Jet quenching in small systems

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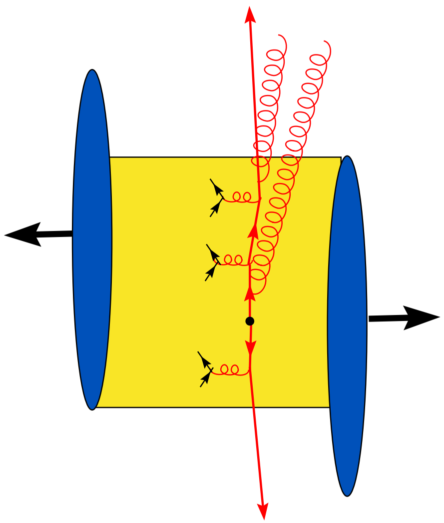
Jet quenching in AA, pA and pp collisions

Radiative and collisional energy losses modify jet evolution. Both these mechanisms should be treated on even footing. We have not such a formalism. But $\Delta E_{coll} \ll \Delta E_{rad}$. The theoretical uncertainties in jet quenching calculations are rather large. Practically we cannot give absolute predictions for the medium suppression. One can expect that it can be used to describe the variation of jet quenching from one experimental situation to another (when the parameters of the model are already fitted to some experimental data). And we do follow this strategy. We calculate the medium suppression for the small-size plasma in pp collisions using the information about the values of α_s which are necessary for description of the data on R_{AA}.



R_{pp} is not an observable quantity. The preliminary data from ALICE [S. Tripathy, arXiv:2103.07218] on I_{pp} at $\sqrt{s} = 5.02$ TeV for the hadron-tagged jets (with the trigger hadron momentum $8 < p_T < 15$ GeV, and the associated away side hadron momentum in the range $4 < p_T < 6$ GeV) show a decrease of I_{pp} with the UE multiplicity by about 20% for the UE multiplicity density range $\sim 5 - 20$. This agrees well with BGZ, Phys. Rev. Lett. 112, 032301 (2014) [arXiv:1307.3674].

- Can we see the effect of mini-QGP in pp collisions on R_{AA} via its A-dependence (say, from heavy ion and O+O data)?
- Is the mini-QGP scenario in contradiction with the LHC data $R_{pA} \approx 1$?

Nuclear modification factor for pp- and AA-collisions

$$R_{AA} = \frac{d\sigma(AA \to hX)/d\vec{p}_T dy}{N_{bin}\, d\sigma(pp \to hX)/d\vec{p}_T dy}\,.$$

If the QGP is produced in pp collisions the real pp cross section differs from that in pQCD by its own medium modification factor R_{pp}

$$d\sigma(pp \to hX)/d\vec{p}_T dy = R_{pp} d\sigma_{pert}(pp \to hX)/d\vec{p}_T dy\,.$$

In this scenario the theoretical quantity which should be compared with the experimental R_{AA} and R_{pA} read

$$R_{AA} = R^{st}_{AA}/R_{pp}\,, \quad R_{pA} = R^{st}_{pA}/R_{pp}$$

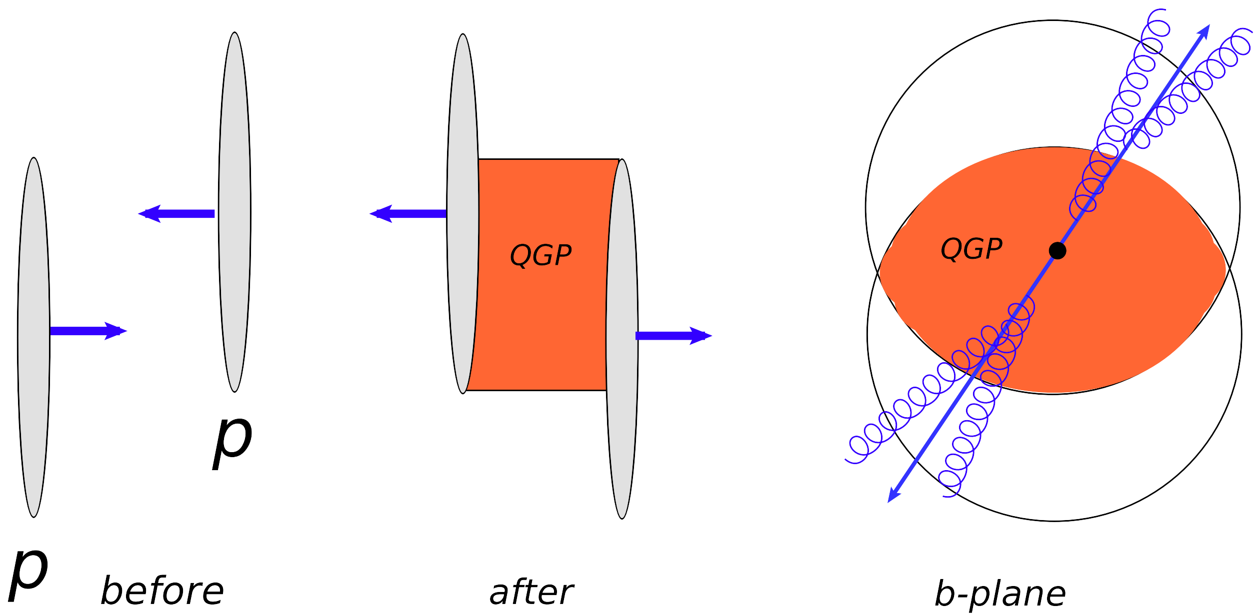
where $R^{st}_{AA,pA}$, are the standard nuclear modification factors calculated using the pQCD predictions for the particle spectrum in pp collisions.

$$\frac{d\sigma_{pert}(pp \to hX)}{d\vec{p}_T dy} = \sum_i \int_0^1 \frac{dz}{z^2} D_{h/i}(z,Q) \frac{d\sigma(pp \to iX)}{d\vec{p}^{\,i}_T dy}\,, \quad \vec{p}^{\,i}_T = \vec{p}_T/z\,,$$

$$\frac{d\sigma(pp \to hX)}{d\vec{p}_T dy} = \sum_i \int_0^1 \frac{dz}{z^2} D^m_{h/i}(z,Q) \frac{d\sigma(pp \to iX)}{d\vec{p}^{\,i}_T dy}\,, \quad \vec{p}^{\,i}_T = \vec{p}_T/z\,.$$

$$D^m_{h/i}(z,Q) = D^{KKP}_{h/k}(Q_0) \otimes D^{ind}_{k/j} \otimes D^{DGLAP}_{j/i}(Q_0,Q)\,, \quad Q \sim p^i_T\,, \quad Q_0 = 2\,\text{GeV}$$

Mini-QGP in *pp*-collisions



To fix T_0 we use the entropy/multiplicity ratio $C = dS/dy \Big/ dN_{ch}/d\eta \approx 7.67$ [B. Müller and K. Rajagopal, Eur. Phys. J. C43, 15 (2005)]. We write the initial entropy density as

$$s_0 = \frac{C}{\tau_0 \pi R_f^2} \frac{dN_{ch}}{d\eta} .$$

We ignore the azimuthal anisotropy, and regard the R_f as an effective plasma radius, which includes all impact parameters. The MIT bag model says that only 25% of jets come from *pp* collisions with the impact parameter larger than the bag radius.
$\Rightarrow$ In jet events typically the fireball has a relatively small eccentricity.

Size and temperature of mini-fireball in *pp* jet events

At $\sqrt{s} = 0.2$ TeV we use K_{ue} from PHENIX [J. Jia, arXiv:0906.3776] obtained by dihadron correlation method and the minimum bias non-diffractive events $dN_{ch}^{mb}/d\eta = 2.65 \pm 0.34$ from UA1 [C. Albajar *et al.* [UA1 Collaboration], Nucl. Phys. B335, 261 (1990)]. For LHC we use ATLAS [JHEP 1207, 116 (2012)] and ALICE [JHEP 09, 109 (2011)] data on the UE at $\sqrt{s} = 0.9$ and 7 TeV. In the plateau region this gives

$$N_{ch}^{UE}[\sqrt{s} = 0.2, 2.76, 5.02, 7 \text{ TeV}] \approx [5.79, 10.5, 12.6, 13.9]\,.$$

It is clear that $R_f \sim R_p \sim 1 - 1.5$ fm, the exact value is not important for our calculations. The variation of R_f by $\pm 30\%$ give very small effect on R_{pp}. In IP-Glasma model R_f [A. Bzdak, B. Schenke, P. Tribedy, and R. Venugopalan, Phys. Rev. C87,064906 (2013)]. R_f grows approximately as linear function of $(dN_g/dy)^{1/3}$ and then flattens. The flat region corresponds to almost head-on collisions. We use parametrization of R_f from L. McLerran, M. Praszalowicz, and B. Schenke, arXiv:1306.2350. From UE $dN_{ch}/d\eta$ in the plateau regions we have

$$R_f[\sqrt{s} = 0.2, 2.76, 5.02, 7 \text{ TeV}] \approx [1.26, 1.44, 1.49, 1.51] \text{ fm}\,.$$

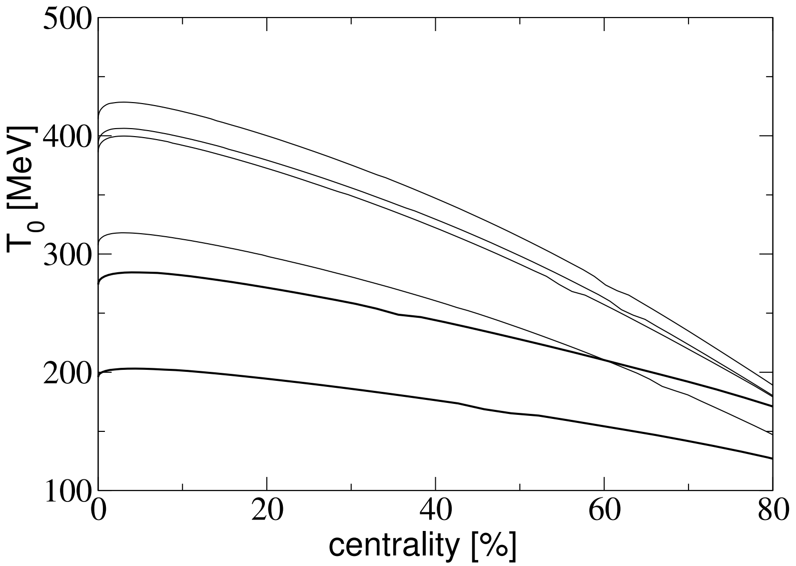
For ideal(lattice) EoS we obtain the initial temperatures of the QGP at $\tau_0 = 0.5$ fm

$$T_0[\sqrt{s} = 0.2, 2.76, 5.02, 7 \text{ TeV}] \approx [195(226), 217(247), 226(256), 232(261)] \text{ MeV}\,.$$

Initial QGP temperature in AA collisions vs centrality

Centrality dependence of the initial fireball temperature at $\tau_0 = 0.5$ fm for the ideal gas model obtained in the Glauber model via the average entropy density for (from top to bottom at low centrality): 5.02 and 2.76 TeV Pb+Pb, 5.44 TeV Xe+Xe, 0.2 TeV Au+Au, 7 and 0.2 TeV O+O collisions.

For heavy nuclei we use Woods-Saxon density $\rho_A(r) = \rho_0/[1 + \exp((r - R_A)/d)]$. (for Pb nucleus $R_A = 6.62$ and $d = 0.546$ fm). We define the AA-overlap region for two circles with $R = R_A + kd$, $k = 2$.



For O+O collisions we use the oscillator shell model nuclear density

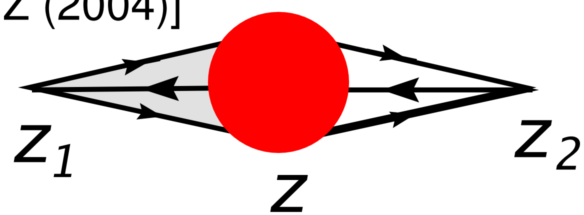
$$\rho_A(r) = \frac{4}{\pi^{3/2} r_A^3}\left[1 + \frac{A-4}{6}\left(\frac{r}{r_A}\right)^2\right] \exp\left(r^2/r_A^2\right)\ ,\ r_A^2 = \left(\frac{5}{2} - \frac{4}{A}\right)^{-1} \left(\langle r_{ch}^2\rangle_A - \langle r_{ch}^2\rangle_p\right)$$

with $\langle r_{ch}^2\rangle_A = 7.29$ fm^2 for ^{16}O and $\langle r_{ch}^2\rangle_p = 0.7714$ fm^2, and the Woods-Saxon density ($R_A = 2.2$ and $d = 0.513$ fm). The difference between R_{AA} for the oscillator shell model and for the Woods-Saxon one is very small.

Induced one gluon emission in LCPI approach

$$dP/dx = \int_0^L dz n(z) d\sigma^{BH}_{eff}(x,z)/dx\,.$$

The effective Bethe-Heitler cross section for $q \to g + q$ [BGZ (1997)] $x = \omega_g/E$, z is the position of the scattering center in QGP. We use the representation [BGZ (2004)]



$$\frac{d\sigma^{BH}_{eff}(x,z)}{dx} = -\frac{P_{Gq}(x)}{\pi\mu(x)}\mathrm{Im}\int_0^z d\xi \alpha_s(Q(\xi),T(z))\,\frac{\partial}{\partial\rho}\left(\frac{F(\xi,\rho)}{\sqrt{\rho}}\right)\Bigg|_{\rho=0}\,,$$

$\mu = Ex(1-x)$, $Q^2(\xi) = 1.85\mu/\xi$, F is the solution to the radial Schrödinger equation for $m = 1$

$$i\frac{\partial F(\xi,\rho)}{\partial\xi} = \left[-\frac{1}{2\mu(x)}\left(\frac{\partial}{\partial\rho}\right)^2 - i\frac{n(z-\xi)\sigma_3(\rho)}{2} + \frac{4m^2-1}{8\mu(x)\rho^2} + \frac{1}{L_f}\right]F(\xi,\rho)$$

with $L_f = 2\mu(x)/\epsilon^2$, $\epsilon^2 = m_q^2x^2 + m_g^2(1-x)$, $F(\xi=0,\rho) = \sqrt{\rho}\sigma_3(\rho)\epsilon K_1(\epsilon\rho)$, $\sigma_3 = \sigma_{q\bar{q}g}$. We take $m_q = 300$, $m_g = 400$ MeV [P. Lévai and U. Heinz (1998)].
$\alpha_s(Q(\xi),T(z)) \to \sqrt{\alpha_s(Q(\xi),T(z-\xi))\alpha_s(Q(\xi),T(z+\xi))}$ gives practically the same results. We solve the Schrödinger equation backward in time to have a smooth boundary condition. A similar method was used by Caron-Huot and Gale (2010) within AMY approach.

Collisional energy loss, $2 \to 2$ processes

$$\frac{dE_{col}}{dz} = \frac{1}{2Ev}\sum_{p=q,g} g_p \int \frac{d\vec{p}'}{2E'(2\pi)^3}\int \frac{d\vec{k}\, n_p(k)}{2k(2\pi)^3}$$

$$\times \int \frac{d\vec{k}'[1+\epsilon_p n_p(k')]}{2k'(2\pi)^3}(2\pi)^4\delta^4(P+K-P'-K')\omega\langle|M(s,t)|^2\rangle\theta(\omega_{max}-\omega)$$

$\omega = E - E'$ is the energy transfer, $v \approx 1$ is the quark velocity, $P=(E,\vec{p})$ and $K=(k,\vec{k})$ 4-momenta for incoming partons, $P'=(E',\vec{p}')$ and $K'=(k',\vec{k}')$ 4-momenta for outgoing partons, $M(s,t)$ is matrix element for $Qp \to Qp$ scattering, $n_q(k) = (e^{k/T}+1)^{-1}$ and $n_g(k)=(e^{k/T}-1)^{-1}$, $\epsilon_q=-1$, $\epsilon_g=1$, $g_q = 4N_cN_f$, $g_g = 2(N_c^2-1)$. $\omega_{max}=E/2$. $\omega = \frac{-t - tk_z/E + 2\vec{k}_\perp \vec{q}_\perp}{2(k-k_z)}$. Bjorken neglected the red terms.
We use the paramertization of $\alpha_s(Q,T)$

$$\alpha_s(Q,T) = \begin{cases} \dfrac{4\pi}{9\log(Q^2/\Lambda_{QCD}^2)} & \text{if } Q > Q_{fr}(T)\,, \\ \alpha_s^{fr}(T) & \text{if } Q_{fr}(T) \geq Q \geq cQ_{fr}(T)\,, \\ \alpha_s^{fr}(T)\times(Q/cQ_{fr}(T)) & \text{if } Q < cQ_{fr}(T)\,, \end{cases}$$

where $Q_{fr}(T) = \Lambda_{QCD}\exp\left\{2\pi/9\alpha_s^{fr}(T)\right\}$ ($\Lambda_{QCD} = 200$ MeV). We perform calculations for $c=0.8$ and $c=0$. We take $Q_{fr}=\kappa T$, we fit κ from data on R_{AA}. The parametrization with $c\sim 1$ is supported by lattice results for in-medium α_s [A. Bazavov *et al.*, Phys. Rev. D98, 054511 (2018)] ($\kappa \sim 4$ if one takes $Q\sim 1/r$).

We treat the collisional loss as a perturbation and incorporate it by a small renormalization of T_{QGP} according to the change in the ΔE due to the collisional energy loss

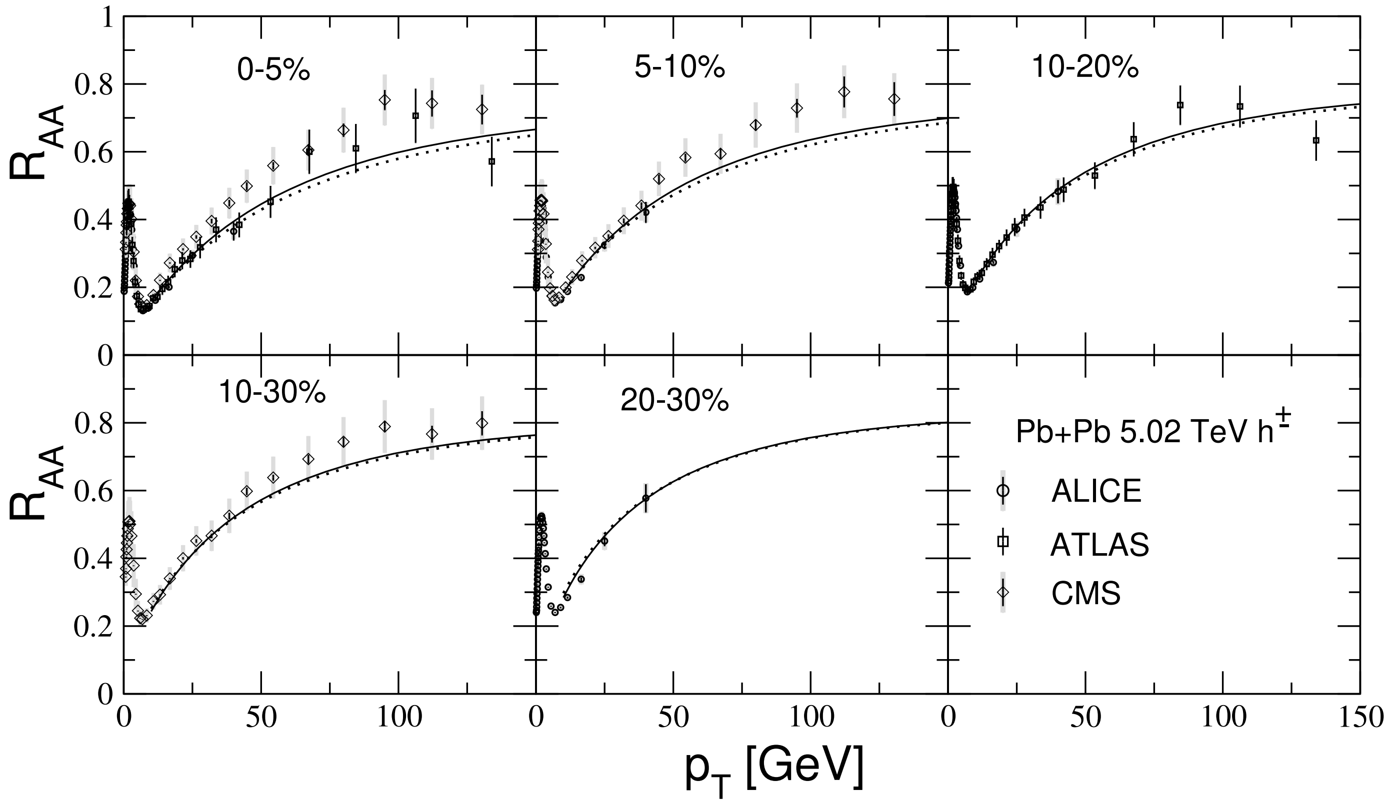
$$\Delta E_{rad}(T') = \Delta E_{rad}(T) + \Delta E_{col}(T)\,.$$

The collisional loss suppresses $R_{AA} \lesssim 15 - 25$ %. We calculate $D_{k/j}^{ind}$ in the approximation of independent gluon radiation [R. Baier, Y.L. Dokshitzer, A.H. Mueller, and D. Schiff, JHEP 0109, 033 (2001)].

For $d\sigma(N+N \to i+X)/d\vec{p}_T^{\,i}dy$ we use the LO pQCD formula with the CTEQ6 PDFs. We account for the nuclear modification of the PDFs with the EPS09 [K.J. Eskola, H. Paukkunen, and C.A. Salgado, JHEP 0904, 065 (2009)] correction. To simulate the higher order K-factor in the hard cross sections we use $\alpha_s(cQ)$ with $c = 0.265$ (like that in PYTHIA) and c=0.13 for the version with $1/R_{pp}$. For $D_{h/q(g)}(z, Q_0)$ we use the KKP parametrization [B. A. Kniehl, G. Kramer, and B. Potter, Nucl. Phys. B582, 514 (2000)].

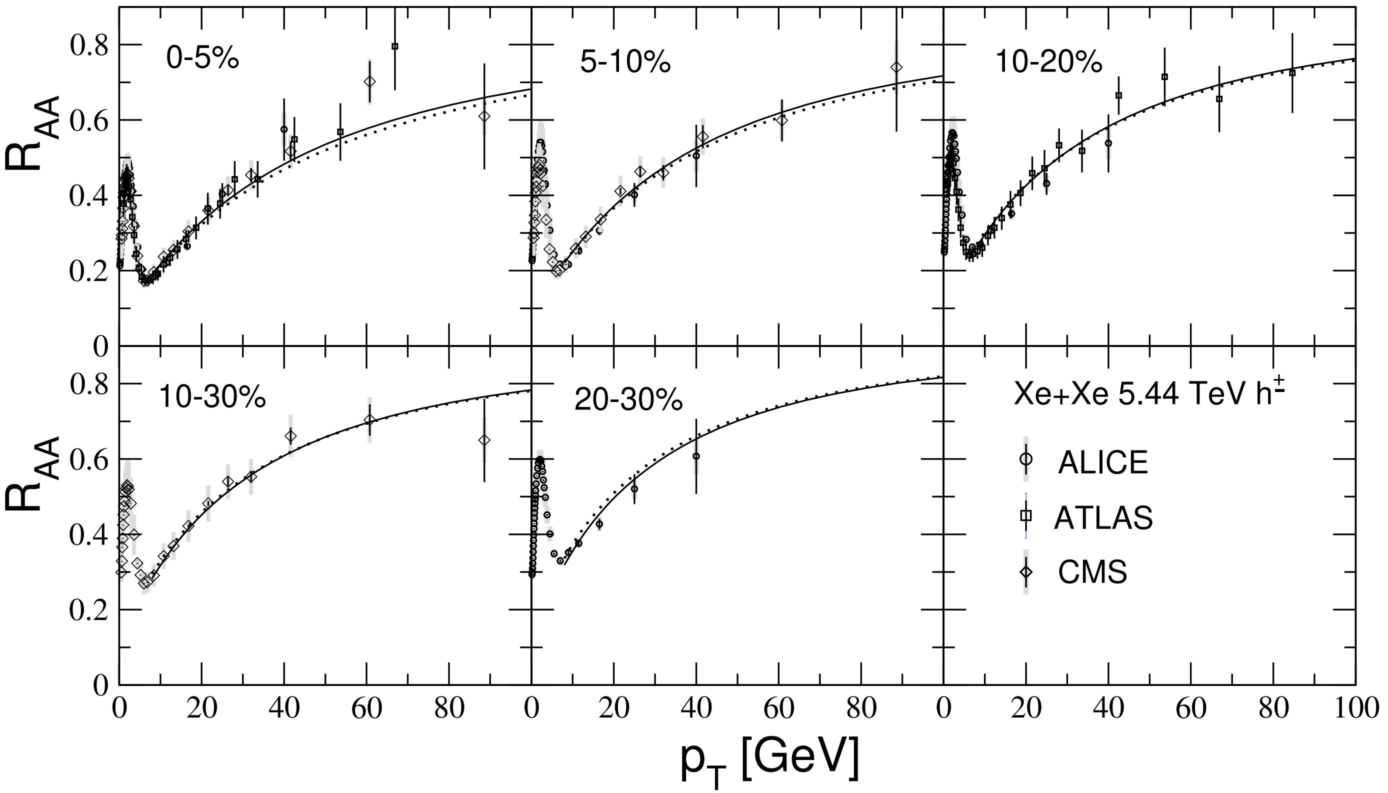
We use the Bjorken $1+1$ QGP expansion $T^3\tau = T_0^3\tau_0$. For each value of the impact parameter b we neglect the variation of T_0 in the transverse directions. We take $\tau_0 = 0.5$ fm and $s \propto \tau$ at $\tau < \tau_0$. For AA collisions we use the medium life/freeze-out time $\tau_{f.o.} \approx 1.05 \times (dN_{ch}/d\eta)^{1/3}$, which is supported by the pion interferometry at RHIC and LHC. We ignore the transverse expansion, which gives a very small effect on the medium suppression (see, B. Betz and M. Gyulassy, AIP Conf. Proc. 1701, 060006 (2016)]. The errors from the approximation of a flat T are also small, for small size systems they are practically negligible.

R_{AA} in 5.02 TeV Pb+Pb collisions

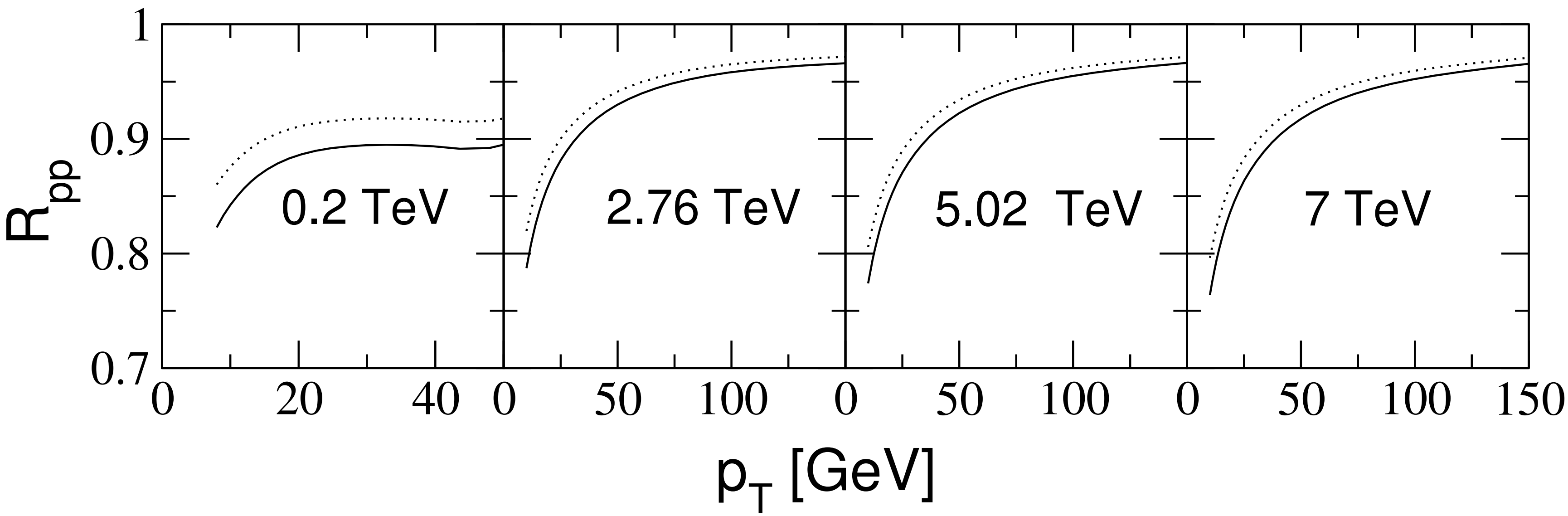


R_{AA} of charged hadrons for 5.02 TeV Pb+Pb collisions from our calculations with $k = 2$, $c = 0.8$, $\tau_0 = 0.5$ fm for scenarios without (solid) and with (dotted) mQGP formation in pp collisions for the optimal parameters $\kappa = 3.47$ and 2.5 obtained by fitting R_{AA} in the range $10 < p_T < 120$ GeV. Data points are from ALICE, ATLAS and CMS.

R_{AA} in 5.44 TeV Xe+Xe collisions

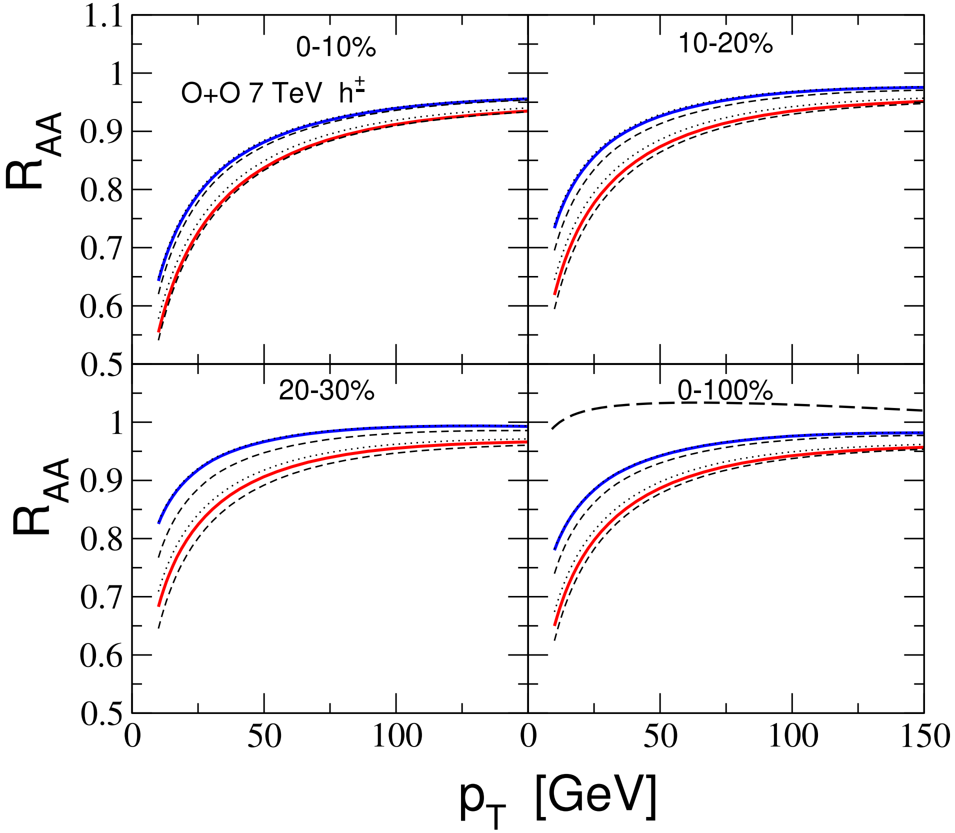


R_{AA} of charged hadrons for 5.44 TeV Xe+Xe collisions from our calculations with $k = 2$, $c = 0.8$, $\tau_0 = 0.5$ fm for scenarios without (solid) and with (dotted) mQGP formation in pp collisions for the optimal parameters $\kappa = 3.59$ and 2.52 obtained by fitting R_{AA} in the range $10 < p_T < 120$ GeV. Data points are from ALICE, ATLAS and CMS.



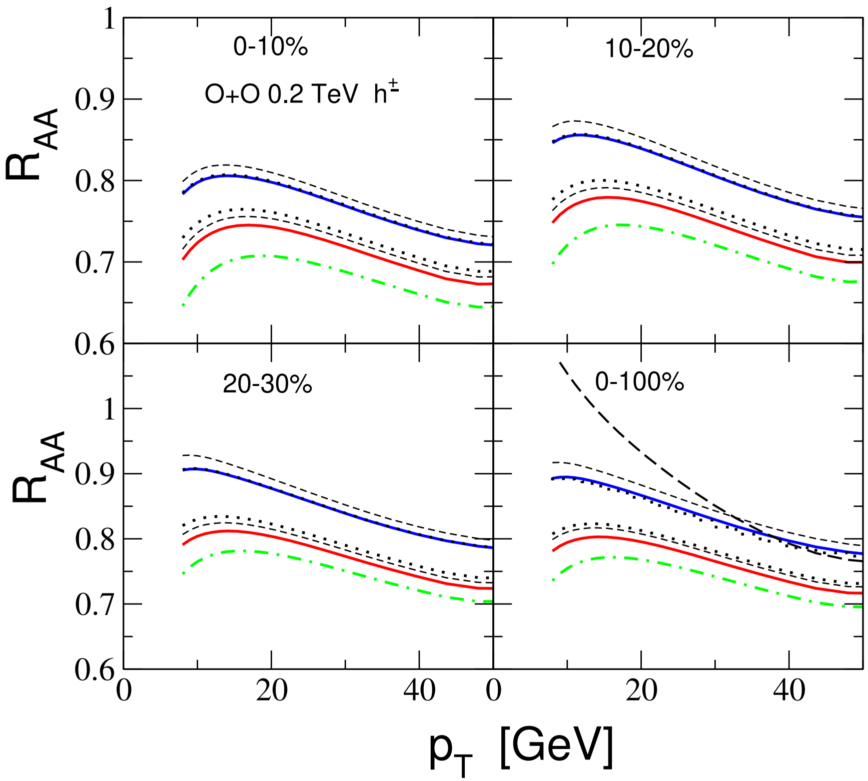
R_{pp} of charged hadrons for 0.2, 2.76, 5.02 and 7 TeV TeV pp collisions from our calculations for $\tau_0 = 0.5$ (solid) and 0.8 fm (dotted) with $\kappa = 2.55$ obtained by fitting all the LHC data on R_{AA} for heavy ion collisions with the geometrical parameter $k = 2$.

R_{AA} in 7 TeV O+O collisions



R_{AA} of charged hadrons for 7 TeV O+O collisions from our calculations for scenarios with(blue) ($\kappa = 2.55$) and without(red) ($\kappa = 3.47$) mQGP formation in pp collisions. The solid and dashed curves are for $\tau_0 = 0.5$, and the dotted ones are for 0.8 fm. The solid and dotted curves are obtained for the geometrical parameter $k = 2$, and the dashed curves are for $k = 3$. The long dashed line shows R_{AA}^{pdf}.

R_{AA} in 0.2 TeV O+O collisions



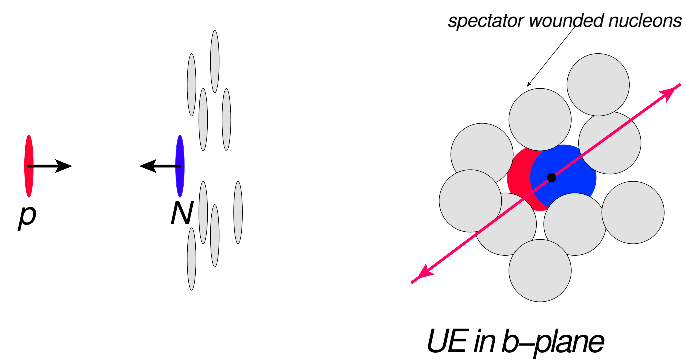
R_{AA} of charged hadrons for 0.2 TeV O+O collisions from our calculations for scenarios with(blue) ($\kappa = 2.55$) and without(red) ($\kappa = 3.47$) mQGP formation in pp collisions. The solid and dashed curves are for $\tau_0 = 0.5$, and the dotted ones are for 0.8 fm. The solid and dotted curves are obtained for the geometrical parameter $k = 2$, and the dashed curves are for $k = 3$. The dash-dotted (green) lines show the results (for $k = 2$, $\tau_0 = 0.5$ fm, $\kappa = 2.55$) for the intermediate scenario when mQGP formation in pp collisions occurs at the LHC energies, but it is absent at RHIC. The long dashed line shows R_{AA}^{pdf}.

Underlying events in pA collisions

In the Glauber model for soft pA min-bias events we have

$$N_{ch} = (1 + N_w^A)N_{ch}^{mb}(pp)/2 = N_{ch}^{mb}(pp) + (N_w^A - 1)N_{ch}^{mb}(pp)/2$$

N_w^A is the number of the wounded nucleons in the nucleus. For the UEs we have one hard event, it gives $N_{ch}^{UE}(pp)$. In this hard collision we have almost central collision of the projectile nucleon and the wounded nucleon, the other wounded nucleons are distributed in the transverse plane like that for a soft pA collision (each of them gives $N_{ch}^{mb}(pp)/2$). Thus we have for the min-bias UE

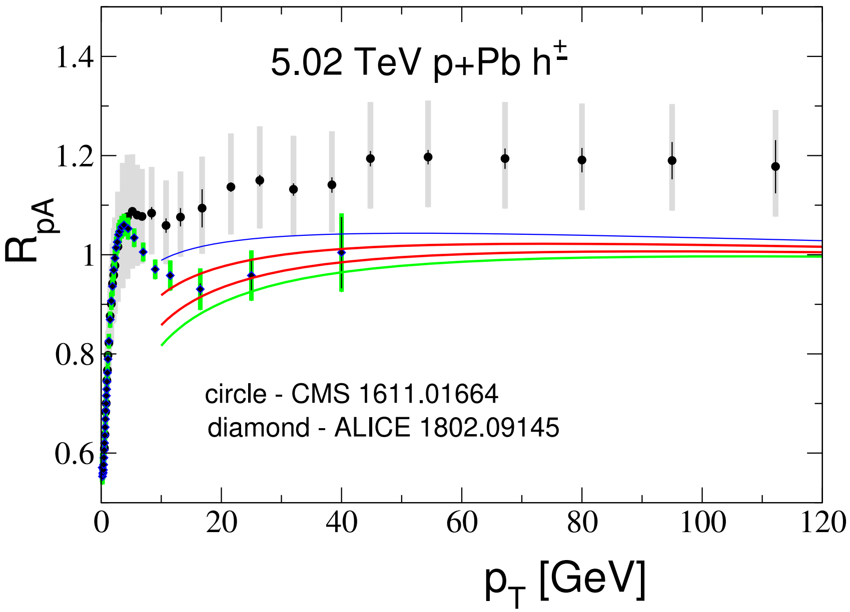


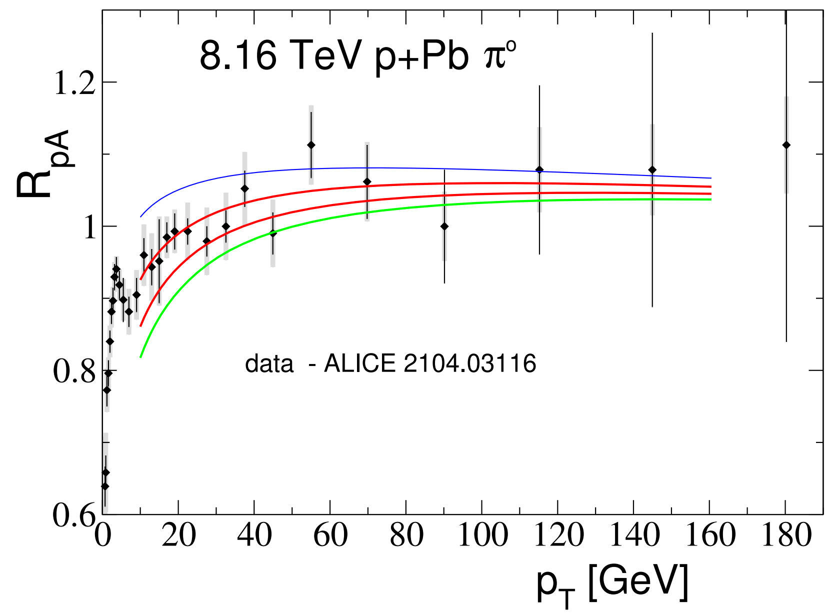
$$N_{ch}^{UE} = N_{ch}^{UE}(pp) + (N_w^A - 1)N_{ch}^{mb}(pp)/2.$$

We have $(N_w^A - 1) \approx 8(8.5)$ at $\sqrt{s} = 5.02(8.16)$ TeV. In b-plane the fireball has a well pronounced peak at $r \lesssim 1$ fm (due to N_{ch}^{UE}), and the broad corona region at $r \gtrsim 1 - 1.5$ fm formed by the spectator wounded nucleons. Each spectator gives $N_{ch}(pp)/2 \approx 2.65(2.86)$. The temperature at $r \sim 1.5 - 2$ fm is $\sim 130 - 200$ MeV, and falls steeply with rising r. The corona wounded nucleons should produce hadrons in free-streaming regime. Only the core region is occupied by the QGP (i.e. $N_{ch}^{QGP} < N_{ch}(pA)$). The number of the corona nucleons $\sim 0.5(N_w^A - 1)$, i.e.,

$N_{ch}^{QGP}(pA) \sim N_{ch}^{UE}(pp) + 0.5(N_w^A - 1)N_{ch}^{mb}(pp)$.

R_{pA} at LHC energies





Curves: (blue) $N_{ch}^{QGP}(pA) = N_{ch}^{UE}(pp)$

(red upper) $N_{ch}^{QGP}(pA) = N_{ch}^{UE}(pp) + \frac{1}{3}(N_w^A - 1)N_{ch}^{mb}(pp)/2$

(red bottom) $N_{ch}^{QGP}(pA) = N_{ch}^{UE}(pp) + \frac{2}{3}(N_w^A - 1)N_{ch}^{mb}(pp)/2$

(green) $N_{ch}^{QGP}(pA) = N_{ch}^{UE}(pp) + (N_w^A - 1)N_{ch}^{mb}(pp)/2$

We have $N_{ch}^{UE}(pp) \approx 12.6(14.5)$, $(N_w^A - 1)N_{ch}^{mb}(pp)/2 \approx 21(25)$ for 5.02(8.16) TeV.

Due to $N_{ch}^{QGP}(pPb) < N_{ch}^{UE}(pPb)$ correlation of I_{pPb} with multiplicity should be weaker than for I_{pp}. This agrees with the preliminary data from ALICE [S. Tripathy, arXiv:2103.07218].

Conclusions:

- Assuming that a mini-QGP may be created in pp and pA collisions, we have evaluated the medium modification factors R_{pp} and R_{pPb} using the free parameter κ obtained by fitting the LHC data on R_{AA} for heavy ion collisions. For charged hadrons at $p_T \sim 10$ GeV we obtained $R_{pp} \sim [0.84,\ 0.78,\ 0.77, 0.76]$ at $\sqrt{s} = [0.2, 2.76, 5.02, 7]$ TeV.
- The presence of R_{pp} gives a small effect on the description of R_{AA} in heavy ion collisions, and its effect may be imitated by some change of κ (i.e., of $\alpha_s(Q, T)$). The effect of the QGP formation in pp collisions for v_2 is small as well. Both the scenarios (w/o and w/ mQGP) are consistent with the LHC data on R_{AA} and v_2 in heavy ion collisions.
- We have found that the scenario with the mQGP formation in pp and pPb collisions may be consistent with the ALICE data on R_{pPb}, but the scenario with mQGP formation only in pPb collisions is excluded. The data on R_{pPb} from CMS are inconsistent with scenario with mQGP formation (and with pQCD calculations w/o mQGP).
- Predictions for $R_{AA} - R_{AA}^{pdf}$ in O+O collisions for scenarios with and without mQGP formation differ substantially. Due to theoretical uncertainties for R_{AA}^{pdf}, and the fact that the p_T-dependence of R_{AA} for both scenarios are similar, it may be difficult to discriminate between these scenarios from comparison with the future LHC data. For 0.2 TeV O+O collisions the difference between these scenarios is somewhat more pronounced.

Thank you for your attention!