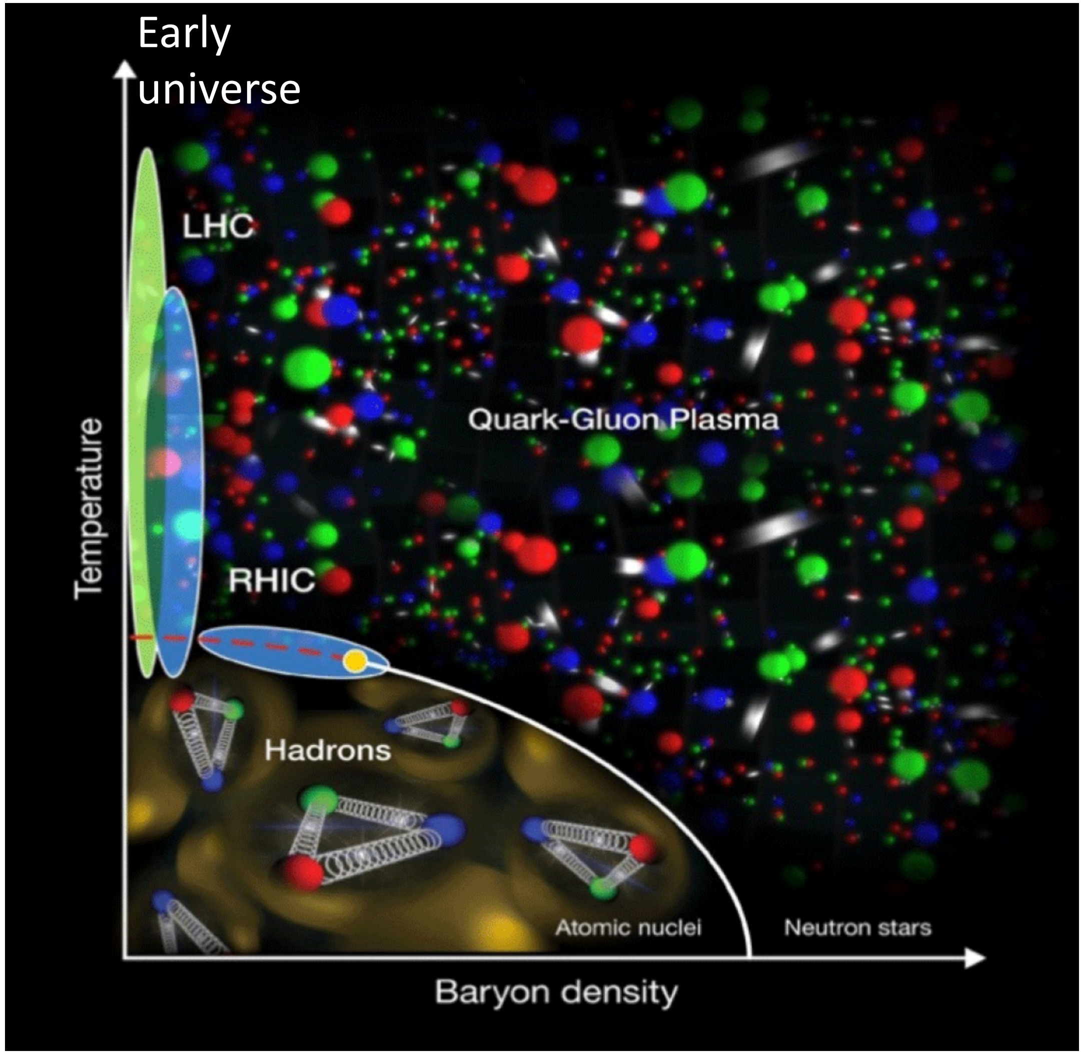
Thermal Dileptons at High Baryon Densities NICA/STAR-BES

Zaochen Ye (SCNU)

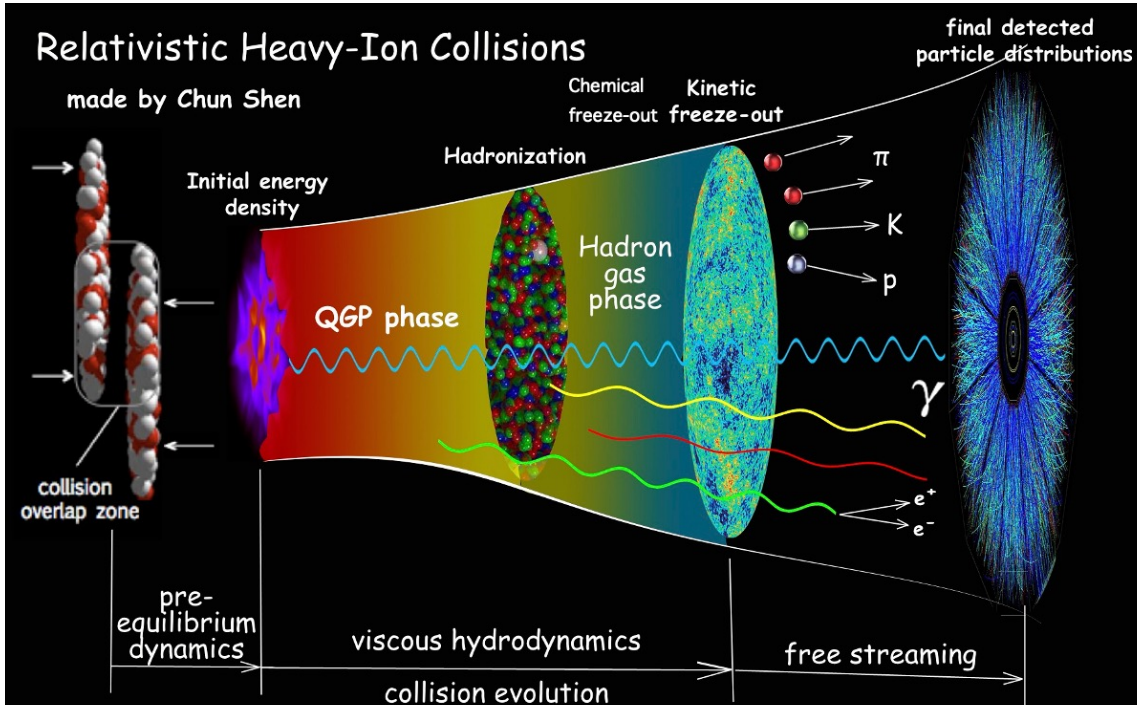
QCD Phase Diagram and Heavy-Ion Collisions



- **QCD phase diagram:**
  - Describes phases of matter under various conditions of temperature (T) and chemical potential (μ_B)

- **Heavy-ion collisions** create extreme conditions:
  - Formation and properties of QGP
  - Explore QCD diagram with different trajectories
  - At low baryon densities:
    - Cross-over transition
    - Early universe
  - At high baryon densities:
    - first-order phase transition and critical end point (CEP)
    - EOS to describe neutron star

Heavy-Ion Collision and Why Dileptons

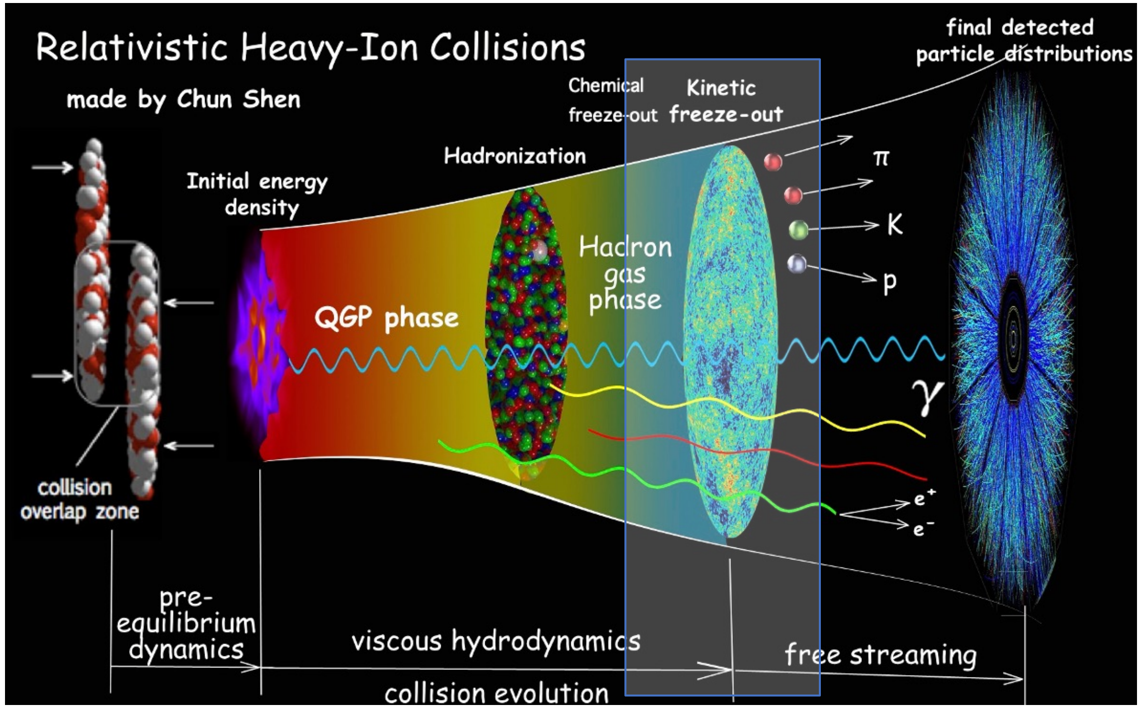


Hadrons

Photons

Leptons

Heavy-Ion Collision and Why Dileptons



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

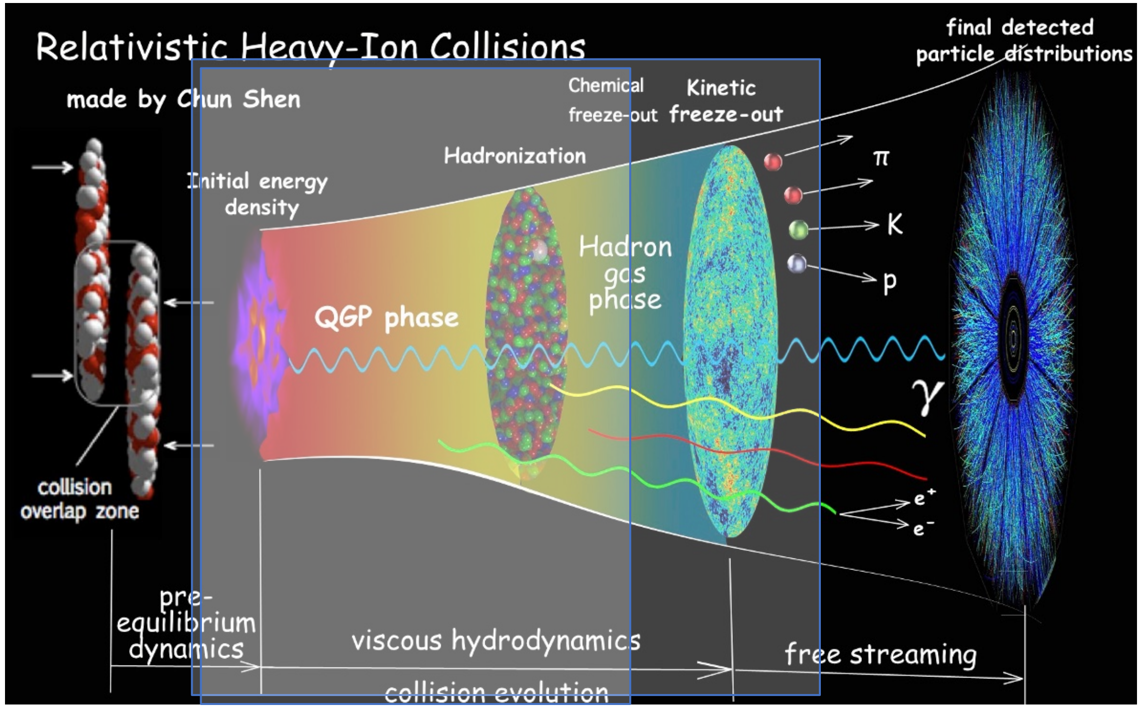
Hadrons (Yield, p_T)

Photons

Leptons

T at early stage is still poorly known ☹

Heavy-Ion Collision and Why Dileptons



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

EM Probes

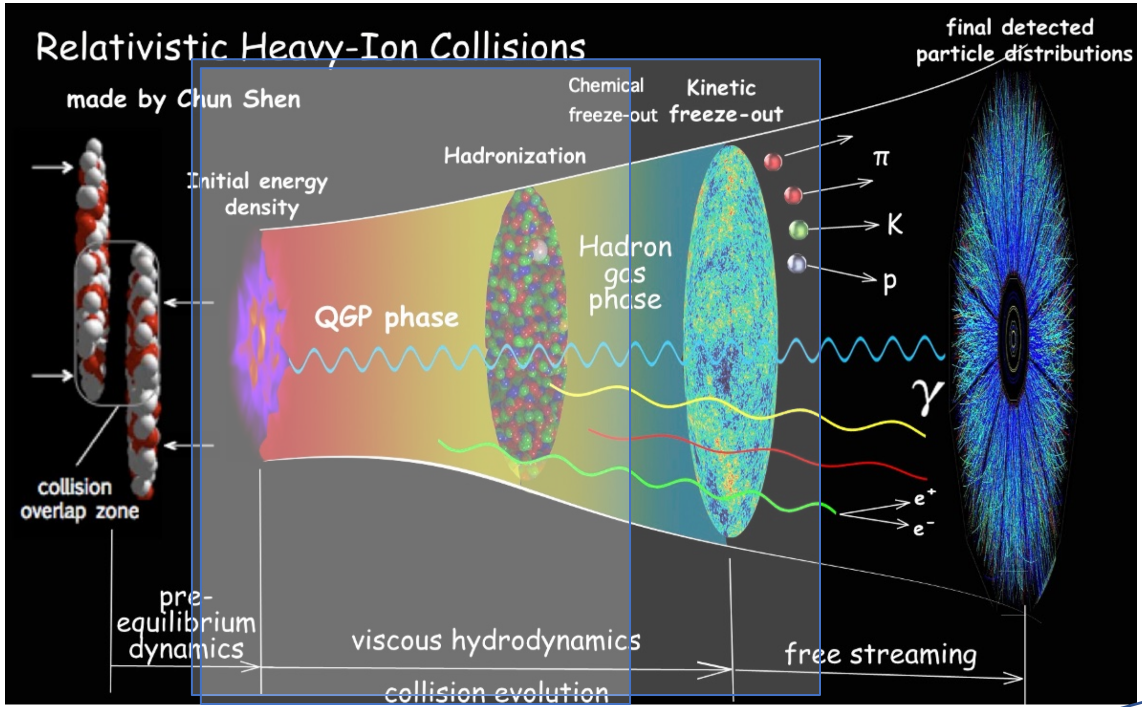
Photons (p_T)

Leptons (M_{ll})

- **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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Leptons (M_{ll})

Inverse slope → Effective temperature
(Doppler shift warning)

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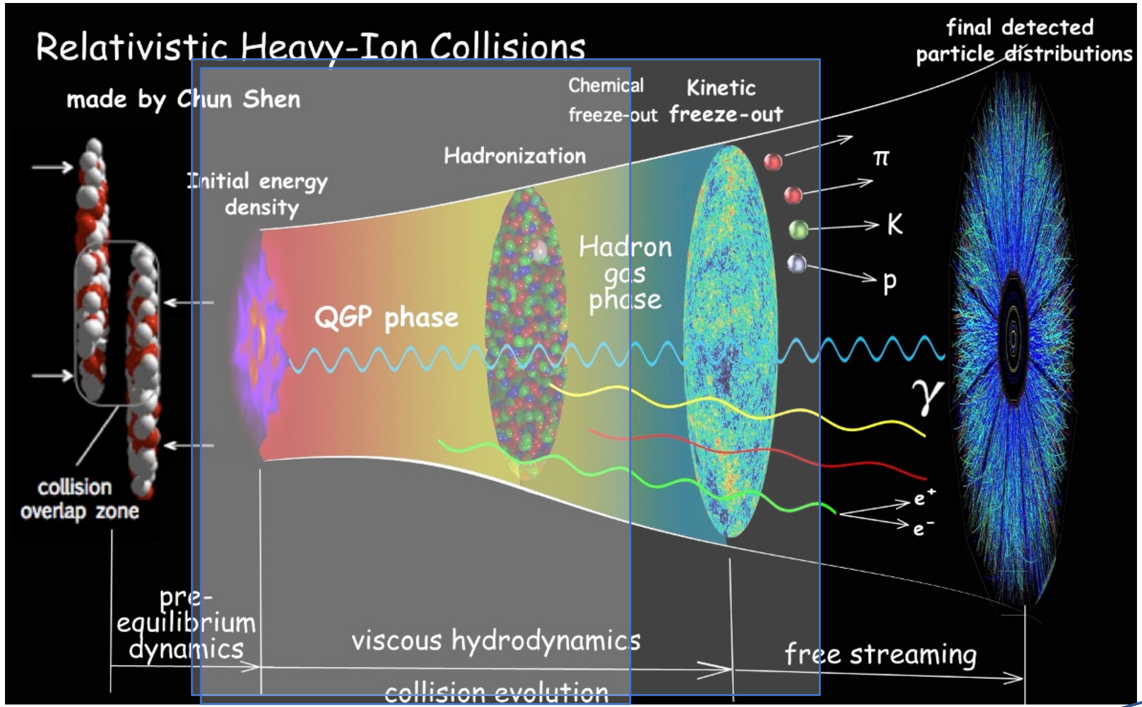
Heavy-Ion Collision and Why Dileptons



Hadrons
(Yield, p_T)

- **Most produced**
- **Freeze-out temperature: T_{ch} and T_{kin}**
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EM Probes

Photons (p_T)

- **Early to final stages**
- **Escape freely (λ~100-500 fm)**
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Inverse slope → Effective temperature
(Doppler shift warning)

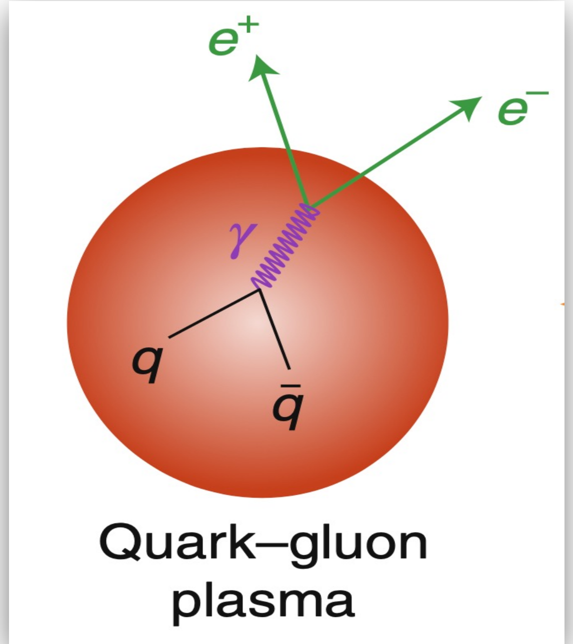
Leptons (M_{ll})

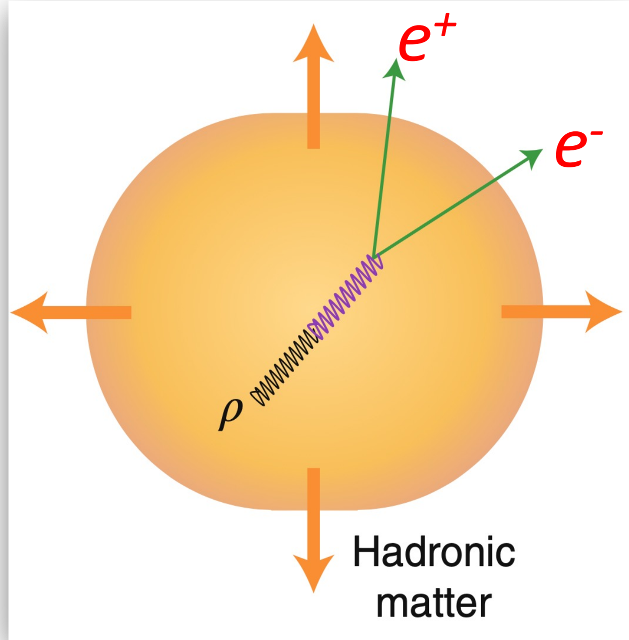
Dileptons

- **Temperature without Doppler-shift effect**
- **Unique probe of in-med. spectral function**
  - Partial restoration of Chiral Symmetry

T at early stage is still poorly known ☹

Thermal Dileptons



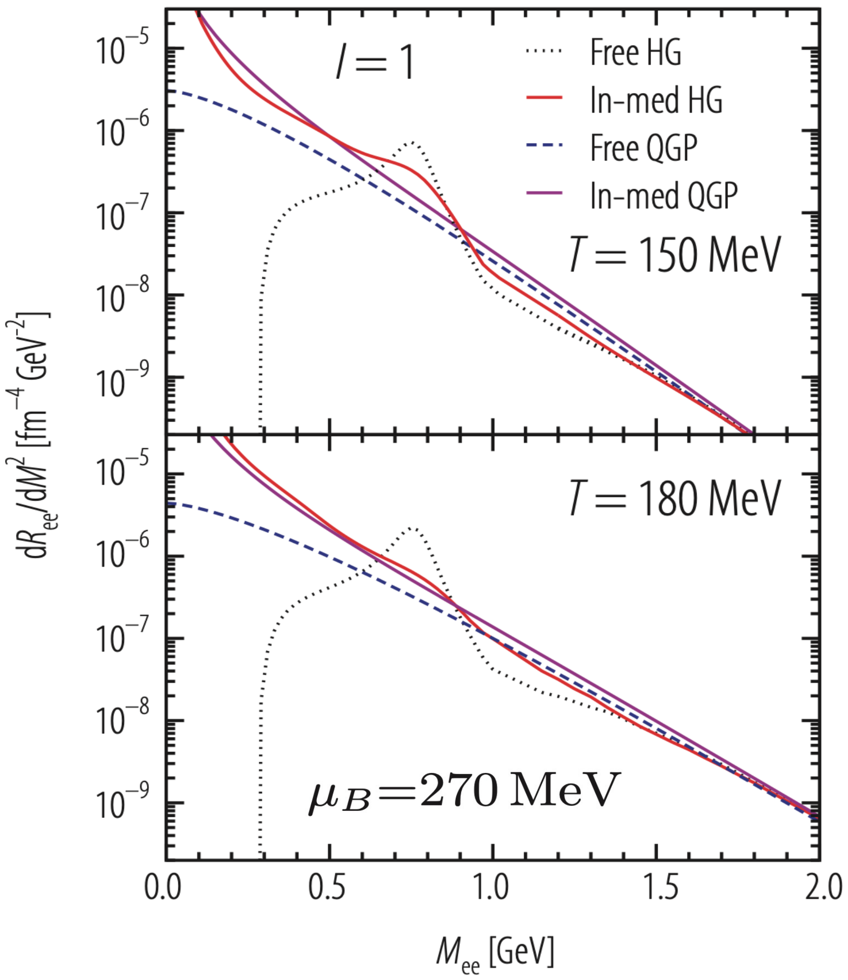


$q + \bar{q} \longrightarrow \gamma^* \longrightarrow e^+ + e^-$ $\pi^+ + \pi^- \longrightarrow \rho \longrightarrow e^+ + e^-$

Courtesy of Ralf Rapp

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

Rapp, Wambach, EPJA 6, 415 (1999)



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

How to Measure Thermal Dileptons

Inclusive signals
(space-time integral)

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

+

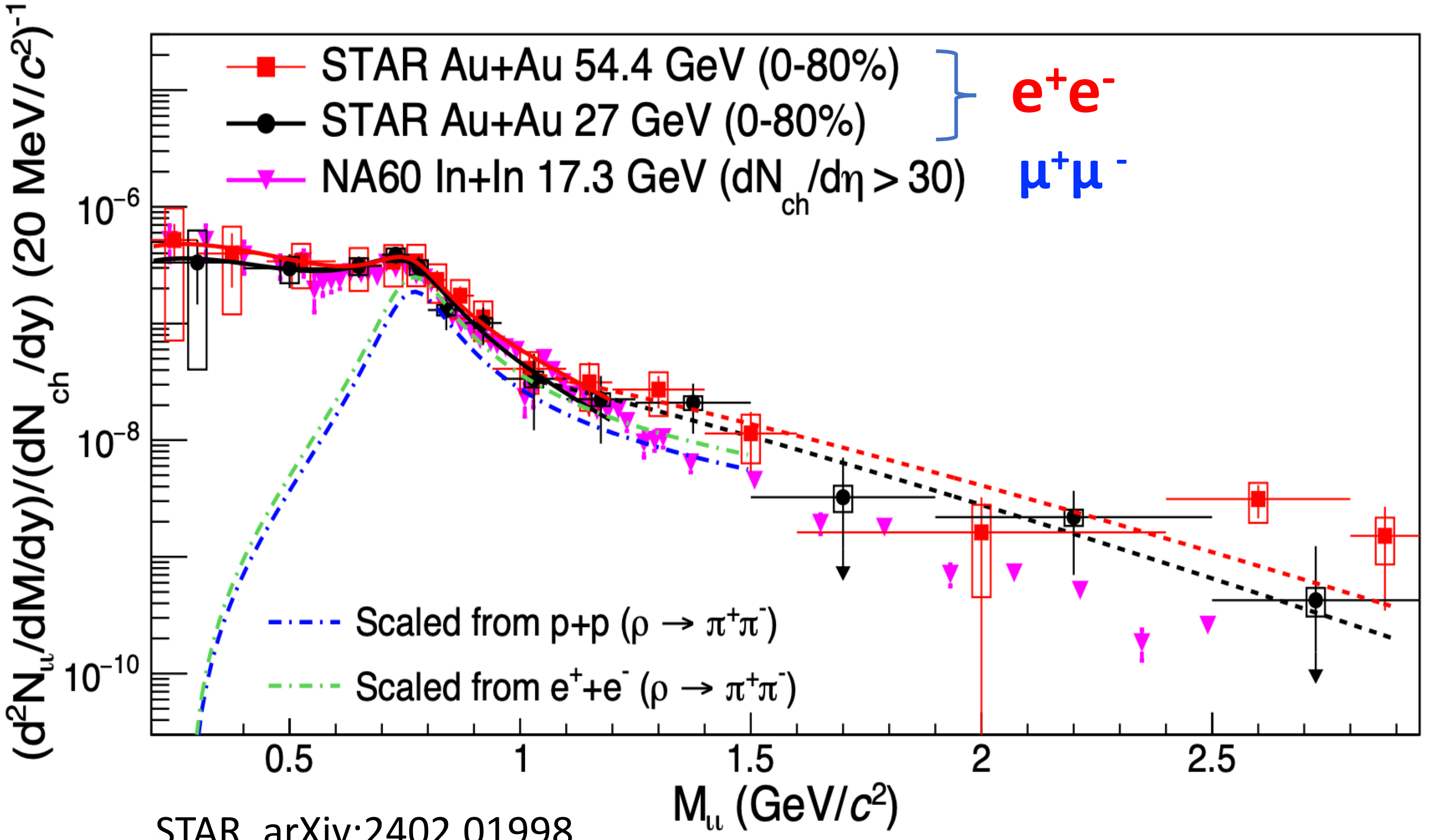
Physical background (Cocktails):
- **Drell-Yan**
- $\pi^0, \eta, \eta' \rightarrow \gamma e^+e^-$
- $\omega, \varphi \rightarrow e^+e^-, \omega \rightarrow \pi^0 e^+e^-, \varphi \rightarrow \eta e^+e^-$
- $J/\psi \rightarrow e^+e^-, c\bar{c} \rightarrow e^+eX$

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

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

Thermal Dilepton at Low Energies

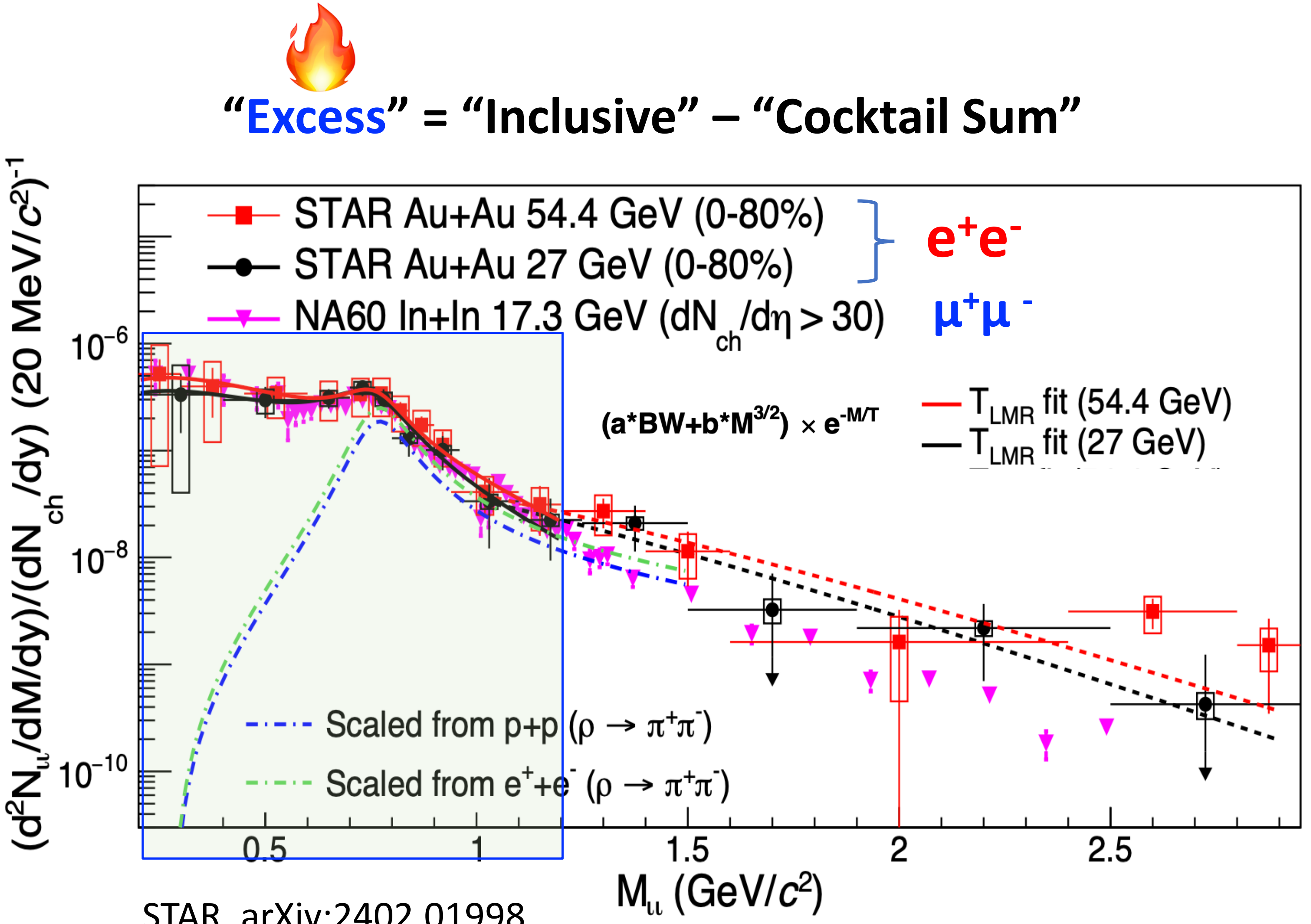
"Excess" = "Inclusive" – "Cocktail Sum"



STAR, arXiv:2402.01998

Thermal Dilepton (LMR) at Low Energies

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



STAR, arXiv:2402.01998

In-medium ρ dominated

- **Similar** mass spectrum

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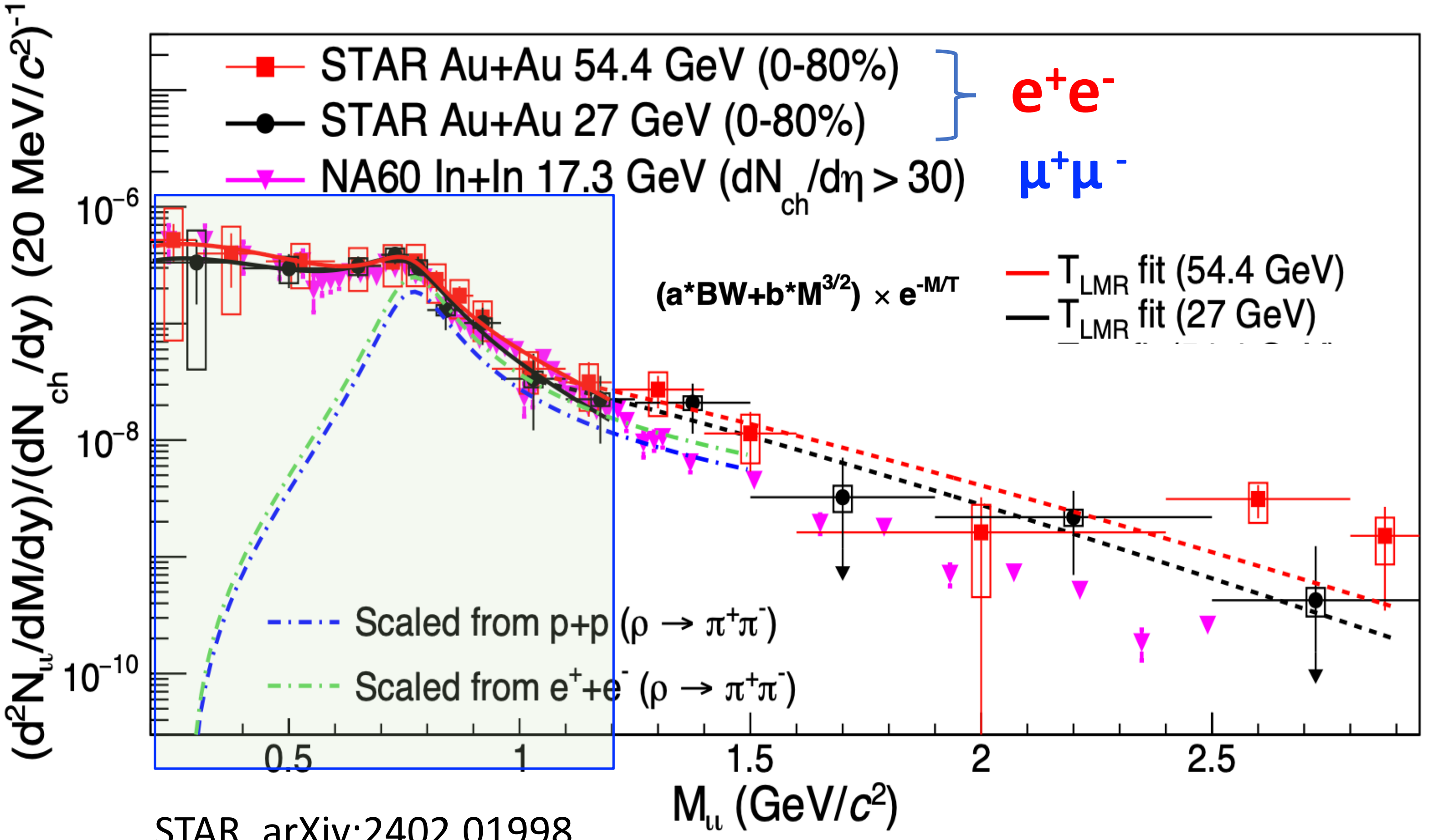


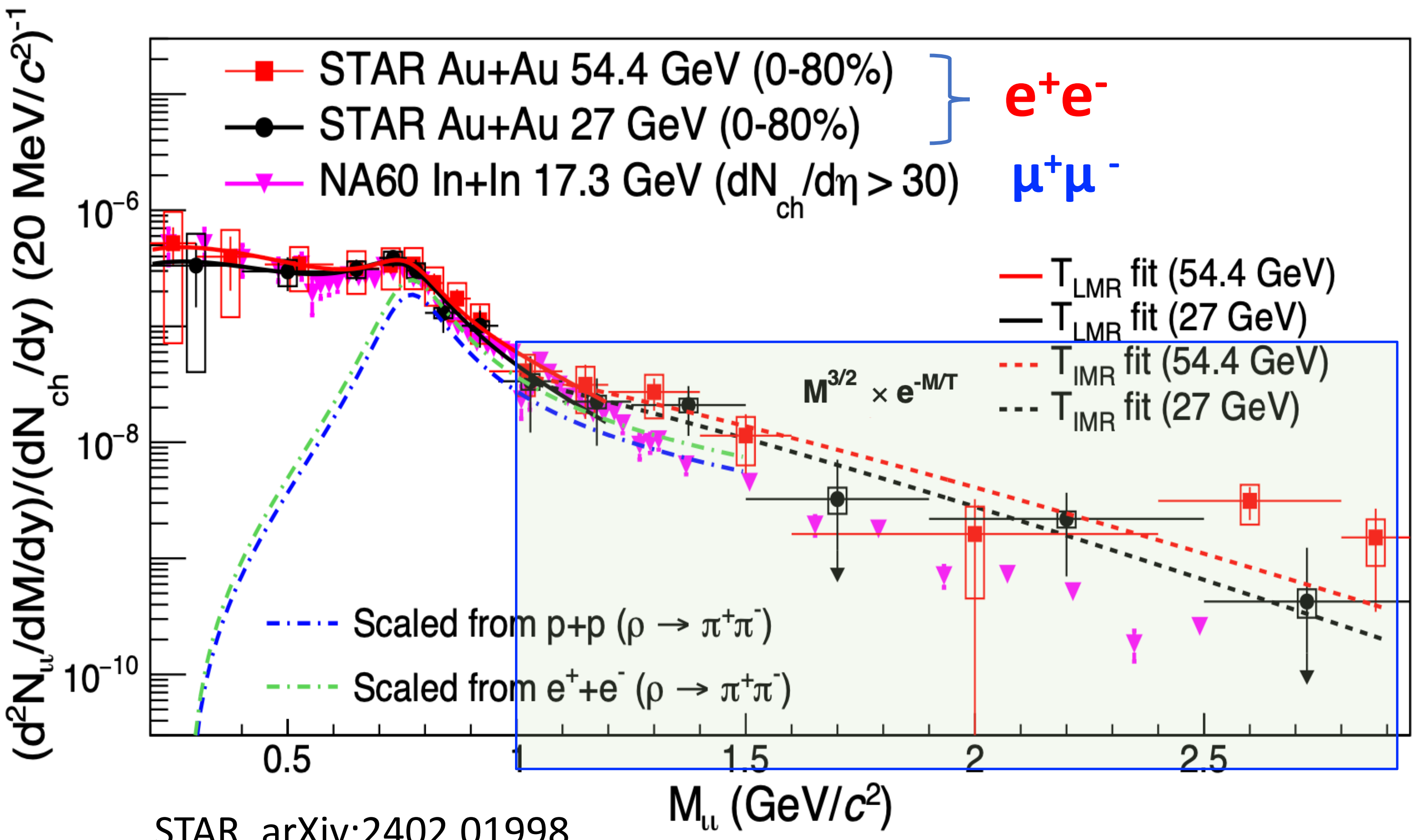
STAR, arXiv:2402.01998

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**" in 27/54.4 GeV Au+Au and 17.3 GeV In+In collisions

Thermal Dilepton (IMR) at Low Energies

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



STAR, arXiv:2402.01998

QGP dominated

T_{IMR} from STAR: **~300 MeV**

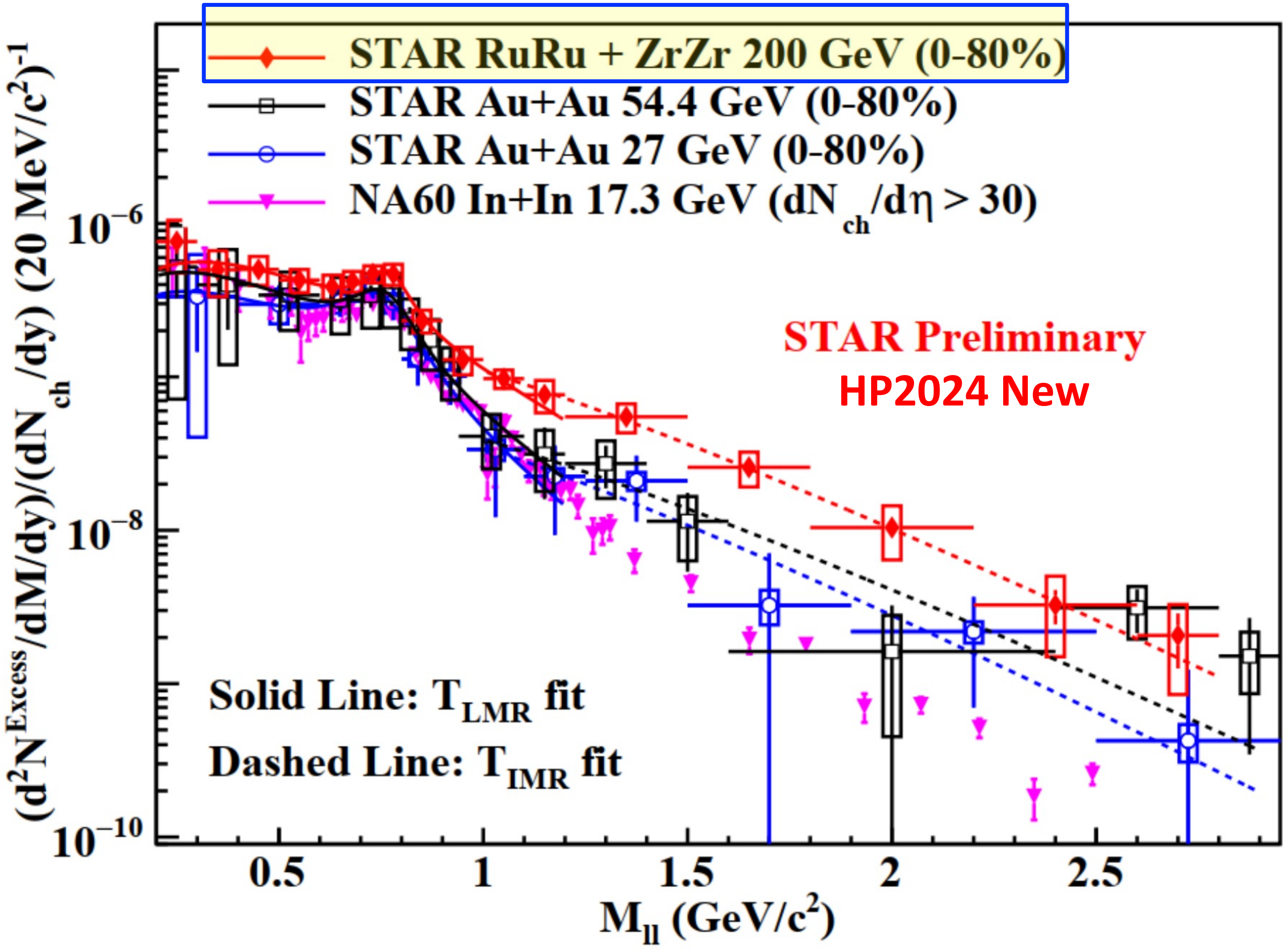
T_{IMR} from NA60:

- **246 ± 17 MeV** (1.2<M<2.5 GeV/c²)
- 205 ± 12 MeV (1.2<M<2.0 GeV/c²)

T_{IMR} > T_{pc} (156 MeV):

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

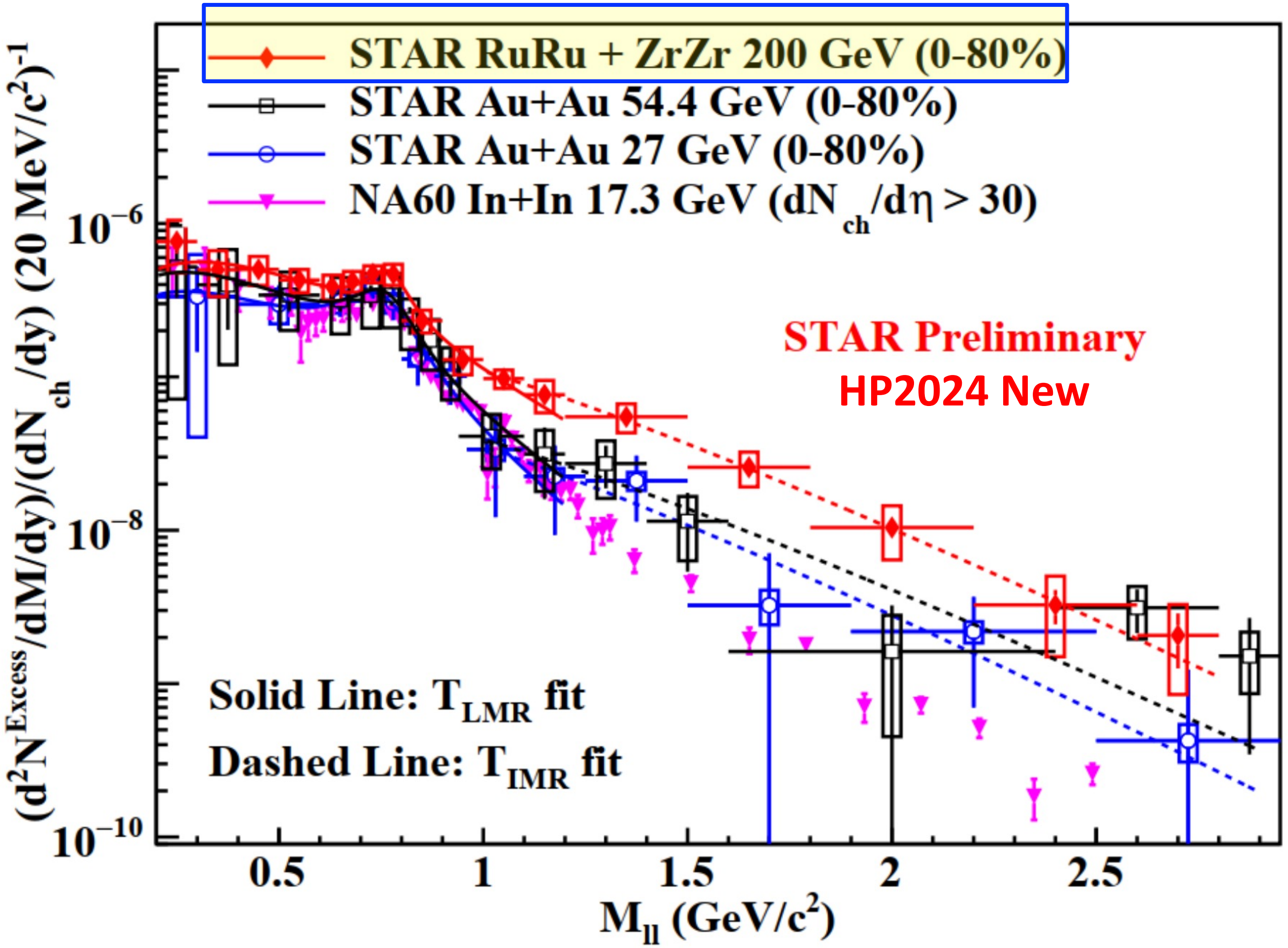
Thermal Dilepton at RHIC Top Energy



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

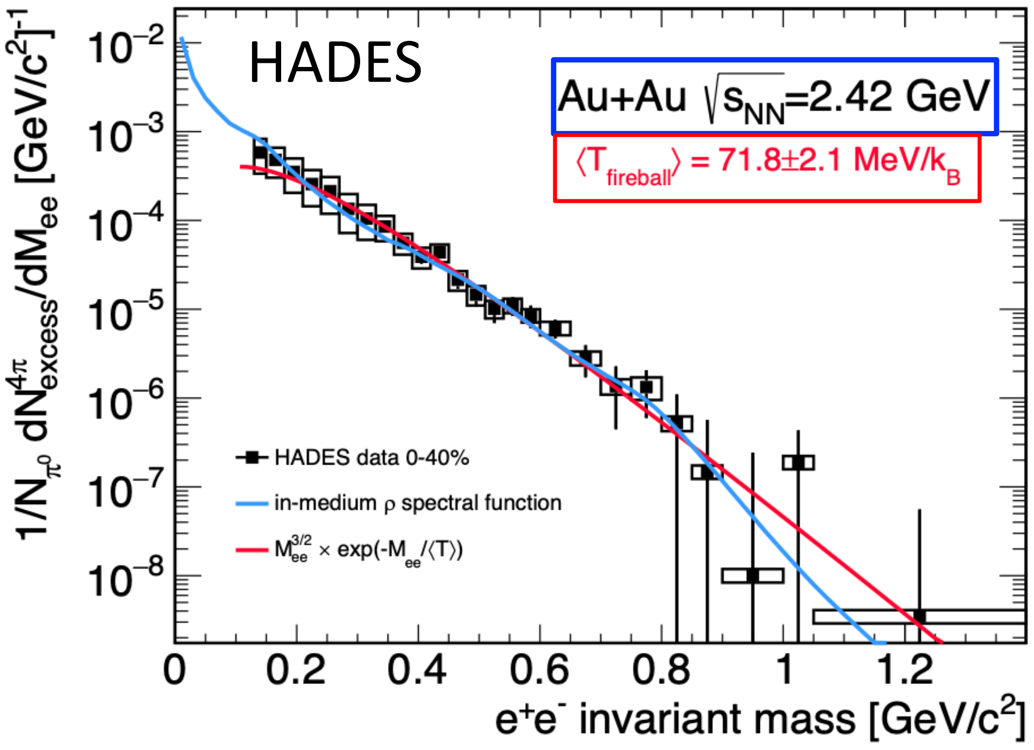


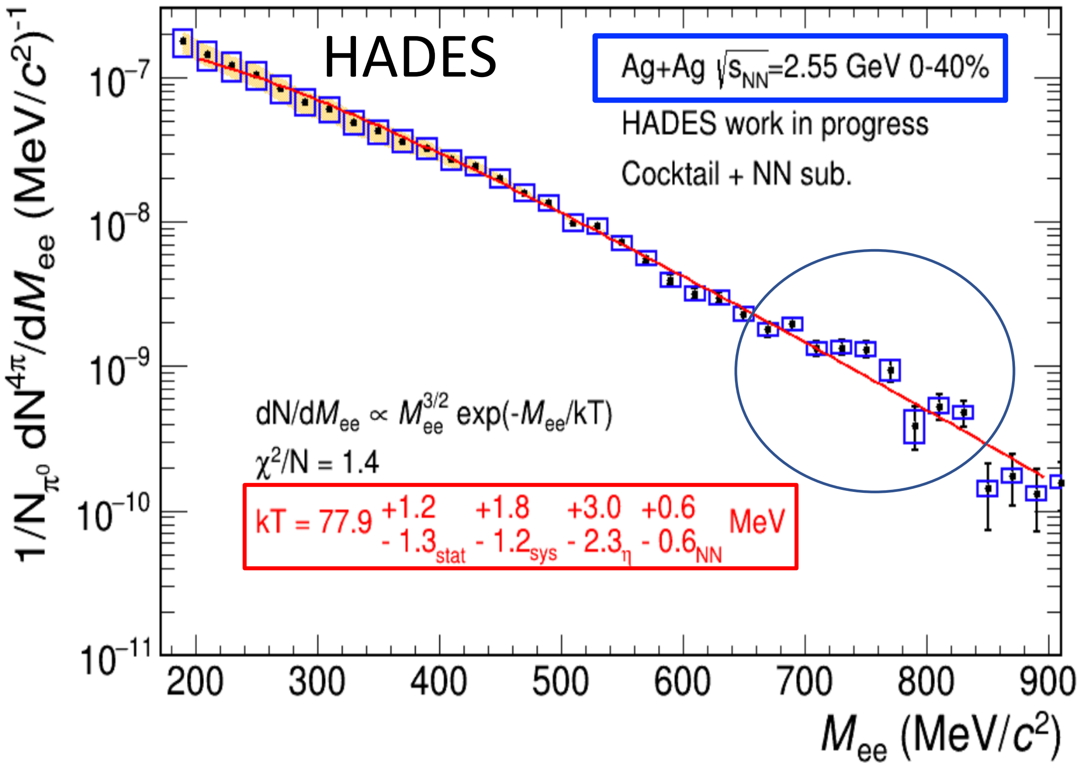
Ru/Zr (A = 96), Au (A = 197), In (A= 115)

- 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)

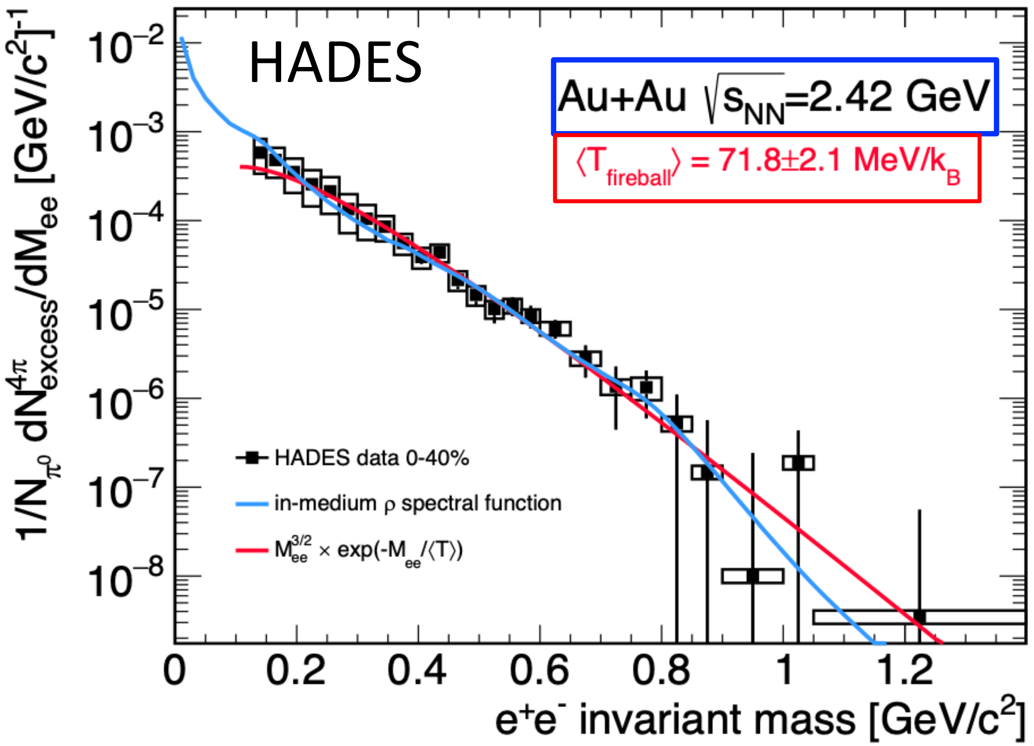




- **In-medium ρ completely melt** via frequent scattering with surrounding baryons
- **T_{LMR} ~ 70-80 MeV**, distribution well reproduced by transport model considering thermal radiation of hot hadronic medium

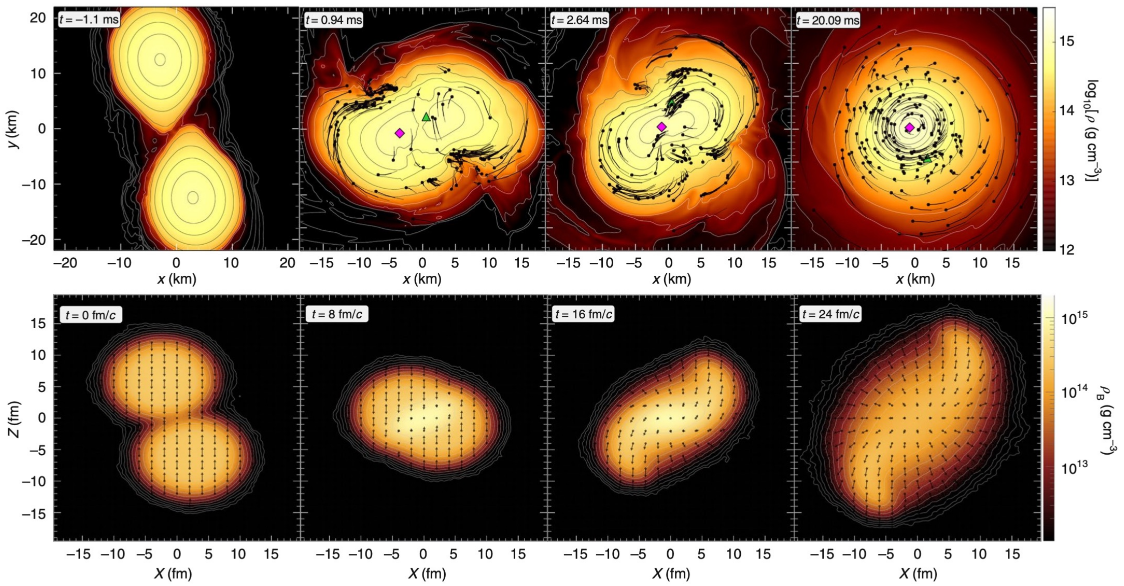
Small Collisions Connected to Big Collisions

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



PLB 122, 061101 (2019)

Binary neutorn star merger



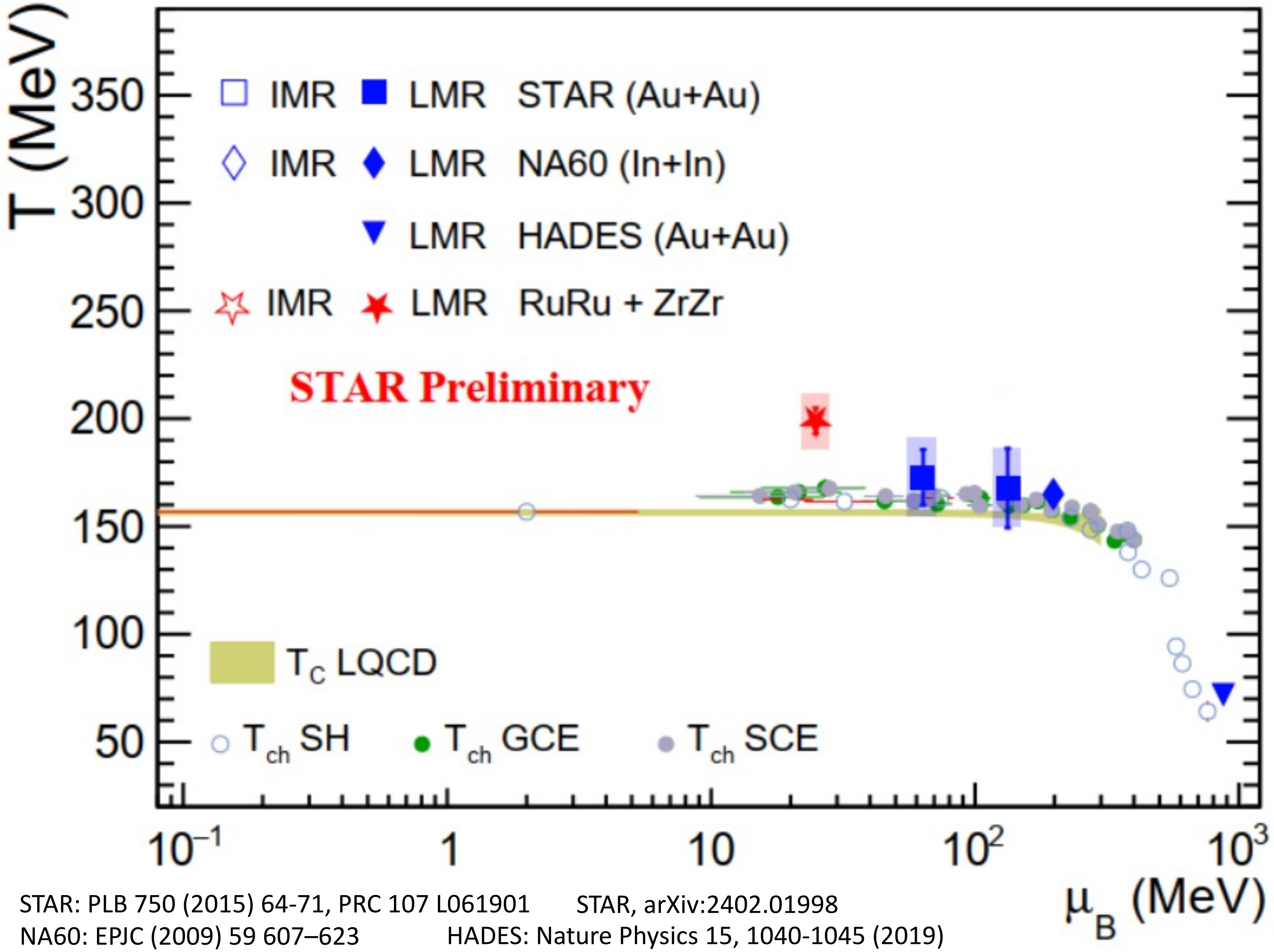
Simulations

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

Summary of Temperatures



Thermal dileptons in LMR

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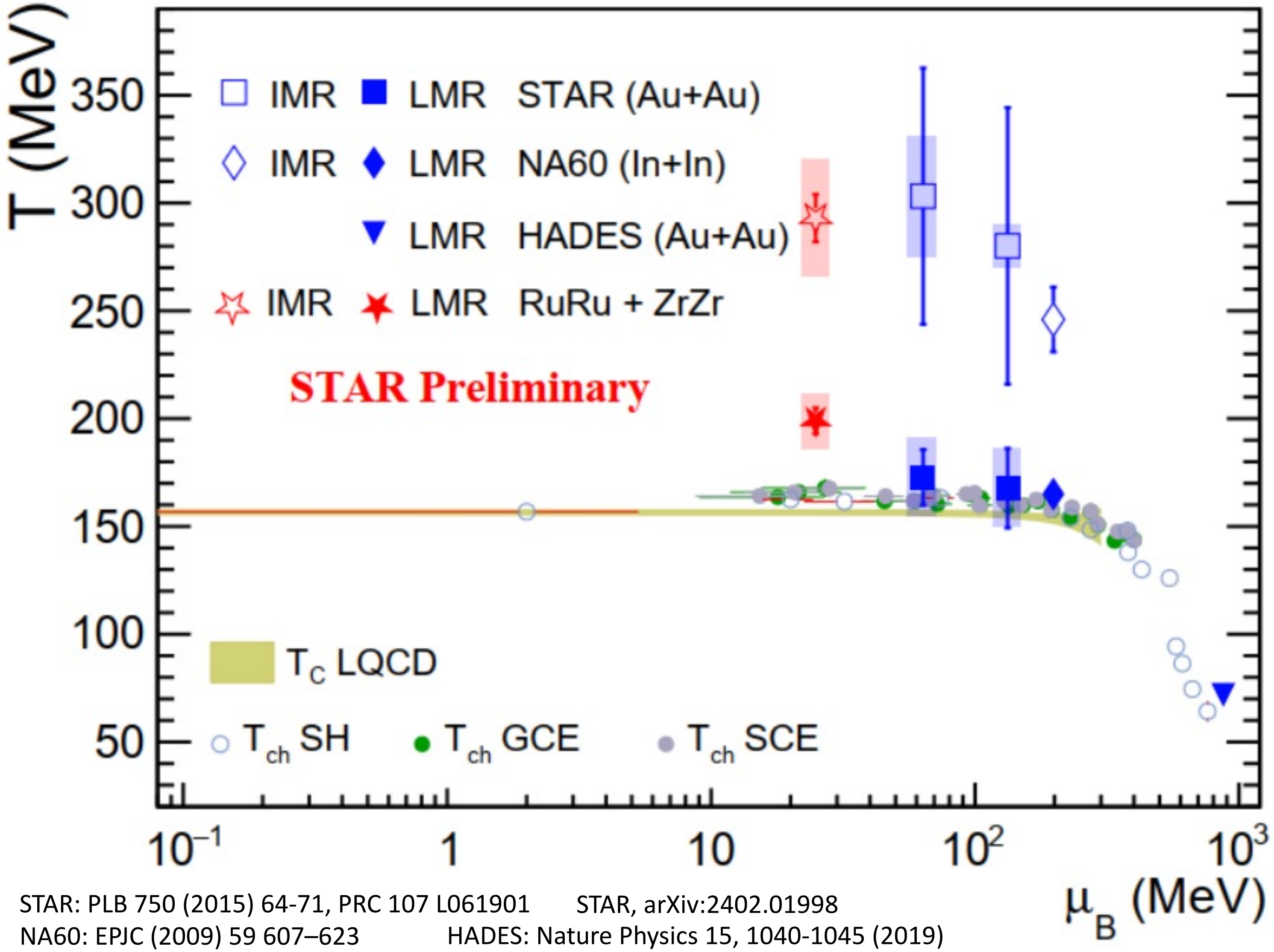

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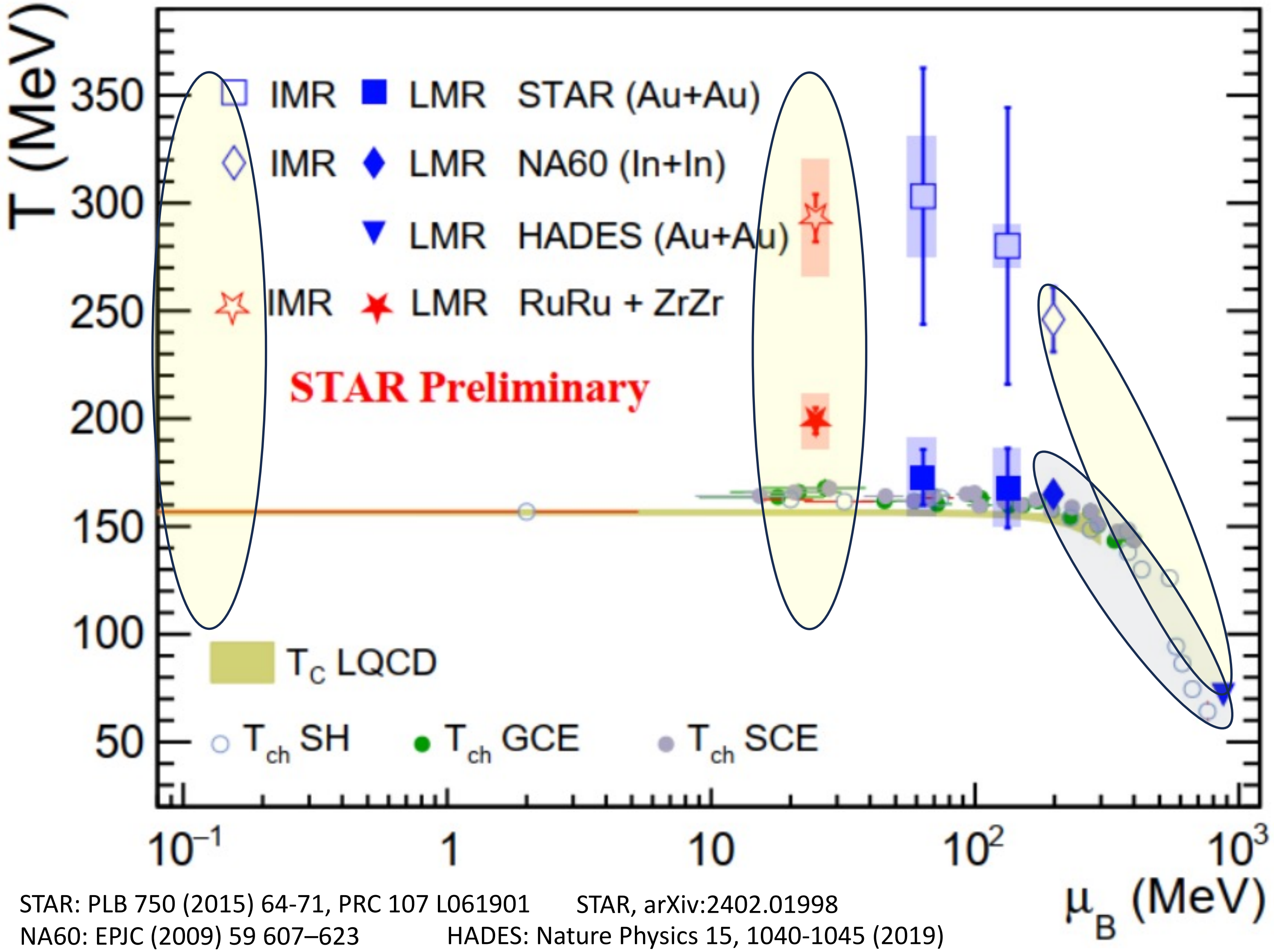
Thermal dileptons in IMR

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

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

Future Temperatures



STAR: PLB 750 (2015) 64-71, PRC 107 L061901 STAR, arXiv:2402.01998
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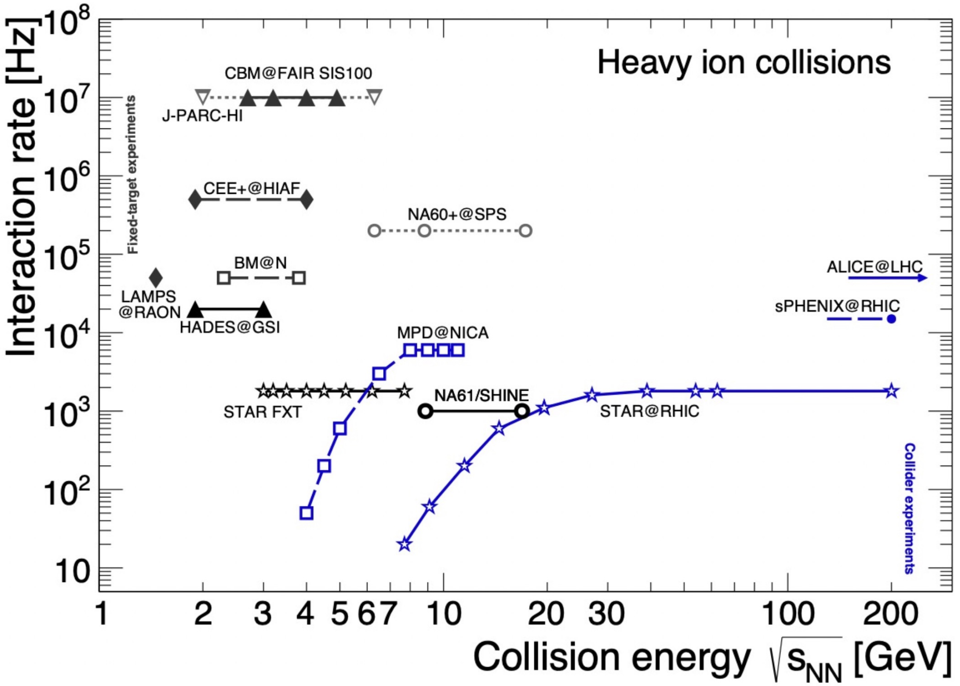


- More high precision data are on the way!
- Especially, detailed scan at high baryon density region, where the 1st-order phase transition and CEP may exist.

Is Chiral Symmetry Restored?

quark condensate $< q\bar{q} >$

- ≠ 0: chiral symmetry breaking ⟹ 98-99% of mass of visible universe
- = 0: chiral symmetry restored ⟹ δM btw chiral partners → 0

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)

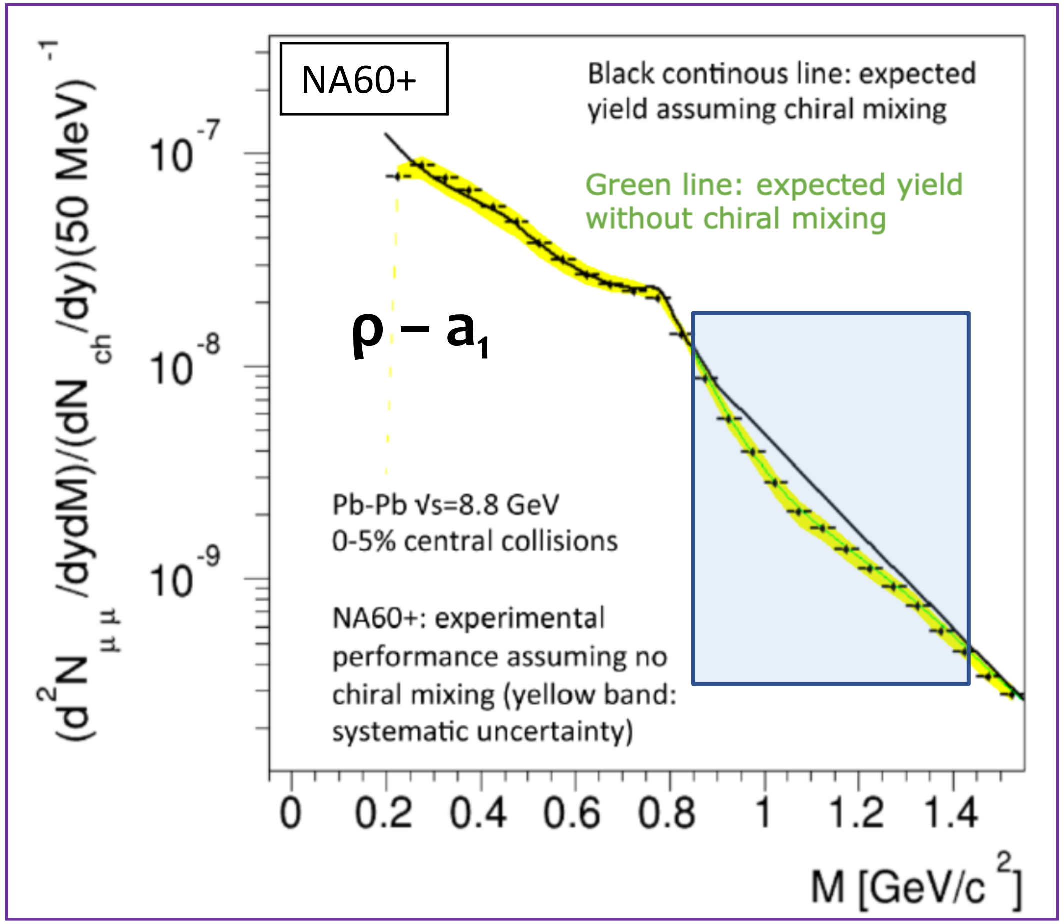
T is hot enough

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

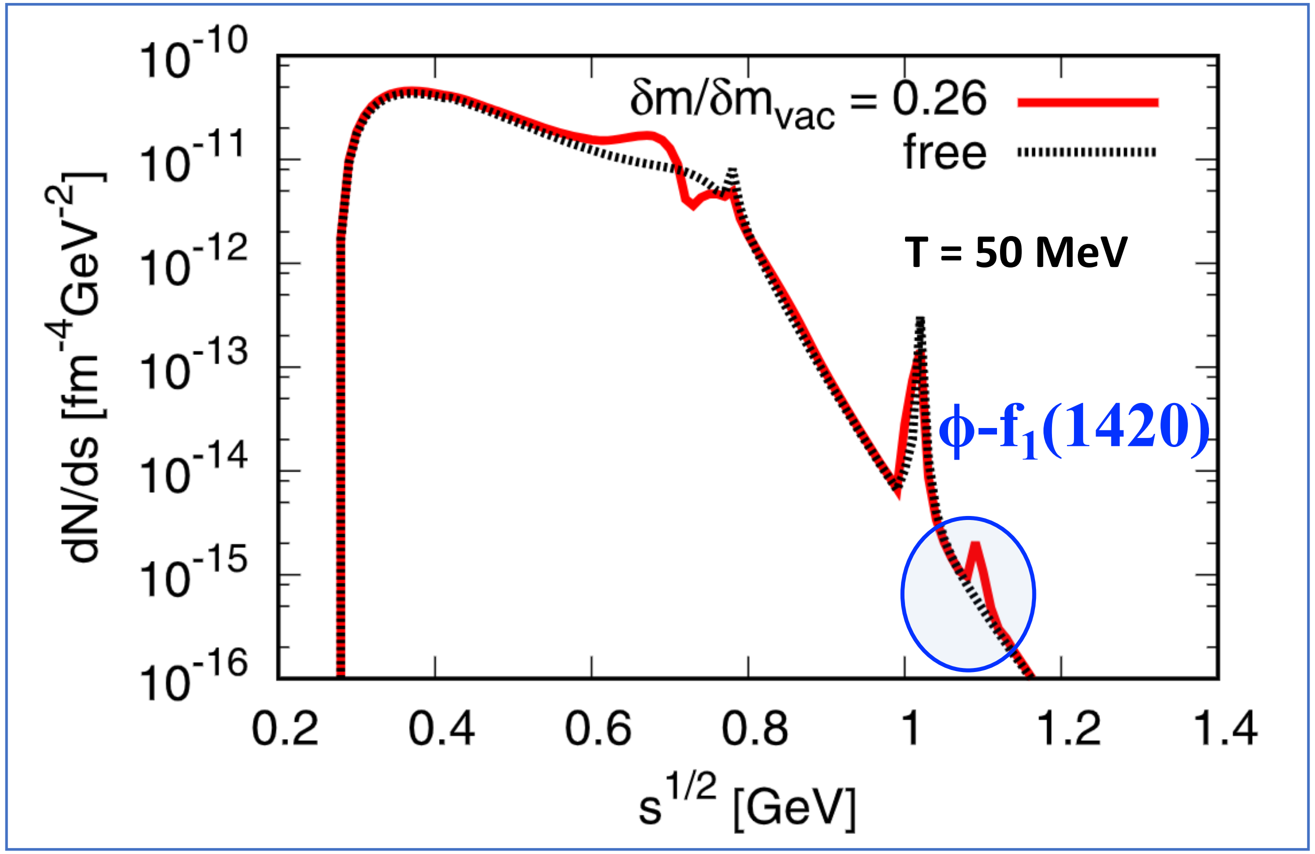
Rapp model: PRC 63 (2001) 054907, Adv HEP 2013 (2013) 148253, PLB 753 (2016) 586
PHSD model: NPA 807, 214 (2008); NPA 619, 413 (1997) PRC 97, 064907 (2018)

Experimental Evidence of CSR

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



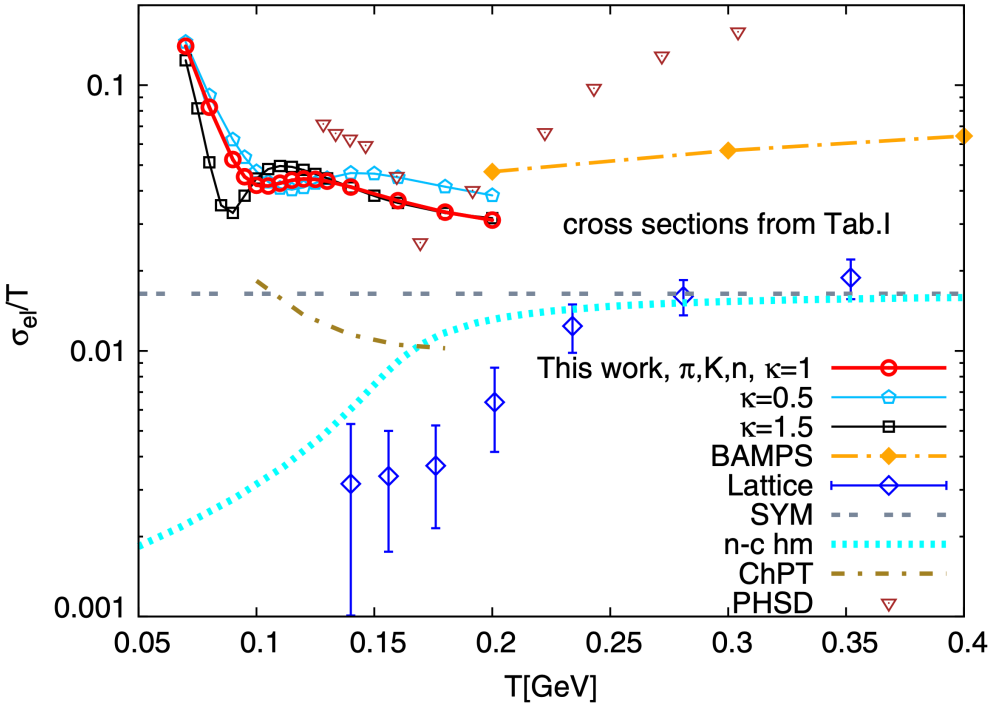
Rapp and Hohler: PLB 731 (2014) 103-109



Chihiro Sasaki, PLB 801 (2020) 135172

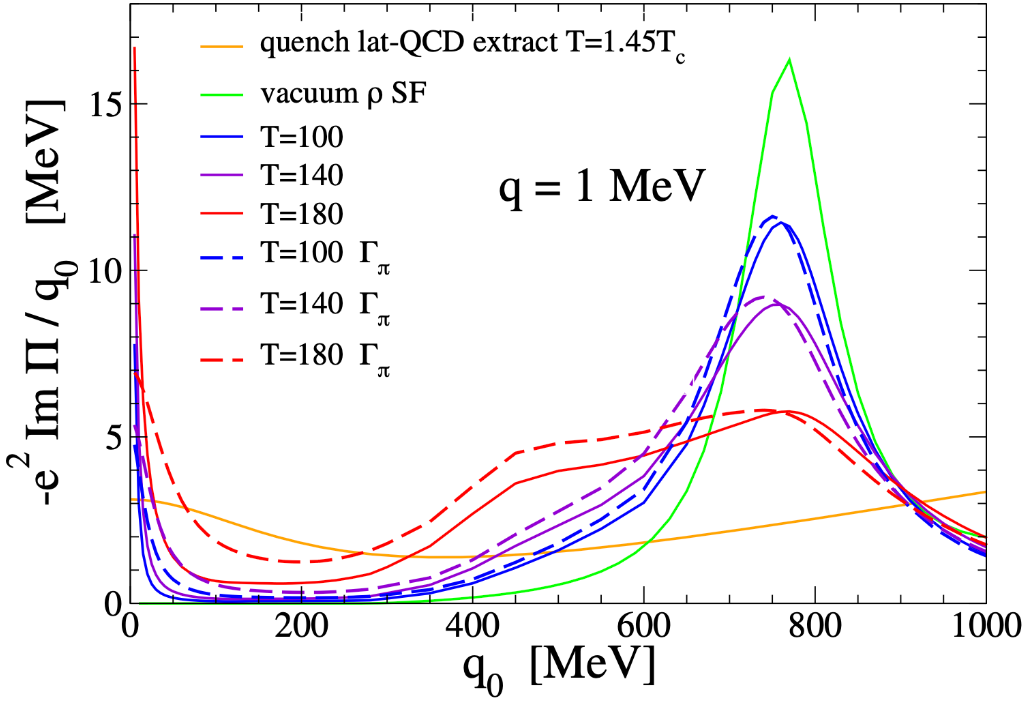
Electric Conductivity of Hot QCD Medium

Large variations in theoretical calculations



M. Greif, C. Greiner, G. S. Denicol, PRD 93, 096012 (2016)

Extract by the EM spectral function at low-energy limit: $\sigma_{\rm el}(T) = -e^2 \lim_{q_0\to 0} \frac{{\rm Im}\Pi_{\rm EM}(q_0, \vec{q}=0, T)}{q_0}$



R. Rapp, et al, NPA 673, 357 (2000)

- Enhancement of dielectron yield at **very low p_T** and **very low mass** region
- Low energy collisions: smaller contributions from QED, QGP

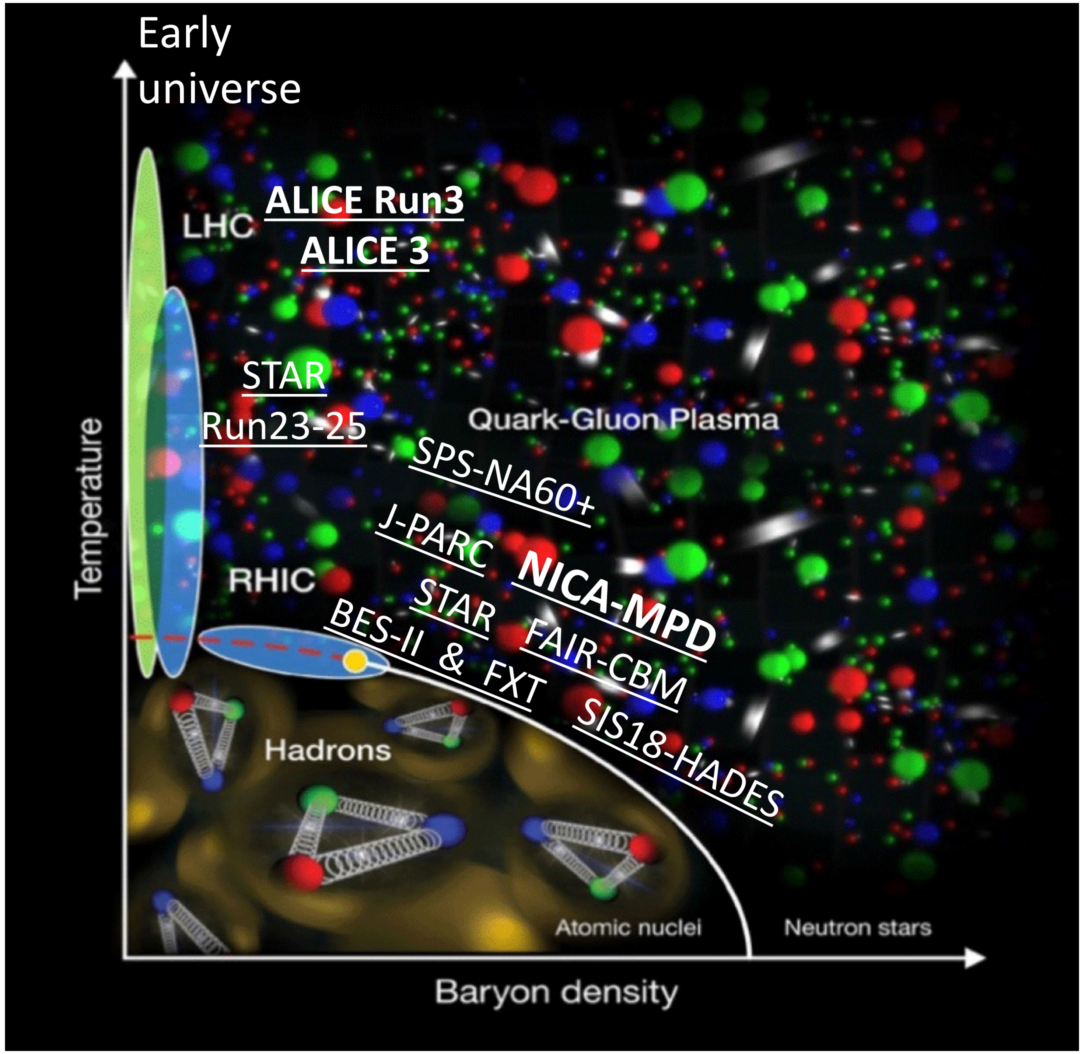
Summary and Outlook

Lessons from exist thermal dileptons:

- In-medium Rho is significantly broaden
- $T_{LMR} \sim T_{ch} \sim$ 70-80 MeV at SIS18
- $T_{LMR} \sim T_{ch} \sim T_{pc}$ at RHIC and SPS
- $T_{IMR} > T_{pc}$ at RHIC and SPS: **QGP**

Future thermal dileptons

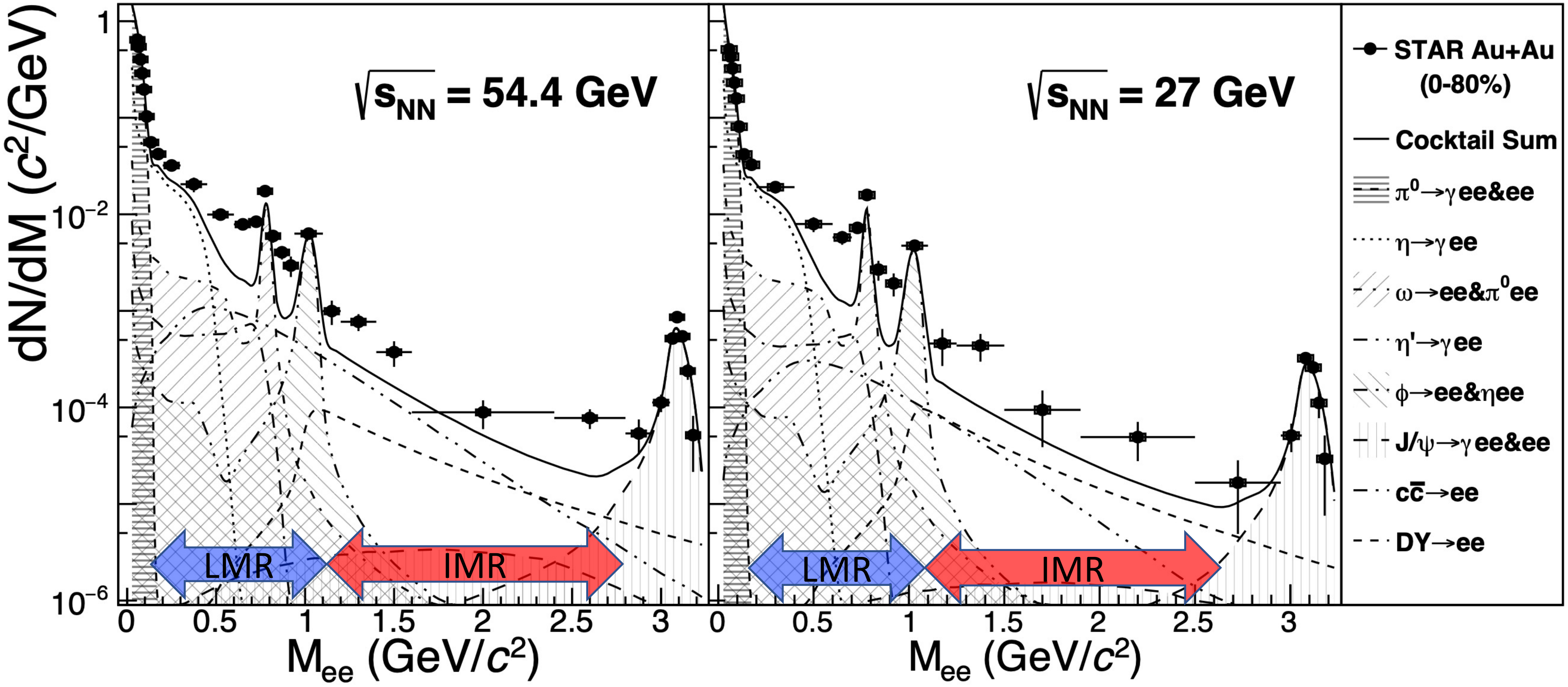
- Huge experimental efforts and detailed energy scan, especially at high baryon densities:
  - Energy, time dependent temperatures
  - Chiral symmetry restoration
  - Critical End Point
  - Electric conductivity



THANKS

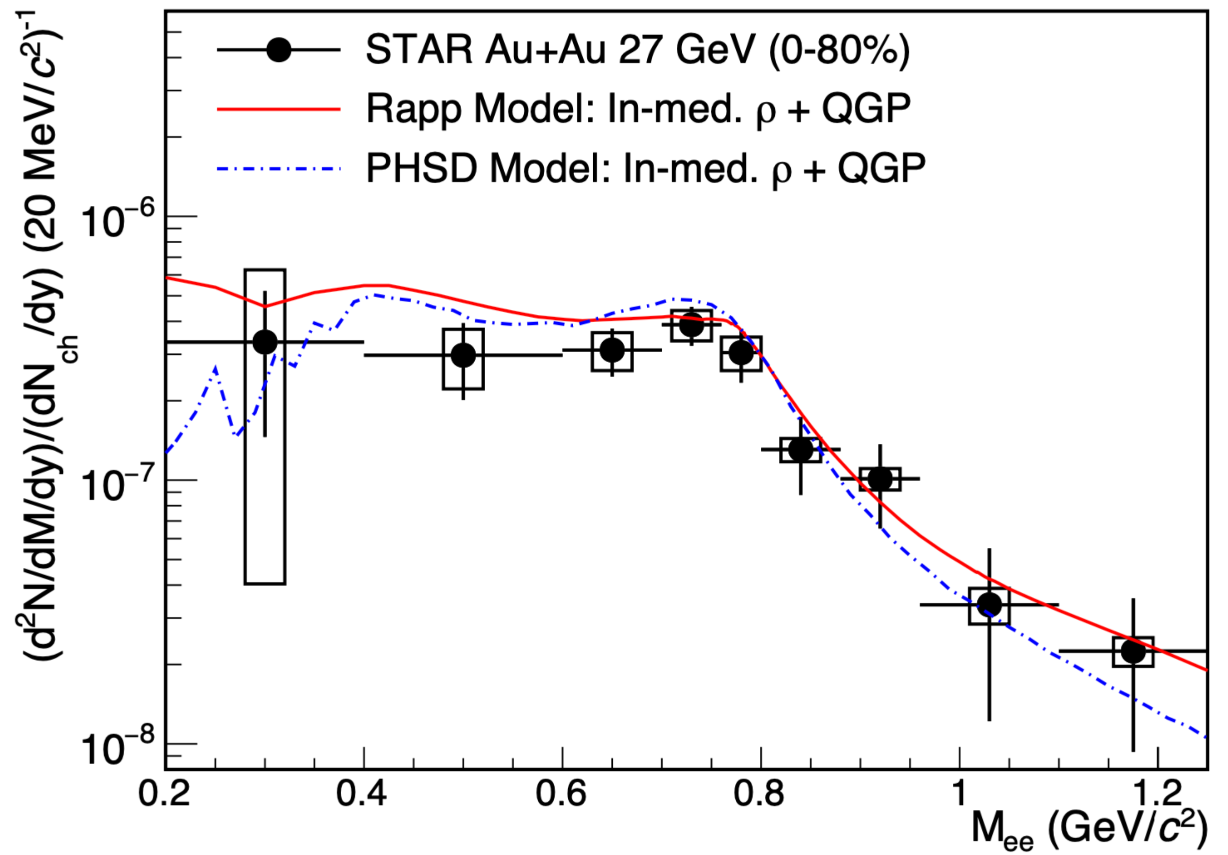
BACKUP SLIDES

Examples of Data vs. Cocktail



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

STAR Data vs. Models



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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

Teff is Enhanced by Radial Flow

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

Thermal photons as a quark-gluon plasma thermometer reexamined

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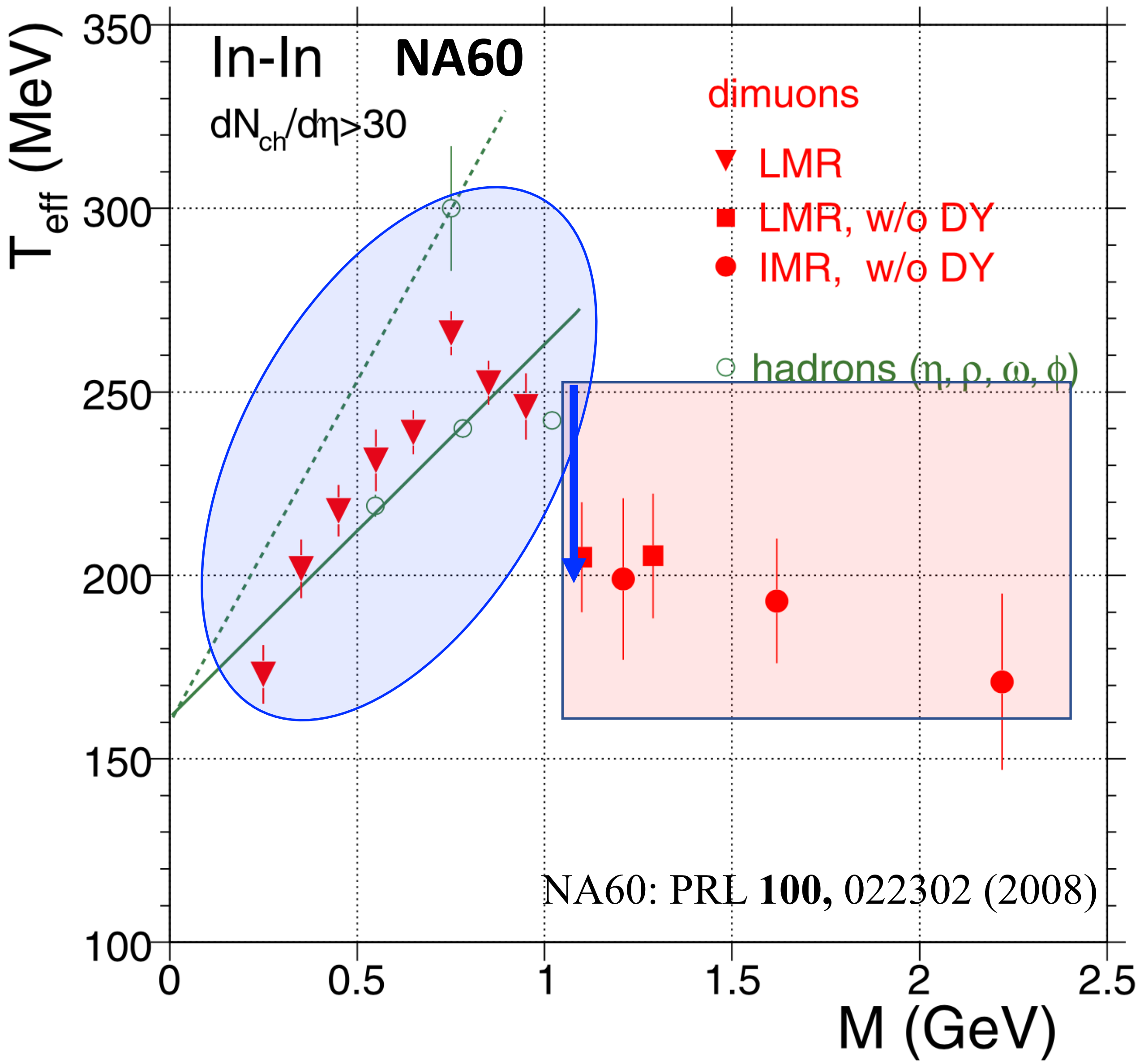
Jean-François Paquet
Department of Physics, McGill University, 3600 University Street, Montreal, Quebec, Canada H3A 2T8

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.**"

Thermal Dilepton ⊕ Medium Flow



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

M < 1 GeV/c²:

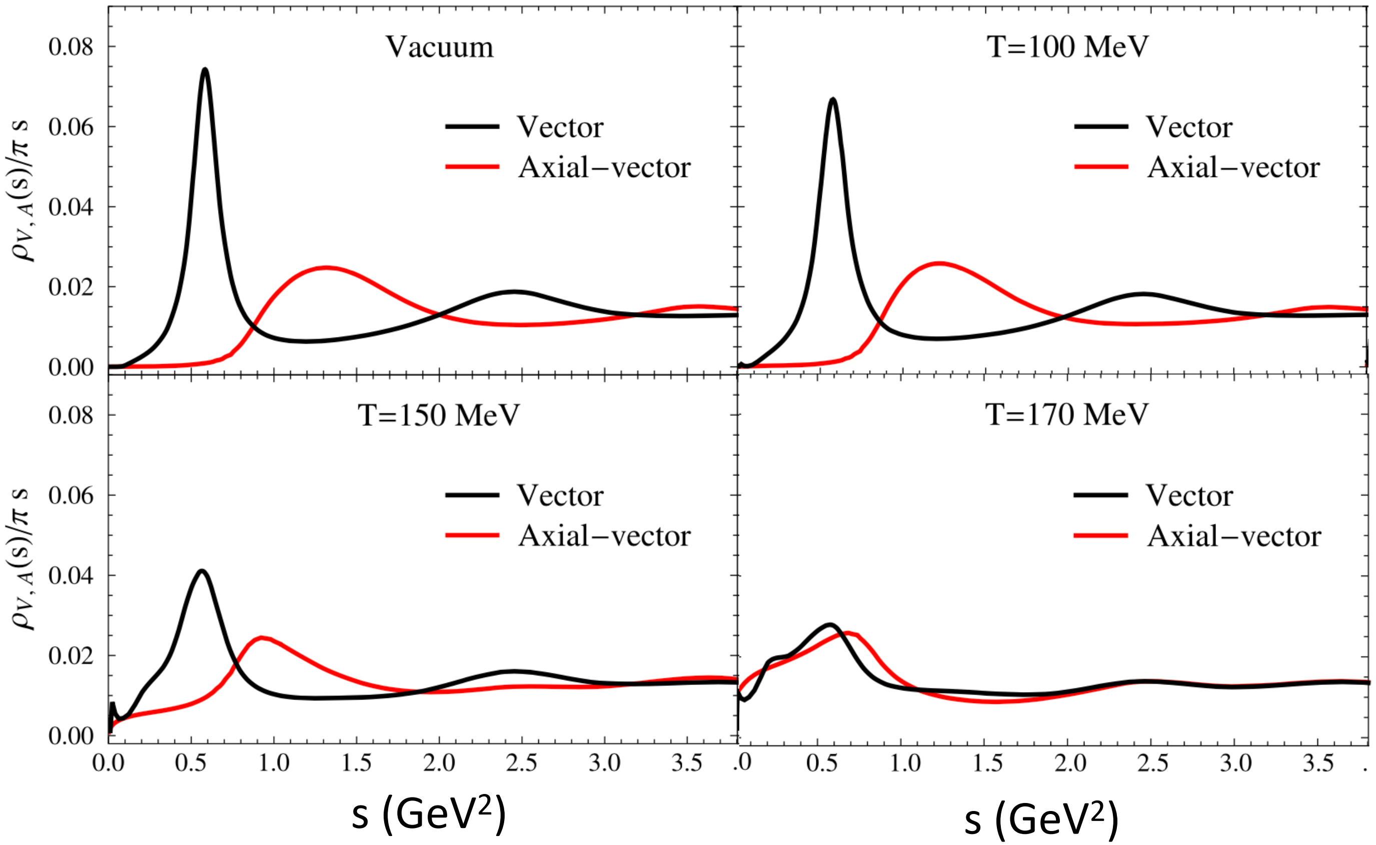
- **T_{eff} rise linearly → In-medium radiation pushed by radial flow**
- **T_{eff} peaks at m_ρ**

M > 1 GeV/c²:

- **T_{eff} suddenly drop ~50 MeV → dominant emission source from hadronic to partonic matter**
- **T_{eff} ~ 200 MeV (< 246 MeV)**

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

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

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

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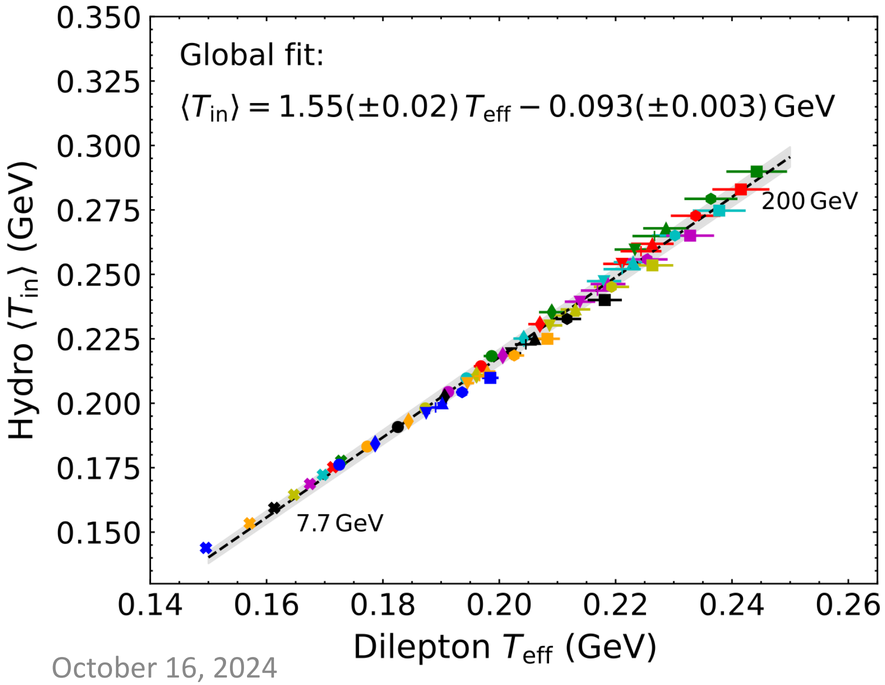
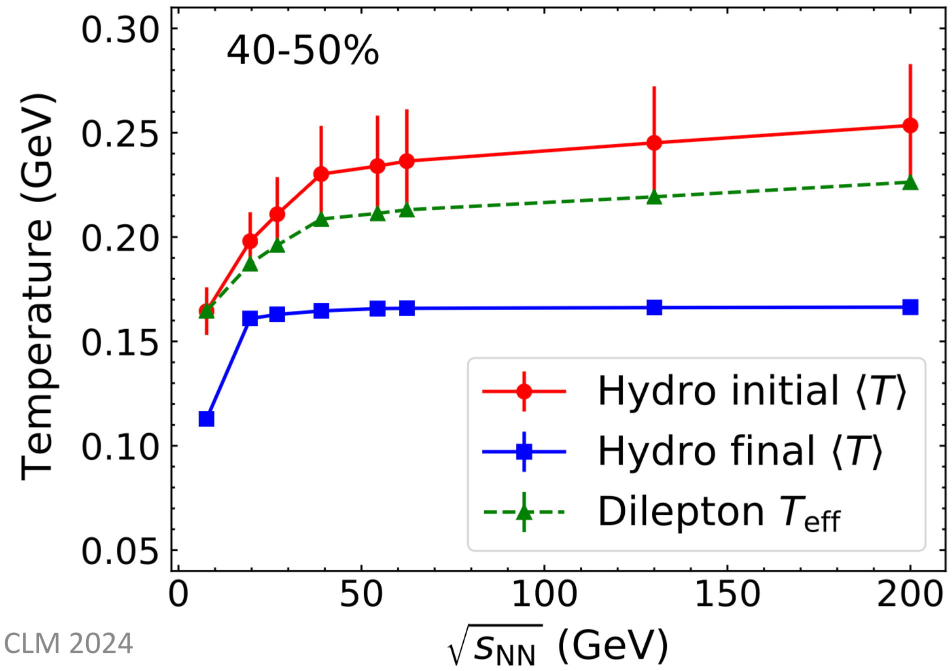
(Received 20 November 2023; revised 18 February 2024; accepted 22 March 2024; published 22 April 2024)

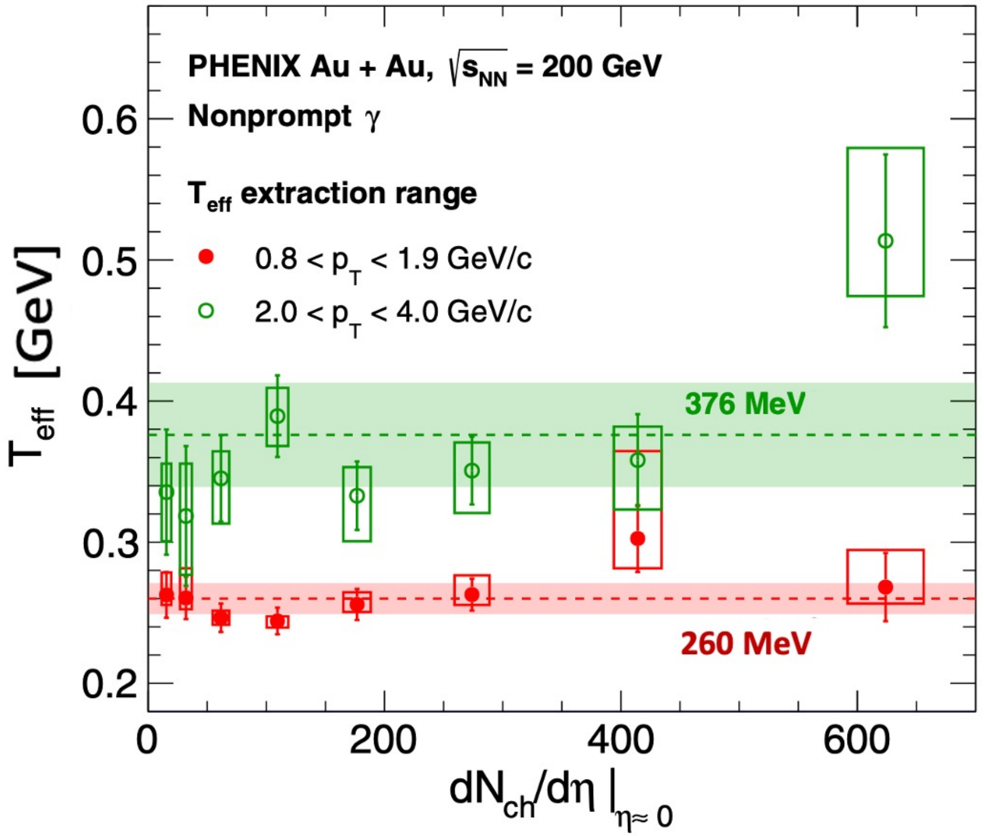
Dileptons produced during heavy-ion collisions represent a unique probe of the QCD phase diagram, and convey information about the state of the strongly interacting system at the moment their preceding off-shell photon is created. In this study, we compute thermal dilepton yields from Au + Au collisions 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.

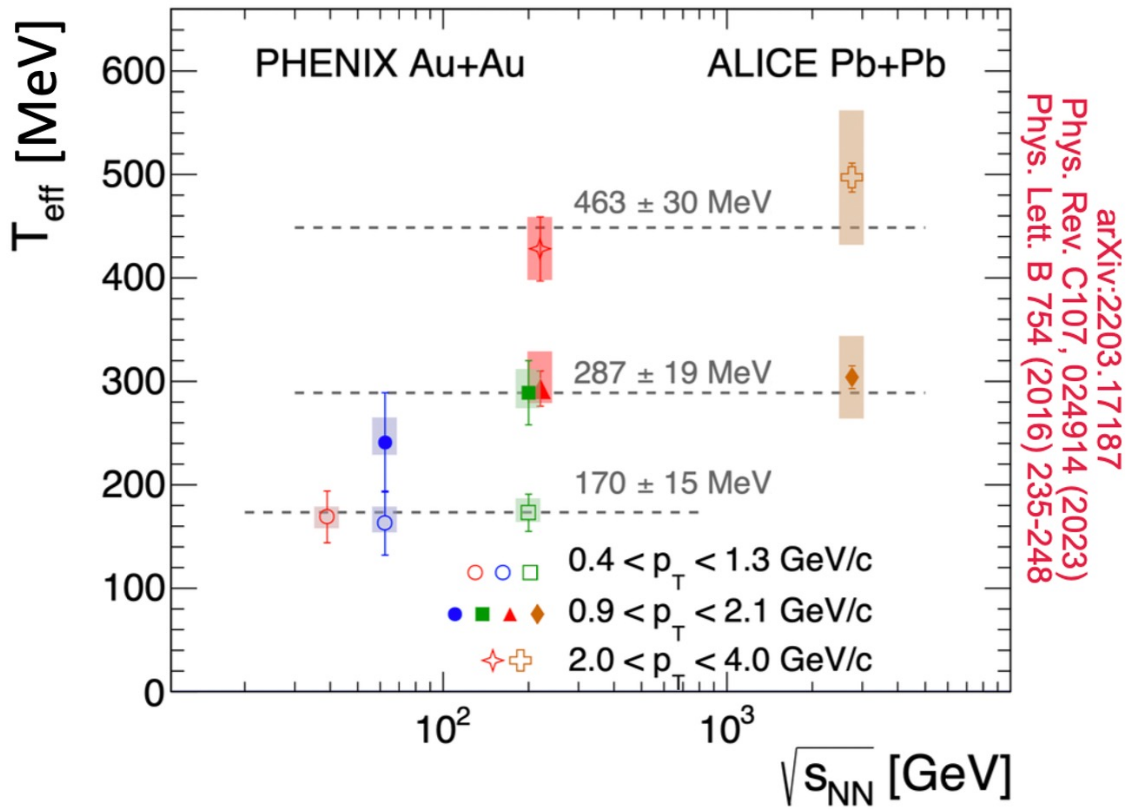
DOI: 10.1103/PhysRevLett.132.172301



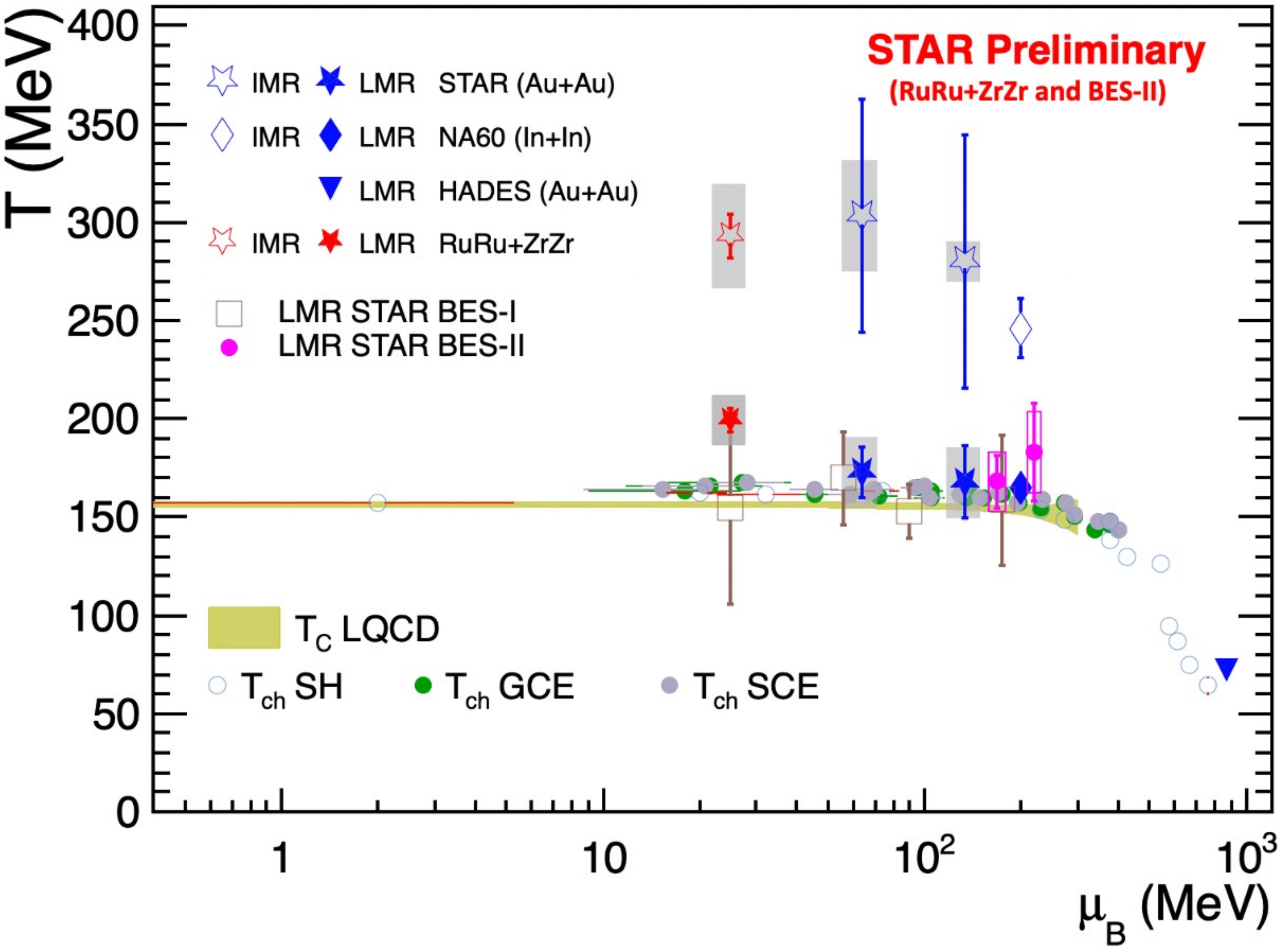


Effective T from Non-Prompt Photons





- 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)



T (MeV)
IMR LMR STAR (Au+Au)
IMR LMR NA60 (In+In)
LMR HADES (Au+Au)
IMR LMR RuRu+ZrZr
LMR STAR BES-I
LMR STAR BES-II
STAR Preliminary
(RuRu+ZrZr and BES-II)
T_C LQCD
T_ch SH
T_ch GCE
T_ch SCE
μ_B (MeV)