Squeezed BBC of φφ in Au+Au and d+Au at RHIC energies

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1. Motivations

- In HEHIC QGP environment, φ meson can produce readily, bypassing the OZI rules [5].
- Small interaction expected between φ meson and hadronic medium makes it as a sensitive probe of the QGP properties [10-12,14-20].
- The results of φ elliptic flow in the HIC at the RHIC indicate that the flow reflects dominantly the anisotropy of the QGP and the hadronic scattering effect is unimportant [10-12,15-20].

1. Motivations

- However, φ meson is also argued to be with a larger hadronic-interaction cross section than the estimations by current theories, based on the recent measurements of the elliptic flow of identified hadrons in the Pb-Pb collisions at $\sqrt{s_{NN}}$ =2.76 GeV at the LHC [21].
- It is still an open issue to determine the inter-action between φ and the hadronic medium.

1. Motivations

- In the particle-emitting sources in HEHIC, the interaction between particle and source medium leads to a modification of the particle mass and a squeezed boson-antiboson correlation, known as back-to-back correlation (BBC) [22–24].
- The measurements of the BBC of φφ may give knowledge of the interaction between φ meson and source medium, and provide a new way to probe the thermal and evolve properties of the hadronic sources [22–26].

2. Bases of squeezed BBC

Two-particle correlation function:

$$C_2(\mathbf{k}_1, \mathbf{k}_2) = \frac{N_2(\mathbf{k}_1, \mathbf{k}_2)}{N_1(\mathbf{k}_1) N_1(\mathbf{k}_2)}$$

where

$$N_1(\mathbf{k}_1) = \omega_{\mathbf{k}_1} \frac{d^3 N}{d\mathbf{k}_1} = \omega_{\mathbf{k}_1} \langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_1} \rangle$$

$$N_2(\mathbf{k}_1, \mathbf{k}_2) = \omega_{\mathbf{k}_1} \omega_{\mathbf{k}_2} \langle a^\dagger_{\mathbf{k}_1} a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_2} a_{\mathbf{k}_1} \rangle$$

Wick Theorem

$$= \omega_{\mathbf{k}_1} \omega_{\mathbf{k}_2} [\langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_1} \rangle \langle a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_2} \rangle + \langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_2} \rangle \langle a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_1} \rangle + \langle a^\dagger_{\mathbf{k}_1} a^\dagger_{\mathbf{k}_2} \rangle \langle a_{\mathbf{k}_2} a_{\mathbf{k}_1} \rangle],$$

HBT-Correlation

Squeezed Correlation

Noninterference term

Interference Term

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2. Bases of squeezed BBC

- **1996, M.Asakawa and T.Csorog put forward the squeezed correlation of boson-antiboson due to their mass modification in medium, back-to-back correlation.**

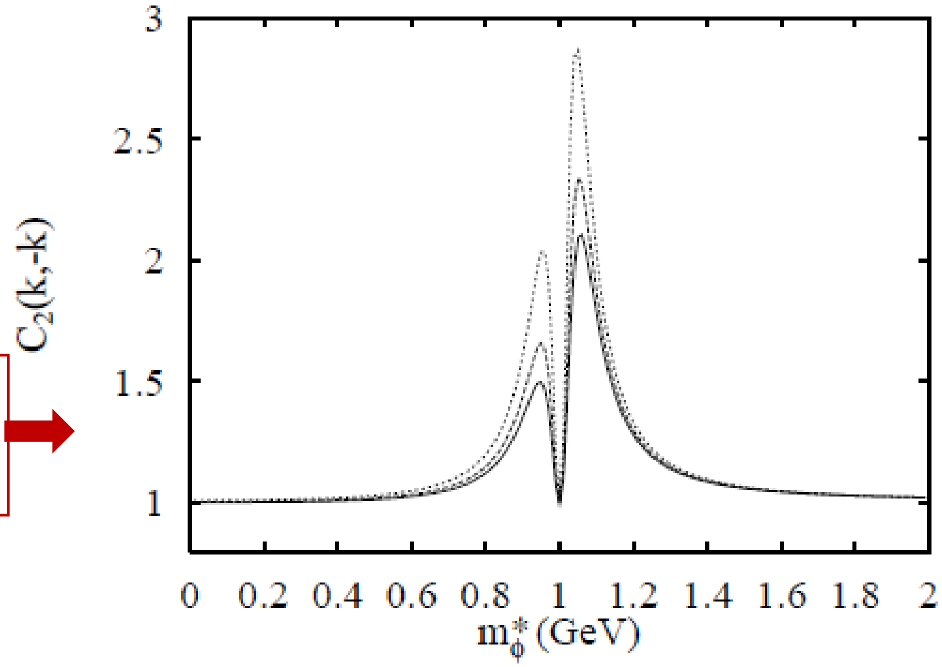
  Heavy Ion Physics, 1996, 4: 233. **Uniform system, without time evolution.**

- **1999, M.Asakawa,T.Csorgo, and M.Gyulassy, back-to-back correlation (BBC) of φφ, Phys. Rev. Lett., 1999, 83: 4013. Uniform system, with**

Emission time factor:

$$F(\tau) = \frac{\theta(\tau-\tau_0)}{\Delta t}\, e^{-(\tau-\tau_0)/\Delta t}$$

The solid, dashed, and dotted lines stand for |**k**|=0, 300, and 500 MeV.



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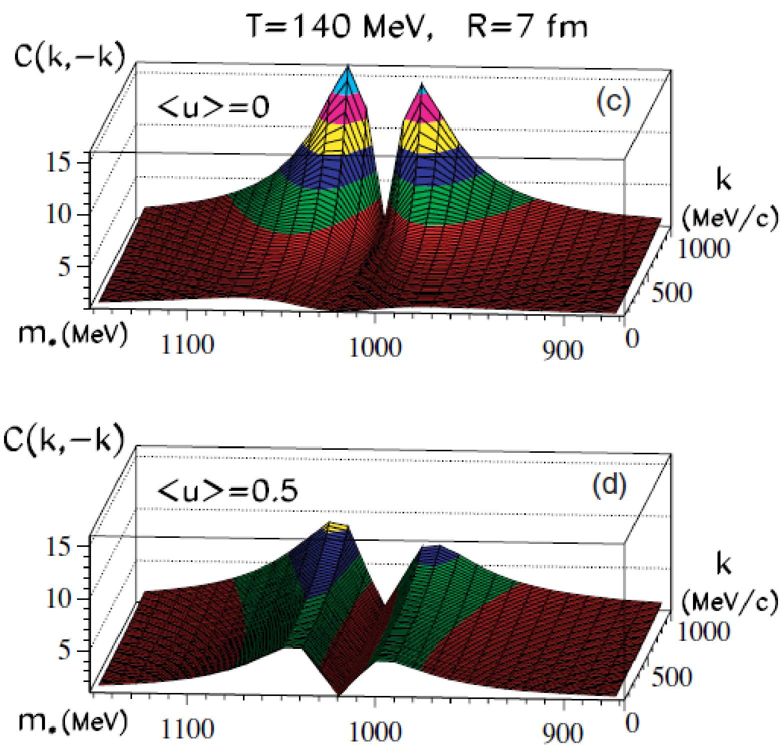
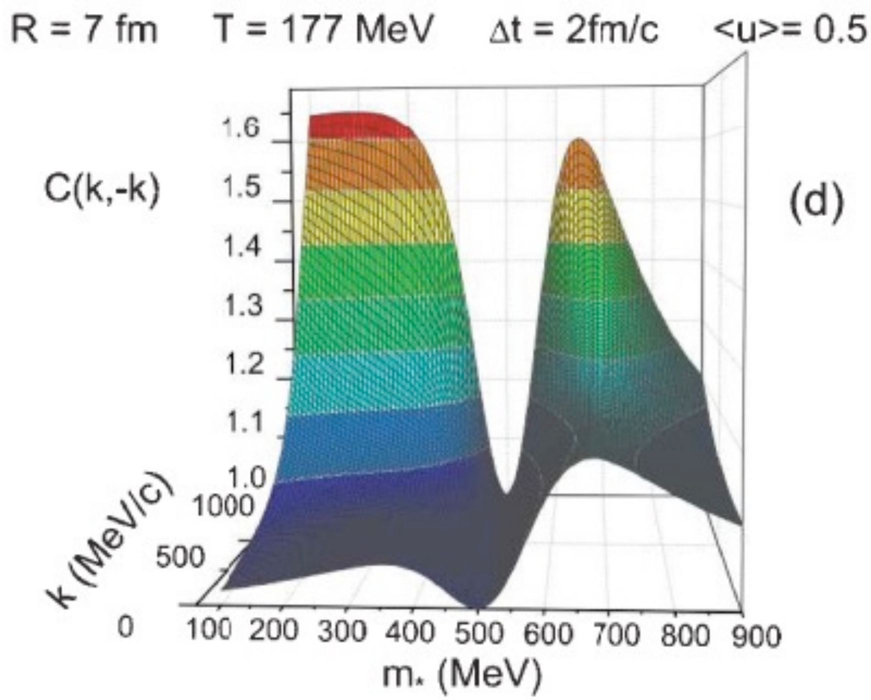
2. Bases of squeezed BBC

2006, S.Padula et al., Phys. Rev. C, 2006, 73: 044906.

2010, S.Padula et al., BBC of K^+K^- Phys. Rev. C, 2010, 82：034905.





2. Bases of squeezed BBC

hadronic gas

quasi-particle (in medium)

Freeze out

$m_* \neq m$

$m_*^2 = m^2 - \delta M^2$

Free Particle (observed)

a_k and b_k are related by Bogoliubov transformation

$$a_{\mathbf{k}} = c_{\mathbf{k}}\, b_{\mathbf{k}} + s_{-\mathbf{k}}^*\, b_{-\mathbf{k}}^\dagger, \quad c_{\mathbf{k}} = \cosh f_{\mathbf{k}}, \quad s_{\mathbf{k}} = \sinh f_{\mathbf{k}}, \quad f_{\mathbf{k}} = \frac{1}{2}\log(\omega_{\mathbf{k}}/\Omega_{\mathbf{k}})$$

$$\omega_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + m^2}, \quad \Omega_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + m_*^2}, \quad n_{\mathbf{k}} = \frac{1}{\exp(\Omega_{\mathbf{k}}/T) - 1}, \quad n_1(\mathbf{k}) = |c_{\mathbf{k}}|^2 n_{\mathbf{k}} + |s_{-\mathbf{k}}|^2 (n_{-\mathbf{k}} + 1).$$

BBC Function

$$C(\mathbf{k}_1, \mathbf{k}_2) = 1 + \frac{|G_s(\mathbf{k}_1, \mathbf{k}_2)|^2}{G_c(\mathbf{k}_1, \mathbf{k}_1) G_c(\mathbf{k}_2, \mathbf{k}_2)},$$

$$C(\mathbf{k}, -\mathbf{k}) = 1 + \frac{V\, |c_{\mathbf{k}}\, s_{\mathbf{k}}^*\, n_{\mathbf{k}} + c_{-\mathbf{k}}\, s_{-\mathbf{k}}^*\, (n_{-\mathbf{k}} + 1)|^2}{V\, [n_1(\mathbf{k})\, n_1(-\mathbf{k})]}$$

The BBC function $C(\mathbf{k}, -\mathbf{k})$ will be 1 if there is no mass modification. However, for a finite mass modification, $\delta m^2 = m^2 - m_*^2$, $f_{\mathbf{k}} \sim \delta m^2/(4\mathbf{k}^2)$ as $|\mathbf{k}| \to \infty$, and the BBC function will increase with increasing particle momentum [2], $C(\mathbf{k}, -\mathbf{k}) \sim 1 + 1/|s_{-\mathbf{k}}|^2 \sim 1 + \mathbf{k}^4/(\delta m^2/4)^2$.

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3. Method & results

We use the VISH2+1 code with event-by-event MC-Glb initial condition to simulate the particle-emitting sources for the Au+Au & d+Au collisions at RHIC energies.

We extract modified mass in medium m* from experimental data.

The BBC function of the two ϕ mesons with momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ is defined as [23, 24]

$$C(\mathbf{k}_1,\mathbf{k}_2) = 1 + \frac{|G_s(\mathbf{k}_1,\mathbf{k}_2)|^2}{G_c(\mathbf{k}_1,\mathbf{k}_1)G_c(\mathbf{k}_2,\mathbf{k}_2)}, \quad (1)$$

where $G_c(\mathbf{k}_1,\mathbf{k}_2)$ and $G_s(\mathbf{k}_1,\mathbf{k}_2)$ are the chaotic and squeezed amplitudes, respectively. For evolution particle-emitting sources, they can be expressed as [23–26, 29]

$$G_c(\mathbf{k}_1,\mathbf{k}_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K^\mu_{1,2}\, e^{i\, q_{1,2}\cdot r} \Big\{ |c'_{\mathbf{k}'_1,\mathbf{k}'_2}|^2\, n'_{\mathbf{k}'_1,\mathbf{k}'_2} + |s'_{-\mathbf{k}'_1,-\mathbf{k}'_2}|^2\, [n'_{-\mathbf{k}'_1,-\mathbf{k}'_2}+1] \Big\}, \quad (2)$$

$$G_s(\mathbf{k}_1,\mathbf{k}_2) = \int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K^\mu_{1,2}\, e^{2i\, K_{1,2}\cdot r} \Big\{ s'^{*}_{-\mathbf{k}'_1,\mathbf{k}'_2}\, c'_{\mathbf{k}'_2,-\mathbf{k}'_1} \times n'_{-\mathbf{k}'_1,\mathbf{k}'_2} + c'_{\mathbf{k}'_1,-\mathbf{k}'_2}\, s'^{*}_{-\mathbf{k}'_2,\mathbf{k}'_1}\, [n'_{\mathbf{k}'_1,-\mathbf{k}'_2}+1] \Big\}, \quad (3)$$

where $d^4\sigma_\mu(r)$ is the four-dimension element of freeze-out hypersurface, $q^\mu_{1,2} = k^\mu_1 - k^\mu_2$, $K^\mu_{1,2} = (k^\mu_1 + k^\mu_2)/2$, and $\mathbf{k}'_i$ is the local-frame momentum corresponding to $\mathbf{k}_i$ (i =

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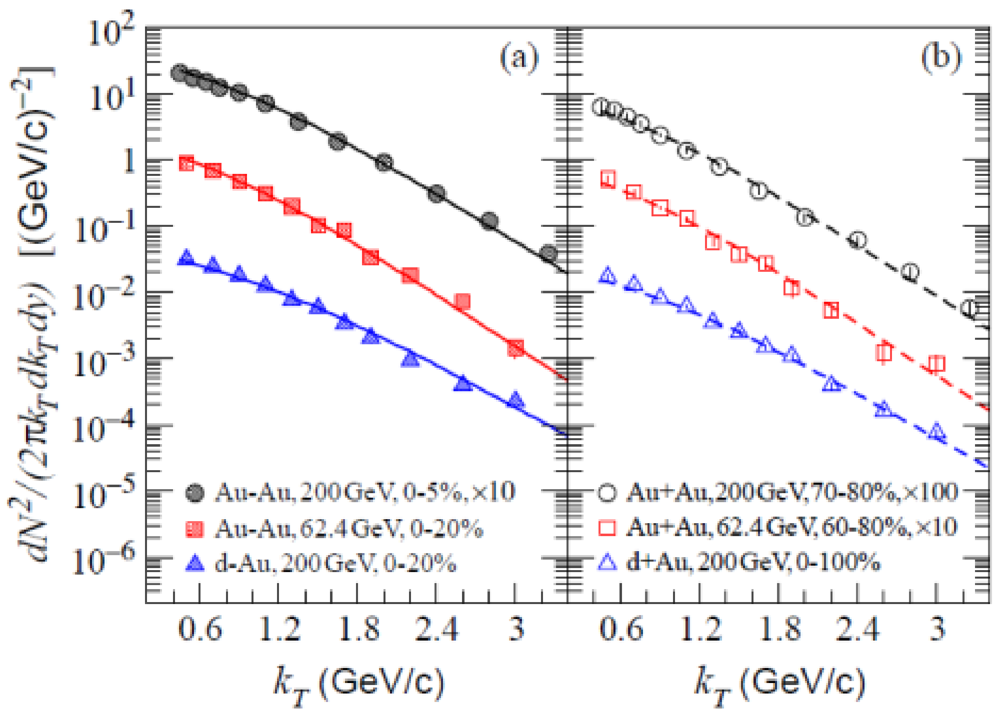
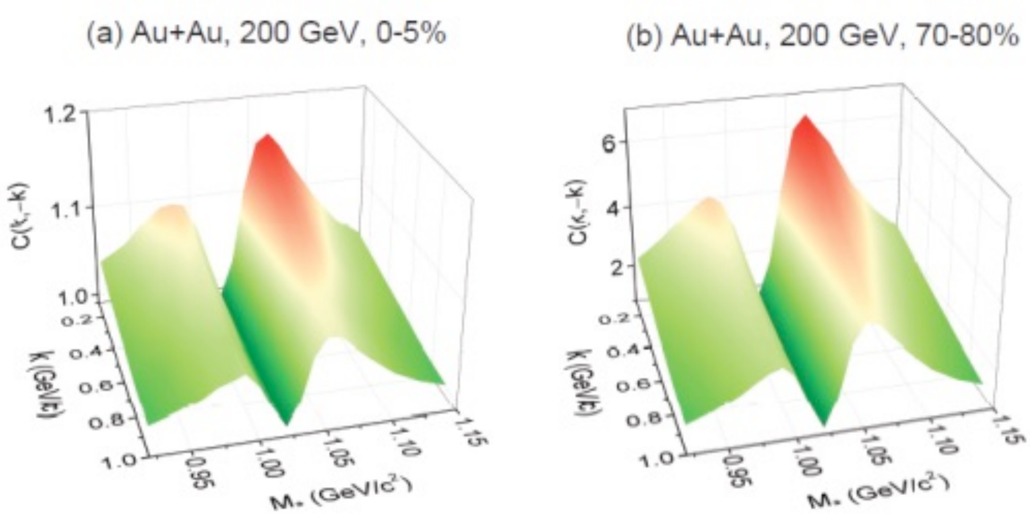
3. Method & results



The transverse-momentum spectra of the φ meson calculated with the viscous hydrodynamic code at the freeze-out temperature T_f=140MeV. The experimental data measured by STAR collaboration [10] are also plotted. The calculated spectra suit the experimental data well.

$$G_s(\mathbf{k}_1,\mathbf{k}_2)=\int \frac{d^4\sigma_\mu(r)}{(2\pi)^3} K^\mu_{1,2}\, e^{2i\,K_{1,2}\cdot r}\Big\{s'^*_{-\mathbf{k}'_1,\mathbf{k}'_2} c'_{\mathbf{k}'_2,-\mathbf{k}'_1} \times n'_{-\mathbf{k}'_1,\mathbf{k}'_2} + c'_{\mathbf{k}'_1,-\mathbf{k}'_2} s'^*_{-\mathbf{k}'_2,\mathbf{k}'_1}\big[n'_{\mathbf{k}'_1,-\mathbf{k}'_2}+1\big]\Big\}.$$



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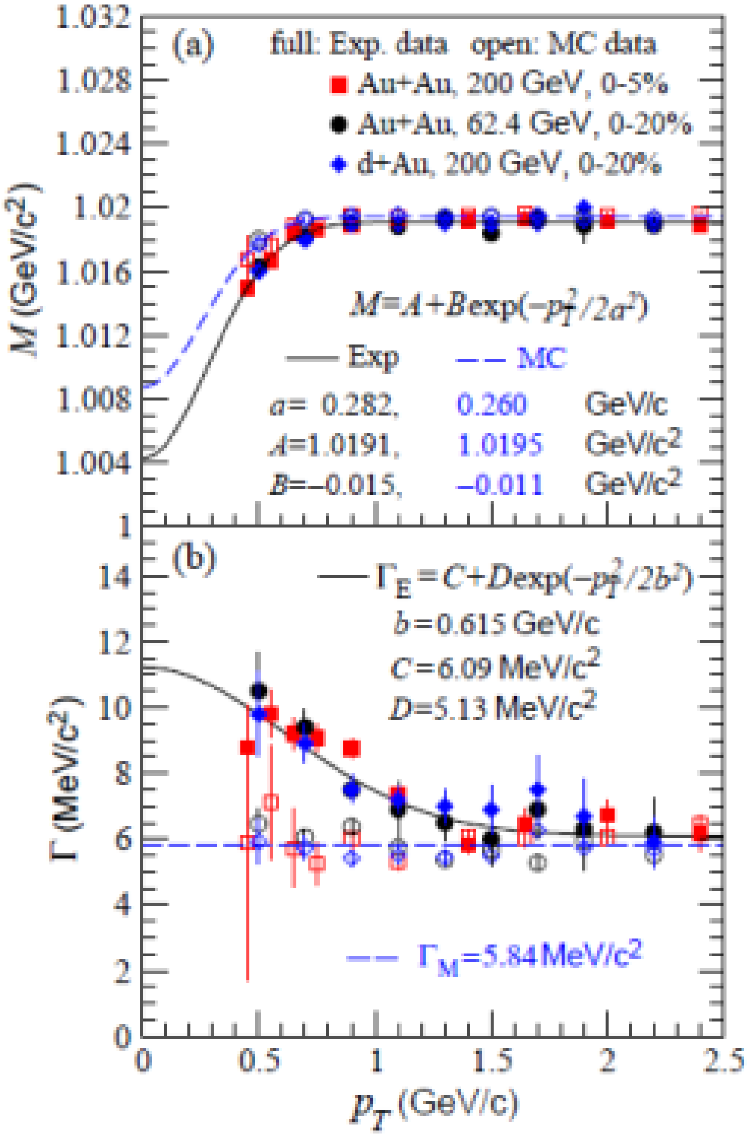
3. Method & results



On the other hand, the φ mesons with larger p_T (v_T) escape the source more easily and with more possibility decaying outside of the source. ($\varphi \rightarrow K^+K^-$)

There are larger differences between the experimental and MC data in the low p_T region.

Considering the φ mesons with small p_T, thus with small average transverse velocity v_T, have more possibility decaying inside the source medium which with a transverse expanding velocity comparable to v_T, the differences between the EXP and MC data at small p_T reflect the medium effects on the measured mass and mass-width.

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3. Method & results

PRL 98, 042501 (2007) PHYSICAL REVIEW LETTERS week ending 26 JANUARY 2007

Evidence for In-Medium Modification of the ϕ Meson at Normal Nuclear Density

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[3]*Department of Physics, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto 606-8502, Japan*
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Invariant mass spectra of e^+e^- pairs have been measured in 12 GeV $p + A$ reactions to detect possible in-medium modification of vector mesons. Copper and carbon targets are used to study the nuclear-size dependence of e^+e^- invariant mass distributions. A significant excess on the low-mass side of the ϕ meson peak is observed in the low $\beta\gamma(= \beta/\sqrt{1-\beta^2})$ region of ϕ mesons ($\beta\gamma < 1.25$) with copper targets. However, in the high $\beta\gamma$ region ($\beta\gamma > 1.25$), spectral shapes of ϕ mesons are well described by the Breit-Wigner shape when experimental effects are considered. Thus, in addition to our earlier publications on ρ/ω modification, this study has experimentally verified vector meson mass modification at normal nuclear density.

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The measurements of the electron-positron decay of φ by the KEK-PS E325 Collaboration are consistent with our analyses.

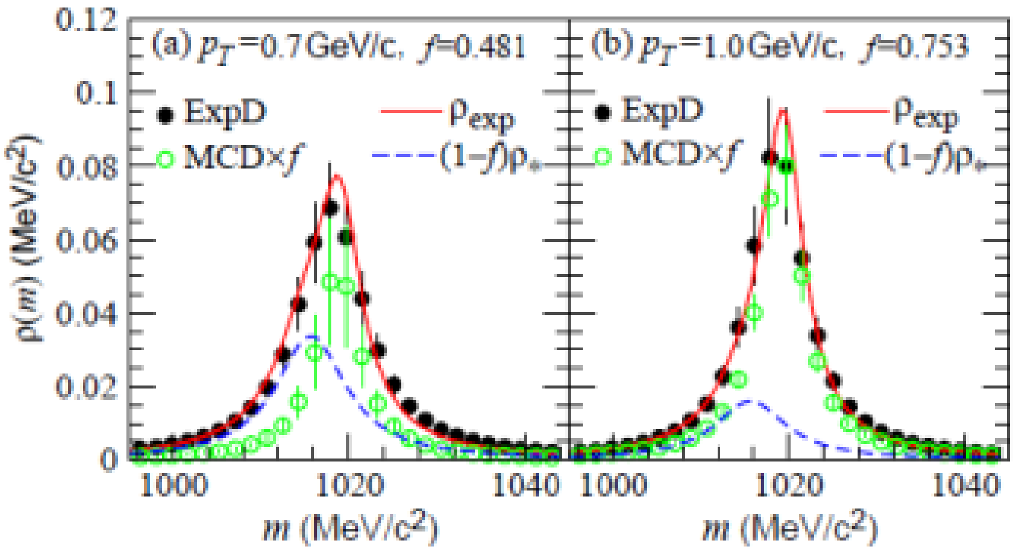
3. Method & results

Assuming the measured mass distribution of K+K− in the experiments [10] consists of the two parts, one from the contribution of the mesons decaying inside the source medium and another from the contribution of the φ decaying outside of the source, we have the normalized density distribution of the mass as,

$$\rho_{\rm exp}(m; M_{\rm exp}, \Gamma_{\rm exp}) = \frac{\Gamma_{\rm exp}/2\pi}{(m - M_{\rm exp})^2 + (\Gamma_{\rm exp}/2)^2}$$
$$= f(p_T)\rho_0(m; M_0, \Gamma_0) + [1 - f(p_T)]\rho_*(m; M_*, \Gamma_*)$$

TABLE I: Results of fitting $\rho_{\rm exp}(M)$ with Eq. (4).

p_T(GeV/c)	m_*(GeV/c^2)	Γ_*(MeV/c^2)	f
0.5	1.0157 ± 0.2110	9.785 ± 0.271	0.000 ± 0.008
0.7	1.0157(fixed)	9.785(fixed)	0.481 ± 0.031
1.0	1.0157(fixed)	9.785(fixed)	0.753 ± 0.014
1.4	1.0157(fixed)	9.785(fixed)	0.853 ± 0.013



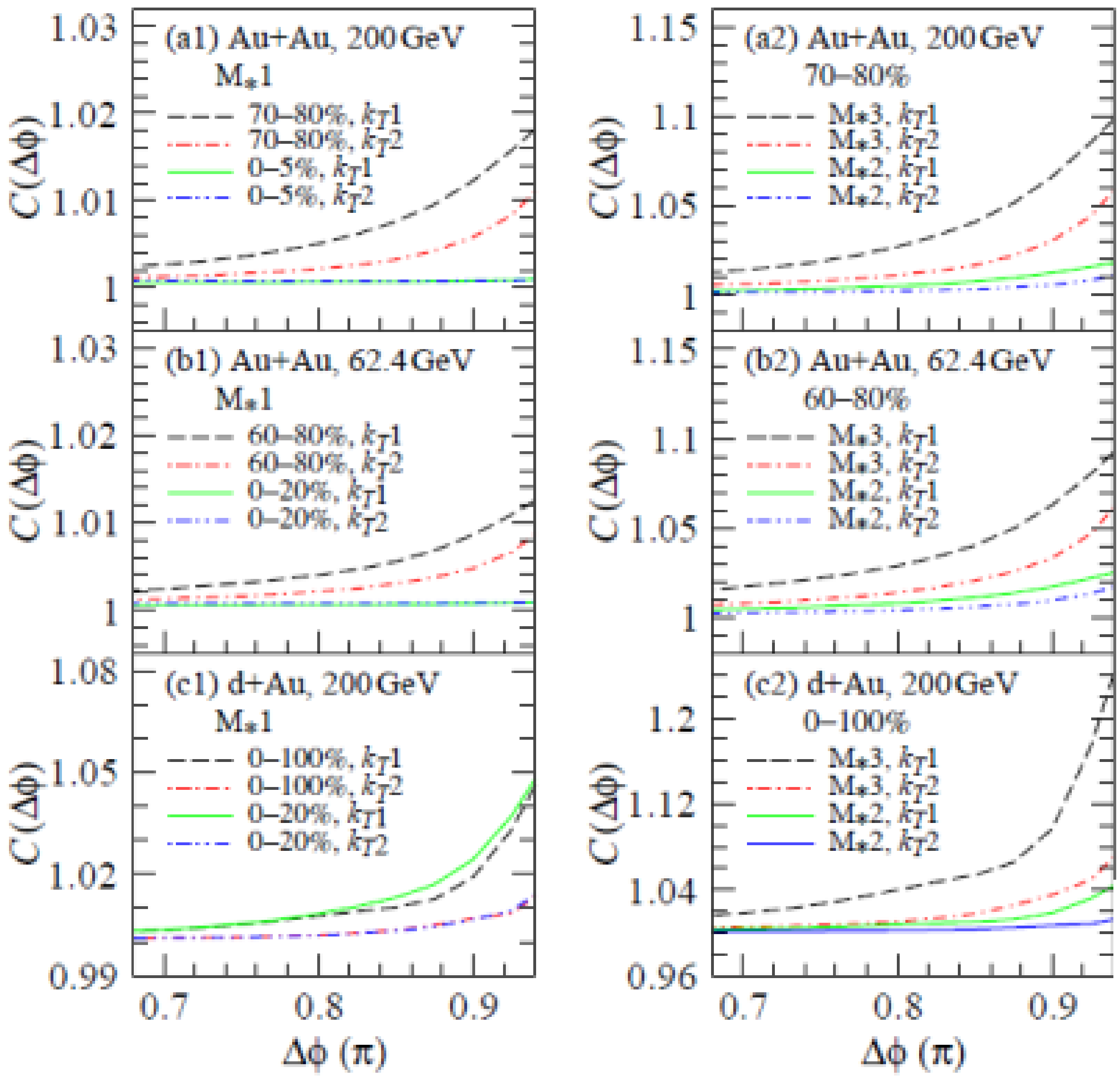
3. Method & results

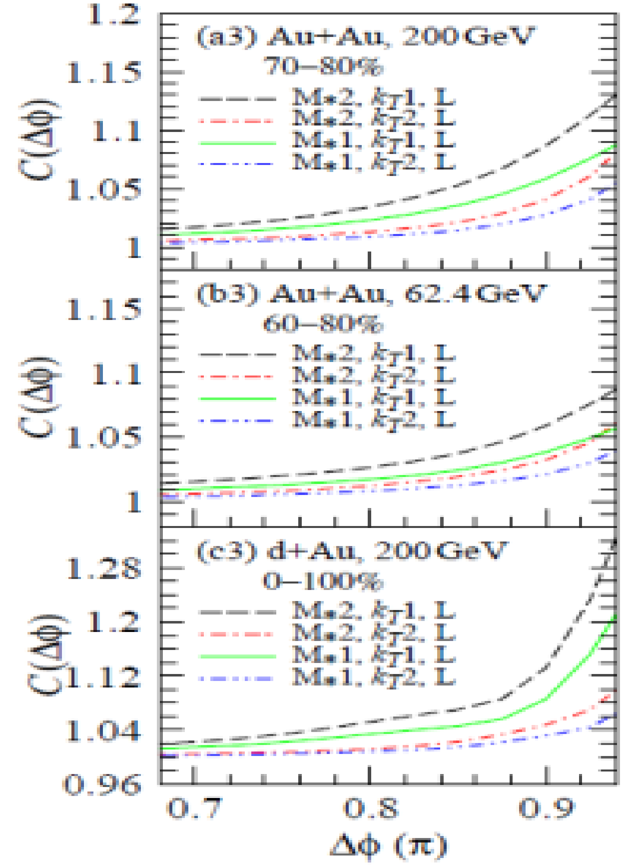
TABLE I: Results of fitting $\rho_{\rm exp}(m)$ with Eq. (4).

	p_T(GeV/c)	M_*(GeV/c^2)	Γ_*(MeV/c^2)	f	χ^2/NBF
Fit 1	0.5	1.0157 ± 0.0003	9.785 ± 0.373	0.000 ± 0.008	0.04/30
	0.7	1.0157(fixed)	9.785(fixed)	0.481 ± 0.031	65.05/30
	1.0	1.0157(fixed)	9.785(fixed)	0.753 ± 0.014	68.43/30
Fit 2	0.5	1.0148 ± 0.0005	12.069 ± 0.921	0.40(fixed)	0.56/30
	0.7	1.0148(fixed)	12.069(fixed)	0.640 ± 0.021	51.98/30
	1.0	1.0148(fixed)	12.069(fixed)	0.829 ± 0.009	65.82/30
Fit 3	0.5	1.0107 ± 0.0016	20.197 ± 5.773	0.80(fixed)	5.95/30
	0.7	1.0107(fixed)	20.197(fixed)	0.846 ± 0.009	71.80/30
	1.0	1.0107(fixed)	20.197(fixed)	0.926 ± 0.004	111.79/30

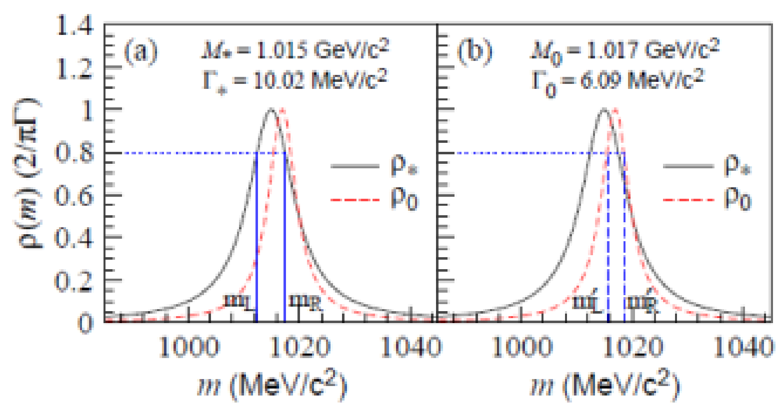
$$\rho_{\rm exp}(m; M_{\rm exp}, \Gamma_{\rm exp}) = \frac{\Gamma_{\rm exp}/2\pi}{(m - M_{\rm exp})^2 + (\Gamma_{\rm exp}/2)^2}$$
$$= f(p_T)\rho_0(m; M_0, \Gamma_0) + [1 - f(p_T)]\rho_*(m; M_*, \Gamma_*)$$

3. Method & results





M*1∽f=0, M*2∽**f=0.4**, M*3∽f=0.8



k_T1 and k_T2 are calculated in the momentum regions $0.4 < |\mathbf{k}_T| < 0.5$ GeV/c and $0.8 < |\mathbf{k}_T| < 0.9$ GeV/c.

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4. Summary & conclusion

We investigate the squeezed BBC of φ meson caused by the mass modification in the source medium for the Au+Au and d+Au collisions at the RHIC energies.

The BBC functions are calculated using the modified masses extracted from experimental data and the source space-time distributions provided by the viscous hydrodynamic code VISH2+1.

It is found that the BBC of may perhaps be observed in the collisions of d+Au and the peripheral collisions of Au+Au at the RHIC energies.

We suggest to measure the BBC experimentally for understanding the mass modifications of the meson in the collisions.

Thanks！

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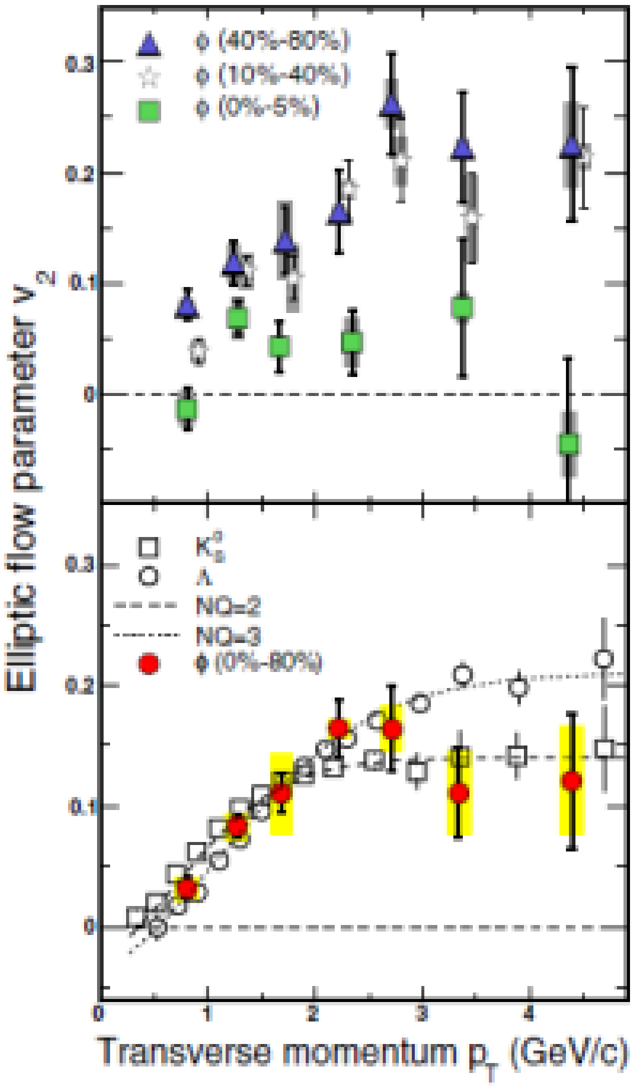
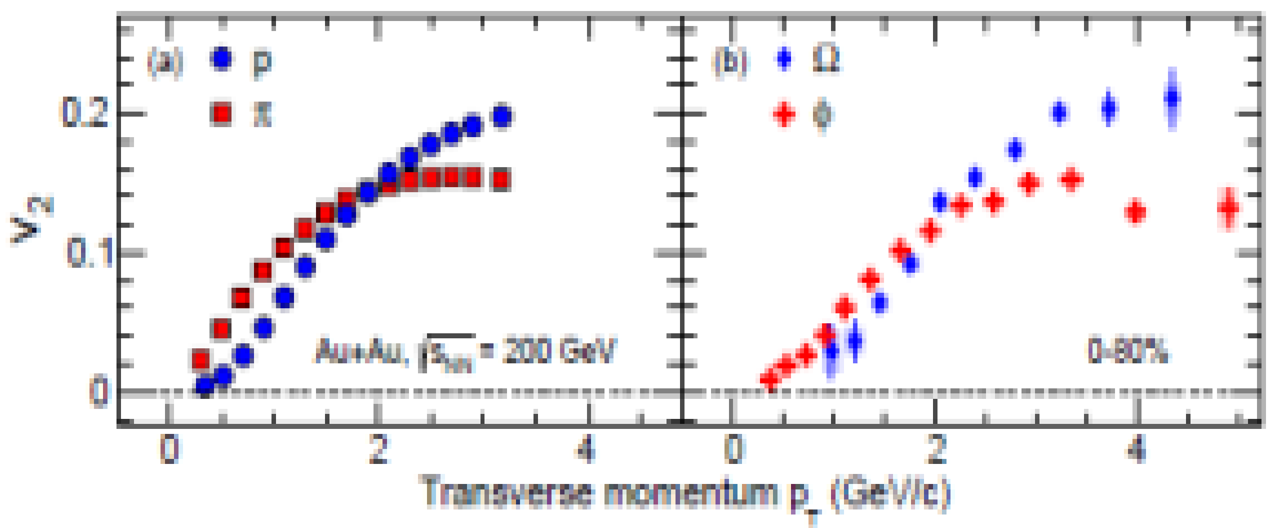
1. Motivations



[11] STAR Collab, PRL99,112301, 2007:
… for *pT*<2GeV/*c*, the *v*2 follows a mass-ordered hierarchy where the values of *v*2, within errors, fall between those of the heavier Λ (open circles) and lighter *K* (open squares). However, at intermediate *pT*, between 2–5GeV/*c*, the *v*2 appears to follow the same trend as *K*.



[20] STAR Collaboration, PRL116,062301, 2016.

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1. Motivations

[16] PHENIX Collab, PRL99,052301, 2007.

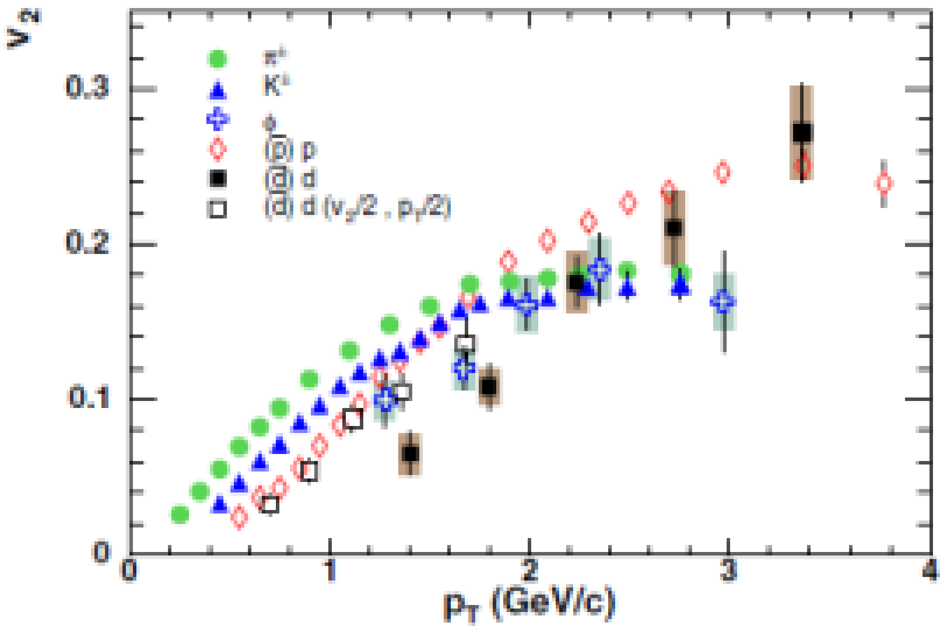

FIG. 2 (color online). Comparison of differential $v_2(p_T)$ for mesons, $(\bar{d})d$, $\pi^{\pm}$, $K^{\pm}$, and $(\bar{p})p$ (as indicated). Results a shown for 20%–60% central Au + Au collisions.

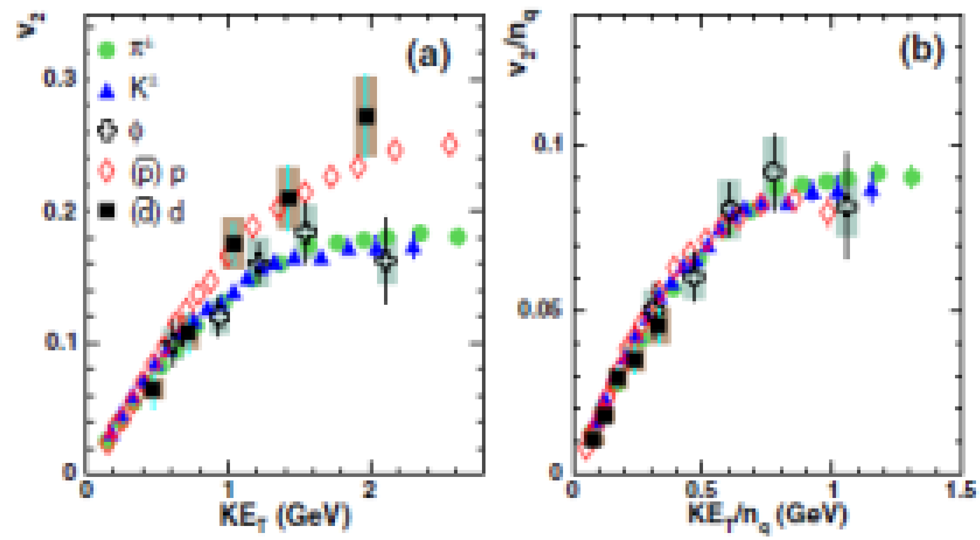

FIG. 3 (color online). (a) v_2 vs KE_T for several identified particle species obtained in midcentral (20%–60%) Au + Au collisions. (b) v_2/n_q vs KE_T/n_q for the same particle species shown in (a). The shaded bands indicate systematic error estimates for $(\bar{d})d$ and ϕ mesons (see text).

$KE_T = m_T - m$

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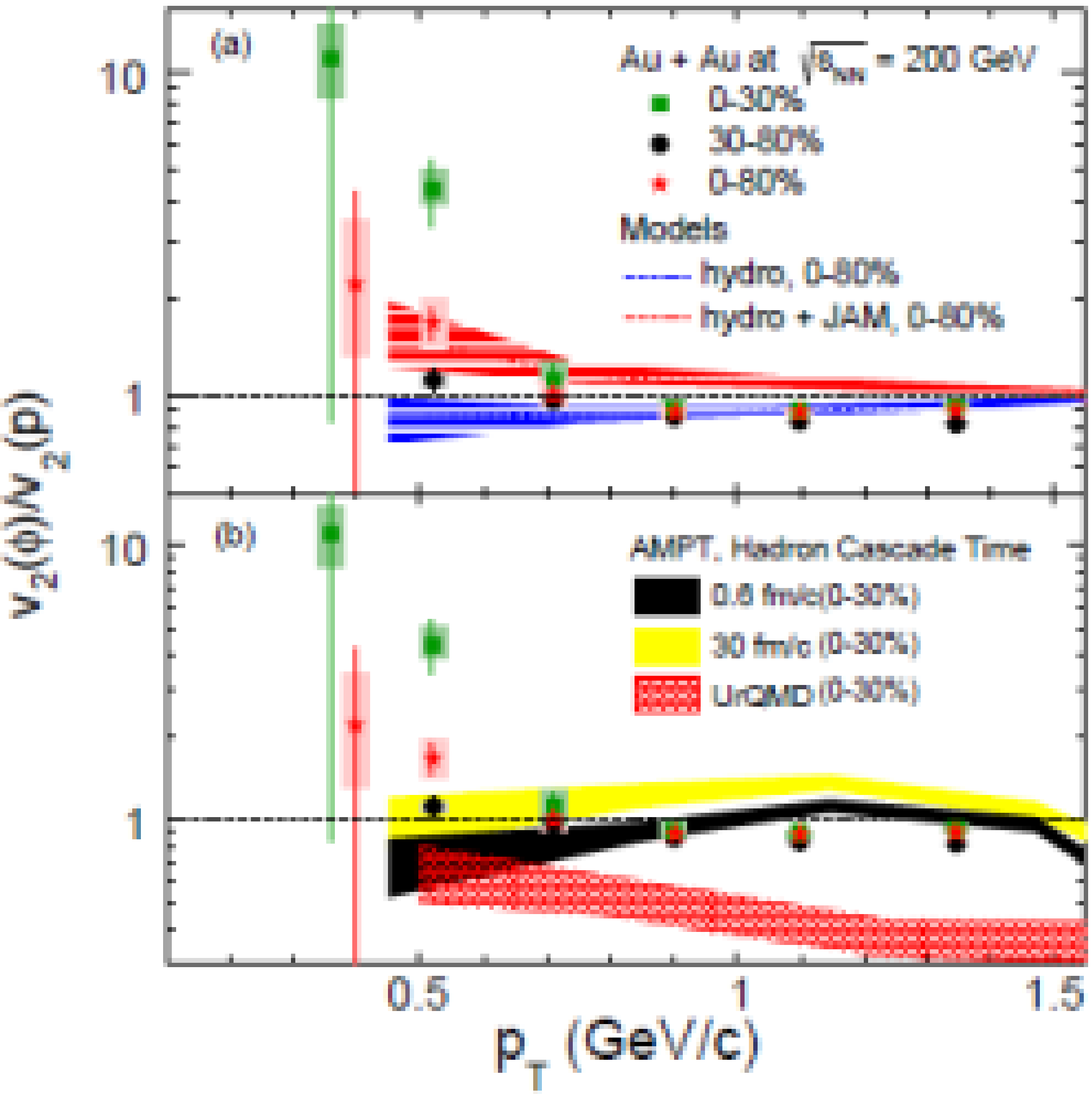
1. Motivations



[20] STAR Collaboration, PRL 116, 062301, 2016: There is a indication of the breakdown of previous observed mass ordering between φ and proton v2 at low transverse momentum in the 0-30% centrality range, possibly indicating late hadronic interactions affecting the proton v2.

1. Motivations

[21] ALICE Collab, JHEP06,190, 2015: The v2 values of the φ-meson in figure 5 indicate that for pT<3 GeV/c it follows the mass-ordered hierarchy. However, for higher pT values the φ data points appear to follow the band of baryons for central events within uncertainties.

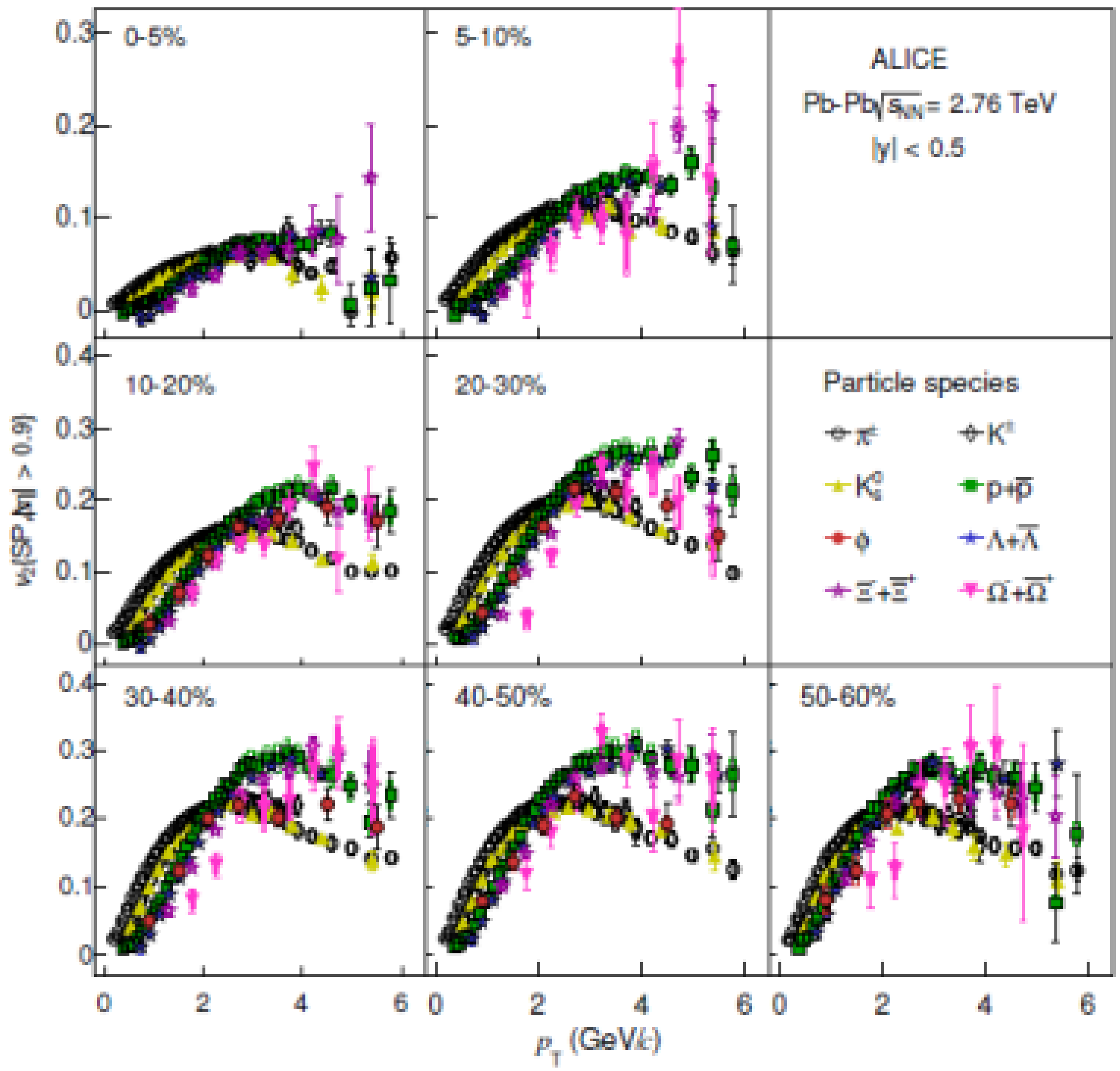


Figure 5. The p_T-differential v_2 for different particle species grouped by centrality class of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

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1. Motivations

[21] ALICE Collab, JHEP06,190, 2015: A distinct mass ordering was found for all centralities in the low transverse momentum region i.e. for pT<3 GeV/c, which is attributed to the interplay between elliptic and radial flow that modifies the v2(pT) according to particle mass.

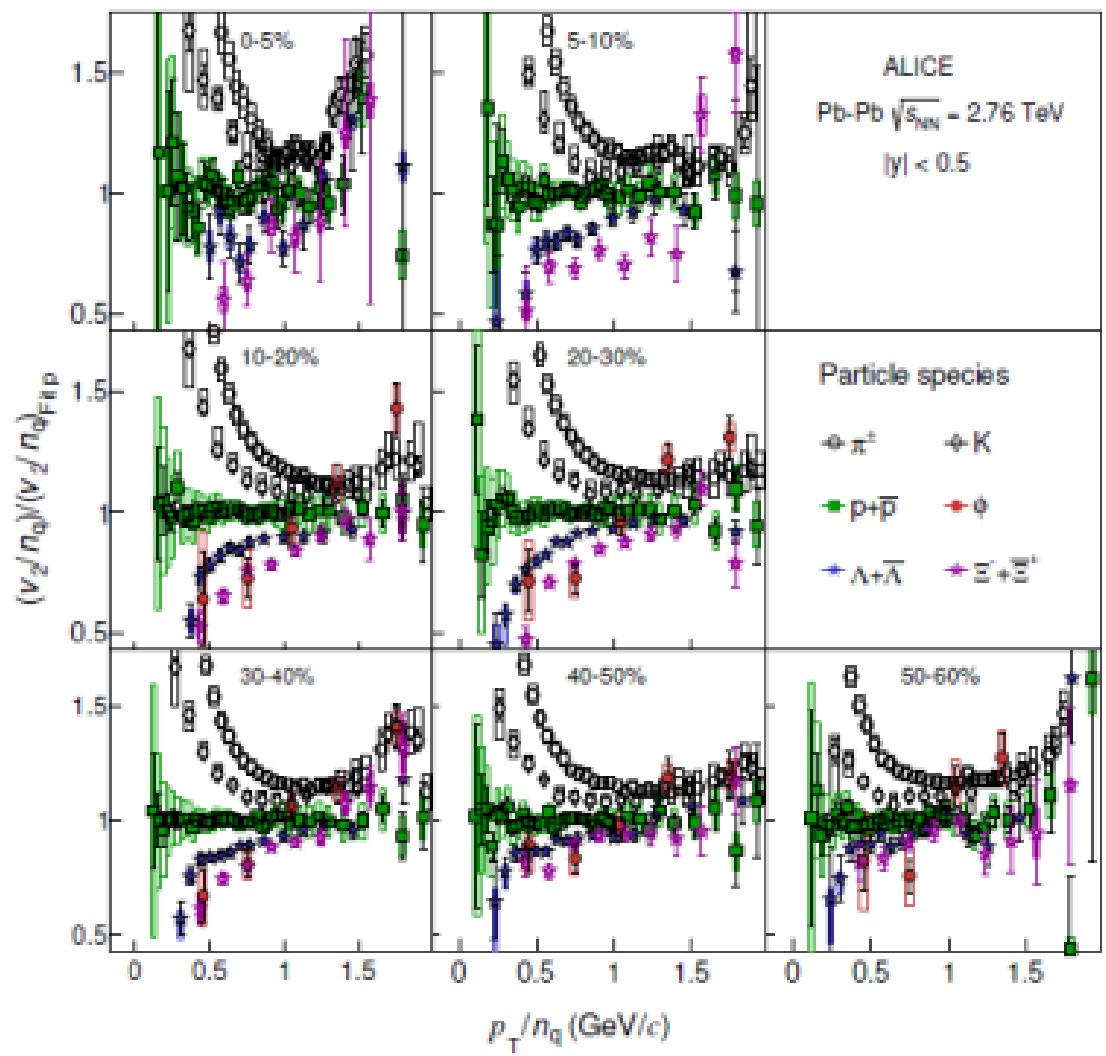


Figure 9. The p_T/n_q dependence of the double ratio of v_2/n_q for every particle species relative to a fit to v_2/n_q of p and $\overline{p}$ (see text for details) for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

2. Bases of BBC

1996年，M.Asakawa和T.Csorog指出当粒子在源内与介质相互作用发生质量改变时，会产生一种正反玻色子对的压缩关联，即背对背关联。

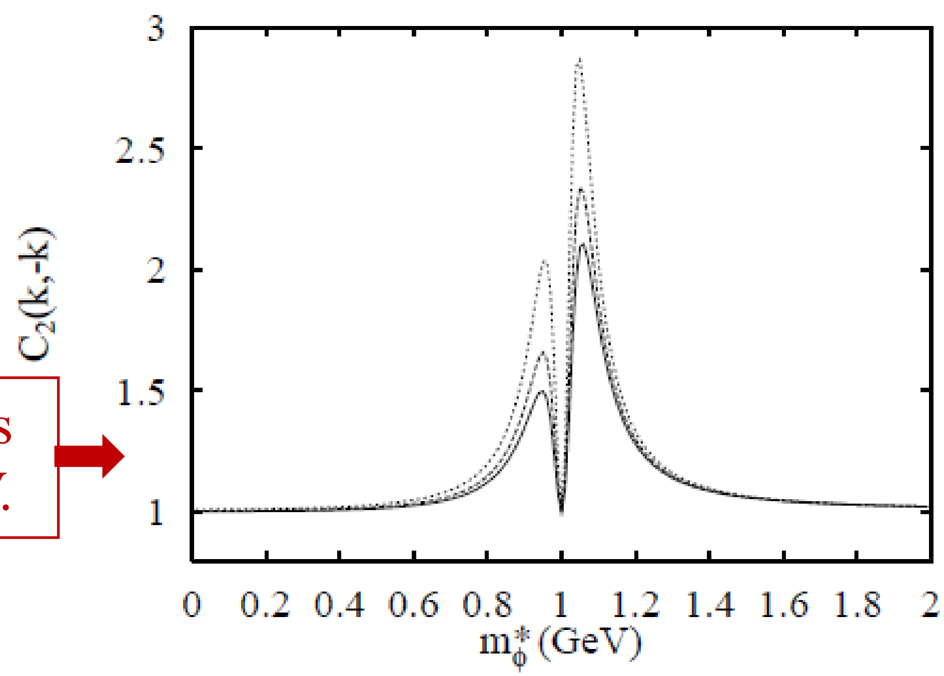
Heavy Ion Physics, 1996, 4: 233. 未考虑源发射时间分布对背对背关联的影响。

1999年，M.Asakawa, T.Csorgo和M.Gyulassy进一步在瞬时冻出假设下，得出了均匀源的φφ背对背关联函数。**Phys. Rev. Lett., 1999, 83: 4013.**

源发射时间分布为：

$$F(\tau) = \frac{\theta(\tau - \tau_0)}{\Delta t}\, e^{-(\tau-\tau_0)/\Delta t}$$

The solid, dashed, and dotted lines stand for |**k**|=0, 300, and 500 MeV.

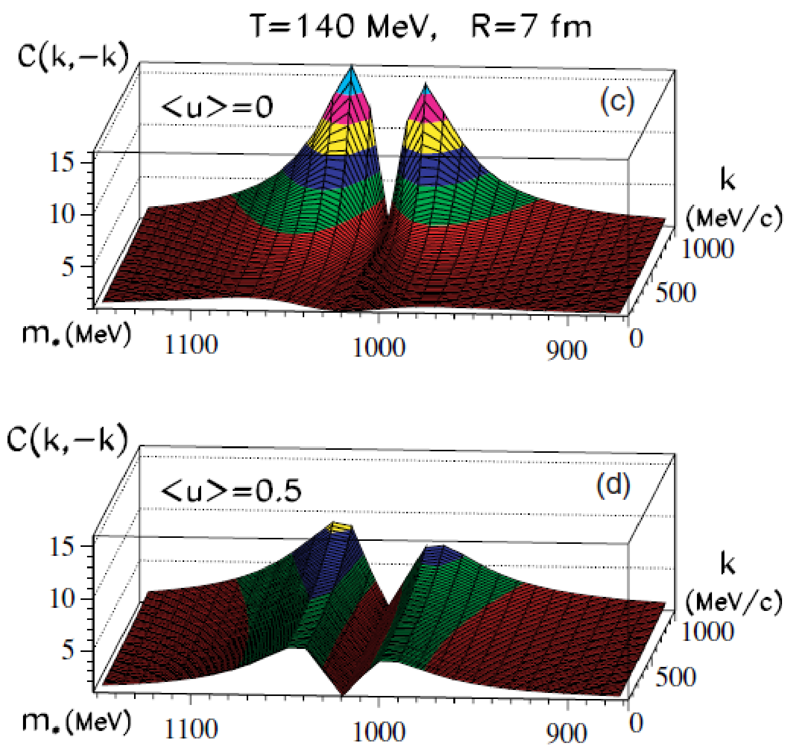


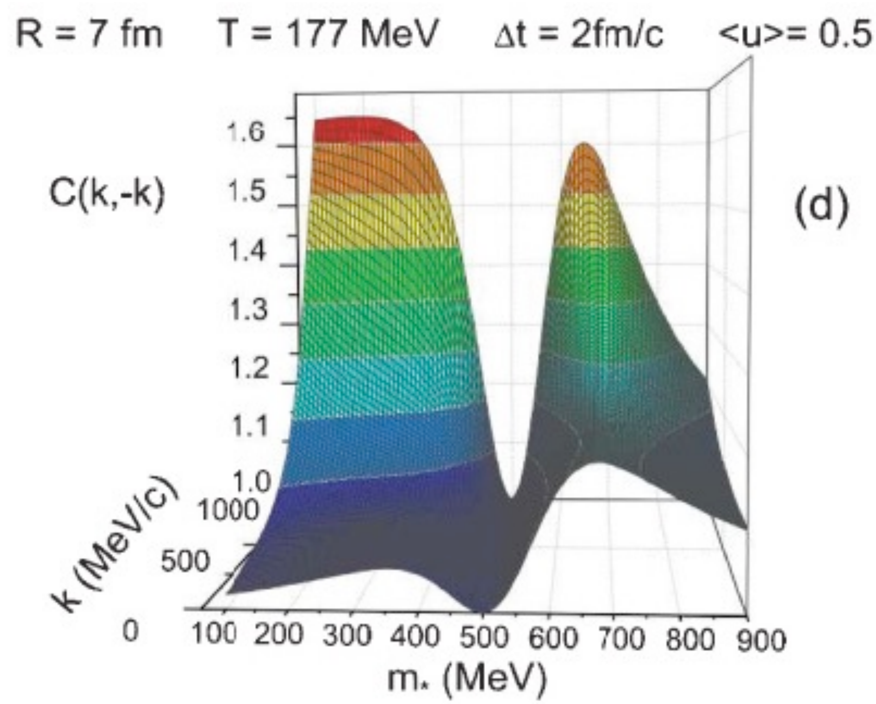
2. Bases of BBC

2006年，S.Padula等人进一步研究了有限大并且膨胀的系统在非相对论情况下的背对背关联。**Phys. Rev. C, 2006, 73: 044906.**

之后，S.Padula等人还进一步研究了同样情况下 K^+K^- 的背对背关联。

Phys. Rev. C, 2010, 82：034905.





2. Bases of BBC

强子气体媒介

准粒子（处于媒介中）

热力学冻出

$m_* \neq m$

$m_*^2 = m^2 - \delta M^2$

自由粒子（实验探测到）

$(b_{\mathbf{k}}^\dagger, b_{\mathbf{k}})$

m_*

$$H = H_0 - \frac{1}{2}\int d\mathbf{x} d\mathbf{y}\, \phi(\mathbf{x})\delta M^2(\mathbf{x}-\mathbf{y})\phi(\mathbf{y})$$

$$H = \int \Omega_k b_k^+ b_k d^3k$$

$$\Omega_k = \sqrt{m_*^2 + k^2}$$

$(a_{\mathbf{k}}^\dagger, a_{\mathbf{k}})$

m

$$H_0 = \frac{1}{2}\int d\mathbf{x}(\dot{\phi}^2 + |\nabla\phi|^2 + m_0^2\phi^2)$$

$$H_0 = \int \omega_k a_k^+ a_k d^3k$$

$$\omega_k = \sqrt{m^2 + k^2}$$

a_k^+与b_k^+由波戈留波夫变换联系 起来

$$a_{\mathbf{k}} = c_{\mathbf{k}}\, b_{\mathbf{k}} + s_{-\mathbf{k}}^*\, b_{-\mathbf{k}}^\dagger, \quad c_{\mathbf{k}} = \cosh f_{\mathbf{k}}\,, \quad s_{\mathbf{k}} = \sinh f_{\mathbf{k}}\,, \quad f_{\mathbf{k}} = \frac{1}{2}\log(\omega_{\mathbf{k}}/\Omega_{\mathbf{k}})$$

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2. Bases of BBC

$$N_2(\mathbf{k}_1, \mathbf{k}_2) = \omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}\langle a^\dagger_{\mathbf{k}_1} a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_2} a_{\mathbf{k}_1}\rangle$$
$$= \omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}\left[\langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_1}\rangle\langle a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_2}\rangle + \langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_2}\rangle\langle a^\dagger_{\mathbf{k}_2} a_{\mathbf{k}_1}\rangle + \langle a^\dagger_{\mathbf{k}_1} a^\dagger_{\mathbf{k}_2}\rangle\langle a_{\mathbf{k}_2} a_{\mathbf{k}_1}\rangle\right],$$

$$a_{\mathbf{k}} = c_{\mathbf{k}}\, b_{\mathbf{k}} + s^*_{-\mathbf{k}}\, b^\dagger_{-\mathbf{k}}$$

$$< a_k a_{-k} > = < c_k^2 b_k b_{-k} + c_k s_k b_k b_k^+ + c_k s_k b_{-k}^+ b_{-k} + s_k^2 b_{-k}^+ b_k^+ >$$
$$= < c_k s_k (1 + b_k^+ b_k) + c_k s_k b_{-k}^+ b_{-k} >$$
$$= 2 c_k s_k n_k + c_k s_k$$
$$n_k = < b_k^+ b_k >$$

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2. Bases of BBC

混沌振幅： $G_c(\mathbf{k}_1, \mathbf{k}_2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\,\langle a^\dagger_{\mathbf{k}_1} a_{\mathbf{k}_2}\rangle,$

压缩振幅： $G_s(\mathbf{k}_1, \mathbf{k}_2) = \sqrt{\omega_{\mathbf{k}_1}\omega_{\mathbf{k}_2}}\,\langle a_{\mathbf{k}_1} a_{\mathbf{k}_2}\rangle,$

背对背关联函数：

$$C(\mathbf{k}, -\mathbf{k}) = 1 + \frac{|G_s(\mathbf{k}, -\mathbf{k})|^2}{G_c(\mathbf{k}, \mathbf{k})G_c(-\mathbf{k}, -\mathbf{k})}$$

对于流体力学演化源，**Makhlin 和Sinyukov推导得出：**

$$G_c(k_1, k_2) = \frac{1}{(2\pi)^3}\int d^4\sigma_\mu K^\mu_{1,2} e^{iq_{1,2}.x} n_c(x, K^\mu_{1,2}u_\mu)$$

$$G_s(k_1, k_2) = \frac{1}{(2\pi)^3}\int d^4\sigma_\mu K^\mu_{1,2} e^{2iK_{1,2}.x} n_s(x, K^\mu_{1,2}u_\mu)$$

Sov. J. Nucl. Phys. 46 (1987) 354;
Nucl.Phys. A566 (1994) 589c

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2. Bases of BBC

$$G_s(k_1,k_2)=\frac{1}{(2\pi)^3}\int d^4\sigma_\mu K_{1,2}^{\mu} e^{2iK_{1,2}.x} n_s(x,K_{1,2}^{\mu}u_\mu)$$

$$e^{i(\omega_1+\omega_2)t}$$

空间部分：

$$d^4\sigma_\mu=(dxdydz,-dtdydz,-dtdxdz,-dtdxdy)$$

采用瞬时冻出假设：（ $dt=0$ ）

$$d^4\sigma_\mu K_{1,2}^{\mu}=K^0 d^3x$$

均匀源

$$C(\mathbf{k},-\mathbf{k})=1+\frac{V\,|c_{\mathbf{k}}\,s_{\mathbf{k}}^{*}\,n_{\mathbf{k}}+c_{-\mathbf{k}}\,s_{-\mathbf{k}}^{*}\,(n_{-\mathbf{k}}+1)|^2}{V\,[n_1(\mathbf{k})\,n_1(-\mathbf{k})]}$$

时间部分：

采用指数衰减发射时间分布：

$$F(\tau)=\frac{\theta(\tau-\tau_0)}{\Delta t}\,e^{-(\tau-\tau_0)/\Delta t}$$

$$\widetilde{F}(\omega)=\int dtF(t)\exp(-i\omega t)$$

$$|\widetilde{F}(\omega_{\mathbf{k}}+\omega_{-\mathbf{k}},\Delta t)|^2=[1+(\omega_{\mathbf{k}}+\omega_{-\mathbf{k}})^2\Delta t^2]^{-1}$$

$$C(\mathbf{k},-\mathbf{k})-1=\frac{|c_{k}^{*}s_{\mathbf{k}}n_{\mathbf{k}}+c_{-\mathbf{k}}^{*}s_{-\mathbf{k}}(n_{-\mathbf{k}}+1)|^2}{n_1(\mathbf{k})\,n_1(-\mathbf{k})}\times|\tilde{F}(\omega_{\mathbf{k}}+\omega_{-\mathbf{k}})|^2,$$

Phys. Rev. Lett., 1999, 83: 4013.

2. Bases of BBC

$$G_s(k_1,k_2)=\frac{1}{(2\pi)^3}\int d^4\sigma_\mu K^\mu_{1,2}e^{2iK_{1,2}.x}n_s(x,K^\mu_{1,2}u_\mu)$$

$$e^{i(\omega_1+\omega_2)t}$$

空间部分：

$$d^4\sigma_\mu=(dxdydz,-dtdydz,-dtdxdz,-dtdxdy)$$

采用瞬时冻出假设：（ $dt=0$ ）

$$d^4\sigma_\mu K^\mu_{1,2}=K^0d^3x$$

高斯球形膨胀源
+ 非相对论近似

时间部分：

采用指数衰减发射时间分布：

$$F(\tau)=\frac{\theta(\tau-\tau_0)}{\Delta t}e^{-(\tau-\tau_0)/\Delta t}$$

$$F(\omega)=\int dtF(t)\exp(-i\omega t)$$

$$|\widetilde{F}(\omega_{\mathbf{k}}+\omega_{-\mathbf{k}},\Delta t)|^2=[1+(\omega_{\mathbf{k}}+\omega_{-\mathbf{k}})^2\Delta t^2]^{-1}$$

S.Padula *et al*. Phys. Rev. C, 2006, 73: 044906

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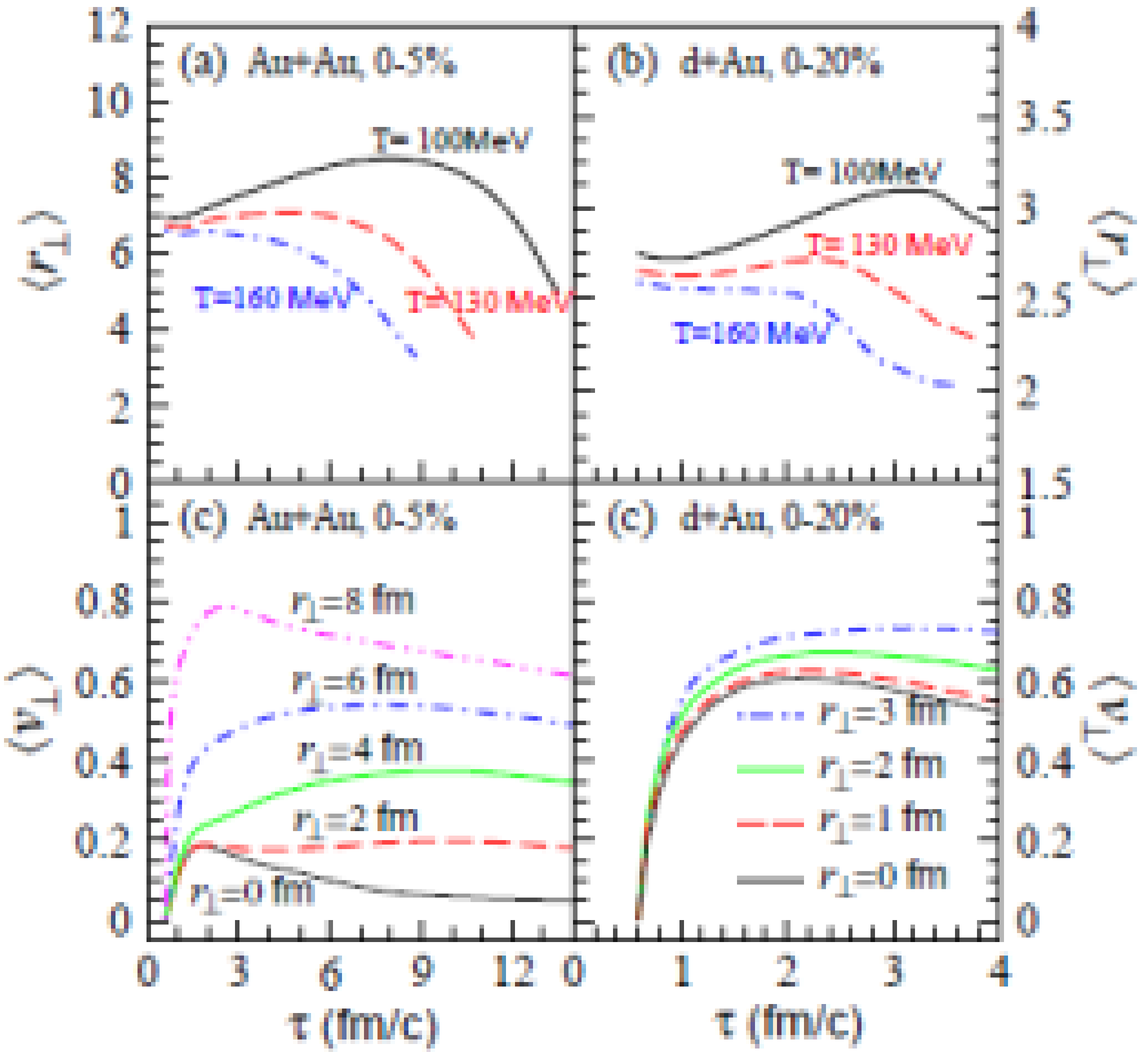
3. Method & results



The source isothermals and average transverse velocities $\langle v_\perp \rangle$ calculated with the 1000 events for the collisions of the Au+Au with 0-5% centrality and the d+Au with 0-20% centrality at $\sqrt{s_{NN}}$ = 200 GeV.

The sources for the d+Au collisions have smaller space-time distribution and evolve faster than that for the Au+Au collisions.

The average velocity $\langle v_\perp \rangle$ at $r_\perp$=0 is small for the collisions of Au+Au because the center of the fireball for each the event is near to $r_\perp$=0 for the symmetric collisions.

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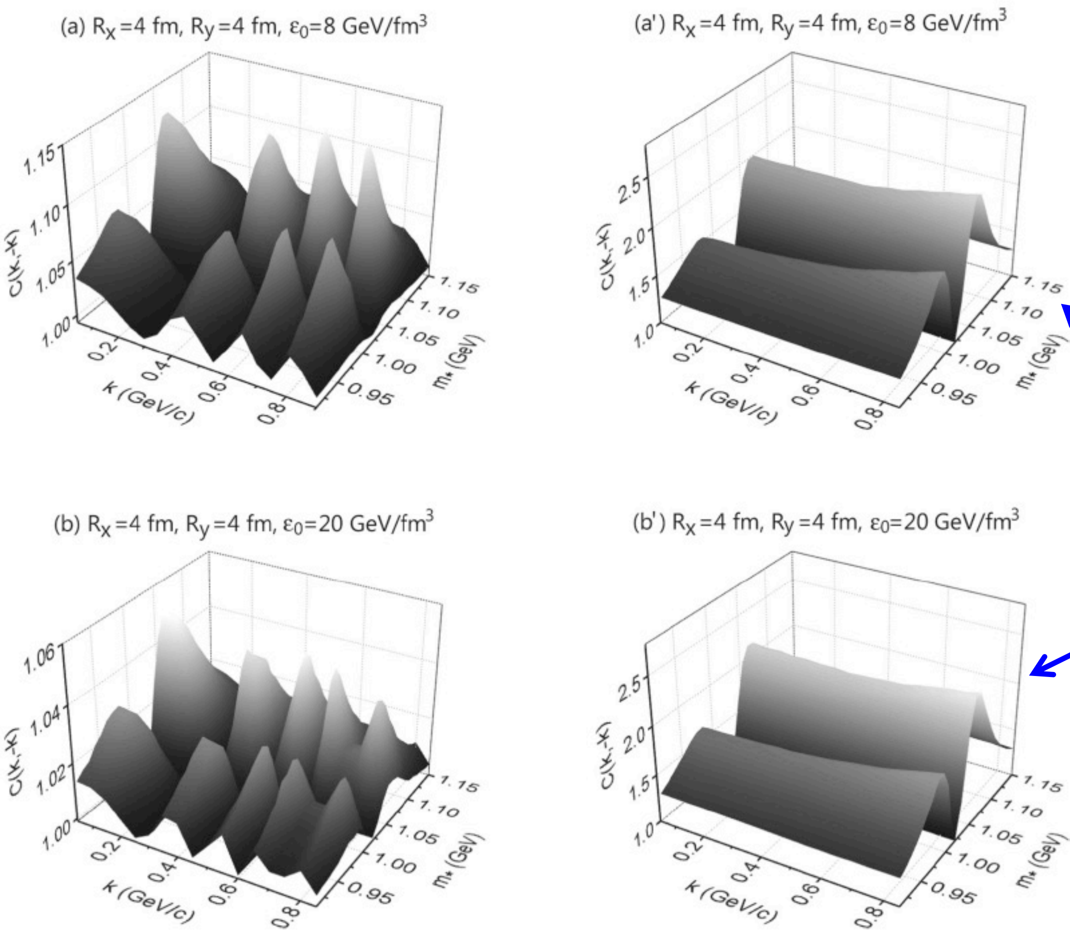
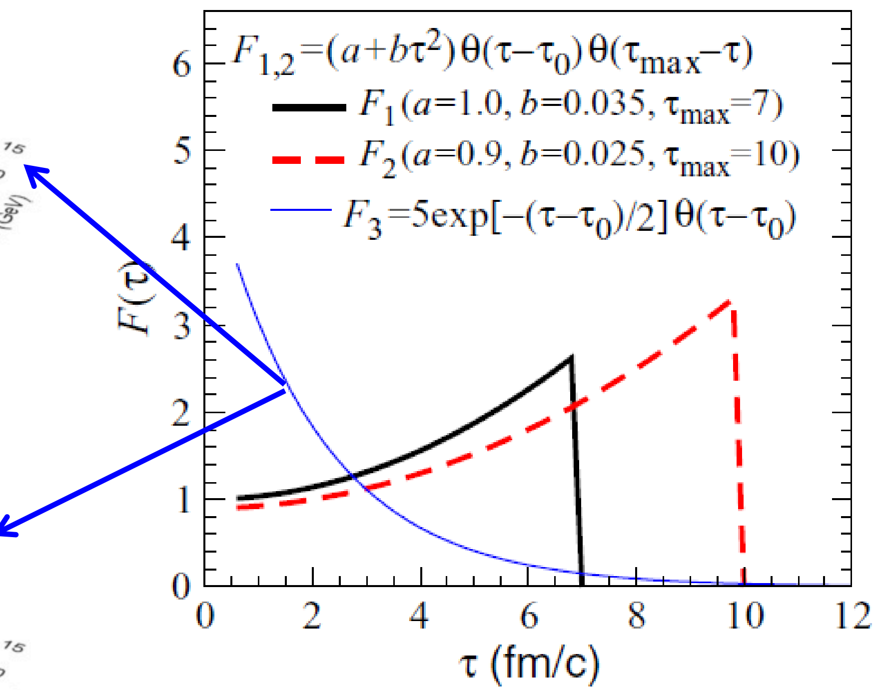
Previous works

流体力学演化源的正反玻色子对的背对背关联（高斯初始条件）





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Previous works

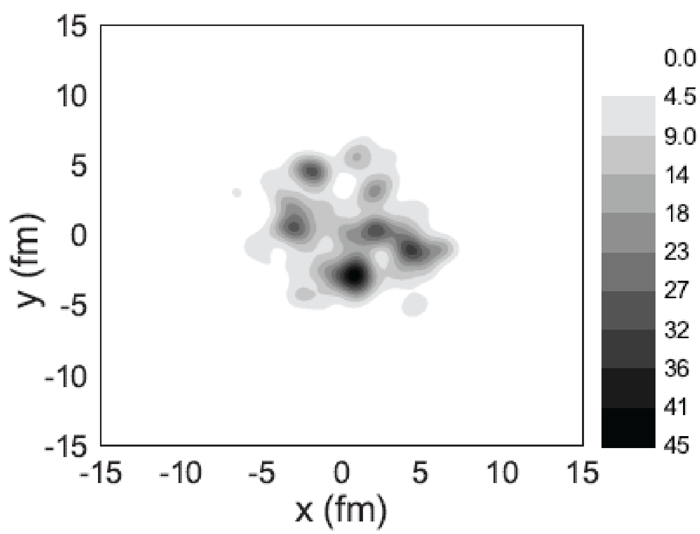
流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）

涨落初始条件(AMPT中的HIJING)：

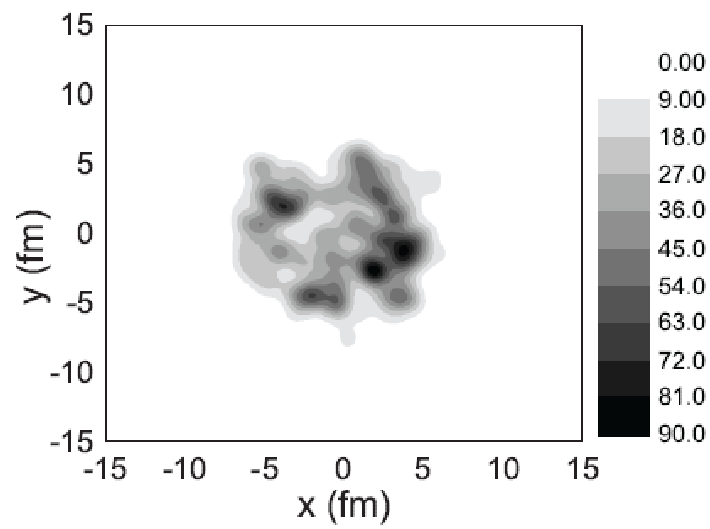
[Ying Hu *et al.* J. Phys. G: Nucl. Part. Phys. 42, 045105 (2015)]

$$\epsilon(x,y) = K\sum_i \frac{p_{\perp i}}{\tau_0}\frac{1}{2\pi\sigma^2} \times \exp\{-\frac{[x-x_i(\tau_0)]^2+[y-y_i(\tau_0)]^2}{2\pi\sigma^2}\}$$

$\sqrt{s_{NN}} = 200$ GeV Au+Au b = 0



$\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb b = 0



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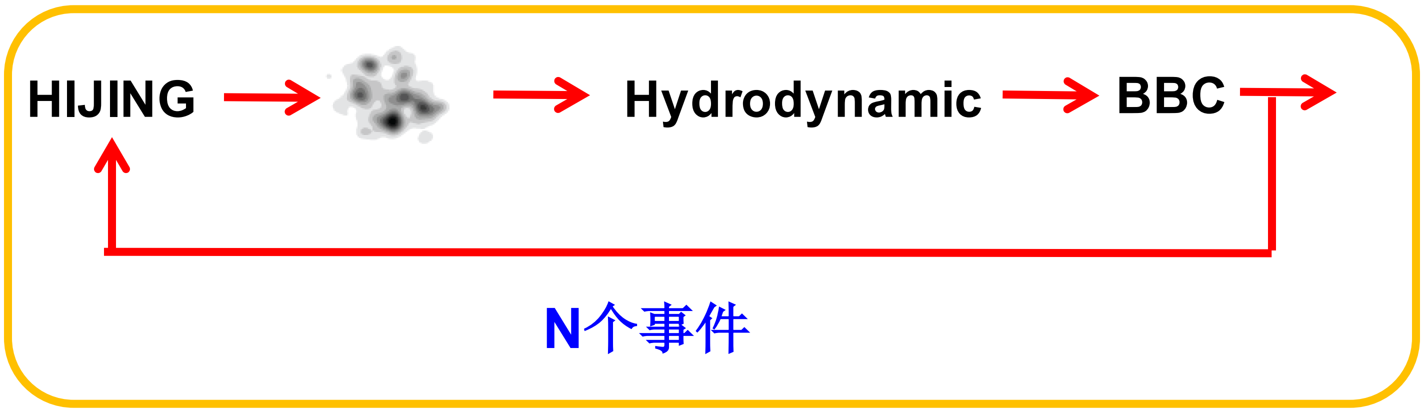
Previous works

流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）



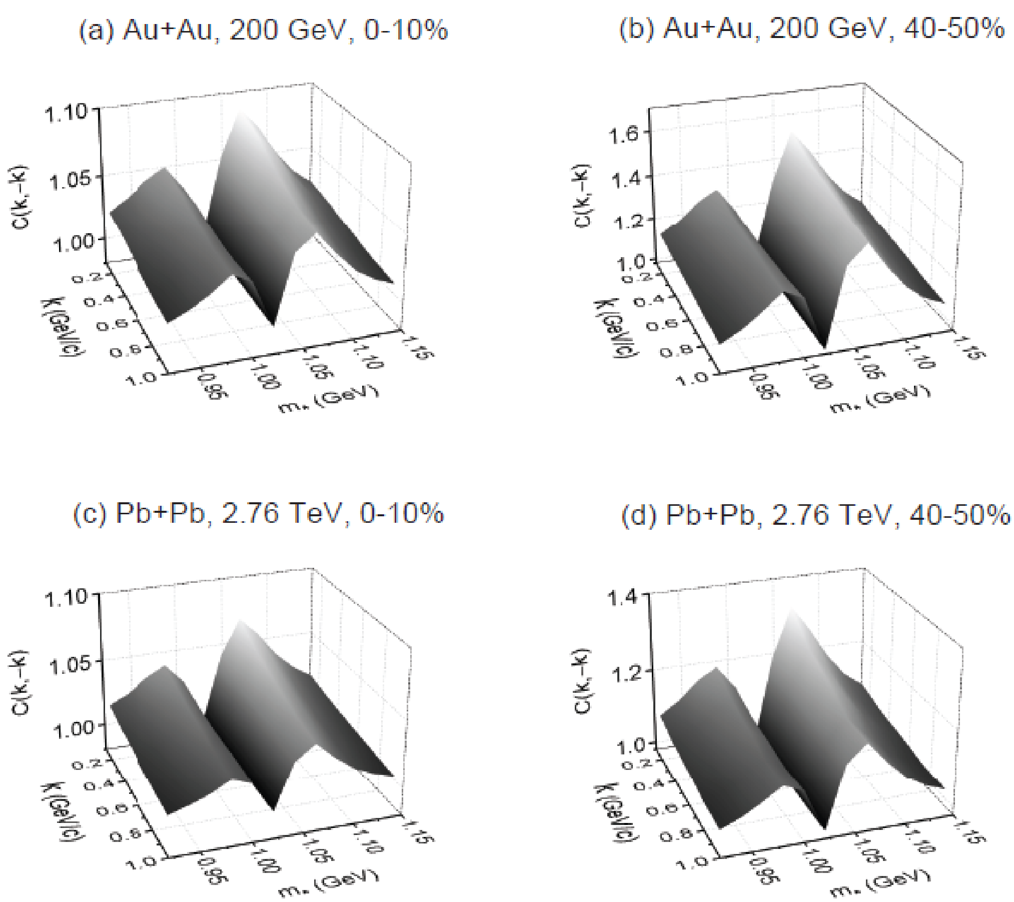
背对背关联函数：

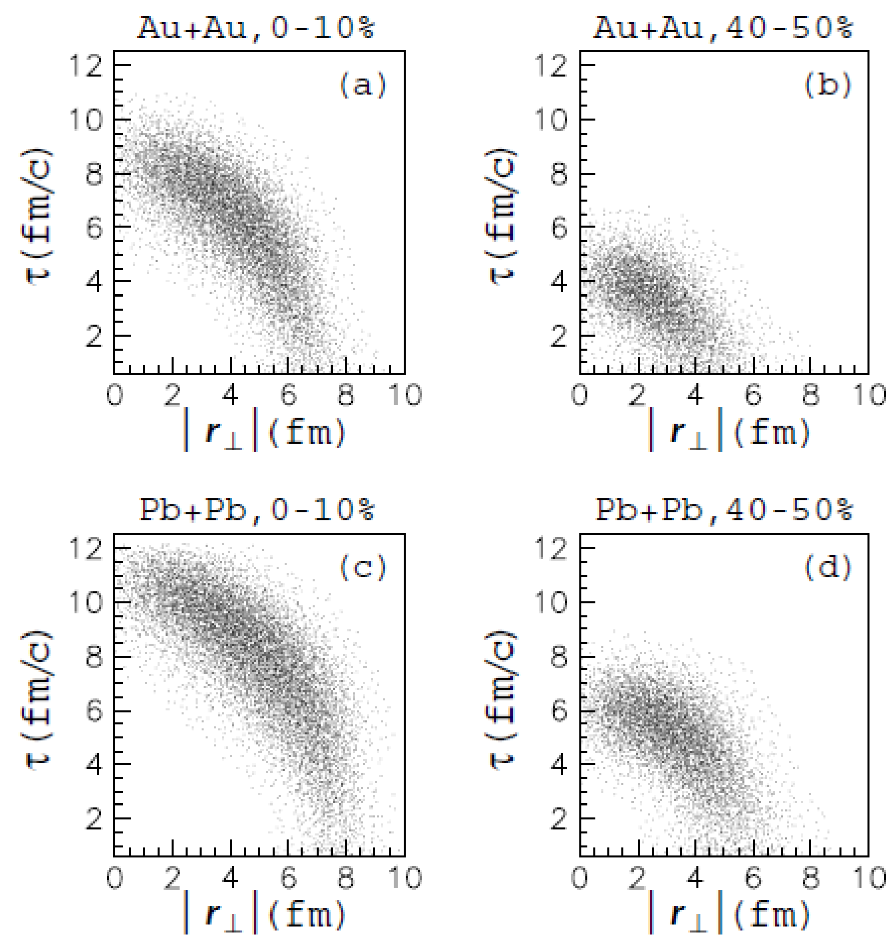
$$C(\mathbf{k},-\mathbf{k}) = \frac{\frac{1}{N_E}\sum_{i=1}^{N_E}\left[G_{ci}(\mathbf{k},\mathbf{k})G_{ci}(-\mathbf{k},-\mathbf{k}) + |G_{si}(\mathbf{k},-\mathbf{k})|^2\right]}{\frac{1}{N_E}\sum_{i=1}^{N_E} G_{ci}(\mathbf{k},\mathbf{k})G_{ci}(-\mathbf{k},-\mathbf{k})}$$

Previous works

流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）

ϕ介子多事件混合后的背对背关联(2000个事件)





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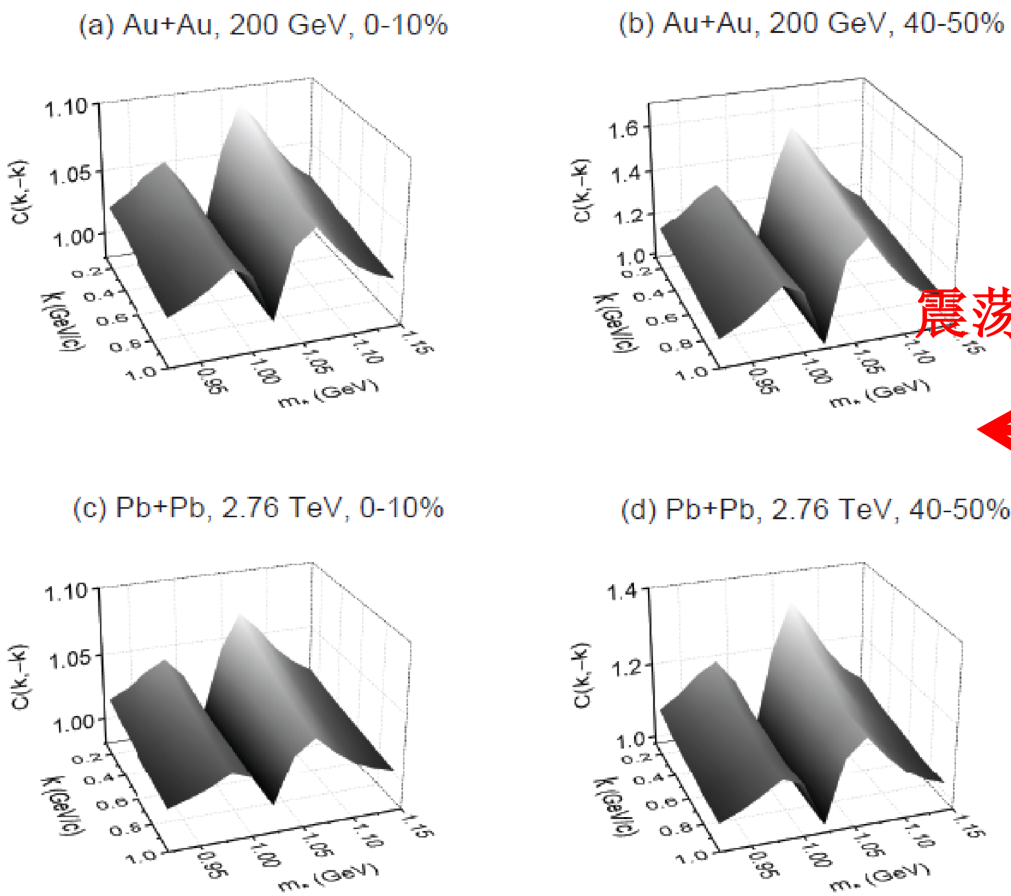
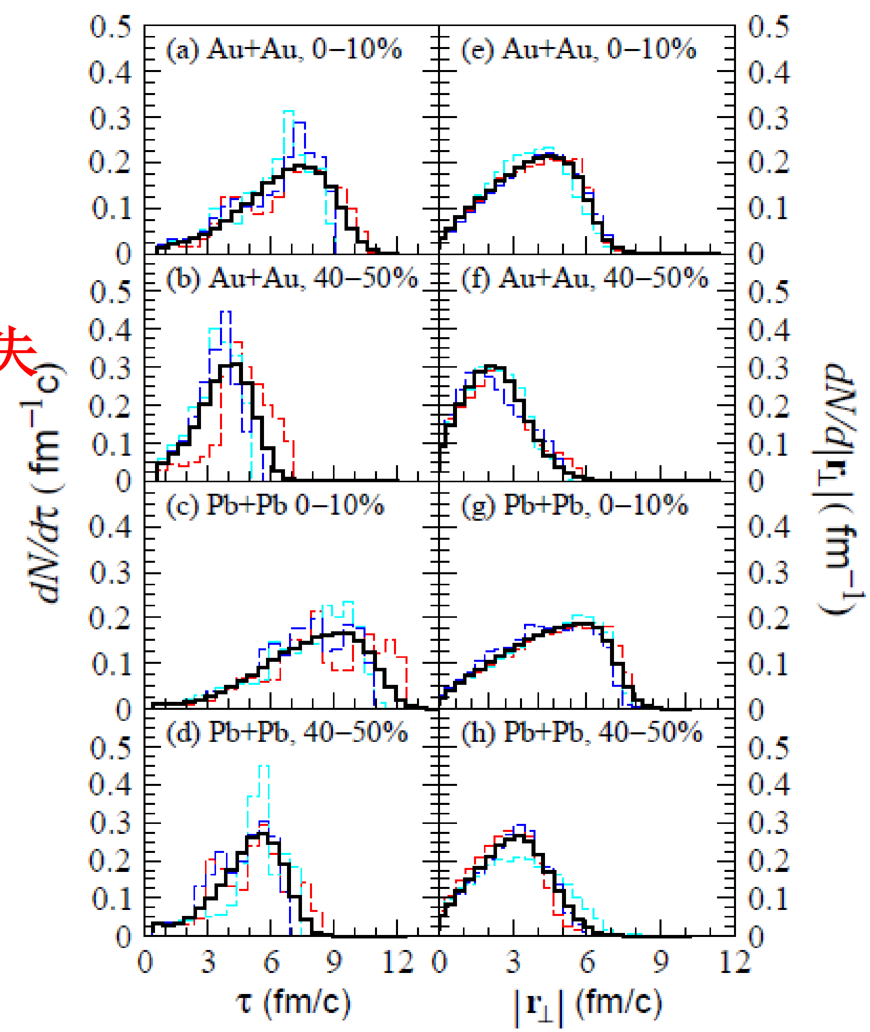
Previous works

流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）

φ介子多事件混合后的背对背关联(2000个事件)



震荡消失



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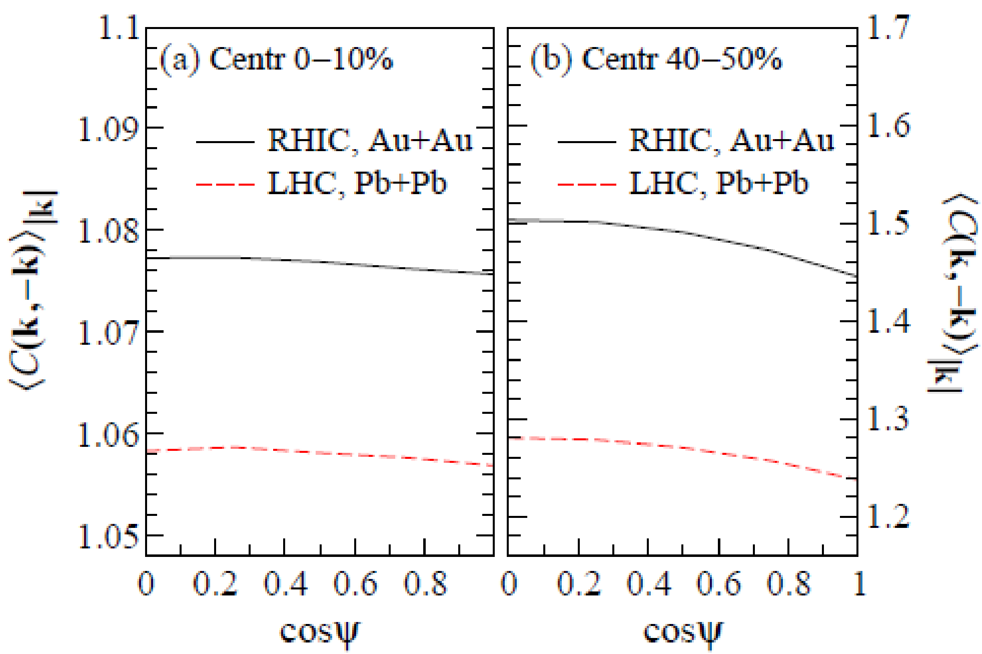
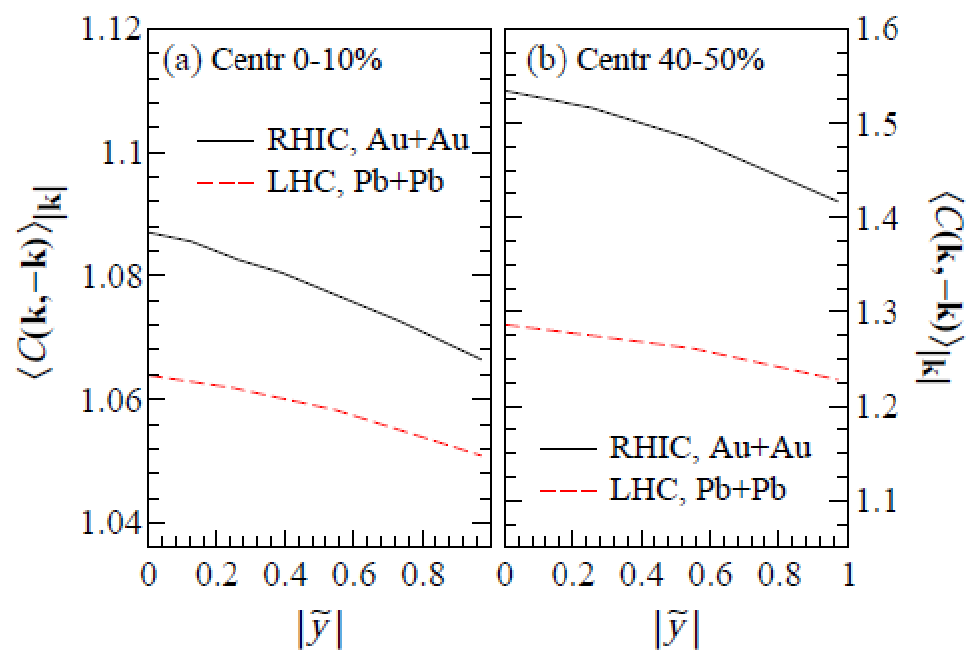
Previous works

流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）

ϕϕ背对背关联对粒子动量方向的依赖

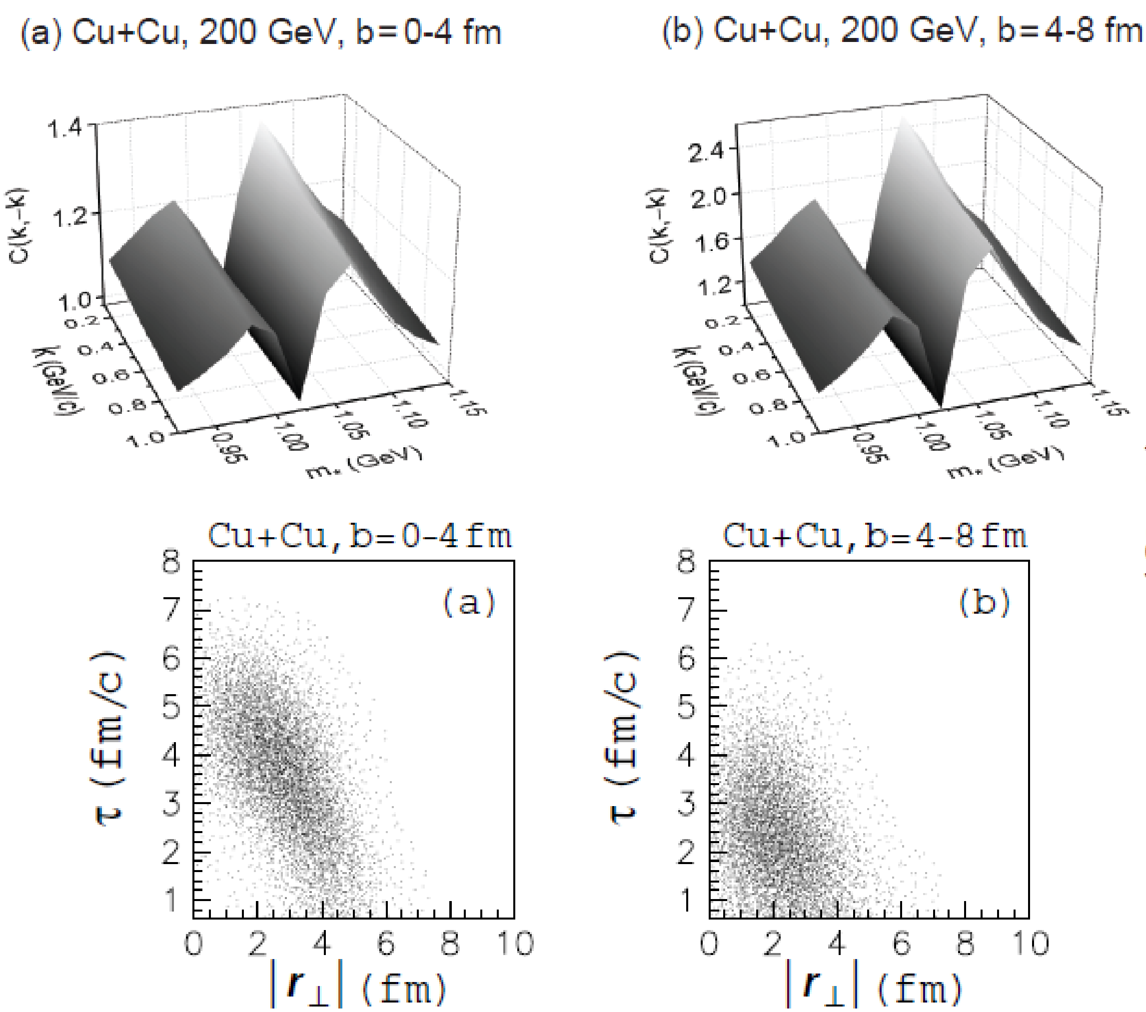


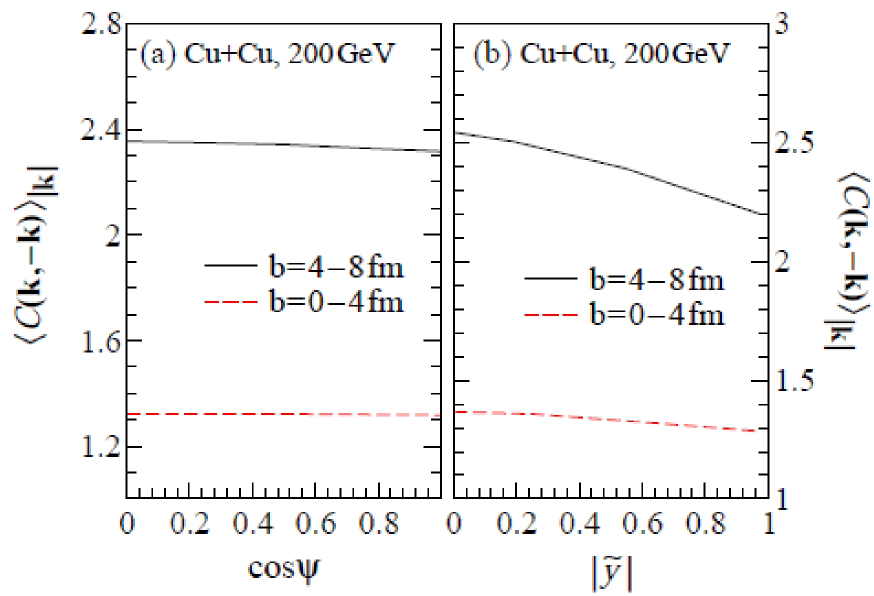


Previous works

流体力学演化源的正反玻色子对的背对背关联（涨落初始条件）

Cu+Cu碰撞φ介子多事件混合后的背对背关联(2000个事件)





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