Intermediate mass dileptons as pre-equilibrium probes in heavy ion collisions

GDR QCD, 25th November 2021, Maurice Coquet

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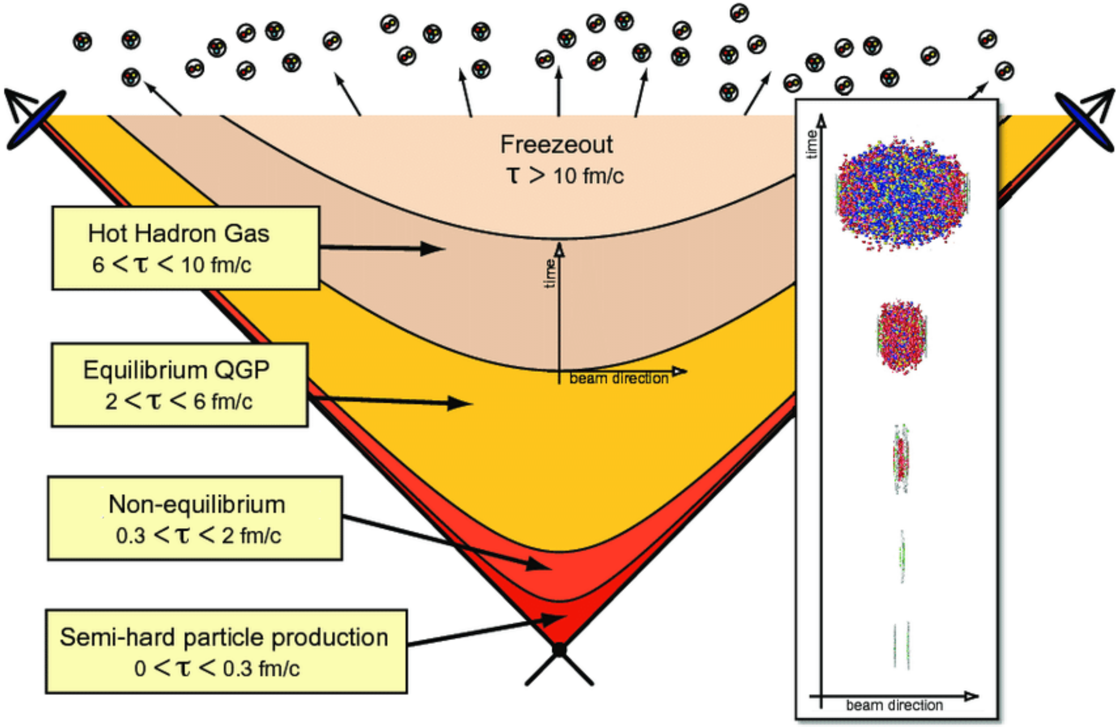
Phys.Lett.B 821 (2021) 136626

Space-time evolution of heavy-ion collisions

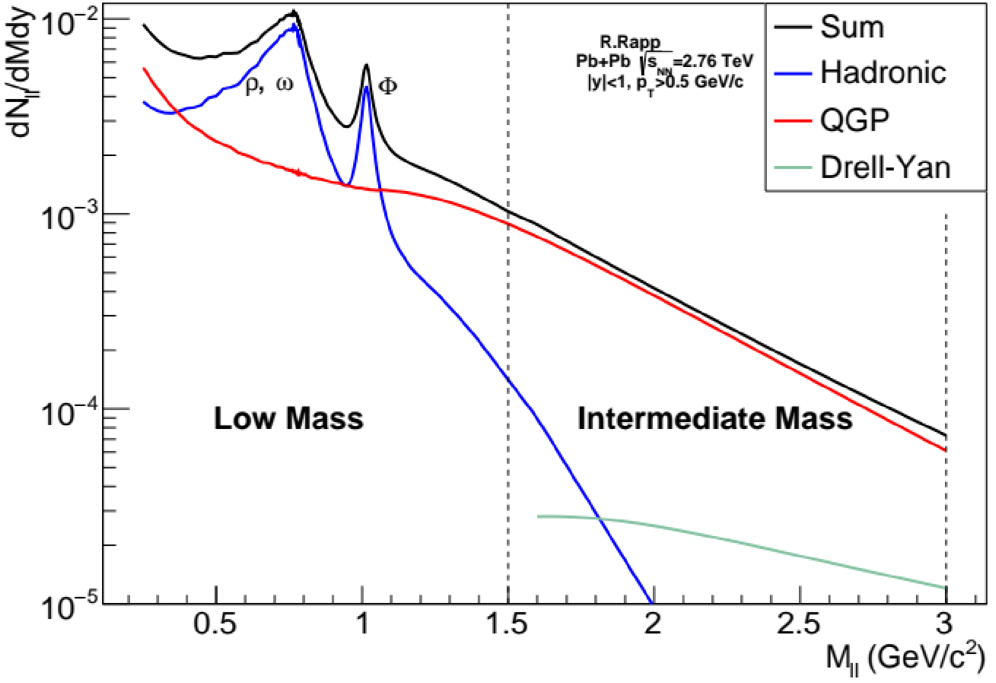
- A+A collisions: different time scales described by different effective theories
- Late stages very accurately modeled by hydrodynamic descriptions of expanding near-equilibrium QGP
- A challenge : matching between far-from-equilibrium initial state and viscous hydrodynamics



M.Strickland, Acta Physica Polonica B 45, 2355 (2014)

Dilepton production as a probe

- Electromagnetic interactions with the QGP have a small cross section
- Produced during all stages of the collision
- Dilepton carry extra information : invariant mass → not affected by blue-shift



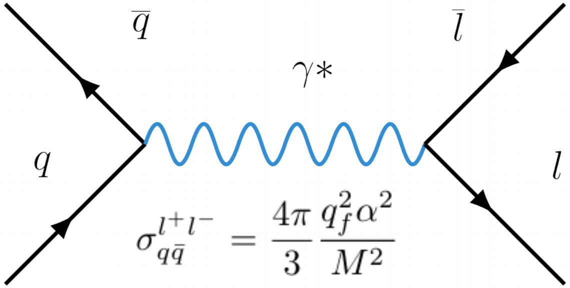
➔ Intermediate mass region (M>1.5 GeV) →<u>Characterized by quarks and gluons degrees of freedom</u>

➔ High mass ↔ High T ↔ early times

$$\frac{dN}{d^4x dM} \propto (MT)^{3/2} \exp\left(-\frac{M}{T}\right)$$

➔ Highly sensitive to early-times/pre-equilibrium emission

Production rate calculation



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

Production rate for dileptons from cross section calculated at LO (quark-anti-quark annihilation)

Cf: Strickland PRD 99 (2019) 3, 034015, Phys. Rev. C 103, 024904 (2021), Ryblewski, Strickland PRD 92, 025026 (2015)

$$\frac{dN^{l^+l^-}}{d^4x d^4K} = \int \frac{d^3\mathbf{p}_1}{(2\pi)^3}\frac{d^3\mathbf{p}_2}{(2\pi)^3} 4N_c \sum_f f_q(x,\mathbf{p}_1) f_{\bar{q}}(x,\mathbf{p}_2) v_{q\bar{q}} \sigma_{q\bar{q}}^{l^+l^-}\, \delta^{(4)}(K - P_1 - P_2)$$

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

$$\frac{dN}{dMdy} = \int \tau d\tau \int d\eta \int d^2x_T \,\frac{dN}{d^4x dM dy}$$

- Assume one dimensional Bjorken expansion :

→ boost invariant along the longitudinal direction
→ homogeneous in the transverse plane
→ Transverse flow neglected (high T ↔ early times)

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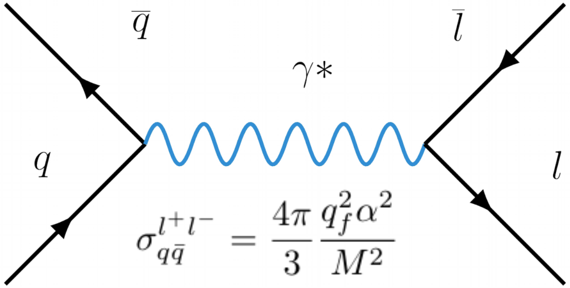

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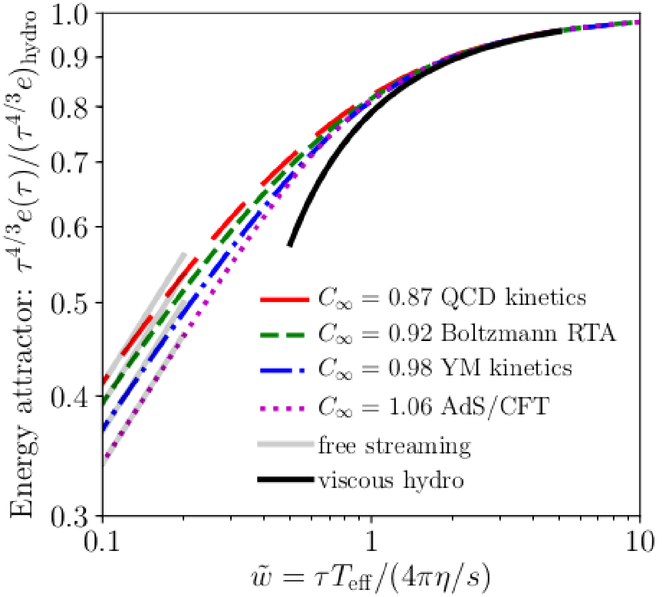
Pre-equilibrium dynamics

- Universality in pre-equilibrium dynamics (attractor solutions) as a function of scaling variable :

$$\tilde{w} = \frac{\tau T_{eff}}{4\pi\eta/s}$$

→ Can choose a specific calculation (QCD kinetics) to determine evolution of energy density and constrain pre-equilibrium dynamics



Giacalone, Mazeliauskas, Schlichting, Phys. Rev. Lett. 123, 262301 (2019)

- For this, need final condition at late times (w>>1):

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

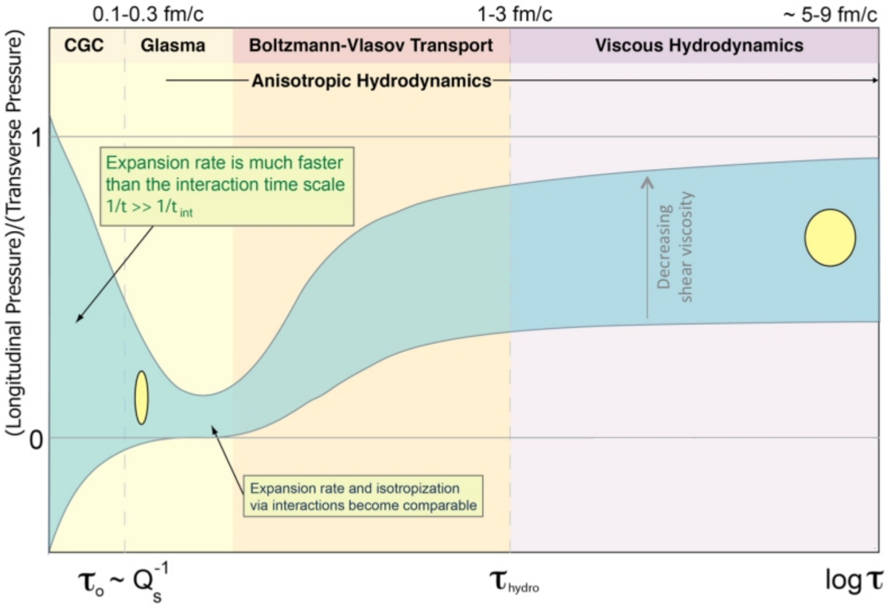
$$e(\tau) \equiv \frac{\pi^2}{30}\nu_{\rm eff} T_{\rm eff}^4(\tau)$$

- Fixed by charged particle multiplicity in the final state

→ final state entropy density $\frac{dS}{d\eta} \propto \frac{dN_{ch}}{d\eta} \approx 1900$ (For η=2 at 5.02 TeV)

Features of pre-equilibrium: pressure asymmetry

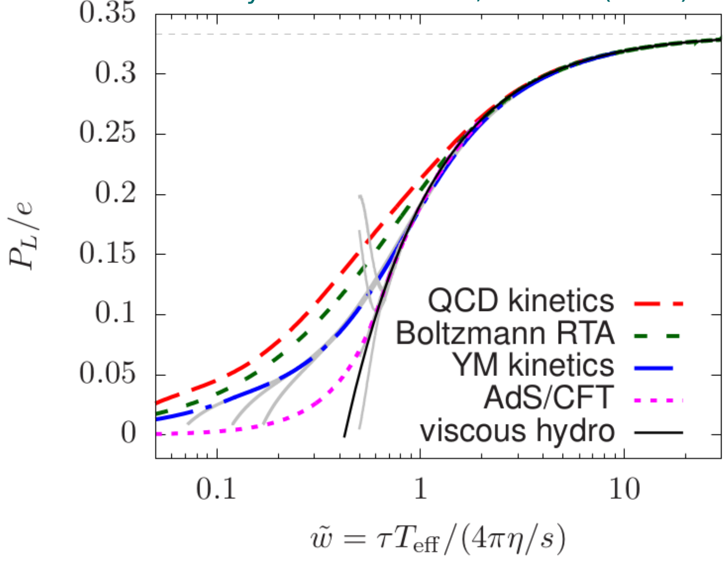
- At early times, rapid longitudinal expansion → $P_L << P_T$
  → *Anisotropy of distributions in momentum space*



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

M.Strickland, Acta Physica Polonica B 45, 2355 (2014)

Phys. Rev. Lett. 123, 262301 (2019)



For typical parameters (e.g. η/s=0.32) :
w=1 → τ=3 fm/c → pL/e=0.2

Features of pre-equilibrium: quark suppression

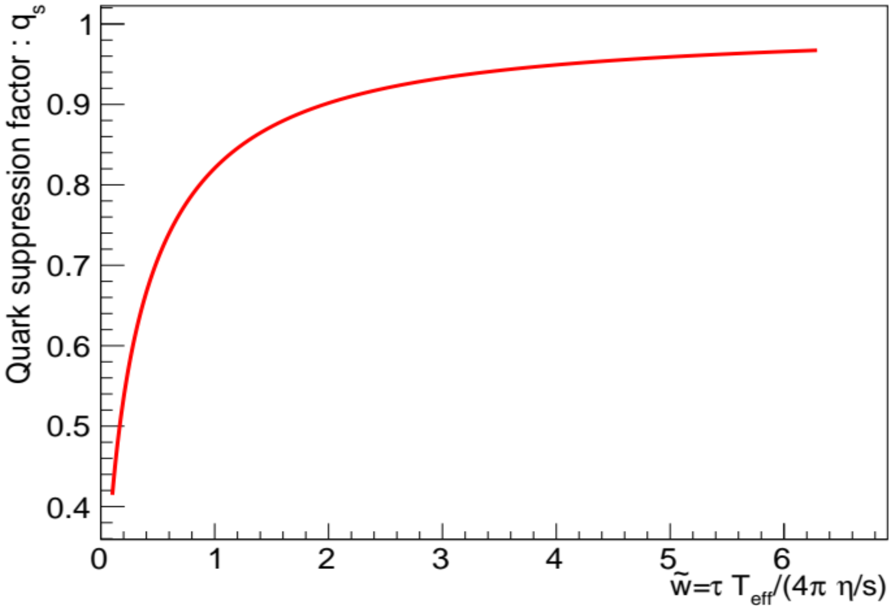
- Initial state theories (e.g. CGC) predict a gluon-dominated medium at early times

  → quark suppression factor, defined as the ratio between quark and gluon energy density :

$$q_s(\tau) \propto \frac{e^{(q)}}{e^{(g)}}\Big(T(\tau)\Big)$$

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

X. Du, S. Schlichting: Phys. Rev. D 104, 054011 (2021)
Phys. Rev. Lett. 127, 122301 (2021)



→ *Calculated in the weak coupling regime with QCD kinetics*

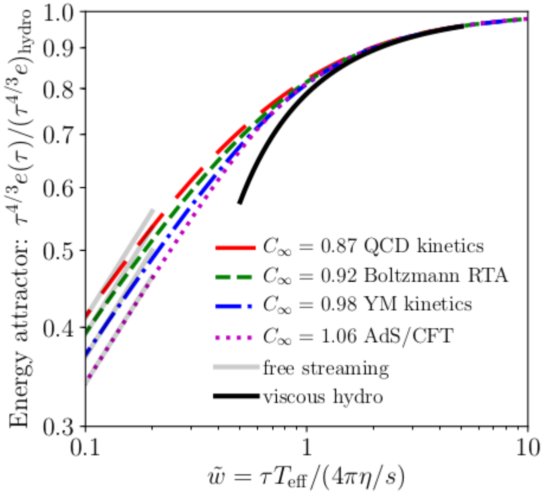
Out-of-equilibrium quark distributions

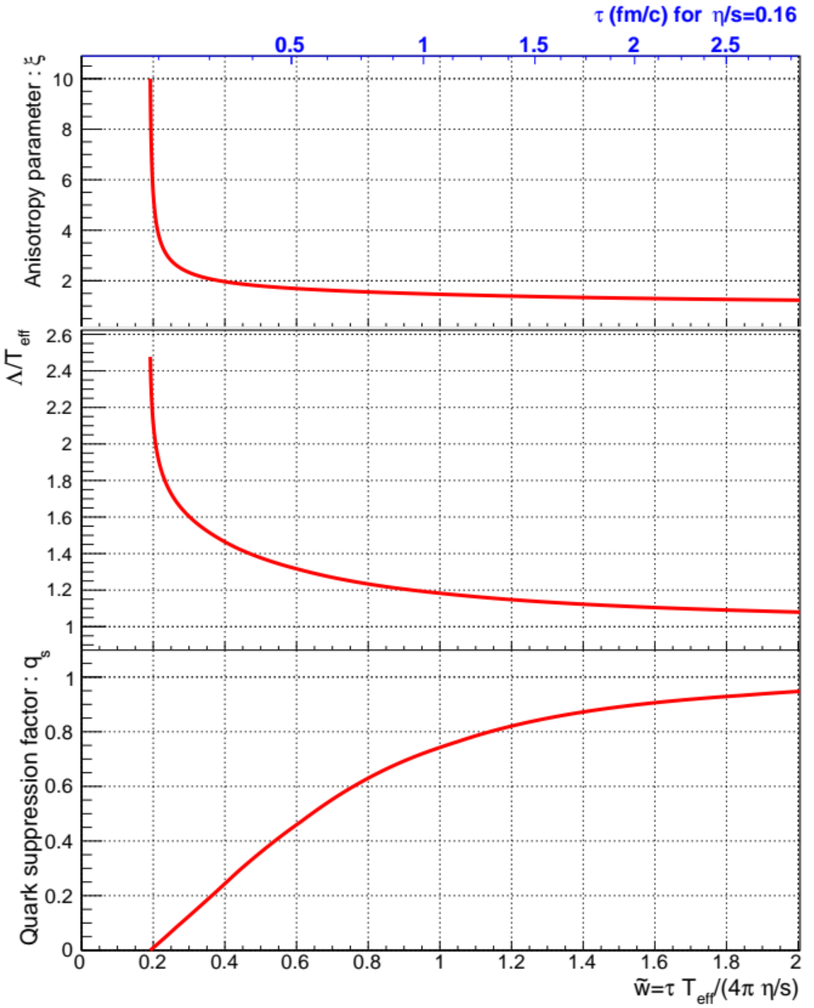
Distribution for quarks anisotropic in momentum space :

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

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

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





Results: mass spectra

- Yields can be fitted by the formula :

$$\frac{dN^{l_+l_-}}{dMdy} = C\left(1+\frac{M}{nT_0}\right)^{-n}$$

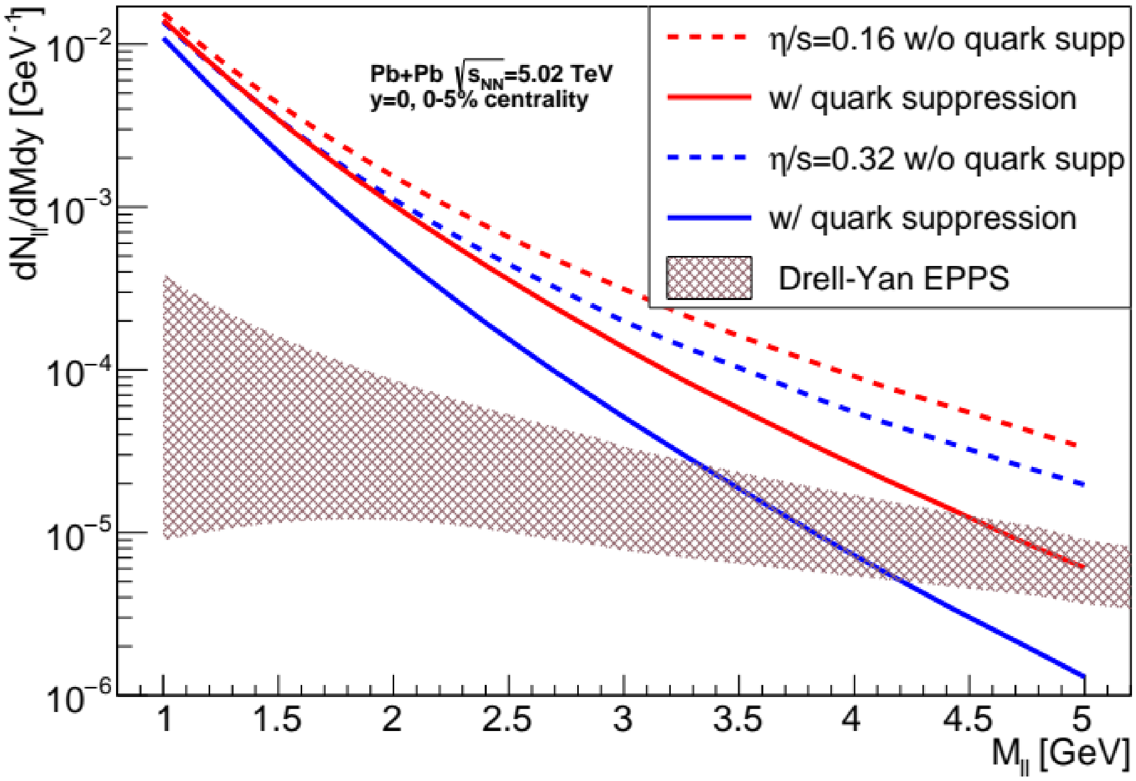
with C = 0.5 GeV^{-1} T_0 = 0.2 GeV and

$$n \simeq 5.3\left(1+4\frac{\eta}{s}\right)$$

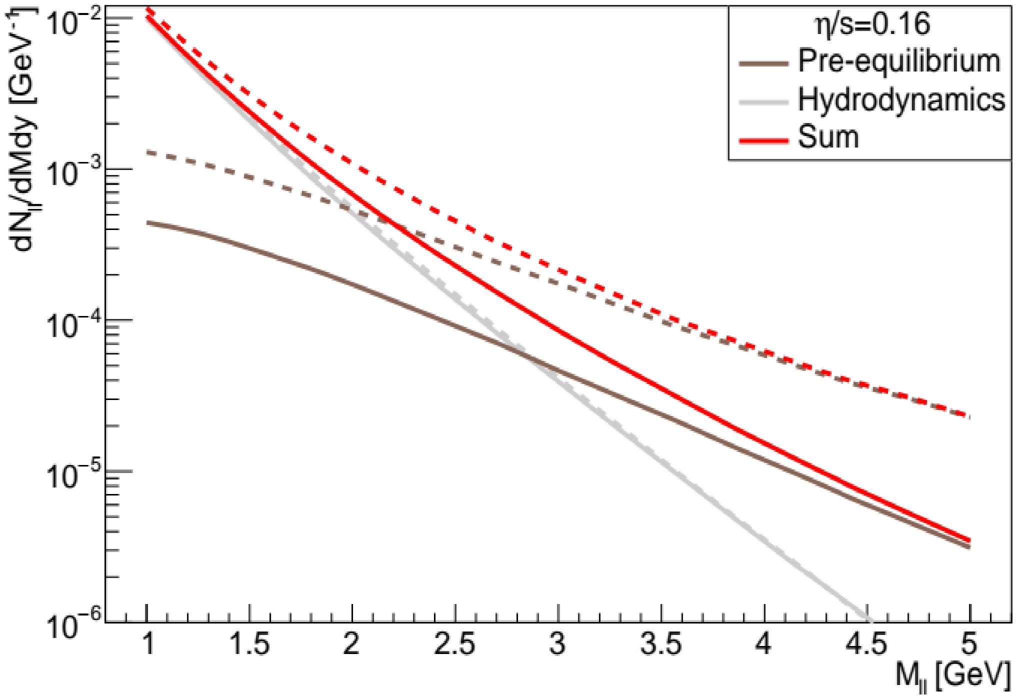
- η/s <u>is not</u> the viscosity in the hydro regime but viscosity at high temperature : controls time scale for applicability of hydrodynamics

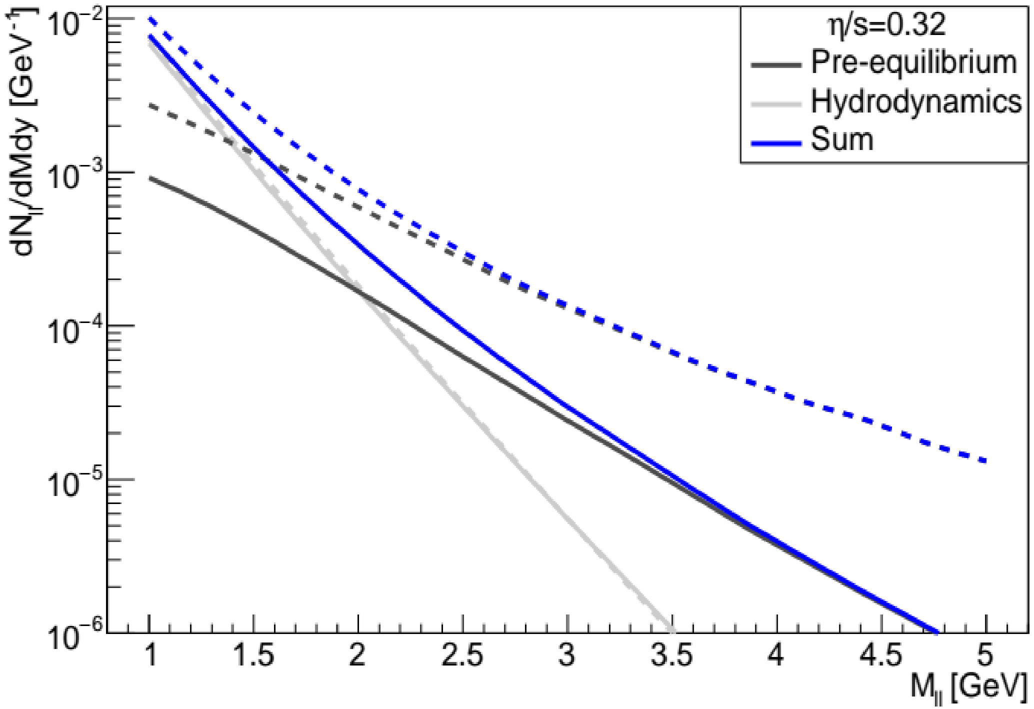
- Drell-Yan process calculated at NLO → dominates dilepton production at high mass

- Pre-equilibrium+hydro production is very sensitive to quark suppression
  → <u>access to early-stage chemistry</u>



Results: time decomposition



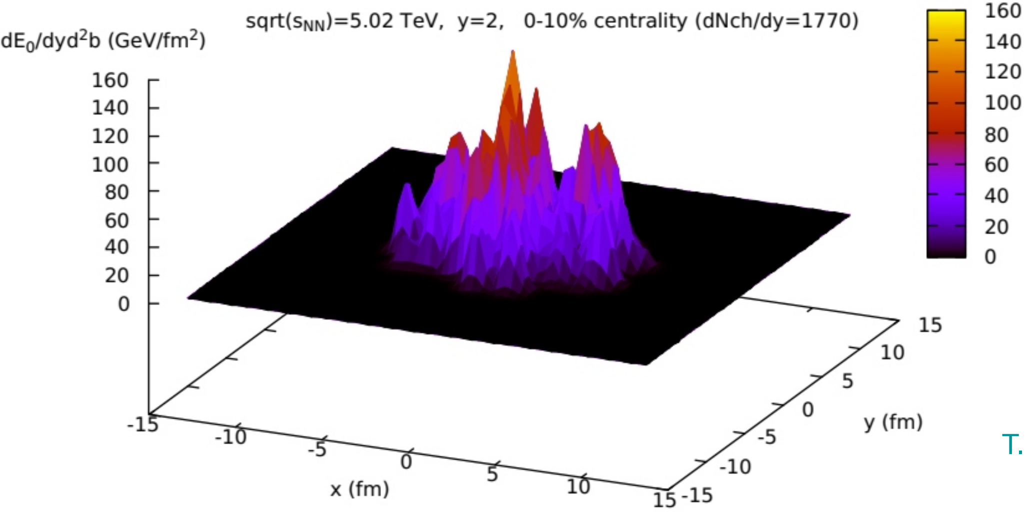


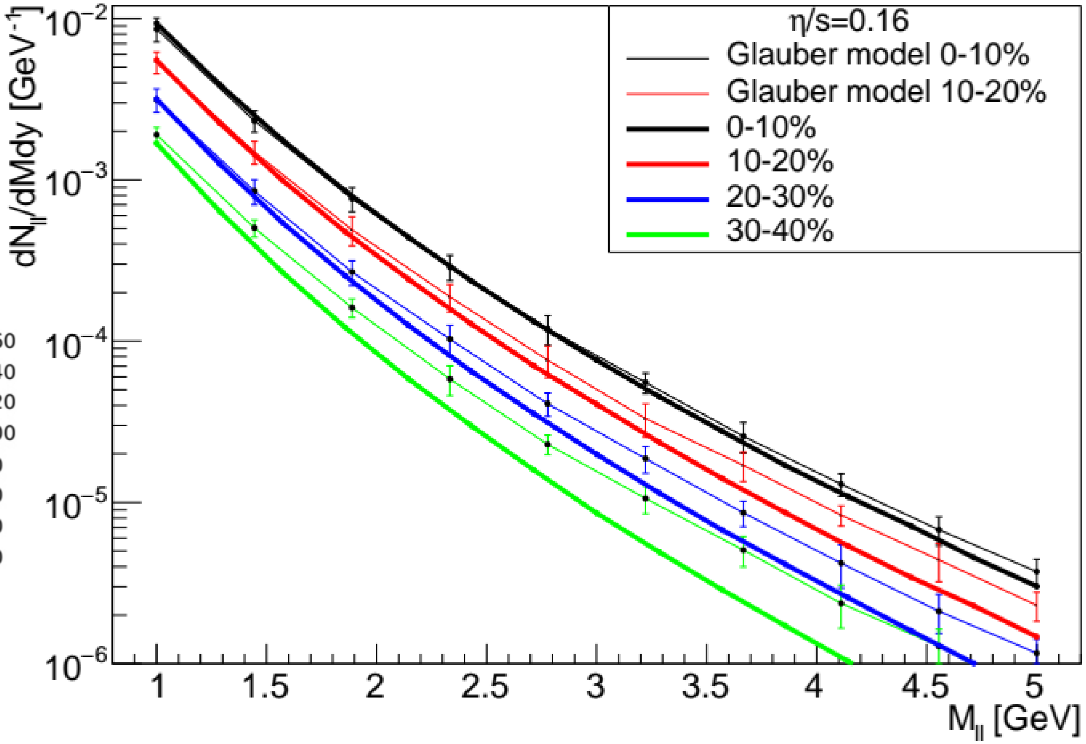
- Since η/s controls time scale for applicability of hydrodynamics; depending on value of η/s considerable contributions from pre-equilibrium regime (w<1)
- → larger viscosity → later thermalization → more contribution from pre-equilibrium

Estimating the transverse fluctuations

- modelling of event-by-event fluctuations (hot spots) using a TMD-Glauber model : parametrization of gluon distributions in nucleons + Glauber
  → parameters tuned to reproduce ALICE data for $dN_{ch}/d\eta$

- important for large invariant mass region in more peripheral events

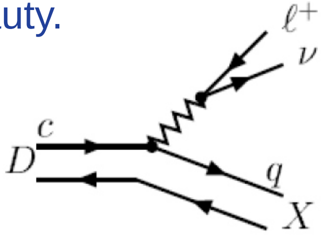


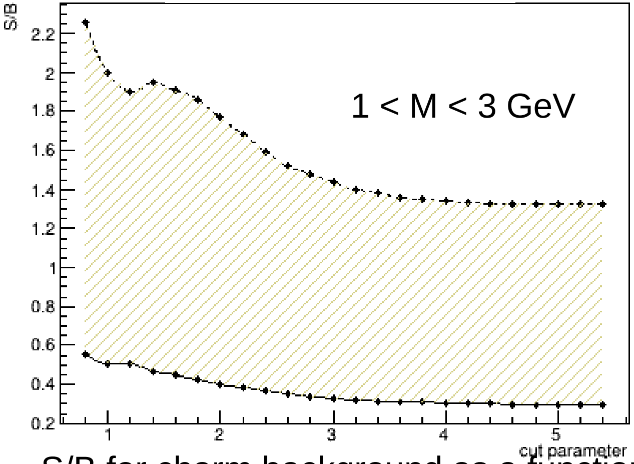


T. Lappi and S. Schlichting, Phys. Rev. D 97 (2018) no.3, 034034
S. Schlichting, X. Du, private communication

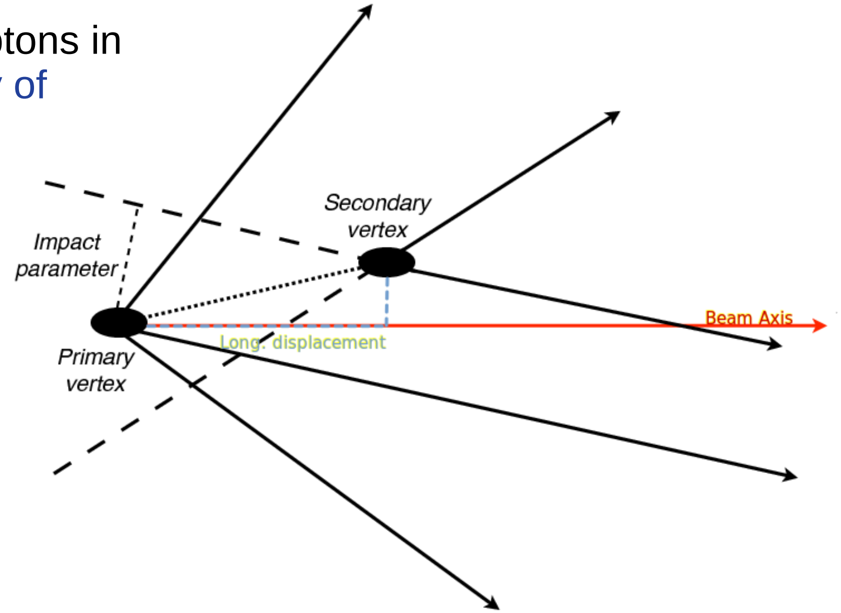
Background suppression with LHCb

→ Dominant background for intermediate mass dileptons in heavy ion collisions at 5.02 TeV : semileptonic decay of charm and beauty.





S/B for charm background as a function of IP cut, with $0.5 < R_{AA} < 1$ for D and Λ_c



Rejection of background:

→ impact parameter of the single-track muons

→ longitudinal displacement of the secondary vertex

- LHCb upgrade 2 setup for heavy ion collisions would provide appropriate secondary vertexing

Conclusion and outlook

- Pre-equilibrium dynamics essential to the high mass spectrum

  → insight into quark suppression & matter properties at early stage

  → extract from the mass spectrum a measure of the thermalization time, i.e. of η/s at early times

- Background suppression : secondary vertexing

  → LHCb gives good performance: small distance between instrument and primary vertex, and longitudinal boost

- Investigating m_T spectrum : m_T scaling as a signature of thermal emission, with small breaking due to pre-equilibrium dynamics

Thank you !

Backup

M_T scaling of dilepton production

In the fluid rest frame :

$$\frac{dN^{l^+l^-}}{d^4x d^4K} = C \exp(-\frac{k_0}{T})$$

For leading-order production, explicit calculation gives :

$$C = \frac{N_c \alpha^2}{12\pi^4} \sum_f q_f^2$$

We assume :

- boost invariance and neglect transverse flow
- that the temperature profile is uniform within a transverse area $A_\perp$
- Local thermal equilibrium holds at all times, hence the expansion is ruled by ideal hydro, with the scaling τT^3=const.

Then, after intergration over space-time :

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

L. D. McLerran and T. Toimela, Phys. Rev. D31(1985), 545

M_T scaling violation

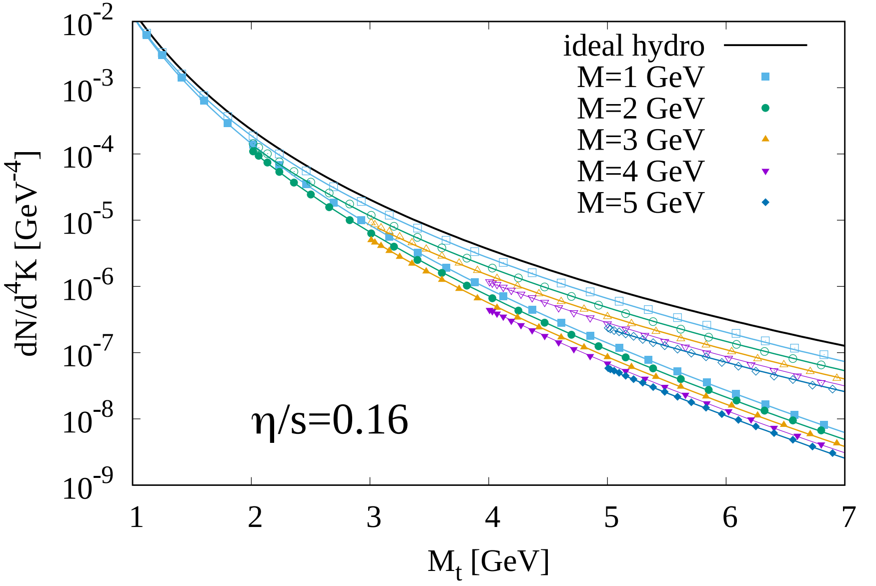
Out of equilibrium, two important effects appear :

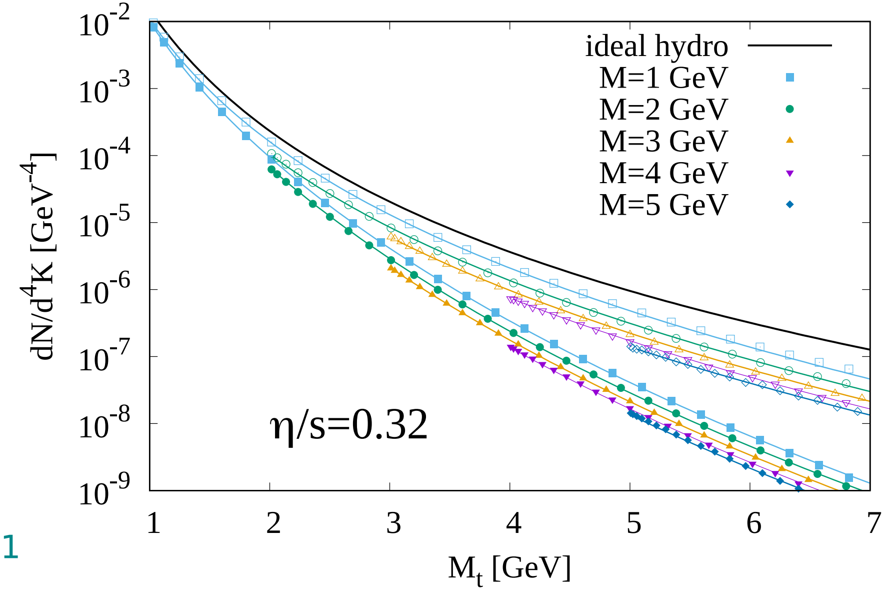
- quark suppression implies a suppression of dilepton production, which is a global factor, i.e. no impact on M_T scaling, but deviation from ideal case, more pronounce at high mass (↔ early times ↔ more quark suppression)

- Fast longitudinal expansion → pressure asymmetry → momentum anisotropy which violates M_T scaling,
- favouring small masses over large masses for a given M_T value

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

With : a = 0.61 GeV^{-2}, b = 1.6 GeV^{-2}, n = 3.1





TMD-Glauber model

T. Lappi and S. Schlichting, Phys. Rev. D 97 (2018) no.3, 034034
S. Schlichting, X. Du, private communication

- K_T factorization for gluon number density is assumed :

$$\frac{dN_g}{d^2\mathbf{b}d^2\mathbf{P}dy} = \frac{\alpha_s N_c}{\pi^4 \mathbf{P}^2 (N_c^2 - 1)} \int \frac{d^2\mathbf{k}}{(2\pi)^2} \Phi_A(x, \mathbf{b} + \mathbf{b}_0/2, \mathbf{k})\ \Phi_B(x, \mathbf{b} - \mathbf{b}_0/2, \mathbf{P} - \mathbf{k})$$

- The gluon distributions are assumed to be adjoint dipole distribution and the GBW saturation model is used :

$$\Phi_{A,B}(x, \mathbf{b}, \mathbf{k}) = 4\pi^2 \frac{(N_c^2 - 1)}{N_c} \frac{\mathbf{k}^2}{Q^2_{s,A,B}(x, \mathbf{b})} \exp\left\{ -\frac{\mathbf{k}^2}{Q^2_{s,A,B}(x, \mathbf{b})} \right\}$$

With : $Q^2_{s,A,B}(x_{A,B}, \mathbf{b}) = Q^2_{s,p}(x_{A,B}) \sigma_0 T_{A,B}(\mathbf{b})$ And $Q^2_{s,p,avg} \approx \sqrt{s_{NN}} x_0 \left(\frac{C_A}{C_F} \left(\frac{Q_0}{\sqrt{s_{NN}} x_0} \right) \right)^{1/(2+\lambda)}$

- Integrating the gluon number density yields the initial energy density :

$$(e\tau)_0 = \frac{\alpha_s (N_c - 1)\sqrt{\pi}}{N_c} \frac{Q_A^2 Q_B^2}{(Q_A^2 + Q_B^2)^{5/2}} \left[2Q_A^4 + 7 Q_A^2 Q_B^2 + 2 Q_B^4 \right]$$