Photon emission at hadronization

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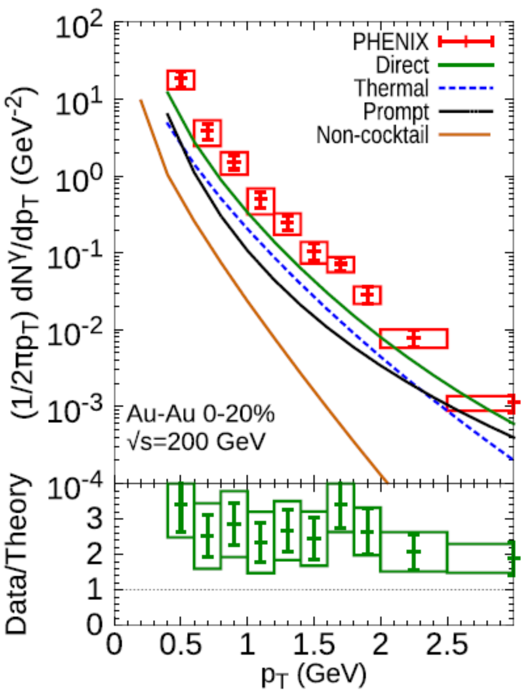
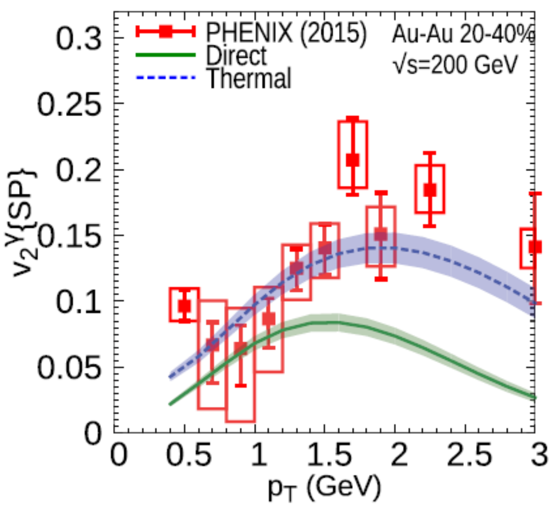
Direct photon puzzle

Direct photons : all photons except decay photons
including prompt photons, thermal photons, etc.

Up-to-date hydrodynamic calculation for thermal photons
(Paquet, Shen, Denicol, Luzum, Schenke, Jeon, Gale 2016)

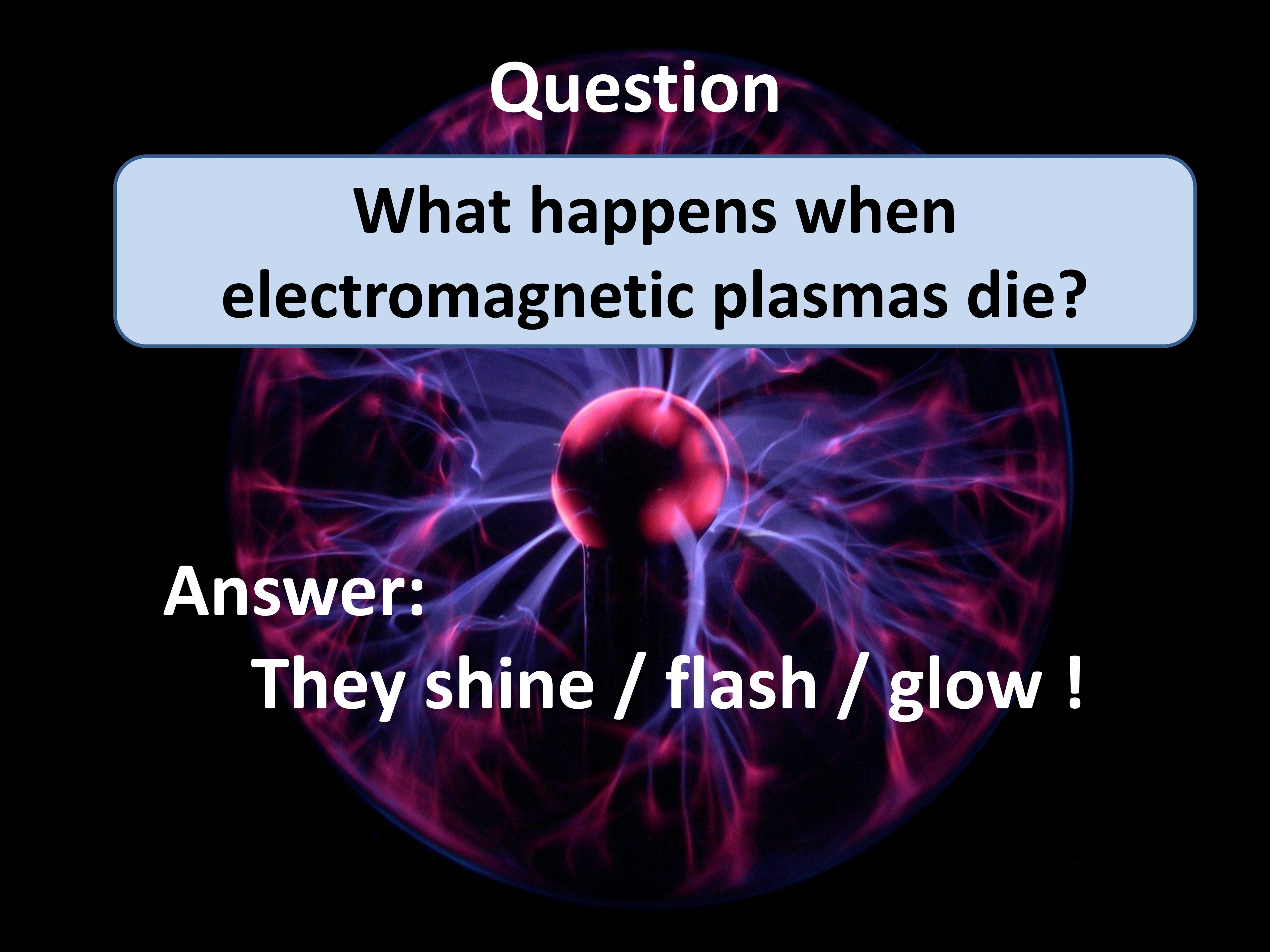




Photons have large v2 of the same order of v2 of pions

Up-to-date thermal photon calculation
- consistent with v2 data
- but underestimates yield by factor of 2 to 3 (at RHIC)

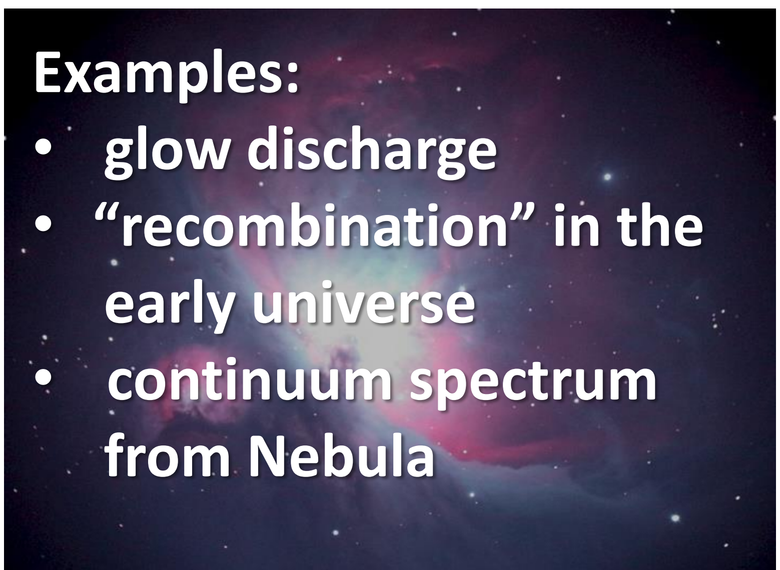
Let's think of another source of photon emission!


Question
What happens when electromagnetic plasmas die?
Answer:
They shine / flash / glow !

Radiative recombination

$$e^{-} + p \rightarrow \mathrm{H} + \gamma$$

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



Similar processes in nuclear reaction in the sun

pp chain

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

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

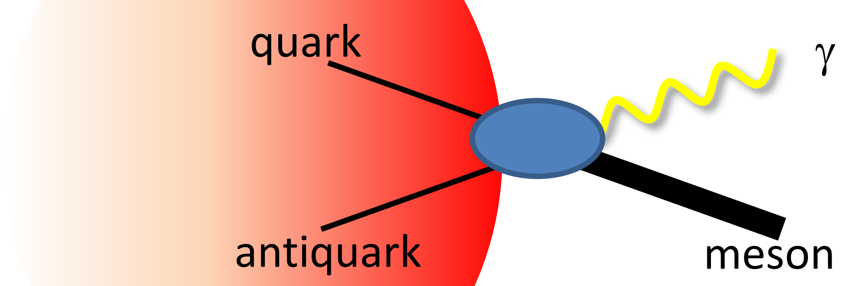
CNO cycle

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

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

Why not in QGP?

What is good about "Radiative Hadronization"?



Photons are emitted at hadronization

→ Photons will have flow as strong as hadrons.

A photon is emitted for each pairing of hadrons

→ Although there might be other processes to compensate the energy difference in QGP, number of photons will be as large as hadrons (pions), leading to huge enhancement of yield.

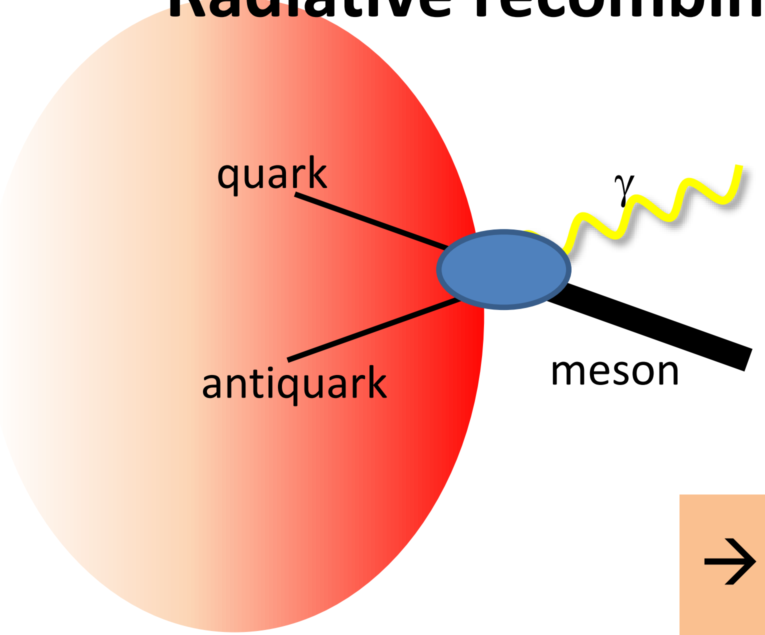
Radiative hadronization has a potential to resolve the direct photon puzzle!

How to formulate "radiative hadronization"?

Radiative recombination in EM plasmas

- **Kramers-Milne relation:**
  to relate recombination X-sec. to inverse process (photoionization)
- **Saha equation:**
  to give ionization ratio as a function of temperature

Radiative recombination in QGP



- Nonperturbative process
- Not possible to use the inverse process
- Photons escape from the reaction region
  → cannot use the Saha-like equation
  for equilibrium plasmas

Maybe can be formulated with quark-meson model (Young-Pratt, 2016)

→ We utilize the **ReCombination Model**
developed by Duke group
(Fries,Mueller,Nonaka,Bass, 2003)

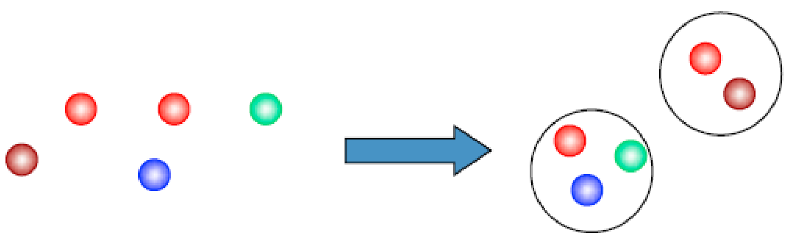
ReCombination model

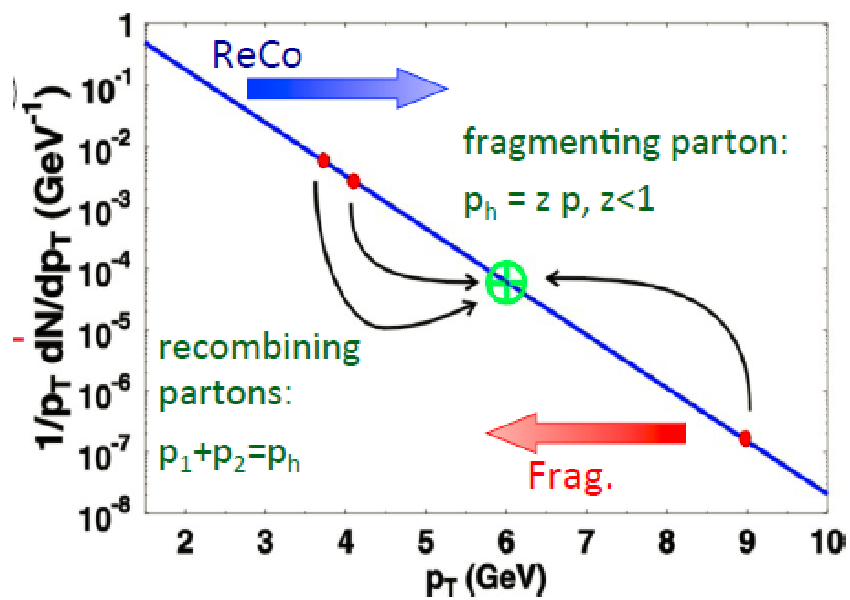
Fries, et al.
PRC68 (2003)

- A successful model for hadronization in middle pt region (2 < pt < 5 GeV)
- Hadronization as recombination of constituent quarks/antiquarks
- Explain the anomalous baryon-to-meson ratio and the quark number scaling

Formation of hadrons

- an abrupt process on the hypersurface
- compute # of hadrons by the overlap btw quark states and hadron states
- essentially a two(or three)-to-one process violating energy conservation





Natural to consider photon emission to resolve the energy/entropy problem

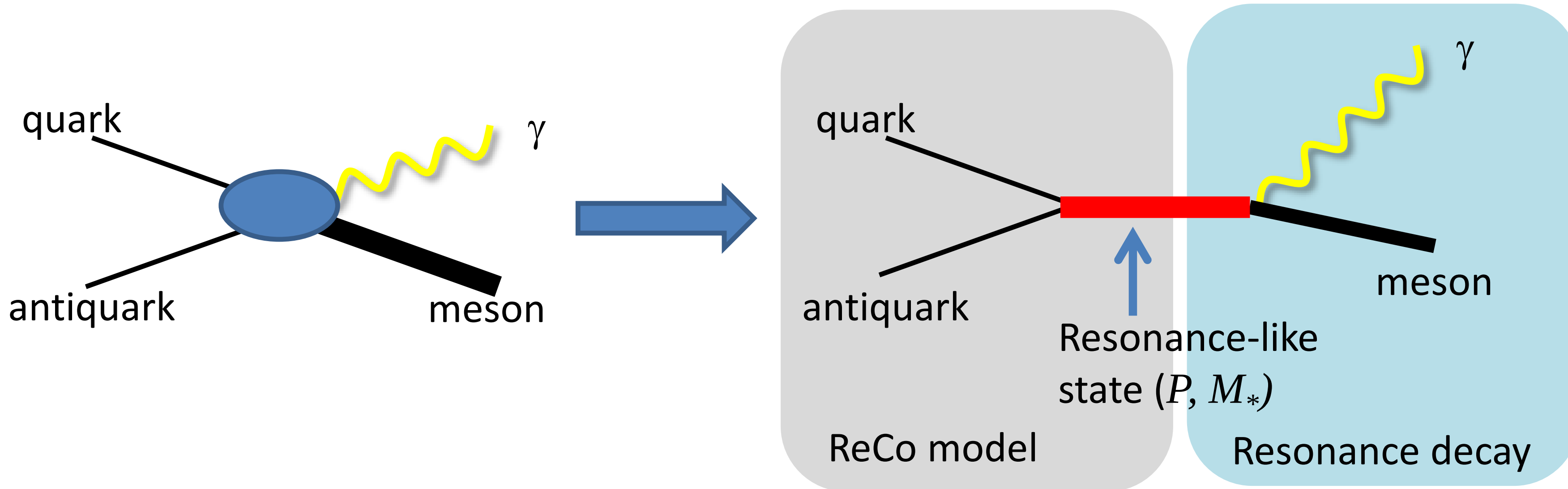
ReCo with photon emission

Interpret the previous ReCo model

as the production of preformed "resonance-like" states

Assume a two-step process:

photons are produced from the decay of resonance-like states



Number of photons from meson formation

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

Number of photons from meson formation

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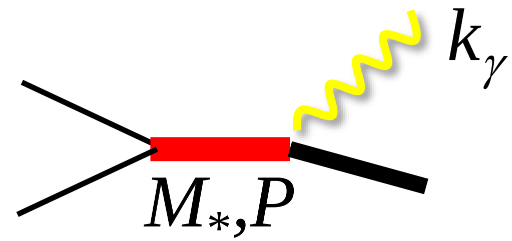


Number of resonance-like states from ReCo

Quarks and antiquarks are thermalized with transverse flow v_T

$$\left. \frac{dN_{M_*}}{d^3P} \right|_{y=0} \sim e^{-P_\perp / T^*_{eff}}, \quad T^*_{eff} = T_h \sqrt{\frac{1+v_T}{1-v_T}}$$

T_h: hadronization temp.

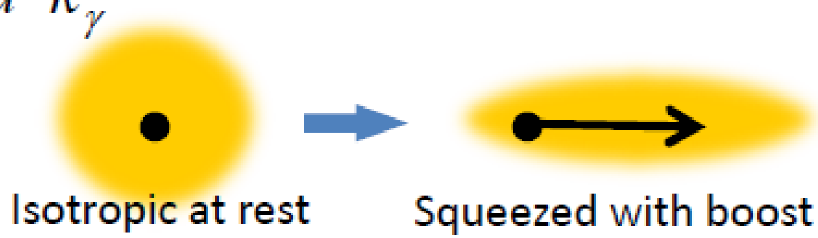
blue shifted by flow

Photon distribution from a resonance-like state

$$\varepsilon_\gamma \frac{dn_\gamma}{d^3k_\gamma} = c\,\delta\left(k^\gamma_{CM}(M_*, P) - k_0\right), \quad k_0 = \frac{M_*^2 - M^2}{2M_*}$$

Photon energy in rest frame of M^*

M: meson mass



Rough estimate

Consider the contribution from a single value of *M**

pt distribution of photon:

$$E_\gamma \frac{dN_\gamma}{d^2k_\perp^\gamma}\bigg|_{y=0} \sim \exp\left(-\frac{k_\perp^\gamma}{T_{eff}^\gamma(M_*)}\right), \qquad T_{eff}^\gamma(M_*) = \left(1-\frac{M^2}{M_*^2}\right)T_{eff}^*$$

exponential with slope parameter smaller than the resonances.

Elliptic flow :

$$v_2^\gamma(k^\gamma) \equiv \int d\phi_\gamma \cos 2\phi_\gamma \left(k^\gamma \frac{dN_\gamma}{d^2k^\gamma d\phi_\gamma}\right) \sim v_2^*\left(\frac{M_*^2}{M_*^2-M^2}k^\gamma\right)$$

v2 of resonance-like state

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

$$\frac{dN_{M_*}}{d^3P} = f_{M_*}(P_\perp)\left(1+2v_2^*(P_\perp)\cos 2\phi\right)$$

Numerical result

We use almost the same parameter set as in the previous ReCo.
Consider only the contribution from M_*=600MeV and pions

RHIC

Transverse flow

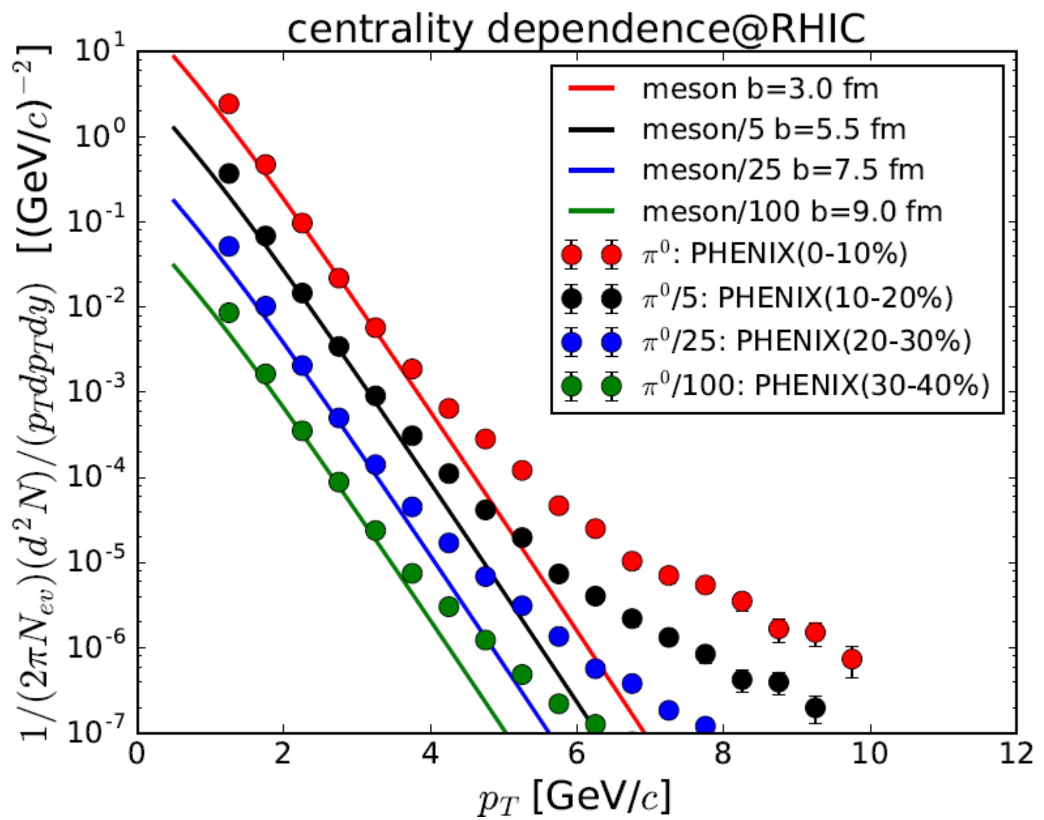
v_T=0.52

Hadronization temperature

T_h=175MeV

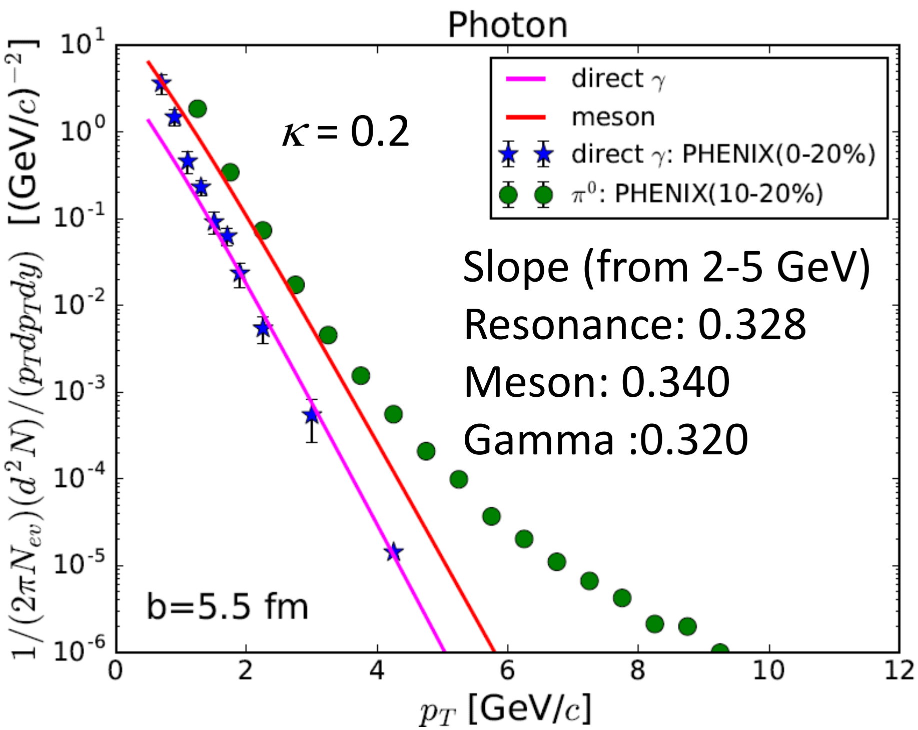
Fugacity

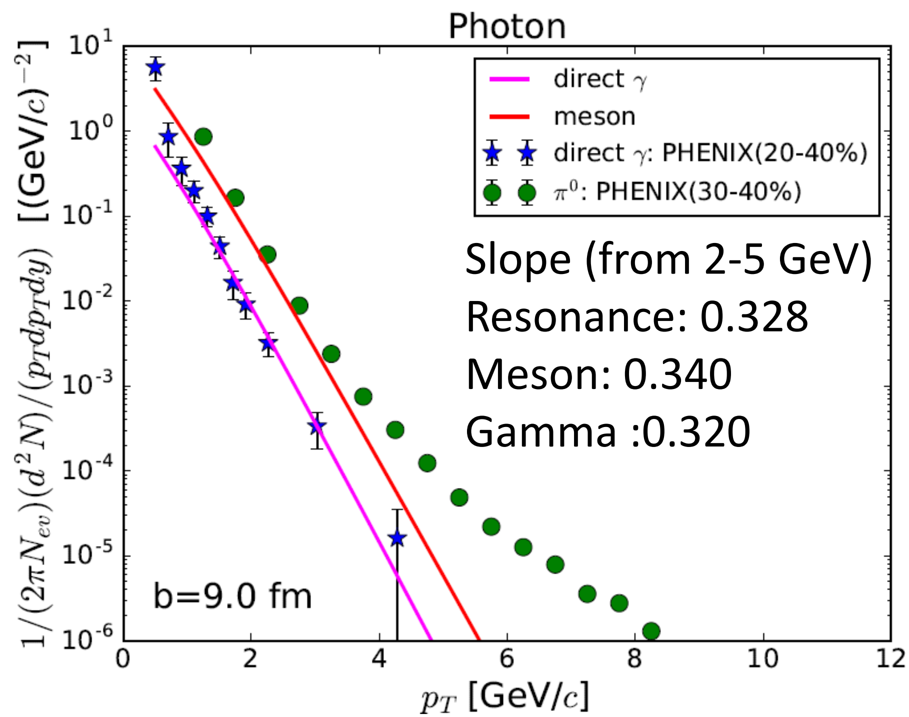
$\gamma_{u,d}$ =1, $\gamma_{ubar,dbar}$=0.9



Can describe centrality dependence
of pion spectrum reasonably well

Photon's pt distribution @ RHIC





Overall factor $\kappa = 0.2$ determined at central collision

Rough estimate

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

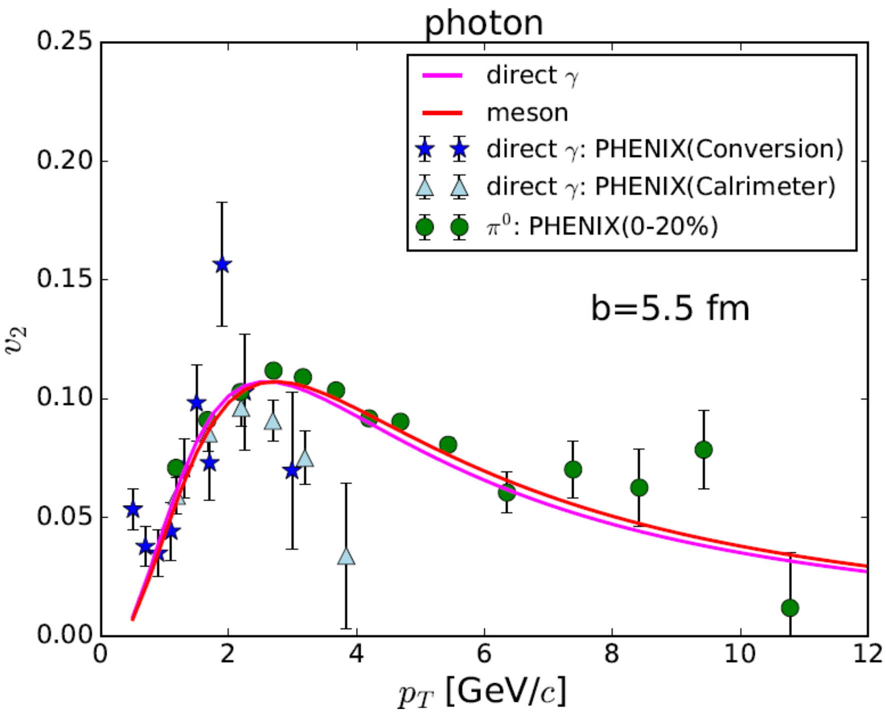
Consistent with numerical result 340/320 ~ 1.06

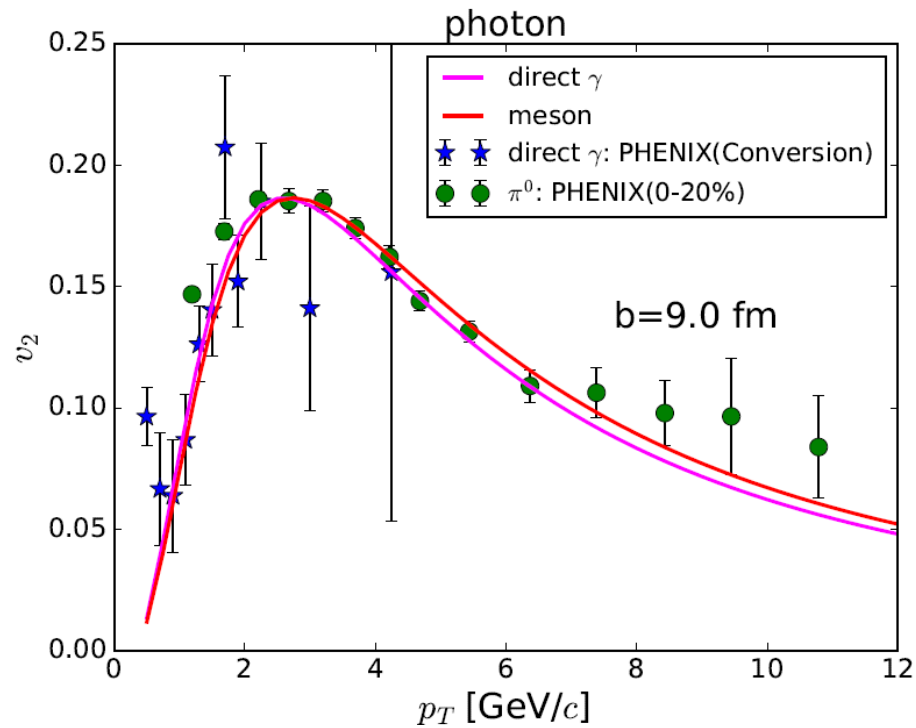
Slope of 320MeV is consistent with data for pt from 2 to 4 GeV.

Photon's effective temperature decreases with increasing M*.

Photon's elliptic flow @ RHIC

Assume parton v2 (a source of flow) $v_2^q(p_T) \propto \frac{1}{1+(p_T/p_0)^3}, \quad p_0 = 1.3\mathrm{GeV}$



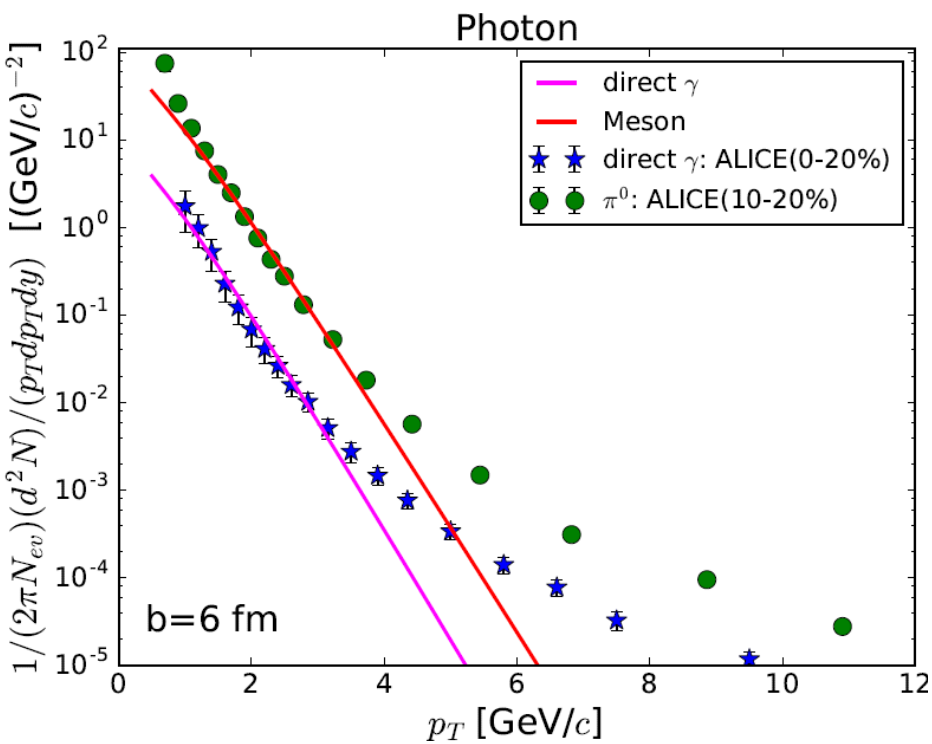


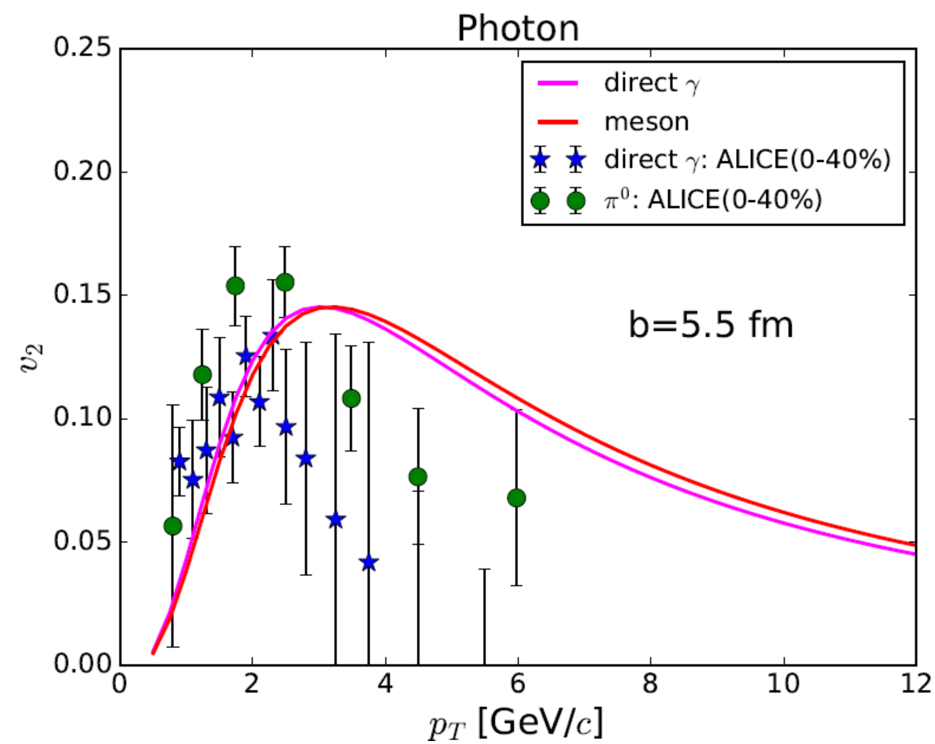
Photon's v2 has the same magnitude and same shape as v2 of pions.
Small momentum difference consistent with scaling (T^M/T^γ=1.06).

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

Cf: violation of NCQ scaling appears in high pt region

Photon's pt distr. & v2 @ LHC





Transverse flow

v_T=0.6

Hadronization temperature

T_h=175MeV

Fugacity

$\gamma_{u,d} = \gamma_{ubar,dbar}$=1

Summary & prospects

- Applied the radiative recombination to hadronization of QGP
- Utilized the ReCo model so that it can allow photon emission to compensate energy difference between initial and final states
- Obtained exponential pt distribution for photons mimicking thermal distribution. Effective temperature is essentially given by the recombination temperature which is blue shifted by transverse flow velocity.
- Photon yield and elliptic flow v2 are as large as those of mesons, providing a potential power to resolve the direct photon puzzle.

- Check the effects of resonance-like spectrum, excitation states (line spectrum), other mesons, NCQ scaling and its violation.
- Dilepton production,, effects of baryons are also in the list of future work.
- Provided a new way of looking at the data to make things more interesting, or maybe have screwed you up? More detailed analysis necessary.

backup

Thermal quark distribution in ReCo

$$w_a(R;p) = \gamma_a e^{-p \cdot v(R)/T} e^{-\eta^2/2\Delta^2} f(\rho, \phi).$$

Parton momentum

$$p^\mu = (m_T \cosh y, p_T \cos \Phi, p_T \sin \Phi, m_T \sinh y)$$

Flow velocity

$$v^\mu(R) = (\cosh \eta_L \cosh \eta_T, \sinh \eta_T \cos \phi, \sinh \eta_T \sin \phi, \sinh \eta_L \cosh \eta_T).$$

Number of resonance-like states

A formula for number of mesons in the previous ReCo model

$$E\frac{N_M}{d^3P} = C_M \int_\Sigma d\sigma_R \frac{P\cdot u(R)}{(2\pi)^3} \int_0^1 dx w_a(R;x\mathbf{P}) |\phi_M(x)|^2$$

$$\times w_b[R;(1-x)\mathbf{P}],$$

We interpret this as the number of resonance-like states

We use the same LC wavefunction, but the results are insensitive to the details.

Thermal parton distribution gives

$$\left.\frac{dN_M}{d^2P_T dy}\right|_{y=0} = C_M M_T \frac{\tau A_T}{(2\pi)^3} 2\gamma_a \gamma_b \, I_0\left[\frac{P_T \sinh \ \eta_T}{T}\right]$$

$$\times \int_0^1 dx |\phi_M(x)|^2 k_M(x, P_T),$$

Yields an exponential distribution for high pt > m

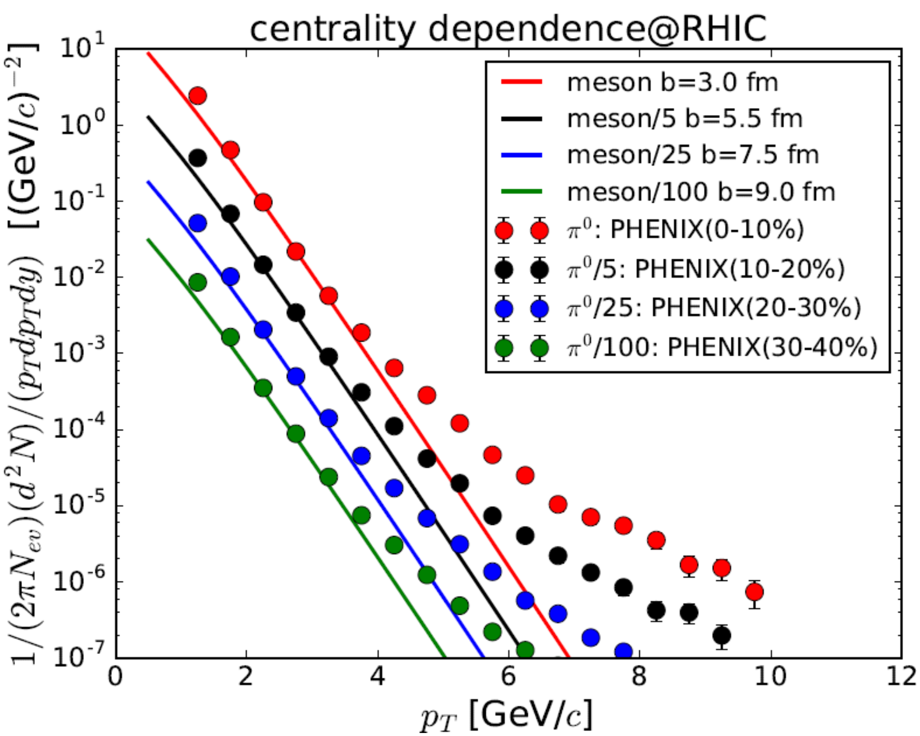
$$k_M(x, P_T) = K_1\left[\frac{\cosh \ \eta_T}{T}[\sqrt{m_a^2 + x^2 P_T^2} + \sqrt{m_b^2 + (1-x)^2 P_T^2}]\right],$$

Centrality dependence

Use the Glauber model to relate N_{coll} and impact parameters

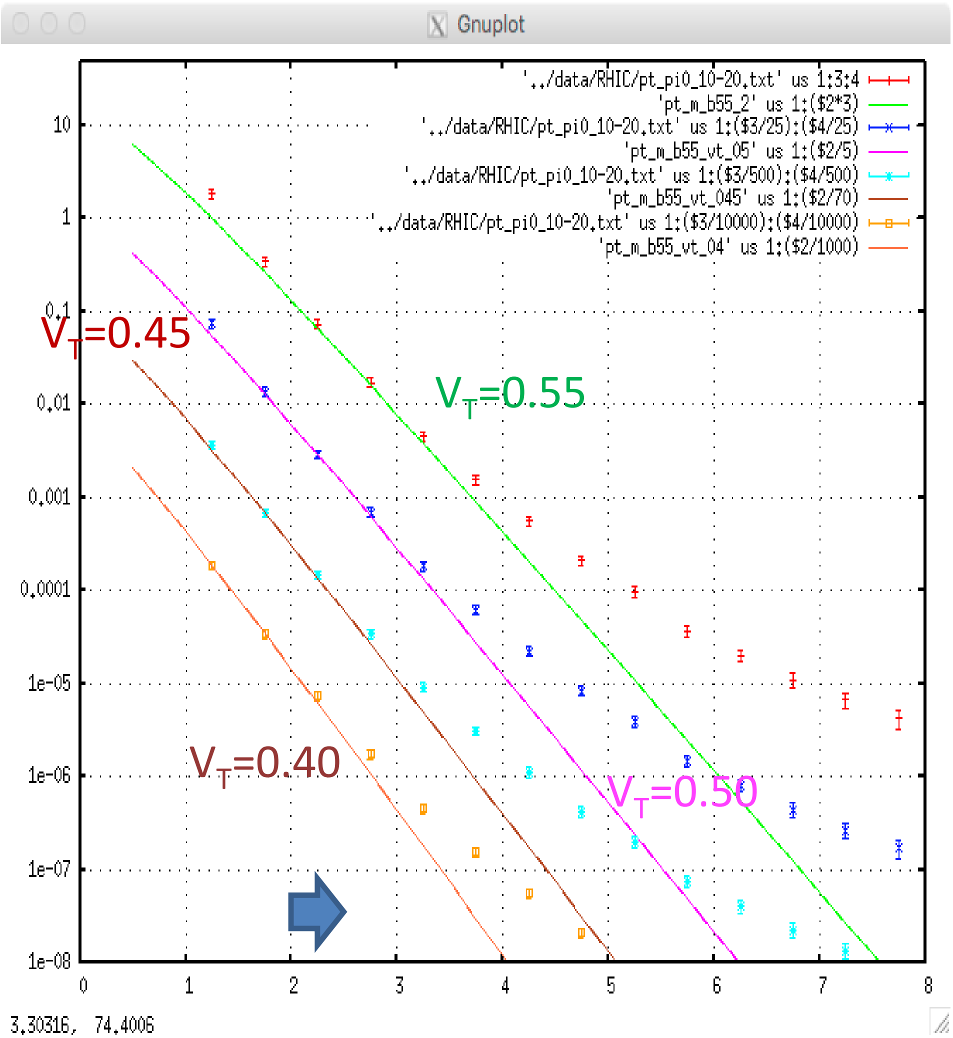
* impact parameters (TABLE I in recombination paper)

b(fm)	0	3	5.5	7.5	9	10	11	12	13	13.9
$N_{\rm coll}$	1146	913	594	350	199	120	61.6	26.0	10.0	5.3
[1]		0-10	10-20	20-30	30-40	40-50	50-60			
		955	602	373	219	120	62			



Centrality dependence of pions
Is well described by the new ReCo

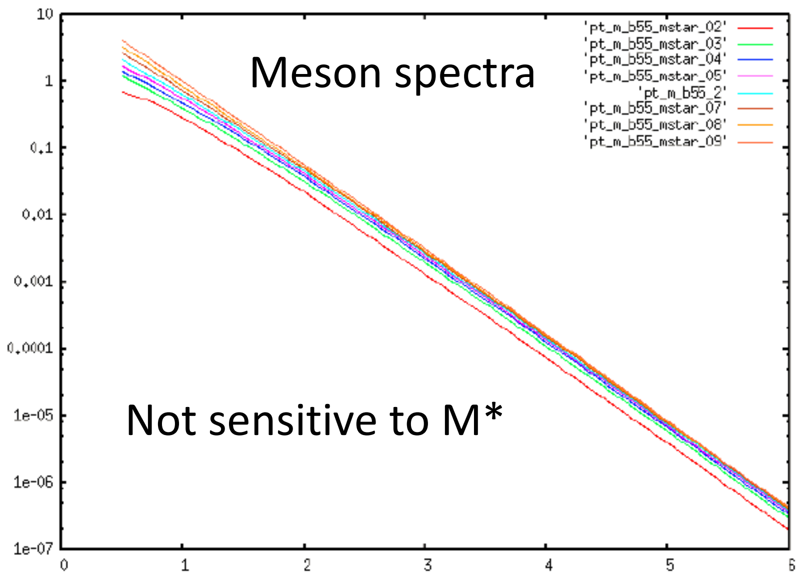
V_T dependence of P_T spectra of pions

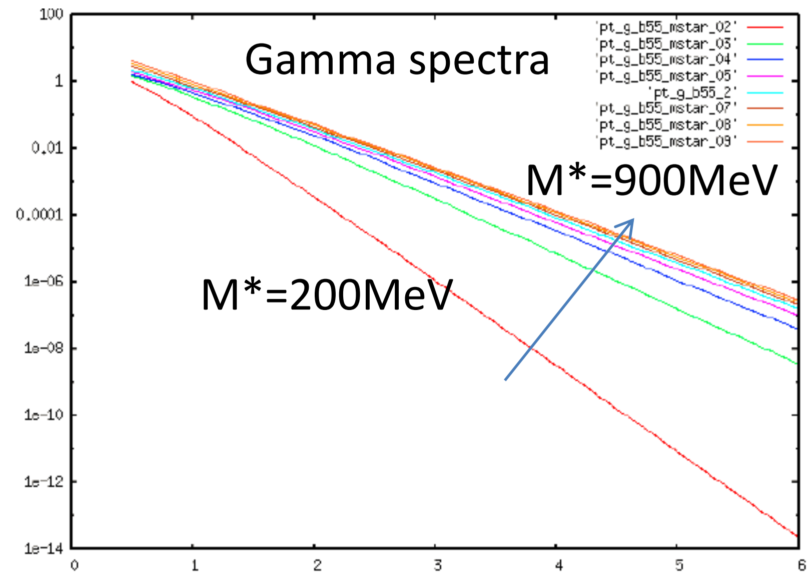


V_T	Slope [GeV]
0.51	0.335
0.52	0.340
0.53	0.345
0.54	0.351

We take vT=0.52 so that the slope of mesons is the same as that of the previous ReCo model.

M* dependence of P_T spectra of M & γ





M* [GeV]	Slope [GeV]
0.2	0.361
0.3	0.363
0.4	0.361
0.5	0.359
0.6	0.356
0.7	0.353
0.8	0.350
0.9	0.346

M* [GeV]	slope [GeV]
0.2	0.174
0.3	0.276
0.4	0.313
0.5	0.328
0.6	0.335
0.7	0.338
0.8	0.338
0.9	0.337