Direct photon production at RHIC and LHC energies

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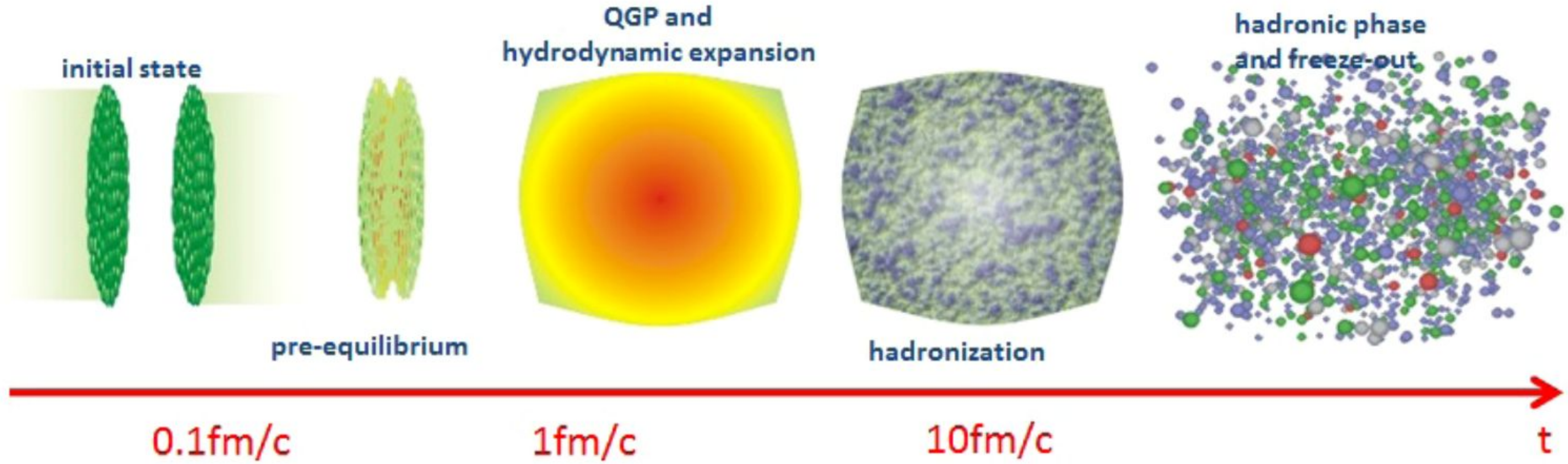
EMMI RRTF meeting 'Direct Photon Puzzle' 24-27 July, 2023

Different stages of heavy ion collisions



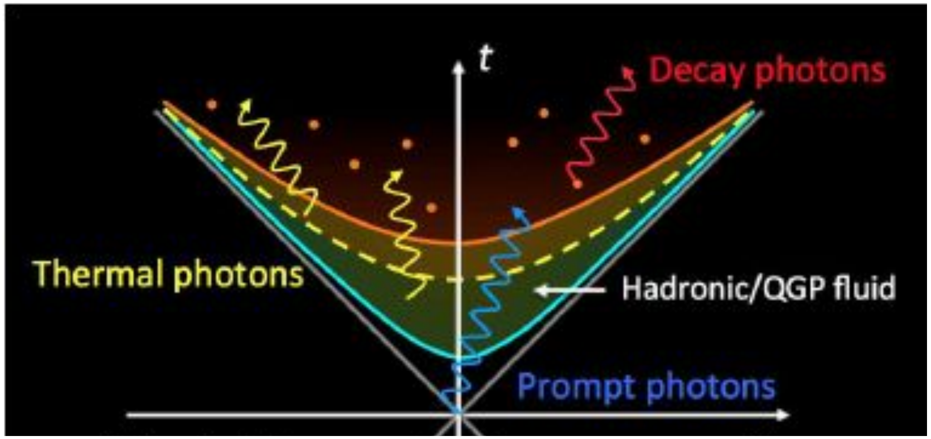
From *Qin, Guang-You Int. J. Mod. Phys. E24 (2015) no.02, 1530001*

The hot and dense matter produced in the relativistic nuclear collisions is expected to have a very transient existence and this makes it quite challenging to extract information on the dynamics and the properties of the earliest and the hottest stage of such collisions.

Information of the whole space-time evolution of the system must be extracted from the various observables measured in the final state.

▲ Electromagnetic radiation has long been considered as one of the promising and efficient tools to probe the hot and dense state of matter produced in the collision of heavy nuclei.

Photons from relativistic heavy ion collisions



Graphics by Akihiko Monnai

The main advantage of studying direct photon observables in heavy ion collisions is that their emission is quite sensitive to the initial state of the produced matter. As a result, even a slight variation in the initial conditions would result in significant change in the final state observables.

The inclusive photon spectrum as obtained from a heavy ion collision experiments is a result of convolution of the emissions from the entire history of the expanding system

Experimental challenges

- **Inclusive photon spectrum contains a huge background.**

One of the earliest motivations to study direct photons in heavy ion collisions:

- ★ to gain access to the initial temperature of the system and to study the properties of the QGP via its thermal radiation.

Several other possibilities with evolving theory:

- ★ anisotropic flow of photons as a quark-gluon plasma viscometer
- ★ momentum anisotropy of the initial partons as well as formation time of quark-gluon plasma using anisotropic flow of thermal photons
- ★ evolution of the system size and information on geometry by photon interferometry
- ★ jet quenching and other aspects of the collision dynamics by photons due to passage of high energy jets through plasma etc.

have come to the fore.

Sources of direct photons

Direct Photons:

Prompt photons

Pre-equilibrium

Jet-photons

Thermal

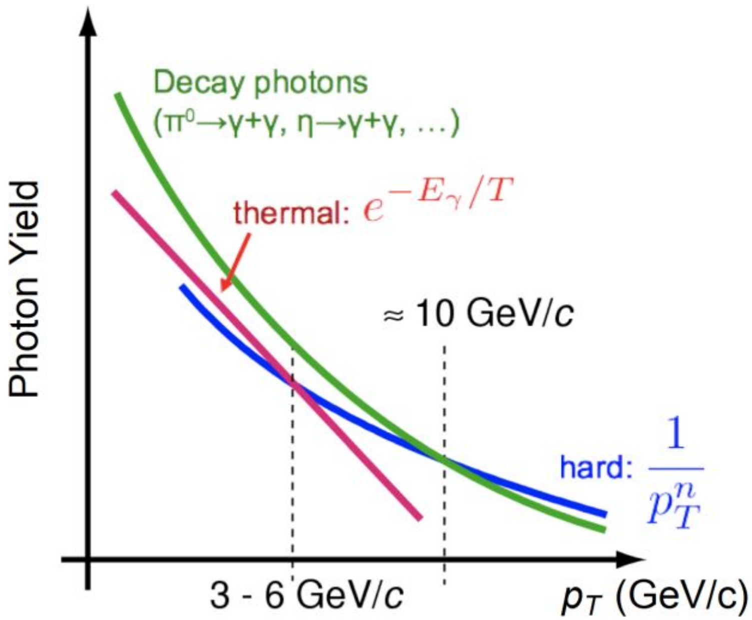


Figure by K. Reygers

- Electromagnetic probes of quark-gluon plasma in relativistic heavy-ion collisions P. V. Ruuskanen, Nucl. Phys. A 544, 169 (1992),
- Photon Production in Hot and Dense Strongly Interacting Matter, Charles Gale, *Landolt-Bornstein* 23 (2010) 445
- Direct real photons in relativistic heavy ion collisions, Gabor David, *Rept.Prog.Phys.* 83 (2020) 4, 046301
- DIRECT PHOTON PRODUCTION IN RELATIVISTIC HEAVY-ION COLLISIONS,Paul StankusAnnu. Rev. Nucl. Part. Sci. 2005. 55:517
- Electromagnetic Probes: Theory and Experiment Ralf-Arno Tripolta and, Frank Geurts Prog.Part.Nucl.Phys. 128 (2023) 104004
- T. Ferbel and W. R. Molzon, “Direct Photon Production in High-Energy Collisions,” Rev. Mod. Phys. 56, 181–221 (1984).
- J. Alam, B. Sinha, and S. Raha, “Electromagnetic probes of quark gluon plasma,” Phys. Rept. 273, 243–362 (1996).
- W. Cassing and E. L. Bratkovskaya, “Hadronic and electromagnetic probes of hot and dense nuclear matter,” Phys. Rept. 308, 65 (1999).
- Thomas Peitzmann and Markus H. Thoma, “Direct photons from relativistic heavy ion collisions,” Phys. Rept. 364, 175–246 (2002)
- Direct Photons in Hydrodynamic Modeling of Relativistic Nuclear Collisions Akihiko Monnai, arXiv::2203.13208
- Direct photons from relativistic heavy-ion collisions, Dinesh K. Srivastava *J.Phys.G* 35 (2008) 104026
- Electromagnetic probes, Rupa Chatterjee,Lusaka Bhattacharya, Dinesh K. Srivastava, *Lect.Notes Phys.* 785 (2010) 219-264
- …

Thermal Photons

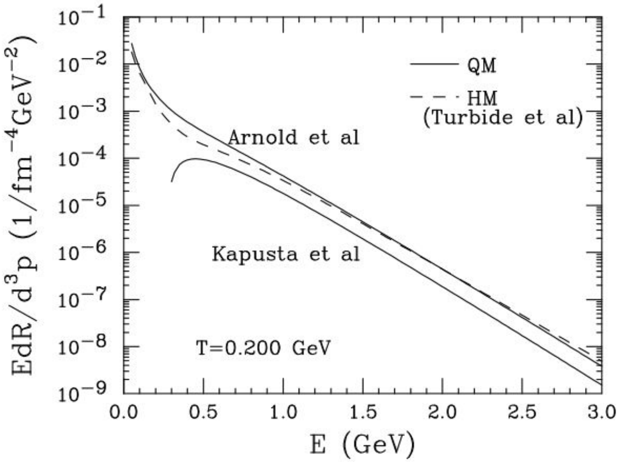
QGP:

P.B. Arnold, G.D. Moore, L.G. Yaffe, JHEP 111, 57 (2001); P.B. Arnold, G.D. Moore, L.G. Yaffe, JHEP 112, 9 (2001).

J. Ghiglieri, J. Hong, A. Kurkela, E. Lu, G.D. Moore, D. Teaney, JHEP 1305, 10 (2013); J. Ghiglieri, O. Kaczmarek, M. Laine, F. Meyer, Phys.Rev. D94, 016005 (2016).

Hadronic sector

J.I. Kapusta, P. Lichard, D. Seibert, Phys.Rev. D44, 2774-2788 (1991); S. Turbide, R. Rapp, C. Gale, Phys.Rev. C69, 014903 (2004); R. Rapp, Acta Phys.Polon. B42, 2823-2852 (2011); M. Heffernan, P. Hohler, R. Rapp, Phys.Rev. C91, 027902 (2015); N.P.M. Holt, P.M. Hohler, R. Rapp, Nucl.Phys. A945, 1-20 (2016)], ...



Complete leading order rates from QGP and exhaustive reactions in hadronic matter

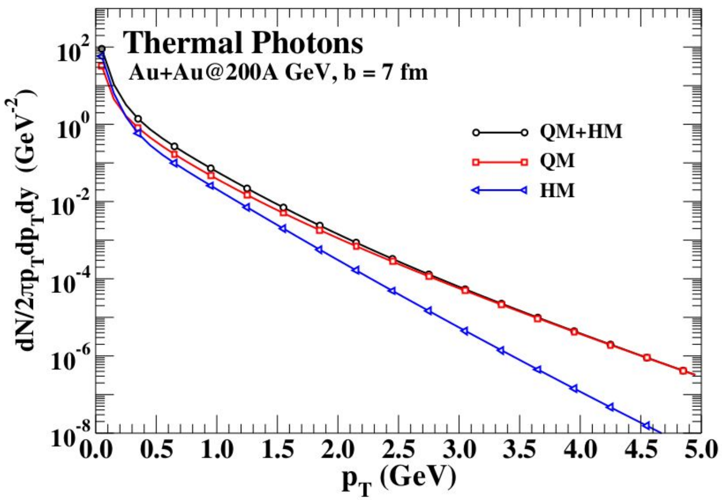
P. Arnold, G. D. Moore, and L. G. Yaffe, JHEP 0112, 009 (2001).

J. Kapusta, P. Lichard, and D. Seibert. Phys. Rev. D 44, 2774 (1991),

S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C 69, 014903 (2004).

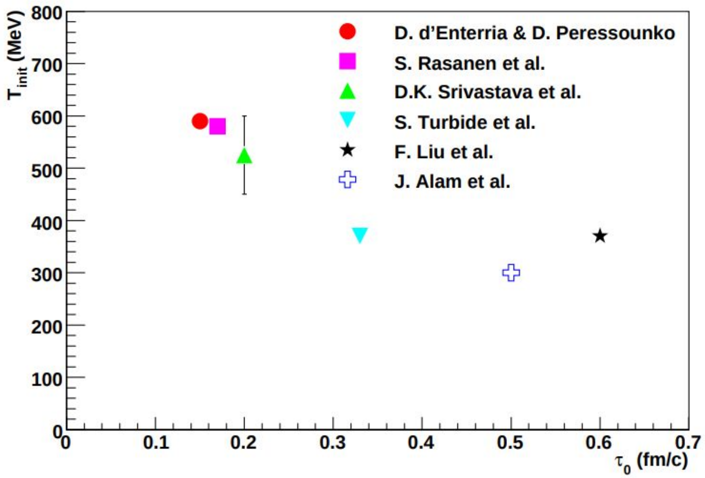
Thermal photons from the QGP and the hadronic sectors are obtained by integrating the rates of emission over the space time history

$$E\frac{dN_\gamma}{d^3p} = \int [\ (\ldots)\ \exp(-\mathrm{p}^\mu \cdot \mathrm{u}_\mu/\mathrm{T}(\mathrm{x}))\ ]\mathrm{d}^4\mathrm{x}\,,$$

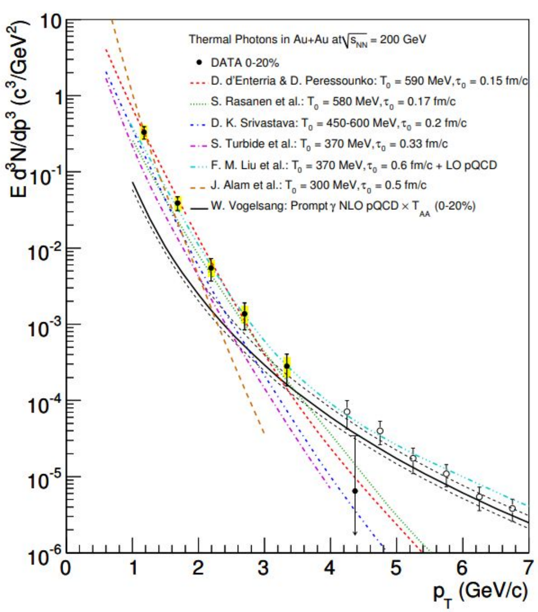


T(x) is the local temperature and p^μ represents the four-momentum of photon and u_μ is the local 4-velocity of the flow field

T_{init} & τ_0 for theoretical calculations



A. Adare et al. (PHENIX Collaboration)
Phys. Rev. C 81, 034911 (2010)



Theoretical calculations of thermal photon emission are compared to direct photon data in central 0-20% Au+Au collisions at RHIC

D. d'Enterria and D. Peressounko, Eur. Phys. J. 46, 451 (2006).

P. Huovinen, P. V. Ruuskanen, and S. S. Rasanen, Phys. Lett. B 535, 109 (2002).

D. K. Srivastava and B. Sinha, Phys. Rev. C 64, 034902 (2001).

S. Turbide, R. Rapp, and C. Gale, Phys. Rev. C 69, 014903 (2004).

F. M. Liu, T. Hirano, K. Werner, and Y. Zhu, Phys. Rev. C 79, 014905 (2009).

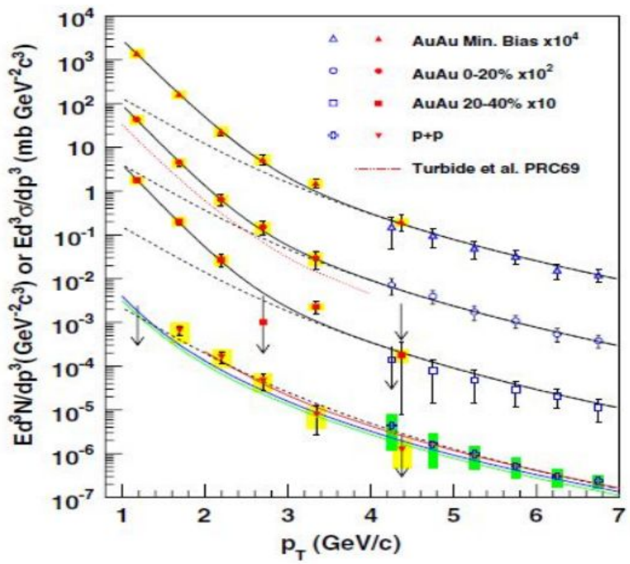
Jan-e Alam, S. Sarkar, T. Hatsuda, T. K. Nayak, and B. Sinha, Phys. Rev. C 63, 021901(R) (2001).

Prompt photons:

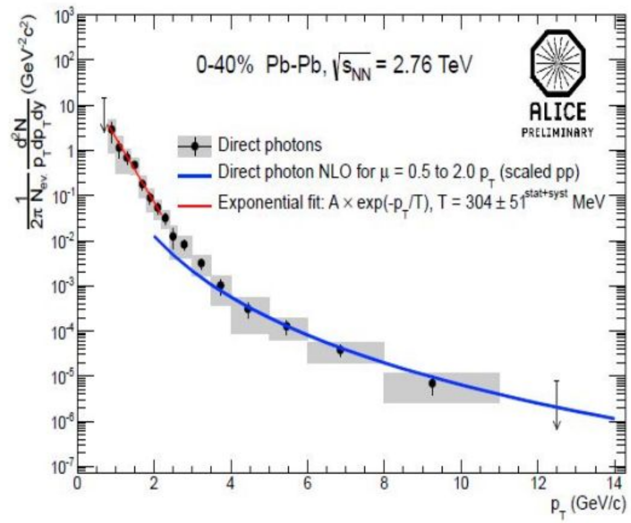
L. E. Gordon and W. Vogelsang, Phys. Rev. D 48, 3136 (1993)

P. Aurenche, J.-P. Guillet, E. Pilon, M. Werlen, and M. Fontannaz, Phys. Rev. D 73, 094007 (2006).

Direct photon spectra at RHIC and LHC

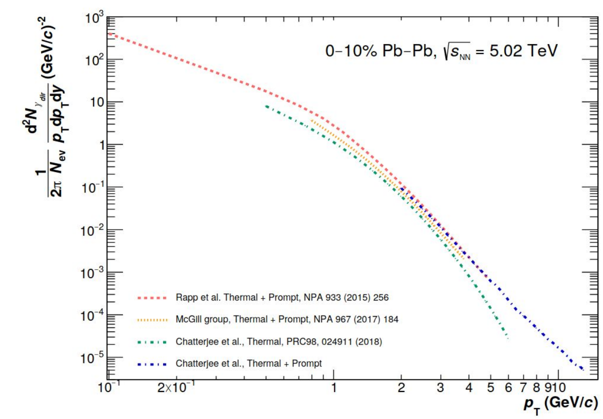


A. Adare *et al.* (PHENIX Collaboration) Phys. Rev. Lett. **104**, 132301 (2010)



M. Wilde, (ALICE Collaboration)
Nuclear Physics A 904, 573c-576c (2013)

$$\frac{dN}{dy\,p_T\,dp_T} \propto e^{-p_T/T_{\rm eff}}$$



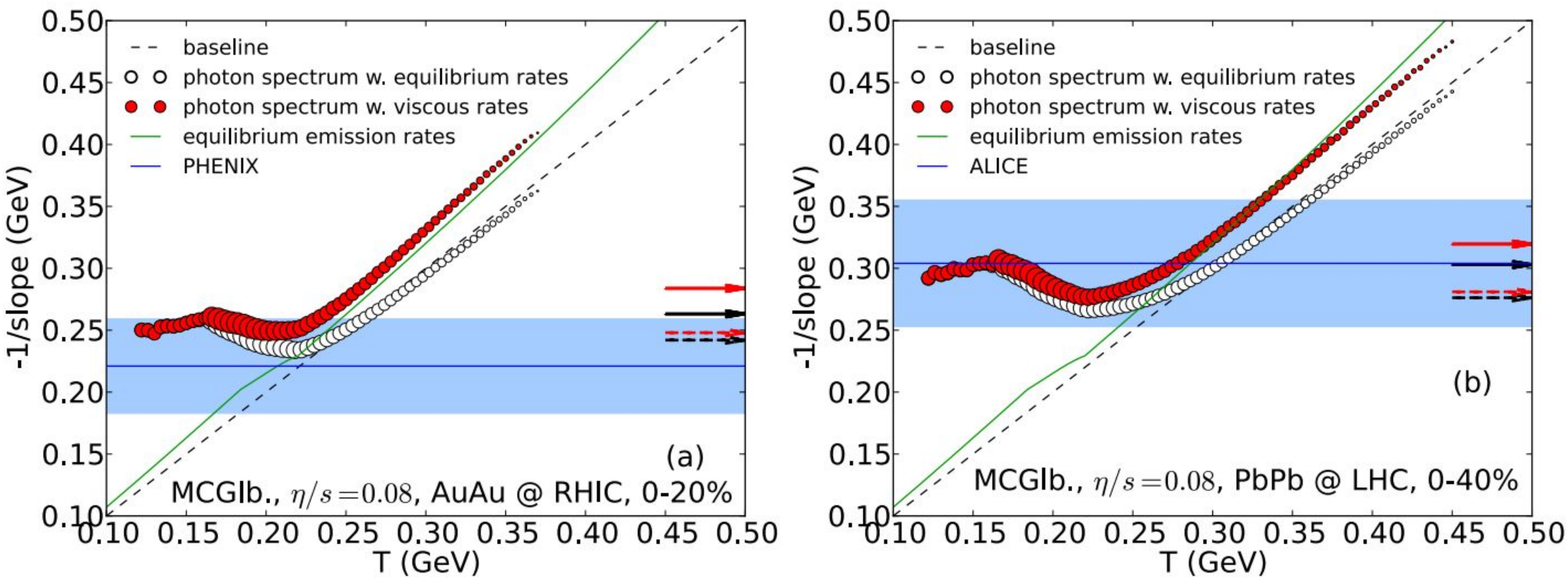
Prediction for direct photon production from Pb+Pb collisions at 5.02A TeV at LHC

Excess of direct photon yield over p+p at p_T<4 GeV/c at RHIC and LHC.

$T_{eff} \approx 221$ MeV in 0-20% Au+Au@RHIC.
$T_{eff} \approx 304$ MeV in 0-40% Pb+Pb@LHC.

the excess is attributed to thermal radiation.

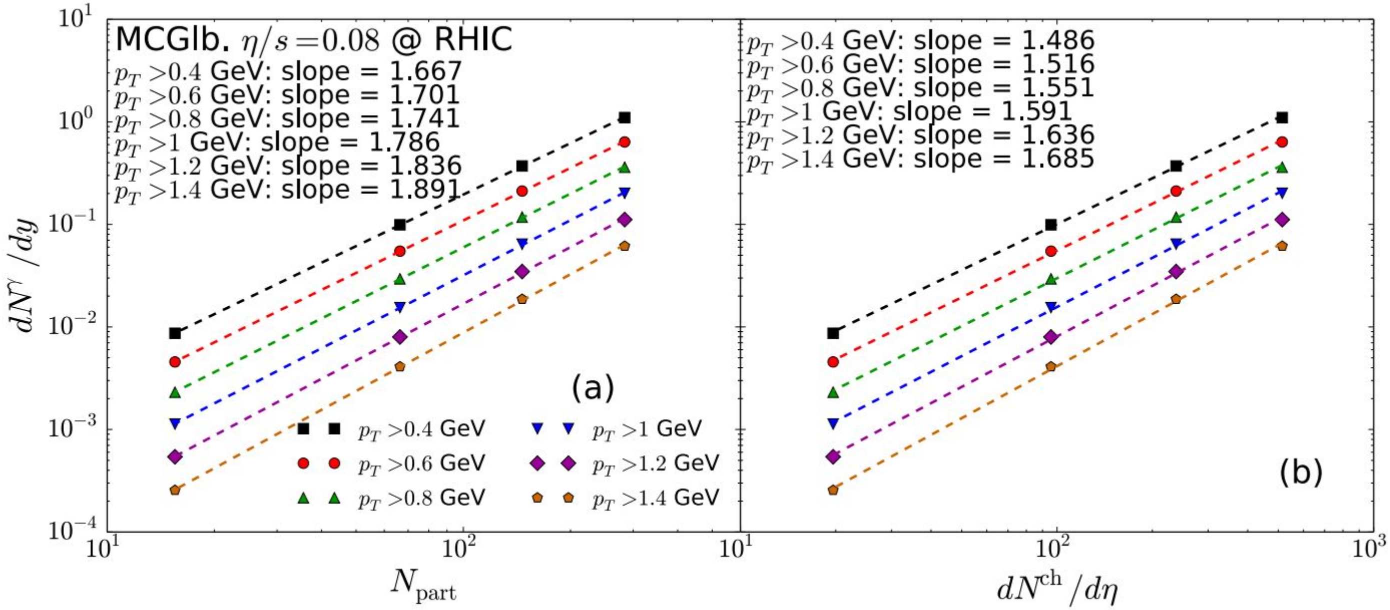
Thermal photons as a quark-gluon plasma thermometer



C. Shen, U. Heinz, J.-F. Paquet, C. Gale, *Phys.Rev.C* 89 (2014) 4, 044910

- **Inverse photon slope parameter T_{eff} = -1/slope as a function of the local fluid cell temperature, from the equilibrium thermal emission rates and from hydrodynamic simulations compared to the experimental values for Au+Au collisions at RHIC (PHENIX) and Pb+Pb collisions at the LHC (ALICE).**
- **T_{eff} at equilibrium emission rates is slightly higher than the true temperature .**
- **Most photons are emitted from fireball regions near the quark-hadron phase transition, their effective temperature is significantly enhanced by strong radial flow.**

Thermal photons as a quark-gluon plasma thermometer:



C. Shen, U. W. Heinz, J.-F. Paquet, and C. Gale, Phys. Rev. C89, 044910 (2014)

Thermal photon yield that grows like a power of N_{part} and as a (different) power of the multiplicity, with exponents stronger than linear.

The powers depend on the lower p_T cutoff.

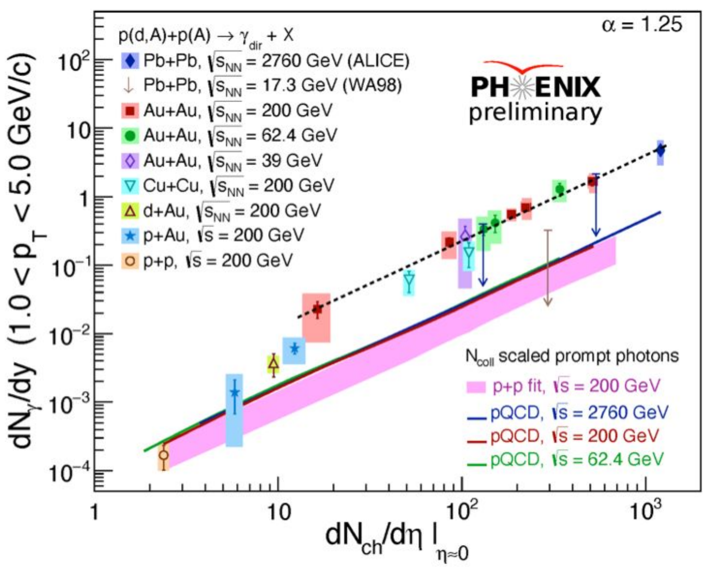
The experimental the slopes α in $dN^\gamma/dy = A\, N^\alpha_{part}$ did not change significantly with the p_T integration limit, and the average value is α = 1.38 ± 0.03(stat) ± 0.07(syst),

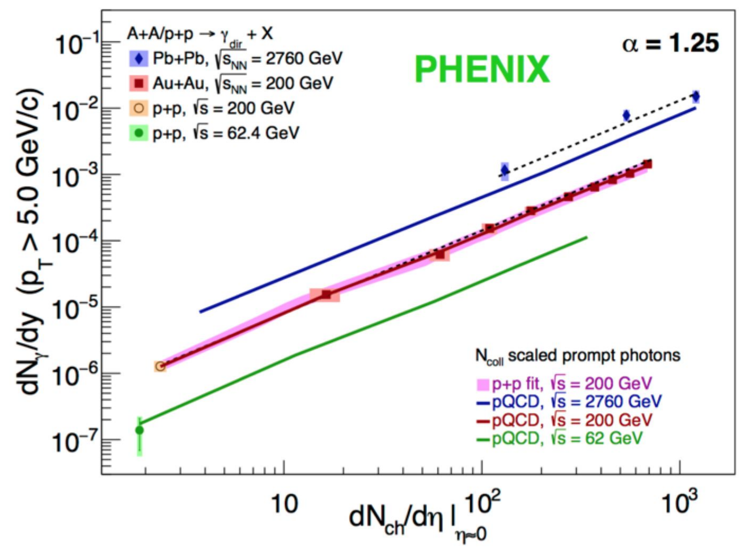
Equation of state of hadronic matter and electromagnetic radiation from relativistic heavy ion collisions

$$\frac{dN_\gamma}{dy} \simeq K \left(\frac{dN_{\rm ch}}{dy}\right)^\alpha ,$$

J. Cleymans, K. Redlich, & D. K. Srivastava
Phys.Lett. B420 (1998) 261-266

where $\alpha \simeq 1.2$ and K depends on the equation of state.



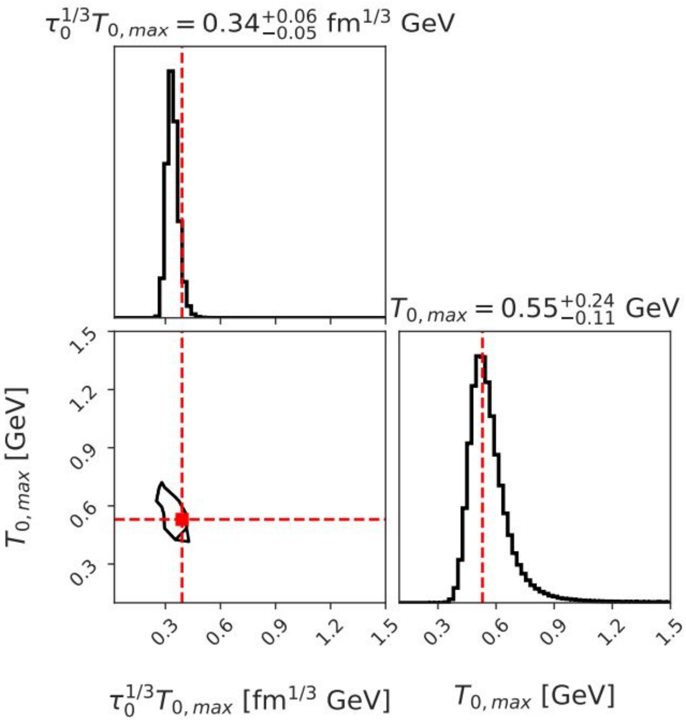


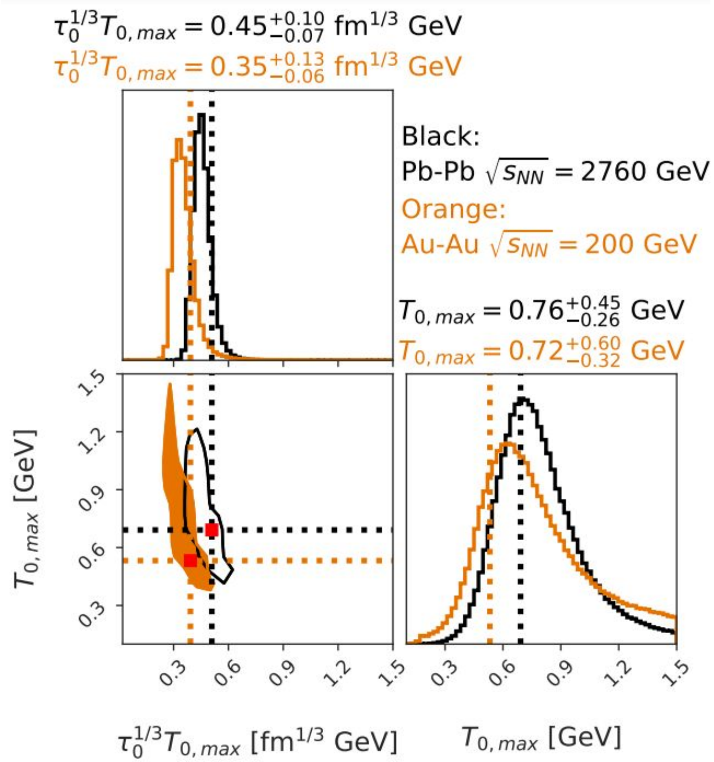
A. Adare *et al.* (PHENIX Collaboration) Phys. Rev. Lett. **123**, 022301 (2019)

A recent analysis from the PHENIX collaboration of available direct photon measurement results in collisions of various systems such as Au+Au, Cu+Cu, and Pb+Pb at different beam energies ranging from 39 to 2760 GeV, has shown a universal, within experimental uncertainties, multiplicity scaling, in which direct photon p_T spectra are scaled with charged hadron pseudorapidity density at mid-rapidity raised to power α=1.25

At a given beam energy, the scaling also holds for high p_T (>5 GeV) but when results from different collision energies are compared, an additional $\sqrt{s_{NN}}$-dependent multiplicative factor is needed to describe the integrated-direct-photon yield.

Electromagnetic measurement of the temperature of quark-gluon plasma produced in central ultrarelativistic nuclear collisions



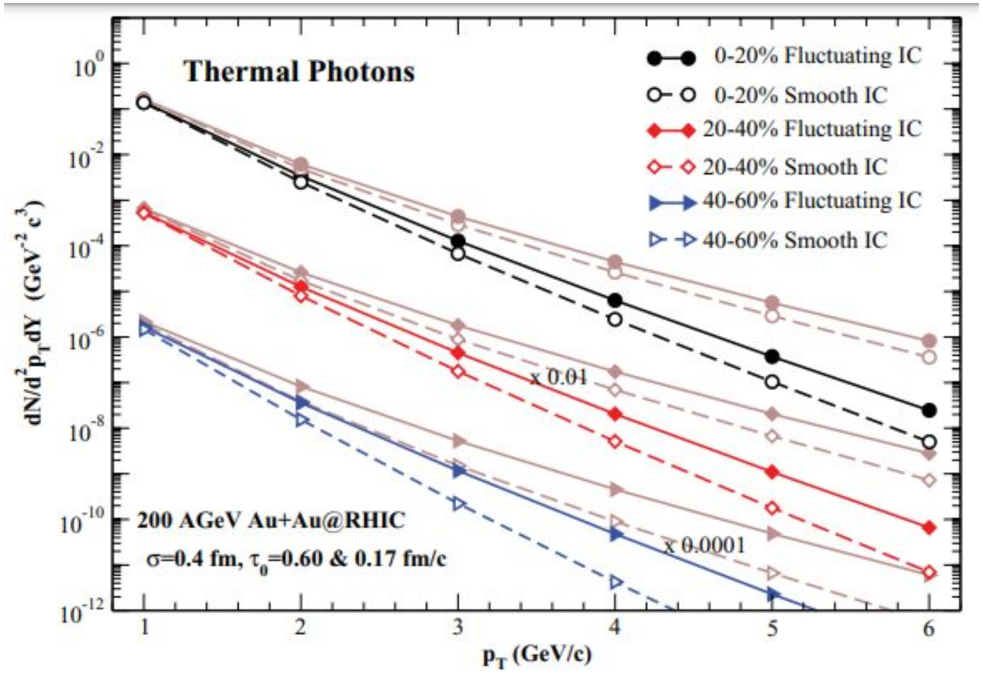


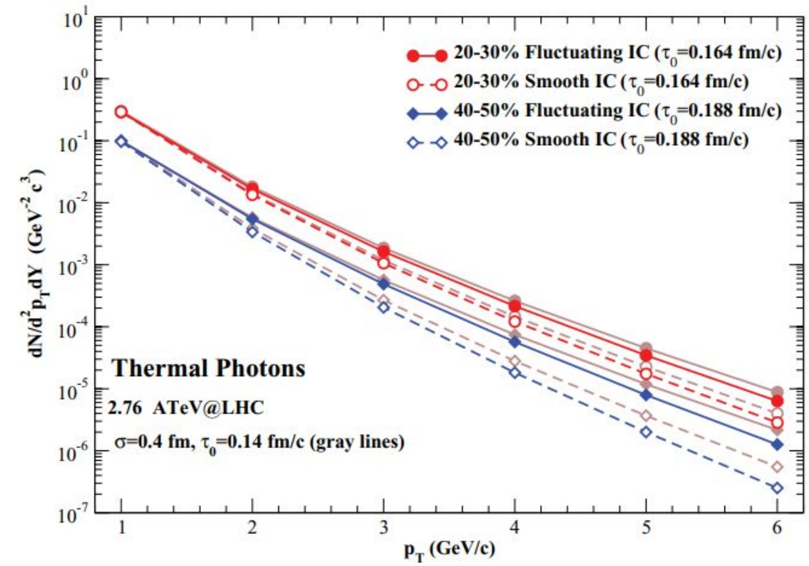
J.-F. Paquet and S. A. Bass, arXiv:2205.12299

$$T(\tau, r)/T(\tau_0, r) = (\tau_0/\tau)^{c_s^2}$$

- **the temperature profile of plasma is inhomogeneous in space and rapidly varying in time. T_{eff} of the photon energy spectrum must represent a convoluted average over the plasma's temperature profile**
- **photon energy spectrum is used to estimate the maximum temperature of the plasma, assuming it undergoes hydrodynamic expansion.**
- **can provide constraints on the product $\tau_0^{1/3}\ T_{0,max}$, and can estimate the plasma's maximum temperature $T_{0,max}$ to be larger than 400 MeV at RHIC and 500 MeV at the LHC.**

Thermal emission is sensitive to the initial state





Centrality bin (%)	p_0 (GeV)	A_{eff}	τ_0 (fm)
0–5	1.39	193	0.140
20–30	1.21	90	0.164
40–50	1.05	40	0.188

A larger τ_0 lowers the production of thermal photons generically. One might also expect that the value of τ_0 is not fixed and it may change with collision centralities.

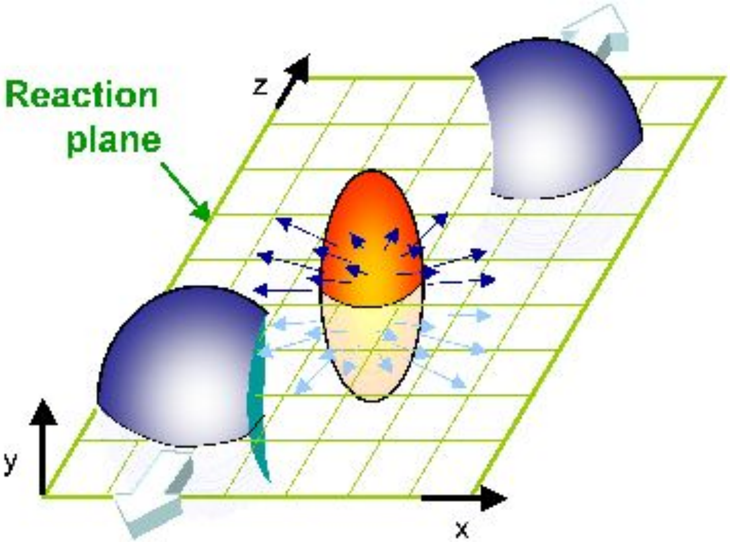
Centrality dependent τ_0 values from the EKRT model.

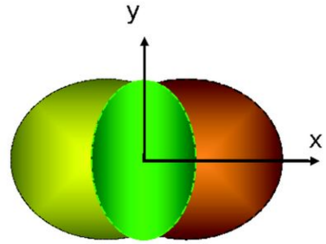
The effect of fluctuations in the IC and a larger value of formation time act in opposite directions by increasing and decreasing the production respectively.

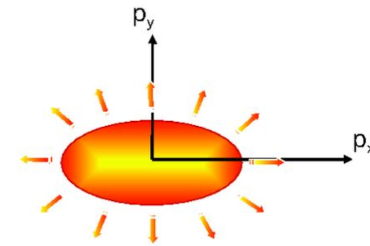
The effect of the IC fluctuations and change in the formation time cannot be distinguished easily only by studying the spectra of thermal photons.

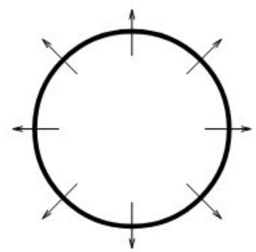
R. Chatterjee, H. Holopainen, T. Renk, and . J. Eskola
PHYSICAL REVIEW C 85, 064910 (2012)

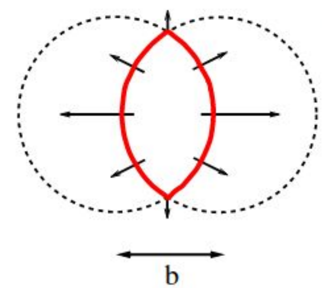
Anisotropic flow or in particular elliptic flow is one of the prominent signatures of the collective behaviour of the system produced in relativistic heavy ion collisions.

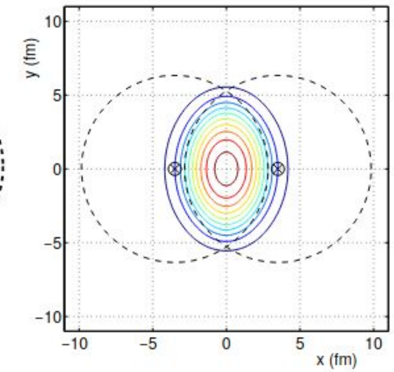


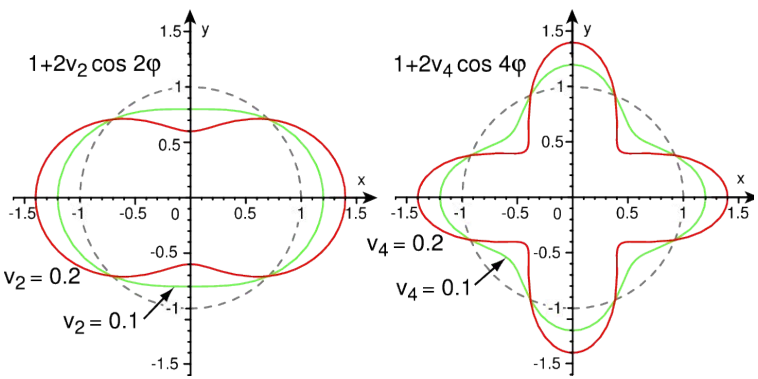












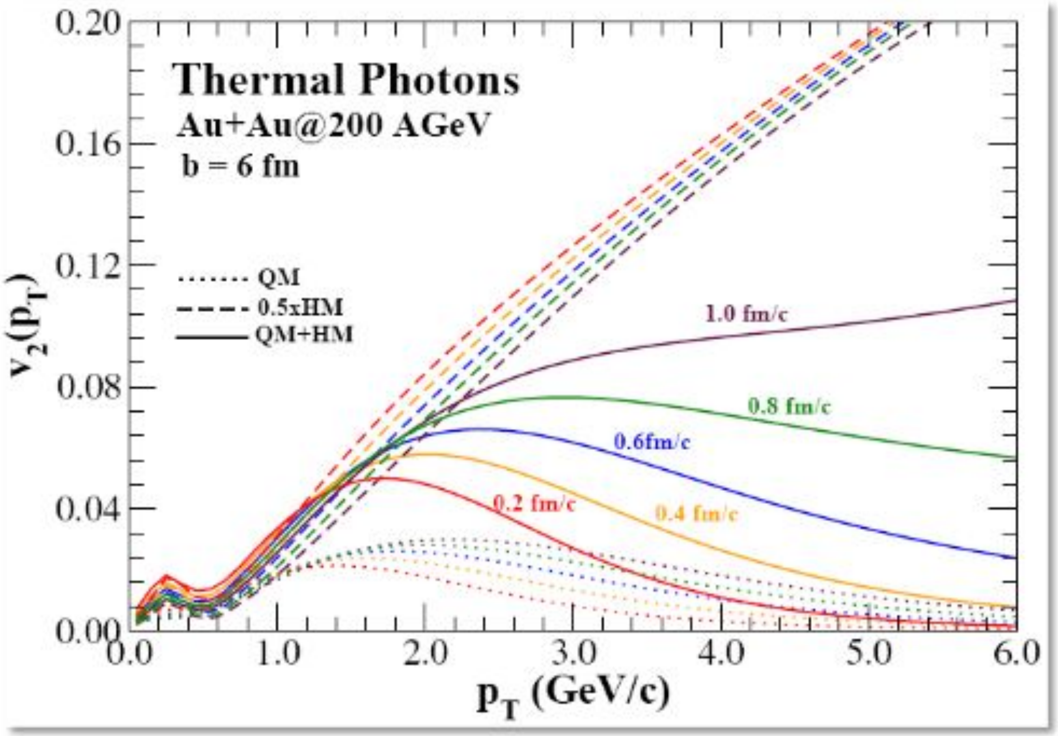
P. Kolb, Phys. Rev. C 68, 031902 (2003).

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)\right]$$

Elliptic flow: a brief review Raimond Snellings, 2011 New J. Phys. 13 055008

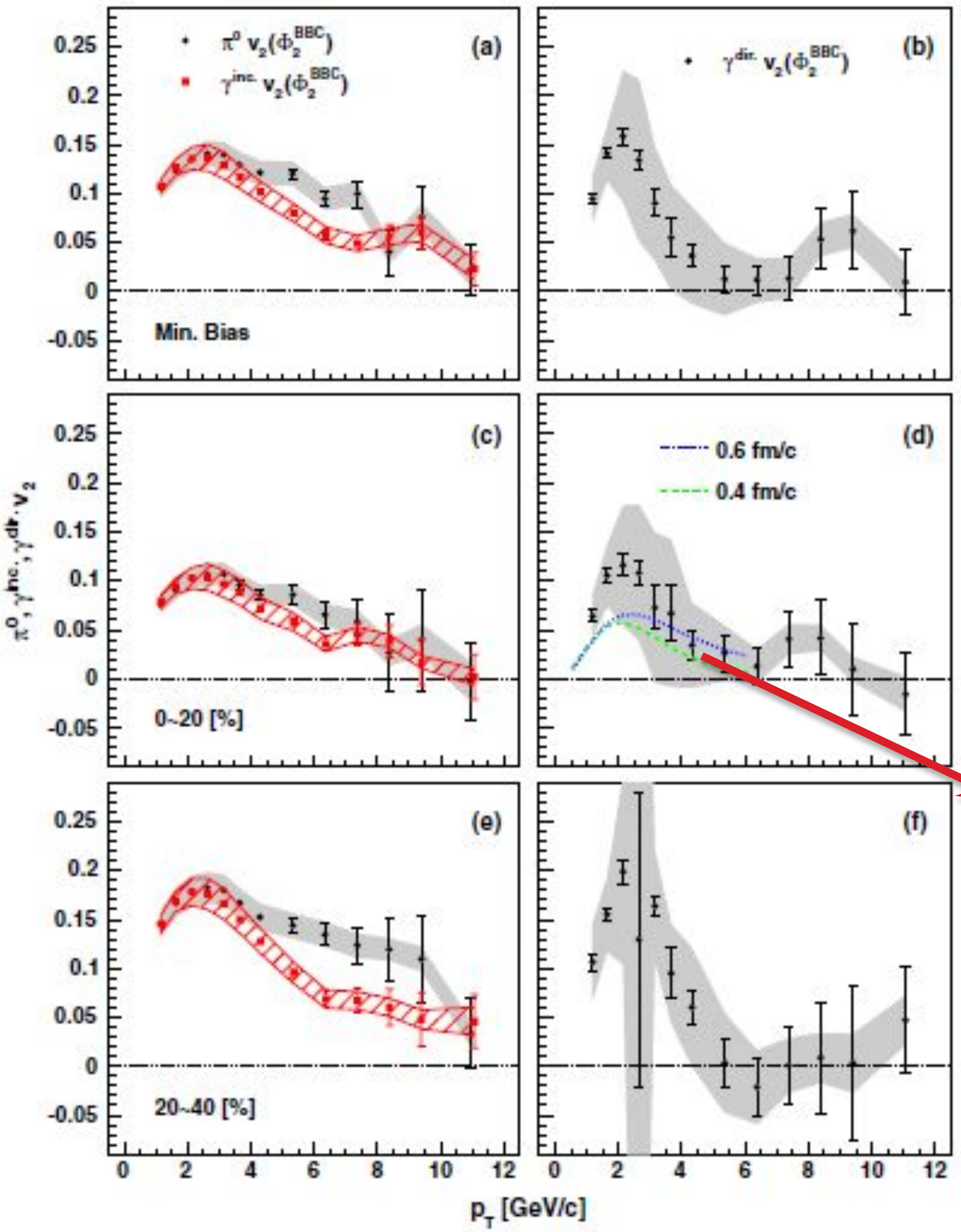
Polar plot of the azimuthal distribution of different Fourier expansions. Distortion of the unit circle through an elliptic component v_2, shown for 10% and 20% . Fourth component v_4 for the same values.

Elliptic flow of thermal photons:



- v_2 for thermal photons reveals a large sensitivity to the initial time τ_0 for p_T greater than about 1.5 GeV/c.

RC, E. Frodermann, U. Heinz, and D. K. Srivastava. PRL 96, 202302 (2006)
RC and D. K. Srivastava. PRC 79, 021901(R) (2009)



Direct Photon v_2

Observation of Direct-Photon Collective Flow in Au+Au Collisions at $\sqrt{s_{NN}}$=200 GeV

A. Adare *et al.* (PHENIX Collaboration)

Phys. Rev. Lett. 109, 122302 (2012)

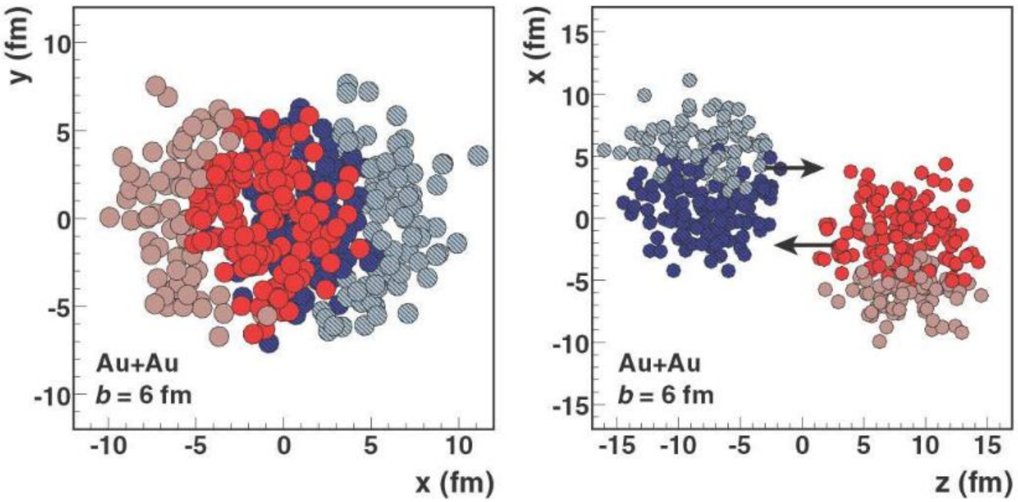
PHENIX preliminary results on direct photon v_2 in the 1-12 GeV/c p_T region.

for p_T >4 GeV/c the anisotropy for direct photons is consistent with zero, which is as expected if the dominant source of direct photons is initial hard scattering.

However, in the p_T <4 GeV/c region, a substantial direct photon v_2 is observed comparable to that of hadrons, whereas model calculations for thermal photons in this kinematic region underpredict the observed v_2..

RC & D. K. Srivastava,
Phys. Rev. C 79, 021901 (R) (2009).
for two different initial times:
0.6 fm and 0.4 fm.

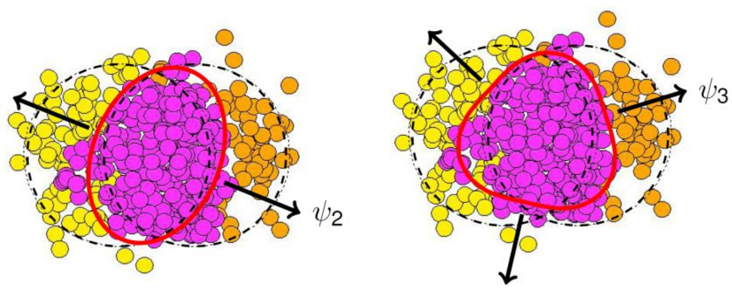
Experimental data shows similar qualitative nature as predicted by theory calculation.



Glauber Modeling in High Energy Nuclear Collisions

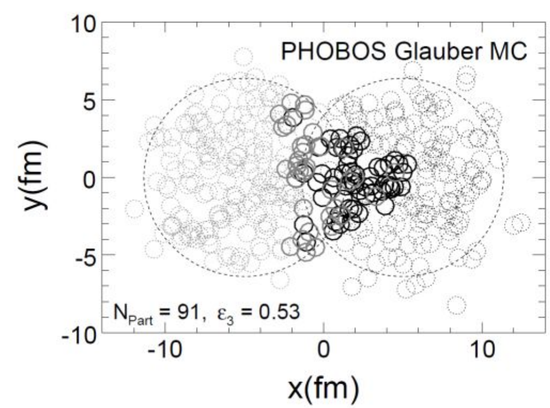
Michael L. Miller, Klaus Reygers, Stephen J. Sanders, Peter Steinberg

Ann.Rev.Nucl.Part.Sci.57:205-243, 2007



The concepts of participant triangularity and triangular flow in heavy-ion collisions is analogous to the definitions of participant eccentricity and elliptic flow.

The participant triangularity characterizes the triangular anisotropy of the initial nuclear overlap geometry and arises from event-by-event fluctuations.



B. Alver and G. Roland, PRC81, 054905 (2010)

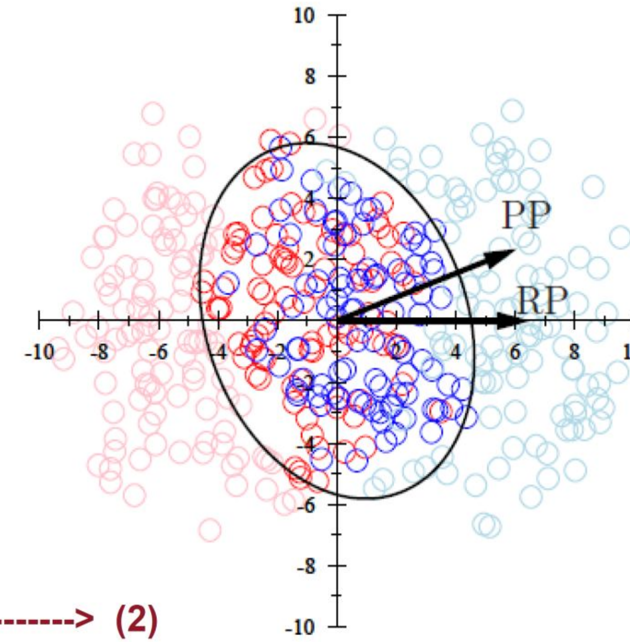
Event-by-event hydrodynamics and initial density profile

- Event-by-event hydrodynamics from Hannu Holopainen et al., Phys. Rev. C 83, 034901 (2011).

- Monte Carlo Glauber Model: two nucleons i and j from different nuclei collide when

$$(x_i - x_j)^2 + (y_i - y_j)^2 \leq \frac{\sigma_{NN}}{\pi}$$

-------> (1)



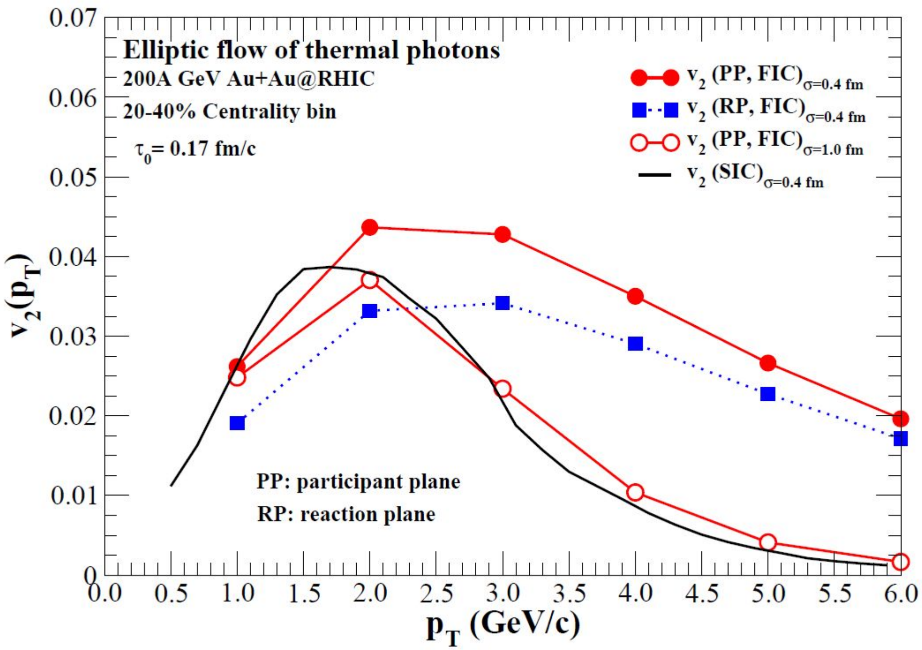
- Entropy density s is distributed in the (x,y) plane around the wounded nucleons using a 2D Gaussian:

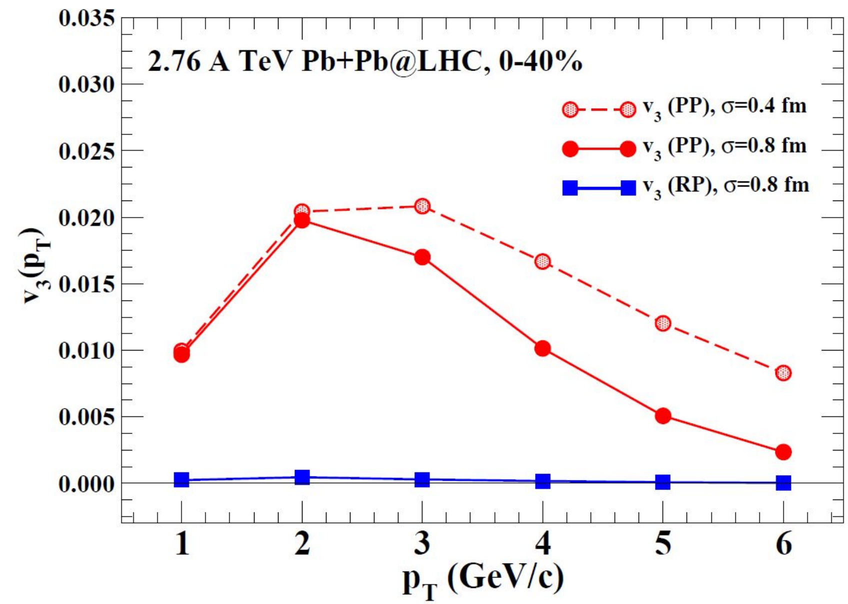
$$s(x,y) = \frac{K}{2\pi\sigma^2} \sum_{i=1}^{N_{WN}} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2} \right)$$

-------> (2)

- σ is a free parameter determining the size of the fluctuation.

Elliptic flow and triangular flow of thermal photons at RHIC and LHC



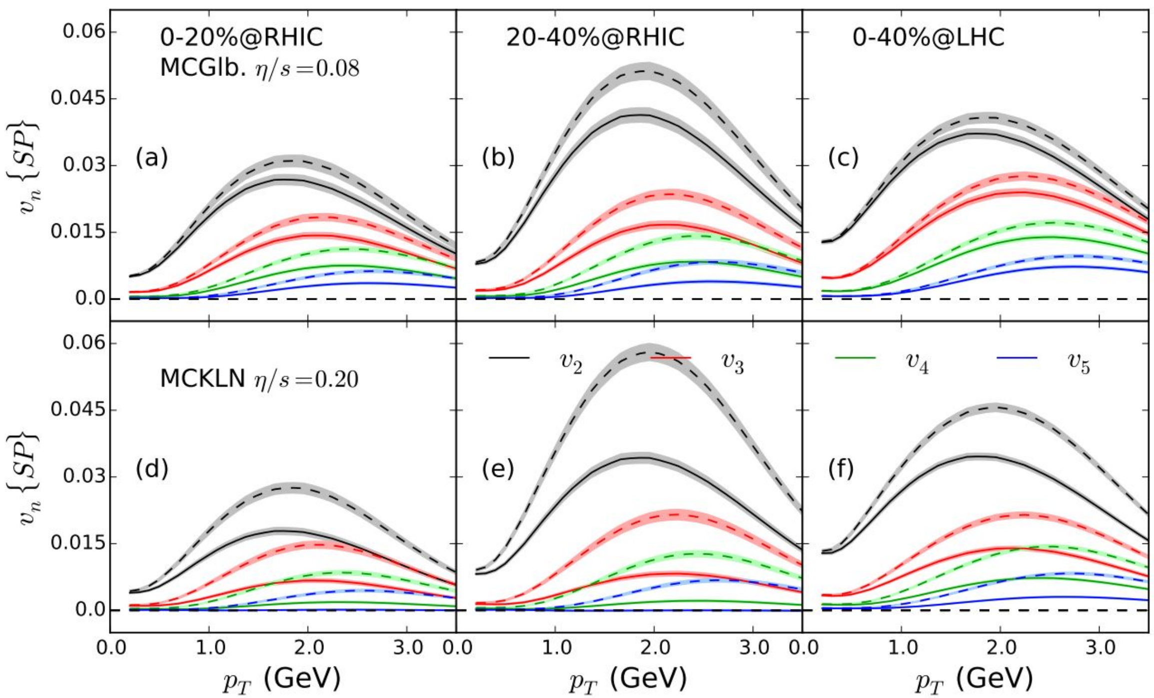


RC, D. K. Srivastava, T. Renk, Phys.Rev. C94 (2016), 014903
RC, H. Holopainen, I. Helenius, T. Renk, K. J. Eskola, Phys. Rev. C88 (2013) 034901

Fluctuation in the initial density distribution gives larger v_2

Photon v_3 is found to be significantly large and shows a similar p_T dependent nature to the elliptic flow parameter.

Anisotropic flow of direct photons at RHIC and LHC

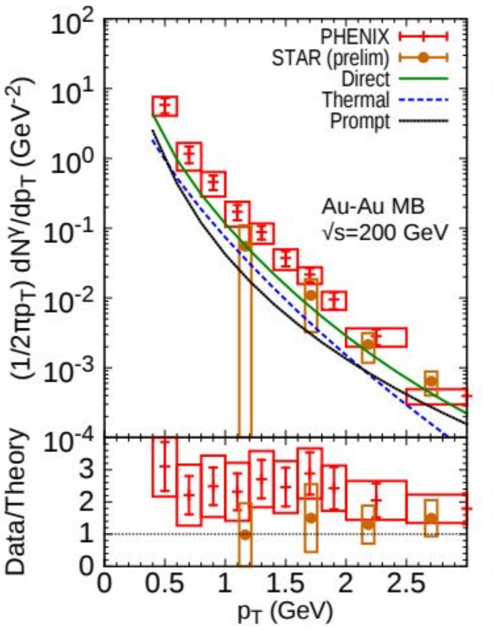


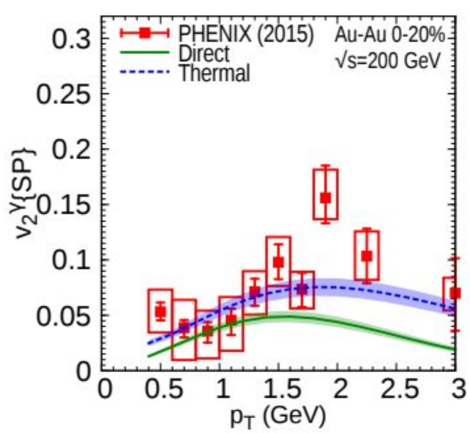
$$v_n^\gamma\{\mathrm{SP}\}(p_T) = \frac{\left\langle \frac{dN^\gamma}{dyp_Tdp_T}(p_T) v_n^\gamma(p_T) v_n^{\mathrm{ch}} \cos\left[n\left(\Psi_n^\gamma - \Psi_n^{\mathrm{ch}}\right)\right]\right\rangle}{\left\langle \frac{dN^\gamma}{dyp_Tdp_T}(p_T)\right\rangle v_2^{\mathrm{ch}}\{2\}}.$$

C. Shen, U. Heinz, J.-F. Paquet, I. Kozlov, and C. Gale

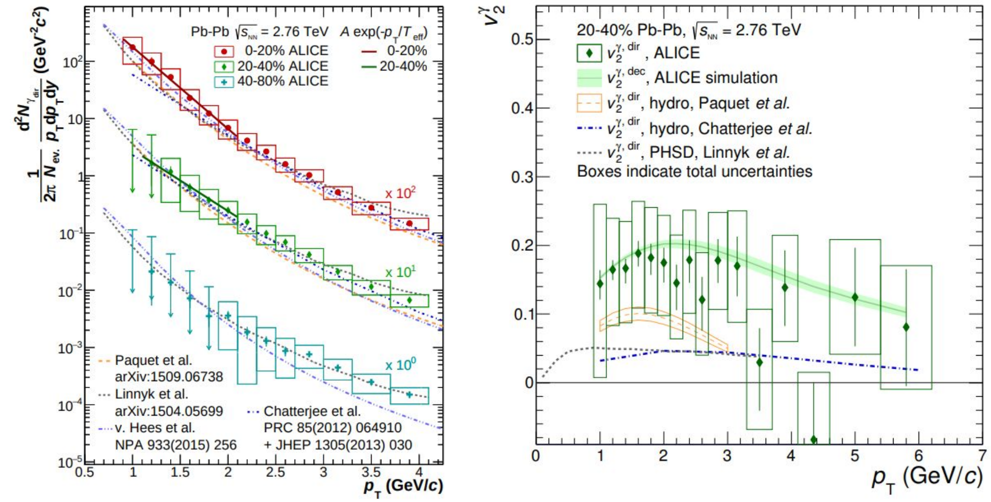
PHYSICAL REVIEW C 91, 024908 (2015)

Spectra and anisotropic flow at RHIC and LHC





J. F. Paquet, C. Shen, G. S. Denicol, M. Luzum, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C 93, no. 4, 044906 (2016).



ALICE Collaboration (J. Adam et al.), Phys. Lett. B 754, 235 (2016),

S. Turbide, C gale, E. Frodermann, and U Heinz, Phys. Rev. C77, 024909 (2008)

H. Holopainen, S. S. Räsänen, and K. J. Eskola, Phys. Rev. C 84, 064903 (2011)

H.-van Hees, C. Gale, and R. Rapp, Phys. Rev. C 84, 054906 (2011)

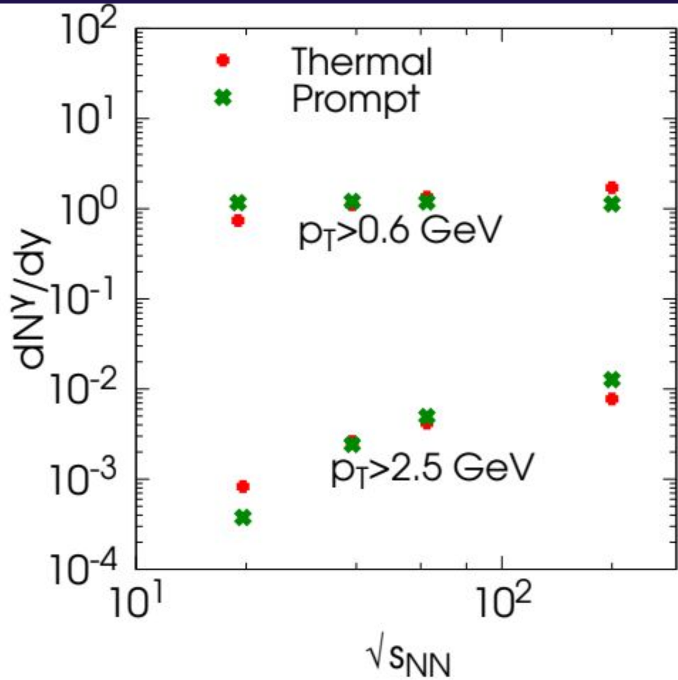
O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing, and E. L. Bratkovskaya, Phys. Rev. C 92, 054914 (2015)

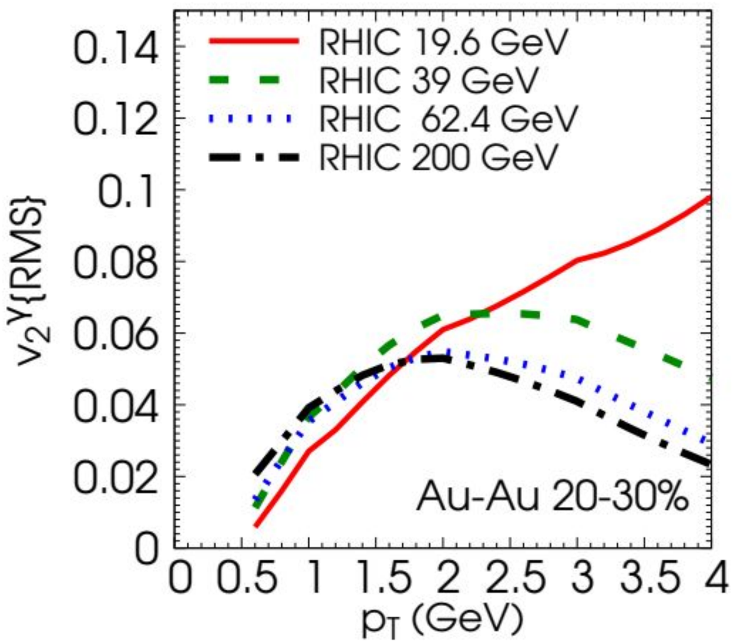
V. Y. Naboka, Y. M. Sinyukov and G. M. Zinovjev, Phys. Rev. C 97, no.5, 054907 (2018).

R. Chatterjee et al.,Phys. Rev. C 96, 014911 (2017)

P. Dasgupta et al. Phys. Rev. C 97, 034902 (2018)

Photon radiation from heavy-ion collisions in the $\sqrt{s_{NN}}$ = 19 − 200 GeV regime



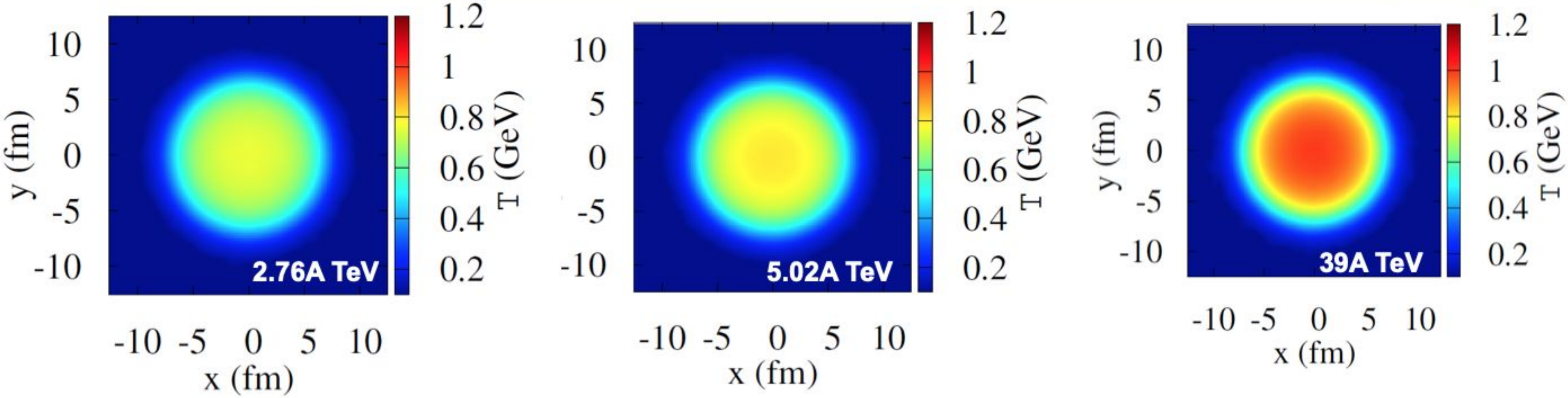


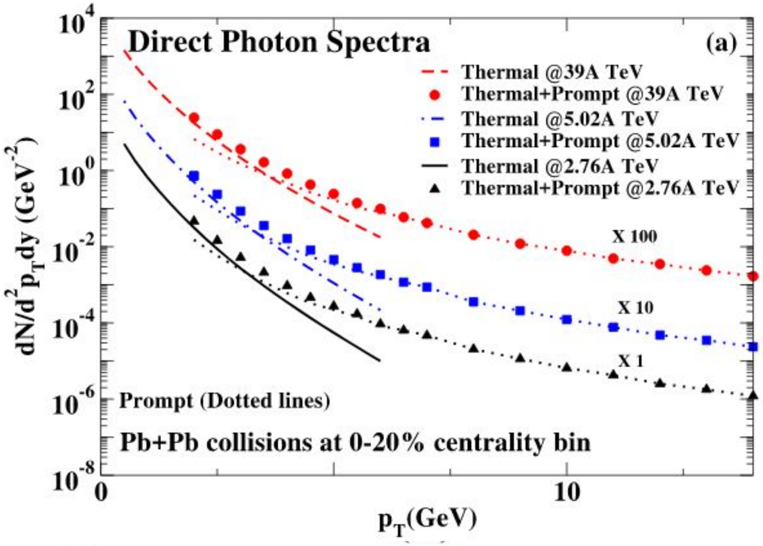
C. Gale, S. Jeon, S. McDonald, J.-F. Paquet, C. Shen Nucl.Phys.A 982 (2019), 767-770

- **calculations of prompt and thermal photon production in gold-gold collisions at various collision energies ranging from 19 GeV to 200 GeV.**
- **insights into the production of photons in heavy-ion collisions across a wide range of collision energies.**
- **emphasizes the potential to measure thermal photons in low collision energies by studying the suppression of prompt photon production.**

Photon production from Pb+Pb collisions at 2.76A TeV and 5.02 A TeV at LHC and at 39 A TeV at the upcoming Future Circular Collider (FCC)

Temperature distribution on the transverse plane at formation time for the three energies





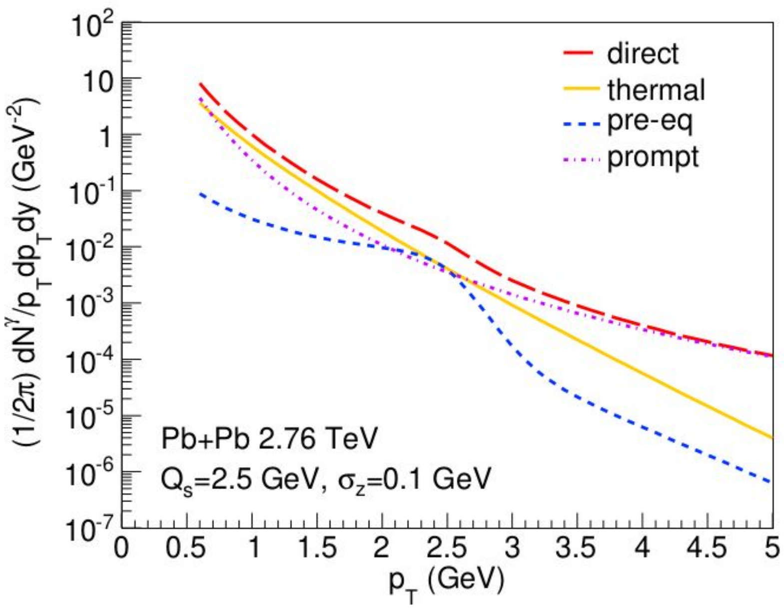
At FCC the central temperature is significantly larger than the maximum central temperatures at the LHC energies from hydrodynamical model calculation.

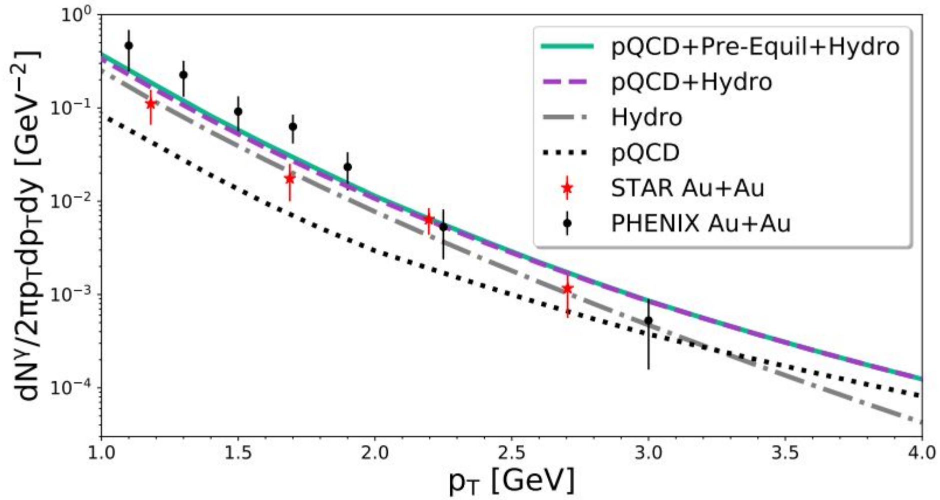
The prompt photons production increases by a factor of 5 to 15 at 39A TeV in the p_T region 2 to 15 GeV compared to 2.76A TeV .

The relative enhancement in the production of thermal photons is found to be more compared to prompt photons at FCC than at the LHC energies.

P. Dasgupta, S. De, RC, and D. K. Srivastava, PRC98, 024911 (2018)

Emission of electromagnetic radiation from the early stages of relativistic heavy-ion collisions





DIRECT PHOTONS IN HYDRODYNAMIC MODELING OF RELATIVISTIC NUCLEAR COLLISIONS

A. Monnai, arxiv:2203.13208

A. Monnai, J. Phys. G 47, 075105 (2020)

★ Pre-equilibrium photons can be as important as thermal and prompt photons for comprehensive understanding of direct photon production.

★ The modification of the slope parameter can also affect the extraction of the effective temperature.

Emission of electromagnetic radiation from the early stages of relativistic heavy-ion collisions

J. Churchill, L. Yan, S. Jeon, and C. Gale Phys. Rev. C 103, 024904 (2021)

Photons from the early stages of relativistic heavy-ion collisions

L. Oliva M. Ruggieri, S. Plumari, F. Scardina, G. X. Peng, and V. Greco

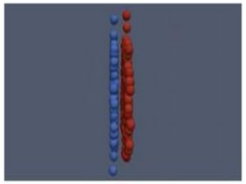
PHYSICAL REVIEW C 96, 014914 (2017)

Parametric estimate of the relative photon yields from the glasma and the quark-gluon plasma in heavy-ion collisions

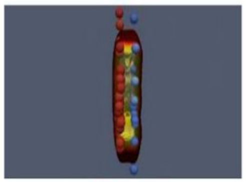
Jürgen Berges, Klaus Reygers, Naoto Tanji, and Raju Venugopalan

Photons: contribution of different sources

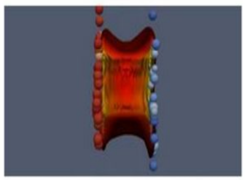
AuAu @ 200 GeV, 20-40%



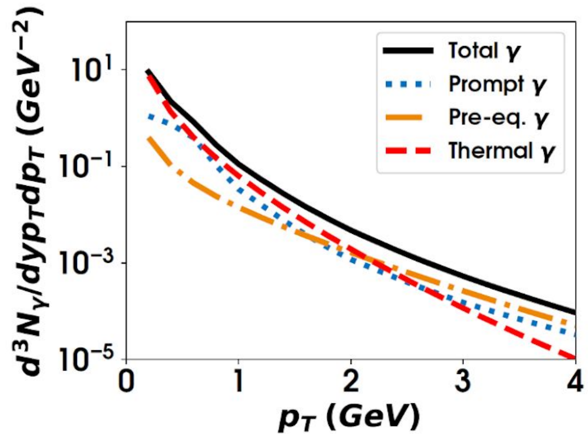
$\tau = "0^+"$:
- Prompt photons

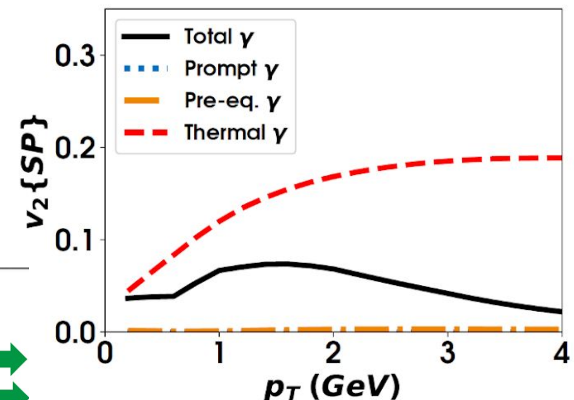


$\tau = 0.1$ fm: KøMPøST
- Pre-equilibrium photons



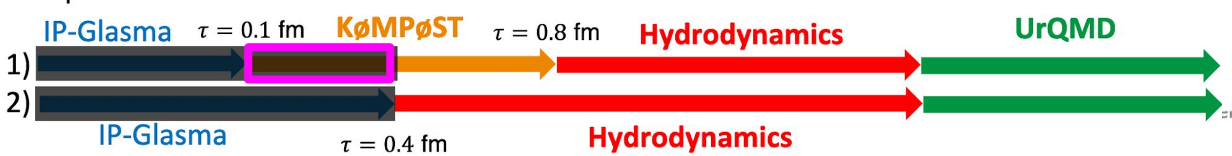
$\tau = 0.8$ fm: Hydrodynamics
- "Thermal" photons



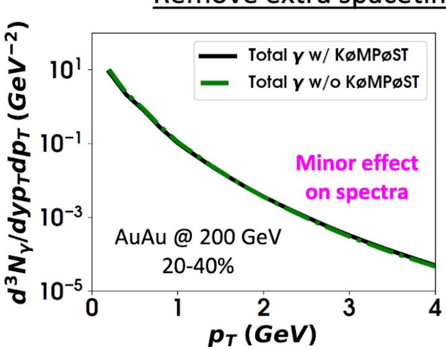


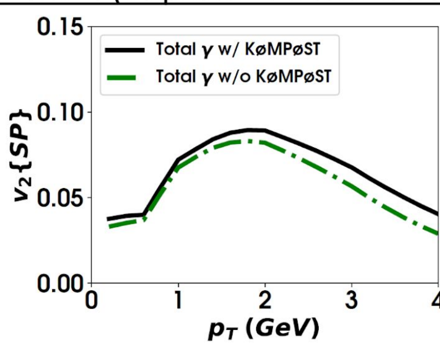
- Thermal photons dominate v_2, and low p_T dN/dp_T
- Pre-eq. photons: large dN/dp_T at high p_T but negligible v_2

Compare:



Remove extra spacetime volume (no photon emission before $\tau = 0.4$ fm)





- Higher v_2 w/ KøMPøST

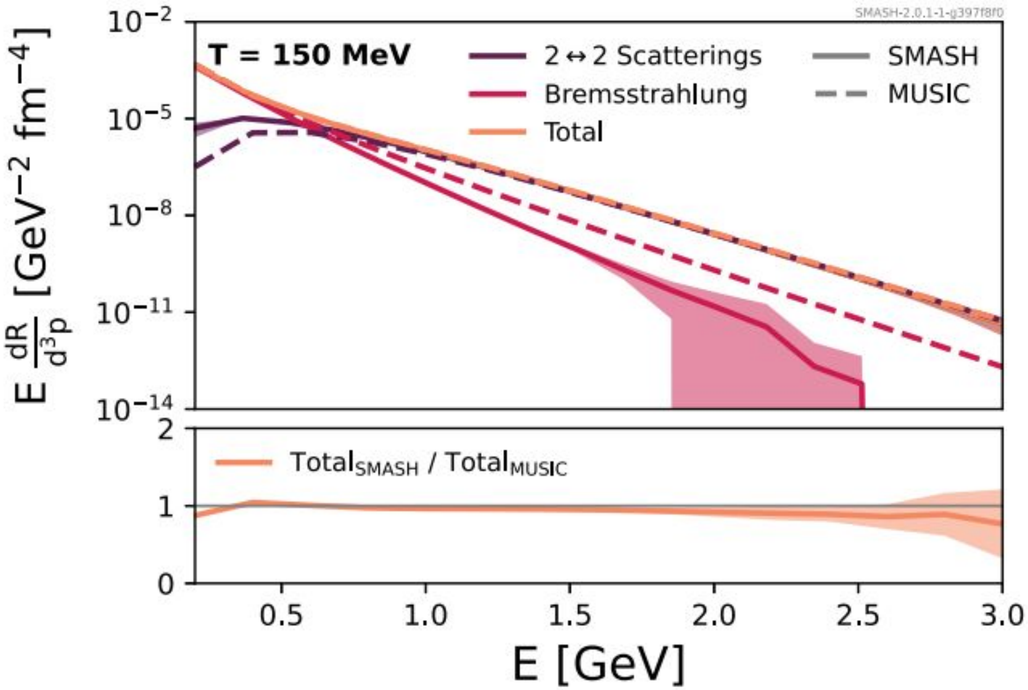
Take home:

Effect of pre-eq. phase depends on question being asked

Jean-François Paquet
HP2020

C. Gale, J.-F. Paquet, B. Schenke, and C. Shen, in 28th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (2020) arXiv:2002.05191.

Photon production in the late stages of relativistic heavy-ion collisions



A. Schäfer, O. Garcia-Montero, J.-F. Paquet, H. Elfner , and C. Gale, Phy. Rev. C 105, 044910 (2022)

A. Schafer, J. M. Torres-Rincon, J. Rothermel, N. Ehlert , C. Gale , and H. Elfner, Phys. Rev. D 99, 114021 (2019)

Non-equilibrium dynamics enhance the late-stage photon production at low pT and decreases it at higher pT compared to the estimate from hydrodynamics.

A significant increase in the momentum anisotropies of these photons due to non-equilibrium dynamics.

Direct photons from recombination model,

H. Fujii, K. Itakura and C. Nonaka, Nucl. Phys. A967, 704

Jet photons

High-energy photons from passage of jets through quark gluon plasma
Rainer J. Fries, Berndt Muller, and Dinesh K. Srivastava,
Phys. Rev. Lett. 90, 132301 (2003),

Photon-jet correlations in p-p and Pb-Pb collisions using JETSCAPE framework
-JETSCAPE Collaboration

It is now well established that jet modification is a multistage effect; hence a single model alone cannot describe all facets of jet modification. The JETSCAPE is a multistage framework that uses several modules to simulate different stages of jet propagation through the QGP medium.

Jet-medium photons as a probe of parton dynamics

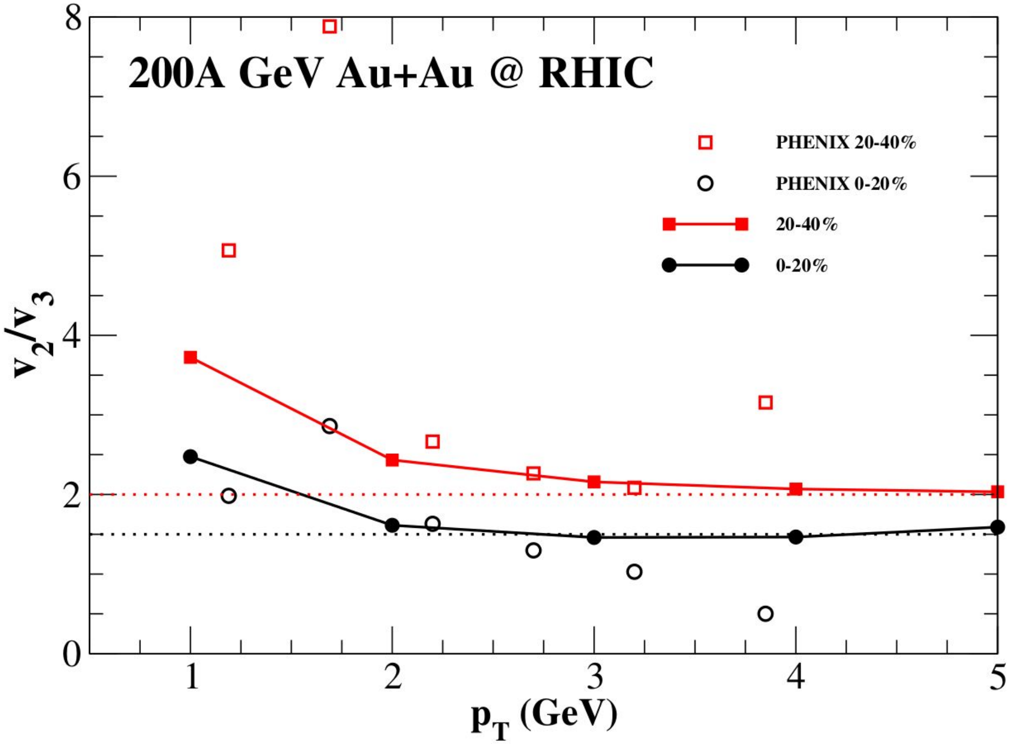
Rouzbeh Modarresi Yazdi, Shuzhe Shi, Charles Gale, Sangyong Jeon, arXiv:2207.12513

Photons resulting from jet-medium interactions offer the opportunity of studying the evolving quark distribution in a heavy ion collision. The spectra of jet-medium photons is presented within the jetscape framework for two different energy loss models, martini and cujet. Jet-medium photons can contribute significantly to the spectrum of direct photons in the intermediate p_T range.

Ratio of photon anisotropic flow

The ratio of photon v_n can be a potential observable to understand the direct photon puzzle by minimizing the non-thermal contributions.

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

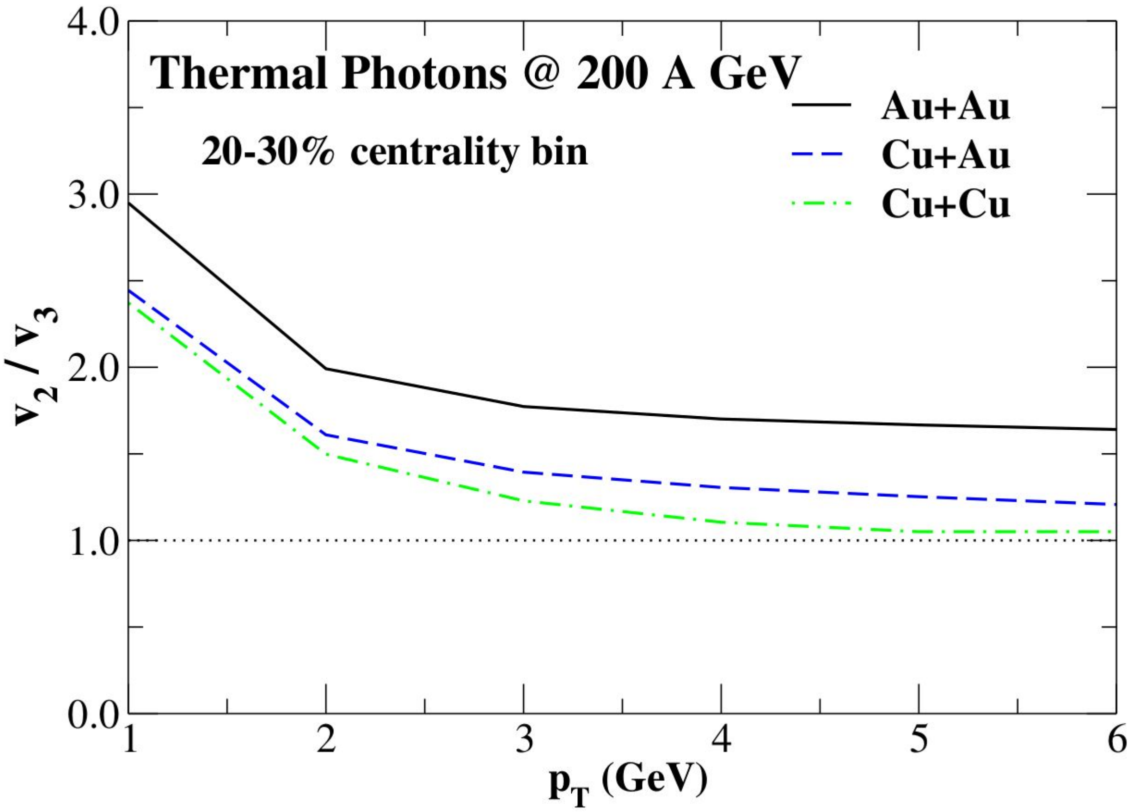


The ratio is found to be larger for peripheral collisions than for central collisions. The p_T dependent behavior of the ratio is found to be different than the individual flow parameters.

The individual v_2 and v_3 results from hydrodynamical model calculations under-estimate the data

RC & P. Dasgupta PRC 104, 064907 (2021)

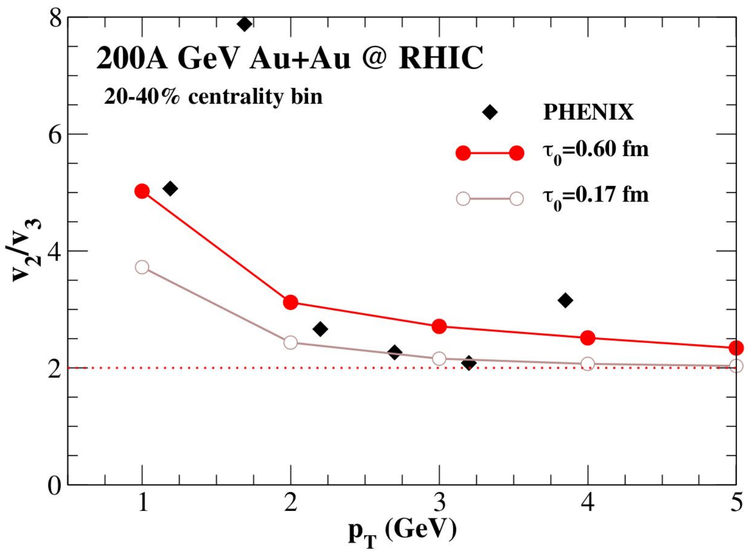
Ratio of photon anisotropic flow

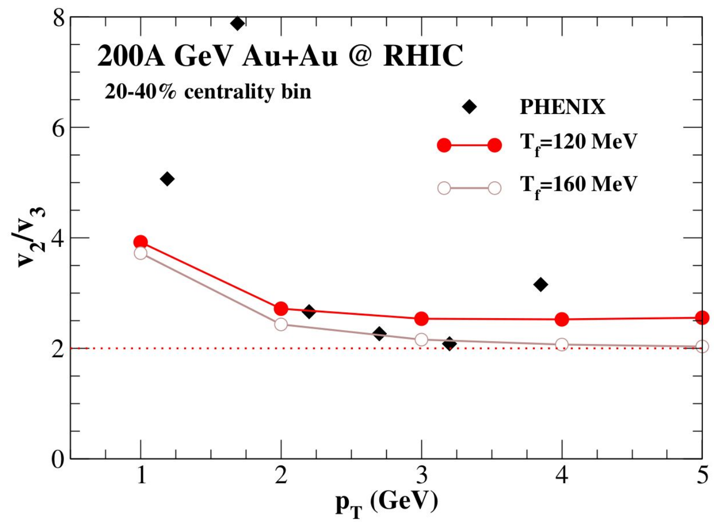


The ratio shows similar qualitative nature for all three cases and is found to be largest for the Au+Au collisions. The results from Cu+Au and Cu+Cu collisions are found to be close to each other.

The effect of initial state fluctuations is more for smaller systems which reduces the gap between v_2 and v_3 and consequently a relatively smaller value of the ratio can be seen for those.

Ratio of photon anisotropic flow





A larger τ_0 increases the anisotropic flow significantly at larger p_T values. Whereas, a larger τ_0 affects the ratio maximum in the lower p_T region.

We consider a constant freeze-out temperature for all the systems at different centrality bins which is fixed by reproducing the charged particle multiplicity.

Even for a much smaller value of T_f , the ratio does not change much in the lower p_T region and a small change can be observed only for larger p_T. However, a smaller T_f increases the photon v_2 and v_3 significantly in the entire p_T region.

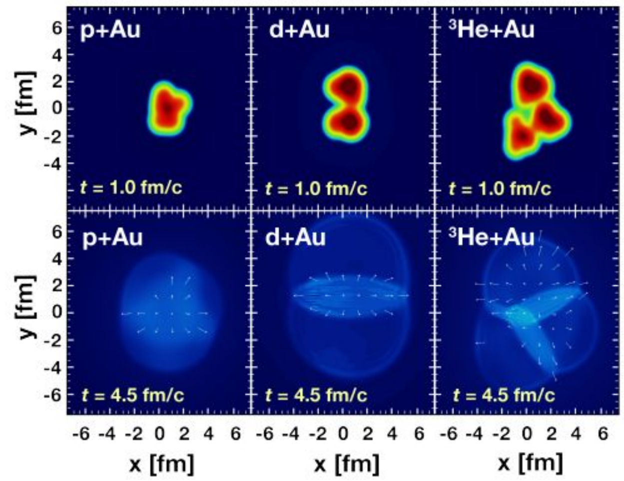
RC & P. Dasgupta PRC 104, 064907 (2021)

Collectivity and electromagnetic radiation in small systems

- Ultra-high temperature nuclear matter in heavy-ion collisions behaves like a nearly inviscid hydrodynamical perfect fluid.

- Surprisingly, similar collective, fluid-like phenomena have been discovered in much smaller collision systems, such as p+p, p+A, d+Au, and ^{3}He+Au, challenging the conventional understanding of system size requirements for collectivity.

- These findings open up new research directions and questions regarding the origin and underlying dynamics of collectivity in various collision system

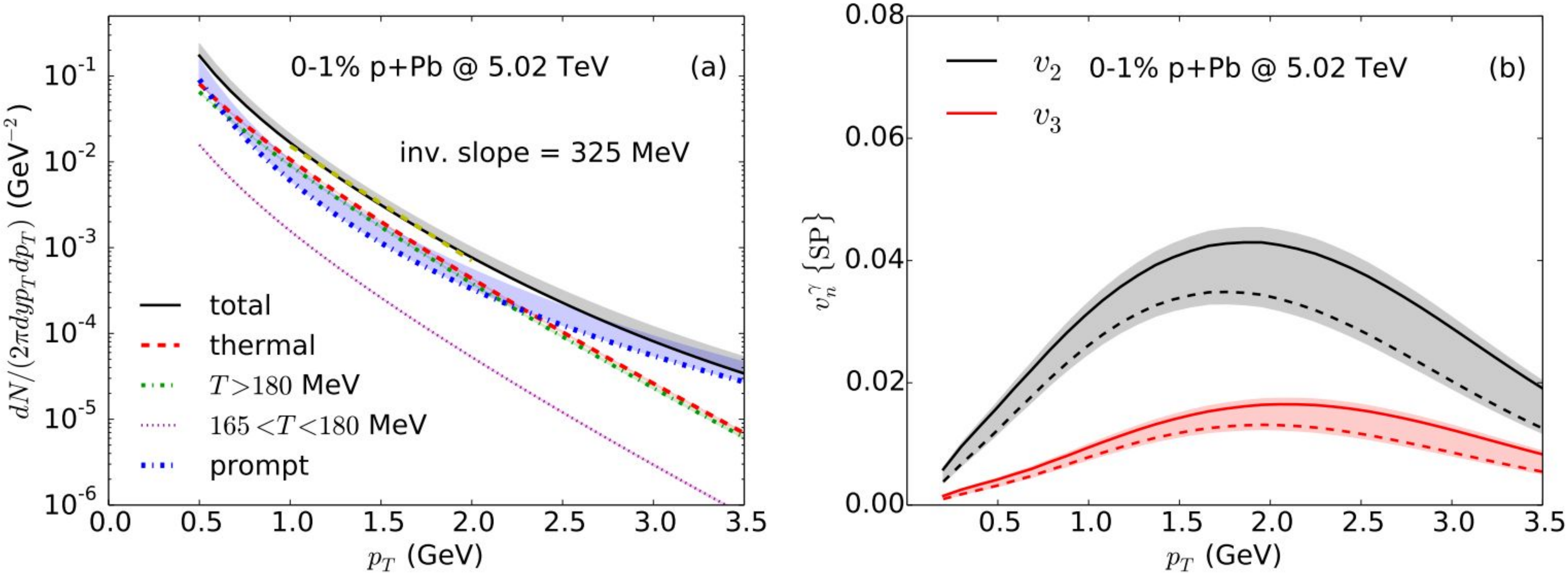


Small System Collectivity in Relativistic Hadronic and Nuclear Collisions
J. L. Nagle & W. A. Zajc
Annual Review of Nuclear and Particle Science 68, 211 (2018)

J. L. Nagle, A. Adare, S. Beckman, T. Koblesky, J. Orjuela Koop, D. McGlinchey, P. Romatschke, J. Carlson, J. E. Lynn, and M. McCumber
Phys. Rev. Lett. 113, 112301 (2014)

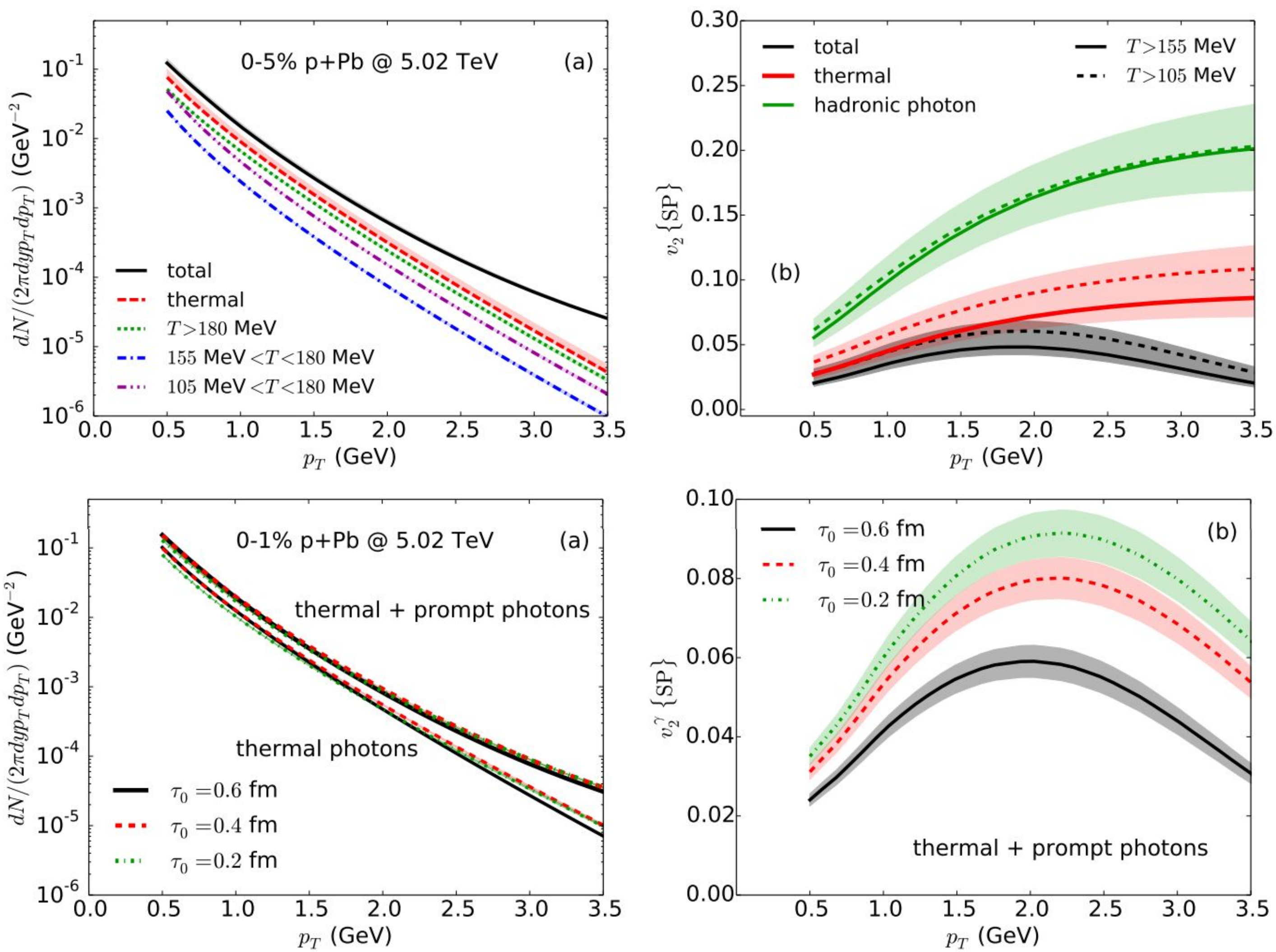
Photons from small system

- ★ The collective behaviour of hadronic particles has been observed in high multiplicity proton-lead collisions at LHC, as well as in deuteron-gold collisions at RHIC.
- ★ Owing to their compact size, these systems can reach temperatures comparable to those in central nucleus-nucleus collisions.
- ★ The thermal photons can thus shine over the prompt background, and increase the low p_T direct photon spectrum by factor of 2-3 in 0-1% p+Pb collisions at 5.02 TeV.
- ★ Thermal photon enhancement can therefore serve as a clean signature of the existence of a hot quark-gluon plasma during the evolution of these small collision systems, as well as validate hydrodynamic behavior in small systems.

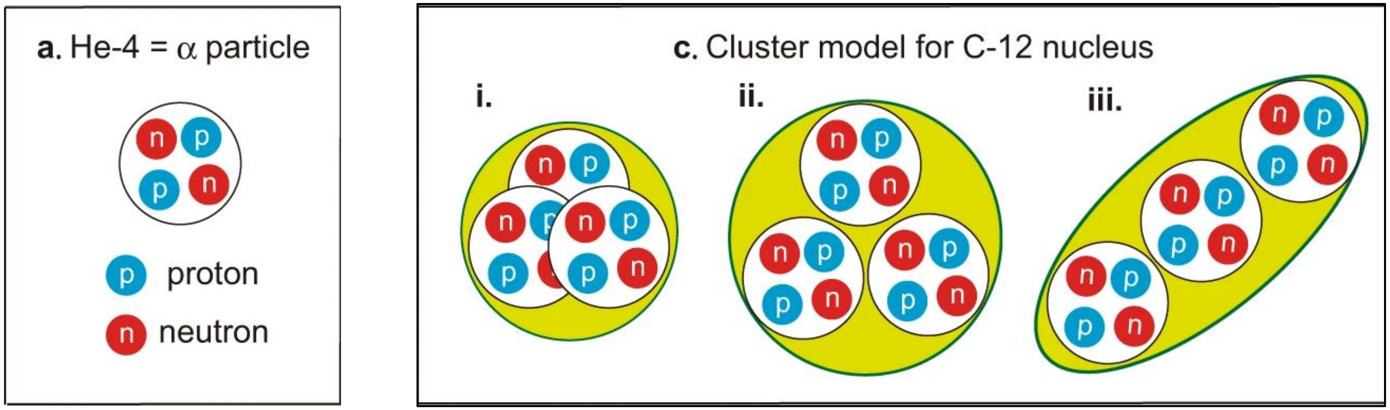


C. Shen, J. -F. Paquet, G.S. Denicol S. Jeon, C. Gale
Phys.Rev.Lett. **116 (2016) 7, 072301**

τ_0 sensitivity



C. Shen, J-F.Paquet, G. Denicol, S. Jeon, and C Gale, PHYSICAL REVIEW C 95, 014906 (2017)



Nature Communications , volume 13, Article number: 2234 (2022)

Clustering has long been known to play a key role in understanding the structure of light nuclei.

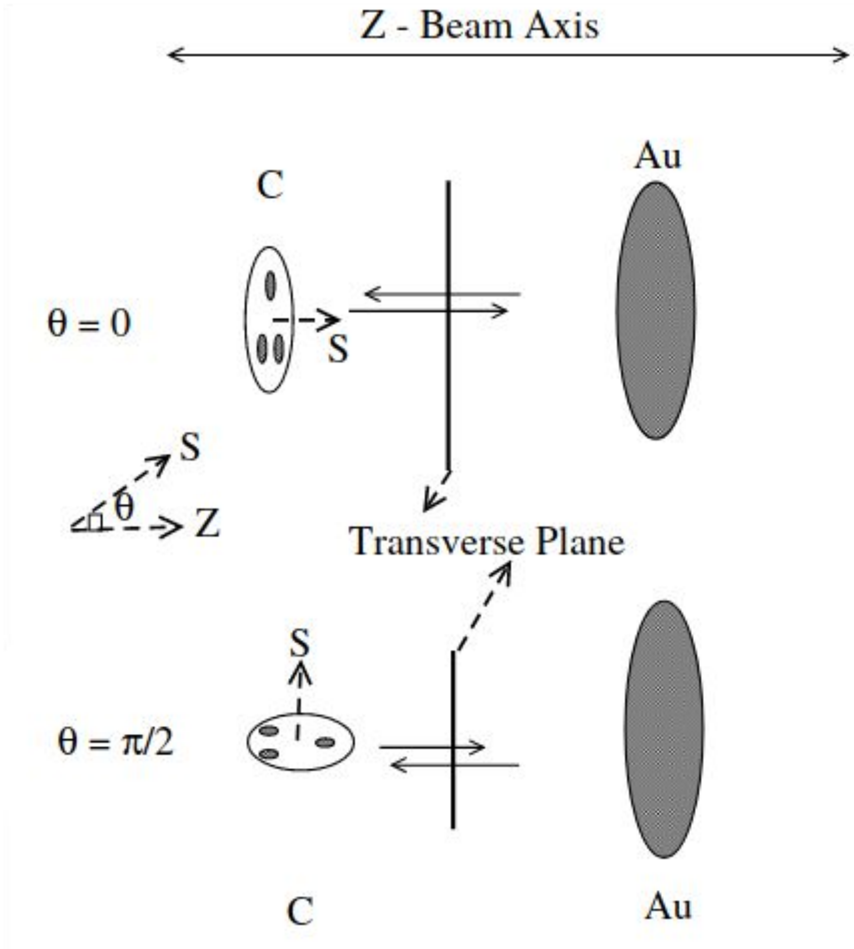
Signatures of α Clustering in Light Nuclei from Relativistic Nuclear Collisions
Wojciech Broniowski and Enrique Ruiz Arriola
Phys. Rev. Lett. **112**, 112501 (2014)

Broniowski et al (Phys. Rev. Lett. 112, 112501) showed that relativistic nuclear collisions may provide experimental evidence of clustering in light nuclei. They illustrate the feasibility of the idea by modeling the C+Pb collisions and point out that very significant quantitative and qualitative differences between the α-clustered and uniform ^{12}C nucleus occur in quantities such as the triangular flow, its e-by-e fluctuations, or the correlations of the elliptic and triangular flows.

Proposals to study collisions with ^{16}O beams at the LHC and at RHIC are presently under serious consideration

M. Rybczyski, M. Piotrowska and W. Broniowski, Phys. Rev. C 97, no.3, 034912 (2018). P. Bozek, W. Broniowski, E. Ruiz Arriola and M. Rybczynski, Phys. Rev. C 90, no.6, 064902 (2014). Y. A. Li, S. Zhang and Y. G. Ma, Phys. Rev. C 102 (2020) no.5, 054907. S. Zhang, Y. G. Ma, J. Chen, W. He and C. Zhong, Phys. Rev. C 95, 064904 (2017). J. He, W. B. He, Y. G. Ma and S. Zhang, Phys. Rev. C 104 (2021), 044902

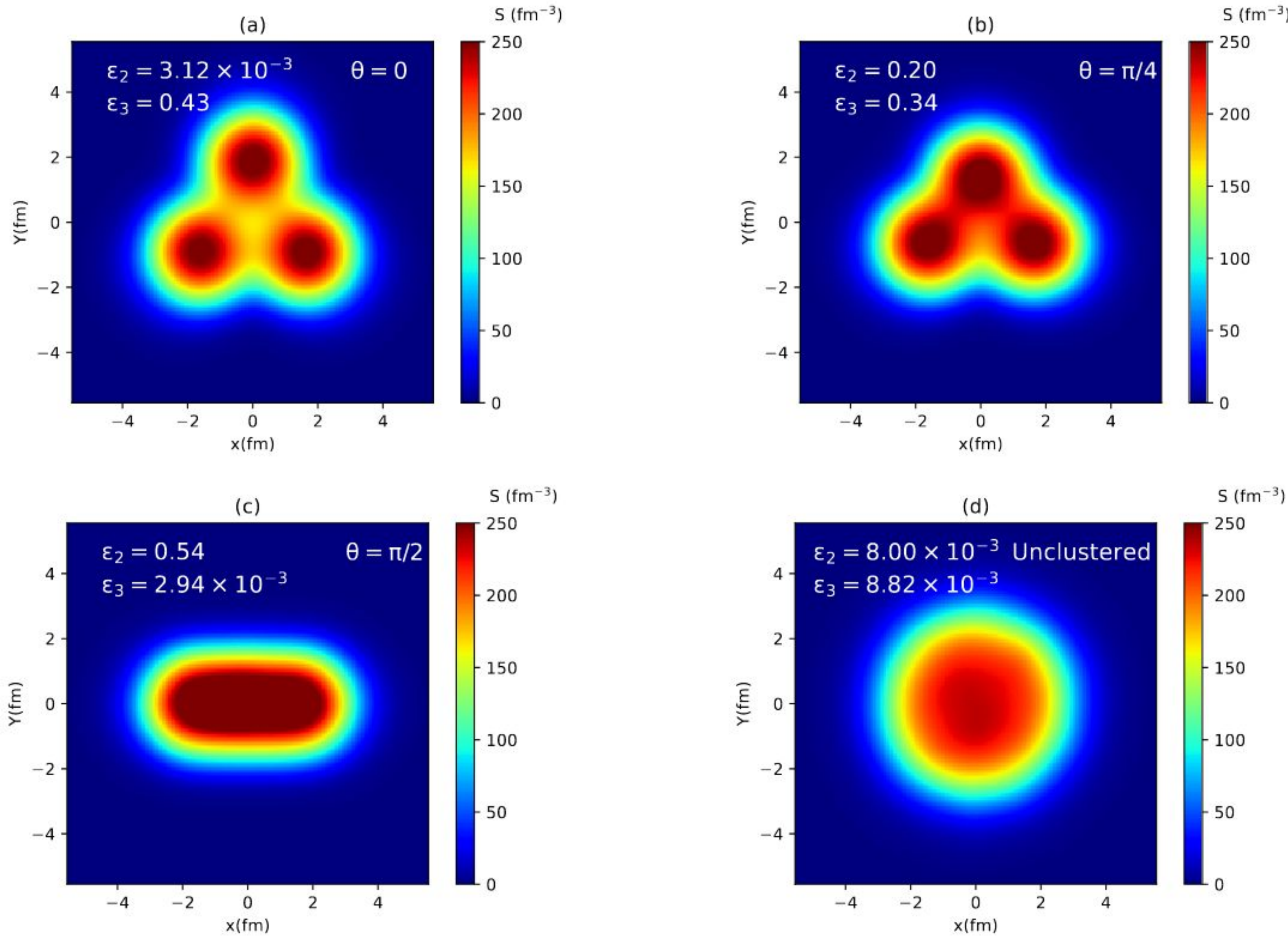
Thermal photons as a sensitive probe of α-cluster in C+Au collisions at RHIC



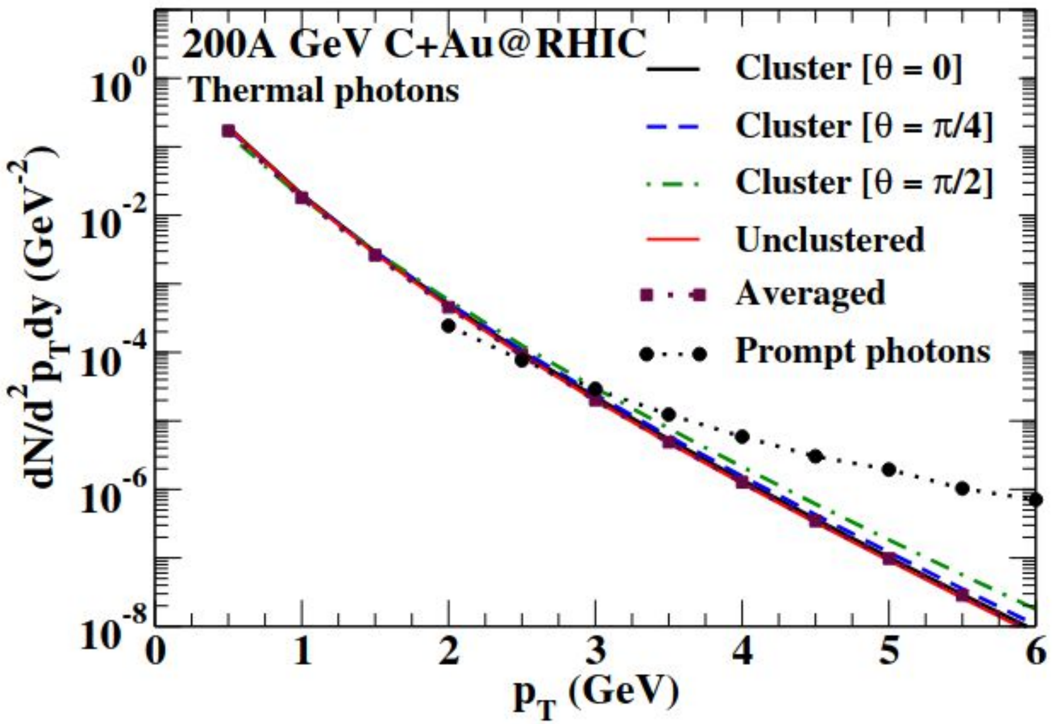
P. Dasgupta. G. Ma, RC, L. Yan, S. Zhang, Y. Ma EPJA (2021)

Different orientations of α-clustered carbon nuclei colliding with heavy nuclei can result in a large variation in the value of anisotropic flow. We focus on the most central collisions where we expect to see more geometry-dominated effects.

Distribution of entropy density at the formation time τ_0 on transverse $(x - y)$ plane

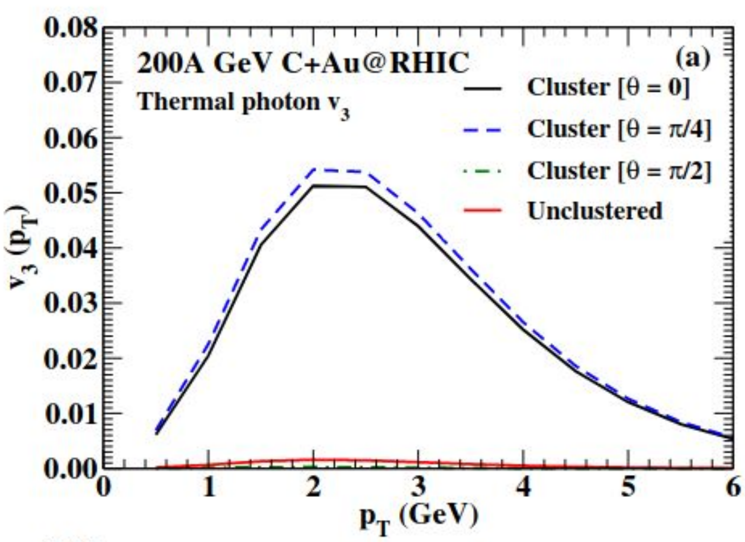


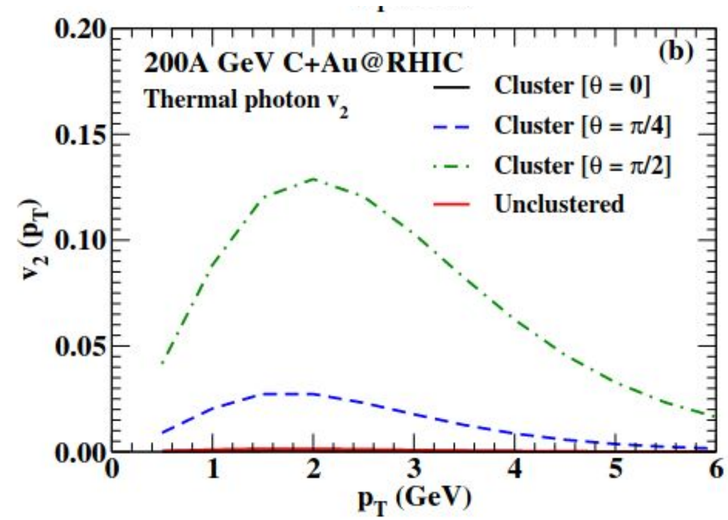
Thermal photon spectra for different configurations of clustered C and Au collisions The spectrum from the collisions of unclustered C and Au is shown for a comparison.



The spectra become slightly sensitive to the orientation angle for $p_T > 2$ GeV. The thermal spectrum for the configuration $\theta = \pi/2$ is found to be slightly above the other spectra in the larger p_T region. On the other hand, photon production from the unclustered carbon is found to be smallest.

Anisotropic flow from different orientations of clustered C+Au collisions



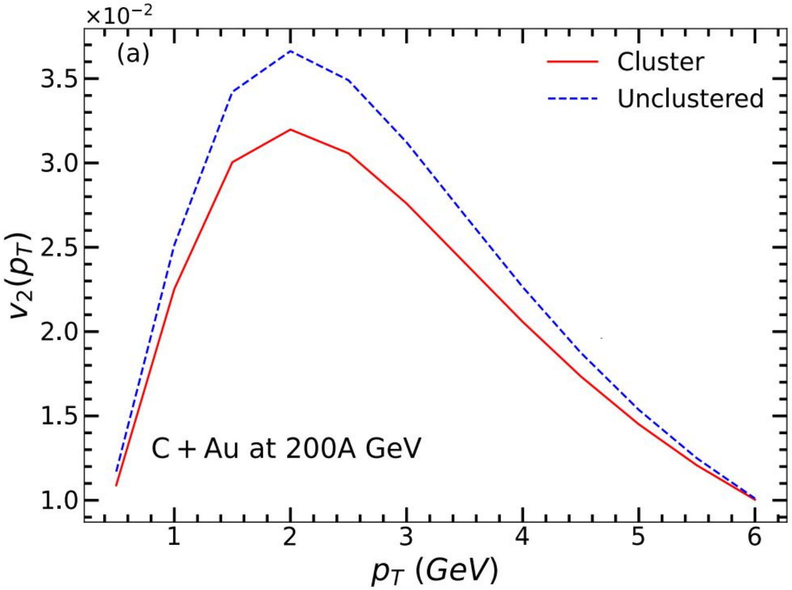


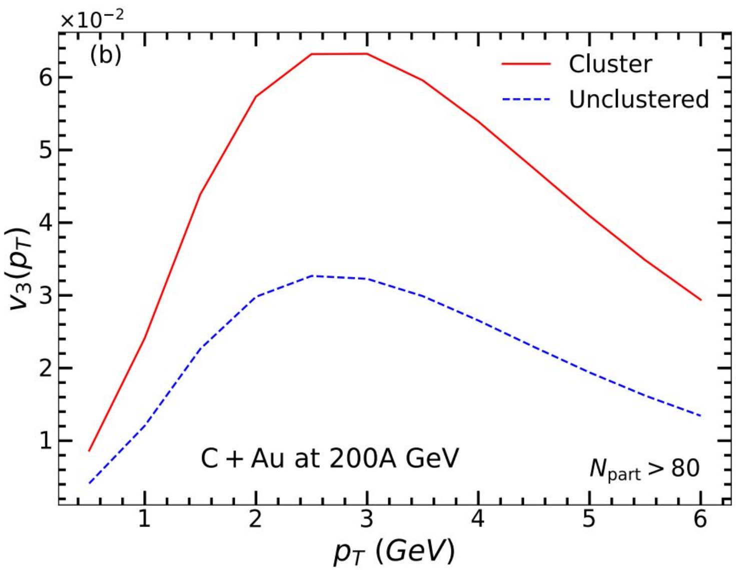
Substantially large thermal photon v_3 for the configurations θ = π/4 and θ = 0.

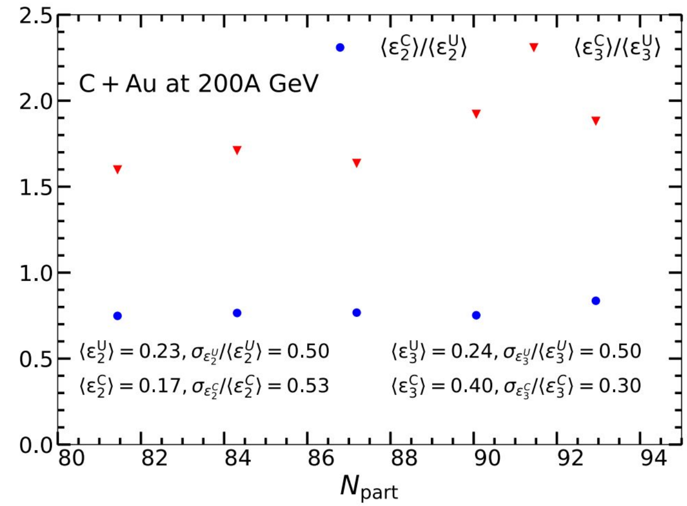
The initial triangular geometry of the entropy density profile produced in the collision of α-clustered carbon and gold nucleus gives rise to the triangular flow.

As there exists no such triangular geometry for the configuration θ = π/2 or the unclustered case, we obtain a vanishingly small thermal photon v_3.

Anisotropic flow from C+Au Collisions







The ratio of α-clustered to unclustered event-averaged initial state elliptic and triangular eccentricities as a function of N_{part} from C + Au collisions.

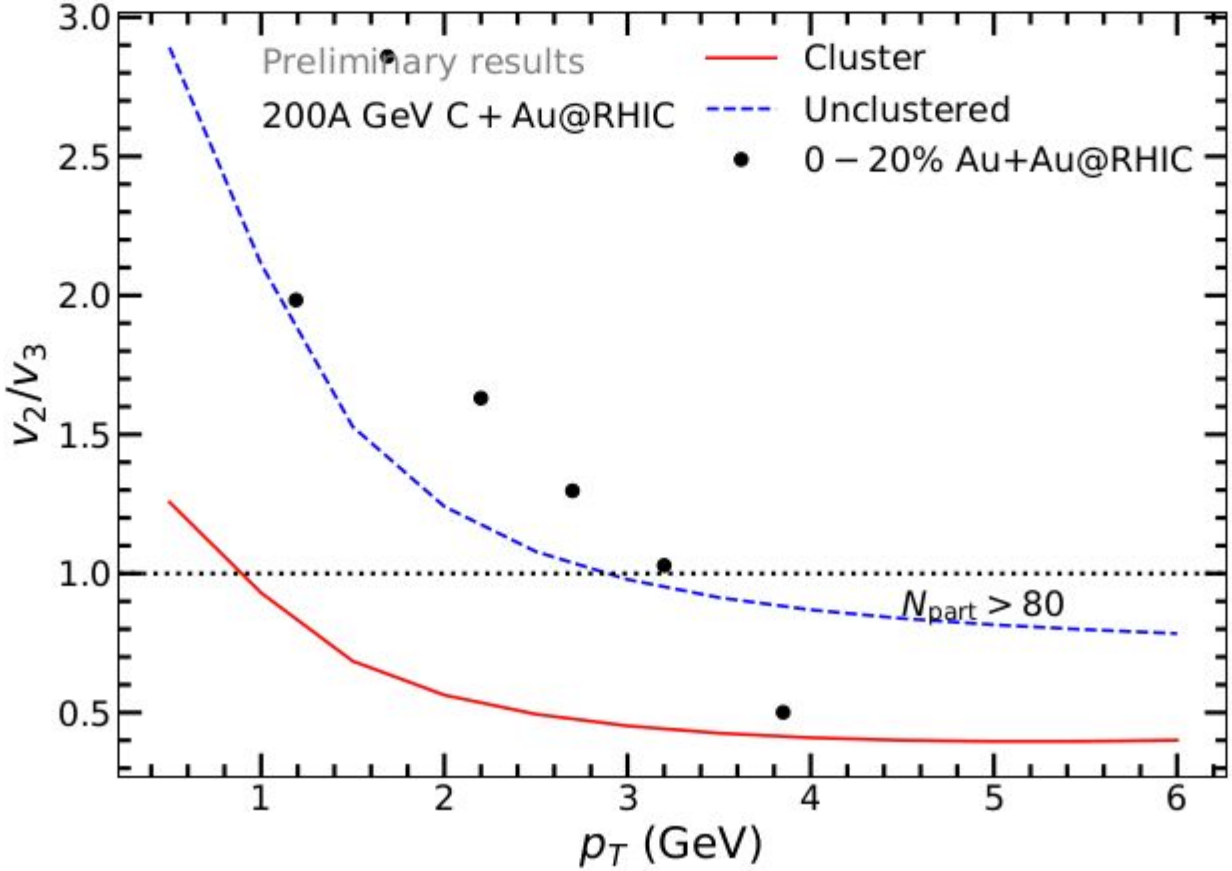
The photon v_3 for the clustered case is found to be twice as large as the same obtained for the unclustered case.
It is similar to the $v_3(p_T)$ obtained from a central collision of α-clustered carbon with Au nucleus at an angle θ = π/4

The v_2 does not show much difference for the two cases.

Photon v_3 in relativistic nuclear collisions can efficiently reflect the initial state triangular anisotropy associated with the triangular α-cluster structure in carbon nucleus

P. Dasgupta. RC, and G Ma

Phys. Rev. C 107, 044908 (2023)

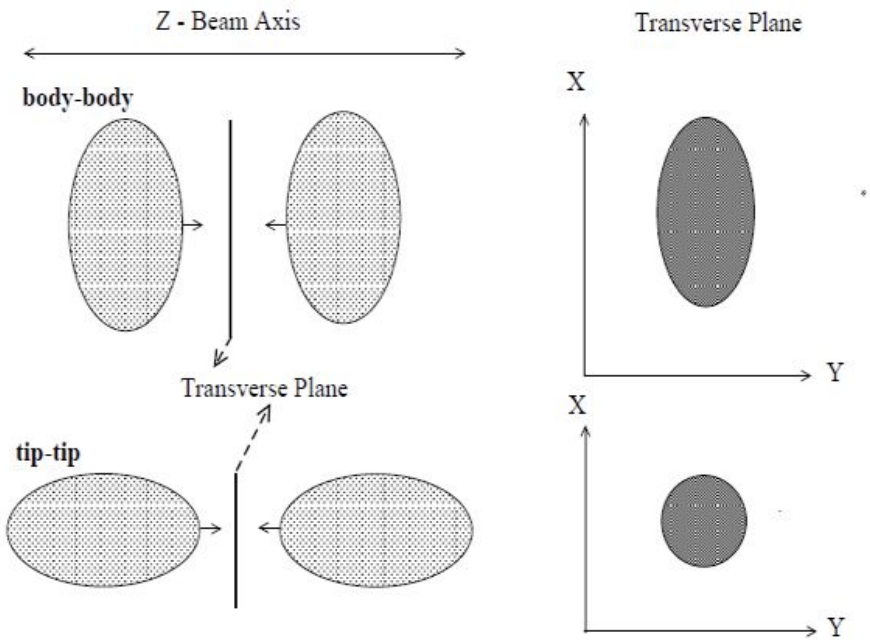


The ratio for the unclustered case, which is found to be about 2.0 at p_T ~ 1.0 GeV, and above p_T > 3 GeV the ratio gets closer to 1. However, for the clustered case, the ratio is smaller than 1 in the region p_T > 1 GeV, which in turn indicates a significantly larger thermal photon v_3 compared to the thermal photon v_2 .

P. Dasgupta. RC, and G Ma

Phys. Rev. C 107, 044908 (2023)

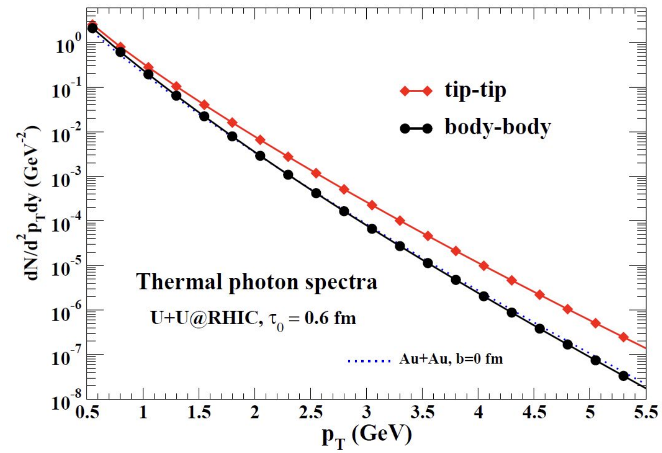
Thermal photon v_2 from full overlap U+U collisions at RHIC

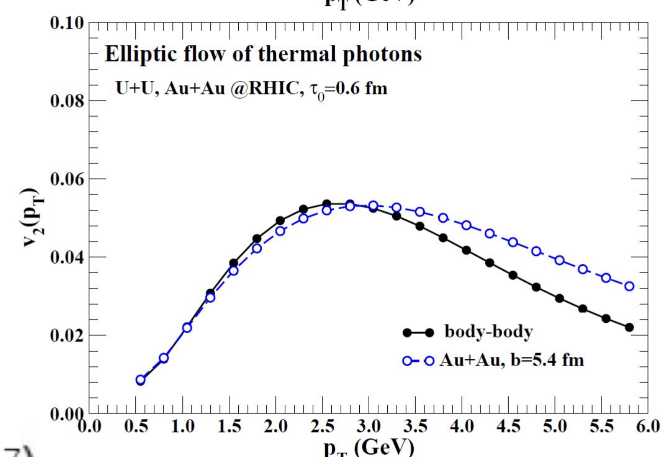


Schematic of tip-tip and body-body collisions of full overlap uranium nuclei

U+U collisions are of special interest due to the non-spherical prolate shape of the colliding nuclei.

The production of thermal photons is found to be significantly larger for tip-tip collisions compared to body-body collisions.





The elliptic flow parameter for body-body collisions is found to be large and comparable to the elliptic flow for mid-central collisions of gold nuclei. For tip-tip collisions the elliptic flow is very small.

The photon results from fully overlapping U+U collisions are complementary to the results from Au+Au collisions at RHIC.

P. Dasgupta, RC, D. K. Srivastava PRC 95, 064907 (2017)

Photon interferometry:

The quantum statistical interference between identical particles emitted in relativistic heavy ion collisions, provide valuable insight about the shape and size of the particle emitting source.
→ direct photons emitted from different stages of the collision dominate the p_T spectra depending on the range of transverse momentum.

→Thus, one can extract space time dimension of the system at different stages of the collision by measuring the correlation radii for photons at different transverse momentum.

Two particle correlation function C(q, K) for photons having momenta k_1 and k_2, emitted from a completely chaotic source can be written as,

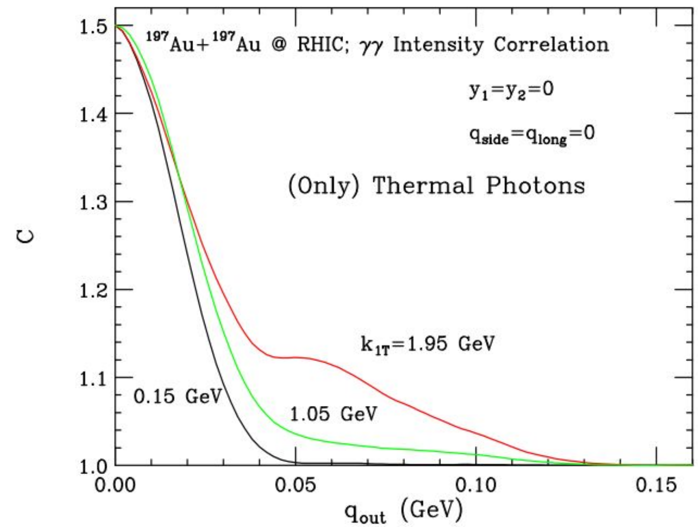
$$C(\boldsymbol{q}, \boldsymbol{K}) = 1 + \frac{1}{2} \frac{|\int d^4x S(x, \boldsymbol{K}) e^{iq.x}|^2}{\int d^4x S(x, \boldsymbol{k_1}) \int d^4x S(x, \boldsymbol{k_2})}$$

$$E \frac{dN}{d^3K} = \int d^4x S(x, \boldsymbol{K})$$

Photon Interferometry of Au+AuCollisions at the BNL Relativistic Heavy-Ion Collider

Steffen A. Bass, Berndt Müller, and Dinesh K. Srivastava

Phys. Rev. Lett. **93** 162301 (2004)



D. K. Srivastava, Phys. Rev. C 71, 034905 (2005).

Probing the evolution of heavy-ion collisions using direct photon interferometry

Oscar Garcia-Montero, Nicole Löher, Aleksas Mazeliauskas, Jürgen Berges, and Klaus Reygers

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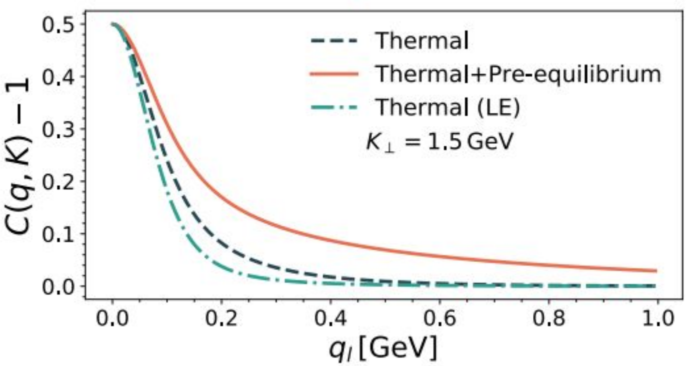
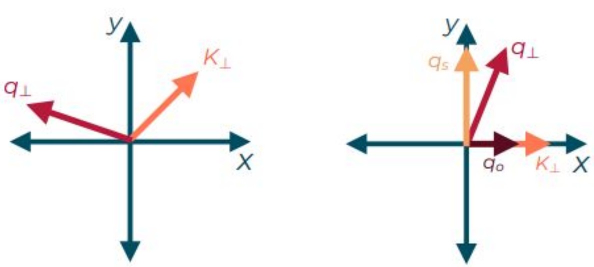
Normalized 2-particle correlator

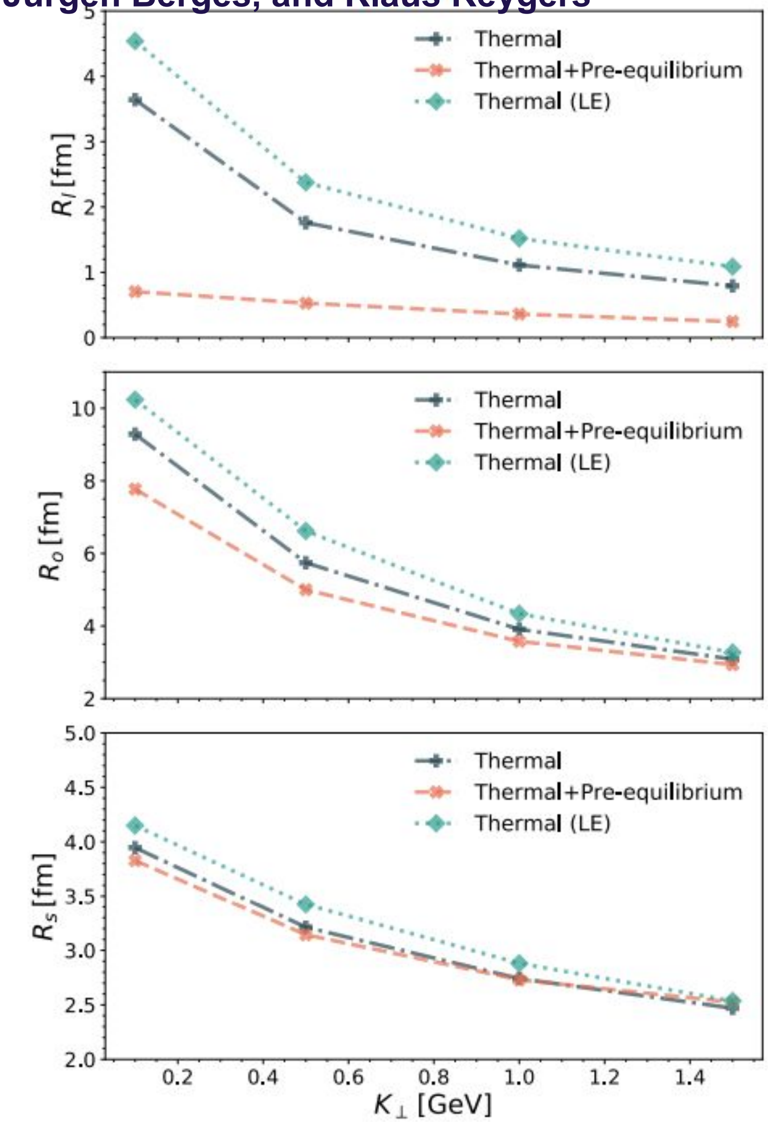


Pair variables

$$K^\mu = (K^0, K_\perp, 0, K^z)$$
$$q^\mu = (q^0, q_\mathrm{o}, q_\mathrm{s}, q_\mathrm{l}) \,,$$



Radii



Recent developments in photon production in relativistic heavy ion collisions have contributed to a deeper understanding of the properties and dynamics of the QGP

- **significant advancement in theoretical framework**
- **comparison with high precision data**

New ideas, new models and experimental access to a wide range of beam energy, systems and observables..

Future looks bright

Thank you