Electromagnetic radiation from the pre-equilibrium/pre-hydro stage of the quark-gluon plasma

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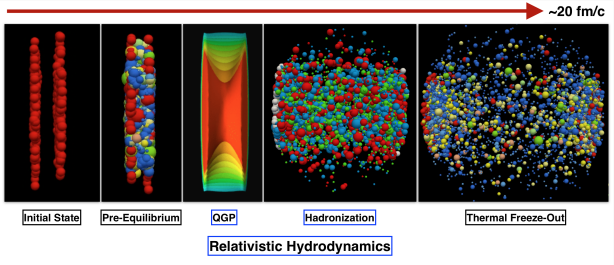
Introduction

Heavy-Ion Collisions



Evolution of quark-gluon plasma has three main stages: **pre-equilibrium**, hydrodynamics, and hadronization.

Pre-equilibrium QGP:

- dense system of gluons produced in a time scale of order $t \sim 1/Q_s$
- evolves as quarks/anti-quarks are created

Photons as Probes of Pre-Equilibrium QGP

Photons are excellent probes of relativistic heavy-ion collisions:

- emitted throughout the entire evolution of the medium
- only interact electromagnetically
    - escape without significant interaction

Pre-equilibrium phase will be studied through photon emission.

Parton population in this phase appear as solutions of the Boltzmann equation.

Solution to the Boltzmann Equation

The Diffusion Approximation

The Boltzmann equation is used in the diffusion approximation

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla_x\right) f_{g/q}(t, \mathbf{x}, \mathbf{p}) \quad = \quad \mathcal{C}_{g/q}[f_g(t, \mathbf{x}, \mathbf{p}), f_q(t, \mathbf{x}, \mathbf{p})] \tag{1}$$

where $\mathcal{C}_{g/q}$ are the collision integrals of $2 \leftrightarrow 2$ scattering processes.

The collision integral is simplified as a Fokker-Planck diffusion term

$$\mathcal{C}_{g/q}[f_g(t, \mathbf{x}, \mathbf{p}), f_q(t, \mathbf{x}, \mathbf{p})] \quad = \quad -\nabla_{\mathbf{p}} \cdot \mathcal{J}_{g/q} + \mathcal{S}_{g/q} \tag{2}$$

where $\mathcal{J}$ and $\mathcal{S}$ are the effective current and source terms[1].

[1] J-P. Blaizot, B. Wu, L. Yan - arXiv:1402.5049v2

Bjorken Expansion of QGP

The early time evolution of QGP, dominated by a longitudinal expansion, is described by the Bjorken model.

The system is initialized at $t_0 Q_s = 1$.

Pure gluons are described by the gluon distribution function[2] inspired by the colour glass picture

$$f_g(t_0, p) = f_0 \theta \left(1 - \frac{\sqrt{p_\perp^2 + p_z^2 \xi^2}}{Q_s} \right) \tag{3}$$

with initial anisotropy ξ.

[2] P. Romatschke and M. Strickland, Phys. Rev., D68:036004, 2003

Bjorken Expansion of QGP

The energy density, initially dominated by gluons, can be expressed as

$$\epsilon(\tau_0) = 4N_c C_F \int \frac{d^3p}{(2\pi)^3} p f_g. \tag{4}$$

Integrating over volume, one may obtain

$$\frac{dE}{d\eta} = 2N_c C_F A_T \frac{f_0 Q_s^3}{(2\pi)^2} \frac{1}{\xi} \mathcal{F}(\xi) \tag{5}$$

where $\mathcal{F}(x) = \frac{1}{2}\int_{-1}^{+1} dy \left[1 - (1-x^2)y^2\right]^{1/2}$ and A_T is the transverse area from Glauber calculation[3].

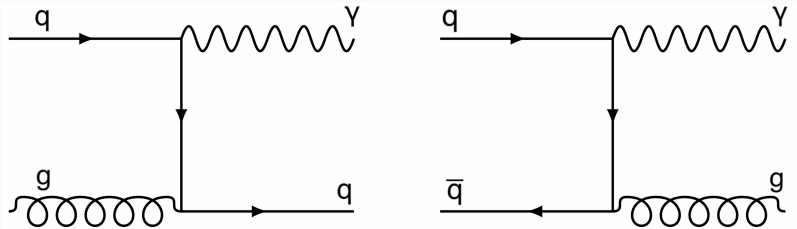
[3] C. Loizides, J. Kamin, D. d'Enterria - arXiv:1710.07098v3

Photon Production in Pre-Equilibrium QGP

Photon Production in Pre-Equilibrium QGP

The production rate of photons is derived from kinetic theory

$$E\frac{d^3R}{d^3p} = \int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{1}{2(2\pi)^3}|\mathcal{M}_i|^2(2\pi)^4 \times\delta^4(P_1+P_2-P_3-P)f_1(\mathbf{p}_1)f_2(\mathbf{p}_2)[1\pm f_3(\mathbf{p}_3)] \quad (6)$$



Photon Production in Pre-Equilibrium QGP

The small-angle approximation, assuming low momentum transfer between scattering particles, gives

$$E\frac{d^3R}{d^3p} = \frac{40}{9\pi^2}\alpha\alpha_s\mathcal{L}f_q(\mathbf{p})\int\frac{d^3p'}{(2\pi)^3}\frac{1}{p'}[f_g(\mathbf{p}') + f_q(\mathbf{p}')] \tag{7}$$

where

$$\mathcal{L} = log\frac{\Lambda_{UV}}{\Lambda_{IR}} \tag{8}$$

is fixed to match NLO AMY[4] rates.

[4] P. Arnold, G. Moore, L. Yaffe, JHEP12(2001)009

Photon Production in Pre-Equilibrium QGP

Upon performing a change of variables

$$\tilde{p_z} = p_\perp \sinh(\sinh^{-1}(p_z/p_\perp) - \eta) \tag{9}$$

to account for a non-zero value of η, an integration over η and τ gives

$$\begin{aligned} \frac{dN}{dy_p d^2\mathbf{p}_\perp} &= \frac{16 A_T}{3\pi^2} \alpha\alpha_s \mathcal{L} \int \tau d\tau d\eta f_q(p_\perp, \tilde{p_z}, \tau) \\ &\times \int \frac{p'_\perp dp'_\perp dp'_z}{(2\pi)^2} \frac{f_g(p'_\perp, p'_z, \tau) + f_q(p'_\perp, p'_z, \tau)}{\sqrt{p'^2_\perp + p'^2_z}}. \end{aligned} \tag{10}$$

Results

Matching to Experiment

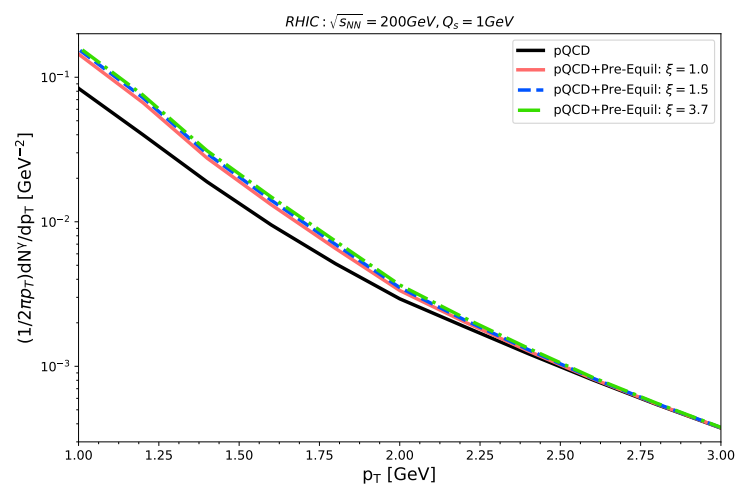
Initial gluon population (f_0) is calculated by matching to experimental $dE/d\eta$[5][6][7]

$$\frac{dE}{d\eta} \propto f_0 Q_s^3 \frac{\mathcal{F}(\xi)}{\xi} \tag{11}$$

	RHIC @ 200 GeV	**LHC @ 2.76 TeV**		**LHC @ 5.02 TeV**	
ξ	$Q_s = 1\text{GeV}$	$Q_s = 1\text{GeV}$	$Q_s = 2\text{GeV}$	$Q_s = 1\text{GeV}$	$Q_s = 2\text{GeV}$
1.0	$f_0 = 0.76$	$f_0 = 2.66$	$f_0 = 0.33$	$f_0 = 3.20$	$f_0 = 0.40$
1.5	$f_0 = 1.27$	$f_0 = 4.44$	$f_0 = 0.56$	$f_0 = 5.35$	$f_0 = 0.67$
3.7	$f_0 = 3.47$	$f_0 = 12.2$	$f_0 = 1.52$	$f_0 = 9.58$	$f_0 = 1.20$

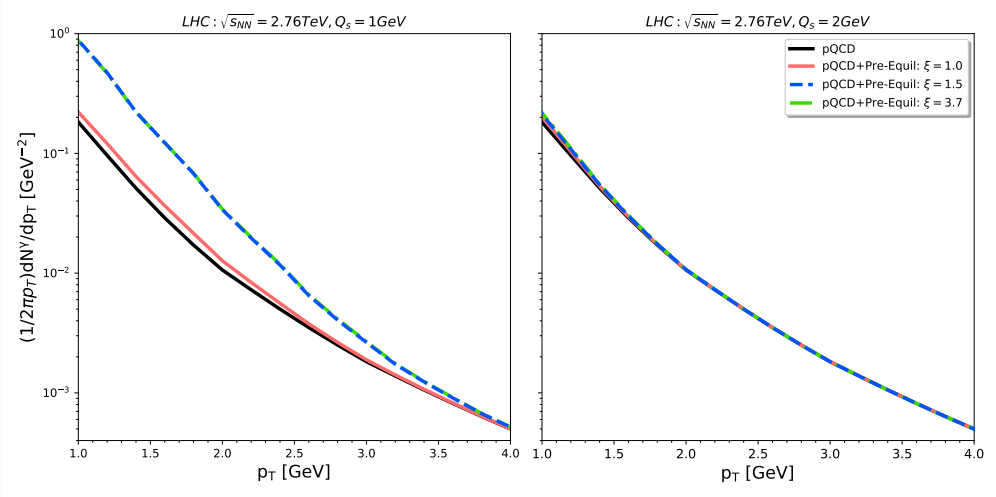
[5] PHENIX - arXiv:nucl-ex/0409015v1
[6] CMS - PhysRevLett.109.152303
[7] ALICE - PhysRevLett.116.222302

pQCD+Pre-Equilibrium Photons: ξ Dependence



*pQCD: J-F Paquet

pQCD+Pre-Equilibrium Photons: ξ Dependence



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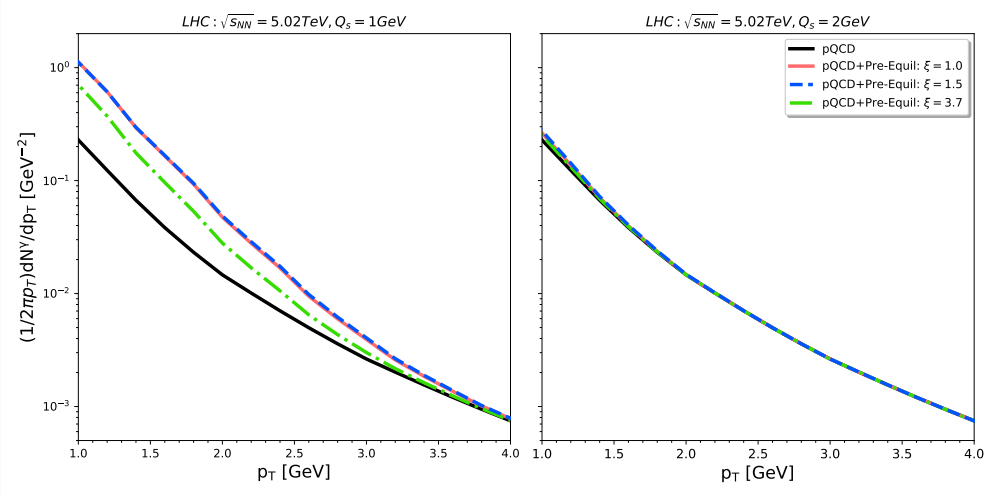
pQCD+Pre-Equilibrium Photons: ξ Dependence



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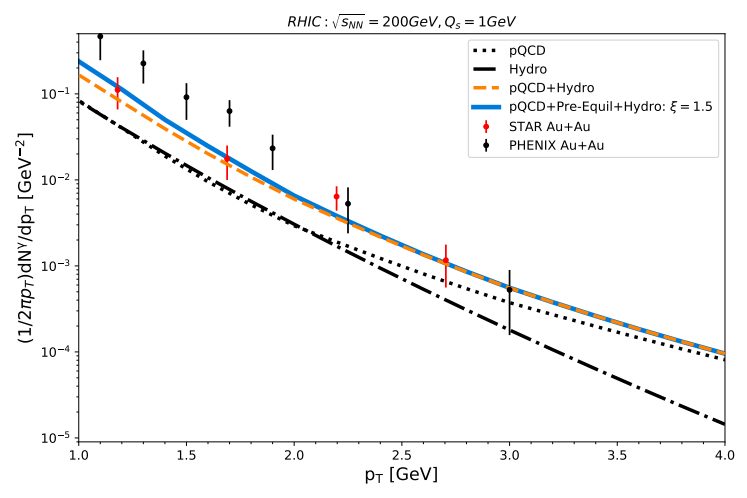
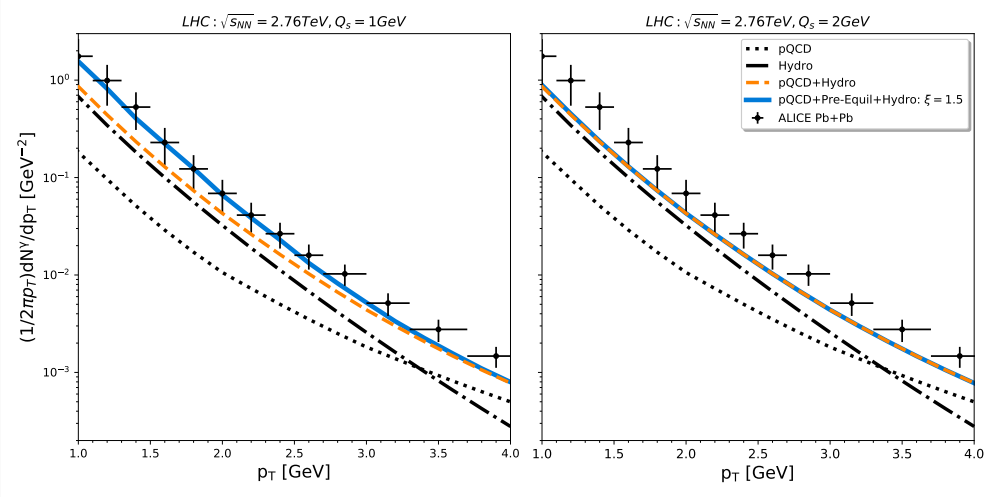
pQCD+Pre-Equilibrium+Hydro Photons: Q_s Dependence



*pQCD+hydro: J-F Paquet, see talk by C. Gale

pQCD+Pre-Equilibrium+Hydro Photons: Q_s Dependence



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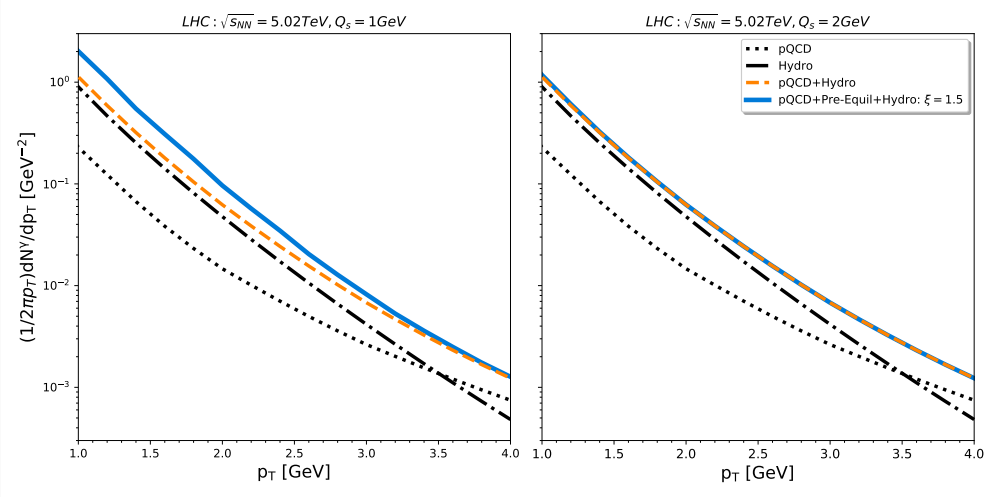
pQCD+Pre-Equilibrium+Hydro Photons: Q_s Dependence



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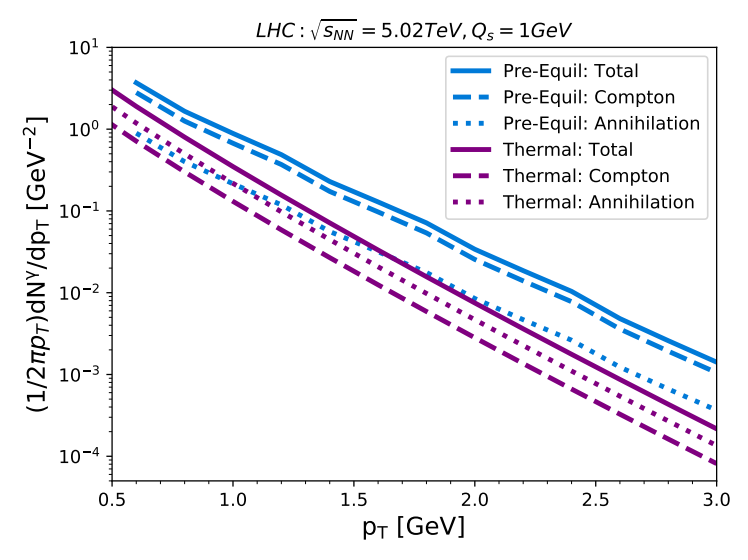
Pre-Equilibrium vs. Thermal: Compton and Annihilation Channels



Conclusions

Conclusion

Photons produced in the pre-equilibrium stage have been quantified

- effect of initial pressure anisotropy ξ
- dependence on saturation momentum Q_s

When $Q_s = 1 GeV$, pre-equilirium photons enhance total photon yield by

- $\sim 40\%$ at RHIC
- $\sim 80\%$ at LHC energies

When $Q_s = 2 GeV$, pre-equilibrium photons are suppressed due to lower f_0.

Results can provide information about Q_s and ξ.

Conclusion

Due to the large gluon population and the lack of $q\bar{q}$ pairs in the initial state

- suppression in the $q\bar{q}$ annihilation channel
- enhancement in the Compton scattering channel

Pre-equilibrium photons do not effect the quality of previous descriptions of overall v_2.

Future work: more realistic, 3+1D Boltzmann solver.

Thank you.

The Diffusion Approximation

The effective currents and sources are

$$\mathcal{J}_g = -4\pi\alpha_s^2 N_c \mathcal{L}\left[\mathcal{I}_a \nabla_{\mathbf{p}} f_g + \mathcal{I}_b \frac{\mathbf{p}}{p} f_g(1+f_g)\right] \tag{12}$$

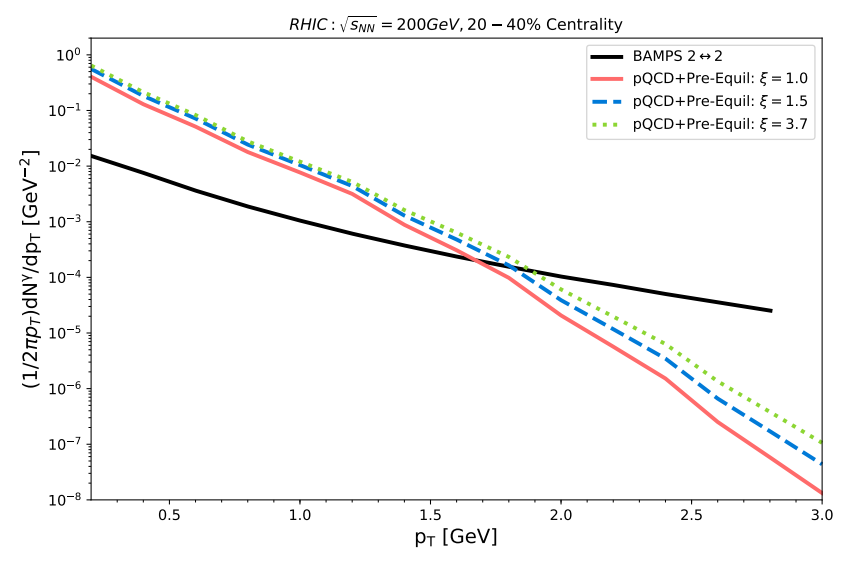
$$\mathcal{J}_q = -4\pi\alpha_s^2 C_f \mathcal{L}\left[\mathcal{I}_a \nabla_{\mathbf{p}} f_q + \mathcal{I}_b \frac{\mathbf{p}}{p} f_q(1-f_q)\right] \tag{13}$$

$$\mathcal{S}_g = \frac{4\pi\alpha_s^2 C_F N_f \mathcal{L}\mathcal{I}_c}{p}[f_q(1+f_g) - f_g(1-f_q)] \tag{14}$$

$$\mathcal{S}_q = -\frac{4\pi\alpha_s^2 C_F^2 \mathcal{L}\mathcal{I}_c}{p}[f_q(1+f_g) - f_g(1-f_q)] \tag{15}$$

and $\mathcal{I}$ are constant integrals.

Pre-Equilibrium vs. BAMPS Photons



Pressure Anisotropy Comparison