What does the slope of the prompt dilepton mass spectrum above 1.5 GeV/c^2 tell us?

Michael Winn

based on:

M. Coquet, X. Du, J.-Y. Ollitrault, S. Schlichting, M. Winn

PLB 821 (2021) 136626, NPA 1030 (2023)

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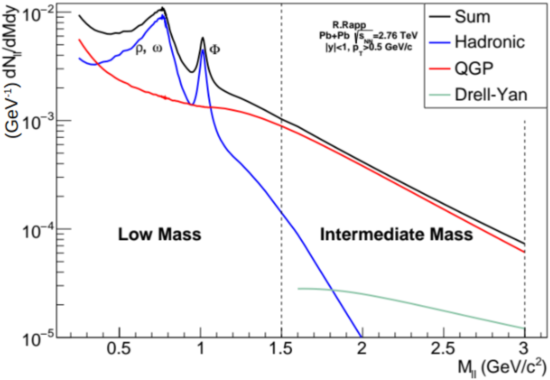
DE LA RECHERCHE À L'INDUSTRIE cea

Gluodynamics

P2IO Physique des 2 Infinis et des Origines

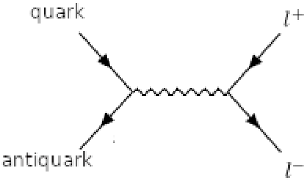
Motivation



- Dileptons: an observable not affected by interactions after production
  → powerful observables complementary to hadronic ones
  → contains information otherwise difficult to access
- major goal of future instrumentation at the LHC: ALICE 2/3, LHCb U2
- important to clarify: which system property we are most sensitive to?
  → focus here on intermediate mass

Dilepton emission from the QGP in equilibrium

McLerran, Tomeila
Phys. Rev. D 31, 545, 1985,
perturbative QCD leading order

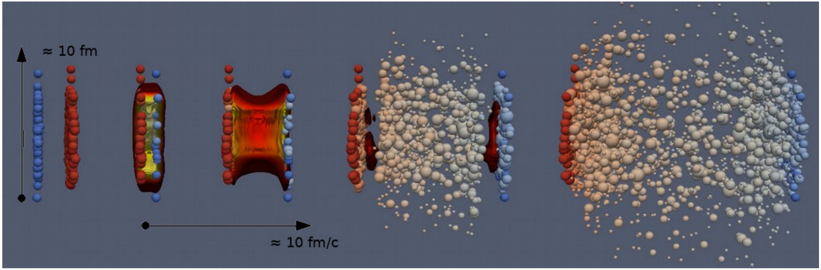


$$\frac{dN^{ll}}{d^4x d^4K} = \int \frac{d^3p_1}{(2\pi)^3 2p_1} \frac{d^3p_2}{(2\pi)^3 2p_2} f_q(x, \mathbf{p_1}) f_{\overline{q}}(x, \mathbf{p_2})$$
$$|A|^2 (2\pi)^4 \delta^{(4)}(P_1 + P_2 - K)$$
$$= C\, exp\left(-\frac{k_0}{T(x)}\right)$$

K: dilepton four-momentum, P1(P2): quark (antiquark) four-momentum, x: space-time coordinate of fluid cell, A: pQCD amplitude

- differential yield proportional to Boltzmann factor $exp(-E/T)$
- need a space-time picture of collision for integrated yield in experiment

General qualitative remarks



Visualisation of a hydrodynamic simulation of a nucleus-nucleus collision by Madai project web page.

- energy density ϵ and temperature T montonically decreasing as function of time τ
- dileptons M$>$1.5 GeV$/c^2$:
  M$>>$T for any T considered in local thermal equilibrium
  $\rightarrow$ early phase important: not immediately in equilibrium
- radiation also present, when matter not in local thermal equilibrium
- temperature T is an equilibrium property, not defined out-of-equilibrium

Idealized picture at colliders

- at RHIC and LHC longitudinal boost invariance: good first approximation for hydrodynamic modeling
- McLerran, Tomeila PRD 31, 545, 1985: result for local thermal equilibrium at all times in Bjorken expansion at leading order for m_T spectrum, neglecting transverse flow

see also Coquet et al. for a derivation and numerical values for LHC NPA 1030 (2023)

$$\left(\frac{dN^{ll}}{d^4K}\right)_{ideal} = \frac{32 N_c \alpha^2 \Sigma_f q_f^2}{\pi^4} \frac{A_\perp (\tau T^3)^2}{M_T^6} \propto \frac{1}{M_T^6} \left(\frac{dN_{ch}}{d\eta}\right)^{4/3}$$

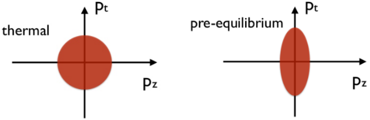
- **result is a power-law:** $\propto M_T^{-6}$**, the slope** $T_{eff} = \frac{M_T}{6}$

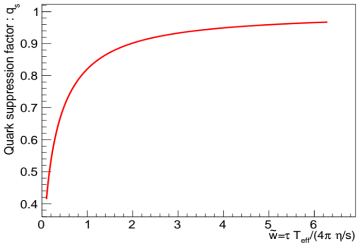
integrating over p_T at fixed M:

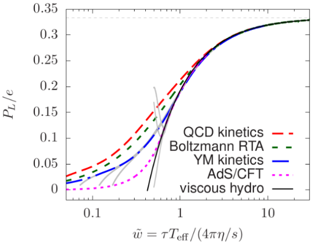
$$\left(\frac{dN^{ll}}{dMdy}\right)_{ideal} = \frac{16 N_c \alpha^2 \Sigma_f q_f^2}{\pi^3} \frac{A_\perp (\tau T^3)^2}{M^3} \propto \frac{1}{M^3} (\frac{dN_{ch}}{d\eta})^{4/3}$$

τT^3 is a constant, $(s\tau)^2_{hydro} \propto (\tau T^3)^2 \propto \left(\frac{1}{A_\perp}\frac{dN_{ch}}{d\eta}\right)^2$, $A_T \propto \frac{dN_{ch}}{d\eta}^{2/3}$

Beyond idealization







left: PRD 104, 054011 (2021), right: Courtesy b. M. Coquet (upper), G. Giacalone et al.PRL 123, 262301 (2019) (lower)

Start from idealization, treat most important non-equilibrium features:

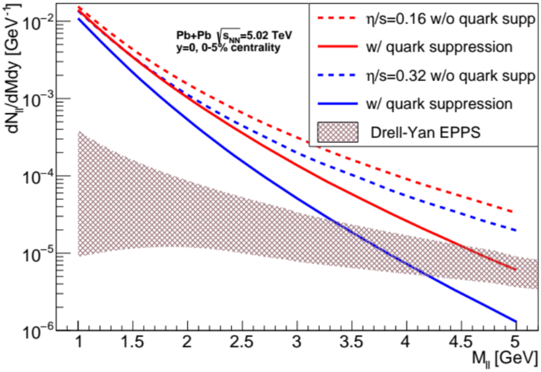
- gluon dominated initial state: quarks suppressed, X. Du, S. Schlichting PRD 104, 054011 (2021), PRL 127, 122301 (2021) *(chemical non-equilibrium)*
- pressure anisotropy: equilibration time scale ($\propto \eta/s$) *(kinetic non-equil.)*

Implemented in Coquet et al., hydrodynamics starts for $\tilde{w} > 1$ with:
$\tilde{w} = \tau T_{eff}/(4\pi\eta/s)$, $T_{eff} = \sqrt[4]{\epsilon}$

Model in a nut-shell

- state-of-the-art non-equilibrium and estimated η/s
- anisotropic hydrodynamics
- longitudinal boost invariance, very good proxy for early times, *Bjorken expansion*
- leading order calculation (as in Rapp-Hees case)
- entropy anchored via final state $dN/d\eta$ as in hydrodynamic calculations

Yield results



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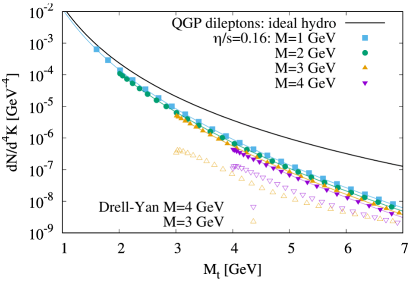
- strong sensitivity to quark suppression and η/s at early times
- at highest masses, before Drell-Yan dominance up to a factor 10

Hydrodynamics starts for $\tilde{w} > 1$ with:
$\tilde{w} = (\tau T_{eff})/4\pi\eta/s$, $T_{eff} = \sqrt[4]{\epsilon}$
η/s larger, later thermalisation, lower initial temperature for fixed final entropy density

Results for the slope



0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1, η/s=0.16

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- deviation from ideal McLerran-Tomeila power-law can be parameterised as function of η/s
- slope can be parameterised as the following

$$T_{eff}(M_T) \approx \frac{M_T}{6 + 2 \cdot a \cdot \eta/s \cdot M_T^2}$$

a: fit parameter related to quark suppression

Relation to Rapp-Hees

- reference PLB 753, 586 (2016)
- Rapp-Hees no emission before thermalisation
  $\rightarrow$ our point: nature does not know about this switch, need preequilibrium
- since M$>>$ T: in Rapp-Hees, slope to first approximation measurement of initial temperature after thermalisation

In our approach, hydrodynamics starts for $\tilde{w} > 1$ with:
$\tilde{w} = (\tau T_{eff})/(4\pi\eta/s)$, $T_{eff} = \sqrt[4]{\epsilon}$
η/s larger, later thermalisation, lower initial temperature for fixed final entropy density
besides quark suppression, most important information encoded in dilepton spectrum

Therefore: we advertize instead saying that we measure the ´first equilibrium temperature´
$\rightarrow$ slope sensitive to thermalisation speed encoded in η/s at early times

Identified caveat not yet treated in depth: sensitivity to initial gluon distribution in momentum space $\rightarrow$ constrain with other measurements

Uncontroversial conclusion

- differential leading order equilibrium rate:
  exponential with temperature slope
- integrated yield, longitudinal boost, neglecting transverse flow, leading order equilibrium rates:
  power-law, local slope $M_T/6$, $M/3$

Conclusion from Coquet et al.

- since M>> T for any τ ($\tau > \tau_{eq}$):
  early times most important (uncontroversial)
- T only defined after thermalisation: T is not a good quantification
- ideal case integrated yield: a power-law $\propto M_T^{-6}, M^{-3}$
- advertize:
  $\rightarrow$ start from ideal case
  $\rightarrow$ parameterise deviation from it
  $\rightarrow$ slope deviation from ideal case controlled by η/s
  $\rightarrow$ works very well
  $\rightarrow$ precious information otherwise not directly accessible

P.S.: polarisation measure of pressure anisotropy, publication in preparation, see talk by M. Coquet at Hard Probes link

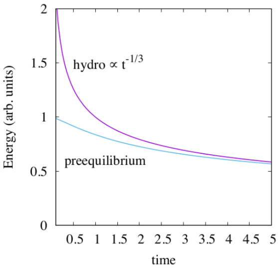
Back-up

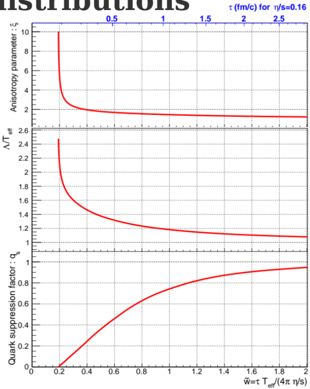
Out-of-equilibrium quark distributions

Distribution for quarks anisotropic in momentum space :

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

→ Depend on Λ (anisotropic effective temperature), anisotropy parameter ξ calculated w/ P_L/e, and quark suppression factor q_s





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