Photon Emission at Hadronization from Quark-Gluon Plasma

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In collaboration with
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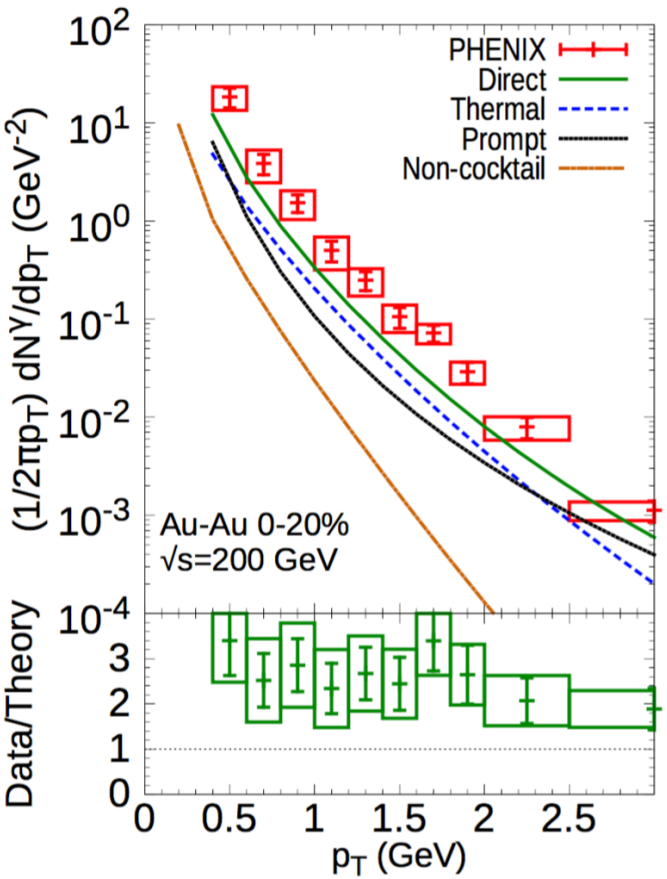
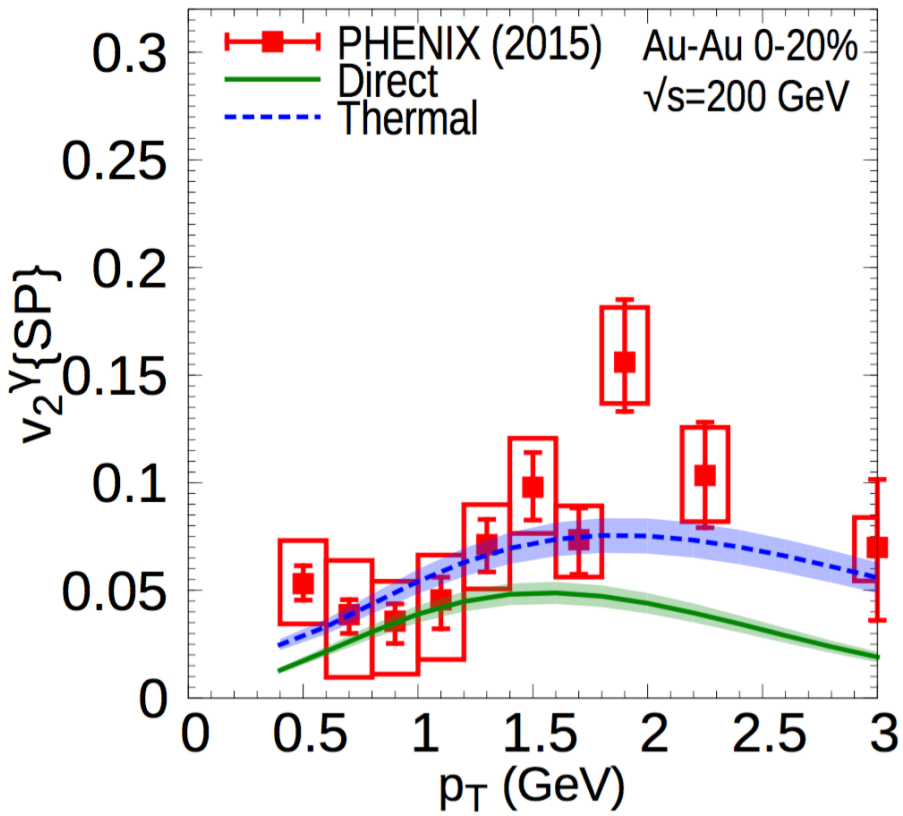
Direct Photon





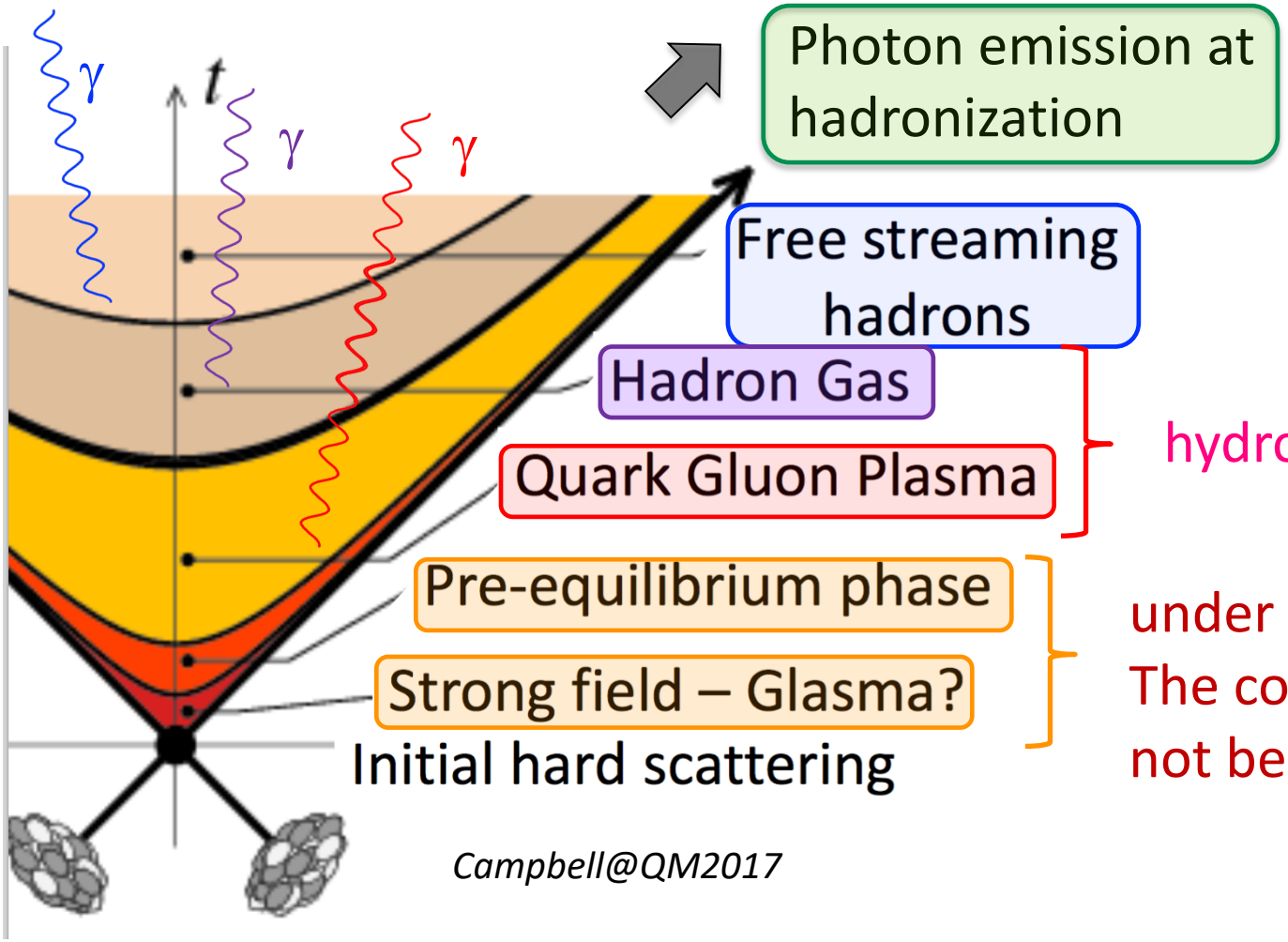
Paquet et.al. PRC93,044906(2016)

The state-of-the-art hydrodynamic model

+ photon production processes except decay photons

The results are smaller than experimental data at RHIC and LHC.

Photon Production



Pratt
Campbell

hydrodynamic model

under discussion
The contribution may not be so small.

Campbell@QM2017

Radiative Recombination in QGP

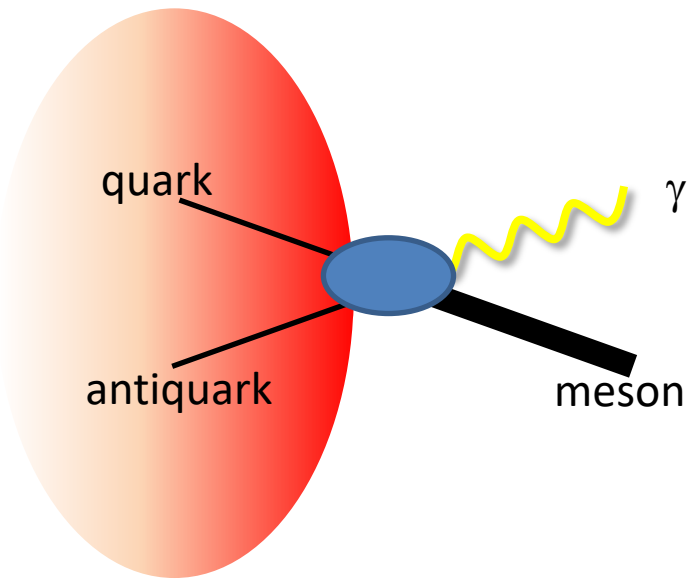
One of Photon Production Processes

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

Radiative Recombination in QGP

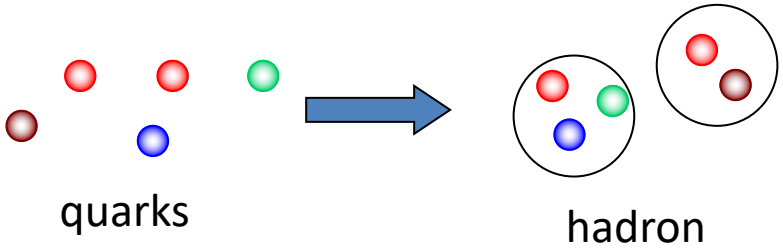
- Non perturbative process
- Not possible to use the inverse process
- Not equilibrium process

⇨ **Recombination Model**



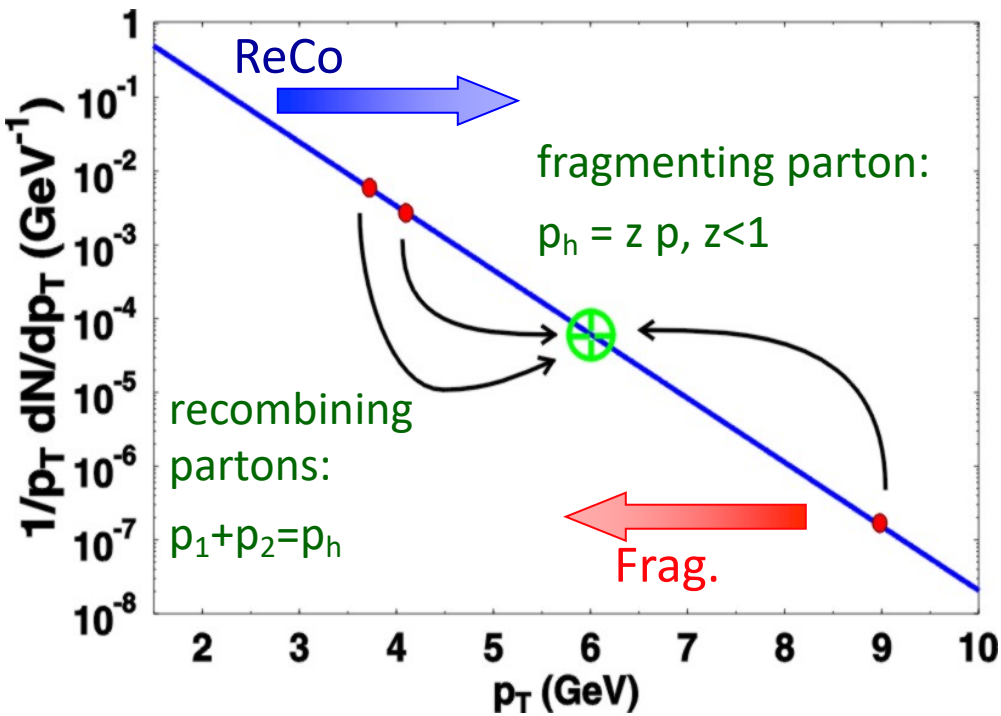
Recombination

- A hadronization model



The recombination process occurs at moderate P_T.

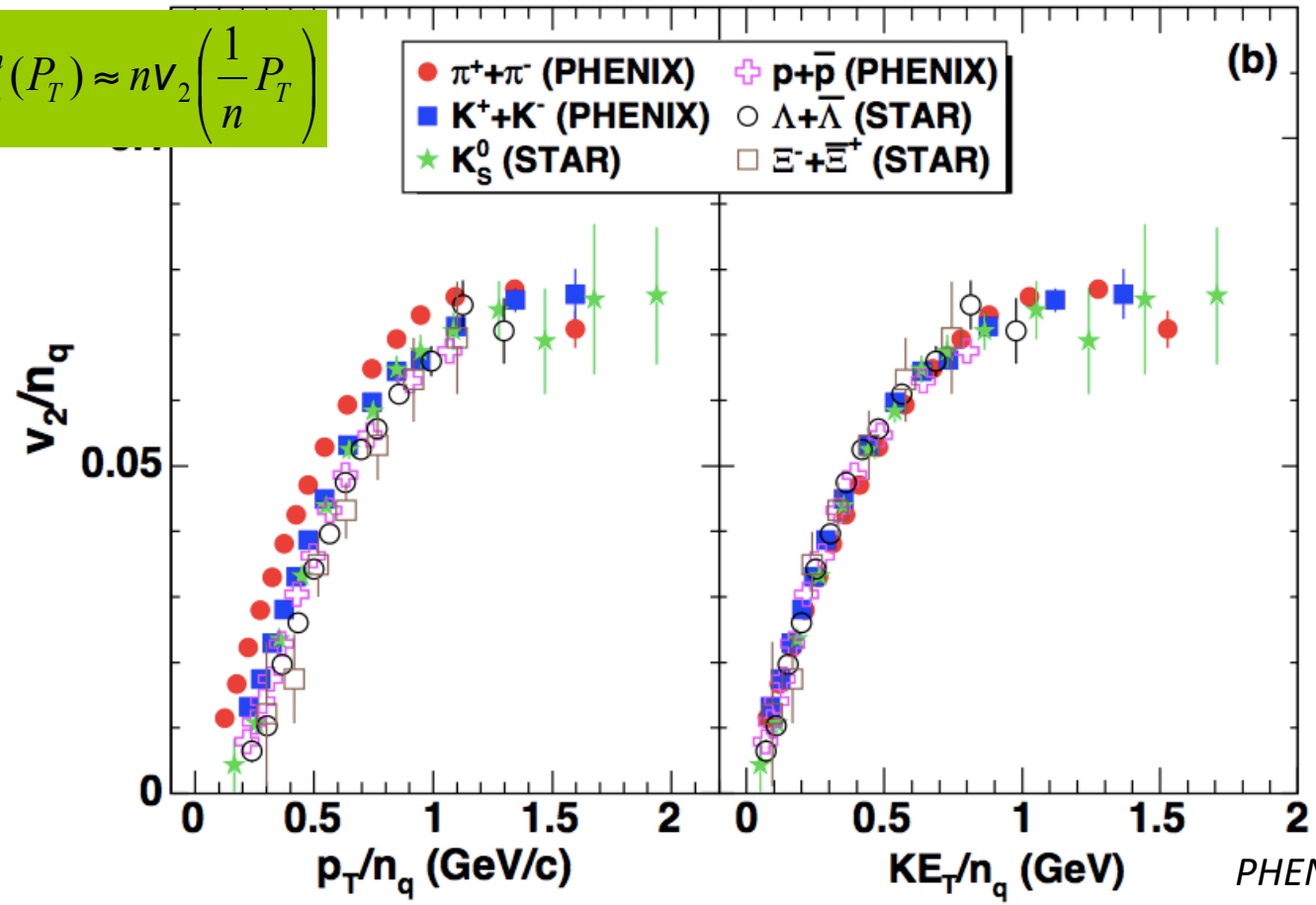
Fries, Mueller, CN and Bass, PRC68(2003)



- One of successful models
  - Baryon/Meson ratios
  - Nuclear modification factors
  - Quark number scaling in elliptic flow

Quark Number Scaling

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



PHENIX,nucl-ex:0608033

Minimum bias Au+Au

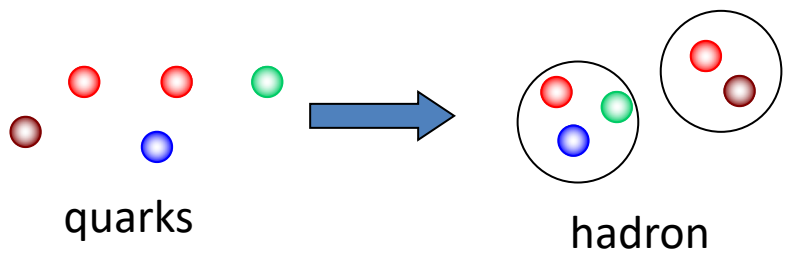
$\sqrt{s_{NN}} = 200$ GeV

$$KE_T = m_T - m$$

Caveat: Braking of quark number scaling is observed at LHC.

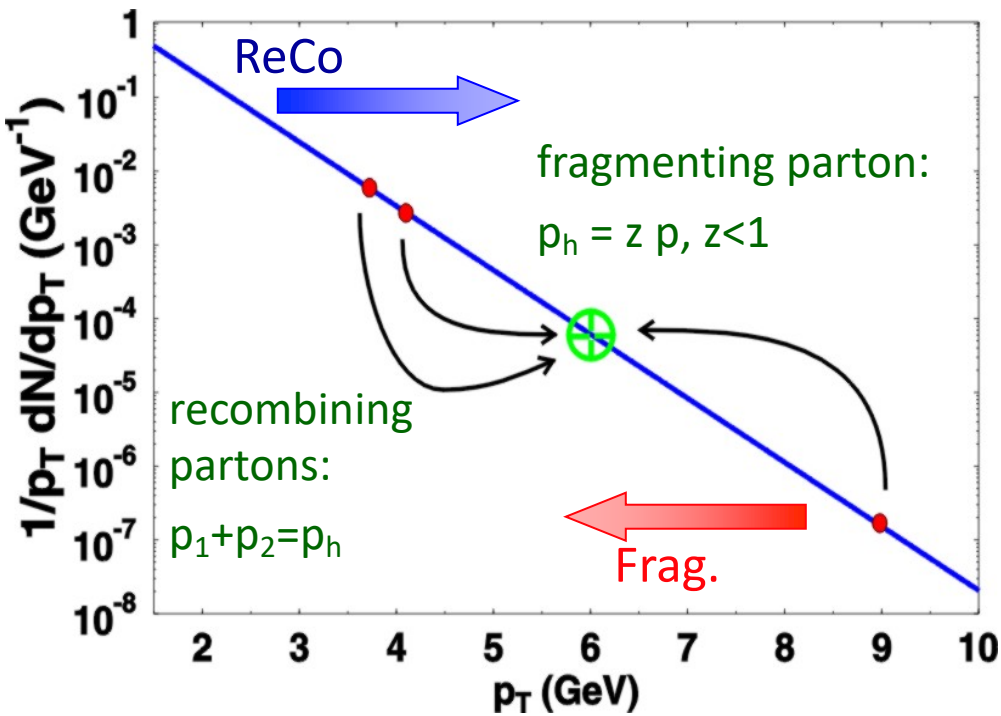
Recombination

- A hadronization model



Ex. Duke
The recombination process occurs at moderate P_T.

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

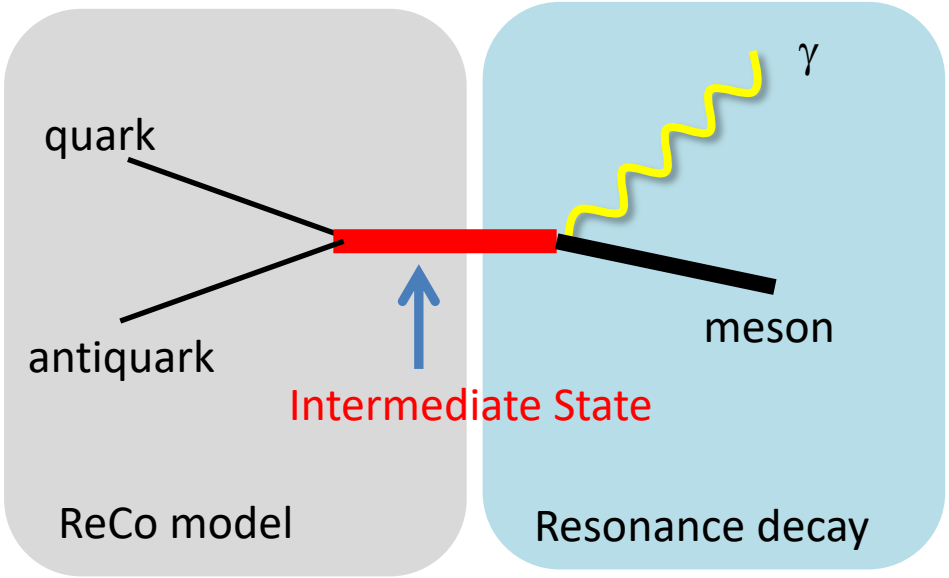


- One of successful models
  - Baryon/Meson rations
  - Nuclear Modification factors
  - Quark number scaling in elliptic flow
- Reduction of entropy and violation of energy conservation

ReCo with Photon Emission

- Entropy and Energy Conservation

Resonance-like state is produced through the recombination model.



Photons are emitted from decay of the intermediate 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

Spectral function of intermediate state

Number of γ from Meson Formation

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

$$\sim \delta(M^* - 2M_q)$$

Recombination

$$\frac{dN_{M_*}}{d^3P} \sim [\omega_p(p)]^2$$

thermal distribution of quarks

$$\sim e^{-P_\perp / T^*_{eff}}$$

*M** distribution

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

blue shifted with transvers flow

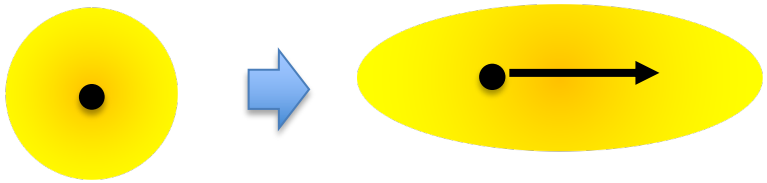
T_h : hadronization temperature

Photon

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

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

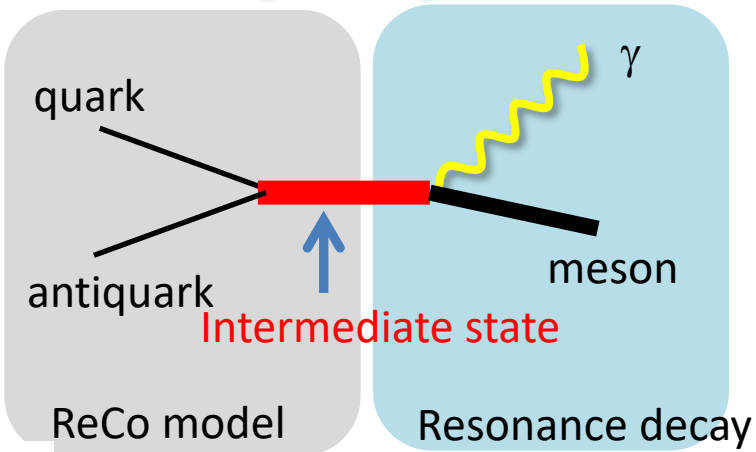
Photons are emitted from moving resonance.



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
  - $T_{\rm eff}$:

$$T_{\rm eff}(M) \sim T_*$$

$$T_{\rm eff}(\gamma) = (1 - \frac{M^2}{M_*^2})T_*$$

- Elliptic flow

$$v_2^M(K_T) \sim v_2^{M_*}(P_T)$$

$$v_2^\gamma(k_T) \sim v_2^{M_*}(\frac{k_T}{1 - \frac{M^2}{M_*^2}})$$

momentum shift

- Quark Number Scaling

Centrality Dependence @RHIC

RHIC

M_*=0.6 GeV

Transverse flow

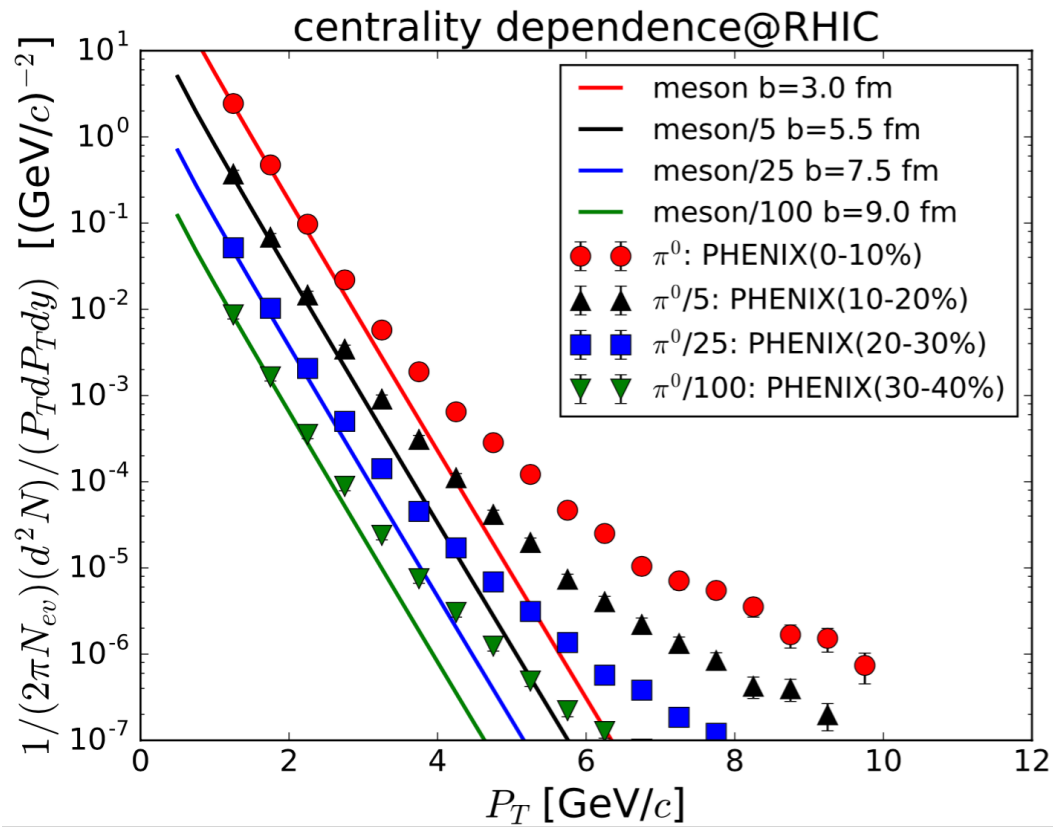
$$v_T = 0.6$$

Hadronization temperature

$$T_h = 155 \text{ MeV}$$

Fugacity

$$\gamma_{u,d} = 1, \gamma_{\bar{u},\bar{d}} = 0.9$$



	Mstar	Meson	gamma
Slope [MeV]	320	303	287

fit function: f(x) = a*exp(-x/b)
Fitting range P_T [2:5]

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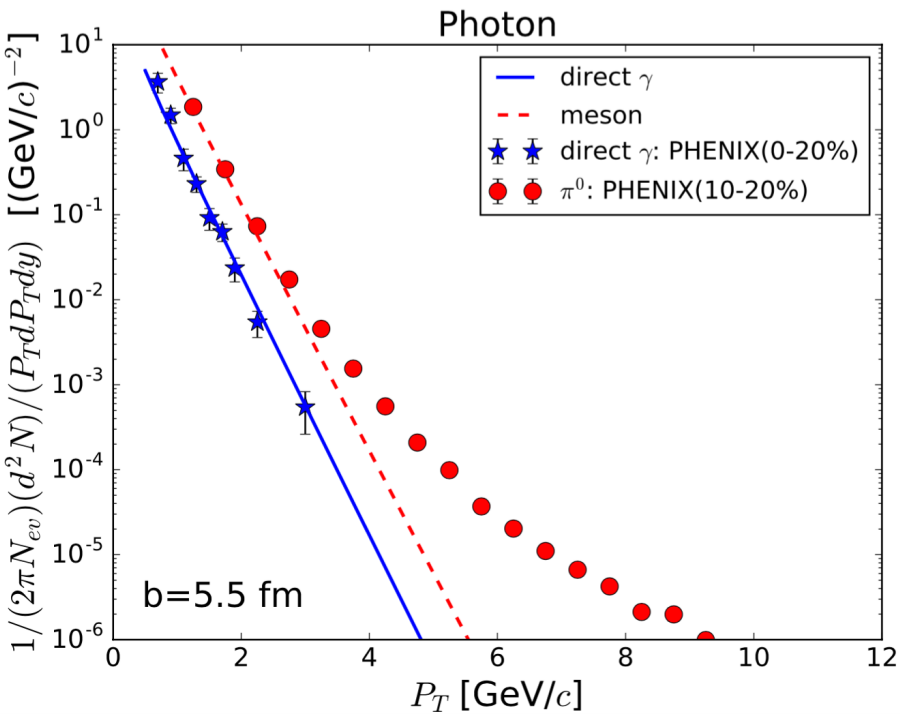
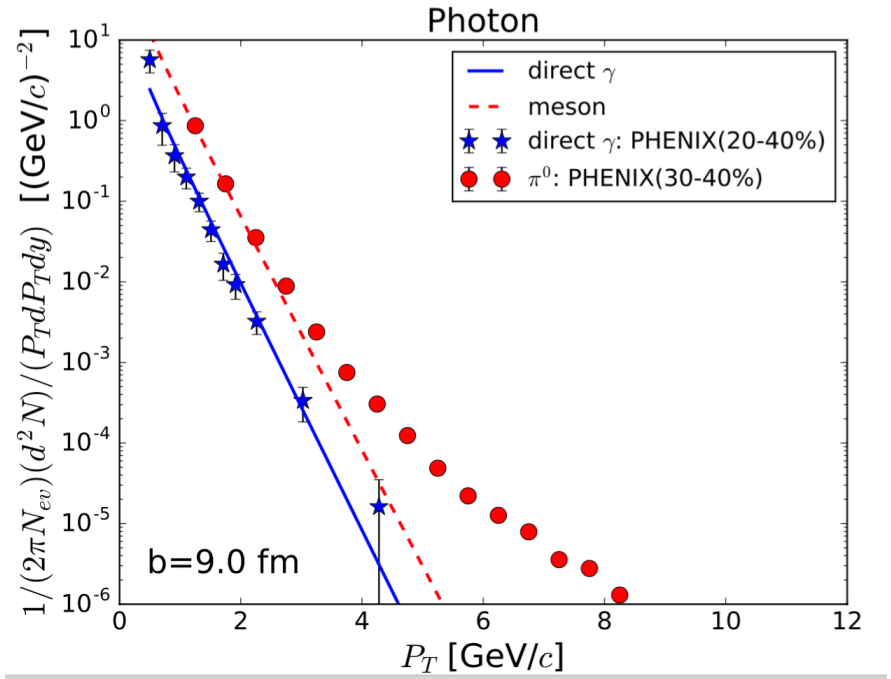
Photon's P_T Spectra @ RHIC





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

2-5 GeV

$$\kappa = 0.1$$

	Mstar	Meson	gamma
Slope [MeV]	320	303	287

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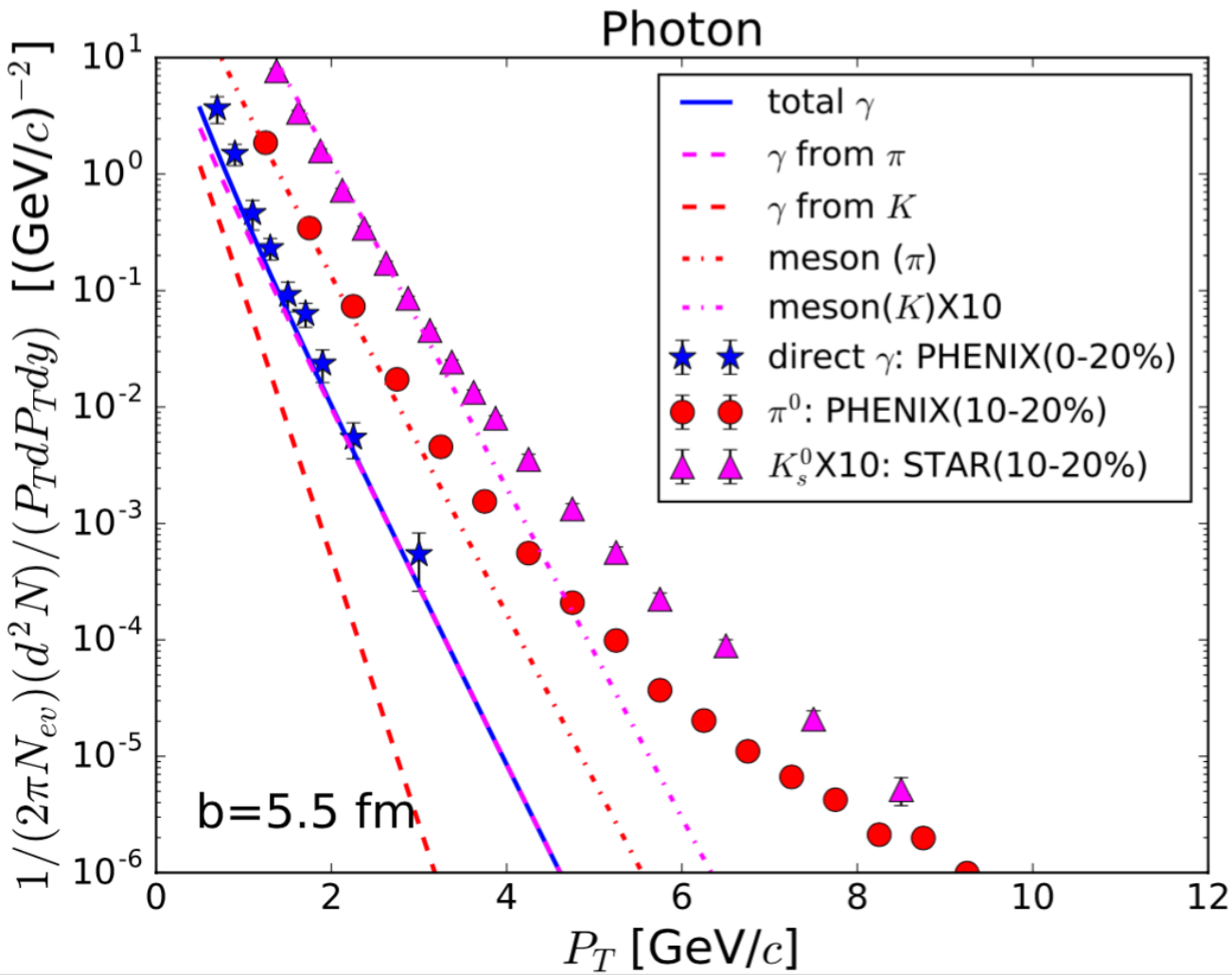
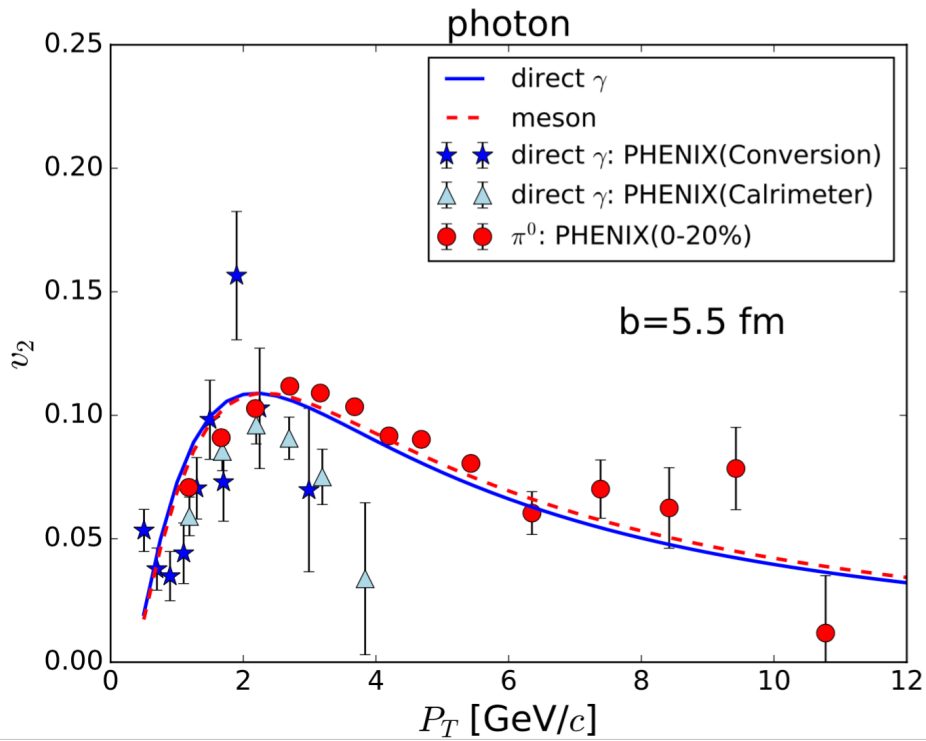
Contribution from Other Resonances

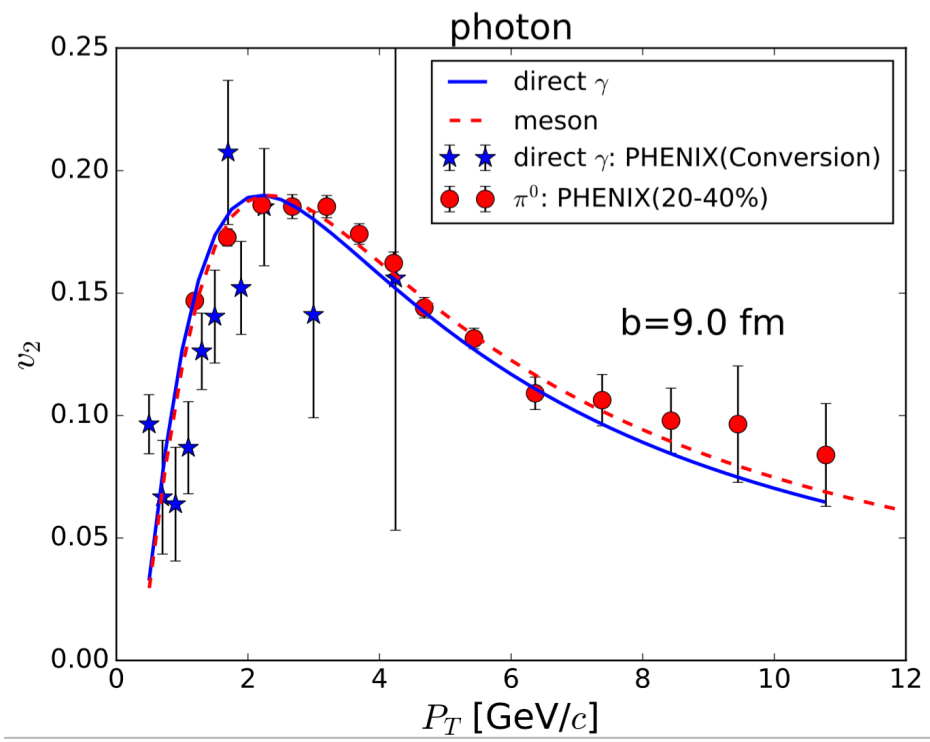


$$\kappa = 0.1$$
$$\kappa(K) = 0.7$$

M$_*$=600 MeV
M$_*$=800 MeV

v_2 for π @RHIC





$$v_2^q(p_T) \leftarrow \frac{\alpha}{(1+p_0/p_T)^{2.5}}$$

$p_0 = 1.0$ GeV

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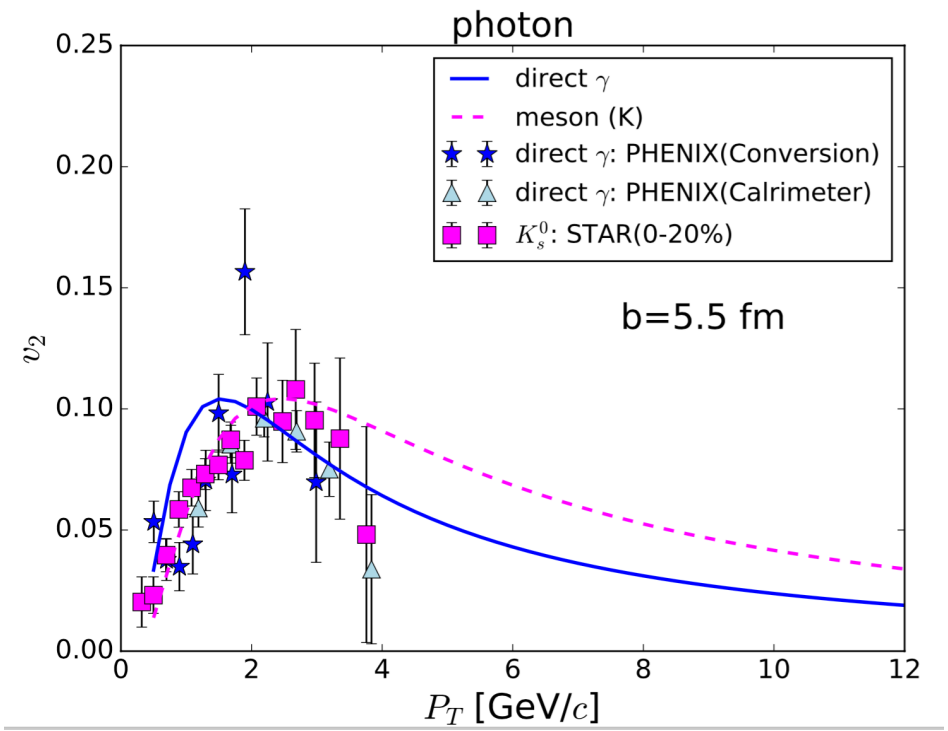
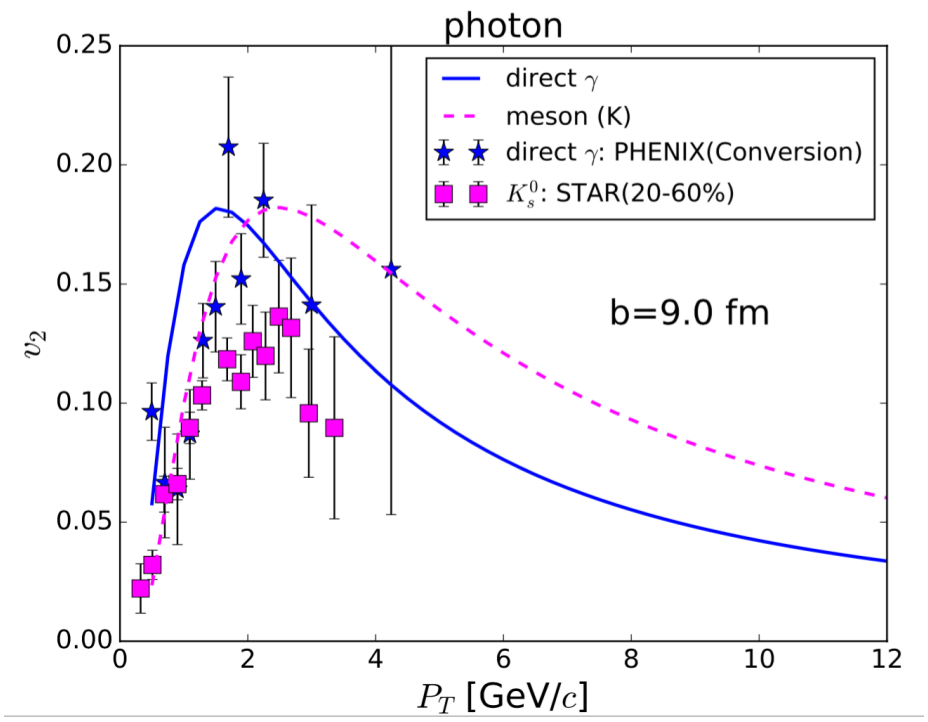
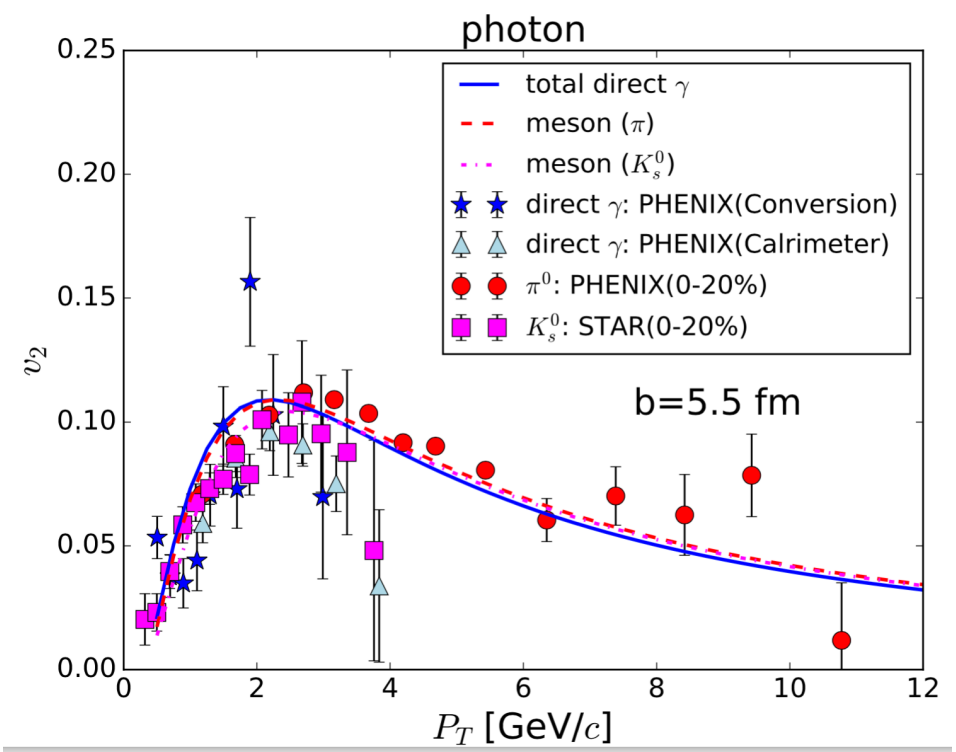
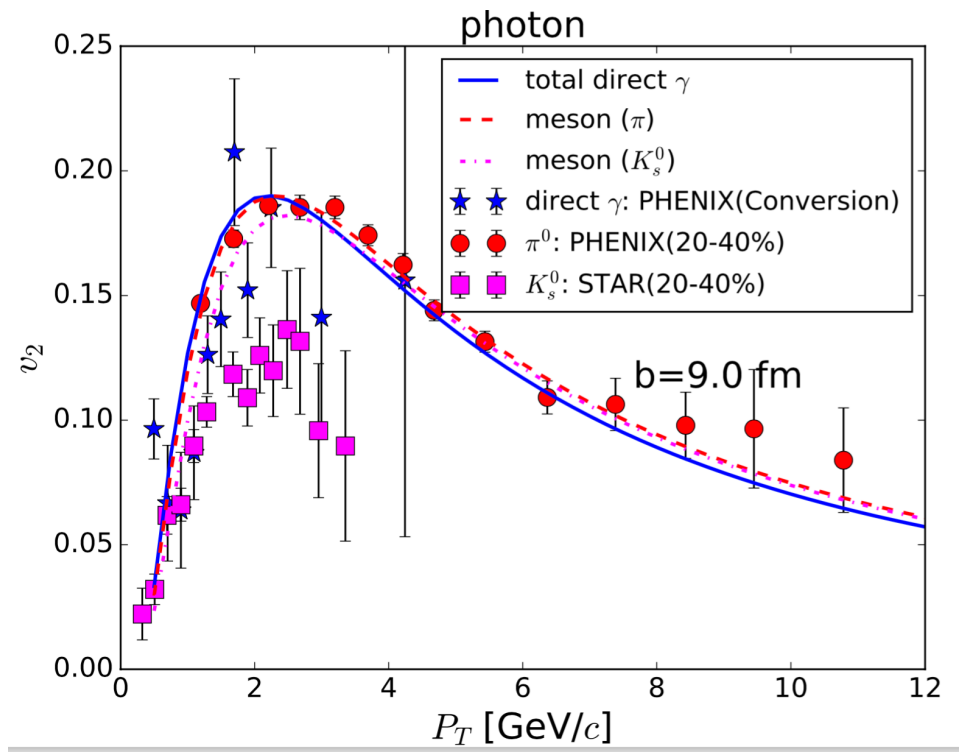
v_2 for K @RHIC


photon
direct γ
meson (K)
direct γ: PHENIX(Conversion)
direct γ: PHENIX(Calrimeter)
K_s^0: STAR(0-20%)
b=5.5 fm
v_2
P_T [GeV/c]

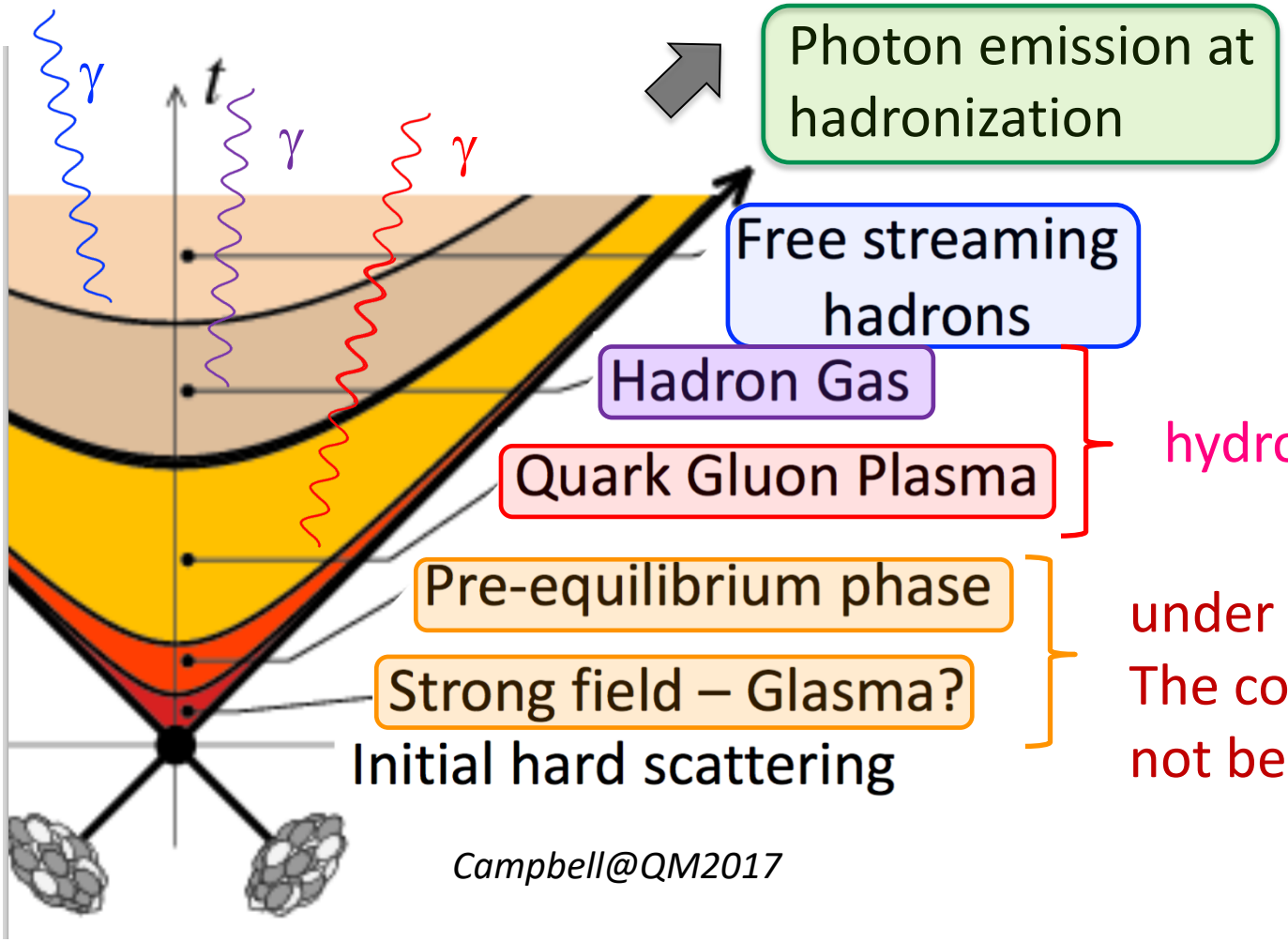

photon
direct γ
meson (K)
direct γ: PHENIX(Conversion)
K_s^0: STAR(20-60%)
b=9.0 fm
v_2
P_T [GeV/c]

v_2 for photon @RHIC





Photon Production



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hydrodynamic model

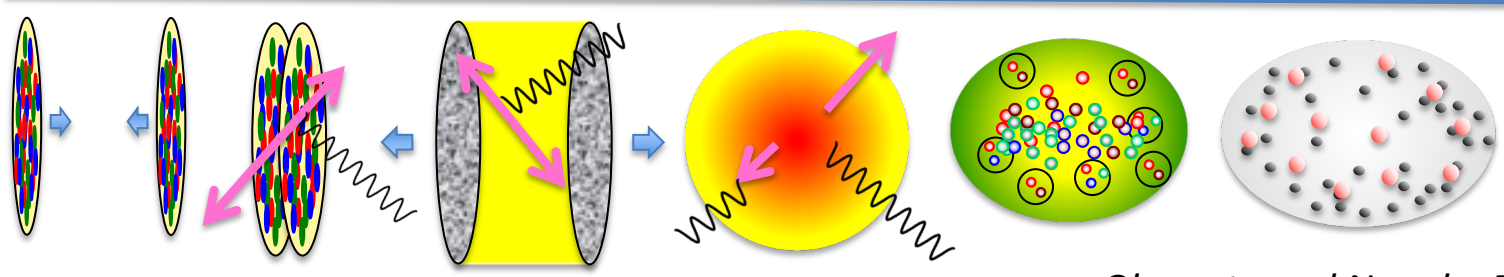
under discussion
The contribution may not be so small.

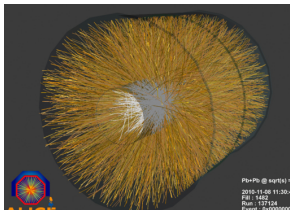
Campbell@QM2017

Quantitative Analyses

Experimental data

collisions thermalization hydro hadronization freezeout





Okamoto and Nonaka,PRC98,054906(2018)

TRENTO

Phenomenological model
Parametrization

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

New hydrodynamics code

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

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

Denicol,Niemi,Molnar,Rischke,PRD85,114047 (2012)

UrQMD

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

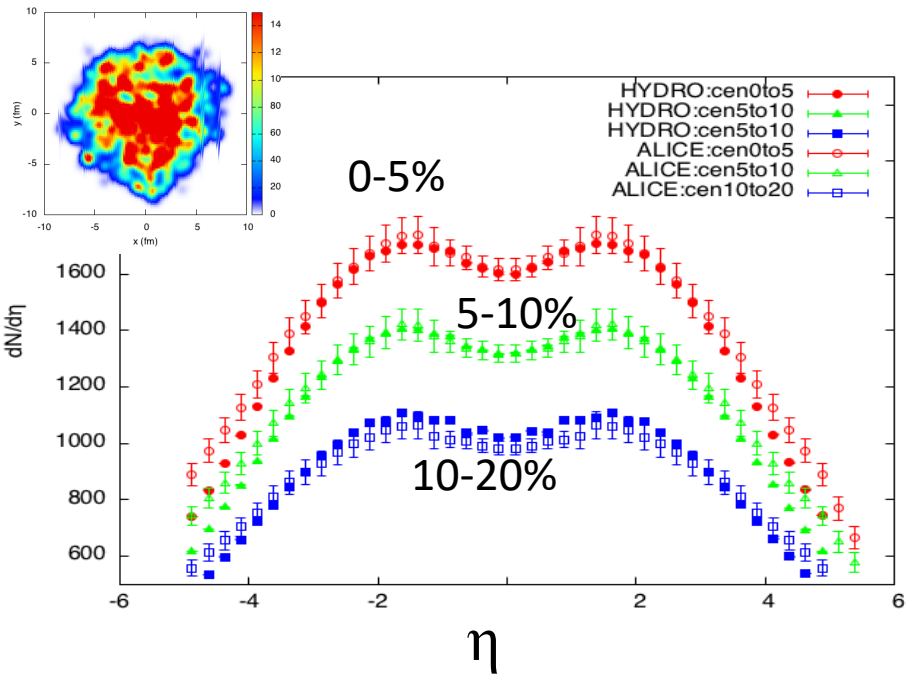
Cornelius, *Huovinen and Petersen*
Cooper-Fry formula

Large and Small Systems

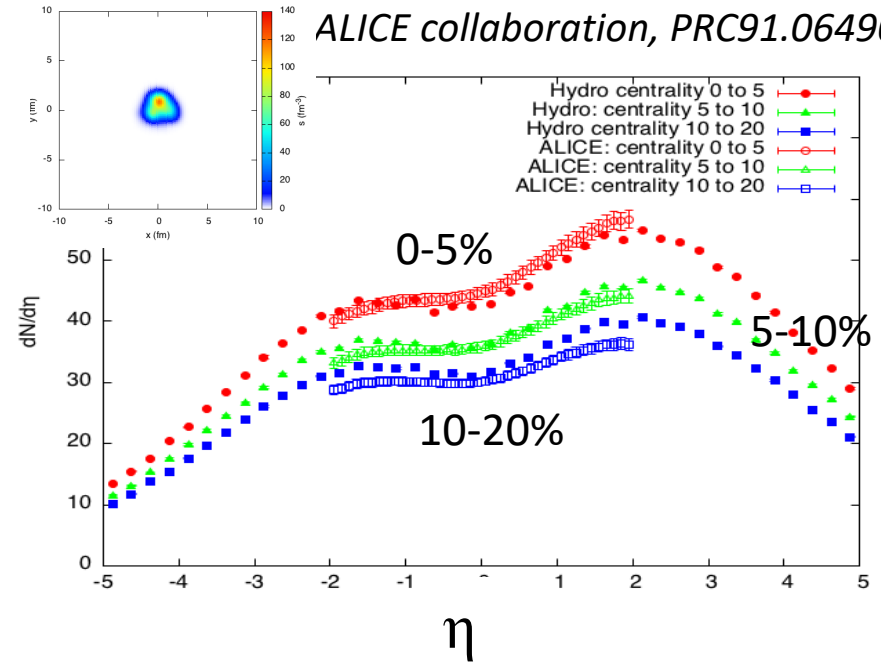
Nakamura and CN, in preparation

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

p+Pb $\sqrt{s_{NN}} = 5.02$ TeV



ALICE collaboration, PRC91.064905

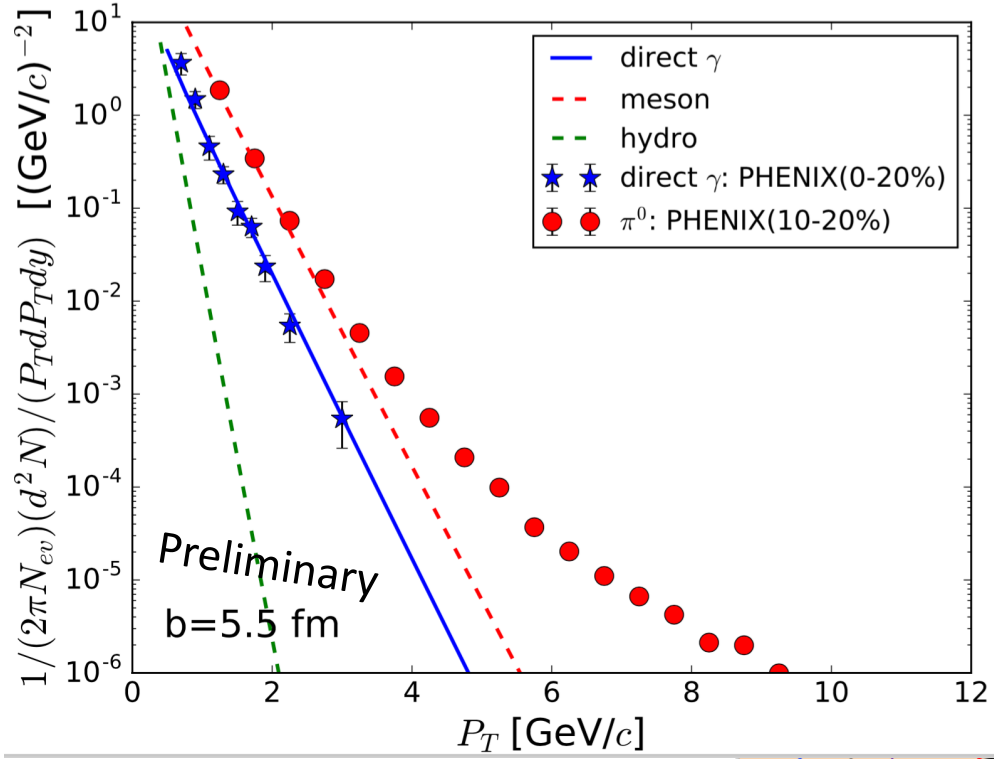


- Parameters in TRENTO are fixed at 0-5 % centrality.
  - p=0.013 (saturation-based theory), n_{PbPb}=98, n_{pPb}=108

Moreland et al, 1808. 02106

- We succeed in reproducing centrality dependence of rapidity distribution in Pb+Pb and p+Pb collisions.

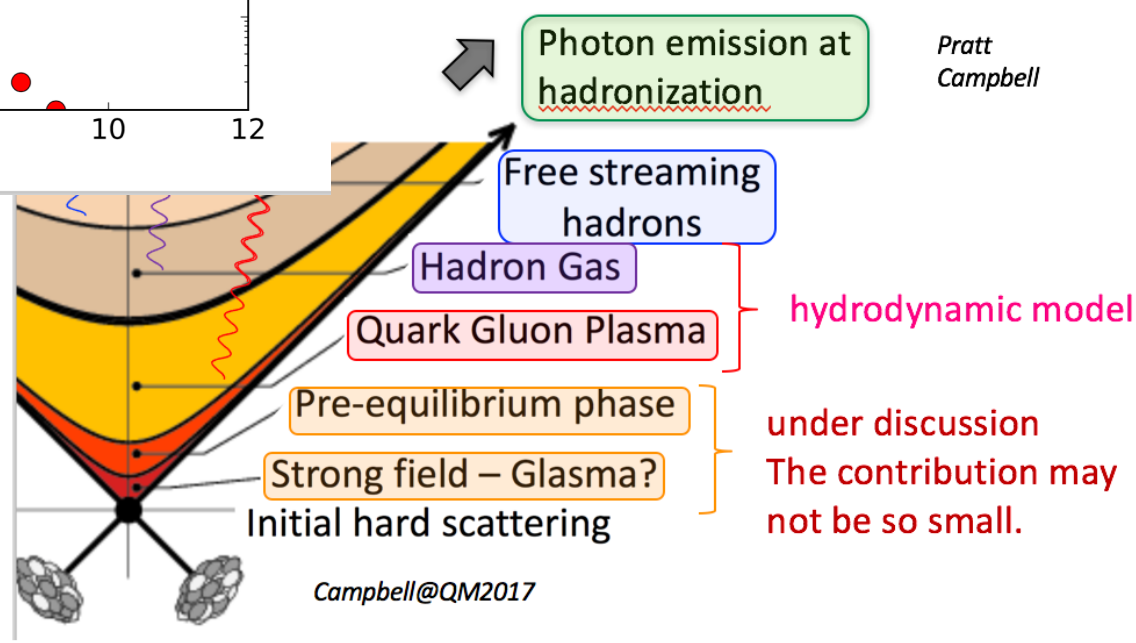
Towards Quantitative Analyses



Thermal photon from Hydrodynamic Model

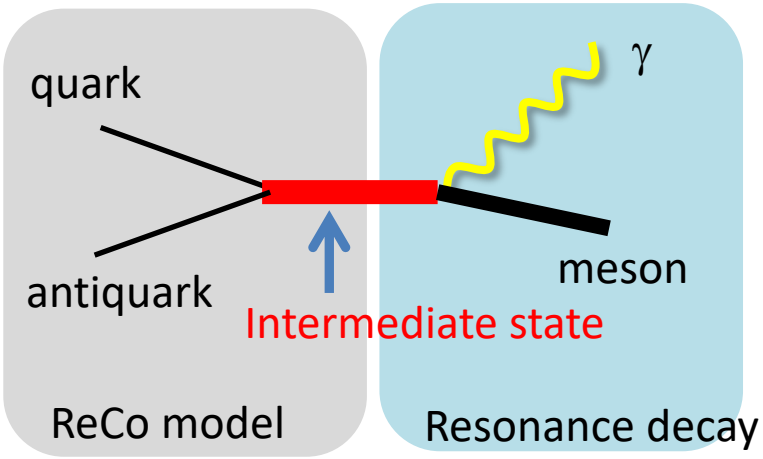
Photon emission ratio

Arnold, Moore, Yaffe, JHEP12(2001)009



Summary

- Photon production through hadronization
  - Hadrons: consistent with ReCo
  - Large yield and v_2 of γ
  - Energy conservation in the recombination model



- Working in progress
  - Effects of baryons
  - Check the violation of quark number scaling
  - Quantitative analyses with hydrodynamic Model