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Measurements of thermal dielectron in isobar collisions at $\sqrt{s_{NN}} = 200$ GeV with STAR

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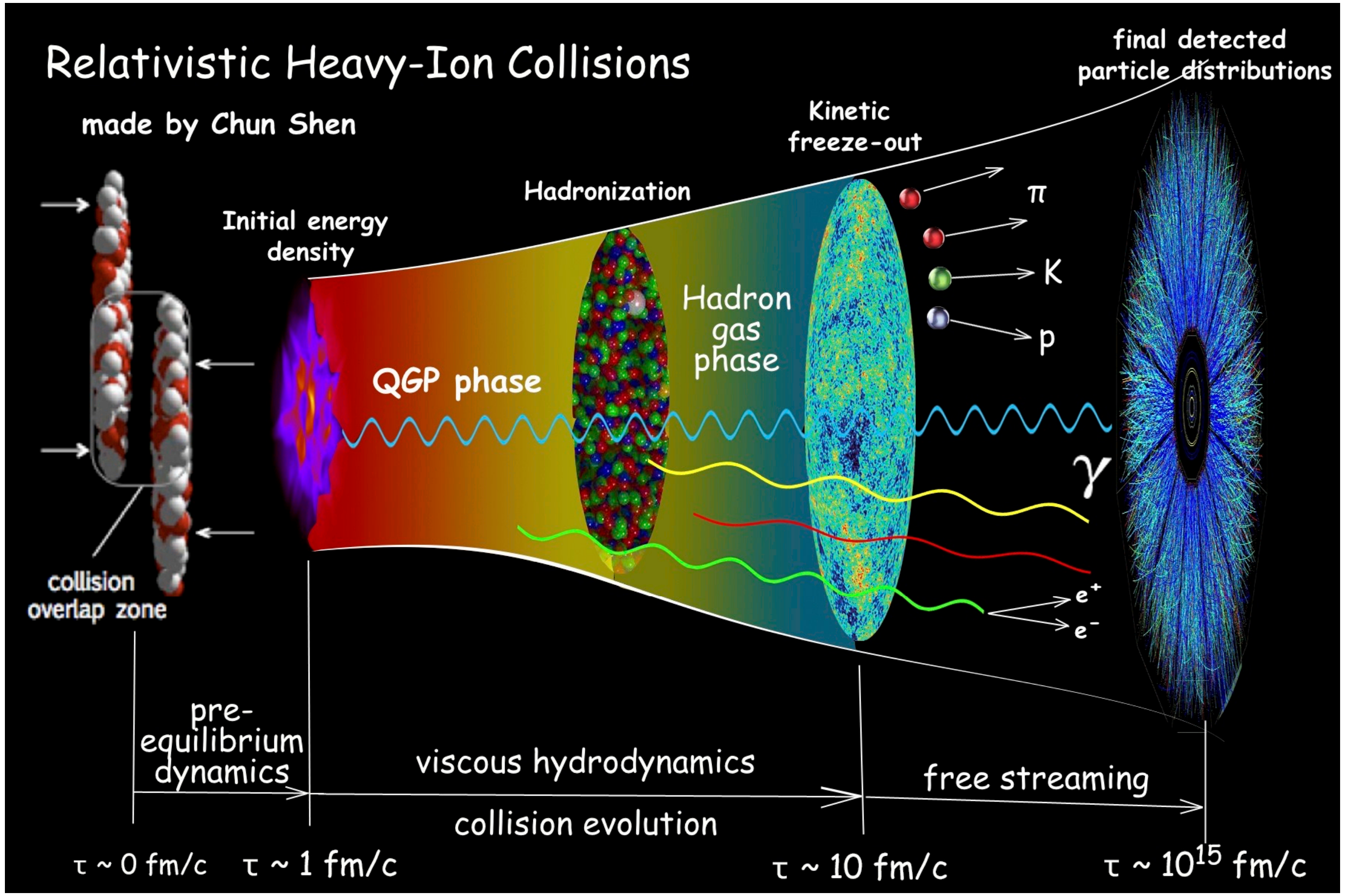
A "Little Bang" in Heavy Ion Collision

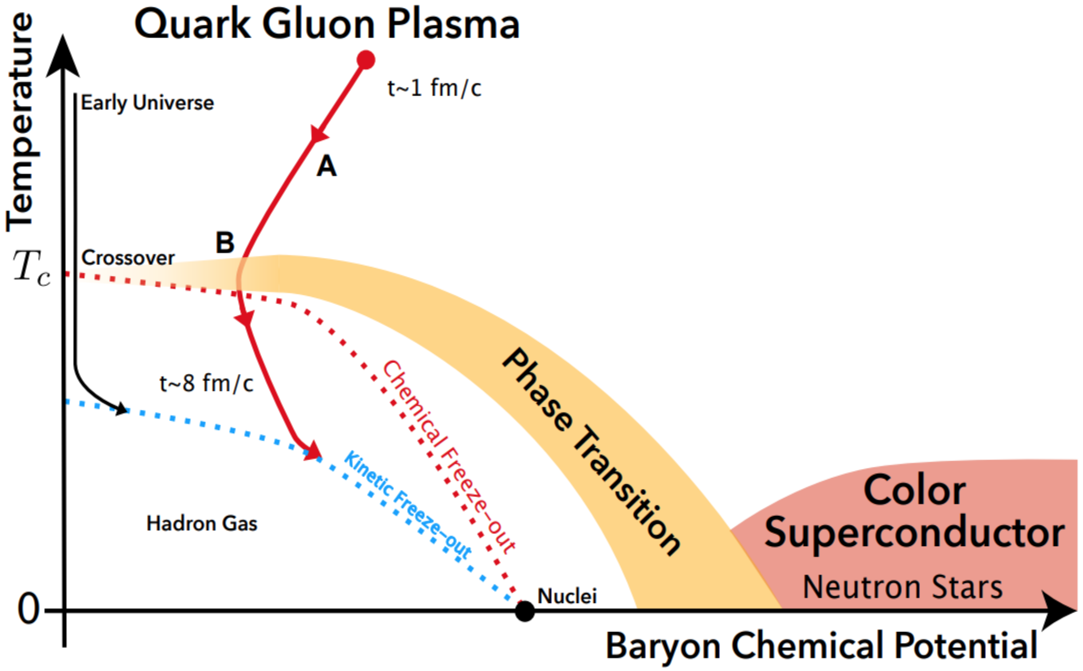


C.Shen https://u.osu.edu/vishnu/2014/08/06/sketch-of-relativistic-heavy-ion-collisions

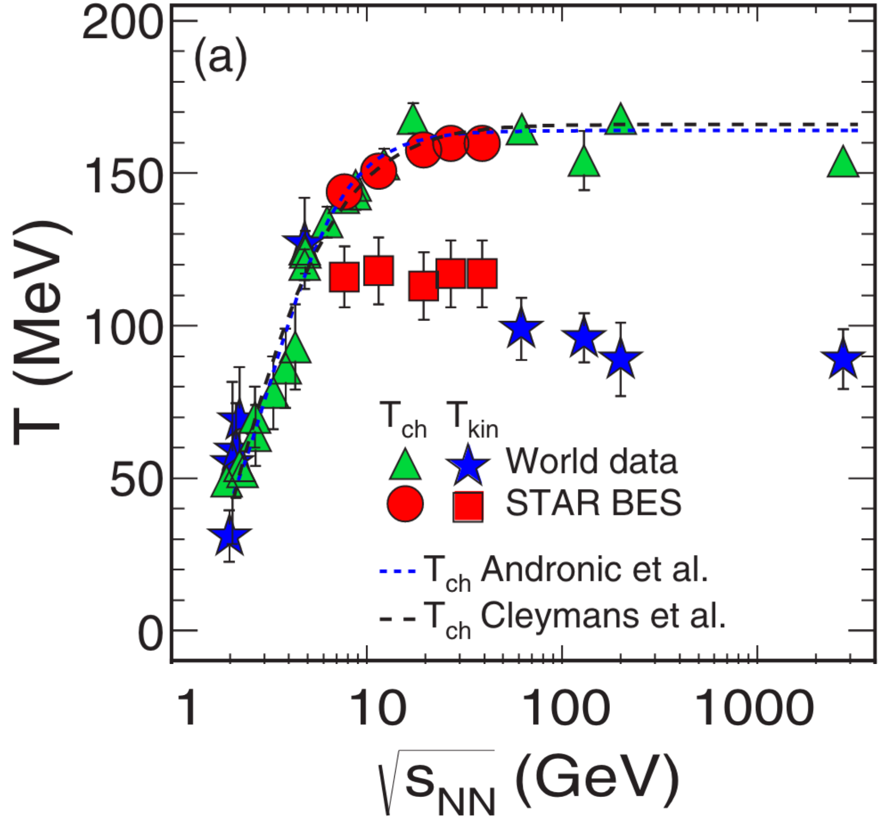
- Deconfined QCD matter produced at extreme high temperature and/or baryon density
- In laboratory: heavy ion collisions
- Temperature, as one of key properties of medium, still poorly known

How to measure temperature

Hadrons (Yield, p_T) → Statistical thermal model / Hydrodynamics-inspired models → Chemical freeze-out T_{ch} / Kinetic freeze-out T_{kin}

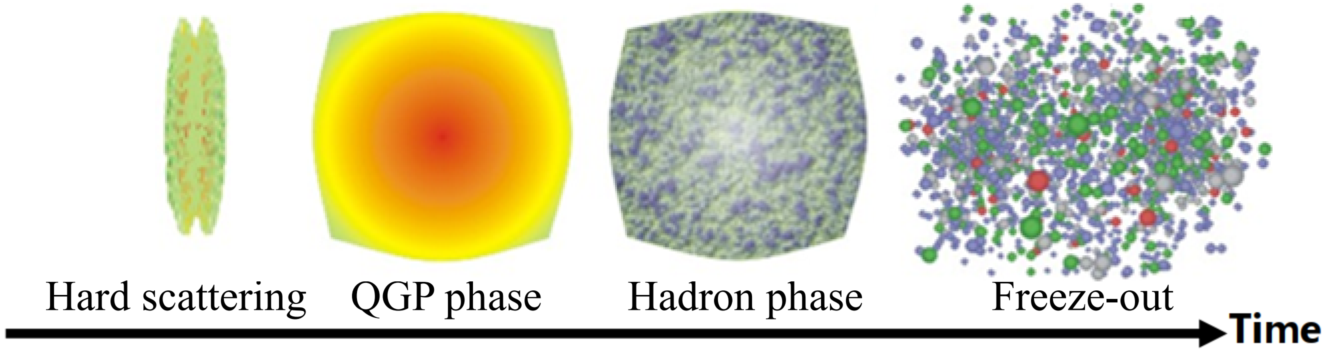


STAR, arXiv: 2402.01998



STAR: Phys. Rev. C 96, 044904 (2017)

How to measure temperature



EM Probes

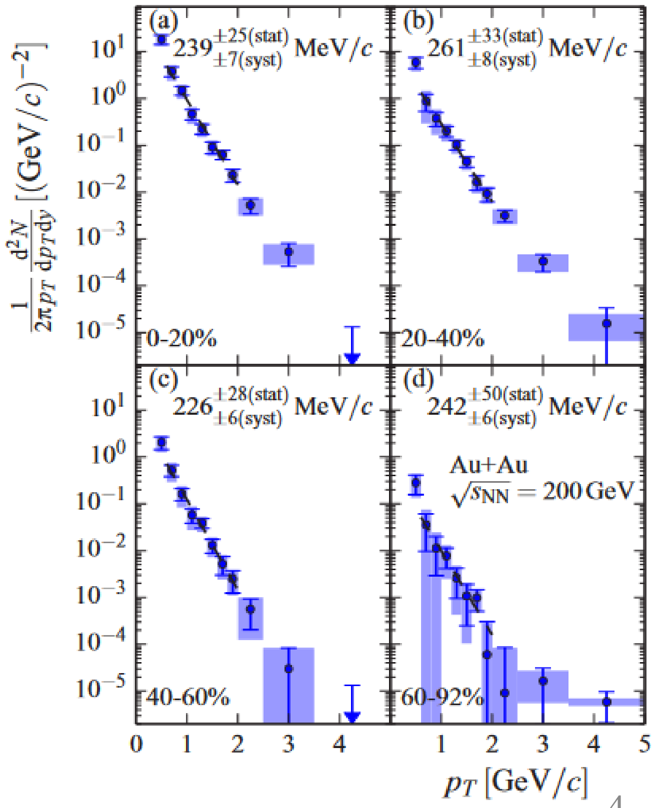
- Emitted from early to final stages
- Minimal interaction with medium
- Carry original information of QGP

Photons **(p_T)**

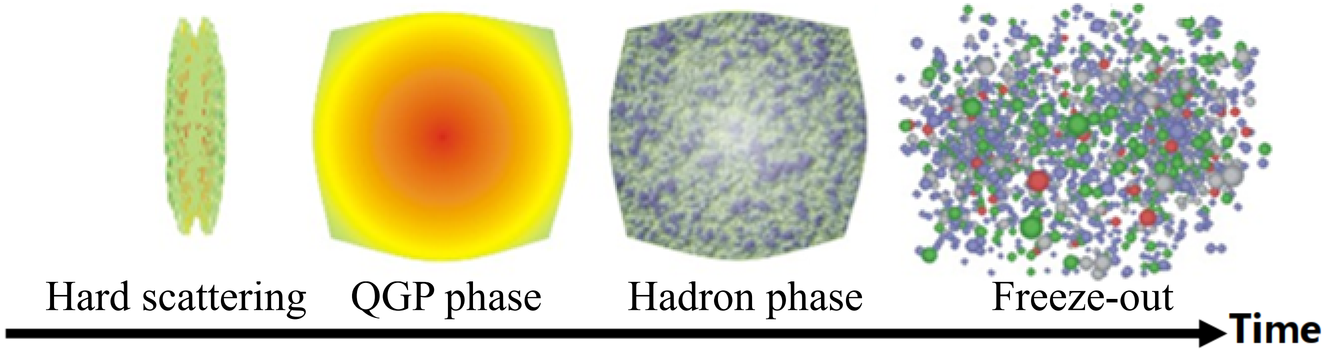
Dileptons **(M_{ll})**

- Extract T_{eff} from p_T spectra
- $T_{eff} \rightarrow T_{QGP}$: blue-shift effect

PHENIX: Phys. Rev. C 91, 064904 (2015)



How to measure temperature



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Photons (p_T)

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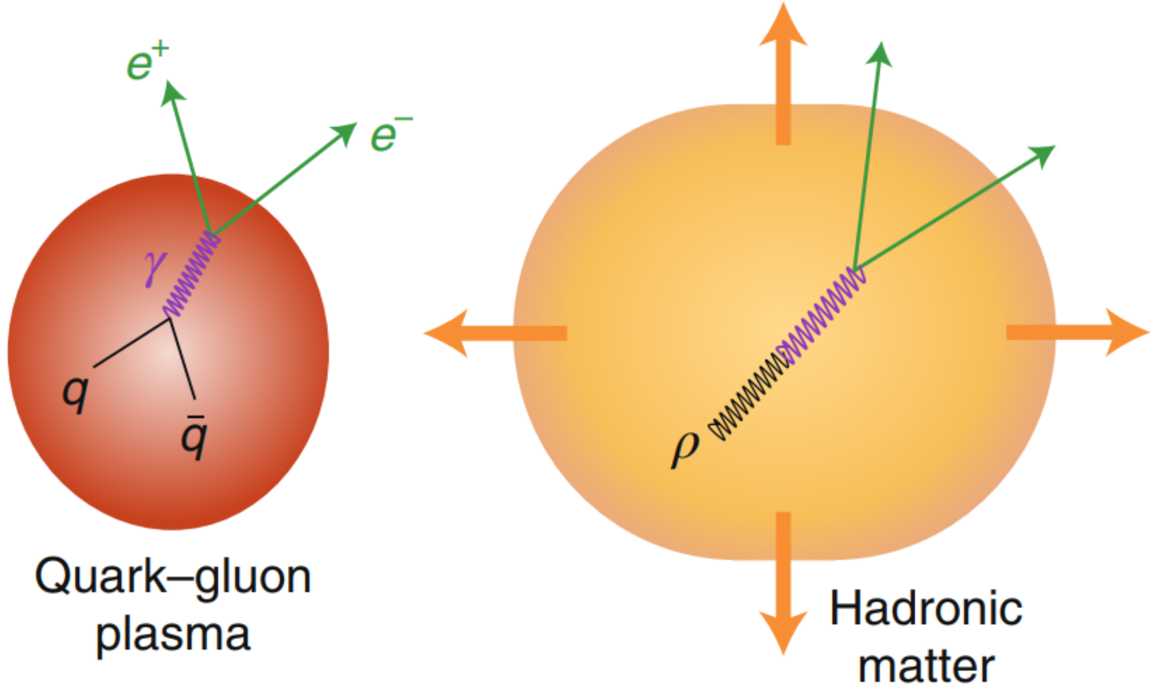
Dileptons (M_{ll})

- T measurement without distortion by blue-shift effects
- Unique observable to directly access in-medium spectral function

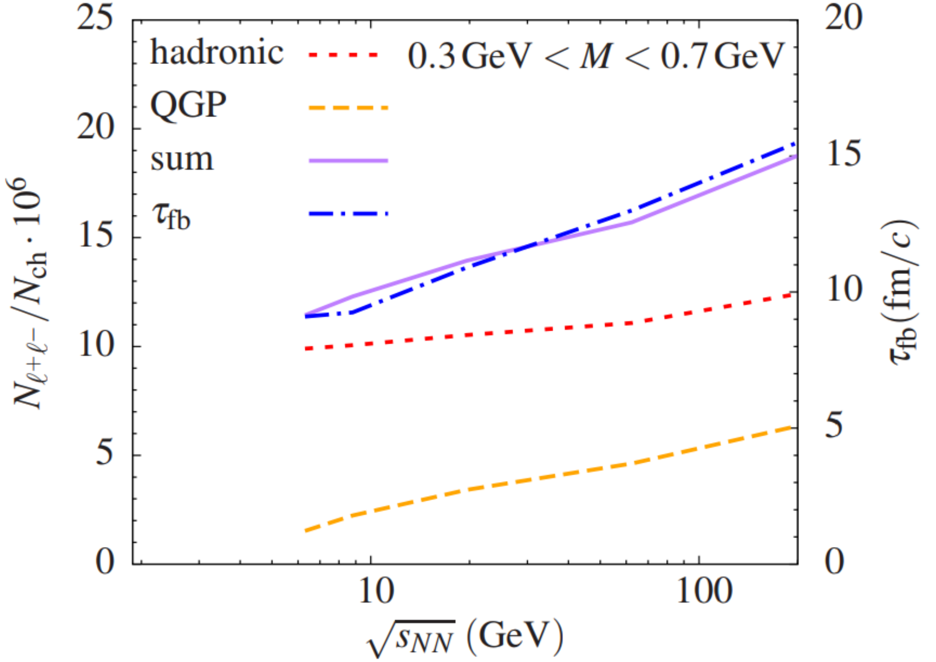
Thermal Dileptons

QGP: $M^{3/2} * e^{-M/T}$ **In-med. ρ:** Relativistic Breit-Wigner $* e^{-M/T}$



R. Rapp, Nat. Phys. 15, 990–991 (2019)
QGP: HADES, Nat. Phys. 15, 1040–1045 (2019)
In-med. ρ: STAR, Phys. Rev. Lett. 92, 092301 (2004)

Integrated thermal dilepton yield and underlying fireball lifetime



R. Rapp, EPJA 52, 257 (2016)

- **Thermometer**: extract **temperature** from mass spectra
- **Chronometer**: predict **lifetime** from integrated yield

Signal and Physical background

Inclusive signal (combinatorial background subtracted)

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

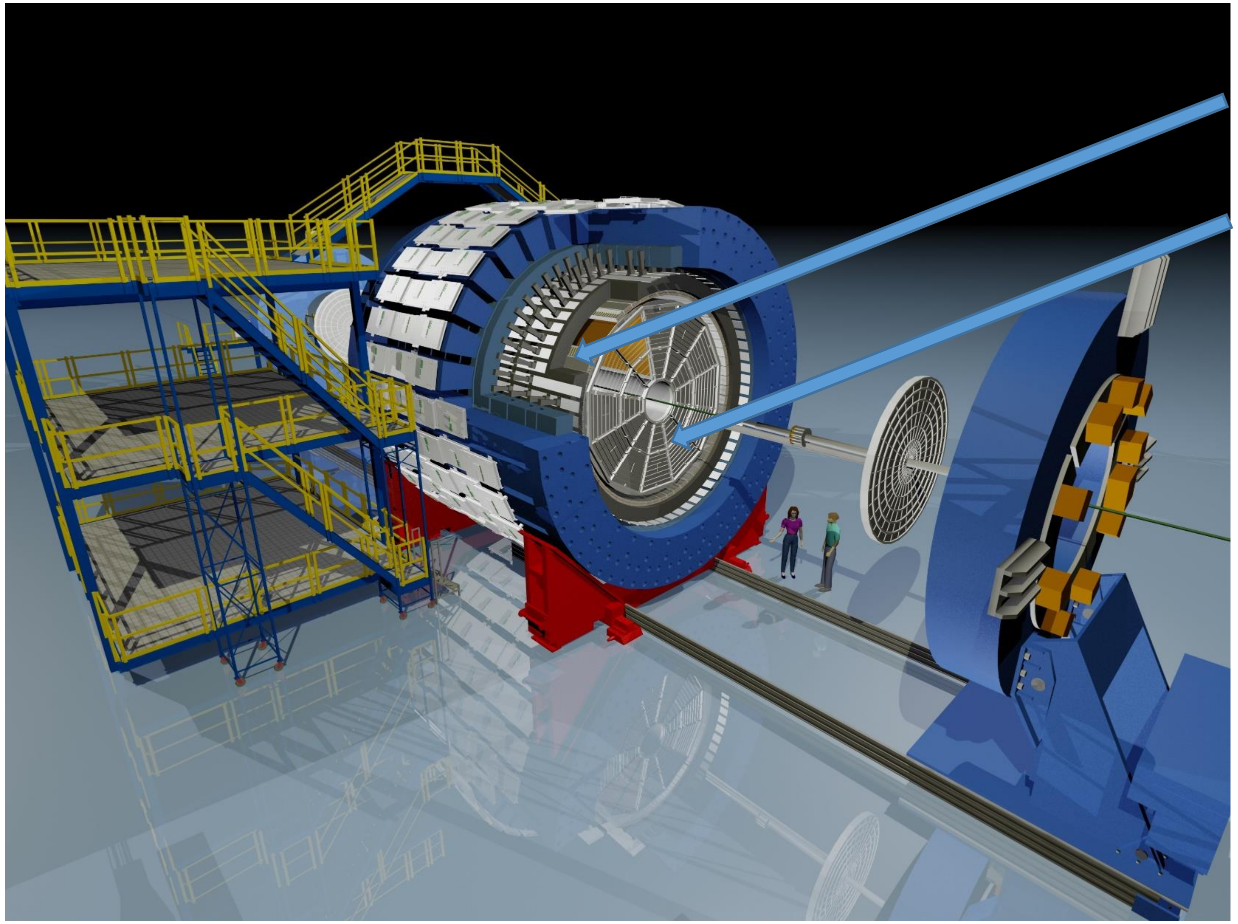
Physical background (Cocktails):
- $\omega, \phi, J/\psi \rightarrow e^{+}e^{-}$
- $\pi^{0}, \eta, \eta' \rightarrow \gamma e^{+}e^{-}$
- $\omega \rightarrow \pi^{0} e^{+}e^{-}$
- $\phi \rightarrow \eta e^{+}e^{-}$
- $c\bar{c}, b\bar{b} \rightarrow e^{+}e^{-}\mathrm{X}$
- Drell-Yan

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

- ➢ Two-body & Dalitz decays: Monte Carlo simulation through the dielectron decay channel, and scaling hadron invariant yields
- ➢ Heavy-flavor decays & Drell-Yan process: PYTHIA simulation in p + p collisions, and scaling by the N_{coll} to AA yields

Thermal dileptons = Inclusive signal – Physical background

The Solenoid Tracker At RHIC



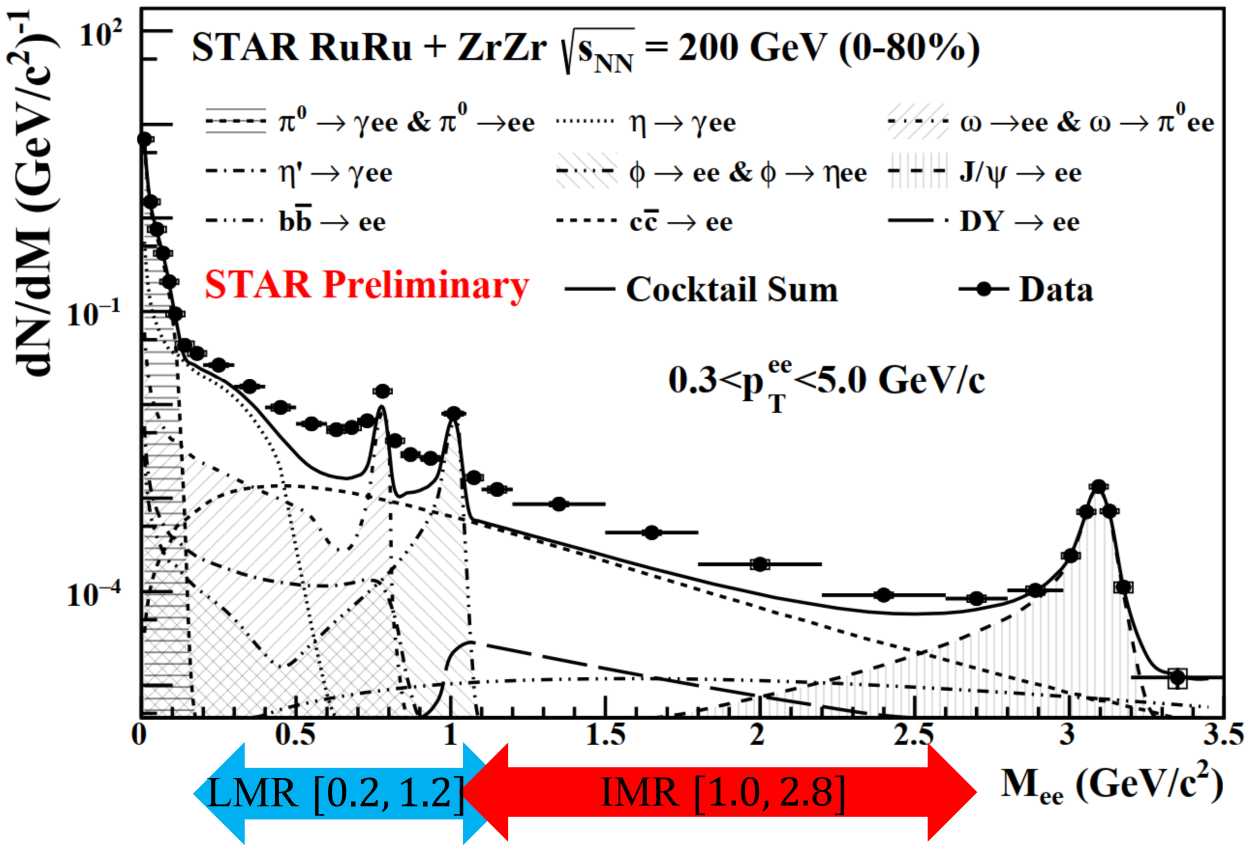
TOF: Time of flight, particle identification

TPC: Tracking, momentum and energy loss

Collision species (taken in 2018, $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV)

- $^{96}_{44}$Ru+$^{96}_{44}$Ru (~2B events)
- $^{96}_{40}$Zr+$^{96}_{40}$Zr (~2B events)

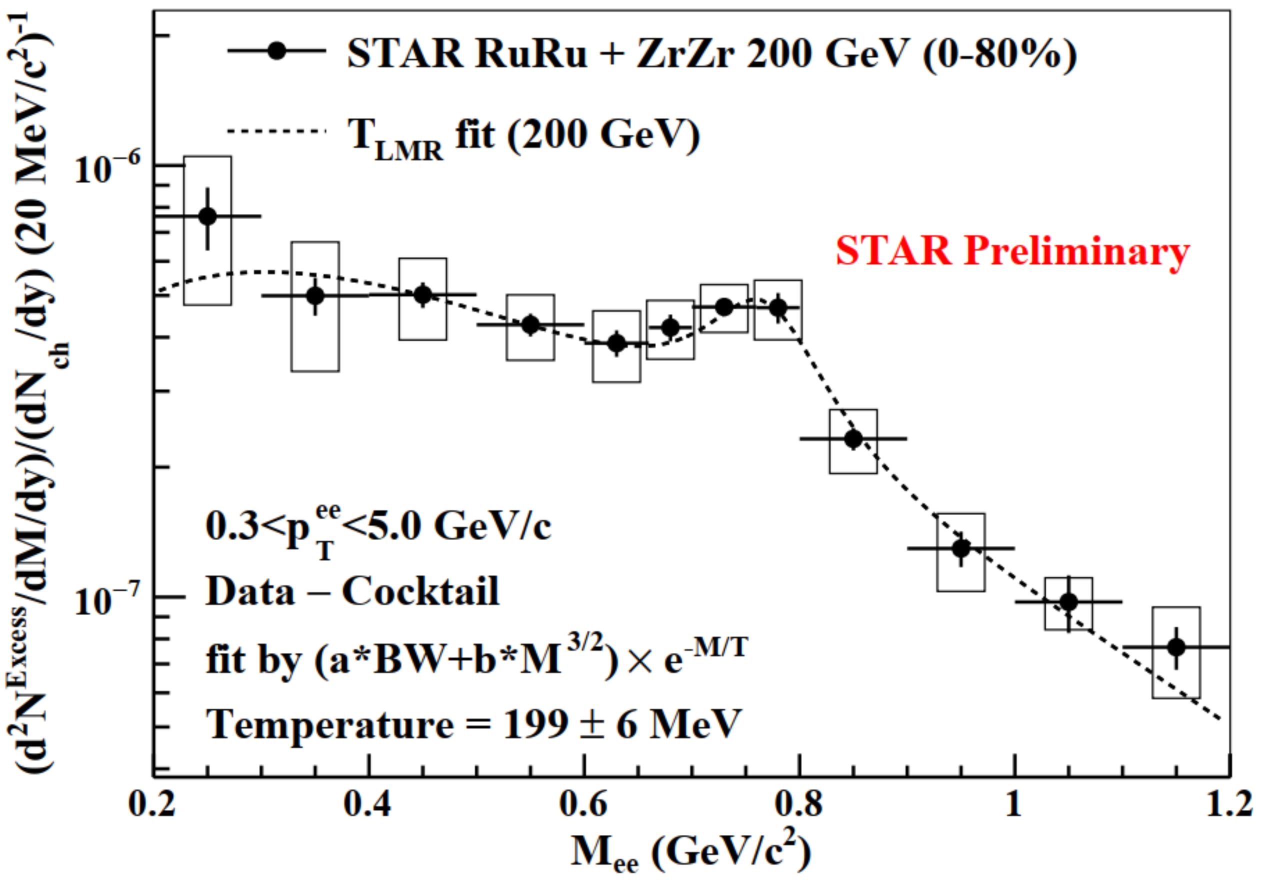
Fully corrected Data vs. Cocktail



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

Temperature extraction from LMR

Excess = data - cocktail



Fitting function: $(a * BW + b * M^{3/2}) \times e^{-M/T}$

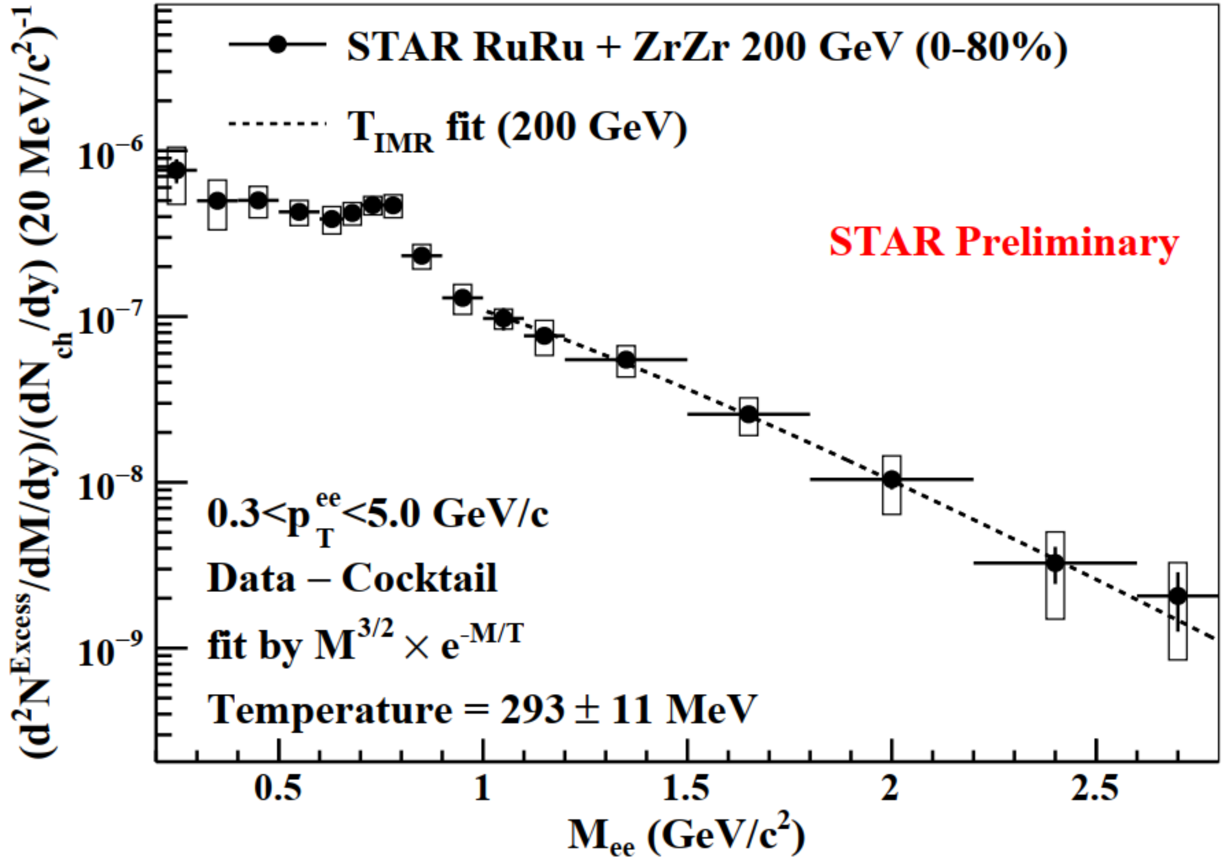
- Excess mass spectra in **Low Mass Region** normalized by the charged particle multiplicity
- Time-average temperature over the fireball evolution
- ~3.0 σ higher than the pseudo critical temperature T_{pc} (156 MeV)

$$T_{LMR}^{Isobar\ 200GeV} = 199 \pm 6\ (stat.) \pm 13\ (sys.)\ MeV$$

T_{pc}: HotQCD, Phys. Lett. B 795, 15-21 (2019)

Temperature extraction from IMR

Excess = data - cocktail



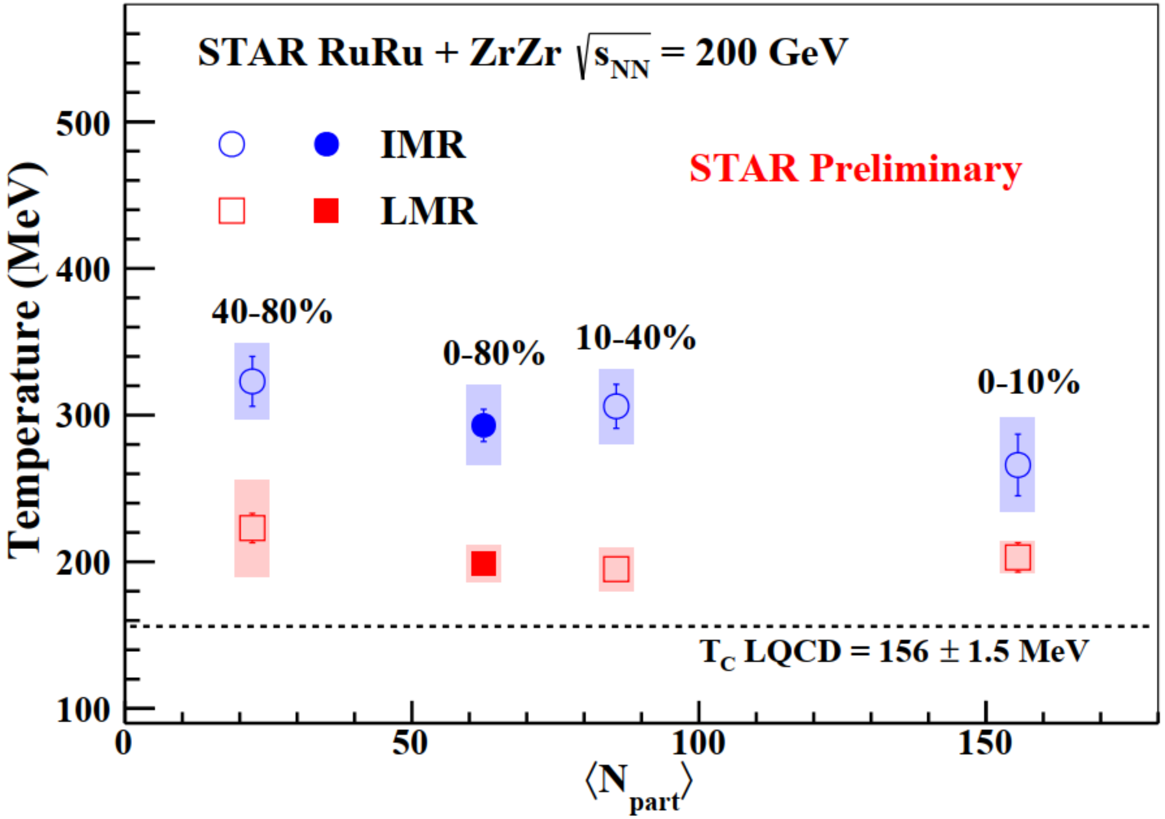
Fitting function: $M^{3/2} \times e^{-M/T}$

- Excess mass spectra in **Intermediate Mass Region** normalized by the charged particle multiplicity
- ~4.7 σ higher than T_{pc}, indicating that the emission is predominantly from deconfined QGP phase

T_{IMR}^{200GeV} **= 293 ± 11 (stat.) ± 27 (sys.) MeV**

T_{pc}: HotQCD, Phys. Lett. B 795, 15-21 (2019)

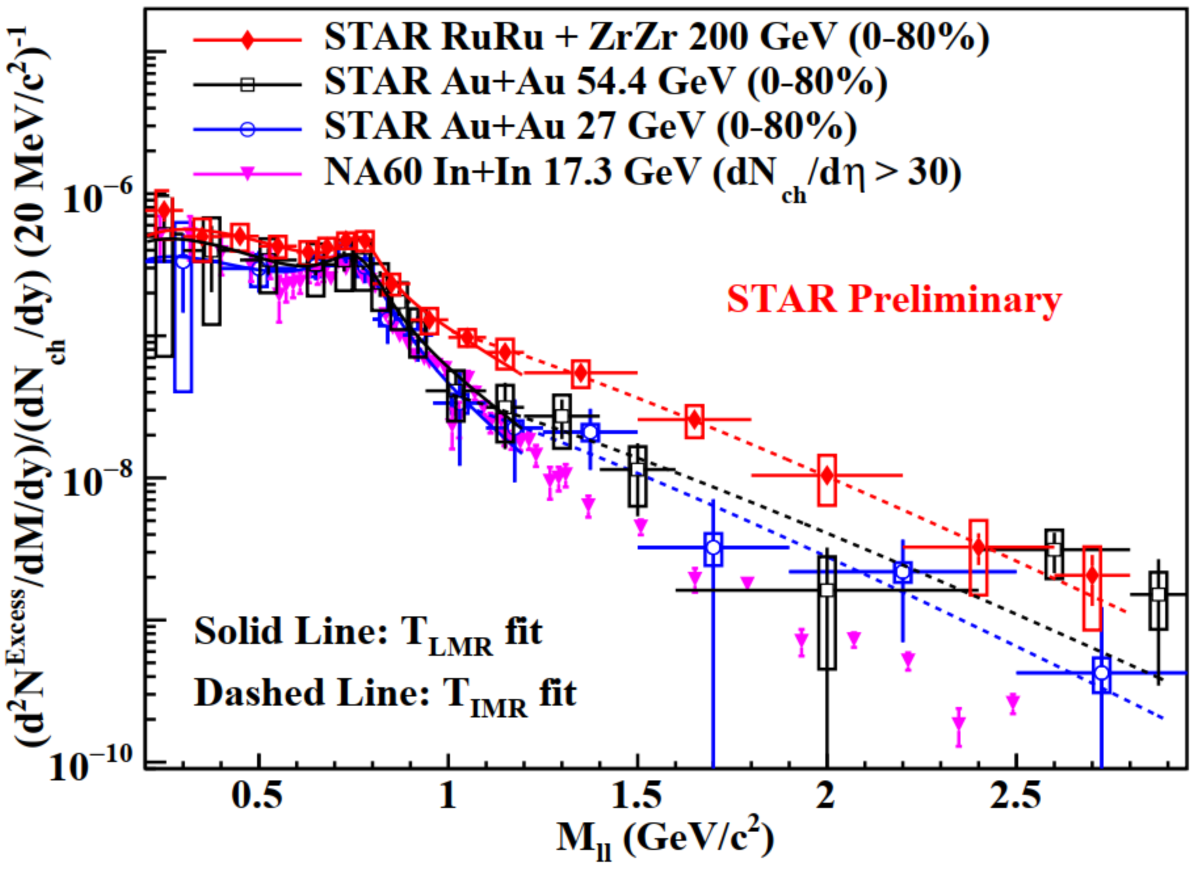
Temperature vs. N_{part}



No clear centrality dependence in both mass regions

- Temperature from low mass region is higher than the pseudo critical temperature
- Temperature from intermediate mass region is higher than that in low mass region

Excess dielectron spectra vs. collision system



Low Mass Region:

- Excess yield (normalized by the charged particle multiplicity) increases with collision energy
- 27 & 54.4 GeV: **in-medium ρ dominant**
- 200 GeV: hint of **higher QGP contribution**

T_{LMR}^{200GeV} = 199 ± 6 (stat.) ± 13 (sys.) MeV

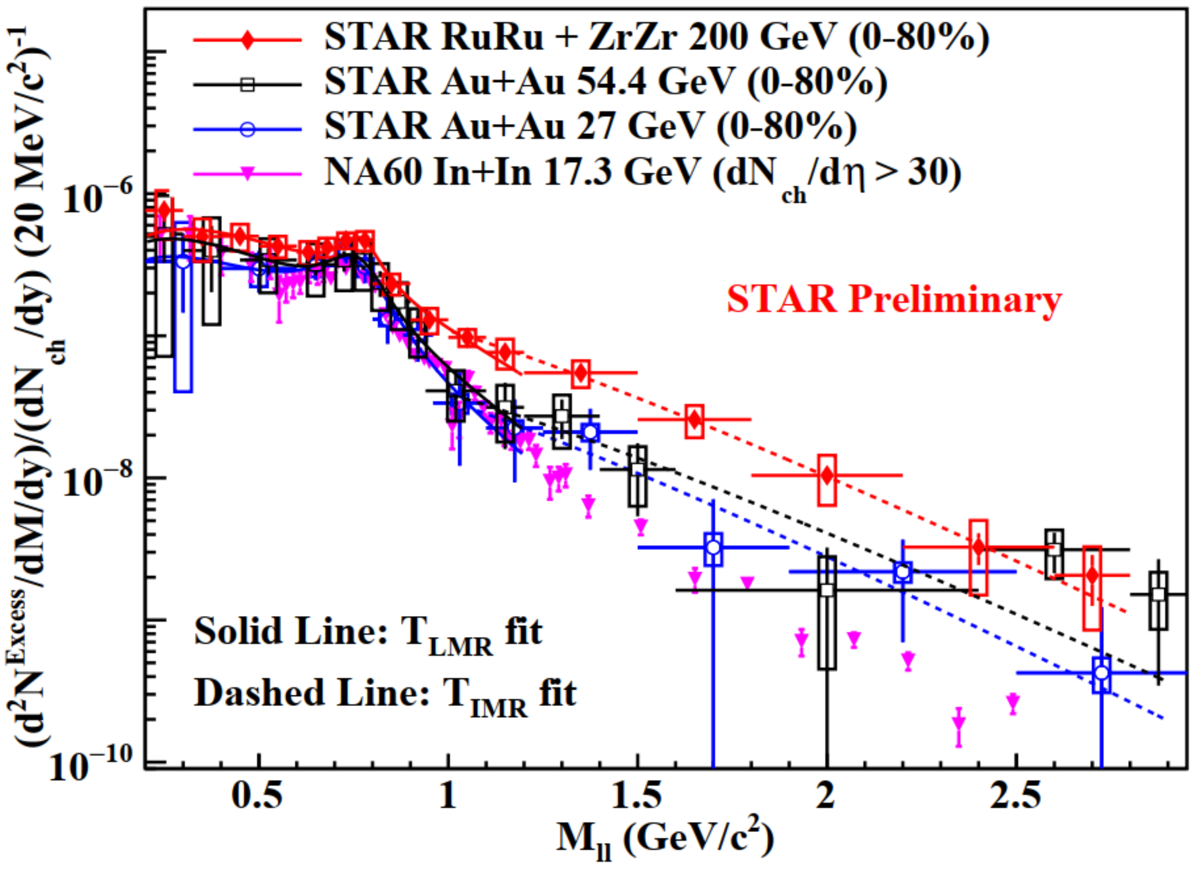
$T_{LMR}^{54.4GeV}$ = 172 ± 12 (stat.) ± 18 (sys.) MeV

T_{LMR}^{27GeV} = 167 ± 21 (stat.) ± 18 (sys.) MeV

$T_{LMR}^{17.3GeV}$ = 165 ± 4 MeV

NA60: EPJC 59, 607–623 (2009)
STAR 27 & 54.4 GeV, arXiv: 2402.01998

Excess dielectron spectra vs. collision system



NA60: EPJC 59, 607–623 (2009)
STAR 27 & 54.4 GeV, arXiv: 2402.01998

Intermediate Mass Region:

- Excess yield at 200 GeV **higher** than lower energy
- **T is similar** within uncertainties **despite** significant **differences** in collision **energy** and system **size**
- T_{IMR} is higher than T_{LMR}, ~ 2.9 σ at 200 GeV

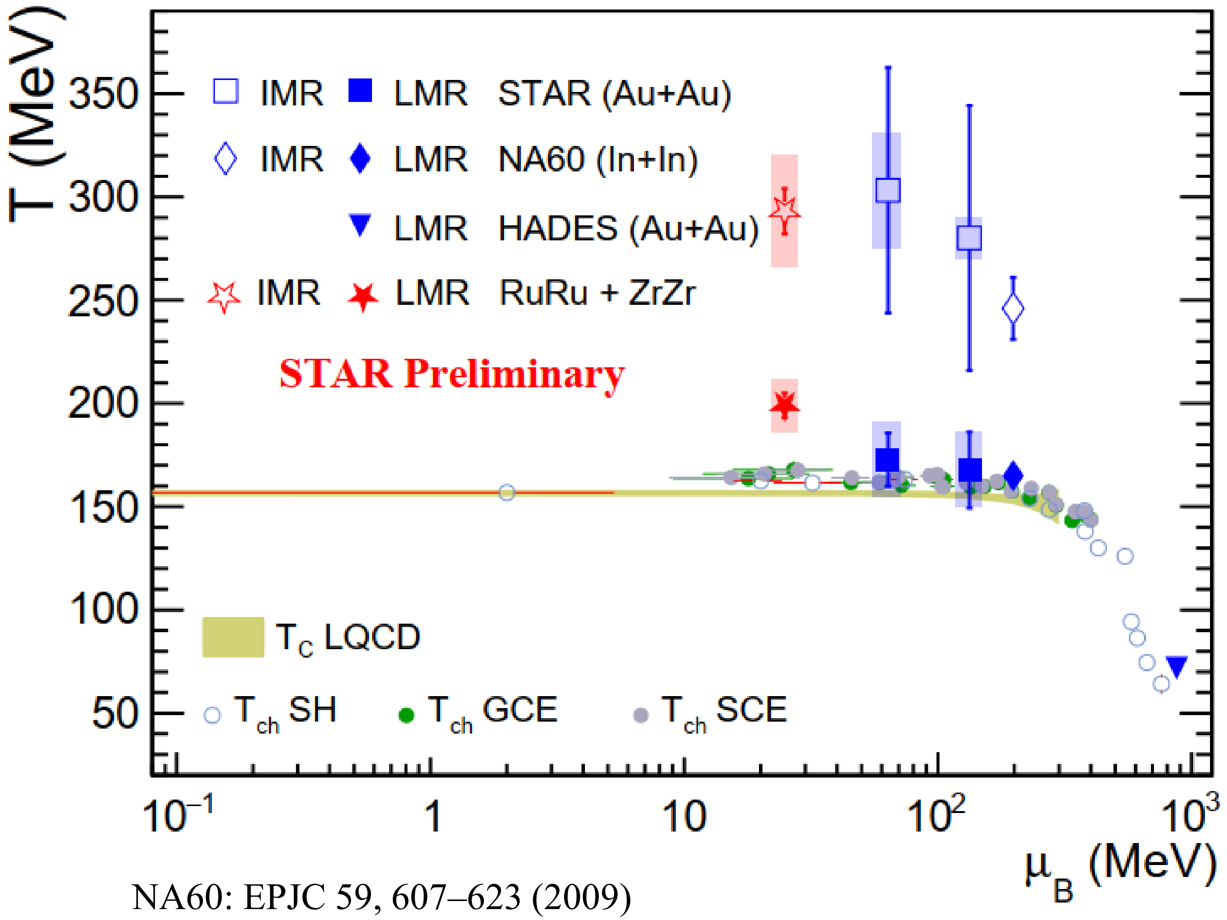
T_{IMR}^{200GeV} = 293 ± 11 (stat.) ± 27 (sys.) MeV

$T_{IMR}^{54.4GeV}$ = 303 ± 59 (stat.) ± 28 (sys.) MeV

T_{IMR}^{27GeV} = 280 ± 64 (stat.) ± 10 (sys.) MeV

$T_{IMR}^{17.3GeV}$ = 245 ± 17 MeV

Temperature vs. μ_B



NA60: EPJC 59, 607–623 (2009)
HADES: Nat. Phys. 15, 1040-1045 (2019)
HotQCD: Phys. Lett. B 795, 15-21 (2019)
T_{ch} SH: P. Braun-Munzinger et al. Nat. 561, 321-330 (2018)
T_{ch} GCE/SCE: STAR Phys. Rev. C 96, 044904 (2017)

Thermal dielectrons in LMR:

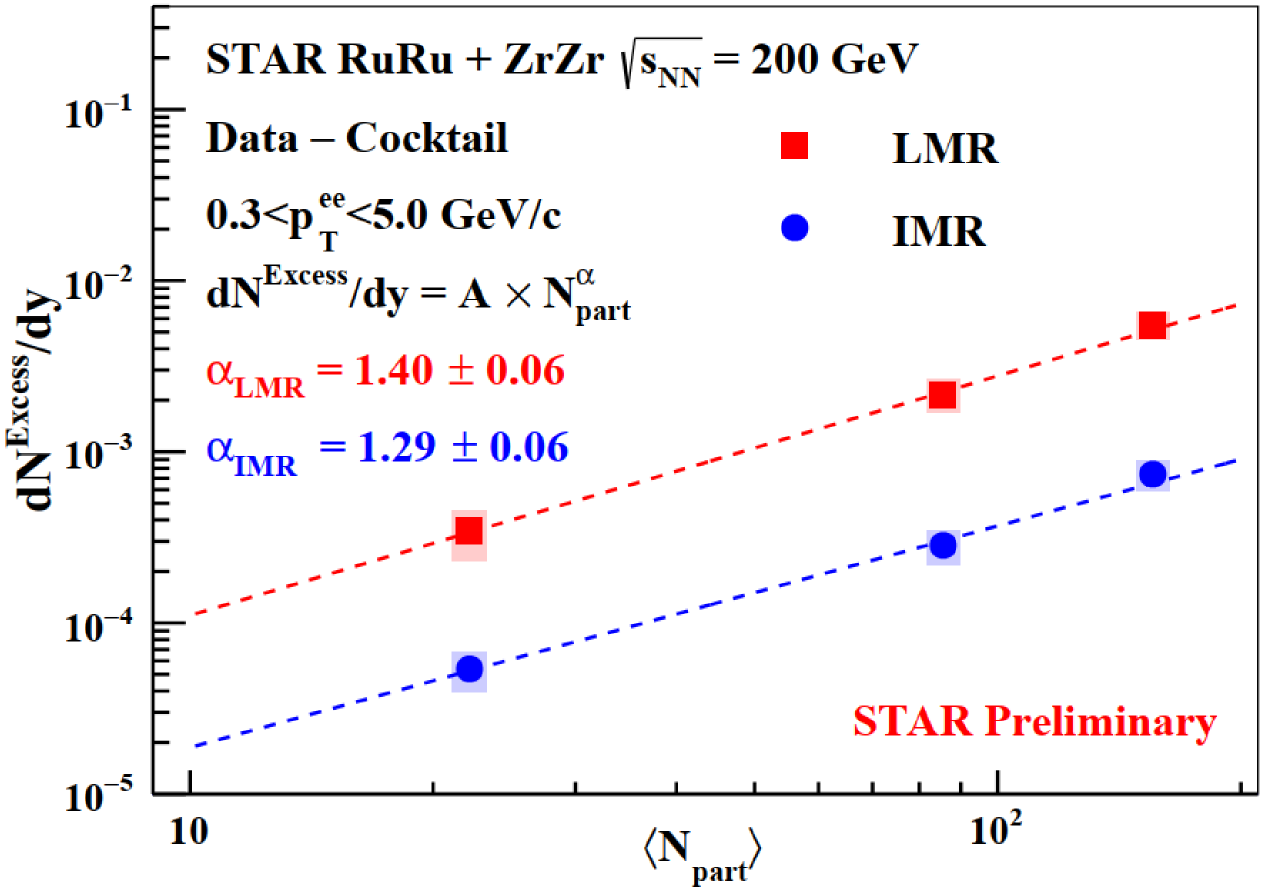
- T_{LMR} at 27 & 54.4 GeV is close to the T_{pc} and T_{ch}
  - ✓ Emitted form the hadronic phase
  - ✓ Dominantly around the **phase transition**
- T_{LMR} at 200 GeV is higher than the T_{pc} and T_{ch}
  - ✓ Hint of **higher QGP contribution**

Thermal dielectrons in IMR:

- T_{IMR} is higher than T_{LMR}, T_{pc} and T_{ch}
- Emitted from the partonic phase

T_{ch}: Chemical freeze-out temperature
T_{pc}: Pseudo critical temperature

Excess Yield vs. N_{part}



Integrated excess yield

- Excess yield in LMR is higher than that in IMR
- Increase with N_{part} in both mass regions

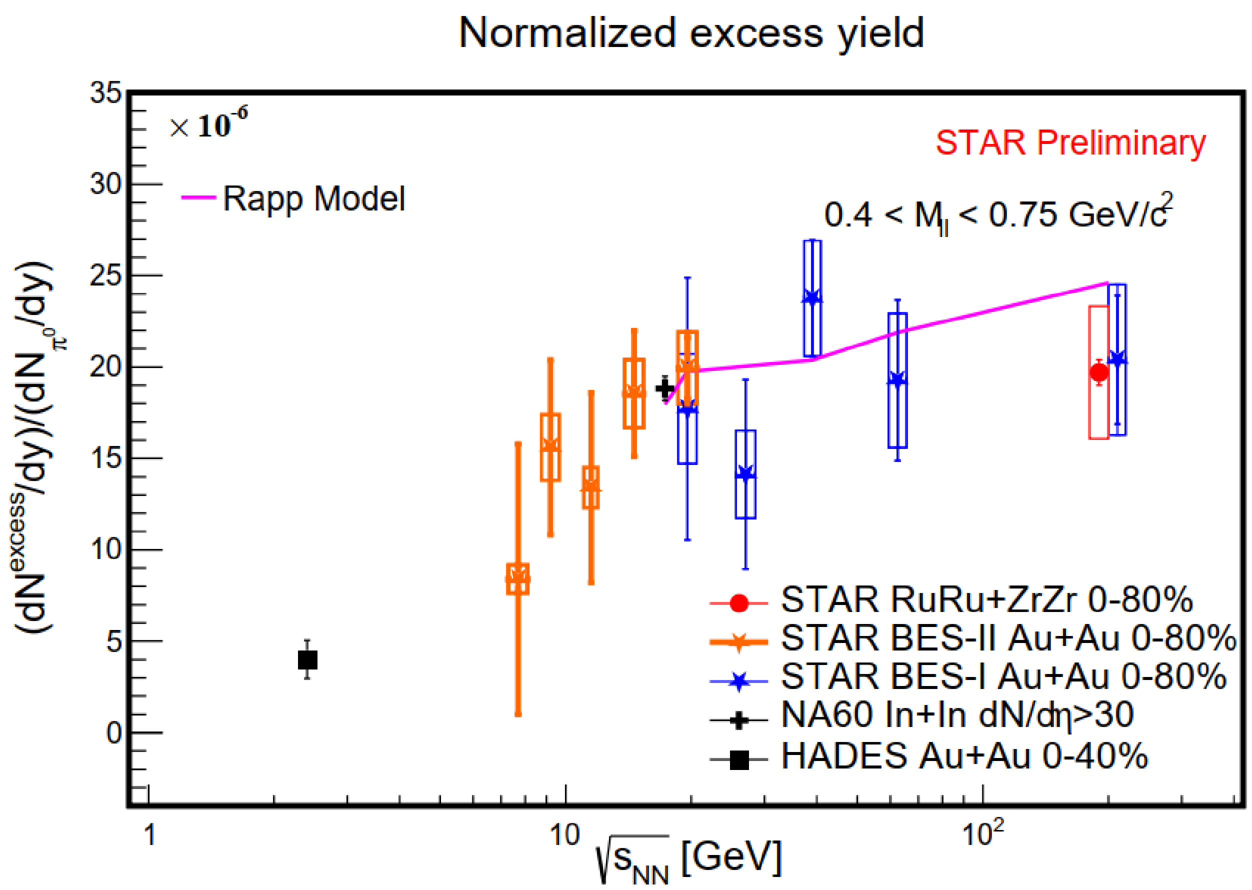
$\alpha_{LMR} = 1.40 \pm 0.06(\text{stat.}) \pm 0.12(\text{sys.})$

$\alpha_{IMR} = 1.29 \pm 0.06(\text{stat.}) \pm 0.07(\text{sys.})$

$\alpha_{\text{thermal photon}}^{\text{200 GeV Au+Au}} = 1.38 \pm 0.03(\text{stat.}) \pm 0.07(\text{sys.})$

PHENIX: Phys. Rev. C 91, 064904 (2015)

Excess yield vs. $\sqrt{s_{NN}}$



Integrated excess yield at different $\sqrt{s_{NN}}$

- Normalized by π^0 yield
- Hint of a decreasing trend from high to low $\sqrt{s_{NN}}$ (higher μ_B)

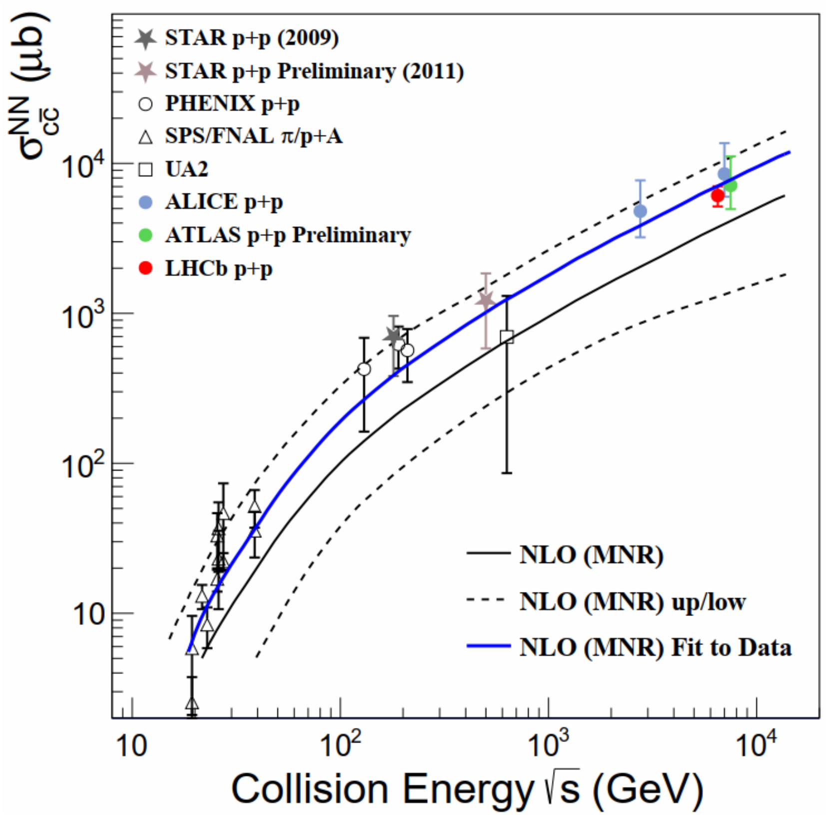
STAR: Phys. Rev. C 107, L061901 (2023)
STAR: Phys. Lett. B 750, 64 (2015)
HADES: Nat. Phys. 15, 1040–1045 (2019)
NA60: EPJC 59, 607–623 (2009)
R. Rapp, Phys. Rev. C 63, 054907 (2001)
H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)

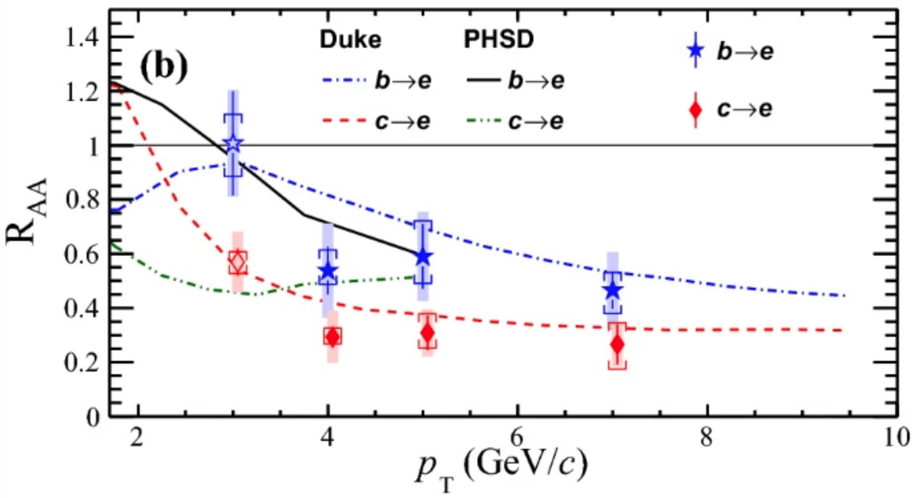
Summary

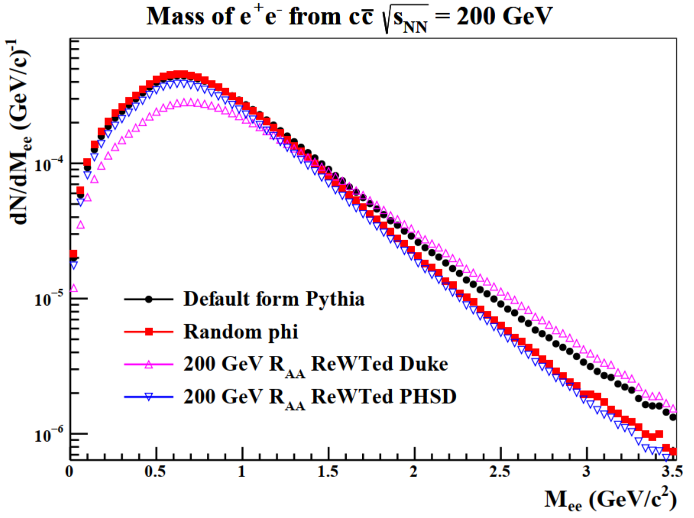
- **Excess mass spectra** in isobar collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV
- **Temperature measurement**:
  - $\mathrm{T_{LMR}}$: **199 ± 6 (stat.) ± 13 (sys.) MeV**
  - ✓ **~3.0 σ** higher than $\mathrm{T_{pc}}$, hint of higher QGP contribution than at lower energies
  - $\mathrm{T_{IMR}}$: **293 ± 11 (stat.) ± 27 (sys.) MeV**
  - ✓ **~4.7 σ** higher than $\mathrm{T_{pc}}$, strong evidence for the existence of QGP
  - ✓ Temperature measurement at 200 GeV without distortion by medium flow
- **Thermal dielectron yields**
  - Integrated excess yield increase with N_{part}
  - Hint of a decreasing trend with decreasing $\sqrt{s_{\mathrm{NN}}}$ in normalized integrated excess yield

Backup

Systematic uncertainty







- The extracted temperature difference to default will the systematic uncertainty of temperatures
- $c\bar{c}$ cross section as a function of collision energy
- $c\bar{c}$ decorrelation: the angles of the single electron and positron are randomly assigned
- Charm R_{AA} reweight: re-weight the p_T of the e^+ and e^- with the theoretical predictions from the Duke model and the PHSD model

Cross section: STAR, arXiv: 2402.01998
R_{AA}: STAR, Eur. Phys. J. C 82, 1150 (2022)
Duke model: Phys. Rev. C 92, 024907 (2015)
PHSD model: Phys. Rev. C 78, 034919 (2008)