Photon emission from viscous hydrodynamics in relativistic heavy-ion collisions

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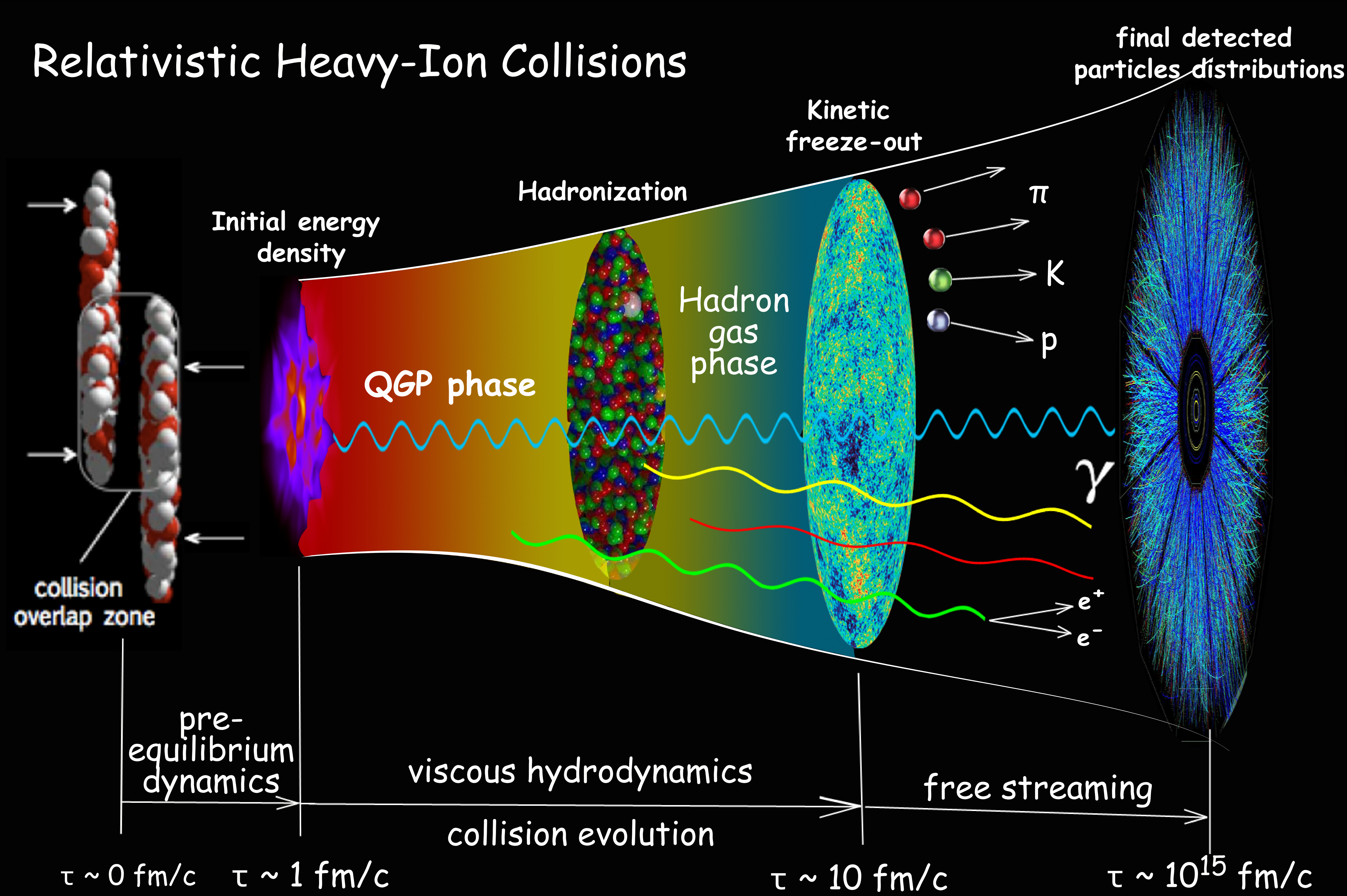
The Ohio State University

In collaboration with Ulrich Heinz, Charles Gale, and Jean-Francois Paquet

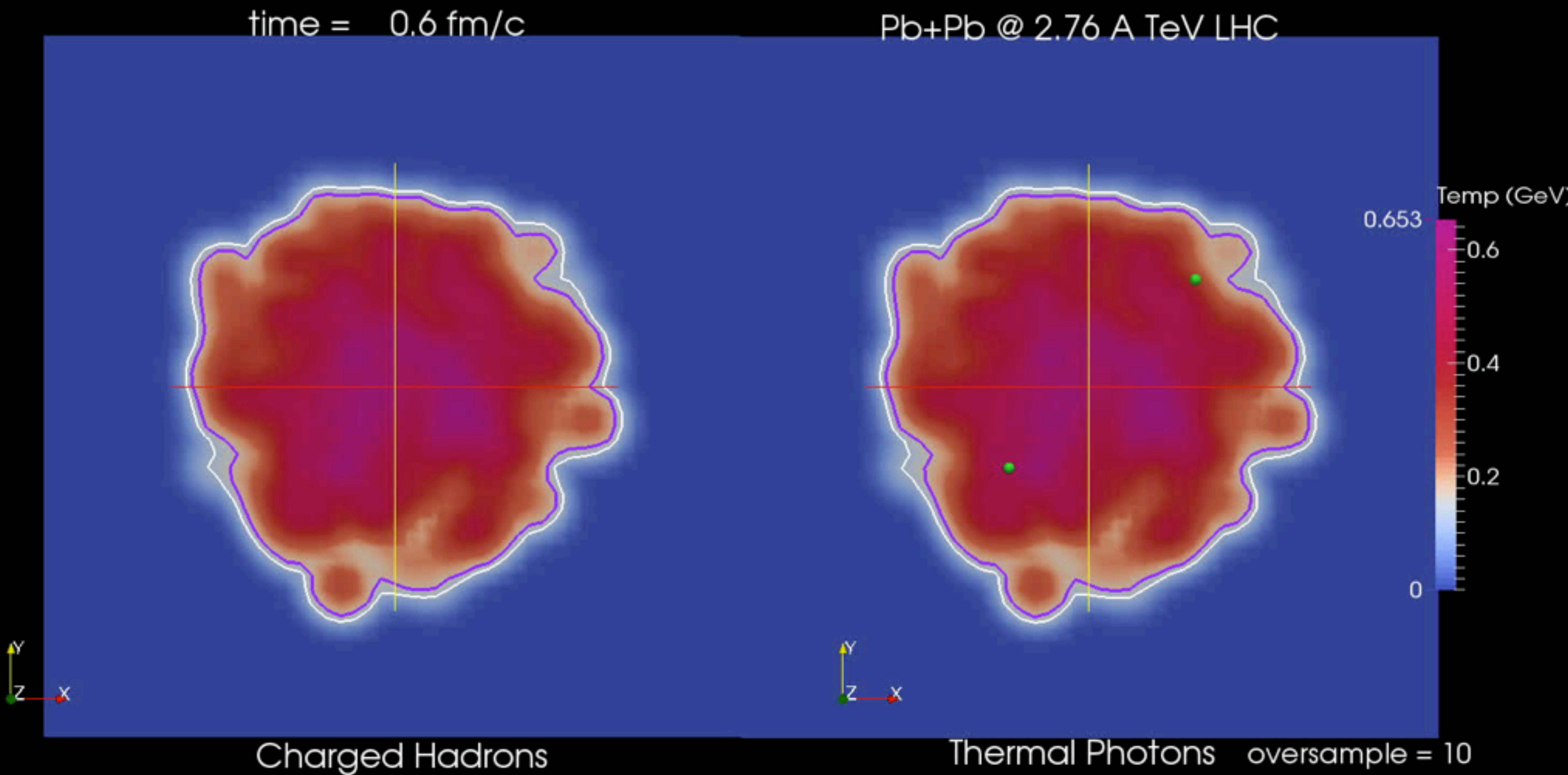
Feb. 24, 2014 EMMI RRTF GSI Darmstadt

Little Bang

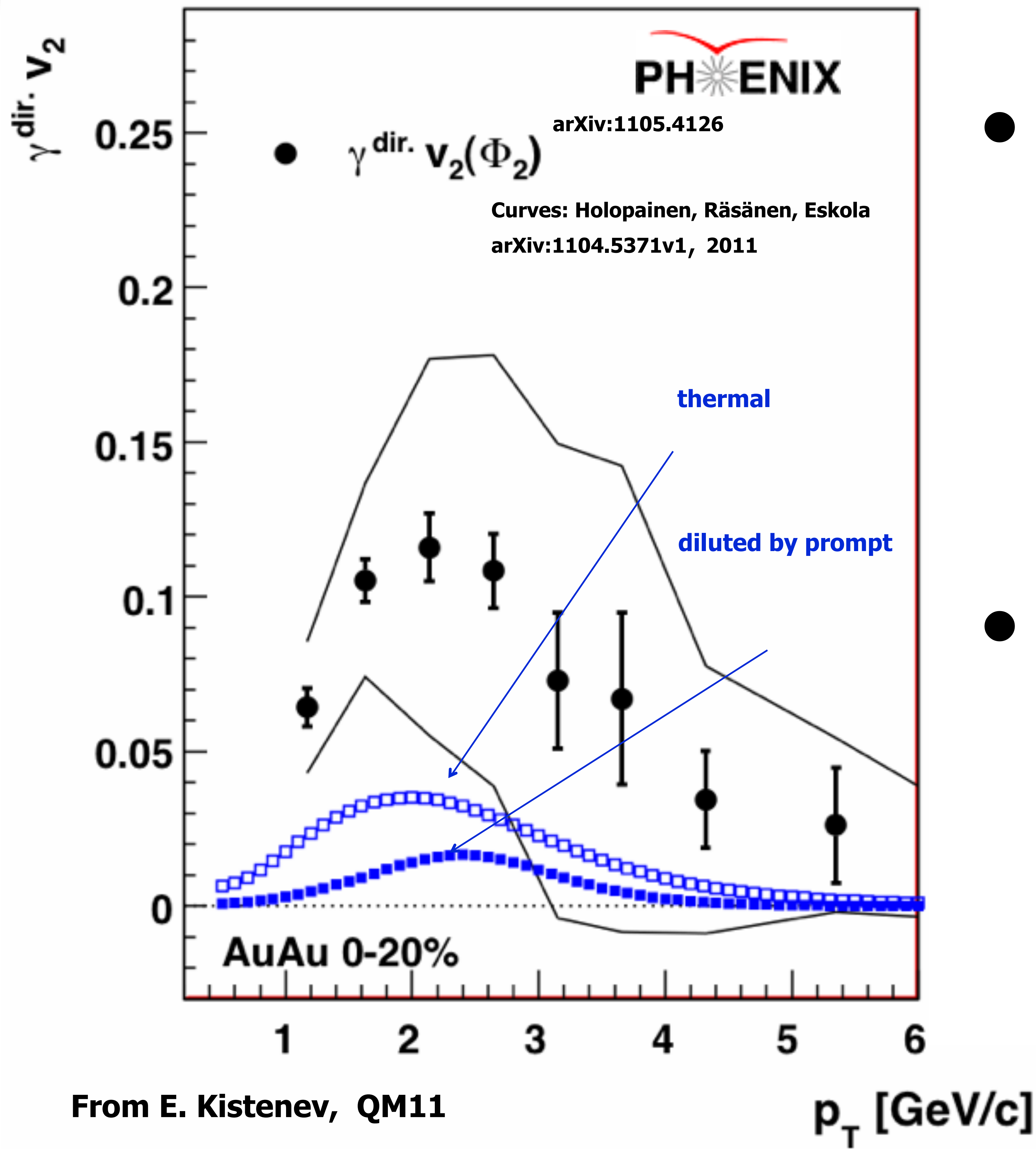


Relativistic Heavy-Ion Collisions
final detected
particles distributions
Kinetic
freeze-out
Hadronization
Initial energy
density
Hadron
gas
phase
QGP phase
π
K
p
γ
e+
e−
collision
overlap zone
pre-
equilibrium
dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

Photons from Heavy-ion Collisions



Challenge from Experiment

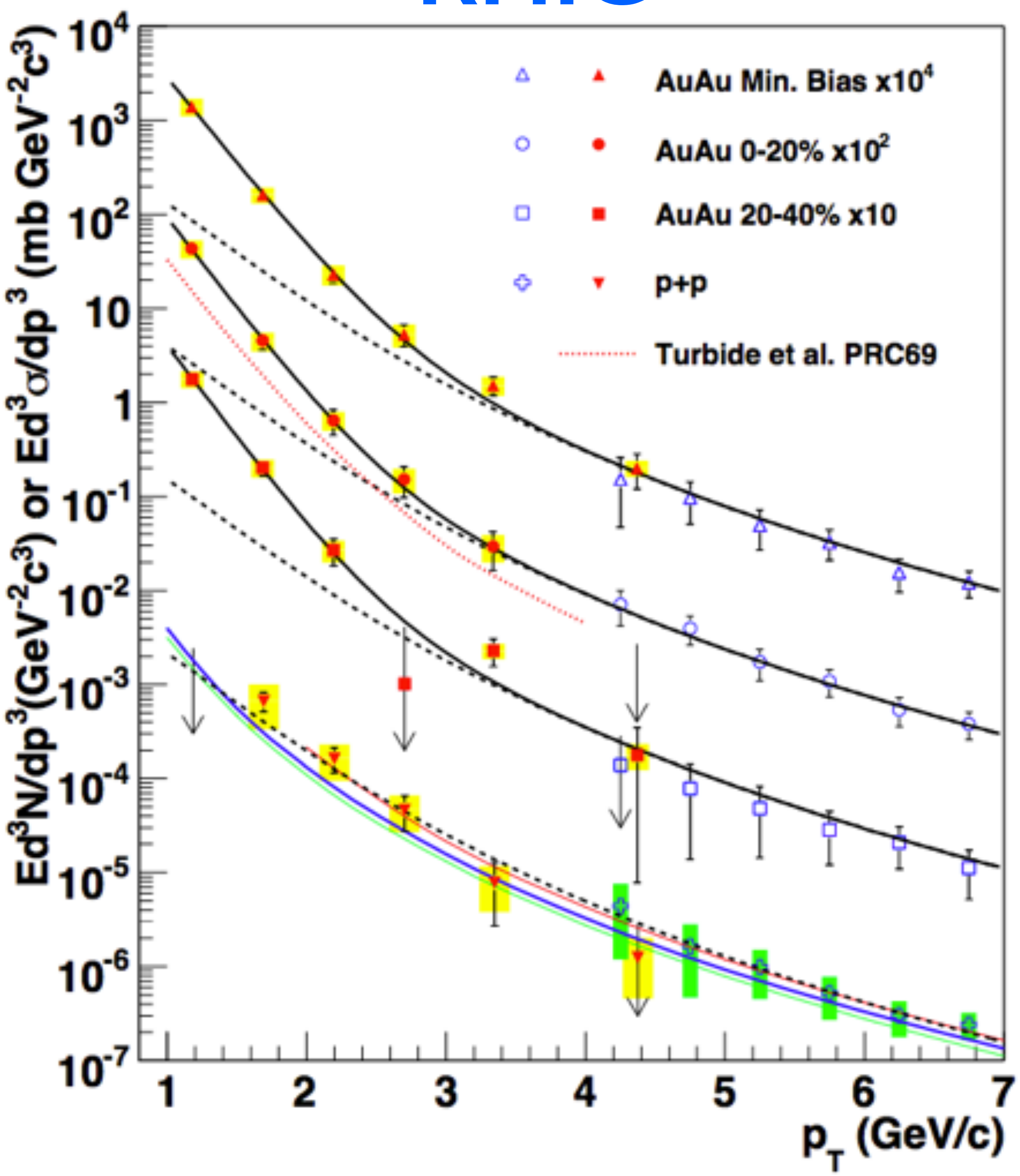


From E. Kistenev, QM11

- PHENIX measurements show large direct photon v_2 at $p_T < 4\ \mathrm{GeV}$
- The state-of-the-art calculation underestimates the data by a factor of 5!

Fitted T_{eff} from Experiments

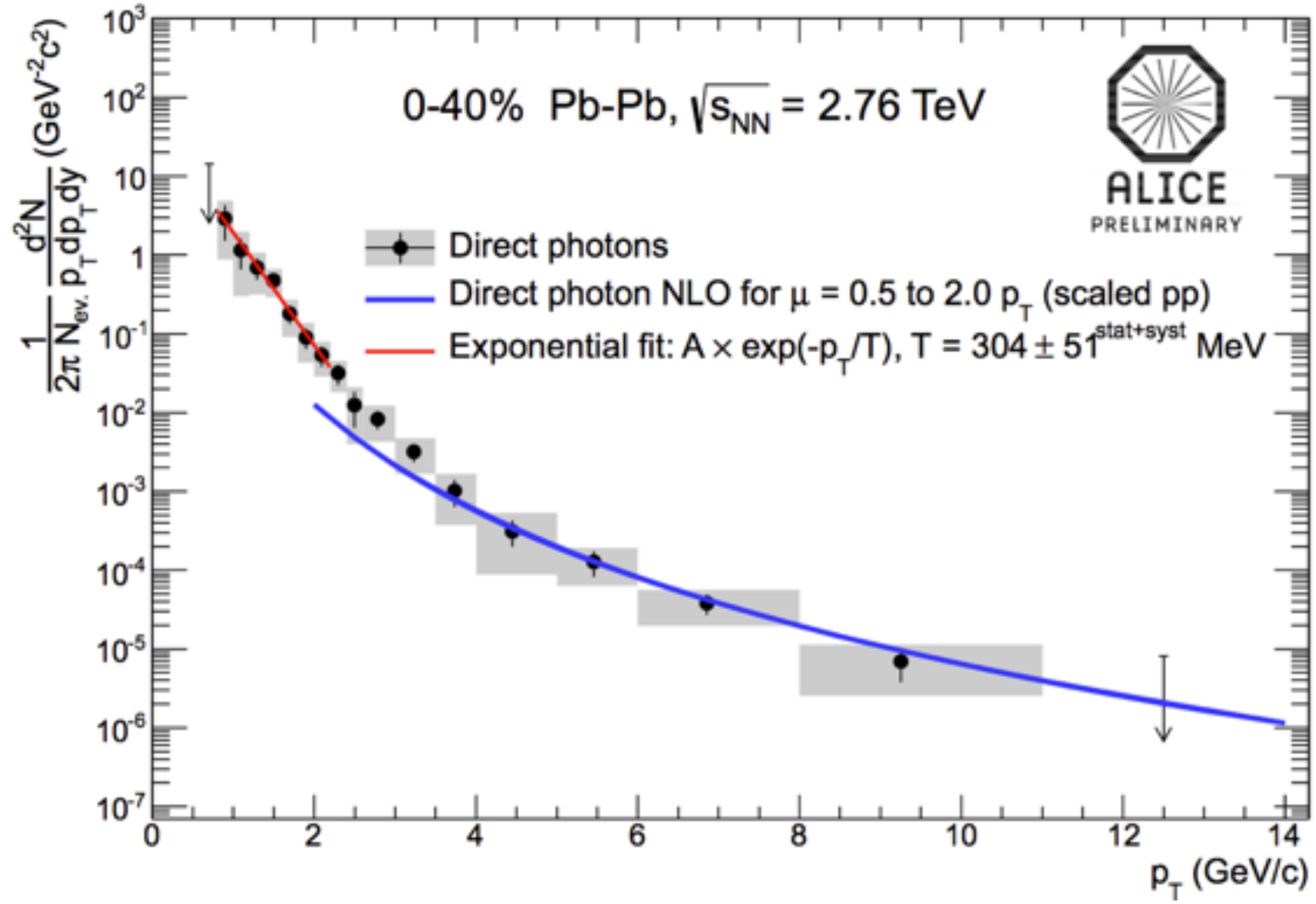
RHIC



$0-20\%$

$T = 221 \pm 19 \pm 19\,\mathrm{MeV}$

LHC



fit: $A\exp(-p_T/T)$

$T = 304 \pm 51^{\mathrm{stat+sys}}\,\mathrm{MeV}$

What does this T mean

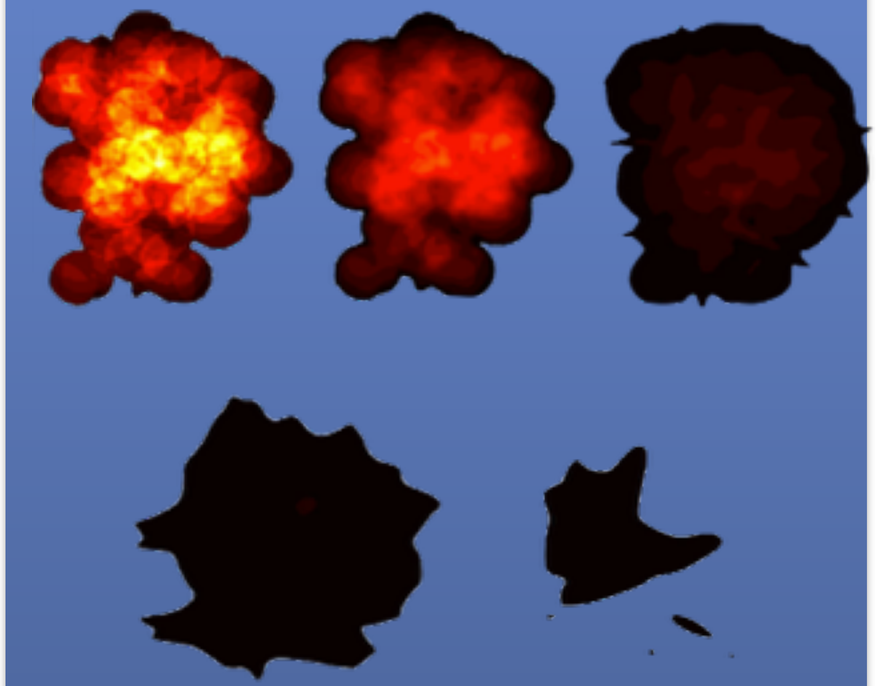
State-of-the-art hydrodynamic modeling

Initial Condition Generators (MC-KLN, MC-Glauber)

https://github.com/chunshen1987/iEBE.git

Thermal Photon Emission Rates

Hydrodynamic Simulations (VISH2+1)



HydroInfo Package

$$e, s, p, T,$$

$$u^\mu, \pi^{\mu\nu}$$

Thermal Photon Interface

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu} q_\mu q_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

$$E\frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q}$$

Hadrons spectra & v_n

Photon spectrum & v_n

State-of-the-art hydrodynamic modeling

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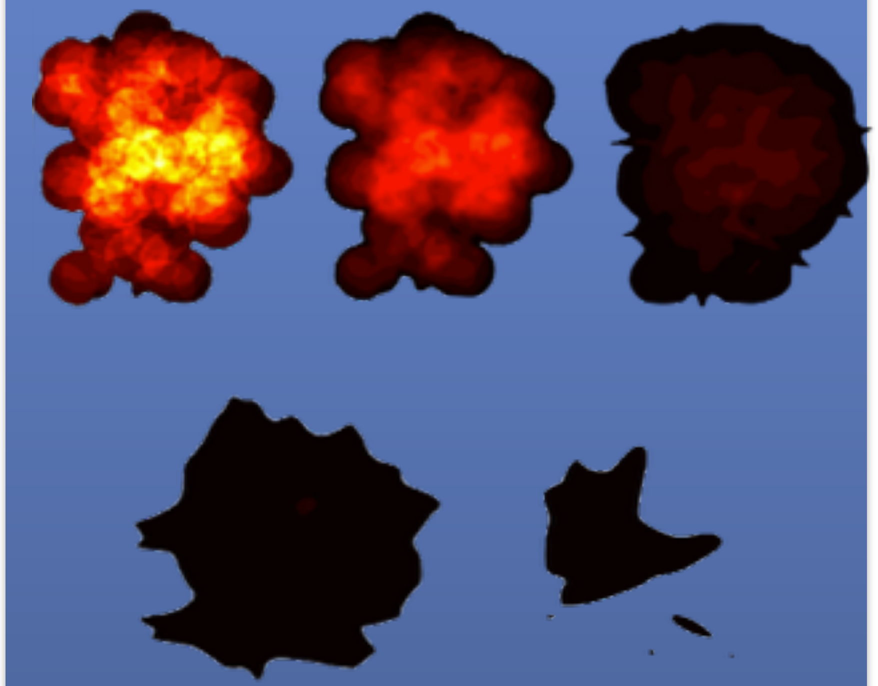

viscous corrections

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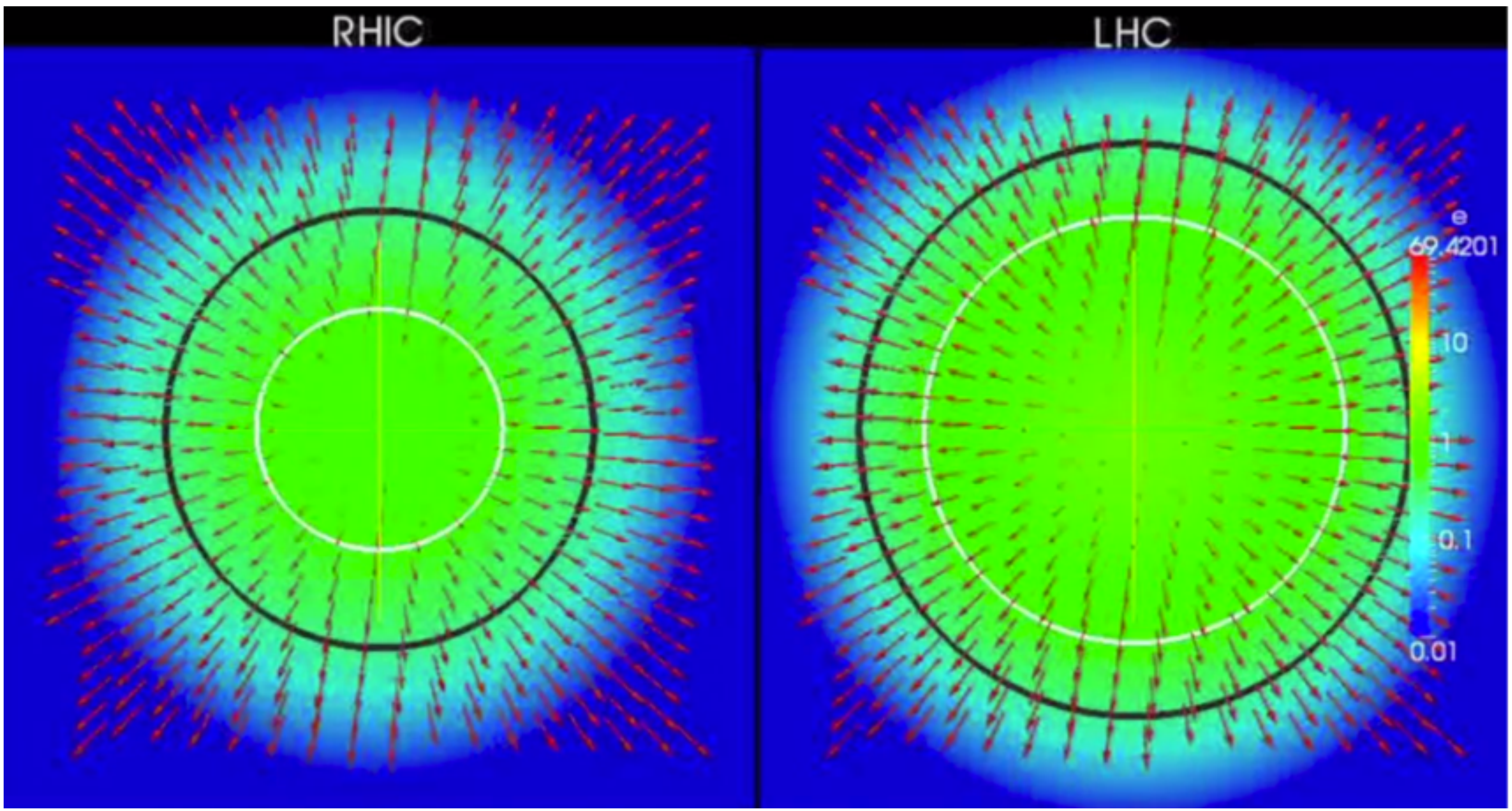
viscous corrections

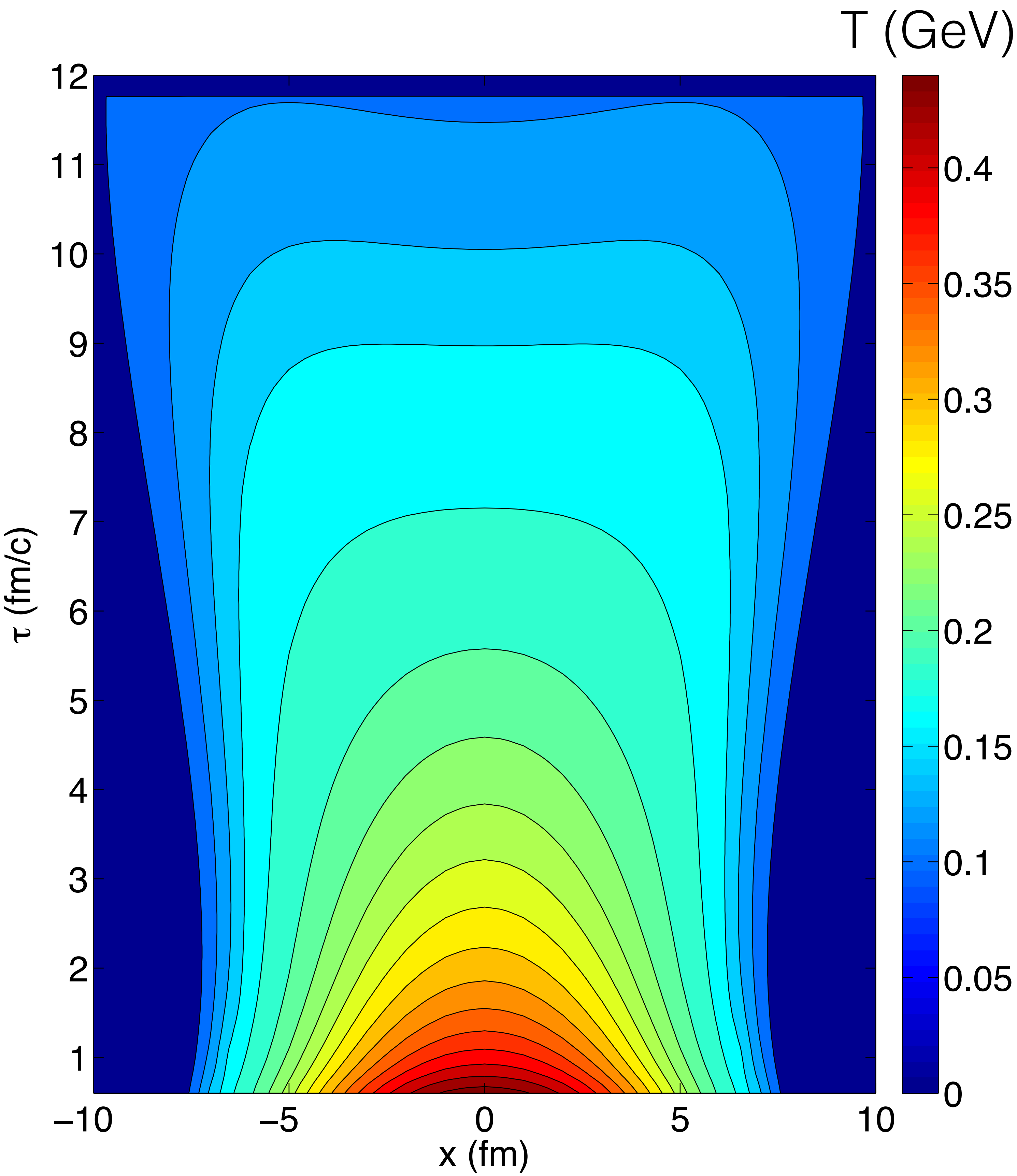
Hadrons spectra & v_n

Photon spectrum & v_n

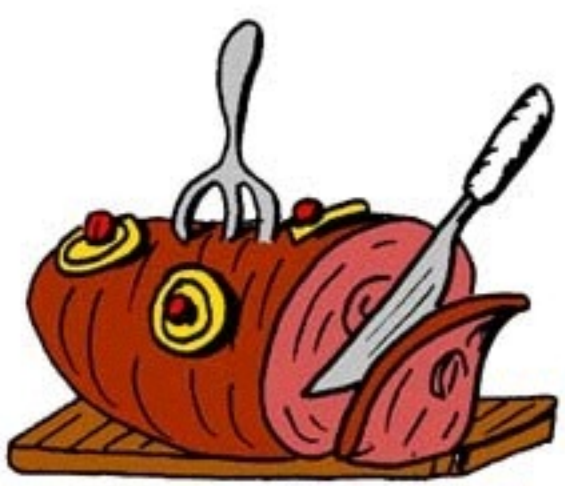
Photon spectra and radial flow



Slope of Photon Spectrum



Slicing the hydrodynamic medium



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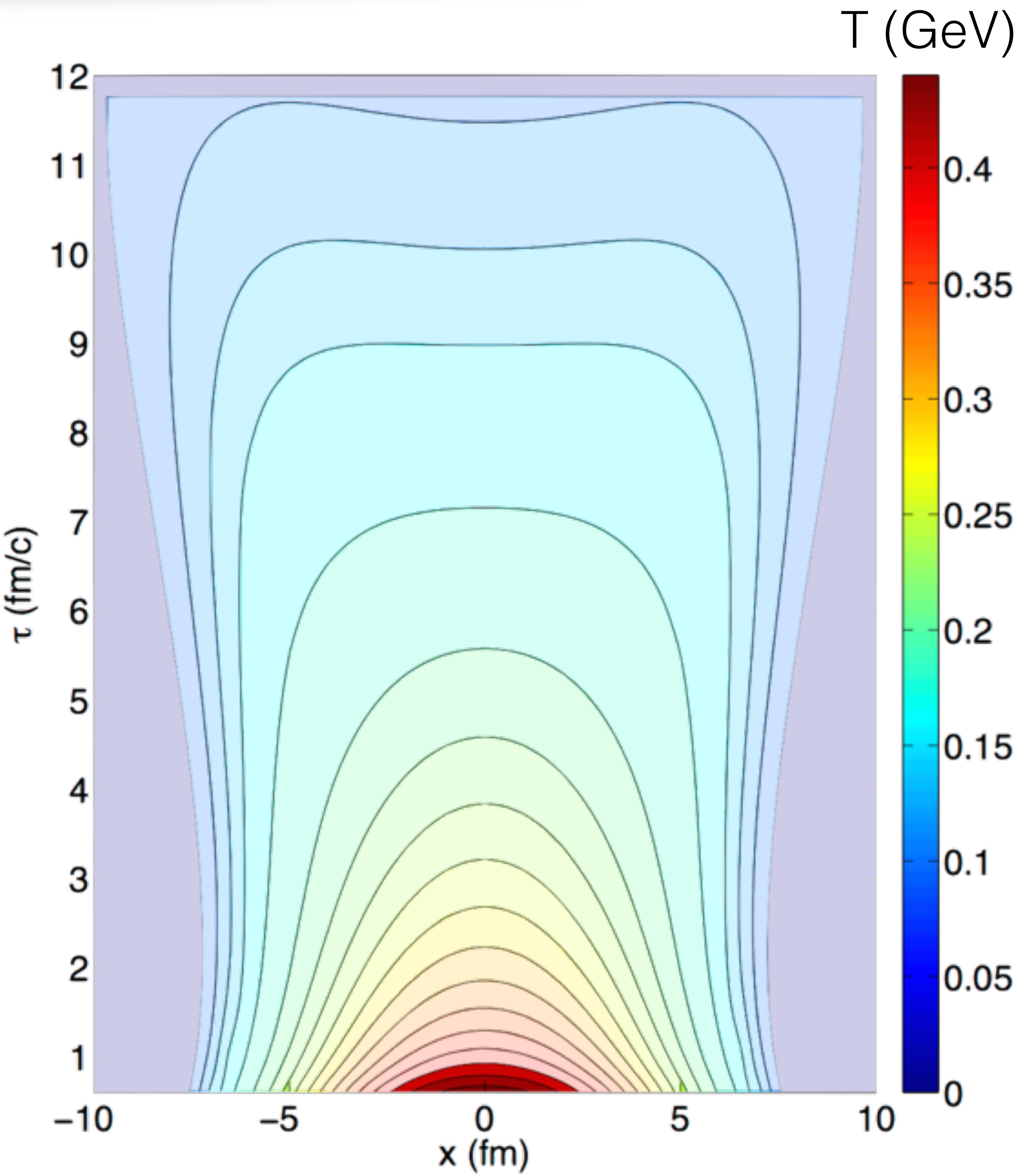
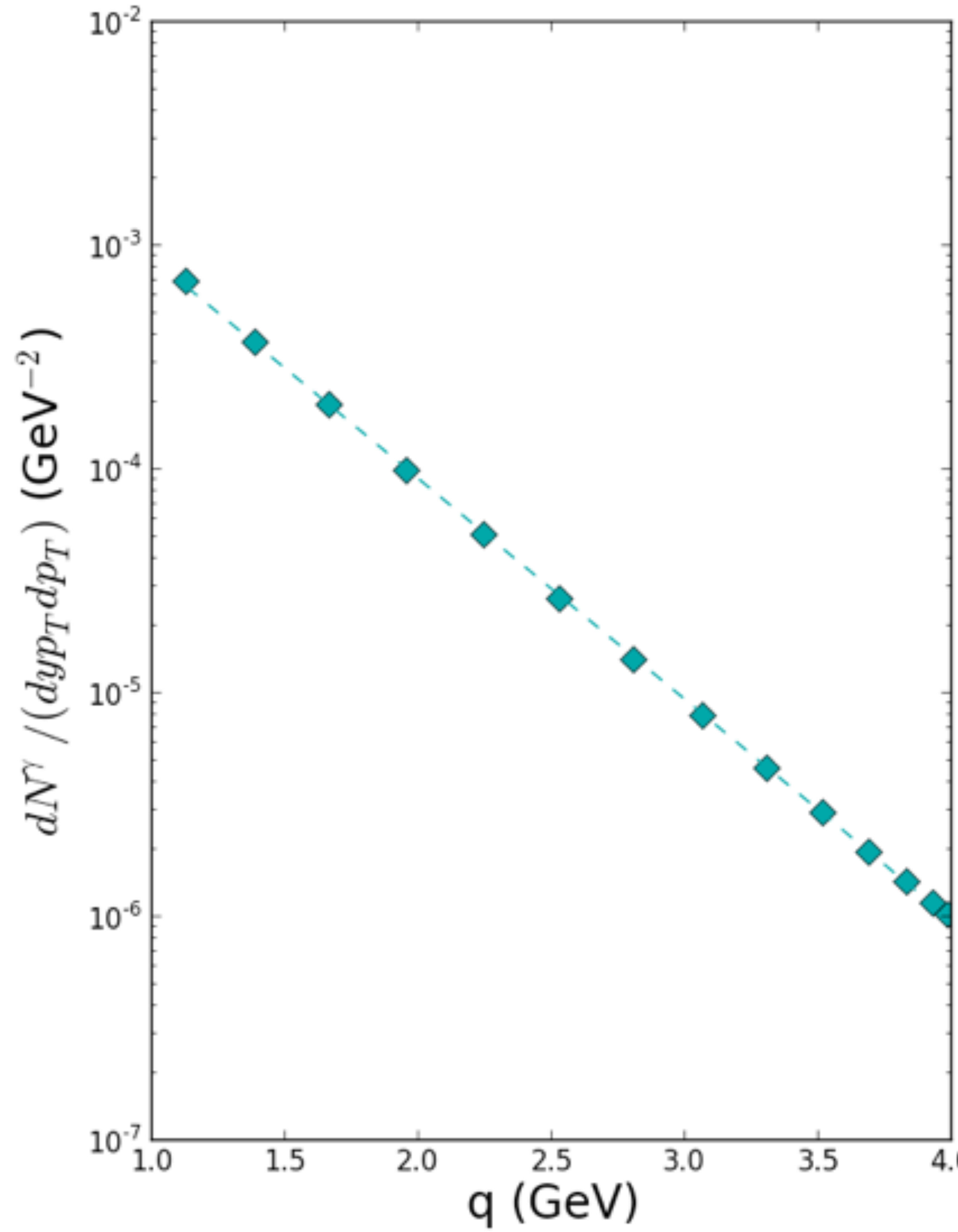
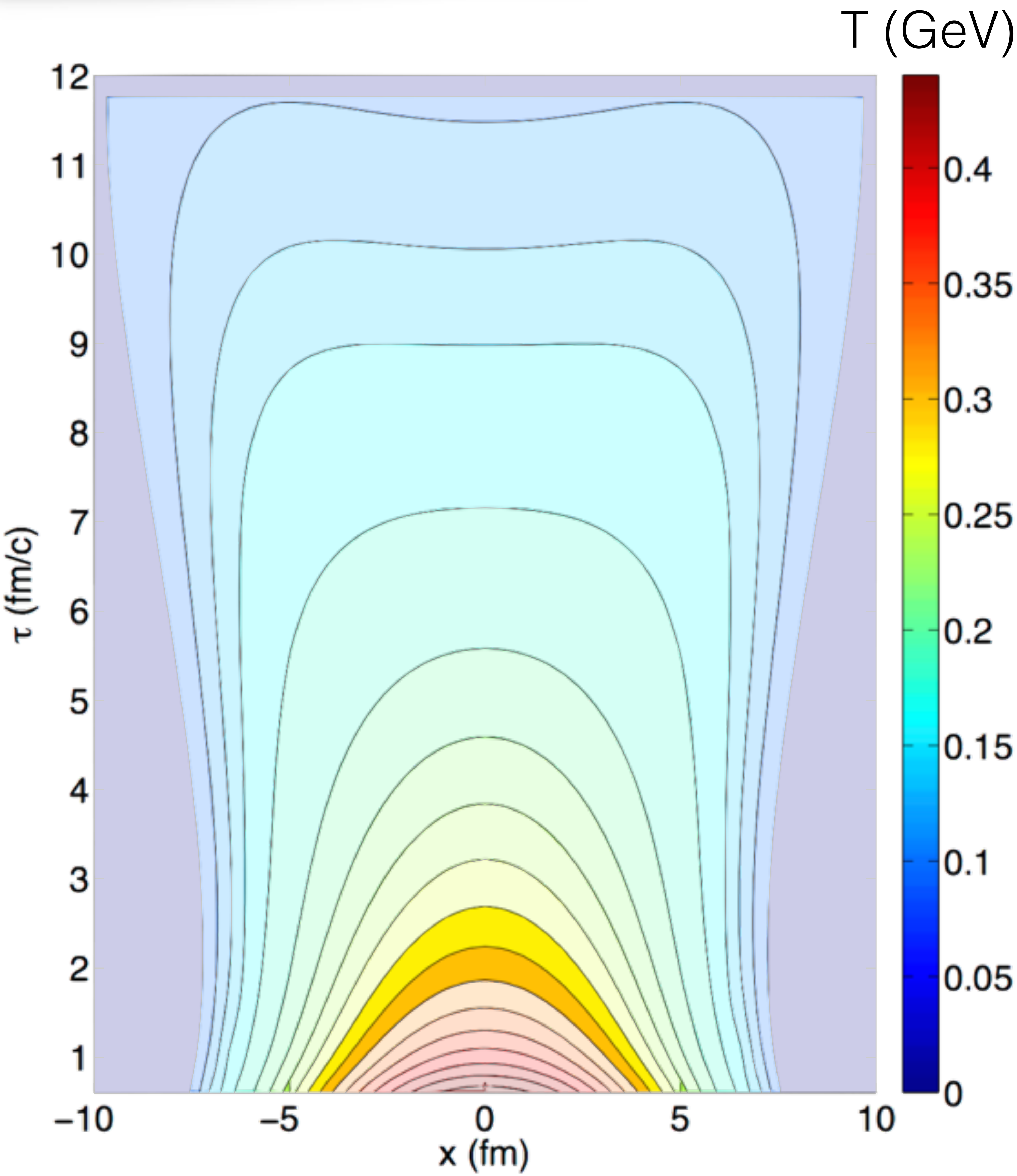


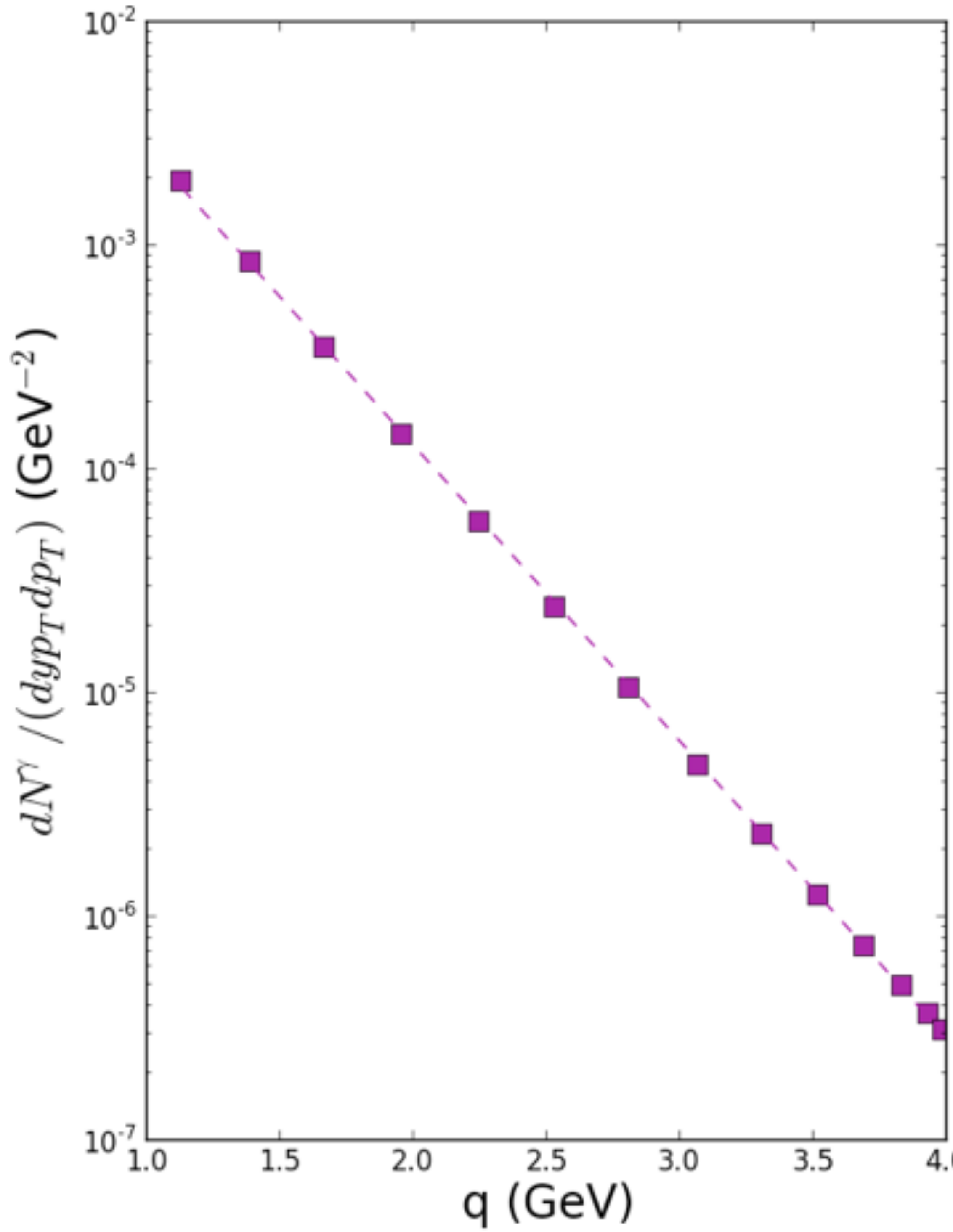
T = 400 MeV



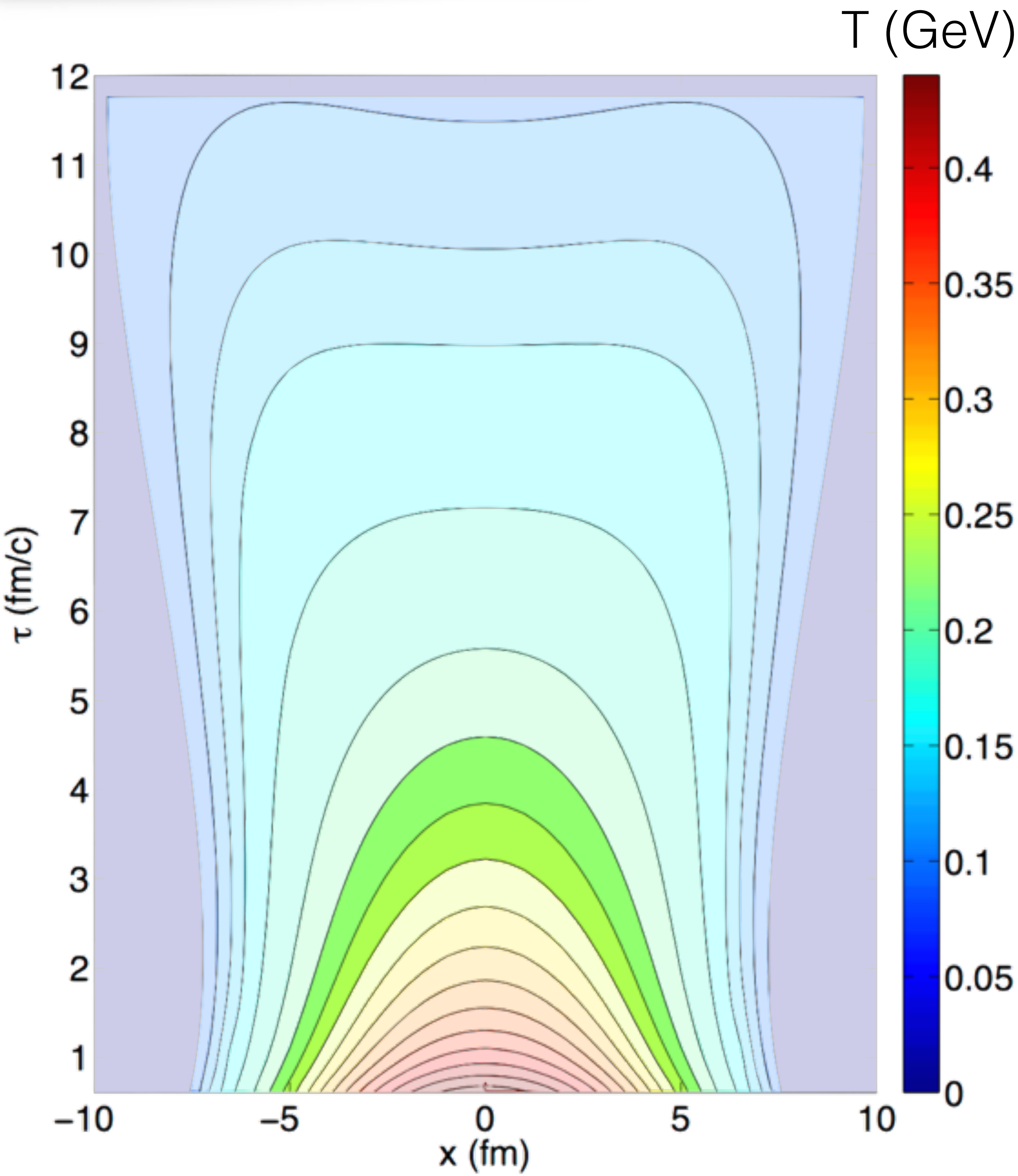
Slope of Photon Spectrum



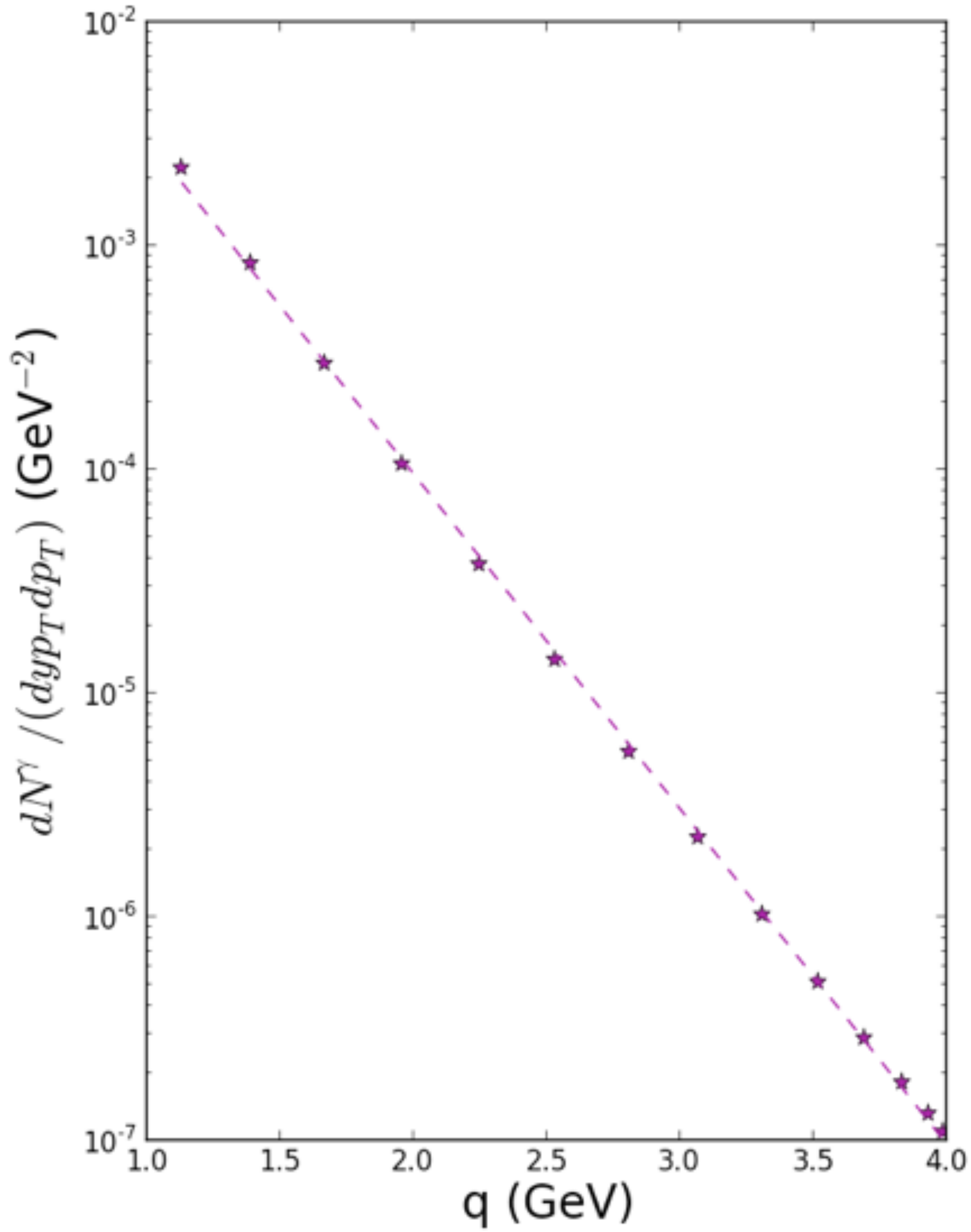
T = 300 MeV



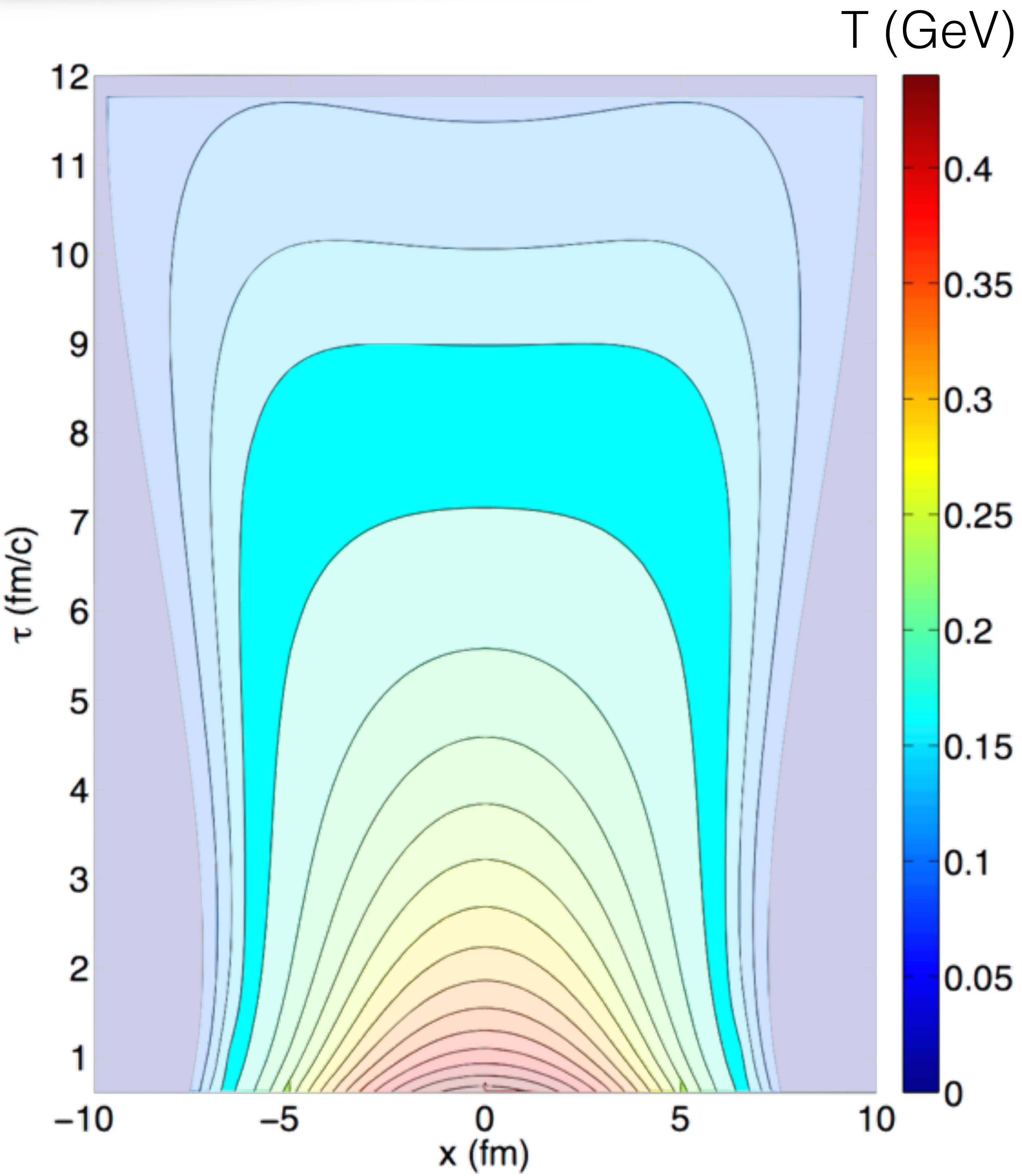
Slope of Photon Spectrum



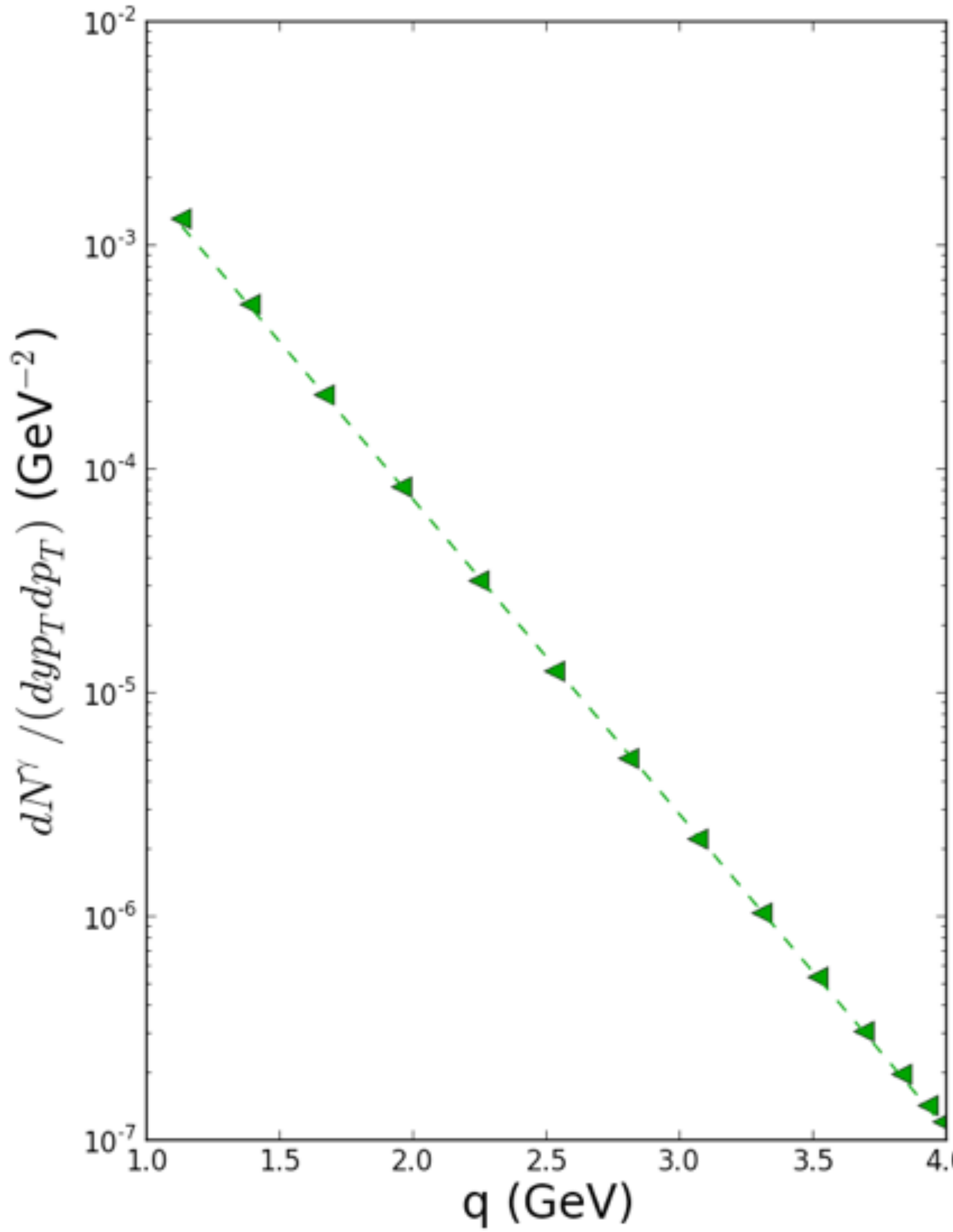
T = 230 MeV



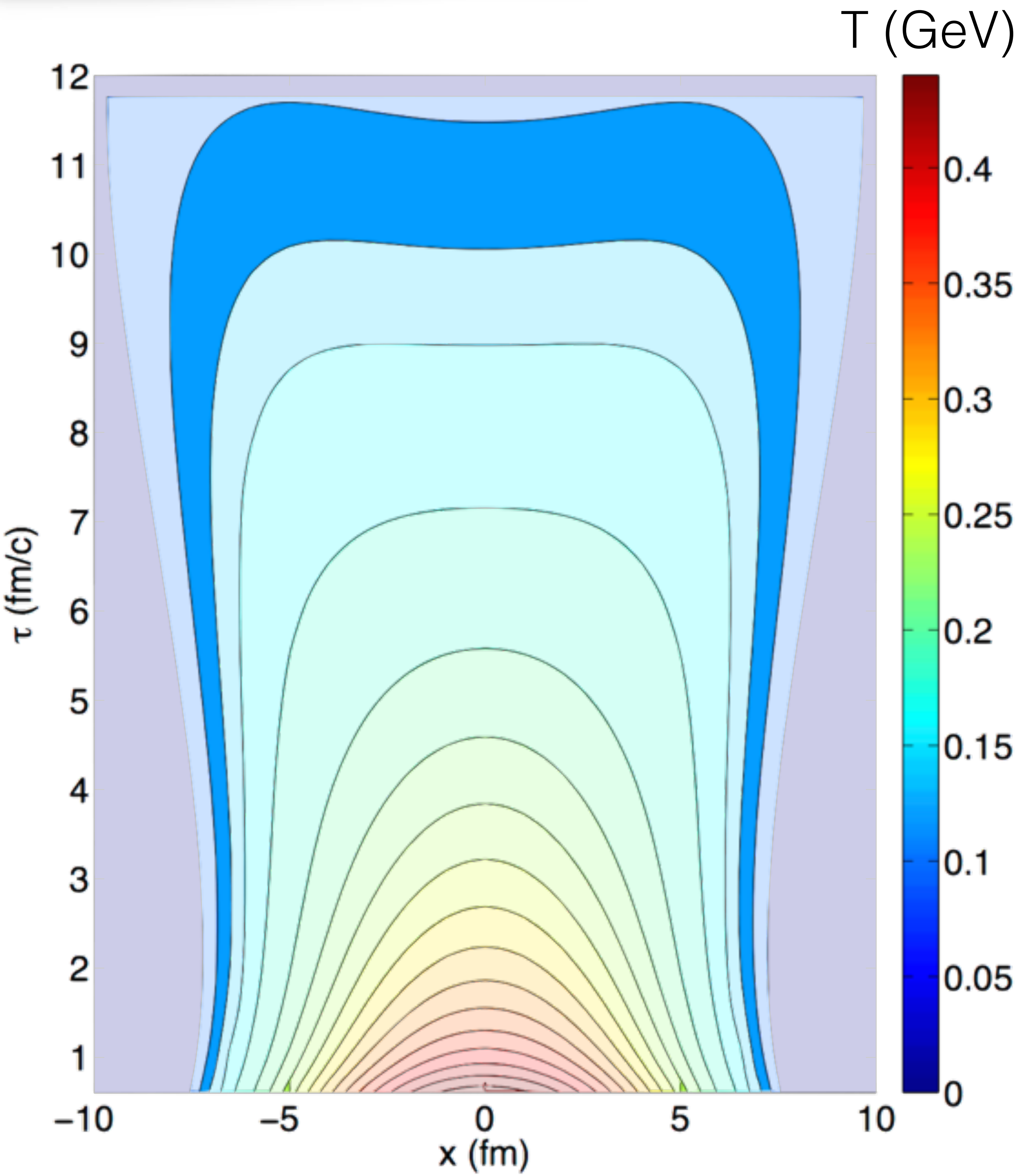
Slope of Photon Spectrum



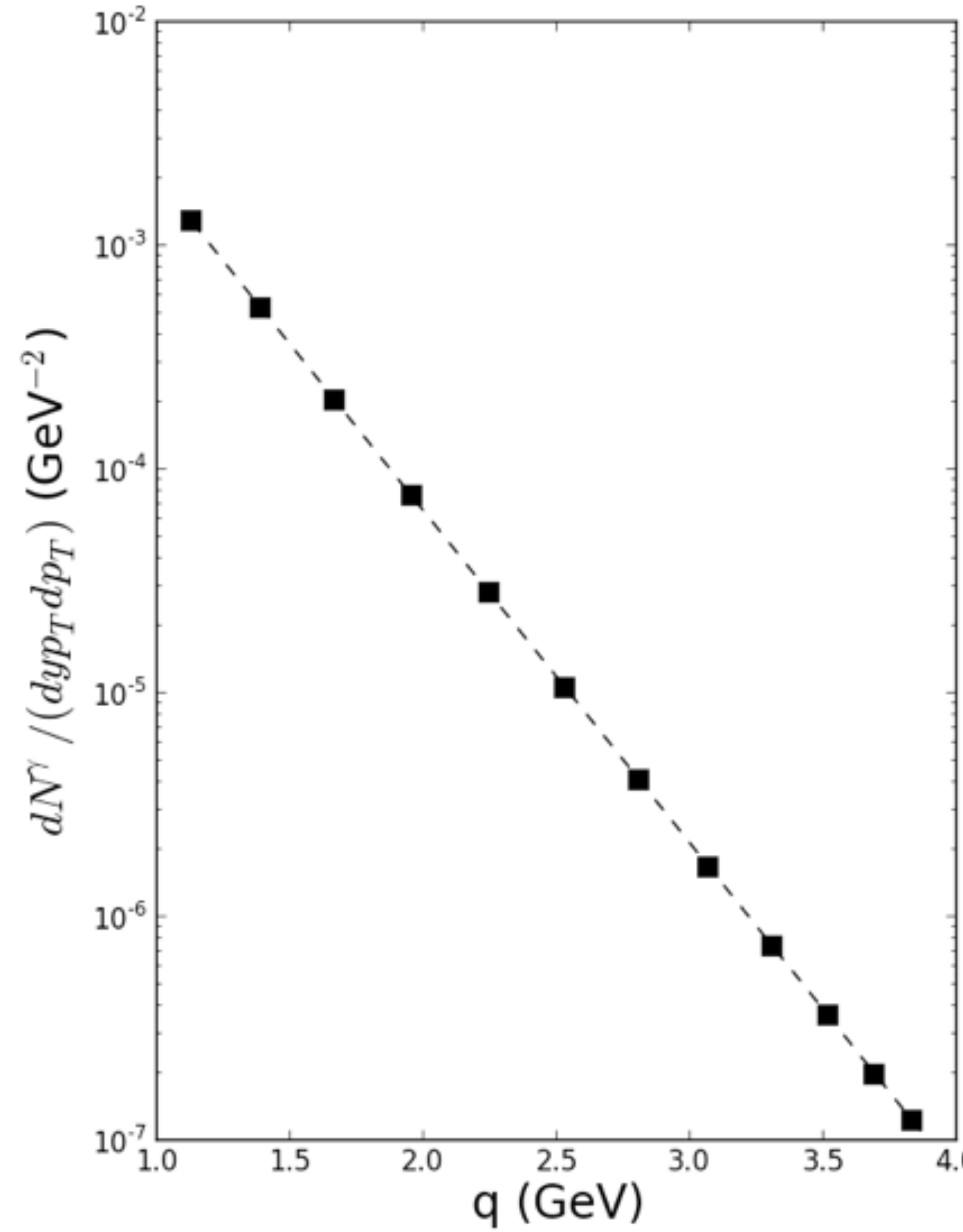
T = 160 MeV



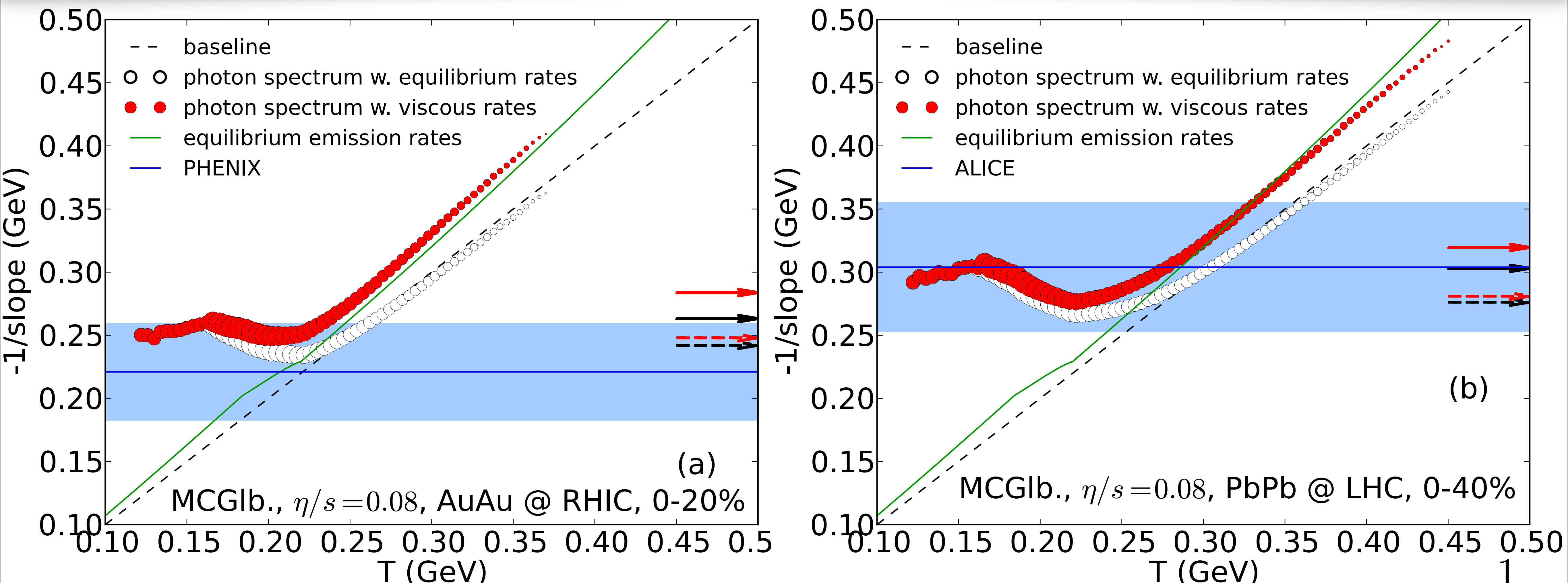
Slope of Photon Spectrum



T = 120 MeV



Fitted $T_{\rm eff}$ vs. True Temperature

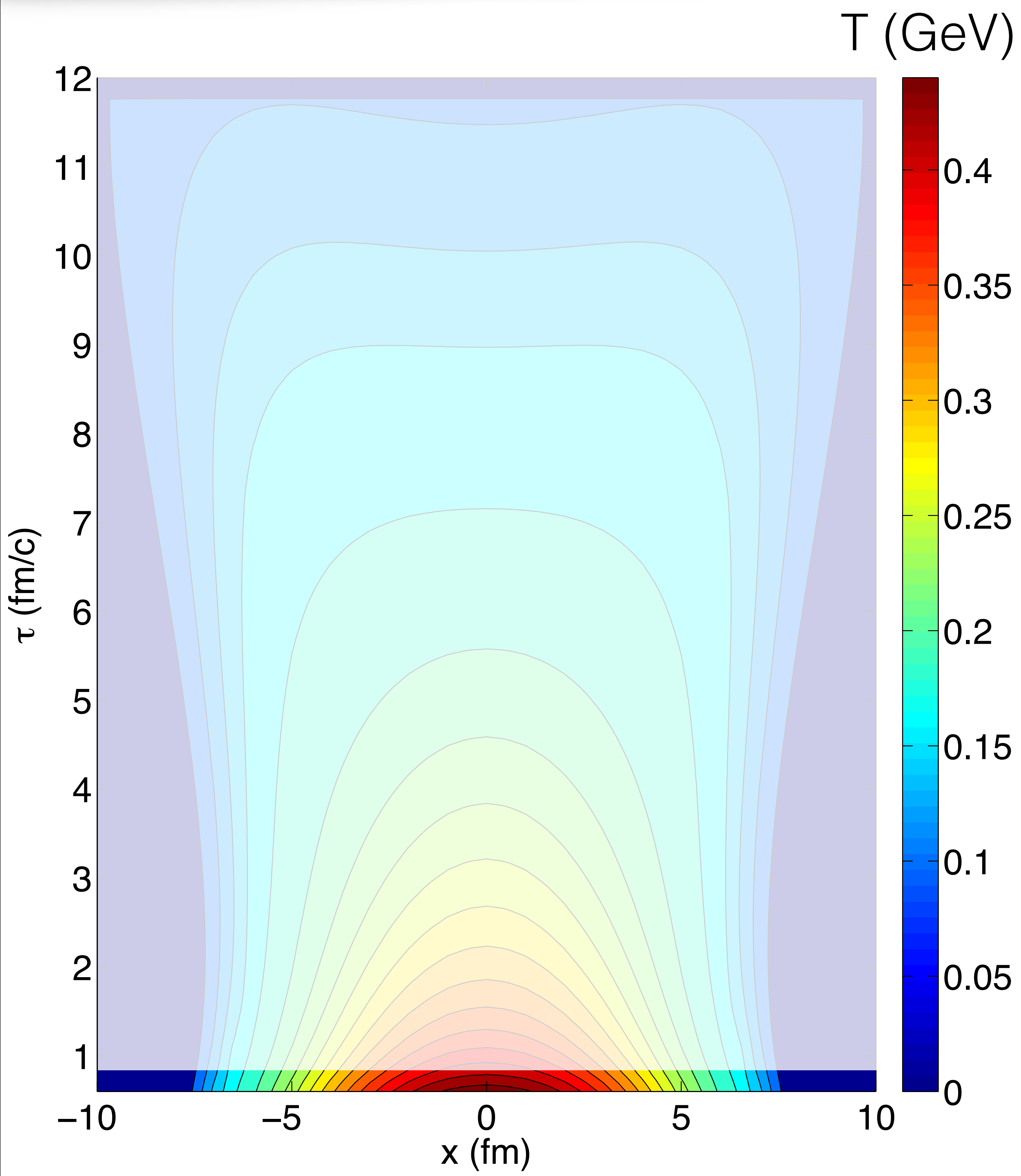


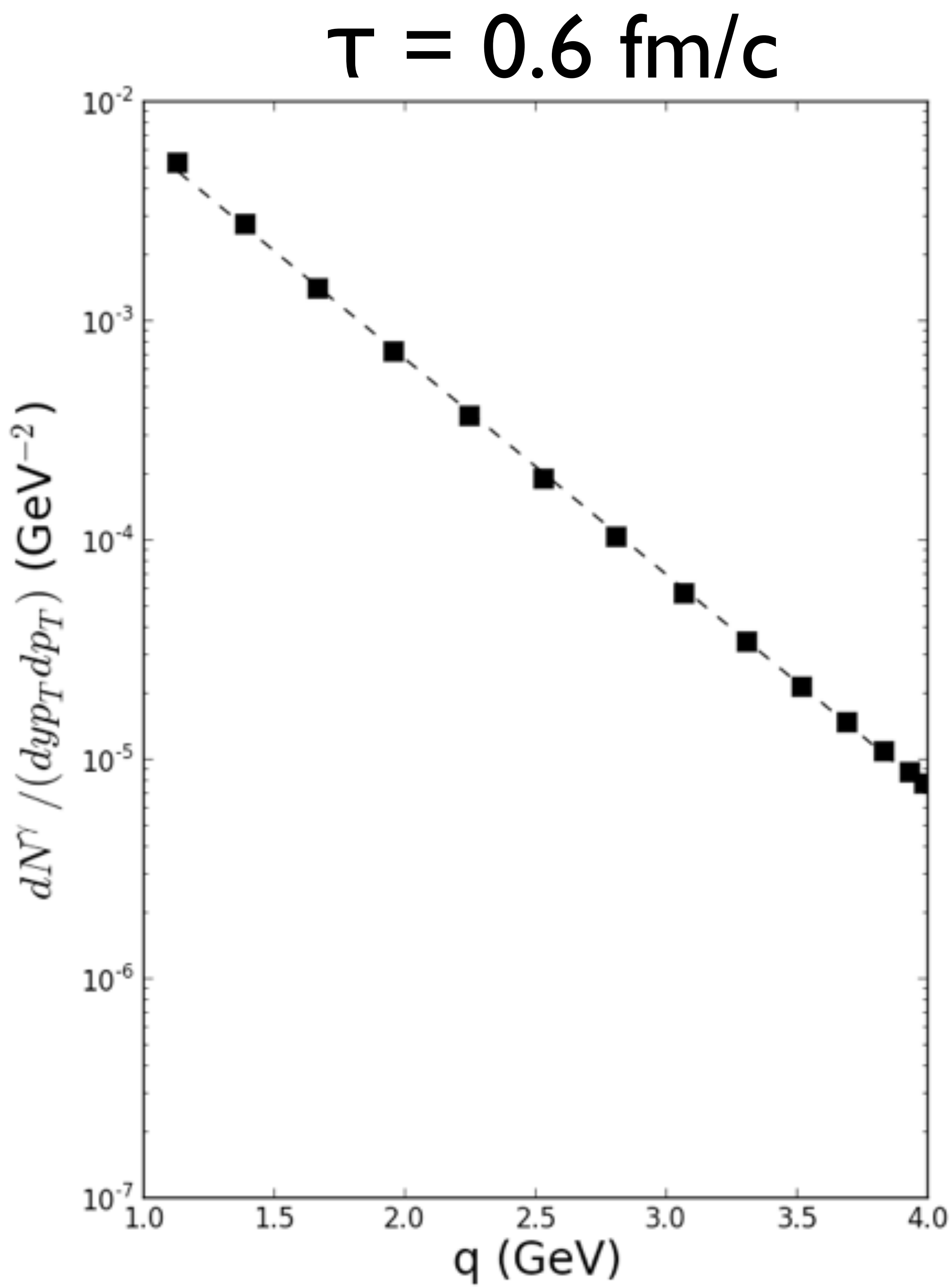
$$T_{\rm eff} = -\frac{1}{\rm slope}$$

- Photon emission rates $\propto \exp(-E/T)\log(E/T)$, $T_{\rm eff} > T$
- **All** photons with T < 250 MeV at RHIC and < 300 MeV at LHC carries $T_{\rm eff}$ within the experimental fitted region
- About **50-60%** of photons are emitted from T = 165~250 MeV, they are strongly blue shifted by radial flow

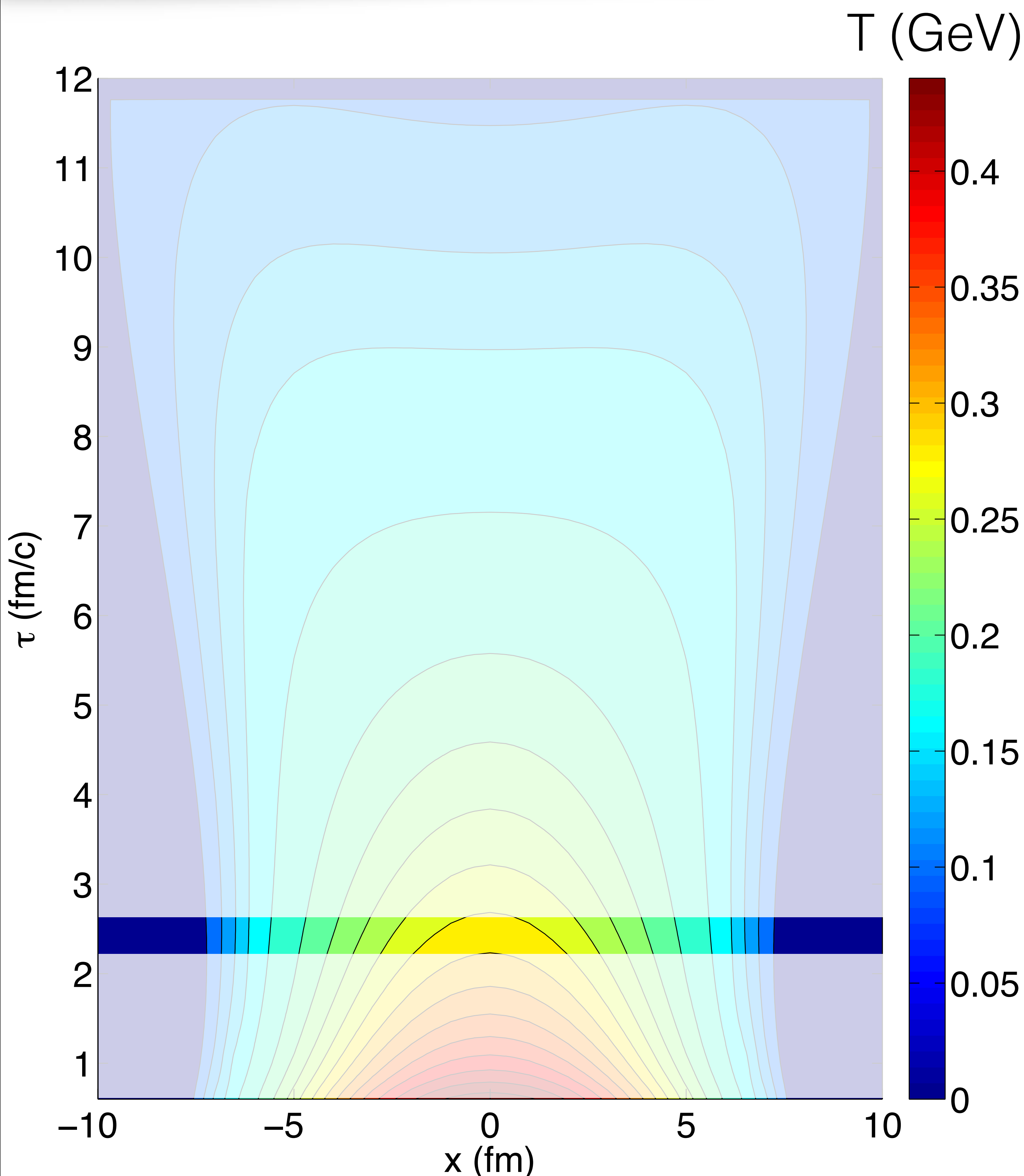
$$T_{\rm eff} = T\sqrt{\frac{1+v}{1-v}}$$

Slope of Photon Spectrum

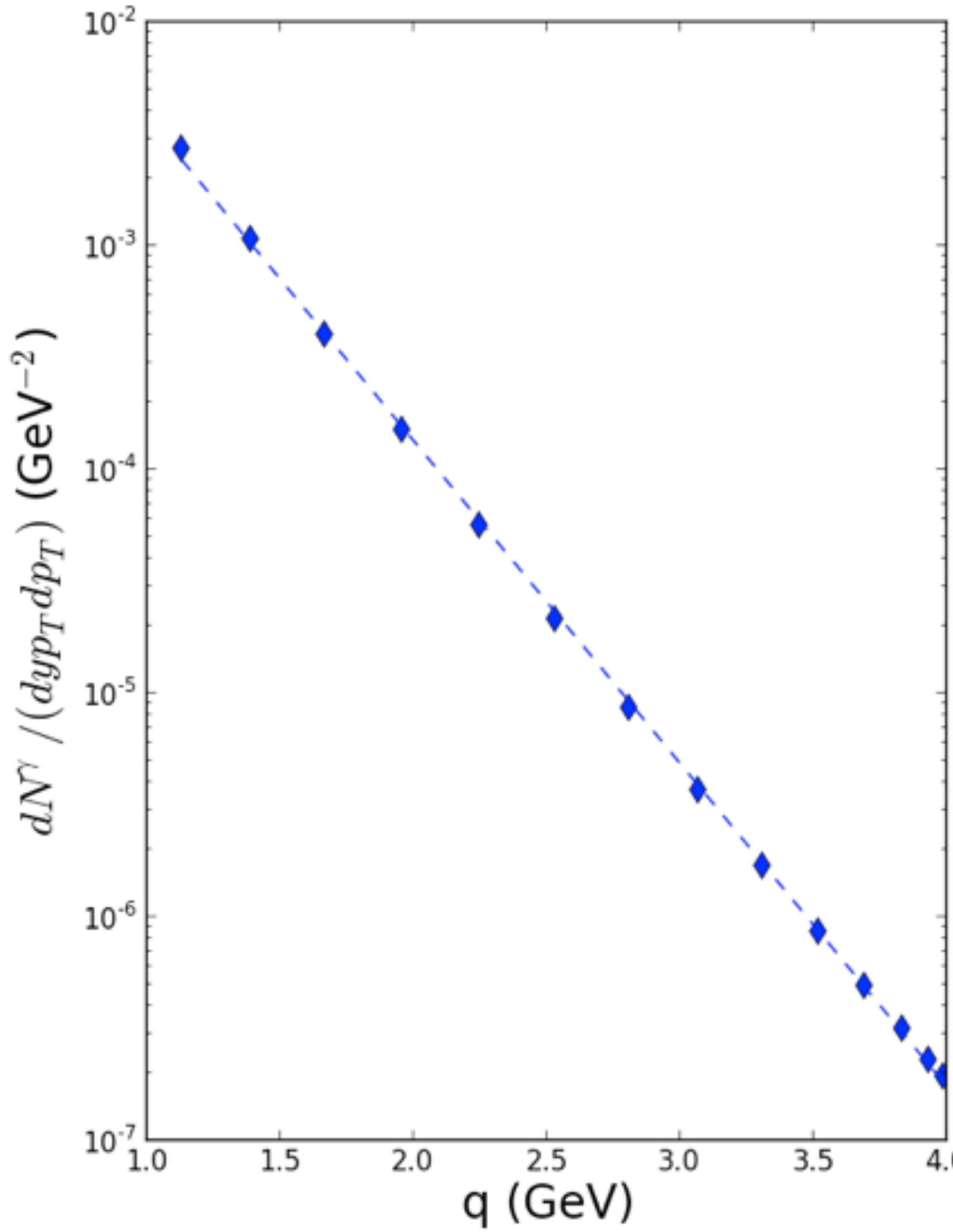




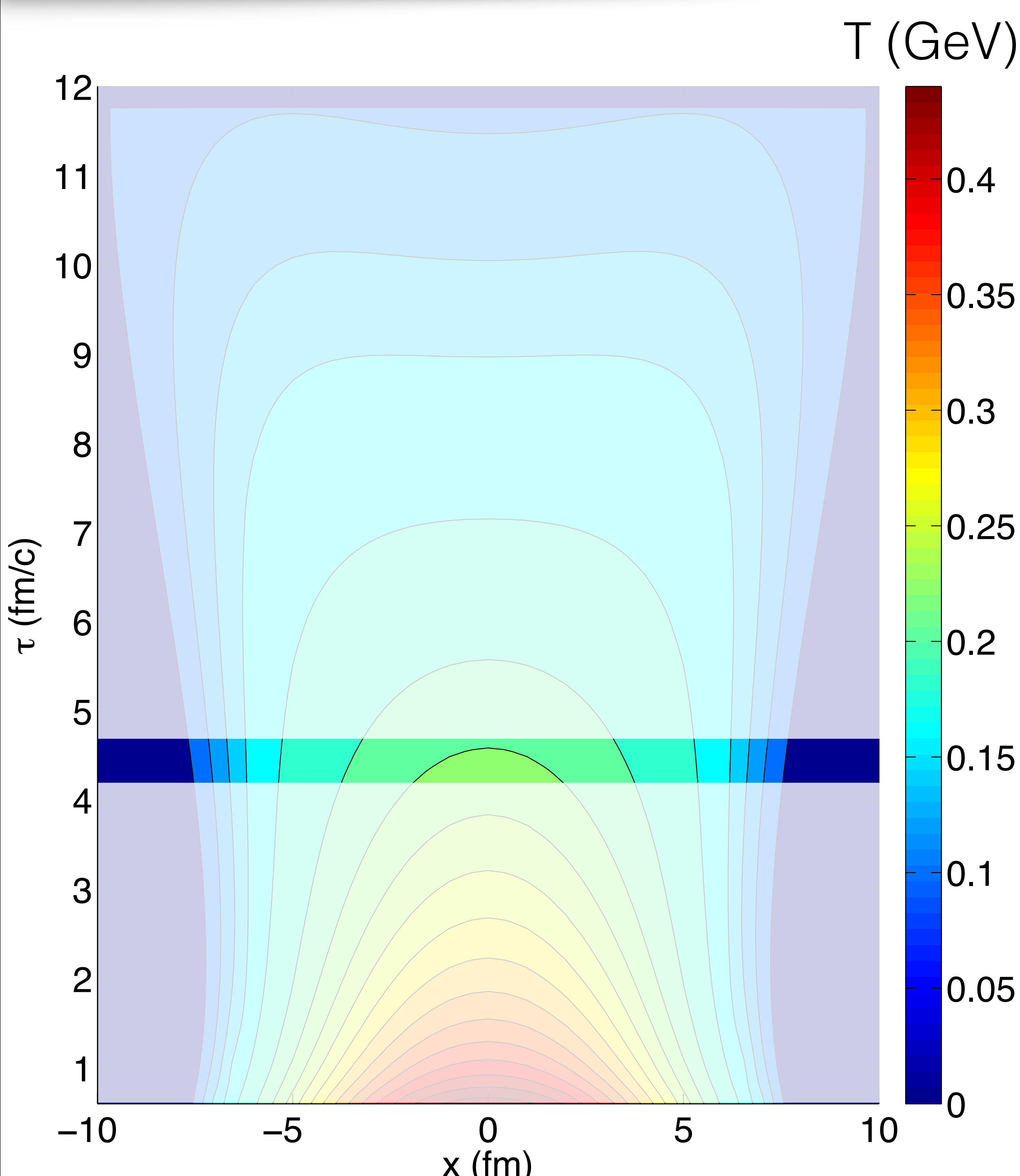
Slope of Photon Spectrum



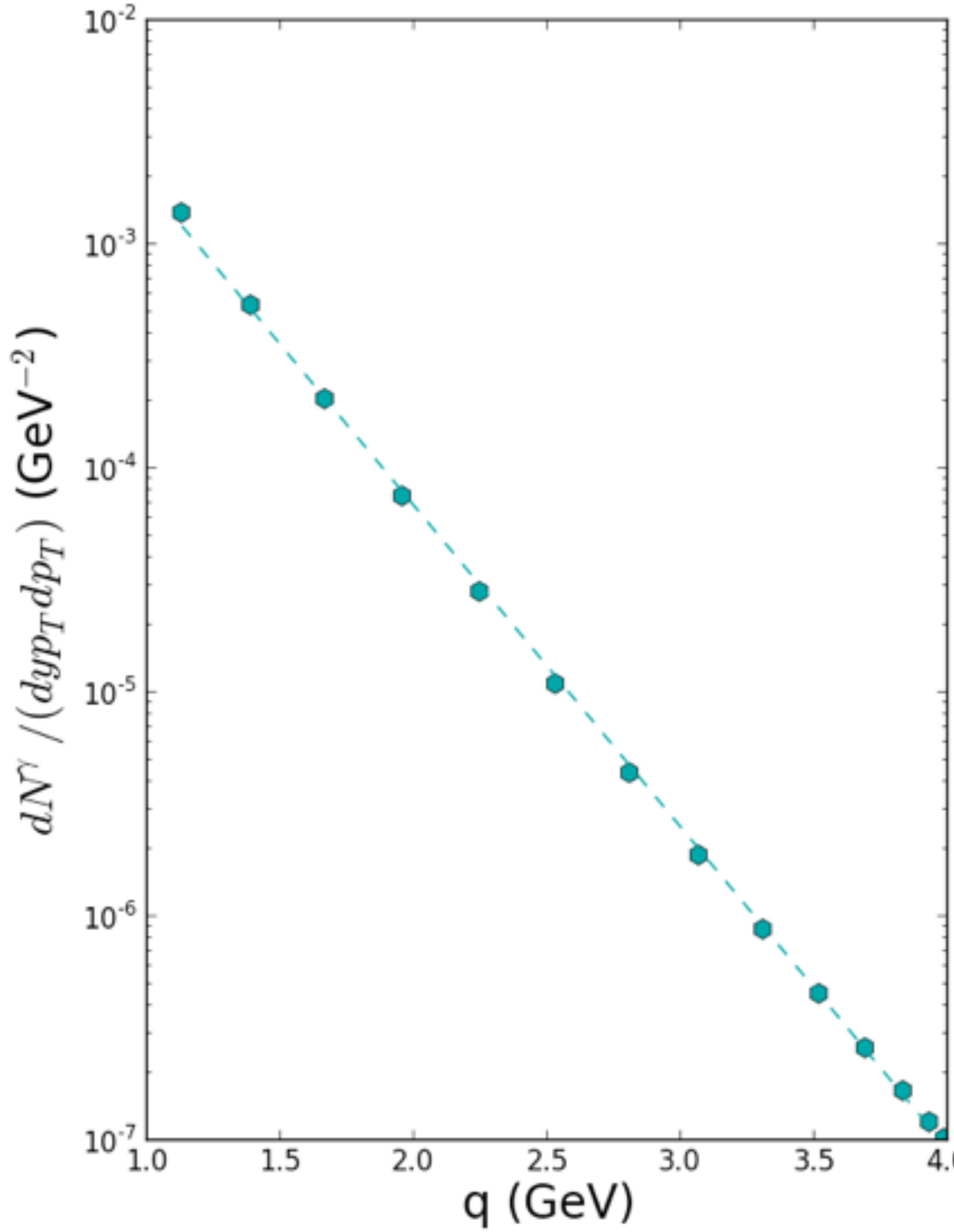
τ = 2.5 fm/c



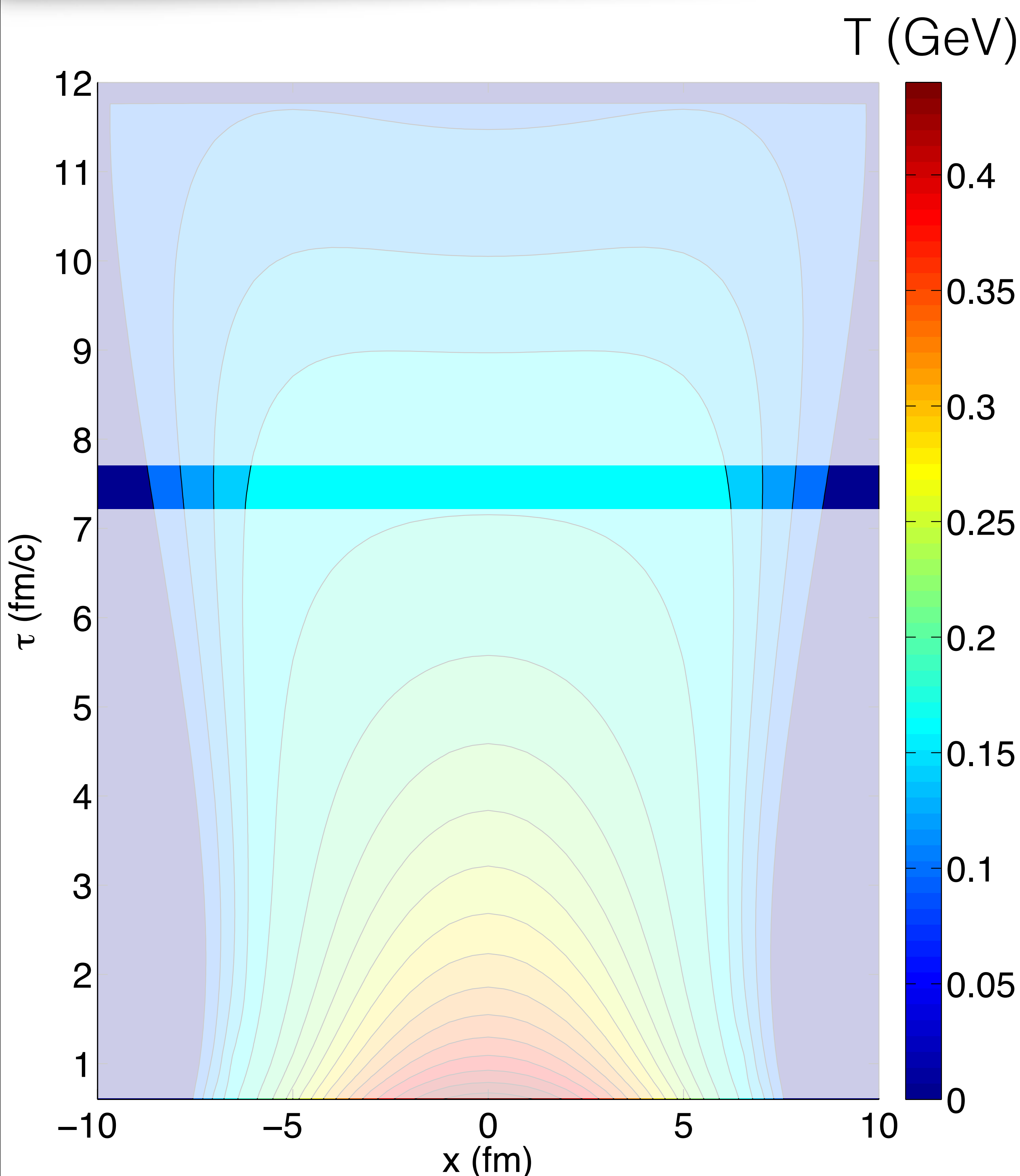
Slope of Photon Spectrum



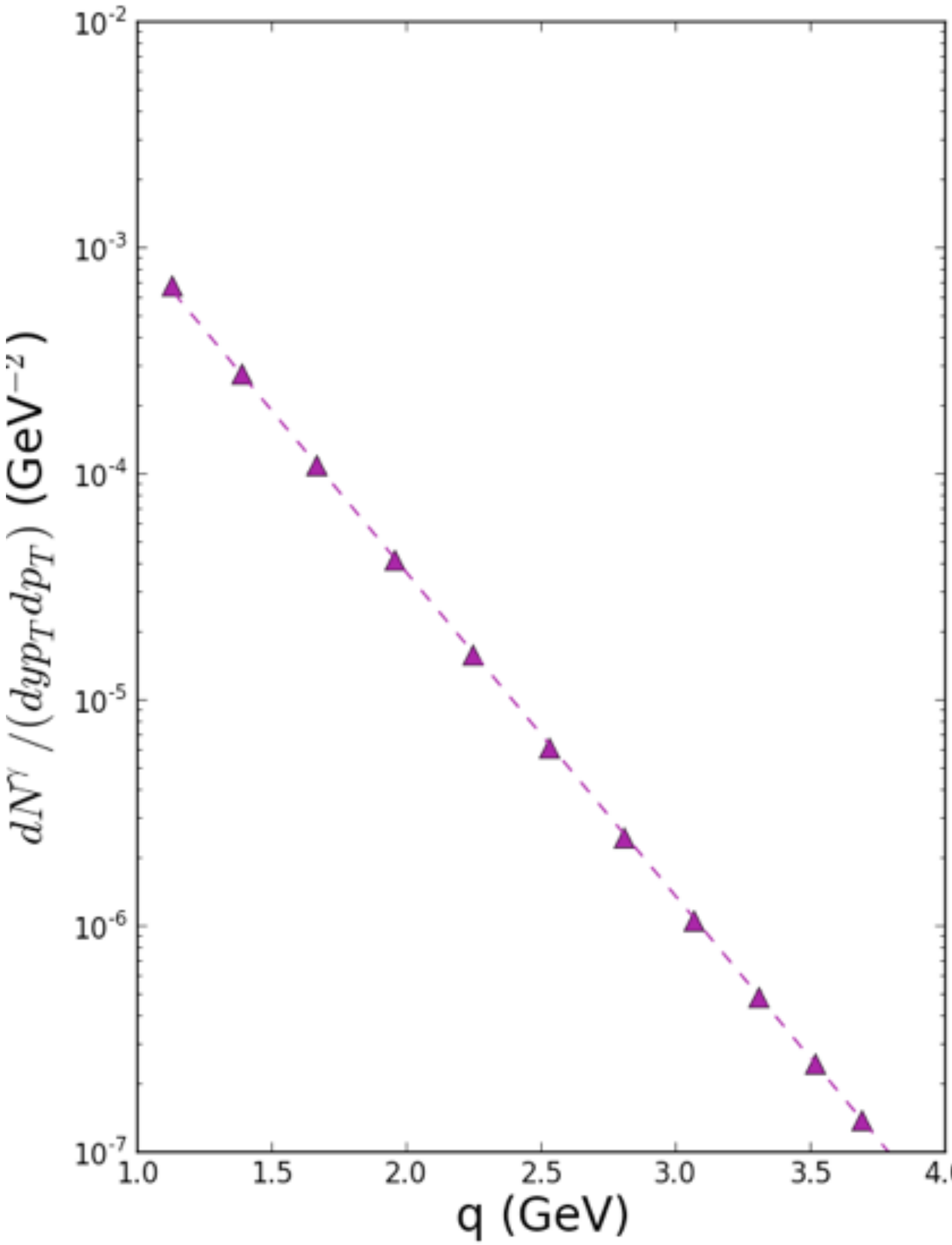
τ = 4.5 fm/c



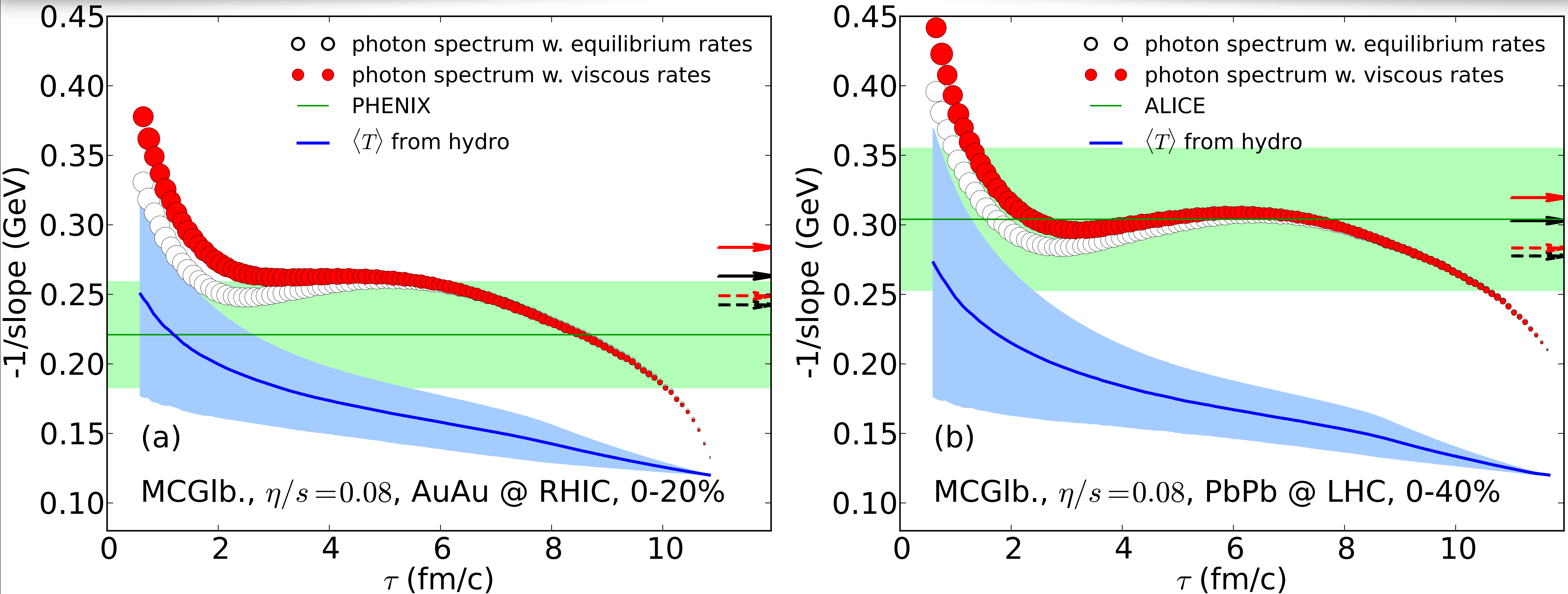
Slope of Photon Spectrum



τ = 7.5 fm/c

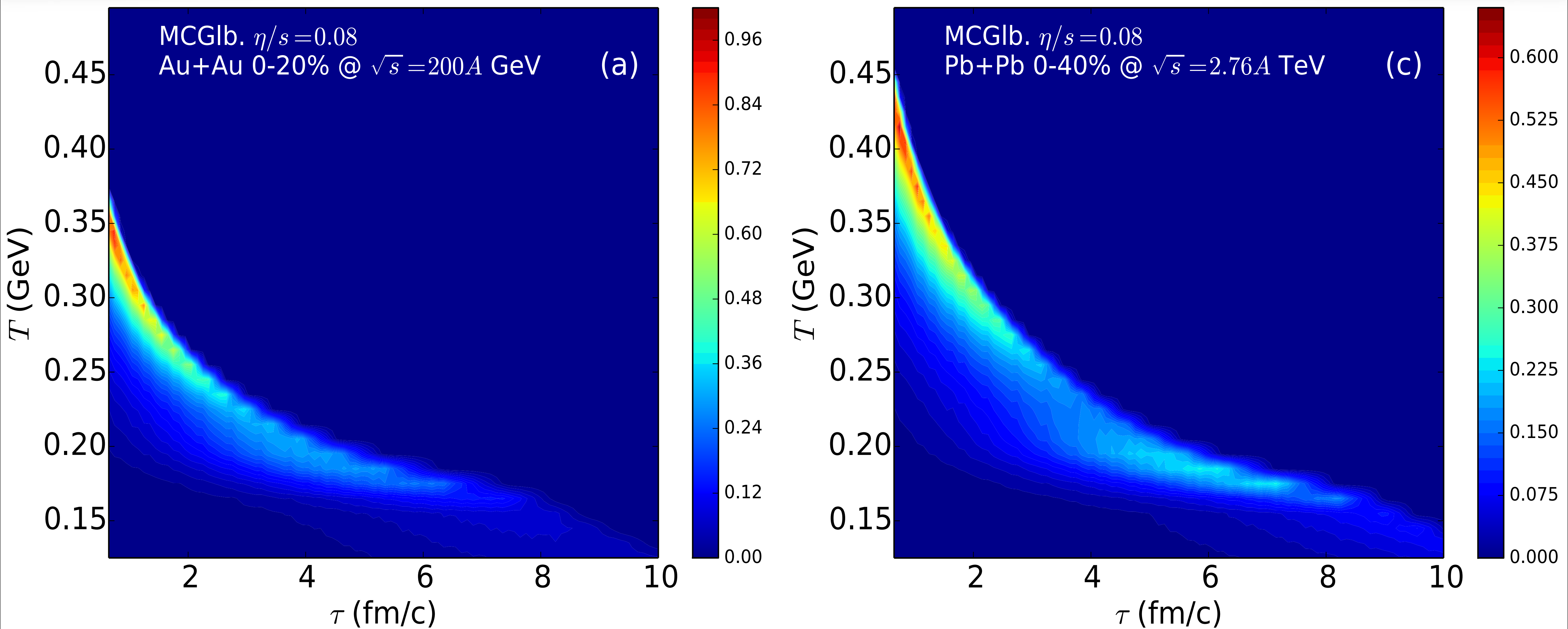


Fitted T_{eff} vs. Emission Time



- About 25% of thermal photons are emitted in the first 2 fm/c
- After 2 fm/c, thermal photons are significantly blue shifted by radial flow
- Viscous corrections to the slope of photon spectra are stronger during the early part of the evolution

Mapping thermal photon emission

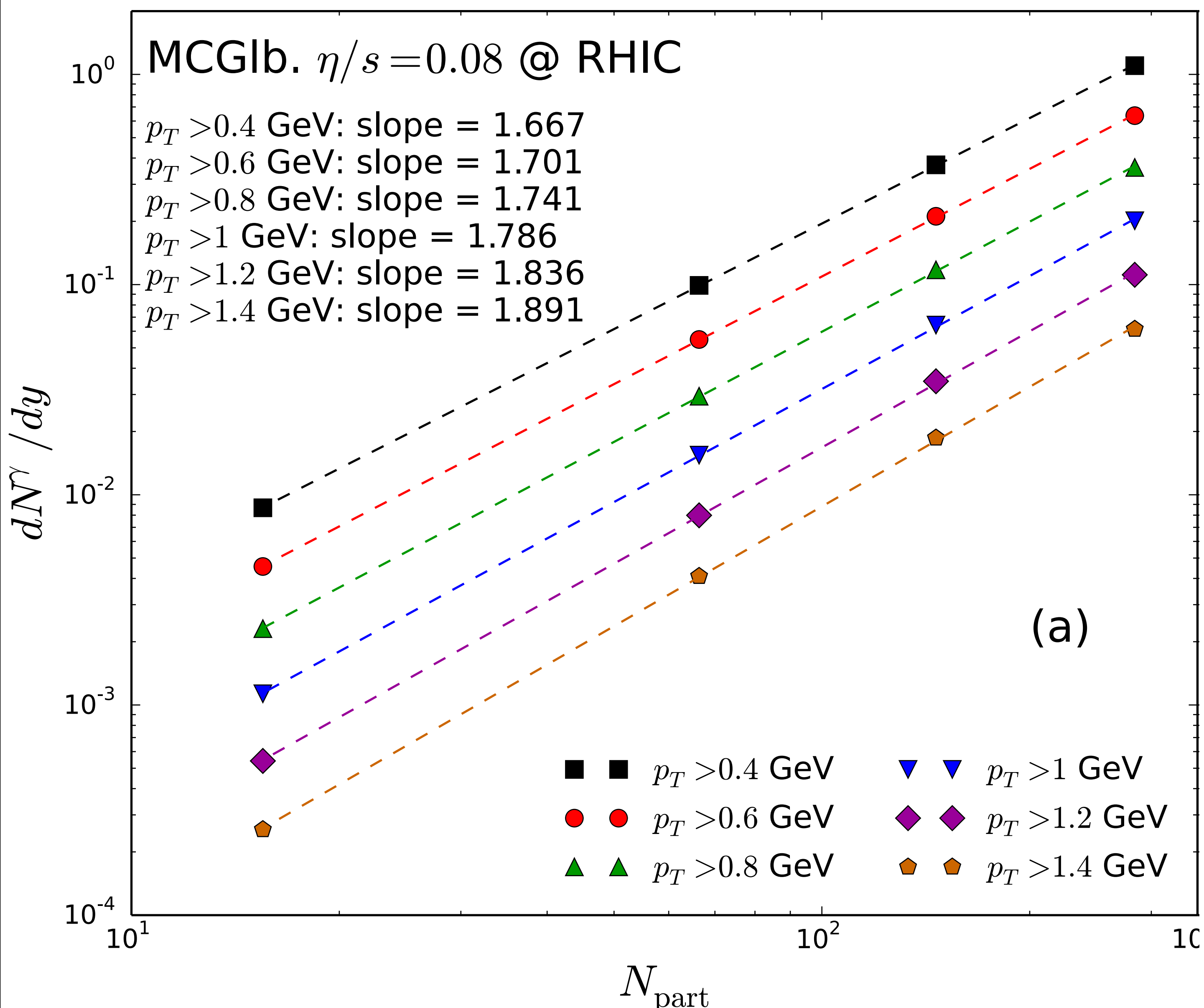


- By cutting hydro medium both in T and tau, we observe a **two-wave** thermal photon production

  early time production — high rates at high temperatures

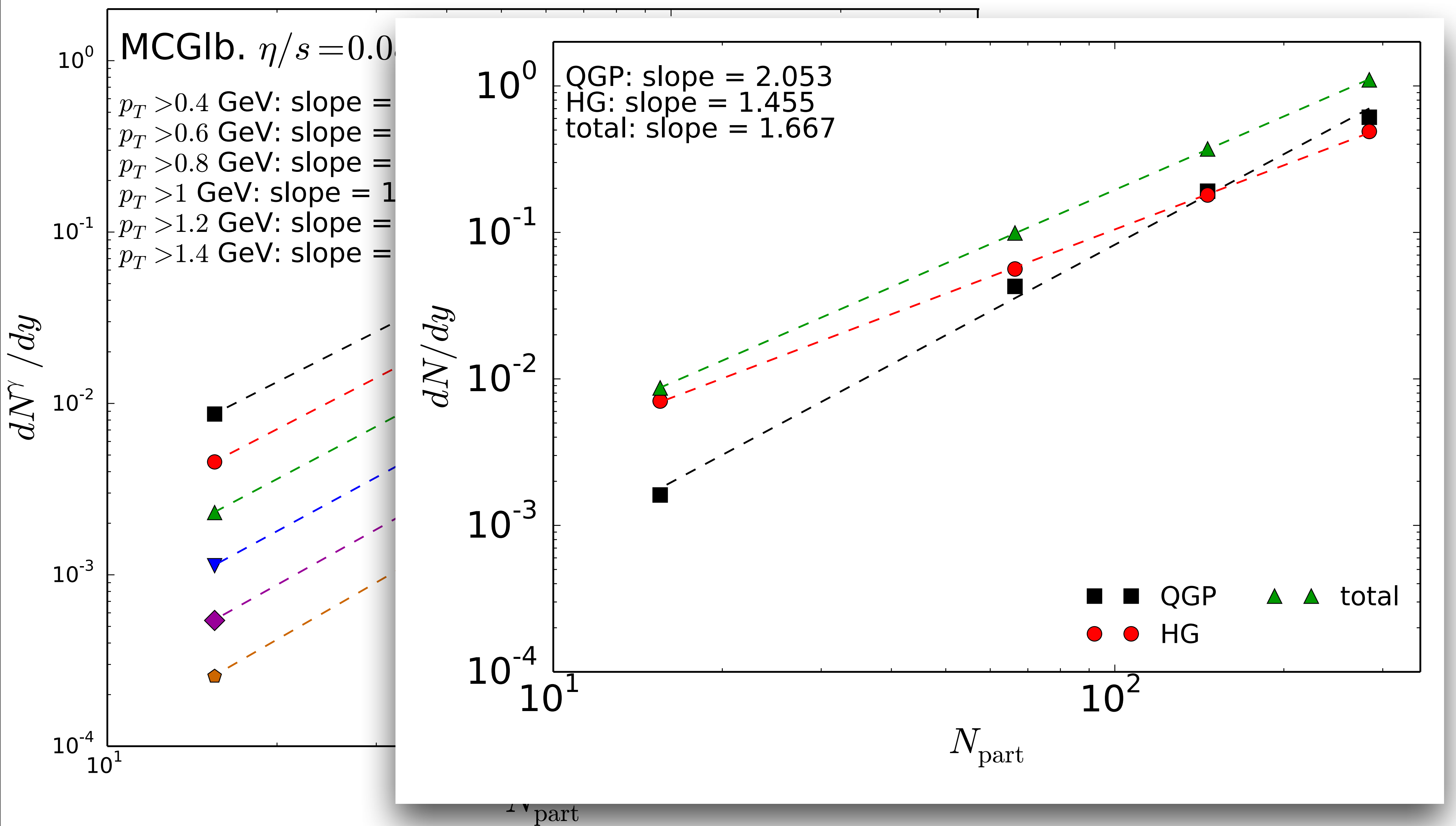
  near transition region — growing of space-time volume

Centrality dependence of photon yield



- Thermal photons from hydrodynamic medium qualitatively reproduce the centrality dependence of the direct excess photon yield at the top RHIC energy

Centrality dependence of photon yield



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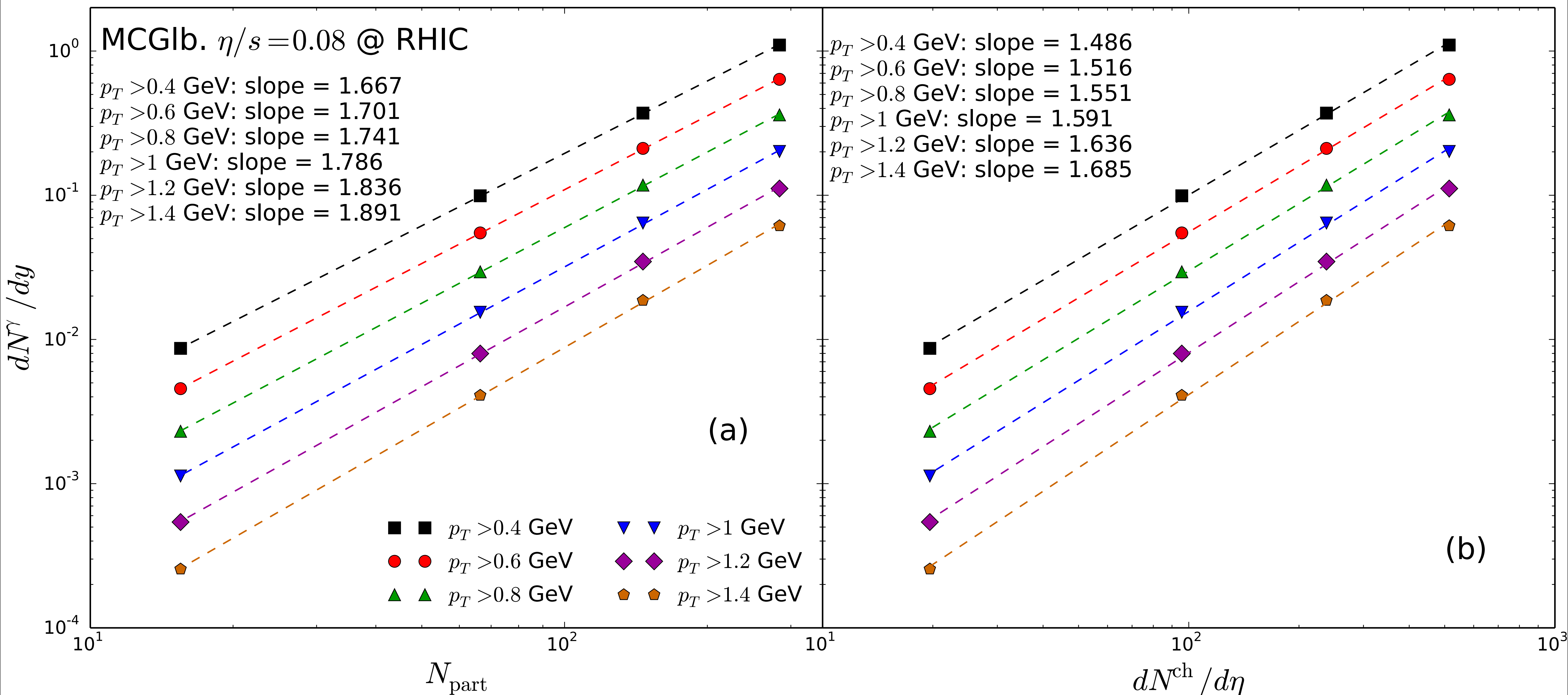
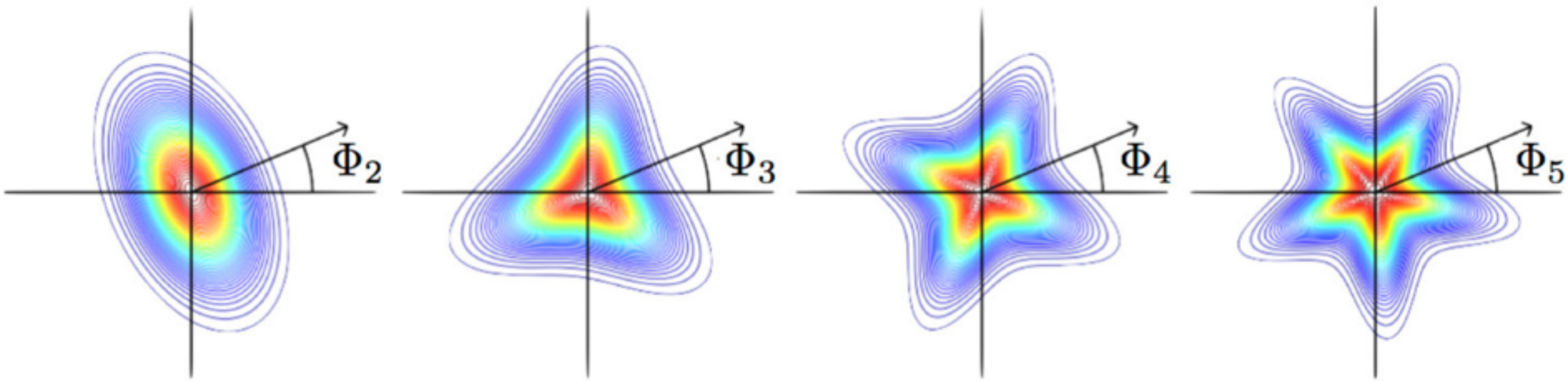
Centrality dependence of photon yield



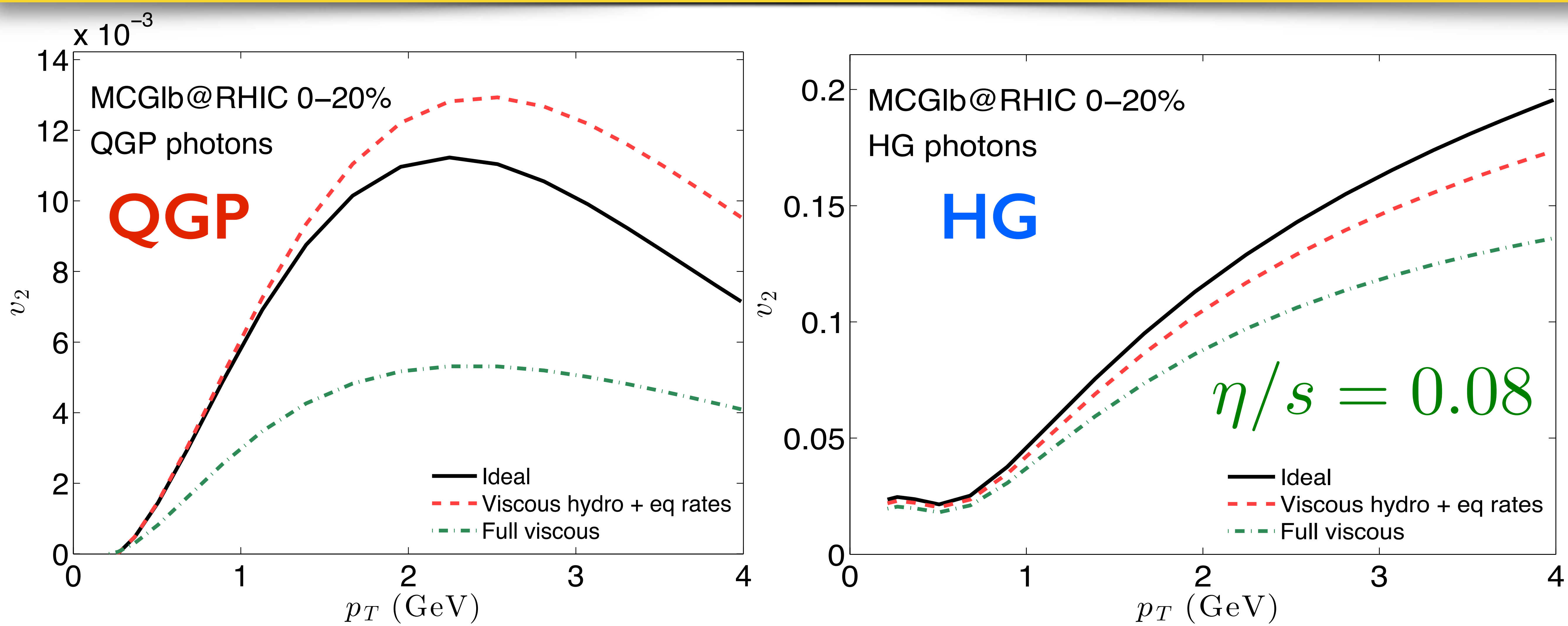
- Thermal photons from hydrodynamic medium qualitatively reproduce the centrality dependence of the direct excess photon yield at the top RHIC energy

dN^γ/dy vs. $dN^{\rm ch}/d\eta$ → **less model dependent comparison**

Photon anisotropic flow



Viscous effects on photon elliptic flow



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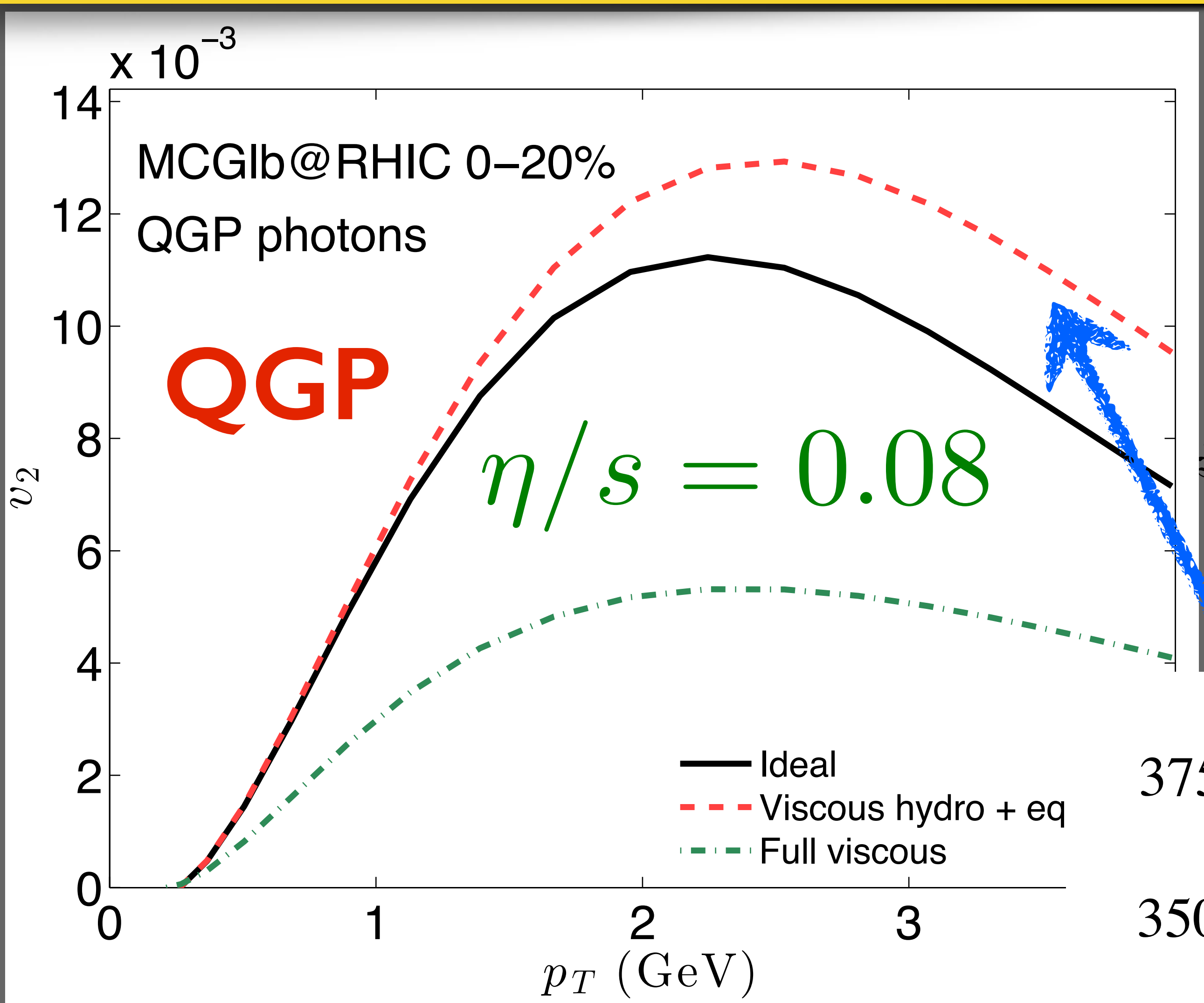

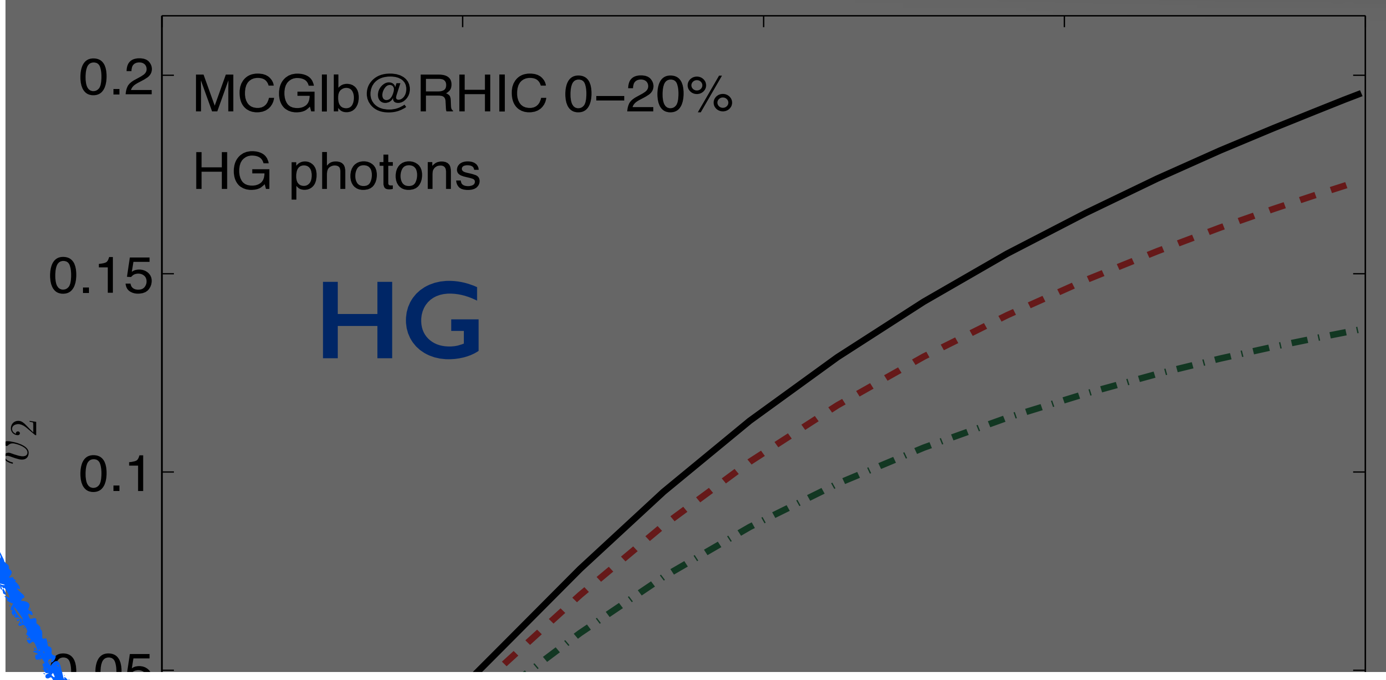

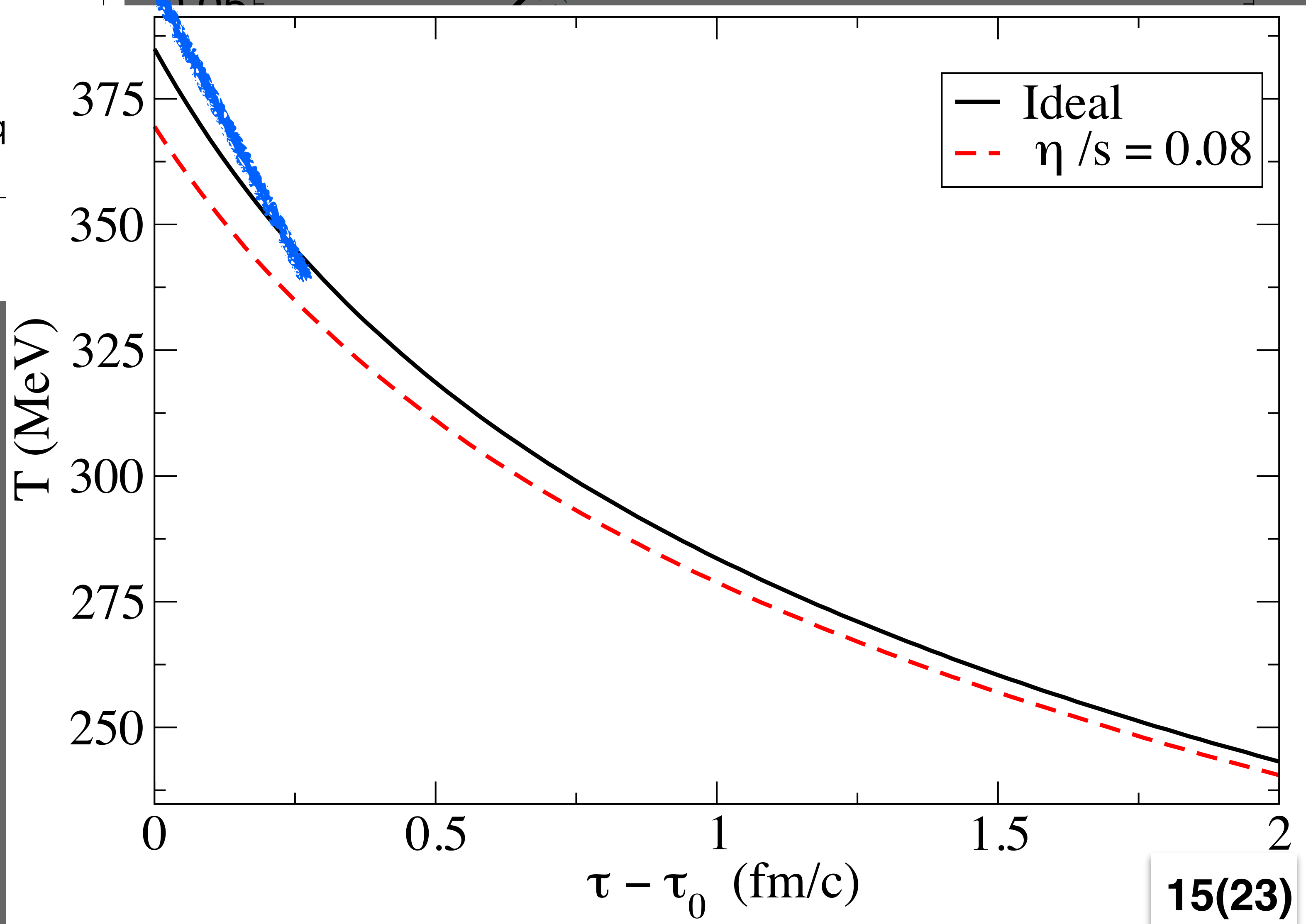

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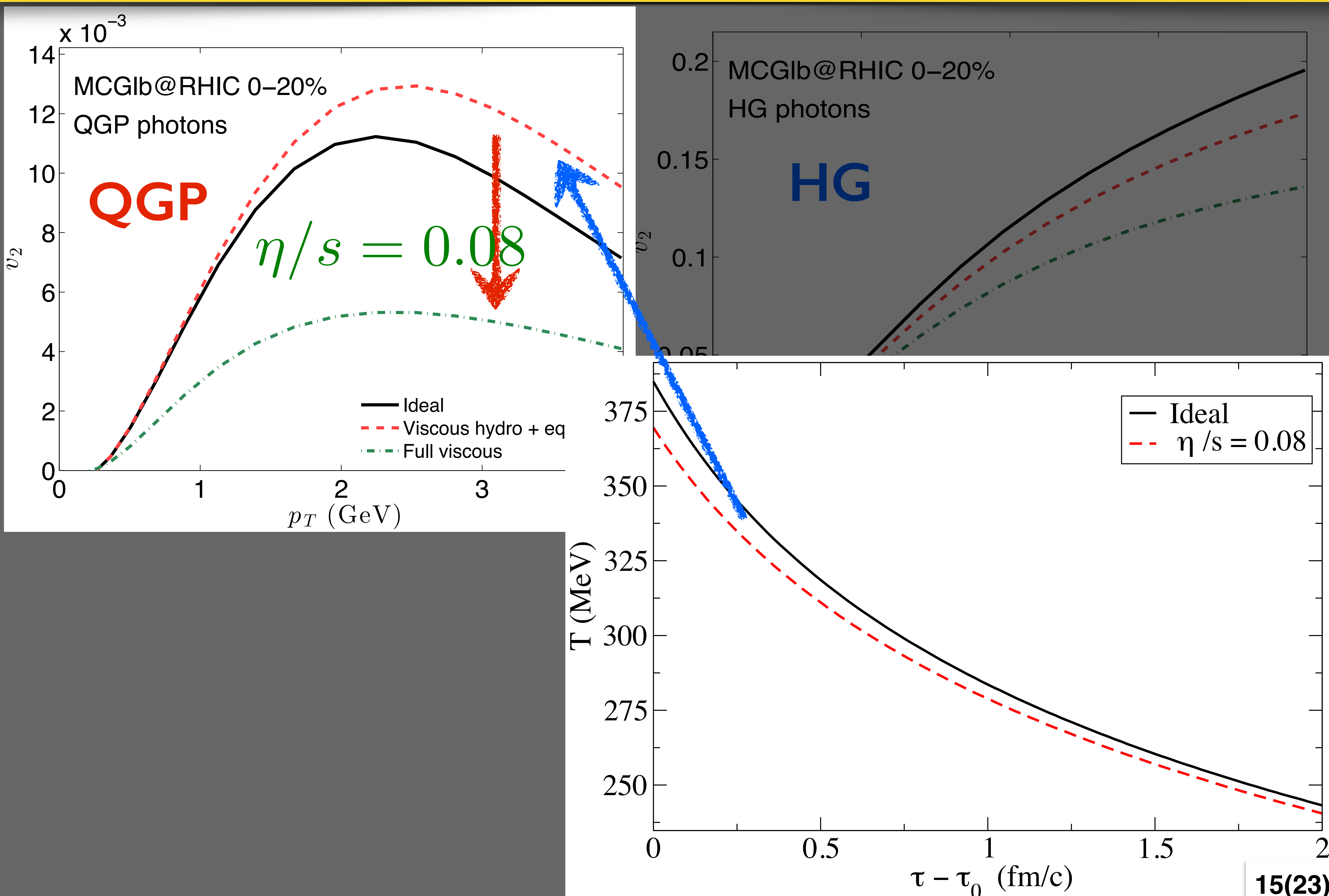

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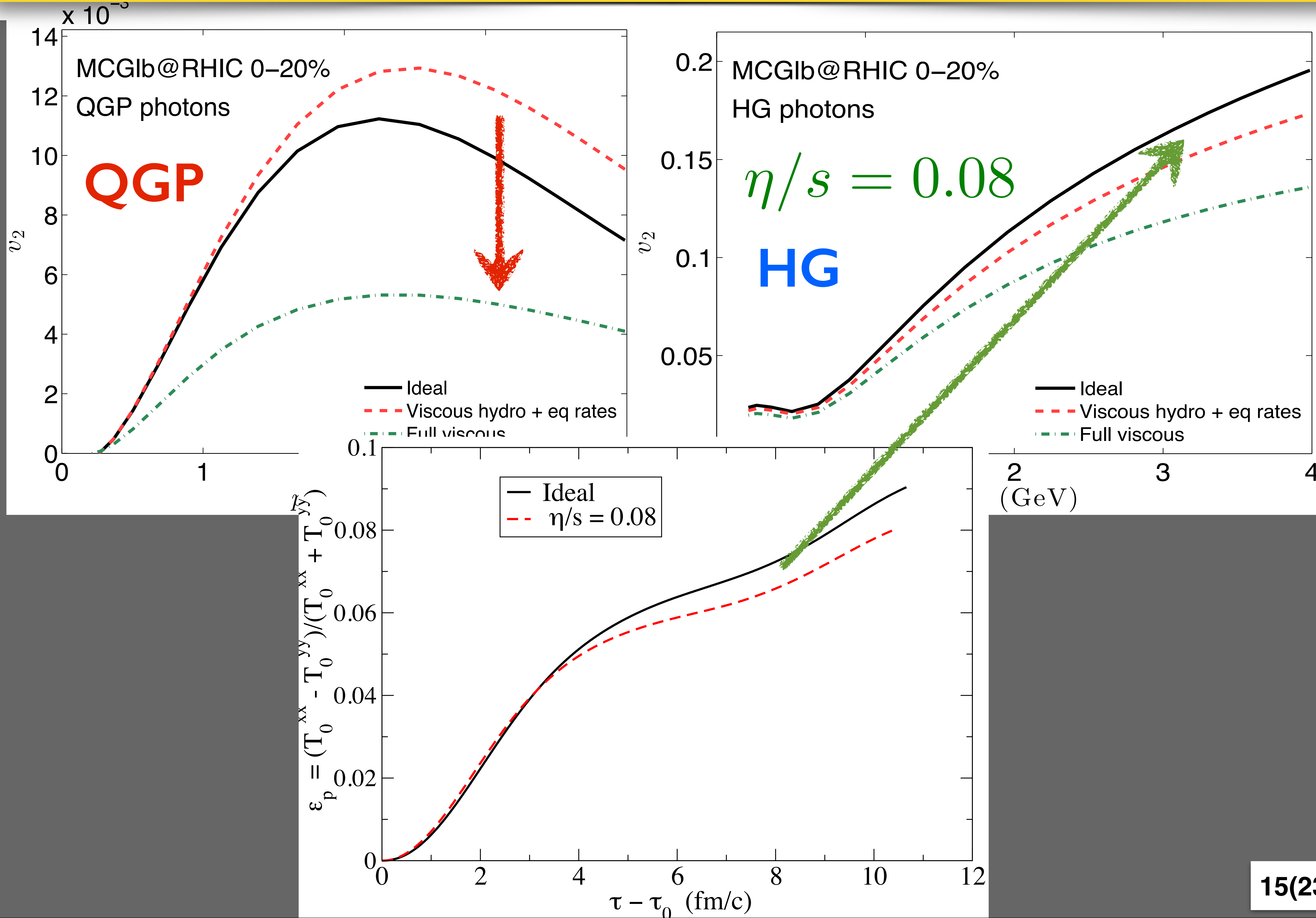

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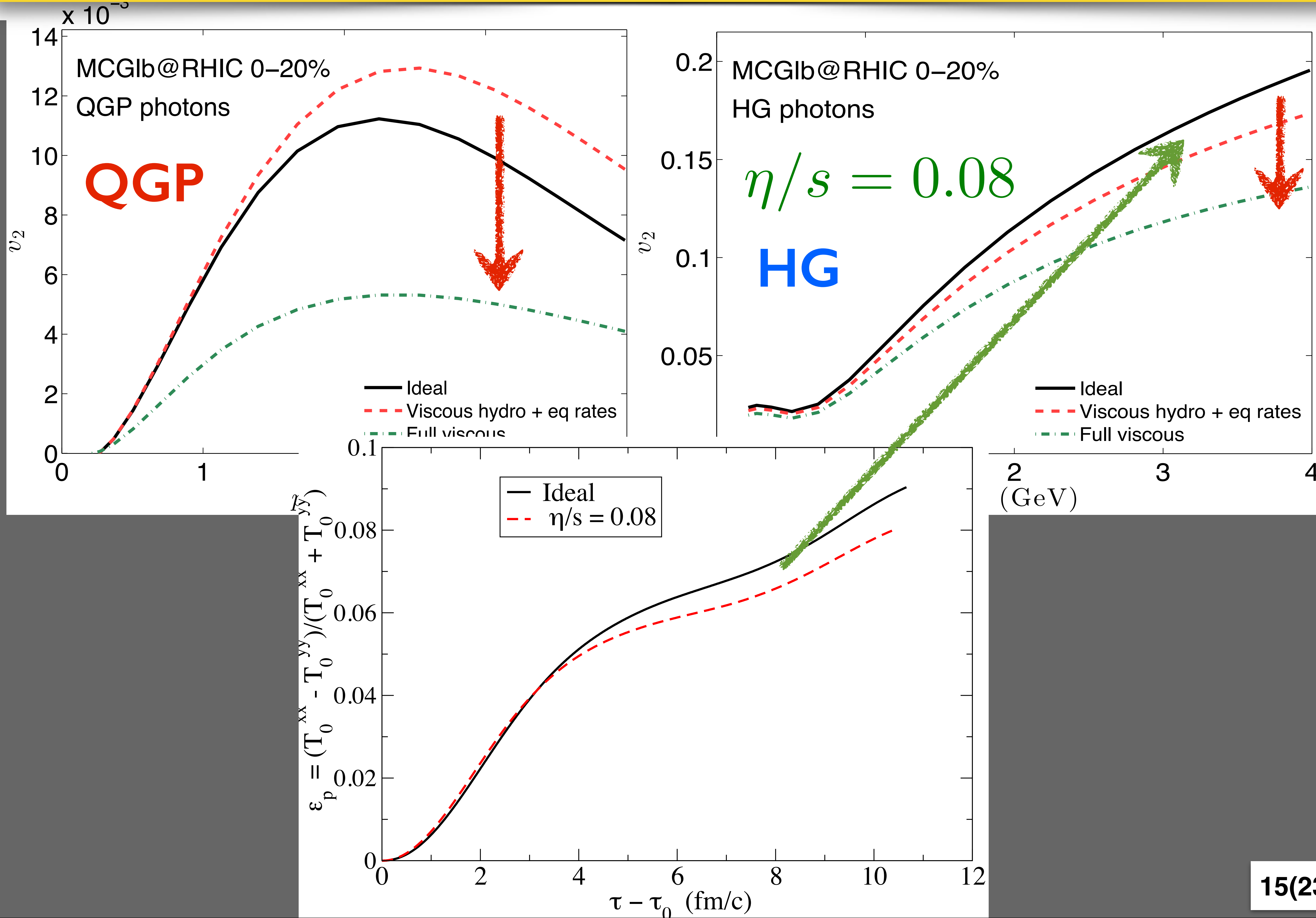

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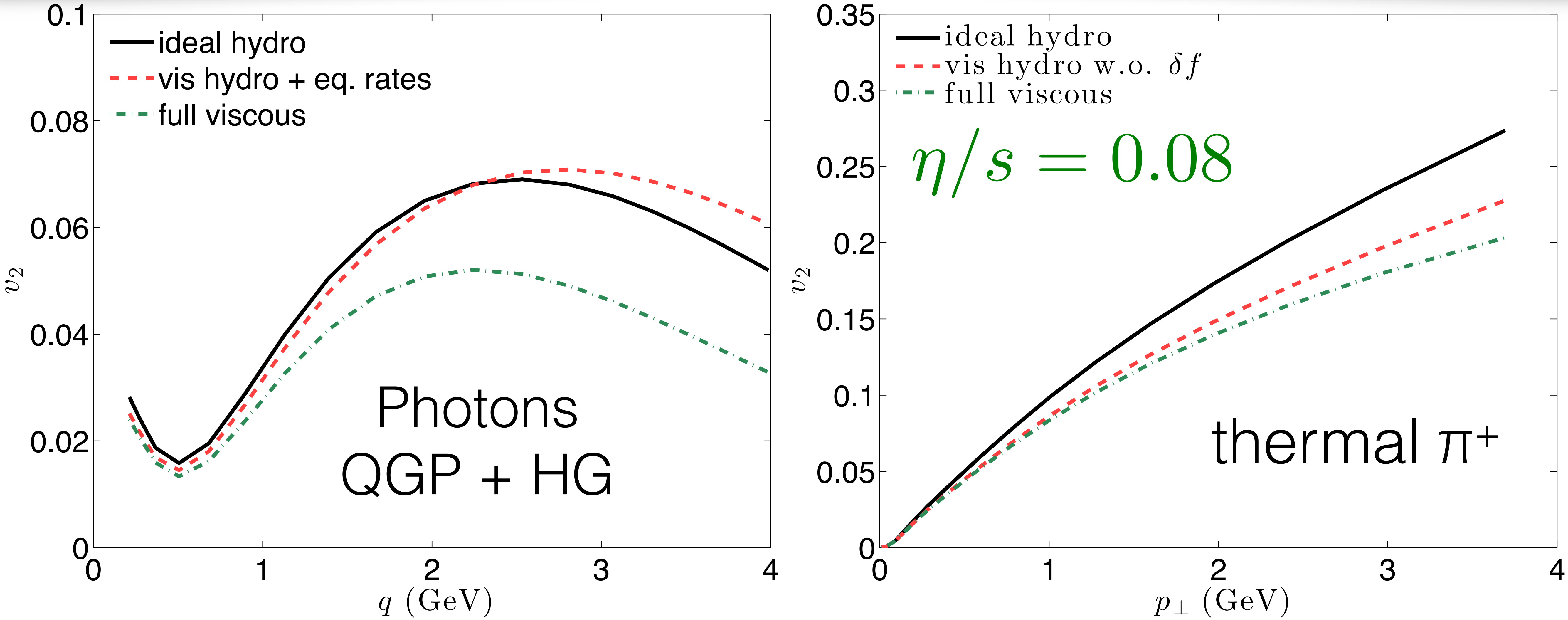
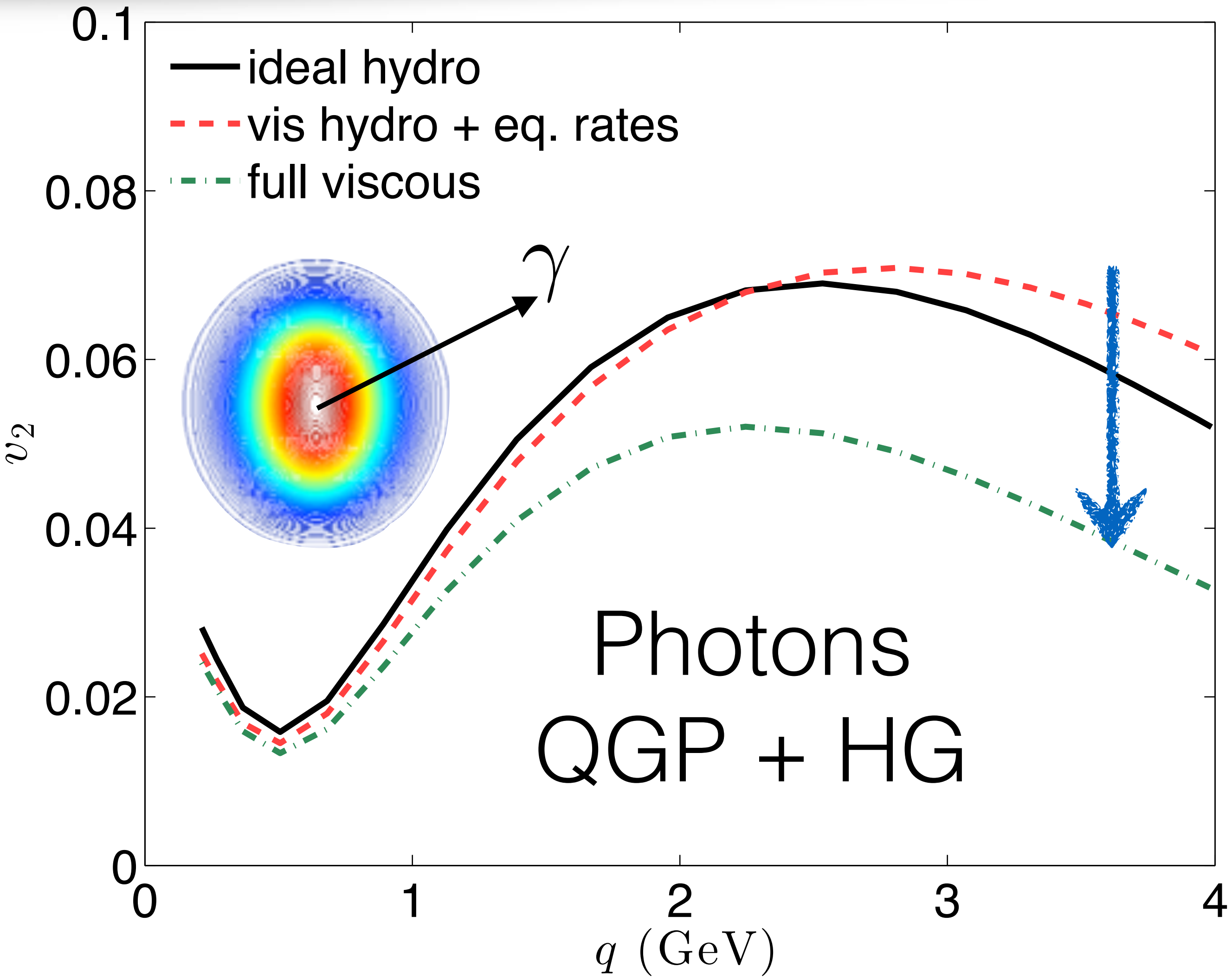
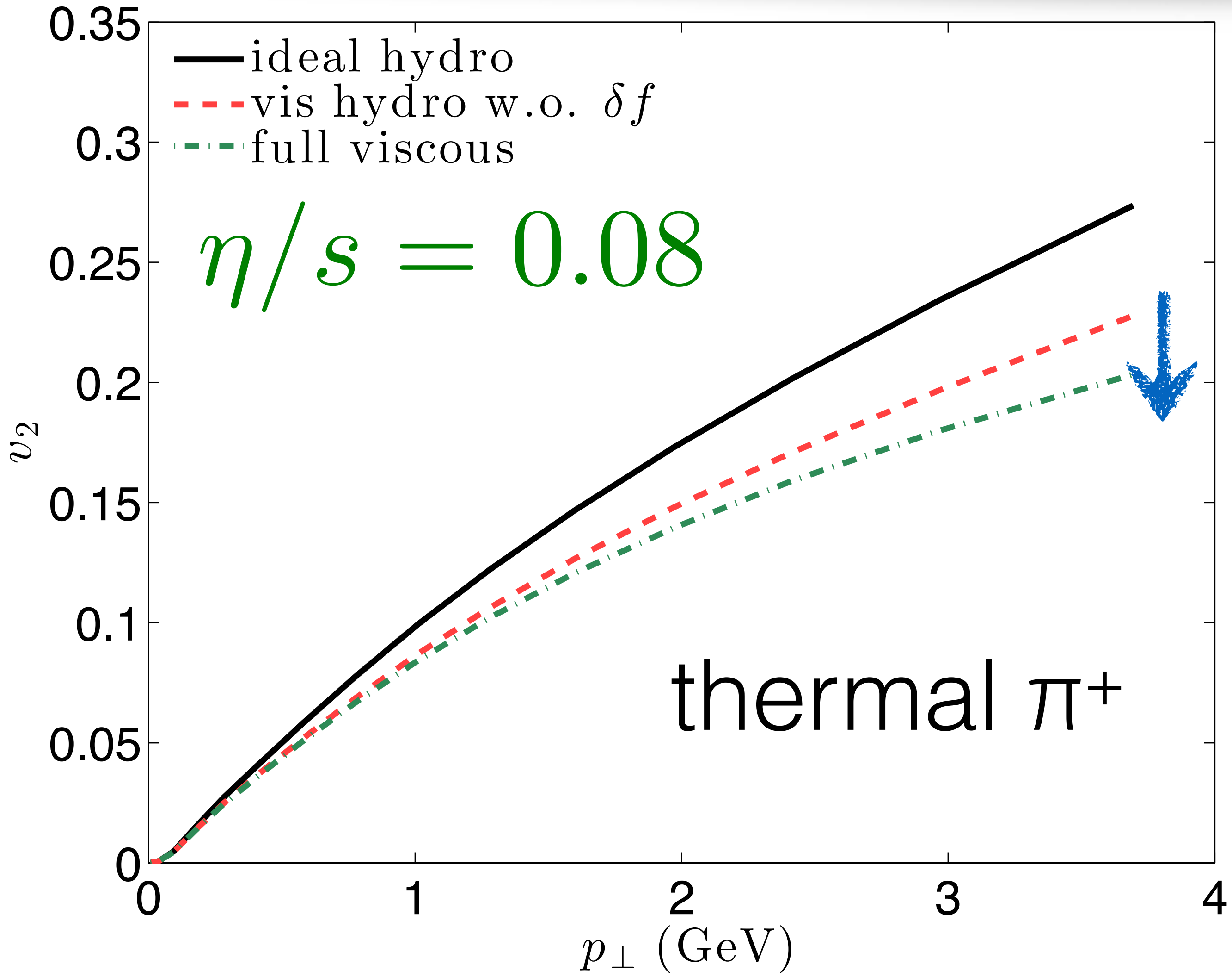


- Shear viscous suppression of photon v_2 is dominated by the viscous corrections to photon emission rates
- Photon elliptic flow is more sensitive to the evolution of shear stress tensor during the early time

Viscous effects on photon elliptic flow





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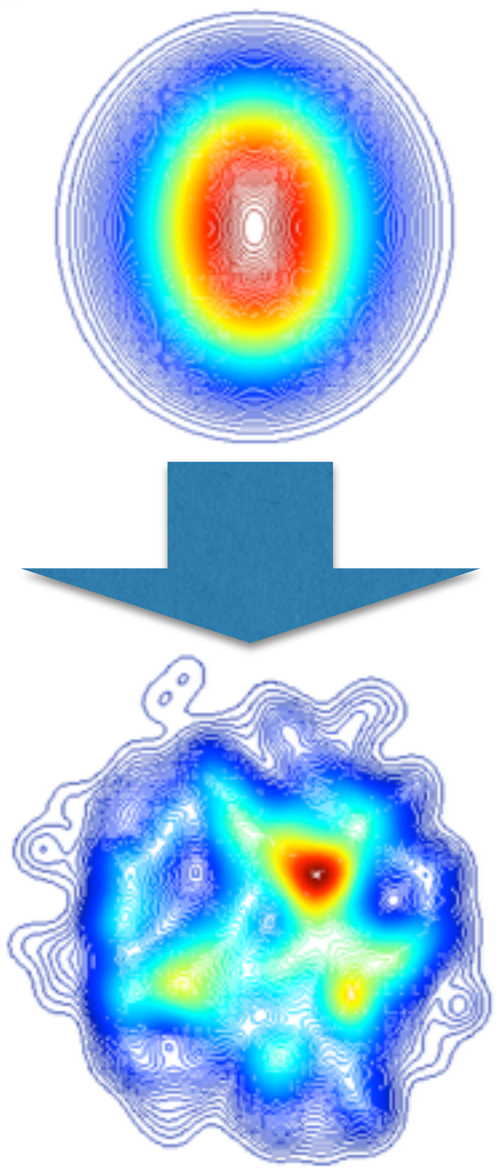
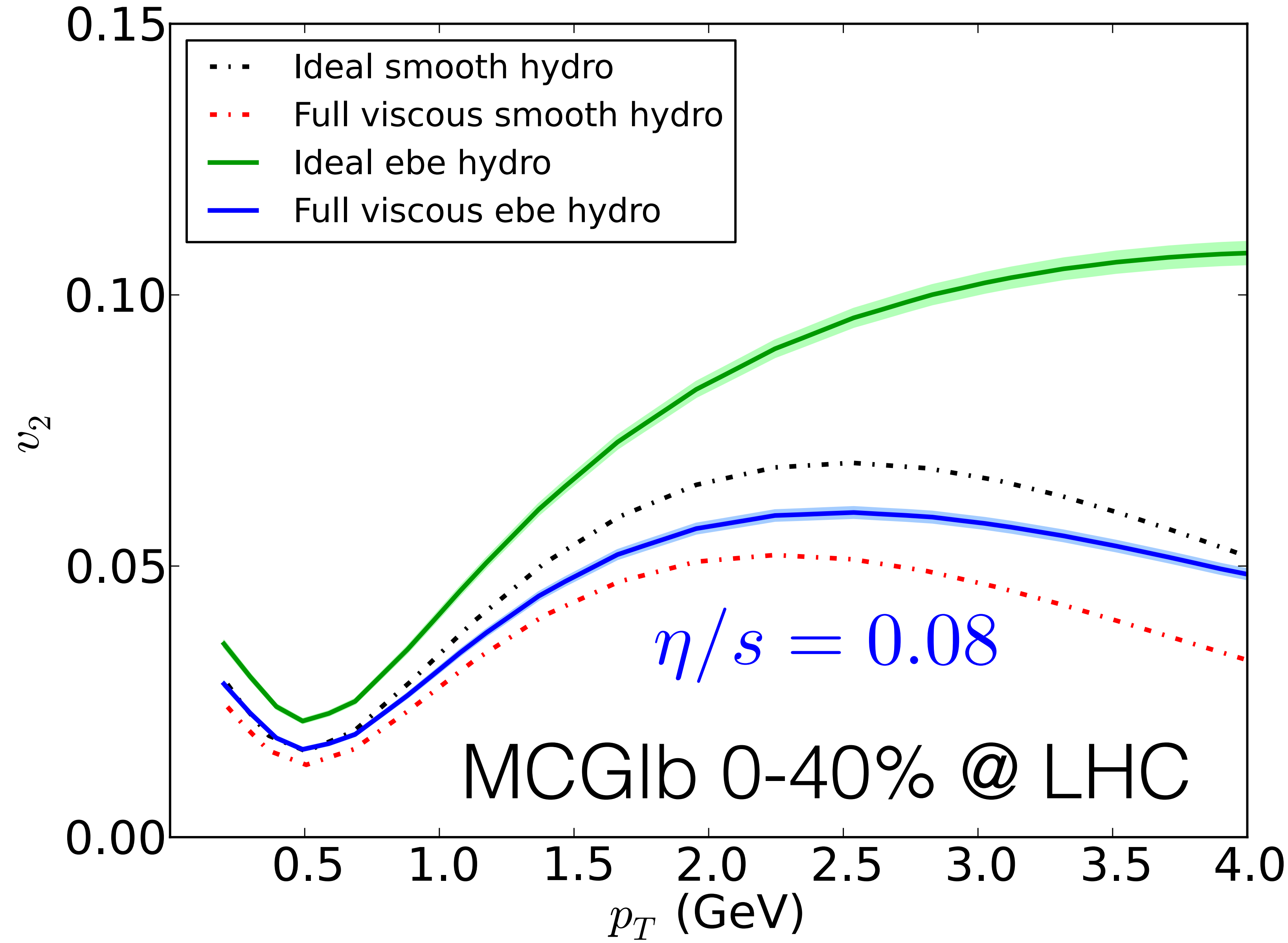
Fluctuation effects on photon elliptic flow





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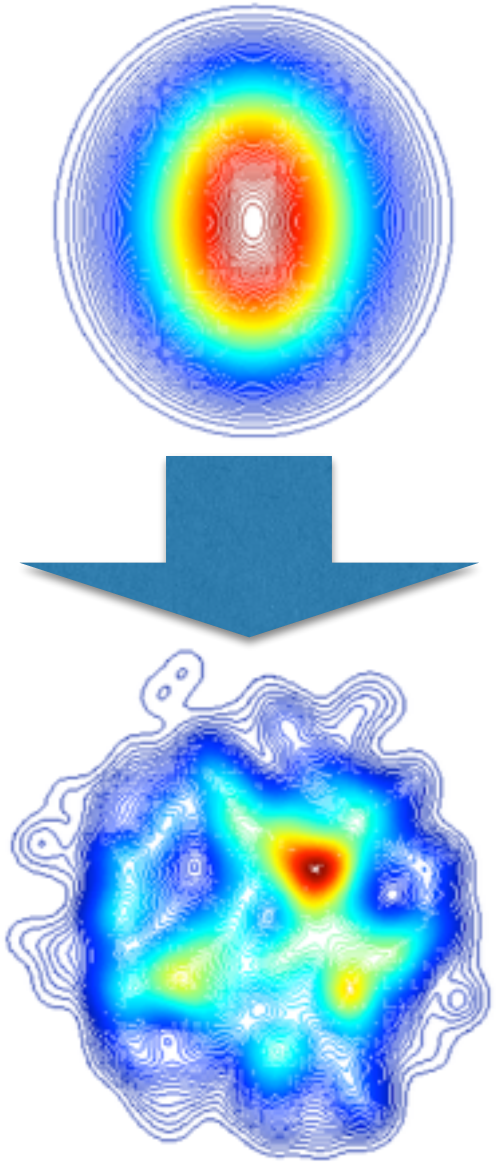
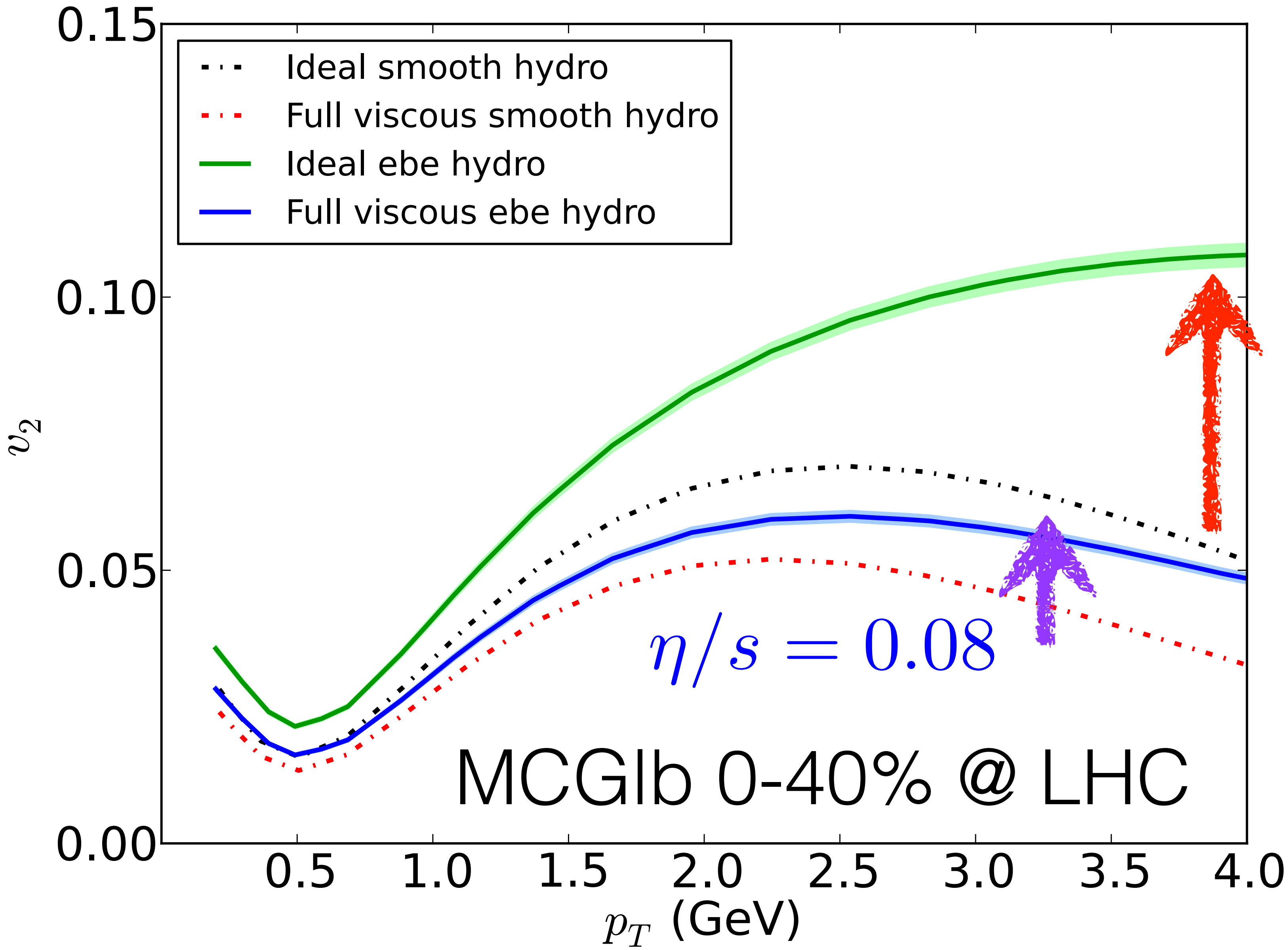
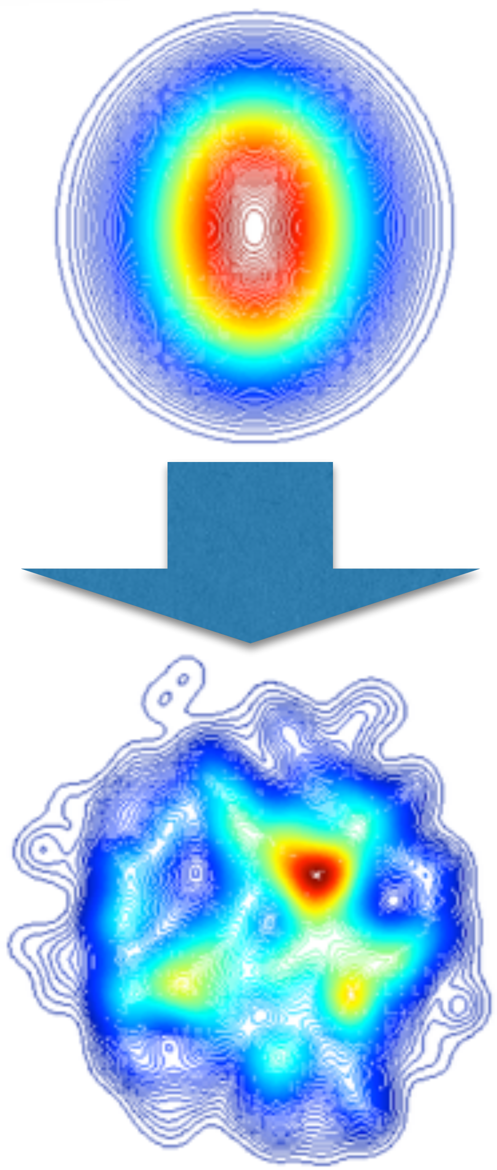
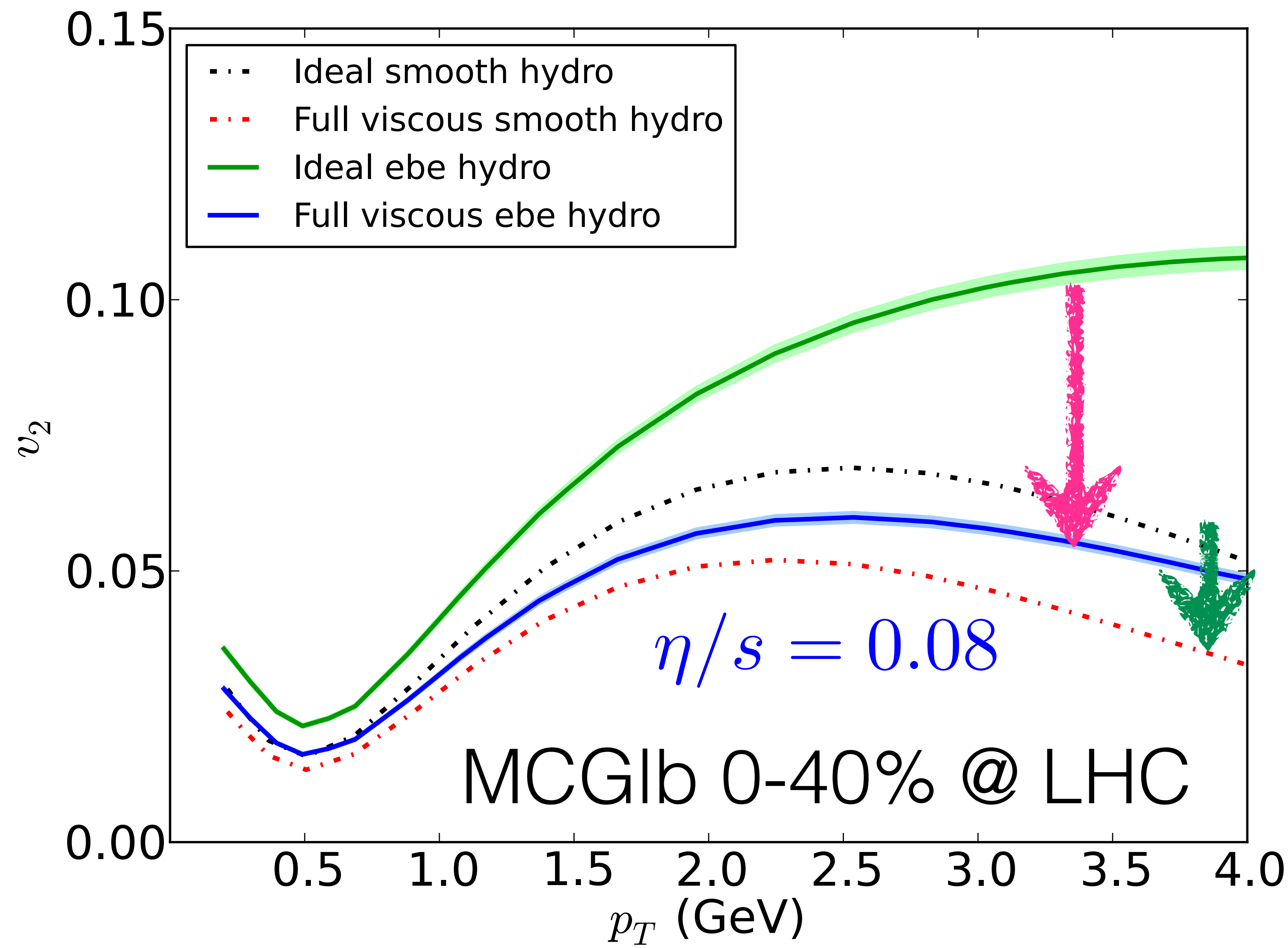




- Initial fluctuations increase photon's elliptic flow

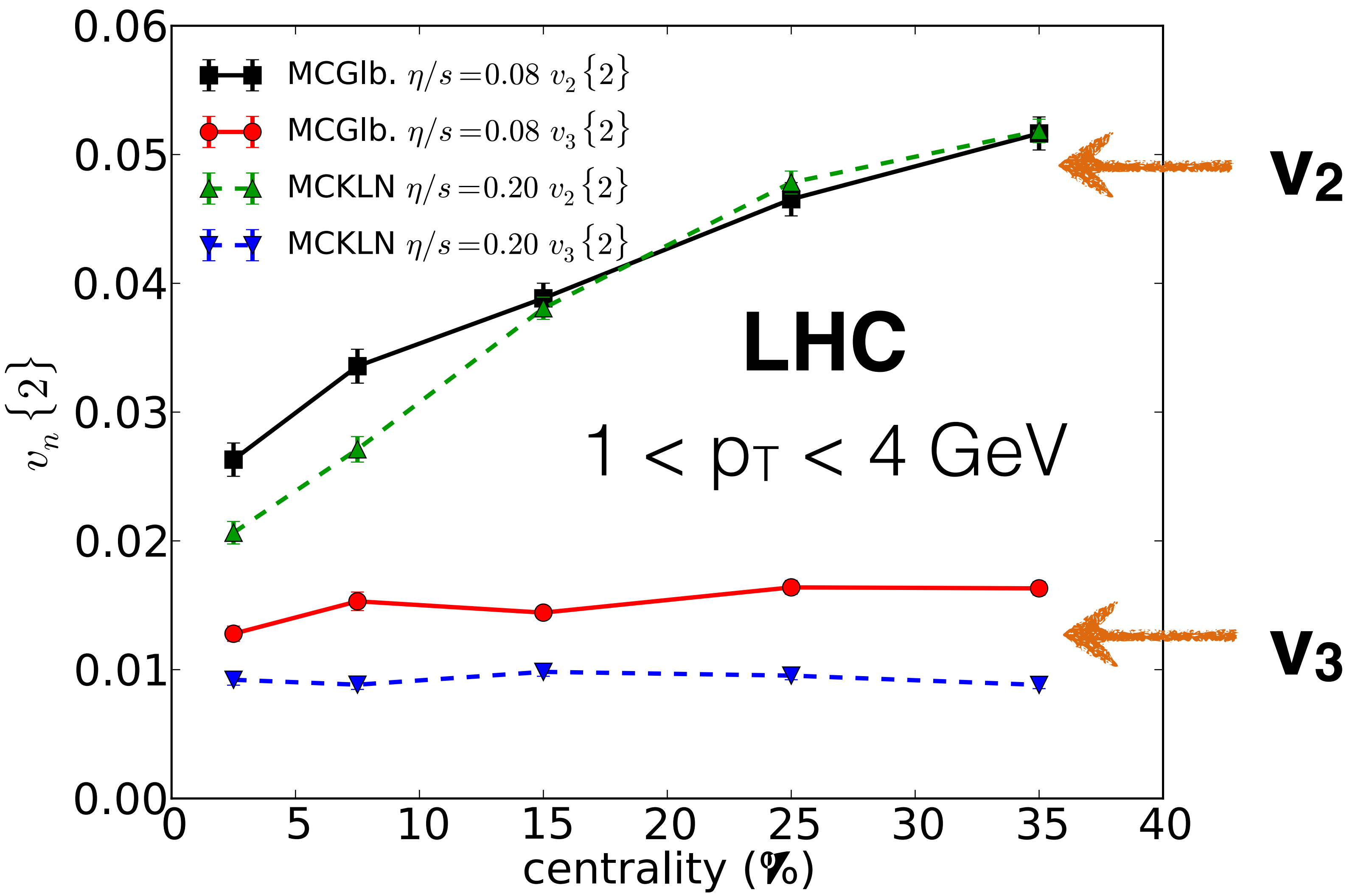
Fluctuation effects on photon elliptic flow





- Initial fluctuations increase photon's elliptic flow
- Viscous suppression is larger in the event-by-event runs

Event-by-Event Full Viscous Photon v_n

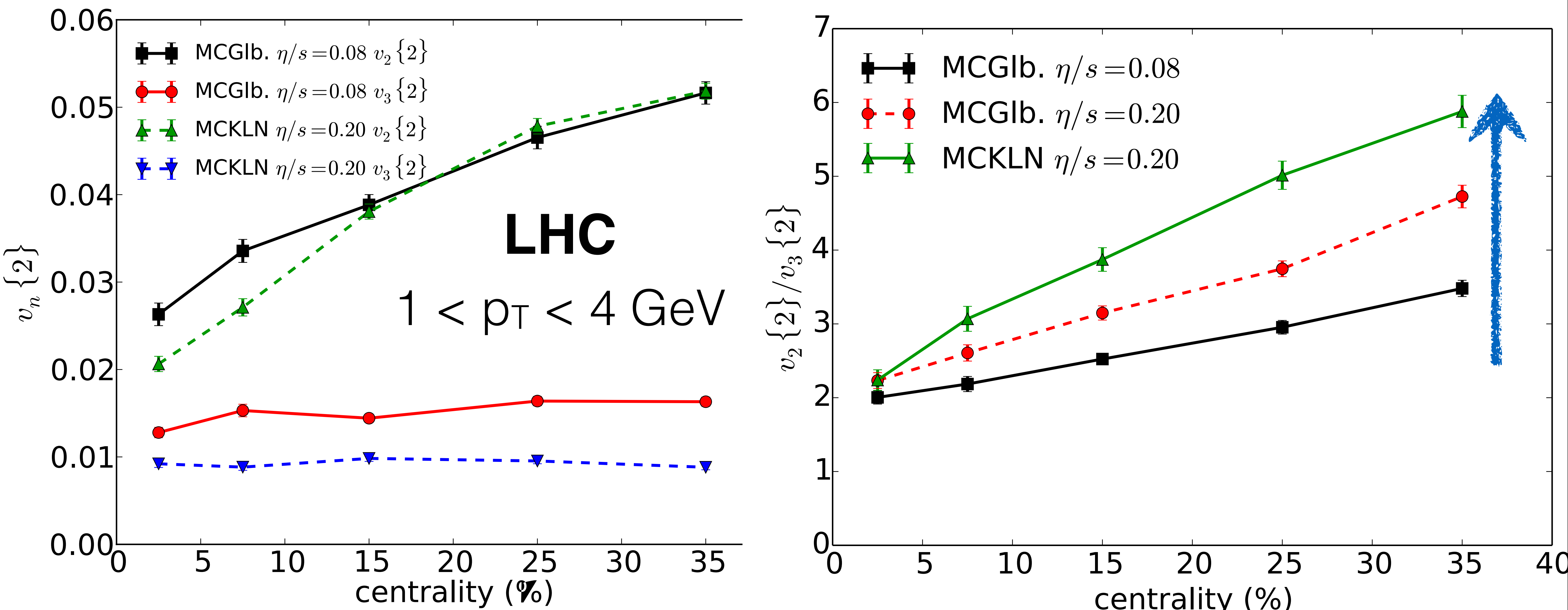


MCGlb. $\eta/s = 0.08$

MCKLN $\eta/s = 0.20$

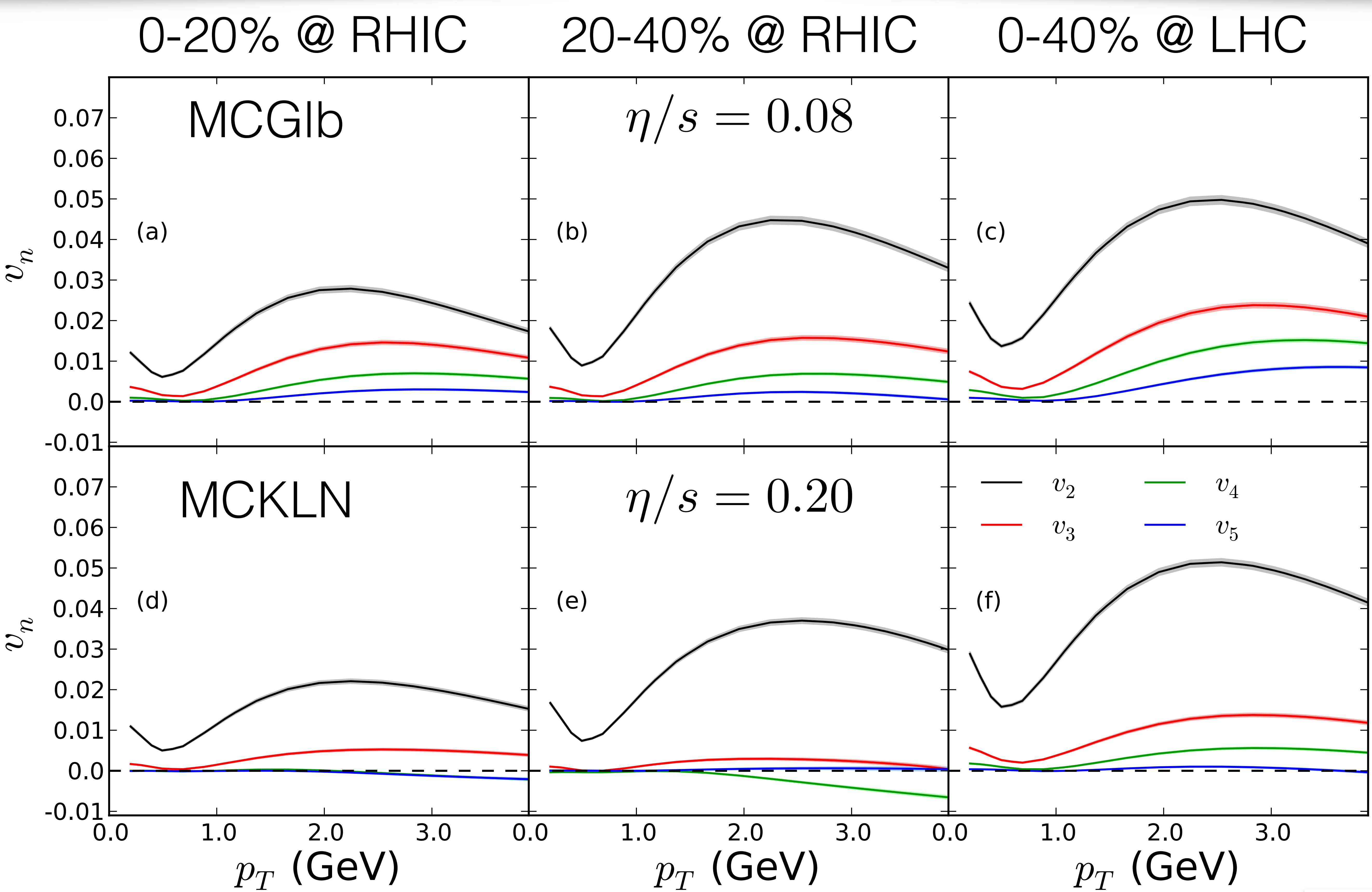
- The anisotropic flows of photons show similar centrality behavior as hadrons v_n

Event-by-Event Full Viscous Photon v_n



- The anisotropic flows of photons show similar centrality behavior as hadrons v_n
- The ratio of v_2/v_3 increase with the shear viscosity.
- The centrality dependence of this ratio is stronger for MCKLN model

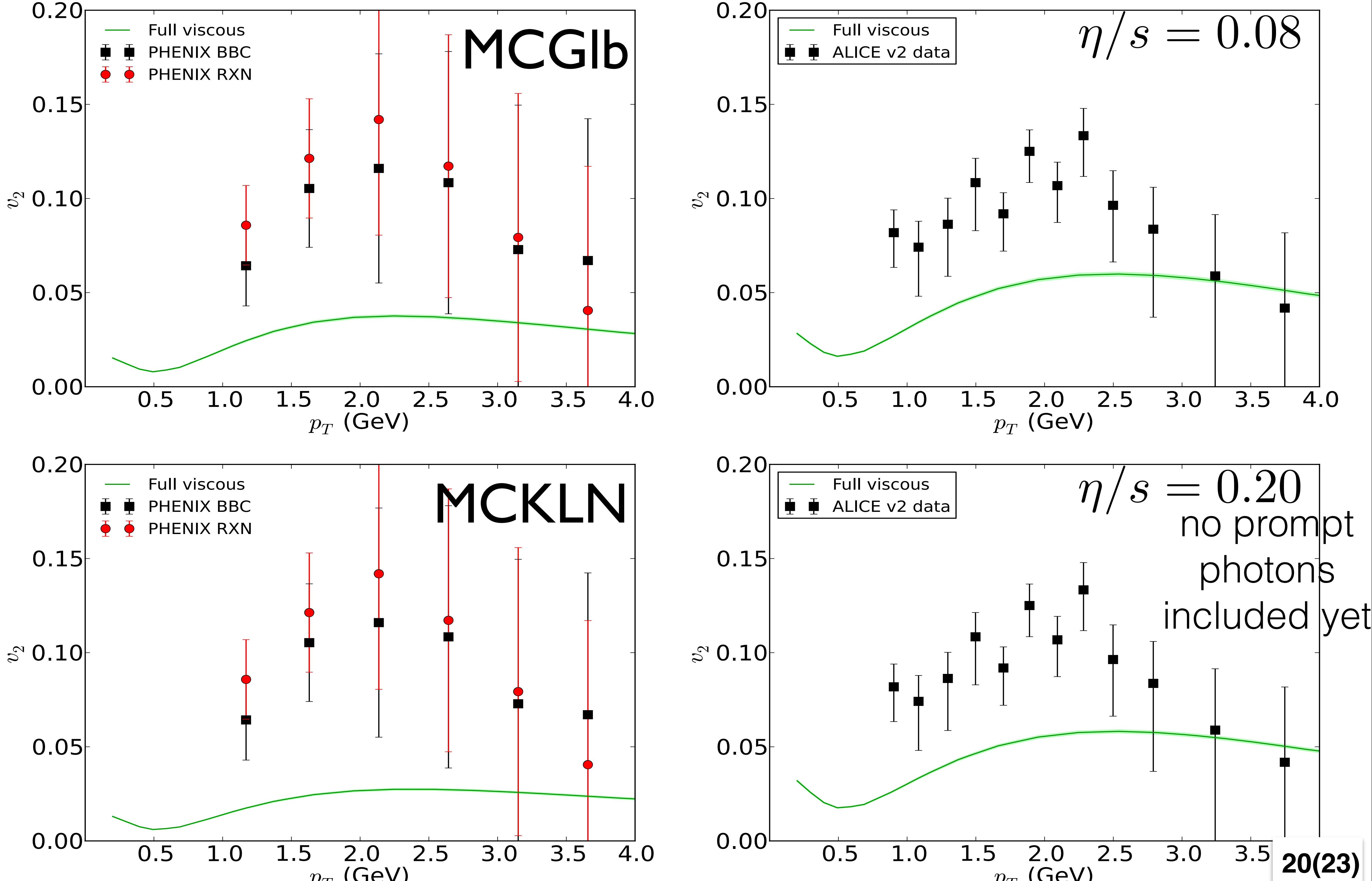
Event-by-Event Full Viscous Photon v_n



1000 events each centrality

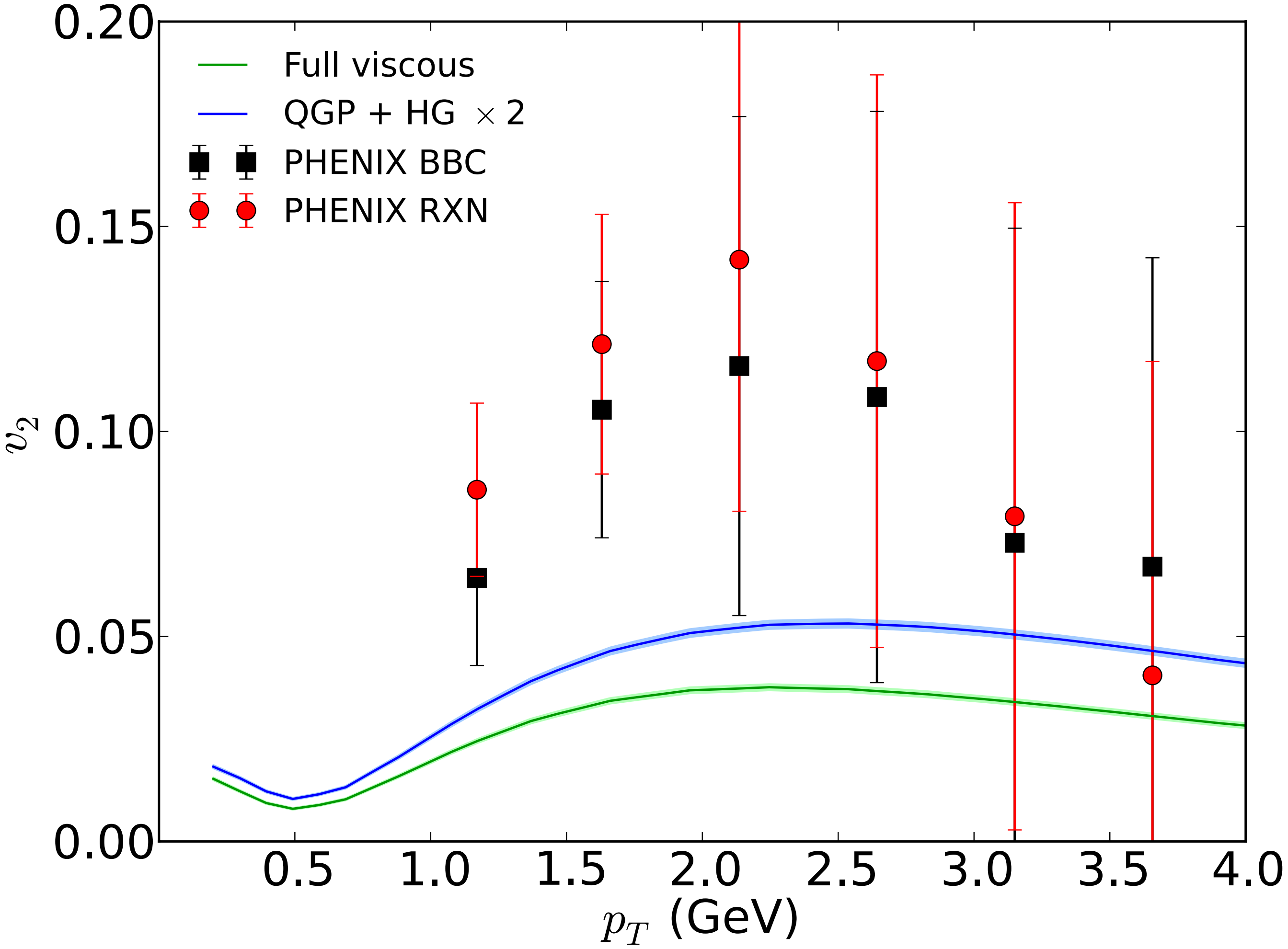
Comparisons with exp. data

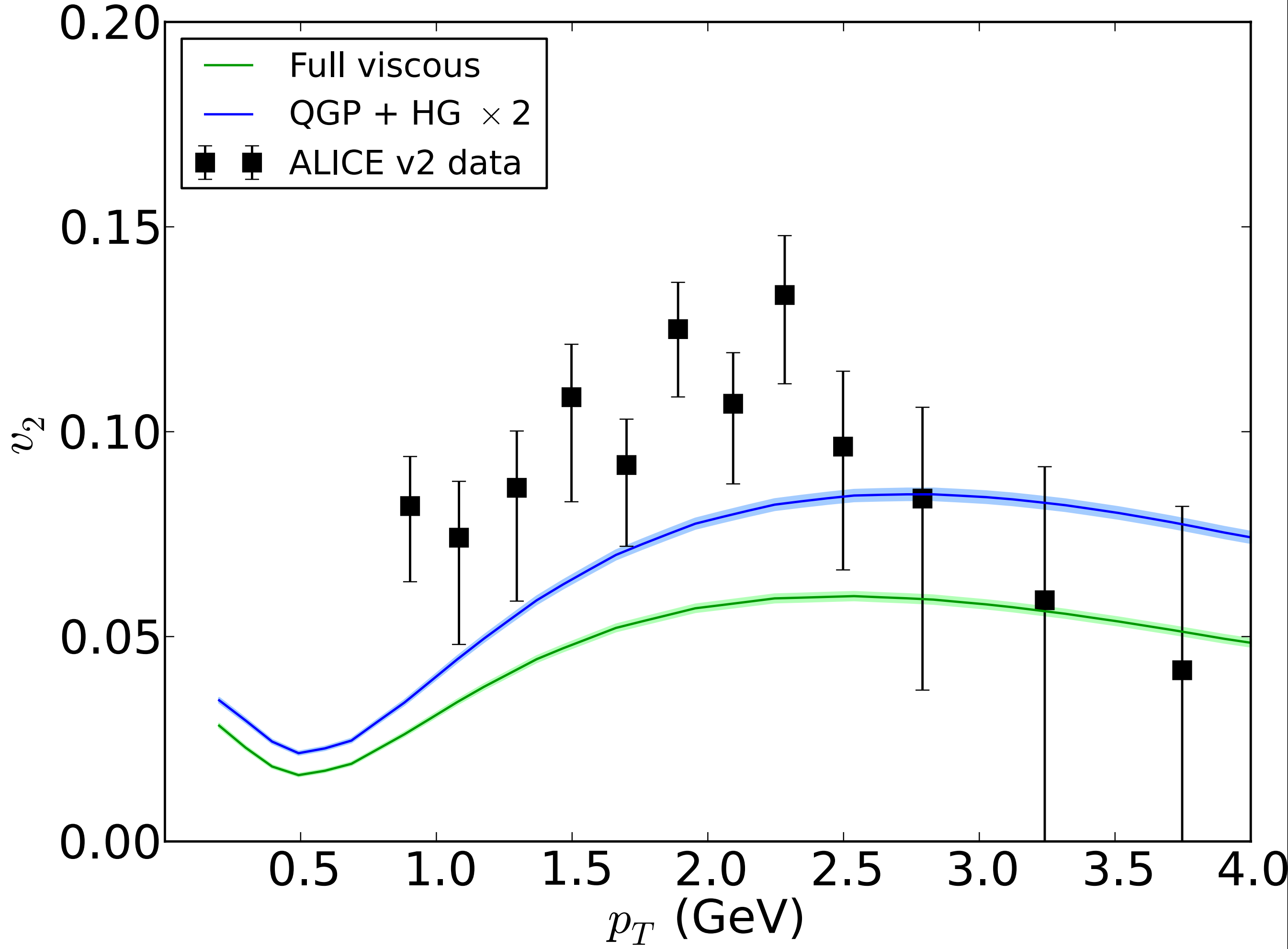
RHIC 0-20% | **LHC 0-40%**



Missing rates in hadronic phase

Photon production rates from **baryonic channels** are missing in the hadronic phase. We can estimate this by increase photon emission rates in hadronic phase by a **factor of 2**,





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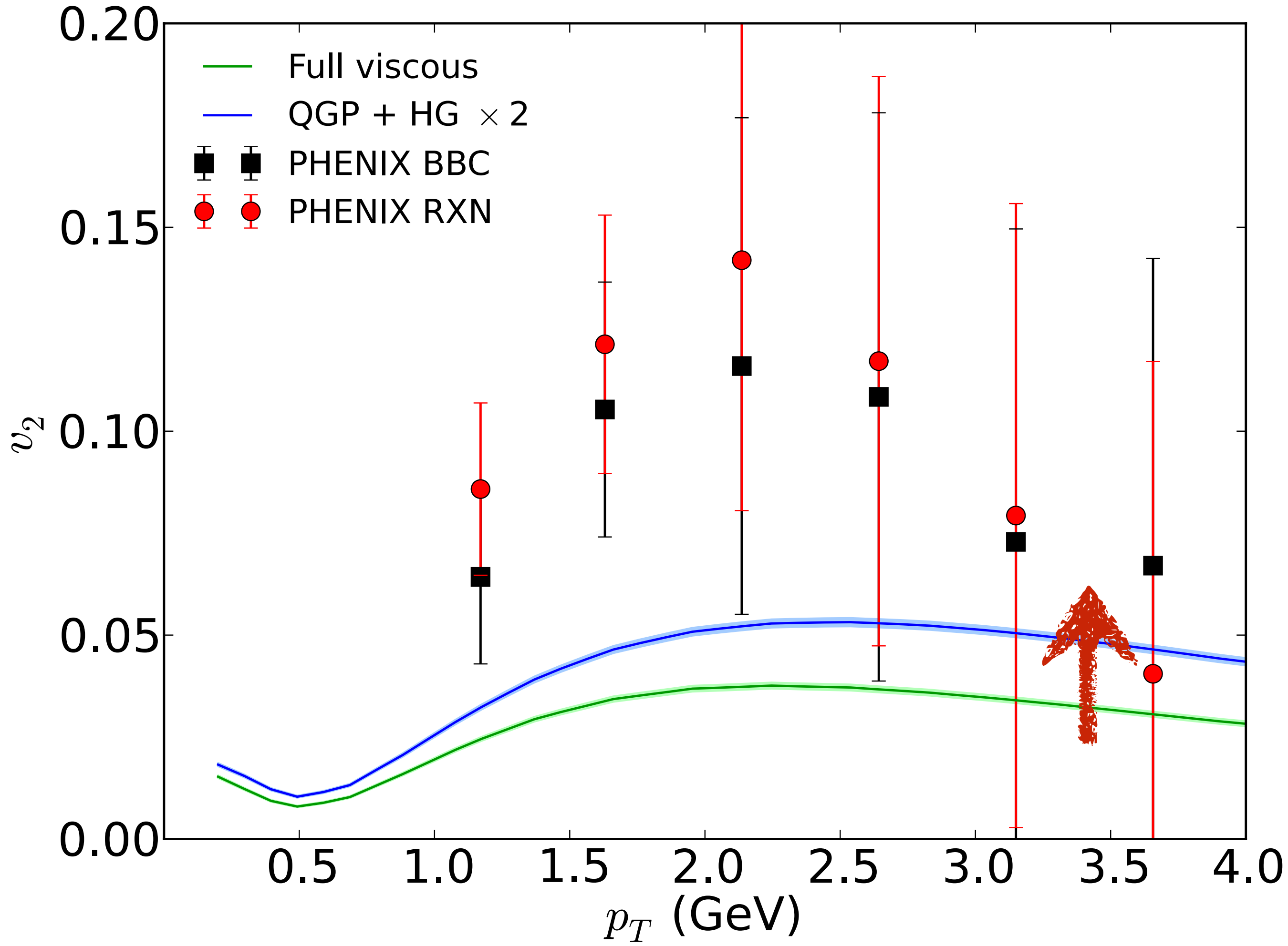
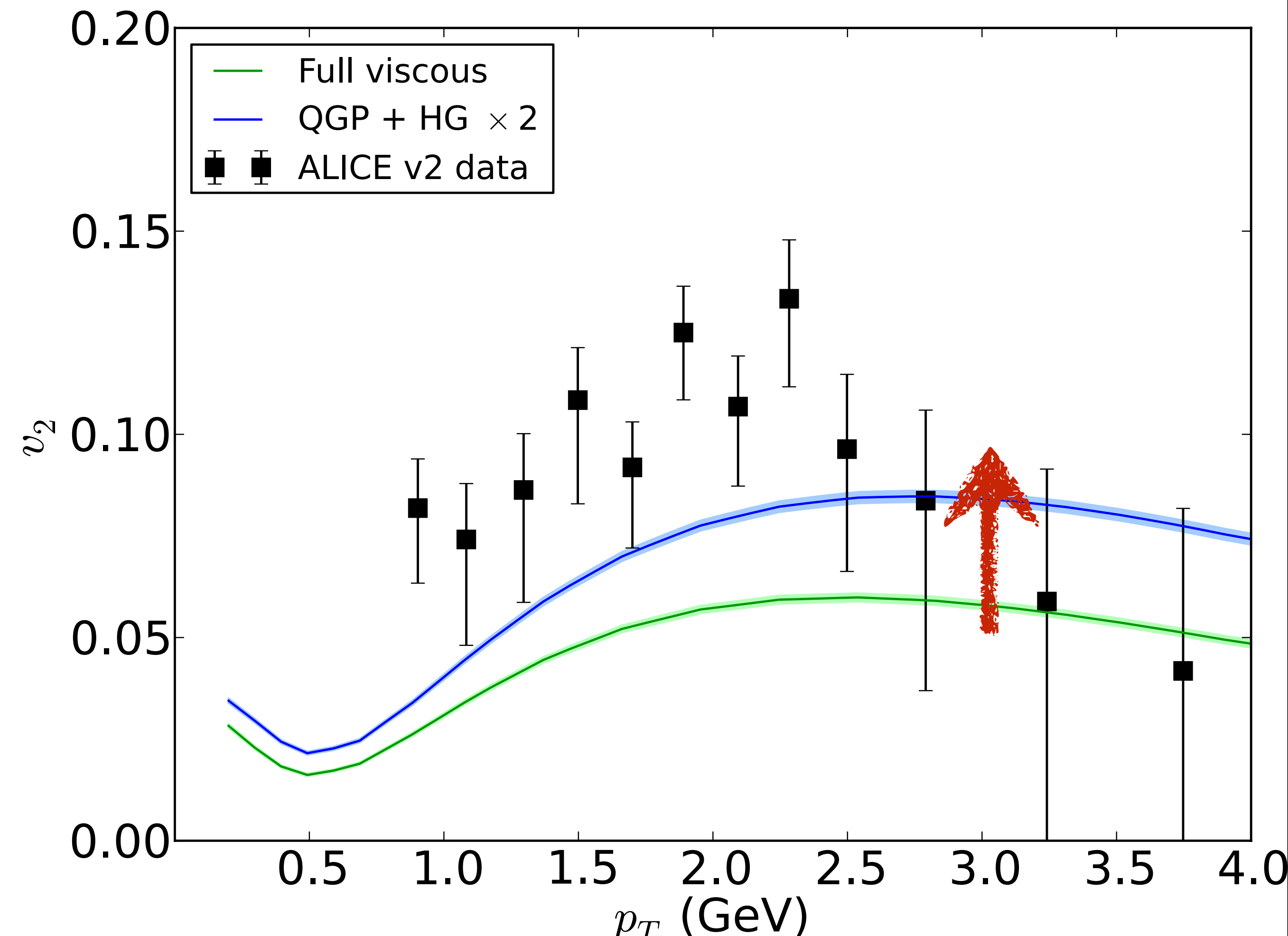




- it increases total photon v_2 by ~45% at both RHIC and LHC energies

Conclusion

- We study photon spectra and their anisotropic flows $\mathbf{v_n}$ from *event-by-event* viscous hydrodynamic medium
- Thermal photon spectra are strongly blue shifted by hydrodynamic radial flow
- Shear viscosity suppresses photon v_n. Dominant suppression comes not from flow, but from the viscous correction to the production rates.
- **Elliptic** and **triangular** flow of photons are more sensitive than hadrons to the shear stress tensor at early time and the initial state fluctuations.
- Our phenomenology study points out larger late stage emissions (e.g. baryonic channels) are needed to improve the agreement between experiment and theory.

arXiv: 1308.2111, 1308.2440 **https://github.com/chunshen1987/iEBE.git**

To Do List

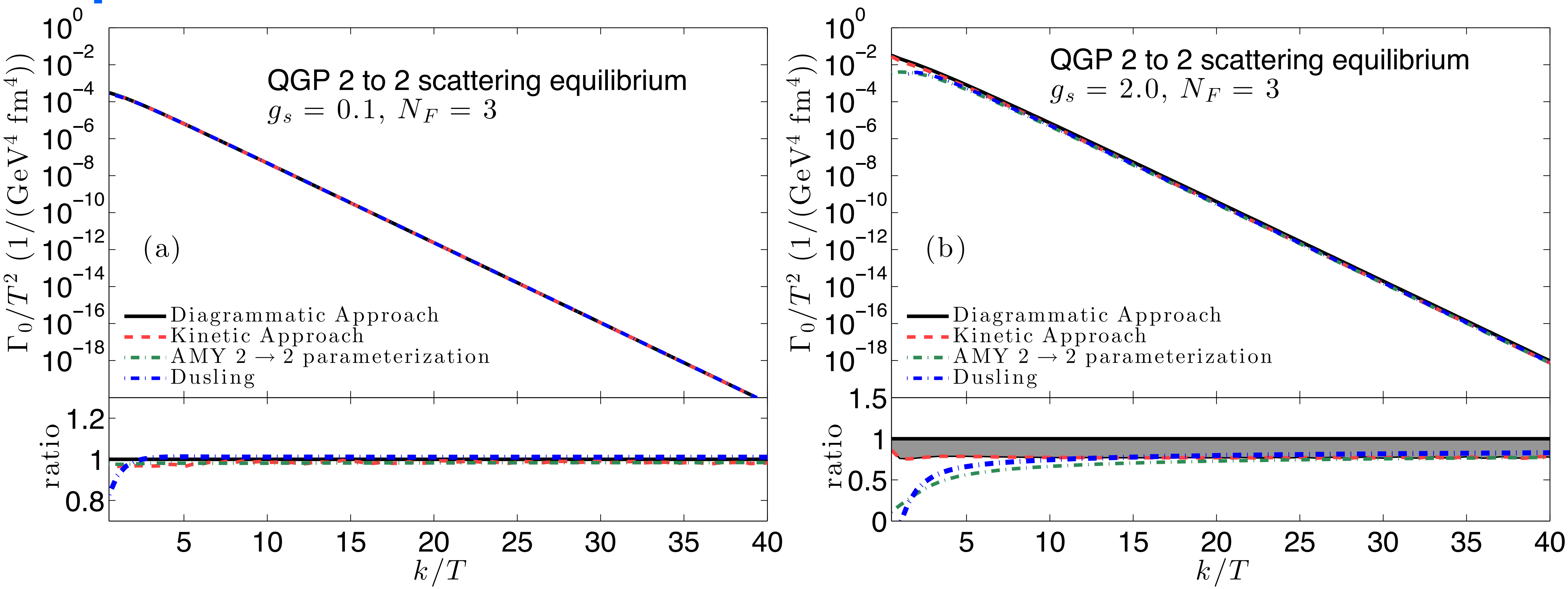
(only from personal point of view)

- Including missing rates from late hadronic phase, meson-baryonic channels as well as bremsstrahlung processes and possibly their viscous corrections
- Bulk viscous corrections to photon emission rates as well as hydrodynamic evolution
- Initial flows and viscous pressure tensor effect from pre-equilibrium evolution

Back up

Photon Rates (QGP 2 to 2 processes only)

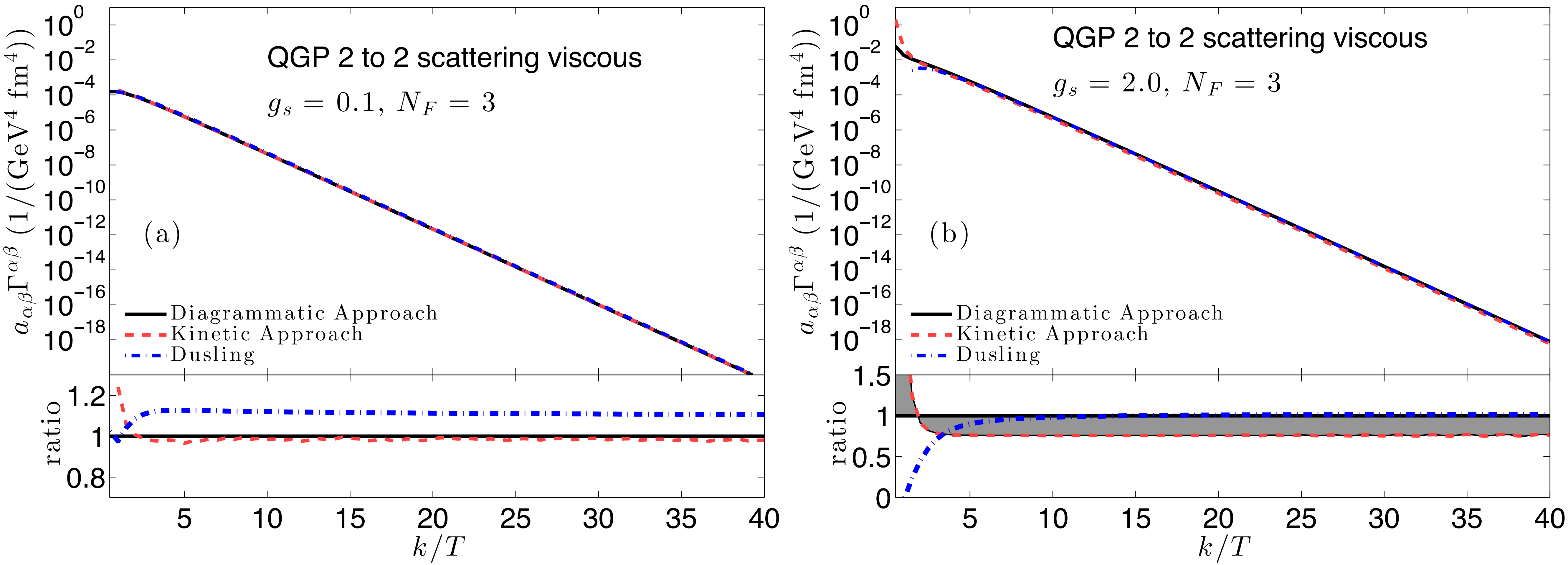
Equilibrium rates:



- For small g, results from diagrammatic approach agree well with kinetic approach and AMY
- For g = 2.0, diagrammatic approach gives 25% larger results compared to kinetic approach; difference are due to cut-off dependence.

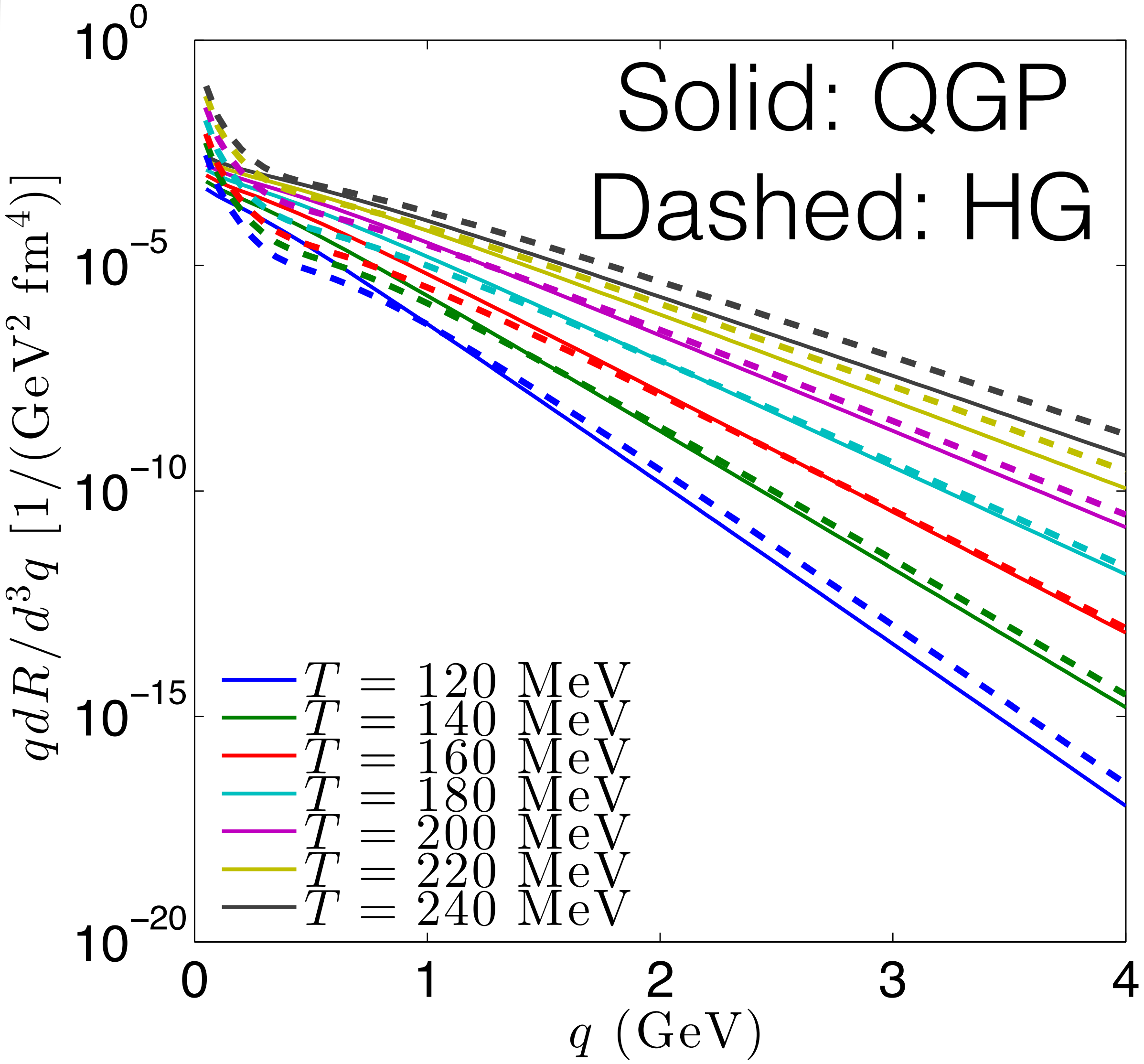
Photon Rates (QGP 2 to 2 processes only)

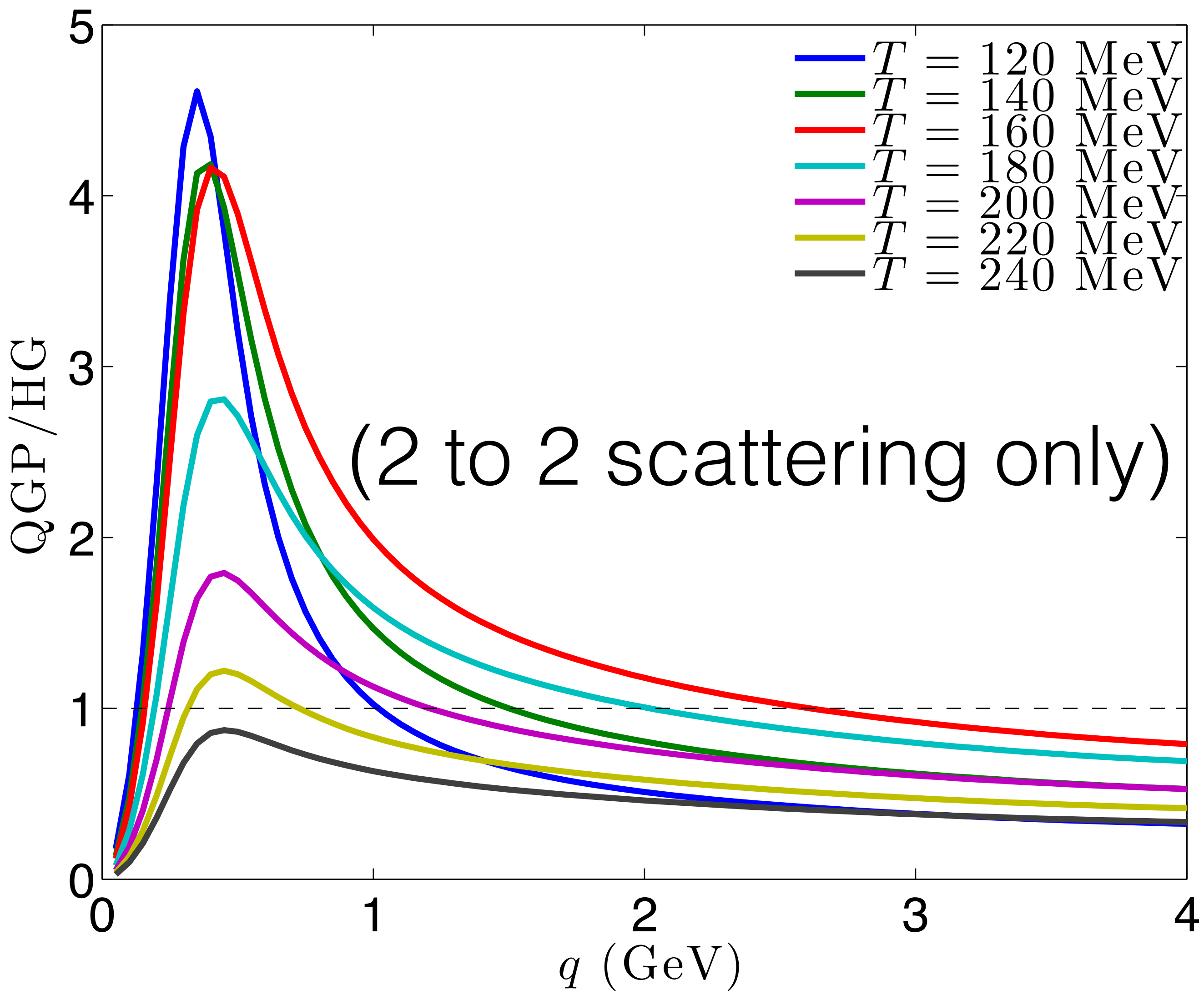
Viscous corrections:



- For small g, diagrammatic approach agrees with kinetic approach
- For g = 2, the deviations at small k/T may originate from different higher order $O(g^2T)$ contributions

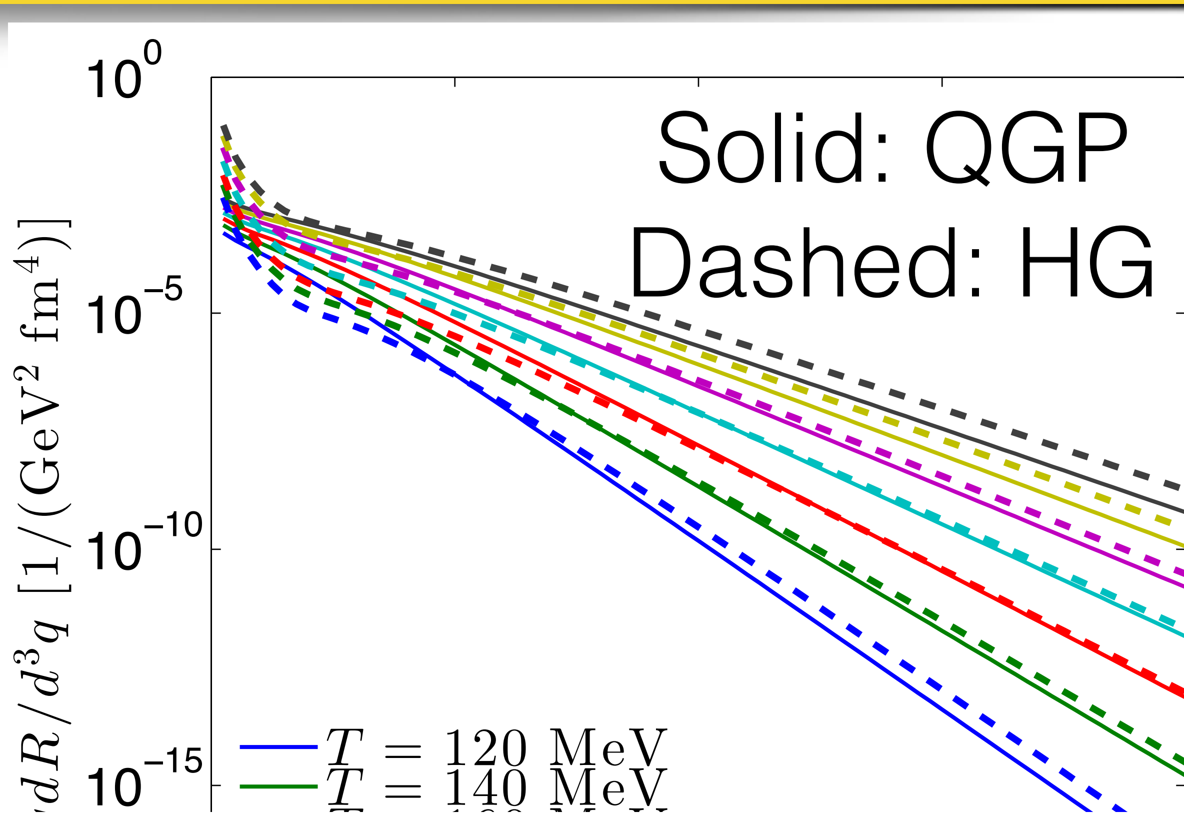
Photon Emission Rates QGP vs HG

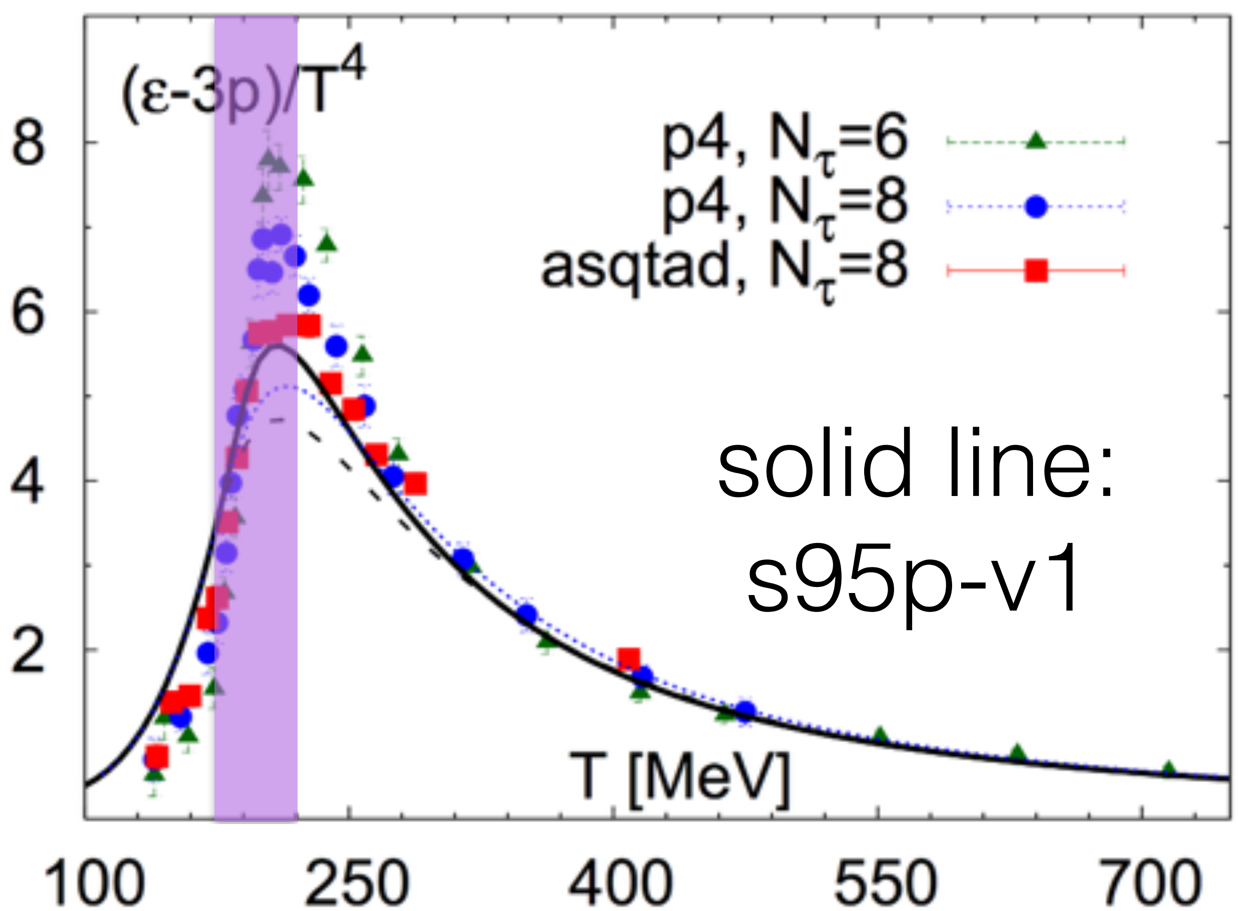


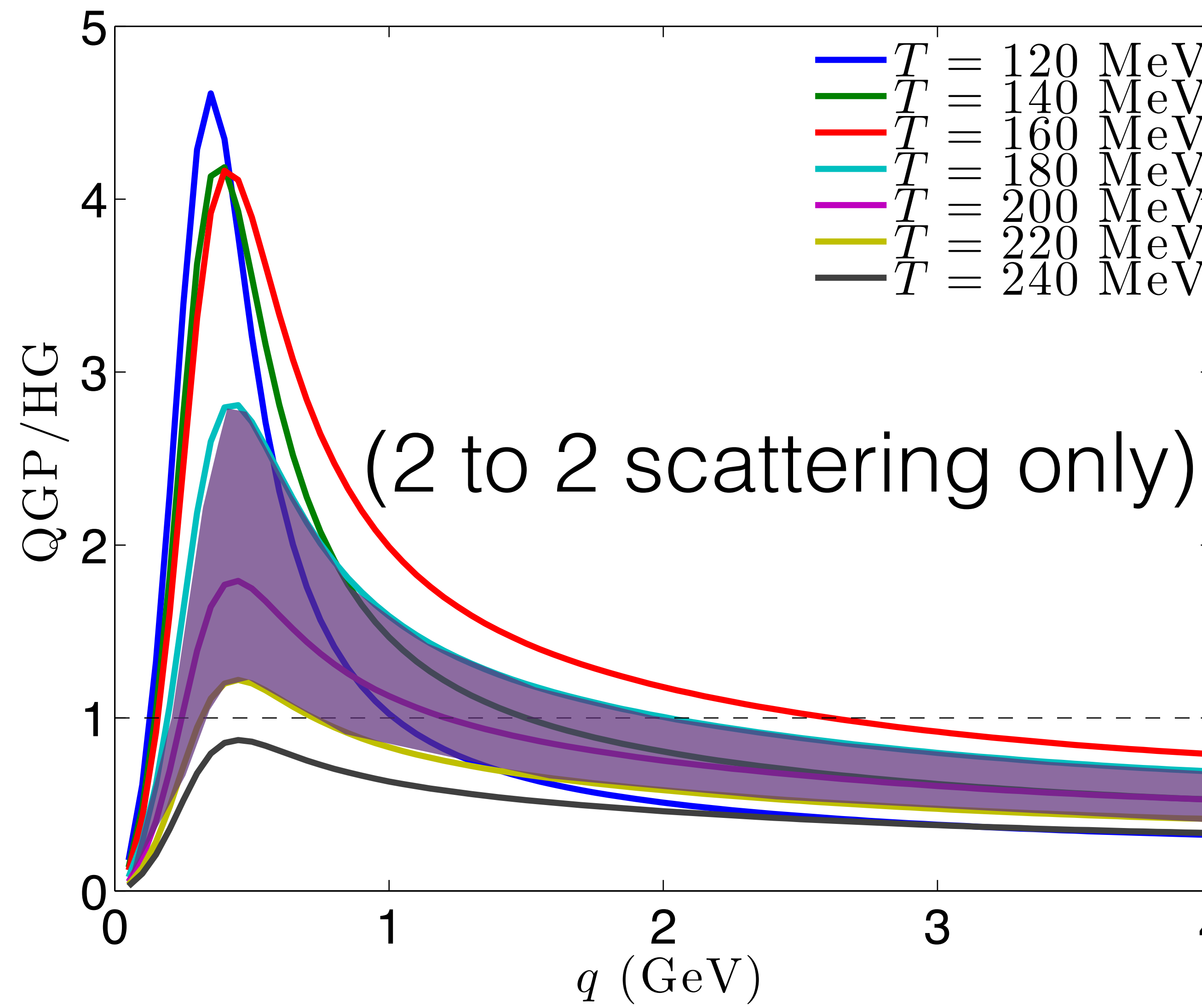


- QGP rates have very different p_T dependence compared to HG rates

Photon Emission Rates QGP vs HG



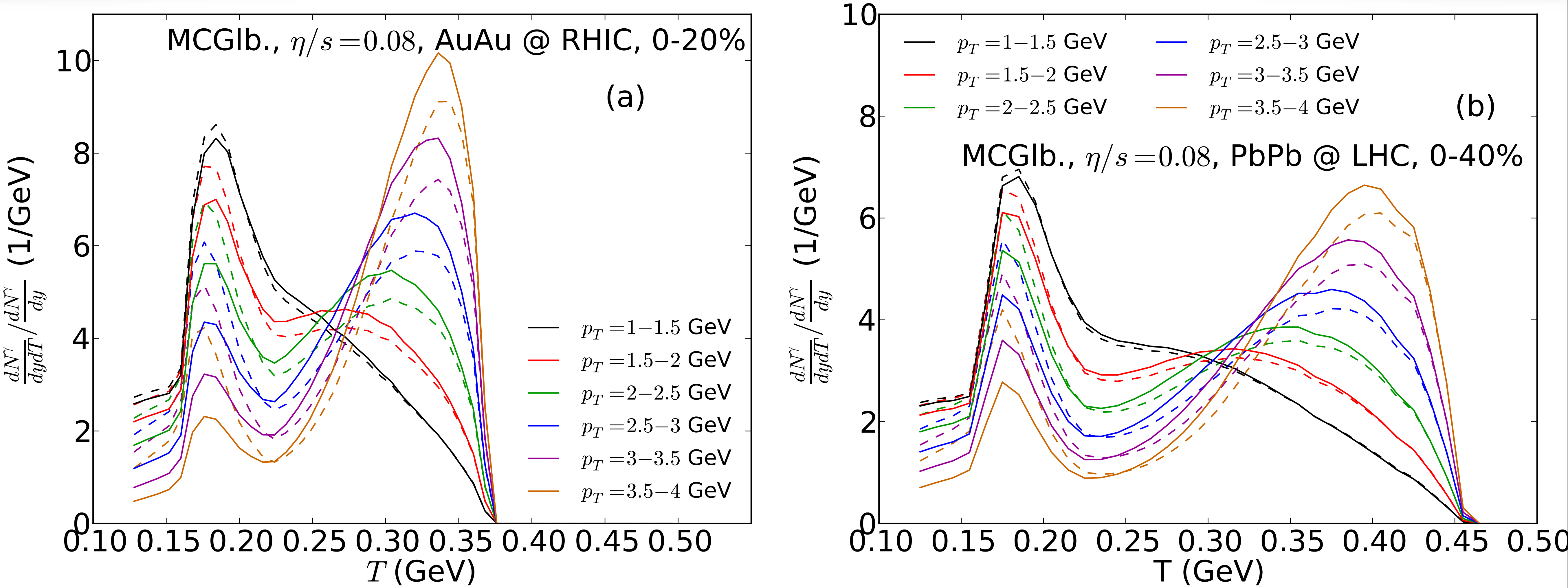




- QGP rates have very different p_T dependence compared to HG rates
- Estimated transition region for production rates, T ~ **184 - 220** MeV

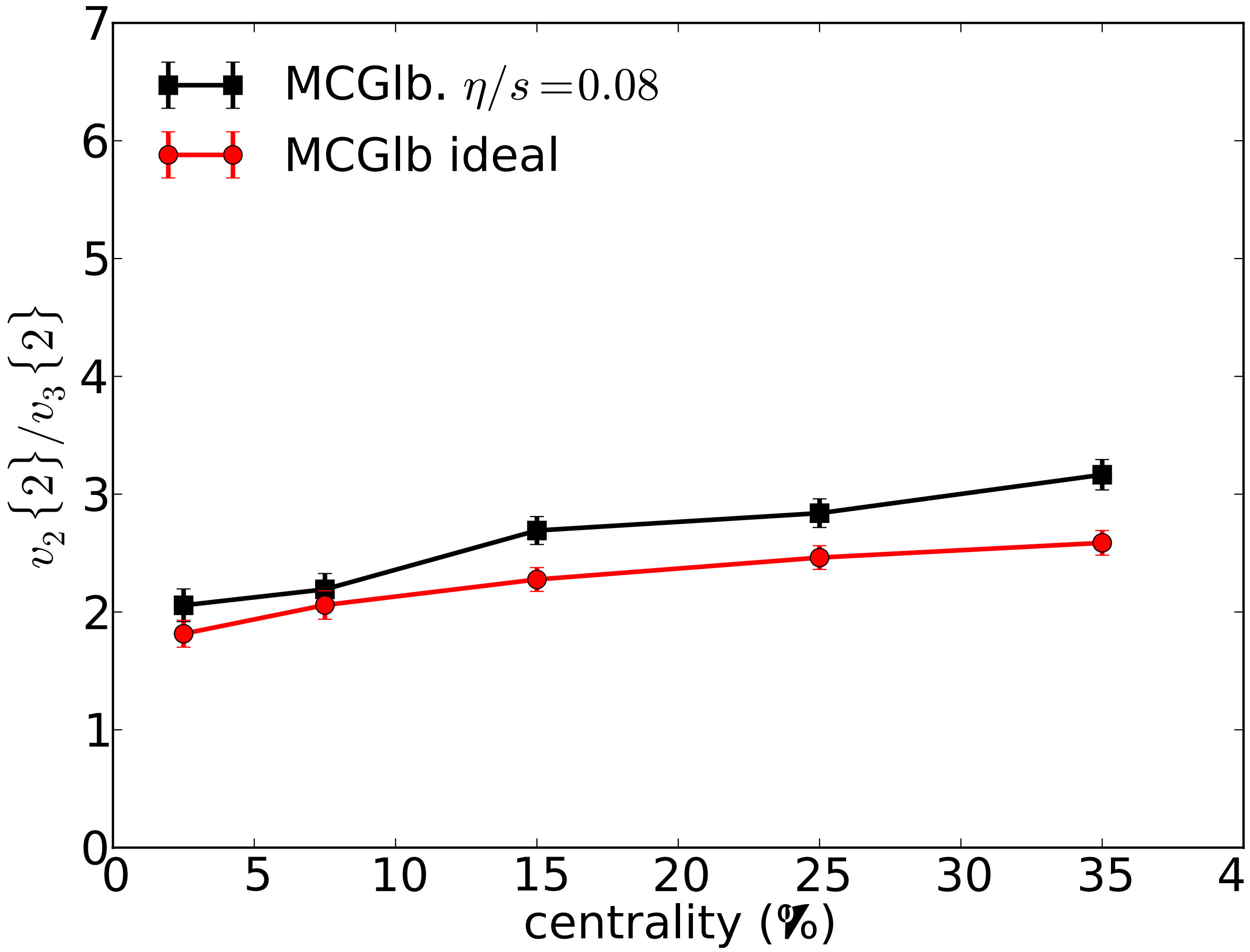
Huovinen & Petreczky, Nucl.Phys. A837 (2010) 26-53

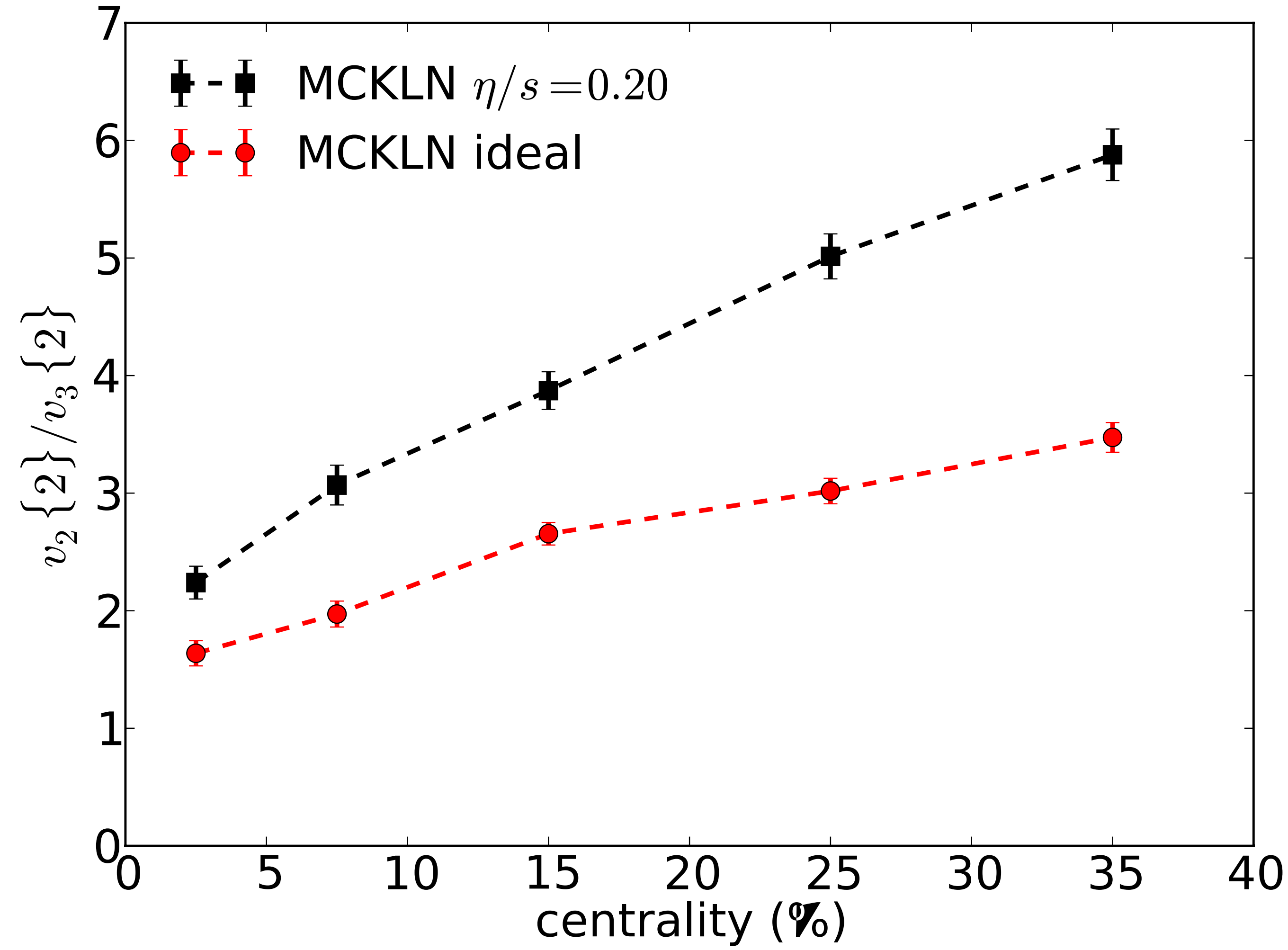
Emission vs. Temperature



- High p_T photons are mostly emitted from high temperature region
- Peak photon production around T = 165-200 MeV due to large hydrodynamic space-time volume

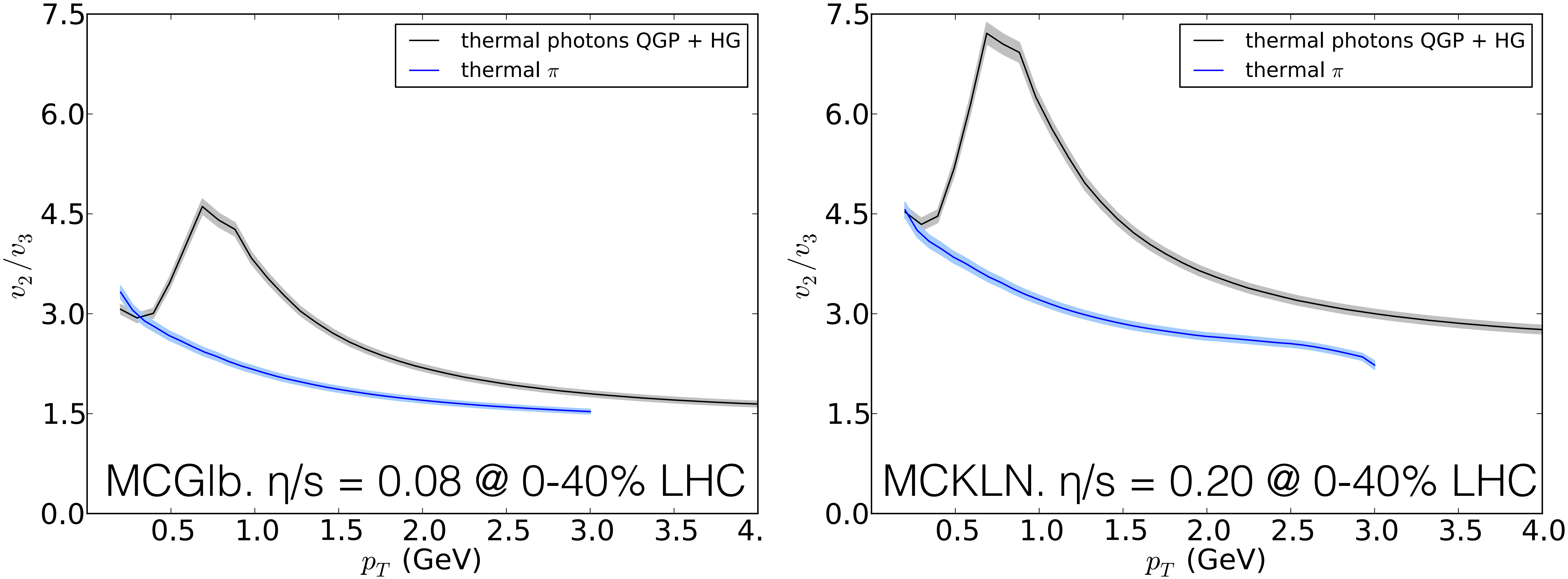
Event-by-Event Full Viscous Photon v_n





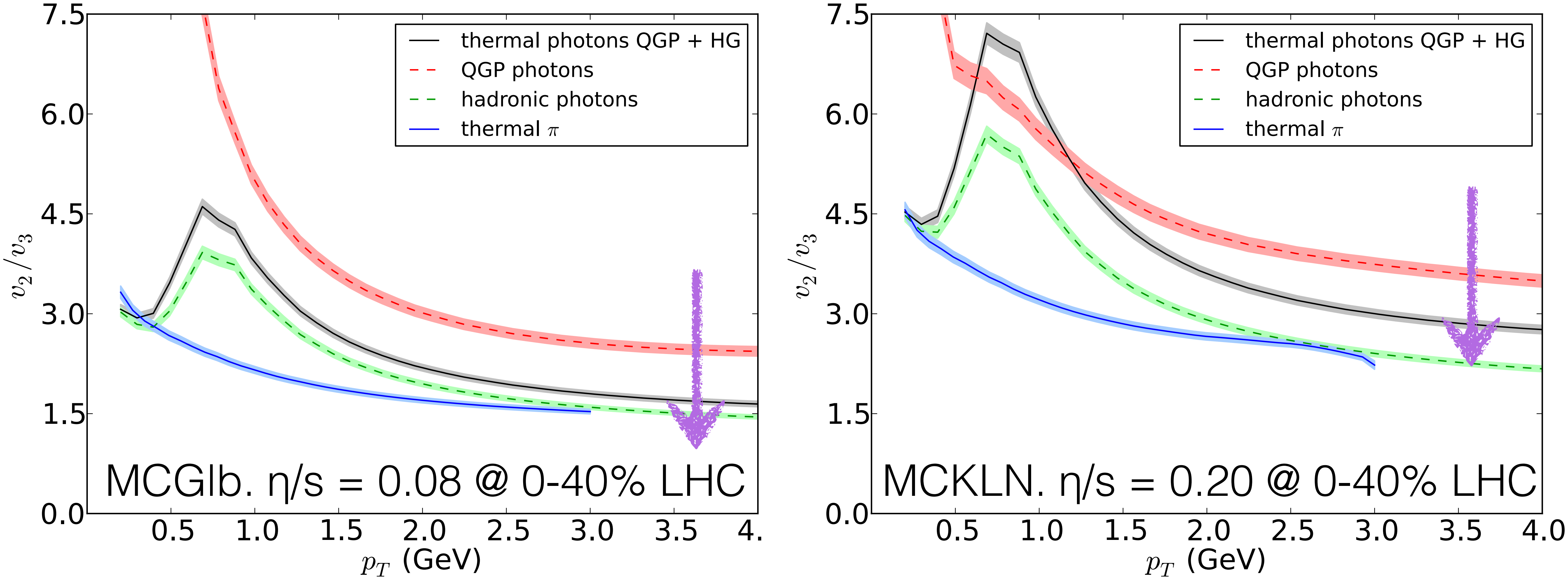
- Comparing with ideal hydro runs, the v_2/v_3 ratio increases with shear viscosity
- MCKLN model shows stronger centrality dependence than MCGlb model

Event-by-Event Full Viscous Photon v_n



- The ratio of v_2/v_3 of photons is larger than the ratio of thermal pions

Event-by-Event Full Viscous Photon v_n



- The ratio of v_2/v_3 of photons is larger than the ratio of thermal pions
- The ratio of v_2/v_3 is larger for QGP photons compared to hadronic photons which indicates triangular flow develops faster than elliptic flow during the late stage of hydrodynamic evolution

Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\pi^{\mu\nu} \hat{p}_\mu \hat{p}_\nu}{2(e+p)} \chi\left(\frac{p}{T}\right)$$

We can expand photon emission rates around the thermal equilibrium:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},$$

$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2}g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3}(\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Viscous Photon Emission Rates: General Formalism

Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3q} = \int \frac{d^3p_1}{2E_1(2\pi)^3} \frac{d^3p_2}{2E_2(2\pi)^3} \frac{d^3p_3}{2E_3(2\pi)^3} \frac{1}{2(2\pi)^3} |\mathcal{M}|^2$$

$$\times f_1(p_1^\mu) f_2(p_2^\mu)(1 \pm f_3(p_3^\mu))(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = \ldots \frac{\pi^{\mu\nu}\hat{p}_\mu\hat{p}_\nu}{\ldots)} \chi\left(\frac{p}{T}\right)$$

We can expa… …und the thermal equilibrium:

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta},$$

$\Gamma_0(q,T)$ $a_{\alpha\beta}\Gamma^{\alpha\beta}(q,T)$

calculated in fluid local rest frame

calculated in lab frame

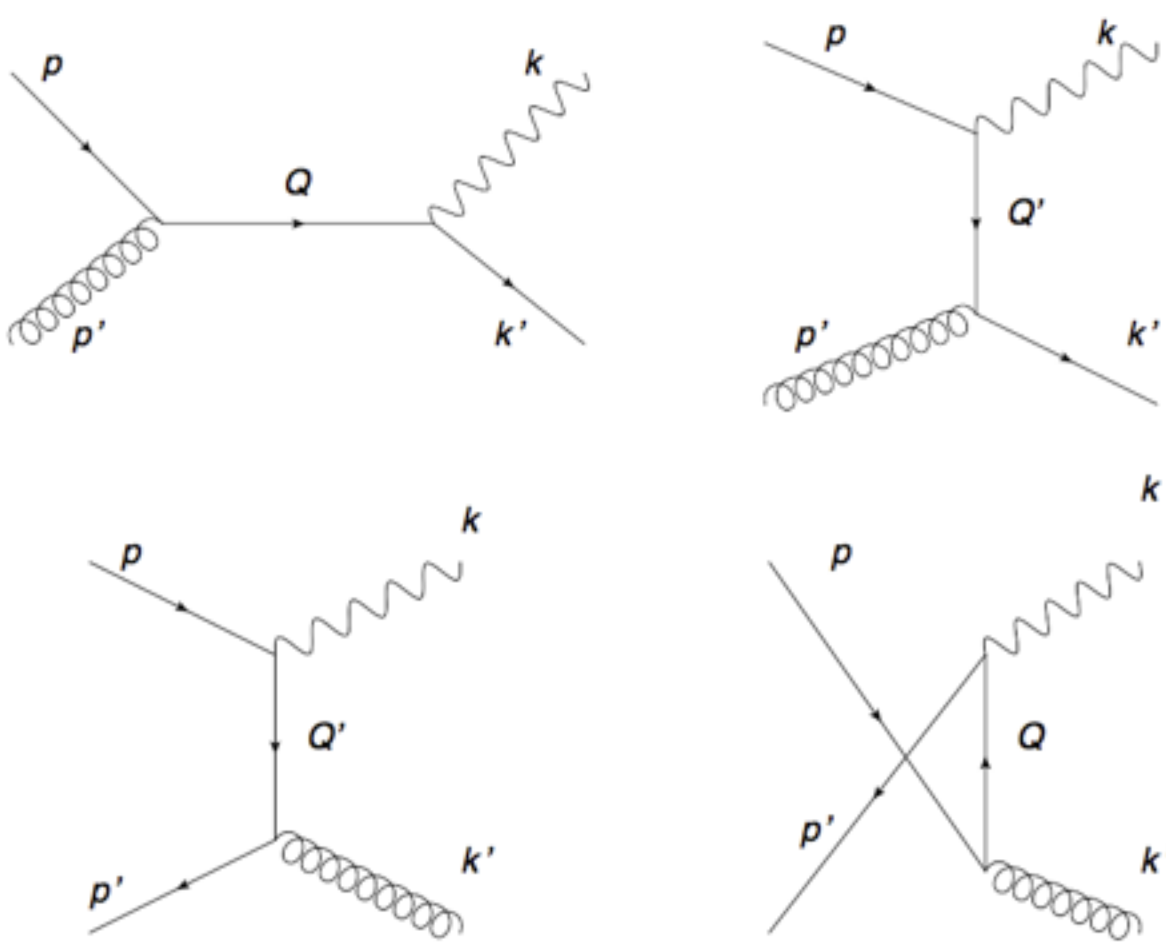
$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{\ldots}{2(u\cdot\hat{q})^{\ldots}} \ldots \mu).$$

Viscous Photon Emission Rates: General Formalism

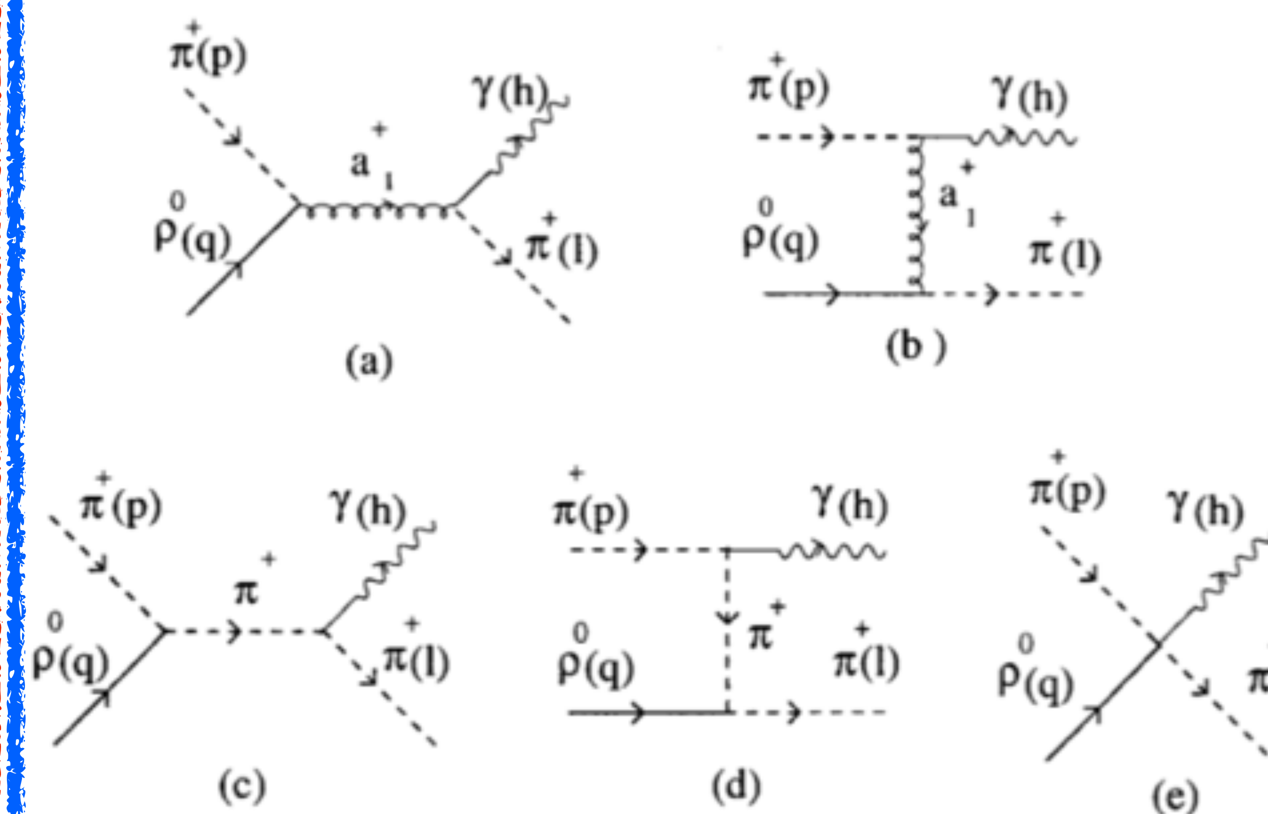
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)}a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

QGP



Hadron Gas



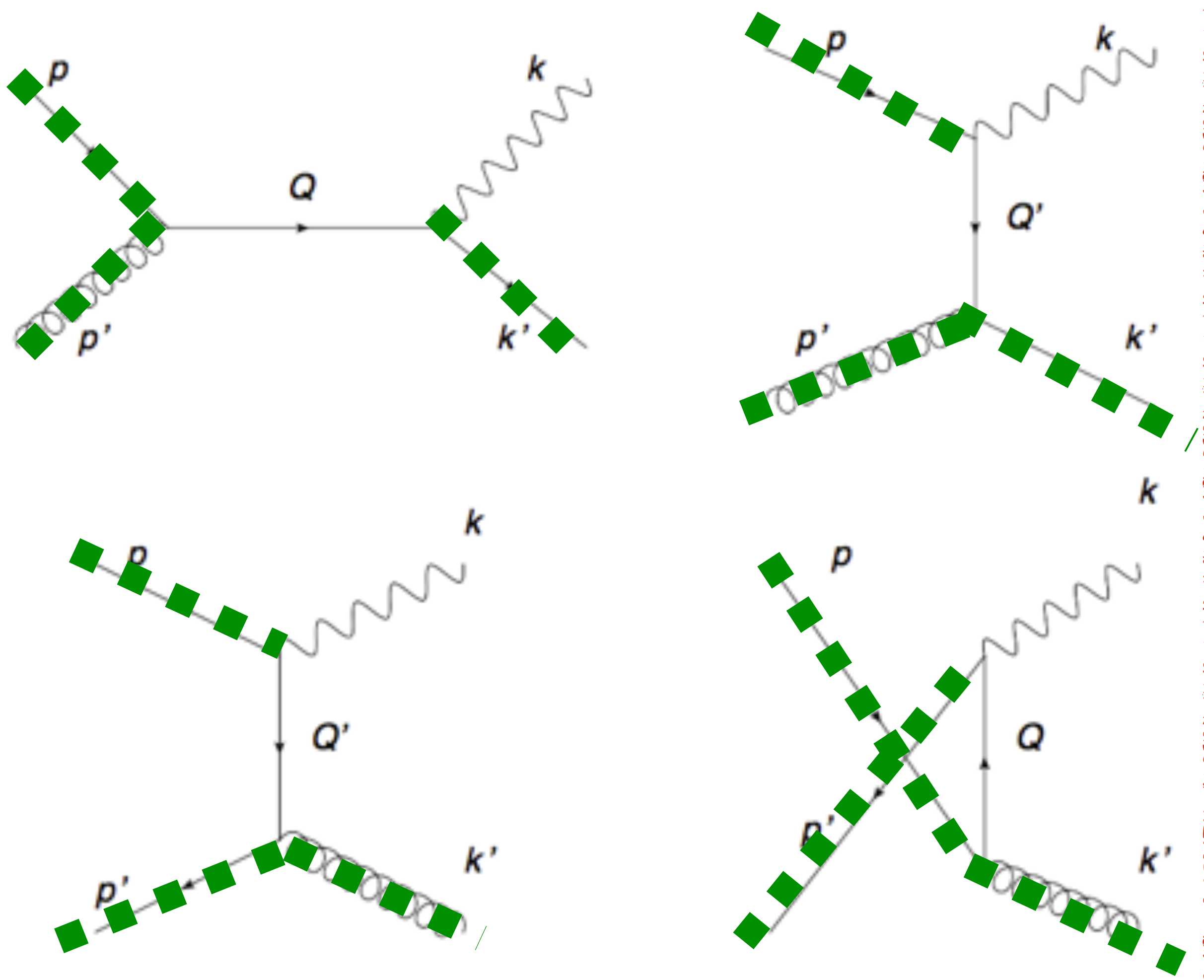
Viscous Photon Emission Rates: General Formalism

$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

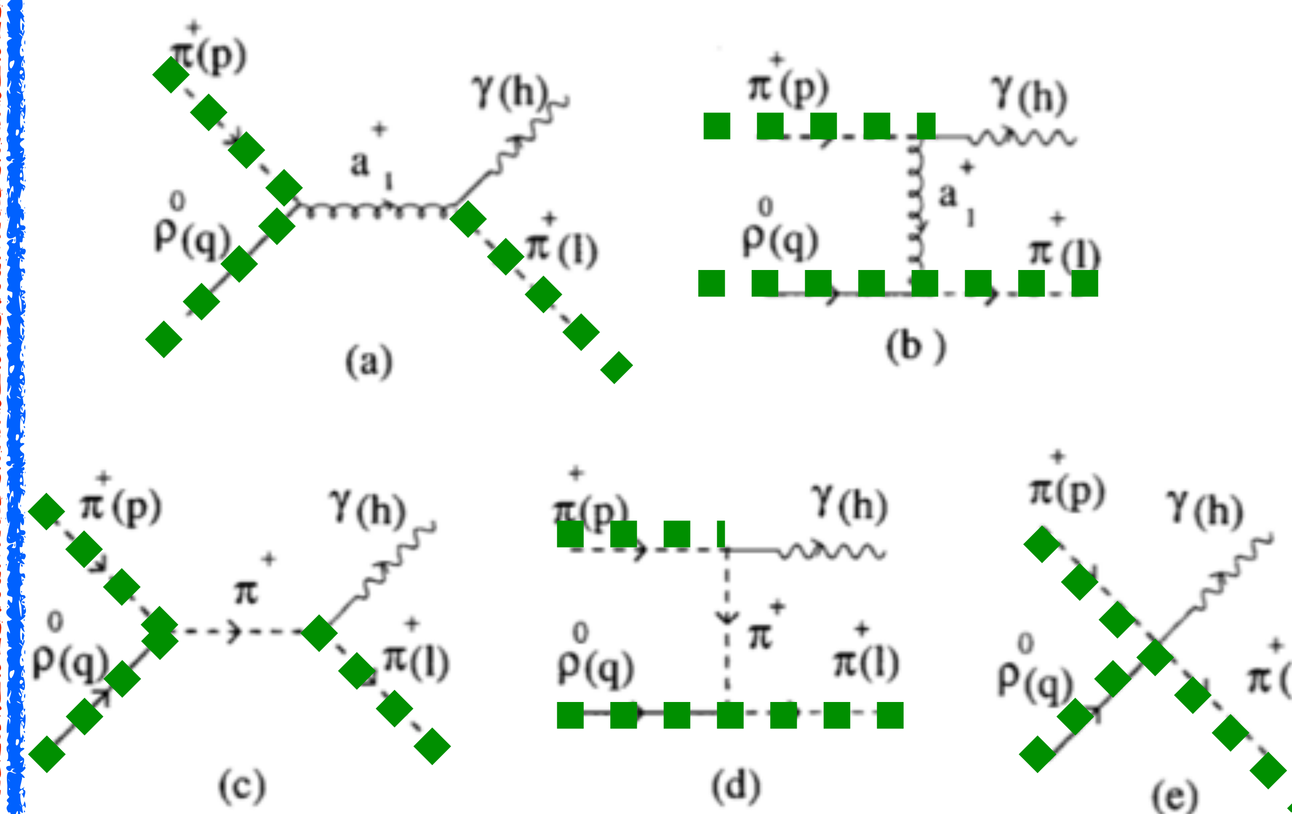
Equilibrium rates

off-equilibrium δf corrections

QGP



Hadron Gas

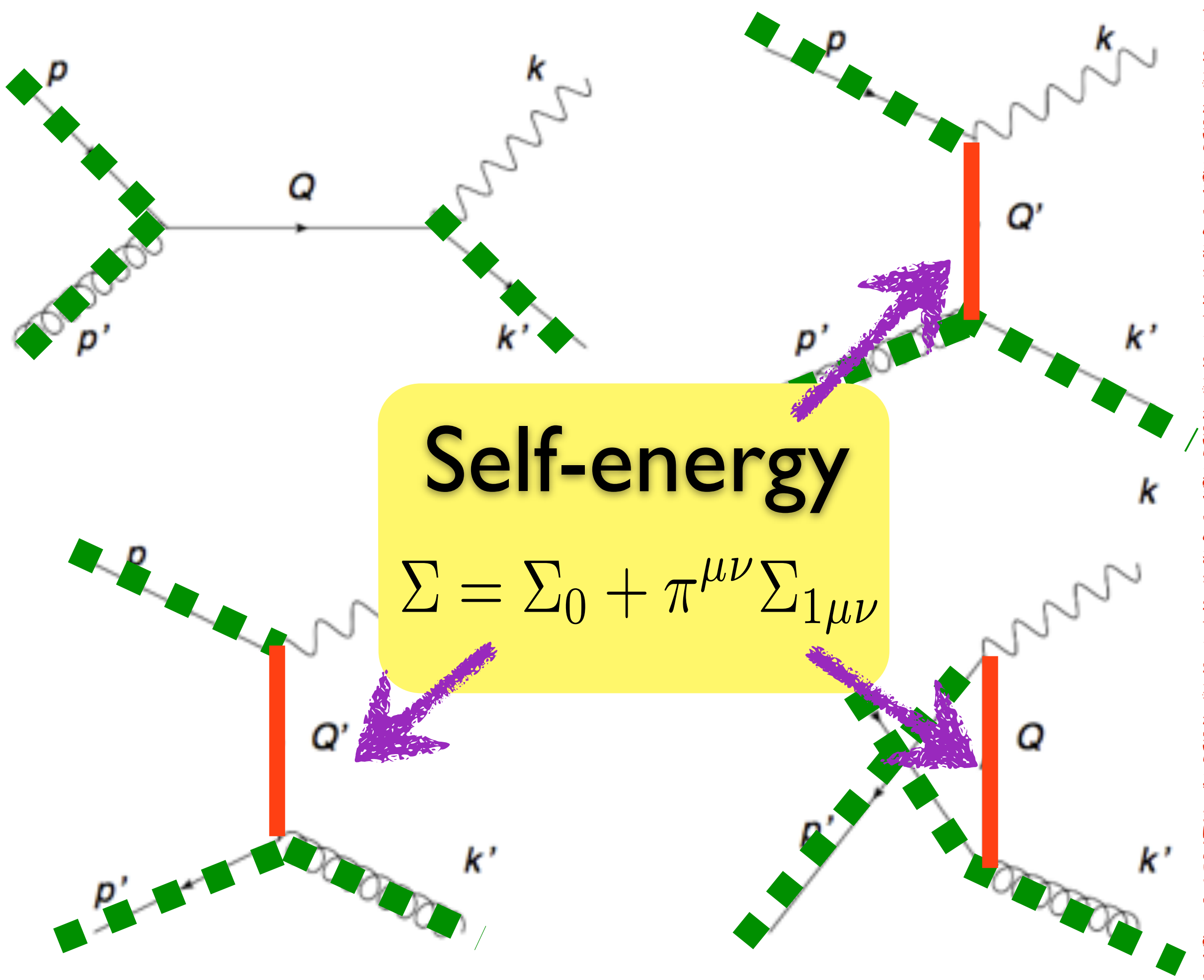


Viscous Photon Emission Rates: General Formalism

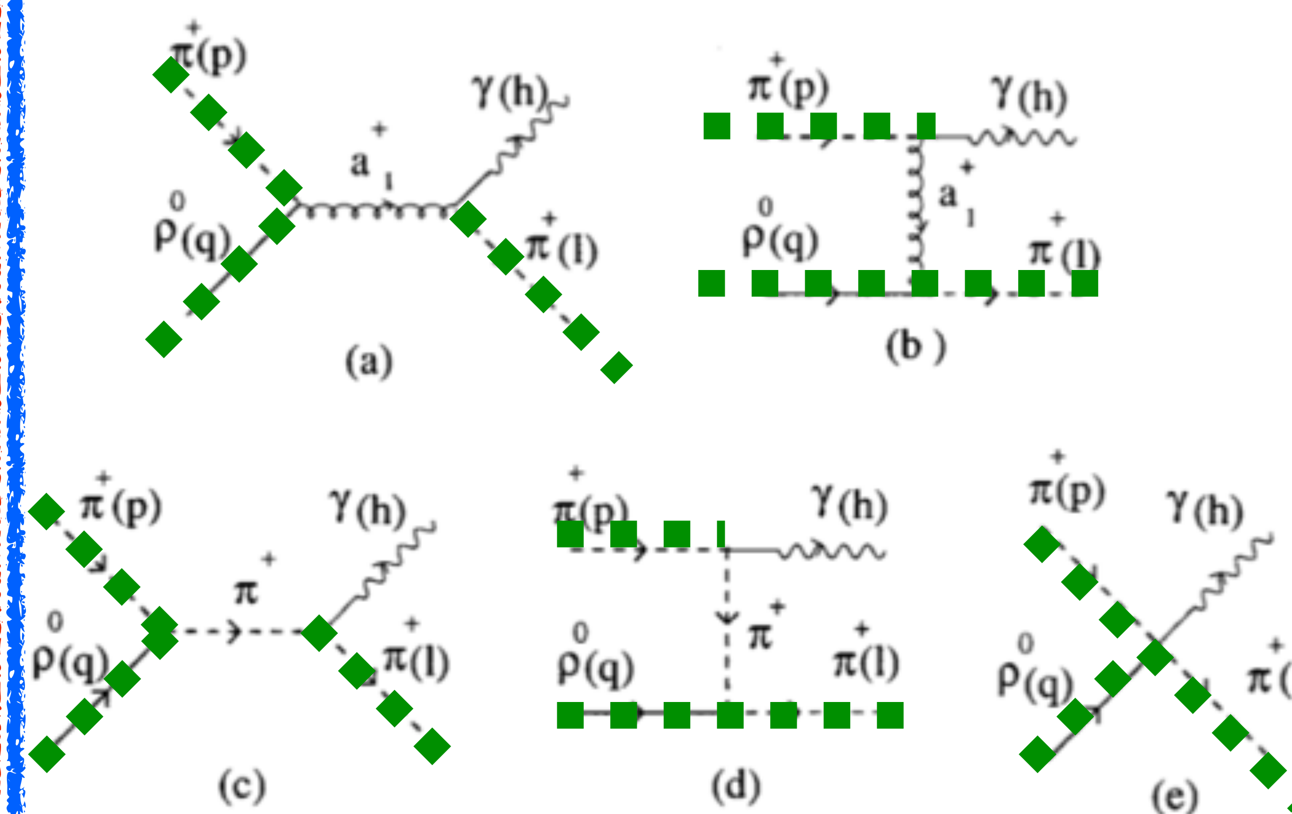
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)} a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates   off-equilibrium δf corrections

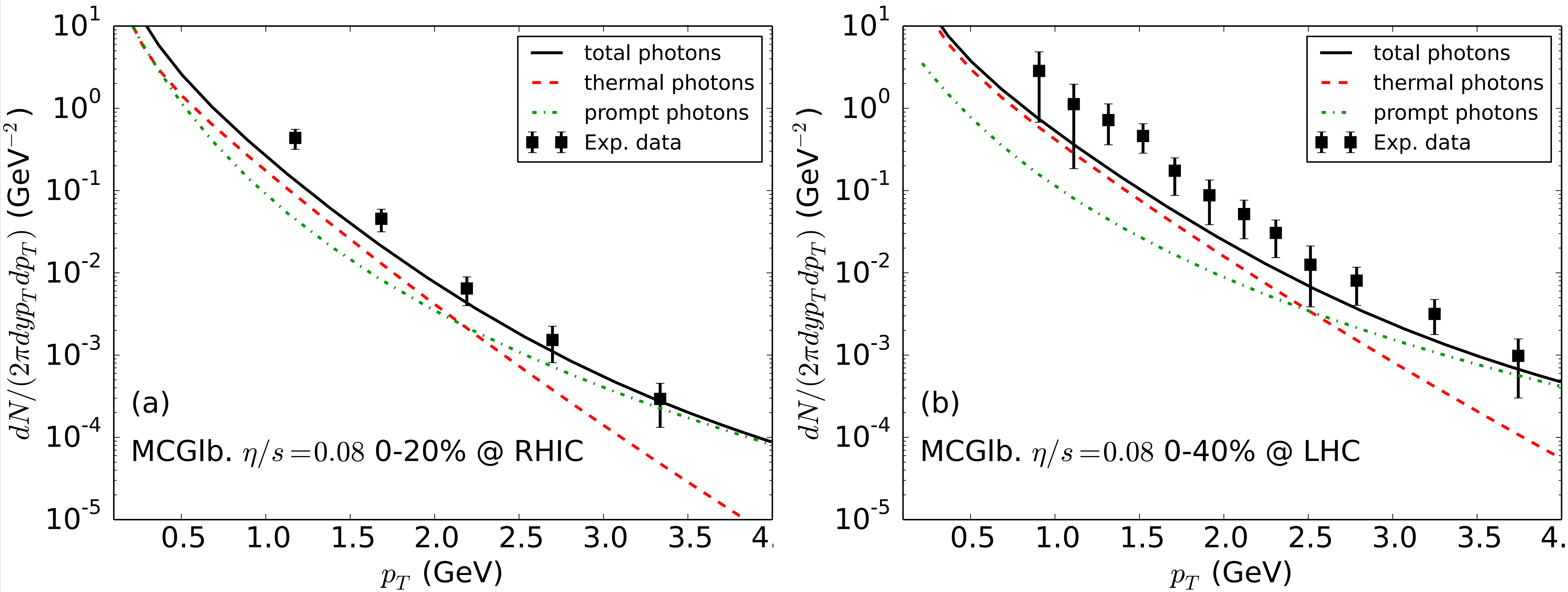
QGP



Hadron Gas

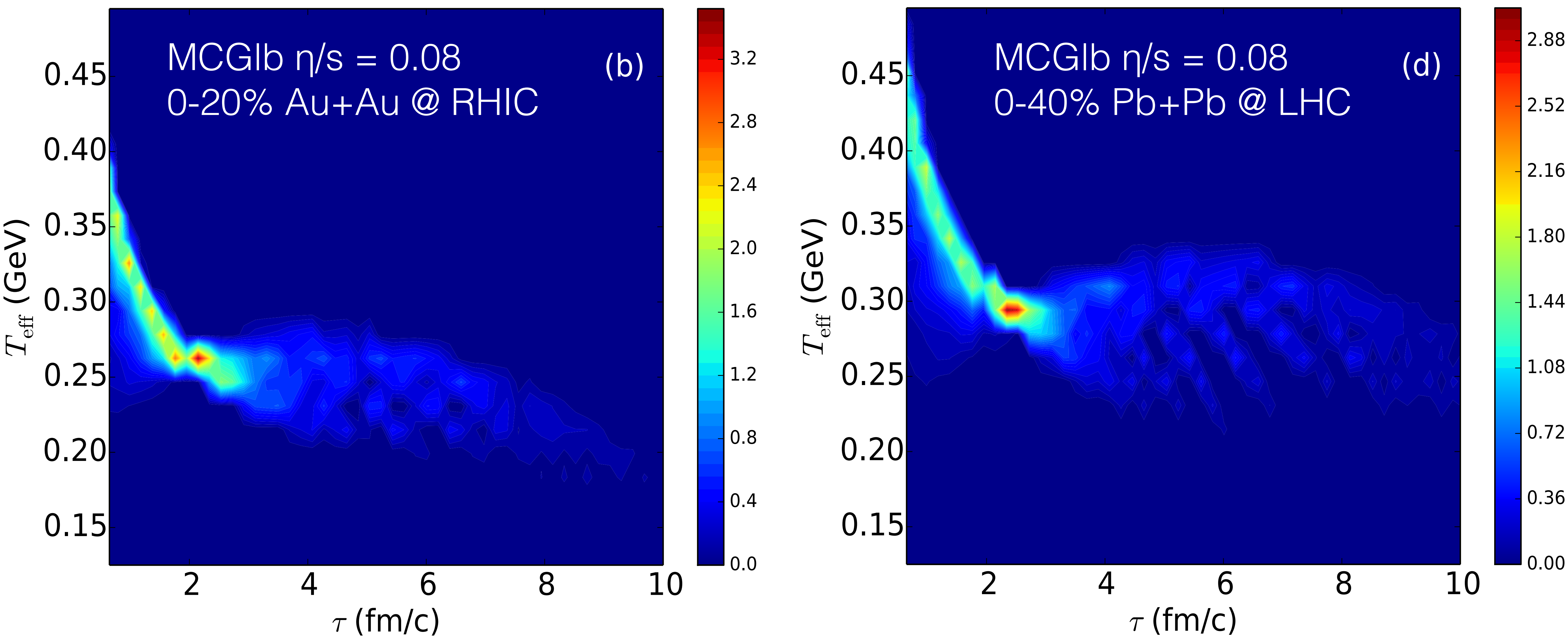


Thermal Photon Spectra



- With all available thermal emission sources, our current calculations still underestimate measured direct photon spectra at low p_T at both RHIC and LHC energies
- Additional emission sources need to be included to improve the agreement between theory and data

Mapping T_{eff}



- Hydrodynamic radial flow strongly blue shifts the slopes of photon spectra
- Around 2 fm/c, it greatly shrinks the photon yield distribution in terms of the effective temperature compared to the real temperature