Thermal photon v_3 from event-by-event fluctuating initial conditions

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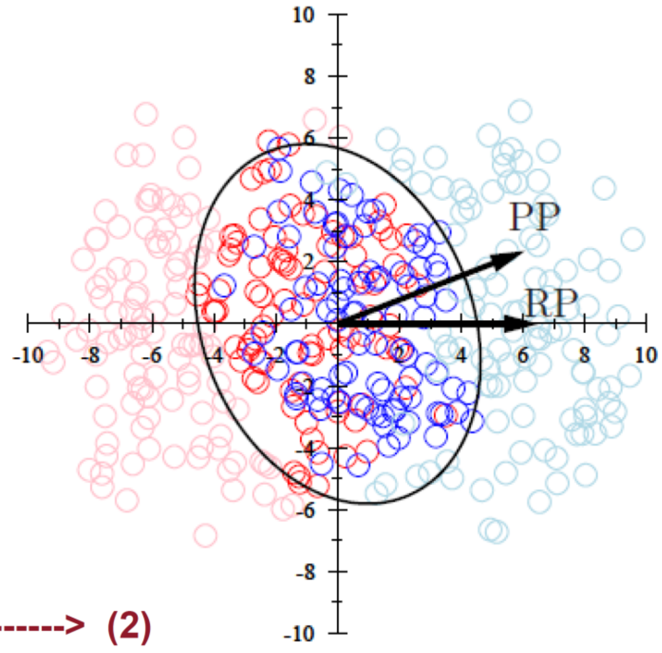
Event-by-event hydrodynamics and initial density profile

- 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

$$(x_i - x_j)^2 + (y_i - y_j)^2 \le \frac{\sigma_{NN}}{\pi}$$ -------> (1)

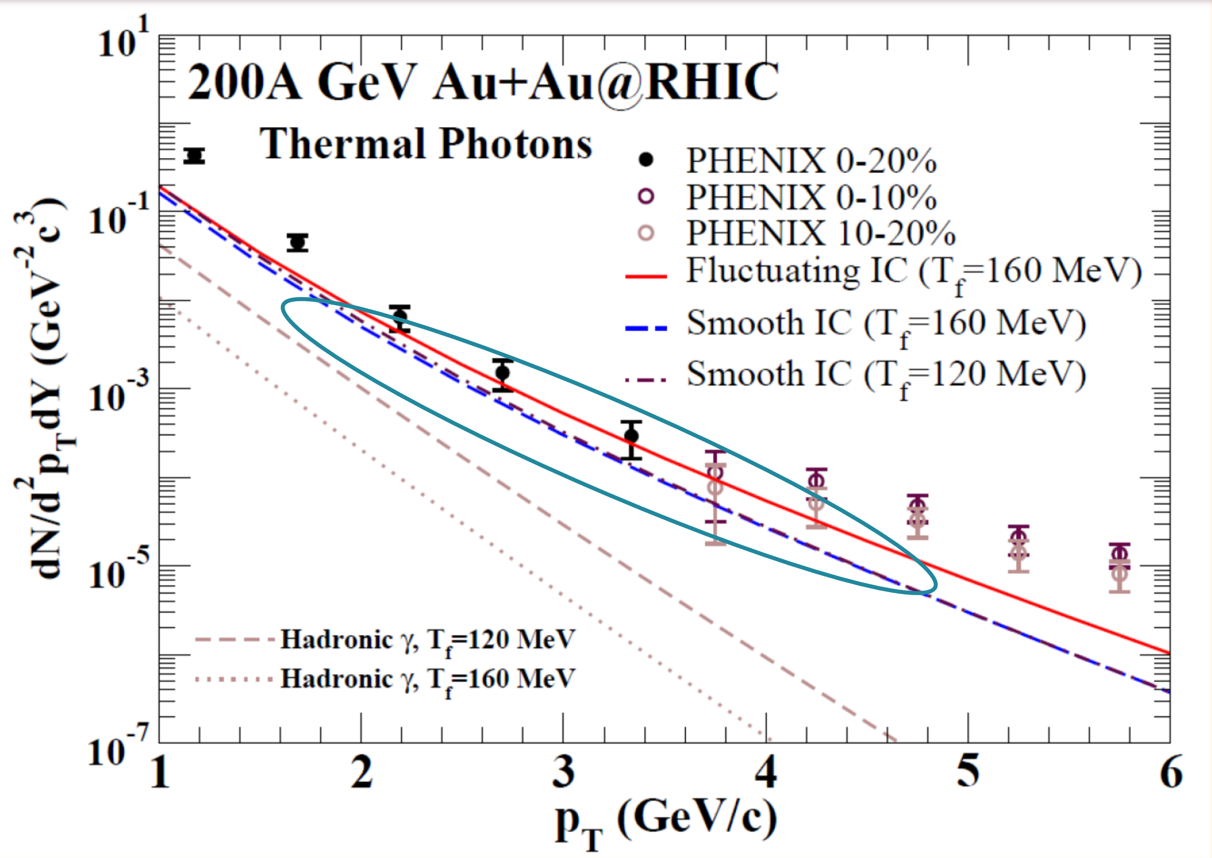


- Entropy density s is distributed in the (x,y) plane around the wounded nucleons using a 2D Gaussian:

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

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

Thermal photons from smooth and fluctuating initial density profiles

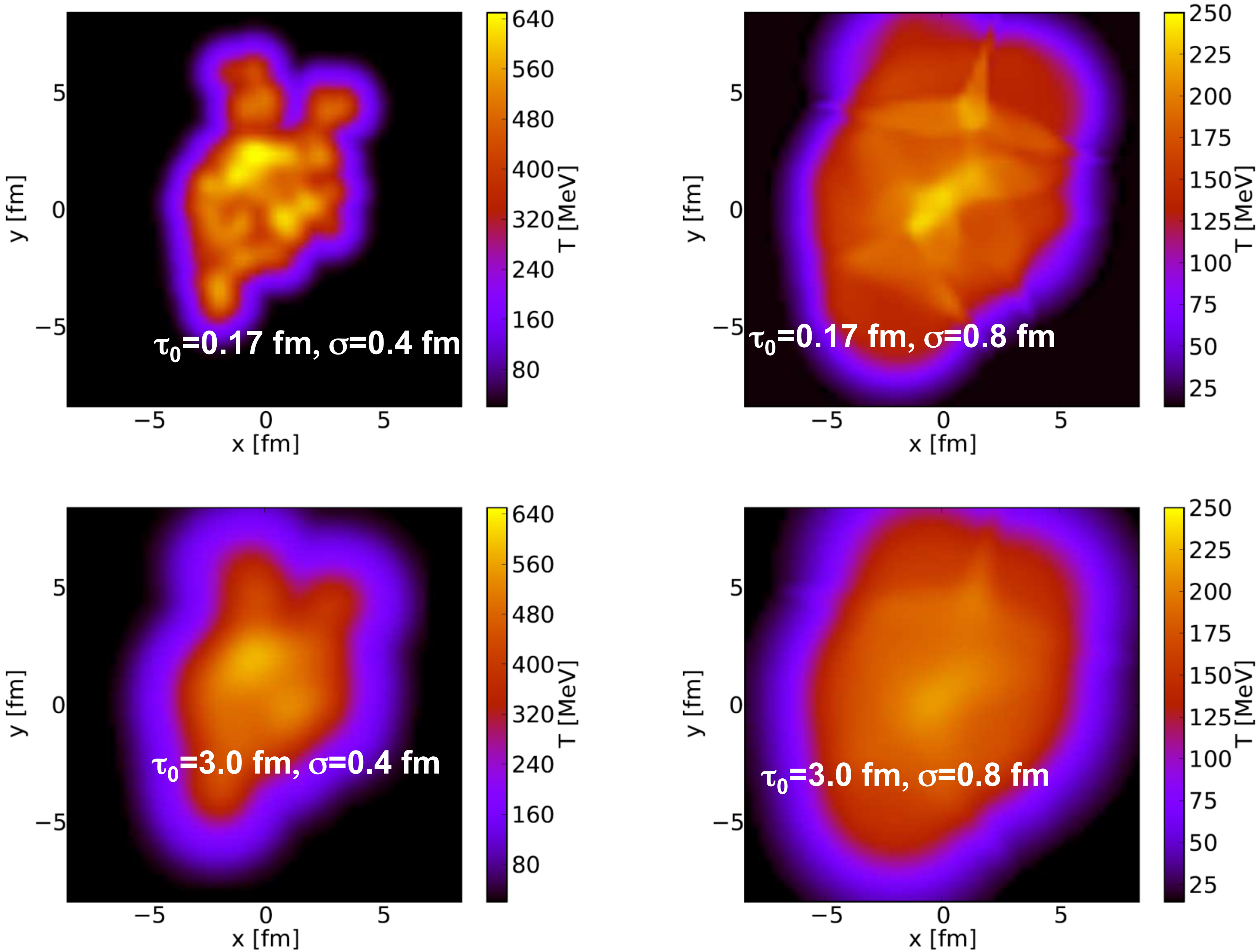


τ_0=0.17 fm/c
σ=0.4 fm

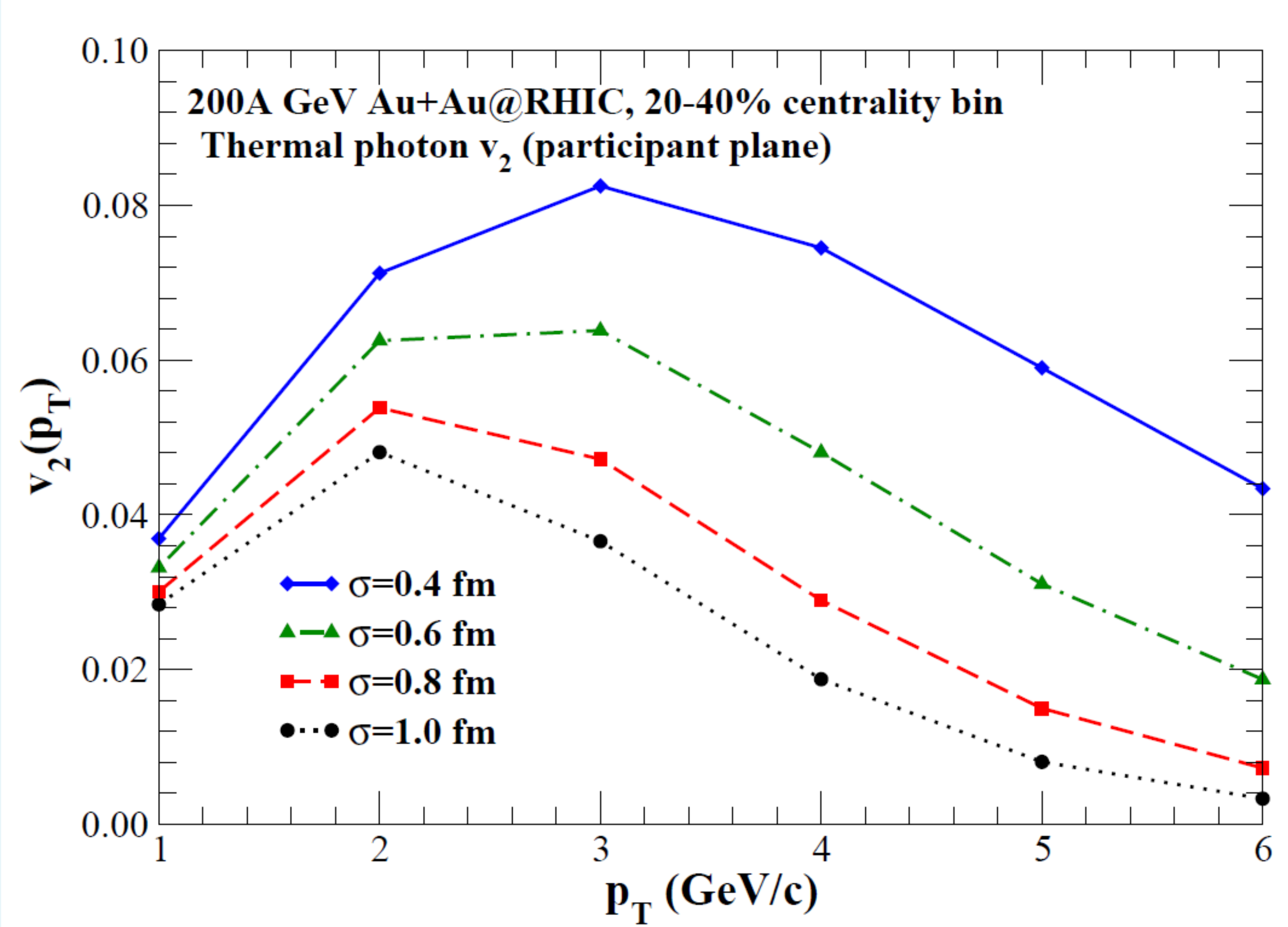
RC, Holopainen, Renk, Eskola
Phys. Rev. C 83, 054908 (2011)

- The hotspots in the fluctuating events produce more high p_T photons compared to the smooth profile.
- Note: Hardening of hadron spectra from fluctuating IC is due to different reason.

RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).



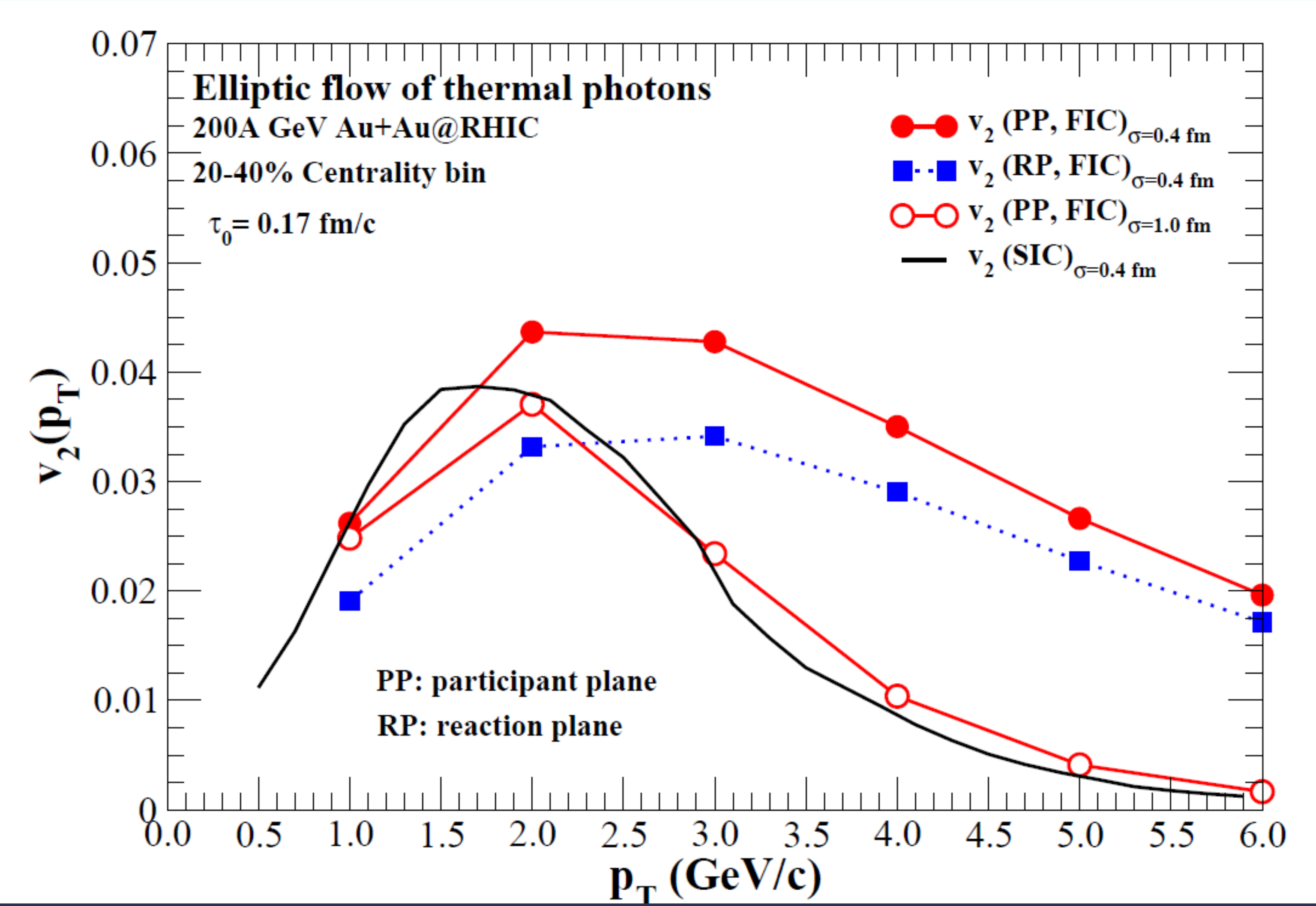
Distributions of temperature in the transverse plane for 200A GeV Au+Au collisions at RHIC.



Elliptic flow of thermal photons for same event with different σ values.

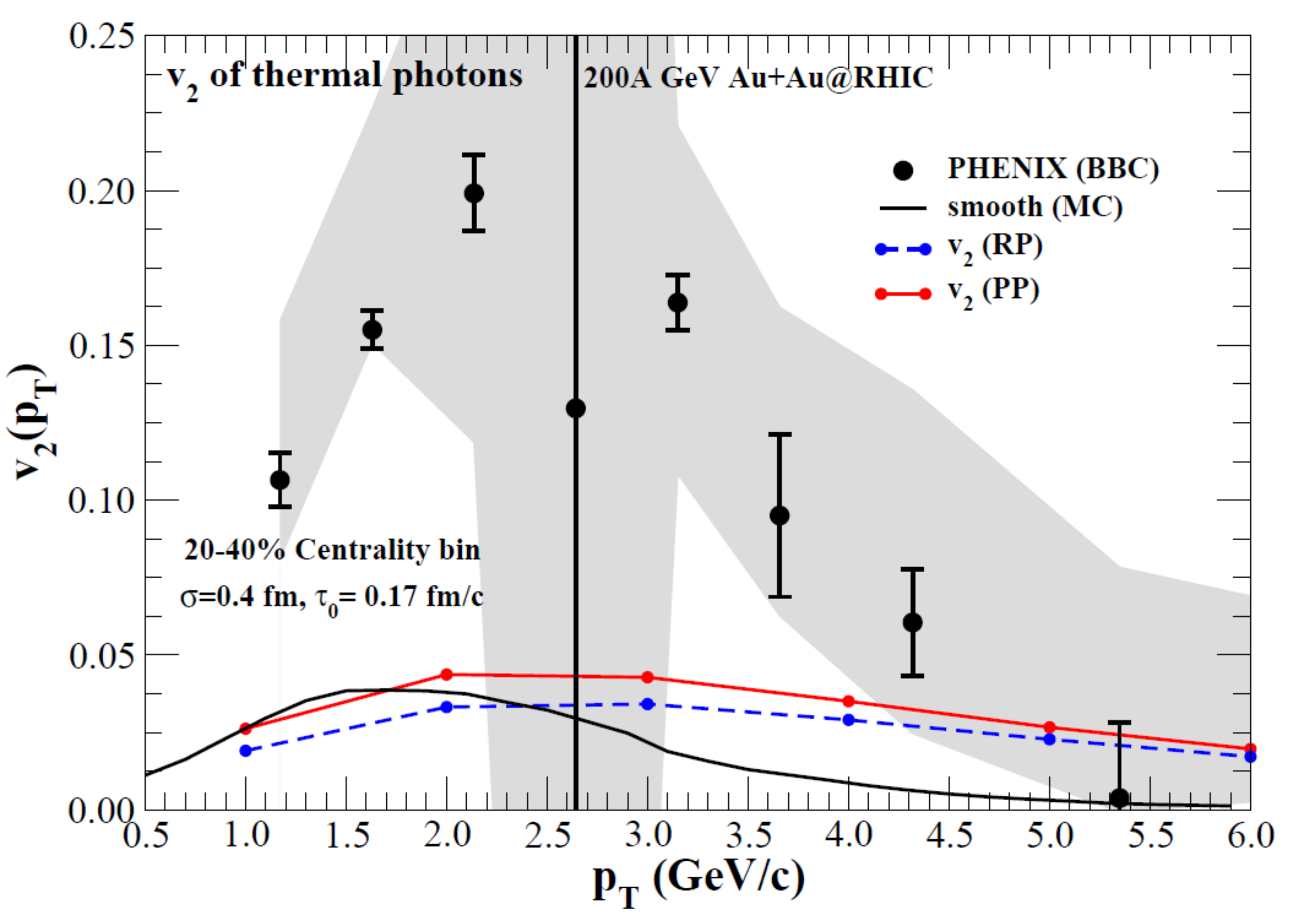
RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).

Elliptic flow of thermal photons from 200A GeV Au+Au collisions at RHIC



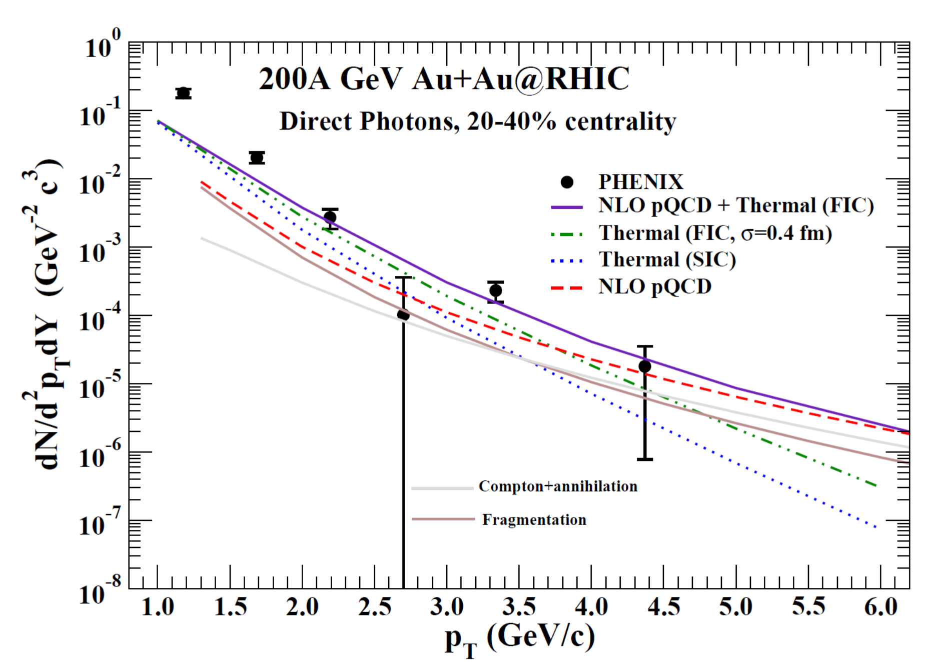
E-by-e calculation gives significantly larger v_2 for $p_T > 2.5$ GeV/c. At $p_T = 4$ GeV/c, the v_2(RP) is about 3 times larger than the result from smooth IC and the difference increases for larger values of p_T . v_2(PP) is even larger than v_2(RP).

RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).



Elliptic flow of thermal photons from 200A GeV Au+Au collisions at RHIC using fluctuating initial conditions and PHENIX direct photon data

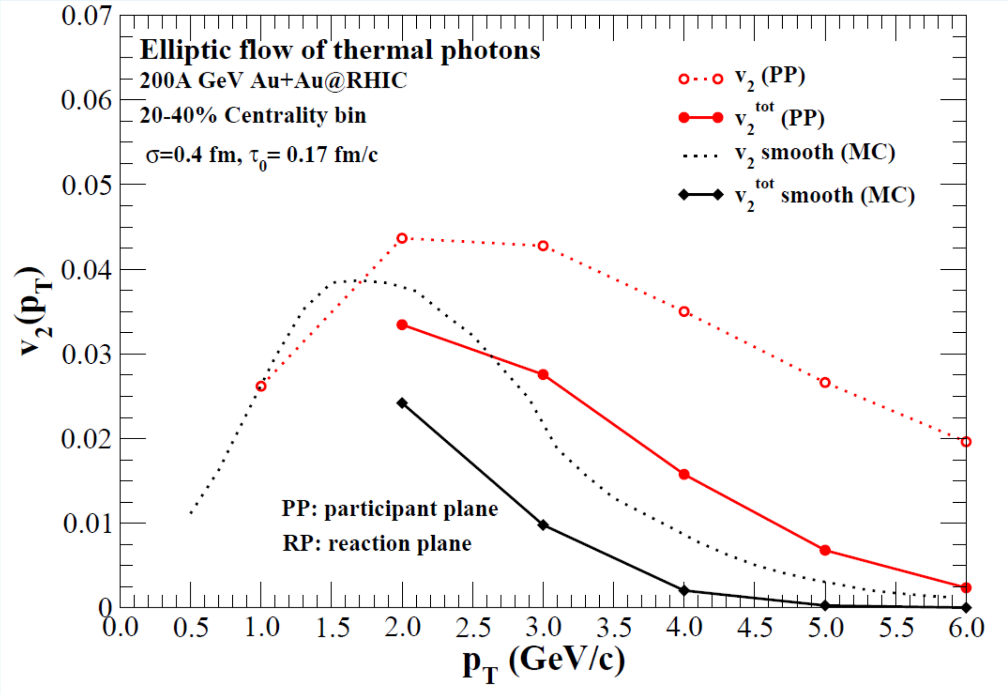
RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).



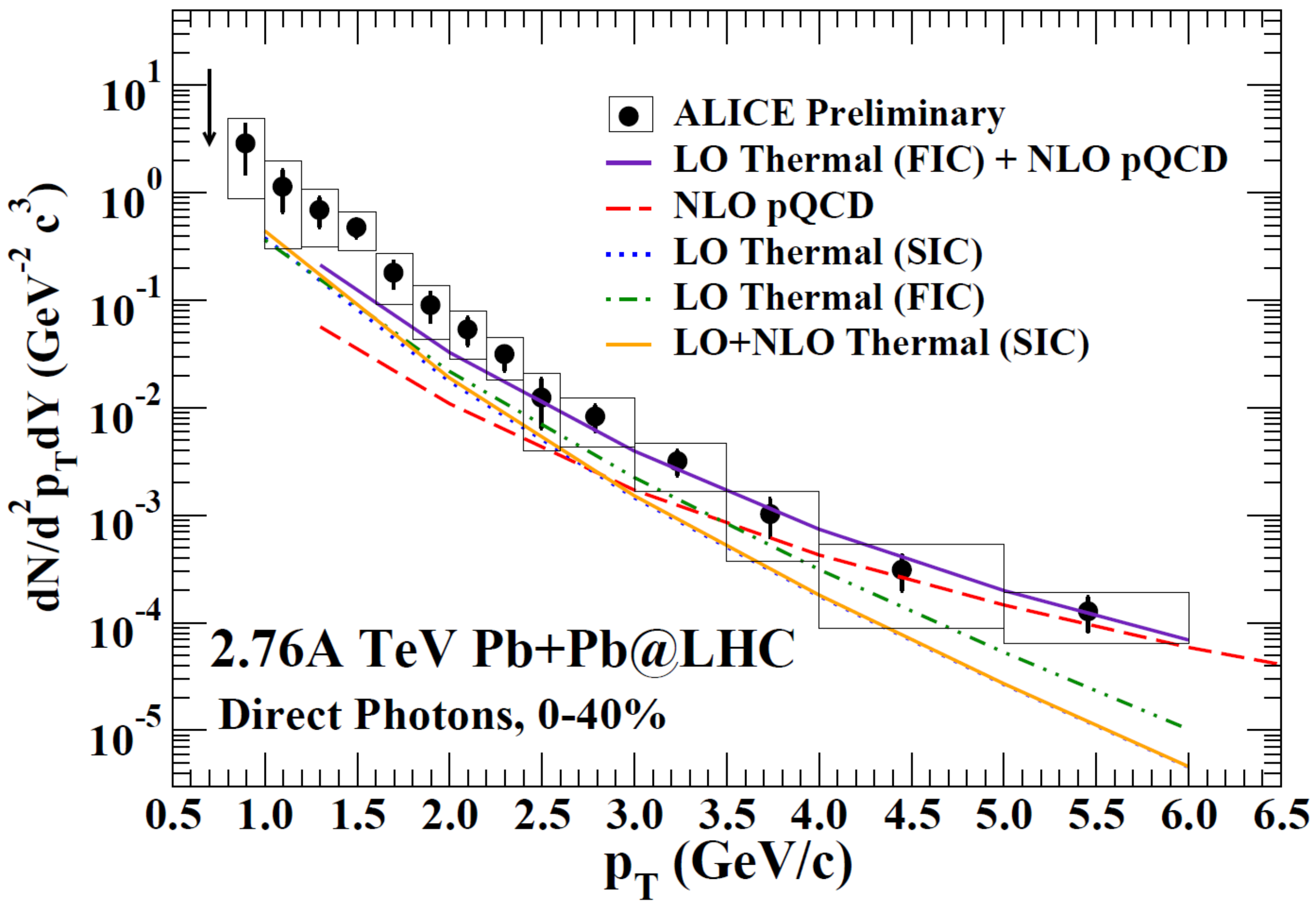
$$v_2 = \frac{v_2^{\rm th}.\,dN^{\rm th} + v_2^{\rm pr}.\,dN^{\rm pr}}{dN^{\rm th} + dN^{\rm pr}} = \frac{v_2^{\rm th}.\,dN^{\rm th}}{dN^{\rm th} + dN^{\rm pr}}$$

Direct photon spectra for 200A GeV Au+Au collisions at RHIC and for 20–40% centrality bin along with prompt and thermal (FIC and SIC) contributions.

v_2 with and without the prompt photon contribution for smooth and fluctuating IC.

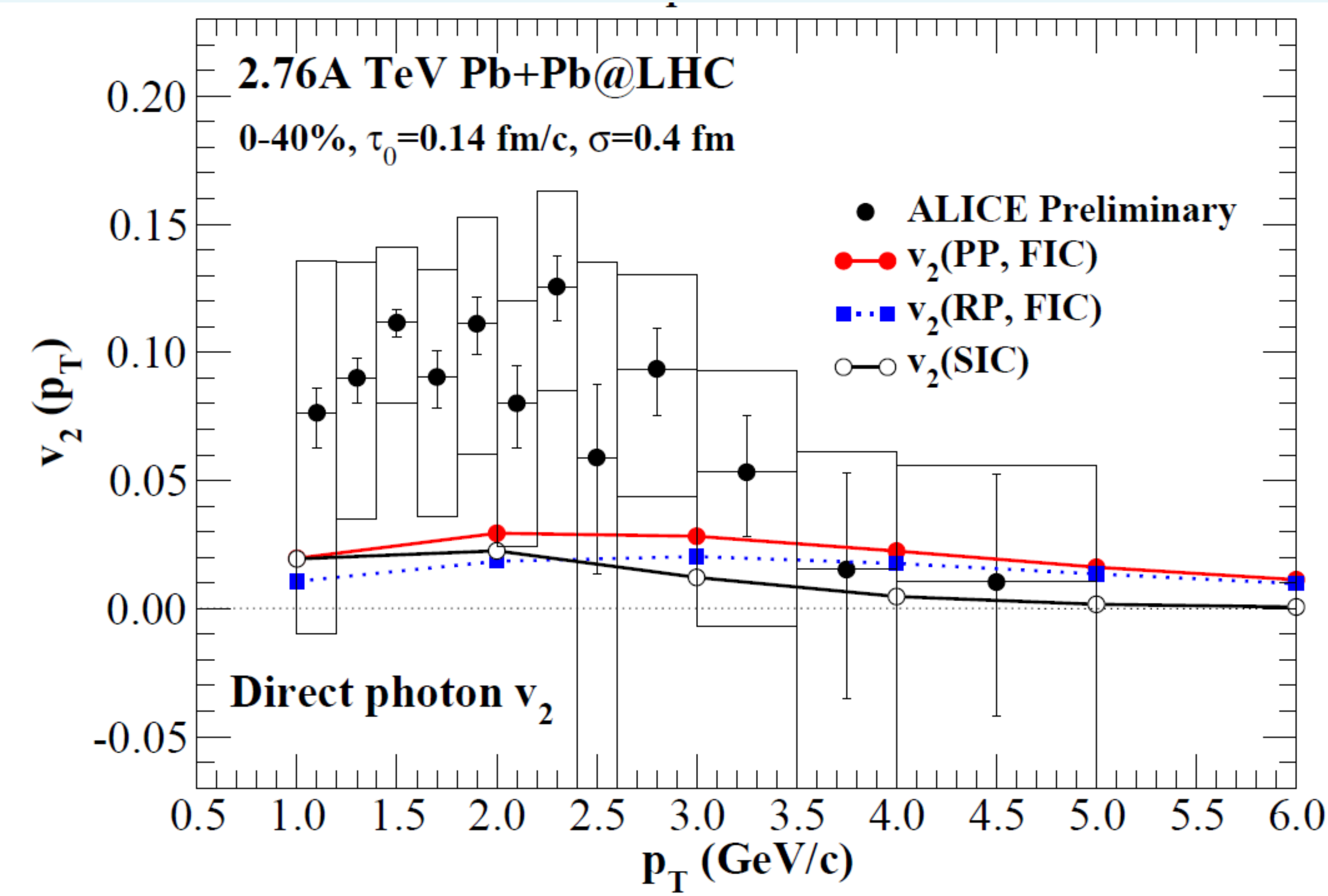


RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).



Thermal photon p_T spectra for 2.76A TeV Pb+Pb collisions at LHC for 0–40% centrality bin.

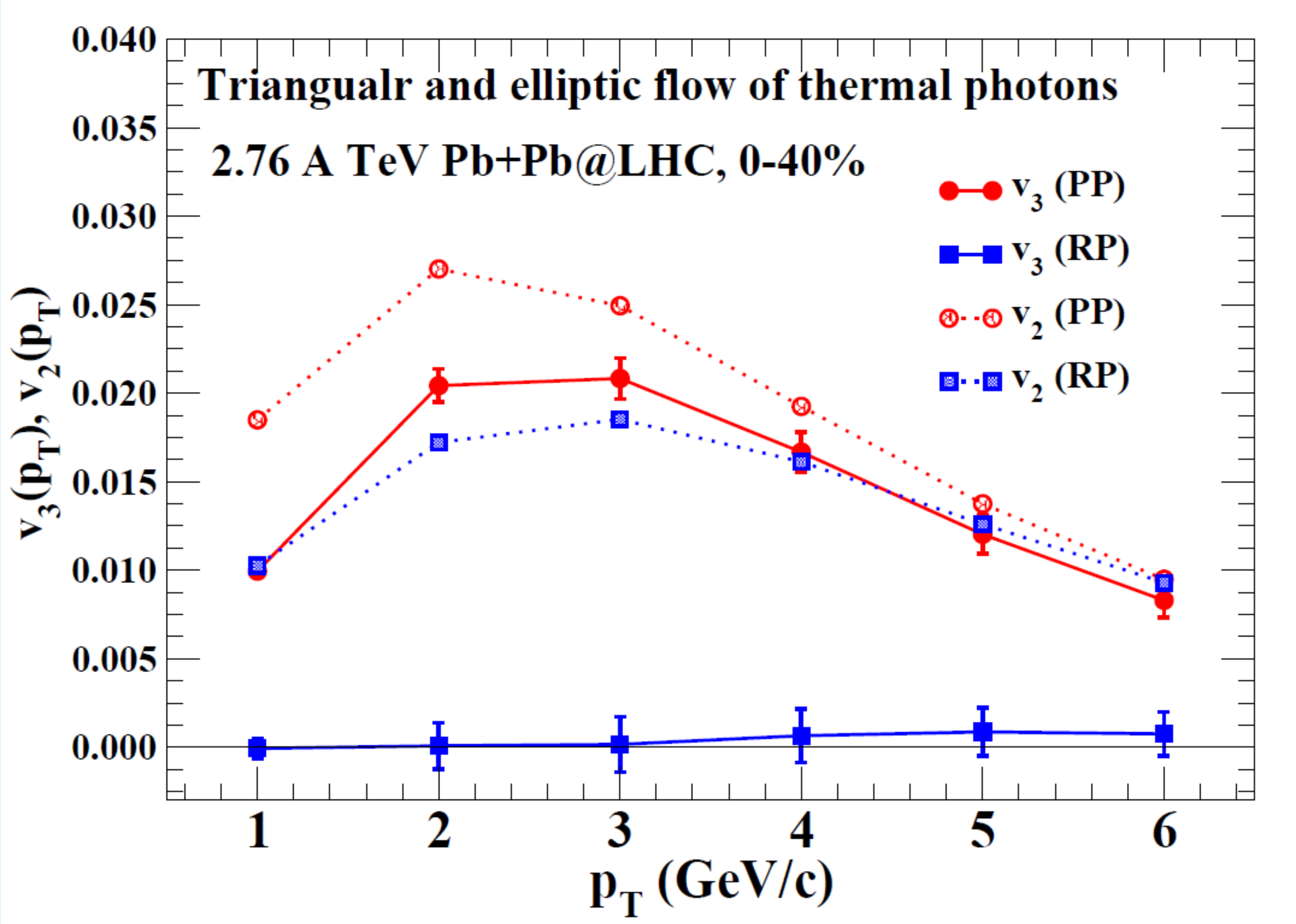
RC, D. K. Srivastava, T. Renk, arXiv:1401.7464



Thermal photon elliptic flow at LHC and ALICE preliminary direct photon v_2

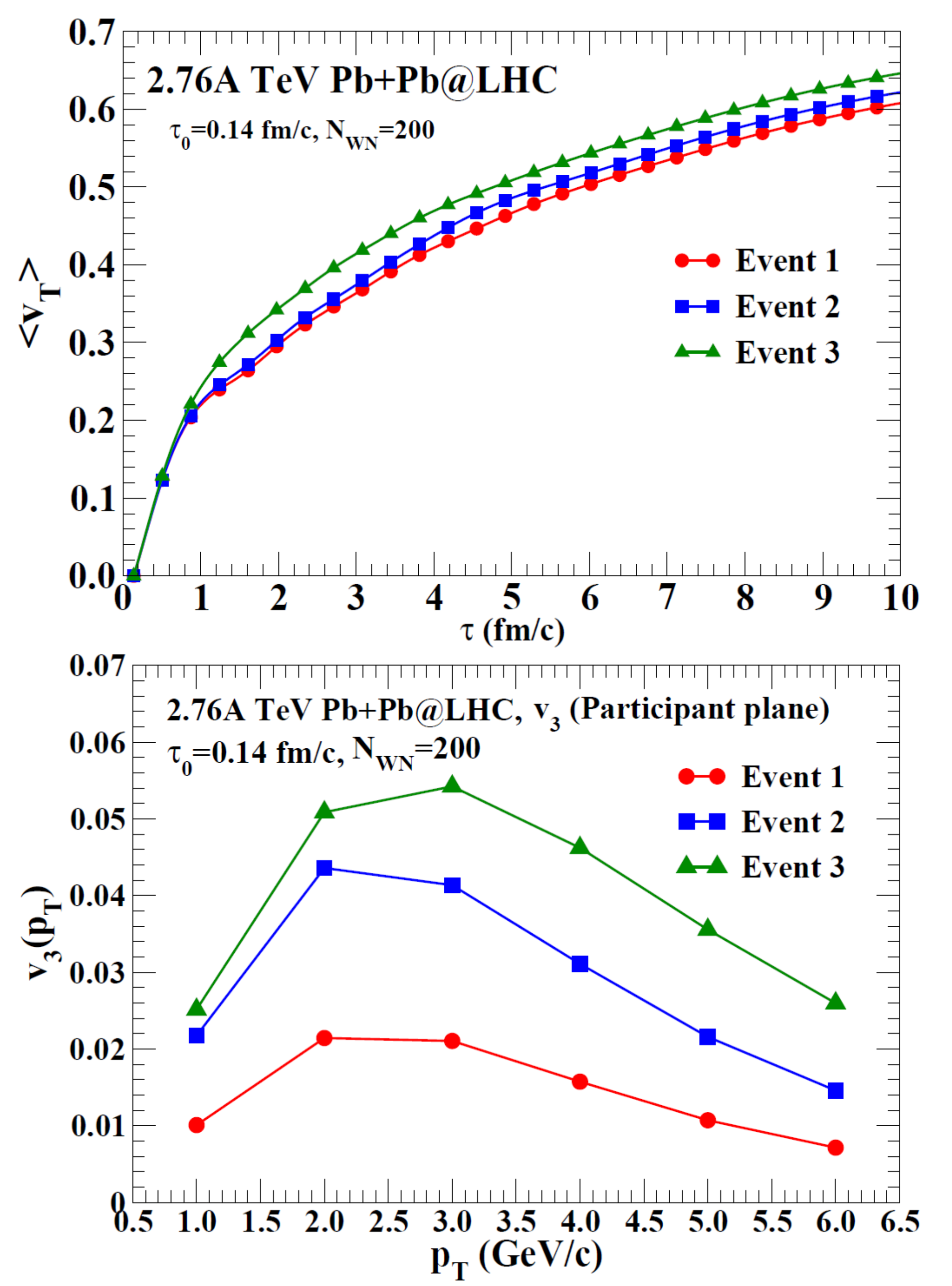
RC, H. Holopainen, I. Helenius, T. Renk, & K. J. Eskola, PRC 88, 034901 (2013).

Triangular and elliptic flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC



RC, D. K. Srivastava, T. Renk, arXiv:1401.7464

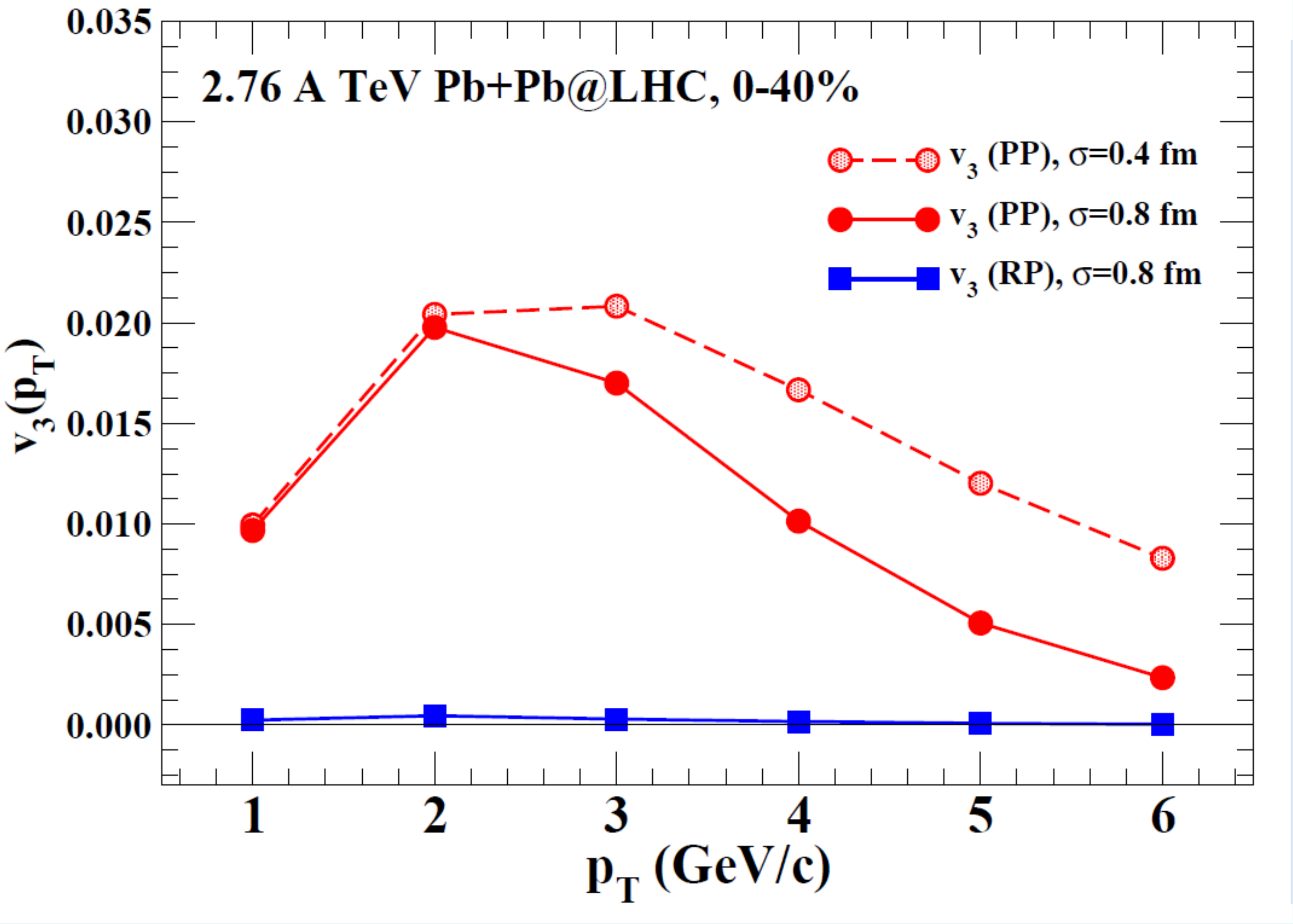
v_3(PP) is non-zero, positive and its p_T dependence is qualitatively similar to the elliptic flow parameter v_2(PP).



Average transverse flow velocities for different events with fixed number of wounded nucleons and v_3(PP) for the same events.

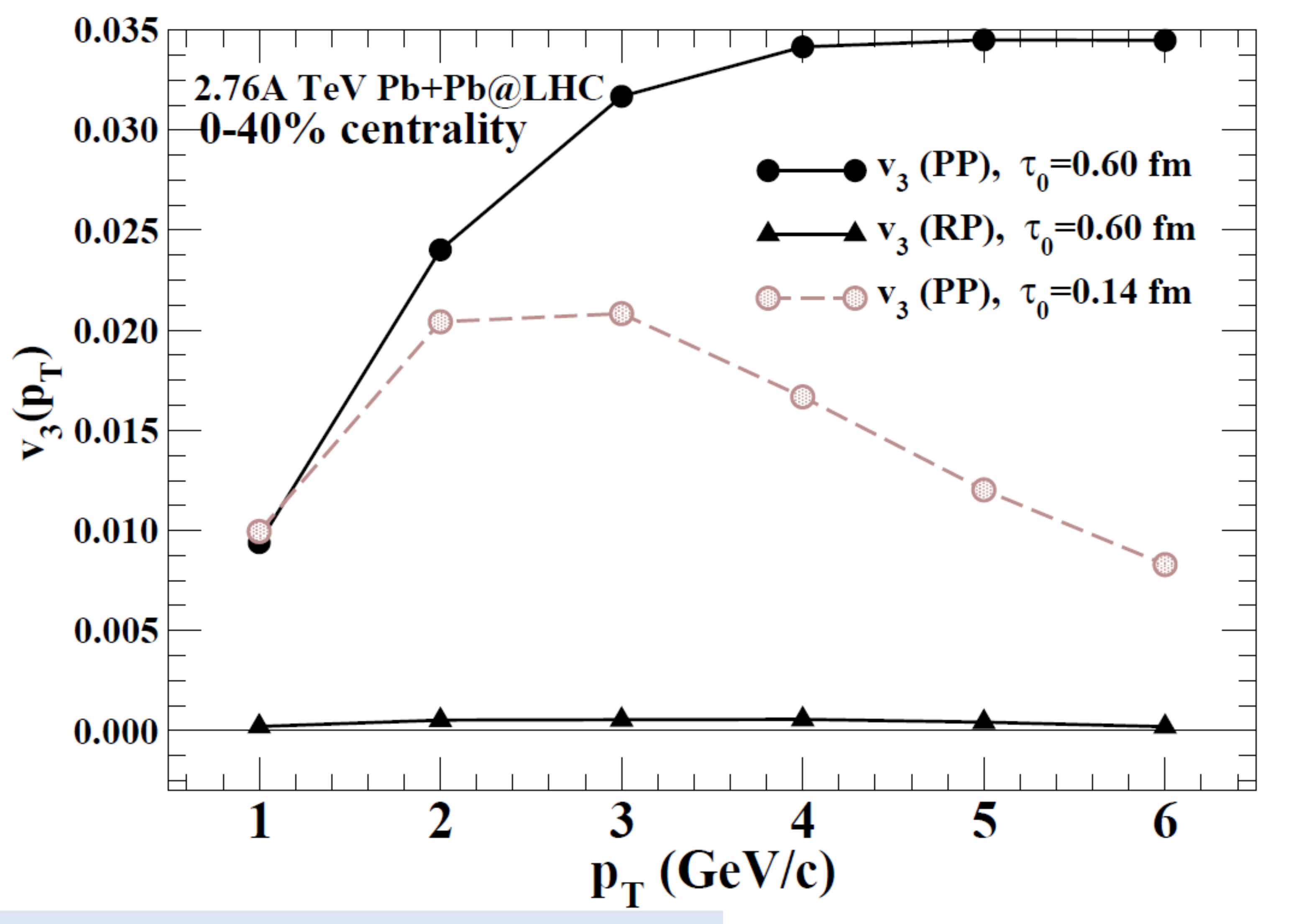
RC, D. K. Srivastava, T. Renk, arXiv:1401.7464

Triangular flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC and for size parameter 0.4 and 0.8 fm



RC, D. K. Srivastava, T. Renk, arXiv:1401.7464

Triangular flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC and formation times 0.14 and 0.6 fm/c



RC, D. K. Srivastava, T. Renk, arXiv:1401.7464

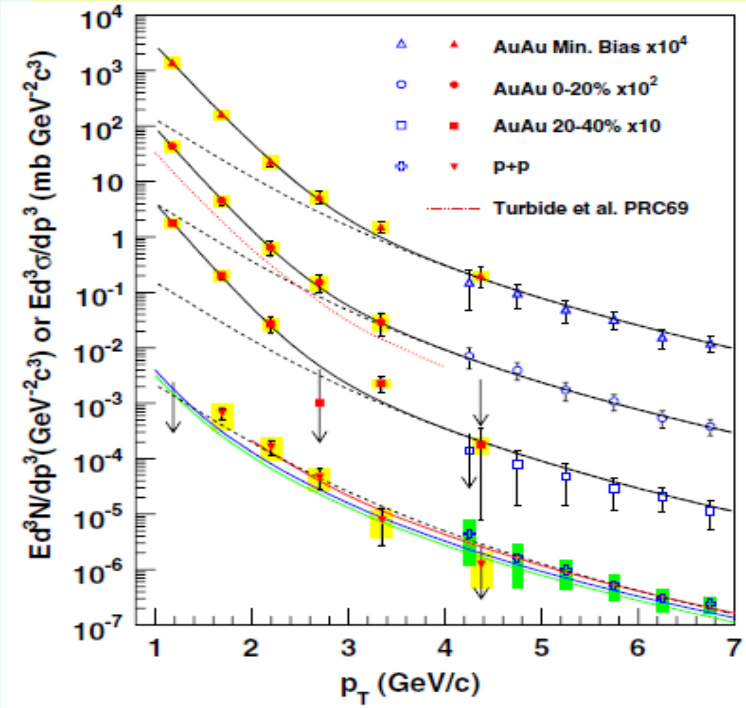
Summary and Conclusions:

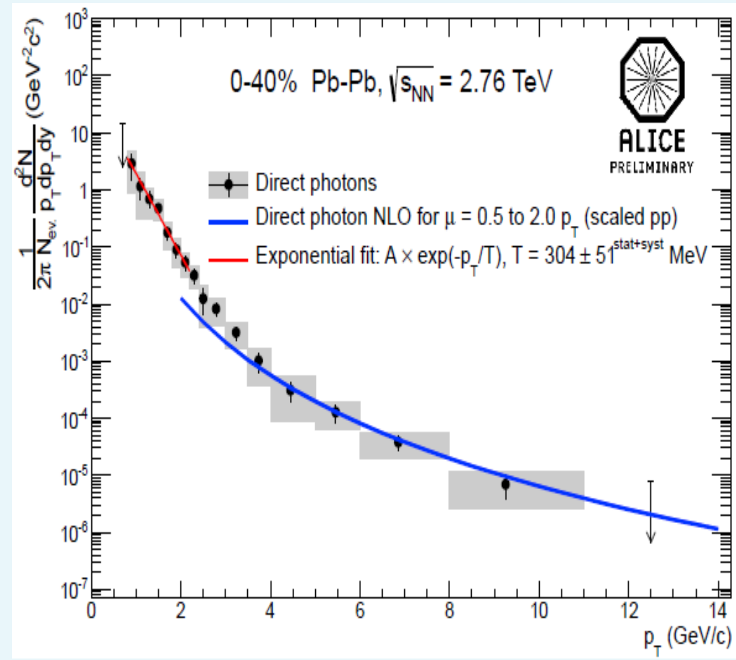
1) Fluctuations in the initial density distribution increase the elliptic flow of thermal photons significantly in the region $p_T > 2$ GeV compared to a smooth initial state averaged profile, however not sufficient to explain the large direct photon elliptic flow.

2) Triangular flow of thermal photons calculated from event by-event hydrodynamics is significantly large and its p_T dependence is qualitatively similar to the elliptic flow result.

Thank You

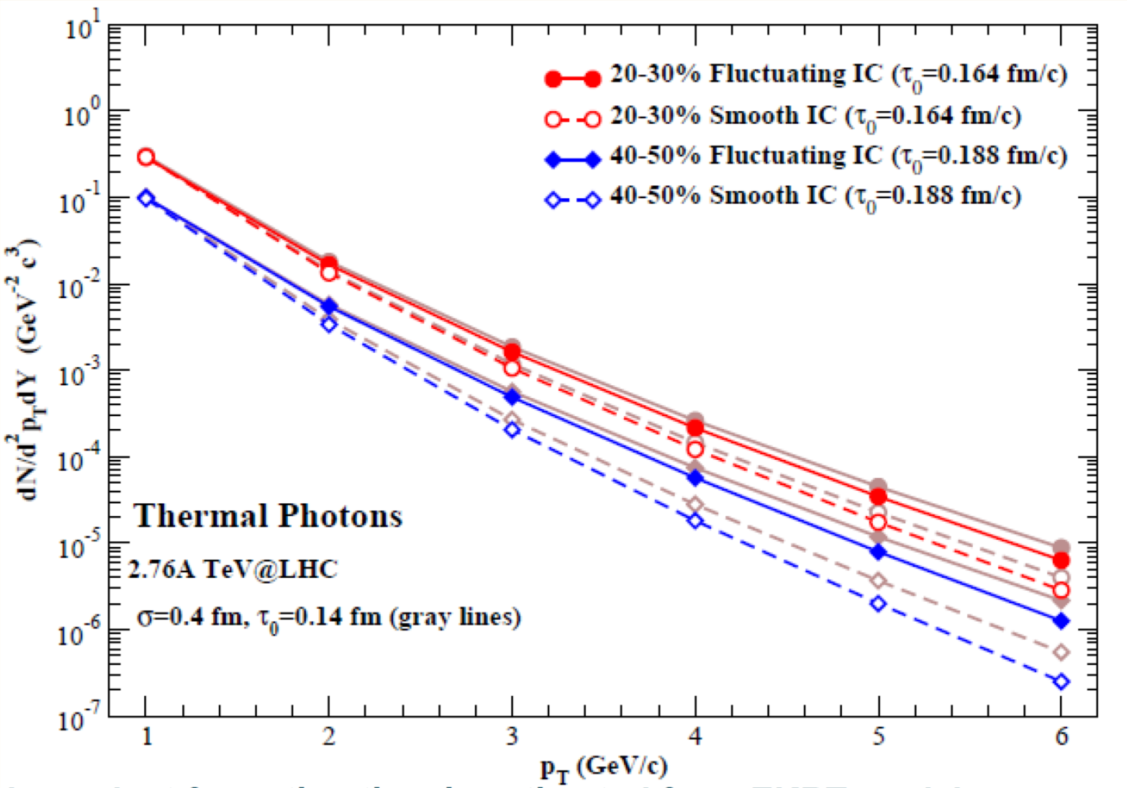
Direct photon spectra at RHIC and LHC





- **Low p_T direct photon elliptic flow measurement** could provide **direct constraints on QGP dynamics (η/s, T, t_0…).**
- **Excess of direct photon yield over p+p: T_{eff}=221 ± 19 ± 19 MeV in 0-20% Au+Au; substantial positive v_2 observed at p_T<4 GeV/c.**
- **Excess of direct photon yield over p+p at p_T<4 GeV/c: T_{eff}=304 ± 51 MeV in 0-40% Pb+Pb.**
- **Di-lepton v_2 versus p_T & M_{ll}: probe the properties of the medium from hadron-gas dominated to QGP dominated.**

Effect of centrality dependent formation time and fluctuating IC



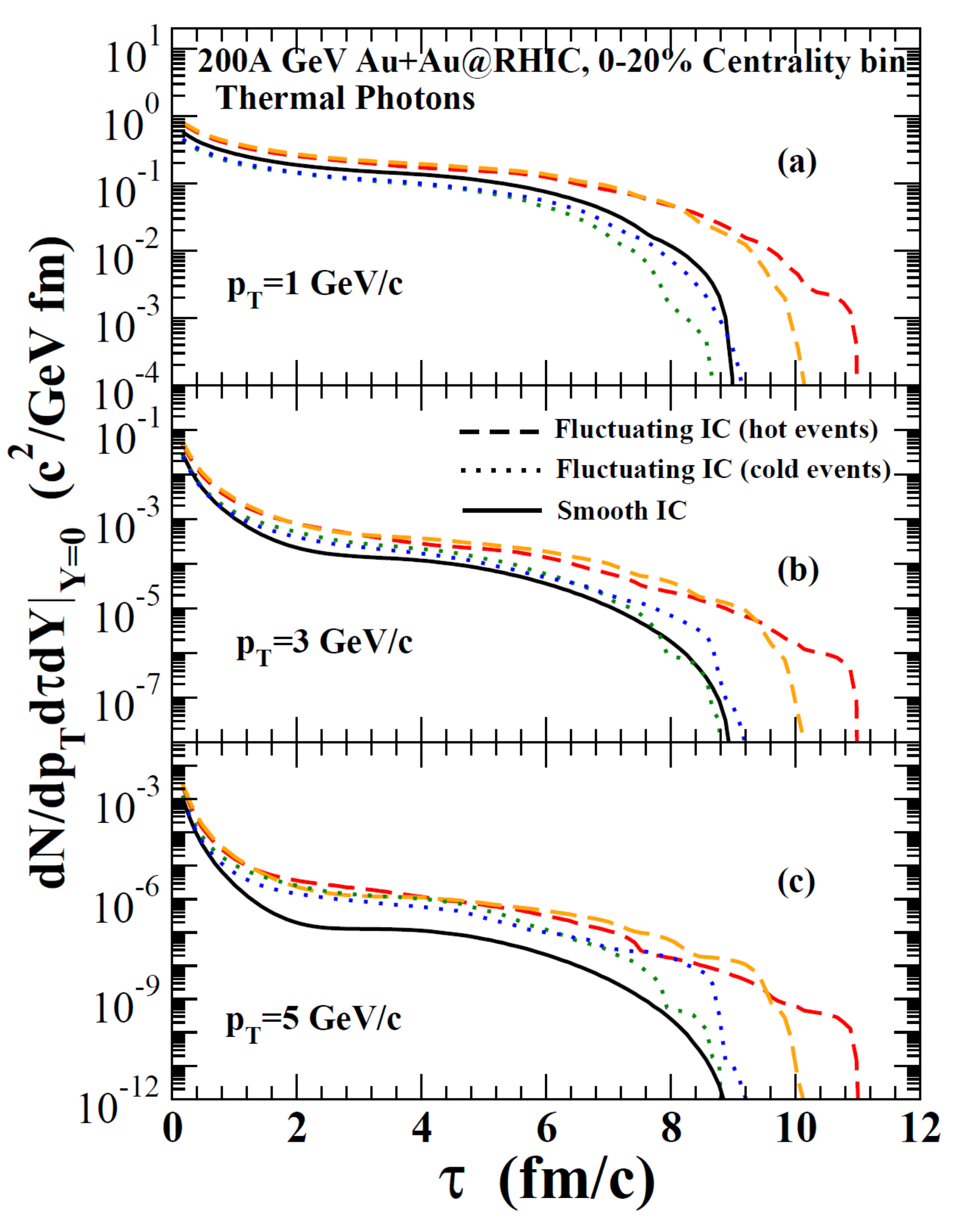
RC, Holopainen, Renk, Eskola arXiv: 1204.2249

Centrality dependent formation time is estimated from EKRT model.

Centrality bin (%)	p_0 (GeV)	A_{eff}	τ_0 (fm)
0 – 5	1.3945	193	0.140
20 – 30	1.2070	90	0.164
40 – 50	1.0507	40	0.188

Table from R. Paatelainen

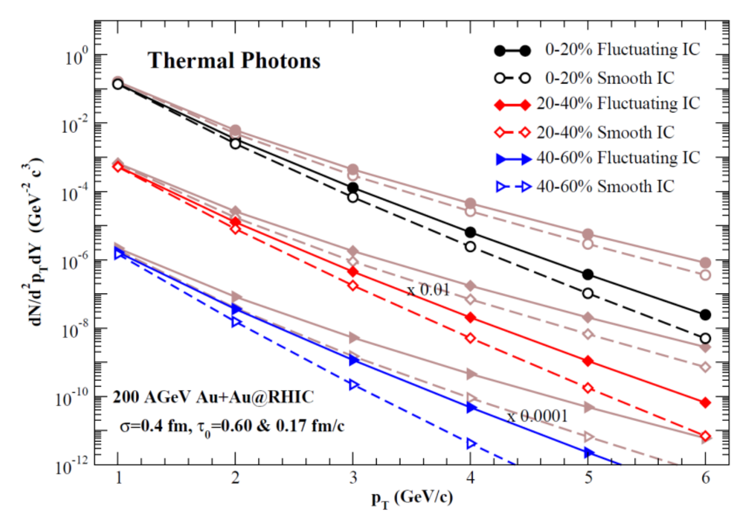
The p_T spectra alone are found to be insufficient to quantify the fluctuations in the IC due to uncertainties in the initial conditions.

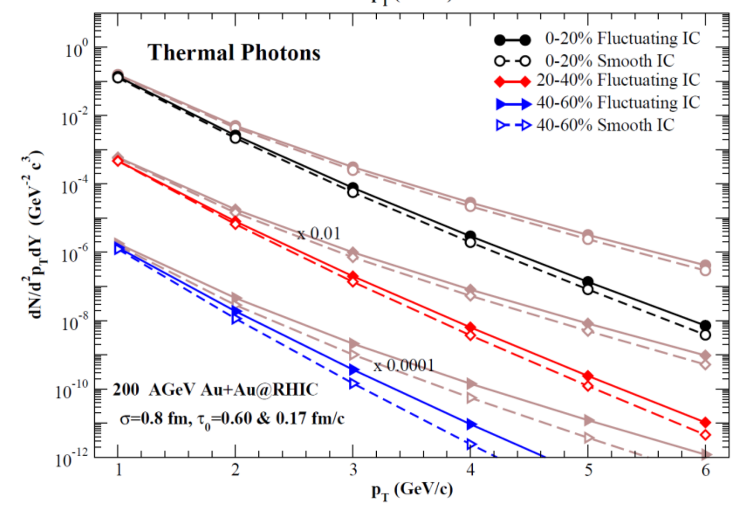


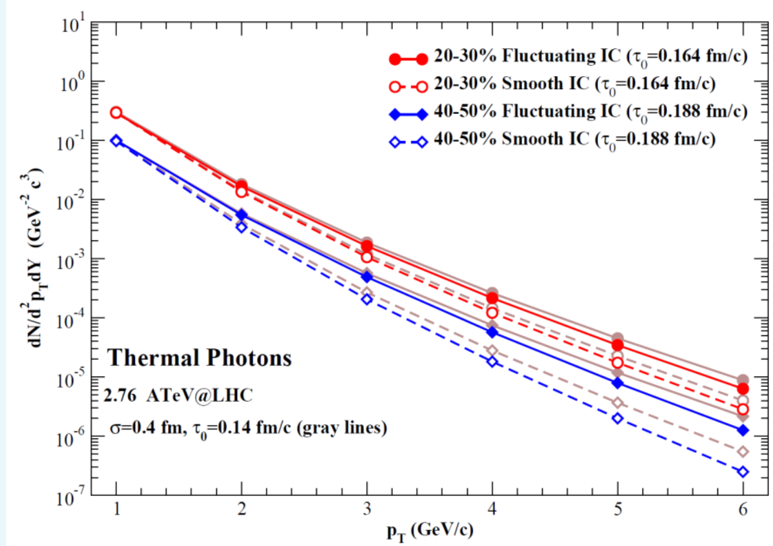
Time evolution of thermal photons for transverse momentum values of (a) 1 GeV/c, (b) 3 GeV/c, and (c) 5 GeV/c.

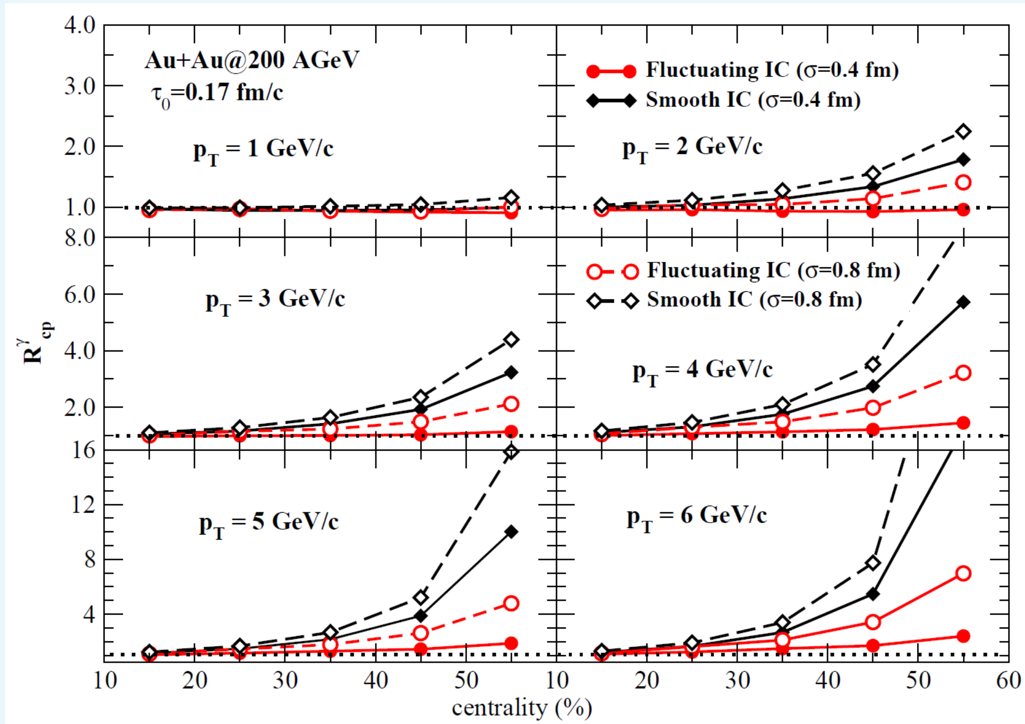
Results are compared with an initial state averaged event and four different random events.

RC, H. Holopainen, T. Renk, and K. J. Eskola, PRC (2011).



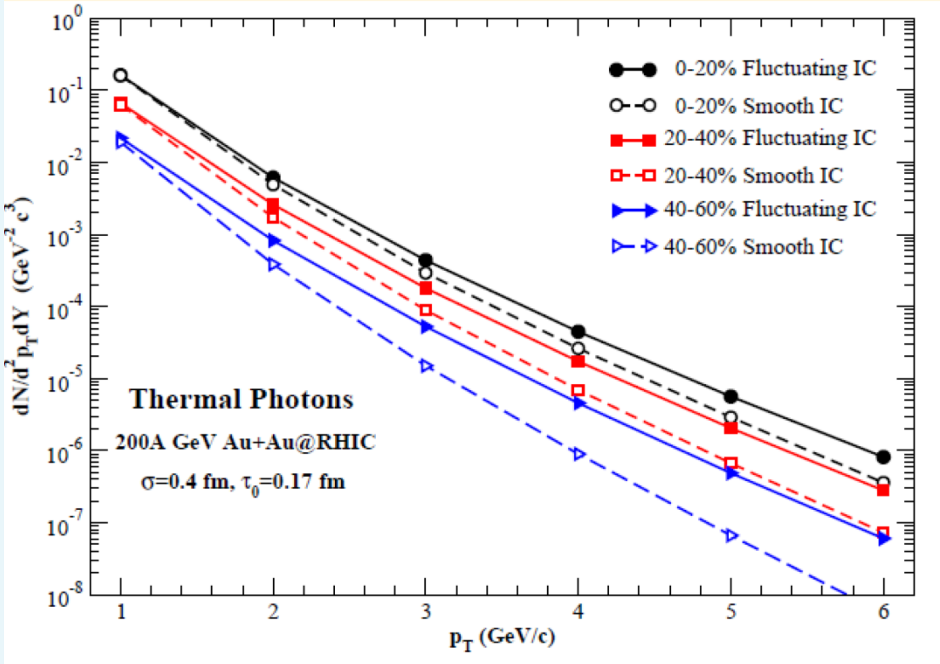


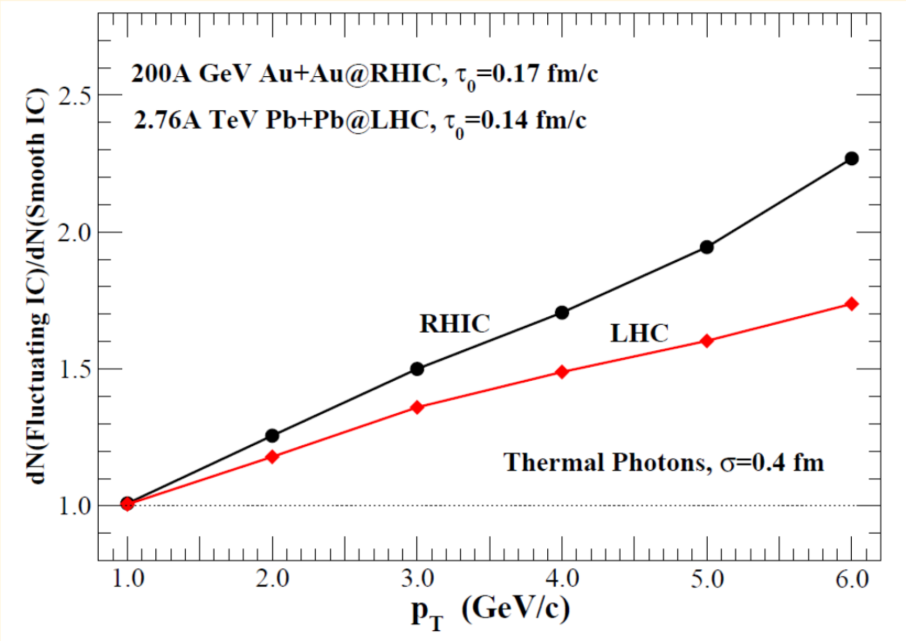




$$R^{\gamma}_{cp}|_i = \frac{dN/d^2p_T dY|_{0-10\%}}{dN/d^2p_T dY|_{i-j\%}} \times \frac{N_{bin}|_{i-j\%}}{N_{bin}|_{0-10\%}}$$

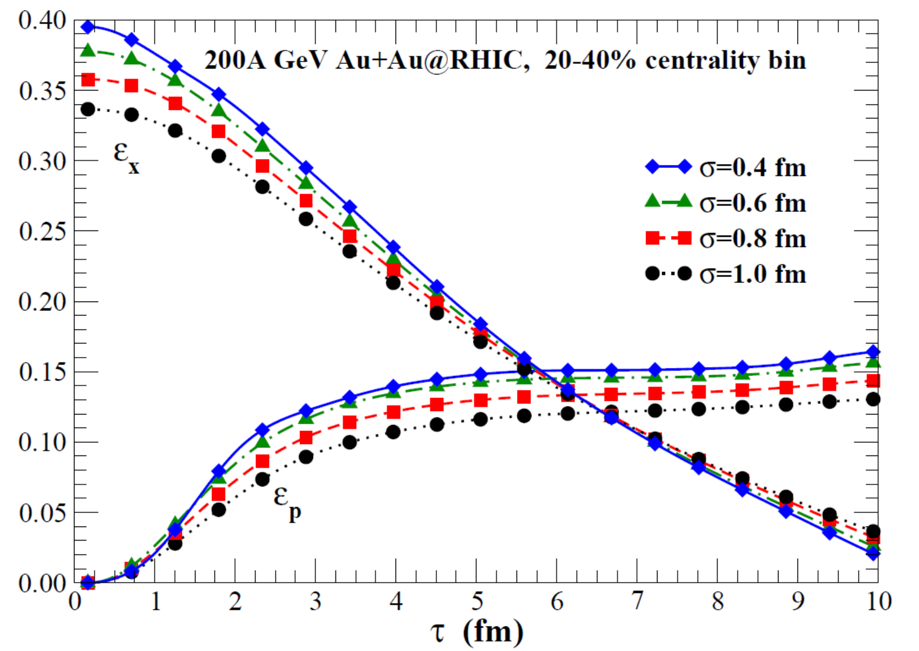
Thermal photons from smooth and fluctuating initial conditions: collision centrality and beam energy dependence

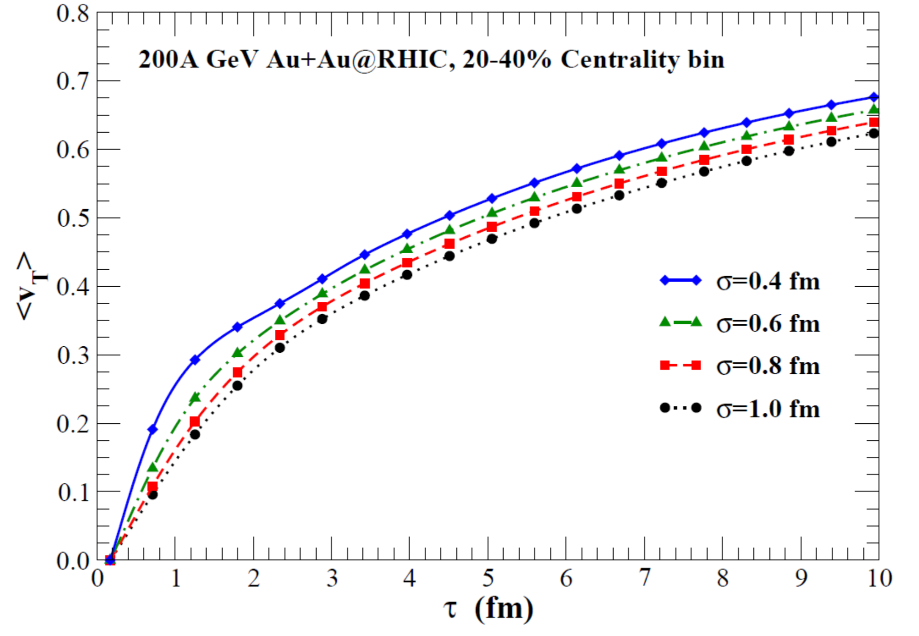




RC, Holopainen, Renk, Eskola; arXiv: 1204.2249

The effect of fluctuations in the IC is more pronounced for peripheral collisions and for lower beam energies.



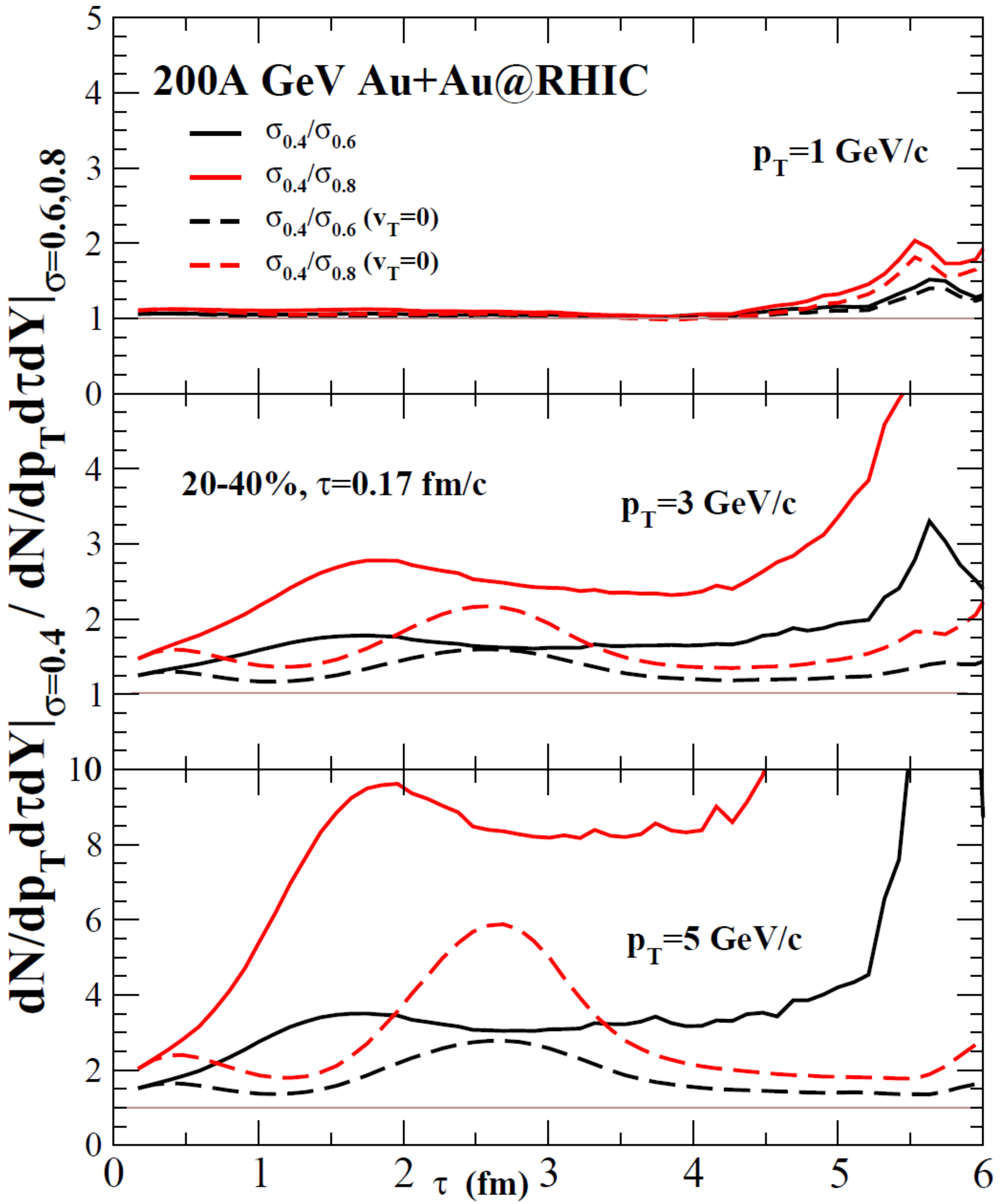


Thermal photons are emitted from different stages of the expanding system and thus in order to gain a better understanding it is useful to study the time evolution of ε_p, ε_x, $\langle v_T \rangle$.

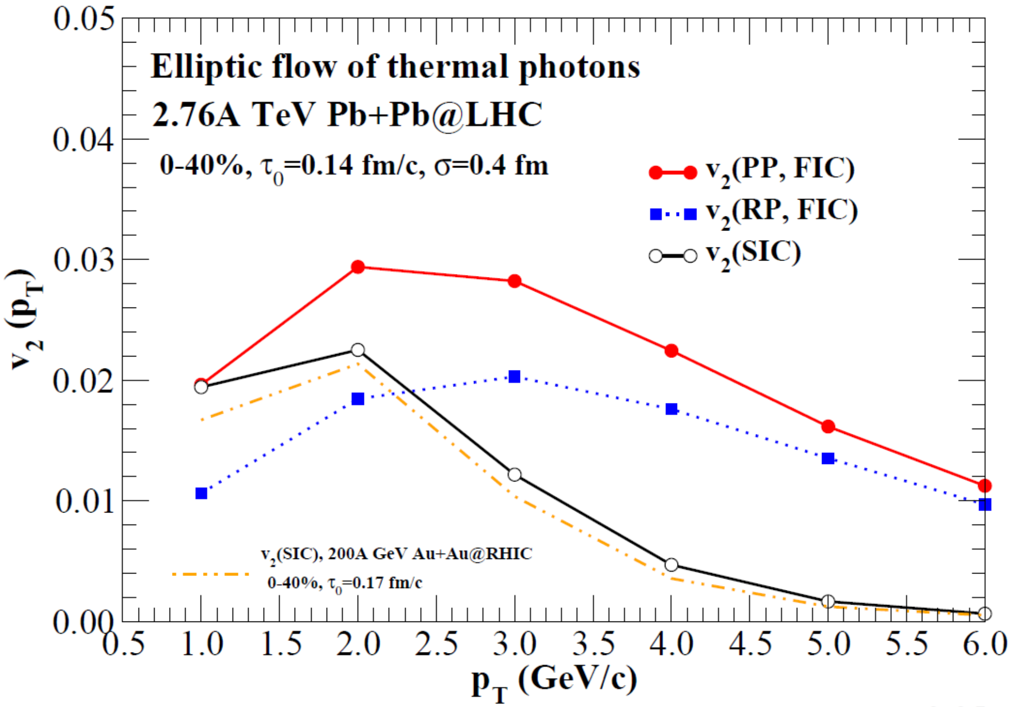
$$\epsilon_x = \frac{\int dx dy\, \varepsilon(x,y)(y^2 - x^2)}{\int dx dy\, \varepsilon(x,y)(y^2 + x^2)},$$

$$\epsilon_p = \frac{\int dx dy\, (T^{xx} - T^{yy})}{\int dx dy\, (T^{xx} + T^{yy})},$$

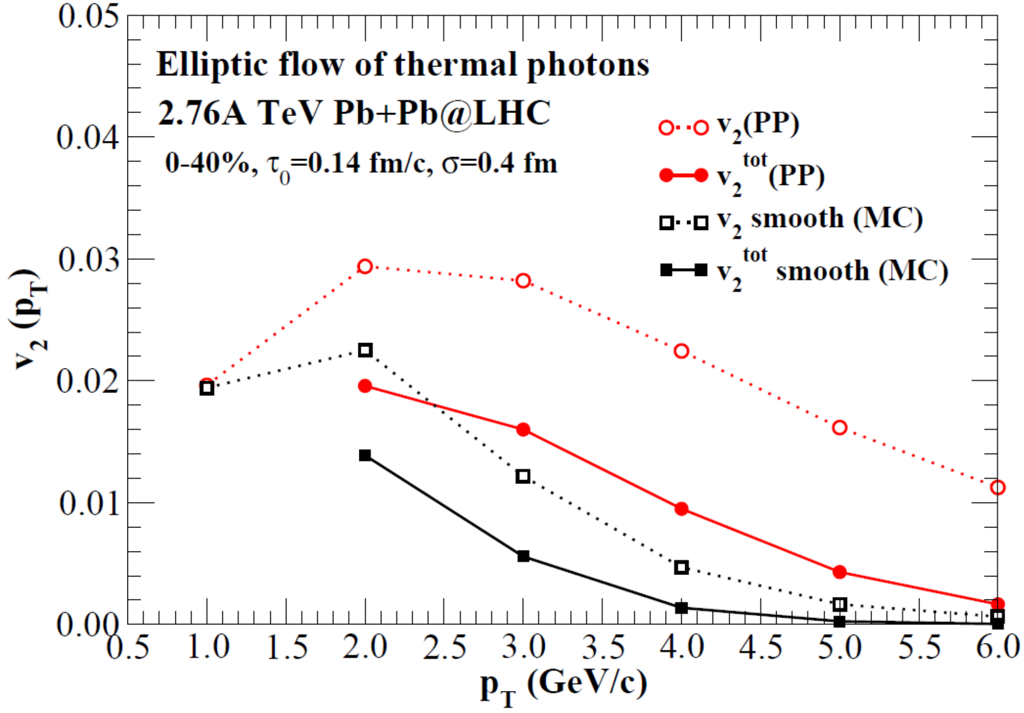
$$\langle v_T \rangle = \frac{\int dx dy\, \varepsilon(x,y)\gamma_T v_T}{\int dx dy\, \varepsilon(x,y)\gamma_T}$$



The ratios of the emitted thermal photon yield as a function of time in a single event with different
size parameters.

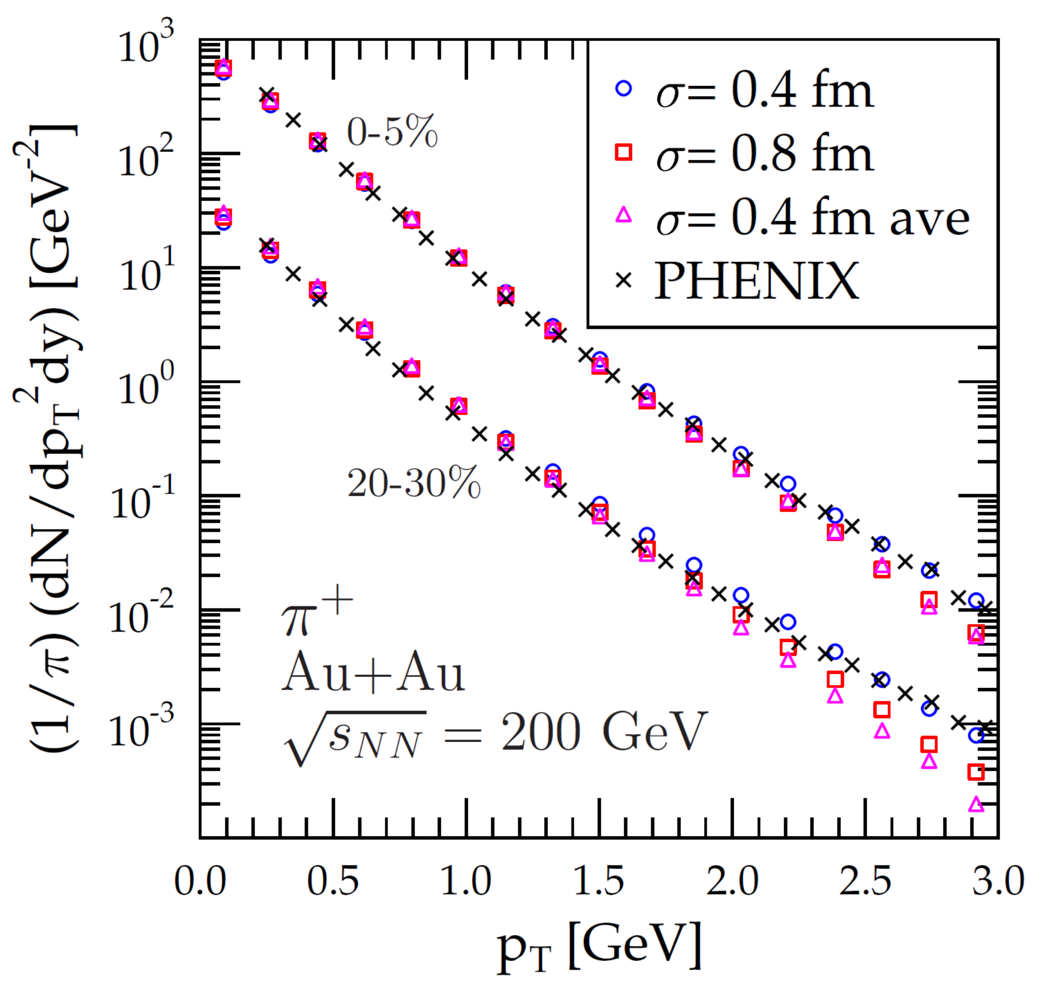


Elliptic flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC.

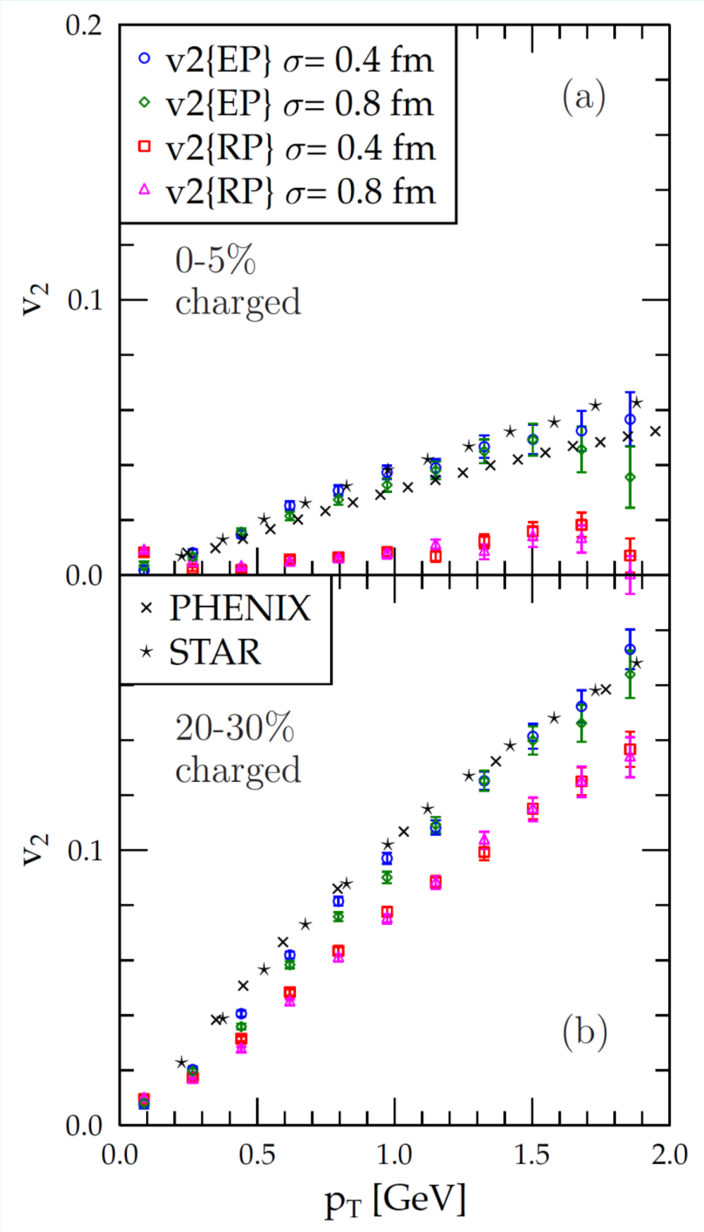


v_2 with and without the prompt photon contribution for smooth and fluctuating IC.

This e-by-e hydrodynamic model successfully reproduces both centrality dependence and p_T shape of charges particle elliptic flow



p_T spectra of positive pions for 200A GeV Au+Au collisions at RHIC calculated with averaged and fluctuating initial states with varying σ.



Elliptic flow of charged particles at different centralities with two different values of σ.