Measuring QGP thermalization time with dileptons

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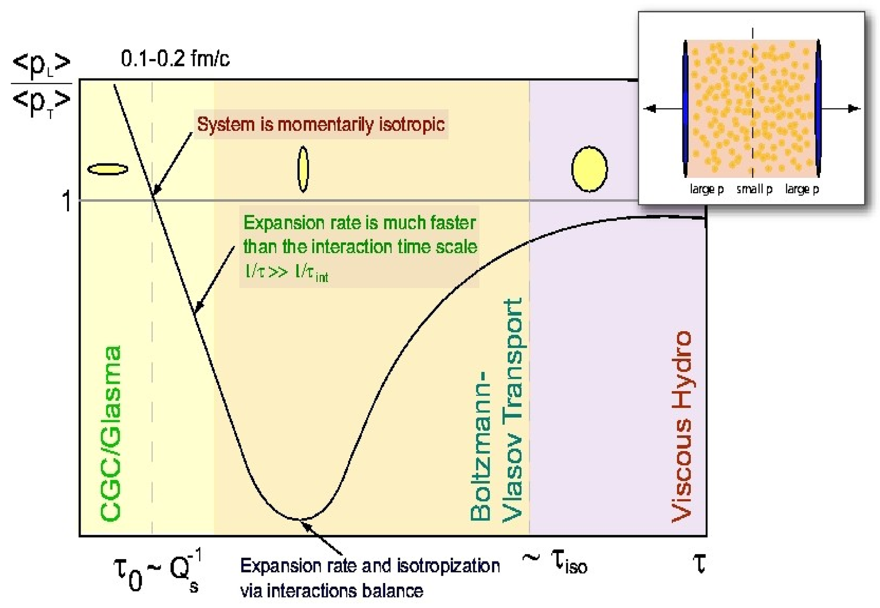
Abstract

We calculate leading-order dilepton production resulting from the annihilation process $q\bar{q}\rightarrow l^+l^-$ from a quark-gluon plasma which has a time-dependent anisotropy in the momentum-space. A phenomenological model for the hard momentum scale, $P_{hard}(\tau)$ and the plasma anisotropy parameter, $\xi(\tau)$, is constructed. The model interpolates between free streaming behaviour at early times and ideal hydrodynamical behaviour at late times. Using this model, we show that for LHC energies, the medium dilepton production increases in the kinematic range $3 < P_T < 8$ GeV. As a result this observable is sensitive to the isotropization time of the system, τ_{iso}. Therefore high-energy dilepton production can be used to probe the degree of momentum-space isotropy of a quark-gluon plasma produced in relativistic heavy ion collisions and the time of onset of hydrodynamic expansion of the QGP.

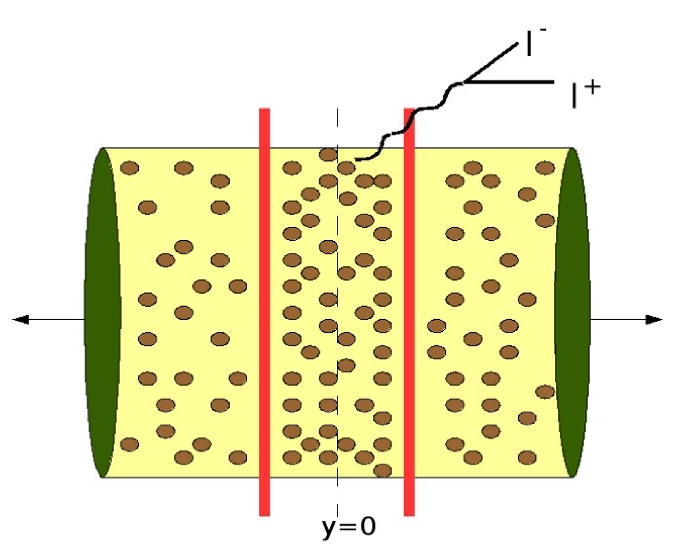
Early time dynamics of the QGP



- At $\tau = \tau_0$, partons decouple from the incoming nucleus and their partonic momentum distributions look isotropic.
- The longitudinal expansion rate of the system is bigger than the interaction rate and this causes an anisotropy in the momentum-space (P_T - P_L plane).
- At $\tau \approx \tau_{iso}$, interactions balance the expansion rate and the system looks isotropic in momentum-space.
- Many details of the pre-equilibrium phase of the QGP are not understood.

One way to go further is studying consequences of the possible early dynamics of the collision on observables sensitive to this stage like electromagnetic signatures.

Electromagnetic Signatures of the QGP



- Photons and electrons can interact only electromagnetically with the interacting medium created after the collision.
- Electromagnetic signatures give information about initial parton distributions and early time dynamics of the collisions.
- For experimentalists it is difficult to measure photons due to large backgrounds.
- Dileptons offer a better option since one can study production as a function of mass and transverse momentum.
- Influence of the momentum-space anisotropy on dilepton production?

Dileptons from an anisotropic plasma

At leading order, the dilepton production is given by:

$$E\frac{dR_{\rm ann}}{d^3P} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3}\frac{d^3\mathbf{p}_2}{(2\pi)^3} f_q(\mathbf{p}_1)\, f_{\bar{q}}(\mathbf{p}_2)\, v_{q\bar{q}}\, \sigma^{l^+l^-}_{q\bar{q}}\, \delta^{(4)}(P-p_1-p_2)$$

The invariant distributions of dilepton production as a function of M and P_T are respectively:

$$\frac{dN}{dM^2dy} = \pi R_T^2 \int d^2P_T \int_{\tau_0}^{\tau_f}\int_{-\infty}^{\infty} \frac{dR_{\rm ann}}{d^4P}\tau d\tau d\eta$$

$$\frac{dN}{d^2P_T dy} = \pi R_T^2 \int dM^2 \int_{\tau_0}^{\tau_f}\int_{-\infty}^{\infty} \frac{dR_{\rm ann}}{d^4P}\tau d\tau d\eta$$

- $dR_{\rm ann}/d^4P$ depends on the direction of the anisotropy and the angle of the dilepton pair respect to the beam axis. Hence, the invariant distributions will be affected by the anisotropy in the momentum-space.
- As an ansatz, an anisotropic phase space for quarks and anti-quarks is given by:

$$f_i(\mathbf{p},\xi,p_{\rm hard}) = f^i_{iso}(\sqrt{\mathbf{p}^2+\xi(\mathbf{p}\cdot\hat{\mathbf{n}})^2}, p_{\rm hard})$$

ξ measures the strength of the anisotropy and it's related to the transverse and longitudinal momentum through the relation $\xi = \langle p_T^2\rangle/2\langle p_L^2\rangle - 1$

Model for an anisotropy in momentum-space

In a free streaming plasma:

$$\xi_{FS}(\tau) = \left(\frac{\tau}{\tau_0}\right)^2 - 1$$

$$\lim_{\tau\gg\tau_0} \mathcal{E}(\tau) \Rightarrow \mathcal{E}_0\left(\frac{\tau_0}{\tau}\right)$$

$$"T" = T_0$$

In a hydrodynamical plasma:

$$\xi(\tau) = 0$$

$$\mathcal{E}(\tau) = \mathcal{E}_0\left(\frac{\tau_0}{\tau}\right)^{4/3}$$

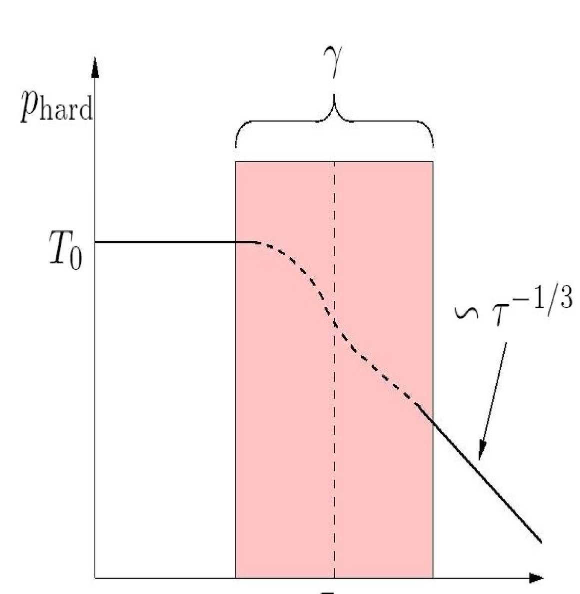
$$T = T_0\left(\frac{\tau_{iso}}{\tau}\right)^{1/3}$$

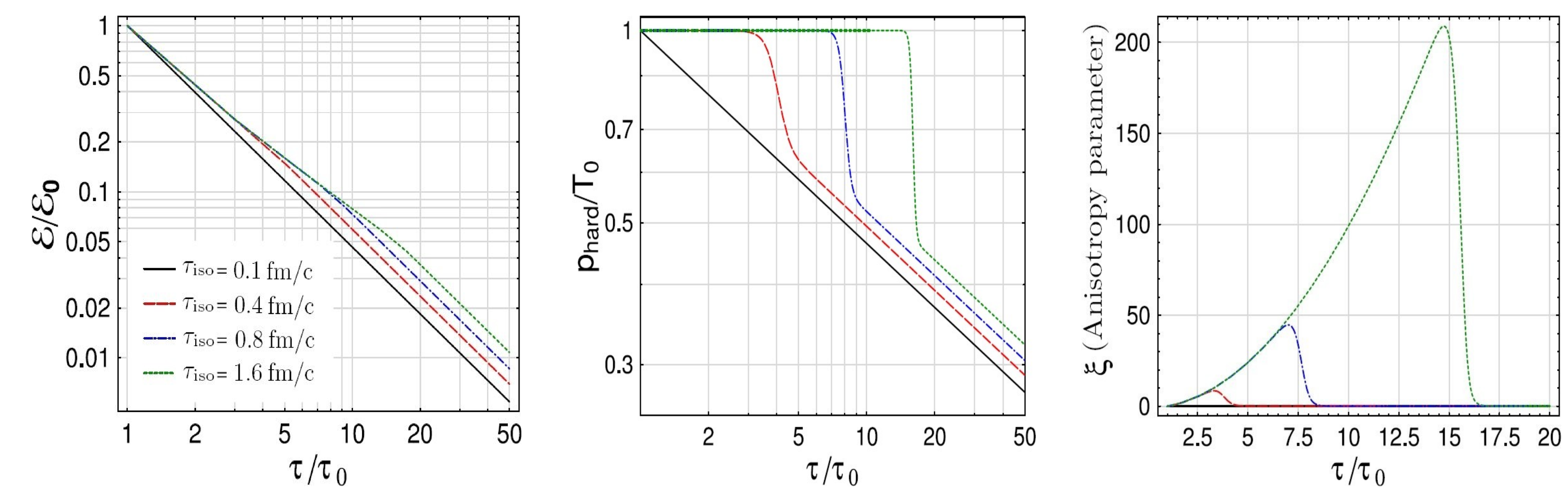
We propose a model that interpolates between free streaming and hydrodynamics using a smeared function $\lambda_\gamma(\tau-\tau_{iso})$:

$$\begin{aligned}\mathcal{E}(\tau) &= \mathcal{E}_{\rm FS}(\tau)\,[\mathcal{U}(\tau)/\mathcal{U}(\tau_0)]^{4/3}\,,\\ p_{\rm hard}(\tau) &= T_0\,[\mathcal{U}(\tau)/\mathcal{U}(\tau_0)]^{1/3}\,,\\ \xi(\tau) &= a^{2(1-\lambda(\tau))}-1\,,\end{aligned}$$

$$\mathcal{U}(\tau) = \left[\mathcal{R}\left(\left(\frac{\tau_{\rm iso}}{\tau}\right)^2-1\right)\right]^{\frac{3\lambda(\tau)}{4}}\left(\frac{\tau_{\rm iso}}{\tau}\right)^{\lambda(\tau)}$$

$$\mathcal{R}(\xi(\tau)) = \left(\frac{1}{1+\xi(\tau)}+\frac{\arctan(\sqrt{\xi(\tau)})}{\sqrt{\xi(\tau)}}\right)$$

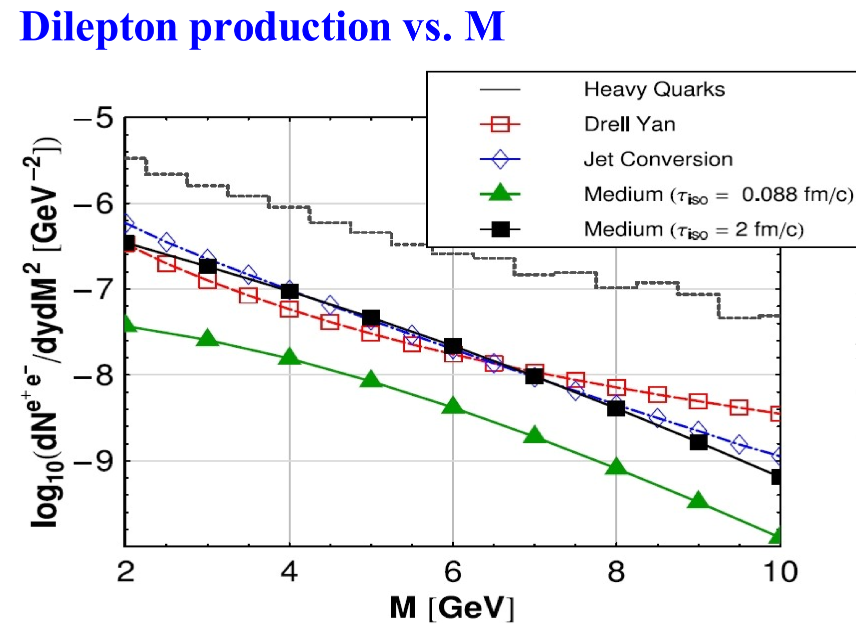




Time dependence of the energy density (left), hard momentum (center) and anisotropy parameter for four different isotropization times using the proposed interpolating model.

Results

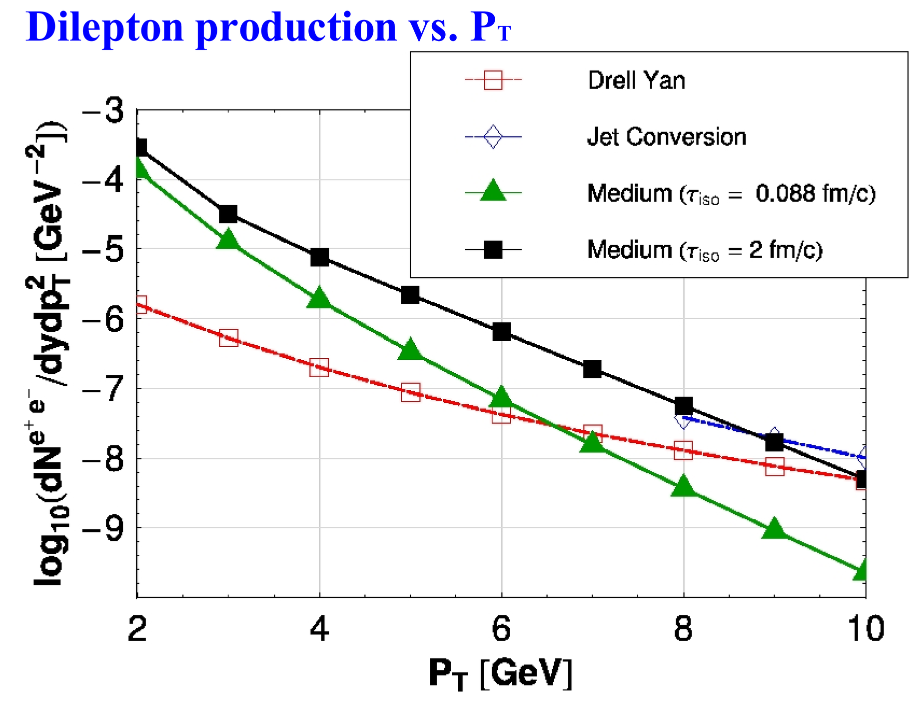
Dilepton production vs. M



Dilepton production as a function of the invariant mass M with a cut $P_T > 8$ GeV. τ_{iso} is taken to be either 0.088 fm/c or 2 fm/c. A K-factor of 1.5 was applied to account for NLO corrections.

- There is an enhancement of the medium dilepton yield when varying τ_{iso}.
- When τ_{iso} = 2 fm/c medium dileptons becomes as important as other sources.
- The enhancement is that longitudinal free streaming preserves more P_T than hydrodynamics.
- However, it makes difficult to measure a clean medium dilepton signal.

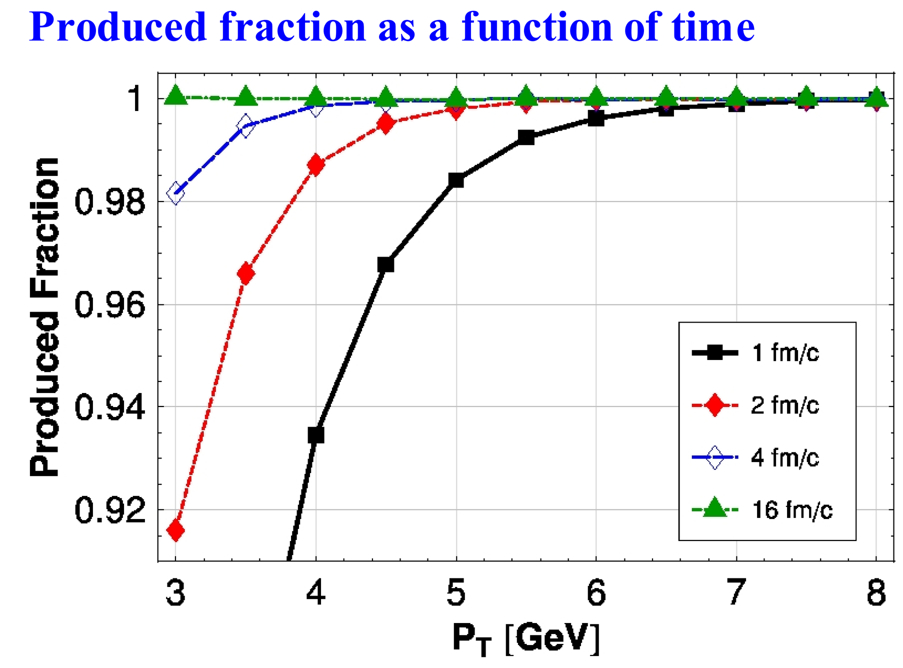
Dilepton production vs. P_T



Dilepton production as a function of the transverse momentum with a cut 0.5< M < 1 GeV. τ_{iso} is taken to be either 0.088 fm/c or 2 fm/c. A K-factor of 6 was applied to account for NLO corrections.

- The medium contribution dominates over other sources for all $P_T \leq 6$ GeV. If τ_{iso} = 2 fm/c, the medium contribution dominates out to $P_T \approx 8$ GeV.
- At P_T = 5 GeV, the expected dilepton yield varies by nearly an order of magnitude depending on τ_{iso}.
- Then, it would be possible to measure τ_{iso} using dilepton production as a function of P_T. Moreover, it could provide a estimative of the anisotropy developed at early-times.

Produced fraction as a function of time



Fraction of dileptons produced at τ = {1,2,4,16} fm/c assuming τ_{iso} = 0.5 fm/c. Cuts are the same as in the P_T dependence.

- By 4 fm/c yields between 3 < P < 8 GeV are saturated.
- At 1 fm/c approx. 94% of all P_T = 4 GeV dileptons have been already produced.
- This highlights the sensitivity of this observable to early-times of the collision.
- Moreover, this justifies neglecting other effects like transverse expansion, and mixed/hadronic phases.

Conclusions

- **We construct an interpolating model between free streaming and hydrodynamics evolution. The model takes into account the time dependence of the anisotropy in the momentum-space.**
- **Dilepton production in the kinematic range $3 < P_T < 8$ GeV provides an estimative of the momentum-space anisotropy and a possible measure of the isotropization time, τ_{iso}.**

M. Martinez and M. Strickland, arXiv:0709.3576.