Investigation of shear viscosity and the generation of anisotropic flow in a hybrid approach

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CRC-TR 211 Strong-interaction matter under extreme conditions

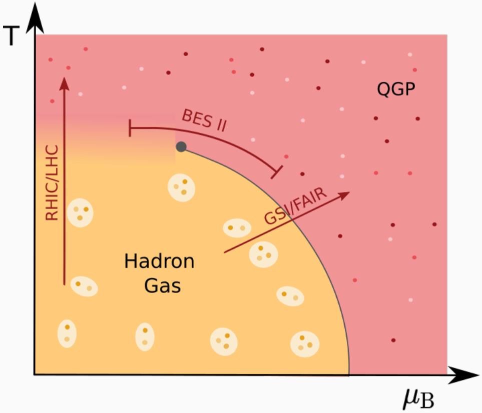
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

GSI

FIAS Frankfurt Institute for Advanced Studies

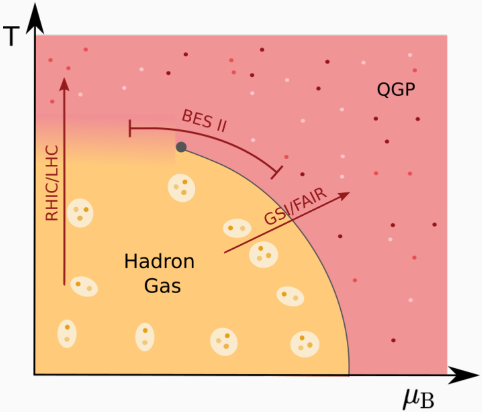
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Exploring the QCD phase diagram



- Want to study the properties of nuclear matter at different densities and temperature
- Study the phase transition and possible critical point
- Build dynamical models to study the evolution of HIC
- Problem: different regions of the phase diagram need different theoretical language

Exploring the QCD phase diagram

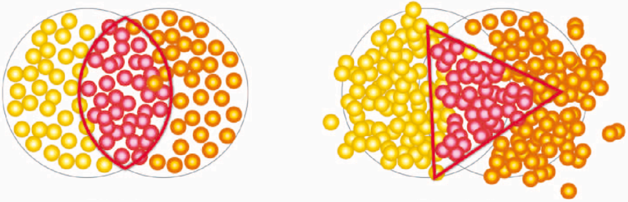


- **Theoretical description**: If mean free path >> system size: hadronic transport, if system size >> mean free path: hydrodynamics
- **Low beam energies**: hadronic transport with nuclear potentials and resonance dynamics
- **High beam energies**: Non-equilibrium initial evolution + hydrodynamics + hadronic rescattering
- Hydrodynamics requires as an input an initial condition, equation of state as well as transport coefficients

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)

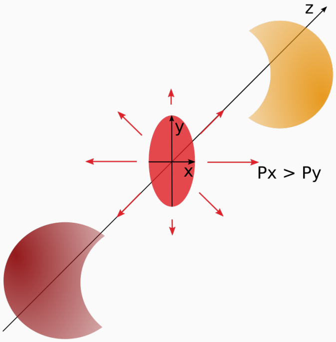
Source of eccentricity

Jacak, Müller: Science 337 (2012)

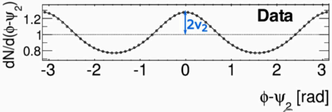


- If the two nuclei hit each other not directly, the resulting fireball will be elliptic $\rightarrow \epsilon_2 > 0$
- Fluctuations of nuclei positions and color charges can introduce higher order eccentricities $\rightarrow \epsilon_3 > 0$
- The asymmetry of the initial state results in a pressure gradient in the fluid

Flow in heavy-ion collisions



ATLAS: PLB 707 (2012)



- Pressure gradient of the fluid causes anisotropic flow
- Azimuthal Fourier decomposition of yields:

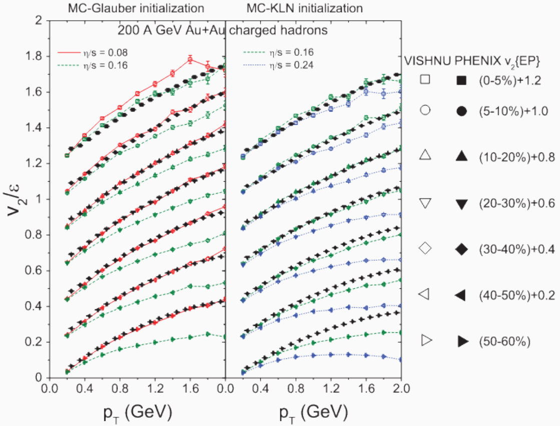
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Psi_n)$$

- $v_{2,3}$ are often approximated as a linear response to $\epsilon_{2,3}$ (ideal hydro: $v_2 \approx 0.2 - 0.3\epsilon_2$)
- Proportionality factor depends on the shear viscosity of the fluid

Qiu, Heinz: PRC 84 (2011)

Shear viscosity in heavy ion collisions

Song et al.: PRC 83 (2011)

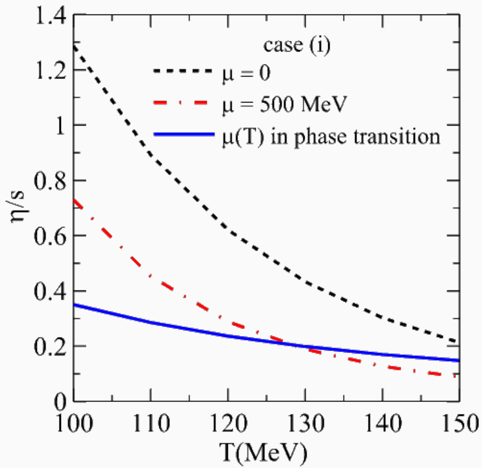


- Flow measurements: QGP behaves like an almost almost perfect fluid, but also evidence for small but non-zero shear viscosity η/s
- Evaluation of η/s in lattice QCD is challenging due to numerical problems
- Extraction from experiment difficult due to uncertainty of initial conditions

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)

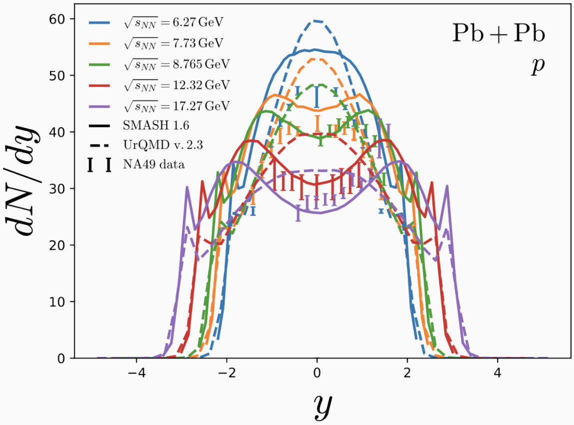
Aim

- 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 ($\sqrt{s_{NN}}$ =7.7 - 39.0 GeV), where impact of μ_B is significant
- Study the generation of elliptic flow in a hybrid approach

Motivation

- Baryon stopping is important for the description of heavy-ion collisions at NA61/SHINE, BES and GSI/FAIR energies
- SMASH is capable of describing proton rapidity spectra across a wide range of collision energies
- Apply SMASH for the initial and final state in a novel hybrid model

Mohs et al.: J.Phys.G 47 (2020)



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

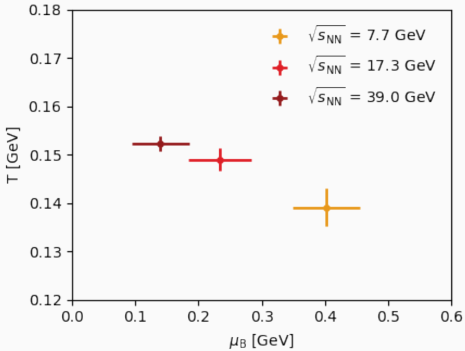
- Cooper-Frye sampler
- Particlization of fluid elements

+

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_{switch} is reached
- **Particlization**: At ϵ_{switch} 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)

SMASH

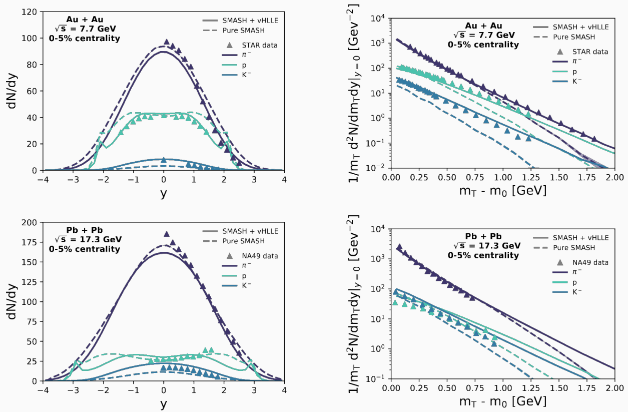
- **S**imulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons
- Numerically solves the Boltzmann-equation:

$$\partial_t f + \frac{p}{m} \nabla f + F \partial_p f = \left(\frac{\partial f}{\partial t} \right)_{coll}$$

- Describes dilute, microscopic, non-equilibirum systems
- Uses (by default) a geometric collision criterion $d_\perp = \sqrt{\sigma_{tot}/\pi}$
- Uses PYTHIA for high energy hadron collisions for string fragmentation and hard scatterings

Results of SMASH-vHLLE-hybrid

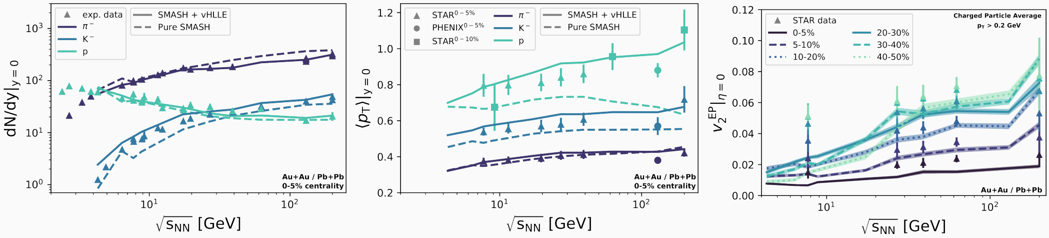
Schäfer et al.: 2112.08724



- Decreases pion production and enhances kaon production
- Decreases width of proton rapidity distribution
- Hardens the midrapidity dN/dm_T spectra of pions, kaons and protons
- Improves agreement with experimental data at intermediate collision energies

Results of SMASH-vHLLE-hybrid

Schäfer et al.: 2112.08724



- Good agreement of yields and mean p_T over a wide range of collision energies
- Decent agreement with experimentally measured flow for systems with long enough fireball lifetime

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

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

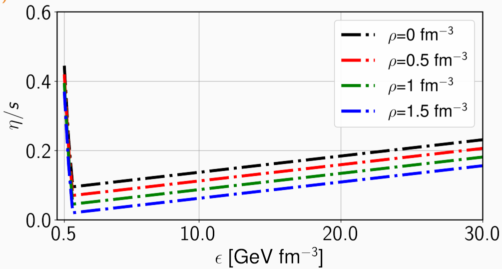
- Even for $S_\rho == 0$: **implicit μ_B dependence**

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_{switch} 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)

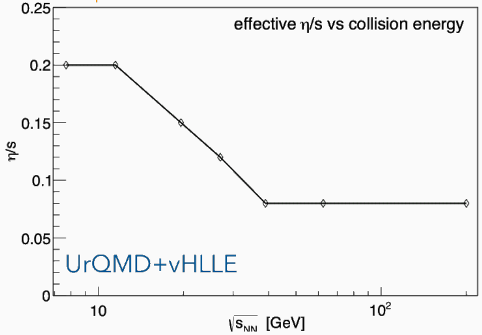


Parameterizations for comparison

1. comparison

effective, constant η/s

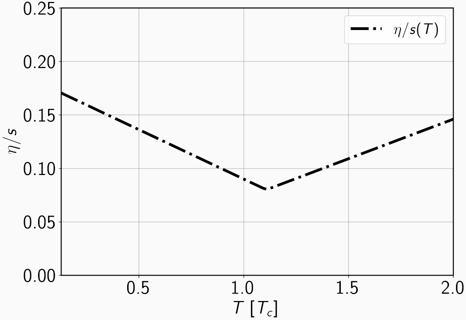
Karpenko et al.: PRC 91 (2015)



originally used in SMASH-vHLLE-hybrid

2. comparison:

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



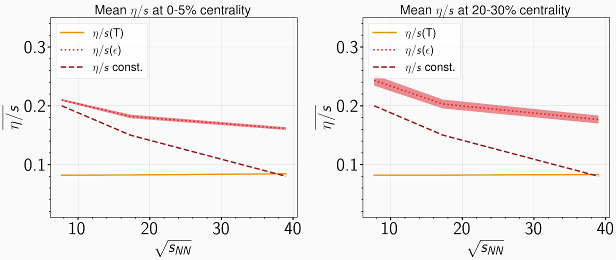
based on results of the JETSCAPE collaboration

JETSCAPE Phys. Rev. Lett. 126 (2021)

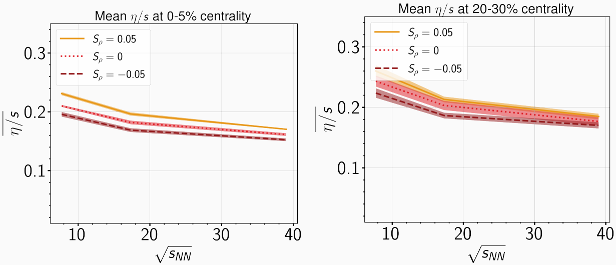
JETSCAPE PRC 103 (2021)

Effective shear viscosity

Comparison parameterizations:



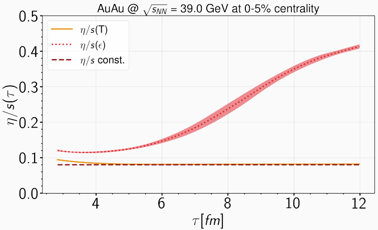
ρ-dependence:



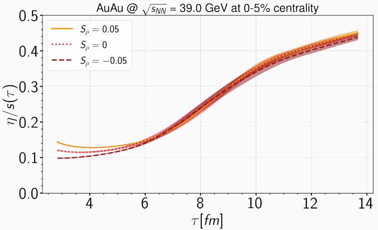
New parameterization gives larger values for shear viscosity, which reduce with increasing energy

Time evolution of shear viscosity

Comparison parameterizations:

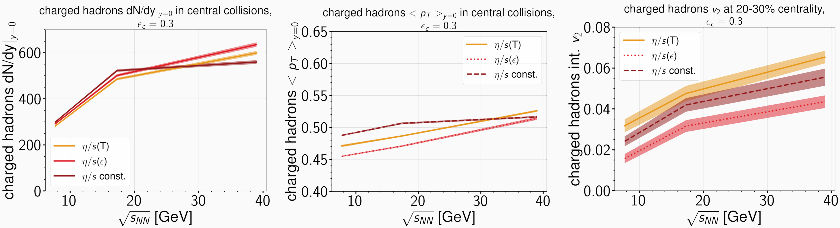


ρ-dependence:

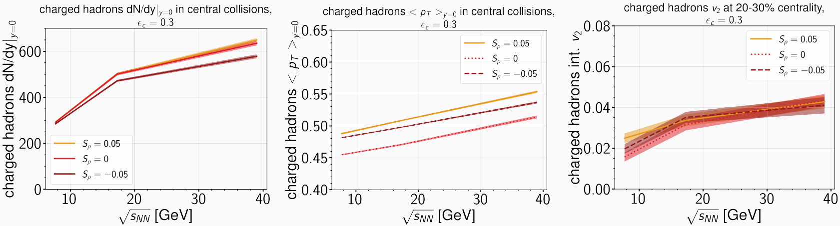


Energy density weighted mean shear viscosity changes significantly during the evolution. Differences due to ρ-dependence are most significant in the beginning of the evolution.

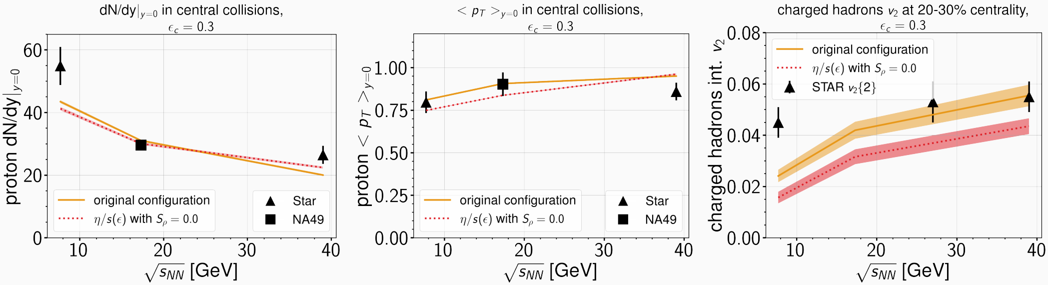
Comparison parameterizations:



ρ-dependence:



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

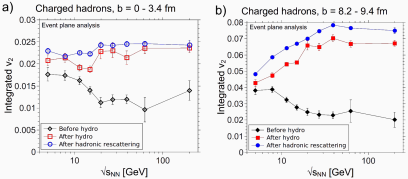


Parameterisation in ϵ reproduces experimental results up to a similar degree than tuned effective η/s

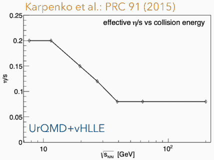
STAR PRC 86 (2012) STAR PRC 96 (2017) NA49 Phys.Rev. Lett. 80 (1998) NA49 Phys.Rev. Lett. 73 (1994)

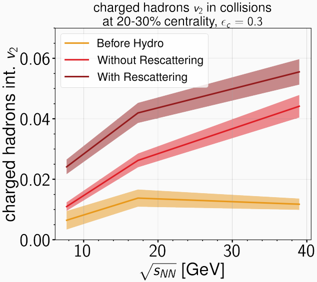
Flow contribution and response

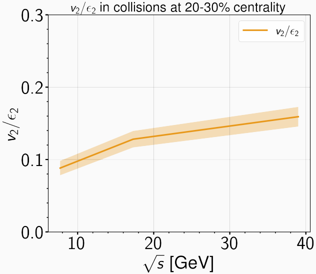
Similar to earlier analysis in UrQMD hybrid (Auvinen et al.: PRC 88 (2013))



Using the constant, effective η/s



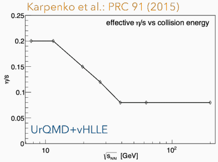




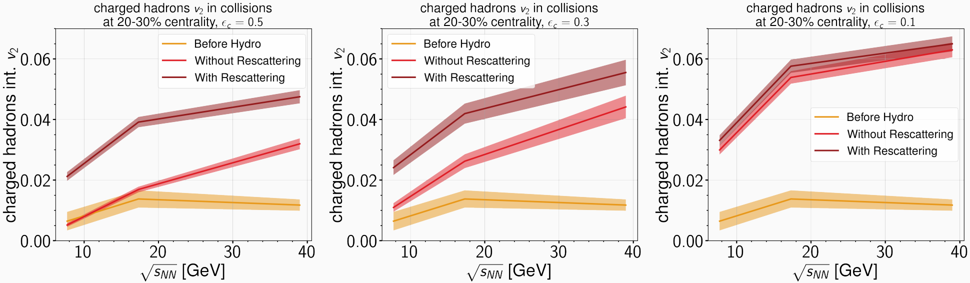
Significant contribution from non-equilibrium SMASH to elliptic flow

Flow contributions depending on ϵ_{switch}

Using the constant, effective η/s



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



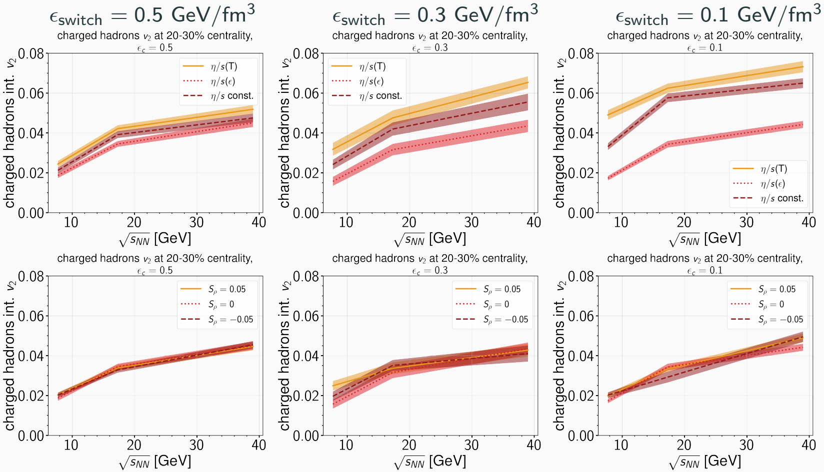
Impact of η/s parameterization becomes more dominant when switching to transport at later time

Impact on flow results

Elliptic Flow at the end of the hybrid evolution

Comparison parameterizations:

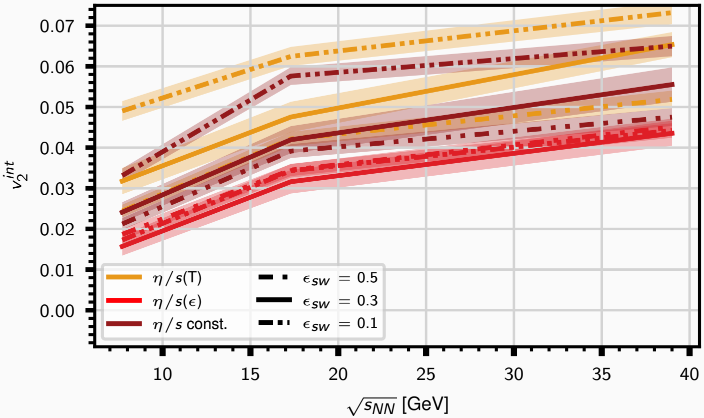
ρ-dependence:



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

Flow for varying ϵ_{switch}

Elliptic Flow at the end of the hybrid evolution



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

Importance of initial condition model

SMASH generates initial conditions dynamically, resulting in non-zero initial flow and fluctuations in the 3D initial conditions, both have a major impact on the results → study the effect of using different initial condition models!

T$_{\mathrm{R}}$ENTo

- Generalized, effective parametric ansatz for reduced thickness function in the transverse plane
- $\left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$
- Fluctuations, but no momentum space information

Moreland et al.: PRC 92 (2015),
JETSCAPE PRL 126 (2021)

IP-Glasma

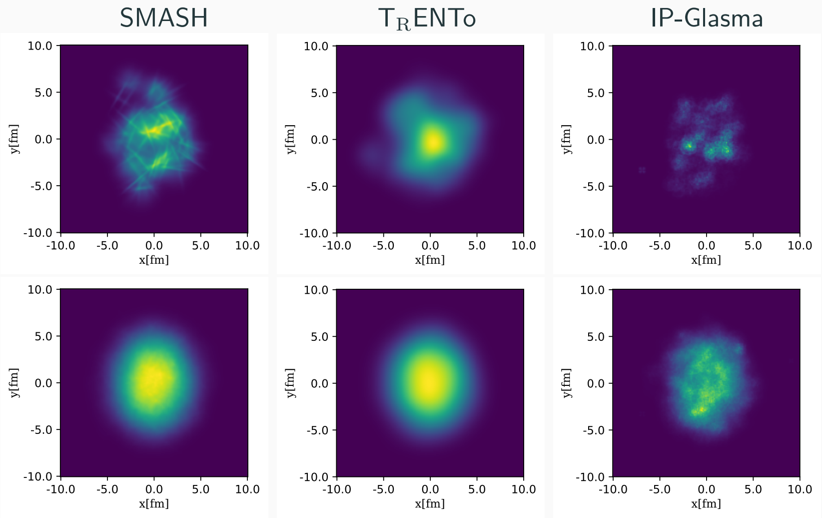
- Yang-Mills initial state model within CGC framework with impact parameter dependent saturation
- Describes both fluctuations of nucleon positions and color charges
- Provides radial flow and momentum anisotropy

Schenke et al.: PRL 108 (2012),
Schenke et al.: PRC 86 (2012)

Transverse plane profiles

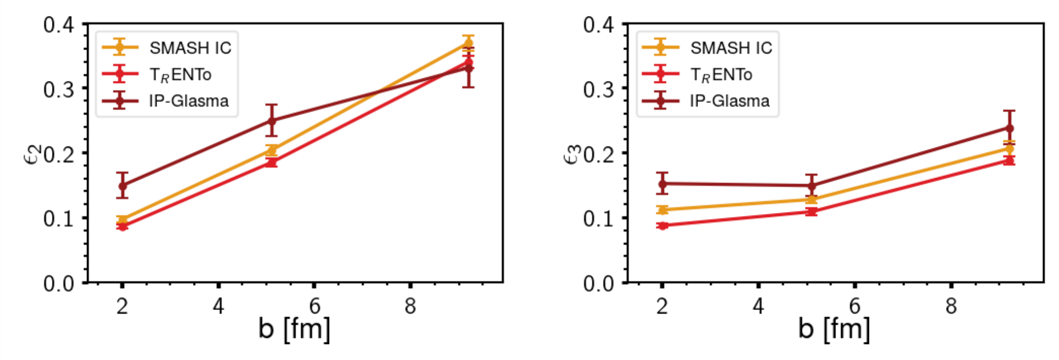
Single Event

Average



Initial condition transverse plane profile for AuAu at 200 GeV and impact parameter $b = 5$ fm

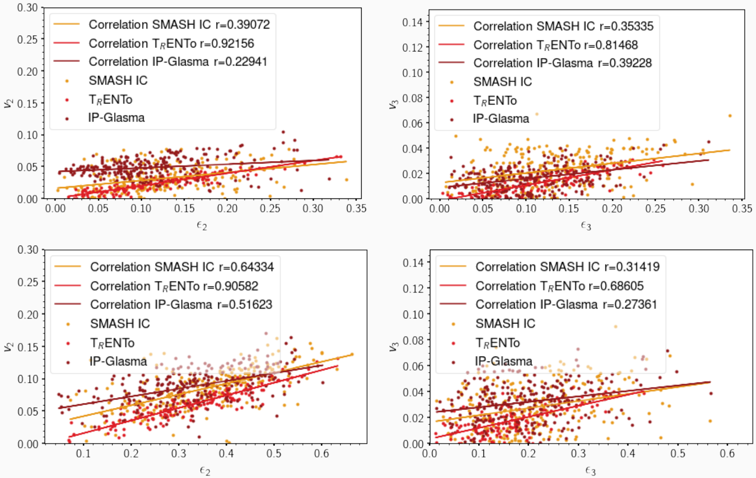
Eccentricity for AuAu @ 200 GeV



Similar eccentricities for all three models.

0-5% centrality

20-30% centrality

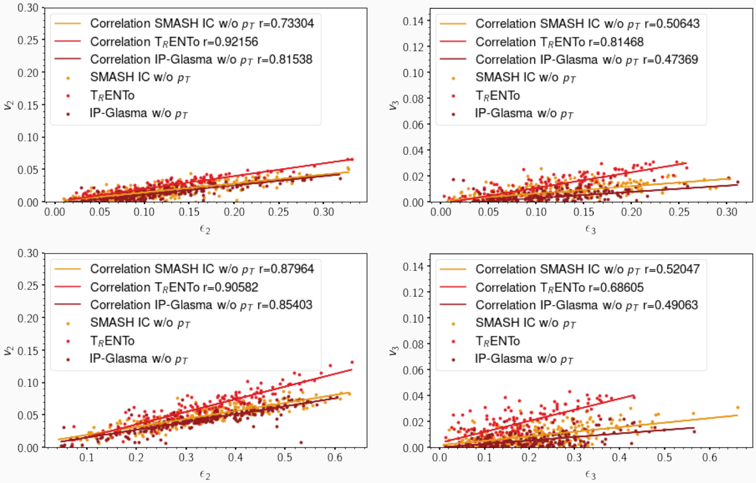


IP-Glasma and SMASH IC have higher flow for small eccentricites. T$_{\mathrm{R}}$ENTo gives stronger correlations.

Impact of initial transverse momentum

0-5% centrality

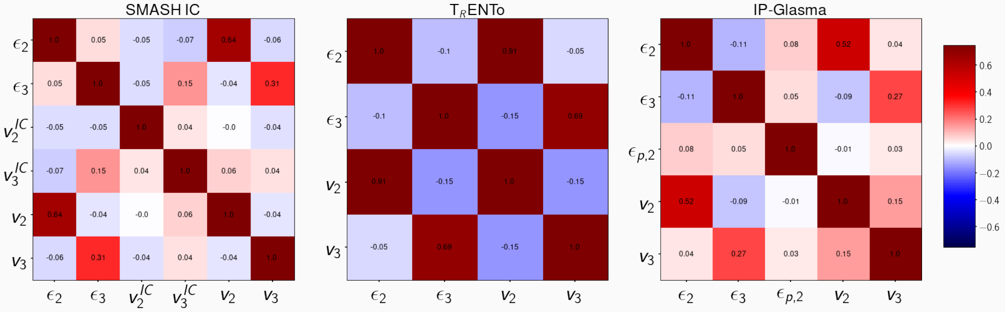
20-30% centrality



Without initial p_T, flow fluctuations at the same eccentricity become strongly reduced and the linear correlation increases. The total flow at midrapidity is reduced to to stronger longitudinal expansion.

Impact of initial flow

Correlations between initial state properties and final state flow for AuAu at 200 GeV, 20-30% centrality

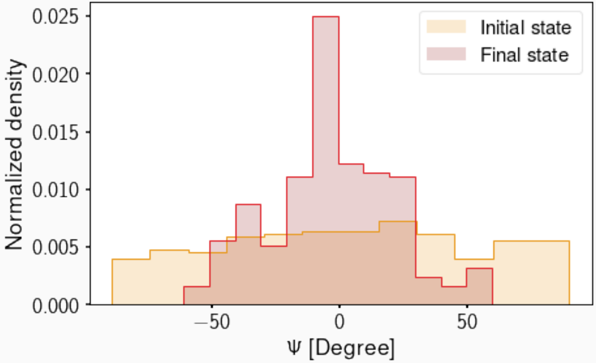


$$\epsilon_{p,2} = \sqrt{\frac{< T^{xx} - T^{yy} >^2 + < 2T^{xy} >^2}{< T^{xx} + T^{yy} >^2}}$$

Schenke et al.: Nuclear Phys A 982 (2019)

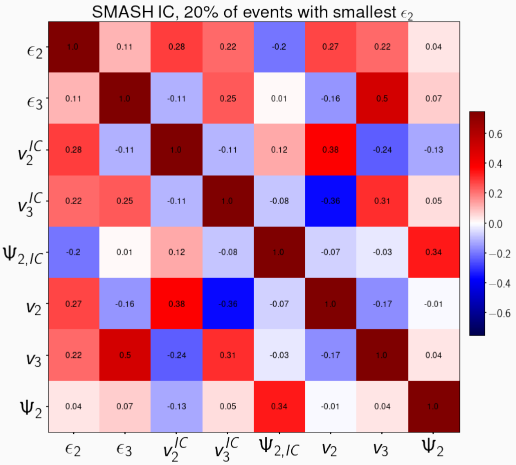
Initial and final event plane angle

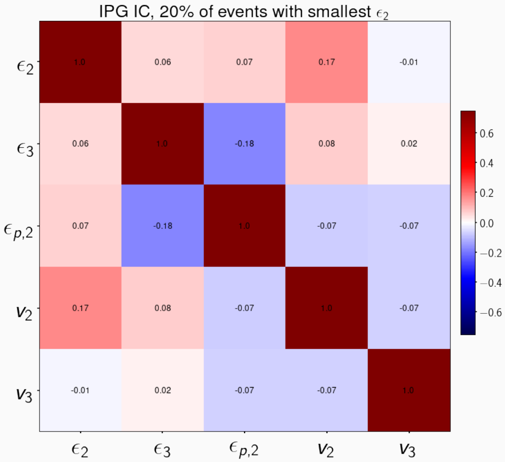
200 GeV, 0-5% centrality



The initial event plane angle is randomly distributed. Due to the fixed collision plane, the geometric information affects hydrodynamic evolution to give a preferred final state event plane angle.

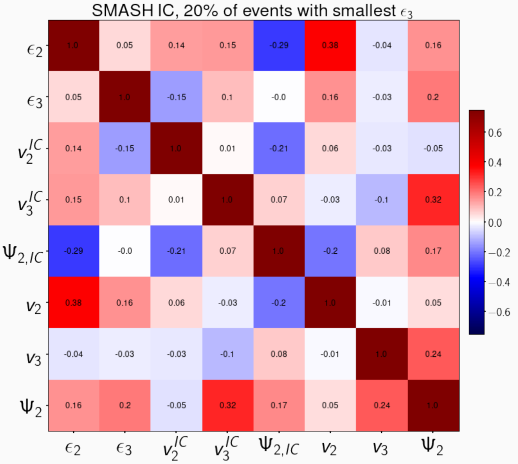
Impact of initial elliptic flow

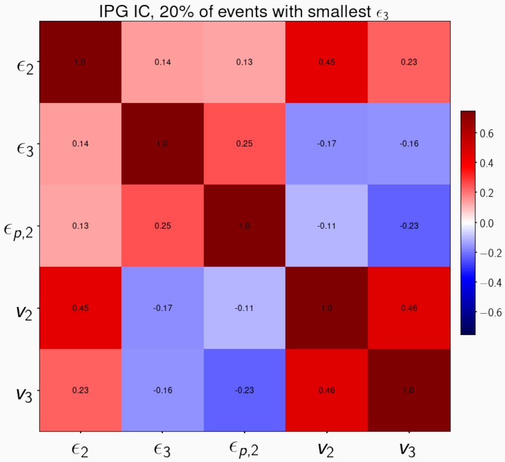




Initial flow from SMASH contributes to final flow when no flow is generated from geometry!

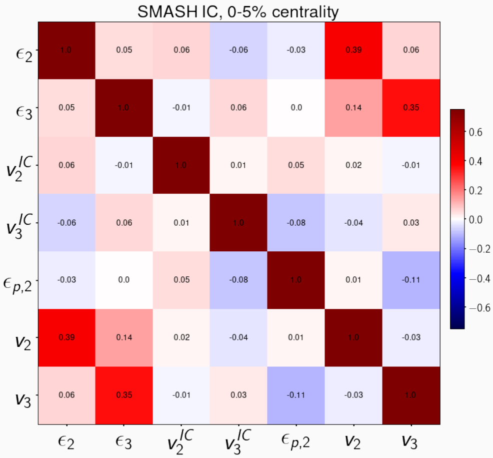
Impact of initial triangular flow





For events with small triangular eccentricity, v_3 is neither generated by ϵ_3 nor initial momentum anisotropy
$\rightarrow$ contribution from afterburner dominant?

Inital momentum anisotropy



$\epsilon_{p,2}$ is not a good proxy for initial flow.

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_{switch}, the proposed parameterization could be a good proxy for η/s in the non-equilibrium hadronic transport stage
- Due to the lack of momentum-space information, T$_{\mathrm{R}}$ENTo realises much stronger the assumption of linear correlation between v_n and ϵ_n
- Correlations between initial and final flow for SMASH when eccentricity is low. For small eccentricites, SMASH and IP-Glasma produce higher flow.
- Momentum space anisotropy $\epsilon_{p,2}$ does not contribute to final flow

Further investigations from here on

- Include a parameterization of ζ/s and study interaction of both viscosities
- Increase range of studied energies
- Study impact of different forms of the δf corrections in the sampling stage for the observed flows
- Study modes of the energy density and baryon density distribution of the initial condition and their impact on flow

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/.