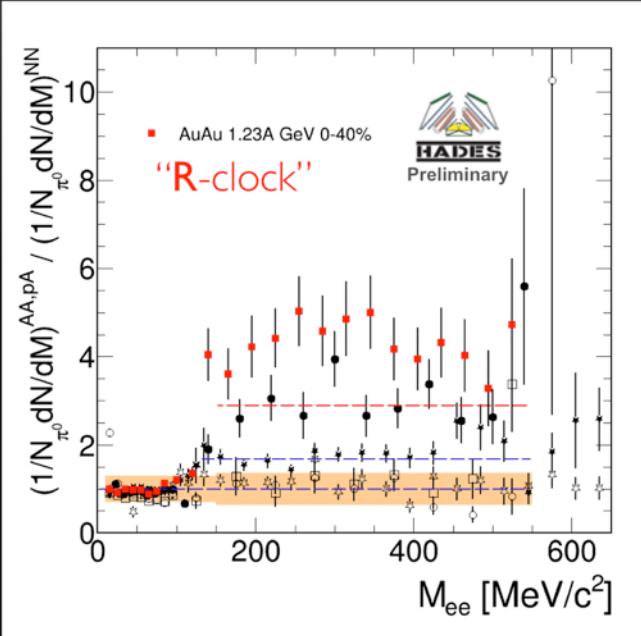


# The dilepton clock

Centrality dependence of spectral shape



System size dependence of excess



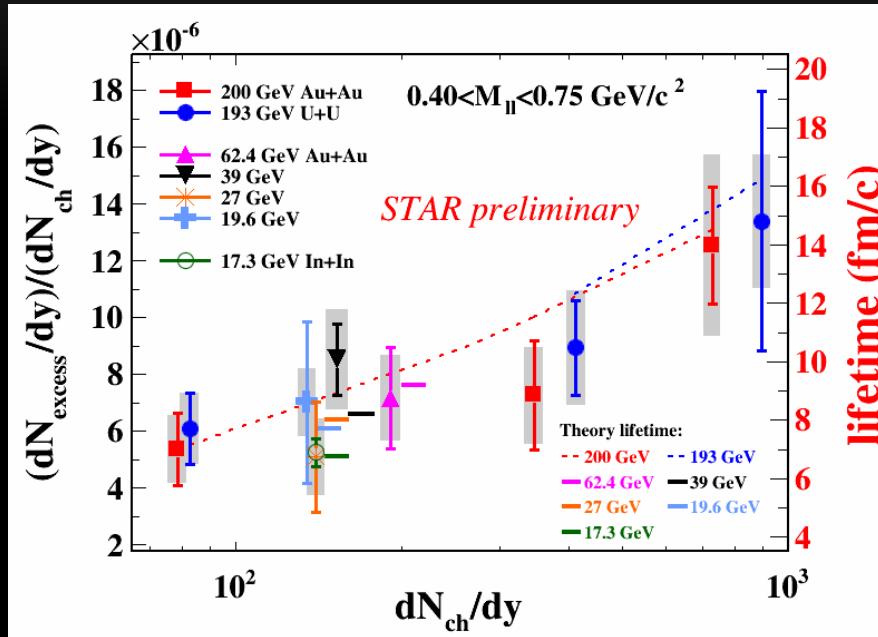
Rapid increase of relative yield reflect the number of  $\rho$ 's / R's regenerated in fireball



U.W. Heinz and K.S. Lee, PLB 259, 162 (1991)

H.W. Barz, B.L. Friman, J. Knoll and H. Schulz, PLB 254, 315 (1991)

# The lifetime of the interacting fireball



- 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
- Note: normalization to the number of pions should be done when going down with energy!



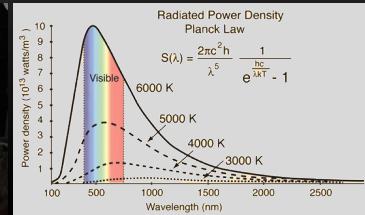
STAR data: arXiv:1612.05484 [nucl-ex]

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



Spectral shape of the light →  
temperature of the emitting object

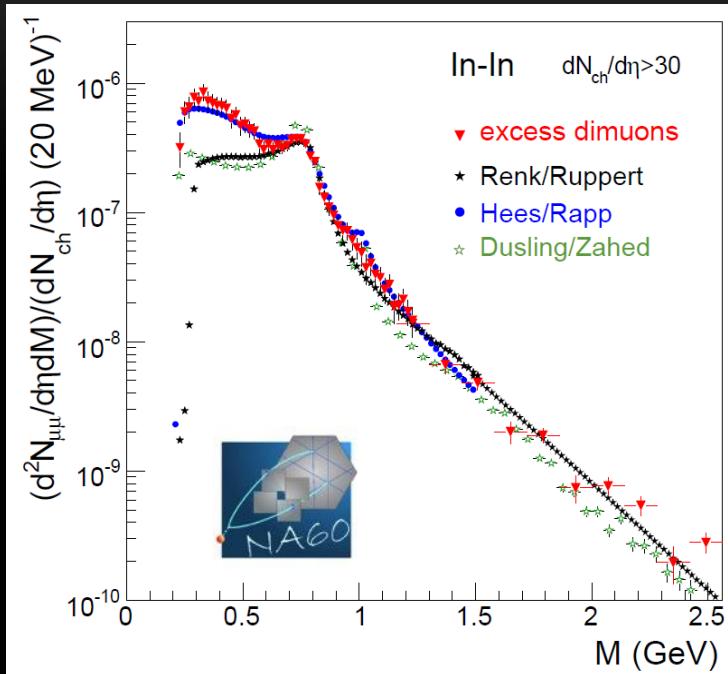
$$E = \hbar\nu = \frac{\hbar c}{\lambda}$$



## Dileptons as thermometer



# Measurement of radiating source temperature at SPS



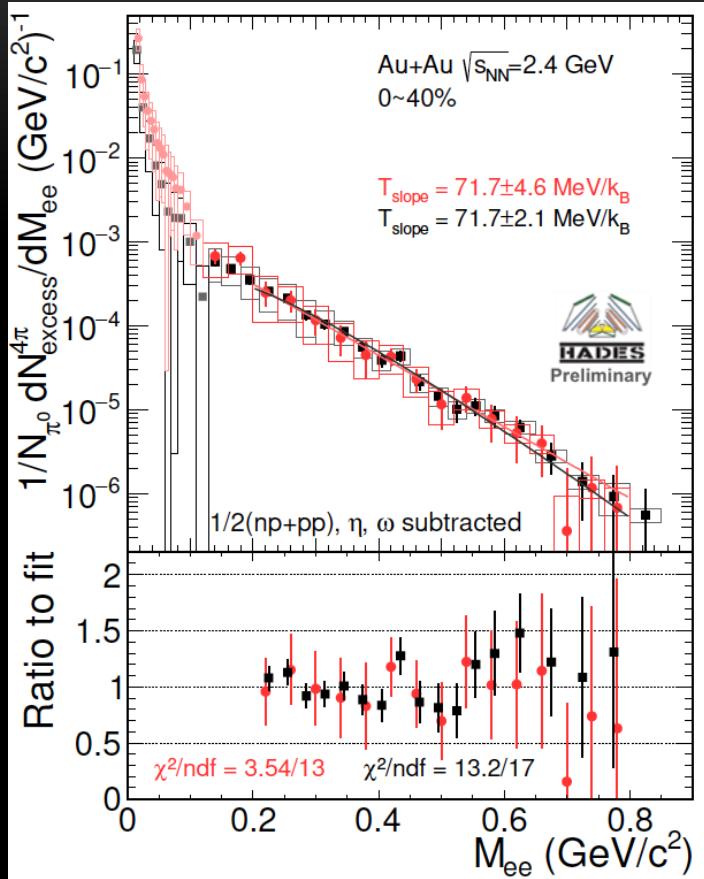
- Acceptance corrected excess yield
- $M_{\mu\mu} > 1 \text{ GeV}/c^2 \sim \text{exponential fall-off - 'Planck-like'}$
- measurement of radiating source temperature
- fit  $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$  to range
- $M = 1.1 - 2.0 \text{ GeV}/c^2: \langle T \rangle_{\text{emitting source}} = 205 \pm 12 \text{ MeV}/k_B$
- $M = 1.1 - 2.4 \text{ GeV}/c^2: \langle T \rangle_{\text{emitting source}} = 230 \pm 10 \text{ MeV}/k_B$



Eur. Phys. J. C 59 (2009) 607-623  
CERN Courier 111/2009, 31-35  
Chiral 2010, AIP Conf. Proc. (2010) 1322

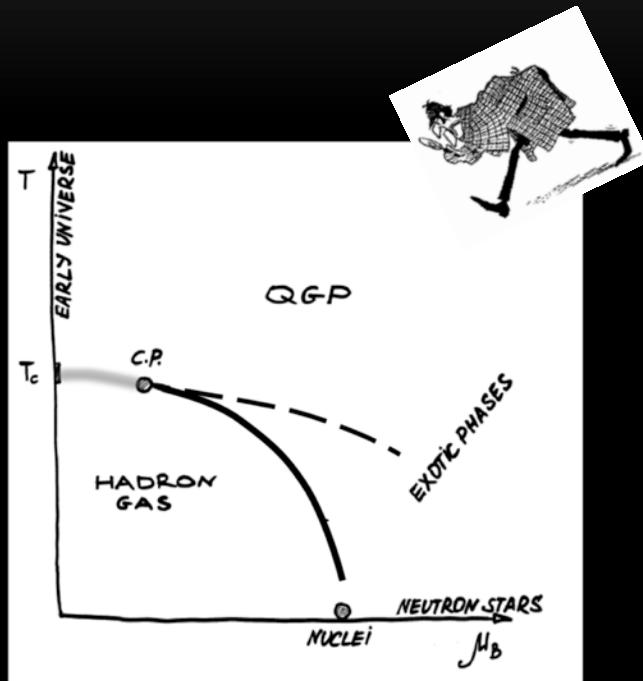
M is the only Lorenz-invariant thermometer of the field

# Virtual photon emission – fireball thermometer at SIS18



- $T_{\text{initial}} \sim 3$  times lower at SIS18 compared to SPS
  - Shifts predominance of early emission from  $M_{ee} > 1.2$  GeV/c<sup>2</sup> at SPS to  $M_{ee} > 0.4$  GeV/c<sup>2</sup> at SIS
- fit  $\frac{dN}{dM} \sim M^{\frac{3}{2}} \times \exp\left(-\frac{M}{T}\right)$  to range  $M=0.2-0.8$  GeV/c<sup>2</sup>
- $\langle T \rangle_{\text{emitting source}} = 72 \pm 2$  MeV/k<sub>B</sub>

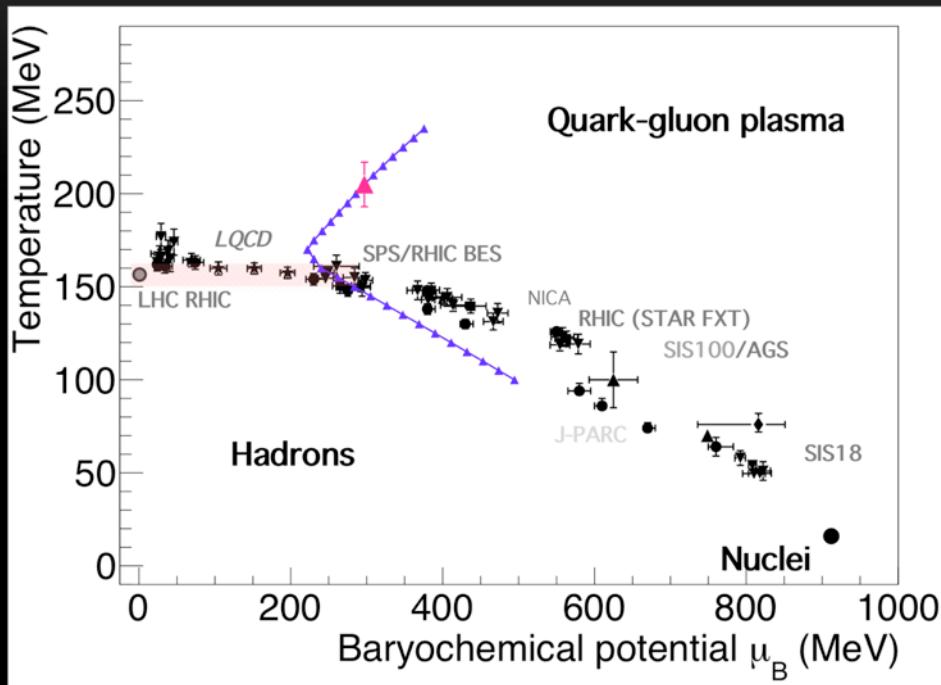
# Dileptons and QCD phase diagram of matter



Excitation functions

- Fireball lifetime
- Emitting source temperature

# Trajectories in the phase diagram



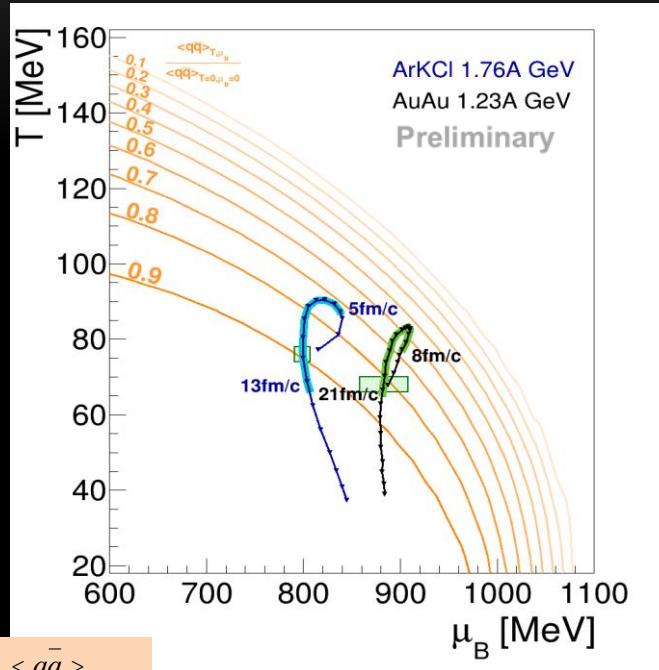
- Hadron production: well described by hadron gas in chemical and thermal equilibrium

$$n_i(\mu_B, T) = d_i \int \frac{d^3 k}{(2\pi)^3} f(E_k; \mu_B, T)$$

- Dileptons - need to construct evolution:
  - Before up to earliest “formation” time  $\tau_0 \leftrightarrow T_0 > T_{\text{chem}}$
  - After: down to thermal freezeout  $\tau_f \leftrightarrow T_{\text{fo}} < T_{\text{chem}}$
- Basic assumption: entropy (+baryon-number) conservation  $\rightarrow$  fixes  $T(\mu_B)$  in the phase diagram



# HADES and QCD phase diagram of matter



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

Ar+KCl data: Nucl. Phys. A931 (2014) c785

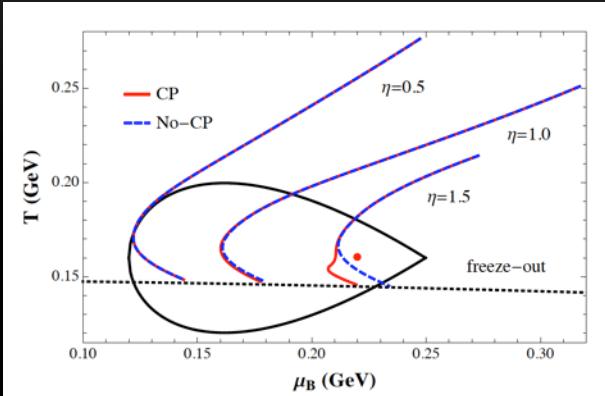
- Chemical freeze-out from measured particle yields analyzed with SHM
- Trajectories extracted from inner cube of cells with coarse-grained UrQMD
- Time-window of dilepton emission → access to hot and dense stage of the heavy-ion collision

$T_{\max} = 85 \text{ MeV}, \rho_{\max} = 3 \rho_0$   
→ Excitation of the vacuum  
(melting of condensate)  
matches spectral medium effects!

$$\frac{\langle\langle\bar{q}q\rangle\rangle(T, \mu_B)}{\langle\bar{q}q\rangle} = 1 - \sum_h \frac{\varrho_h^s \Sigma_h}{m_\pi^2 f_\pi^2}$$

# Mapping QCD phase diagram with dileptons

Hydrodynamic evolution trajectories



 A. Monnai, S. Mukherjee, Y. Yin: arXiv: 1606.00771

Diverging bulk viscosity at QCD critical point

$$\zeta \sim \tau_{\Pi} \sim \tau_{\sigma} \sim \xi^3$$

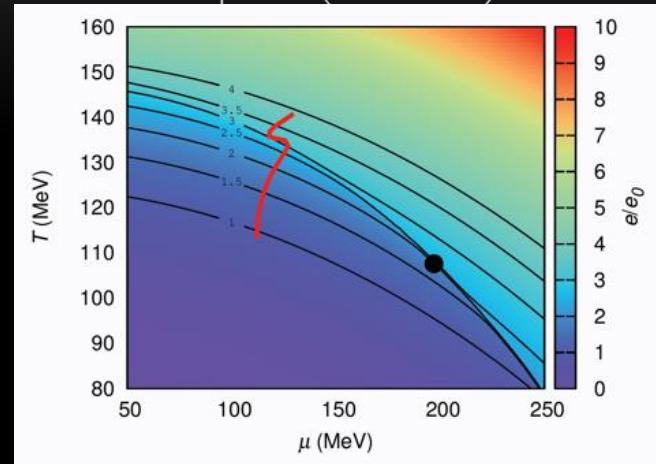
Bulk viscosity

Bulk relaxation time

Relaxation time for the critical mode

Correlation length<sup>3</sup>

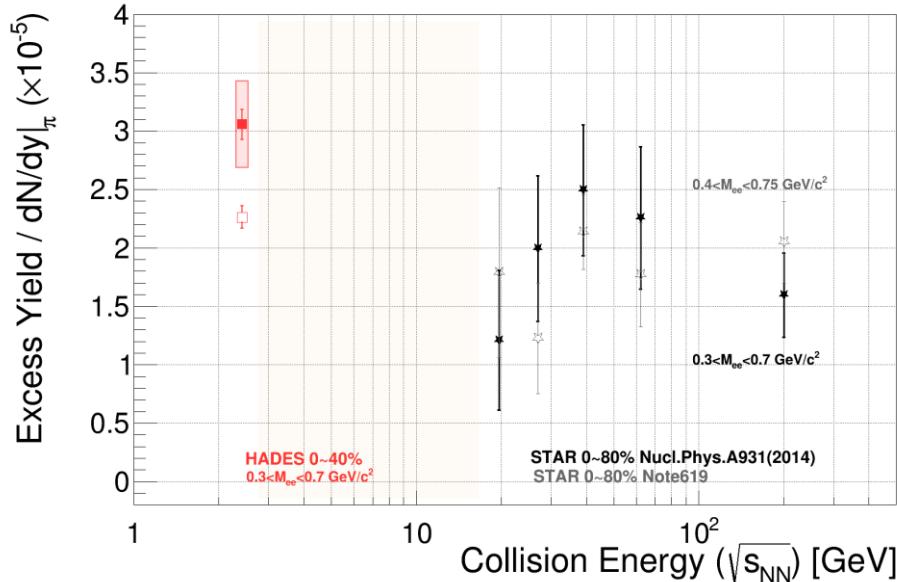
Event-averaged trajectory near the critical point (black dot)



 C. Herold, M. Nahrgang, Y. Yan and C. Kobdaj, PRC93 (2016)

What are the possible signatures in dilepton radiation?

# Energy dependence of low-mass excess

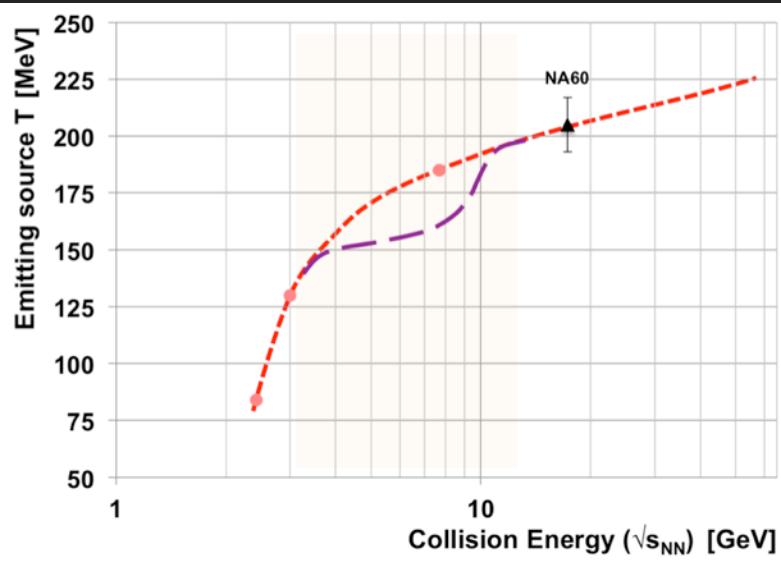


- Yield in low-mass window tracks fireball lifetime
- Search for anomalous fireball lifetime around phase transition & critical point
  - 2019 - STAR at RHIC BES II
  - 2024 - CBM at FAIR

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



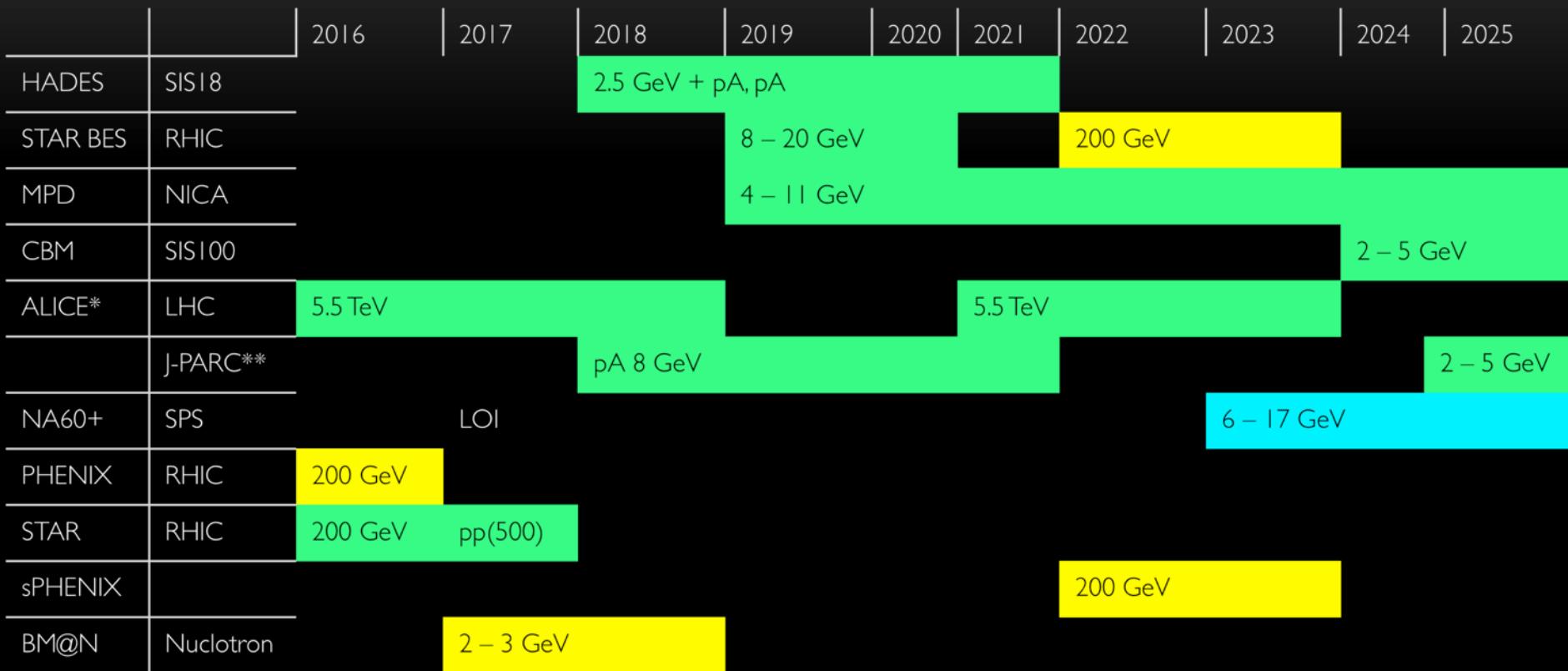
# Energy dependence of intermediate mass slope



*Dashed violet curve corresponds to a speculated shape with phase transition*

- Measures the emitting source temperature (true, no blue shift)
- Measure  $T_s$  (note,  $T_s < T_{\text{initial}}$ ) "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

# “You may say I’m a dreamer... but I’m not the only one”



\* - ITS, 50kHz, lower field

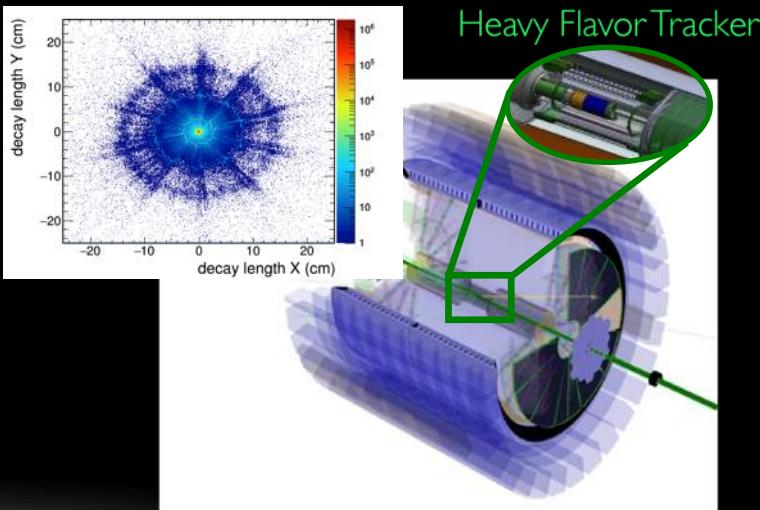
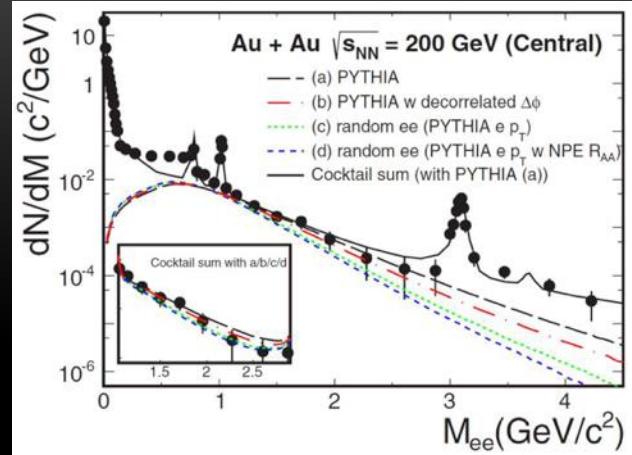
\*\* - Proposal to J-PARC → If approved, construction of HI injector and detectors in 10 years ?

# STAR dielectrons ongoing analysis $\text{Au+Au } \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$

- $\mu_B \ll T$ , 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  $\sim 4 \times 10^9$ )

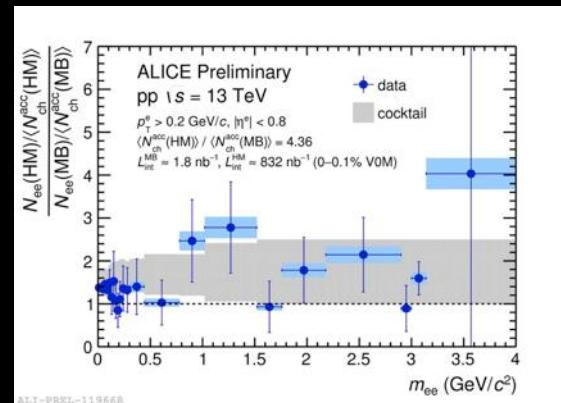
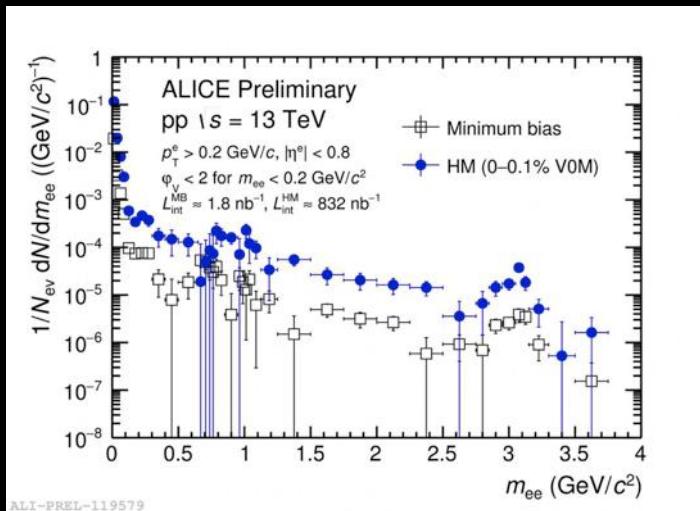


# pp at $\sqrt{s} = 13$ TeV: High-Multiplicity studies

- New (or heavy-ion like) phenomena in High-Multiplicity (HM) pp events:
  - Production/destruction of  $\rho$  mesons
  - Multiplicity scaling of light hadrons, open heavy flavours and direct photons

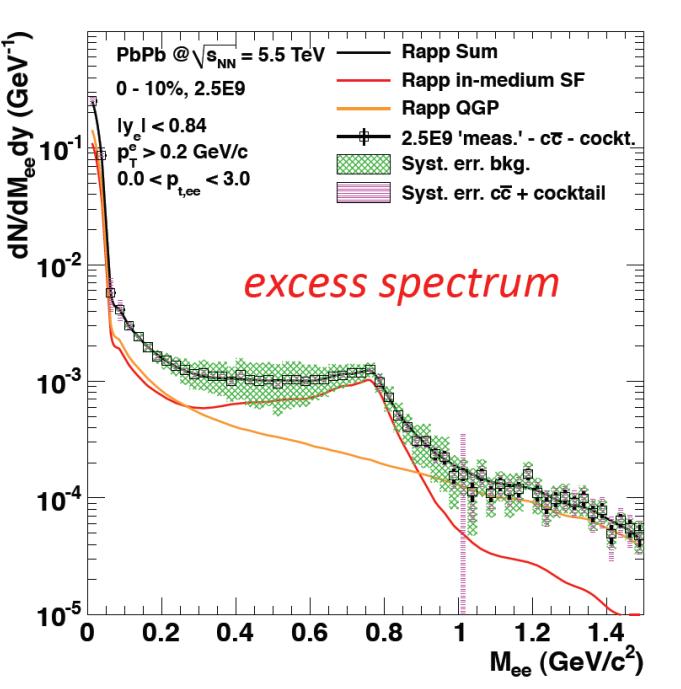
- Thermal radiation? in HM events

→ So far: compare dielectron yield (uncorrected) in MB and HM pp collisions

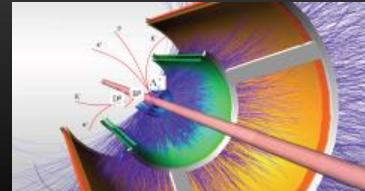


x 5 more pp data recorded in 2016

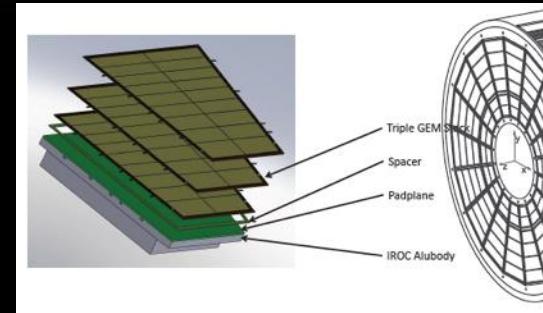
# Future: Pb+Pb from ALICE



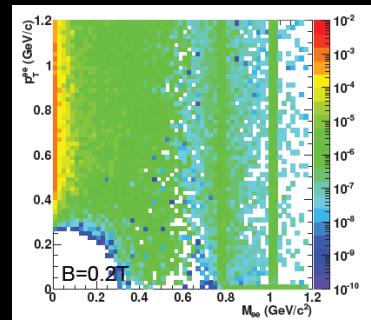
New ITS  
→ charm



New TPC readout chambers with GEMs  
→ 50kHz, statistics



Low magnetic field run  
→ acceptance

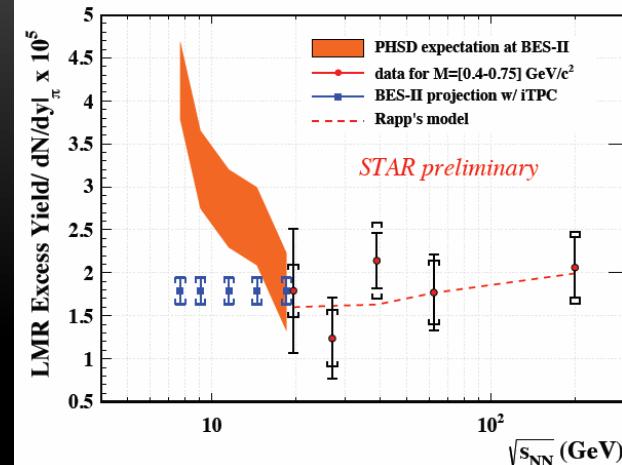


# STAR dielectrons

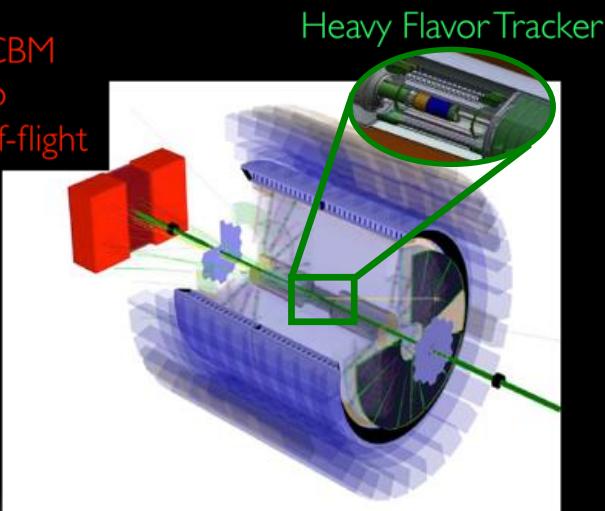
## Beam Energy Scan II

### 2019 - 2020

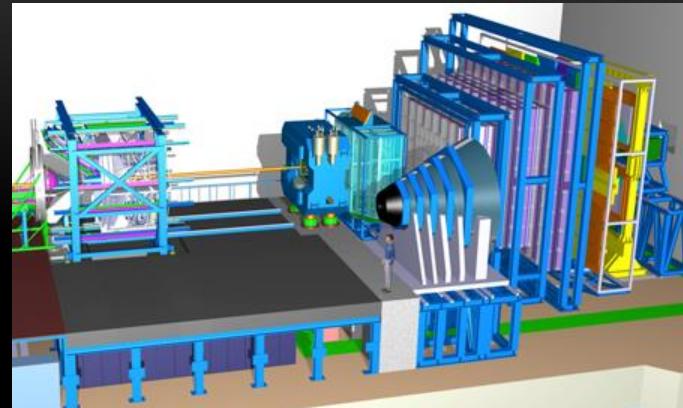
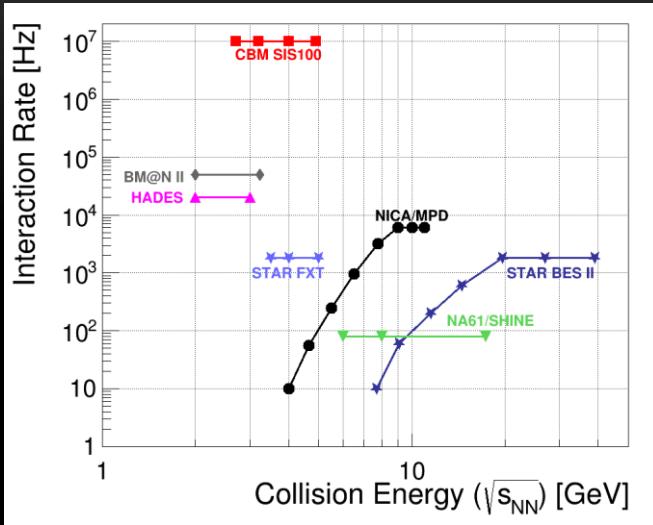
- Improve statistics for existing low energy samples
- Quantify lifetime and baryon density dependence of the  $\rho$  spectral function
- Disentangle various model calculations
  
- Inner TPC upgrade
- Installation of eToF (CBM Phase-0)
- Collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV



STAR/CBM  
end-cap  
Time-of-flight

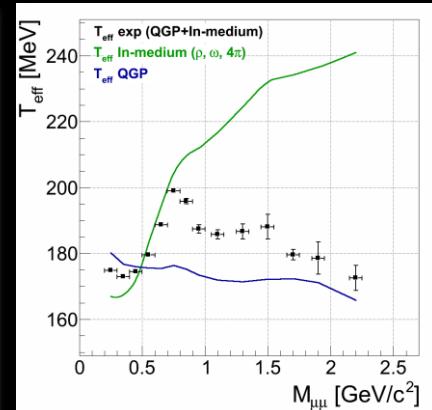
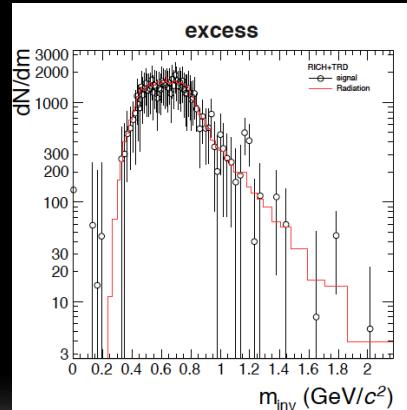


# Compressed Baryonic Matter experiment at FAIR

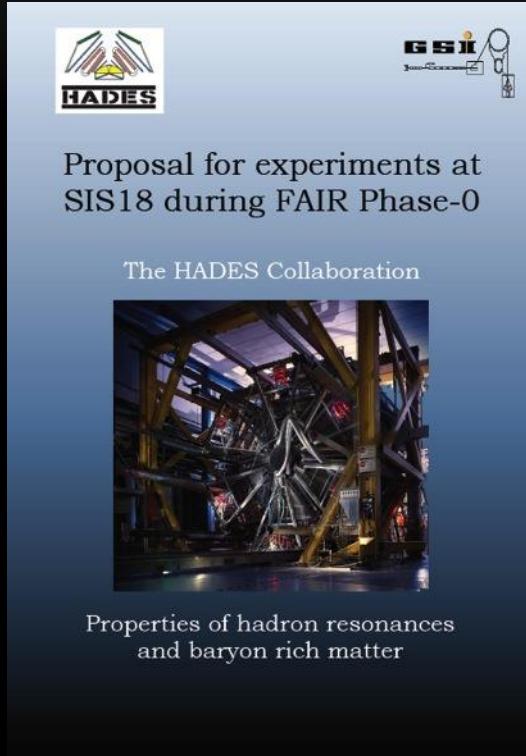


CBM Collab., EPJA, 53 3 (2017) 60

- **CBM** will play play a unique role in the exploration of the QCD phase diagram in the region of high net-baryon densities
- 4π processes:  $\pi a_1 \rightarrow \gamma^* \rightarrow l^+l^-$  (chiral mixing) is a dominant hadronic source in IMR: correlated charm contribution, Drell-Yan, QGP are suppressed



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

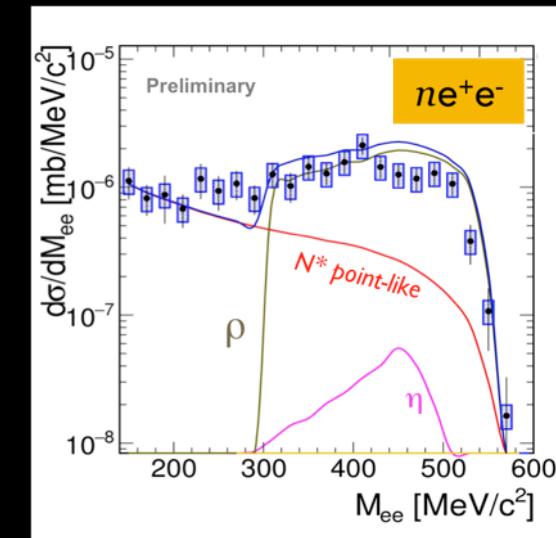
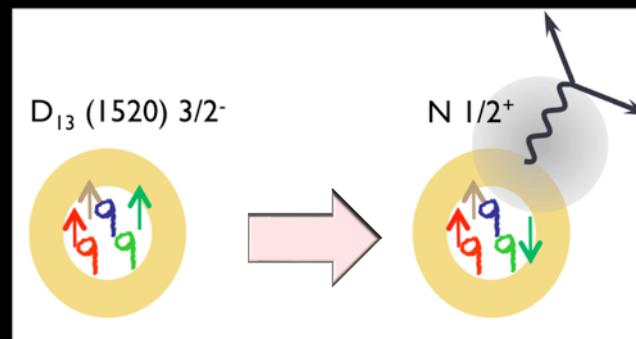
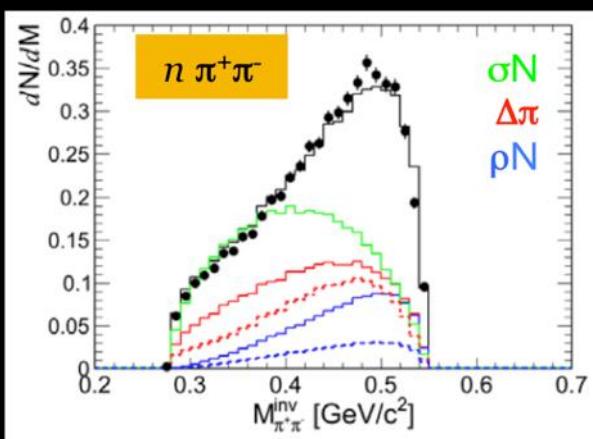
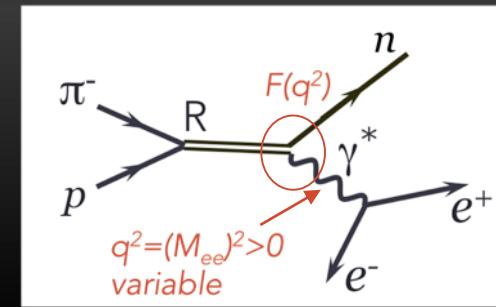


- HADES at SIS18 and SIS100
  - High statistics  $\pi+p$ ,  $\pi+A$ ,  $p+A$ ,  $A+A$
- Results in elementary collisions provide an important baseline for current and future explorations in HIC

# EM baryon-resonance decays

## $\pi^-$ (683,5 MeV/c) $p \rightarrow N^*$

- Worldwide unique combination of  $\pi$  beams (at low energies) with dilepton spectrometer
- Access to time-like etFF of baryons



→  $D_{13}(1520)$  is dominant in  $\rho$  production!

$$\frac{d\sigma}{dM_{ee}} = \frac{d\sigma}{dM_{\pi\pi}} c_p \left( \frac{m_\rho}{m_{ee}} \right)^3$$

→ First measurement demonstrating the dominant role of intermediate  $\rho$  propagation in  $N^* \rightarrow Ne^+e^-$  transition

# Résumé and prospects

- 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
- Future experiments allows for overlap and independent confirmation of results



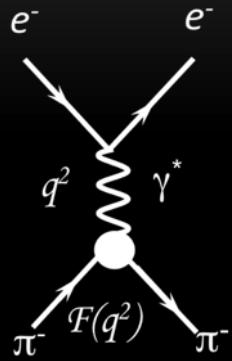
*There is no mission impossible*

Thank you  
for your attention!

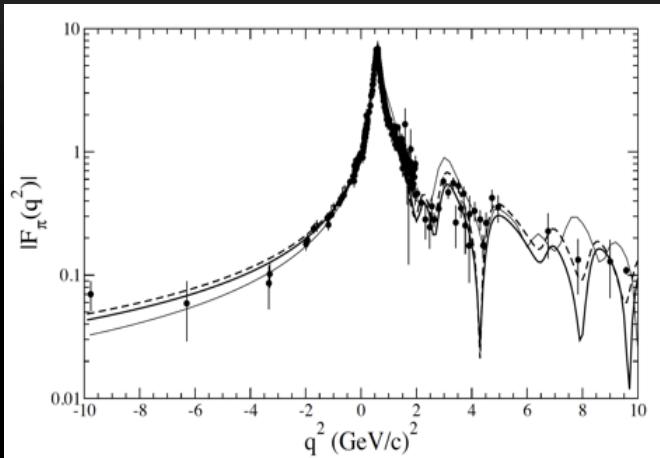
## Bonus slides

# How do photons couple to hadrons?

space-like photons

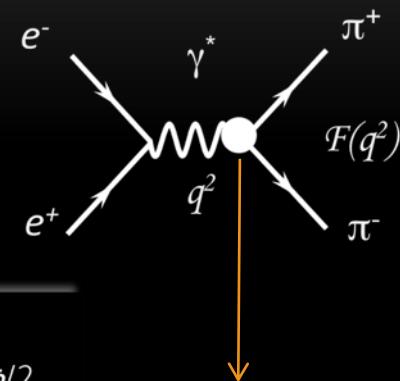


$$q^2 < 0 \\ \Delta p \Delta x \geq \hbar/2$$



De Melo et al., Phys. Rev. D73 (2006) 070413

time-like photons



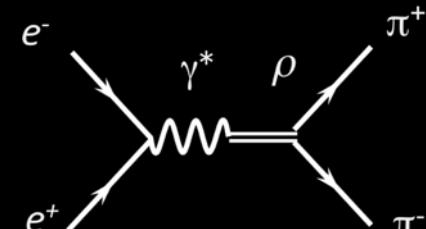
$$q^2 > 0 \\ \Delta E \Delta t \geq \hbar/2$$

$J^P = 1^-$  for both  $\gamma^*$  and Vector Meson

$$F(q^2) = \frac{d\sigma/dq^2}{\left(\frac{d\sigma/dq^2}{dq^2}\right)_{point\ like}} \\ q^2 = (\Delta E)^2 - (\Delta p)^2$$

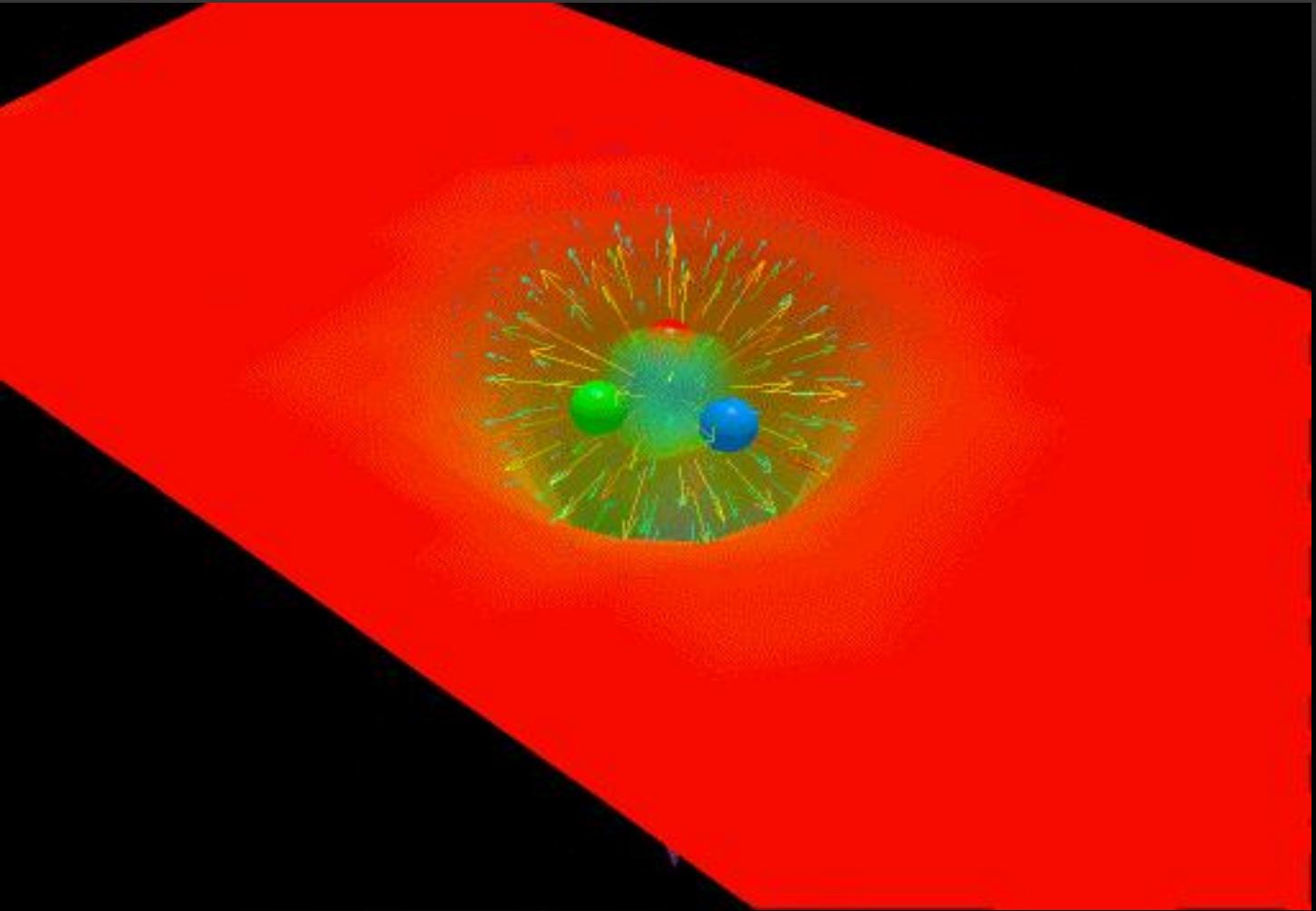
→ Form factor

→ Squared 4-momentum

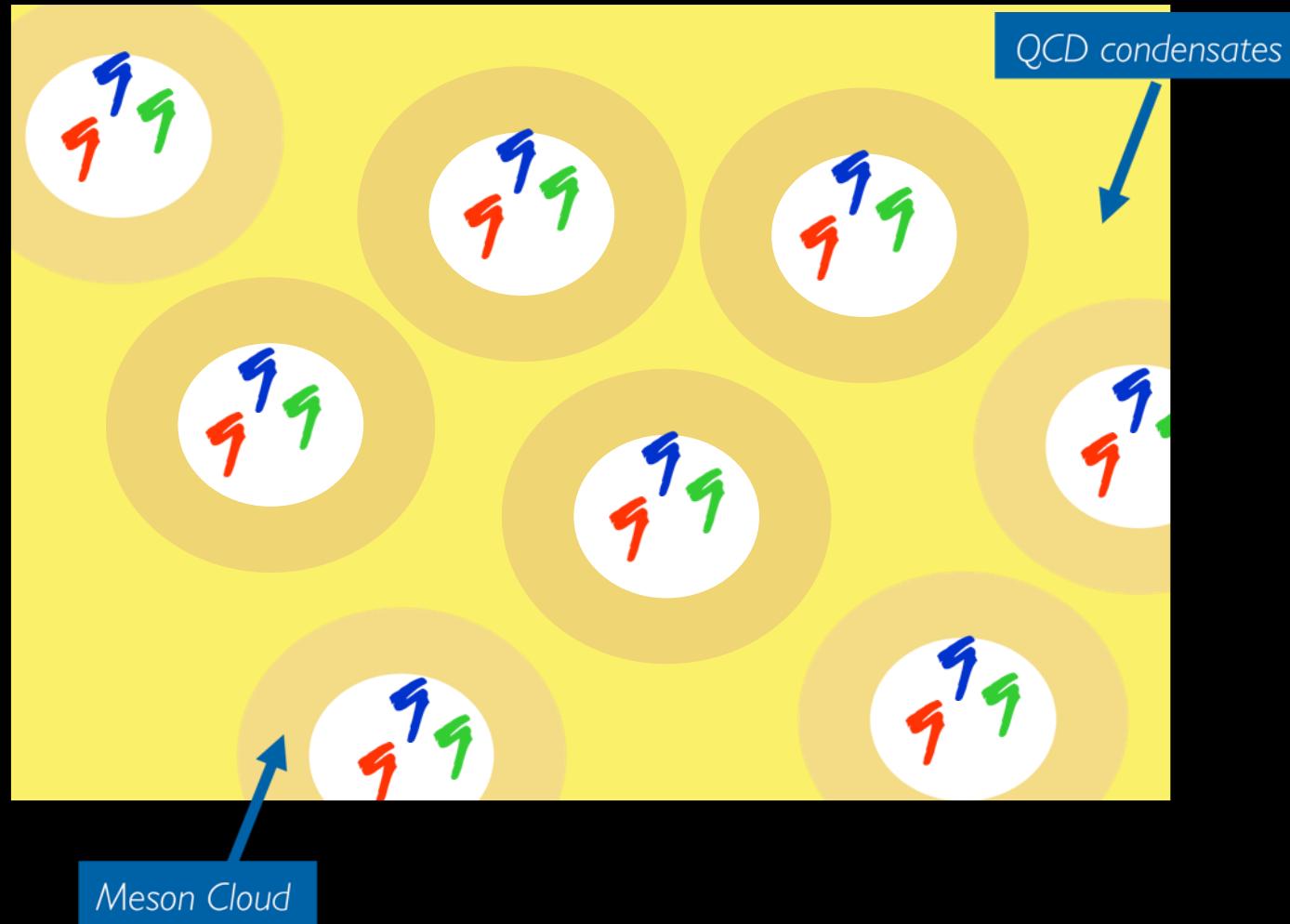


- Strong coupling of  $\gamma^*$  to Vector Meson  
→ Vector Meson Dominance model
- Observable: vector mesons ( $\rho, \omega, \phi$ )

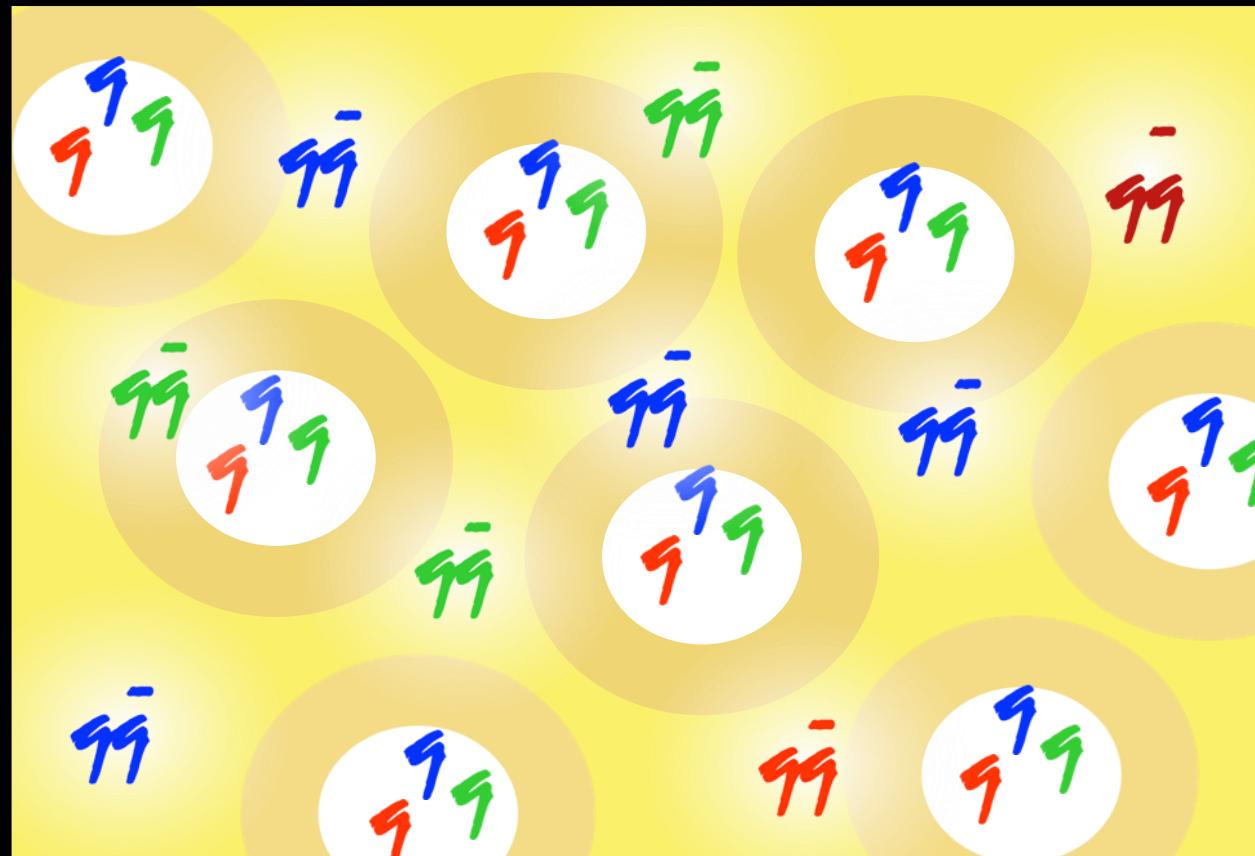
## Nucleon on Lattice QCD



# Swiss Cheese Picture of Nuclear Matter

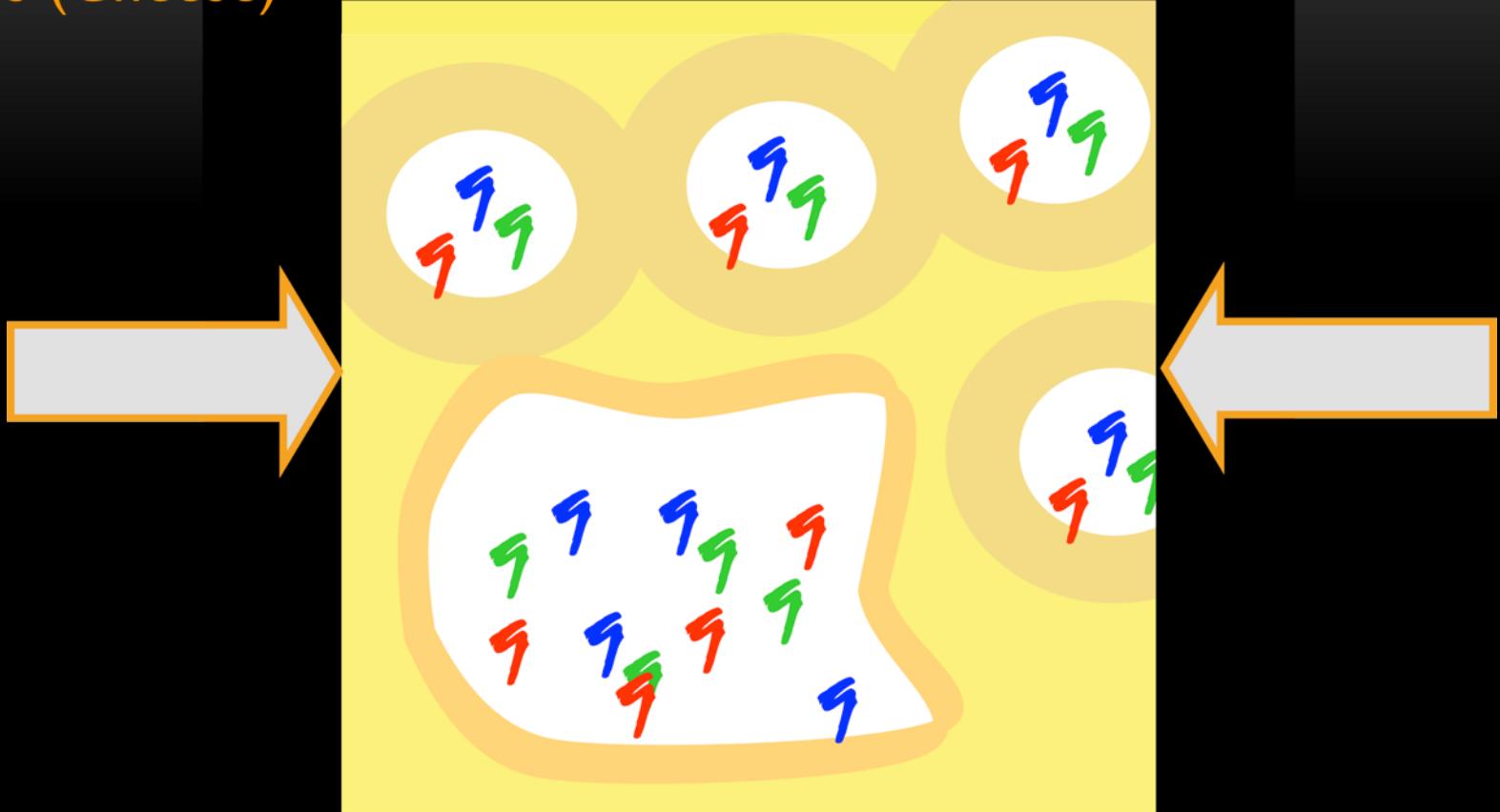


# Swiss (Cheese) Fondue



SSSSS

# More Swiss (Cheese) Raclette



# Dileptons as barometer

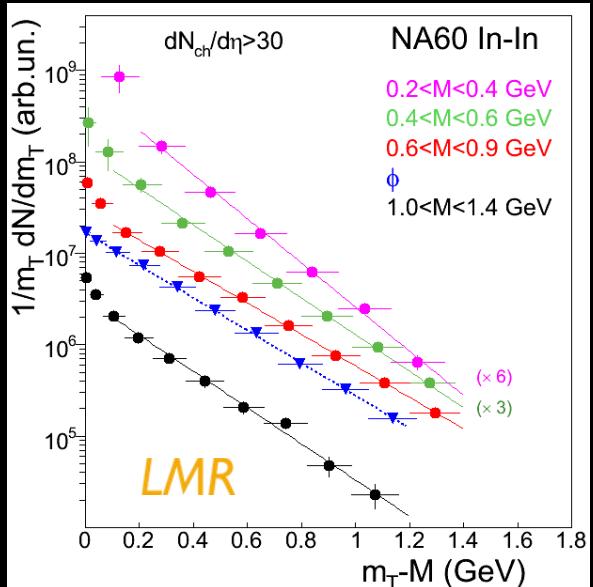


# Transverse mass distributions of excess

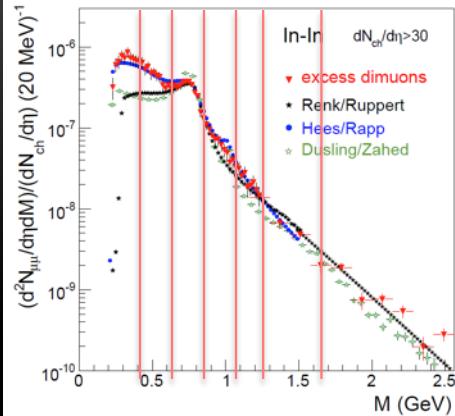
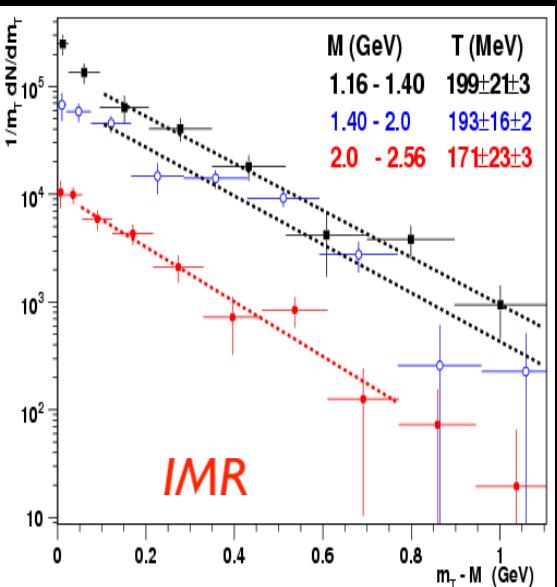
- For each bin of  $\mu^+\mu^-$  project transverse mass spectrum:  $m_T = (\vec{p}_T^2 + M^2)^{1/2}$



Phys. Rev. Lett. 100 (2008) 022302

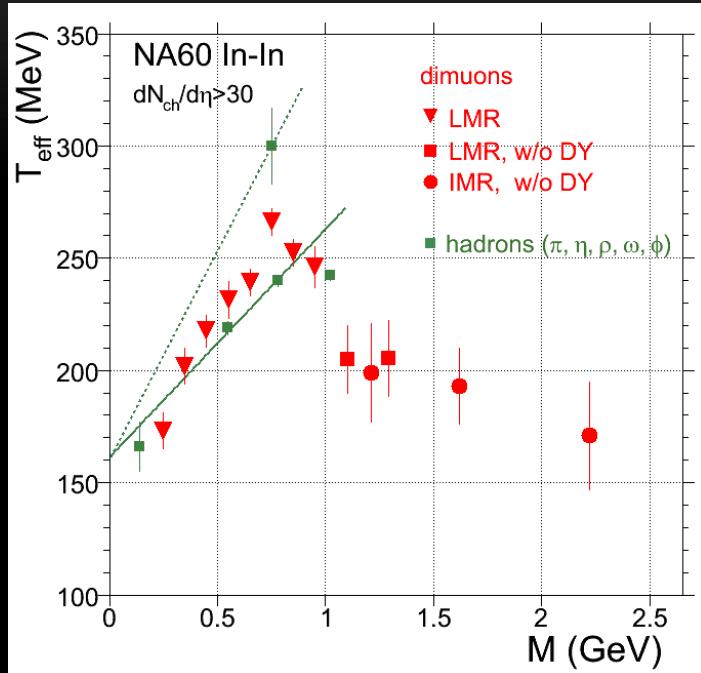


Eur. Phys. J. C 59 (2009) 607



- $m_T$  spectra exponential for  $m_T \cdot M > 0.1 \text{ GeV}; < 0.1 \text{ GeV} ??$
- Fit with  $1/m_T dN/dm_T \sim \exp(-m_T/T_{eff})$
- Extract  $T_{eff}$  aa a function of mass

# The rise and fall of $T_{\text{eff}}$ of thermal dimuons



- $M < 1 \text{ GeV}/c^2$ 
  - Strong, almost linear rise of  $T_{\text{eff}}$  with dimuon mass
  - Follows trend set by hadrons
  
- $M > 1 \text{ GeV}/c^2$ 
  - Drop of  $T_{\text{eff}}$  by  $\sim 50$  MeV
  - followed by an almost flat plateau

Phys. Rev. Lett. 100 (2008) 022302

What can we learn from  $m_T$  spectra?  
→ Radial Flow  
→ Origin of dileptons

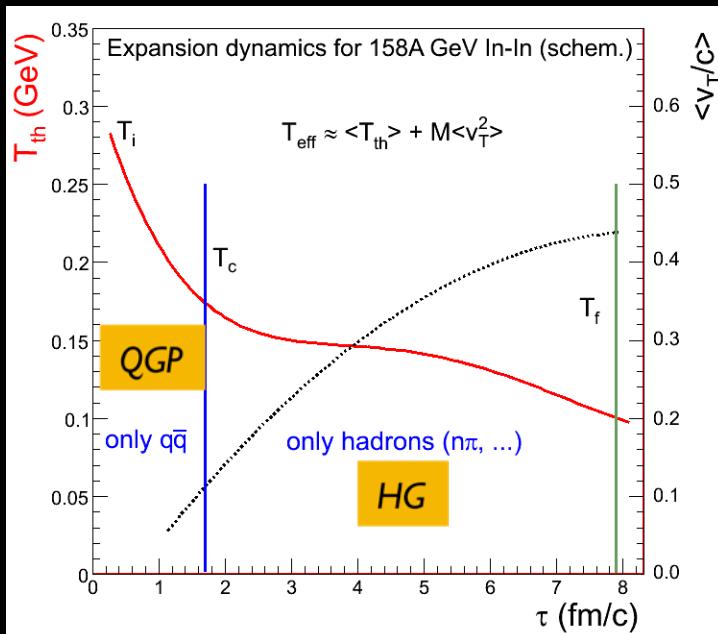
# Interpretation of the dilepton $m_T$ ( $p_T$ ) spectra

$T$  - dependence of thermal distribution of "mother" hadrons/partons

$m$  - dependent collective radial flow ( $v_T$ ) of "mother" hadrons/partons

( $p_T$  - dependence of spectral function; dispersion relation)

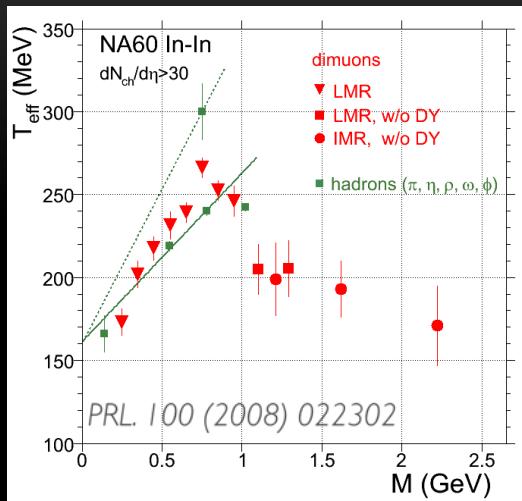
$$p_T = p_T^{th} + m v_T \quad \rightarrow \quad T_{eff} \sim T_f + \frac{1}{2} m \langle v_T \rangle^2$$



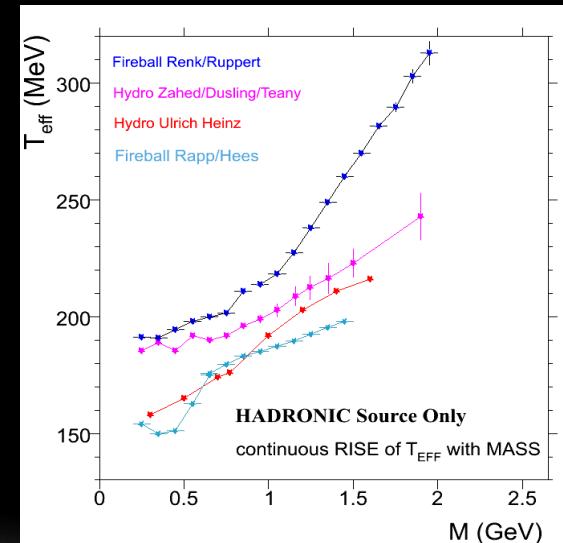
- Hadron  $p_T$  spectra: determined at  $T_{final}$  (restricted information)
- Dilepton  $p_T$  spectra: superposition from all fireball stages
  - early emission  $\rightarrow$  high  $T$ , low  $v_T$
  - late emission  $\rightarrow$  low  $T$ , high  $v_T$
- Final spectra from space-time folding over  $T$ - $v_T$  history from  $T_{initial} \rightarrow T_{final}$   
note: small flow in the QGP phase

→ Handle on emission region,  
i.e. nature of emitting source

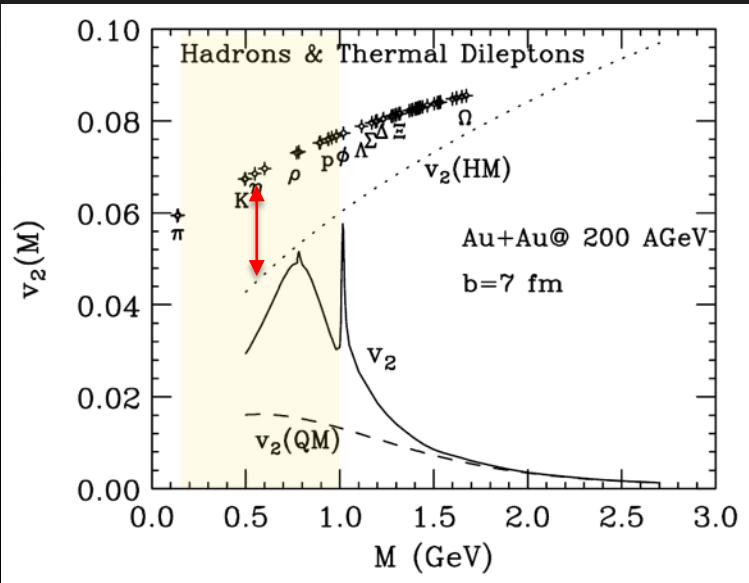
# Quantifying the average temperatures $\langle T_{th} \rangle$



- $M < 1 \text{ GeV}/c^2$ 
  - extrapolate  $T_{eff}$  to  $M=0$  (zero flow)
  - $\langle T_{th} \rangle = 130 - 140 < T_c = 170 \text{ (MeV)}$
  - *hadronic phase*
  
- $M > 1 \text{ GeV}/c^2$ 
  - $T_{eff}$  independent of mass, negligible flow
  - $\langle T_{th} \rangle \sim 200 \text{ MeV} > T_c = 170 \text{ (MeV)}$
  - *partonic phase* ( $T_{initial} \sim 250 \text{ MeV}$ )



# Azimuthal anisotropy of virtual photons



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

- Very clean tool to diagnose the collective expansion dynamics, i.e. origin of the electromagnetic emission source
- $v_2$  vs  $T_{\text{eff}}$ :  $T_{\text{eff}}$  is superposition of  $T$  and  $v_T$
- $M < 1 \text{ GeV}/c^2$ :  $v_2$  is large  
→ late emissions → hadronic matter
- $M > 1 \text{ GeV}/c^2$ :  $v_2$  is small  
→ early emission → partonic matter

So far:

- STAR  $v_2$  of inclusive  $e^+e^-$  (not of excess  $e^+e^-$ )
- HADES  $v_2$  of excess radiation (coming soon)