Quenching minijets in a concurrent jet+hydro framework

Mayank Singh

VANDERBILT UNIVERSITY

UNIVERSITY OF MINNESOTA

In Collaboration with Daniel Pablos, Sangyong Jeon and Charles Gale

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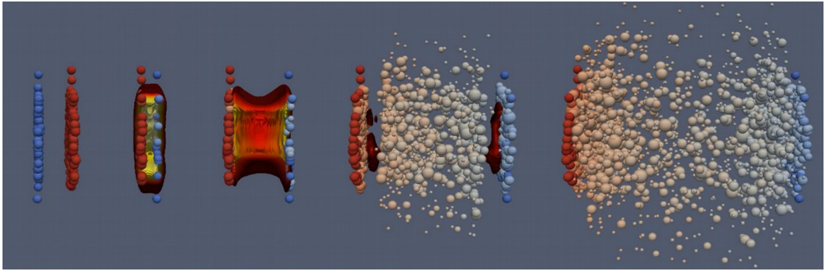
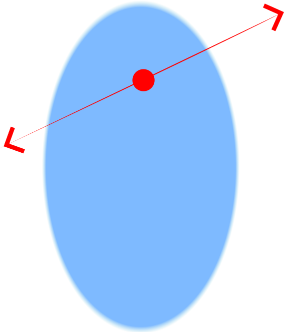
Standard picture of heavy-ion collisions



MADAI Collaboration, H Petersen, J Bernhard

Bulk of partons in colliding nuclei are produced at saturation scale Q_s and undergo hydrodynamic expansion

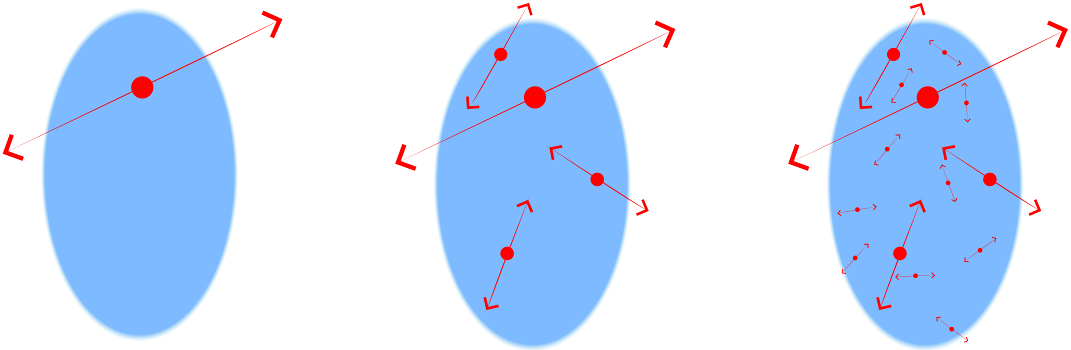
Intermediate Energy Partons



- Partons with $p > Q_s$ created by initial scatterings
- The processes are perturbative
- They can split and shower
- Randomly oriented in space adding additional source of fluctuations
- Number proportional to N_{coll}

Number of minijets depends strongly on the minimum p_T being considered. For $p > 20$ GeV, there is less than one jet pair per event

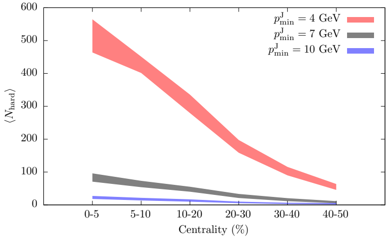
Intermediate Energy Partons

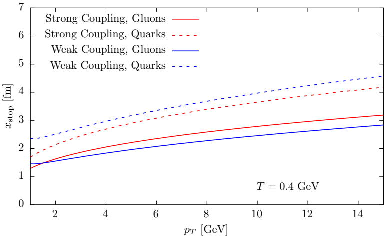


The number grows as one considers smaller and smaller p_T

Need for concurrent evolution

- Bulk matter composed of partons near saturation scale $Q_s \approx 2$ GeV at LHC
- Minijets thermalization time longer than the typical hydro start time of 0.2 to 1.5 fm
- Evolution and thermalization of minijets need to be done concurrent to the hydrodynamic evolution





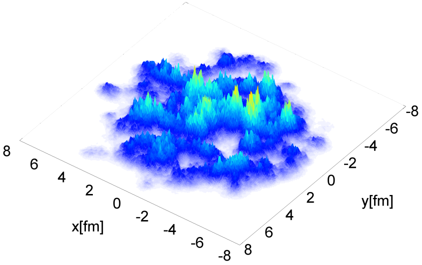
$$x_{\rm stop}^{\rm pQCD} = \frac{1}{a_i \alpha_s^2 T}\sqrt{\frac{E/T}{\ln(E/T)}}$$

Arnold, Cantrell, Xiao, PRD 2010

$$x_{\rm stop}^{\rm AdS/CFT} = \frac{1}{\kappa_i T}\left(\frac{E}{T}\right)^{1/3}$$

Chesler et al., PRD 2009, Gubser et al., JHEP 2008

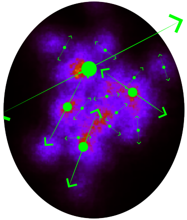
Initial state



- Soft particles below saturation scale Q_s are initialized by IP-Glasma
- Matched to hydro at $\tau_0 = 0.4$ fm
  $T^{\mu\nu}_{\mathrm{IP_Glasma}}(\tau_0) = T^{\mu\nu}_{\mathrm{hydro}}(\tau_0)$

Schenke, Tribedy, Venugopalan, PRL 2012

- Hard particles with $p > p^{\mathrm{J}}_{\mathrm{min}}$ initialized using hard processes in PYTHIA

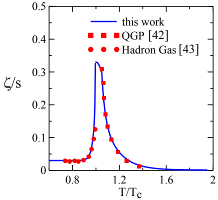


Hydrodynamics

- Viscous 3+1 D relativistic hydro equations with source terms solved using MUSIC

$$\partial_\nu T^{\mu\nu} = J^\mu$$

- Temperature dependent ζ/s and a constant η/s are used



Ryu et al., PRL 2015

- Energy loss of minijets governed by hybrid strong weak coupling model

Casalderrey-Solana et al. JHEP 2014

- Lost energy-momentum is written in form of a current convoluted with a gaussian

$$J^\mu = \sum_i \frac{\Delta P_i^\mu}{\Delta\tau (2\pi)^{3/2} \sigma_x^2 \sigma_\eta \tau} e^{-\frac{\Delta x_i^2 + \Delta y_i^2}{2\sigma_x^2} - \frac{\Delta \eta_i^2}{2\sigma_\eta^2}}$$

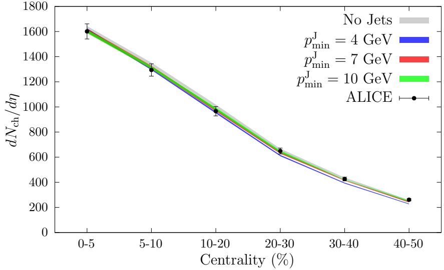
Hadronization

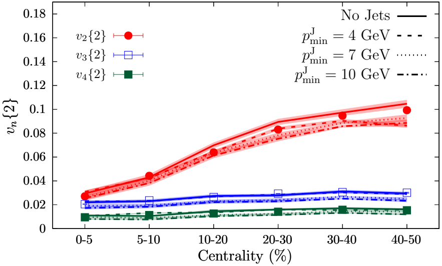
- Thermal medium incorporating initial thermalized energy (from IP-Glasma) and the energy deposited by minijets hadronized using Cooper-Frye
- Minijet partons close to hypersurface hadronize by forming color neutral strings with a sampled thermal parton
- Remaining “corona” partons hadronize with one another
- All hadrons cascade in UrQMD

Similar approaches

- EKRT: Eskola, Kajantie, Ruuskanen, Tuominen, NPB (2000)
- Tachibana et al. (JETSCAPE), QM 2022
- Yan, Jeon, Gale, PRC 2018
- Kanakubo, Tachibana, Hirano, PRC 2020
- Ke, Wang, JHEP 2021

Parameters



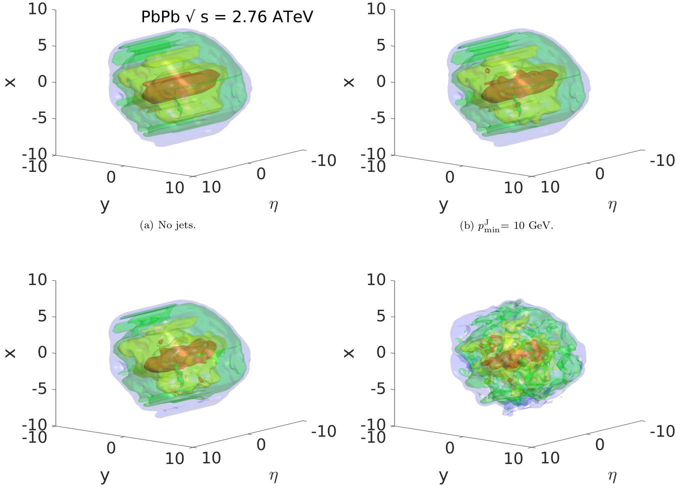


- Minimal tuning needed to explain data. Same parameter fits all centralities

p^J_{min}	s_{factor}	η/s
4 GeV	0.45	0.02
7 GeV	0.82	0.1
10 GeV	0.9	0.125
No Jets	0.915	0.13

- The overall normalization of initial entropy in hydro, the s_{factor}, needs to be adjusted to account for entropy contribution from minijets
- Shear viscosity is adjusted to account for additional fluctuations

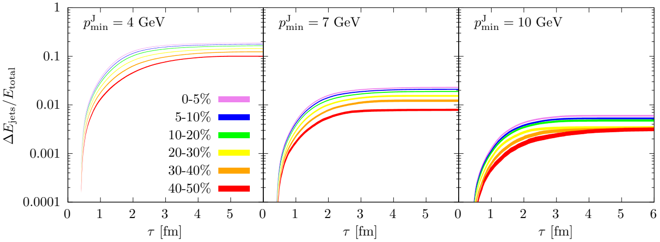
Effect on bulk evolution



(a) No jets.
(b) $p^{\mathrm{J}}_{\mathrm{min}}$= 10 GeV.
(c) $p^{\mathrm{J}}_{\mathrm{min}}$= 7 GeV.
(d) $p^{\mathrm{J}}_{\mathrm{min}}$= 4 GeV.

Isotherms at
220 MeV (red)
195 MeV (yellow)
170 MeV (green)
145 MeV (blue)
Leads to a spikier evolution

Effect on bulk evolution - Energy contribution

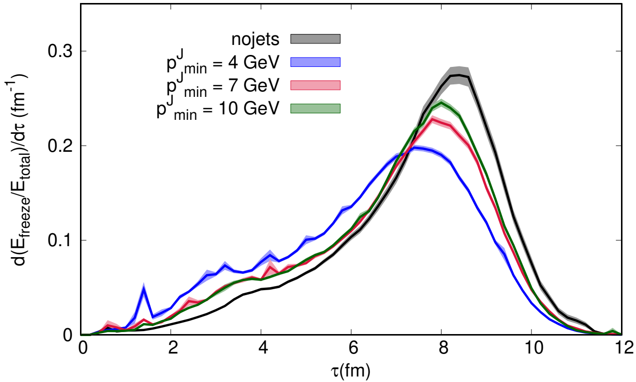


- Ratio of energy injected from minijets to total energy in hydro
- Saturates around $\tau = 2.5$ fm as minijets thermalize

- Fragmented (un-thermalized) partons can be a significant source of hadrons
- More likely for peripheral collisions where partons escape un-quenched

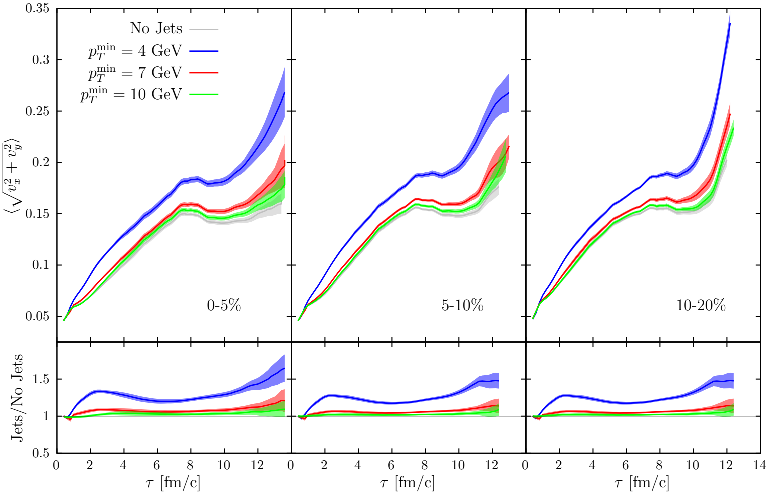
$p^{\rm J}_{\rm min}$	$\langle N_{\rm frag.}/N_{\rm total}\rangle_{0-5\%}$	$\langle N_{\rm frag.}/N_{\rm total}\rangle_{40-50\%}$
4 GeV	0.077(1)	0.252(3)
7 GeV	0.0125(5)	0.033(2)
10 GeV	0.0042(3)	0.014(2)

Effects on bulk evolution - Cooling



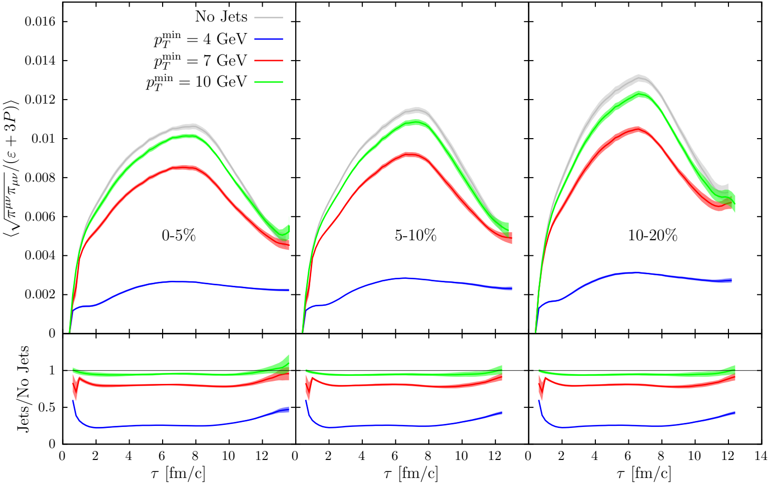
- Fraction of energy frozen out of a 145 MeV hypersurface as a function of τ for $30-40\%$ centrality
- System cools down faster as minijets drag energy with them

Effects on bulk evolution - Flow



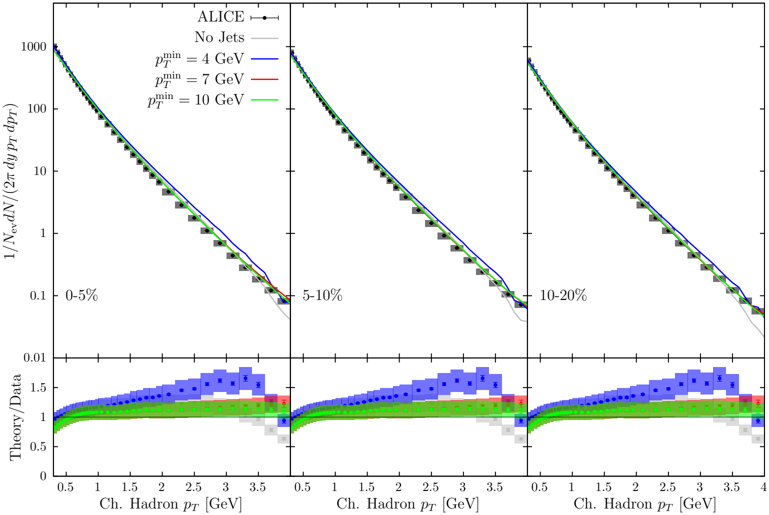
- Flow develops faster

Effects on bulk evolution - Viscosity



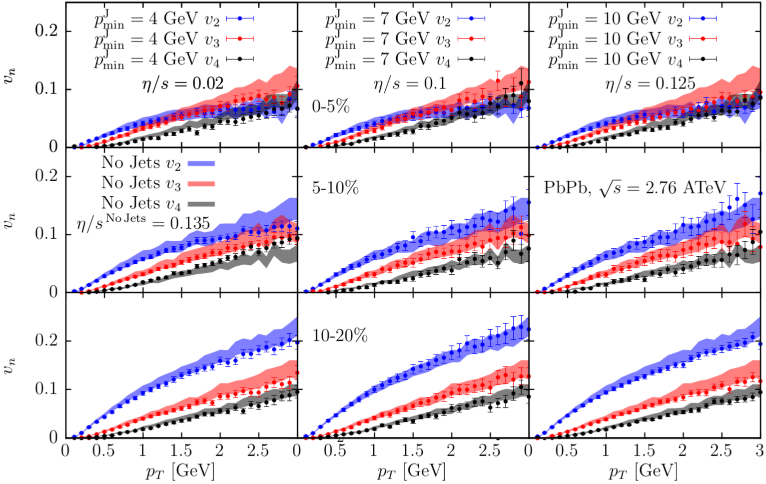
- Consequent rescaling of shear reduces viscosity

Differential spectra



- The $p^{\rm J}_{\rm min} = 4$ GeV case overestimates differential particle yield. Likely overcounting
- Minijets tend to improve agreement with data at intermediate p_T

Differential v_n



- Good agreement with differential v_n subject to readjustment of η/s
- Minijets lead to re-tuning of shear viscosity

Conclusions and Outlook

- Minijets can significantly modify the bulk evolution of QGP medium and modify the extracted transport coefficients
- It will be preferable to account for minijets in Bayesian model-to-data comparisons
- Model can be improved by adding pre-equilibrium energy loss Ipp et al., PLB 2020; Carrington et al., PRC 2022
- More fluctuation sensitive observables like event=plane correlators need to be evaluated
- It will be interesting to see the effect of modified hydro on jet-quenching (computationally expensive)
- Modified hydro will affect electromagnetic observables