Thermal Dileptons as a Probe of Extreme QCD Matter Created in Heavy-Ion Collisions

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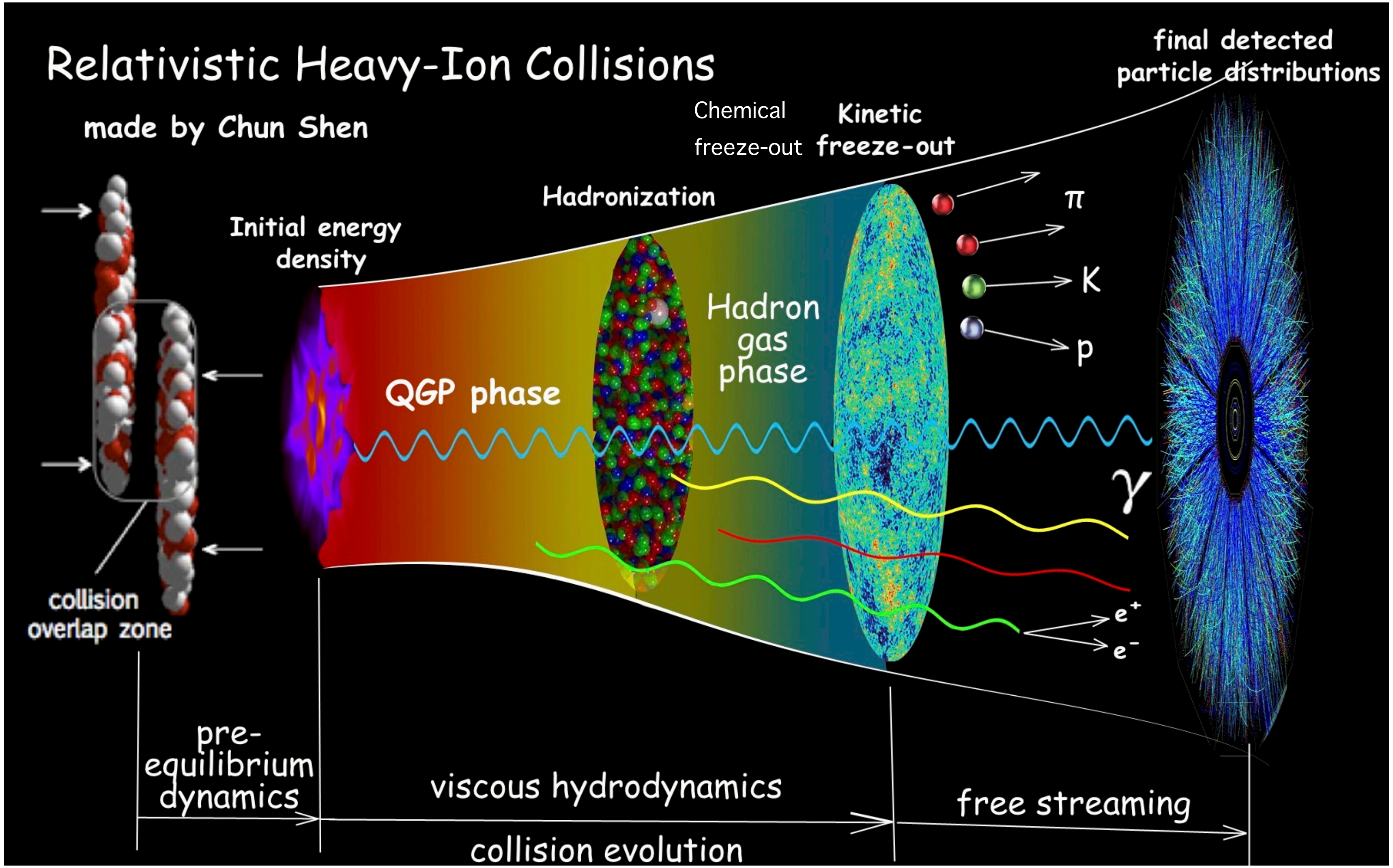
RICE

Outlines

- Why dileptons
- How to measure thermal dileptons
- Recent progresses
- Future experiments
- Summary and discussions

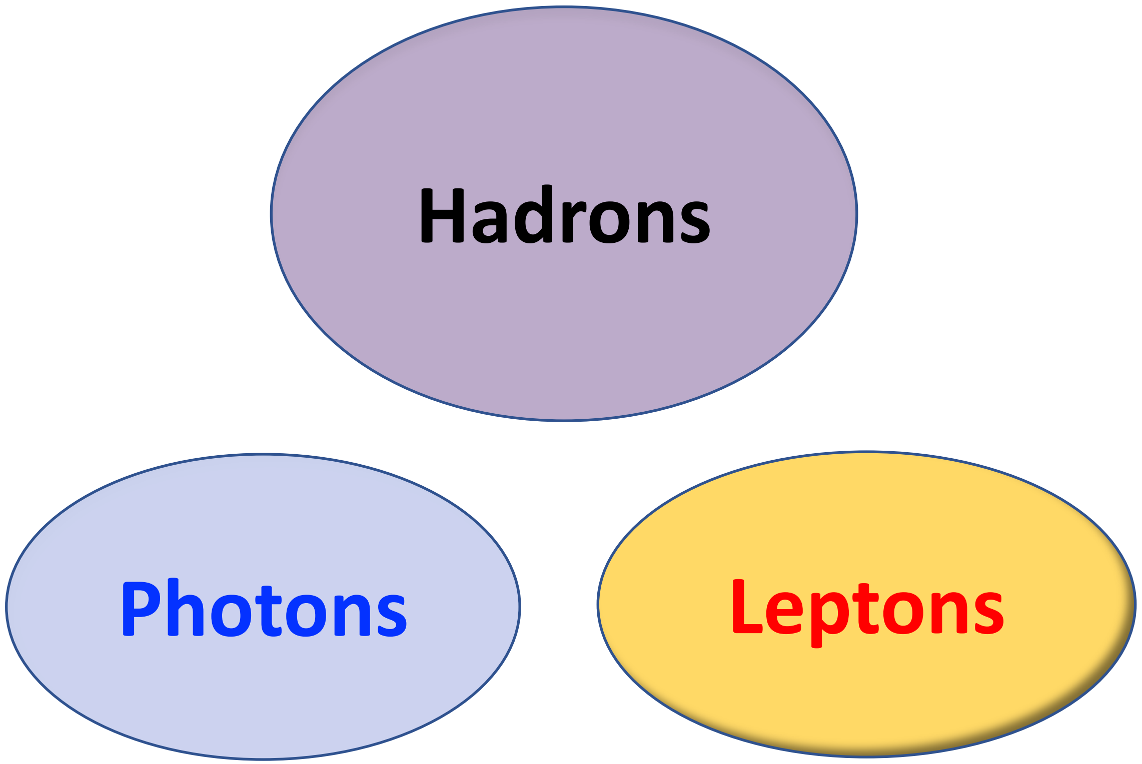
A “Little Bang” in Heavy-Ion Collision



Heavy-**I**on collisions as a lab to mimic the universe at t ~ 10^{-6} s

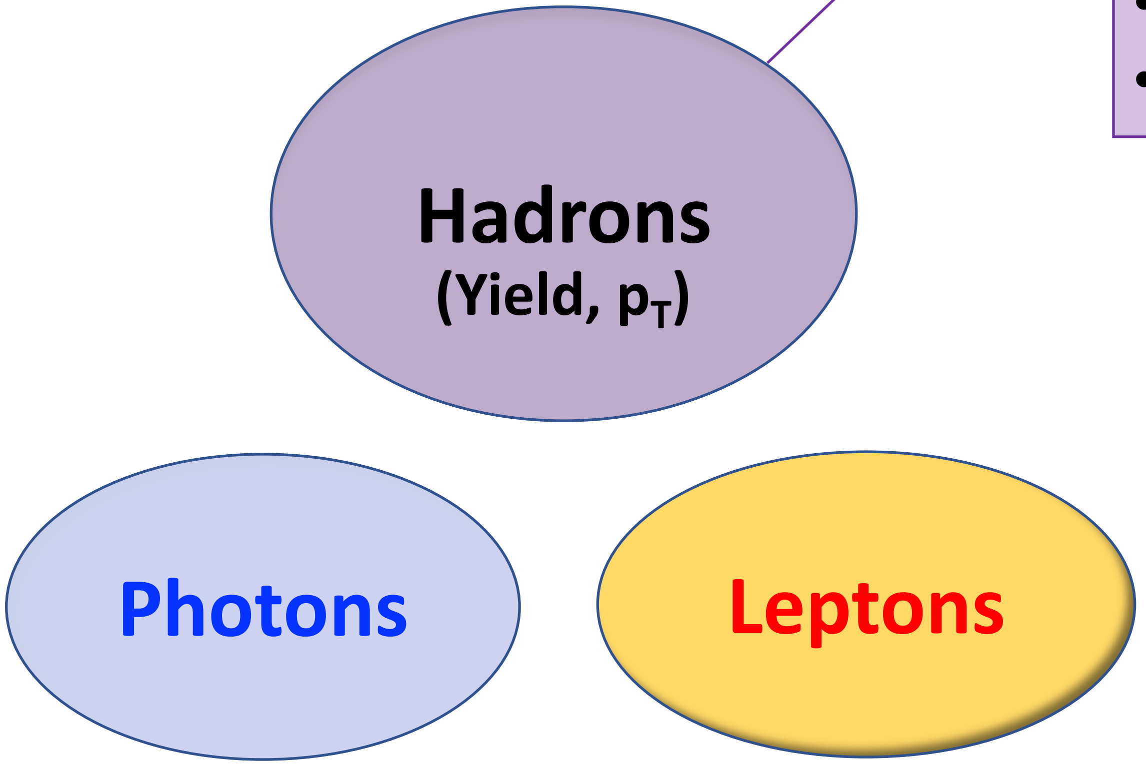
Study **early-stage evolution** from **final** detected particles

Why Dileptons?



Why Dileptons?

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



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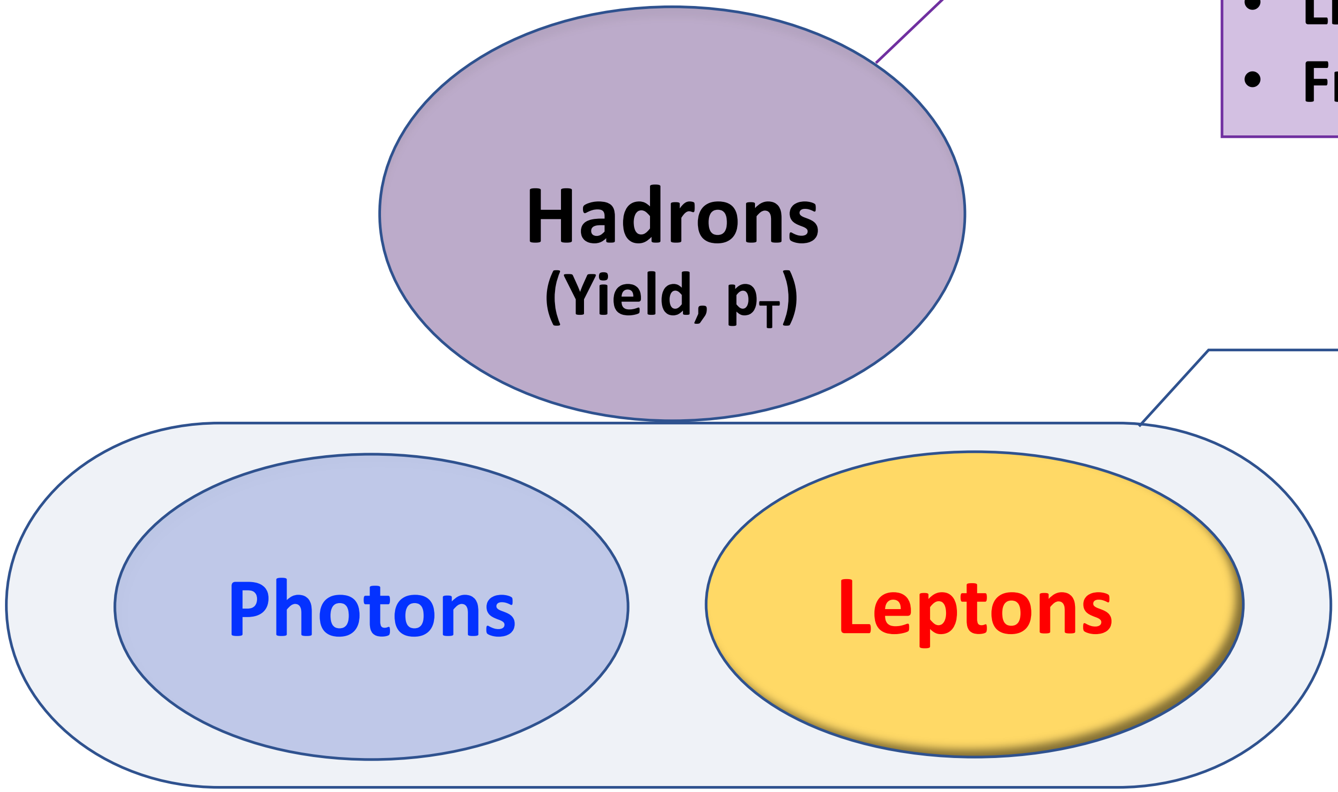

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EM Probes

- Emitted from early to final stages
- Escape freely after emission
- Probe earlier and hotter phases of medium

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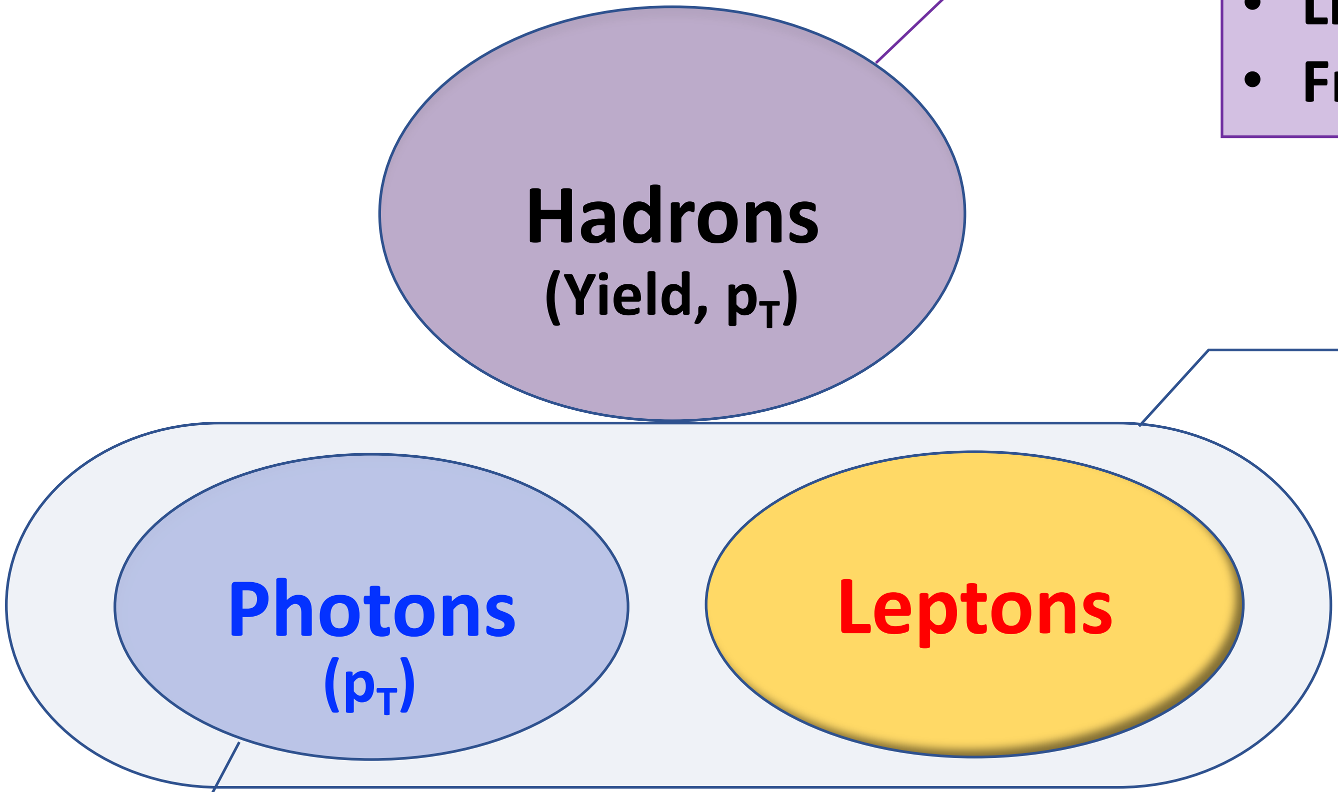

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T_{eff}, WARNING: blue-shift effects

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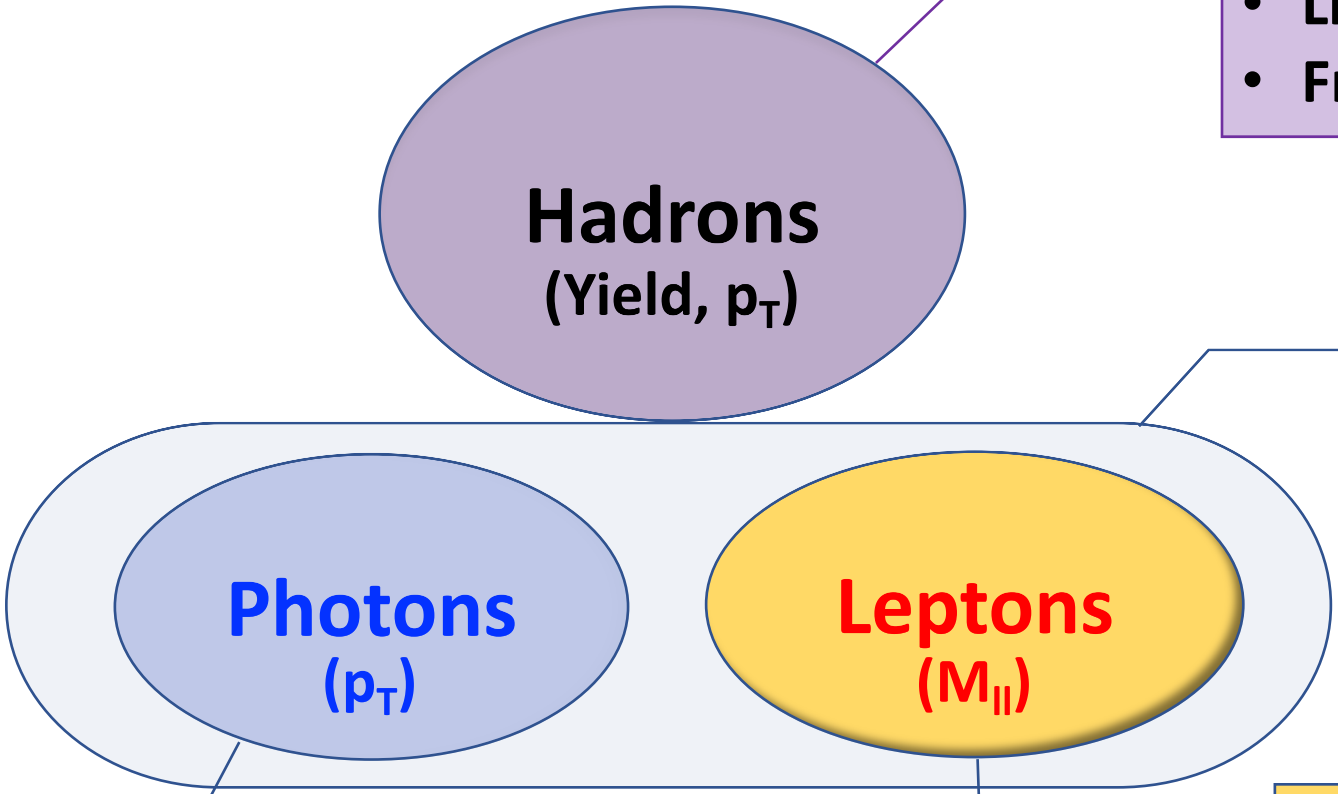

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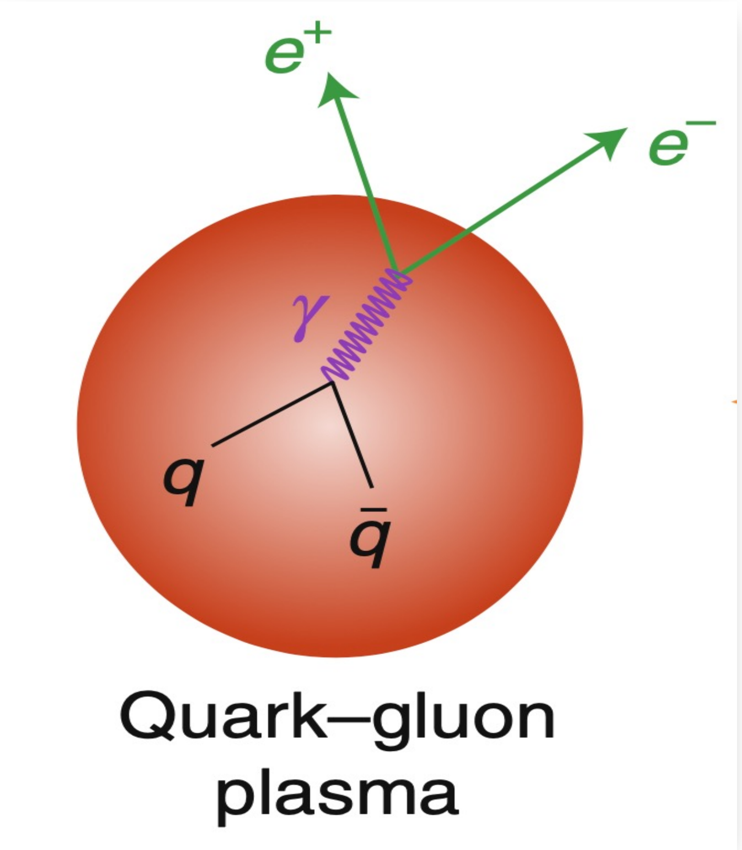
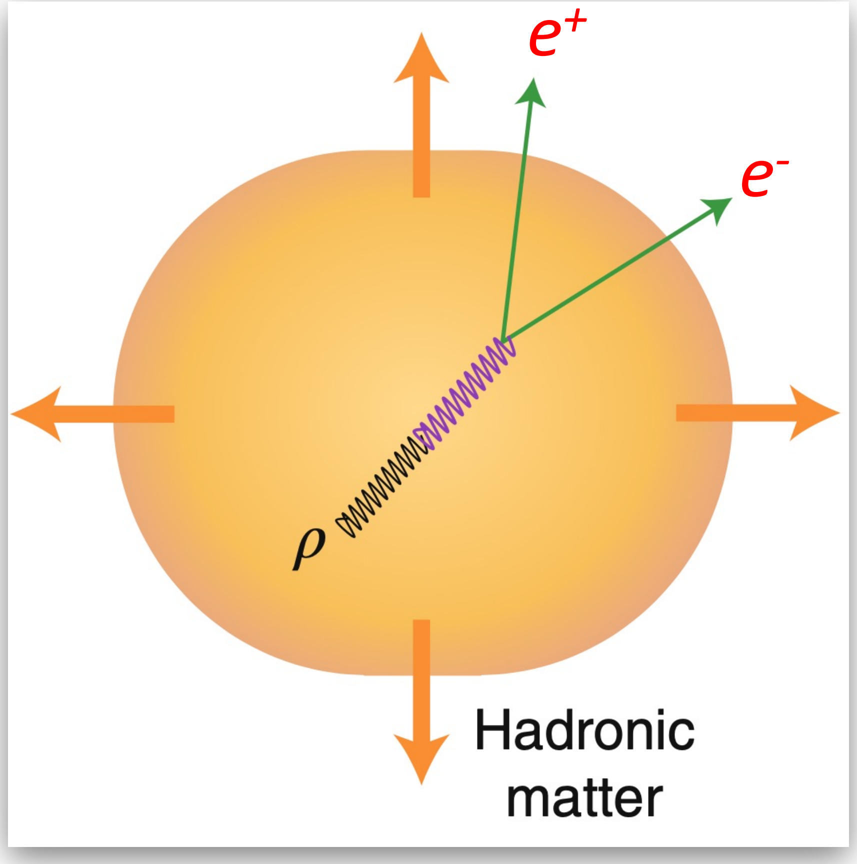
T_{eff}, WARNING: blue-shift effects

Dileptons

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

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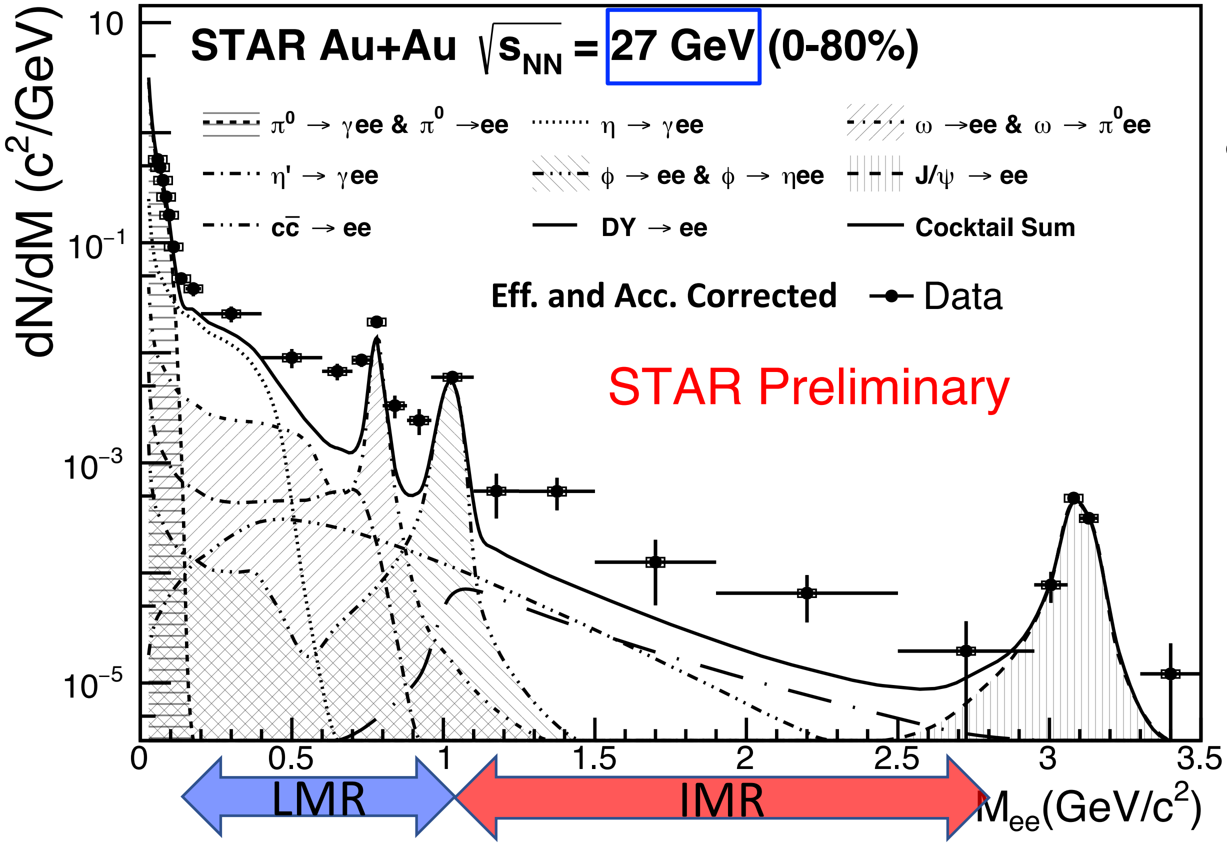
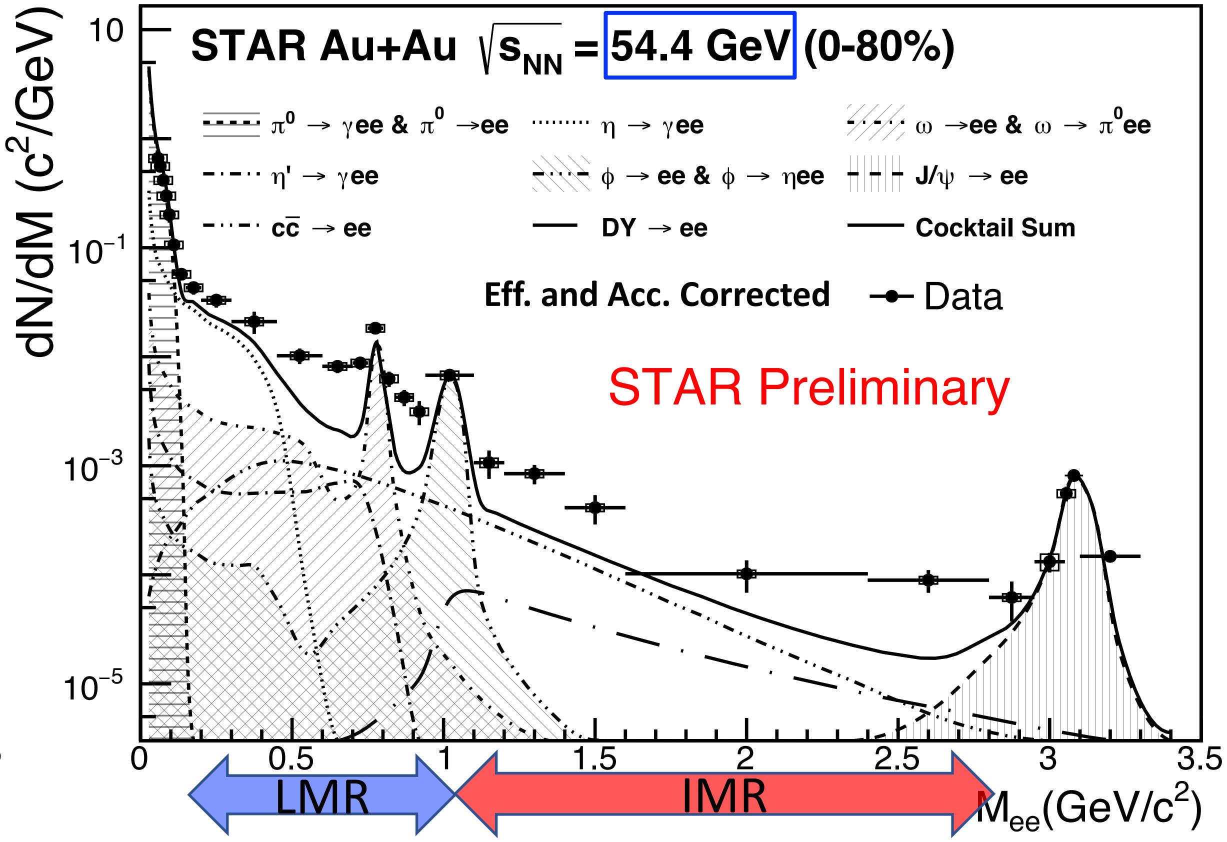
Physical background can be determined using the well-established cocktail simulation techniques

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

Examples of Data vs. Cocktail

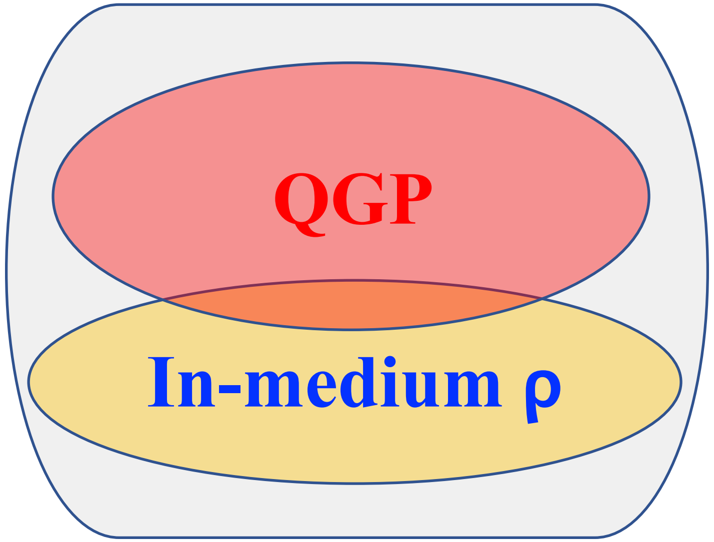




Clear enhancement compared to cocktail contributions in both low mass region (**LMR**) and intermediate mass region (**IMR**)

Dileptons as a Thermometer of Hot Medium

Emission source



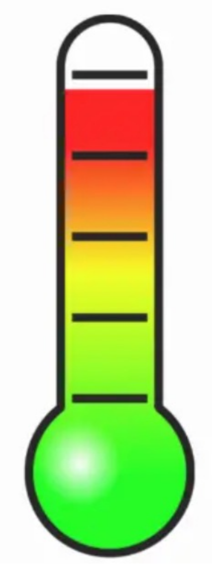
Mass analyzer

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

In-med. ρ: Breit-Wigner * $e^{-M/T}$

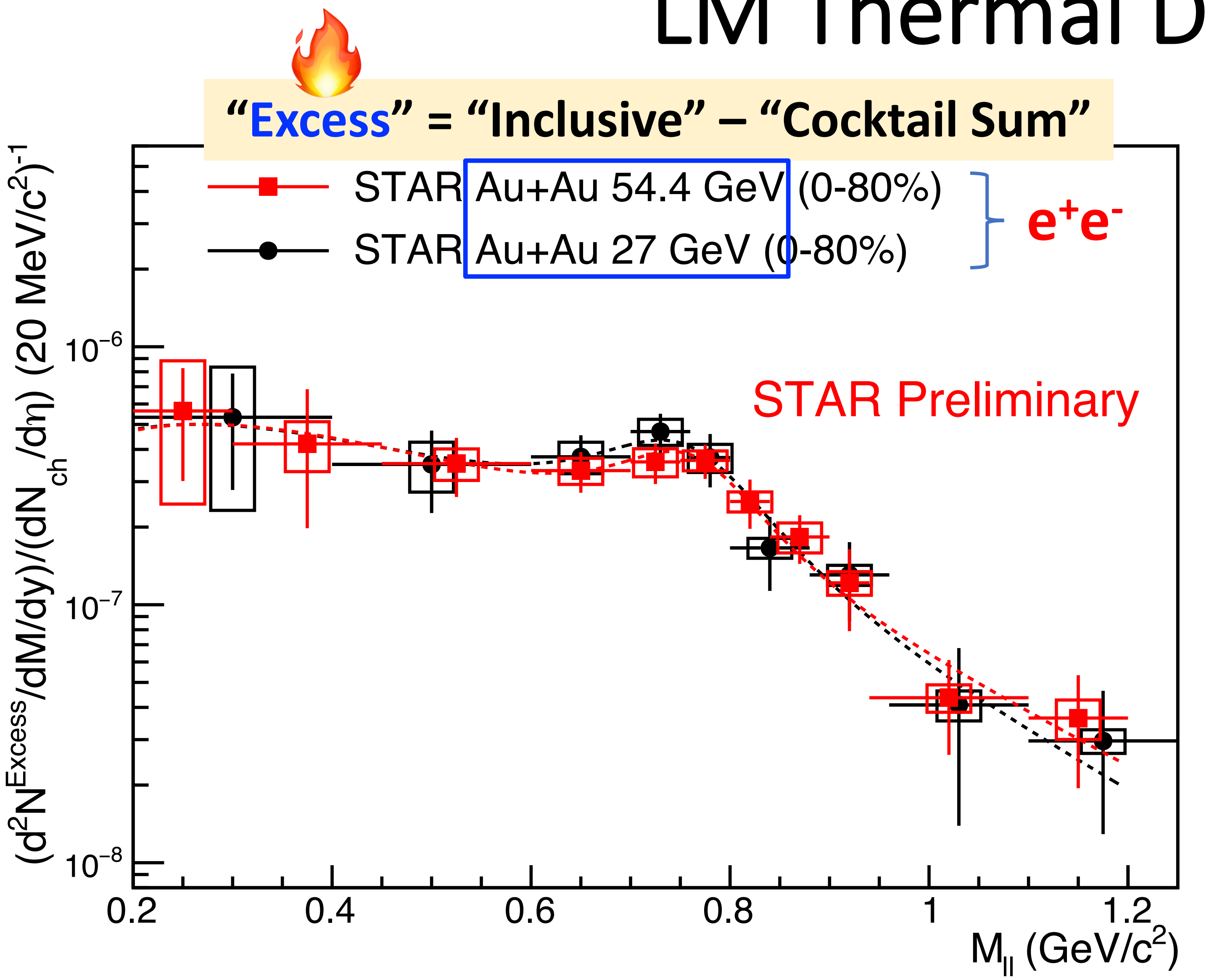
Rapp and v. Hess, PLB 753 (2016) 586
Shuryak and Brown, NPA 717, 322 (2003)
STAR, PRL 92, 092301 (2004)

Thermometer



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

LM Thermal Dilepton



In-medium ρ dominated

Similar mass spectrum

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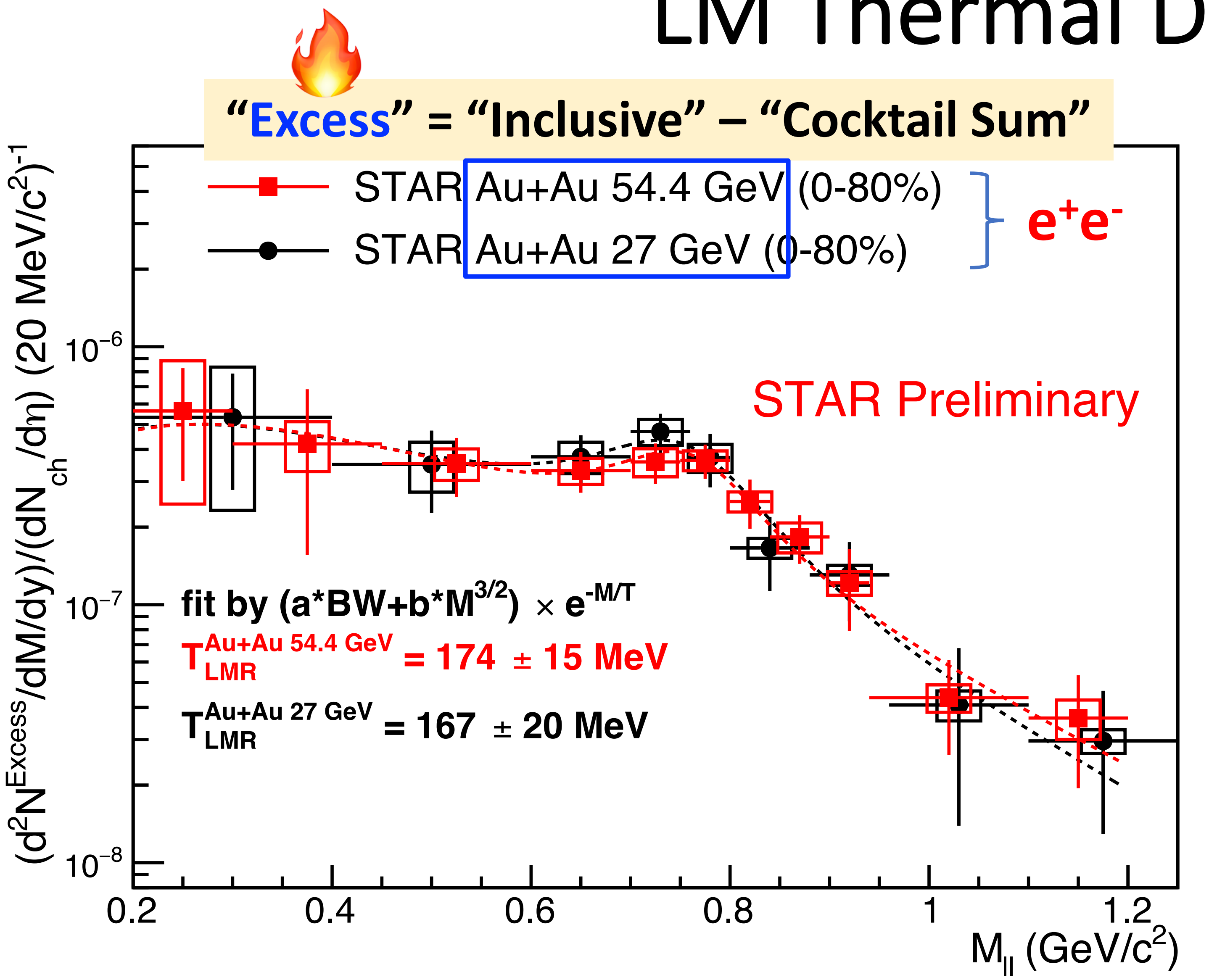

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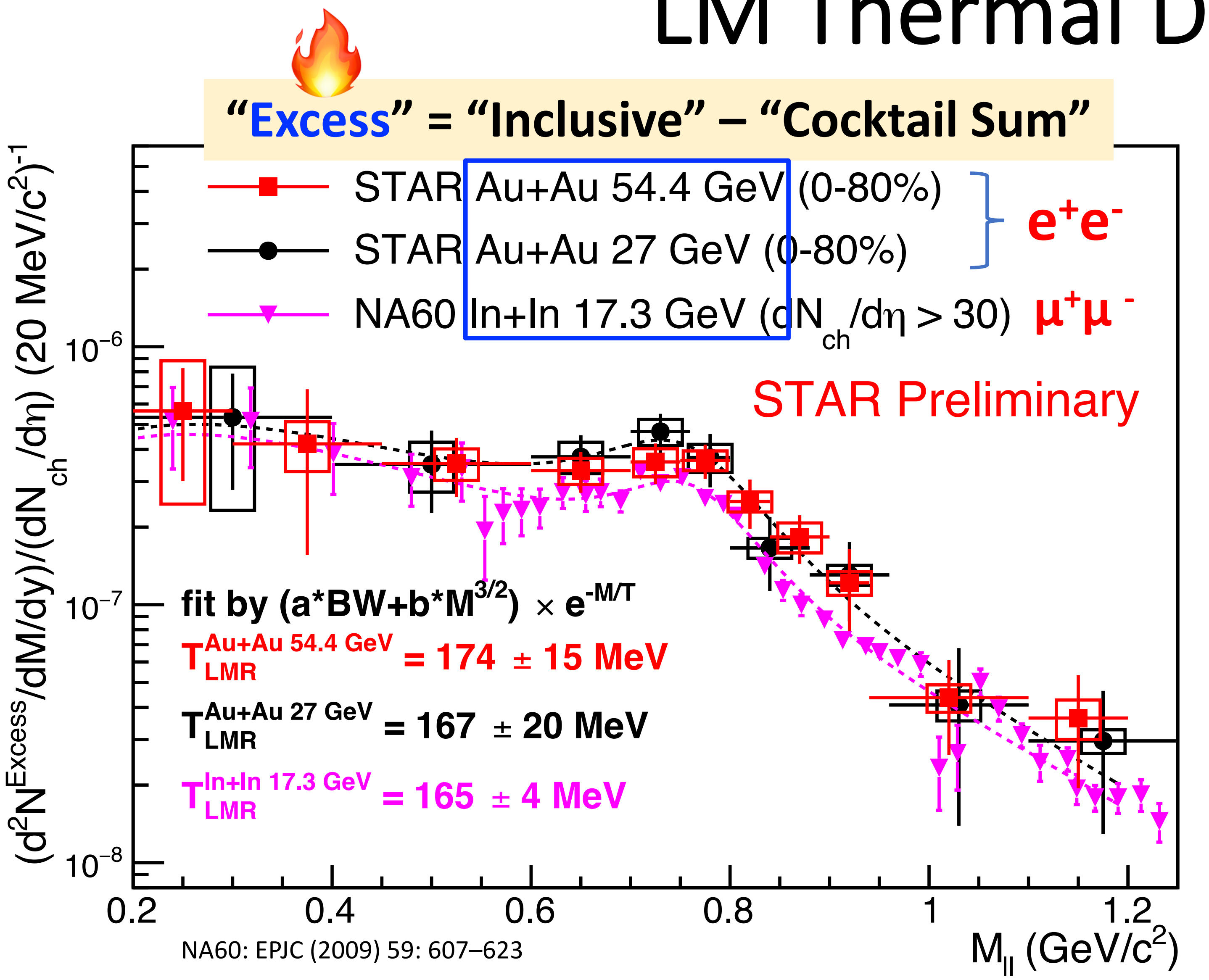

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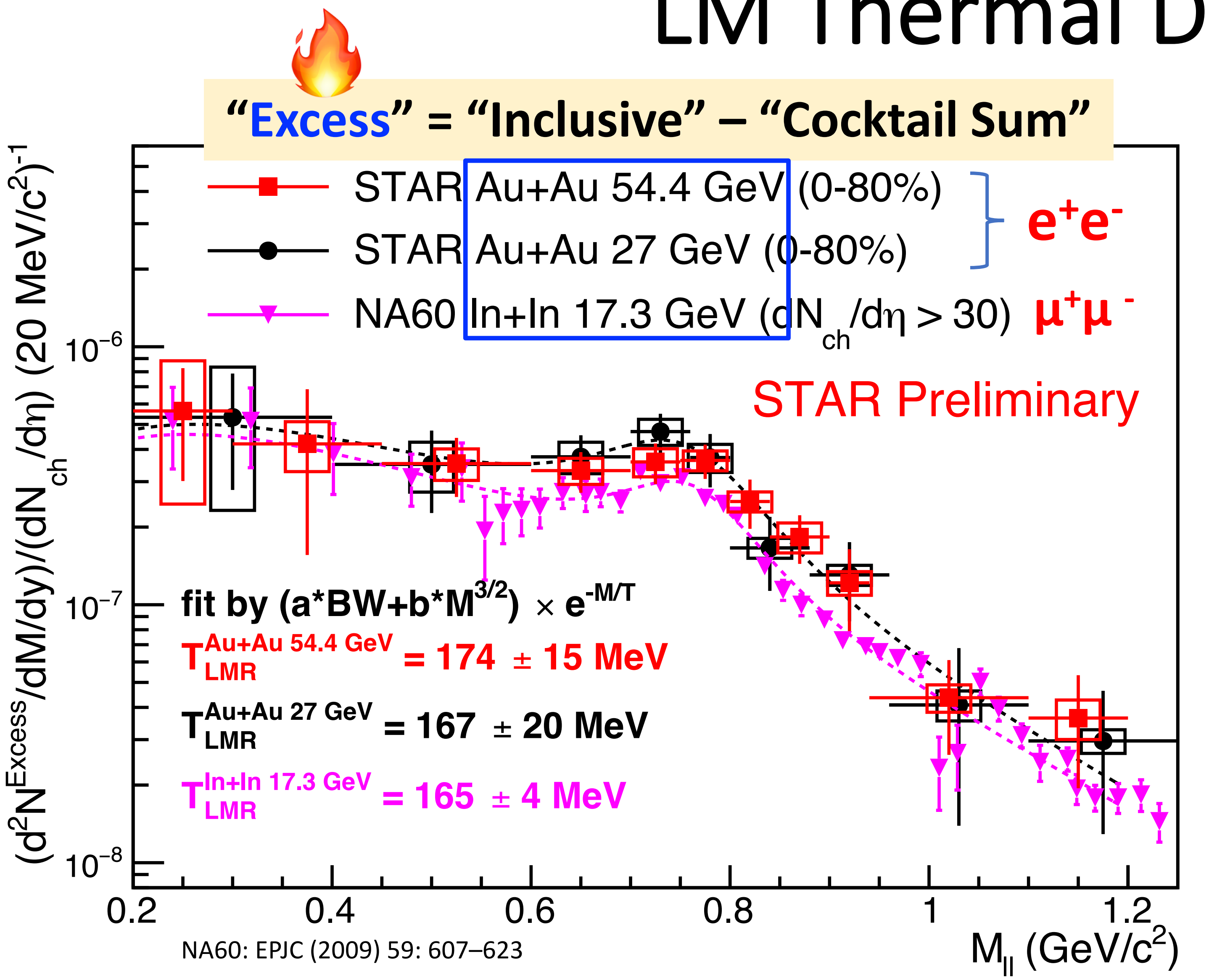
“**Excess**” = “Inclusive” – “Cocktail Sum”



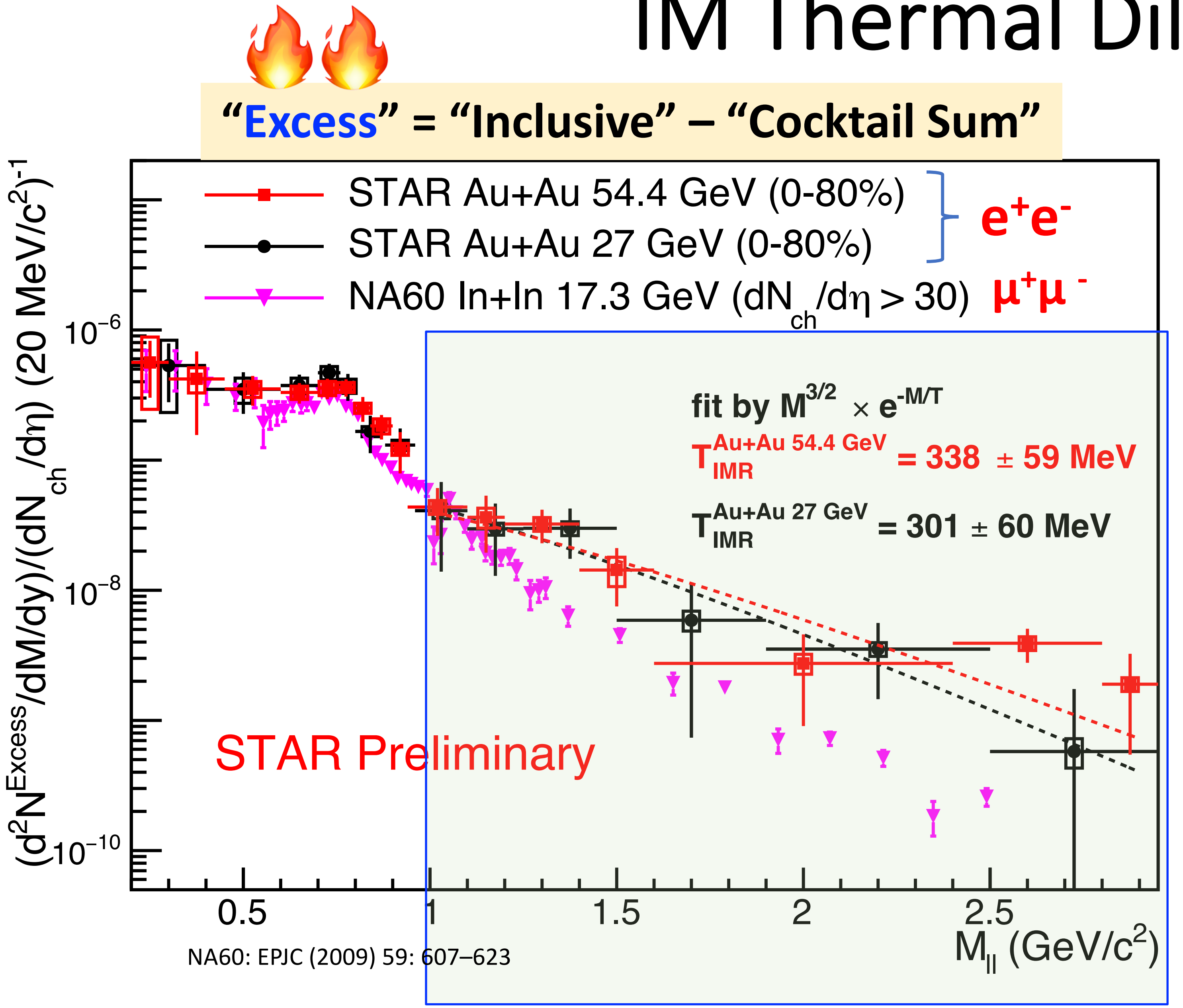
In-medium ρ dominated

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



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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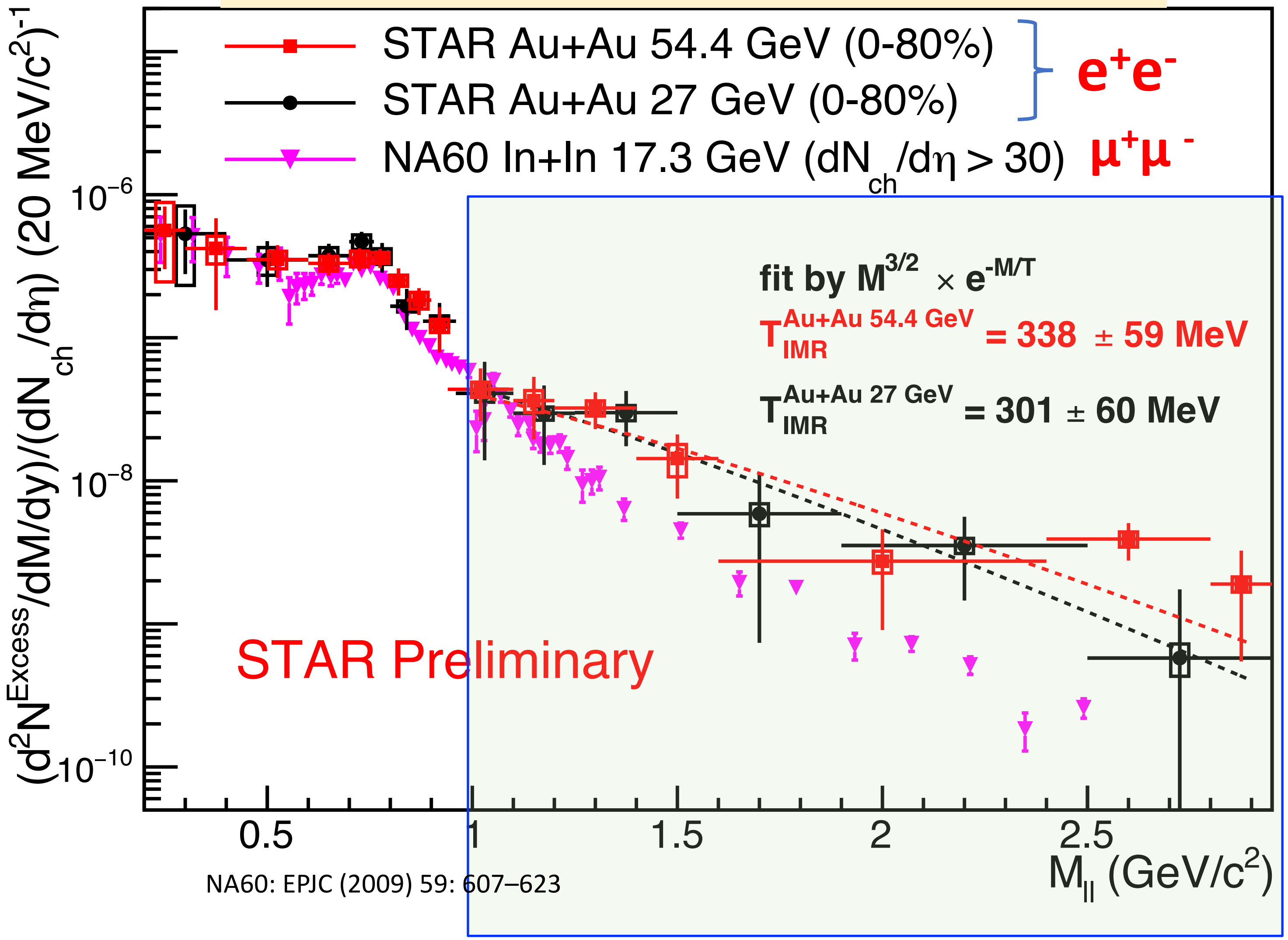

NA60: EPJC (2009) 59: 607–623

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

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LM+IM Thermal Dilepton

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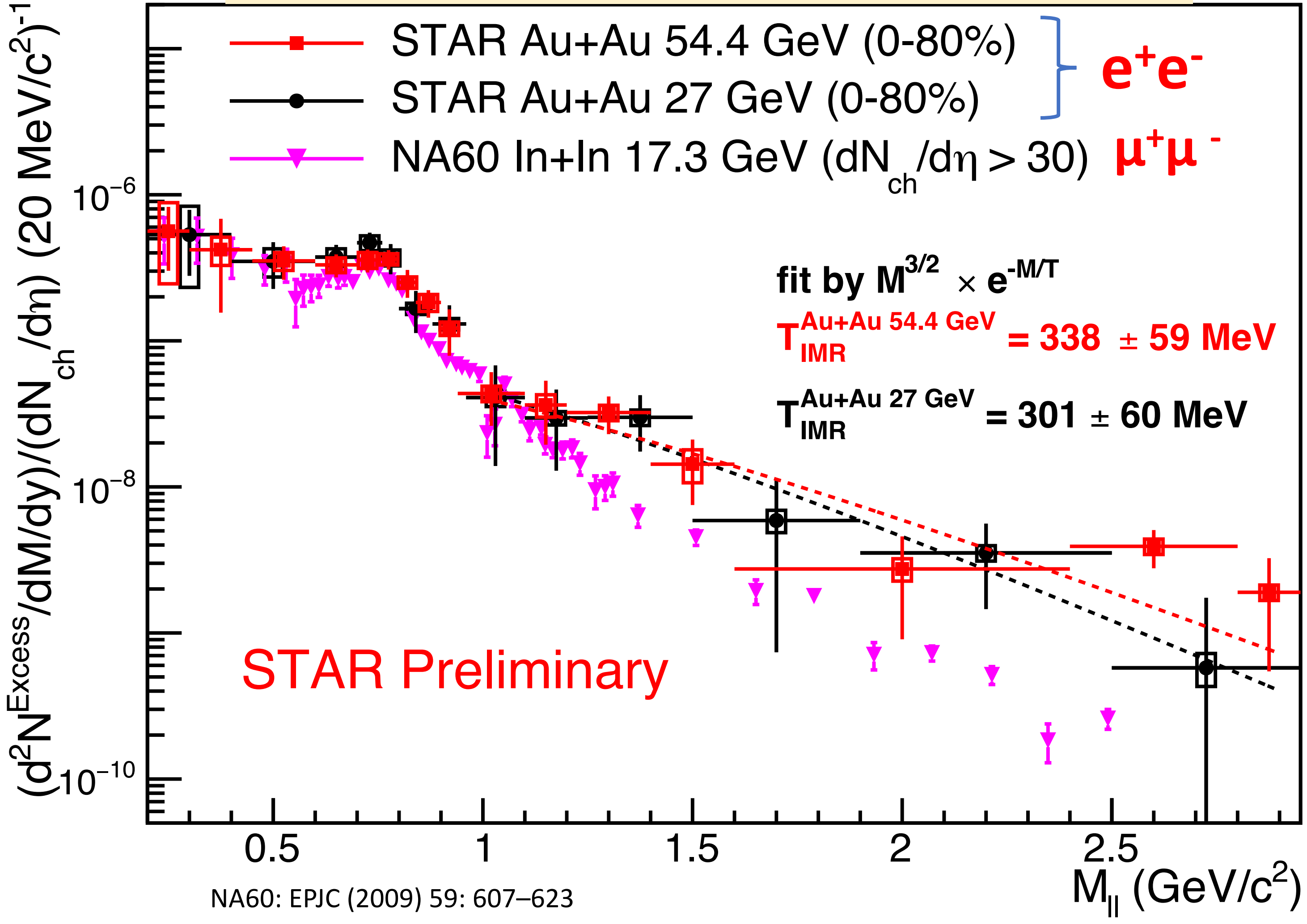

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STAR data is **higher** than NA60 data, due to longer **medium lifetime**?

[1]: Hans J. Specht, AIP Conf. Prcd 1322, 1 (2010)
[2]: Private comm. with Berndt Muller

Thermal Dilepton ⊕ Medium Flow

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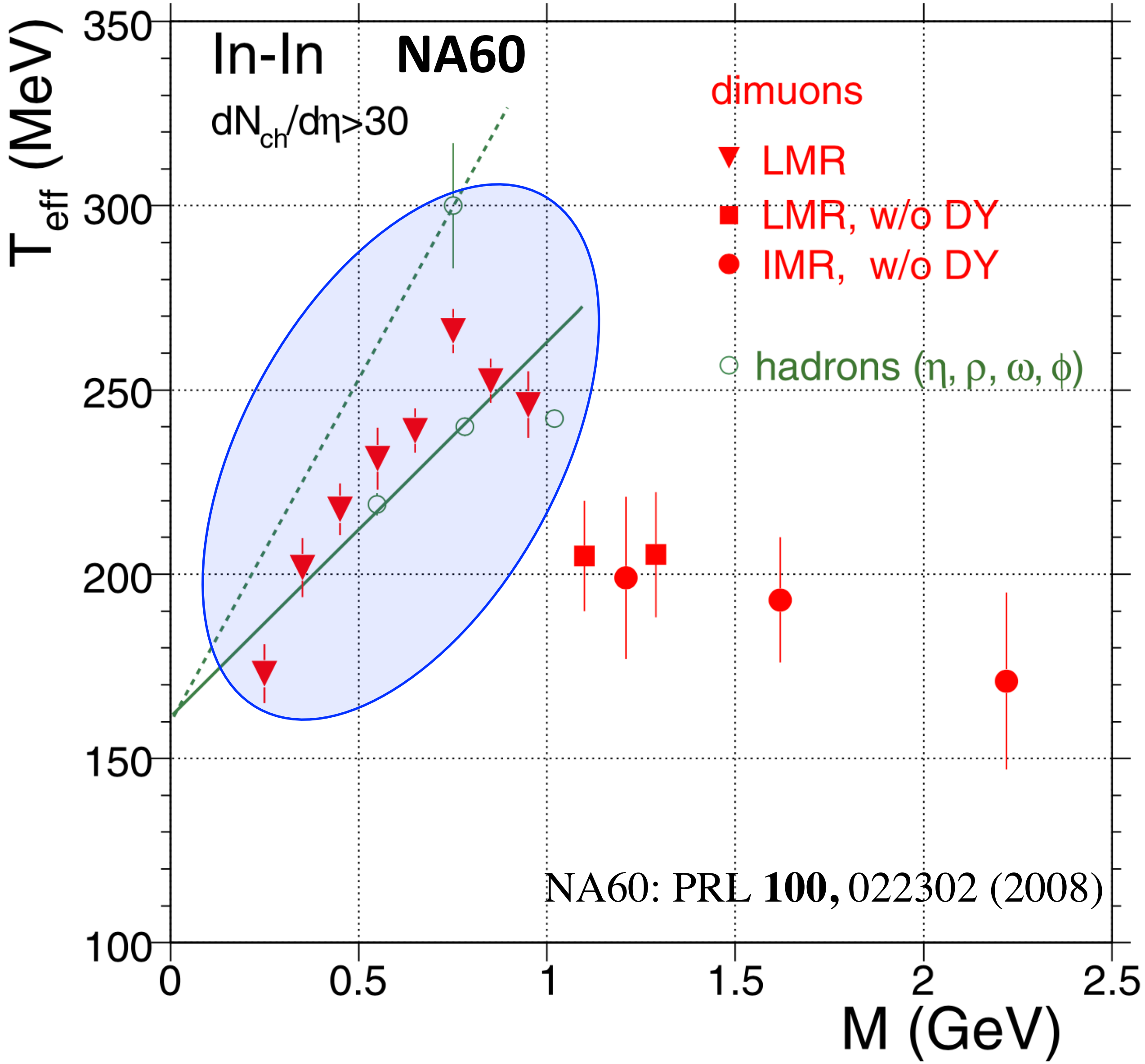
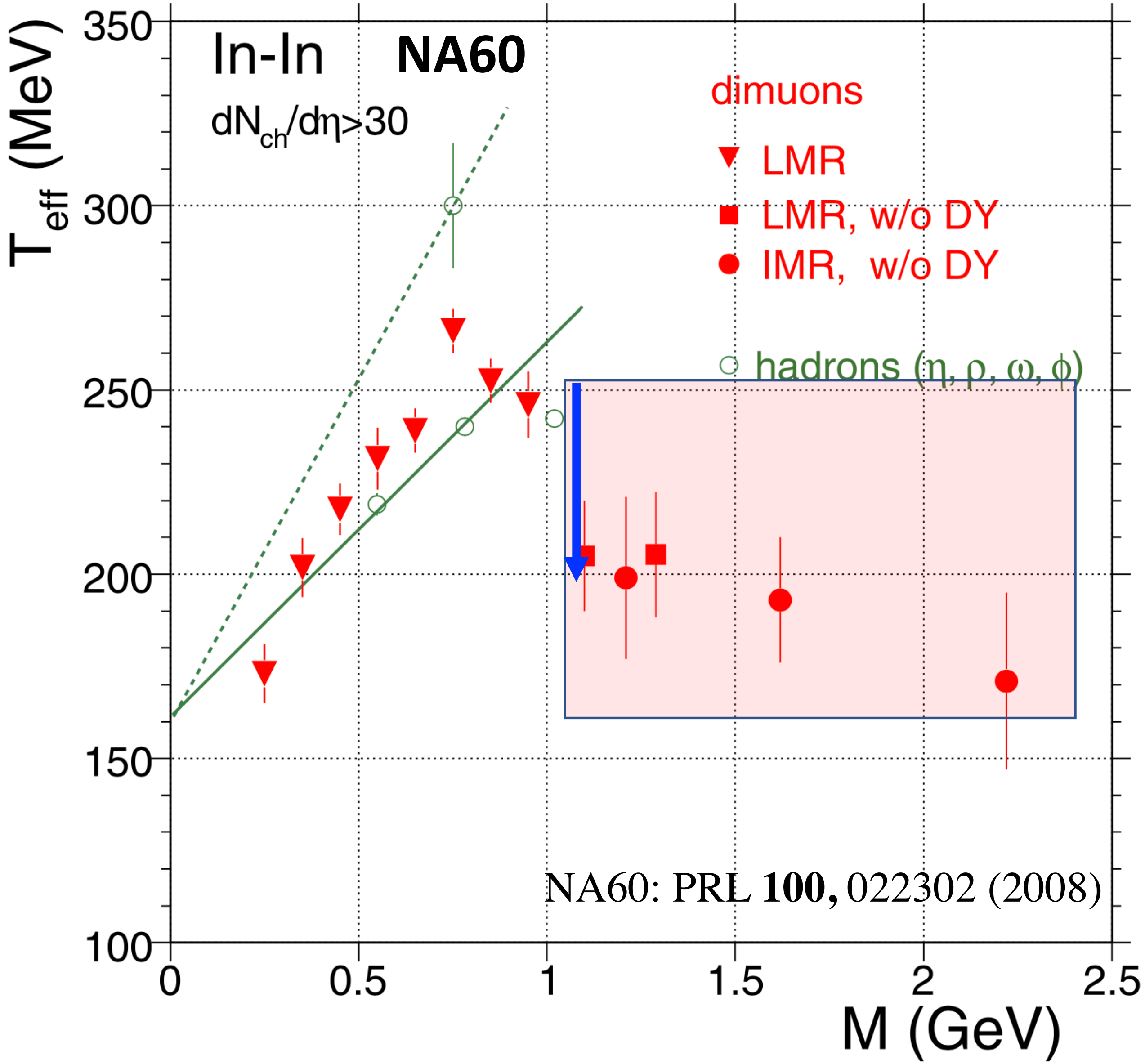


$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \exp(-\frac{m_T}{T_{eff}})$$

$M < 1\ GeV/c^2$:

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

Thermal Dilepton ⊕ Medium Flow



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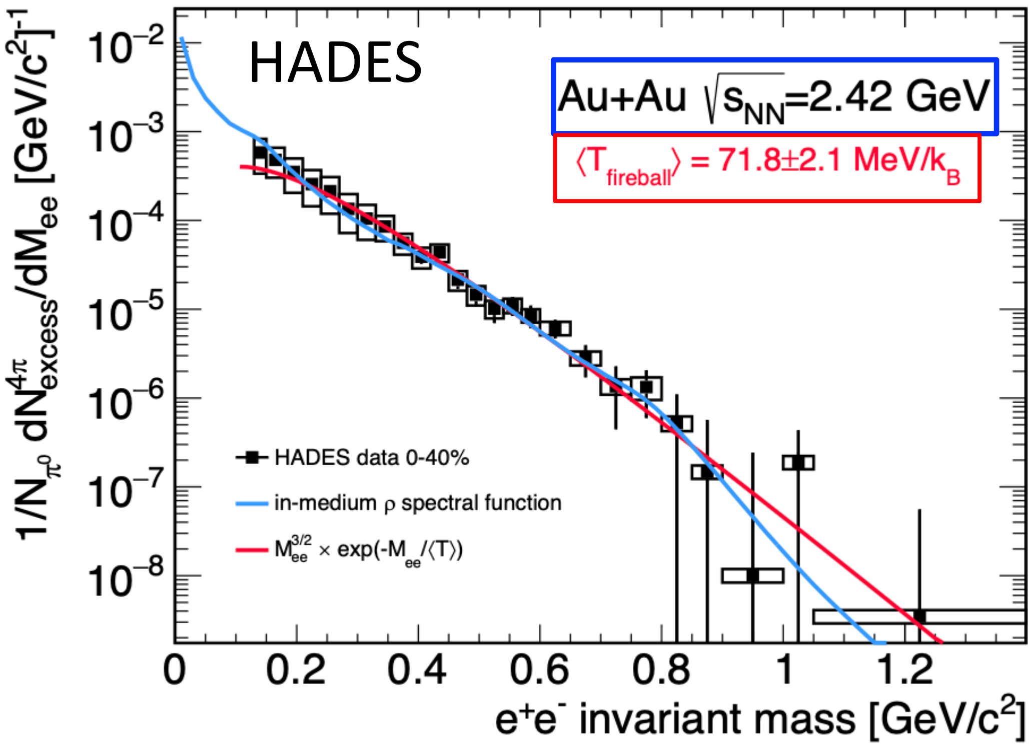
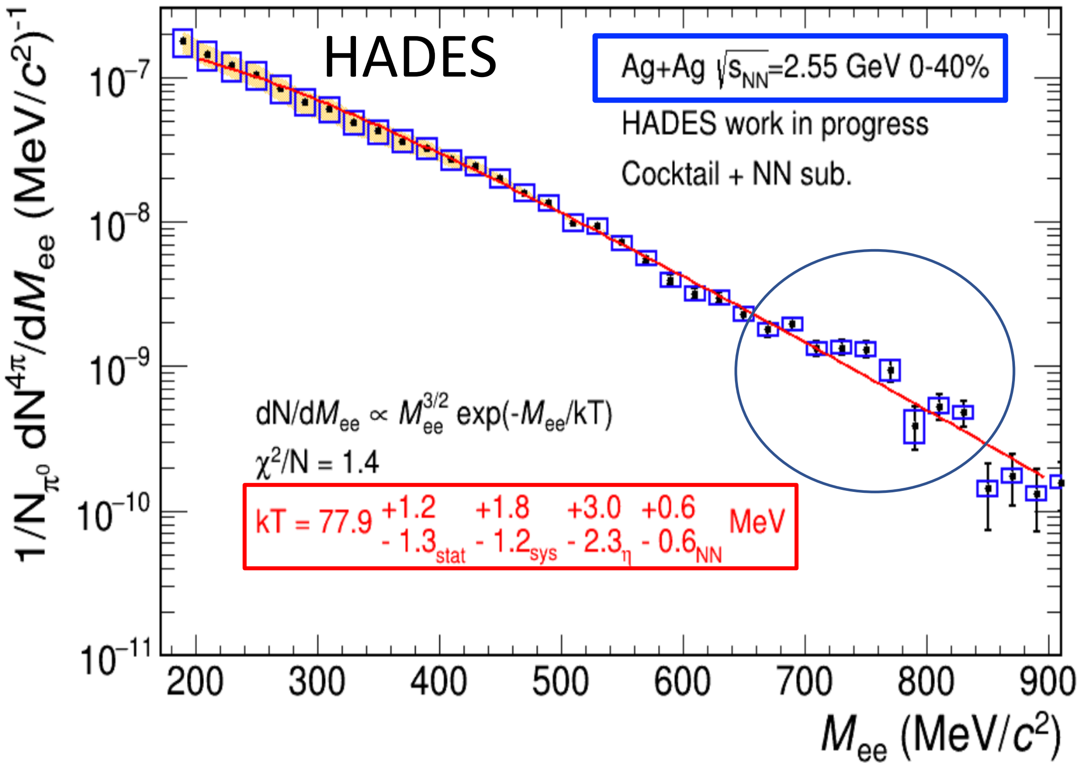
M > 1 GeV/c²:

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

LM Thermal Dilepton at Low Energy Collisions

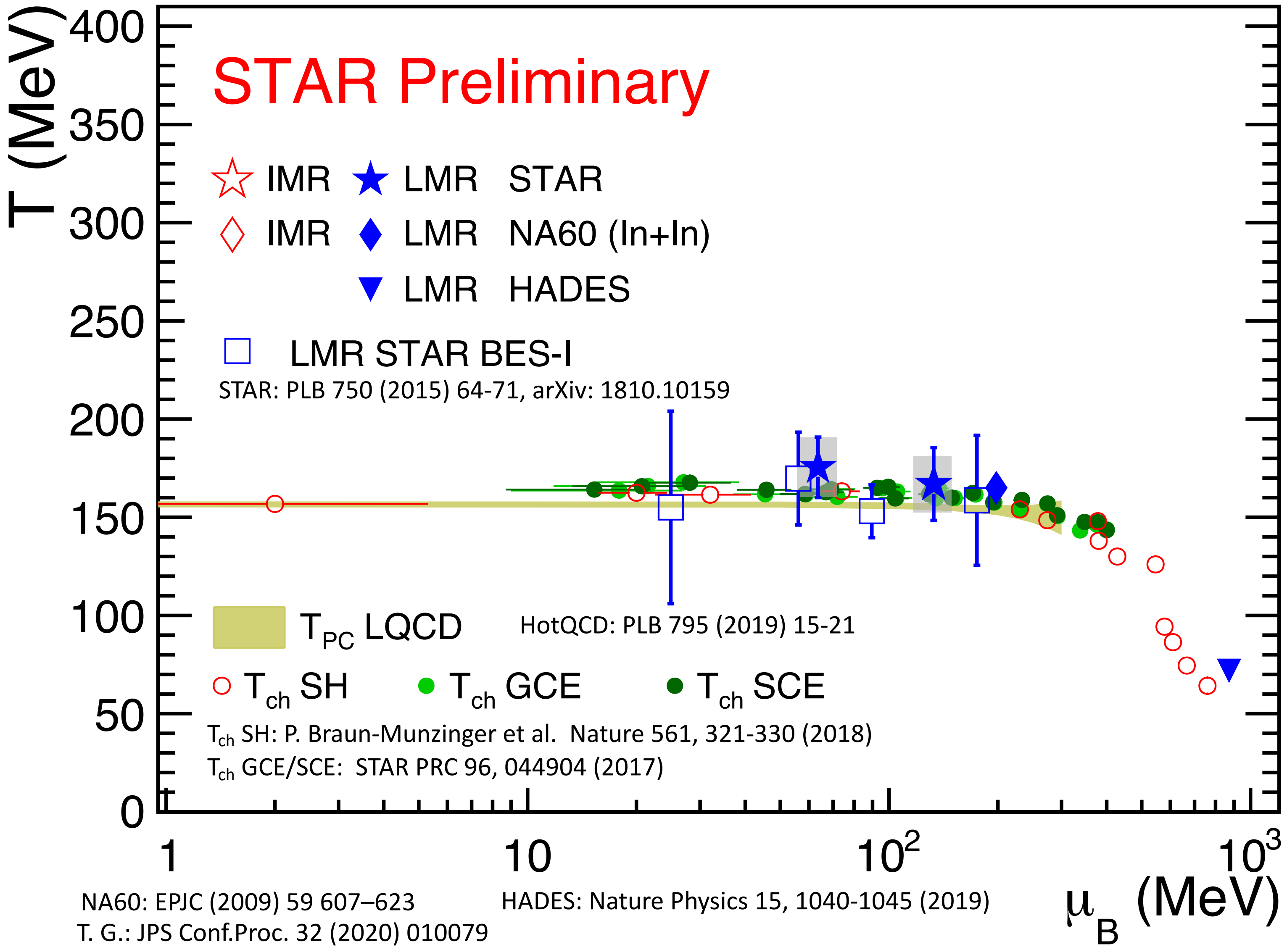
HADES: Nature Physics 15, 1040-1045 (2019)





- 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

Summary of Temperatures



NA60: EPJC (2009) 59 607–623
T. G.: JPS Conf.Proc. 32 (2020) 010079

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Thermal dileptons in LMR

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

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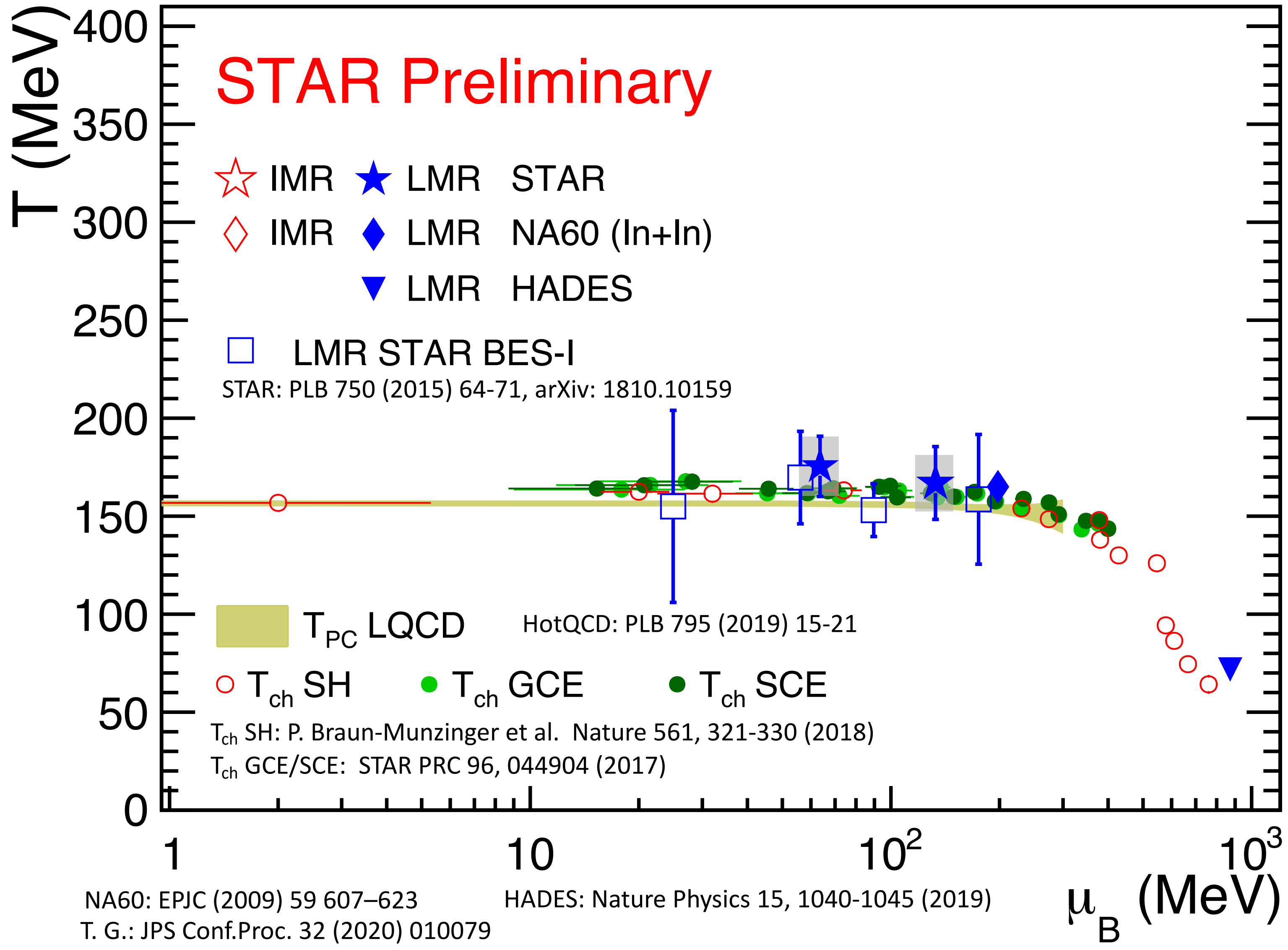

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Thermal dileptons in LMR

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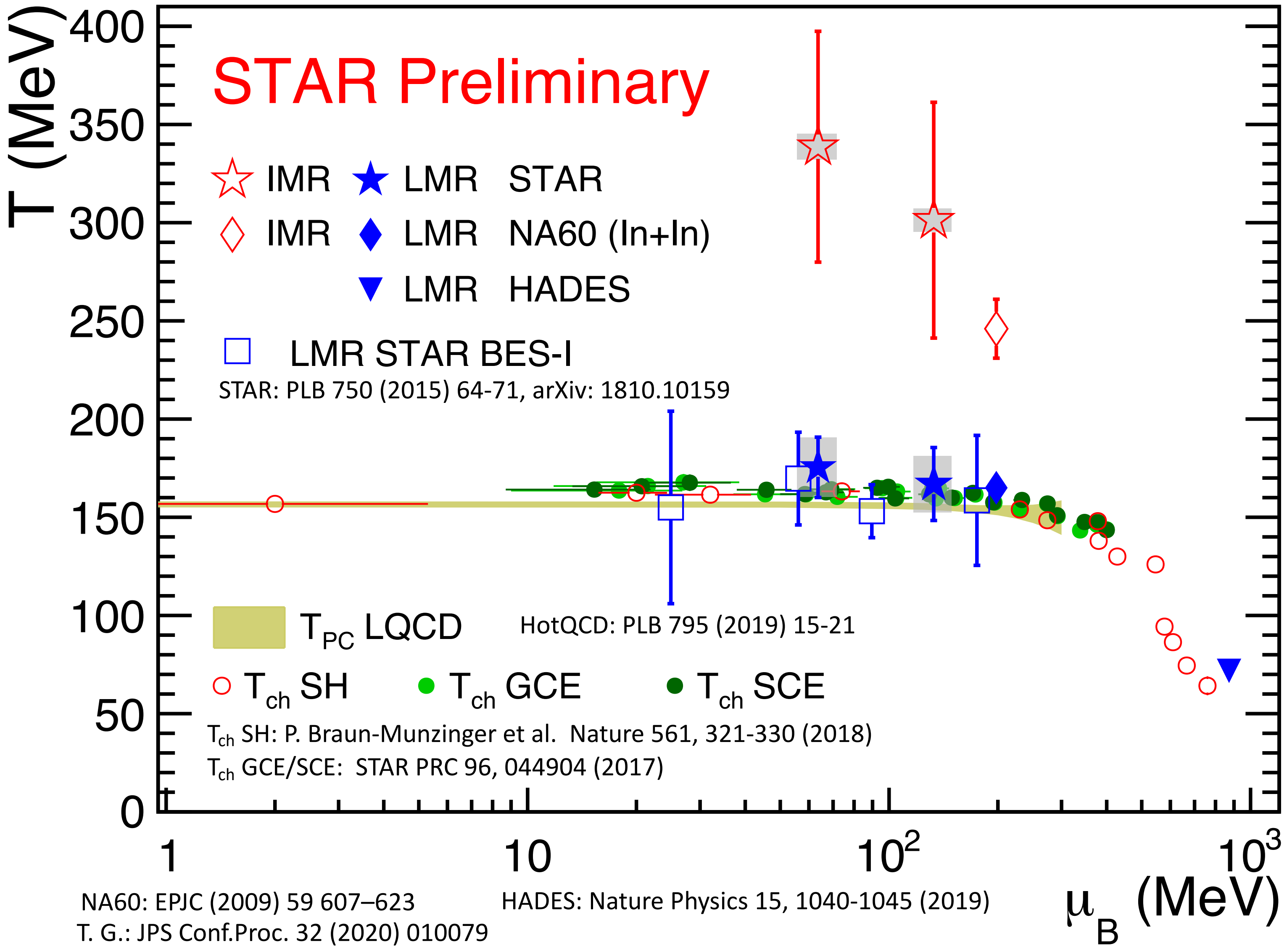

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Thermal dileptons in LMR

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Thermal dileptons in IMR

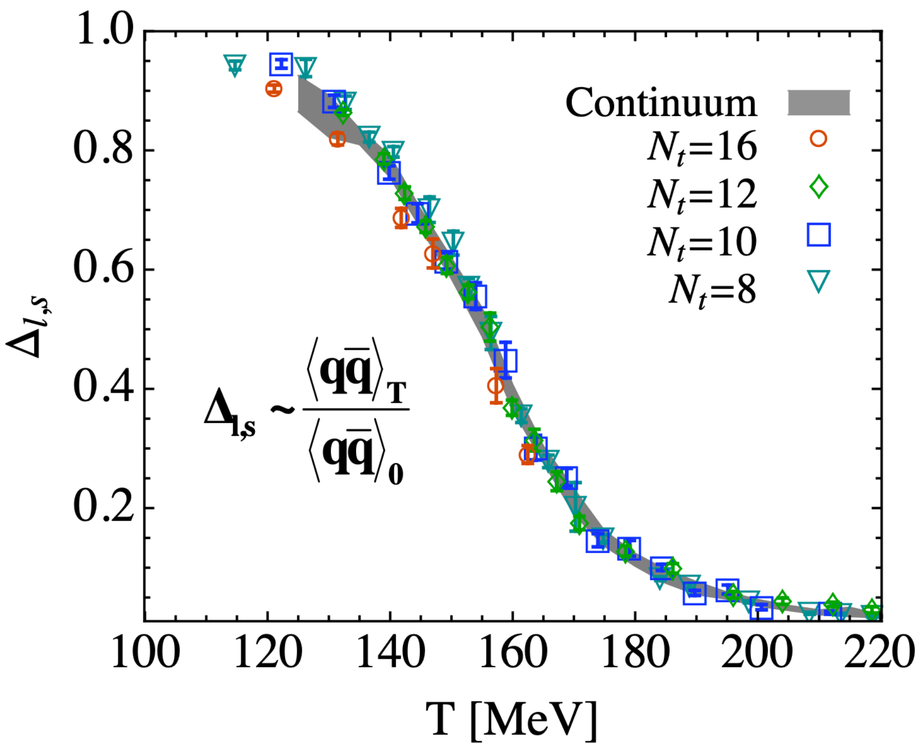
- **T is higher than T_{pc}**
- **Emitted from QGP phase**

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

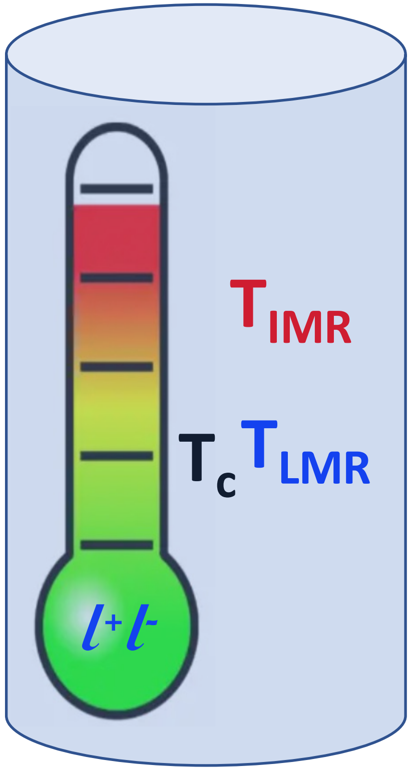
Is Chiral Symmetry Restored?

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 chiral symmetry restoration

Experimental evidence?

Is Chiral Symmetry Restored?

Chiral symmetry restoration → **mass difference disappears** btw. **chiral partners**

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

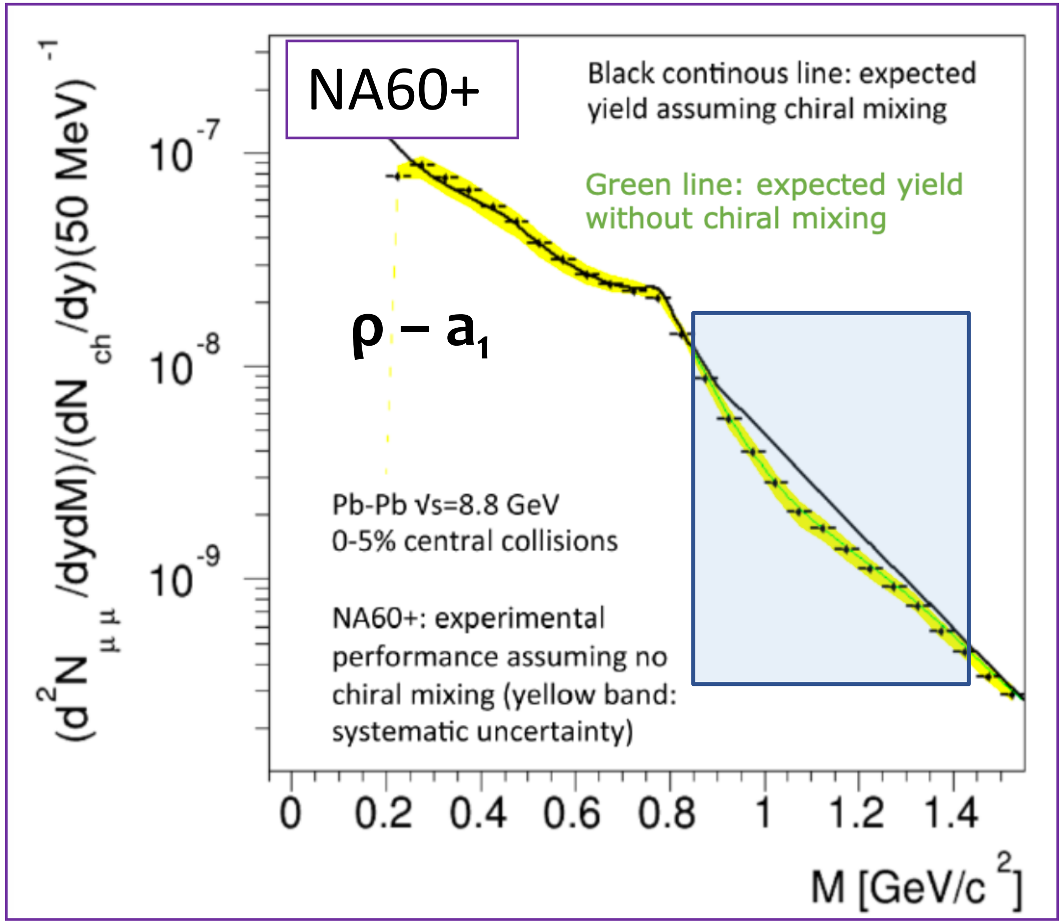
Axial-Vector meson (a_1) → No dilepton decays (**a_1**, chiral partner of ρ)

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

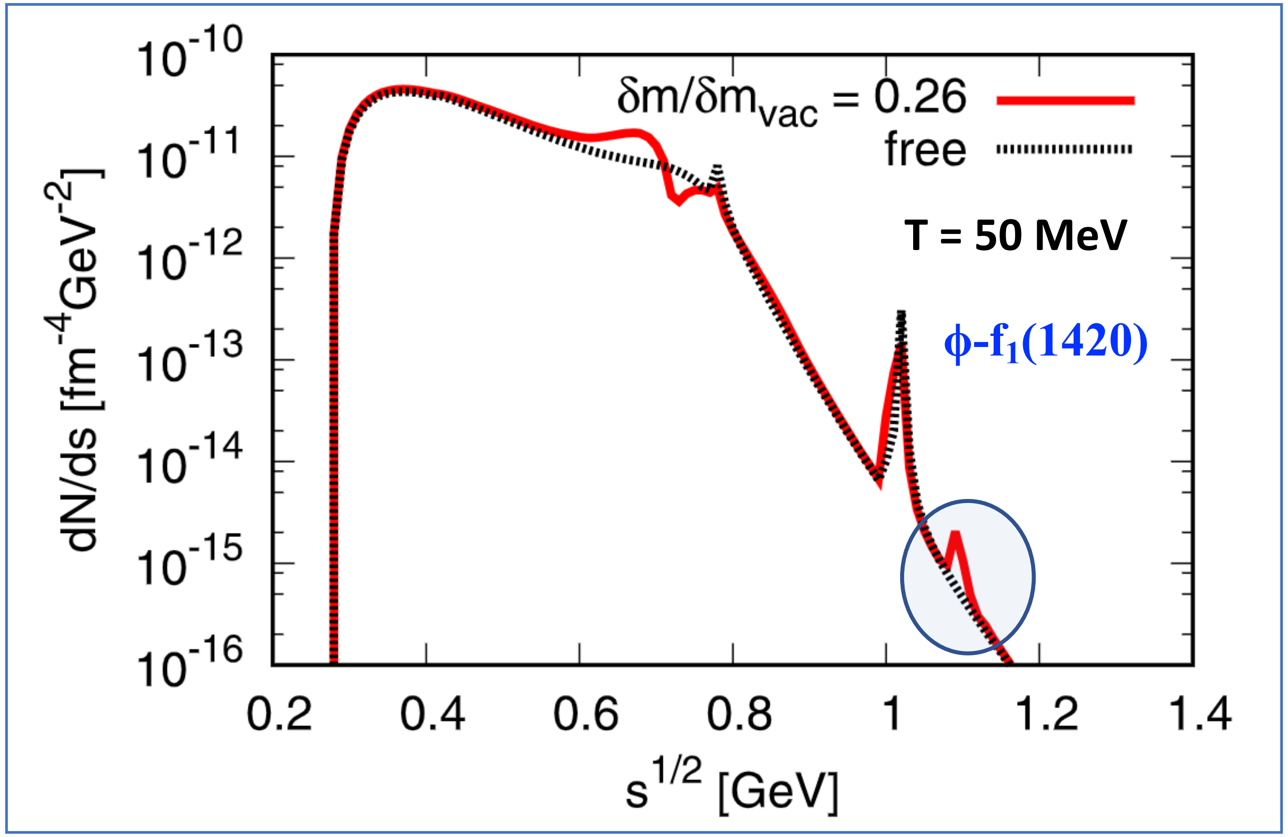
Rapp model: PRC 63 (2001) 054907, Adv HEP 2013 (2013) 148253, PLB 753 (2016) 586
PHSD model: NPA 807, 214 (2008); NPA 619, 413 (1997) PRC 97, 064907 (2018)

Future Measurements Related to CSR

Chiral symmetry restoration → **Axial-vector meson show up in Vector meson spectrum inside the medium via chiral mixing**

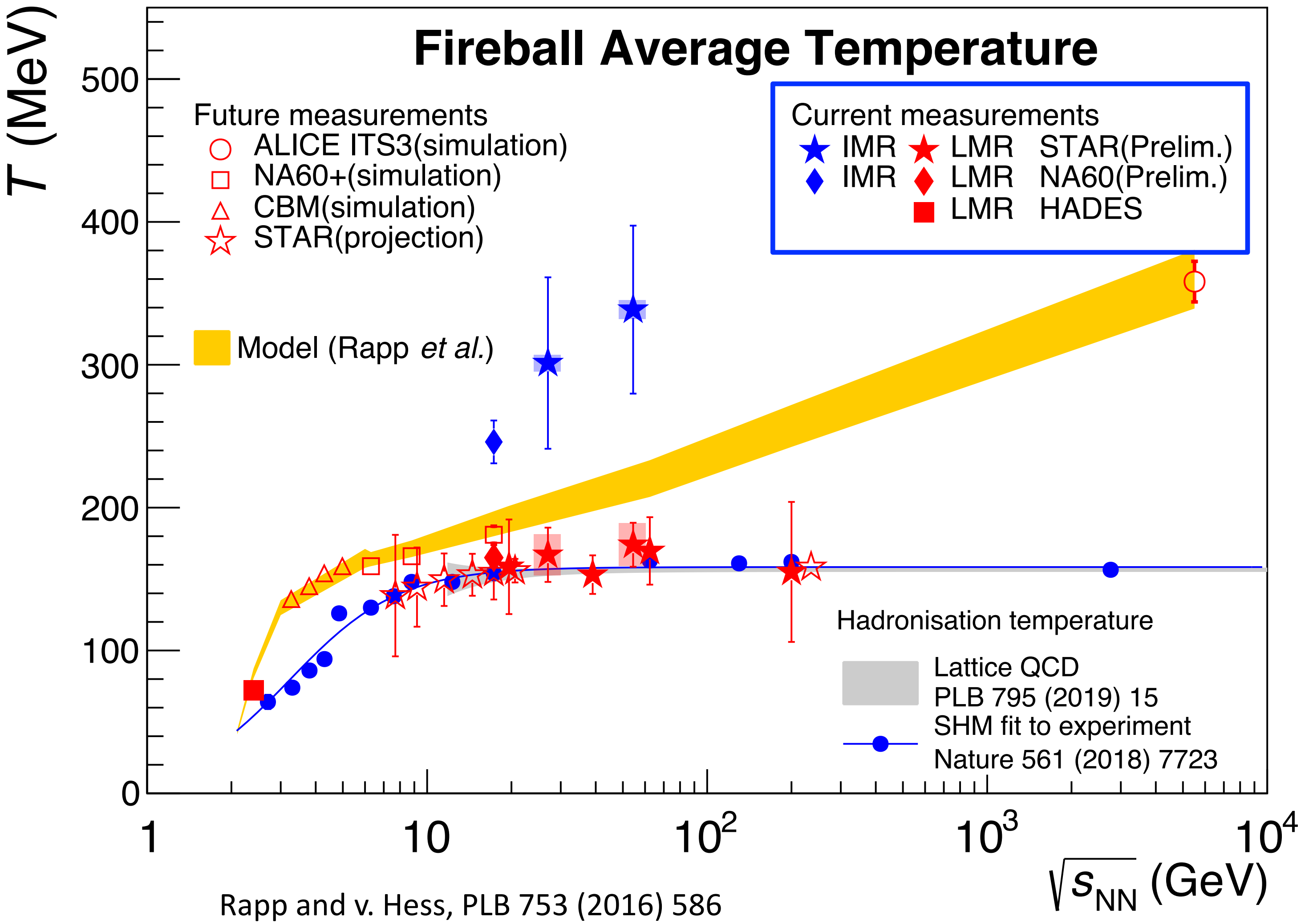


Rapp and Hohler: PLB 731 (2014) 103-109



Chihiro Sasaki, PLB 801 (2020) 135172

Future Thermal Dilepton Measurements



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TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

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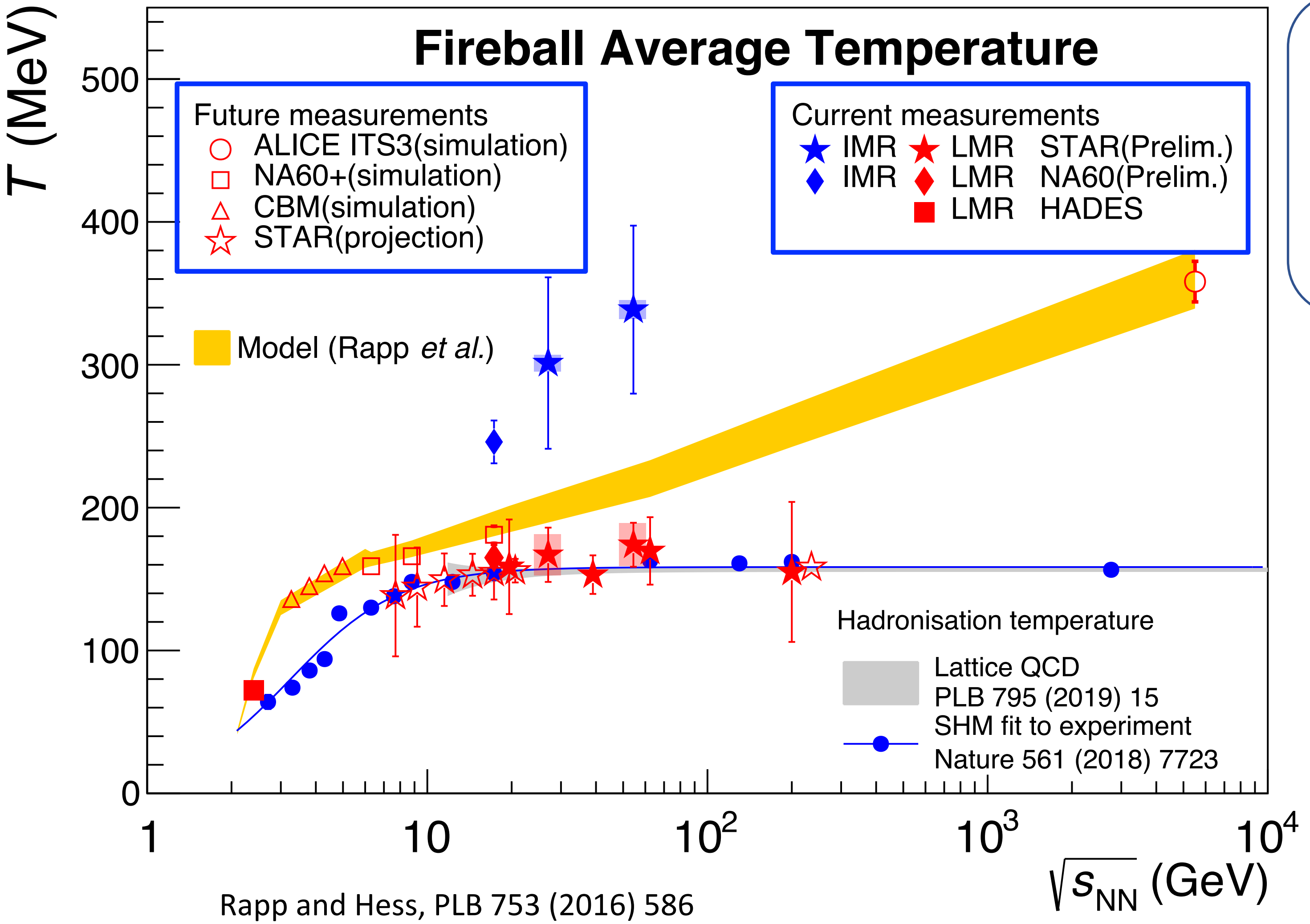

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TG *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

- **STAR BES-II/FXT, Run23+Run25@RHIC**
- **ALICE ITS3**
- **NA60+@SPS**
- **HADES, CBM@FAIR**
- **MPD@NICA**

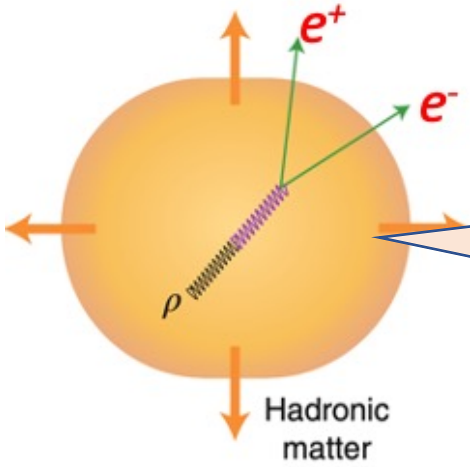
energy scan ⇩ μ_B scan

- **Mass spectra**
- **Temperature/Yield**

⇩

- **T vs. collision energy?**
- **In-med. ρ broaden mechanism?**
- **Critical endpoint?**
- **Partial chiral symm. restoration?**
- **Medium conductivity**

Summary and Discussions



T^{LMR} ~ 170 MeV, constant, >∼ T_{ch} ∼ T_{pc} at RHIC and SPS

T^{LMR} ~ 70-80 MeV at SIS18, still >∼ T_{ch}?

- **Rho completely melt or lack of production rate?**

[1]: Rapp and Hees, PLB 753 (2016) 586
[2]: Coquet, et.al. , PLB 821 (2021) 136626
[3]: Kasmaei and Strickland, PRD 99, 034015 (2019)

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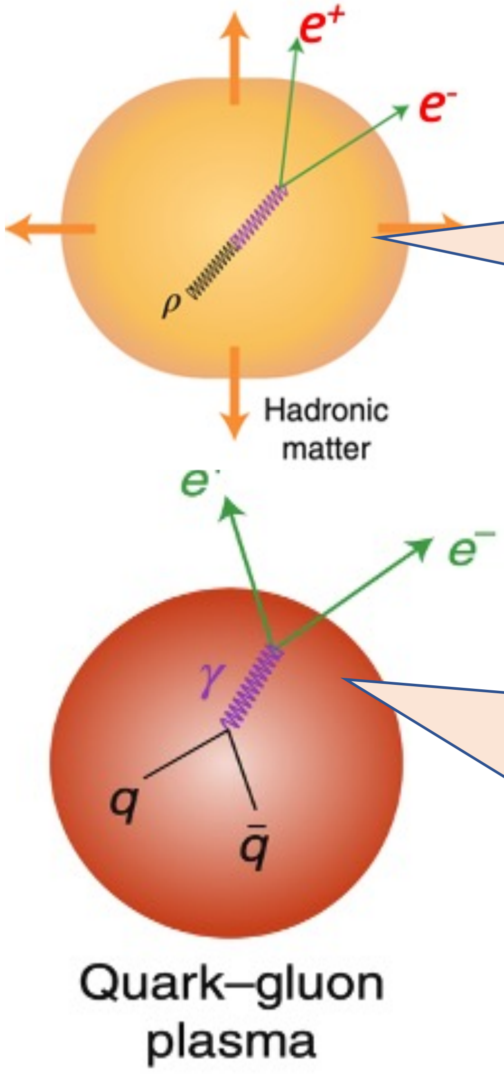

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T^{IMR}(SPS) ~ 246 ± 15 MeV, T^{IMR}(RHIC) ~ 320 ± 60 MeV

- **T^0** [MeV]~**240** (17.3 GeV) , **255** (27 GeV), **280** (54.4 GeV) in theoretical model [1]
- Data suggest higher initial temperature T^0?
- Pre-equilibrium radiation contribution [2]?
- Initial momentum anisotropy contribution[3]?

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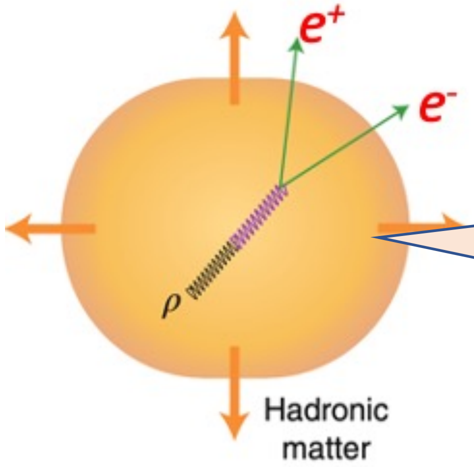

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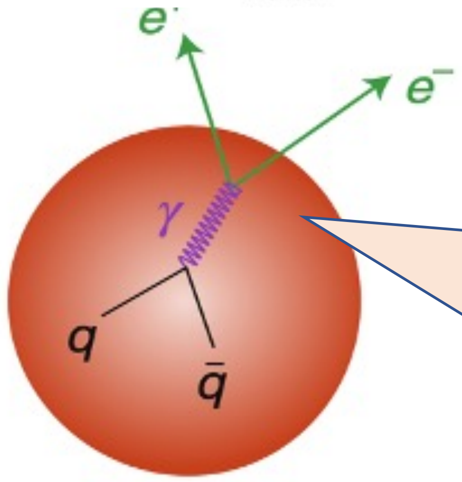

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Future thermal dilepton measurements will tell us more

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[2]: Coquet, et.al. , PLB 821 (2021) 136626
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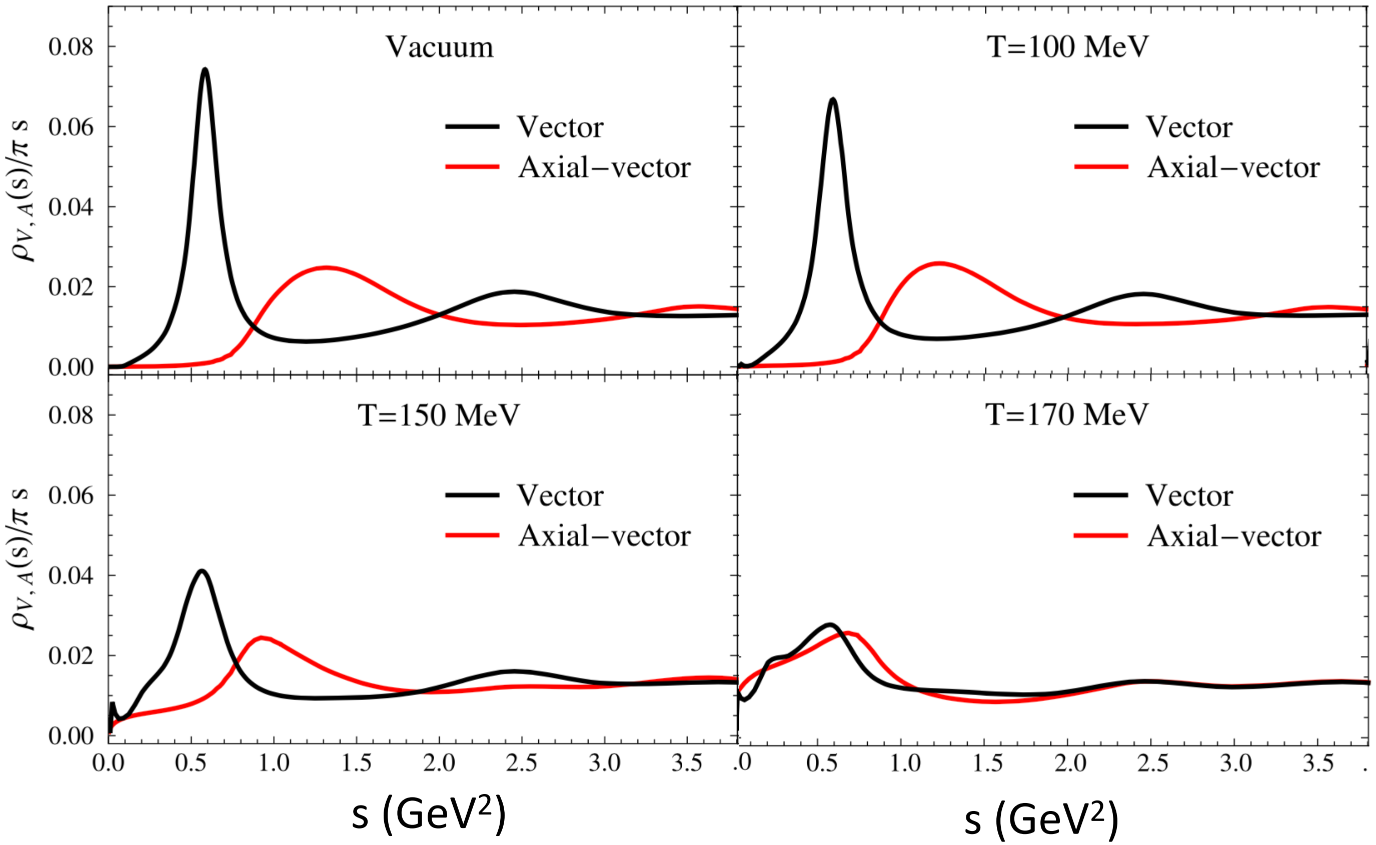
THANKS

BACKUP SLIDES

Chiral Symmetry Restoration

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



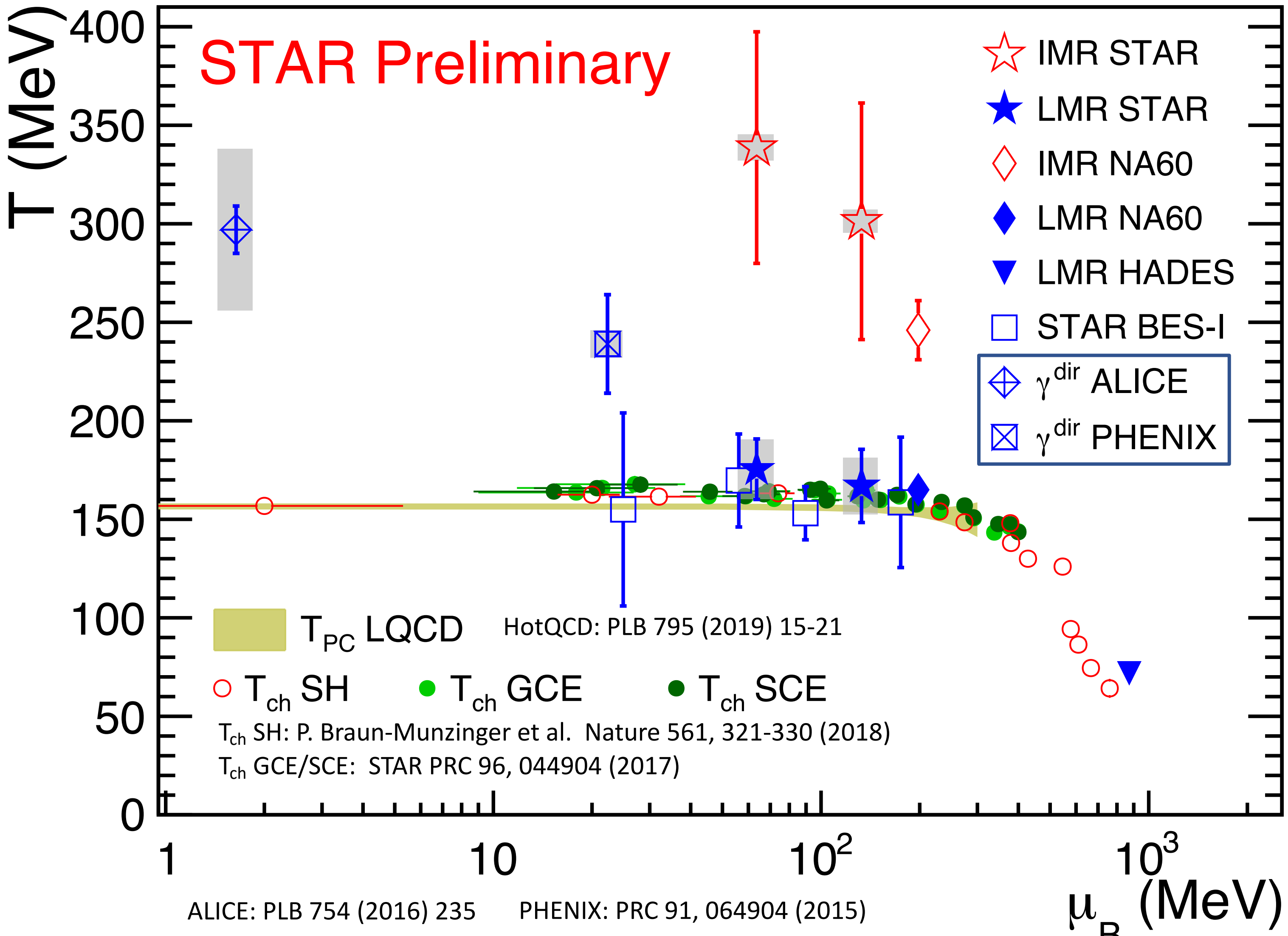
Measure a_1 theoretically

- 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

Summary of Temperatures from EM probes



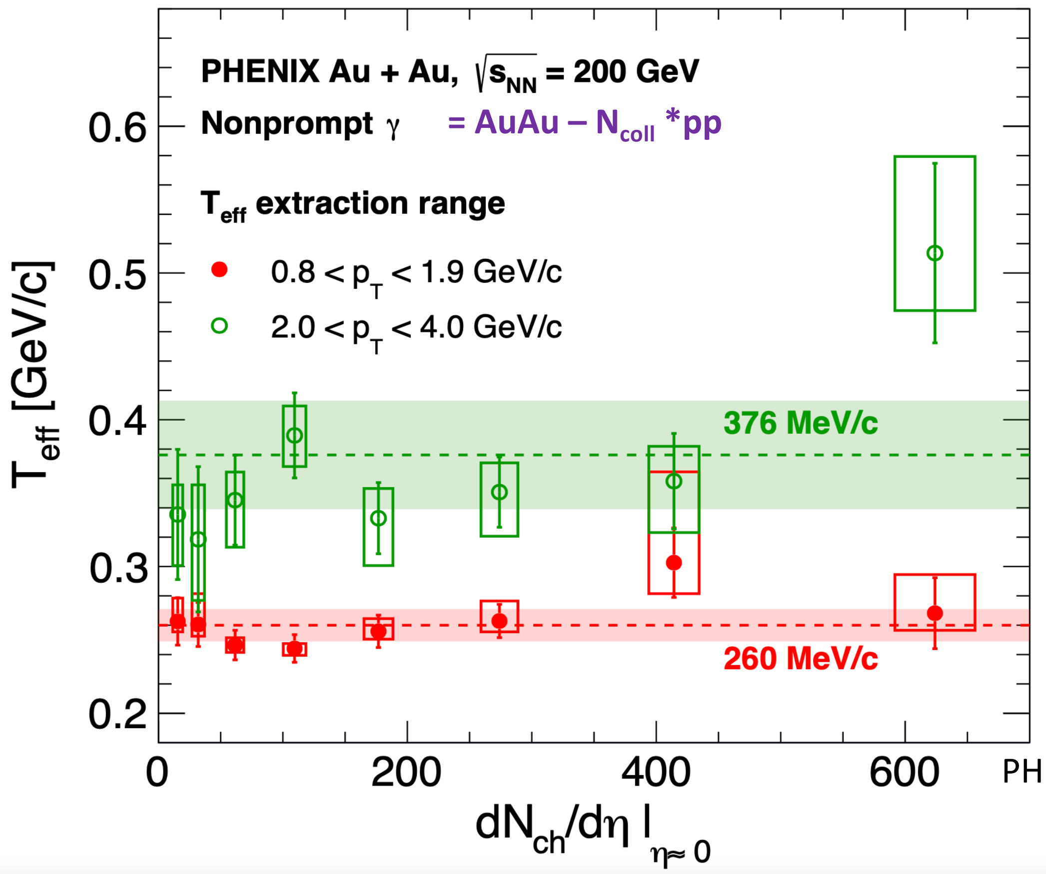
ALICE: PLB 754 (2016) 235 PHENIX: PRC 91, 064904 (2015)

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

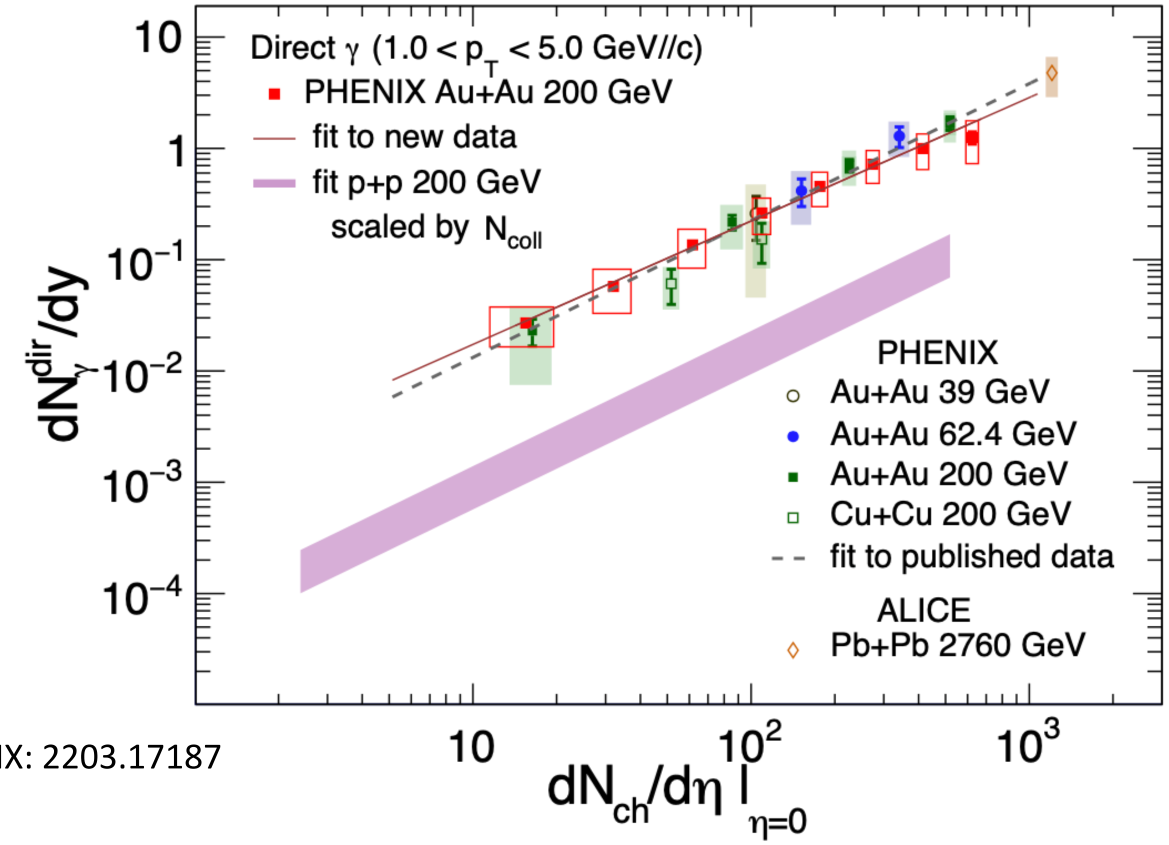
--- C. Shen, U. Heinz, J-F Paquet, C. Gale: PRC 89, 044910 (2014)

STAR: PLB 750 (2015) 64-71, arXiv: 1810.10159 NA60: EPJC (2009) 59 607–623 HADES: Nature Physics 15, 1040-1045 (2019) T.G.: JPS Conf.Proc. 32 (2020) 010079

Recent Direct Photon Measurements



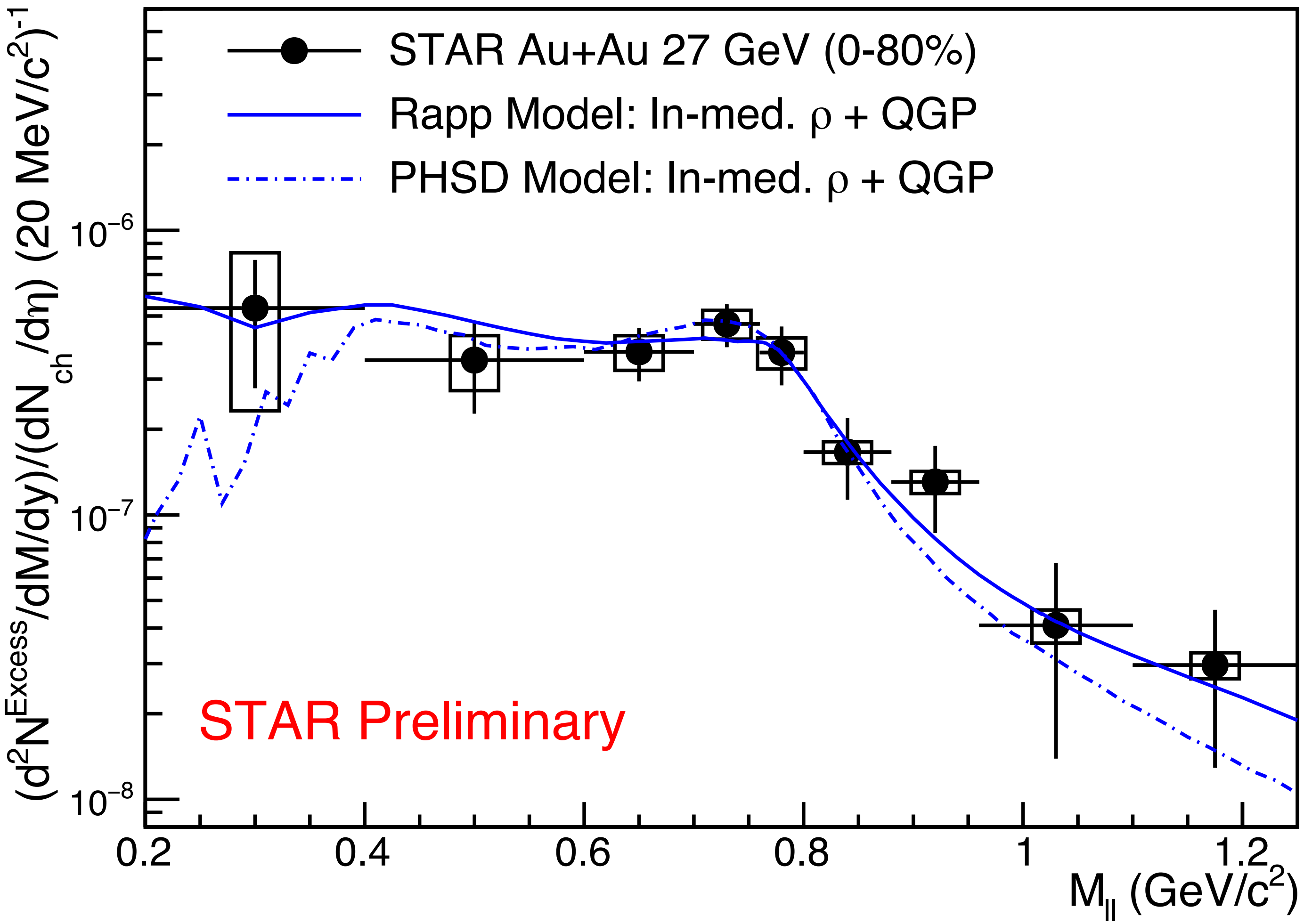
PHENIX: 2203.17187



[Talk: EW probe in heavy-ion collisions, Andre G. S. Leiton]

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

Compare to Models



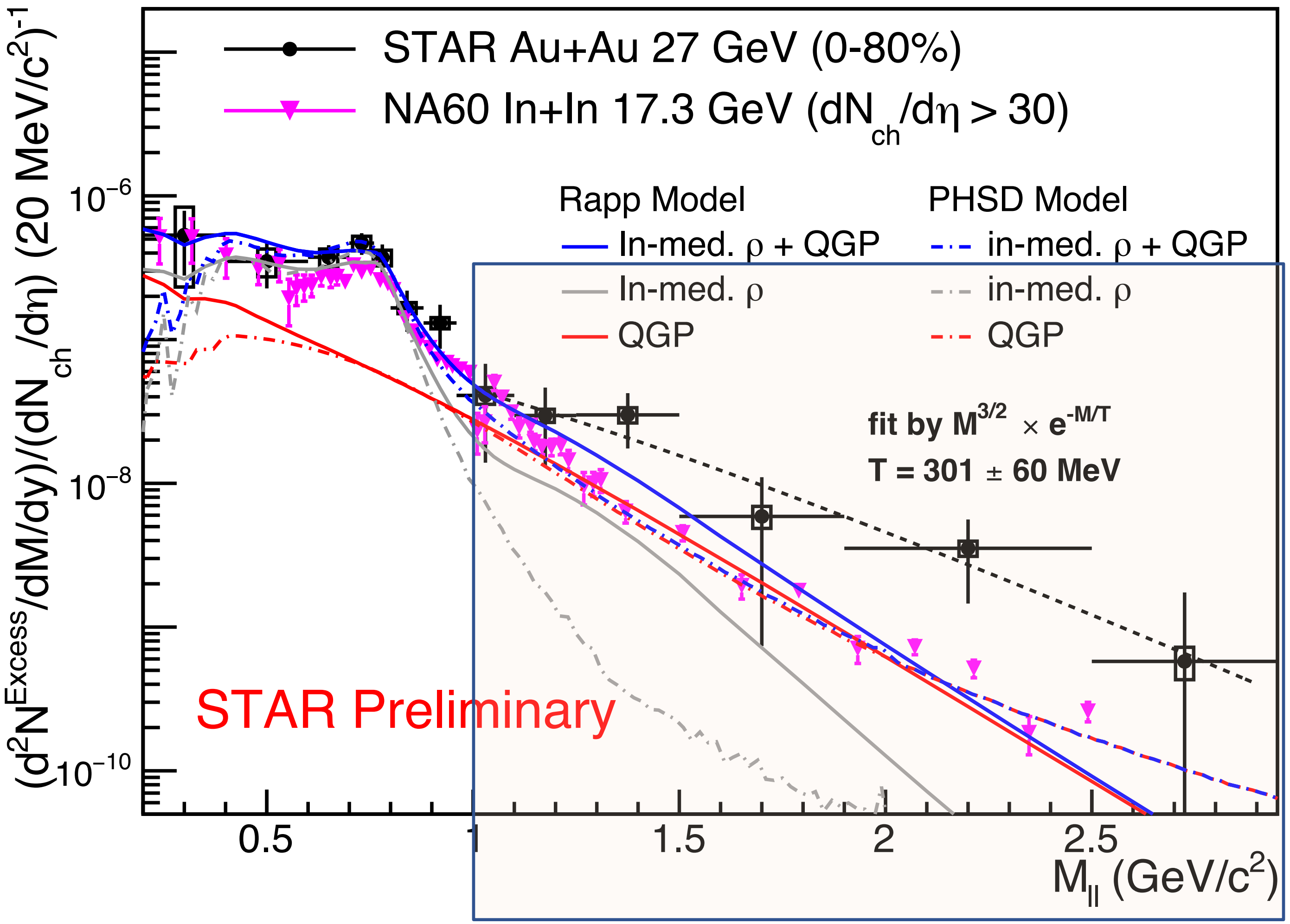
Rapp model: PRC 63 (2001) 054907, Adv HEP 2013 (2013) 148253, PLB 753 (2016) 586
PHSD model: NPA 807, 214 (2008); NPA 619, 413 (1997) PRC 97, 064907 (2018)

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

Compare to 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 but underestimate the IMR → QGP is hotter** than model expectation

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