THE STATUS OF THE LOW-MASS DILEPTONS

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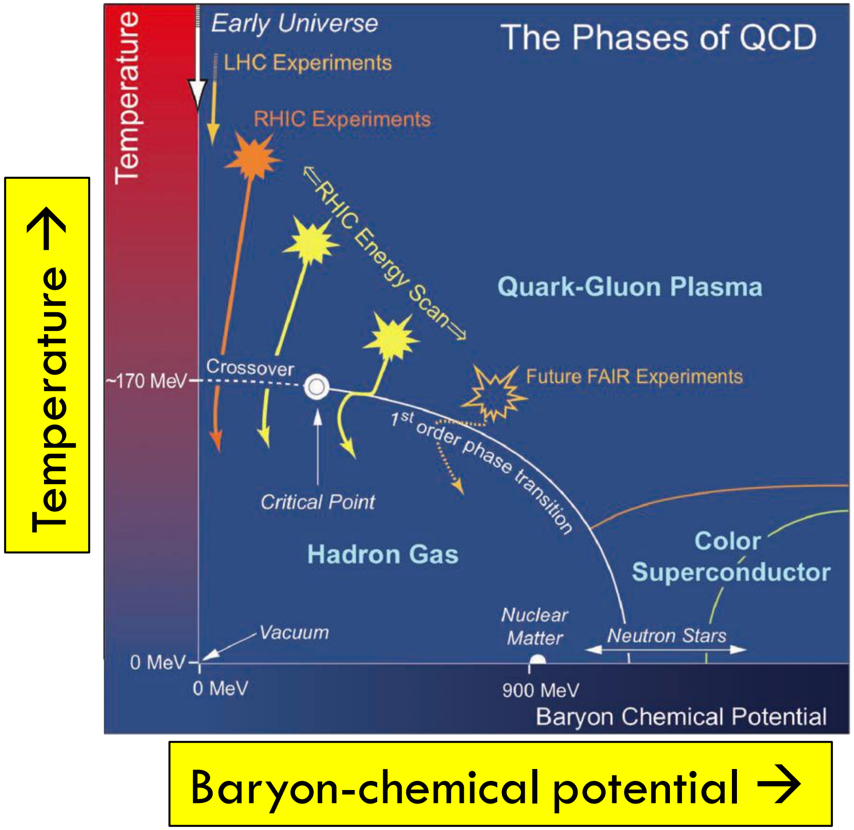
16. Zimányi WINTER SCHOOL ON
HEAVY ION PHYSICS, Budapest, 2016

Outline

- Introduction to dilepton measurements
- The overview of the experimental results
- Comparison with the models
- Summary and outlook

Different states of matter

QCD phase-diagram



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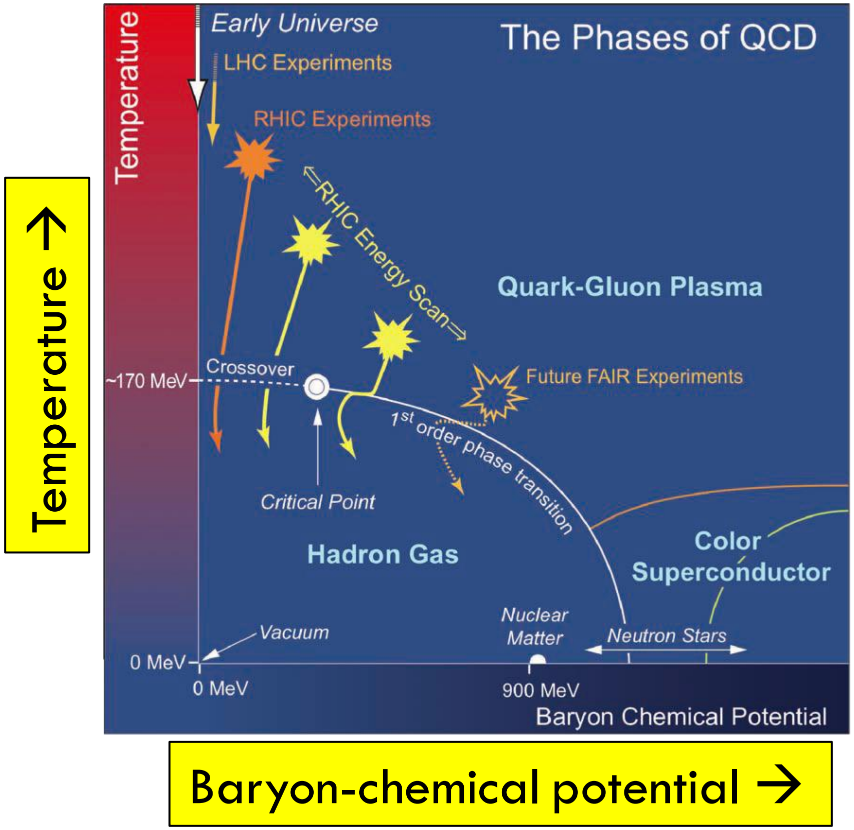
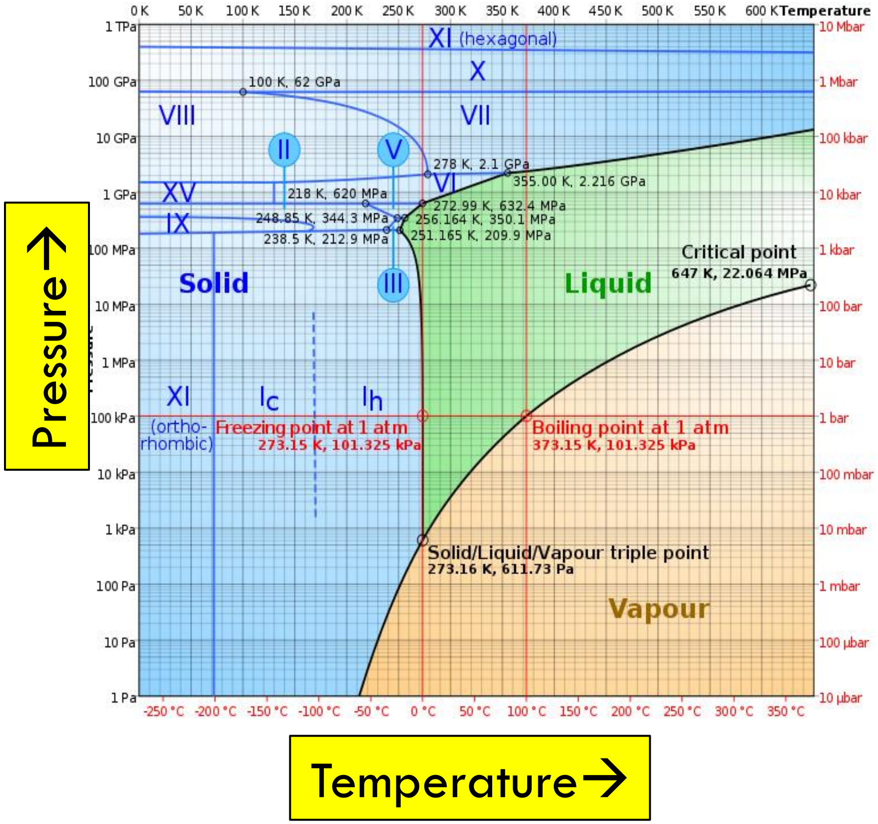


Phase-diagram of water



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

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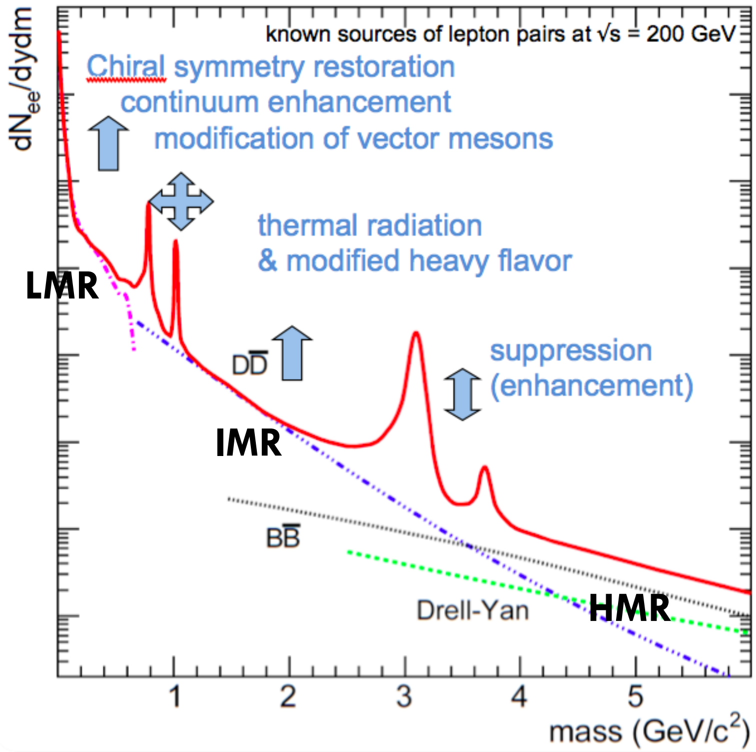

Known sources of dielectrons at RHIC:

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

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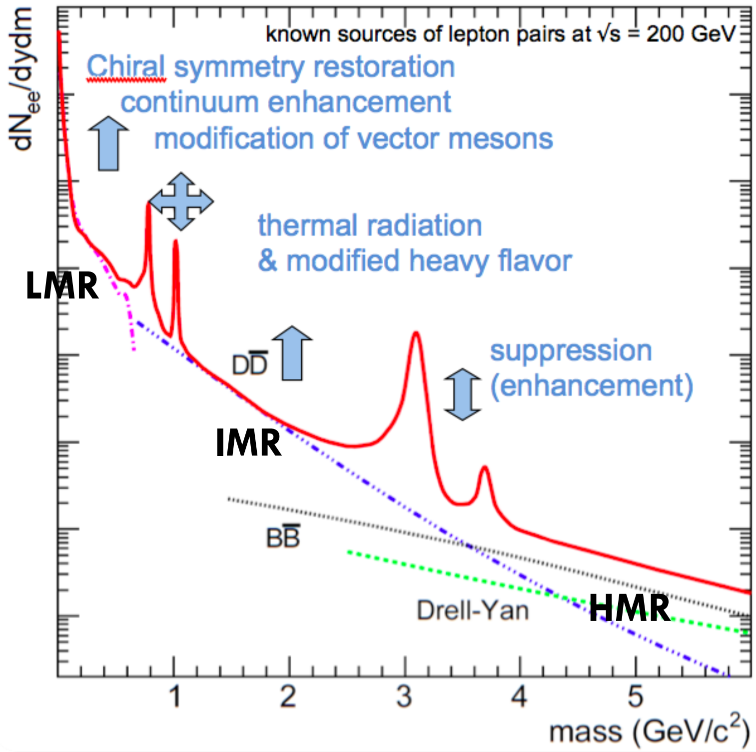

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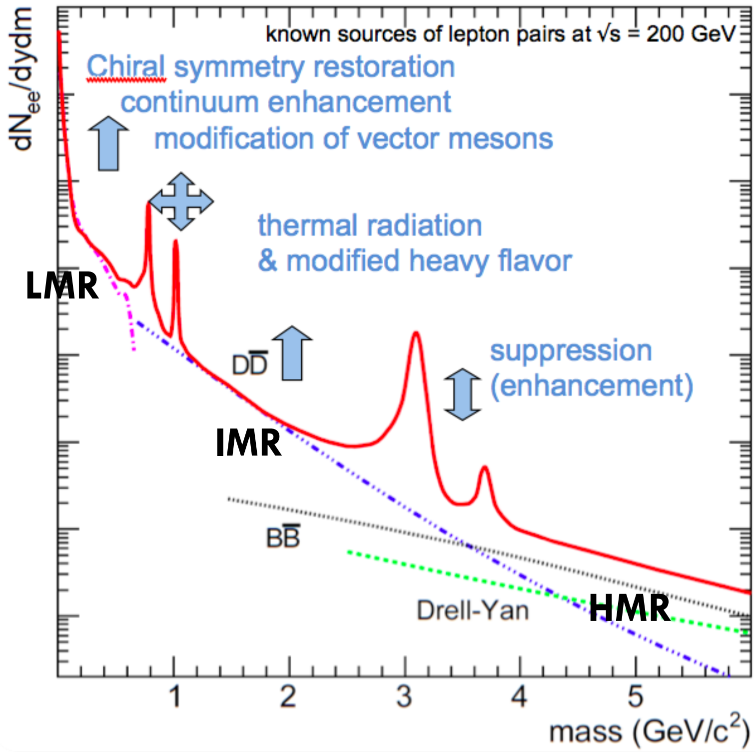

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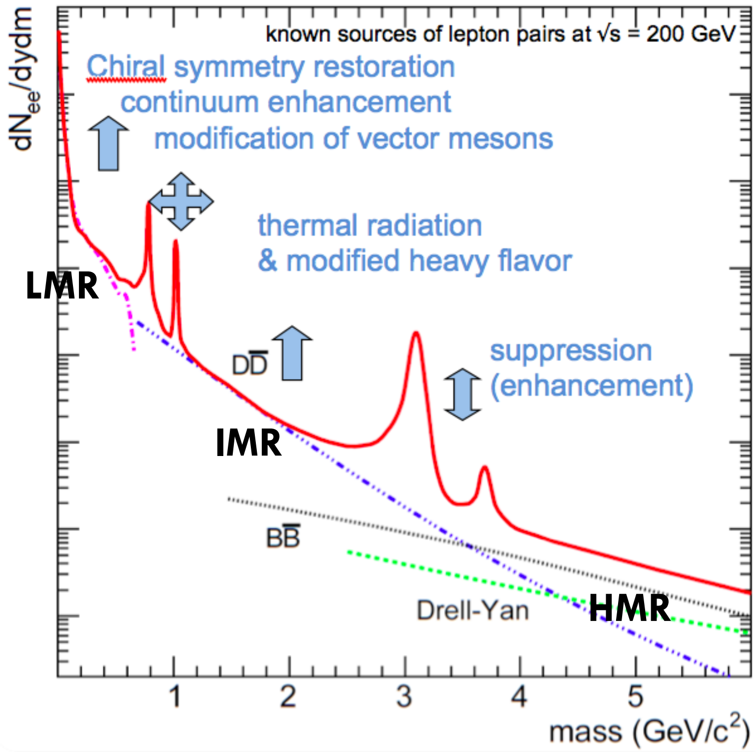

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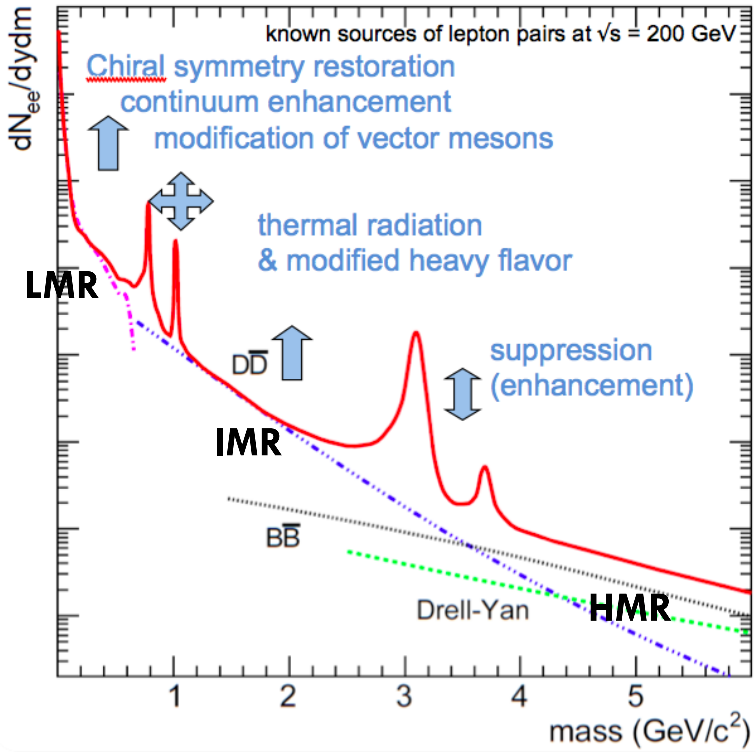

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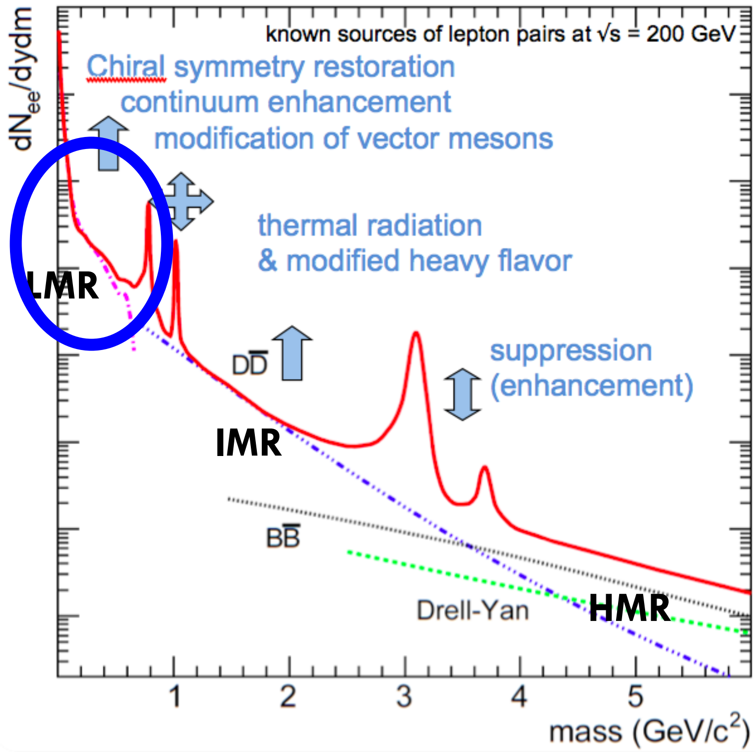

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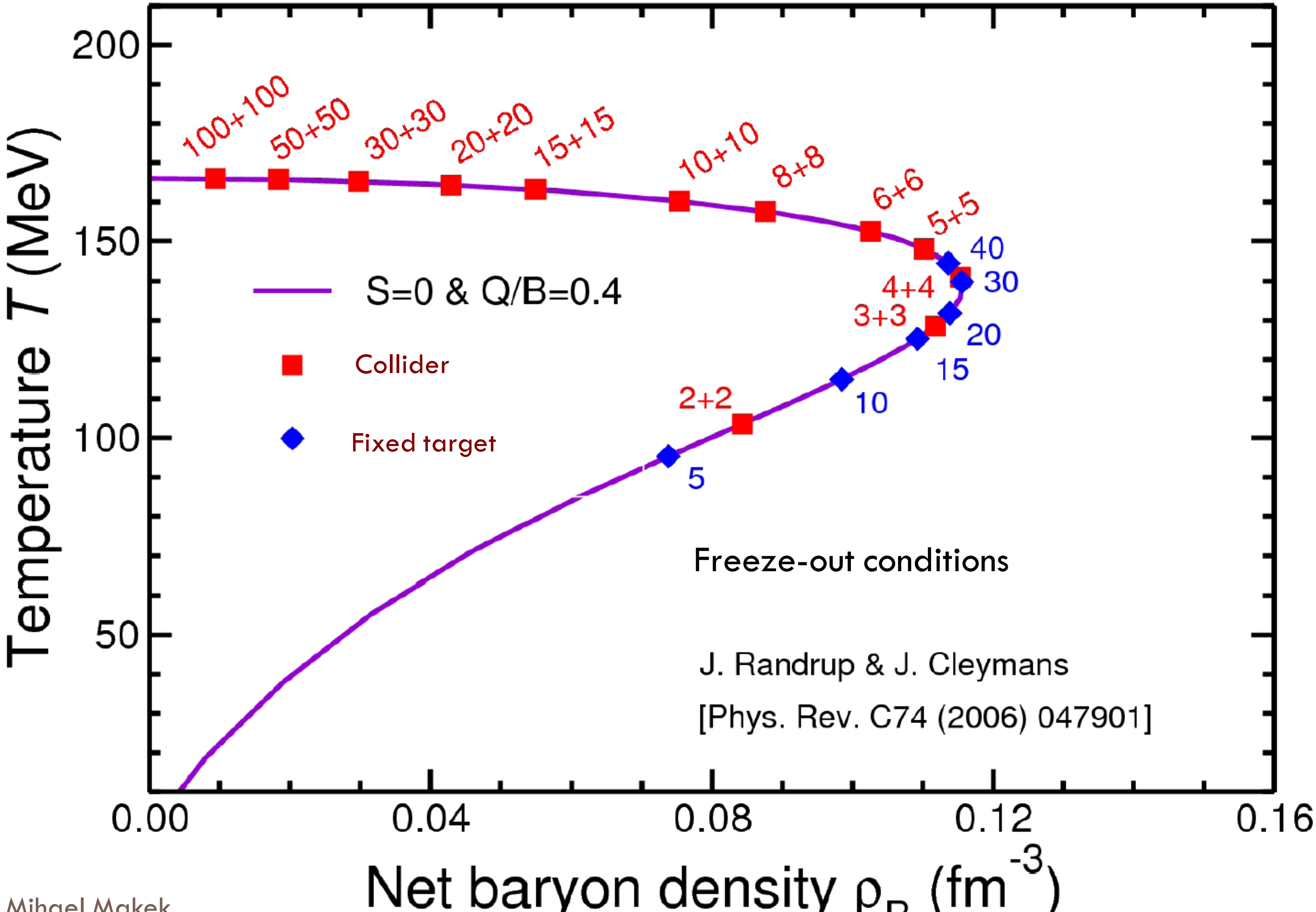
Experimental framework

for the low-mass dielectron measurements

- Collider experiments:
  - **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
- Fixed target experiments:
  - **CERES, NA60** at SPS
  - **HADES** at GSI
- Other
  - **ALICE** at LHC (dielecton results in p+p and p+Pb)

- **Major experimental challenge**: low S/B typically (1/1000-1/200) and a large hadron contamination

Experimental framework



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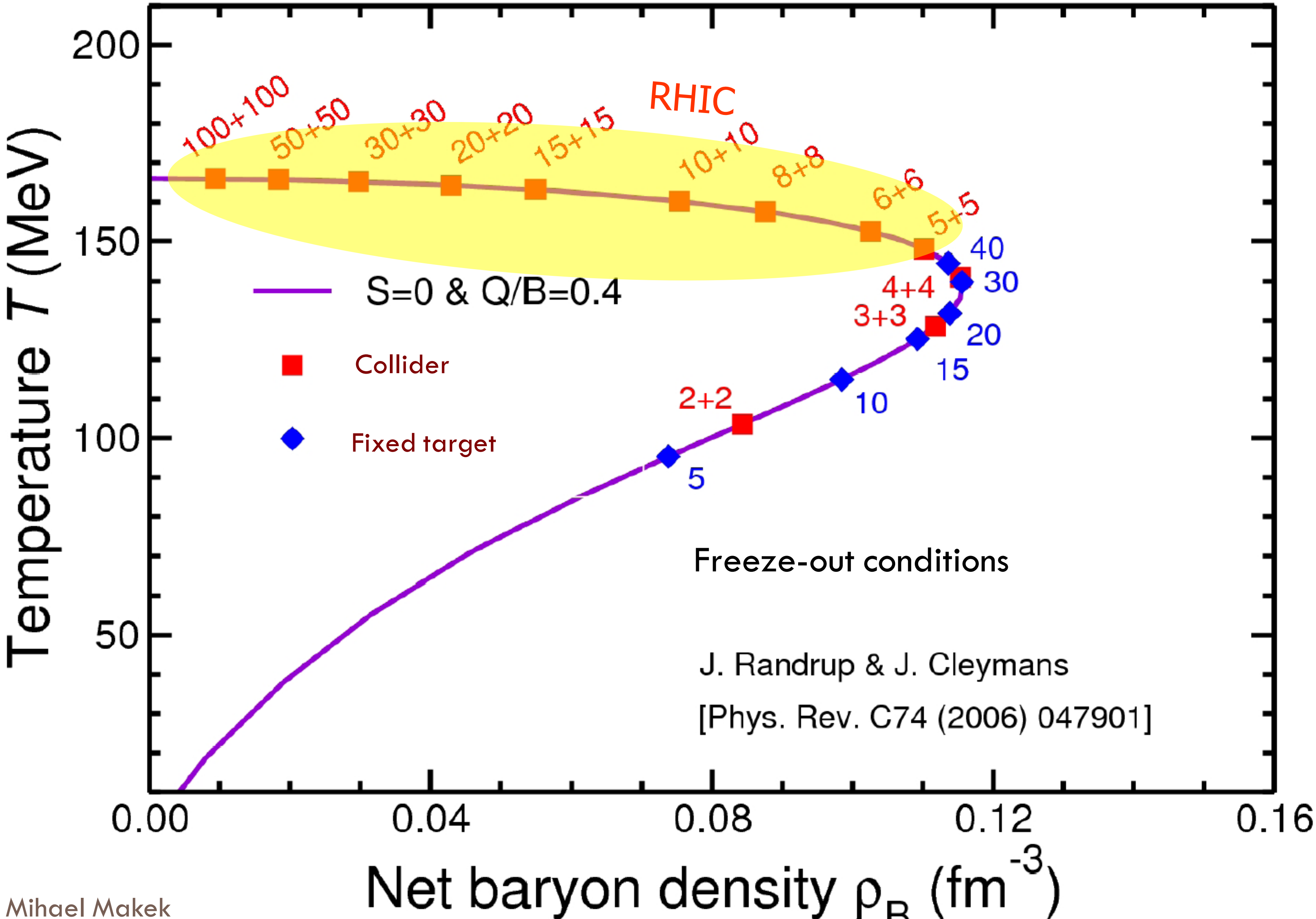

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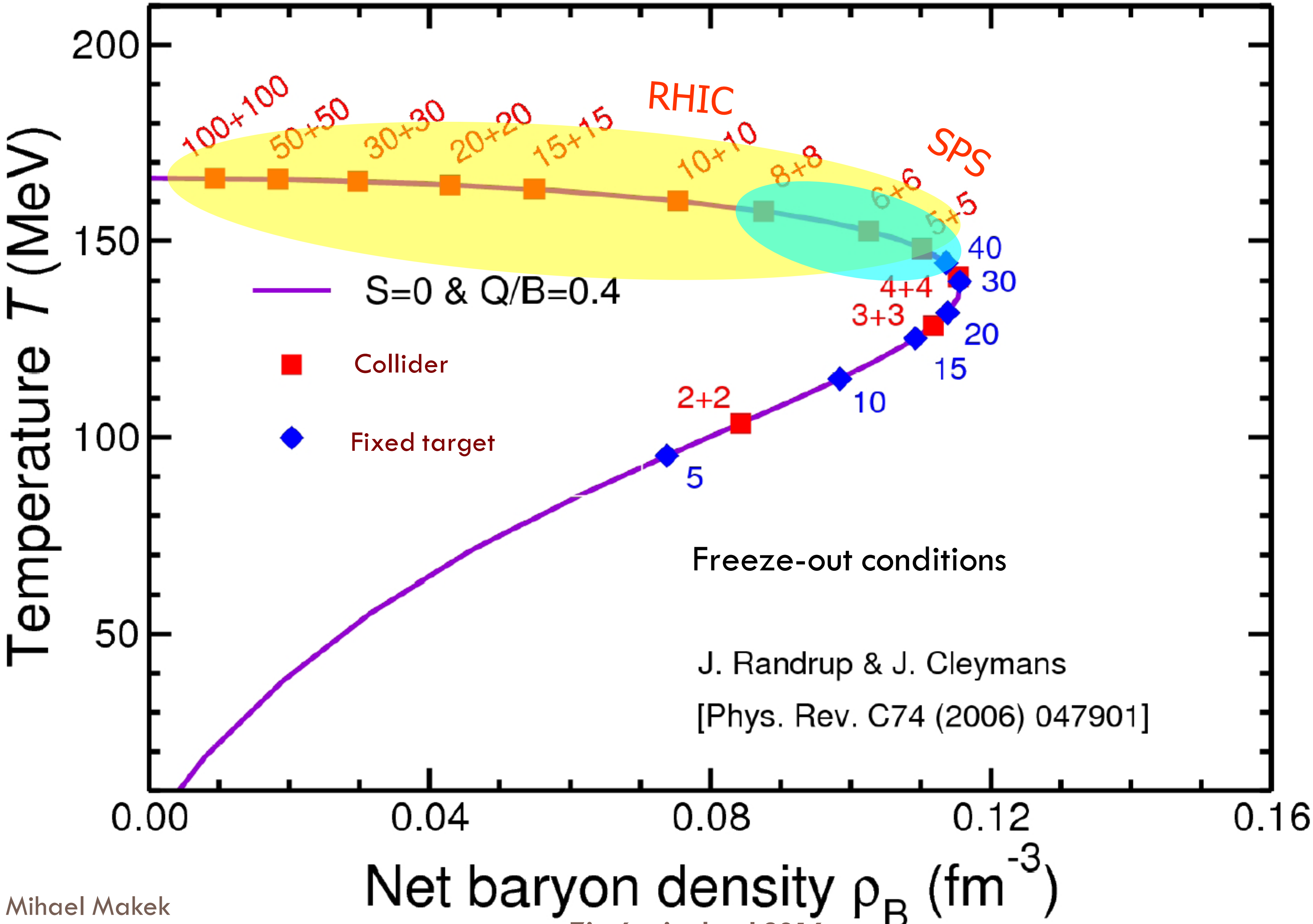

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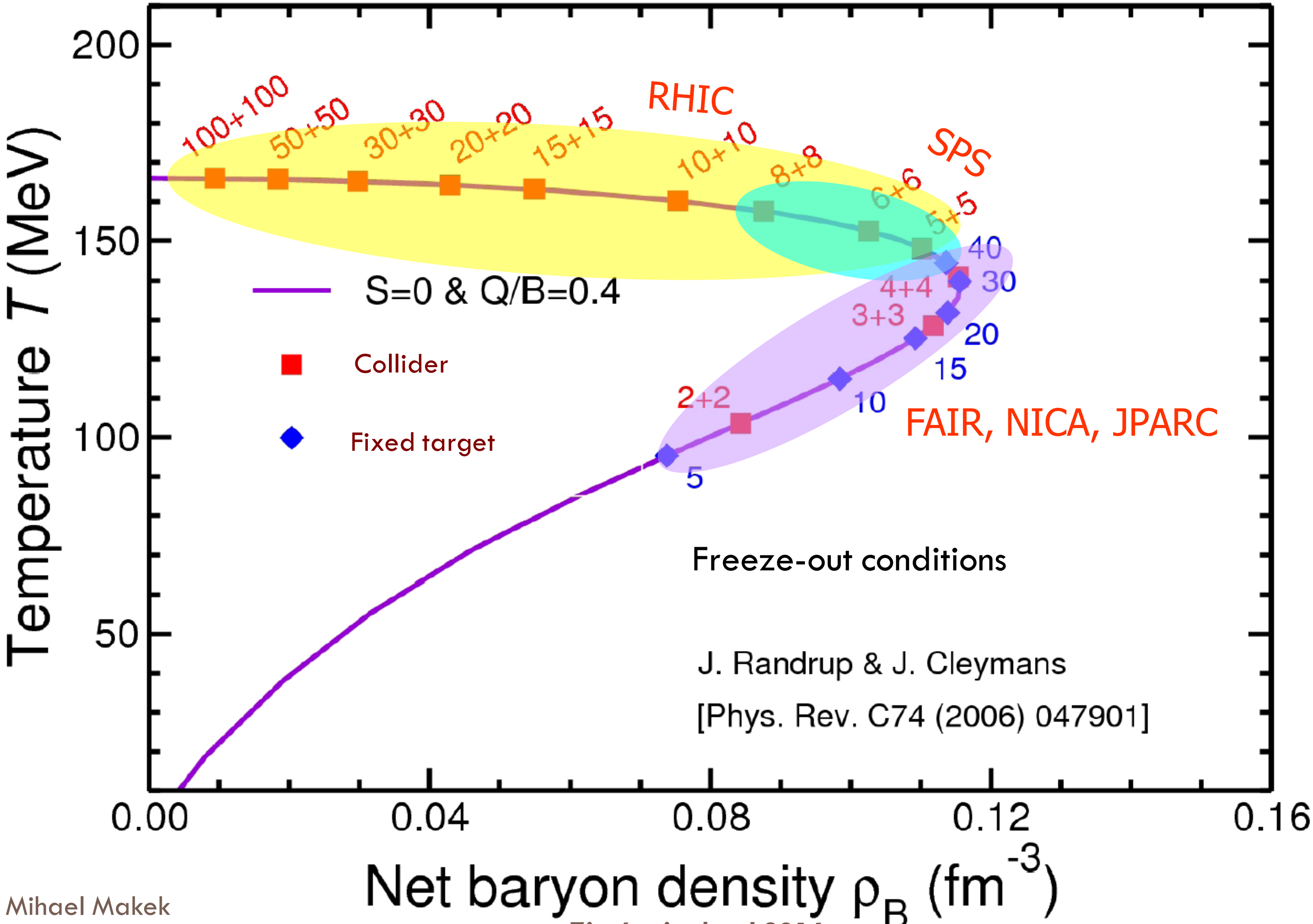
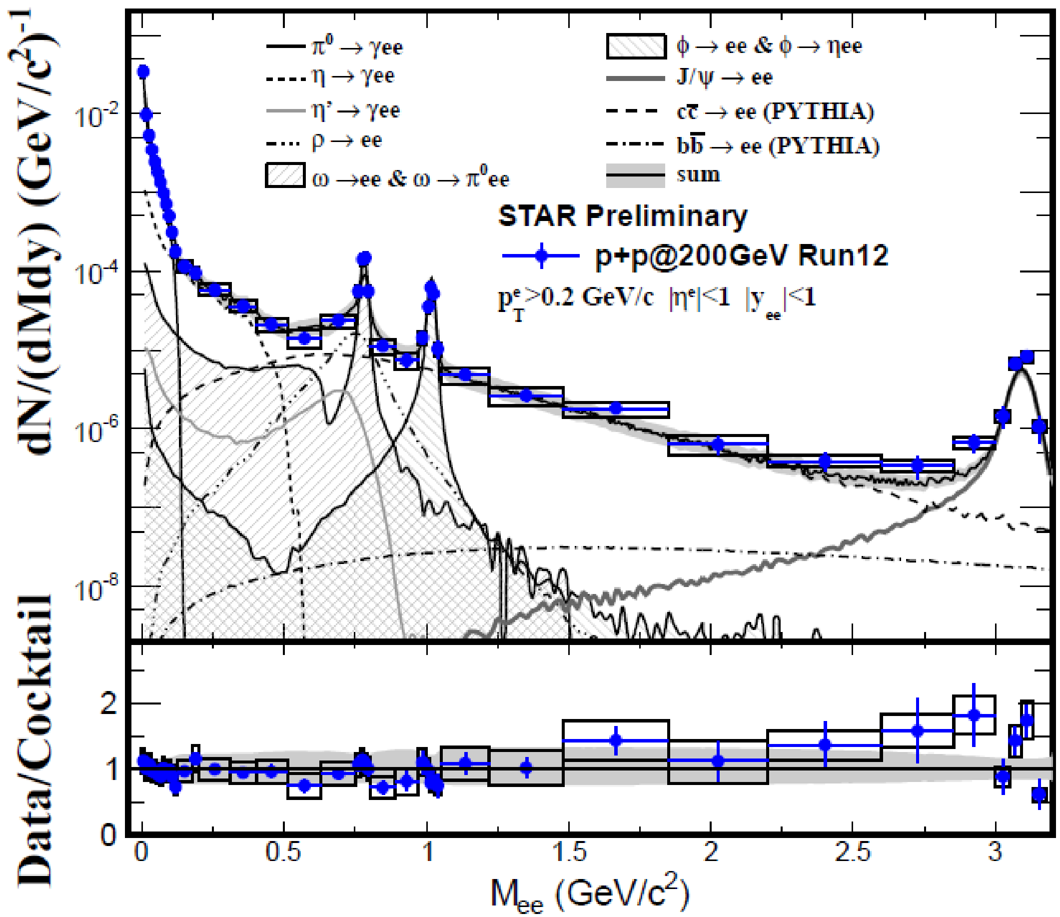


The reference systems

- To determine QGP properties need reference systems:
  - p+p collisions (reference for vacuum properties)
  - d+Au, p+Pb (reference 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 √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 hadronic cocktail (PHENIX)

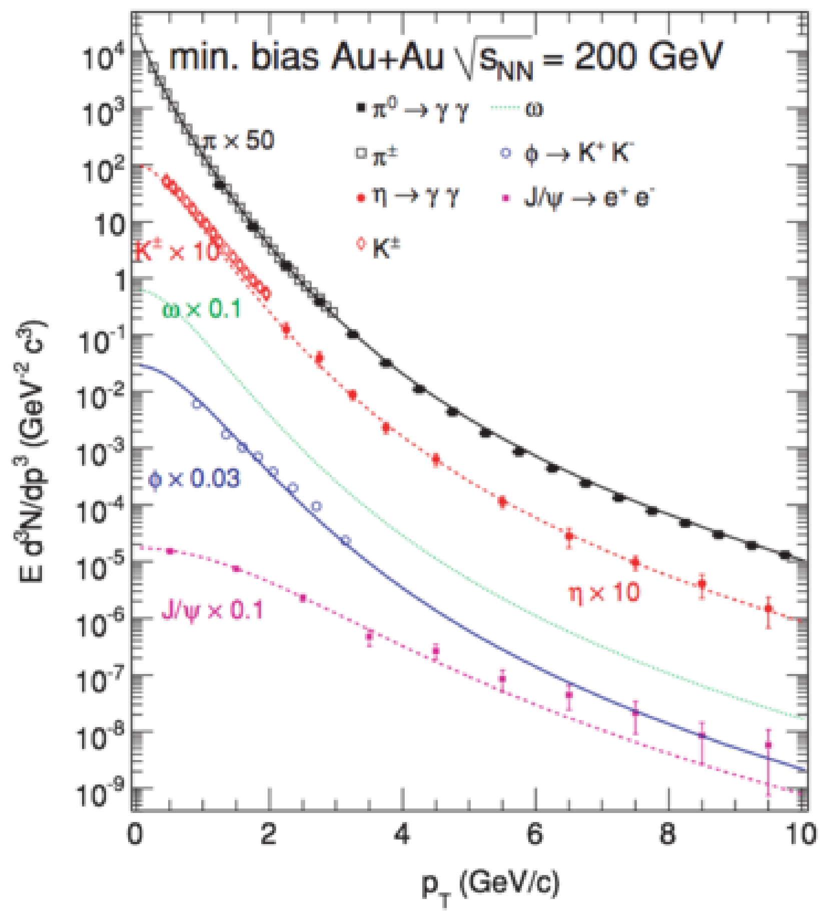
- Hadron decays simulated in EXODUS
- Fit π^0 and $\pi^\pm$ data p+p or Au+Au to modified Haggedorn function:

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

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

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

- 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 resolution
- Normalization
  - In m_{ee}<0.1 GeV/c^2 and p_T/m_{ee}>5
  - Normalize to measured $\pi^0 + \eta +$ direct γ



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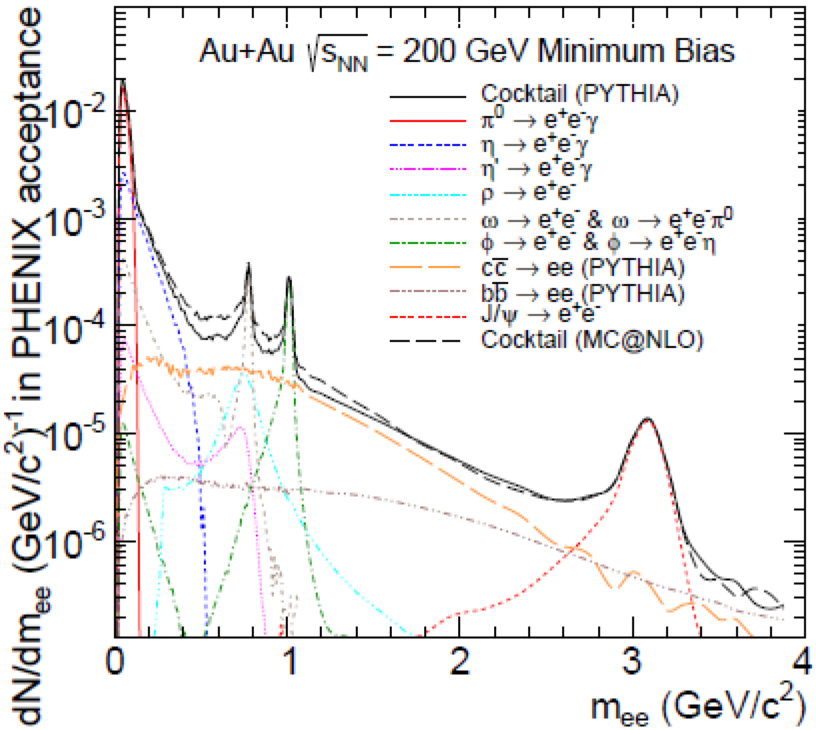
PHENIX PRC 93, 014904 (2016)



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

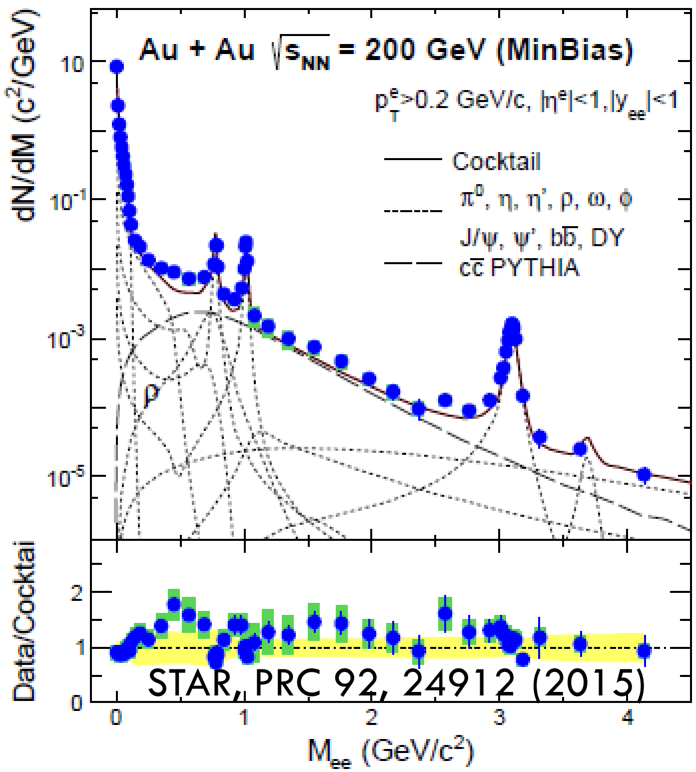
→ **PYTHIA cocktail** and **MC@NLO cocktail**

Experimental results

Dielectron results from STAR

Invariant mass spectra from:

- Au+Au @20-200 GeV



STAR, PRC 92, 24912 (2015)

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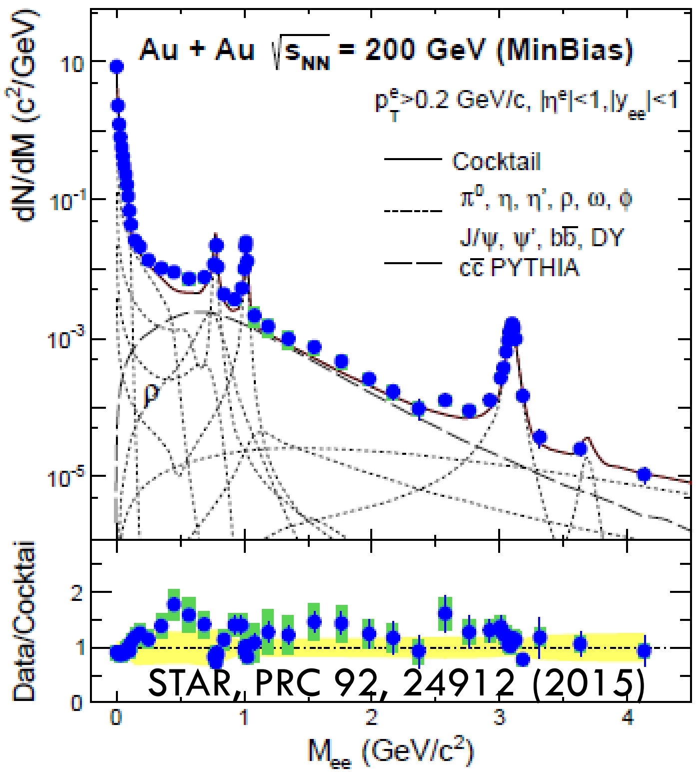

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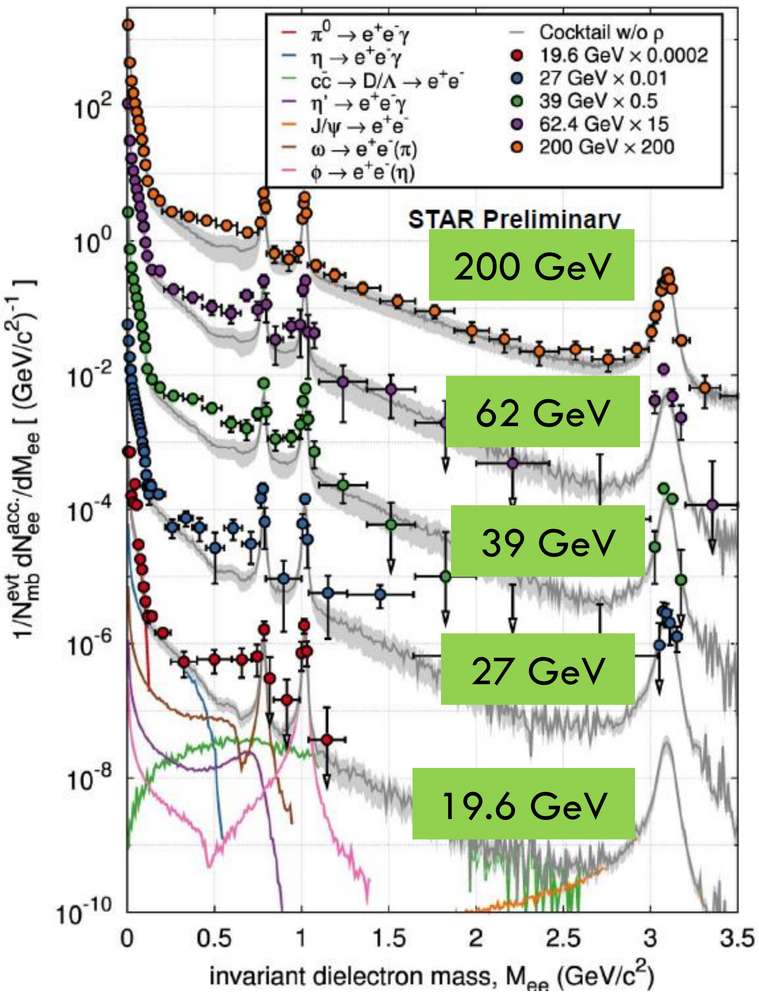

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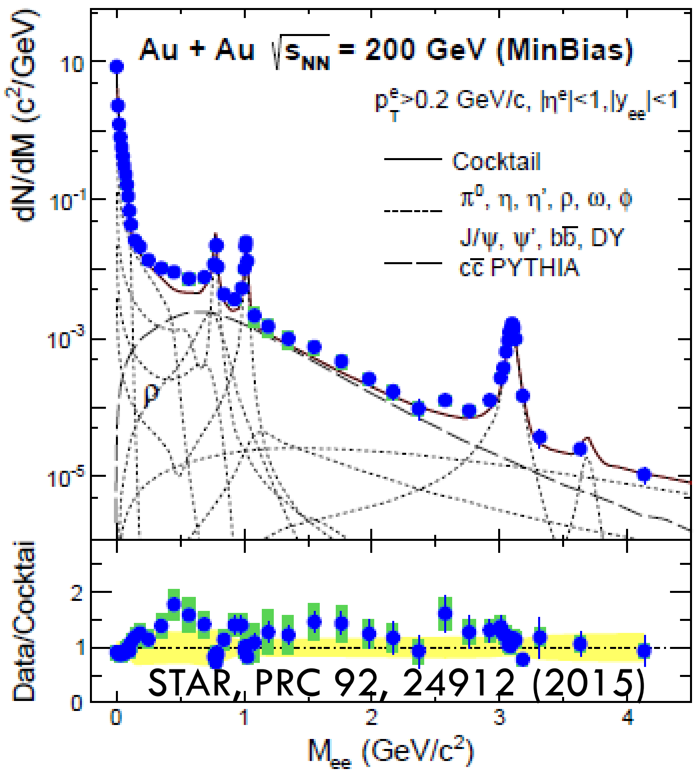
Invariant mass spectra from:

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



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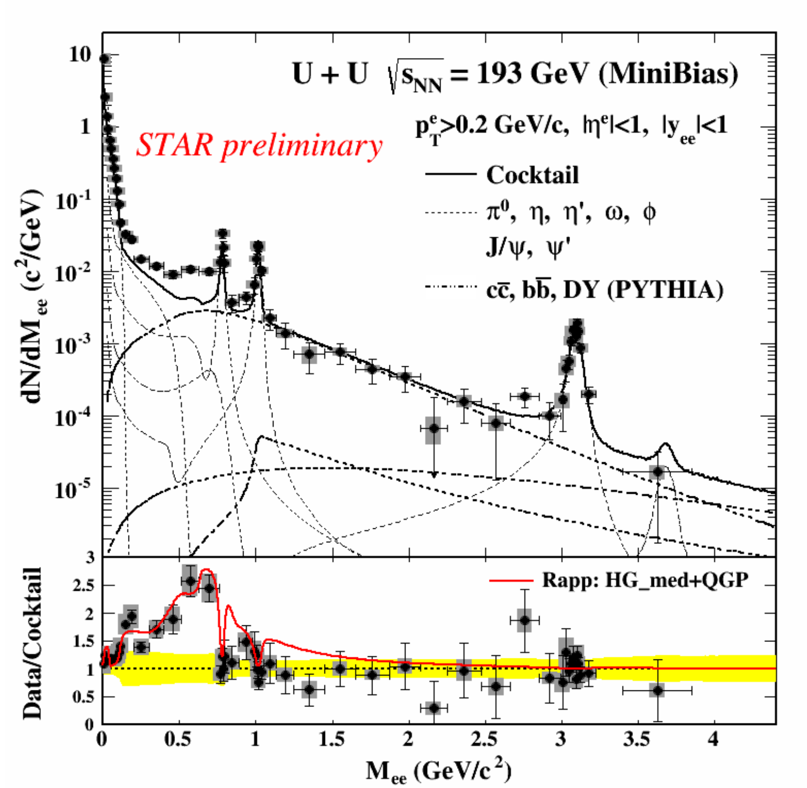

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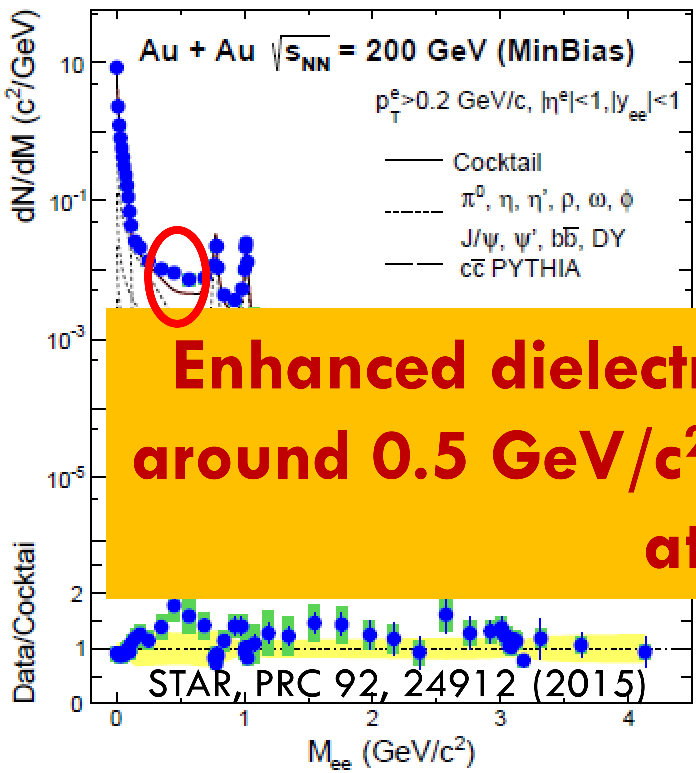
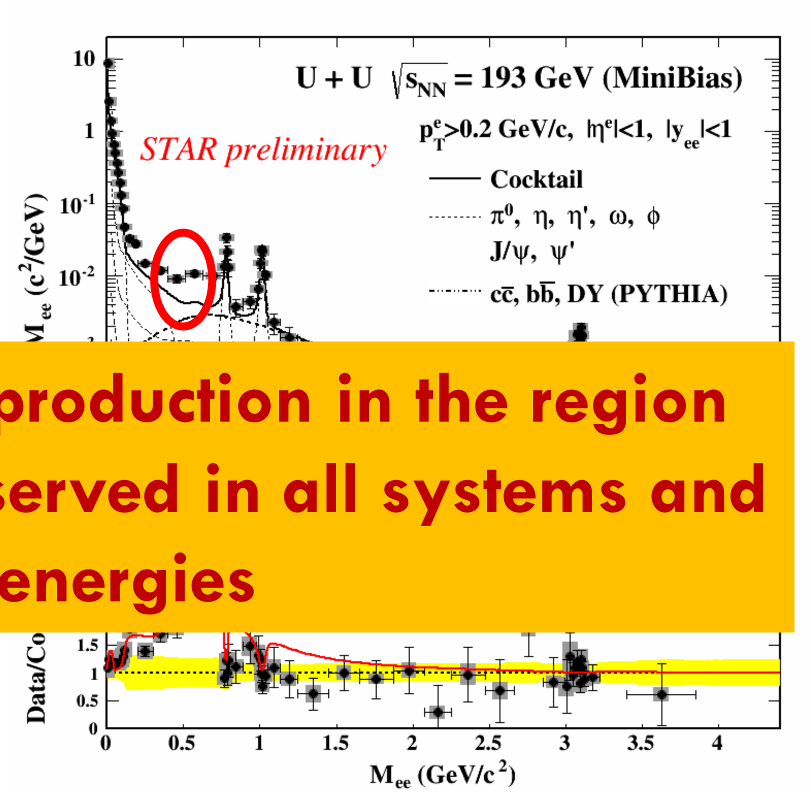
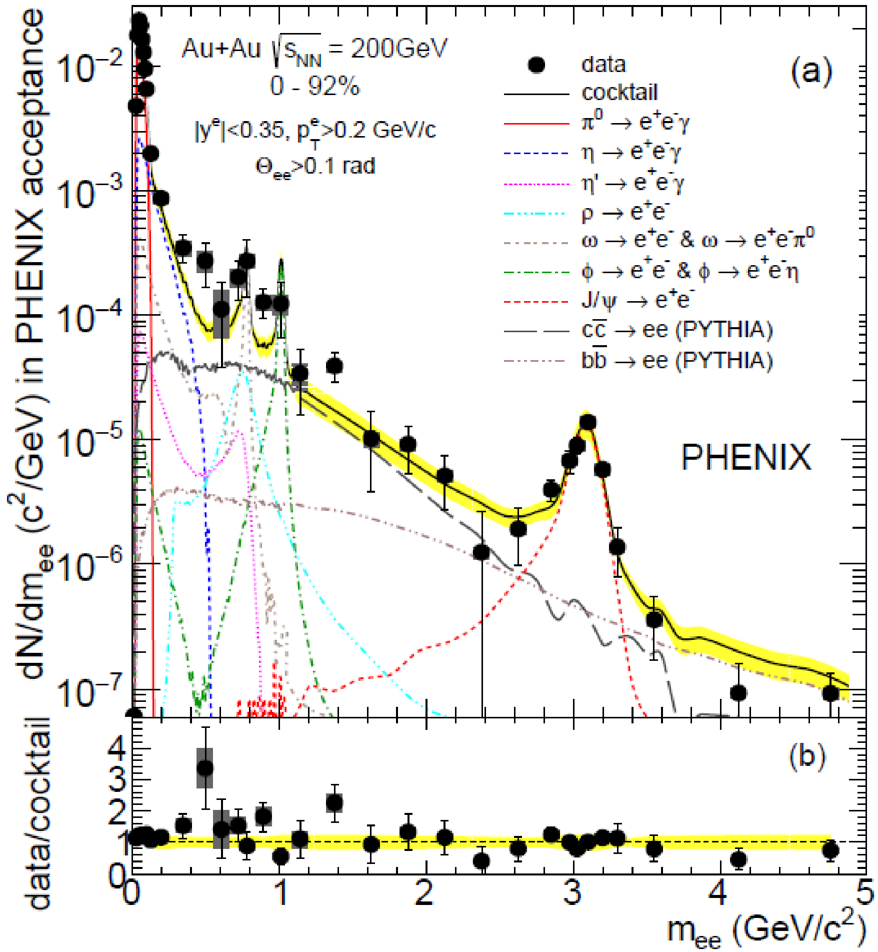




Enhanced dielectron production in the region around 0.5 GeV/c² observed in all systems and at all energies

Dielectron results from PHENIX

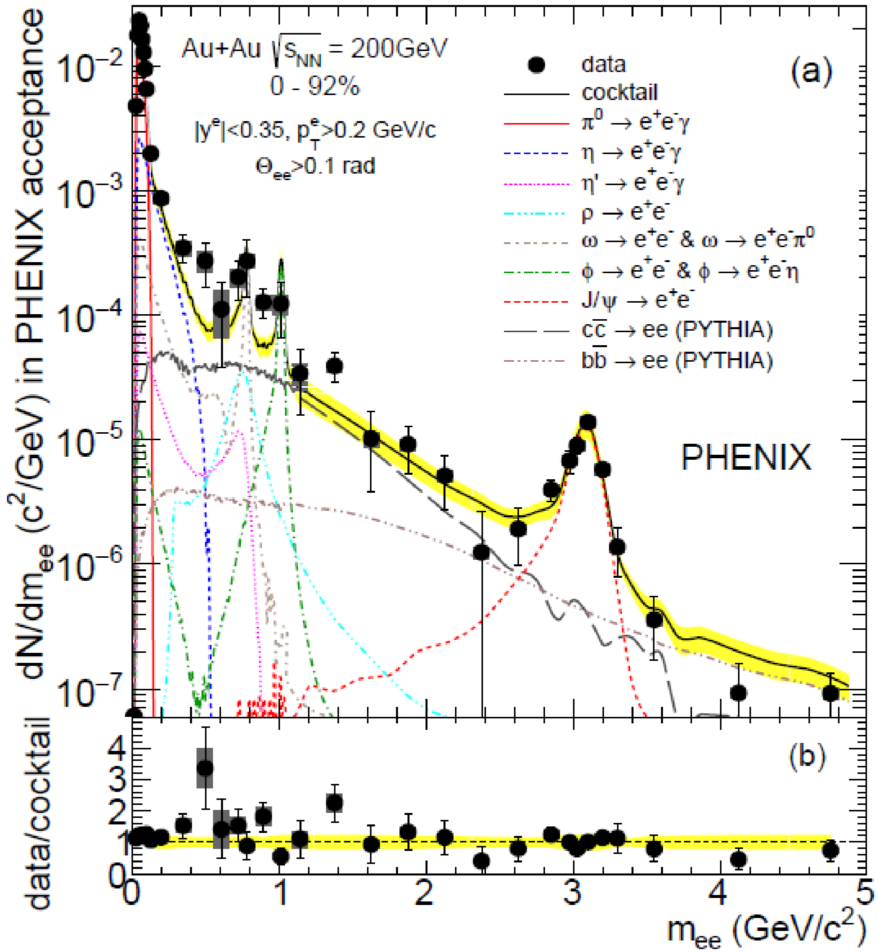
Minimum bias

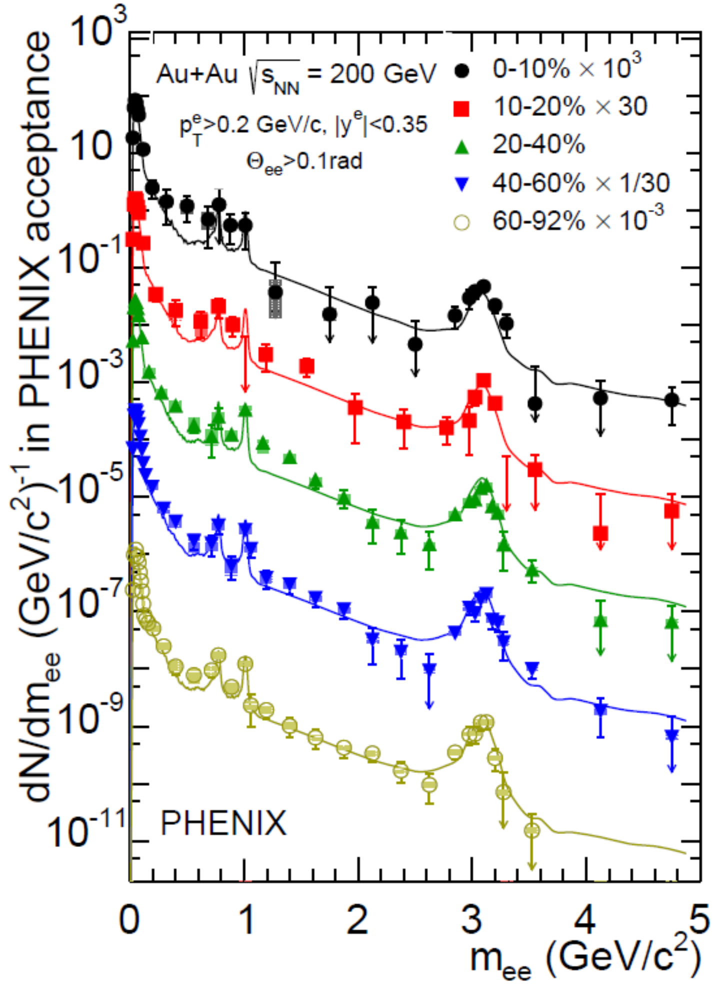


PHENIX PRC 93, 014904 (2016)

Dielectron results from PHENIX

Minimum bias | **Centrality dependence**





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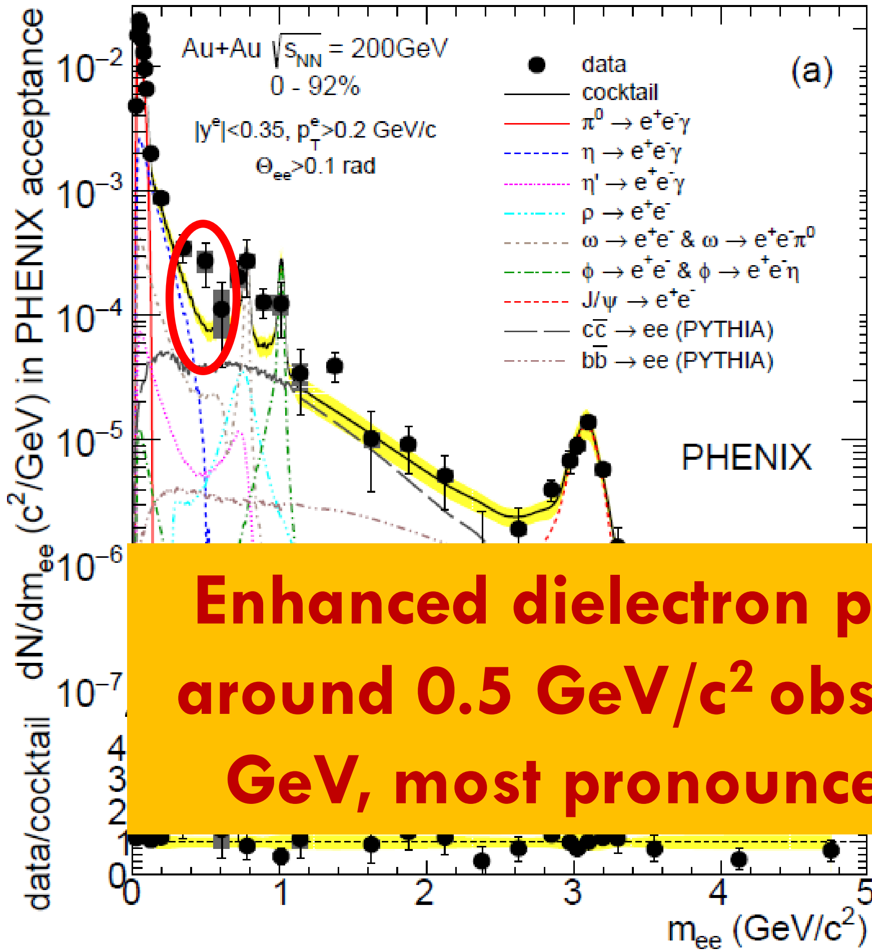
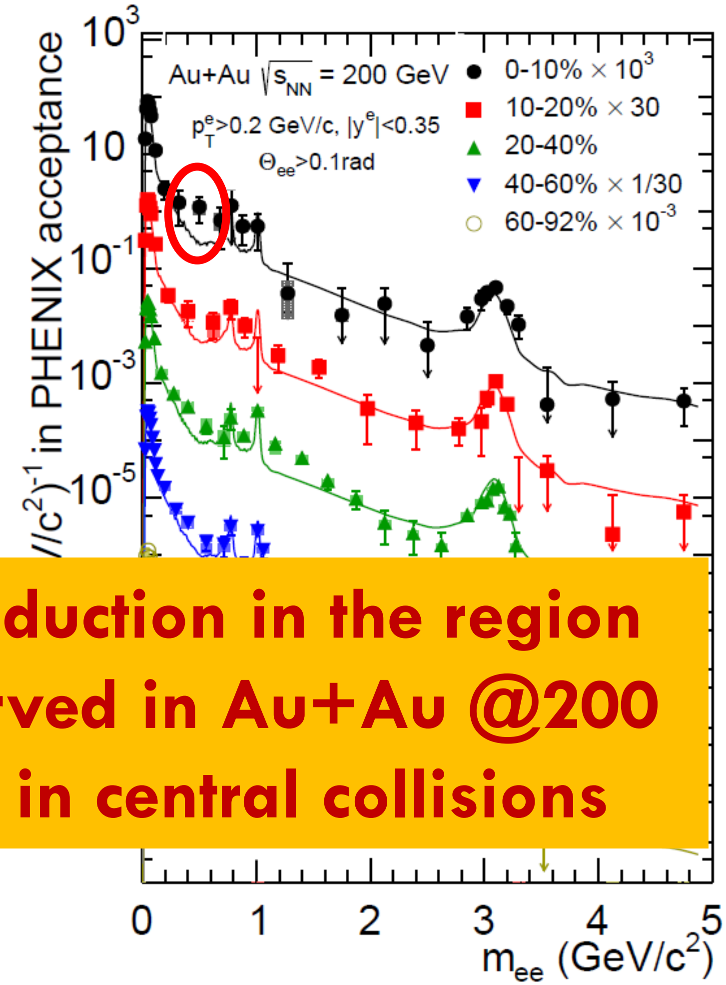


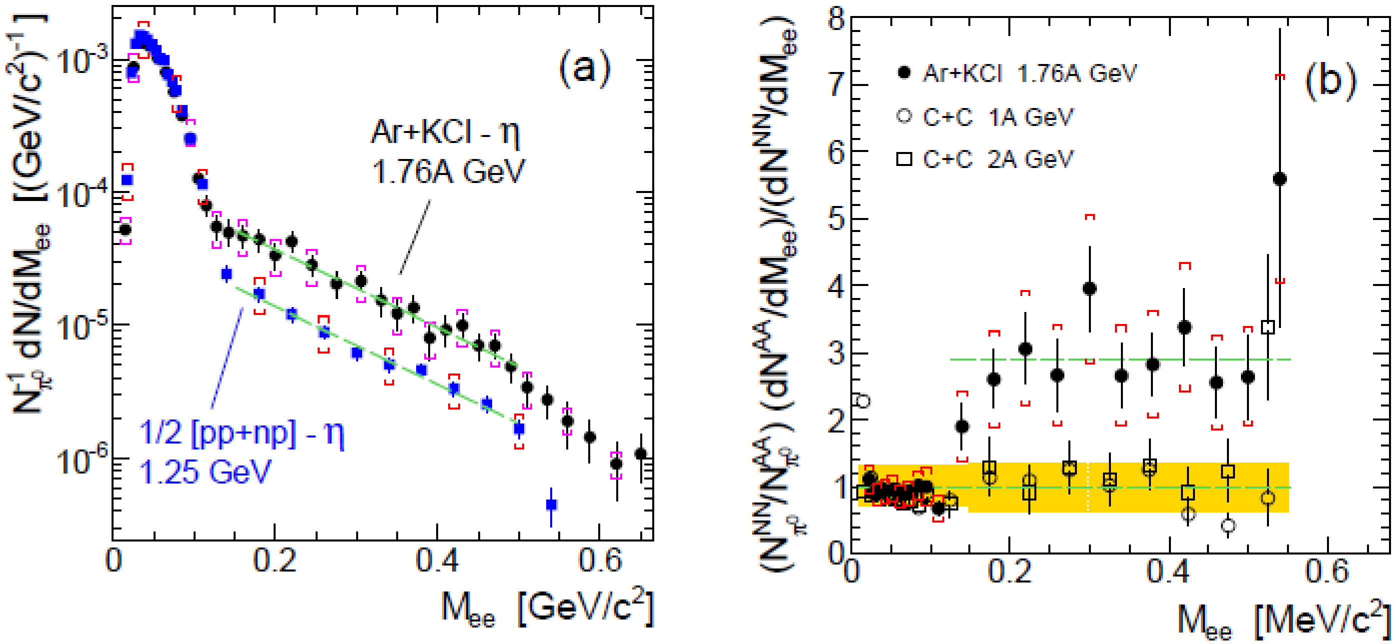


Enhanced dielectron production in the region around 0.5 GeV/c^2 observed in Au+Au @200 GeV, most pronounced in central collisions

PHENIX PRC 93, 014904 (2016)

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

Recent theoretical models

- **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.

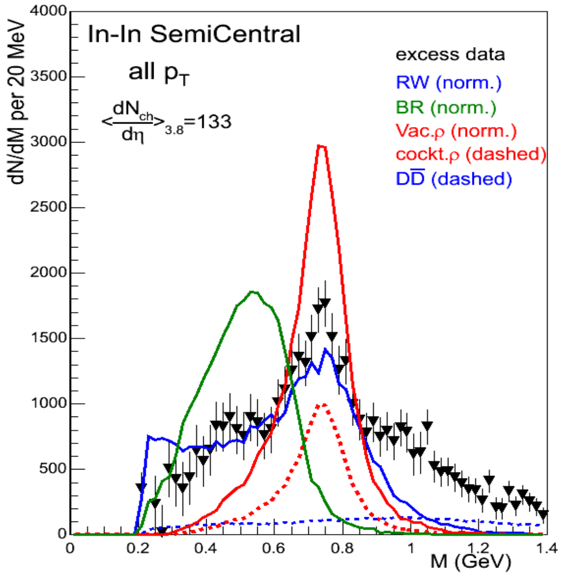
- **Microscopic transport dynamic models.** E.g. Parton-Hadron String Dynamic (PHSD) or Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

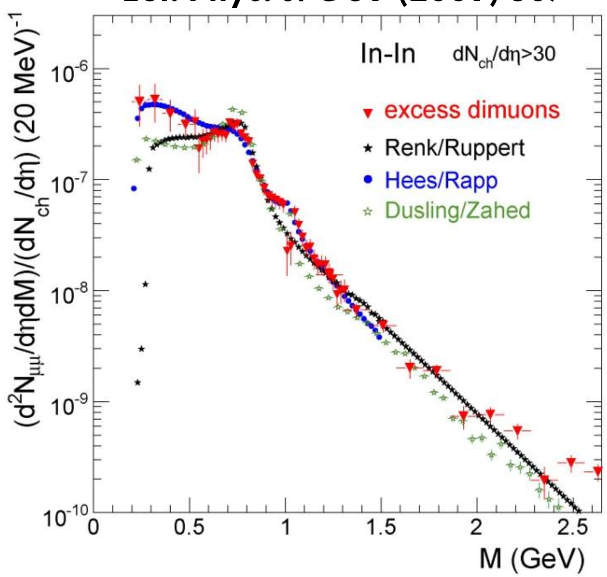
- **Coarse-graining models.** Dynamics based on microscopic description (e.g. UrQMD), with phase-space cells averaged over many events allow describing the dynamics in (macroscopic) terms of temperature and barion-chemical potential.

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

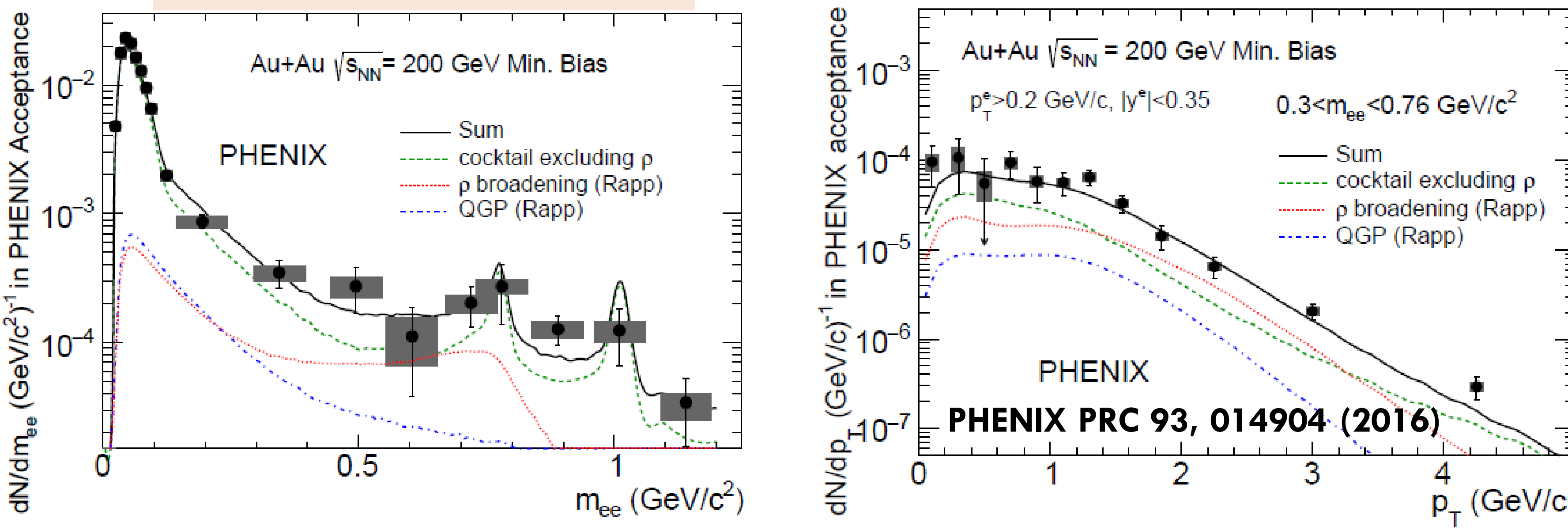




- Excess dimuons well explained by thermal radiation from the hadron gas ($\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$) in the LMR and thermal radiation from the QGP in the IMR

Rapp's model: comparison to PHENIX

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



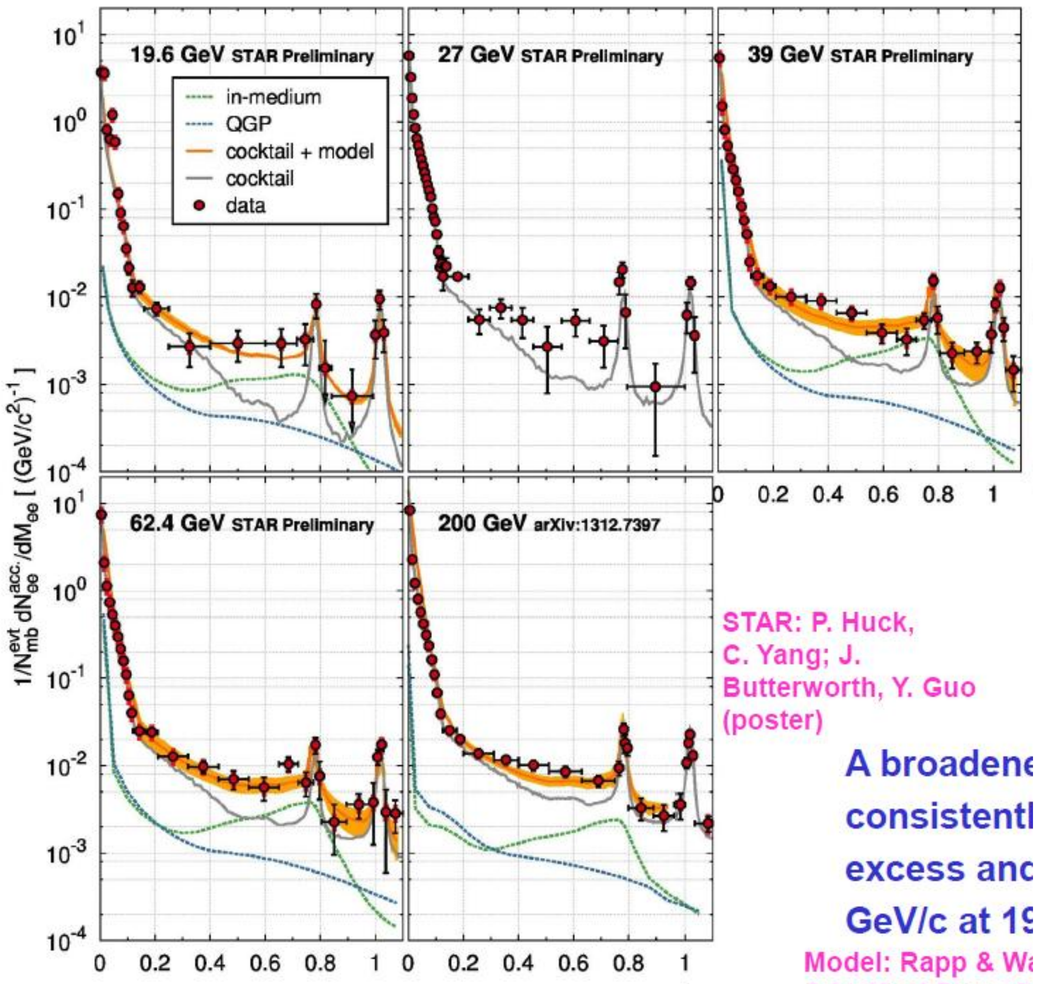
PHENIX PRC 93, 014904 (2016)

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

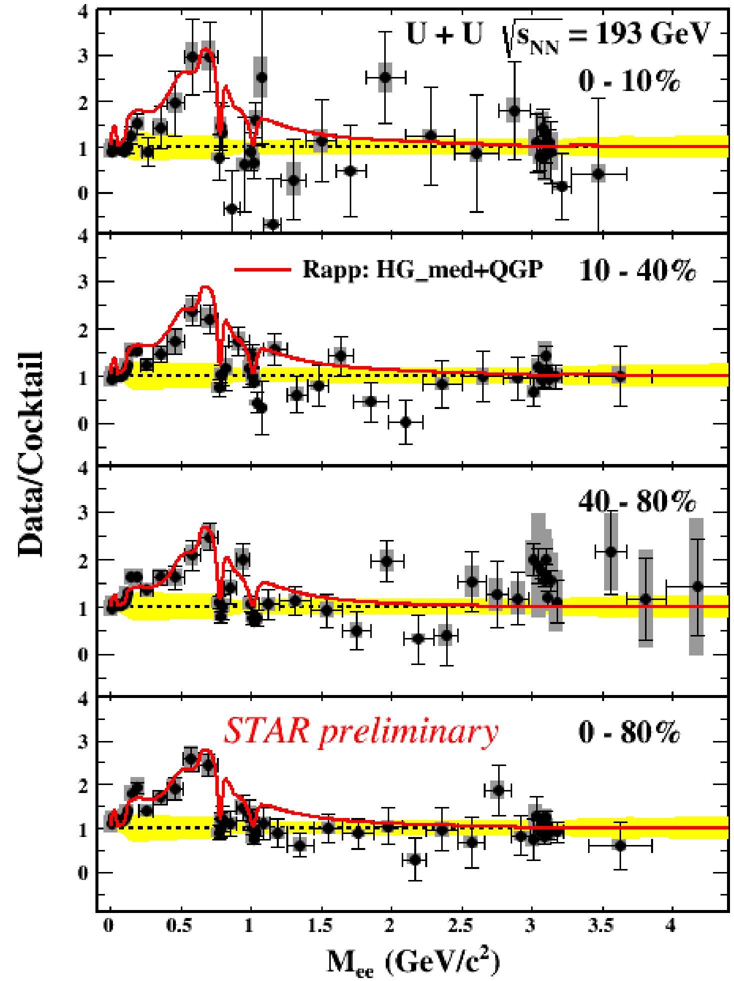
- In-medium ρ broadening due to scatter off baryons in hadrons gas as the system approaches the critical temperature
- A small contribution from the QGP thermal dielectron emission.

Rapp's model:
comparison to STAR

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



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



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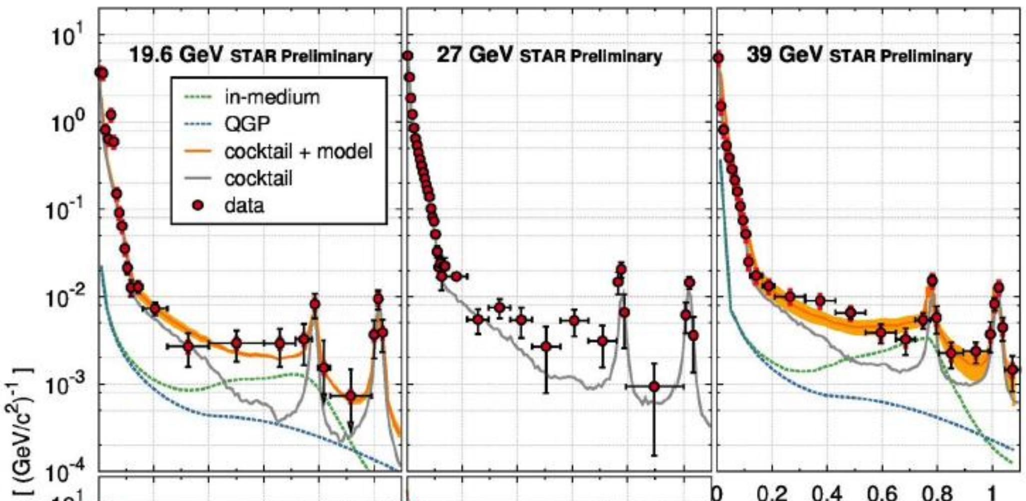

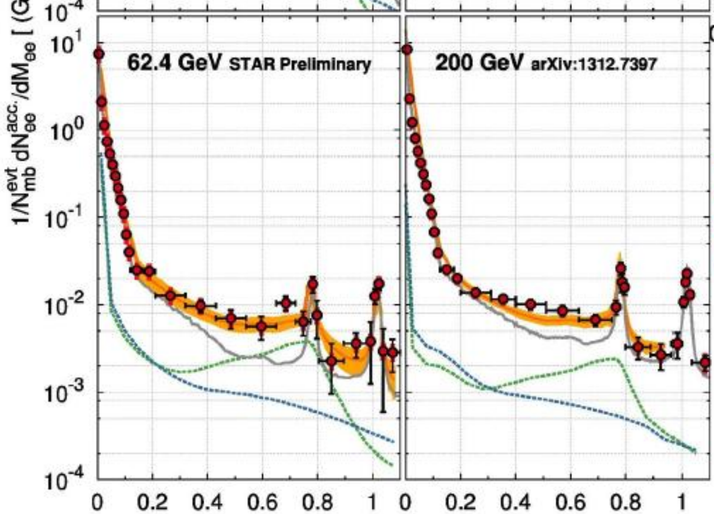

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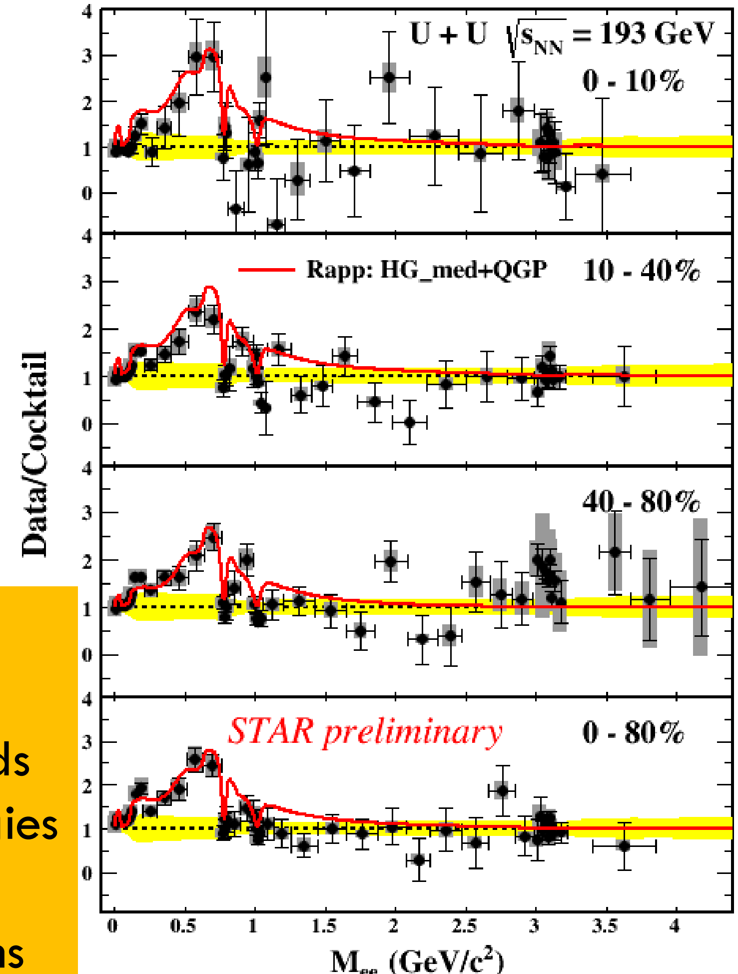
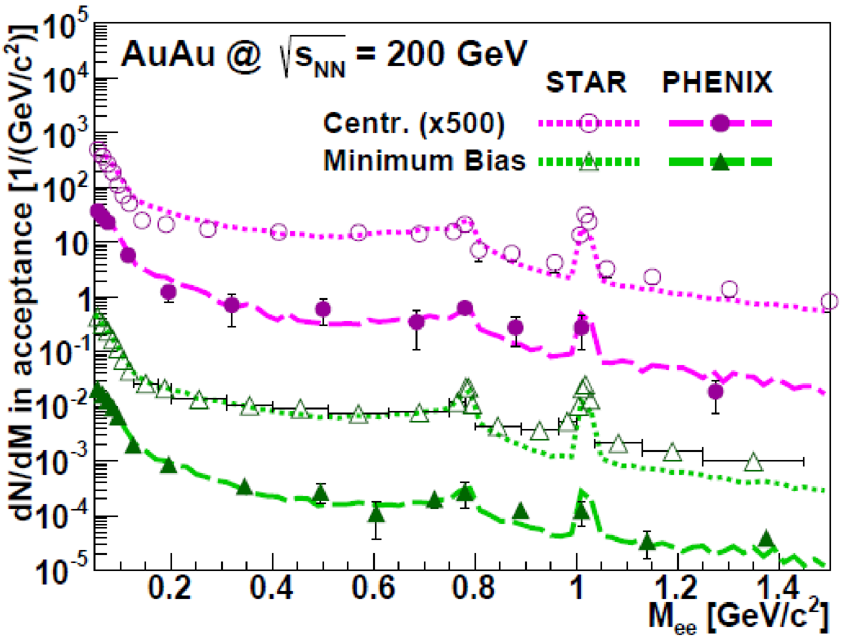
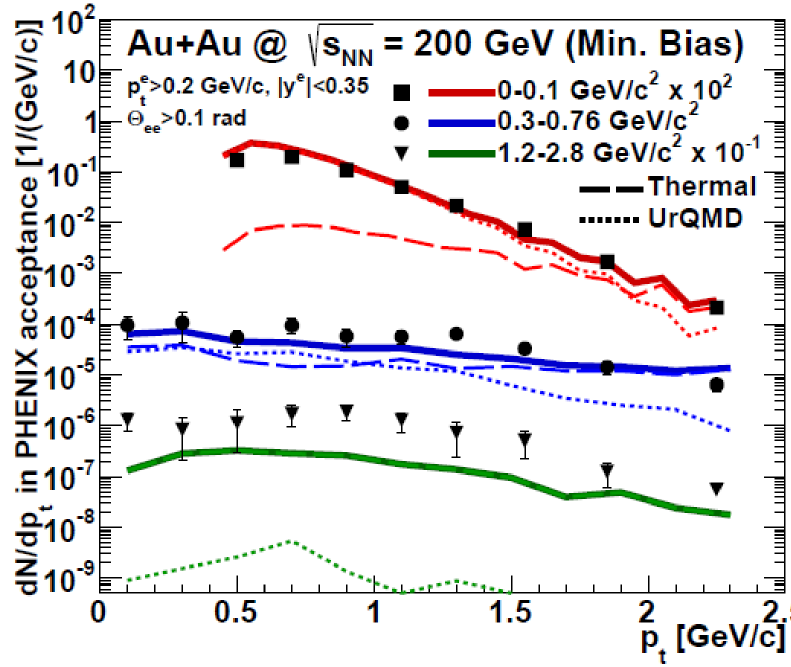


The model describes dielectron yields at various energies and different collision systems

Coarse-graining model:
comparison to PHENIX and STAR

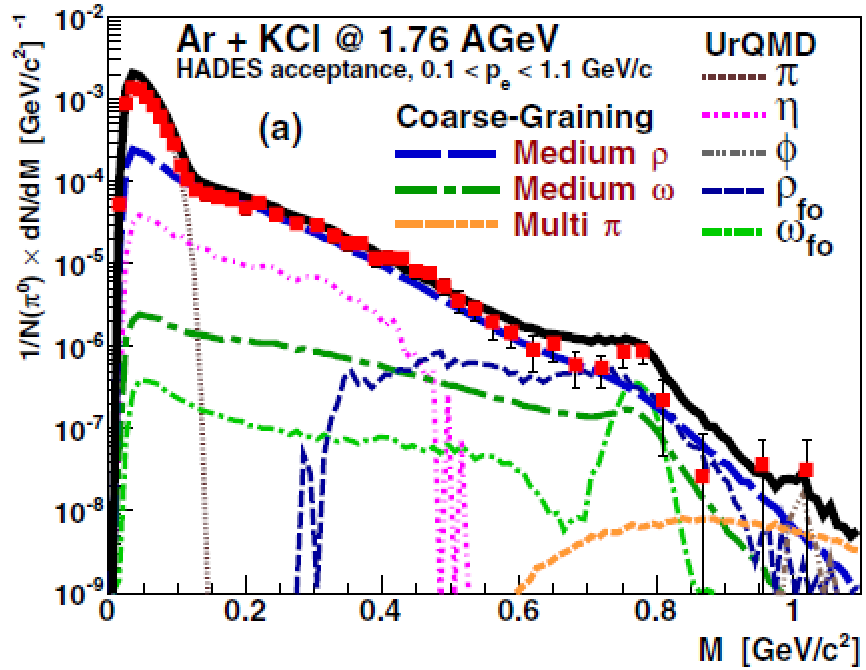




- Dielectron excess in the LMR well described by the ***coarse-graining model*** (Endres, van Hees, Bleicher PRC94 024912 (2016))
  - The curves include the hadronic contributions (the cocktail) from the UrQMD and the thermal dielectron emission
  - The data described well in invariant mass and transverse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

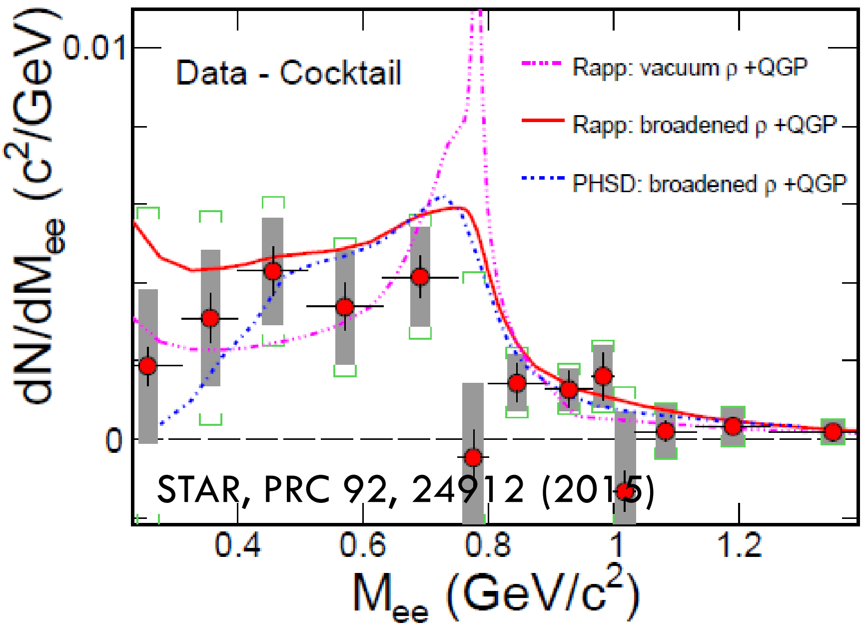
Coarse-graining model:
comparison to HADES

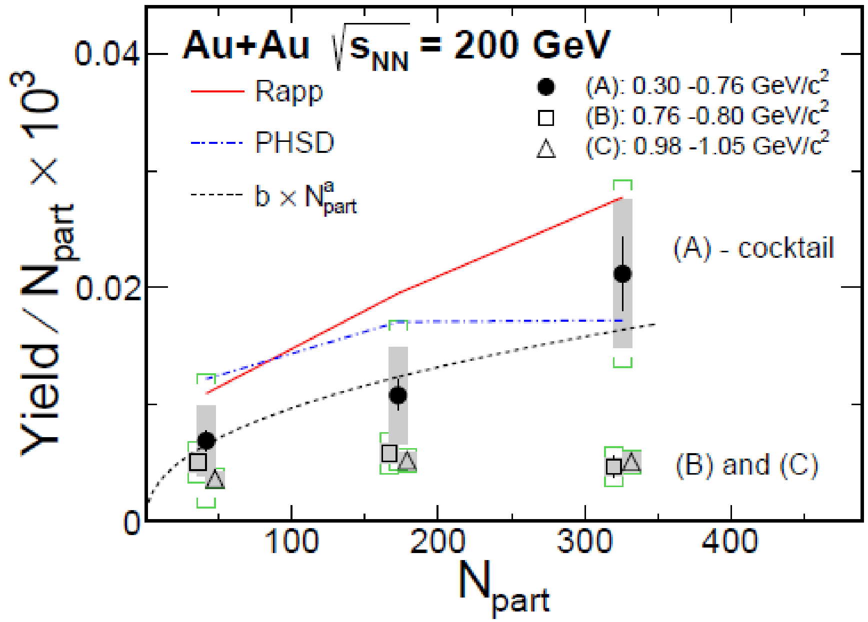
- Dielectrons from Ar+KCl @ 1.76 AGeV recorded by HADES **PRC 84 014902 (2011)**
- The coarse-graining model provides satisfactory descri-ption **PRC 92 014911 (2015)**
- The dominant contribution from broadened ρ meson in the presence of **baryonic matter**
- Non-negligible broadening of omega meson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



Rapp vs. PHSD: comparison to STAR

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

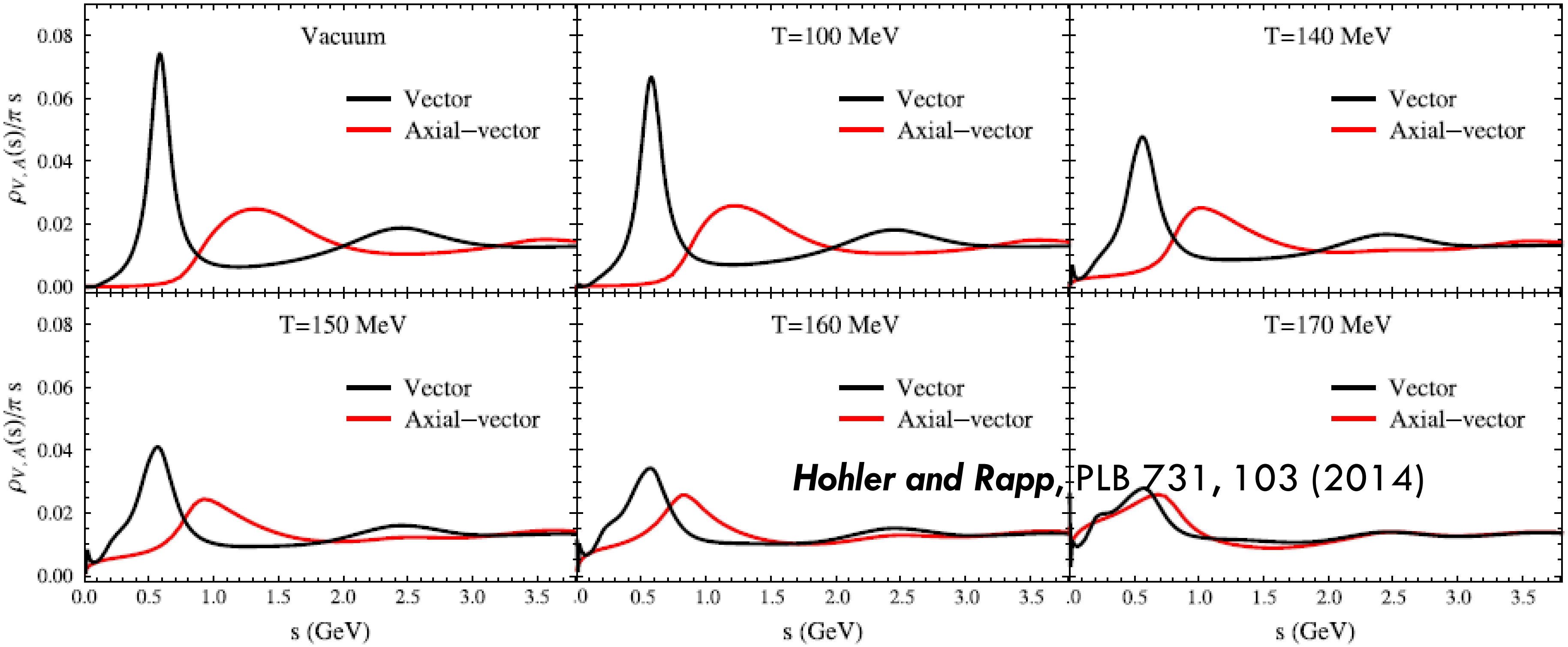




- Dielectron excess described within the experimental errors by the models ***Rapp*** (Rapp, PoS CPOD2013, 008 (2013)) and ***PHSD*** (Linnyk et al., PRC 85, 024910 (2012)):
  - The excess is due to in-medium ρ broadening
  - A small contribution from the QGP thermal dielectron emission.
  - Centrality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

What have we learned?

→ 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)

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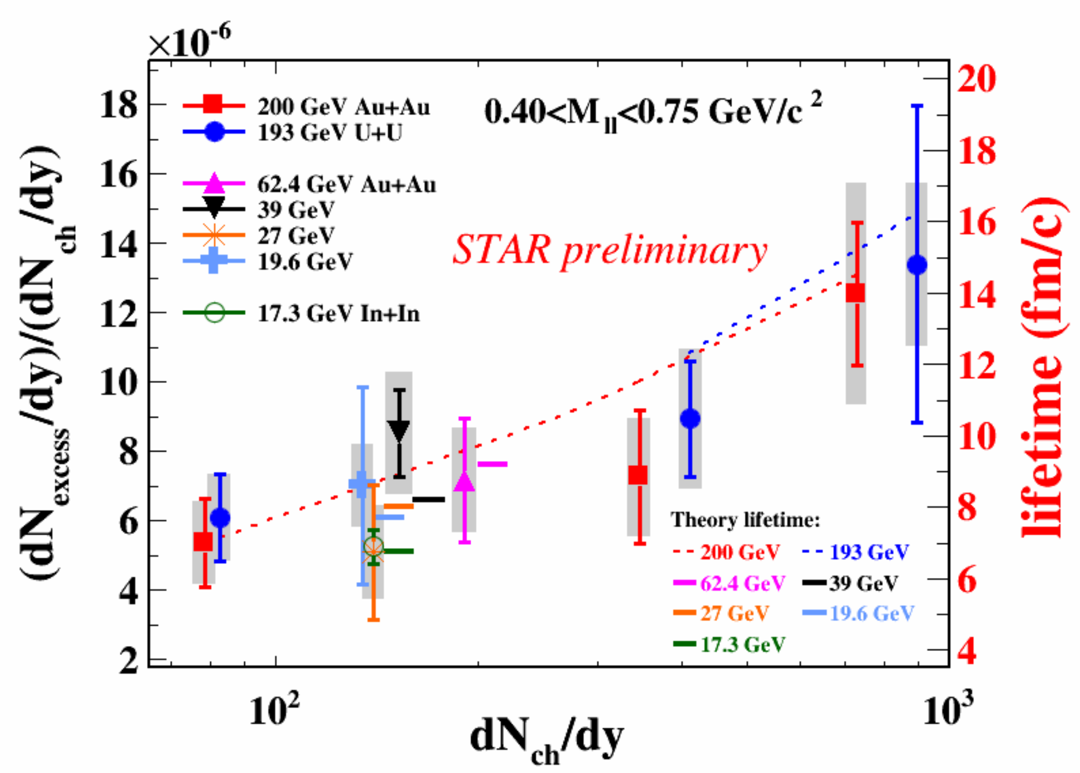


- longer in central collisions
- longer at higher energies

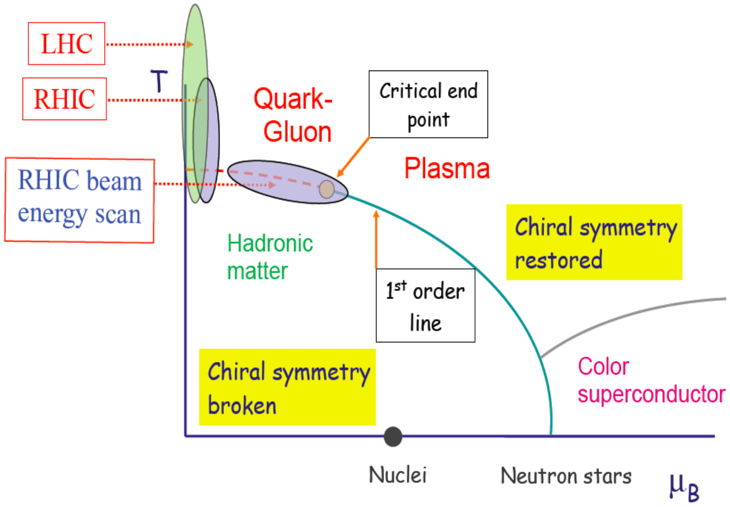
Van Hees and Rapp, Nucl. Phys. A 806, 339 (2008);
Rapp, Adv. High Energy Phys. 2013 148253 (2013)

Summary and outlook

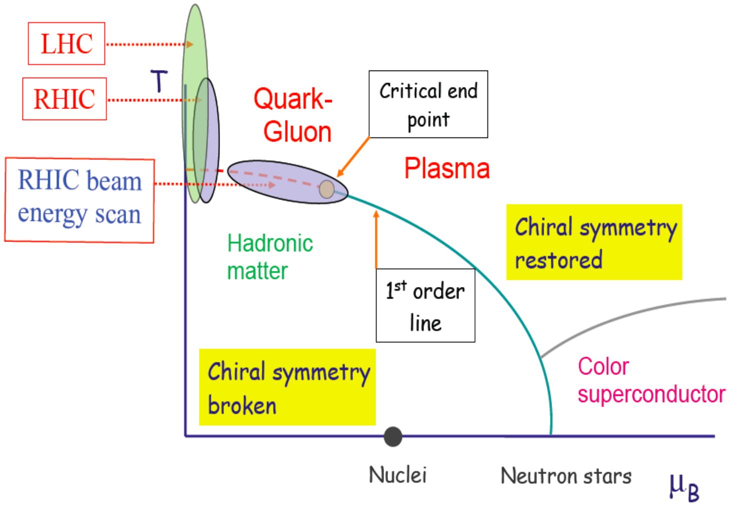
- Low-mass dielectron excess observed in a broad energy range
- Confirmed by different experiments (STAR, PHENIX, CERES, NA60, HADES)
- Current theoretical models reproduce the measurements (within the given precision) by dominantly introducing a broadening of the ρ spectral function as the system approaches the critical temperature
- To do list:
  - Precise determination of the charm contribution
  - Higher precision (statistics) to discriminate between the models
  - Test the models at lower temperatures and higher baryon densities
- Outlook:
  - STAR upgrade and BES II (2018 -)
  - ALICE upgrade (2020 -)
  - MPD@NICA (2019?)
  - FAIR (2022?)
  - JPARC – Heavy ion program?

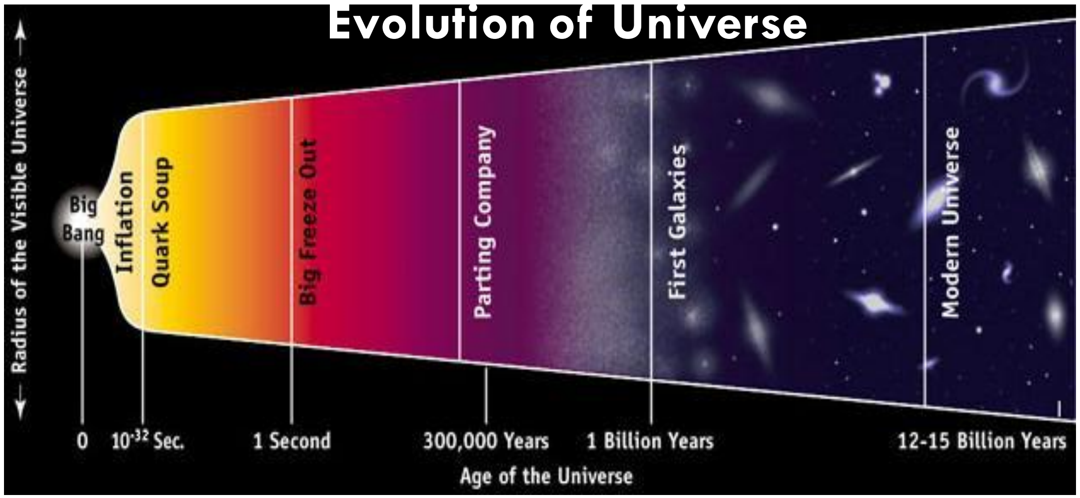
BACKUP

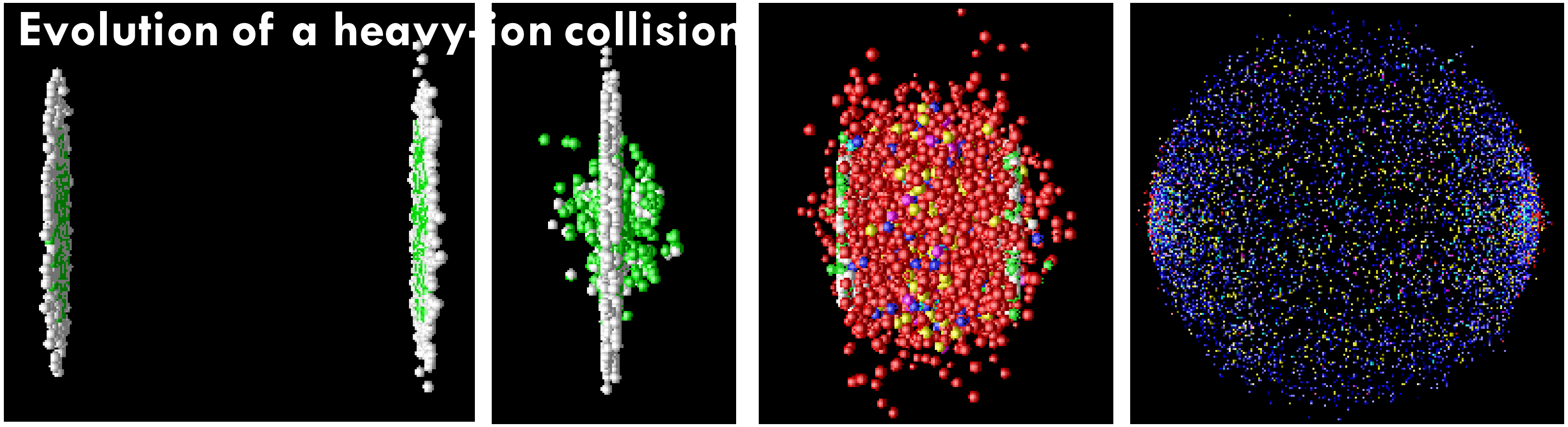
Why heavy ion collisions?



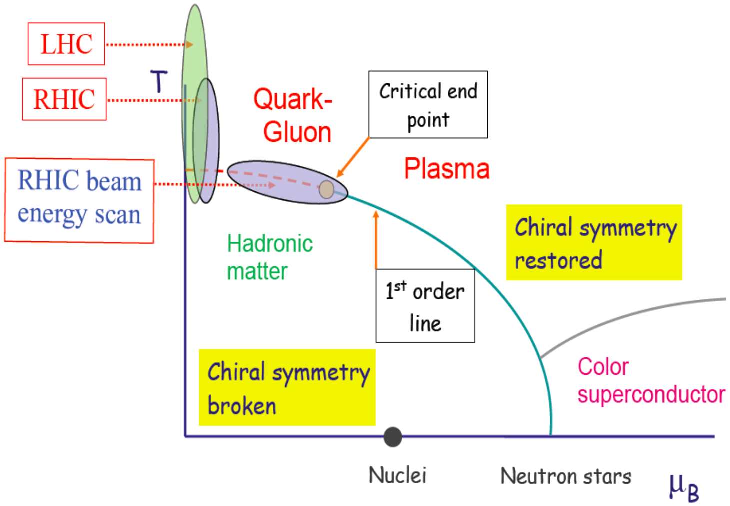
Why heavy ion collisions?

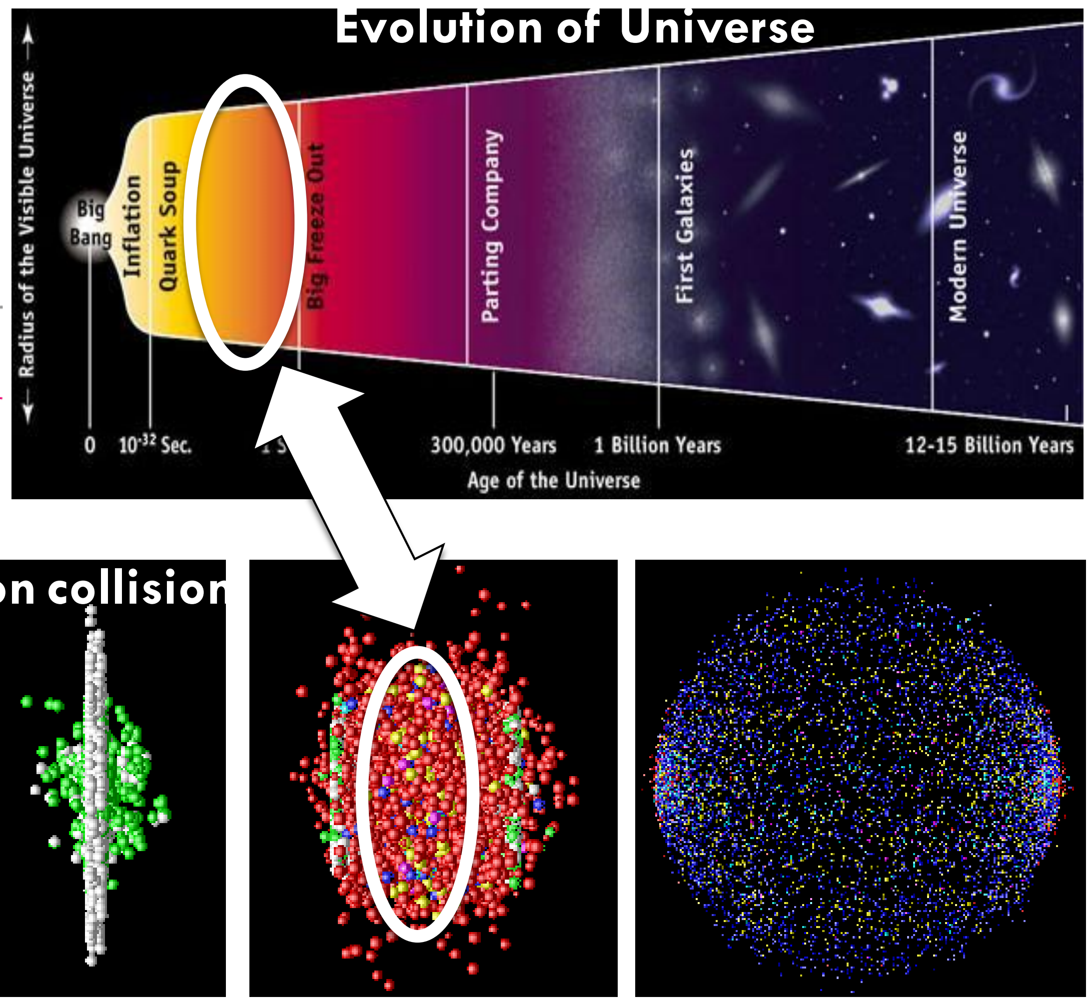






Why heavy ion collisions?

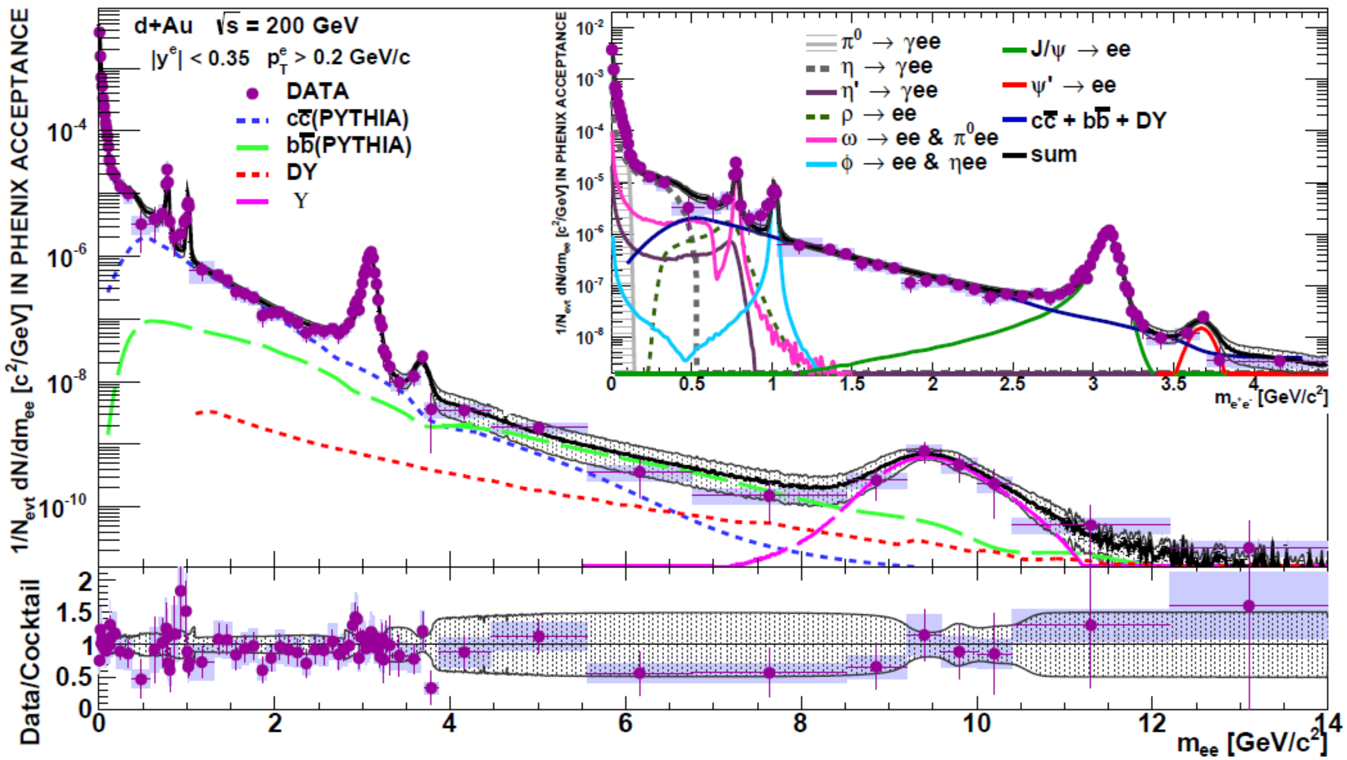




The reference systems: d+Au collisions

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

PHENIX PRC 91, 014907 (2015)



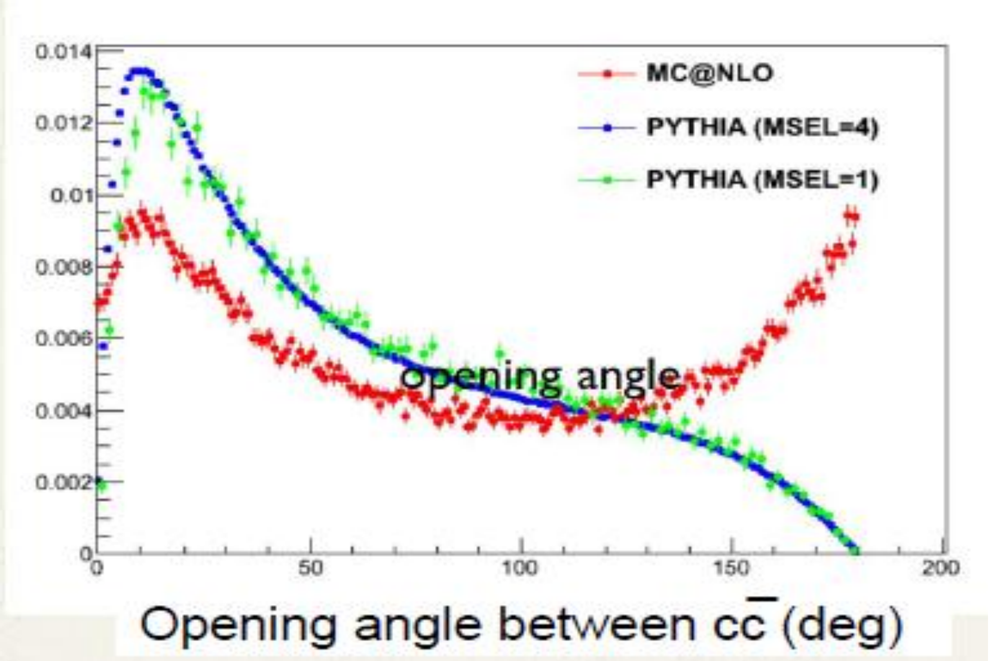
Data consistent with the cocktail within the uncertainties → no excess or suppression at any invariant mass → no considerable cold nuclear matter effect in dielectron channel

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))

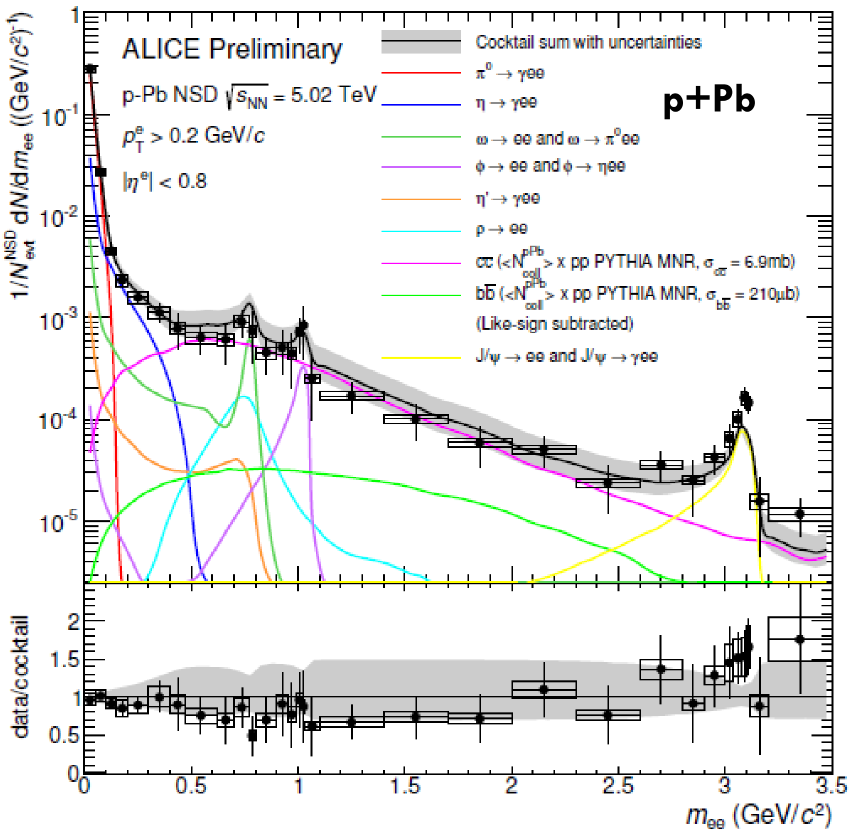
• The two models differ in extrapolation to lower invariant masses caused by their different charm p_t and opening angle distributions

• 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}

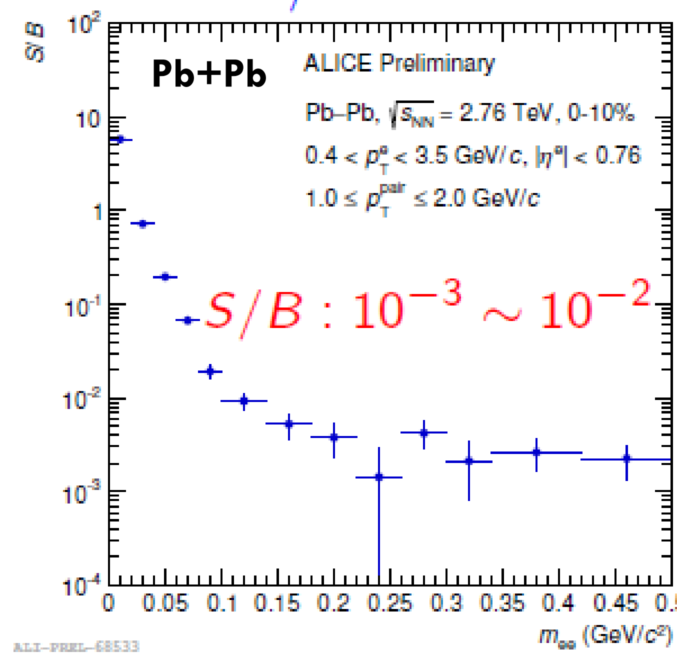


Dielectron measurements from ALICE

- 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



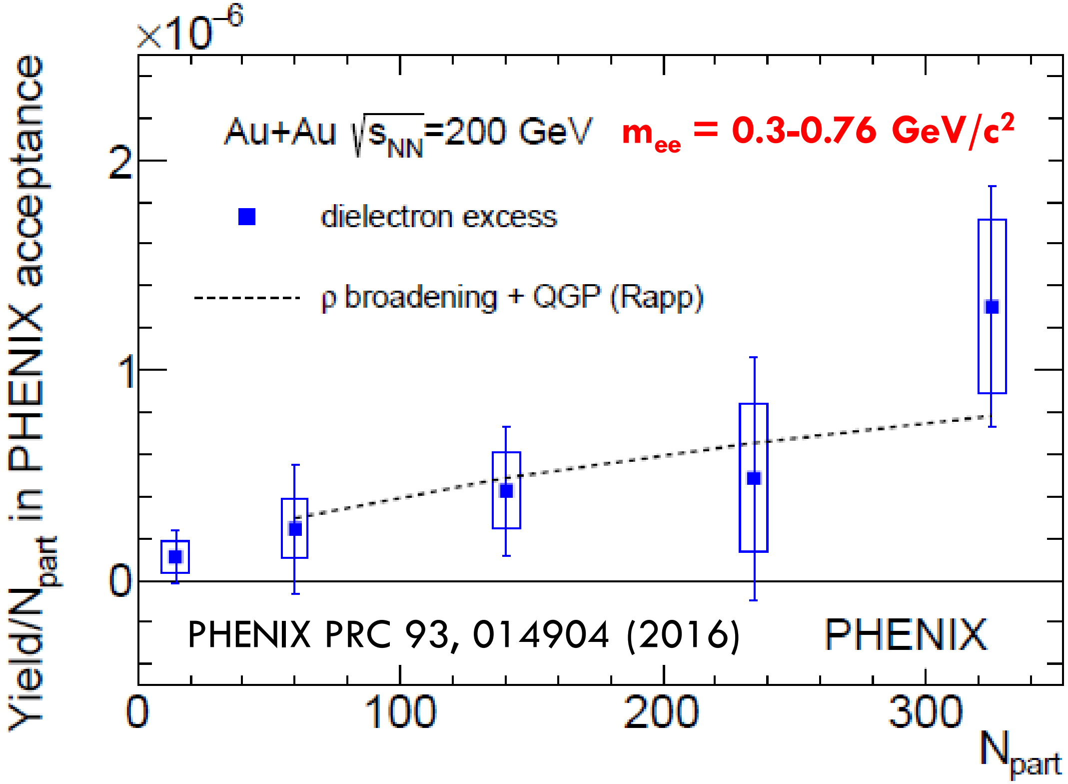
Comparison to model (PHENIX): centrality dependence

- Centrality dependence of the Rapp model consistent with the data

Model yield scales with:

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

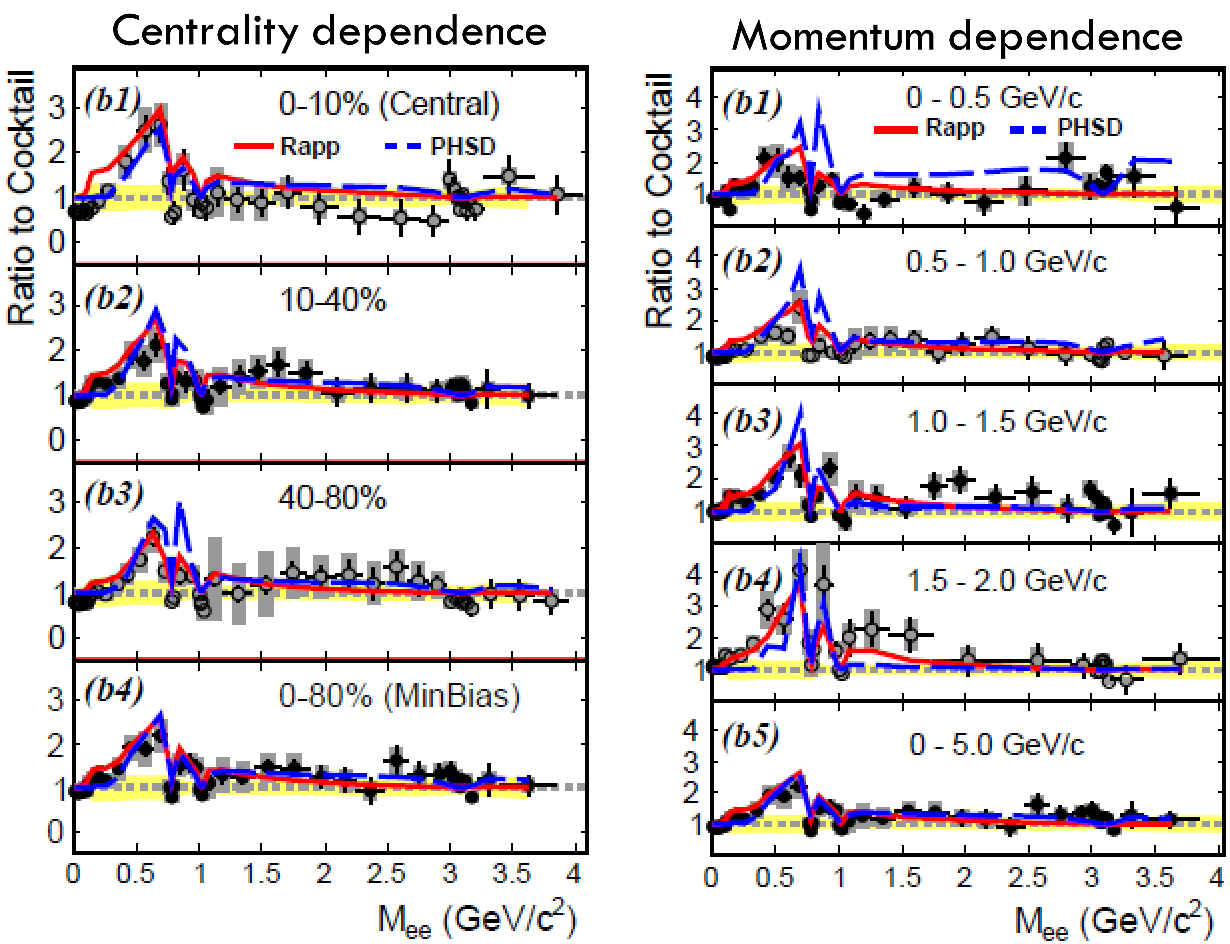
(R. Rapp)



Comparison to models (STAR vs. Rapp and PHSD)

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

STAR, PRC 92, 24912 (2015)



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

More about Rapp’s model

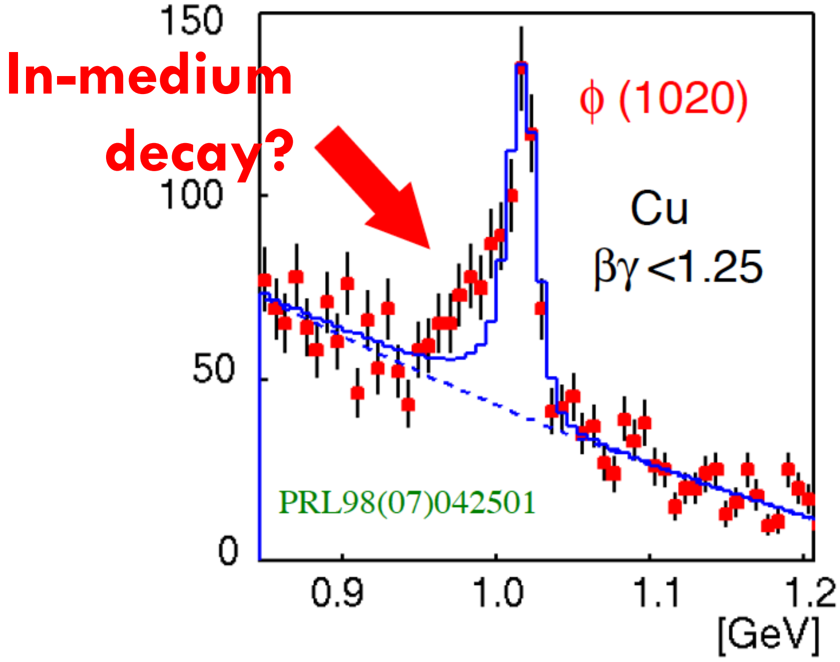
- In the LMR the spectral function is dominated by vector mesons, ρ in particular. The latest model includes non-perturbative QCD EoS and QGP emission (qq annihilation at $T>T_c$) based on lattice QCD
- Dilepton rates calculated by integration of the thermal rates over the space-time evolution of the 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.

Alternative approaches to explain the low mass enhancement?

- 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!

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)

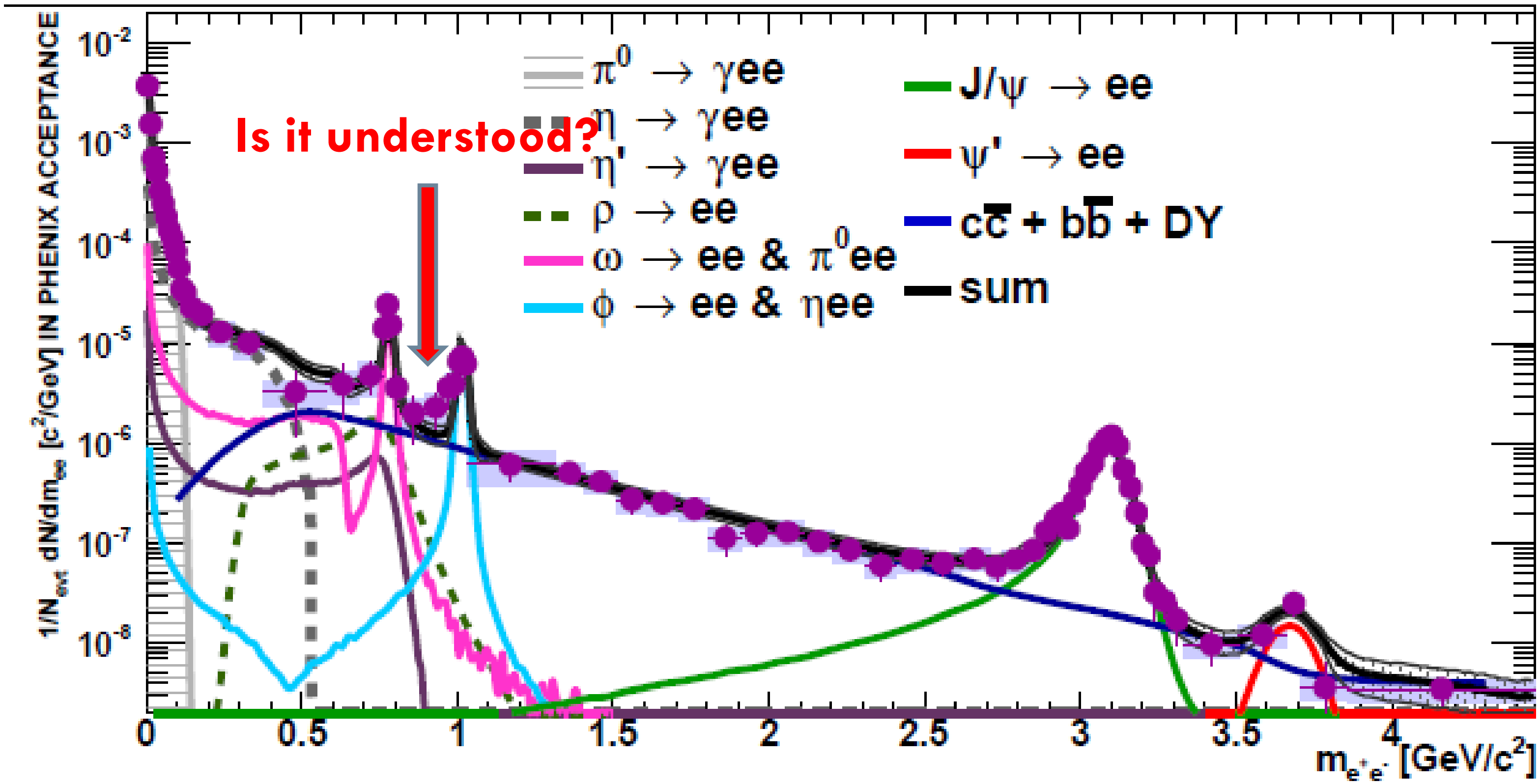


The proposed E16 experiment to:
- boost the statistics x100
- to double the resolution

→ Allow mass separation

In-medium ϕ from PHENIX

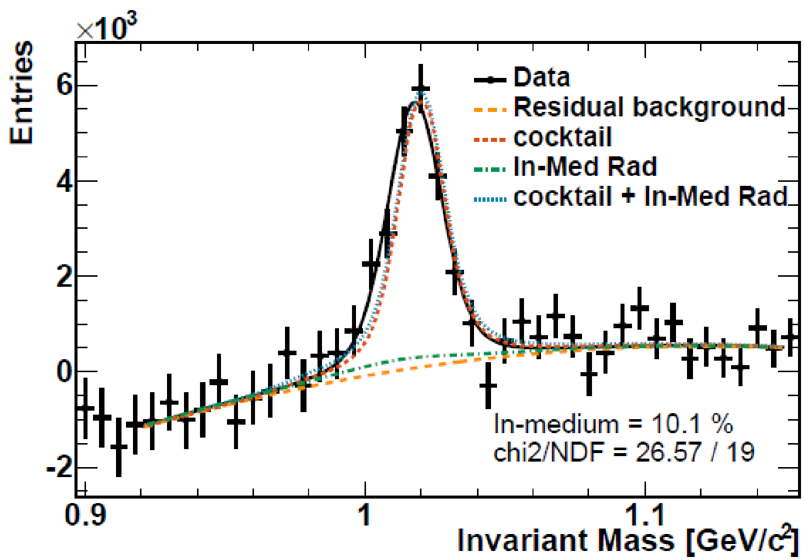
- ϕ->ee from d+Au collision at 200 GeV

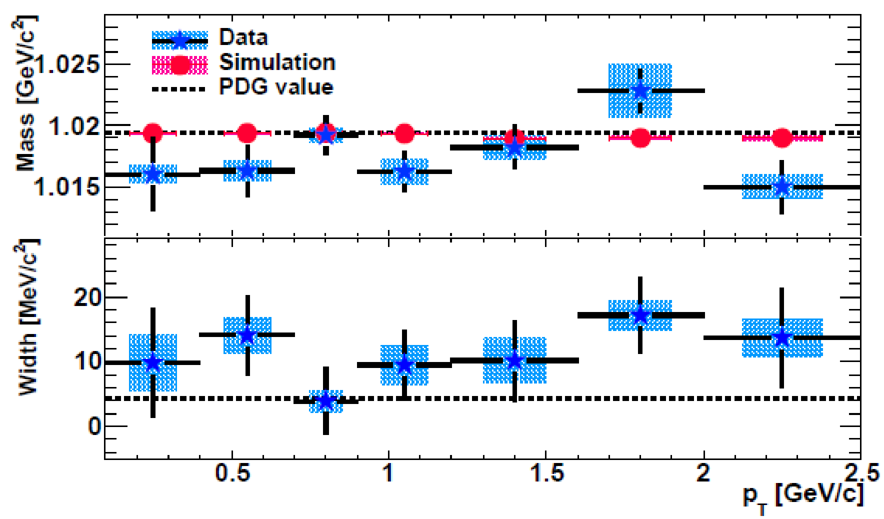


PHENIX PRC 91, 014907 (2015)

In-medium ϕ from STAR

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





arXiv:1503.04217