Pre-equilibrium dilepton production: concepts, estimates and feasibility

IS 2021, January 12 2021, Maurice Coquet

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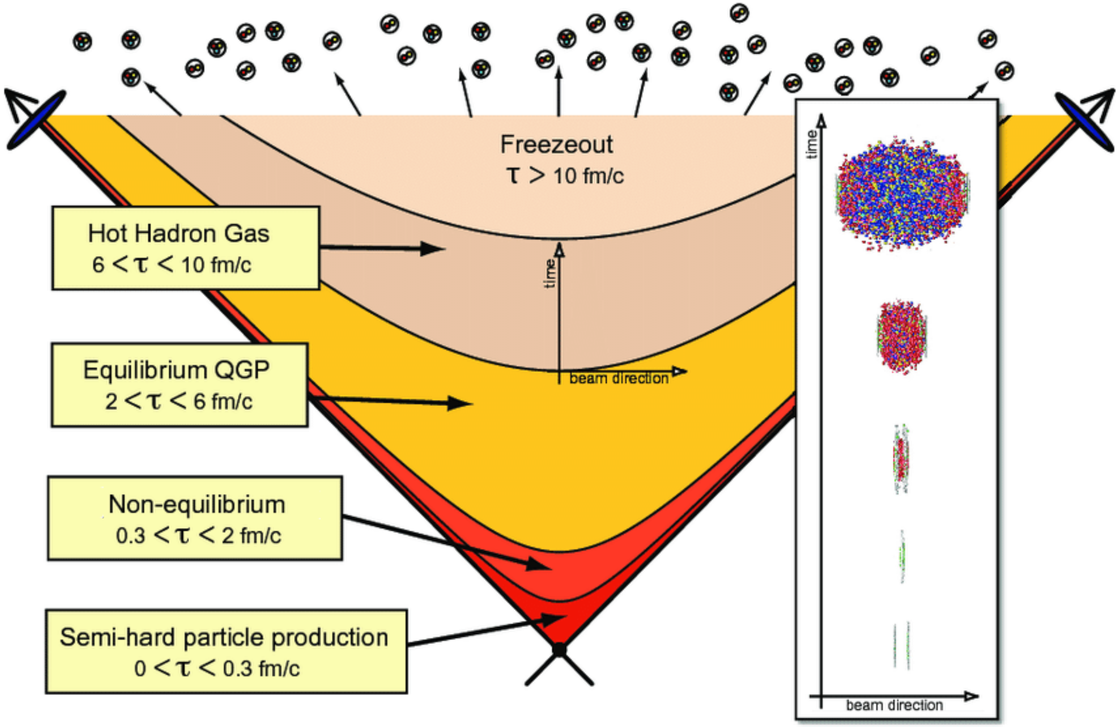
Space-time evolution of heavy-ion collisions

- Heavy-ion collisions: different time scales described by different effective theories

- Late stages very accurately modeled by hydrodynamic descriptions for expanding near-equilibrium QGP

- A challenge : matching between far-from-equilibrium initial state predicted by CGC and viscous hydrodynamics

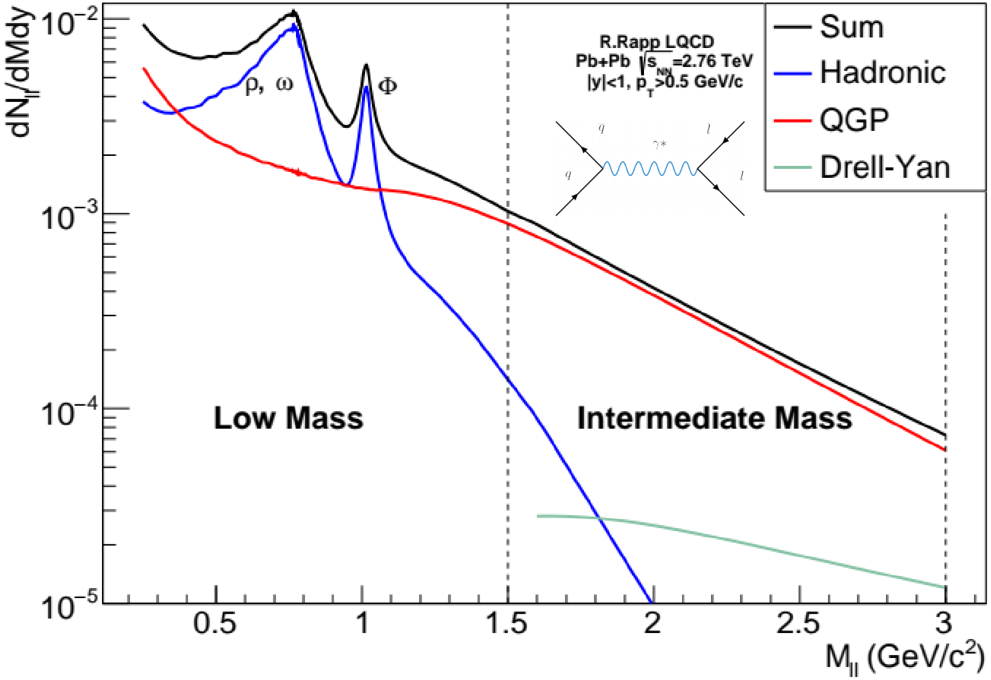


M.Strickland, Acta Physica Polonica B 45, 2355 (2014)

Dilepton production as a probe

R.Rapp and J.Wambach Eur. Phys. J. A6(1999)415;
R. Rapp and H. van Hees, Nucli. Phys. 806 (2008) 339;
R.Rapp, Adv. High Energy Phys. 2013 (2013) 148253,
R.Rapp, private communication

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



Production rate given by current-current correlator :

$$\frac{dN^{l^+l^-}}{d^4x\,d^4Q} = -\frac{\alpha_{em}^2}{6\pi^3 Q^2}\sum_f q_f^2\,\Pi^{\mu,<}_{\mu}(Q)$$

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

➢ Isolate early-times/pre-equilibrium emission

Production rate calculation: pressure anisotropy

- At early times, the system is highly anisotropic due to rapid longitudinal expansion

→ *P_L<< P_T and hydrodynamic description does not apply*

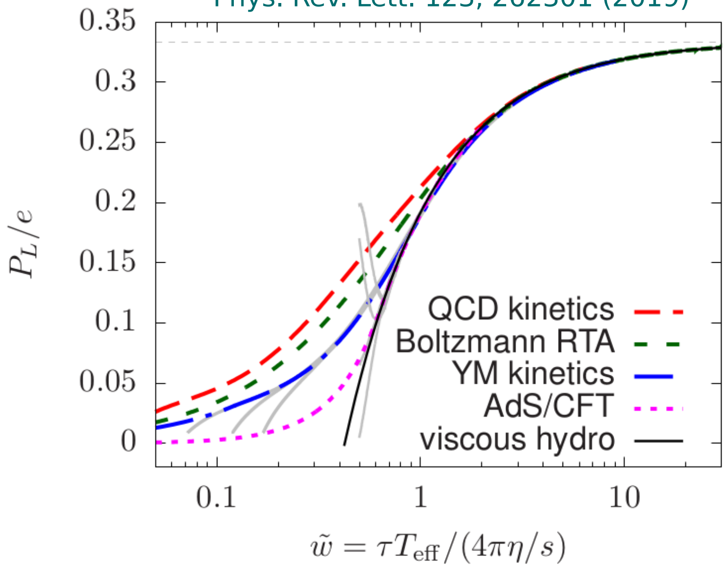
- Convergence towards attractor : universal feature of all microscopic descriptions of early-time dynamics

- Local pressure isotropy occurs at late times, but *applicability of viscous hydro better than anticipated*

  → $\tau_{hydro} << \tau_{eq}$

- Evolution of energy-stress tensor is calculated w/ QCD kinetics in weak coupling regime

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

Production rate calculation: quark suppression

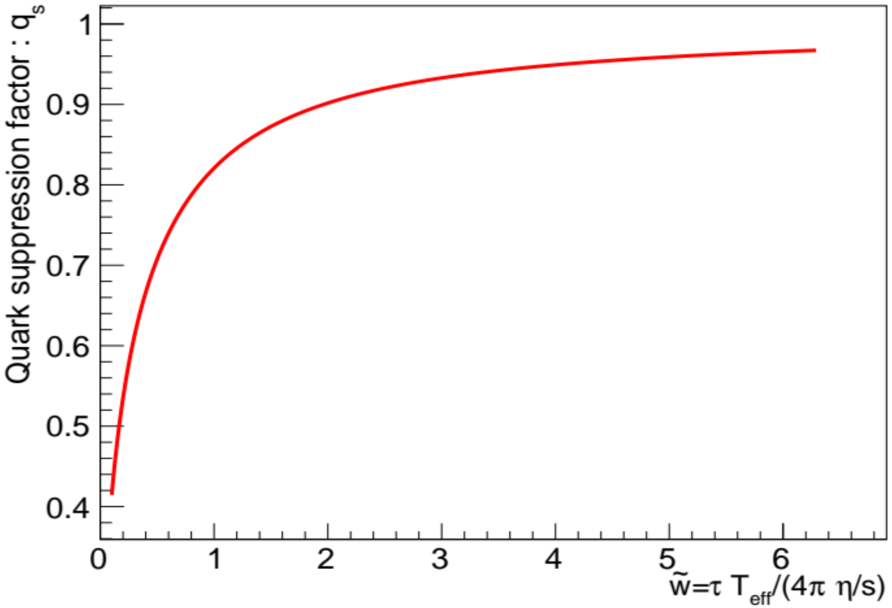
- Initial state theories (CGC) predict a gluon-dominated medium at early times

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

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

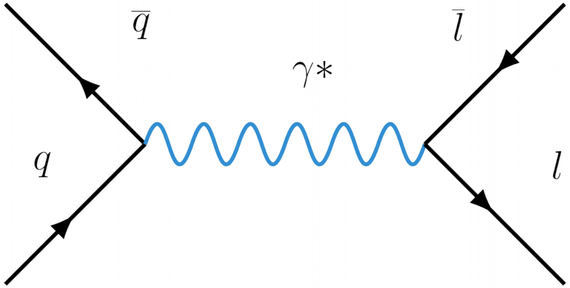
- Transition of highly gluon-dominated system towards a chemically equilibrated medium

X. Du, S. Schlichting: arXiv:2012.09079, 2012.09068



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

Production rate calculation : Correlator



Anisotropic (out-of-equilibrium) current-current correlator calculated at LO (quark-anti-quark annihilation)

cf: Strickland PRD 99 (2019) 3, 034015, Churchill, Yan, Jeon, Gale arXiv:2008.02902, Ryblewski, Strickland PRD 92, 025026 (2015)

$$\Pi^{\mu,<}_{\mu}(Q) = -\frac{N_c Q^2}{4\pi^2 q}\int d^3p\,\frac{1}{p^2}\delta\Big(\cos\theta_{pq} - \frac{q^2+2pq_0-q_0^2}{2pq}\Big) f_q(p) f_{\bar{q}}(q-p)\,\theta(q^- < p < q^+)$$

We introduce distribution functions for quarks which are 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

Space-time picture : Hydrodynamic attractor

$$\frac{dN^{l^+l^-}}{dQdy} = -\int d^2x_T \int d\tau \int d^3q \frac{Q}{q_0}\tau \frac{dN^{l^+l^-}}{d^4xd^4Q}$$

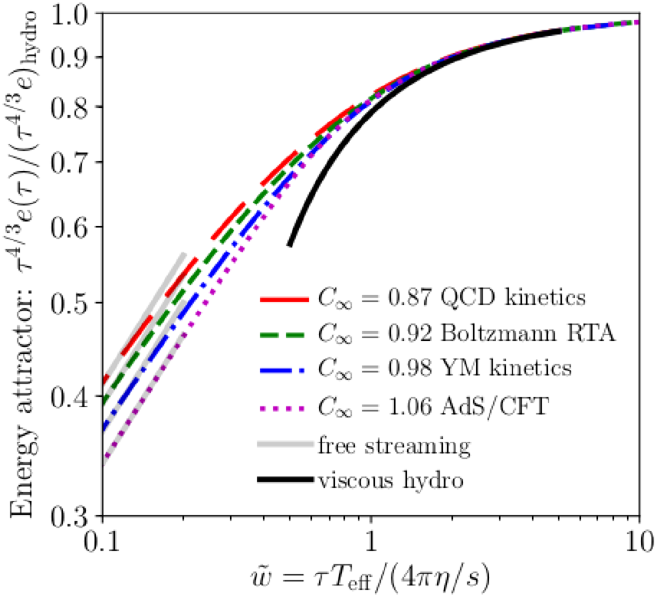
→ Integrate over space-time evolution of the medium to calculate the dilepton yield

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

$$e(T_{\text{eff}}(\tau)) = e(q_s(\tau), \xi(\tau), \Lambda(\tau))$$

With : $e(\tau) \equiv \frac{\pi^2}{30}\nu_{\text{eff}}T^4_{\text{eff}}(\tau)$

→ Use of a hydrodynamic attractor : effective curve that gives access to early evolution of energy density



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

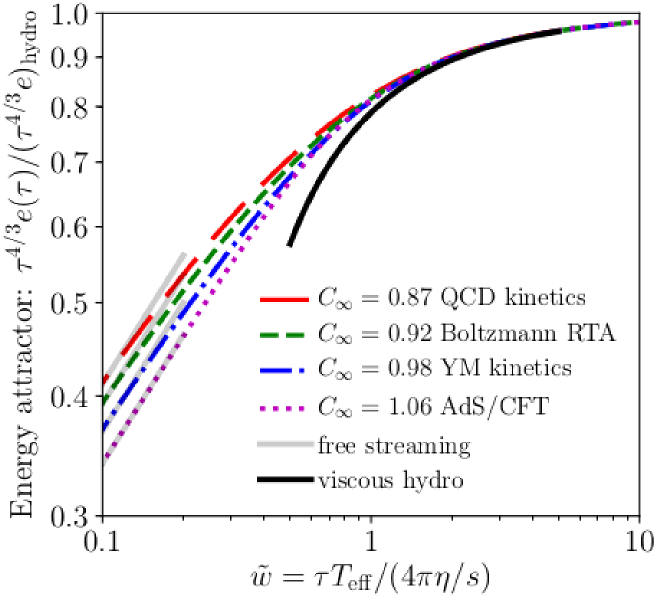
$$\frac{e(\tau)\tau^{4/3}}{e_{hydro}\tau^{4/3}_{hydro}} = \mathcal{E}(\tilde{w}) \qquad \tilde{w} = \frac{\tau T_{eff}}{4\pi\eta/s}$$

Space-time picture : Hydrodynamic attractor

- Assume one dimensional Bjorken expansion :

→ boost invariant along the longitudinal direction

→ translationally invariant in transverse directions



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

- Entropy approximately conserved during hydro expansion → entropy and particle production come from pre-equilibrium stage

→ Final condition at late times (w>>1):

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

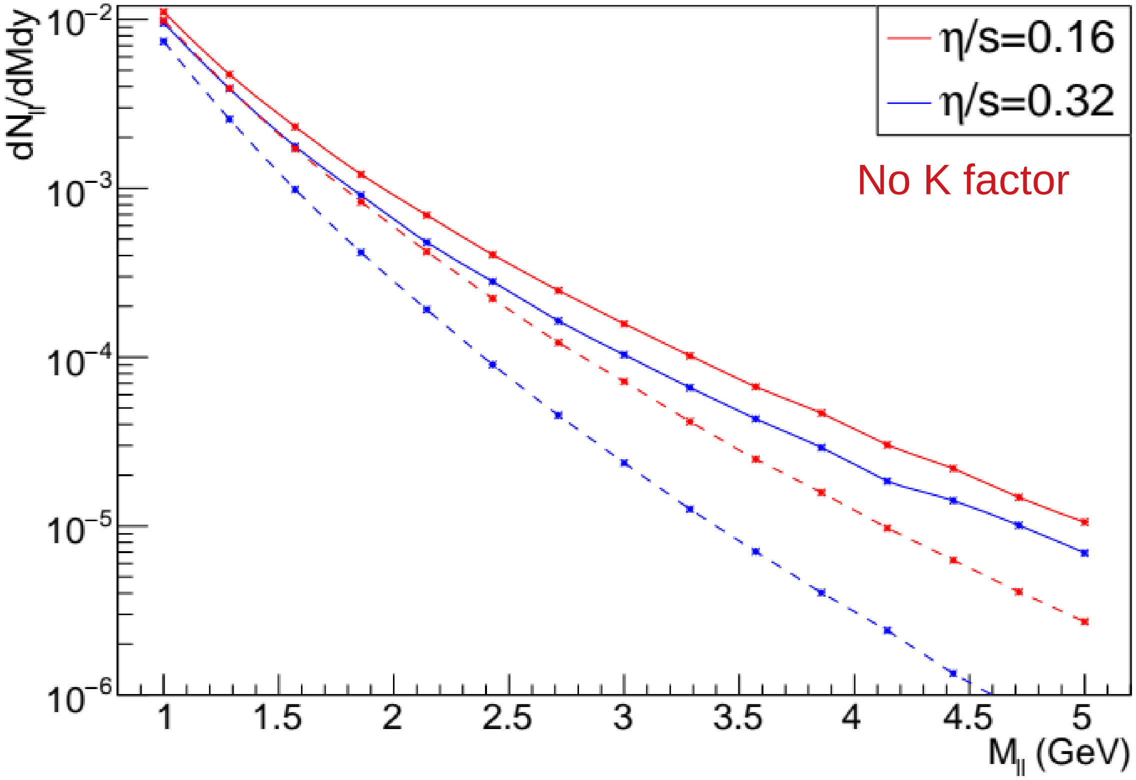
Fixed by charged particle multiplicity in the final state
→ final state entropy density

$$\frac{dS}{d\,\eta} \propto \frac{dN_{ch}}{d\,\eta} \approx 1900$$

(For η=2 at 5.02 TeV)

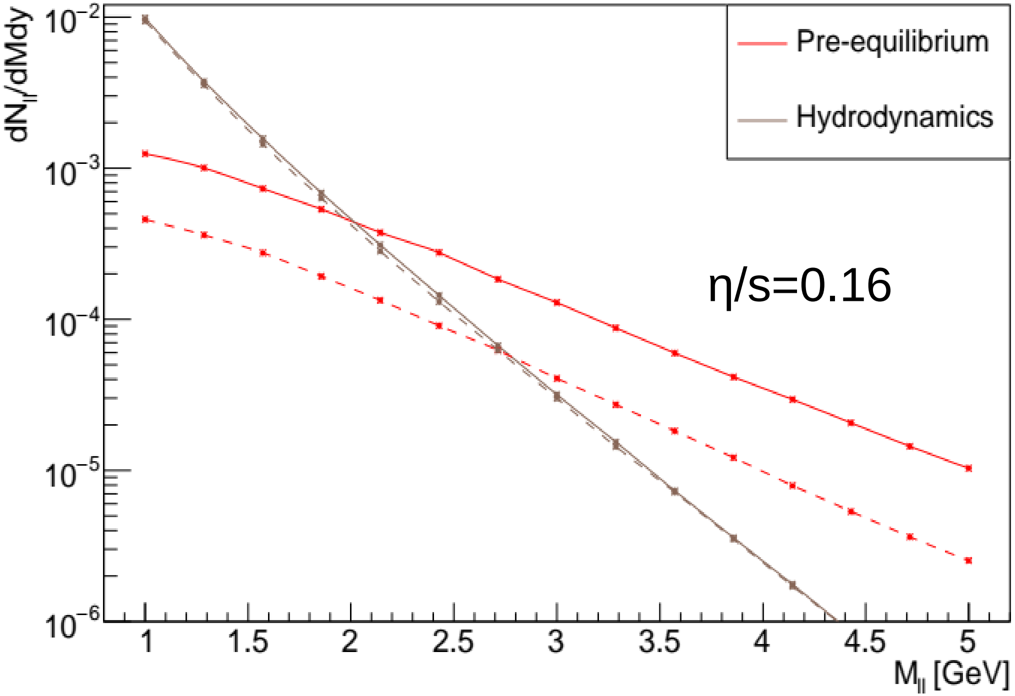
Results: mass spectra

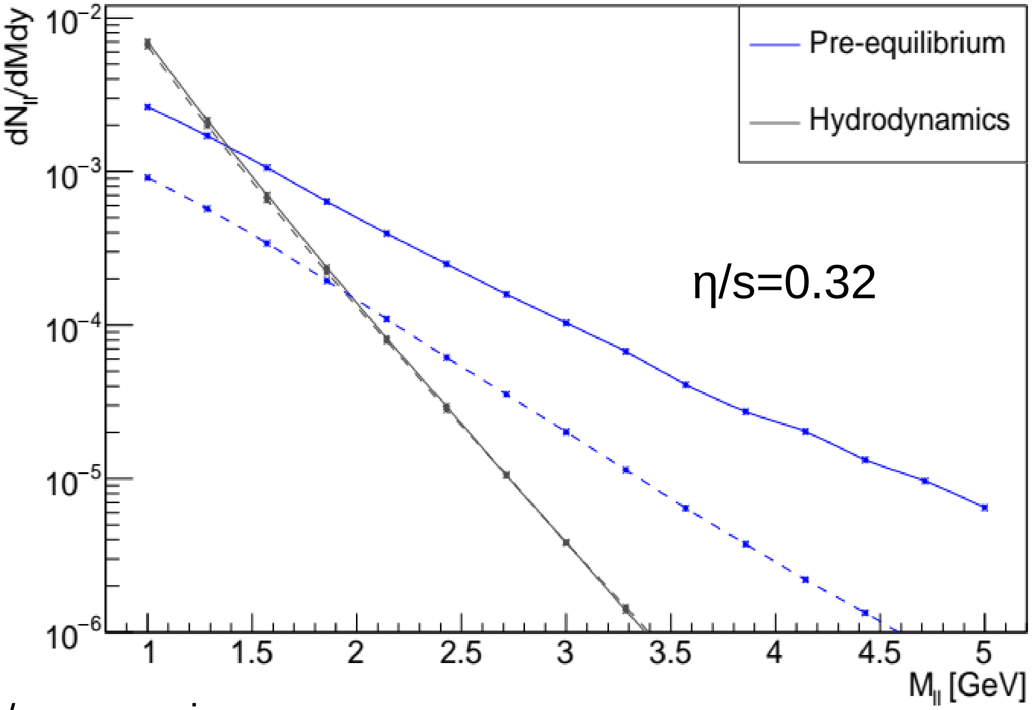
- Total dilepton rates as a function of dilepton invariant mass, for different shear viscosities
- η/s is not the usual viscosity in the hydro regime but viscosity at high temperature : speed of system equilibration
- Lower η/s : quicker system equilibration
  → higher initial energy density
  → higher dilepton yield for fixed final condition



Full lines : w/o quark suppression, Dotted lines : w/ suppression

Results: time decomposition



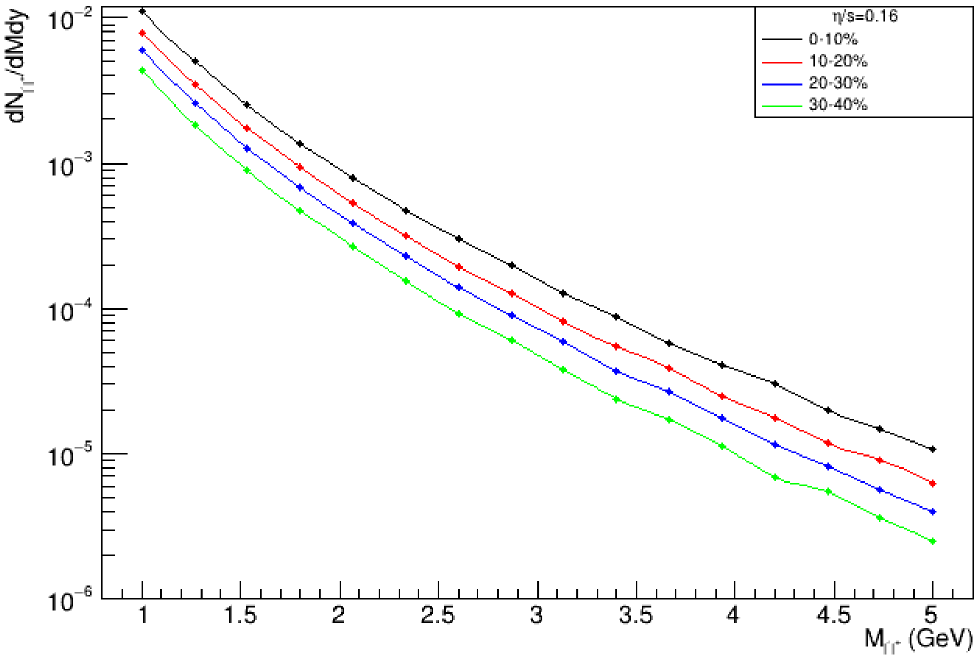


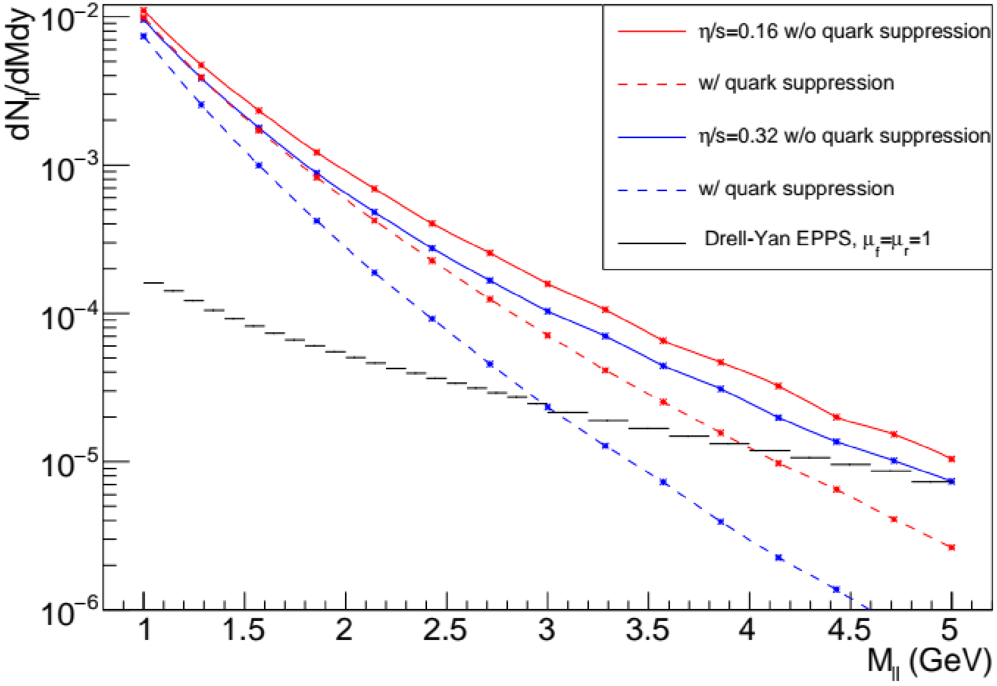
- Full lines : w/o quark suppression, dotted lines : w/ suppression
- Different slopes, higher masses dominated by early emission
- Strong sensitivity to η/s and to quark suppression
  → measurement to learn about chemistry and medium properties in pre-equilibrium phase

Comparison with Drell-Yan and centrality dependence

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

- Pre-equilibrium+hydro production is very sensitive to quark suppression
  → direct access to early-stage chemistry and potentially direct measurement

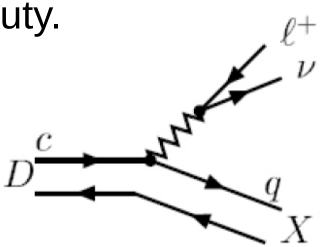


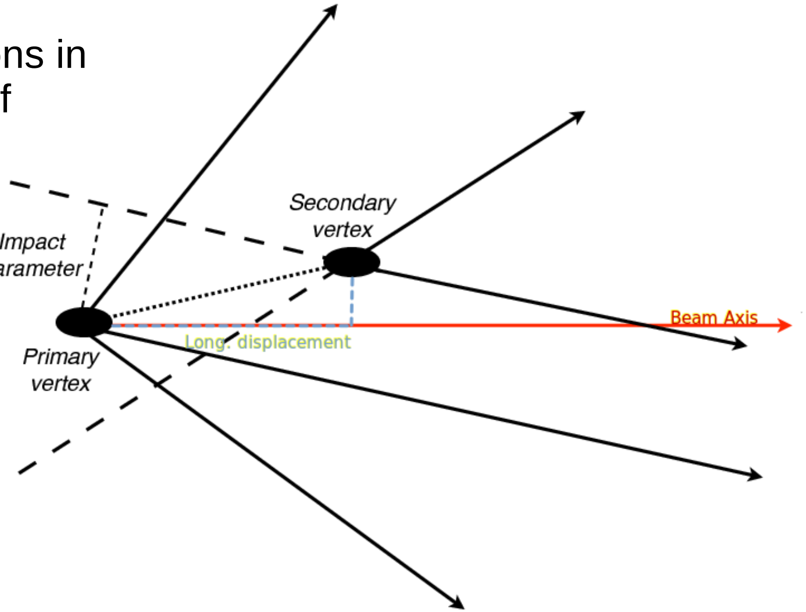


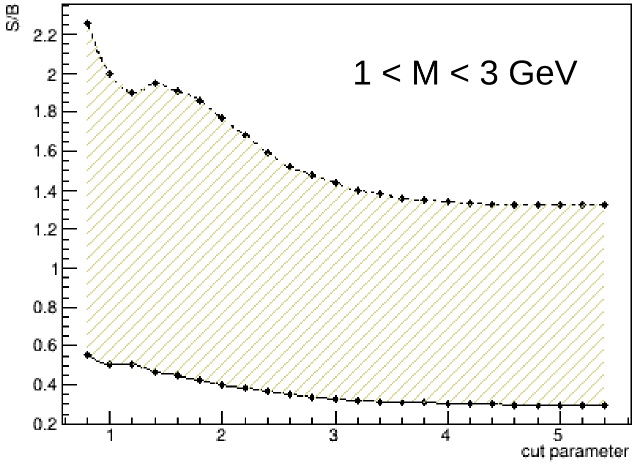
- Significant centrality dependence
  → initial-state energy grows with charged particle multiplicity : $dE_0/d\eta \propto (dN_{ch}/d\eta)^{3/2}$

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

Conclusion and outlook

- Window of dominating pre-equilibrium production identified

  → insight into quark suppression & matter properties at early stages

- Transverse momentum spectra can be used as an additional discriminator
  (Strickland PRD 99 (2019) 3, 034015, Churchill, Yan, Jeon, Gale arXiv:2008.02902, Ryblewski, Strickland PRD 92, 025026 (2015))

- Background suppression : secondary vertexing

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

Thank you !

Backup

Heavy-flavour background

We approximate the charm/beauty yield in Pb-Pb with the p-p cross sections computed with FONLL, and the nuclear form factor from ALICE at 5 TeV:

In centrality bin $0-10\%$, $2 < \eta < 5$:

$\sigma_C^{pp} = 0.94$ mb, $< T_{AA,C} >= 23.26$ /mb

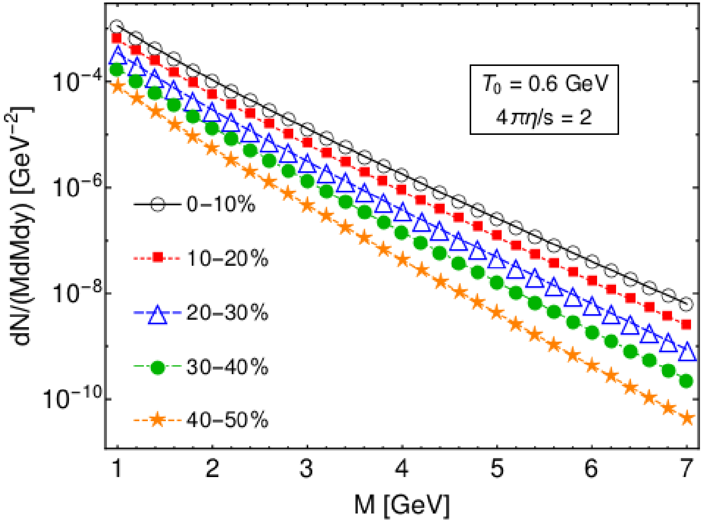
$$\langle T_{AA} \rangle = \frac{A^2}{\sigma^{AA}} \qquad R_{AA} = \frac{N^{AA}}{\langle T_{AA} \rangle \sigma^{pp}}$$

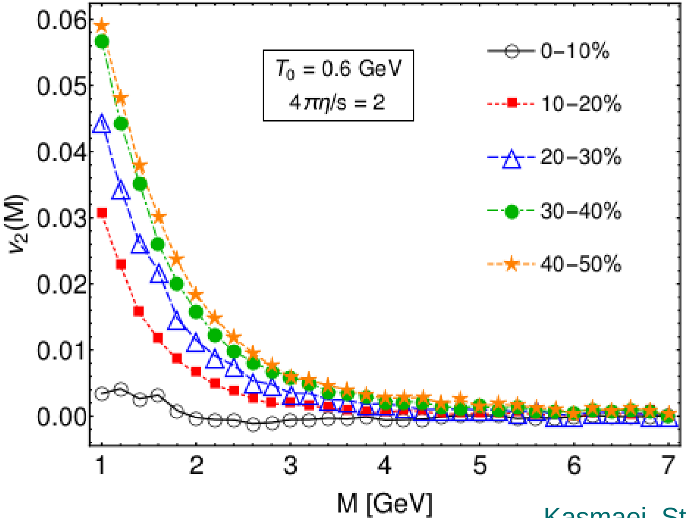
$$N_C^{AA} =< T_{AA} > \sigma_C^{pp} \approx 87 \left\{ \begin{array}{c} \xrightarrow{\mathrm{f=0.232}} D^{\pm} \xRightarrow{\mathrm{BR=0.16}} \\ \xrightarrow{\mathrm{f=0.549}} D^{0} \xRightarrow{\mathrm{BR=0.065}} \\ \xrightarrow{\mathrm{f=0.120}} \Lambda_C \xRightarrow{\mathrm{BR=0.045}} \end{array} \right\} \mu$$

$\sigma_B^{pp} = 0.04$ mb, $< T_{AA,C} >= 23.26$ /mb

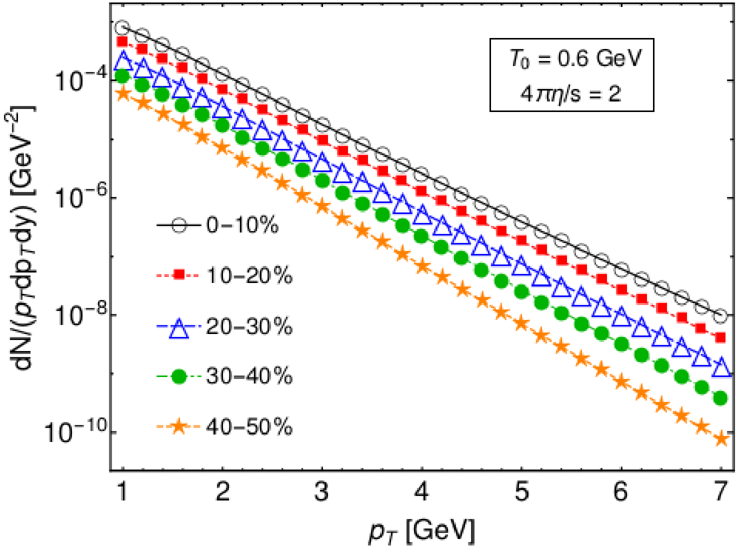
$$N_B^{AA} =< T_{AA} > \sigma_B^{pp} \approx 4 \left\{ \begin{array}{c} \xrightarrow{\mathrm{f=0.403}} B^{\pm} \xRightarrow{\mathrm{BR=0.10}} \\ \xrightarrow{\mathrm{f=0.403}} B^{0} \xRightarrow{\mathrm{BR=0.11}} \end{array} \right\} \mu$$

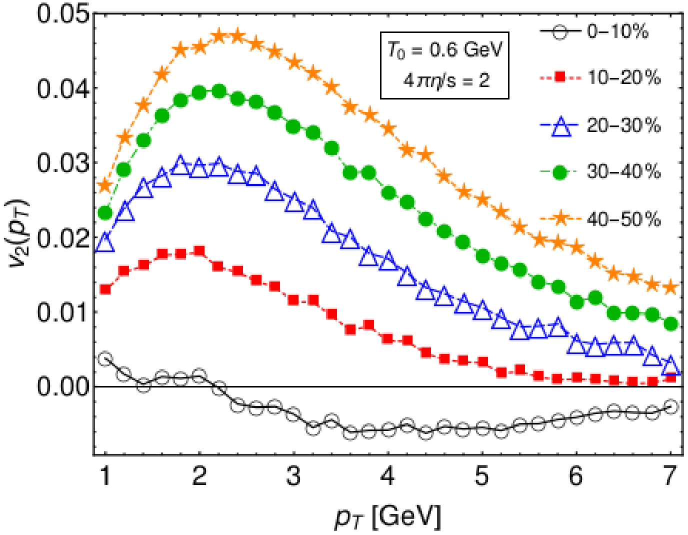
We assume an $R_{AA}=1$



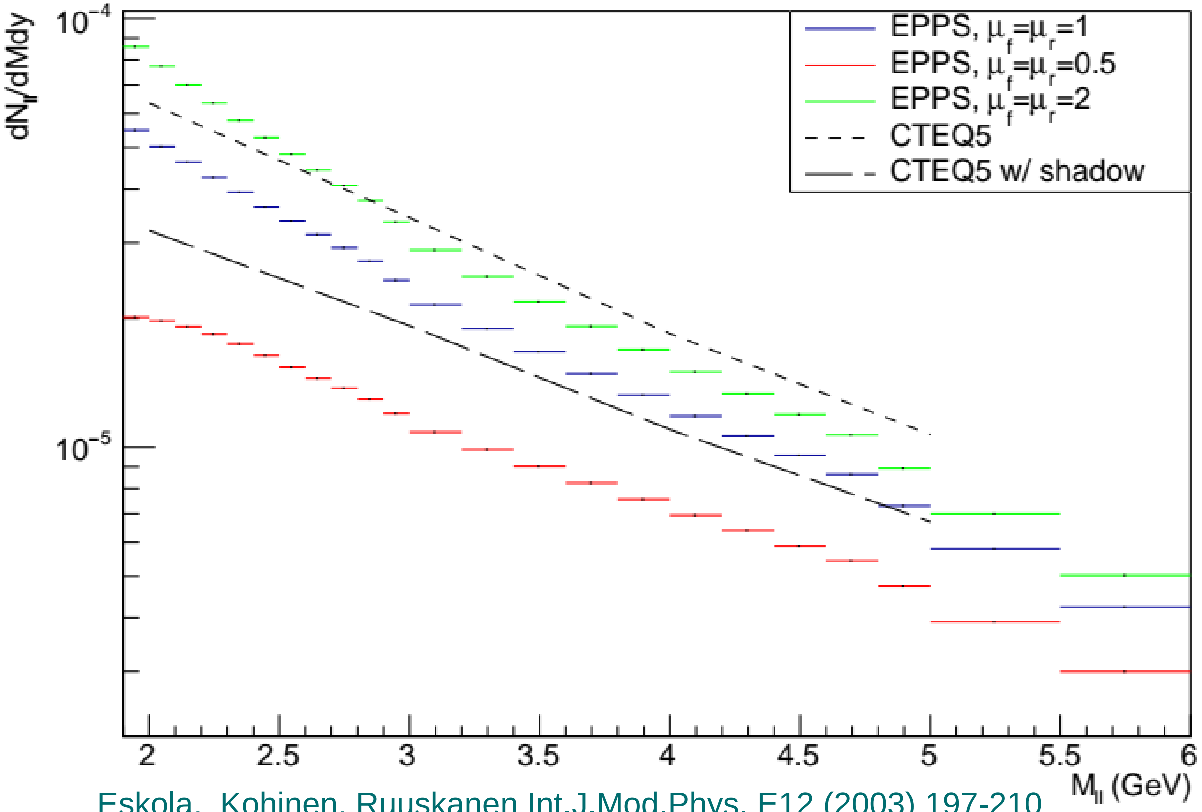


Kasmaei, Strickland PRD 99 (2019) 3, 034015





Scale variation in Drell-Yan calculation



Eskola, Kohinen, Ruuskanen Int.J.Mod.Phys. E12 (2003) 197-210
DYTurbo, arXiv:1910.07049