Thermal photon emission in relativistic heavy-ion collisions

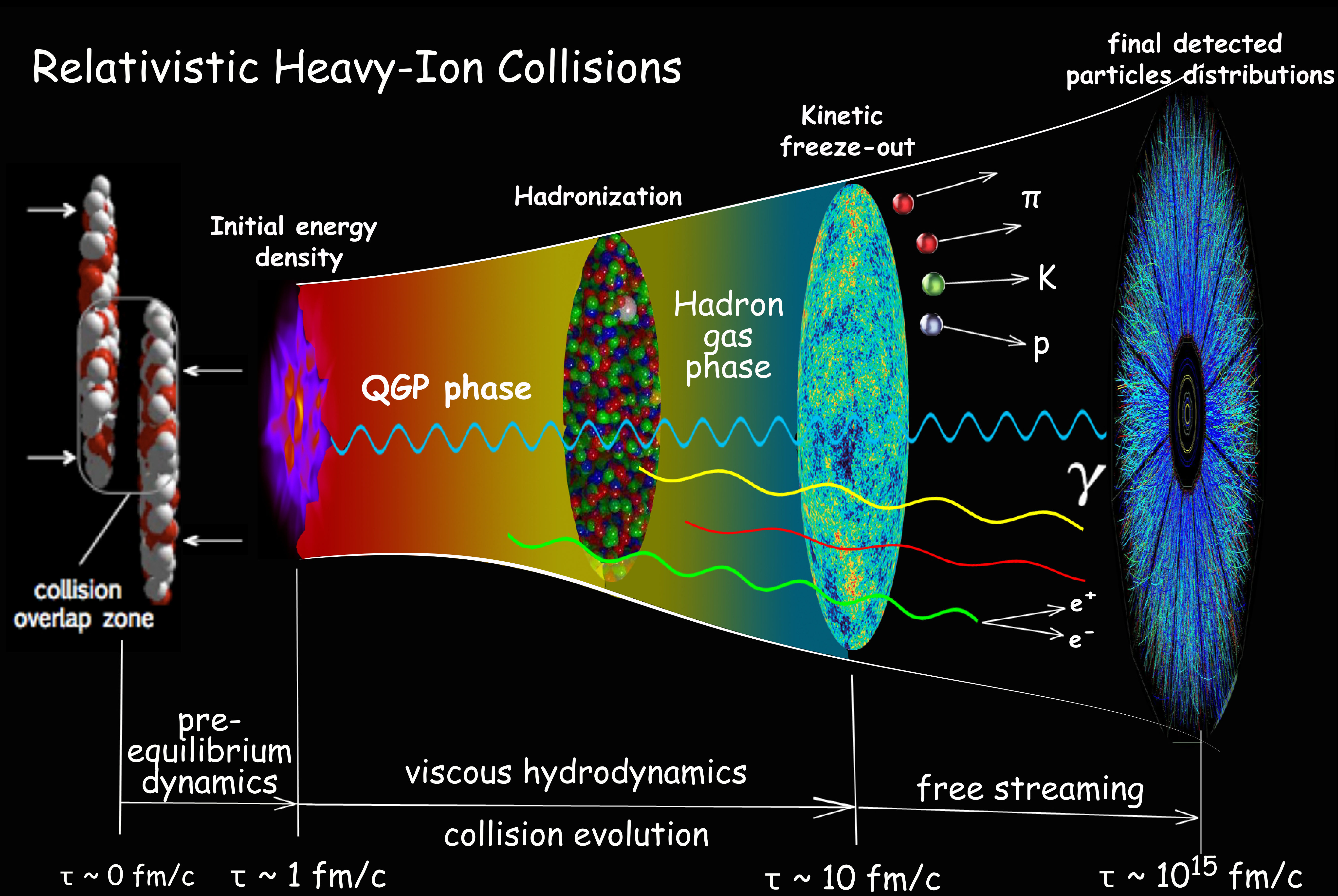
Chun Shen
The Ohio State University

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

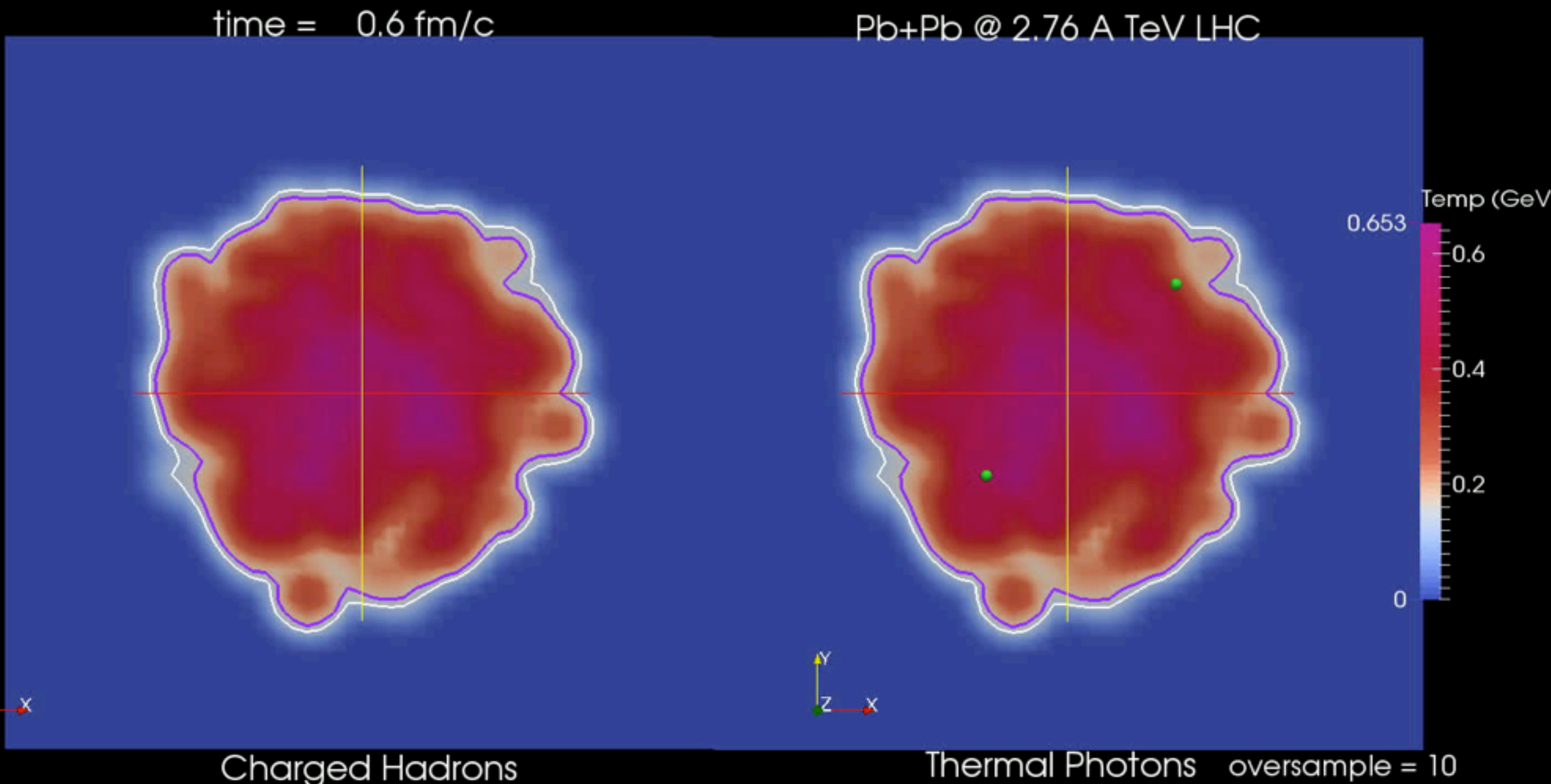
June 2014, Jet Summer School

arXiv: 1308.2111, 1308.2440, 1403.7558

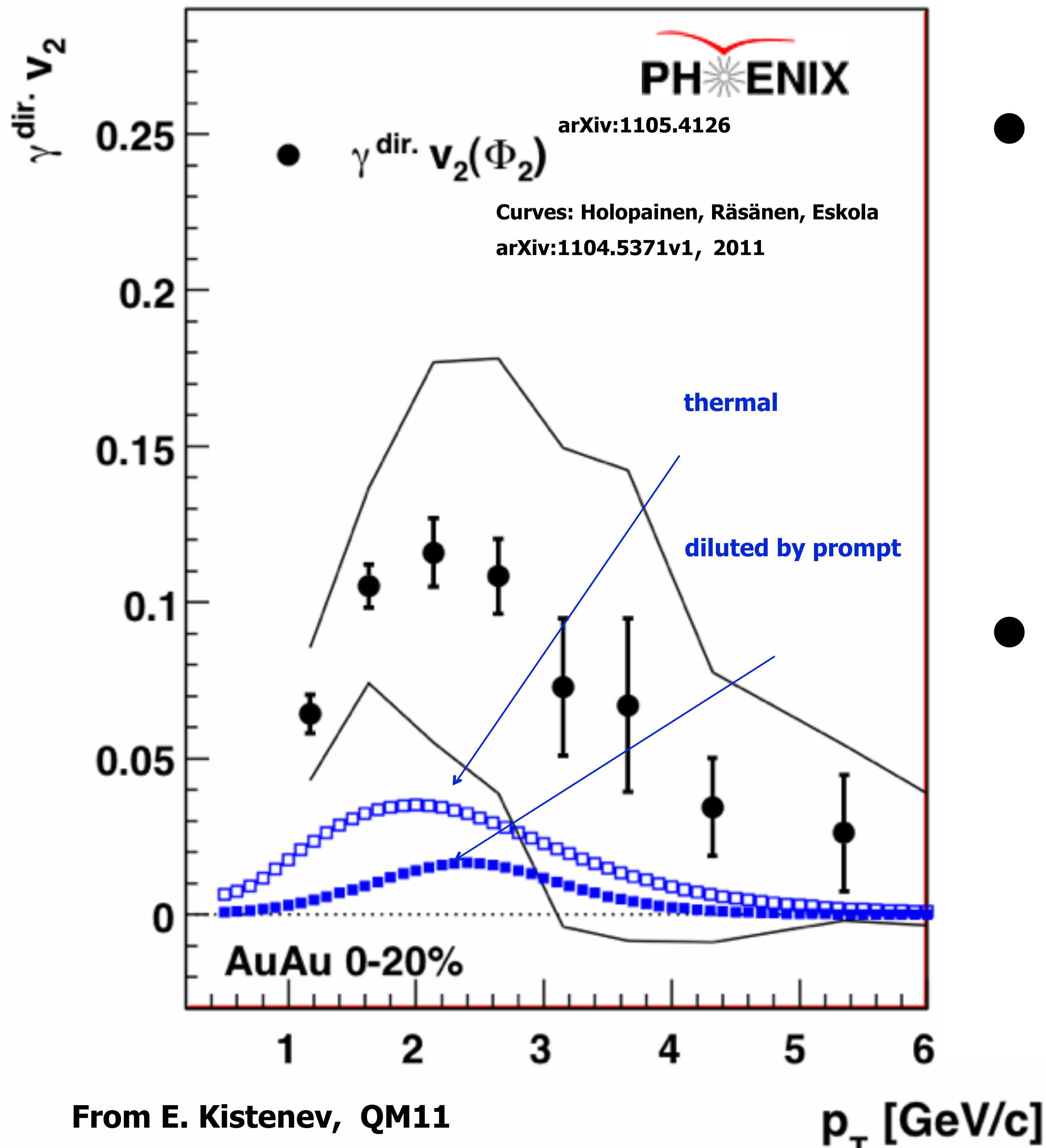
Little Bang


Relativistic Heavy-Ion Collisions
final detected particles distributions
Kinetic freeze-out
Hadronization
Initial energy density
π
K
p
Hadron gas phase
QGP phase
γ
collision overlap zone
e+
e−
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



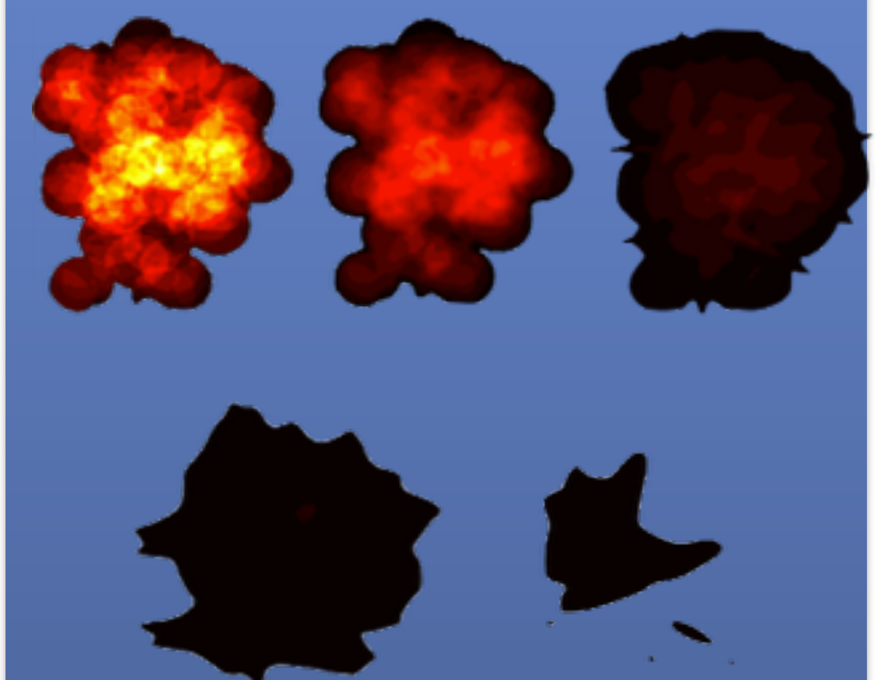
From E. Kistenev, QM11

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

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

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

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

Photon spectrum & v_n

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viscous corrections

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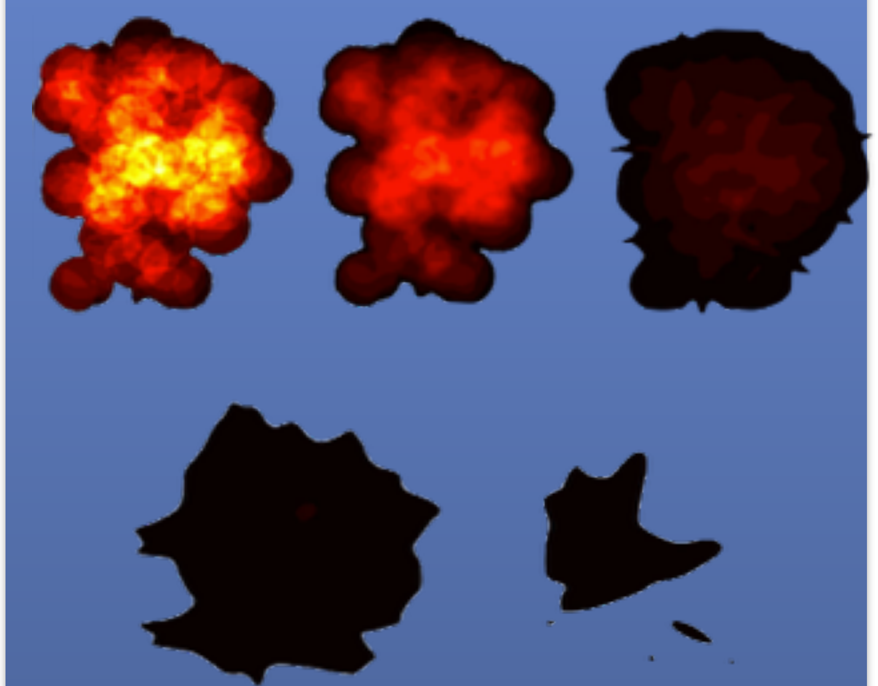

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viscous corrections

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

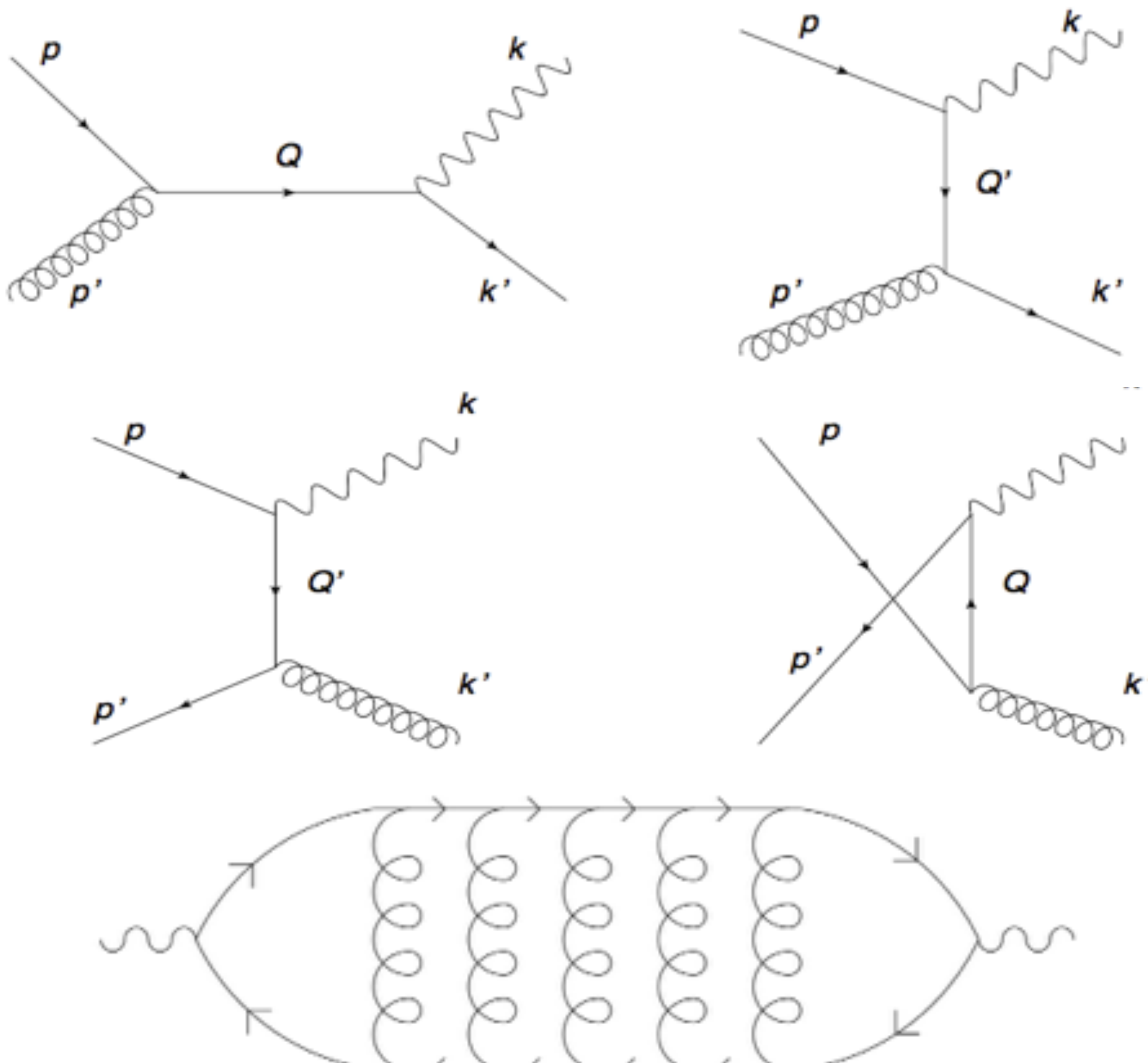
$$a_{\mu\nu} = \frac{3}{2(u\cdot\hat{q})^4}\hat{q}_\mu\hat{q}_\nu + \frac{1}{(u\cdot\hat{q})^2}u_\mu u_\nu + \frac{\ldots}{2(u\cdot\hat{q})^2} \ldots \mu).$$

Viscous Photon Emission Rates: General Formalism

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

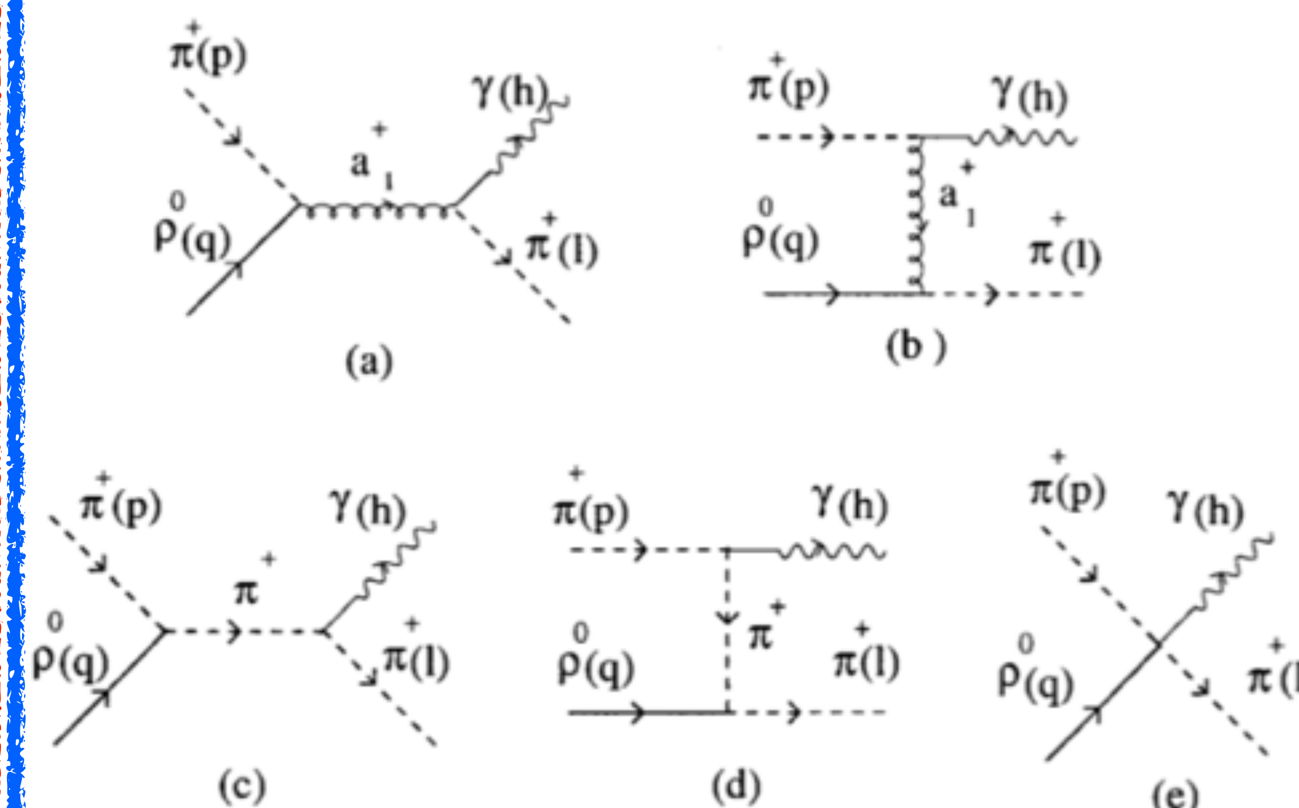
Equilibrium rates

QGP (AMY 2001)



Hadron Gas

(TRG 2004)

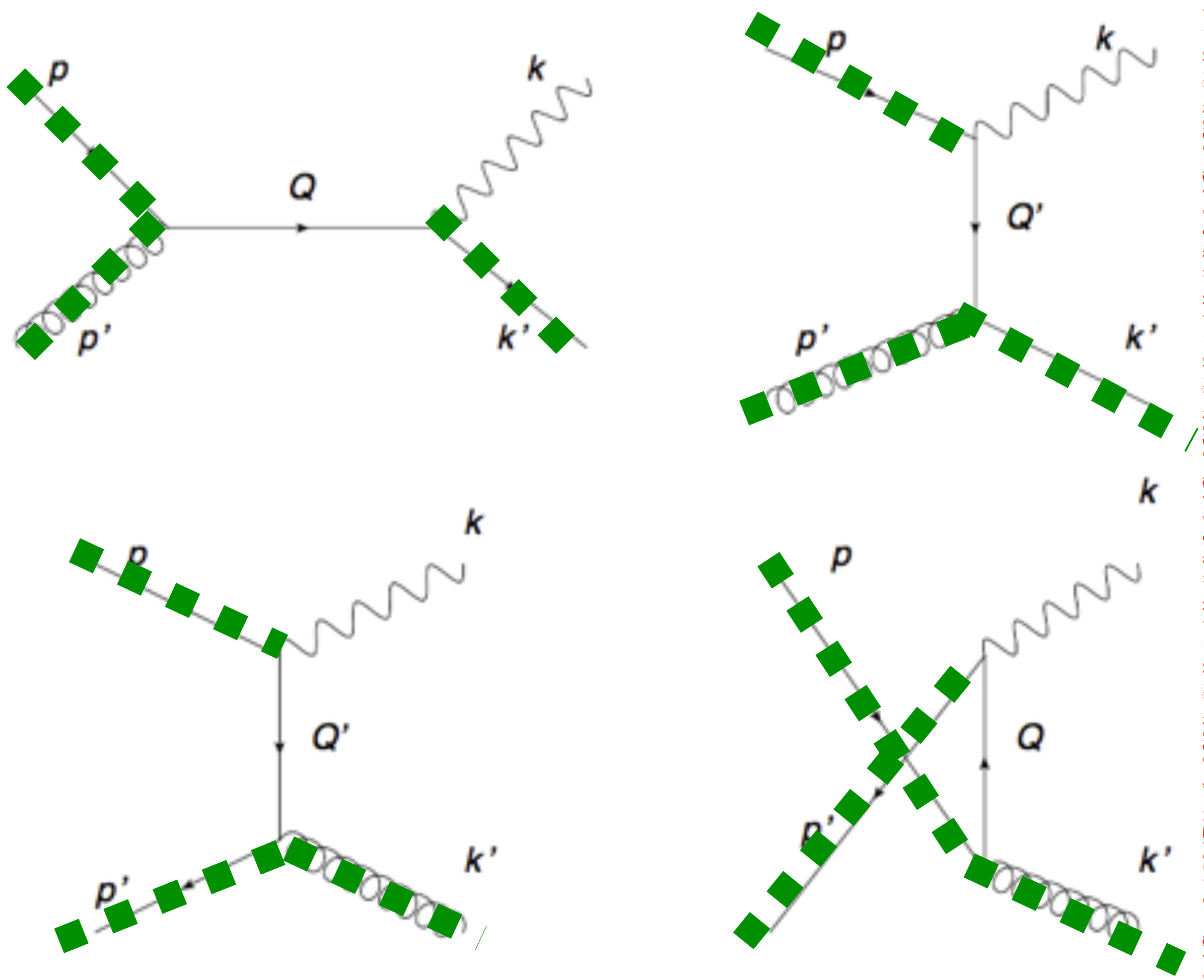


Viscous Photon Emission Rates: General Formalism

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

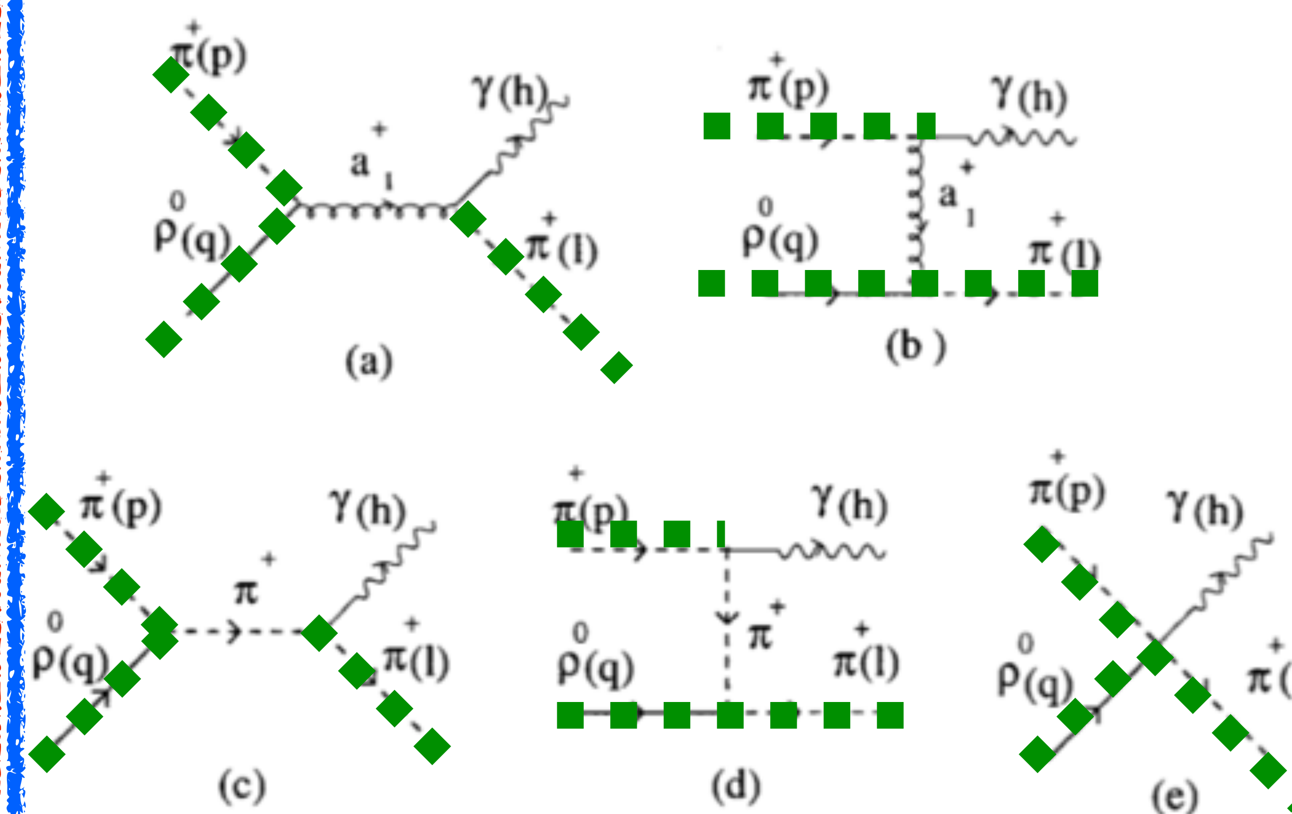
Equilibrium rates　　　off-equilibrium δf corrections

QGP



Dusling NPA839 (2010) 70

Hadron Gas



Dion et al. PRC84 (2011) 064901

Viscous Photon Emission Rates: General Formalism

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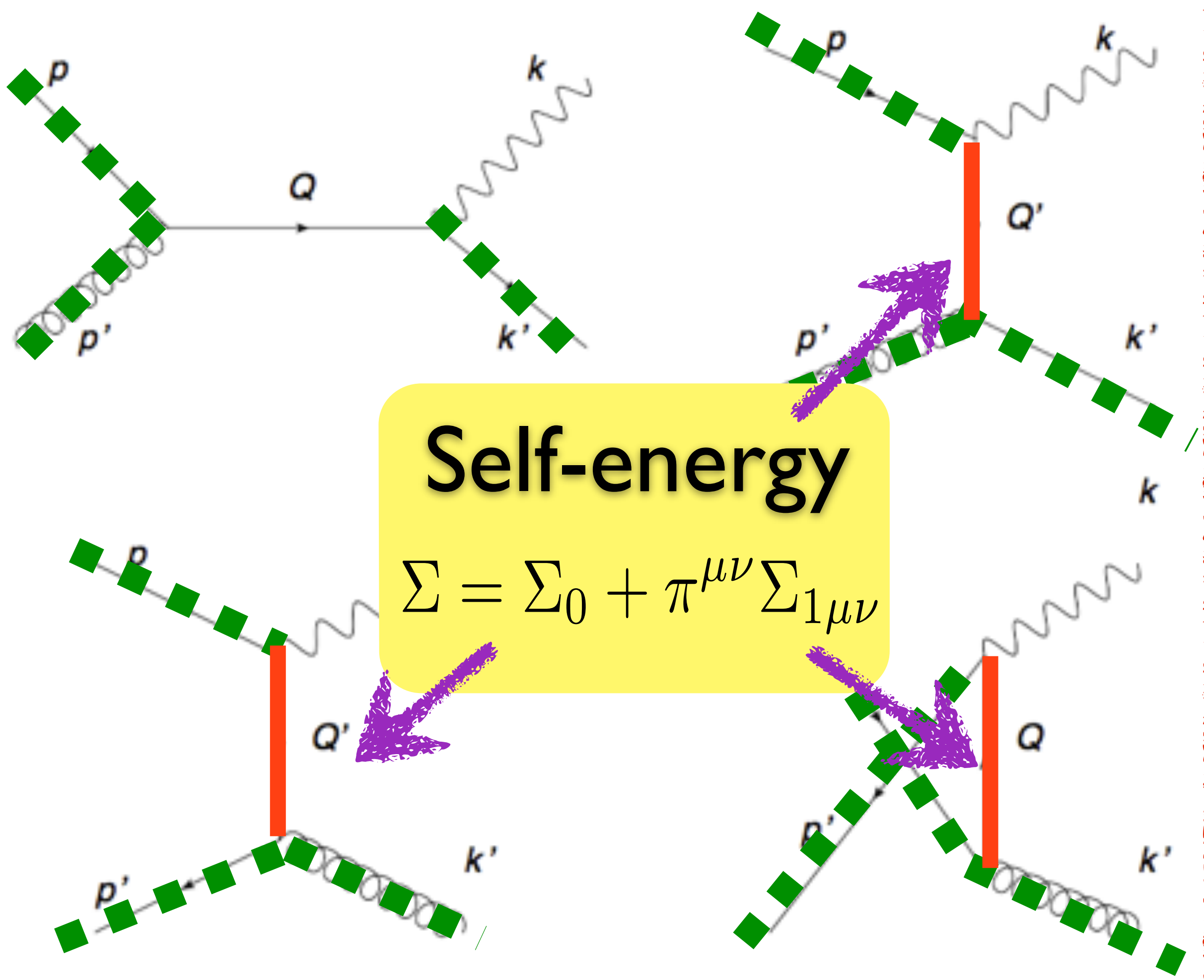
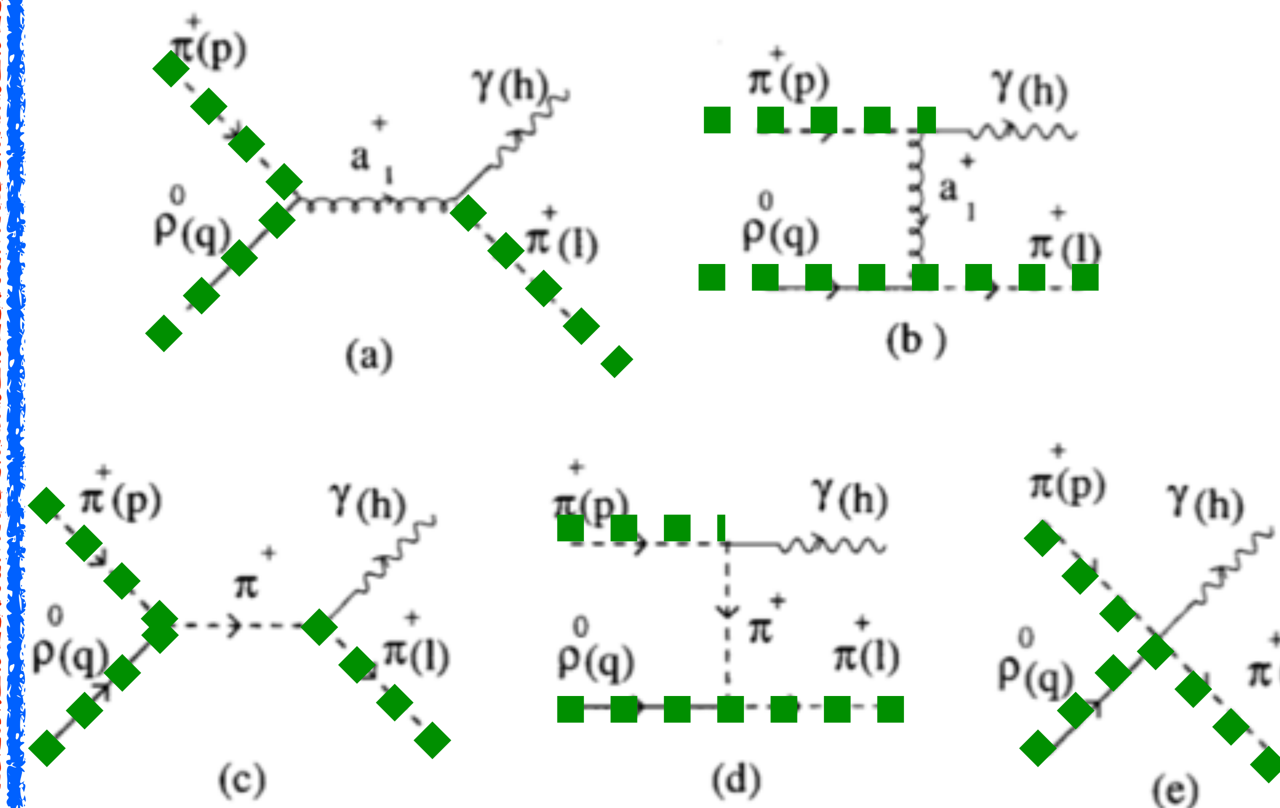
Equilibrium rates — off-equilibrium δf corrections

QGP

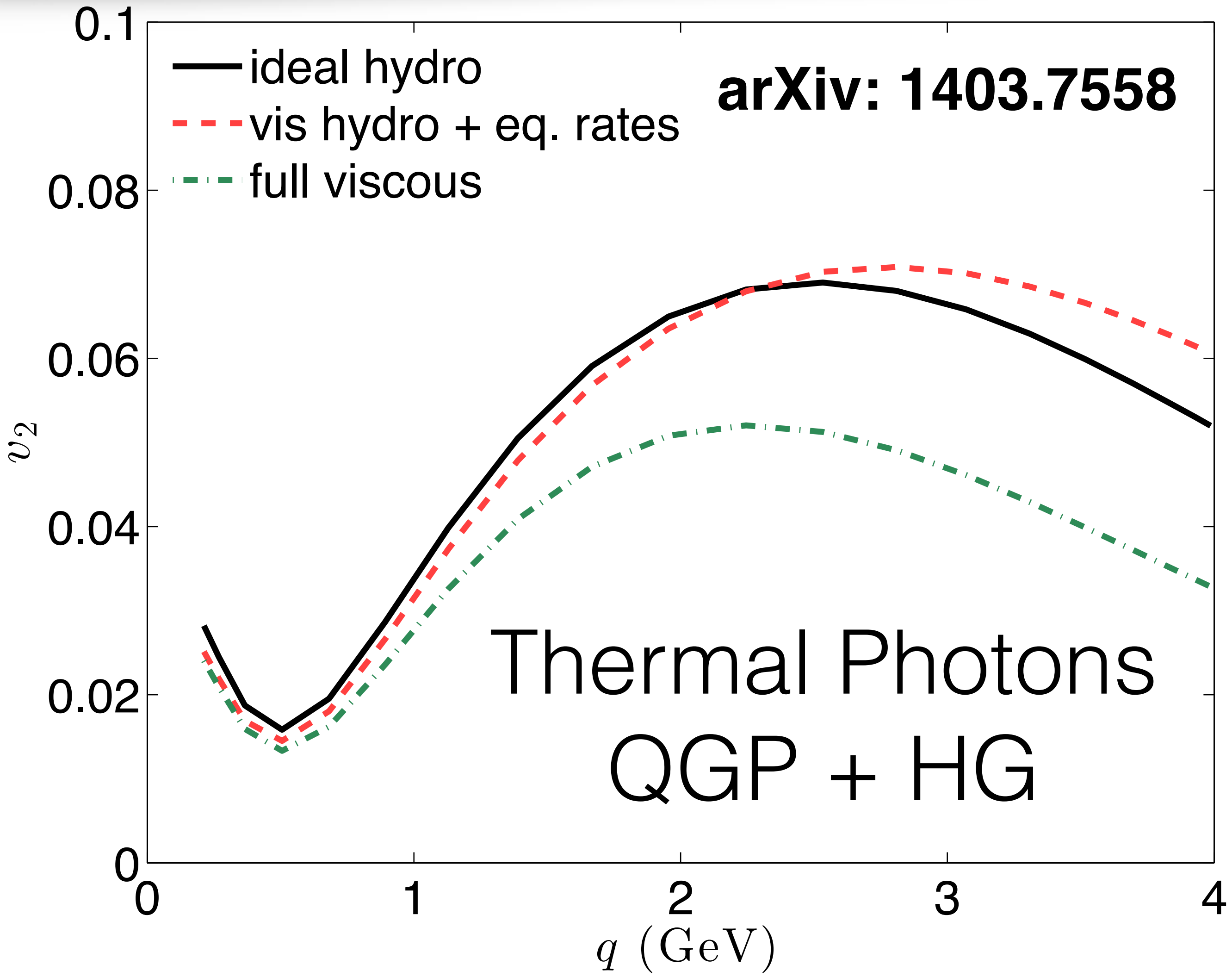


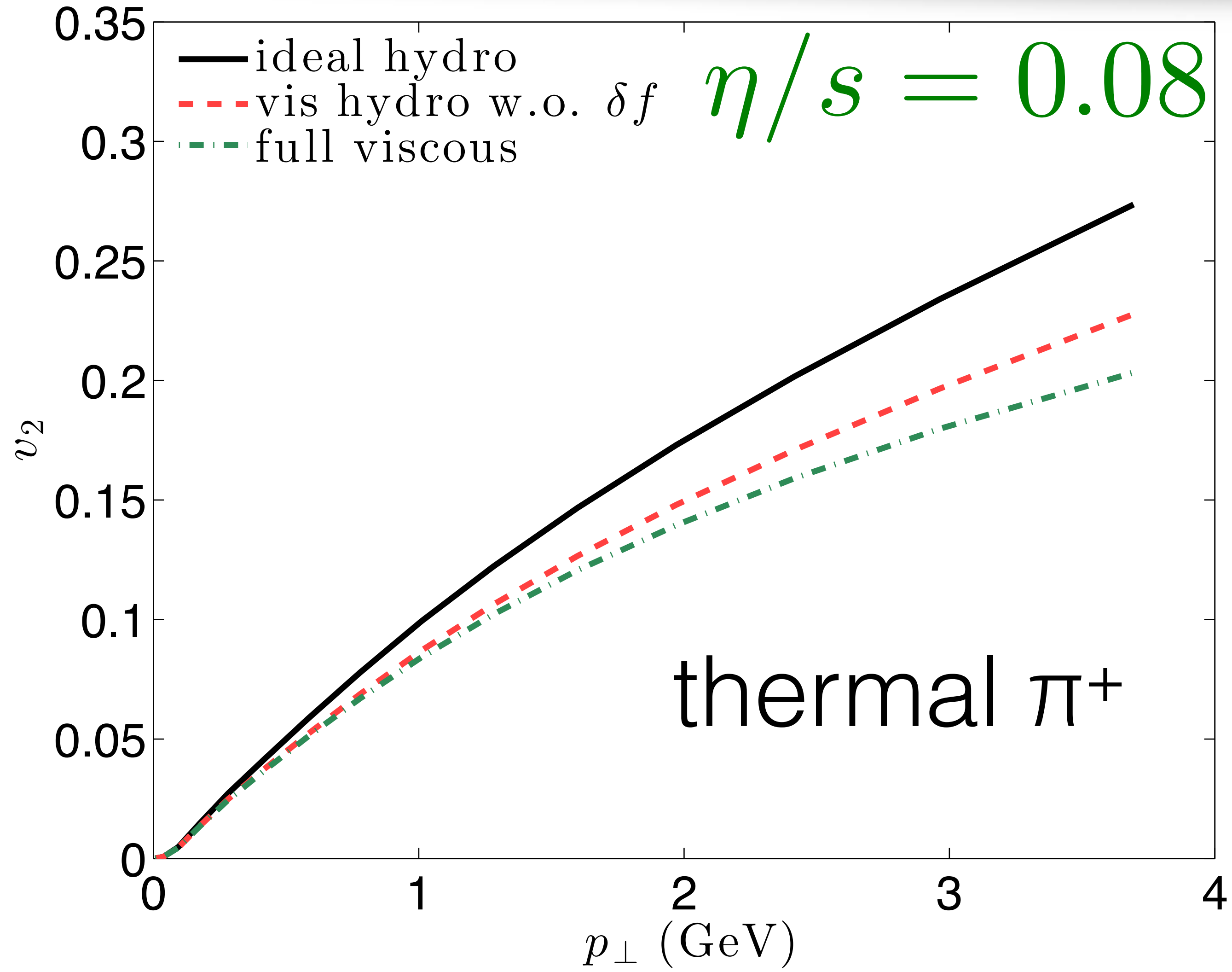
Shen, Paquet et al. (2014)

Hadron Gas



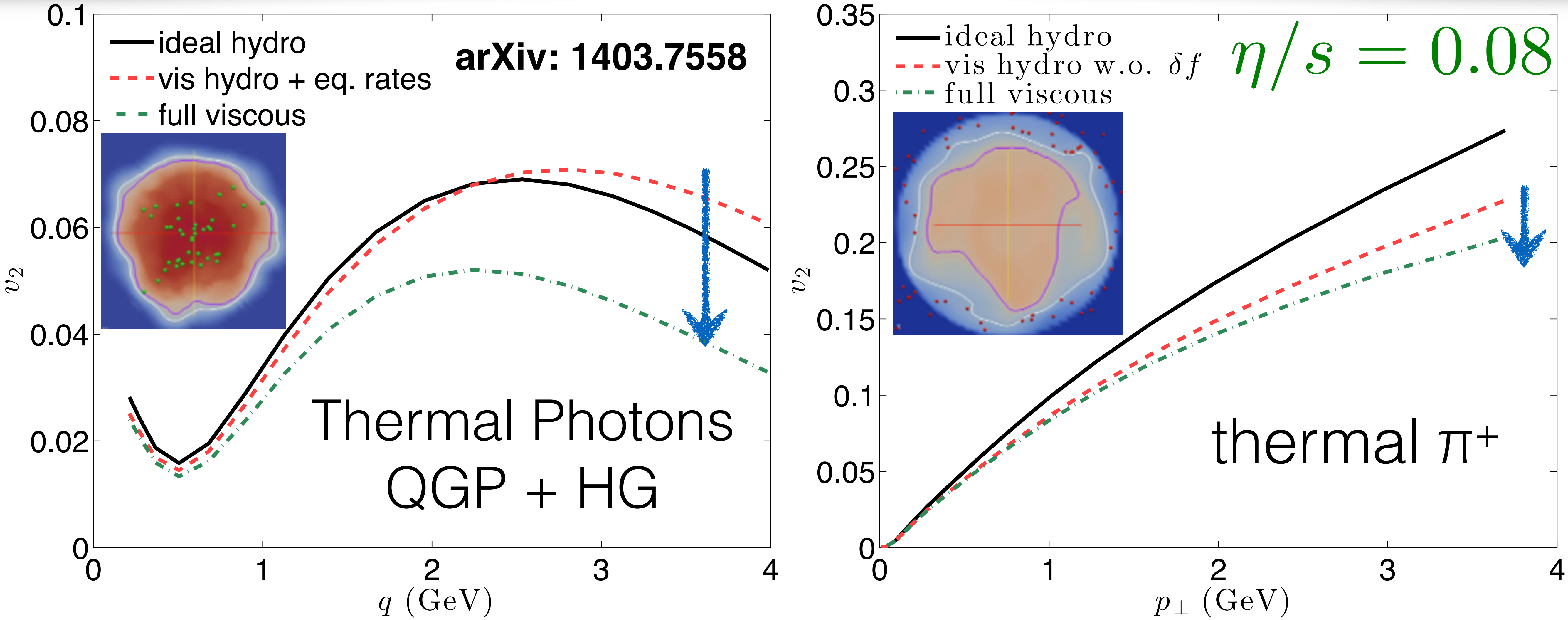
Viscous effects on photon elliptic flow





- 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

Viscous effects on photon elliptic flow



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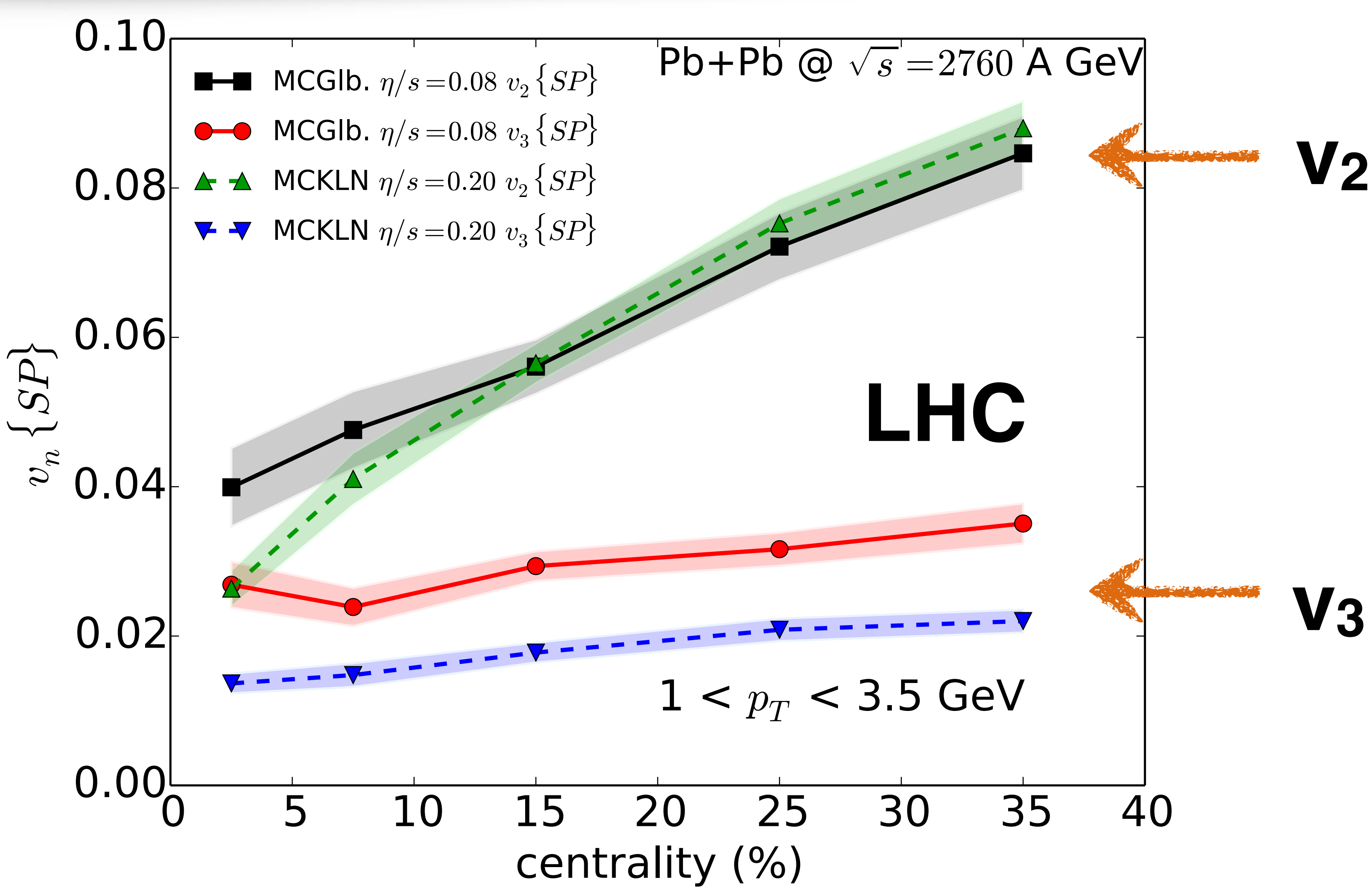
Event-by-Event Full Viscous Photon v_n

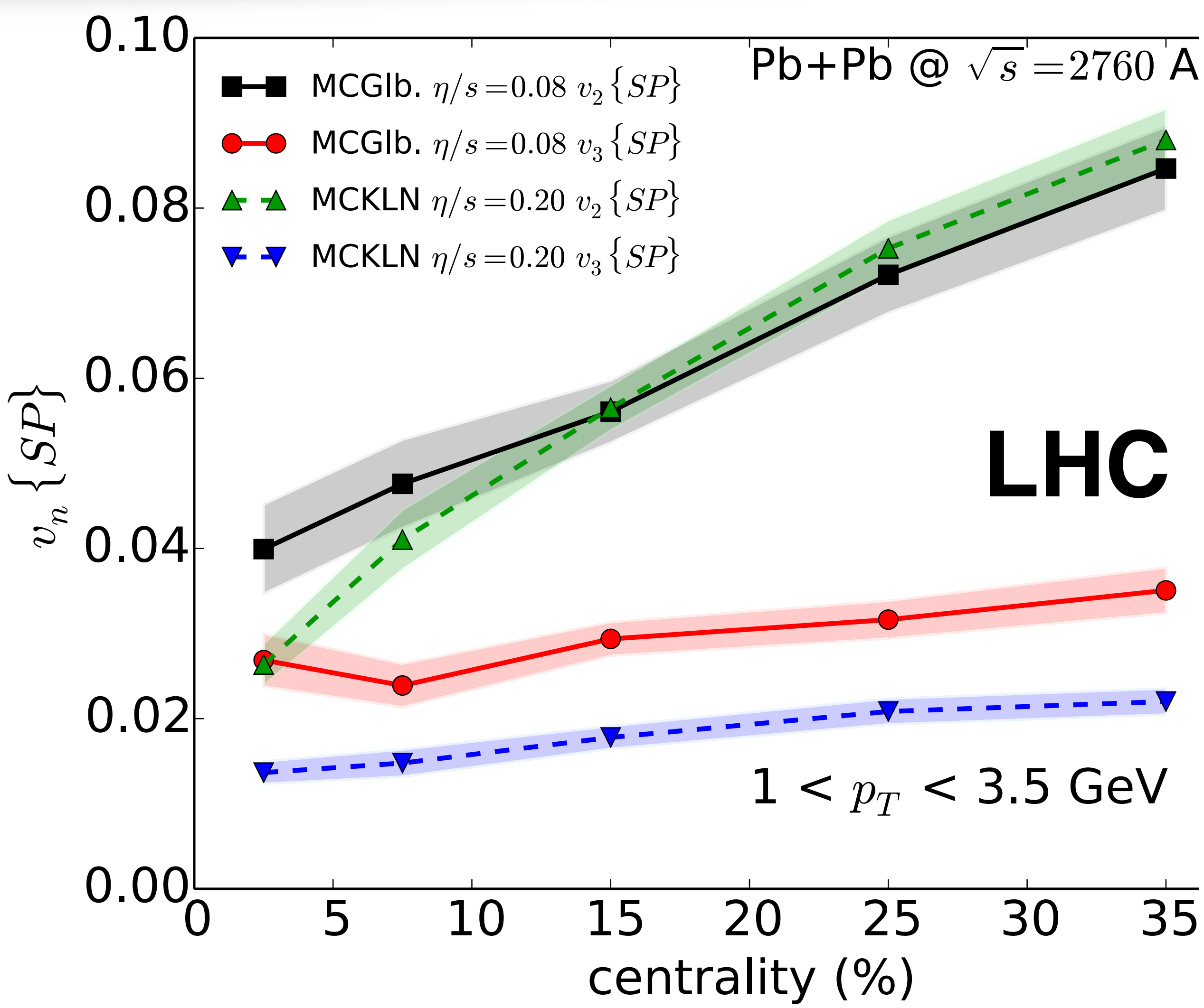


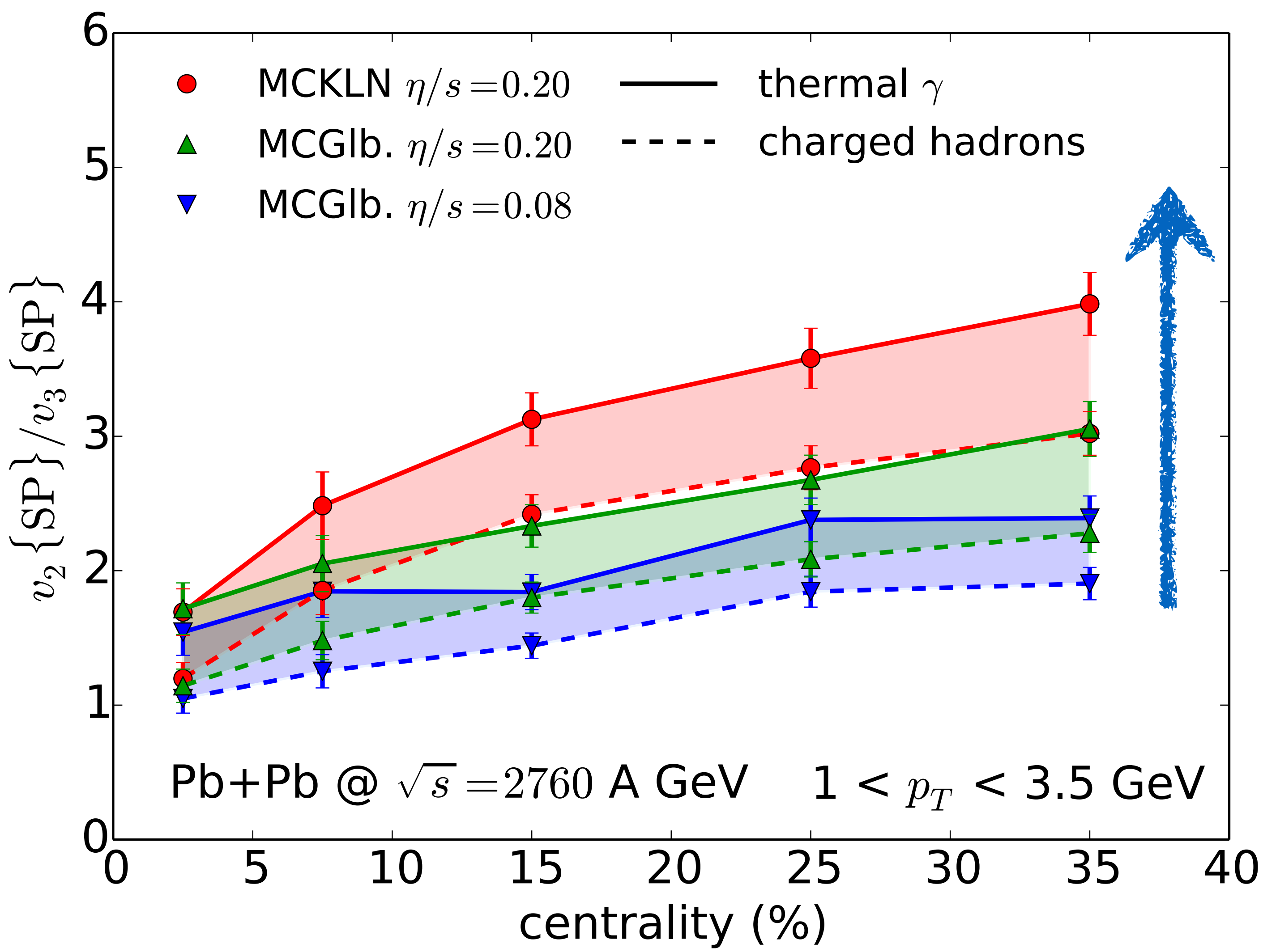
MCGlb. $\eta/s = 0.08$

MCKLN $\eta/s = 0.20$

- The anisotropic flows of photons show similar centrality dependence as hadron v_n

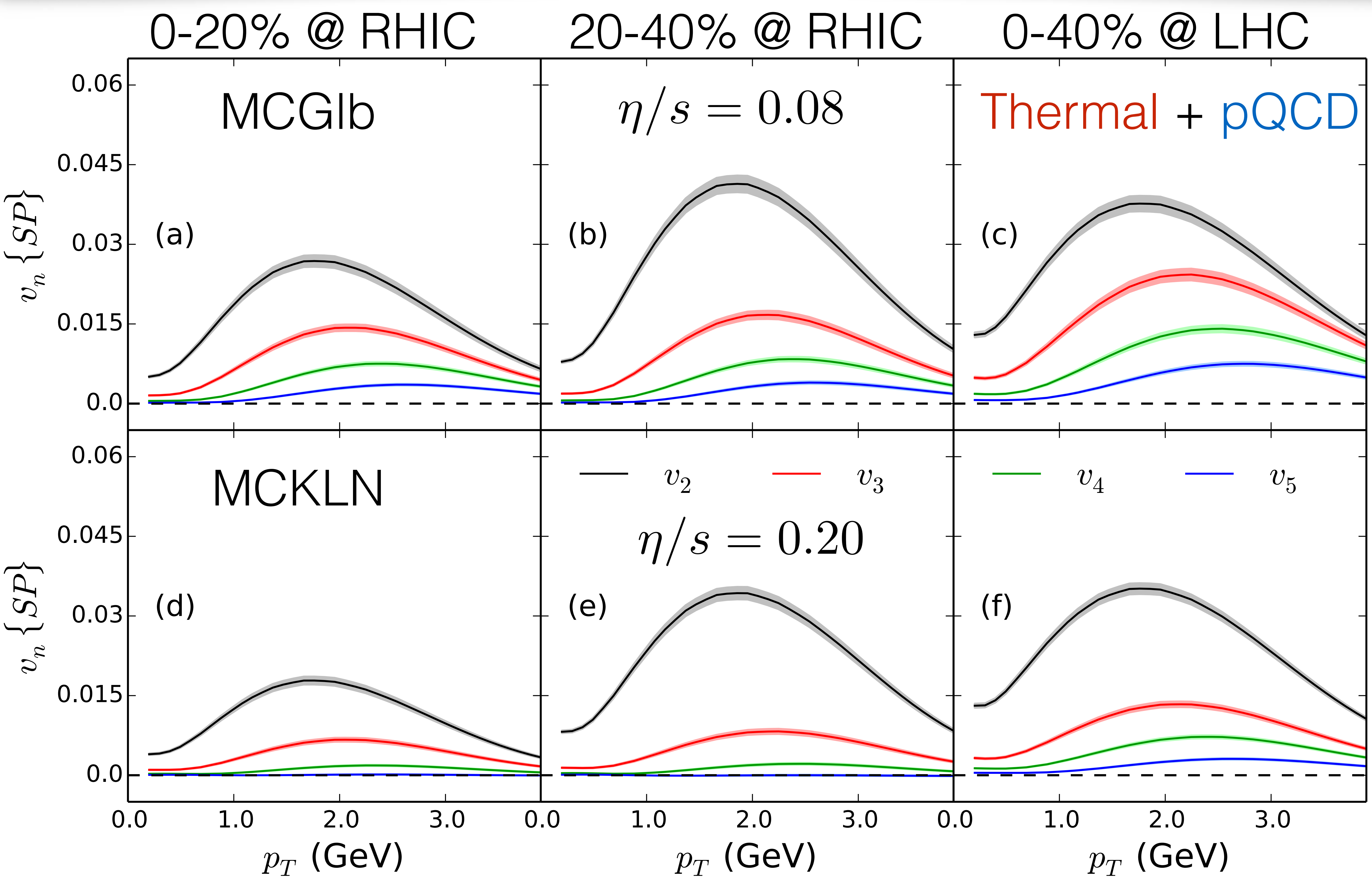
Event-by-Event Full Viscous Photon v_n





- The anisotropic flows of photons show similar centrality dependence as hadron v_n
- The ratio v_2/v_3 increases with the shear viscosity
- The centrality dependence of this ratio is stronger for the MCKLN model, driven by ε_2

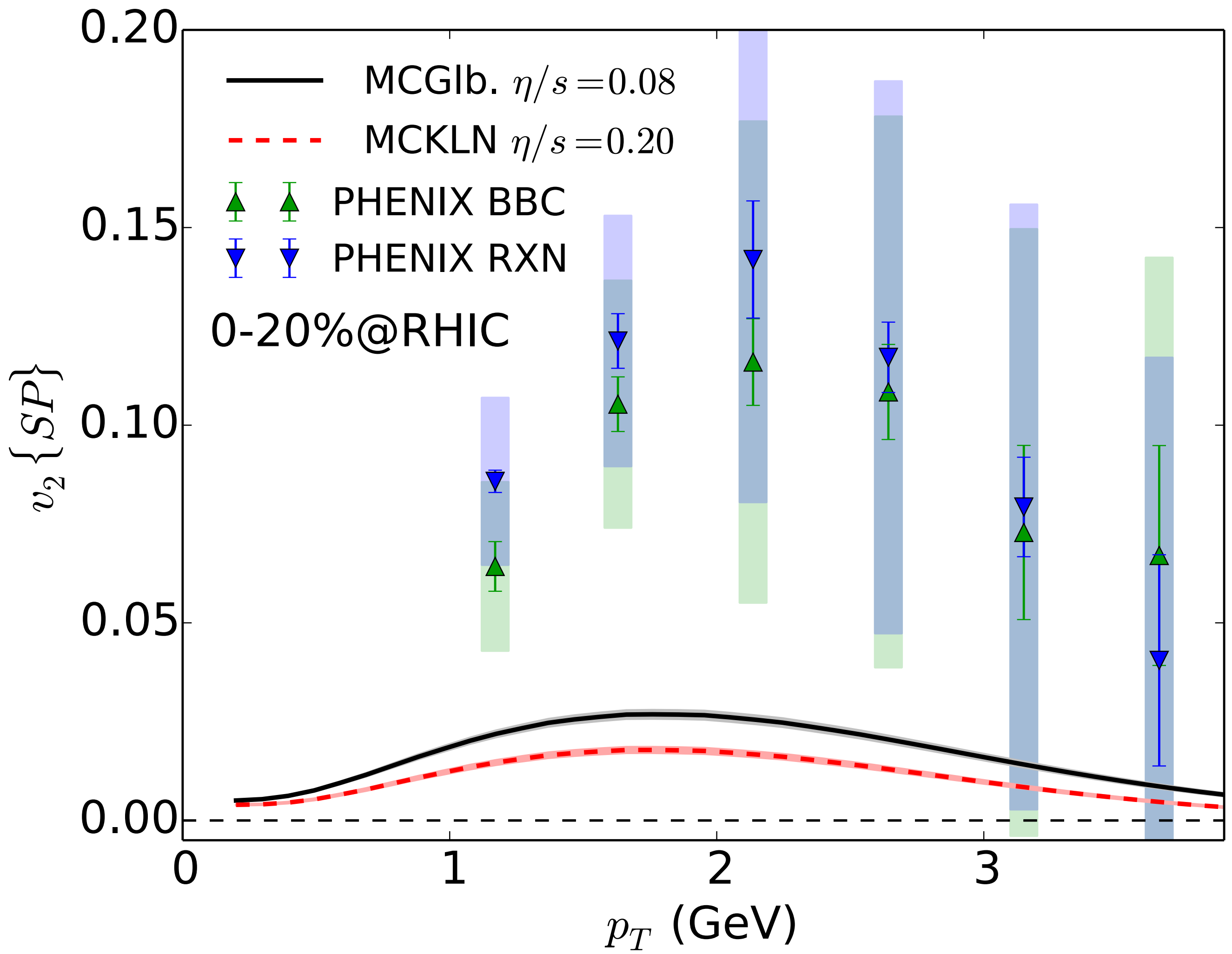
Event-by-Event Full Viscous Photon v_n



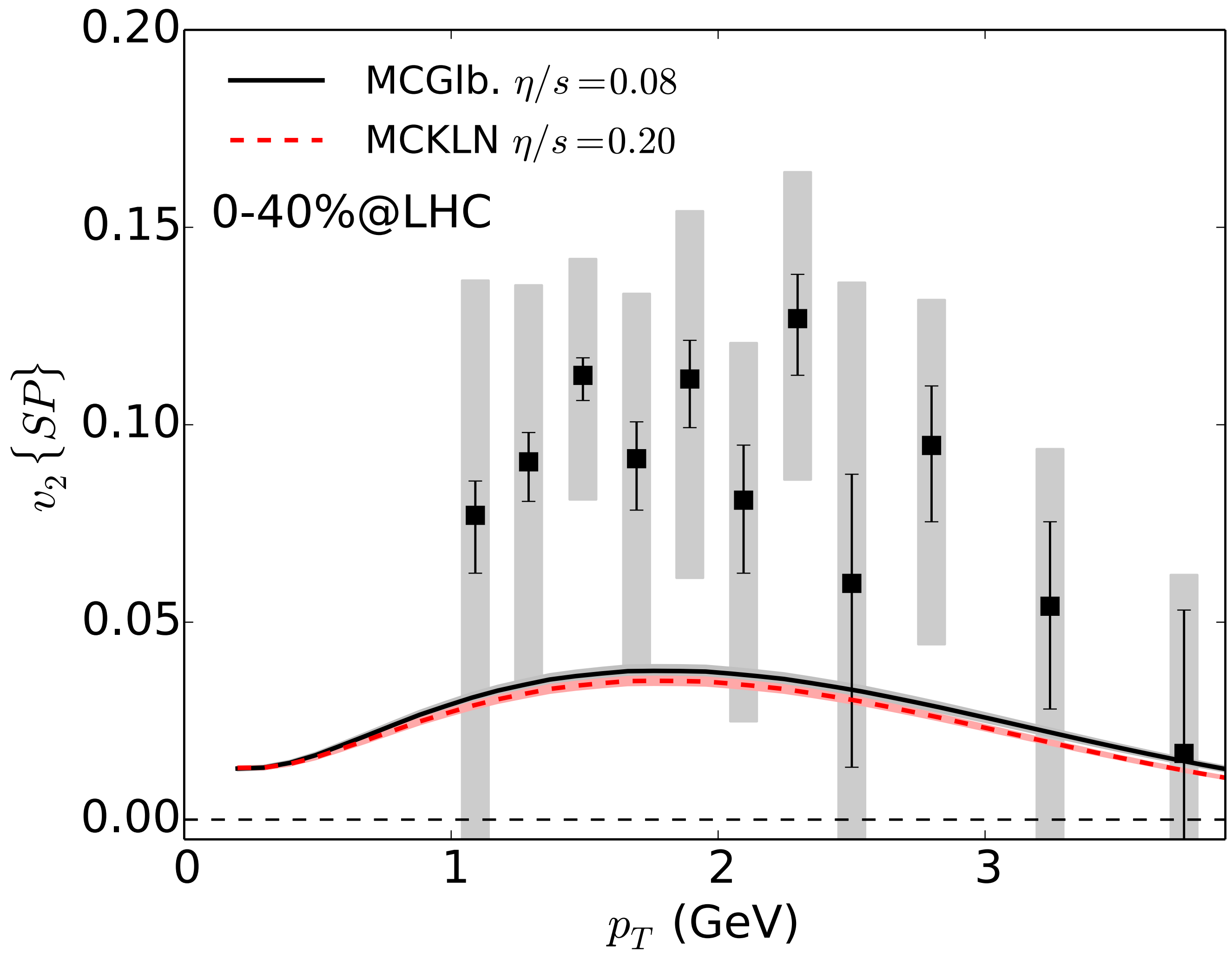
arXiv: 1308.2111

Comparisons with exp. data

RHIC 0-20%



LHC 0-40%



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

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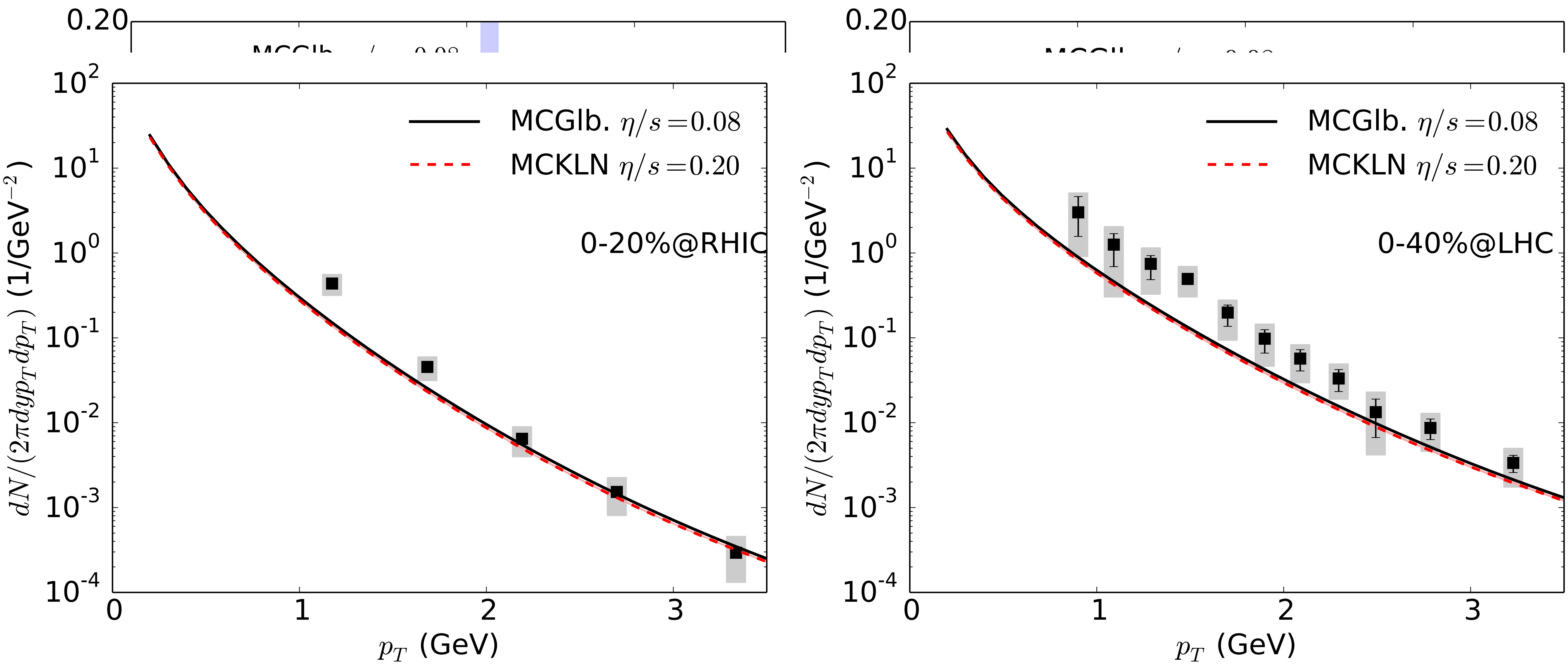
Comparisons with exp. data

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



- 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 p_T

arXiv: 1308.2111

Conclusions

- We studied photon spectra and their 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 shear stress at early times and to initial state fluctuations.
- Still, experimental **data** appear to **require significantly more photon rate from the late evolution stage** than in implemented in the model

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