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arXiv:2204.03116

Photon Production in High-Energy Heavy-Ion Collisions: Thermal Photons and Radiative Recombination

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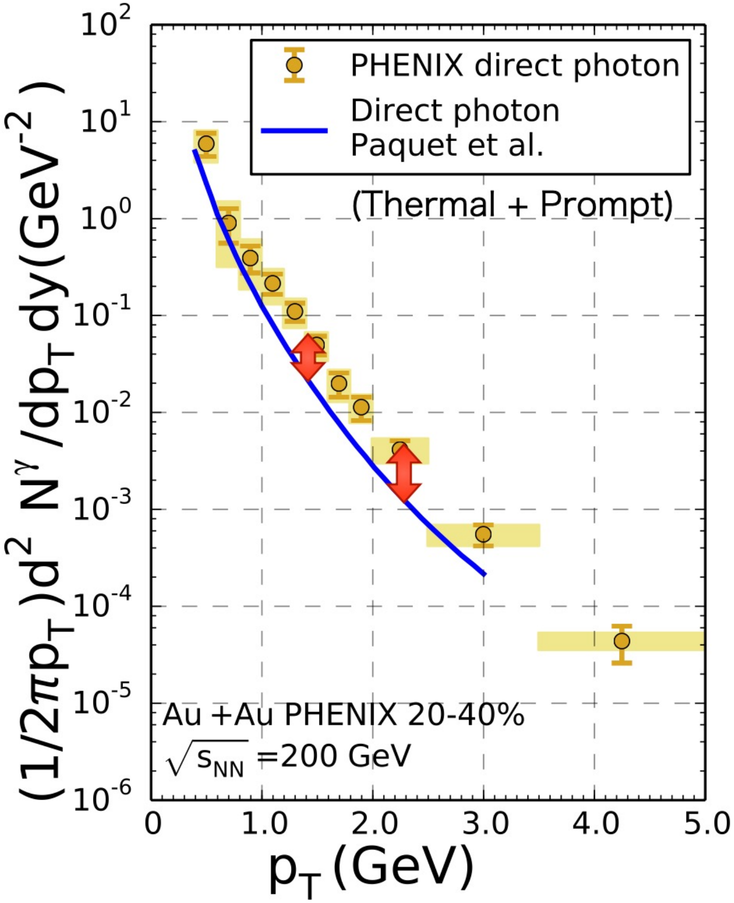
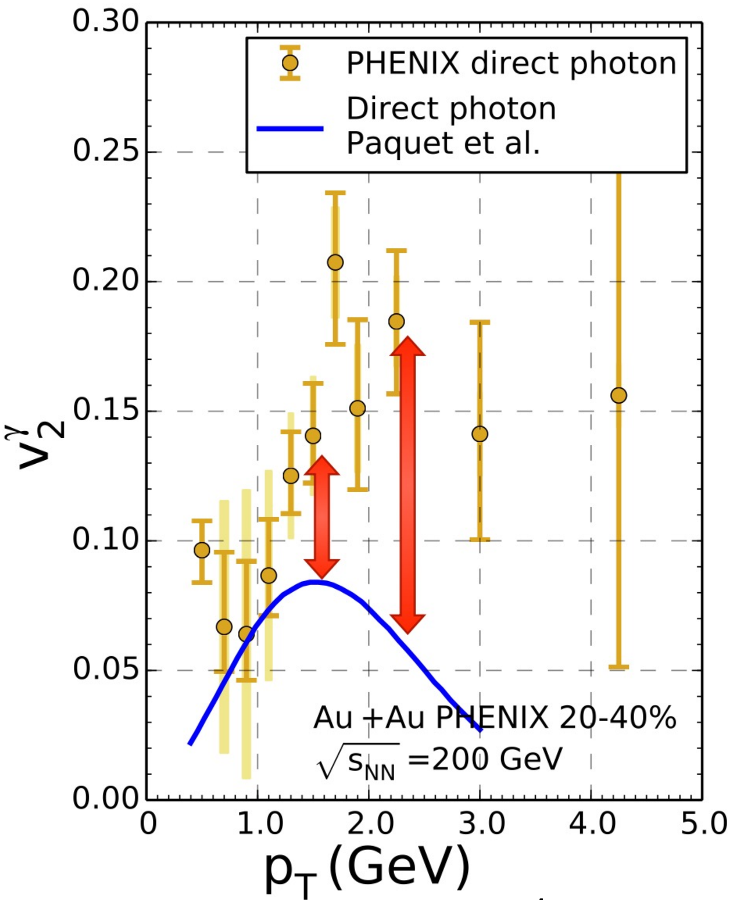
April 7 , 2022

Photon Puzzle

p_T spectra



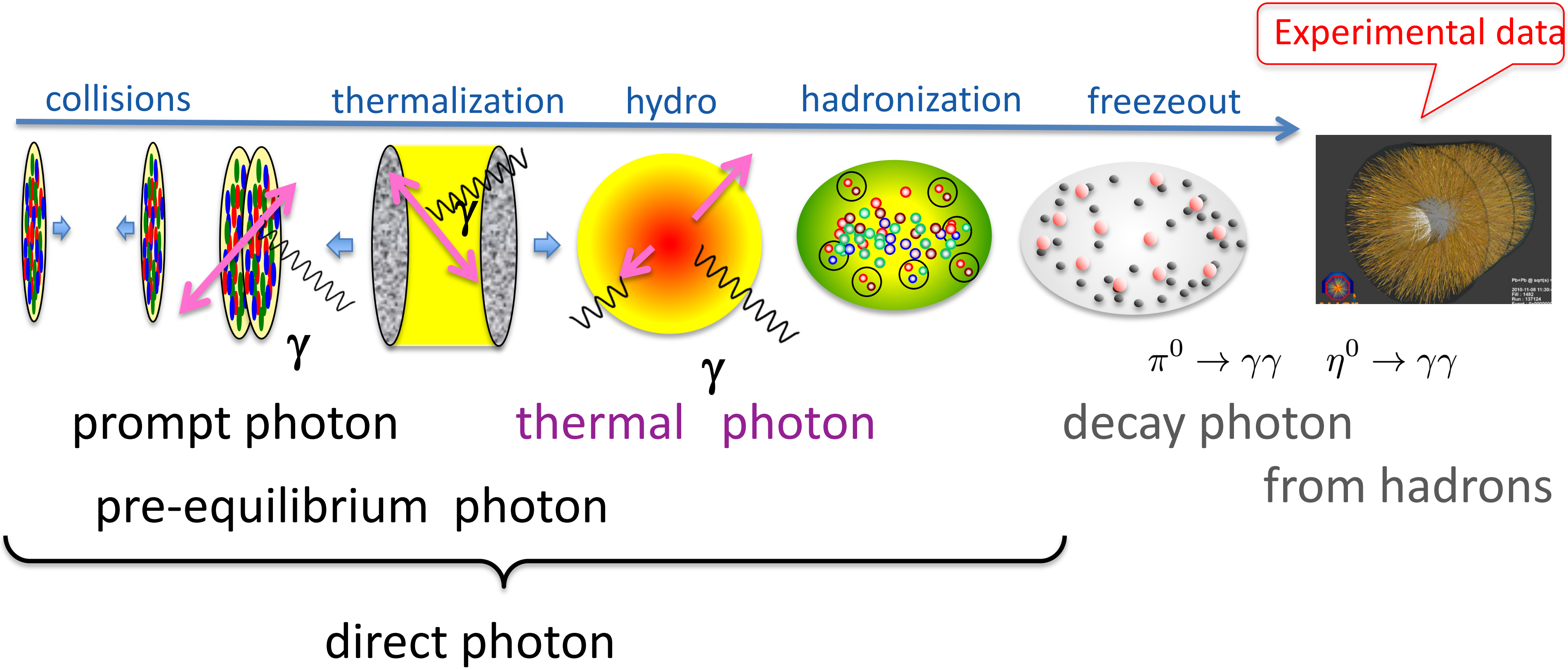
elliptic flow



Paquet et.al. PRC93,044906(2016)

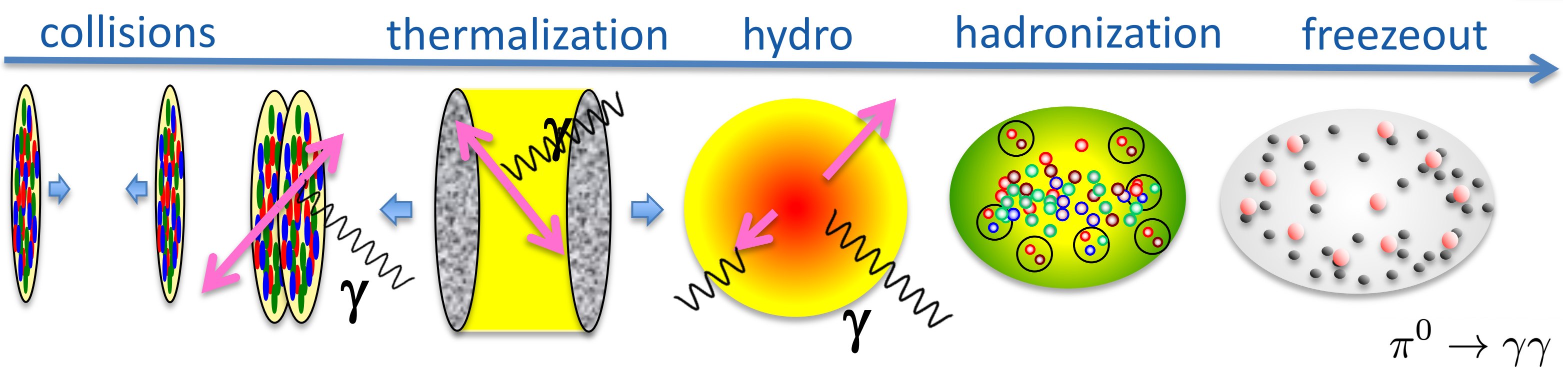
Theoretical calculations of photon yield and flow are smaller than experimental data at RHIC and the LHC.

Possible Photon Sources

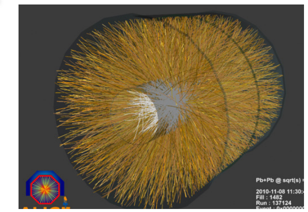


Thermal Photons from Hydrodynamics

Okamoto and CN, PRC98, 054906(2018)



Experimental data

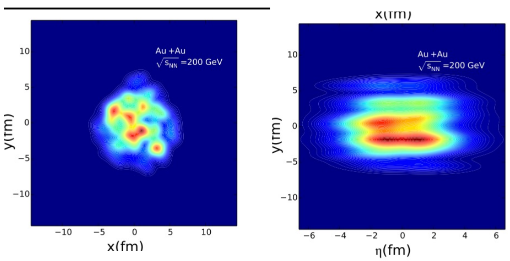


$\pi^0 \to \gamma\gamma \quad \eta^0 \to \gamma\gamma$

TRENTO

Phenomenological model
Parametrization

Moreland et al., PRC92, 011901(2015)
Ke et al., PRC96, 044192(2017)

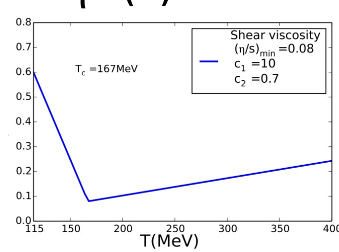


Hydrodynamic Expansion

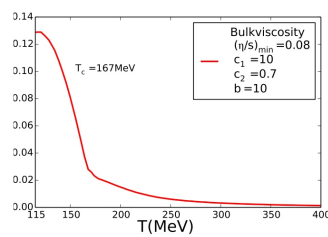
$$\partial_\mu T^{\mu\nu} = 0$$

Denicol et al, PRD85, 114047 (2012)
lattice QCD
+ hadron resonance gas EoS

η/s(T)



ζ/s(T)



UrQMD

Bass et al., Prog.Part.Nucl.Phys.(1998)
Bleicher et al., J.Phys.G25,1859(1999)

$T_{\rm SW} = 150 \text{ MeV}$

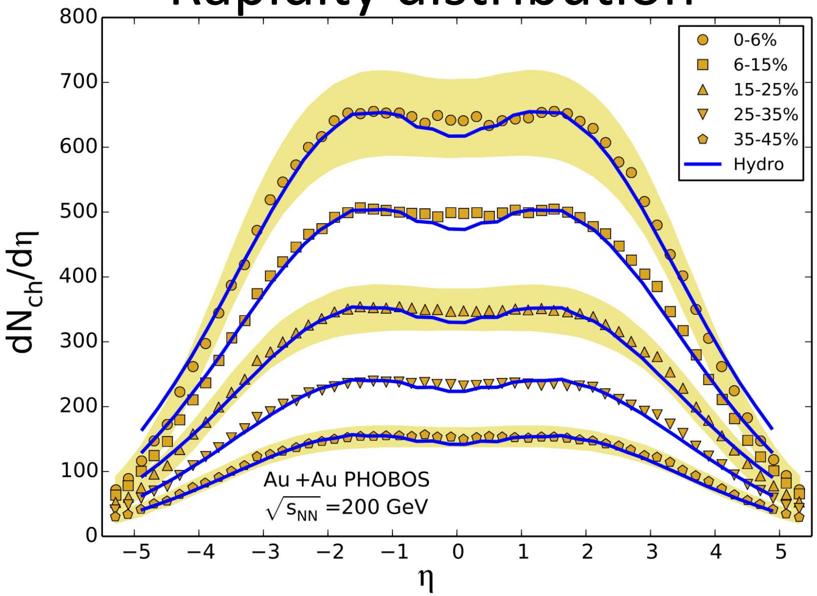
Cornelius, *Huovinen and Petersen*
Cooper-Fry formula

RHIC: Hadron's Yields and Flows

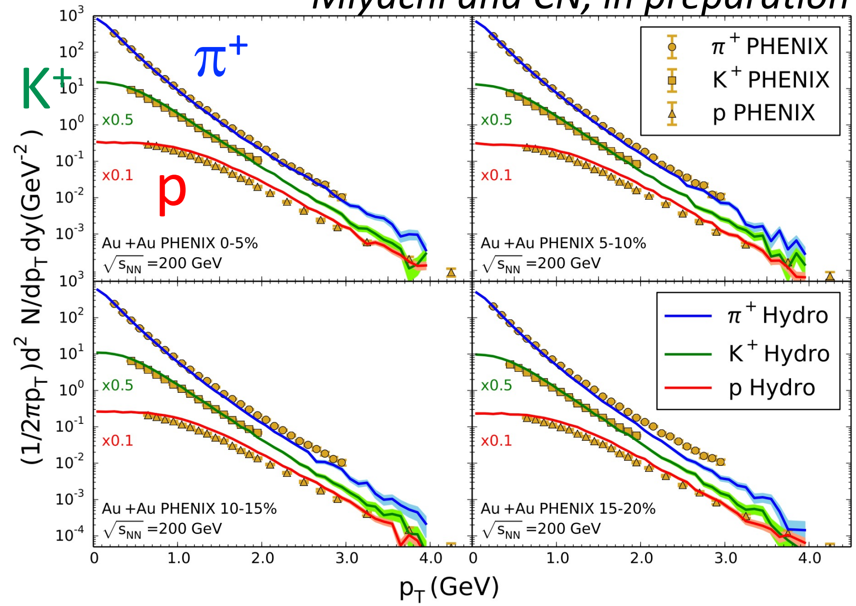
- $\sqrt{s_{NN}} = 200$ GeV

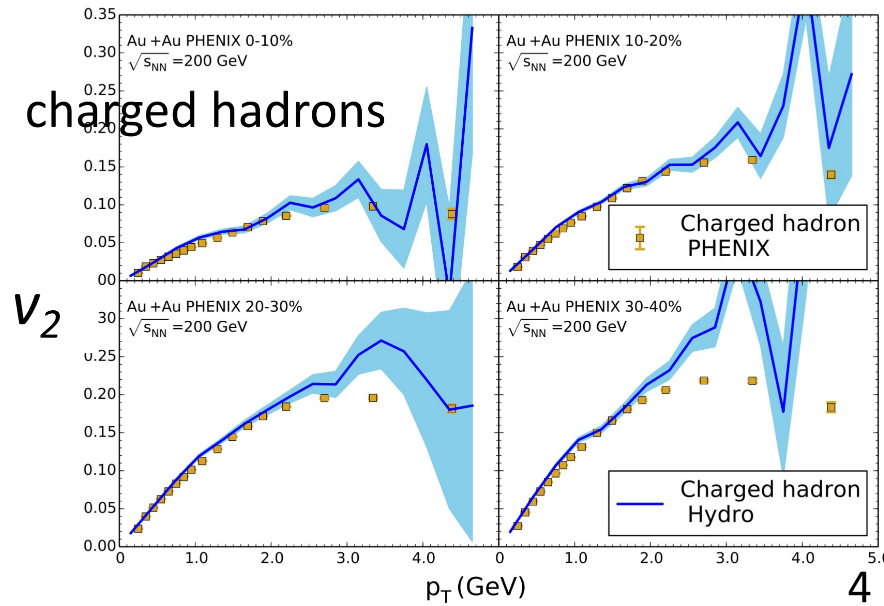
  Au+Au collisions

Rapidity distribution



Miyachi and CN, in preparation





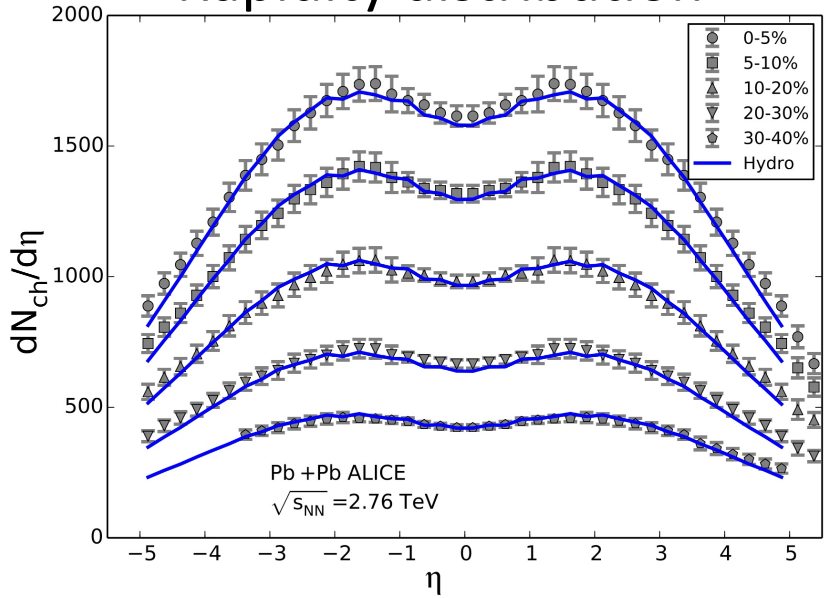
- Our hydrodynamic model reproduces hadron data at RHIC.

LHC: Hadron's Yields and Flows

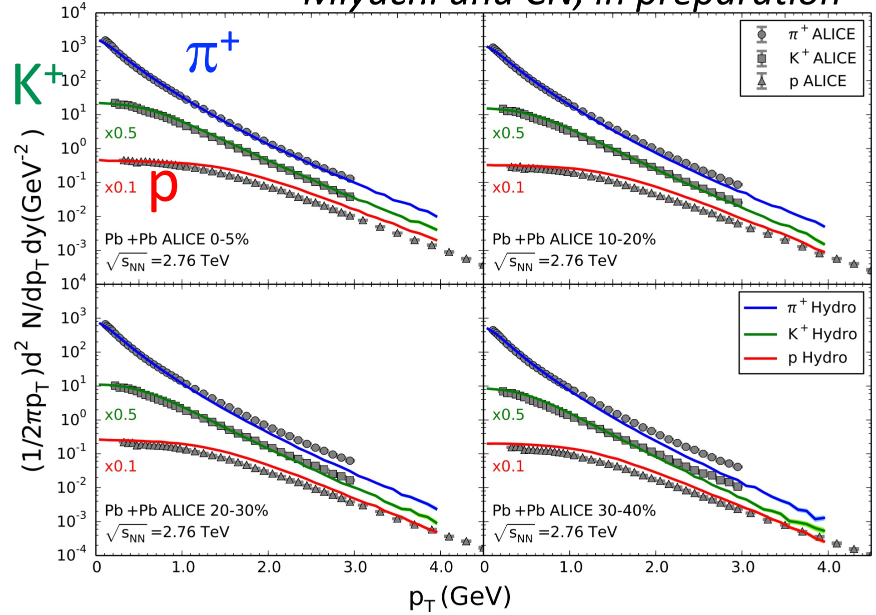
- $\sqrt{s_{NN}} = 2.76$ TeV

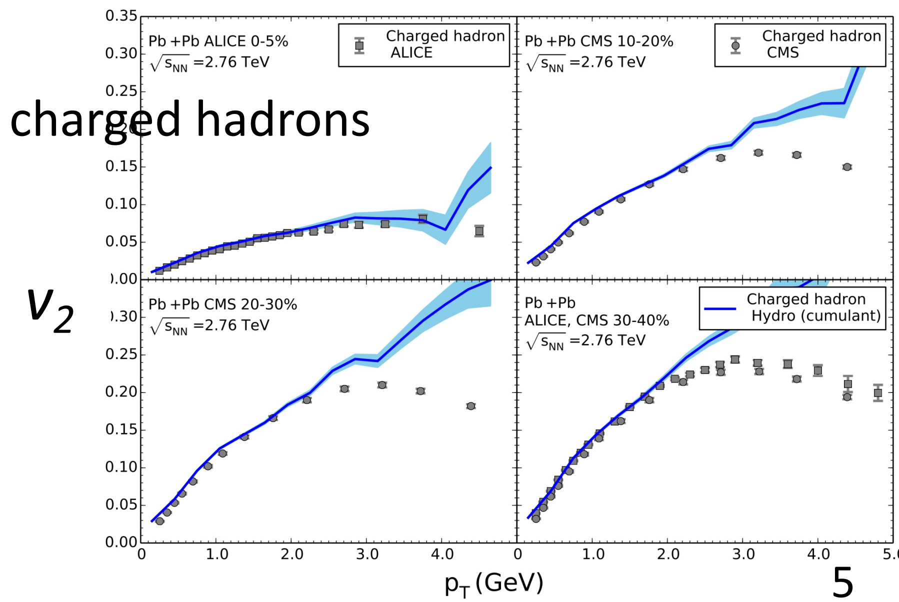
  Pb+Pb collisions

Rapidity distribution



Miyachi and CN, in preparation





- Our hydrodynamic model reproduces hadron data at the LHC.

Photon Emission Rate

QGP Phase — Crossover Phase Transition — Hadron Phase

QGP pQCD LO

AMY, JHEP 0112:009 (2001)

π, ρ, ω mesons

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

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

$T_c = 170$ MeV

Monnai, J. Phys. G 47 075105 (2019)

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

We evaluate photon production at late stage by hydrodynamic expansion, instead of calculation of photon production from UrQMD.

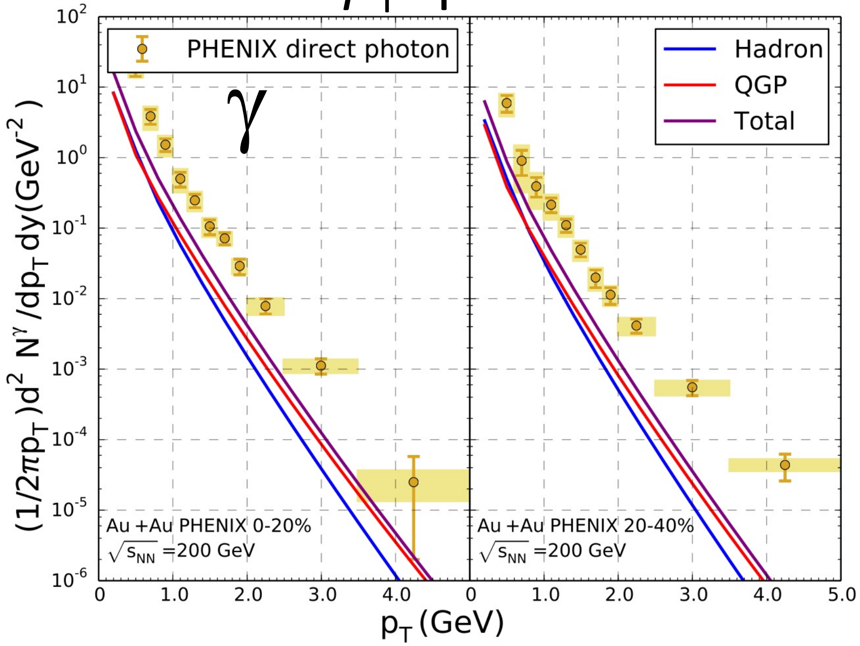
T_f=116 MeV: $v_2^{\gamma} \sim v_2^{had}$

RHIC: Thermal Photons

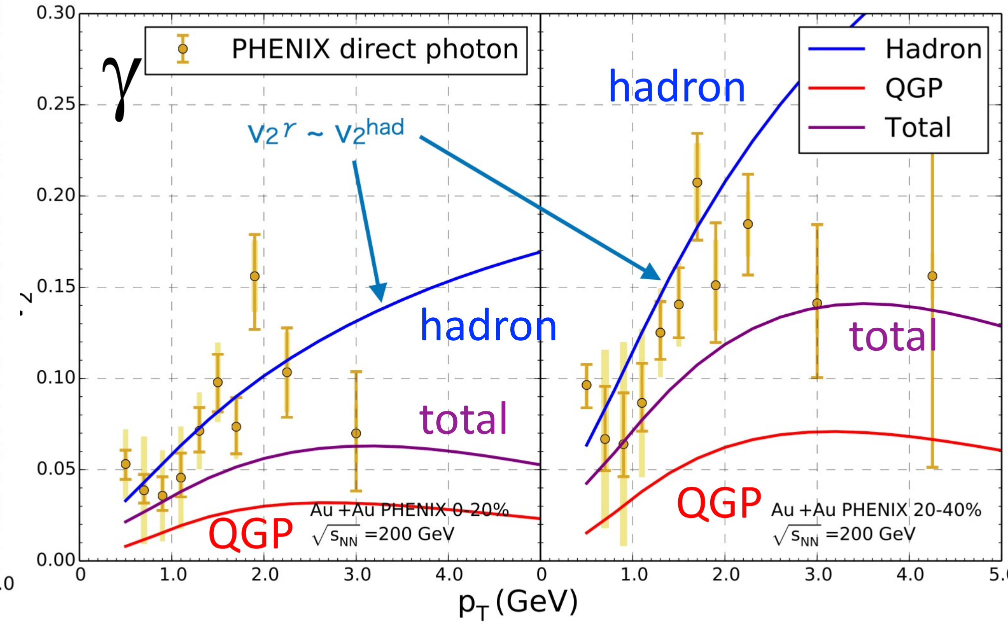
Miyachi and CN, in preparation

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

p_T spectra



Elliptic flow

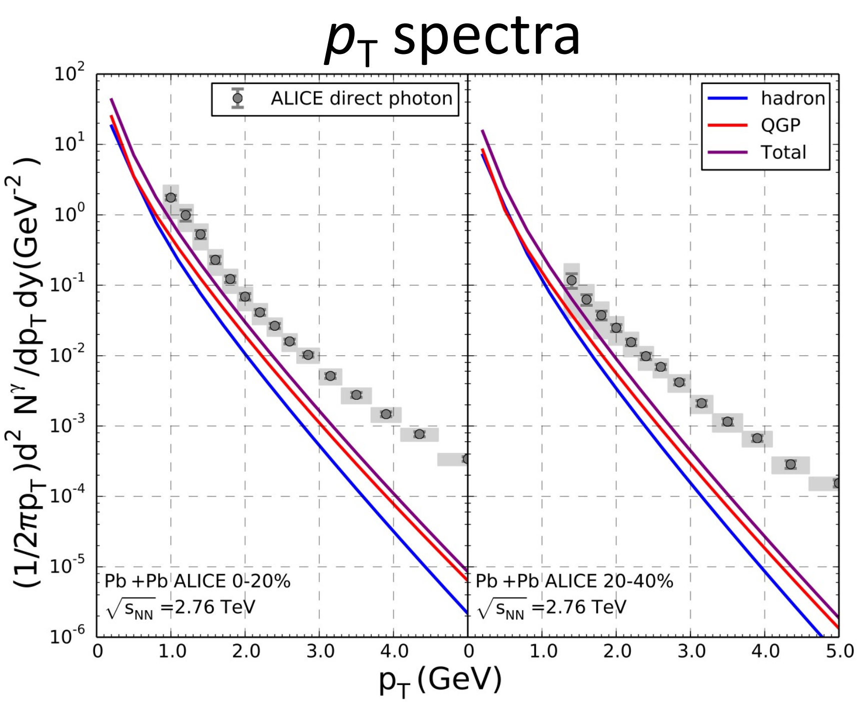


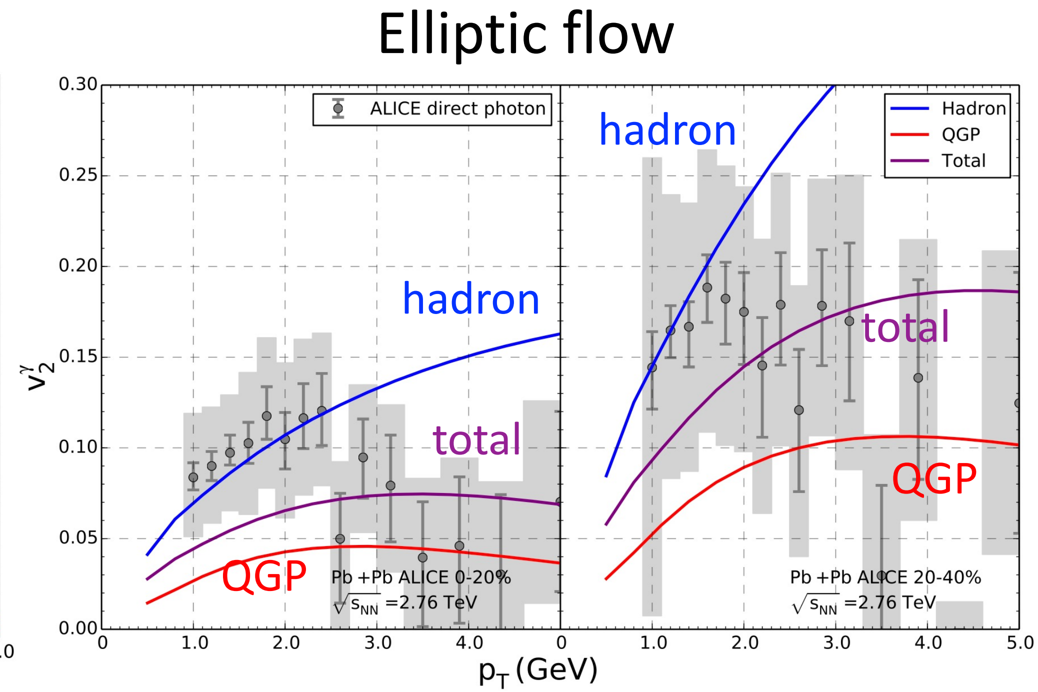
- Photon's yield and flow are smaller than those of experimental data.

LHC: Thermal Photons

Miyachi and CN, in preparation

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





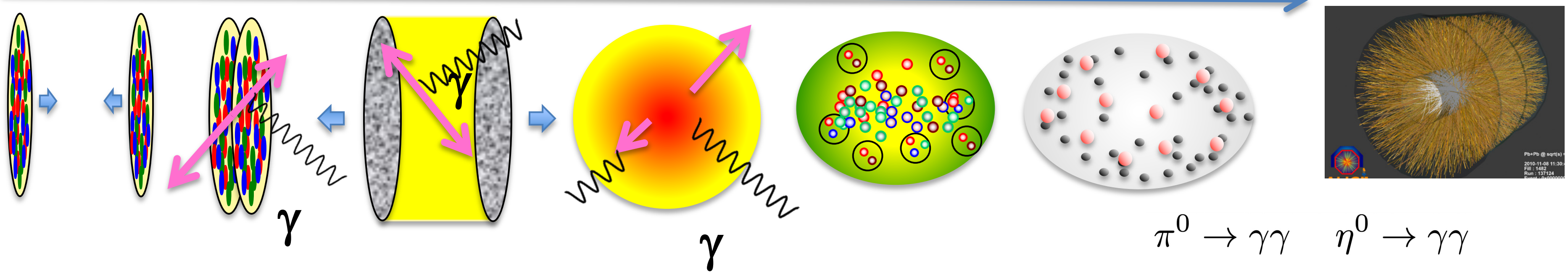
- Photon’s yield and flow are smaller than those of experimental data.

Thermal photon is not enough for explanation.

Photon Production at Hadronization

Experimental data

collisions thermalization hydro hadronization freezeout



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

prompt photon

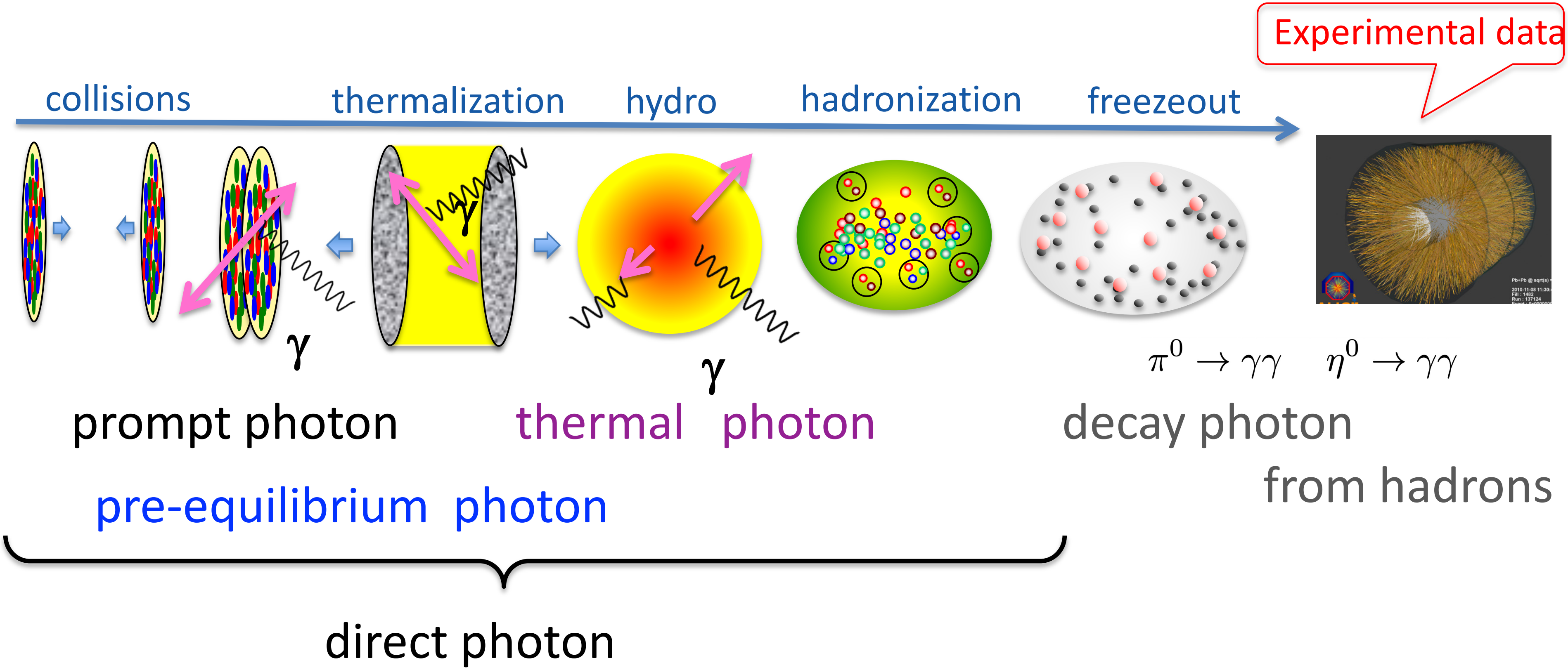
thermal photon

decay photon from hadrons

pre-equilibrium photon

direct photon

Photon Production at Hadronization



Pre-equilibrim Glasma stage
Berges et al., PRC95,054904(2017)
Monnai, JPG47,075105(2020)

radiative recombination

at hadronization

KOMPOST+hydro
Gale et al., PRC105,014909(2022)

Radiative Recombination in QGP

Fujii, Itakura, CN, NPA 967 (2017)

One of Photon Production Processes

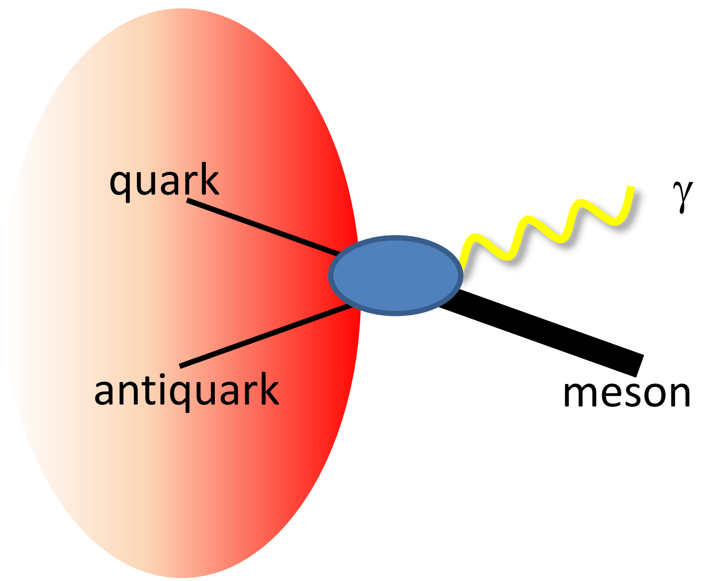
- Photon emission at hadronization process
  - Photon's flow is as strong as hadrons' flow.
- A photon is produced from pairing of quarks
  - Radiative recombination brings enhancement of photon yield.

Radiative Recombination in QGP

- Non perturbative process
- No inverse process in HIC
- Non equilibrium process

⇨ Construction of dynamical model

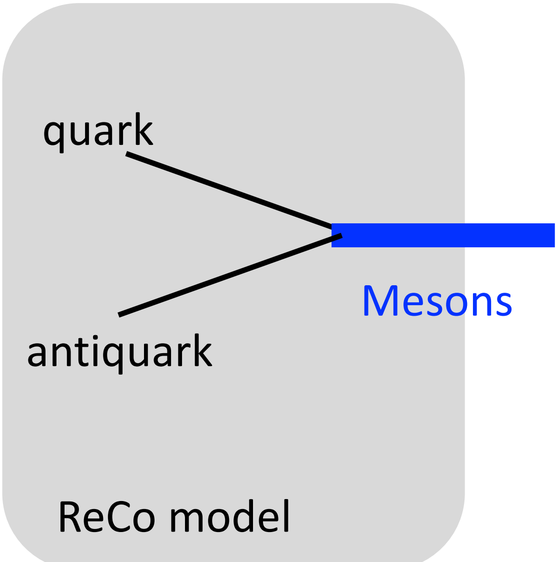
Recombination Model



Recombination Model

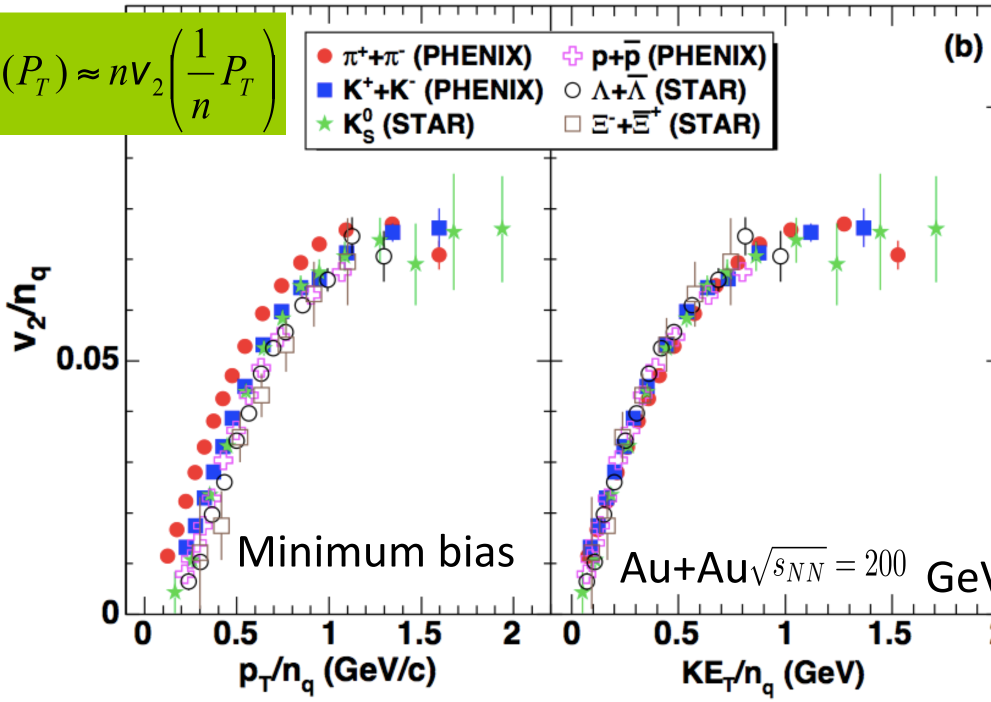
Fries, Mueller, CN and Bass, PRC68(2003)

- One of successful models



Ex: Quark number scaring

$$v_2^h(P_T) \approx n v_2\left(\frac{1}{n}P_T\right)$$



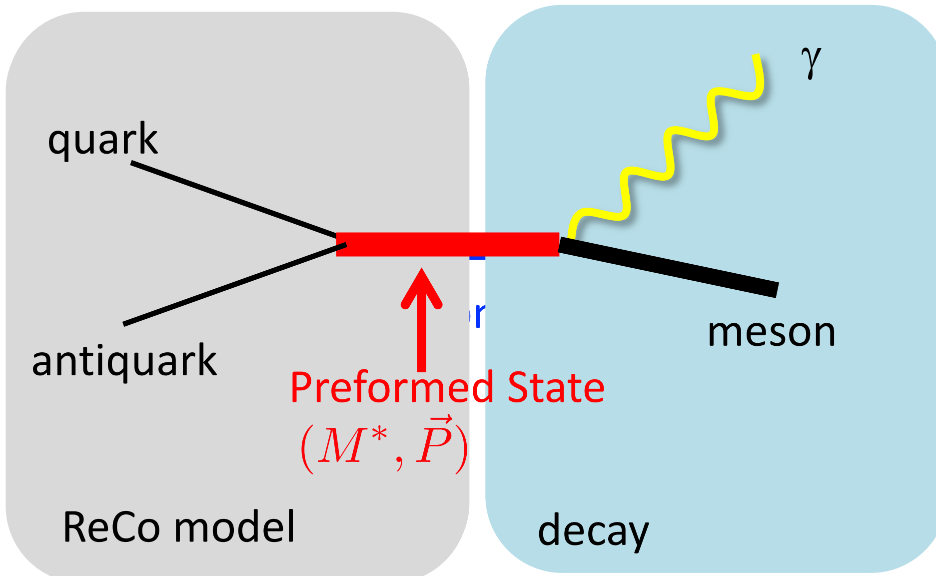
PHENIX,nucl-ex:0608033

- Baryon/Meson ratios
- Nuclear modification factors
- Quark number scaling in elliptic flow

ReCo with Photon Emission

- Entropy and Energy Conservation

Preformed state is produced through the recombination process.



Photons are emitted from decay of the preformed state.

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

normalization

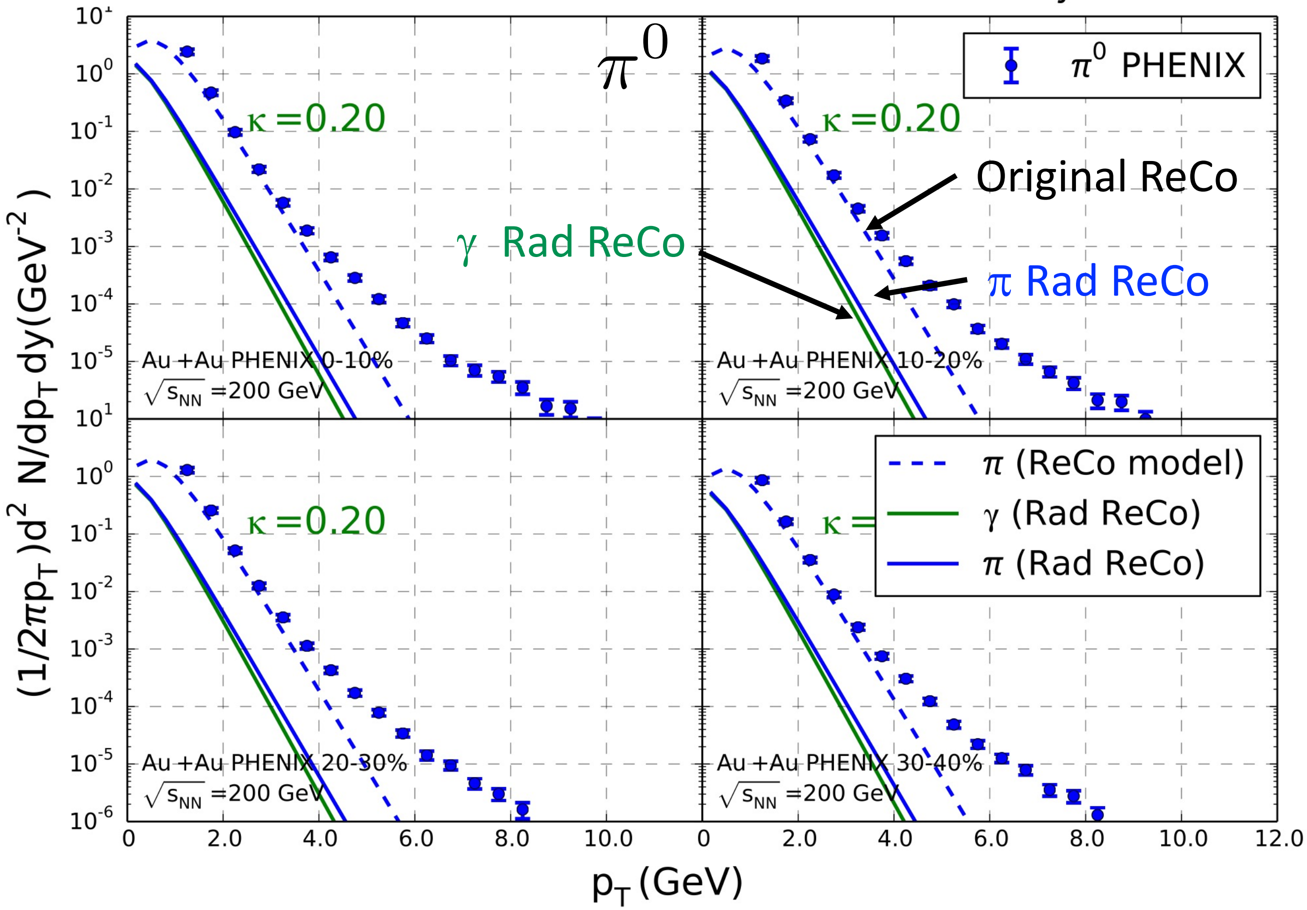
Preformed state

RHIC: Radiative Recombination

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

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

Normalization — ReCo model — Decay



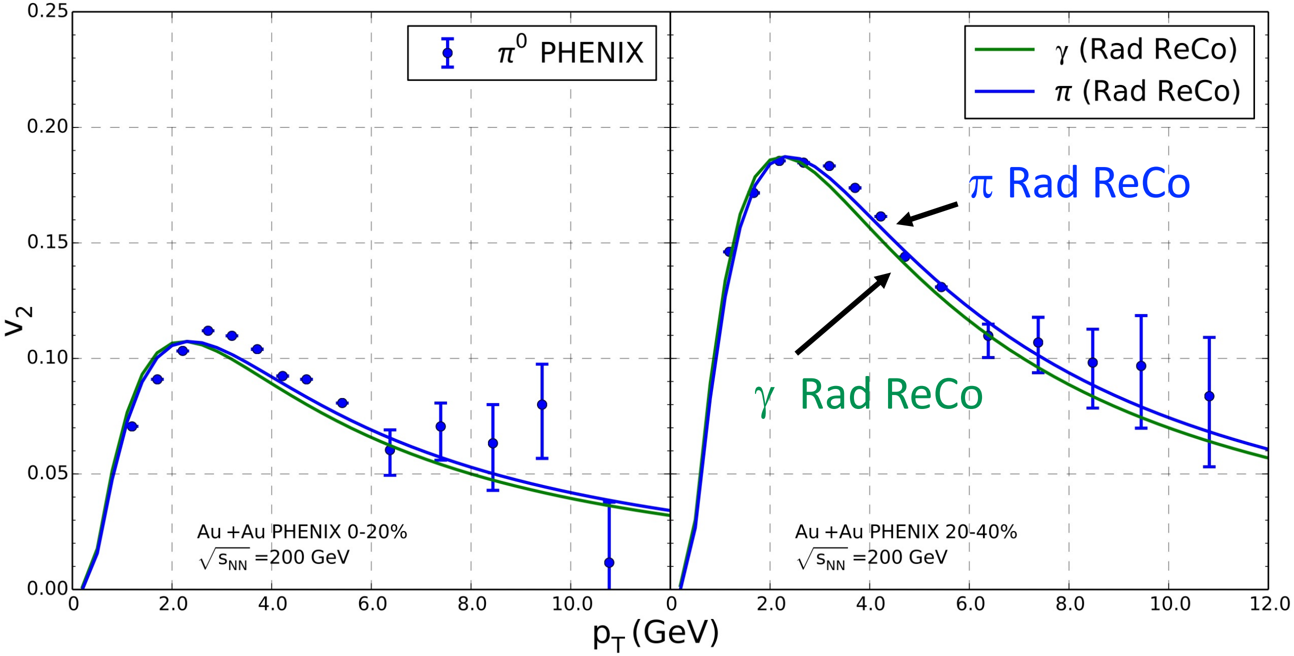
- κ is determined from γ yield.
- Yield of π from Rad ReCo is much smaller than that from original ReCo.
- Rad ReCo does not affect the feature of original ReCo.
- Quark number scaling keeps.

RHIC: Elliptic Flow from Rad ReCo

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

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

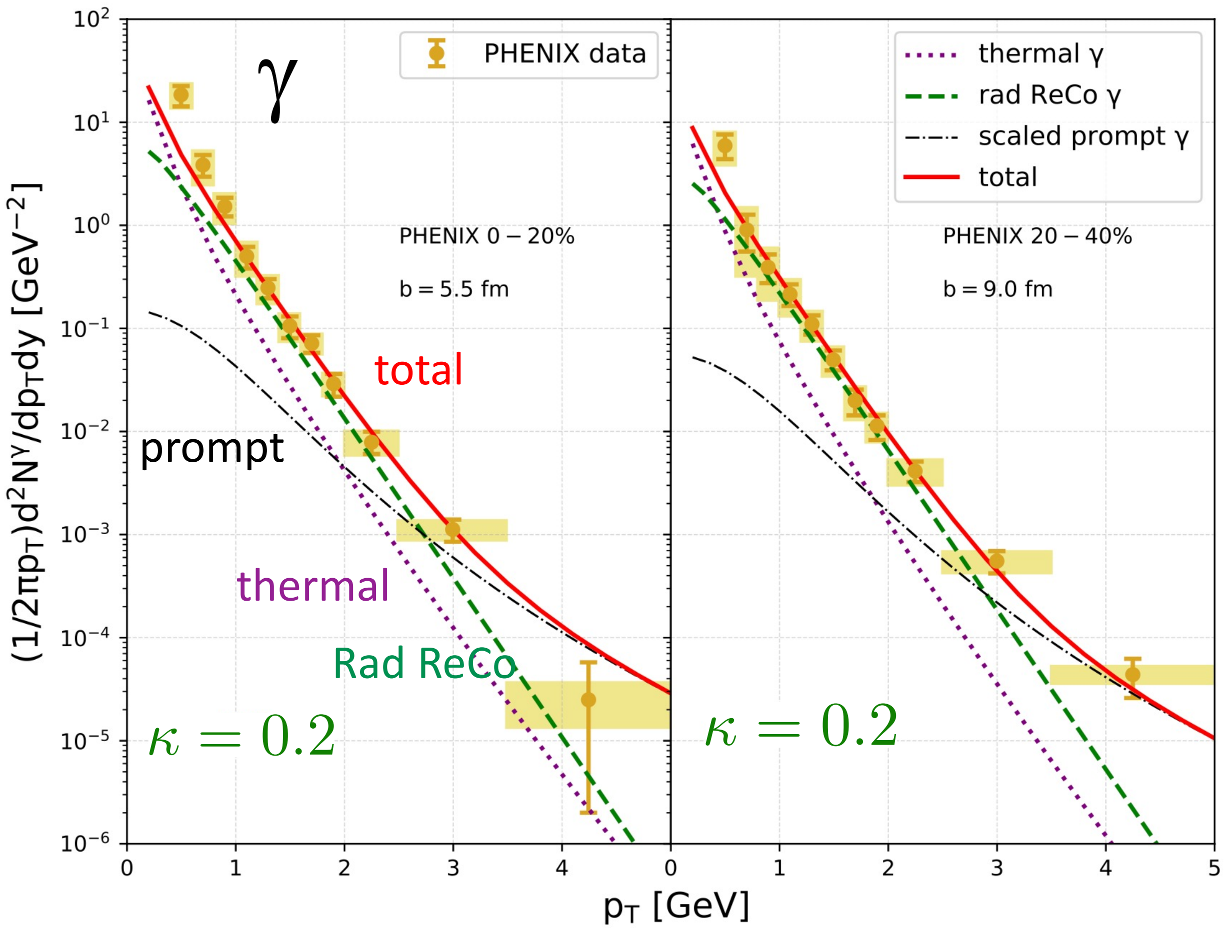
Normalization — ReCo model — Decay



- Photon's v_2 ~ π's v_2
- Quark number scaling keeps.

RHIC: Prompt + Thermal + Rad ReCo

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



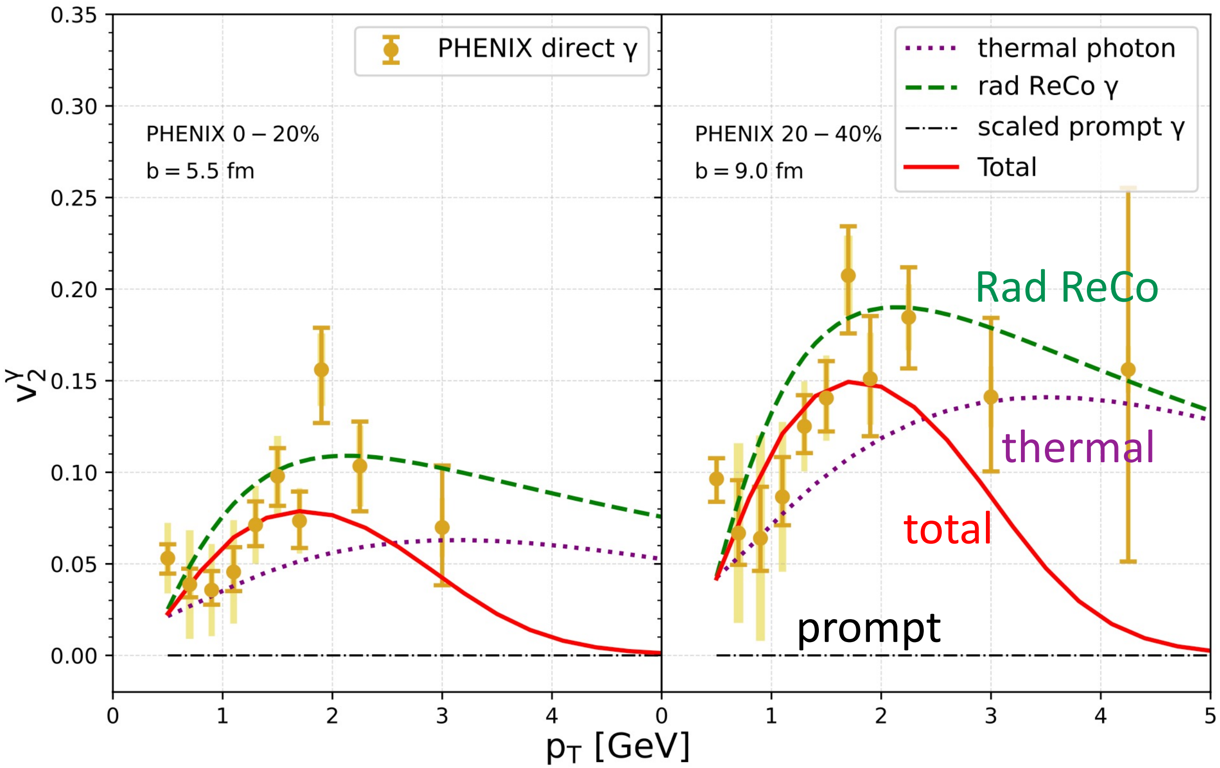
- κ=0.2 is determined from γ yield.
- At low p_T, thermal photon is dominant.
- In $1 < p_T < 3$ GeV, radiative recombination plays an important role.
- At high p_T, prompt photon becomes a main source.

- **Deficit of photon yield is filled with radiative recombination.**

RHIC: Prompt + Thermal + Rad ReCo

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

Elliptic flow



- At low p_T, v_2 becomes large due to radiative recombination.
- At high p_T, prompt photon makes v_2 small.

- **Total photon's v_2 is as large as experimental data.**

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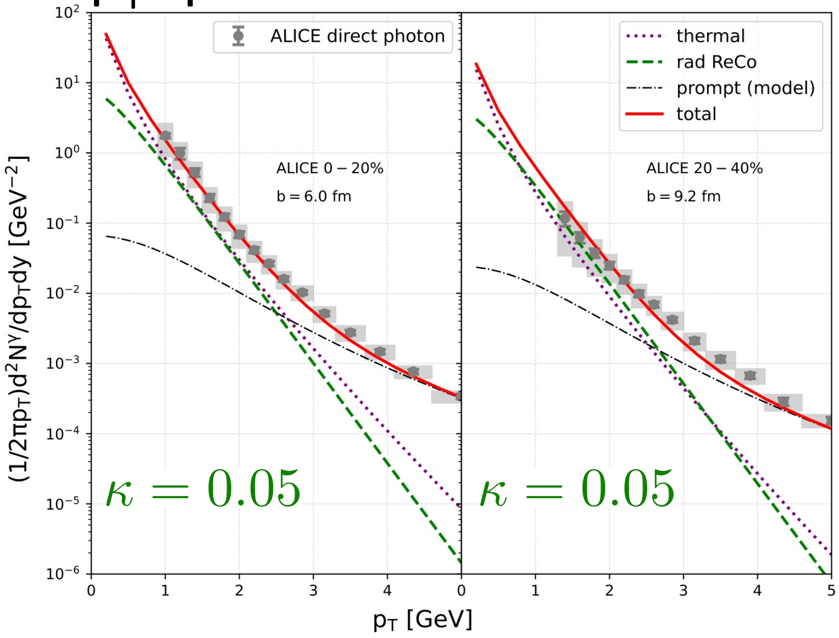
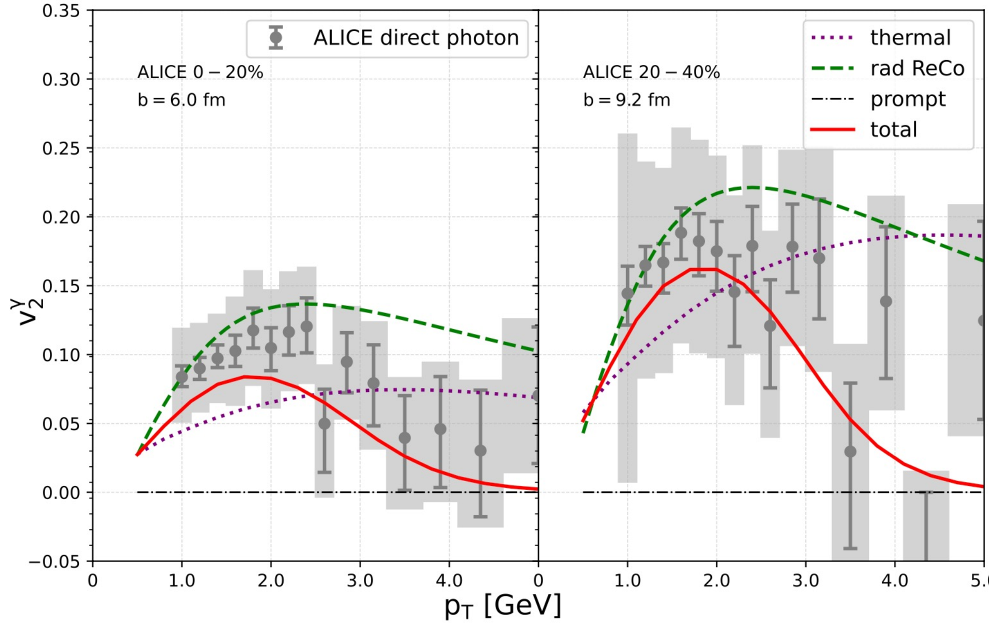
LHC: Prompt + Thermal + Rad ReCo

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

p_T spectra



Elliptic flow



- **Radiative Recombination makes photon's yields and flows enlarge at the same time.**

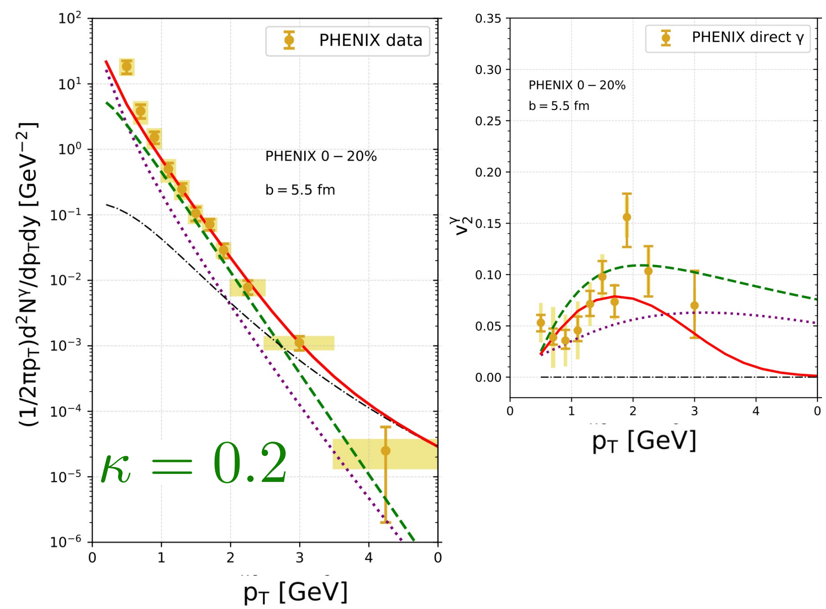
Summary

arXiv:2204.03116

Comprehensive analyses for photon production at RHIC and the LHC

- New photon production source at hadronization: Radiative recombination model
- Thermal photons from the state-of-the-art hydrodynamic model.

- Discussions
  - Interpretation of κ?
  - Preformed state?



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Back Up

Thermal Photons

- How to analyze v2 of thermal photons

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

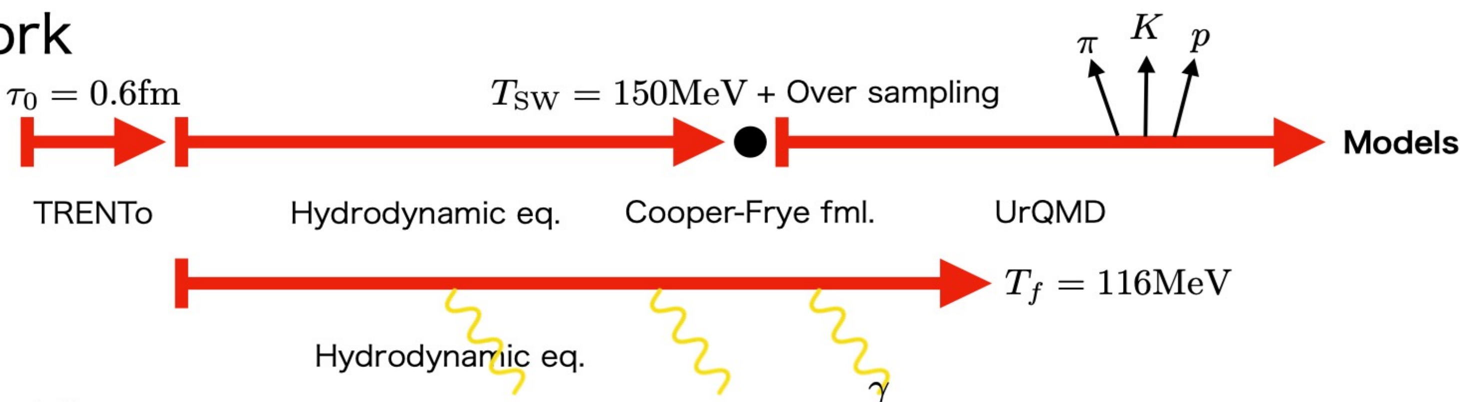
- Experiment

Event plane method (Event plane is determined by hadron correlation.)

Inclusive photons − Decay photons

$$v_n^{\mathrm{dir}} = \frac{R_\gamma v_n^{\mathrm{inc}} - v_n^{\mathrm{dec}}}{R_\gamma - 1}$$

- In this work



photon-hadron correlations

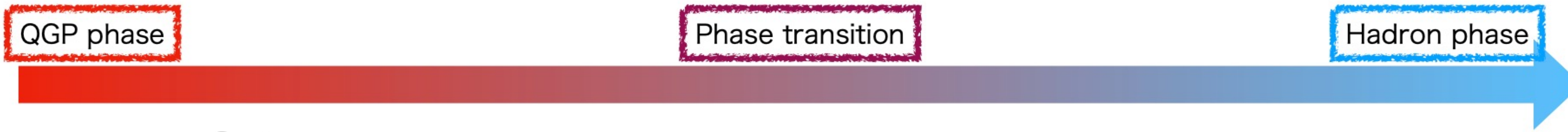
$$v_2^s = \frac{\int dp_T dy d\phi \left(E\frac{d^3N^s}{d^3p}\right)\cos\left[2\left(\phi - \Psi_2^s\right)\right]}{\int dp_T dy d\phi \left(E\frac{d^3N^s}{d^3p}\right)}$$

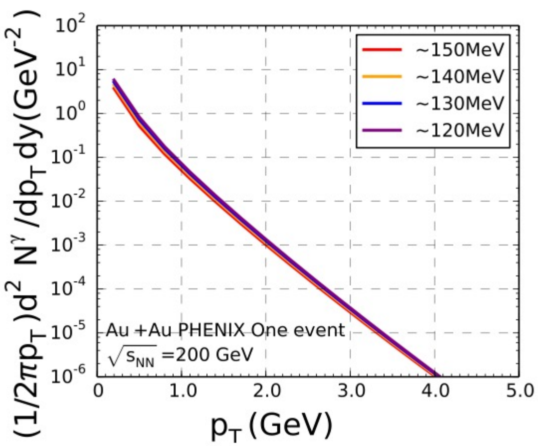
$$v_2^\gamma\{EP\}\left(p_T^\gamma\right) = \frac{\left\langle v_2^\gamma\left(p_T^\gamma\right) v_2^h \cos\left(n\left(\Psi_2^\gamma\left(p_T^\gamma\right) - \Psi_2^h\right)\right)\right\rangle}{\sqrt{\left\langle \left(v_2^h\right)^2 \right\rangle}}$$

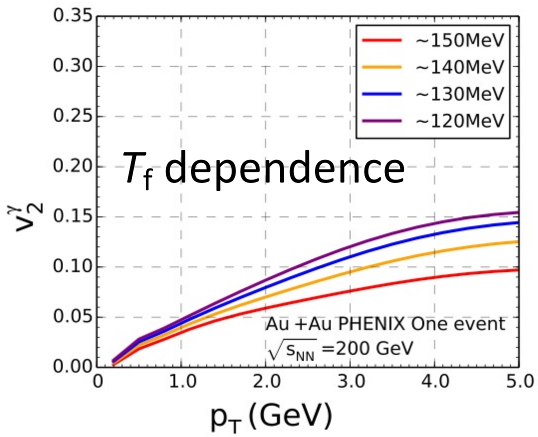
By courtesy of Miyachi

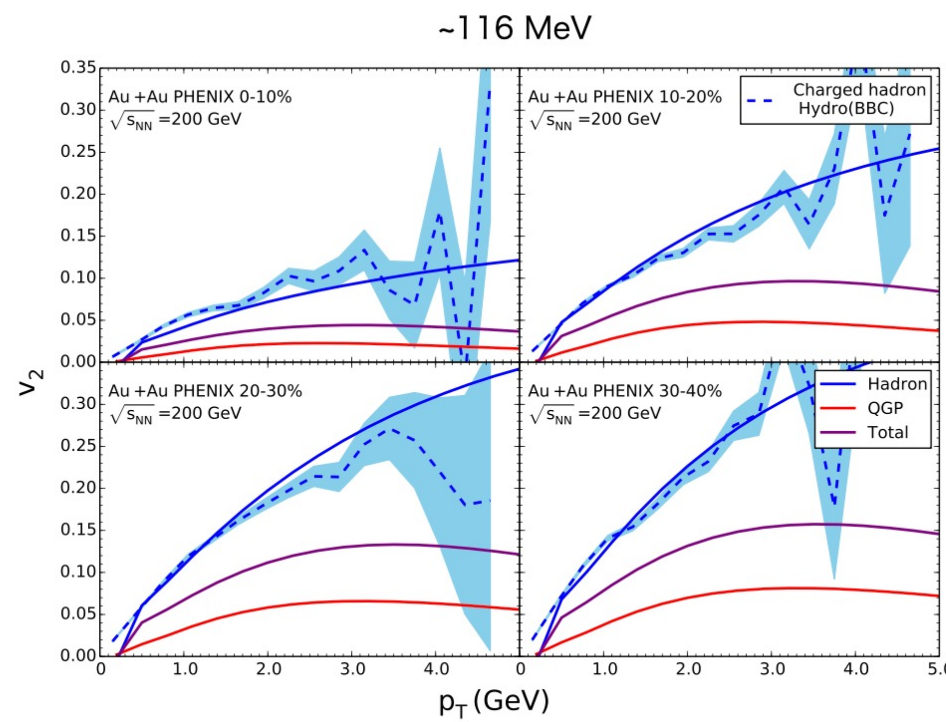
T_f Dependence

- Tf dependence









By courtesy of Miyachi

Characteristic Features

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

Normalization (κ); $\rho(M_*) \rightarrow \delta(M^* - 2M_q)$; ReCo model $\left(\frac{dN_{M_*}}{d^3P}\right)$; Decay $\left(\epsilon_\gamma \frac{dn_\gamma(M_*,P)}{d^3k_\gamma}\right)$

Recombination

$$E_{M_*} \frac{dN_{M_*}}{d^3P}\bigg|_{\eta=0} \sim [\omega_p(p)]^2$$

thermal distribution of quarks

$$\sim e^{-P_T/T^*_{\rm eff}}$$

$$T^*_{\rm eff} = T_{\rm reco}\sqrt{\frac{1+v_T}{1-v_T}}$$

blue shifted with transvers flow

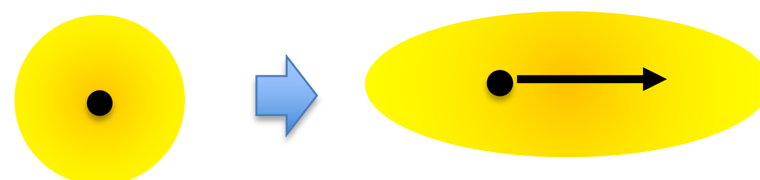
$T_{\rm reco}$: hadronization temperature in original ReCo

Photon

$$\epsilon_\gamma \frac{dn_\gamma}{d^3k_\gamma} = c\delta(k^\gamma_{CM}(M_*,P) - k_0)$$

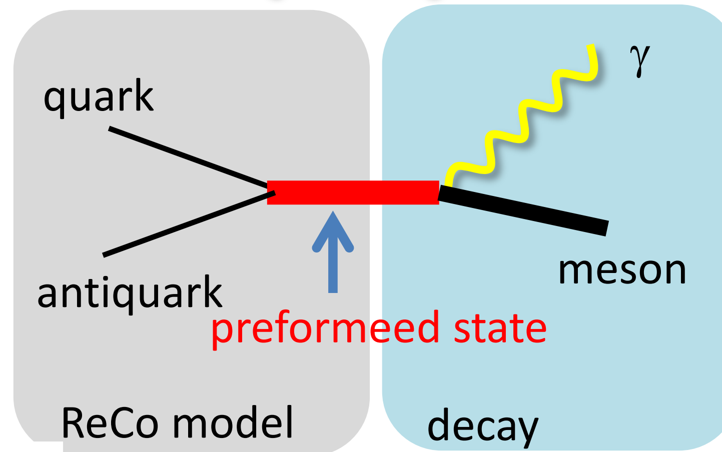
$$k_0 = \frac{M_*^2 - M^2}{2M_*}$$

Photons are emitted from moving resonance.



Isotropic at rest　　squeezed with boost

Features of the Model (2D)



$$M^* \rightarrow M + \gamma$$

- P_T distribution
  - M and γ : shift to low P_T
  - Kinematics: threshold value
  - T_{eff} : $T_{\text{eff}}(M) \sim T_*$ $\quad T_{\text{eff}}(\gamma) = (1 - \frac{M^2}{M_*^2})T_*$
- Elliptic flow

$$v_2^M(K_T) \sim v_2^{M_*}(P_T) \qquad v_2^\gamma(k_T) \sim v_2^{M_*}\left(\frac{k_T}{1-\frac{M^2}{M_*^2}}\right)$$

momentum shift

- Quark Number Scaling