Describing the thermal radiation

with a new analytic formula

GÁBOR KASZA

9TH DAY OF FEMTOSCOPY

GYÖNGYÖS, 30/10/2023

Importance of direct photon spectrum

Direct photons (DP): those photons that not coming from hadron decays

Probe towards our ***understanding of the evolution of relativistic heavy ion collisions***

Small cross section of electromagnetic interaction → ***DP traverse the medium unmodified***

Penetrating photons → ***encode information of the environment*** (temperature, collective motion)

Low p_T regime: mostly the ***thermal component of the spectrum → can be evaluated by hydro***

High p_T regime: photons from high scattering processes

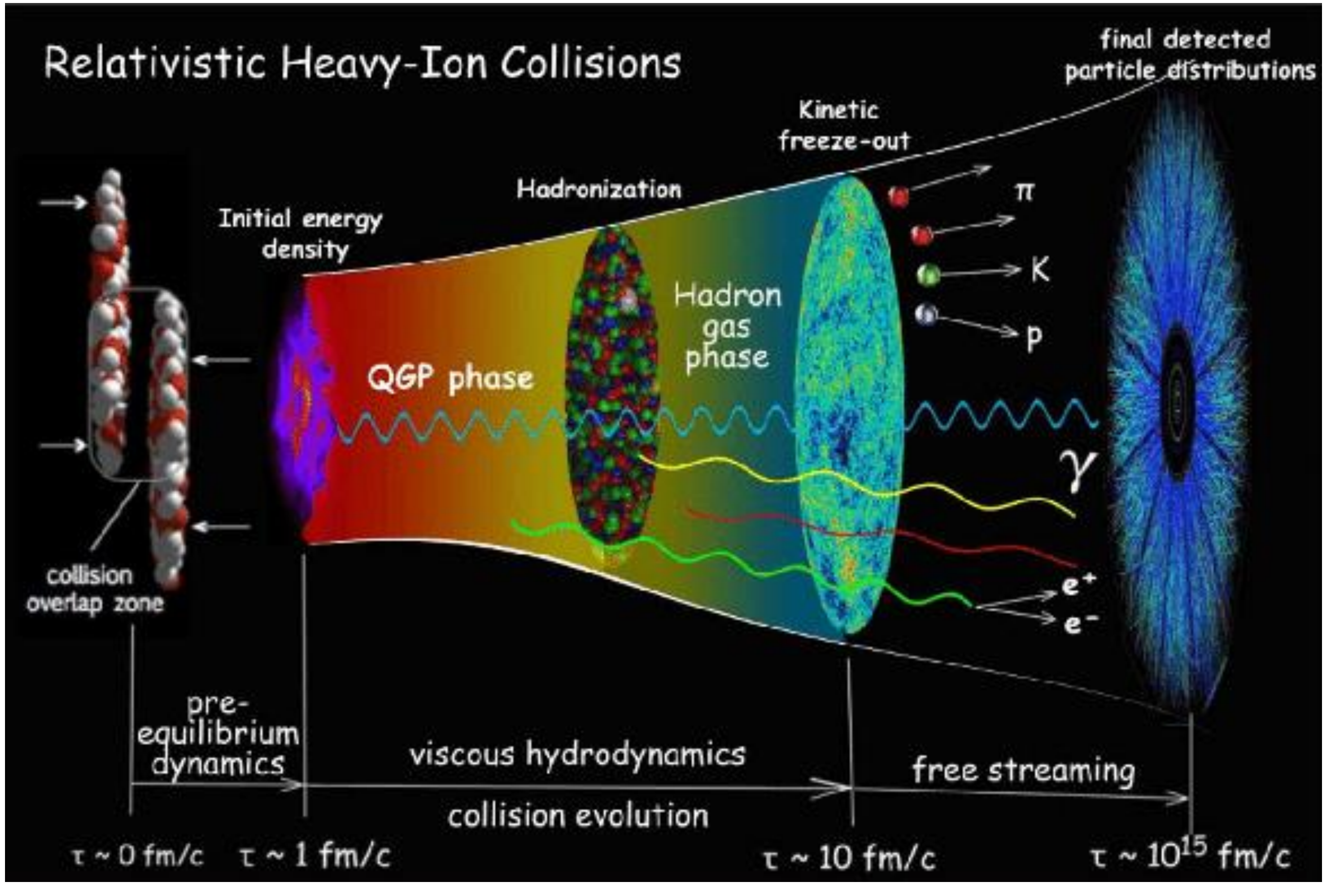
Today's presentation:

- ***A new analytic formula has been found based on the Csörgő-Kasza-Csanád-Jiang solution*** *Universe* 4 (2018) 6, 69
- ***This formula is compared to PHENIX Au+Au@200 GeV 0-20% dataset*** arXiv:2203.17187

Similar efforts was done by Csanád and Májer in 2012: *Central Eur.J.Phys.* 10 (2012)

Nonprompt spectrum of direct photons

The evolution of relativistic heavy-ion collisions:



Nonprompt spectrum of direct photons

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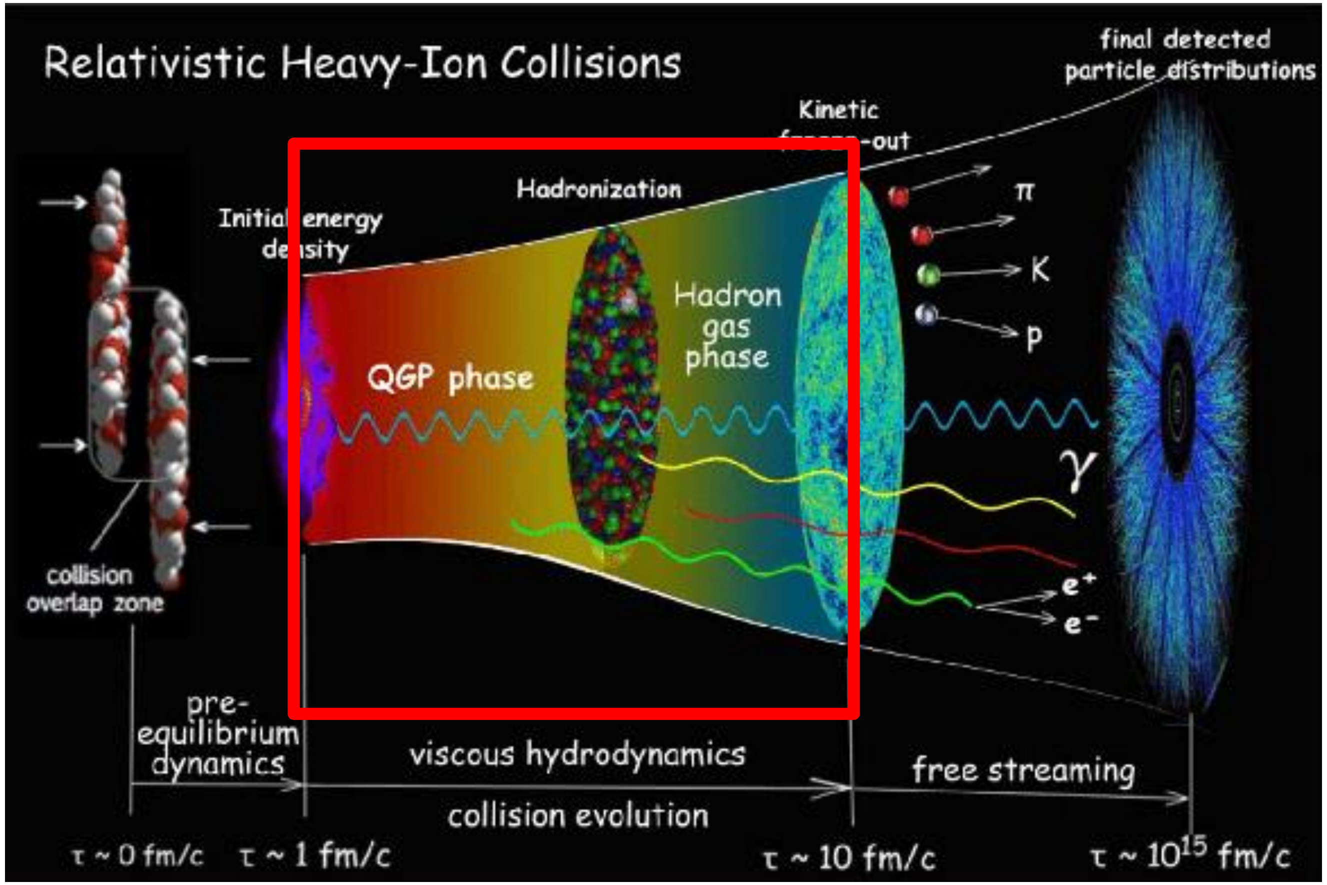
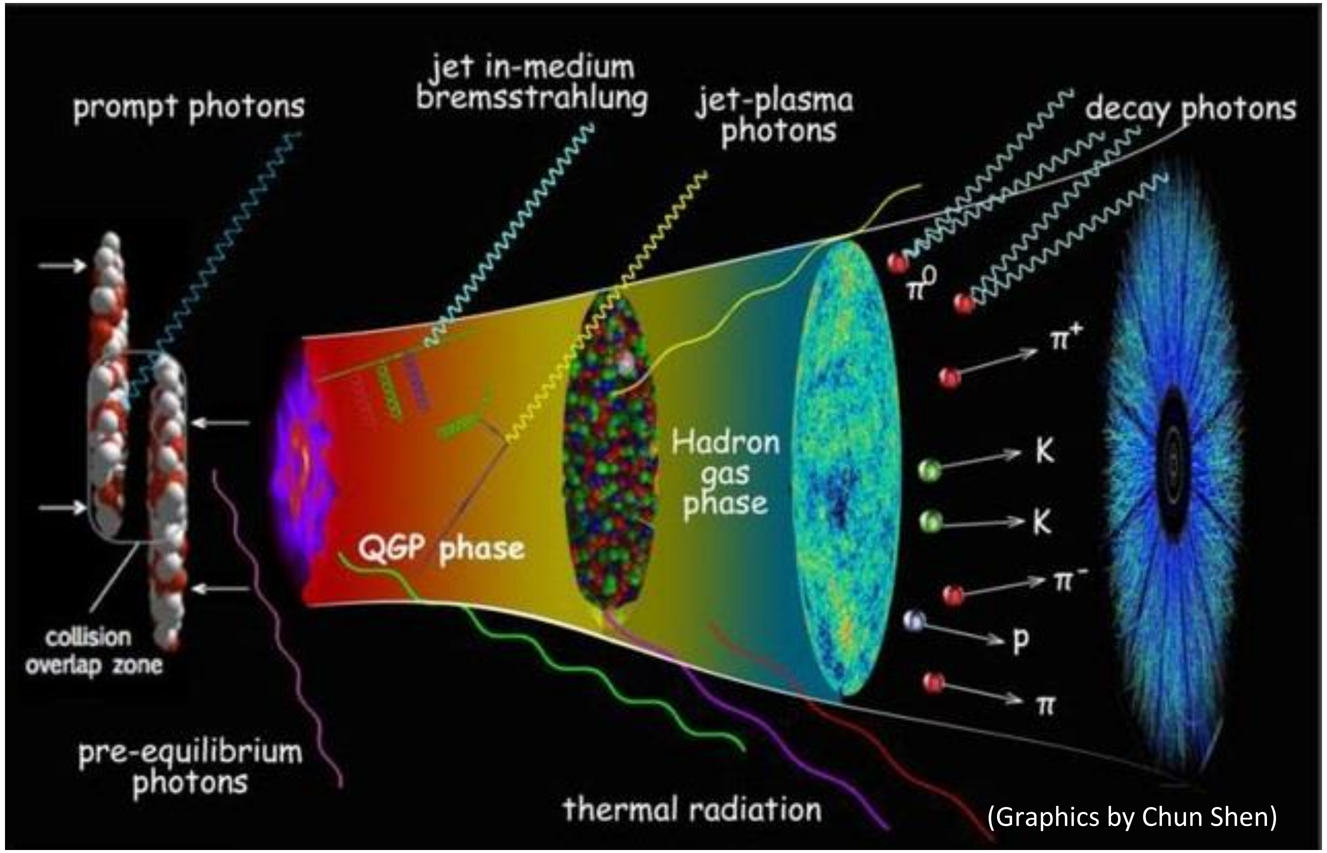


Period of our interest

Nonprompt spectrum of direct photons

Focusing on photons:

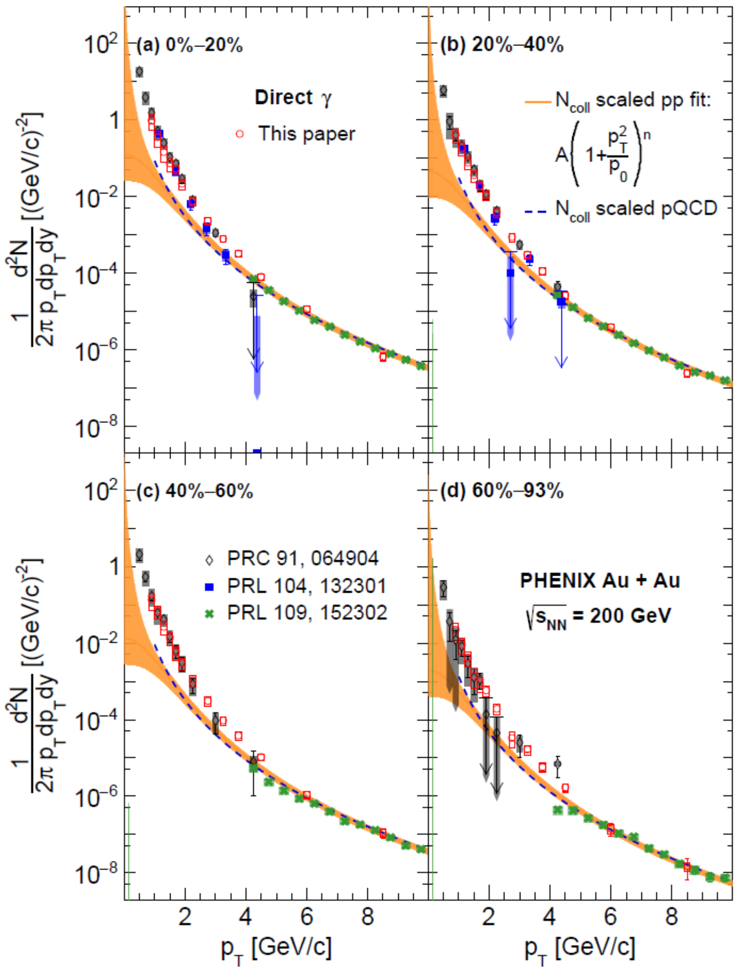


Direct photons =
Inclusive photons – Decay photons

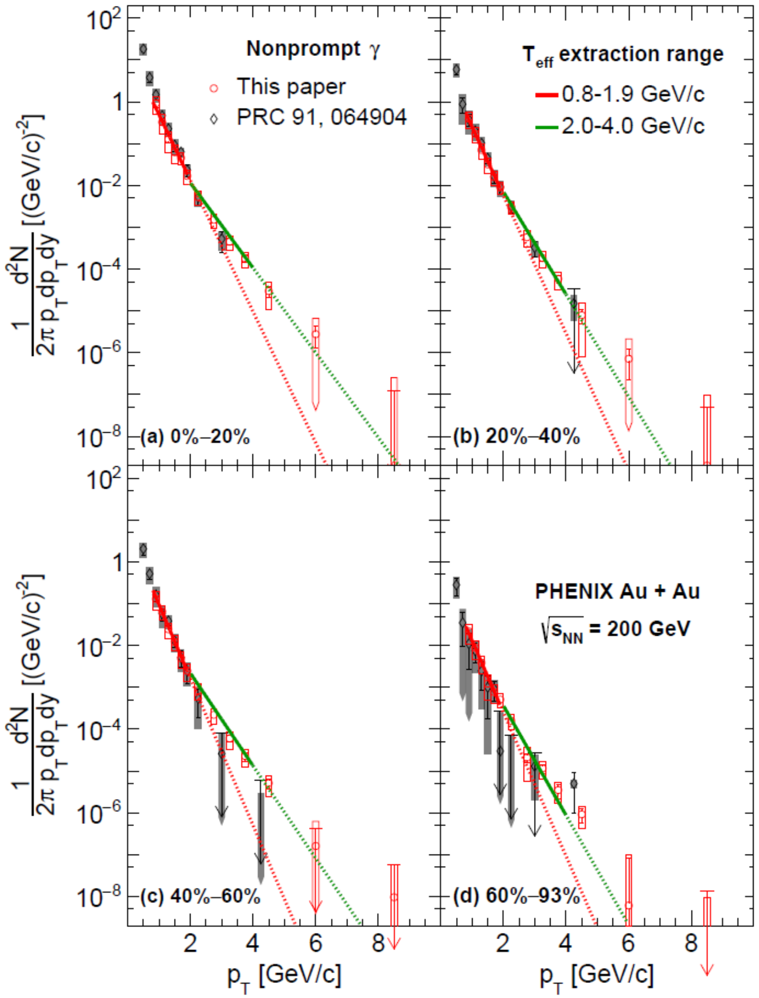
Nonprompt photons ≈ Thermal photons =
Direct photons – Prompt photons

Initial temperature can be extracted from thermal component!

Nonprompt spectrum of direct photons



N_{coll} scaled *p+p* fit is substracted from the *Au+Au* data



PHENIX: arXiv:2203.17187

Csörgő-Kasza-Csanád-Jiang (CKCJ) hydro solution

- Rindler coordinates, velocity field:

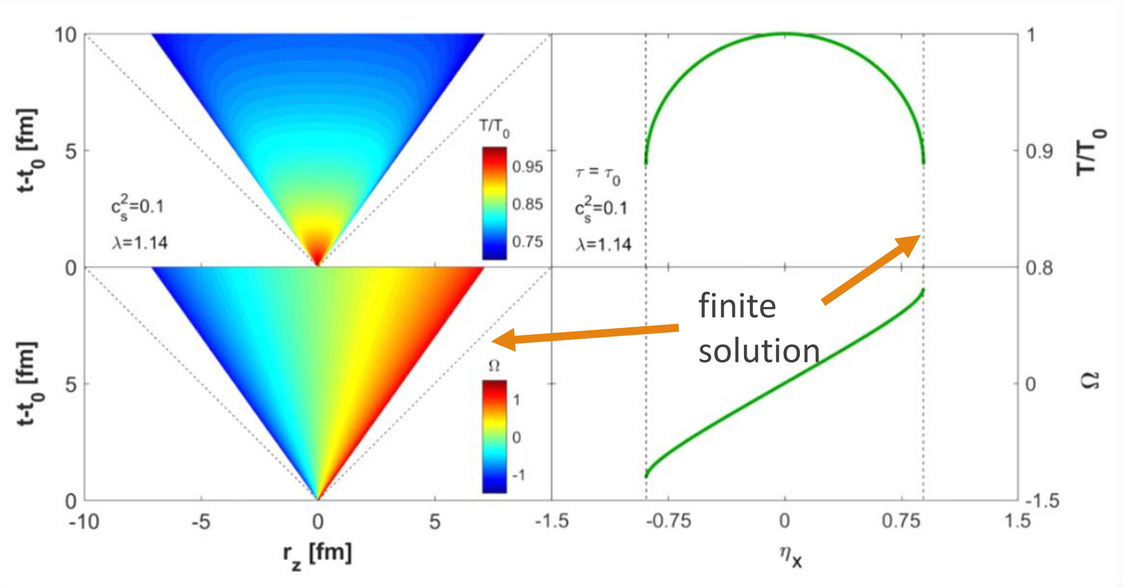
$$(\tau, \eta_x) = \left(\sqrt{t^2 - r_z^2}\,, \frac{1}{2}\ln\left[\frac{t + r_z}{t - r_z}\right] \right)$$

$$u^\mu = (\cosh(\Omega), \sinh(\Omega))$$

- 1+1 dimensional perfect fluid solution:

$$\begin{aligned}
\eta_x(H) &= \Omega(H) - H, \\
\Omega(H) &= \frac{\lambda}{\sqrt{\lambda-1}\sqrt{\kappa-\lambda}}\arctan\left(\sqrt{\frac{\kappa-\lambda}{\lambda-1}}\tanh(H)\right) \\
\sigma(\tau, H) &= \sigma_0 \left(\frac{\tau_0}{\tau}\right)^{\lambda} \mathcal{V}_\sigma(s) \left[1 + \frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\frac{\lambda}{2}}, \\
T(\tau, H) &= T_0 \left(\frac{\tau_0}{\tau}\right)^{\frac{\lambda}{\kappa}} \mathcal{T}(s) \left[1 + \frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\frac{\lambda}{2\kappa}}, \\
\mathcal{T}(s) &= \frac{1}{\mathcal{V}_\sigma(s)}, \\
s(\tau, H) &= \left(\frac{\tau_0}{\tau}\right)^{\lambda-1} \sinh(H) \left[1 + \frac{\kappa-1}{\lambda-1}\sinh^2(H)\right]^{-\lambda/2}
\end{aligned}$$

Universe 4 (2018) 6, 69



Equation of State:

$$\varepsilon = \kappa p$$

(with μ=0)

λ: acceleration parameter

↓

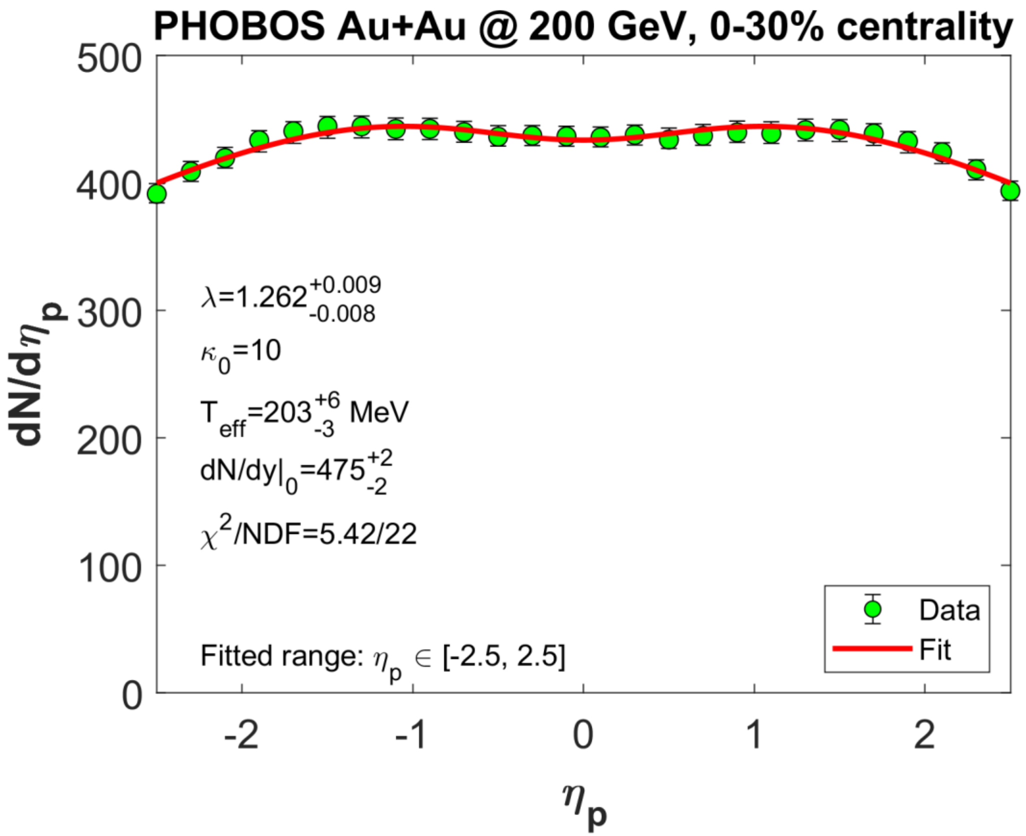
accelerating solution

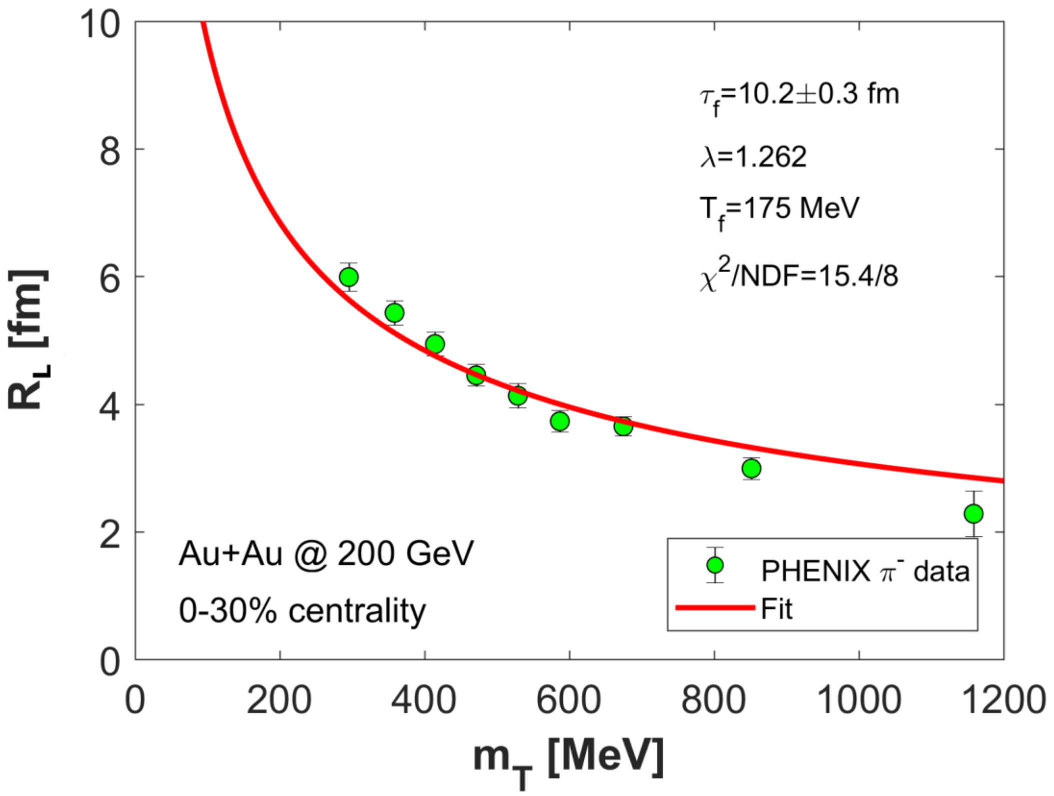
realistic $dN/d\eta_p$

Some earlier success with the CKCJ solution

Quantitatively acceptable description of $dN/d\eta_p$ and R_{long} in $Au+Au$@200 GeV collisions

Int.J.Mod.Phys.A 34 (2019) 26, 1950147

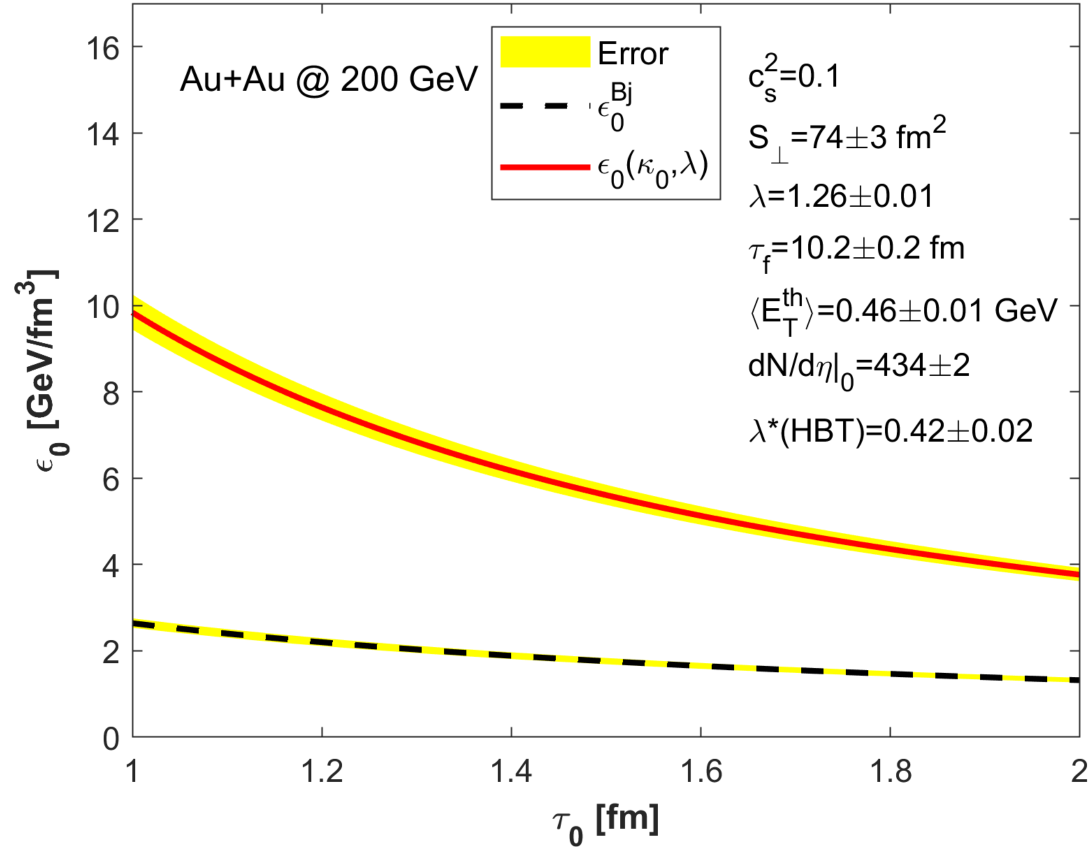




Some earlier success with the CKCJ solution

Significant correction to Bjorken's initial energy density

Int.J.Mod.Phys.A 34 (2019) 26, 1950147



Derivation of the thermal radiation

Double differential spectrum, based on the following integrals:

$$\frac{d^2N}{2\pi p_T dp_T dy} = \frac{g}{(2\pi\hbar)^3} \int H(\tau) \frac{d\Sigma^\mu p_\mu}{\exp\left(\frac{p^\mu u_\mu}{T}\right) - 1}$$

Using the **1+1 dimensional** CKCJ solution: $d\Sigma^\mu = \frac{u^\mu \tau d\tau d\eta_z dr_x dr_y}{\cosh(\Omega - \eta_z)}$

↓

Assuming **homogeneous transverse distribution** of temperature

Using Boltzmann approximation of the integrand

Motivated by earlier results: ***λ* was assumed to be close to 1**

The integral was perfromed by **saddle point approximation**

The result is evaluated at **midrapidity (*y≈0*)**

Analytic formula for the thermal radiation

The new analytic formula, derived from the CKCJ solution:

$$\frac{d^2N}{2\pi p_T dp_T} = \langle N \rangle \frac{2\alpha}{3\pi^{3/2}} \left[\frac{1}{T_{\mathrm{f}}^{\alpha}} - \frac{1}{T_0^{\alpha}}\right]^{-1} p_T^{-\alpha-2} \left[\Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_0}\right) - \Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_{\mathrm{f}}}\right)\right]$$

λ and κ are collapsed into α (typical behaviour of hydro): $\alpha = \frac{2\kappa}{\lambda} - 3$

T_{f}: freeze-out temperature

T_0: initial temperature

$\langle N \rangle$: multiplicity at midrapidity

Fit to experimental data

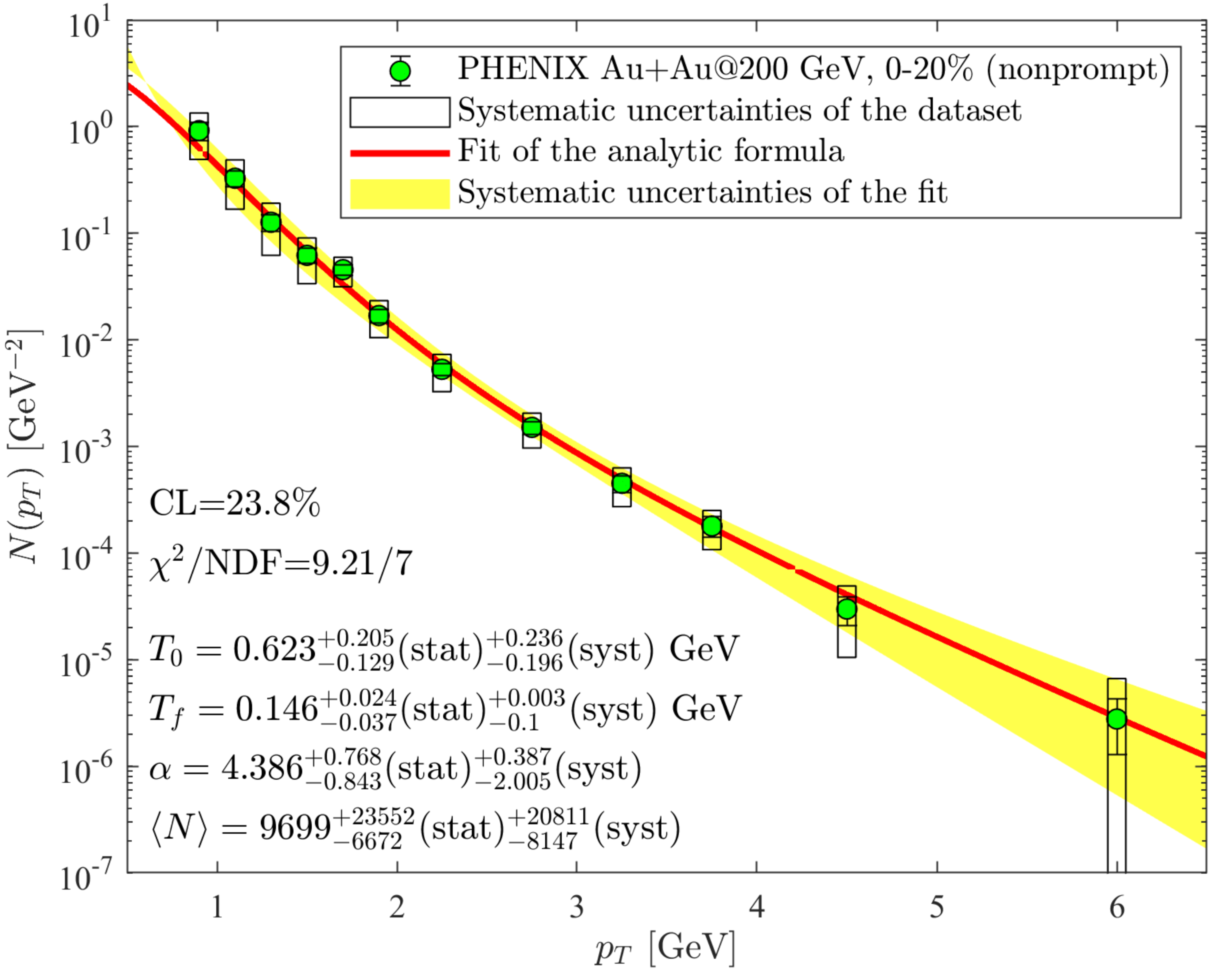
Good confidence level with realistic values of physical parameters

Intermediate p_T regime → ***T*₀ can be determined more precisely**

The analytic formula **scales with *α***

Earler results: λ was determined by $dN/d\eta_p$ fits → ***κ* can be extracted from *α***

Data is from: arXiv:2203.17187



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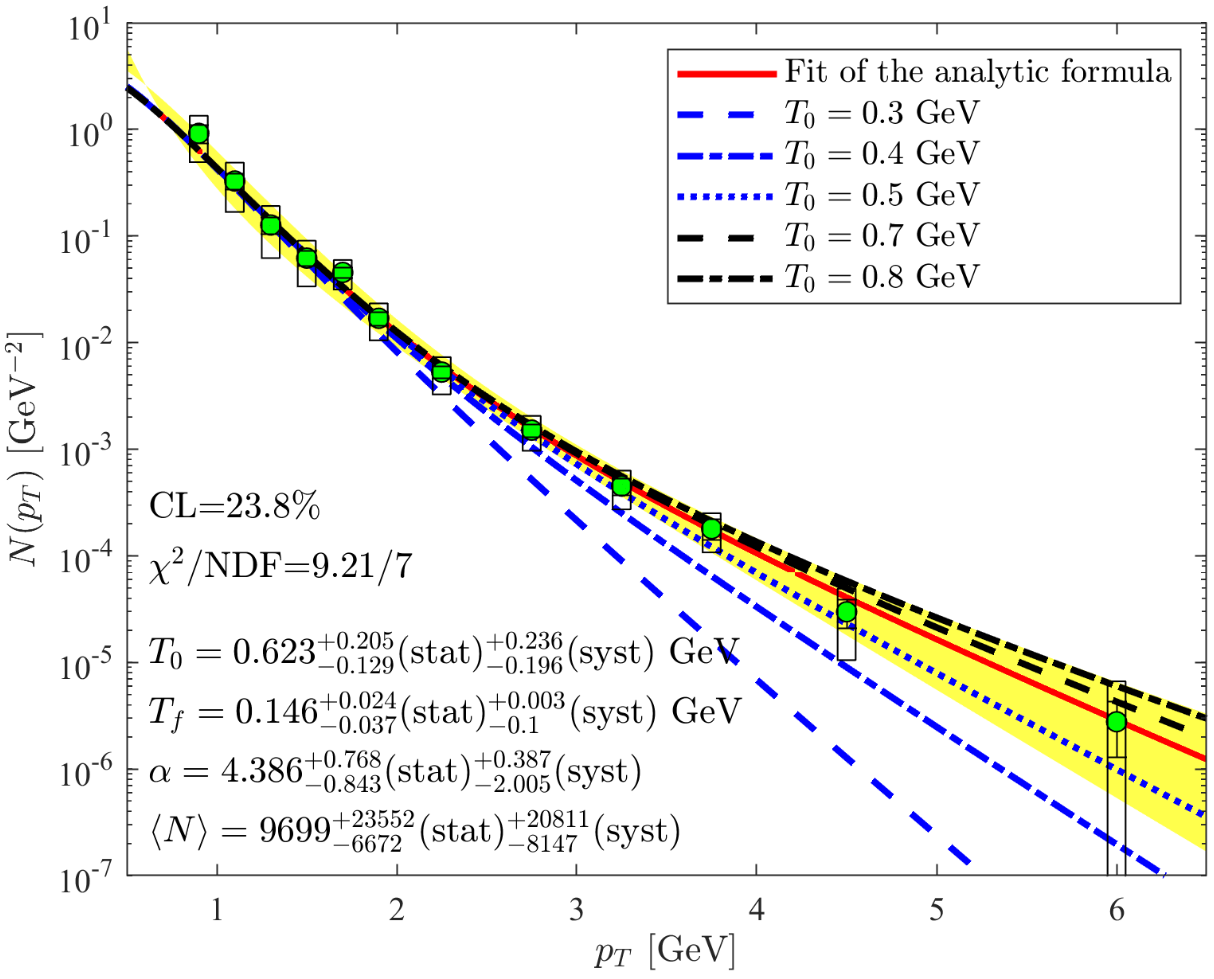

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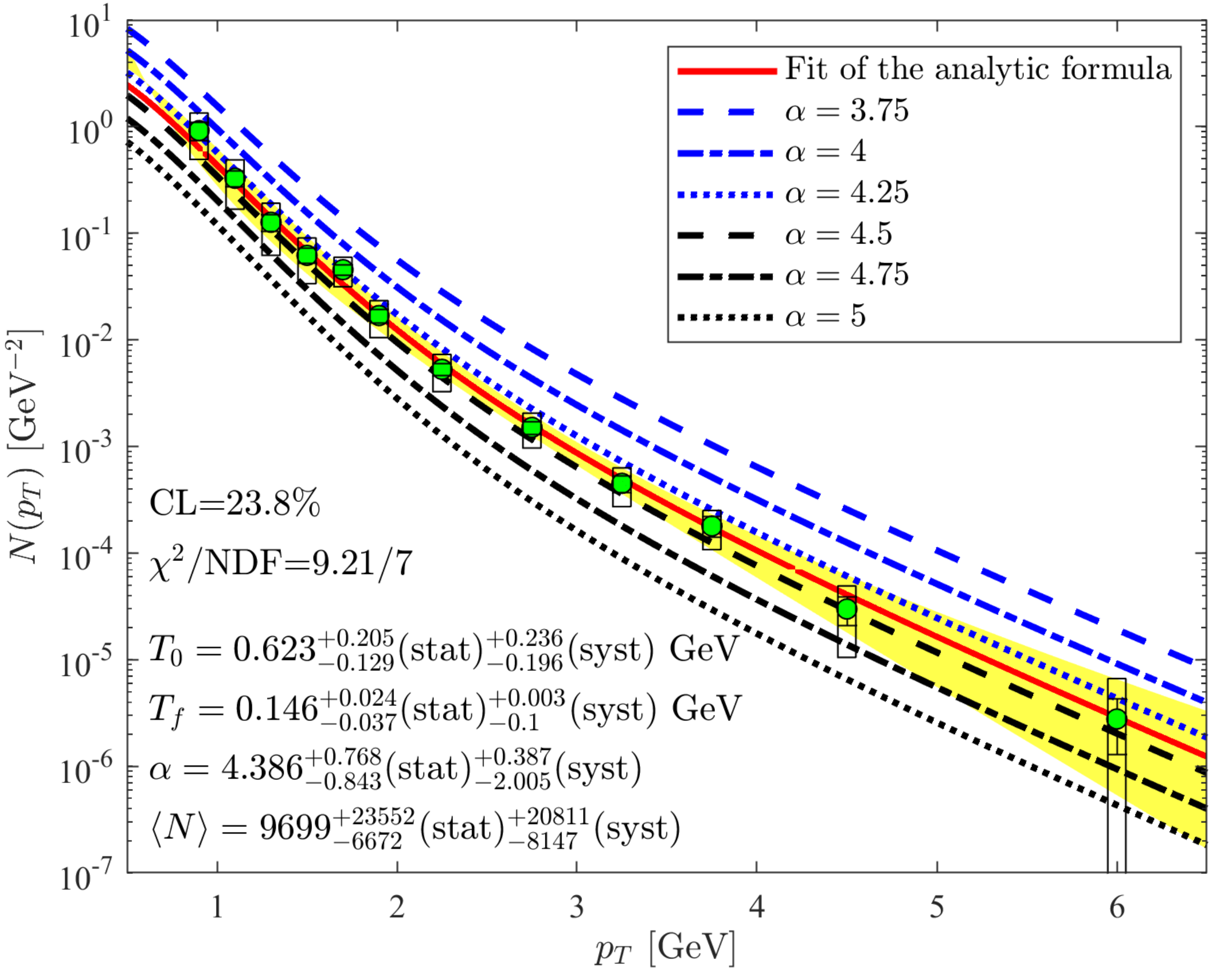

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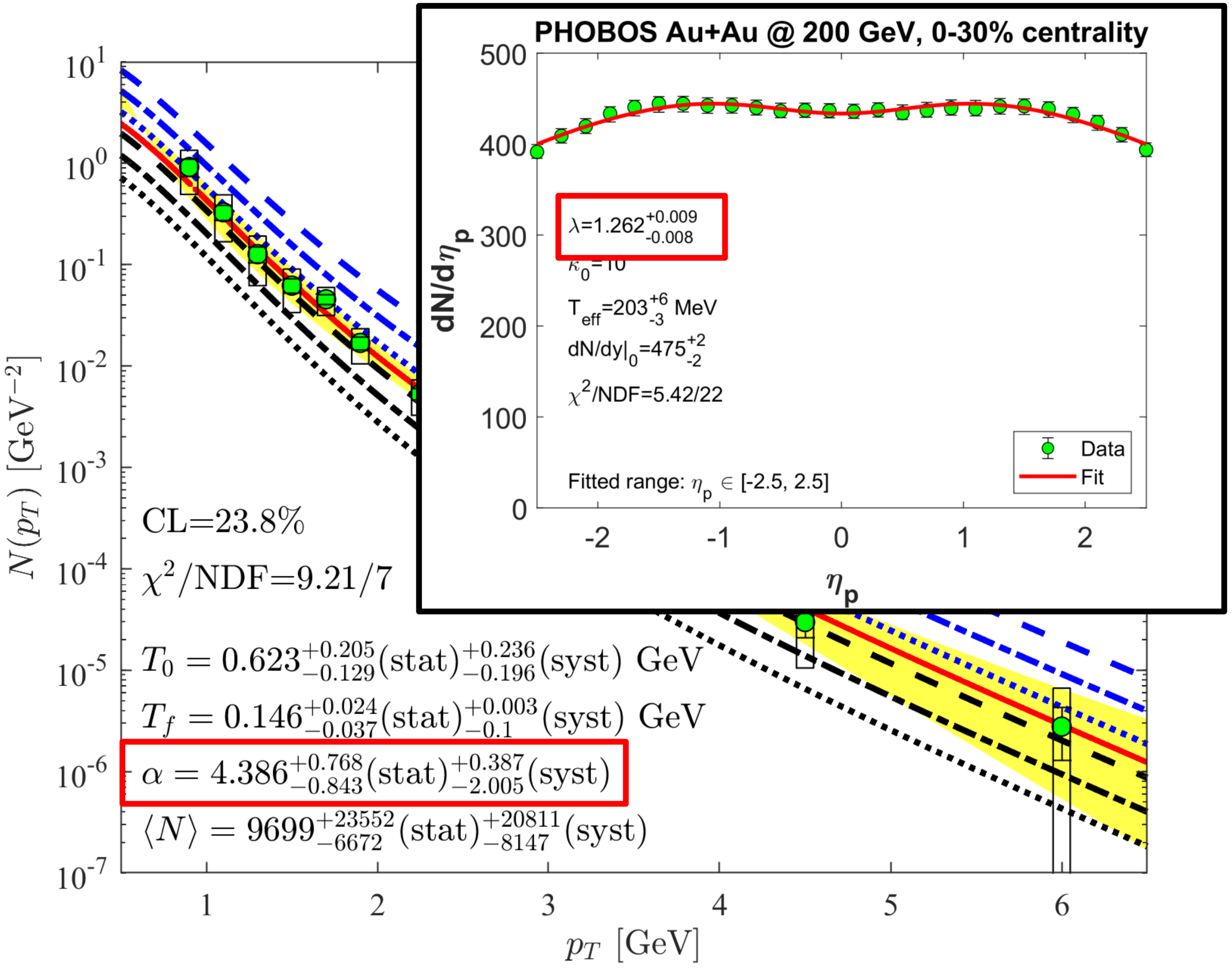

Conclusions

New analytic formula for the thermal radiation based on the CKCJ solution:

- Describes well the nonprompt spectrum of the 0-20% Au+Au@200 GeV dataset
- The new formula lacks of radial flow → **further corrections are justified**
- CKCJ solutions lacks of viscosity → it seems **viscous effects are not necessary** to describe the data

According to my result, the initial temperature is clearly higher than the Hagedorn temperature:

$$T_{\mathrm{H}} \ll T_0 = 0.6^{+0.2}_{-0.1}(\mathrm{stat})^{+0.2}_{-0.2}(\mathrm{syst})\ \mathrm{GeV}$$

My result confirms the earlier conclusion of PHENIX:

The initial temperature of the created medium is too high for hadronic matter.