Temperature and net baryochemical potential dependence of η/s in a hybrid approach

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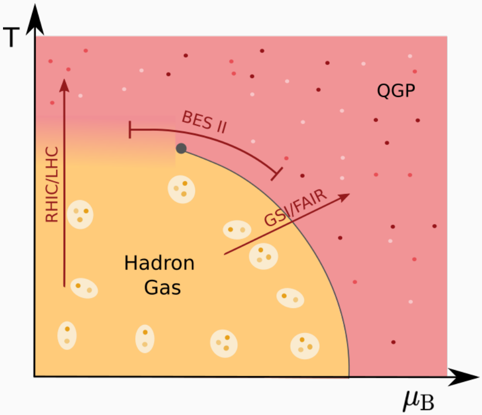
in collaboration with Hannah Elfner

Exploring the QCD phase diagram

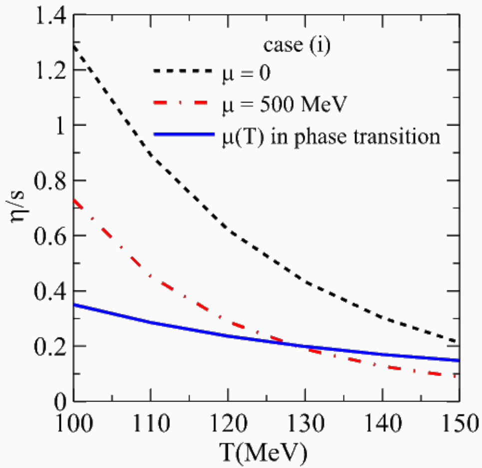


- Want to study the properties of nuclear matter at different densities and temperature
- Hybrid approaches, combining hadronic transport and hydrodynamic evolution, describe dynamics of heavy-ion collisions well
- Input: EoS and transport coefficients
- Flow measurements: almost perfect fluid, but also evidence for small but non-zero shear viscosity η/s
- Evaluation of η/s in lattice QCD is challenging due to numerical problems

Karpenko et al.: PRC 91 (2015) Akamatsu et al.: PRC 98 (2018) Du et al.: Comp.Phys.Com. 251 (2020)
Nandi et al.: PRC 102 (2020) Schäfer et al.: 2112.08724 Shen: 2001.11858
Everett et al.: Phys. Rev. Lett. 126 Kovtun et al.: JHEP 0310 (2003) Ghiglieri et al.: JHEP 1803 (2018)

Non-constant shear viscosity

Denicol et al.: PRC 88 (2013)



- All known fluids have a temperature dependent η/s, and a minimum of η/s is predicted near transition
- Theoretical predictions for the hadron gas phase favour strong μ_B dependence
- **Does non-constant η/s have a strong impact on the evolution and observables?**

Csernai et al.: Phys. Rev. Lett. 97 (2006) Ikatura et al.: PRD 77 (2008) Gorenstein et al.: PRC 88 (2008)

Aim

- Parameterize $\eta/s\ (T, \mu_B)$ using available constraints
- Study the qualitative effect on bulk observables, especially elliptic flow, in comparison with constant η/s or $\eta/s(T)$ in a hybrid approach
- Compare for low to intermediate energies, where impact of μ_B is significant
- Study the generation of elliptic flow in a hybrid approach

SMASH-vHLLE-hybrid

- Modular hybrid approach for the description of intermediate and high energy heavy-ion collisions
- Open-source and public
- Available on Github
- In good agreement with experimental data across a wide range of collision energies
- Conserves all charges (B, Q, S)

Schäfer et al.: 2112.08724
Weil et al.: PRC 94 (2016)
DOI: 10.5281/zenodo.3484711
Cooper and Frye: PRD 10 (1974)
Huovinen et al.: Eur. Phys. J A 48 (2012)
Karpenko et al.: PRC 91, 064901 (2015)
Karpenko et al.: Comput. Phys. Commun. 185 (2014)

SMASH

- Hadronic transport approach
- Initial conditions

+

vHLLE

- 3+1D viscous hydrodynamics
- CORNELIUS routine to determine freezeout surface

+

smash-hadron-sampler

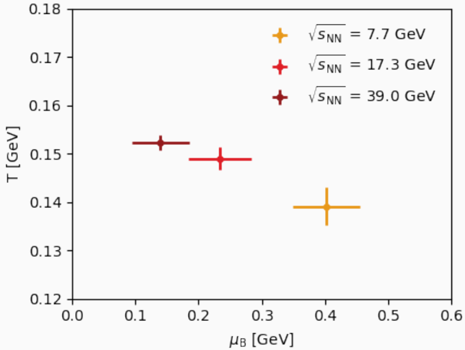
- Cooper-Frye sampler
- Particlization of fluid elements

+

SMASH

- Hadronic transport approach
- Evolution of the late hadronic rescattering stage

SMASH-vHLLE-hybrid

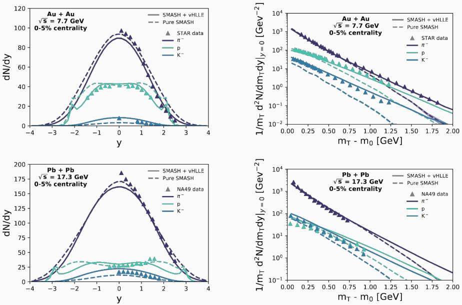


- **Initial Conditions**: Particles propagate and interact until hypersurface of constant proper time (= passing time of nuclei) is crossed
- **Fireball evolution**: QGP phase is evolved according to chiral model EoS and given transport coefficients until hypersurface with constant energy density ϵ_c is reached
- **Particlization**: At ϵ_c according to SMASH HRG EoS
- **Afterburner**: Final propagation and interactions. Collisions can be turned off

Steinheimer et al.: J.Phys.G 38 (2011)   Schäfer et al.: 2112.08724   Karpenko et al.: PRC 91 (2015)

Results of SMASH-vHLLE-hybrid

Schäfer et al.: 2112.08724



SMASH-vHLLE-hybrid reproduces rapidity and m_T spectra at different energies well

Poster presentation 3 T11-4

Exploring the high baryon-density regime of the QCD phase diagram within a novel hybrid approach - Anna Schäfer

Parameterization of η/s

Ansatz

- Parameterization in (ϵ, ρ) instead of (T, μ_B), as those quantities are evolved in hydrodynamic evolution
- Linear dependence on ϵ and ρ assumed
- η/s as approximation for $\eta T/(\epsilon + p)$ at finite μ_B

$$\eta/s = \max\left(0, (\eta/s)_{\text{kink}} + \begin{cases} S_{\epsilon,H}(\epsilon - \epsilon_{\text{kink}}) + S_\rho \rho, & \epsilon < \epsilon_{\text{kink}} \\ S_{\epsilon,Q}(\epsilon - \epsilon_{\text{kink}}) + S_\rho \rho & \epsilon > \epsilon_{\text{kink}} \end{cases}\right)$$

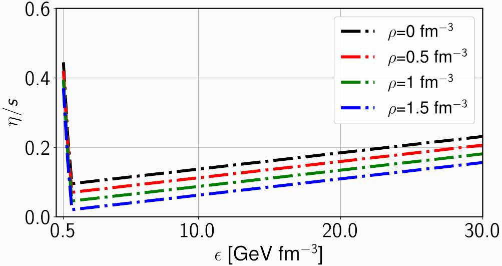
- Even for $S_\rho == 0$: **implicit μ_B dependence**

Parameterization of η/s

Constraints

- ϵ_{kink} is set to the critical energy density of 1 GeV/fm^3
- $(\eta/s)_{\text{kink}}$ is set to the KSS bound
- $S_{\epsilon,Q}$ is set to match the (N)LO-pQCD limit at $T = 400$ MeV
- $S_{\epsilon,H}$ is set to match η/s from box calculations in SMASH at ϵ_c and $\mu_B = 0$

Borsányi et al.: Phys. Lett. B 730 (2014) Cleymans et al.: Jour. Phys. G 32 (2006) Kovtun et al.: JHEP 0310 (2003)
Ghiglieri et al.: JHEP 1803 (2018)

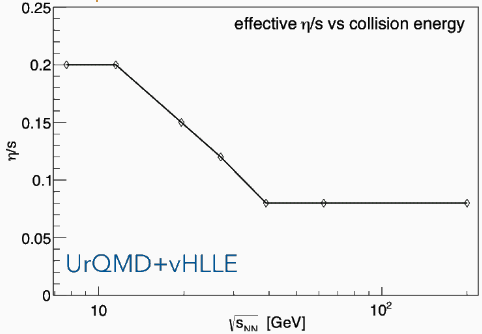


Parameterizations for comparison

1. comparison

effective, constant η/s

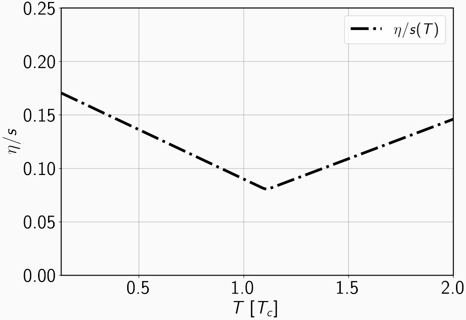
Karpenko et al.: PRC 91 (2015)



originally used in SMASH-vHLLE-hybrid

2. comparison:

$\eta/s(T)$ from Bayesian inference



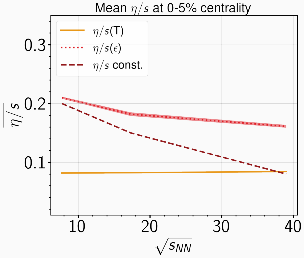
based on results of the JETSCAPE collaboration

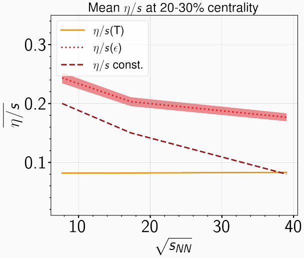
JETSCAPE Phys. Rev. Lett. 126 (2021)

JETSCAPE PRC 103 (2021)

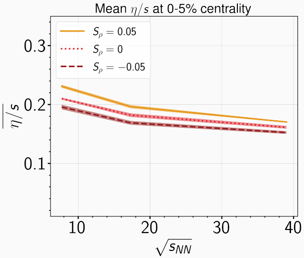
Effective shear viscosity

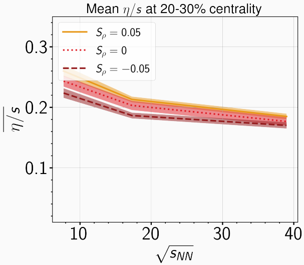
Comparison parameterizations:





ρ-dependence:

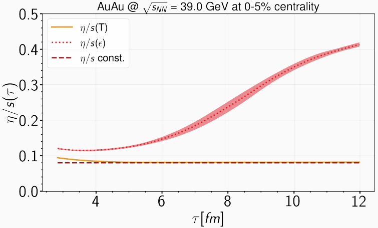




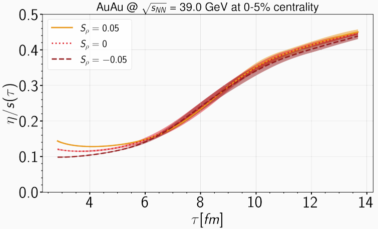
New parameterization gives larger values for shear viscosity, which reduce with increasing energy

Time evolution of shear viscosity

Comparison parameterizations:



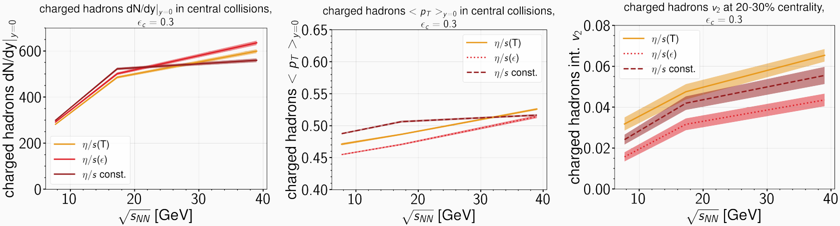
ρ-dependence:



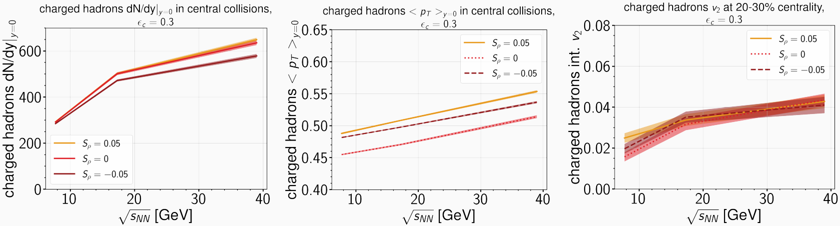
Energy density weighted mean shear viscosity changes significantly during the evolution. Differences due to ρ-dependence are most significant in the beginning of the evolution.

Impact on bulk observables

Comparison parameterizations:

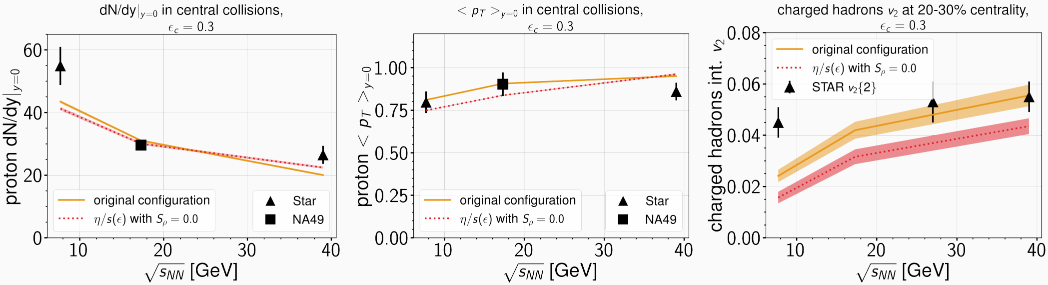


ρ-dependence:



Midrapidity yield shows stronger differences at higher energies. Mean p_T is sensitive to ρ-dependence, elliptic flow not.

Comparison to data

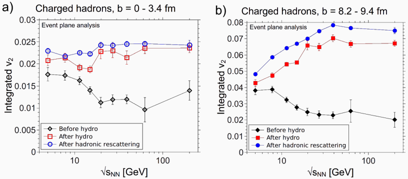


Parameterisation in ϵ reproduces experimental results up to a similar degree than tuned effective η/s

STAR PRC 86 (2012) STAR PRC 96 (2017) NA49 Phys.Rev. Lett. 80 (1998) NA49 Phys.Rev. Lett. 73 (1994)

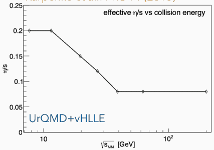
Flow contribution and response

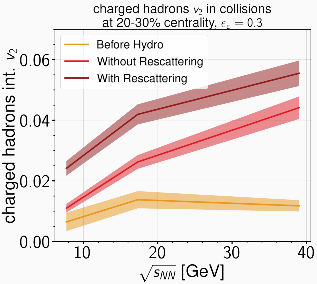
Similar to earlier analysis in UrQMD hybrid (Auvinen et al.: PRC 88 (2013))

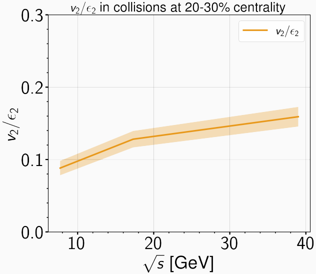


Using the constant, effective η/s

Karpenko et al.: PRC 91 (2015)



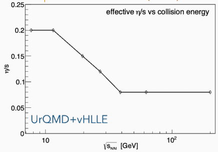




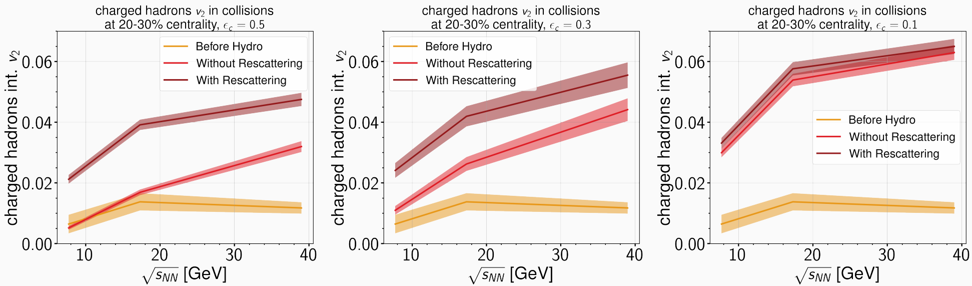
Significant contribution from non-equilibrium SMASH to elliptic flow

Using the constant, effective η/s

Karpenko et al.: PRC 91 (2015)



$\epsilon_c = 0.5$ GeV$/\text{fm}^3$ $\epsilon_c = 0.3$ GeV$/\text{fm}^3$ $\epsilon_c = 0.1$ GeV$/\text{fm}^3$



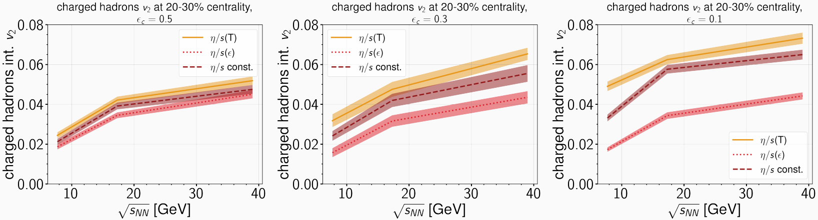
Impact of η/s parameterization becomes more dominant when switching to transport at later time

Impact on flow results

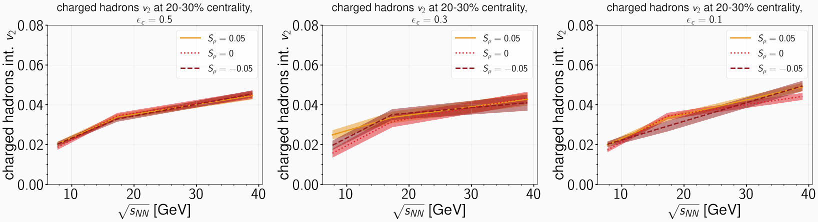
Elliptic Flow at the end of the hybrid evolution

$\epsilon_c = 0.5\ \mathrm{GeV/fm^3}$ $\epsilon_c = 0.3\ \mathrm{GeV/fm^3}$ $\epsilon_c = 0.1\ \mathrm{GeV/fm^3}$

Comparison parameterizations:

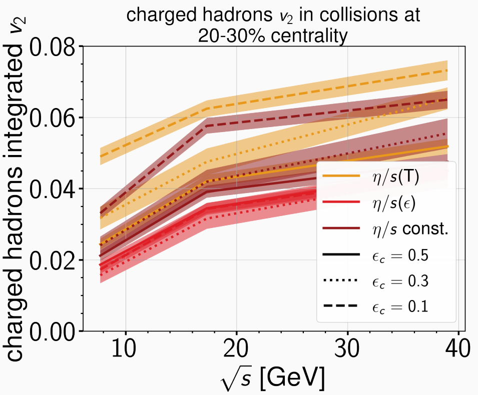


ρ-dependence:



$\rightarrow$ Cells with significant ρ do hardly contribute to flow

Elliptic Flow at the end of the hybrid evolution



v_2 for $\eta/s(\epsilon)$ does not change as function of $\epsilon_c \rightarrow \eta/s(\epsilon)$ close to shear viscosity in transport simulation

Conclusions

- In the hybrid approach SMASH-vHLLE-hybrid, a parameterization $\eta/s(\epsilon, \rho)$ based on known constraints was tested
- The dependence on ρ was shown to have no significant impact on elliptic flow, it increases however the yield.
- Based on the virtually unchanged values of v_2 when changing ϵ_c, the proposed parameterization could be a good proxy for η/s in the non-equilibrium hadronic transport stage

Further investigations from here on

- Include a parameterization of ζ/s and study interaction of both
- Increase range of studied energies

More about SMASH

SMASH and SMASH-vHLLE-hybrid are available at https://github.com/smash-transport.
More information can be also found at https://smash-transport.github.io/.

Upcoming:

Poster presentation 3 T11-4

Exploring the high baryon-density regime of the QCD phase diagram within a novel hybrid approach
- Anna Schäfer

Poster presentation 3 T10

Collective flow at SIS energies within a hadronic transport approach: Influence of light nuclei formation and equation of state - Justin Mohs

Poster presentation 3 T16

Multi-particle collisions in the hadronic stage: Influence of annihilation and catalysis reactions on proton and deuteron yields - Jan Staudenmaier

Available online:

Poster presentation 1 T02

Angular Momentum in Heavy-Ion Collisions via the Hadronic Transport Approach SMASH
- Nils Sass

Poster presentation 2 T13

Enhancement of photon momentum anisotropies during the late stages of relativistic heavy-ion collisions
- Oscar Garcia-Montero

Poster presentation 1 T07_1

Impact of hadronic interactions and conservation laws on cumulants of conserved charges in a dynamical model
- Jan Hammelmann

Poster presentation 1 T02

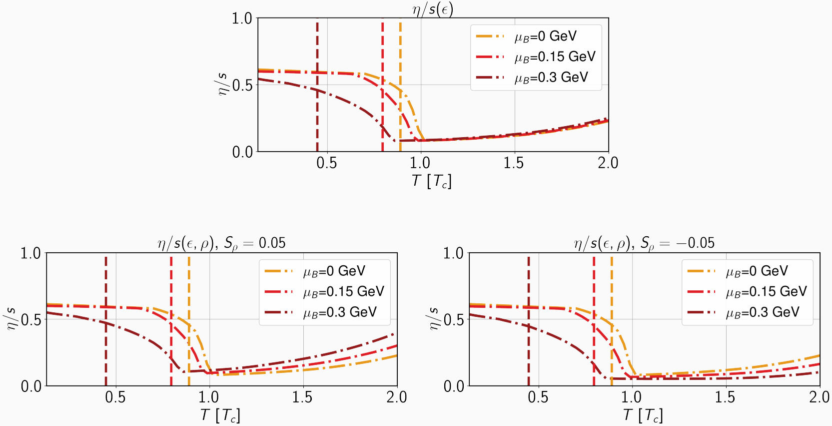
Impact of the nuclear structure on the isobar run at RHIC
- Hannah Elfner

Poster presentation 2 T13

Dynamical broadening of vector-meson spectral functions - Renan Hirayama

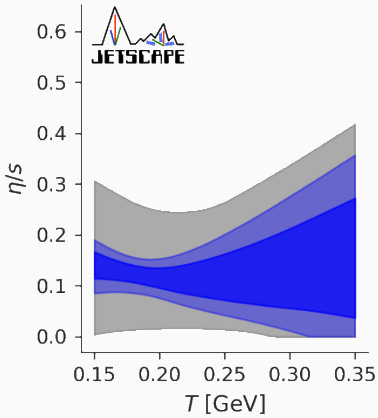
Backup

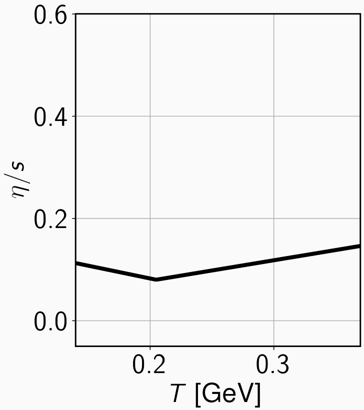
Parameterization in ϵ



The conversion $(\epsilon, \rho) \rightarrow (T, \mu_B)$ is performed using the same EoS as in the hydrodynamic evolution, a chiral hardon-quark EoS (Steinheimer et al.: J.Phys.G 38 (2011)).

Parameterization in T





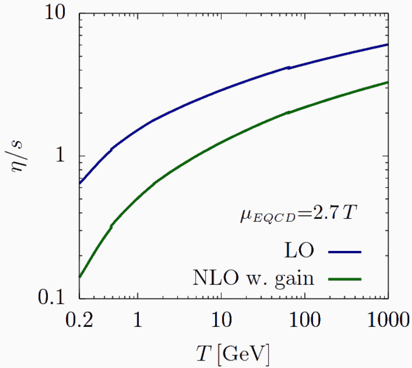
Chosen $\eta/s(T)$ parameterization lies inside the 90% confidence interval of Bayesian inference.

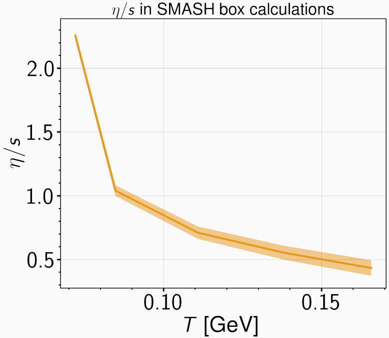
JETSCAPE Phys. Rev. Lett. 126 (2021)

JETSCAPE PRC 103 (2021)

Constraints

Input used for fixing the steepness of $\eta/s(\epsilon)$





pQCD constraint from
Ghiglieri et al.: JHEP 1803 (2018)

Parameters

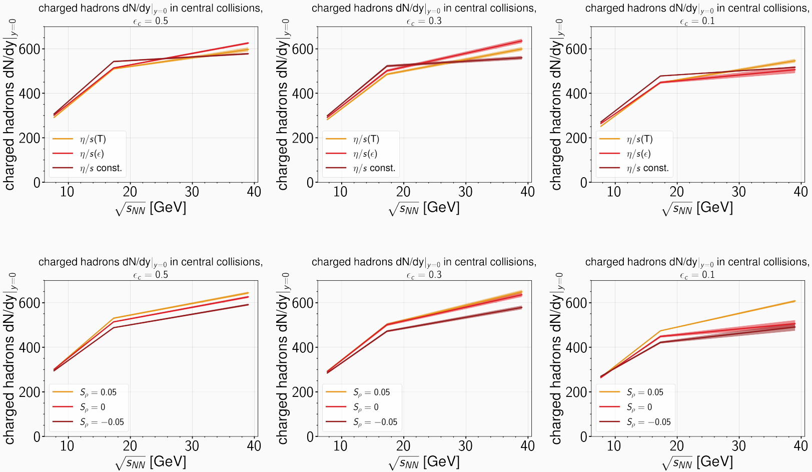
Parameters used for non-constant η/s

Parameterization	ϵ-dependent	ρ-dependent	T-dependent	ϵ_{kink} [$\frac{GeV}{fm^3}$] / T_{kink} [GeV]	$(\eta/s)_{kink}/(\eta/s)_{min}$	$S_{\epsilon/T,H}$ [$\frac{fm^3}{GeV}$]/[GeV^{-1}]	$S_{\epsilon/T,Q}$ [$\frac{fm^3}{GeV}$]/[GeV^{-1}]	S_ρ [fm^3]
$\eta/s(\epsilon)$	Y	N	N	1	0.08	-0.7/-0.54/-0.53	0.0047	0
$\eta/s(\epsilon,\rho)^+$	Y	Y	N	1	0.08	-0.7/-0.54/-0.53	0.0047	0.03
$\eta/s(\epsilon,\rho)^-$	Y	Y	N	1	0.08	-0.7/-0.54/-0.53	0.0047	-0.03
$\eta/s(T)$	N	N	Y	0.205	0.08	-0.05	0.4	0

Parameters used for constant η/s as well as chosen smearing parameters (both from Karpenko et al.: PRC 91 (2015))

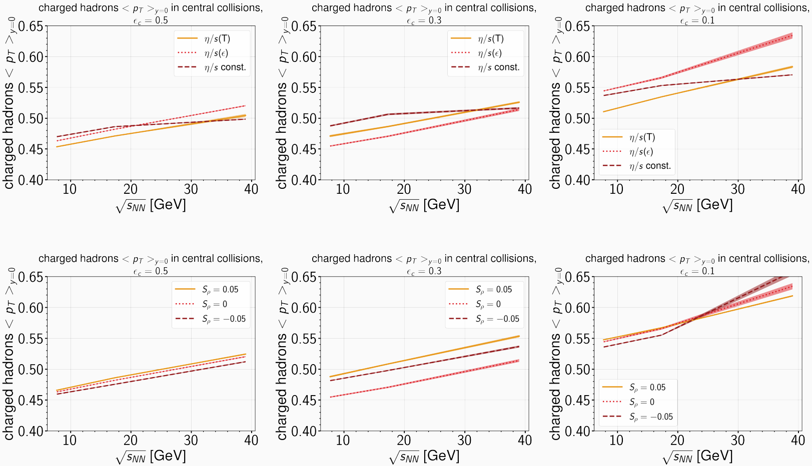
system	$\sqrt{s}$	η/s	$R_\perp$	R_η
Au + Au	7.7	0.2	1.4	1.2
Pb+Pb	17.3	0.15	1.4	0.7
Au + Au	39.0	0.08	1.0	0.3

ϵ_c: Impact on midrapidity yield



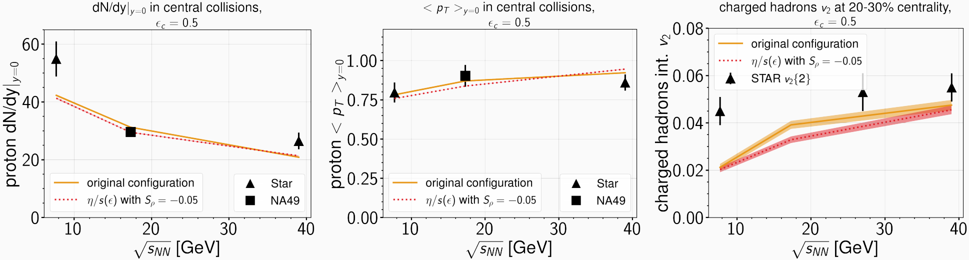
Longer hydro reduces yield. A positive ρ-dependence reduces this effect.

ϵ_c: Impact on mean transverse momentum



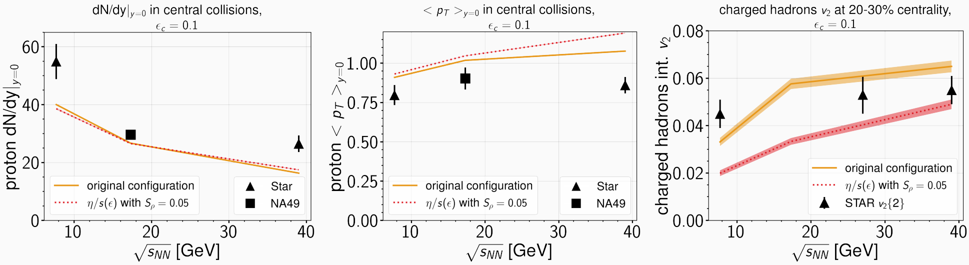
Longer hydro increases $< p_T >$. For high $\sqrt{s}$, this effect is increased for negative ρ-dependence

Comparison to data



STAR PRC 86 (2012) STAR PRC 96 (2017) NA49 Phys.Rev. Lett. 80 (1998) NA49 Phys.Rev. Lett. 73 (1994)

Comparison to data



A late transition to transport produces excess transverse momentum.

STAR PRC 86 (2012) STAR PRC 96 (2017) NA49 Phys.Rev. Lett. 80 (1998) NA49 Phys.Rev. Lett. 73 (1994)