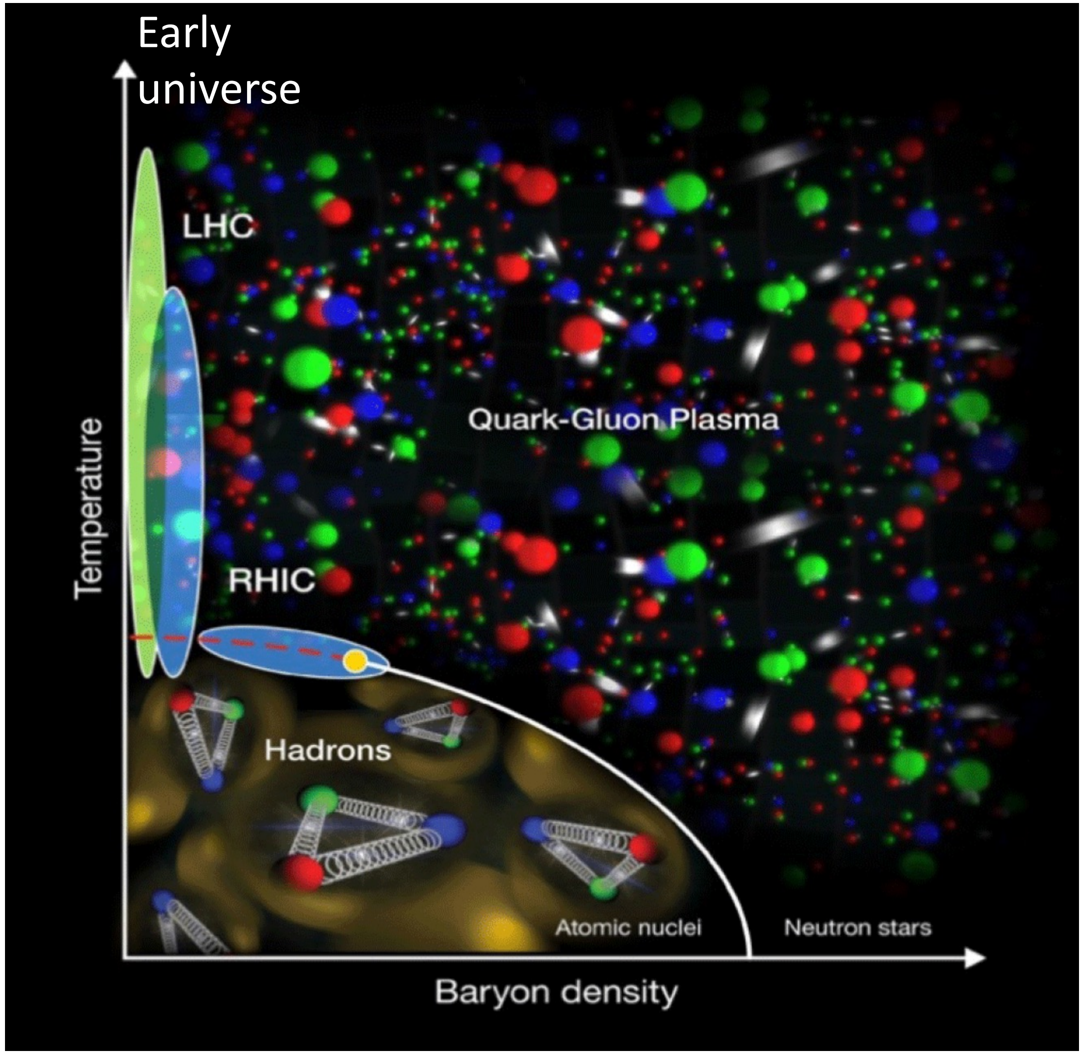
Electromagnetic Probe at High Baryon Densities

Zaochen Ye (SCNU)

Qingdao, September 10-12, 2024

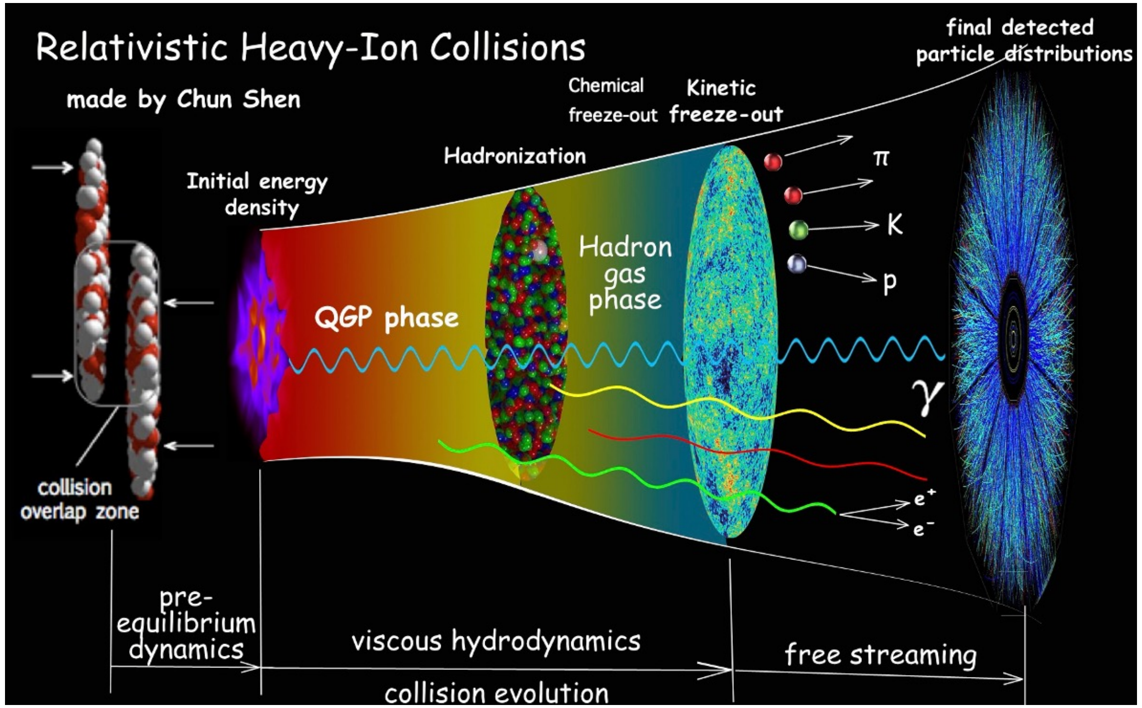
2nd China-Russia Joint Workshop on NICA Facility

QCD Phase Diagram and Heavy-Ion Collisions



- QCD phase diagram describes different phases of matter under various conditions T vs. μ_B
- Heavy-ion collisions create extreme conditions:
  - Explore QCD diagram with different trajectories
  - Create and study properties of QGP
  - 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 EM Probes

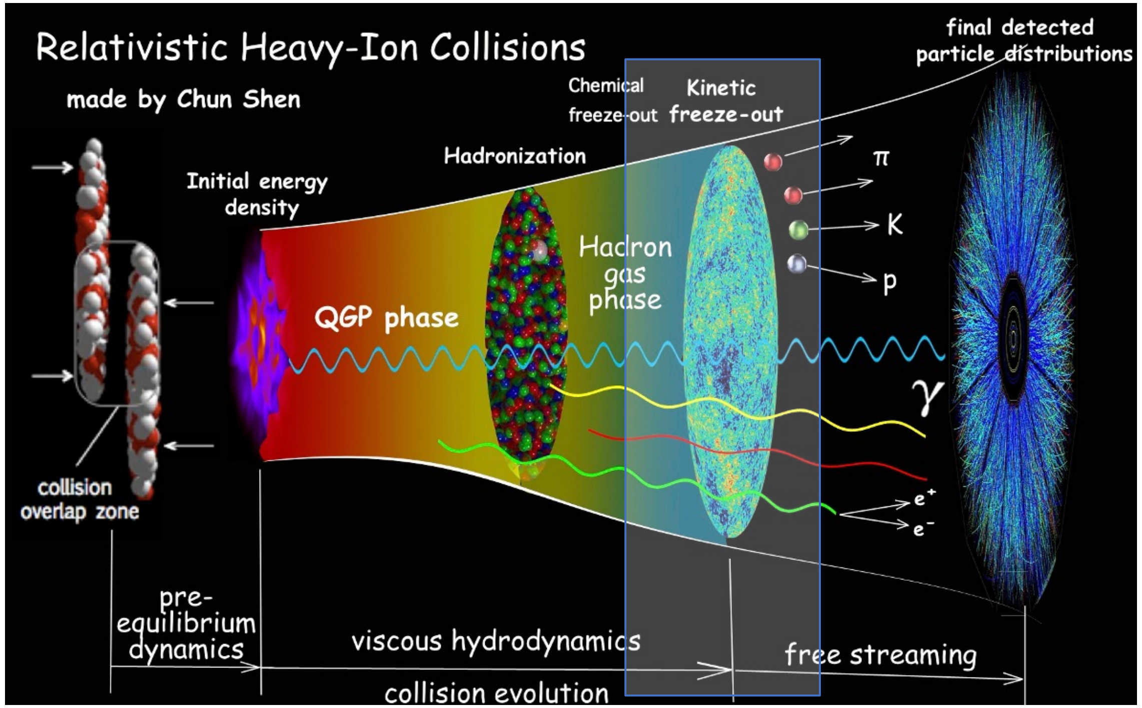


Hadrons

Photons

Leptons

Heavy-Ion Collision and Why EM Probes



Hadrons
(Yield, p_T)

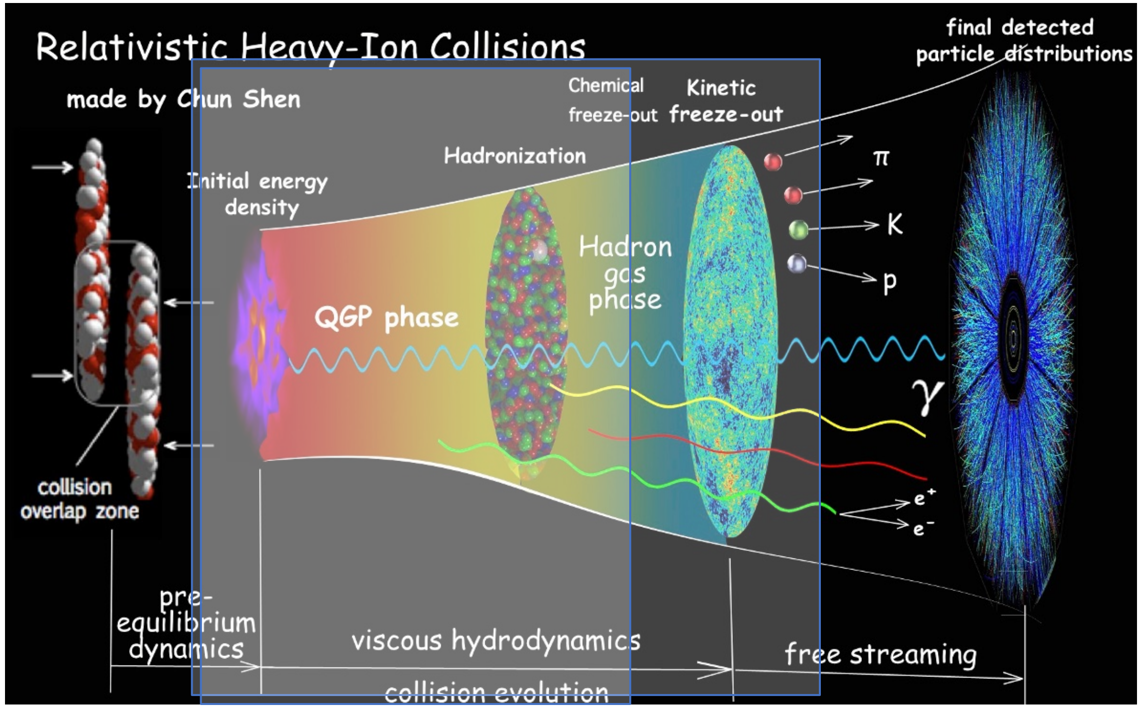
- **Most produced**
- **Freeze-out temperature: T_{ch}, T_{kin}**
- **Limitation: formation and decouple**

Photons

Leptons

T at early stage is still poorly known ☹

Heavy-Ion Collision and Why EM Probes



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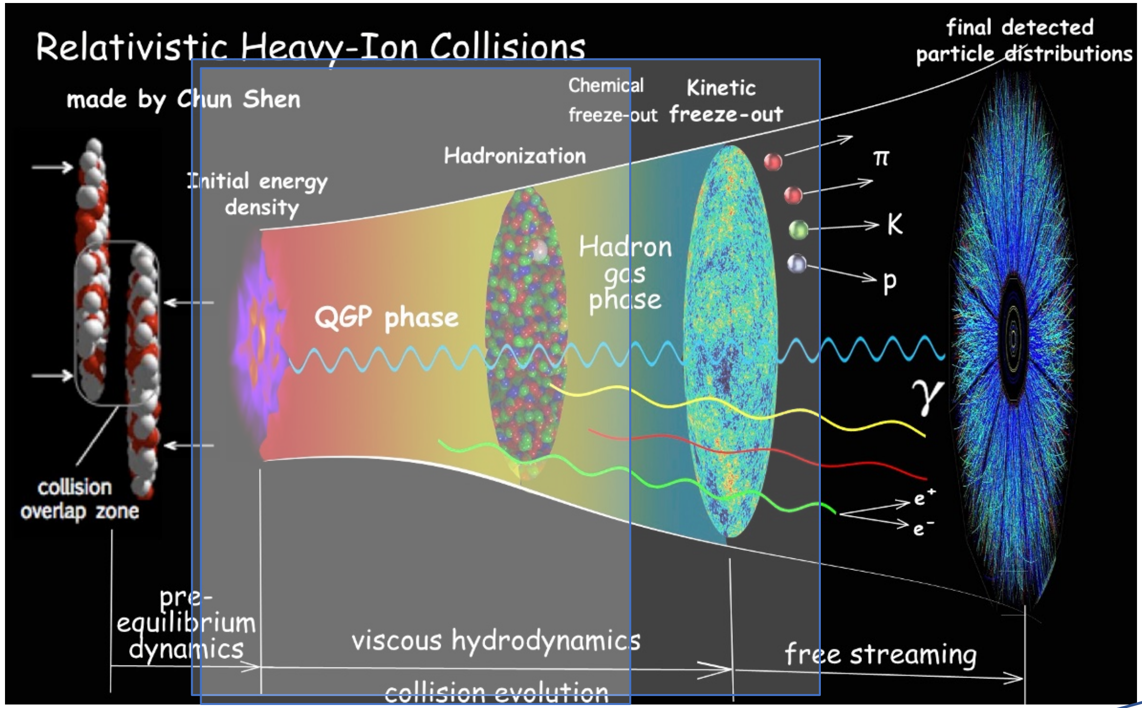
Leptons (M_{ll})

- **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 EM Probes



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EM Probes

Inverse slope → Effective temperature
(Doppler shift warning)

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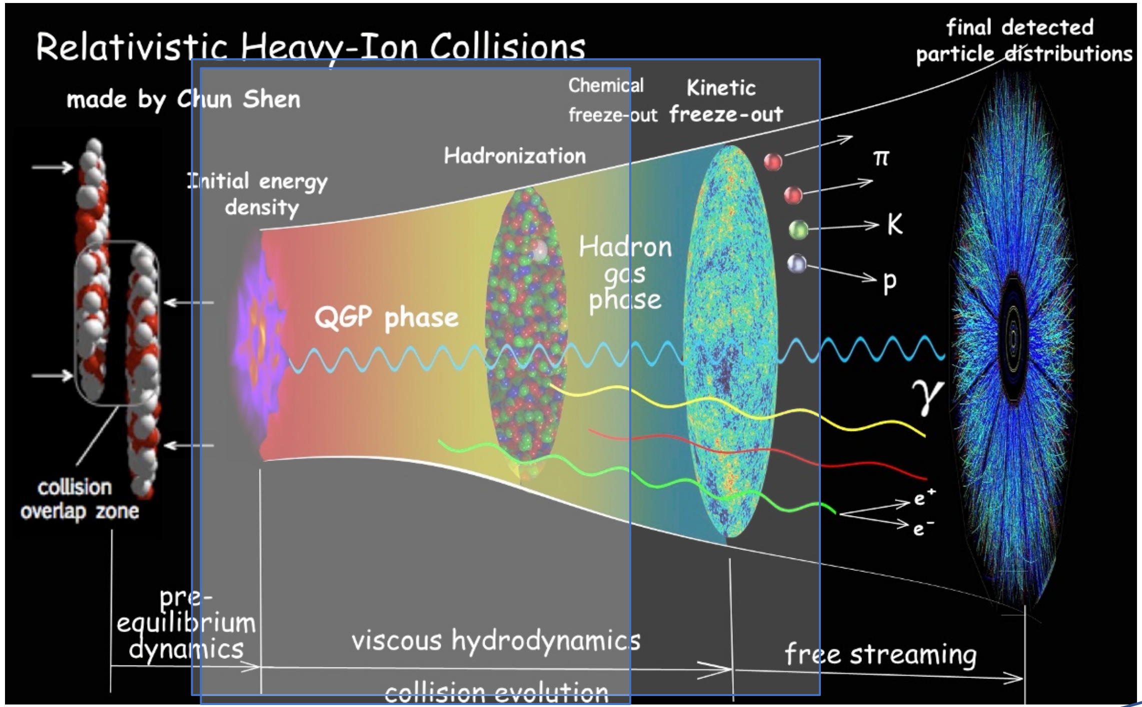

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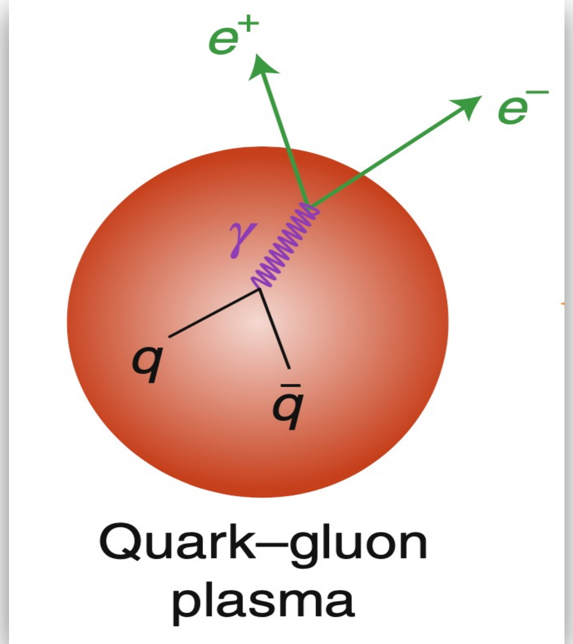
Inverse slope → Effective temperature
(Doppler shift warning)

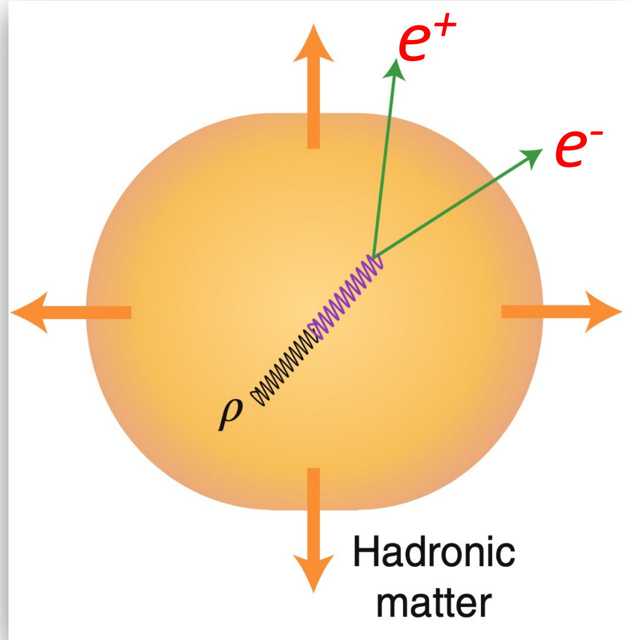
Dileptons

- **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



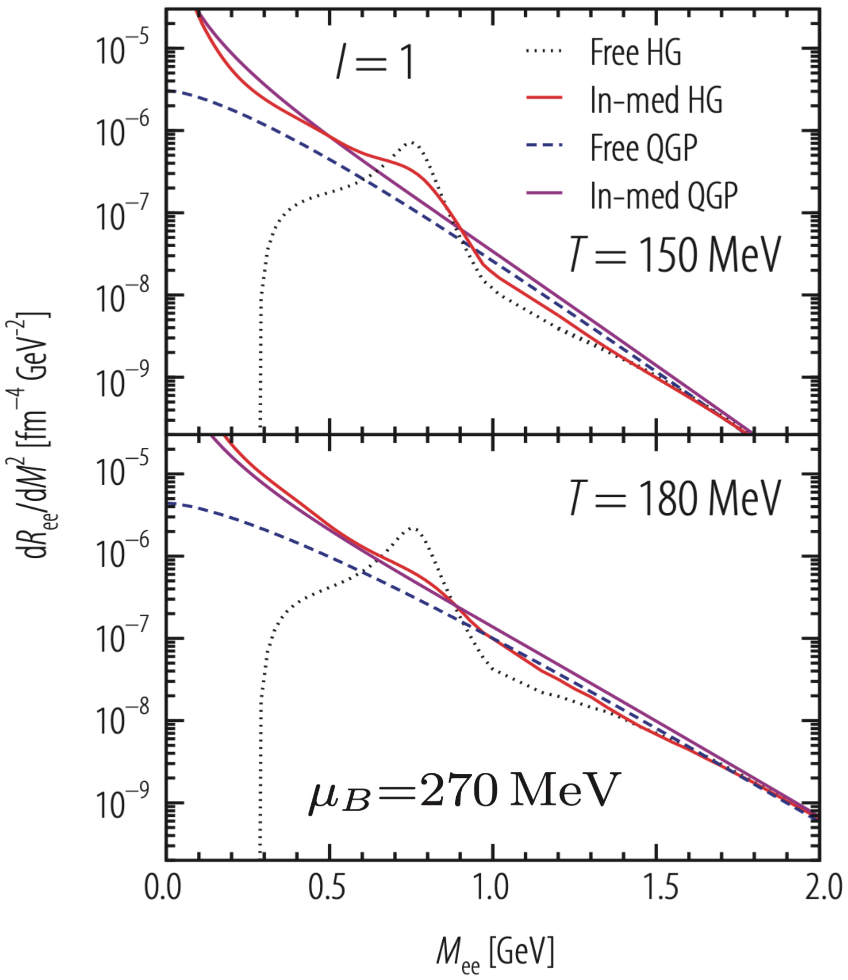


$$q + \bar{q} \longrightarrow \gamma^* \longrightarrow e^+ + e^- \qquad \pi^+ + \pi^- \longrightarrow \rho \longrightarrow e^+ + e^-$$

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 source: T? partonic/hadronic phase? CSR?...

How to Measure Thermal Dileptons

Inclusive signals
(space-time integral)

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

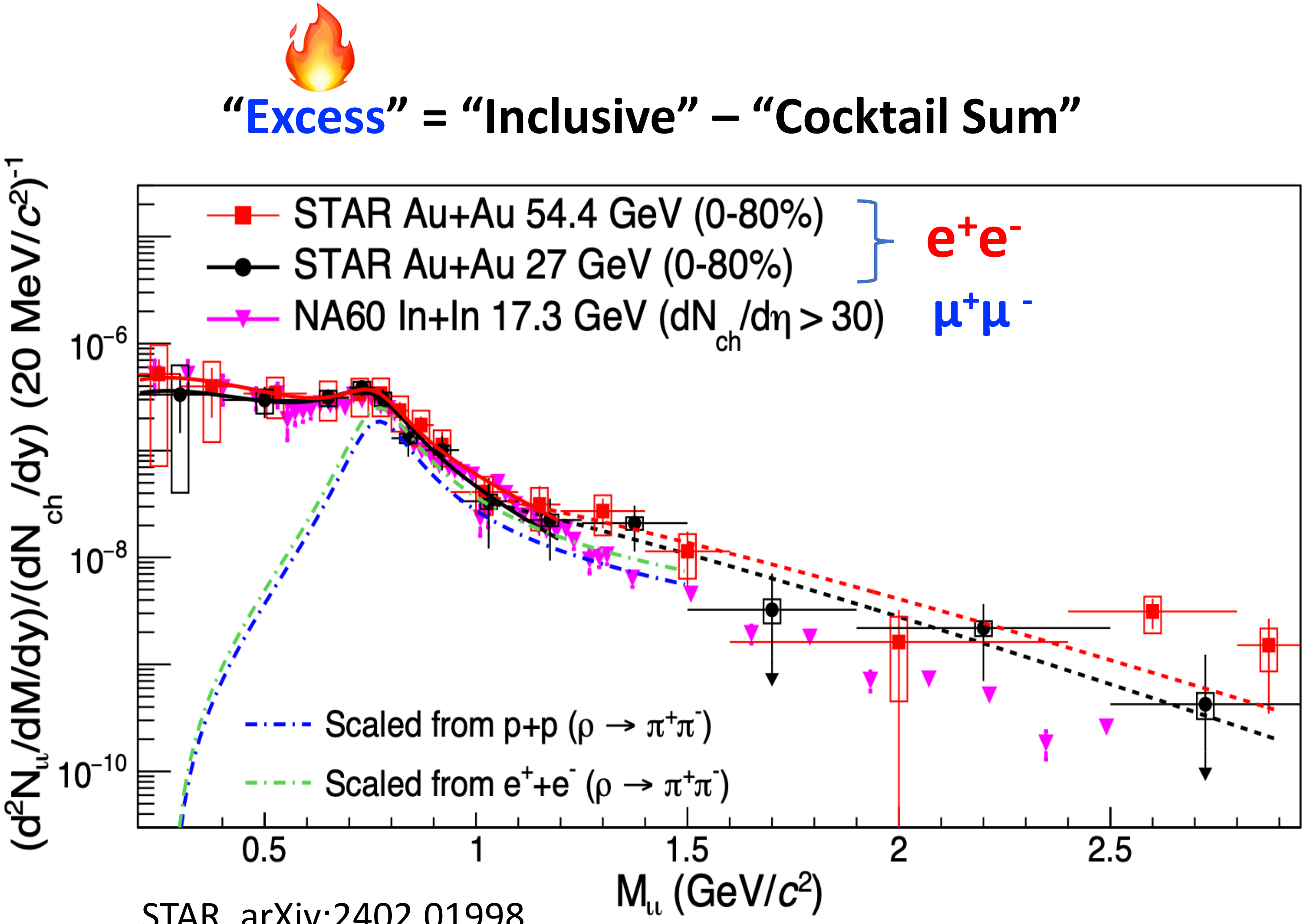
+

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 RHIC



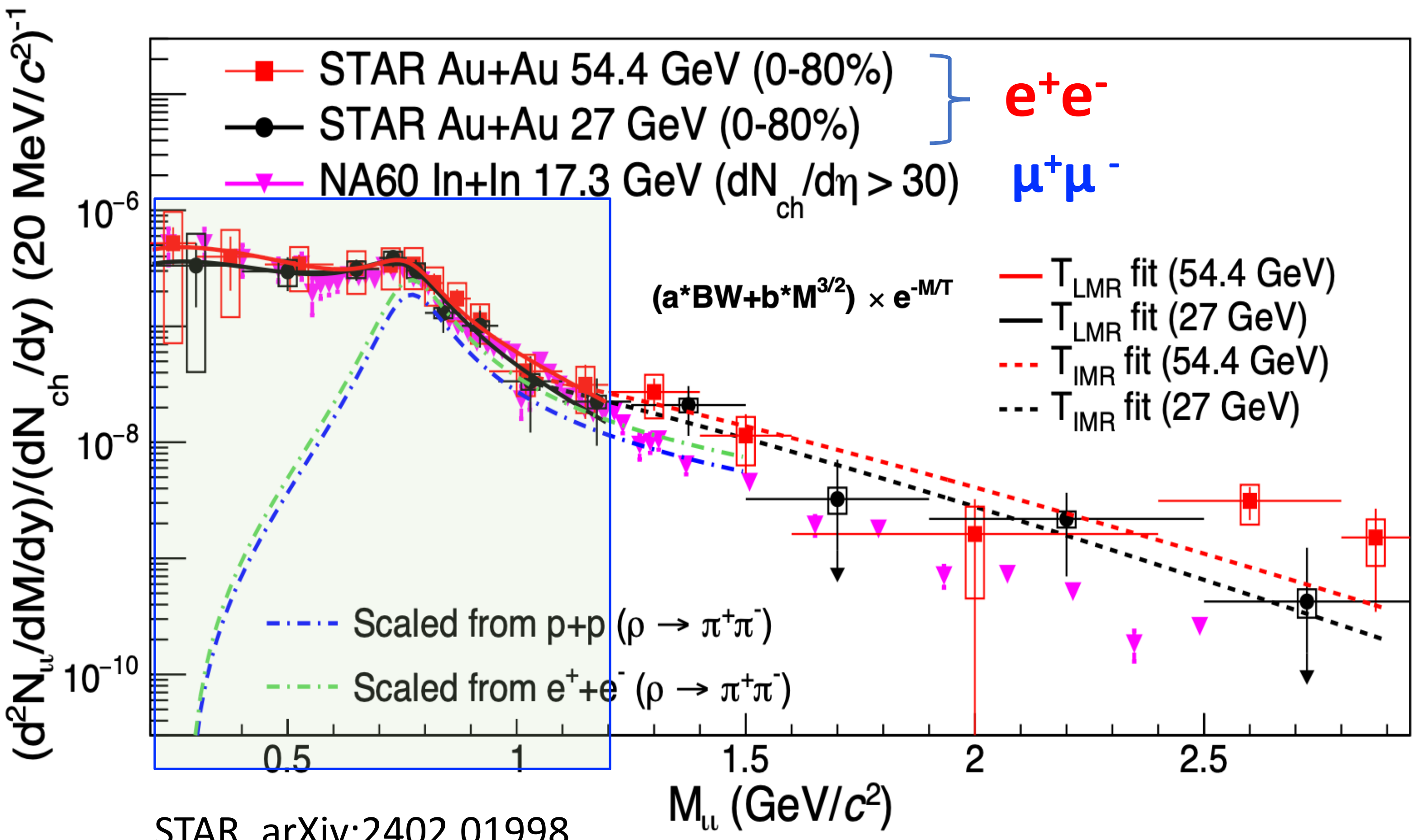
STAR, arXiv:2402.01998

In-medium ρ dominated

- **Similar** mass spectrum

Thermal Dilepton (LMR) at RHIC

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



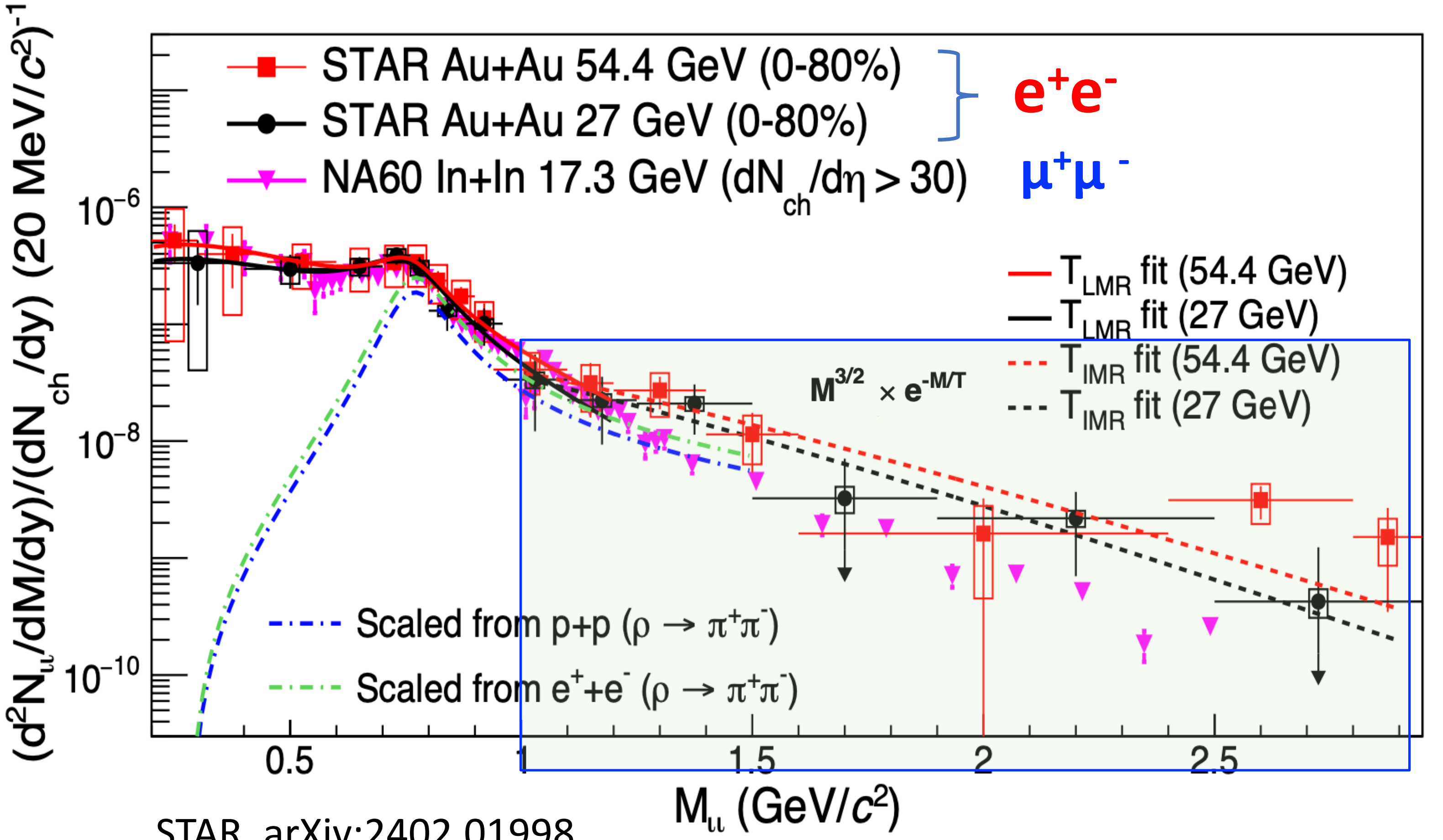
STAR, arXiv:2402.01998

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 RHIC

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



STAR, arXiv:2402.01998

QGP dominated

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

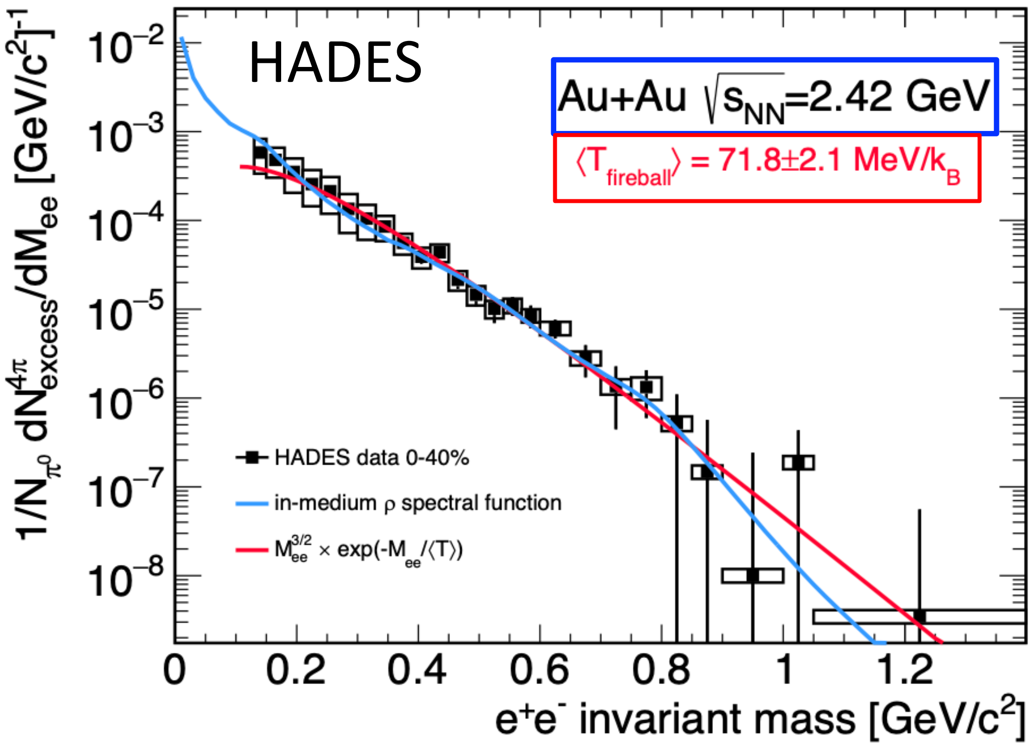
T_{IMR} from NA60:

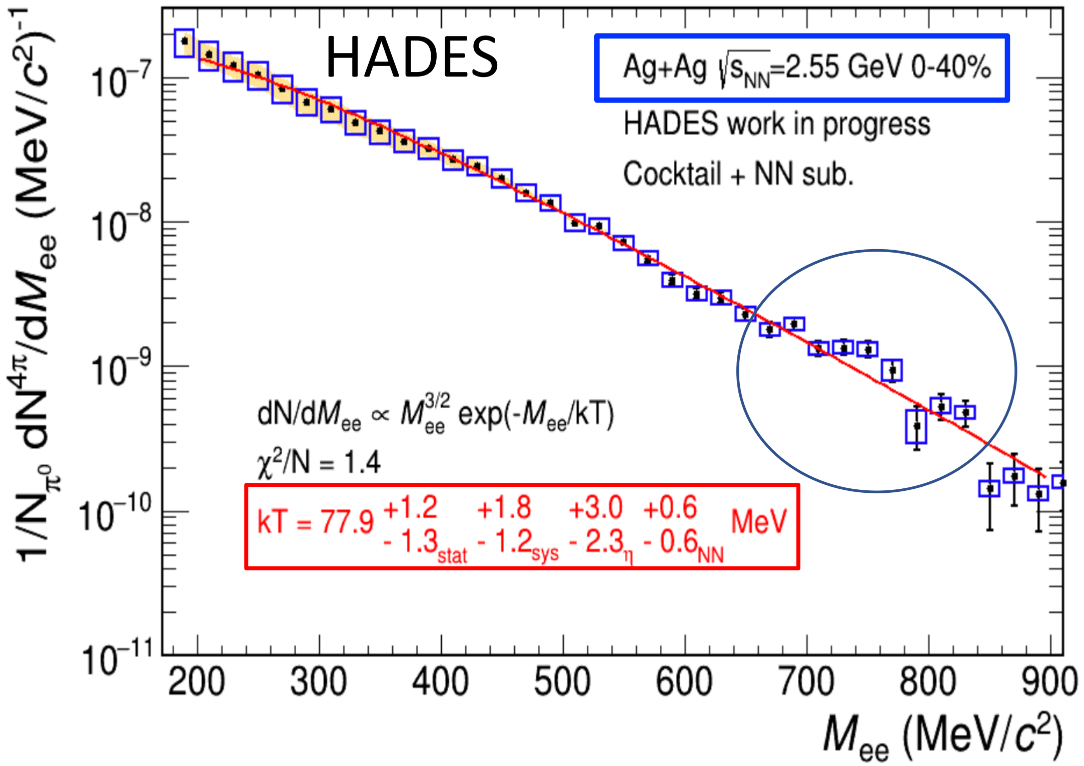
- **205 ± 12 MeV** (1.2<M<2.0 GeV/c^2)
- **246 ± 15 MeV** (1.2<M<2.5 GeV/c^2)

T_{IMR} > T_{pc} (156 MeV): emission source is dominantly the **partonic phase - QGP**

Thermal Dilepton at SIS18

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

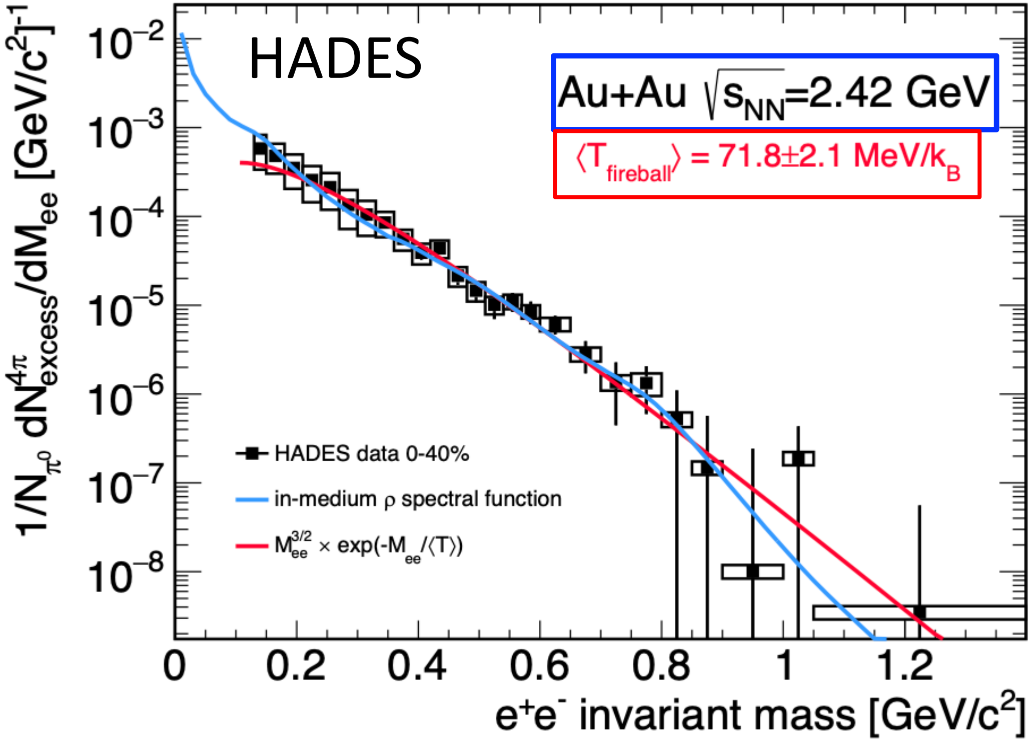




- In-medium ρ completely melt via frequent scattering with surrounding baryons
- T_{LMR} ~ 70-80 MeV, distribution well reproduced by transport model considering thermal hadronic medium radiation

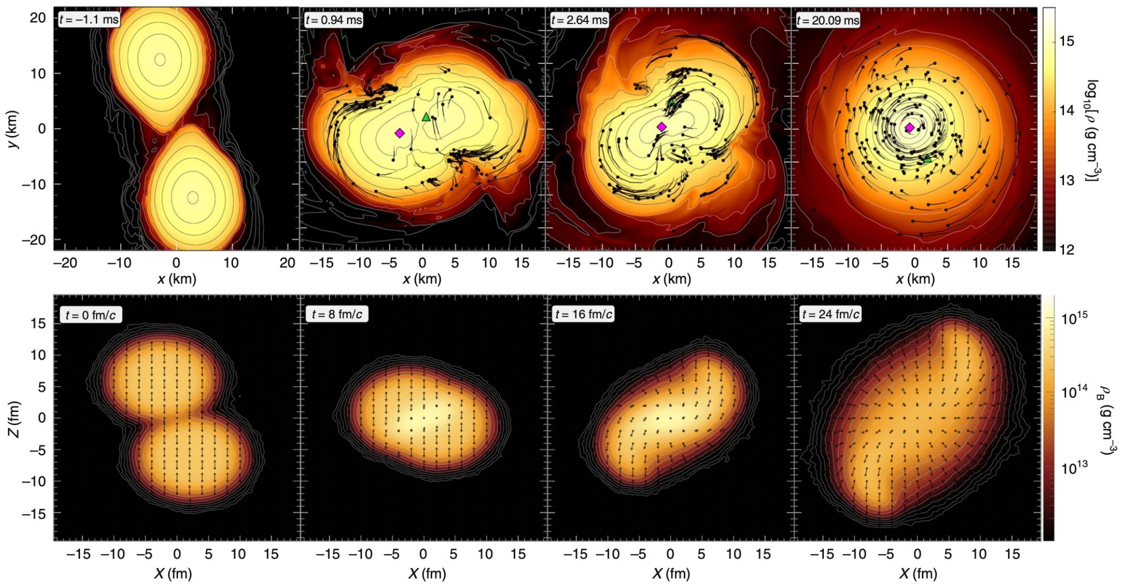
Small Collisions Connected to Big Collisions

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



PLB 122, 061101 (2019)

Binary neutorn star merger



Au+Au@2.42GeV

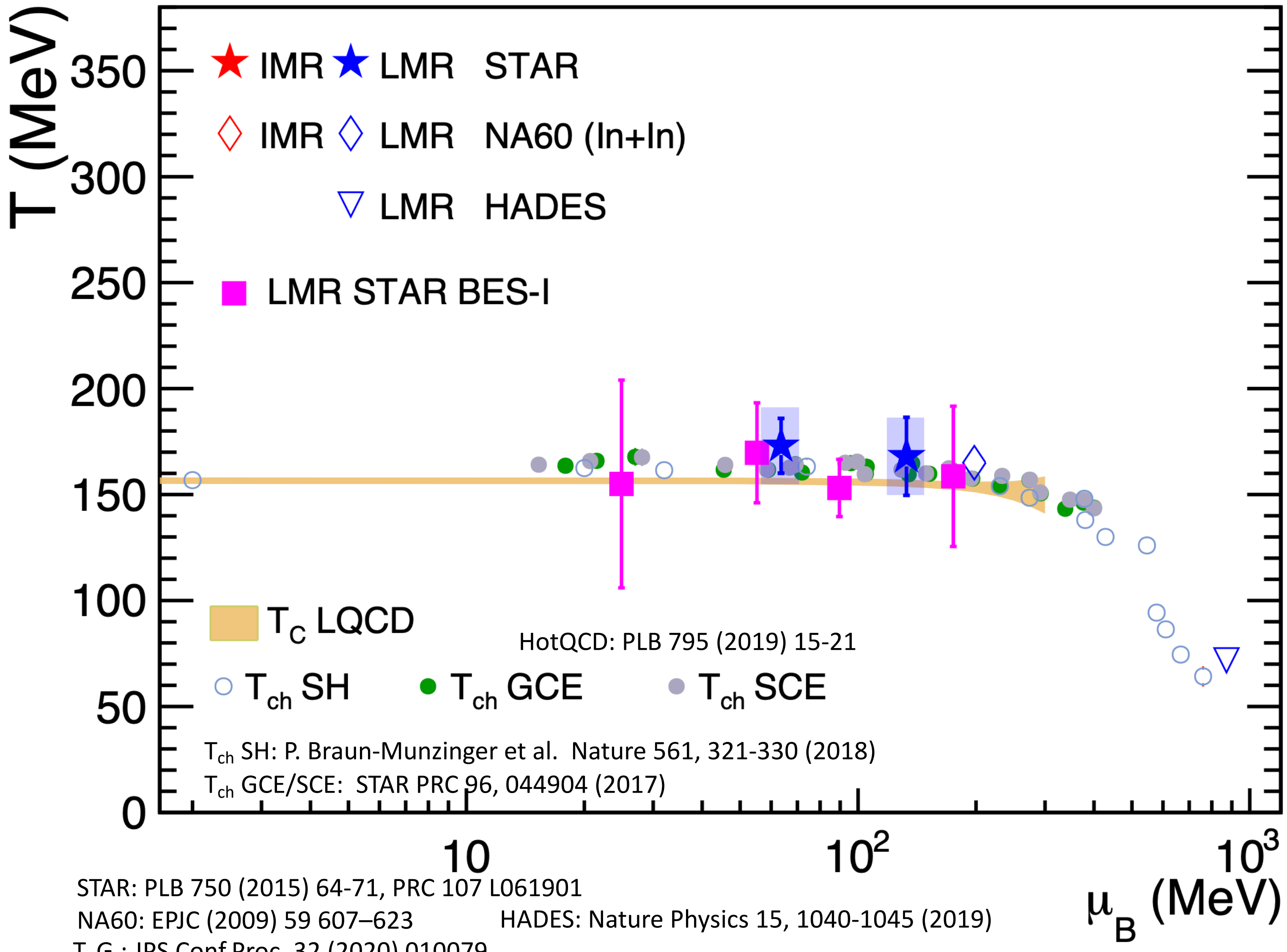
PPNP 41, 255-369 (1998)

simulations

- 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

STAR, arXiv:2402.01998



STAR: PLB 750 (2015) 64-71, PRC 107 L061901
NA60: EPJC (2009) 59 607–623 HADES: Nature Physics 15, 1040-1045 (2019)
T. G.: JPS Conf.Proc. 32 (2020) 010079

Thermal dileptons in LMR

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

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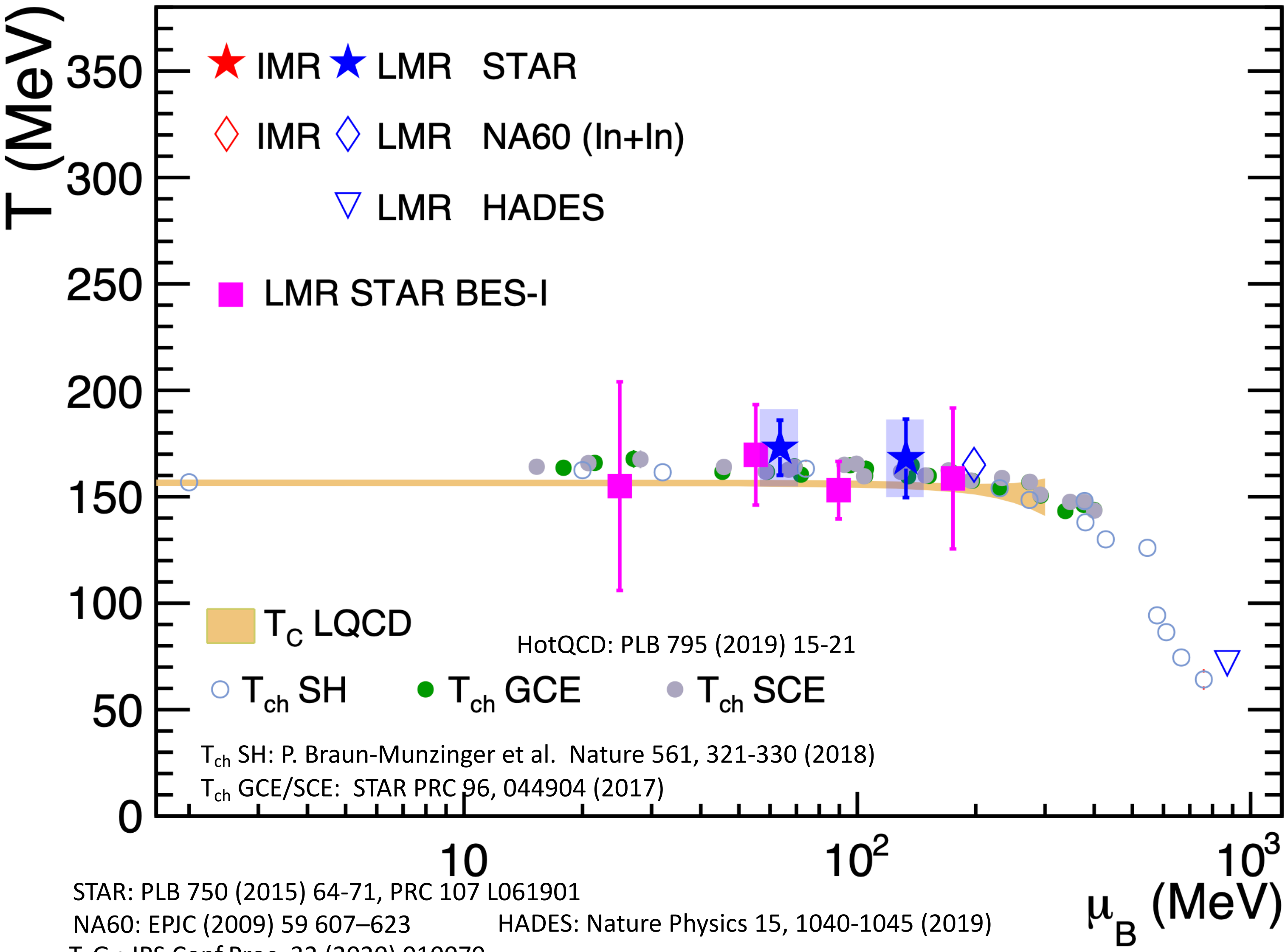

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Thermal dileptons in LMR

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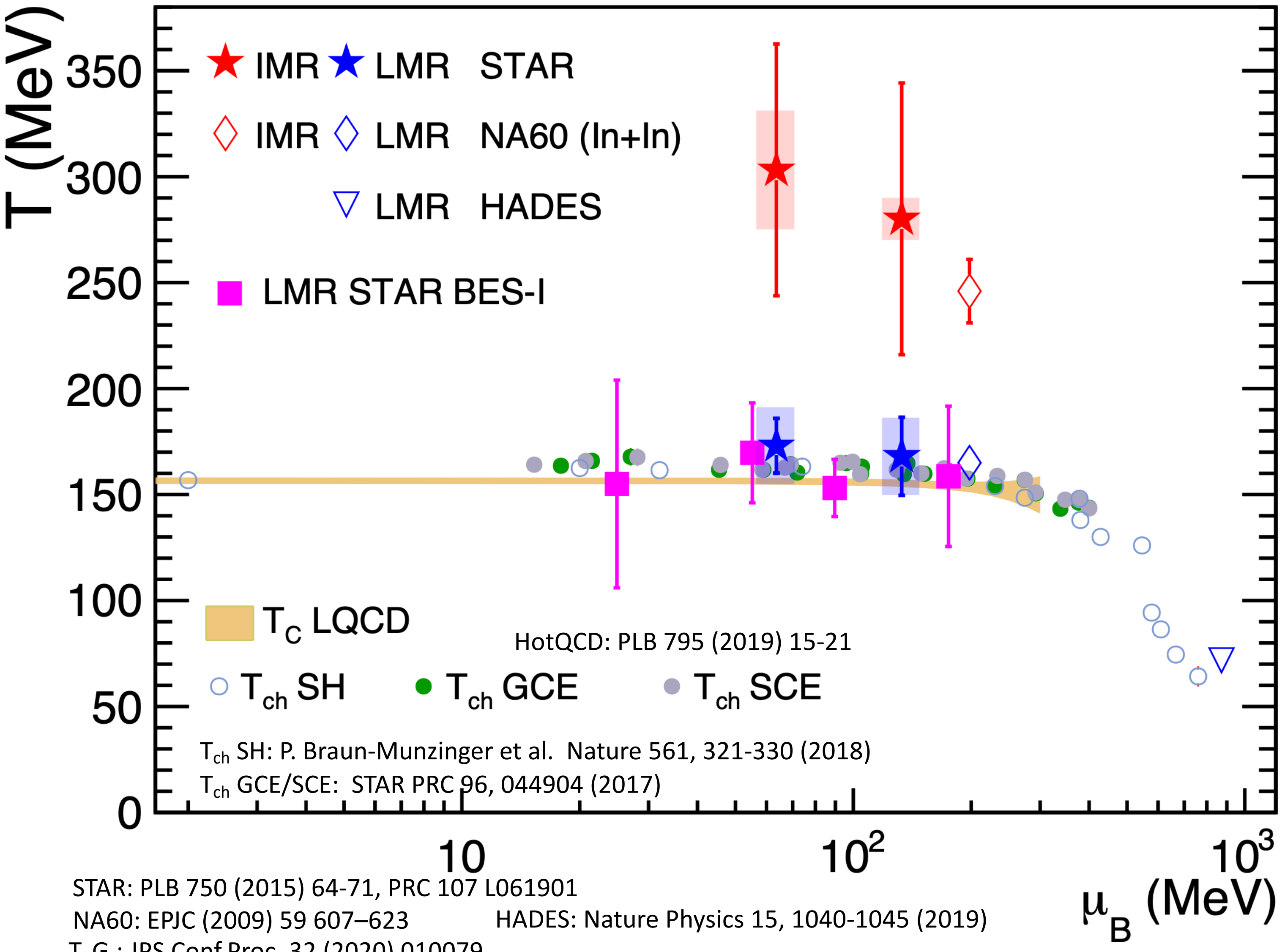

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T. G.: JPS Conf.Proc. 32 (2020) 010079

Thermal dileptons in LMR

- **T close to both T_{ch} and T_{pc}**
- **Emitted from hadronic phase, dominantly around phase transition**

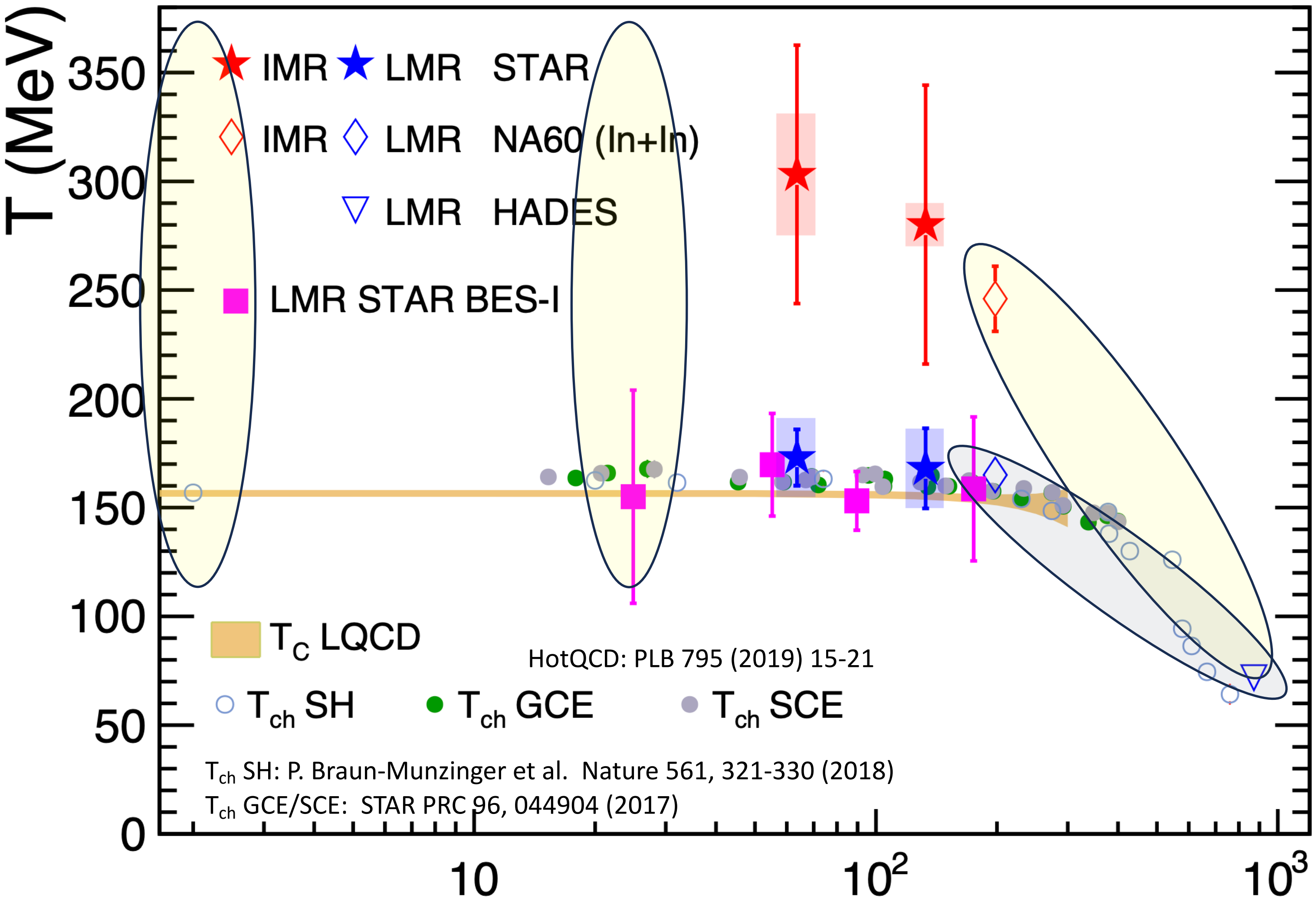
Thermal dileptons in IMR

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

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

Future Temperatures

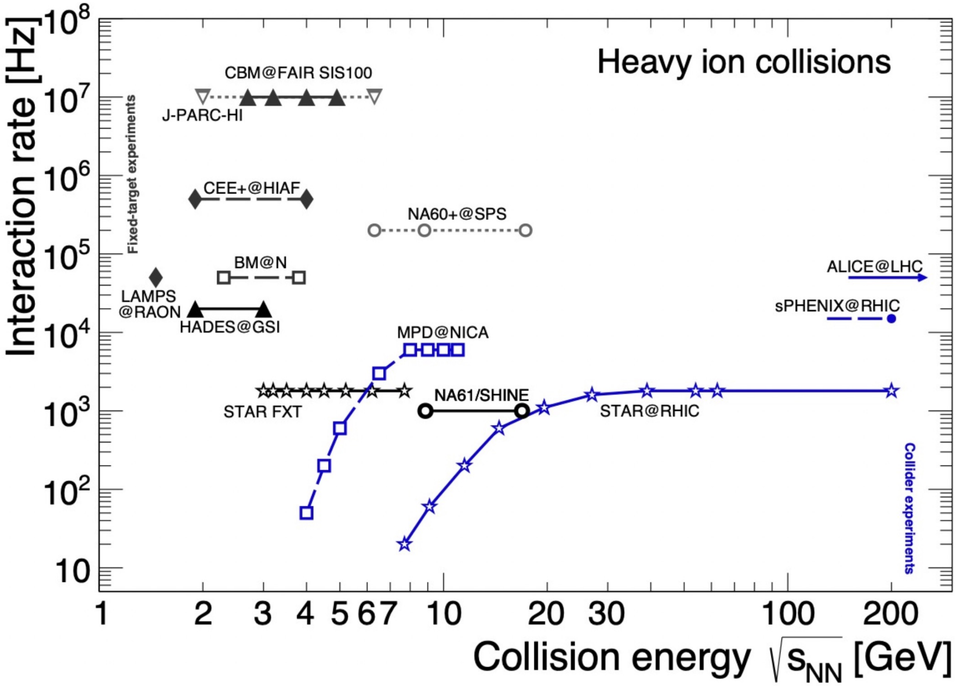
STAR, arXiv:2402.01998



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

NA60: EPJC (2009) 59 607–623 HADES: Nature Physics 15, 1040-1045 (2019)

T. G.: JPS Conf.Proc. 32 (2020) 010079



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

Is Chiral Symmetry Restored?

quark condensate

$< q\bar{q} >$

- $\neq 0$: chiral symmetry breaking $\Longrightarrow$ 98-99% of mass of visible universe
- $= 0$: chiral symmetry restored $\Longrightarrow$ δM btw chiral partners → 0

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

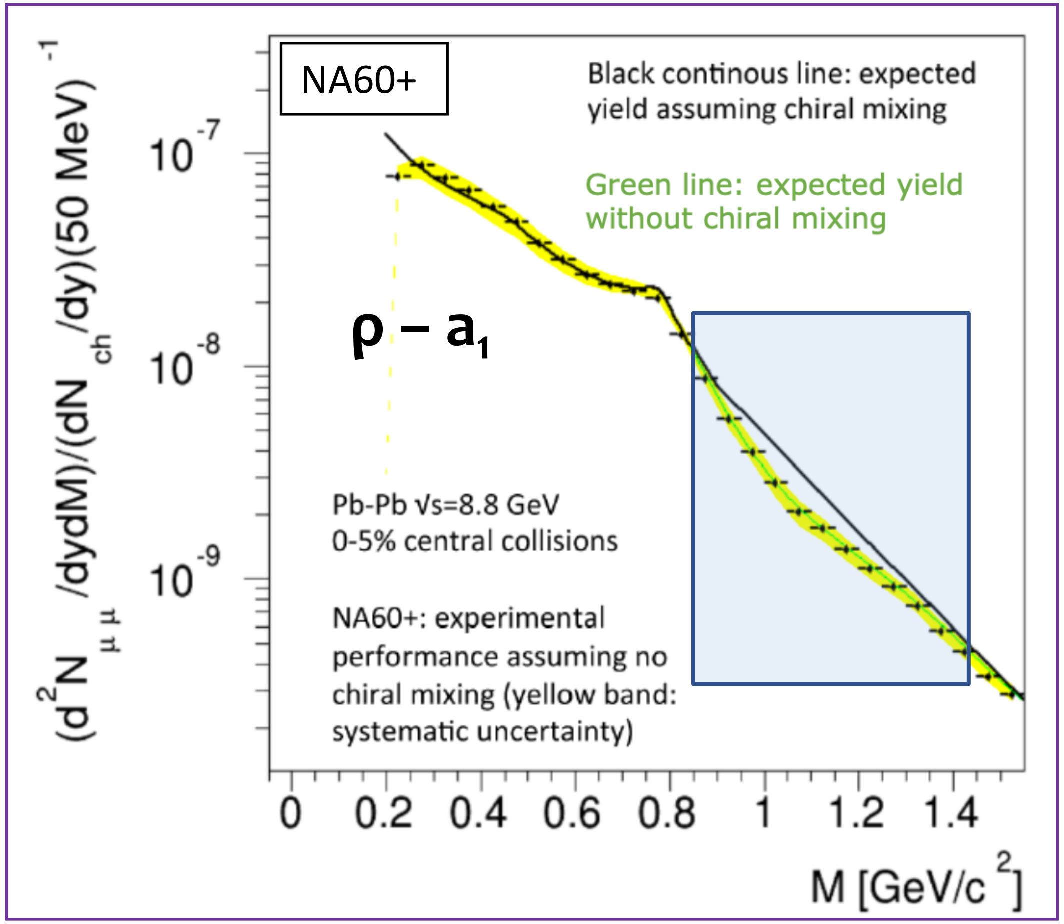
Axial-Vector meson (a_1) → No dilepton decays (chiral partner of ρ)

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

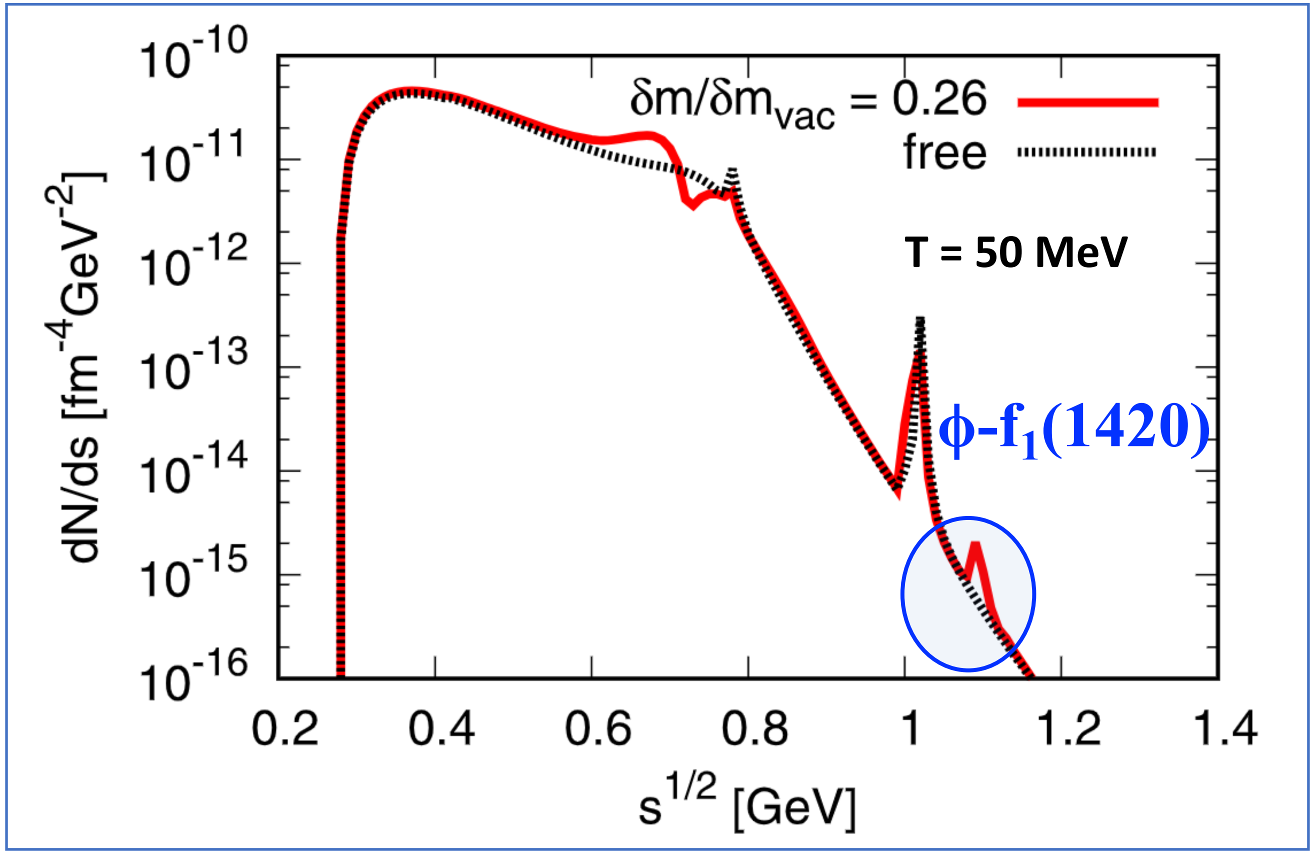
Rapp model: PRC 63 (2001) 054907, Adv HEP 2013 (2013) 148253, PLB 753 (2016) 586
PHSD model: NPA 807, 214 (2008); NPA 619, 413 (1997) PRC 97, 064907 (2018)

Experimental Evidence of CSR

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



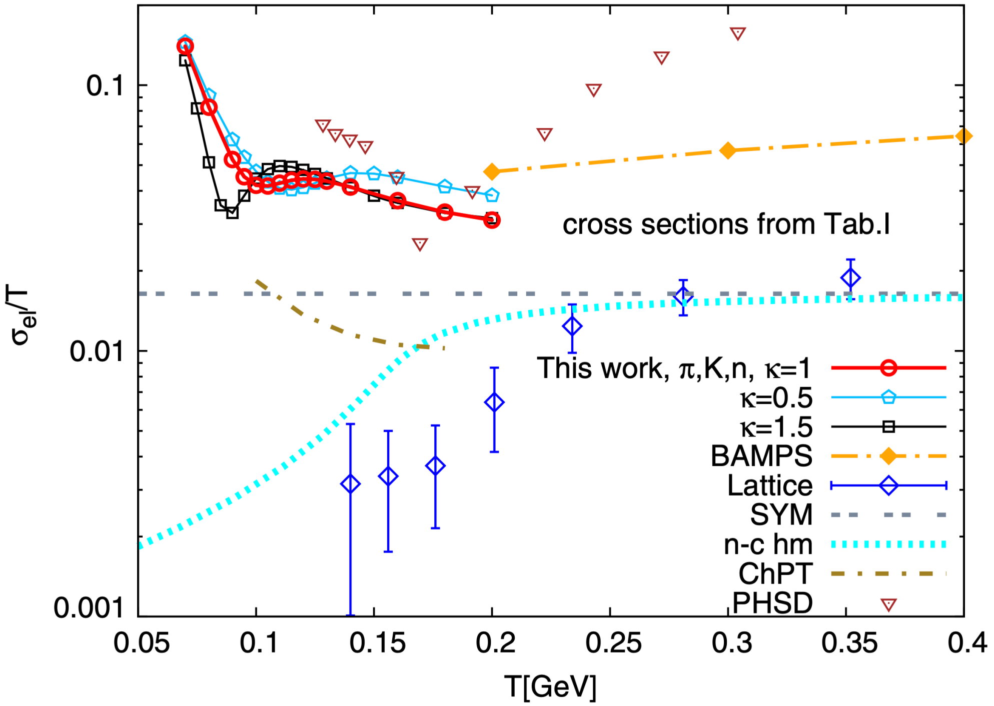
Rapp and Hohler: PLB 731 (2014) 103-109



Chihiro Sasaki, PLB 801 (2020) 135172

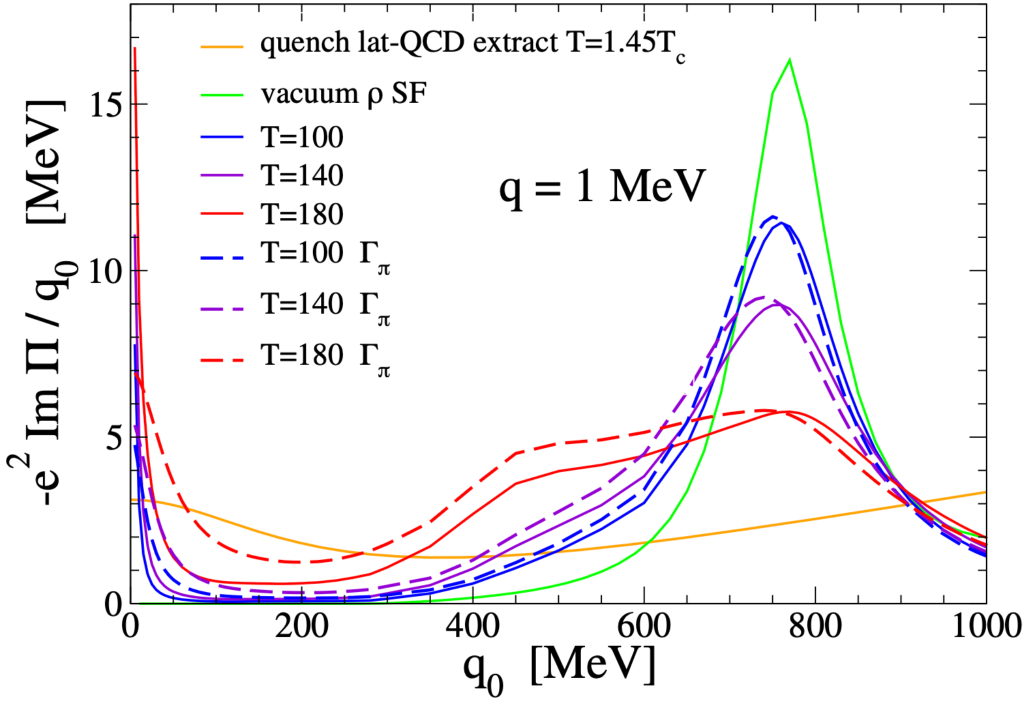
Electric Conductivity of Hot QCD Medium

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 low mass**
- **Low energy collisions: smaller contributions from QED, QGP**

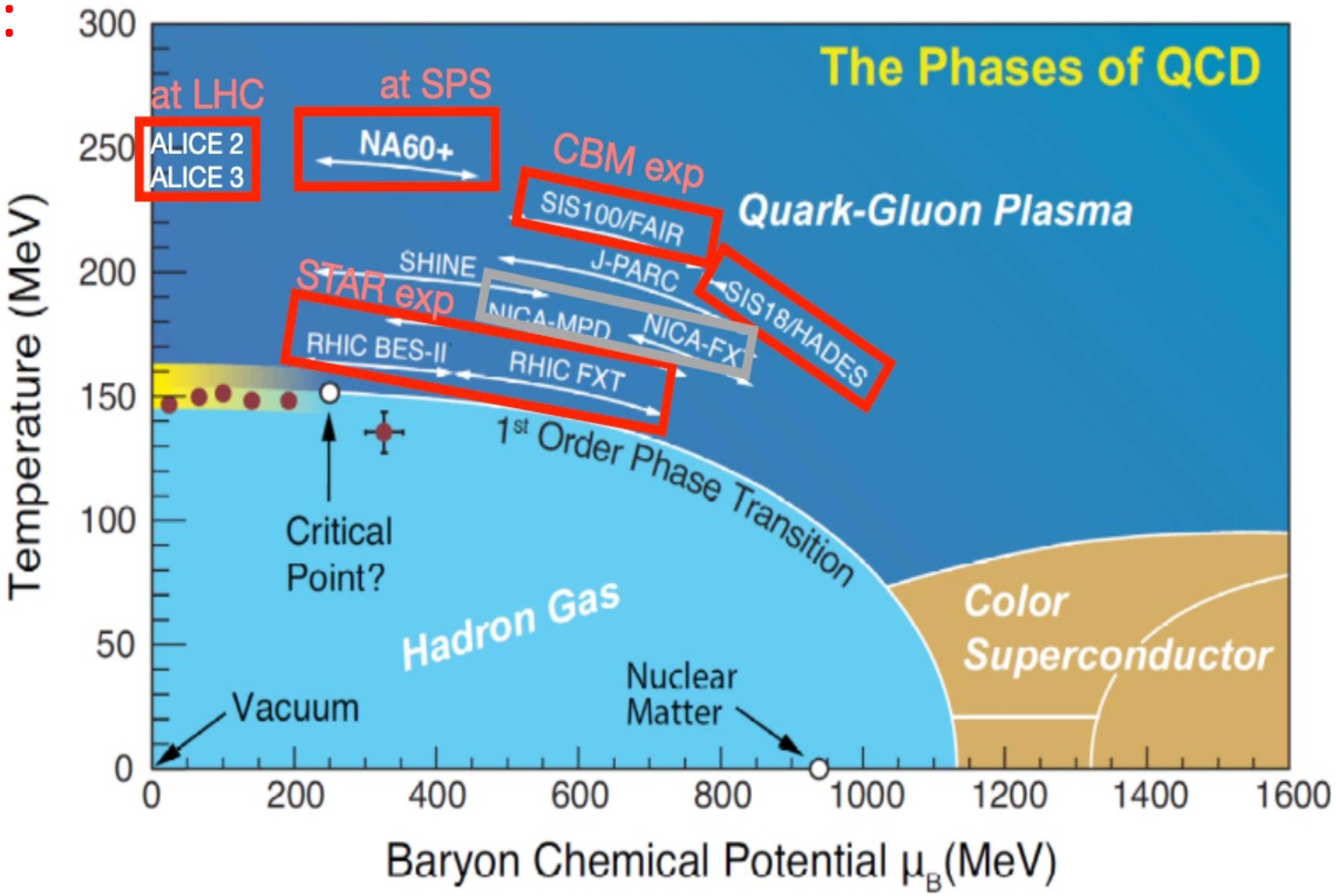
Summary and Next

Lessons from exist thermal dileptons:

- In-medium rho is significantly broaden
- $T^{LMR} \sim T_{ch} \sim T_{pc}$ at both RHIC and SPS
- $T^{LMR} \sim$ 70-80 MeV at SIS18
- $T^{IMR} > T_{pc}$ at both 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

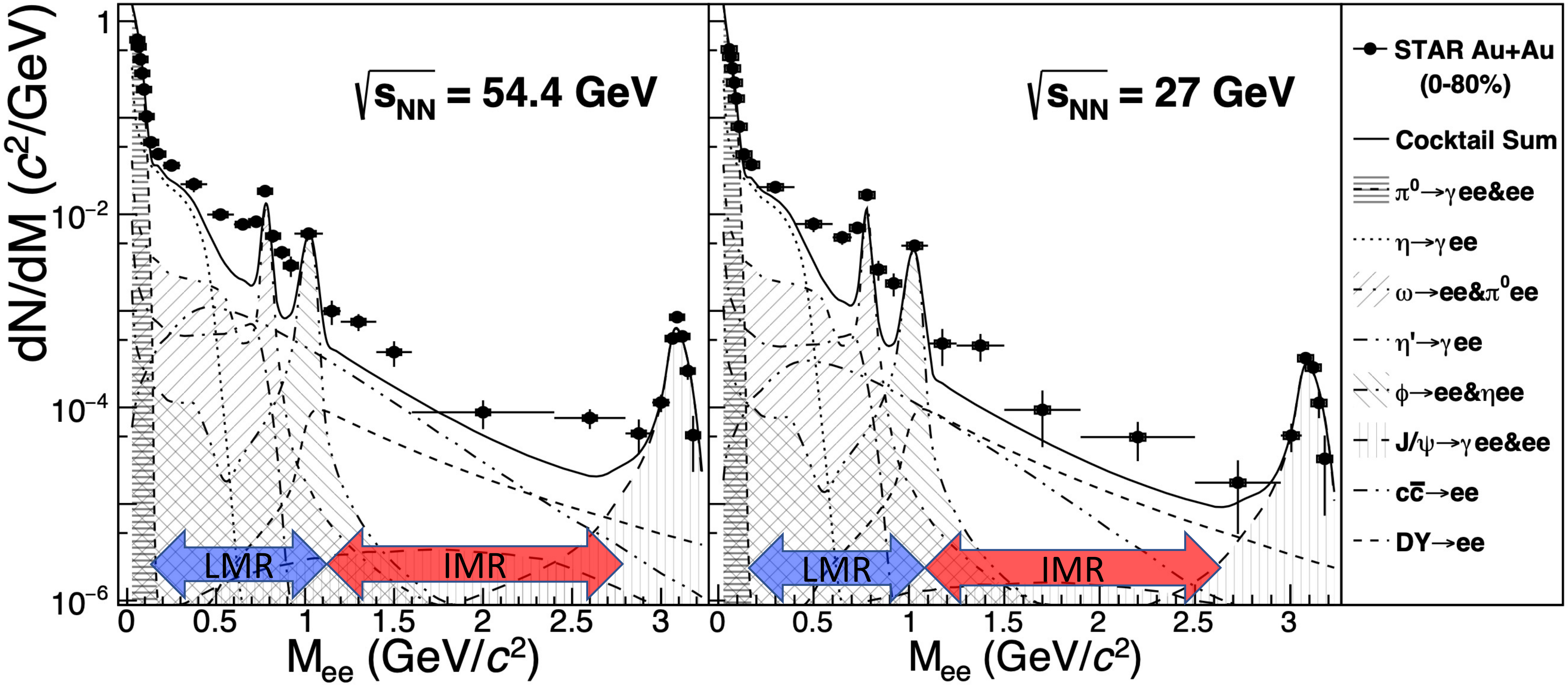


Sunset 2024-09-10

THANKS

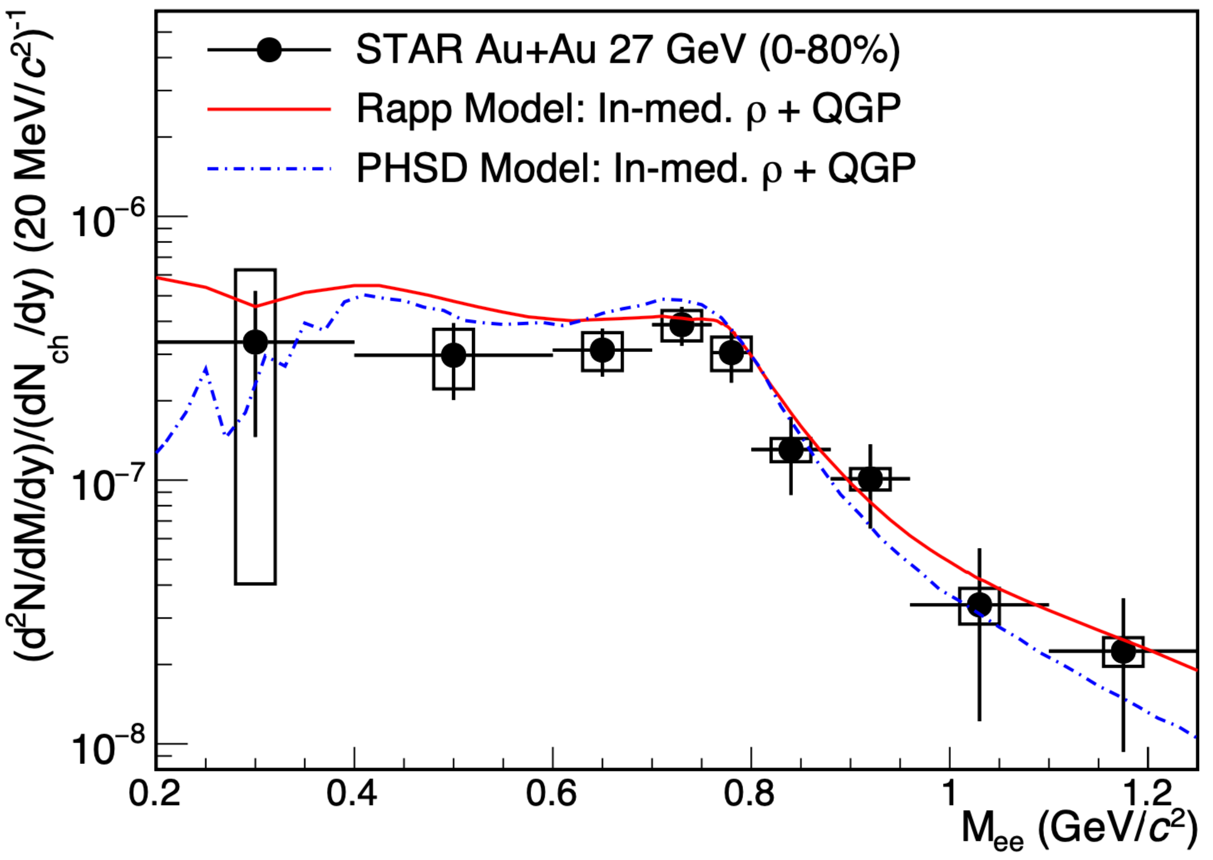
BACKUP SLIDES

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



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)

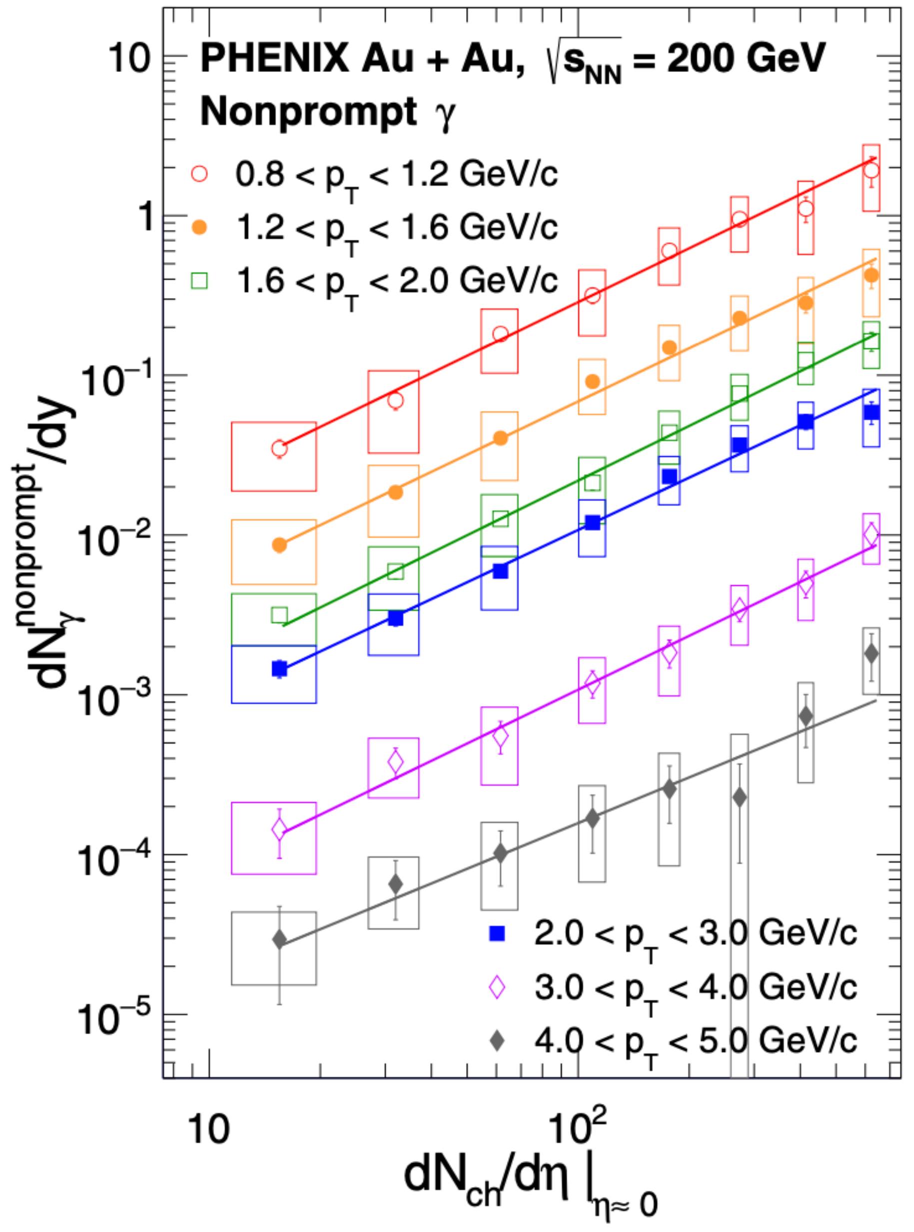
Both models can **well describe the ρ broadening at LMR**

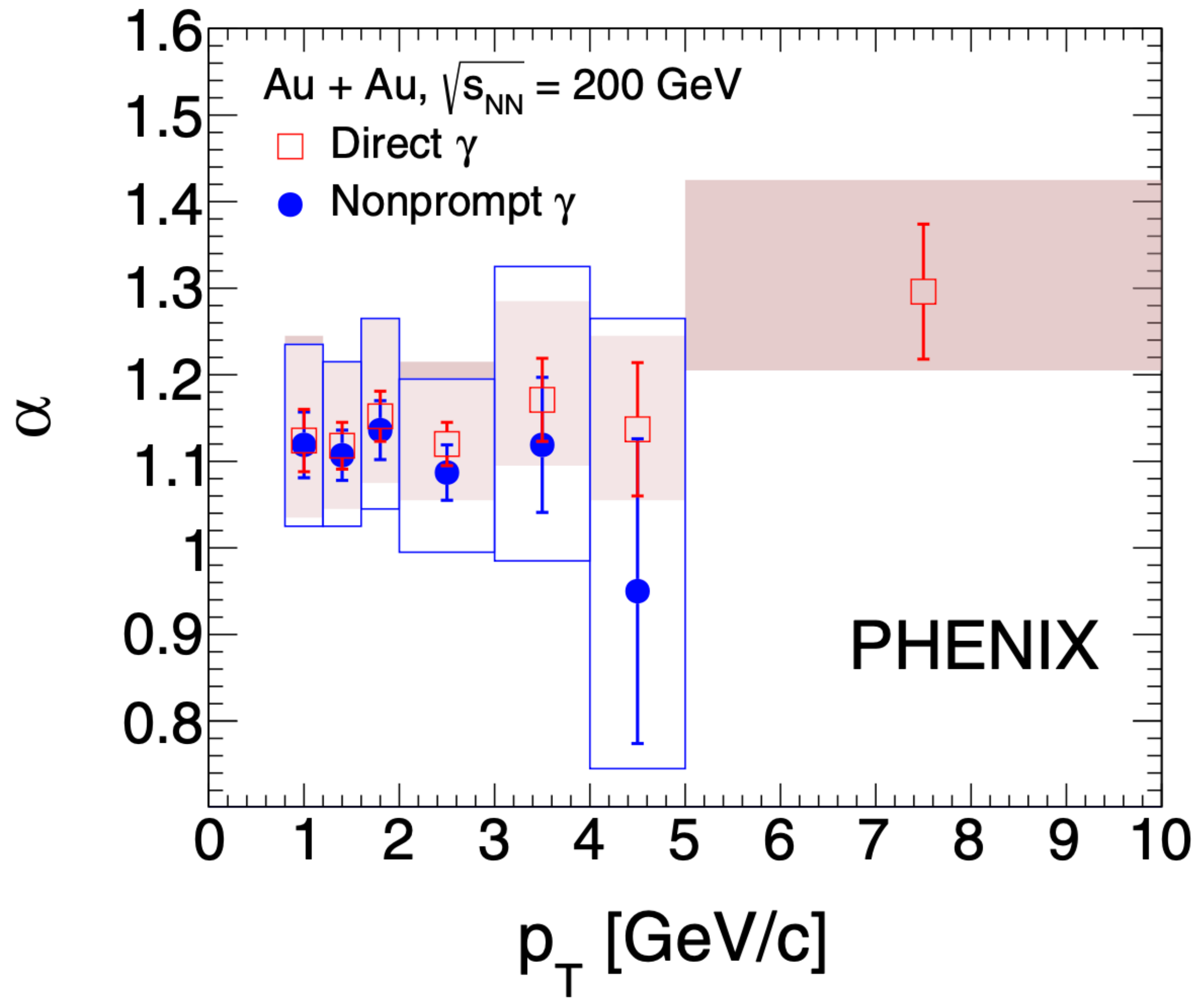
Rapp model: macroscopic many-body approach
medium described by cylindrical expanding fireball with lQCD EoS; in-medium ρ-propagator; resonance + π cloud + baryons

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

PHENIX, PRC **109**, 044912 (2024)

Scaling of Non-Prompt photons





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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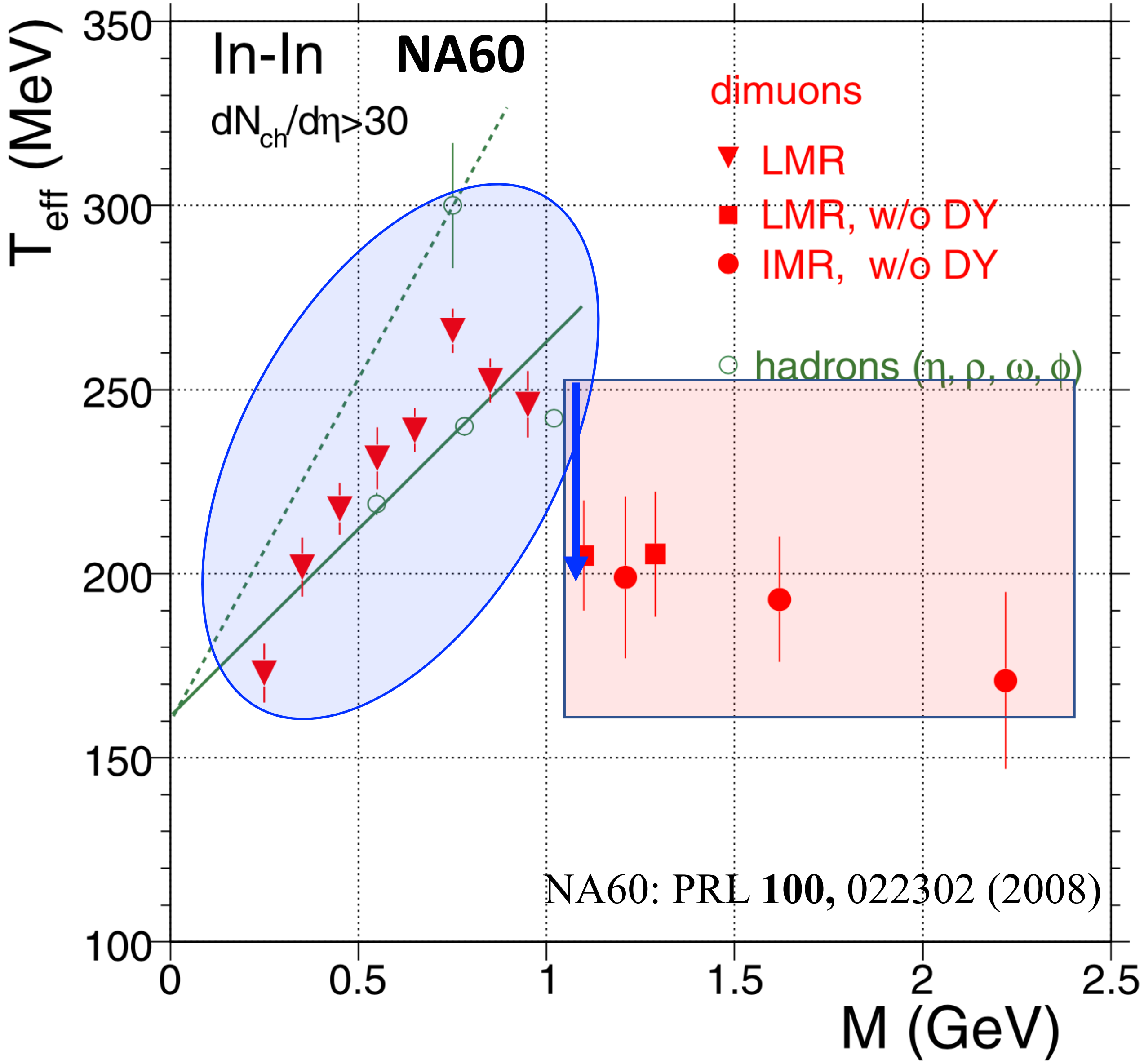
(Received 11 August 2013; revised manuscript received 28 March 2014; published 28 April 2014)

"**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:

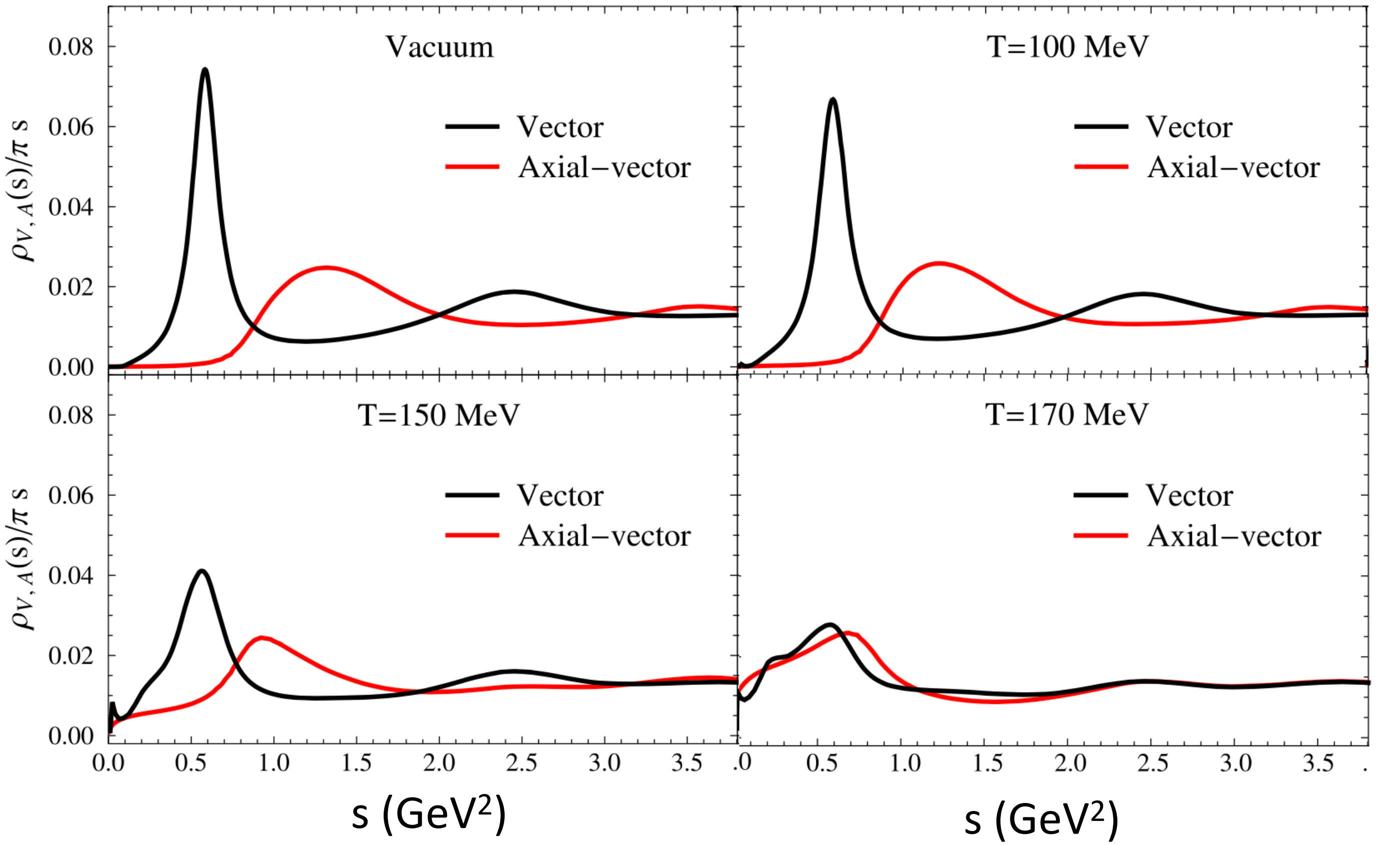
- **T_{eff} rise linearly → In-medium radiation pushed by radial flow**
- **T_{eff} peaks at m_ρ**

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

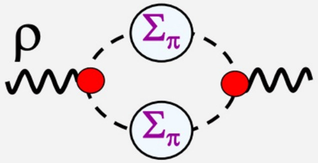
$$\frac{dN_{ee}}{d^4x\,d^4Q} = \frac{-\alpha_{em}^2}{\pi^3 Q^2}\, f^B(q_0,T)\; Im\,\Pi_{em}(M,q;T,\mu_B)$$

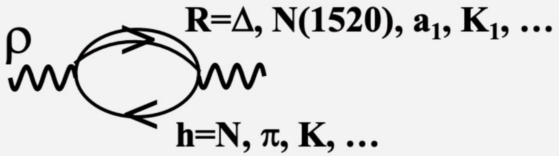
EM Correlation Fct.: $\Pi_{em}^{\mu\nu}(Q) = -i\int d^4x\, e^{iQx}\,\langle\langle j_{em}^{\mu}(x)\, j_{em}^{\nu}(0)\rangle\rangle$

- **Quark basis:** $j_{em}^{\mu} = \frac{2}{3}\bar{u}\gamma^{\mu}u - \frac{1}{3}\bar{d}\gamma^{\mu}d - \frac{1}{3}\bar{s}\gamma^{\mu}s$ **Continuum**
- **Hadron basis:** $j_{em}^{\mu} = \frac{1}{2}(\bar{u}\gamma^{\mu}u - \bar{d}\gamma^{\mu}d) + \frac{1}{6}(\bar{u}\gamma^{\mu}u + \bar{d}\gamma^{\mu}d) - \frac{1}{3}\bar{s}\gamma^{\mu}s$

$$= \frac{1}{\sqrt{2}}\, j_{\rho}^{\mu} + \frac{1}{3\sqrt{2}}\, j_{\omega}^{\mu} - \frac{1}{3}\, j_{\phi}^{\mu}$$

$D_{\rho}(M,q;\mu_B,T) = [M^2 - (m_{\rho}^{(0)})^2 - \Sigma_{\rho\pi\pi} - \Sigma_{\rho B} - \Sigma_{\rho M}]^{-1}$

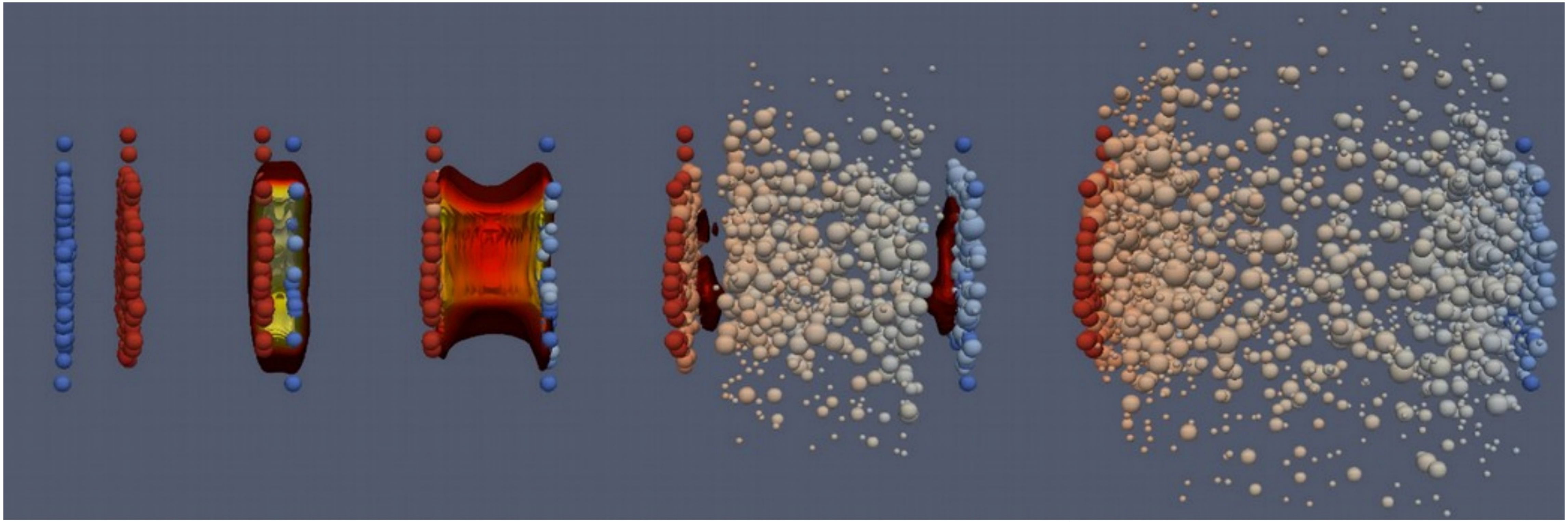
$\Sigma_{\rho\pi\pi} =$ 

$\Sigma_{\rho B,M} =$ 

Prompt photons

"Thermal" photons

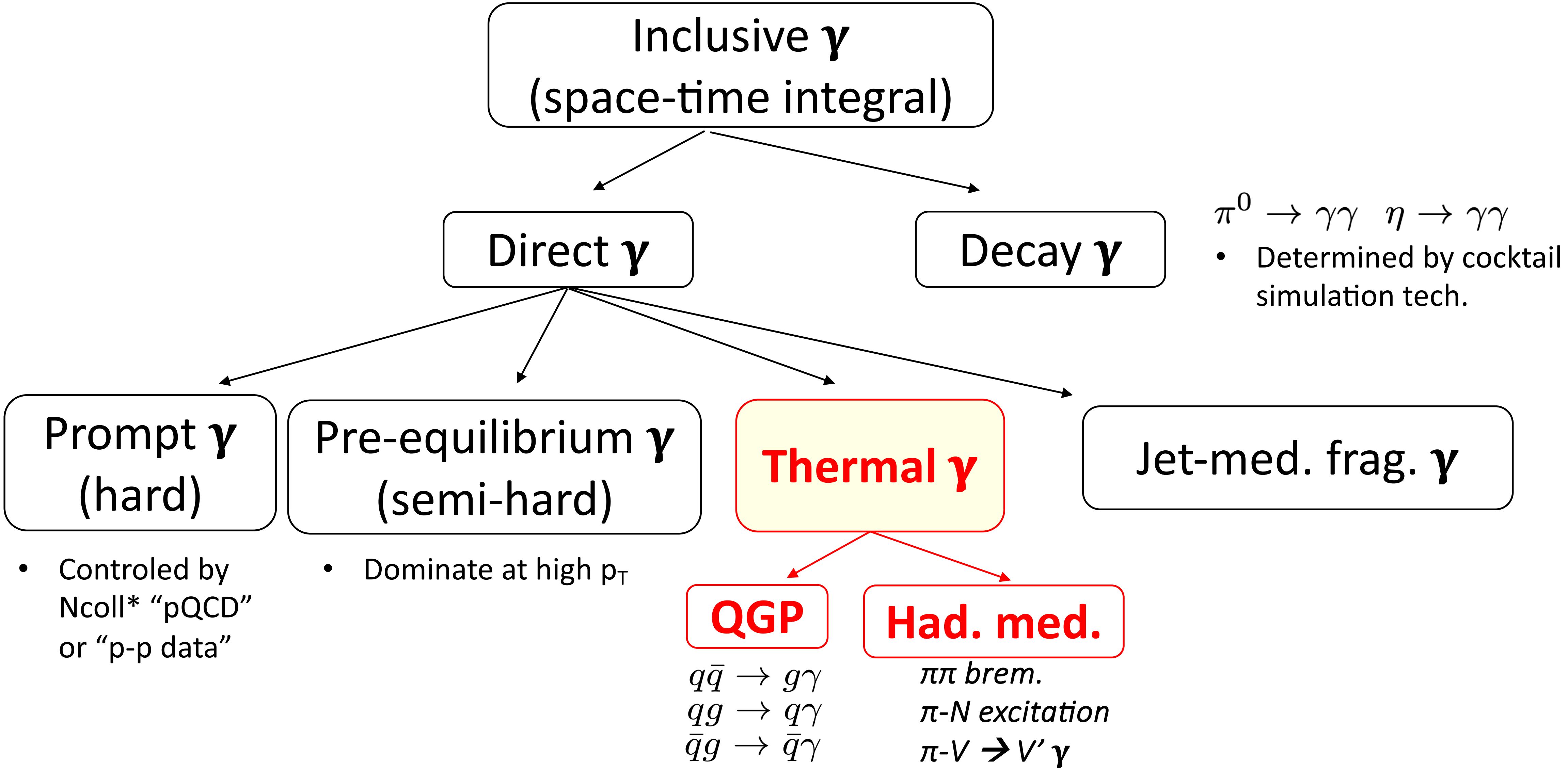
~~Decay photons~~ (e.g. ~~$\pi^0 \rightarrow \gamma\gamma$~~)



Pre-equilibrium emission

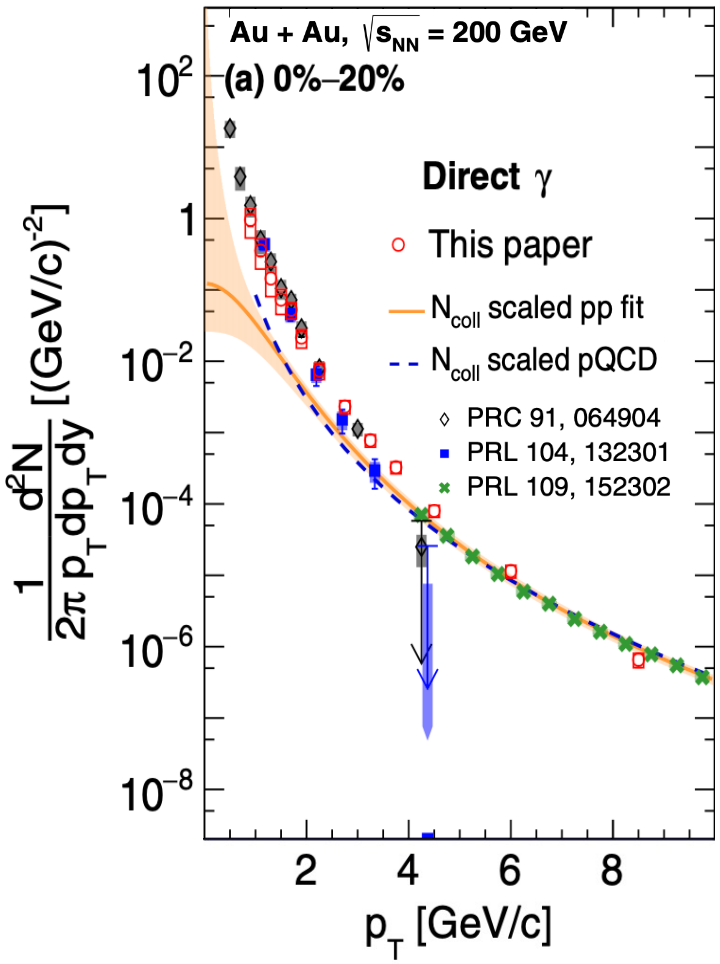
Late stage emission (e.g. $\pi\rho \rightarrow \pi\gamma$)

Photons in Heavy Ion Collisions



Direct Photons at RHIC

PHENIX, PRC **109**, 044912 (2024)

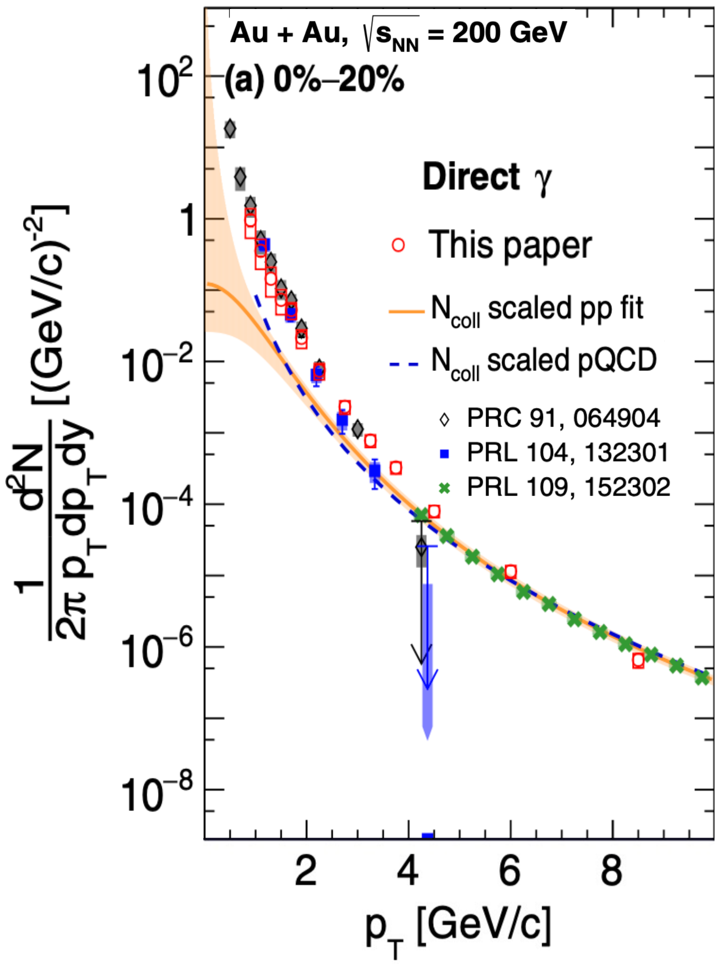


Direct γ = Inclusive γ − Decay γ

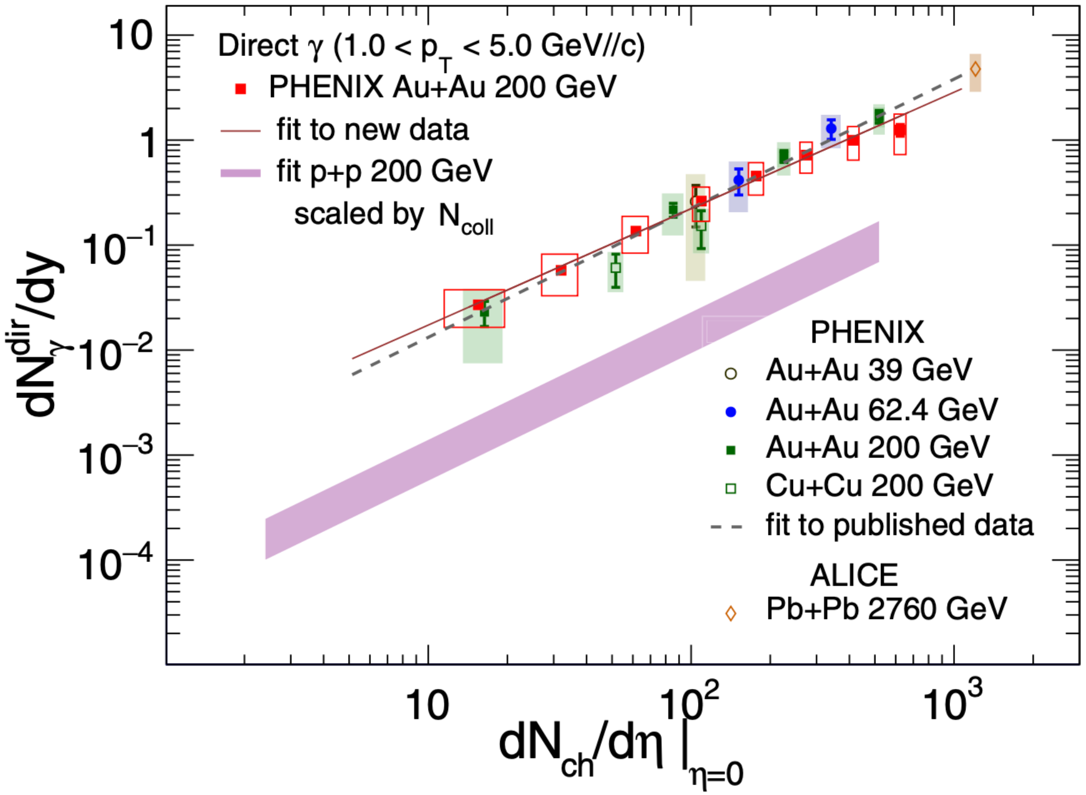
- PHENIX new data consistent with previous published results, significant excess at low p_T

Direct Photons at RHIC

PHENIX, PRC **109**, 044912 (2024)



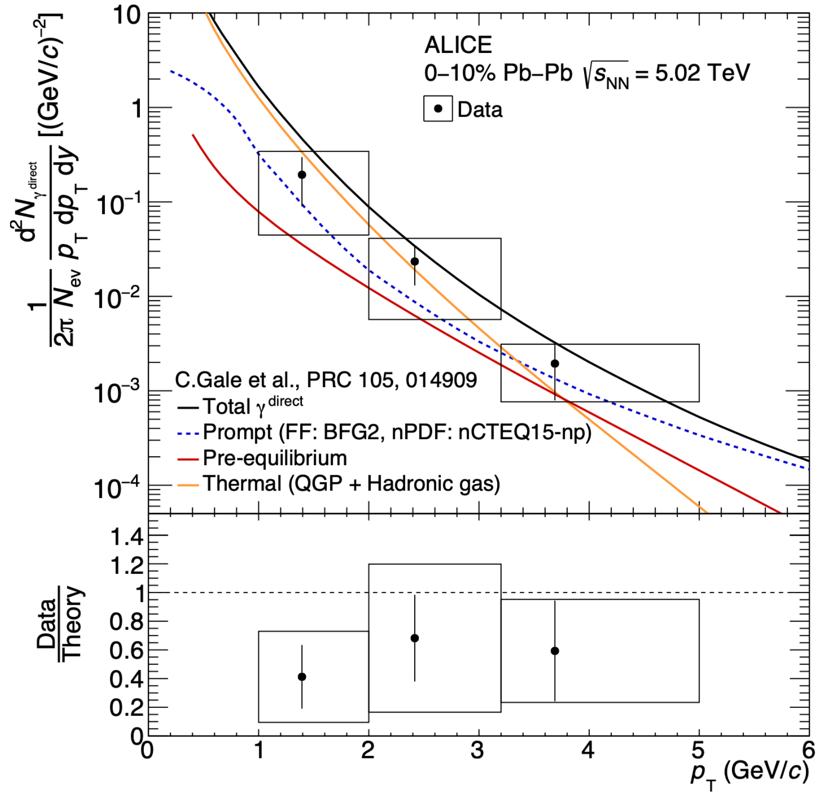
Universal scalling: $\frac{dN_\gamma}{dy} = A \times \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$



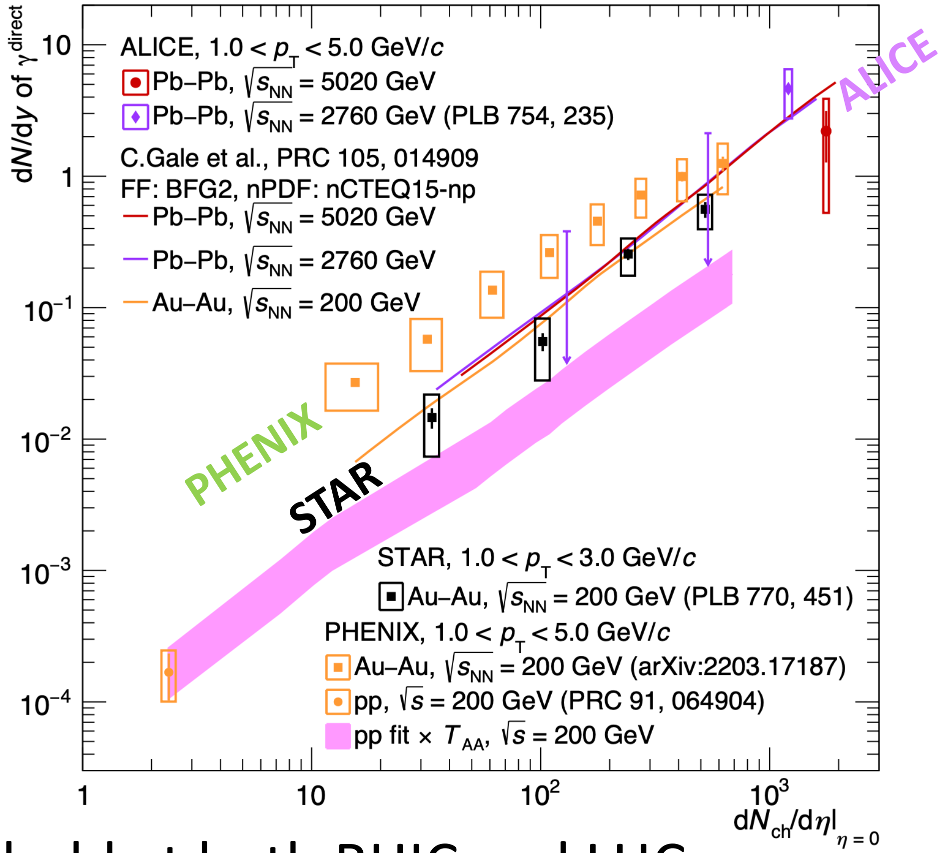
- PHENIX new data consistent with previous published results, significant excess at low p_T
- Universal scaling behaviour in A+A collisions at different collision energies and systems

Direct Photons at RHIC and LHC

ALICE, arXiv:2308.16704

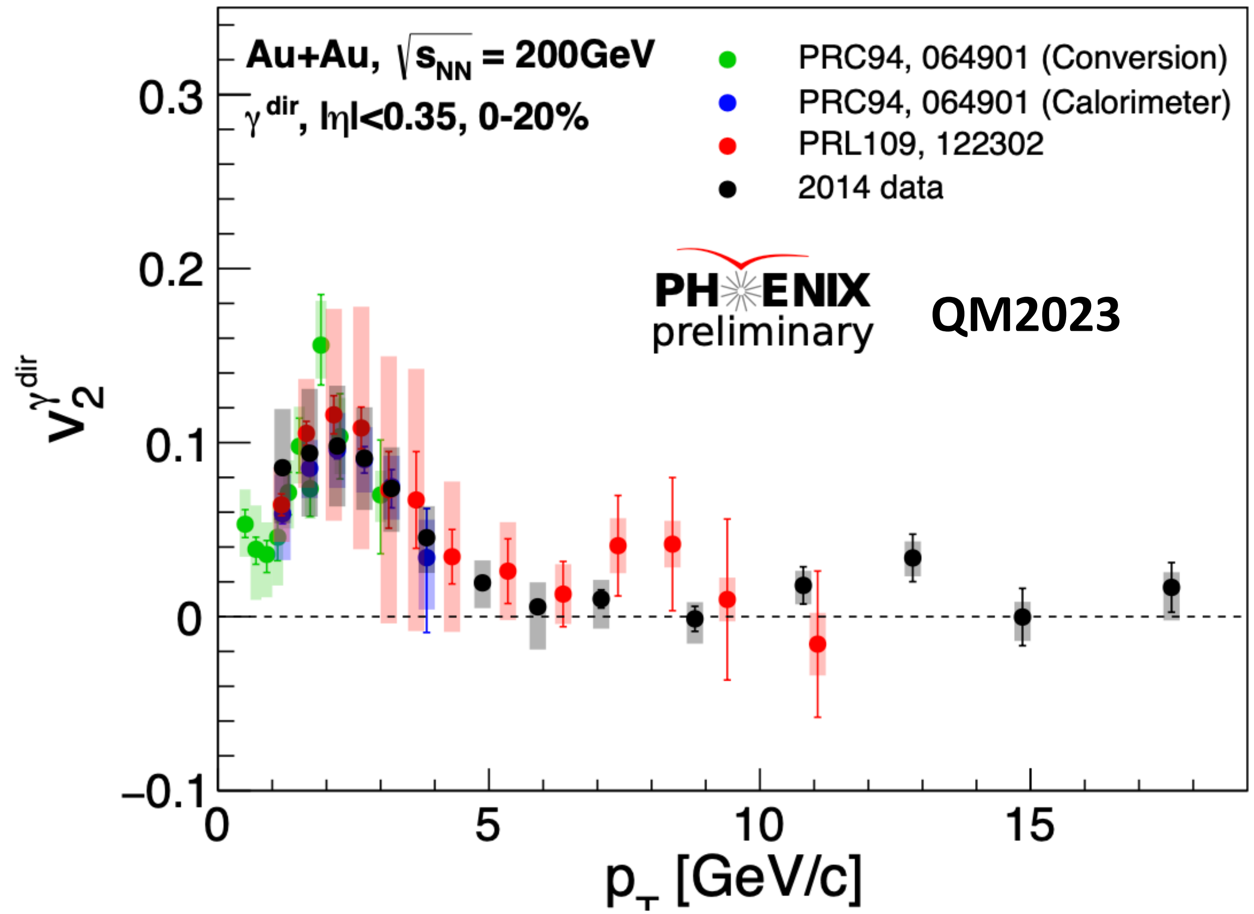


Universal scalling: $\frac{dN_\gamma}{dy} = A \times \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$

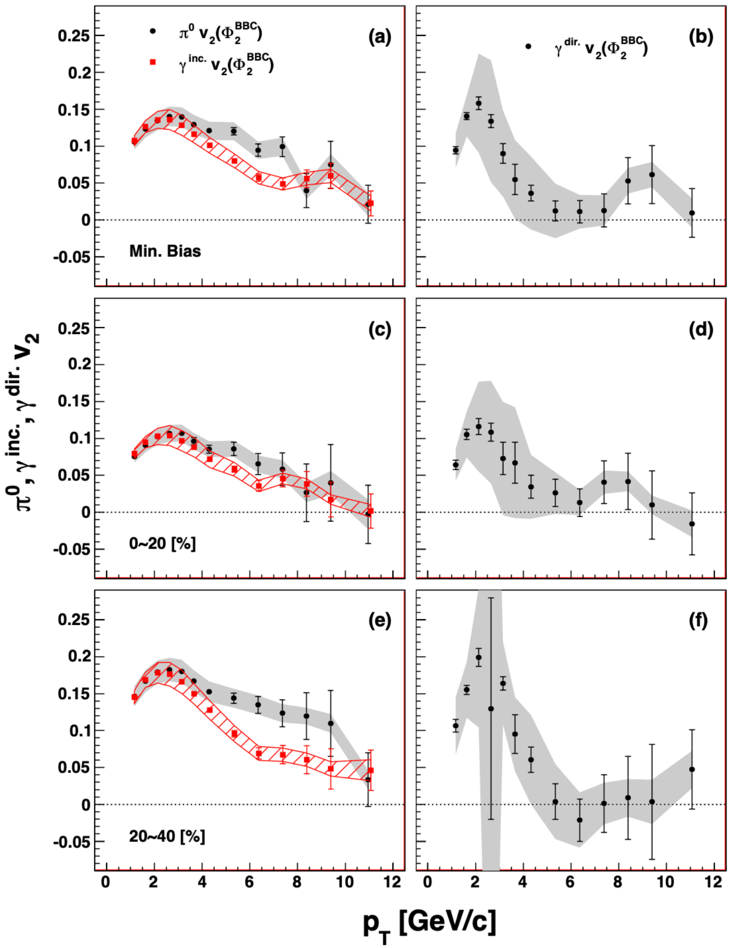


- Universal charge density scaling behaviour hold at both RHIC and LHC
- However: ALICE data agrees with both STAR and PHENIX data within large uncertainty while STAR and PHENIX show clear discrepancy

Flow (v_2) of Direct Photons at RHIC

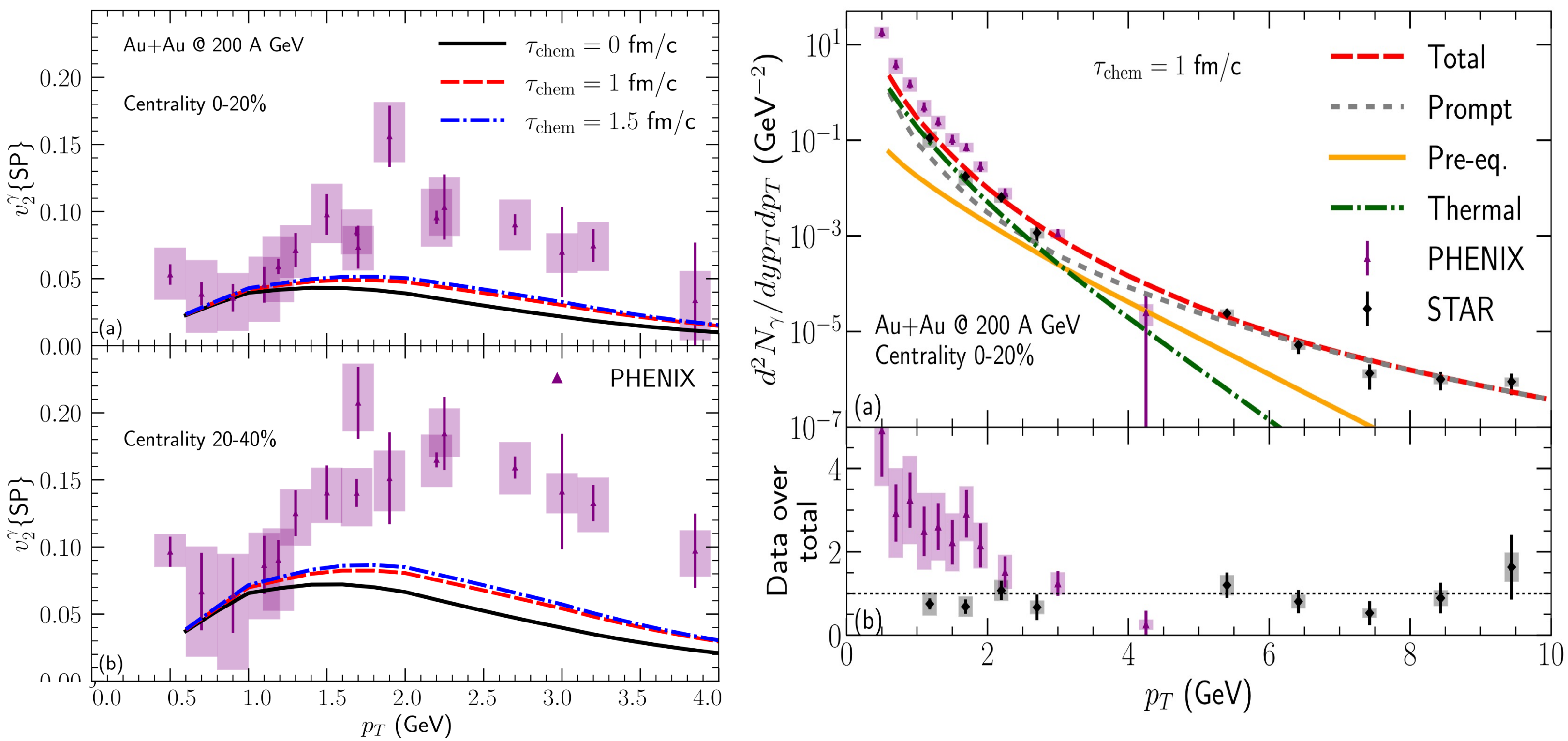


PHENIX: PRL 109, 122302 (2012)

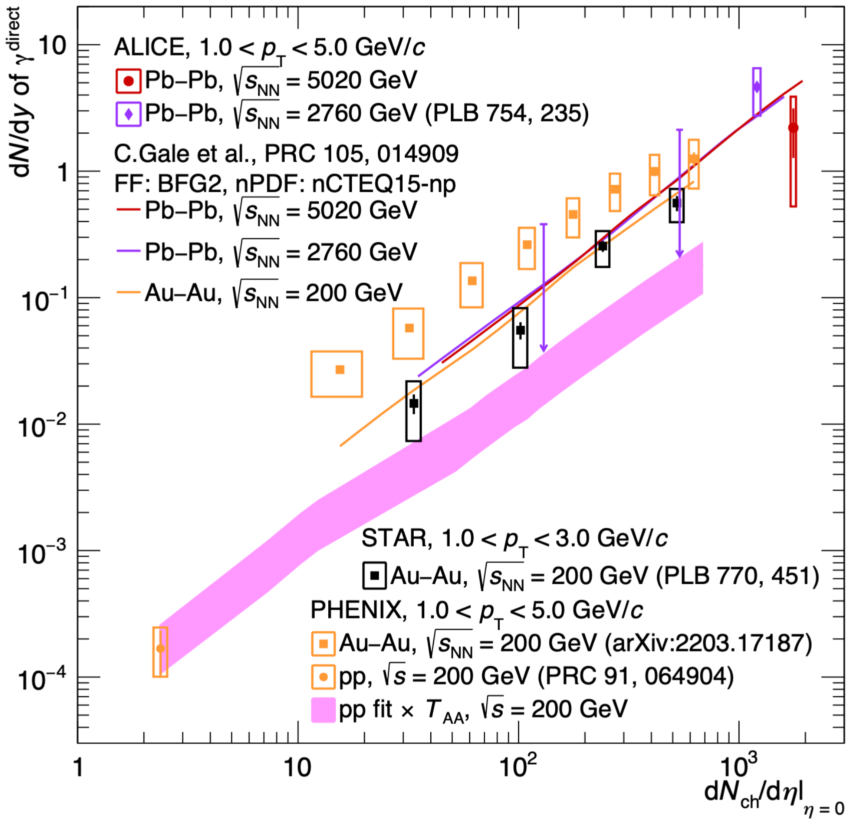


- v_2 of direct photons is comparable to that of π^0 and decay photons
  → direct photons are mostly produced at late stage

Direct Photon Puzzle is Still Unsolved



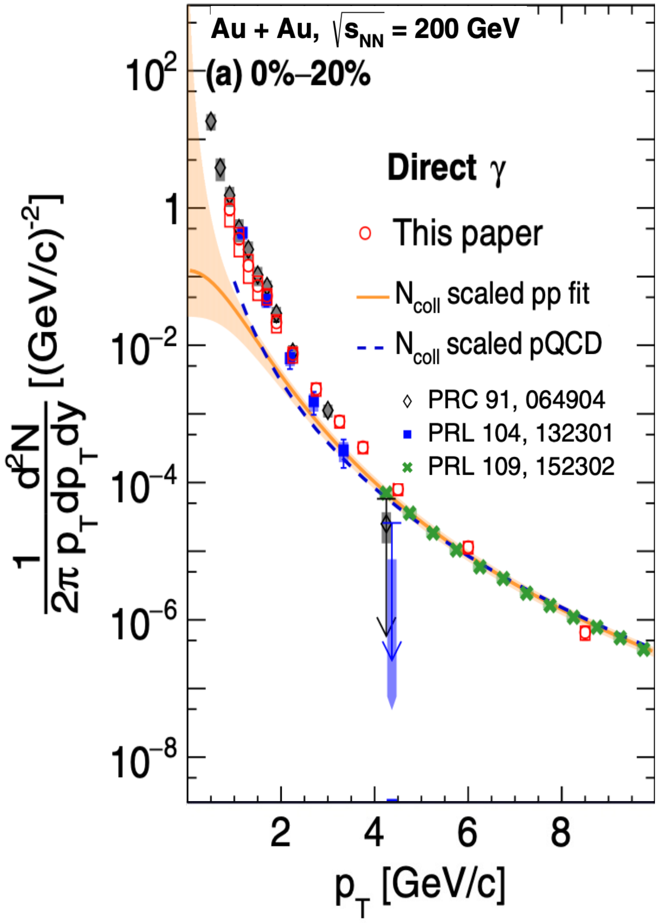
C. Shen, U.W. Heinz, J.F. Paquet, C. Gale: PRC 89 044910 (2014)

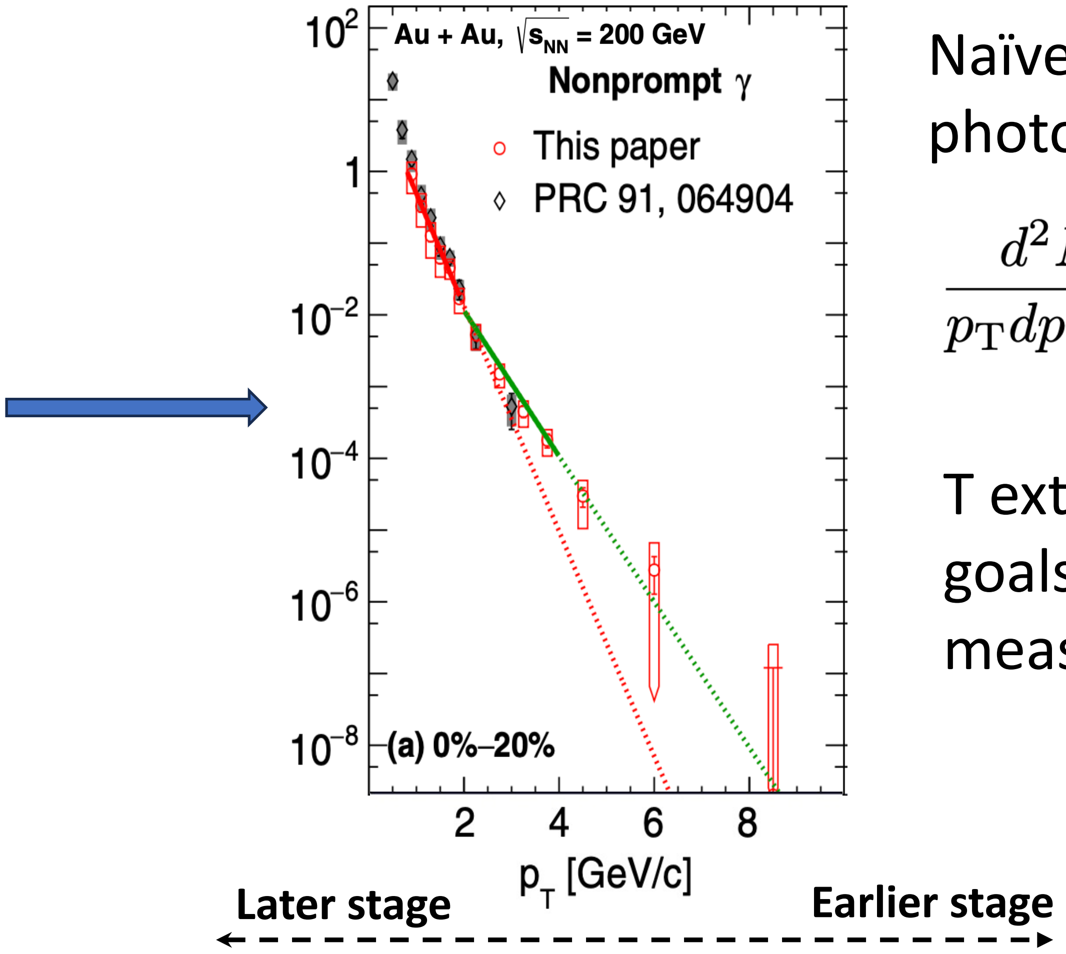


- Observed v_2 and yield from PHENIX cannot be simultaneously decribed by theory, while p_T and size dependent yields from STAR can be well reproduced by theory

Non-Prompt Photons and Effective Temperature

$$\gamma_{\mathrm{non-prompt}} = \gamma_{\mathrm{dir}} - \gamma_{\mathrm{prompt}}^{\mathrm{estimated}}$$





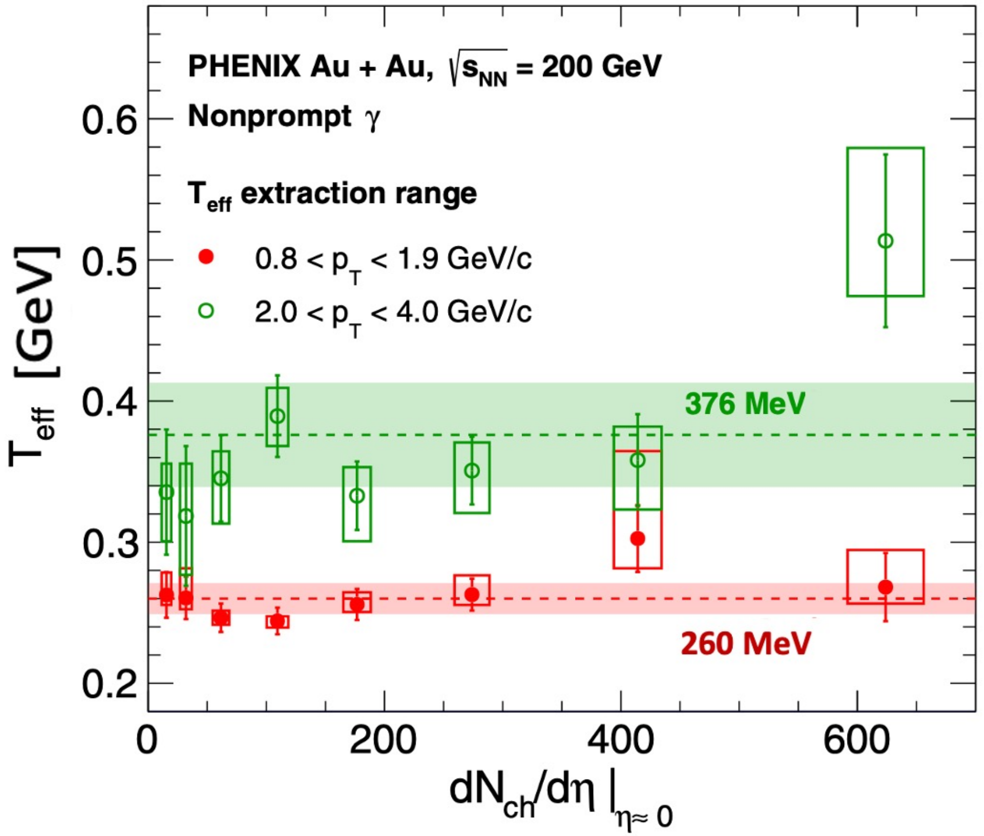
Naïve expectation on thermal photons:

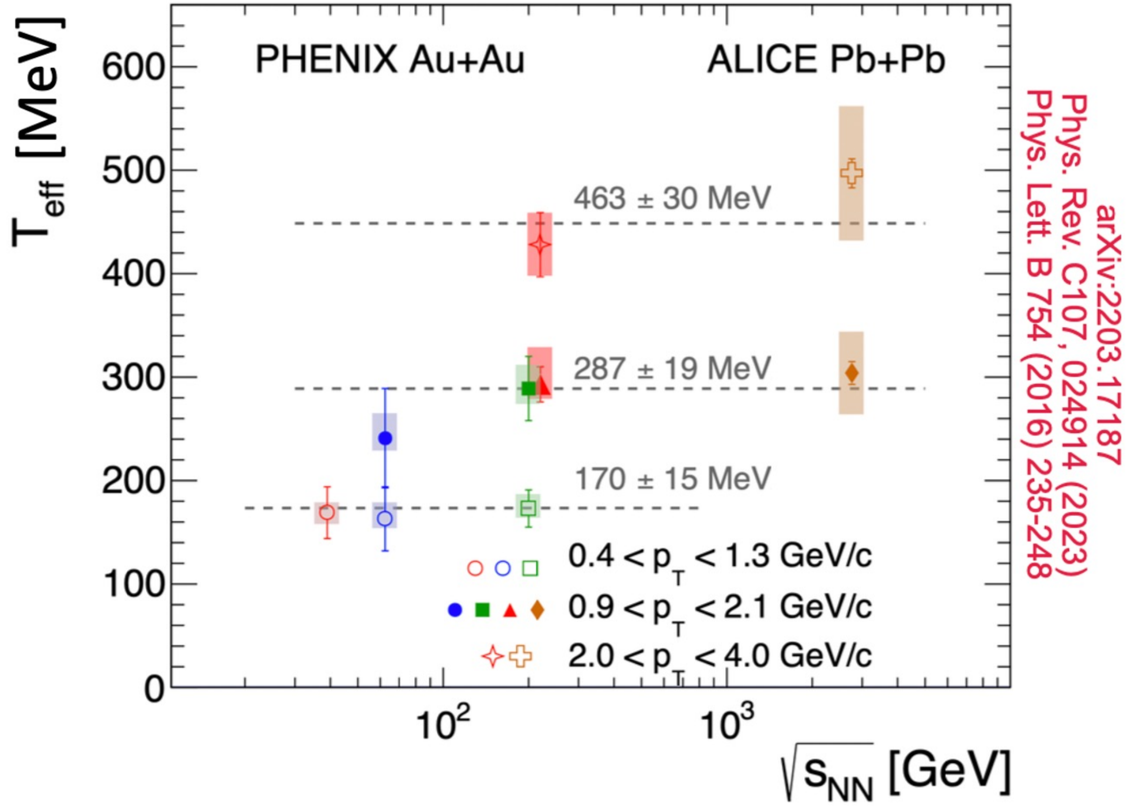
$$\frac{d^2N}{p_T dp_T dy} \sim A \cdot \exp(-p_T/T_{\mathrm{eff}})$$

T extraction was one of the key goals for thermal photon measurements

- Effective temperature can be extracted as the inverse slope of p_T spectra

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)

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

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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.

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