Intermediate mass dileptons as a speedometer of QGP equilibration

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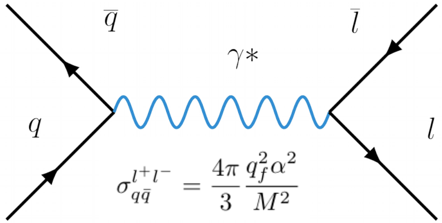
Introduction : The ideal spectrum

- Dileptons are created throughout the history of the collision → probe entire space-time dynamics including early stages and thermalization

- At LO, production by quark-antiquark annihilation :

$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2) |\mathcal{A}|^2 (2\pi)^4 \delta^{(4)}(P_1 + P_2 - K),$$

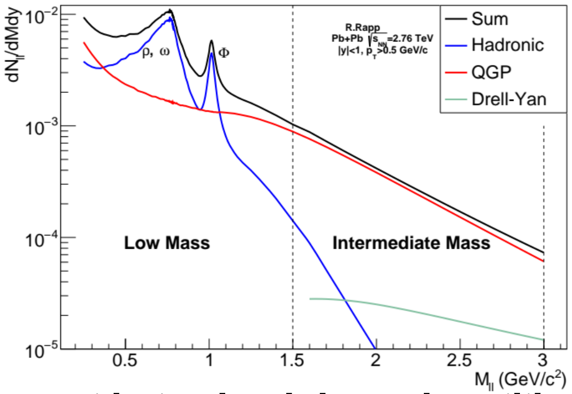


$$\sigma_{q\bar{q}}^{l^+l^-} = \frac{4\pi}{3} \frac{q_f^2 \alpha^2}{M^2}$$

- Thermal dileptons from QGP dominate invariant mass spectrum for M ≳ 1.5 GeV/c²

→ how early pre-equilibrium effects manifest themselves in the spectra of dileptons ?

R.Rapp, Adv. High Energy Phys. (2013) 148253, private communication



Start by considering local thermal equilibrium (LTE):

- Assuming boost invariance of the expanding QGP at early times and neglecting transverse flow, production rate **depends only on transverse mass M_t** :

$$\frac{dN^{l^+l^-}}{d^4K} = C \int d\mathbf{x}_\perp \int_0^\infty \tau d\tau \int_{-\infty}^{+\infty} dy_f \exp\left(-\frac{M_t \cosh(y-y_f)}{T(\mathbf{x}_\perp,\tau)}\right)$$

- Further assuming a conformal equation of state and a uniform temperature profile in transverse plane, one finds the McLerran-Tomeila formula :

$$\left(\frac{dN^{l^+l^-}}{d^4K}\right)_{\text{ideal}} = \frac{32 N_c \alpha^2 \sum_f q_f^2}{\pi^4} \frac{A_\perp (\tau T^3)^2}{M_t^6}$$

Pre-equilibrium dynamics

Effects of pre-equilibrium dynamics :

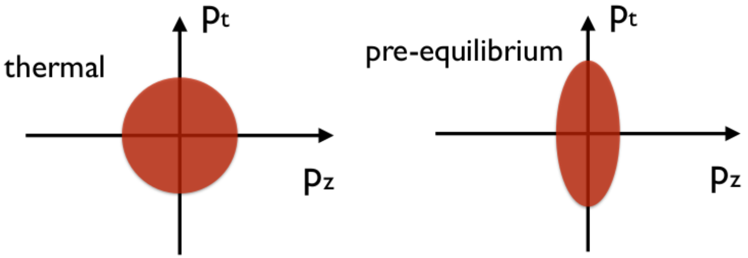
- Quarks are underpopulated relative to gluons at early times
- Momentum distributions of quarks and gluons are anisotropic (rapid longitudinal expansion)

→ Encapsulated in parametrization of the quark distribution:

Strickland PRD 92, 025026 (2015), PRD 99 3, 034015 (2019)

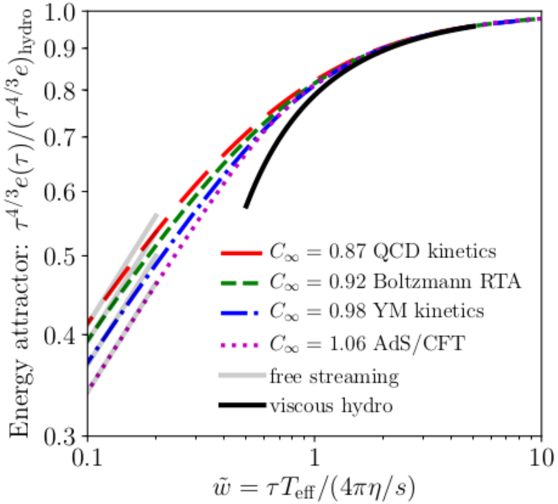
$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2}/\Lambda(\tau)\right)$$

q_s : quark suppression factor, ξ : anisotropy parameter, Λ: anisotropic temperature



→ Evolution of parameters computed in **QCD kinetics**

(X.Du Poster Session 1 T01) X. Du, S. Schlichting: PRD 104, 054011 (2021)



PRL 123, 262301 (2019)

- Quark suppression implies suppression of dilepton production, which is a global factor → **preserving M_t scaling**

  Deviation from LTE calculation, more pronounced at high mass (↔ early times ↔ fewer quarks). Relative suppression scales like :

$$Re^{-1}(M_t) \equiv \frac{\eta}{s}\frac{M_t^2}{\tau T^3}$$

  η/s : early time shear to entropy density ratio → departure from local thermal equilibrium

- Fast longitudinal expansion → pressure asymmetry → momentum anisotropy which **breaks M_t scaling**, favoring small masses for a given M_t value

Quantitative results

- Breaking of M_t scaling modest, compared to overall suppression of production yield due to quark underpopulation
- Spectra well fitted by the following formula :

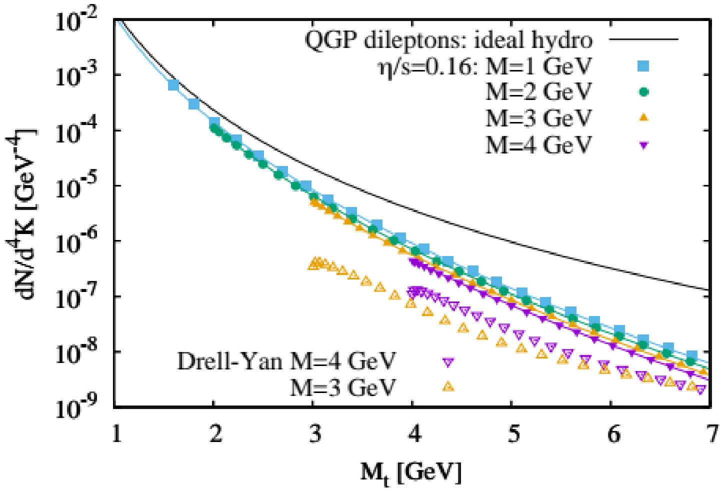
$$\frac{dN^{l^+l^-}}{d^4K} \simeq \left(\frac{dN^{l^+l^-}}{d^4K}\right)_{\text{ideal}} \frac{\left(1 + a\frac{\eta}{s}M_t^2/n\right)^{-n}}{\sqrt{1 + b\frac{\eta}{s}M^2}}$$

a : M_t dependent suppression of the production, b : breaking of M_t scaling
→ corrections to ideal yield linear in η/s for small η/s.
→ ~1/M for large η/s, showing breaking of M_t scaling.

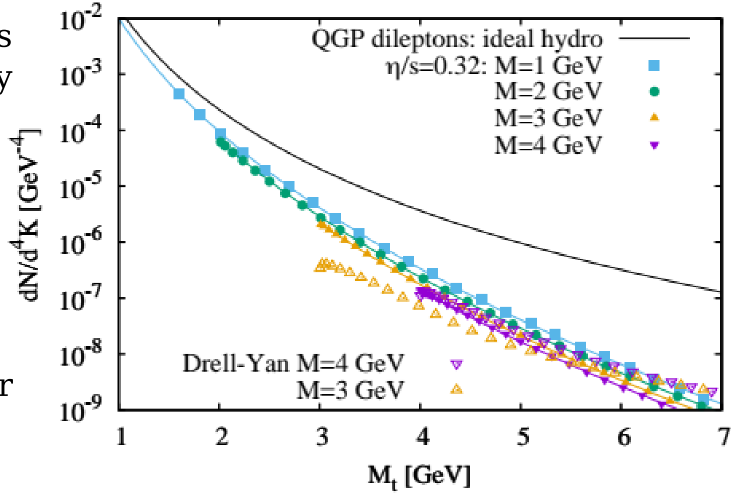
- larger η/s → later thermalization → temperature starts decreasing as $\tau^{-1/3}$ later on → lower initial temperature for fixed final energy density
- Inverse slope of the M_t spectrum → effective temperature :

$$T_{\text{eff}}(M_t) \equiv -\left[\frac{d}{dM_t}\ln\left(\frac{dN^{l^+l^-}}{d^4K}\right)\right]^{-1} \rightarrow \quad T_{\text{eff}}(M_t) \simeq \frac{M_t}{6 + 2a\frac{\eta}{s}M_t^2}$$

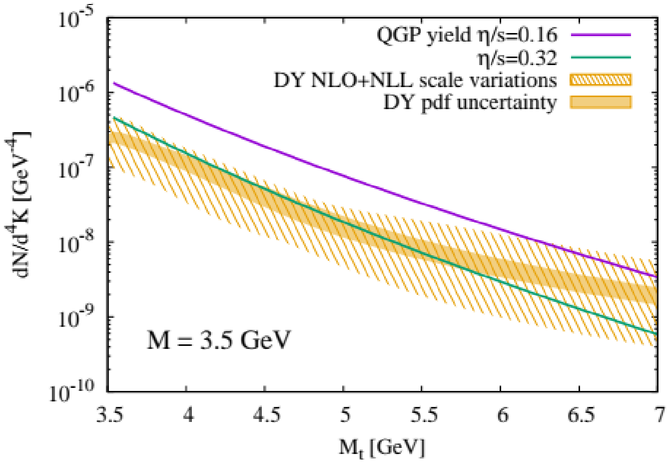
- Drell-Yan dominates spectrum at high M_t → DY enhanced for larger values of M at fixed M_t, **opposite behavior to QGP emission**.



0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1



Backgrounds & scalings



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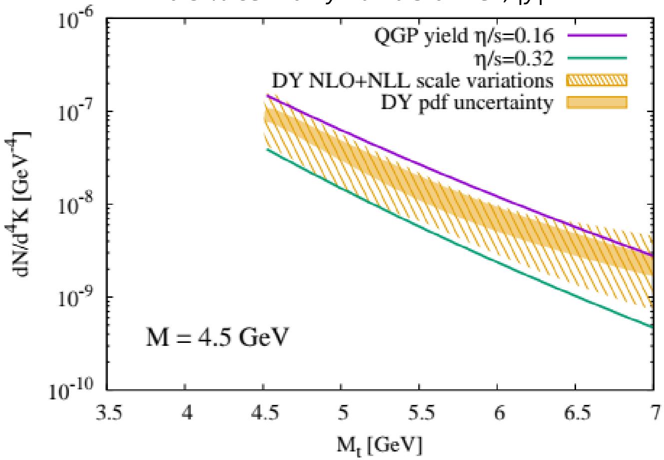

- Main backgrounds in intermediate mass region :
  → semileptonic decays of heavy flavours (rejectable based on displacement from primary vertex)
  → Drell-Yan production in the initial state.
- Drell-Yan contribution calculated using DYTurbo software, evaluated at NLO with resummed NLL (+Sudakov form factor includes non-perturbative contribution)

<u>Scaling properties</u>

- <u>System size/centrality:</u> Ideal spectrum scales with system size like $(dN_{ch}/d\eta)^{4/3}$
  → scales like space-time volume
  → pre-equilibrium effects (a & b parameters) scale like $(dN_{ch}/d\eta)^{-1/3}$ (up to event by event fluct.)
- <u>Collision energy:</u> Ideal spectrum scales with $\sqrt{s_{NN}}$ like $(dN_{ch}/d\eta)^2$
  → pre-equilibrium effects scale like $(dN_{ch}/d\eta)^{-1}$

Conclusion

- Dilepton spectrum gives **access to η/s** that controls the **equilibration time** (→ can be inferred by measuring the slope), as well as early-stage chemistry
- Distinguish experimentally QGP production from Drell-Yan production by studying variation of yield as a function of **M at fixed M_t**
- Our calculation : neglected transverse flow, sizeable effect for $\tau_T > 5$ fm/c. Estimated fraction of dilepton yield emitted after τ_T : for M_t=2 GeV 25 % of spectrum, for M_t=3 GeV only 4 % of the spectrum is late emission.

Thank you !