Possible Resolution to the Direct Photon Puzzle

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe
Department of Physics, Nagoya University

H-lab (Quark-Hadron Theory Group)

Chiho NONAKA

In collaboration with

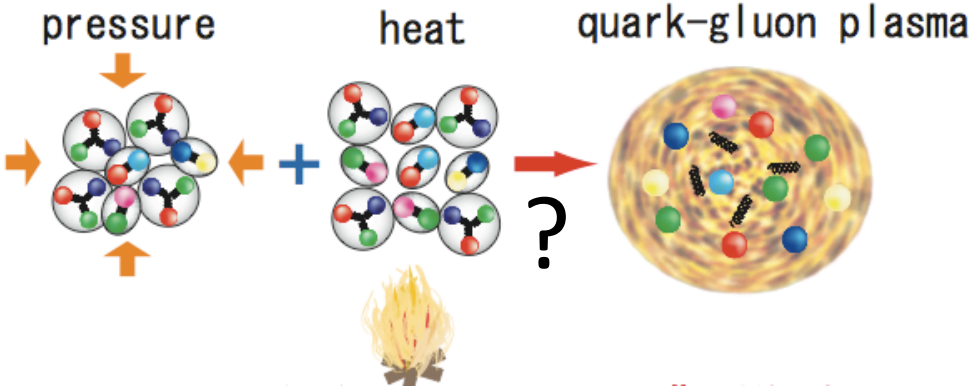
Kazunori ITAKURA (KEK) and Hirotsugu FUJII (Tokyo U.)

May 10, 2017@KMI topics

What is the QGP?

Quark-Gluon Plasma

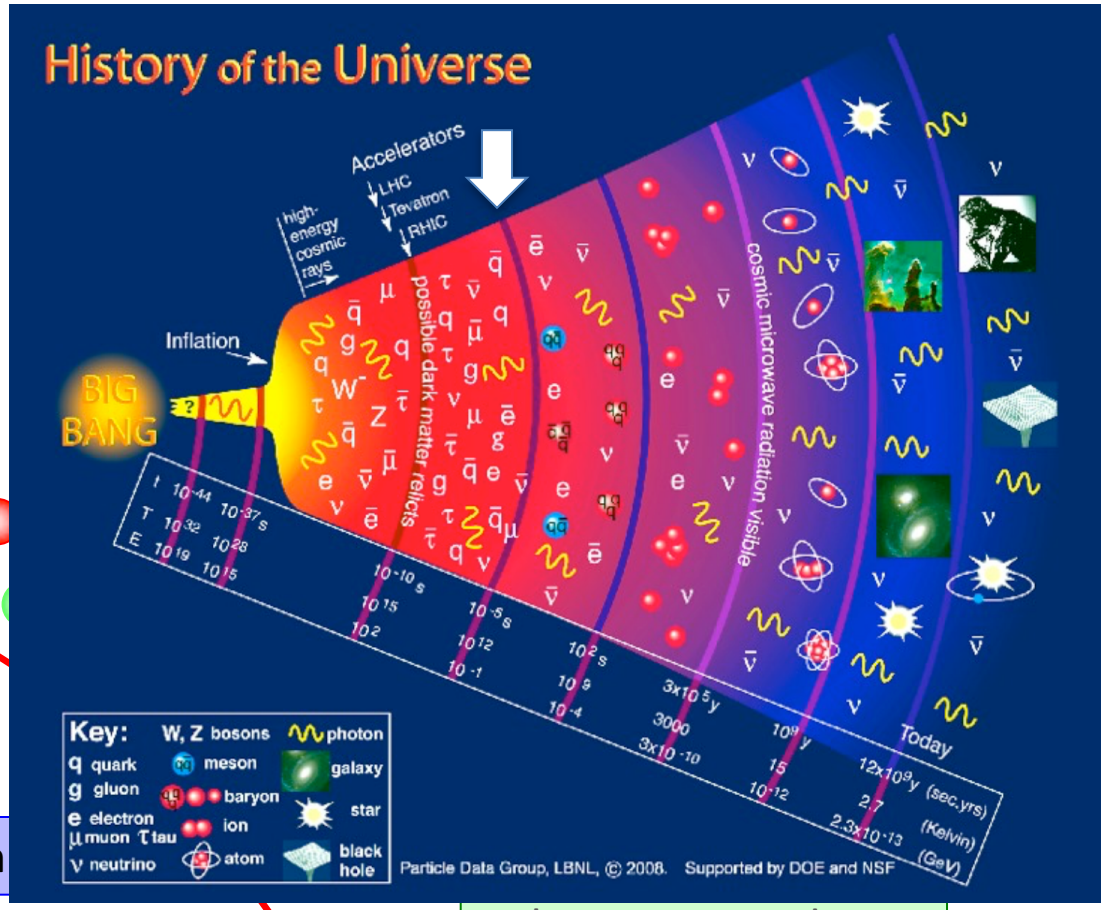
- Quarks and gluons at extreme conditions
  - High temperature and/or high density



What is the QGP?

Quark-Gluon Plasma

- Quarks and gluons at extreme conditions
  - Early Universe



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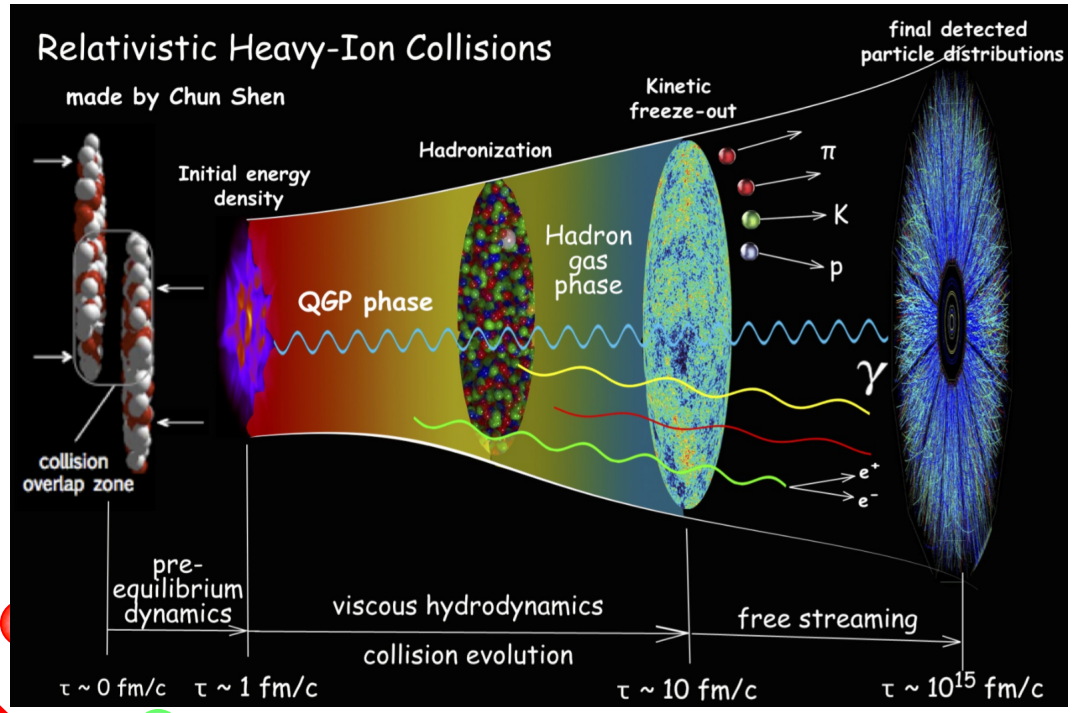
What is the QGP?

Quark-Gluon Plasma

- Quarks and gluons at extreme conditions
  - Relativistic Heavy Ion Collisions : Little Bang



Heinz

T

Quark-Gluon Plasma

QCD Critical Point

Hadron Phase

?

Color Super Conductor

Neutron star

μ_B

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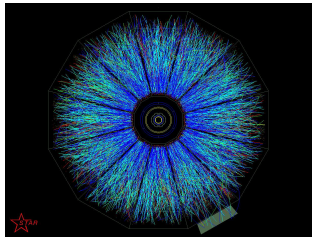
What is the sQGP?

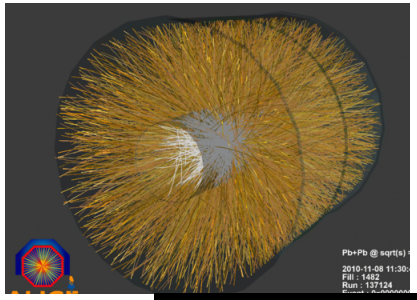
Quark-Gluon Plasma

- Quarks and gluons at extreme conditions
  - Relativistic Heavy Ion Collisions



2000: Relativistic Heavy Ion Collider

Success of relativistic hydrodynamic model



LHC:2010

Heavy Ion collisions start!

T

Strongly Interacting

Quark-Gluon Plasma

QCD Critical Point

?

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μ_B

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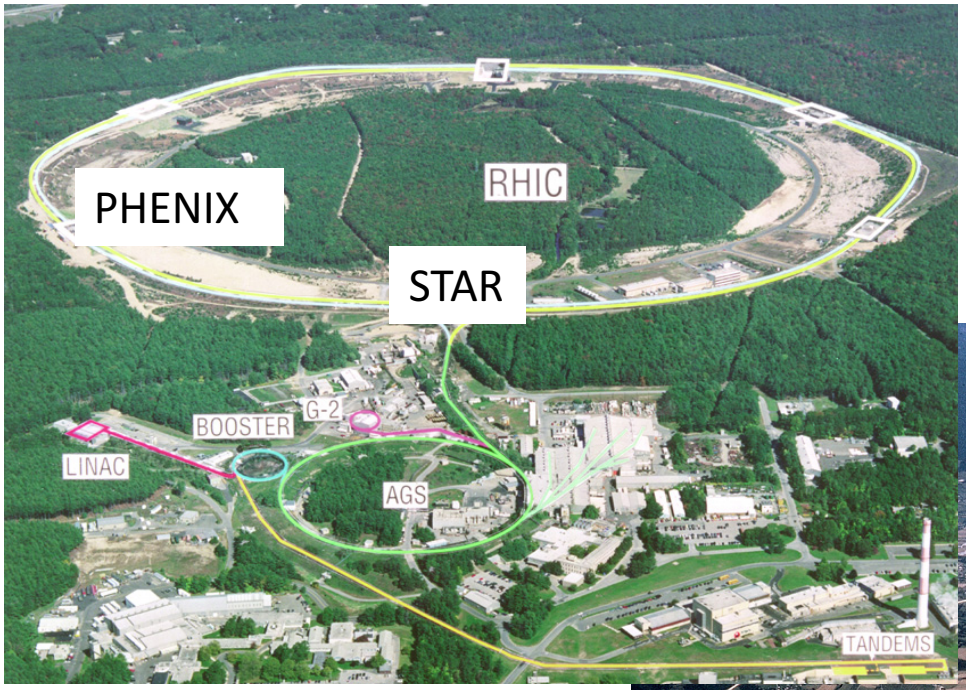
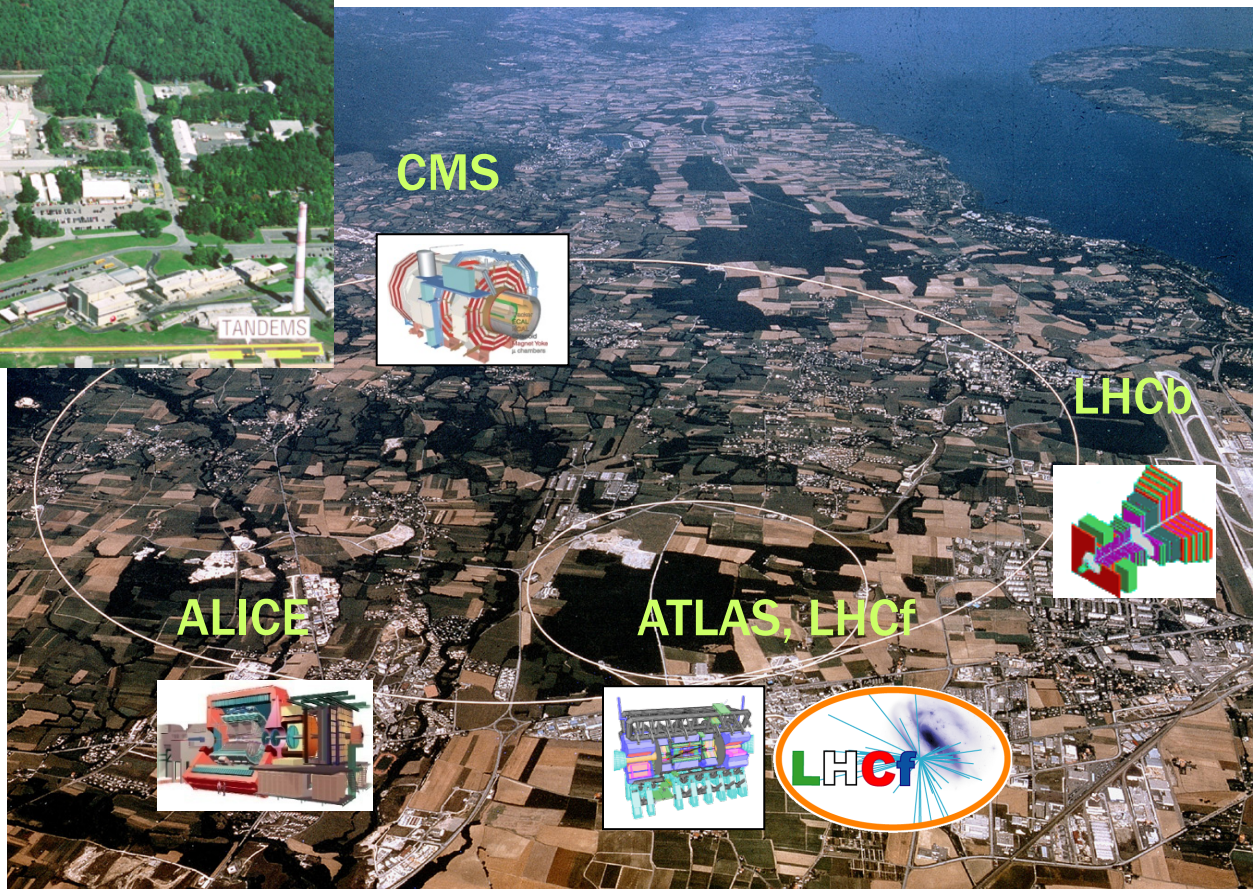
Heavy Ion Collisions



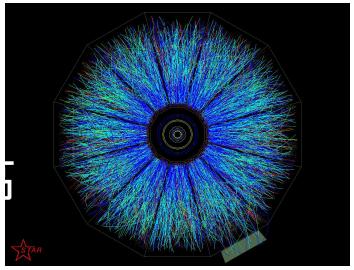
RHIC@BNL

Large Hadron Collider@CERN

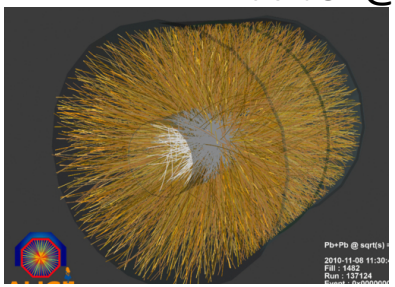


Heavy Ion Collisions@QM2017

STAR@RHIC



ALICE@LHC



Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

Pb+Pb
2760

p+Pb
Pb+Pb
5020 GeV

RHIC

LHC

$\sqrt{s_{NN}}$

Statistical Model

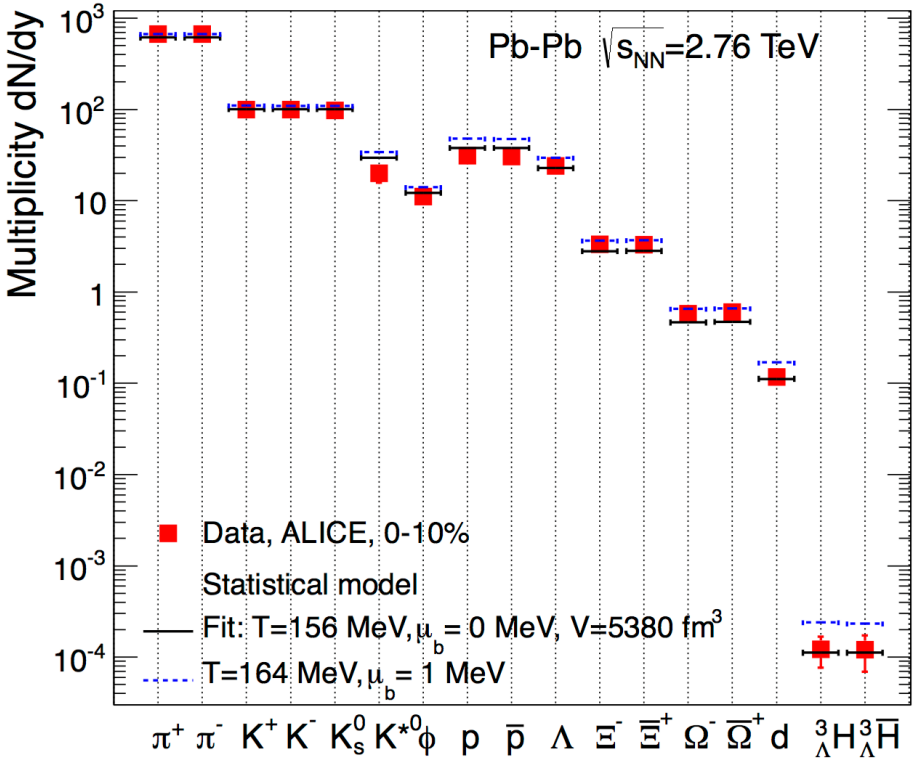
Au+Au(Beam Energy Scan) 7.7, 11.5, 19.8, 27, 39

p+p, d+Au,He+Au U+U, Au+Au, 200

Pb+Pb 2760

p+p p+Pb Pb+Pb 5020 GeV

Experimental data → Location on the QCD Phase diagram



$$n_i = N_i/V = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{-(\epsilon_i(p)-\mu)/T} \pm 1}$$

Pb+Pb 2760 GeV
-> ~ T=156 MeV, μ=0

Ex:Stachel et al, arXiv:1311.4662

Heavy Ion Collisions and QCD phase diagram

Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

p+p,
d+Au,He+Au
U+U, Au+Au,
200

Pb+Pb
2760

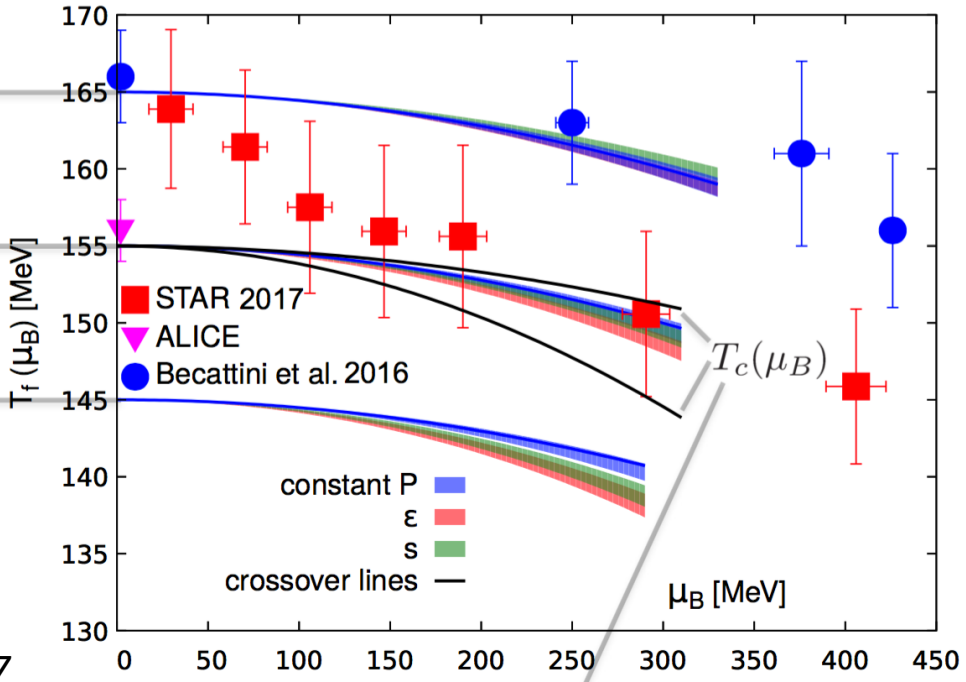
p+p
p+Pb
Pb+Pb
5020

GeV

T=165 MeV
ϵ = 0.556(57) GeV/fm^3

T=155 MeV
ϵ = 0.346(41) GeV/fm^3

T=145 MeV
ϵ = 0.203(27) GeV/fm^3



Lattice QCD
Tc=154(9) MeV
HotQCD
PRD85,054503
(2012)

Kaczmarek@QM2017

compare well with estimates of the crossover line: $T_c(\mu_B) = T_c(0)\left(1 - \kappa_2^c \left(\frac{\mu_B}{T_c(0)}\right)^2\right)$

Heavy Ion Collisions and QCD phase diagram

Quark Matter 2017

Au+Au(Beam Energy Scan)
7.7, 11.5, 19.8, 27, 39

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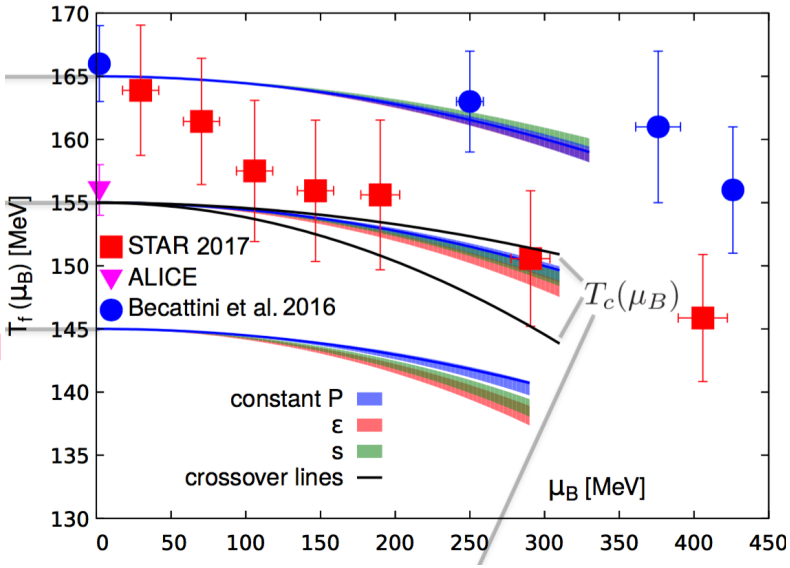

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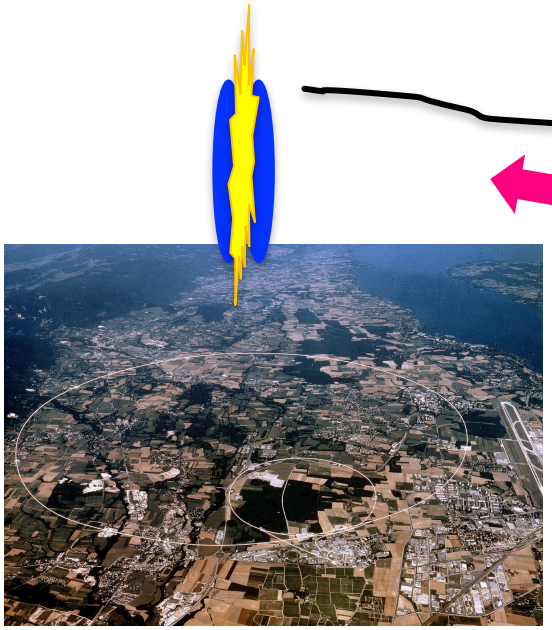
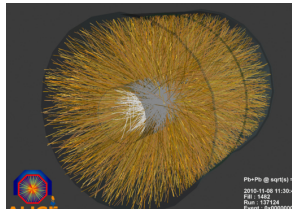
QGP Production?



?

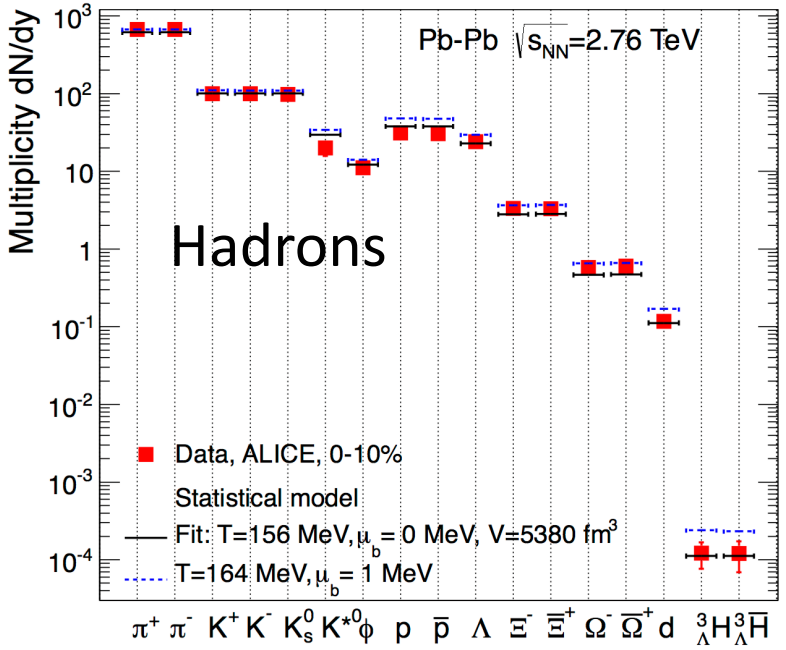
Experimental data



Theory, Model

QGP production ?

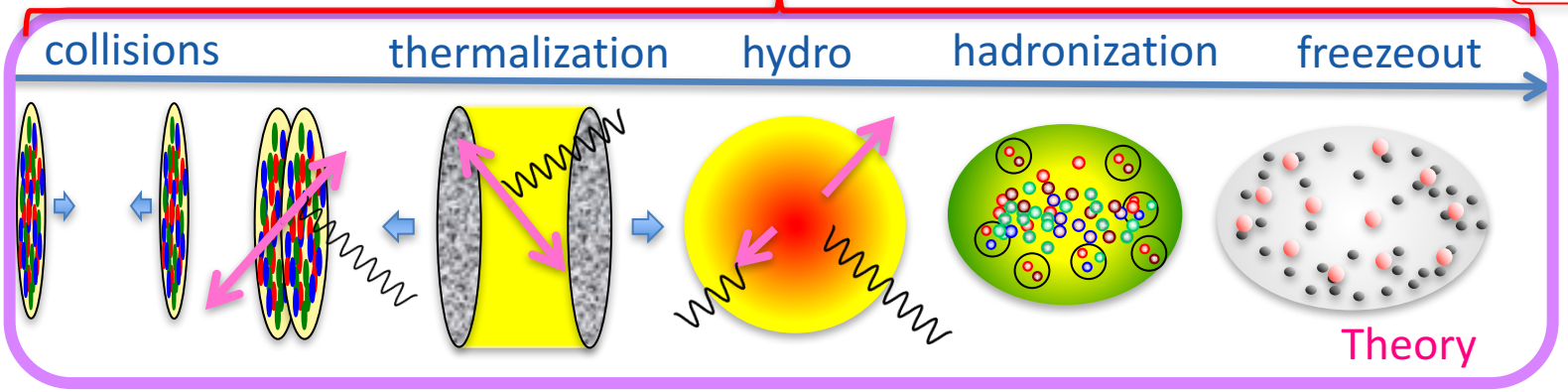
?



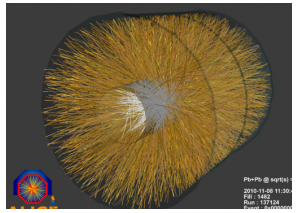
QGP Bulk Property

- Development of hydrodynamic model

What we want to understand



Experimental data



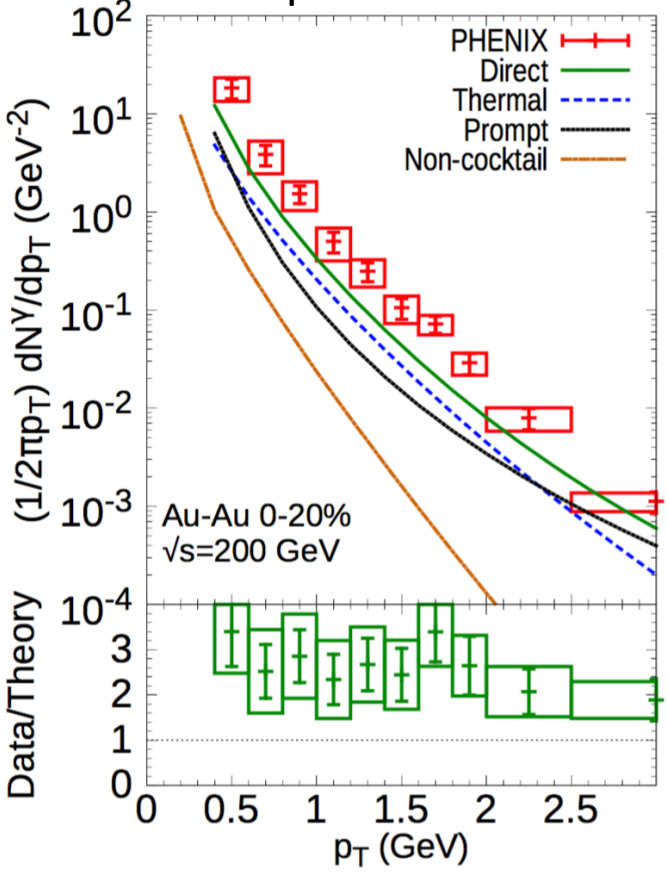
Initial conditions	Hydrodynamics	Final state interactions
Fluctuations: Glauber, KLN, IP-Glasma…	QGP bulk property EoS: lattice QCD Shear and bulk viscosities	Hadron based event generator

Our developing dynamical model

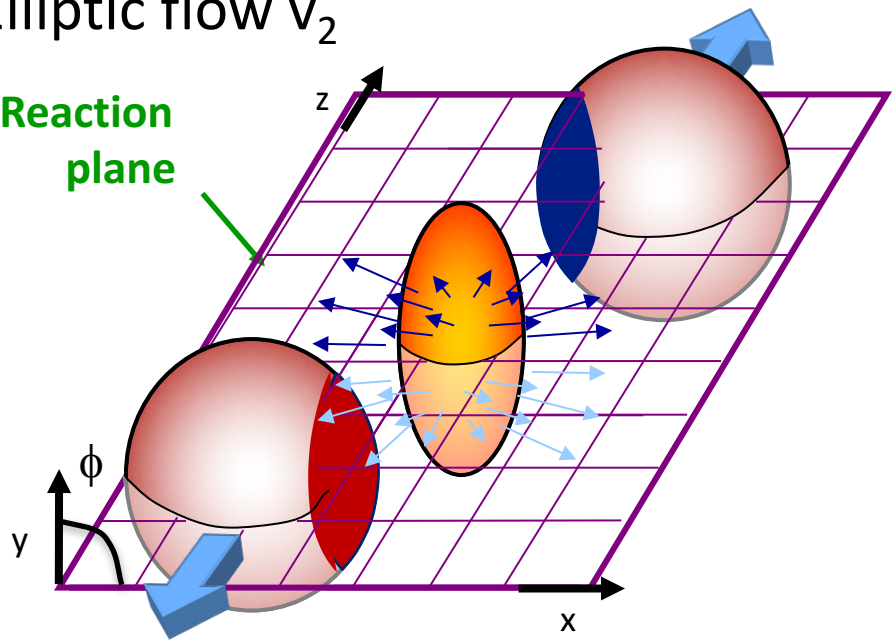
TRENTO	Hydrodynamics	UrQMD
Duke	Okamoto	

Direct Photon Puzzle

Direct photon = Inclusive photon – decay photon from hadrons



Elliptic flow v_2



$$\frac{dN}{d\phi} \sim N_0(1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi)$$

Paquet et.al. PRC93,044906(2016)

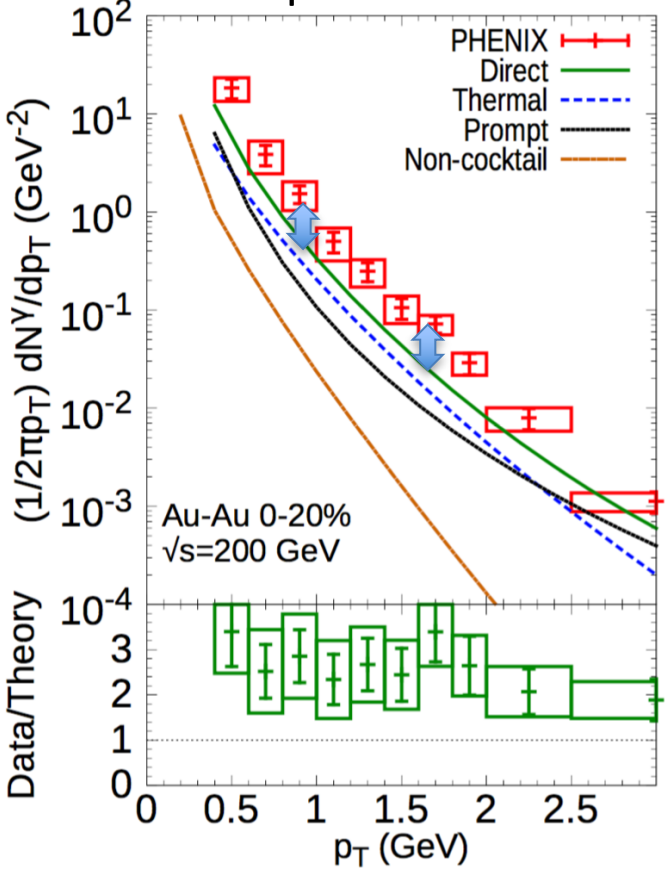
The state-of-the-art hydrodynamic model

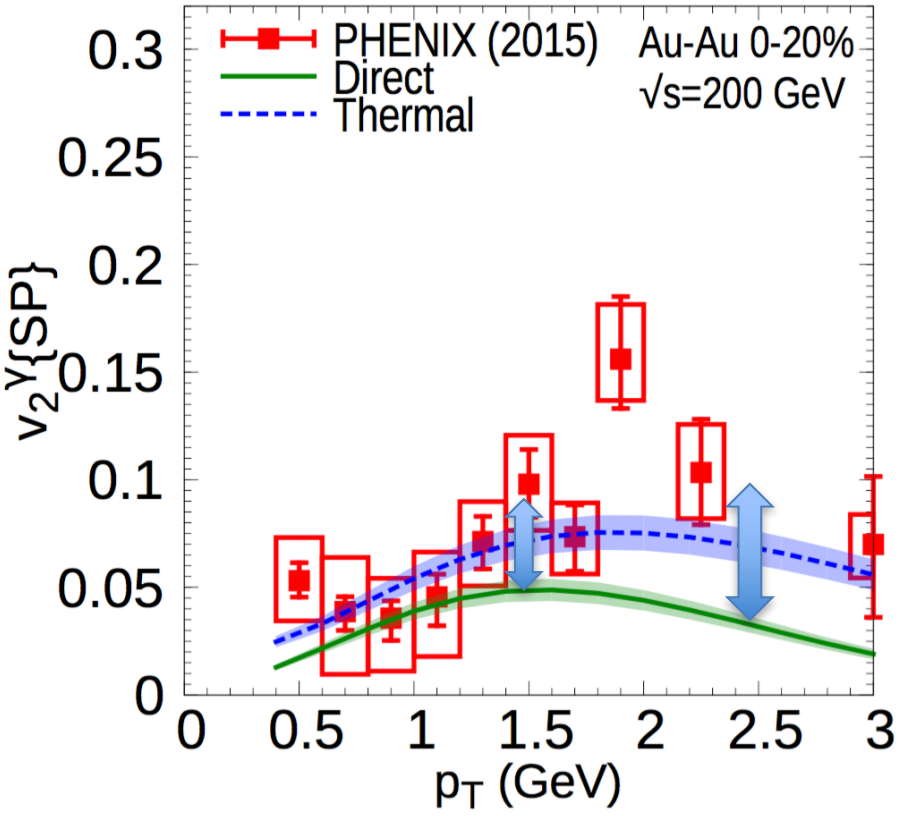
+ photon production processes except decay photons

The results are smaller than experimental data at RHIC and LHC

Direct Photon Puzzle

Direct photon = Inclusive photon – decay photon from hadrons





Paquet et.al. PRC93,044906(2016)

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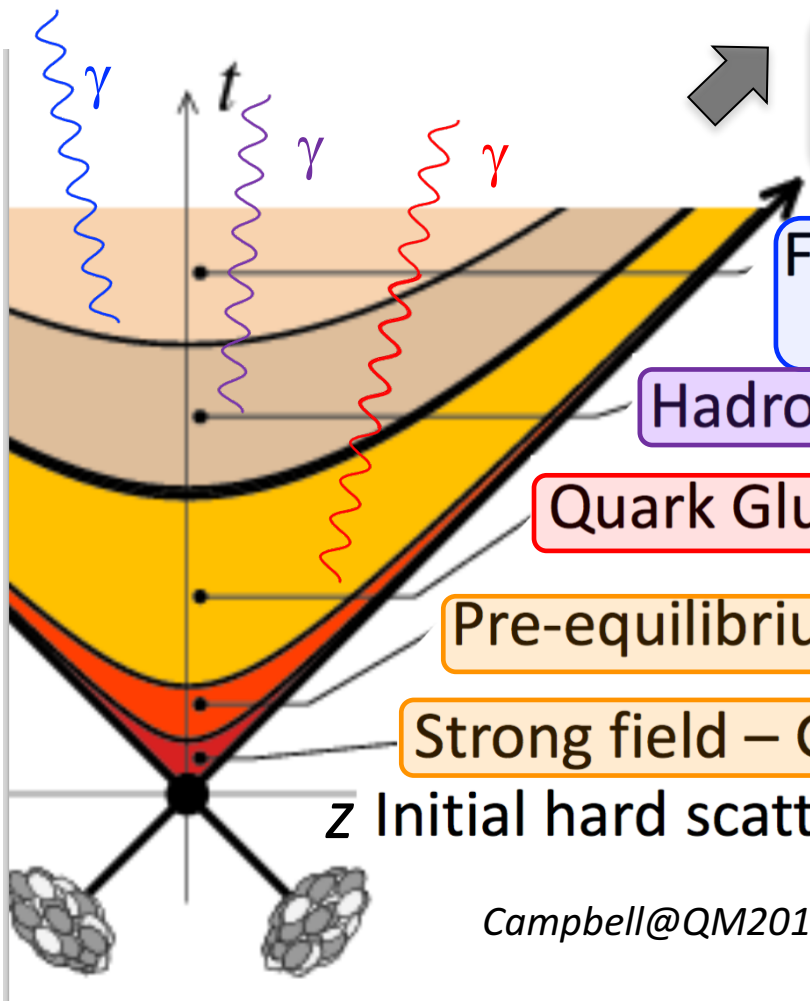
Photon Production in HIC



Photon emission at hadronization

Pratt
Campbell

Free streaming hadrons

Hadron Gas

Quark Gluon Plasma

hydrodynamic model

Pre-equilibrium phase

Strong field – Glasma?

under discussion
The contribution may not be so small.

Initial hard scattering

Campbell@QM2017

Radiative Recombination

with Itakura and Fujii

$$e^- + p \rightarrow H + \gamma$$

- A fundamental process in plasma physics and astrophysics
- Photon emission is necessary to compensate energy difference between initial (continuum) state and final (bound) state ⇨ "free-bound" transition

Examples:

- glow discharge
- "recombination" in the early universe
- continuum spectrum from Nebula

Similar processes in nuclear reaction in the sun

<u>pp chain</u>

$D + p \rightarrow {}^3He + \gamma$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$, etc

<u>CNO cycle</u>

$p + {}^{12}C \rightarrow {}^{13}N + \gamma$

$p + {}^{13}C \rightarrow {}^{14}N + \gamma$, etc

Radiative Recombination in QGP

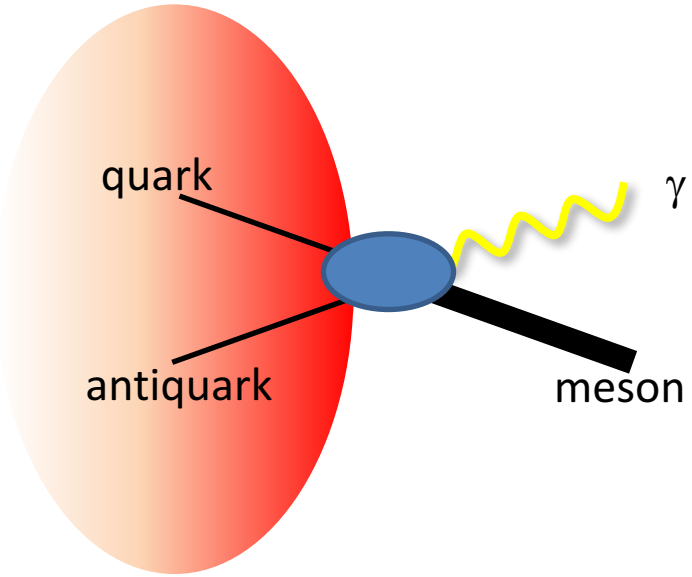
Possible resolution to the direct photon puzzle

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

Radiative Recombination in QGP

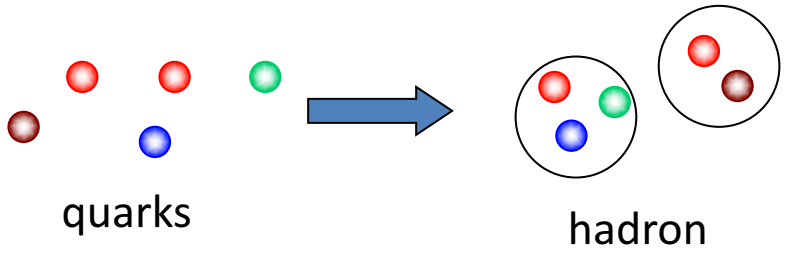
- Non perturbative process
- Not possible to use the inverse process
- Not equilibrium process

⇨ **Recombination Model**



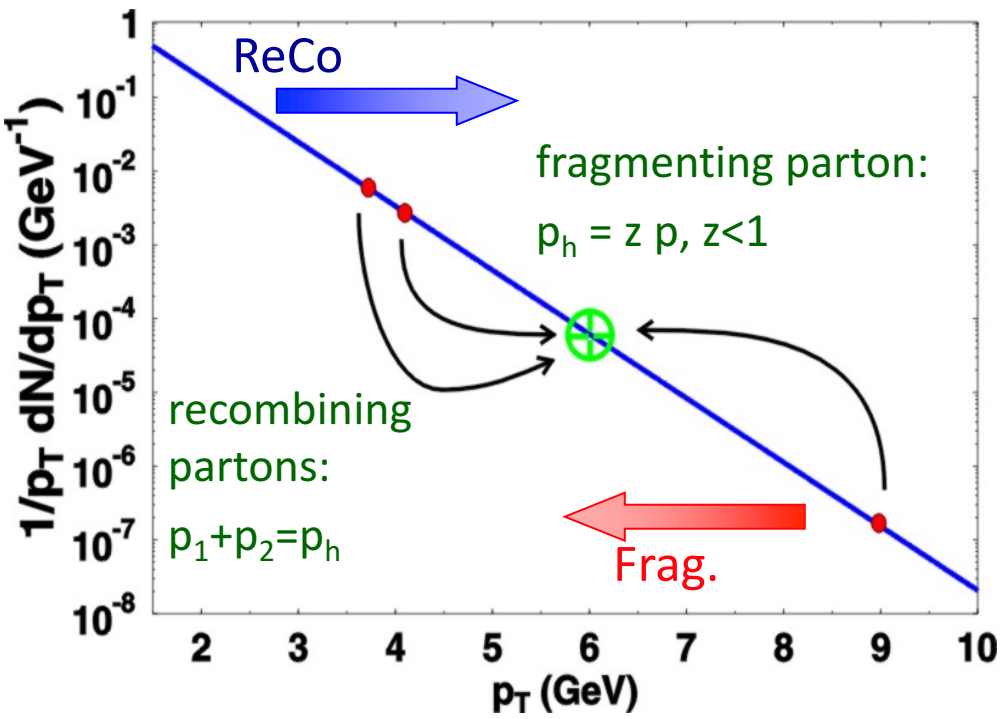
Recombination

- A hadronization model



The recombination process occurs at moderate P_T.

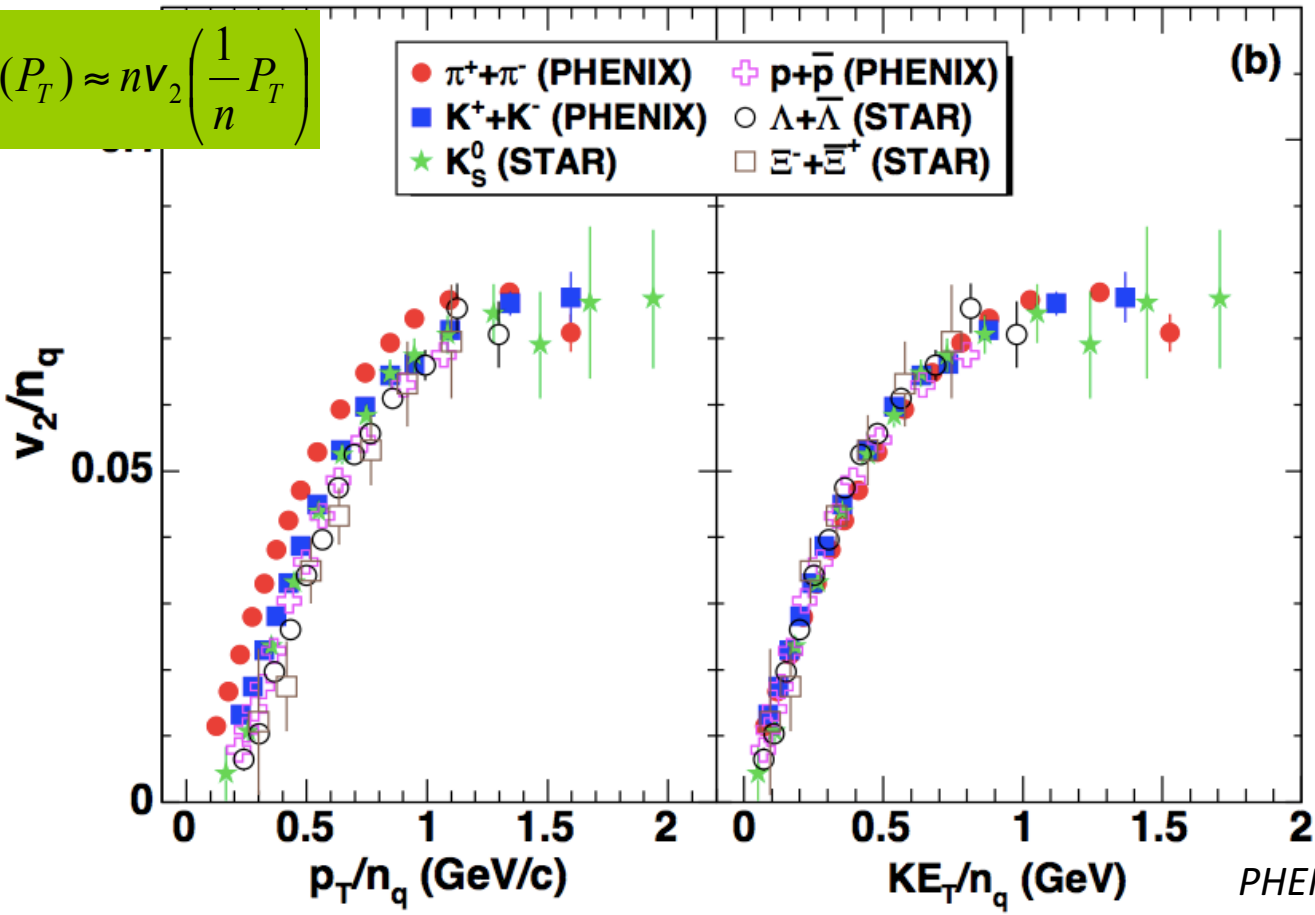
Fries, Mueller, CN and Bass, PRC68(2003)



- One of successful models
  - Baryon/Meson rations
  - 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

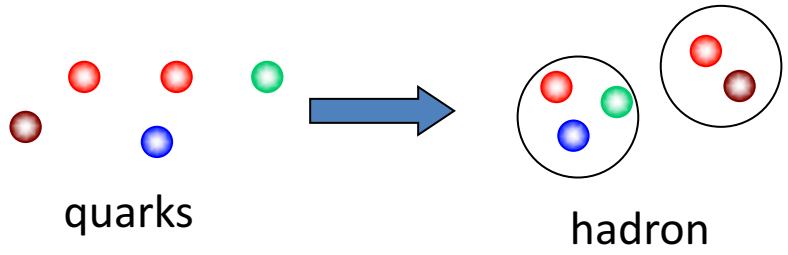
$\sqrt{s_{NN}} = 200$ GeV

$$KE_T = m_T - m$$

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

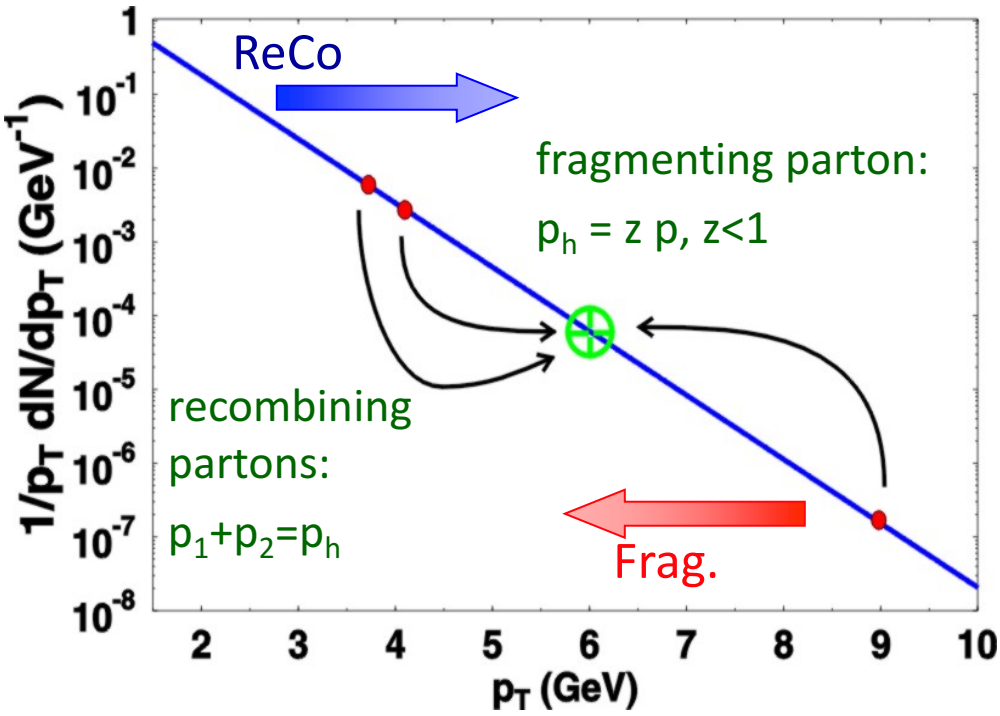
Recombination

- A hadronization model



Ex. Duke
The recombination process occurs at moderate P_T.

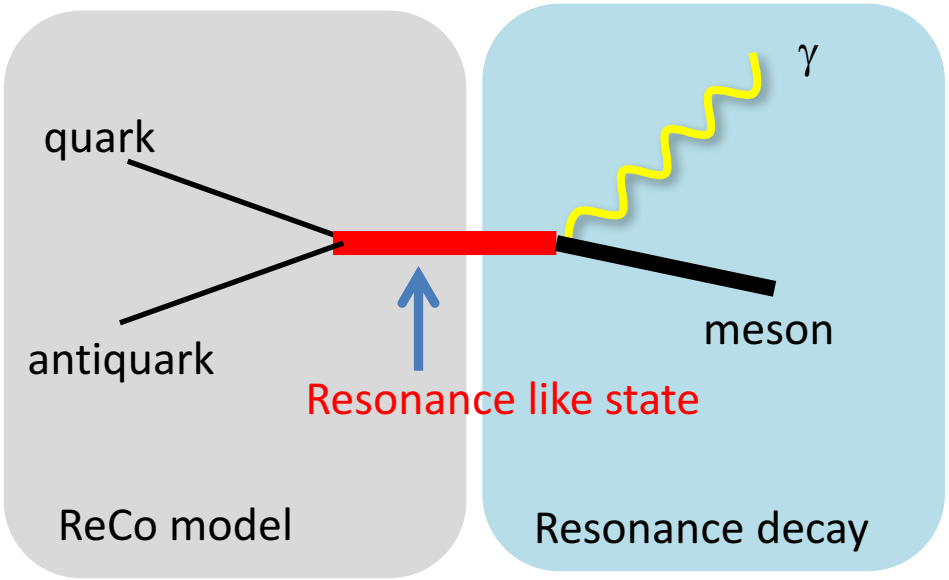
Fries, Mueller, CN and Bass, PRC68(2003)



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

ReCo with Photon Emission

Resonance-like state is produced through the recombination model.



Photons are emitted from decay of the resonance particle.

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

Spectral function of resonance state

Centrality Dependence @RHIC

RHIC

M_*=0.6 GeV

Transverse flow

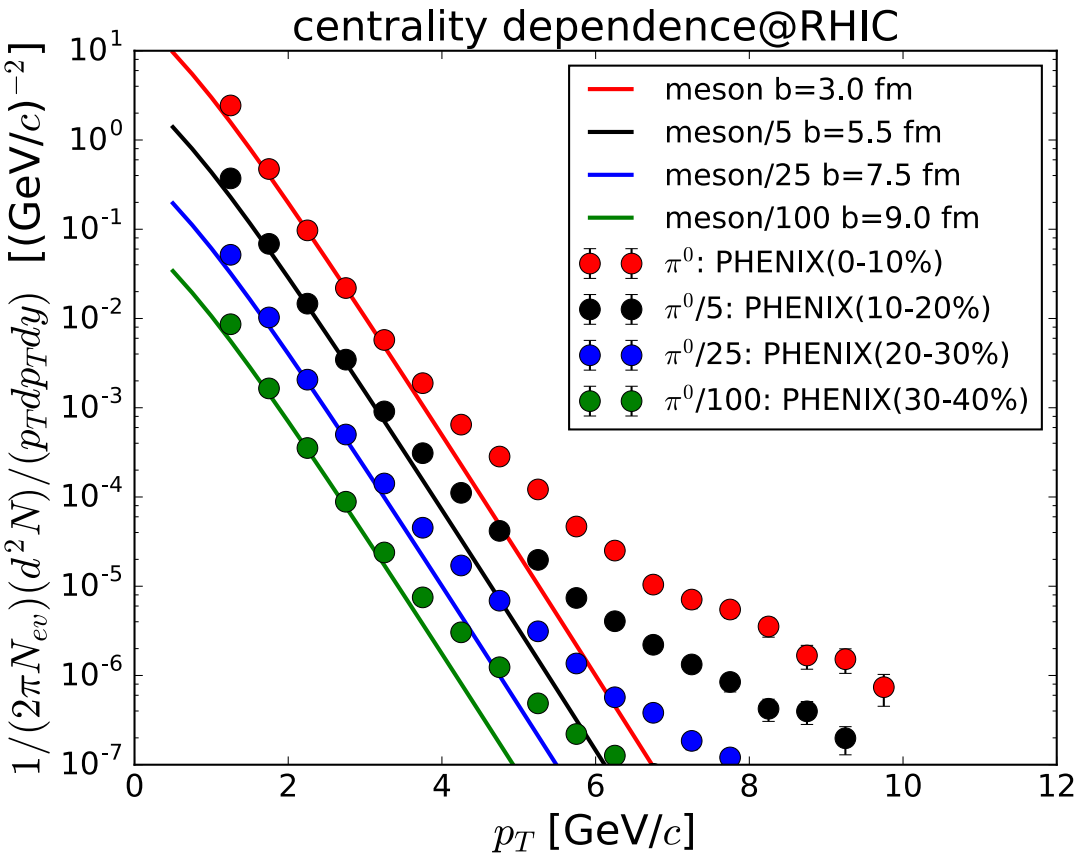
$$v_T = 0.6$$

Hadronization temperature

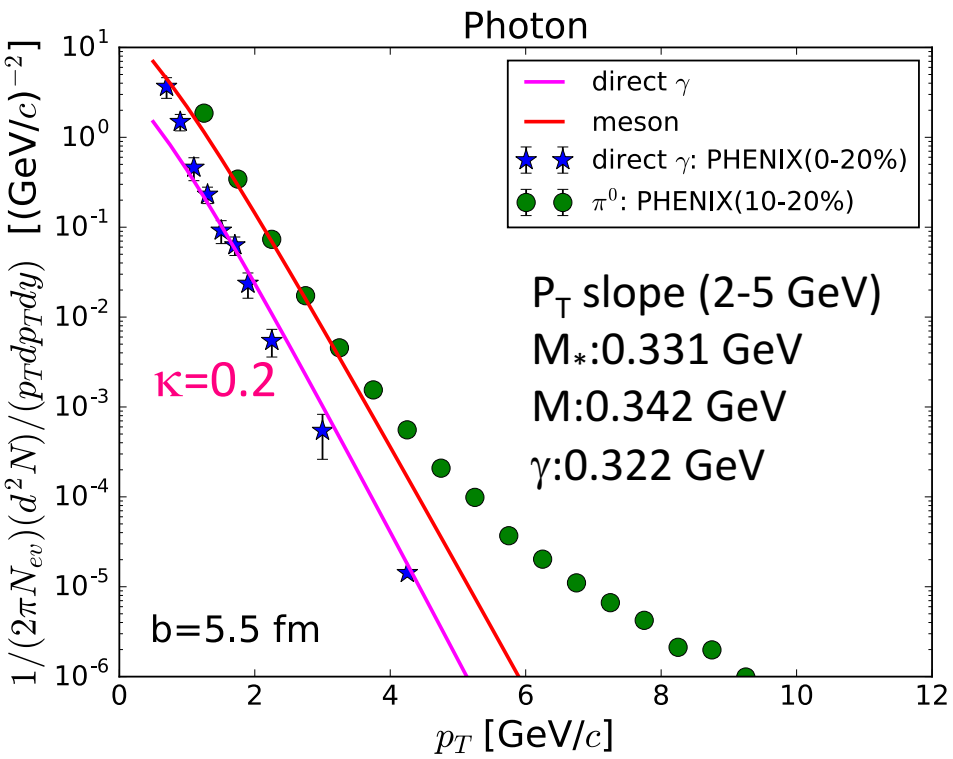
$$T_h = 155\ \mathrm{MeV}$$

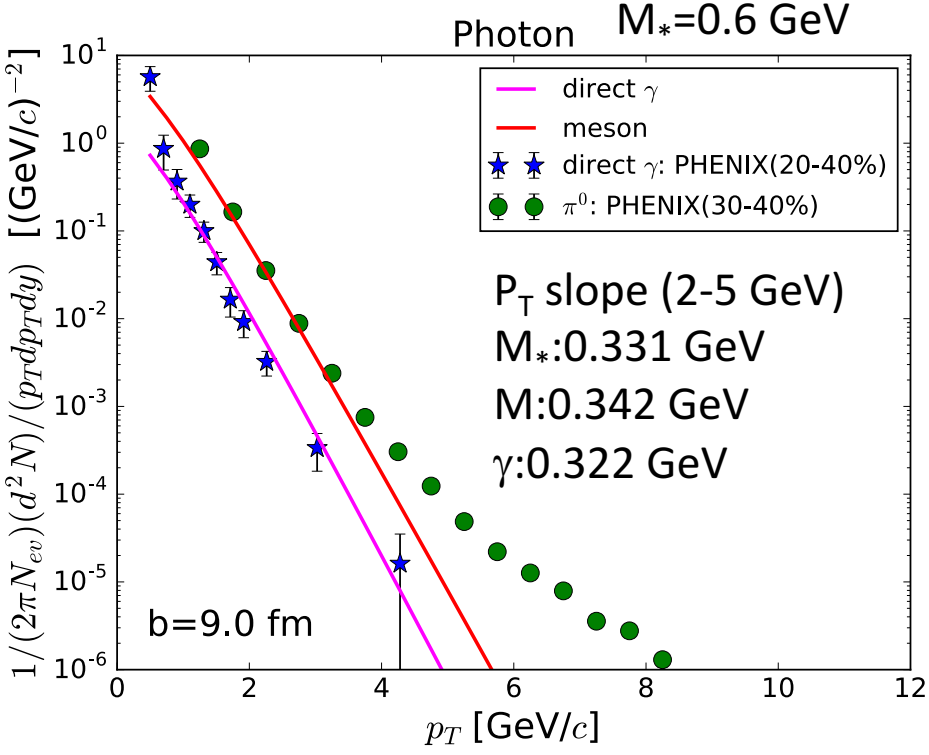
Fugacity

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



Photon's P_T Spectra @ RHIC





Overall factor κ=0.2 is determined at central collision.

$$T_{eff}^{M,\gamma} = \left(1 \pm \frac{M^2}{M_*^2}\right)\sqrt{\frac{1+v_T}{1-v_T}}T_h \qquad \frac{T_{eff}^{M}}{T_{eff}^{\gamma}} = \frac{M_*^2+M^2}{M_*^2-M^2} \sim 1.1$$

~ 1.06
(numerical calculation)

- P_T spectra photon from 2 to 5 GeV show good agreement with experimental data.
- Photon's effective temperature decreases with increasing M_*.

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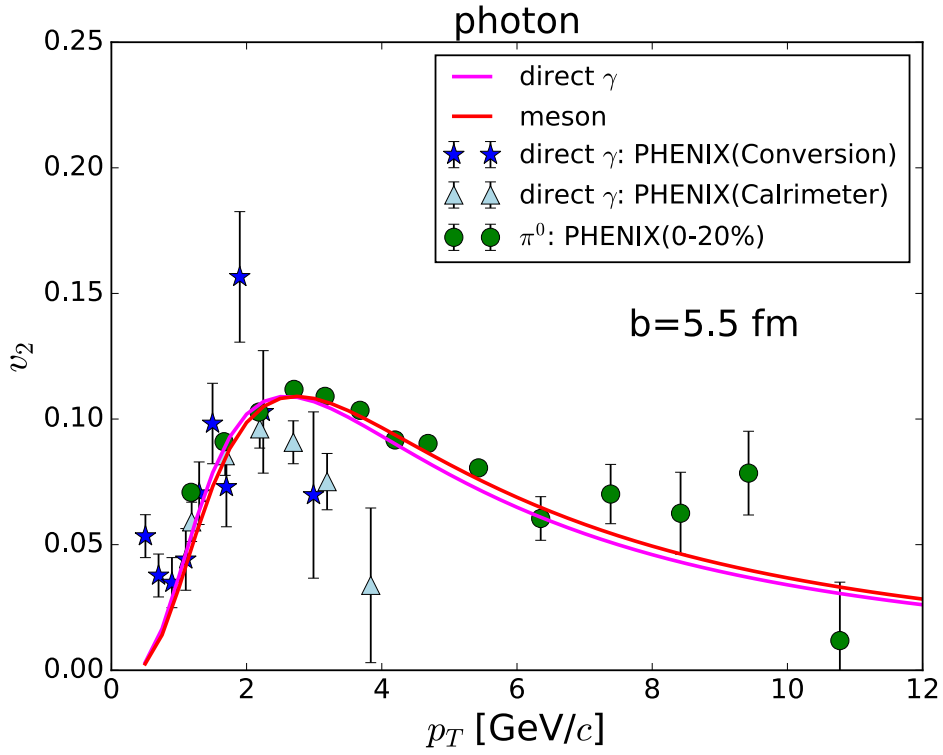
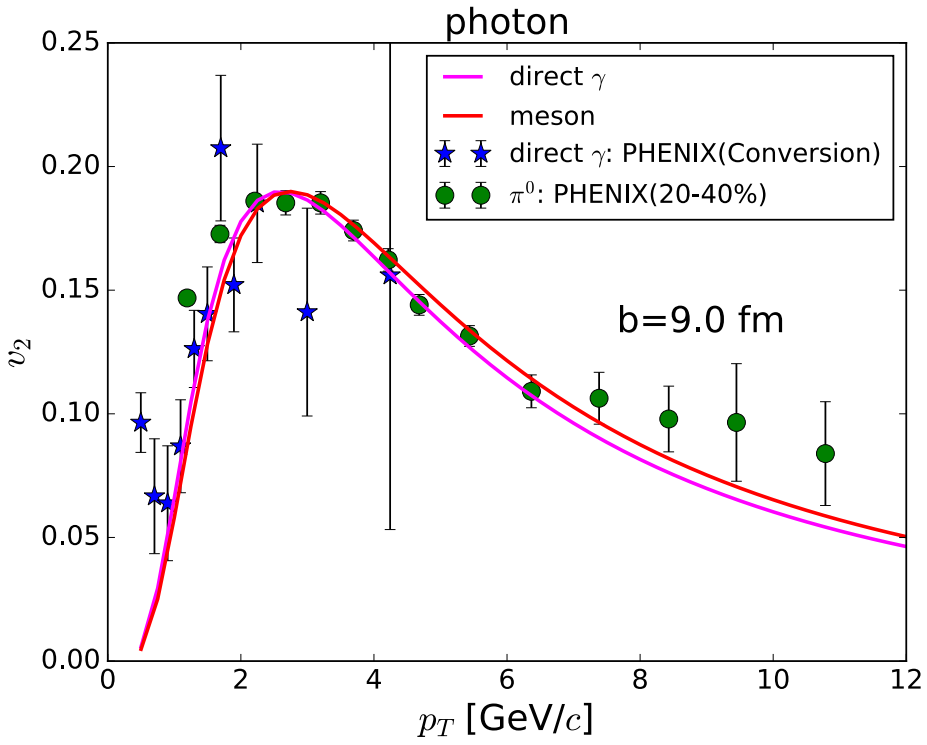
Photon's Elliptic Flow @ RHIC

Input of recombination model: parton v_2 $v_2^q(p_T) \propto \dfrac{1}{1+(p_T/p_0)^3}$ p_0=1.2 GeV





- Photon's v_2 is as large as meson's v_2.
- Small momentum difference is consistent with scaling (T^M/T^γ=1.06)

$$v_2^M(k) \sim v_2^{M_*}\left(\frac{M_*^2}{M_*^2+M^2}k\right) \qquad v_2^\gamma(k^\gamma) \sim v_2^{M_*}\left(\frac{M_*^2}{M_*^2-M^2}k^\gamma\right)$$

Violation of quark number scaling appears in high P_T region

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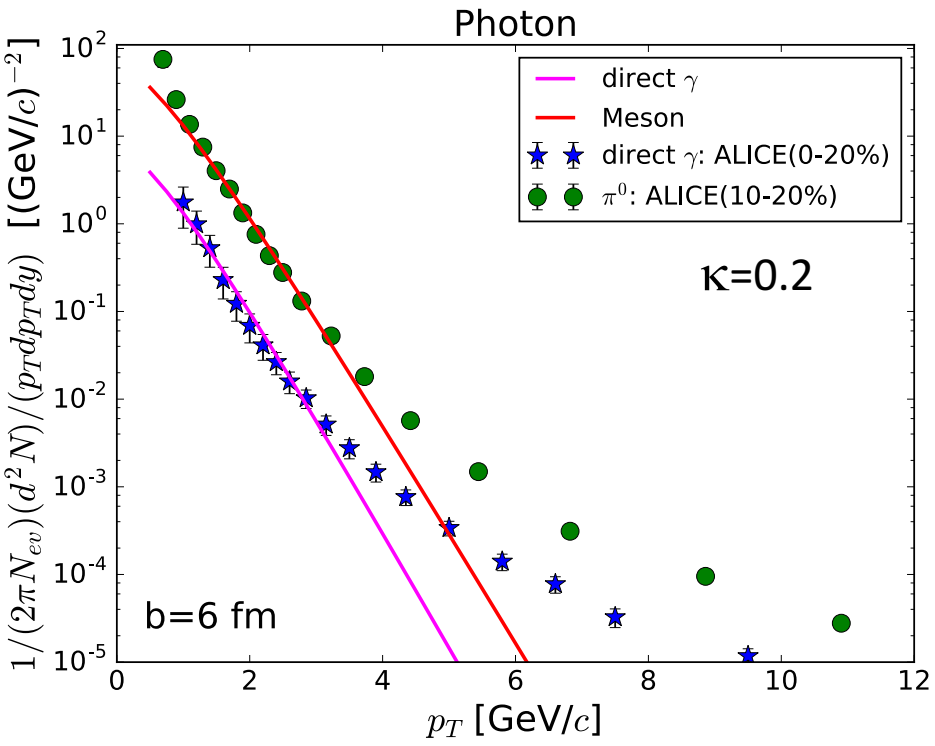
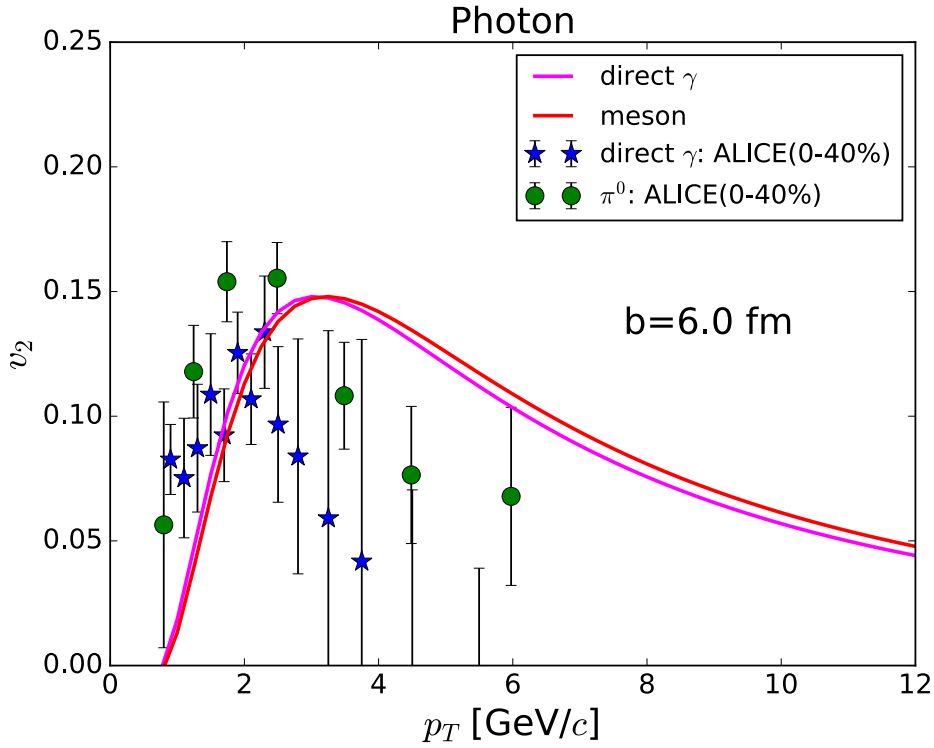
Photon's P_T Spectra and v_2 @LHC





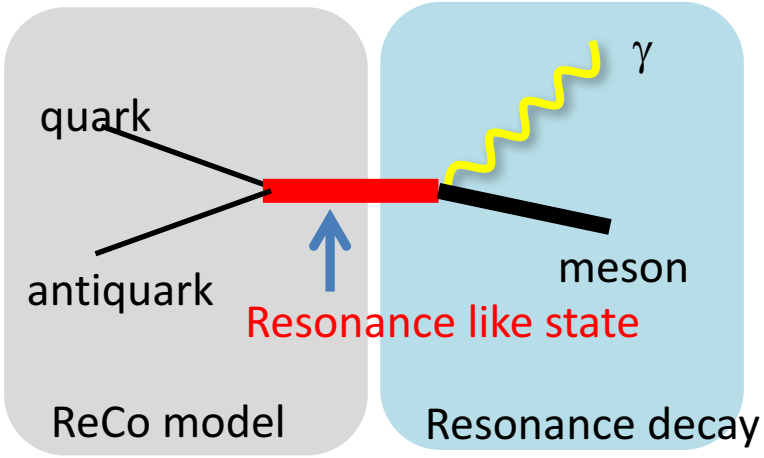
Transverse flow $v_T = 0.65$

Hadronization temperature $T_h = 155\ \mathrm{MeV}$

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

Summary

- High-energy heavy ion collisions at RHIC and LHC
  - Experimental data and the QCD phase diagram
  - Development of hydrodynamic model
- We propose a possible resolution to the photon puzzle
  - Radiative recombination
  - Large yield and v_2 of γ
  - Energy conservation in the recombination model



- Working in progress
  - Include other resonance-like states
  - Effects of baryon
  - Check the violation of quark number scaling
  - Dileptons