Physics of the Fragmentation Region

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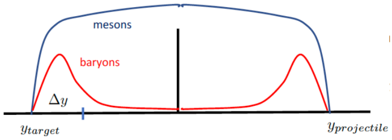
Initial Stages 2021

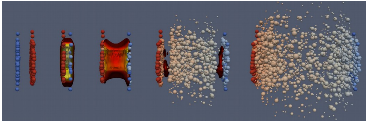
UNIVERSITY of WASHINGTON

IS2021
The VI[th] International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR
COLLISIONS

Introduction



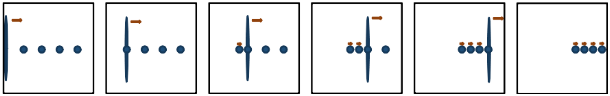
L. McLerran, EPJ Web Conf. **172**, 03003 (2018)



[Ref:MADAI Collaboration, Hannah Petersen and Jonah Bernhard]

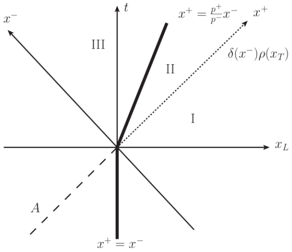
- High baryon density system in the presence of strong color fields
- $Q^{sat\,2}_{projectile} \sim A^{1/3}\Lambda^2_{QCD}\, e^{\kappa(y_{projectile}+|y_{target}|-\Delta y)} \gg Q^{sat\,2}_{target}$.
  With $\kappa \sim 0.2 - 0.3 \implies Q^{sat}_{projectile} \sim 2 - 6\,\mathrm{GeV}$ at the LHC and $\sim 1 - 2$GeV at RHIC.

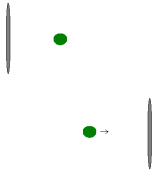
[Credit: Isobel Kolbe]



- Nucleus will be compressed thereby increasing baryon and energy densities in the fragmentation region [Anishetty *et al.* **Phys. Rev. D 22 , 2793 (1980)**], [W. Busza and A. S. Goldhaber, **Phys Lett 139B, 235 (1984)**]. We aim to express these ideas in the language of saturation physics.
- We want to build an intuitive framework to understand the evolution of the fragmentation region. Consider 1+1-D motion of nuclear matter.
- Work in the target rest frame and assume free classical trajectories of struck quarks.

Interaction of classical particle and CGC





K.Kajantie, L.D. McLerran, R. Paatelainen :

Phys. Rev. D 100, (2019), **Phys. Rev. D 101, (2020)**

EOM for a classical colored particle: $\frac{dp^\mu}{d\tau} = g\mathbf{T}\cdot\mathbf{F}^{\mu\nu}u_\nu$

In A^+ gauge, we have: $F^{+i} = -\partial^i A^+$, $\frac{dp^-}{d\tau} = 0$.

Momentum-kick distribution

and also

$$p^i(x_\perp) = gT^a \frac{\partial^i}{\nabla_T^2} \rho^a(\vec{x}_\perp)$$

MV Model: $W_{[\rho]} = \frac{1}{\mathcal{N}} \exp\left\{-\frac{1}{2\mu_A^2} \int d^2x \rho^a(\vec{x}_\perp)\rho^a(\vec{x}_\perp)\right\}$

$\therefore$ we can extract a probability distribution over $\vec{p}_T$:

$$\frac{dP(\vec{p}_T)}{d^2 p_T} = \frac{1}{2\pi} \frac{1}{m\bar{p}} \exp\left(-\frac{p_T^2}{2m\bar{p}}\right) \quad (1)$$

$$\bar{p} = Q_s^2/m \quad (2)$$

Constituent quark mass $m \approx 300\,\text{MeV}$.

p^- is unchanged by the interaction so

$$p_{\text{before}} = (m/\sqrt{2}, m/\sqrt{2}, 0_\perp) \tag{3}$$
$$p_{\text{after}} = (p^+, m/\sqrt{2}, \mathbf{p}_\text{T}) \ . \tag{4}$$

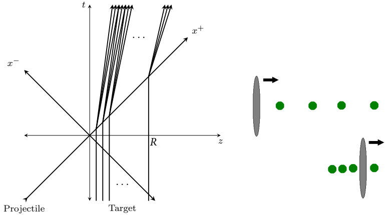
This then means $\mathbf{p}_\text{T}$ and p^z after the collision are related. To see this, note that imposing the mass-shell condition on eq. (4) gives

$$p^+ = \frac{m^2 + p_\text{T}^2}{\sqrt{2}m} \tag{5}$$

$$\therefore p^z = \frac{p^+ - p^-}{\sqrt{2}} = \frac{p_\text{T}^2}{2m} \ . \tag{6}$$

$$\frac{dP(p^z)}{dp^z} = \frac{1}{\bar{p}} e^{-\frac{p^z}{\bar{p}}} \tag{7}$$

Target space-time picture

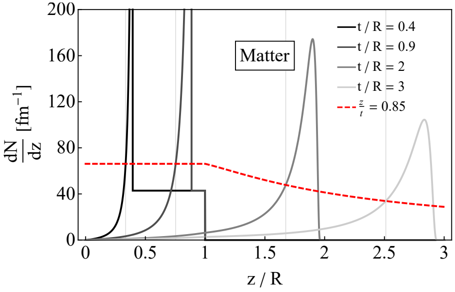


We want the one-particle distribution for, an initially uniform (line density $\lambda = N/R$.) 1D array of particles that is struck by a sheet of colored glass.

$$f(x,p) = \frac{N}{R}\theta(t-z)\theta\left(z - \frac{tp}{p+m}\right)\theta\left(\frac{p(t-R)}{p+m} + R - z\right)\left(1+\frac{p}{m}\right)\frac{1}{\bar{p}}e^{-p/\bar{p}} + \frac{N}{R}\theta(z-t)\theta(z)\theta(R-z)\delta(p), \quad (8)$$

where $x = (t, z)$, p is the z-component of the quark's momentum.

Number density: Compression?



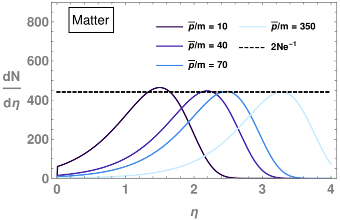
The red curve is $\left.\frac{dN}{dz}\right|_{\frac{z}{t}=0.85}$. The faint vertical lines represent a frame moving at $v = 0.85$. $R = 14$ fm/c, $N = 600$

- 1-D Number density $\frac{dN}{dz}(z, t) = \int dp f(x, p)$
- Sharp fall-off of the initial distribution $\Longrightarrow$ kink at $z = R$.
- For $z < t$ & $z < R$, $\frac{dN}{dz}$ depends only on z/t.
- Compression for $z < R$ and expansion afterwards

Baryon stopping

Changing variables to $\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$ and $\tau^2 = t^2 - z^2$

$$\frac{dN^{\text{Mat.}}}{d\eta} = \frac{dz}{d\eta}\frac{dN^{\text{Mat.}}}{dz} \xrightarrow{\tau\to\infty} \frac{m}{\bar{p}} N \exp\left\{2\eta - \left(\frac{m}{2\bar{p}}\right)e^{2\eta} + \left(\frac{m}{2\bar{p}}\right)\right\}$$



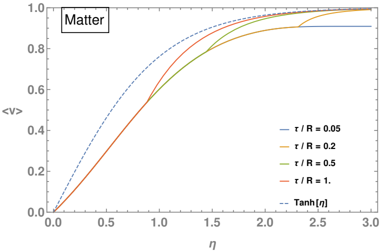
cf. W. Busza and A. S. Goldhaber, **Phys Lett 139B, 235 (1984)**, W. Busza et al **arXiv:1802.04801**

Peak at $\eta = \eta_0 = \frac{1}{2}\log\frac{2\bar{p}}{m} \sim \log\frac{Q_s}{m}$. Height $= \left.\frac{dN^{\text{Mat.}}}{d\eta}\right|_{\eta=\eta_0} = 2Ne^{\left(\frac{m}{2\bar{p}}-1\right)} \xrightarrow{Q_s \gg m} 2Ne^{-1}$.

Local fluid velocity and compression

Information about the local velocity of the quarks is contained in $f(x,p)$.

$$\frac{d\mathrm{P}(p'|z,t)}{dp'} = \frac{f(x,p')}{\int dp f(x,p)}\,, \qquad \langle v\rangle^{\mathrm{Mat.}}(z,t) = \int dp^z\,\frac{p^z}{p^0}\,\frac{d\mathrm{P}(p^z|z,t)}{dp^z}$$



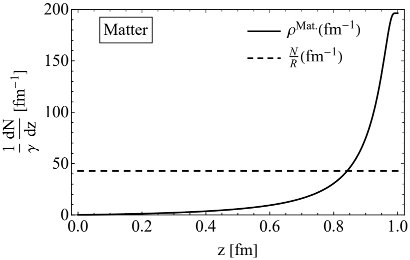
- P above is the probability of finding a particle with momentum p at $x = (z, t)$

How much is the nuclear matter compressed?

The co-moving density $\frac{dN'^{\text{Mat.}}}{dz'} = \frac{1}{\gamma}\frac{dN}{dz}\Big|_{t<R,z<t}$, depends only on z/t, peaks on the light front $z = t$. $\left(1/\gamma = \sqrt{1-\langle v\rangle^2_{\text{Mat.}}(z,t)}\right)$

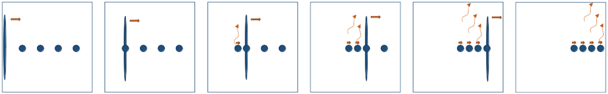
$$\max\left\{\frac{dN^{\text{Mat.}}}{dz'}\right\} = \frac{N}{R}\sqrt{1+\frac{2\bar{p}}{m}}\,.$$

The co-moving baryon density is therefore enhanced by a factor of $\sim\sqrt{1+\frac{2\bar{p}}{m}} \sim Q_s/m$. This is $\sim 10 - 20$ at the LHC and $\sim 5 - 10$ at RHIC.



local density at t=R

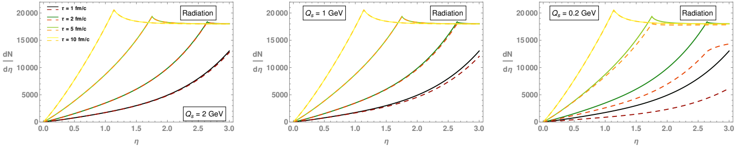
Radiation distribution



[Credit: Isobel Kolbé]

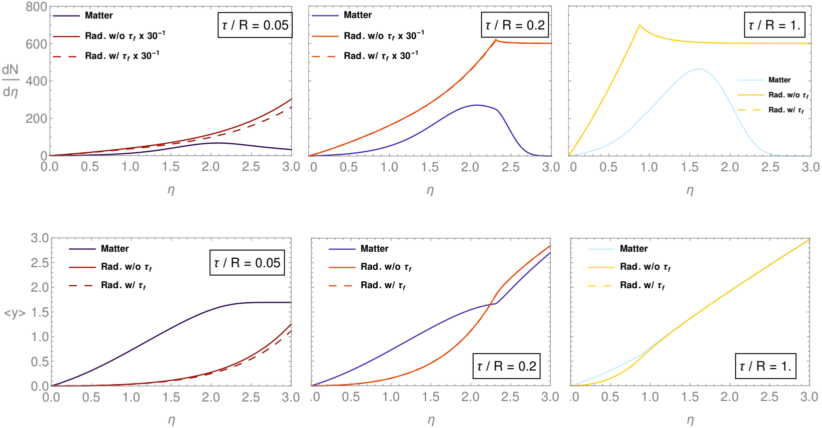
We assume a flat rapidity spectrum for the gluon radiation.

$$f^{z_i}(z,t,y) = F\,\Theta\,(t-t_i)\;\delta(z-z_i-(t-t_i)\tanh y).$$



$\mathcal{T}_f = 1/Q_s$

Evolution of matter and radiation



The matter and the radiation have very different rapidity distributions at early times: suggests that a treatment of the early time dynamics in the fragmentation region may involve the dynamics of two fluids.

Summary

- Used the MV model to find a distribution of p_T and p_L for a classical particle interacting with a sheet of colored glass.
- Expressed compression and baryon stopping in terms of Q_s.
- There are two distinct fluids in the fragmentation region.
- We need an improved radiation calculation to make more quantitative statements.

Thank You