



Gluodynamics

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

Labex P2IO, 26th November 2021, Maurice Coquet

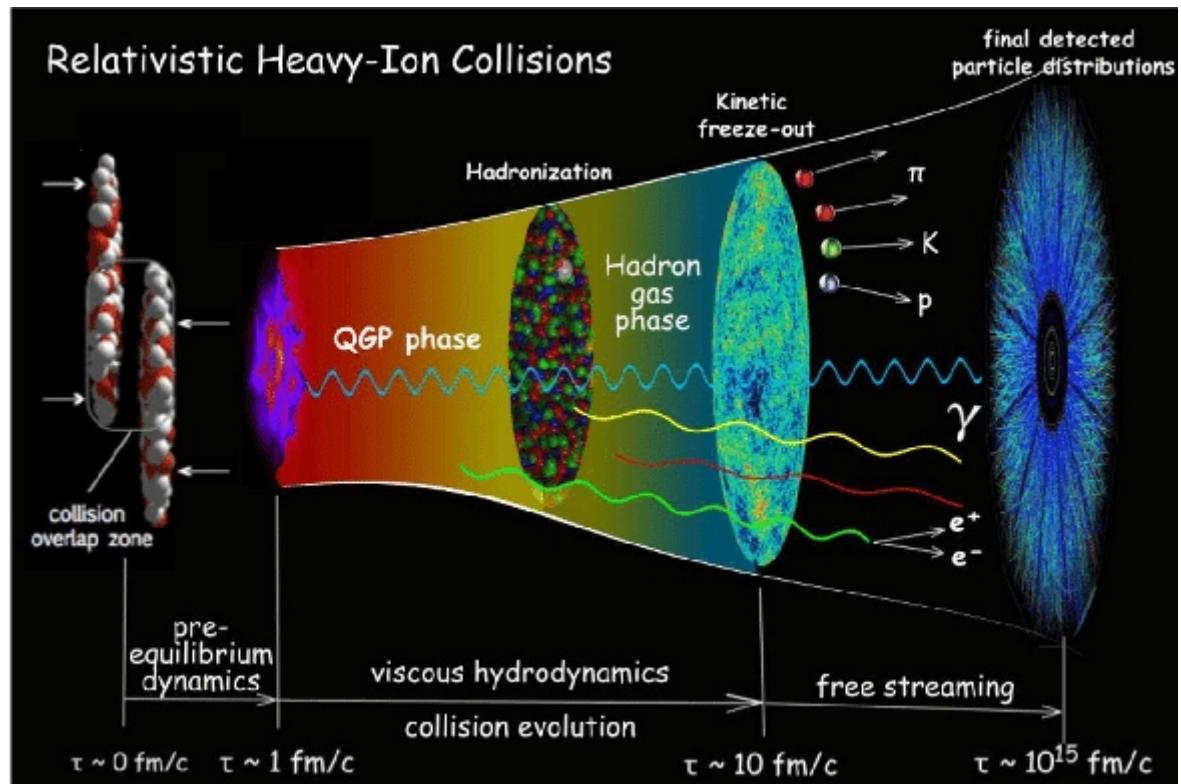
MC, Xiaojian Du, Jean-Yves Ollitrault, Sören Schlichting, Michael Winn

To introduce myself

- Maurice Coquet : second year PhD student in Irfu/CEA-Saclay, co-supervised by Michael Winn.
- Part of gluodynamics project and ALICE collaboration
 - Working on new ALICE measurements in run 3 (starting next year)
 - Today, present parallel work :
phenomenology study on **thermal dileptons in heavy-ion collisions**, collaboration with X. Du, S. Schlichting (Bielefeld university) and J-Y. Ollitrault (IPhT)

Space-time picture of heavy-ion collisions

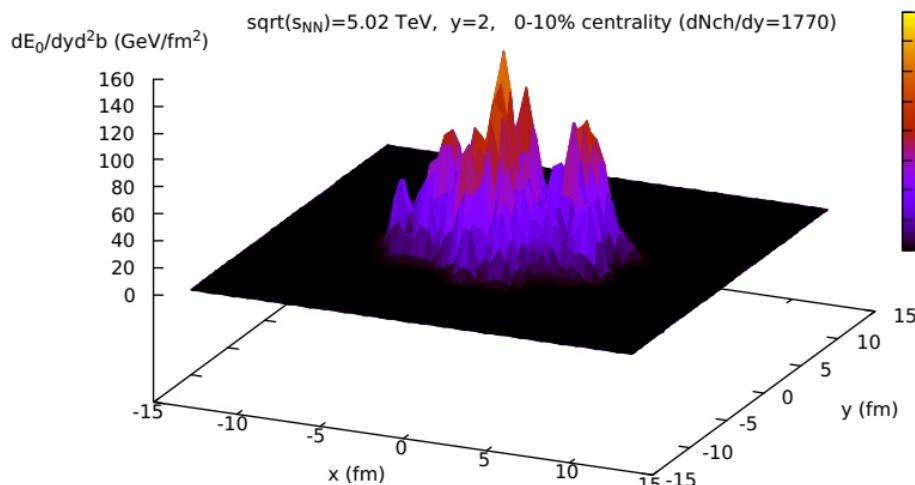
- Separation of time scales defines different successive stages
 - Initial state
 - Quark Gluon Plasma (QGP) phase, described by hydrodynamics
 - Hadron gas phase
 - Freeze-out
- A challenge : matching between far-from-equilibrium initial state and stage where hydro can be applied



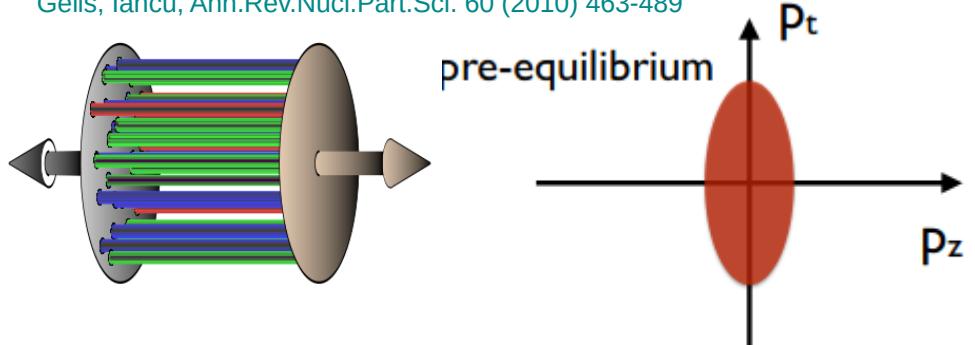
Shen, C.; Heinz, U. Nucl. Phys. News 2015, 25, 6–11

Initial state & gluon distribution

- In heavy ion collisions : colliding nuclei modeled as sheets of densely packed gluons



Gelis, Iancu, Ann.Rev.Nucl.Part.Sci. 60 (2010) 463-489

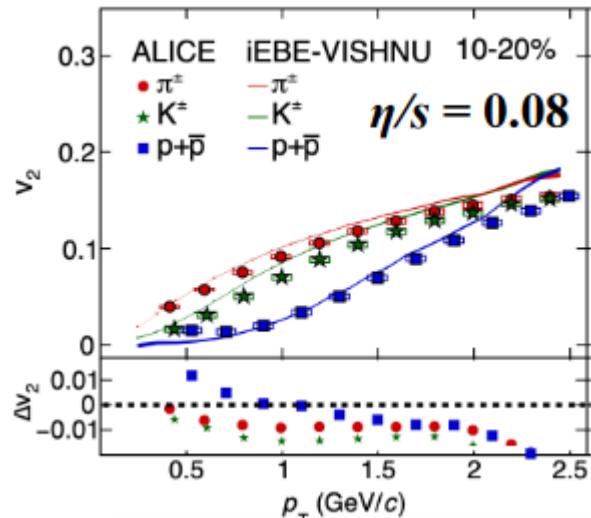


- Energy deposited by gluons in overlap zone known as « initial state »
- Far from chemical equilibrium (only gluons, no quarks)

- Also far from kinetic equilibrium :
 - Due to rapid longitudinal expansion, distribution of gluons in momentum space highly anisotropic
 - Gluons have small longitudinal momentum vs transverse (*in local rest frame*)

Hydrodynamics

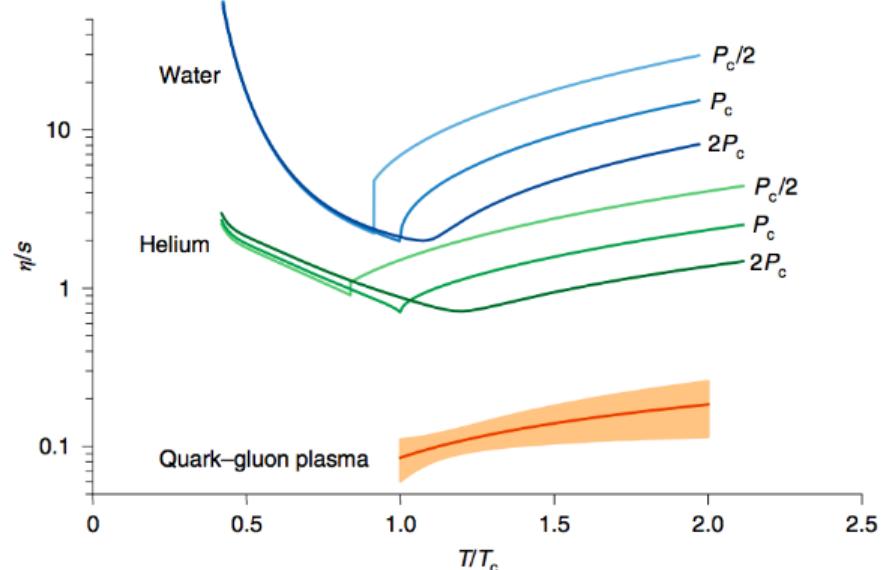
- Relativistic equivalent of Navier-Stokes describes remarkably well so called « flow » observables in heavy ion collisions :
 - anisotropy of final-state particles



A. Ohlson CERN-Fermilab Physics Summer School 2021

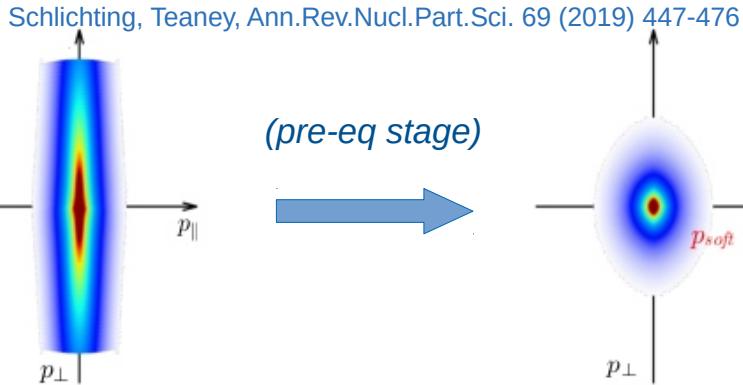
- Elliptic flow → Nearly ideal fluid, i.e. very low viscosity ($\eta/s \sim 0.08$, close to lower theoretical bound)

Bernhard, J.E., Moreland, J.S. & Bass, S.A. Nat. Phys. 15, 1113–1117 (2019)

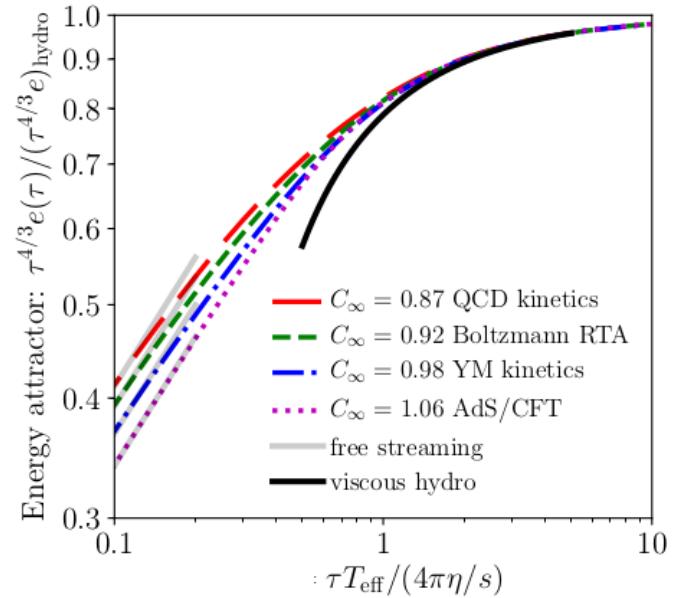


Pre-equilibrium dynamics

- How do we interpolate between far-from-equilibrium free-streaming initial state and near equilibrium hydro ?
 - Multiple approaches : different assumptions
 - All follow remarkably similar behavior !



- universality in pre-equilibrium dynamics as a function of a single scaling variable
 - 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)

T_{eff} : energy density

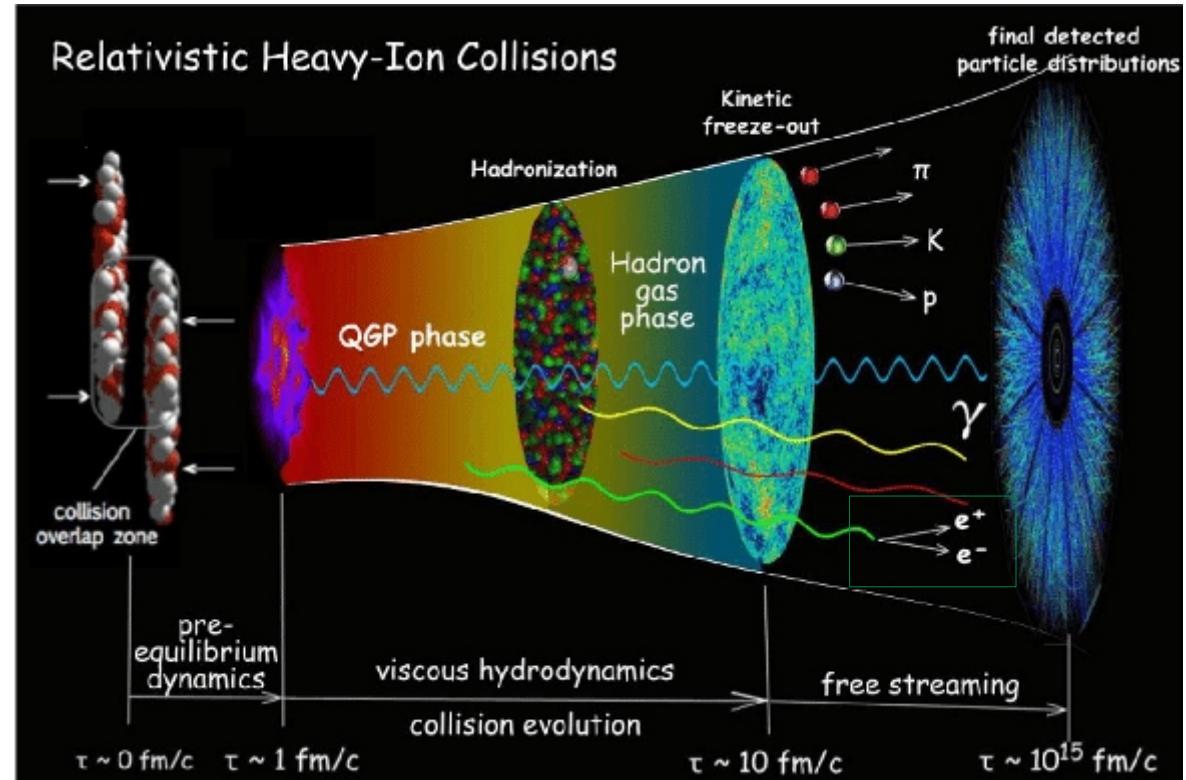
η/s : early-times viscosity

Dilepton production as a probe

- Hadronic observables : suffer many interactions before measurement
- Are produced at hadronization stage

Dileptons (lepton-anti-lepton pairs) :

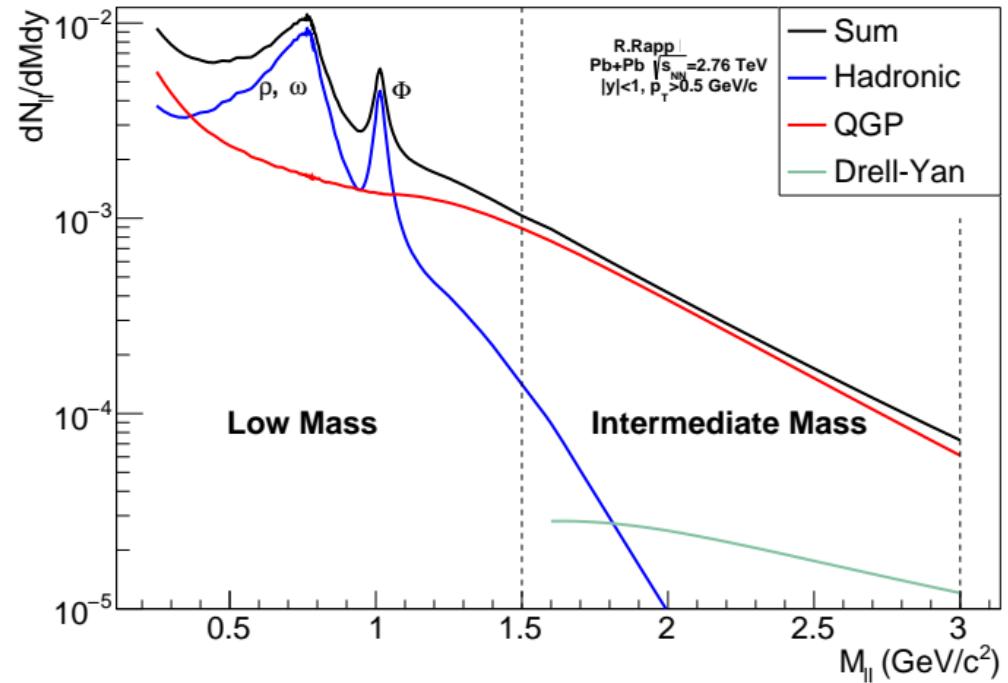
- Electromagnetic probes : small interaction cross section with the QGP
- Produced during all stages of the collision



Dilepton production as a probe

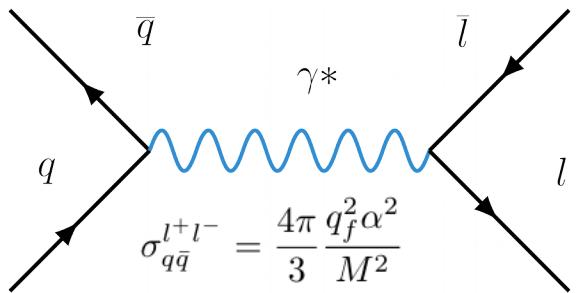
- Low mass region : dominated by decay of hadronic resonances
- Intermediate mass region ($M > 1.5$ GeV)
→ Characterized by quarks and gluons degrees of freedom (i.e. *deconfined phase*)
- High mass \leftrightarrow High T \leftrightarrow early times

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



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

Production rate calculation



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

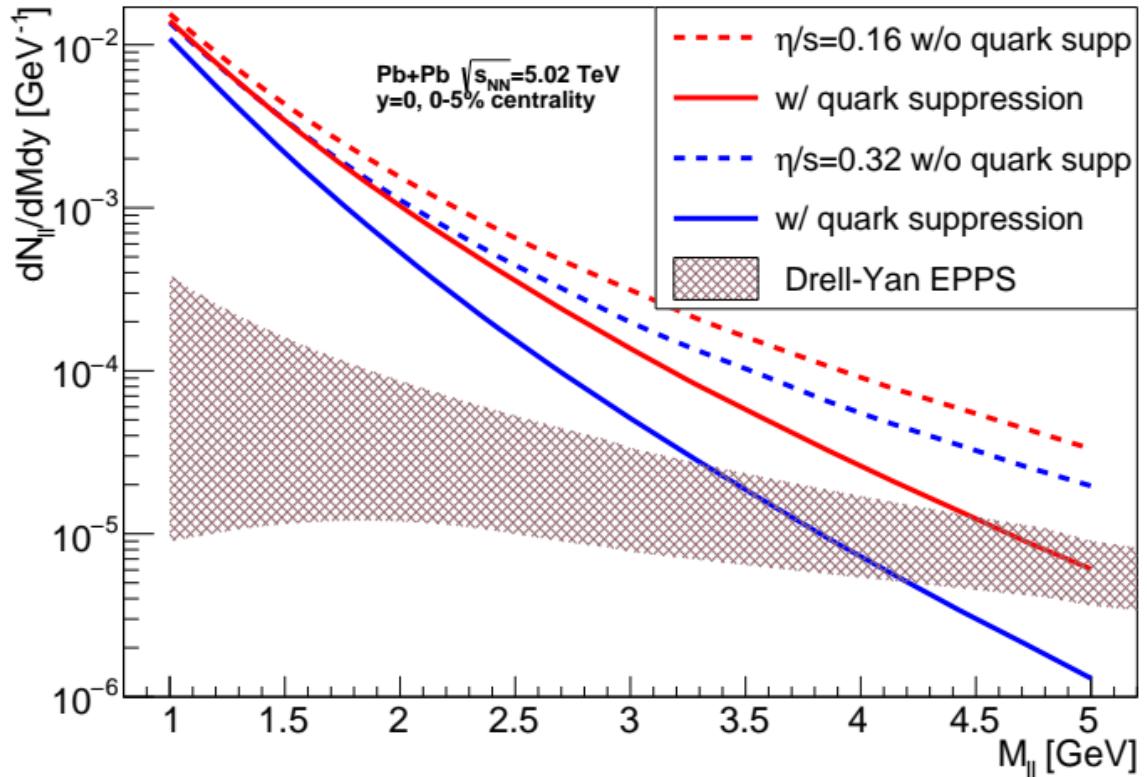
Cf: Strickland PRD 99 (2019) 3, 034015, Phys. Rev. C 103, 024904 (2021),
Ryblewski, Strickland PRD 92, 025026 (2015)

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

- With quark distributions $f(p) \sim \exp(-p/T)$
- Integrate over space-time evolution of the medium to calculate the dilepton yield
- Assume 1-D expansion :
- **boost invariant** along the longitudinal direction (direction of rapid expansion)
- **homogeneous** in the transverse plane

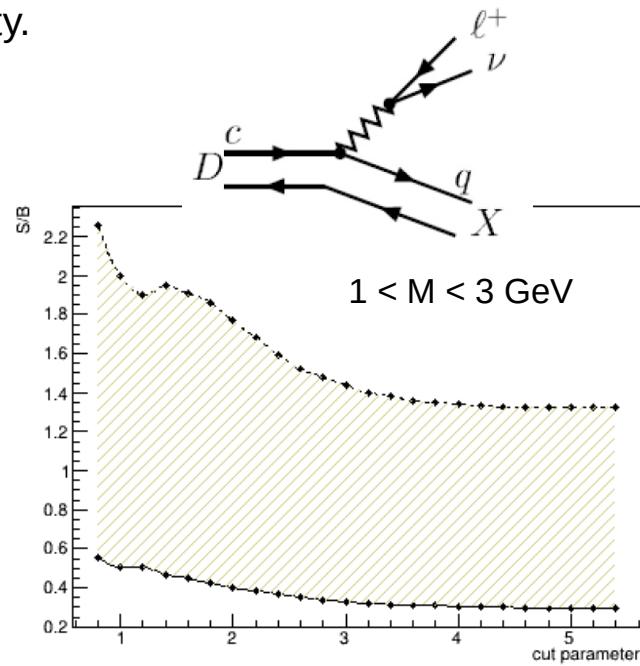
Results: mass spectra

- η/s is not the viscosity in the hydro regime but viscosity at high temperature : controls time scale for applicability of hydrodynamics
→ constrained by mass spectrum
- Initial state production of lepton pairs (Drell-Yan) → dominates dilepton production at high mass
- Pre-equilibrium+hydro production is very sensitive to quark suppression
→ access to early-stage chemistry

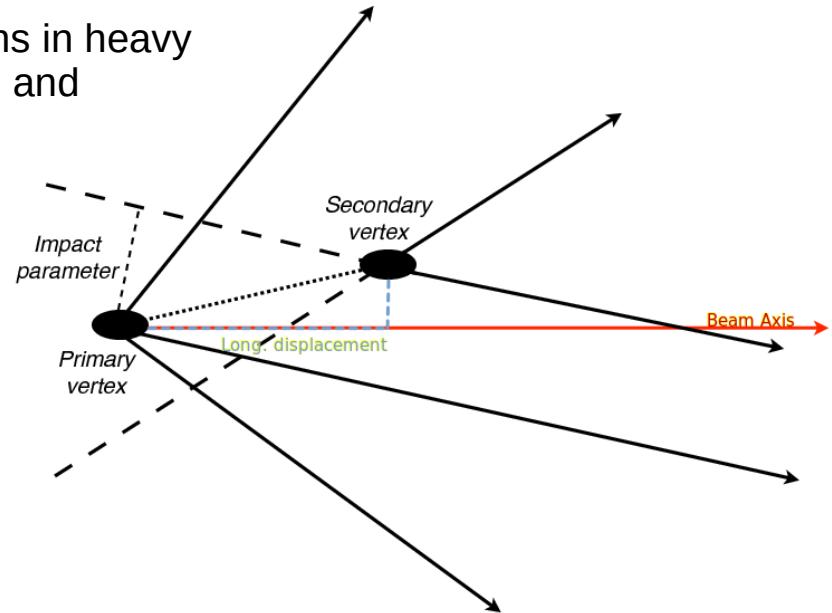


Background suppression with LHCb

- 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



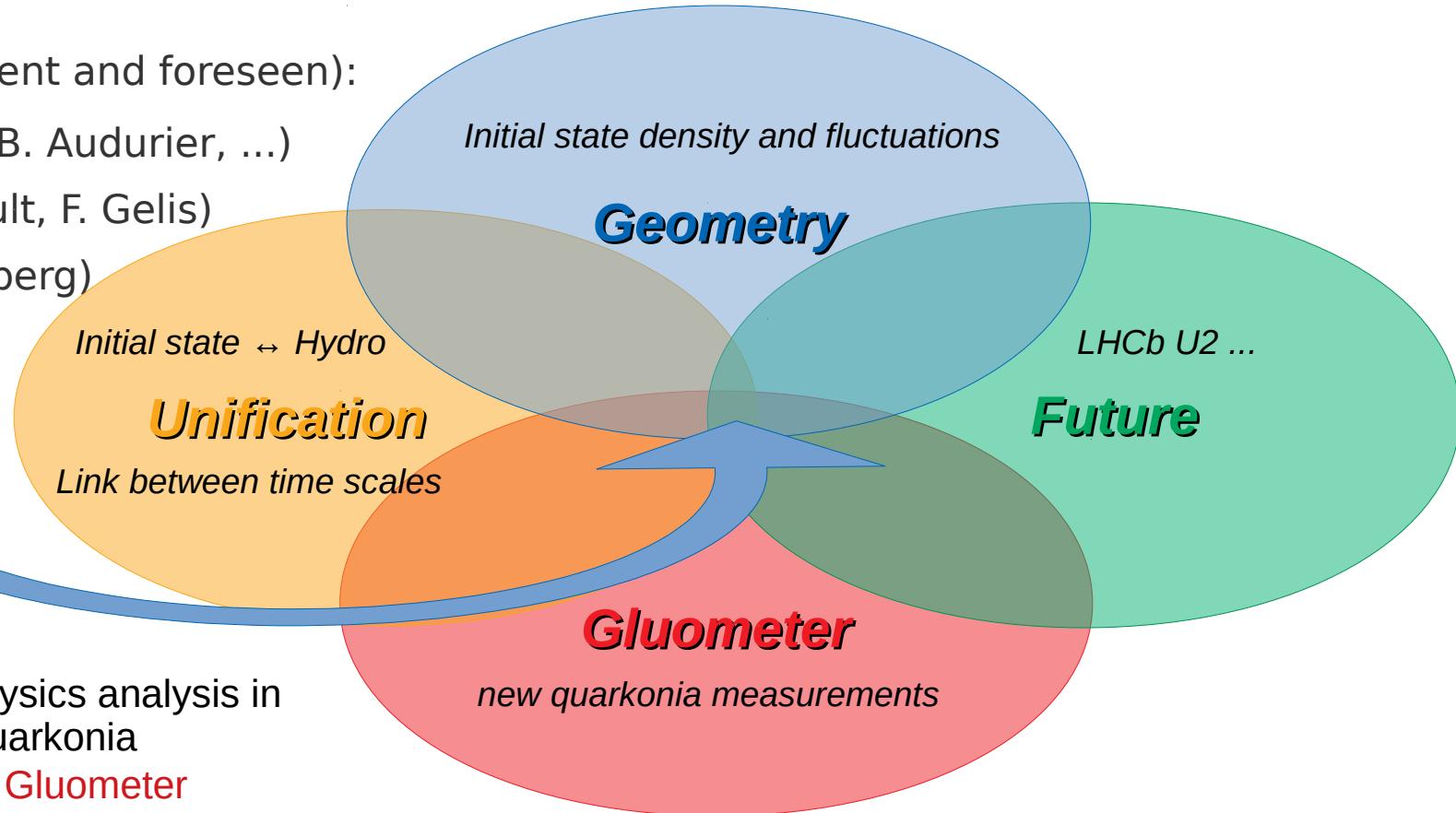
- Rejection of background:
 - impact parameter of the single-track muons
 - longitudinal displacement of the secondary vertex
- Requires LHCb upgrade 2 setup for heavy ion collisions

Synergies within Gluodynamics

- Collaborations (current and foreseen):
 - LLR (F. Fleuret, B. Audurier, ...)
 - IPhT (J-Y. Ollitrault, F. Gelis)
 - IJClab (J-P. Lansberg)

We are here !

Remaining of PhD : Physics analysis in
ALICE (new quarkonia
measurements) → **Gluometer**



Conclusion and outlook

- Dilepton spectrum very sensitive to pre-equilibrium dynamics of heavy-ion collisions (especially at high mass)
 - insight into matter properties at early stage
 - probing gluon distribution of initial state
- Experimental feasibility : secondary vertexing is essential
 - LHCb upgrade would give good performance: small distance between instrument and primary vertex, and longitudinal boost



Thank you !

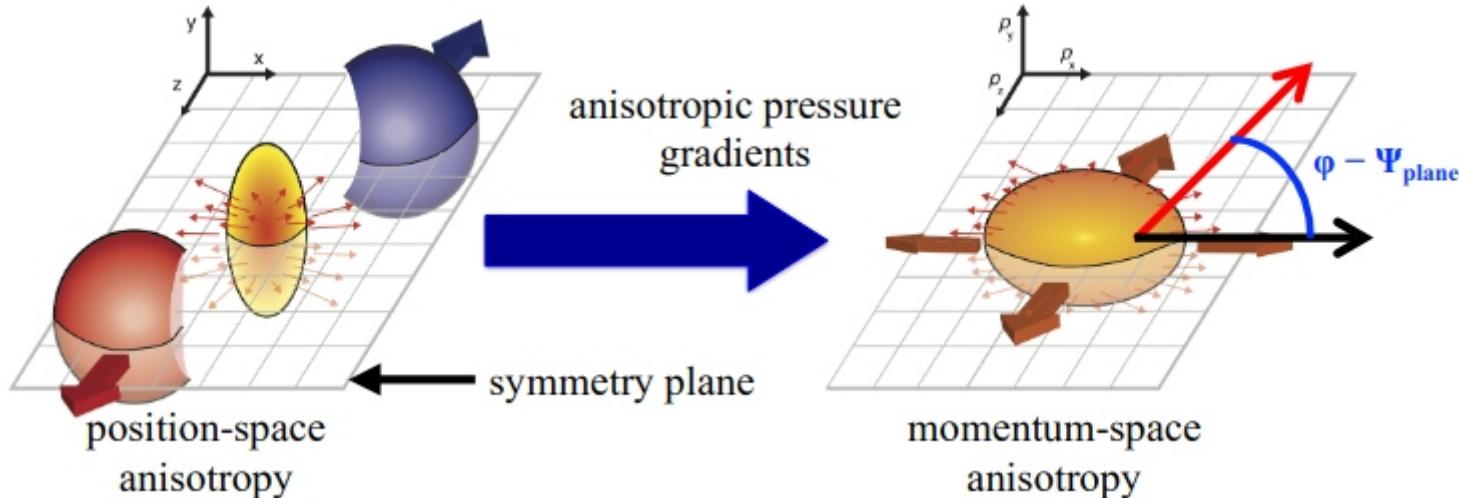


Backup

Hydrodynamics

- « flow » observables in heavy ion collisions : anisotropy of final-state particles
- Elliptic flow → Nearly ideal fluid, i.e. very low viscosity ($\eta/s \sim 0.08$, close to lower theoretical bound)

$$dN/d\phi \sim 1 + 2v_2 \cos(2(\phi - \Psi_2))$$



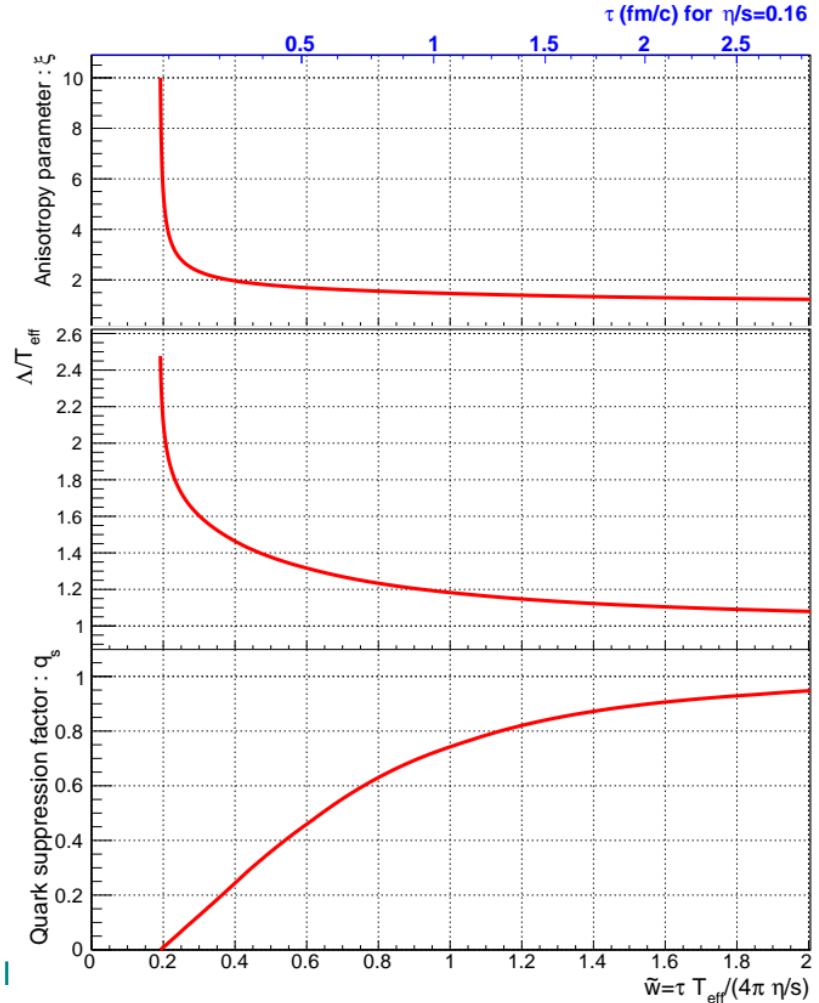
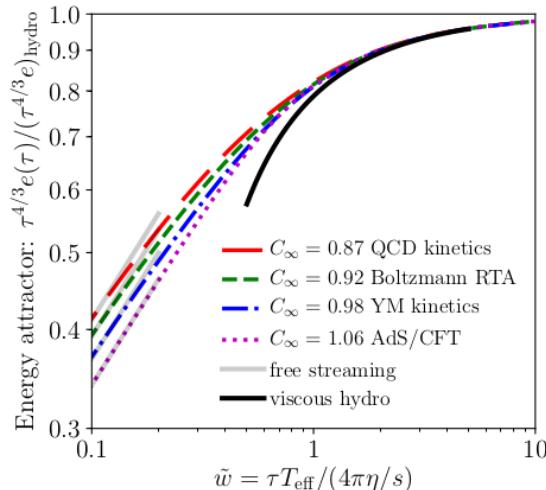
Out-of-equilibrium quark distributions

Distribution for quarks anisotropic in momentum space :

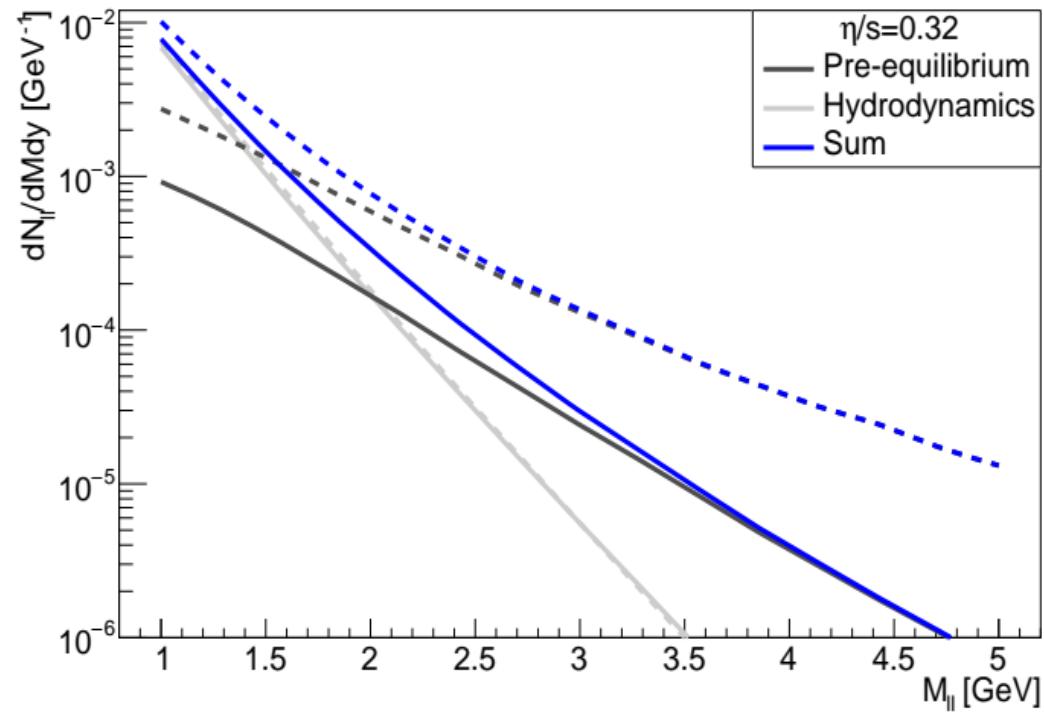
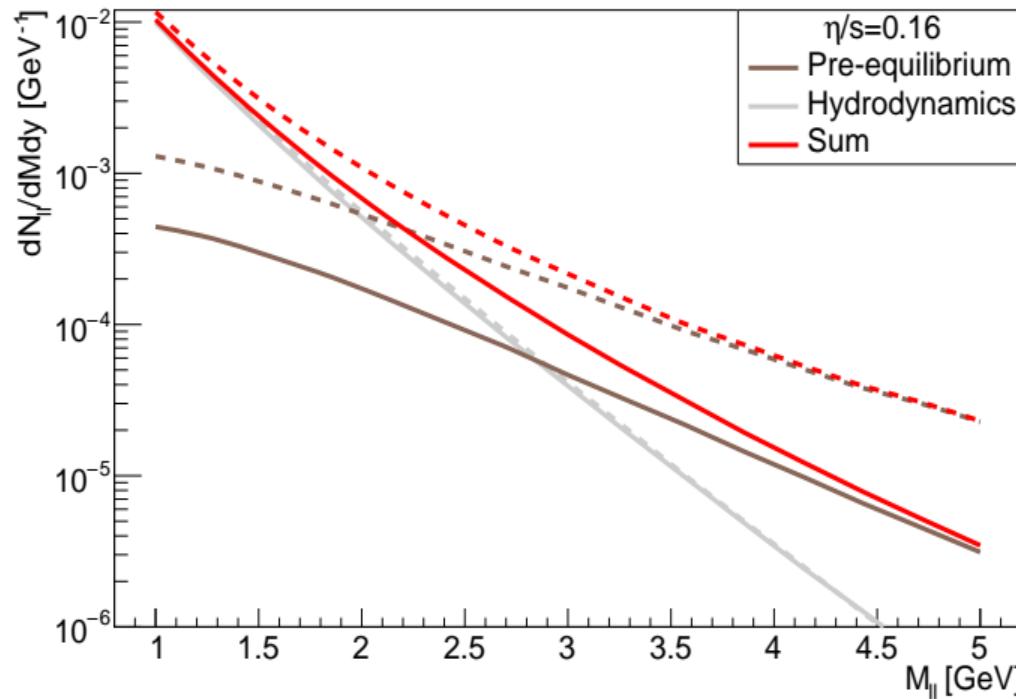
$$f_q(\tau, p_T, p_L) = q_s(\tau) f_{FD} \left(-\sqrt{p_T^2 + \xi^2(\tau)p_L^2} / \Lambda(\tau) \right)$$

→ 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 :



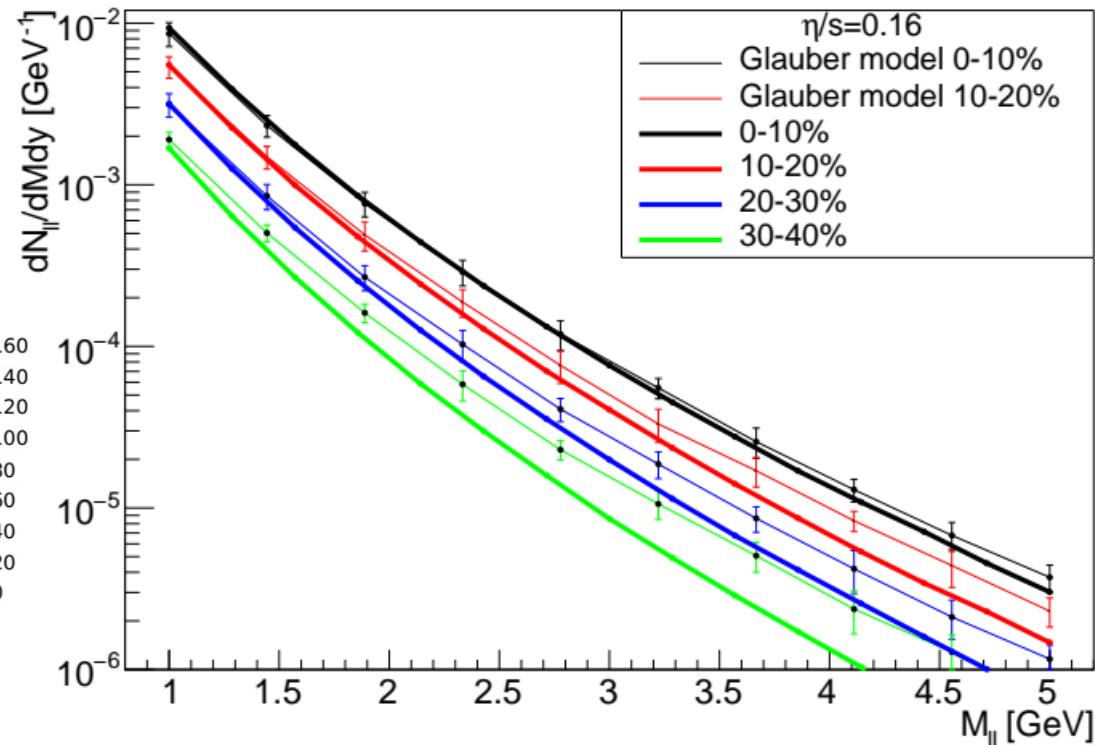
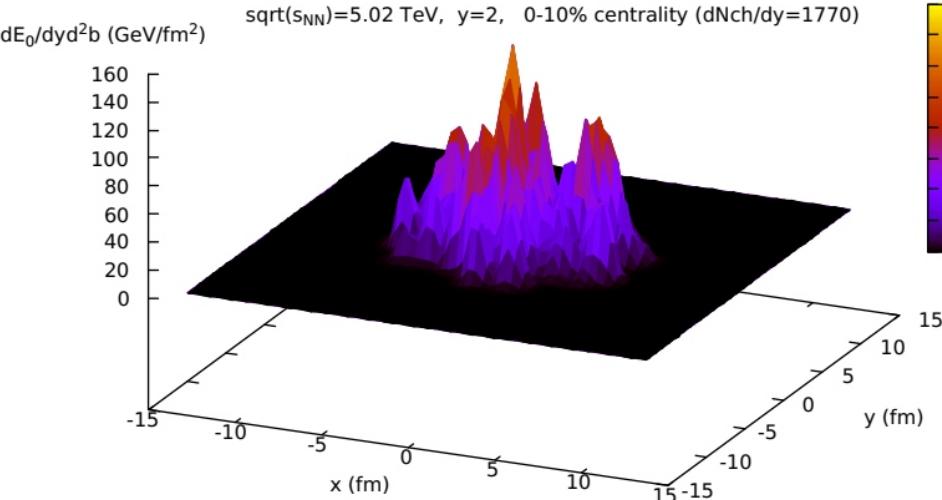
Results: time decomposition



- 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