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

Maurice Coquet, HIC School 2022, IMT Atlantique Nantes

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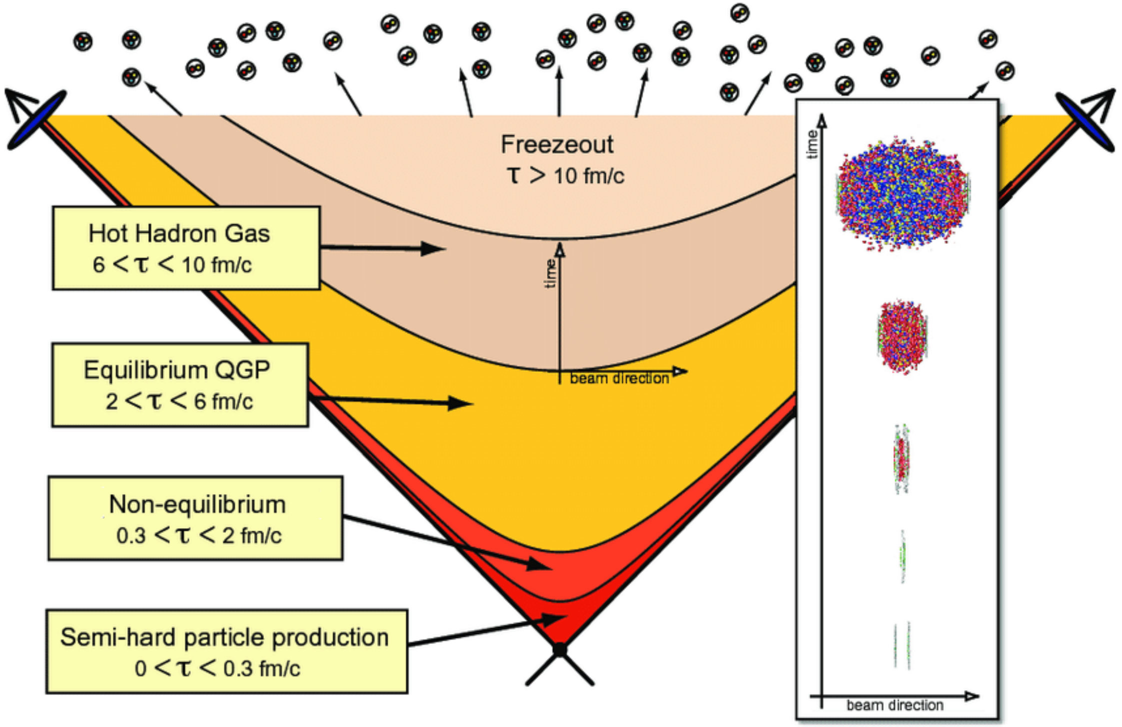
arXiv:2112.13876

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 hydrodynamics



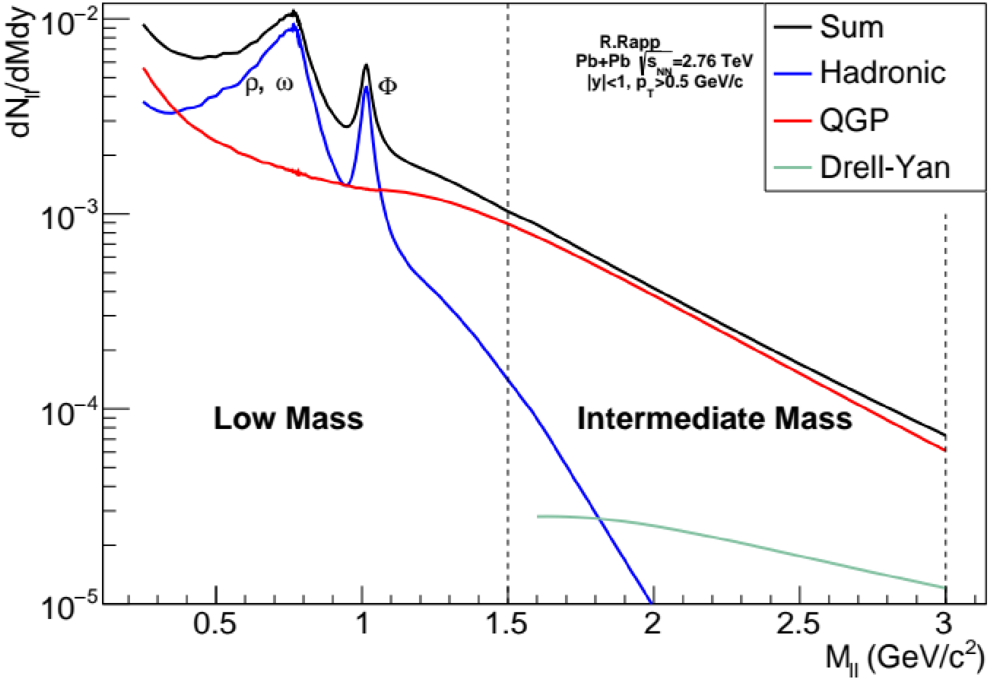
M.Strickland, Acta Physica Polonica B 45, 2355 (2014)

Dilepton production as a probe

- Electromagnetic interactions with the QGP have a small cross section

- Produced throughout the history of the collision → probe entire space-time dynamics

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



- Intermediate mass region (M > 1.5 GeV/c²) →Characterized by quarks and gluons degrees of freedom

- High mass ↔ High T ↔ early times

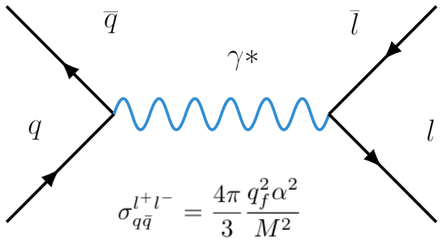
$$\frac{dN}{d^4x dM} \propto (MT)^{3/2} \exp\left(-\frac{M}{T}\right)$$

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

The ideal spectrum: M_t scaling

- 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

Start by considering local thermal equilibrium (LTE):

- Assuming boost invariance of the expanding QGP at early times, 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 conformal equation of state and uniform temperature profile in transverse plane, one finds the McLerran-Tomeila formula :

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

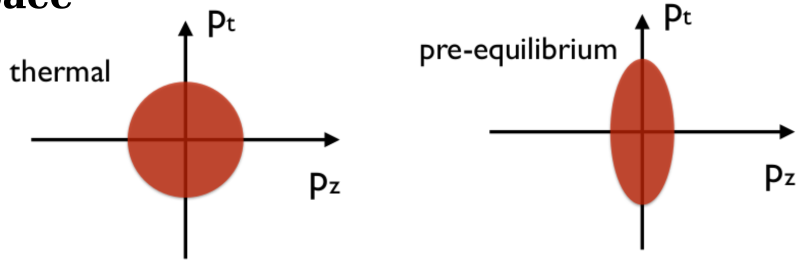
L. D. McLerran and T. Toimela, Phys. Rev. D31(1985), 545

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

Features of pre-equilibrium: pressure asymmetry

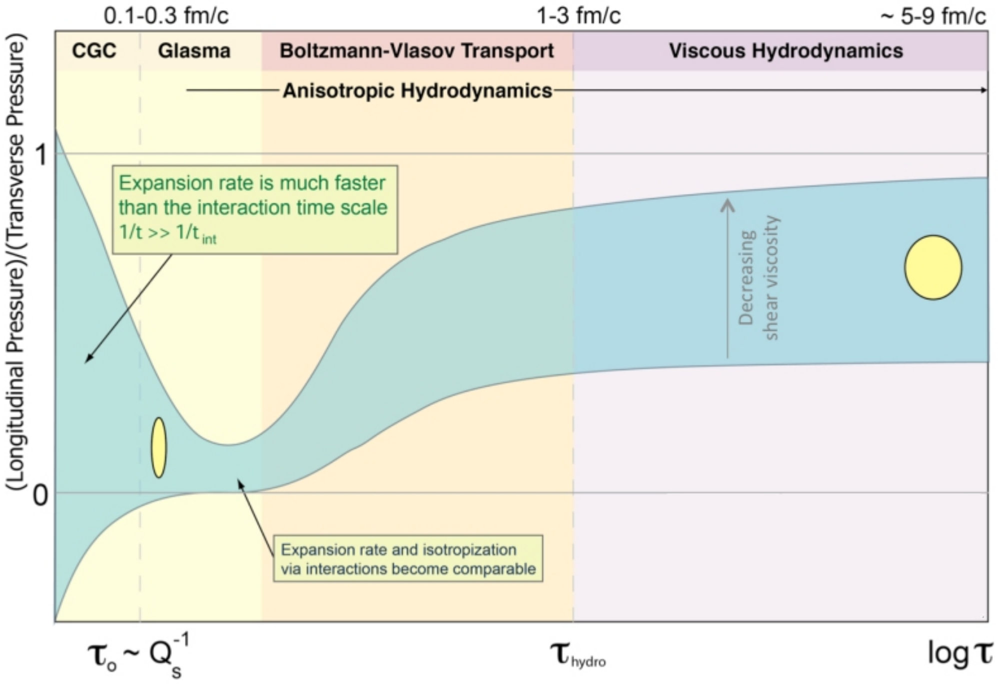
- At early times, rapid longitudinal expansion
  → $P_L << P_T$

  → **Anisotropy of distributions in momentum space**



  → momentum anisotropy which **breaks M_t scaling**, favoring small masses for a given M_t value

- Local pressure isotropy occurs at late times, but *applicability of viscous hydro can happen before*
  → $\tau_{hydro} << \tau_{eq}$



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

Features of pre-equilibrium: quark suppression

- Initial state theories predict a gluon-dominated medium at early times

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

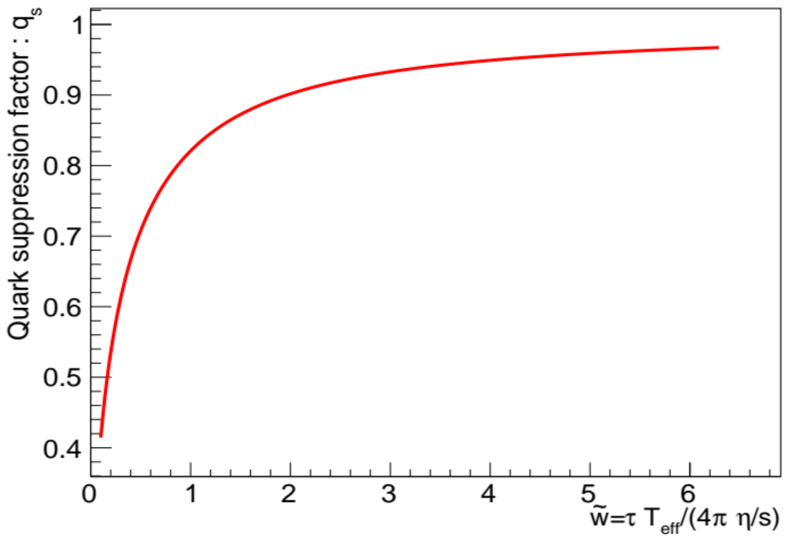
$$q_s(\tau) \propto \frac{e^{(q)}}{e^{(g)}}\Big(T(\tau)\Big)$$

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

- Quark suppression implies suppression of dilepton production, which is a global factor

  → **preserving M_t scaling**

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 :

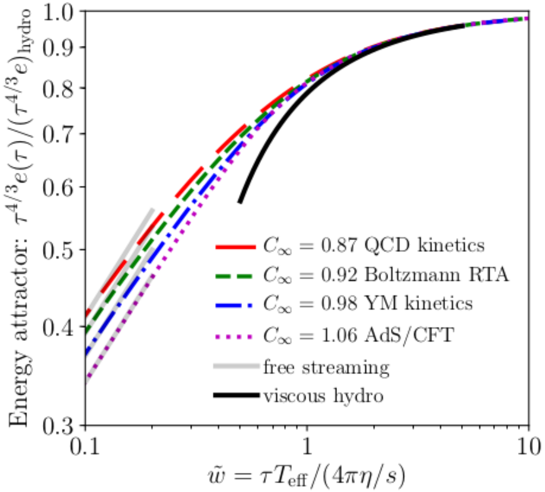
$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2} / \Lambda(\tau) \right)$$

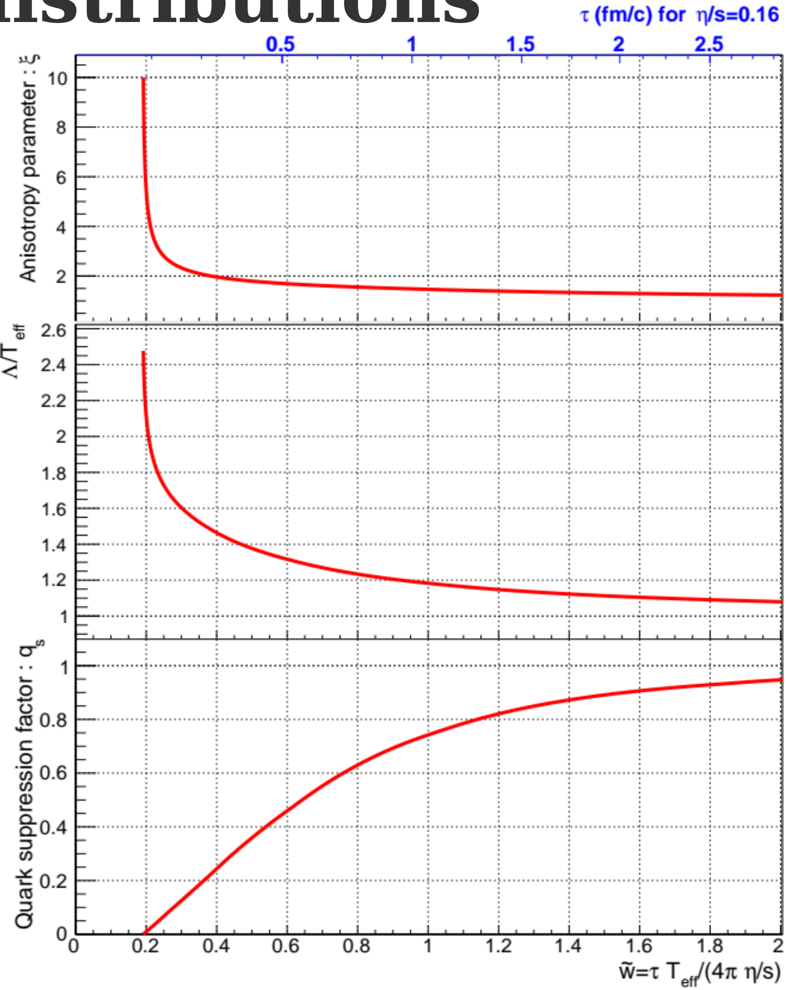
→ Depend on Λ (anisotropic effective temperature), anisotropy parameter ξ calculated w/ P_L/e, and quark suppression factor q_s

→ **Universality in pre-equilibrium** dynamics (attractor solutions) → Can choose a specific calculation to constrain pre-equilibrium dynamics

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

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





Results: mass spectra

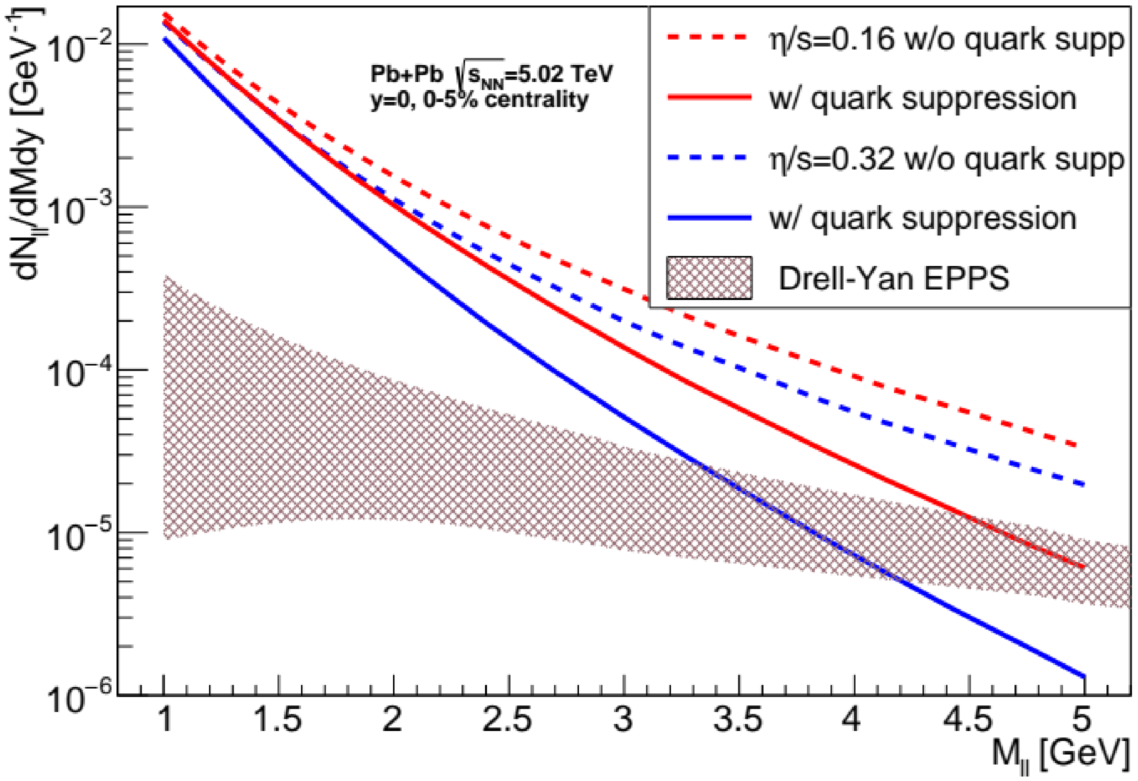
- Yields can be fitted by the formula :

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

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 is not the viscosity in the hydro regime, controls **time scale of applicability of hydro**
- larger η/s → later thermalization → temperature starts decreasing as $\tau^{-1/3}$ later on → lower initial temperature for fixed final energy density
- Drell-Yan process calculated at NLO **dominates dilepton production at high mass**
- Very sensitive to quark suppression **→access to early-stage chemistry**

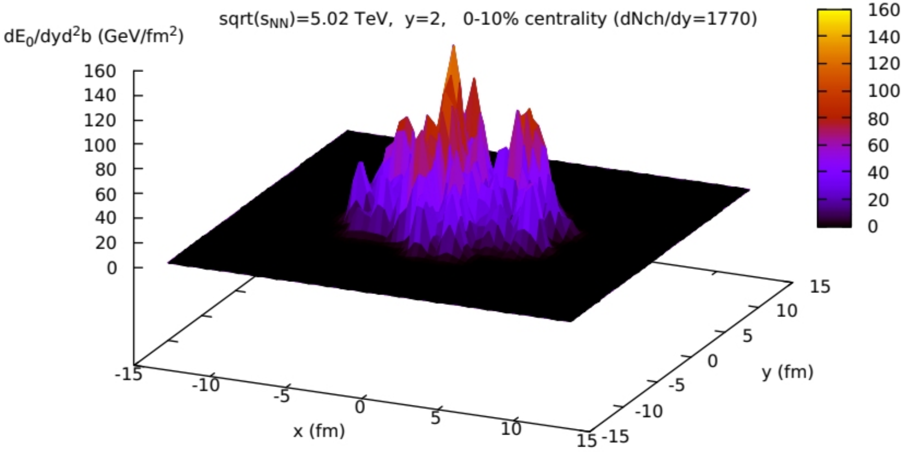


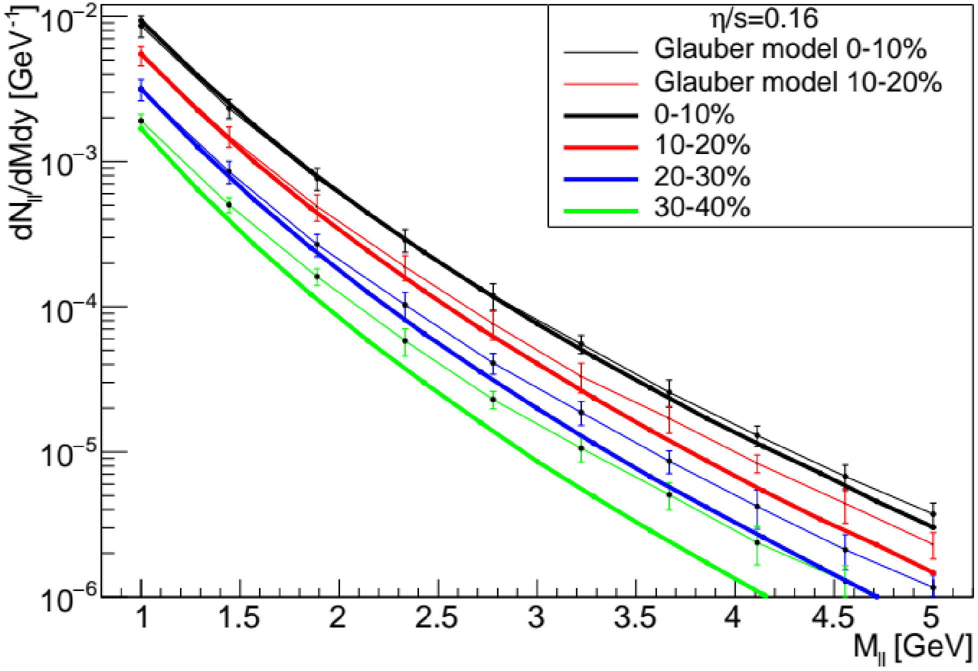
Estimating the transverse fluctuations

- 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 $dN_{ch}/d\eta$

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

- 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

Results : M_t spectra

- **Breaking of M_t scaling** due to momentum anisotropy, favoring small masses for a given M_t value, is modest, compared to overall suppression of production yield due to **quark suppression**
- 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

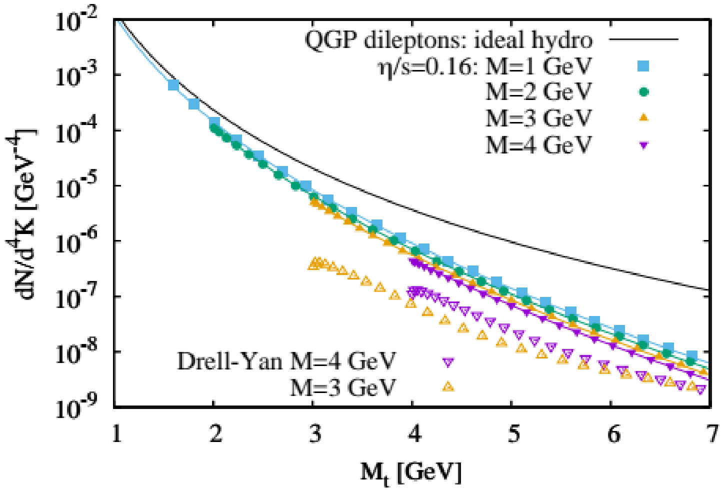
→ corrections to ideal yield linear in η/s for small η/s.

→ ~1/M for large η/s, showing breaking of M_t scaling.

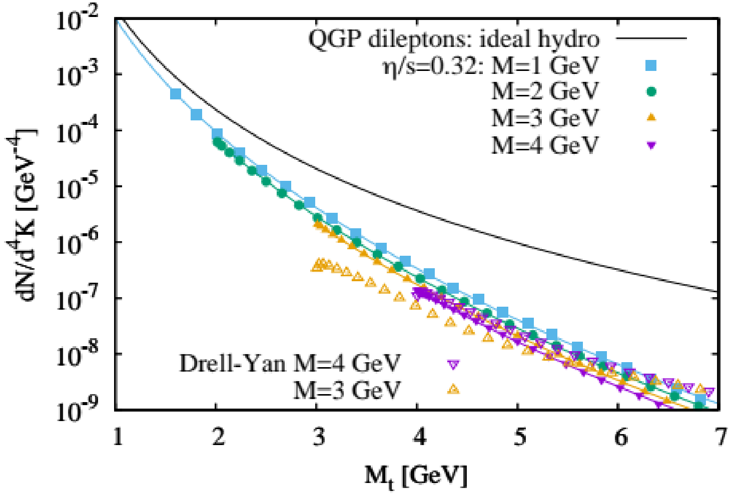
- Inverse slope of the M_t spectrum → effective temperature :

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

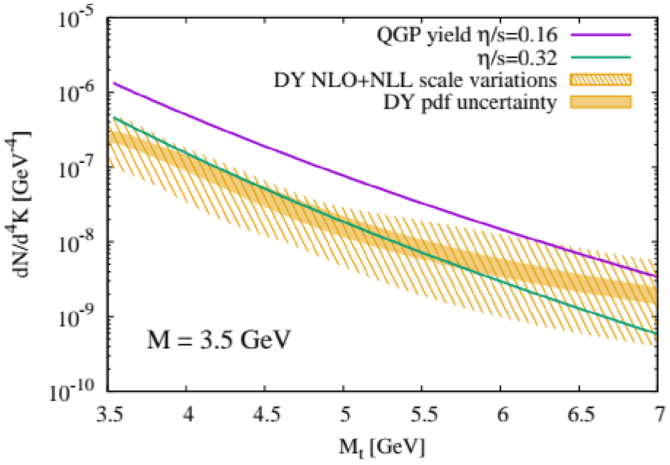
- Drell-Yan dominates spectrum at high M_t → DY enhanced for larger values of M at fixed M_t, **opposite behavior to QGP emission**.



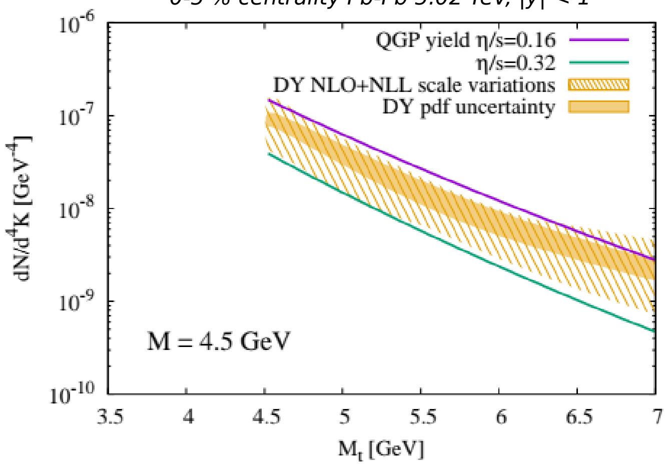
0-5 % centrality Pb-Pb 5.02 TeV, |y| < 1



Backgrounds & scalings



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



- 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)

Scaling properties

- System size/centrality: 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.)
- Collision energy: 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

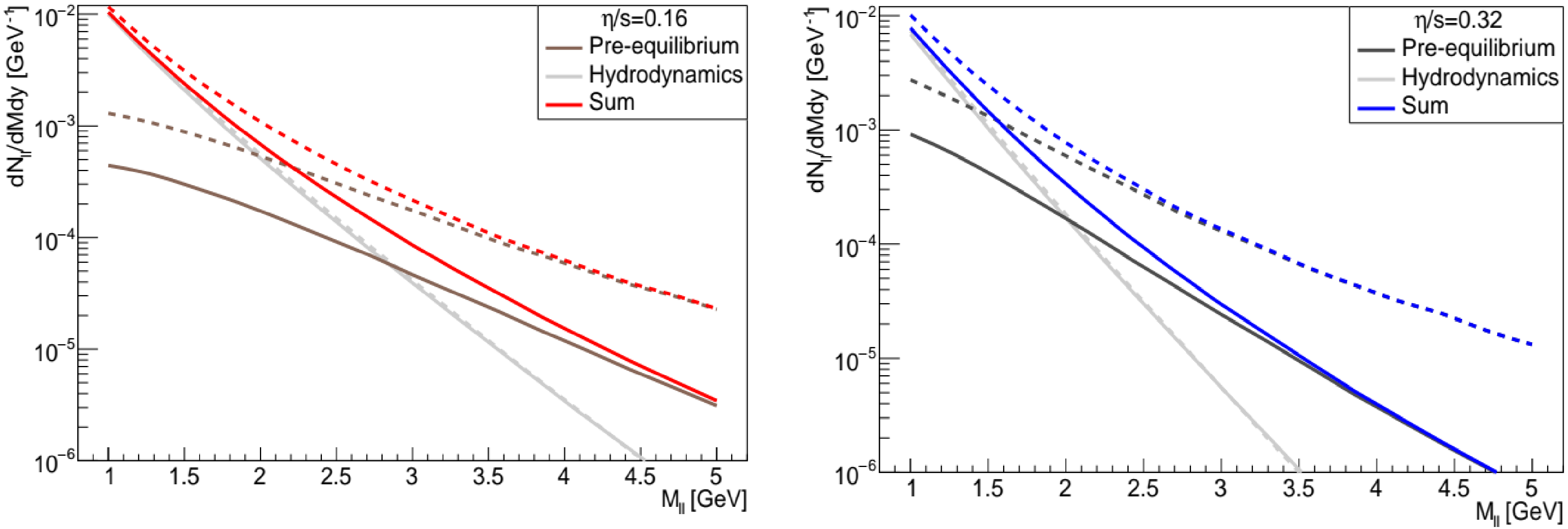
- Distinguish experimentally QGP production from Drell-Yan production by studying variation of yield as a function of **M at fixed M_t**

- 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 !

Backup

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

Pre-equilibrium dynamics

Effects of pre-equilibrium dynamics :

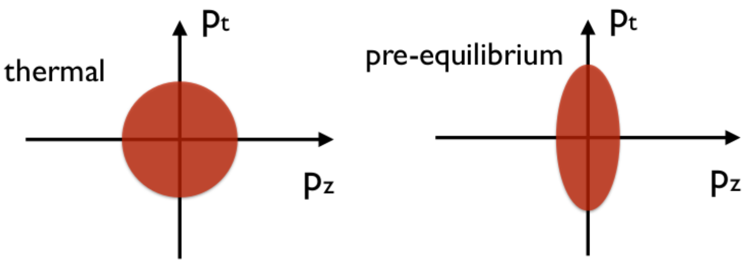
- Quarks are underpopulated relative to gluons at early times
- Momentum distributions of quarks and gluons are anisotropic (rapid longitudinal expansion)

→ Encapsulated in parametrization of the quark distribution:

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

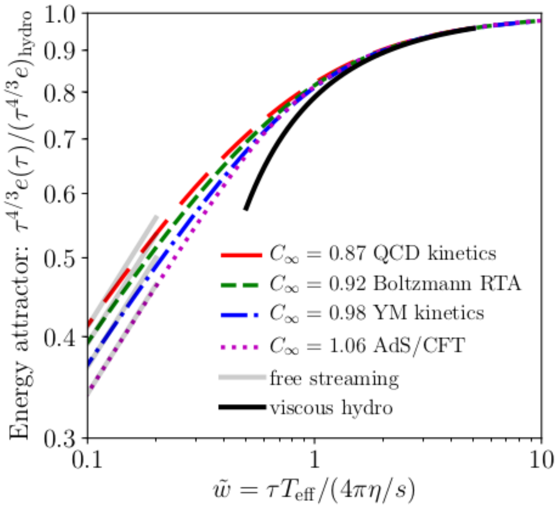
$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD}\left(-\sqrt{p_T^2 + \xi^2(\tau) p_L^2}/\Lambda(\tau)\right)$$

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

Pre-equilibrium dynamics

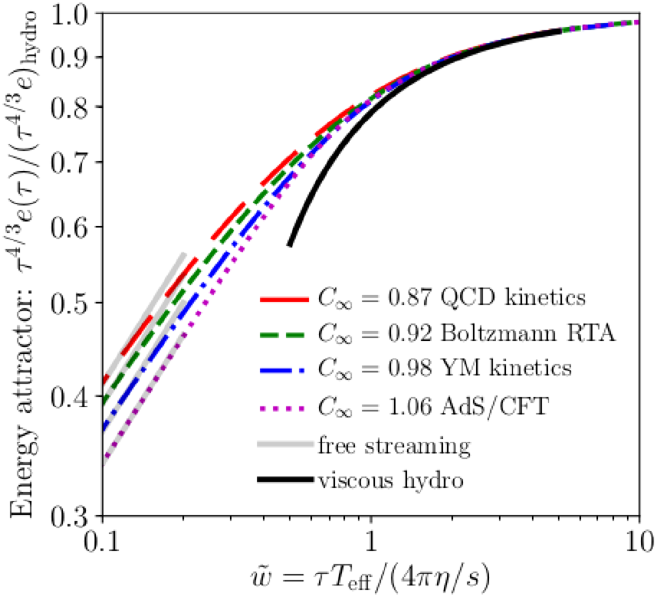
- Universality in pre-equilibrium dynamics (attractor solutions)
- → Can choose a specific calculation (QCD kinetics) to determine evolution of energy density and constrain pre-equilibrium dynamics

- For this, need final condition at late times (w>>1): $\frac{e(\tau)\tau^{4/3}}{e_{hydro}\tau_{hydro}^{4/3}} = \mathcal{E}(\tilde{w})$

- 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)

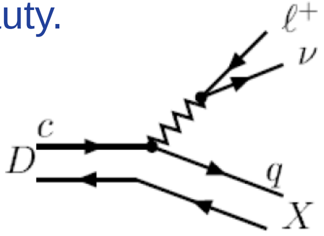


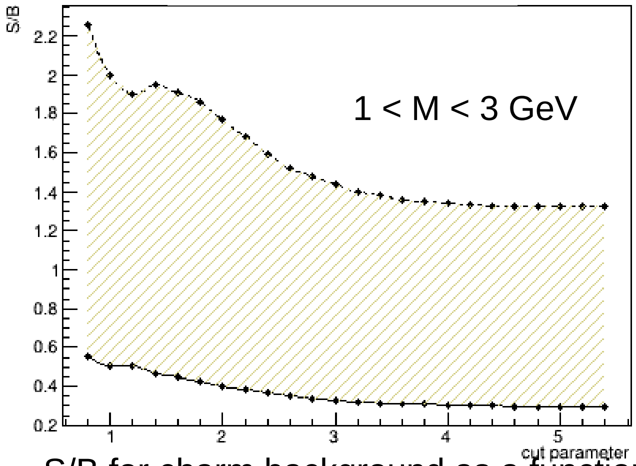
Giacalone, Mazeliauskas, Schlichting, Phys. Rev. Lett. 123, 262301 (2019)

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

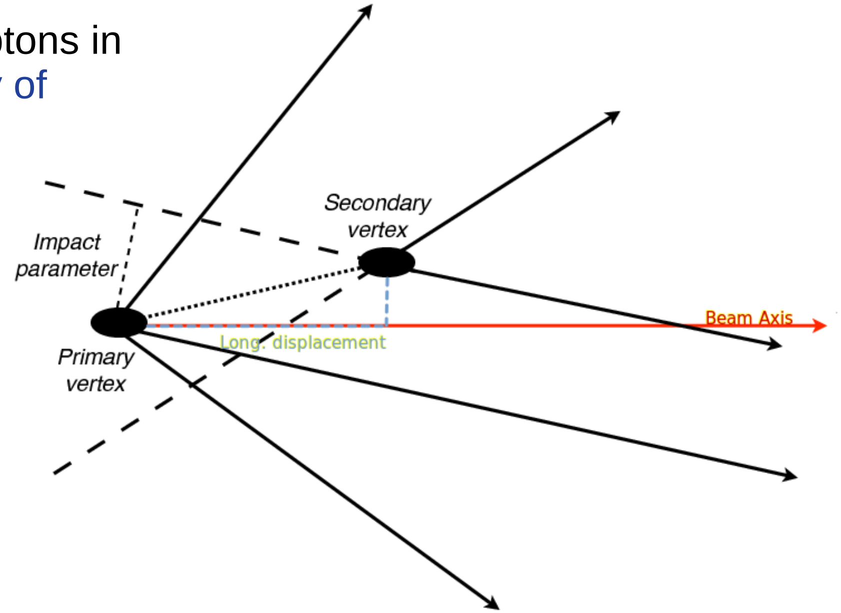
Background suppression with LHCb

→ 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

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 :

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

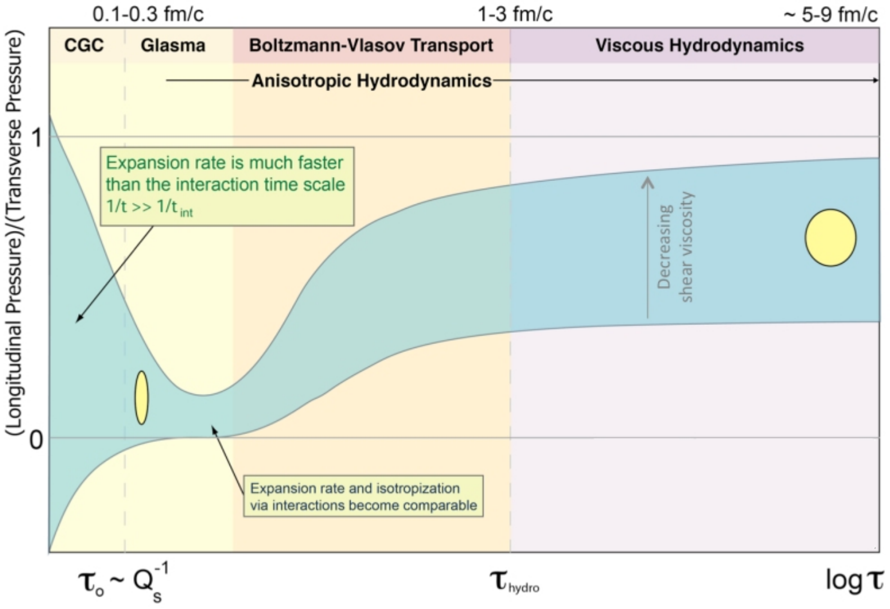
With : $Q^2_{s,A,B}(x_{A,B}, \mathbf{b}) = Q^2_{s,p}(x_{A,B}) \sigma_0 T_{A,B}(\mathbf{b})$ And $Q^2_{s,p,avg} \approx \sqrt{s_{NN}} x_0 \left(\frac{C_A}{C_F} \left(\frac{Q_0}{\sqrt{s_{NN}} x_0} \right) \right)^{1/(2+\lambda)}$

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

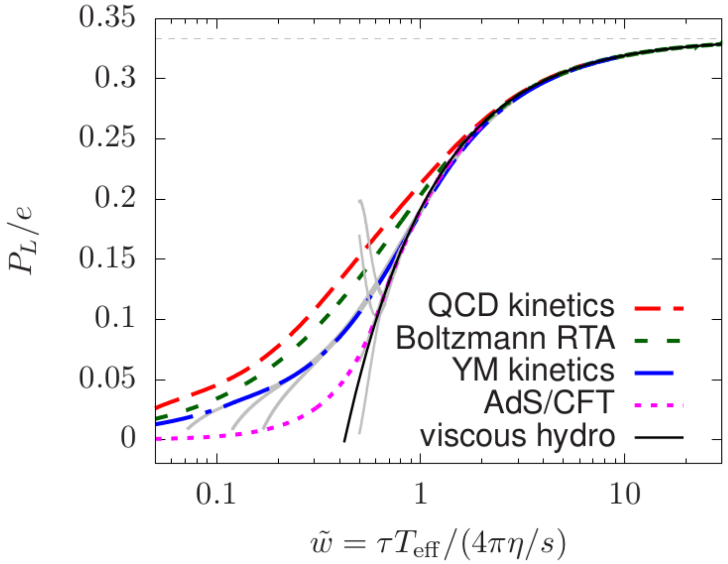
$$(e\tau)_0 = \frac{\alpha_s (N_c-1)\sqrt{\pi}}{N_c} \frac{Q_A^2 Q_B^2}{(Q_A^2+Q_B^2)^{5/2}} \left[2Q_A^4 + 7 Q_A^2 Q_B^2 + 2Q_B^4 \right]$$

Features of pre-equilibrium: pressure asymmetry

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



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

- Local pressure isotropy occurs at late times, but a*pplicability of viscous hydro can happen before* → $\tau_{hydro} << \tau_{eq}$

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