Probing the Hot QCD Medium via Thermal Dileptons in Heavy Ion Collisions

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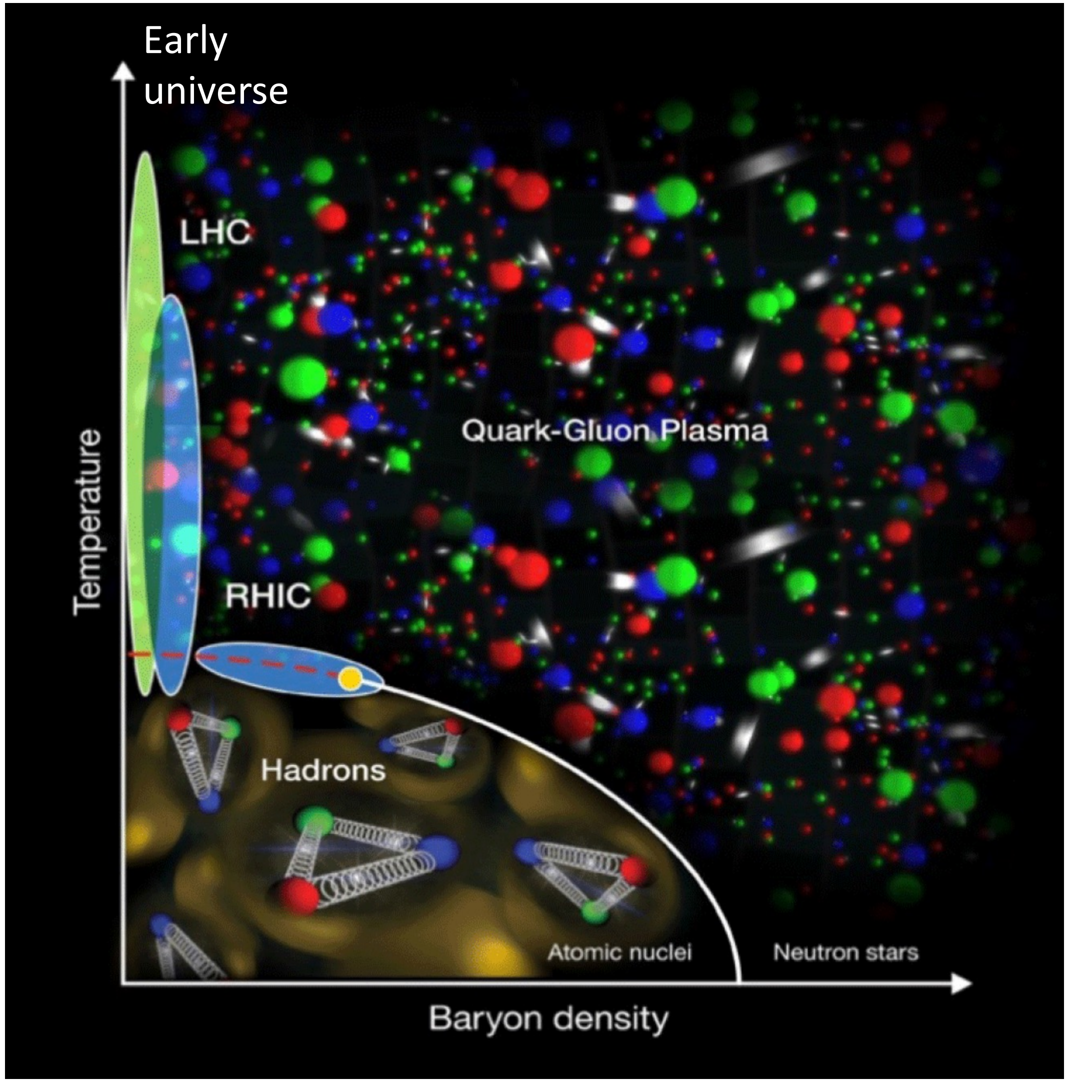
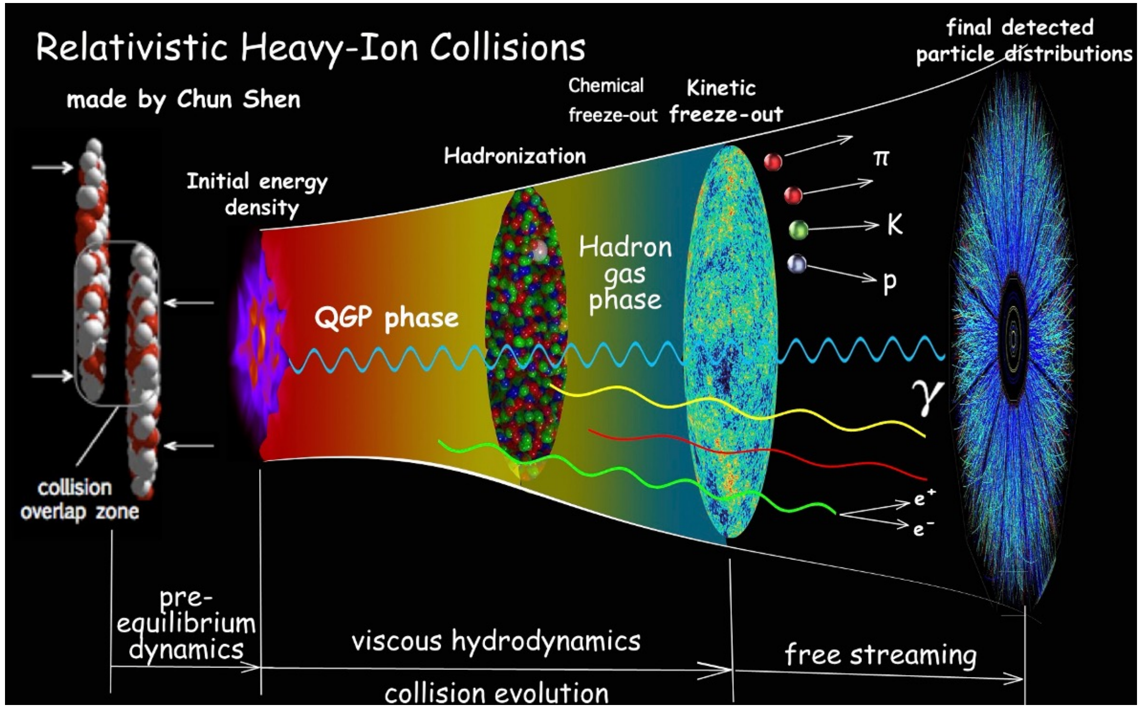
HHaS Collaboration Metting, Huizhou, November 28 – 30, 2025

Extreme QCD Matter in Heavy-Ion Collisions



- **QCD phase diagram:**
  - Maps phases of strongly interacting matter under various conditions (e.g. $\boldsymbol{T}$ vs. $\boldsymbol{\mu_B}$)
- **Heavy-ion collisions** create extreme conditions:
  - Create QGP and study its properties
  - Explore different trajectories of QCD phase diagram
- **Temperature: a key thermodynamic parameter**
  - Governs formation, evolution, and properties of QGP

Heavy-Ion Collision and Why Dileptons

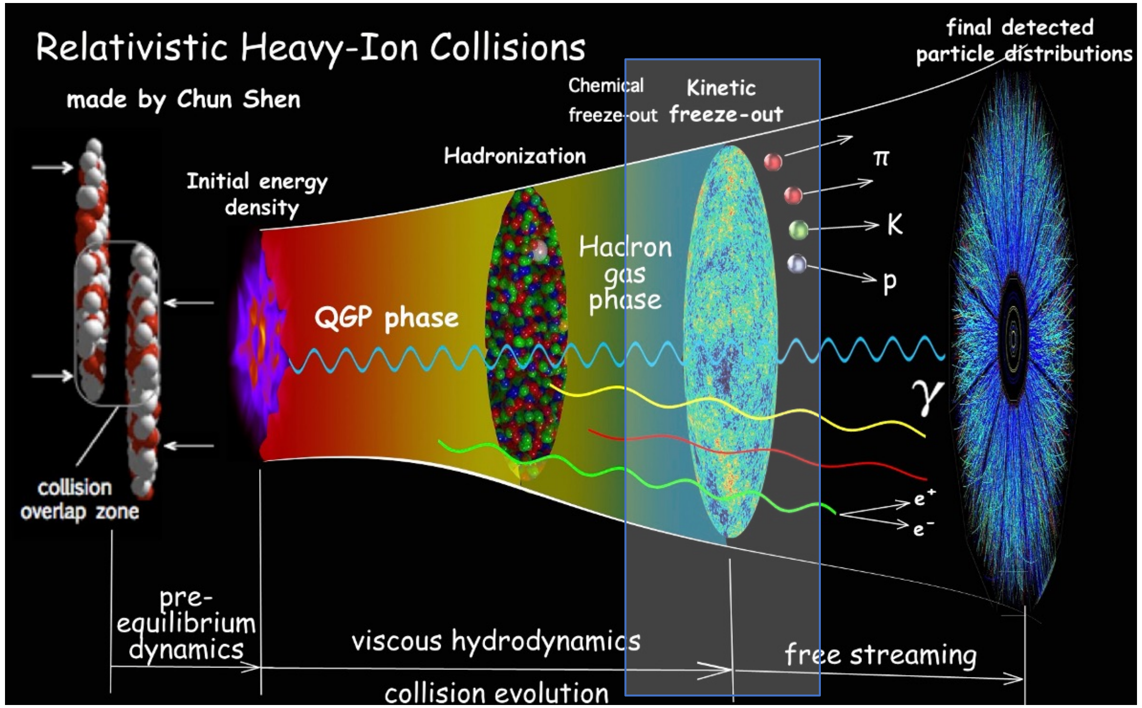


Hadrons

Photons

Leptons

Heavy-Ion Collision and Why Dileptons



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

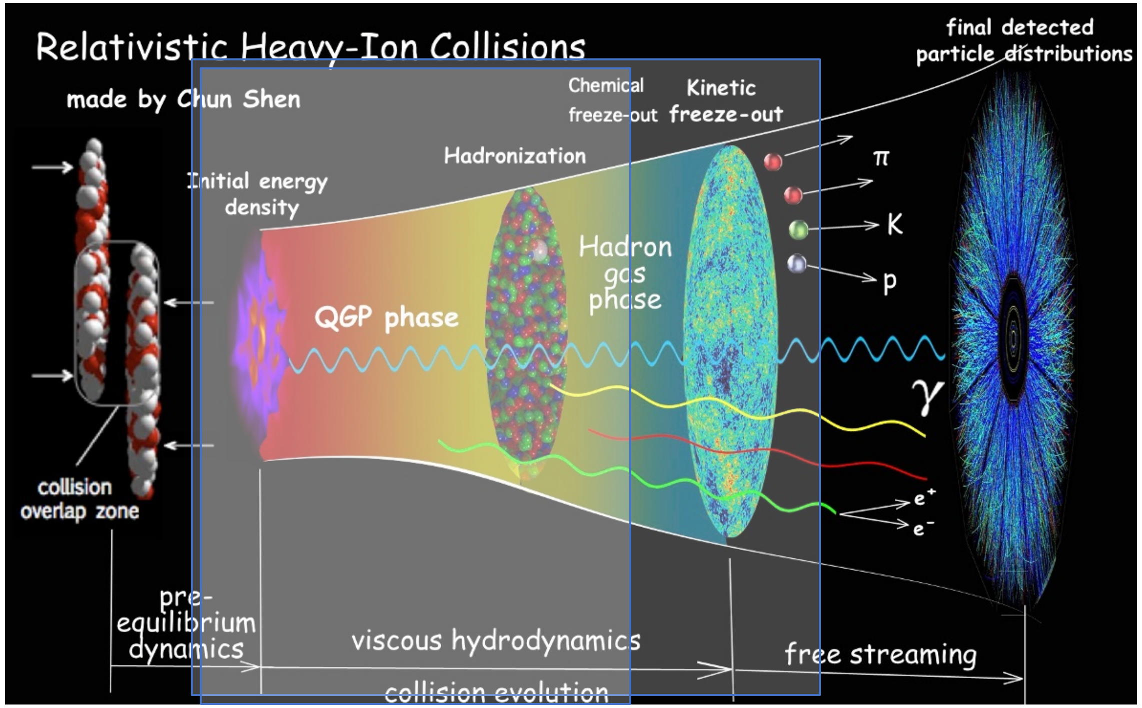
Hadrons (Yield, p_T)

Photons

Leptons

T at early stage is still poorly known ☹

Heavy-Ion Collision and Why Dileptons



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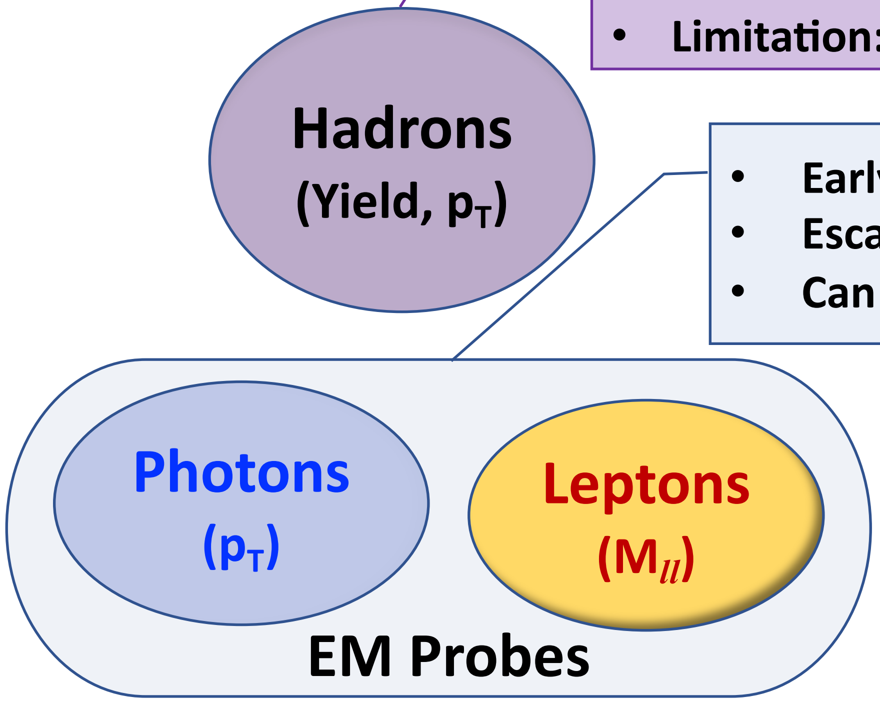
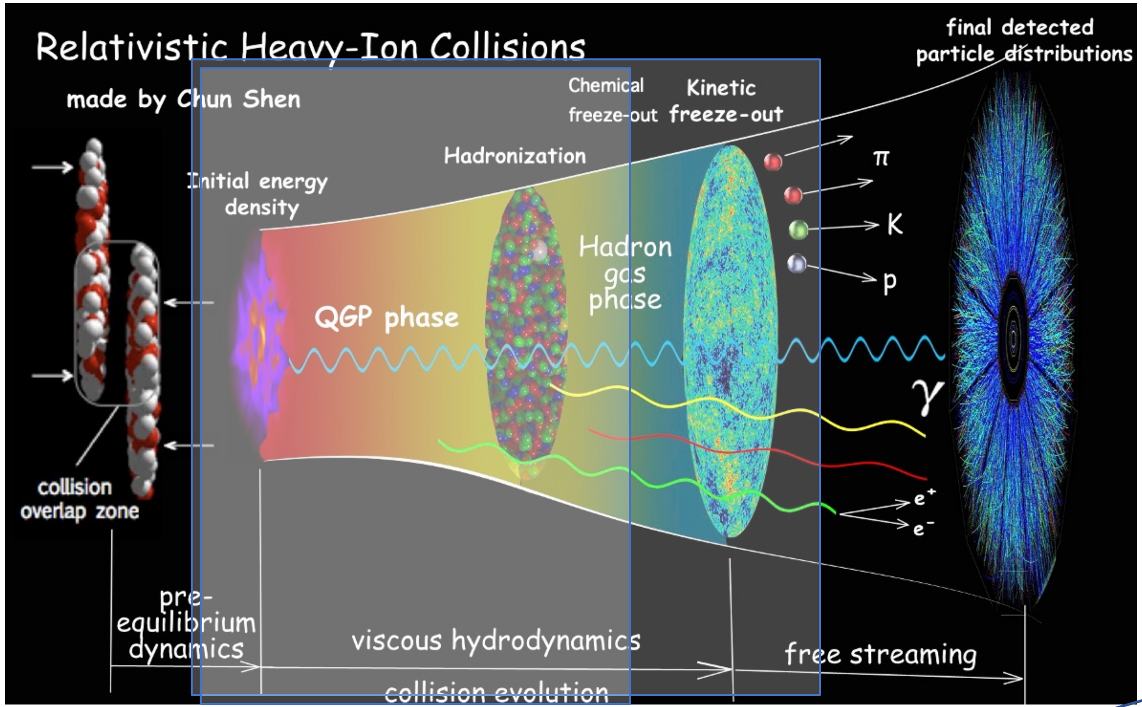


- Early to final stages
- Escape freely (λ~100-500 fm)
- Can probe earlier phases

T at early stage is still poorly known ☹️

Heavy-Ion Collision and Why Dileptons



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EM Probes

Photons (p_T)

Leptons (M_{ll})

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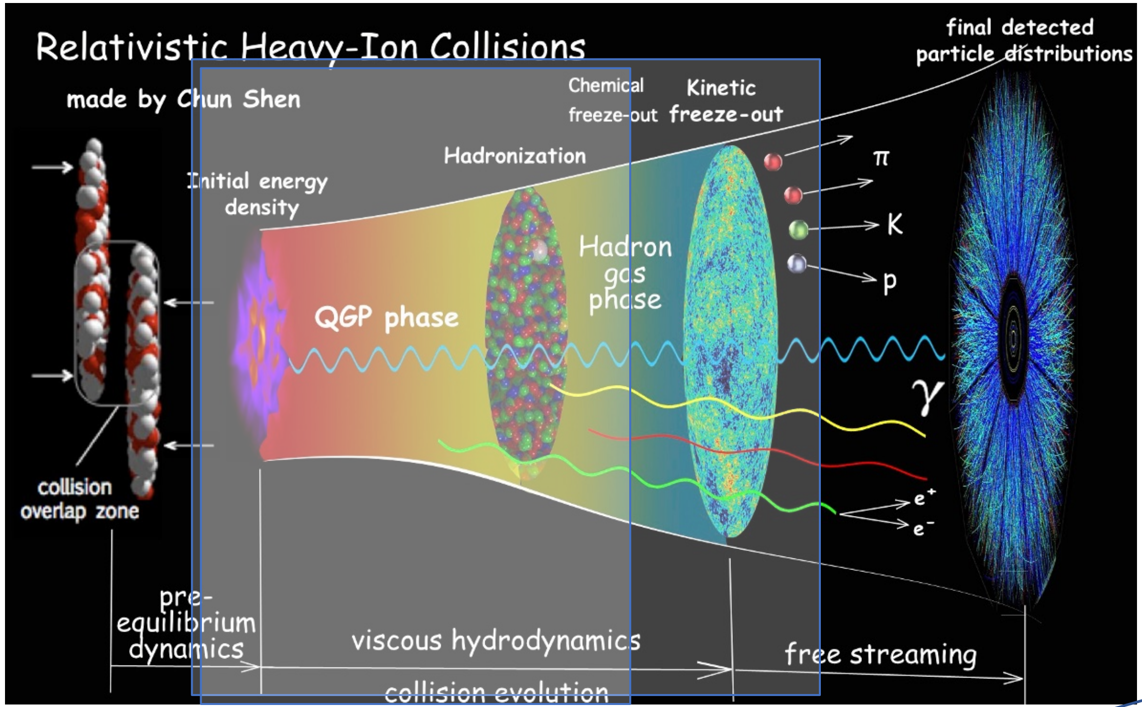
- **Can probe earlier phases**

Inverse slope → Effective temperature
(Doppler shift warning)

T at early stage is still poorly known ☹

Heavy-Ion Collision and Why Dileptons



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EM Probes

Photons
(p_T)

Leptons
(M_{ll})

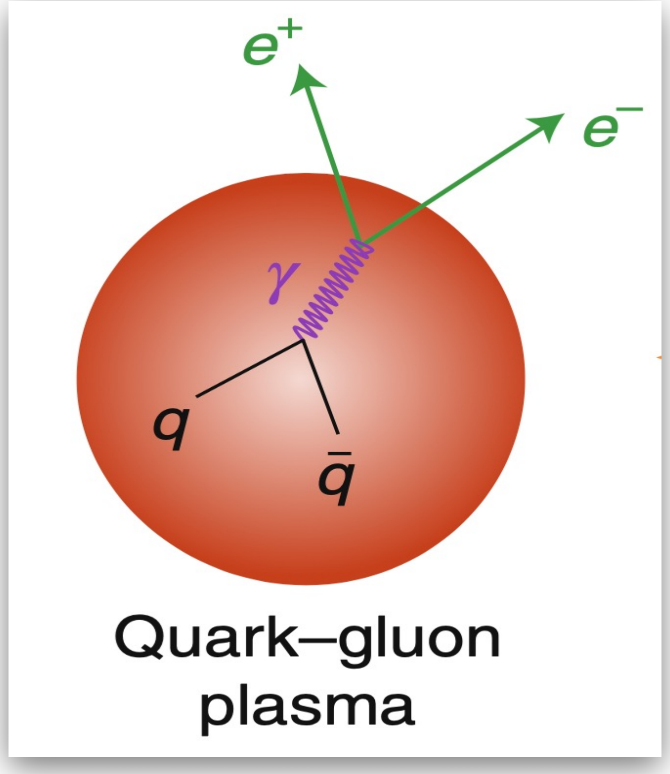
Inverse slope → Effective temperature
(Doppler shift warning)

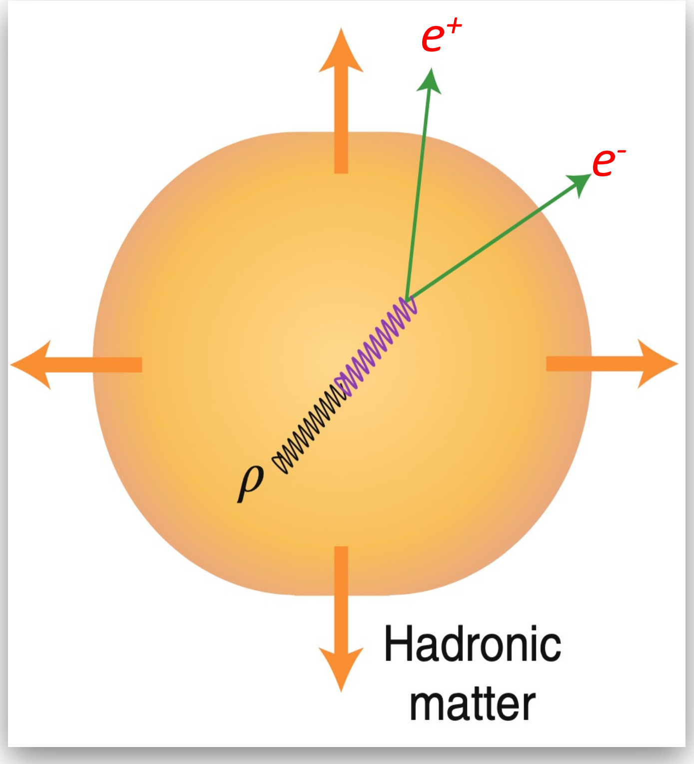
Dileptons

- **Temperature without Doppler-shift effect**
- **Unique probe of in-medium spectral function**

T at early stage is still poorly known ☹

Thermal Dileptons





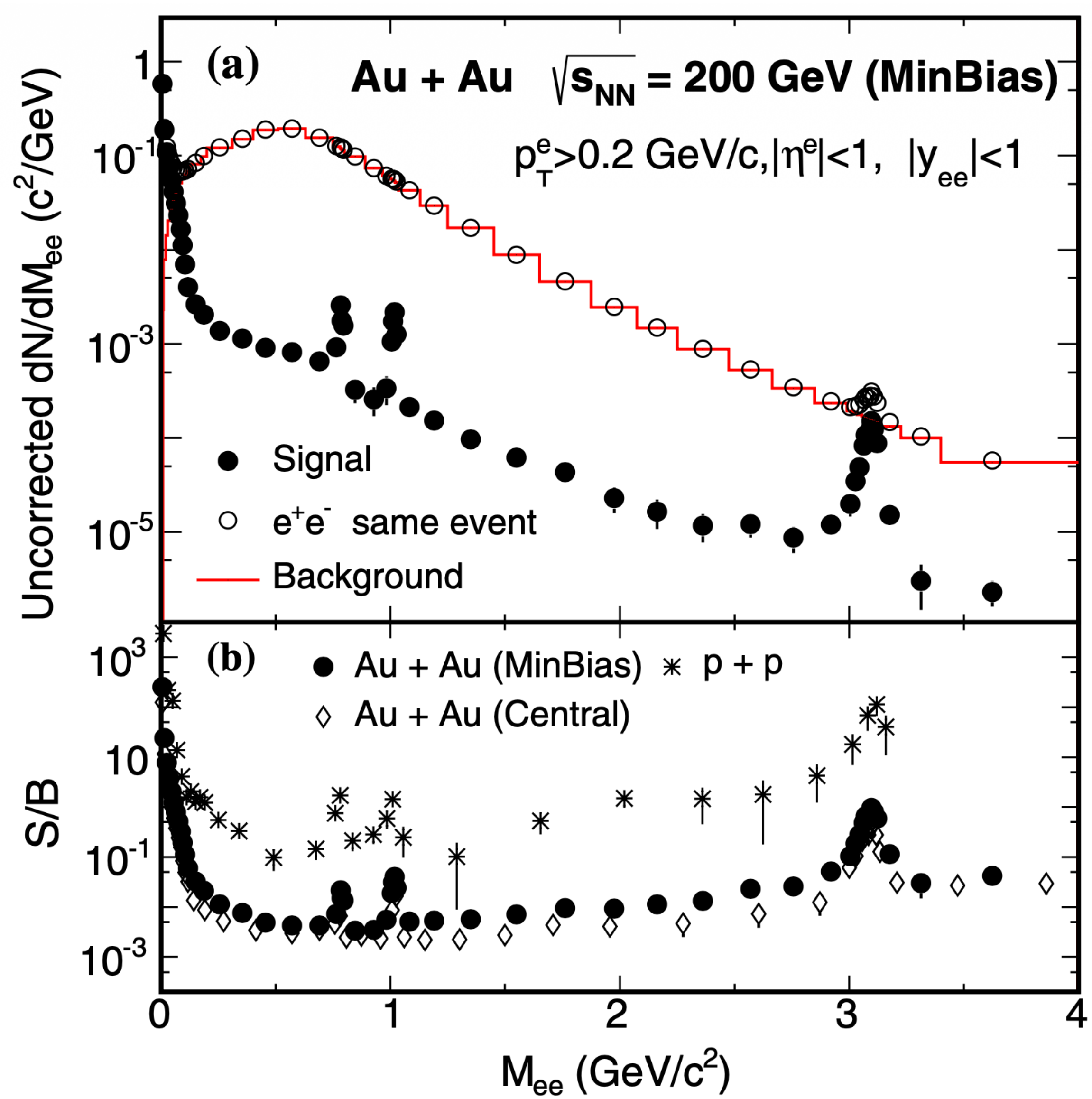
$$q + \bar{q} \longrightarrow \gamma^* \longrightarrow e^+ + e^-$$

$$\pi^+ + \pi^- \rightleftharpoons \rho^* \longrightarrow e^+ + e^-$$

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

How thermal dileptons distribute their invariant mass will reveal properties of emission sources: temperature, partonic/hadronic phase...

Experimental Challenge of Dileptons



- Requires excellent electron identification
- Requires well-constrained and robust combinatorial background subtraction

STAR, PRL 113, 022301 (2014)

How to Measure Thermal Dileptons

Inclusive signals (space-time integral)

Thermal 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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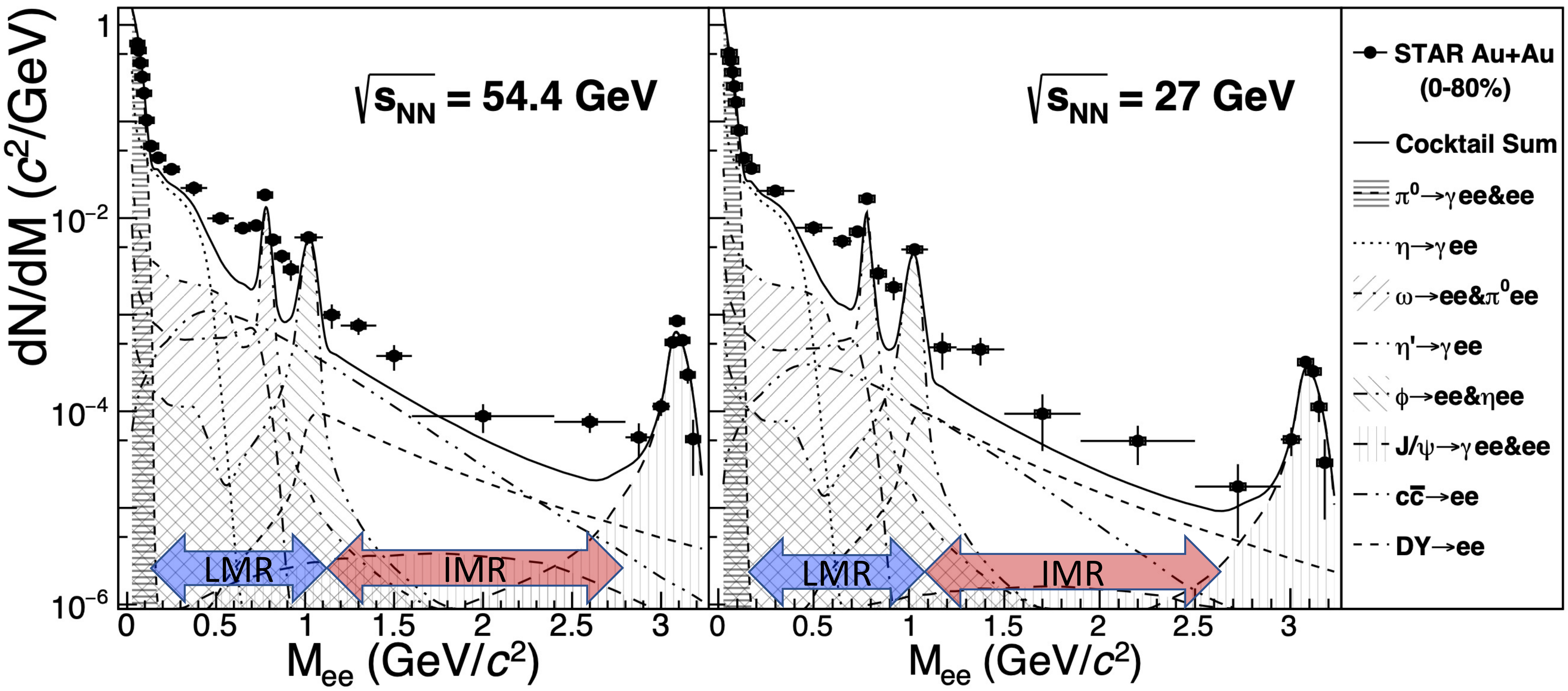
- $J/\psi \rightarrow e^+e^-, c\bar{c} \rightarrow e^+eX$

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

Thermal signals = **Inclusive signals** − **Physical background**

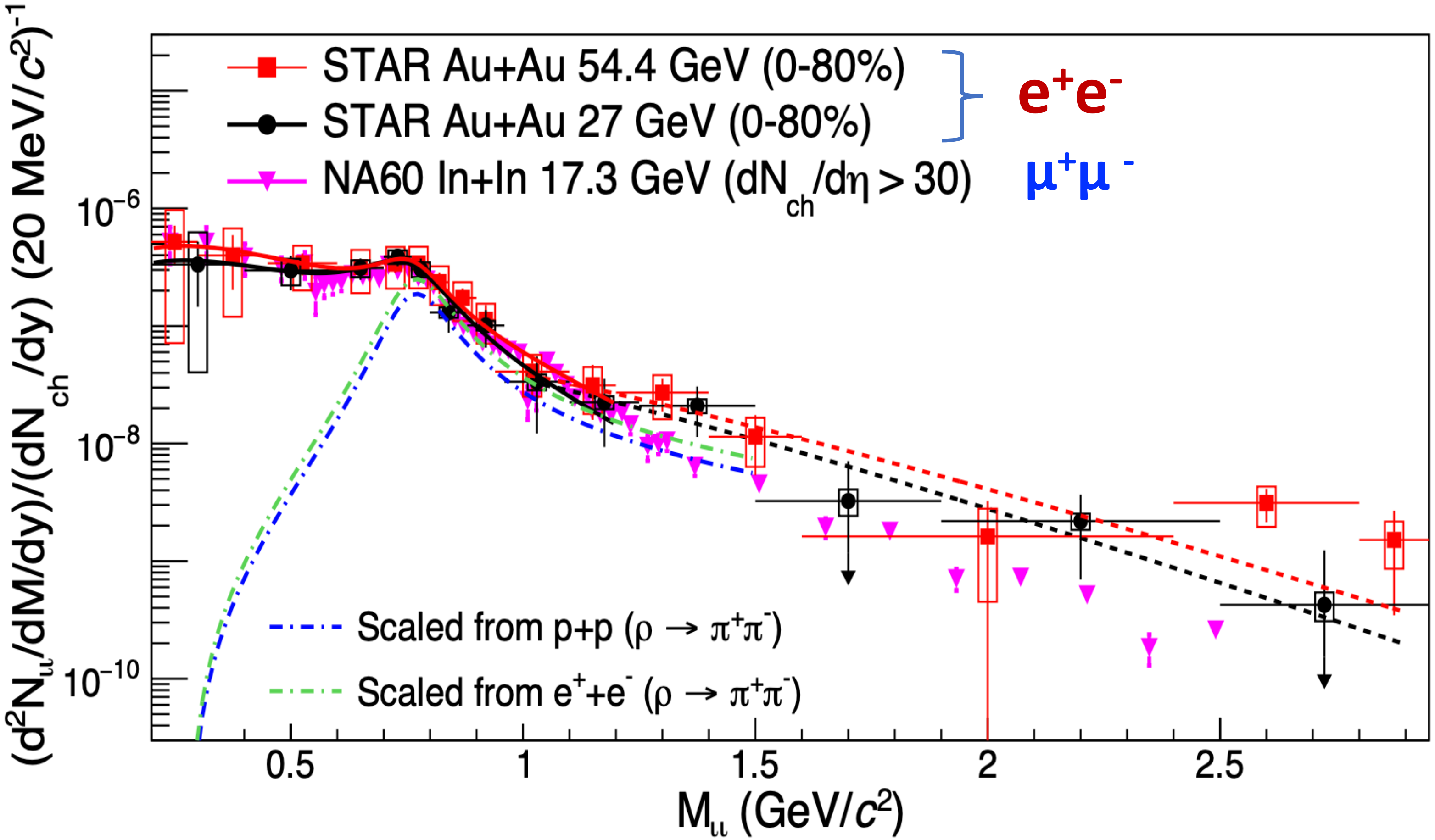
Examples of Data vs. Physical B.G. (Cocktails)



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

Thermal Dilepton at Low Energies

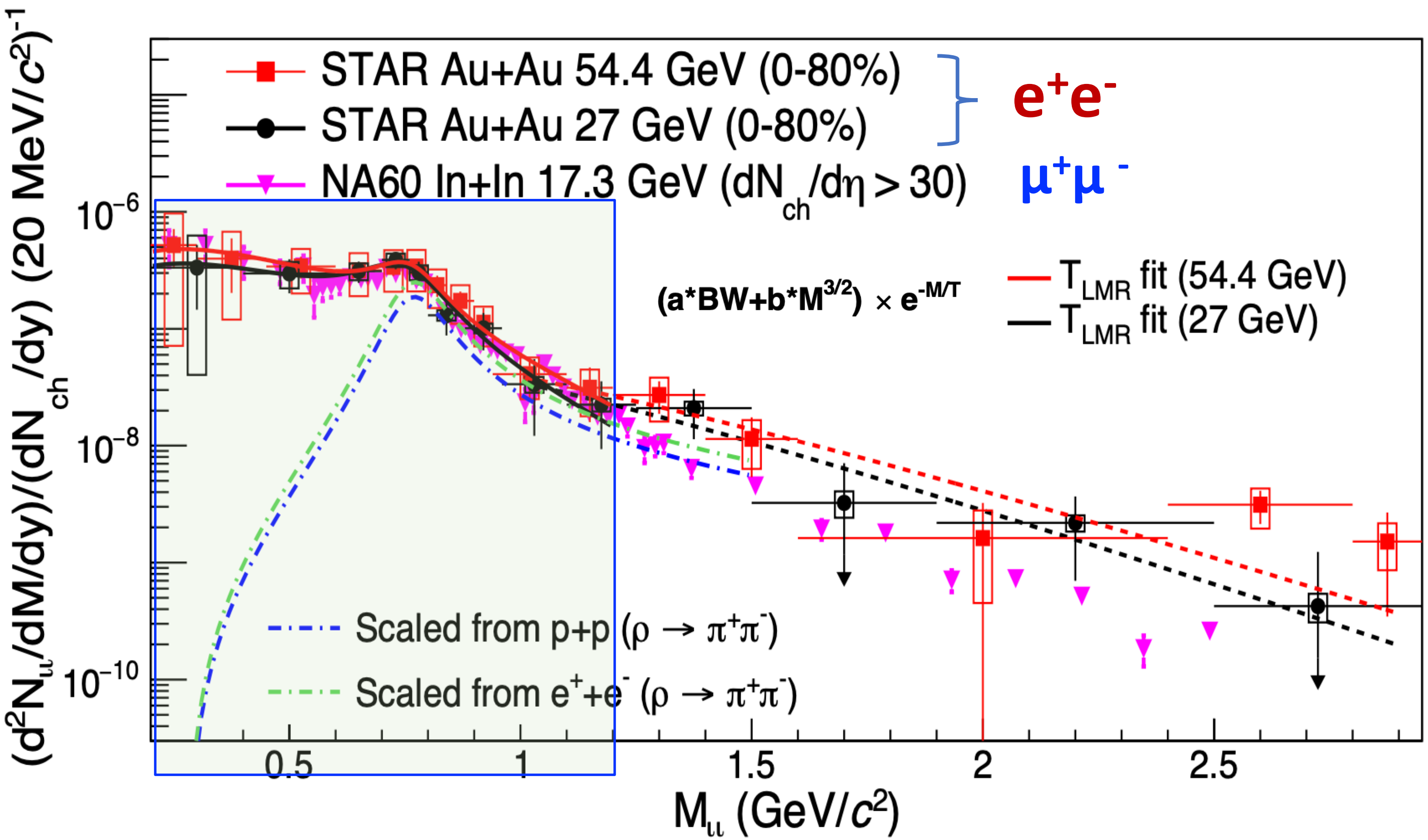
“Excess” = “Inclusive” – “Cocktail Sum”



STAR, Nature Communications 16 9098 (2025)

Thermal Dilepton (LMR) at Low Energies

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



STAR, Nature Communications 16 9098 (2025)

In-medium ρ dominated

- **Similar** mass spectrum

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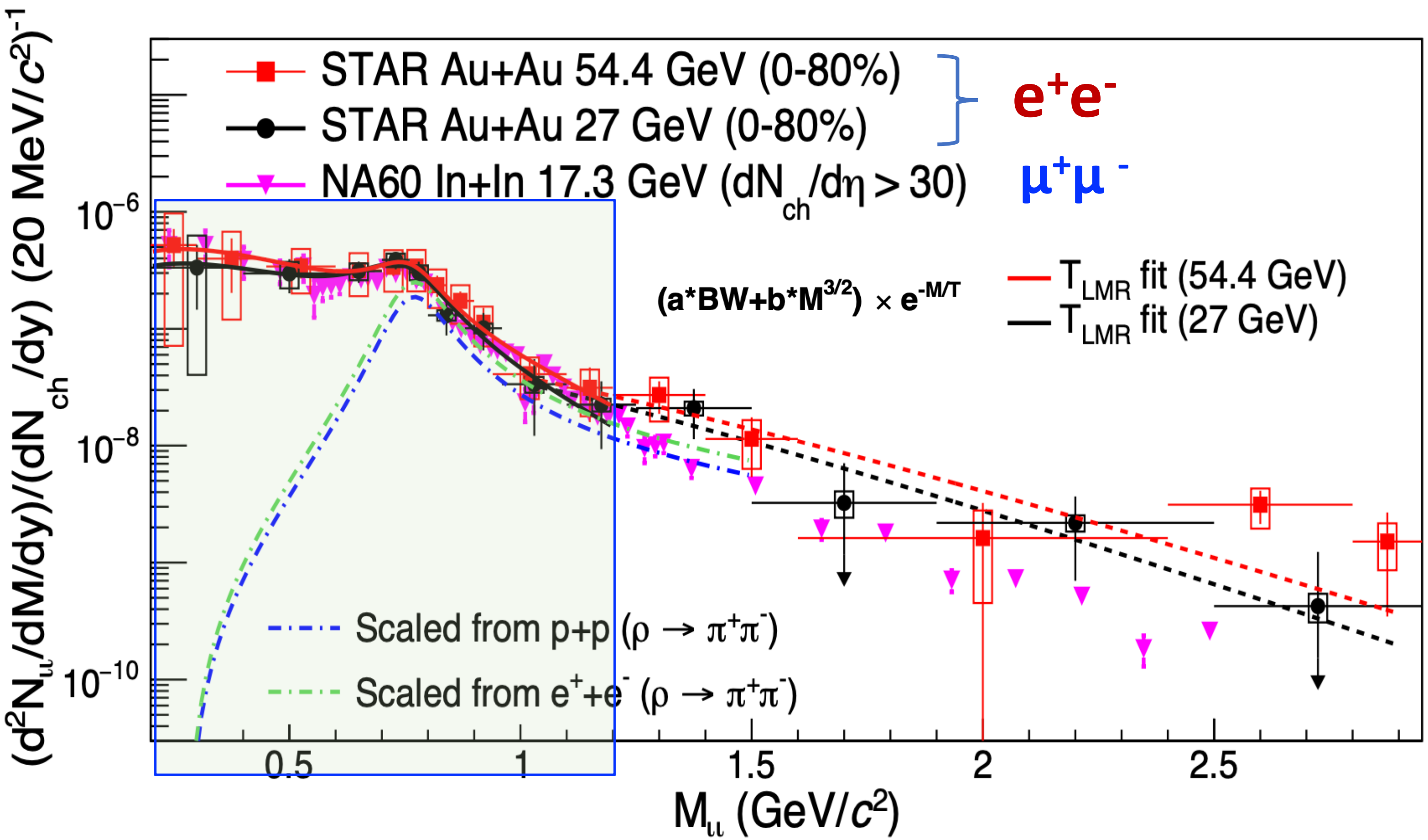

STAR, Nature Communications 16 9098 (2025)

In-medium ρ dominated

- **Similar** mass spectrum
- **Similar** temperature
  - $T_{LMR}^{27GeV} = 167 \pm 21 \pm 18$ (MeV)
  - $T_{LMR}^{54.4GeV} = 172 \pm 13 \pm 18$ (MeV)
  - $T_{LMR}^{17.3GeV} = 165 \pm 4$ (MeV)
- Indicating radiation source is a "**similar hot bath**"

Thermal Dilepton (IMR) at Low Energies

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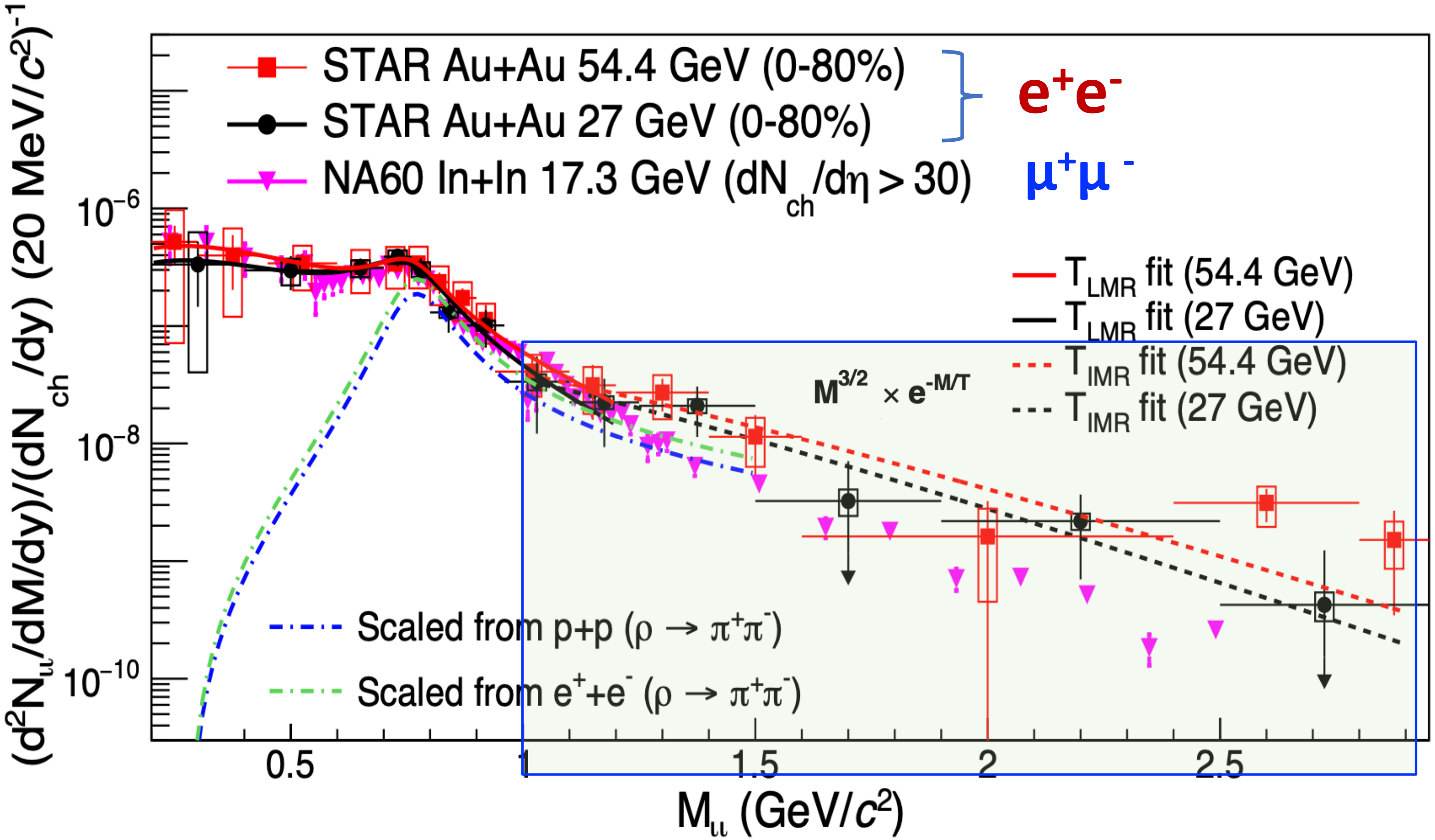

STAR, Nature Communications 16 9098 (2025)

QGP dominated

T_{IMR} from STAR: ~300 MeV

T_{IMR} from NA60:

- **246 ± 17 MeV** (1.2<M<2.5 GeV/c^2)
- 205 ± 12 MeV (1.2<M<2.0 GeV/c^2)

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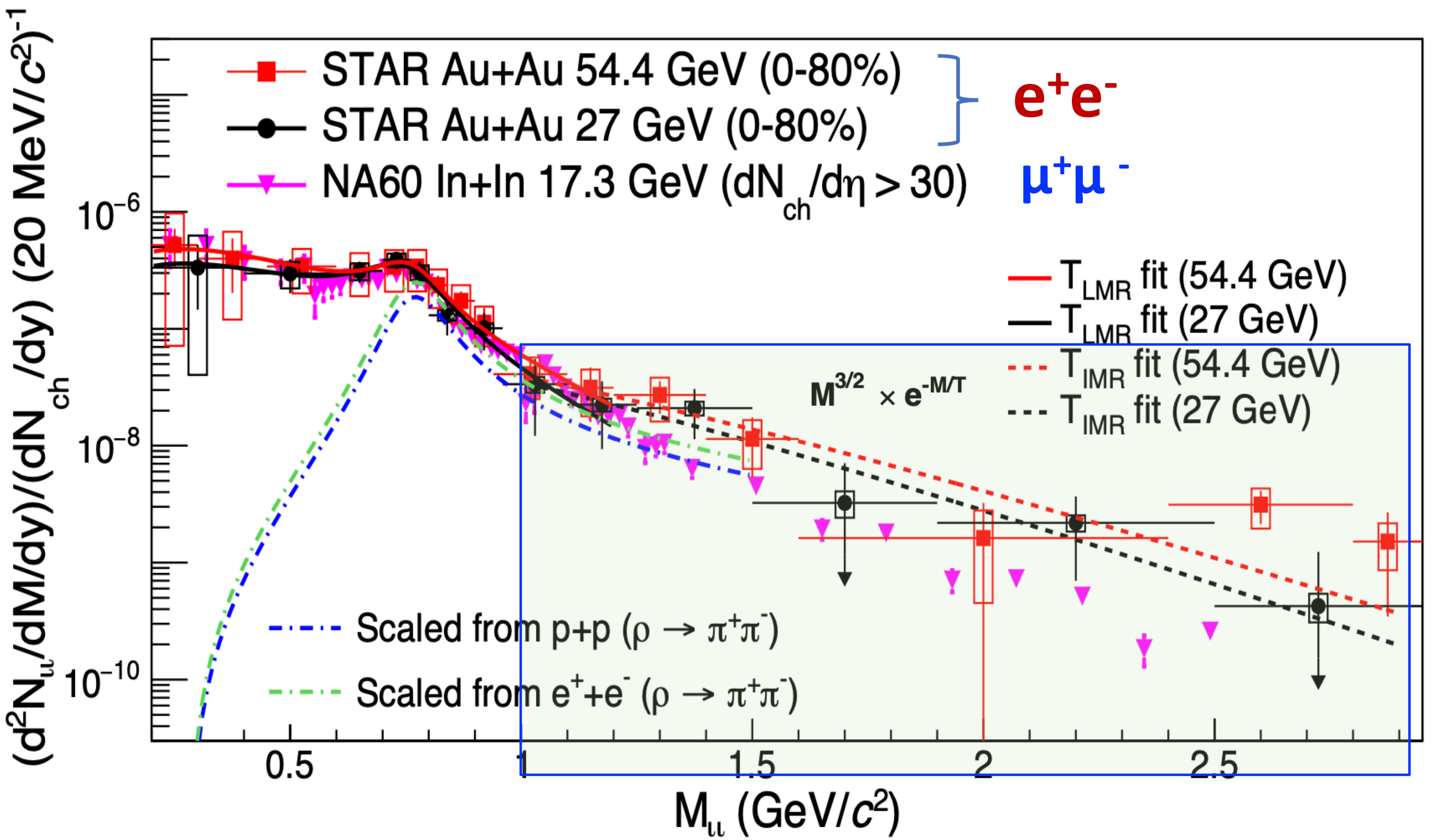

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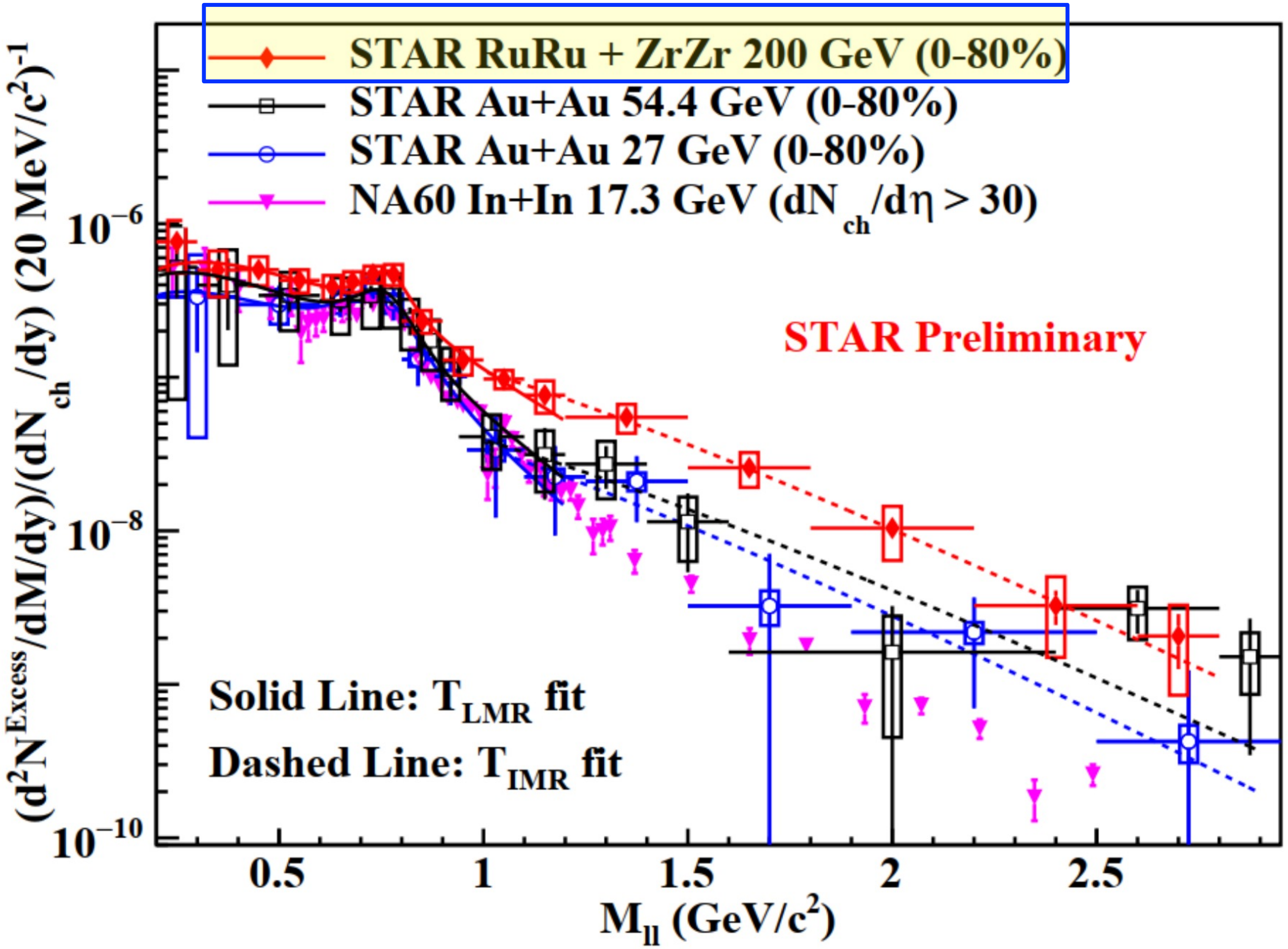
T_{IMR} > T_c (156 MeV):

- emission source is dominantly the **partonic phase - QGP**

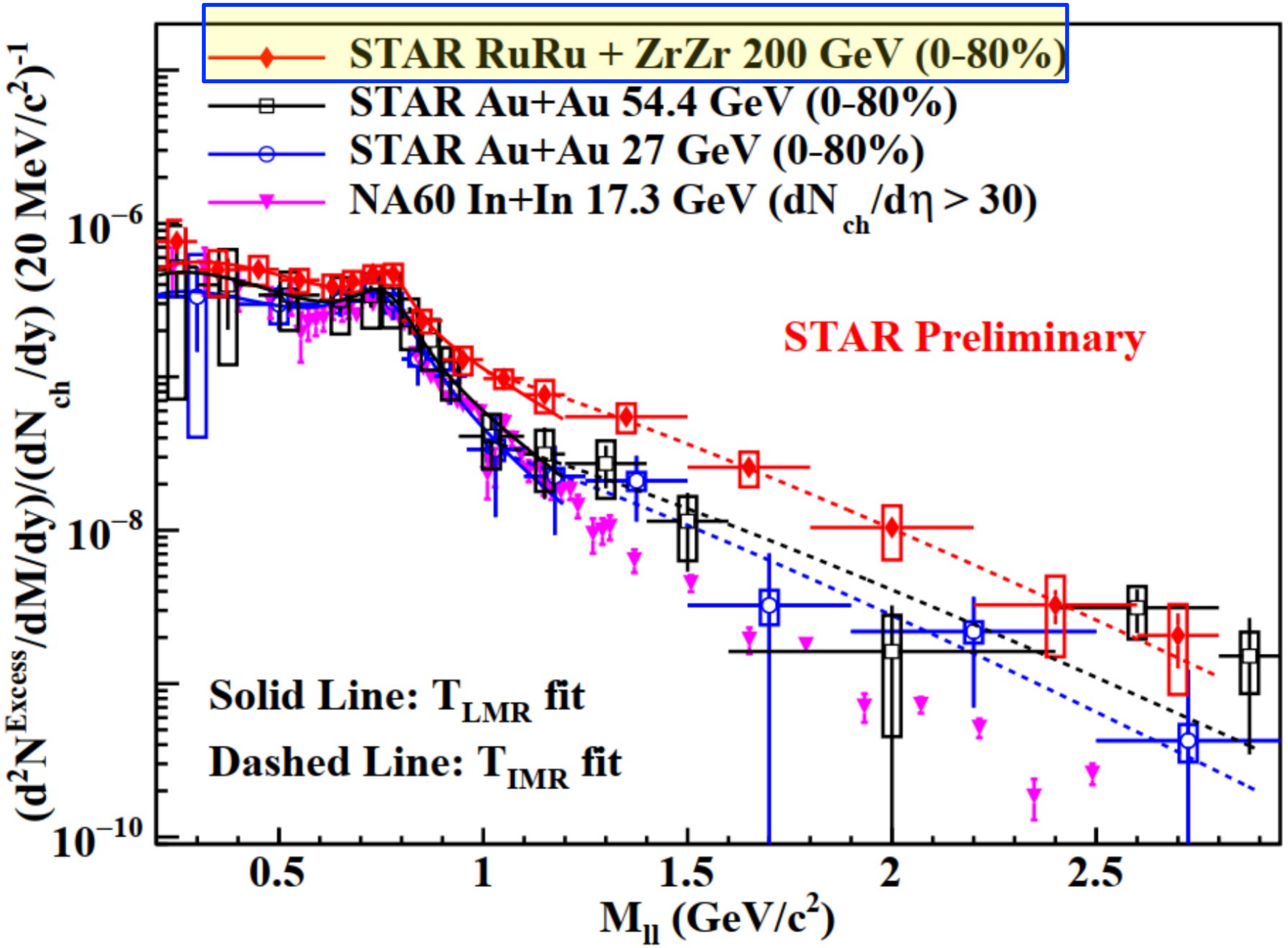
Thermal Dilepton at RHIC Top Energy



Ru/Zr (A = 96), Au (A = 197), In (A= 115)

- High precision measurement at 200 GeV isobaric collisions
- Similar mass spectrum but with higher yield at IMR than low energy collisions

Thermal Dilepton at RHIC Top Energy

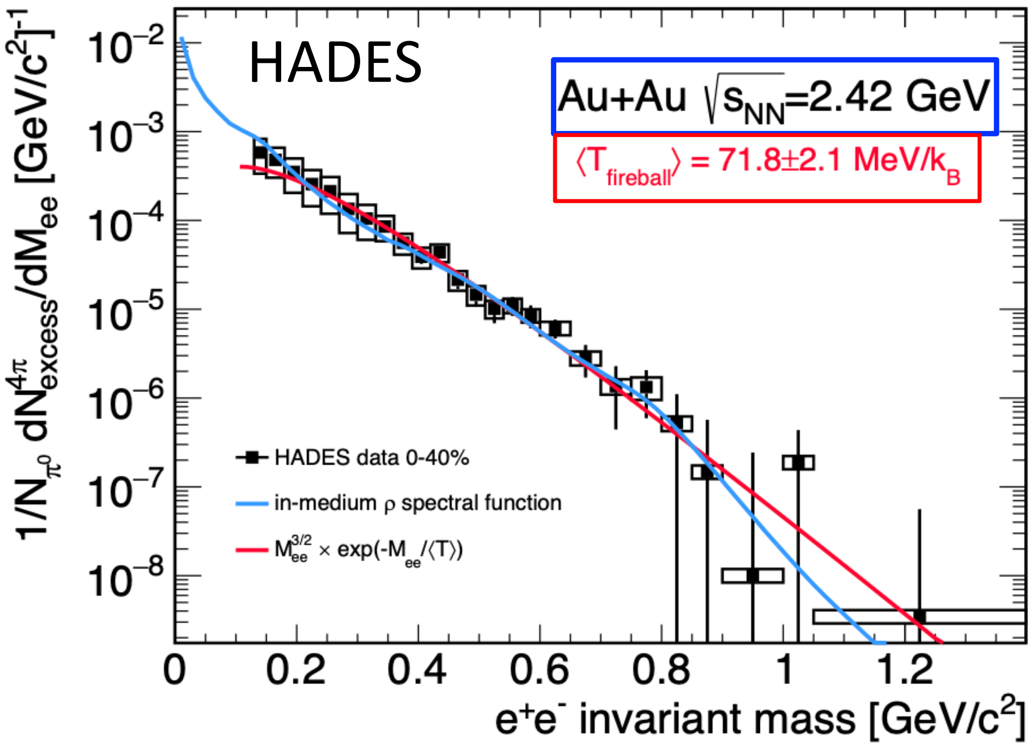


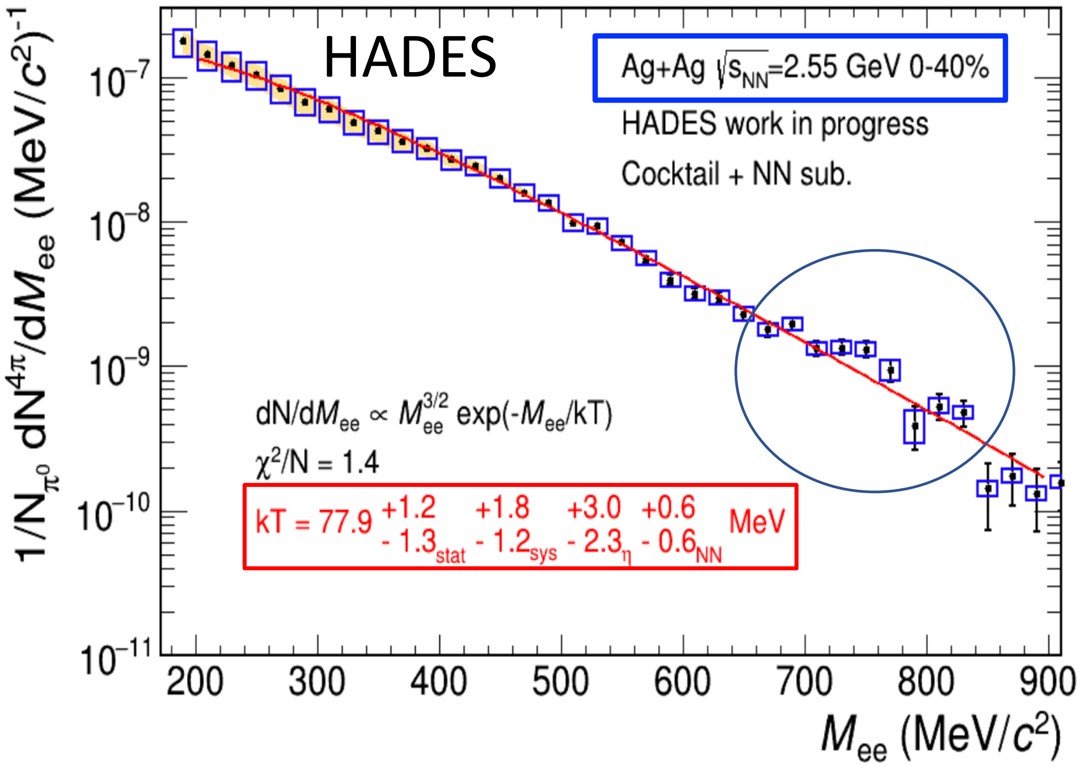
Ru/Zr (A = 96), Au (A = 197), In (A= 115)

- High precision measurement at 200 GeV isobaric collisions
- Similar mass spectrum but with higher yield at IMR than low energy collisions
- **T_{LMR} = 199 ± 6 (stat.) ± 13 (sys.) MeV**
  - Higher than T_{pc}
  - Hint of higher QGP contribution
- **T_{IMR} = 293 ± 11 (stat.) ± 27 (sys.) MeV**
  - Similar to that from 27 and 54.4 GeV

Thermal Dilepton at SIS18

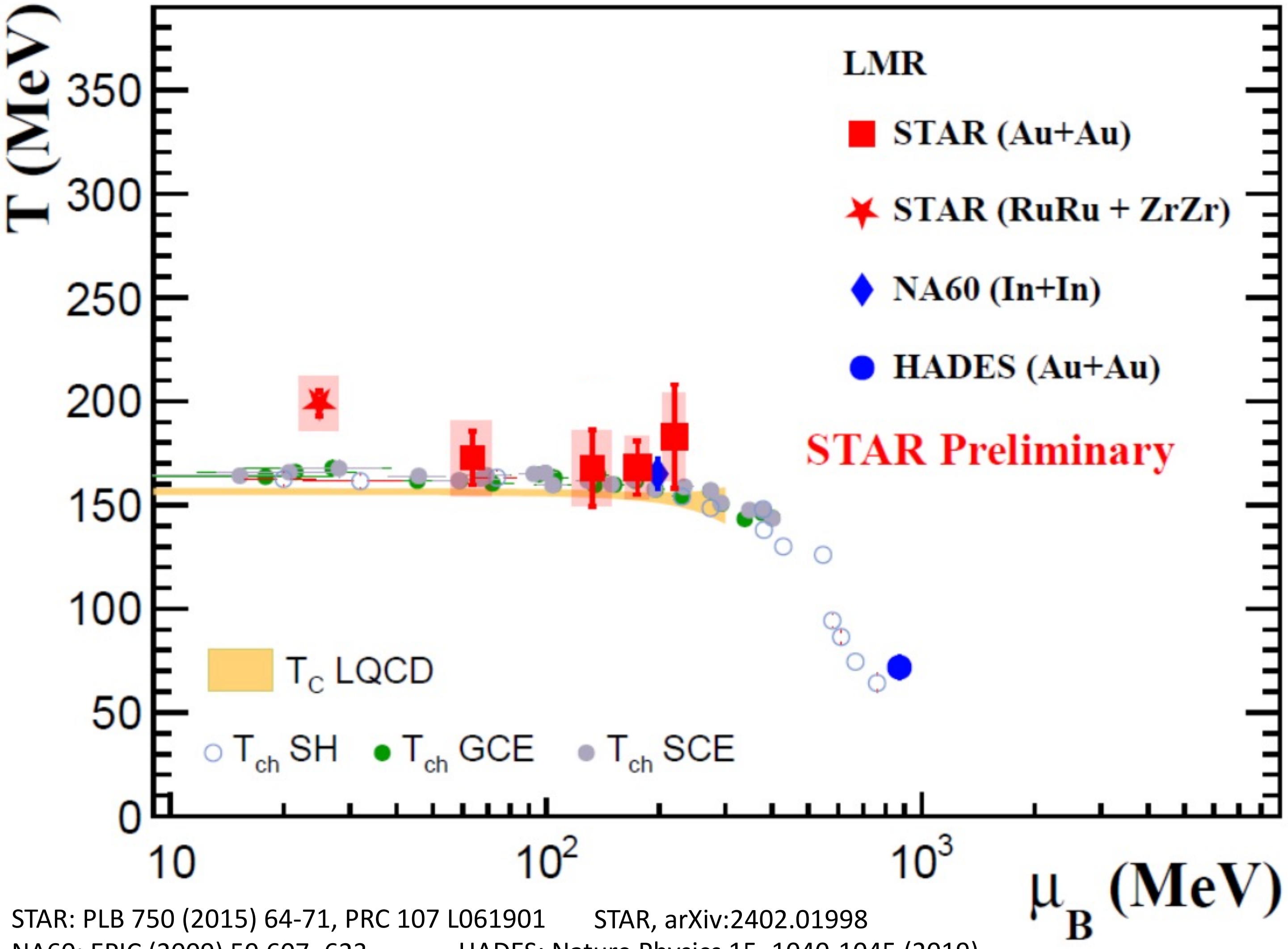
HADES: Nature Physics 15, 1040-1045 (2019)





- **In-medium ρ completely melt** via frequent scattering with surrounding baryons
- **T_{LMR} ~ 70-80 MeV**, mass spectra is well reproduced by transport model considering thermal radiation of hot hadronic medium

Current Temperature Measurements



Thermal dileptons in LMR

- T close to both T_{ch} and T_c
- Dominantly emitted around phase transition
- T(200 GeV) is higher, hint of more QGP contribution

STAR: PLB 750 (2015) 64-71, PRC 107 L061901 STAR, arXiv:2402.01998
NA60: EPJC (2009) 59 607–623 HADES: Nature Physics 15, 1040-1045 (2019)

T_{ch} SH: P. Braun-Munzinger et al. Nature 561, 321-330 (2018) HotQCD: PLB 795 (2019) 15-21
T_{ch} GCE/SCE: STAR PRC 96, 044904 (2017)

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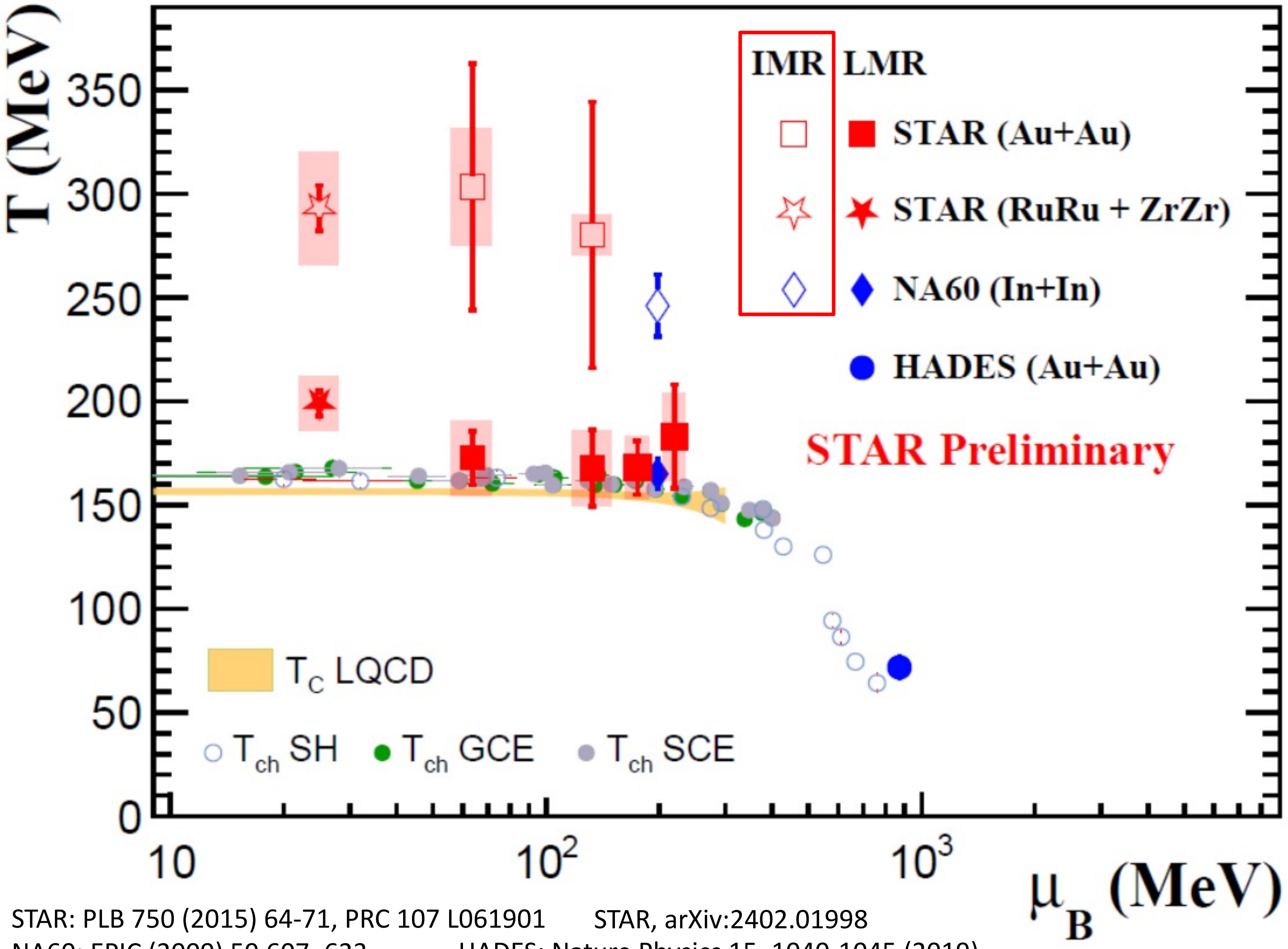

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Thermal dileptons in LMR

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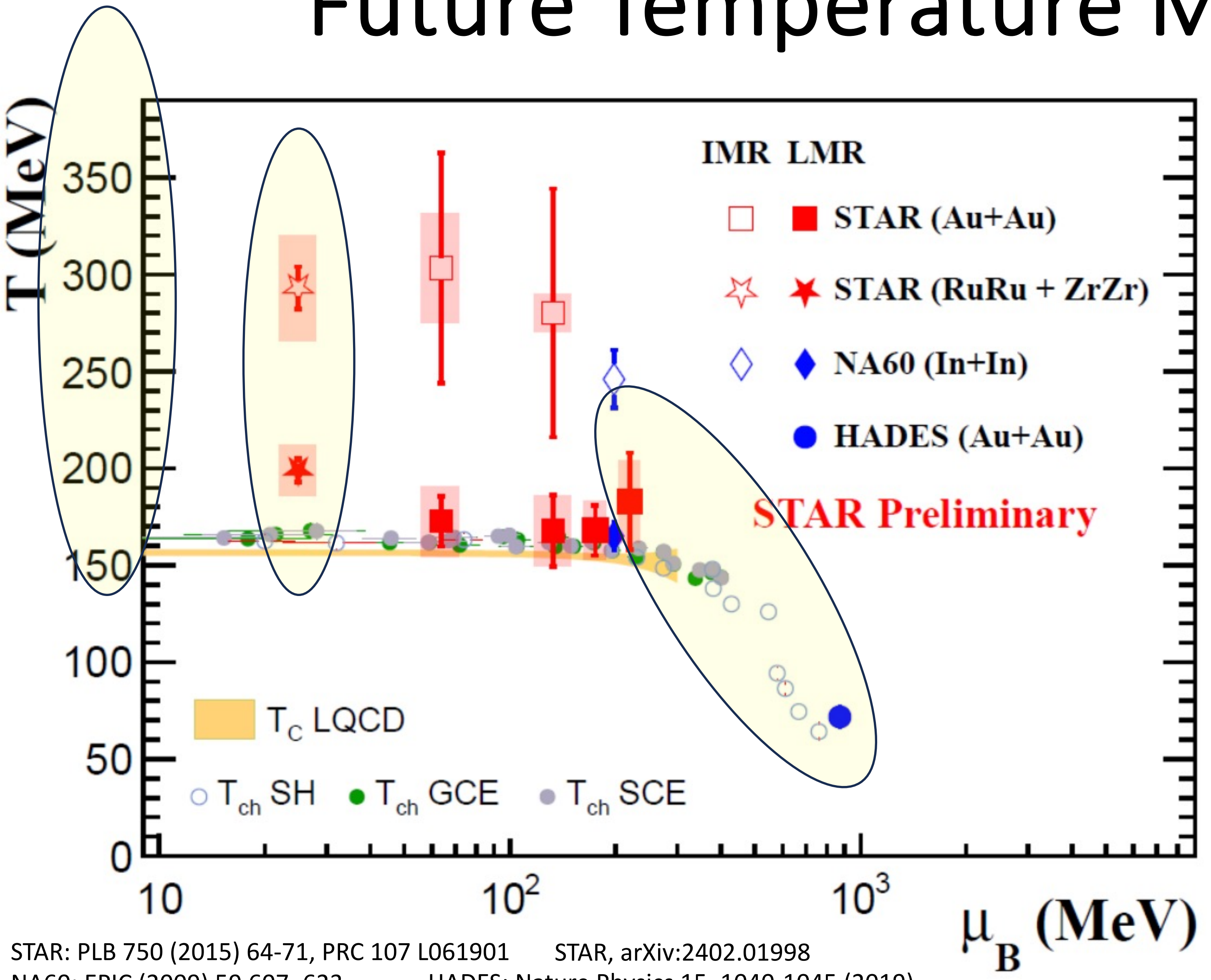
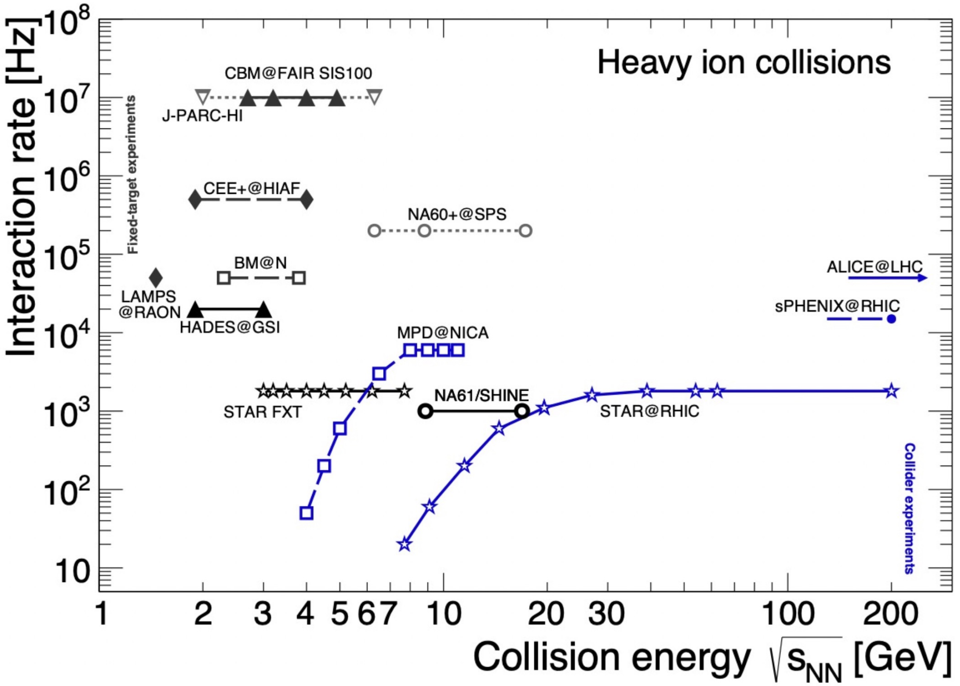
Thermal dileptons in IMR

- T is higher than T_{LMR}, T_{ch}, T_c
- Emitted from QGP phase

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

Future Temperature Measurements





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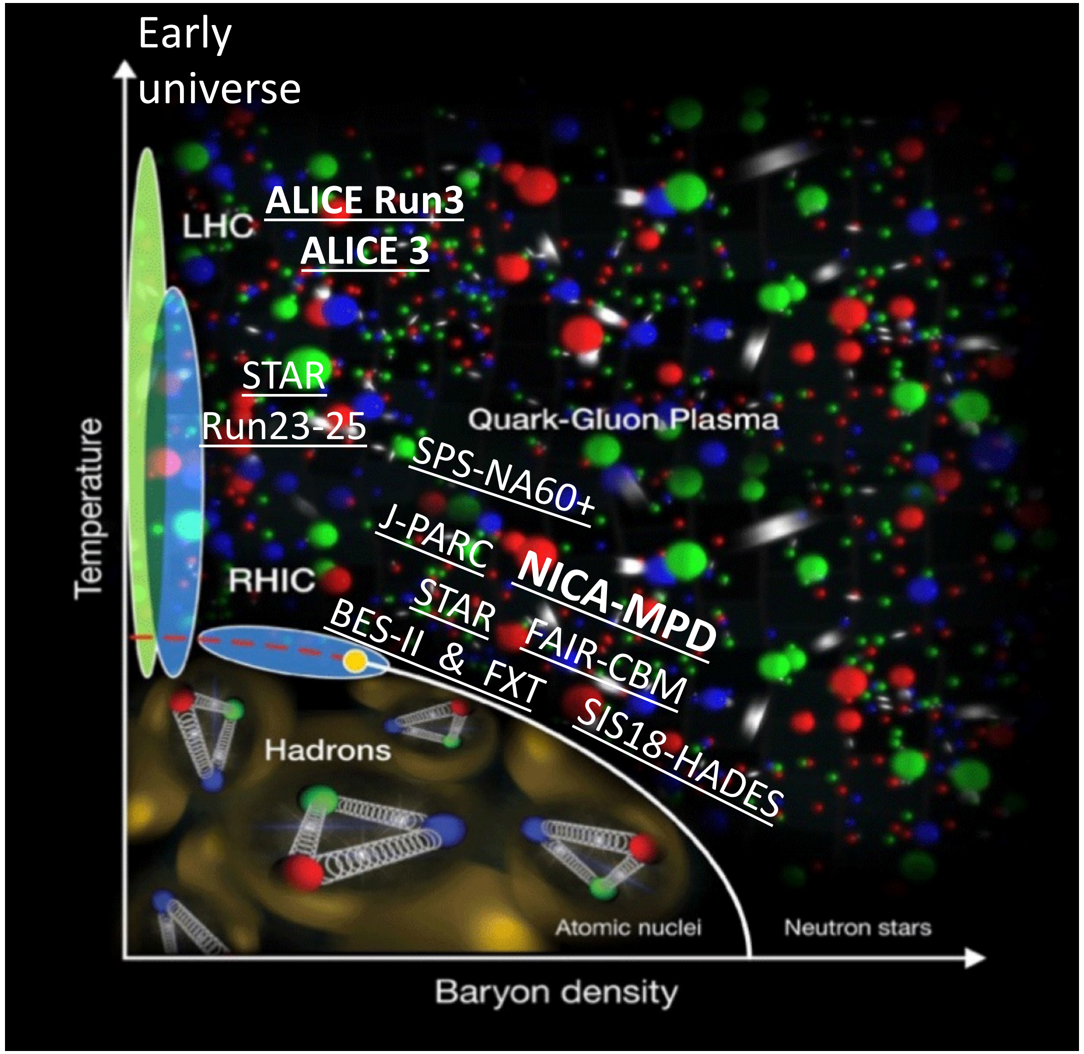
- More high precision data are on the way!
- Especially, **detailed scan at high baryon densities**, where the 1st-order phase transition and Critical End Point may exist.

Summary and Outlook

- **The current thermal dileptons:**
  - In-medium ρ is significantly broadened
  - T_{LMR} ~70-80 MeV at SIS18
  - $\mathbf{T_{LMR} \sim T_{ch} \sim T_c}$ at RHIC and SPS
  - $\mathbf{T_{IMR} > T_c}$ at RHIC and SPS: **QGP**

- **The future thermal dileptons:**
  - Huge experimental efforts and detailed energy scan, especially at high baryon densities:
    - ✓ Energy, time dependent temperatures
    - ✓ Partial chiral symmetry restoration
    - ✓ Critical end point

High precision is the key!!!

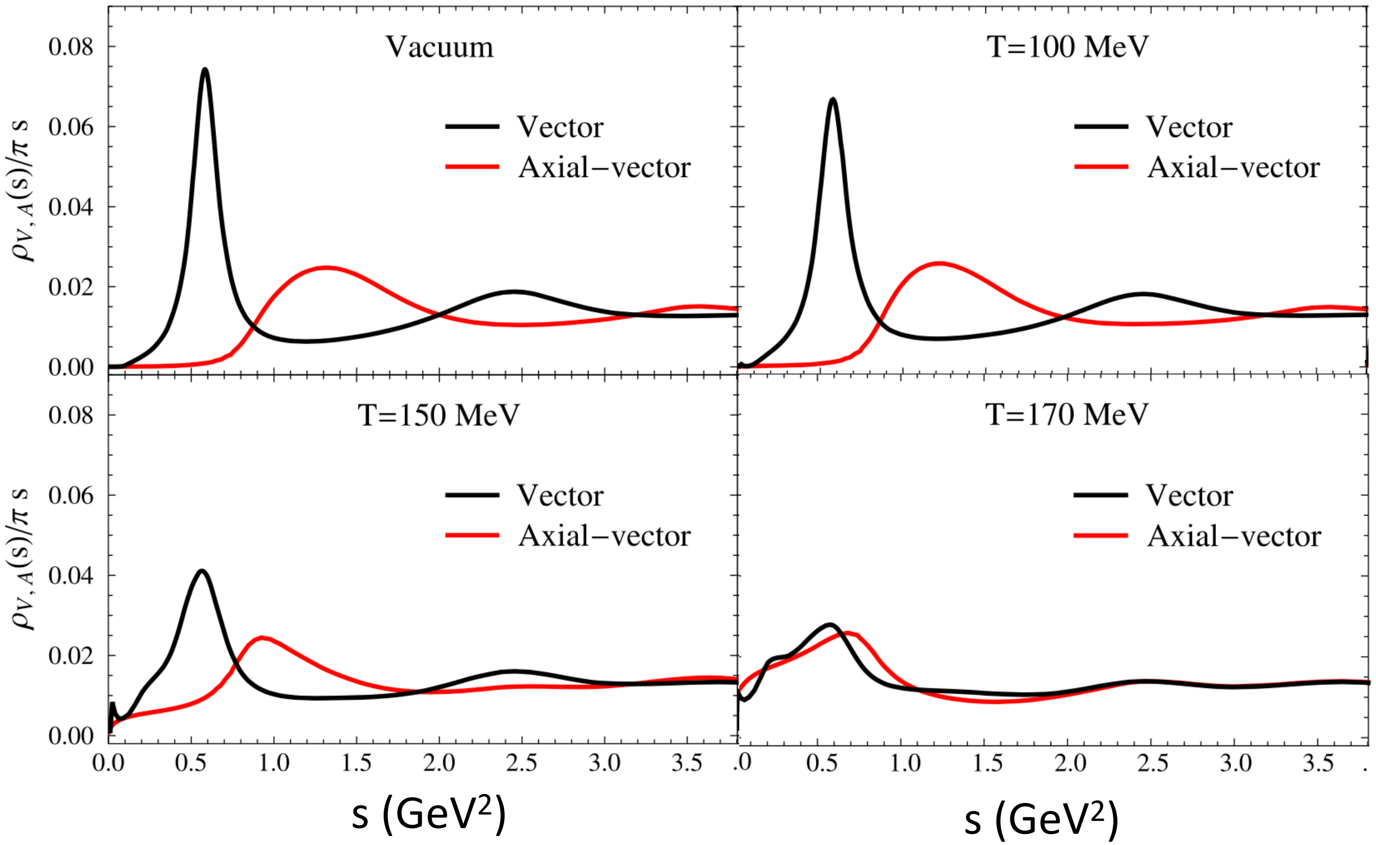


Thank you for your attention!

BACKUP SLIDES

Chiral Symmetry Partial 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

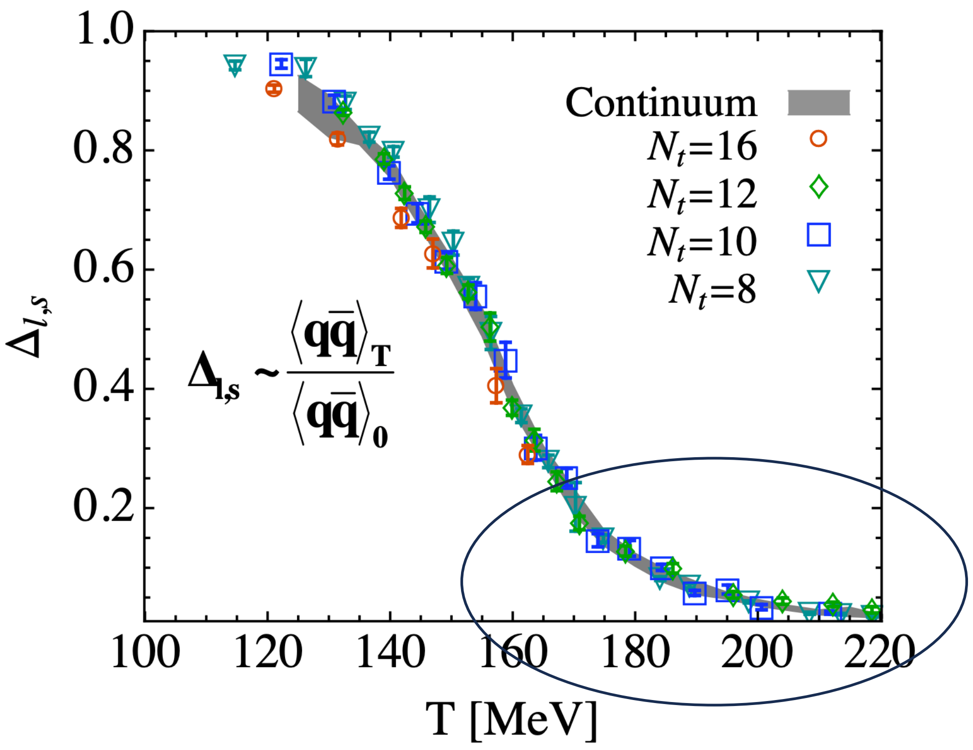
Experimental evidence is needed for final answer!

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

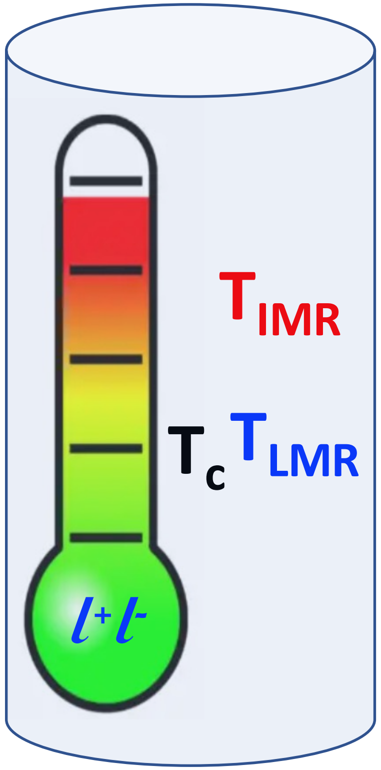
Is Chiral Symmetry Partially Restored?

scalar quark condensate

$< q\bar{q} >$ **≠ 0: chiral symmetry breaking;** **= 0: chiral symmetry restored.**



LQCD BMW Collaboration: JHEP 09 (2010) 073



Dilepton thermometer says: medium is hot enough to achieve the CSR

Direct evidence?

Is Chiral Symmetry Restored?

scalar quark condensate

$< q\bar{q} >$ **≠ 0: chiral symmetry breaking;** **= 0: chiral symmetry restored.**

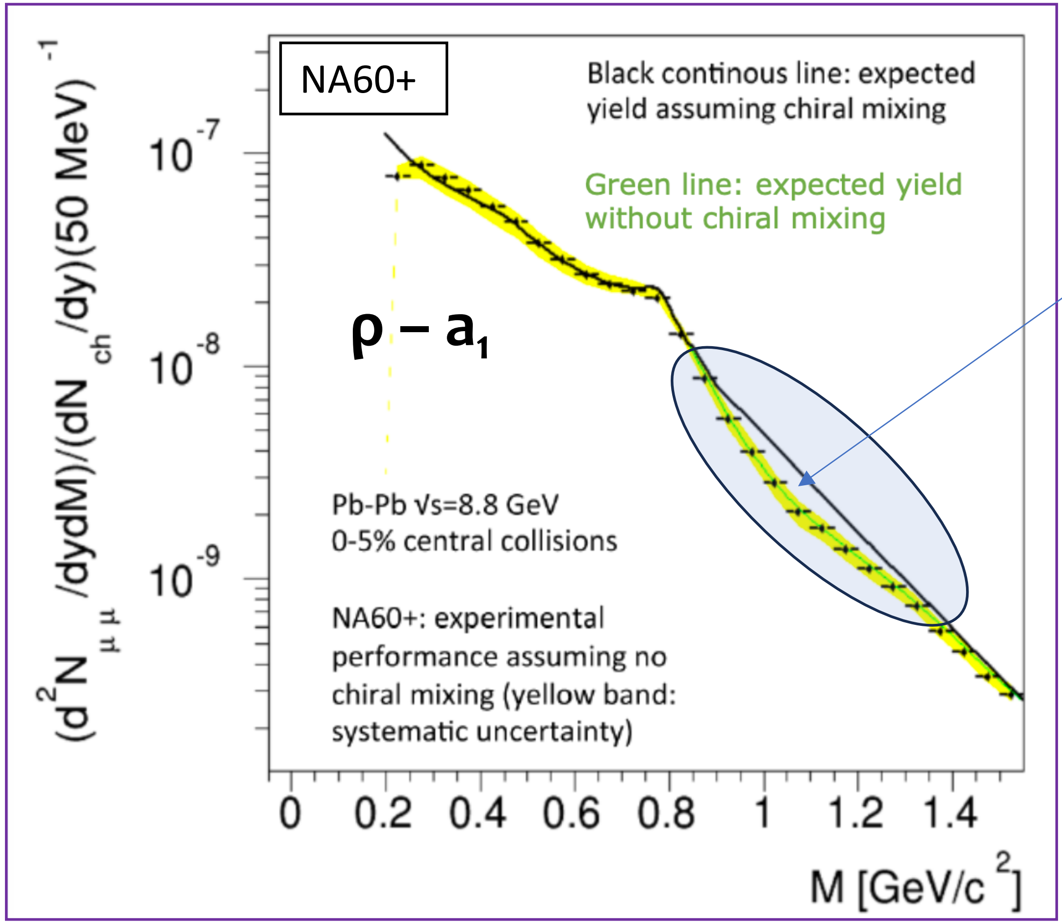
Vector meson (ρ…) → In-medium broaden **ρ** at RHIC, SPS can be well described by models considering **CSR**

Axial-Vector meson (a_1…) — No dilepton decays (chiral partner of ρ)

⇒ **Direct V vs. A comparison is not available!**

Experimental Evidence of CSR

CSR ⇨ **Axial-VM show up in VM spectra inside the medium via chiral mixing**



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

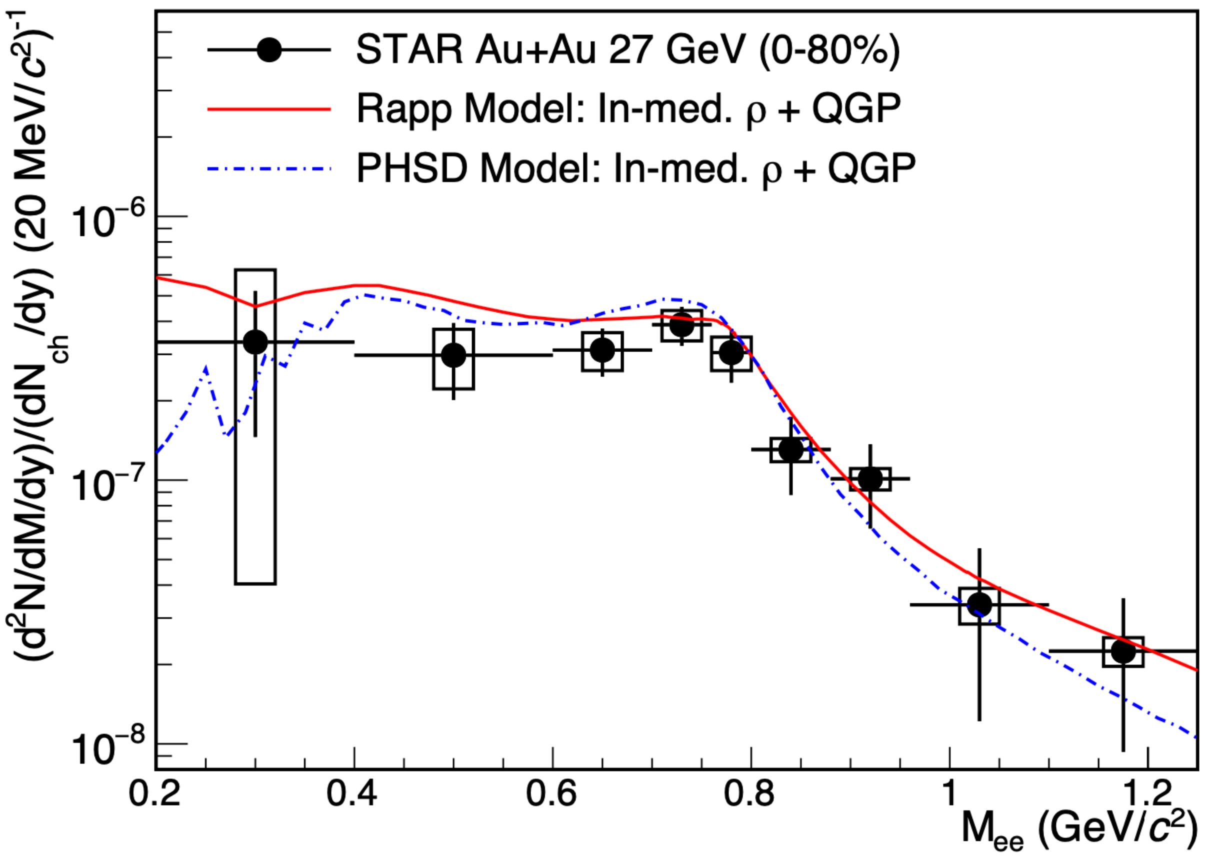
20-30% extra excess

Challenges:

- Phi meson (yield and shape potential modification)
- Definition of dip structure (model uncertainties)

High precision is the key!!!

STAR Data vs. Models



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 + meson/baryon cloud

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

PHYSICAL REVIEW LETTERS **132,** 172301 (2024)

Virtual Photons Shed Light on the Early Temperature of Dense QCD Matter

Jessica Churchill,[1] Lipei Du,[1,*] Charles Gale,[1] Greg Jackson,[2,3] and Sangyong Jeon[1]
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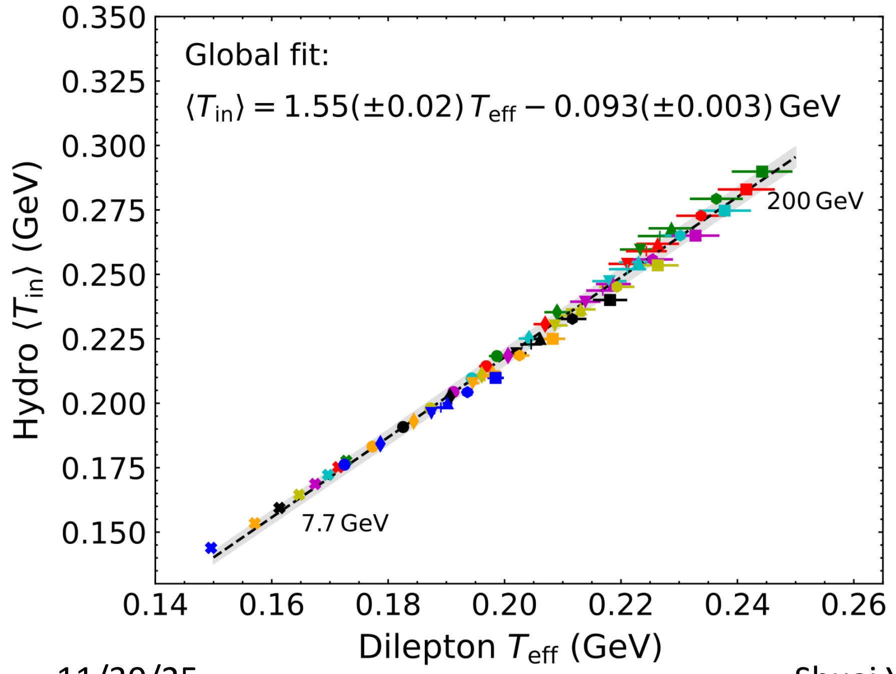
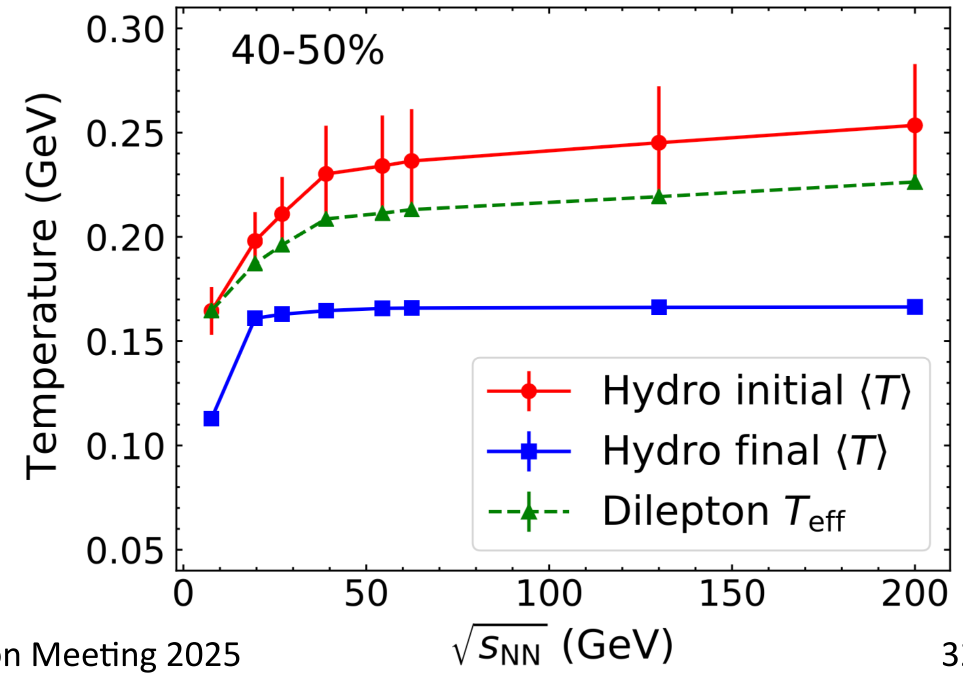
(Received 20 November 2023; revised 18 February 2024; accepted 22 March 2024; published 22 April 2024)

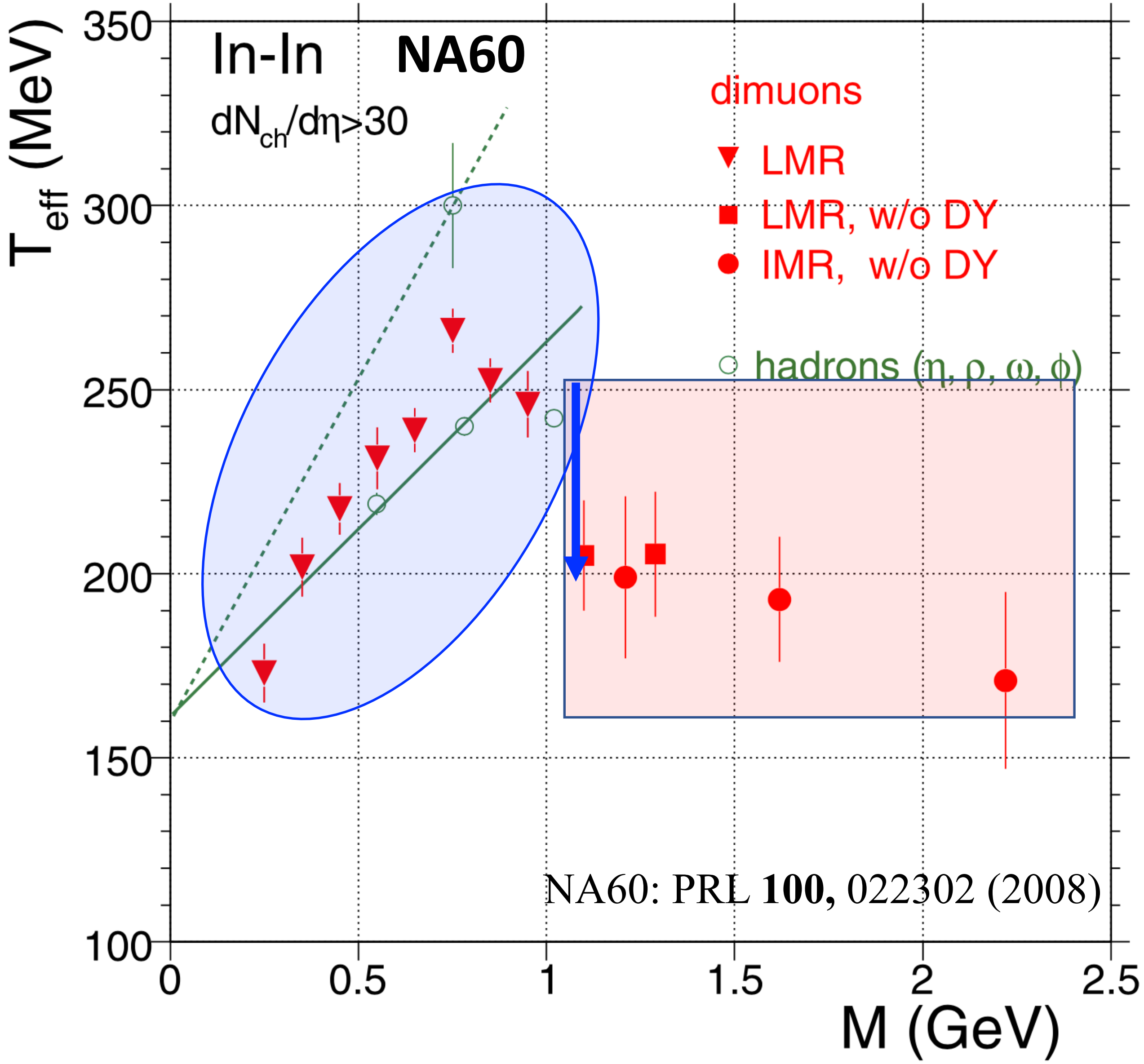
Dileptons produced during heavy-ion collisions represent a unique probe of the QCD phase diagram, and convey information about the state of the strongly interacting system at the moment their preceding off-shell photon is created. In this study, we compute thermal dilepton yields from Au + Au collisions performed at different beam energies, employing a (3 + 1)-dimensional dynamic framework combined with emission rates accurate at next-to-leading order in perturbation theory and which include baryon chemical potential dependencies. By comparing the effective temperature extracted from the thermal dilepton invariant mass spectrum with the average temperature of the fluid, we offer a robust quantitative validation of dileptons as an effective probe of the early quark-gluon plasma stage.

DOI: 10.1103/PhysRevLett.132.172301





Thermal Dilepton ⊕ Medium Flow



$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \exp\left(-\frac{m_T}{T_{eff}}\right)$$

$M < 1$ GeV/c^2 :

- **T_{eff} rise linearly → In-medium radiation pushed by radial flow**
- **T_{eff} peaks at m_ρ**

$M > 1$ GeV/c^2:

- **T_{eff} suddenly drop ~50 MeV → dominant emission source from hadronic to partonic matter**
- **T_{eff} ~ 200 MeV**

Teff is Enhanced by Radial Flow

PHYSICAL REVIEW C **89**, 044910 (2014)

Thermal photons as a quark-gluon plasma thermometer reexamined

Chun Shen* and Ulrich Heinz
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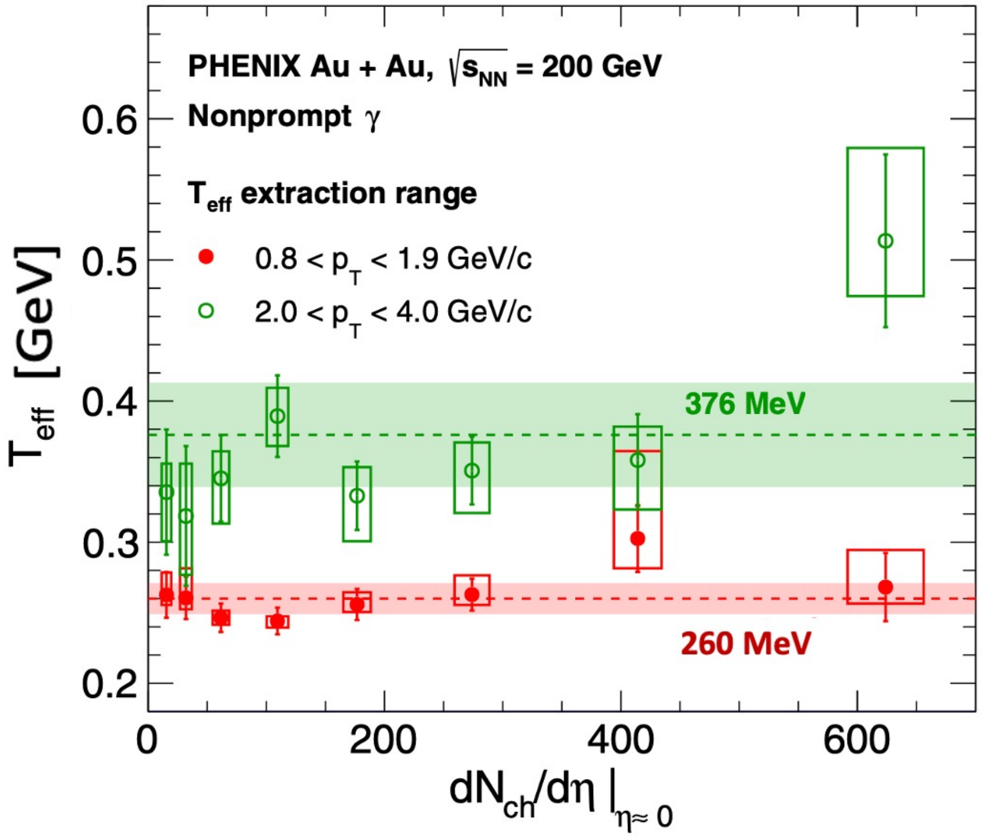
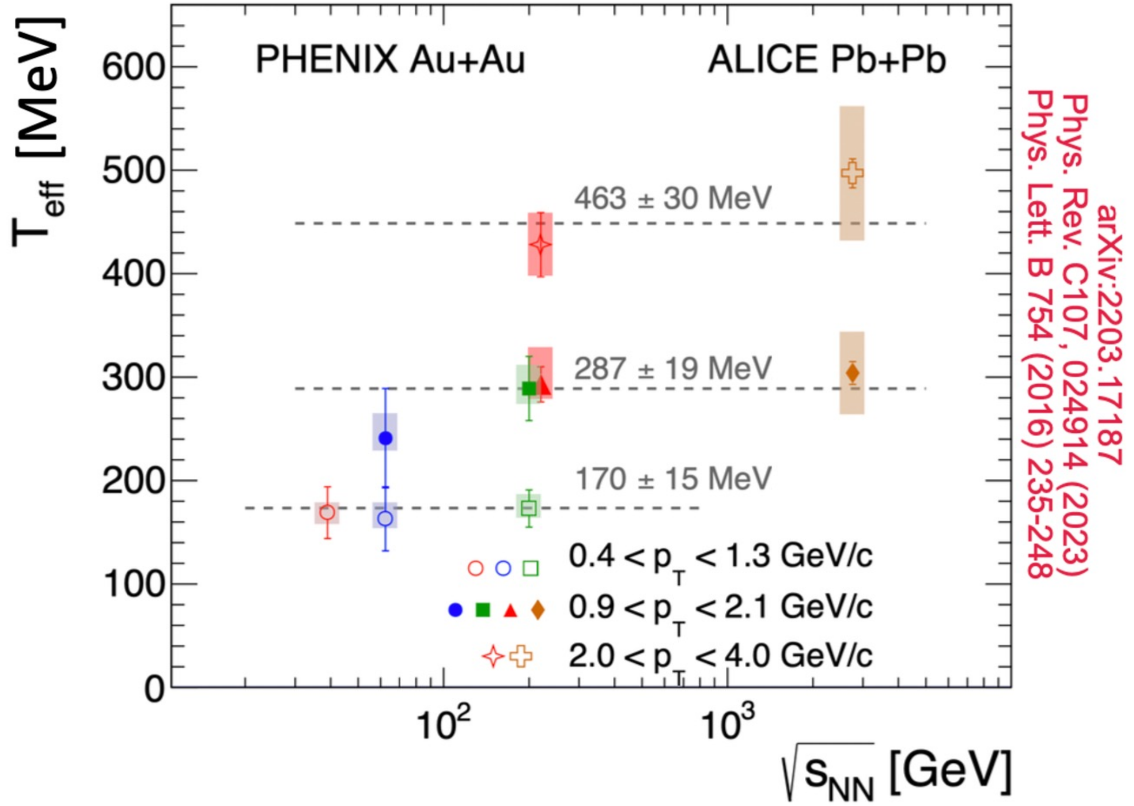
Charles Gale
Department of Physics, McGill University, 3600 University Street, Montreal, Quebec, Canada H3A 2T8
and Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, D-60438 Frankfurt am Main, Germany
(Received 11 August 2013; revised manuscript received 28 March 2014; published 28 April 2014)

"**Most photons are emitted from fireball regions with $T \sim T_c$** near the quark-hadron phase transition, but that **their effective temperature is significantly enhanced by strong radial flow.**"

Effective T from Non-Prompt Photons

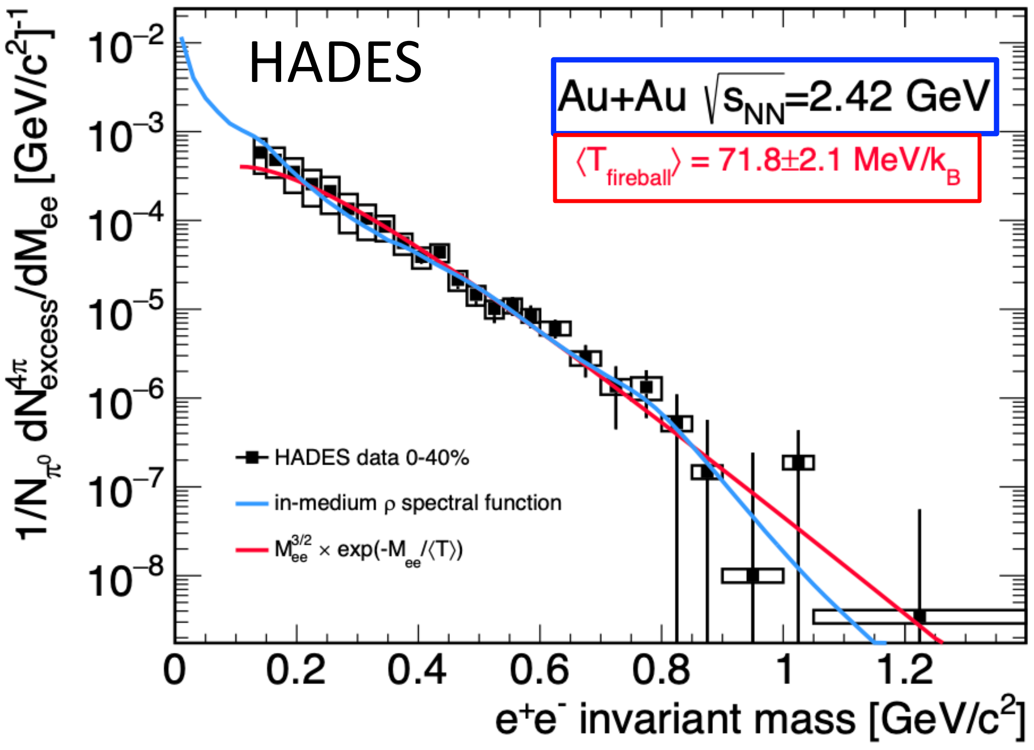




- T_{eff} are higher the T_{pc}, shows no clear system size dependence
- Clear p_T dependence, no clear dependence on collision energy
- However, interpretation of T_{eff} is complicated (radial flow, pre-equilibrium…)
  - Most of photons is radiated around T_C --- C. Shen, U.W. Heinz, J.F. Paquet, C. Gale: PRC 89 044910 (2014)

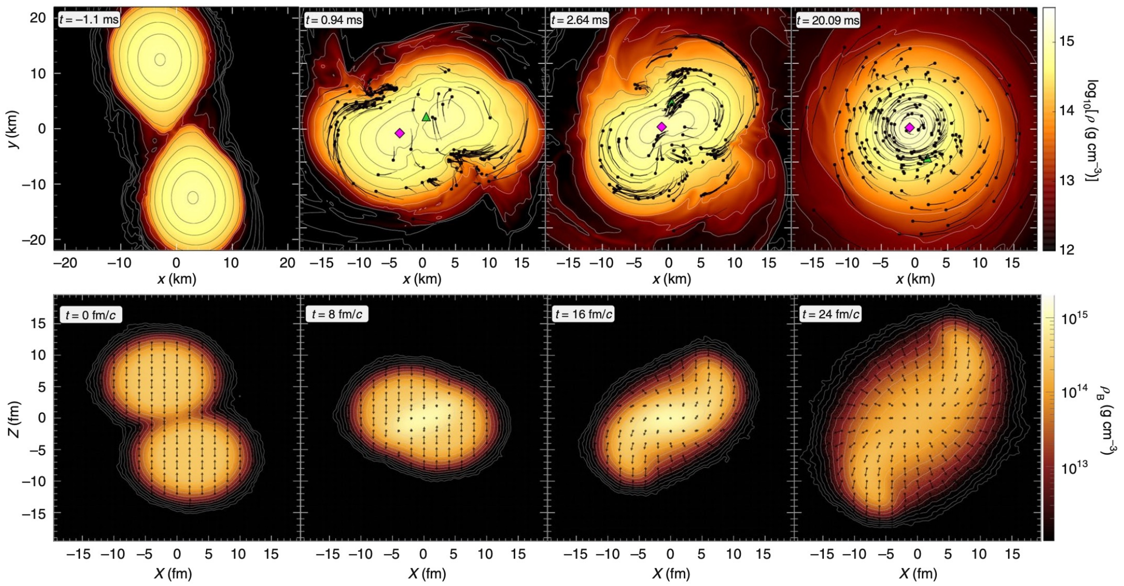
Small Collisions Connected to Big Collisions

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



PLB 122, 061101 (2019)

Binary neutorn star merger



Au+Au@2.42GeV

PPNP 41, 255-369 (1998)

- **Space and time scales differ by 10^{20}**, yet matter with **similar temperature and density**
- Thermal dileptons in HIC can advance the understanding of neutron star merger