Photon tomography of relativistic heavy-ion collisions

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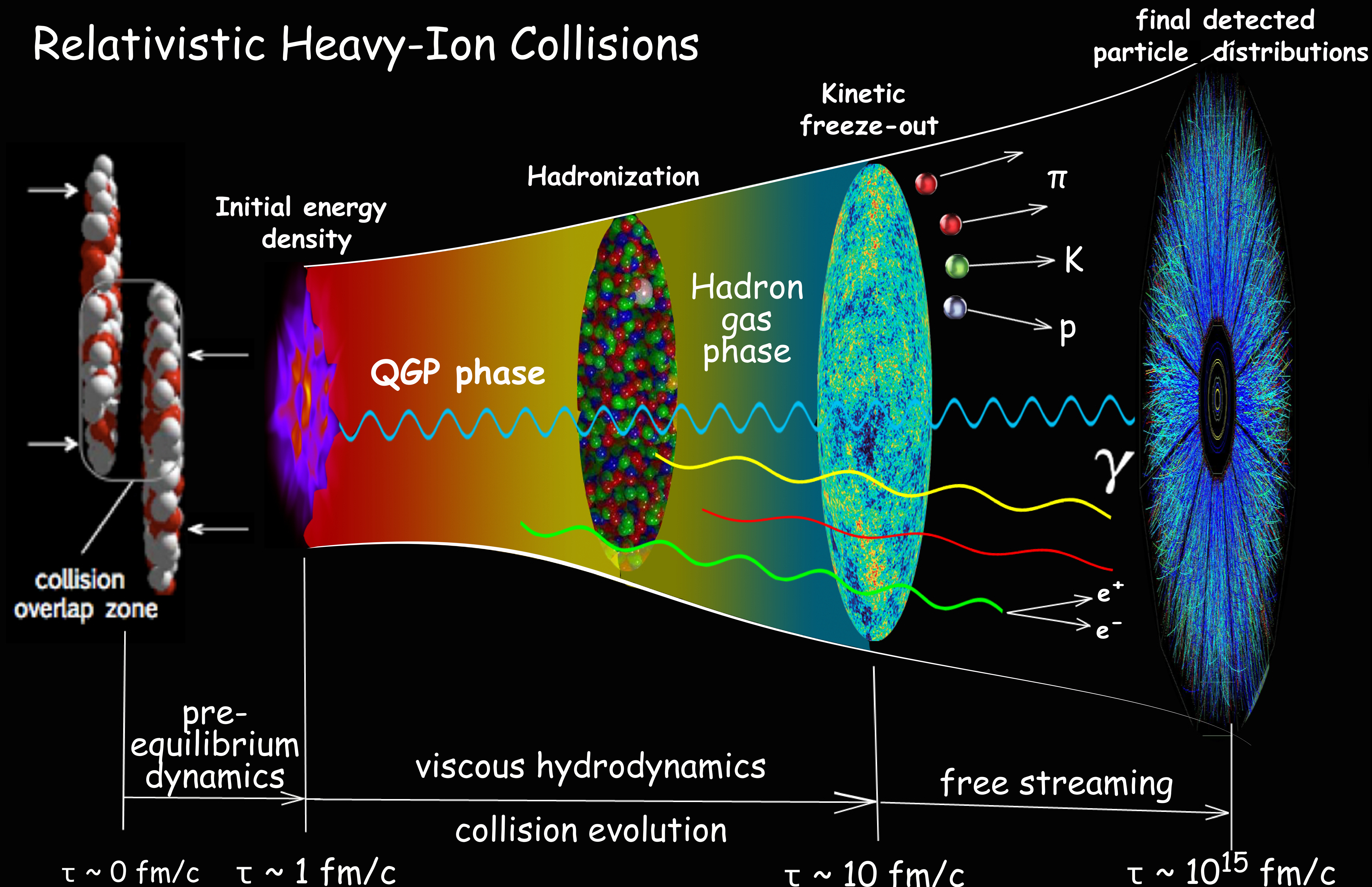
The Ohio State University

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

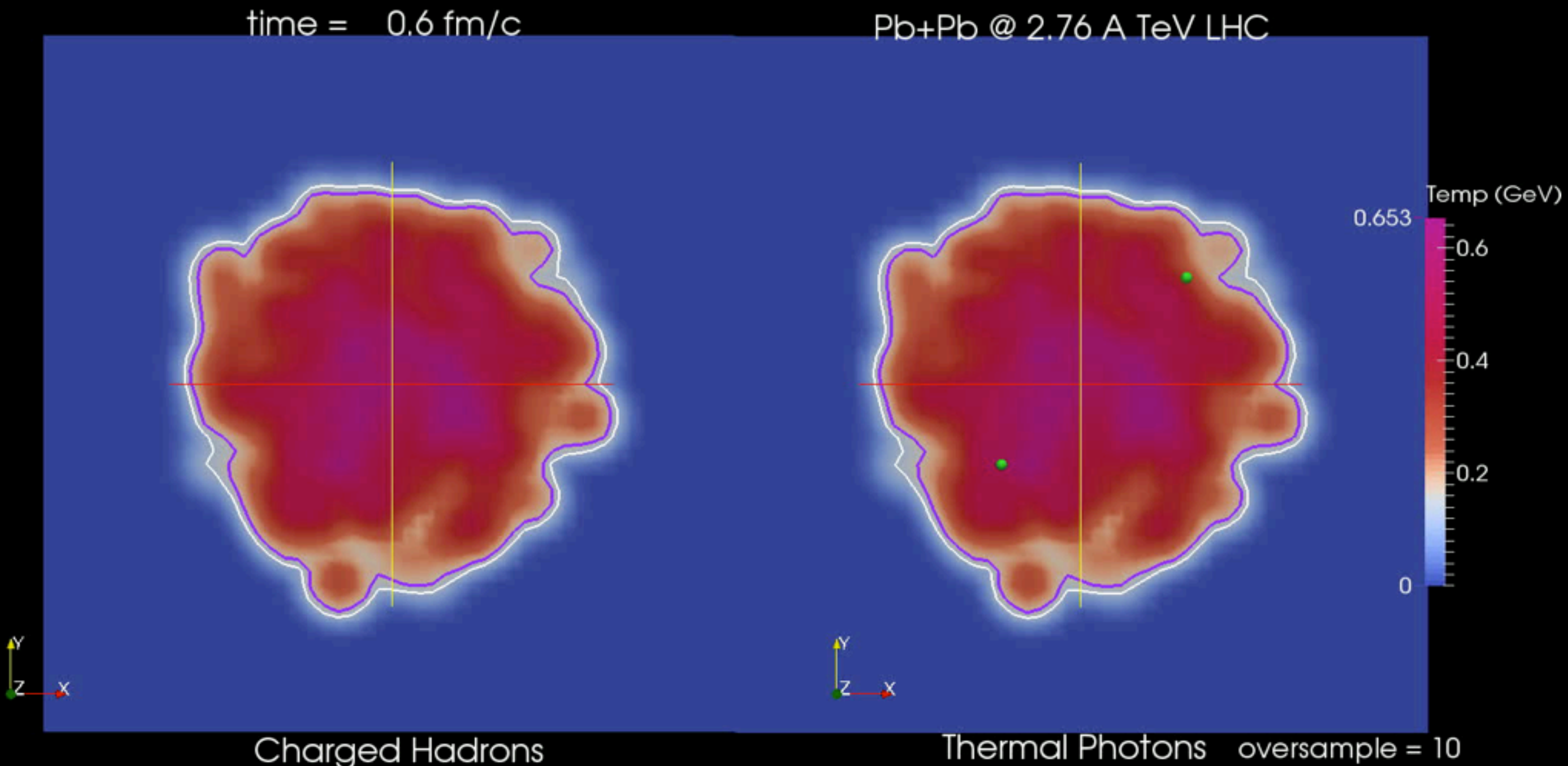
Aug. 20, 2014 Thermal Photons and Dileptons in Heavy-Ion Collisions BNL

Little Bang



Relativistic Heavy-Ion Collisions
final detected particle 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

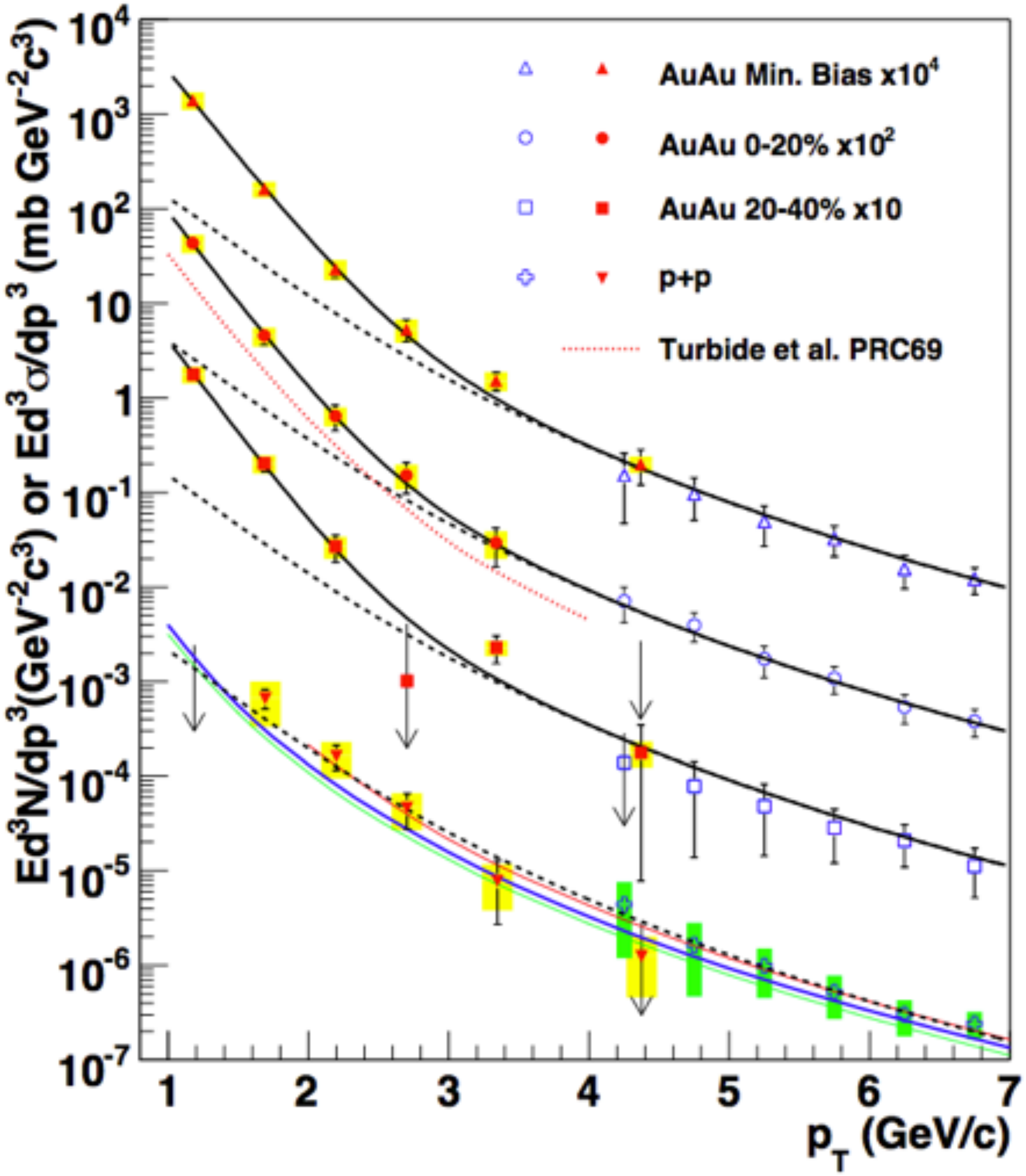
Photons from Heavy-ion Collisions



http://youtu.be/oMFboC7O1DU

Fitted T_{eff} from Experiments

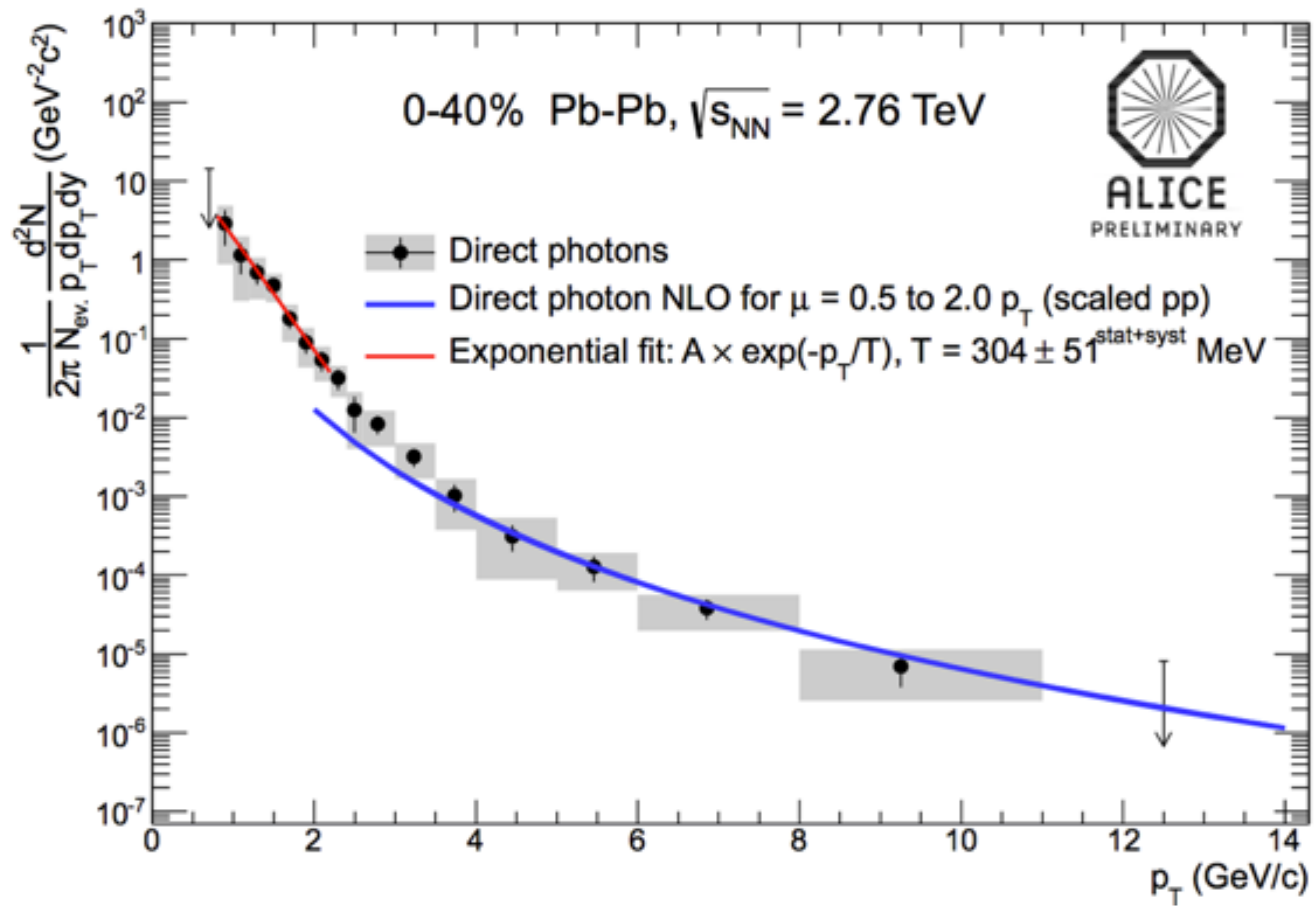
RHIC



$0 - 20\%$

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

LHC



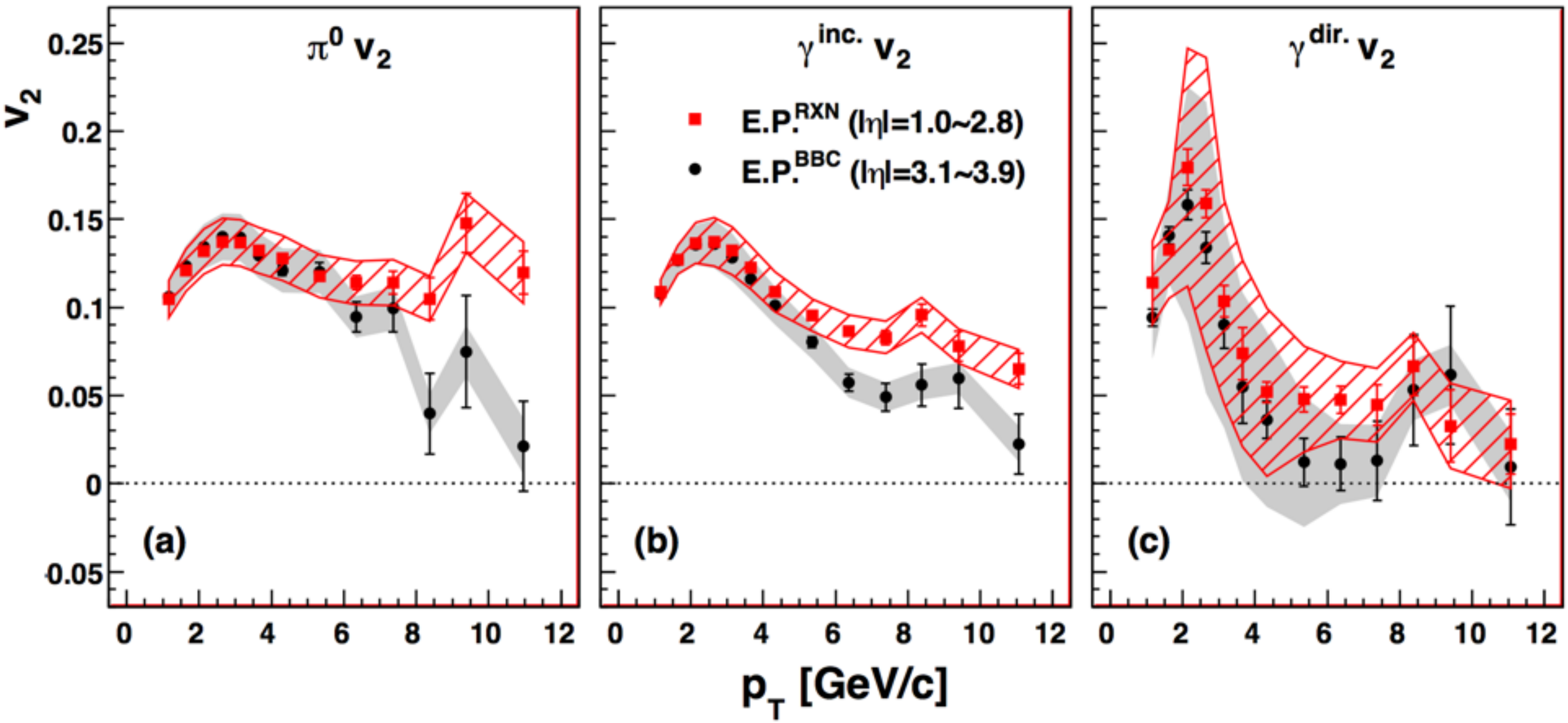
fit: $A\exp(-p_T/T)$

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

What does this T mean

Photon v_n from Experiment

A. Adare *et al.* [PHENIX Collaboration] Phys. Rev. Lett. **109**, 122302 (2012)



- PHENIX measurements show large direct photon v_2 at $p_T < 4$ GeV

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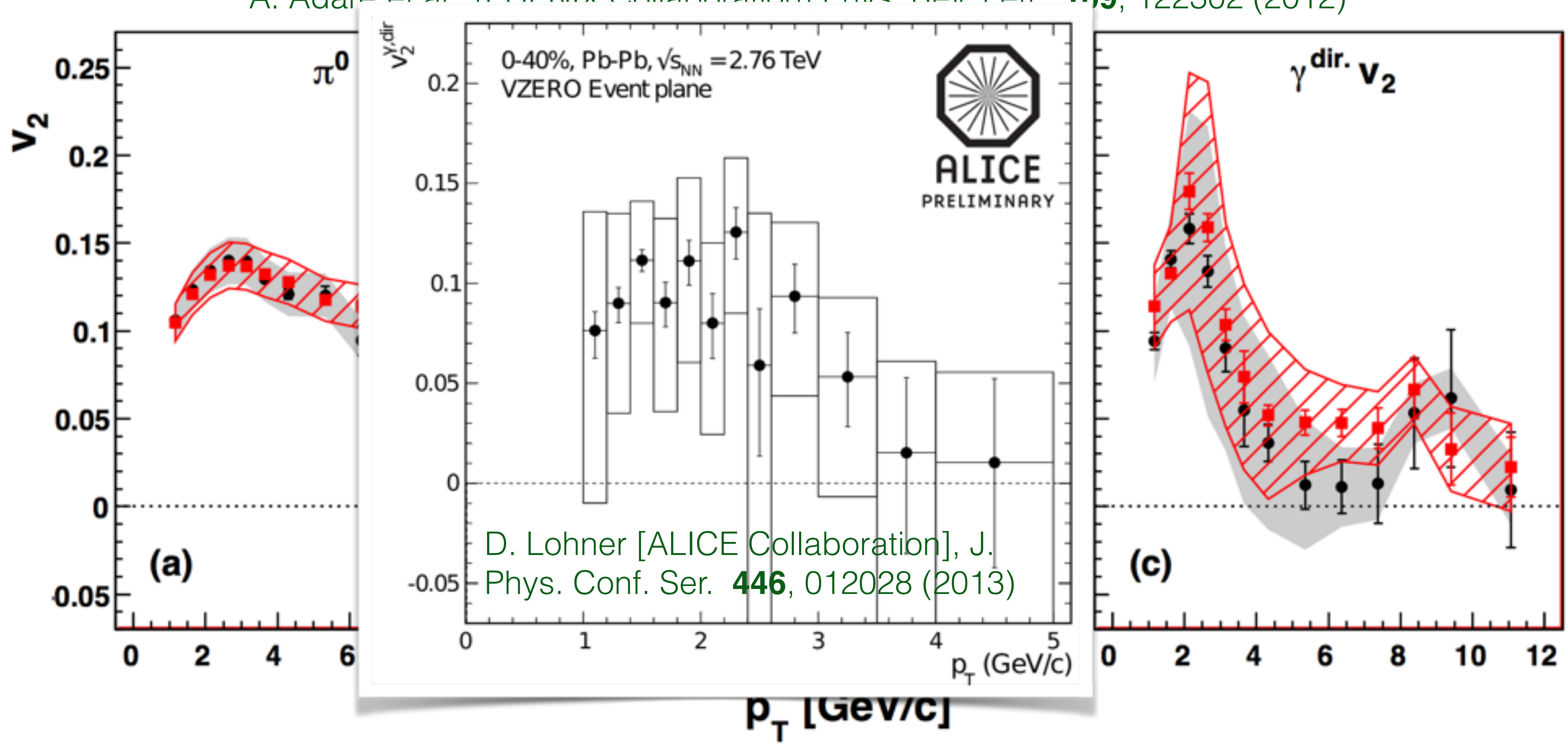


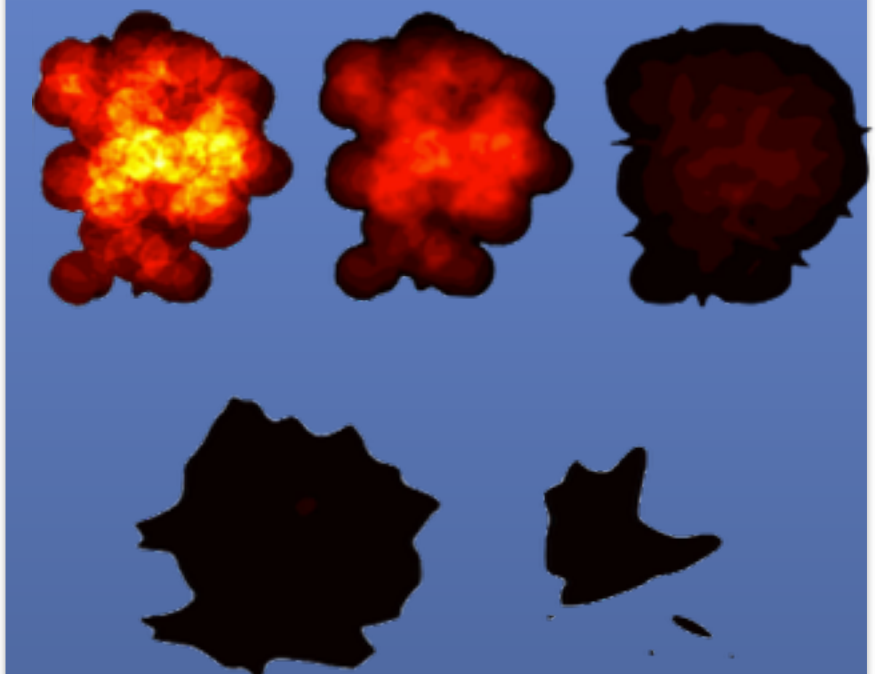
D. Lohner [ALICE Collaboration], J. Phys. Conf. Ser. **446**, 012028 (2013)

- PHENIX measurements show large direct photon v_2 at $p_T < 4$ GeV
- ALICE also measured similar large direct photon elliptic flow at LHC

State-of-the-art hydrodynamic modeling

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

Hydrodynamic Simulations (VISH2+1)



Hadrons spectra & v_n

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

JET Collaboration

HydroInfo Package

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

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

Thermal Photon Emission Rates

Thermal Photon Interface

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

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

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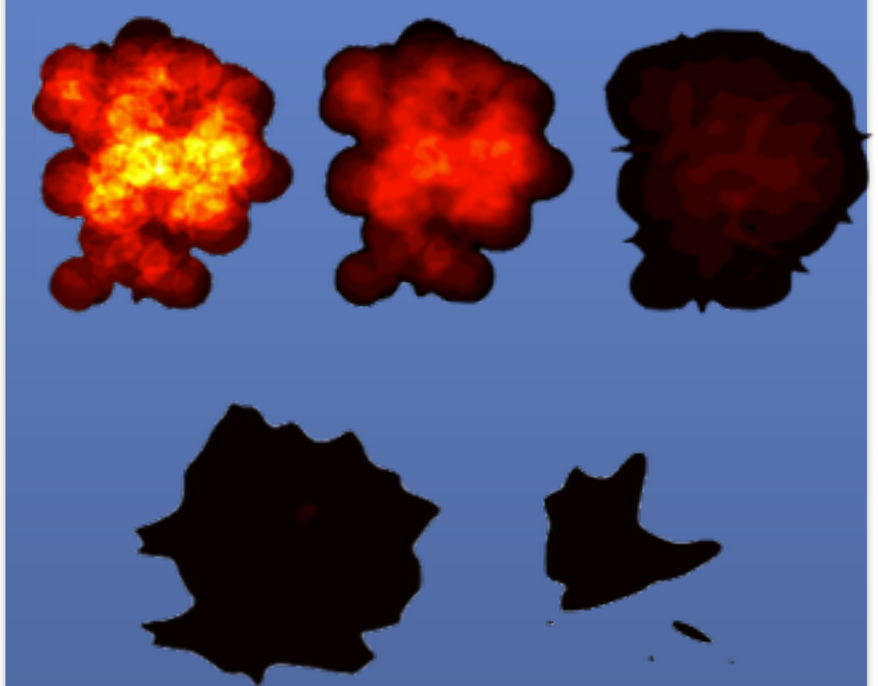

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Hadrons spectra & v_n

Photon spectrum & v_n

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

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

With

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

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

calculated in fluid local rest frame

We can expa… …und the thermal equilibrium:

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

calculated in lab frame

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

Viscous Photon Emission Rates

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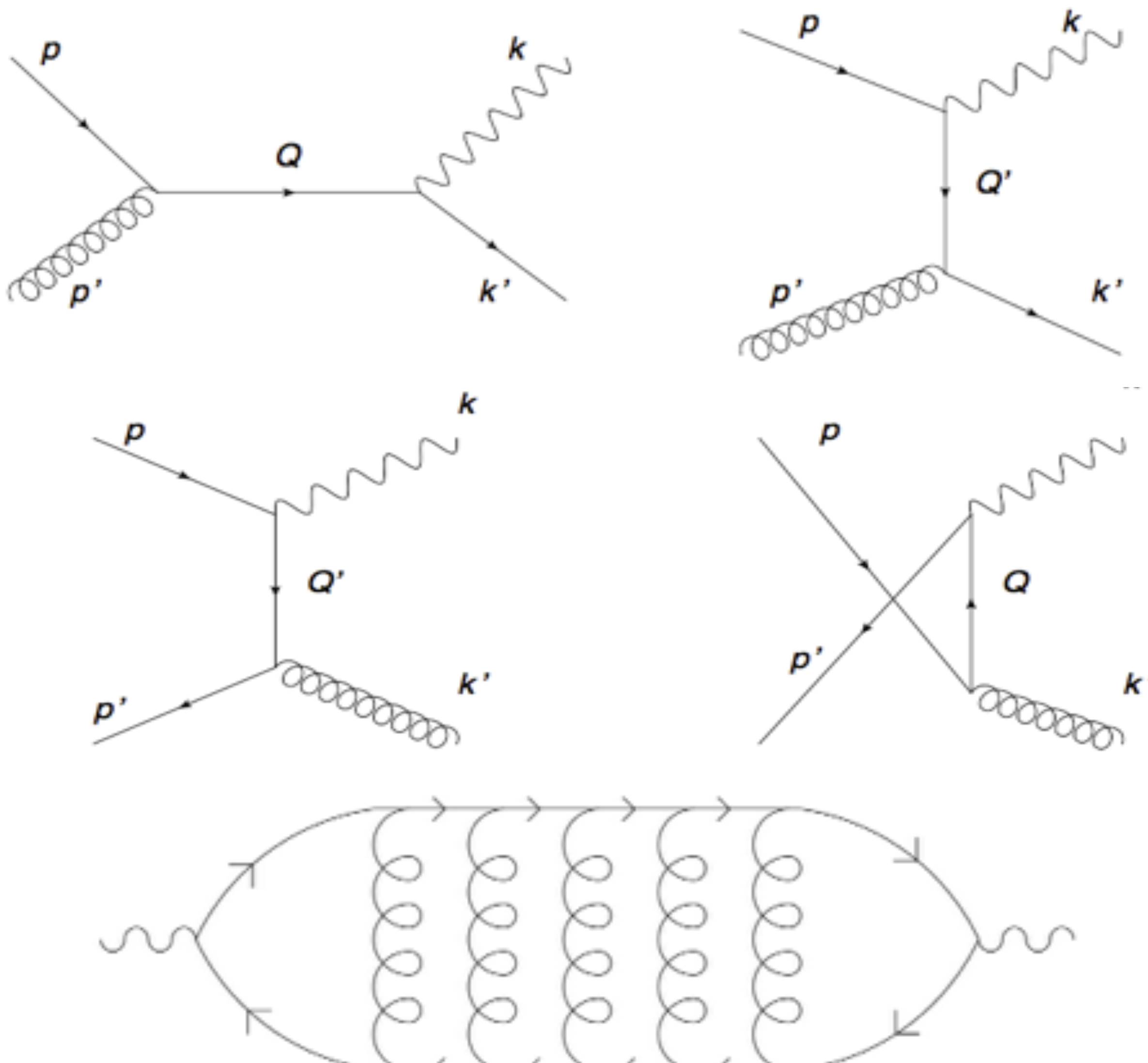
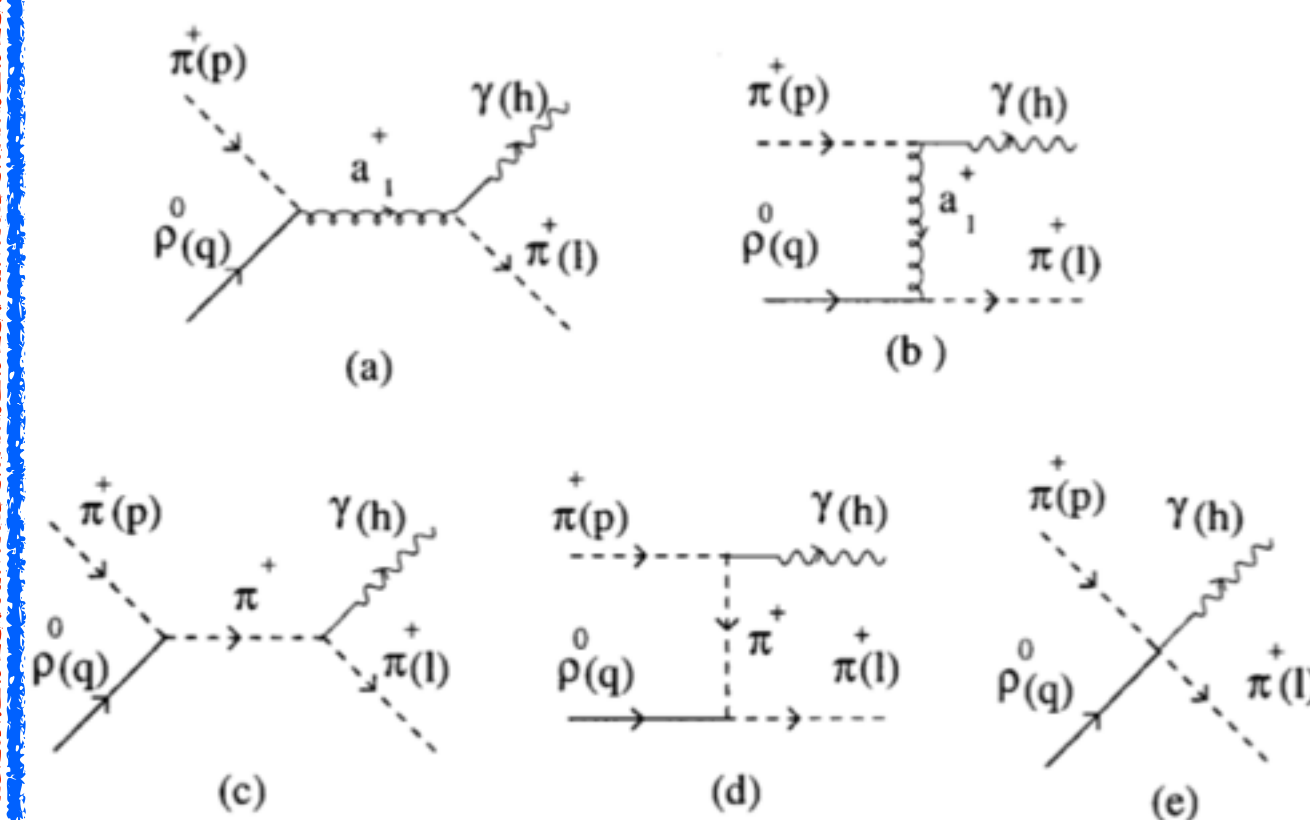
Equilibrium rates

QGP (AMY 2001)



Hadron Gas

(TRG 2004)



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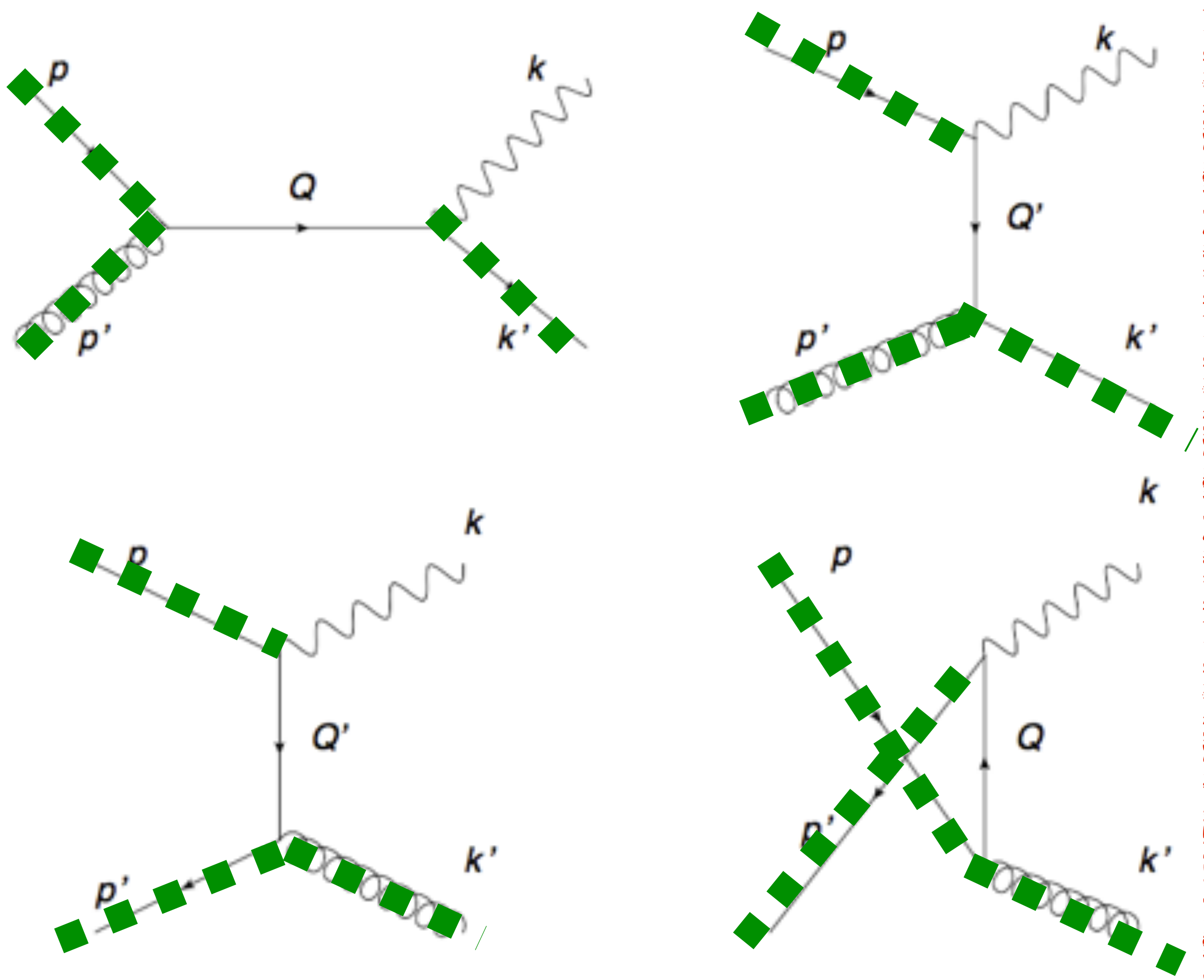
Equilibrium rates

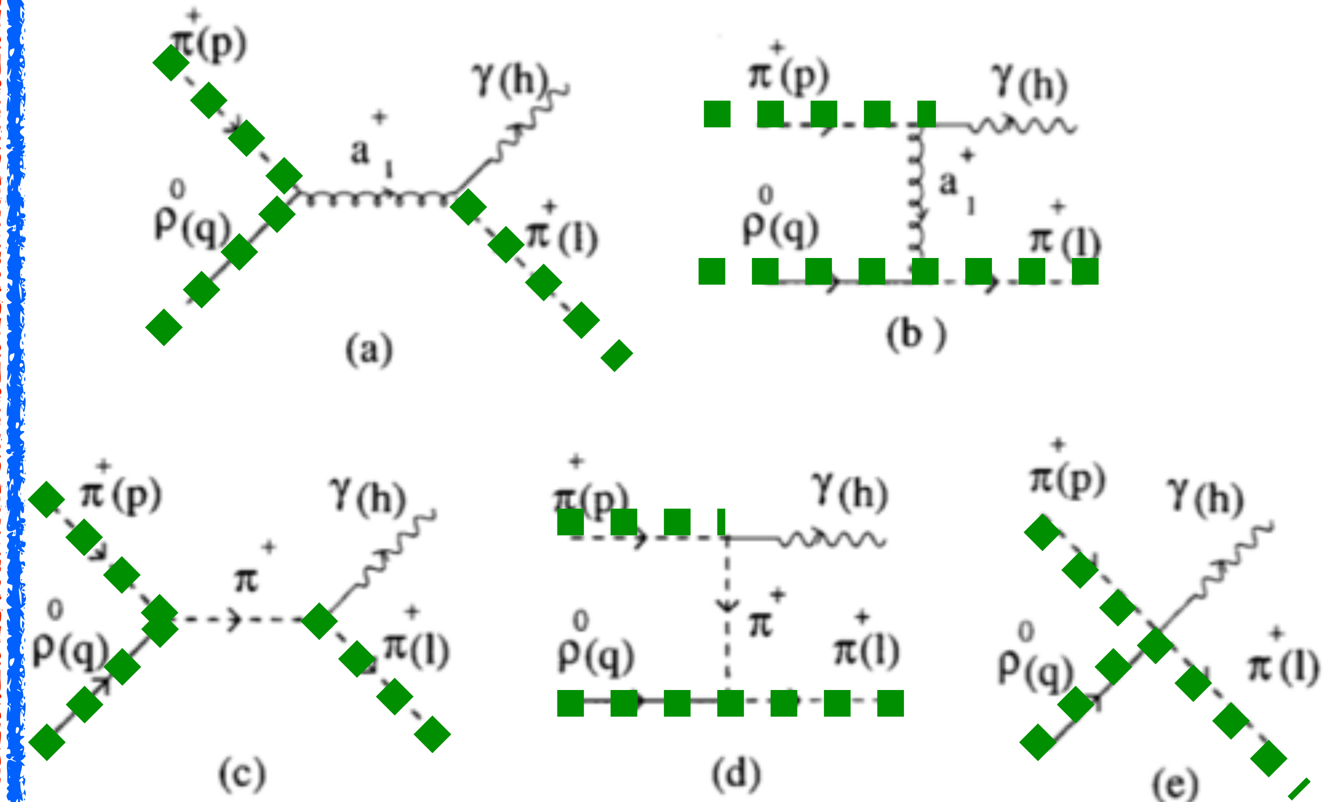
off-equilibrium δf corrections

QGP



Dusling NPA839 (2010) 70

Hadron Gas



Dion et al. PRC84 (2011) 064901

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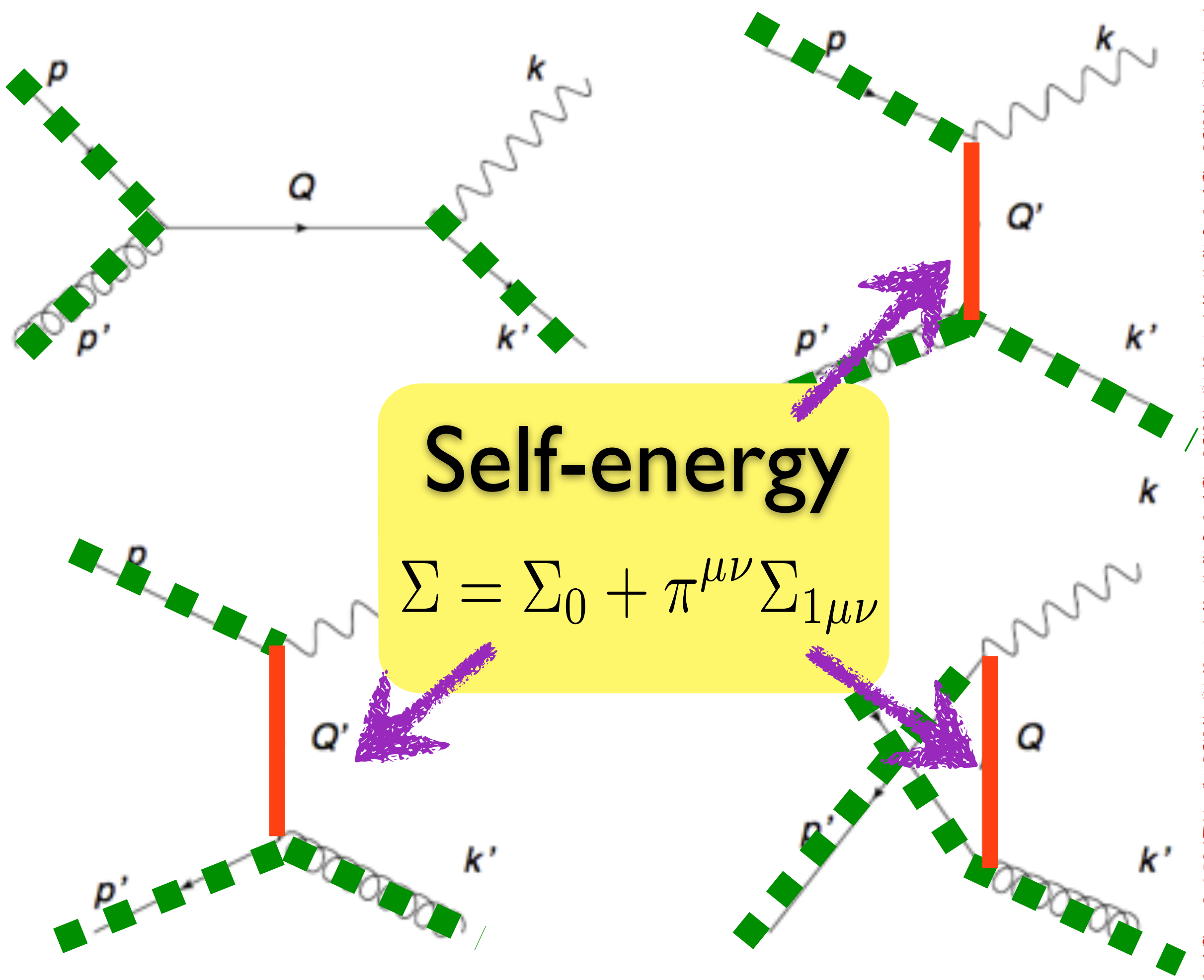
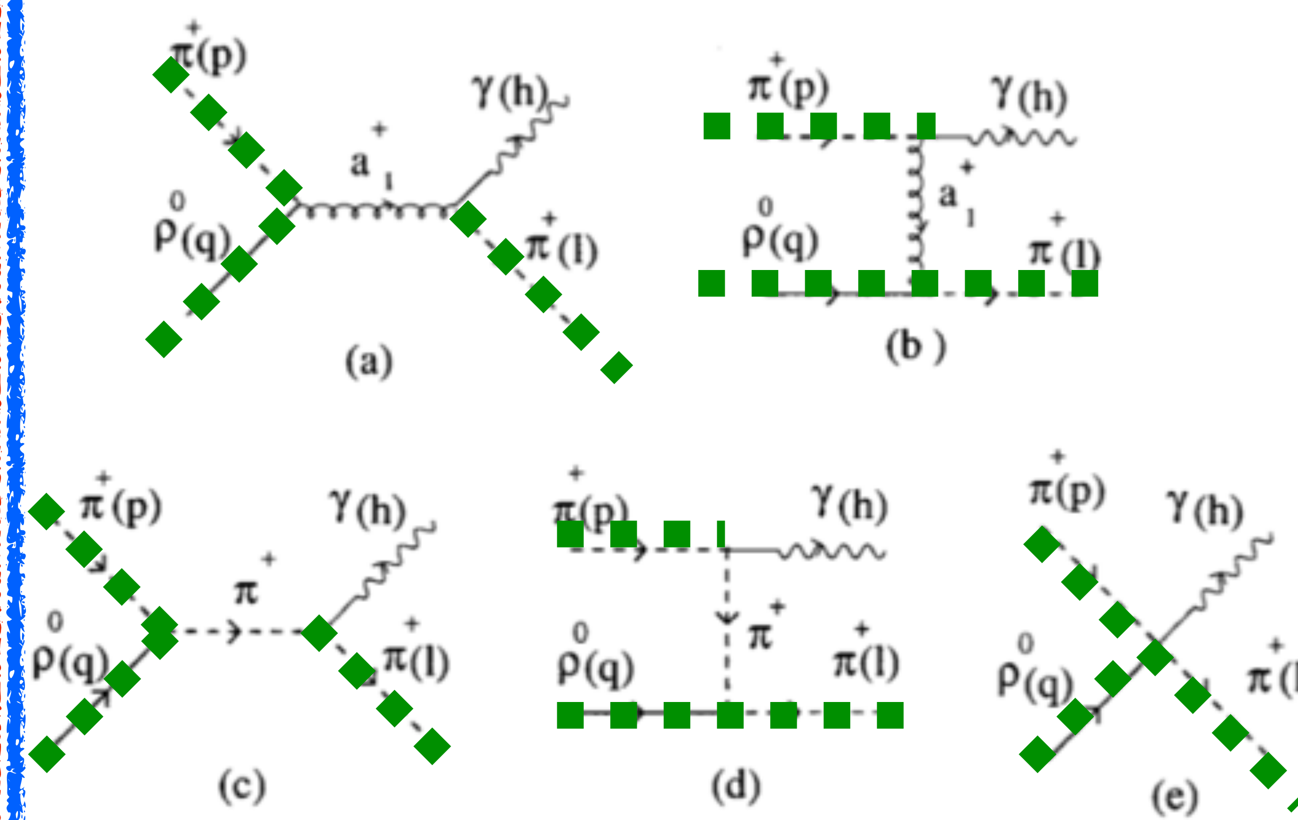
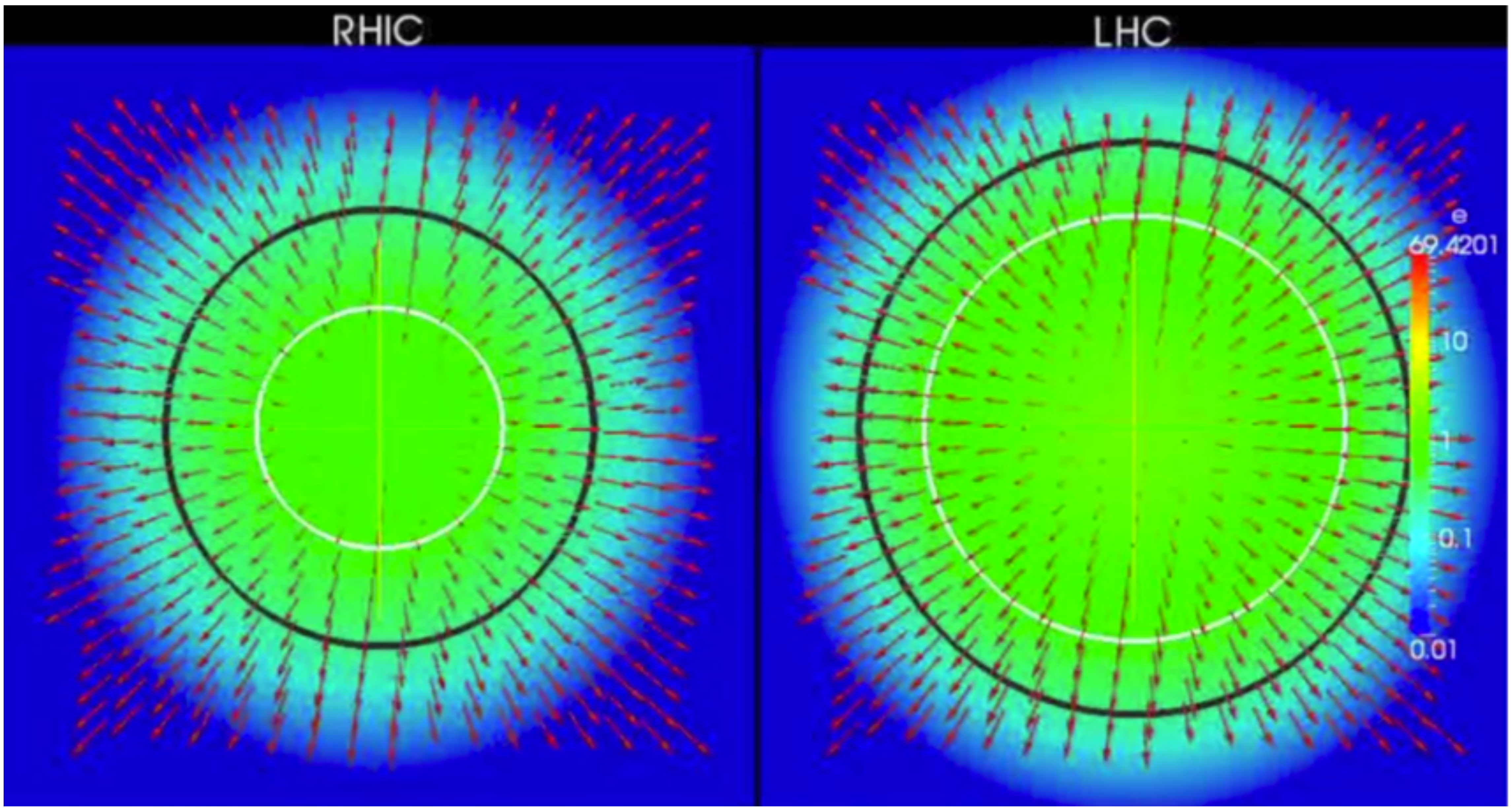


Shen, Paquet et al. (2014)

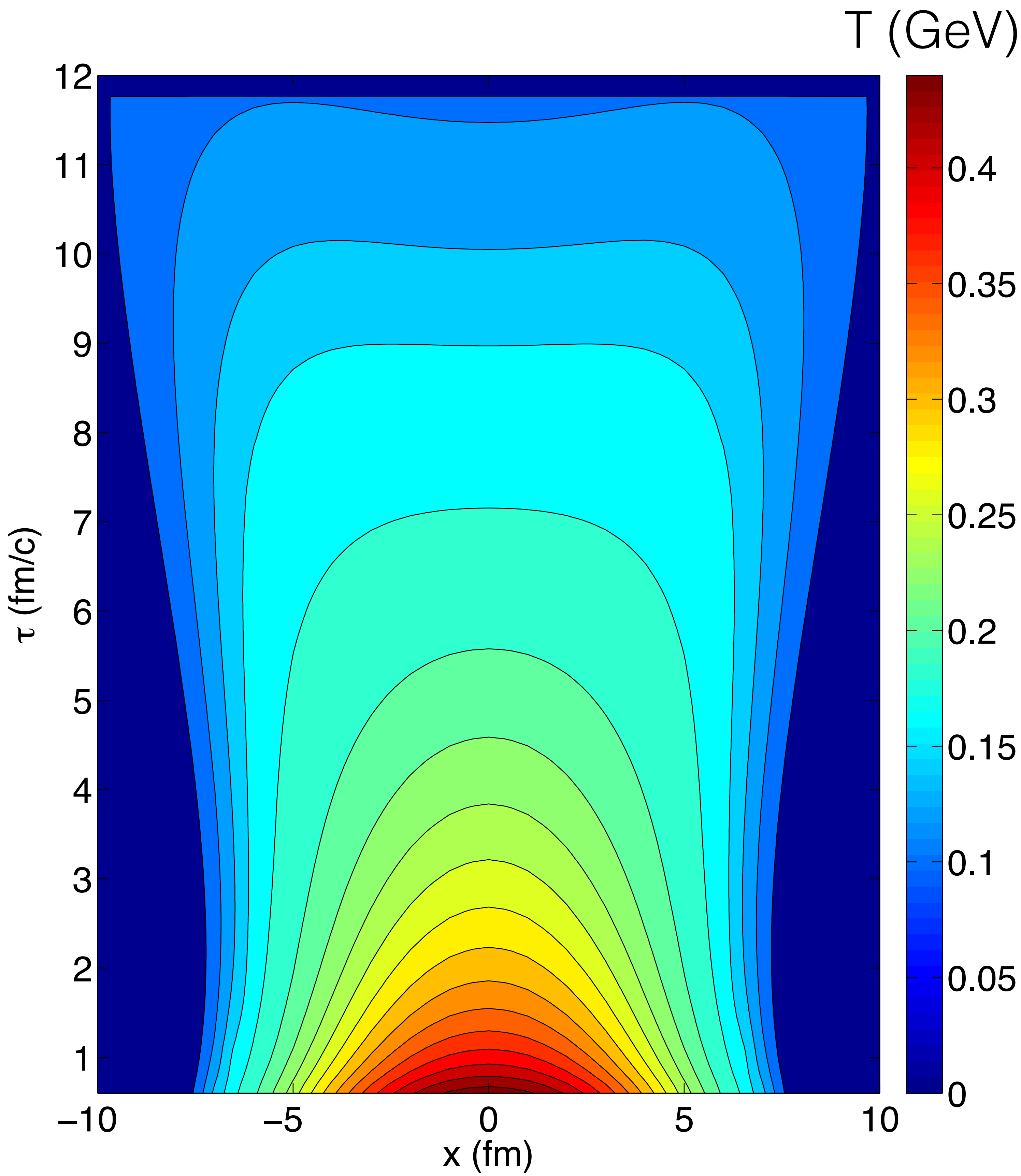
Hadron Gas



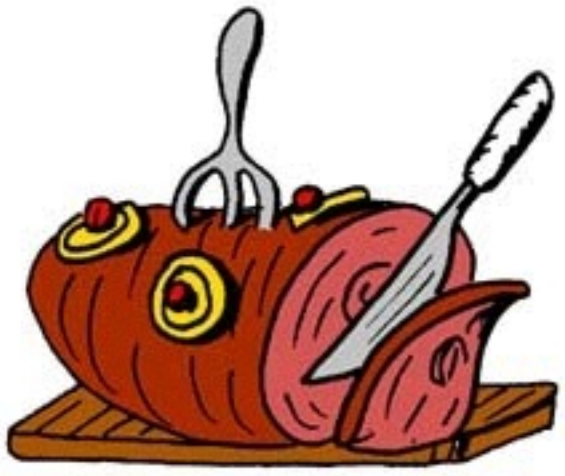
Photon spectra and radial flow



Slope of Photon Spectrum



Slicing the hydrodynamic medium



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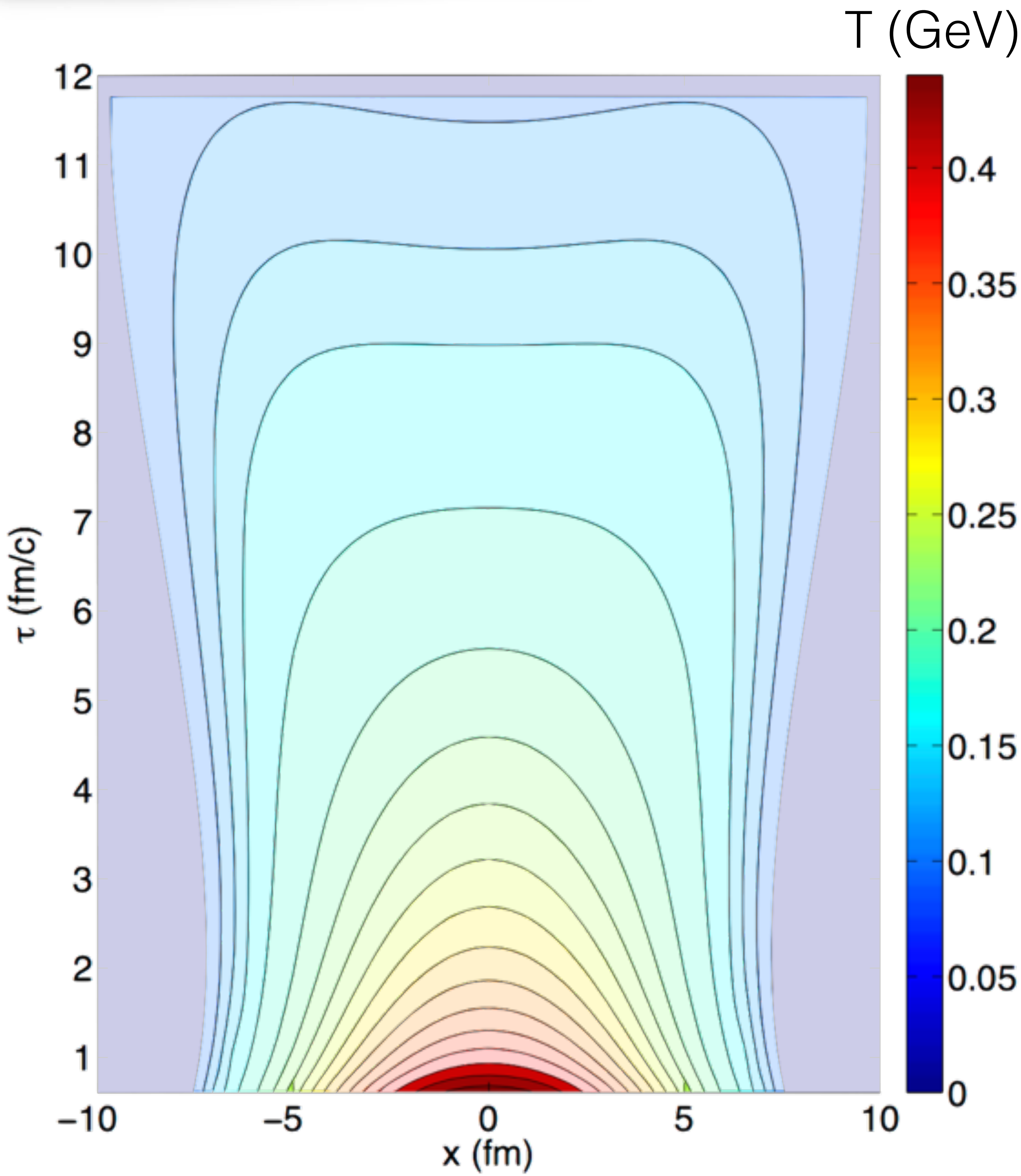

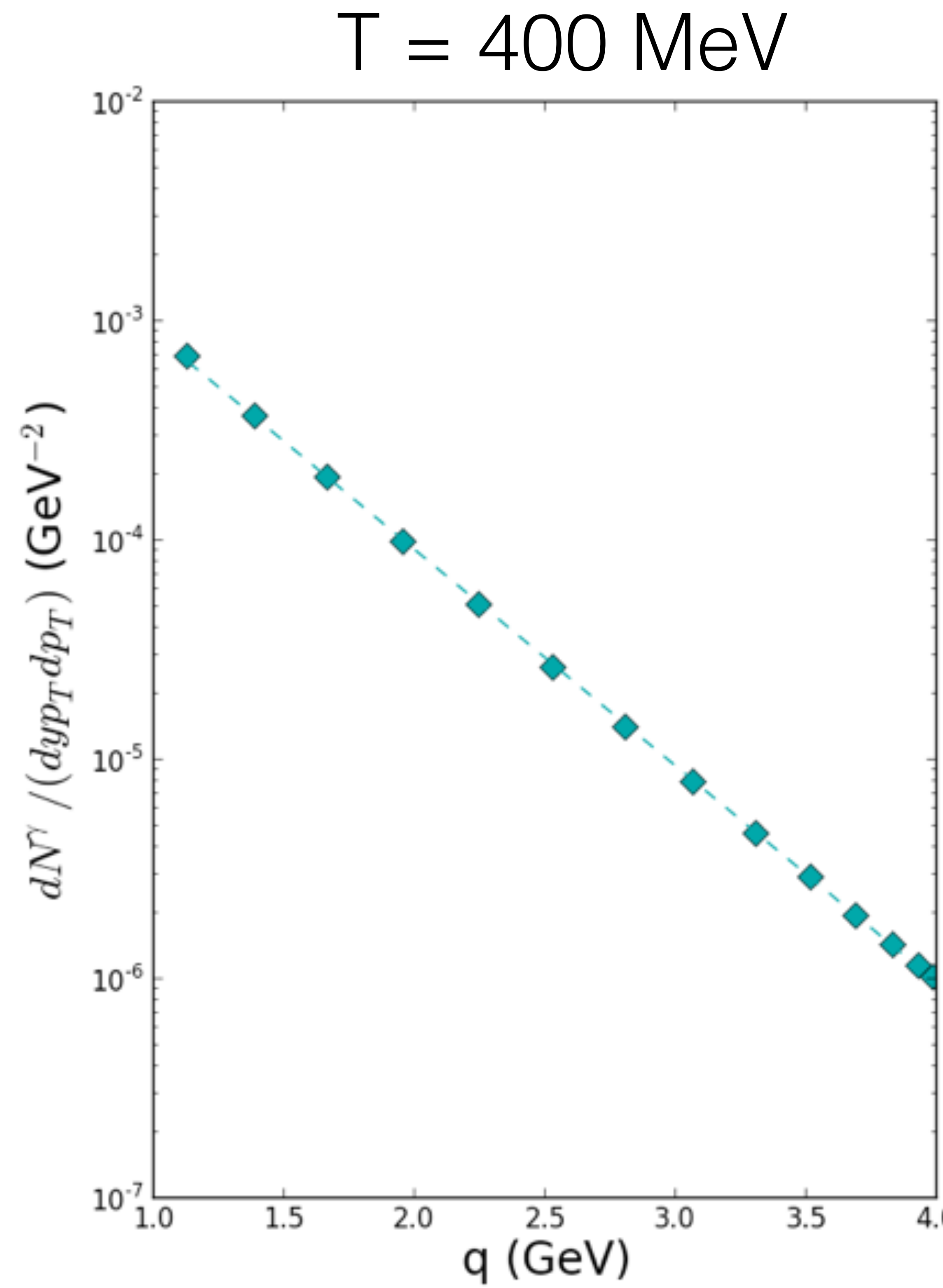

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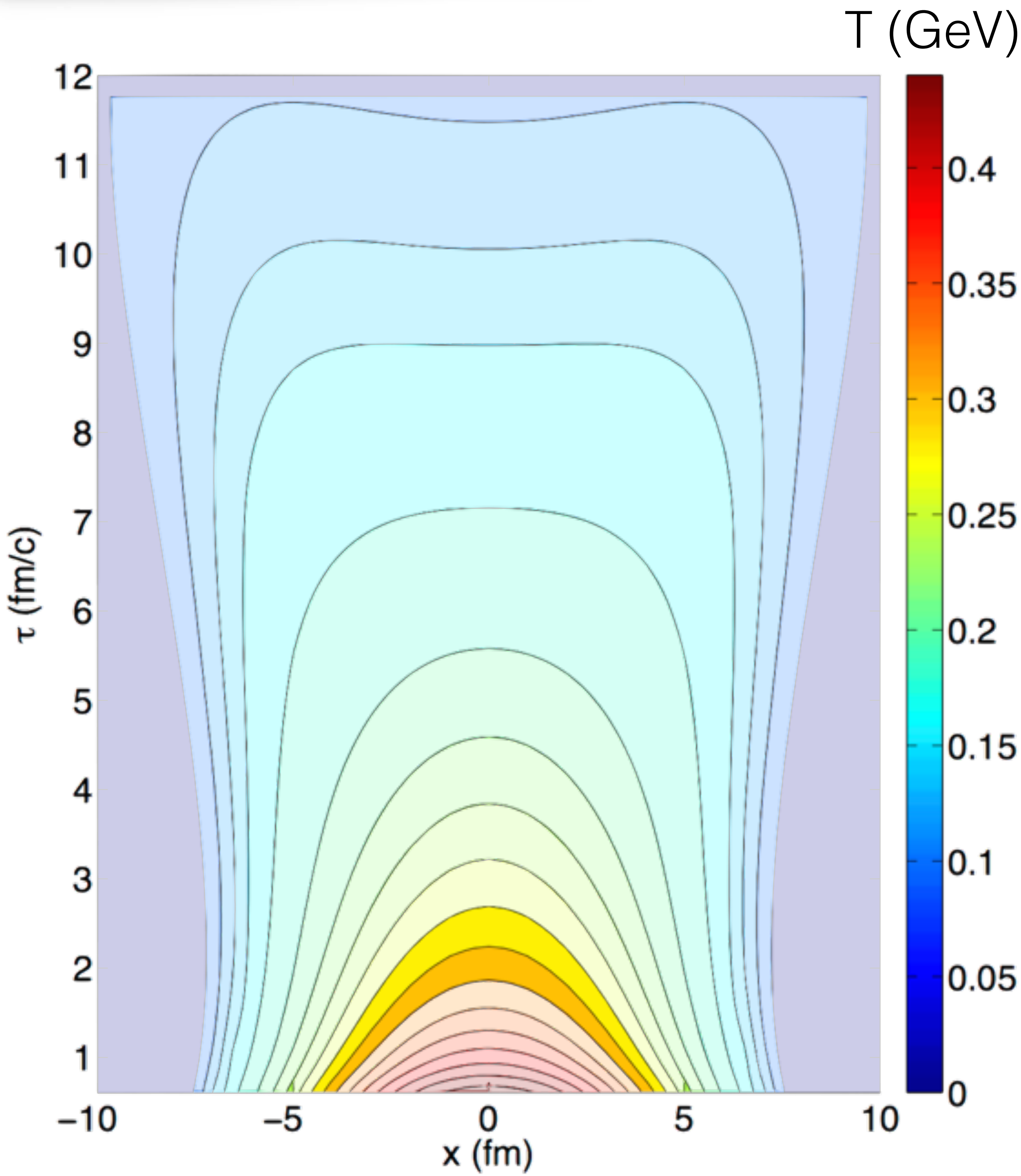

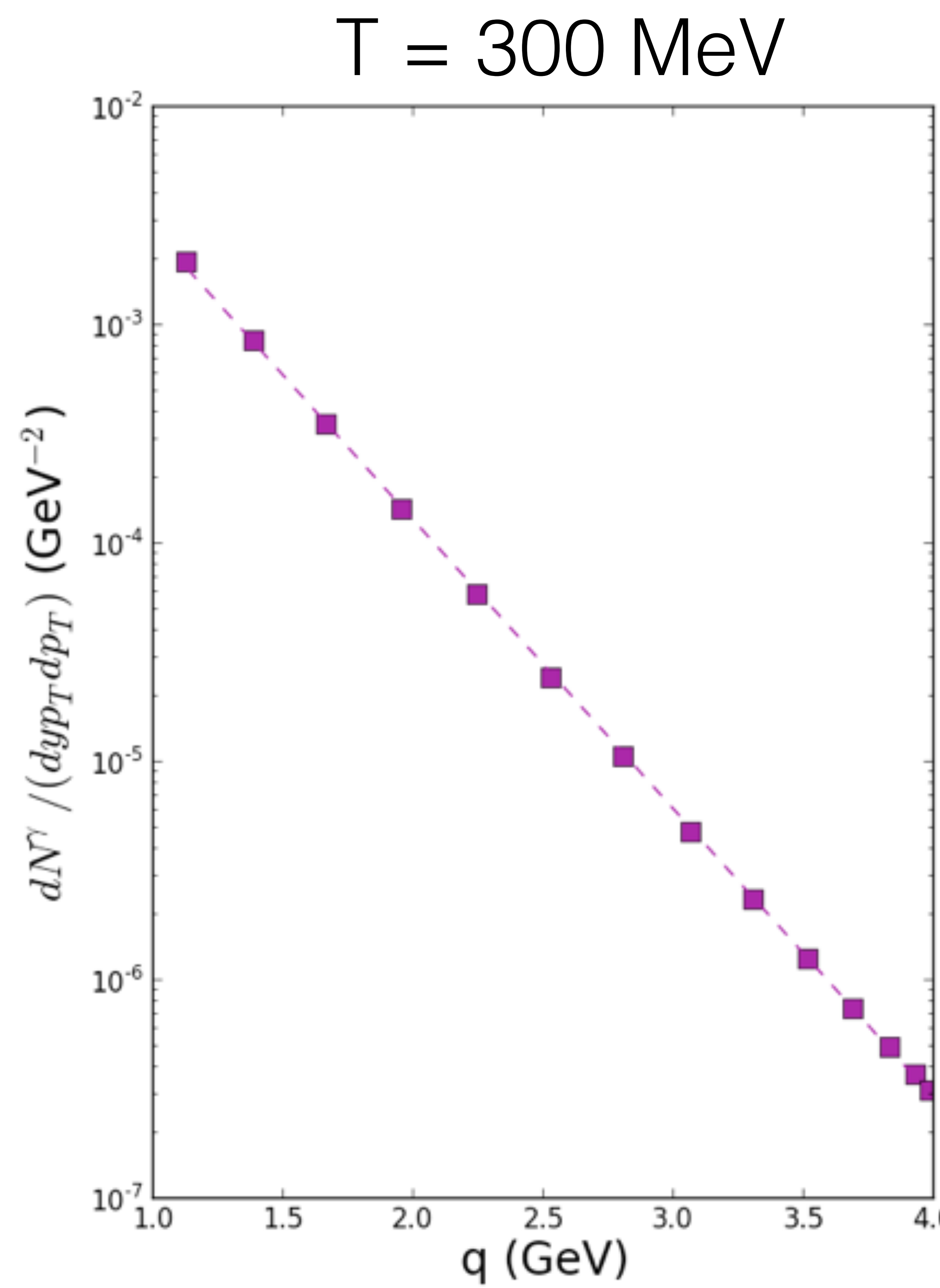

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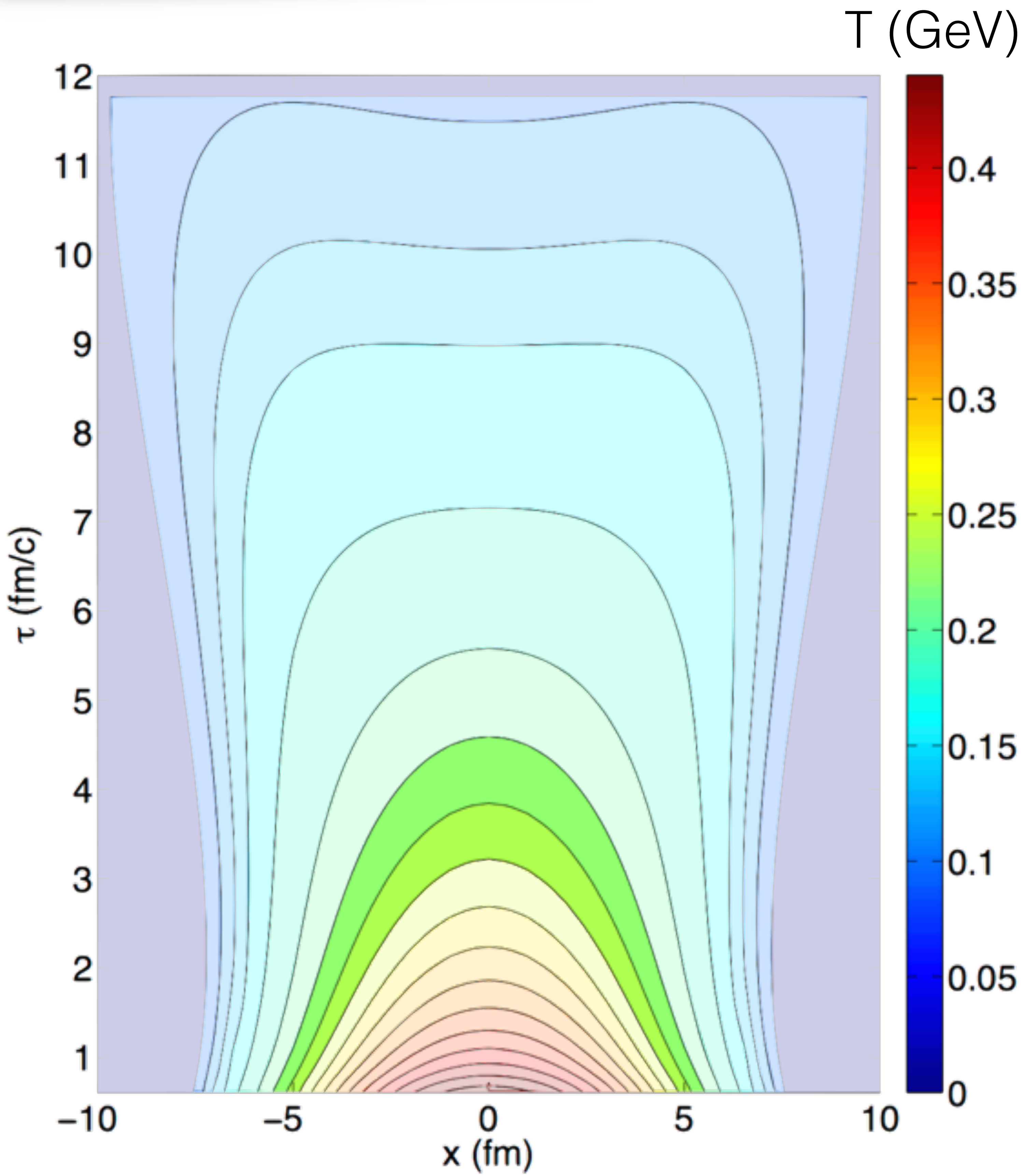

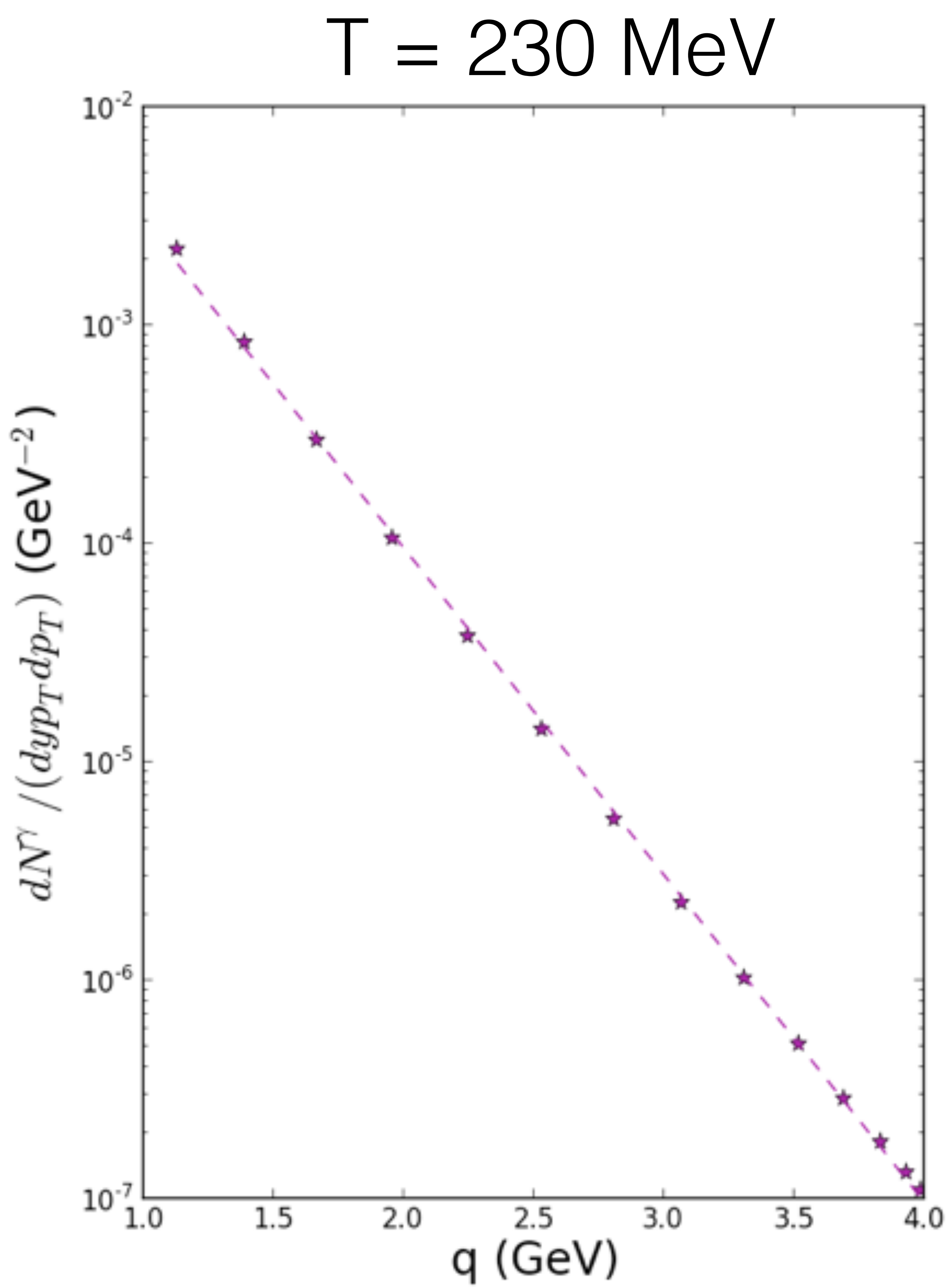

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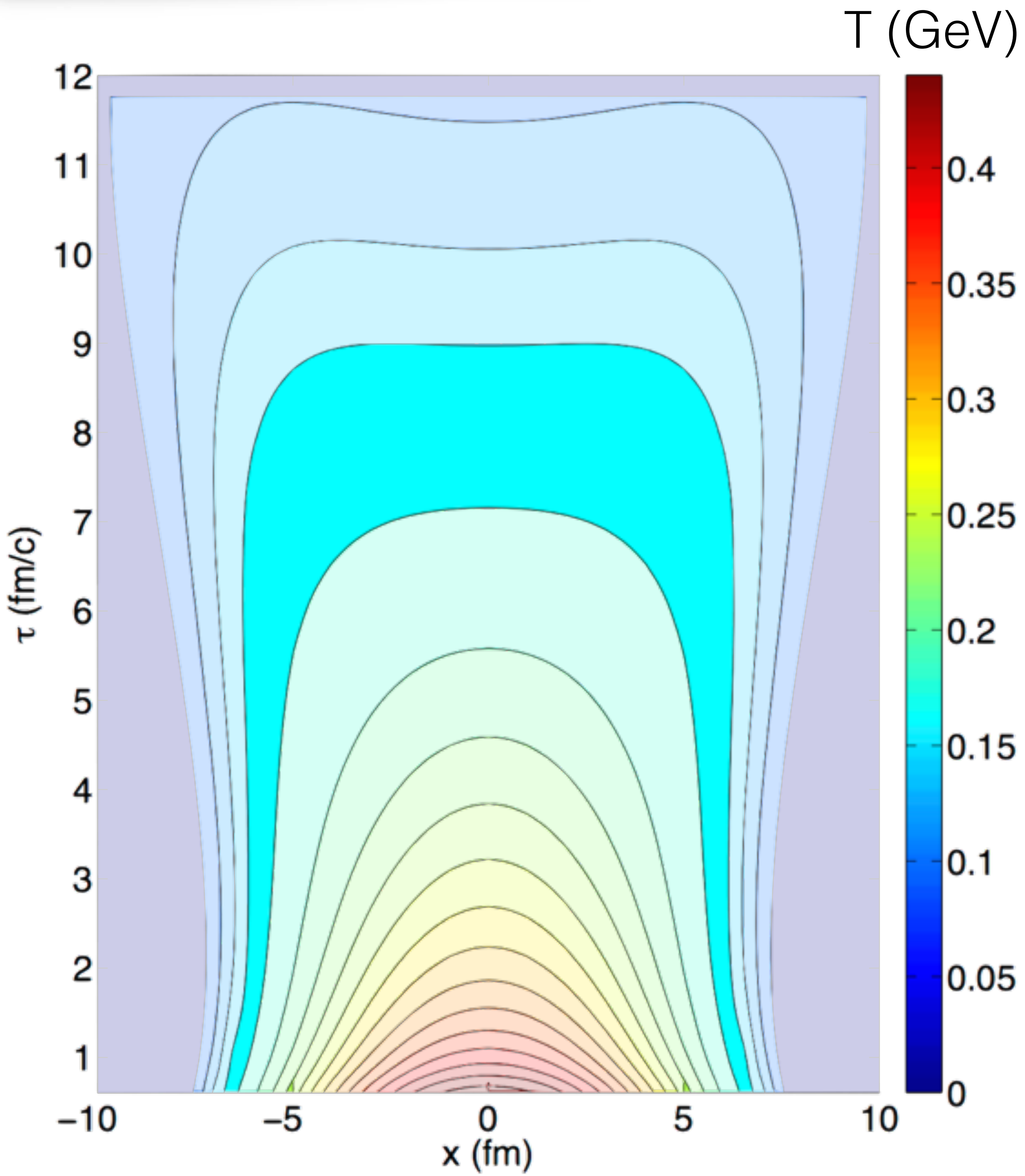

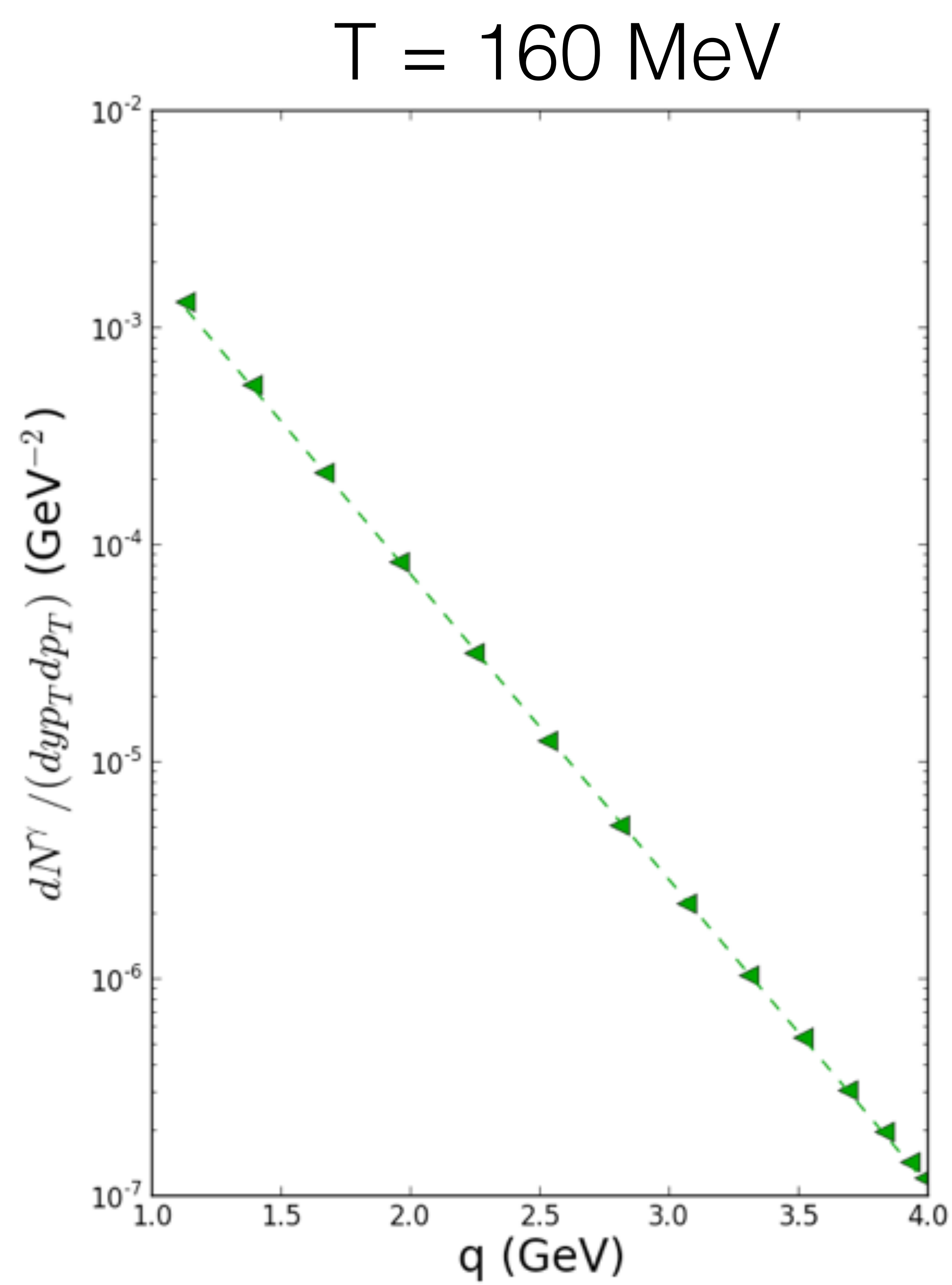

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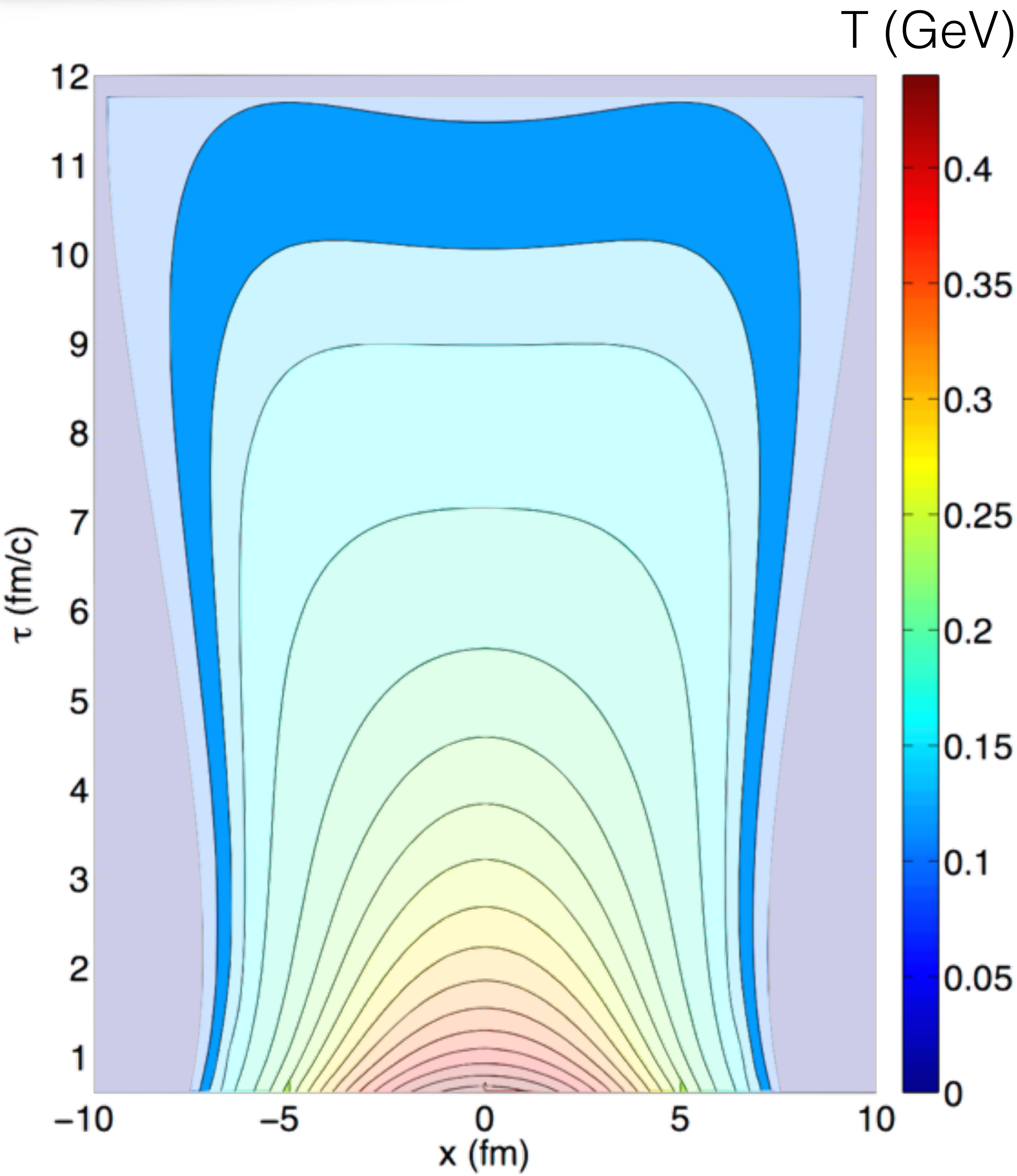
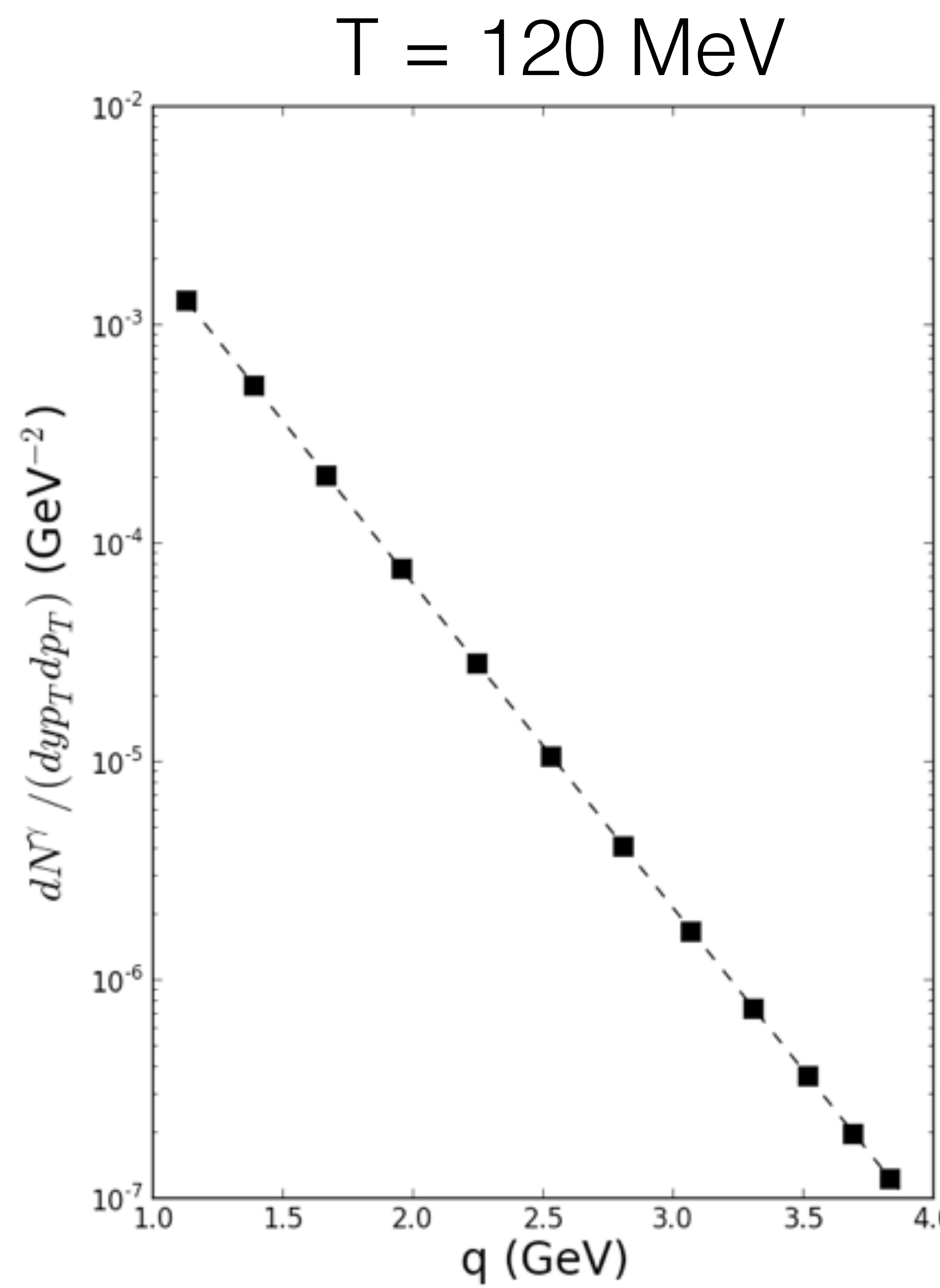
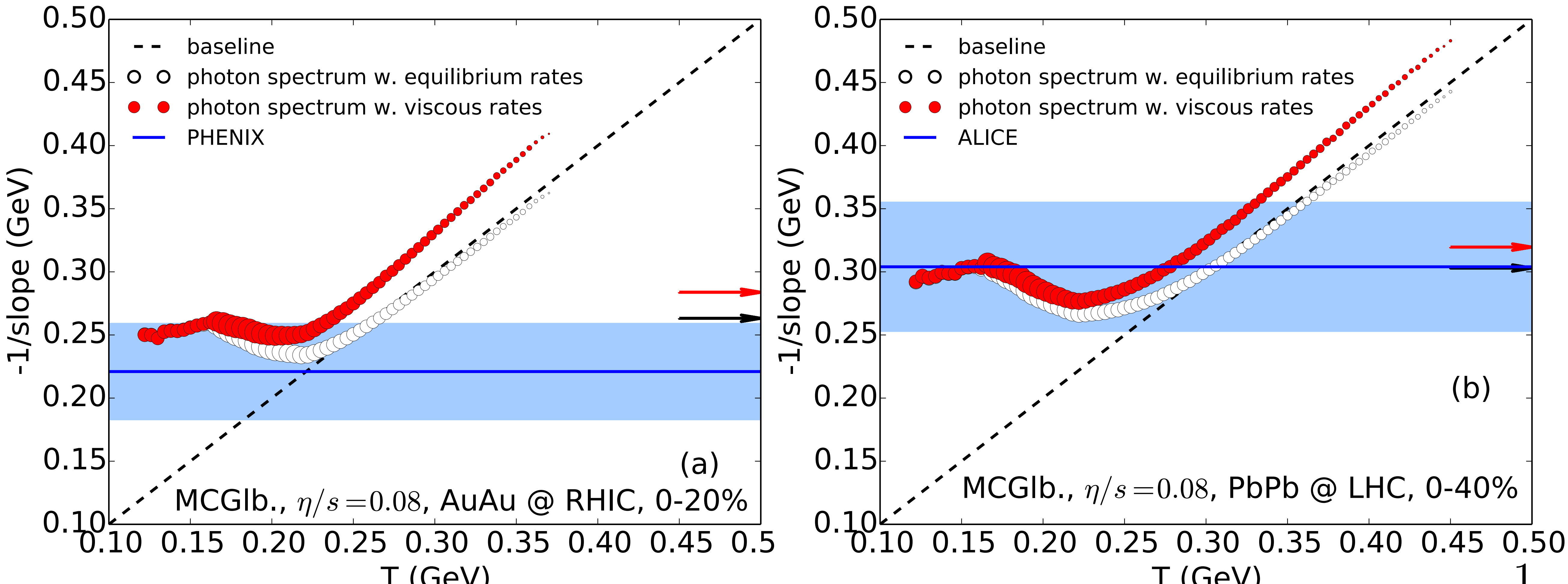




Fitted T_{eff} vs. True Temperature

C. Shen, U. Heinz, J.-F. Paquet and C. Gale, Phys. Rev. C 89, 044910 (2014)

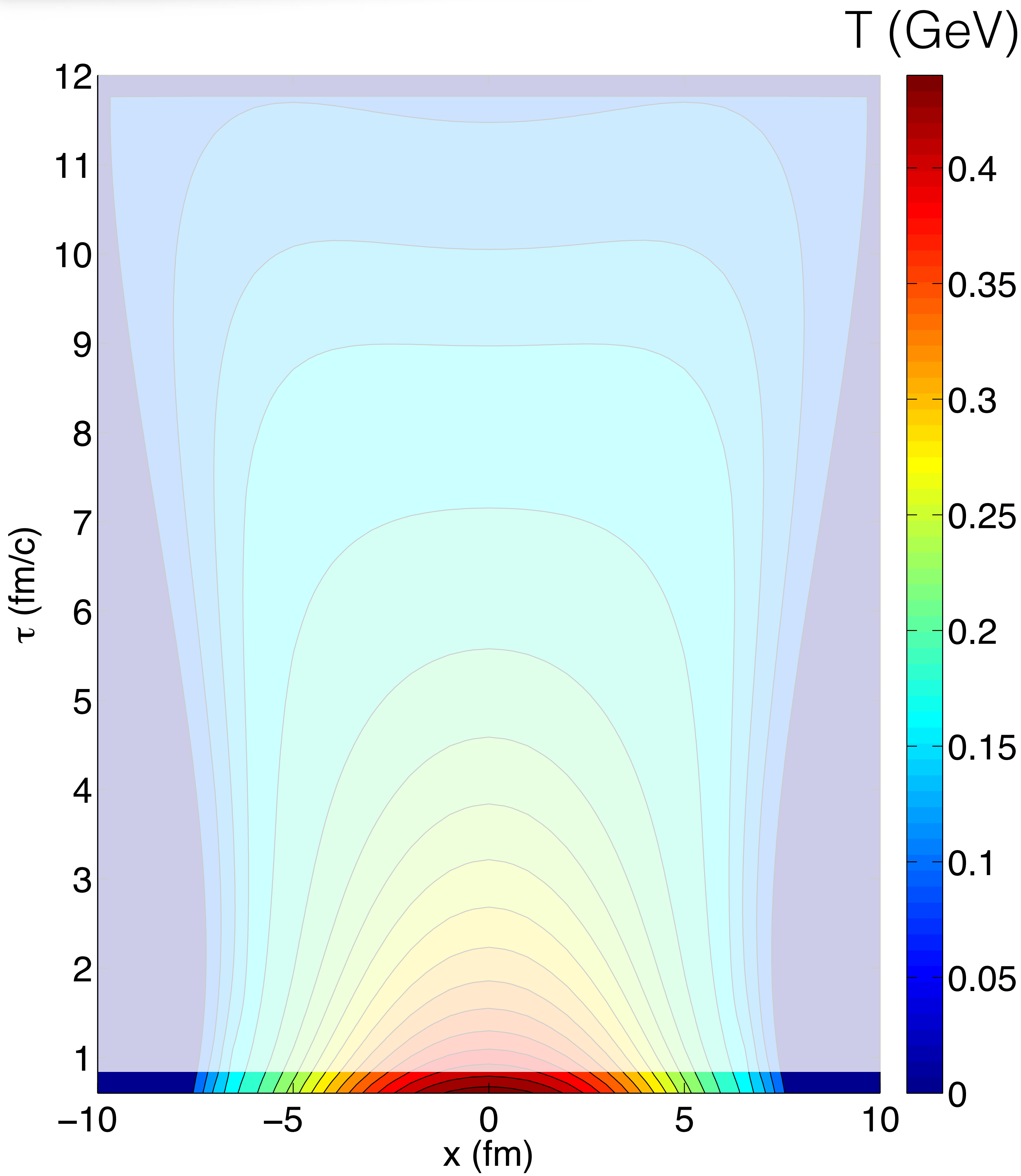


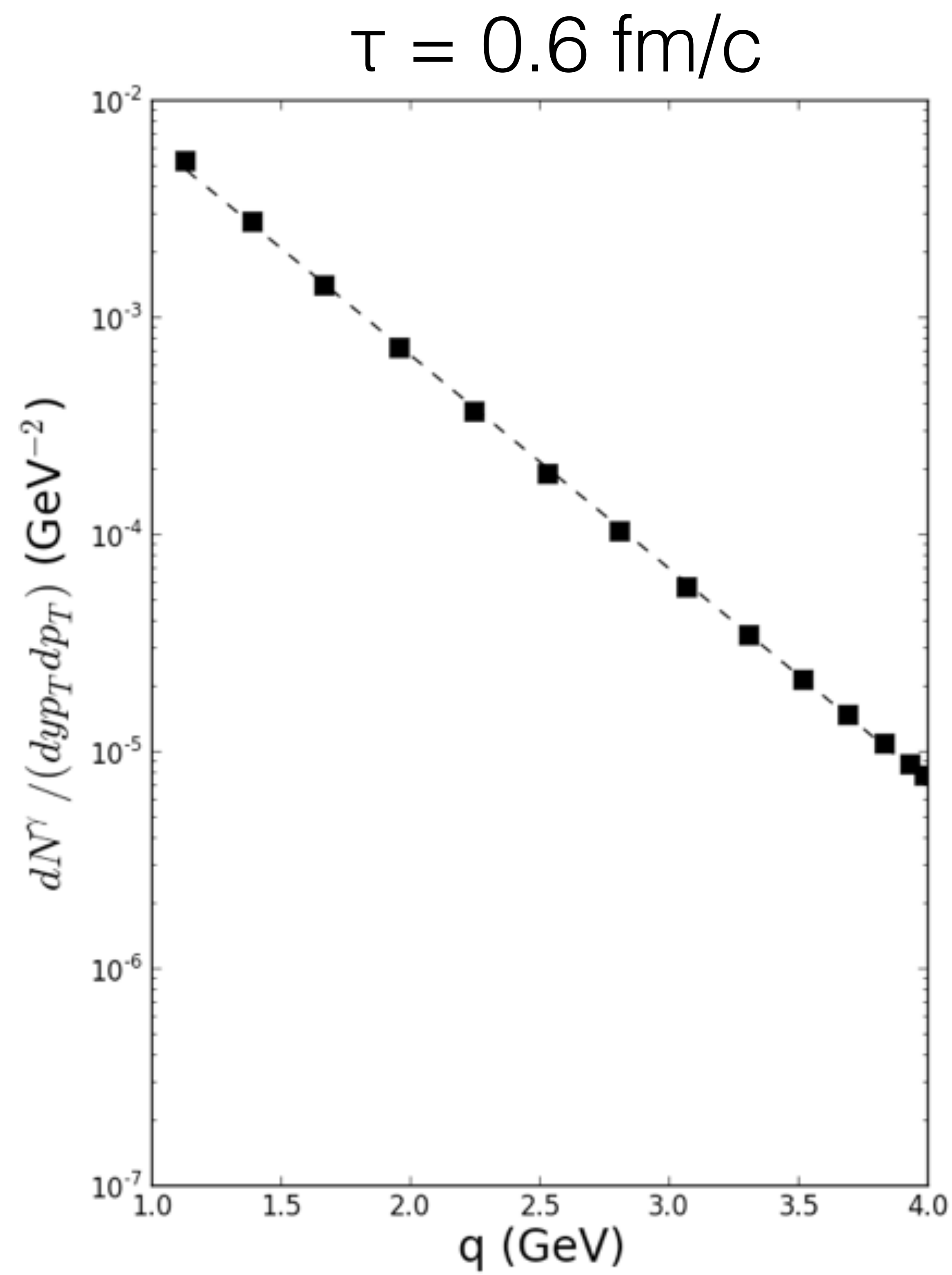
$$T_{\rm eff} = -\frac{1}{\rm slope}$$

- **All** photons with T < 250 MeV at RHIC and < 300 MeV at LHC carries T_{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





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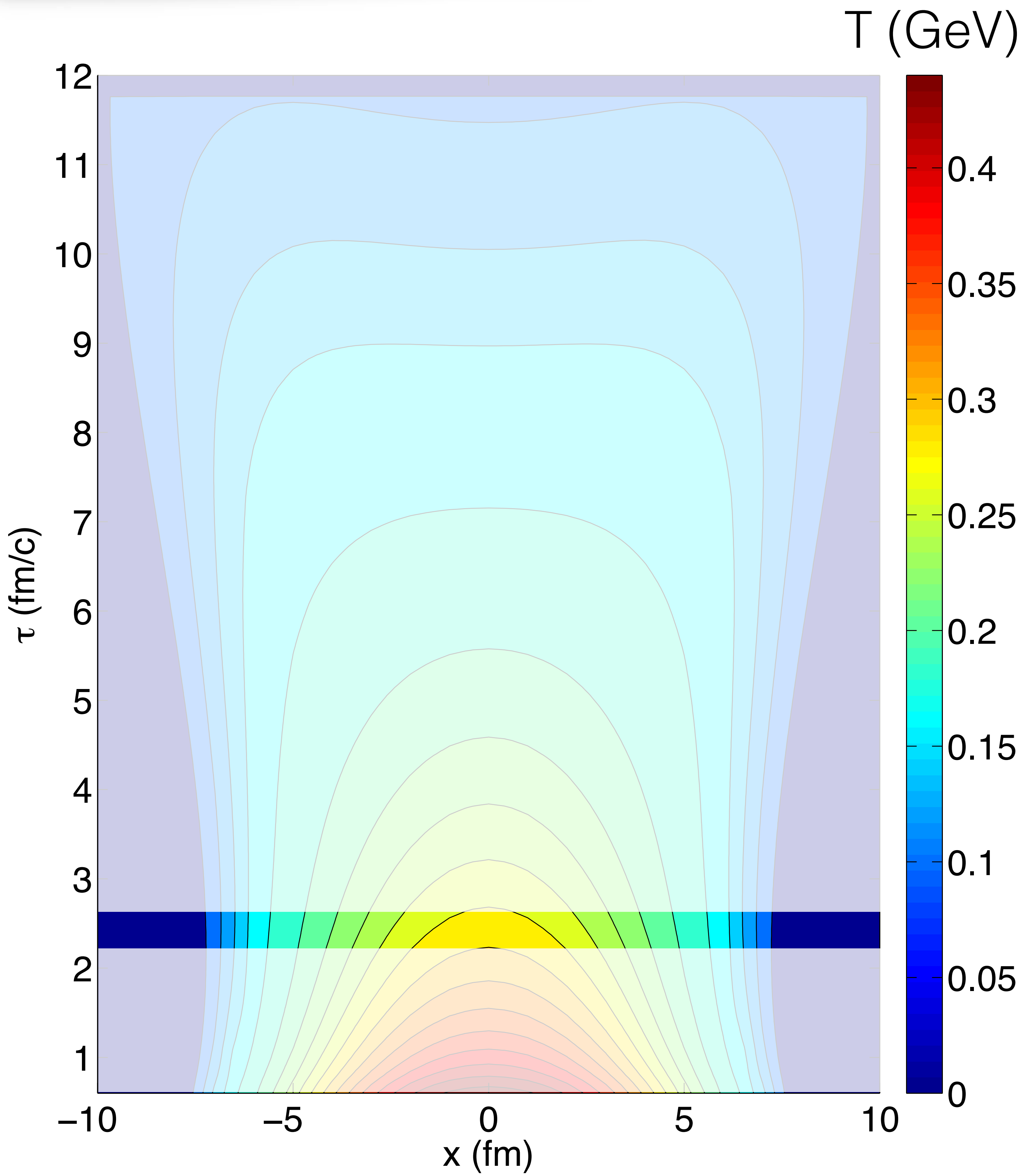

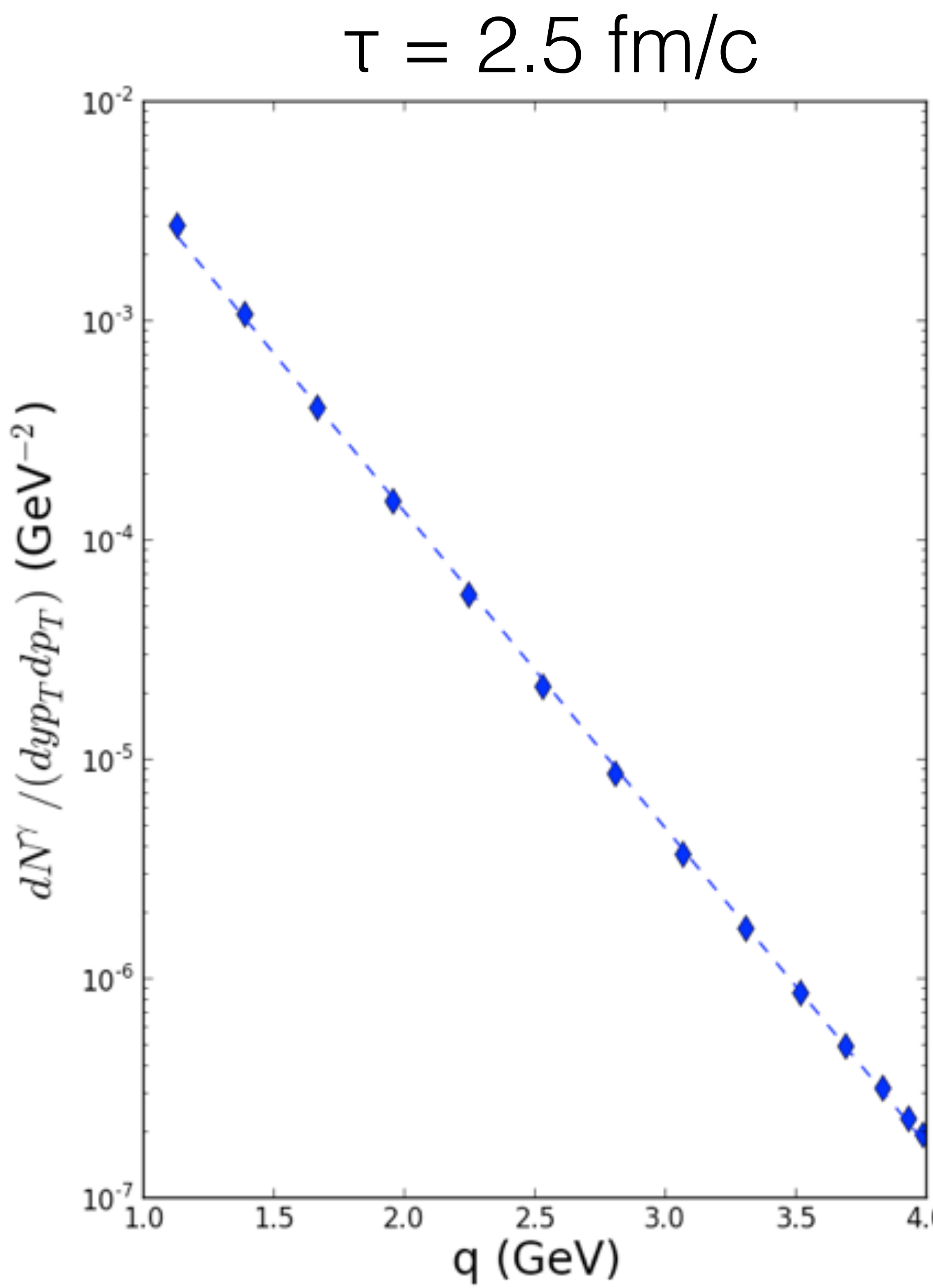

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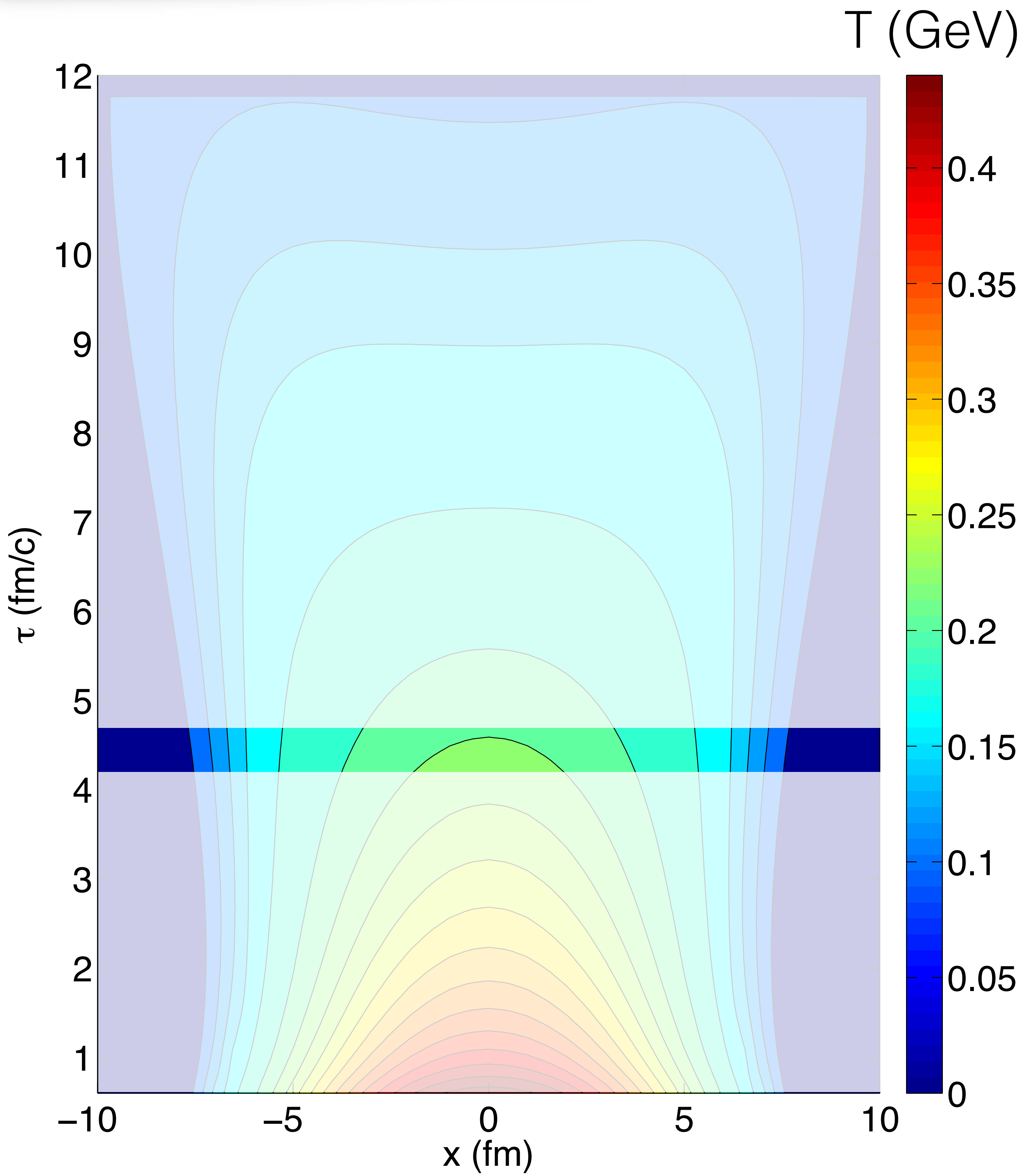

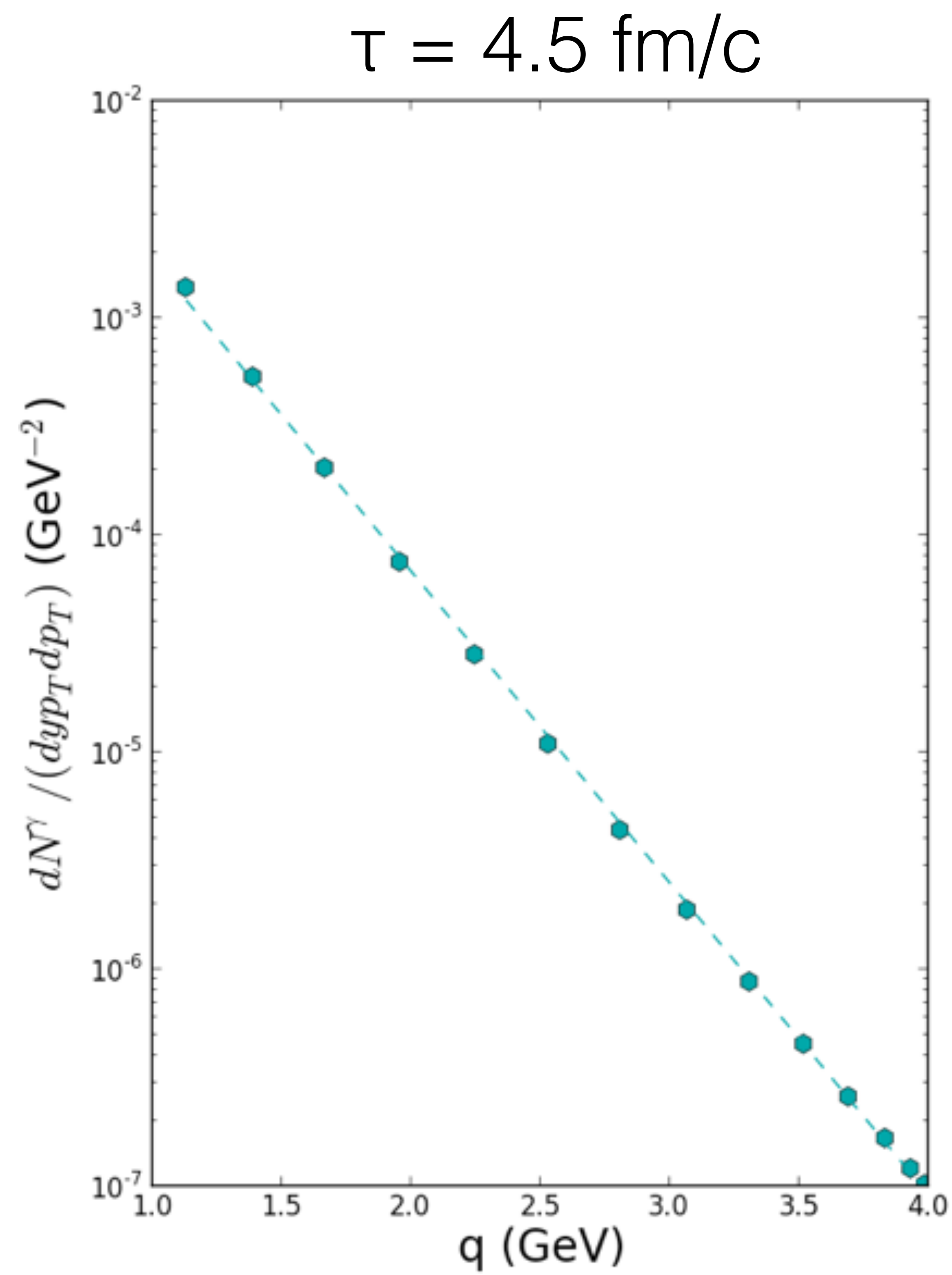

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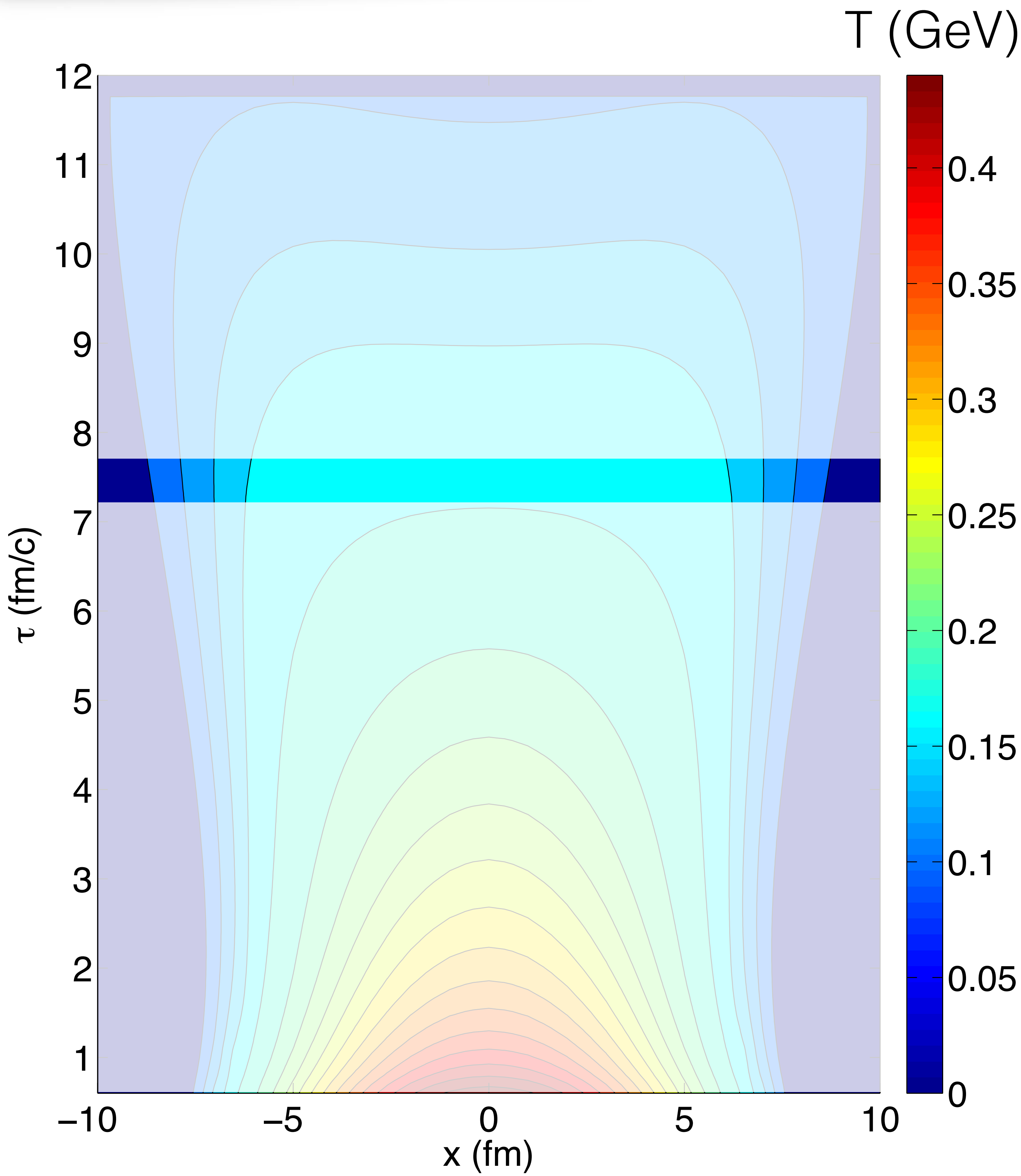
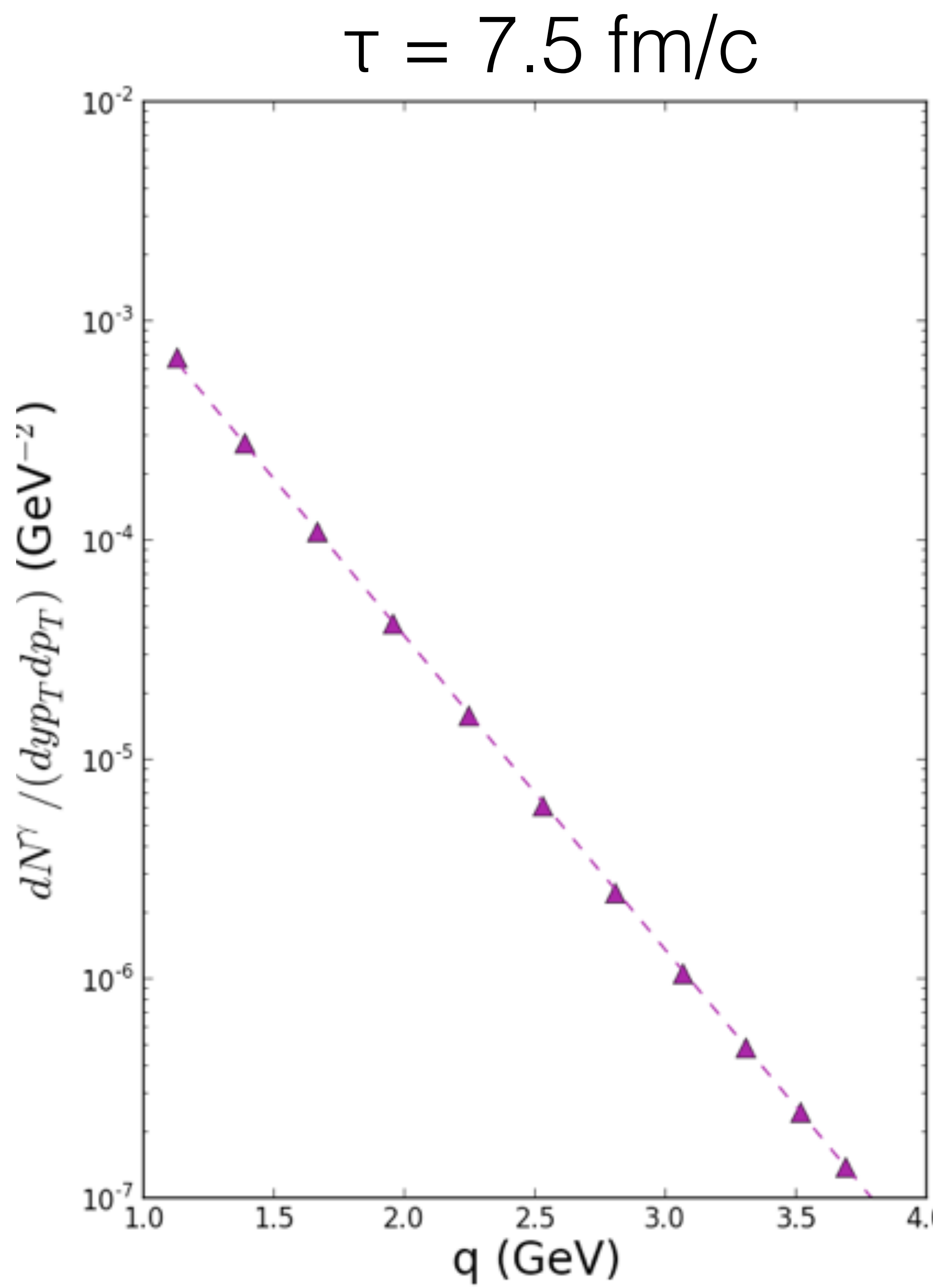
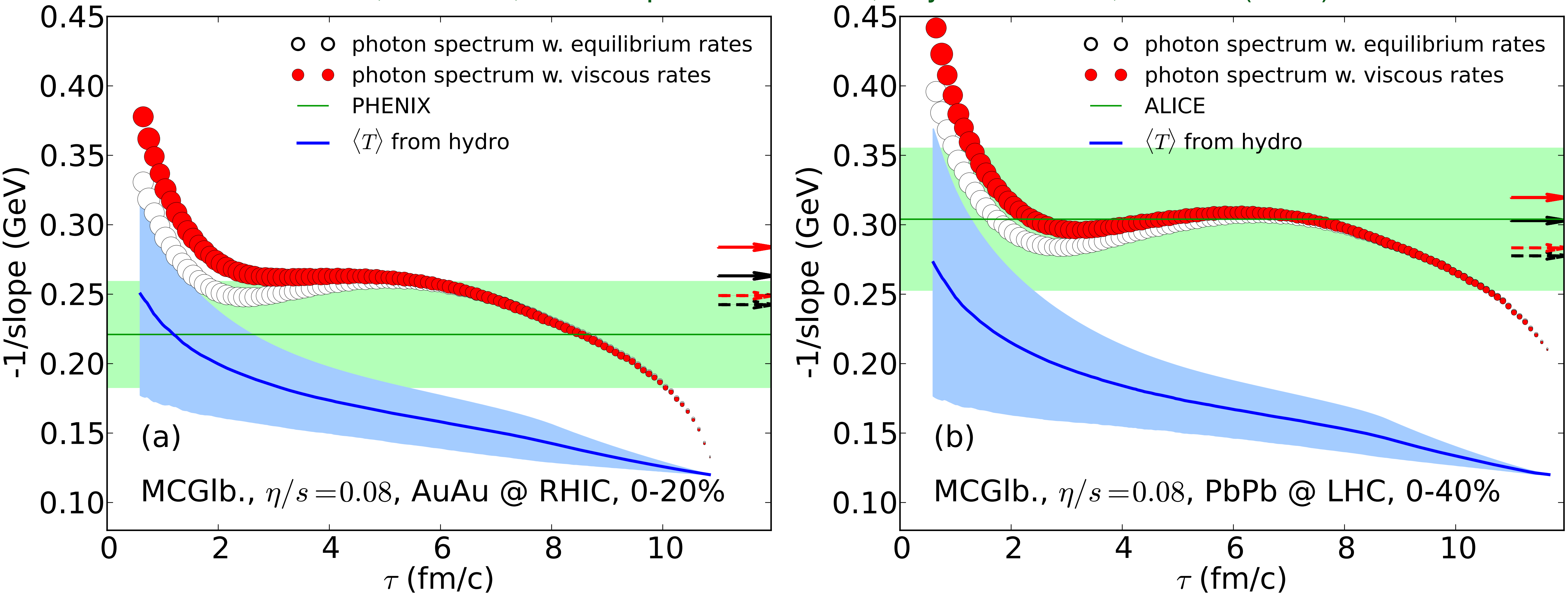




Fitted T_{eff} vs. Emission Time

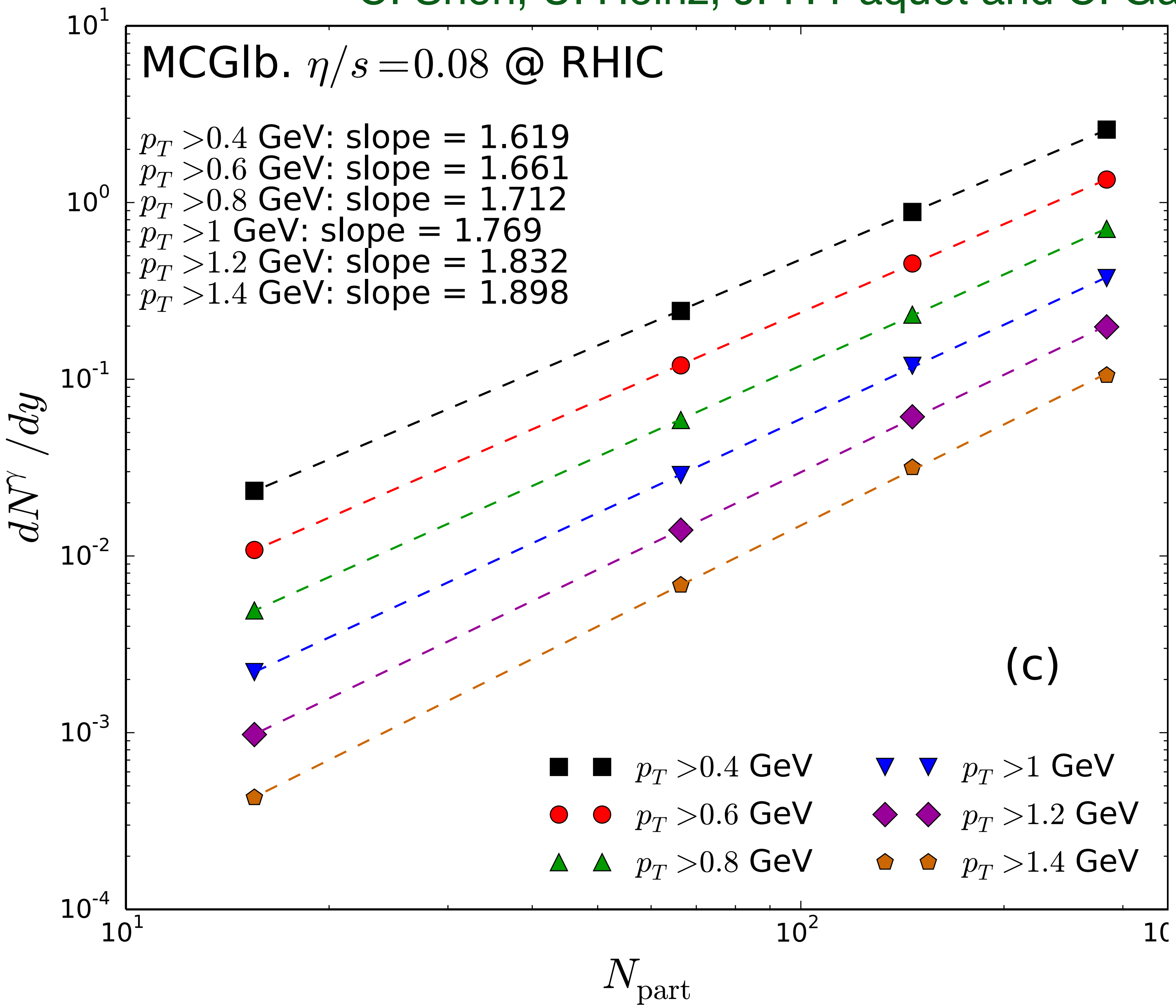
C. Shen, U. Heinz, J.-F. Paquet and C. Gale, Phys. Rev. C 89, 044910 (2014)



- 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

Centrality dependence of photon yield

C. Shen, U. Heinz, J.-F. Paquet and C. Gale, Phys. Rev. C 89, 044910 (2014)



$$\frac{dN^\gamma}{dy} \propto N_{\mathrm{part}}^{\alpha}$$

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

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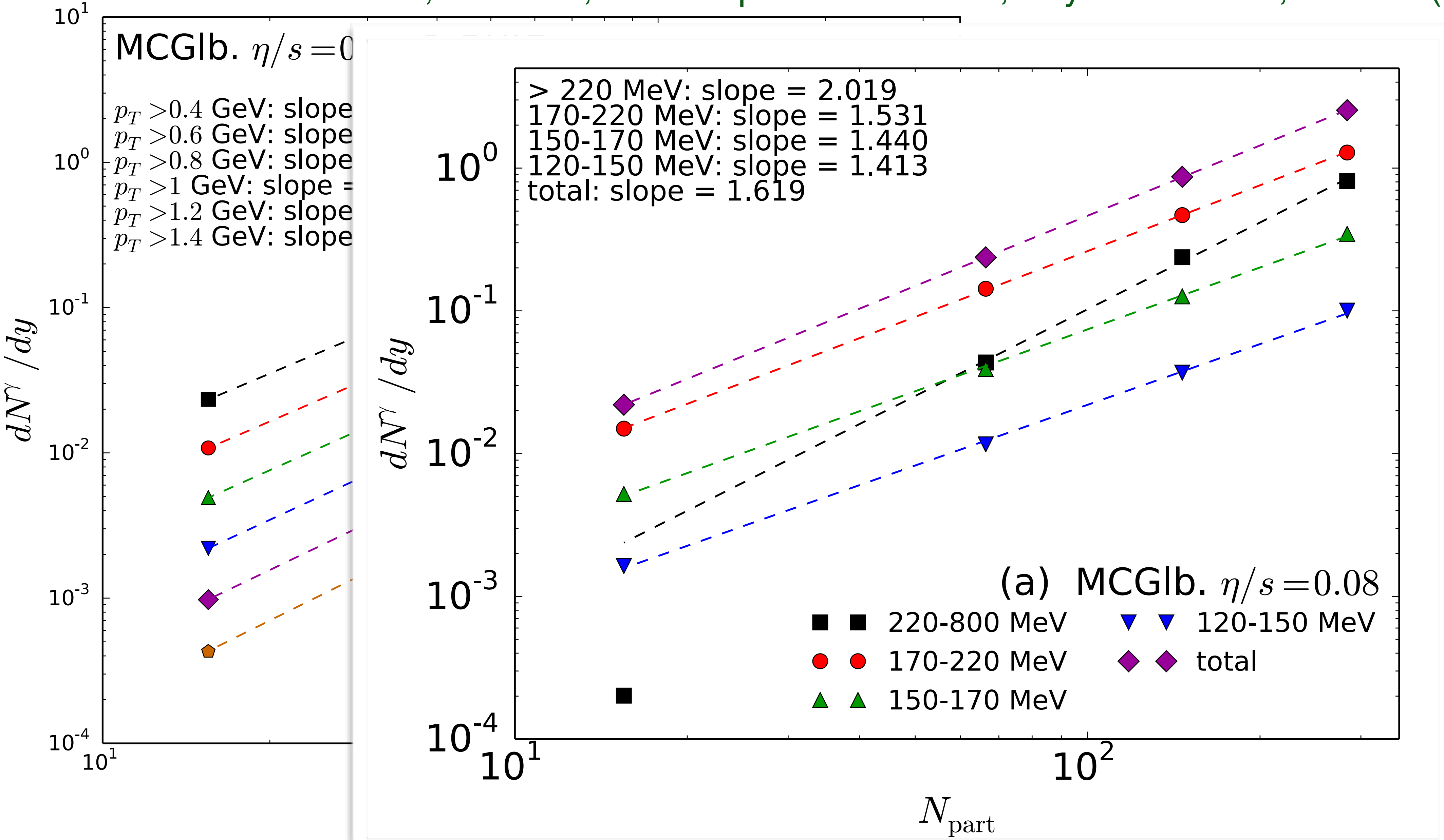

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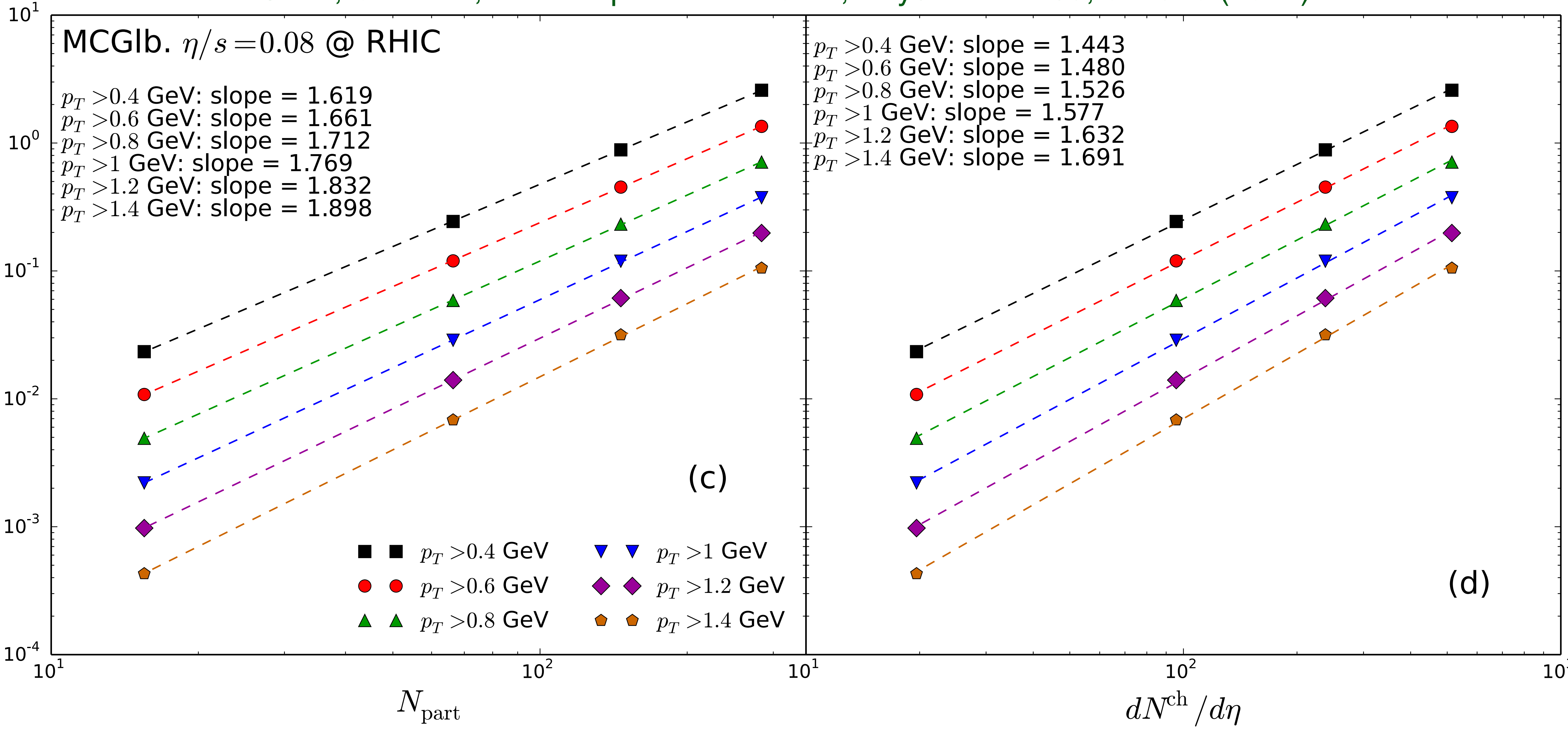

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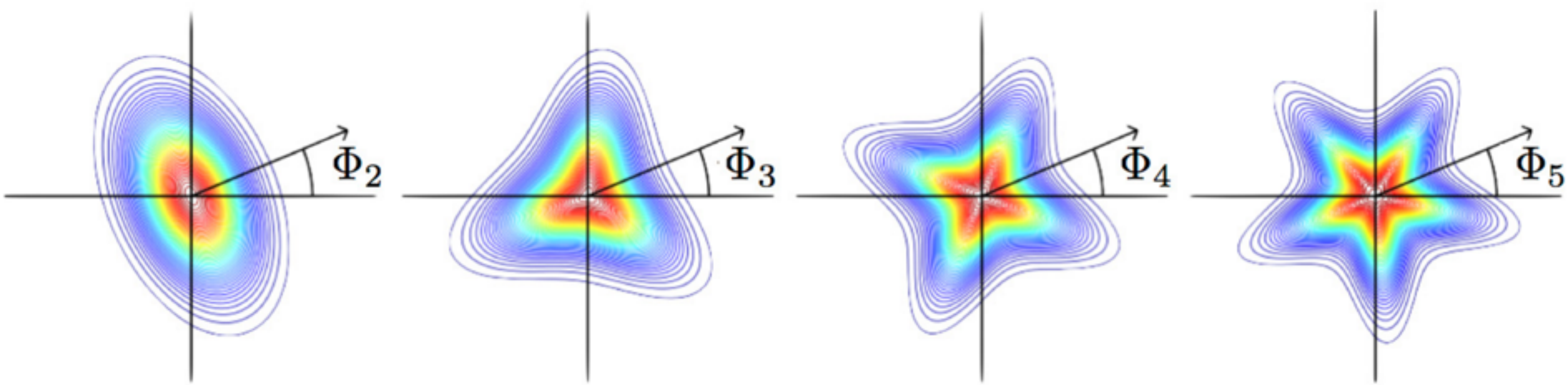
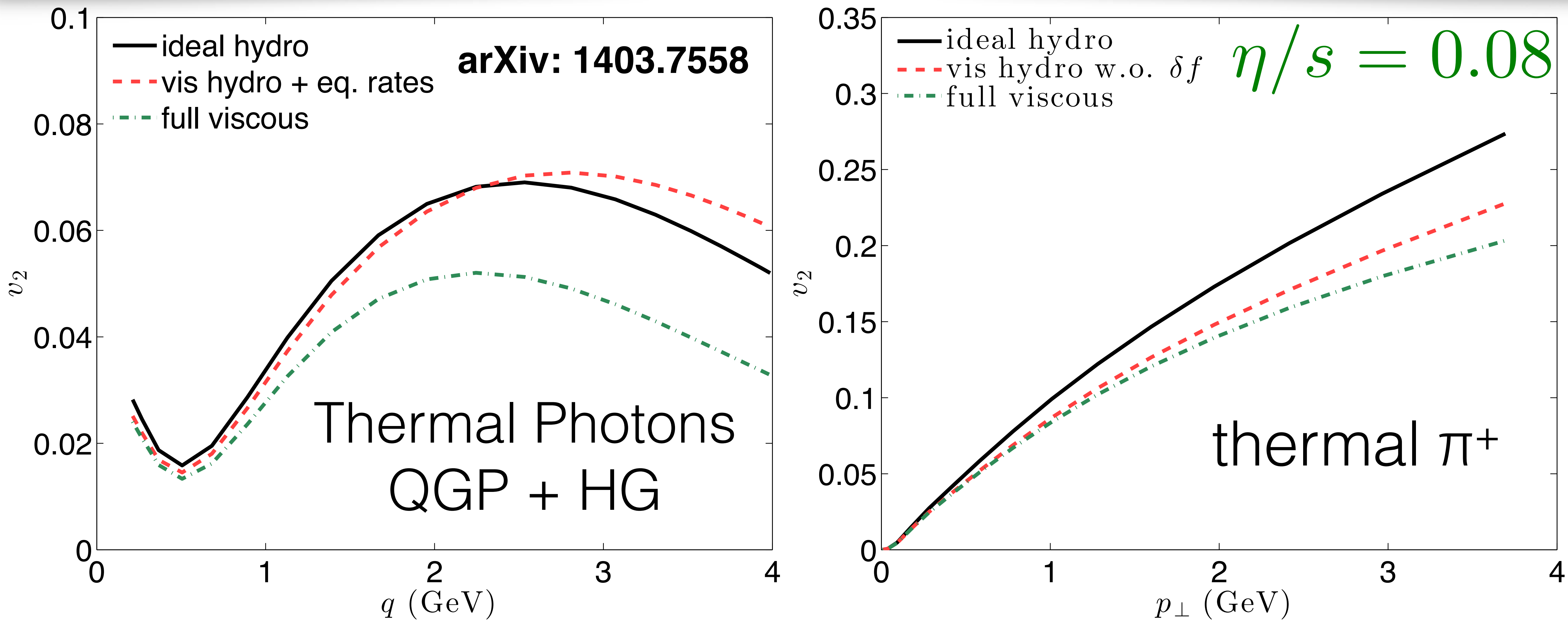
$$dN^\gamma/dy \text{ vs. } dN^{\text{ch}}/d\eta$$ → **less model dependent comparison**

Photon anisotropic flow

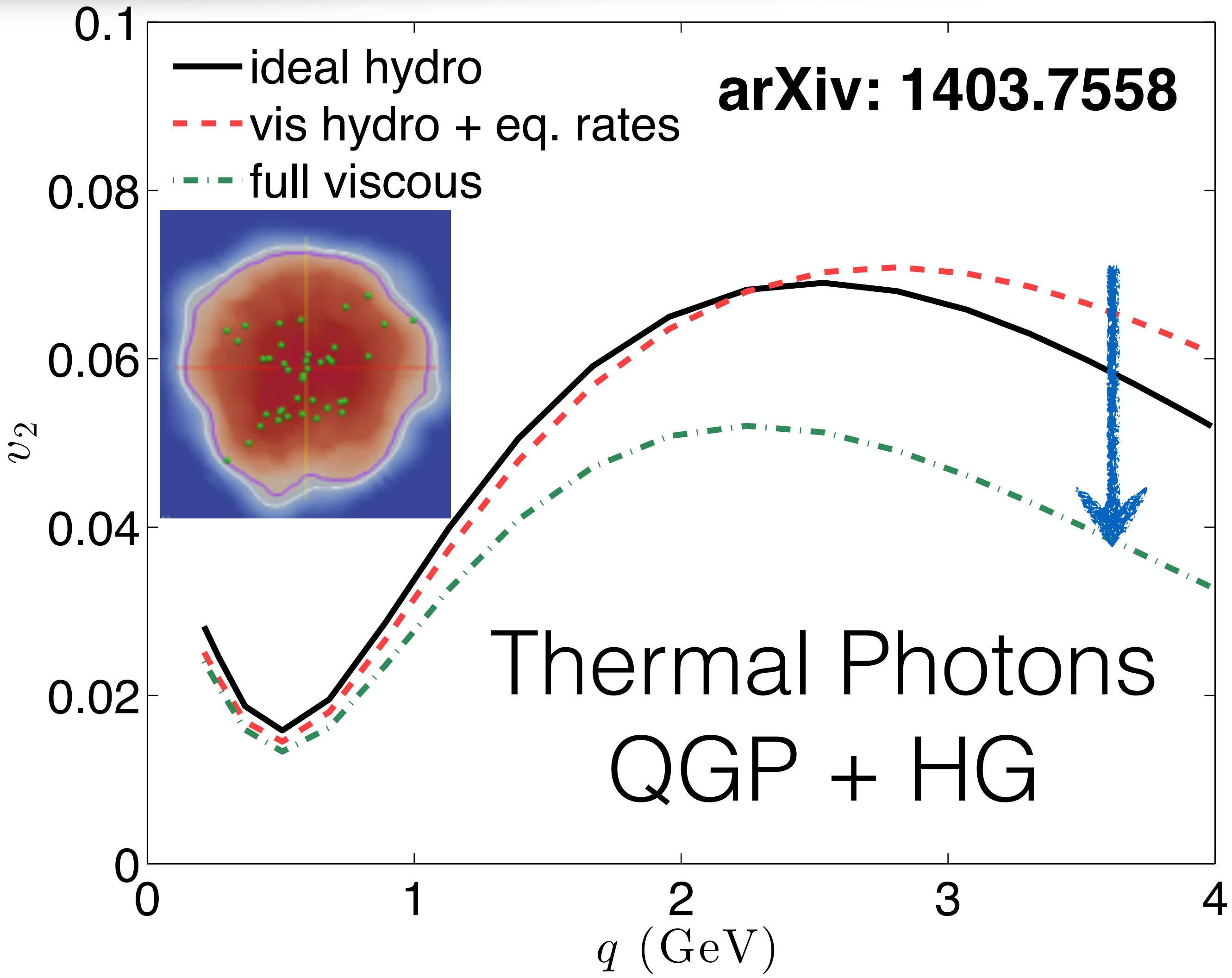


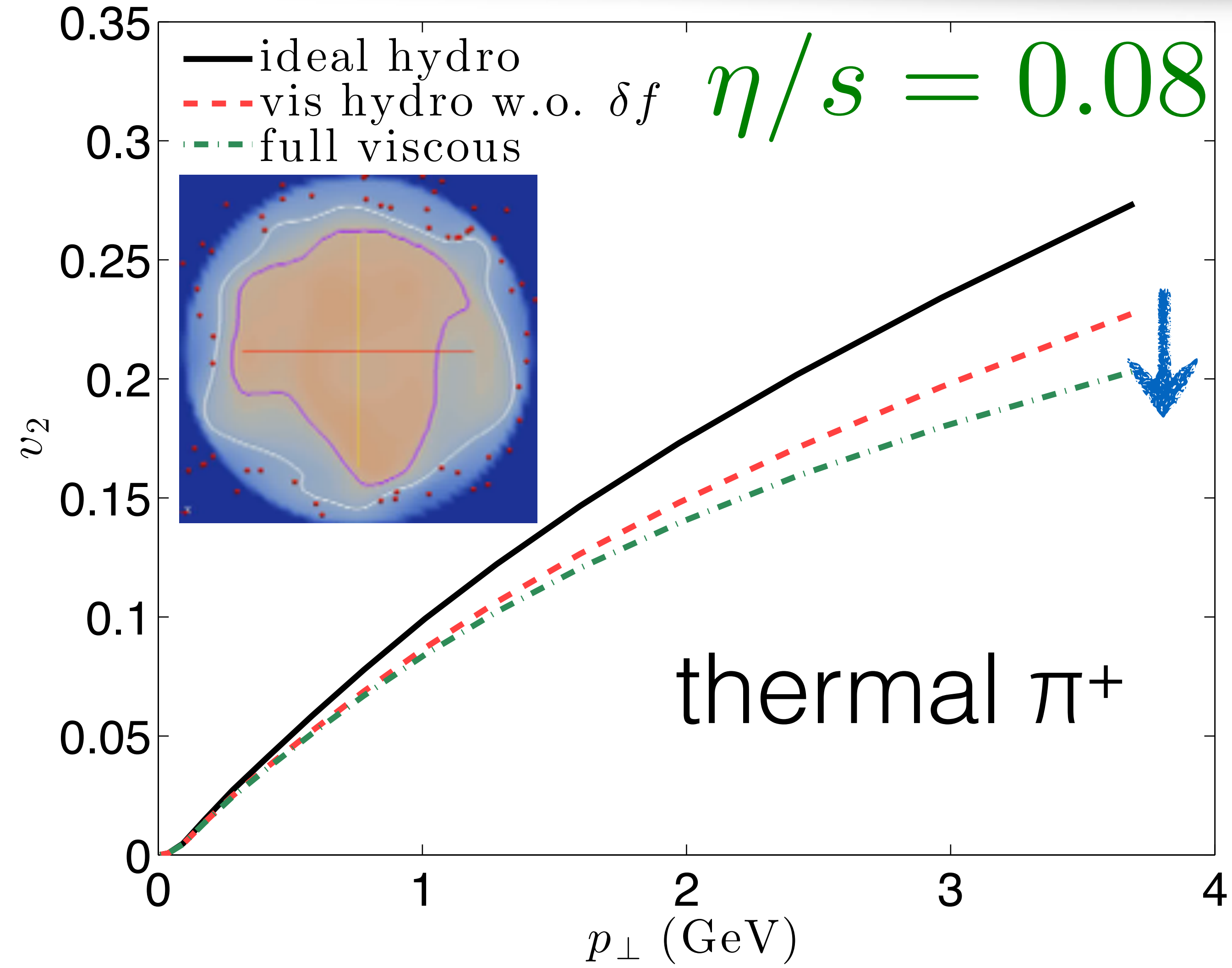
Shear viscous effects on photon elliptic flow



- Shear viscous suppression of photon v_2 is dominated by the viscous corrections to the photon emission rate
- Photon elliptic flow is sensitive to the larger shear stress tensor at early times

Shear viscous effects on photon elliptic flow





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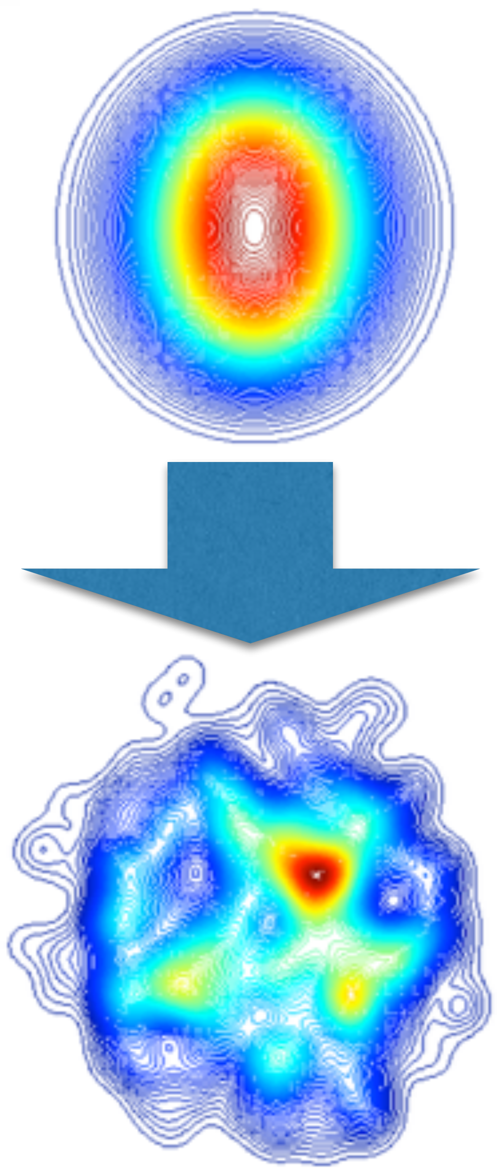
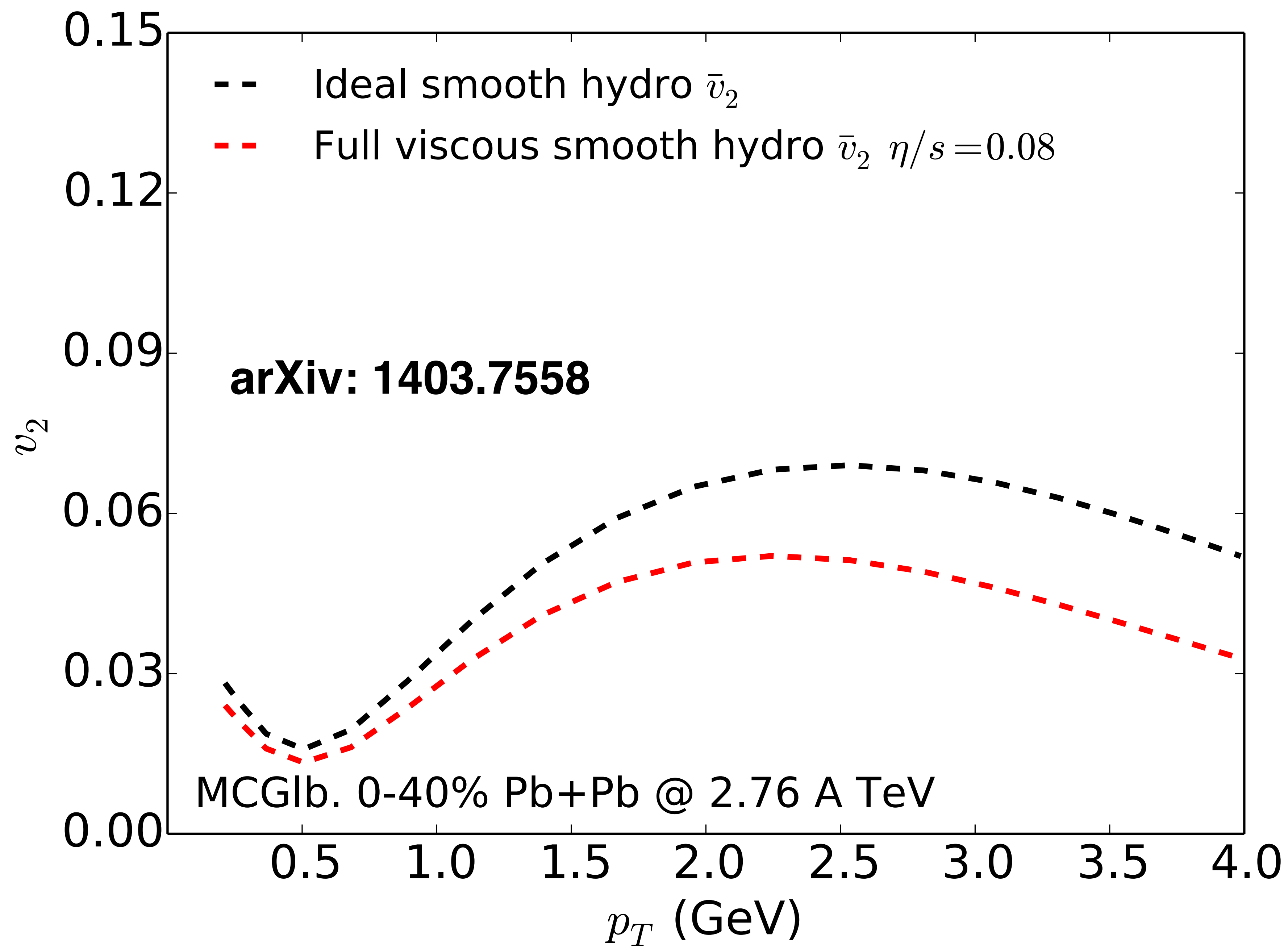
Fluctuation effects on photon elliptic flow





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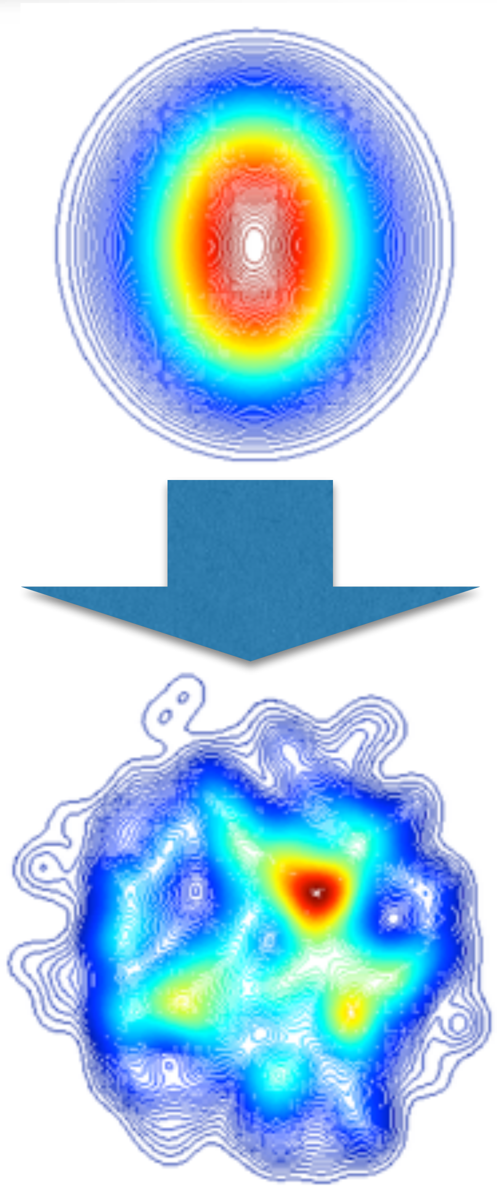
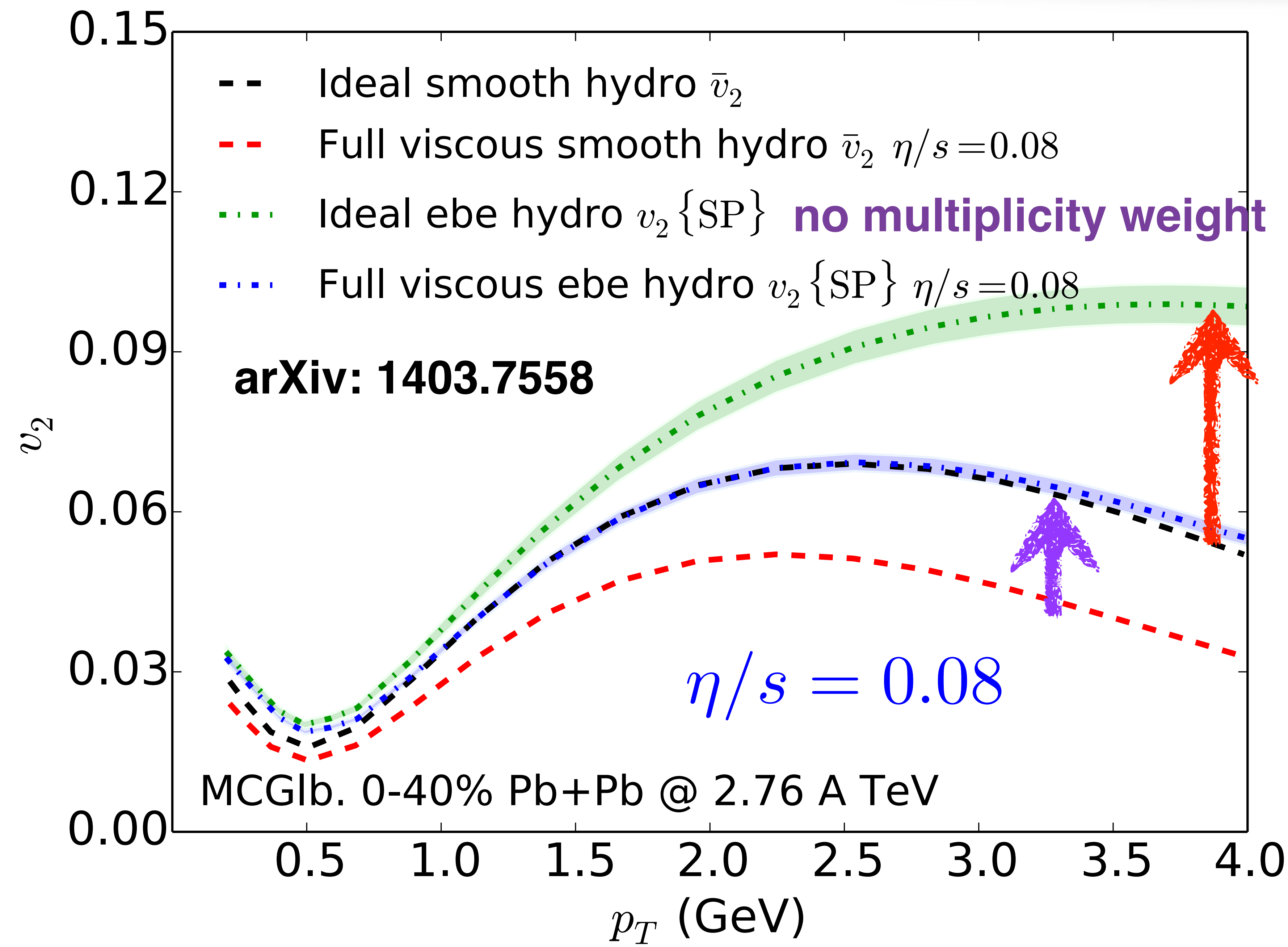
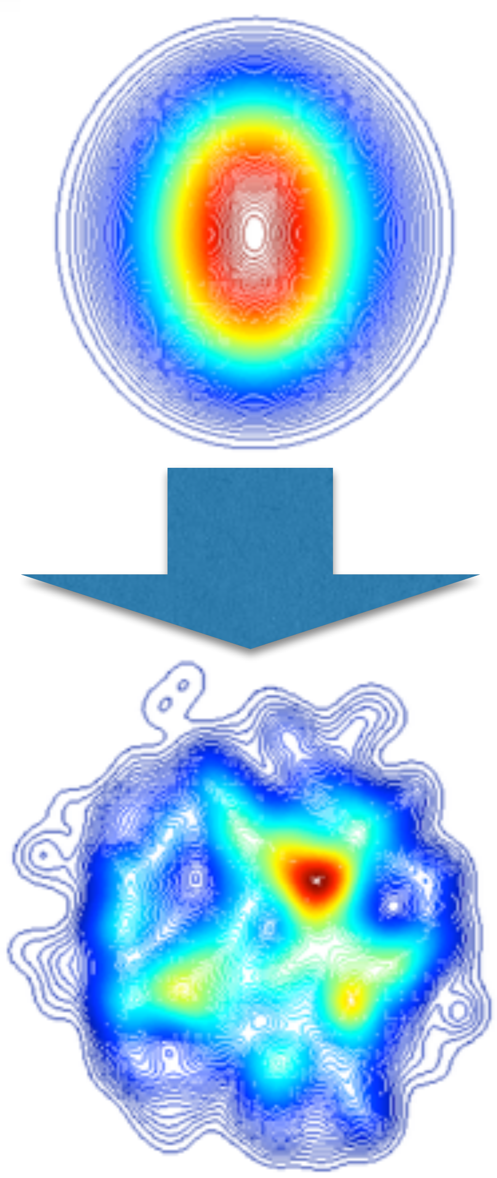
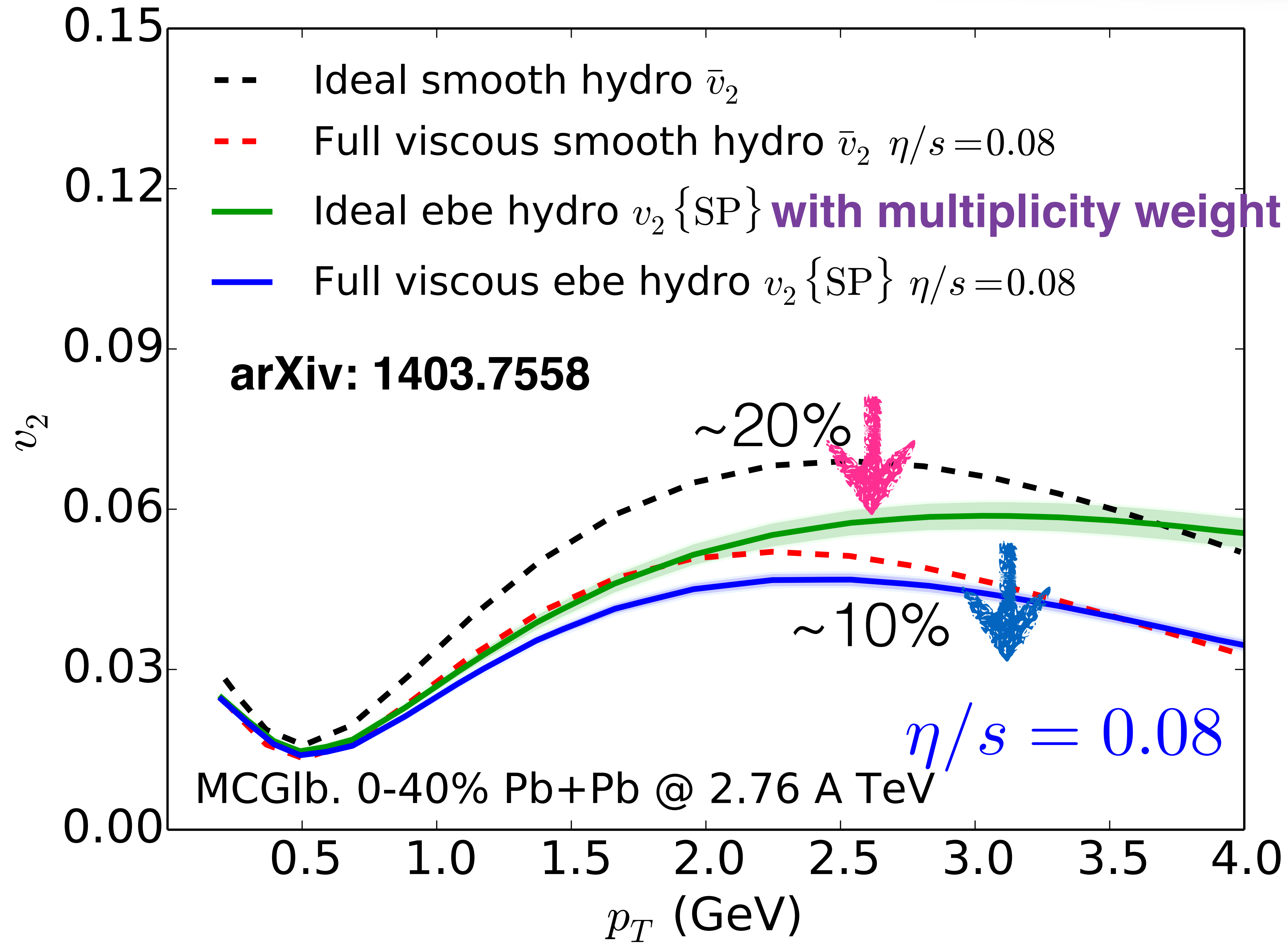




- Initial fluctuations increase photons' elliptic flow

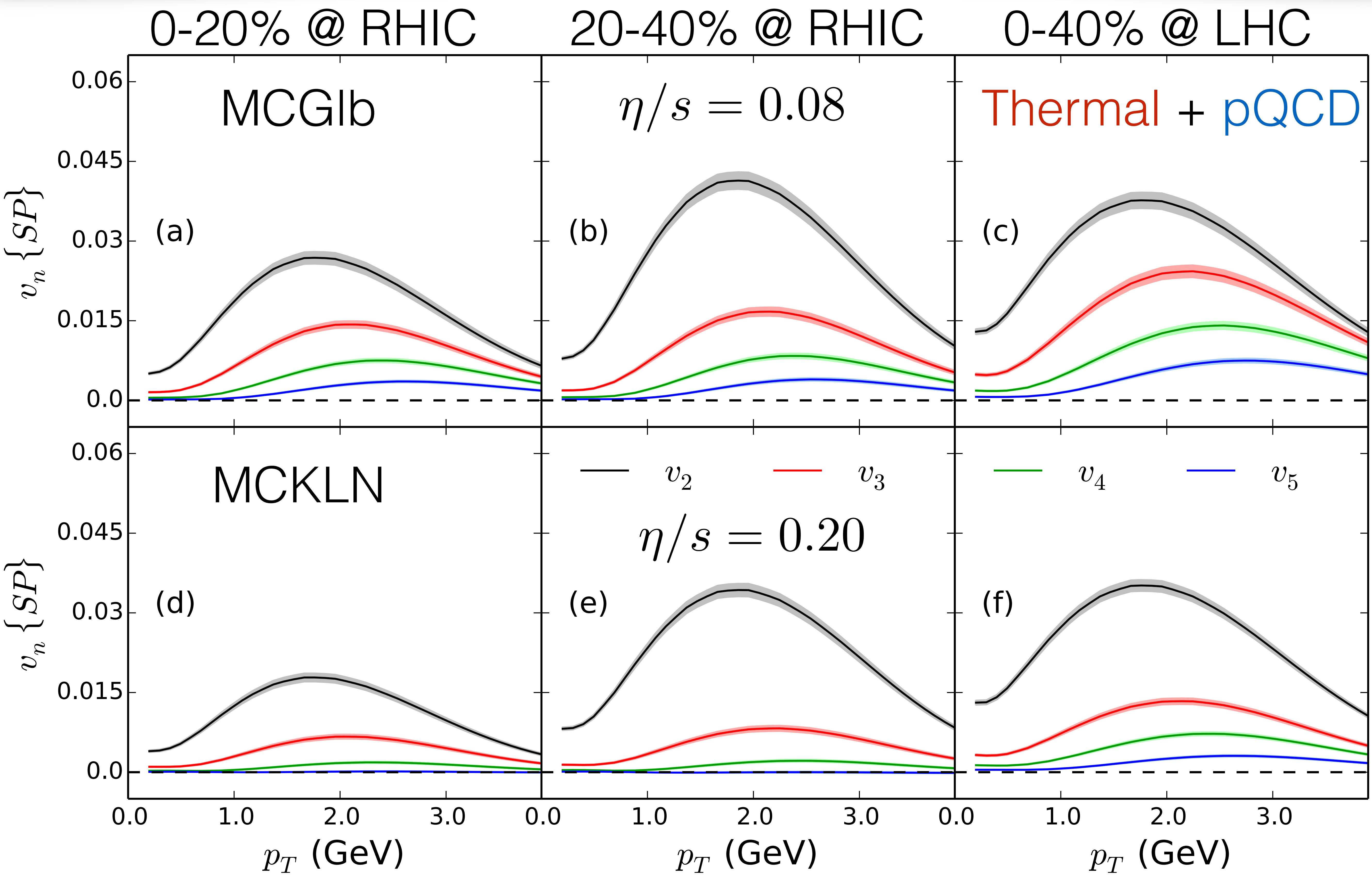
Fluctuation effects on photon elliptic flow





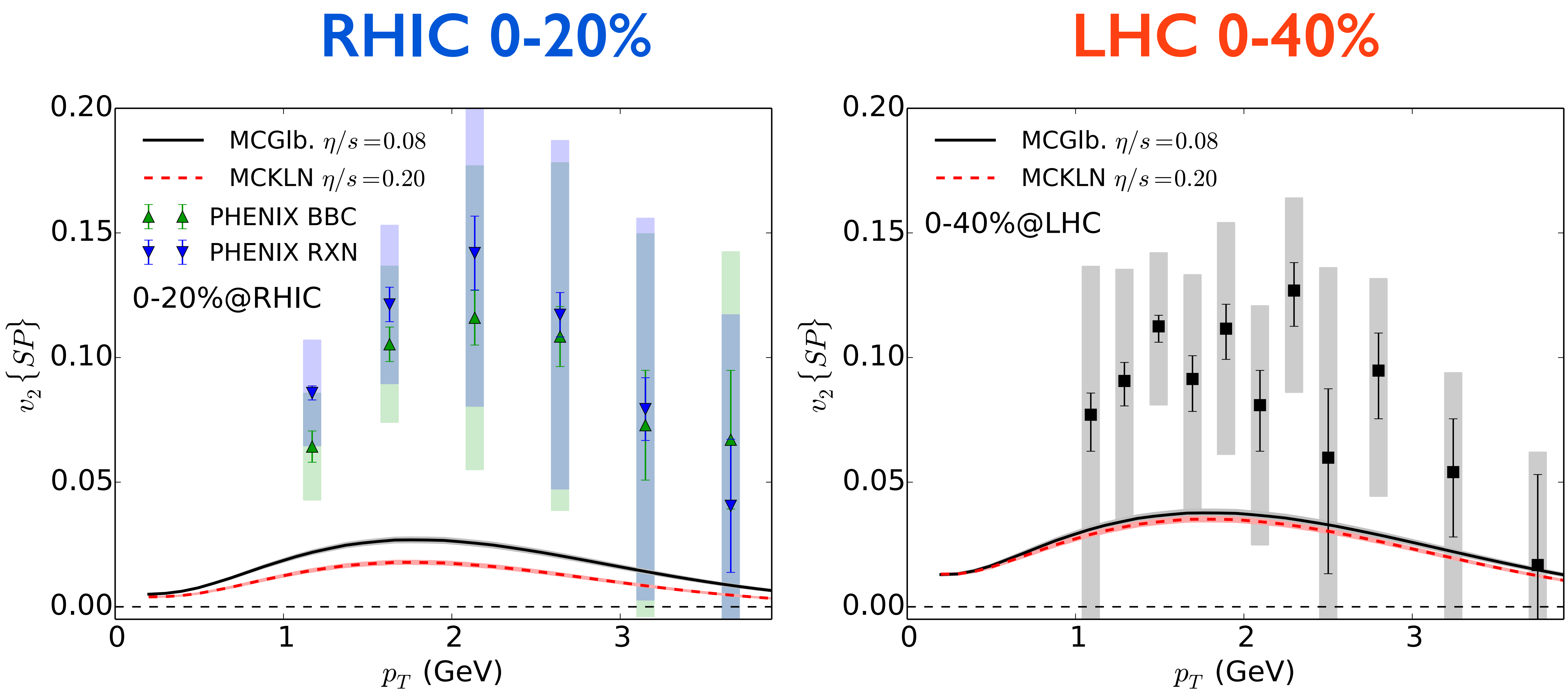
- Initial fluctuations increase photons' elliptic flow
- The additional photon multiplicity weighting biases e-b-e v_2 towards central collisions, resulting in ~10-20% smaller v_2 compared to smooth hydro

Event-by-Event Full Viscous Photon v_n



arXiv: 1308.2111

The sky falls …



- Current calculations still underestimate the experimental data by a factor of 3!

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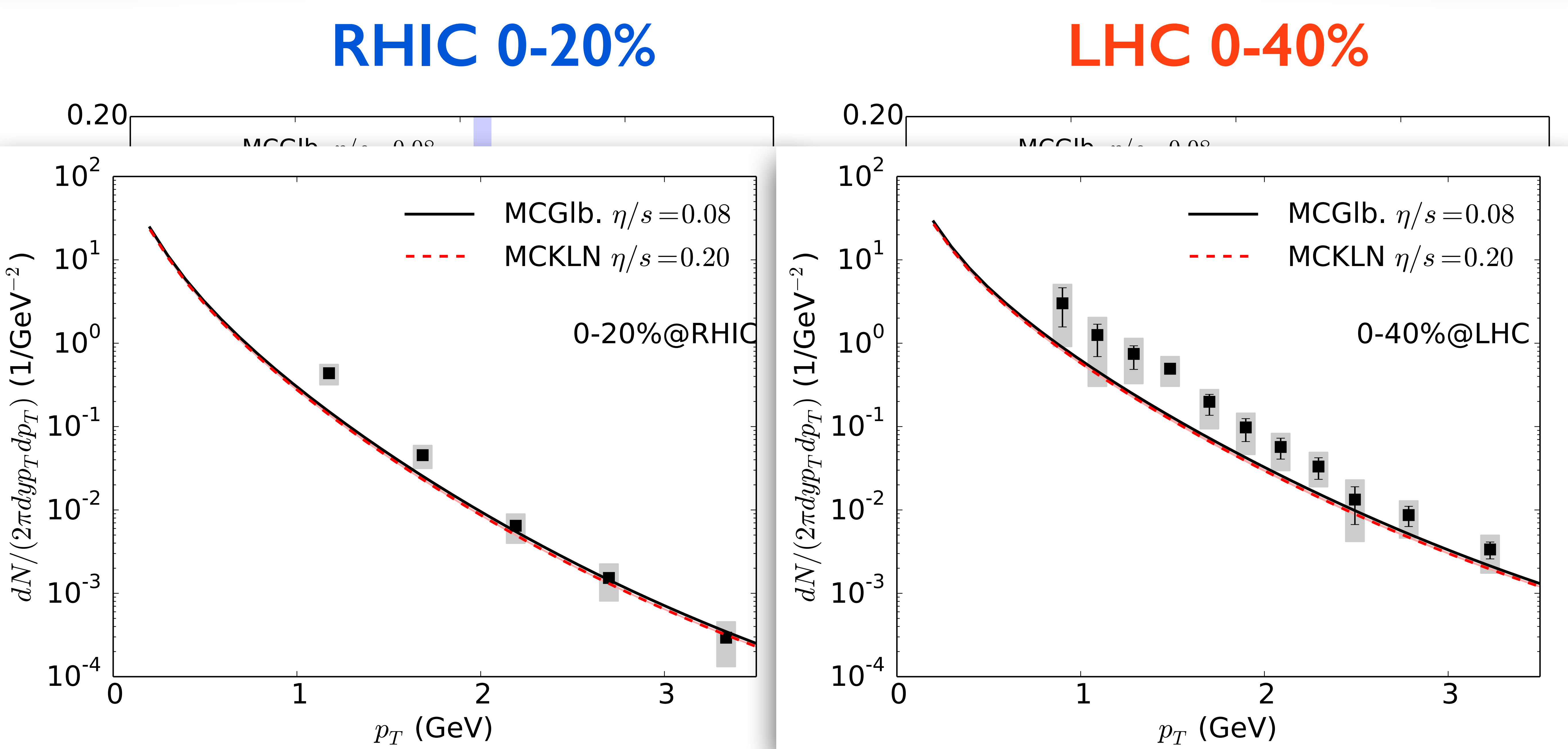
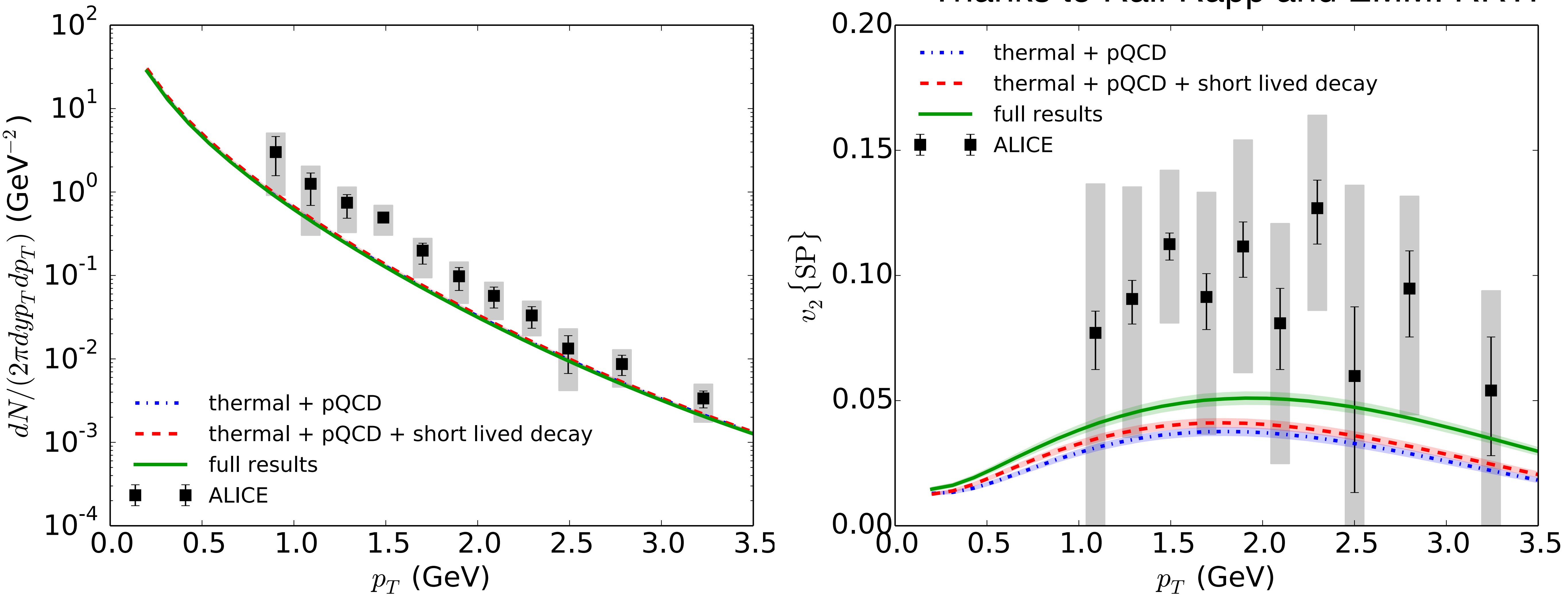


- Current calculations still underestimate the experimental data by a factor of 3!
- Thermal yield is also missing in the azimuthally integrated photon spectra at low

arXiv: 1308.2111

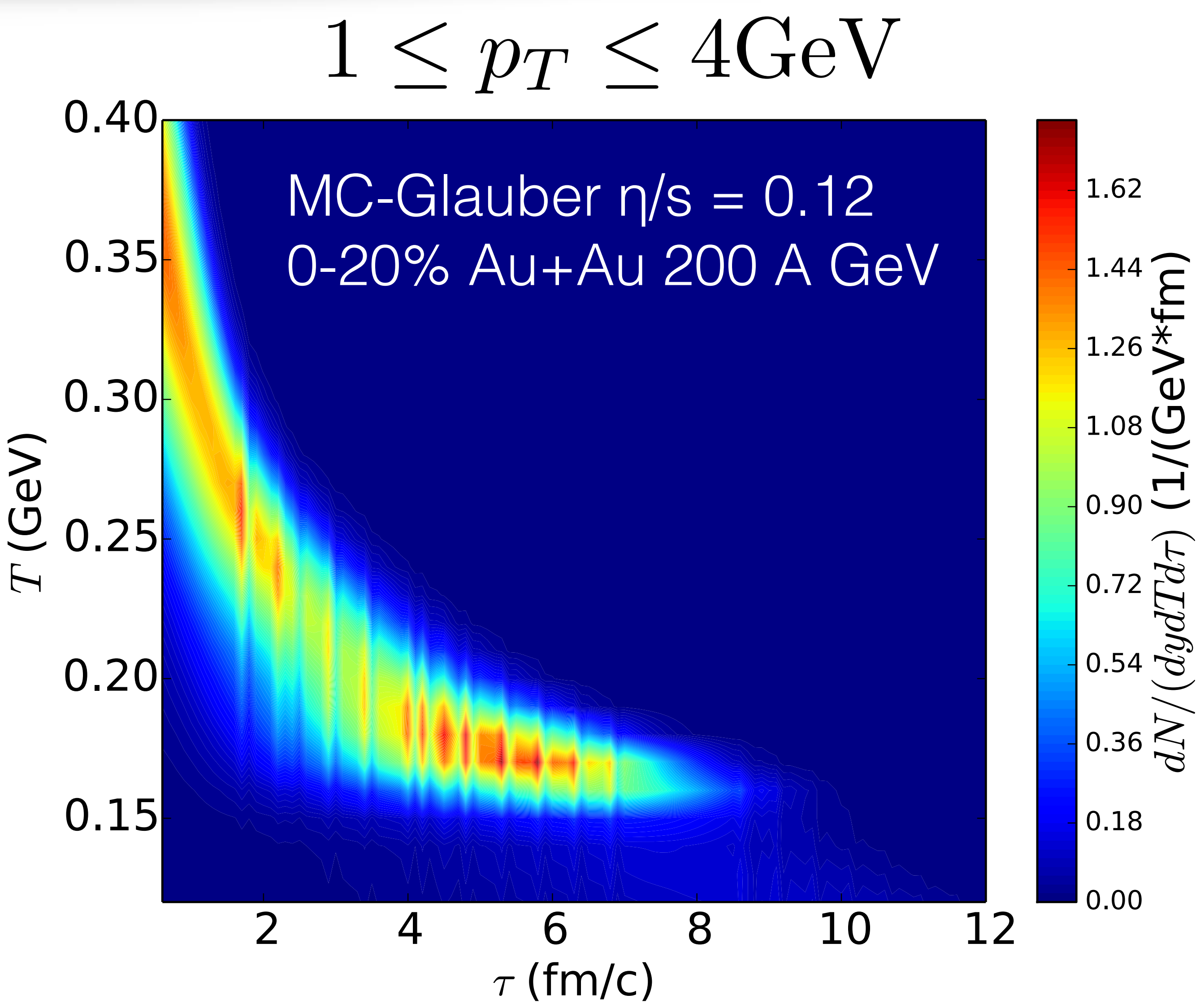
Efforts to resolve the photon flow puzzle

Thanks to Ralf Rapp and EMMI RRTF



- The post freeze-out short-lived resonances give small but positive contributions
- Pre-equilibrium flow helps the fireball to develop the flow anisotropy more quickly and improves the theoretical calculations

Thermal photon tomography

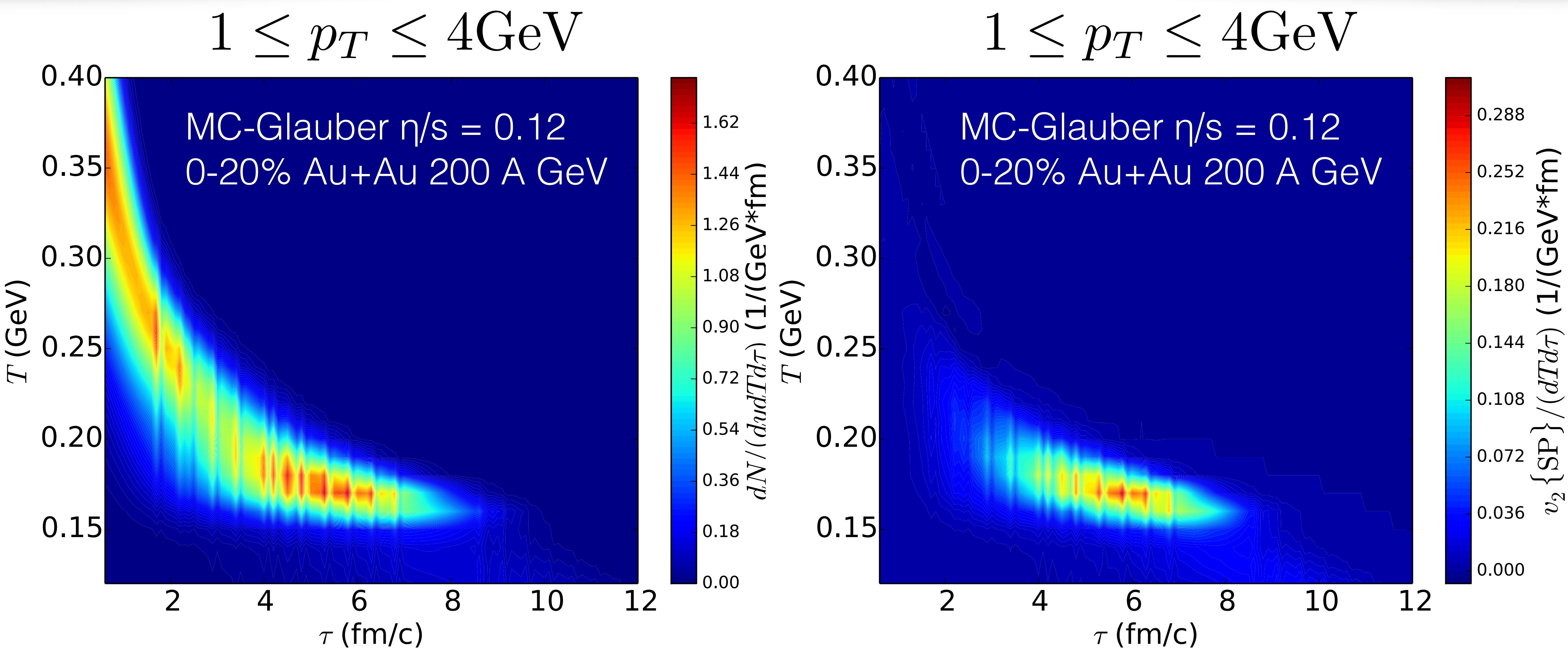


- By cutting hydro medium both in T and τ, we observe a **two-wave** thermal photon production

early time production — high rates at high temperatures

near transition region — growing of space-time volume

Thermal photon tomography



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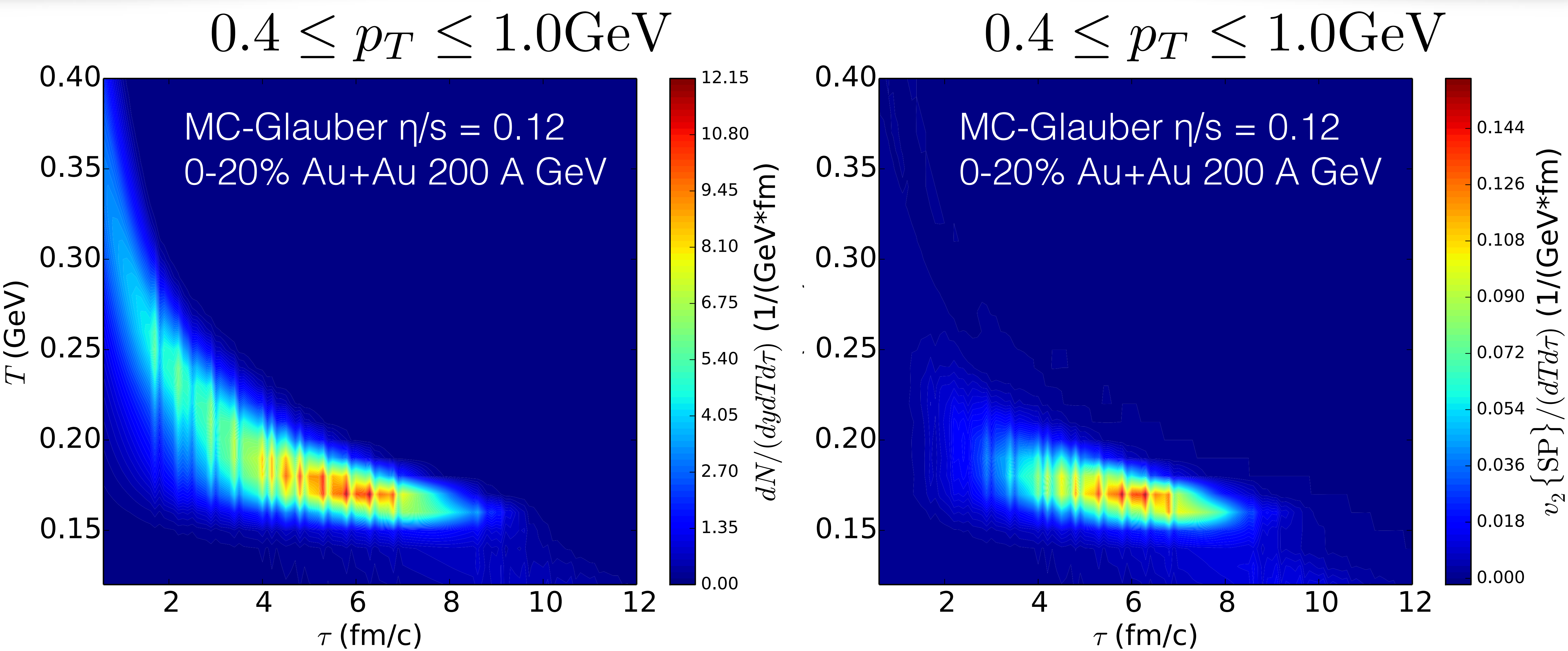
- Thermal photon v_2 is mostly coming from the transition region, T = 150~ 200 MeV, τ = 3 ~ 8 fm @ RHIC

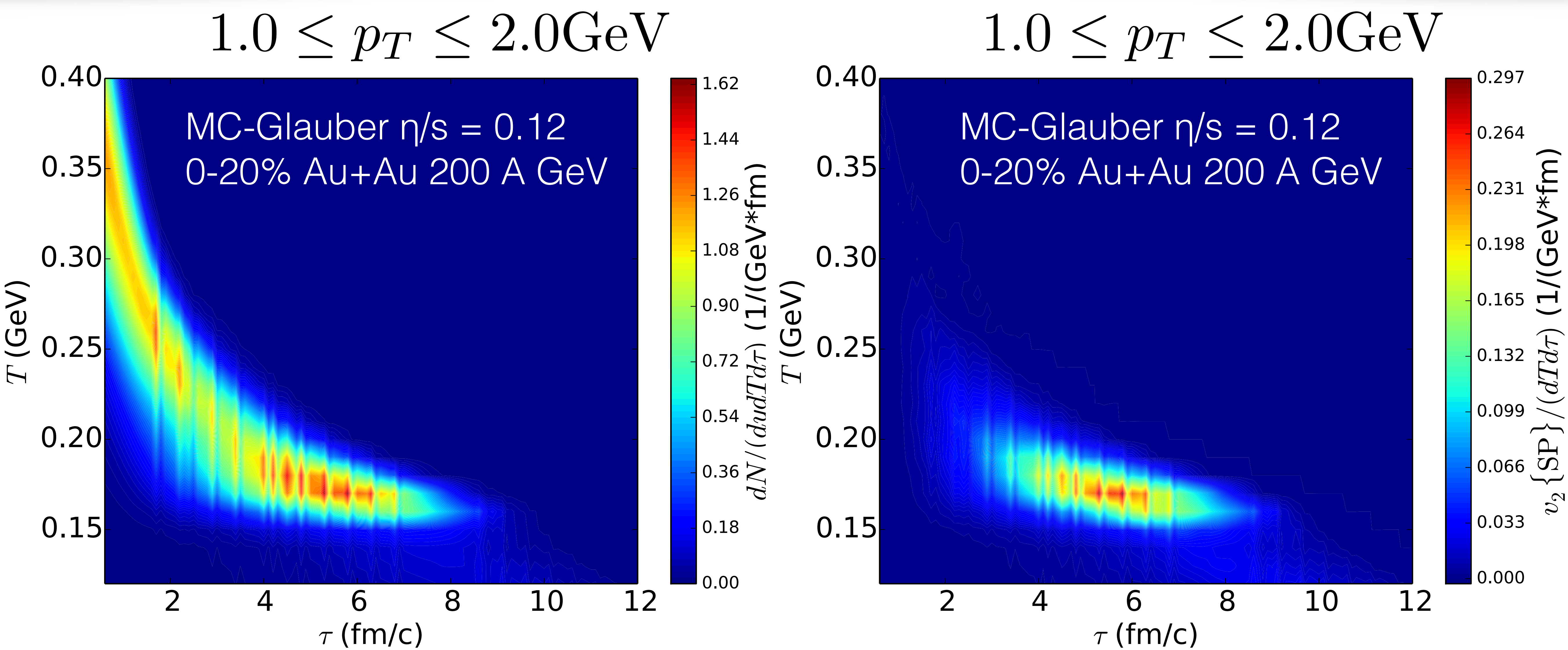
Thermal photon tomography



- Thermal photons with p_T = 0.4 ~ 1.0 GeV are mostly produced around transition region, their v_2 also reflect the flow anisotropy in this region.

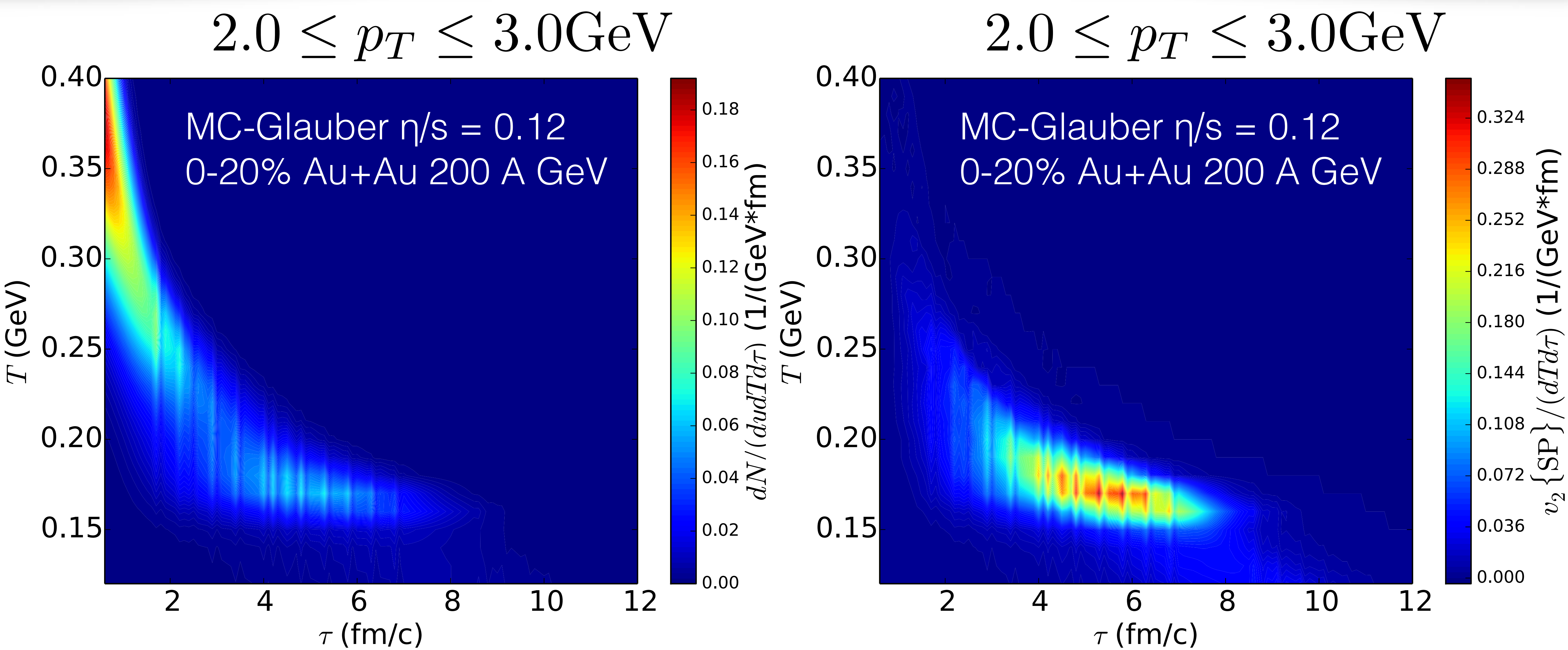
T = 150~ 200 MeV @ RHIC

Thermal photon tomography



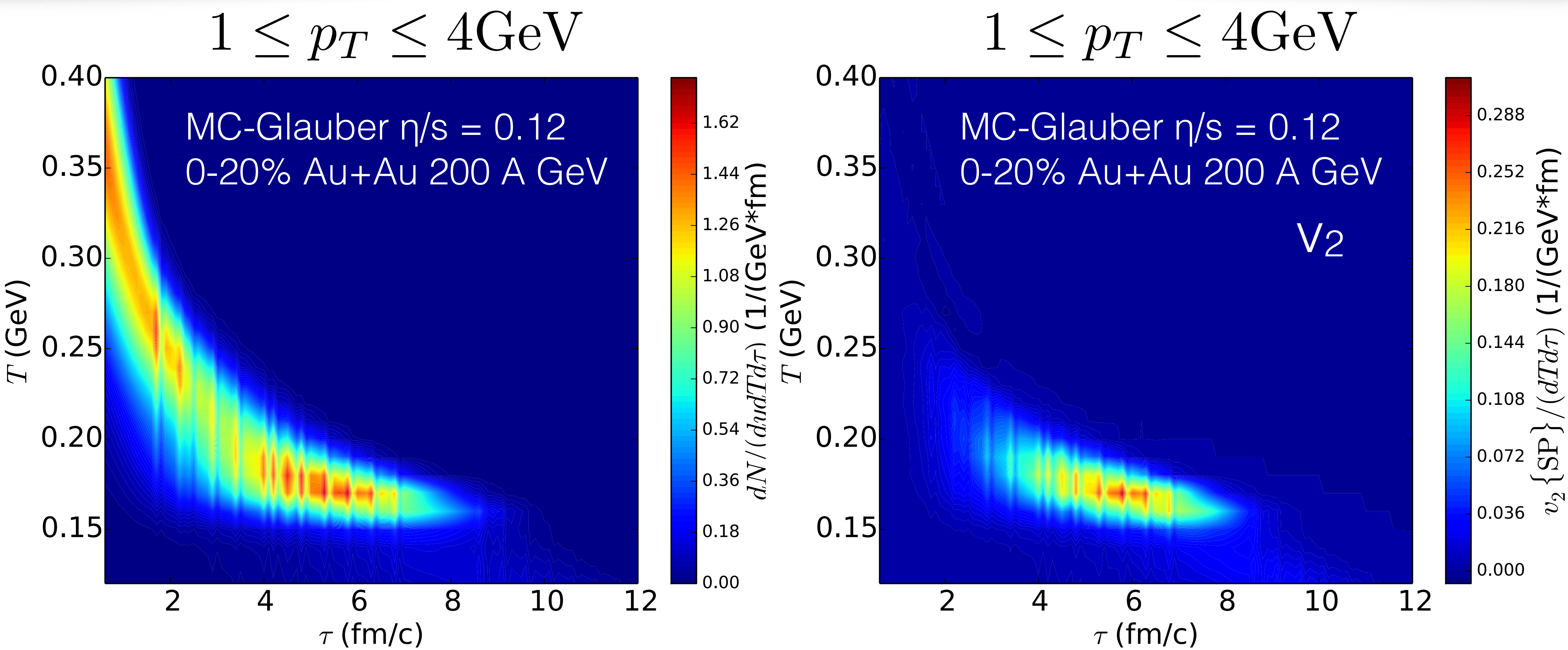
- Thermal photons with p_T = 1.0 ~ 2.0 GeV are produced in two waves, their v_2 reflect the flow anisotropy around the transition region. T = 150~ 200 MeV @ RHIC

Thermal photon tomography



- Thermal photons with p_T = 2.0 ~ 3.0 GeV are produced very early, however their v_2 still probes the transition region T = 150~ 200 MeV @ RHIC

Thermal photon tomography



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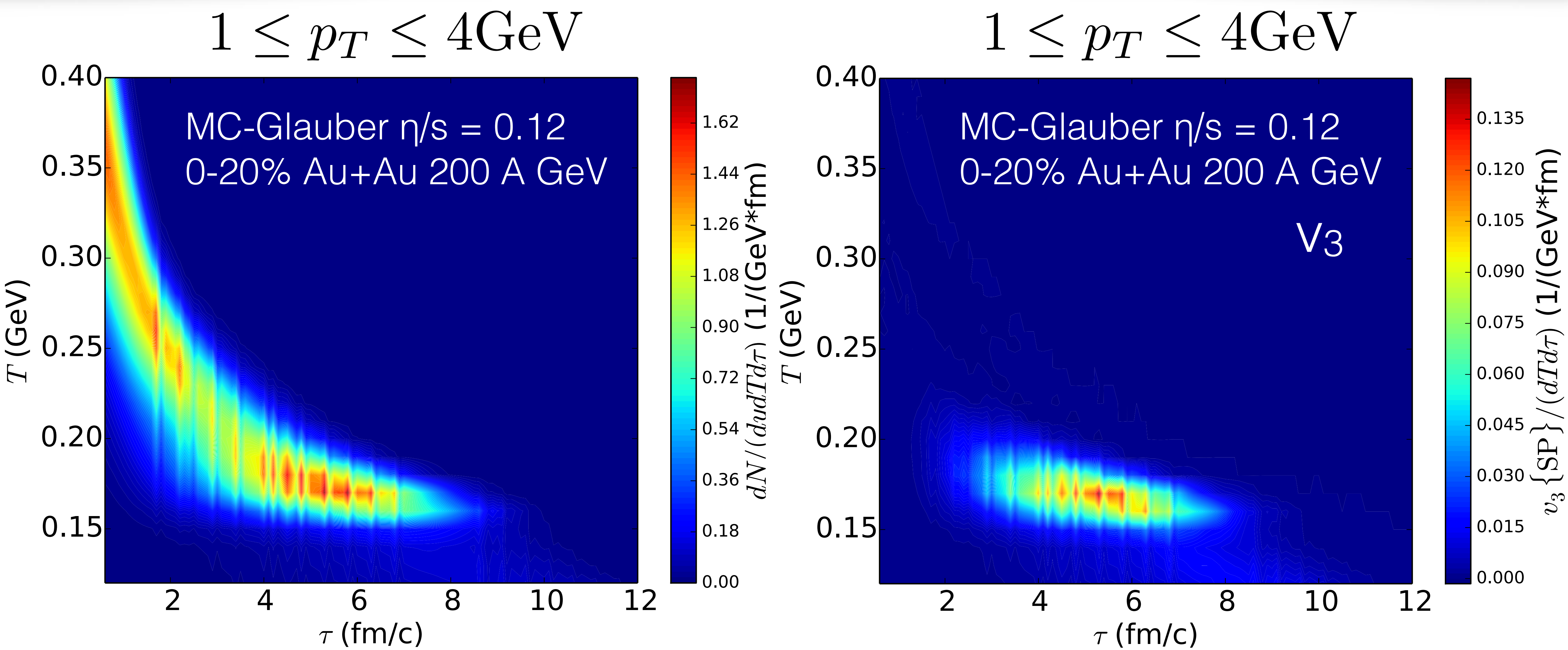

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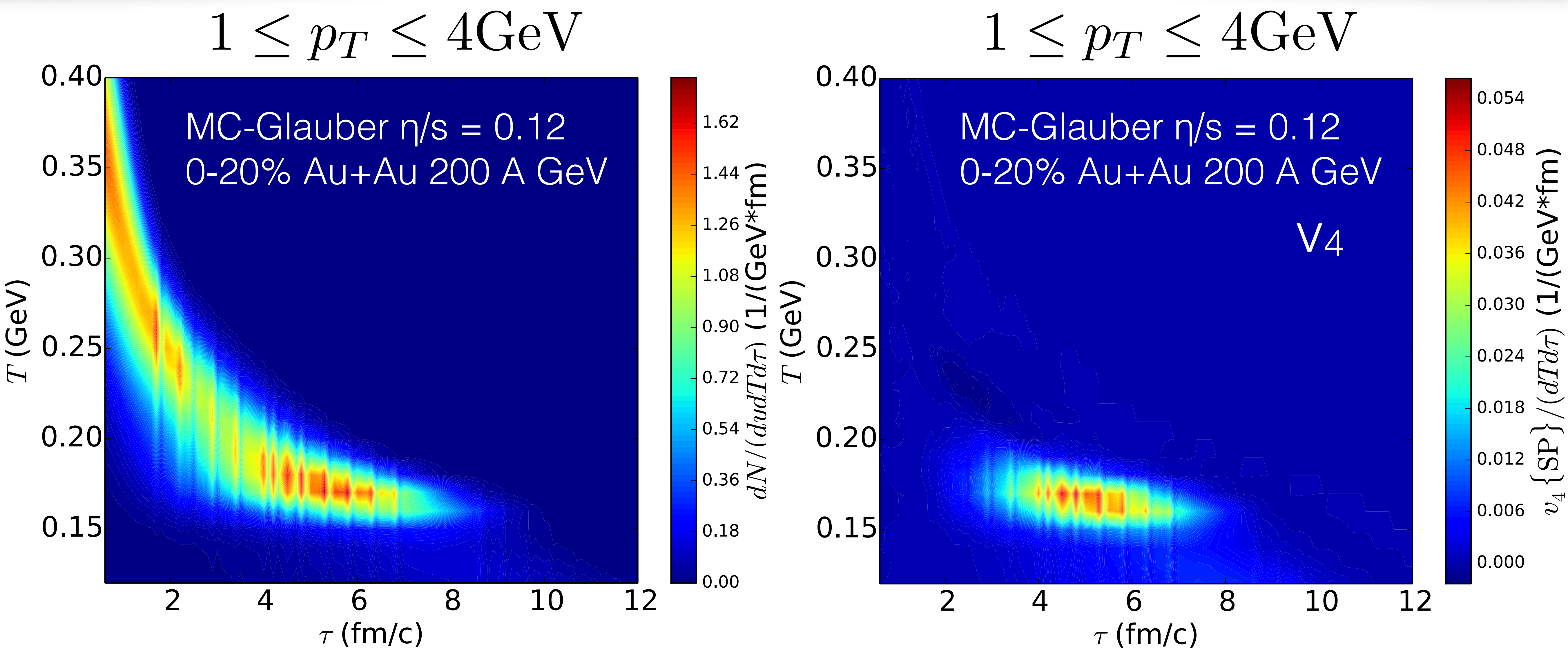

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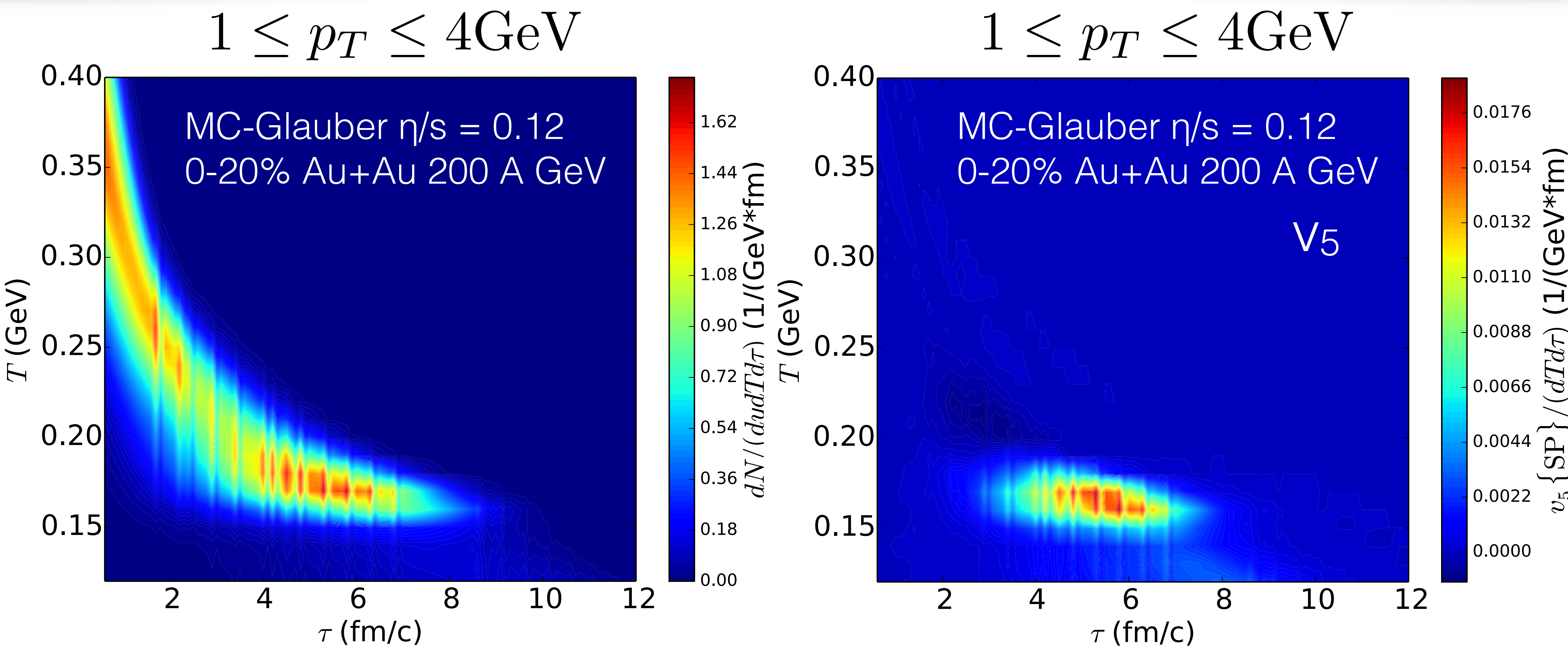

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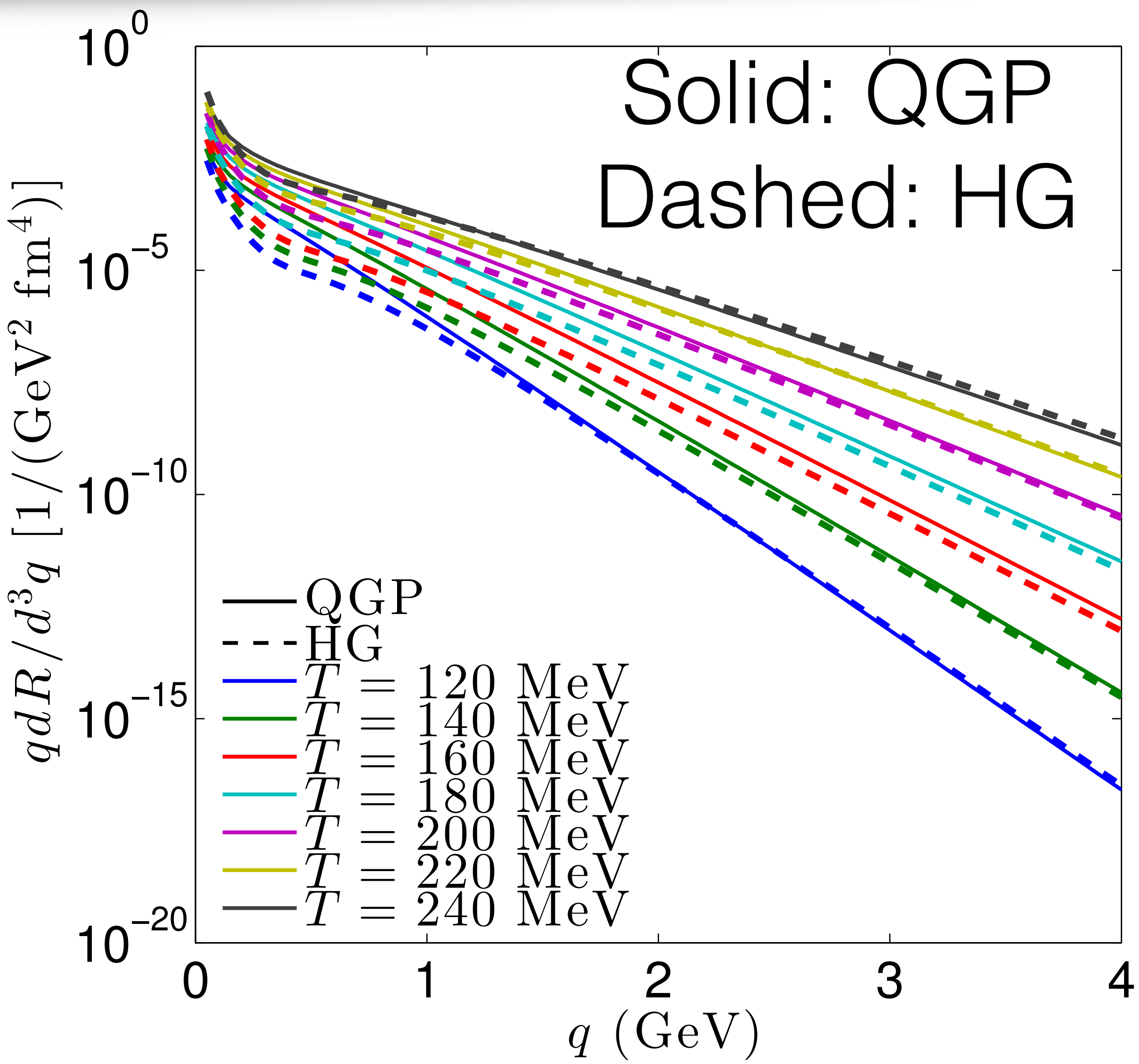
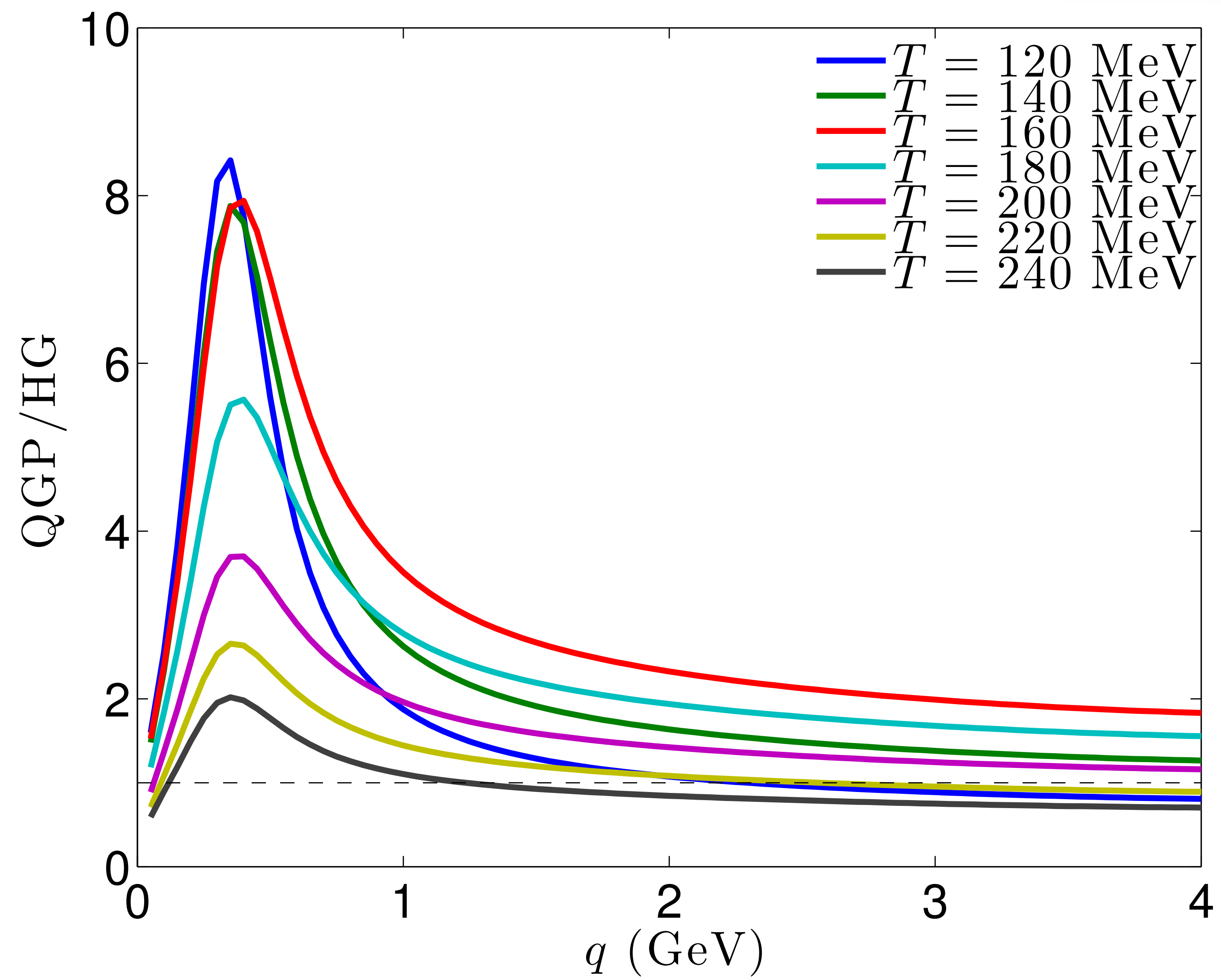
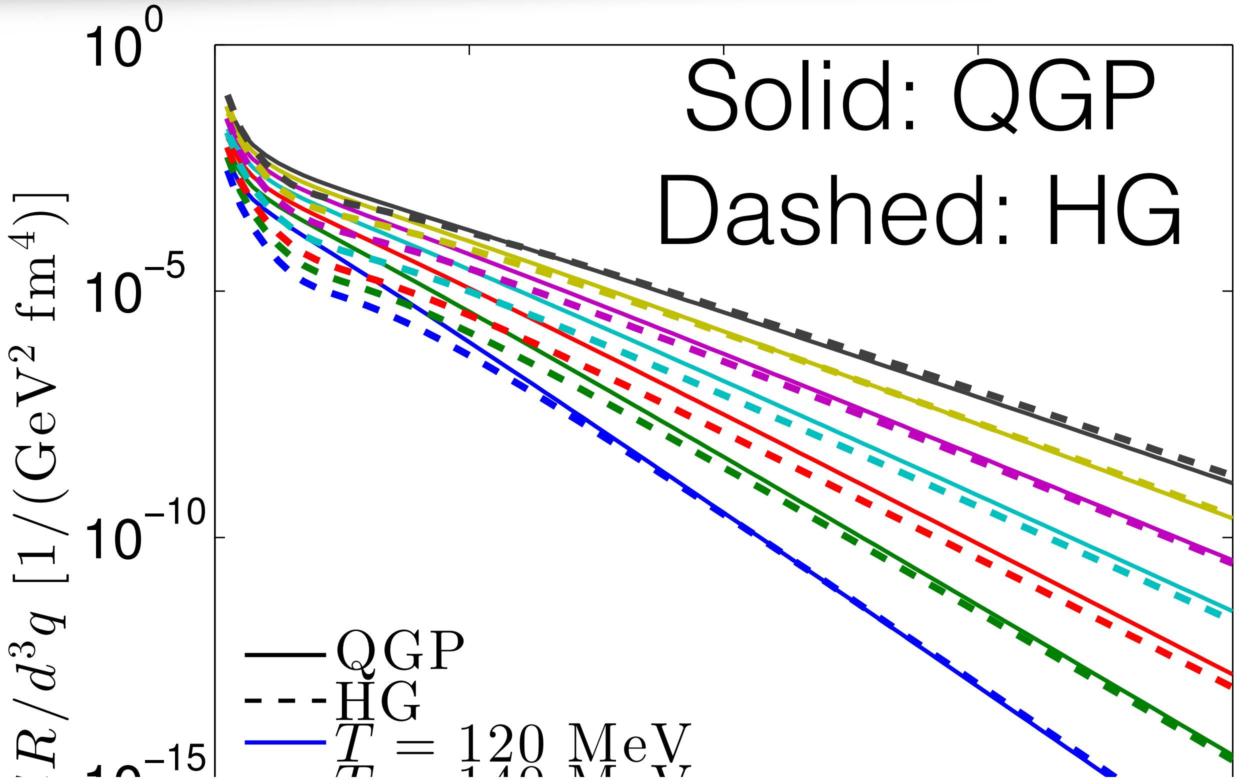
Photon Emission Rates in the transition region

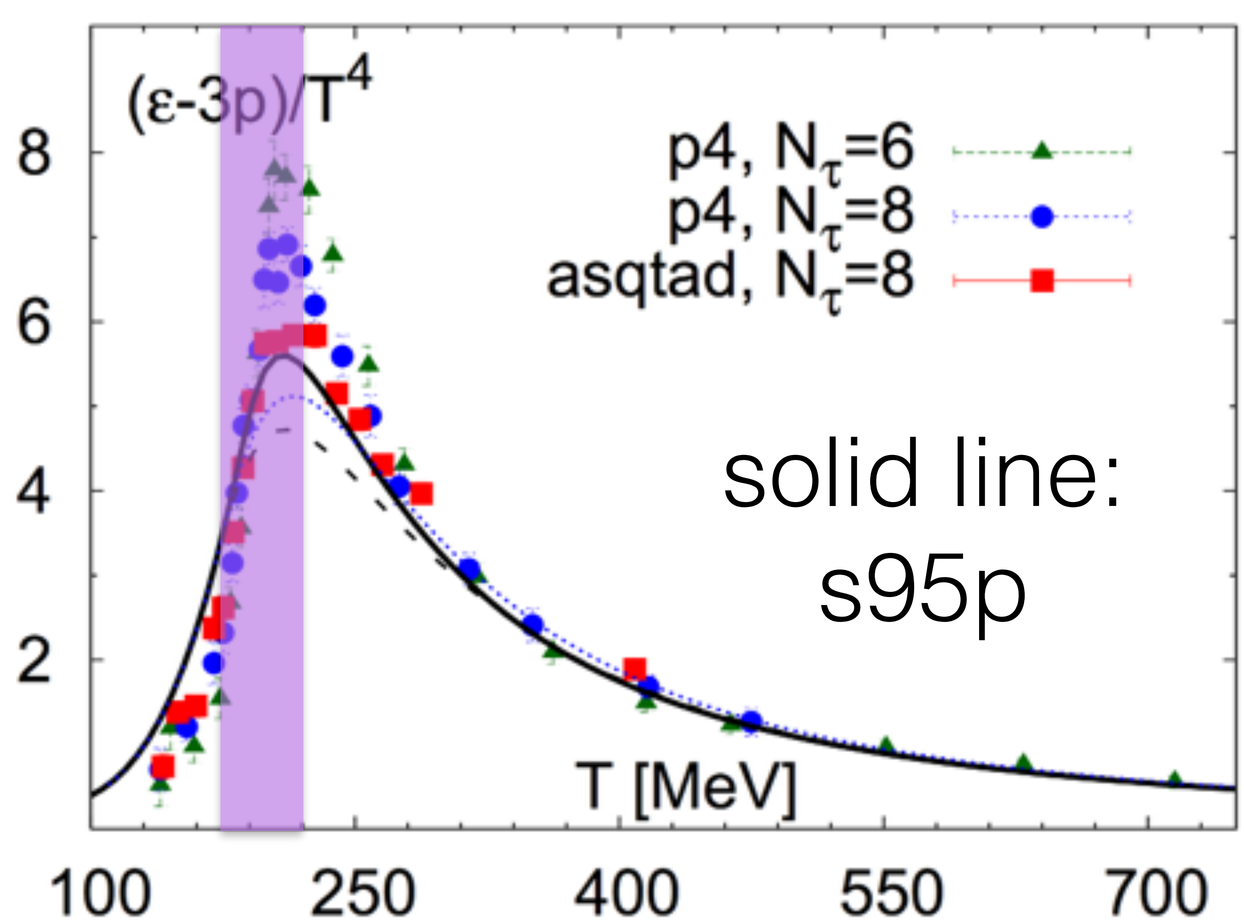


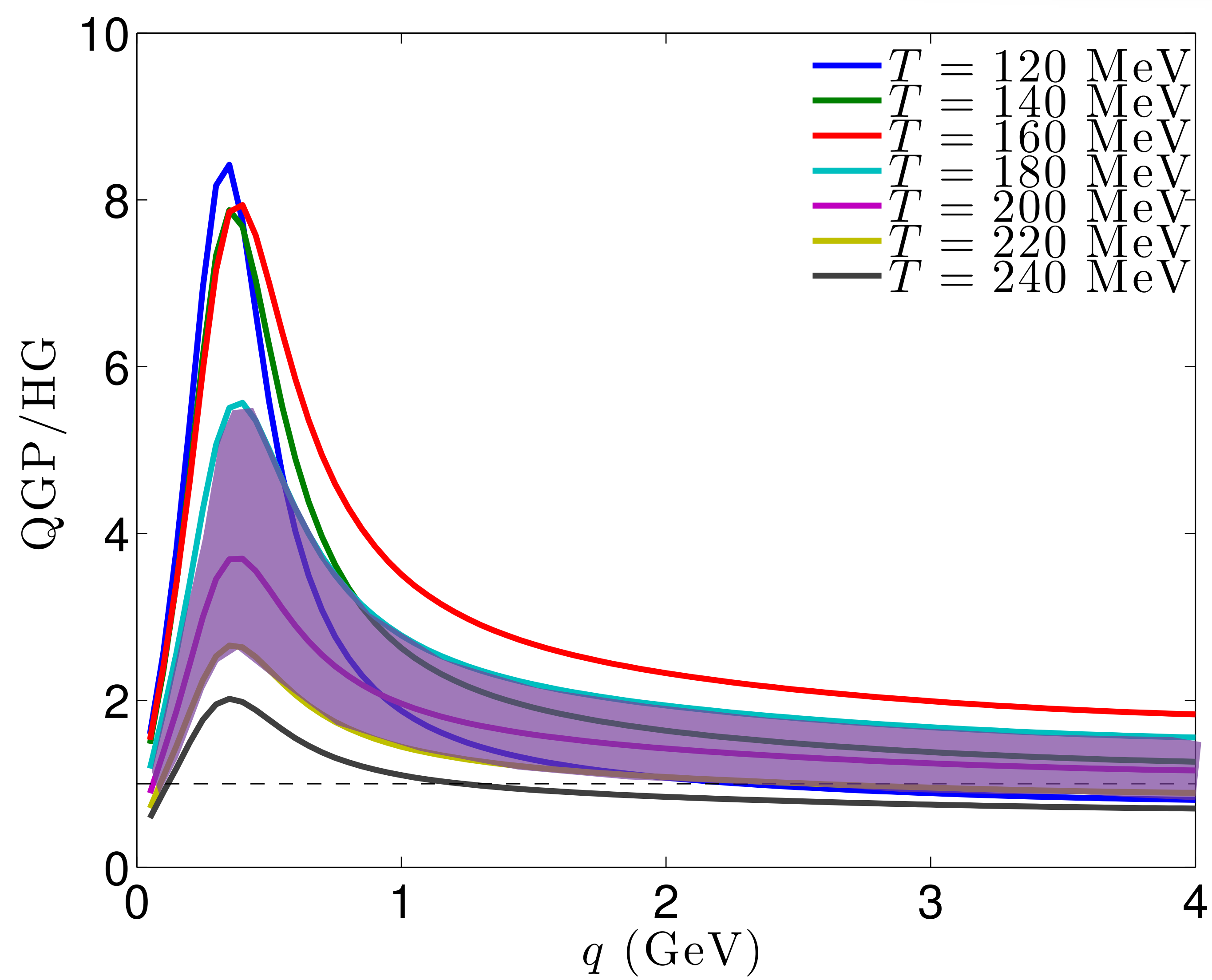


- QGP rates have very different p_T dependence compared to HG rates

Photon Emission Rates in the transition region



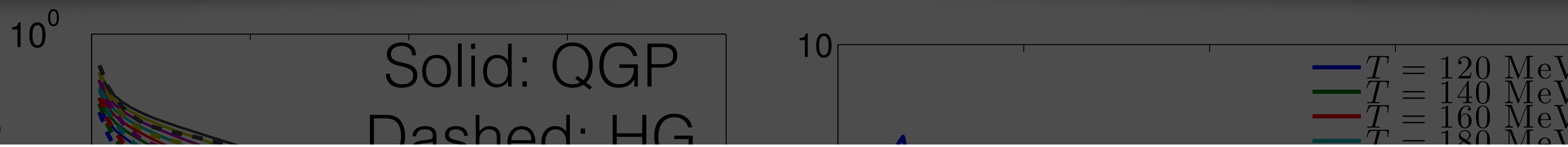


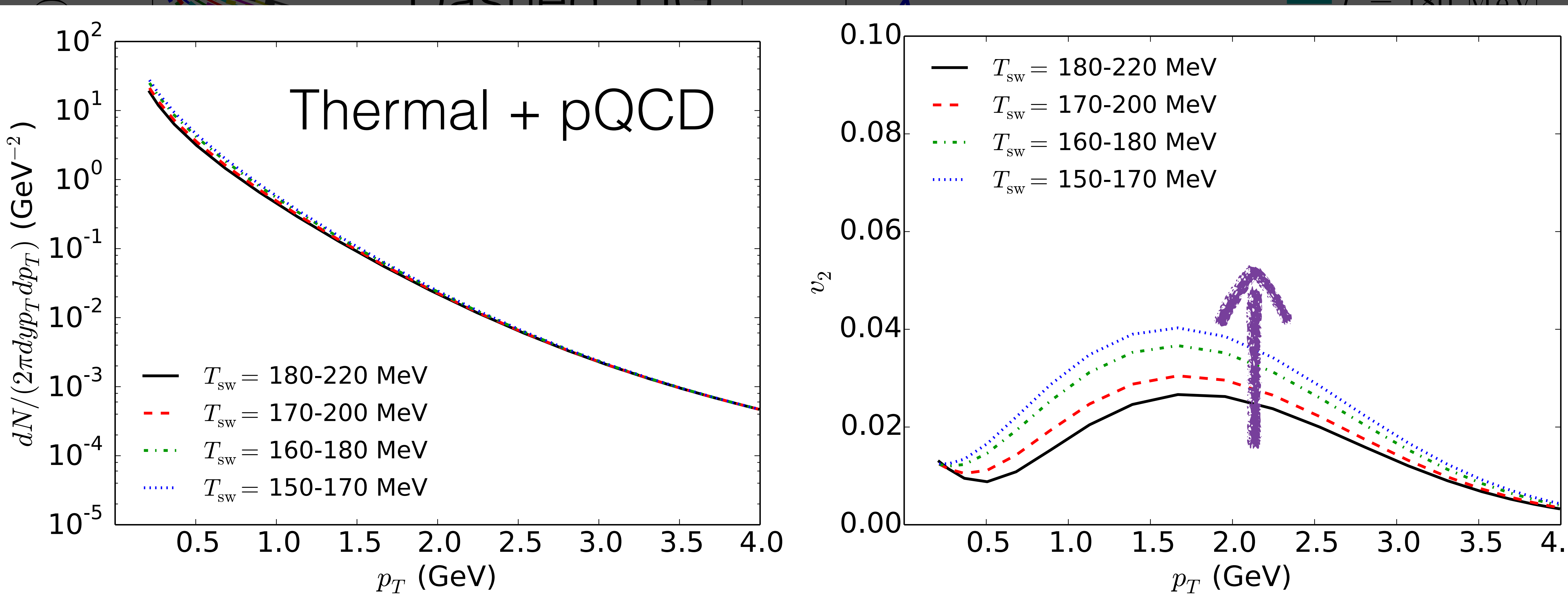


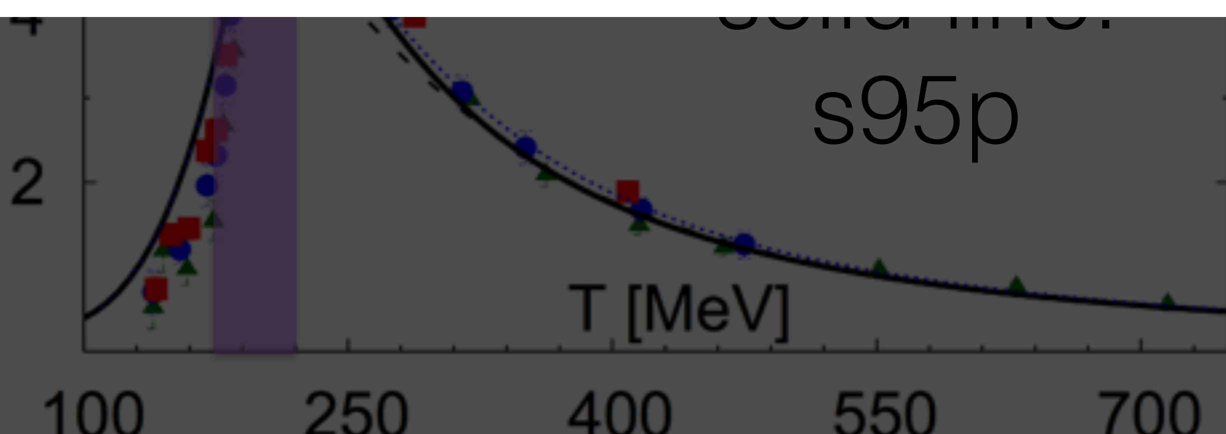
- QGP rates have very different p_T dependence compared to HG rates
- Estimated transition region for production rates, T ~ **184 - 220** MeV

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

Photon Emission Rates in the transition region







HG rates

- Estimated transition region for production rates, T ~ **184 - 220** MeV

Huovinen & Petreczky, Nucl.Phys. A... arXiv:1407.8533

Bulk viscous corrections to photon emission rates

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

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

$$+ f_0^i(p \cdot u)(1 \pm f_0^i(p \cdot u)) \Pi (B^i(T) + D^i(T)(p \cdot u) + E^i(T)(p \cdot u)^2)$$

We can expand photon emission rates around the thermal equilibrium:

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

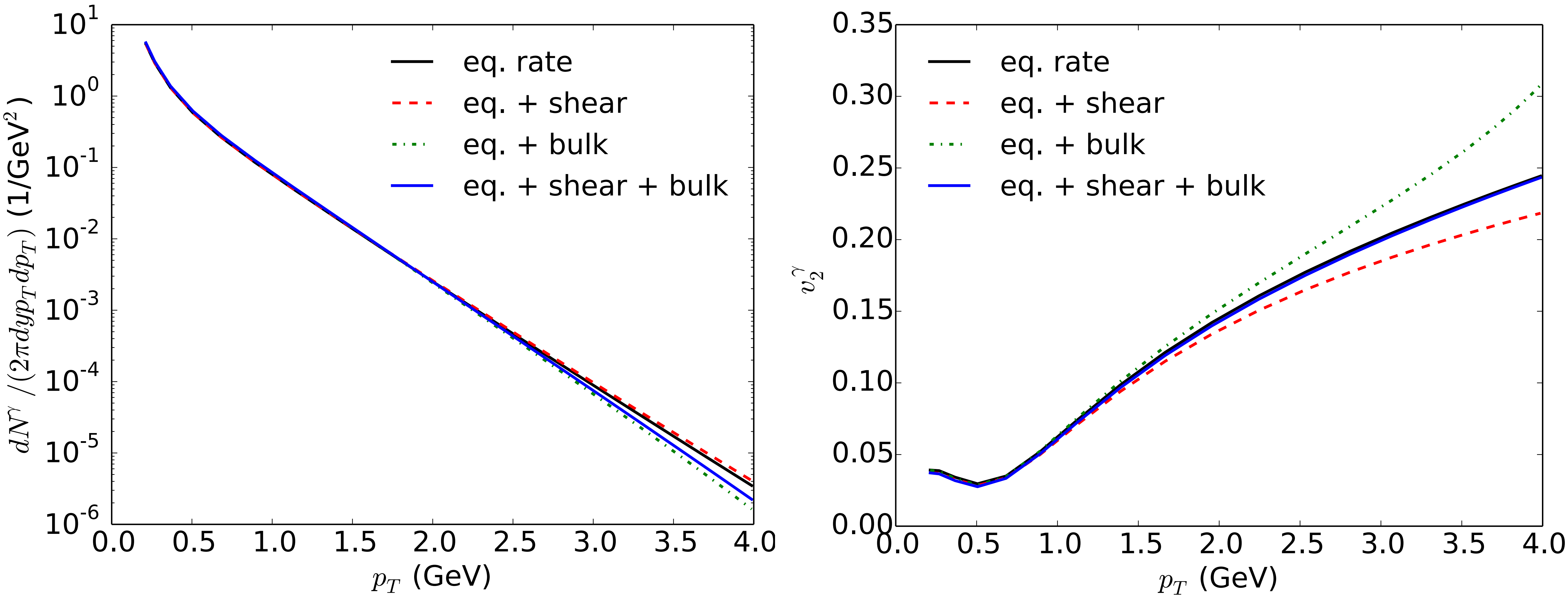
$$a_{\mu\nu} = \frac{3}{2(u \cdot \hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u \cdot \hat{q})^2} u_\mu u_\nu + \frac{1}{2(u \cdot \hat{q})^2} g_{\mu\nu} - \frac{3}{2(u \cdot \hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

Peek of bulk viscous effects on thermal photon observables

$$\frac{\zeta}{s} = \frac{1}{2}\frac{\eta}{s}\left(\frac{1}{3} - c_s^2\right) \quad \eta/s = 0.08$$

J. Noronha-Hostler, G. S. Denicol, J. Noronha, R. P. G. Andrade and F. Grassi, Phys. Rev. C **88**, 044916 (2013)

Hadronic photons:



- Bulk viscosity steepens thermal photon spectrum
- It increases thermal photon pT differential elliptic flow

reduces hydrodynamic radial flow

Conclusion

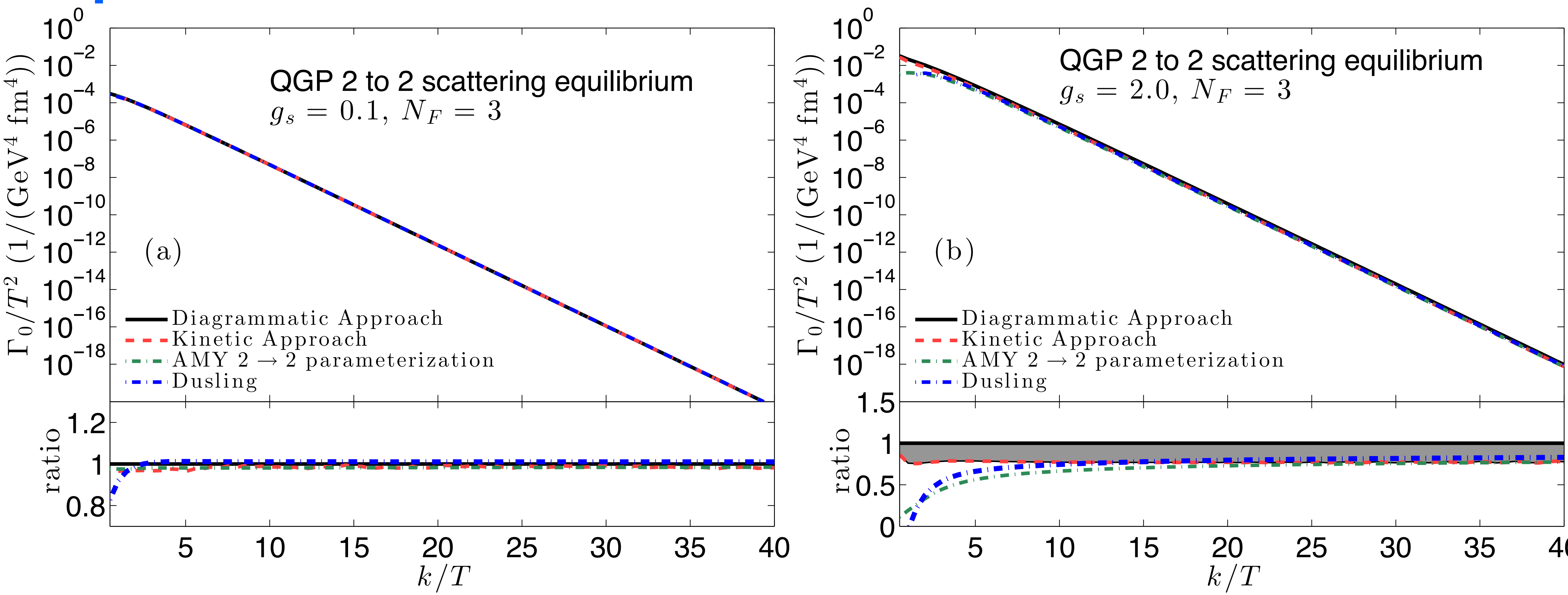
- We study photon spectra and their anisotropic flows $\mathbf{v_n}$ from *event-by-event* viscous hydrodynamic medium
- Thermal photon spectra are strongly blue shifted by hydrodynamic radial flow
- Shear viscosity suppresses photon v_n. Dominant suppression comes not from flow, but from the viscous correction to the production rates.
- Uncertainty of the photon emission rates in the transition region plays a crucial role in the theoretical calculations
- The interplay between bulk and shear viscous effects need to be carefully studied

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

Back up

Photon Rates (QGP 2 to 2 processes only)

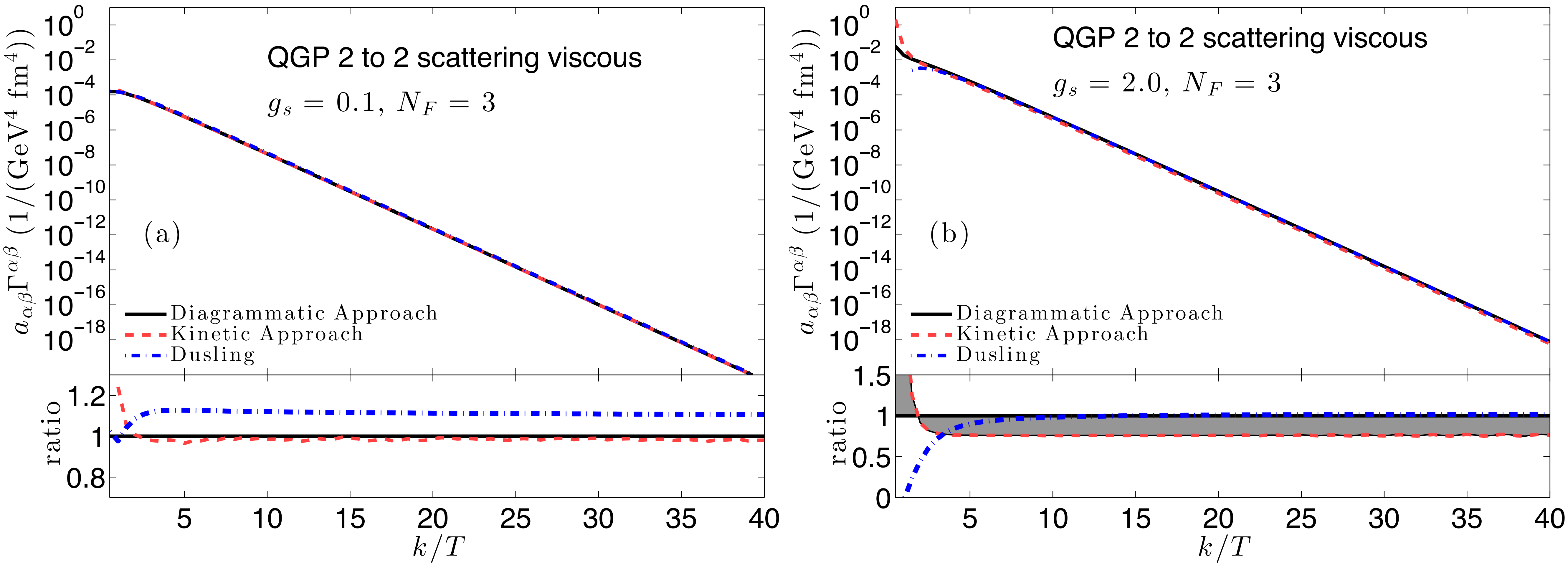
Equilibrium rates:



- 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.

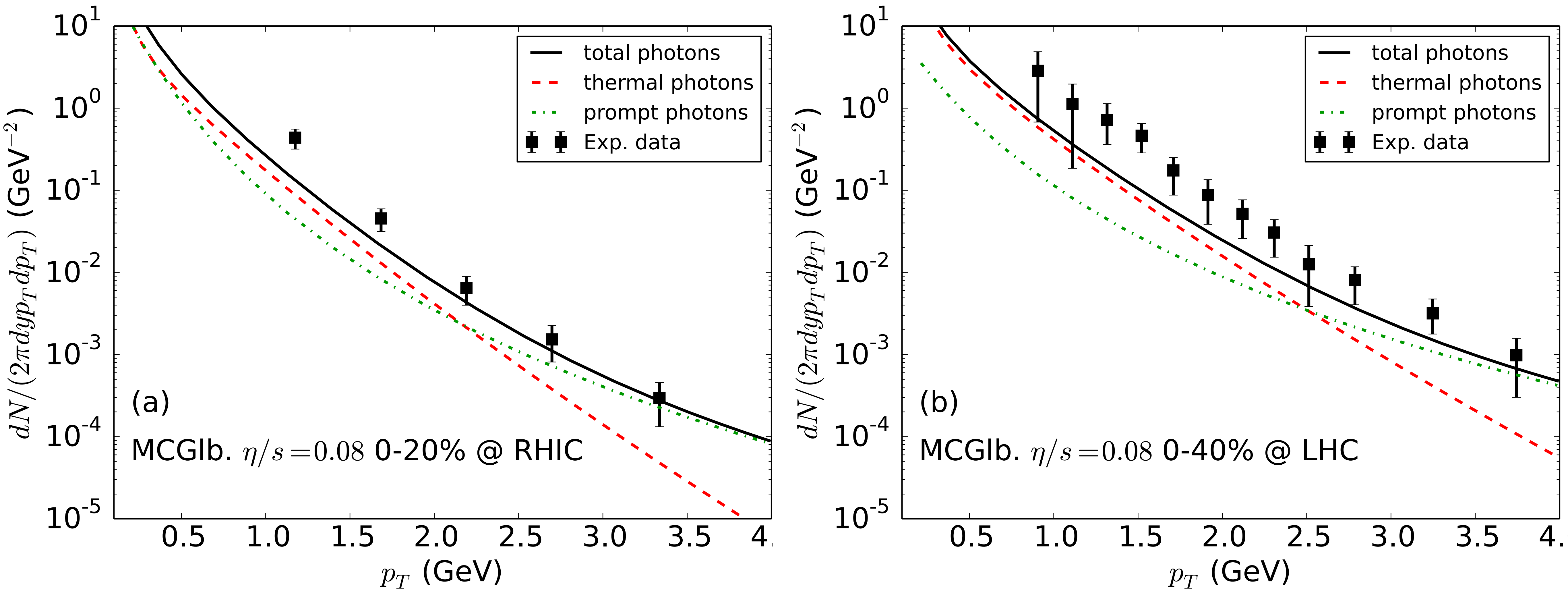
Photon Rates (QGP 2 to 2 processes only)

Viscous corrections:



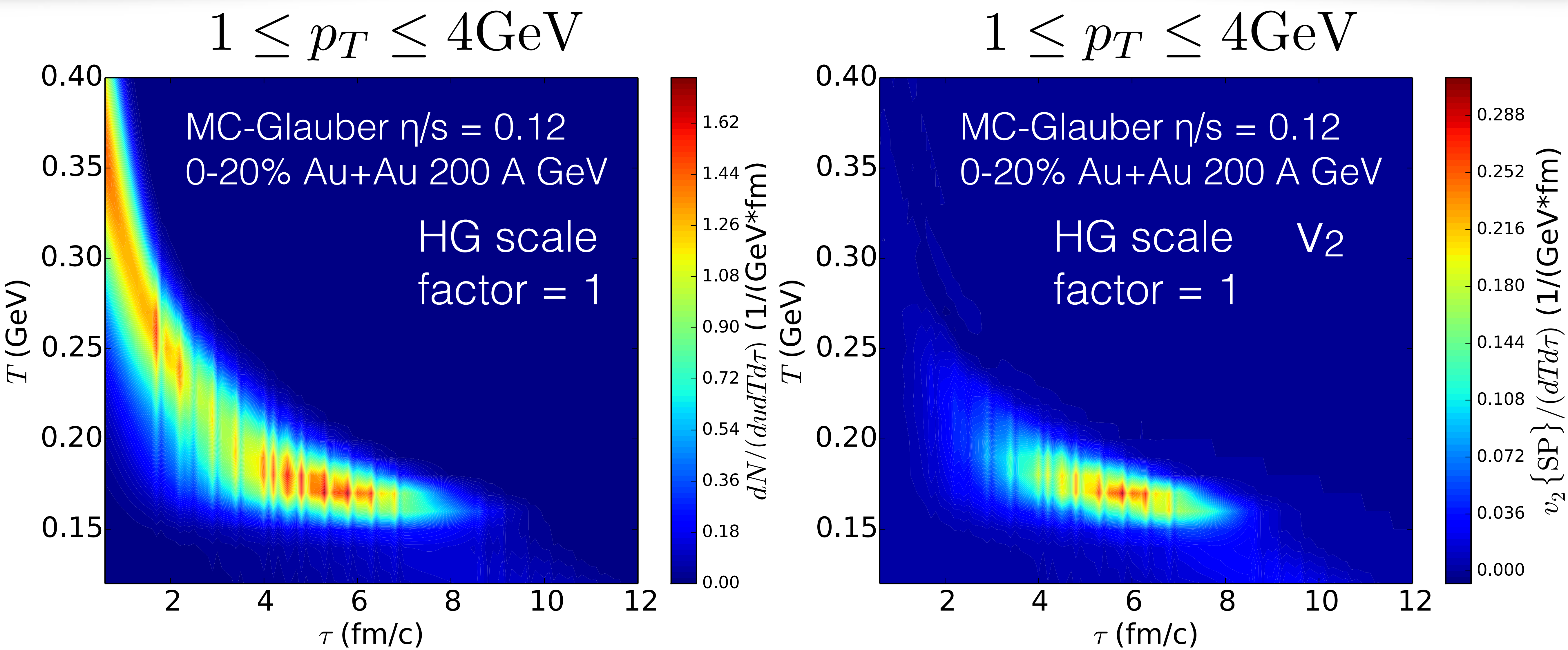
- For small g, diagrammatic approach agrees with kinetic approach
- For g = 2, the deviations at small k/T may originate from different higher order $O(g^2T)$ contributions

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

Thermal photon tomography



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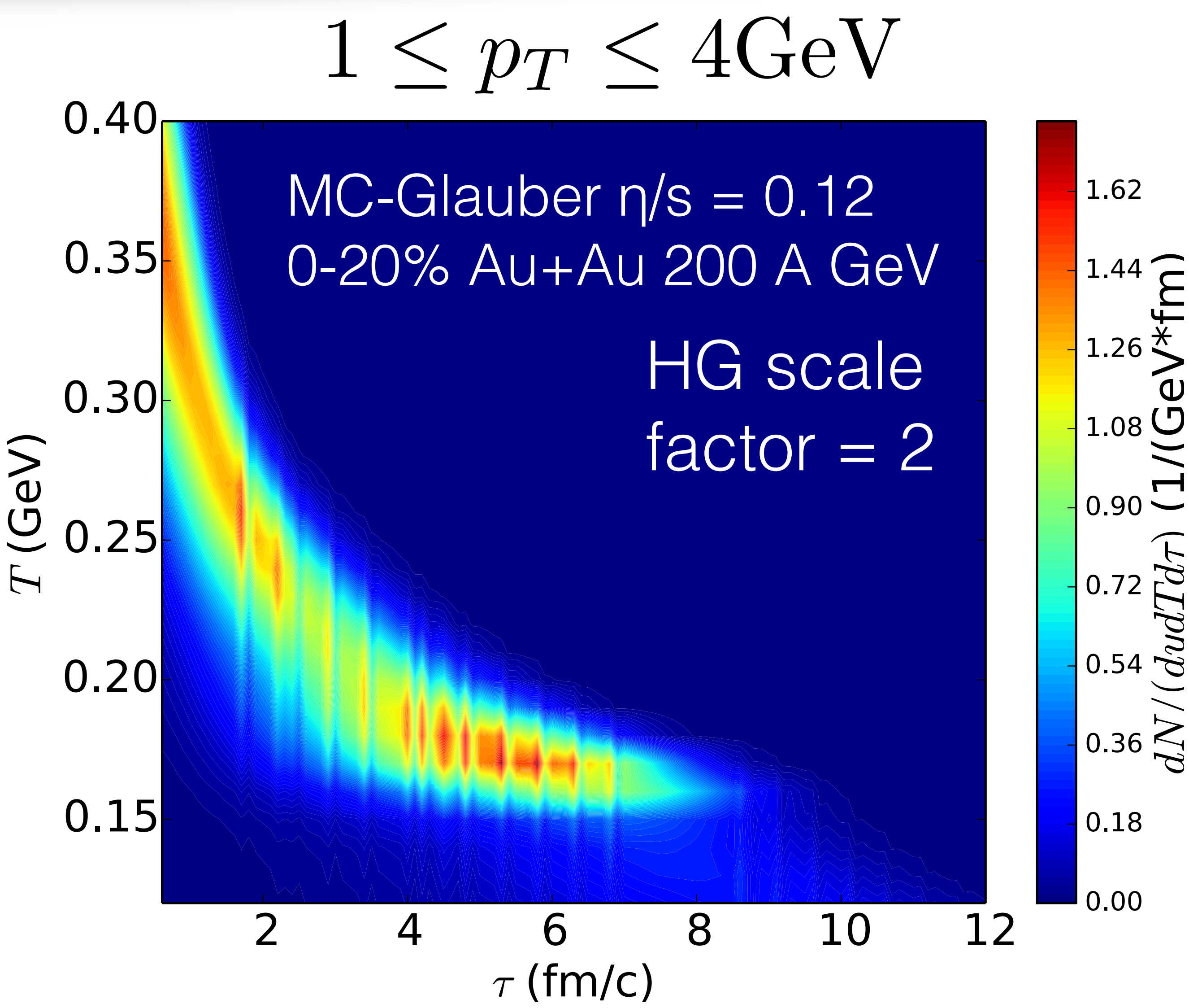

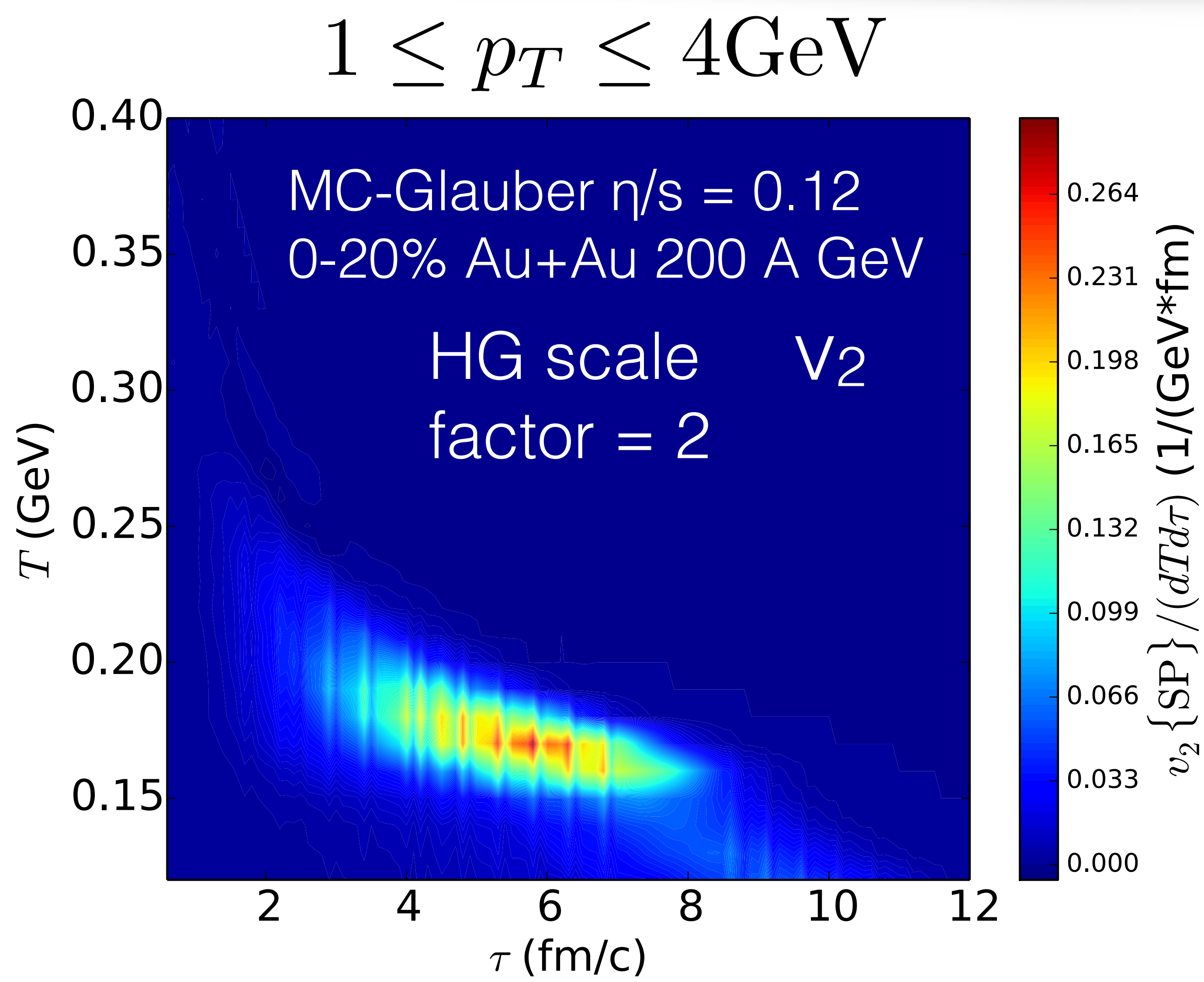

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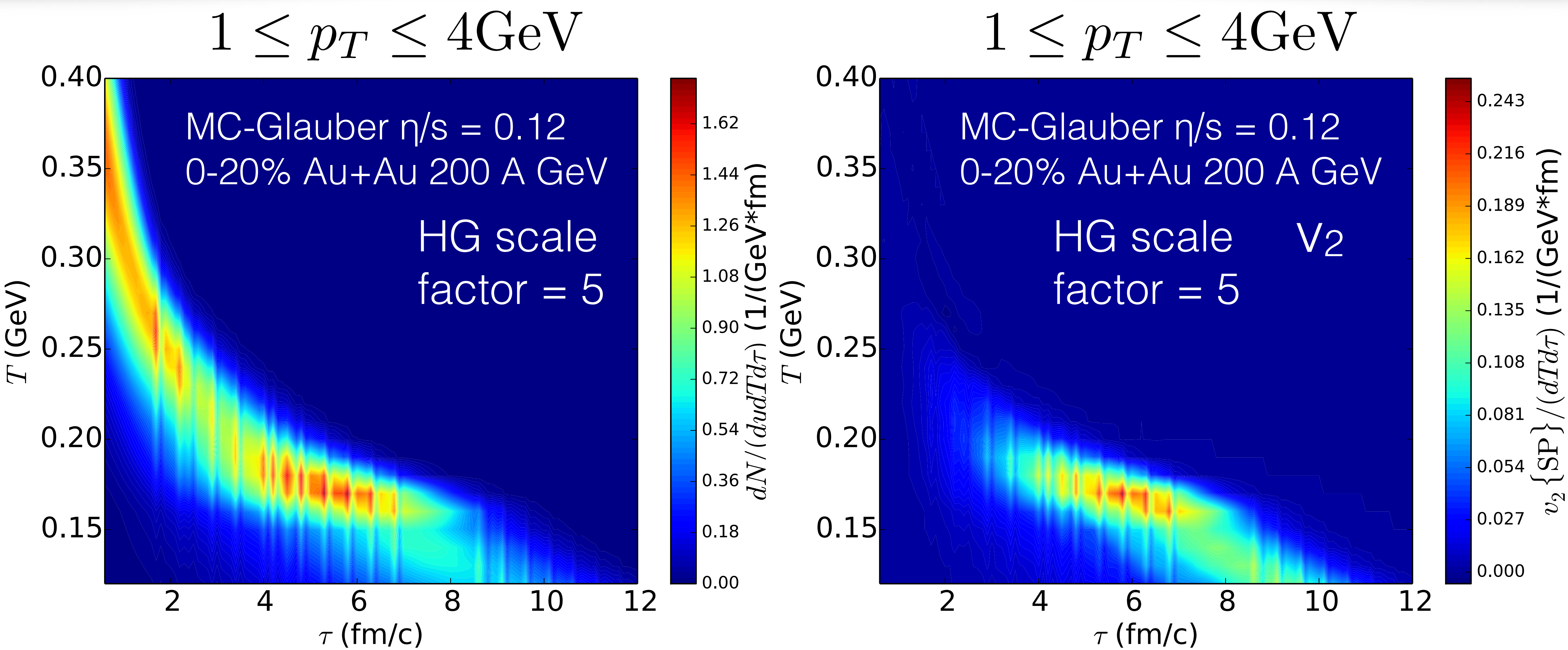

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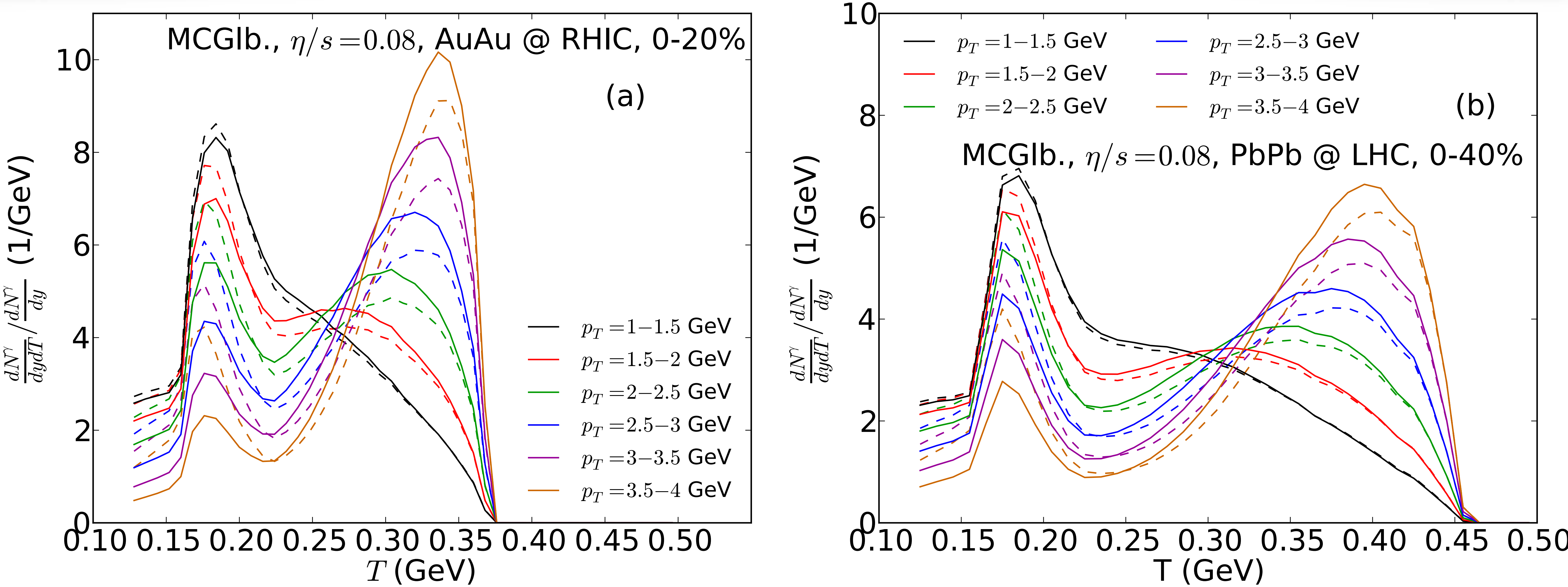
Emission vs. Temperature



- 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