Production and anisotropic flow of direct photons in relativistic heavy ion collisions

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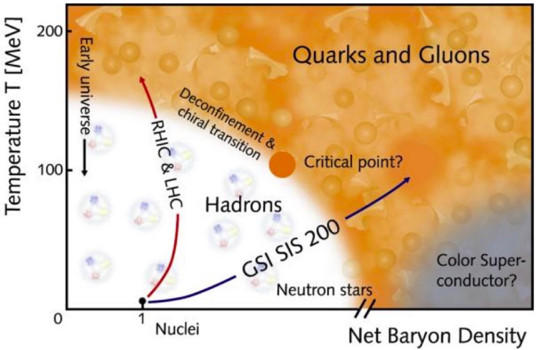
"Electromagnetic Radiation from Hot and Dense Hadronic Matter"
organized by ECT*, Trento

29^{th} November, 2018

Outline

QCD phase diagram

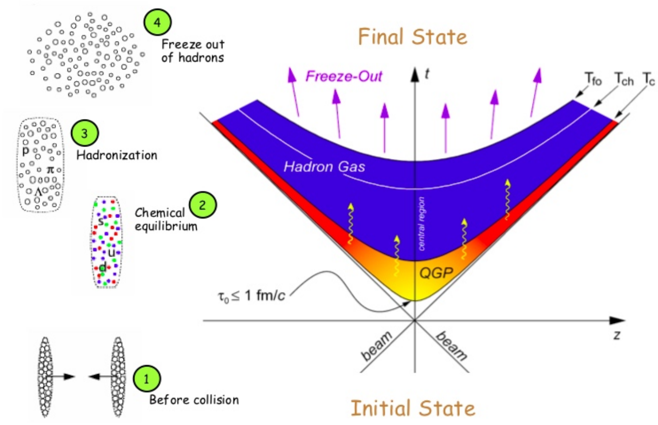


inspirehep.net

- To explore properties of matter under extreme conditions.
- Dynamical charectarization of systems produced in relativistic heavy ion collisions.

Heavy ion collision

Space-time evolution



http://inspirehep.net/record/1397855/files/fig-HIC_evolution.png

Hydrodynamics

A system with large no. of constituents can be treated as a fluid if:

$$\lambda << L$$

where, λ →mean free path of collision between the constituents and L → characteristic length scale of that system.

Postulate:
An arbitrary local state of a fluid can be expressed with $T^{\mu\nu}$ (energy-momentum tensor), J^{μ} (particle 4-flow) and S^{μ} (entropy flow) where they must satisfy the following relations :

$$\partial_\mu T^{\mu\nu}(x) = 0$$
$$\partial_\mu J_i^{\mu}(x) = 0 \ [i = 1, 2....., M]$$
$$\partial_\mu S^{\mu} \geq 0$$

Anisotropic flow

Due to hydrodynamic expansion, any initial spatial anisotropy (i.e. anisotropic distribution of energy density) in a system is converted into the momentum-space anisotropy via action of azimuthally anisotropic pressure gradient.

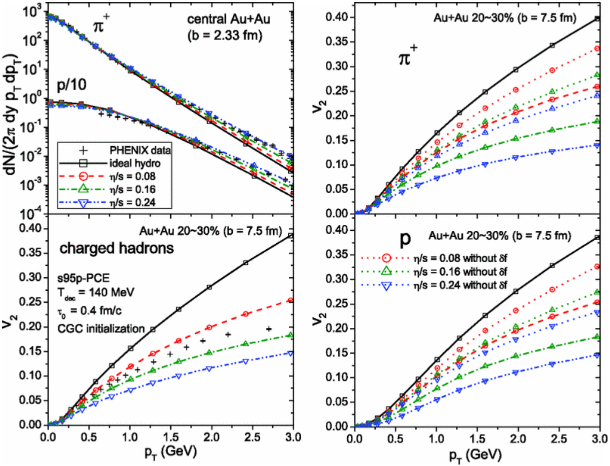
The anisotropic flow parameters are quantified by decomposing the particle distribution in Fourier expansion as :

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos(\mathrm{n}\phi)]$$

$$v_n(p_T) \;=\; \langle\cos(n\phi)\rangle \;=\; \frac{\int_0^{2\pi}\, d\phi\cos(n\phi)\,\frac{dN}{p_T dp_T dy d\phi}}{\int_0^{2\pi}\, d\phi\,\frac{dN}{p_T dp_T dy d\phi}}$$

Hadron spectra and v_2 using hydrodynamical model

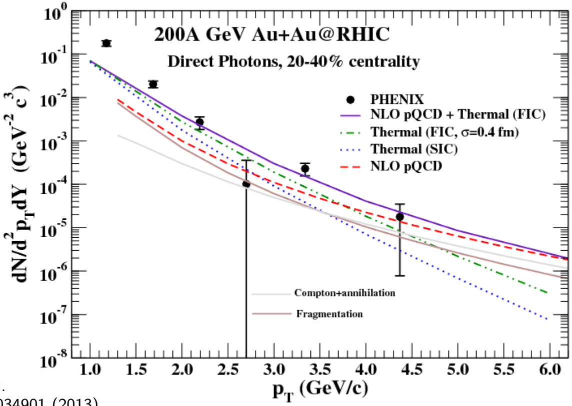
Hydrodynamical models have successfully reproduced the experimental data of particle spectra and elliptic flow.



Chun Shen *et. al.*
Phys. Rev. C 82, 054904 (2010)

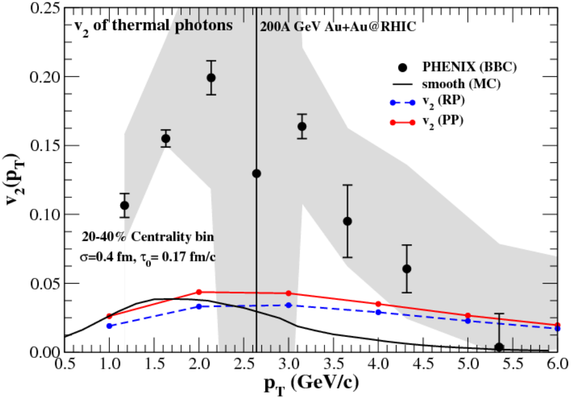
Direct photons

Direct photons = Inclusive photons − Decay photons



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

Direct photon v_2 puzzle (!!!!)



Hydrodynamical calculation under-predicts data by a large margin

Motivation

The photon flow observable v_2 depends on these following parameters :

- Initial geometry. It also depends on the description of the initial state (i.e. how we incorporate fluctuations). These two, together determine the initial-state anisotropy in a system and thus the flow anisotropy.
- Formation time.
- Intrinsic properties of the fluid (i.e. shear, bulk viscosity, ...).
- Relative contributions of non-thermal photons (i.e. prompt photons, ...).

We have systematically studied photon production and flow parameters (v_1, v_2 and v_3) for different colliding nuclei (symmetric, asymmetric and deformed) and for different collision energies (RHIC,LHC and FCC) and we try to understand the "direct photon puzzle" from these results.

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. Schroder, 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:

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

Results

A. Directed Flow Anisotropy

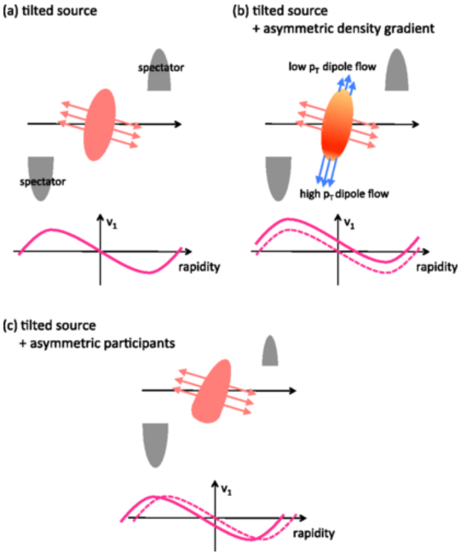
Directed flow

L. Adamczyk et al. (STAR Collaboration)

Phys. Rev. C **98**, 014915

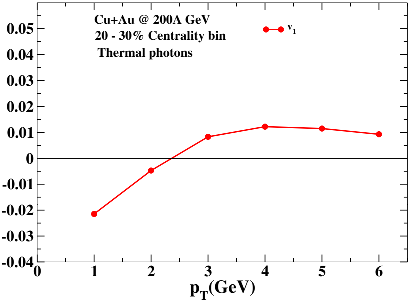
Sources of the directed flow can be the following :

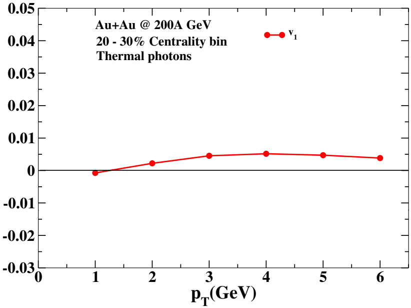
- Tilted source gives rise to rapidity odd v_1.
- Dipole like asymmetry due to initial state fluctuations gives rise to rapidity even v_1.
- Collision of asymmetric source can also produce v_1 due to change in rapidity of the "fireball" center-of-mass.



v_1 from Cu+Au and Au+Au collisions @200A GeV

PD, R. Chatterjee and D.K.Srivastava
(In preparation)

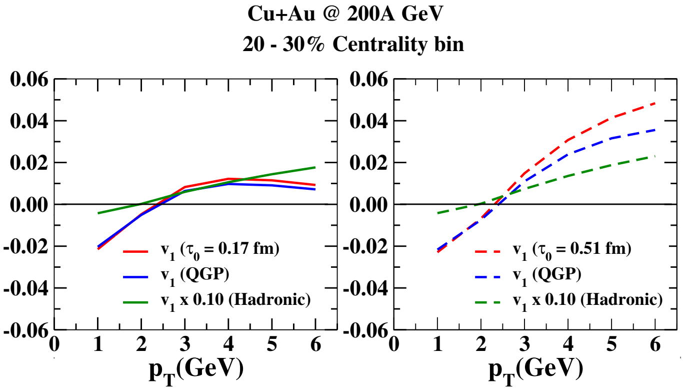




- We find v_1 to be significant for asymmetric nucleus-nucleus collision whereas, it is rather small for symmetric nucleus-nucleus collisions.

[Note : This v_1 is rapidity even contribution, measured with respect to the event plane. This carries signature of dipole-like asymmetry in the transverse plane only (No rapidity asymmetric initial energy deposition is considered yet)].

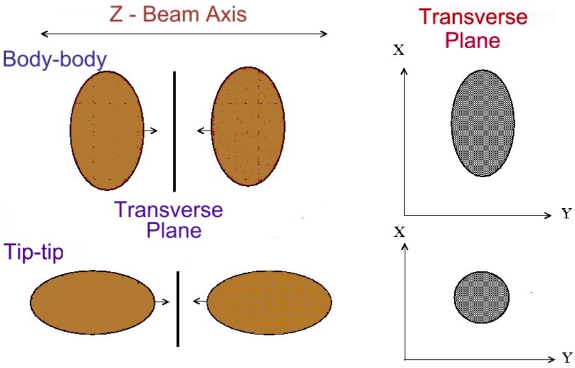
Different formation time



- v_1 is found to be more sensitive to the QGP contribution than hadronic contribution.

B. Elliptic Flow Anisotropy

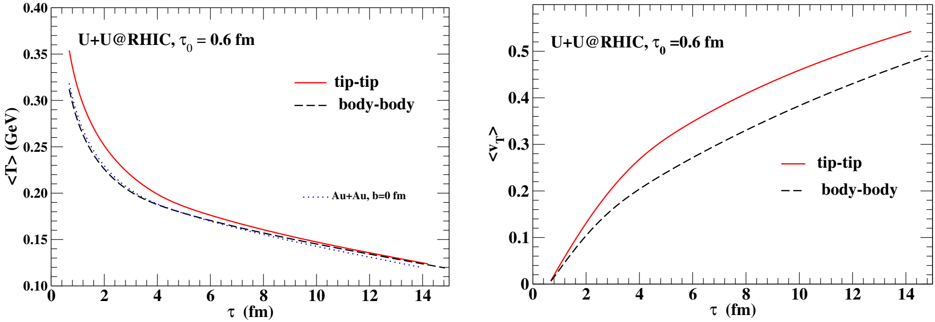
Deformed initial geometry from full overlap U+U collisions



PD, R. Chatterjee and D.K. Srivastava
Phys. Rev. C 95, 064907 (2017)

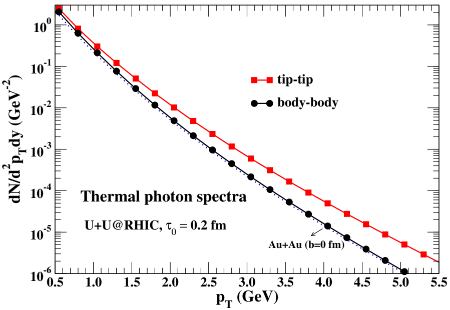
- Different orientations of collisions can introduce different anisotropy in the initial state.
- We consider two extreme cases of multiplicities of full overlap U+U collisions.

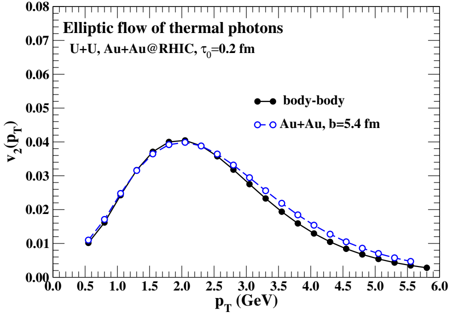
Evolution of hydrodynamic parameters



- The initial temperature for the tip-tip collisions is almost 40 MeV larger than for the body-body collisions.
- We see much faster expansion for the tip-tip collisions compared to the body-body collisions.

Thermal photon spectra and v_2





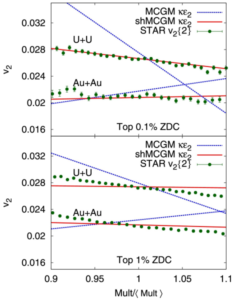
- Thermal photon spectra from body-body collisions is very similar to the photon spectra from central Au+Au collisions.
- We observe a large thermal photon v_2 for the body-body collisions. It is comparable to the v_2 of photons from the mid-central Au+Au collisions.
- These observations are independent of formation time and the choice of hardness factor in "Glauber model" initial condition.

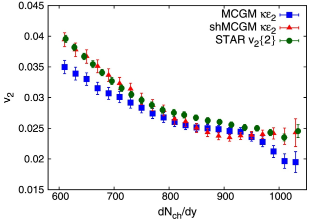
Nucleon shadowing in Glauber model initial condition

"all the participants and binary collisions should not be treated equally - the contribution to energy deposition by nucleons seated deep inside the nucleus should be shadowed by those leading in front"

S. Chatterjee et al.
Physics Letters B **758**, 269–273(2016)

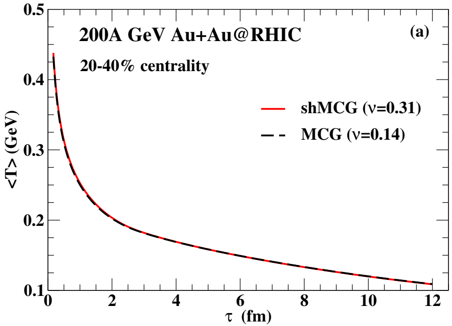
Success of shadowed Glauber model initial condition

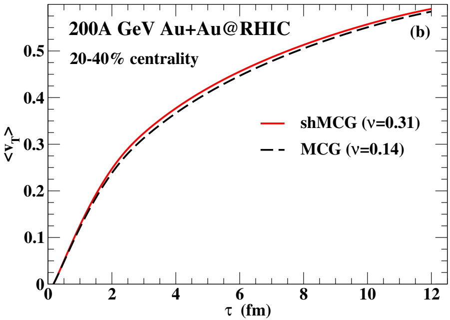




- The Shadowed Monte Carlo Glauber Model (ShMCG) has successfully explained the correct anti-correlation between dN_{ch}/dy and v_2 for full overlap U+U collisions.
- Eccentricity distributions for mid central Au+Au and U+U collisions has been predicted successfully with ShMCG.

Effects on the hydrodynamic parameters

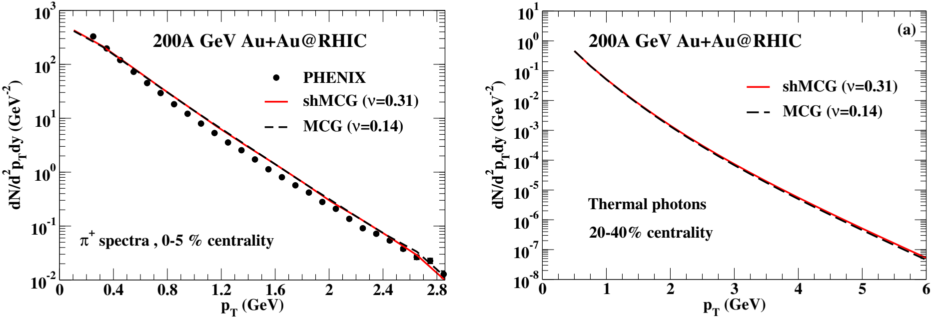




- Evolution of average temperature $\langle T \rangle$ and transverse flow velocity $\langle v_T \rangle$ for MCG and shMCG are almost similar. However, we see slightly faster expansion for the case of shMCG.

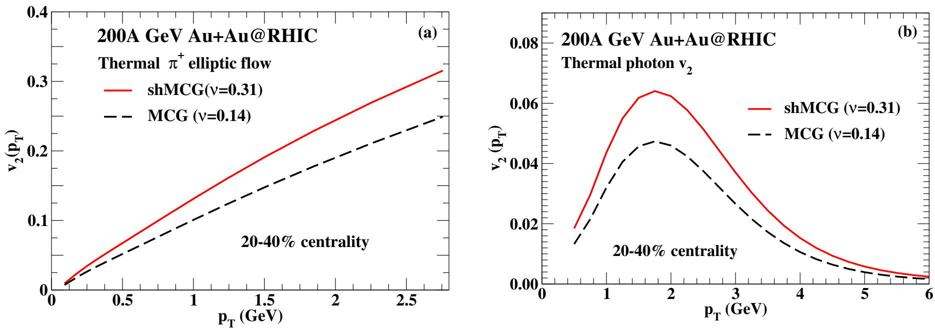
PD, S. K. Singh, R Chatterjee and J. Alam
Phys. Rev. C 97, 034902 (2018)

Effects on the hadronic and thermal photon spectra



- We see the pion spectra as well as the thermal photon spectra for both MCG and shMCG are quite similar.

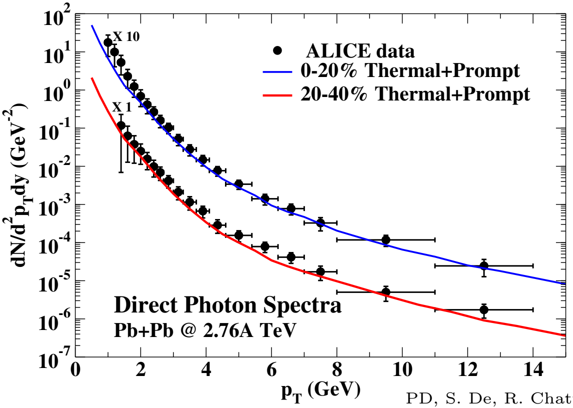
Effects on the hadronic and thermal photon v_2



- Effect of initial state nucleon shadowing is more prominent on the photon flow observable compared to the hadronic flow observable.
- We observe similar behavior of the thermal photon and hadronic flow observable at the LHC energy as well.

Direct photon production at increasing energies of collisions

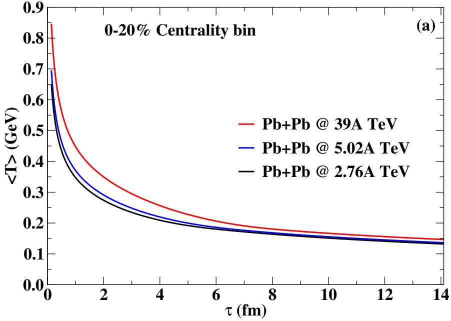
Direct photon spectra from Pb+Pb@2.76A TeV

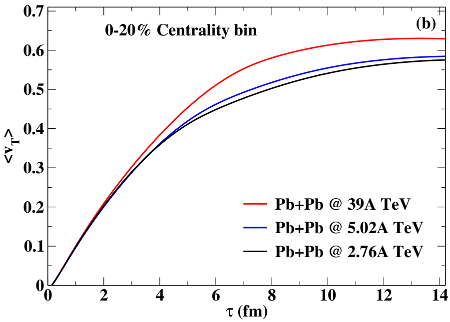


PD, S. De, R. Chatterjee and D.K. Srivastava
Phys. Rev. C 98, 024911 (2018)

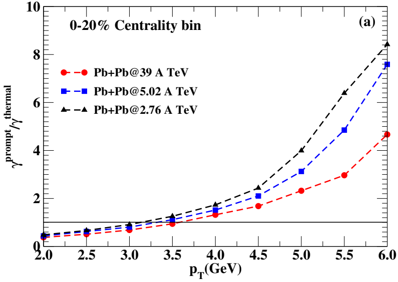
Future Circular Collider

Future Circular Collider is a future facility for heavy ion collision with $\sqrt{s_{NN}}$ = 39A TeV for Pb+Pb. Presently, topmost energy for Pb+Pb collision available at LHC is now, 5.02A TeV.

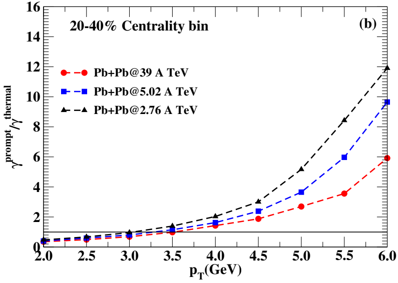


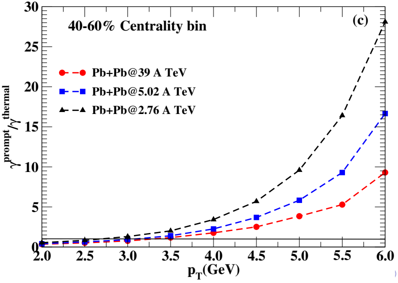


Prompt to thermal ratio

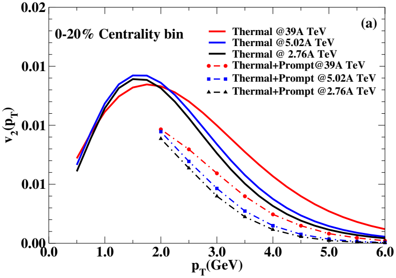


- Thermal photon production at FCC is dominating contribution over the prompt production up to a larger p_T.
- Relative contribution from the QGP phase is higher at higher energies.

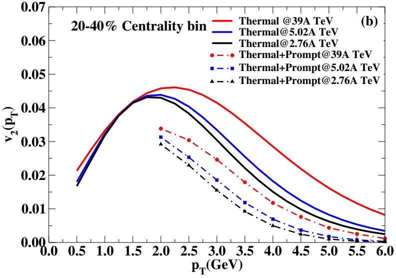


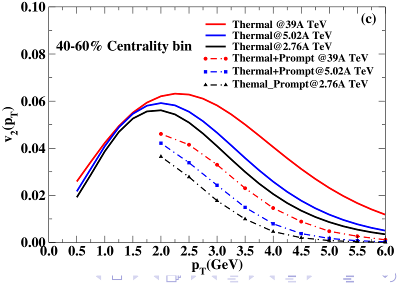


v_2 from LHC to FCC



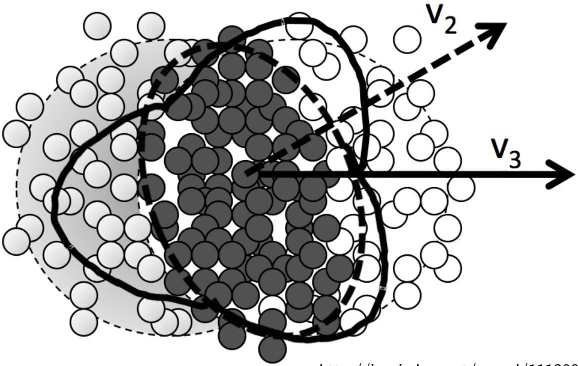
- Direct photon v_2 with increasing energy doesn't change much for all centralities.
- Simultaneous description of spectra and v_2 would constraint the theory.





C. Triangular Flow Anisotropy

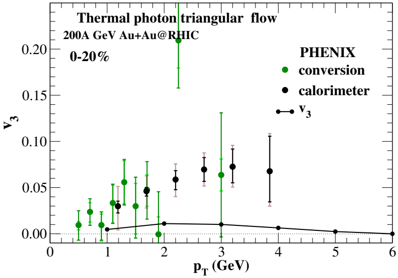
Triangular flow



http://inspirehep.net/record/1112008/files/fig_v3.png

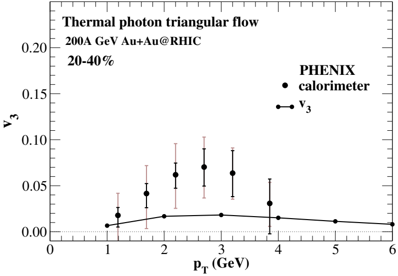
- Unlike ϵ_2 (eccentricity) which can appear both due to 'collision geometry' and initial-state fluctuations, ϵ_3 (triangularity) appears due to only initial-state fluctuations.
- Triangular anisotropy in the initial state gives rise to triangular anisotropy in momentum space (v_3).

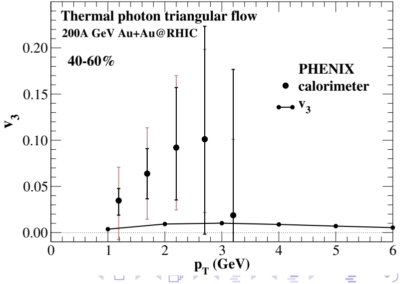
Thermal photon v_3 from Au+Au@200A GeV at RHIC



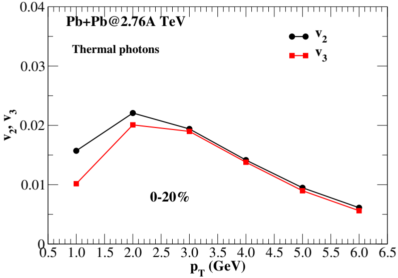
- Thermal photon v_3 does not show any strong centrality dependence.
- Data points are much above the theoretical predictions.

R. Chatterjee, PD and D.K. Srivastava
Phys. Rev. C 96, 014911 (2017)

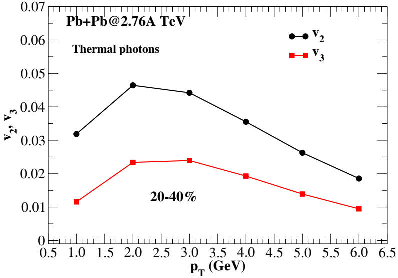


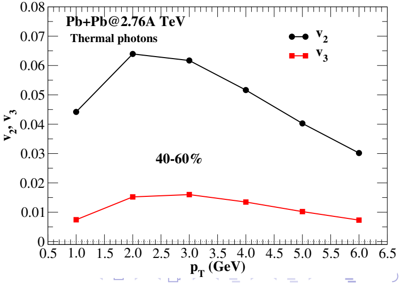


Thermal photon v_3 from Pb+Pb@2.76A TeV at LHC

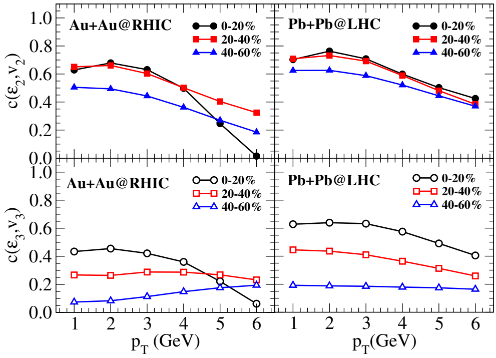


- We see similar centrality dependence of thermal photon v_3 at the LHC as well.
- Thermal photon v_3 at LHC is slightly larger than the thermal photon v_3 at RHIC.



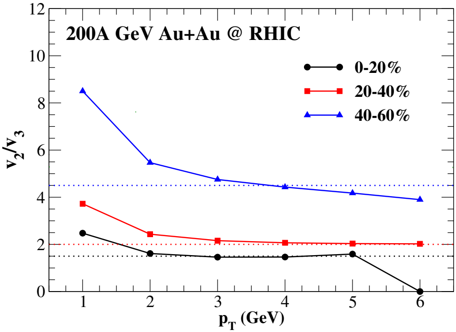


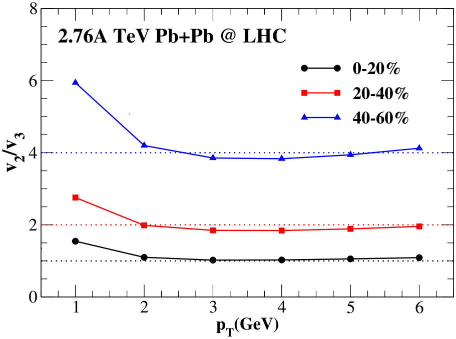
Correlation between initial anisotropies and flow observables



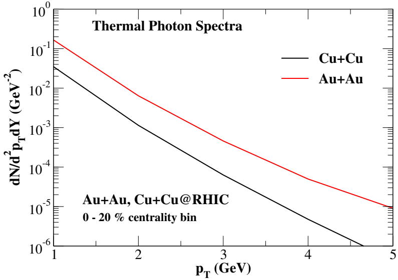
- With higher centralities fluctuations tend to increase however correlation strength tends to decrease. Therefore flow plays an important role.
- v_2 is more strongly correlated to the initial state eccentricity than v_3 to initial state triangularity.

Ratio of elliptic and triangular flow parameters

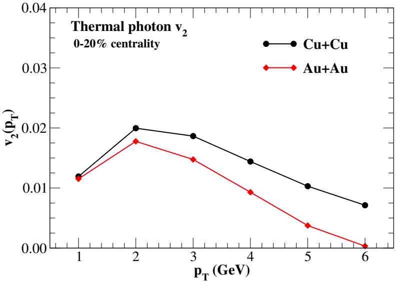


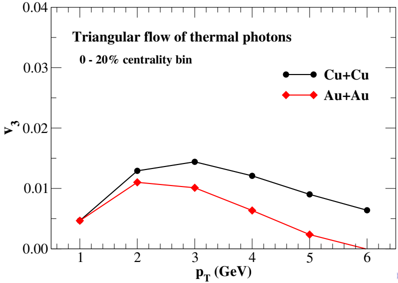


Cu+Cu collisions@200A GeV



- Thermal photon spectra for Cu+Cu collisions is much smaller compared to the Au+Au collisions.
- v_2 and v_3 from Cu+Cu collisions are found to be larger compared to those from Au+Au collisions.





Summary & conclusion

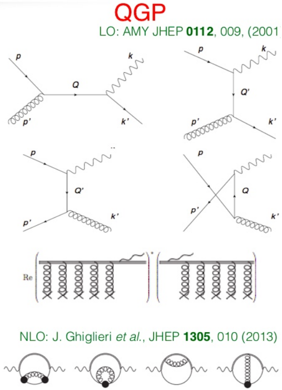
- We observe significant amount of directed flow for the collision of two asymmetric nuclei. In order to study the directed flow of thermal photons extensively, we need to use 3+1 e-by-e hydro for asymmetric collision systems.
- Uranium-Uranium study might play a significant role in understanding the v_2 puzzle.
- We see a small correction to the initial state can affect thermal photon v_2 by a significant amount. We observe effects on the thermal photon v_2 is larger compared to the hadronic v_2.
- A simultaneous description of the direct photon spectra and their elliptic flow at increasing energies of heavy ion collision will put a strong constraints on the theoretical description.
- Thermal photon v_3 doesn't show any strong centrality dependence. Data are much bigger than the theoretical prediction.

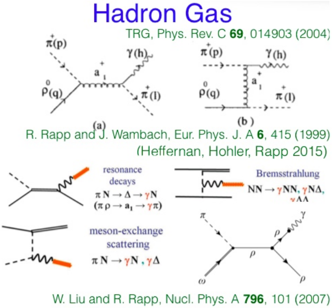
Acknowledgments

I sincerely thank my supervisor Prof. Dinesh K. Srivastava and Dr. Rupa Chatterjee for their continuous support, enthusiasm and discussions. I also thank Prof. Jane Alam, Sushant K. Singh and Dr. Somnath De for their contributions and enormous support. We acknowledge VECC computing facility.

Thank You

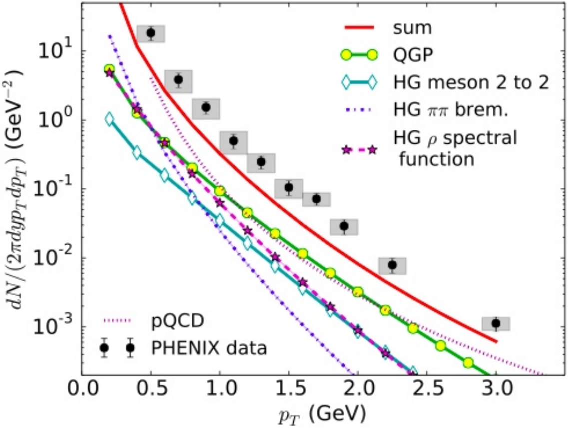
Thermal emission processes





https://meetings.aps.org/Meeting/APR17/Content/3244

Thermal emission processes



Prompt photons

Prompt photons are the dominant source of direct photons in the high p_T region ($p_T \geq 4$ GeV). The leading production channels of prompt photons are

- Quark-gluon Compton scattering ($q\ (\bar{q}) + \mathrm{g} \longrightarrow q\ (\bar{q}) + \gamma$)
- Quark-anti-quark annihilation ($q + \bar{q} \longrightarrow \mathrm{g} + \gamma$)
- Bremsstrahlung emission from final state partons ($q(\bar{q}) \longrightarrow q(\bar{q}) + \gamma$)

Differential cross section of prompt photon production

The prompt photon production cross section in elementary hadron-hadron (A+B) collisions can be expressed as:

$$\frac{d^2\sigma^\gamma}{d^2p_T dy} = \sum_{i,j} \int dx_1 f_A^i(x_1, Q_f^2) \int dx_2 f_B^j(x_2, Q_f^2)$$
$$\times \sum_{c=\gamma,q,g} \int \frac{dz}{z^2} \frac{d\sigma_{ij\to cX}(x_1, x_2; Q_R^2)}{d^2p_T^c dy_c} D_{c/\gamma}(z, Q_F^2)$$

The fragmentation function ($D_{c/\gamma}$) reduces to $\delta(1-z)$ when a photon is emitted in the direct process i.e., $c=\gamma$. The term $\sigma_{ij\to cX}$ signifies the hard parton-parton cross-section for all the relevant processes in which a photon is produced either directly or fragmented off the final state partons (q or g).

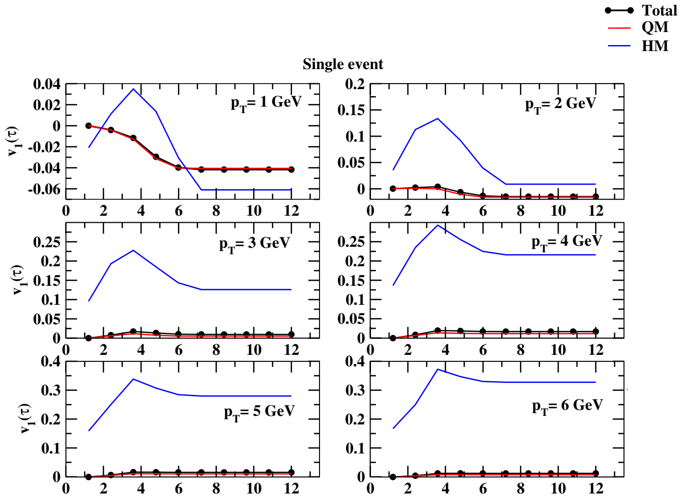
For the nucleus-nucleus (A+A) collisions we replace the elementary nucleon PDF by the isospin averaged nuclear PDF:

$$f_A^i(x, Q^2) = R_A(x, Q^2)\left[\frac{Z}{A} f_p^i(x, Q^2) + \frac{A-Z}{A} f_n^i(x, Q^2)\right], \qquad (1)$$

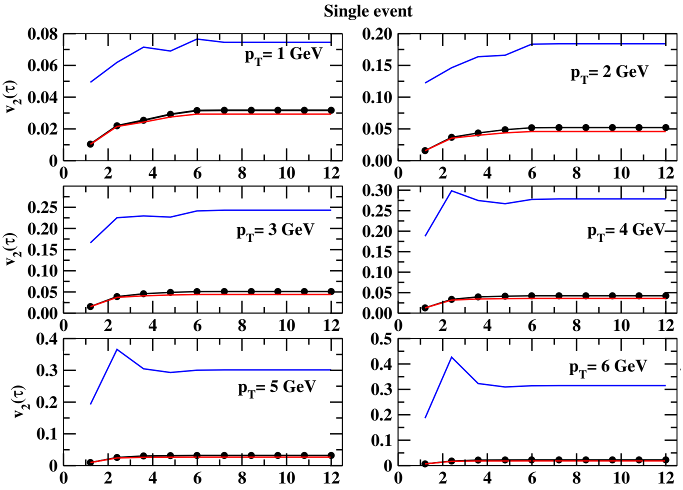
where, $R_A(x, Q^2)$ is the nuclear modification to the PDF and f_p^i, f_n^i are the free proton and neutron PDFs respectively. We have used EPS09 parameterization of nuclear shadowing function in this study.

We use Monte Carlo code JETPHOX (version 1.2.2) to calculate prompt photon spectra in the rapidity range $|y| \leq 0.5$ where, parton distribution functions are taken from CTEQ6.6 and photon fragmentation functions taken from BFG-II.

v_1 vs. τ


Total
QM
HM
Single event
p_T= 1 GeV
p_T= 2 GeV
p_T= 3 GeV
p_T= 4 GeV
p_T= 5 GeV
p_T= 6 GeV
$v_1(\tau)$

v_2 vs. τ



Single event
$v_2(\tau)$
p_T= 1 GeV
p_T= 2 GeV
p_T= 3 GeV
p_T= 4 GeV
p_T= 5 GeV
p_T= 6 GeV
0.08
0.06
0.04
0.02
0
0.20
0.15
0.10
0.05
0.00
0.25
0.30
0.4
0.3
0.2
0.1
0.5
2
4
6
8
10
12

Generation of flow anisotropy in time