

Does the hadronic phase of relativistic nuclear collisions feature a hydrodynamic regime?

Based on: Ronald Scaria, Captain R. Singh and Raghunath Sahoo
[arXiv:2208.14792 \(2022\)](https://arxiv.org/abs/2208.14792)



Ronald Scaria

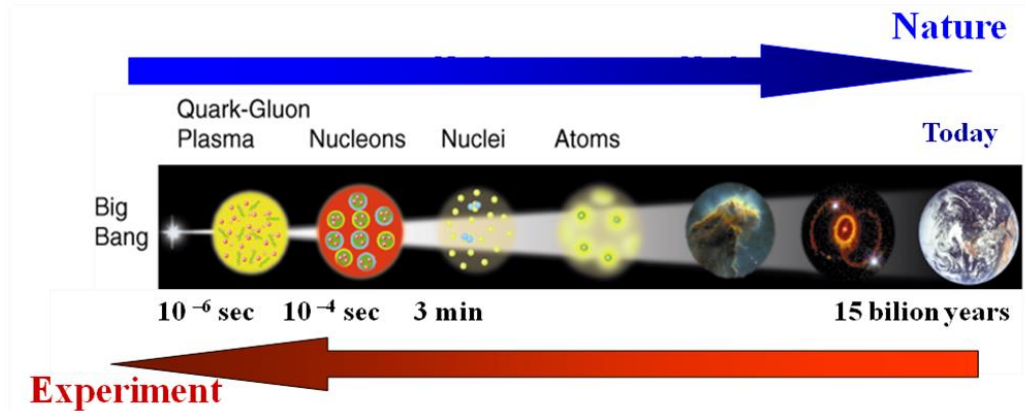
Indian Institute of Technology Indore, India
ICPAQGP 2023

Outline

- Relativistic Heavy Ion Collisions
- Hadronic Phase and Resonances
- Hydrodynamics: The Hadronic Phase question
- Methodology
- Results
- Summary

Relativistic Heavy Ion Collisions

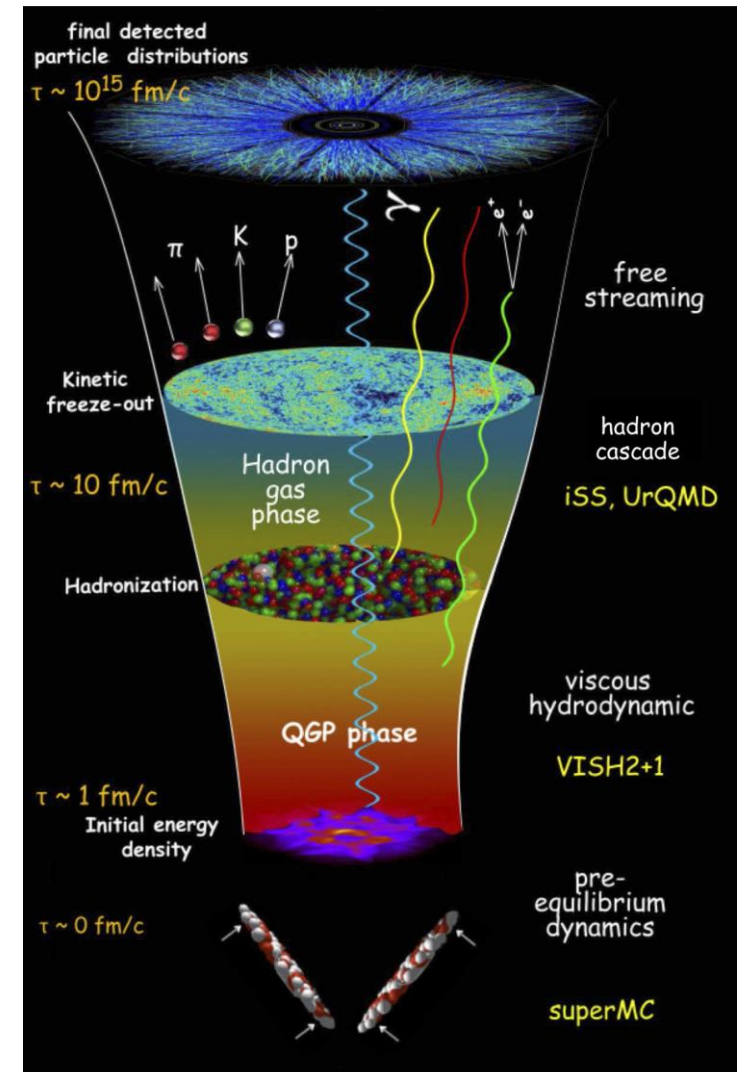
- Pre-Equilibrium Phase
- Quark Gluon Plasma – Thermalized partons
- It is believed that QGP existed in the early universe a few microseconds after the big bang



- Chemical freeze out – Particle production stops
- Hadron Gas phase – Elastic interactions
- Kinetic freeze out – Momentum freeze out

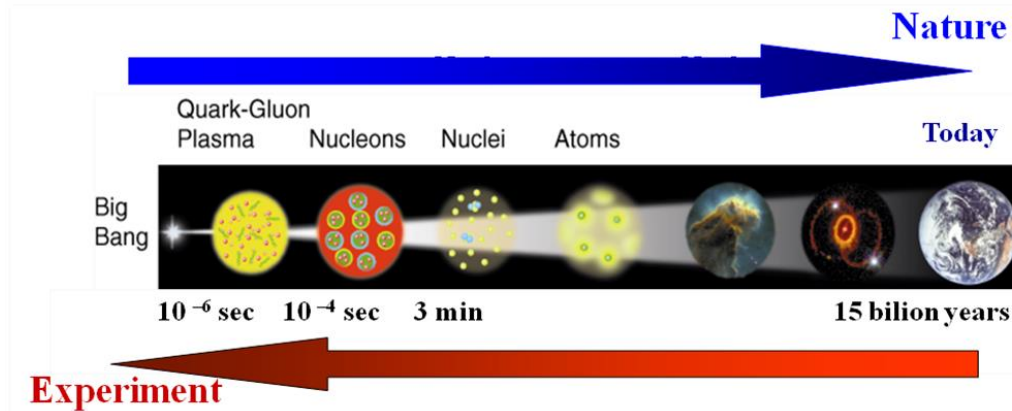
[1] C. Shen et. al., *Comput. Phys. Commun.* 199, 61 (2016)

[2] R. Sahoo, and T. K. Nayak, *Curr. Sci.* 121, 1403 (2021)



Relativistic Heavy Ion Collisions

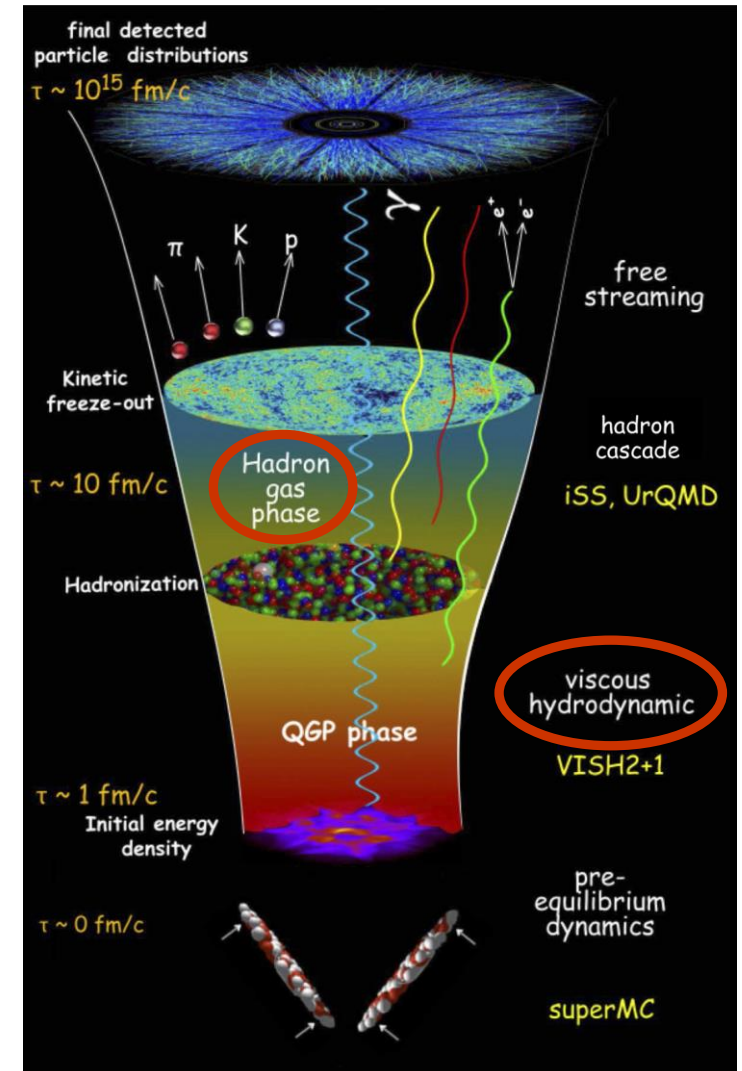
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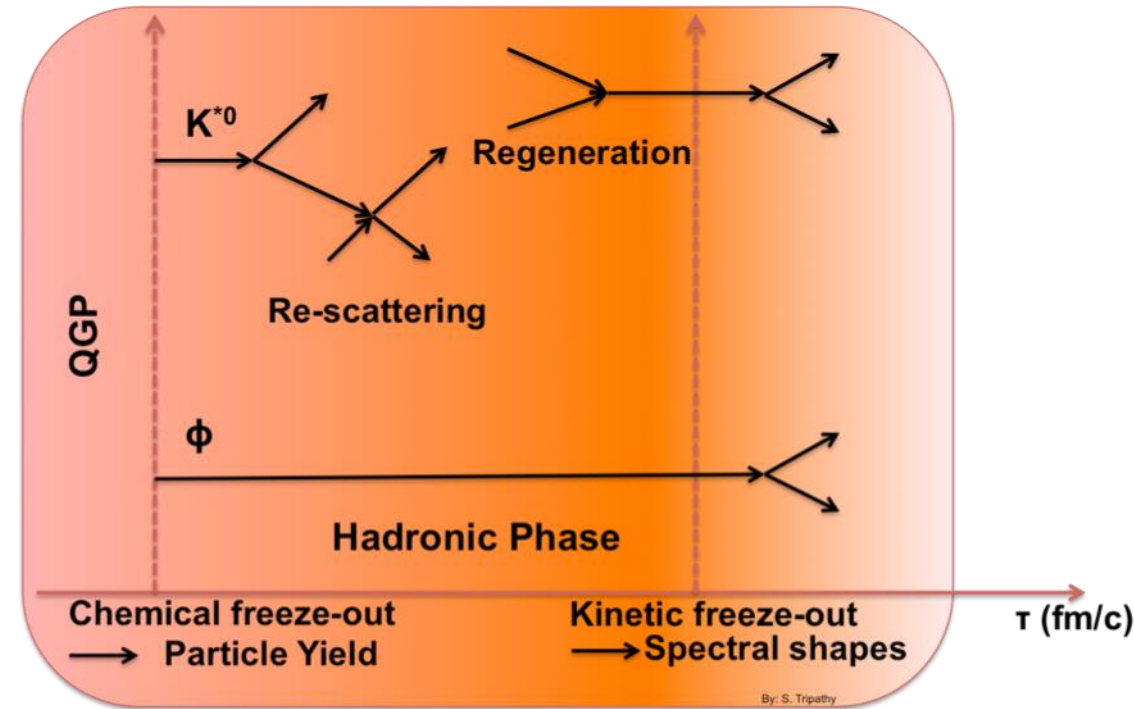
[2] R. Sahoo, and T. K. Nayak, *Curr. Sci.* 121, 1403 (2021)



Hadronic Phase and resonances

- Short-lived resonances are generally used to determine properties of the hadronic phase
- Resonance particles undergo re-scattering and regeneration within the hadronic phase, thus altering their initial yields
- The $K^*(892)^0$ meson has a lifetime of 4.16 fm/c which is comparable with the hadronic phase lifetime
- A simple toy model may be used based on these particle yields to determine the hadronic phase lifetime

$$[K^*/K]_{kin} = [K^*/K]_{chemical} \exp(-\Delta\tau/\tau_l)$$

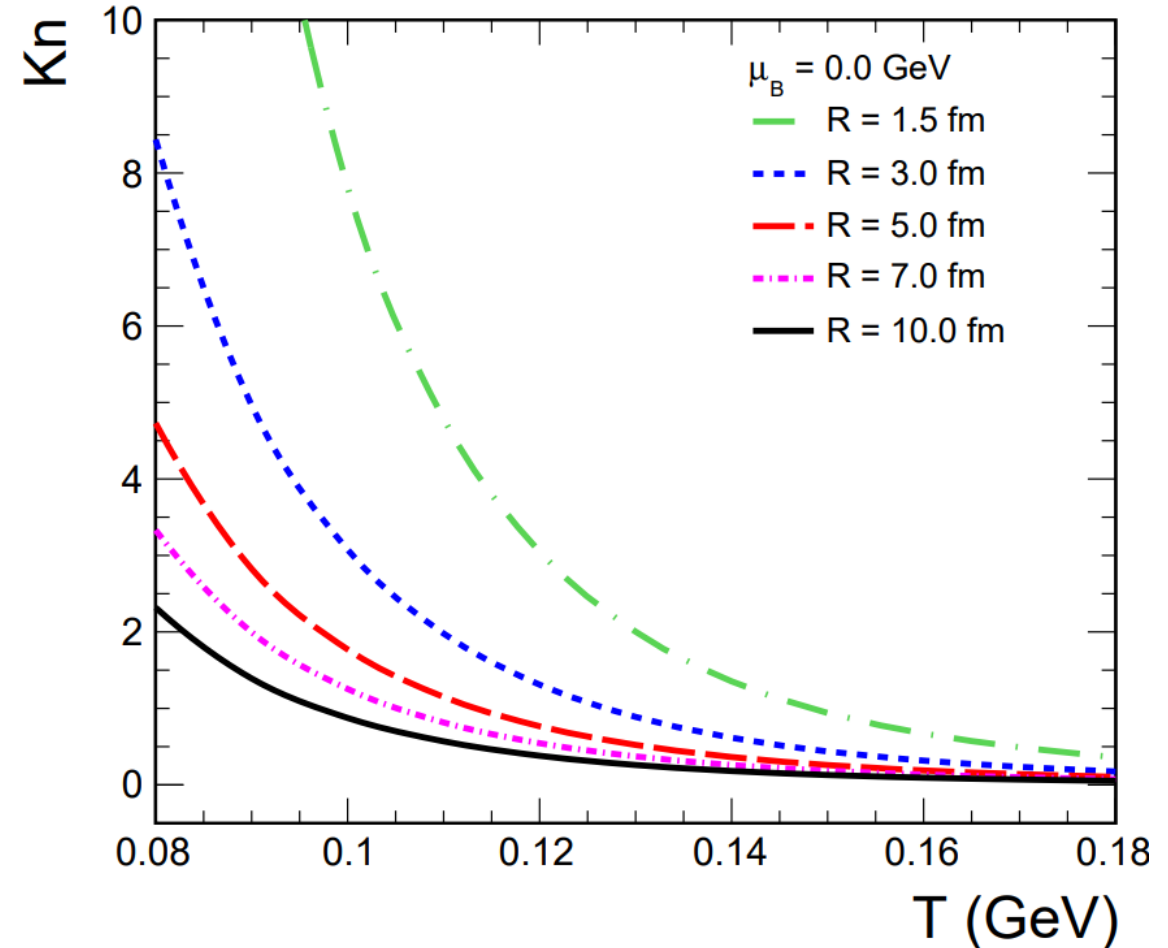


[1] D.Sahu et. al., Phys. Rev. C 101, 014902 (2020)

Hydrodynamics: The Hadronic Phase question

- Knudsen number can be used as a measure of the degree of thermalization in a medium over different system sizes
- $Kn \ll 1$: The system is thermalized, and hydrodynamics is applicable
- $Kn = \lambda/L$; λ is mean free path
- Kn decreases - the system becomes more thermalized
- Increase in number density decreases λ , which is reflected in Kn

[1] R. Scaria et.al, arXiv:2201.08096 (2022)



Temperature Evolution

- Initial yields of all hadrons with mass < 2.25 GeV is determined from the EVHRG model at critical temperature, $T_c = 0.156$ GeV
- Massless case:**

$$\frac{dT}{d\tau} = -\frac{T}{3\tau} + \frac{\phi}{12aT^3\tau}$$

$$\frac{d\phi}{d\tau} = -\sigma bT^3\phi - \frac{1}{2} \left(\frac{1}{\tau} - 5 \frac{1}{T} \frac{dT}{d\tau} \right) + \frac{8aT^4}{9\tau}$$

- Massive case:**

$$\frac{dT}{d\tau} = -\frac{c_s^2 T}{\tau} + \frac{\phi c_s^4}{n\tau(c_s^2 + 1)}$$

$$\frac{d\phi}{d\tau} = -\frac{\phi}{\tau_\phi} - \frac{\phi}{2} \left[\frac{1}{\tau} - \frac{T(c_s^2 + 1)}{m^2 + 6(c_s^2 + 1)T^2} \left\{ 12 + \frac{6}{c_s^2} + \frac{m^2}{T^2(c_s^2 + 1)} \left(4 + \frac{1}{c_s^2} \right) \right\} \frac{dT}{d\tau} \right] + \frac{4}{3\tau} \frac{T^3(c_s^2 + 1)^2 n}{m^2 + 6(c_s^2 + 1)T^2}$$

$$\phi = 0 \quad \text{Perfect fluid (PF)}$$

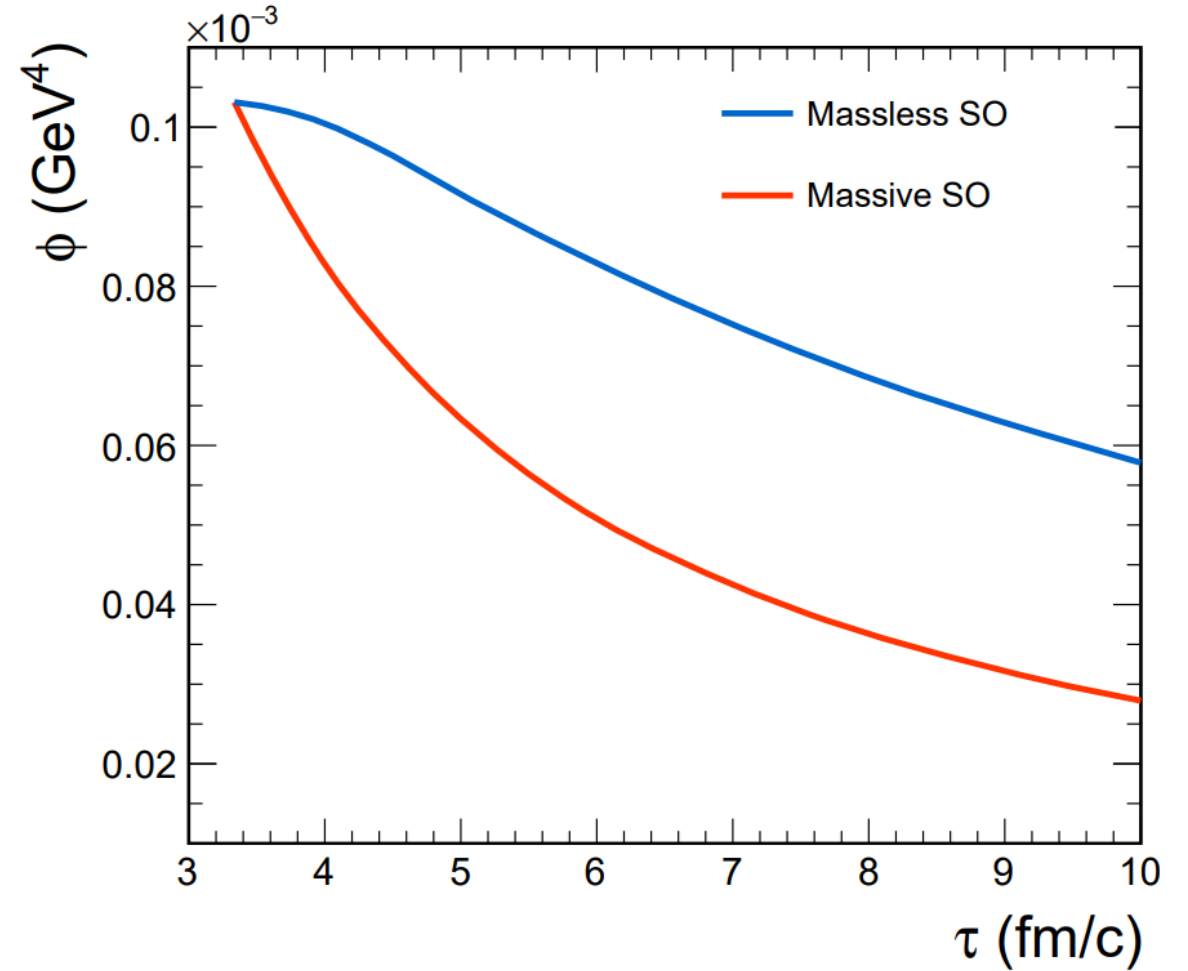
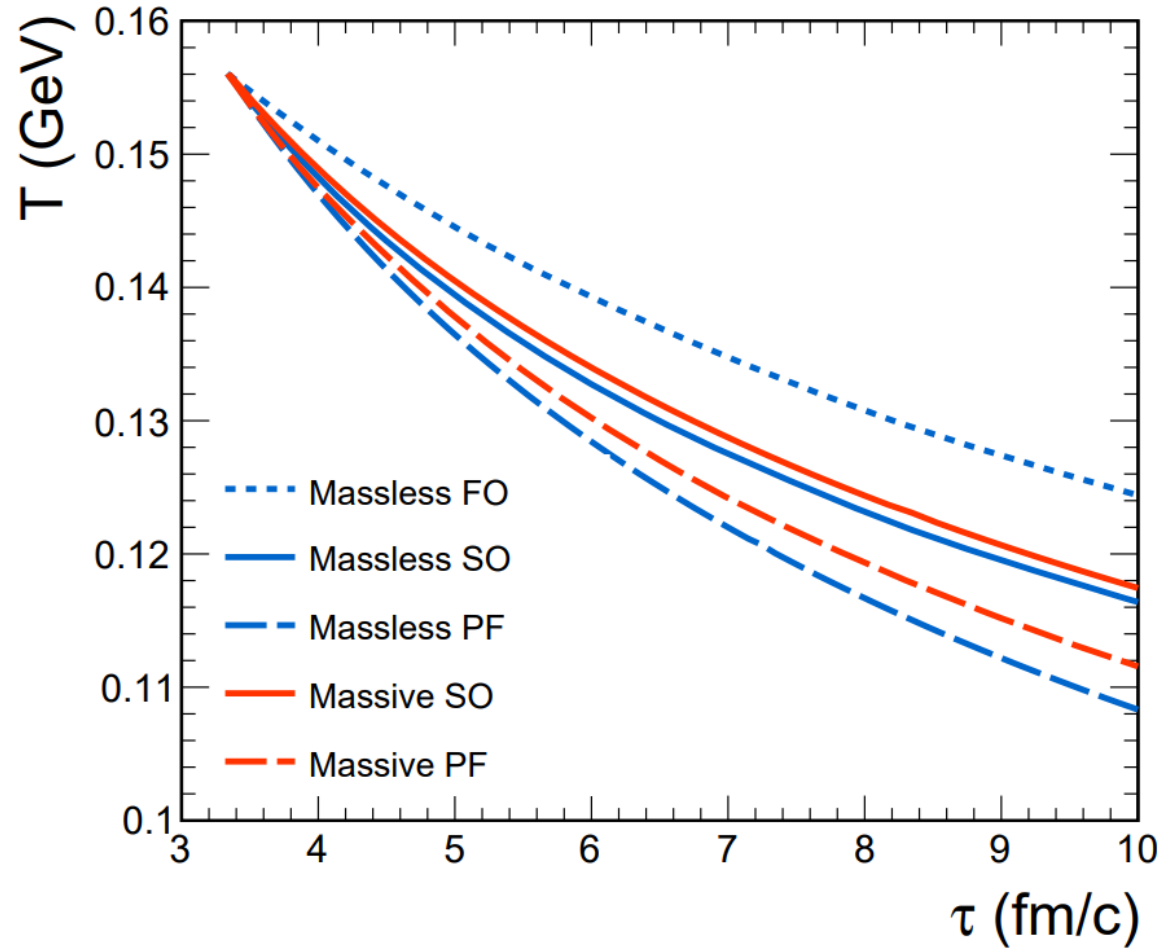
$$\phi = \frac{4}{3} \frac{\eta}{\tau} \quad \text{First order (FO)}$$

$$\frac{d\phi}{d\tau} = -\frac{\phi}{\tau_\phi} - \frac{\phi}{2} \left[\frac{1}{\tau} + \frac{1}{\beta_2} T \frac{d}{d\tau} \left(\frac{\beta_2}{T} \right) \right] + \frac{2}{3} \frac{1}{\beta_2 \tau} \quad \text{Second order (SO)}$$

[1] A. Muronga, Phys. Rev. C 69, 034903 (2004)

[2] W. Israel, Ann. Phys. (N.Y.) 100, 310 (1976)

Temperature Evolution



Resonance Yield Estimation

- Rescattering and Regeneration effects are included by using a modified kinetic formation model

$$N_f(\tau_f) = \varepsilon(\tau_f)\lambda_D(\tau_f)[N_i(\tau_i) + N_\pi N_K \times \int_{\tau_i}^{\tau_f} \Gamma_F[V(\tau)\varepsilon(\tau)\lambda_D(\tau)]^{-1}d\tau]$$

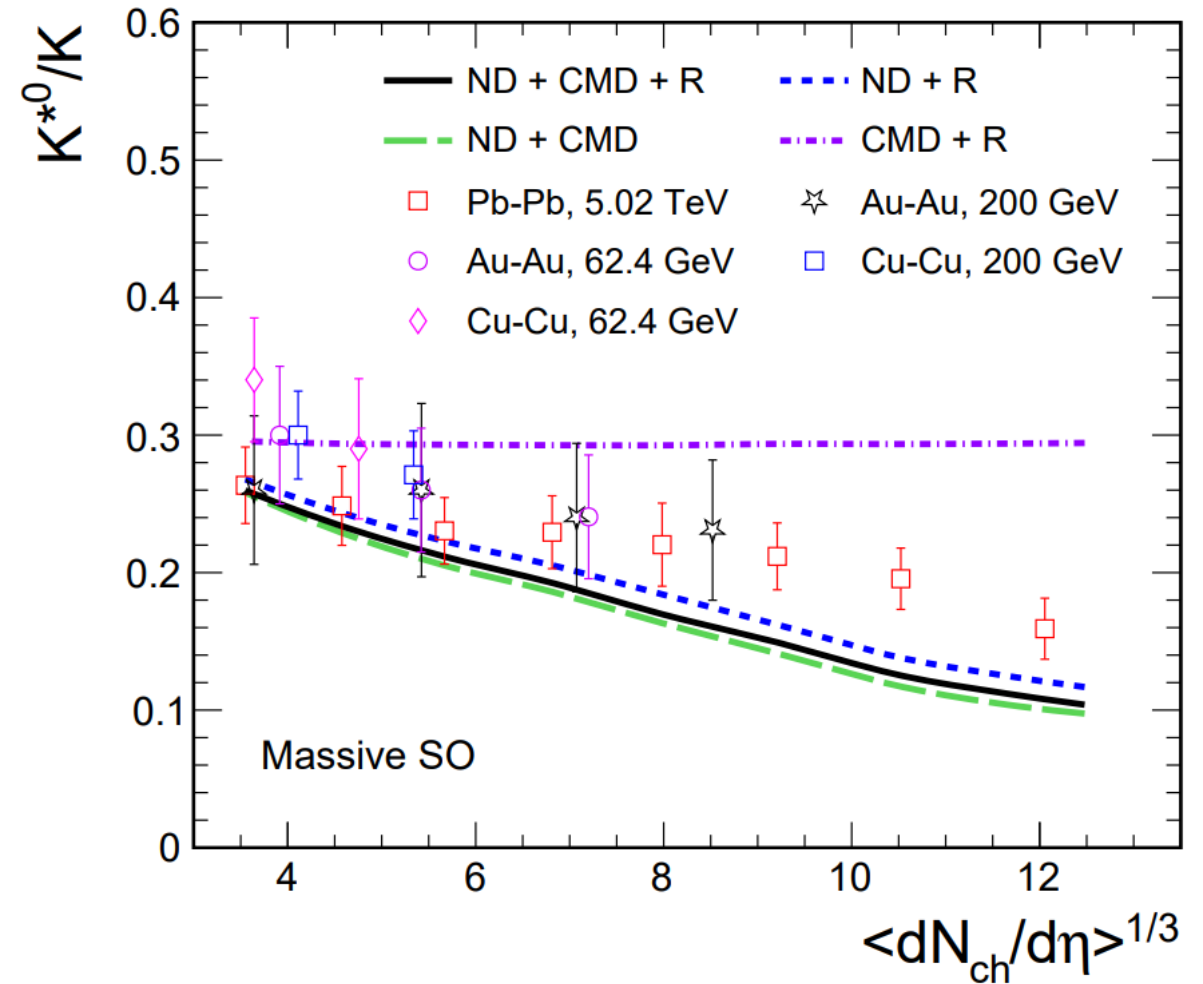
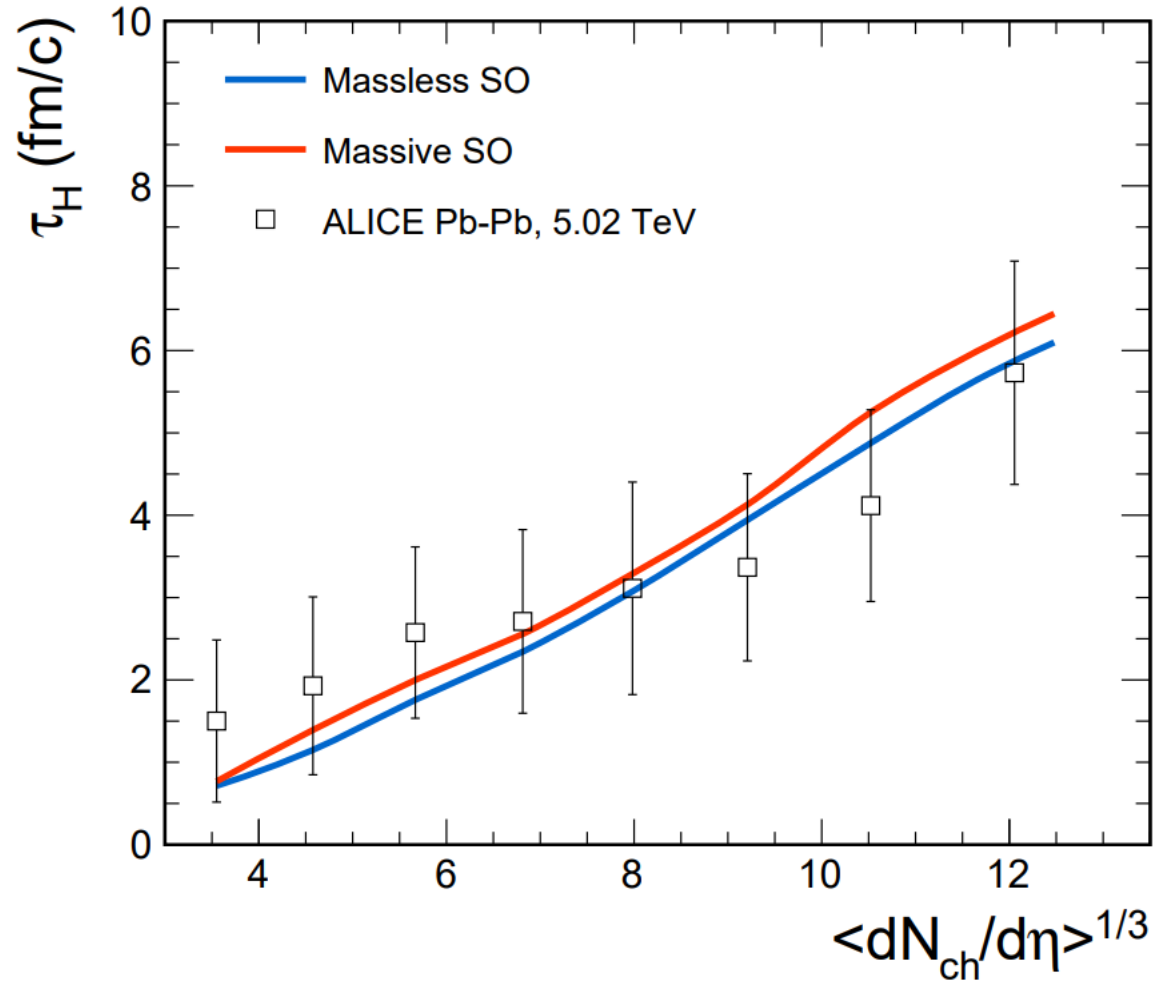
- $\lambda_D(\tau) = \exp(-\frac{\tau-\tau_i}{\tau_l})$ gives the natural decay contribution
- $\varepsilon(\tau) = \exp(-\int_{\tau_i}^{\tau} \Gamma_D N_{co} V(\tau)^{-1}d\tau)$ gives re-scattering due to co-moving hadrons
- Γ_D and Γ_F denotes the rate of co-mover induced decay and regeneration interactions, respectively:

$$\Gamma_D = \langle \sigma_{co} v_{rel} \rangle_{K^*,co}$$

$$\Gamma_F = \langle \sigma_{reg} v_{rel} \rangle_{K,\pi}$$

[1] R. L. Thews, Nucl. Phys. A 702, 341 (2002)

Results



Summary

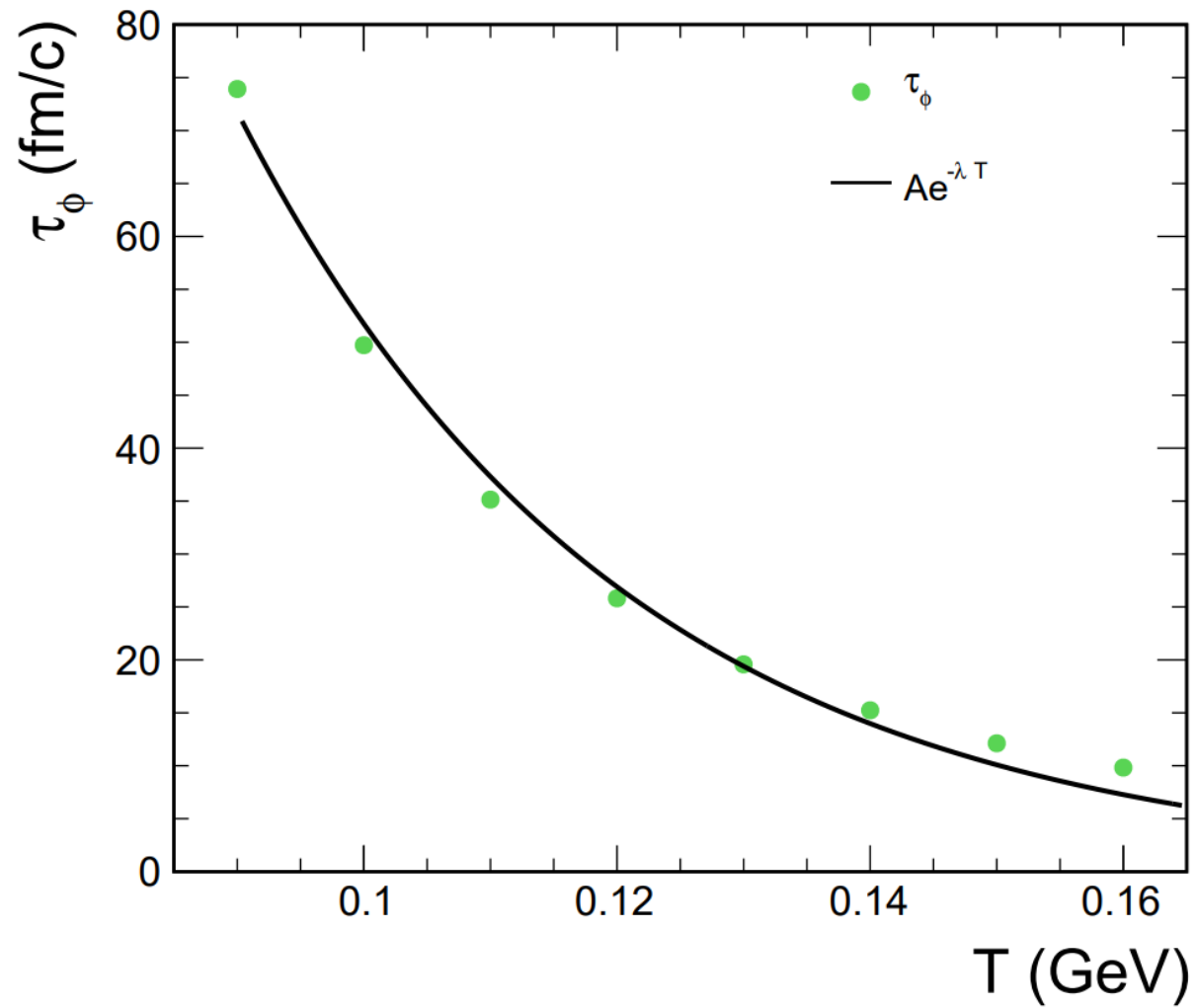
- A hydrodynamical model with both massive and massless particles has been applied for the evolution of the hadronic phase.
- A model has been introduced within the hydrodynamic framework to incorporate the re-scattering and regeneration effects of resonances.
- The effect of natural decay, co-mover-induced decay and regeneration are explored individually.
- The model results show a good agreement with experimental results.
- Although natural decay is the main driver determining the yield of the hadronic phase, the effect of co-mover induced decay and regeneration might be non-trivial at high multiplicities.

Thank You

For the attention

Backup Slides

Backup: Relaxation Time



Backup: η/s of hadron gas

