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Dilepton production as a probe of nuclear deformation in relativistic heavy-ion collisions

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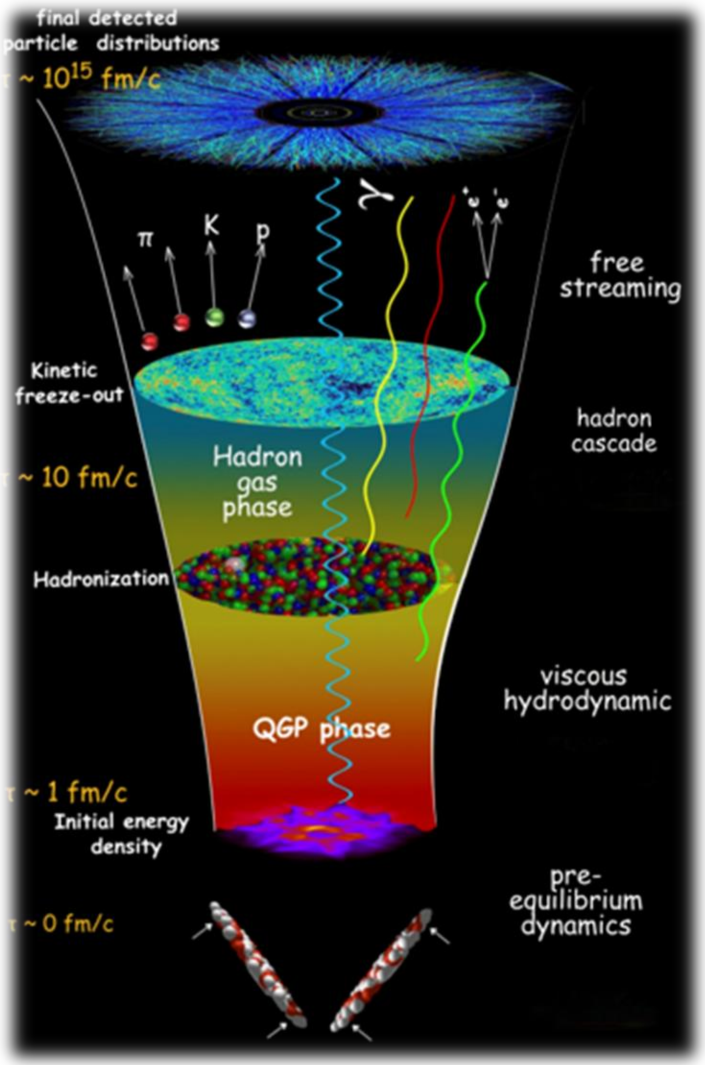
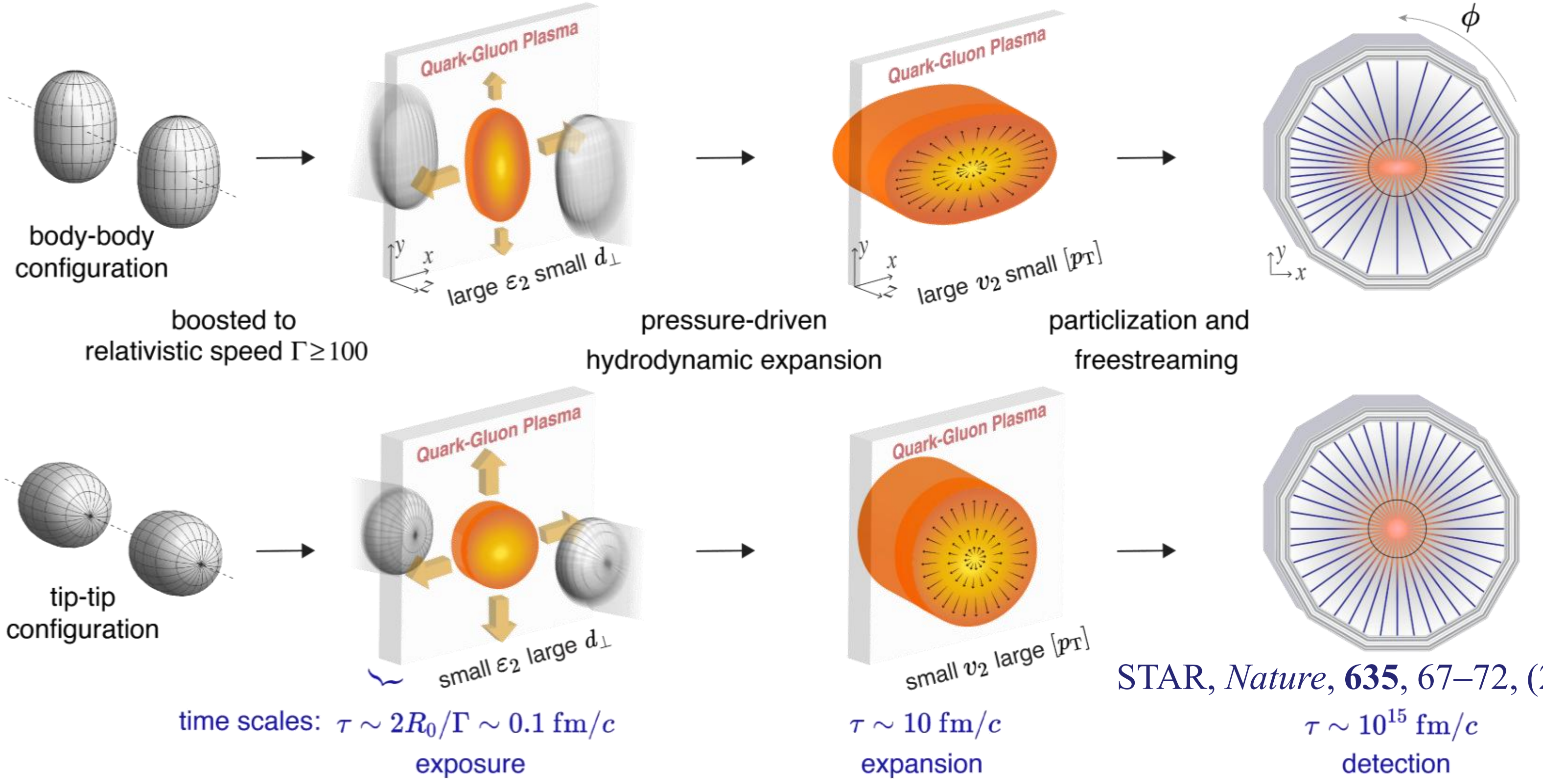
Based on: ArXiv: 2507.18189 and 2412.18895

Outline

- 1. Backgrounds and motivation
- 2. Dilepton productions and method
- 3. Transport approach
- 4. Results and discussions
- 5. Summary and outlook

Backgrounds





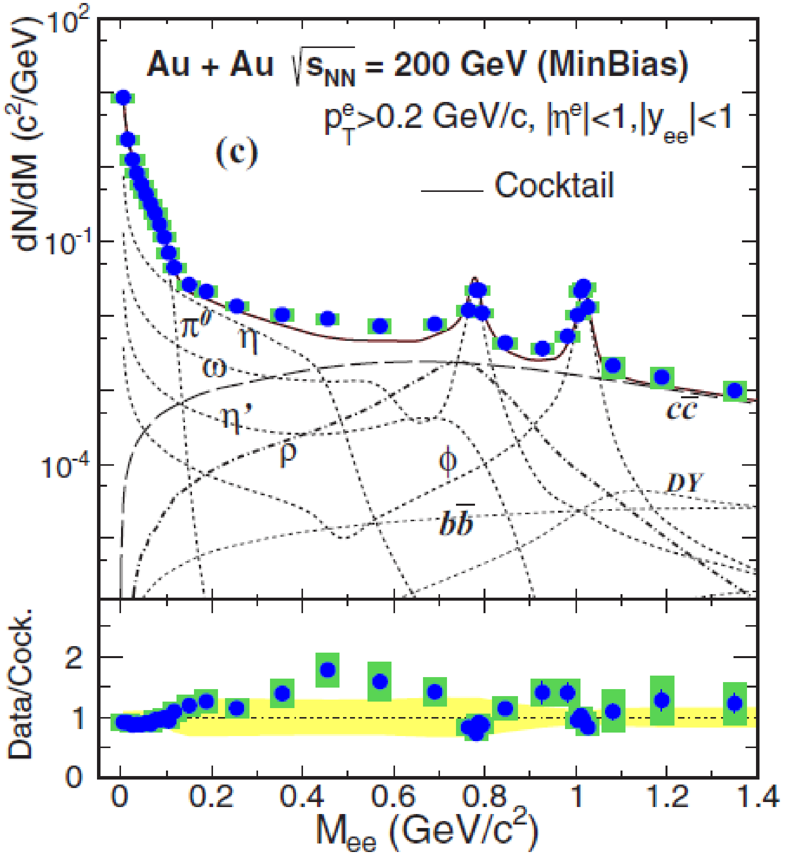
STAR, *Nature*, **635**, 67–72, (2024).

- The spatial anisotropy, caused by the initial deformed nuclear profiles, can be converted into the momentum space anisotropy; STAR, *PRC*, **107**, 024901 (2023).
- Dilepton and photon productions are not affected by strong force and emitted continuously at all stages of evolution. F. Seck, *et al.*, *PRC* **106**, 014904 (2022).

J. Jia, *et al.*, *PRC* **107**, L021901 (2023); W. Ryssens, *et al.*, *PRL* **130**, 212302 (2023); L.-M. Liu, *et al.*, *PLB* **838**, 137701 (2023); Z. Wang, *et al.*, *PRC* **110**, 034907 (2024); J. Luo, *et al.*, *PRC* **108**, 054906 (2023); S. Lin, *et al.*, *PRD* **107**, 054004 (2023) ...

Dilepton productions

- dilepton sources



STAR, *PRC* **92**, 024912 (2015).

Source	B.R.
$\pi^0 \to \gamma ee$	1.174×10^{-2}
$\eta \to \gamma ee$	7×10^{-3}
$\eta' \to \gamma ee$	4.7×10^{-4}
$\rho \to ee$	4.72×10^{-5}
$\omega \to ee$	7.28×10^{-5}
$\omega \to \pi^0 ee$	7.7×10^{-4}
$\phi \to ee$	2.95×10^{-4}
$\phi \to \eta ee$	1.15×10^{-4}

- Dileptons are perturbatively produced both in partonic and hadronic phases.

$$\Delta N_{\rho\to e^+e^-} = \sum_{t=0}^{t_F}\left(1-\exp\left(-\frac{\Gamma_{\rho\to e^+e^-}(M)\Delta t}{\gamma\hbar c}\right)\right)$$

O. Linnyk, *et al.*, *PPNP* 87, 50 (2016).

- Cocktail means hadronic phase contributions.
- **"Excess" = "Data" – "Cocktail"**

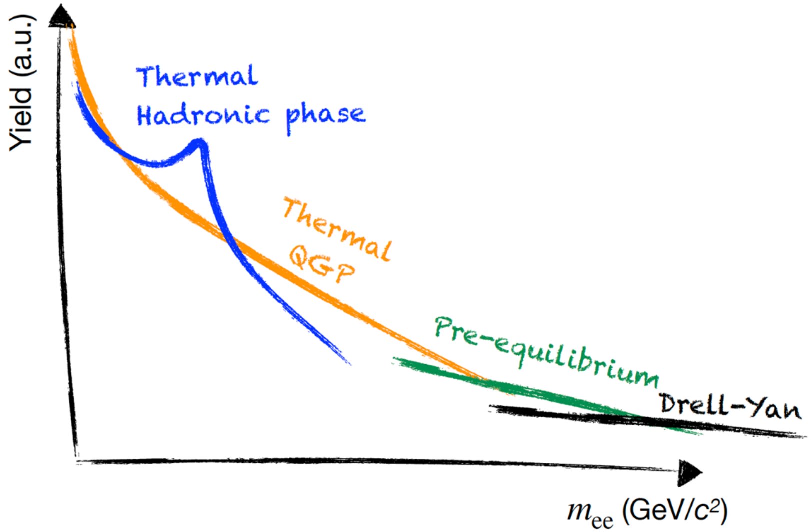
Mainly include QGP and ρ in-medium.

- QGP: $$\sigma_{q\bar{q}\to e^+e^-} = \frac{4\pi\alpha^2 e_q^2}{9s}\frac{1+2m^2/s}{\sqrt{1-4m^2/s}}$$

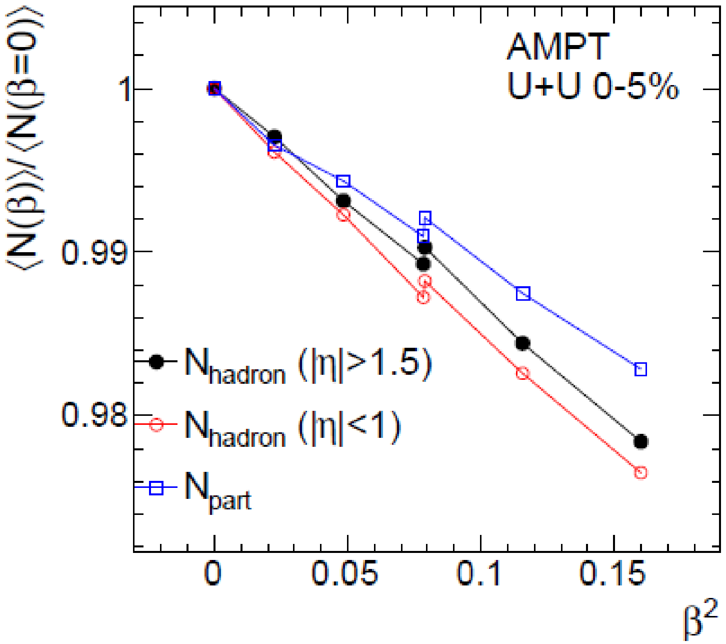
- ρ^0: $$\sigma_{\pi^+\pi^-\to\rho}(M) = \frac{12\pi\hbar^2}{q^{*2}}\Gamma_\rho^* \mathcal{A}_\rho^*(M)\left(\frac{q}{q^*}\right)^4\left(\frac{m_\rho^*}{M}\right)^6,$$
$$q = \frac{1}{2}\sqrt{M^2-4m_\pi^2},\ q^* = \frac{1}{2}\sqrt{m_\rho^{*2}-4m_\pi^2}.$$

G.-Q. Li and C. M. Ko, *NPA* **582**, 731 (1995).

Schematic view of dielectron invariant mass spectrum



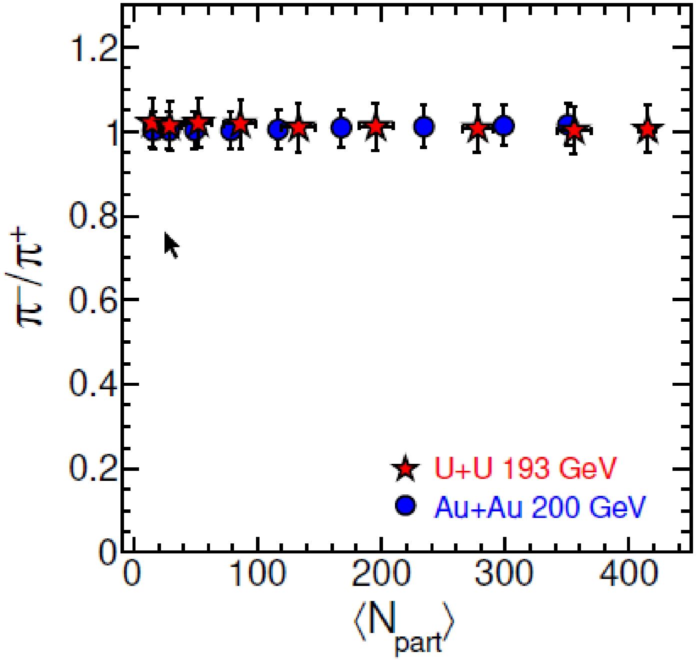
Methodology



- Participator number is linear-related to β_2^2.

$$N_{\mathbf{hadron}} = a_0 + b_0\beta_2^2$$

J.-Y. J., *PRC*, **105**, 014906 (2022).



- In the relativistic energy and the most central collision, we can assume the numbers of positive and negative particles are equal.

$$N_q \approx N_{\bar{q}}$$

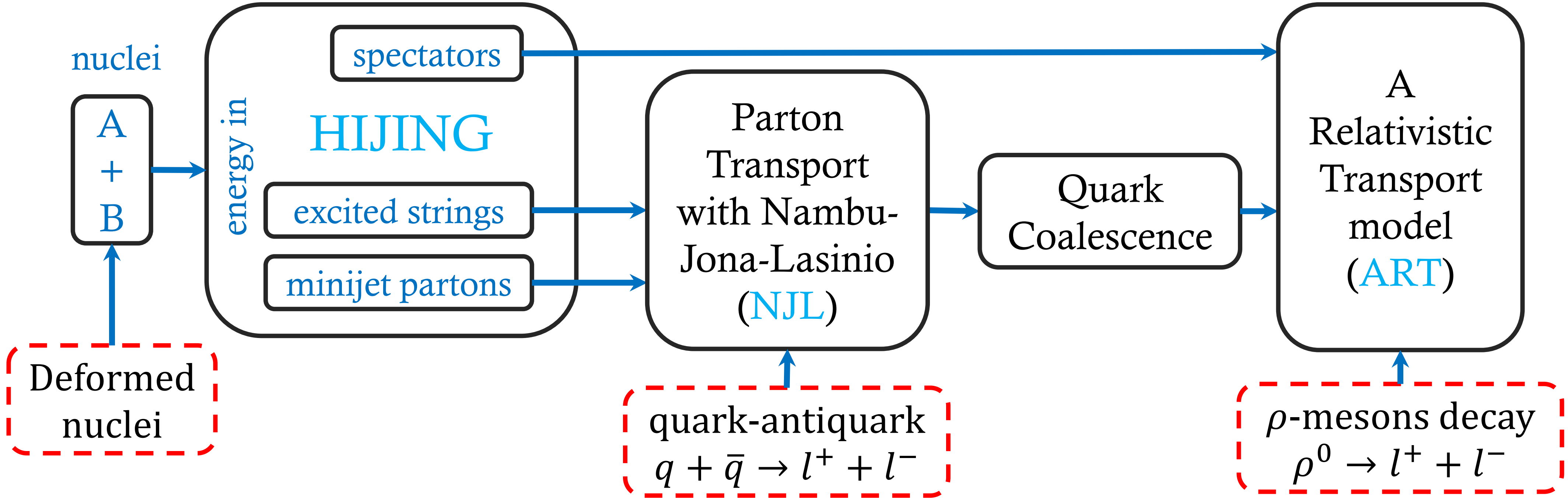
STAR, *PRC*, **107**, 024901 (2023).

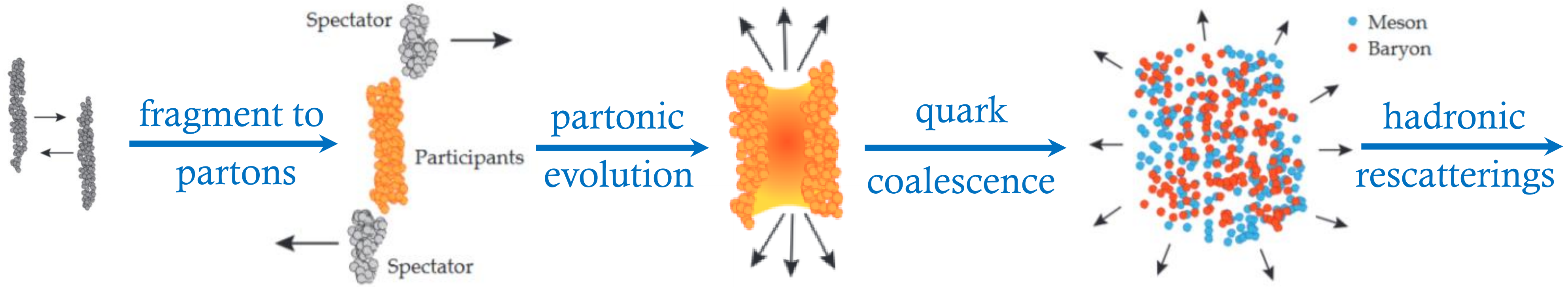
- We assume that the dilepton yields are proportional to the product of quarks and antiquarks numbers in QGP.

$$N_{ll} \propto N_q \cdot N_{\bar{q}}$$
$$\propto \left(N_q + N_{\bar{q}}\right)^2 \propto N_{\mathbf{quark}}^2$$
$$\propto N_{\mathbf{ch}}^2 \propto N_{\mathbf{hadron}}^2$$

$$\boxed{\begin{aligned} R_{\mathrm{U-Au}} &= \frac{(\mathrm{d}N_{ll}^{\mathrm{U}}/\mathrm{d}y)/(\mathrm{d}N_{\mathrm{ch}}^{\mathrm{U}}/\mathrm{d}y)}{(\mathrm{d}N_{ll}^{\mathrm{Au}}/\mathrm{d}y)/(\mathrm{d}N_{\mathrm{ch}}^{\mathrm{Au}}/\mathrm{d}y)} \\ &= k_2 \cdot \beta_2^2 + k_0 \end{aligned}}$$

Extended AMPT model





Transport approach

$$\mathcal{L}_{\rm NJL} = \bar\psi(i\gamma^\mu\partial_\mu - \hat m)\psi + \frac{G_S}{2}\sum_{a=0}^{8}[(\bar\psi\lambda_a\psi)^2 + (\bar\psi i\gamma_5\lambda_a\psi)^2] - K\{\det{}_f[\bar\psi(1+\gamma_5)\psi] + \det{}_f[\bar\psi(1-\gamma_5)\psi]\}$$

scalar

KMT interaction

- Mean field approximation

Y. Nambu and G. Jona-Lasinio, *Rhys. Rep.* **122**, 235 (1961); **124**, 246 (1961).

$$\mathcal{L}_{\rm NJL} \approx \bar\psi(\gamma^\mu(i\partial_\mu - A_\mu)) - \hat M)\psi - G_S(\sigma_u^2+\sigma_d^2+\sigma_s^2) + 4K\sigma_u\sigma_d\sigma_s$$

- Semiclassical approximation
  - Single particle Hamiltonian

$$H_i = \sqrt{M_i^2 + \vec k_i^2}$$

  - Equation of motions

$$\frac{{\rm d}\vec r_i}{{\rm d}t} = \frac{\vec k_i}{E_i} = \vec v_i, \qquad \frac{{\rm d}\vec k_i}{{\rm d}t} = -\frac{M_i}{E_i}\vec\nabla M_i$$

C. M. Ko, *et al.*, *NST* **24**, 050525 (2013).

- Boltzmann equation

$$\frac{\partial f_i}{\partial t} + \frac{\vec k_i}{E_i}\cdot\vec\nabla f_i - \vec\nabla H_i\cdot\vec\nabla_k f_i = I_{\rm coll}$$

- Stochastic collision criterion for more accurate thermalization

$$P_c = v_{\rm rel}\frac{\sigma}{N_{\rm test}}\frac{\Delta t}{\Delta V} \qquad v_{\rm rel} = \frac{\sqrt{[s-(M_1+M_2)^2][s-(M_1-M_2)^2]}}{2E_1E_2}$$

Z. Xu, C. Greiner, *PRC* **71**, 064901 (2005).

- Pauli blocking process is considered

$$P_b = 1-(1-f_1(\vec r_1,\vec k_1))(1-f_2(\vec r_2,\vec k_2))$$

- Test particle method C.-Y. Wong, *PRC* **25**, 1460 (1982).

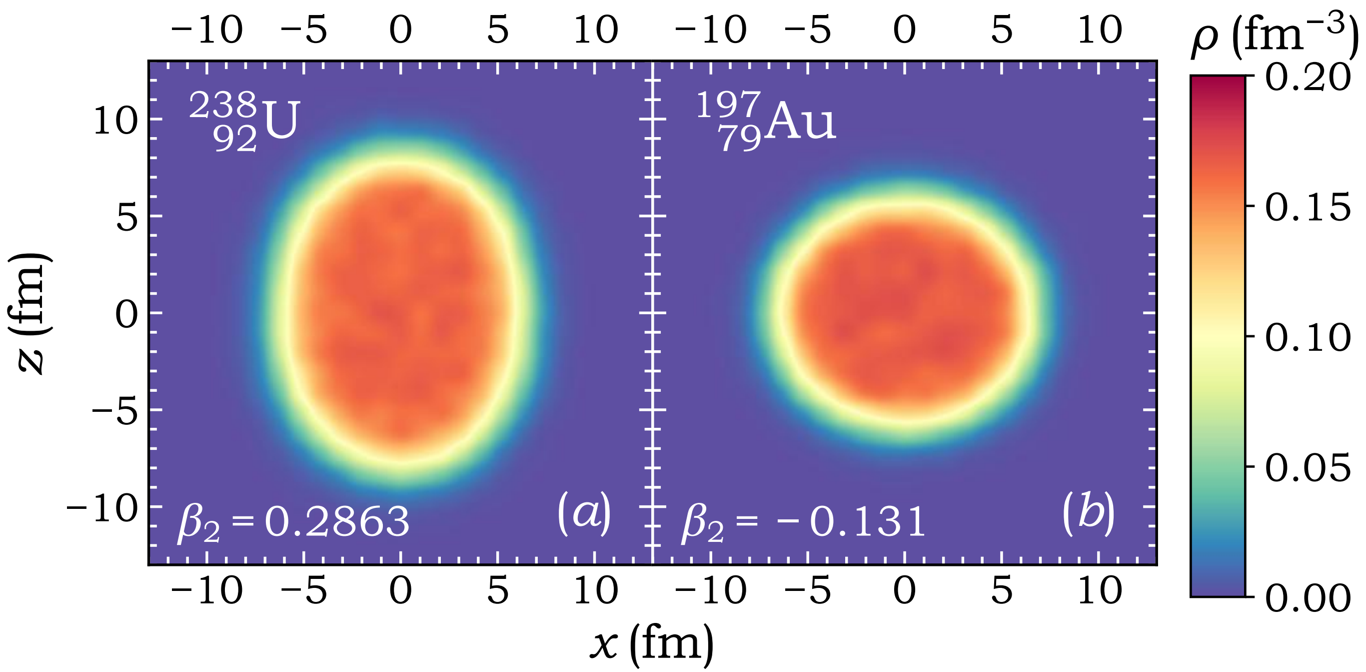
- Dilepton productions in QGP and ρ^0 decay are considered perturbatively

G.-Q. Li and C. M. Ko, *NPA* **582**, 731 (1995).

Initial nuclei

- Woods-Saxon nuclear profiles

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+\exp\left[\frac{r-R_{\rm WS}(1+\beta_2 Y_{2,0}(\theta,\phi))}{a_{\rm WS}}\right]}$$



- $^{197}_{79}$Au and $^{238}_{92}$U nuclei with non-zero β_2

- Woods-Saxon parameters

Nucleus	$R_{\rm WS}$(fm)	$a_{\rm WS}$(fm)
$^{238}_{92}$U	6.8054	0.605
$^{197}_{79}$Au	6.38	0.535

- Euler angles

$$\vec{r} = R_3(\gamma)R_2(\beta)R_1(\alpha)\vec{r}_0$$

$$R_1(\eta) = R_3(\eta) = \begin{pmatrix} \cos\eta, & -\sin\eta, & 0 \\ \sin\eta, & \cos\eta, & 0 \\ 0, & 0, & 1 \end{pmatrix}$$

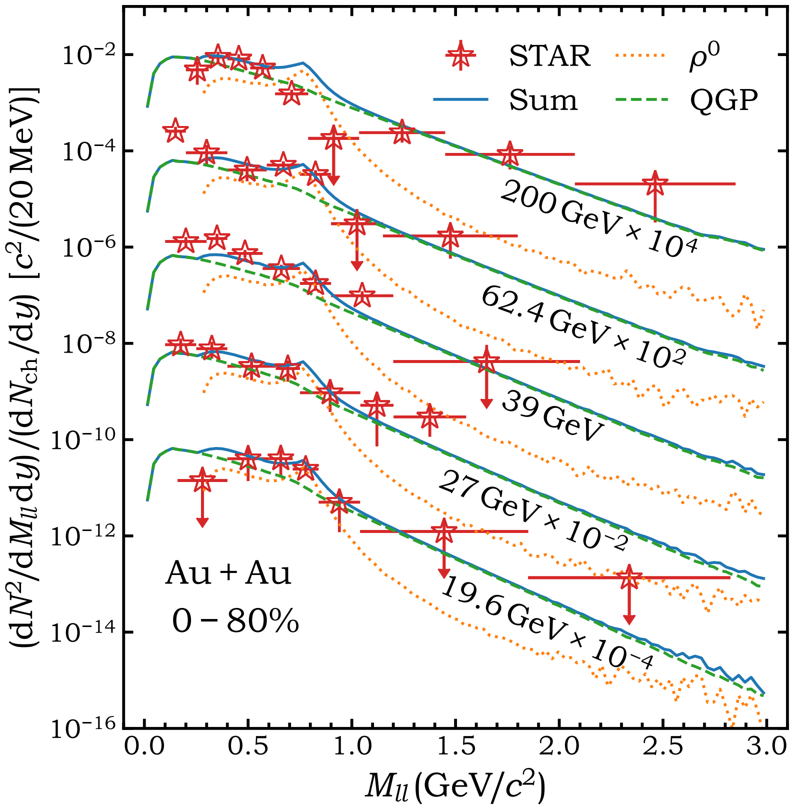
$$R_2(\eta) = \begin{pmatrix} 1, & 0, & 0 \\ 0, & \cos\eta, & -\sin\eta \\ 0, & \sin\eta, & \cos\eta \end{pmatrix}$$

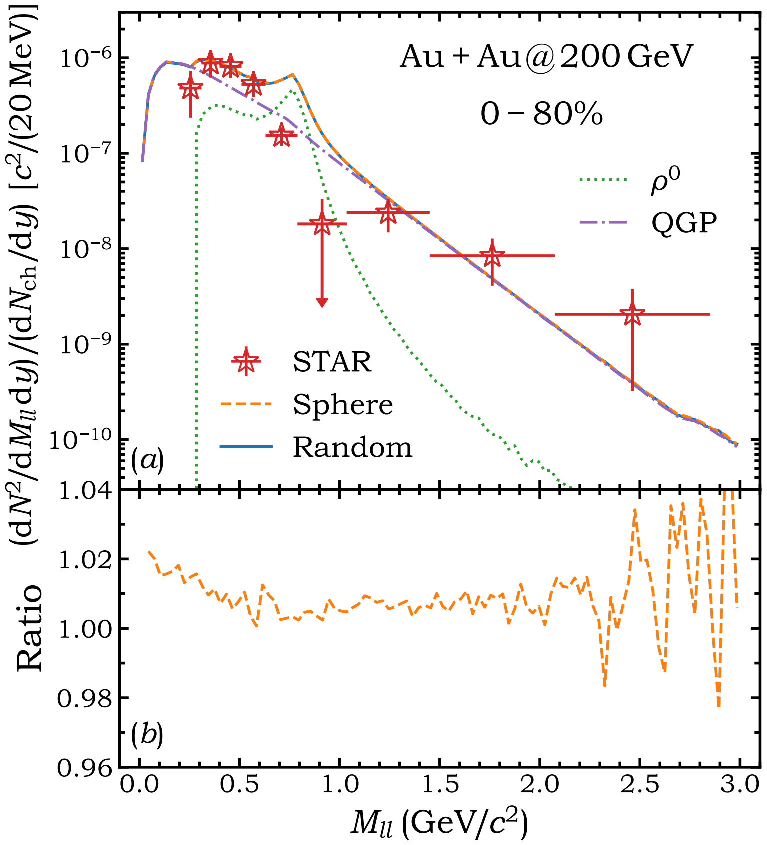
- Two cases

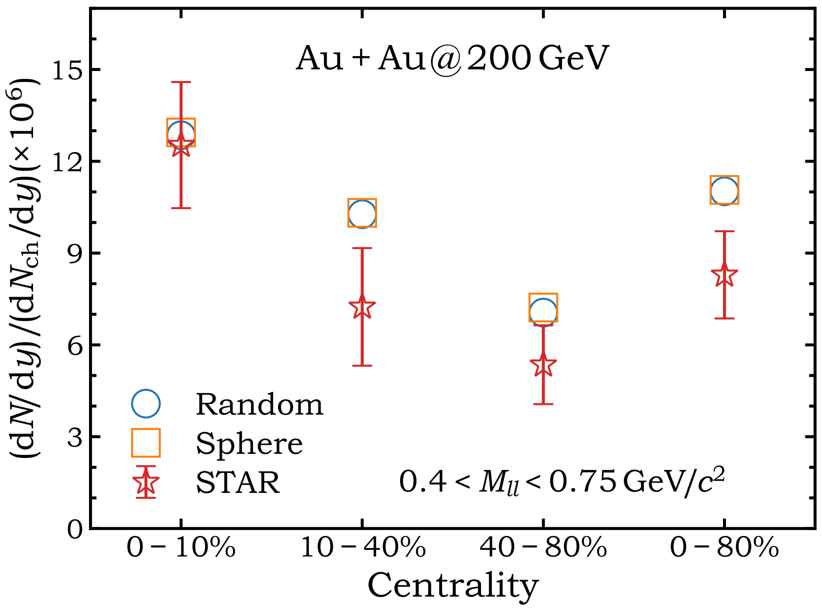
1. Sphere case: $\beta_2 = 0$
2. Random case: Uniform

$\alpha, \gamma \in [0, 2\pi]$, $\cos\beta \in [-1,1]$

Dilepton production in Au+Au system







- ➢ Integral invariant mass yields of dileptons

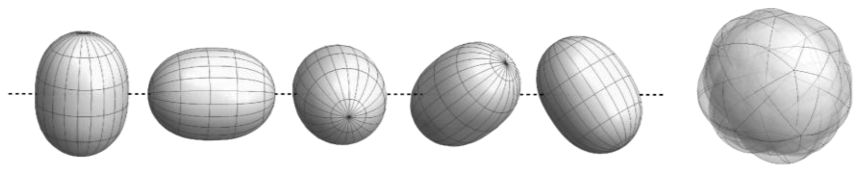
- ➢ Invariant mass spectra of dileptons

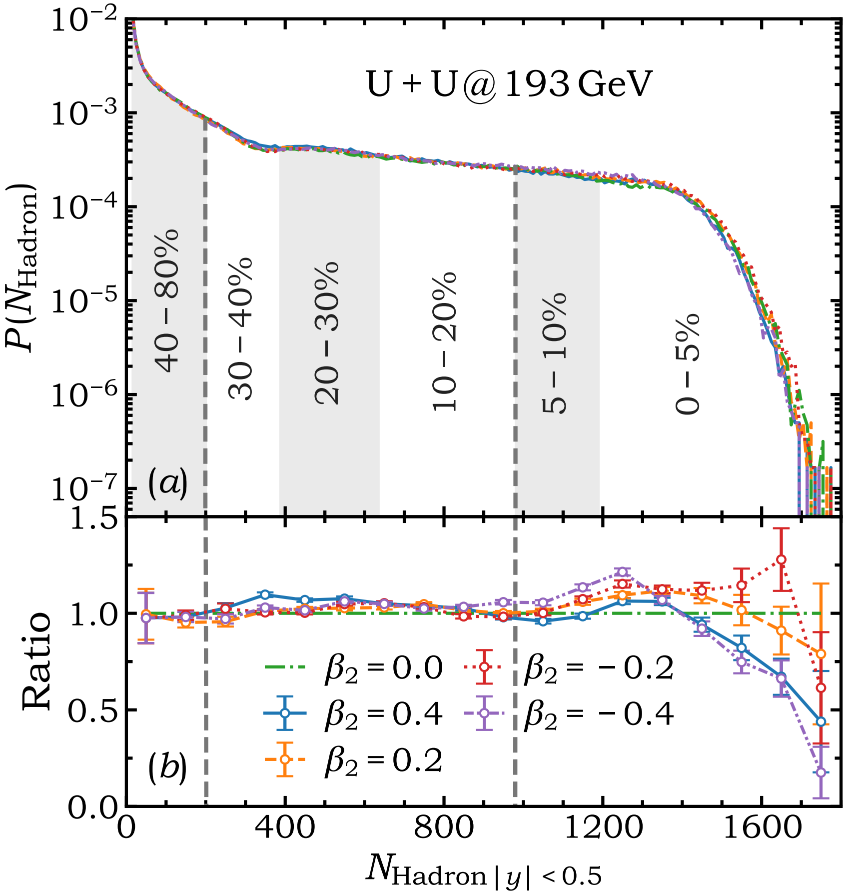
- ➢ Dilepton yields are normalized by charge particles yields to reduce the volume effect and model dependence.

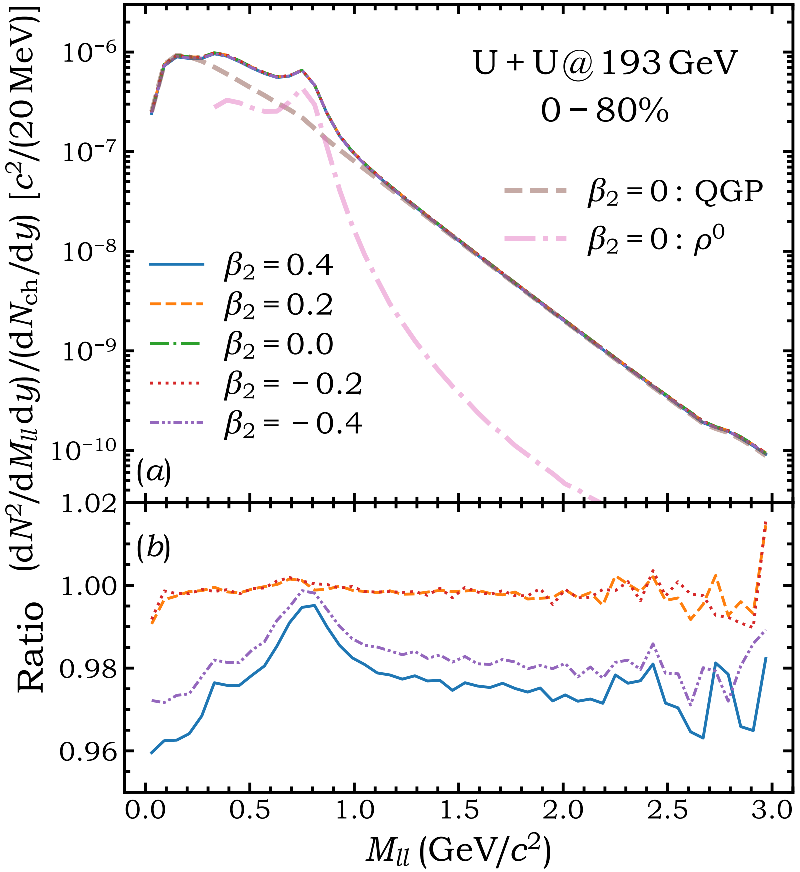
- ➢ LMR is dominated by ρ^0 decay;

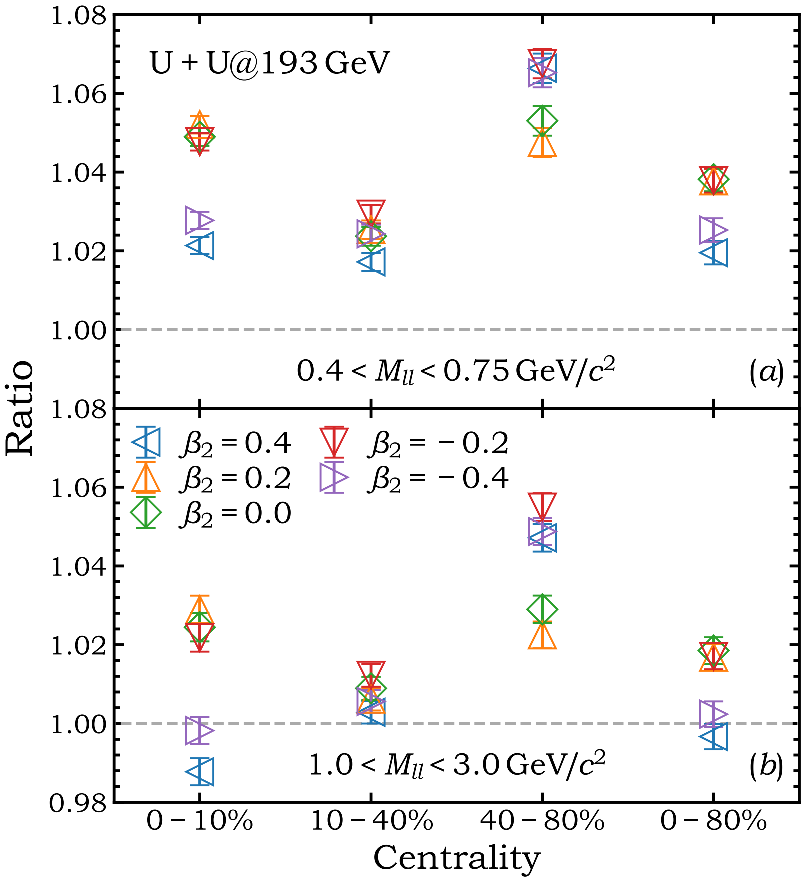
- ➢ IMR is dominated by quark and antiquark annihilations.

Dilepton production in U+U system



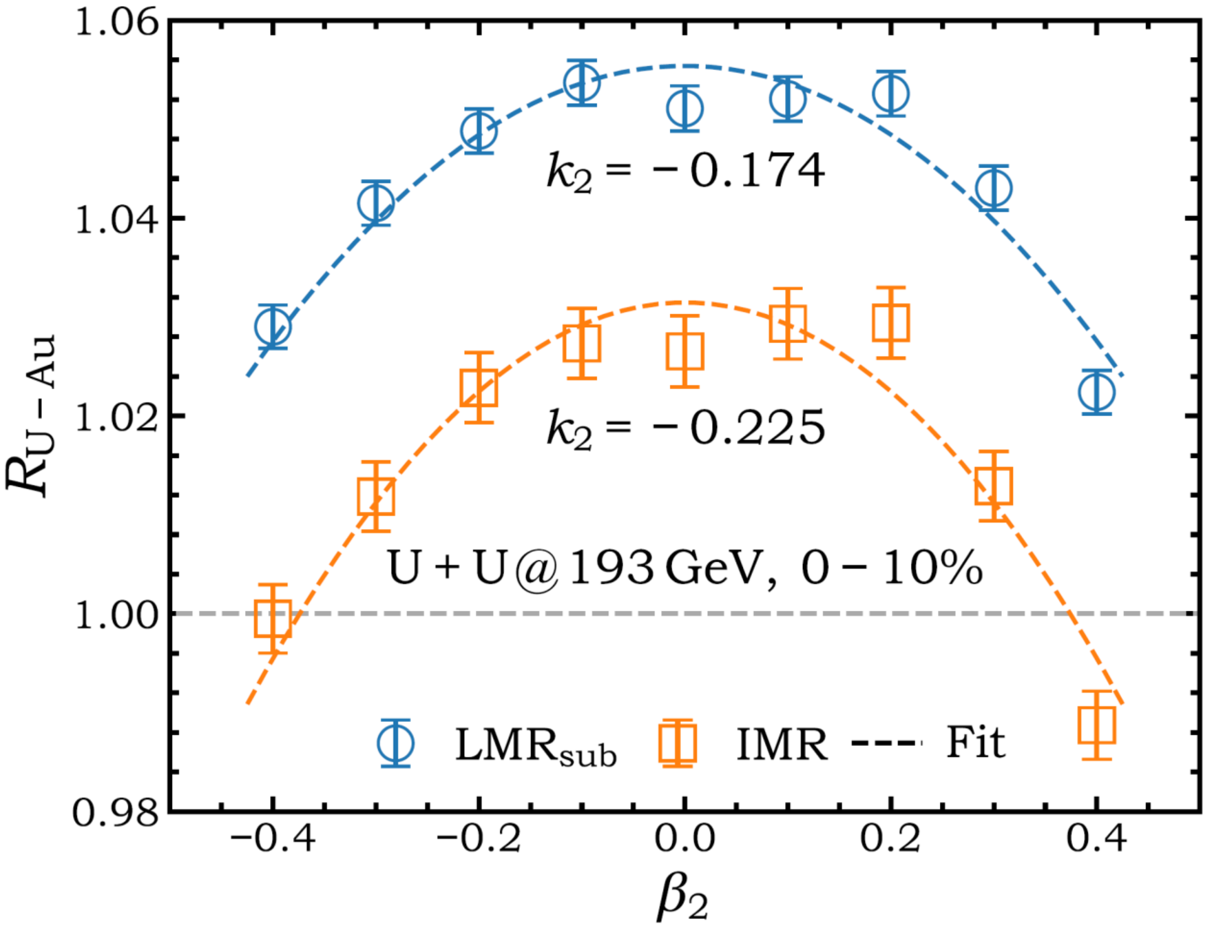






- ➢ Larger $|\beta_2|$ has a big suppression of the multiplicity at the central collision.
- ➢ Result in a big suppression of the dilepton production, in particular, in the most central collision.

Dilepton production in U+U system



$$R_{\mathrm{U-Au}} = \frac{(\mathrm{d}N_{ll}^{\mathrm{U}}/\mathrm{d}y)/(\mathrm{d}N_{\mathrm{ch}}^{\mathrm{U}}/\mathrm{d}y)}{(\mathrm{d}N_{ll}^{\mathrm{Au}}/\mathrm{d}y)/(\mathrm{d}N_{\mathrm{ch}}^{\mathrm{Au}}/\mathrm{d}y)} = k_2 \cdot \beta_2^2 + k_0$$

- The dilepton yields in IMR is more sensitive than in LMR, due to that the more pure dilepton production from QGP.

Summary and outlook

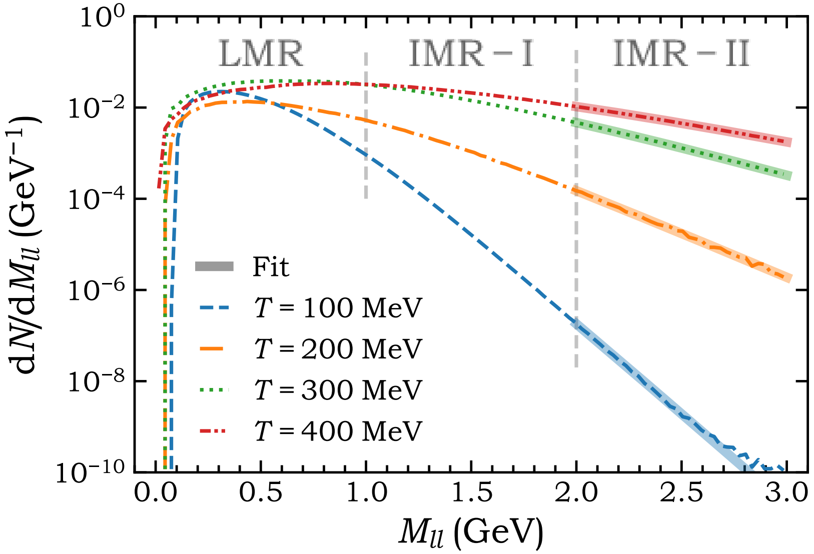
Main points:

- The dilepton production can serve as a probe of the nuclear deformations;
- The normalized dilepton yields is linear-related to the square of the β_2;
- The dilepton yields in IMR is more sensitive than in LMR.

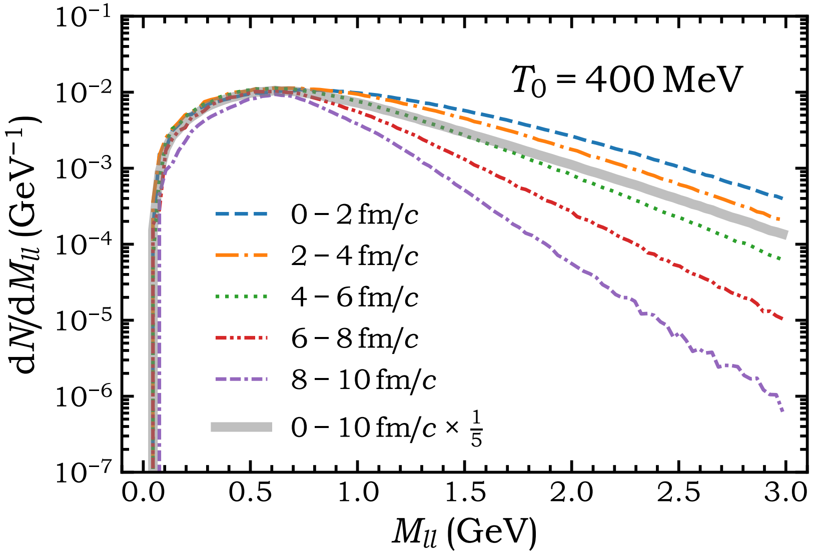
Future plan:

- The effect of initial nucleus structures on temperature extraction by dilepton spectra in isobar systems.

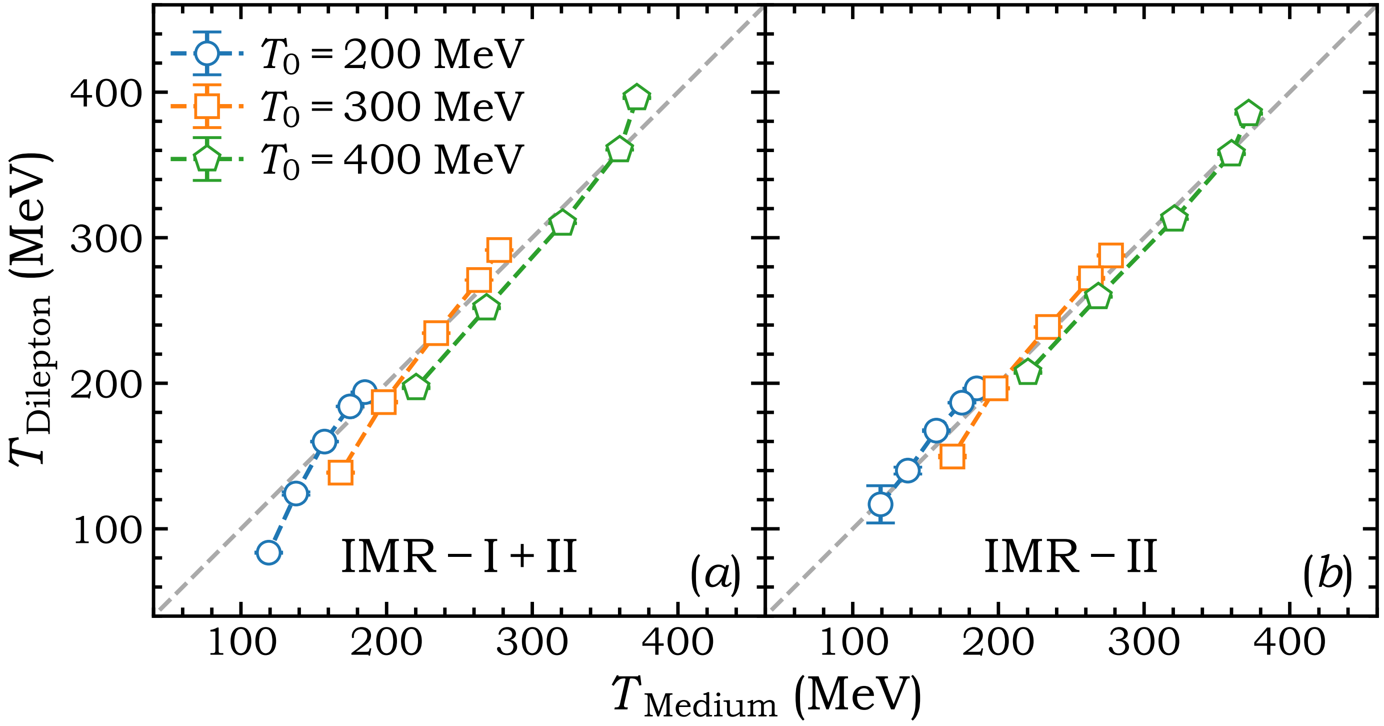
Thanks for your attention!



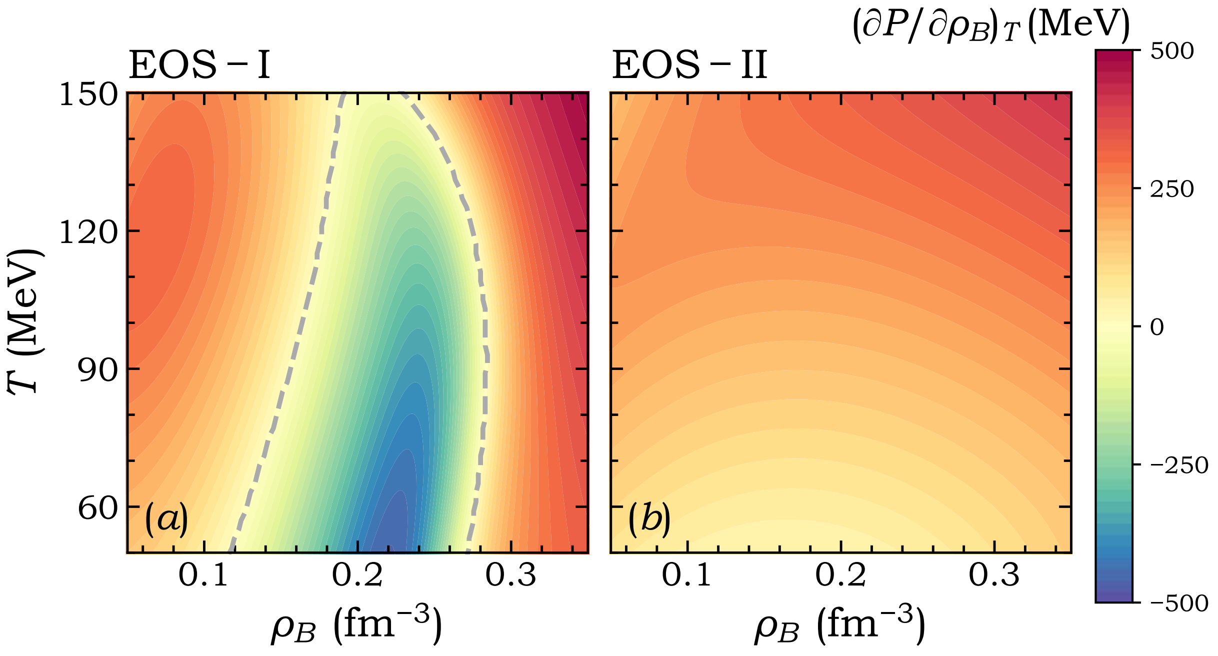
LMR
IMR − I
IMR − II
Fit
T = 100 MeV
T = 200 MeV
T = 300 MeV
T = 400 MeV
dN/dM_ll (GeV^-1)
M_ll (GeV)

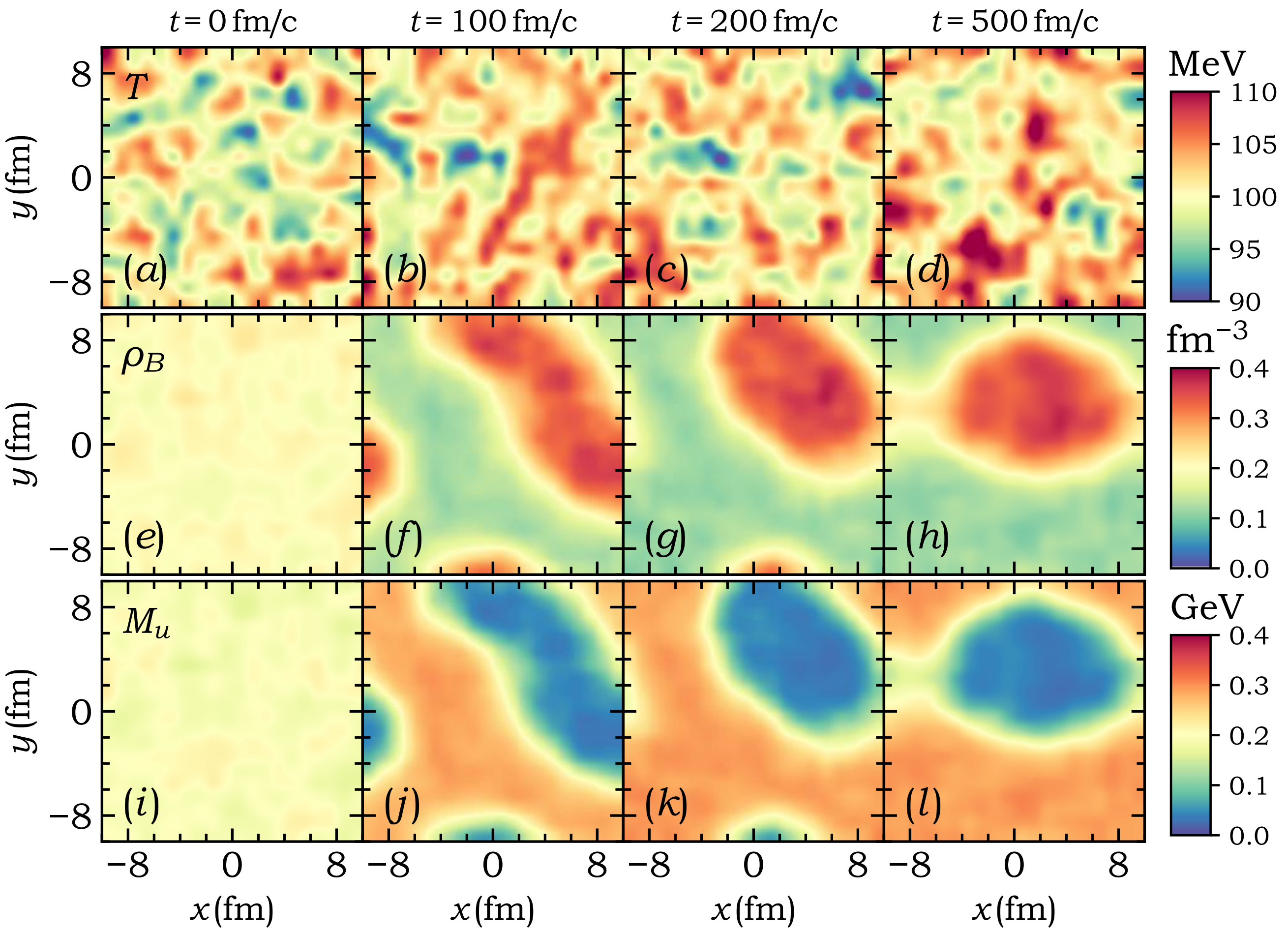


T_0 = 400 MeV
0 − 2 fm/c
2 − 4 fm/c
4 − 6 fm/c
6 − 8 fm/c
8 − 10 fm/c
0 − 10 fm/c × 1/5
dN/dM_ll (GeV^-1)
M_ll (GeV)



T_0 = 200 MeV
T_0 = 300 MeV
T_0 = 400 MeV
IMR − I + II
(a)
IMR − II
(b)
T_Dilepton (MeV)
T_Medium (MeV)


EOS − I
EOS − II
$(\partial P/\partial \rho_B)_T$ (MeV)
500
250
0
−250
−500
T (MeV)
150
120
90
60
0.1
0.2
0.3
ρ_B (fm^{-3})
(a)
(b)


$t = 0$ fm/c
$t = 100$ fm/c
$t = 200$ fm/c
$t = 500$ fm/c
T
ρ_B
M_u
y (fm)
x (fm)
−8
0
8
(a) (b) (c) (d)
(e) (f) (g) (h)
(i) (j) (k) (l)
MeV
110
105
100
95
90
fm^{-3}
0.4
0.3
0.2
0.1
0.0
GeV
0.4
0.3
0.2
0.1
0.0