OVERVIEW OF IN-MEDIUM MASS MODIFICATION RESULTS FROM RHIC, LHC AND LOWER ENERGIES

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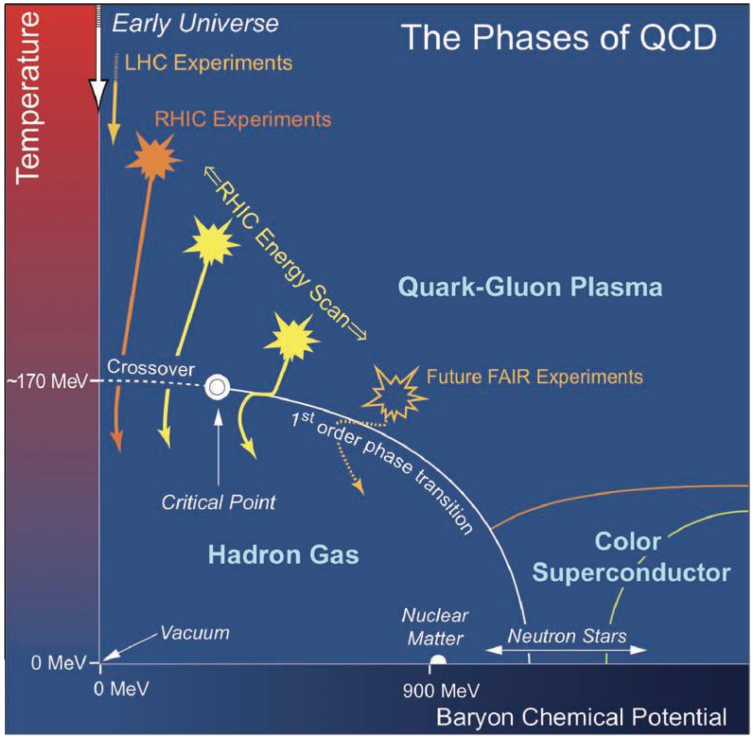
Outline

- Introduction
  - QCD phase diagram
  - The role of dileptons
  - Experimental framework
  - The reference systems
- The overview of the experimental results
  - STAR
  - PHENIX
  - ALICE
  - HADES
- Comparison with the models
- Summary and outlook

Different states of matter

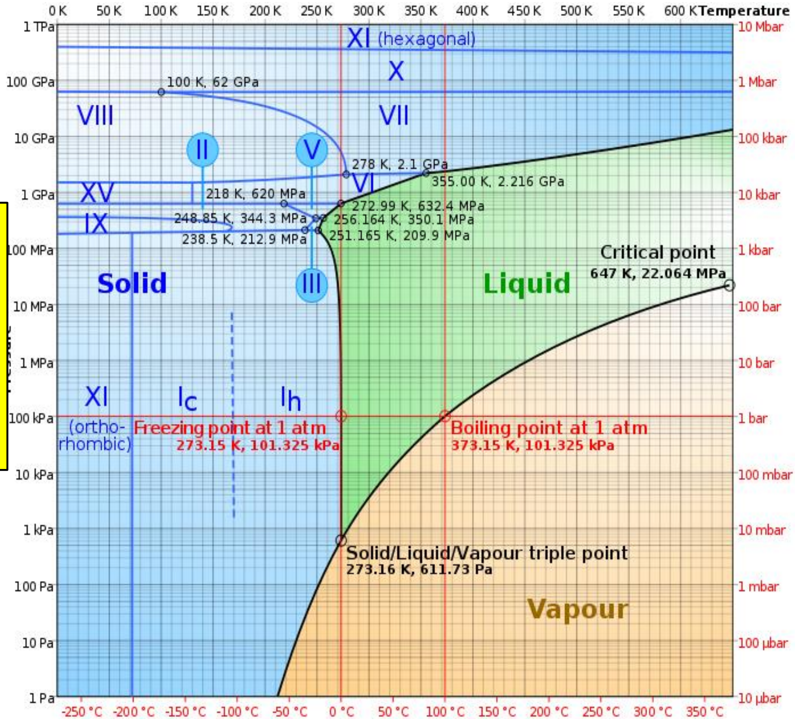
QCD phase-diagram



Temperature →

Baryon-chemical potential →

Phase-diagram of water

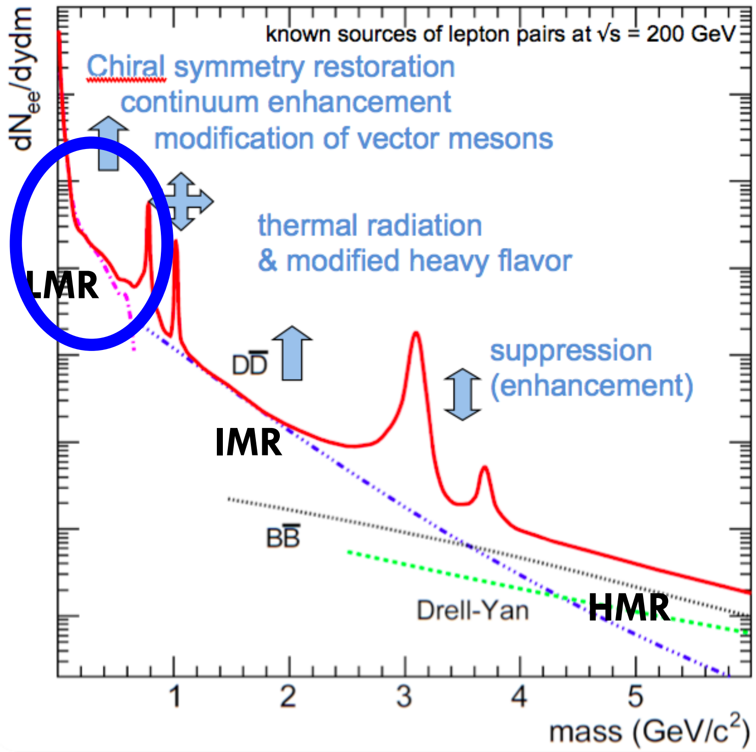


Pressure →

Temperature →

The role of dileptons

- **Dileptons pairs: dielectons (e^+e^-) and dimuons ($\mu^+\mu^-$)**
  - Emitted throughout the space-time evolution of the collision
  - Electomagentic probes, not sensitive strong interactions
  - Probe the medium at the time of their creation
- **Modifications to the dilepton spectrum due to the QCD phase transition:**
  - Change in the spectral shape of light vector mesons linked to chiral symmetry restoration
  - Continuum enhancement related to QGP thermal radiation
  - Medium effects on hard probes - Heavy flavor energy loss



Known sources of dielectrons at RHIC:

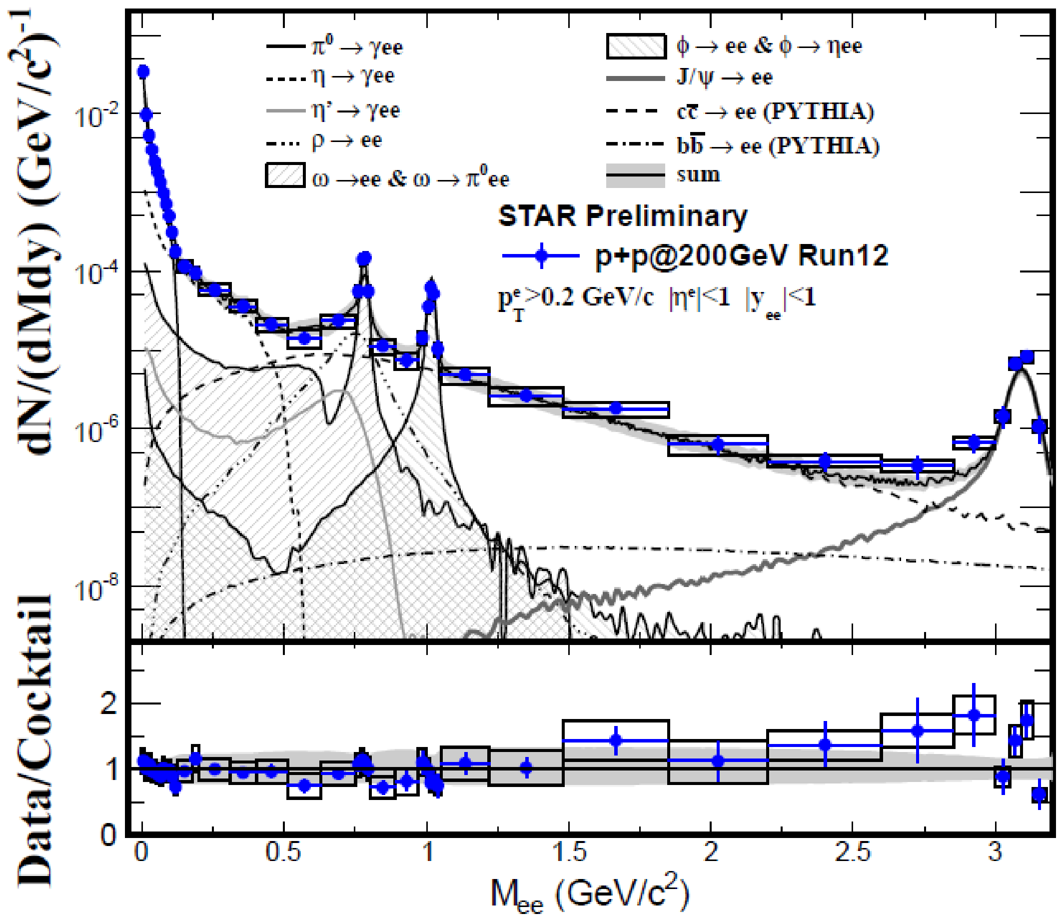
- Dalitz decays of π^0, η, η', ω
- Direct decays of ρ, ω, ϕ
- Charm (beauty) production
- Drell-Yan

Experimental framework

- Collider experiments
(with the ability to measure dielectrons in heavy ion collisions):
  - **PHENIX** and **STAR** at **RHIC**: study of various collisions systems (Au+Au, Cu+Cu, U+U) at $\sqrt{s_{NN}}$ ranging from 19.6 to 200 GeV
  - **ALICE** at **LHC** (Pb+Pb collisions at $\sqrt{s_{NN}}$ 2.76 and 5.02 TeV)
  - Major issues: low S/B typically (1/1000-1/200) and alarge hadron contamination
- Other experiments:
  - CERES, NA60, HADES (lower energy)
  - FAIR, NICA, J-Parc (future)
- To determine QGP properties need <u>reference systems</u>:
  - p+p collisions (base-line for vacuum properties)
  - d+Au, p+Pb (base-line for cold-nuclear matter effects)
  - Hadronic cocktail (simulated contributions of all known sources at a given energy and collision system)

The reference systems: p+p collisions

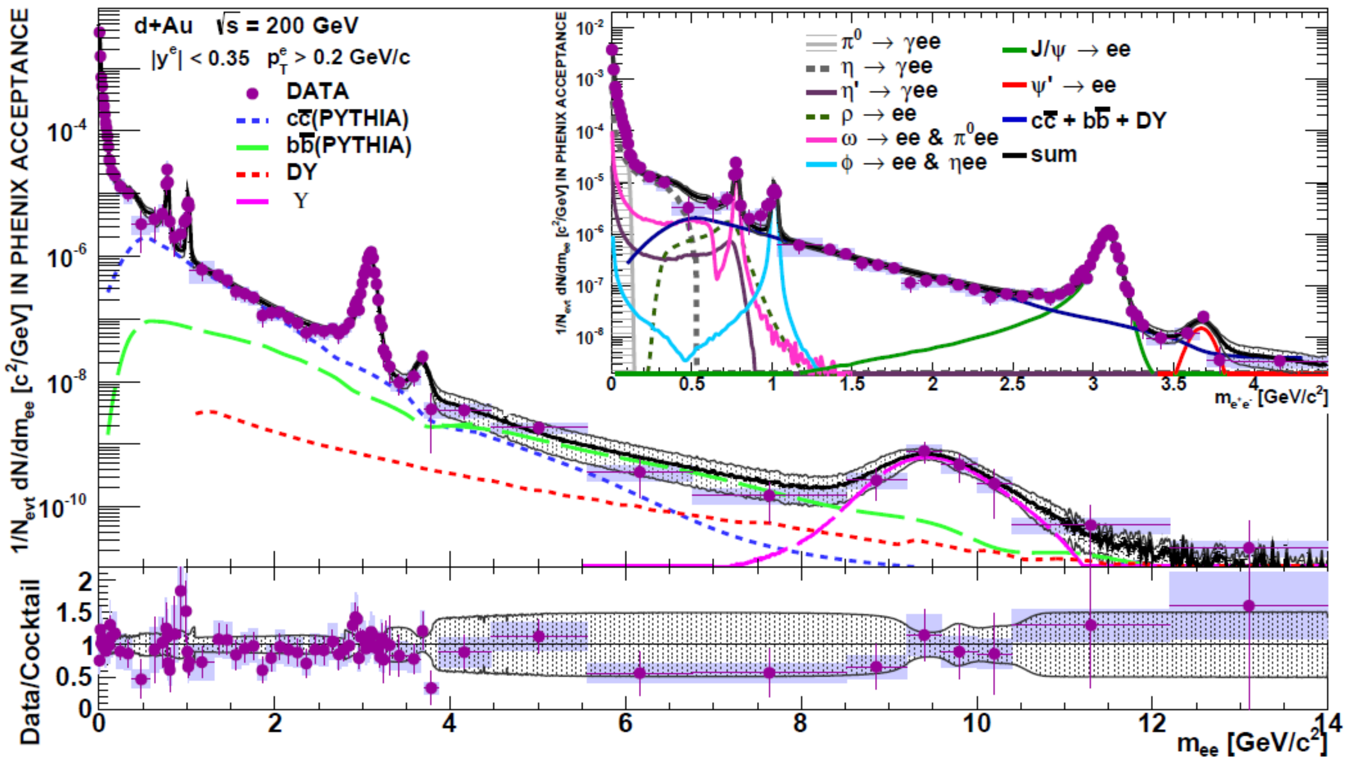
- **STAR** data from p+p collisions at $\sqrt{s}$=200 GeV (example)
- Data consistent with the cocktail → no excess suppression at any invariant mass
- Proof of principle for understanding of both the cocktail and the data



The reference systems: d+Au collisions

- **PHENIX** d+Au collisions at $\sqrt{s_{NN}}$=200 GeV (example)

PHENIX PRC 91, 014907 (2015)



Data consistent with the cocktail within the uncertainties → no excess or suppression at any invariant mass → no considerable cold nuclear matter effect in dielectron channel

The hadronic cocktail (PHENIX)

- Hadron decays simulated in EXODUS
- Fit π^0 and π$^\pm$ data p+p or Au+Au to modified Haggedorn function:

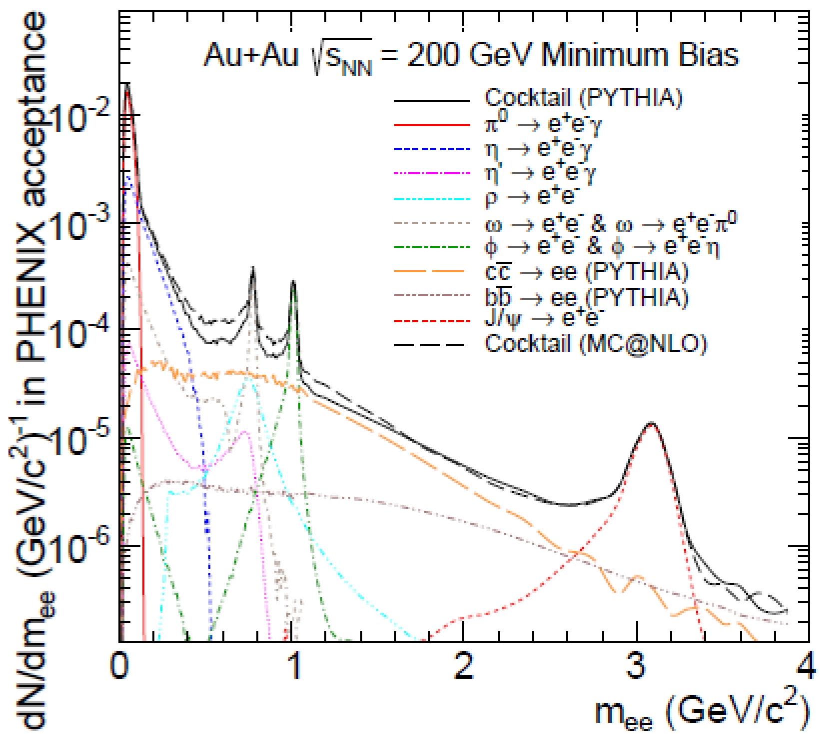
$$E\frac{d^3}{dp^3} = \frac{A}{(e^{-(ap_T+bp_T^2)} + p_T/p_0)^n}$$

- for other mesons η, ω, ρ, φ, J/Ψ etc. use pion parametrization and replace:

$$p_T \to \sqrt{p_T^2 + m^2 - m_{\pi^0}^2}$$

- The absolute normalization of each meson provided by meson to π^0 ratio at high p_T
- Open heavy flavor (c,b) simulated with MC@NLO and PYTHIA
- The cocktail filtered through detector acceptance and smeared with detector resolution
- Normalization
  - In m_{ee}<0.1 GeV/c^2 and p_T/m_{ee}>5
  - Normalize to measured $\pi^0 + \eta$ + direct γ

PHENIX PRC 93, 014904 (2016)



Uncertainty in the charm cross-section and shape - PHENIX PRC 91, 014907 (2015)

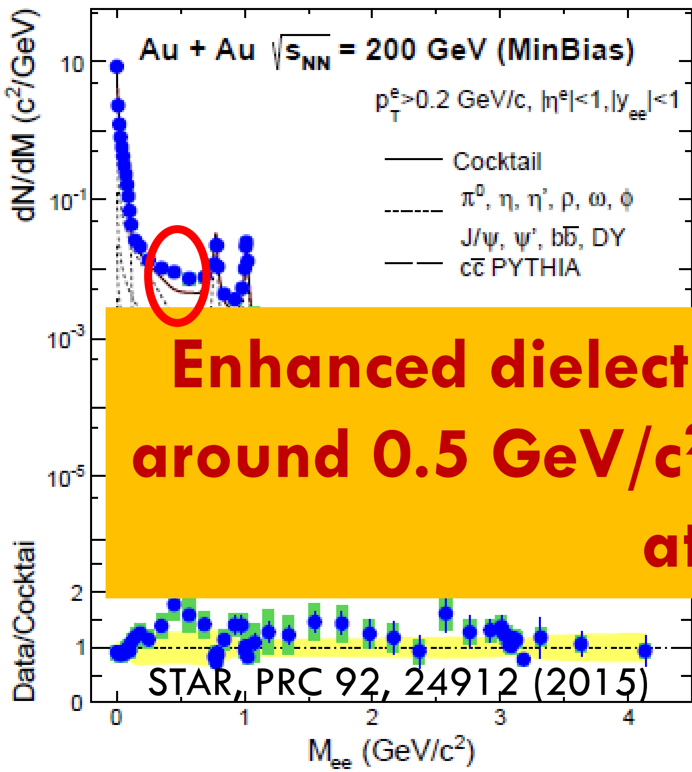
→ **PYTHIA cocktail** and **MC@NLO cocktail**

Experimental results

Dielectron results from STAR

Invariant mass spectra from:

- Au+Au @20-200 GeV
- U+U @193 GeV



Enhanced dielectron pr
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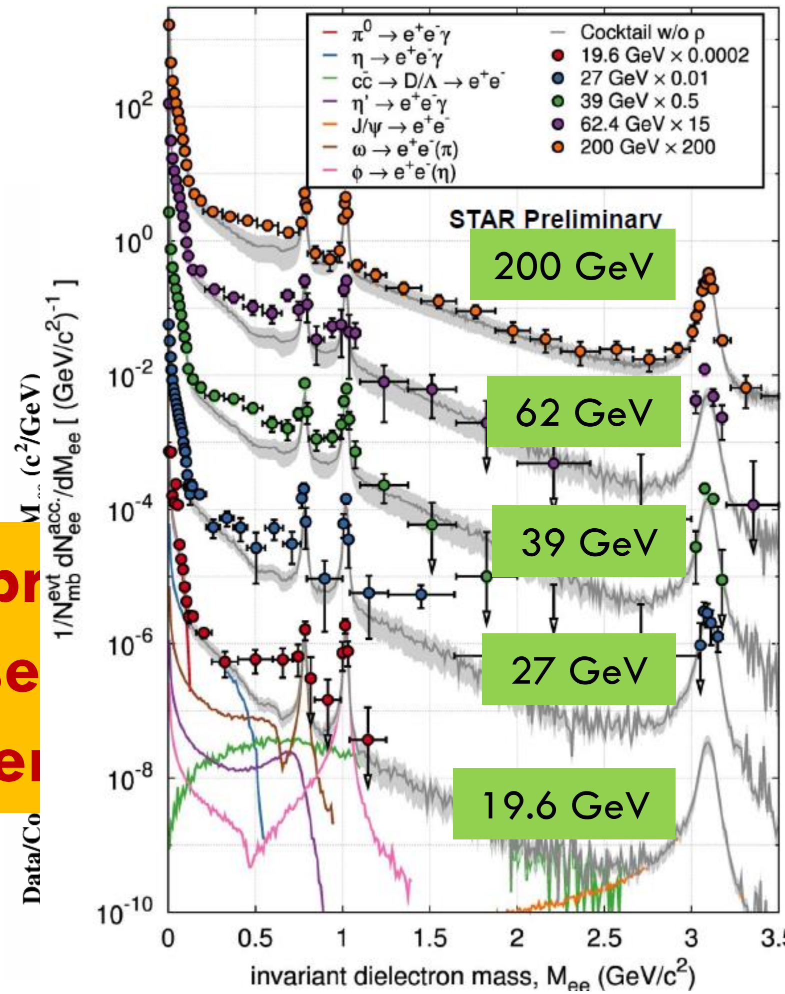
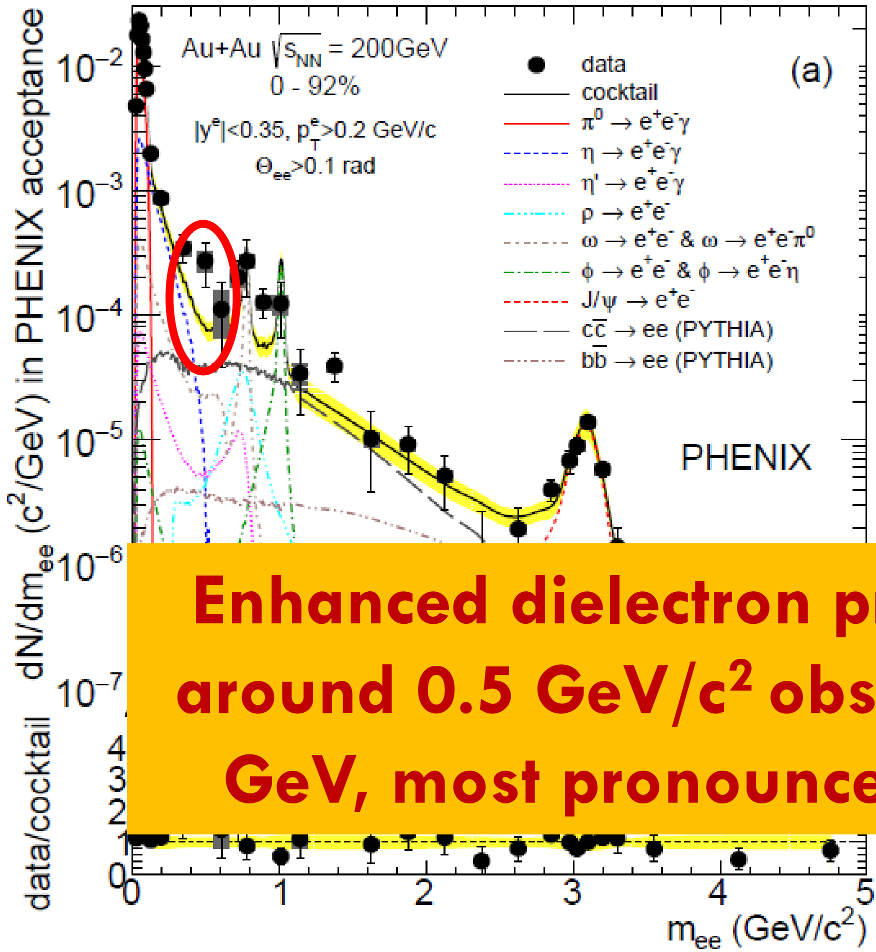


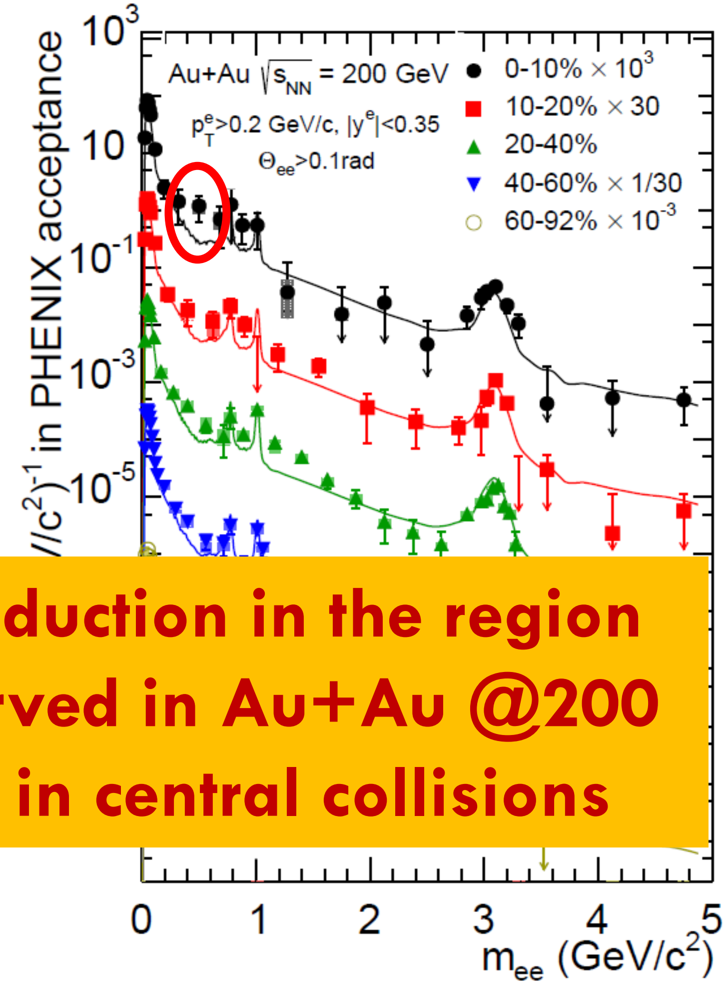
Dielectron results from PHENIX

Minimum bias



PHENIX PRC 93, 014904 (2016)

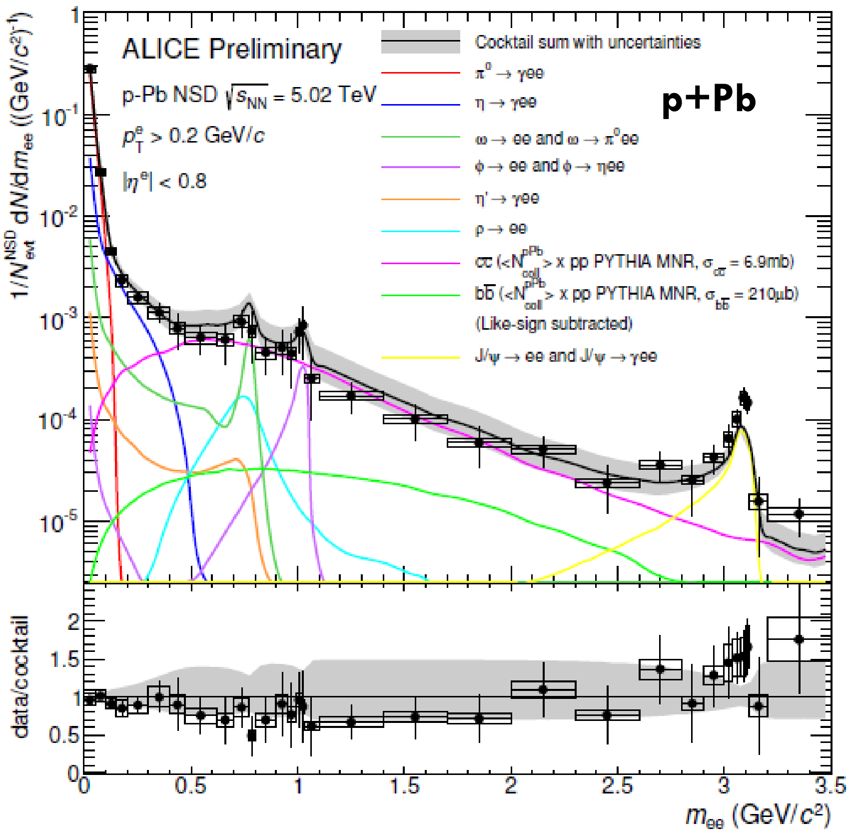
Centrality dependence



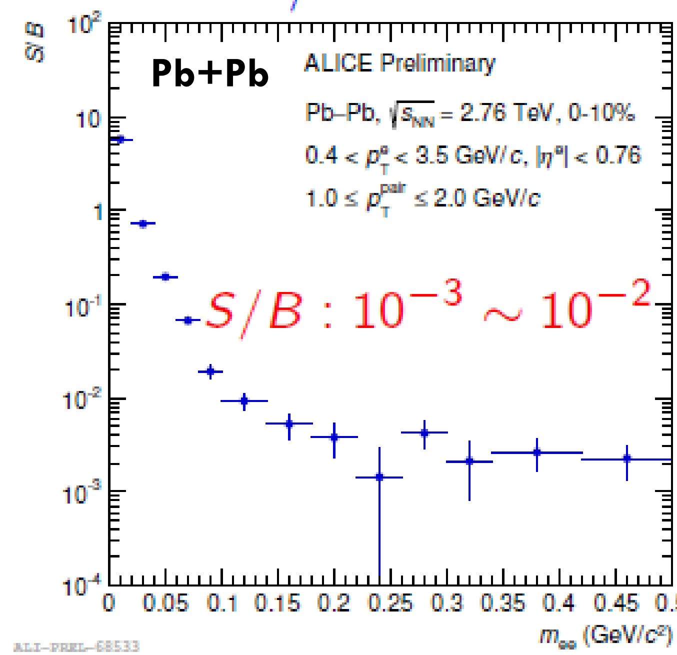
Enhanced dielectron production in the region around 0.5 GeV/c^2 observed in Au+Au @200 GeV, most pronounced in central collisions

Dielectron measurements from ALICE

- Preliminary results in p+p and p+Pb
- In Pb+Pb very low S/B and high hadron contamination prevent precise signal extraction

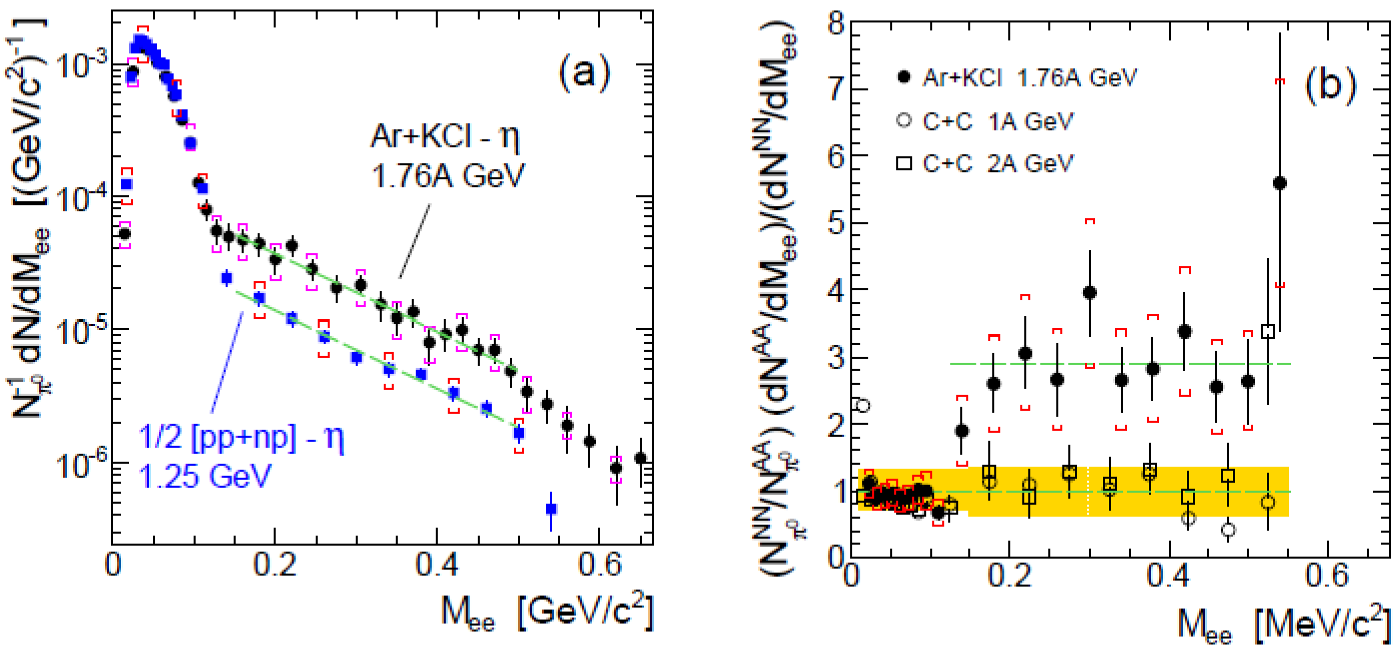


S/B ratio



Recent results at lower energies

- Results from HADES@GSI
  - Ar+KCl @ 1.76 AGeV, **PRC 84 014902 (2011)**



  - Dielectron excess in Ar+KCl x2-3 larger than in C+C collisions

Theoretical models

Models on the market

- **Macroscopic effective many-body theory models.** E.g. model originally developed by ***Rapp and Wambach,*** which uses an effective Lagrangian and many-body approach to calculate the EM spectral function.

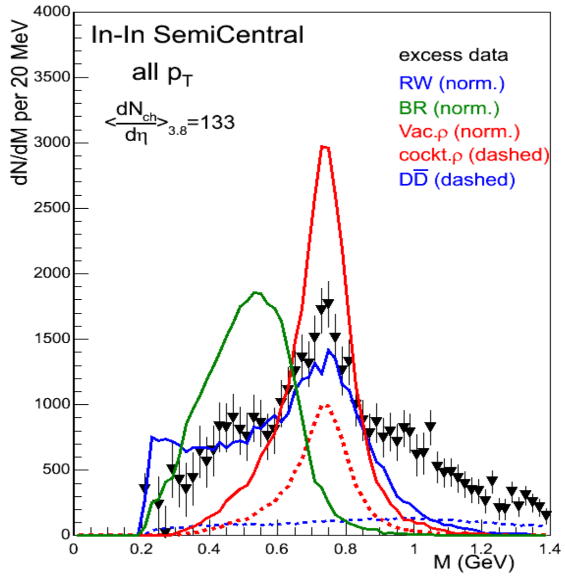
- **Microscopic transport dynamic models.** E.g. Parton-Hadron String Dynamic (PHSD) or Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

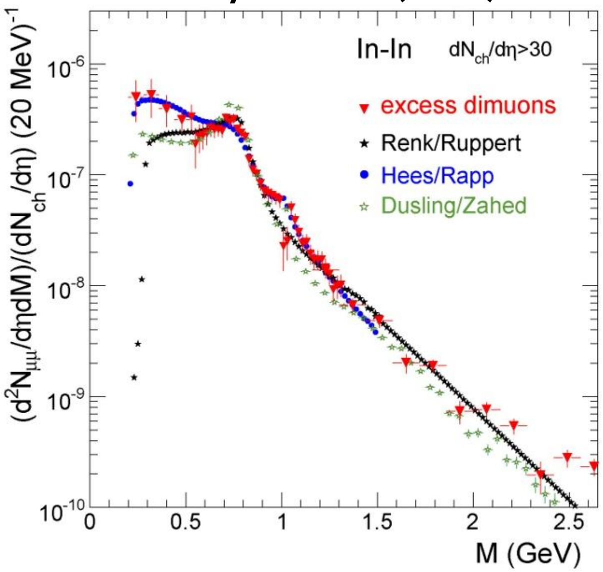
- **Coarse-graining models.** Dynamics based on microscopic description (e.g. UrQMD), with phase-space cells averaged over many events allow describing the dynamics in (macroscopic) terms of temperature and barion-chemical potential.

What happens with the ρ meson in medium?

- Results from NA60@SPS – high precision dimuons
  - In+In collisions 158 AGeV favor broadening and rule out dropping rho–mass scenario

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

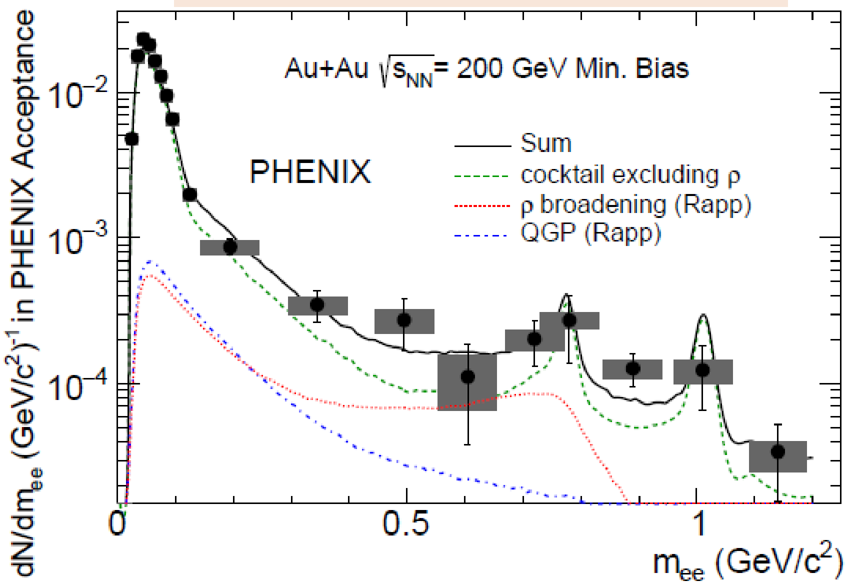


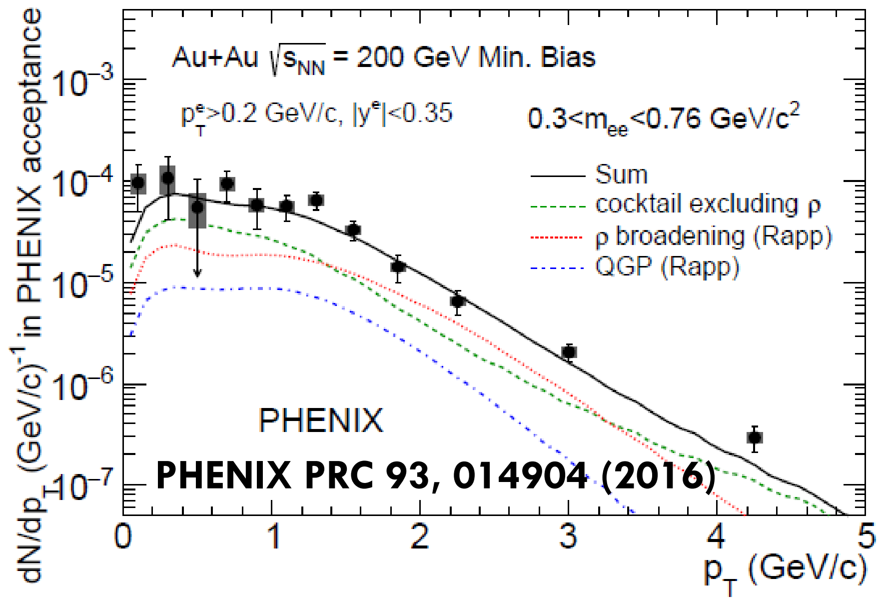


- Excess dimuons well explained by thermal radiation from the hadron gas ($\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$) in the LMR and thermal radiation from the QGP in the IMR

Comparison to models (PHENIX vs. Rapp)

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

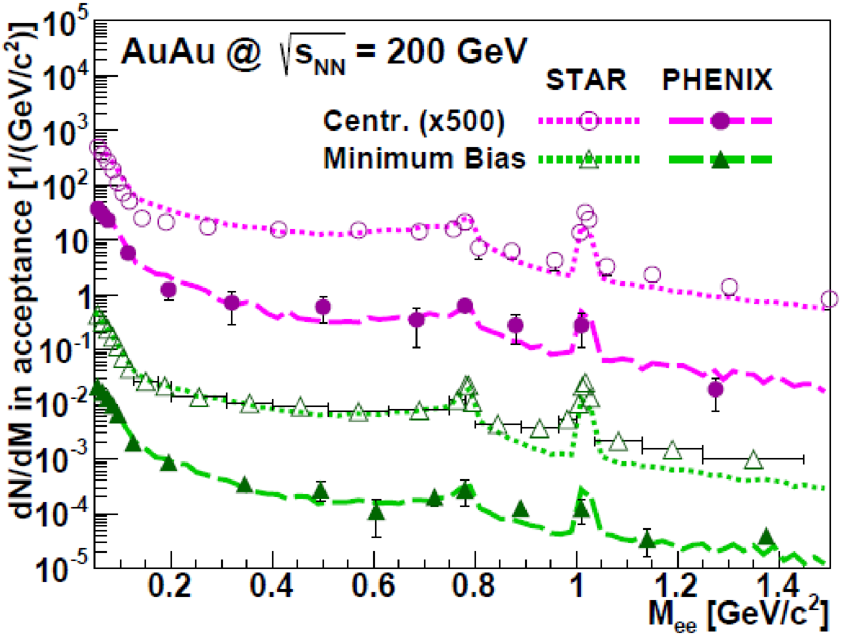


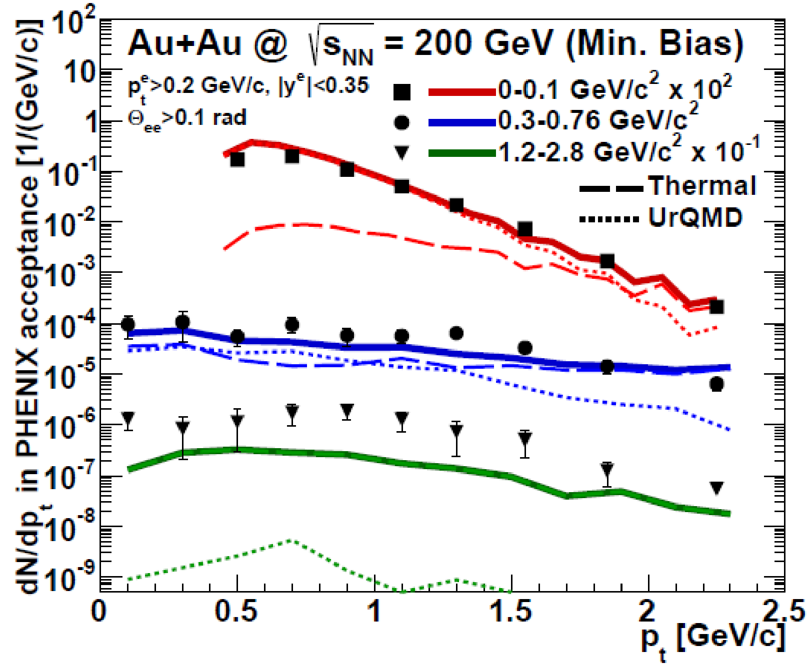


Dielectron excess well described by the model of ***R. Rapp:***
(Rapp and Wambach, EPJ C 6, 415 (1999); Rapp, PRC 63, 054907 (2001))

- In-medium ρ broadening due to scatter off baryons in hadrons gas as the system approaches the critical temperature
- A small contribution from the QGP thermal dielectron emission.

Comparison to models (PHENIX and STAR vs. Coarse-graining)

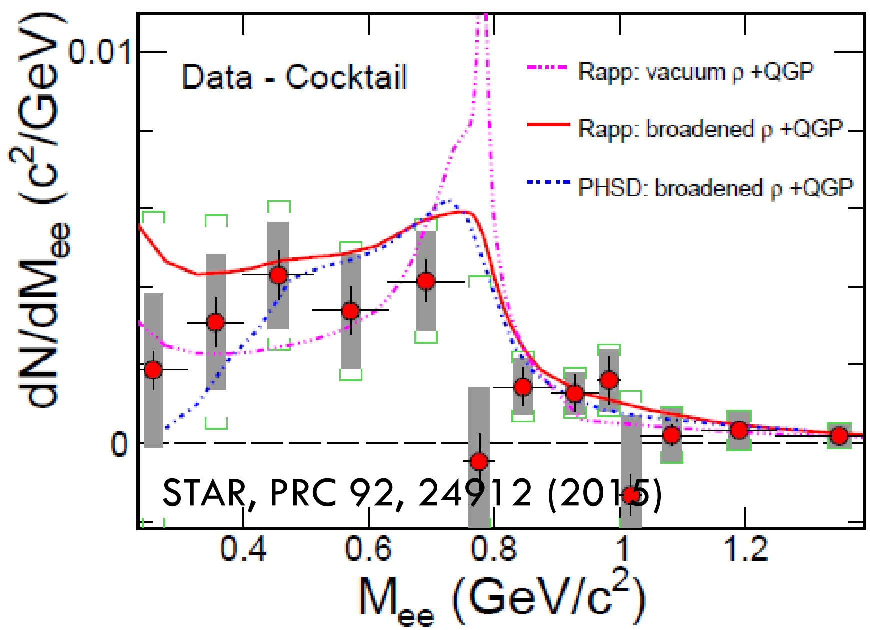


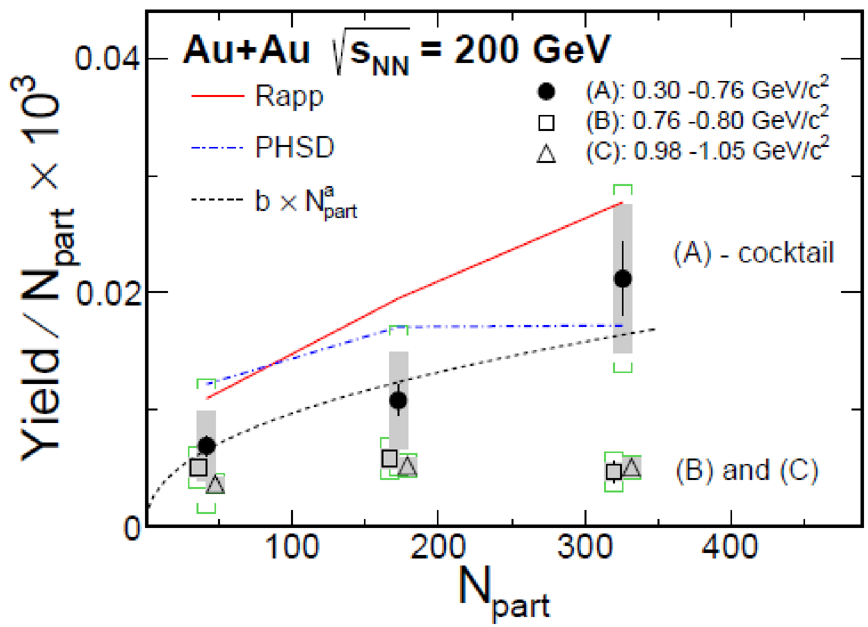


- Dielectron excess in the LMR well described by the ***coarse-graining model*** (Endres, van Hees, Bleicher PRC94 024912 (2016))
  - The curves include the hadronic contributions (the cocktail) from the UrQMD and the thermal dielectron emission
  - The data described well in invariant mass and transverse momentum

Comparison to models (STAR vs. Rapp and PHSD)

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

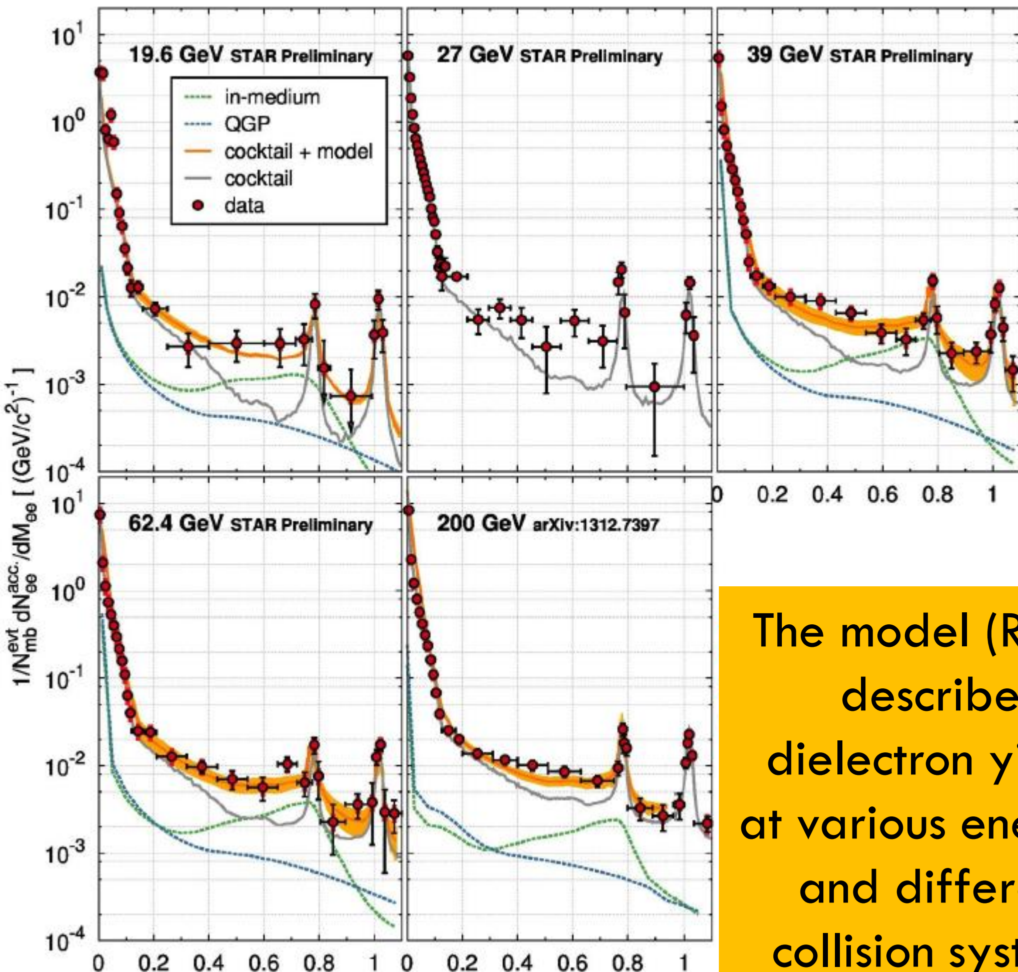




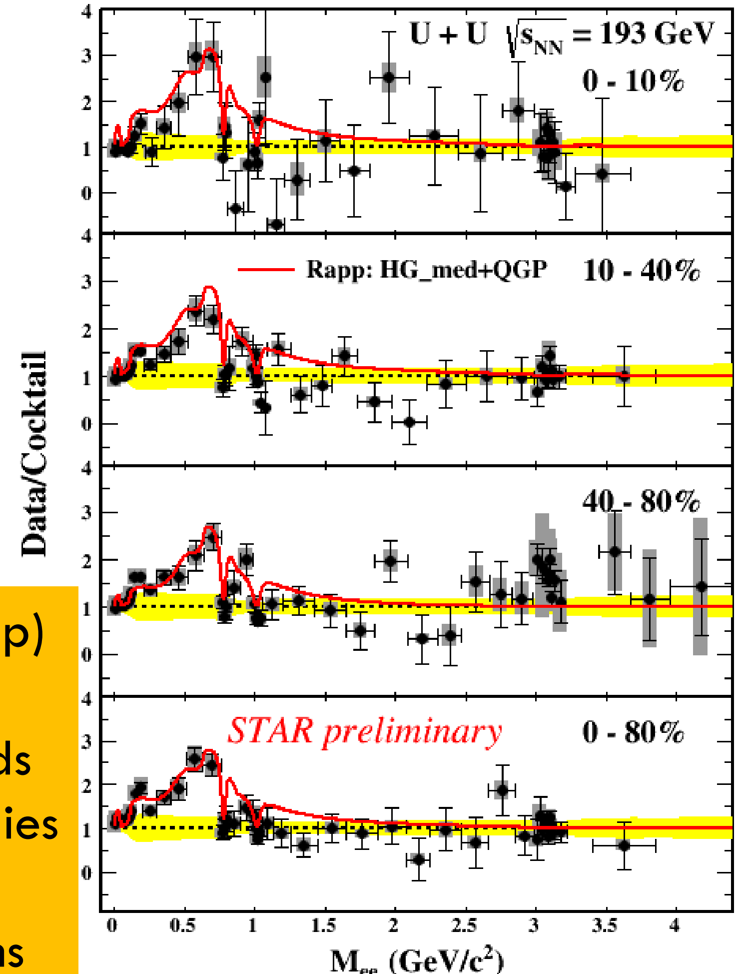
- Dielectron excess described within the experimental errors by the models ***Rapp*** (Rapp, PoS CPOD2013, 008 (2013)) and ***PHSD*** (Linnyk et al., PRC 85, 024910 (2012)):
  - The excess is due to in-medium ρ broadening
  - A small contribution from the QGP thermal dielectron emission.
  - Centrality dependence is well described

Comparison to models (STAR vs. Rapp)

Au+Au at $\sqrt{s_{NN}}$=20-200 GeV



U+U at $\sqrt{s_{NN}}$=193 GeV



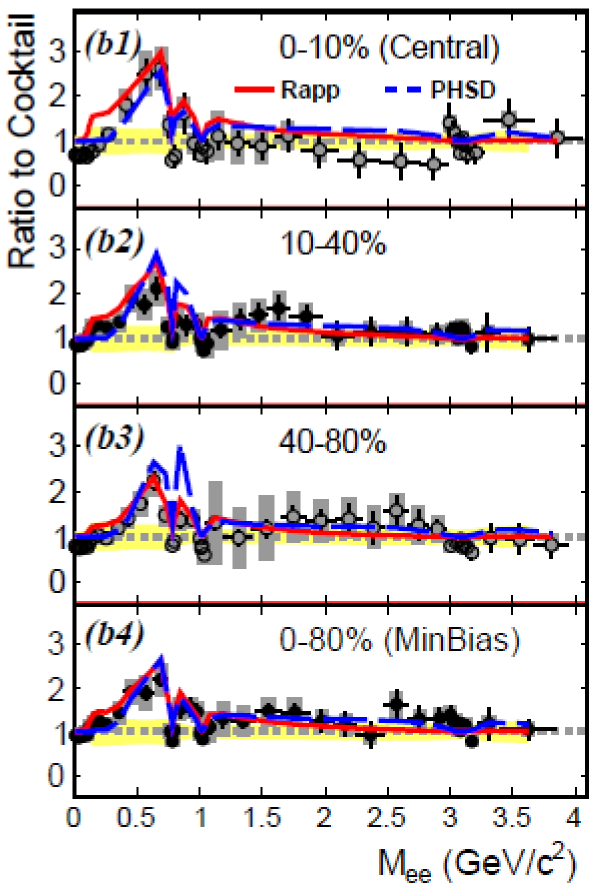
The model (Rapp) describes dielectron yields at various energies and different collision systems

Comparison to models (STAR vs. Rapp and PHSD)

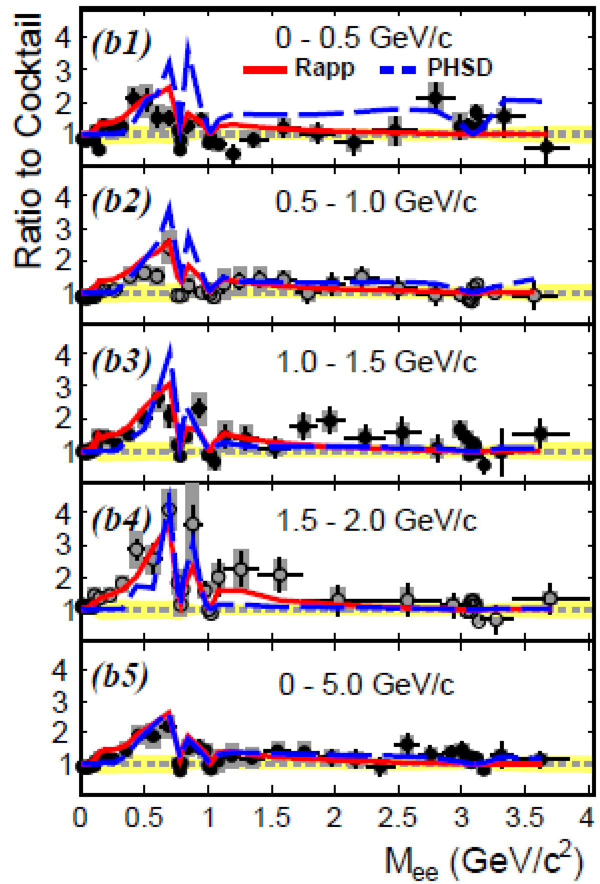
Au+Au at $\sqrt{s_{NN}}$=200 GeV

STAR, PRC 92, 24912 (2015)

Centrality dependence



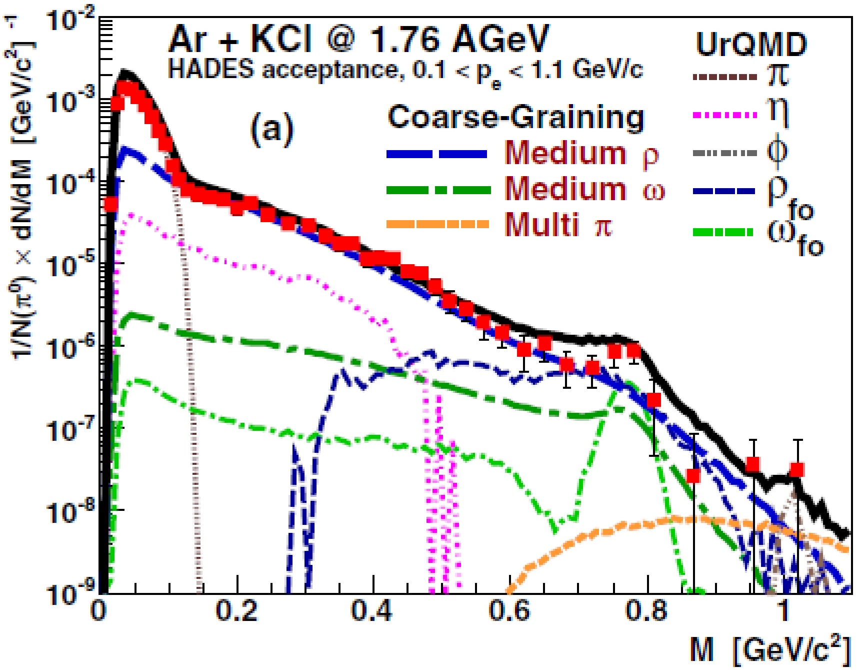
Momentum dependence



- Centrality and transverse momentum dependence well described
- Precision measurements needed to discriminate between the models

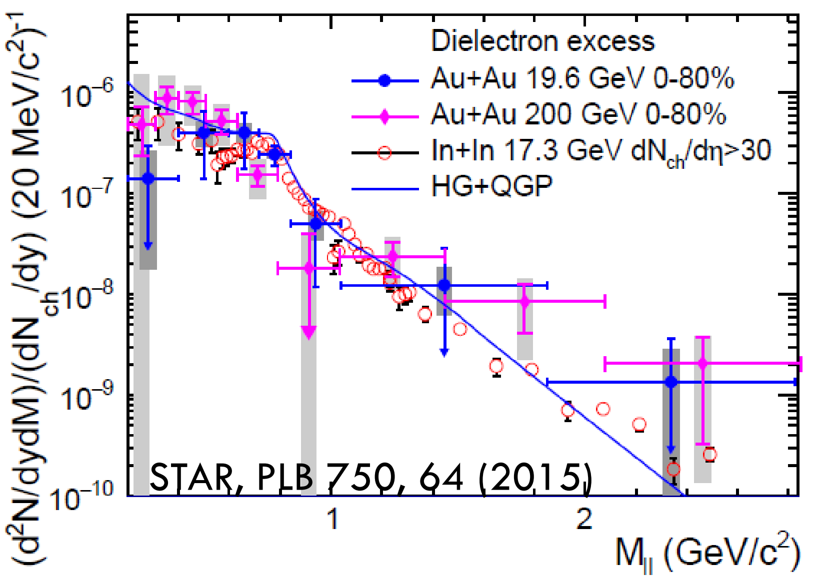
Comparison to models (HADES vs. coarse-graining model

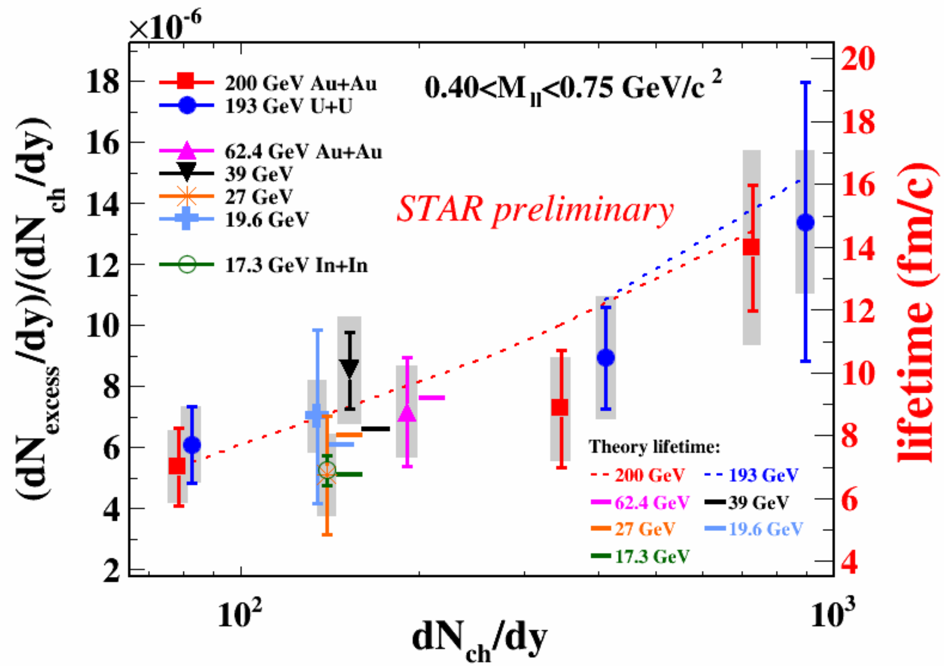
- Dielectrons from Ar+KCl @ 1.76 AGeV recorded by HADES **PRC 84 014902 (2011)**
- The coarse-graining model provides satisfactory descri-ption **PRC 92 014911 (2015)**
- The dominant contribution from broadened ρ meson in the presence of **baryonic matter**
- Non-negligible broadening of omega meson
- Slight overestimation of data at ρ pole-mass



Testing model on different data

- **Acceptance corrected results – comparison of different data possible**





→The same model describes the NA60 data and STAR data at different energies

Van Hees and Rapp, Nucl. Phys. A 806, 339 (2008); ***Rapp***, Adv. High Energy Phys. 2013 148253 (2013)

The model enables extraction of the fireball lifetime:

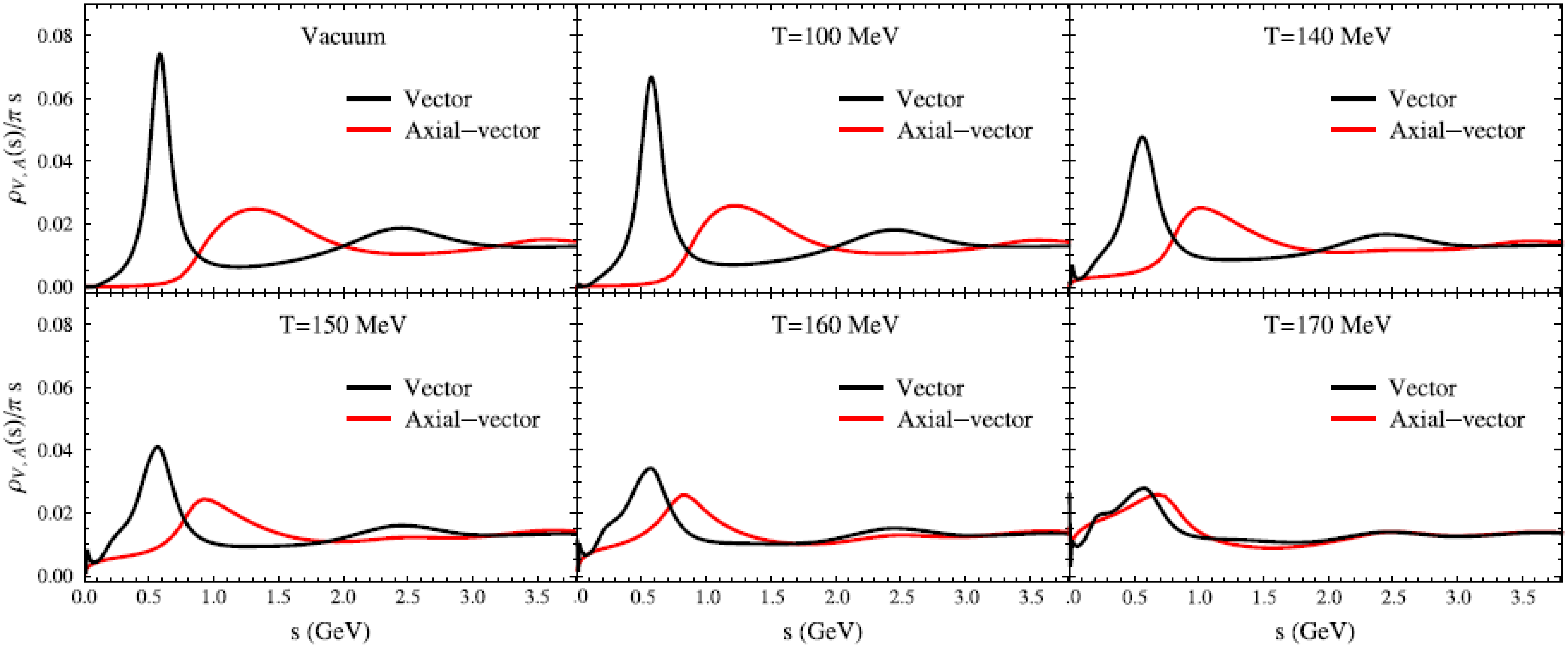
→ longer in central collisions

→ longer at higher energies

Emerging picture of the chiral symmetry restoration?

Suggested approach to chiral symmetry restoration: a_1 and ρ become degenarate as the system approaches critical temperature

Hohler and Rapp, PLB 731, 103 (2014)



Is there room for other approaches?

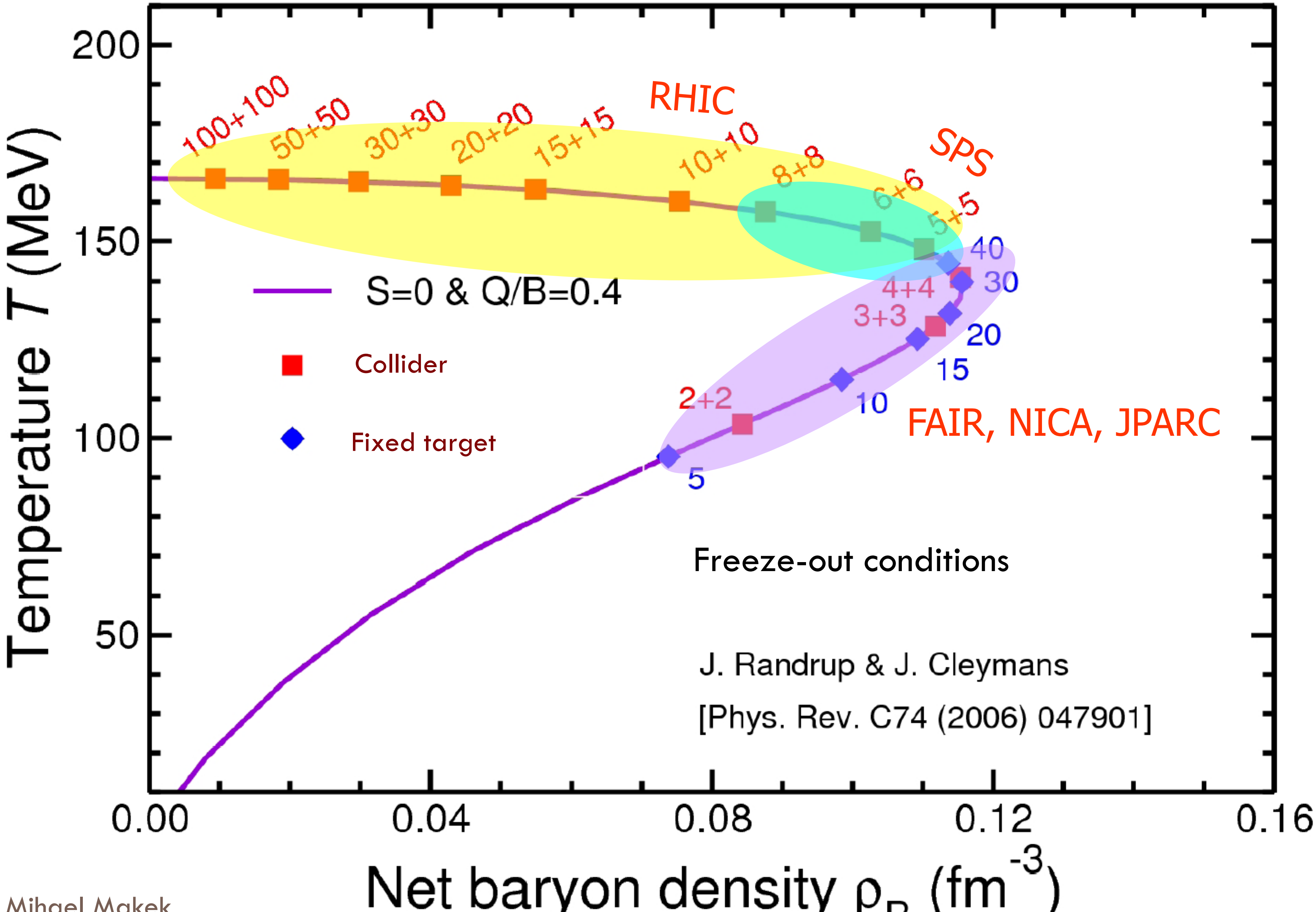
- Shown models are robust in explaining the enhancement, however…
- The uncertainties of experiments and models are quite large, do they leave room for other/additional inputs?
- A suggestion to explain (a part of) low mass dilepton excess (arXiv:1211.1166):
  - Drop of η' mass in nuclear medium?
  - Radial flow – boosts low p_T part of the spectrum?
  - η' chain decays to other mesons?
  - The best confirmation would require direct η' observation – challenging!

Summary and outlook

- PHENIX and STAR measure consistent dielectron excess yields 200 Au+Au; STAR also measures dielectron excess at lower energies and U+U collisions
- Dielectron in-medium excess observed at lower energies with NA60, CERES and HADES
- Various theoretical models reproduce the measurements across a wide energy range, they dominantly include broadening of the ρ spectral function as the system approaches the restoration of the chiral symmetry
- Outlook:
  - **Precise determination of the charm contribution**
  - **Higher precision to discriminate between the models**
  - **Lower energies to test the models at lower temperatures and higher baryon densities**
  - STAR upgrade and BES II (2018 -)
  - ALICE upgrade (2020 -)
  - MPD@NICA (2019?) and FAIR (2022?)
  - JPARC – Heavy ion program?
  - JPARC – precise measurement of the LVM spectral function in the nuclear matter

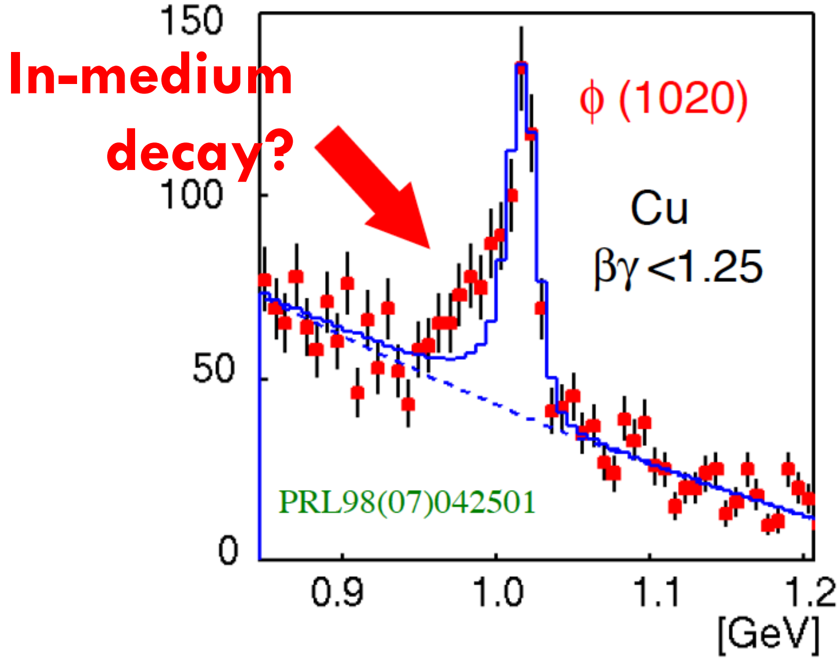
BACKUP

Temperature vs. net baryon density



JPARC–E16 experiment

- The goal: precise measurement of the LVM spectral function in nuclear matter
- KEK-PS result (R. Muto et al., PRL 98(2007) 042501)

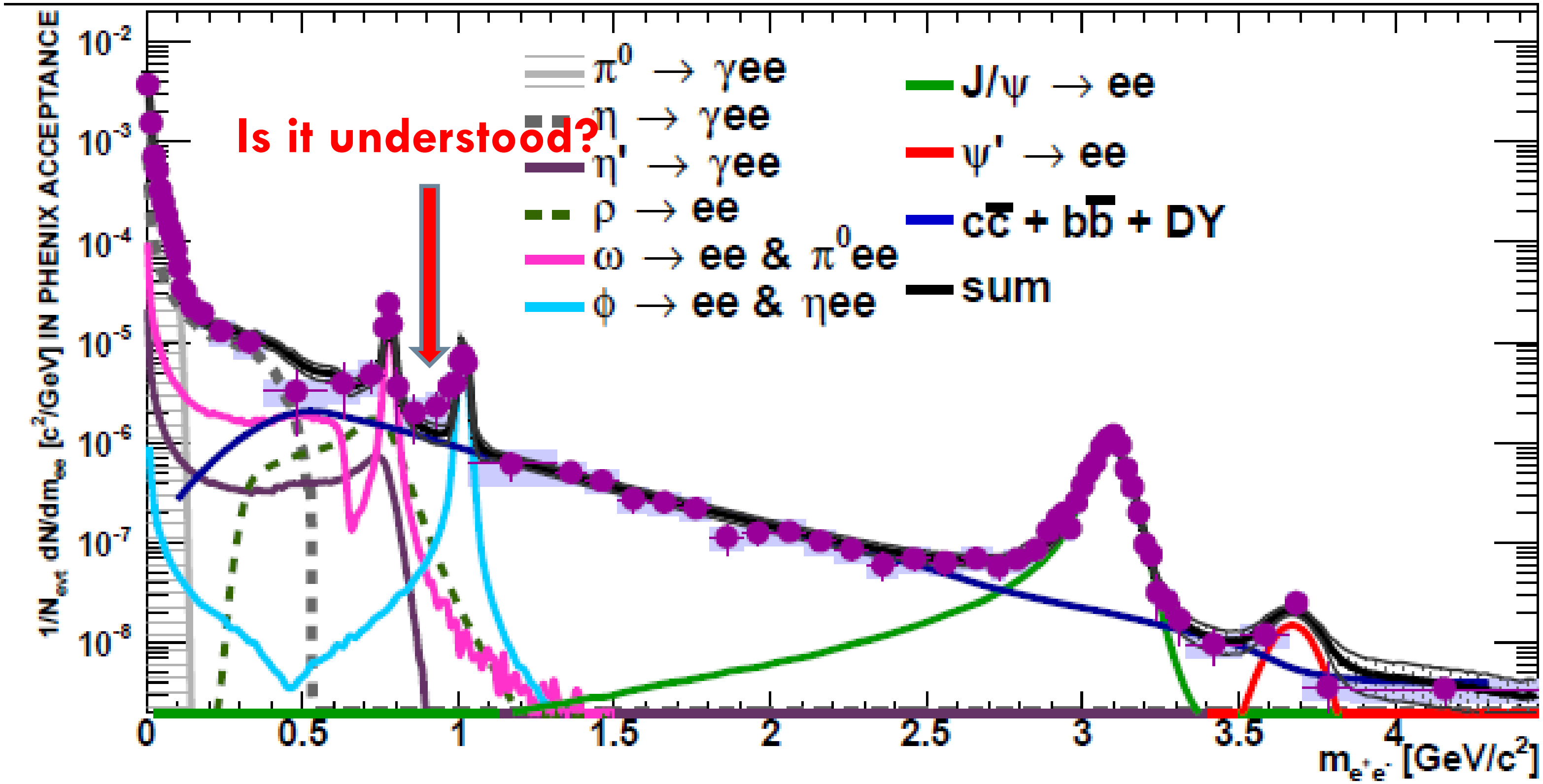


The proposed E16 experiment to:
- boost the statistics x100
- to double the resolution

→ Allow mass separation

In-medium ϕ from PHENIX

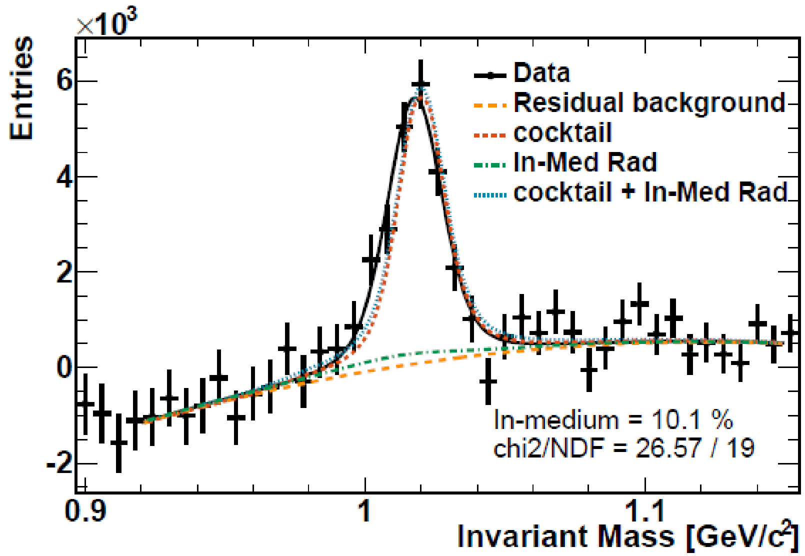
- ϕ->ee from d+Au collision at 200 GeV

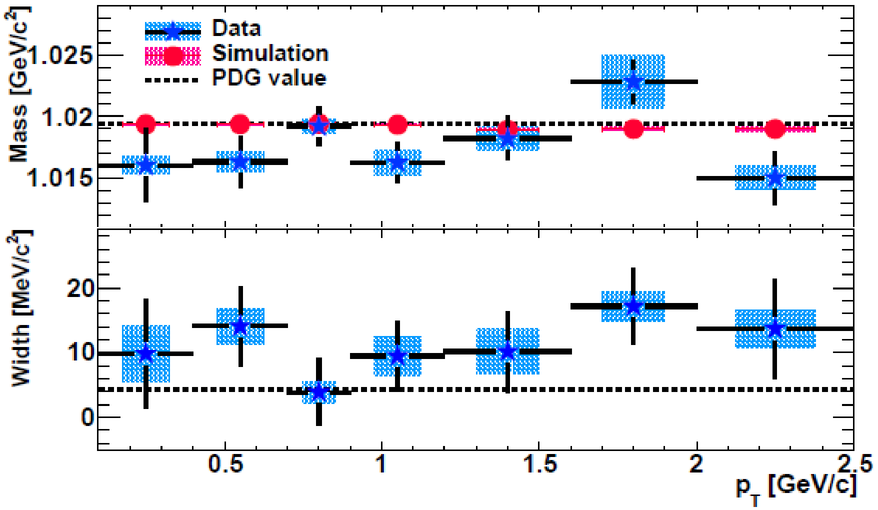


PHENIX PRC 91, 014907 (2015)

In-medium ϕ from STAR

- ϕ->ee in Au+Au collisions at 200 GeV
- Hints of spectral shape modification?





arXiv:1503.04217

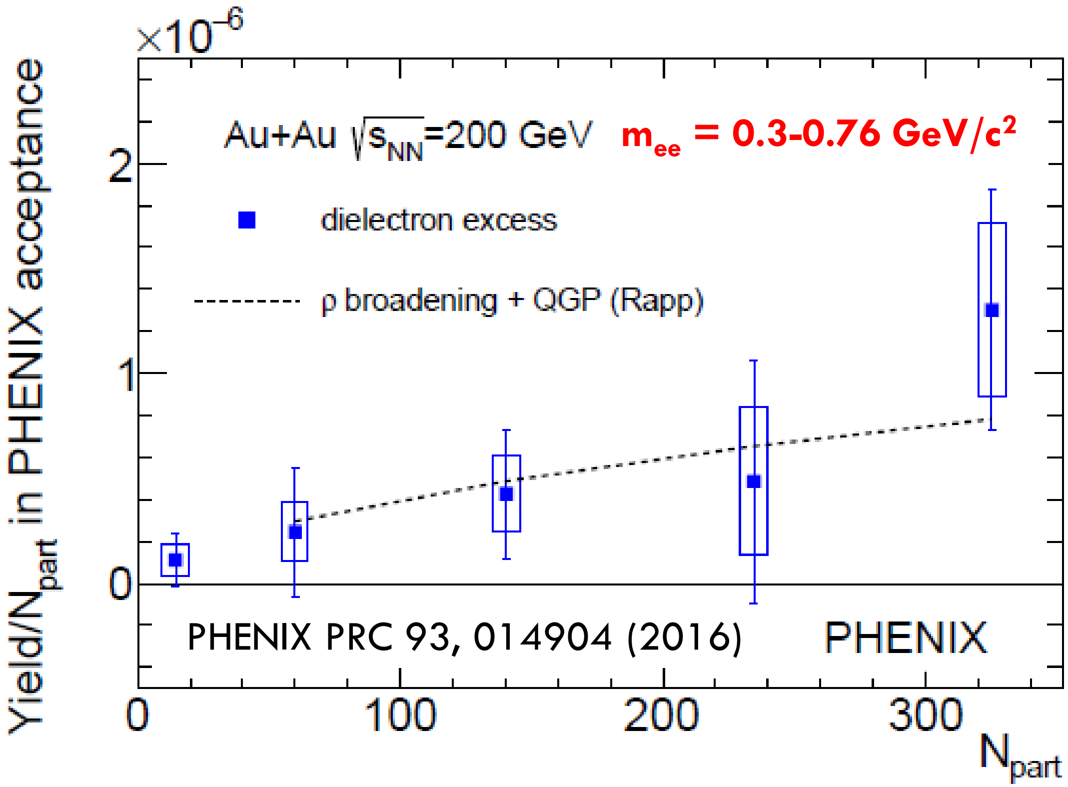
Comparison to model (PHENIX): centrality dependence

- Centrality dependence of the Rapp model consistent with the data

Model yield scales with:

$(dN_{ch}/dy)^{1.45}$

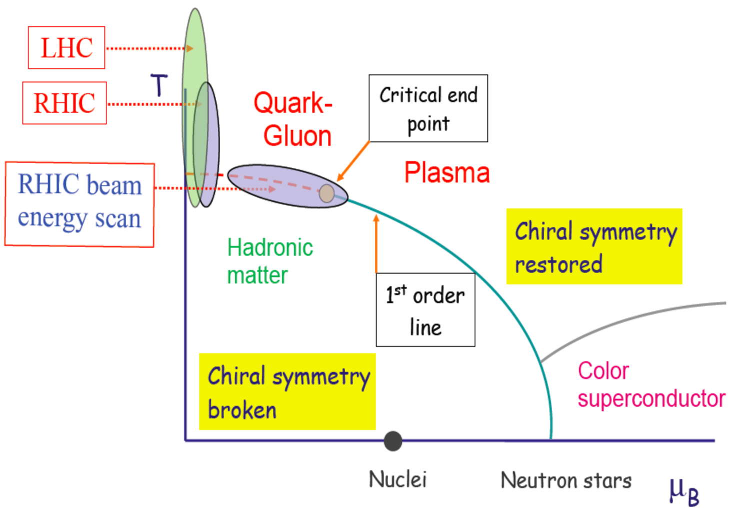
(R. Rapp)

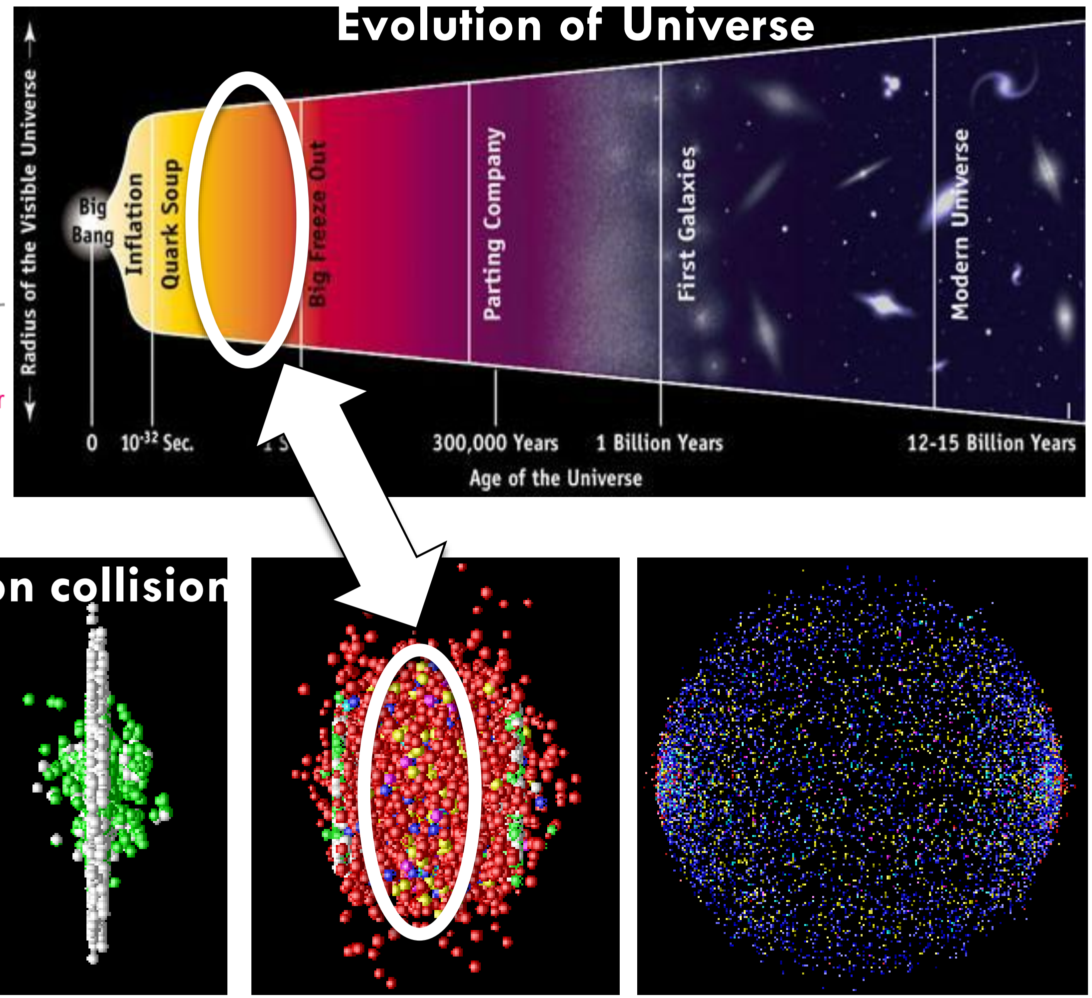


More about Rapp's model

- In the LMR the spectral function is dominated by vector mesons, ρ in particular. The latest model includes non-perturbative QCD EoS and QGP emission (qq annihilation at $T>T_c$) based on lattice QCD
- Dilepton rates calculated by integration of the thermal rates over the space-time evolution of the fireball
- Successfully describes data from SPS to RHIC energies: the broadening (melting) originates mainly from the hadronic phase ($\pi^+\pi^- \rightarrow \rho \rightarrow e^+e^-$), when the phase boundary is approached, while the contribution from the QGP (qq annihilation) is small.
- The model is able to extract the total fireball life-time from the LMR excess yields and the early temperature from the IMR slopes.
- The model is compatible with (the approach) to chiral symmetry restoration, for which a suggested mechanism is broadening of both ρ and a_1, with the accompanied drop of a_1 spectral function towards the ρ mass as the system approaches the critical temperature.

Why heavy ion collisions?





Simulating charm contributions in PHENIX

- Uncertainty in the cross-section and shape depending on MC@NLO or PYTHIA:
  - The cross-sections extracted from fit to dielectrons in d+Au in the *intermediate mass region* – both models decribe the data well (PRC 91, 014907 (2015))

• The two models differ in extrapolation to lower invariant masses caused by their different charm p_t and opening angle distributions

• The difference is more significant in Au+Au collisions where cc and bb contributions scale with N_{coll} while the other contributions scale with N_{part}