Nuclear modification of heavy flavor hadron decayed dielectrons in relativistic heavy-ion collisions
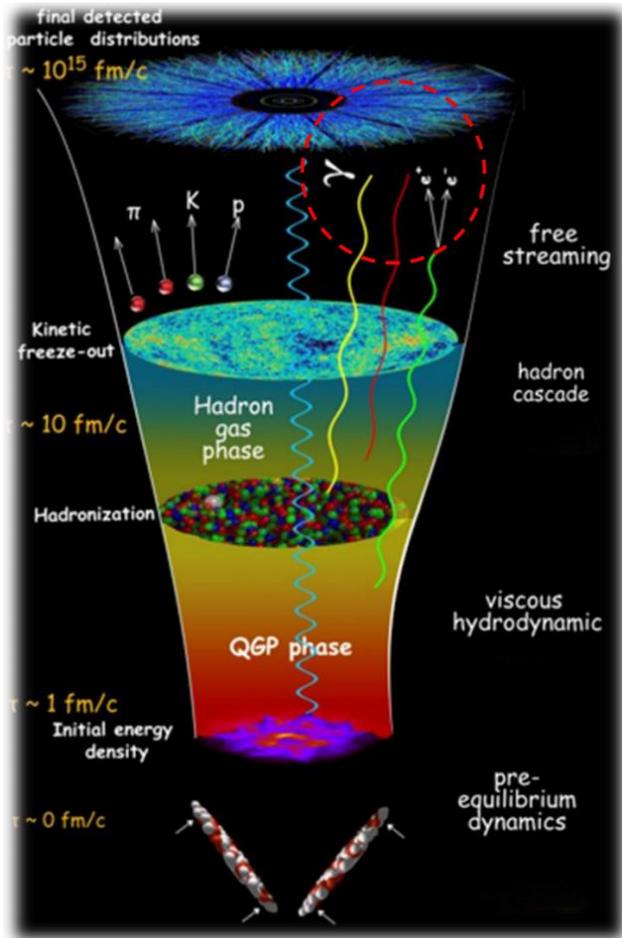
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In collaboration with Wen-Jing Xing, Shanshan Cao, Qian Yang
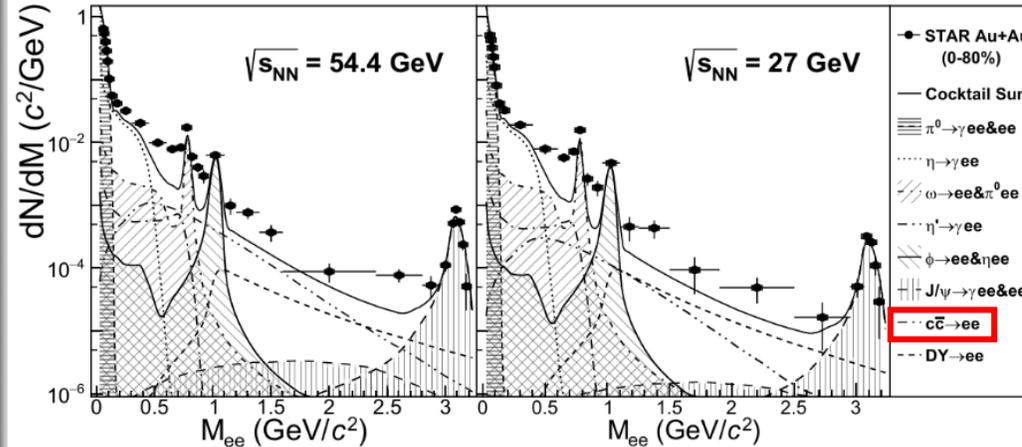
Outline of my talk

☐ **Introduction**

☐ **Linear Boltzmann Transport Model**

☐ **Angular correlations of dielectrons**

☐ **Dielectron invariant-mass spectra**

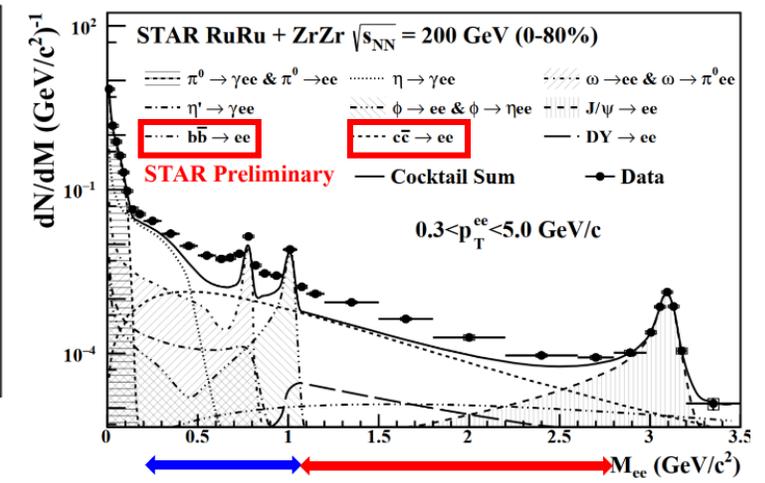☐ **Summary**

Introduction to dielectron invariant-mass spectra

Relativistic heavy-ion collisions produce the **quark-gluon plasma (QGP)**.

[STAR, Nature Commun. 16 (2025) 9098]

[STAR Preliminary, Quark Matter 2025]

T at IMR : $(3.25 \pm 0.60) \times 10^{12}\ K$

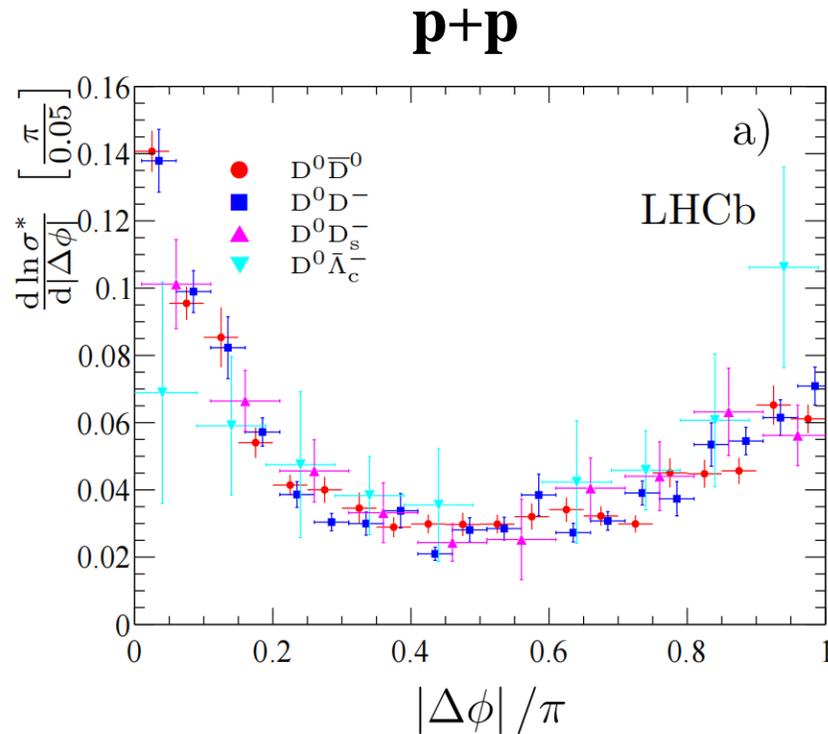➤ Thermometer: invariant-mass spectra of **thermal dileptons**

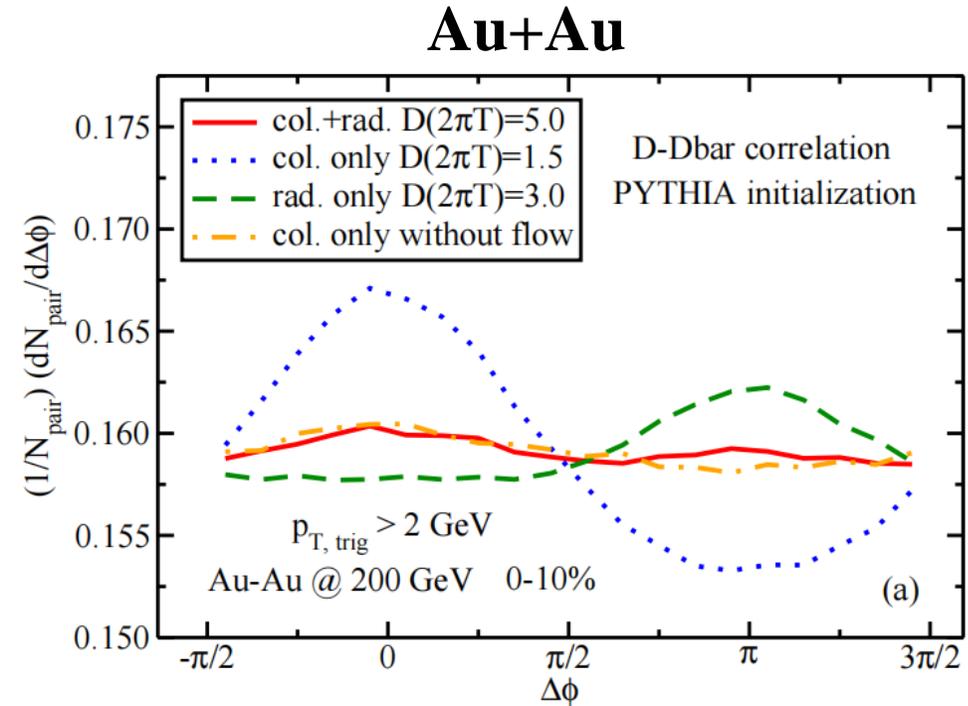➤ Intermediate-mass region (IMR):

- Thermal radiation : extract QGP temperature

- Heavy flavor semileptonic decays : **subtract**

➤ We study the effects of **nuclear modification** on dielectron invariant-mass spectra from heavy flavor hadron decays and the impact on the extraction of the QGP temperature

Introduction to angular correlation

p+p

[LHCb, JHEP 06 (2012) 141]

Au+Au

[Cao, Qin, Bass, Phys. Rev. C 92 (2015) 054909]

➤ Heavy-flavor pair angular correlations can probe the **interaction mechanisms** between heavy quarks and the QGP

➤ We study the effects of **perturbative and non-perturbative** interaction mechanisms on e^+e^- pairs from charm hadron decays

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Linear Boltzmann transport model

- **Boltzmann equation**:

$$p_a \cdot \partial f_a(x_a, p_a) = E_a[\boldsymbol{C_{el}} + \boldsymbol{C_{inel}}]$$

- **Elastic scattering:**

$$\Gamma_{el}^a(\vec{p}_a, T) = \sum_{b,(cd)} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} \frac{d^3 p_i}{E_i (2\pi)^3} f_b(E_b, T)(2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) \underline{|M_{ab \to cd}|^2}$$
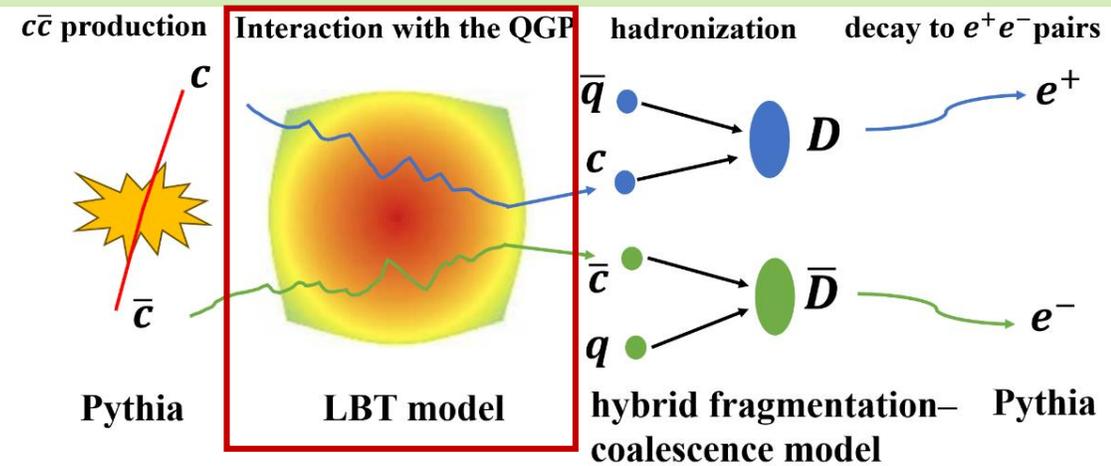
potential scattering model

- **Inelastic scattering:** $\Gamma_{inel}^a = \int dx dl_\perp^2 \underline{\dfrac{dN_g^a}{dx dl_\perp^2 dt}}$ **Higher-twist formalism**

[X.F. Guo et.al., PRL 85 (2000) 3591; B.-W. Zhang et.al., PRL 93 (2004) 072301]

- QGP background: (3+1)-dimensional viscous hydrodynamic model CLVisc

[Wu, Qin, Pang, Wang, Phys.Rev.C 105 (2022) 3, 034909]

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Perturbative and non-perturbative interactions

- Heavy quark-QGP interaction potential: [Xing, Qin, Cao, PLB 838 (2023) 137733]

$$V(r,T) = \boxed{-\frac{4}{3}\alpha_s \frac{e^{-m_d r}}{r}} \boxed{-\frac{\sigma}{m_s}e^{-m_s r}}$$

Yukawa(perturbative) **string(non-perturbative)**

in which $m_d = a + b * T$ and $m_s = \sqrt{a_s + b_s * T}$ are the respective screening masses, α_s and σ are the respective Yukawa and string interaction strength.

- By Fourier transformation,

$$V(\vec{q},T) = -\frac{4\pi\alpha_s C_F}{m_d^2 + |\vec{q}|^2} - \frac{8\pi\sigma}{(m_s^2 + |\vec{q}|^2)^2}$$

- For $Qq \rightarrow Qq$ process, we express the scattering amplitude with effective potential propagator,

$$iM = iM_Y + iM_S = \bar{u}\gamma^\mu u V_Y \bar{u}\gamma^\nu u + \bar{u}u V_s \bar{u}u$$
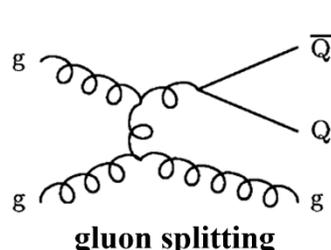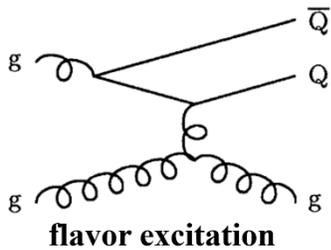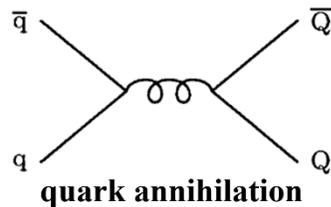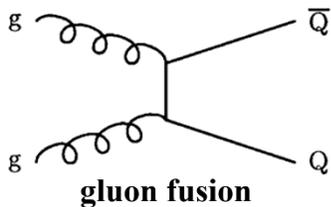
Angular correlations of dielectrons in p+p

- Charm quark production : Pythia 8

parm **PhaseSpace:pTHatMin** (default = 0.; minimum = 0.)
The minimum invariant *pT*.

parm **PhaseSpace:pTHatMax** (default = −1.)
The maximum invariant *pT*. A value below pTHatMin means there is no upper limit.

$$\frac{\sum_i \sigma_i \frac{dN^i_{pair}}{d\Delta\phi}}{\sum_i \sigma_i N^i_{pair}}$$
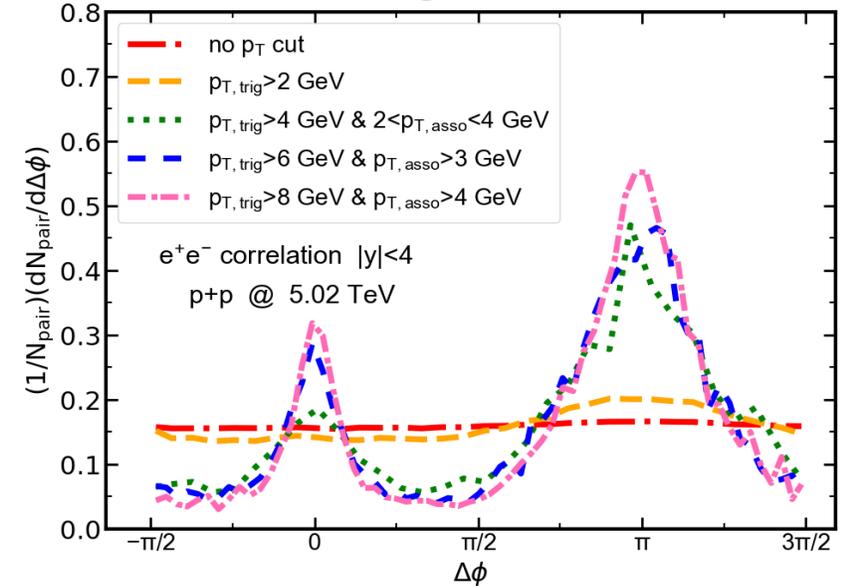
- Away-side $(\frac{\pi}{2}, \frac{3\pi}{2})$ peak: back-to-back production of the initial $c\bar{c}$ pairs

- Near-side $(-\frac{\pi}{2}, \frac{\pi}{2})$ peak: initial gluon splitting process

- Low initial $\widehat{p_T}$ bins: away-side peak is stronger

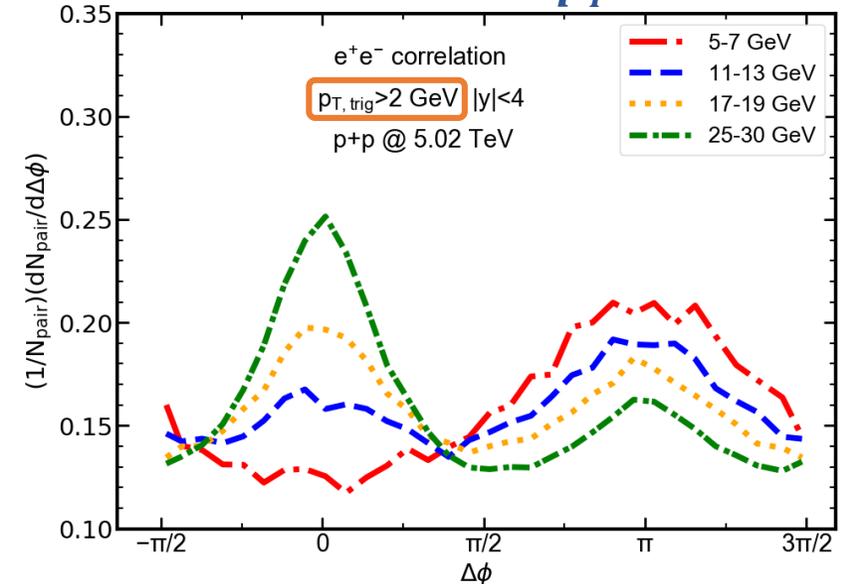- High initial $\widehat{p_T}$ bins: near-side peak is stronger

gluon fusion   **quark annihilation**

flavor excitation   **gluon splitting**

[Norrbin and Sjostrand, Eur.Phys.J.C17,137-161 (2000)]

[Combridge, NPB151 (1979) 429-456]

Final e^+e^- angular correlation

legend:
- no p_T cut
- $p_{T,trig}$>2 GeV
- $p_{T,trig}$>4 GeV & 2<$p_{T,asso}$<4 GeV
- $p_{T,trig}$>6 GeV & $p_{T,asso}$>3 GeV
- $p_{T,trig}$>8 GeV & $p_{T,asso}$>4 GeV

e^+e^- correlation |y|<4
p+p @ 5.02 TeV

Individual initial $\widehat{p_T}$ bins

e^+e^- correlation
$p_{T,trig}$>2 GeV |y|<4
p+p @ 5.02 TeV

legend:
- 5-7 GeV
- 11-13 GeV
- 17-19 GeV
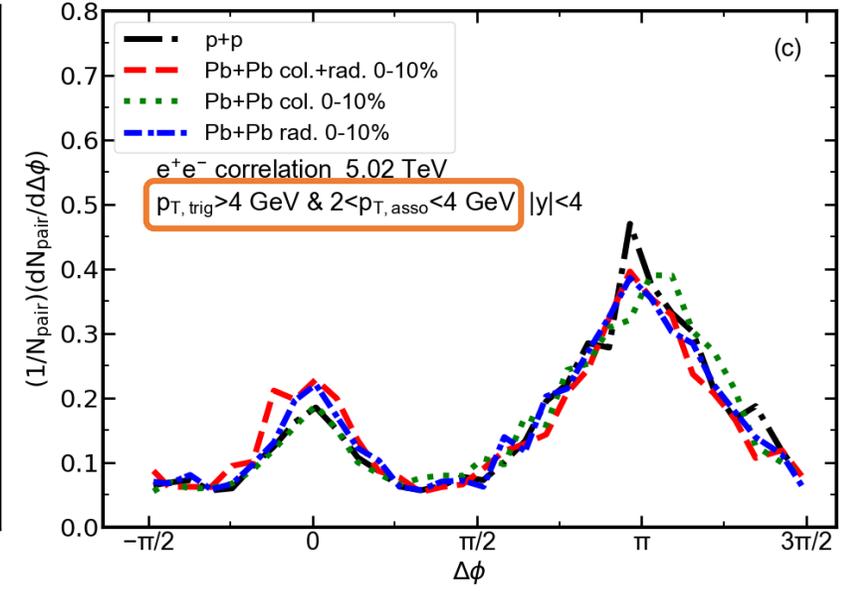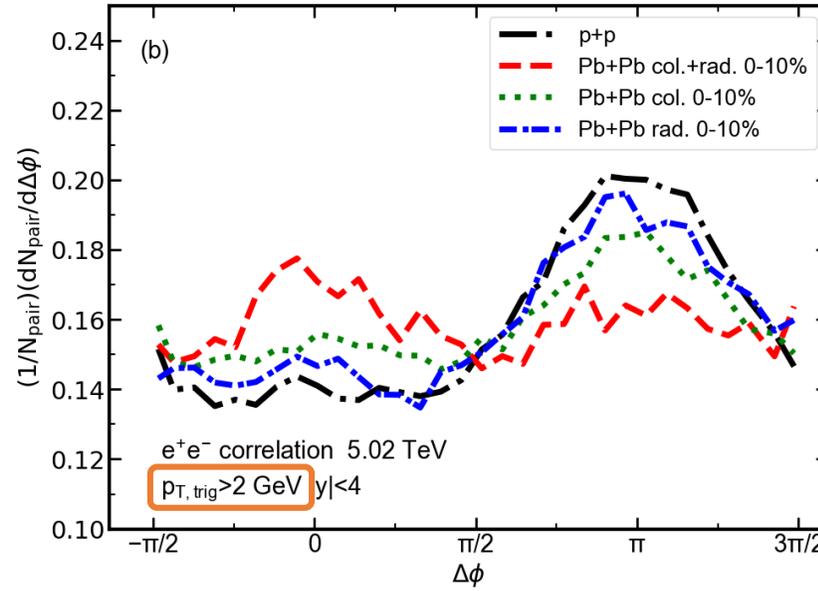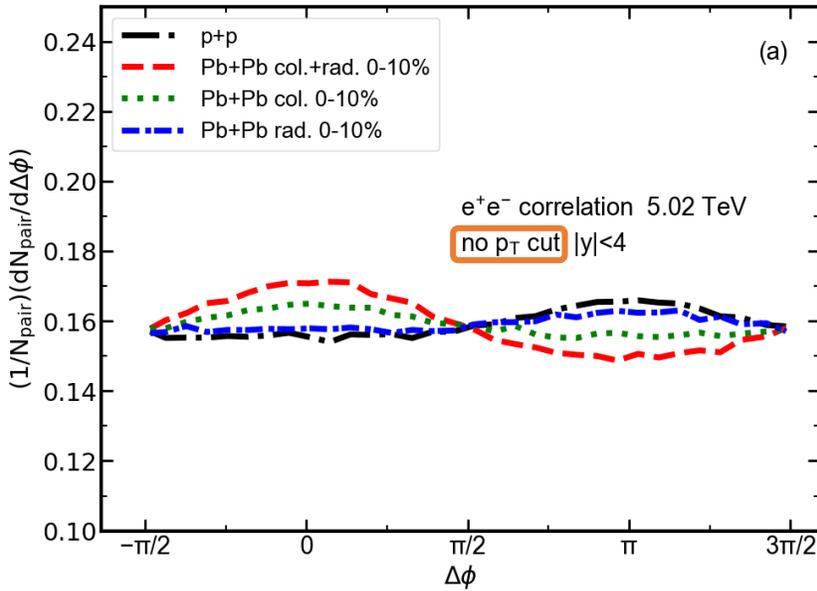- 25-30 GeV

> Yukawa + string interactions:

  - Near-side peak enhanced: the strong collective flow of the QGP
  - Away-side peak suppressed: transverse momentum broadening of heavy quarks in the QGP

> Yukawa interactions:

  - Near-side peak flatter: weak scattering → weak coupling to QGP flow
  - Away-side peak less suppressed: weak scattering → small transverse momentum broadening

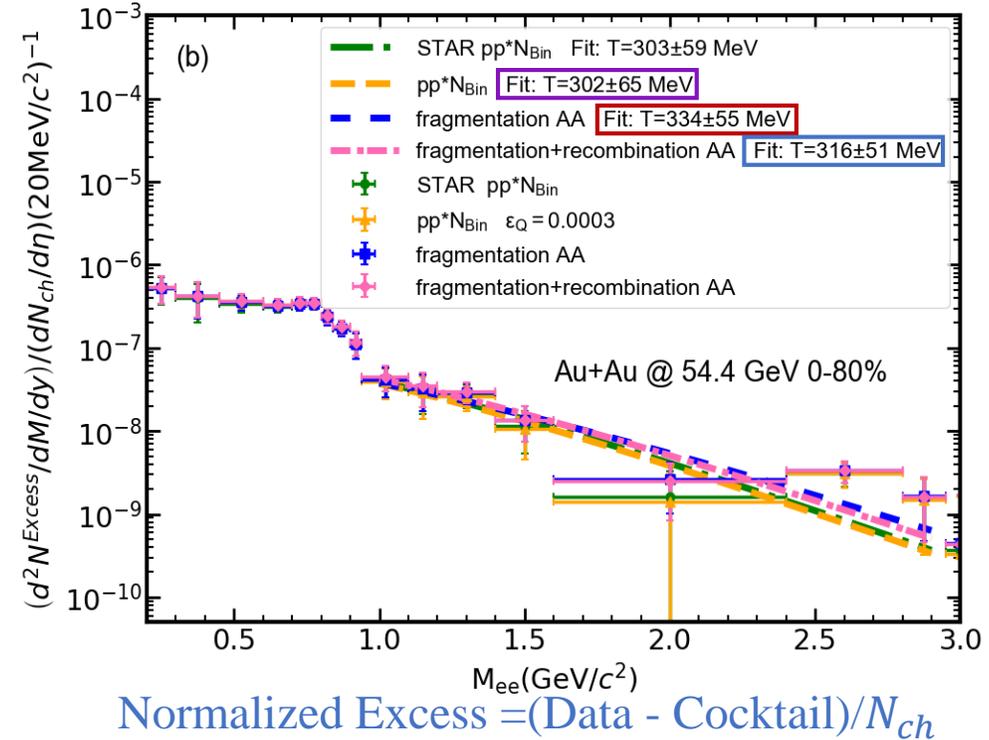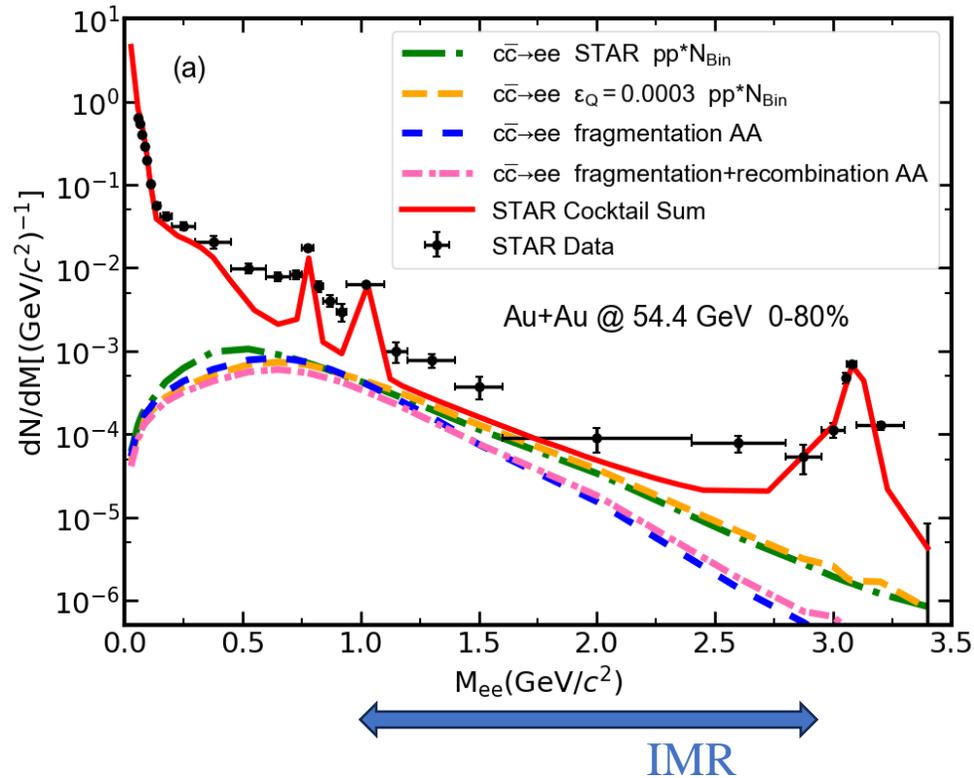> Dielectron angular correlations sensitive to non-perturbative interaction mechanisms

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col. : collisional energy loss

rad. : radiative energy loss

➢ Gluon radiation:
    nearly collinear → minor effect on angular correlation

➢ Elastic scattering:
    alter the propagation direction of heavy quarks →
    away-side suppressed, near-side enhanced

Normalized Excess =(Data - Cocktail)/N_{ch}

- Peterson fragmentation function: $D_Q^H(z) = \dfrac{N}{z[1 - (1/z) - \epsilon_Q/(1-z)]^2}$ $\boldsymbol{\epsilon_Q = 0.0003}$

- Fragmentation: energy loss in QGP shifts the dielectron spectrum to lower invariant mass

- Fragmentation+recombination: coalescence with light quarks slightly shifts the spectrum to higher mass

- Extract the QGP temperature by fitting the Boltzmann function: $M^{3/2} \times e^{-M/T}$

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- At high energies, the bb → ee contribution is non-negligible for temperature extraction

- Fragmentation: bb → ee dielectrons are similar between pp and AA collisions due to the small energy loss of bottom quarks.

- Fragmentation+recombination: bb → ee dielectrons are suppressed due to the different branching ratios in fragmentation versus recombination.

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Extracted temperature from thermal dielectrons

Au+Au @ 54.4 GeV

centrality	p+p (MeV)	frag (A+A) (MeV)	frag+recomb (A+A) (MeV)	Uncertainty (MeV)
0-10%	347±148	367±116	348±108	**1-20**
10-40%	263±61	292±55	280±52	**17-29**
0-80%	302±65	334±55	316±51	**14-32**
40-80%	286±73	306±64	296±63	**10-20**

RuRu+ZrZr @ 200 GeV

centrality	p+p (MeV)	frag (A+A) (MeV)	frag+recomb (A+A) (MeV)	Uncertainty (MeV)
0-10%	271±22	313±20	306±19	**35-42**
10-40%	313±15	351±15	340±13	**27-38**
0-80%	295±11	330±11	320±10	**25-35**
40-80%	333±18	357±18	345±17	**12-24**

- The uncertainty depends on the hadronization mechanism
- Energy loss and hadronization mechanism both affect QGP temperature extraction

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Summary

- Dielectron angular correlations are sensitive to the interaction mechanisms between heavy quarks and the QGP, with non-perturbative interactions and elastic scatterings playing a dominant role.

- Transverse momentum broadening suppresses the away-side peak in the angular correlation, while QGP collective flow enhances the near-side peak.

- Heavy-quark energy loss and hadronization affect dielectron invariant-mass spectra, leading to sizable systematic uncertainty in the extracted QGP temperature.

Thank You!