Monte Carlo Simulation Studies of the Elastic Energy Loss of High-energy Gluons and Light Quarks in a Strongly Interacting Medium

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ABSTRACT

A strong suppression of heavy-flavor hadrons has been seen in ultrarelativistic heavy ion collisions at BNL-RHIC and CERN-LHC. This surprising result has challenged the view of gluon radiation dominating over elastic 2-to-2 processes as the cause of parton energy loss in a quark-gluon plasma. To study the effectiveness of elastic collisions as the suppression mechanism in detail, we have developed a sophisticated Monte Carlo simulation describing the non-eikonal propagation of high-energy gluons and light quarks interacting with the quarks and gluons from the expanding QCD medium. The partonic collision rates are computed in leading-order perturbative QCD, while four, increasingly detailed models are utilized for the QCD medium.
We compare our results with the neutral pion suppression observed in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC and charged hadron suppression in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions in the LHC. We find that a model with purely incoherent collisions is not supported by the experimental data. In addition, initial state density fluctuations are not observed to have a significant effect on the elastic energy loss.

1 The Monte Carlo simulation

- Scattering rate for a scattering process X:

$$\Gamma_X = \frac{1}{2E_1}\int \frac{d^3p_2}{(2\pi)^3 2E_2} f(p_2,T) \int \frac{d^3p_3}{(2\pi)^3 2E_3} \int \frac{d^3p_4}{(2\pi)^3 2E_4} \cdot (2\pi)^4 \delta^{(4)}(p_1+p_2-p_3-p_4)\,|M|^2_X. \quad (1)$$

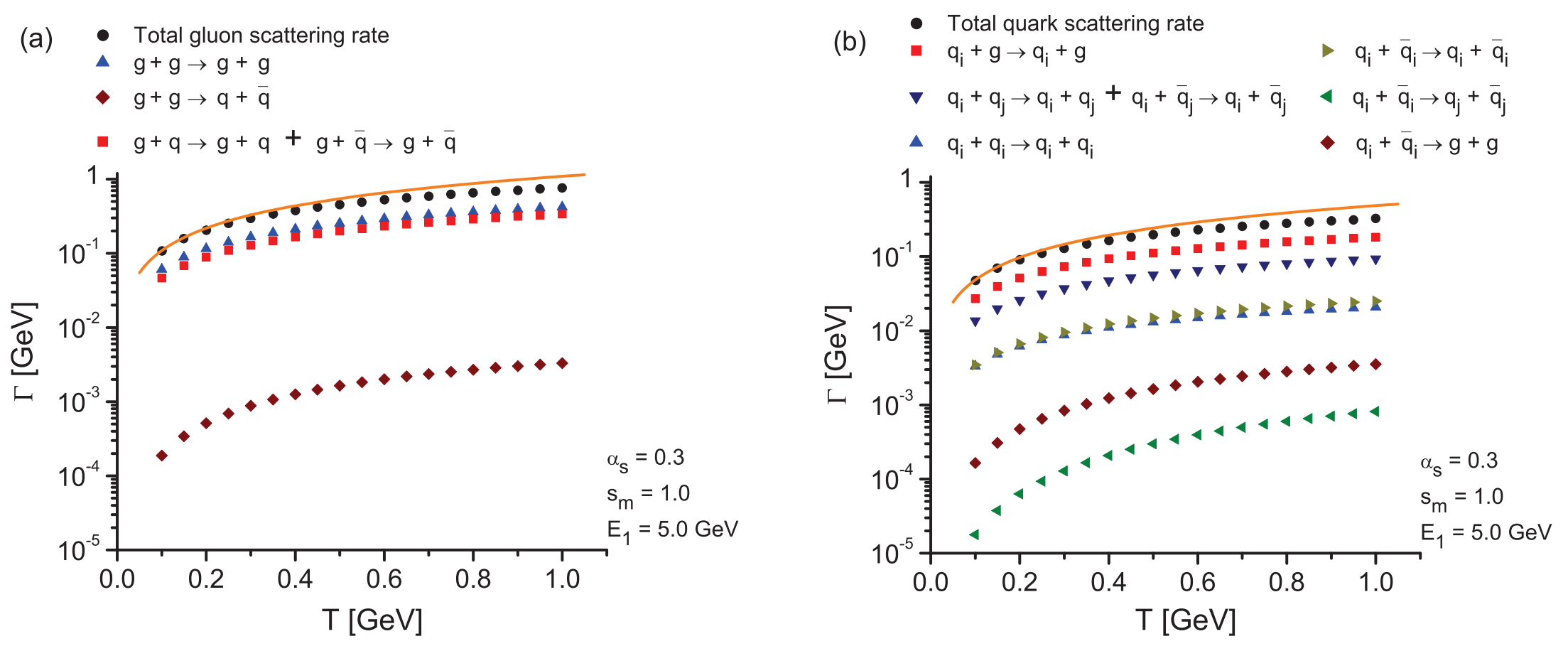

Fig. 1: The scattering rates Γ_X for a gluon (a) and quark (b) as a function of temperature T for a QCD plasma at rest. Flavour- and quark-antiquark -summed contributions from different processes and the analytical estimates for the total rates are also shown (solid lines).

- The total scattering rate: $\Gamma = \sum_X \Gamma_X$.
- The probability for having one or more collisions in a small time step Δt is

$$P(\text{number of collisions} \geq 1) = 1 - e^{-\Gamma\Delta t}.$$

If the step is small enough, it is safe to assume that only one collision happens.

- The energy and the collision angle of the plasma particle are sampled from the expression (1).
- The cross section of the process determines the distribution of scattering angle.
- The procedure continues until plasma temperature has decreased to hadron gas phase.

2 Hydrodynamical background

The hydro background used in our central collisions study (Ref. [1]) is described in [2]:

- Longitudinal boost-invariance and azimuthal symmetry leave (1+1)-dimensional equations for densities and radial flow to be solved.
- Initial conditions from pQCD+saturation (EKRT) model [3].

Non-central collisions study [4] uses hydro based on [5]:

- Smooth sWN profile [6] is used as an initial state.
- Assuming longitudinal boost-invariance reduces the hydrodynamical evolution equations into (2+1) dimensions.
- Centrality classes defined using the optical Glauber model.

Our most advanced study [7] has event-by-event hydro calculations with fluctuating initial state [5]:

- The eBC profile [6] is used; the centrality classes are defined using the Monte Carlo Glauber.

3 Static medium

- Static medium allows for studying the form of the energy loss probability distribution [8].

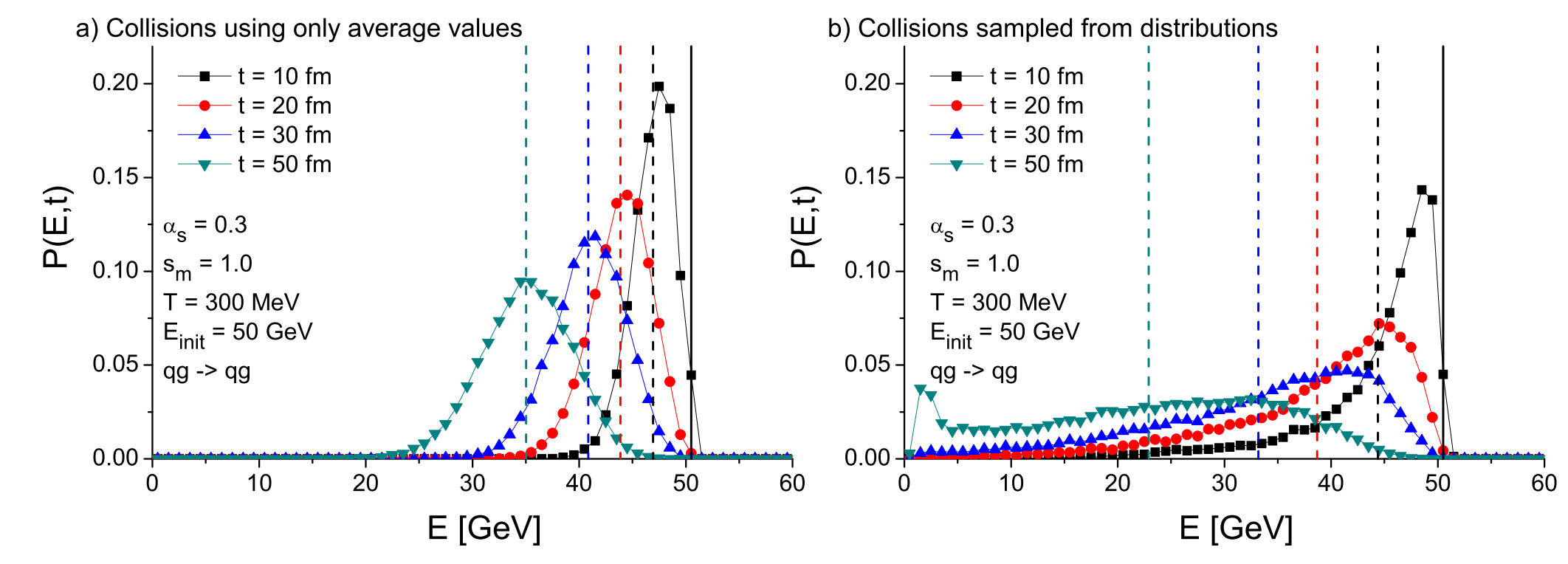

Fig. 2: The probability distribution for the energy of a 50-GeV quark after traveling in gluon plasma of temperature $T = 300$ MeV for different periods of time. In a), the average values are used for the momentum exchange $\hat{t}$, thermal particle energy E_2 and collision angle $\cos\theta_{12}$. In b), the aforementioned scattering variables are sampled from their respective distributions.

- Significant difference between simple approximation and Monte Carlo sampling.

4 The nuclear modification factor R_{AA}

- Running the simulation both with and without plasma effects allows us to see the effect of elastic collisions on the nuclear modification factor.

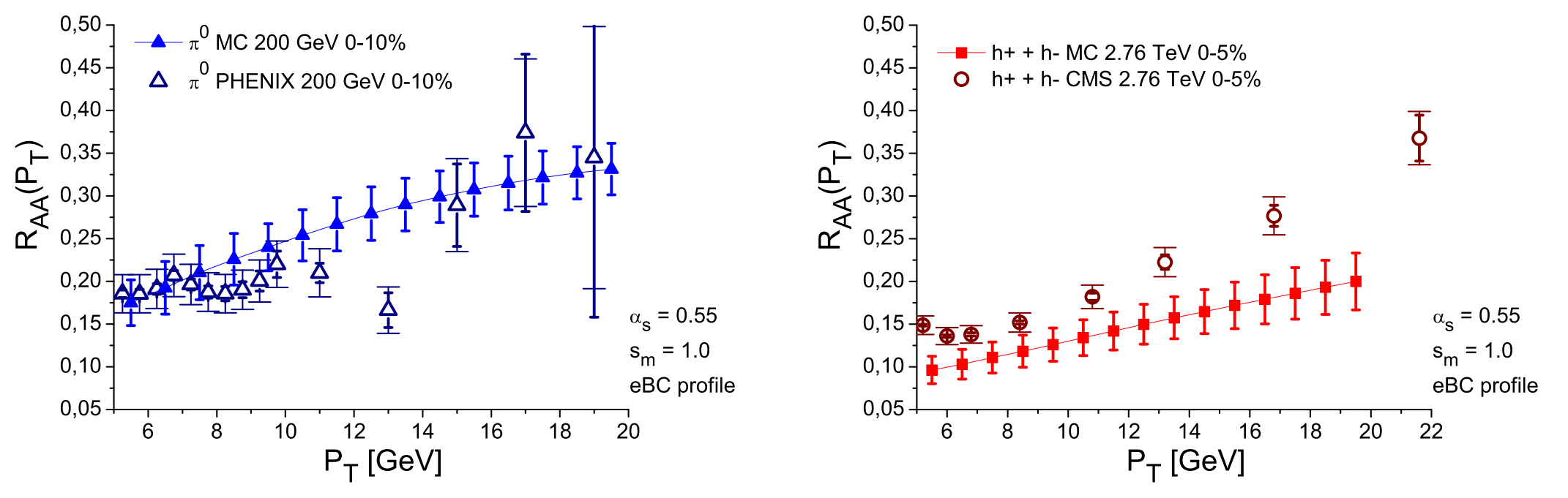

Fig. 3: Comparison of the elastic energy loss Monte Carlo simulation (MC) and experimental data for neutral pion $R_{AA}(P_T)$ in RHIC $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions and charged hadron $R_{AA}(P_T)$ in LHC $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions. The PHENIX data (open triangles) are from [9] and CMS data (open circles) are from [10].

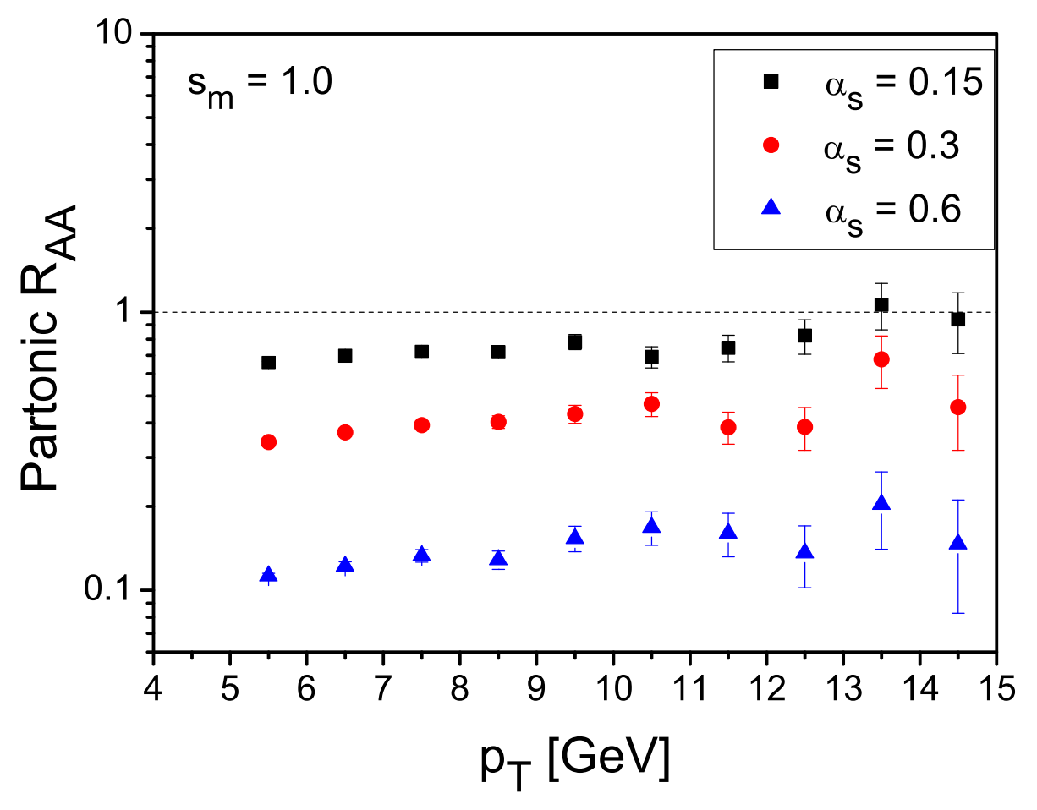

Fig. 4: The nuclear modification at the partonic level for three different values of the strong coupling constant α_s.

- The suppression gained is strongly dependent of the value of the strong coupling constant.
- The coupling value which produces the right amount of suppression at RHIC gives over-suppression in the LHC

⇒ Running coupling required?

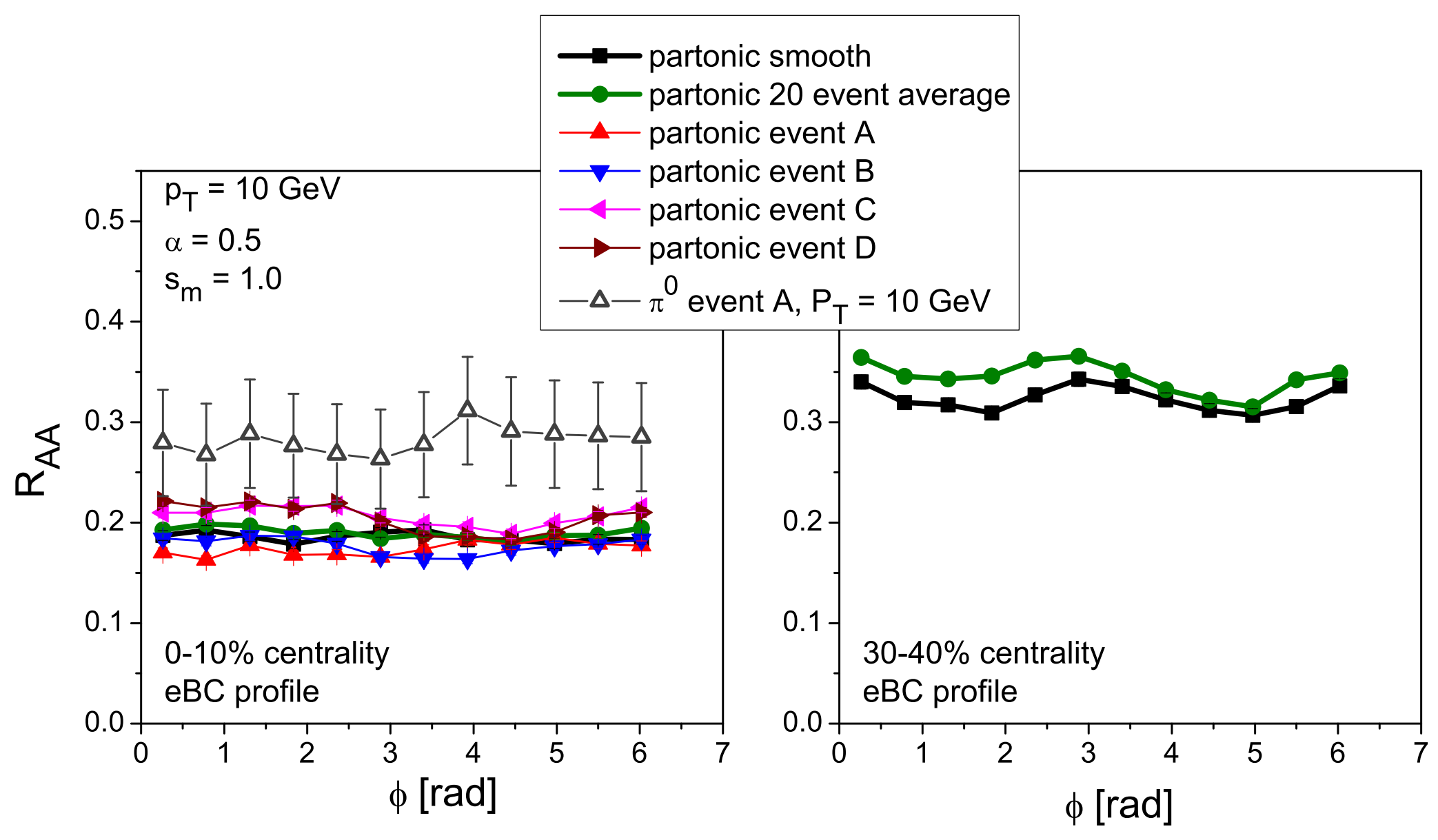

Fig. 5: R_{AA} at $p_T = 10$ GeV as a function of the angle of outgoing partons with the event plane shown for smooth initial conditions, fluctuating initial conditions and for average over 20 fluctuation events [7].

- The initial state fluctuations average out in central collisions.
- In non-central collisions, the average over fluctuations gives slightly less suppression compared to smooth hydro.

5 R_{AA} and centrality

- Azimuthal asymmetry in the more non-central collisions: More matter in the out-of-plane direction than in the in-plane direction ⇒ R_{AA} depends on the particle's angle with respect to the reaction plane.

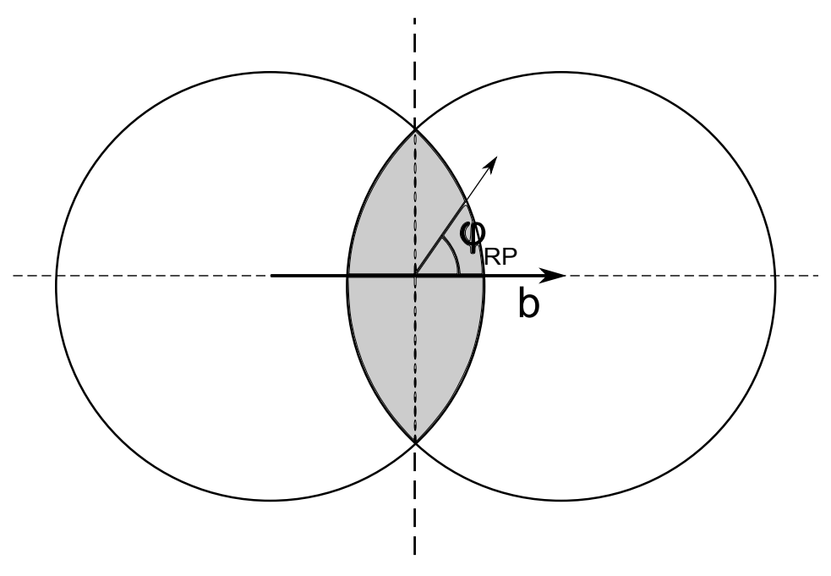

Fig. 6: Azimuthal asymmetry and the angle ϕ with respect to the reaction plane.

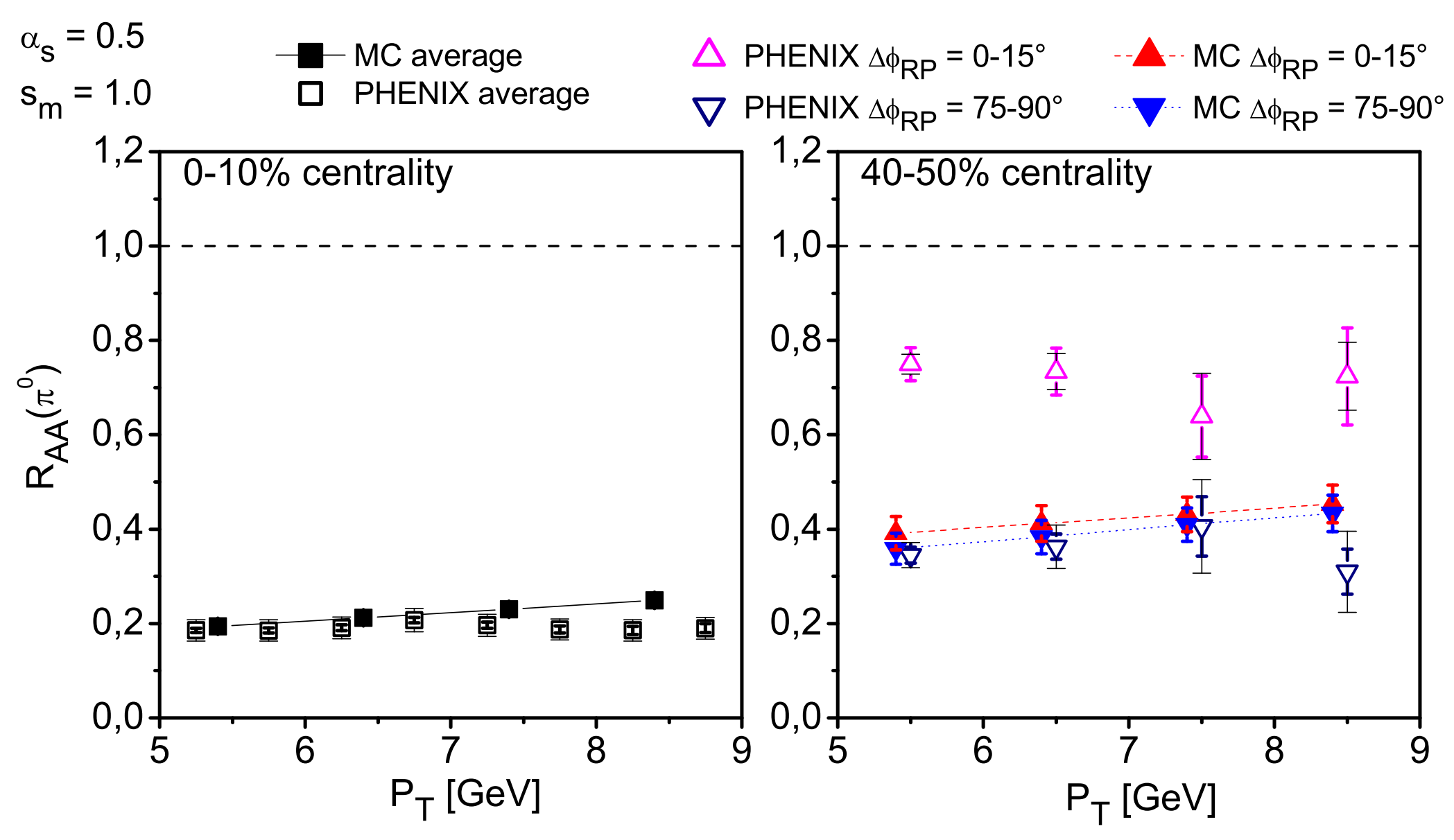

Fig. 7: Left panel: The π^0 nuclear modification factor, averaged over the reaction plane angle ϕ, for 0-10% centrality. Right panel: The π^0 nuclear modification factor dependence on the angle $\Delta\phi$ for 40-50% centrality. PHENIX data are from [9] (0-10% centrality) and [11] (40-50% centrality).

- The elastic energy loss model is insensitive to the reaction plane angle: $v_2(P_T) \approx 0$.
- The model produces too much suppression in the non-central collisions.

6 Conclusions

- The utilized approximations can significantly affect the shape of the elastic energy loss probability distributions and consequently the shape of $R_{AA}(P_T)$.
- Elastic energy loss is very sensitive to the value of strong coupling constant. Maximum effect - reproducing the RHIC $R^{\pi^0}_{AA}(P_T)$ in the 0-10% centrality with purely elastic energy loss - is achieved already with $\alpha_s \approx 0.5$ and thermal mass $m = \sqrt{4\pi\alpha_s}T$.
- The initial state fluctuations seem to have small effect on the nuclear modification.
- Fully incoherent energy loss mechanism is unable to reproduce the measured dependencies on the reaction plane angle and centrality

⇒ Quantum coherence important for explaining R_{AA}!

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