# Thermal dielectron measurements with the STAR experiment

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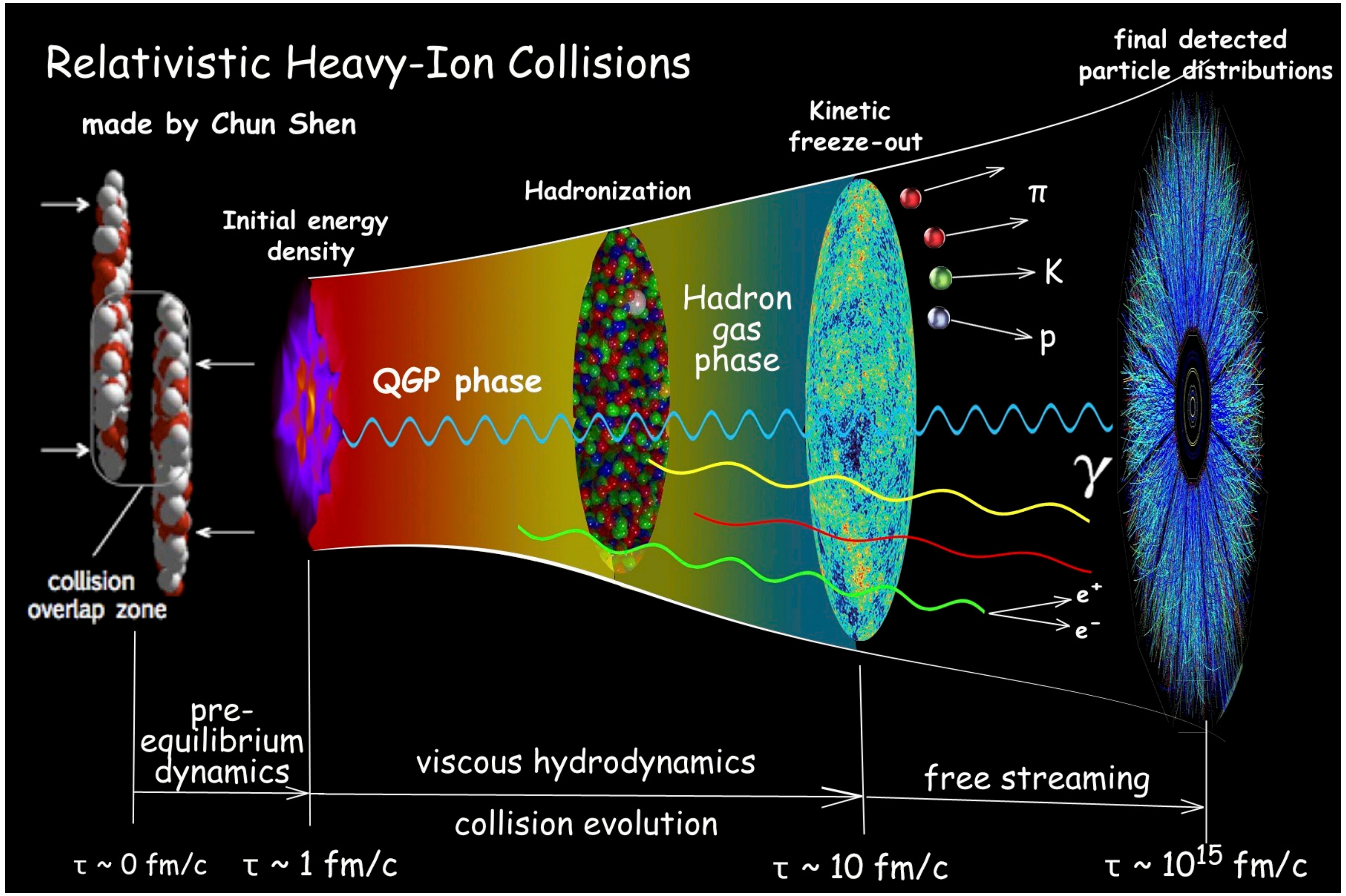
中国科学技术大学
University of Science and Technology of China

STAR Collaboration

# A "Little Bang" in Heavy Ion Collision

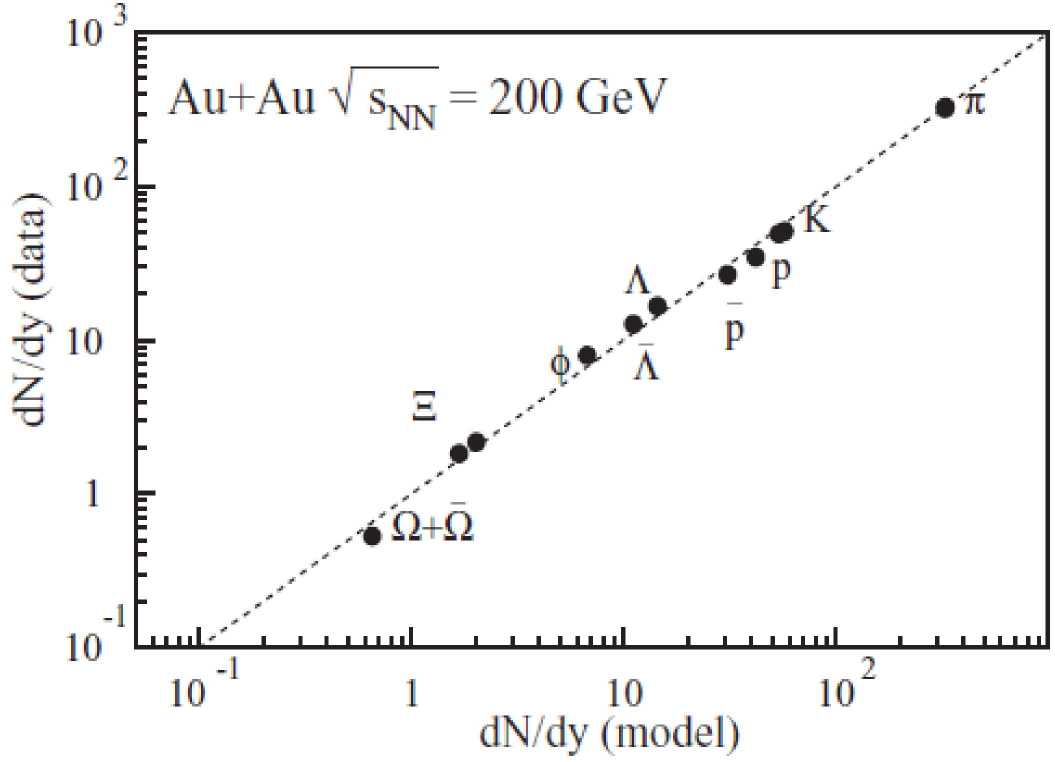



*C.Shen https://u.osu.edu/vishnu/2014/08/06/sketch-of-relativistic-heavy-ion-collisions*

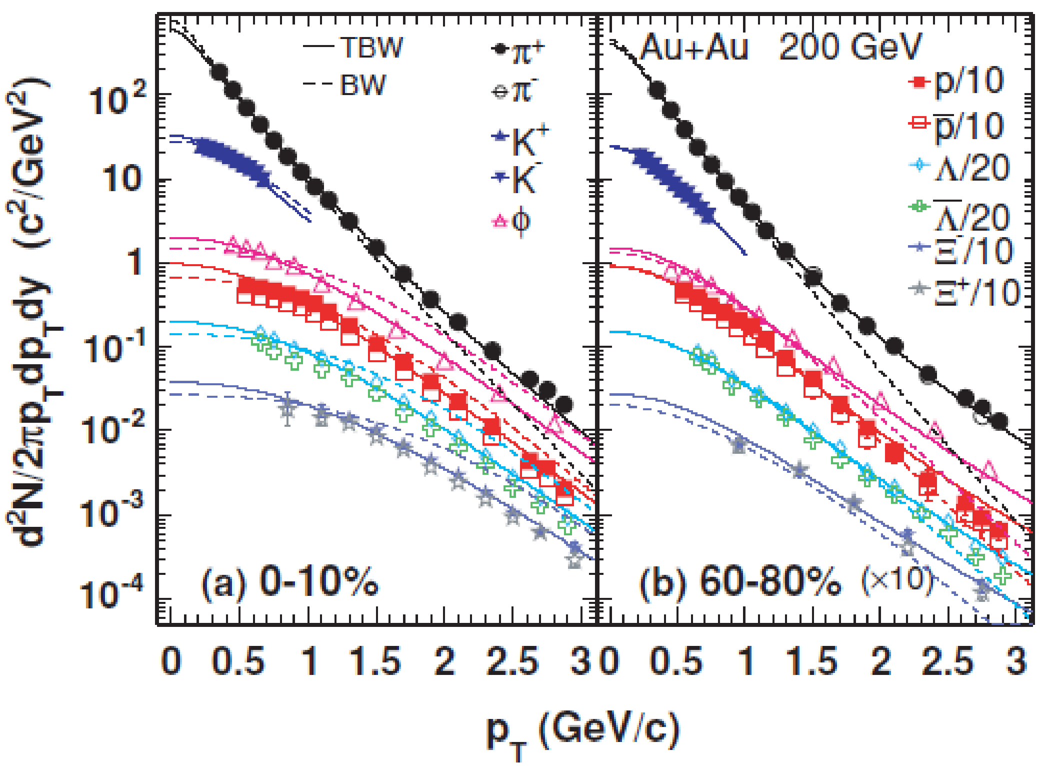
- Deconfined QCD matter produced at extreme high temperature and/or baryon density
- Create and study QGP in heavy ion collisions
- Temperature, one of key properties characterizing the medium, remains poorly known

# How to measure temperature

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




*J. Manninen and F. Becattini, Phys. Rev. C 78 054901 (2008)*




*Z. Tang, et al., Phys. Rev. C 79, 051901 (2009)*

# How to measure temperature

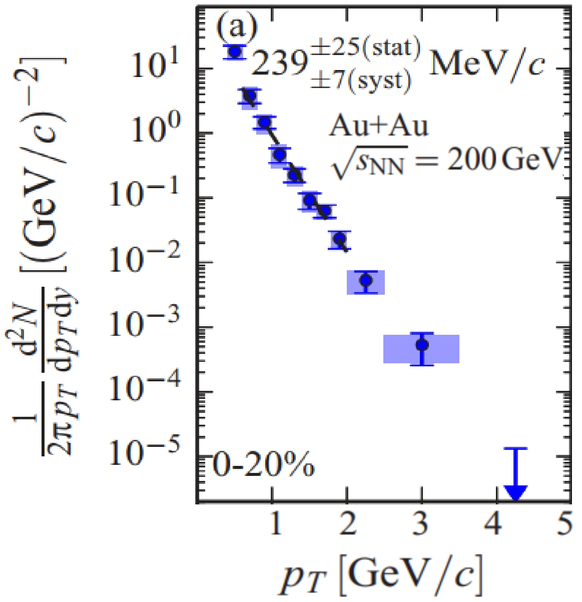
**Hadrons (Yield, $p_T$)** → Statistical model / Hydrodynamics-inspired models → Chemical freeze-out $T_{ch}$ / Kinetic freeze-out $T_{kin}$

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

**Photons ($p_T$)** →
- Extract $T_{eff}$ from $p_T$ spectra
- Modification from **blue-shift effect**

**Dileptons ($M_{ll}$)**

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



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**Photons ($p_T$)** →

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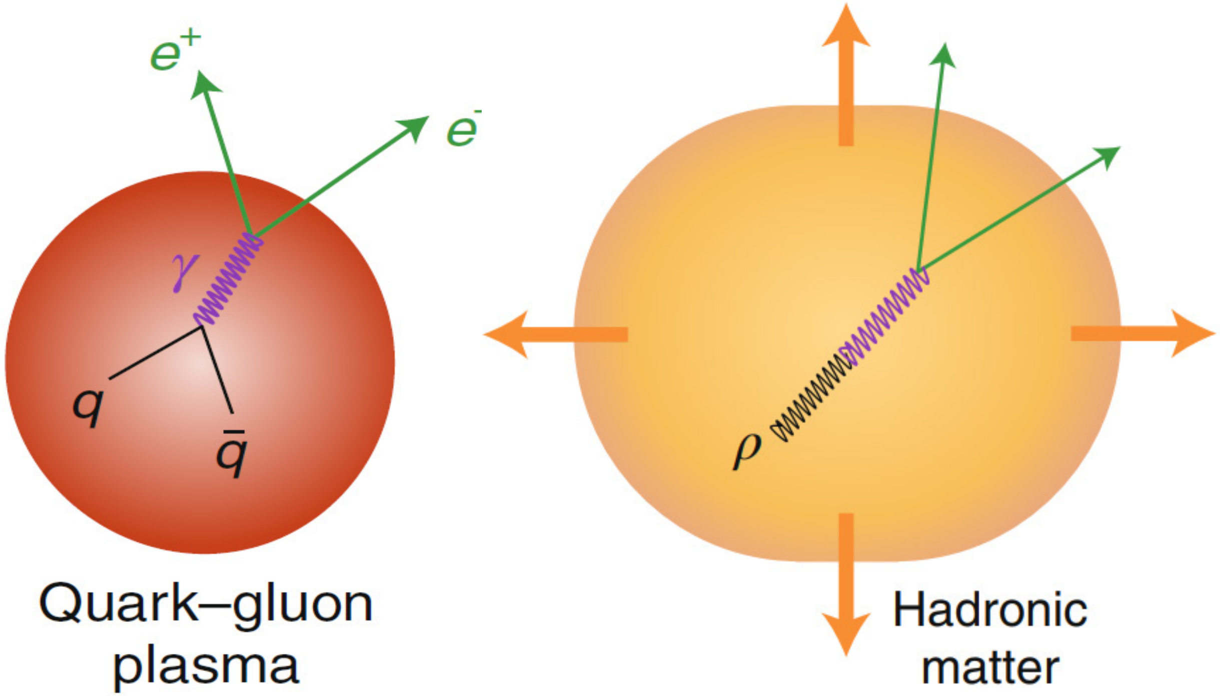
- Modification from blue-shift effect

**Dileptons ($M_{ll}$)** →

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

# Thermal Dileptons

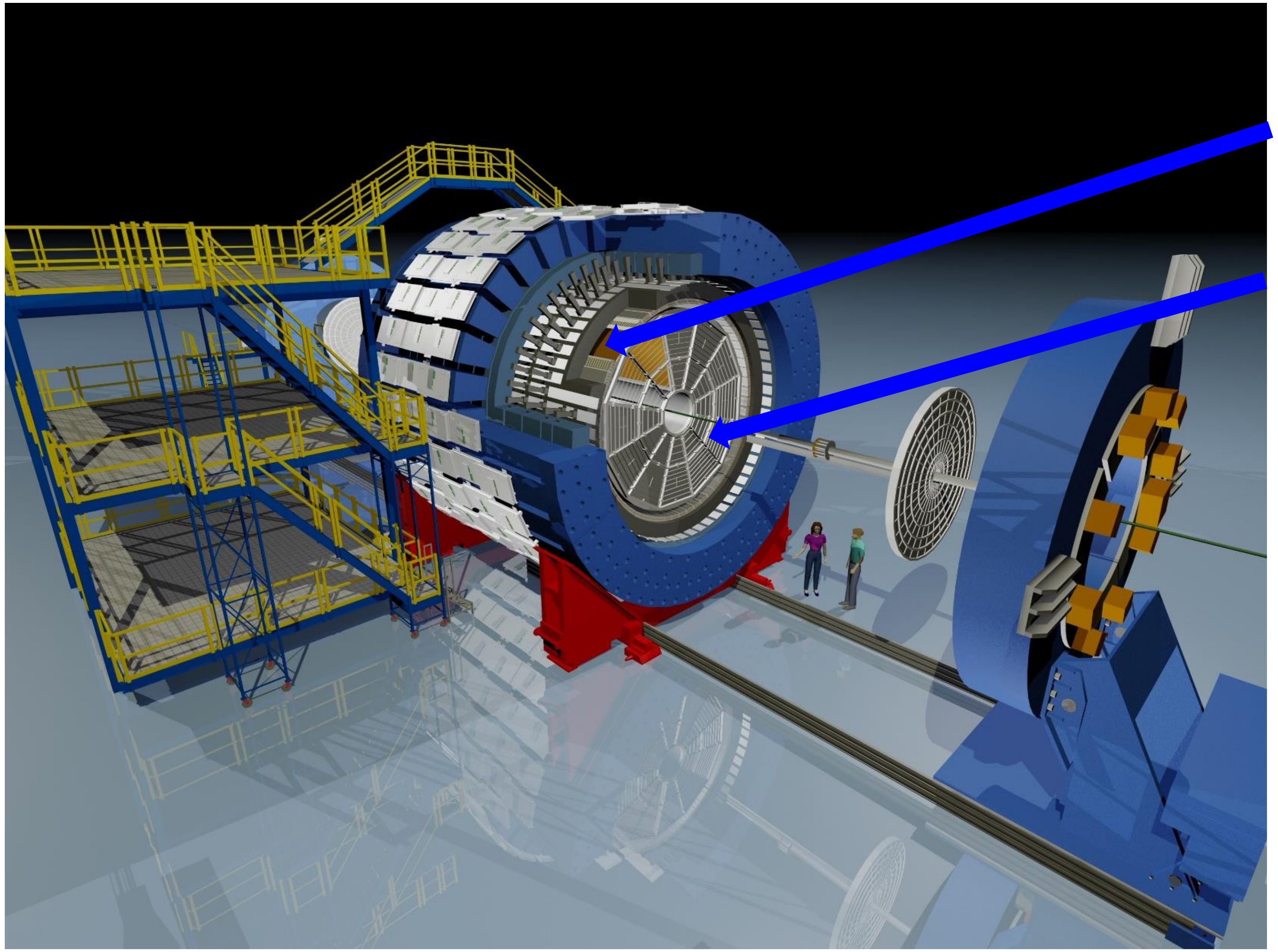
**QGP:** $M^{3/2} * e^{-M/T}$ **In-med. $\rho$:** Relativistic Breit-Wigner $* e^{-M/T}$




*R. Rapp, Nat. Phys. 15, 990–991 (2019)*
*HADES, Nat. Phys. 15, 1040–1045 (2019)*
*STAR, Phys. Rev. Lett. 92, 092301 (2004)*
*STAR, Phys. Rev. Lett. 113 22301 (2014)*

➢ Thermometer: **invariant mass spectra** of thermal dileptons can reveal temperature of the hot medium at both QGP phase and hadronic phase

# STAR experiment



- ✓ **TOF:**

Time of flight, particle identification

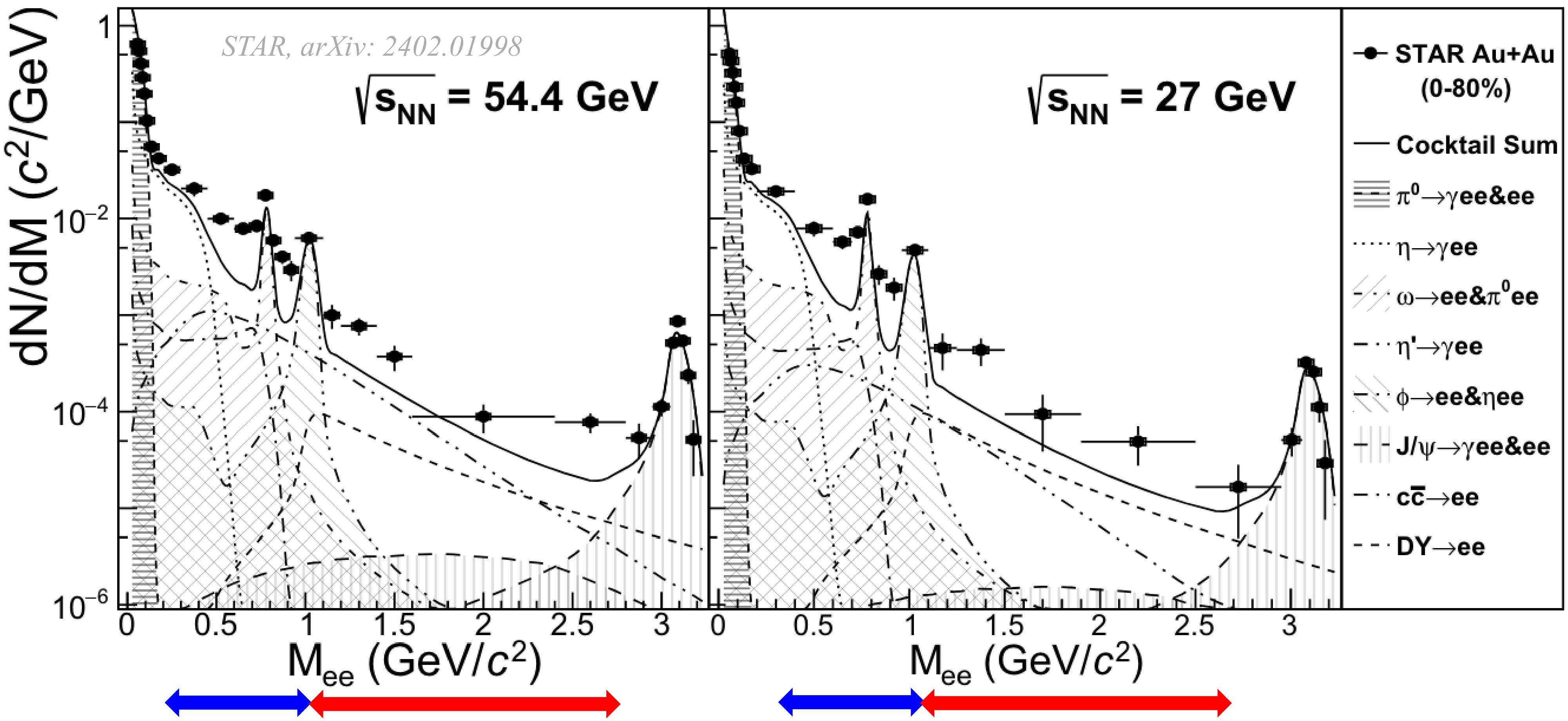
- ✓ **TPC:**

Tracking, momentum and energy loss

Collision species

- Au+Au at $\sqrt{s_{\text{NN}}}$ = 7.7 – 54.4 GeV
- Ru+Ru/Zr+Zr at $\sqrt{s_{\text{NN}}}$ = 200 GeV

# Dielectron spectra at 27 and 54.4 GeV

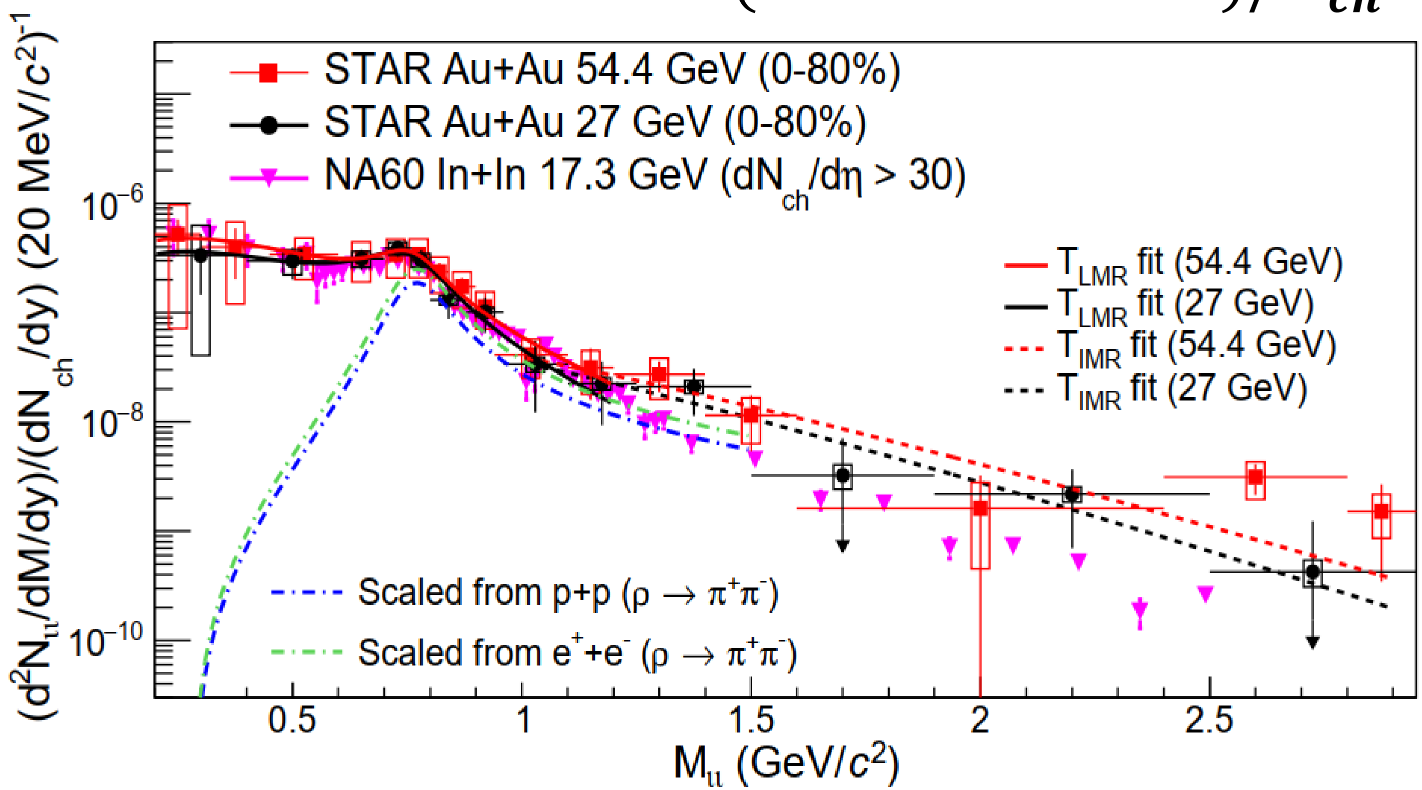



Clear enhancement compared to hadronic cocktail in both low mass region (LMR) and intermediate mass region (IMR)

**Thermal dileptons = Inclusive signal – Physical background**

# Temperature measurement at 27 and 54.4 GeV

**Normalized Excess = (Data − Cocktail)/$N_{ch}$**




| Collisions System | T at LMR (MeV) | T at IMR (MeV) |
|---|---|---|
| 54.4 GeV Au+Au | 172 ± 12 (stat.) ± 18 (sys.) | 303 ± 59 (stat.) ± 28 (sys.) |
| 27 GeV Au+Au | 167 ± 21 (stat.) ± 18 (sys.) | 280 ± 64 (stat.) ± 10 (sys.) |
| 17.3 GeV In+In | 165 ± 4 | 245 ± 17 |

## Low Mass Region

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

- Similar $T_{LMR}$ for STAR and NA60 measurements
- $T_{LMR}$ ~ pseudo critical temperature $T_{pc}$ (156 MeV)

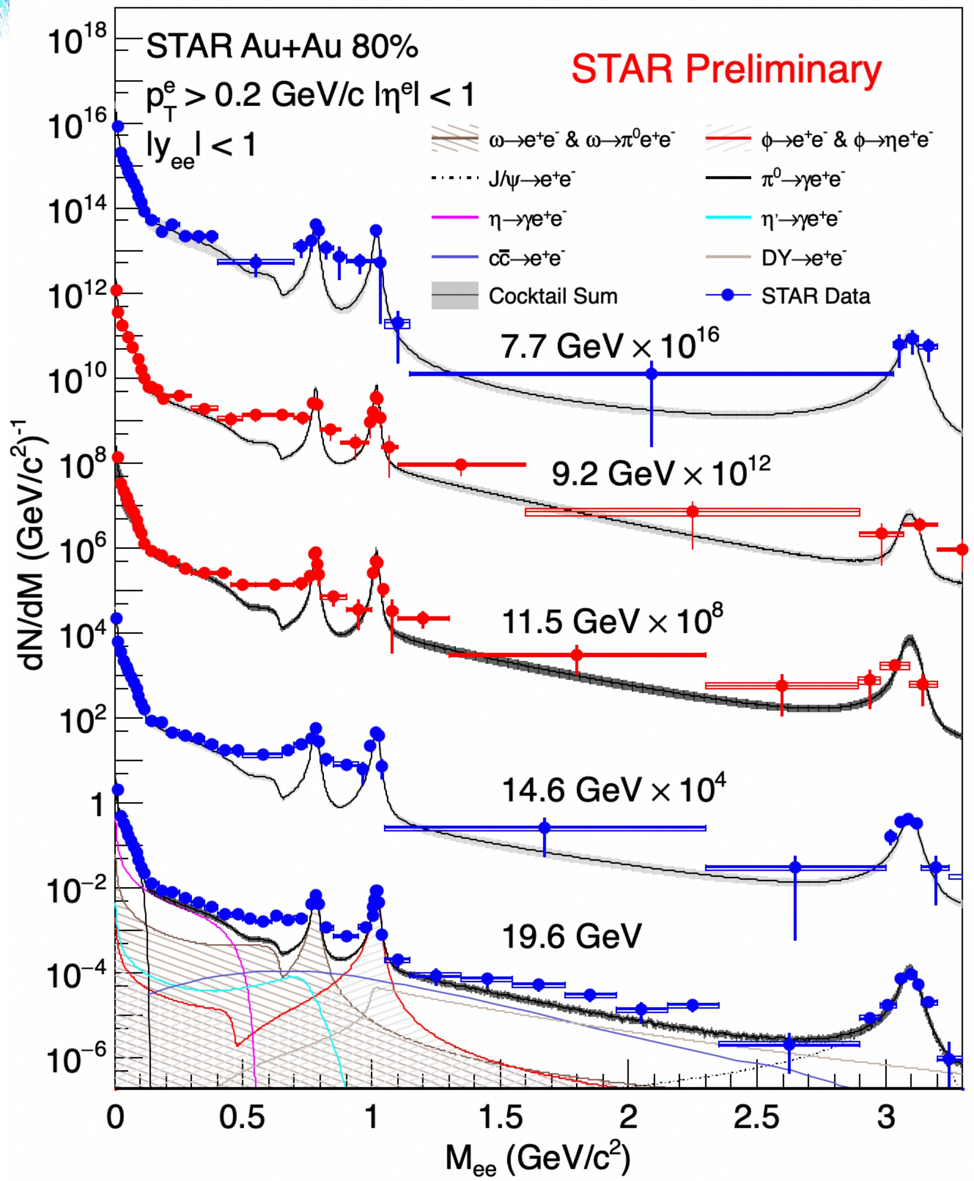
## Intermediate Mass Region

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

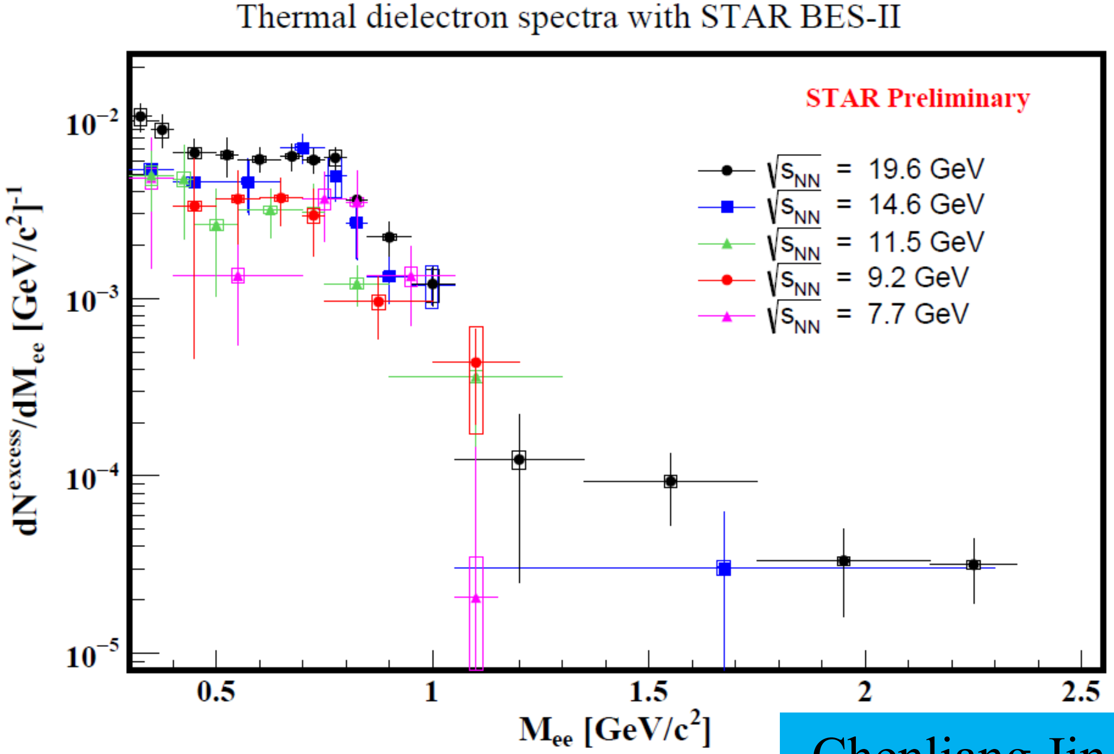
- QGP thermal radiation is predicted to be the dominant source
- $T_{IMR}$ is **higher** than $T_{pc}$


*STAR, arXiv: 2402.01998*
*NA60: EPJC 59, 607–623 (2009)*
*$T_{pc}$: HotQCD, Phys. Lett. B 795, 15-21 (2019)*

# STAR BES-II dielectron spectra



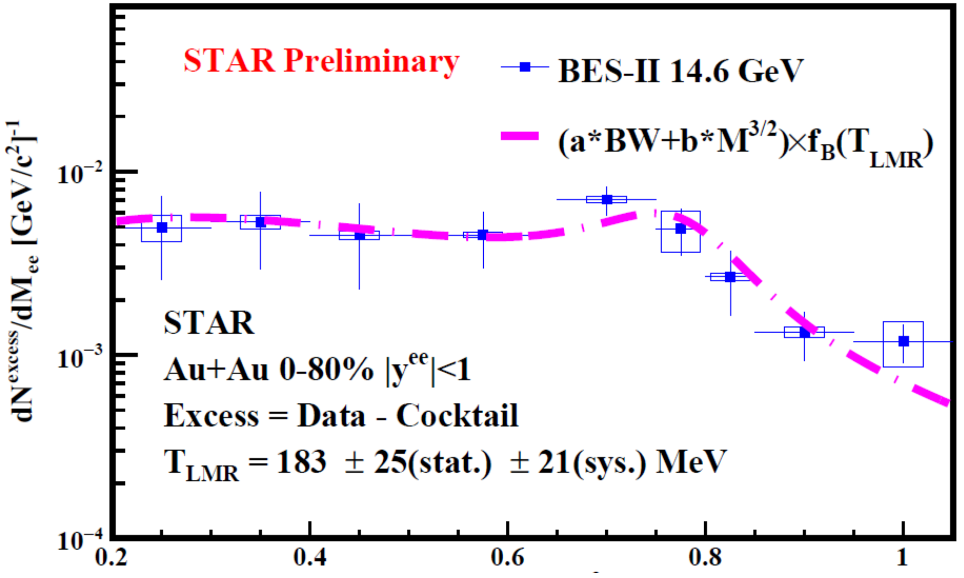

Excess yield observed in Au+Au collisions at BES-II energies ($\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6 and 19.6 GeV)

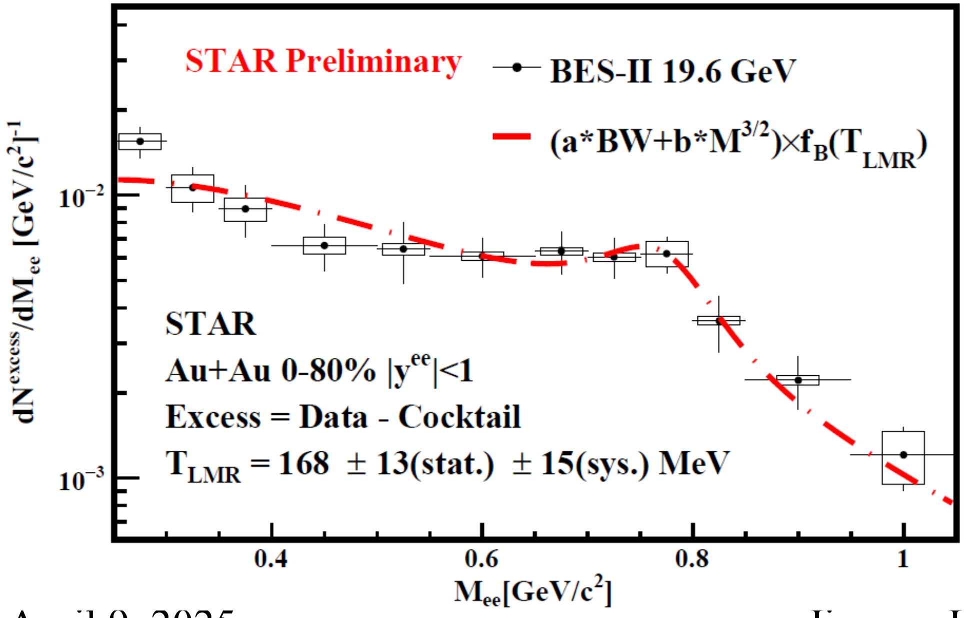



**Excess = Data - Cocktail**

Chenliang Jin
Poster ID: 666

# Temperature measurement at 14.6 and 19.6 GeV




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

$\mathbf{T_{LMR}^{BESII\ 14.6\ GeV} = 183 \pm 25\ (stat.) \pm 21\ (sys.)\ MeV}$

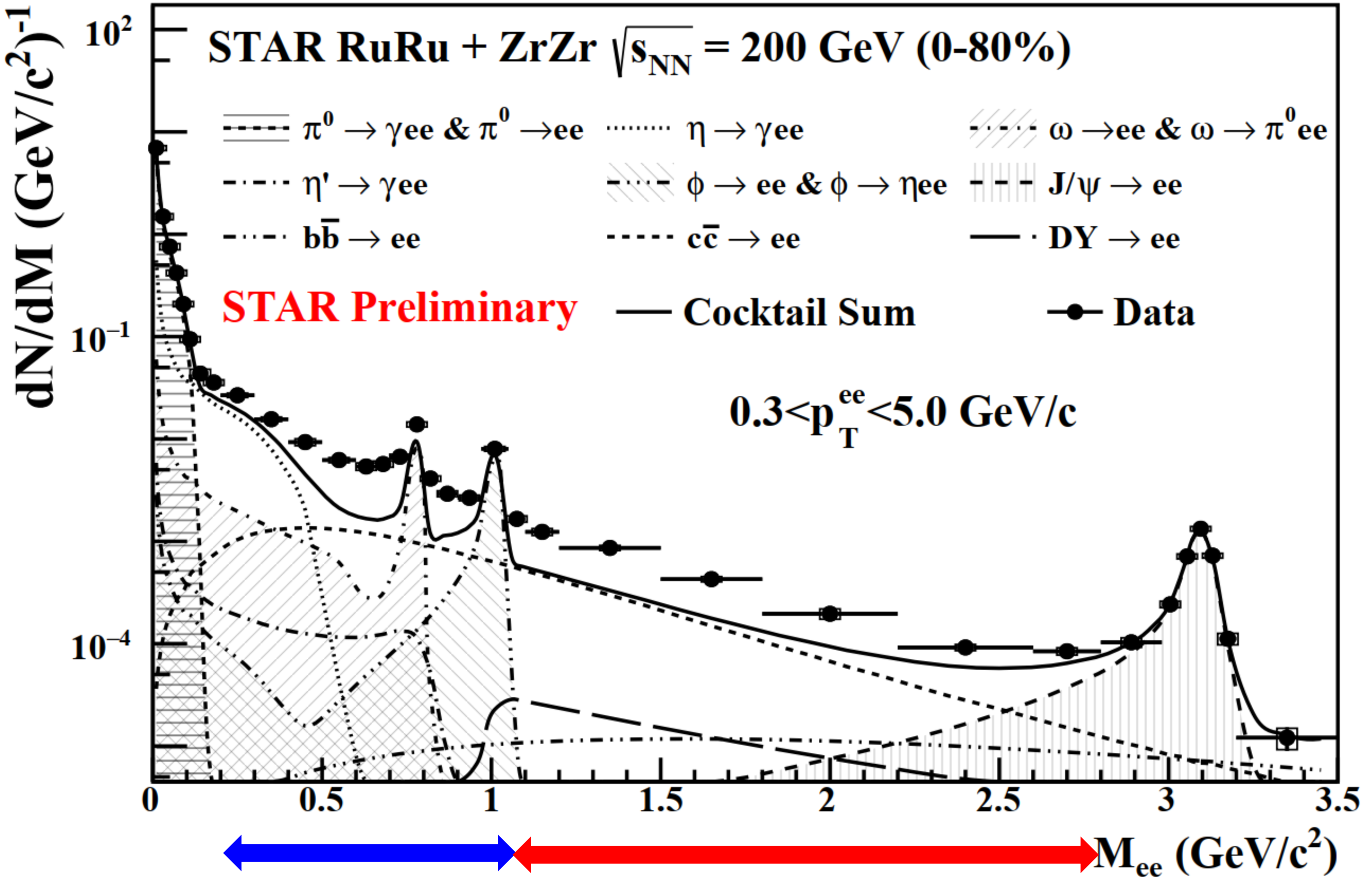
$\mathbf{T_{LMR}^{BESII\ 19.6\ GeV} = 168 \pm 13\ (stat.) \pm 15\ (sys.)\ MeV}$

LMR temperature extraction

- T is close to pseudo critical temperature
- Thermal dielectron is mainly produced around the phase transition

Chenliang Jin
Poster ID: 666

# Dielectron spectra in isobar collisions

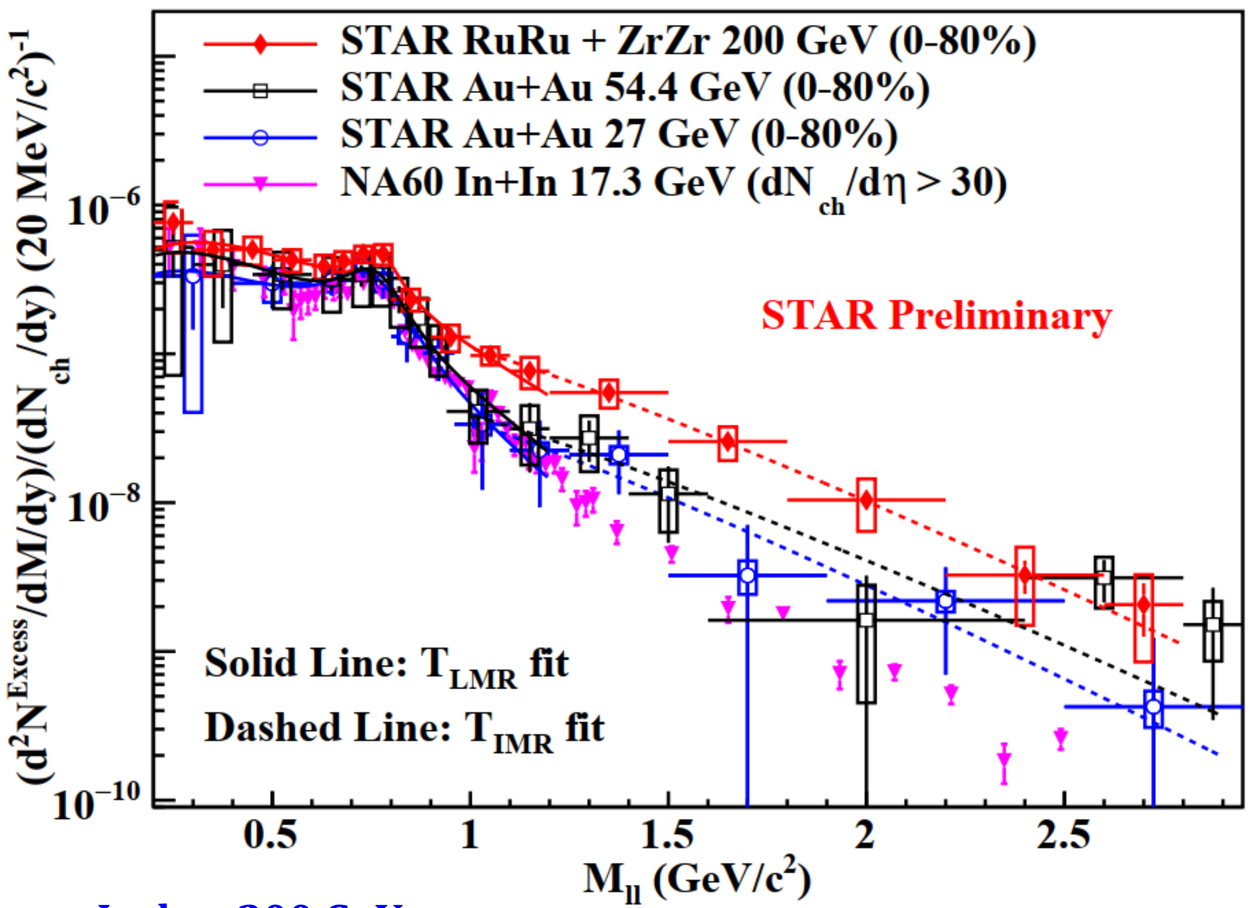



➢ The highest-precision dielectron measurement at RHIC

➢ Clear enhancement compared to cocktail in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV

# Temperature measurement in isobar collisions

**Normalized Excess = (Data − Cocktail)/$N_{ch}$**




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

$T_{IMR}^{Isobar\ 200\ GeV} = 293 \pm 11\ (stat.) \pm 27\ (sys.)\ MeV$

## Low Mass Region

- $T_{LMR}$ at 200 GeV higher than $T_{pc}$
- Hint of QGP radiation or non-equilibrium contribution

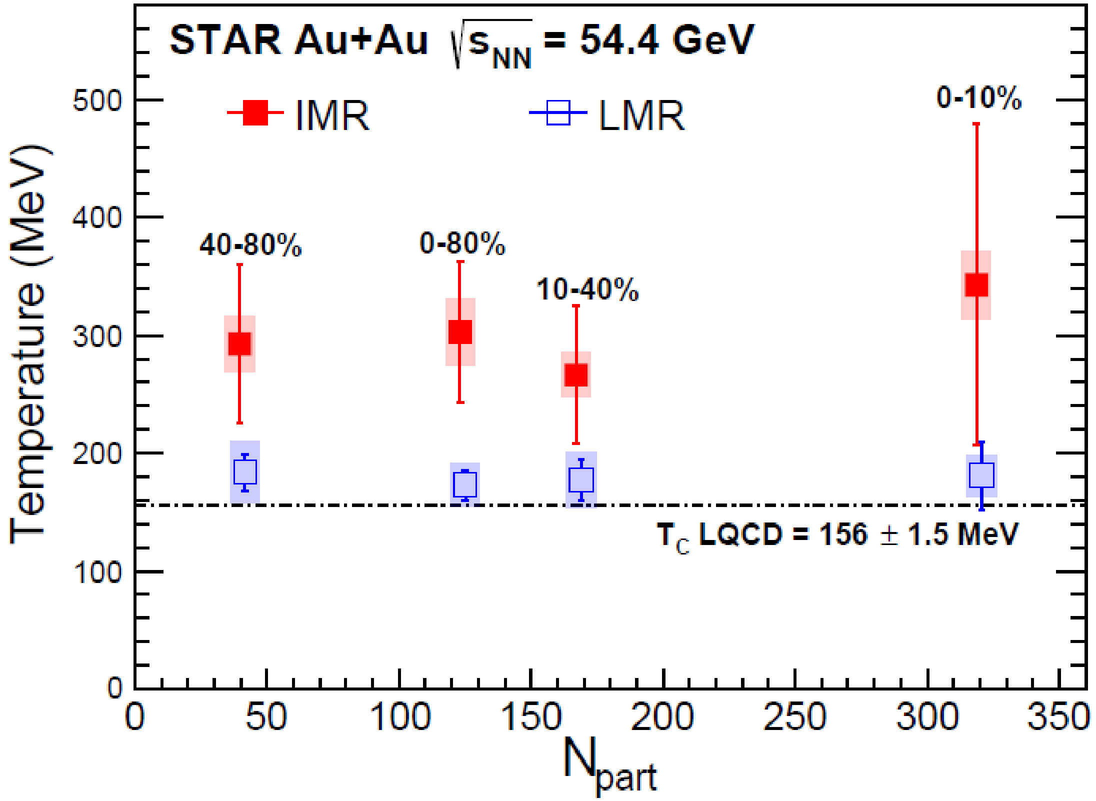
## Intermediate Mass Region

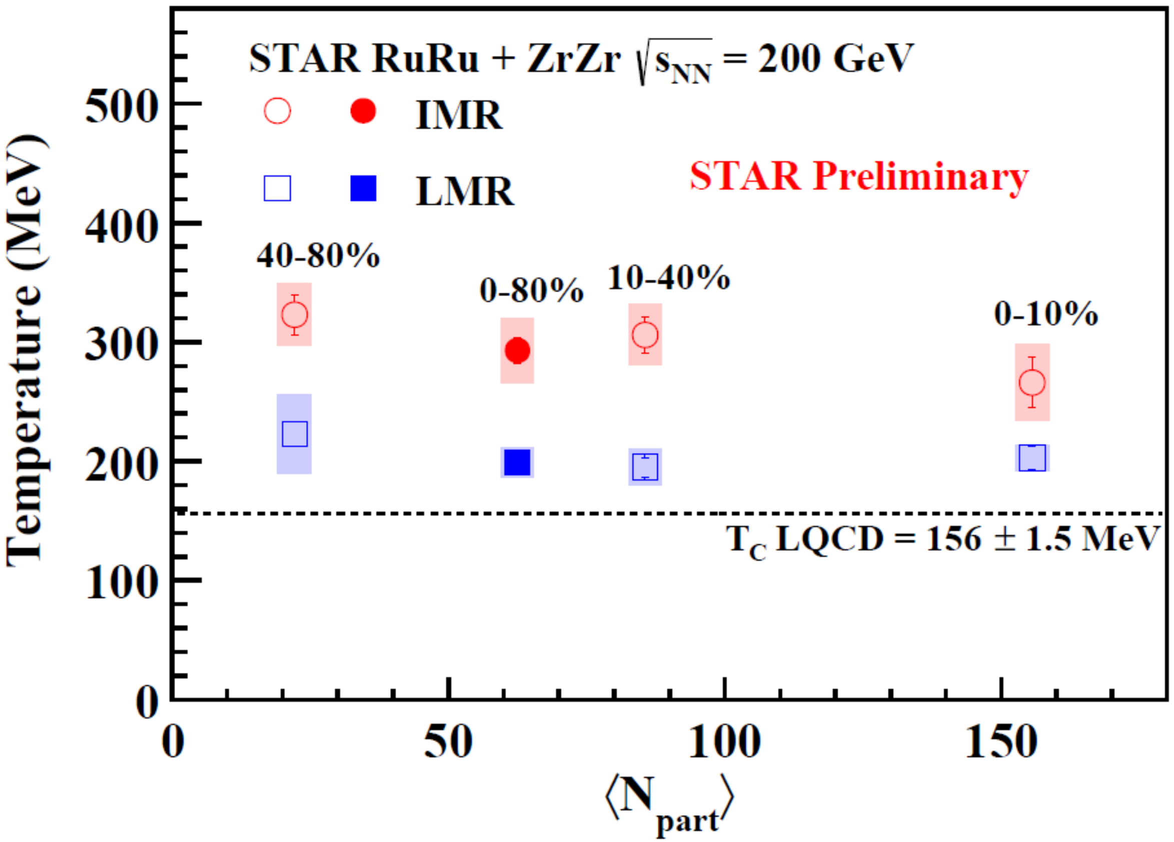
- Normalized excess yield at 200 GeV higher than that at lower energies
- $T_{IMR}$ ~ 4.7 $\sigma$ higher than $T_{pc}$, emitted from the partonic phase

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

# Temperature vs. $N_{part}$

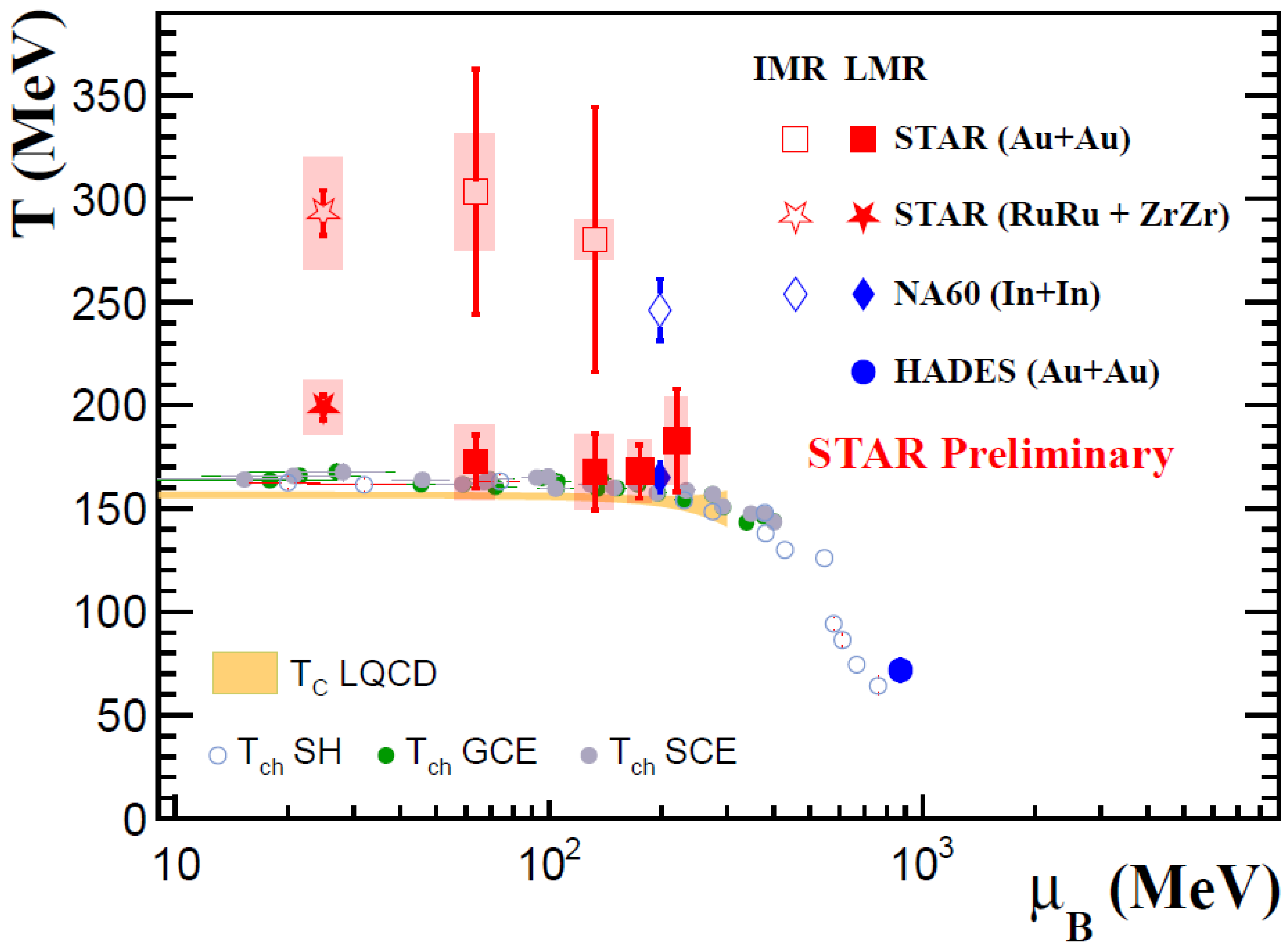
*STAR, arXiv: 2402.01998*




- **No clear centrality dependence in both mass regions**
- Temperature from IMR is higher than that in LMR

# Temperature vs. $\mu_B$

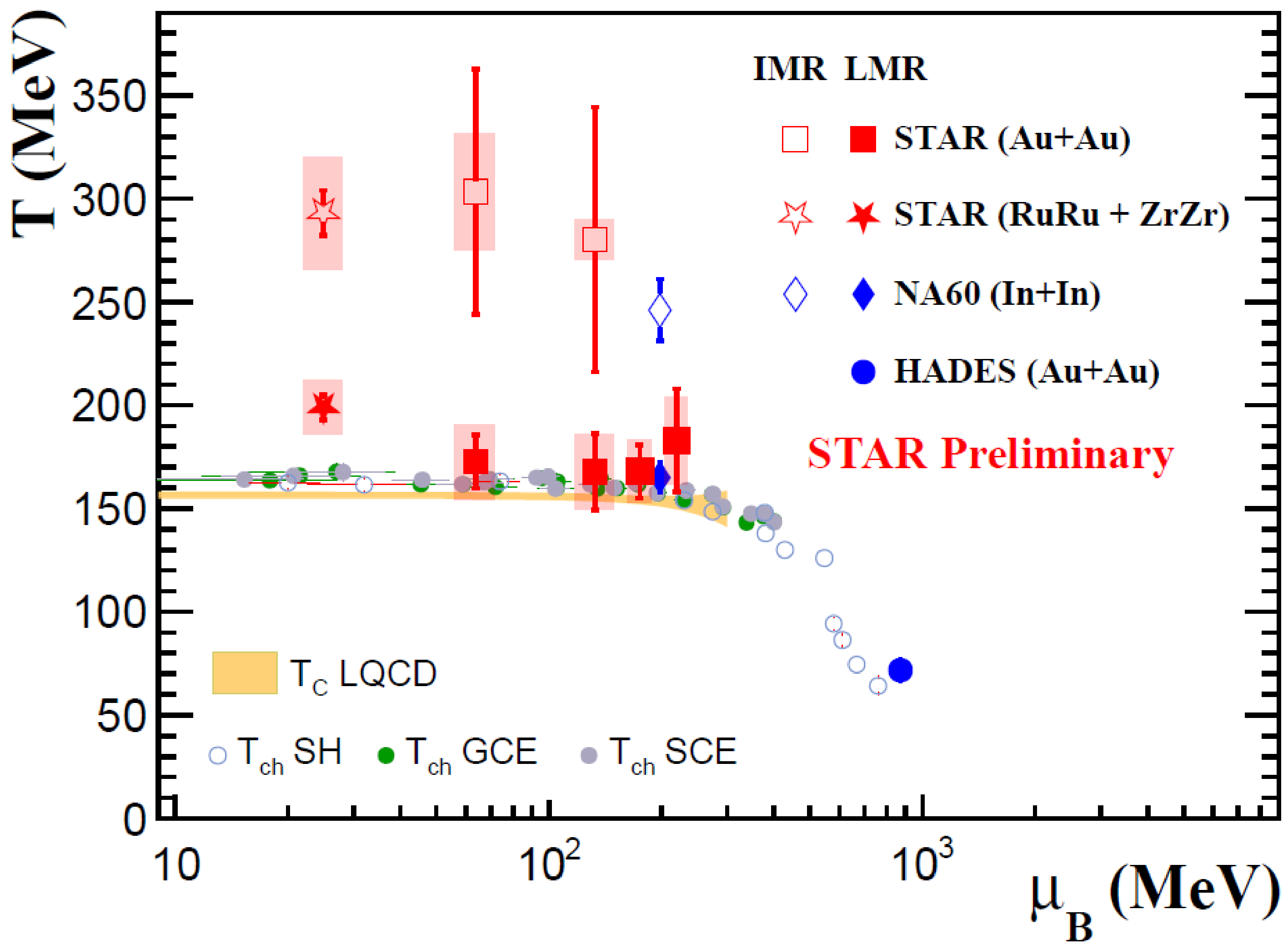



**Thermal dielectrons in LMR**

- $T_{LMR}$ at lower energies ~ $T_{pc}$ 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 $T_{ch}$, indication of QGP radiation or non-equilibrium contribution

*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)*

# Temperature vs. $\mu_B$




**Thermal dielectrons in IMR**

- $T_{IMR}$ is higher than $T_{LMR}$, $T_{pc}$ and $T_{ch}$
- Emitted from the partonic phase
- **Strong evidence of thermal radiation from early QGP**

*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)*
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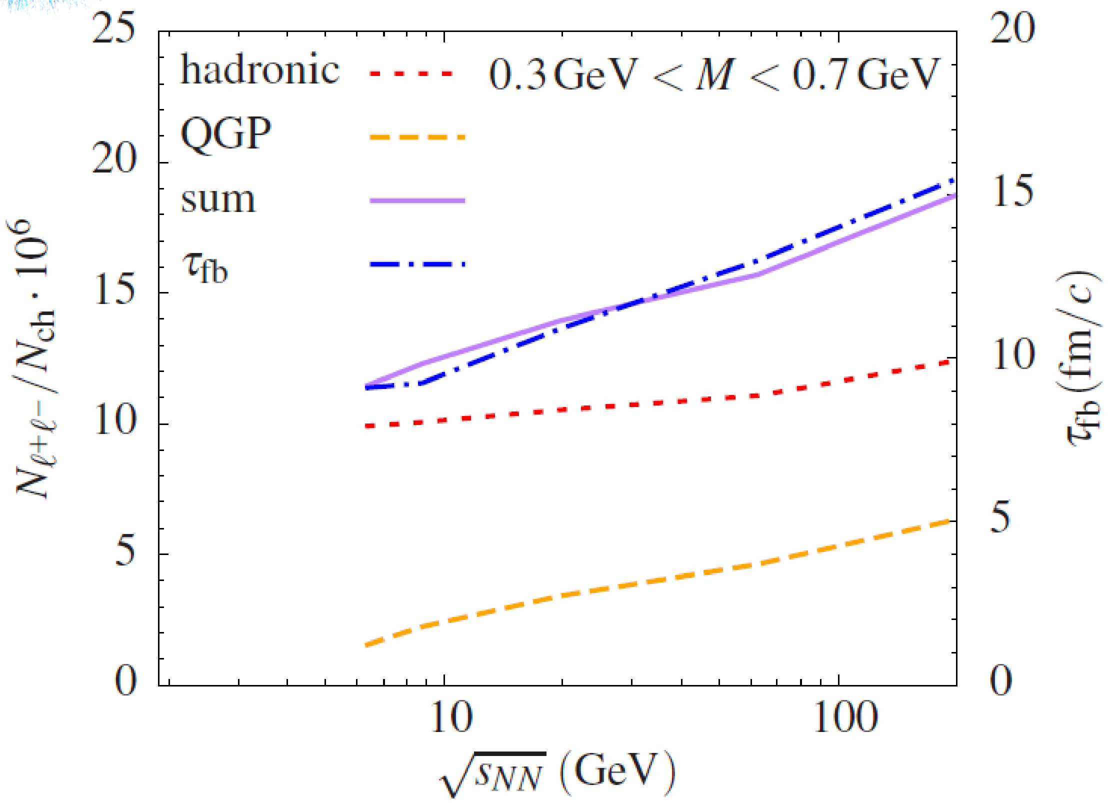
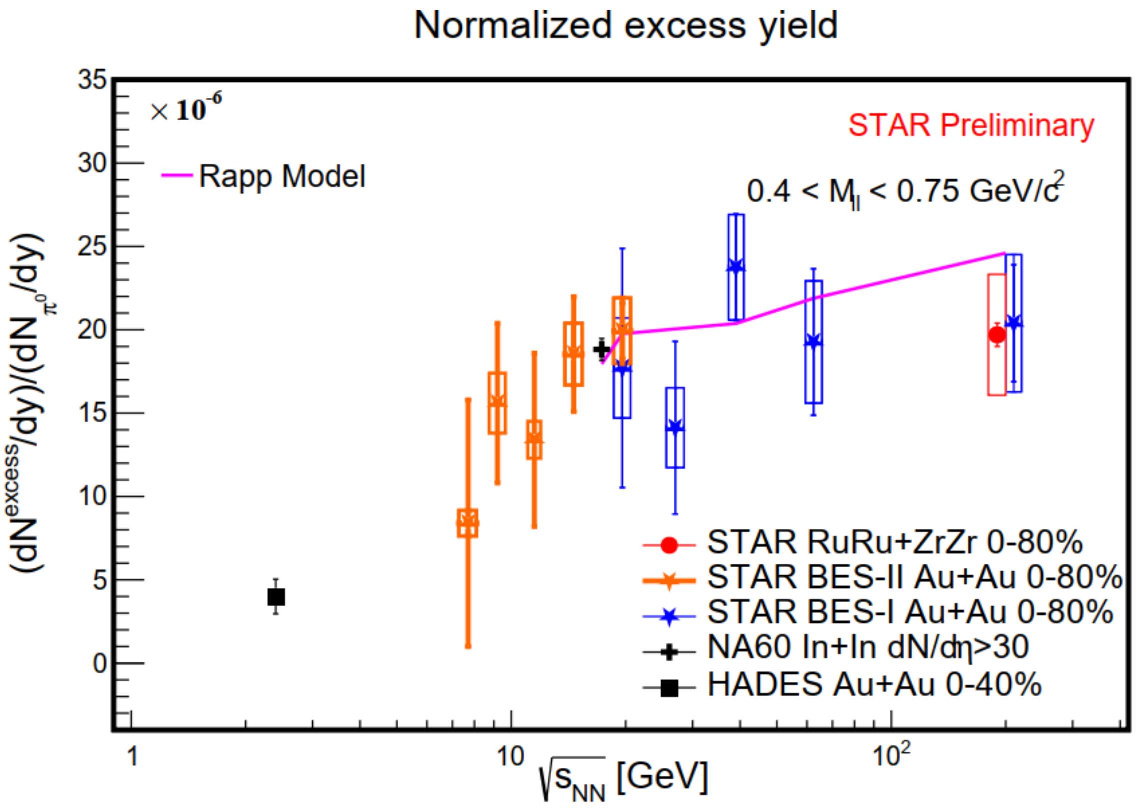
# Excess yield vs. $\sqrt{s_{\mathrm{NN}}}$




- **Chronometer**: the normalized integrated yield is sensitive to lifetime
- Hint of a decreasing trend from high to low $\sqrt{s_{\mathrm{NN}}}$ (higher $\mu_B$)

*R. Rapp, EPJA 52, 257 (2016)* *R. Rapp, Phys. Rev. C 63, 054907 (2001)*
*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)*
*H. van Hees and R. Rapp, Phys. Rev. Lett. 97, 102301 (2006)*

# Summary and Outlook

**Thermal dielectron mass spectra** in Au+Au collisions at 7.7 – 54.4 GeV and isobar collisions at 200 GeV are measured

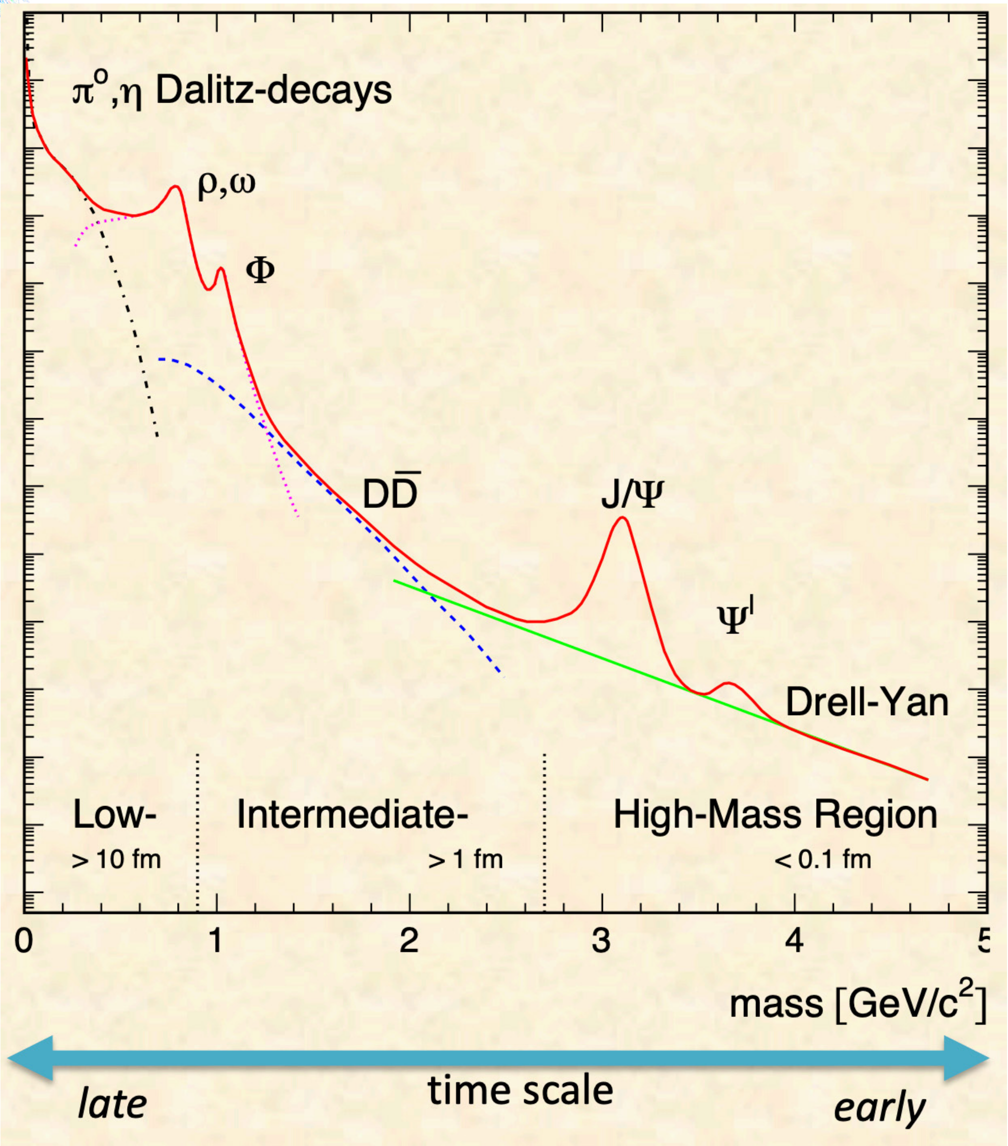
- Low mass region:
  - ✓ Temperature close to $T_{pc}$ at lower energies, higher than $T_{pc}$ at 200 GeV
  - ✓ Normalized integrated excess yield: hint of **decreasing trend** towards lower collision energy
- Intermediate mass region temperature:
  - ✓ **Significantly higher** than $T_{pc}$, strong evidence of thermal radiation from early QGP

## Outlook

- ➢ Transverse momentum dependence of thermal dielectron production
- ➢ Collision species dependence of thermal dielectron temperature
- ➢ Angular dependence of thermal dielectron production

# Backup

# Dilepton invariant mass spectrum




courtesy of Axel Drees

**High Mass Range**

- Drell-Yan: $q\bar{q} \rightarrow e^{+}e^{-}$
- Heavy quarkonia: J/ψ and ψ(2s)

**Intermediate Mass Range**

- QGP thermal radiation
- Heavy flavor quark semi-leptonic decay: $c\bar{c} \rightarrow e^{+}e^{-}X$

**Low Mass Range**

- In-medium vector mesons
- Light meson decays: $\pi^{0}$, $\eta$ Dalitz decays

# Signal and Physical background

**Inclusive signal (combinatorial background subtracted)**

**Interested signals:**

- **QGP radiation**
- **In-medium $\rho$ decays**

**Physical background (Cocktails):**

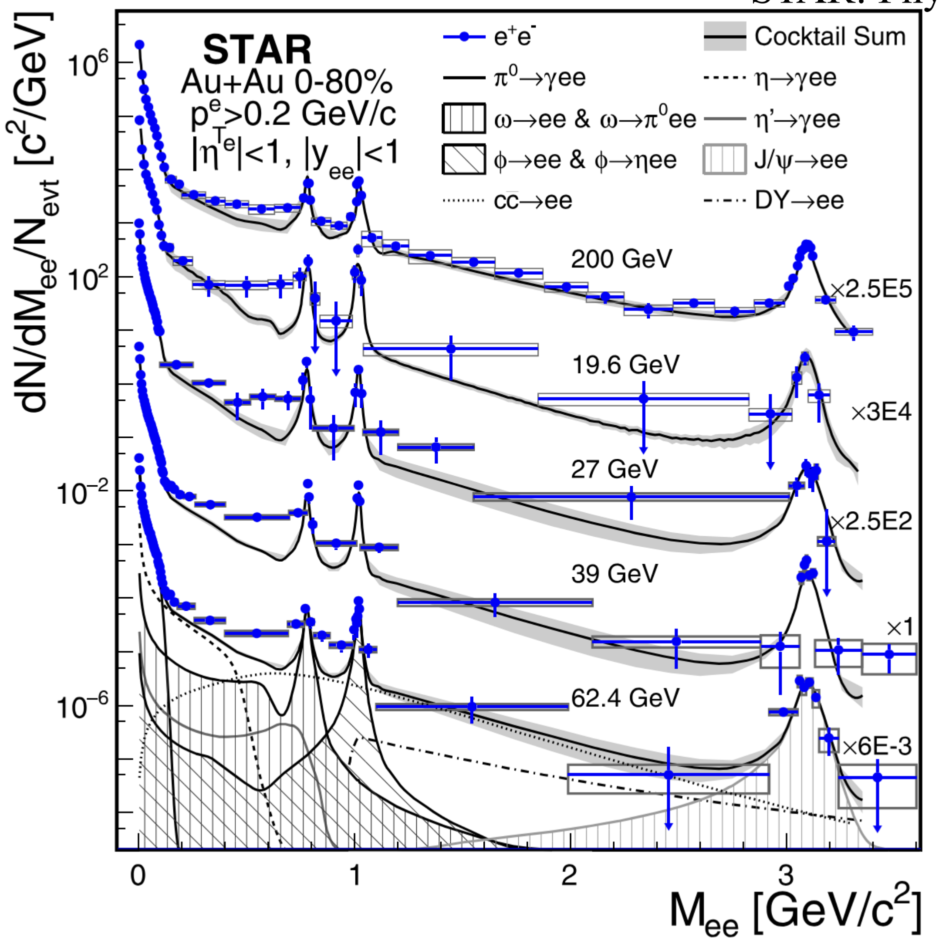
- $\omega, \phi, J/\psi \rightarrow e^{+}e^{-}$
- $\pi^{0}, \eta, \eta' \rightarrow \gamma e^{+}e^{-}$
- $\omega \rightarrow \pi^{0}e^{+}e^{-}$
- $\phi \rightarrow \eta e^{+}e^{-}$
- $c\bar{c}, b\bar{b} \rightarrow e^{+}e^{-}\mathrm{X}$
- Drell-Yan

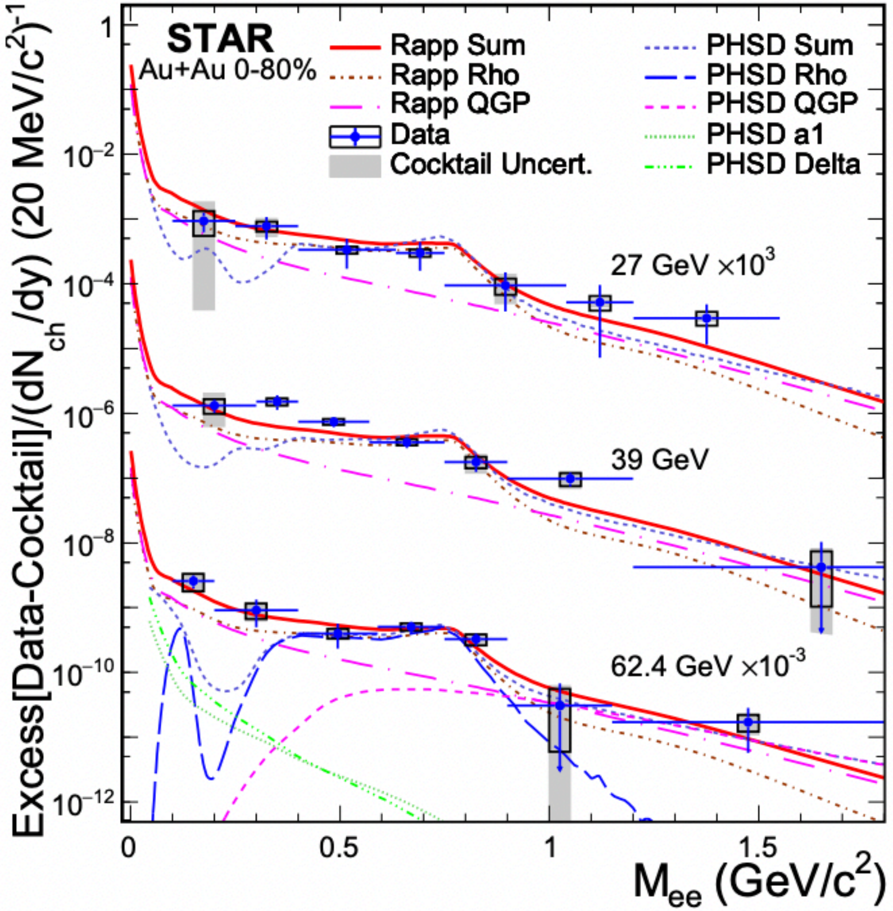
**Physical background can be determined using the well-established cocktail simulation techniques**

**Thermal dileptons = Inclusive signal – Physical background**

# STAR BES-I dielectron measurements

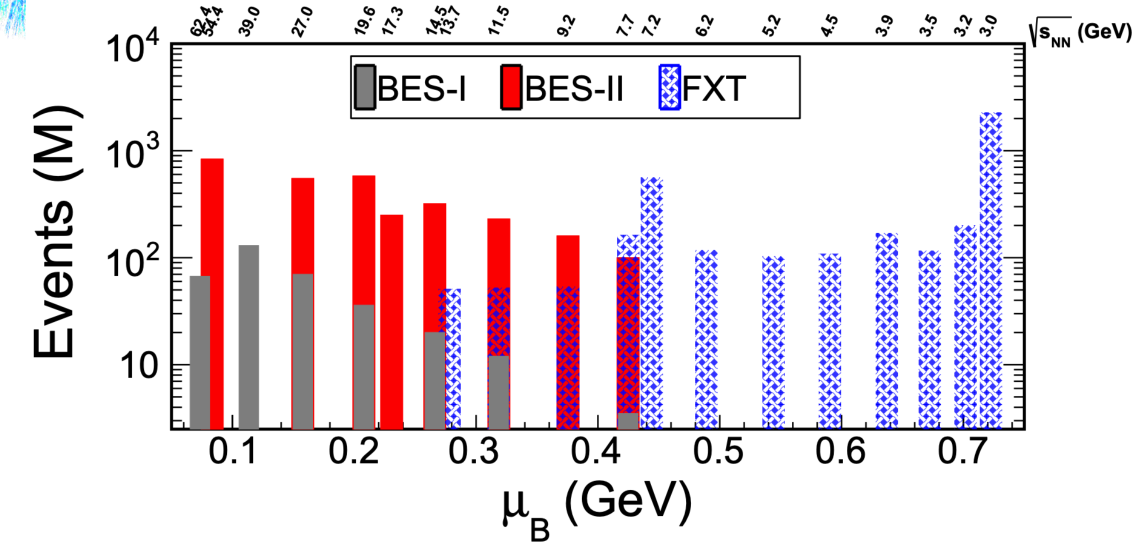
STAR: Phys. Rev. C 107, L061901 (2023)

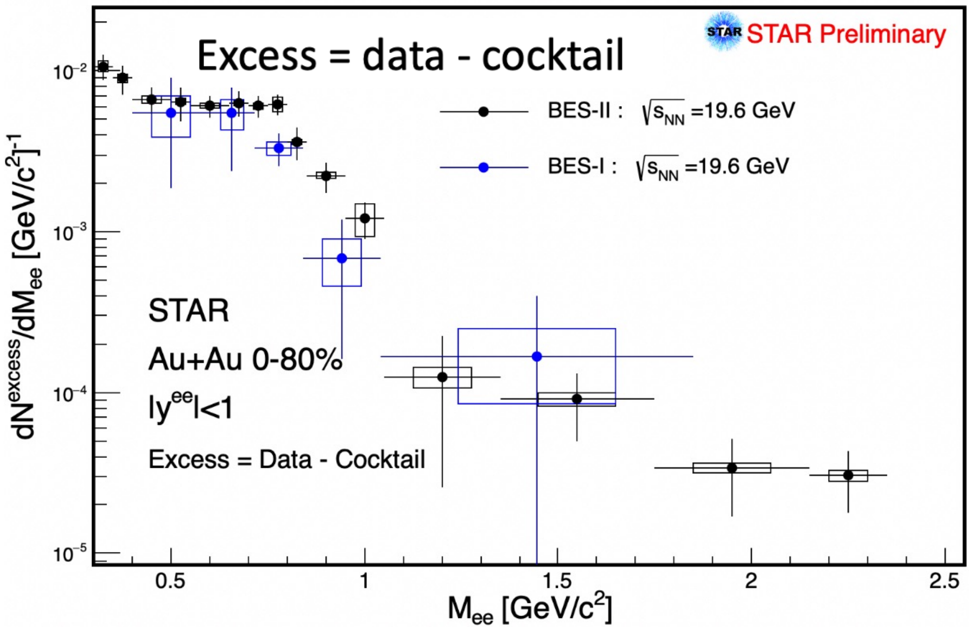



- ➢ Excess yield is well described by the in-medium $\rho$ + QGP emission models
- ➢ Hard to obtain excess mass spectra in intermediate mass region from BES-I data

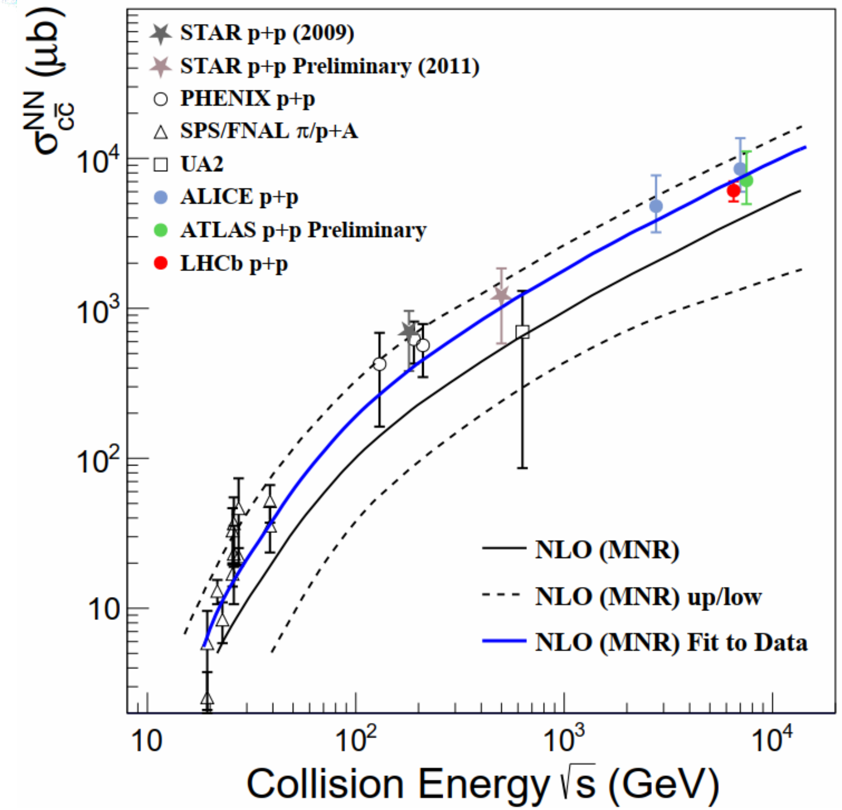
# BES-I vs. BES-II

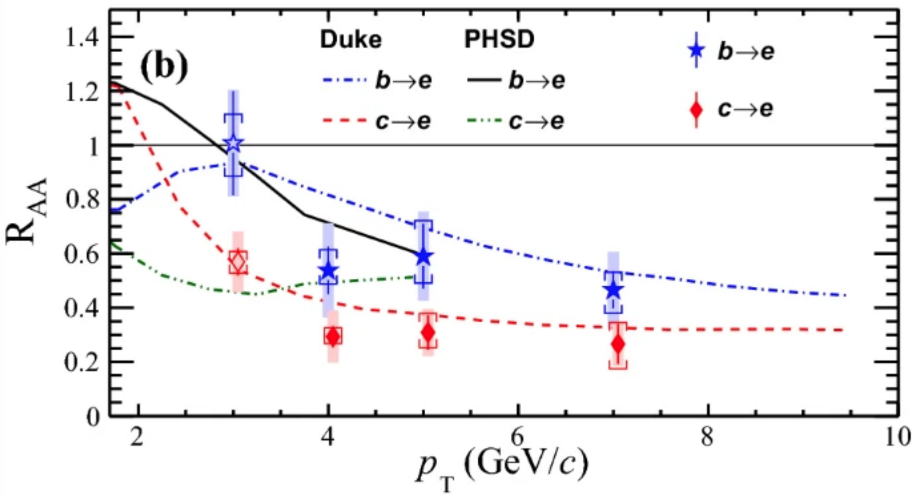


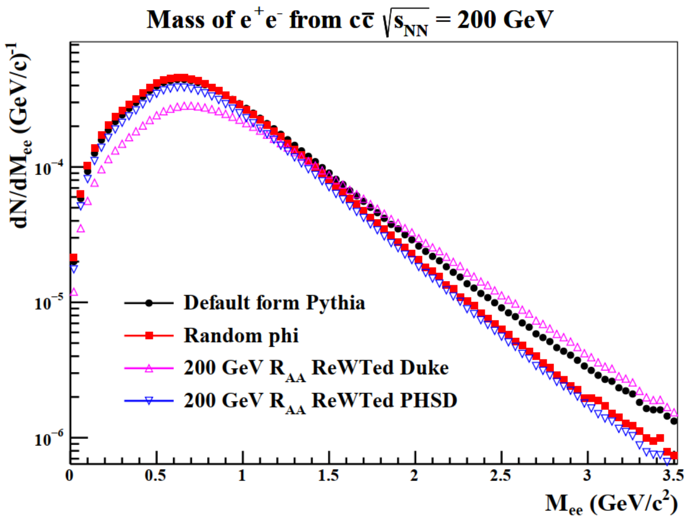




- ➢ BES-II has ~ 10 times more statistics than BES-I
- ➢ BES-I and BES-II excess mass spectra at 19.6 GeV are consistent
- ➢ Much better statistical and systematic uncertainties at BES-II, total error reduced by a factor of ~4
- ➢ Clear mass spectra in IMR, better precision for extended analysis

# Systematic uncertainty




- ☐ $c\bar{c}$ 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)*