# MINIJET QUENCHING IN A CONCURRENT JET+HYDRO EVOLUTION AND THE NONEQUILIBRIUM QUARK-GLUON PLASMA

In collaboration with D. Pablos, M. Singh, and S. Jeon

Based on Phys. Rev. C **106** (2022) 3, 034901

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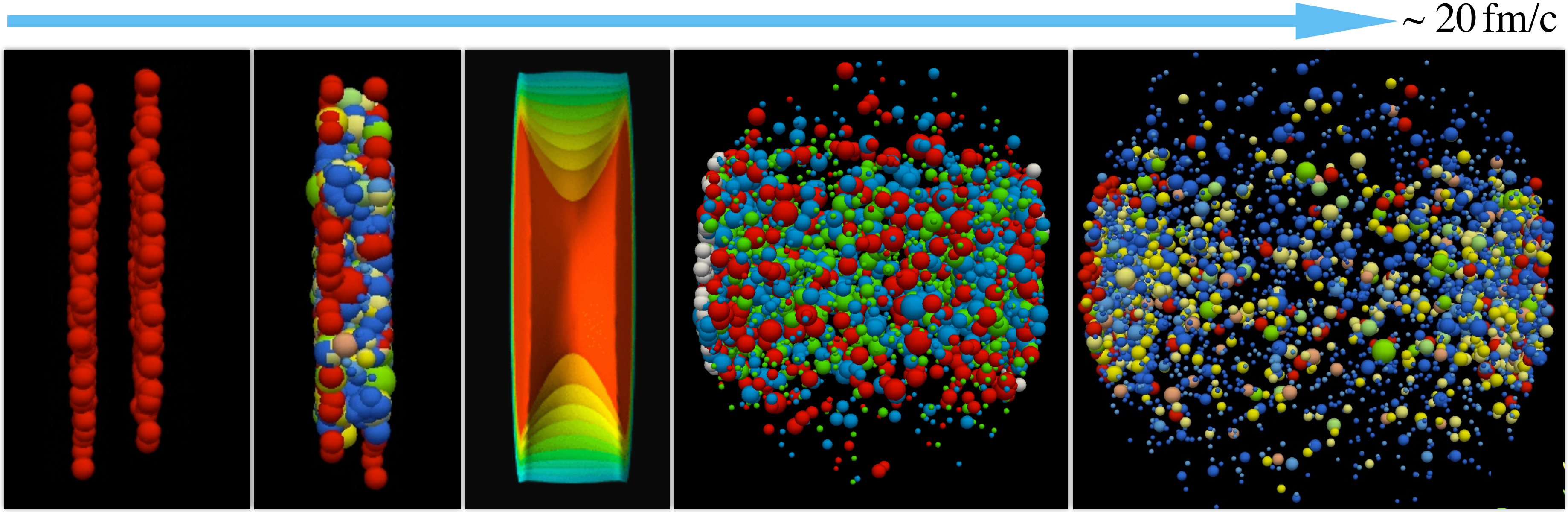
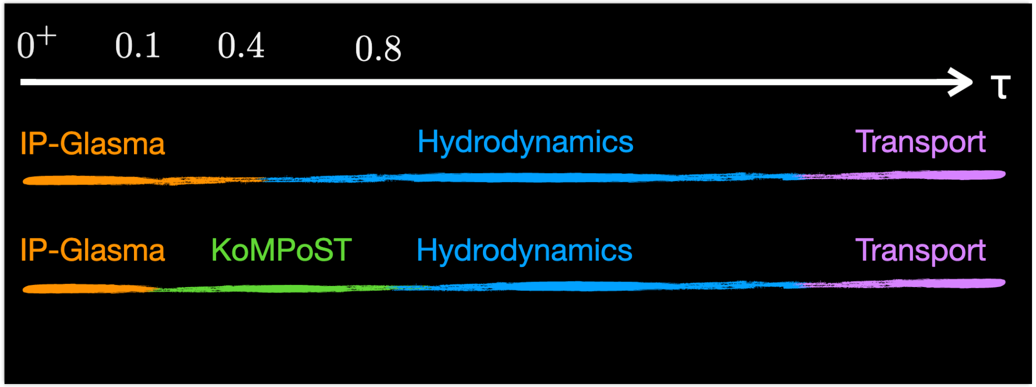
# Relativistic nuclear collisions: The “standard picture”



$$T^{\mu\nu}_{\rm IP-Glasma}(0^+) \to \left[+\ \text{pre}-\text{hydrodynamization}\right] \to T^{\mu\nu}_{\rm hydro}(\tau_0) \to T^{\mu\nu}_{\rm UrQMD/SMASH}(\tau_{\rm CF})$$


$0^+$ 0.1 0.4 0.8 $\tau$

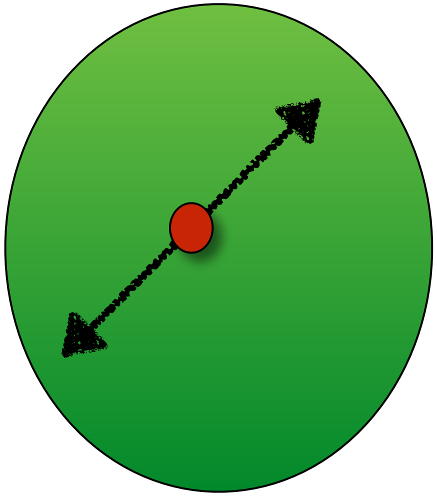
IP-Glasma Hydrodynamics Transport

IP-Glasma KoMPoST Hydrodynamics Transport

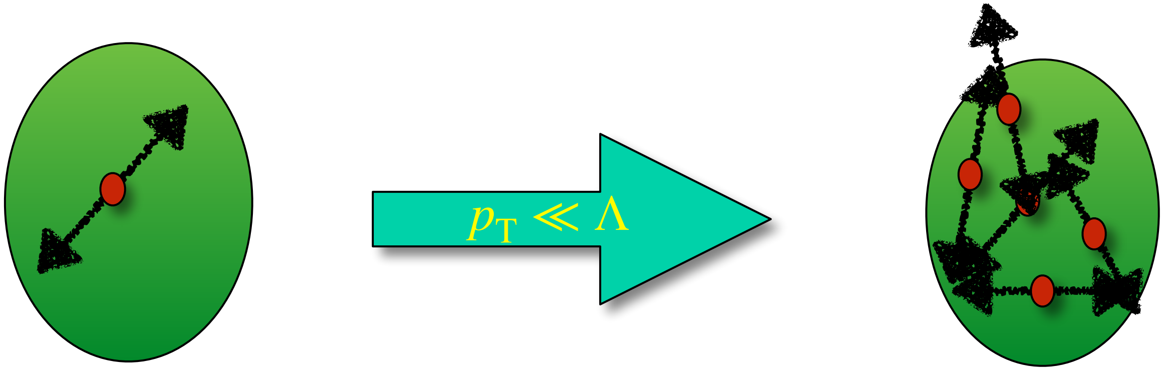
$$p_{\rm Glasma} \lesssim Q_s$$

Gale, Paquet, Schenke, Shen, PRC (2022)

# At high enough energies, the wave function will contain harder partons from initial collisions

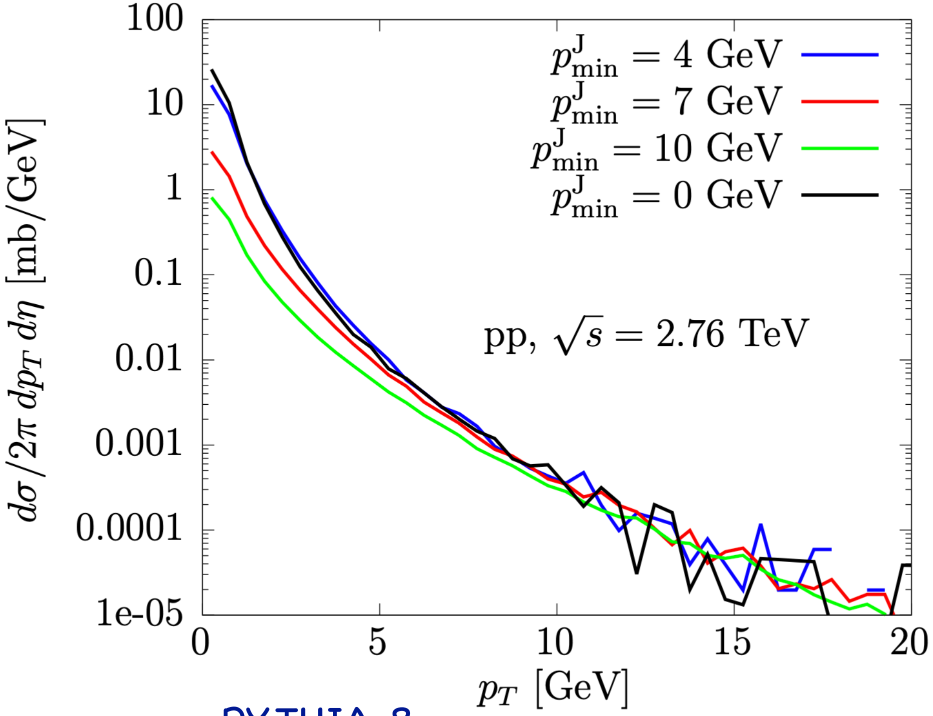


- Perturbative process
- Production probability proportional to $N_{coll}$
- Partons can split & shower
- Random orientation in transverse plane & rapidity
  - Minijets are additional sources of fluctuation
- Minijet multiplicity is a rapidly-varying function of energy and minimum transverse momentum



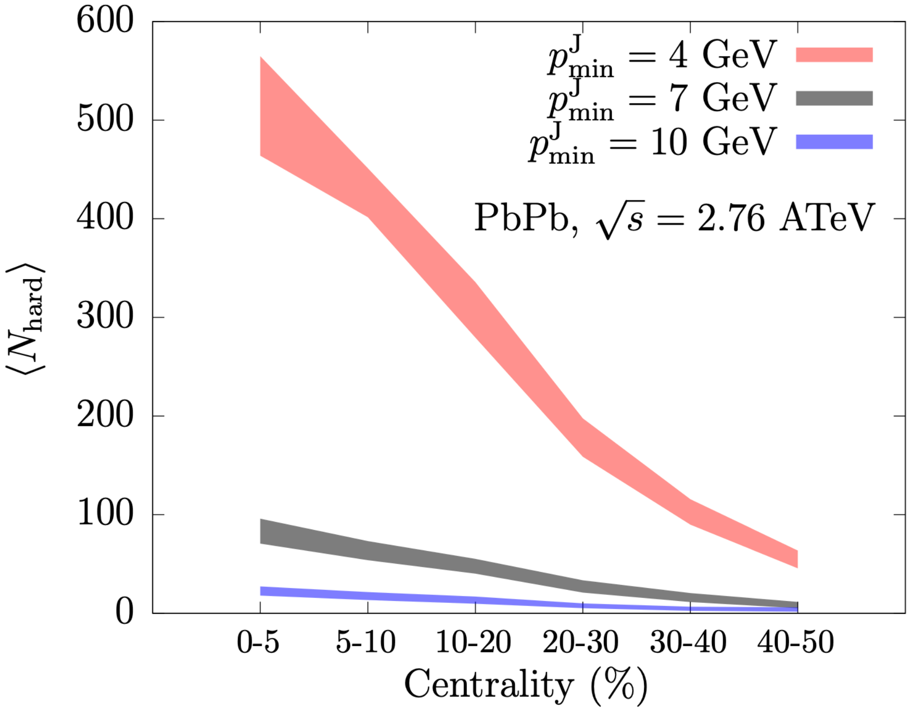
# Details of the initial state

- Physics at low x described by CGC effective theory, IP-Glasma, governed by scale $Q_s$
- Harder QCD processes, i.e. minijet production decoupled from the physics of the condensate: $p^J_{\mathrm{min}} > Q_s$



PYTHIA 8

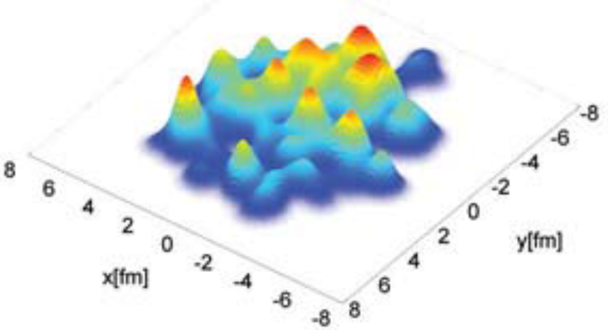
Charged hadron production $|\eta| < 2$



# of hard collisions with momentum transfer > $p^J_{\mathrm{min}}$

# $p < Q_s$ : IP-Glasma

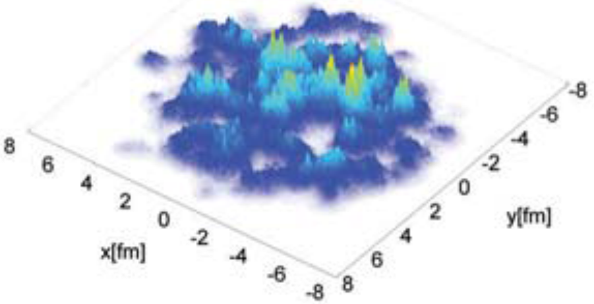
Energy density



MC-Glauber

Nucleons

$$S_{\text{CGC}} = \int d^4x \left( -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} + J^{\mu a} A^a_\mu \right)$$



IP-Glasma

Colour fields

$$Q_s^2 \sim A^{1/3} x^{-\lambda}$$

$$\left[ D_\mu, F^{\mu\nu} \right] = J^\nu$$

Solved and evolved on the lattice

Schenke, Tribedy, and Venugopalan, PRL (2012)

Schenke, Jeon, and Gale PRL (2011)

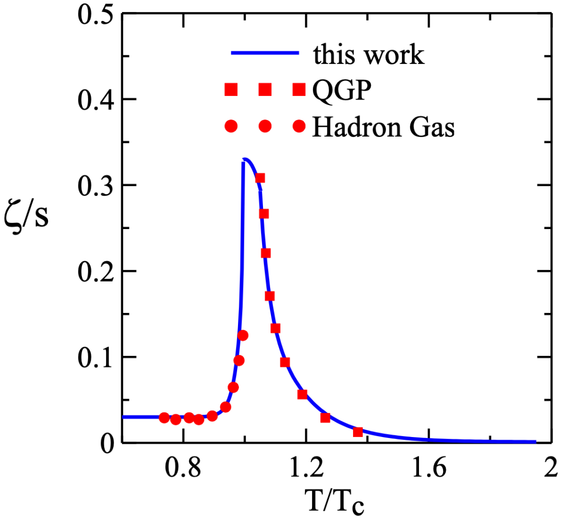
$$T^{\mu\nu}_{\text{IP-Glasma}}(\tau_0) = T^{\mu\nu}_{\text{hydro}}(\tau_0)$$

# Next link in the chain of the soft dynamics: the hydro

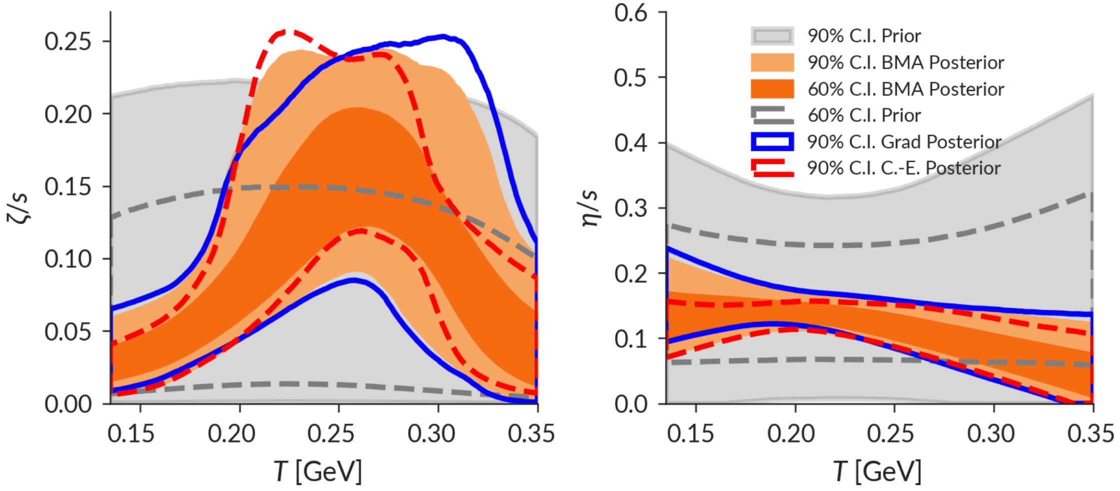
- MUSIC: 2nd order in flow gradients
- With viscous evolution: shear $\eta$ and bulk $\zeta$

$$\eta/s = 0.135$$

McDonald et al., PRC (2017)



- Transport parameters extracted from data
- Currently; global Bayesian analysis:



Heffernan, Gale, Jeon, Paquet, arXiv: 2302.09478

- Bernhard, Moreland, Bass, Nature (2019); Everett et al. (JETSCAPE), PRL (2021); Nijs, van der Schee, PRL (2021)

# Minijets $\Longleftrightarrow$ hydro
# Concurrent evolution workflow

- (Soft) initial state from IP-Glasma
- Finite minijet production probability at each binary collision (consider all QCD processes involving light partons)
- Hydro $T_0^{\mu\nu}$ from IP-Glasma at $\tau_0 = 0.4$ fm/c
- Minijets lose energy (hybrid model) after $\tau_0$ and above $T_c$
- Gaussian sources into hydro
- Cooper-Frye freeze-out
- Hadronize non-stopped partons using Lund string model
  - Parton close to hypersurface, sample thermal parton to form colourless string
  - If away from HS, construct colourless string from "corona" partons
- Evolve hadrons with UrQMD

Similar in spirit:

- 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)

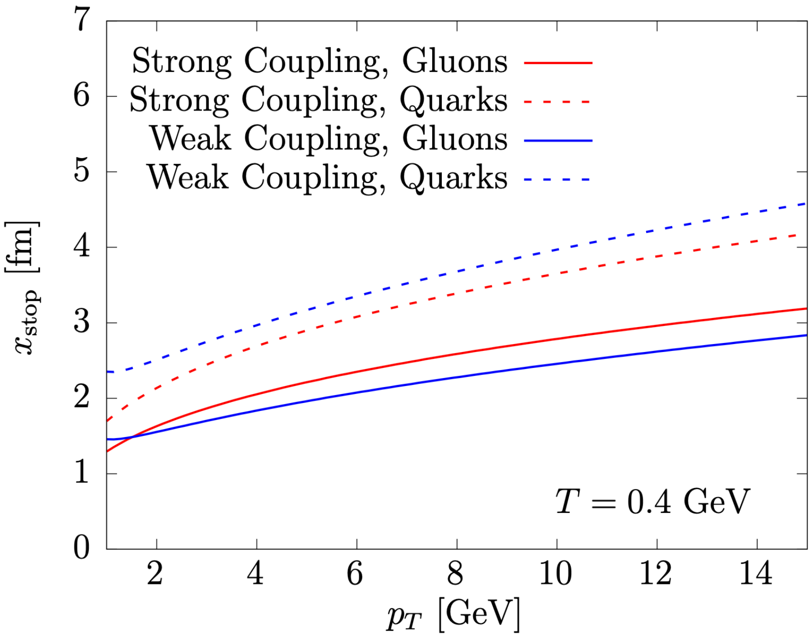
# Stopping distance of a parton jet

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

Arnold, Cantrell, Xiao, PRD (2010)

$$x_{\text{stop}}^{\text{AdS/CFT}} = \frac{1}{\kappa_i T}\left(\frac{E}{T}\right)^{1/3} \qquad \left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi}E_{\text{inc}}\frac{x^2}{x_{\text{stop}}^2}\frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

Casalderrey-Solana, et al., PRC (2019); Chesler, et al., PRD (2009)



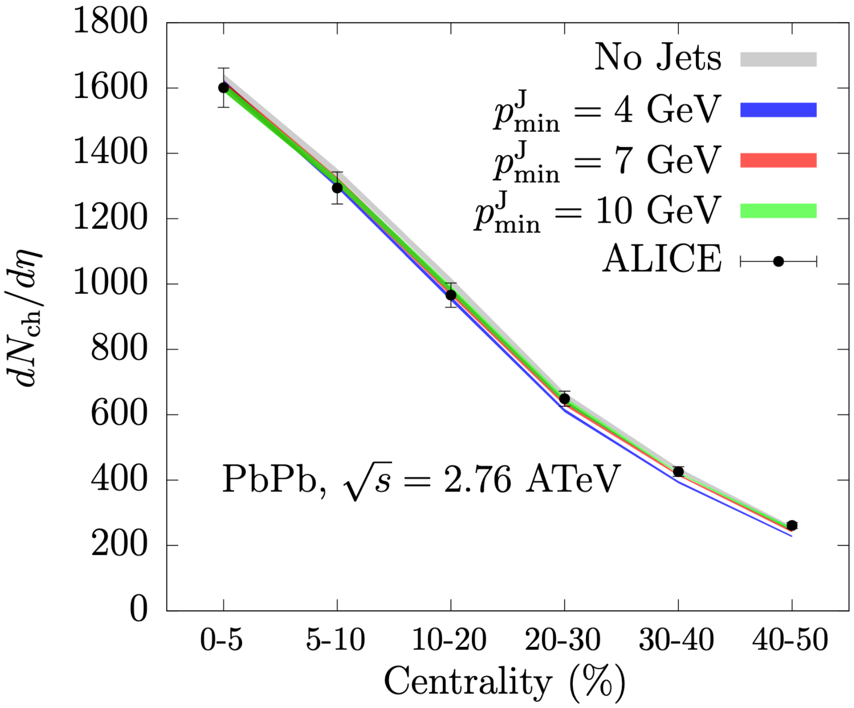
$$J^\nu = \sum_i \frac{\Delta P_i^\nu}{\Delta\tau(2\pi)^{3/2}\sigma_x^2\sigma_\eta\tau} e^{-\frac{\Delta x_i^2 + \Delta y_i^2}{2\sigma_x^2}} e^{-\frac{\Delta\eta_i^2}{2\sigma_\eta^2}}$$

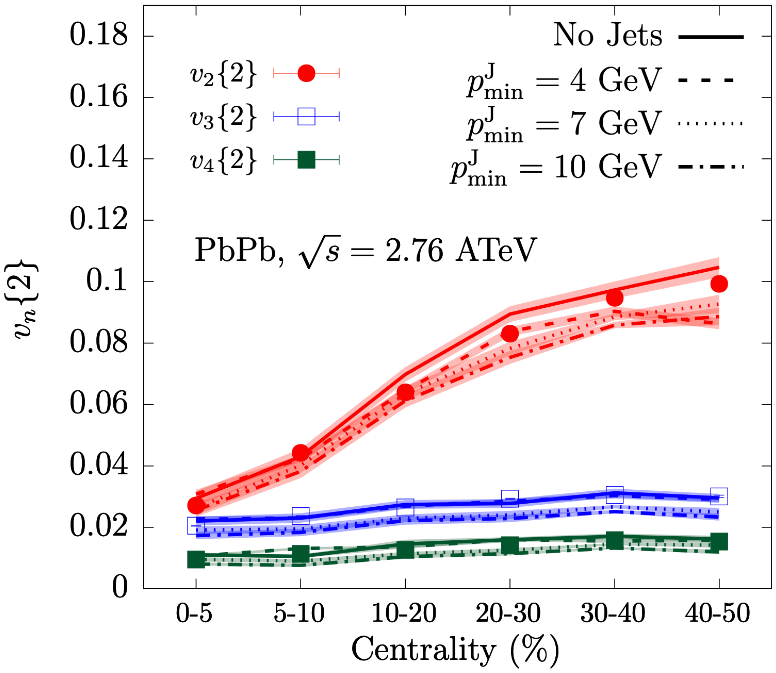
$$\partial_\mu T_{\text{hydro}}^{\mu\nu} = J^\nu$$

Concurrent evolution

With minijets, no single hydrodynamization time

# Jet influence on the hydro (What this talk is really about)

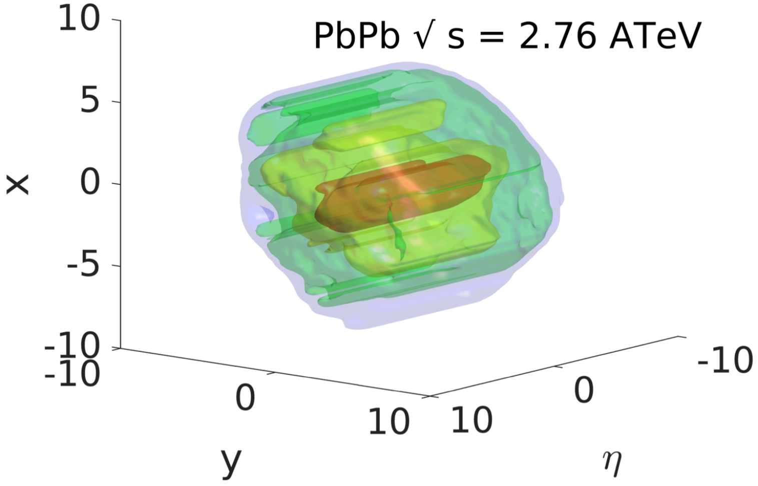




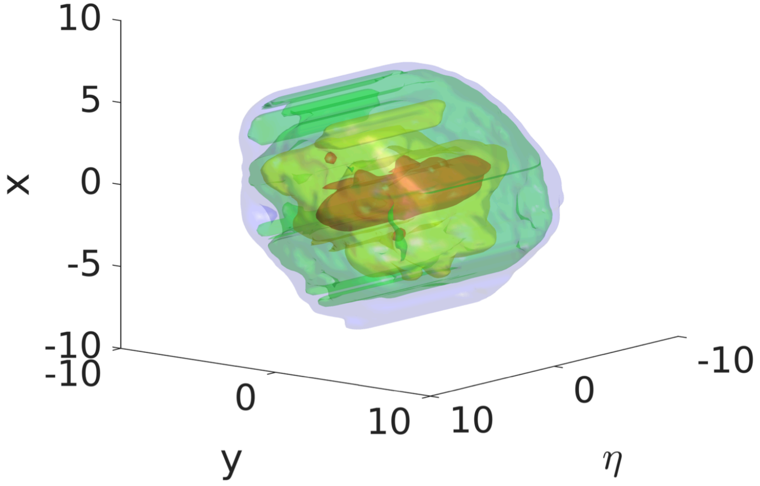
| $p^J_{min}$ | $s_{factor}$ | $\eta/s$ |
|---|---|---|
| 4 GeV | 0.45 | 0.02 |
| 7 GeV | 0.82 | 0.1 |
| 10 GeV | 0.9 | 0.125 |
| No Jets | 0.915 | 0.13 |

- Minijets add entropy & energy
- Minijets are randomly oriented

# Modified hydro evolution

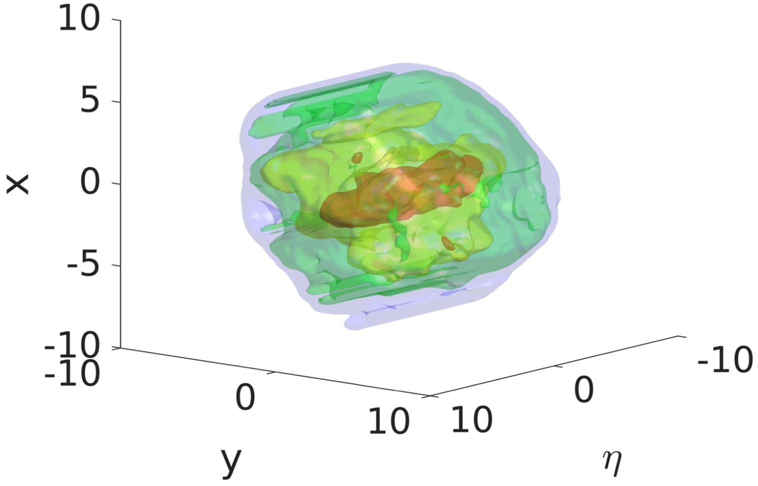


(a) No jets.

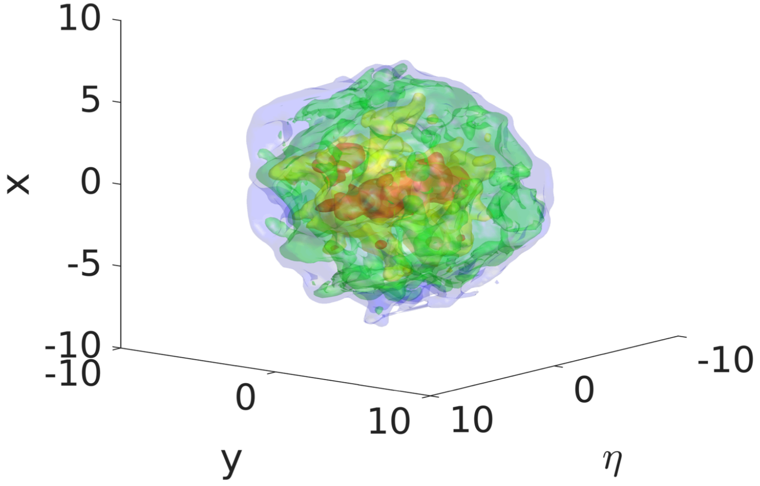


(b) $p^{\rm J}_{\rm min}$= 10 GeV.

3 fm/c



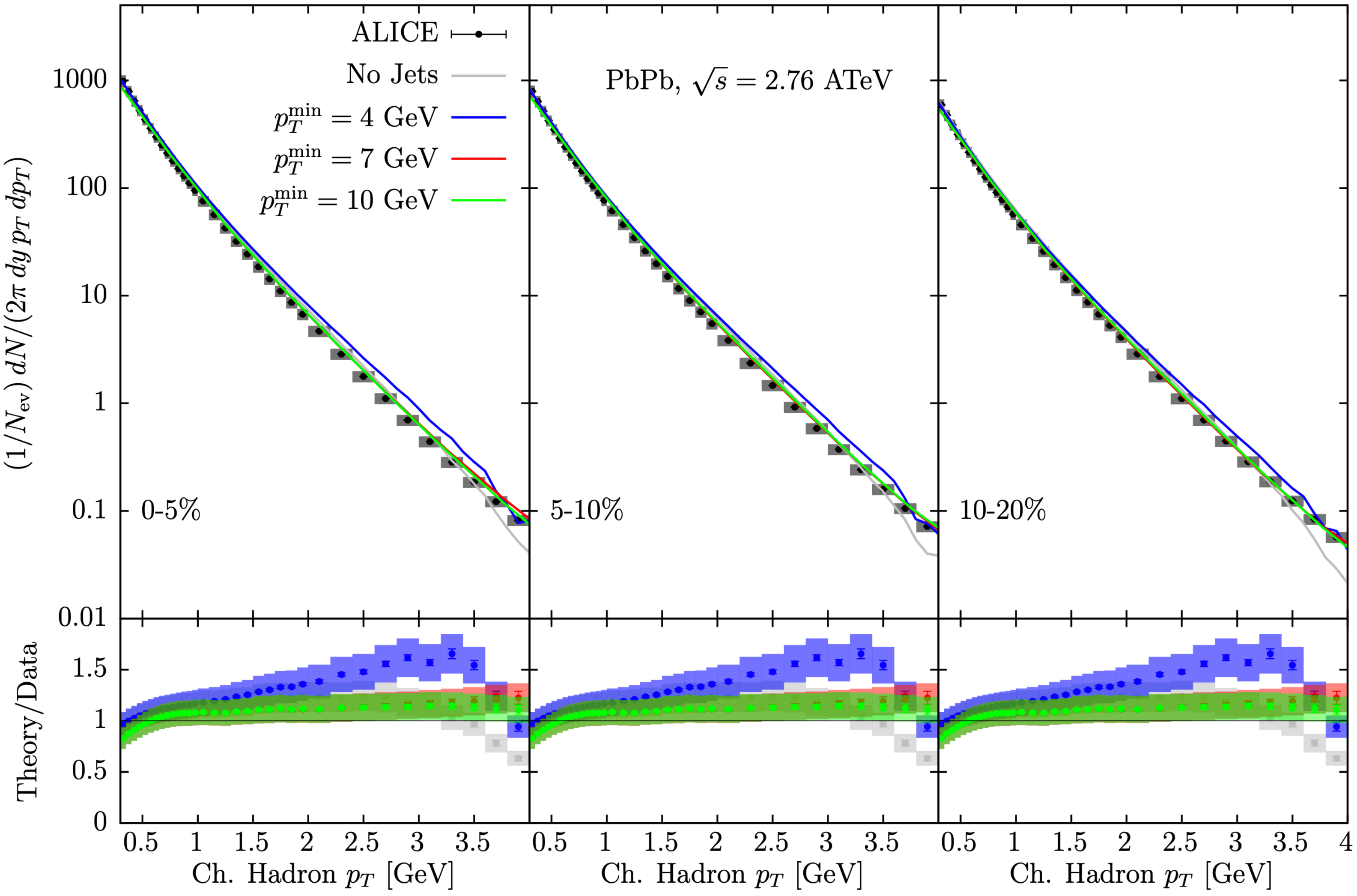
(c) $p^{\rm J}_{\rm min}$= 7 GeV.



(d) $p^{\rm J}_{\rm min}$= 4 GeV.

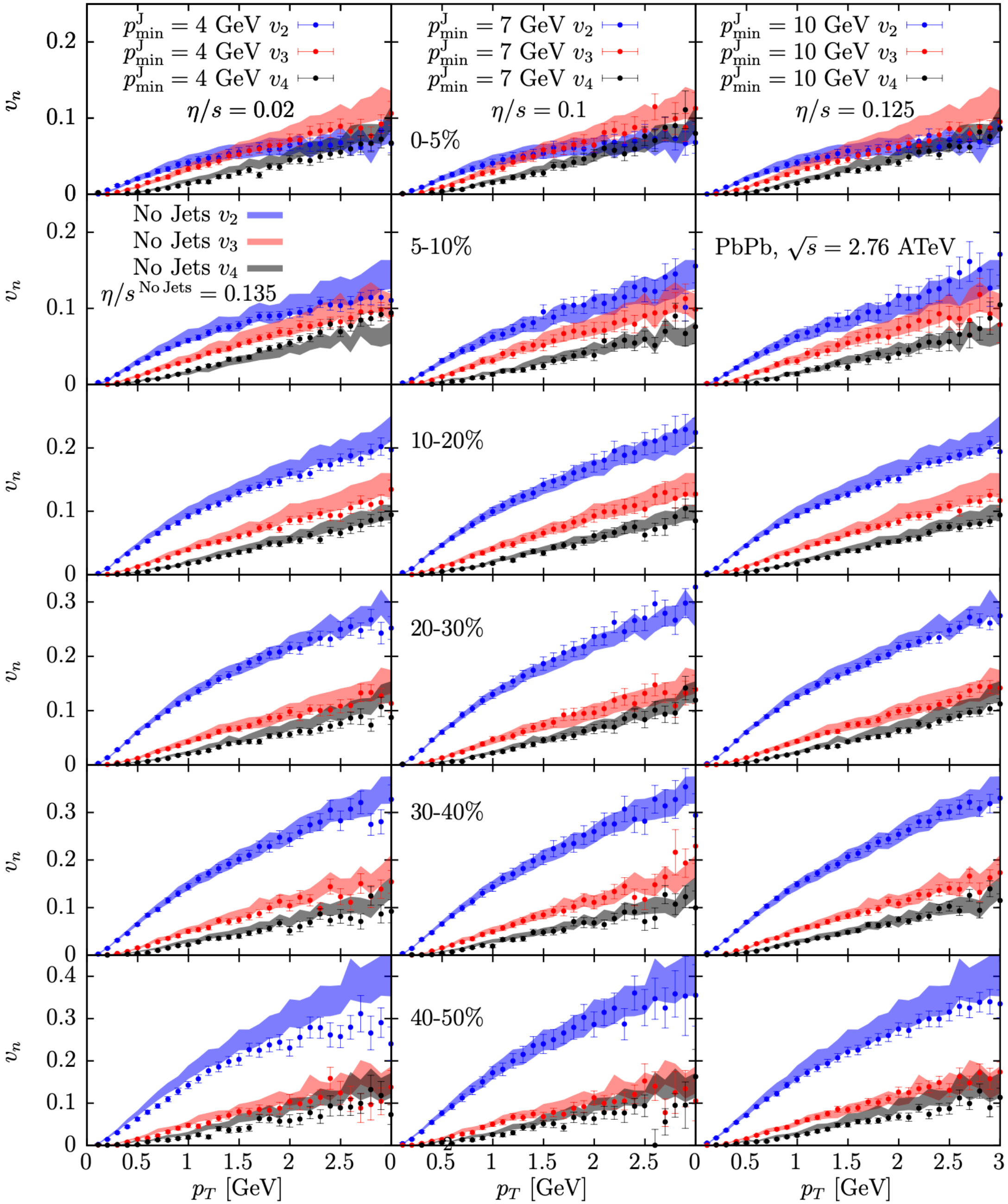
Isotherms: 220 MeV (red), 195 MeV (yellow), 170 MeV (green), 145 MeV (blue)

# Effect on more differential observables (1)



$p^j_{\rm min} = 4$ overshoots data

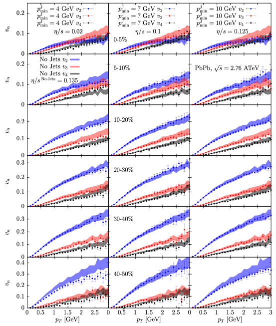
# Effect on more differential observables (2)



Comparison of two calculations

- With jets (and rescaled $\eta/s$)
- Without jets
- The two approaches track well over a large multiplicity window
- Main effect of minijets is to rescale transport coefficient

# Effect on more differential observables (2)



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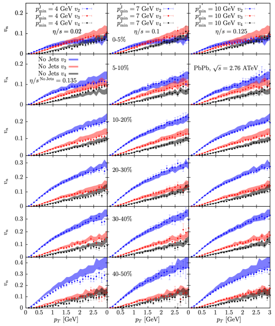

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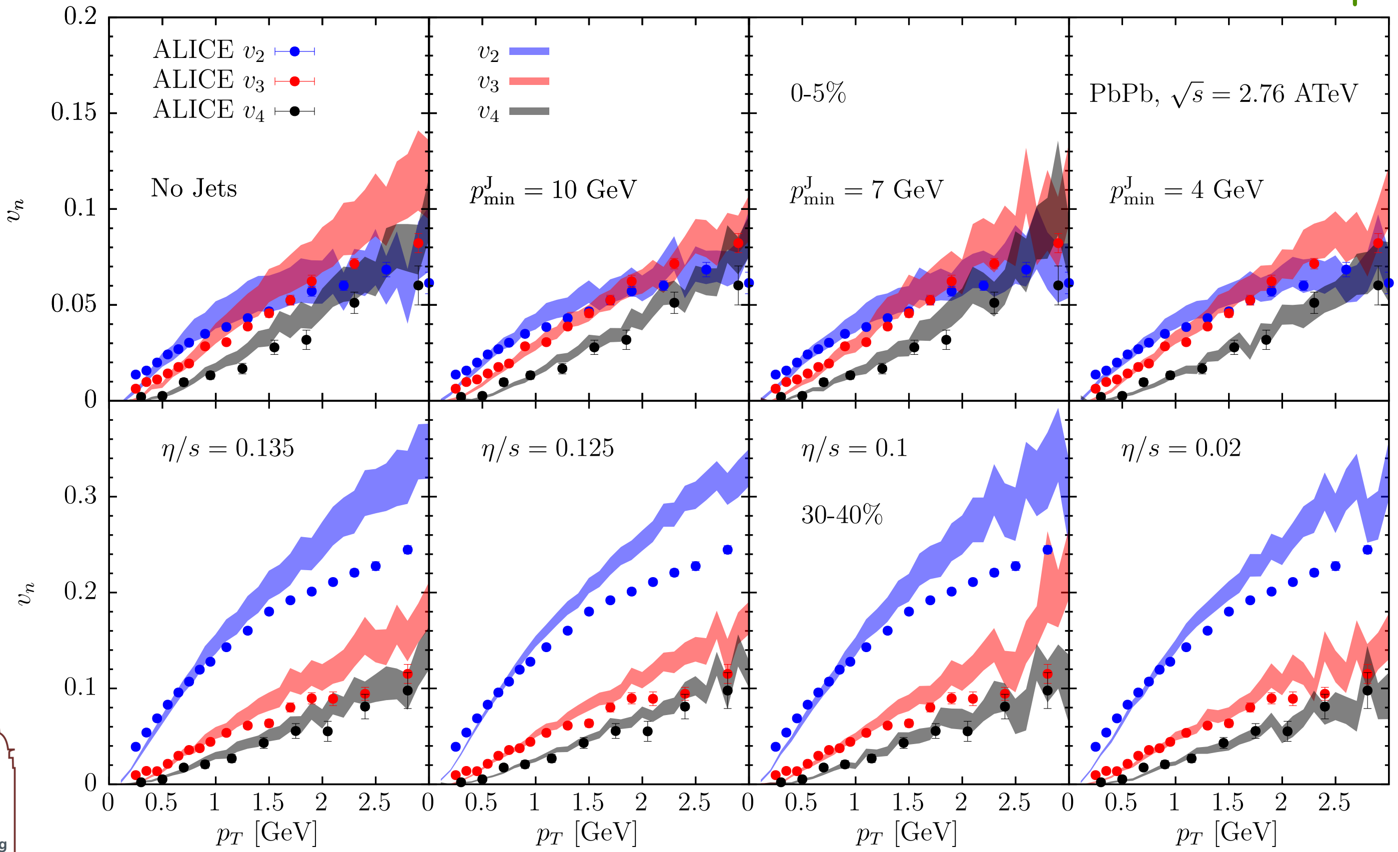
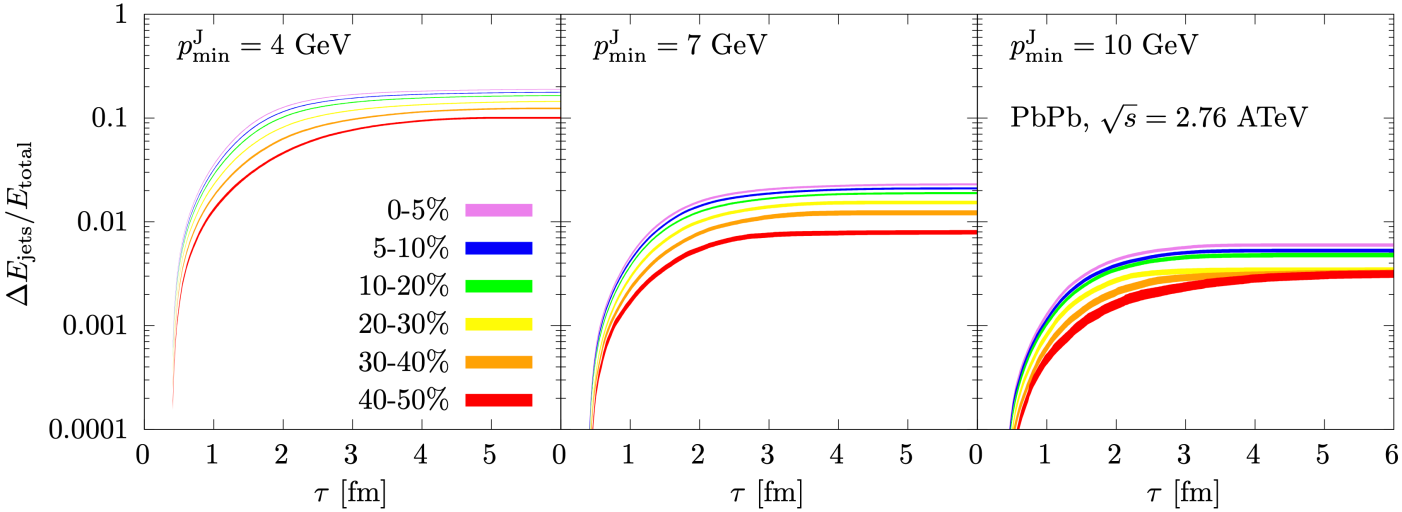
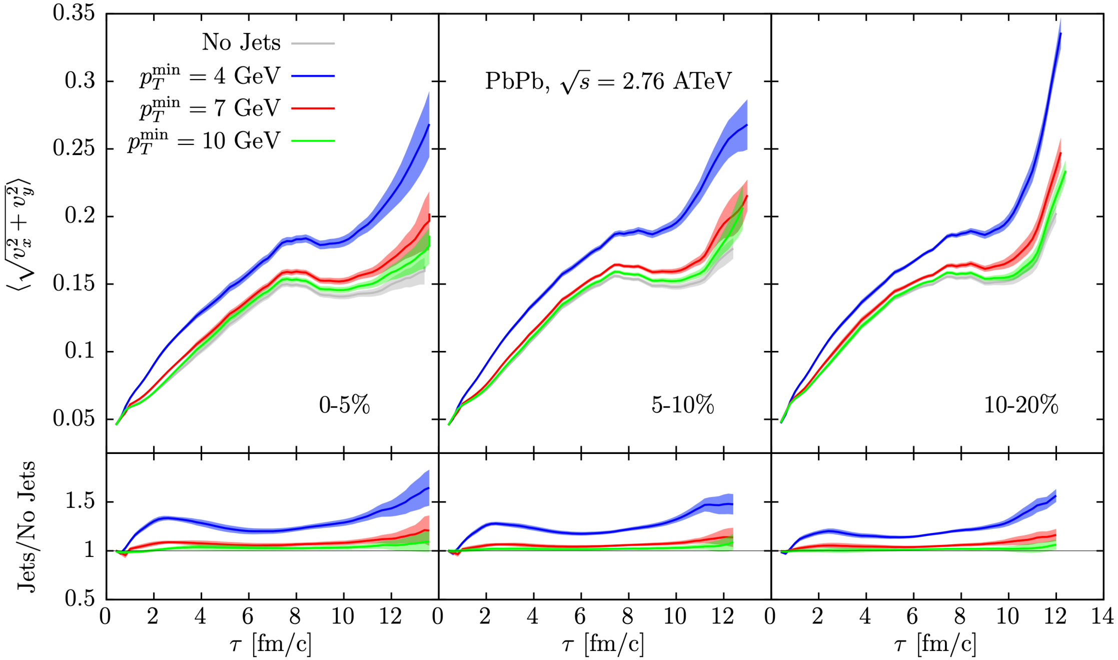


# Inside the hydro (1)



Energy contributed by jets

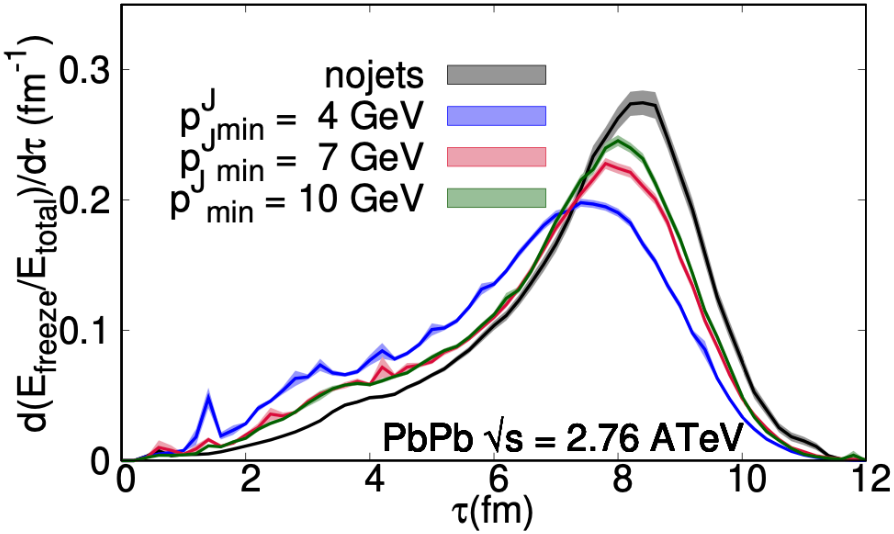


Effect on transverse velocity

# Inside the hydro (2)

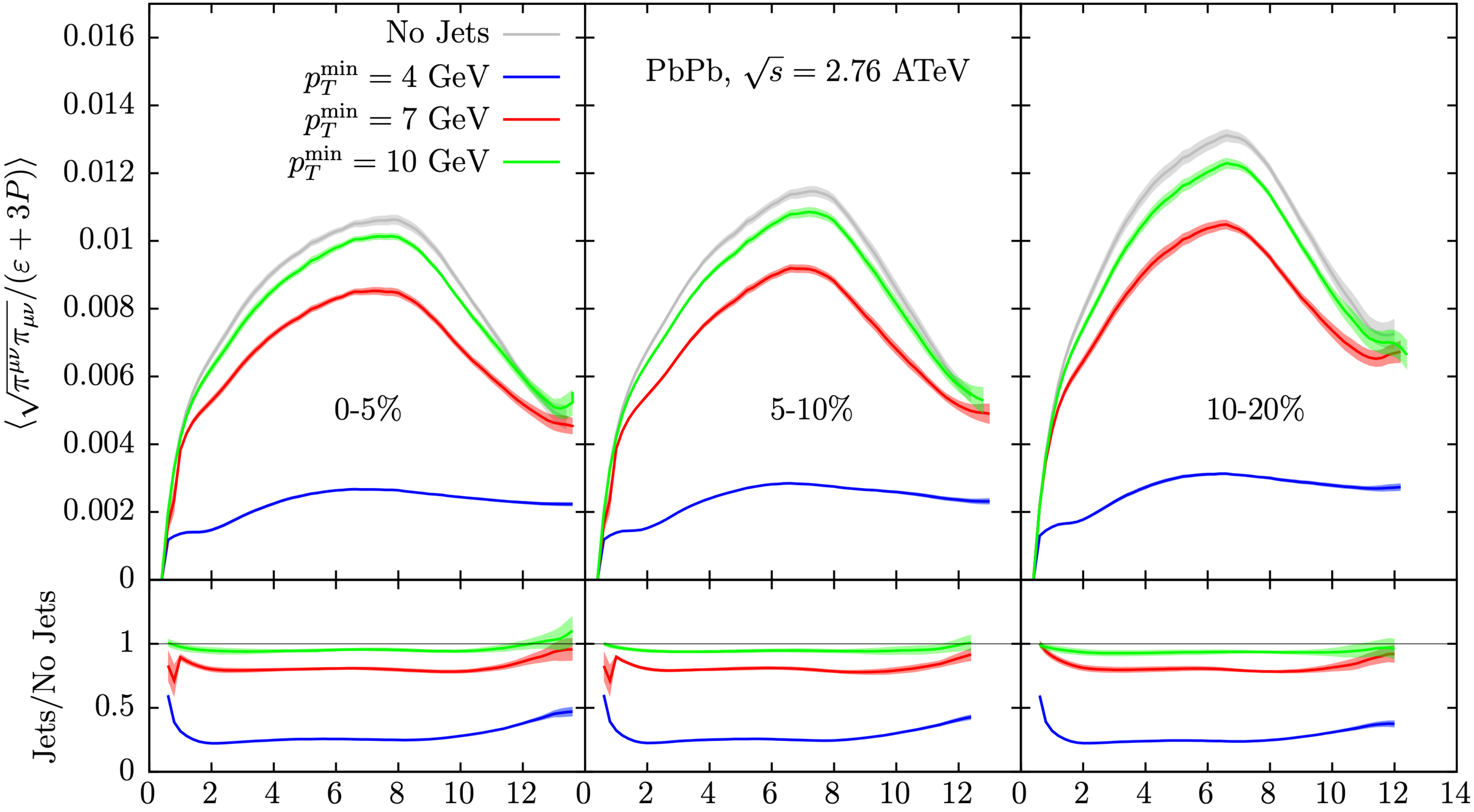
| $p^{\mathrm{J}}_{\mathrm{min}}$ | $\langle N_{\mathrm{frag.}}/N_{\mathrm{total}}\rangle_{0-5\%}$ | $\langle N_{\mathrm{frag.}}/N_{\mathrm{total}}\rangle_{40-50\%}$ |
|---|---|---|
| 4 GeV | 0.077(1) | 0.252(3) |
| 7 GeV | 0.0125(5) | 0.033(2) |
| 10 GeV | 0.0042(3) | 0.014(2) |

- # of hadrons coming from non-stopped partons w.r.t total hadrons at particlization time
- Increases with centrality; partons are more likely to escape



- Fraction of energy frozen out of the 145 MeV hypersurface as a function of proper time for the 30-40% centrality bin

# Inside the hydro (3)

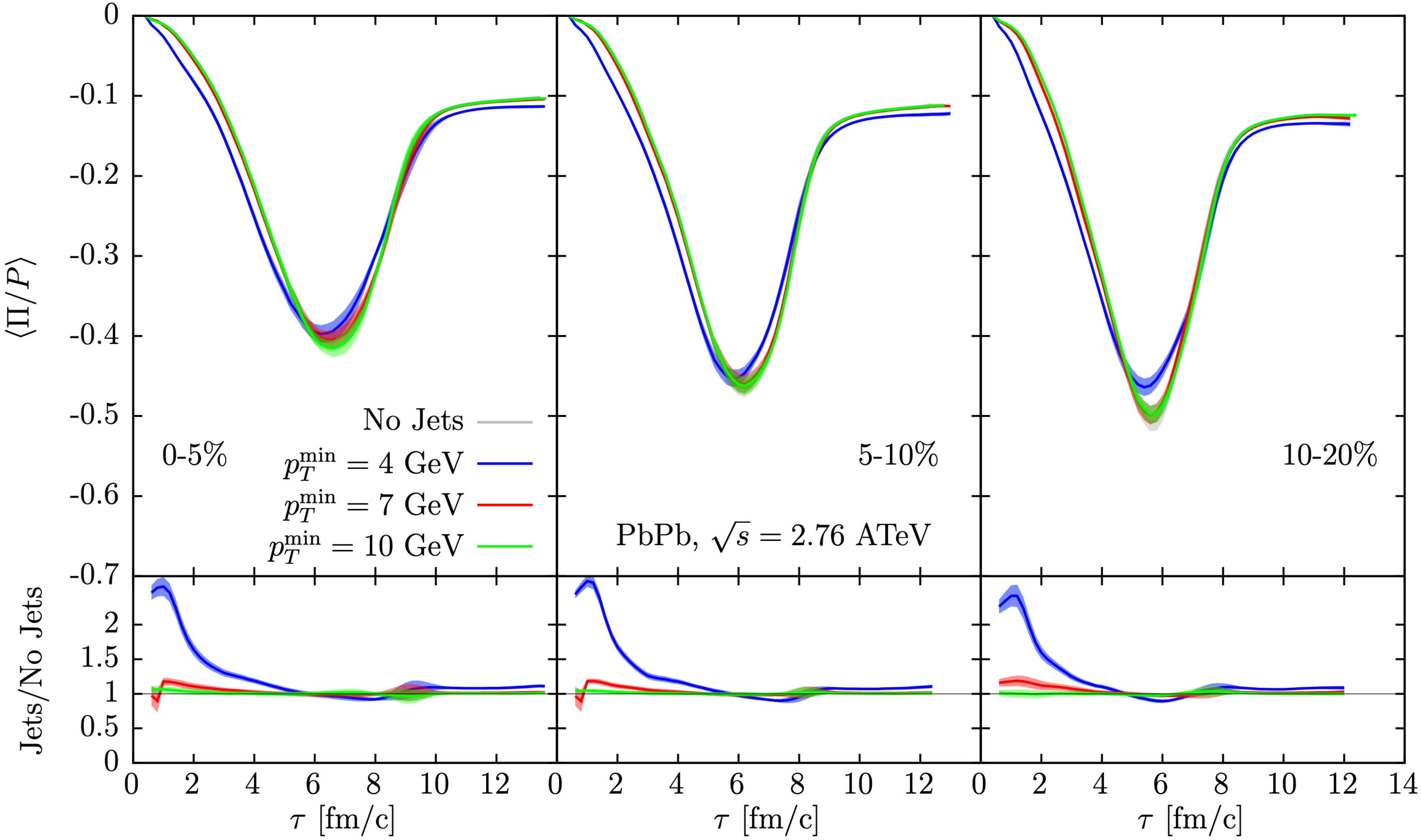


Injection of minijets has an important effect on the viscosity (mainly because of the rescaling)

# Conclusions and outlook

- Minijets affect soft observables and influence strongly extraction of transport parameters; all aspects of hydro evolution are touched
- Improve model: include the interval between minijet creation and fluid-dynamical initialization Ipp et al., PLB (2020); Carrington et al., PRC (2022)
- Analysis with differential observables and correlations (e.g. $\rho(v_2^2, [p_\mathrm{T}])$, event plane correlations,…)
- Way forward: include pre-hydro components like this one in Global Bayesian analyses
- EM probes will be sensitive to the modified fluid-dynamical environment **and** to minijet conversions

# Inside the hydro (3)



Little changes to bulk viscosity: no rescaling