Anisotropic flow of thermal photons as a quark-gluon plasma viscometer

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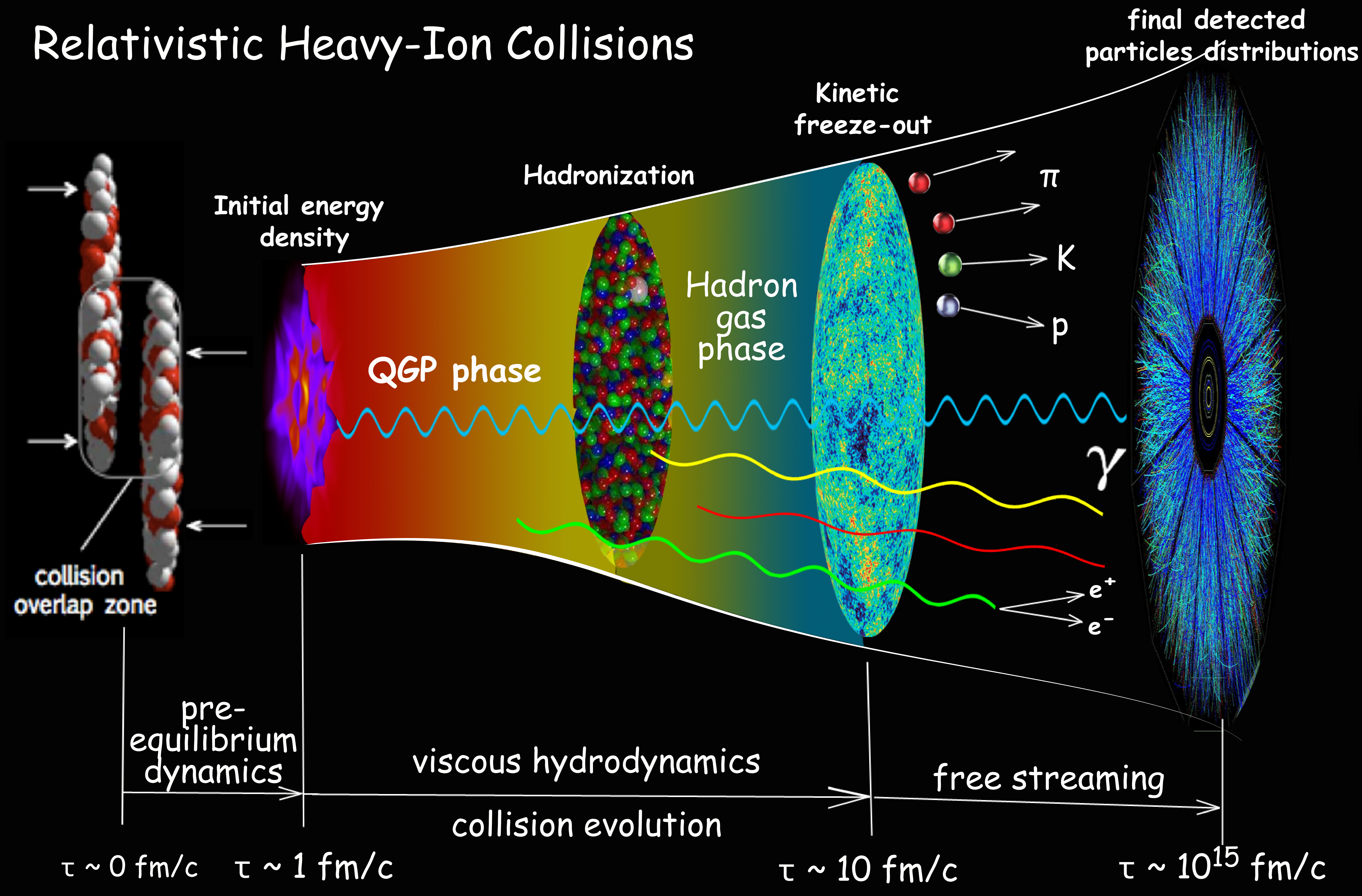
The Ohio State University

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

Nov. 4, 2013 Hard Probes

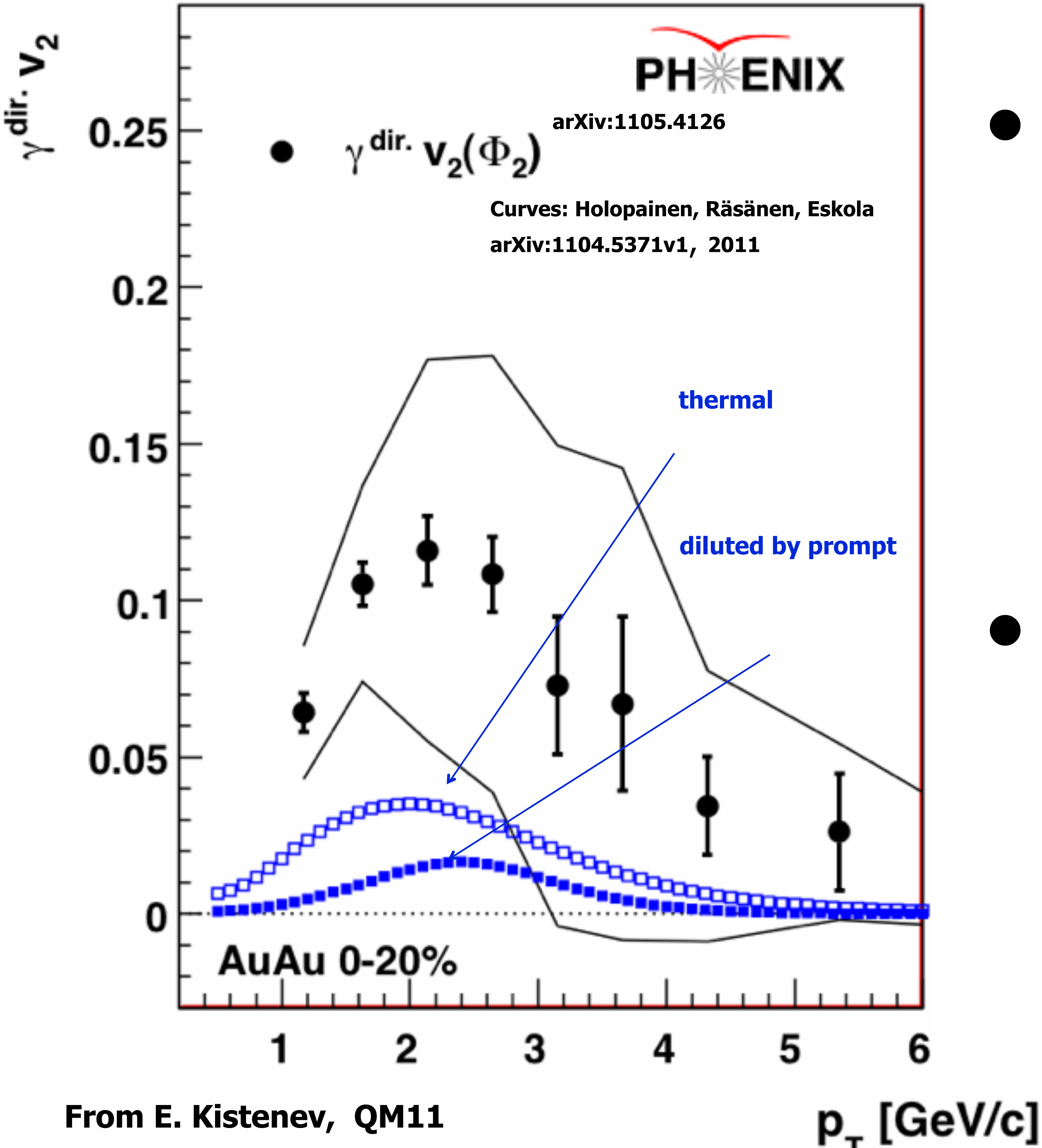
arXiv: 1308.2111, 1308.2440

Little Bang



Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
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

Challenge from Experiment



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

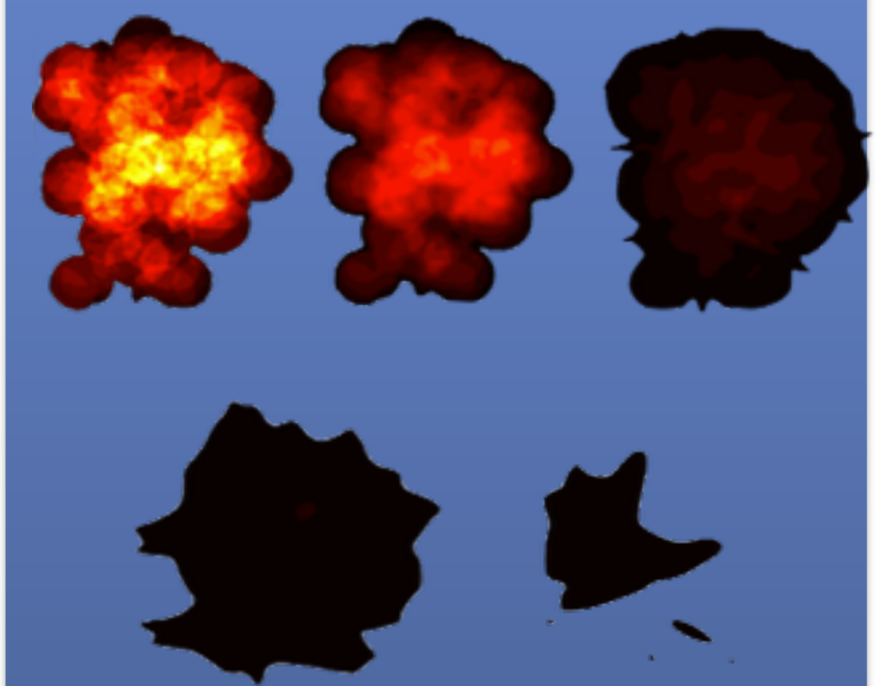
From E. Kistenev, QM11

Work flow of Theoretical Calculation

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

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

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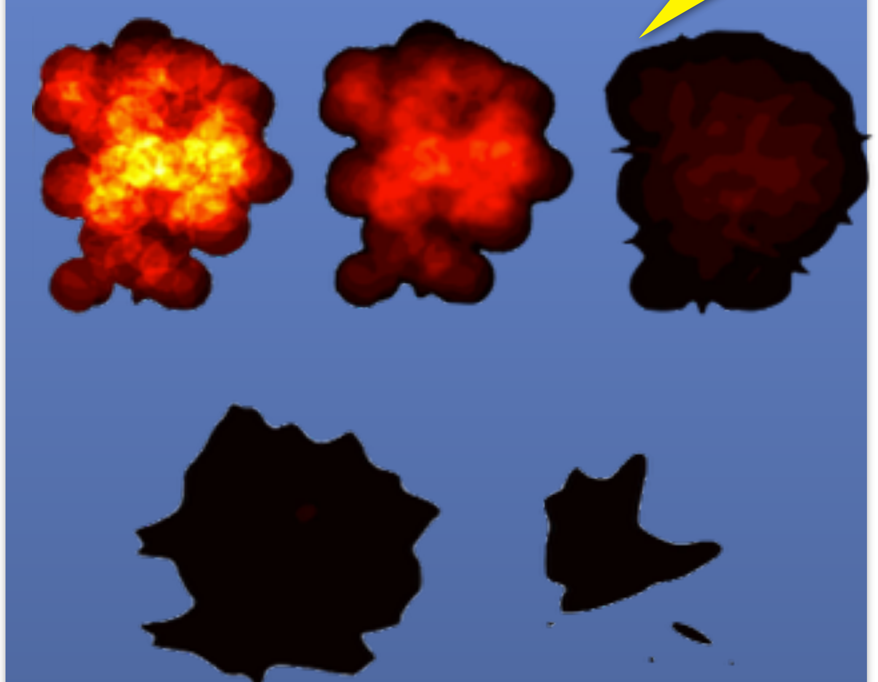

viscous corrections

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Thermal Photon Emission Rates

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viscous corrections

Hadrons spectra & v_n

Photon spectrum & v_n

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:

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

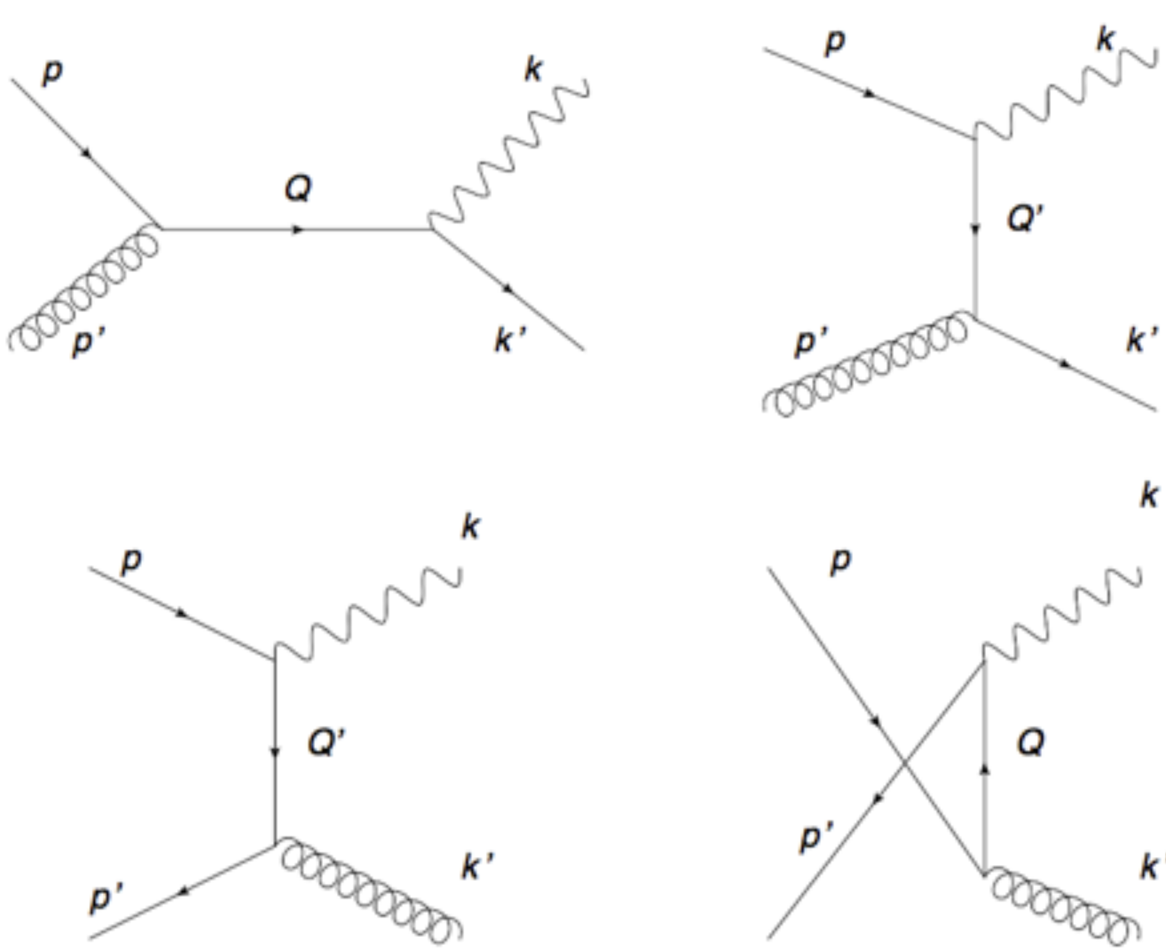
$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2} u_\mu u_\nu + \frac{1}{2(u\cdot\hat{q})^2} g_{\mu\nu} - \frac{3}{2(u\cdot\hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).$$

General Formalism

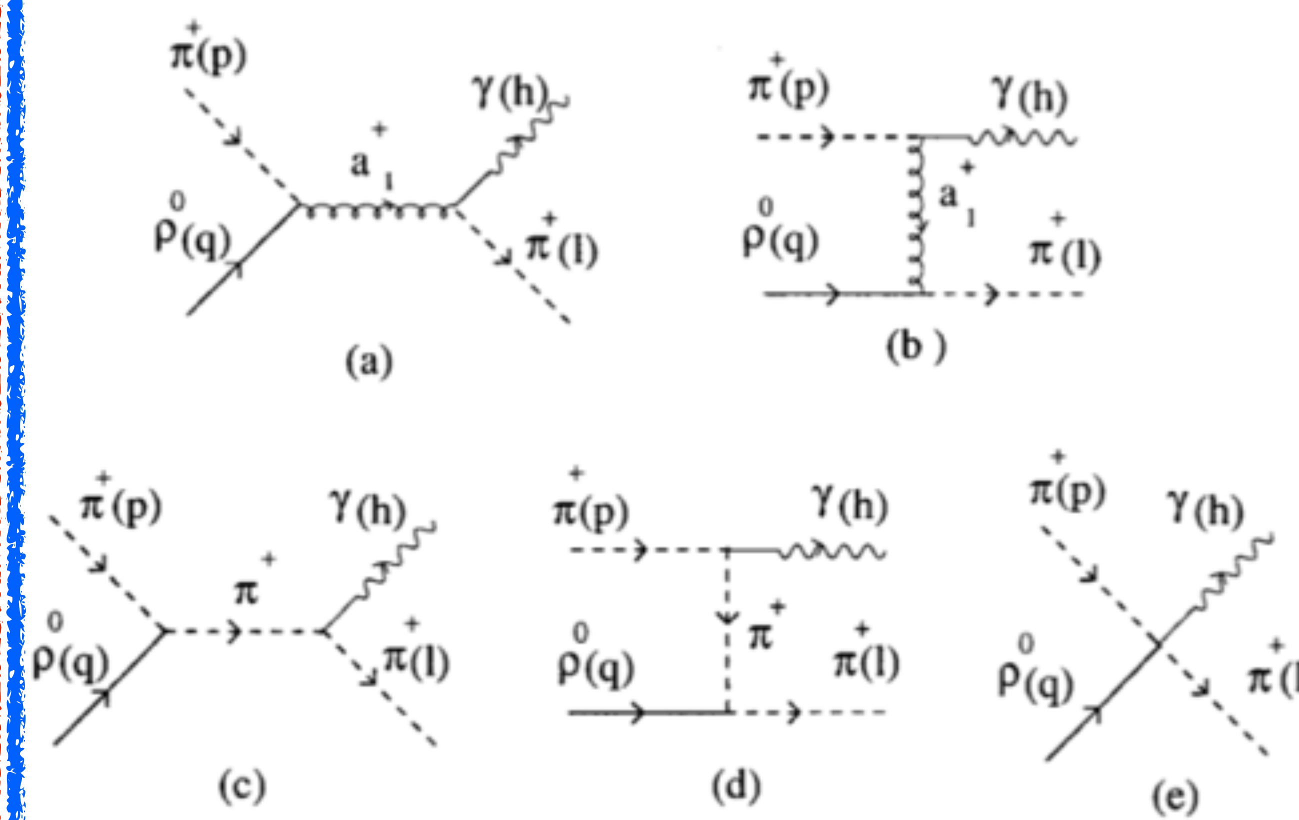
$$q\frac{dR}{d^3q} = \Gamma_0 + \frac{\pi^{\mu\nu}\hat{q}_\mu\hat{q}_\nu}{2(e+p)}a_{\alpha\beta}\Gamma^{\alpha\beta}$$

Equilibrium rates

QGP



Hadron Gas



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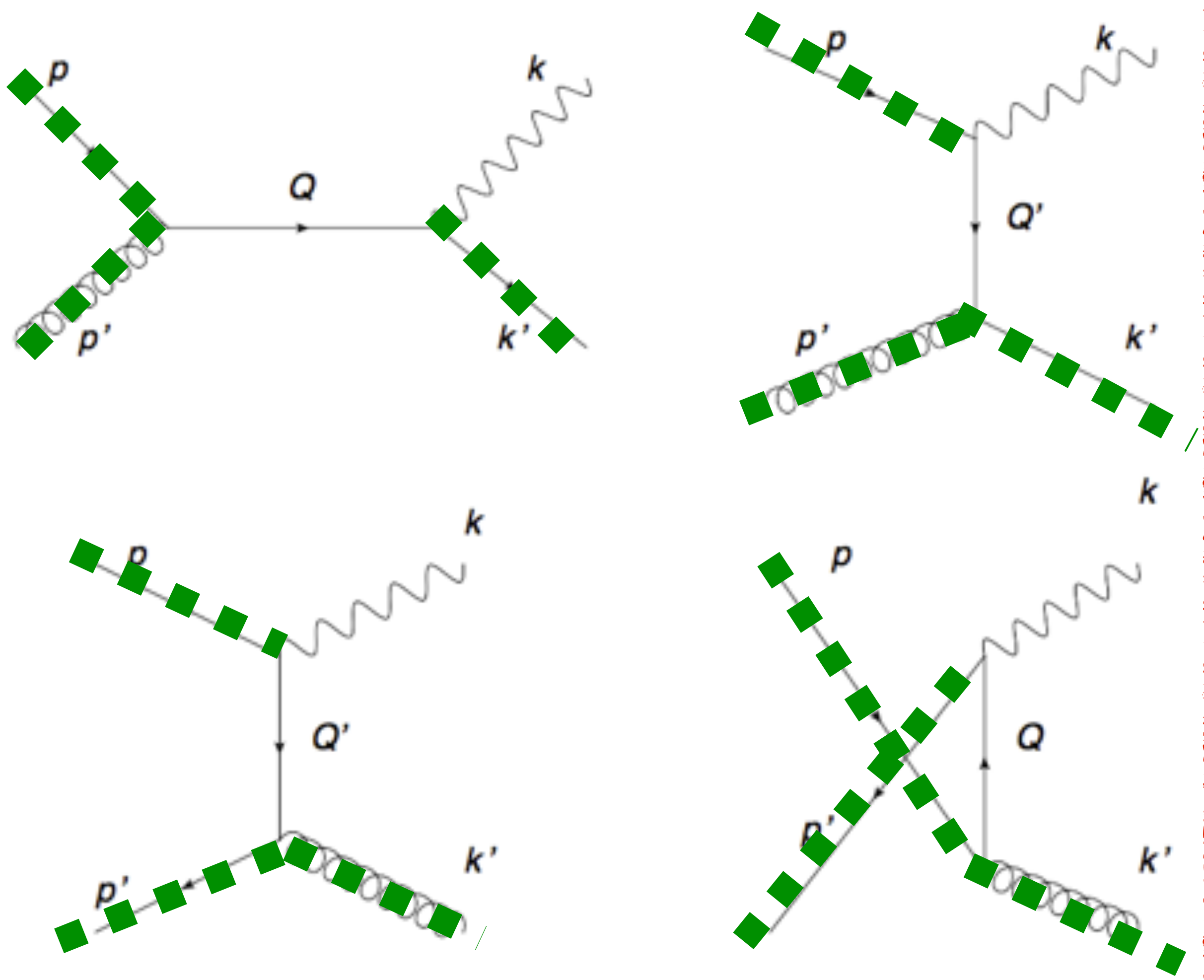
Equilibrium rates   off-equilibrium δf corrections

QGP



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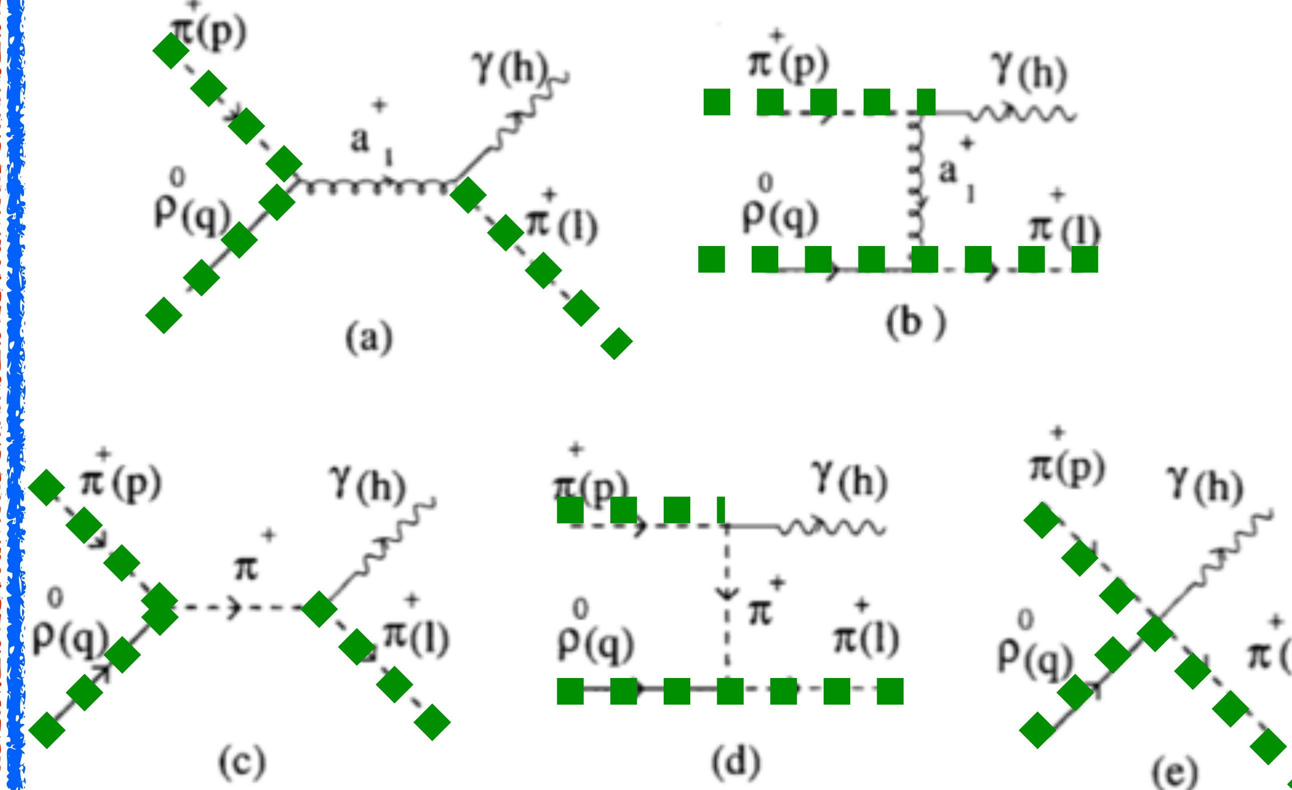

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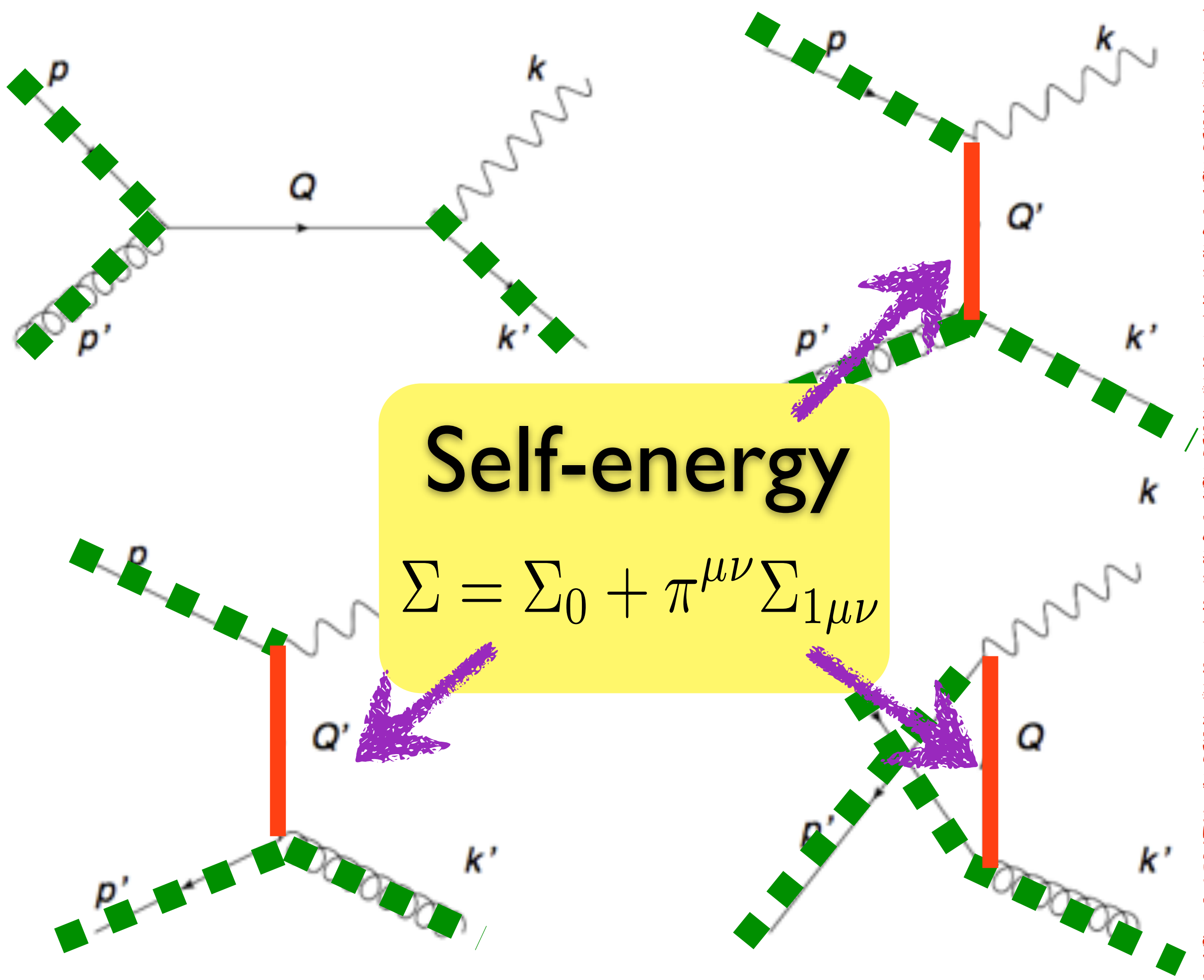

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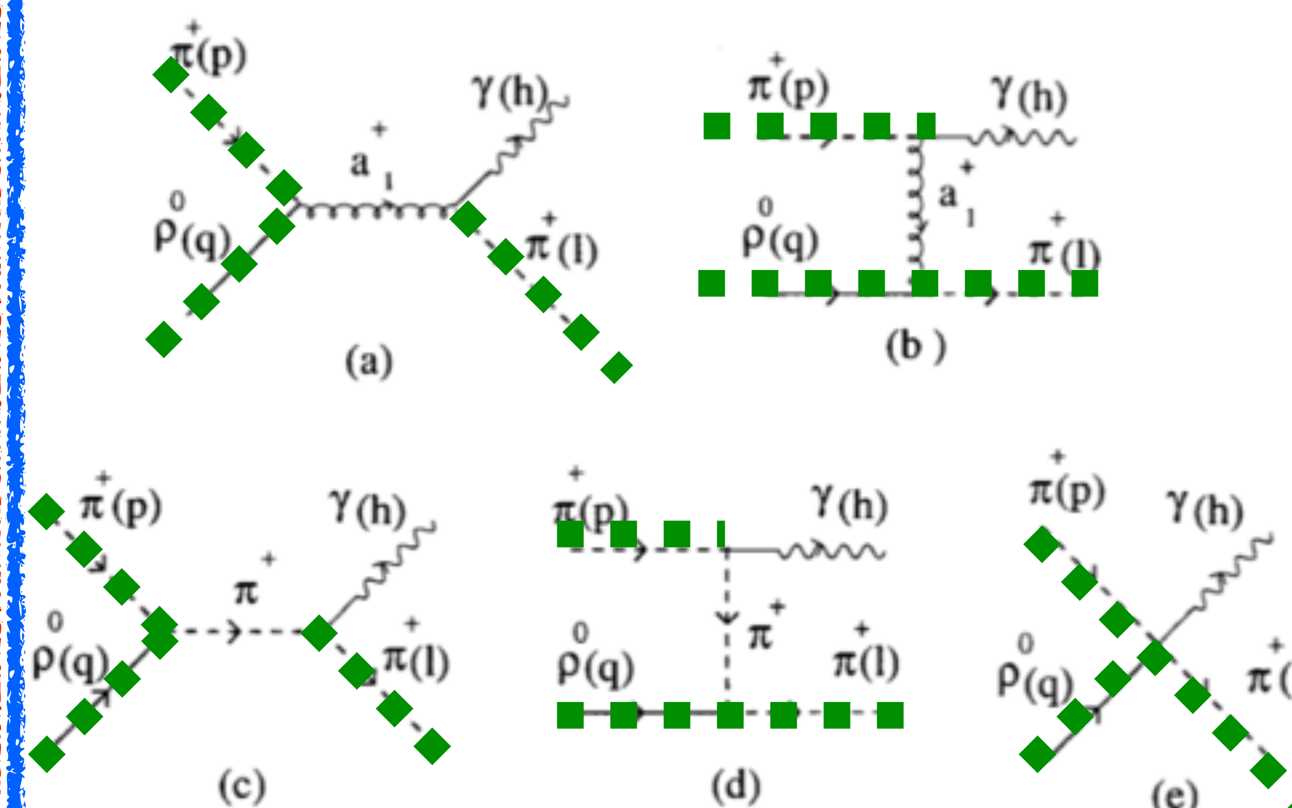
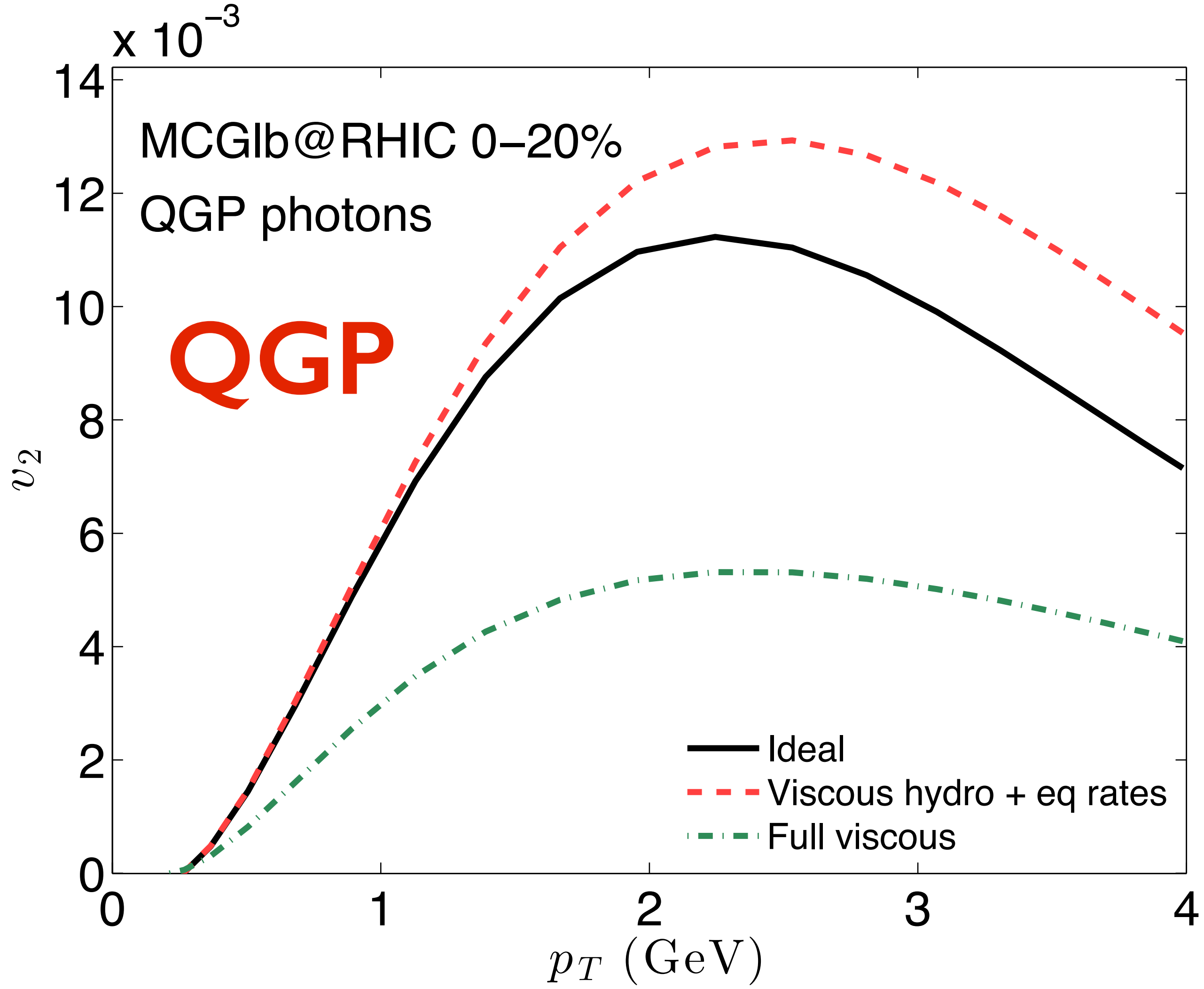
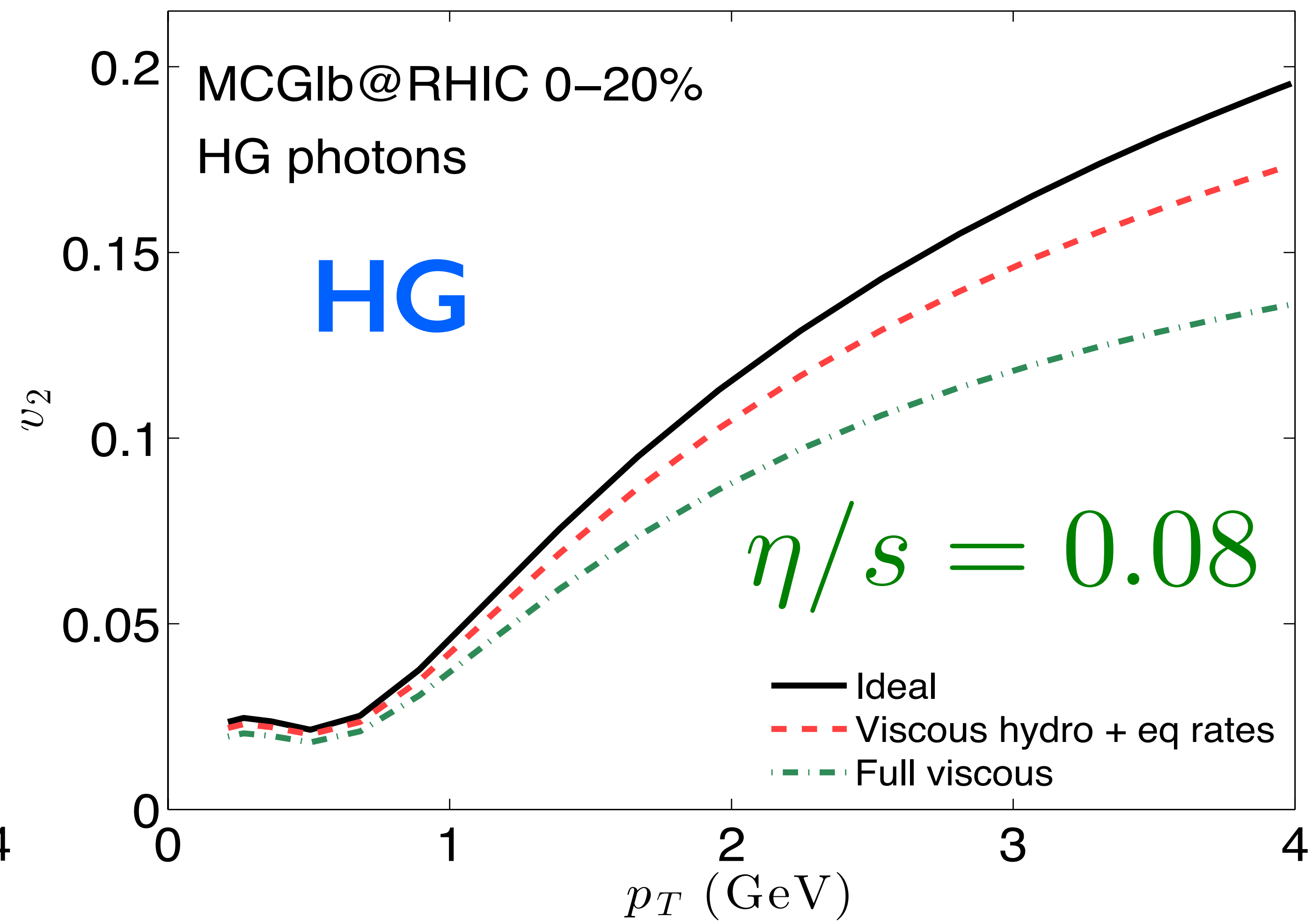


Viscous effects on photon elliptic flow





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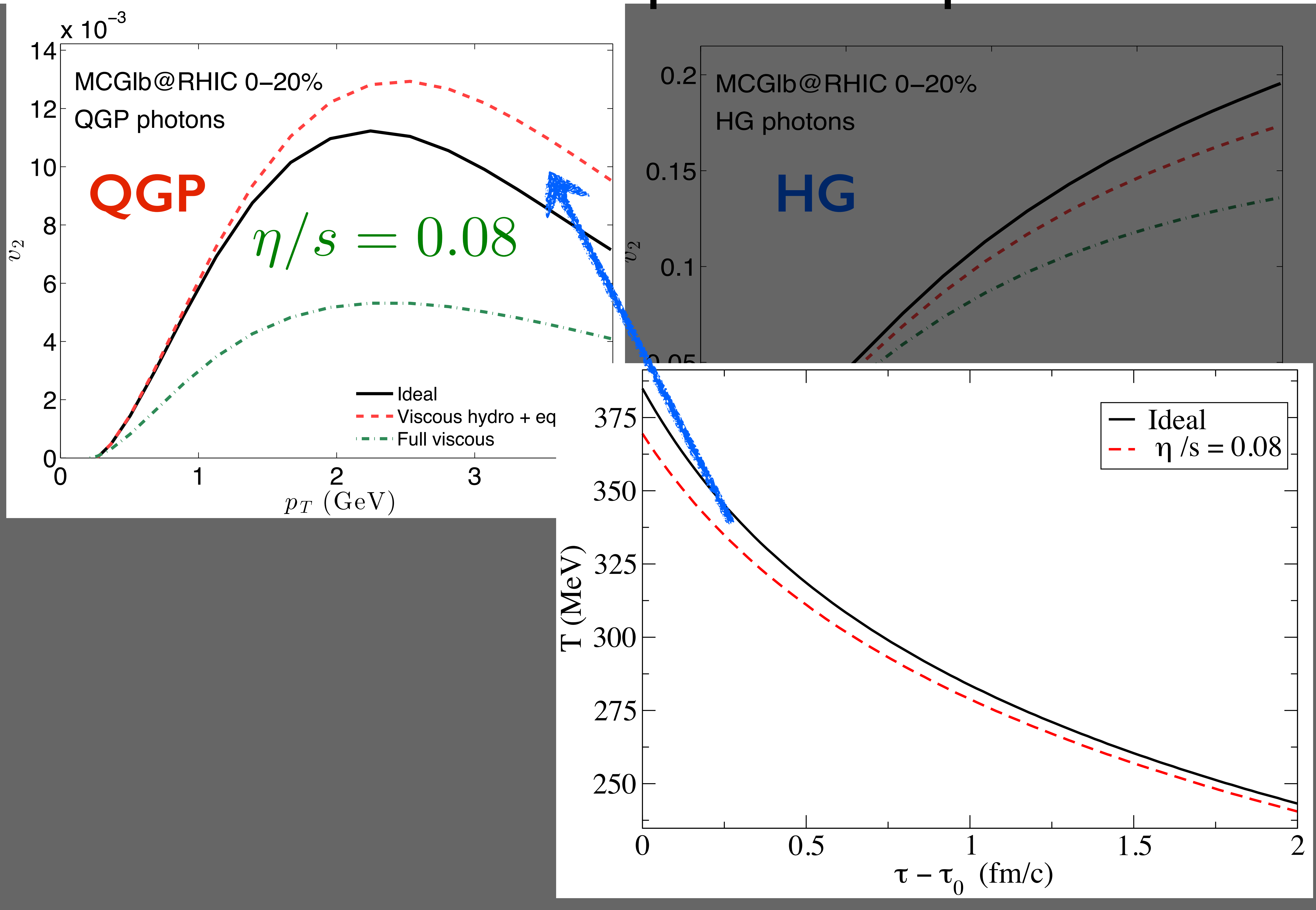

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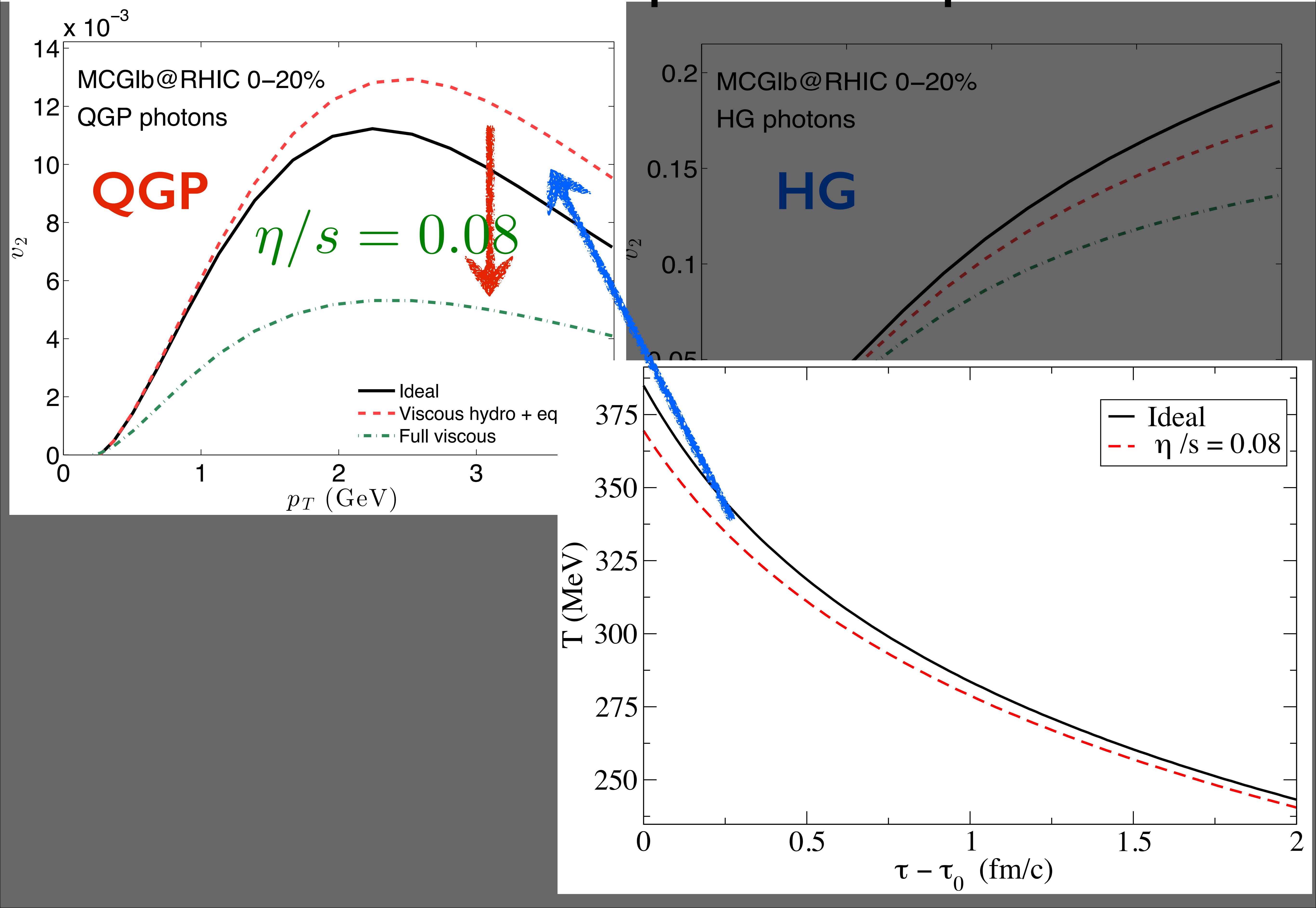

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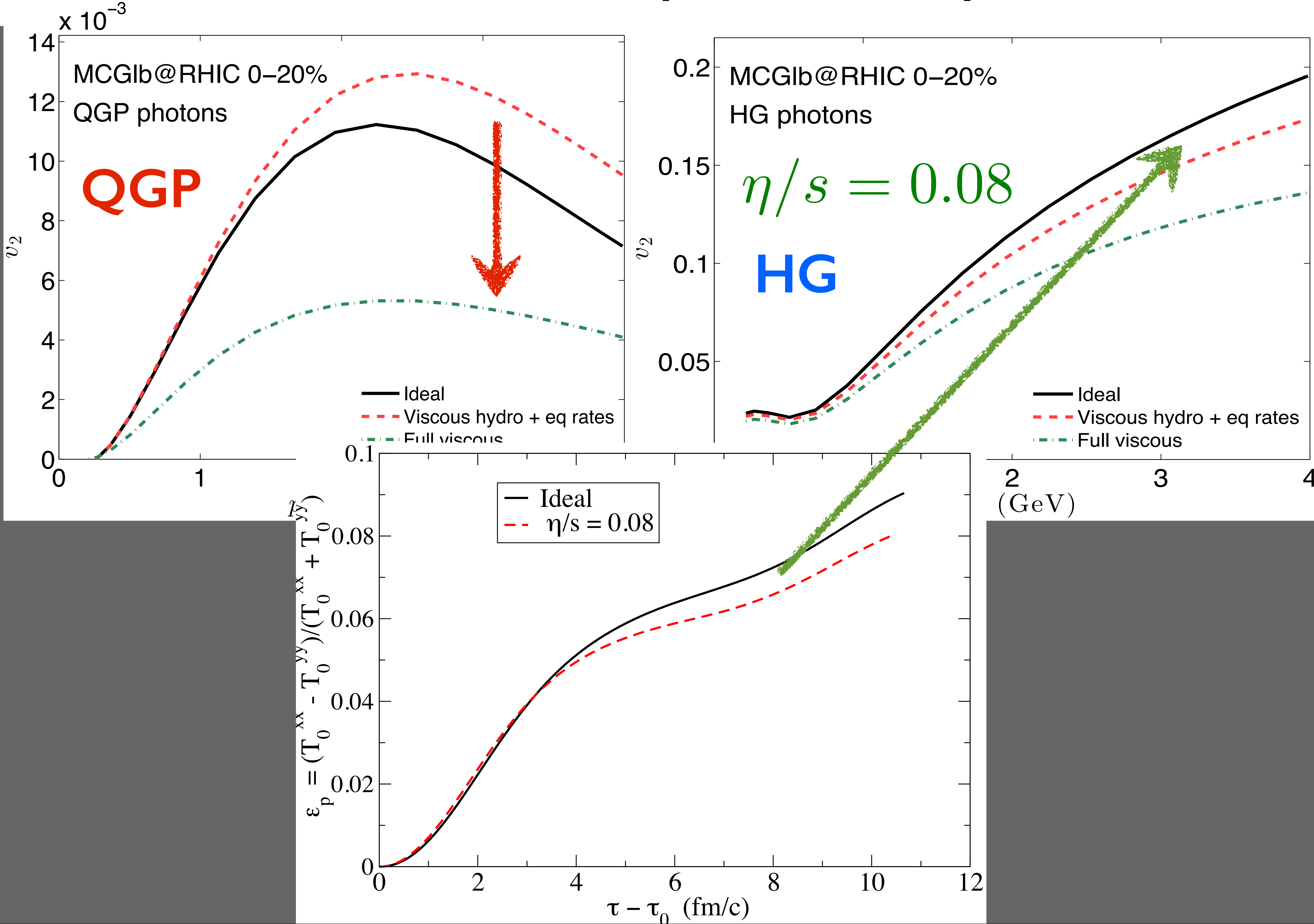

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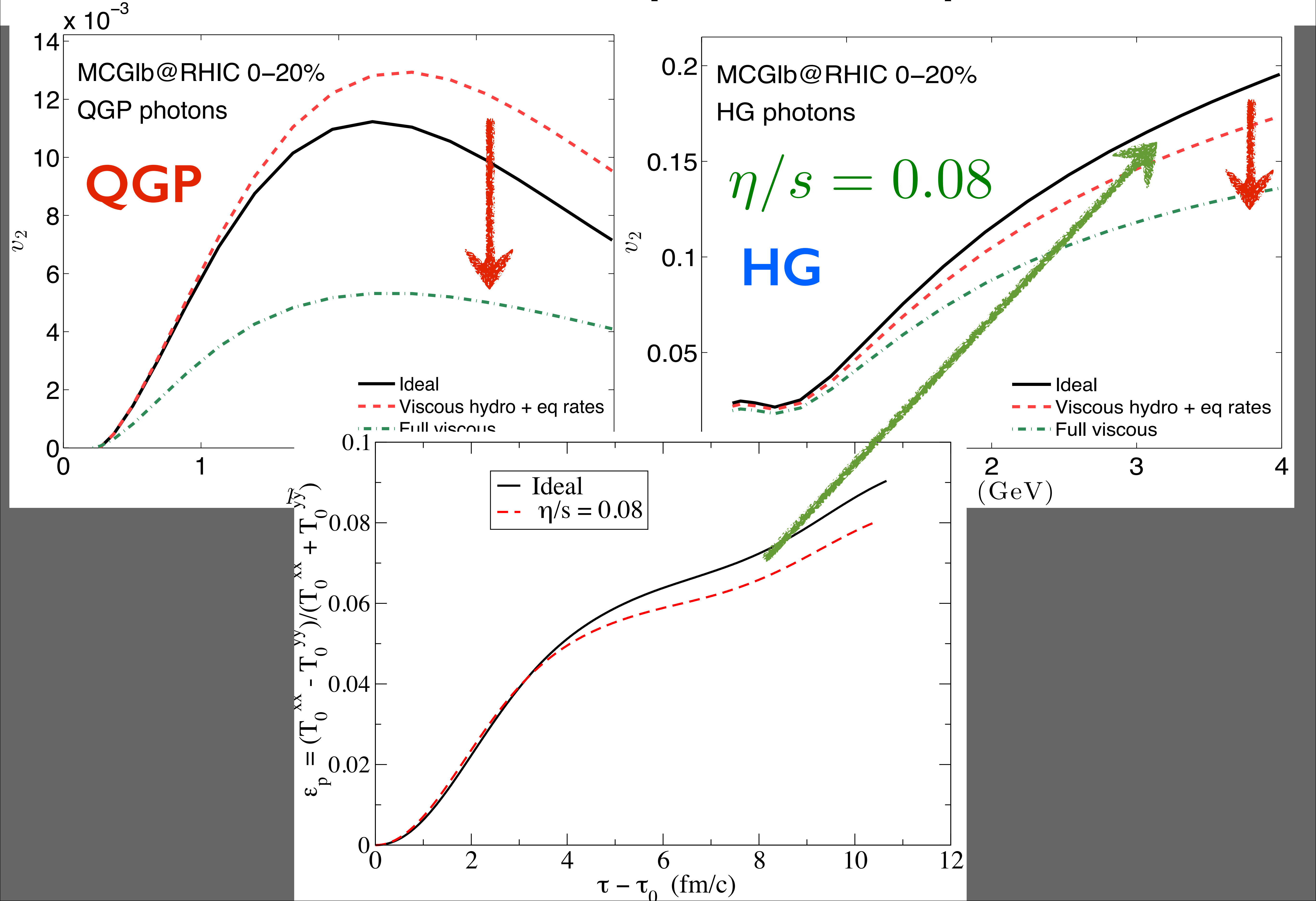

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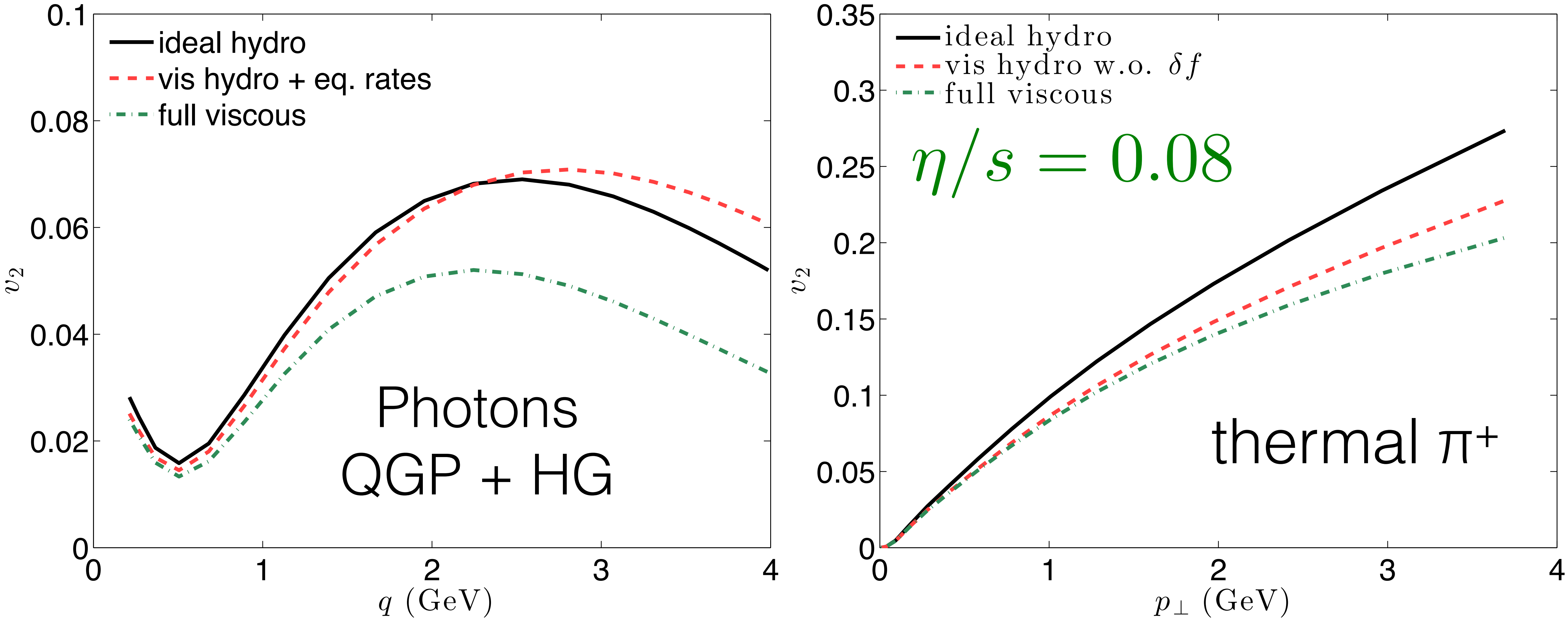
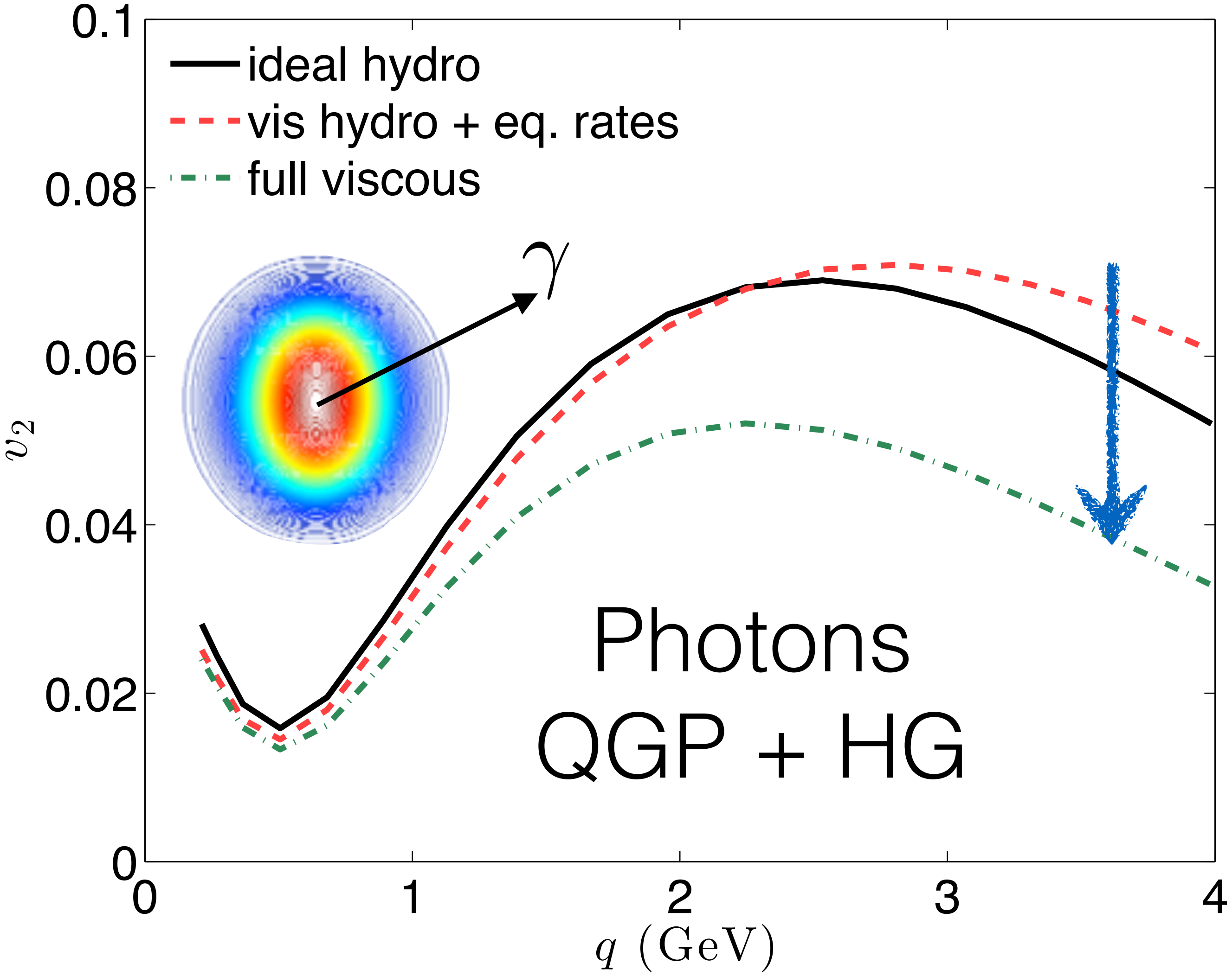
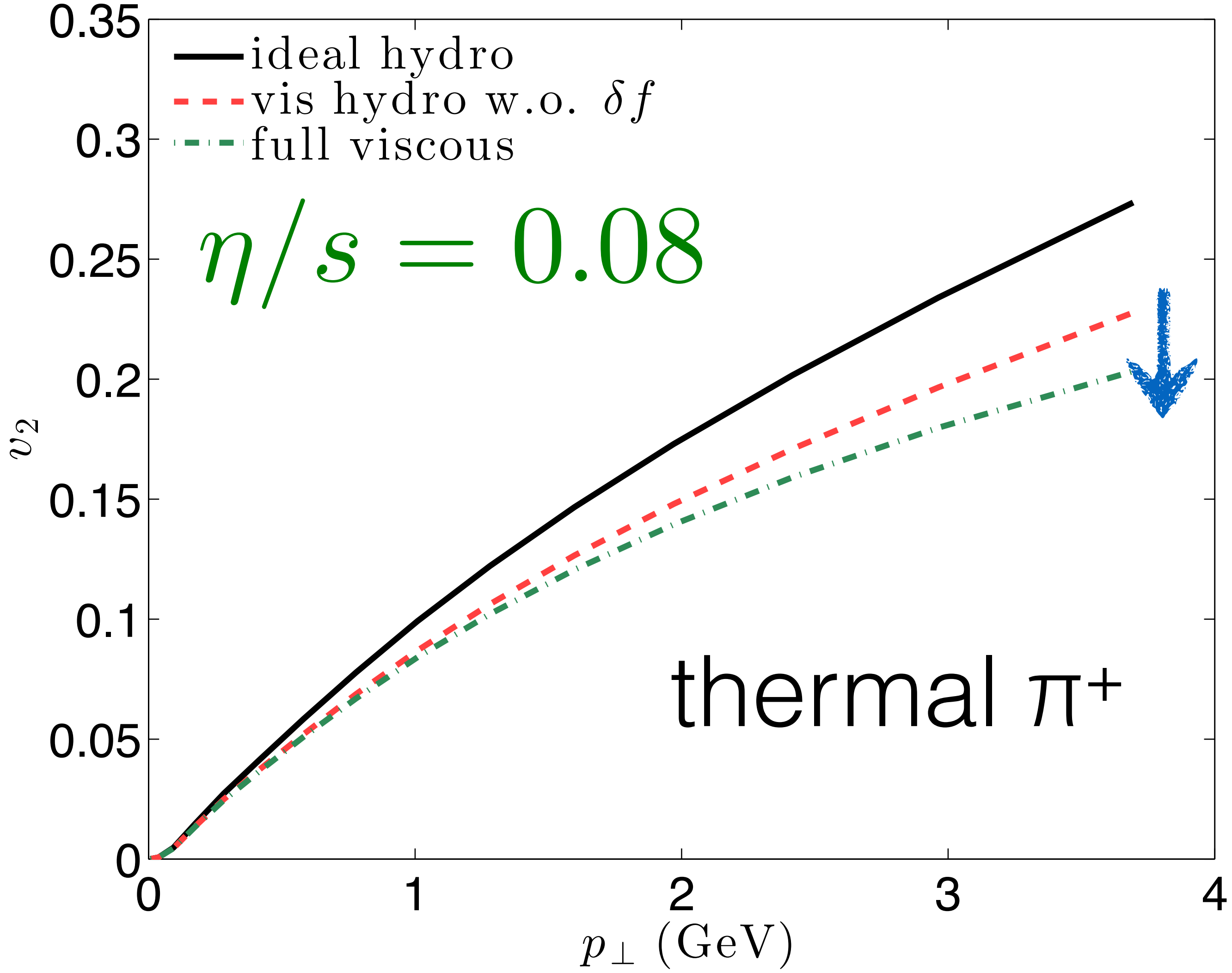


- Shear viscous suppression of photon v_2 is dominated by the viscous corrections to photon emission rates
- Photon elliptic flow is more sensitive to the evolution of shear stress tensor during the early time

Viscous effects on photon elliptic flow





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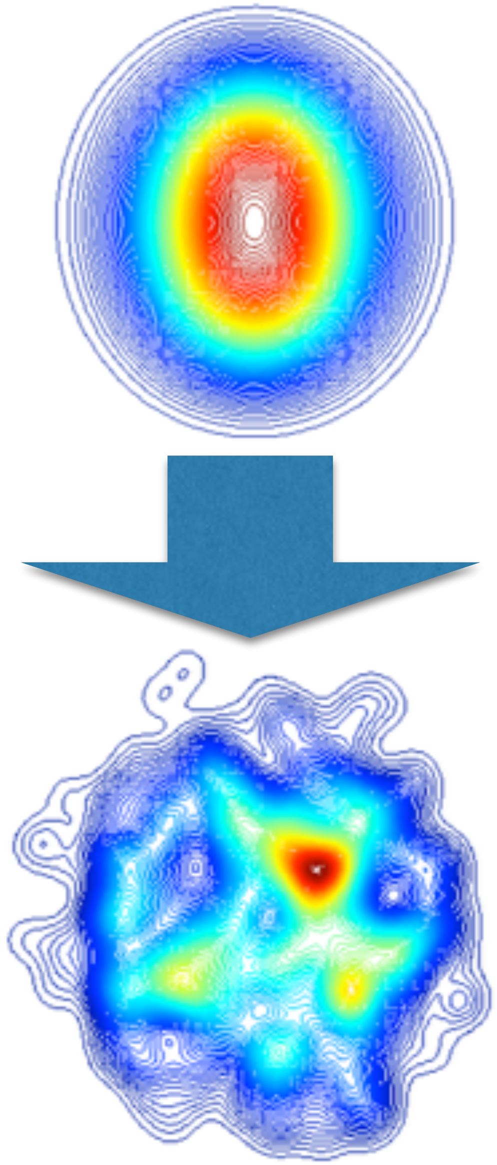
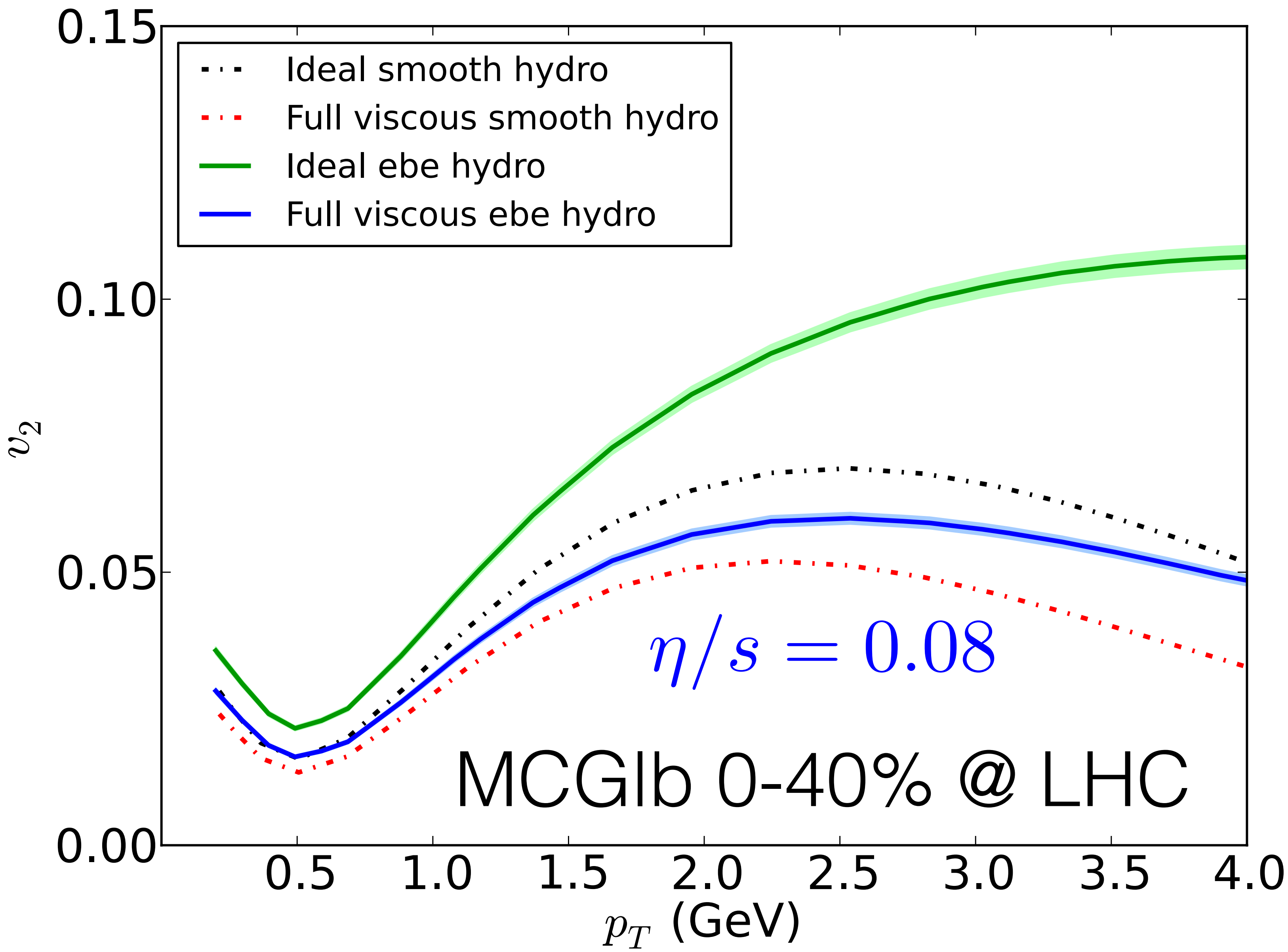
Fluctuation effects on photon elliptic flow





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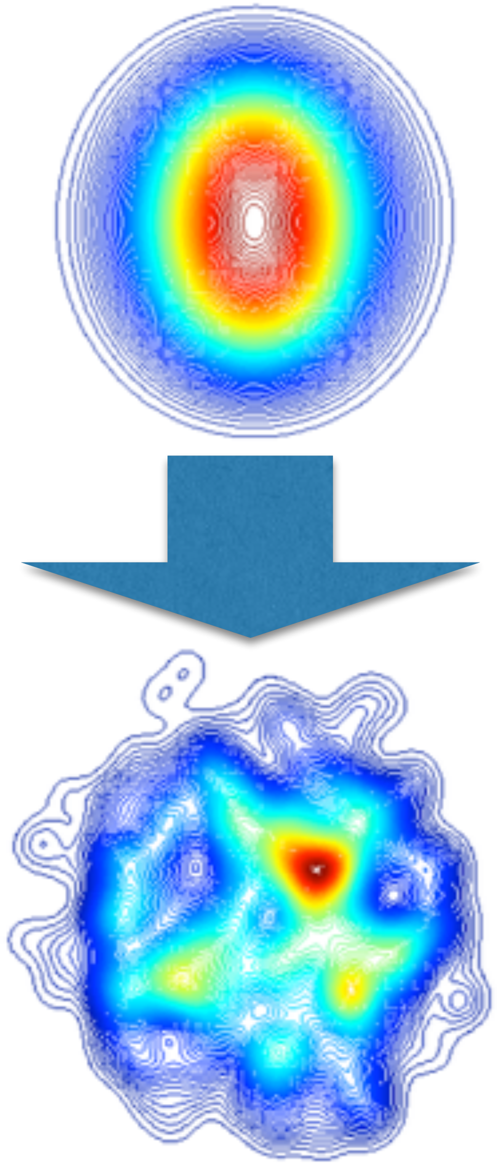
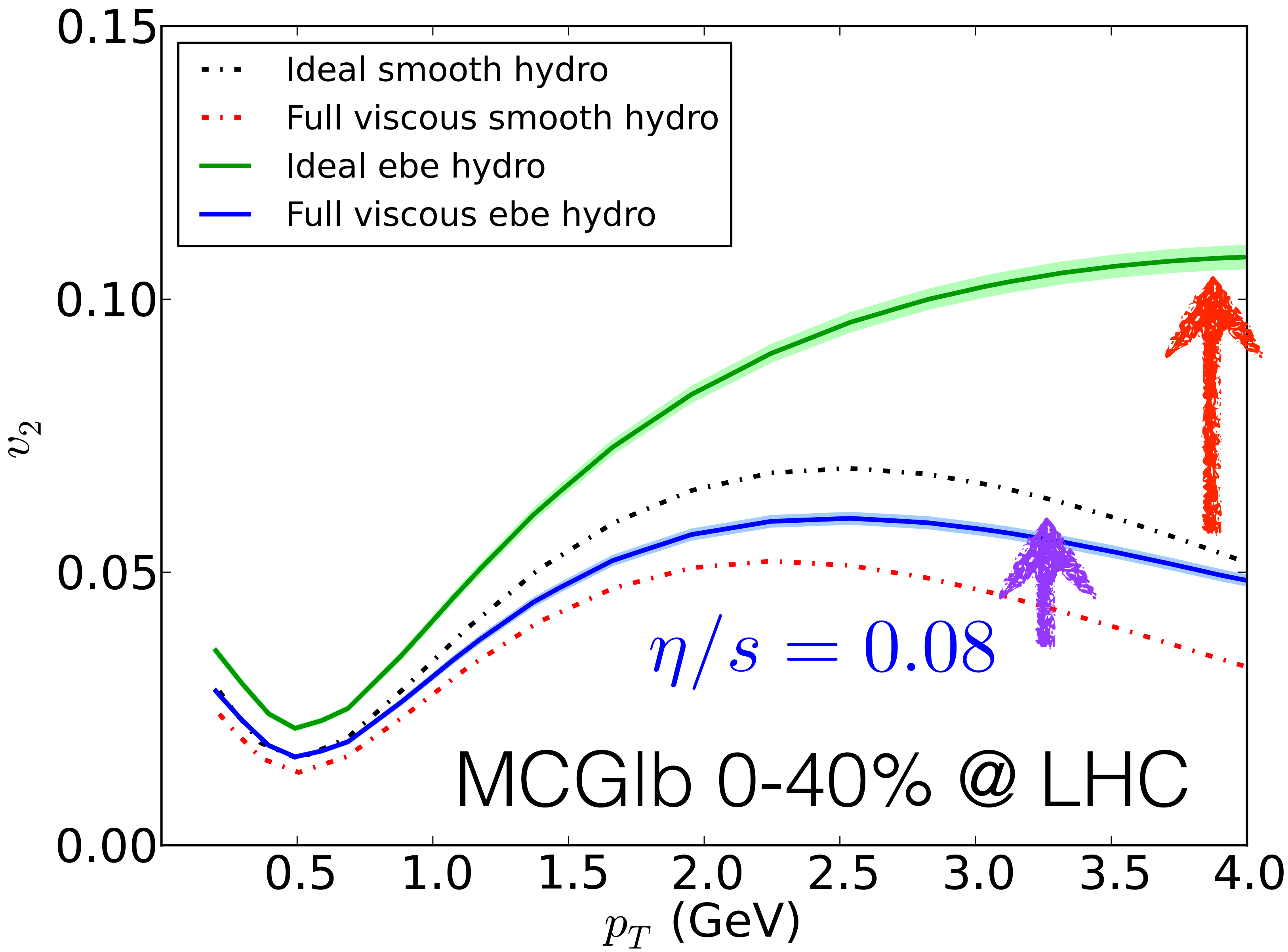
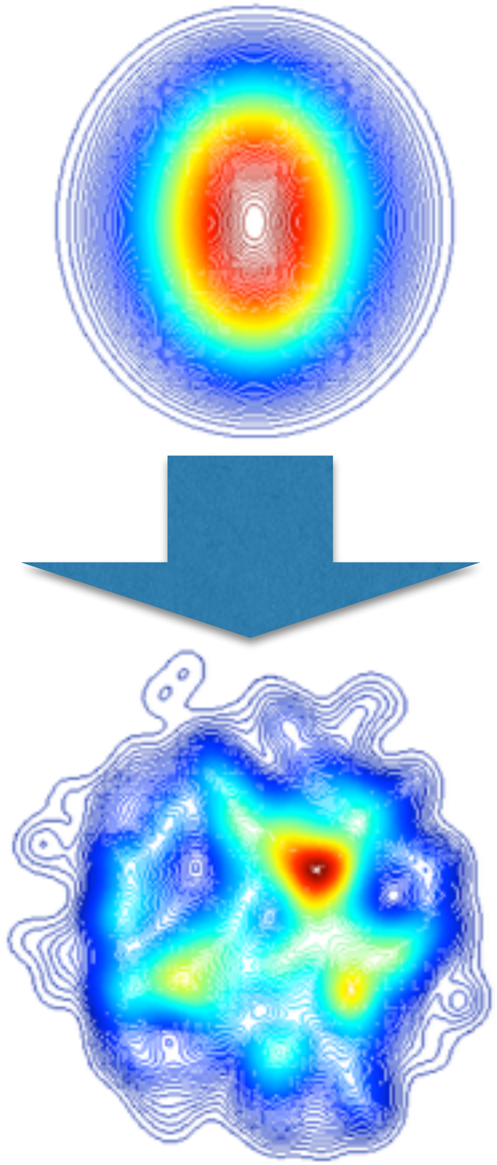
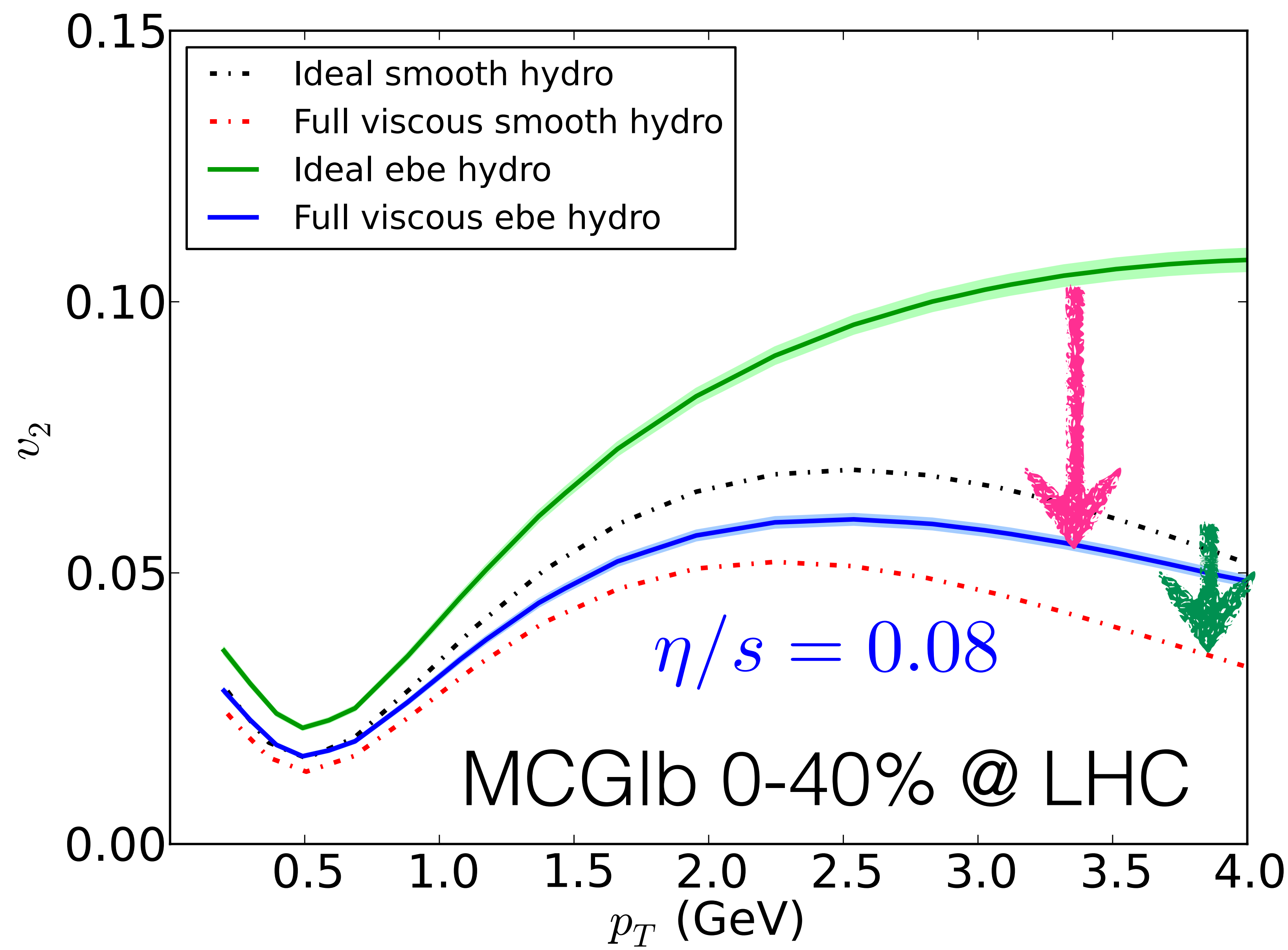




- Initial fluctuations increase photon's elliptic flow

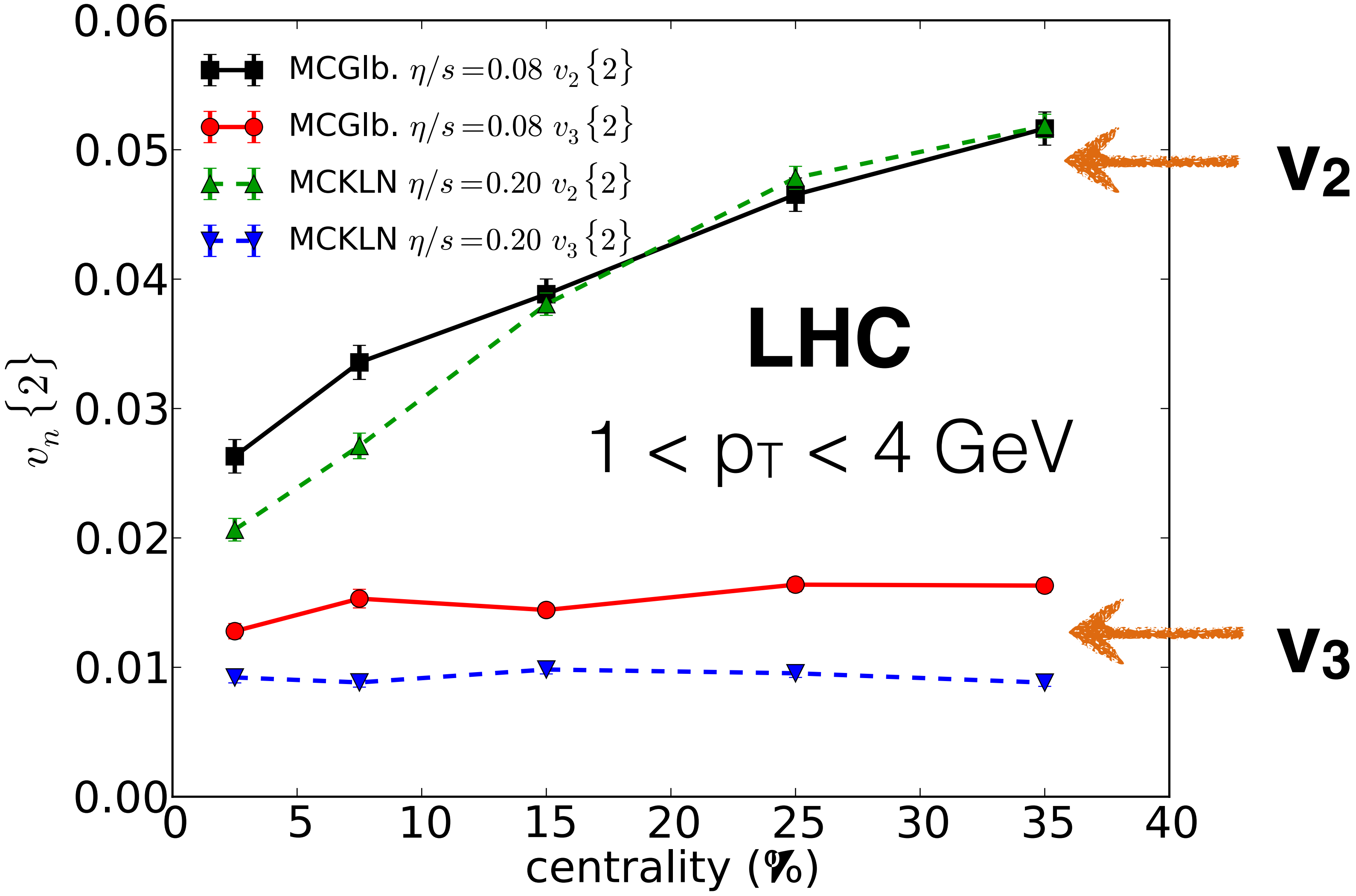
Fluctuation effects on photon elliptic flow





- 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

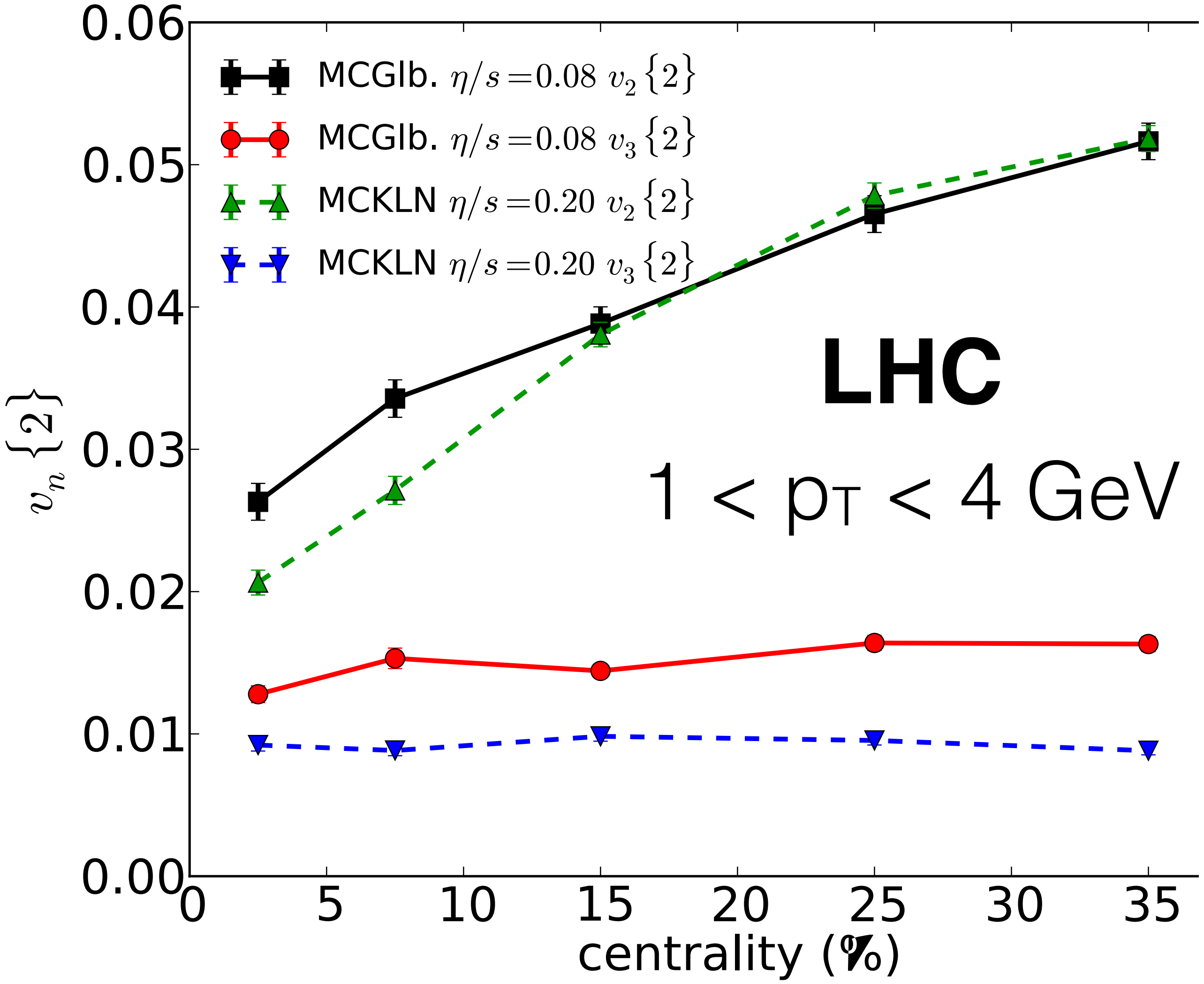


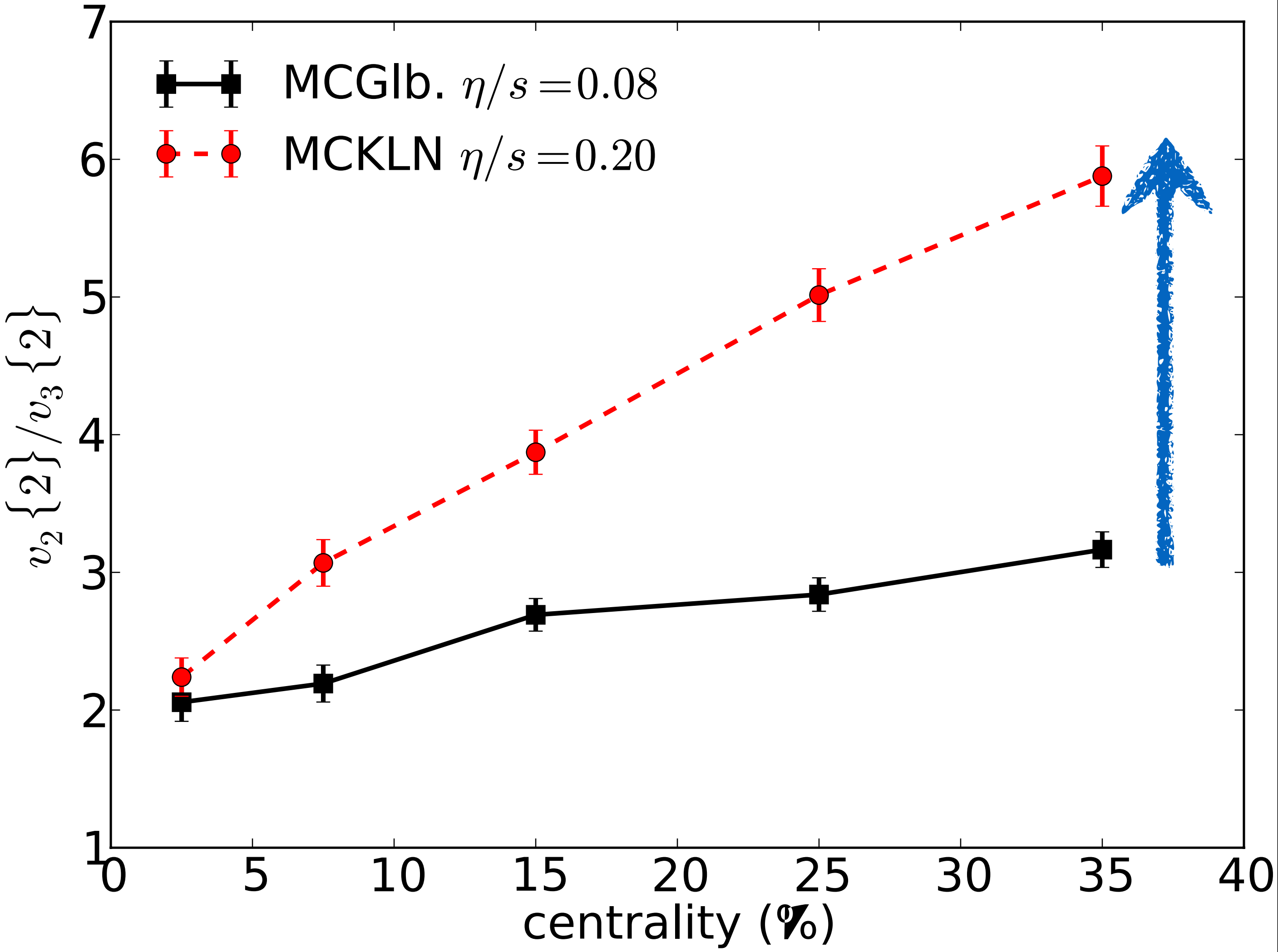
MCGlb. $\eta/s = 0.08$

MCKLN $\eta/s = 0.20$

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

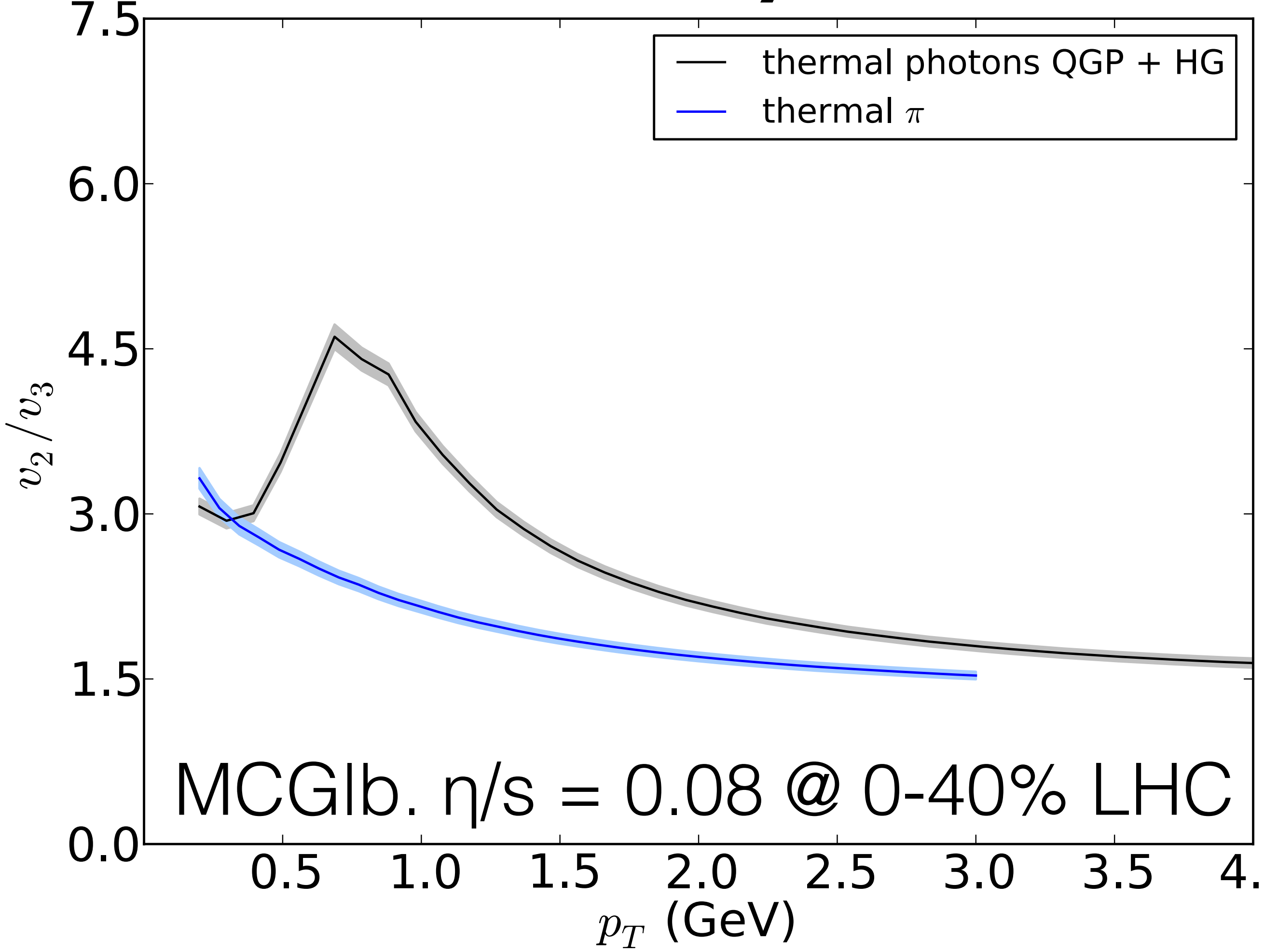
Event-by-Event Full Viscous Photon v_n

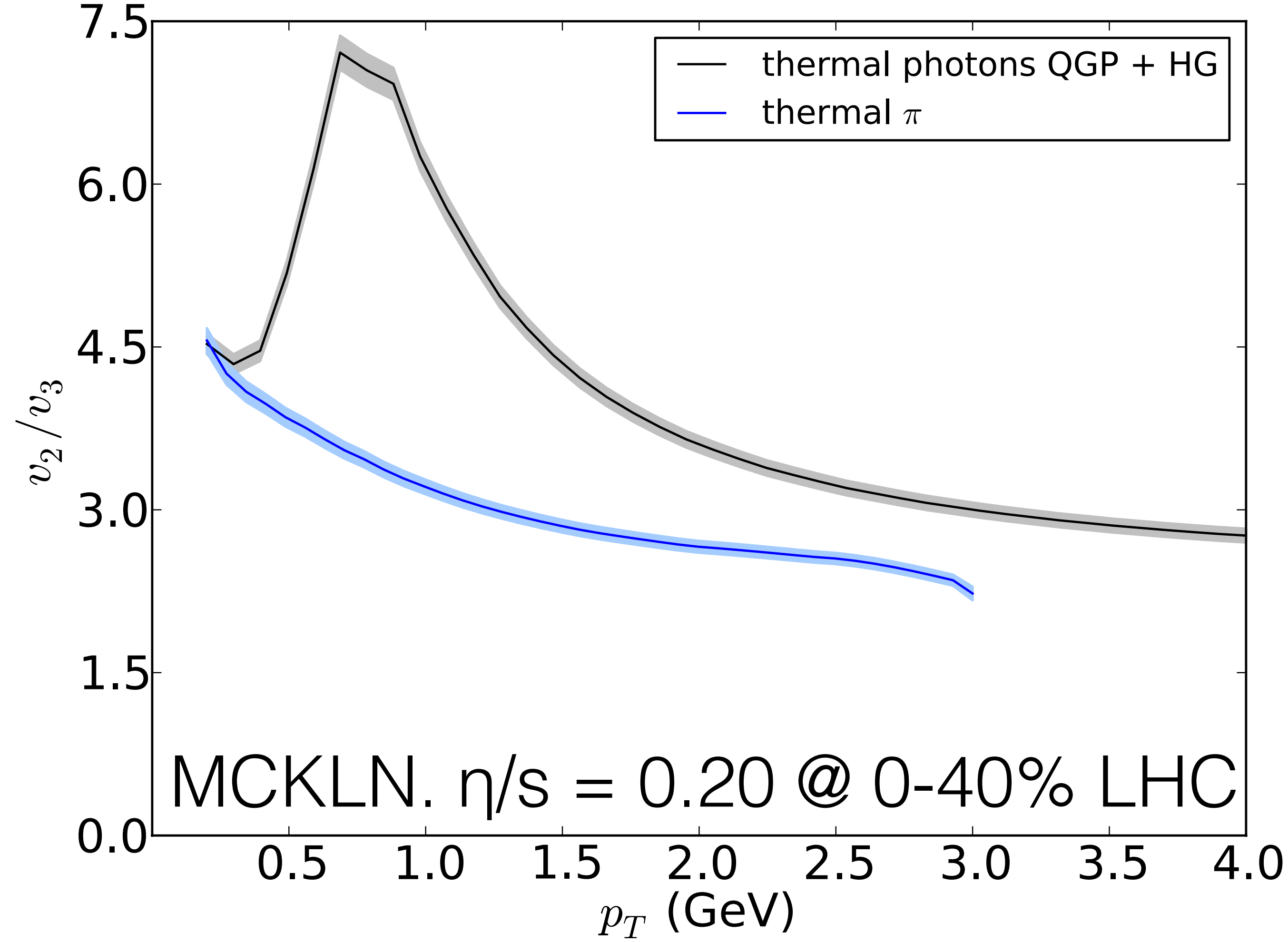




- The anisotropic flows of photons show similar centrality behavior as hadrons v_n
- The ratio of v_2/v_3 increase with the shear viscosity.
- The centrality dependence of this ratio is stronger for MCKLN model

Event-by-Event Full Viscous Photon v_n





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

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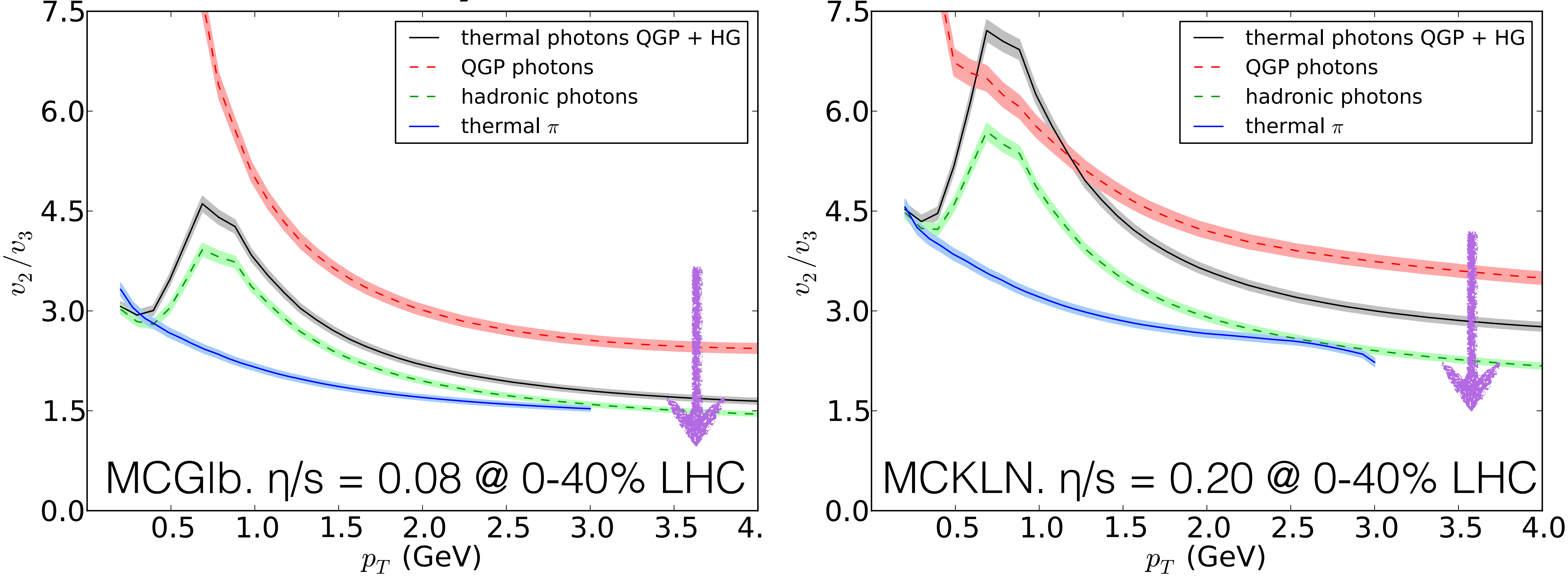
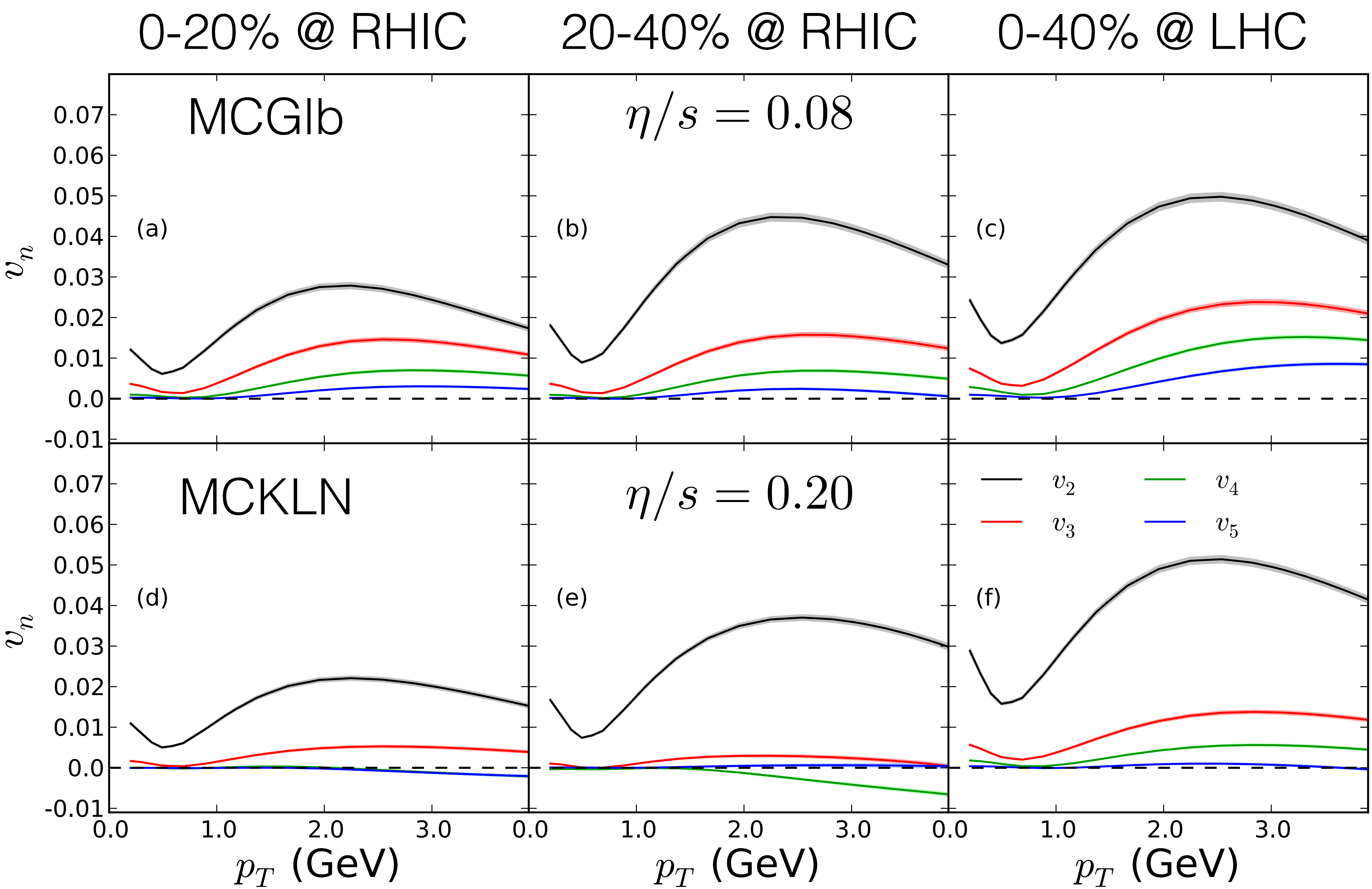


- The ratio of v_2/v_3 of photons is larger than the ratio of thermal pions
- The ratio of v_2/v_3 is larger for QGP photons compared to hadronic photons which indicates triangular flow develops faster than elliptic flow during the late stage of hydrodynamic evolution

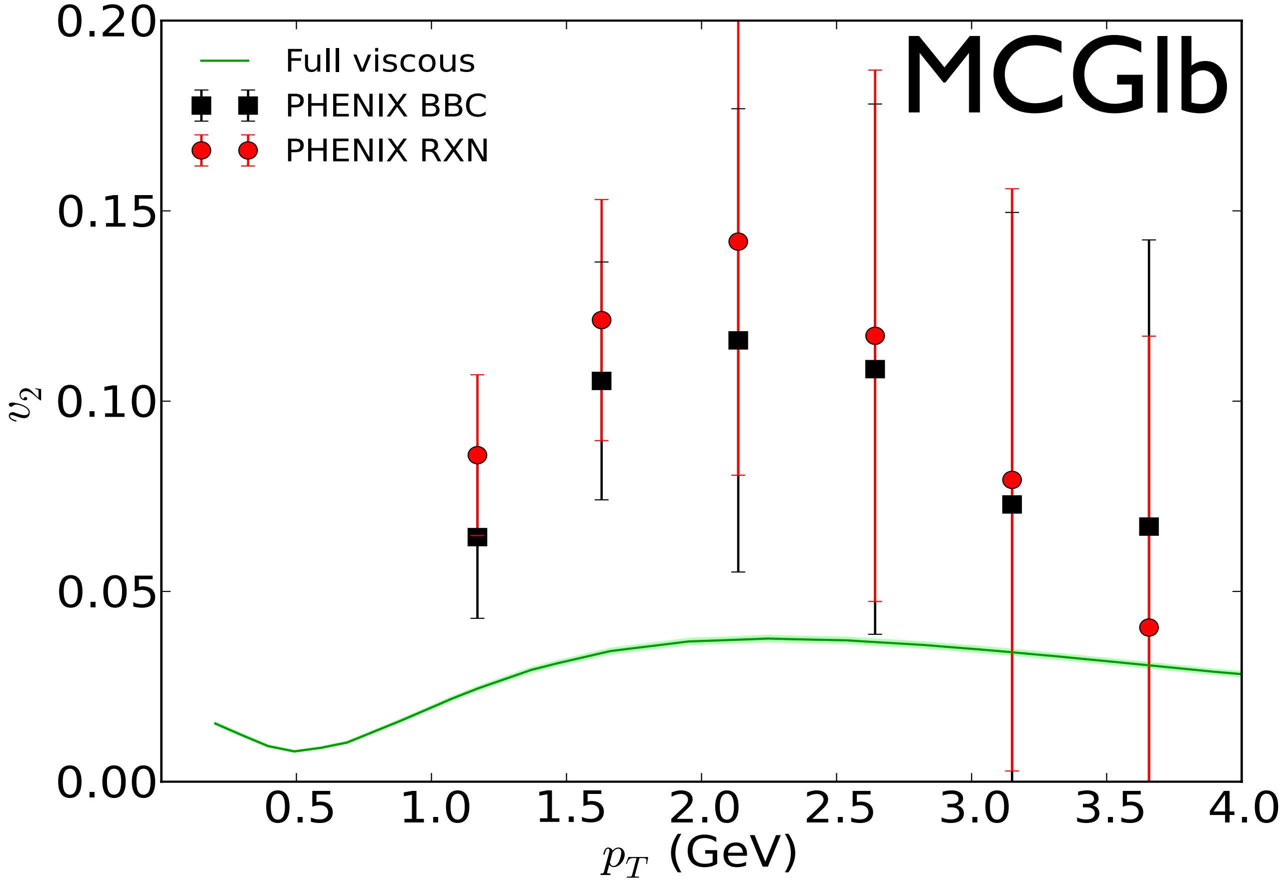
Event-by-Event Full Viscous Photon v_n

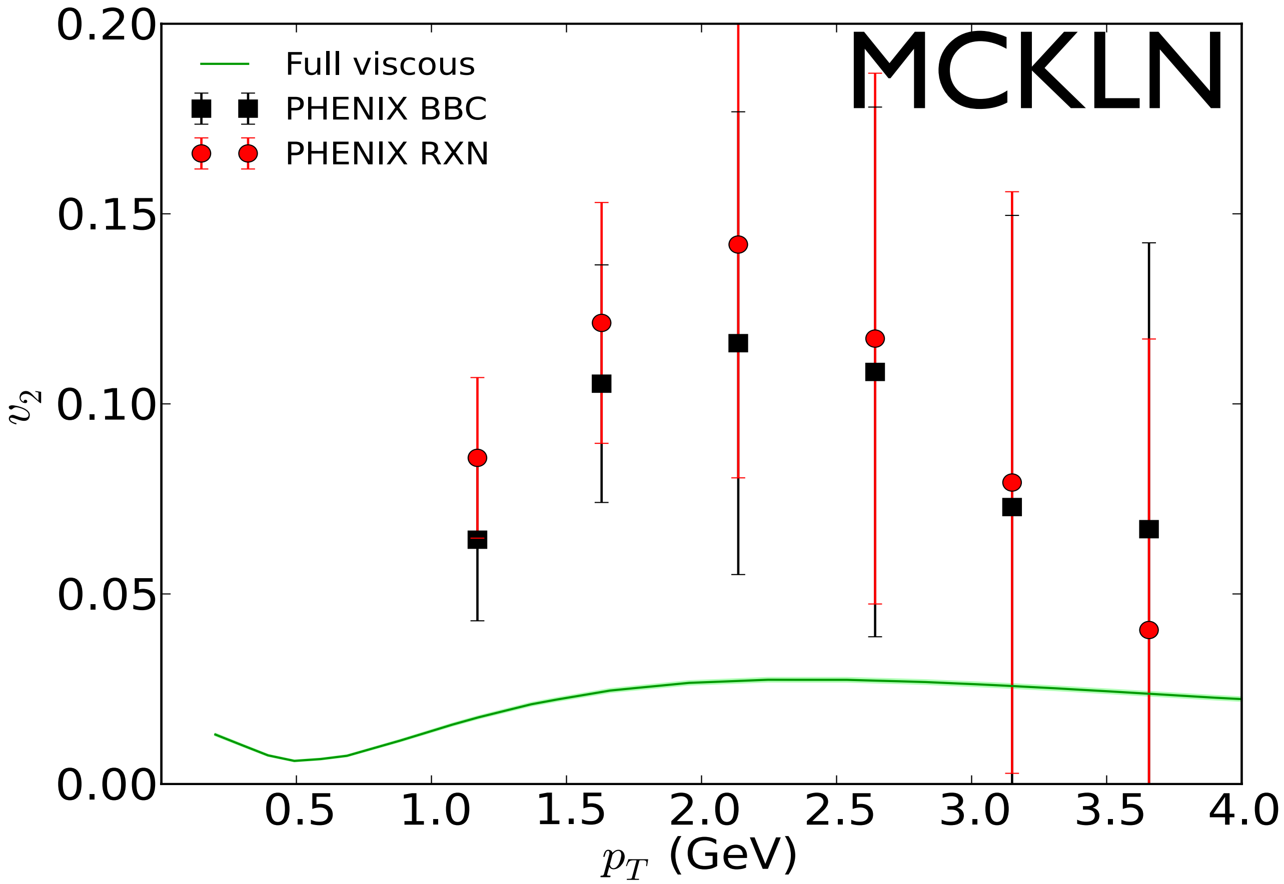


1000 events each centrality

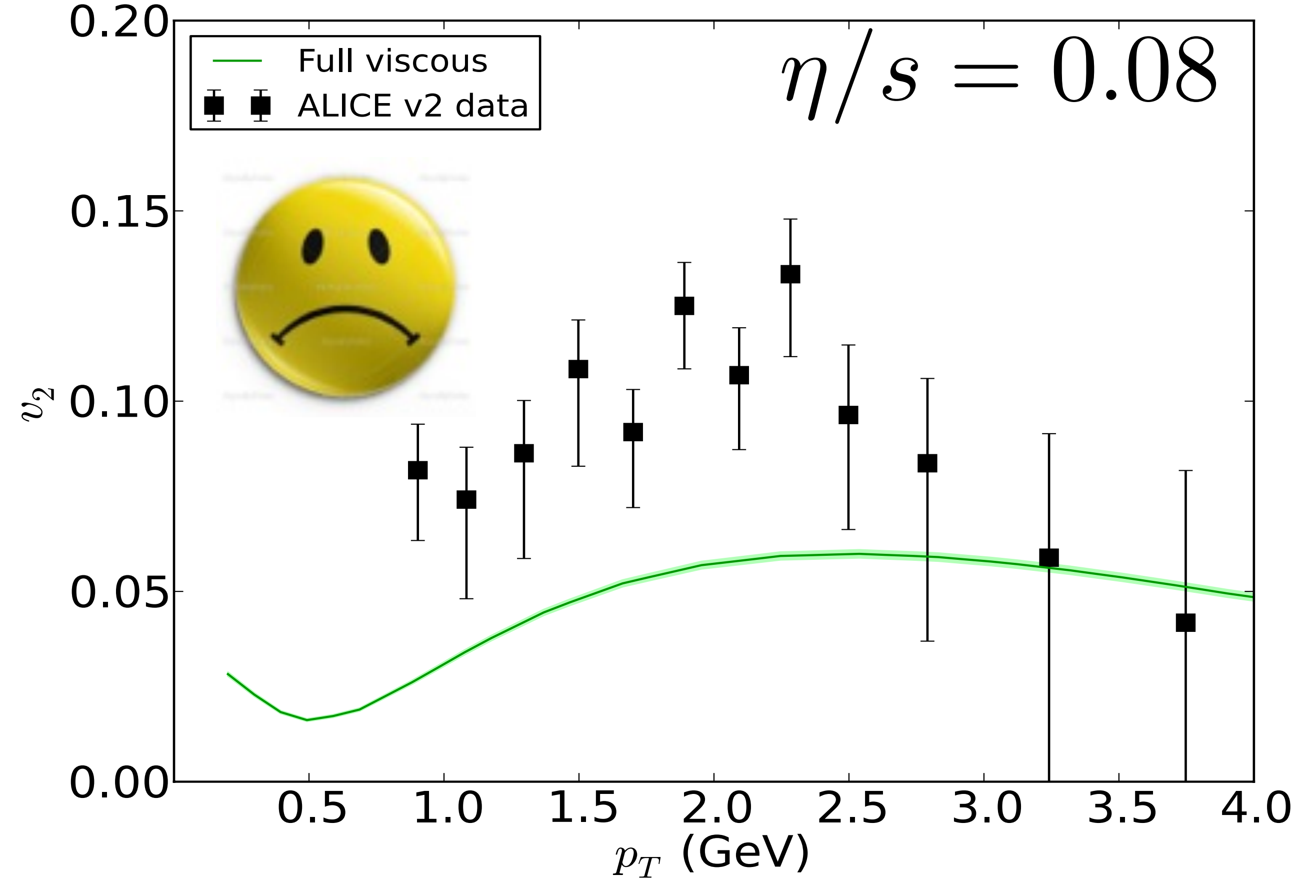
Comparisons with exp. data

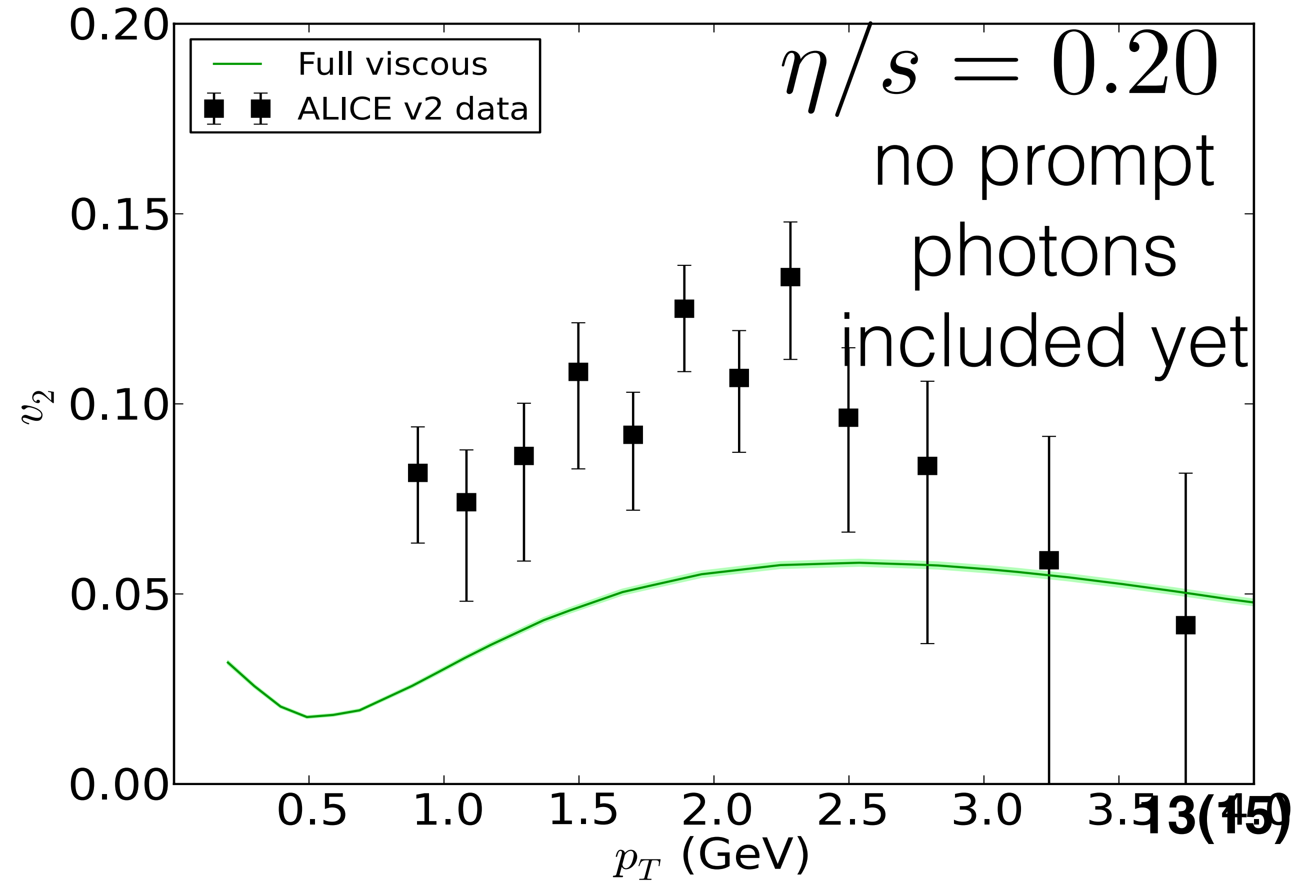
RHIC 0-20%





LHC 0-40%





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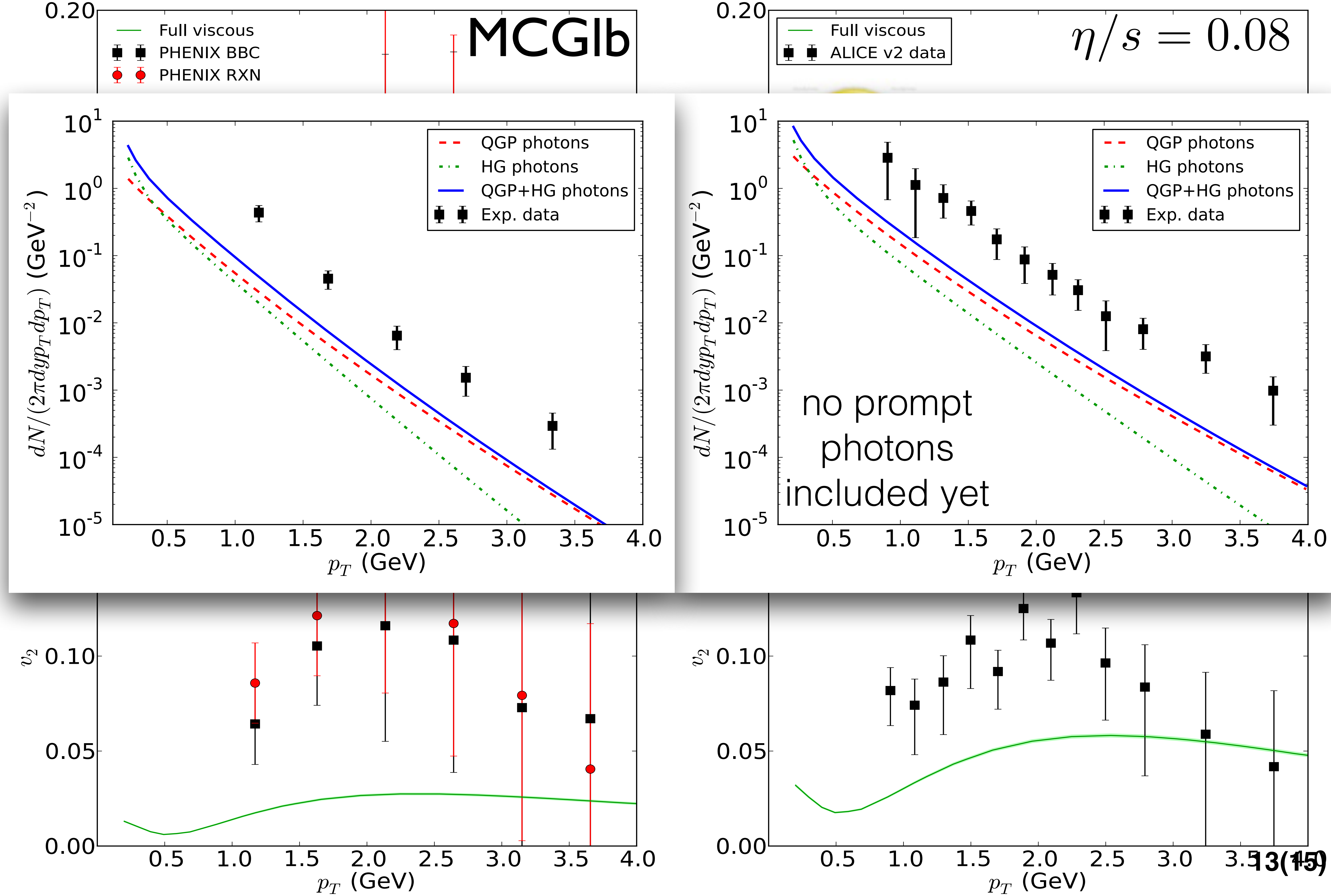
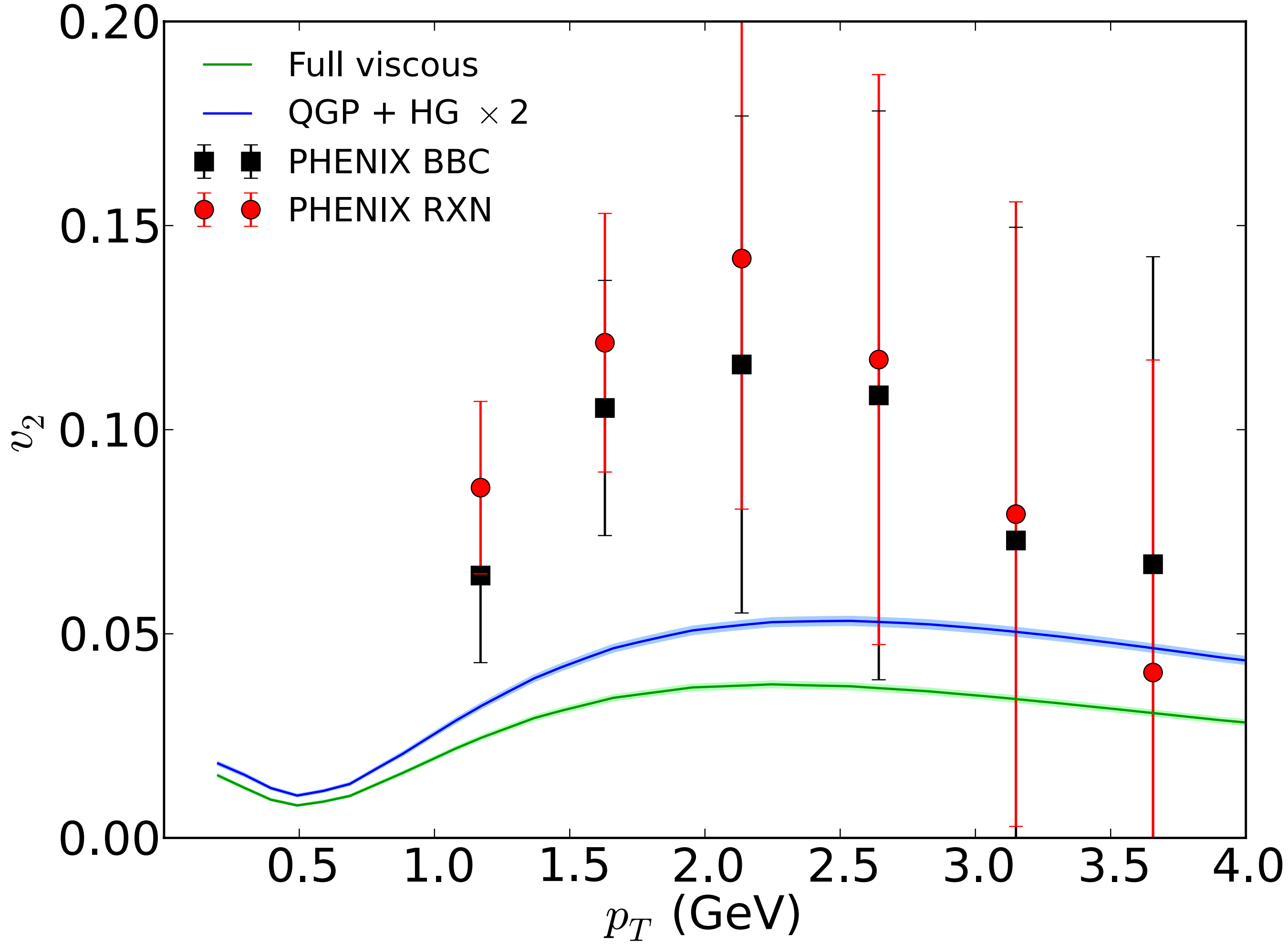
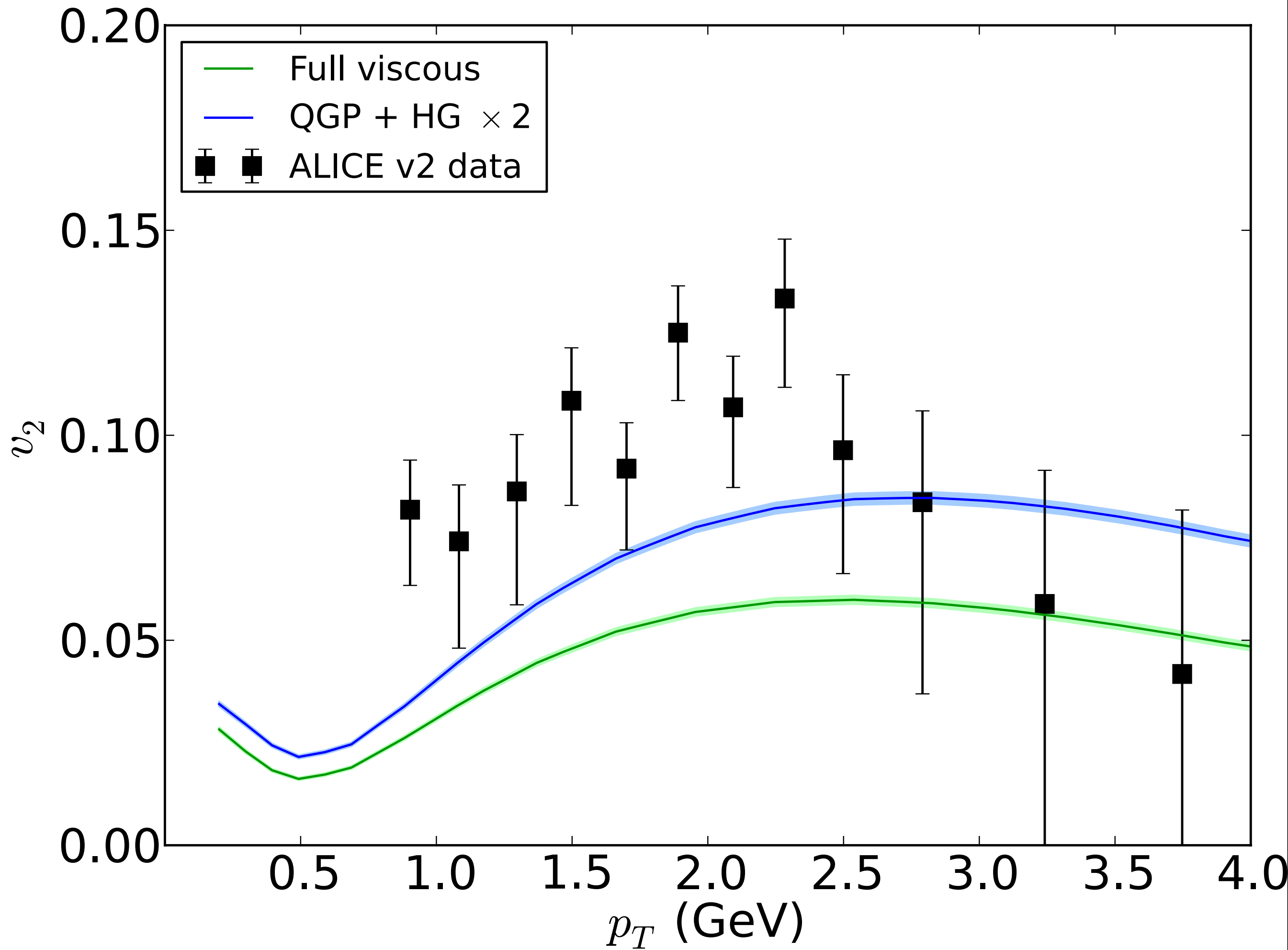


Missing rates in hadronic phase

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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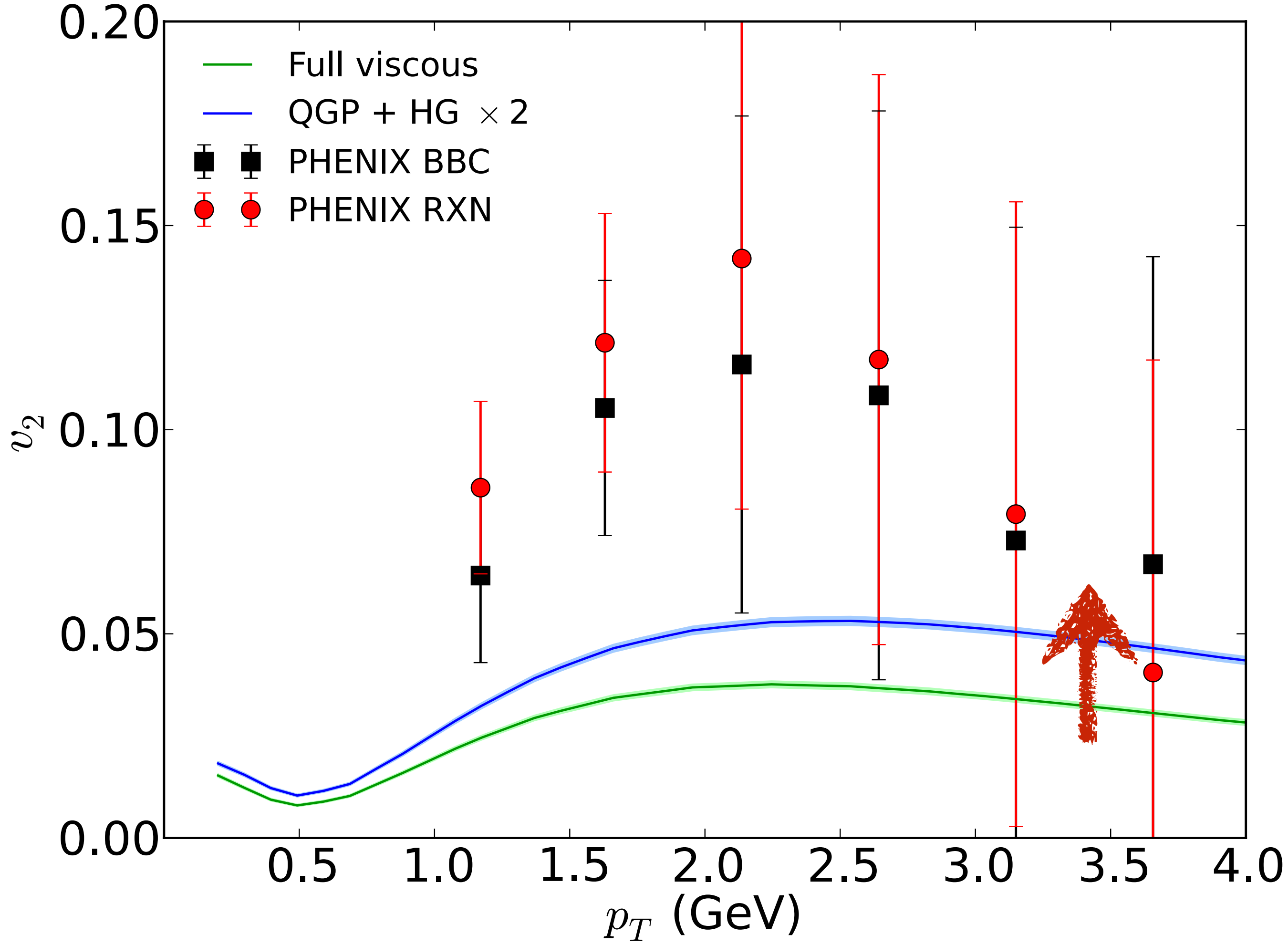

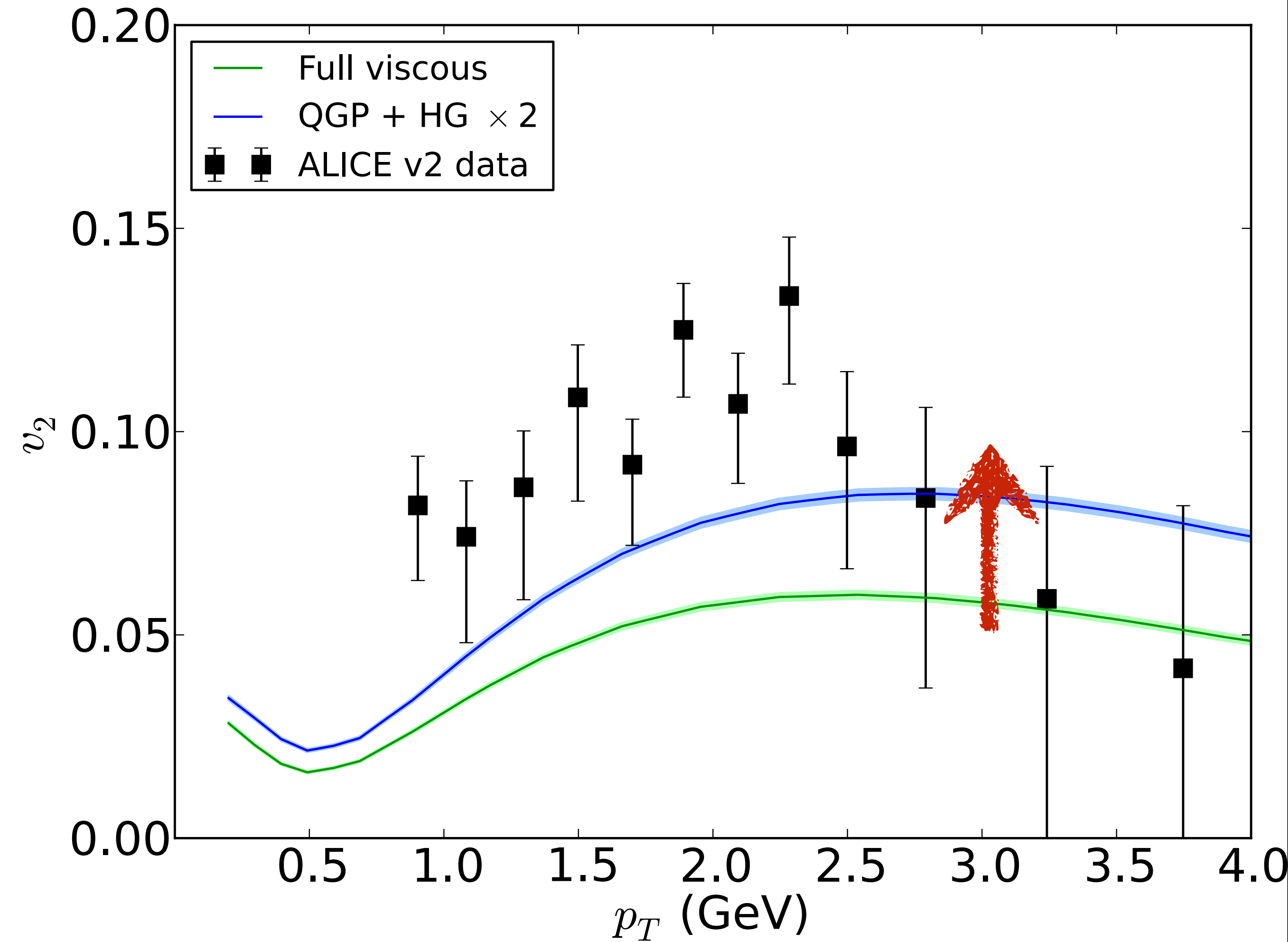

- it increases total photon v_2 by ~45% at both RHIC and LHC energies

Conclusion

- We calculate photon anisotropic flows $\mathbf{v_n}$ from *event-by-event* viscous hydrodynamic medium

- 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.

- Photon production from missing sources (e.g. baryonic channels) are needed to improve the agreement between experiment and theory.

arXiv: 1308.2111, 1308.2440

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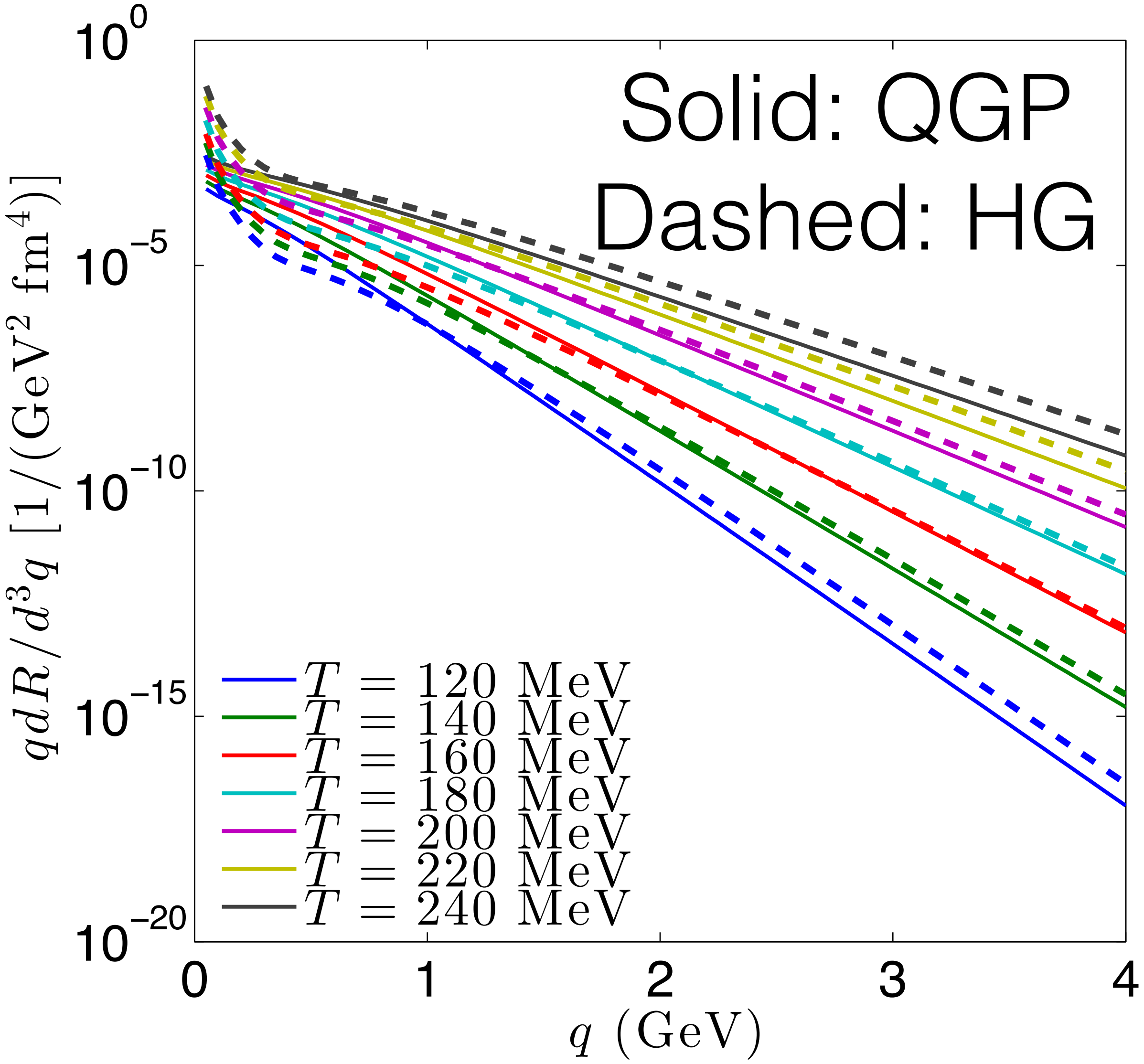
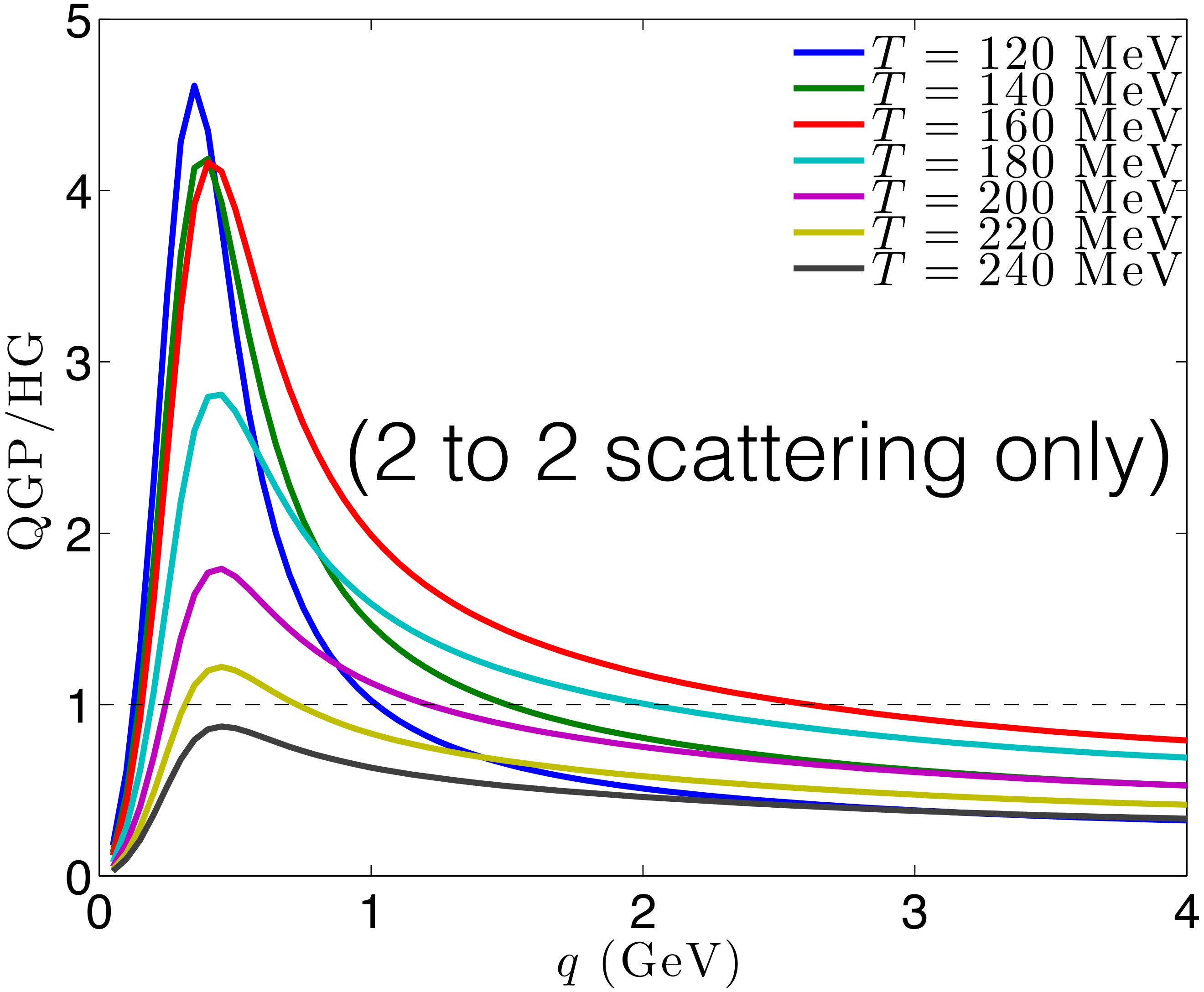
Viscous effects on dilepton flow: Gojko Vujanovic Tue 2:30

arXiv: 1308.2111, 1308.2440

Back ups …

Photon Emission Rates QGP vs HG





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

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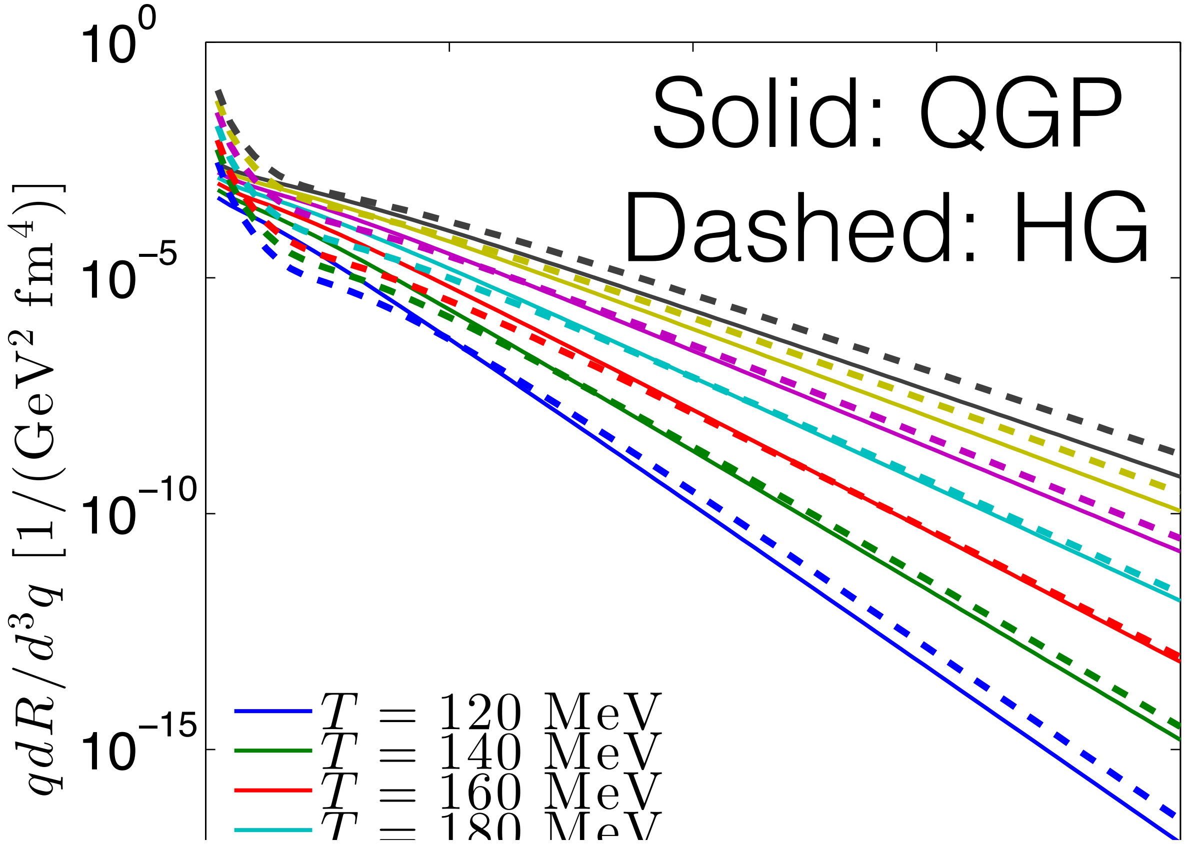
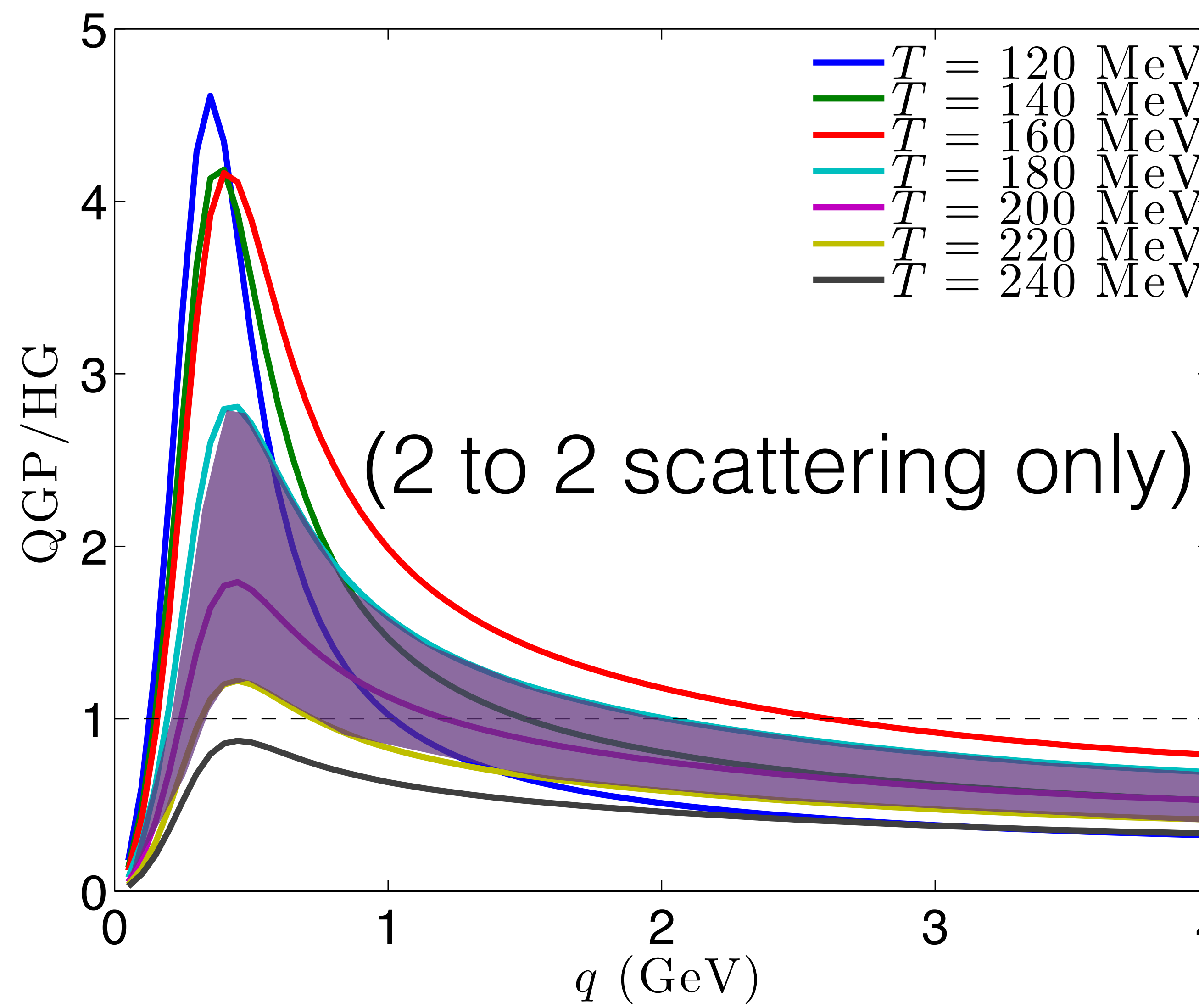
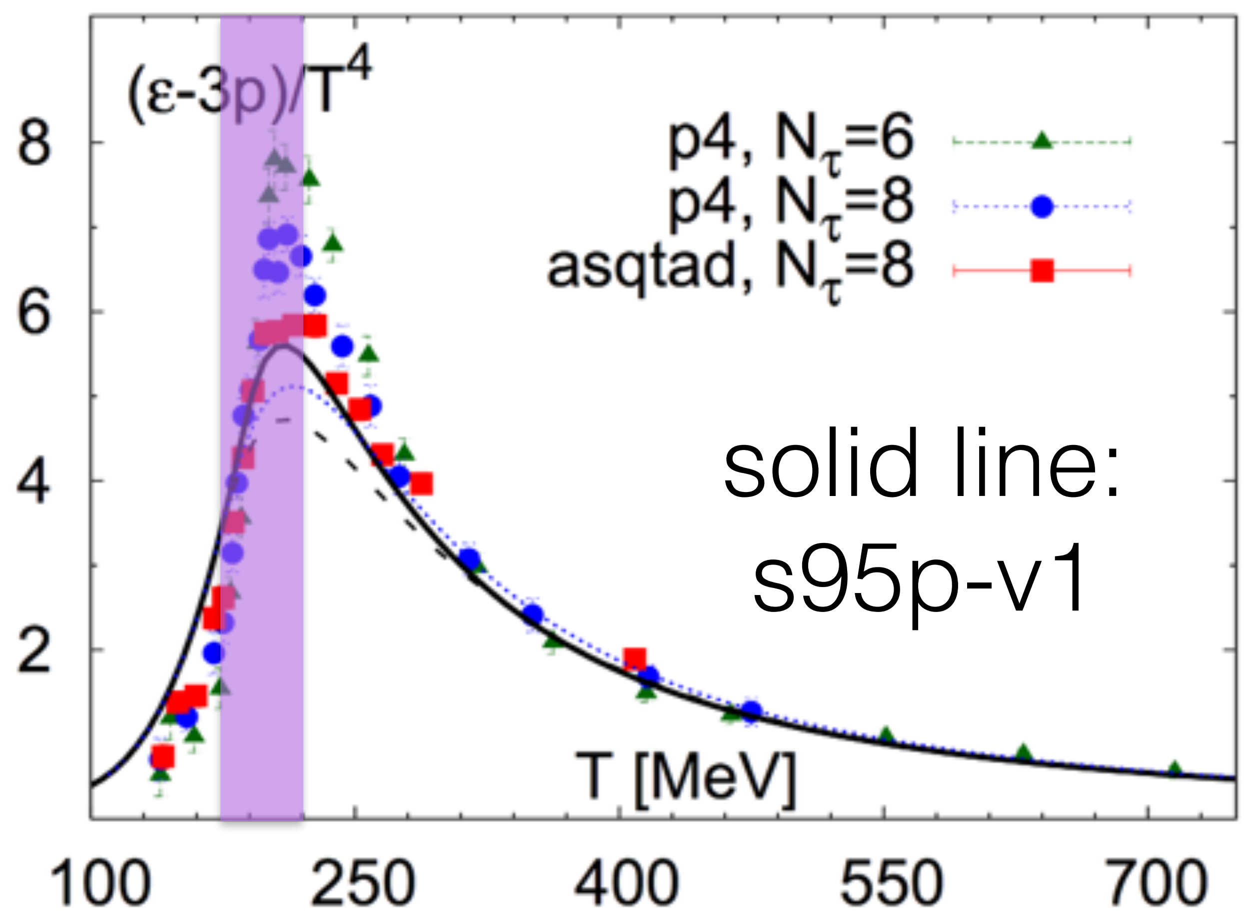


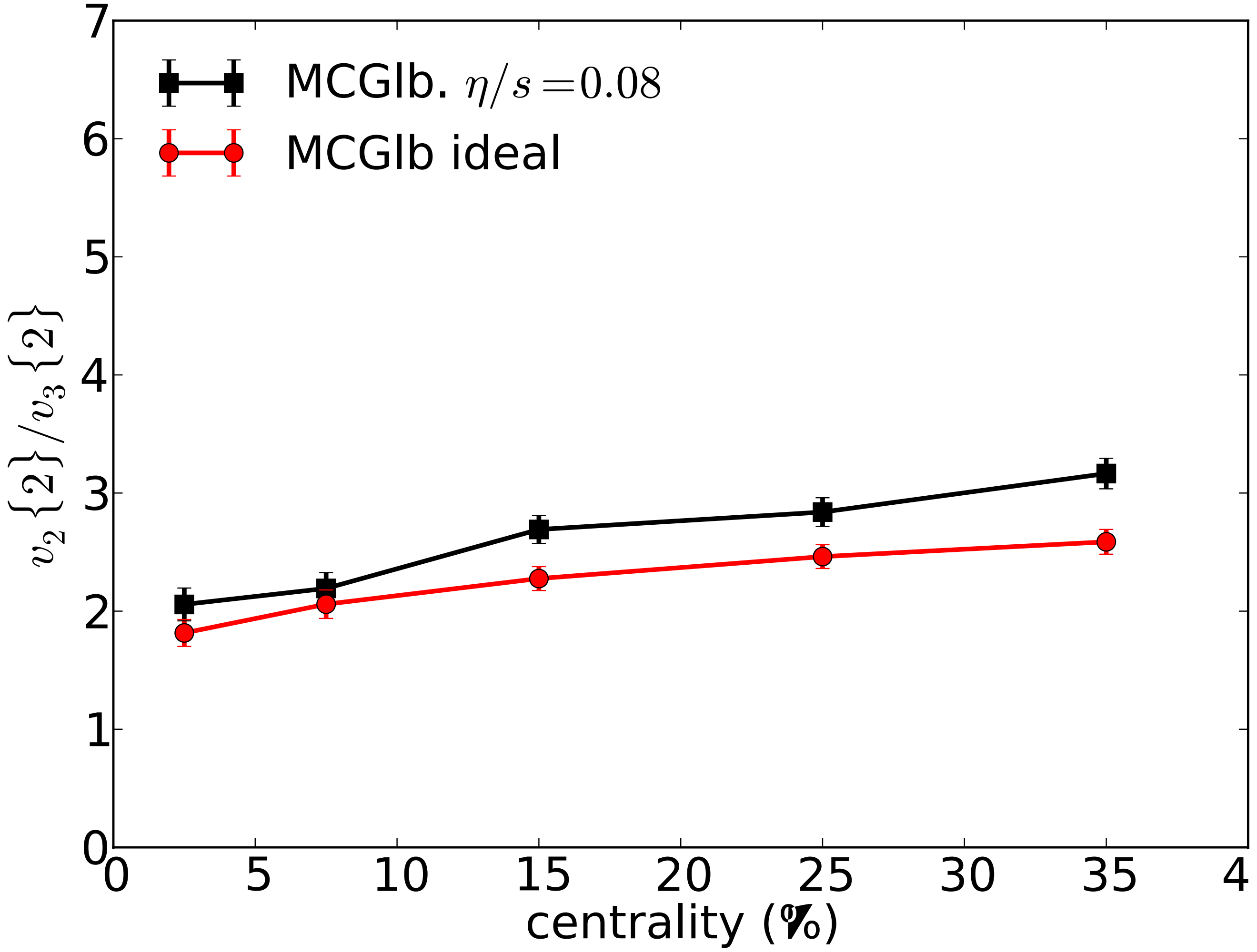


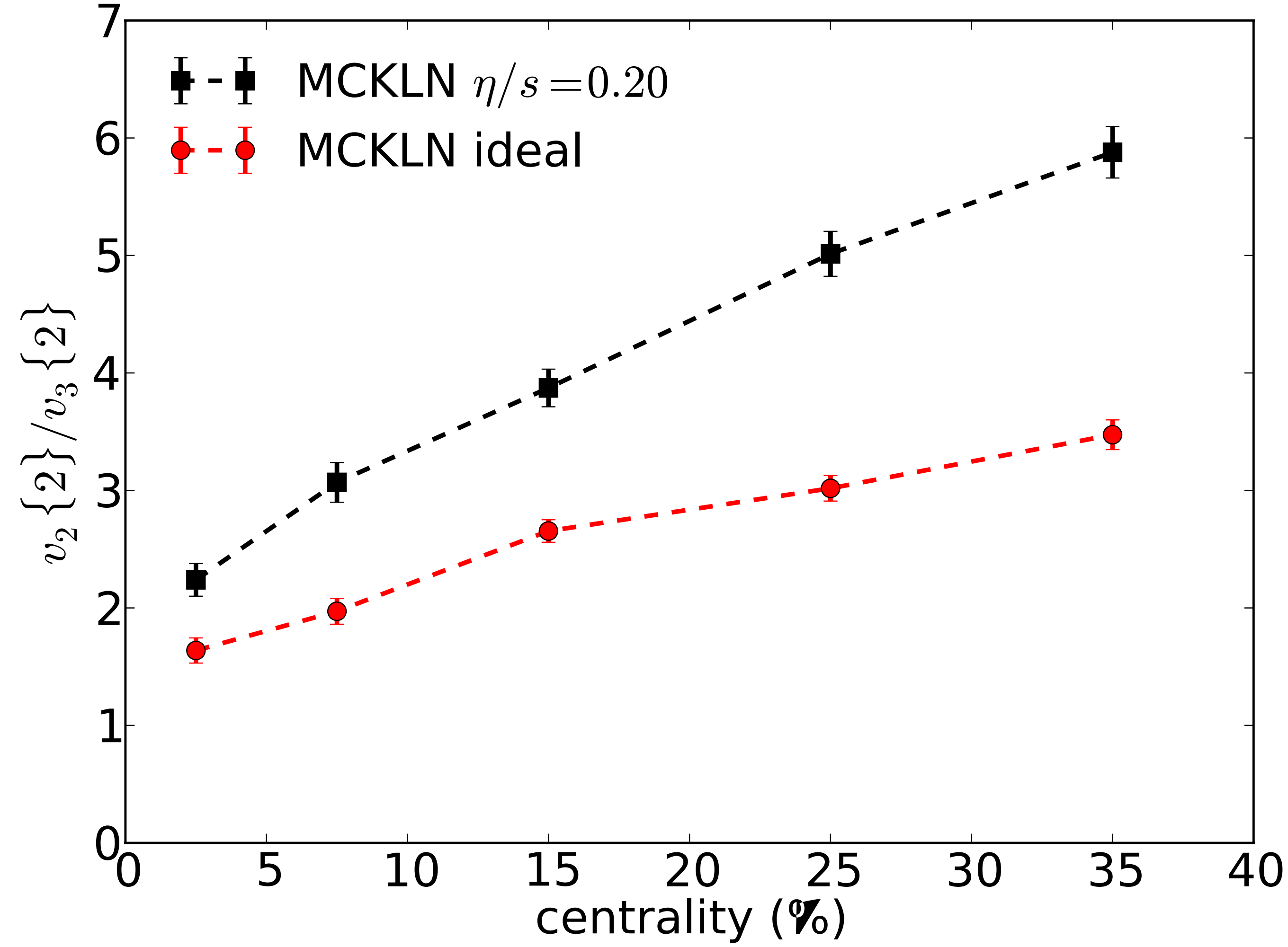


- QGP rates have very different p_T dependence compared to HG rates
- Estimated transition region for production rates, T ~ **184 - 220** MeV

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

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