QGP formation time and direct photons from heavy ion collisions

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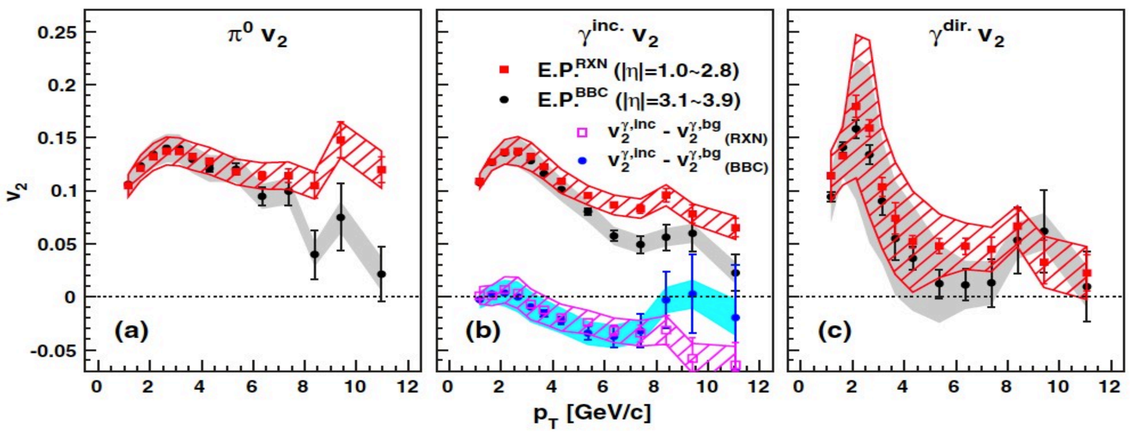
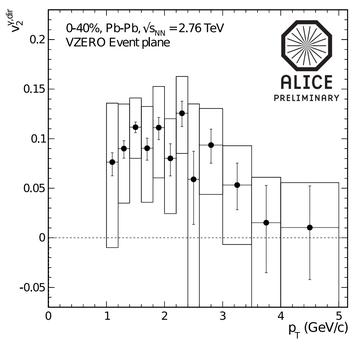
I. Motivations

The elliptic flow of direct photons is observed so large!





The large elliptic flow of photons puzzles people.
New sources of photons are suggested to explain it:

- G. Basar, D. E. Kharzeev, and V. Skokov, Phys. Rev. Lett. **109**, 202303 (2012).
- A. Bzdak and V. Skokov, Phys. Rev. Lett. **110**, 192301 (2013).

…

But constraints must be respected:

1. The large collection of hadronic data.
2. The measured pt spectrum and v2 of direct photons.
3. Prediction power to higher order harmonics, ie, the triangular flow v3.

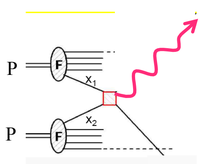
Our Strategy:

- Incorporate hadronic data with a realistic hydro evolution.
- Keep the hydro evolution valid and EoS consistently.
- Explain photon data & Predict simultaneously.

II. Calculation Approach

IIa. Main sources of direct photons:

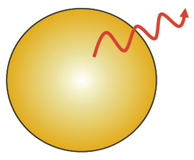
- Prompt photons



$$\frac{d\sigma^{\rm Prompt}}{dyd^2p_t} = \sum_{ab} dx_a dx_b G_{a/A}(x_a,M^2) G_{b/B}(x_b,M^2) \frac{\hat{s}}{\pi}\frac{d\sigma}{d\hat{t}}(ab\to cd)\delta(\hat{s}+\hat{t}+\hat{u})$$
$$+\sum_{c=q,g}\int dz_c \frac{d\sigma^c}{dyd^2p_t}\frac{1}{z_c^2} D^0_{\gamma/c}(z_c,Q^2)$$

Energy loss, JPC F.M.Liu 2009, PHENIX 2012

- Thermal photons



$$\frac{dN^{\rm thermal}}{dyd^2p_t}(v) = \int d^4x \Gamma_{\rm thermal}(E^*,T), \quad E^* = p^\mu u_\mu$$

Emission rates depend on the constituents.

IIb. Space-time evolution: (3+1)-D ideal hydrodynamics.

- AuAu at 200 GeV, T.Hirano, et al, PRC77, 044909(2008)
- PbPb at 2.76 TeV, K.Werner, et al, PRC85, 064907 (2012)

IIc. Two time scales at the early stage of heavy ion collisions.

Assumption: During (τ_0, τ_{QGP}), quark fugacity ξ increases from 0 to 1 linearly. Consequences:

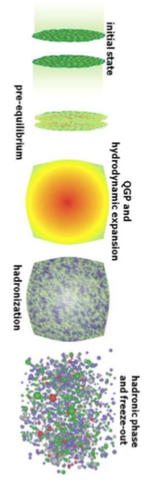
1. Photon emission rate is between

$$\Gamma^{\rm low} = \xi\cdot\Gamma_{\rm Compton} + \xi^2\cdot\Gamma_{\rm annihilation}$$
$$\Gamma^{\rm up} = \xi\cdot\Gamma_{\rm Compton} + \xi^2\cdot(\Gamma_{\rm AMY} - \Gamma_{\rm Compton})$$

2. EoS (note: hydro is still valid.)

$$\epsilon = (d_g + \xi d_q)\frac{\pi^2}{30}T^4$$

IId. Photon emission during the whole evolution:



(i) At $\tau = 0$, prompt photons are counted according to the next-to-leading-order QCD.
(ii) At $0 < \tau \leqslant \tau_0$, we have $\xi = 0$ and photon emission rate $\Gamma = 0$.
(iii) At $\tau_0 < \tau < \tau_{QGP}$, emission is estimated with $\Gamma^{\rm low} < \Gamma < \Gamma^{\rm up}$.
(iv) For $\tau \geqslant \tau_{QGP}$, the thermal photon emission rate covers

QGP phase, AMY 2001
HG phase, Rapp, 2004 without hadronic form factor.

III. Results: Extract QGP formation time from data

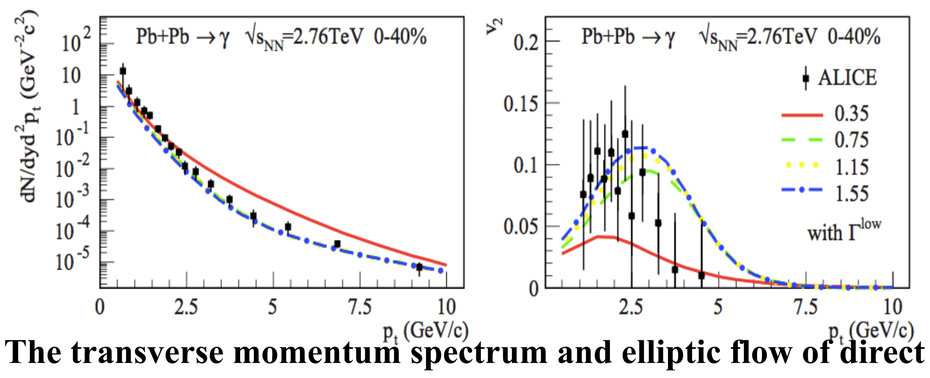


Fig 1. The transverse momentum spectrum and elliptic flow of direct photons with different QGP formation times, 0.35fm/c, 0.75fm/c, ….

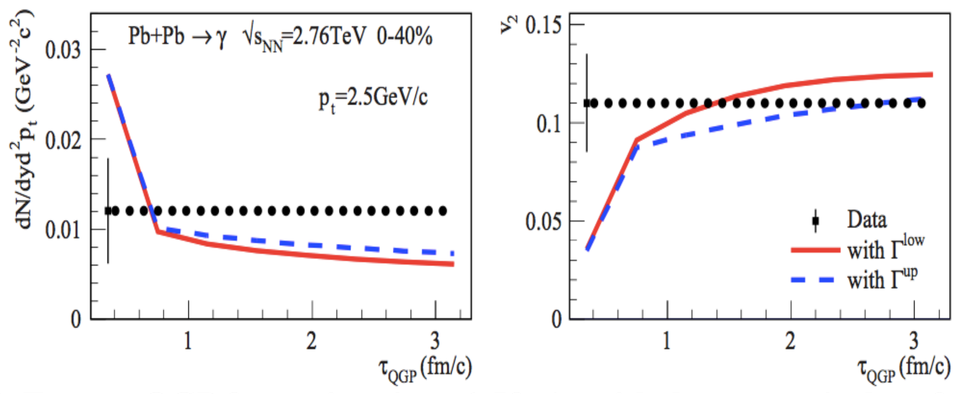
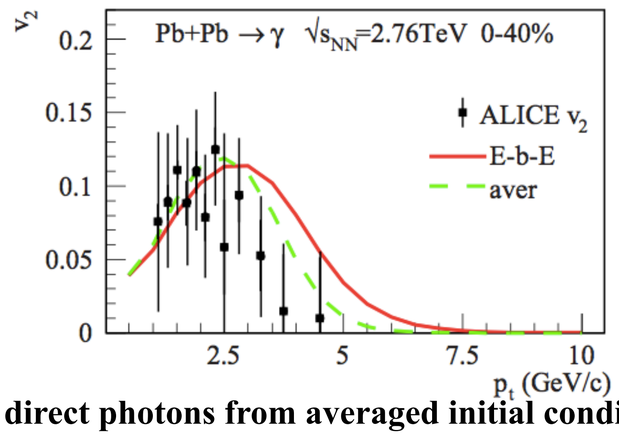
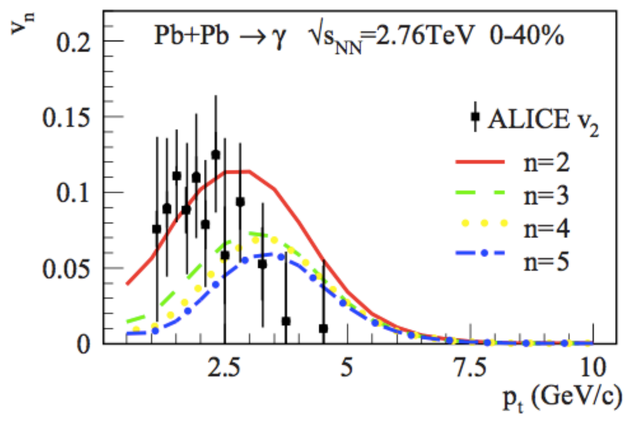


Fig 2. Extract QGP formation time, 1.5fm/c, with data at typical pt, 2.5GeV/c



$\tau_{QGP} \approx 1.5\, fm/c$

Fig 3. V2 of direct photons from averaged initial condition and e-b-e result.



$\tau_{QGP} \approx 1.5\, fm/c$

Fig 4. Prediction of high order harmonics of direct photons.

IV. Conclusions

- QGP formation time has been exacted from data, $\tau_{QGP} \approx 1.5\, fm/c$ which is later than local thermalization time $\tau_0 \approx 0.35\, fm/c$
- Measurement of high order harmonics of direct photons are highly expected to test our model and the others.

ACKNOWLEDGMENTS

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F. M. Liu and S.X. Liu, Phys.Rev.C 89, 034906 (2014).