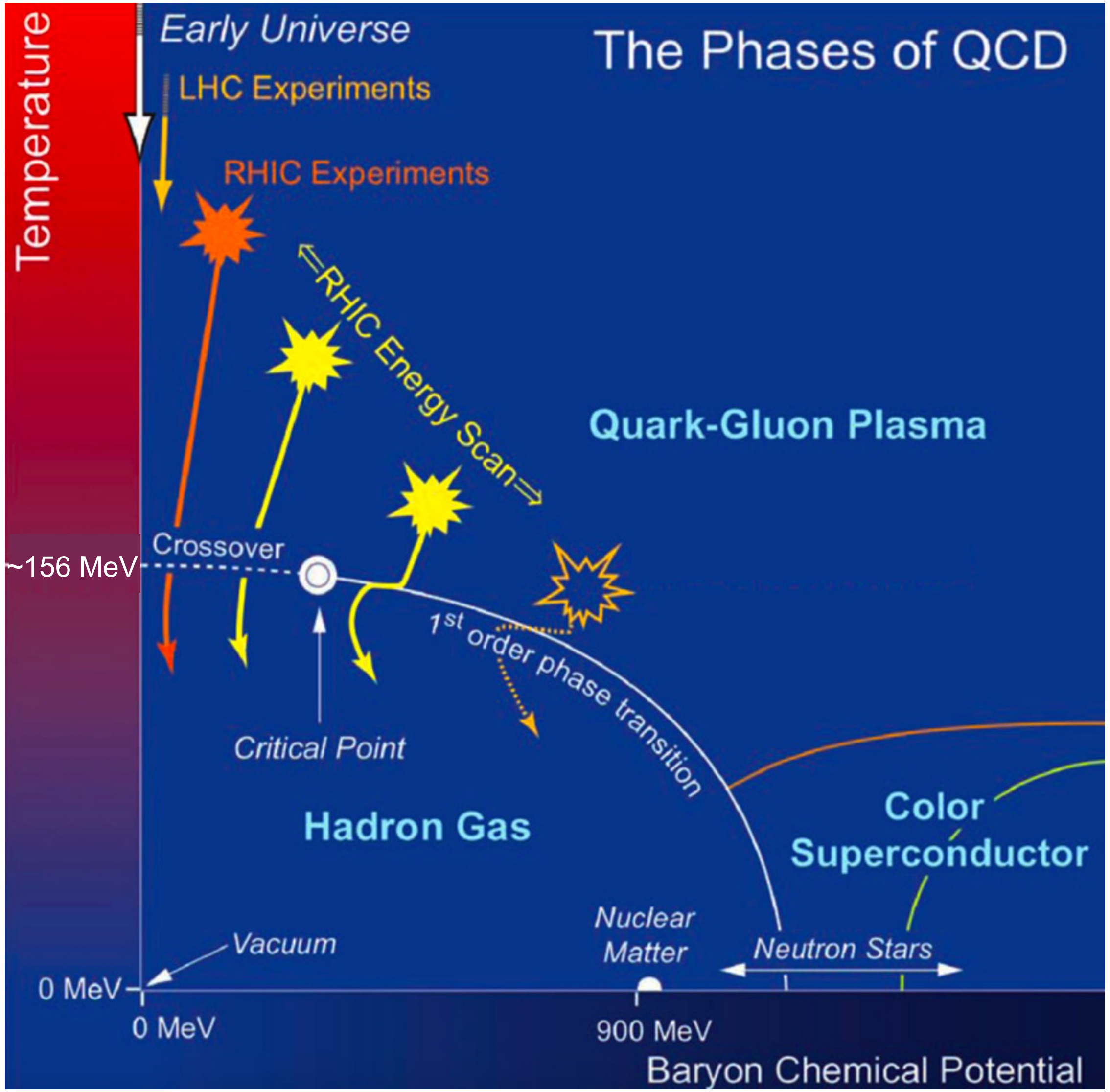
Thermal Dileptons with Beam Energy Scan Program at RHIC

Zaochen Ye (Rice University)

Supported in part by the U.S. DEPARTMENT OF ENERGY | Office of Science

RICE

QCD Phase Diagram and RHIC Beam Energy Scan



STAR White Paper 2014

- **Determine QCD phase diagram via high energy heavy-ion collisions.**
- **Formation of QGP**
- **Crossover at μ_B close to 0**
- **1st-order phase transition**
- **Critical point**

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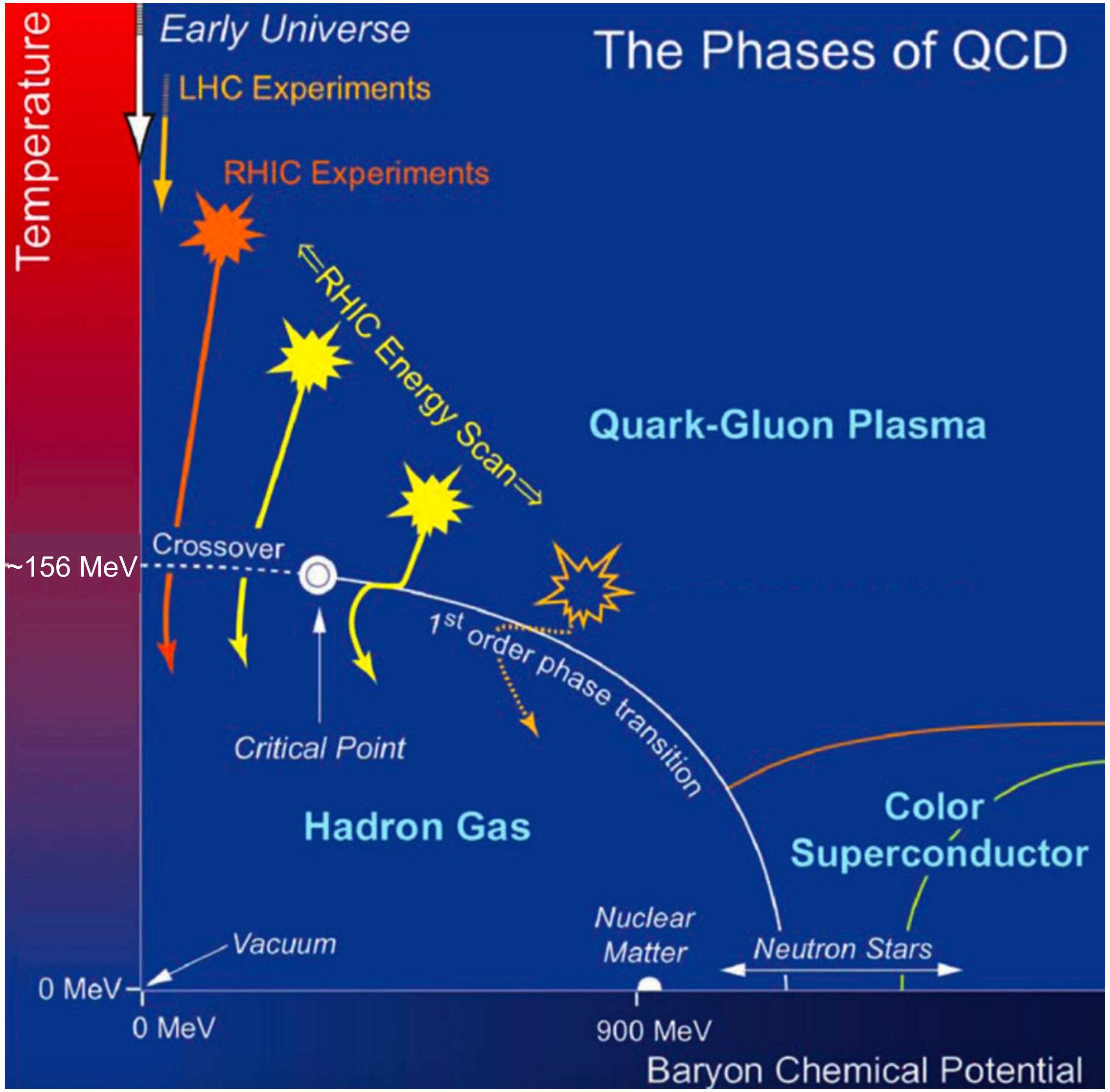
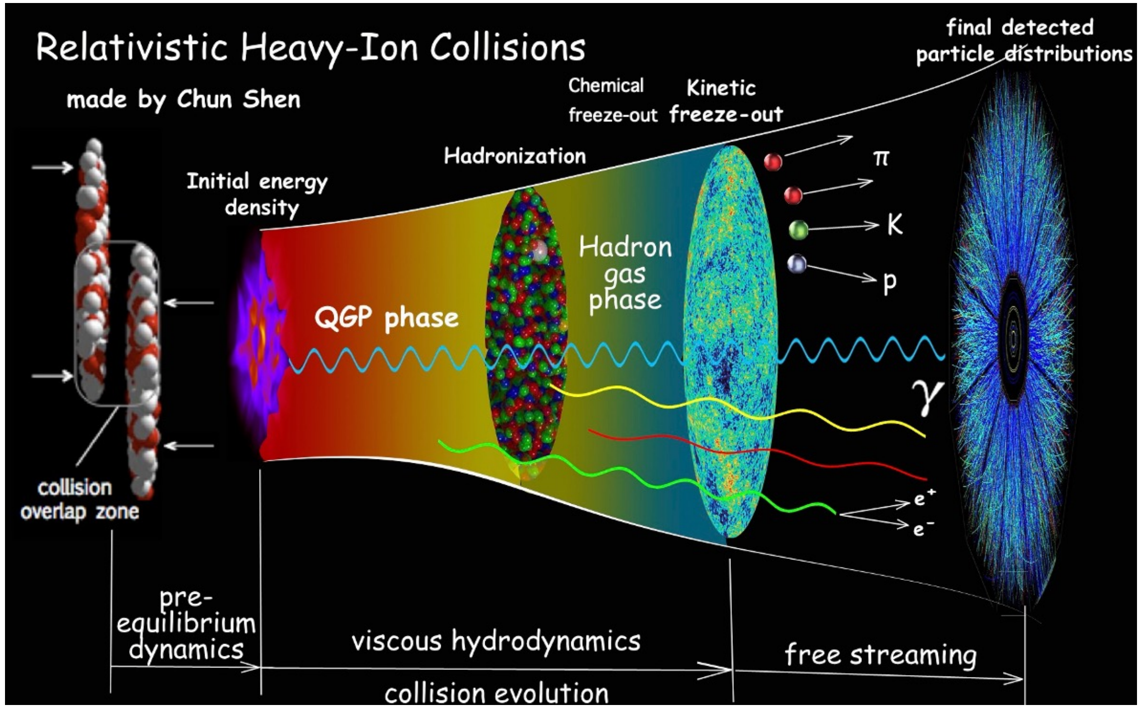


- **Determine QCD phase diagram via high energy heavy-ion collisions.**
- **Formation of QGP**
- **Crossover at μ_B close to 0**
- **1st-order phase transition at high μ_B**
- **Critical point**
- **Beam Energy Scan program at RHIC:**
  - **Vary initial T and μ_B**
  - **Explore different reaction trajectories cross phase boundary**

[STAR White Paper 2014]

Heavy-Ion Collision and Why Dileptons



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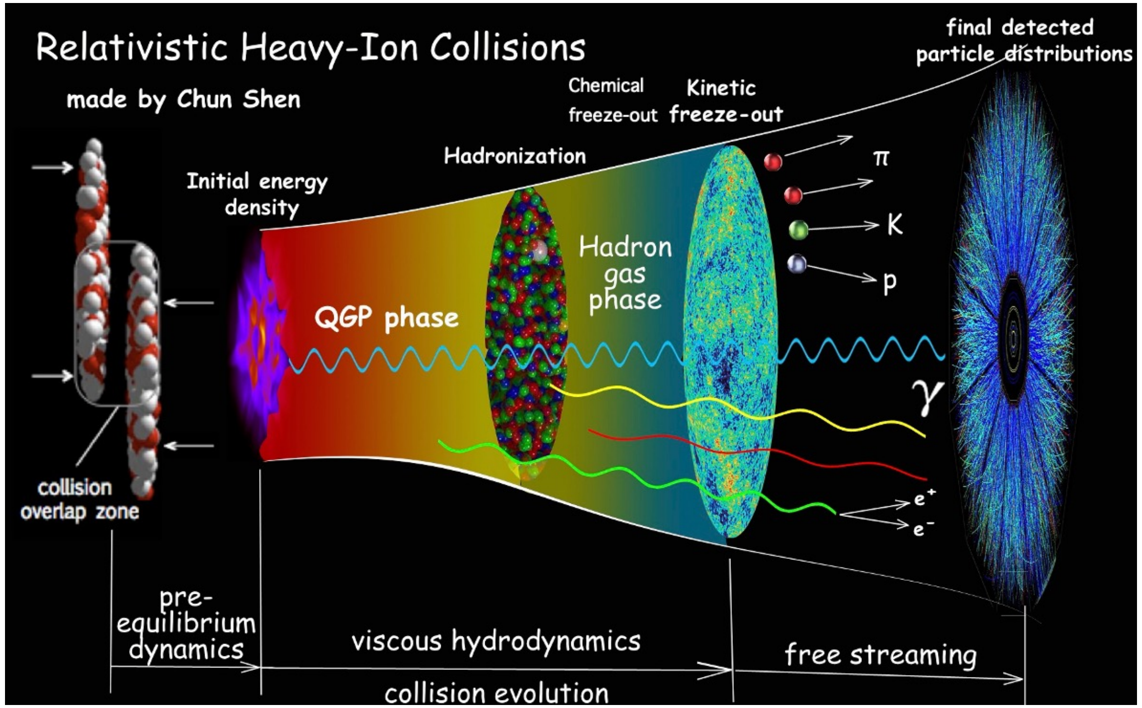

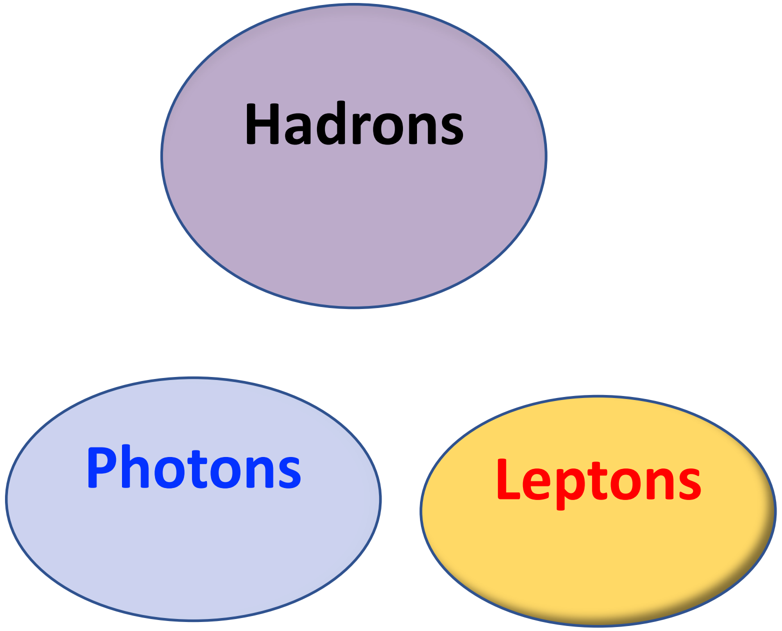

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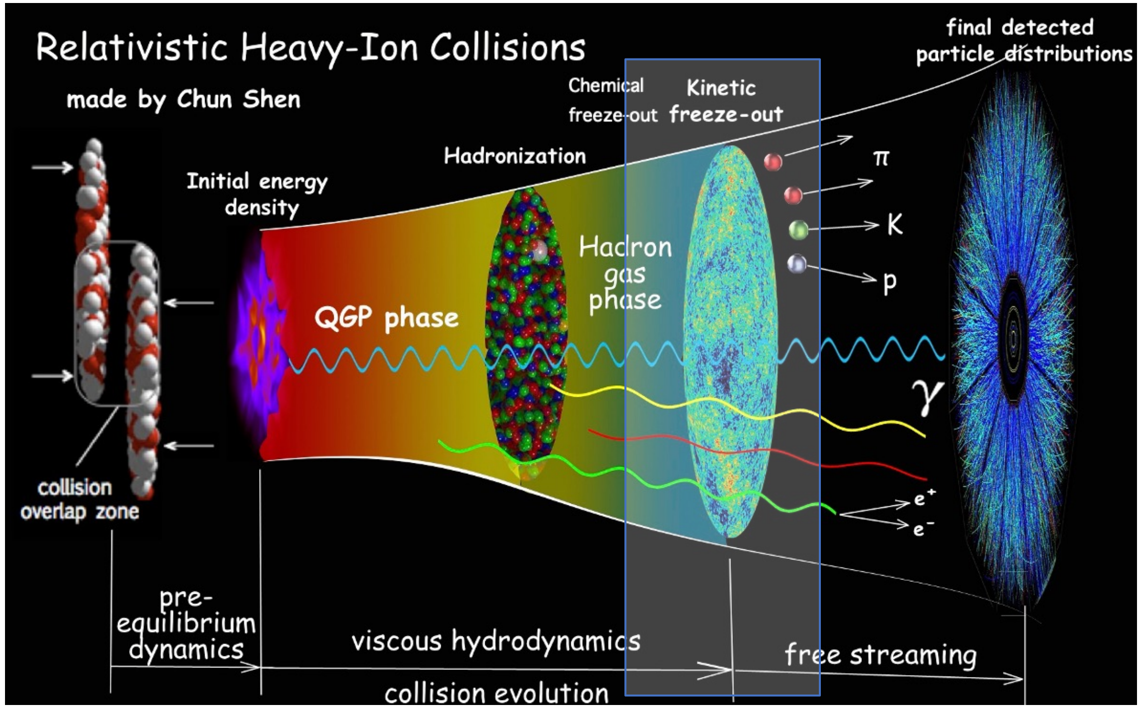

- **Most produced**
- **Freeze-out temperature: T_{ch}, T_{kin}**
- **Limitation: formation and decouple**

Hadrons
(Yield, p_T)

Photons

Leptons

T at early stage is still poorly known ☹

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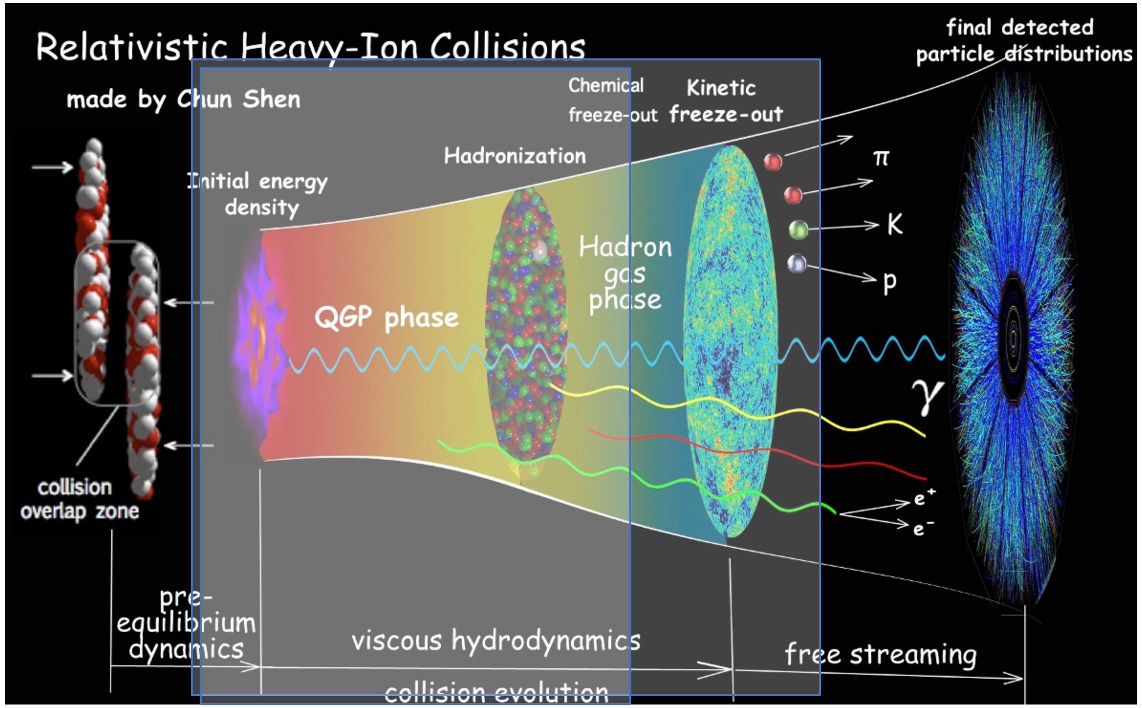

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- **Early to final stages**
- **Escape freely**
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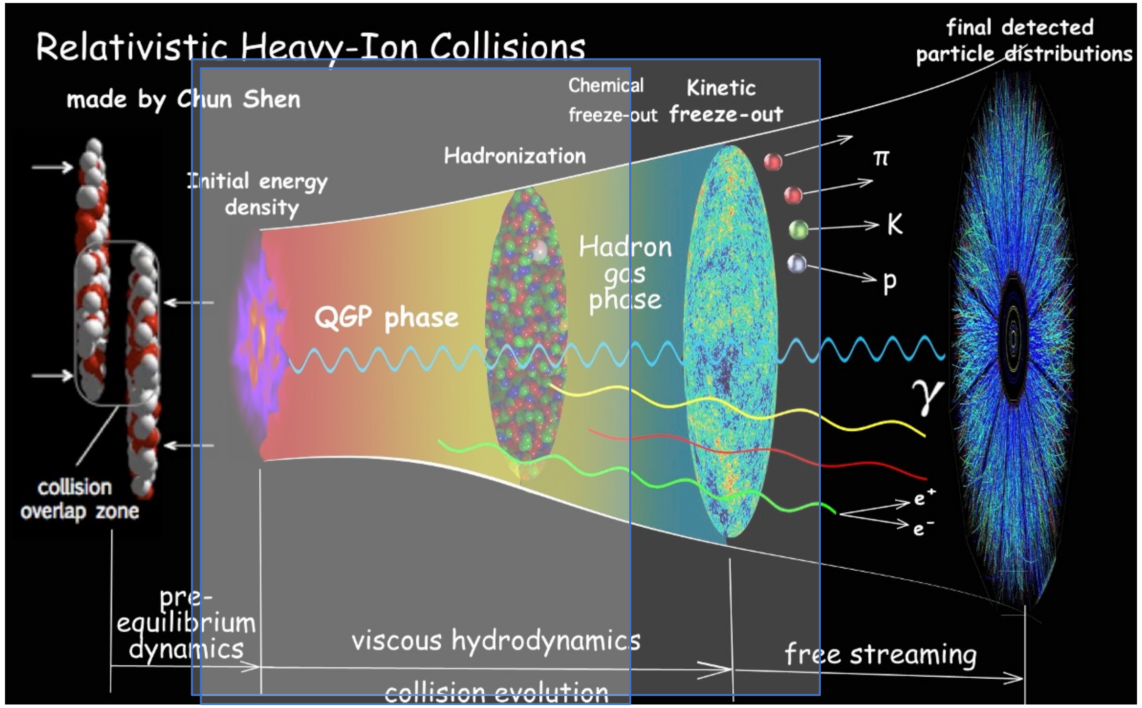

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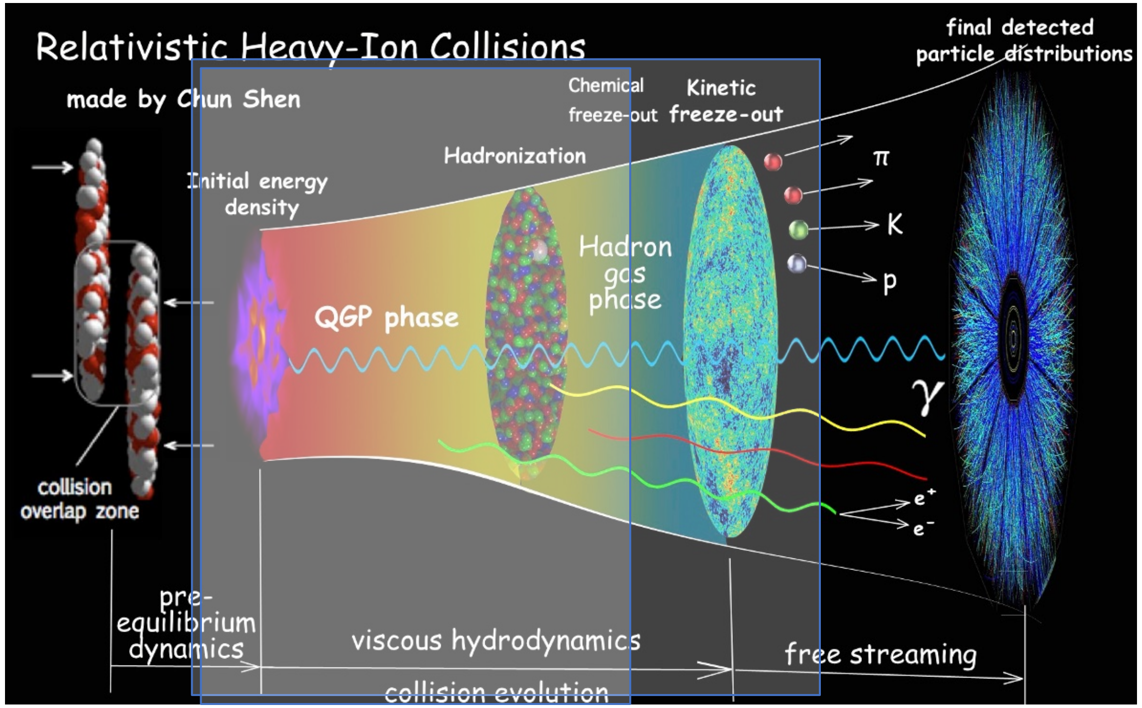

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Leptons (M_{ll})

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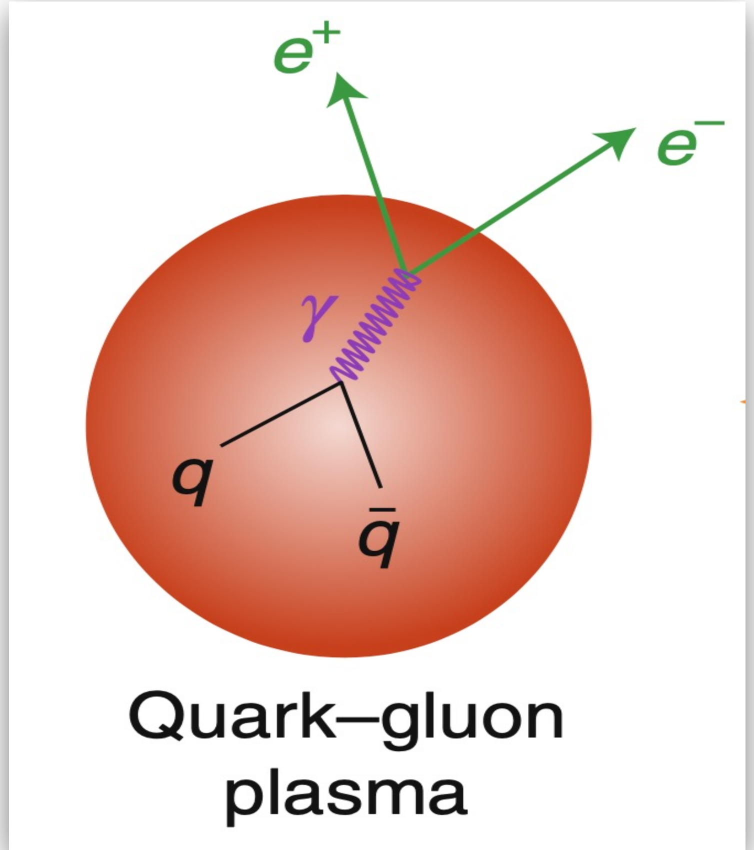
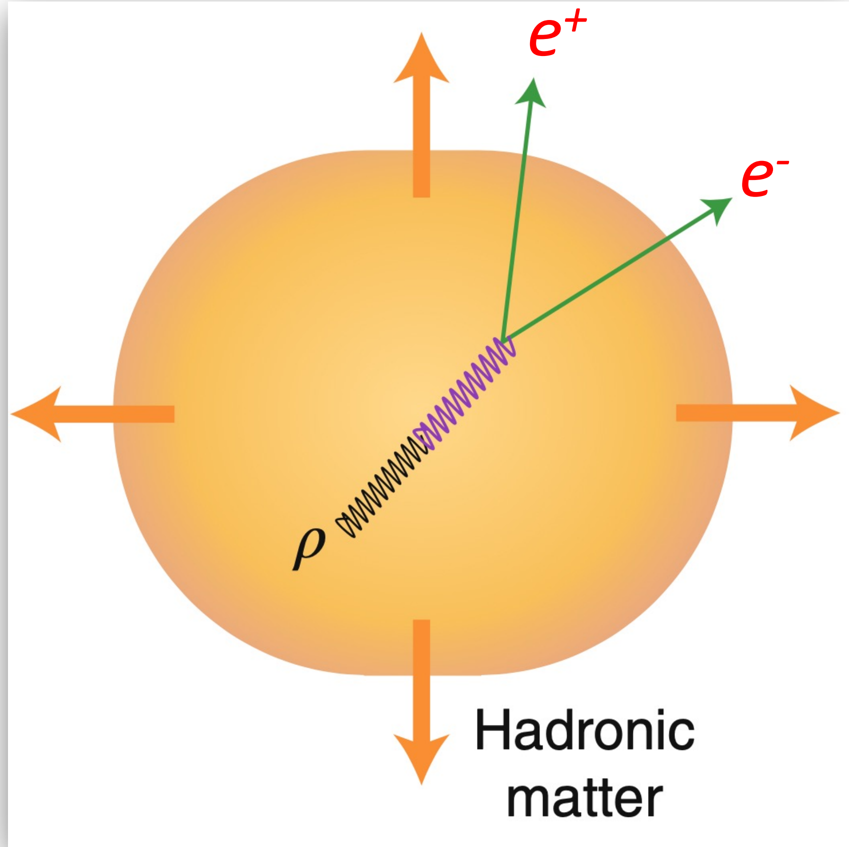
Dileptons

- **Temperature without blue-shift effect**
- **Only observable to directly access in-medium spectral function**

T at early stage is still poorly known ☹

Heavy-Ion Collision and Why Dileptons





$q + \bar{q} \longrightarrow \gamma^* \longrightarrow e^+ + e^-$ Courtesy of Ralf Rapp $\pi^+ + \pi^- \longrightarrow \rho \longrightarrow e^+ + e^-$

Thermal dileptons can direct access the hot QCD medium at both QGP phase and hadronic phase

How to Measure Thermal Dileptons?

Inclusive signals
(space-time integral)

Interested signals:
- **QGP radiation**
- **In-medium ρ decays**

+

Physical background (Cocktails):
- **Drell-Yan**
- $\pi^0, \eta, \eta' \rightarrow \gamma e^+e^-$
- $\omega, \varphi \rightarrow e^+e^-, \omega \rightarrow \pi^0 e^+e^-, \varphi \rightarrow \eta e^+e^-$
- $J/\psi \rightarrow e^+e^-, c\bar{c} \rightarrow e^+eX$

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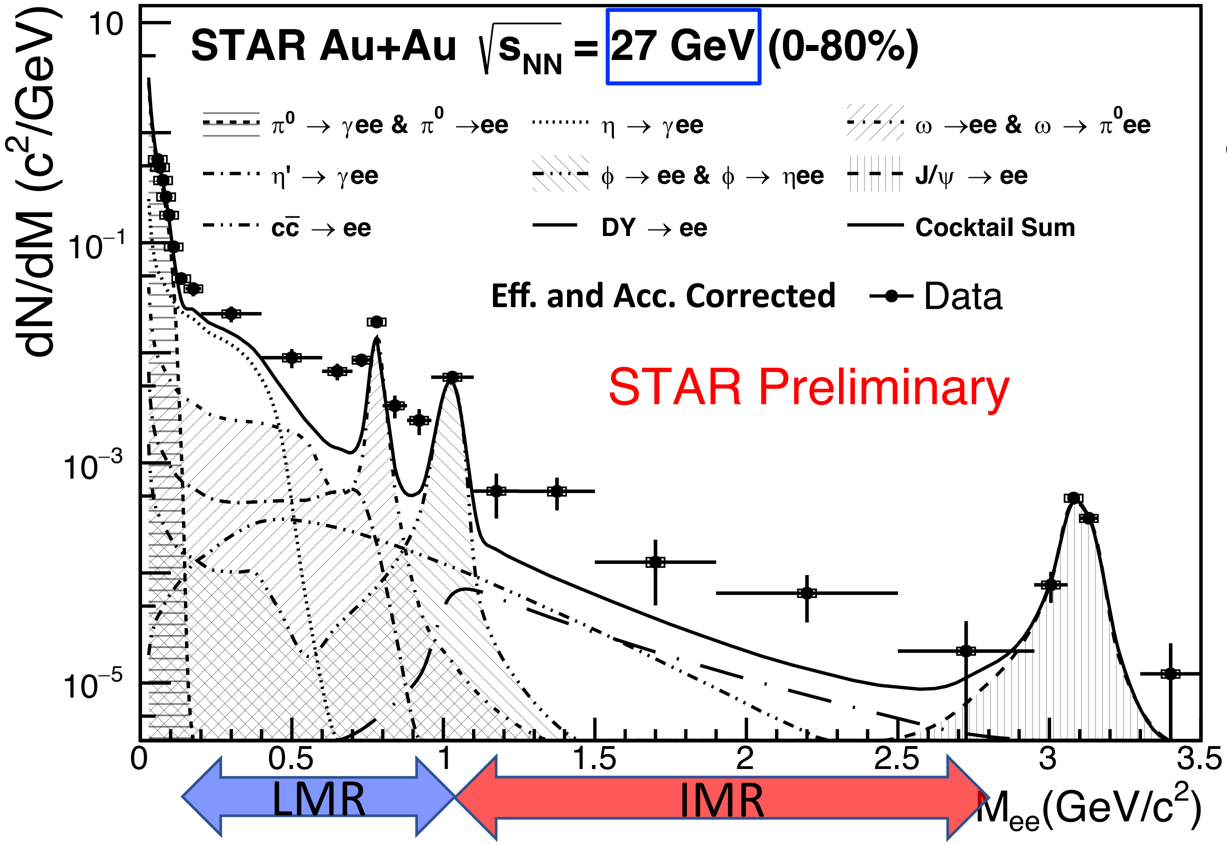
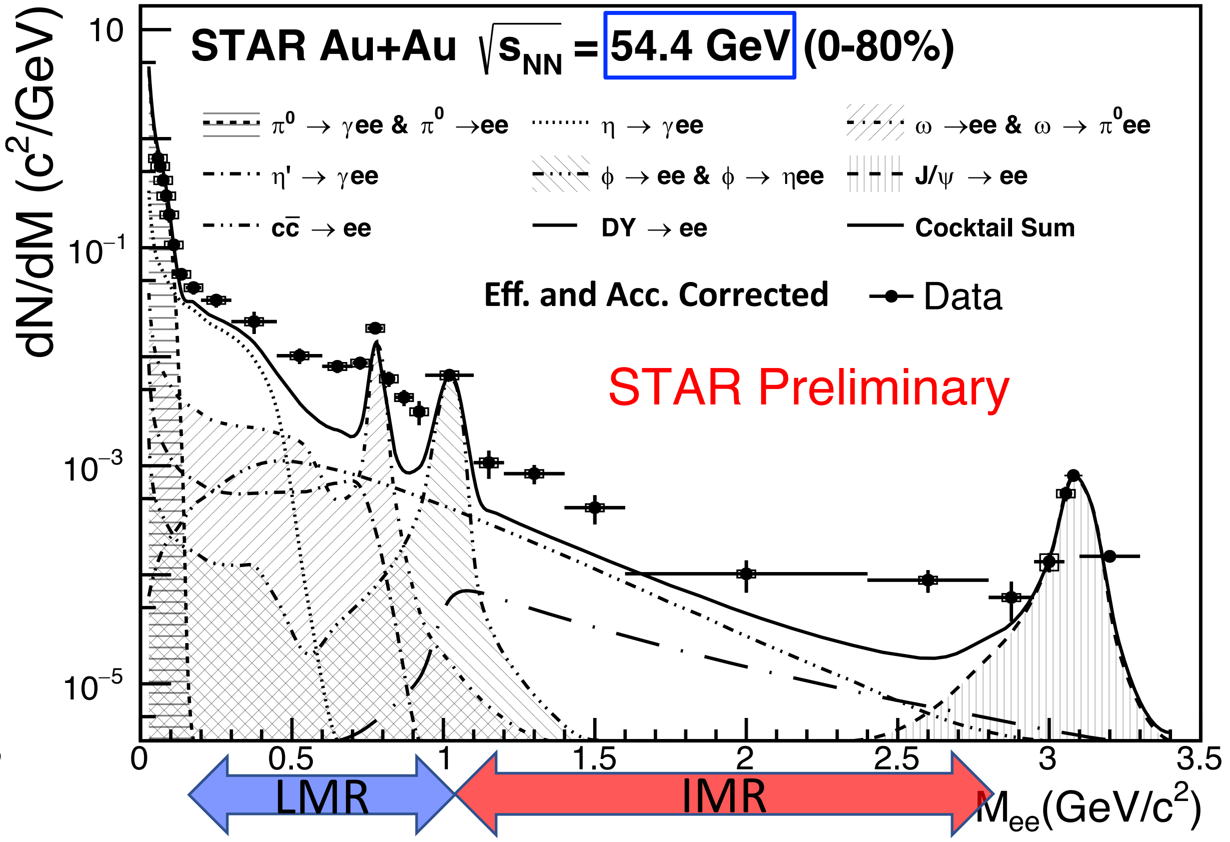
Physical background can be determined using the well-established cocktail simulation techniques

🔥 **Interested signals** = **Inclusive signals** − **Physical background** ❄️

Examples of Data vs. Cocktail

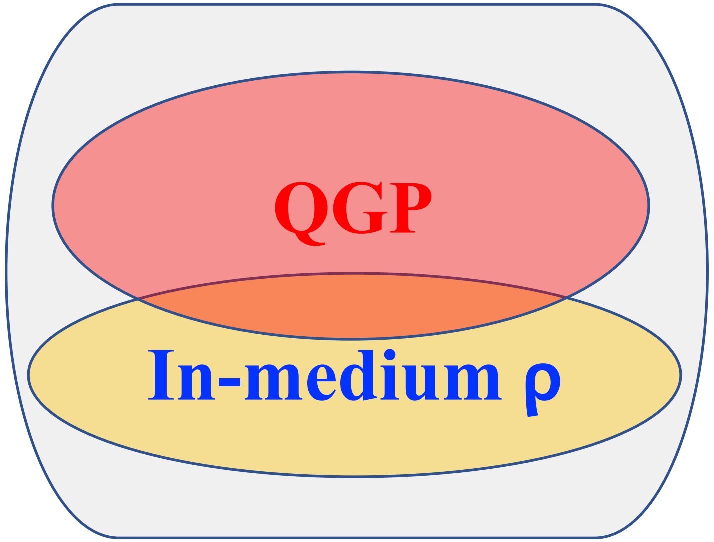




Clear enhancement compared to cocktail contributions in both low mass region (**LMR**) and intermediate mass region (**IMR**)

Dileptons as a Thermometer of Hot Medium

Emission source



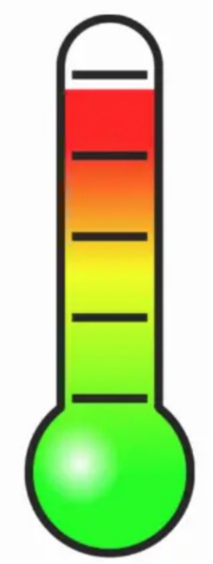
Mass analyzer

QGP: $M^{3/2} * e^{-M/T}$

In-med. ρ: Breit-Wigner $* \ e^{-M/T}$

Rapp and v. Hess, PLB 753 (2016) 586
Shuryak and Brown, NPA 717, 322 (2003)
STAR, PRL 92, 092301 (2004)

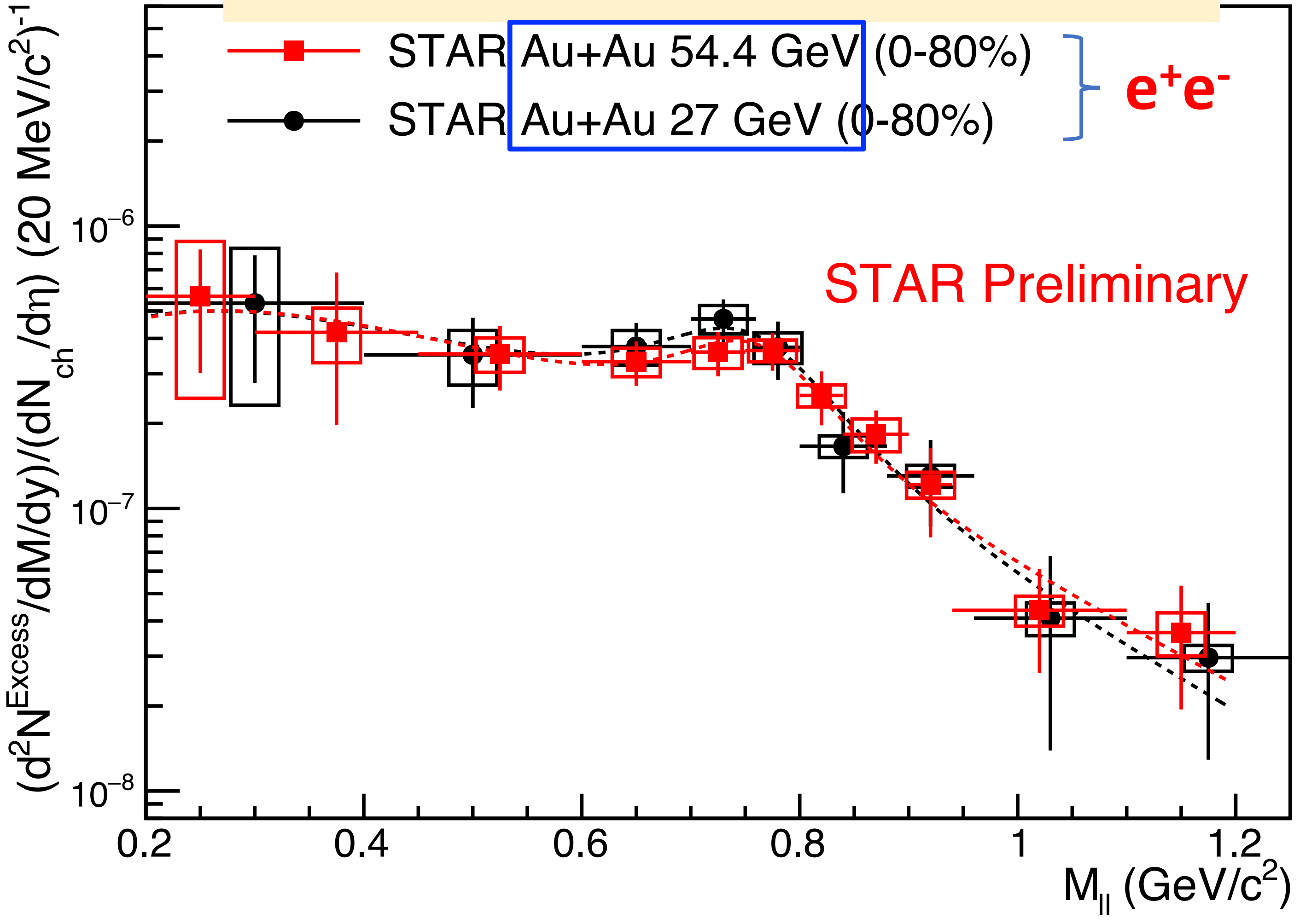
Thermometer



How thermal dileptons distribute their invariant mass will reveal the temperature of their emission source

LM Thermal Dilepton

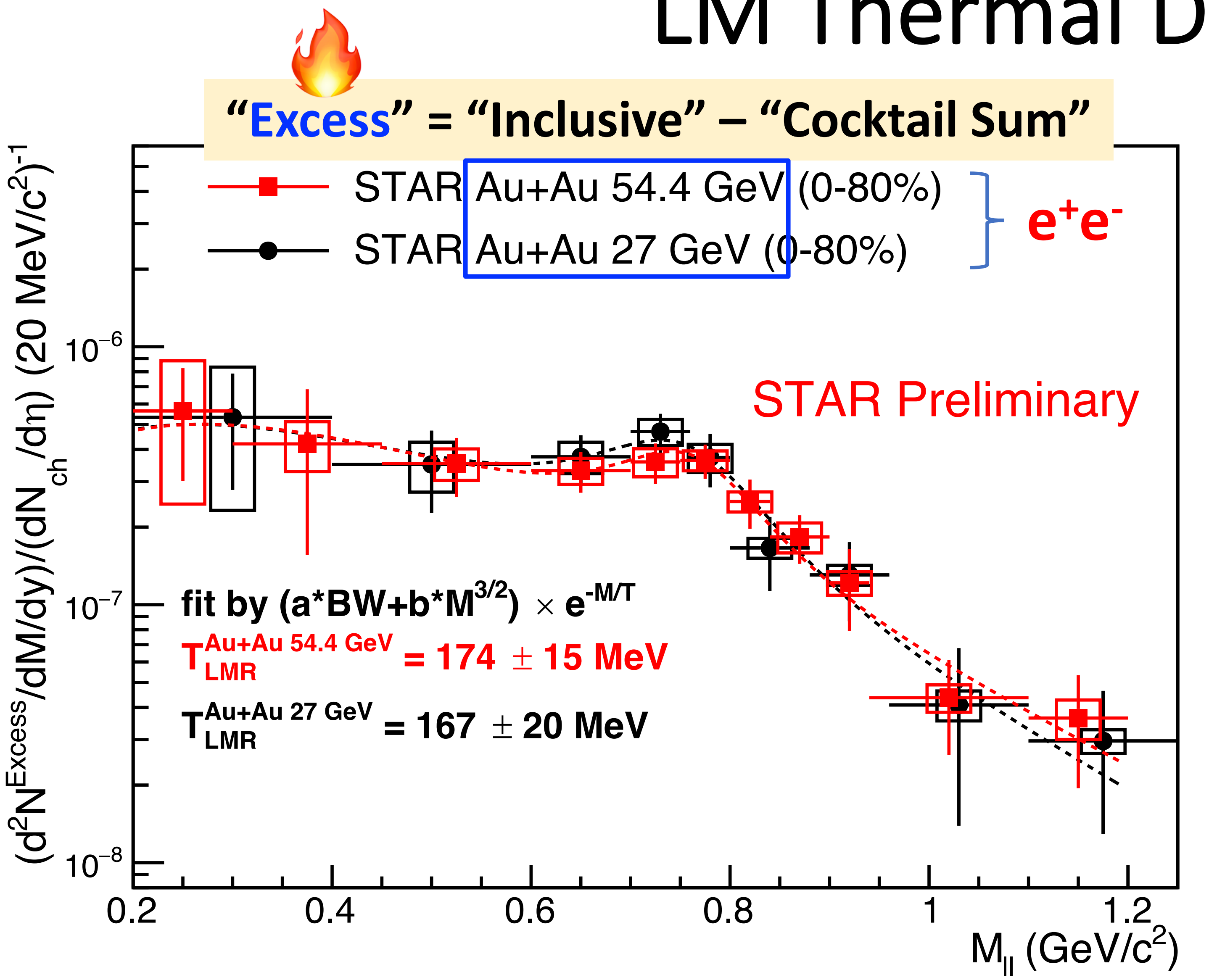
"**Excess**" = "Inclusive" – "Cocktail Sum"



In-medium ρ dominated

Similar mass spectrum

LM Thermal Dilepton



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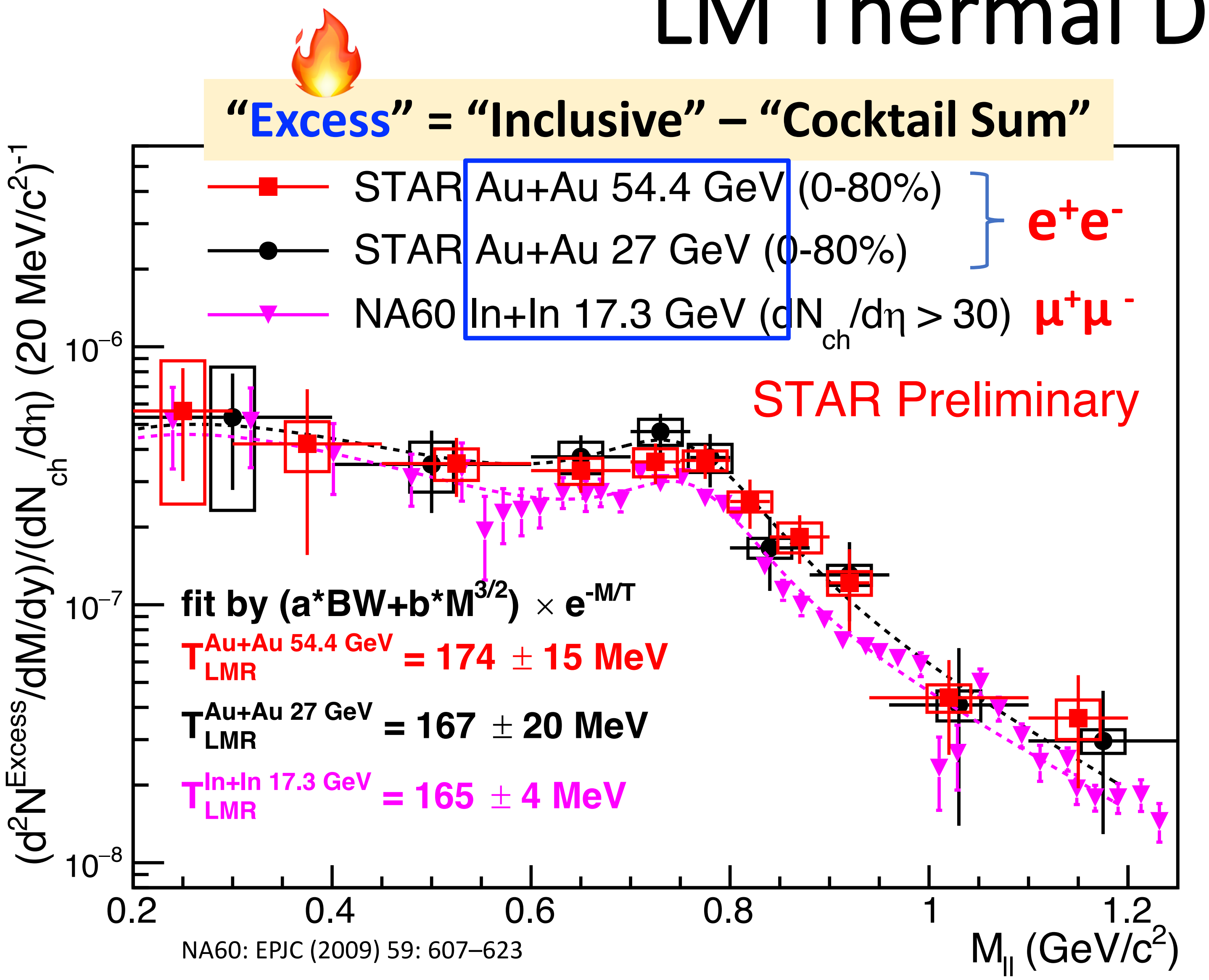

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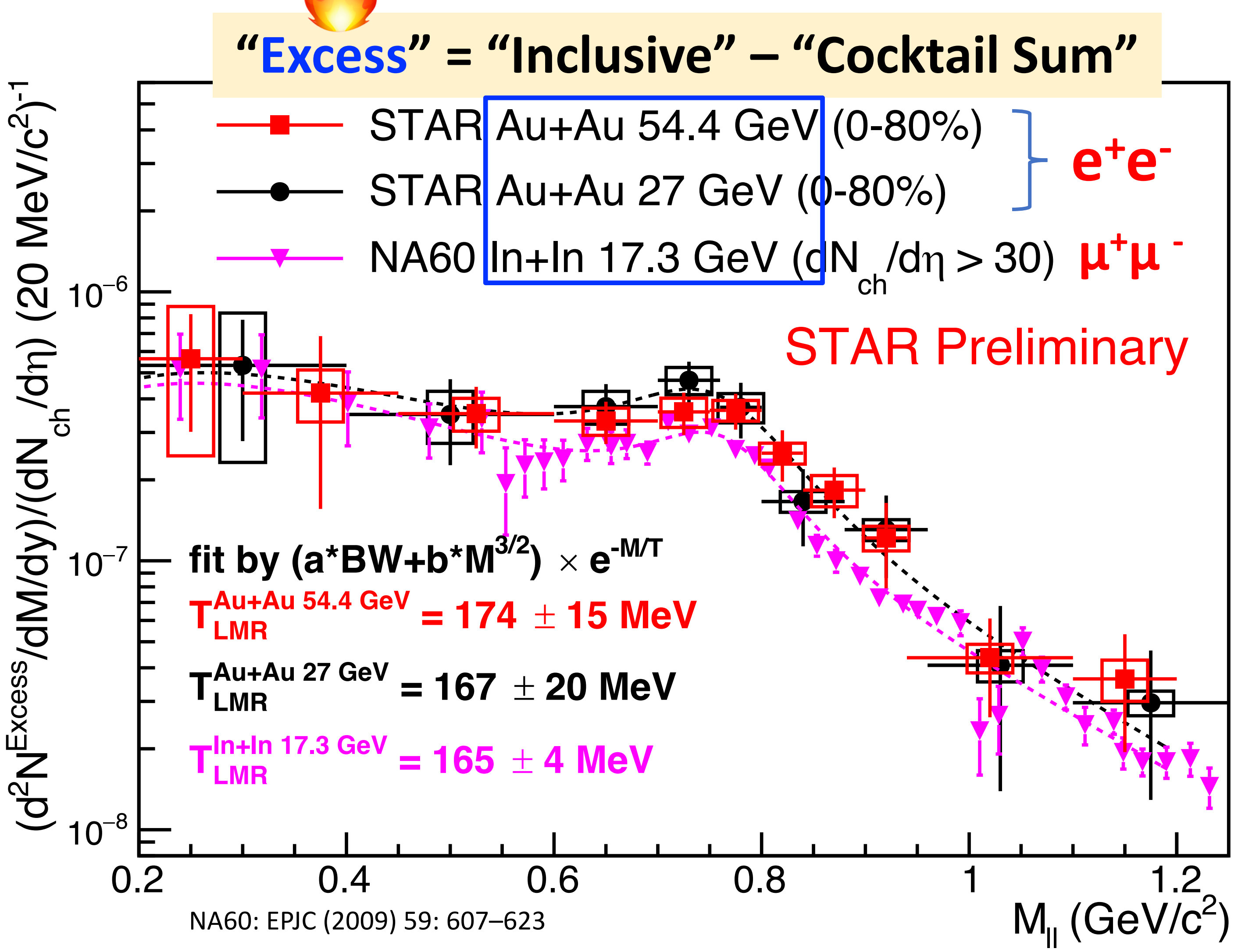


In-medium ρ dominated

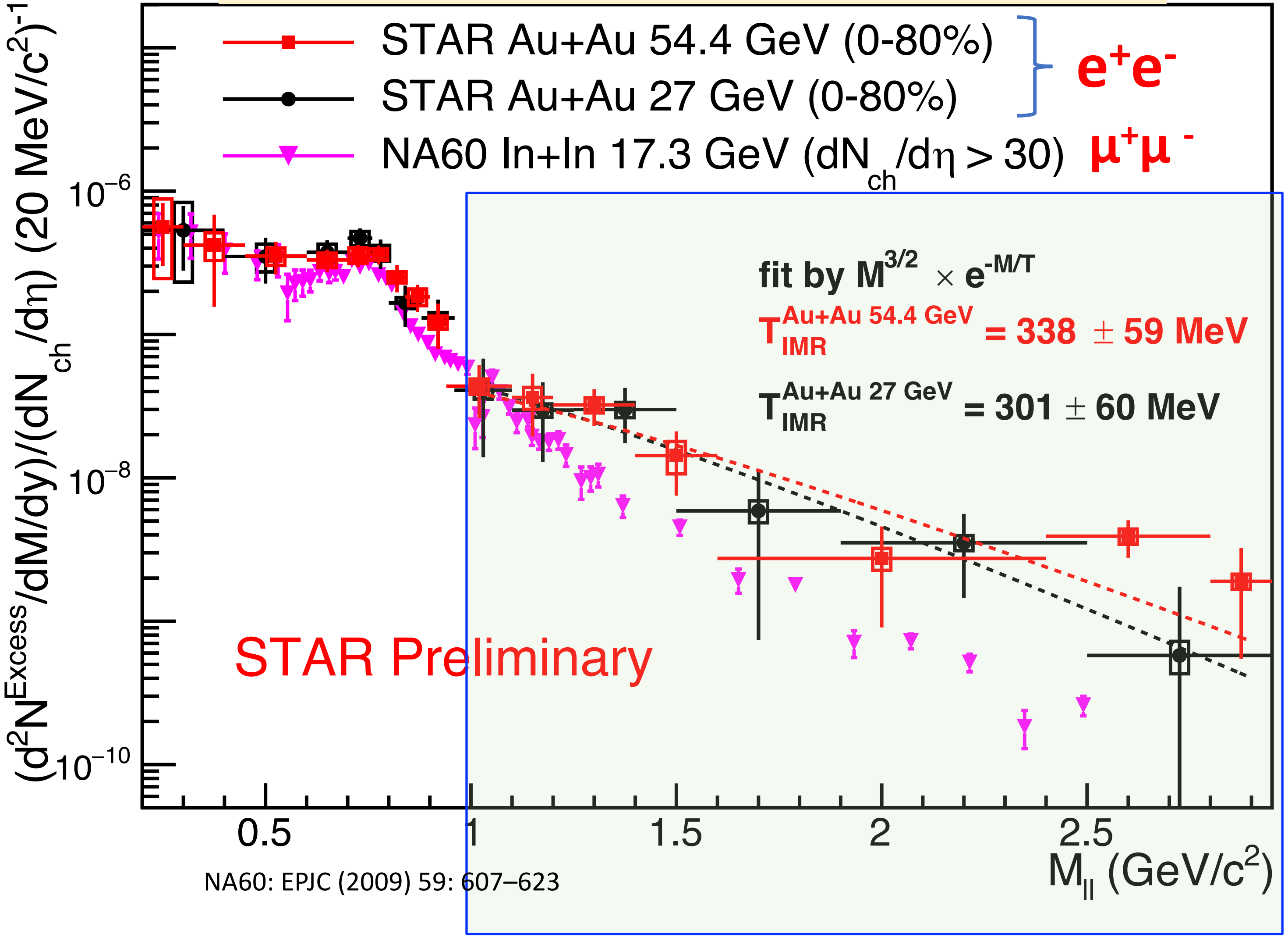
Similar mass spectrum

Similar temperature

In medium ρ is produced from a "**similar hot bath**" in 27/54.4 GeV Au+Au and 17.3 GeV In+In

IM Thermal Dilepton

"Excess" = "Inclusive" – "Cocktail Sum"



QGP dominated

T_{IMR} from STAR data: ~ 320 MeV

T_{IMR} from NA60 data:

- **205 ± 12 MeV** (1.2<M<2.0 GeV/c^2) [1]
- **246 ± 15 MeV** (1.2<M<2.5 GeV/c^2) [2]

[1]: Hans J. Specht, AIP Conf. Prcd 1322, 1 (2010)
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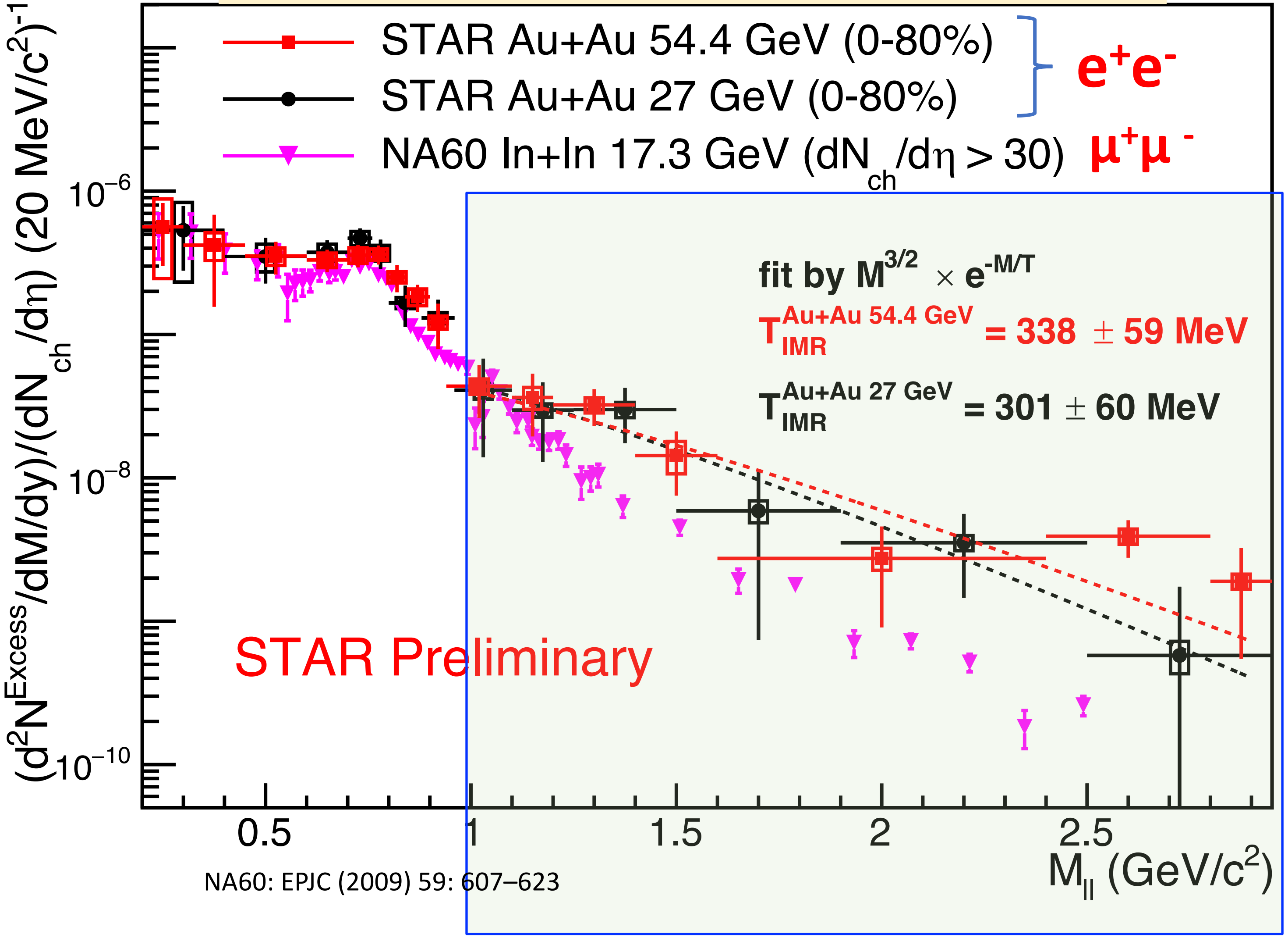

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LM+IM Thermal Dilepton

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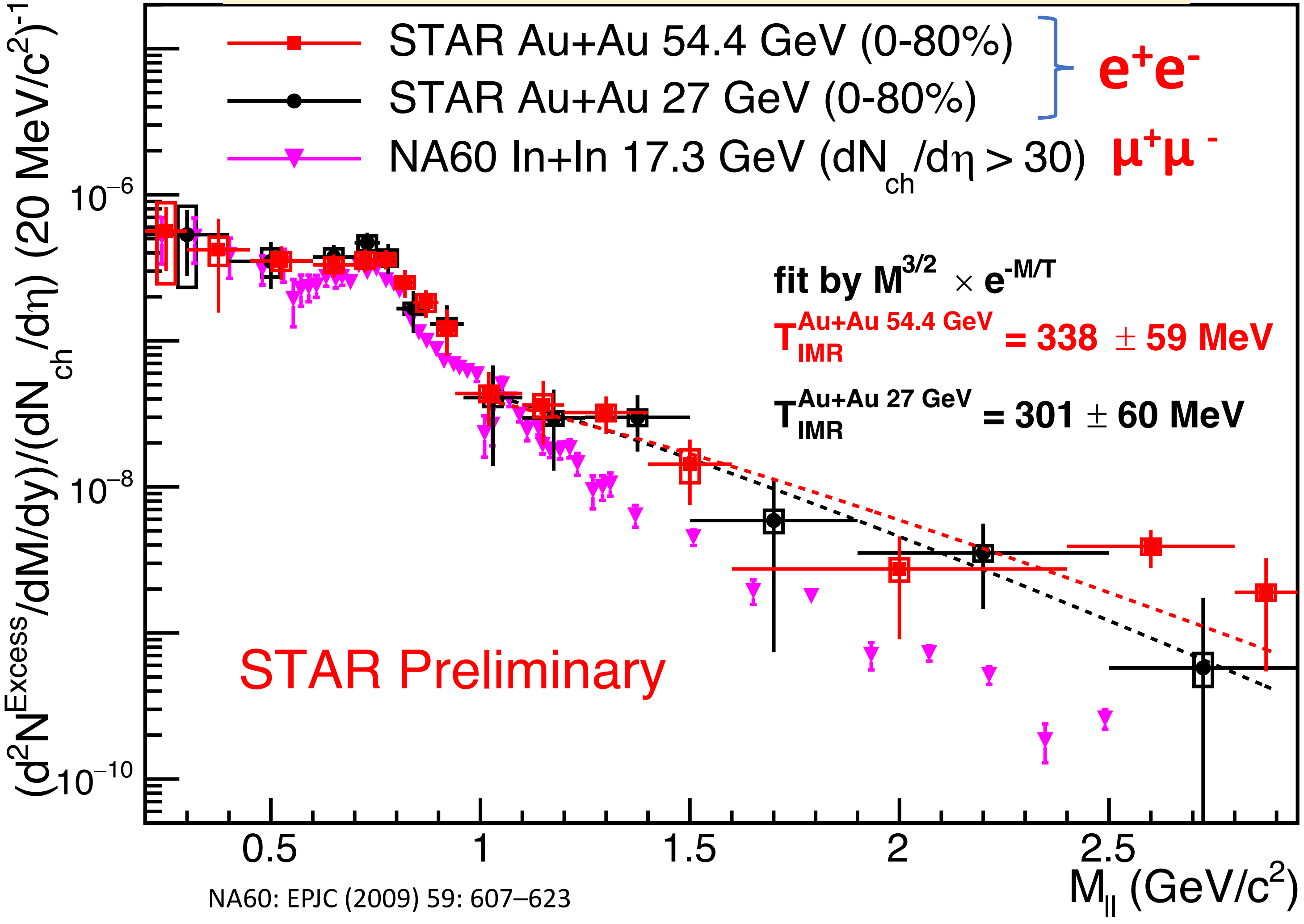

NA60: EPJC (2009) 59: 607–623

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STAR data is **higher** than NA60 data, due to longer **medium lifetime**?

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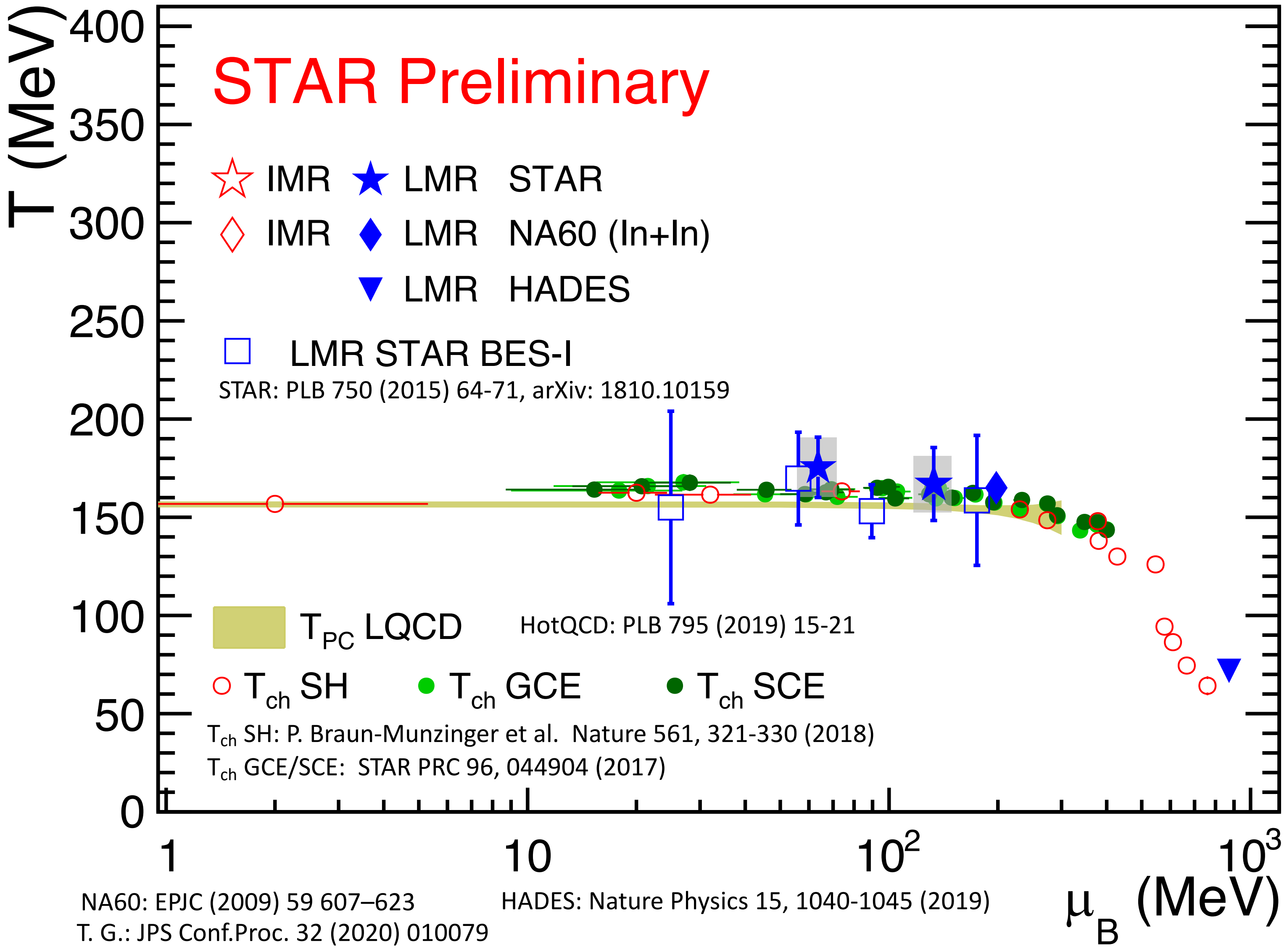
Summary of Temperatures



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T. G.: JPS Conf.Proc. 32 (2020) 010079
HADES: Nature Physics 15, 1040-1045 (2019)

Thermal dileptons in LMR

- **T close to both T_{ch} and T_{pc}**

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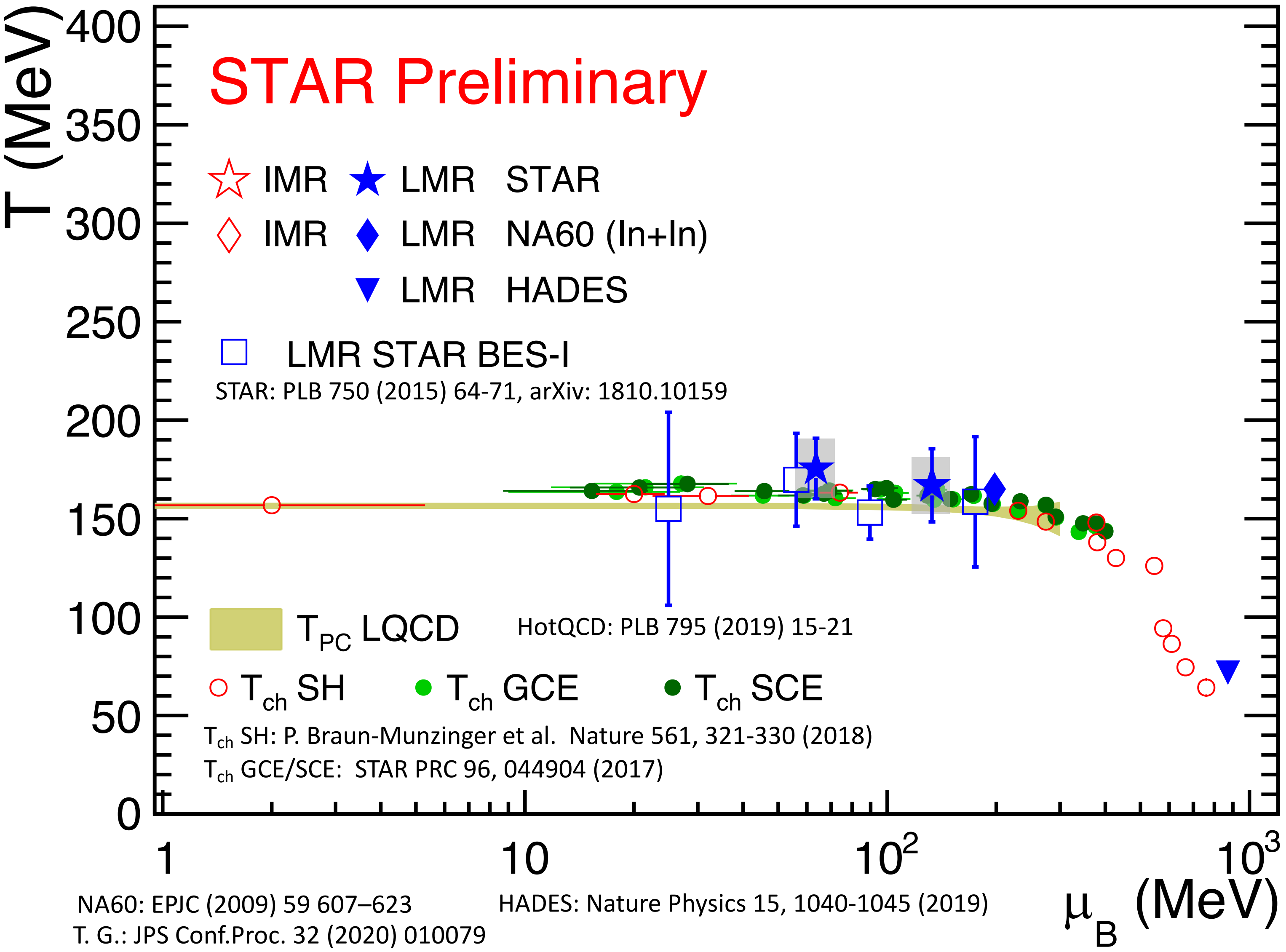

Thermal dileptons in LMR

- **T close to both T_{ch} and T_{pc}**
- **Dominantly emitted around phase transition**

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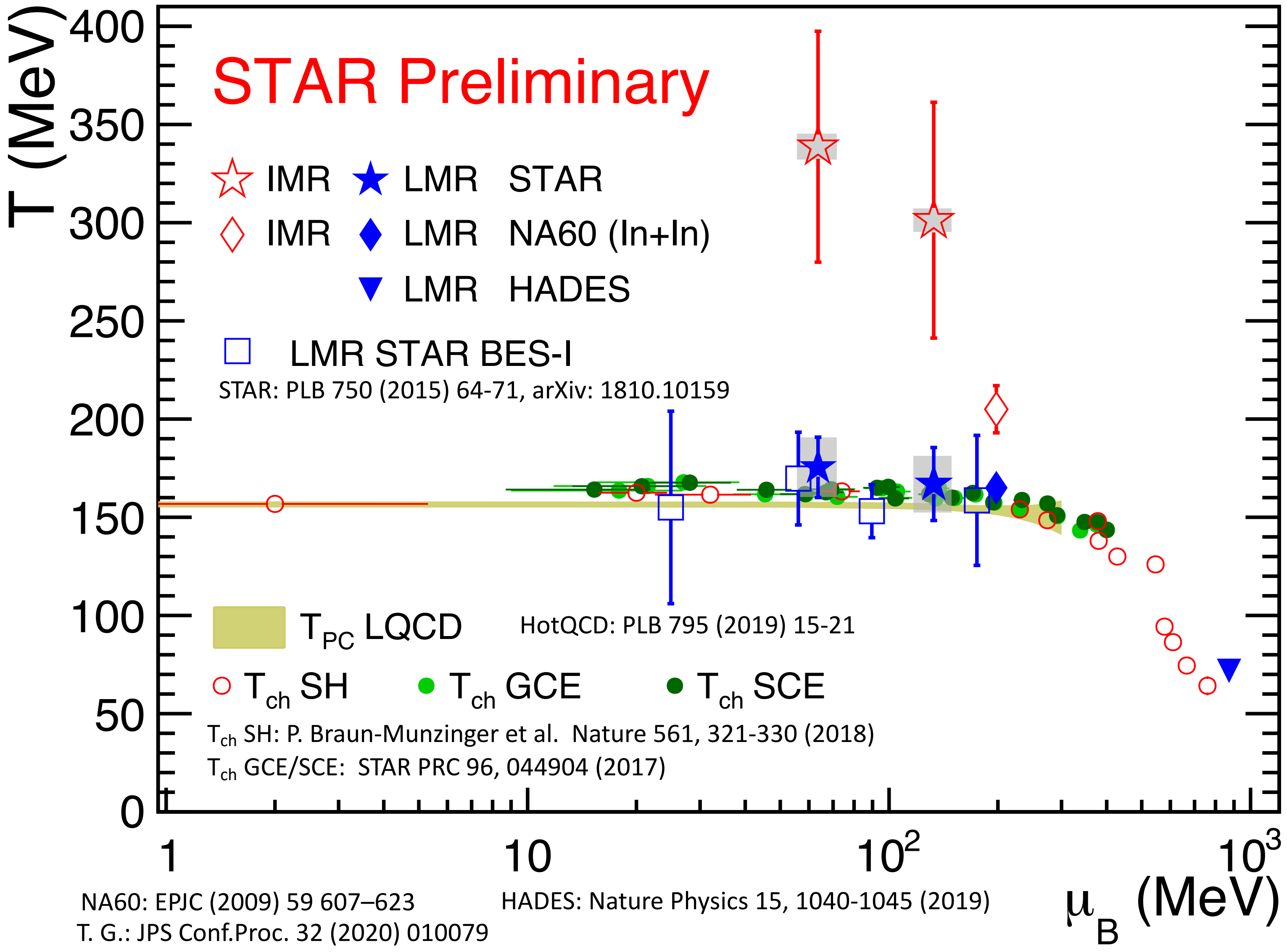

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Thermal dileptons in LMR

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- **Dominantly emitted around phase transition**

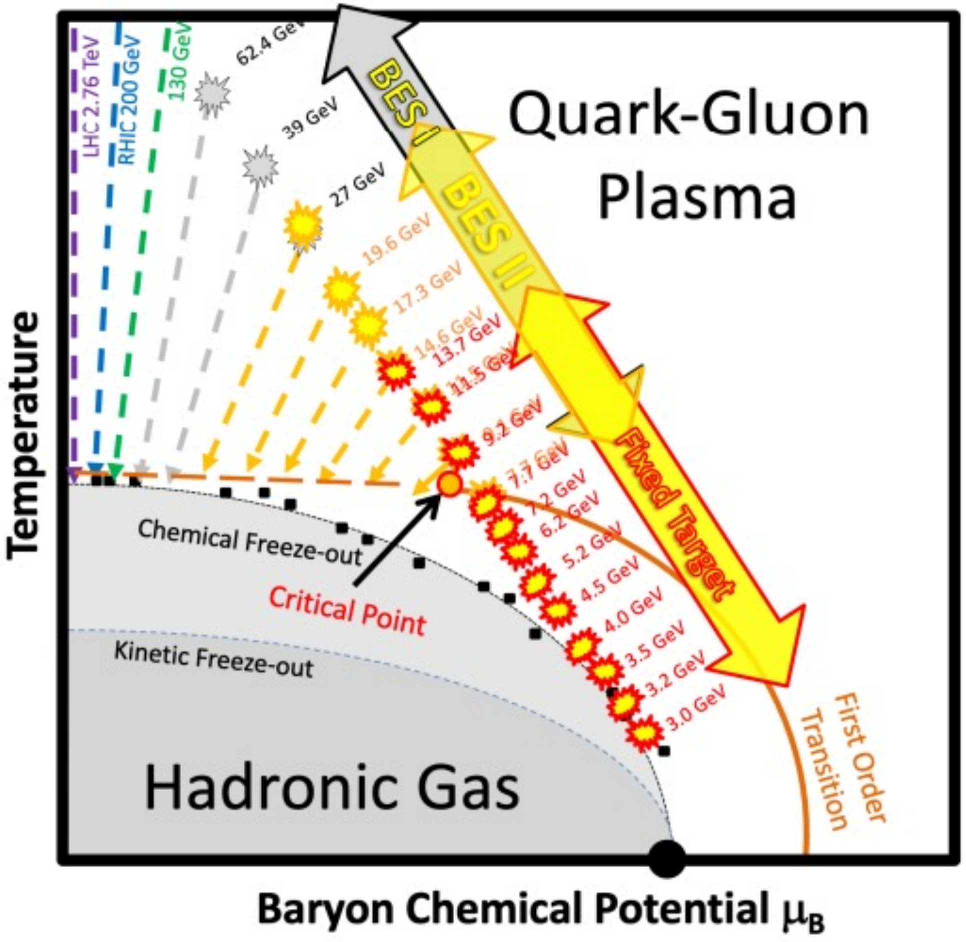
Thermal dileptons in IMR

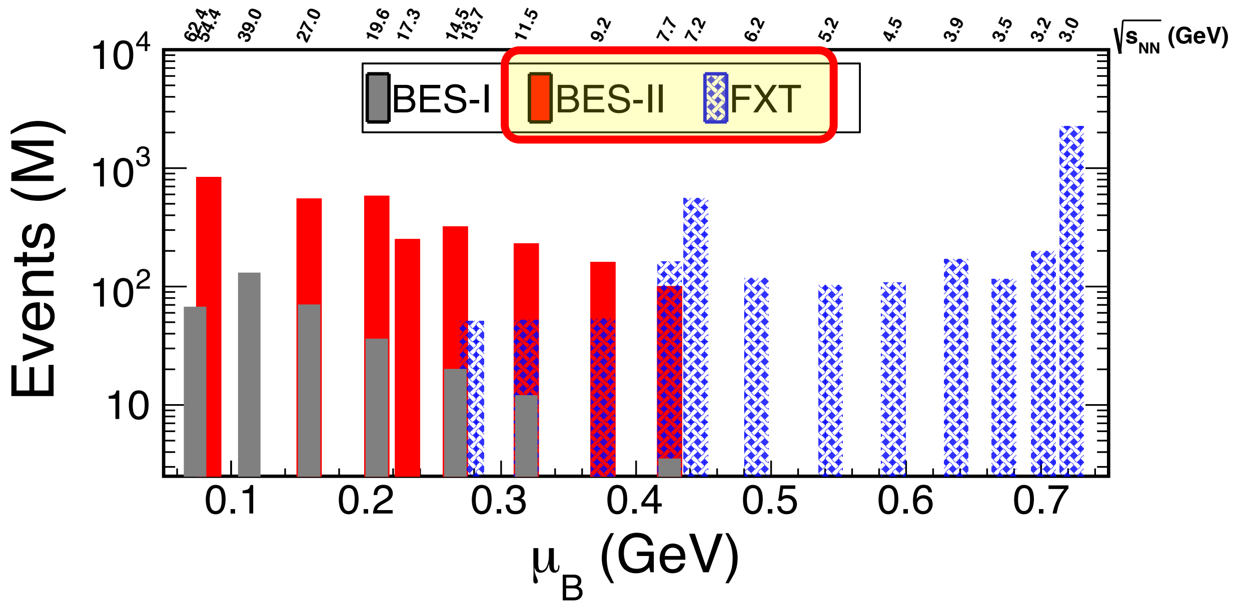
- **T is higher than T_{pc}**
- **Emitted from QGP phase**

Note: μ_B (QGP) ≠ μ_B (Ch. freeze-out)

Incoming Dielectrons with BES-II and FXT

Large datasets with iTPC upgrade **~10 × BES-I**





Exciting new results are coming soon:

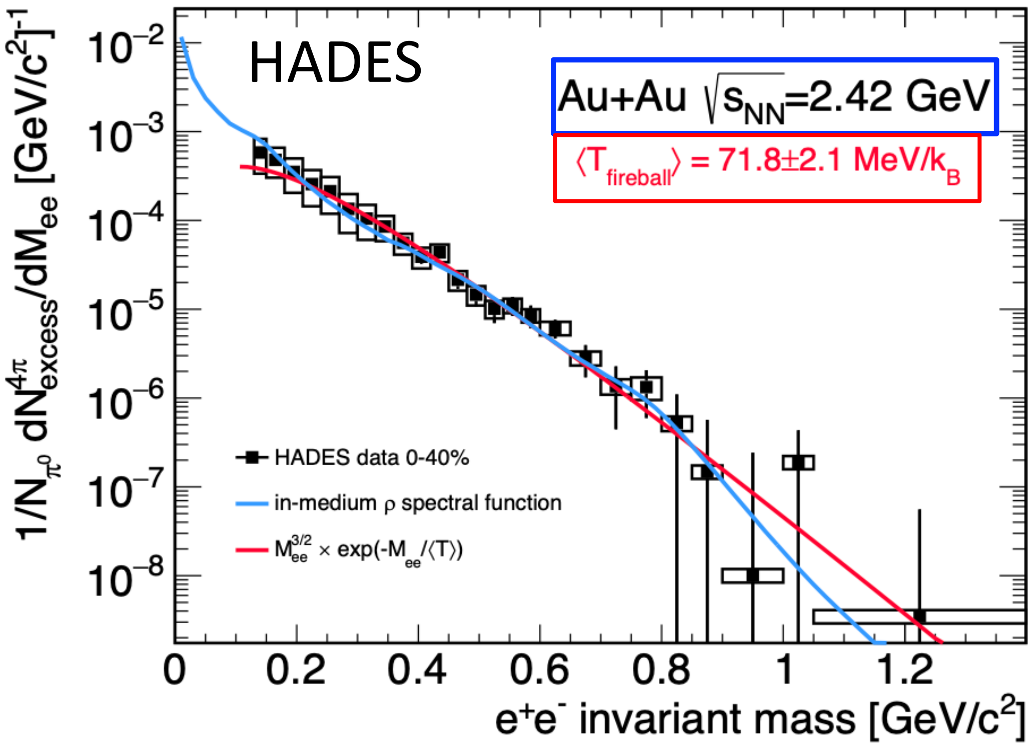
- **Temperature measurements towards lower energy collisions (higher μ_B)**
- **Search for non-trivial enhanced thermal dilepton yield → a potential critical point**

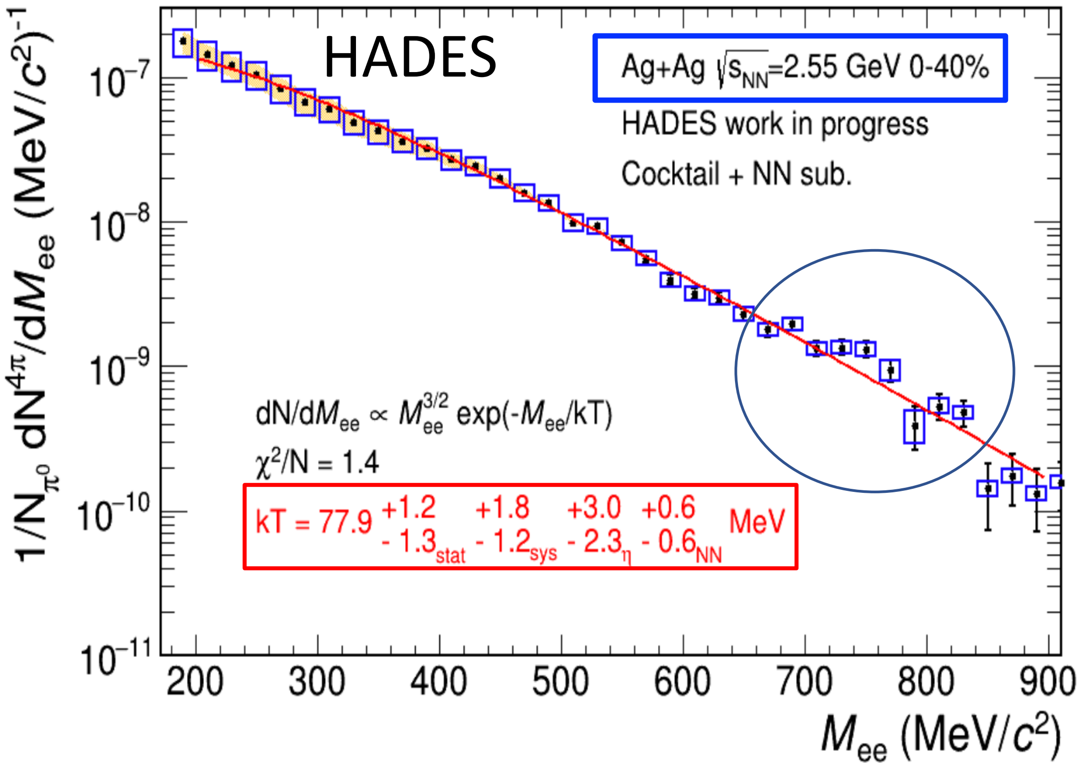
THANKS

BACKUP SLIDES

LM Thermal Dilepton at Low Energy Collisions

HADES: Nature Physics 15, 1040-1045 (2019)

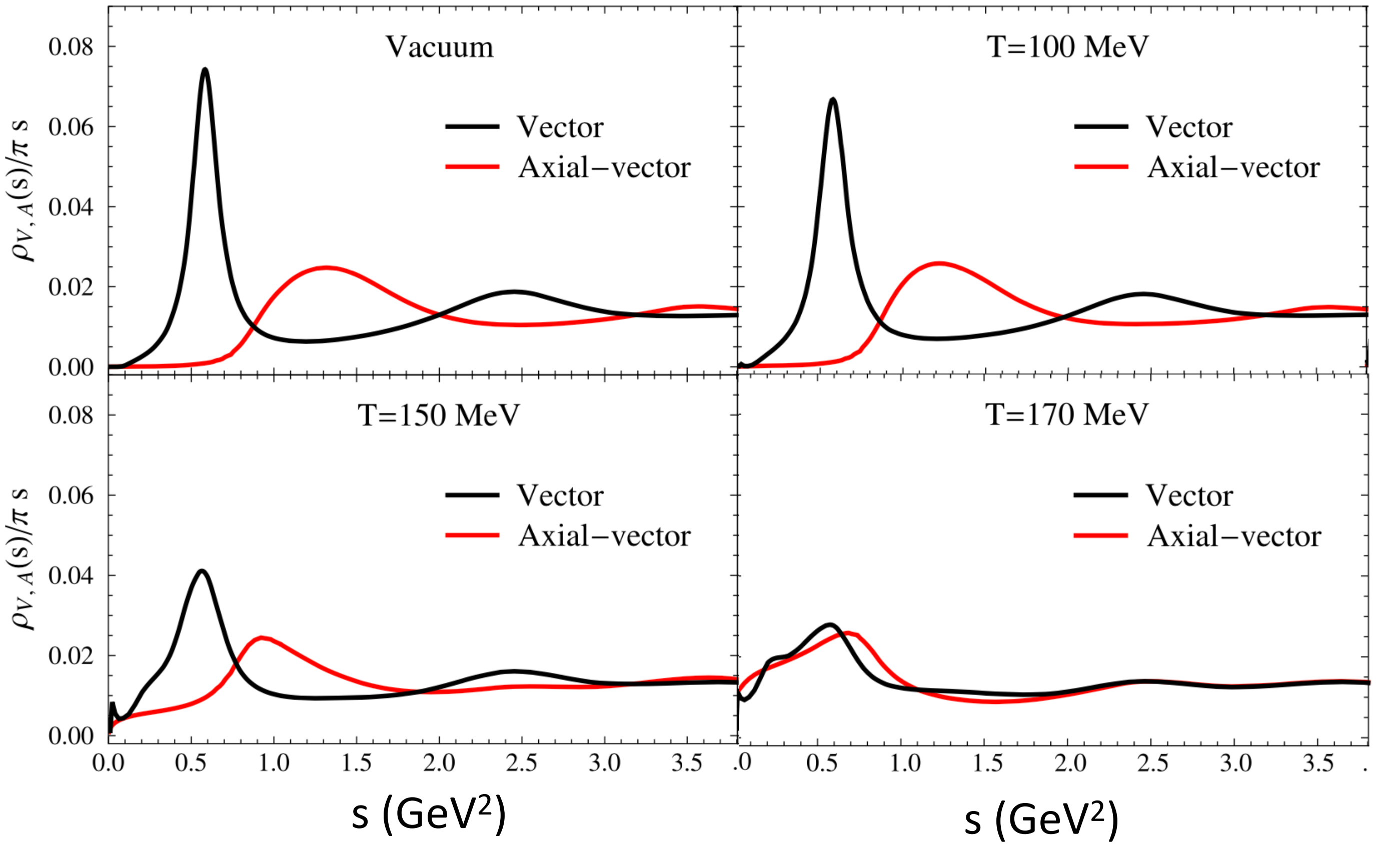




- High baryon density, μ_B~700-900 MeV
- **In-medium ρ melt via frequent scattering with surrounding baryons**
- **T_{LMR} ~ 70-80 MeV**, much lower than that at RHIC and SPS

Chiral Symmetry Restoration

Rapp and Hohler: PLB 731 (2014) 103-109



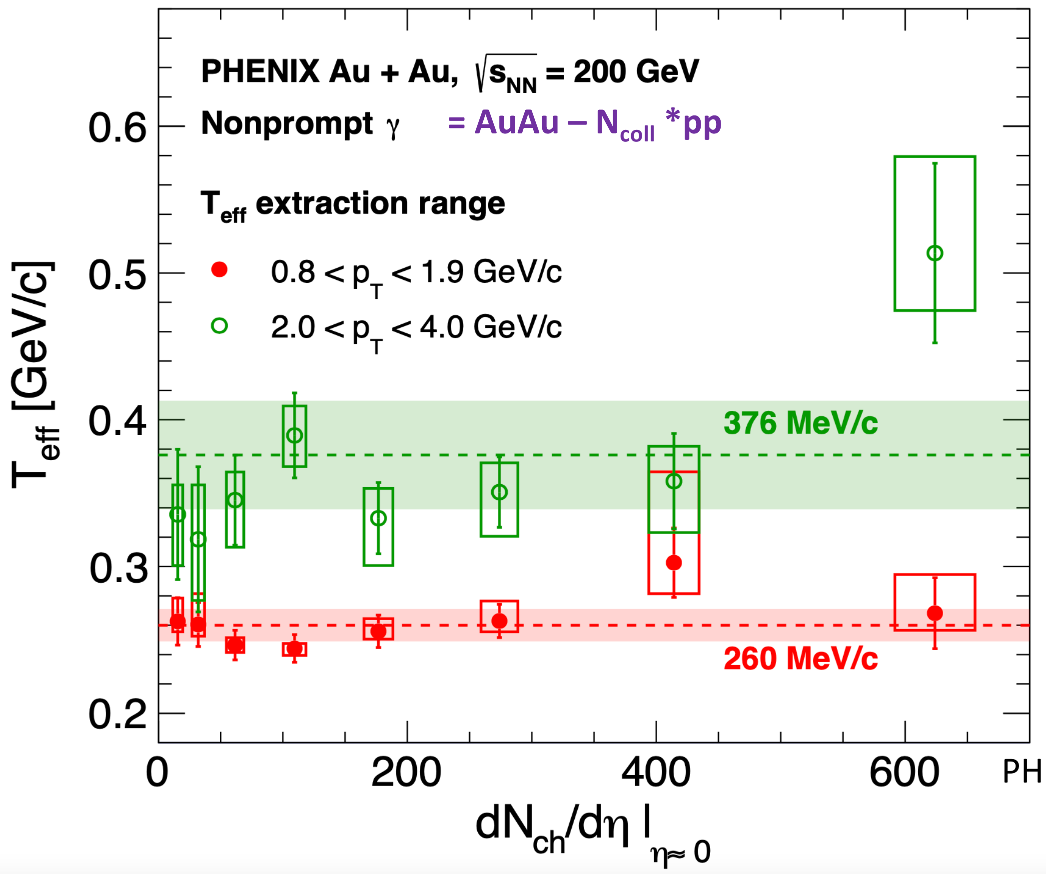
Measure a_1 theoretically

- Utilizing in-medium Weinberg sum rules to relate a_1 and ρ spectral function
- ρ spectral function and T dependent order parameters describing RHIC/SPS data as input
- **Observe** how does a_1 spectral function behave under finite temperatures

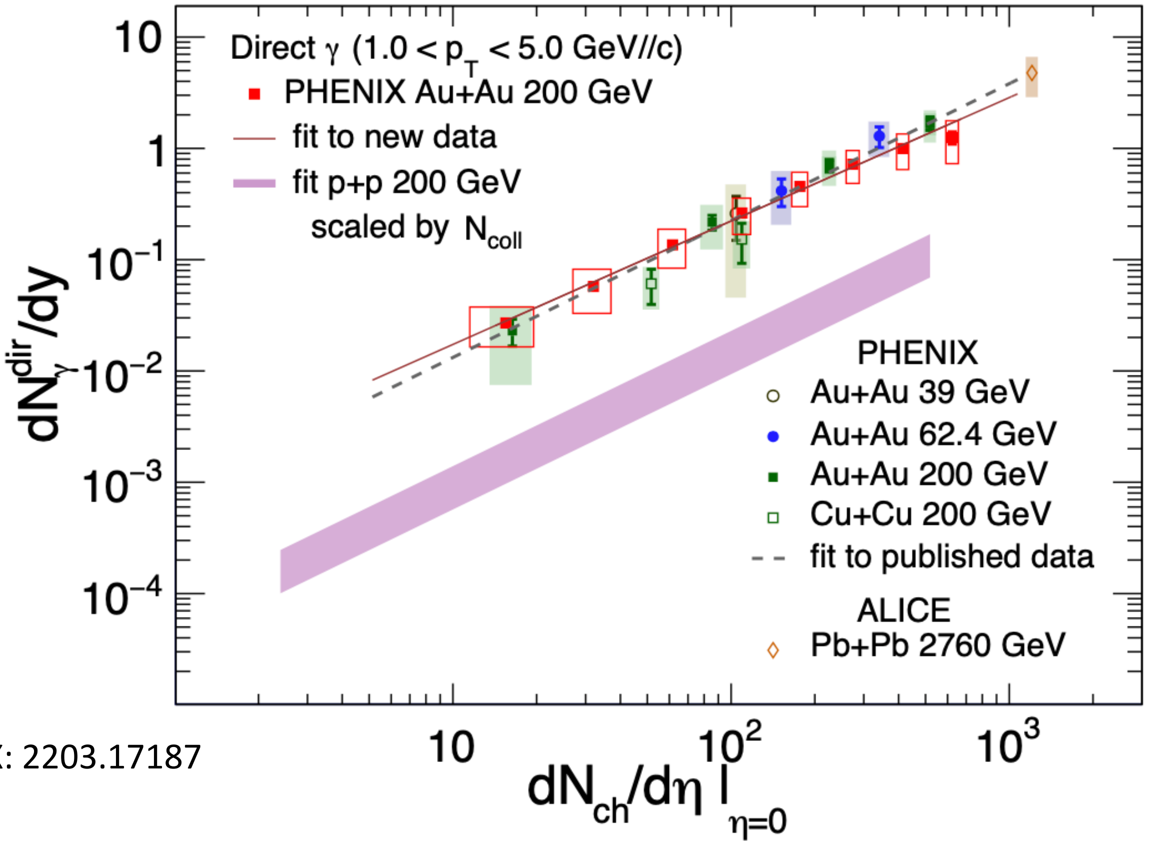
Experimental evidence is needed for final answer!

a_1 is **theoretically observed** to be merged with ρ in hot medium → chiral symmetry is restored

Recent Direct Photon Measurements

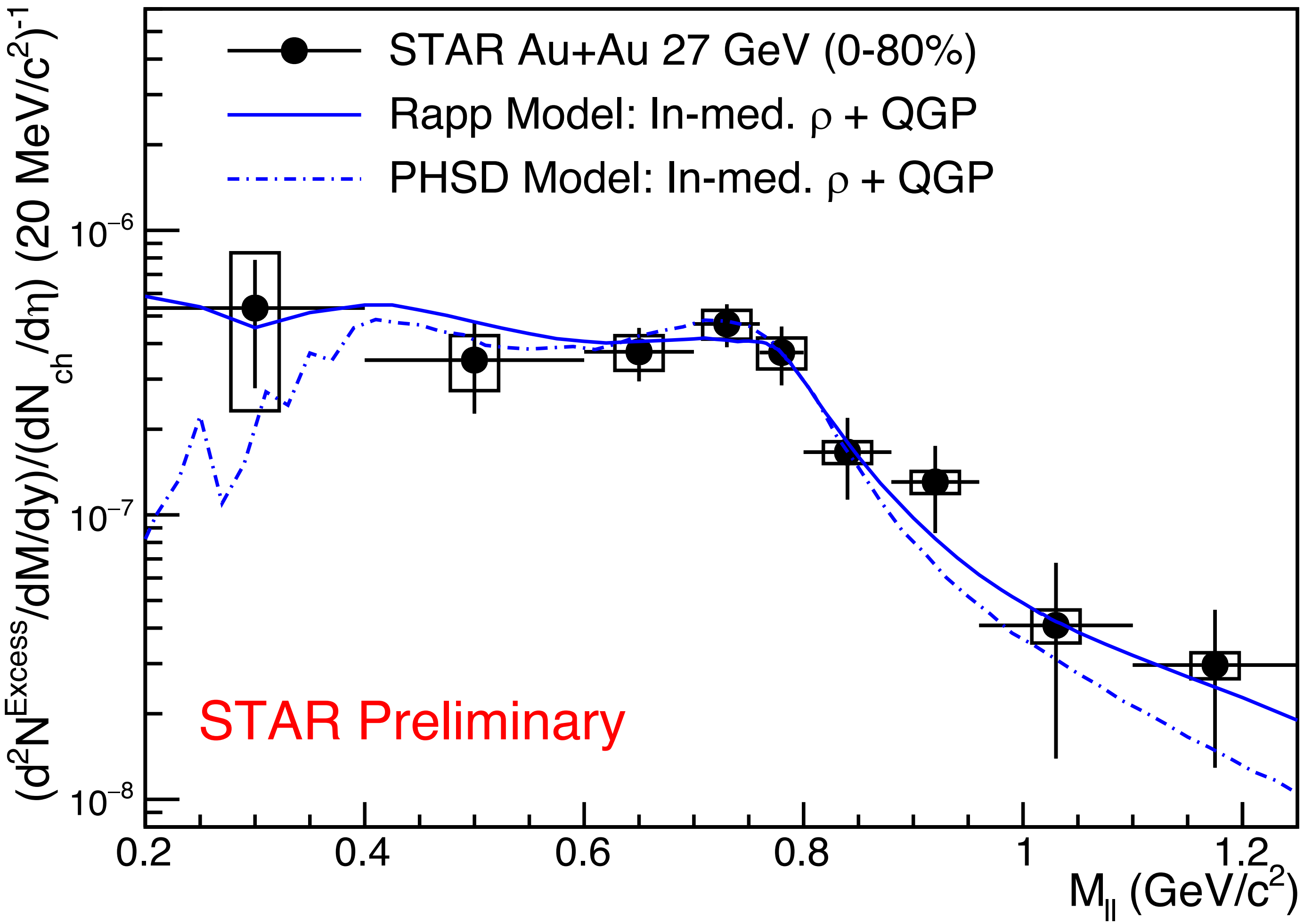


PHENIX: 2203.17187



- **Extracted T_{eff} is larger at a higher p_T region**
- **Universal scaling of production yield with $dN_{ch}/d\eta$**

Data vs. Model



Rapp model: PRC 63 (2001) 054907, Adv HEP 2013 (2013) 148253, PLB 753 (2016) 586
PHSD model: NPA 807, 214 (2008); NPA 619, 413 (1997) PRC 97, 064907 (2018)

Both models can **well describe the ρ broadening at LMR**

Rapp model: macroscopic many-body approach
medium described by cylindrical expanding fireball with lQCD EoS; in-medium ρ-propagator; resonance + π cloud + baryons

PHSD model: microscopic transport approach
medium described by Dynamical Quasi-Particle Model (DQPM); microscopic partonic or hadronic scattering; collisional broadening

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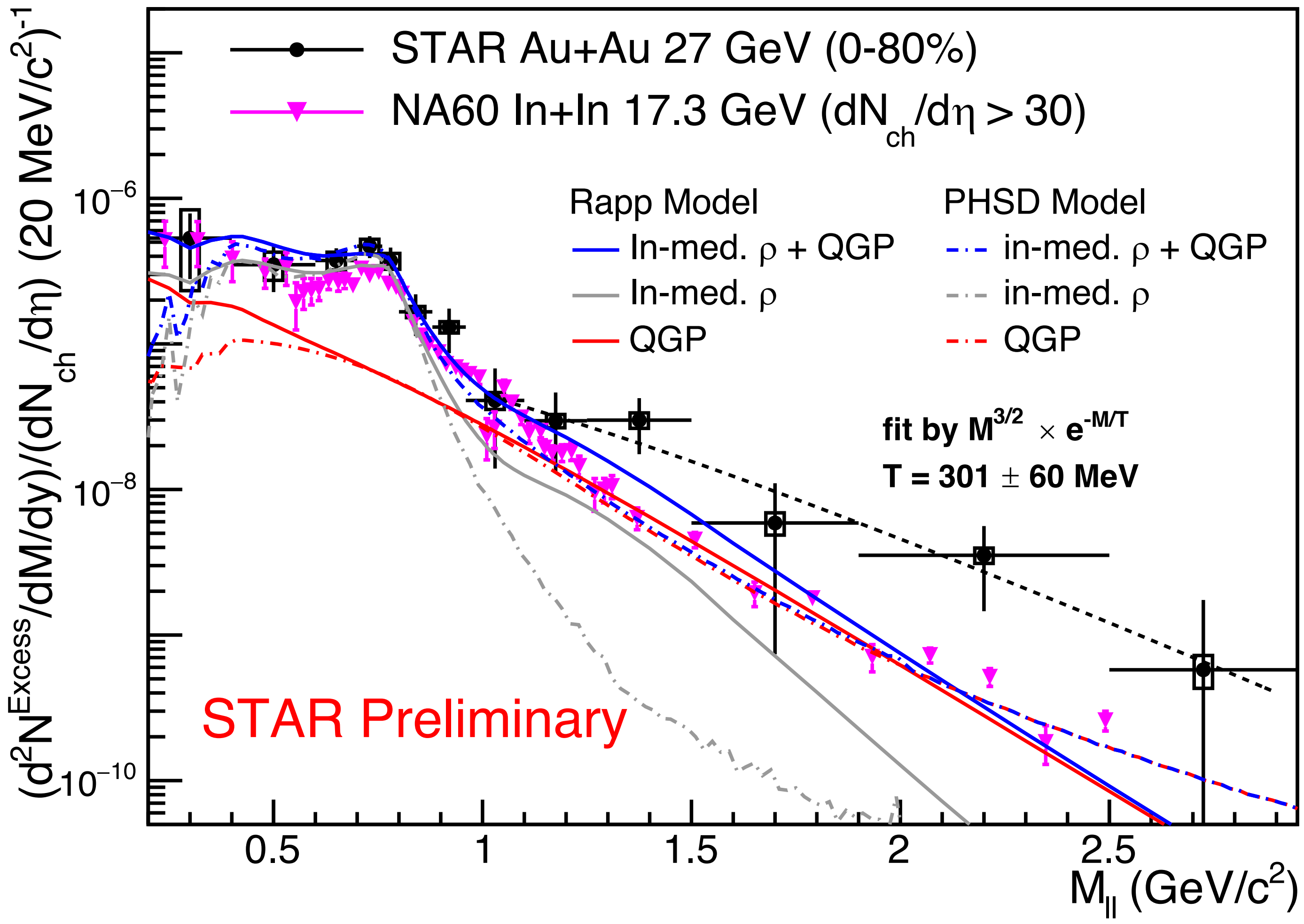

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Both models can **well describe the ρ broadening at LMR but underestimate the IMR → QGP is hotter** than model expectation

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