Photon production in hadronization stage

H. Fujii
(U Tokyo, Komaba)

in collaboration with
K. Itakura, C. Nonaka

(36th Heavy Ion Cafe at Sophia U.)

https://www.nasa.gov/jpl/herschel/crab-nebula-pia17563

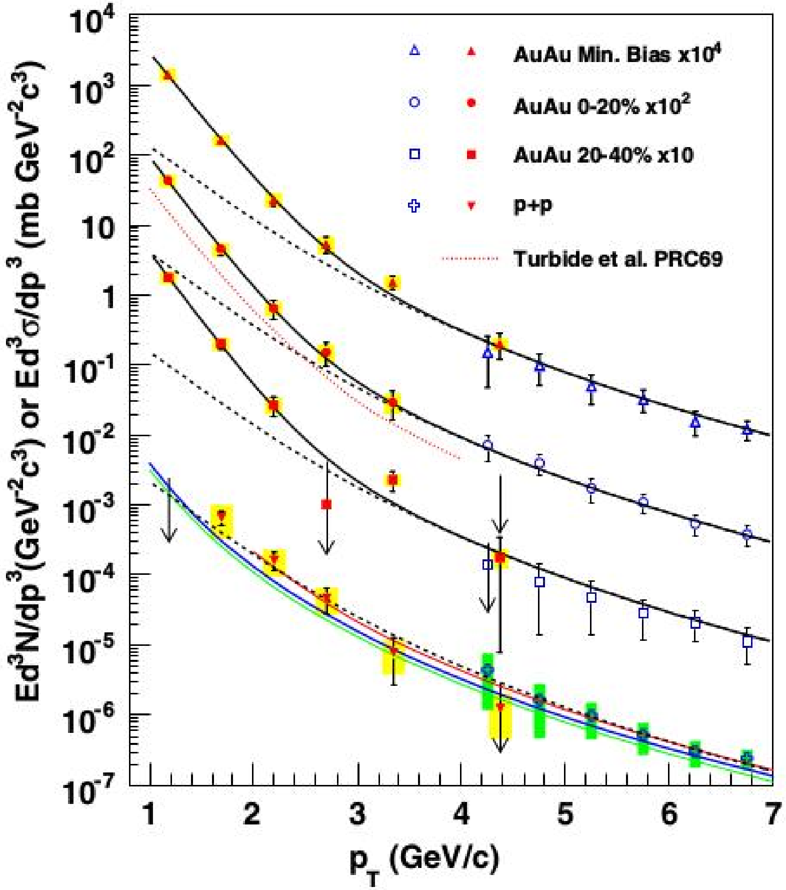
PRL 104, 132301 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 2 APRIL 2010

Enhanced Production of Direct Photons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV and Implications for the Initial Temperature

A.Adare et al. (PHENIX)

The production of e^+e^- pairs for $m_{e^+e^-} < 0.3$ GeV$/c^2$ and $1 < p_T < 5$ GeV$/c$ is measured in $p+p$ and Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. An enhanced yield above hadronic sources is observed. Treating the excess as photon internal conversions, the invariant yield of direct photons is deduced. In central Au + Au collisions, the excess of the direct photon yield over $p+p$ is exponential in transverse momentum, with an inverse slope $T = 221 \pm 19^{\mathrm{stat}} \pm 19^{\mathrm{syst}}$ MeV. Hydrodynamical models with initial temperatures ranging from $T_{\mathrm{init}} \sim 300$–$600$ MeV at times of ~ 0.6–0.15 fm$/c$ after the collision are in qualitative agreement with the data. Lattice QCD predicts a phase transition to quark gluon plasma at ~ 170 MeV.

- **Increase of direct γ!**
- **T_{slope} = 221±19±19 MeV**
- **T_{init} ~ 300–600 MeV ≫ Tc**
  - **at 0.6 – 0.15 fm/c (hydro model calc)**

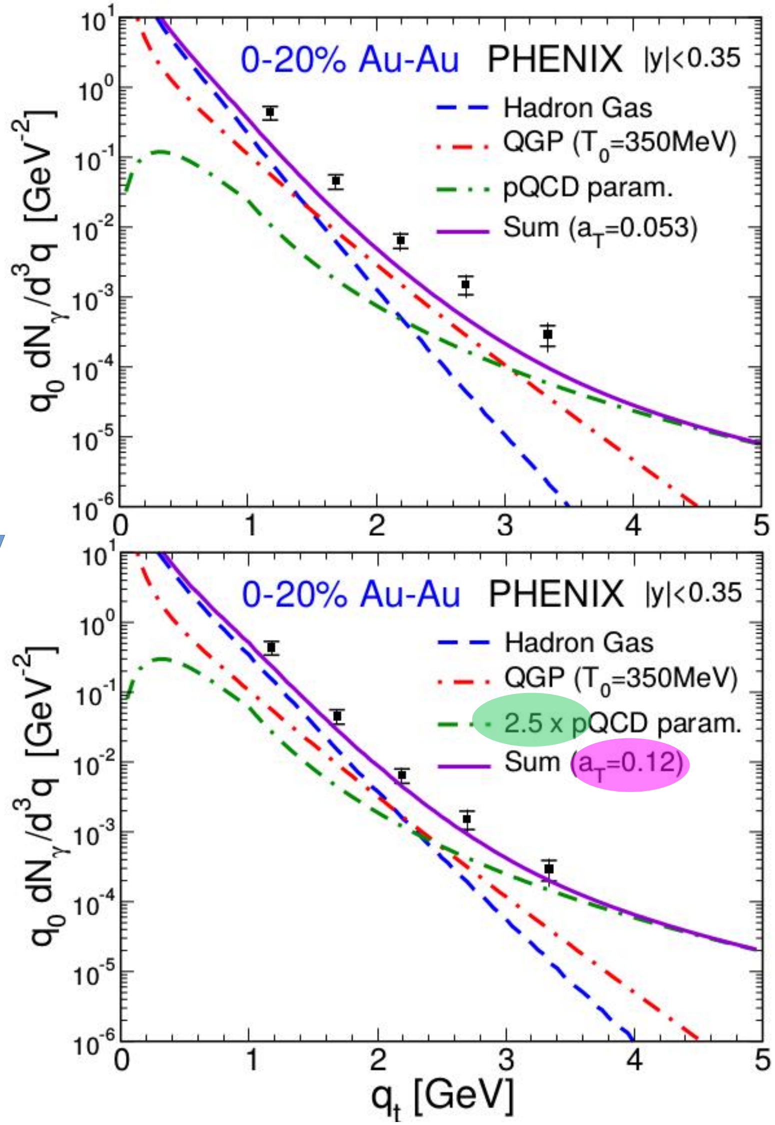


Direct photon “puzzle”

PHENIX, PRL109 (2012)

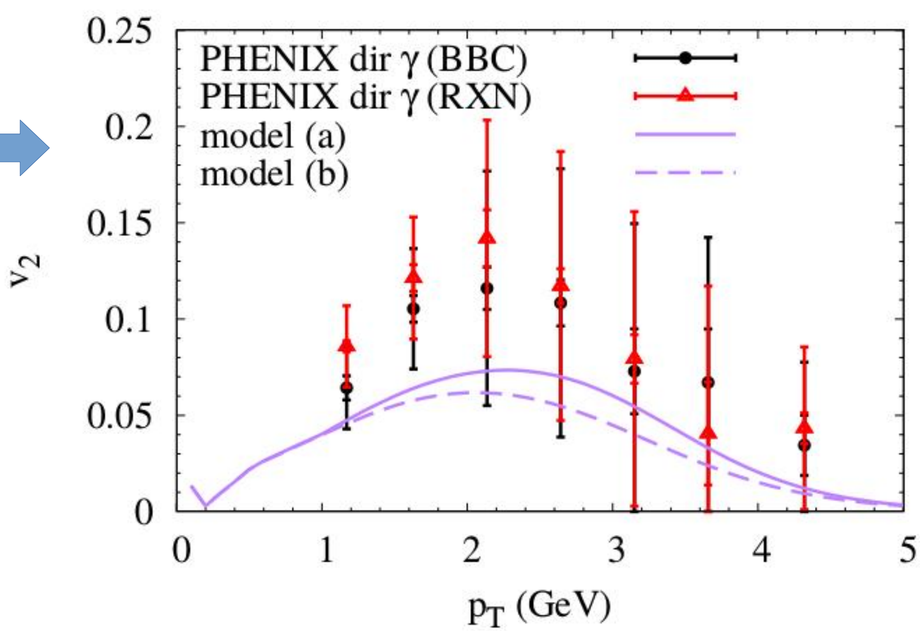
High yield (high T?) vs. strong flow (hadronic?)

Increasing the yield



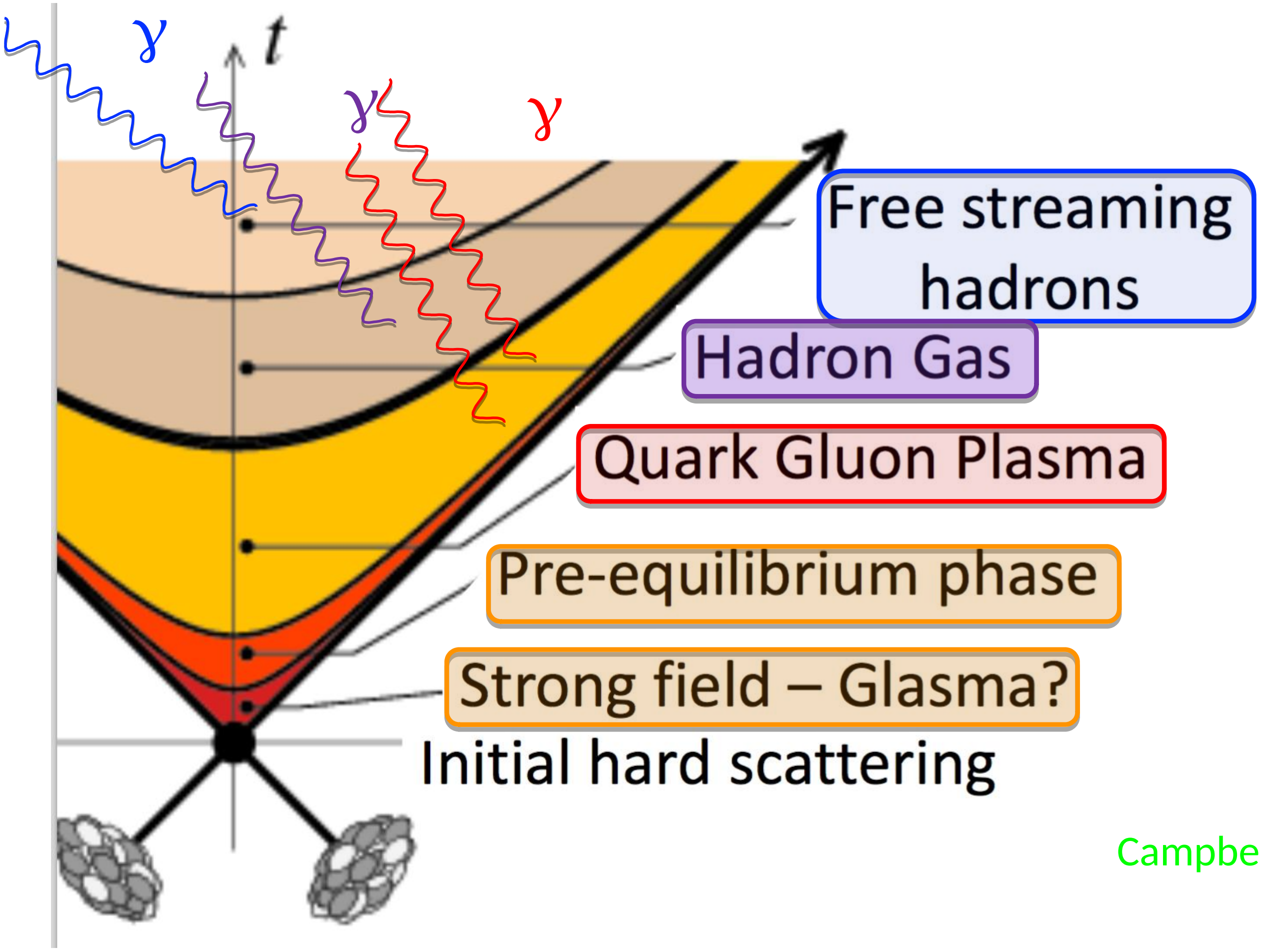
van Hees et al. PRC84,054906 (2011)

E.g., simple fireball model
(a_T : radial flow acceleration)



Photon sources

- **Penetrating = integral of all stages**
- **Direct γ = all – hadronic origin**



Campbell@QM2017

Thermal photons ($k_T < 2-3\,\mathrm{GeV}/c$)

- **Plasma**: HTL calc

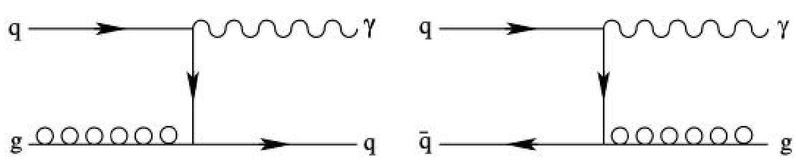
  Quarks

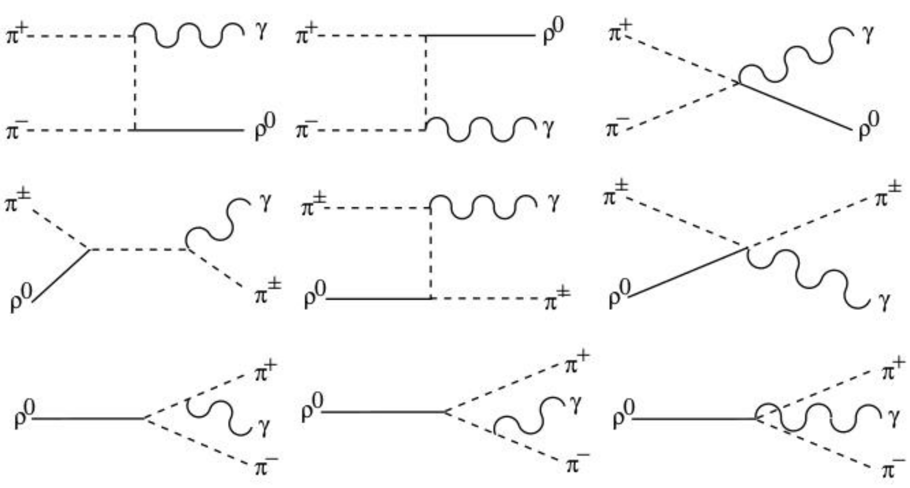
  High T ⇒ High rate

- **Hadronic**: Model calc

  pions

  Low T ⇒ Low rate





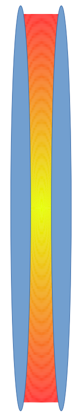
Thermal photons ($k_T < 2-3\,\mathrm{GeV}/c$)

- **Plasma**: HTL calc

  Quark brems.

  High T ⇒ High rate

  but small volume

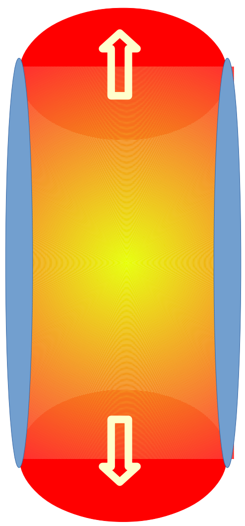


- **Hadronic**: Model calc

  pions

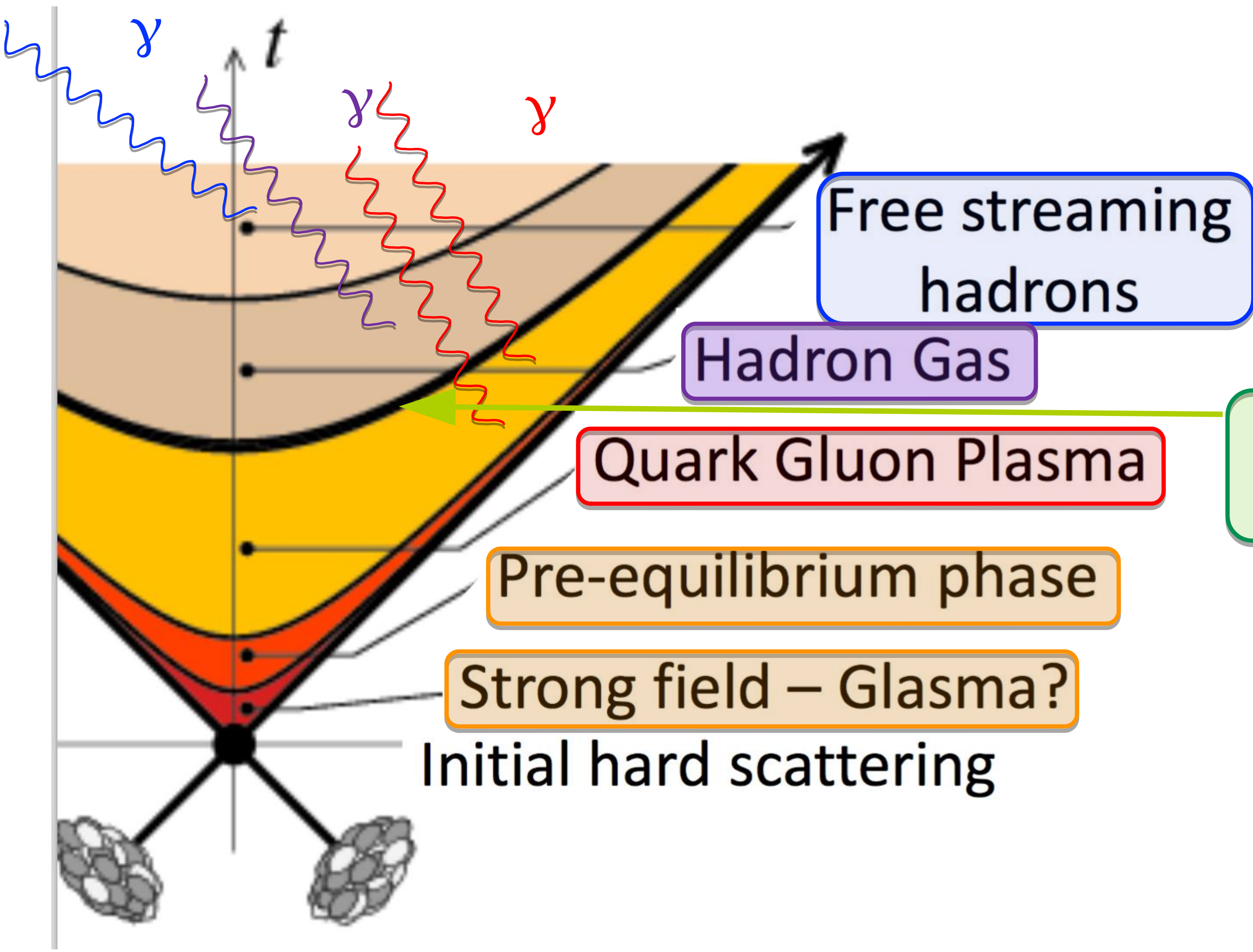
  Low T ⇒ Low rate

  Large volume + flow (T_{eff})



All stages give significant contributions

Photon souces (revised)



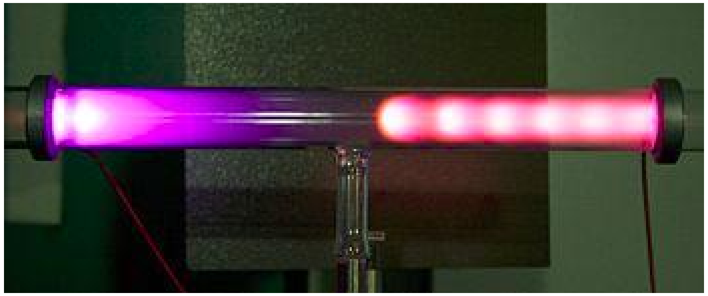
Photon emission at hadronization

Young-Pratt
Campbell
HF-Itakura-Nonaka

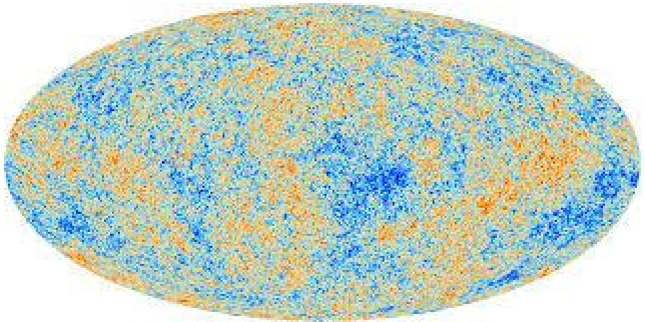
modifined from Campbell@QM2017

Radiative recombination

- **Glow: e+I⁺ → A+γ**
- **CMB: e+p → H+γ**
- **Nebula: e+p →H+γ**
- **pp chain, CNO cycle, ..**



https://en.wikipedia.org/wiki/Glow_discharge

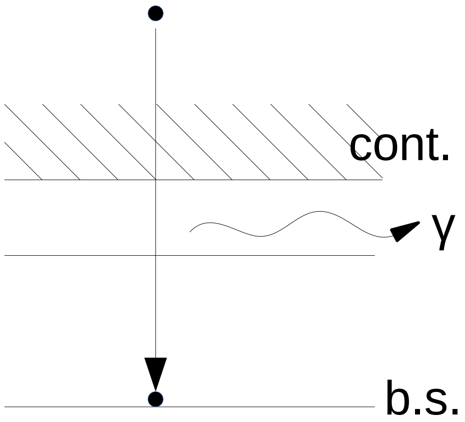


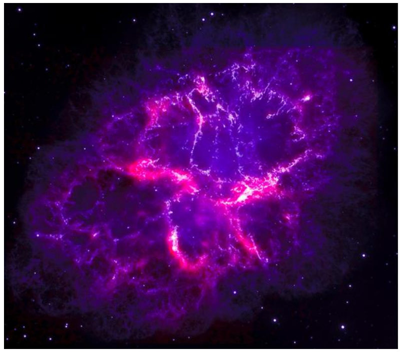
http://m.esa.int/spaceinimages/Images/2013/03/Planck_CMB

https://apod.nasa.gov/

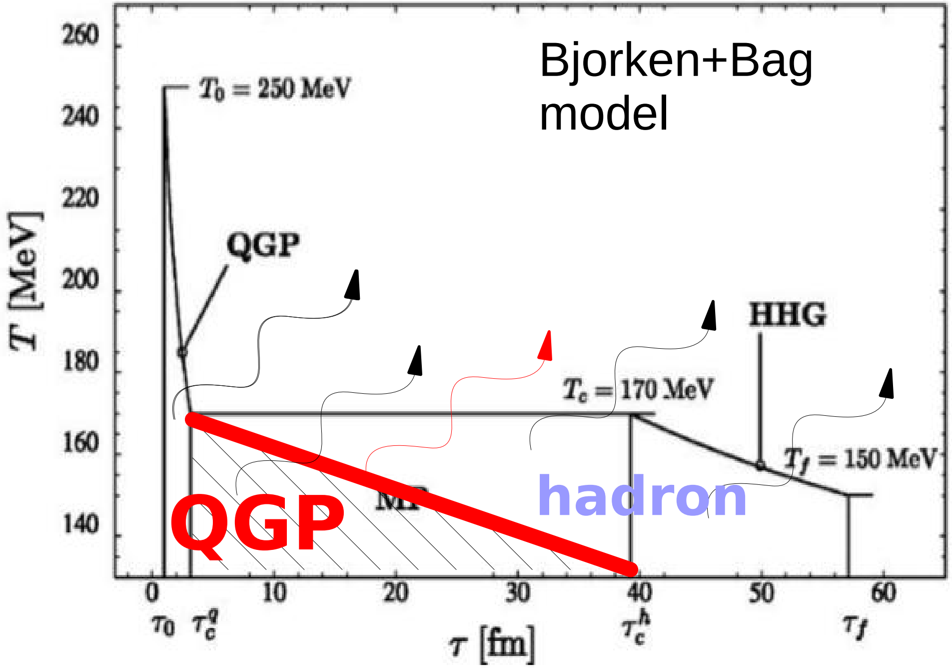
Radiative reco & hadronization

- **free-bound trans.**
  - **E-M cons requires energy release**





- **“free”-”free” trans**
  - **QGP therm. rad.**
  - **Hadronic therm. rad**



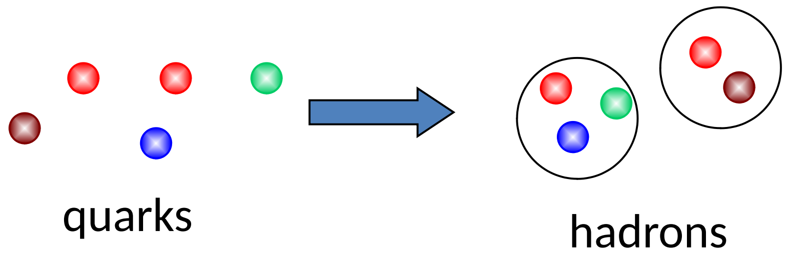
Radiative ReCo may solve the “photon puzzle”

Fig: Phys.Rept.364 (modified)

Hadronization via ReCo

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

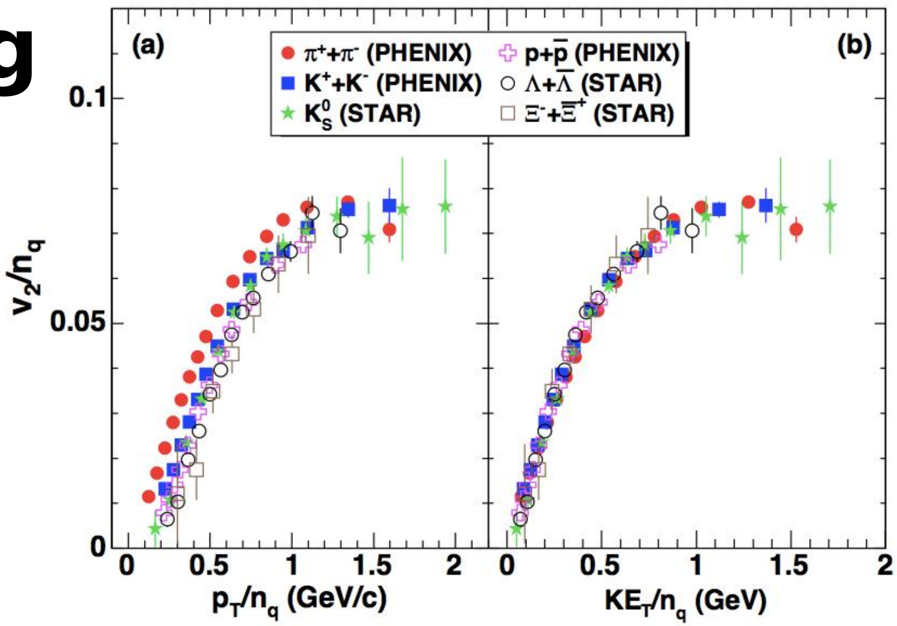
- **Quark Reco model for p_T ~ 2GeV**



thermal + flow

- **Cost. Quark # scaling**

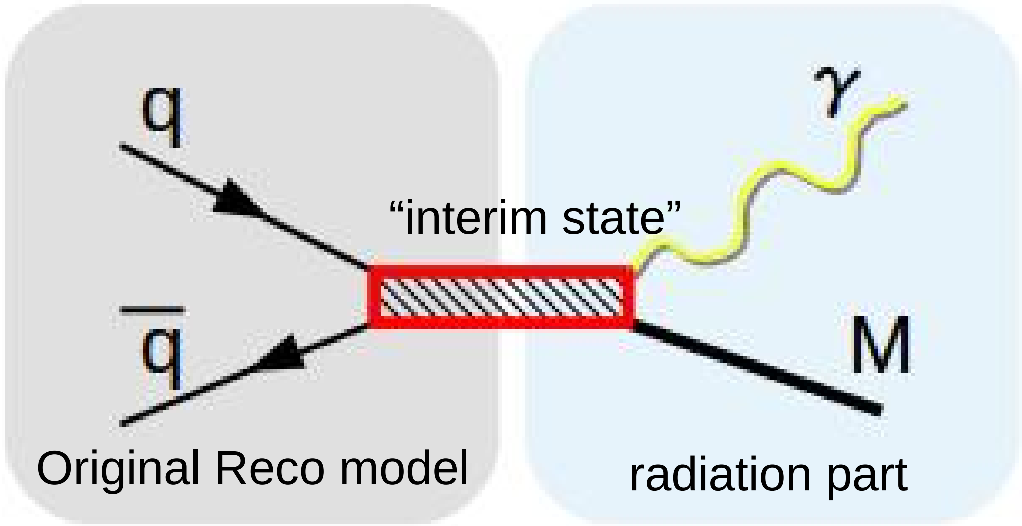
$$v_2(p_T) \sim n_q\, v_2^q(p_T^q) = n_q v_2^q(p_T/n_q)$$



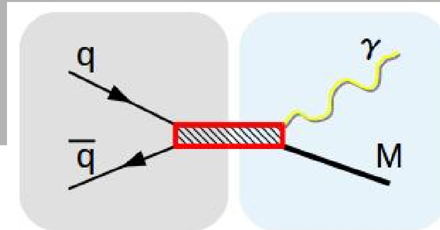
PHENIX,nucl-ex:0608033

Modeling radiative ReCo

- **Subtleties in original ReCo:**
  - **Entropy reduction? E-M conservation?**
- **Radiative ReCo model**
  - **2-step model= interim state + radiation**
  - **satisfying conservation laws**



Estimate of γ production



Normalization

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

- **Interim state**

  ρ(M*)

  cont spectrum in general, but

  for simplicity

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

- **ReCo**

  Quark dist.

  themal+flow

  →

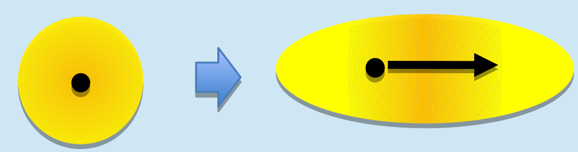
  Interim M* dist

  $$\frac{dN_{M*}}{d^3P} \sim e^{-P/T_*}$$

- **γ emission**

  Isotropic in M* rest frame

  Boosted in P direction



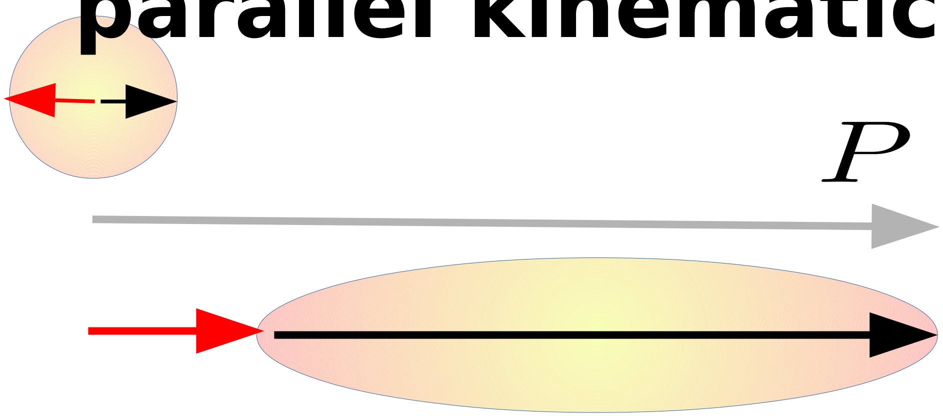
2D model for M* --> M+γ

- **Dist shifted to lower kT**

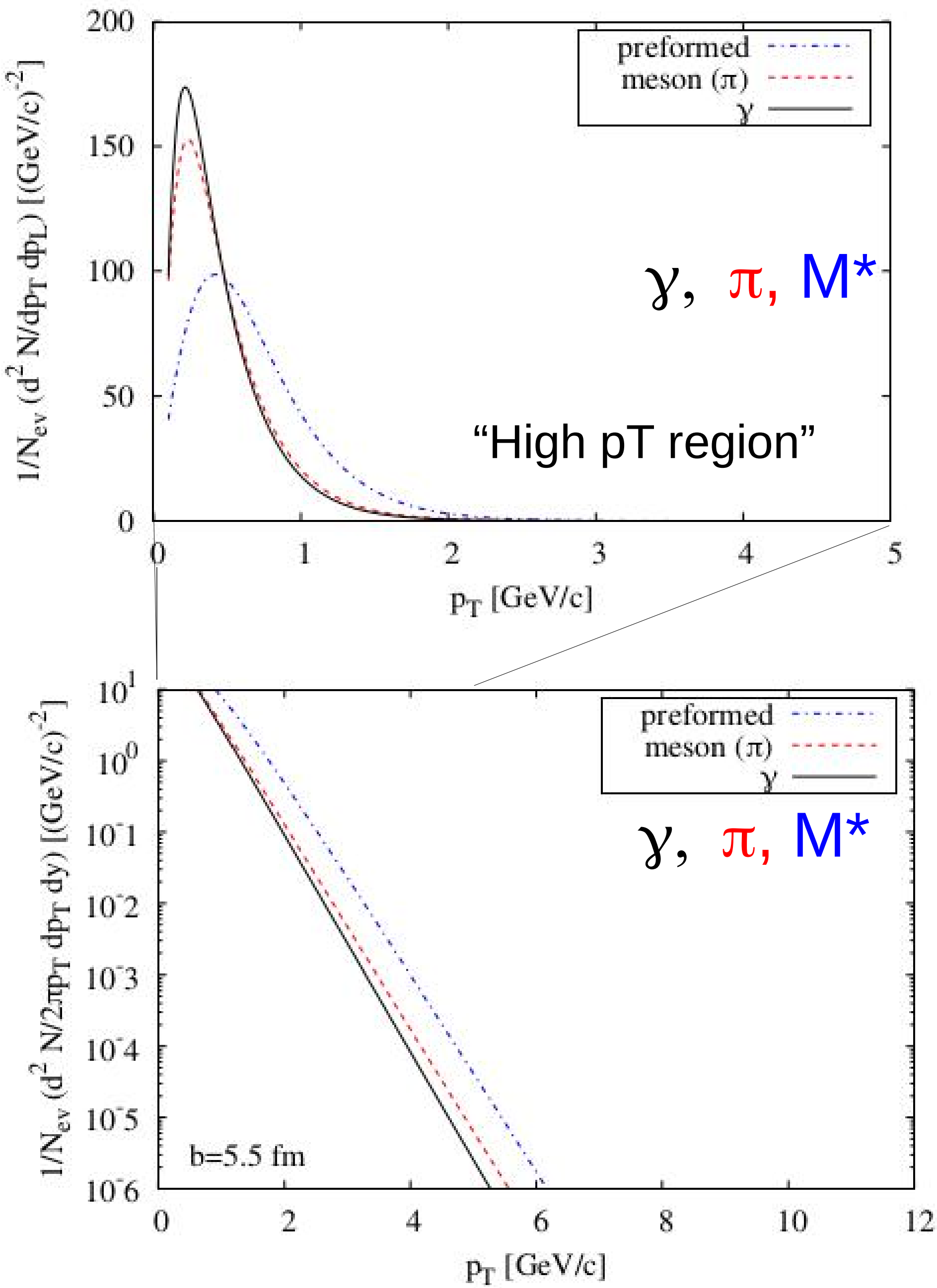
$$E_* \frac{d^2 N_*}{d^2 P_T dP_L} \sim e^{-P_T/T_*}$$

$$\epsilon \frac{d^2 N}{d^2 k_T dk_L} \sim \frac{\#}{\sqrt{k_T}} e^{-k_T/T_{\rm eff}}$$

- **High pT meson from parallel kinematics**



$$K = \frac{M^2}{M_*^2} P \qquad k = (1 - \frac{M^2}{M_*^2}) P$$



T_{eff} of mesons & photons

- $P_T/T_* = k_T/T_{eff}$

$$E_* \frac{d^2 N_*}{d^2 P_T dP_L} \sim e^{-P_T/T_*}$$

  - high K_T meson + soft γ

$$K_T \sim P_T \qquad k_T \sim 0$$

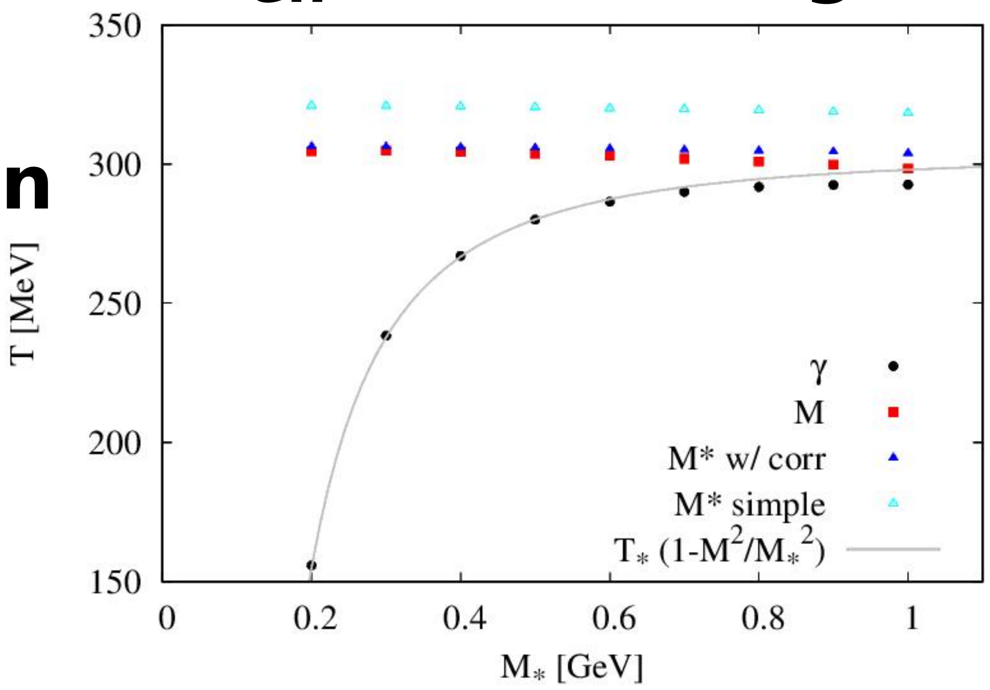
$$T_{\rm eff}(M) \sim T_*$$

  - high k_T γ + soft meson

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

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

- T_{eff}(M) unchanged



v2 -- CQN scaling

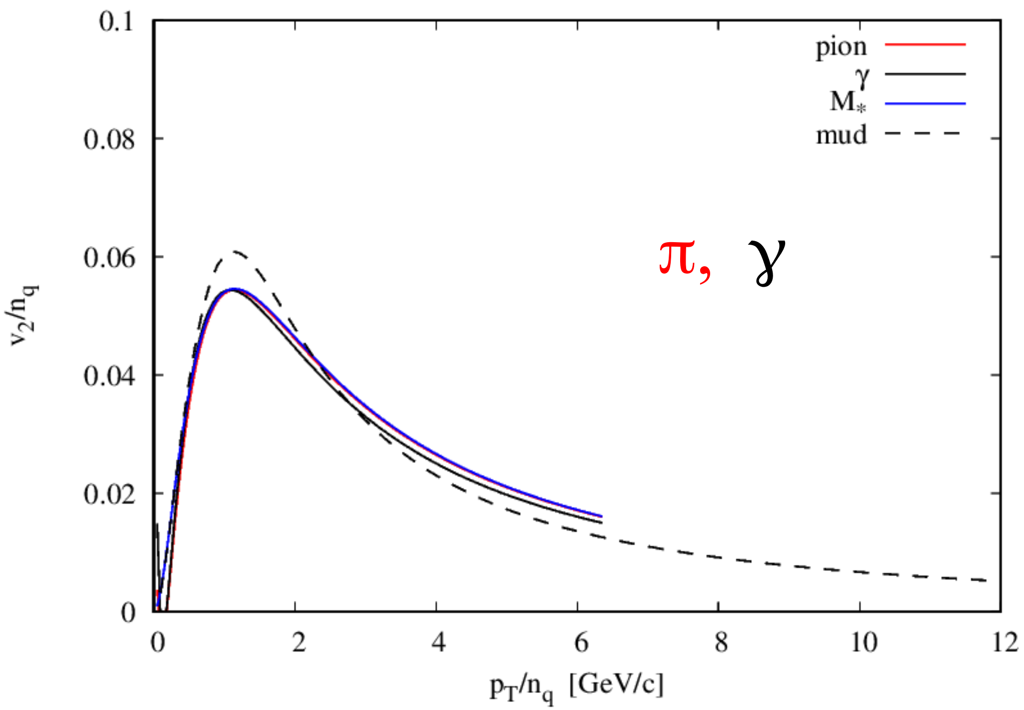
input: quark v2

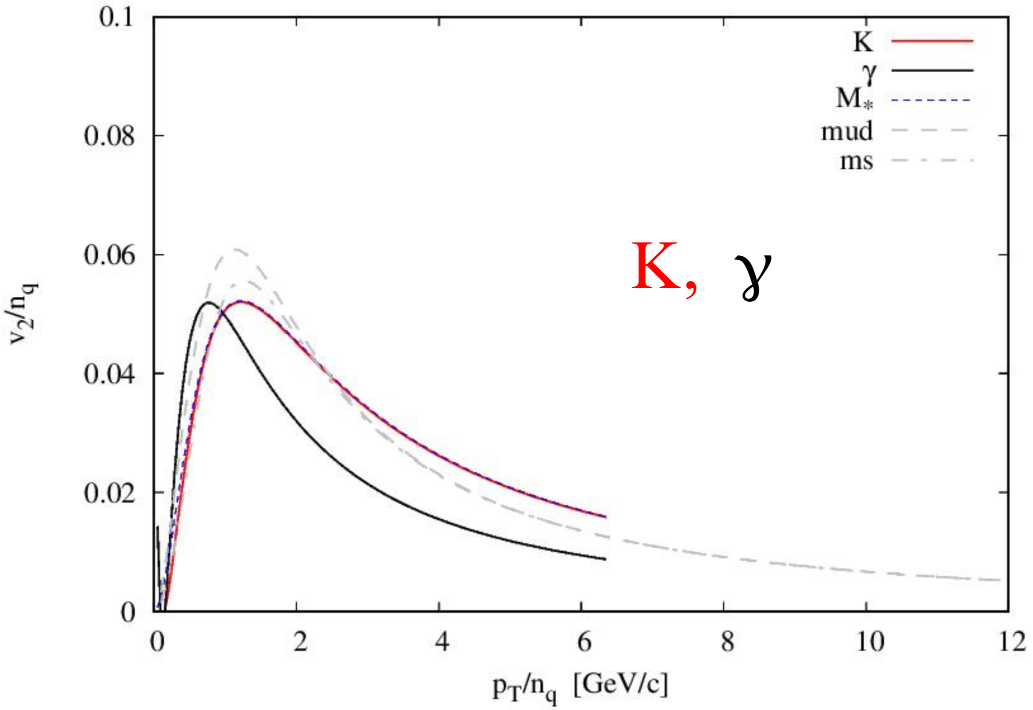
$$v_2^q(p_T) \leftarrow \frac{\alpha}{1+(p_0/p_T)^{2.5}}$$

- **v2(M) ~ v2(M*)**
- **v2(γ) ~ v2(M) + mom shift**

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

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





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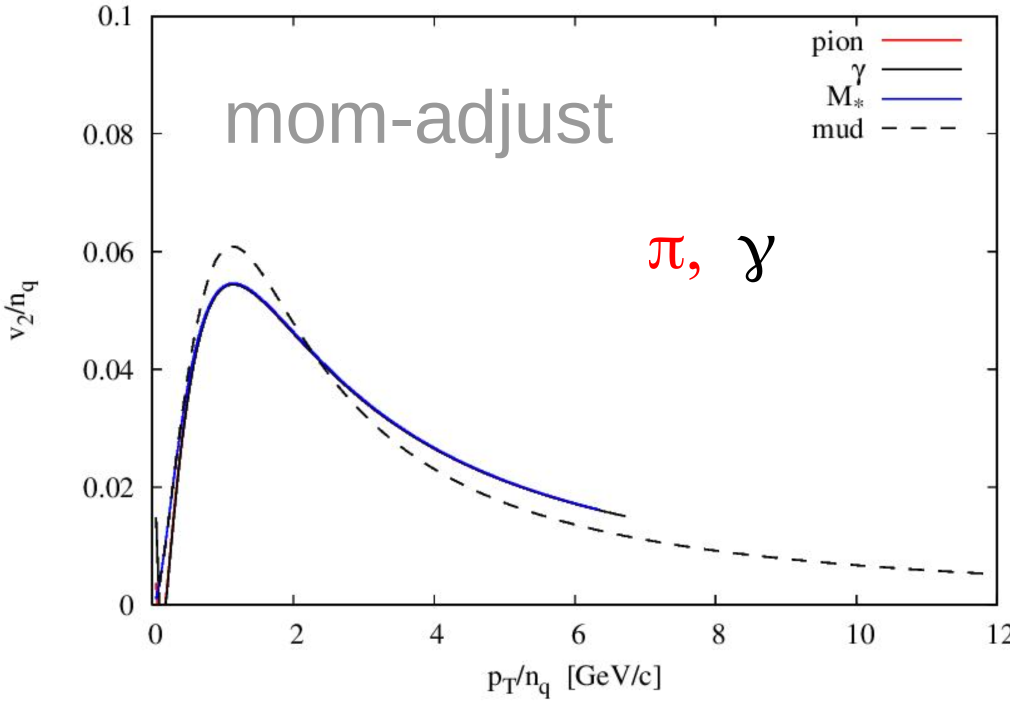
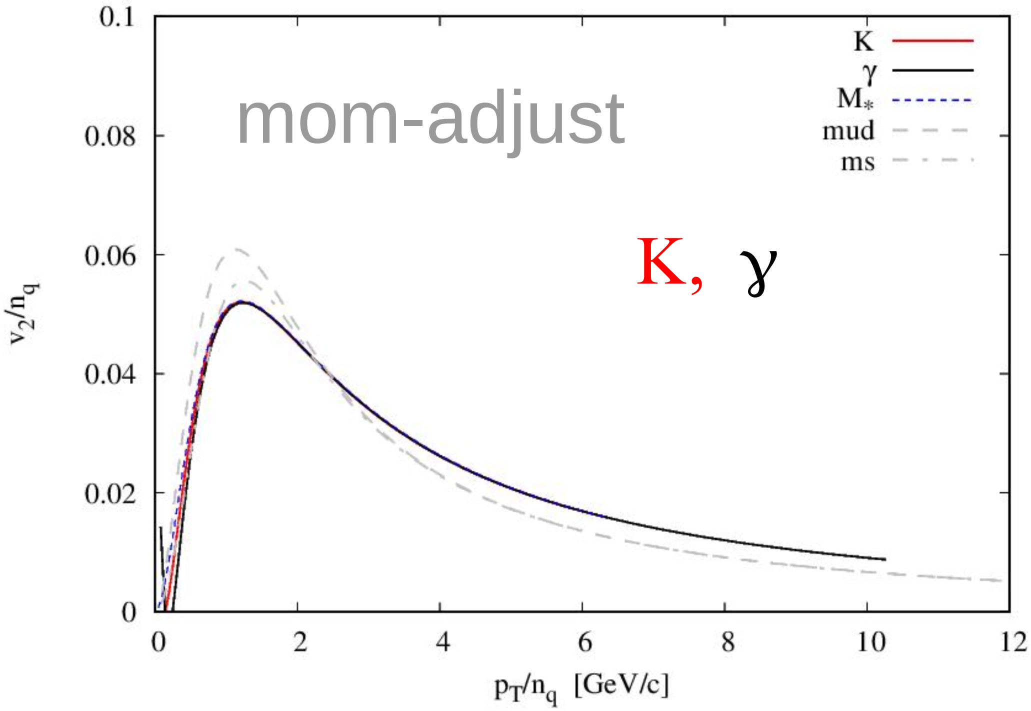




Result of Rad-ReCo only

Comparison to RHIC data

Not aiming at a data fit

Hadron yield vs Centrality

- **params for π**

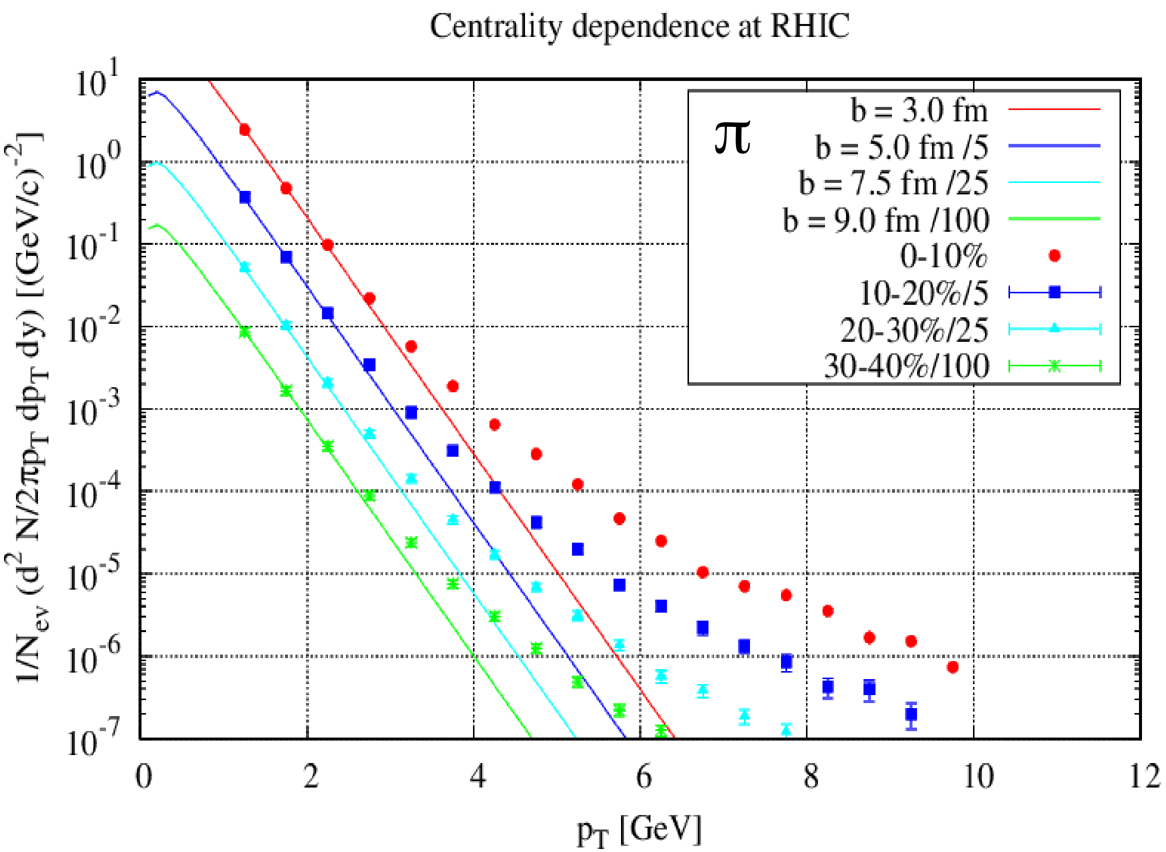
  $M^* = 2M_q = 0.6$ GeV

  $v_T = 0.6$

  T_h = 155 MeV

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

  norm
  - **needs × 10**



Success of ReCo for π is intact

γ production

- **params for γ**

  κ=0.1

- **result:**

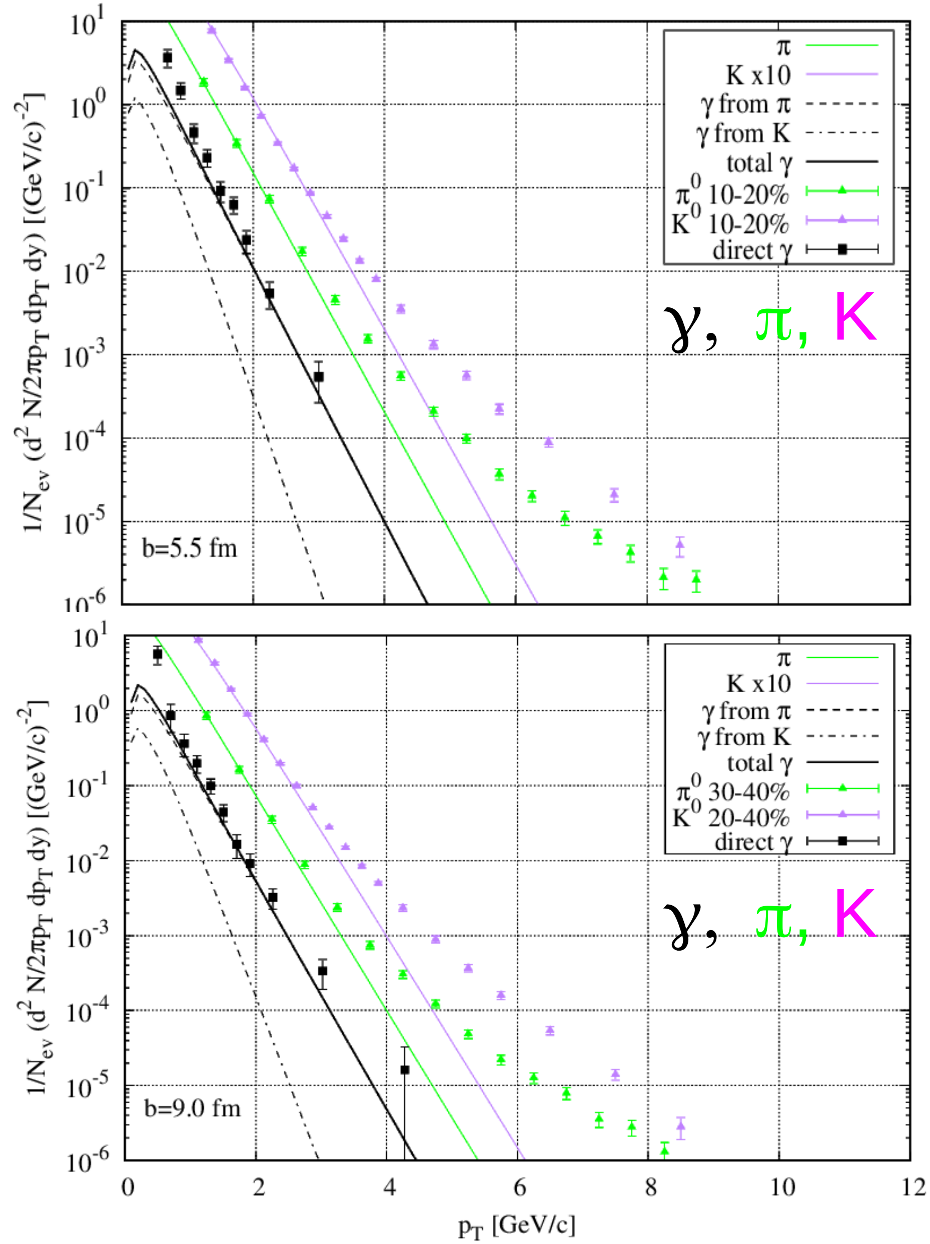
  T_{slope} (2-5 GeV)

  M* … 320 MeV

  π … 303 MeV

  γ … 287 MeV

- **γ dist is blue-shifted as mesons**



γ production

- **params for γ**

  κ=0.1

  κ(K)=0.7

- **result:**

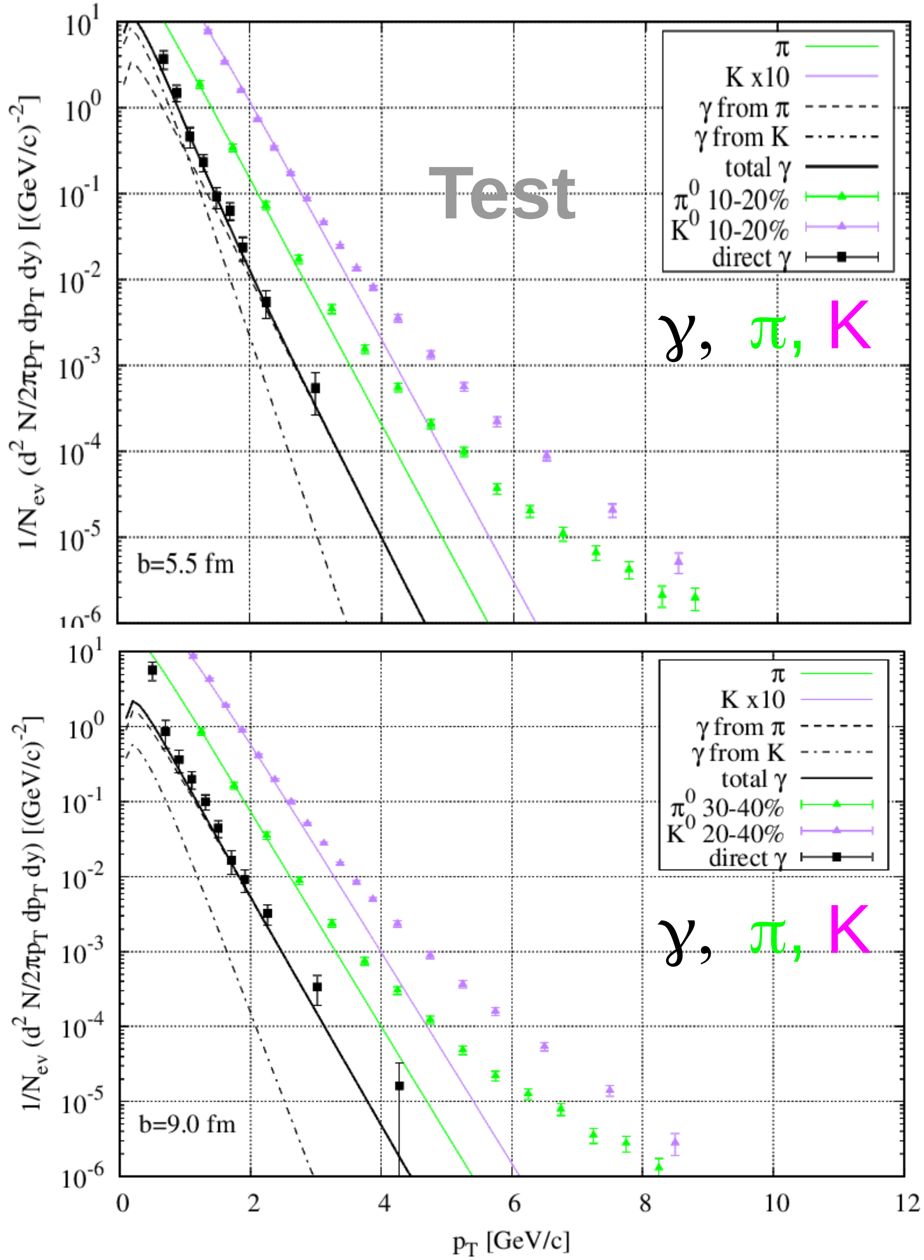
  T_{slope} (2-5 GeV)

  M* ... 320 MeV

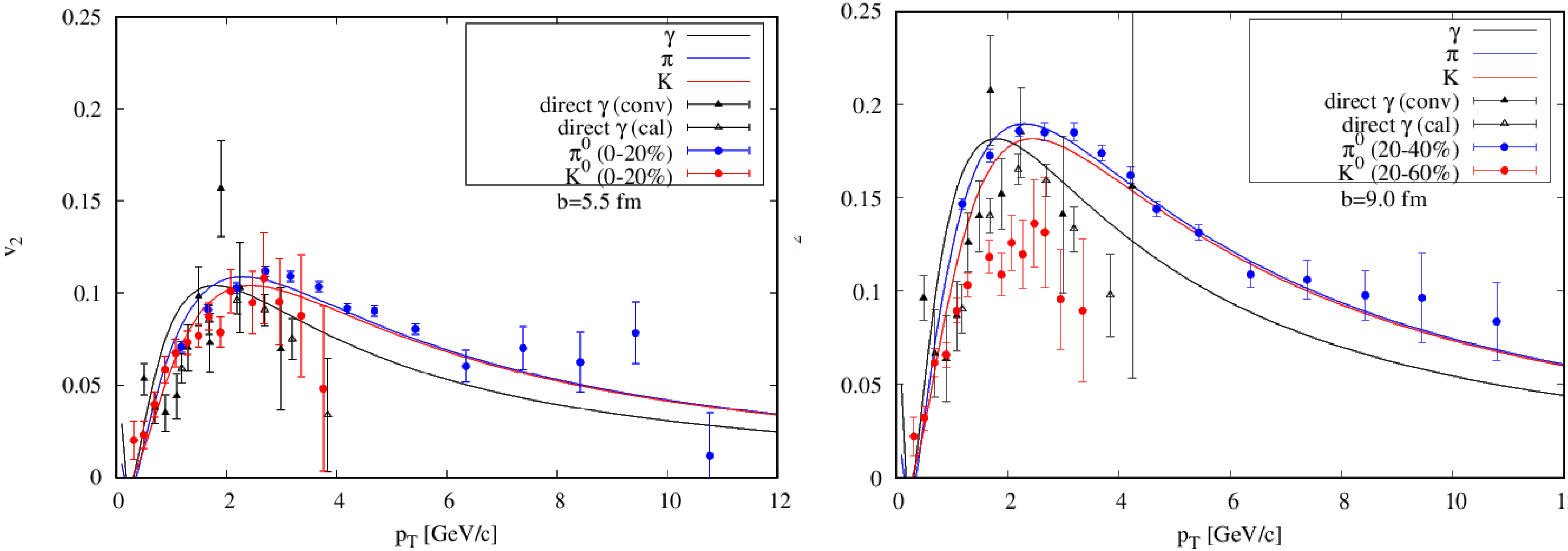
  π ... 303 MeV

  γ ... 287 MeV

- **γ dist is blue-shifted as mesons**



γ elliptic flow v2



- **Input: quark** $v_2^q(p_T) \leftarrow \dfrac{\alpha}{1+(p_0/p_T)^{2.5}}$ (p_0 = 1.0 GeV)
- **Output: similar v2 for K, π、γ**

Summary & Outlook

- γ production in hadronization has been modeled as a 2-step process
  - Rad-ReCo keeps characters of original ReCo
  - implies larger γ yield and its large v2

- For quantitative model of Rad-ReCo
  - Baryons? Interim states spectrum?
  - Compiling all γ sources
  - Hydro simulations