Effect of radiative hadronization on thermal photons

~9th Nov. ATHIC 2021~

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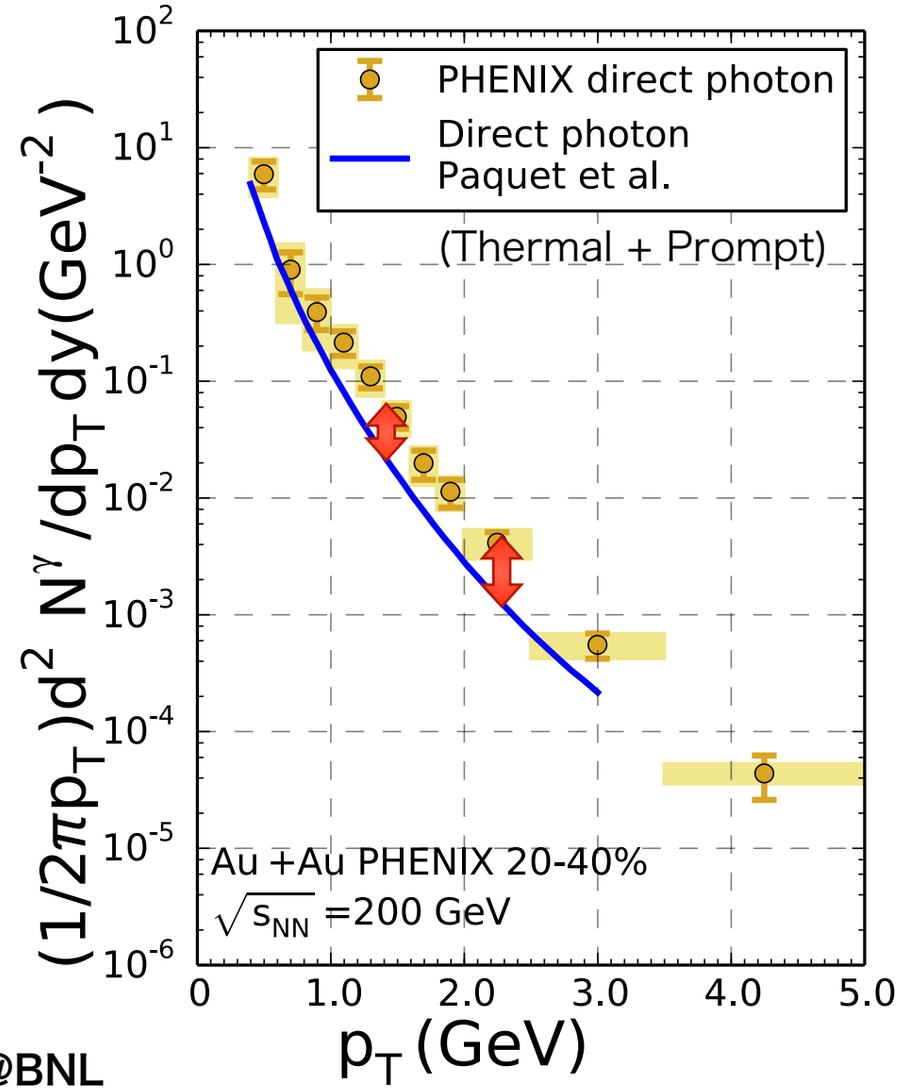
What is the direct photon puzzle?

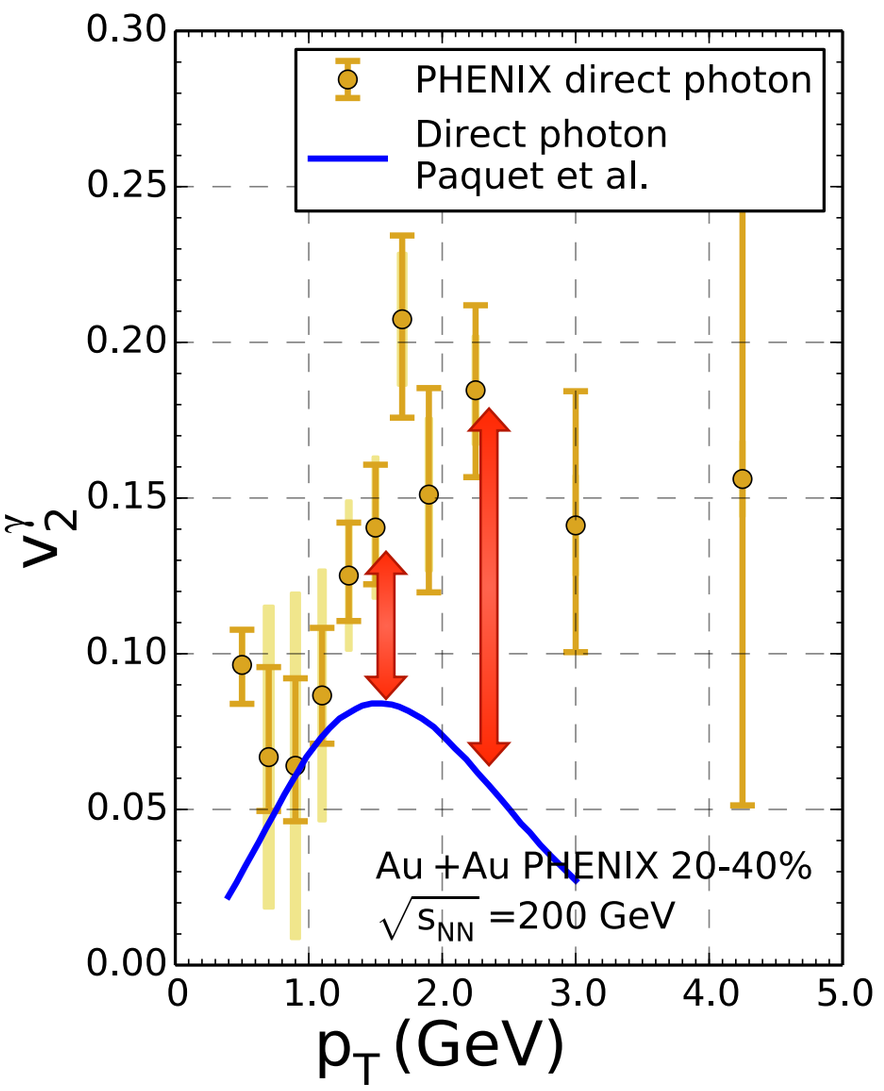
- Observed yield and flow of direct photons are larger than the estimations of any theoretical models.

Direct photon = Inclusive photon - decay photon from hadrons

p_T distribution



elliptic flow



RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

[Paquet et al. PRC 93 (2016) 4, 044906.]

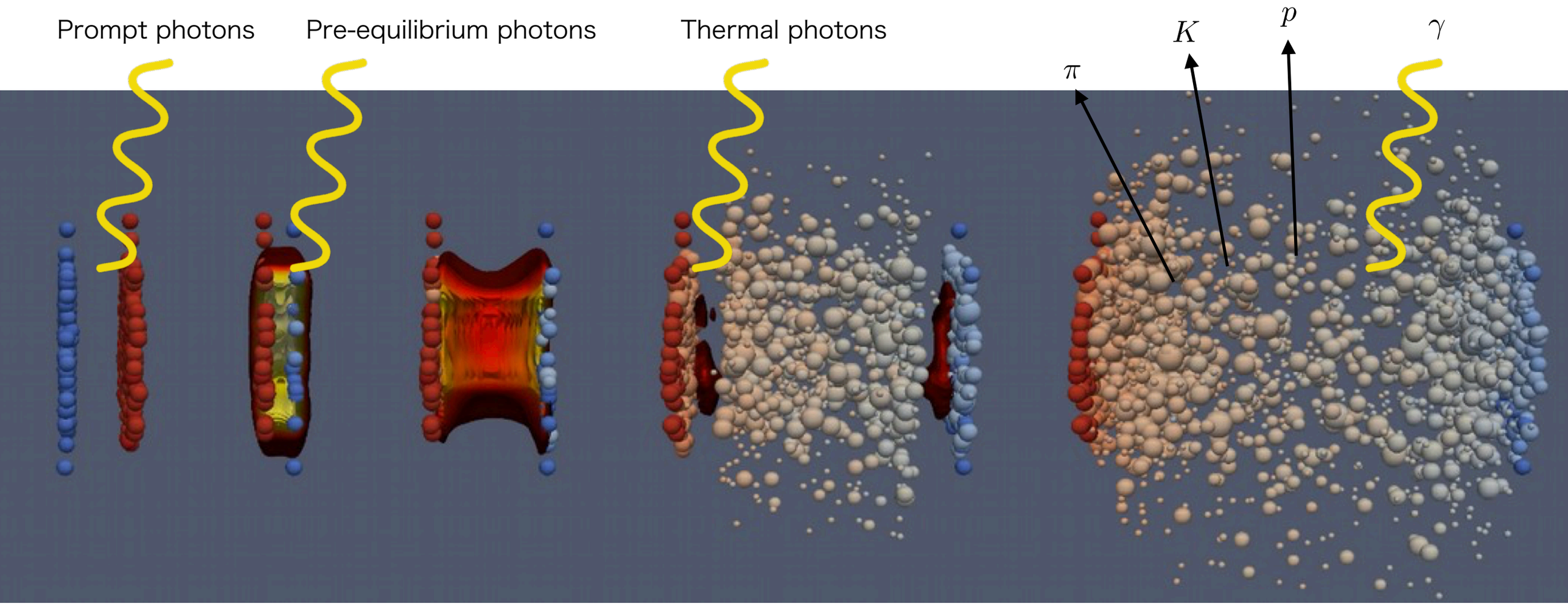
Photon sources

- Process of heavy ion collision

Prompt photons Pre-equilibrium photons Thermal photons

Decay photon from hadrons

$\pi^0 \to \gamma\gamma$ $\eta^0 \to \gamma\gamma$



[J.Bernhard, Duke]

Time

Bef. collision Collision QGP is created Hadronization

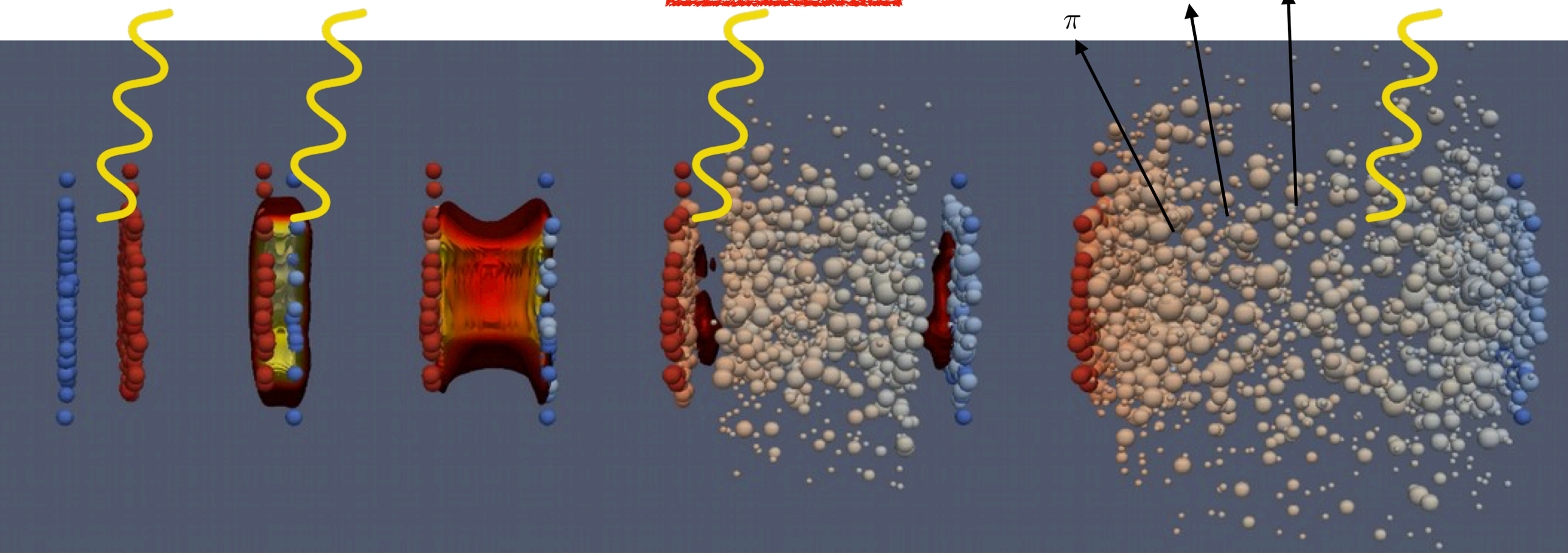
Observed photons

Direct photons Decay photon from hadrons

Thermal photons

- Process of heavy ion collision

Prompt photons Pre-equilibrium photons **Thermal photons**



Decay photon from hadrons

$\pi^0 \to \gamma\gamma$ $\eta^0 \to \gamma\gamma$

[J.Bernhard, Duke]

Bef. collision → Collision → QGP is created → Hadronization → **Time**

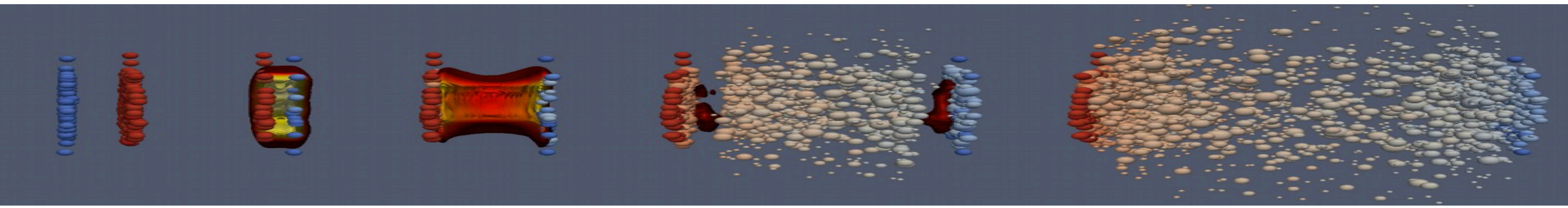
TRENTo → Hydrodynamic eq. → Cooper-Frye fml. → UrQMD → **Models**

[K. Okamoto, C. Nonaka, PRC 98 (2018) 5, 054906.]

Hydrodynamic models

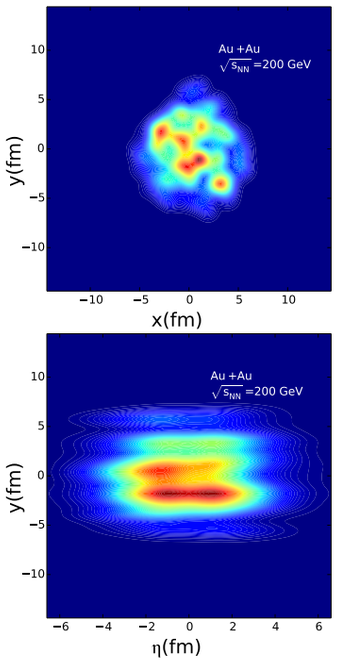
- 3D relativistic viscous hydrodynamic models

[K. Okamoto, C. Nonaka, PRC 98 (2018) 5, 054906.]



①TRENTo $\tau_0 = 0.6$ fm → ②Hydrodynamic eq. → ③Cooper-Frye fml. $T_{\rm SW} = 150$ MeV → ④UrQMD + Over sampling → **Models**

①TRENTo

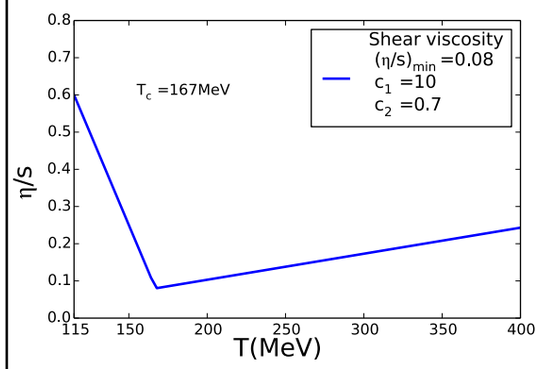


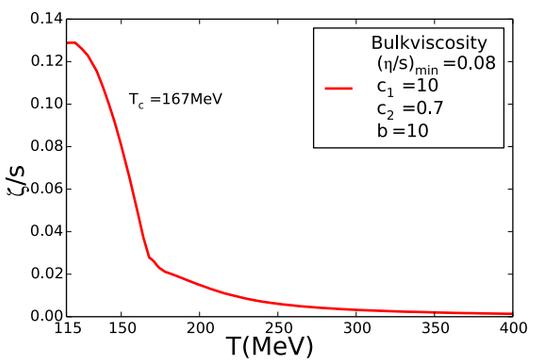
[J. Scott Moreland et al. PRC 92, 011901 (2015)]

②Hydrodynamic eq.

$$T^{\mu\nu} = eu^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\frac{\zeta}{s} = b\frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right)^2$$





$\partial_\mu T^{\mu\nu} = 0$ + EoS based on Lattice QCD

$(N_B^\mu = 0)$ [M. Bluhm et al. NPA 929, 157 (2014)]]

③Cooper-Frye fml.

$$E\frac{dN_i}{d^3p} = \frac{g_i}{2\pi}\int_\Sigma f_i(x,p)p^\mu d^3\sigma_\mu$$

Shear and bulk viscous correction

[J. Scott Moreland et al. PRC 92, 011901 (2015)]

④UrQMD

Decay and scattering of hadrons

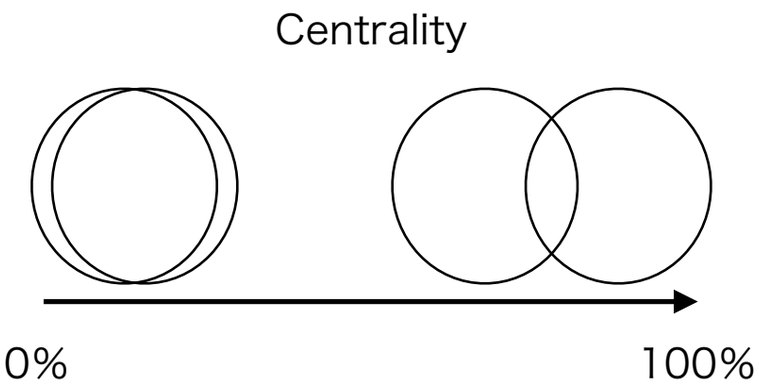
[M. Bleicher et al. J. Phys. G25:1859-1896 (1999)]

Hadron's yield and flow

- Parameters in the model are fixed in comparison with the experimental data of hadrons.

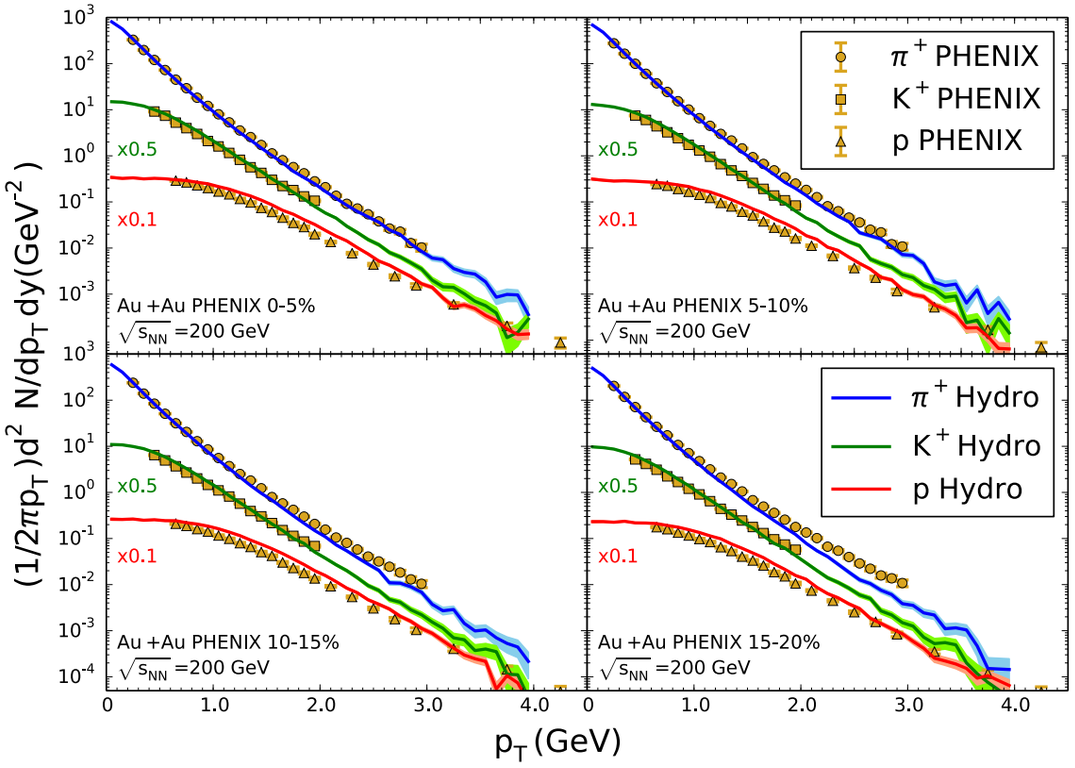
RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

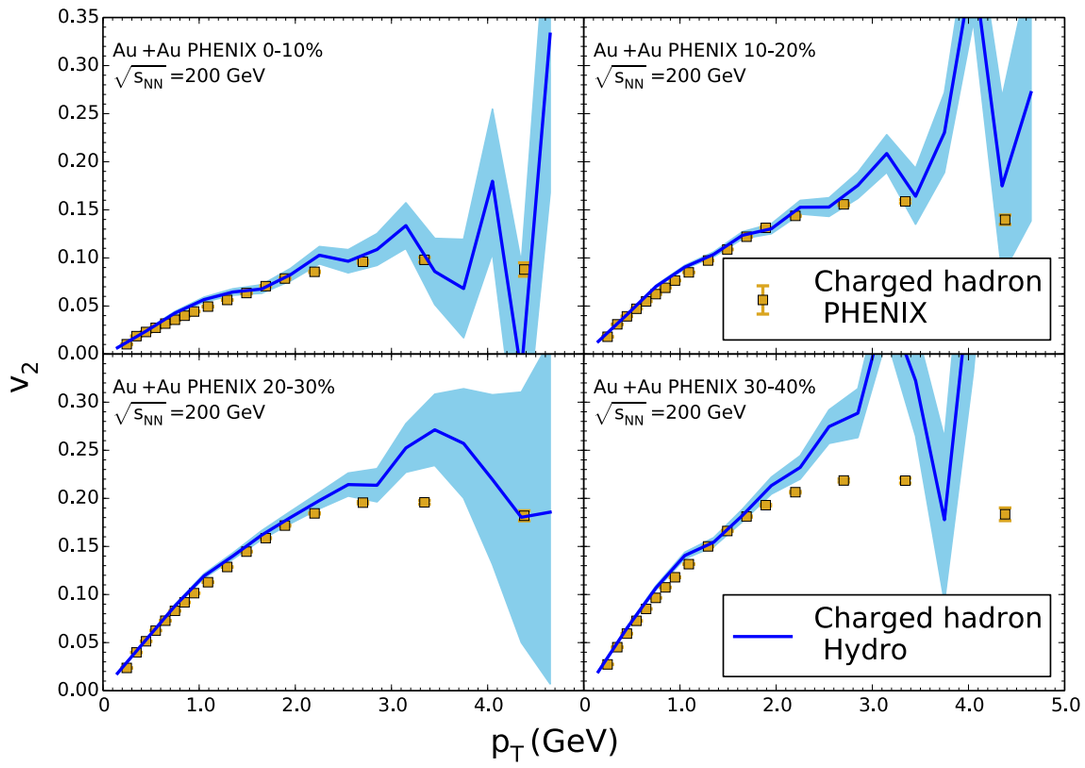


- The model can reproduce the experimental data up to 2 GeV.

p_T distribution



elliptic flow



Photon emission rate

- Thermal photon emission rate

thermal field theory, relativistic kinetic theory $R_\gamma = \dfrac{dN_\gamma}{dtd^3x}$

QGP phase — Phase transition — Hadron phase

QGP LO

[AMY. JHEP 0112:009 (2001)]

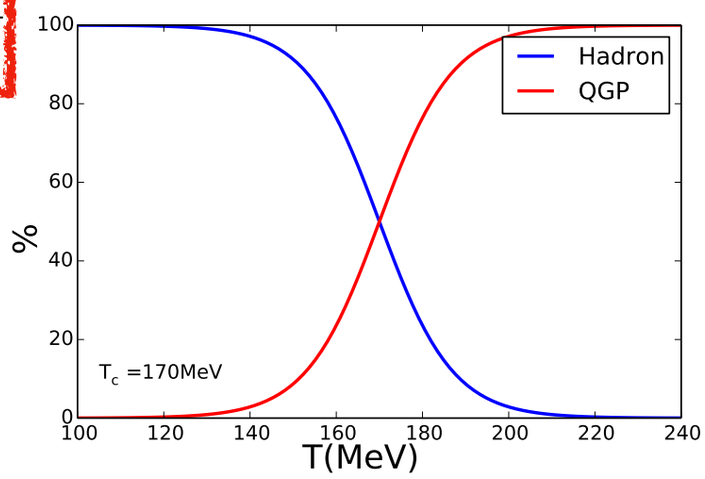
Meson gas + baryons
+ π brem. + $\pi\ \rho\ \omega$

[Rapp et al. PRC 69, 014903 (2004)]
[Rapp et al. PRC 91, 027902 (2015)]
[Rapp et al. NPA 945 (2016) 1-20]

- Interpolation of QGP and hadronic matter

$$E\frac{dR^\gamma_{\rm th}}{d^3p} = \frac{1}{2}\left(1-\tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\rm had}}{d^3p} + \frac{1}{2}\left(1+\tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\rm QGP}}{d^3p}$$

[A. Monnai J. Phys. G 47 075105 (2019)]



$$E\frac{dN^\gamma_{\rm th}}{d^3p}(p_T) = \frac{1}{\Delta y}\int_{y_{\rm min}}^{y_{\rm max}} dy \frac{1}{\Delta\phi}\int_{\phi_{\rm min}}^{\phi_{\rm max}} d\phi \int d\tau\tau V \left(E\frac{dR^\gamma_{\rm th}}{d^3p}\right)$$

$T_{\rm f} = 116\ {\rm MeV}$ For simplicity, we evaluate photon emission at late stage by hydrodynamic expansion.

Thermal photons

- Thermal photons from hydrodynamic expansion

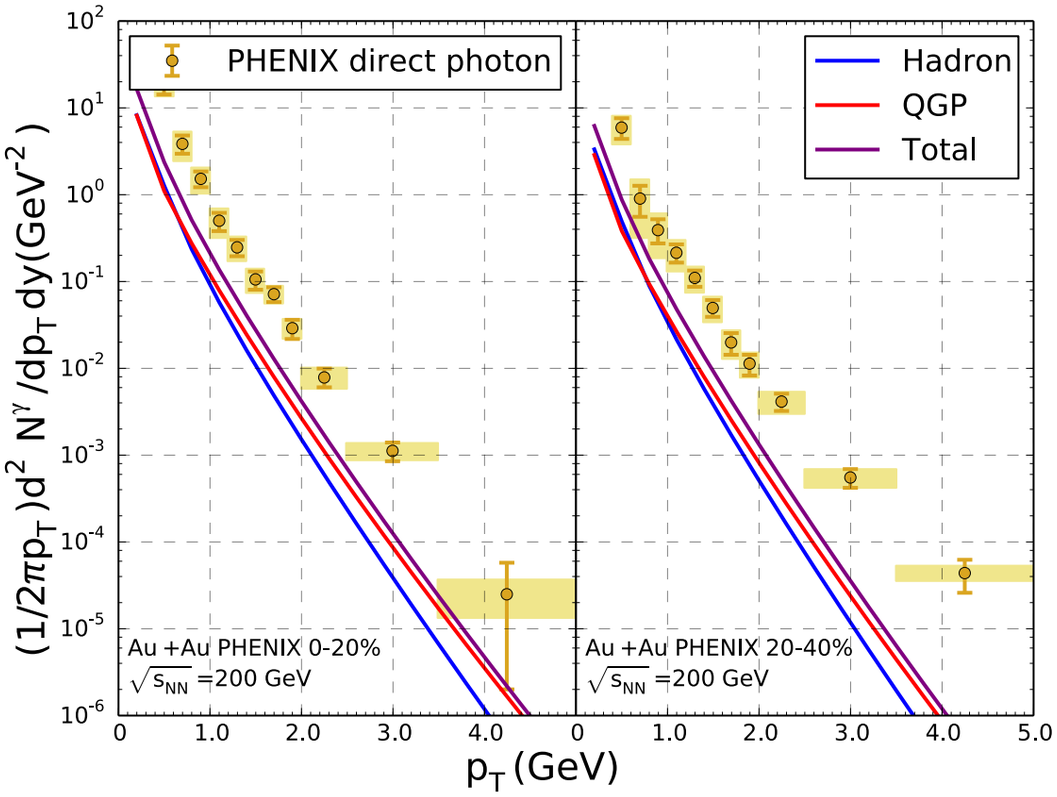
QGP phase → Phase transition → Hadron phase

RHIC@BNL

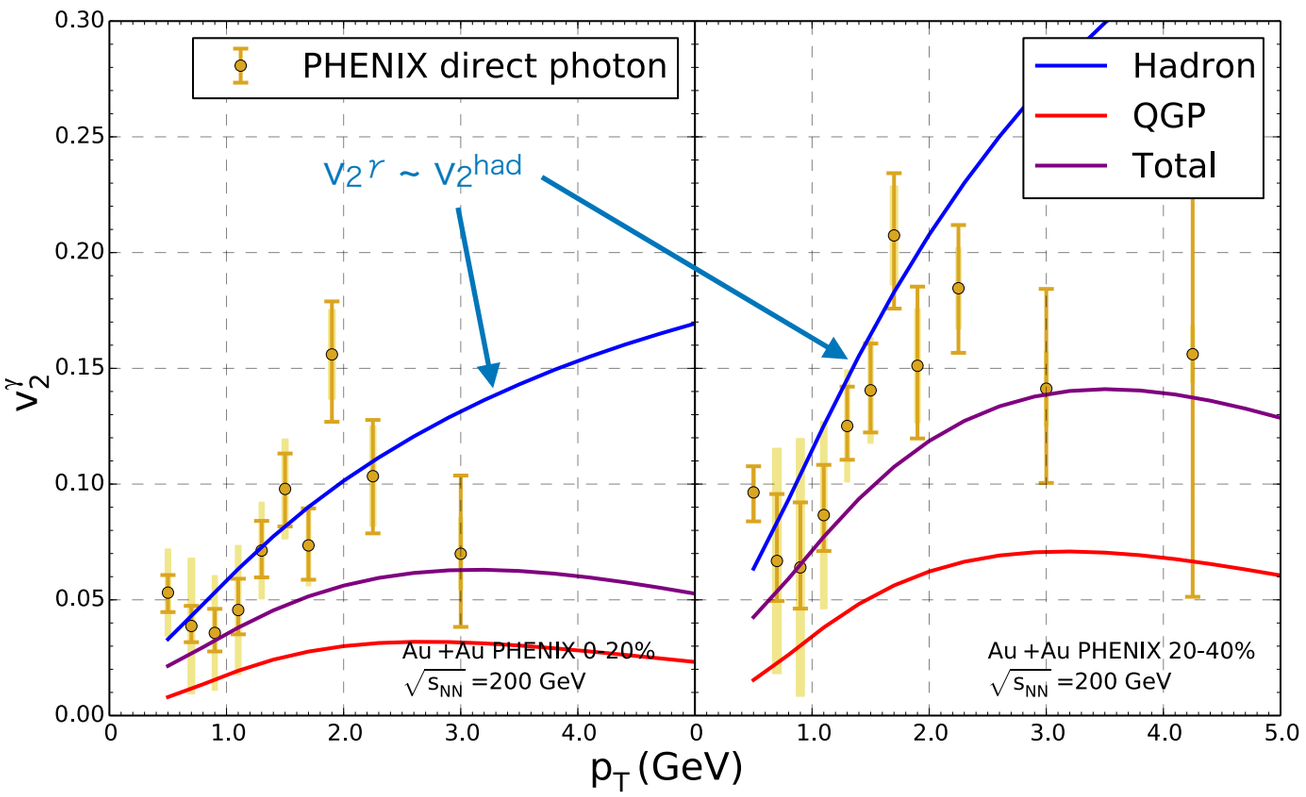
Au+Au $\sqrt{s_{NN}}$ = 200 GeV

- Thermal photon from QGP phase is dominant at high p_T region.
- v_2^{γ} from QGP phase < v_2^{γ} from hadron phase
- The calculation underestimates the PHENIX data.

p_T distribution



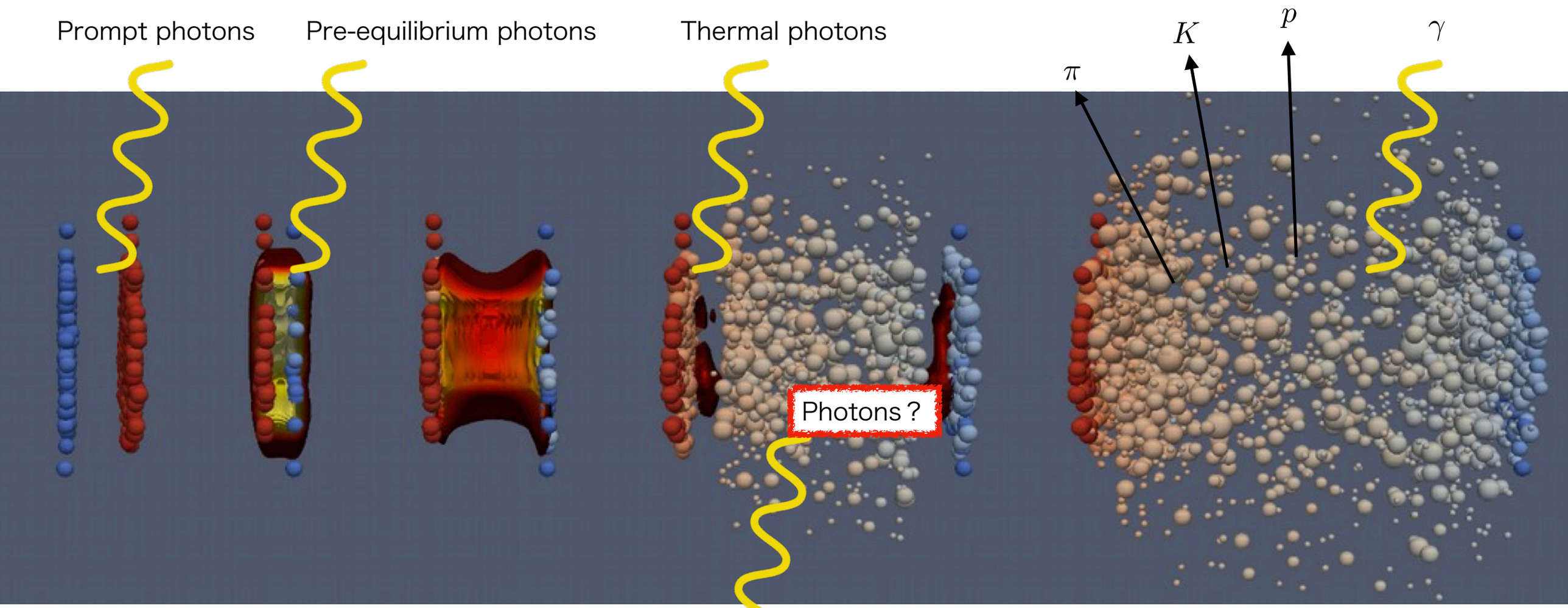
elliptic flow



Photon emission at hadronization

- We propose photon emission at hadronization.

Decay photon from hadrons $\pi^0 \to \gamma\gamma$ $\eta^0 \to \gamma\gamma$



Recombination model

- The model provides a phenomenological description of hadronization for hadron production ($2 < p_T < 5$ GeV).
  - Meson/baryon ratio
  - Quark number scaling of elliptic flow

[R. J. Fries et al. PRC 68, 044902 (2003)]

Input
parton's dist. and flow

$$q + \bar{q} \to M$$

ReCo model

Constituent quark mass

$300\mathrm{MeV}$ quark

$300\mathrm{MeV}$ antiquark

meson

In the case of pion

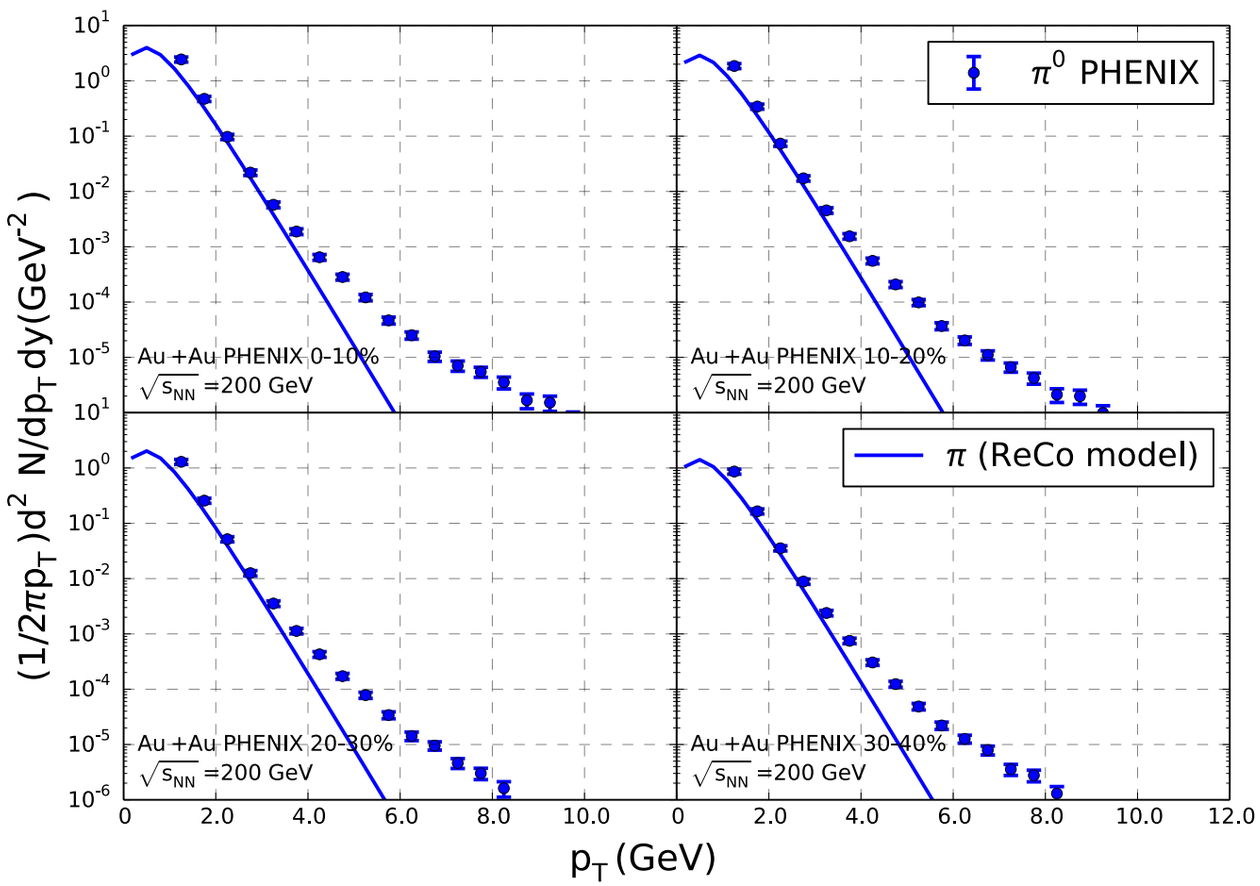
$140\mathrm{MeV}$

The model violates energy conservation law.

RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

p_T distribution



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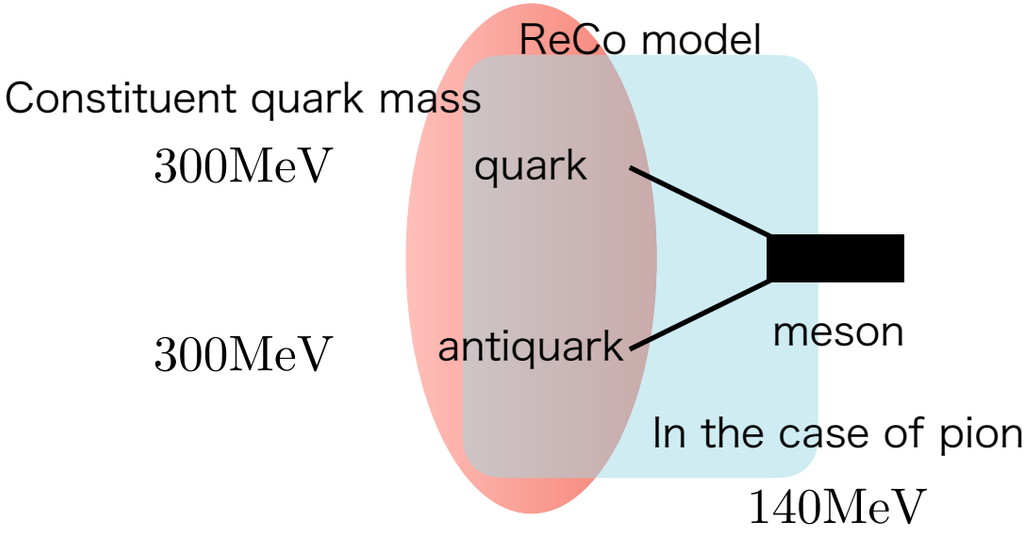
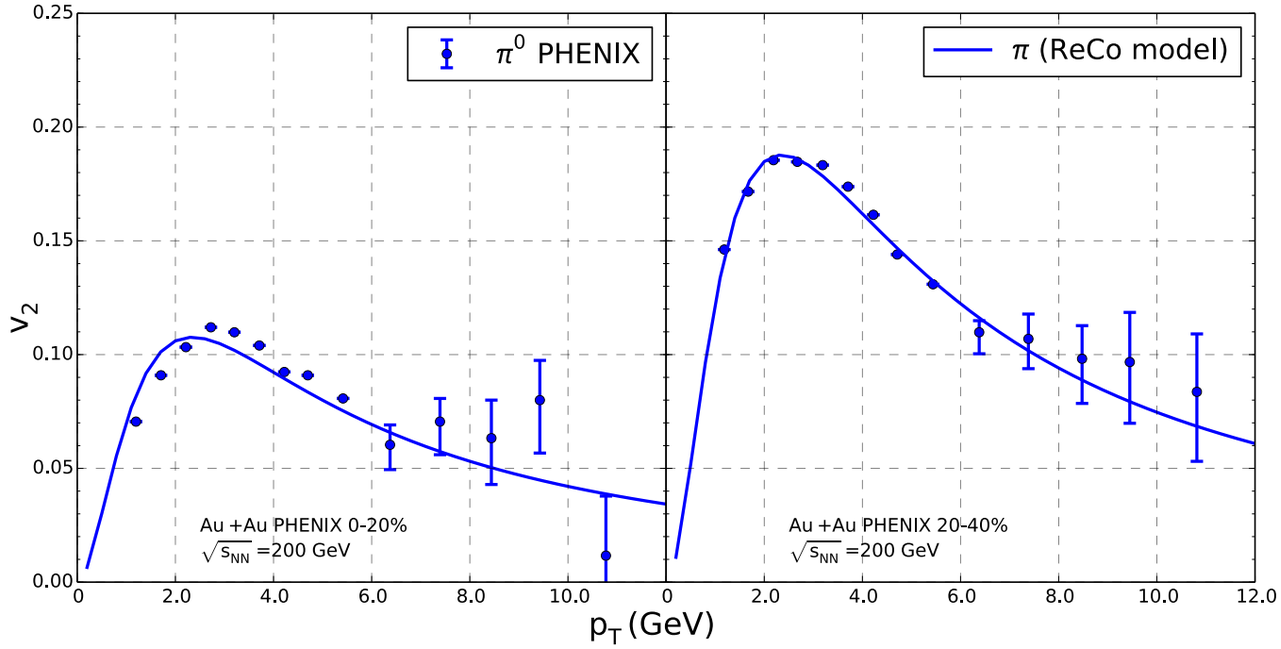


elliptic flow



The model violates energy conservation law.

Radiative recombination model

- We modify the ReCo model to satisfy energy conservation law by photon emission. [H. Fujii, K. Itakura, C. Nonaka NPA 967 (2017)]

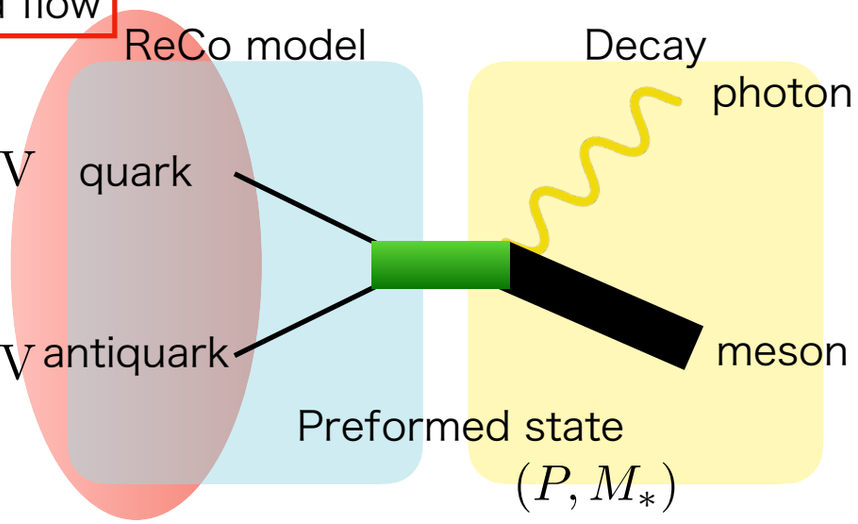
The number of photons emitted from preformed states

$$E_\gamma \frac{dN_\gamma}{d^3k_\gamma} = \kappa \int dM_* \rho(M_*) \int d^3P \left(\frac{dN_{M_*}}{d^3P}\right) \left(\epsilon_\gamma \frac{dn_\gamma(M_*, P)}{d^3k_\gamma}\right)$$

Normalization — ReCo model — Decay

Input
parton's dist. and flow

$$q + \bar{q} \to M + \gamma$$



$m_1 = 300\mathrm{MeV}$

$m_2 = 300\mathrm{MeV}$

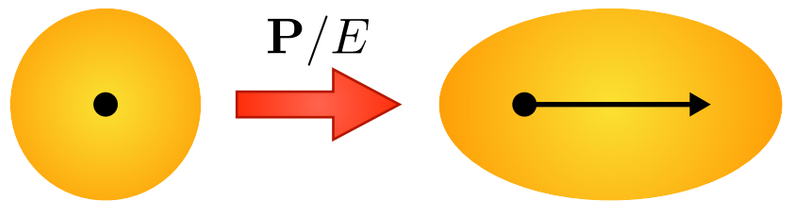
In the case of pion

$$\rho(M_*) = \delta(M_* - (m_1 + m_2))$$

$$M_* = m_1 + m_2 = 600\ \mathrm{MeV}$$

A photon emitted from
a moving preformed state

$$\epsilon^\gamma_{\mathrm{CM}} \frac{dn_\gamma}{d^3k^\gamma_{\mathrm{CM}}} = c\delta(k^\gamma_{\mathrm{CM}} - k_0)$$



Isotropic at M* rest frame — Boosted by velocity

Radiative recombination model

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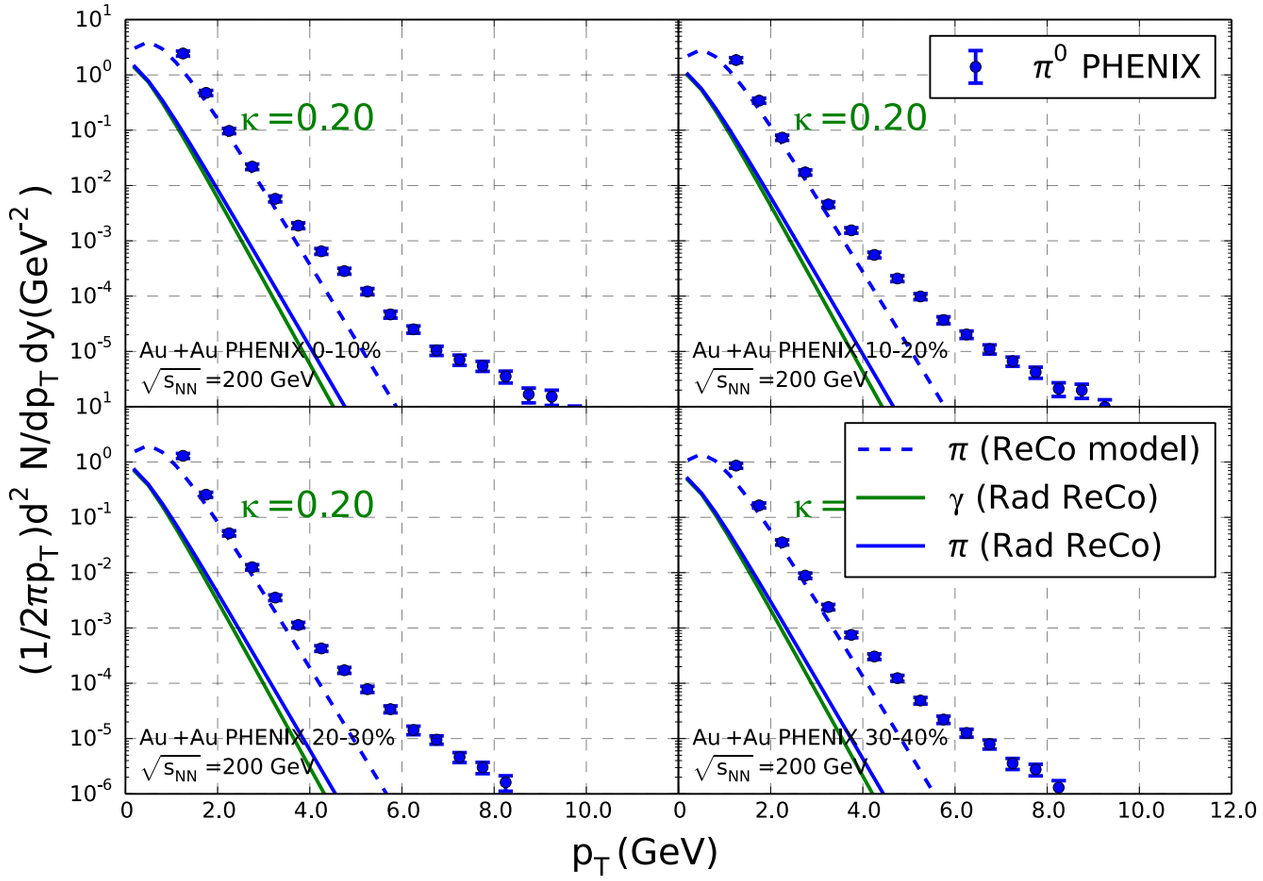
Normalization — ReCo model — Decay

p_T distribution



RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

- κ is determined by experimental data of direct photon yield.
- Yield of pions with photon emission is very small compared to yield of pion from original ReCo model.

Radiative hadronization in pion production is subdominant process.

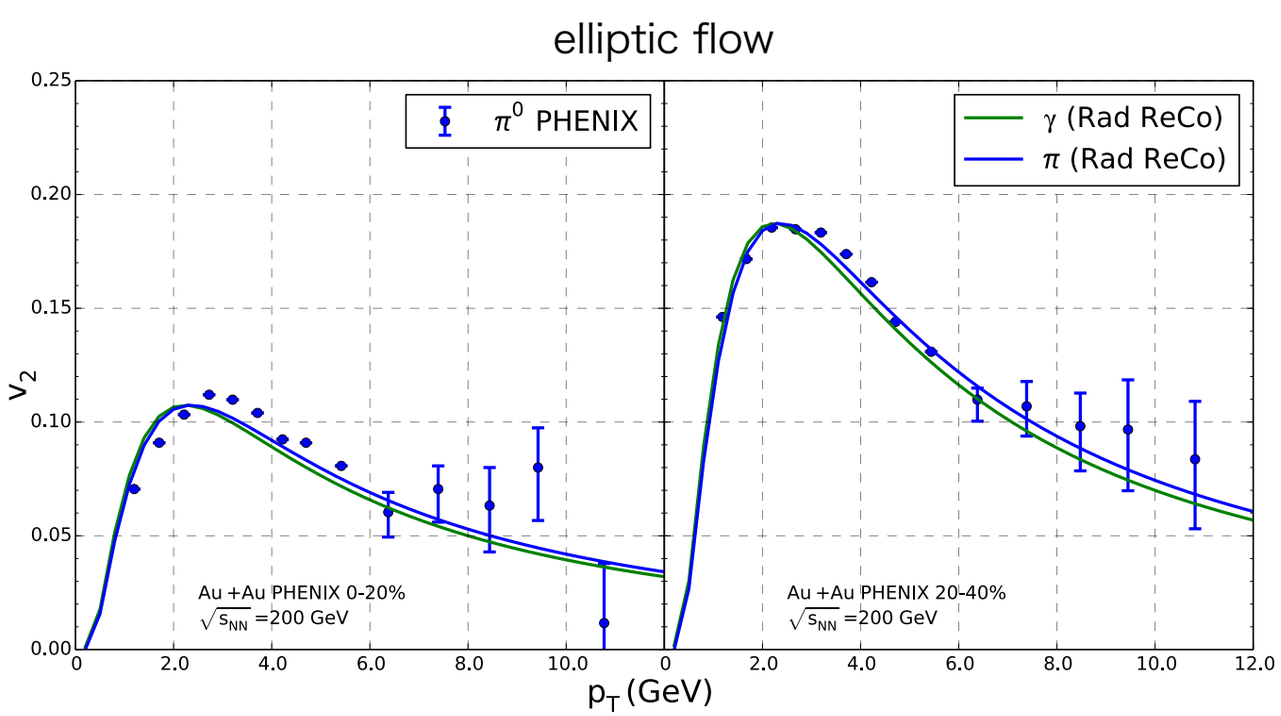
Radiative recombination model

- We modify the ReCo model to satisfy energy conservation law by photon emission. [H. Fujii, K. Itakura, C. Nonaka NPA 967 (2017)]

The number of photons emitted from preformed states

$$E_\gamma \frac{dN_\gamma}{d^3k_\gamma} = \kappa \int dM_* \rho(M_*) \int d^3P \left(\frac{dN_{M_*}}{d^3P}\right) \left(\epsilon_\gamma \frac{dn_\gamma(M_*, P)}{d^3k_\gamma}\right)$$

Normalization　　ReCo model　　Decay



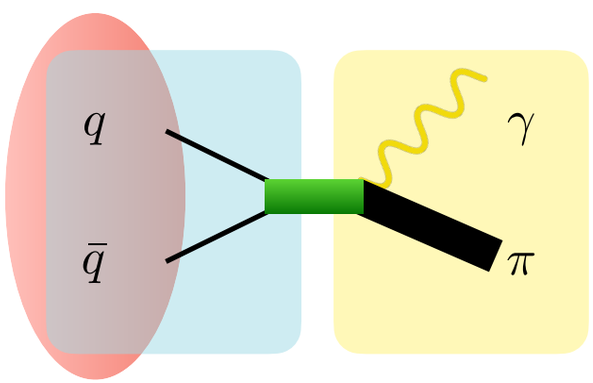
RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

- Photon's v_2 is as large as pion's v_2.

Thermal + Rad ReCo

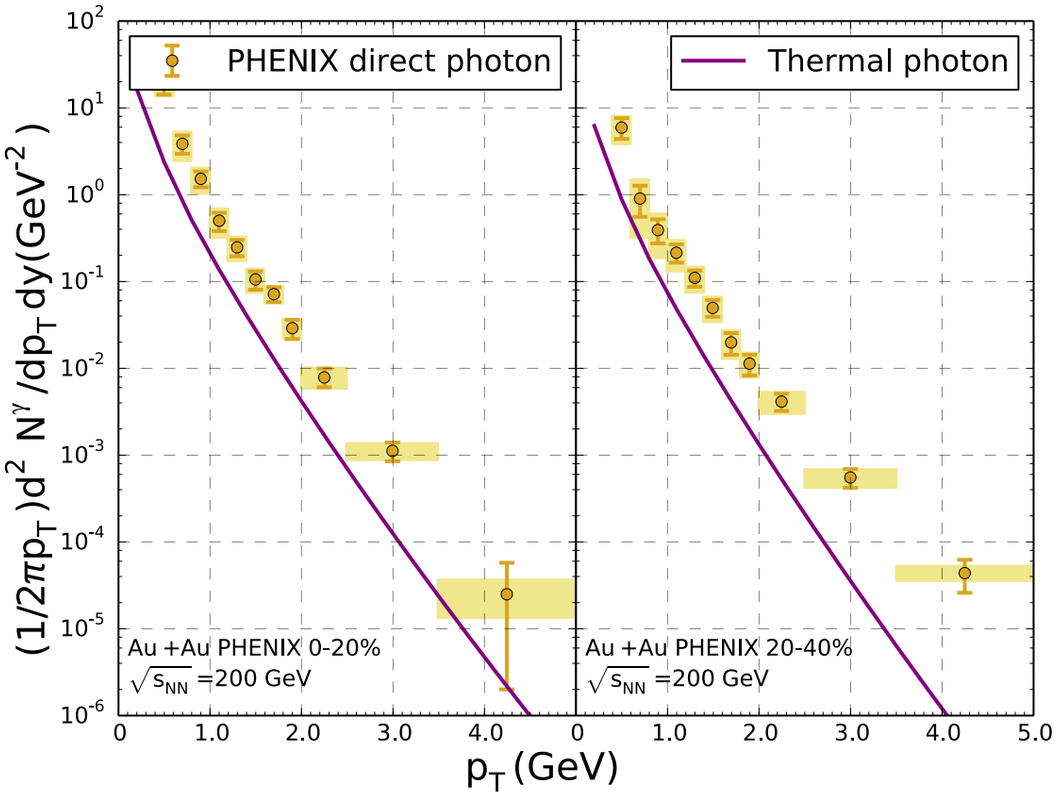
- Results of thermal photons and photons emitted at hadronization



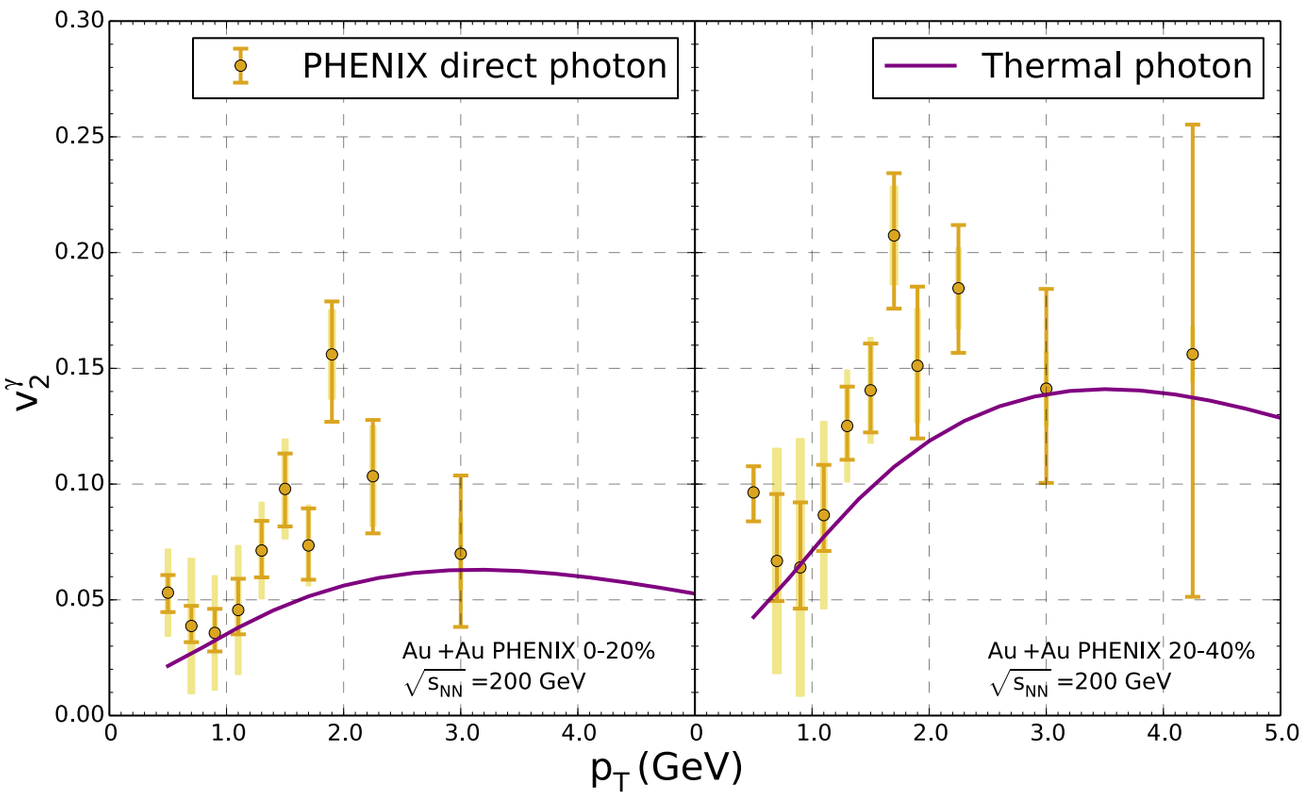
RHIC@BNL

Au+Au $\sqrt{S_{NN}}$ = 200 GeV

p_T distribution

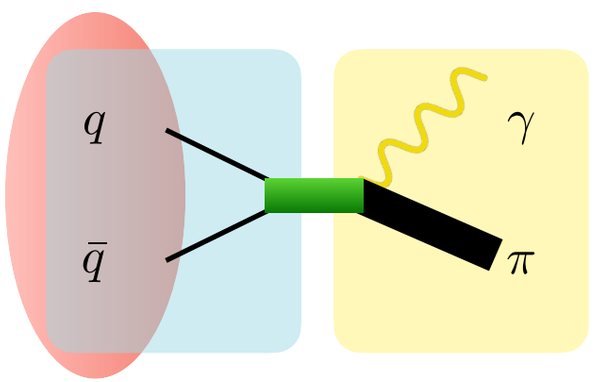


elliptic flow



Thermal + Rad ReCo

- Results of thermal photons and photons emitted at hadronization

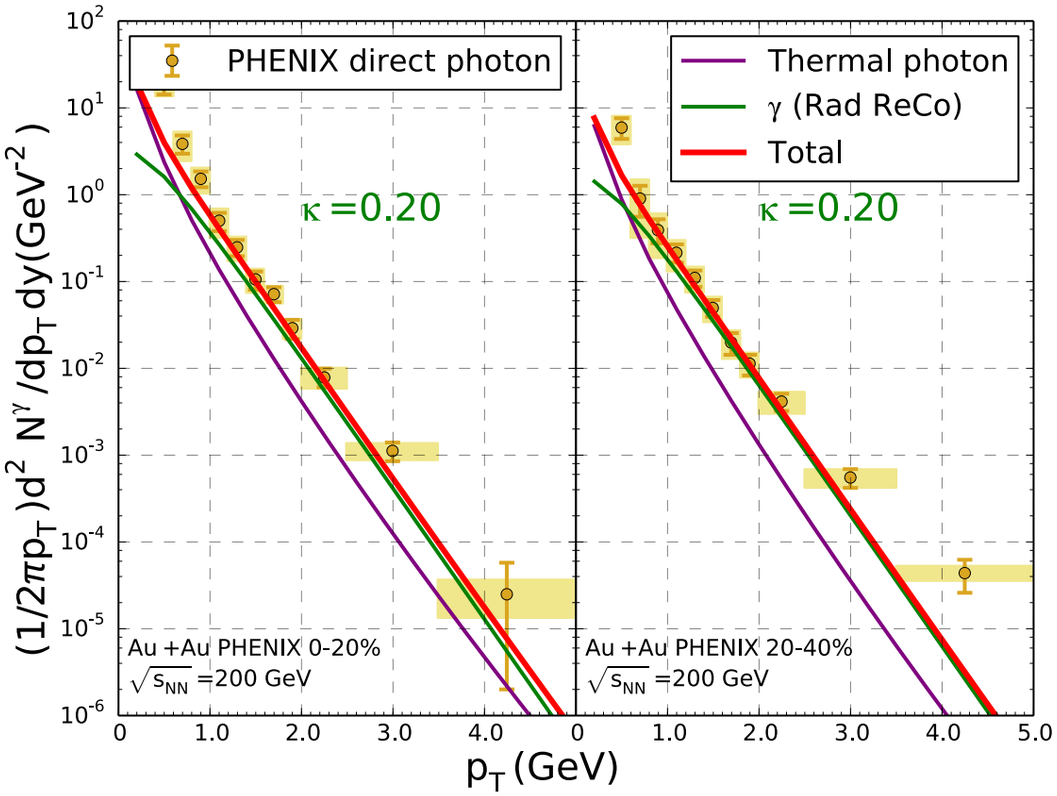


- Photon emission at hadronization enhance both direct photon yield and flow at the same time!
- Radiative hadronization in photon production give a significant contribution.

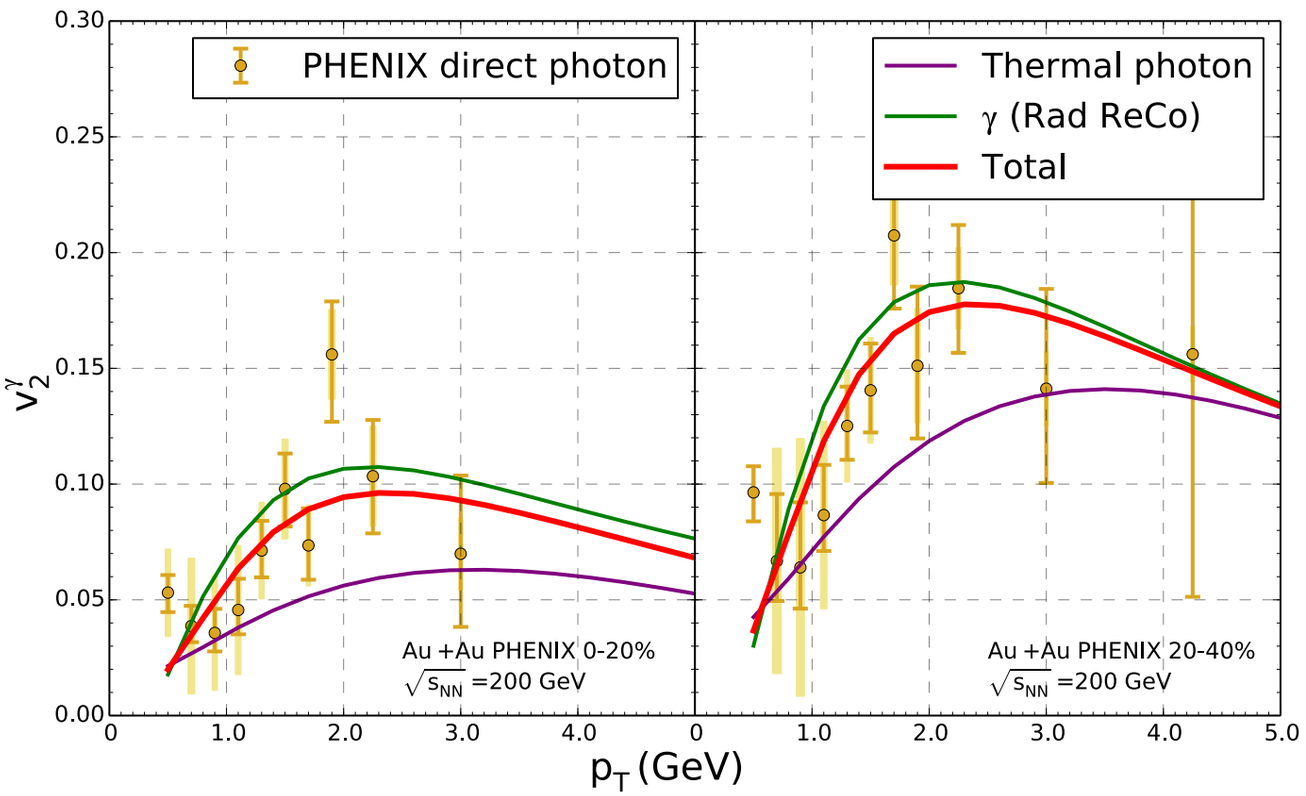
RHIC@BNL

Au+Au $\sqrt{s_{NN}}$ = 200 GeV

p_T distribution



elliptic flow



Thermal + Rad ReCo

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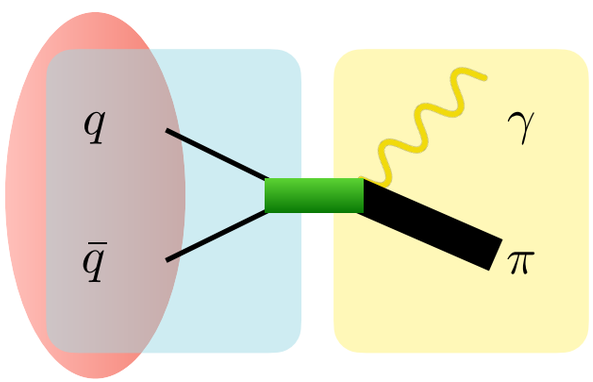
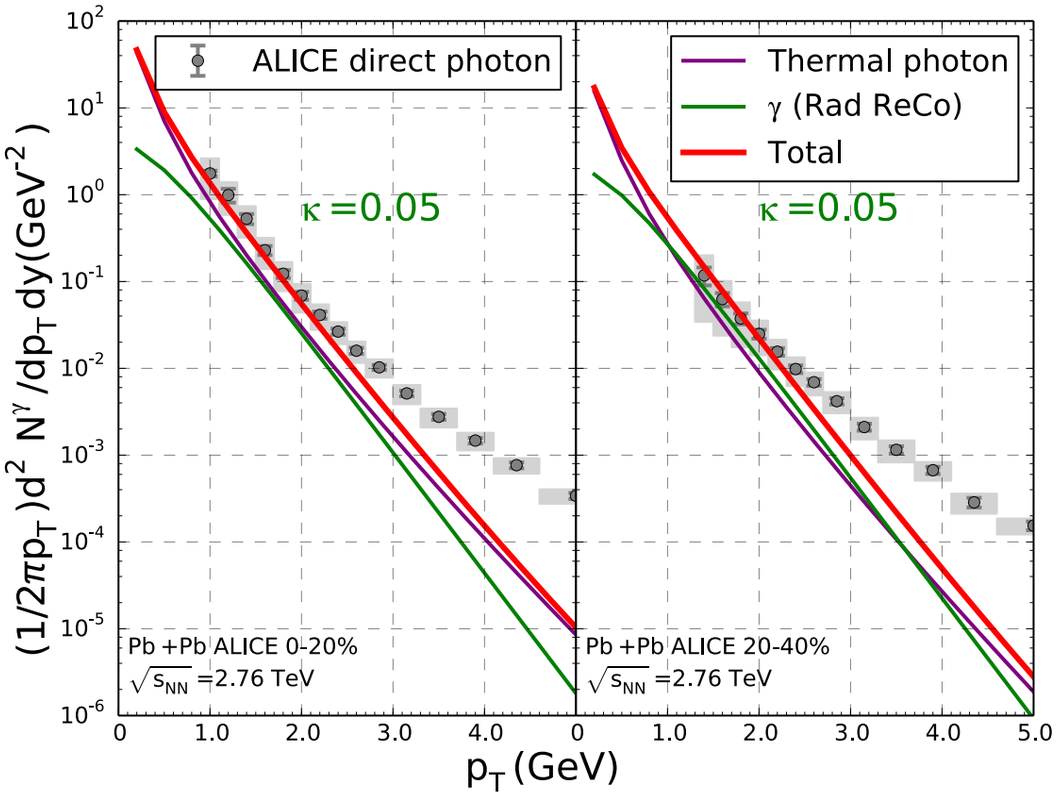


- Photon emission at hadronization enhance both direct photon yield and flow at the same time!
- Radiative hadronization in photon production give a significant contribution.
- κ is small compared to the PHENIX result.

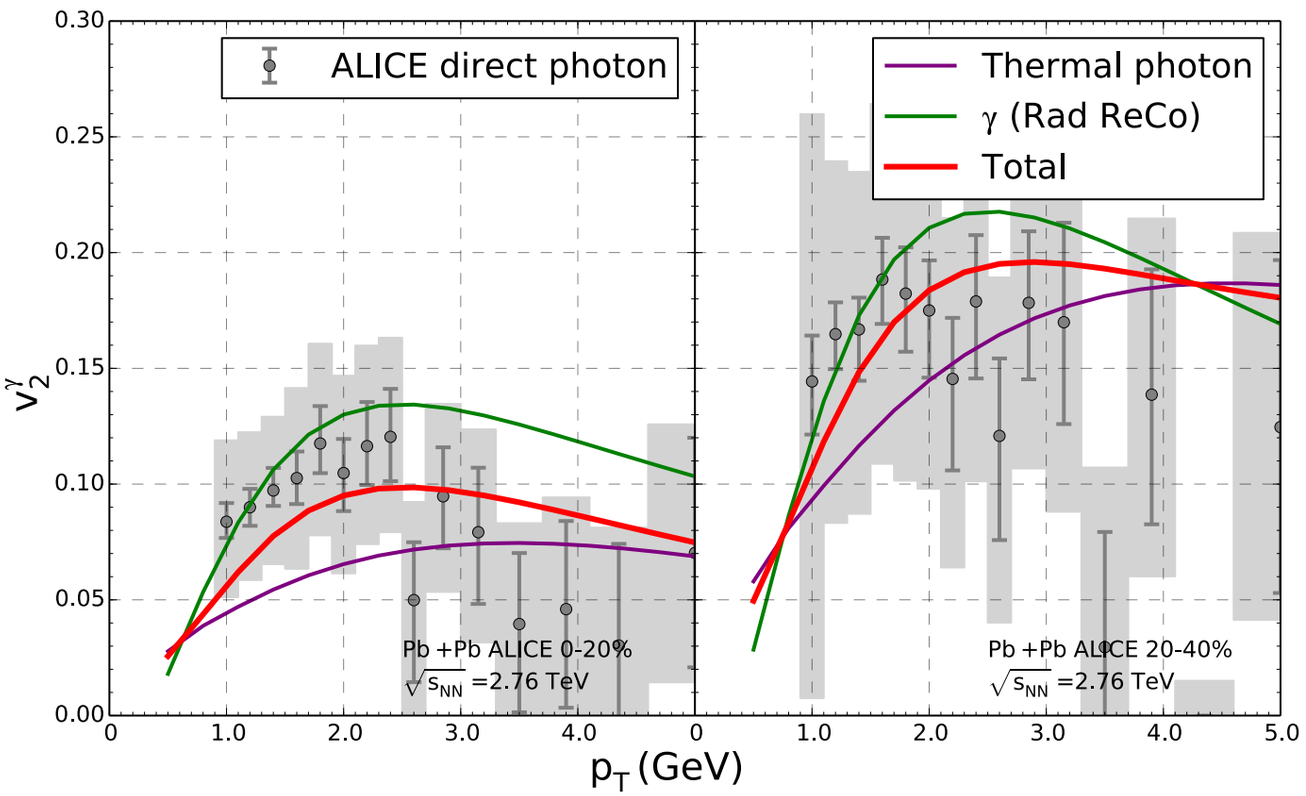
LHC@CERN

Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV

p_T distribution



elliptic flow



Summary

- We propose photon emission at hadronization. As a result, we succeed to enhance both direct photon yield and elliptic flow at the same time and reproduce experimental data at RHIC and LHC.