# Photon production in the bottom-up thermalization of heavy-ion collisions

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collaboration with

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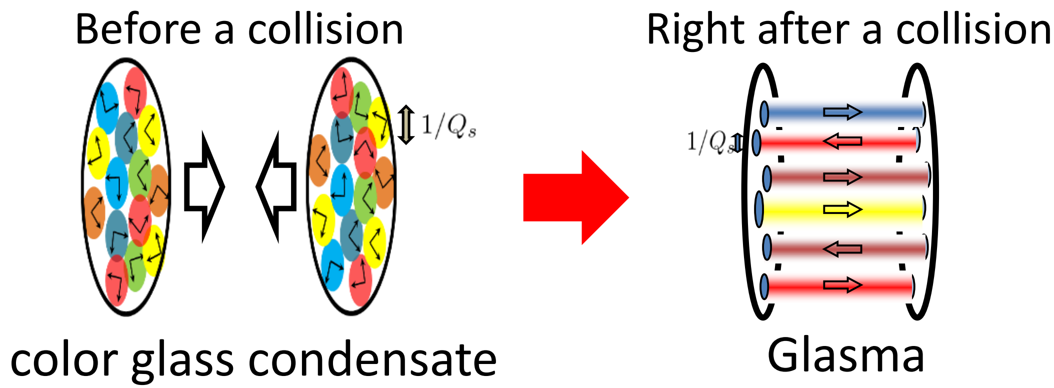
# Early times in heavy-ion collisions




**strong color fields** $A \sim Q_s/g$

**strongly interacting non-equilibrium system**

In weak coupling $\alpha_s \ll 1$ , **classical-statistical simulations** can describe such systems.

Recent classical-statistical simulations of expanding Glasma have established
**the bottom-up thermalization scenario**
as the correct weak-coupling effective theory for early stage of heavy-ion collisions.

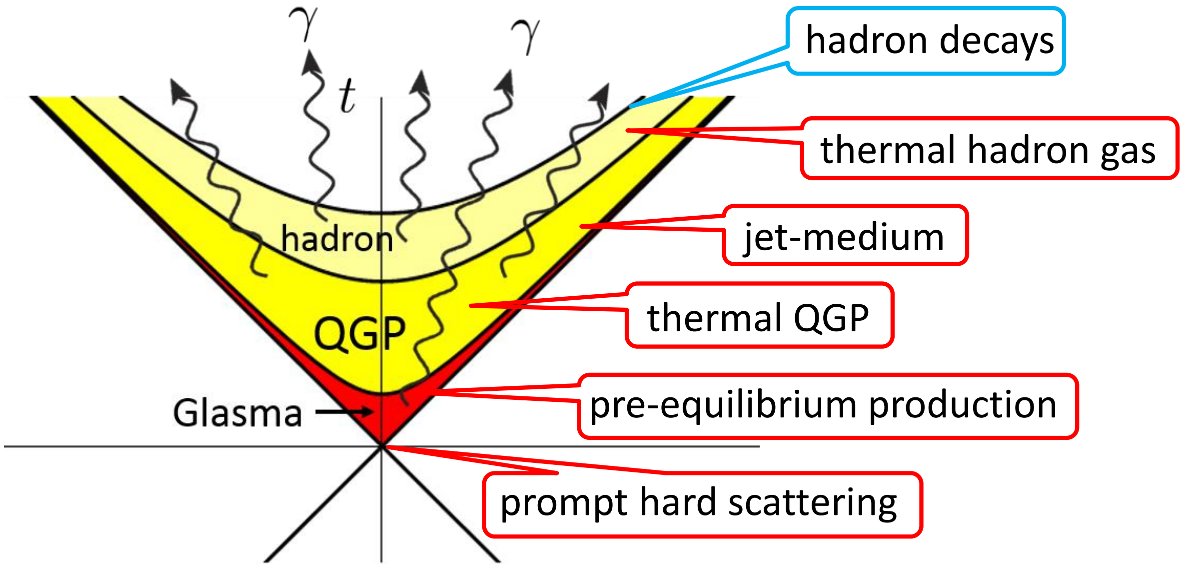
What is a phenomenological consequence?

Photon production at early times

# Photons in heavy-ion collisions

Large mean free path

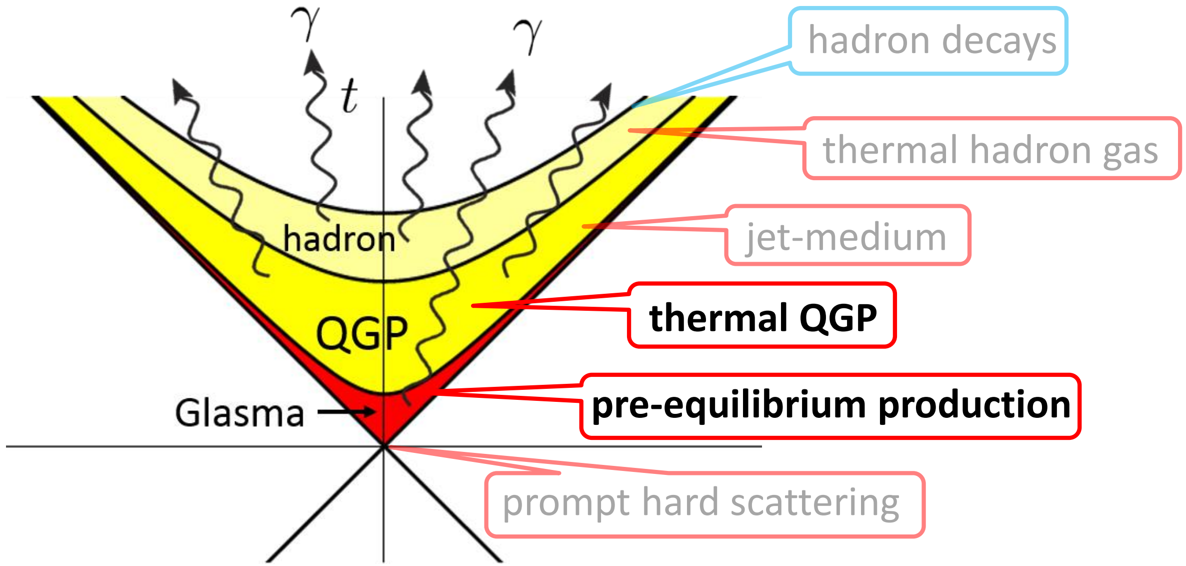
Clean penetrating probe



# Photons in heavy-ion collisions

Large mean free path

Clean penetrating probe




The photon production in the pre-equilibrium stage is not included in the state-of-the-art calculations based on hydrodynamic and transport models.

Does Glasma shine brightly?

Parametric estimate of the photon yields in the Glasma and thermal QGP phases based on the bottom-up thermalization scenario.

# Bottom-up thermalization scenario

Baier, Mueller, Schiff, Son (2001)

Weak coupling effective kinetic description of thermalization in heavy-ion collisions

consistent with the use of the weak coupling formula for the photon production

1. Classical scaling regime

$$Q_s^{-1} \ll \tau \ll Q_s^{-1}\alpha_s^{-3/2}$$

2. Formation stage of soft gluon bath

$$Q_s^{-1}\alpha_s^{-3/2} \ll \tau \ll Q_s^{-1}\alpha_s^{-5/2}$$

3. Heating up stage

$$Q_s^{-1}\alpha_s^{-5/2} \ll \tau \ll Q_s^{-1}\alpha_s^{-13/5}$$

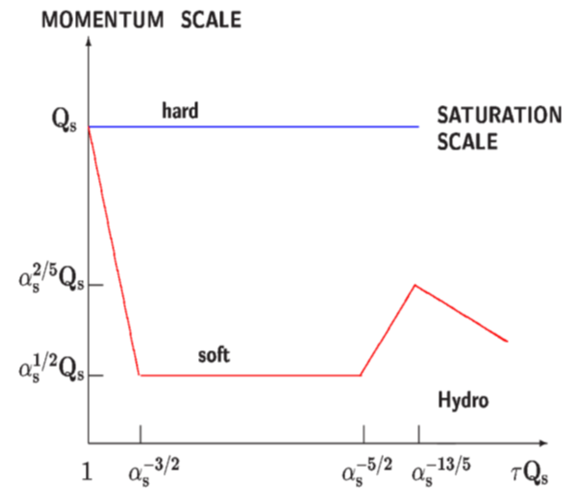



FIG. 1. Characteristic momentum scales for the "bottom-up" scenario.

from Baier, Mueller, Schiff, Son (2002)

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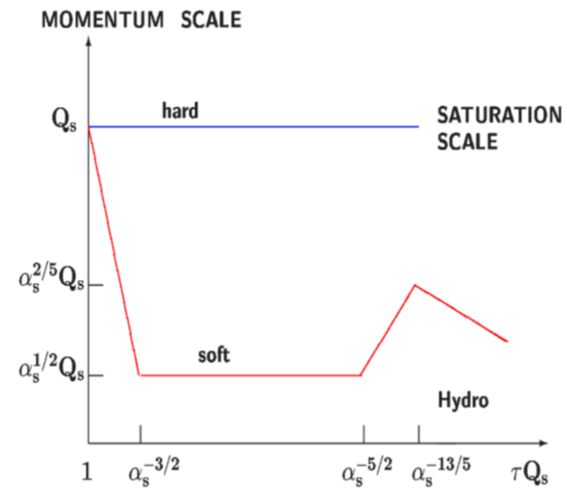



FIG. 1. Characteristic momentum scales for the "bottom-up" scenario.

from Baier, Mueller, Schiff, Son (2002)

# Bottom-up thermalization scenario

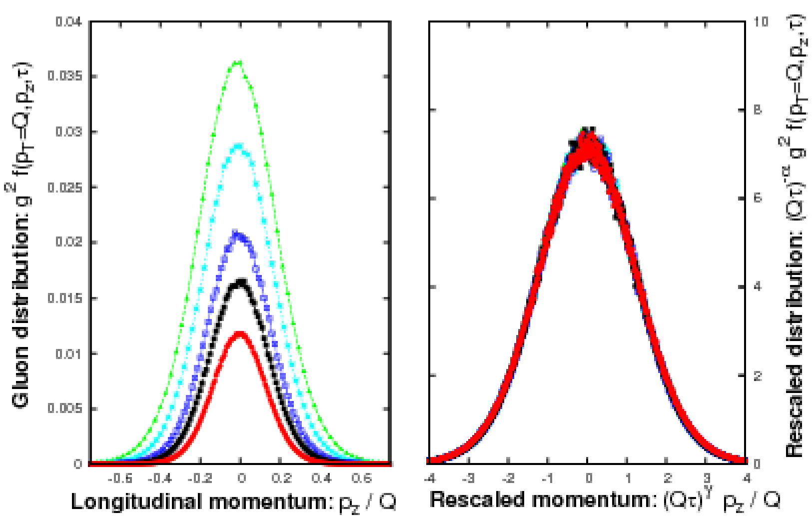
Baier, Mueller, Schiff, Son (2001)

1. Classical scaling regime $Q_s^{-1} \ll \tau \ll Q_s^{-1}\alpha_s^{-3/2}$

- The system is dominated by hard gluons whose transverse mom. is $p_\perp \sim Q_s$ .
- The occupancy of the hard gluons is much larger than one. $f_{hard} \gg 1$
- 2-2 elastic (small angle) scatterings among hard gluons dominate the dynamics.

Scaling behavior $f_g(\tau, p_\perp, p_z) = (Q_s\tau)^{-2/3} f_S\left(p_\perp, (Q_s\tau)^{1/3} p_z\right)$

Confirmed by the classical-statistical simulations and the kinetic theory computations




Berges et al. (2014)

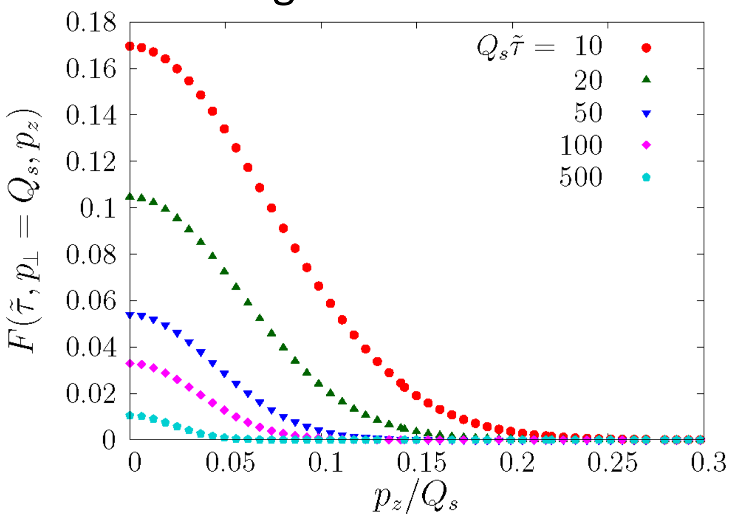
# Scaling behavior of Quarks

What about quarks?

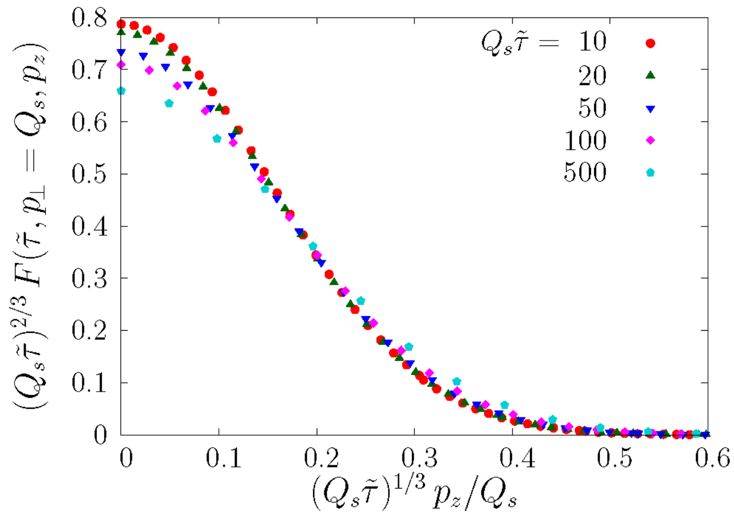
We numerically solved the Boltzmann eqs. for 2-2 scattering among quarks and gluons.

NT, Venugopalan, arXiv:1702.xxxx

original distribution




rescaled distribution




$$f_q(\tau, p_\perp, p_z) = (Q_s\tau)^{-2/3} F_S\left(p_\perp, (Q_s\tau)^{1/3} p_z\right)$$

In the first stage of the bottom-up thermalization, the quark distribution show the same scaling behavior as the gluon distribution.

# Bottom-up thermalization scenario

Baier, Mueller, Schiff, Son (2001,02)

2. Formation stage of soft gluon bath $Q_s^{-1}\alpha_s^{-3/2} \ll \tau \ll Q_s^{-1}\alpha_s^{-5/2}$

- $f_{hard} < 1$
- Soft gluons are produced by collinear splitting processes.
- The number density is still dominated by hard gluons, but the Debye mass is dominated by soft gluons.

3. Heating up stage $Q_s^{-1}\alpha_s^{-5/2} \ll \tau \ll Q_s^{-1}\alpha_s^{-13/5}$

- Soft gluons form a thermal bath, and it is heated by the remaining hard gluons.

$$T(\tau) = c_T \alpha_s^3 Q_s^2 \tau$$

thermalization time $\tau_{\rm th} = c_{\rm eq}\alpha_s^{-13/5} Q_s^{-1}$

temperature at that time $T_{\rm th} = c_{\rm eq} c_T \alpha_s^{2/5} Q_s$

Unknown numerical coefficients, which can be constrained by measured charged hadron multiplicity

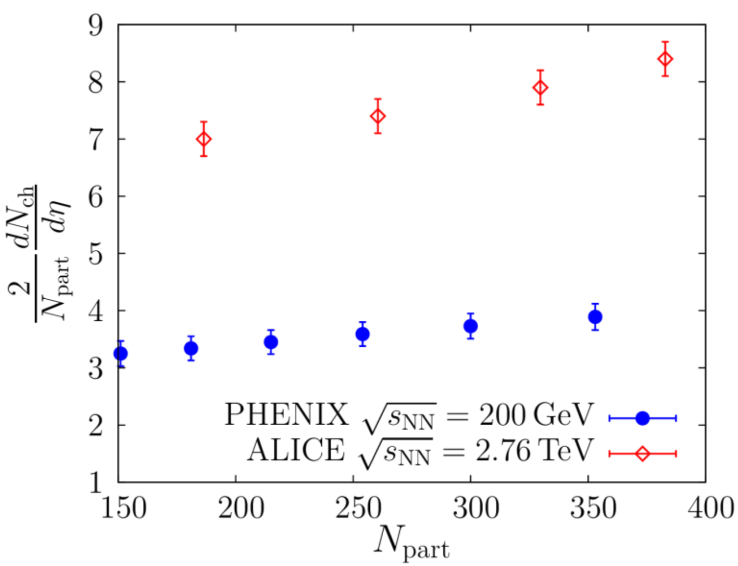
# Constraint for the coefficients

Entropy conservation after $\tau_{\rm th}$

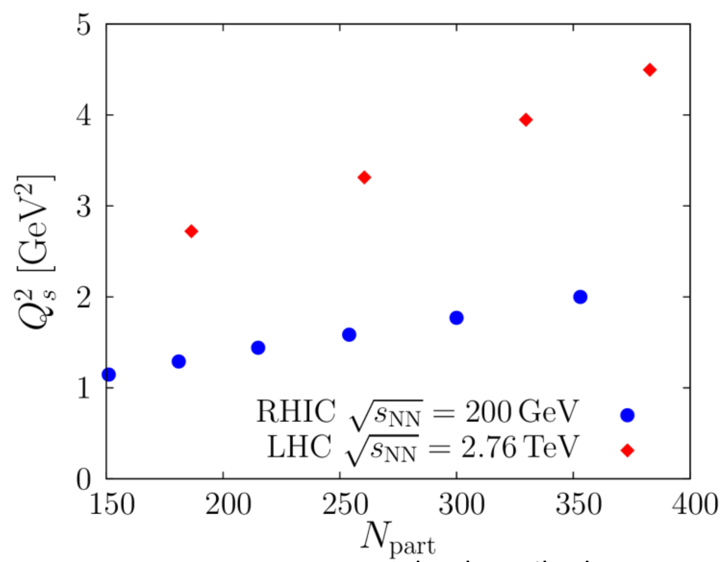
$$\frac{dS_{\rm QGP}}{d\eta} = \frac{74\pi^2}{45} S_\perp \, \tau T^3 \quad \Longleftrightarrow \quad \frac{dS_{\rm hadron}}{d\eta} = k \frac{dN_{\rm ch}}{d\eta} \qquad k \simeq 7.2$$

Pal, Pratt (2004)

Charged hadron multiplicity




$N_{\rm part}$ dependence from the IP-Glasma model



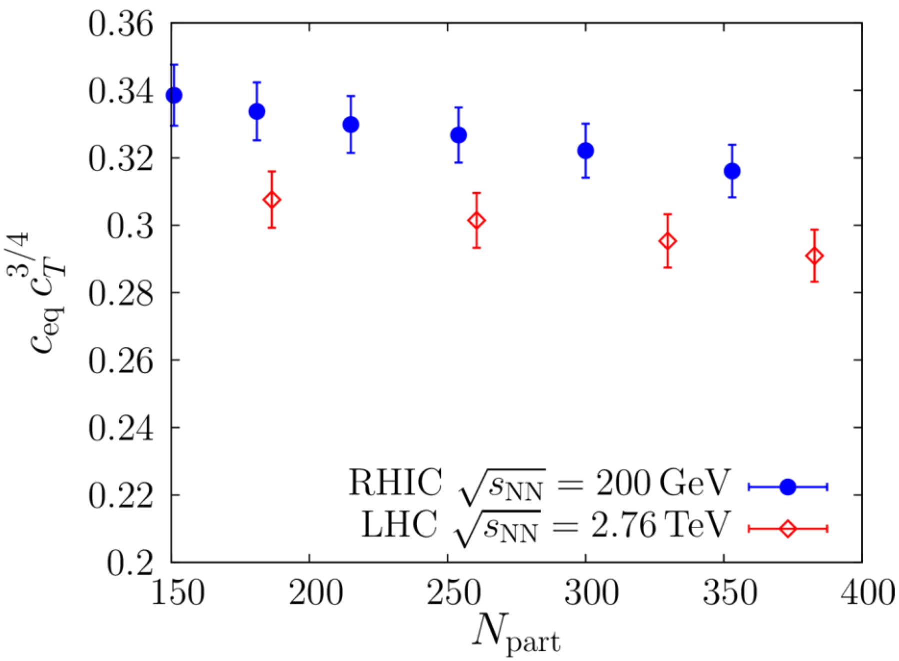

Schenke, Tribedy, Venugopalan (2012)

We treat $Q_s$ for a fixed $N_{\rm part}$ as a free parameter,
while adopting the $N_{\rm part}$ dependence from the IP-Glasma model.

RHIC and LHC values are related by $(2.76/0.2)^{0.3}$.

# Constraint for the coefficients

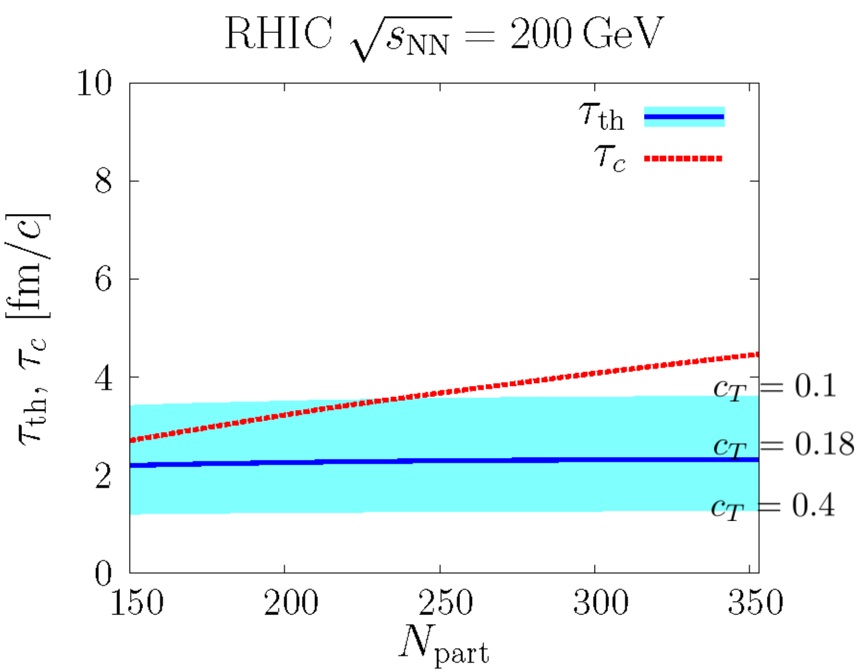
The combination $c_{\rm eq} c_T^{3/4}$ is constrained.

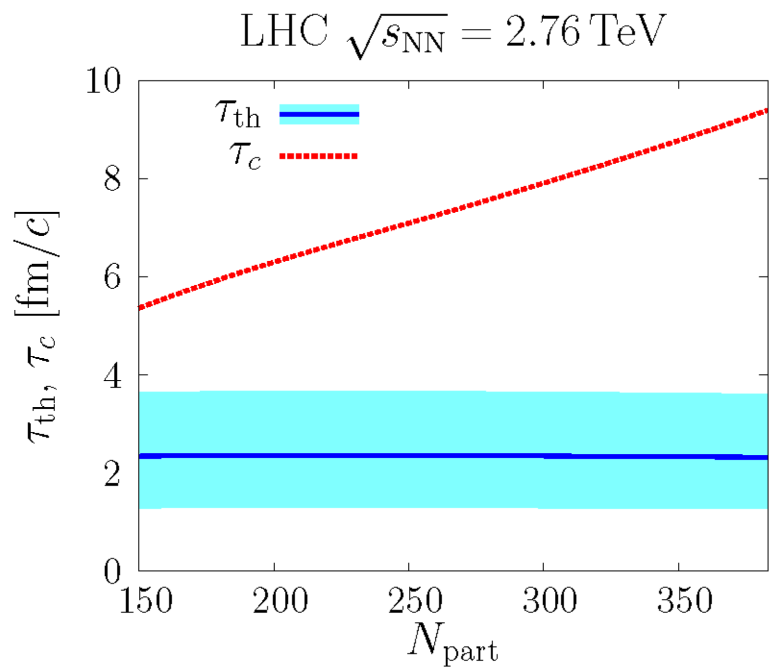



The dependence on $N_{\rm part}$ is mild.

BMSS estimate $c_T \simeq 0.18$ to logarithmic accuracy.
We vary between $c_T = 0.1$ and $0.4$

# Thermalization time vs. Hadronization time

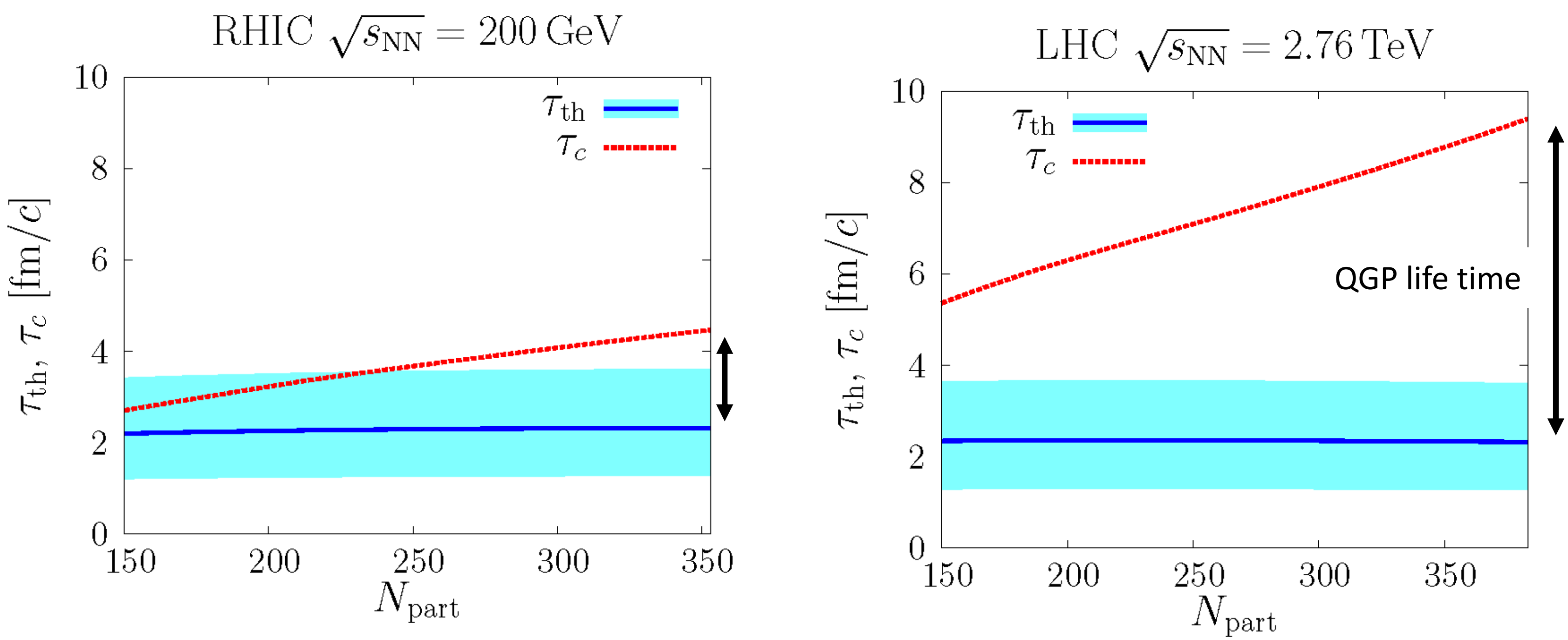



Thermalization time $\tau_{\rm th} = c_{\rm eq}\alpha_s^{-13/5} Q_s^{-1}$

Hadronization time $\tau_c = \dfrac{45}{74\pi^2} k \dfrac{1}{S_\perp} \dfrac{dN_{\rm ch}}{d\eta} \dfrac{1}{T_c^3}$ $\qquad T_c = 154\,\mathrm{MeV}$

# Thermalization time vs. Hadronization time




Thermalization time $\tau_{\mathrm{th}} = c_{\mathrm{eq}} \alpha_s^{-13/5} Q_s^{-1}$

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QGP life time is much longer for the LHC than RHIC.

# Estimation of the photon yields

Production rate via the annihilation and Compton processes

$$E\frac{dN}{d^4X d^3p} = \frac{1}{2(2\pi)^3}\int_{p_1,p_2,p_3} |\mathcal{M}|^2 (2\pi)^4 \delta^4(P_1+P_2-P_3-P) f_1(p_1) f_2(p_2)\left[1 \pm f_3(p_3)\right]$$

## ➢ Thermal phase

$$E\frac{dN^{\mathrm{th}}}{d^4x d^3p} = \frac{5}{9} C \frac{\alpha\alpha_s}{2\pi^2} T^2 e^{-E/T} \qquad C \sim \log(1/\alpha_s)$$

Kapsta, Lichard, Seibert (1991)

Ideal 1+1d expansion $T(\tau) = T_{\mathrm{th}}\left(\frac{\tau_{\mathrm{th}}}{\tau}\right)^{1/3}$

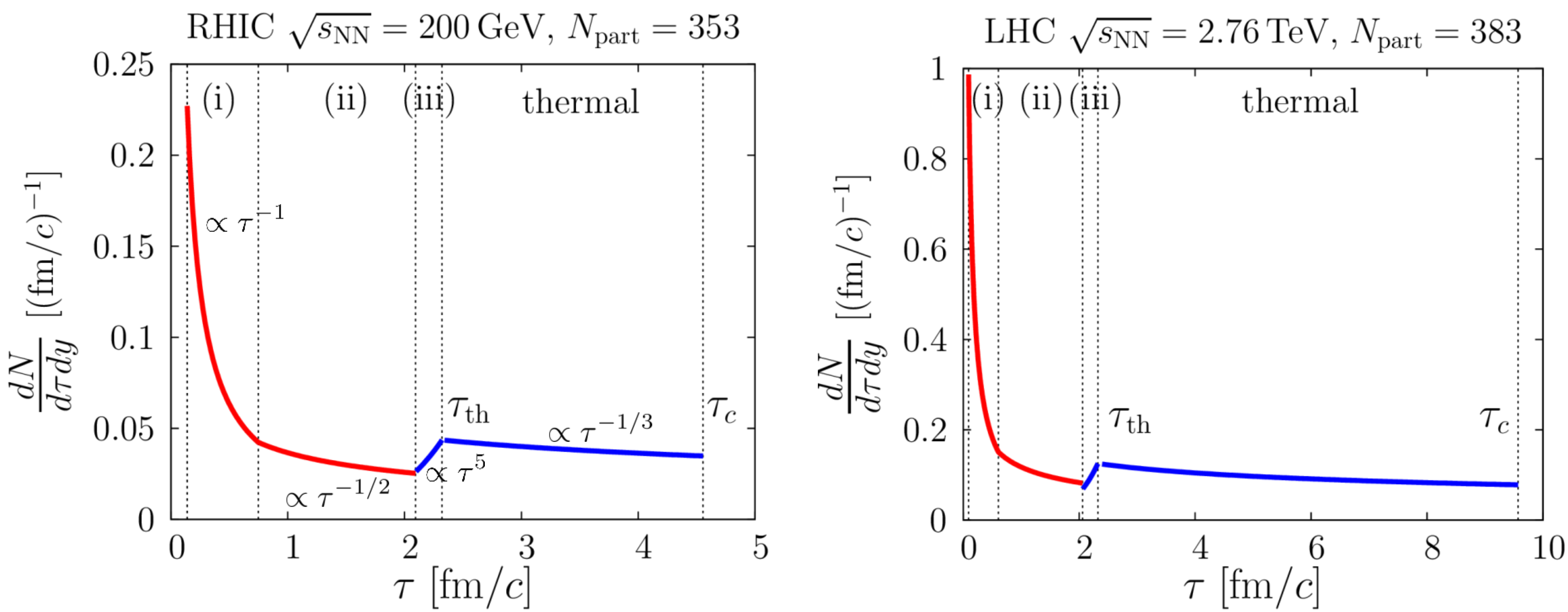
## ➢ Glasma phase

small-angle approximation

$$E\frac{dN}{d^4X d^3p} = \frac{40}{9\pi^2}\alpha\alpha_s \mathcal{L} f_q(\boldsymbol{p}) \int \frac{d^3p'}{(2\pi)^3}\frac{1}{p'}\left[f_g(\boldsymbol{p}') + f_q(\boldsymbol{p}')\right] \qquad \mathcal{L} \sim \log(1/\alpha_s)$$

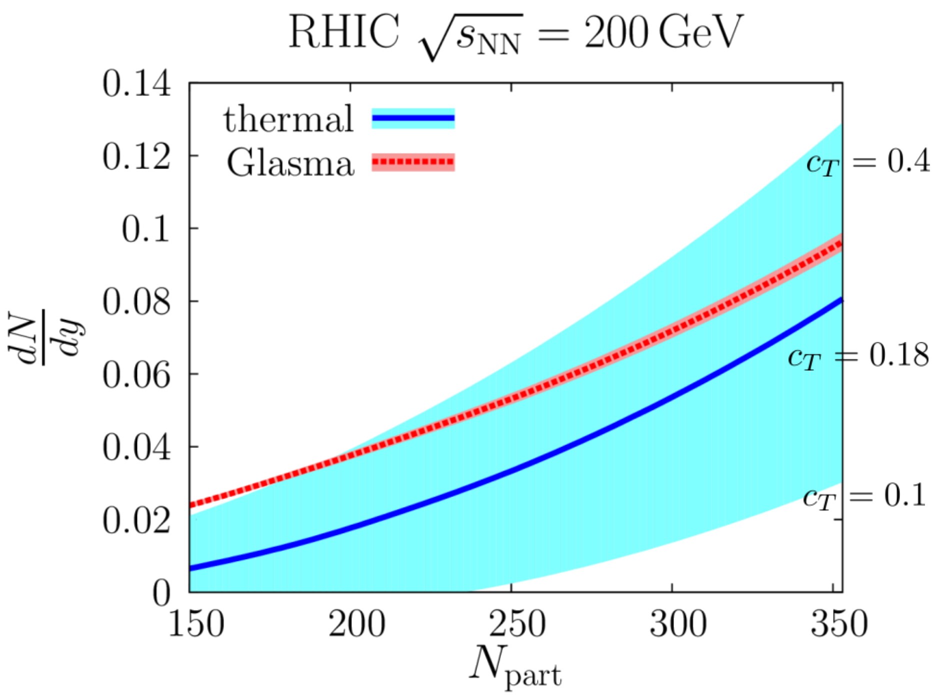
- We integrate these rates over the expanding space-time.
- We consider the total photon yield by integrating over pT.

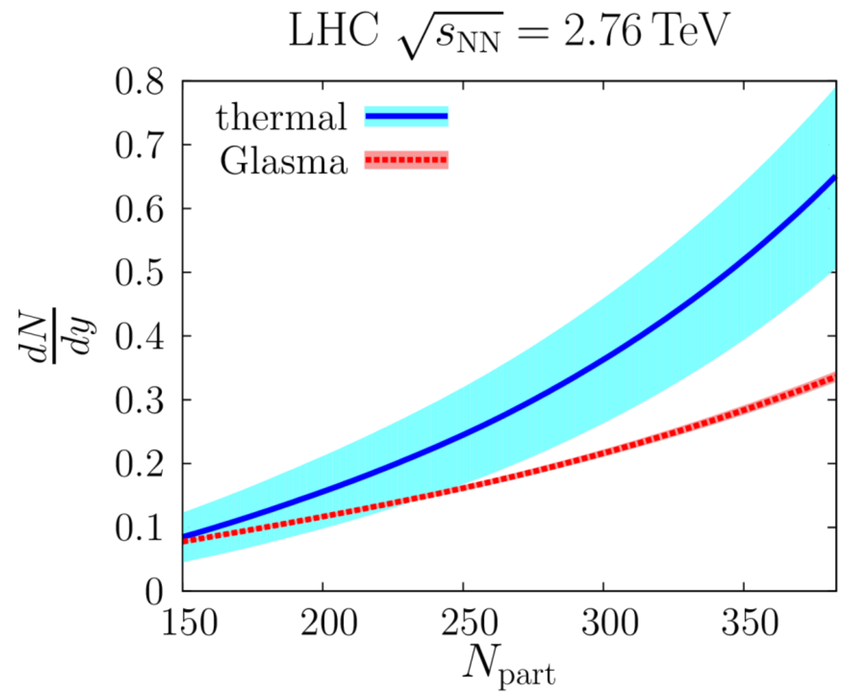
# Photon production rate




Area under these lines $= \dfrac{dN}{dy}$

# Thermal vs. Glasma photon yields

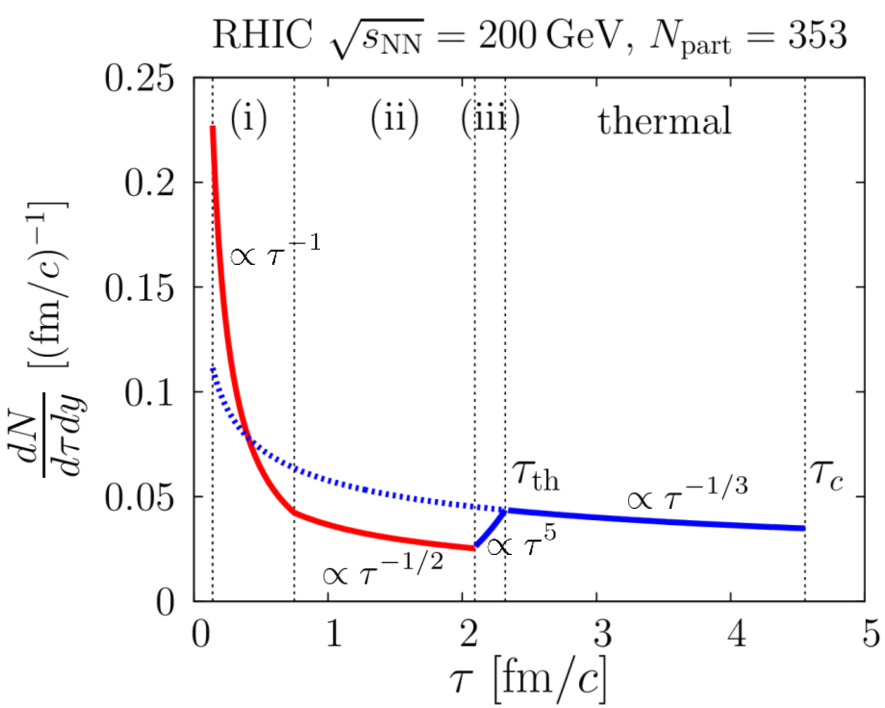


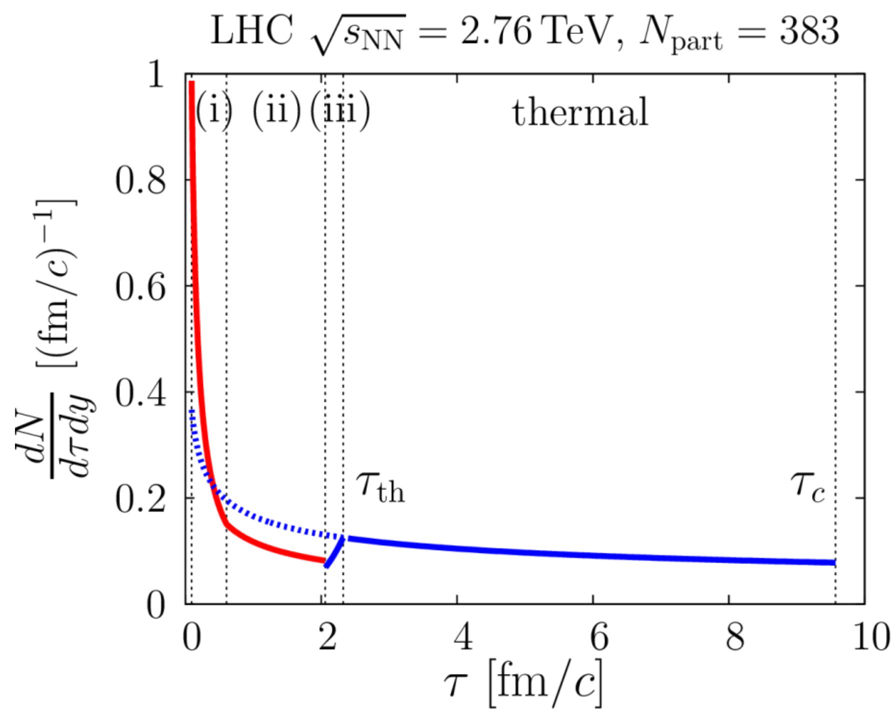




- For lower collision energy,
- For less central collisions,

the Glasma contribution is relatively more important.

# Bottom-up scenario vs. Early-hydro scenario

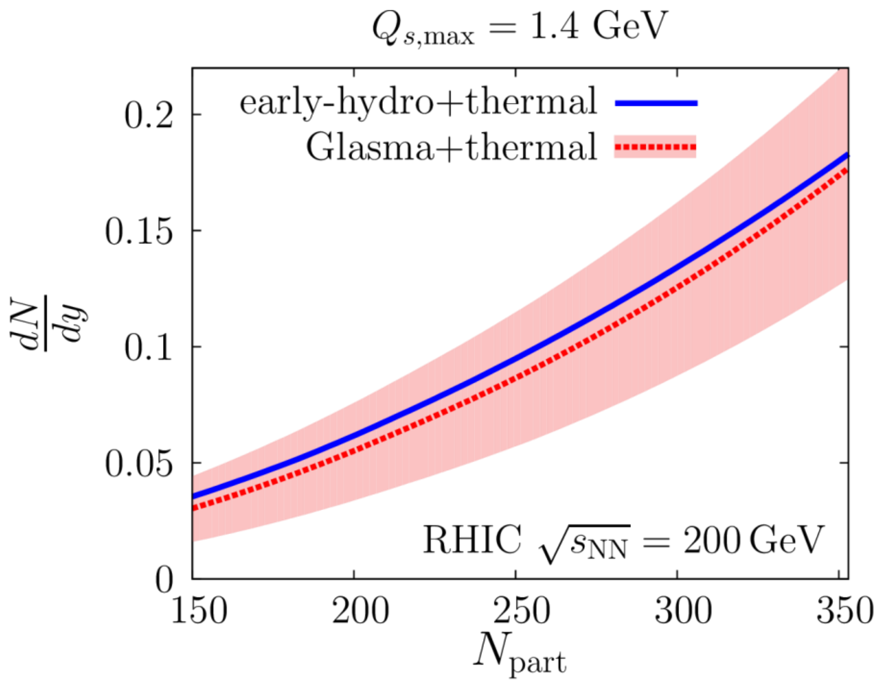


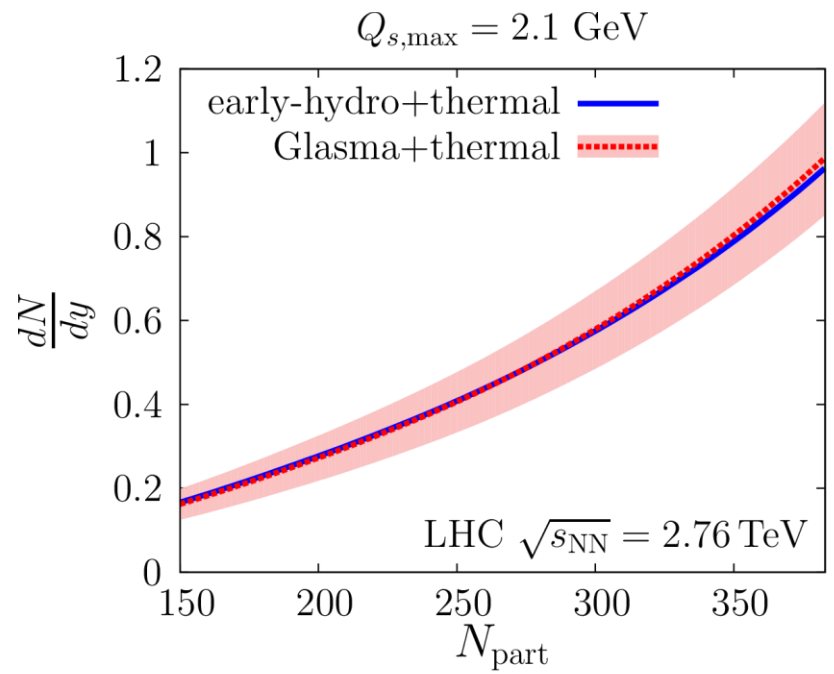




- Bottom-up thermalization scenario:
  Glasma (i), (ii), (iii) + Thermal ( $\tau_{\rm th} < \tau$ )

- Hydro scenario that assumes early-thermalization:
  Early-hydro ( $\tau_0 < \tau < \tau_{\rm th}$ ) + Thermal ( $\tau_{\rm th} < \tau$ )

# Bottom-up scenario vs. Early-hydro scenario

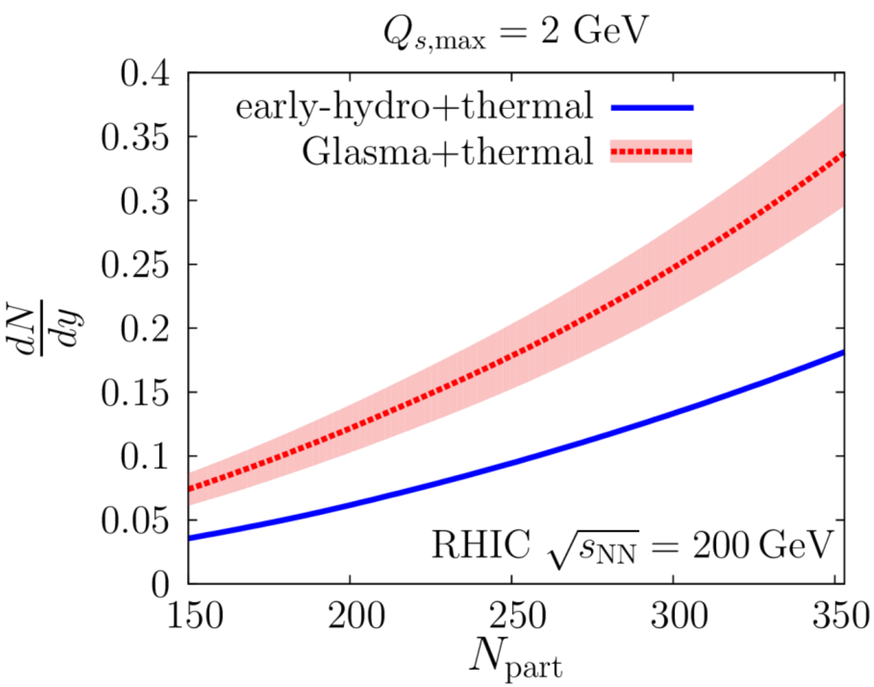


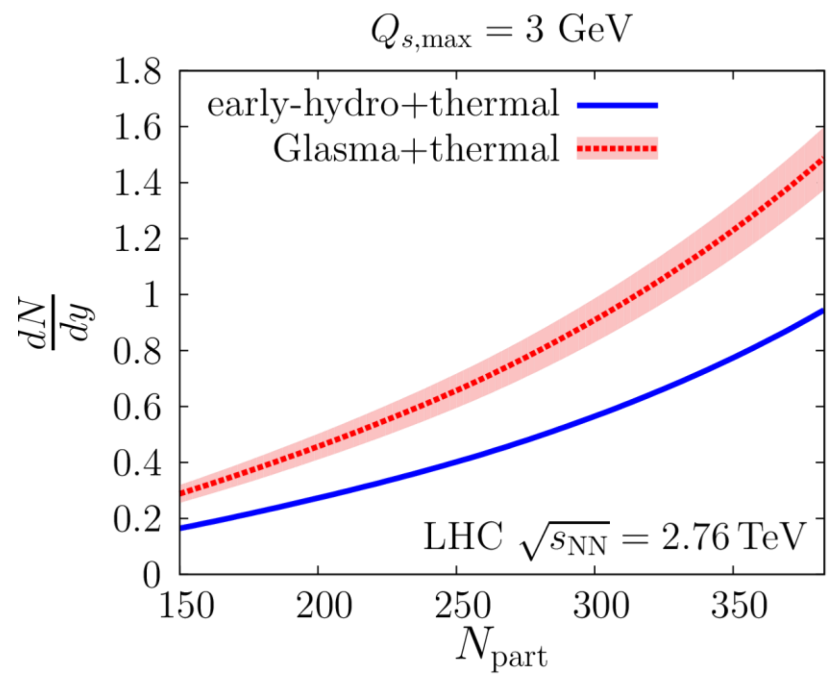




For this value of the saturation scale ($Q_s = 1.4$ GeV for the RHIC most central collision), the two scenarios give the comparable photon yields.

For larger value of the saturation scale…

# Bottom-up scenario vs. Early-hydro scenario



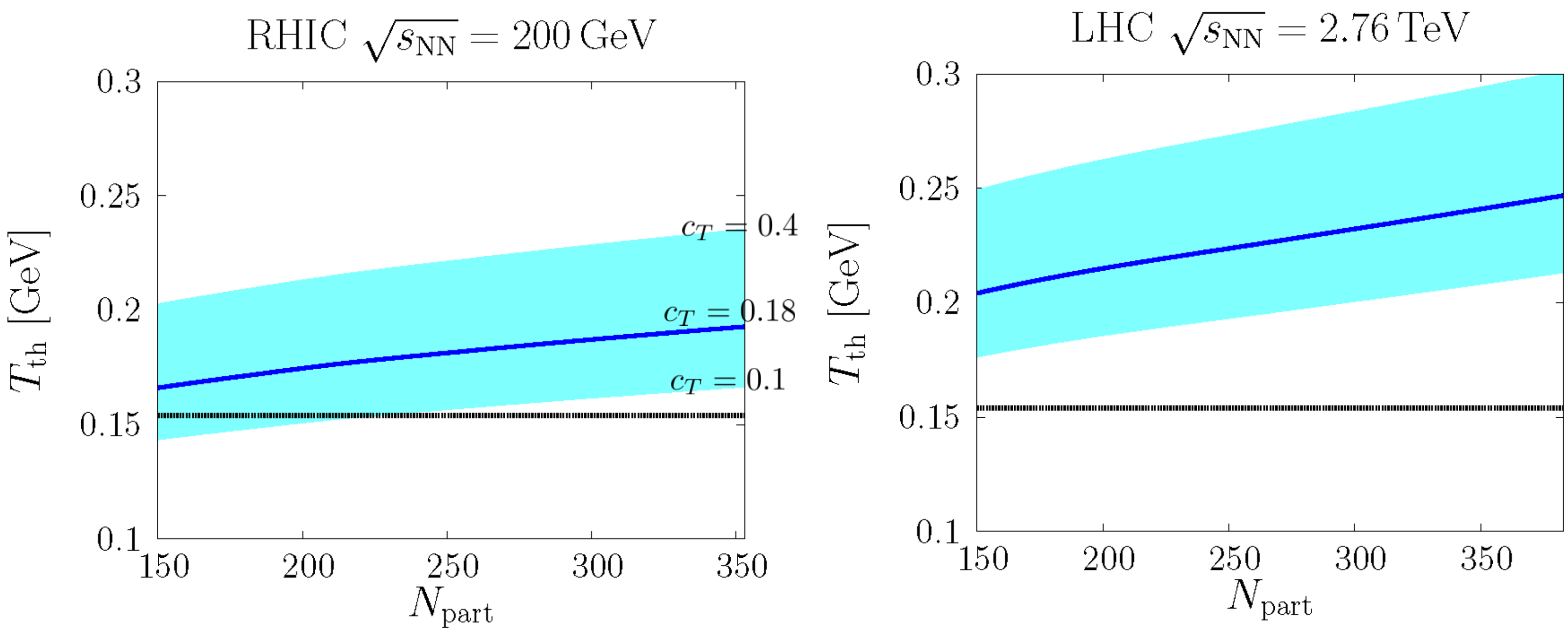

For a larger value of the saturation scale ($Q_s = 2$ GeV for the RHIC most central collision), the bottom-up thermalization scenario gives more photons.

# Summary and outlook

- Parametric estimates of the photon yields in the Glasma and the thermal QGP phases based on the bottom-up thermalization scenario.
- The Glasma contribution is not negligible although the space-time volume is small at early times.
- For lower collision energy or less central collisions, the Glasma contribution is relatively more important.
- In comparison between the bottom-up scenario and the early-hydro scenario, the former can give more photons for a large value of the saturation scale.
- Mini-jet photon?
- Ab-initio calculations (kinetic theory, classical-statistical simulations) are necessary to compute the photon spectrum and address v2.

# backup slides

# Initial temperature at the thermalization time

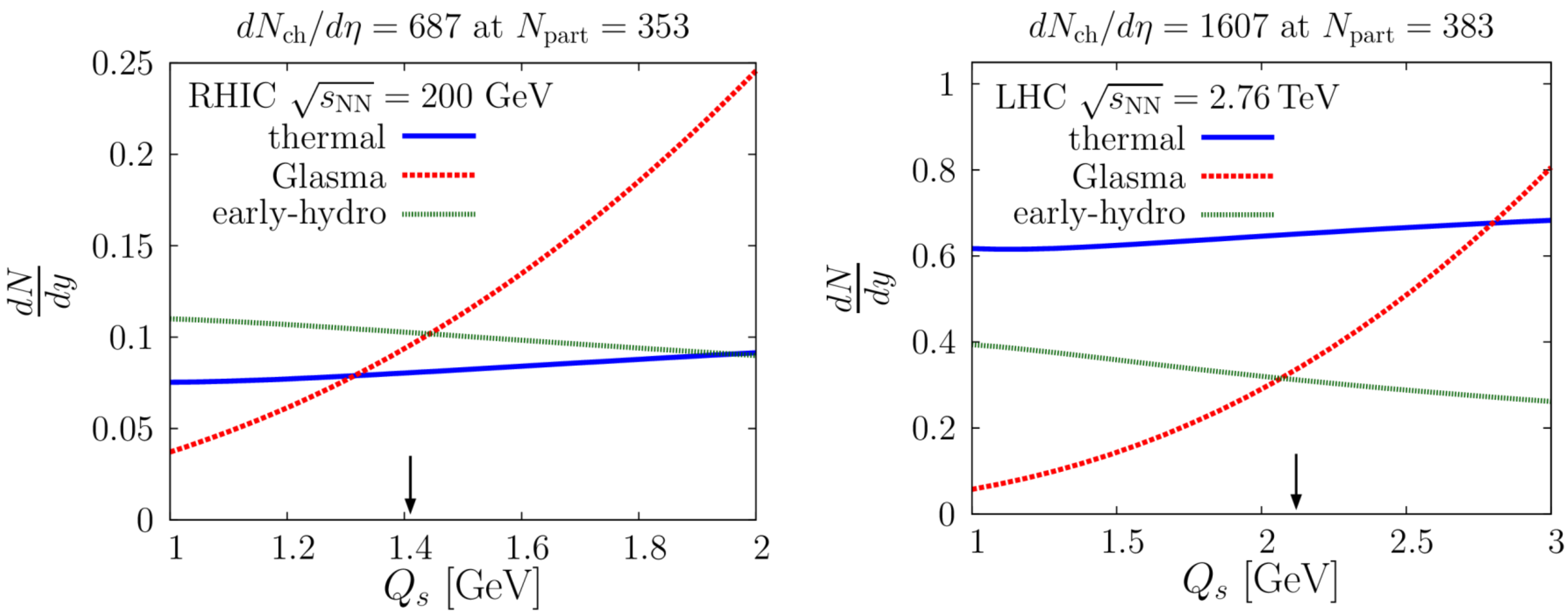



Initial temperature for the QGP phase $T_{\mathrm{th}} = c_{\mathrm{eq}} c_T \alpha_s^{2/5} Q_s$

Critical temperature $T_c = 154\,\mathrm{MeV}$

# Qs-dependence

For given hadron multiplicities, we vary the value of the saturation scale.




- The thermal and early-hydro contributions are not strongly dependent of $Q_s$.
- The Glasma photon yield is nearly proportional to $Q_s^2$ .
- For larger $Q_s$ , the Glasma contribution dominates.