Evaluation of the thermal photon radiation
from a recent solution of relativistic hydrodynamics

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XVI WORKSHOP ON PARTICLE CORRELATION AND FEMTOSCOPY & IV RESONANCE WORKSHOP

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arXiv:2311.03568

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***

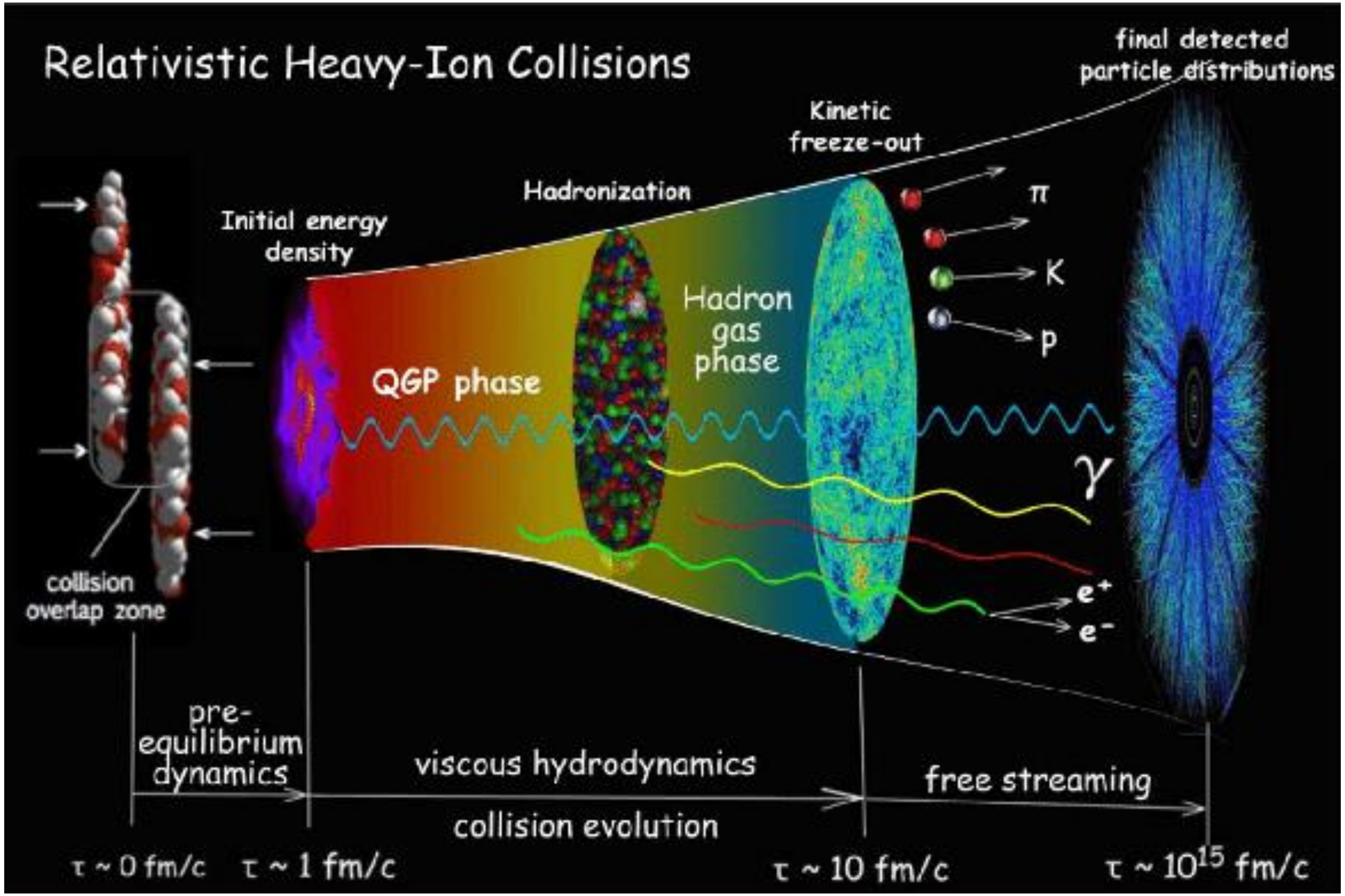
High p_T regime: photons from high scattering processes

Today's presentation:

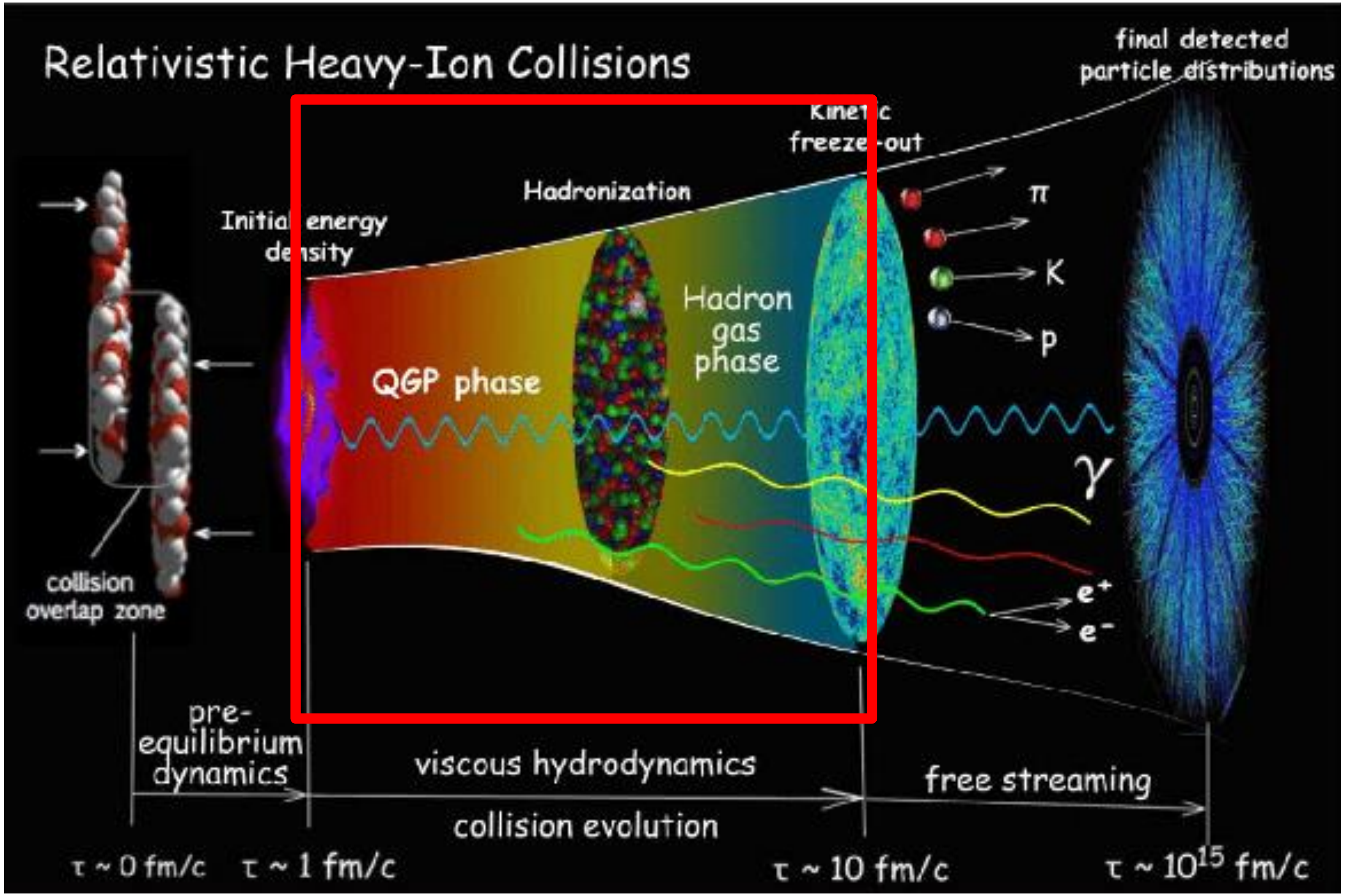
- ***A new analytic formula has been found based on the Csörgő-Kasza-Csanád-Jiang solution*** *Universe* 4 (2018) 6, 69
- ***This formula is compared to PHENIX Au+Au@200 GeV 0-20% dataset*** arXiv:2203.17187

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

The evolution of relativistic heavy-ion collisions



The evolution of relativistic heavy-ion collisions



Period of our interest

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:

$$\eta_x(H) = \Omega(H) - H,$$

$$\Omega(H) = \frac{\lambda}{\sqrt{\lambda - 1}\sqrt{\kappa - \lambda}}\arctan\left(\sqrt{\frac{\kappa - \lambda}{\lambda - 1}}\tanh(H)\right)$$

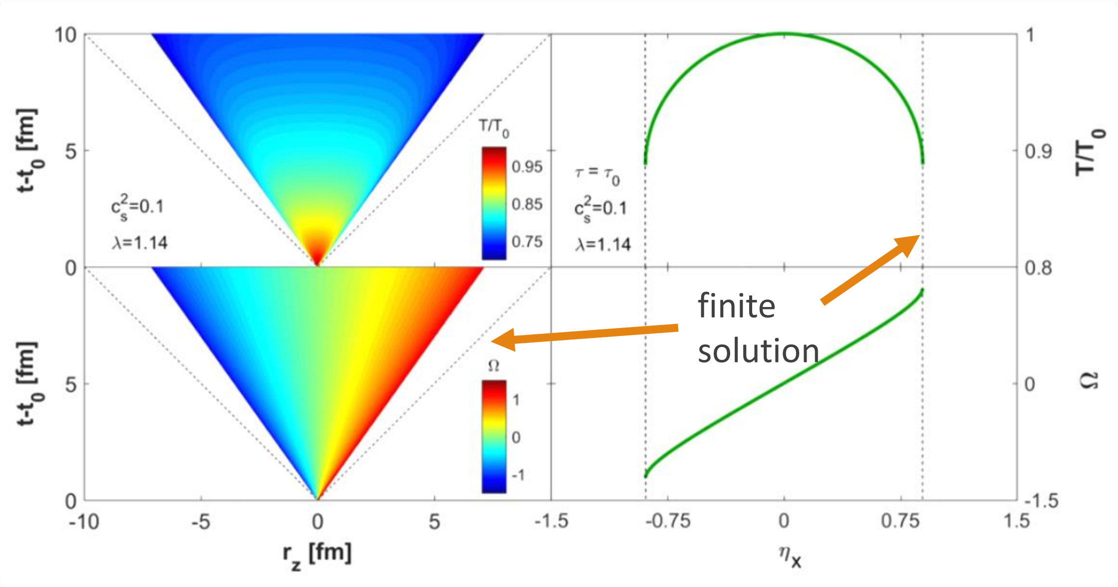
$$\sigma(\tau, H) = \sigma_0 \left(\frac{\tau_0}{\tau}\right)^\lambda \mathcal{V}_\sigma(s)\left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\frac{\lambda}{2}},$$

$$T(\tau, H) = T_0 \left(\frac{\tau_0}{\tau}\right)^{\frac{\lambda}{\kappa}} \mathcal{T}(s)\left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\frac{\lambda}{2\kappa}},$$

$$\mathcal{T}(s) = \frac{1}{\mathcal{V}_\sigma(s)},$$

$$s(\tau, H) = \left(\frac{\tau_0}{\tau}\right)^{\lambda - 1}\sinh(H)\left[1 + \frac{\kappa - 1}{\lambda - 1}\sinh^2(H)\right]^{-\lambda/2}$$

Universe 4 (2018) 6, 69



Equation of State:

$$\varepsilon = \kappa p$$

(with μ=0)

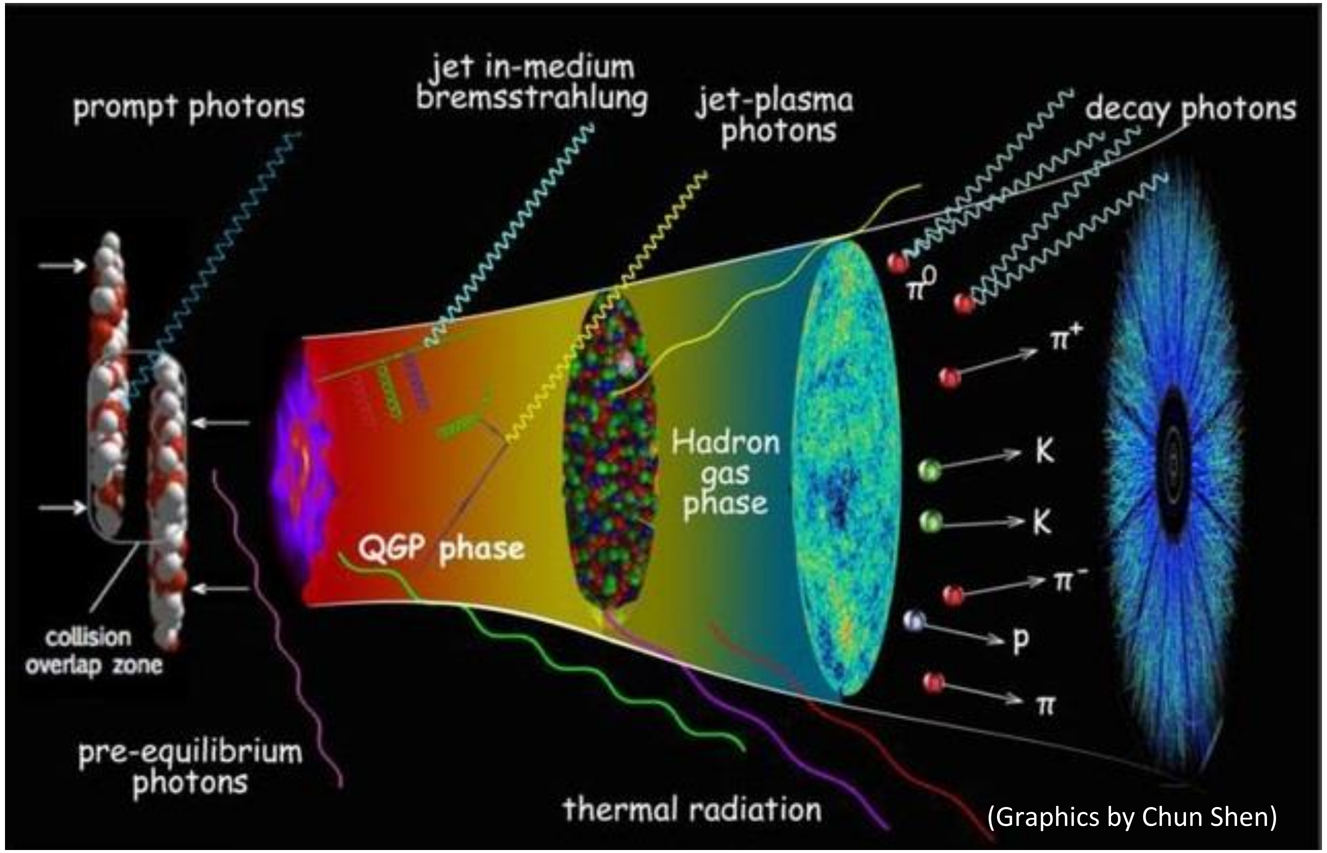
λ: acceleration parameter

↓

accelerating solution
realistic $dN/d\eta_p$

Nonprompt spectrum of direct photons

Focusing on photons:



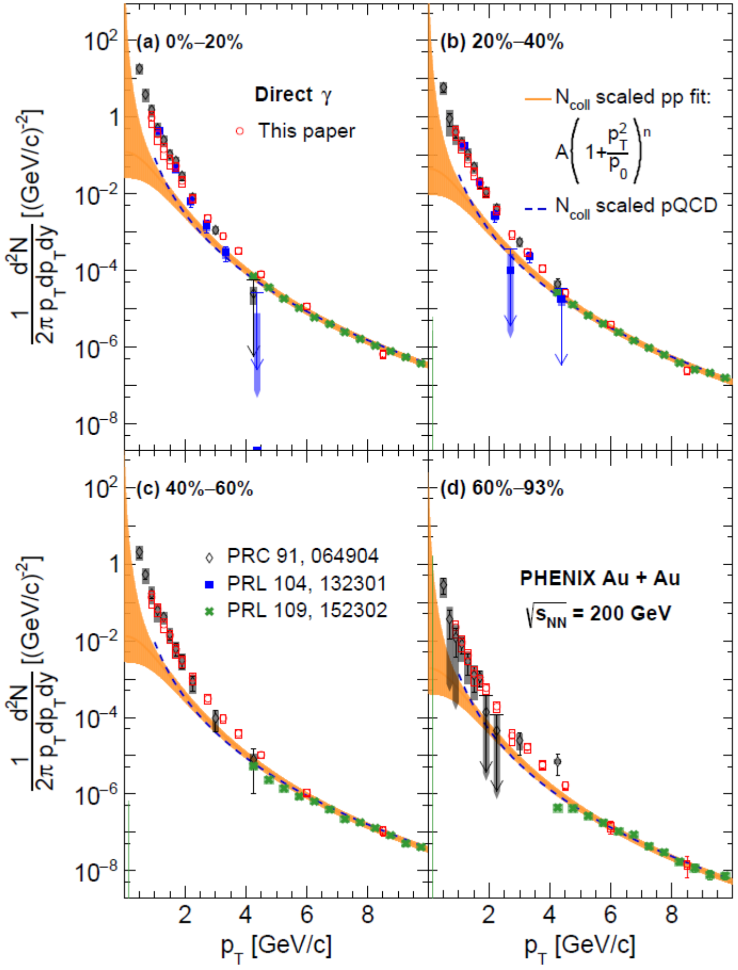
(Graphics by Chun Shen)

Direct photons =
Inclusive photons – Decay photons

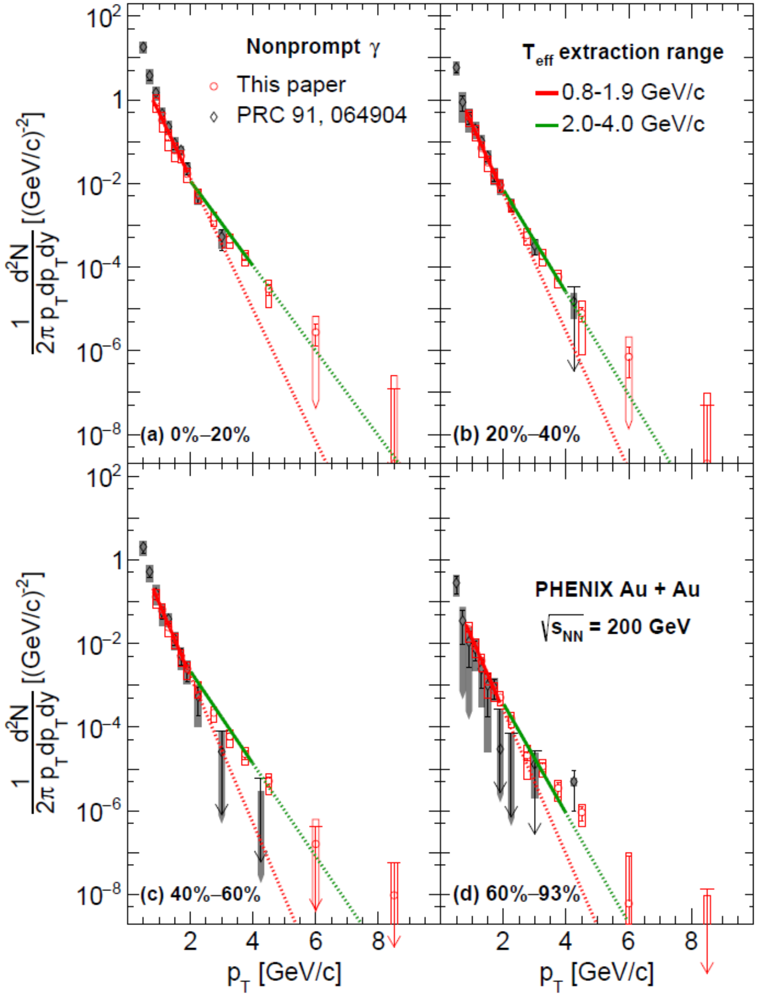
Nonprompt photons ≈ Thermal photons =
Direct photons – Prompt photons

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

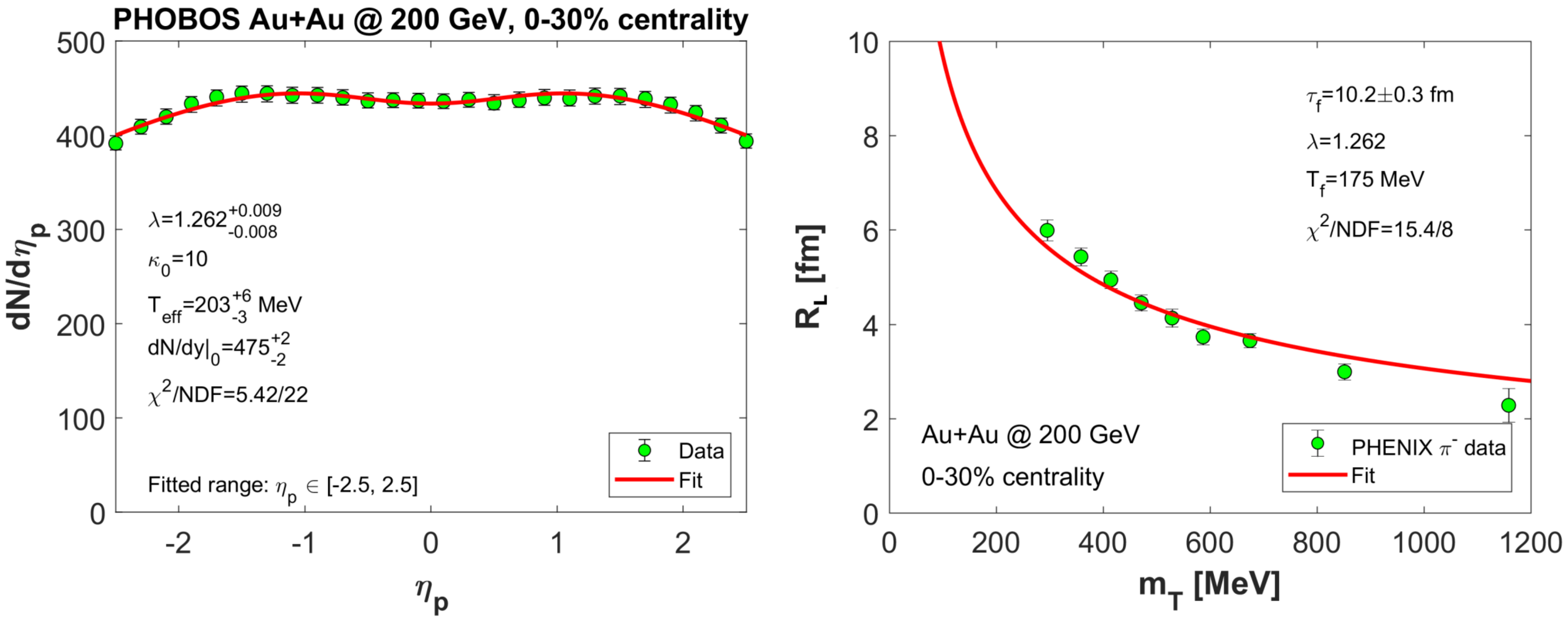


PHENIX: arXiv:2203.17187

Some earlier success with the CKCJ solution

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

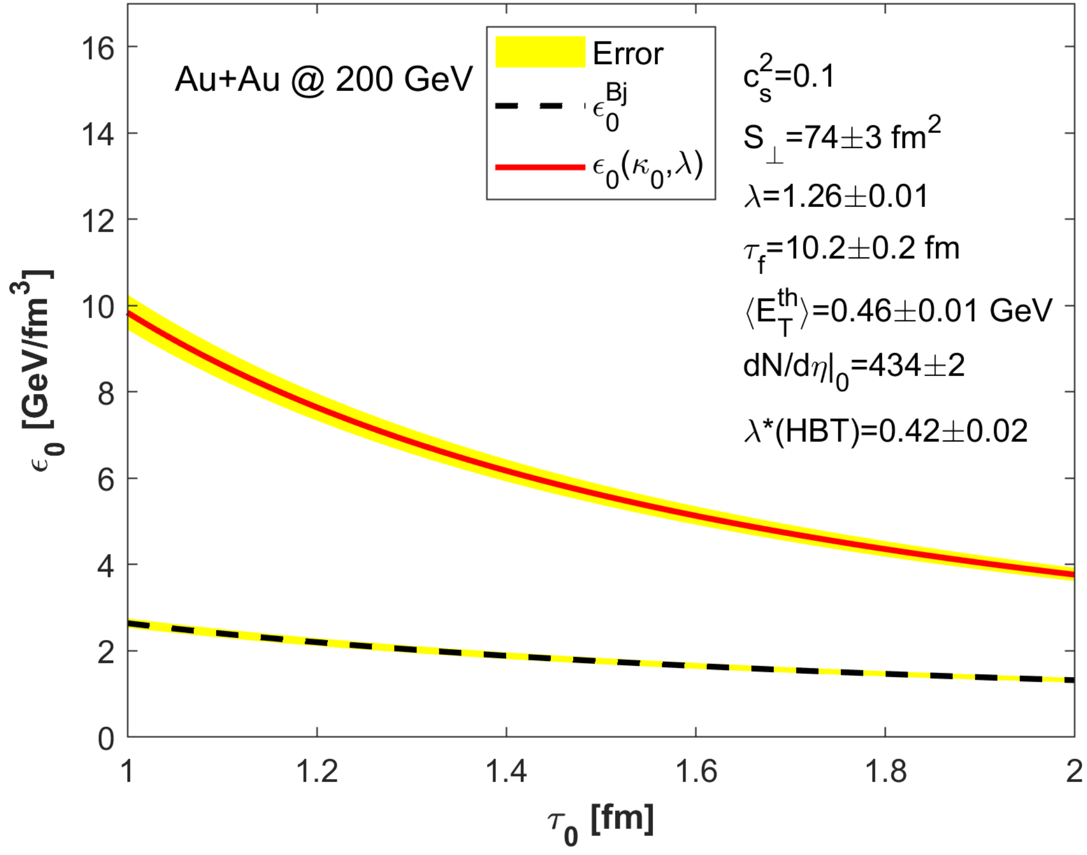
Int.J.Mod.Phys.A 34 (2019) 26, 1950147



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

Source function:

$$S\left(x^{\mu},p^{\mu}\right)d^{4}x=\frac{g}{(2\pi\hbar)^{3}}\frac{H(\tau)p_{\mu}d\Sigma^{\mu}}{\exp\left(\frac{p^{\mu}u_{\mu}}{T}\right)-1}$$

Using the **1+1 dimensional** CKCJ solution:

$$d\Sigma^{\mu}=\frac{u^{\mu}\tau d\tau d\eta_{z}dr_{x}dr_{y}}{\cosh\left(\Omega\left(\eta_{z}\right)-\eta_{z}\right)}$$

Assuming **homogeneous transverse distribution** of temperature

Window function: probability distribution of photon emission

$$H(\tau)=\frac{\Theta\left(\tau-\tau_{\mathrm{f}}\right)-\Theta\left(\tau-\tau_{0}\right)}{\tau_{\mathrm{f}}-\tau_{0}}$$

The new analytic formula for the thermal radiation

The source function is integrated over space and time

- 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*)**

$$\left.\frac{d^2N}{2\pi p_T dp_T dy}\right|_{y=0} = N_0 \frac{2\alpha}{3\pi^{3/2}} \left[\frac{1}{T_\mathrm{f}^\alpha} - \frac{1}{T_0^\alpha}\right]^{-1} p_T^{-\alpha-2} \left[\Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_0}\right) - \Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_\mathrm{f}}\right)\right]$$

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

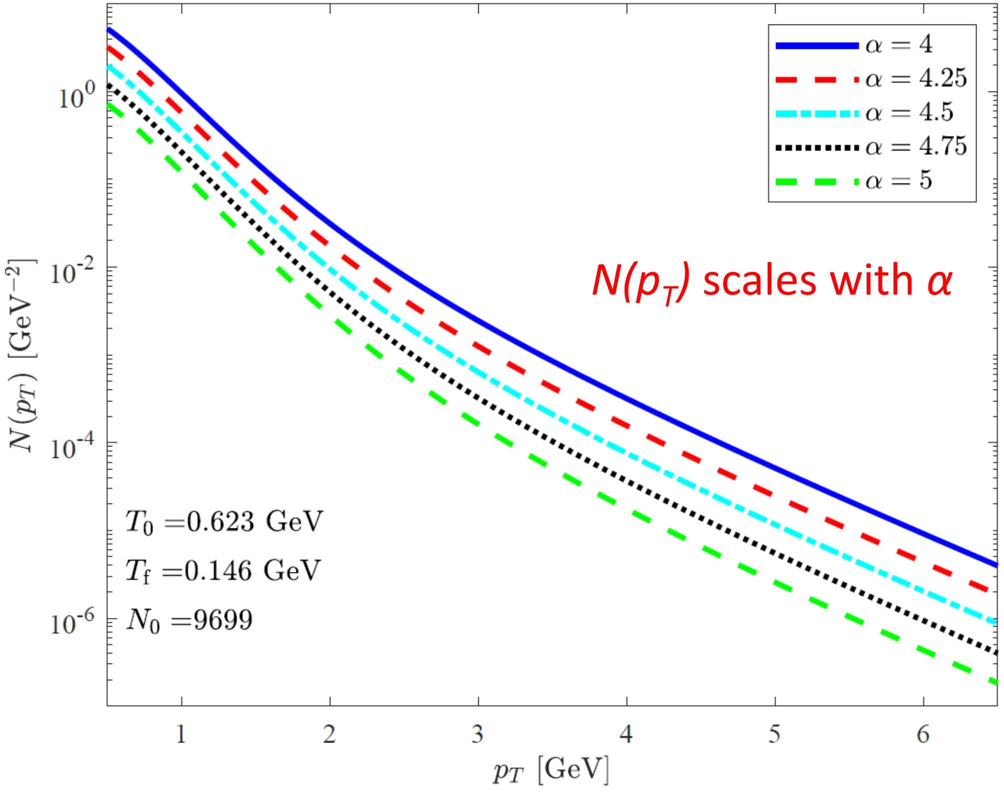
T_f: freeze-out temperature

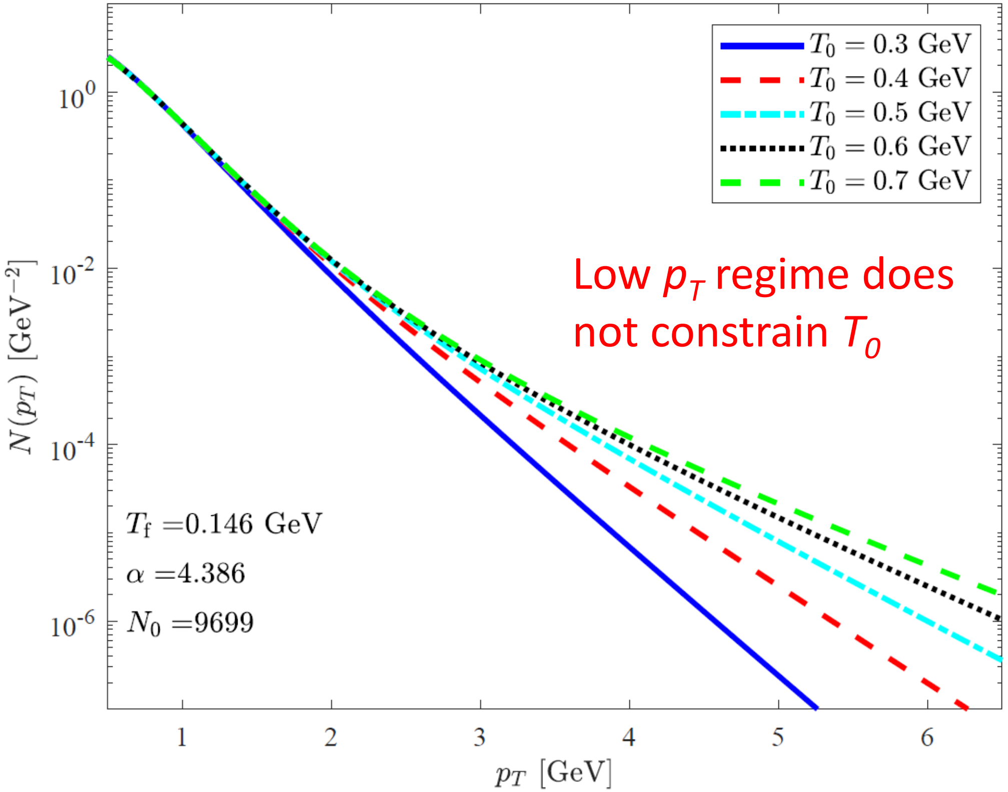
T_0: initial temperature

N_0: multiplicity at midrapidity

The new analytic formula for the thermal radiation

$$\left.\frac{d^2N}{2\pi p_T dp_T dy}\right|_{y=0} = N_0 \frac{2\alpha}{3\pi^{3/2}} \left[\frac{1}{T_f^\alpha} - \frac{1}{T_0^\alpha}\right]^{-1} p_T^{-\alpha-2} \left[\Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_0}\right) - \Gamma\left(\alpha+\frac{7}{2}, \frac{p_T}{T_f}\right)\right]$$





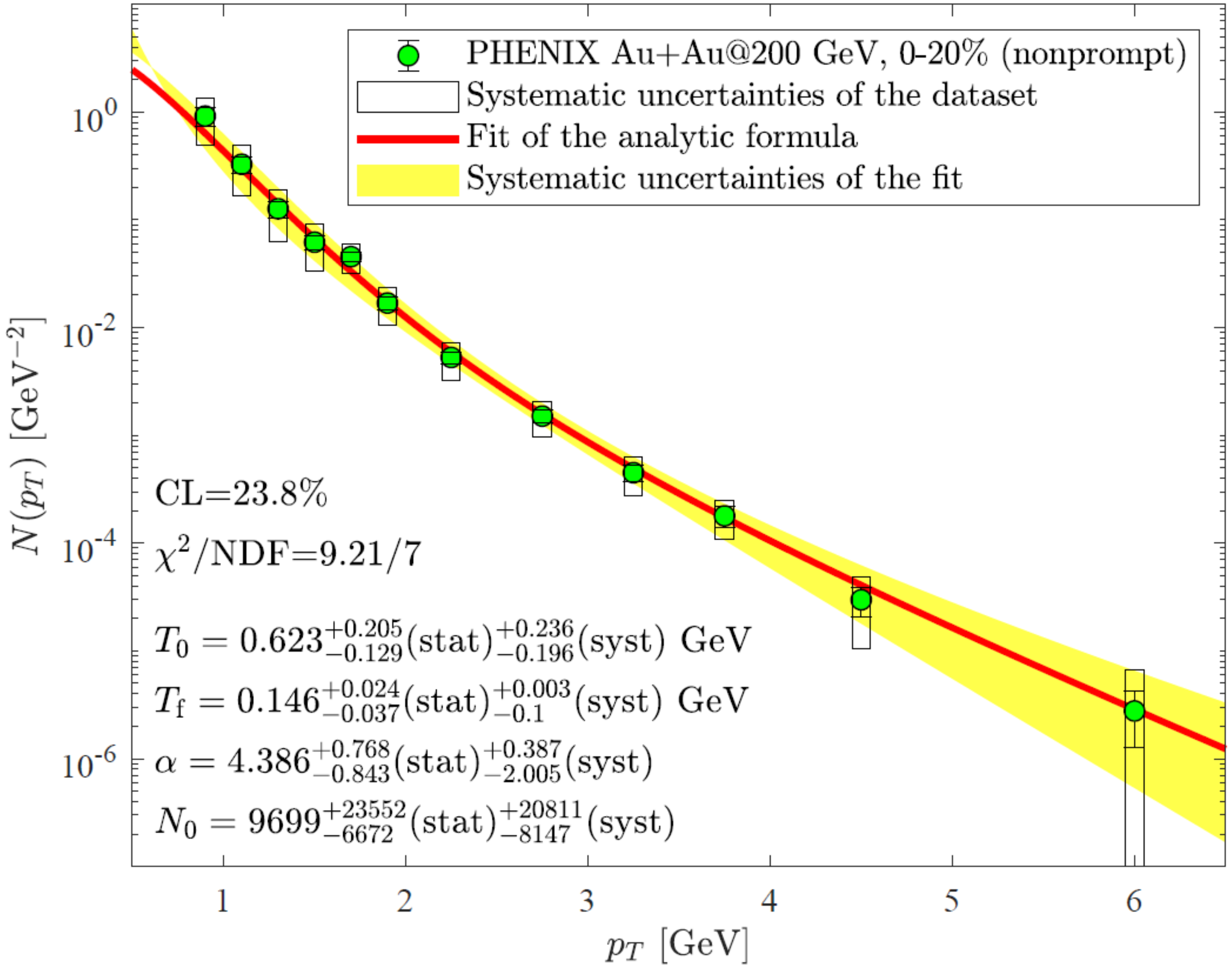
Fit to experimental data

Good confidence level with realistic values of physical parameters

Intermediate p_T regime → ***T_0* can be determined more precisely**

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

Data is from: [arXiv:2203.17187](https://arxiv.org/abs/2203.17187)



Fit to experimental data

Good confidence level with realistic values of physical parameters

Intermediate p_T regime → $\boldsymbol{T_0}$ **can be determined more precisely**

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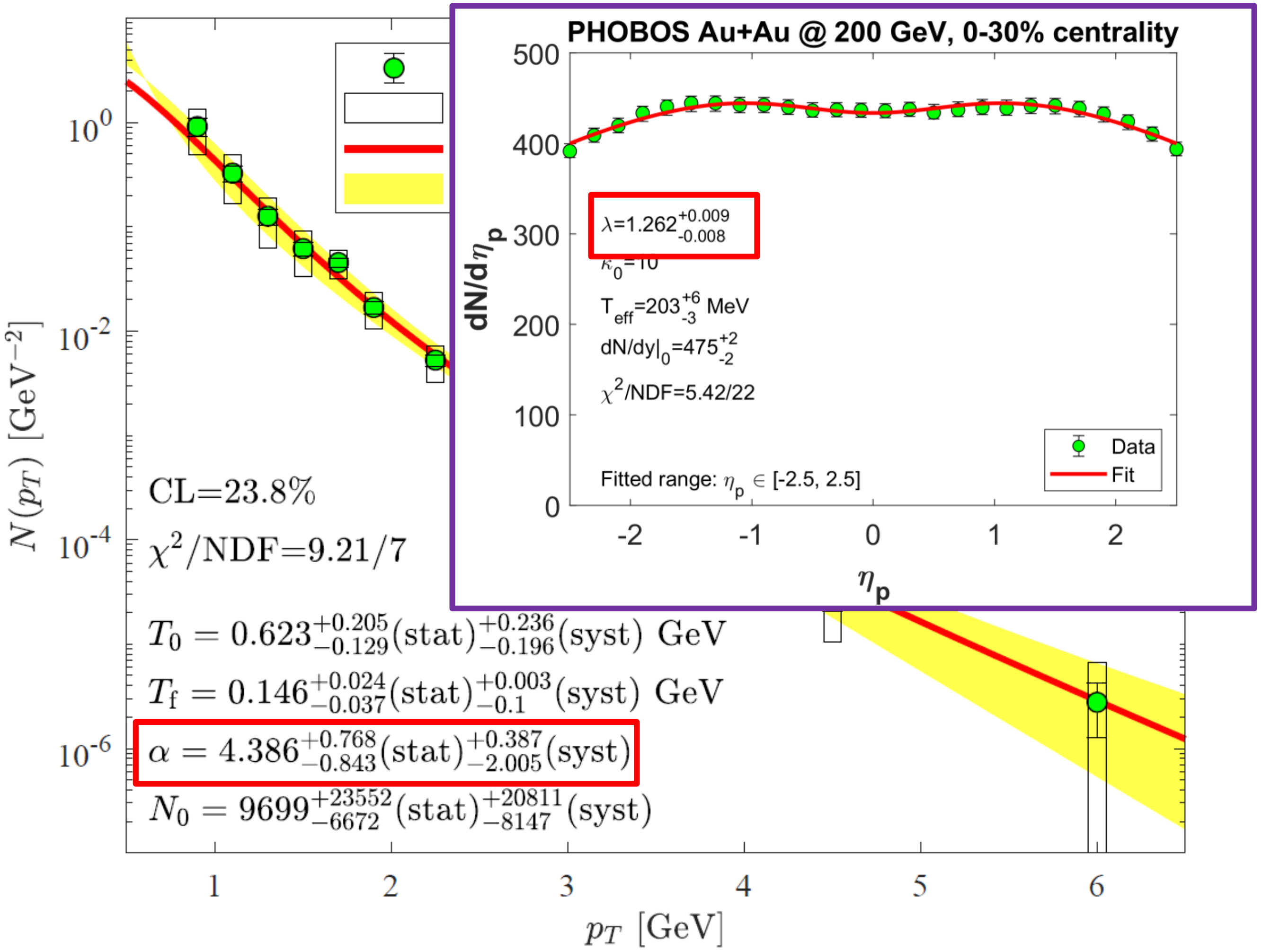

Conclusions

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**
- The new formula lacks of viscous effects → it seems **viscosity are not necessary** to describe the data

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

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

$$0.14\ \mathrm{GeV} < T_{\mathrm{H}} < 0.34\ \mathrm{GeV}$$

Broniowski, Florkowski: Phys. Lett. B 490 (2000), pp. 223–227.
Broniowski, Florkowski, Glozman: Phys. Rev. D 70 (2004), p. 117503.
Cohen, Krejcirik: J. Phys. G 39 (2012), p. 055001.
Cleymans, Worku: Mod. Phys. Lett. A26 (2011), pp. 1197–1209.

My result confirms the earlier conclusion of PHENIX:

At the beginning the temperature of the created medium is too high for hadrons to exist.

PHENIX: Phys. Rev. Lett. 104 (2010), p. 132301.

Thank you for your attention!