Pre-equilibrium dilepton production: concepts, estimates and feasibility

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Space-time evolution of heavy-ion collisions

- Heavy-ion collisions: different time scales described by different effective theories

- Late stages very accurately modeled by hydrodynamic descriptions for expanding near-equilibrium QGP

- A challenge: matching between far-from-equilibrium initial state predicted by CGC and viscous hydrodynamics

Dilepton production as a probe

- Electromagnetic interactions with the QGP have a small cross section → large mean free path in the medium

- Produced during all stages of the collision

- Dilepton carry extra information: invariant mass → not affected by blue-shift

Production rate given by current-current correlator:

\[
\frac{dN^{++}}{dx dq^2} = - \frac{\alpha_{em}^2}{6\pi^3 Q^2} \sum_f q^2 \Pi^{\mu,\mu}_f(Q)
\]

Intermediate mass region (M>1.5 GeV) → Characterized by quarks and gluons degrees of freedom

➢ Isolate early-times/pre-equilibrium emission

Production rate calculation: pressure anisotropy

- At early times, the system is highly anisotropic due to rapid longitudinal expansion
  $P_L << P_T$ and hydrodynamic description does not apply.

- Convergence towards attractor: universal feature of all microscopic descriptions of early-time dynamics.

- Local pressure isotropy occurs at late times, but applicability of viscous hydro better than anticipated.
  $\tau_{\text{hydro}} << \tau_{\text{eq}}$.

- Evolution of energy-stress tensor is calculated with QCD kinetics in weak coupling regime.

\[ \tau = \frac{\tau_{\text{eff}}}{(4\pi\eta/s)} \]

For typical parameters (e.g. $\eta/s=0.32$):
$\tilde{w}=1 \rightarrow \tau=3 \text{ fm/c} \rightarrow P_L/e=0.2$
Production rate calculation: quark suppression

- Initial state theories (CGC) predict a gluon-dominated medium at early times
  
  → quark suppression factor, defined as the ratio between quark and gluon energy density:

  \[ q_s(\tau) \propto \frac{e(q)}{e(g)} \left( T(\tau) \right) \]

- Transition of highly gluon-dominated system towards a chemically equilibrated medium

  \[ \text{Calculated in the weak coupling regime with QCD kinetics} \]

Production rate calculation : Correlator

Anisotropic (out-of-equilibrium) current-current correlator calculated at LO (quark-anti-quark annihilation)


\[ \Pi^{\mu,\nu}_{\mu}(Q) = -\frac{N_c Q^2}{4\pi^2 q} \int d^3 p \frac{1}{p^2} \delta \left( \cos \theta_{pq} - \frac{q^2 + 2pq_0 - q_0^2}{2pq} \right) f_q(p)f_{\bar{q}}(q-p) \theta(q^- < p < q^+) \]

We introduce distribution functions for quarks which are anisotropic in momentum space:

\[ f_q(\tau, p_T, p_L) = q_s(\tau)f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau)p_L^2}/\Lambda(\tau)\right) \]

→ Depend on \( \Lambda \) (anisotropic effective temperature), anisotropy parameter \( \xi \) calculated w/ \( P_L/e \), and quark suppression factor \( q_s \)
Space-time picture : Hydrodynamic attractor

\[ \frac{dN^{+\pm}}{dQdy} = -\int d^2 x_T \int d\tau \int d^3 \vec{q} \frac{Q}{q_0} \tau \frac{dN^{+\pm}}{d^4 x d^4 Q} \]

→ Integrate over space-time evolution of the medium to calculate the dilepton yield

→ Evolution of non-equilibrium parameters constrained by the evolution of energy density:

\[ e(T_{\text{eff}}(\tau)) = e(q_s(\tau), \xi(\tau), \Lambda(\tau)) \]

With:

\[ e(\tau) \equiv \frac{\pi^2}{30} \nu_{\text{eff}} T_{\text{eff}}^4(\tau) \]

→ Use of a hydrodynamic attractor: effective curve that gives access to early evolution of energy density

\[ \frac{e(\tau) \tau^{4/3}}{e_{\text{hydro}} \tau_{\text{hydro}}^{4/3}} = \mathcal{E}(\tilde{w}) \quad \tilde{w} = \frac{\tau T_{\text{eff}}}{4\pi \eta/s} \]

**Space-time picture : Hydrodynamic attractor**

- Assume one dimensional Bjorken expansion:
  - boost invariant along the longitudinal direction
  - translationally invariant in transverse directions

- Entropy approximately conserved during hydro expansion → entropy and particle production come from pre-equilibrium stage

→ Final condition at late times ($w >> 1$):

\[
\frac{e(\tau)\tau^{4/3}}{e_{\text{hydro}}\tau_{\text{hydro}}^{4/3}} = \mathcal{E}(\tilde{w})
\]

Fixed by charged particle multiplicity in the final state → final state entropy density

\[
\frac{dS}{d\eta} \propto \frac{dN_{\text{ch}}}{d\eta} \approx 1900 \quad \text{(For } \eta=2 \text{ at 5.02 TeV)}
\]

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Results: mass spectra

- Total dilepton rates as a function of dilepton invariant mass, for different shear viscosities

- $\eta/s$ is not the usual viscosity in the hydro regime but viscosity at high temperature: speed of system equilibration

- Lower $\eta/s$: quicker system equilibration
  $\rightarrow$ higher initial energy density
  $\rightarrow$ higher dilepton yield for fixed final condition

No K factor

Full lines: w/o quark suppression, Dotted lines: w/ suppression
Results: time decomposition

- Full lines: w/o quark suppression, dotted lines: w/ suppression
- Different slopes, higher masses dominated by early emission
- Strong sensitivity to $\eta/s$ and to quark suppression
  → measurement to learn about chemistry and medium properties in pre-equilibrium phase
Comparison with Drell-Yan and centrality dependence

- Drell-Yan process calculated at fixed-order NLO → dominates dilepton production at high mass

- Pre-equilibrium + hydro production is very sensitive to quark suppression → direct access to early-stage chemistry and potentially direct measurement

\[ \frac{dE_0}{d\eta} \propto \left( \frac{dN_{\text{ch}}}{d\eta} \right)^{3/2} \]

- Significant centrality dependence → initial-state energy grows with charged particle multiplicity
Dominant background for intermediate mass dileptons in heavy ion collisions at 5.02 TeV: semileptonic decay of charm and beauty.

Rejection of background:

- Impact parameter of the single-track muons
- Longitudinal displacement of the secondary vertex

Requires LHCb upgrade 2 setup for heavy ion collisions.
Conclusion and outlook

• Window of dominating pre-equilibrium production identified
  → insight into quark suppression & matter properties at early stages

• Transverse momentum spectra can be used as an additional discriminator

• Background suppression: secondary vertexing
  → LHCb best performance: small distance between instrument and primary vertex, and longitudinal boost
Thank you!
Backup
Heavy-flavour background

We approximate the charm/beauty yield in Pb-Pb with the p-p cross sections computed with FONLL, and the nuclear form factor from ALICE at 5 TeV:

In centrality bin 0 – 10%, 2 < \eta < 5:
\sigma_C^{pp} = 0.94 \text{ mb, } <T_{AA,C}> = 23.26 \text{ /mb}

\( \langle T_{AA} \rangle = \frac{A^2}{O_{AA}} \)
\( R_{AA} = \frac{N_{AA}^{AA}}{\langle T_{AA} \rangle O_{pp}} \)

\( \sigma_B^{pp} = 0.04 \text{ mb, } <T_{AA,C}> = 23.26 \text{ /mb} \)

\( N_{C}^{AA} = <T_{AA}> \sigma_C^{pp} \approx 87 \)
\[ \begin{align*}
  f=0.232 & \quad D^+ \quad BR=0.16 \\
  f=0.549 & \quad D^0 \quad BR=0.065 \\
  f=0.120 & \quad \Lambda_C \quad BR=0.045
\end{align*} \]

\( N_{B}^{AA} = <T_{AA}> \sigma_B^{pp} \approx 4 \)
\[ \begin{align*}
  f=0.403 & \quad B^+ \quad BR=0.10 \\
  f=0.403 & \quad B^0 \quad BR=0.11
\end{align*} \]
Scale variation in Drell-Yan calculation