Pre-equilibrium di-lepton production

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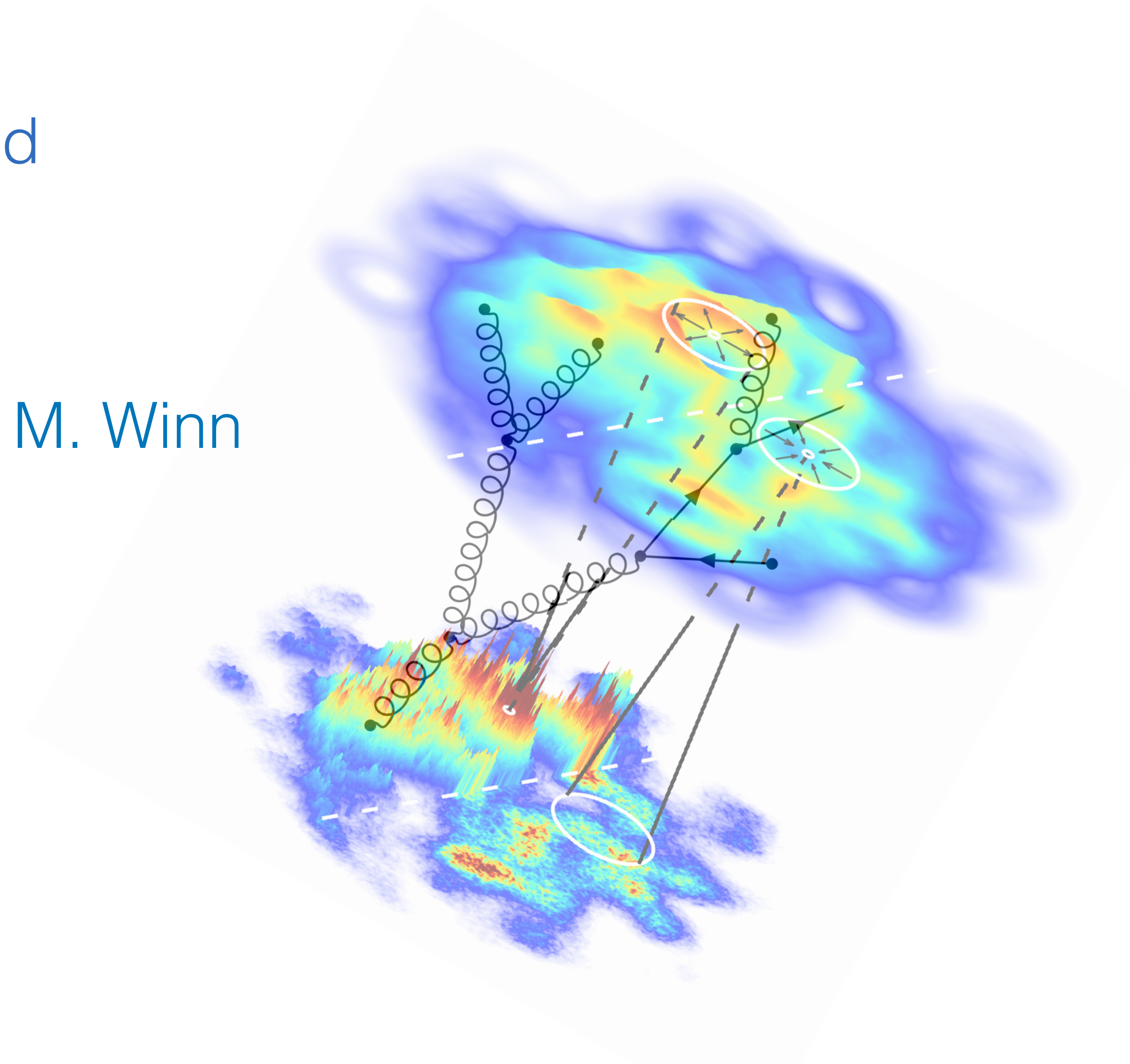


Based on
M.Coquet, X.J.-Du, J.-Y. Ollitrault, SS, M. Winn
Phys.Lett.B 821 (2021) 136626

EMMI Rapid Reaction Task Force on
Real and Virtual Photon production
Sept 2021

CRC-TR 211 Strong-interaction matter under extreme conditions

P2IO Physique des 2 Infinis et des Origines

Gluodynamics

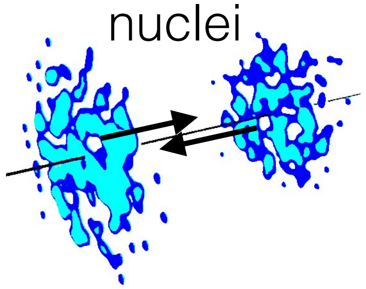
UNIVERSITÄT BIELEFELD

Dynamics of HICs

Dynamical description of heavy-ion collisions from underlying theory of QCD remains an outstanding challenge

Standard model of nucleus-nucleus (A+A) collisions based on eff. descriptions of QCD exploiting separation of time scales in the reaction dynamics

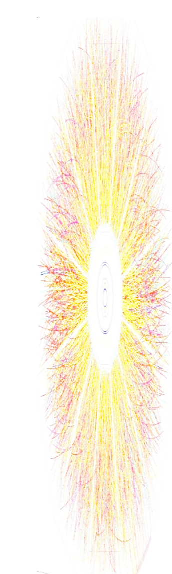
colliding nuclei



non-equilibrium QGP

near-equilibrium QGP

hadron gas



$\tau_{\rm coll} \ll 1{\rm fm/c}$

$\tau_{\rm Hydro} \sim 1{\rm fm/c}$

$T \sim 4T_c$

$\tau_{\rm freeze-out} \sim 10{\rm fm/c}$

$T \sim T_c$

energy deposition

rapid long. expansion + equilibration

long. and transverse expansion

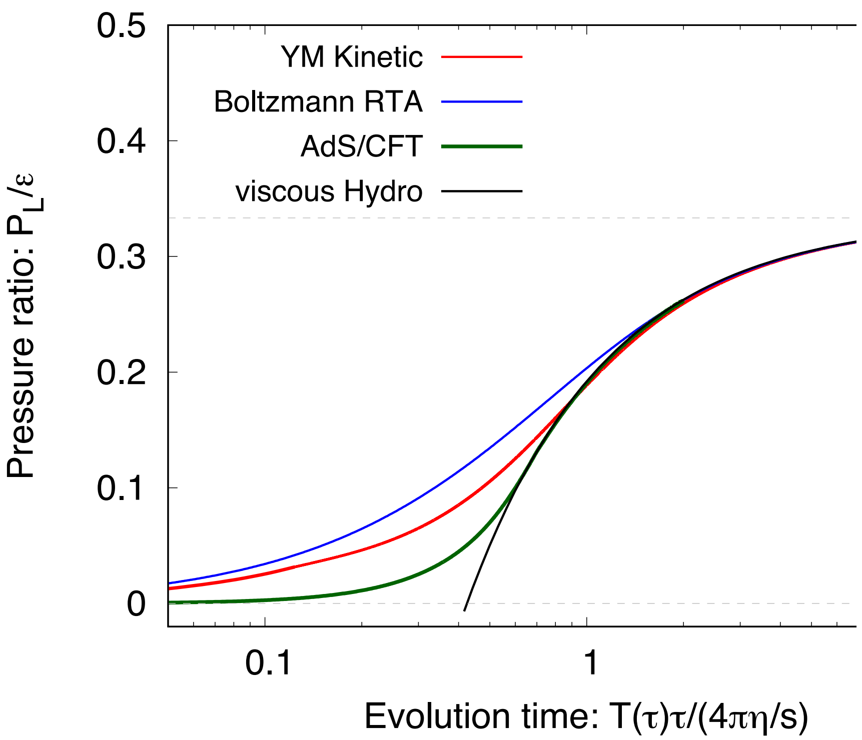
free-streaming + hadronic scatterings

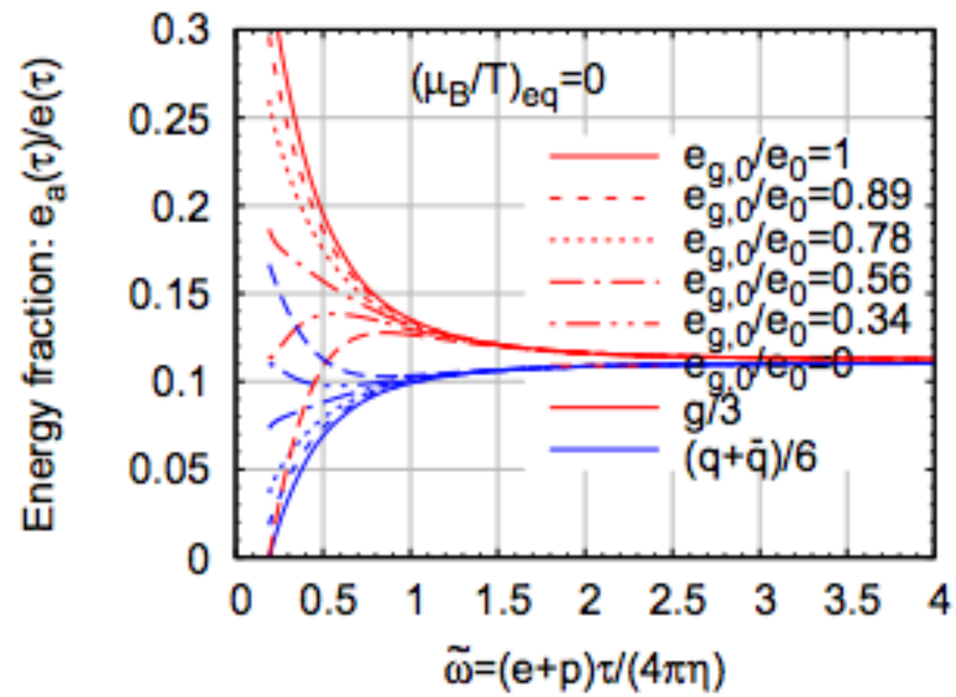
Theoretical description based on multi-stage evolution models

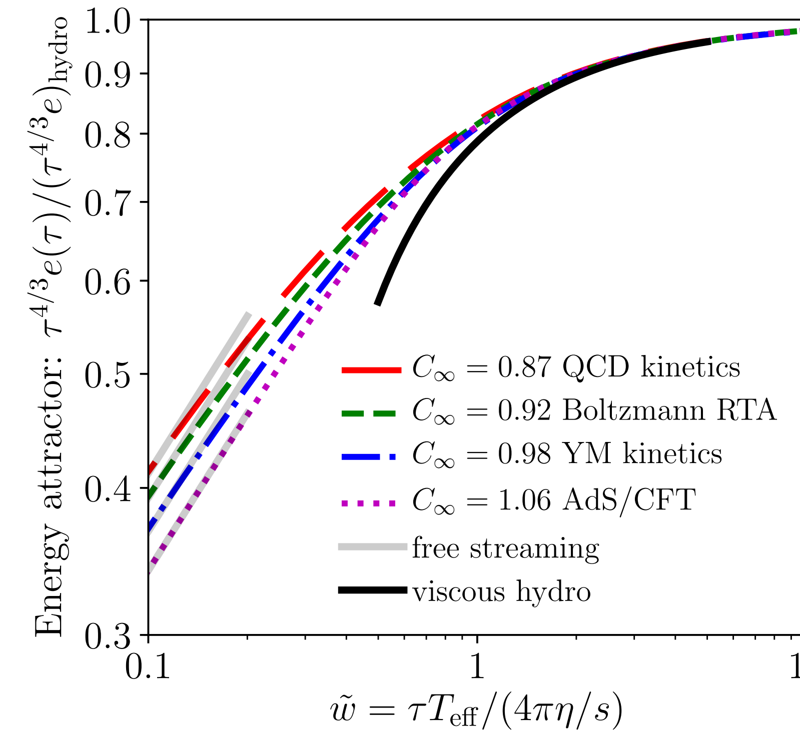
Color Glass Condensate	QCD Kinetic Theory	rel. visc. hydrodynamics	hadronic cascade
IP-Glasma	KoMPoST	MUSIC	SMASH

Pre-equilibrium evolution

Significant progress in weak/strong coupling limits of QCD







Early pre-equilibrium QGP is highly anisotropic, gluon dominated and cools less rapidly than thermal QGP

$$\tilde{w} = \frac{T_{\rm eff}(\tau)\tau}{4\pi\eta/s} \simeq 1$$

Hydrodynamization (≠ kinetic thermalization) occurs on time scale of one equilibrium relaxation time

$$\tau_{\rm hydro} \approx 1.1\,{\rm fm}\left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}}\left(\frac{\langle\tau s\rangle}{4.1\,{\rm GeV}^2}\right)^{-1/2}$$

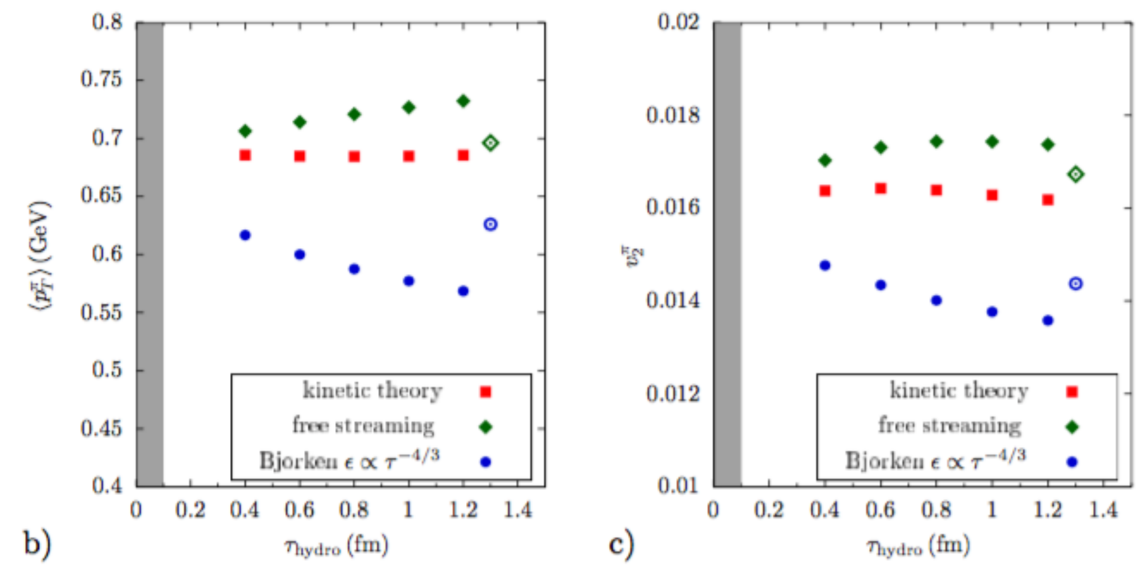
YM: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910
QCD: Kurkela, Mazeliauskas PRL 122 (2019) 142301; SS, Du arXiv:2012.09079 ; RTA:Kamata, Martinez, SS PRD 102 (2020) 5
AdS/CFT: Romatschke PRL 120 (2018) no.1, 012301

Dynamics of HICs

Now there are practical tools to include pre-equilibrium evolution into dynamical description of HICs

KoMPoST: Event-by-event pre-equilibrium dynamics & initial conditions for Hydro Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

Small effects of pre-equilibrium dynamics on typical observables (v_n,$<p_T>$,…) dominated by transverse expansion of QGP (~1-10fm/c)



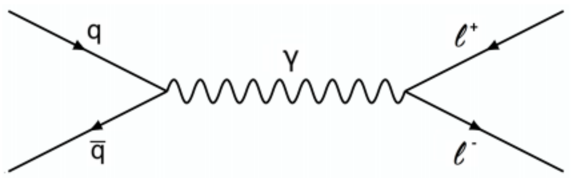
Kurkela, Mazeliauskas, Paquet, SS, Teaney
PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

Controlled extraction of near-equilibrium and transport properties of QGP (EoS,η/s,..) based on hydrodynamic simulations

Difficult to gain access to early time non-equilibrium dynamics in from typical hadronic measurements in A+A collisions

Pre-equilibrium di-lepton production

Electro-magnetic probes are produced throughout the entire lifetime of the QGP and escape the plasma without re-interaction



Equilibrium di-lepton production rate at LO:

$$\frac{dN^{l^+l^-}}{d^4x d^4Q} = -\frac{\alpha_{em}^2}{6\pi^3 Q^2}\theta(Q^2-4m^2)\left(1+\frac{2m^2}{Q^2}\right)\left(1-\frac{4m^2}{Q^2}\right)^{1/2}\sum_f q_f^2 \Pi^{\mu,<}_{\mu}(Q)\,.$$

$$\Pi^{\mu<}_{\mu}(Q)\Big|_{\rm eq} \overset{Q^2\gg T^2}{\simeq} -\frac{N_c Q^2}{2\pi} n_{BE}(q_0)$$

Early stages are different from thermal QGP emission

non-equilibrium QGP is hotter, highly anisotropic, not in chemical equilibrium

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

=> Explore high invariant mass di-leptons as probe of early QGP

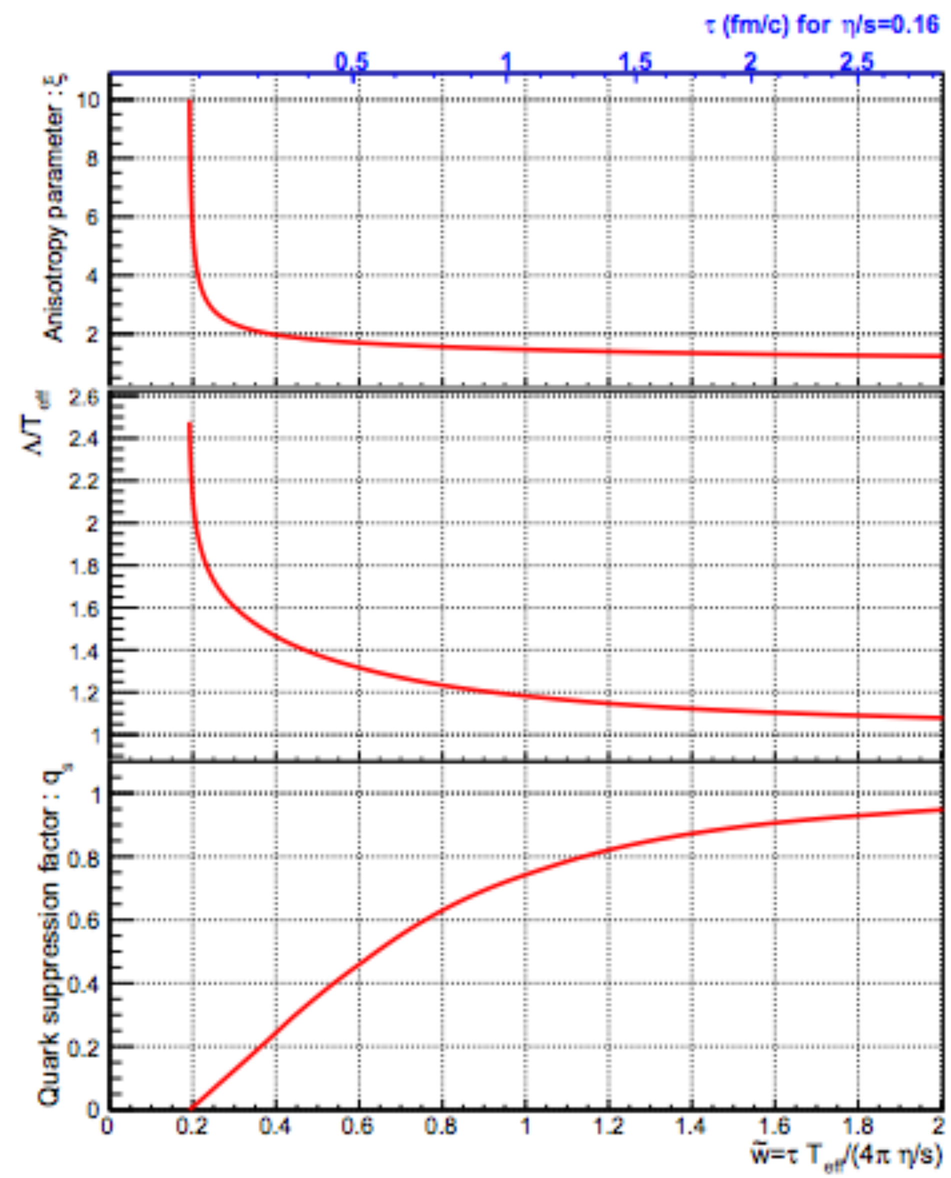
see also Martinez, Strickland PRC 78 (2008) 034917; Ryblewski, Strickland PRD 92, 025026 (2015); Kasmaei, Strickland PRD 99 (2019) 3, 034015
Churchill, Yan, Jeon, Gale arXiv:2008.02902

Di-lepton production

We employ LO di-lepton rate with parametrized phase-space distribution of the aHydro form

$$f_g(\tau, p_t, p_z) = f_{BE}\left(\frac{\sqrt{p_t^2 + \xi^2(\tau) p_z^2}}{\Lambda(\tau)}\right) \qquad f_{q/\bar{q}}(\tau, p_t, p_z) = q(\tau) f_{FD}\left(\frac{\sqrt{p_t^2 + \xi^2(\tau) p_z^2}}{\Lambda(\tau)}\right)$$

with anisotropy parameter, eff. temperature and quark supression factor matched to evolution of P_L/e, e_q/e_g and e for non-equilibrium attractors from QCD kinetic theory



We neglect transverse expansion at early times and assume transversely homogenous Bjorken expansion with energy density

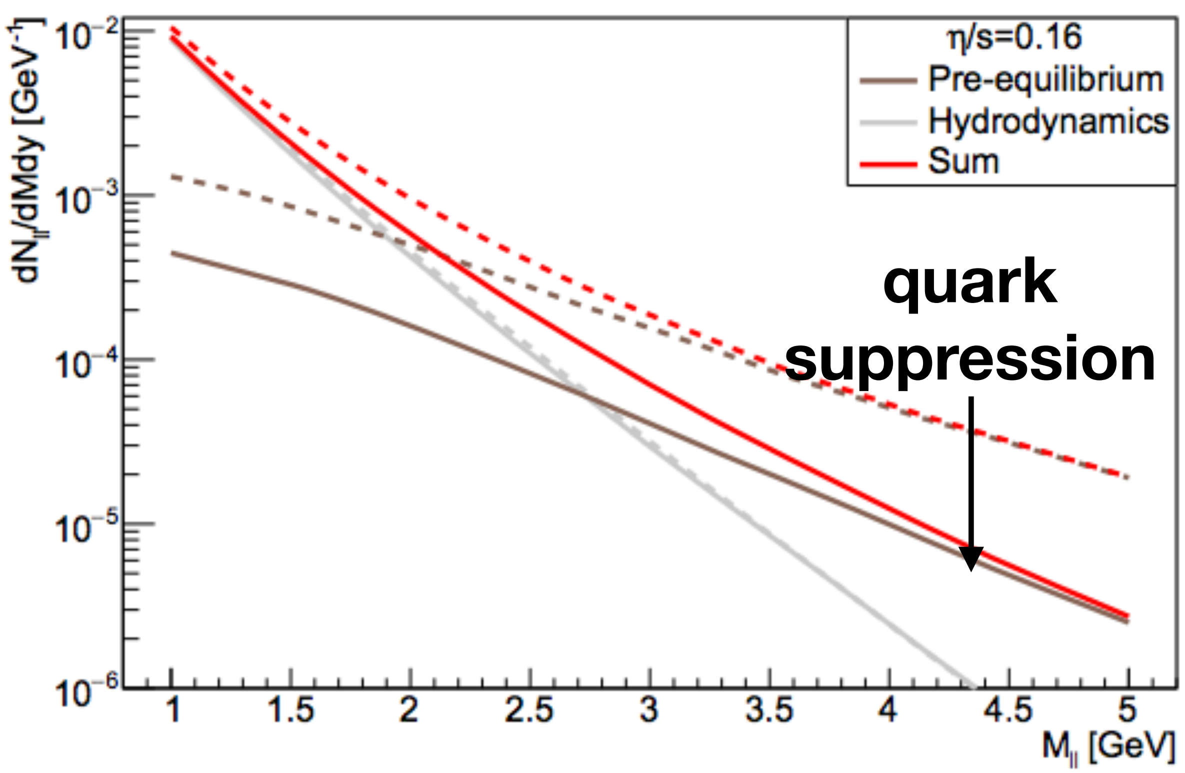
$$e(\tau) = \frac{\pi^2}{30} \nu_{\text{eff}} T_{\text{eff}}^4(\tau)$$

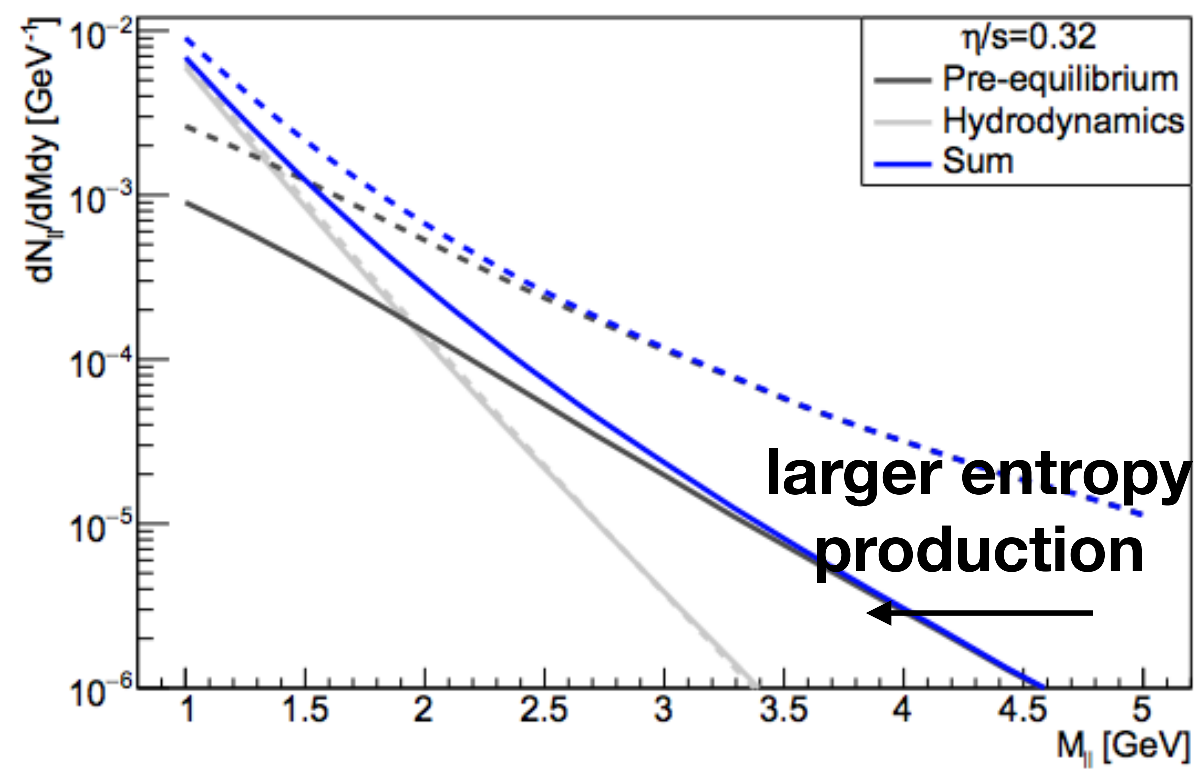
matched to dN_{ch}/dy

Di-lepton production

Di-lepton production vs. invariant mass M_{ll} of di-lepton pair

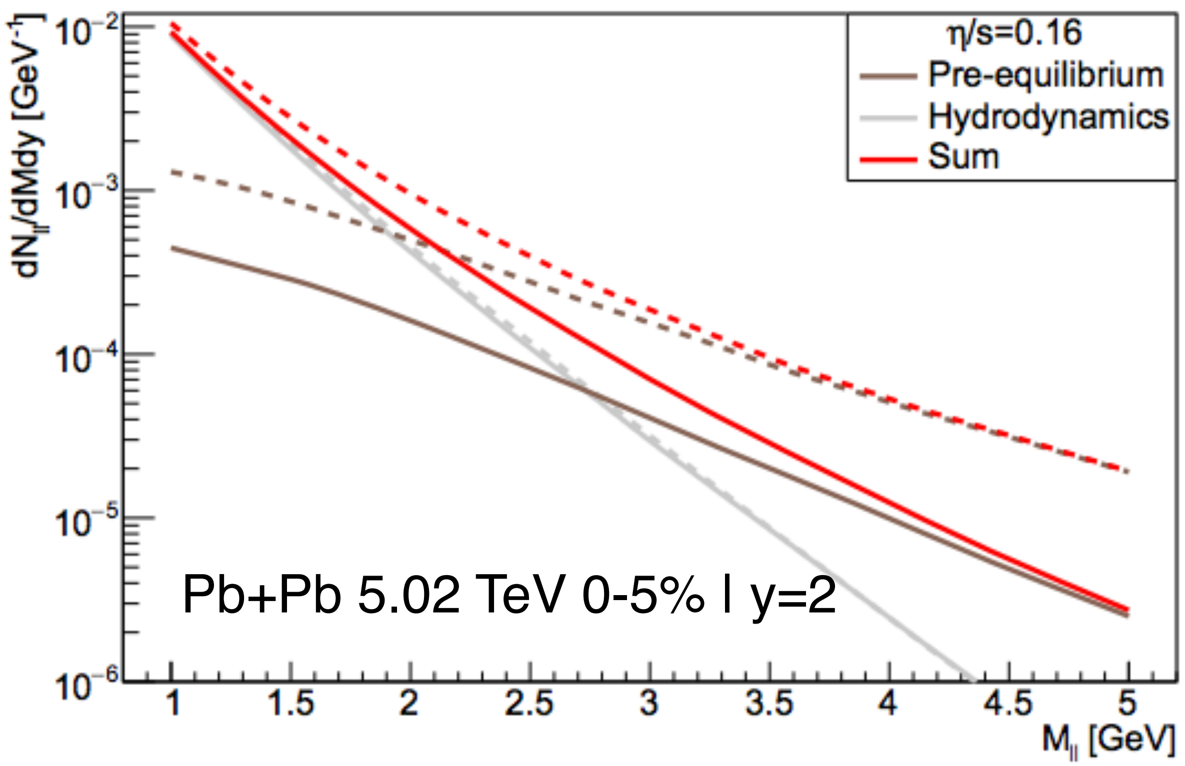
Pb+Pb 5.02 TeV 0-5% l y=2 (LHCb kinetimatics)

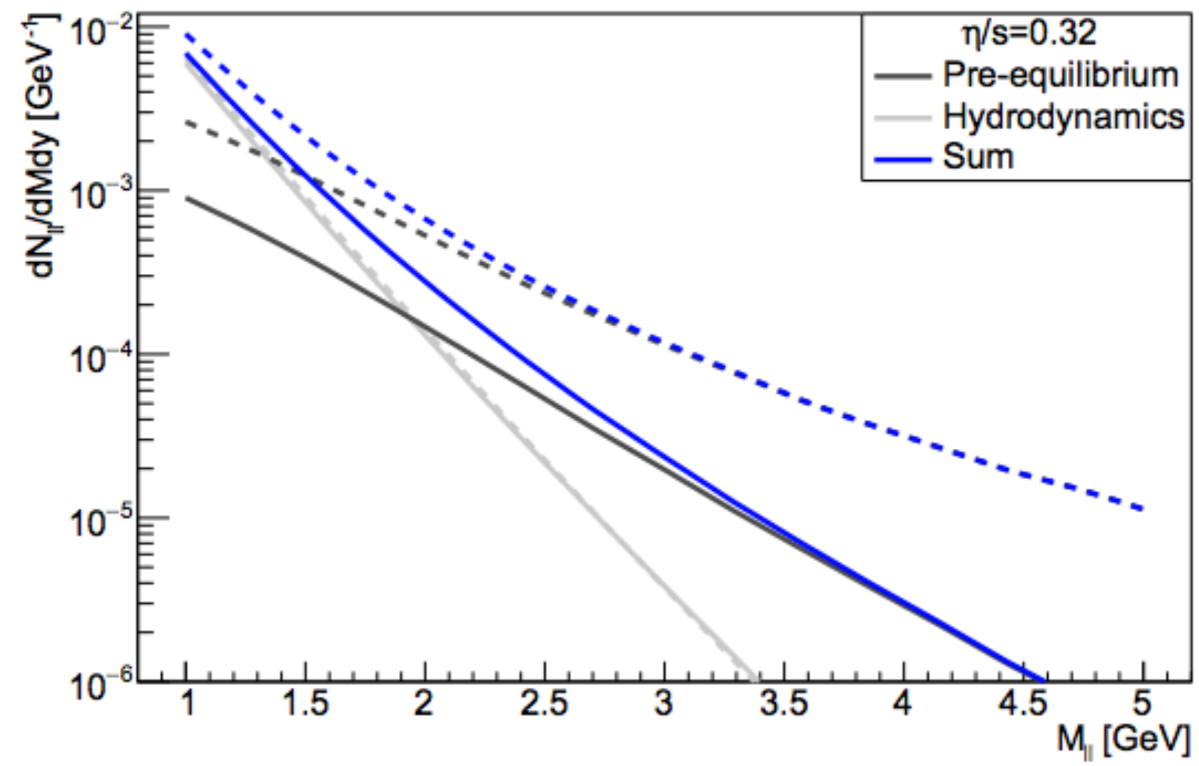




Since η/s controls time scale for applicability of hydrodynamics; depending on value of η/s considerable contributions from pre-equilibrium regime (w<1) for M_{ll} >2-3 GeV

Di-lepton production





Empirically, yields are well described by pocket formula

$$\frac{dN^{l+l-}}{dMdy} = C\left(1+\frac{M}{nT_0}\right)^{-n} \qquad n \simeq 5.3\left(1+4\frac{\eta}{s}\right). \quad C \simeq 0.5\ \mathrm{GeV}^{-1},\ T_0 \simeq 0.2\ \mathrm{GeV}$$

intuitively the inverse log. slope $T_{Inv}(M)=T_0+M/n$ gives the effective temperature where dileptons are produced

larger M => higher eff. temperature

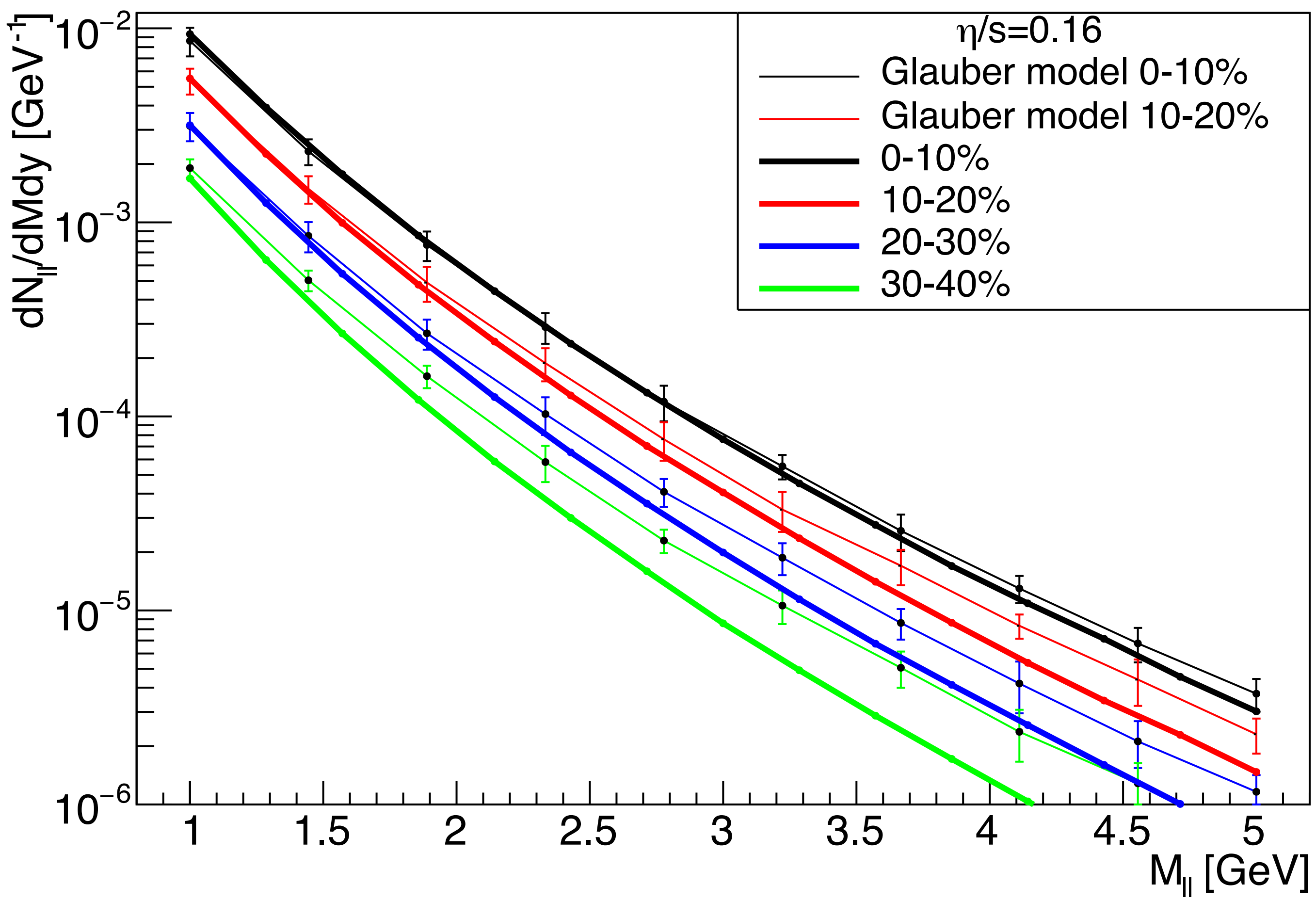
larger viscosity => later thermalization => lower eff. temperatures

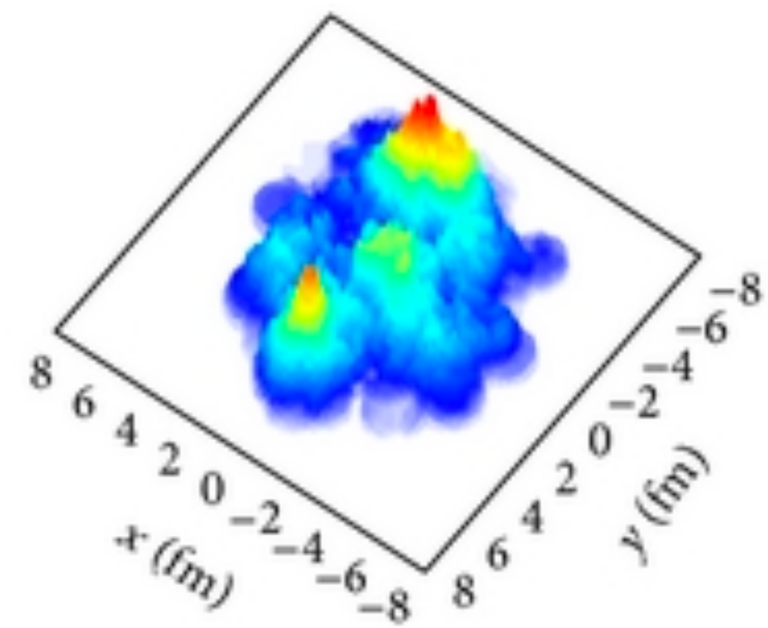
Di-lepton production

Significant centrality dependence as $dE_0/d\eta \sim (dN_{ch}/dy)^{3/2}$

Pb+Pb 5.02 TeV I y=2 (LHCb kinematics)

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301





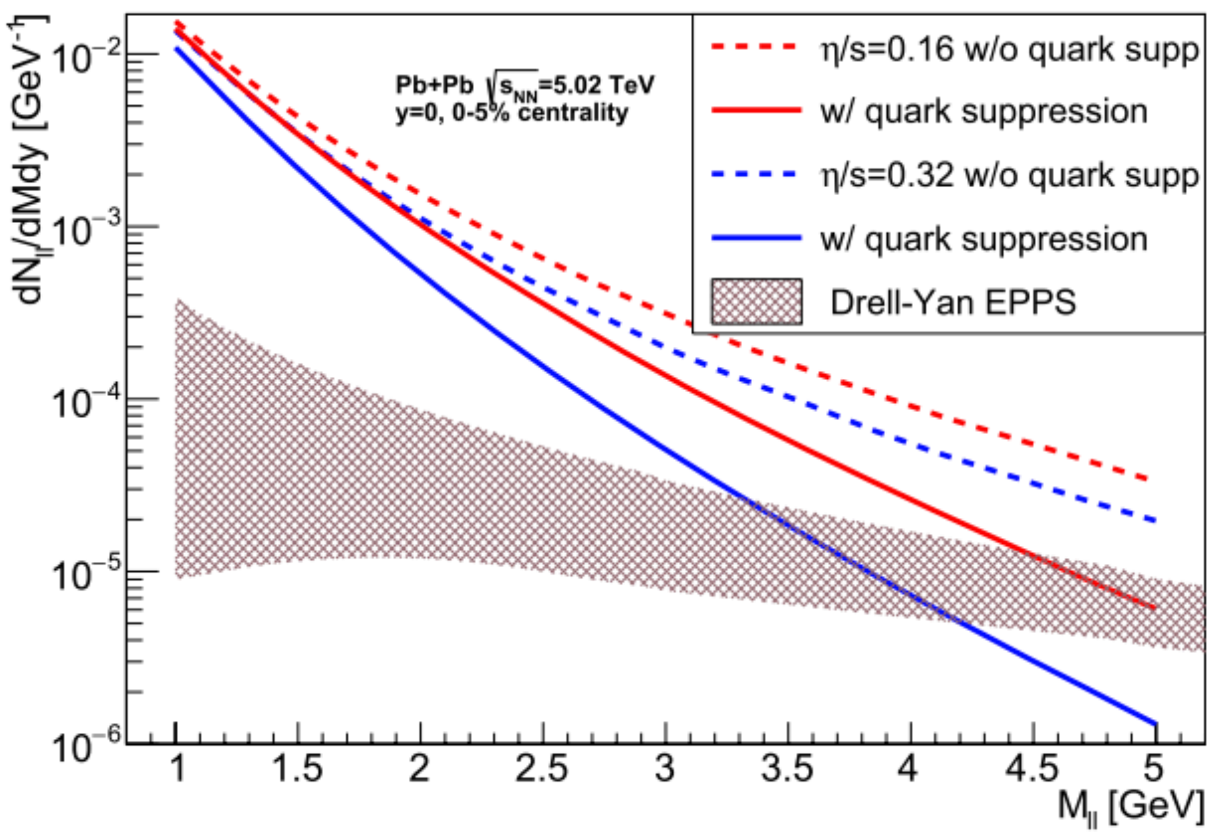
Non-trivial dependence on dilepton invariant mass M

Realistic modelling of event-by-event fluctuations (hot spots) important for large invariant mass region in more peripheral events

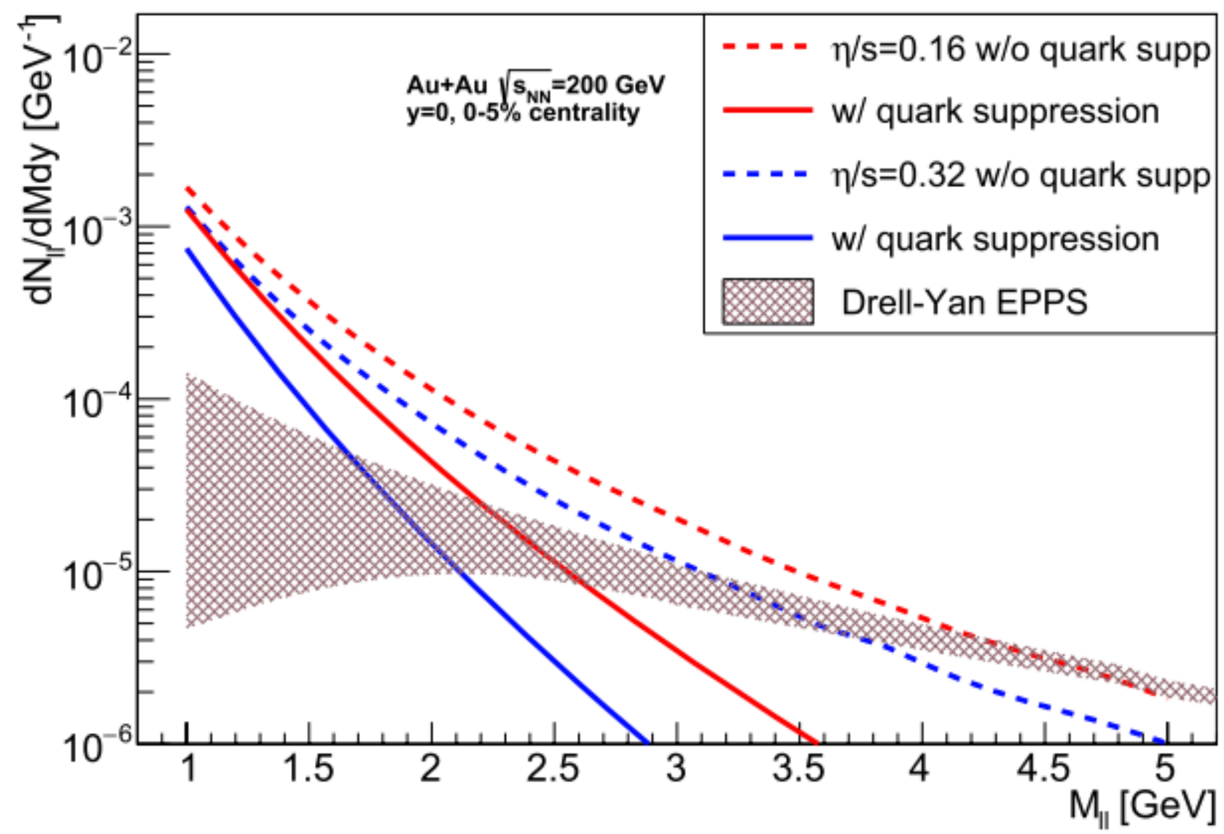
Backgrounds

Dominant background from heavy-flavor decays (S/B ~1/100) can in principle be suppressed with secondary vertexing

Pb+Pb 5.02 TeV | y=0 (ALICE kinematics)



Au+Au 200 GeV | y=0 (STAR/sPHENIX kinematics)

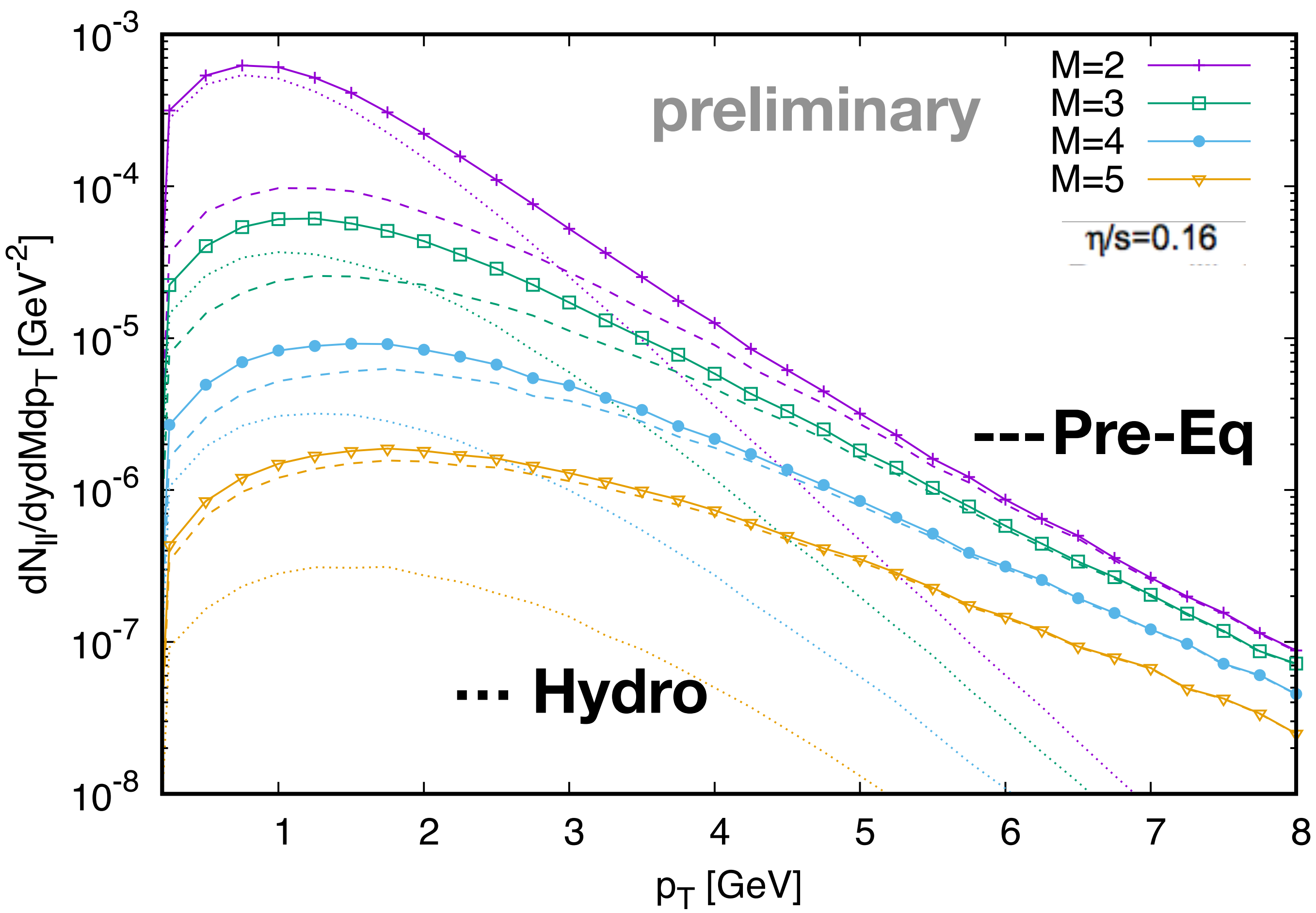


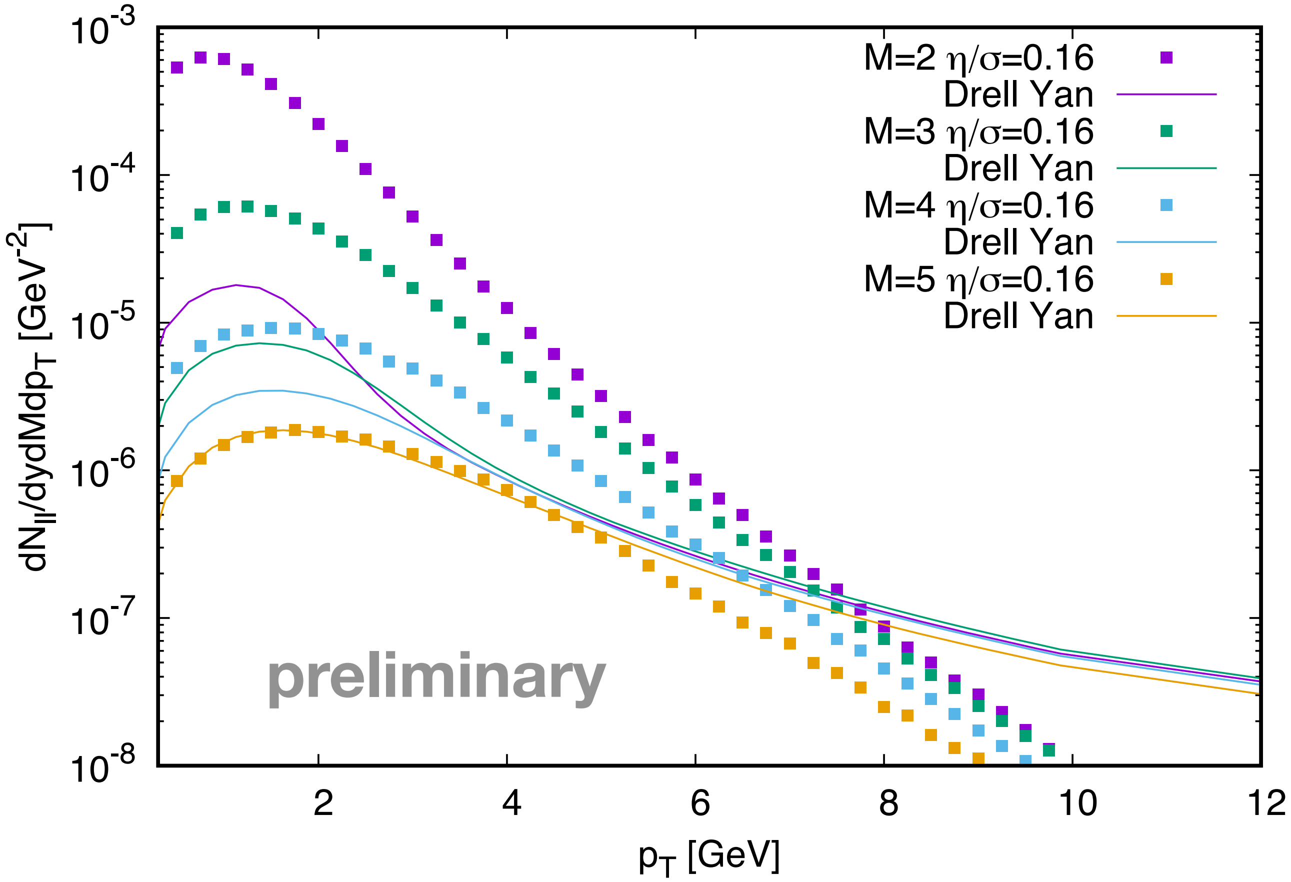
Irreducible Drell-Yan background eventually dominates at very high M_{ll} but appear to be sub-dominant for M_{ll} <3-4 GeV

Potentially employ other features (pT) for additional discrimination

pT dependence

Pb+Pb 5.02 TeV 0-5% | y=0





Should expect (at least minor) modifications due to transverse flow not included in the model

Drell-Yan calculations based on NLO pQCD (Drell-Yan turbo), does not include intrinsic kT

work in progress M.Coquet, X.J.-Du, J.-Y. Ollitrault, SS, M. Winn

Conclusions & Outlook

Pre-equilibrium di-lepton production sensitive to early time non-equilibrium dynamics of QGP

Expected signal between $2<M_{ll}<5$ GeV down to very low $p_T \sim 1$ GeV

Discrimination of displaced vertices crucial to isolate signal from heavy-flavor decay background

Extend calculations to include full non-equilibrium phase-space distribution, beyond LO emission rates for photons/di-leptons

photon production: $\sim f_q$ di-lepton production: $\sim f_q f_q$

Electro-magnetic probes as a possible window into QGP chemistry at early times!

See also related studies by other groups
Kasmaei, Strickland *PRD 99 (2019) 3, 034015* Churchill; Yan, Jeon, Gale *Phys.Rev.C* 103 (2021) 2, 024904