Anisotropic flow of thermal photons in most-central α-clustered C+Au collisions at $\sqrt{s_{NN}} = 200$A GeV

Pingal Dasgupta
pingaldg@fudan.edu.cn

Collaborators : Dr. Rupa Chatterjee and Dr. Guo-Liang Ma

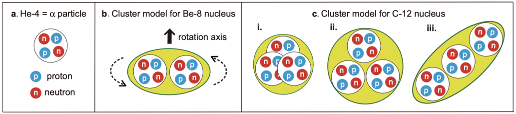
CETHENP 2022

November 15, 2022

Outline

1. α-clustering in light nuclei
2. Direct photon probe
3. Photon production from α-clustered C+Au collisions
4. Event-by-event study of thermal photon production
5. Summary

α-clustering in light nuclei



[1] T. Otsuka *et. al.*, Nat Commun 13, 2234 (2022)

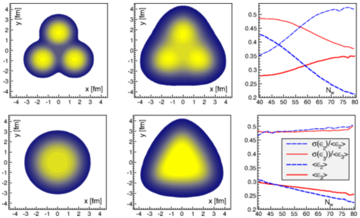
- Clustering refers to a phenomenon where nuclei (with $A = 4N$ such as Be, C, O etc.) behave like a molecule composed of α-clusters.
- In the context of nucleosynthesis, both theoretical and experimental understandings of such states are important.
- However, theory as well as experiment both still lack direct proof in support of α-clustering.

  A recent study[1] based on quantum many-body simulation from first principle has shown how such α-clustreing can appear in ^{8}Be and ^{12}C.

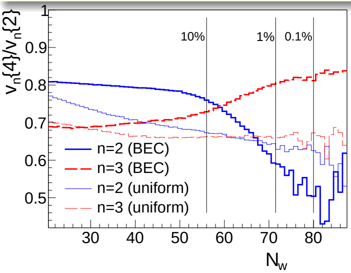
Probing α-clustered structure in collider experiments

- "Signatures of alpha clustering in light nuclei from relativistic nuclear collisions"- Wojciech Broniowski and Enrique Ruiz Arriola, Phys.Rev.Lett. **112**, 112501(2014).
- "α clusters and collective flow in ultrarelativistic carbon–heavy-nucleus collisions"- P. Bozek *et. al.*, Phys.Rev.C **90** 6, 064902 (2014).
- "Nuclear cluster structure effect on elliptic and triangular flows in heavy-ion collisions"- S. Zhang *et. al.*,Phys. Rev. C **95**, 064904 (2017).
- "Signatures of α-clustering in ultra-relativistic collisions with light nuclei"- Maciej Rybczyński *et. al.*, Phys. Rev. C **97**, 034912 (2018).
- "Collective flows of α-clustering ^{12}C + ^{197}Au by using different flow analysis methods"- S. Zhang *et. al.*, Eur. Phys. J. A **54**, 161 (2018).
- "Machine-learning-based identification for initial clustering structure in relativistic heavy-ion collisions"- Junjie He *et. al.*, Phys. Rev. C **104**, 044902 (2021).

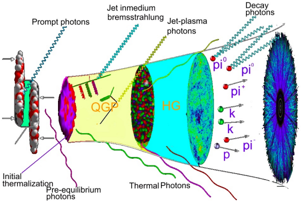
C+Pb @ 17A GeV using GLISSANDO



C+Au @ 200A GeV using HYDRO

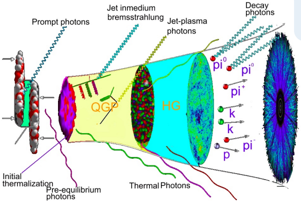


Direct photon probe



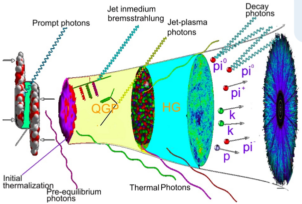
https://u.osu.edu/vishnu/2015/07/22/photon-emission-from-relativistic- heavy-ion-collisions/ , Credit: Chun Shen

Direct photon probe



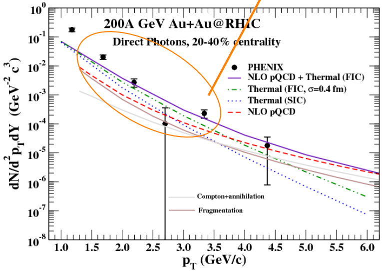
Direct photons = Inclusive photons−Decay photons

Direct photon probe



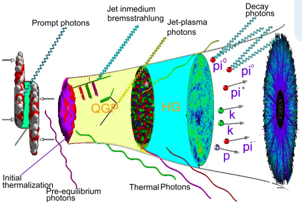
Direct photons = Inclusive photons−Decay photons

- Thermal (using **hydrodynamical description**) + Prompt photon contribution satisfactorily explain the direct photon data above ∼ 1.5 GeV.



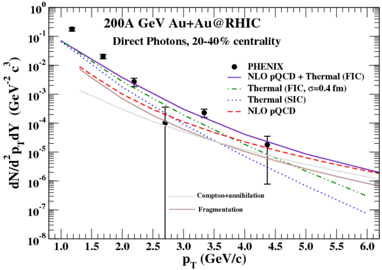
R. Chatterjee *et al.*
Phys. Rev. C 88, 034901 (2013)

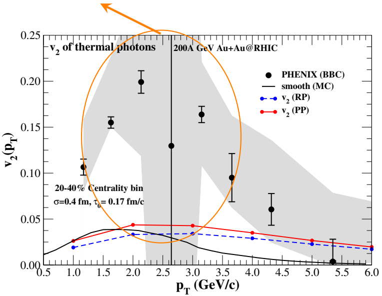
Direct photon probe



Direct photons = Inclusive photons−Decay photons

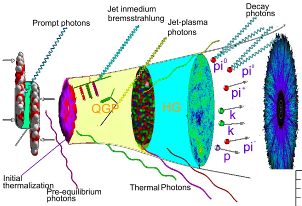
- However model calculations under-predict the v_2 data by a significant margin.





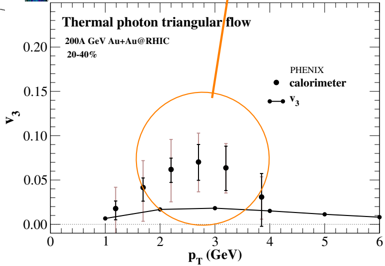
R. Chatterjee *et al.*
Phys. Rev. C 88, 034901 (2013)

Direct photon probe



- There is discrepancy for the v_3 as well.

Together they are dubbed as “direct photon puzzle”.



- Recent studies involving viscosities and modified photon production rates have improved the prediction but the puzzle has not been resolved fully.

Probing nuclear deformation using photon

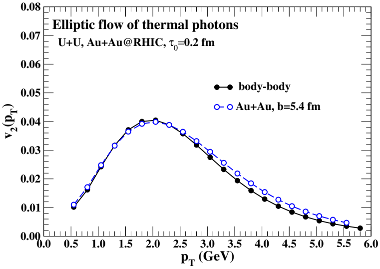
The photon flow observables have been found to be sensitive to :

- Initial-state geometry and fluctuations.
- Formation time.
- Dynamical and thermodynamic properties of the produced fireball.

Probing nuclear deformation using photon

The photon flow observables have been found to be sensitive to :

- Initial-state geometry and fluctuations.
- Formation time.
- Dynamical and thermodynamic properties of the produced fireball.

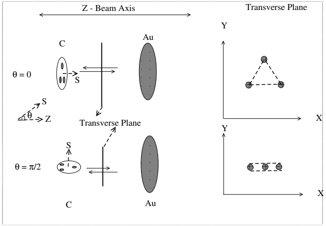


PD, Rupa Chatterjee, Dinesh K. Srivastava,
Phys. Rev. C **95**, 064907 (2017)

Anisotropic nuclear matter distribution of ^{238}U can be probed with photon v_2.

- For example, the body-body configuration of U+U collision @193A GeV can produce a significantly large thermal photon v_2, comparable to the photon v_2 from mid-central Au+Au collisions.

α-clustered C+Au collision at 200A GeV

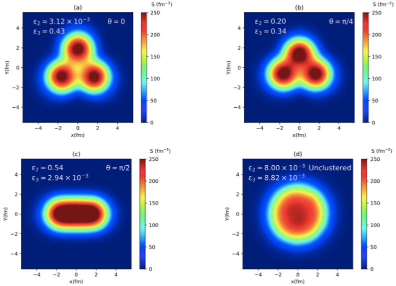


A schematic of α-clustered ^{12}C colliding with a heavy ion (Au) at relativistic energy.

PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)

Initial entropy density distribution $\rightarrow s(x, y, \tau_0)$ (Initial-state averaged) for different orientations α-clustered C+Au collisions @200A GeV.

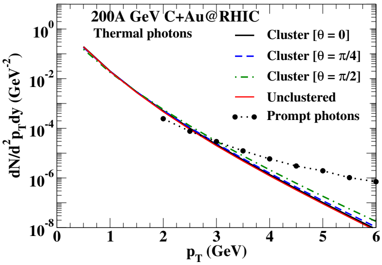
$\theta = 0$ $\qquad$ $\theta = \pi/4$



$\theta = \pi/2$ $\qquad$ Unclustered C+Au

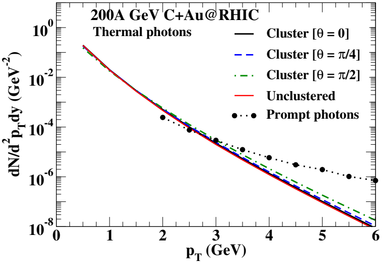
Photon production and anisotropic flow

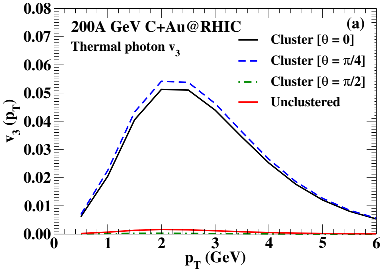
PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)



- Thermal photon spectra for different configurations of collisions are almost similar.

PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)

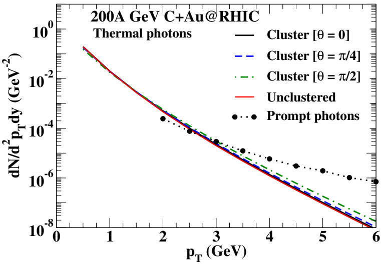




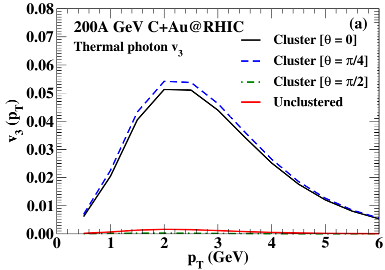
- Thermal photon spectra for different configurations of collisions are almost similar.
- Thermal photon v_3 is significantly large for $\theta = \pi/4$ and $\theta = 0$.

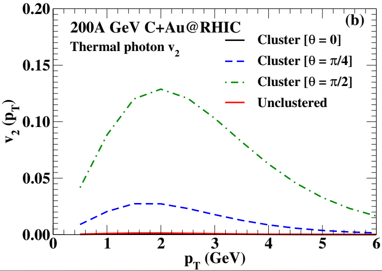
Photon production and anisotropic flow

PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)



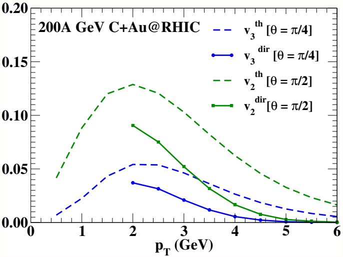
- Thermal photon spectra for different configurations of collisions are almost similar.
- Thermal photon v_3 is significantly large for $\theta = \pi/4$ and $\theta = 0$.
- On the other hand, the thermal photon v_2 is significantly large for $\theta = \pi/2$.





Photon production and anisotropic flow

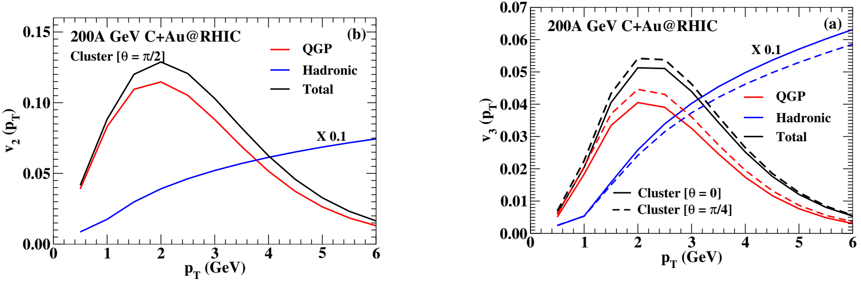
PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)



- Inclusion of prompt contribution dilutes the photon v_2 and v_3.
- The values are comparable to photon v_n's obtained in $0-20\%$ Au+Au and Pb+Pb collisions at RHIC and LHC energies respectively.

QGP and hadronic contribution

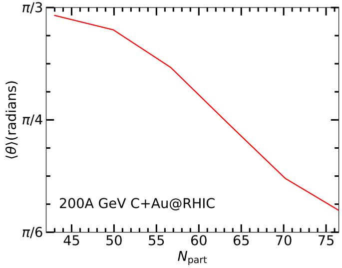
PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)

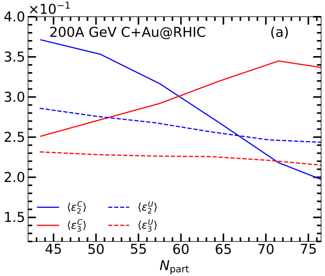


- Both photon v_2 and v_3 are sensitive to the QGP phase. Measurements of these observables thus can provide us insight to understand the "direct photon puzzle".

Realistic scenario (event-by-event)

PD, Guo-Liang Ma, Rupa Chatterjee, *et al.*,
Eur. Phys. J. A 57 (4) 134 (2021)



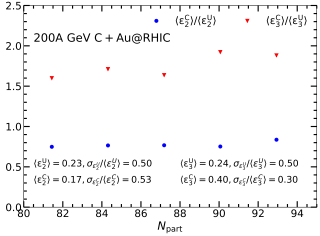


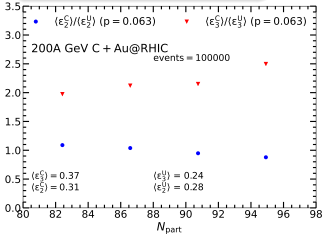
- The average angle is reduced significantly with increasing N_{part}.
- Due to the intrinsic triangular geometry of the clustered-carbon, $\langle\epsilon_3^{\rm C}\rangle$ increases with N_{part}, whereas $\langle\epsilon_2^{\rm C}\rangle$ decreases.
- The difference becomes substantial at larger N_{part}, which indicates an obvious anti-correlation between ellipticity and triangularity in α-clustered C + Au collisions.

Most-central collisions (≈0-1% centrality)

Glauber IC :
$s(x, y, \tau_0) \propto [\nu N_{coll}(x, y) + (1 - \nu) N_{part}(x, y)]$

TRENTO IC :
$s(x, y, \tau_0) \propto \left(\frac{T_A^p + T_B^p}{2} \right)^{1/p}$



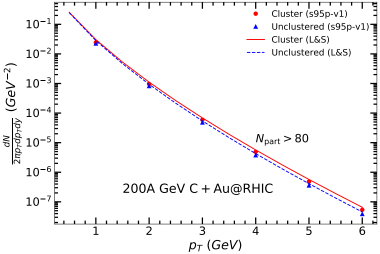


PD, Rupa Chatterjee, Guo-Liang Ma, arXiv:2204.00235

- Both Glauber and TRENTO model predict $\langle \epsilon_3^C \rangle$ is almost twice as large as $\langle \epsilon_3^U \rangle$, whereas, $\langle \epsilon_2^C \rangle$ is close to $\langle \epsilon_2^U \rangle$.
- The relative fluctuation of ϵ_3^C is found to be about 60% that of the same for the unclustered case.

Thermal photon production and anisotropic flow

PD, Rupa Chatterjee, Guo-Liang Ma, arXiv:2204.00235



- The thermal spectra are found to be close to each other. However, we see a small difference at high p_T due to initial hot-spots for the clustered case.

[1]

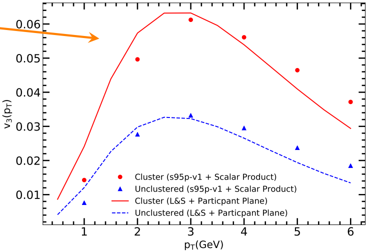
[1] $\langle \frac{dN^\gamma}{dyp_T dp_T}(p_T)\rangle$ and $v_n^\gamma\{PP\}$ are represented as $\frac{dN}{dyp_T dp_T}(p_T)$ and v_n respectively in the plots.

Thermal photon production and anisotropic flow

Participant plane method (Lines):

$$v_n^{\gamma}(p_T) \;=\; \frac{\int_0^{2\pi} d\phi \cos[\,n(\phi-\psi_n^{PP})]\, \frac{dN^{\gamma}}{p_T\,dp_T\,dy\,d\phi}}{\int_0^{2\pi} d\phi\, \frac{dN^{\gamma}}{p_T\,dp_T\,dy\,d\phi}}$$

$$v_n^{\gamma}\{\mathrm{PP}\}(p_T) = \langle v_n^{\gamma}(p_T)\rangle = \frac{\sum_{i=1}^{\mathrm{N_{events}}} \frac{dN^{\gamma(i)}}{d^2p_T\,dy}\, v_n^{\gamma(i)}(p_T)}{\sum_{i=1}^{\mathrm{N_{events}}} \frac{dN^{\gamma(i)}}{d^2p_T\,dy}}$$



- We find a significantly large thermal photon v_3 for the clustered C+Au collisions. However, the thermal photon v_2 are found to be close to each other.

PD, Rupa Chatterjee, Guo-Liang Ma, arXiv:2204.00235 [1]

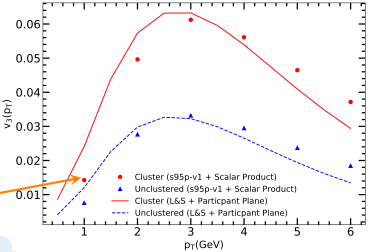
[1] $\langle \frac{dN^{\gamma}}{dyp_Tdp_T}(p_T)\rangle$ and $v_n^{\gamma}\{PP\}$ are represented as $\frac{dN}{dyp_Tdp_T}(p_T)$ and v_n respectively in the plots.

Thermal photon production and anisotropic flow

Participant plane method (Lines):

$$v_n^{\gamma}(p_T) = \frac{\int_0^{2\pi} d\phi \cos[n(\phi - \psi_n^{PP})] \frac{dN^{\gamma}}{p_T dp_T dy d\phi}}{\int_0^{2\pi} d\phi \frac{dN^{\gamma}}{p_T dp_T dy d\phi}}$$

$$v_n^{\gamma}\{\mathrm{PP}\}(p_T) = \langle v_n^{\gamma}(p_T) \rangle = \frac{\sum_{i=1}^{\mathrm{N_{events}}} \frac{dN^{\gamma(i)}}{d^2 p_T dy} v_n^{\gamma(i)}(p_T)}{\sum_{i=1}^{\mathrm{N_{events}}} \frac{dN^{\gamma(i)}}{d^2 p_T dy}}$$



Scalar product method (Symbols):

$$v_n^{\gamma}\{\mathrm{SP}\}(p_T) = \frac{\left\langle \frac{dN^{\gamma}}{dy p_T dp_T}(p_T) v_n^{\gamma}(p_T) v_n^{\mathrm{ch}} \cos(n(\Psi_n^{\gamma}(p_T) - \Psi_n^{\mathrm{ch}})) \right\rangle}{\left\langle \frac{dN^{\gamma}}{dy p_T dp_T}(p_T) \right\rangle v_n^{\mathrm{ch}}\{2\}}$$

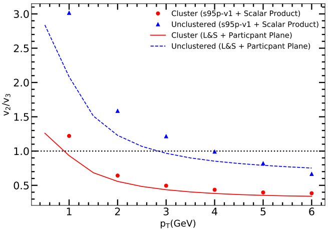
- We find a significantly large thermal photon v_3 for the clustered C+Au collisions. However, the thermal photon v_2 are found to be close to each other.

PD, Rupa Chatterjee, Guo-Liang Ma, arXiv:2204.00235 [1]

[1] $\langle \frac{dN^{\gamma}}{dy p_T dp_T}(p_T) \rangle$ and $v_n^{\gamma}\{PP\}$ are represented as $\frac{dN}{dy p_T dp_T}(p_T)$ and v_n respectively in the plots.

v_2 / v_3 ratio

PD, Rupa Chatterjee, Guo-Liang Ma, arXiv:2204.00235



R. Chatterjee and P. Dasgupta, Phys. Rev. C **104**, 064907 (2021).

$$v_n = \frac{v_n^{\mathrm{th}} \times dN^{\mathrm{th}}}{dN^{\mathrm{th}} + dN^{\mathrm{non-th}}}$$

$$\frac{\langle v_n(p_T)\rangle}{\langle v_m(p_T)\rangle} = \frac{\sum_{i=1}^{N_{\mathrm{event}}} v_n^{\mathrm{th}(i)} dN^{\mathrm{th}(i)}}{\sum_{j=1}^{N_{\mathrm{event}}} v_m^{\mathrm{th}(j)} dN^{\mathrm{th}(j)}}$$

- The ratio minimizes the uncertainties arising due to the non-thermal contributions.

- A significant difference in the photon anisotropic flow ratio has been observed between the two cases of most-central (i.e. events with $N_{part} > 80$) C+Au collisions.
- We expect the ratio to be an important observable to distinguish between the clustered and unclustered state of carbon nucleus.

[2] $\langle v_n(p_T)\rangle / \langle v_m(p_T)\rangle$ is represented as v_n/v_m

Summary

- This study reveals the effect of non-uniform nuclear density distribution of α-clustered carbon on photon flow observables. We see that the elliptic and triangular flow of photons are significantly large depending on the orientation of collisions.
- Both thermal photon v_2 and v_3 are sensitive to the QGP evolution history rather than the hadronic phase.
- An event-by-event study indicates that the v_2/v_3 ratio can distinguish between the clustered and unclustered state of carbon in most-central C+Au collisions.

Thank You

Formalism

Ideal Hydrodynamics

The local state of any fluid cell is an equilibrium-state and thus net entropy flux vanishes :

$$\partial_\mu S^\mu = 0$$

To solve ϵ, P, and 3 components of the fluid velocity $\vec{v}$ [n_B is negligible in transparent region of collision].

Hydro framework: Boost invariant ideal hydrodynamic framework.

H. Holopainen, H. Niemi, and K. Eskola, Phys. Rev. C **83**, 034901 (2011).

Equation of State: Lattice based equation of state.

M. Laine and Y. Schroeder, Phys. Rev. D **73**, 085009 (2006).

Initial condition: We consider Glauber Model to find initial entropy density profile in the transverse plane of a collision event:

$$s(x, y) = s_0[\nu n_{coll}(x, y) + (1 - \nu)n_{part}(x, y)]$$

Thermal photons

QGP rates → P. Arnold et. al. JHEP **0112**, 009 (2001).
(leading order contributions)
→ J.Ghiglieri et. al. JHEP **1305**, 010 (2013).
(next-to-leading order contributions)

Hadronic rates → S. Turbide et. al. Phys. Rev. C **69** 014903 (2004).

Thermal photons spectrum is calculated by integrating the emission rates over the space-time 4-volume as follows:

$$\mathrm{E}\frac{\mathrm{dN}_\gamma}{\mathrm{d}^3\mathrm{p}} = \int [\ (...)\ \exp(-\mathrm{p.u(x)/T(x)})\ ]\mathrm{d}^4\mathrm{x}$$