Exploring the high baryon-density regime of the QCD phase diagram within a novel hybrid model

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CRC-TR 211 Strong-interaction matter under extreme conditions

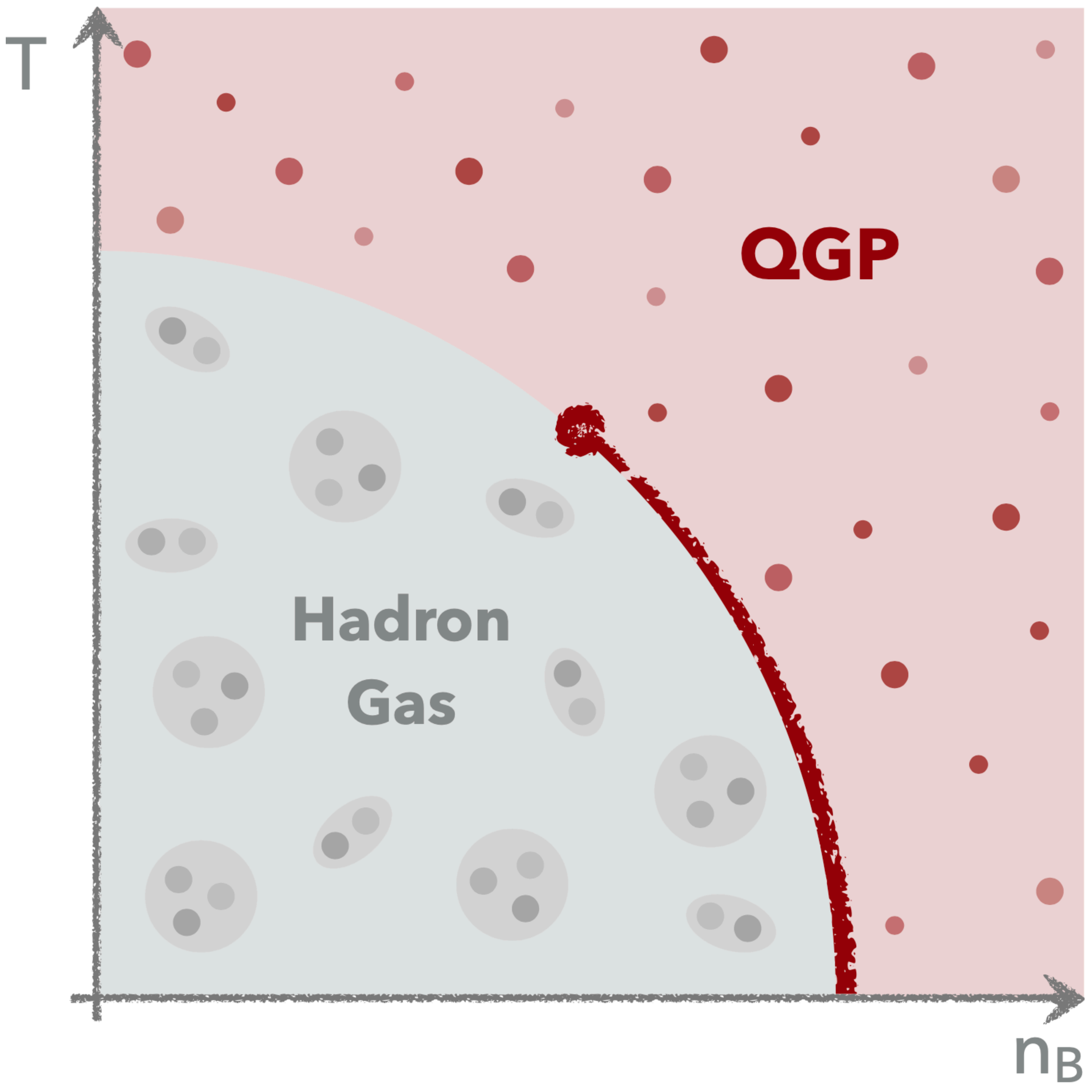
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

GSI

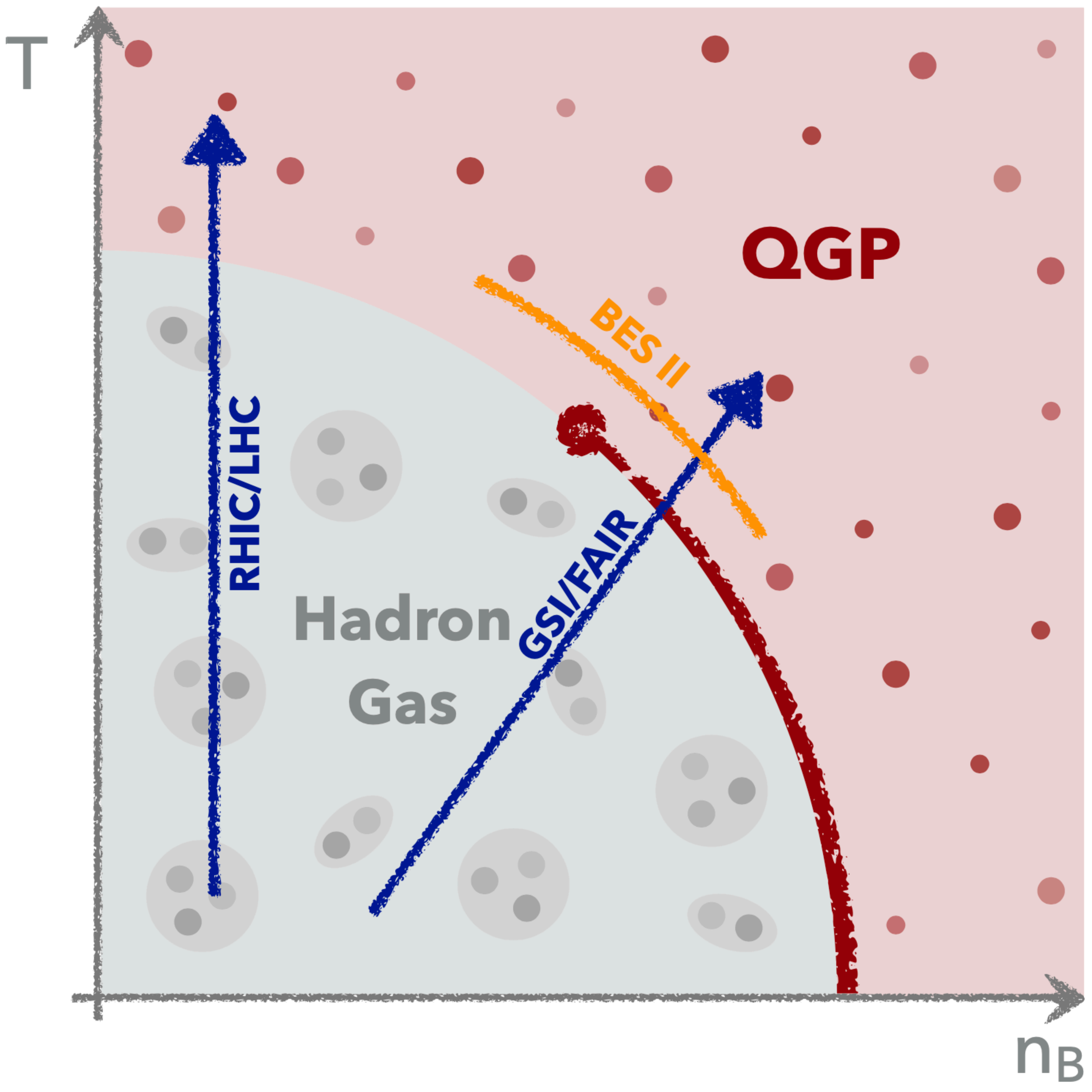
FIAS Frankfurt Institute for Advanced Studies

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

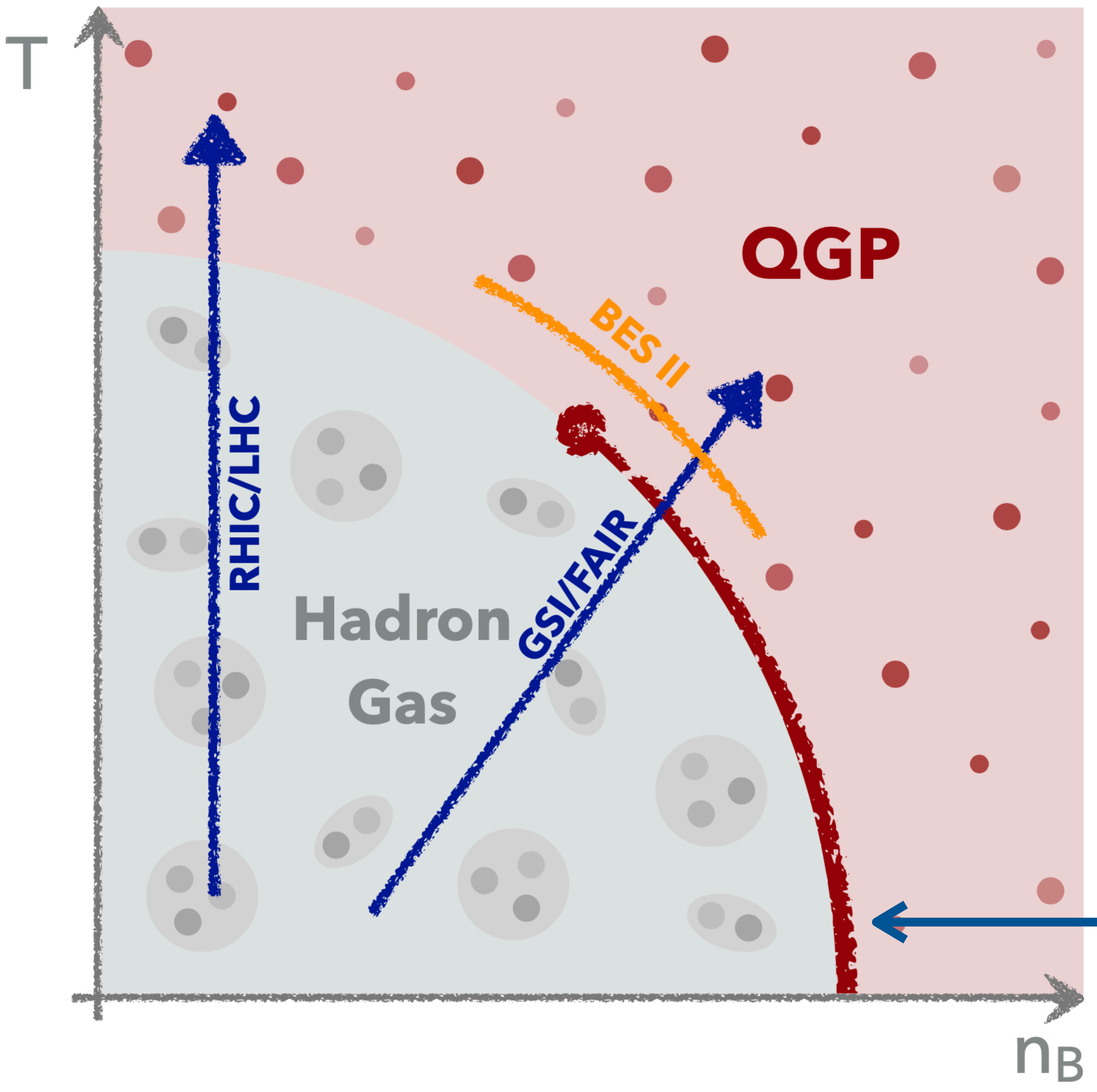
Exploring the QCD phase diagram



Exploring the QCD phase diagram



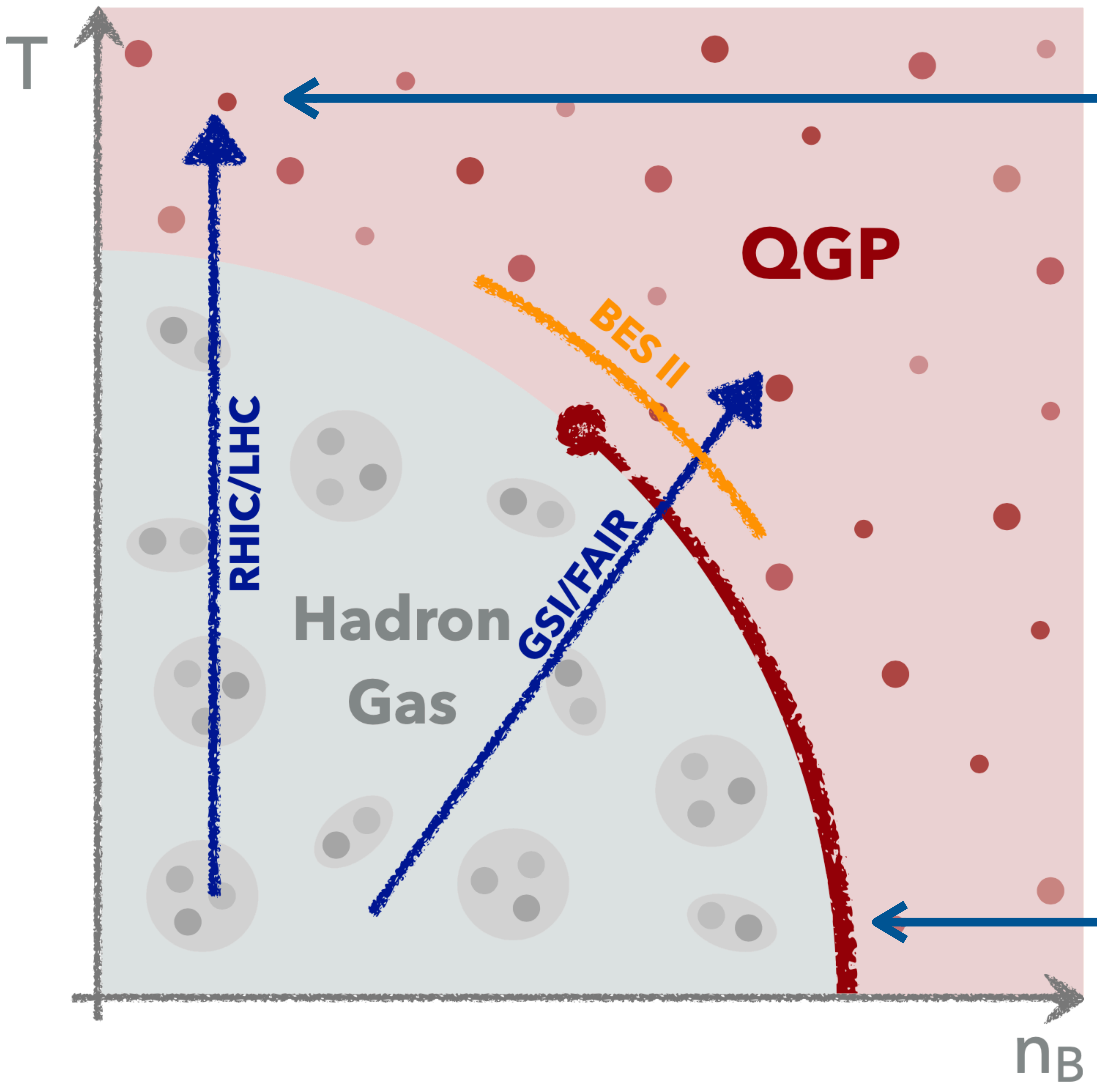
Exploring the QCD phase diagram



Standard description at low collision energies:

- Hadronic transport approaches
- Resonance dynamics and nuclear potentials

Exploring the QCD phase diagram



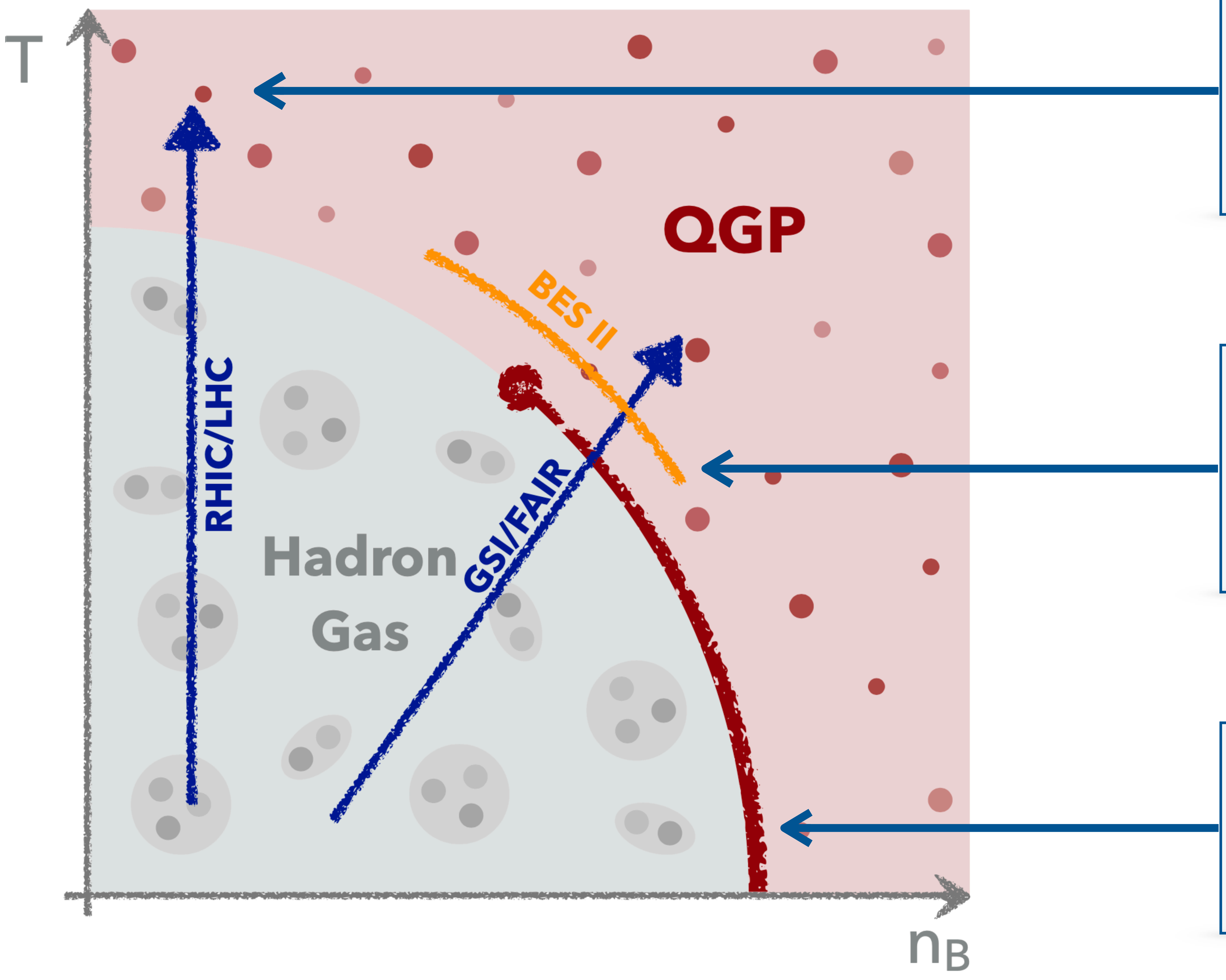
Standard description at high collision energies:

- Hybrid approaches with out-of-equilibrium initial state coupled to viscous hydrodynamics
- Hadronic rescattering stage

Standard description at low collision energies:

- Hadronic transport approaches
- Resonance dynamics and nuclear potentials

Exploring the QCD phase diagram

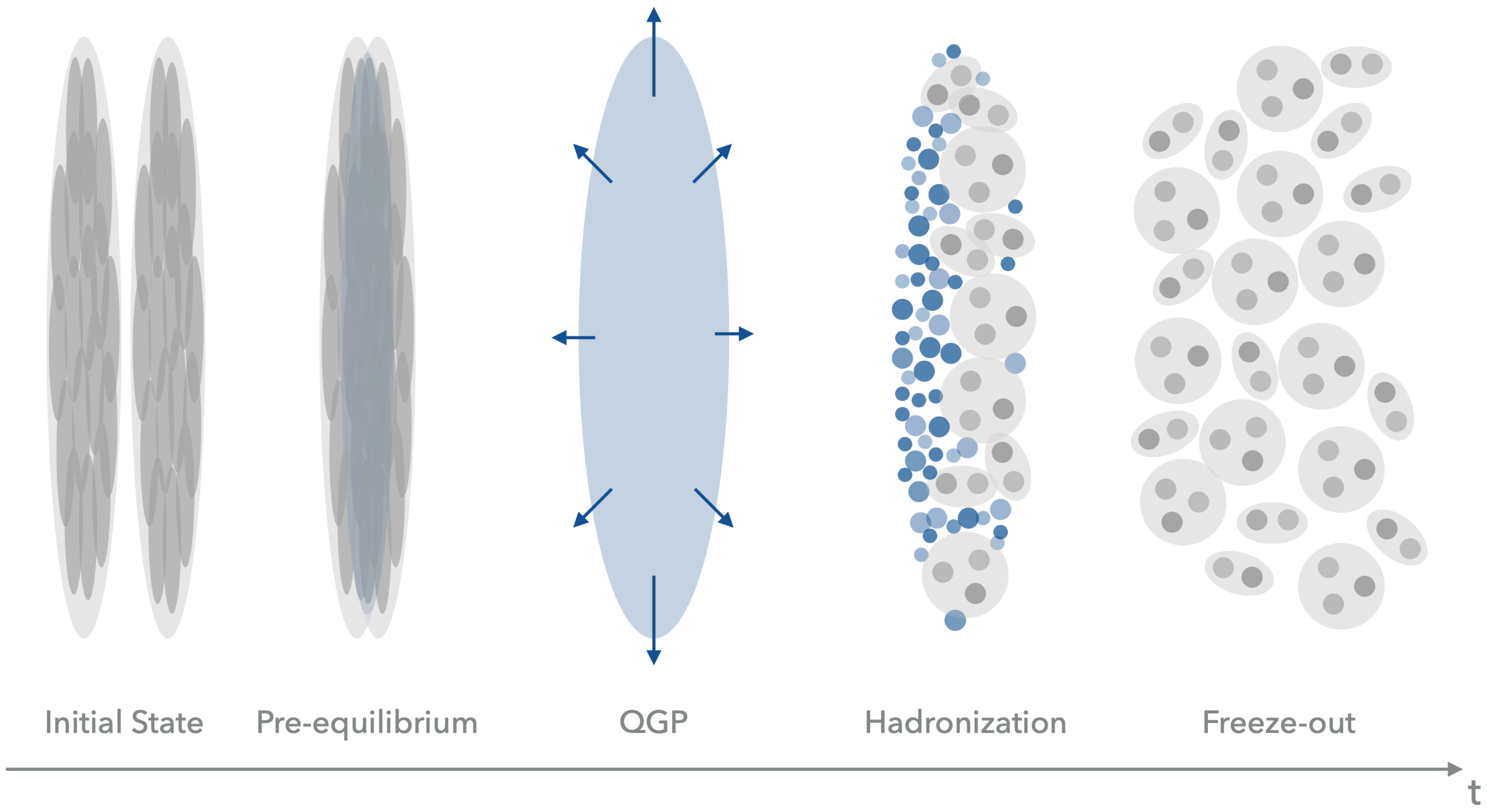


Standard description at high collision energies:
- Hybrid approaches with out-of-equilibrium initial state coupled to viscous hydrodynamics
- Hadronic rescattering stage

Standard description at intermediate collision energies:
- ?
- Intermediate collision energies remain a challenge
- Hybrid approaches with dynamical initial conditions?

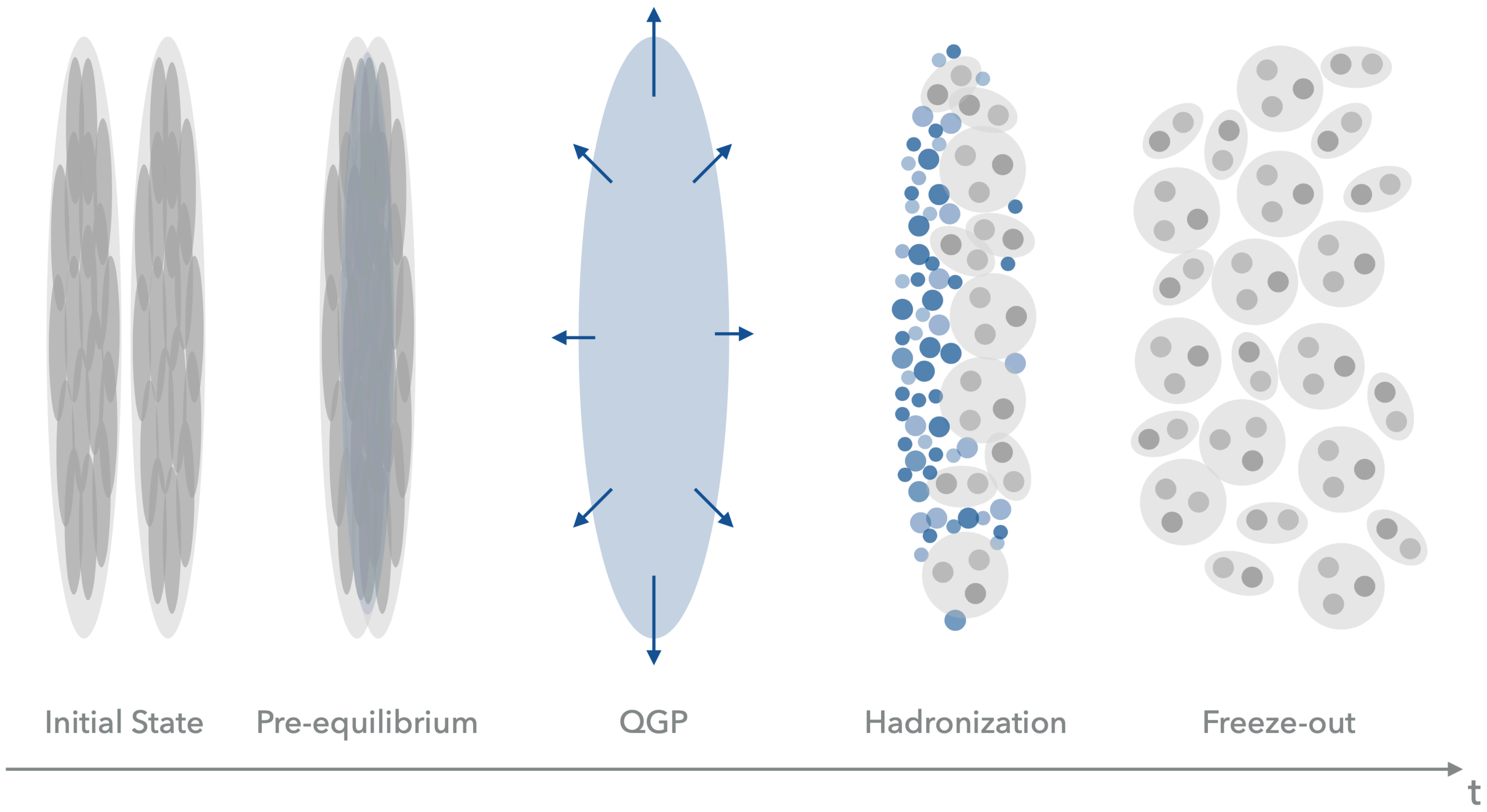
Standard description at low collision energies:
- Hadronic transport approaches
- Resonance dynamics and nuclear potentials

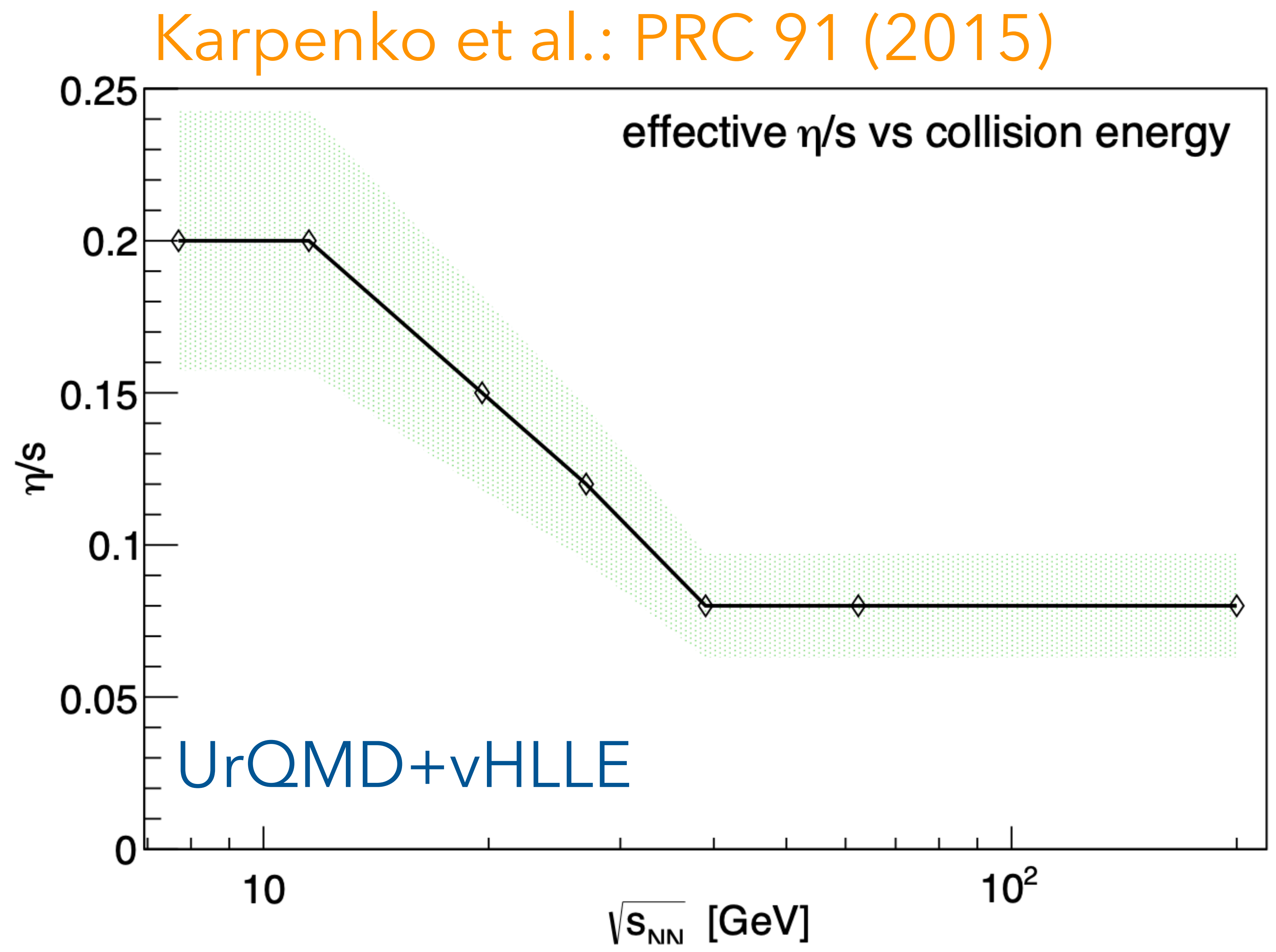
Hybrid Approaches at Intermediate Collision Energies



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)

Hybrid Approaches at Intermediate Collision Energies





- Multistage hybrid models are successfully applied in describing the evolution of a system with different degrees of freedom
- Previous works include e.g. UrQMD+hydro, JAM+hydro, BEShydro, AMPT ...

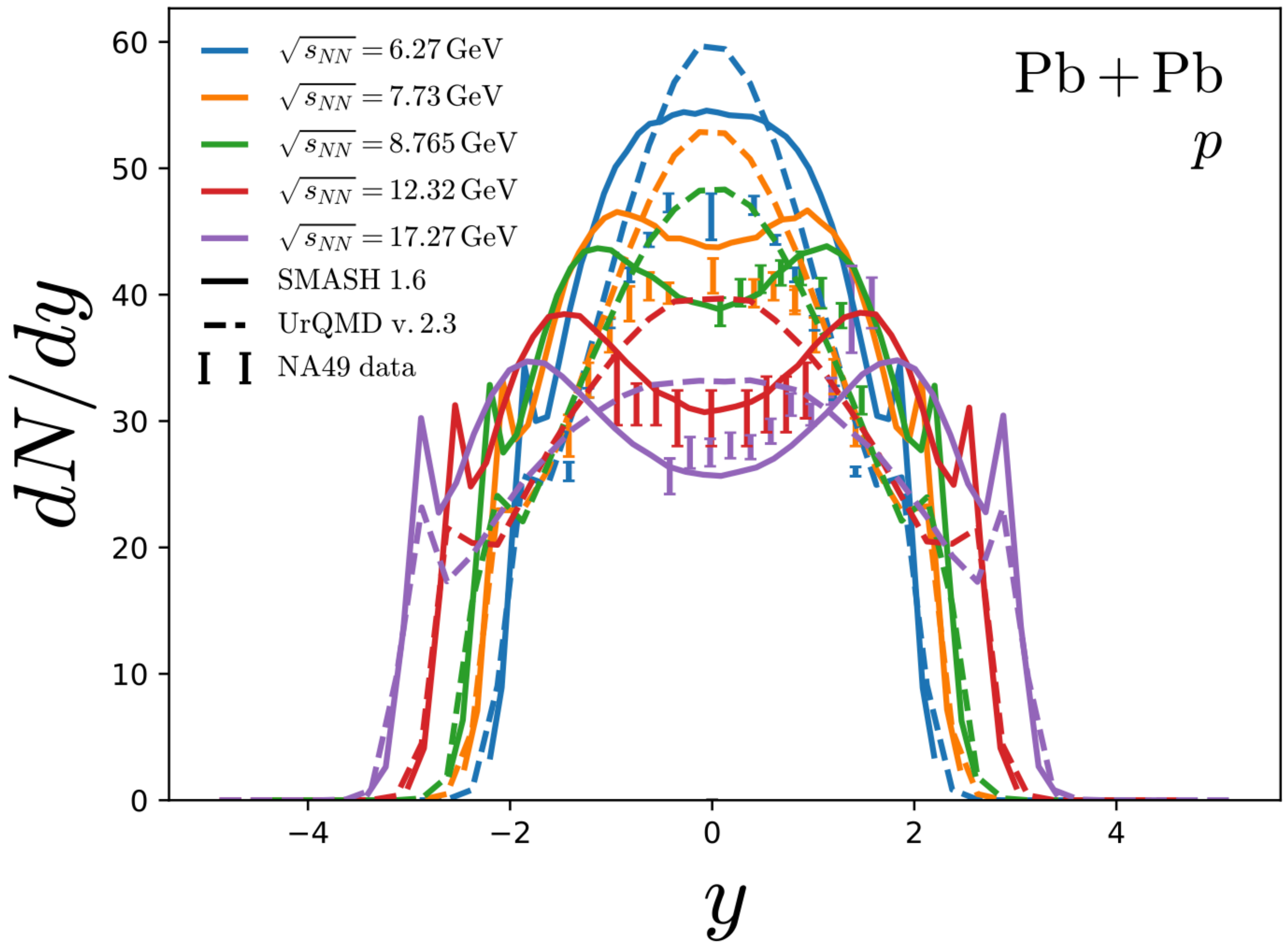
Karpenko et al.: PRC 91 (2015) Akamatsu et al.: PRC 98 (2018) Du et al.: Comp.Phys.Com. 251 (2020) Nandi et al.: PRC 102 (2020)

Why Another Hybrid Approach?

- 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

=> SMASH-vHLLE-hybrid

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



The SMASH-vHLLE-Hybrid

- Modular hybrid approach for the description of intermediate and high energy heavy-ion collisions
- Open-source and public
- https://github.com/smash-transport/smash-vhlle-hybrid

SMASH

- Hadronic transport approach
- Initial conditions

+

vHLLE

- 3+1D viscous hydrodynamics (event-by-event)
- 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

Schäfer et al.: 2109.08578
Weil et al.: PRC 94 (2016)
DOI: 10.5281/zenodo.3484711
Cooper and Frye: Phys.Rev.D 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)

The SMASH-vHLLE-Hybrid: Configuration Details

Initial Conditions

- Propagate particles and perform interactions until hypersurface of constant proper time is crossed
- τ_0: geometrical interpretation of the passing time of the two nuclei, but enforcing $\tau_0 \geq 0.5$
- $\tau_0 = (R_p + R_t) \Big/ \sqrt{\left(\sqrt{s_{\mathrm{NN}}} / (2\, m_{\mathrm{N}})\right)^2 - 1}$

Evolution of the hot and dense fireball

- Quark gluon phase is evolved according to chiral model EoS
- Particlization on hypersurface of constant energy density: e_{crit} = 0.5 GeV/fm^3
- Particlization according to SMASH HRG EoS

System	√s	η/s	$R_\perp$	R_η
Au + Au	4.3 GeV	0.2	1.4	1.3
Au + Au	7.7 GeV	0.2	1.4	1.2
Pb + Pb	8.8 GeV	0.2	1.4	1.0
Pb + Pb	17.3 GeV	0.15	1.4	0.7
Au + Au	27.0 GeV	0.12	1.0	0.4
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Au + Au	62.4 GeV	0.08	1.0	0.6
Au + Au	130.0 GeV	0.08	1.0	0.8
Au + Au	200.0 GeV	0.08	1.0	1.0

Parameters for hydrodynamical evolution, unless stated differently on the plots

$R_\perp$, R_η: transverse and longitudinal smearing parameter

Central collisions are modeled

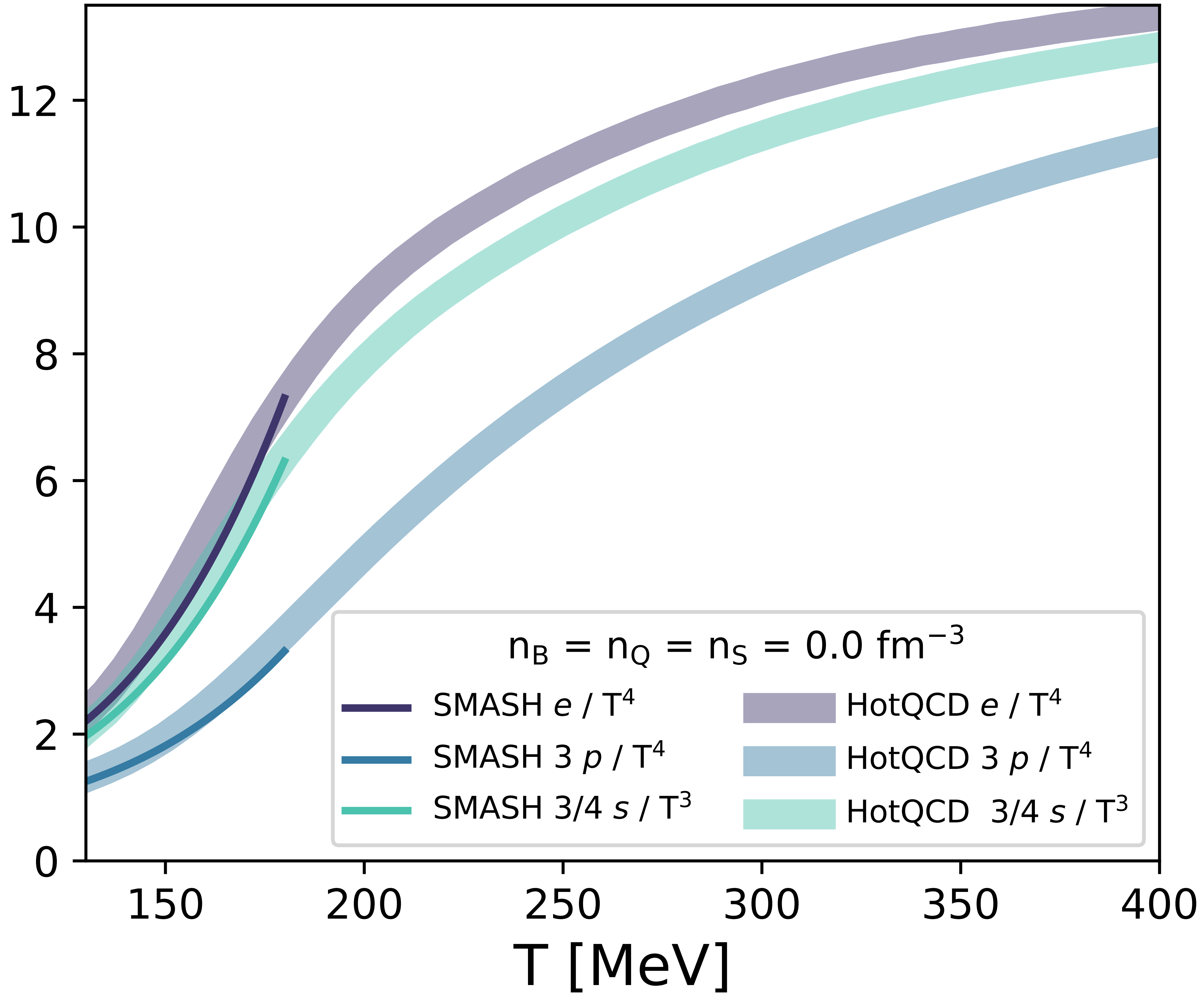
Steinheimer et al.: *J.Phys.G* 38 (2011)

Schäfer et al.: 2109.08578

Karpenko et al.: PRC 91 (2015)

The SMASH Hadron Resonance Gas Equation of State

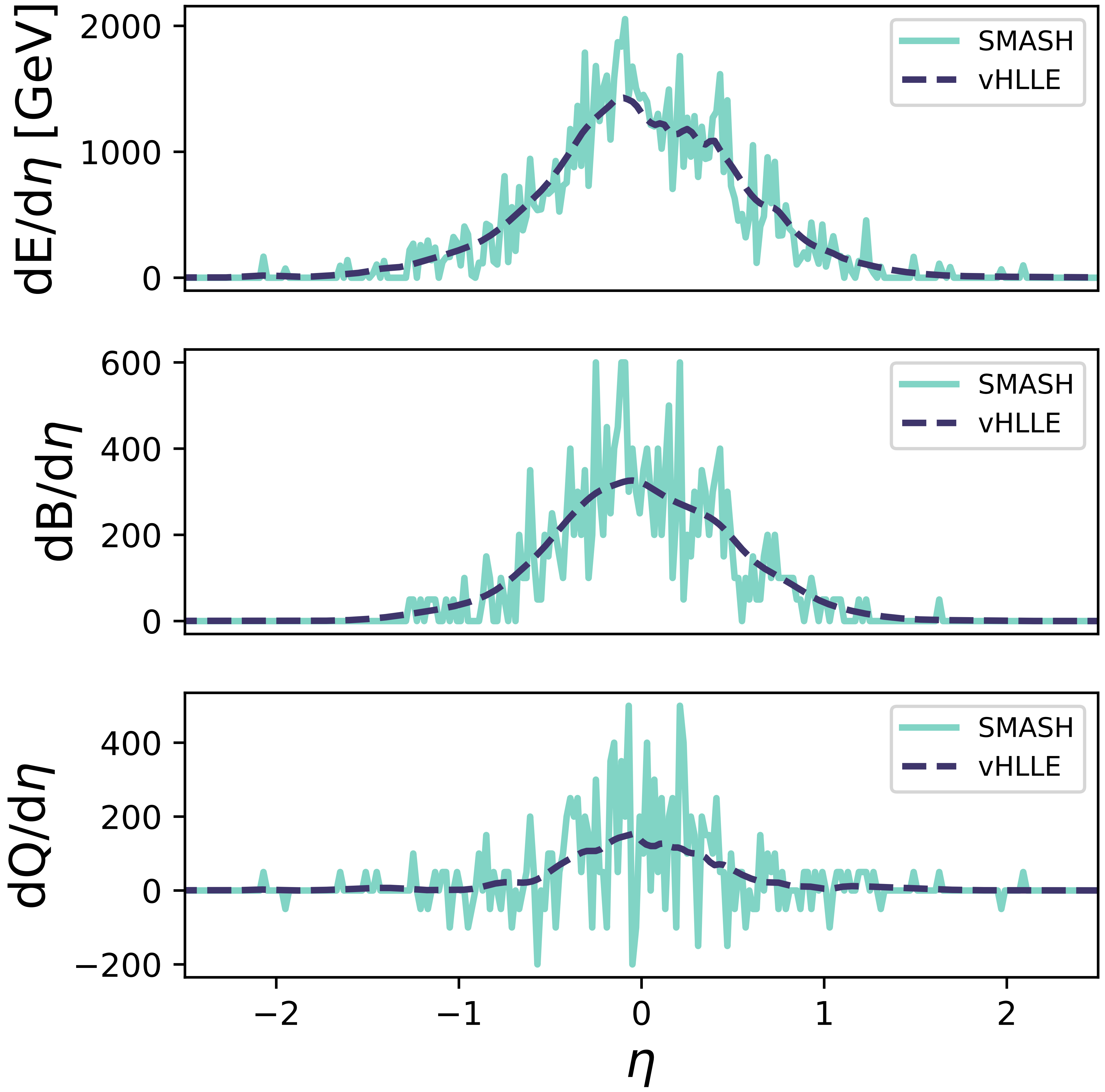
- Equation of state extracted for hadron resonance gas with SMASH degrees of freedom
- Mapping: $(e, n_\mathrm{B}, n_\mathrm{Q}) \rightarrow (T, p, \mu_\mathrm{B}, \mu_\mathrm{Q}, \mu_\mathrm{S})$
- Good agreement with Lattice QCD equation of state in (2+1)-flavour QCD
- SMASH HRG EoS is required as input for particlization of fluid elements in hybrid model



Schäfer et al.: 2109.08578

Bazavov et al.: PRD 90 (2014)

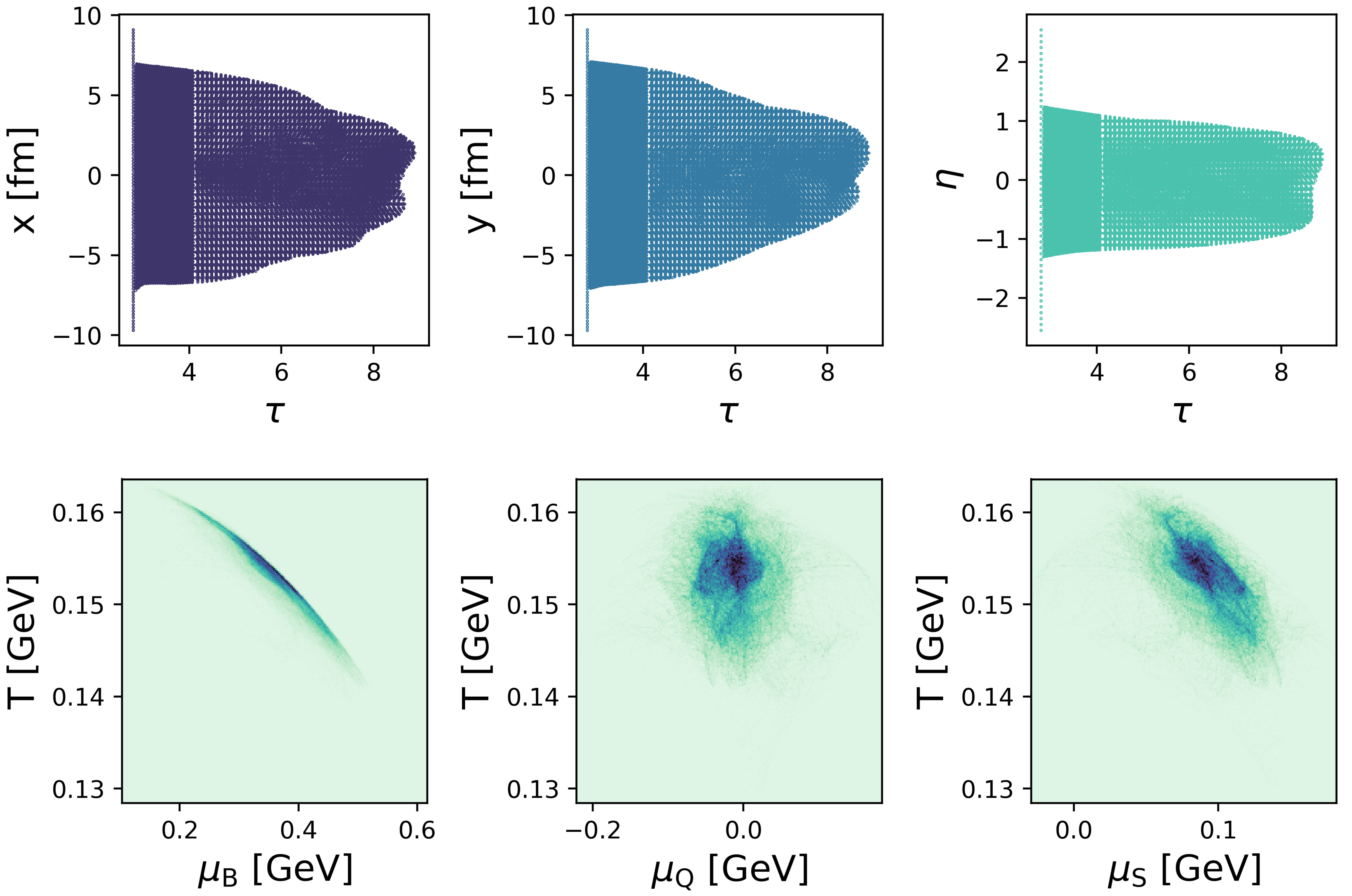
Sanity Checks at the Interfaces I



SMASH → vHLLE

- Example: Pb + Pb @ $\sqrt{s}$ = 8.8 GeV
  -> 1 single SMASH event
- Initial particle distributions on the SMASH τ_0-hypersurface are smeared with $R_\perp$, R_η
  -> smooth initial conditions for hydrodynamics
  -> prevention of shock waves
- Energy, baryon number and electric charge are conserved at initialization of hydrodynamics

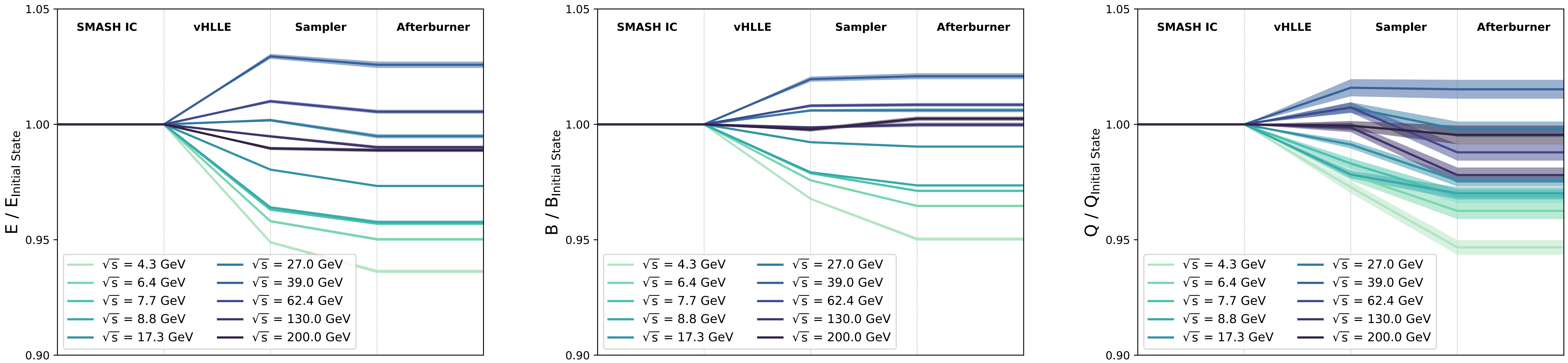
Sanity Checks at the Interfaces II



vHLLE → hadron-sampler

- Example:
  Pb + Pb @ $\sqrt{s}$ = 8.8 GeV
- Freezeout hypersurface is smooth and without holes
- Properties of fluid elements on the freezeout hypersurface correspond to hadron gas equation of state

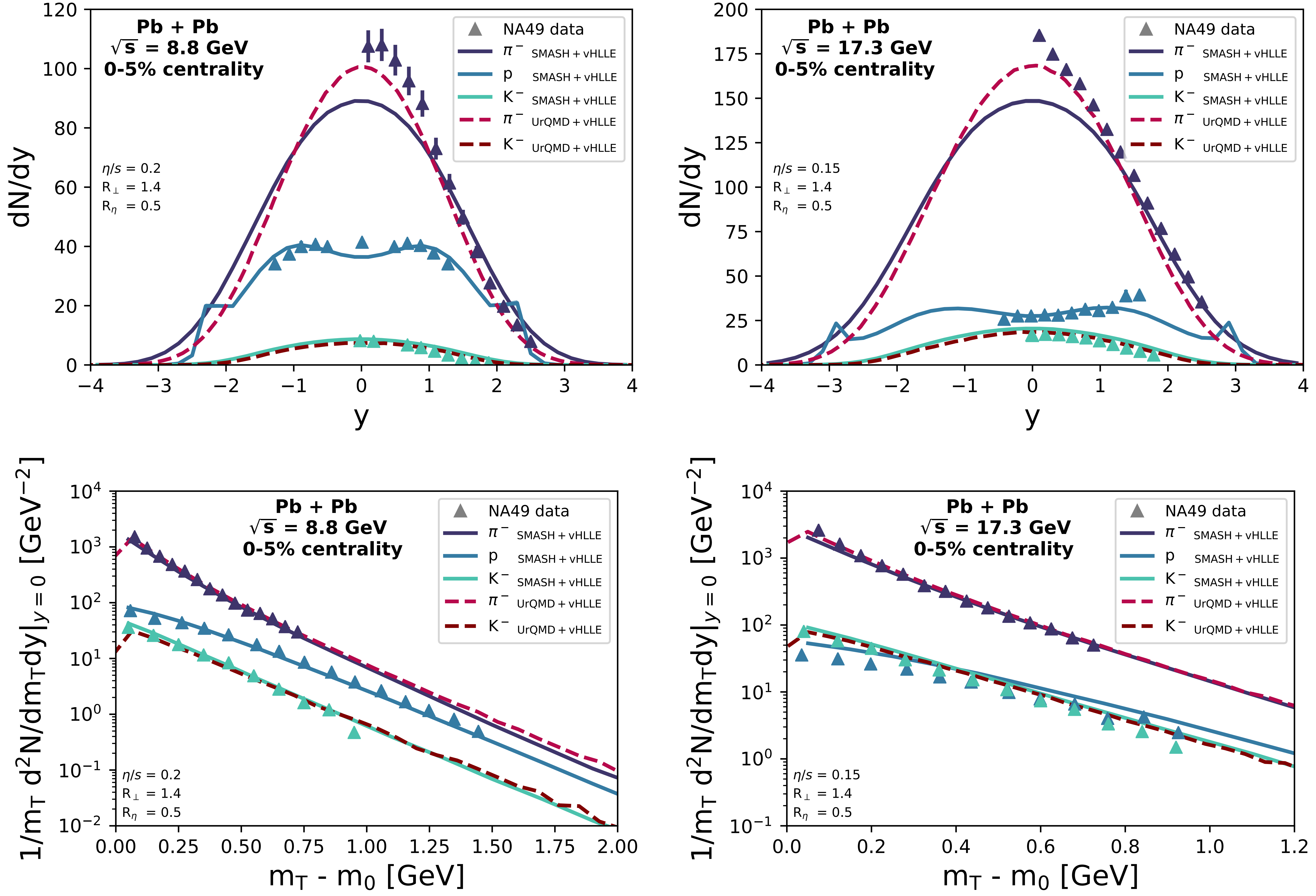
Global Quantum Number Conservation



- Energy, baryon number and electric charge are globally conserved in full SMASH-vHLLE-hybrid run
- Violations are of the order of < 7% for collisions ranging from $\sqrt{s}$ = 4.3 GeV to $\sqrt{s}$ = 200.0 GeV
- Energy, baryon number and electric charge gain and loss stem from finite grid effects in the hydrodynamic stage

Schäfer et al.: 2109.08578

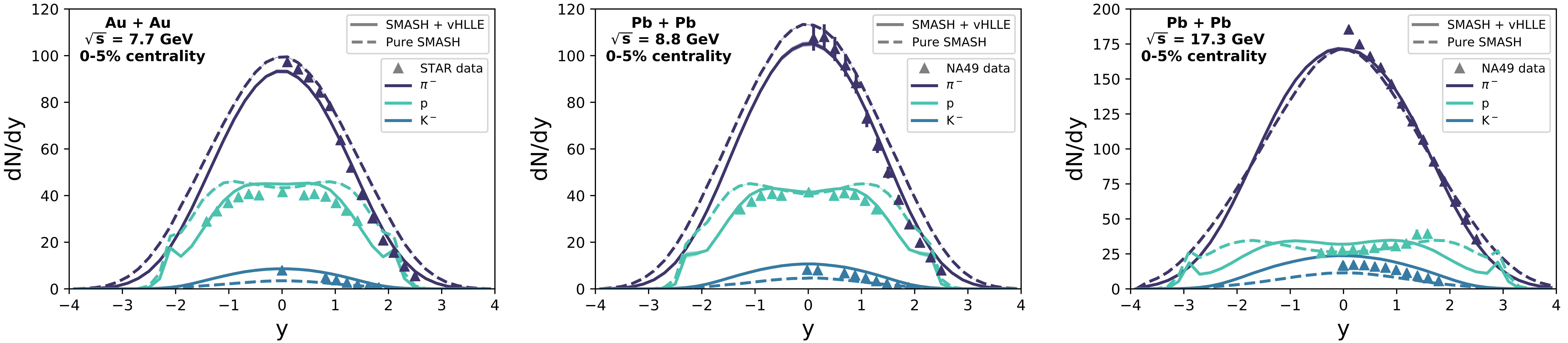
SMASH-vHLLE-hybrid vs. UrQMD-vHLLE-hybrid



- Identical values for η/s and smearing parameters in both setups
- dN/dy spectra and m_T spectra show differences for π^- and K^-
- Differences in particle spectra can be attributed to differences in the underlying evolution in the transport phase, originating from slightly different resonance dynamics

Karpenko et al.: Phys.Rev.C 91 (2015)

SMASH-vHLLE-hybrid vs. SMASH: dN/dy spectra

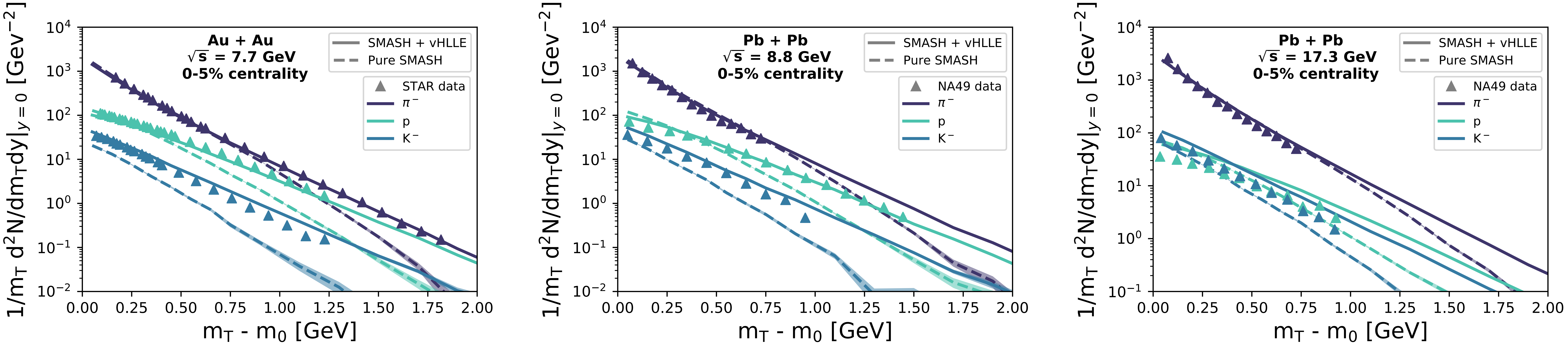


- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution …
  - -> Decreases pion production and enhances kaon production
  - -> Decreases width of proton rapidity distribution
  - -> Improves agreement with experimental data at intermediate collision energies

STAR Collaboration: Phys.Rev.C 96 (2017)

NA49 Collaboration: Phys.Rev.C 66 (2002)

SMASH-vHLLE-hybrid vs. SMASH: d^2N/dm_Tdy spectra



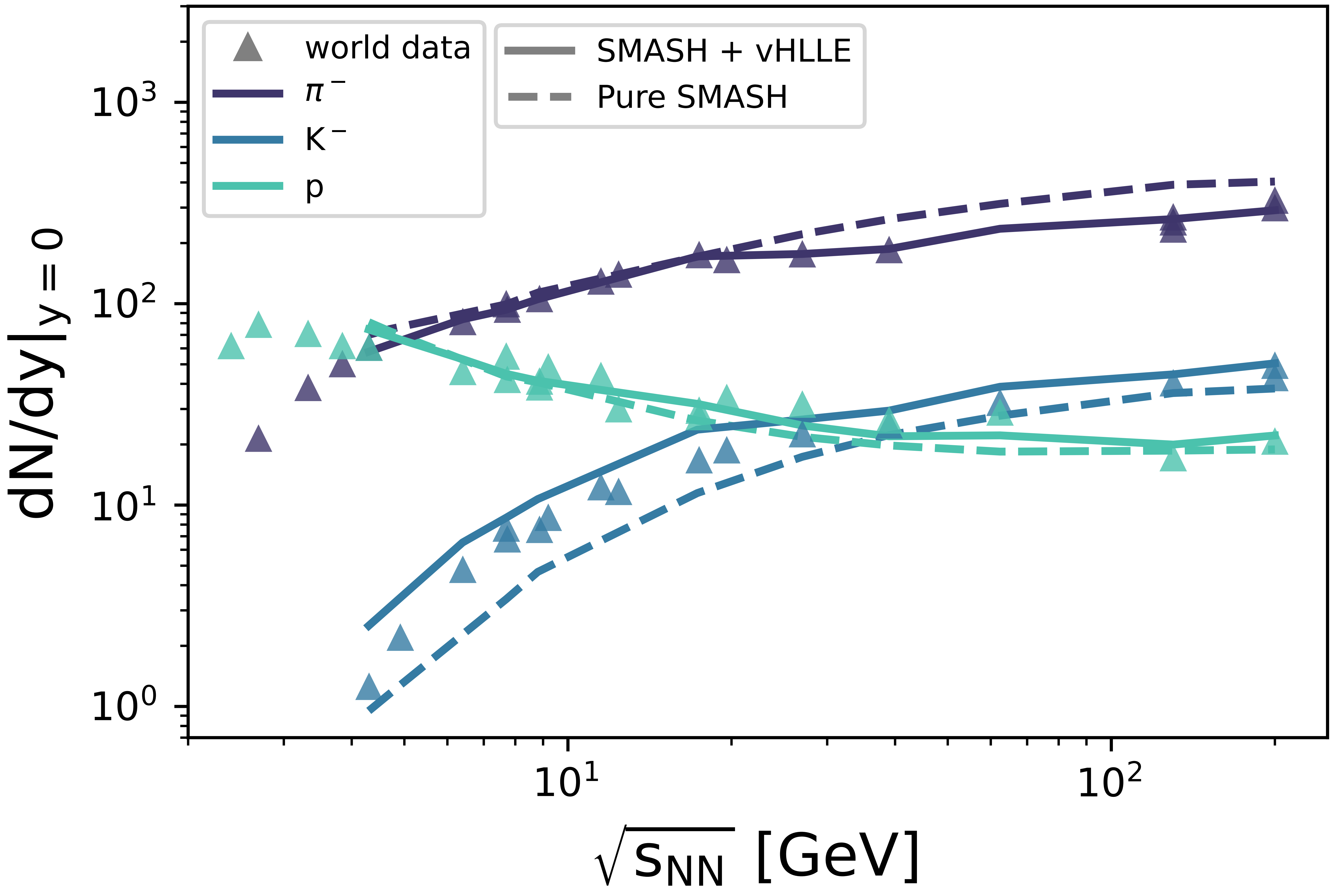
- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution …
  - -> Hardens the midrapidity dN/dm_T spectra of pions, kaons and protons
  - -> Improves agreement with experimental data at intermediate collision energies

STAR Collaboration: Phys.Rev.C 96 (2017)

NA49 Collaboration: Phys.Rev.C 66 (2002)

Excitation function: $dN/dy|_{y=0}$

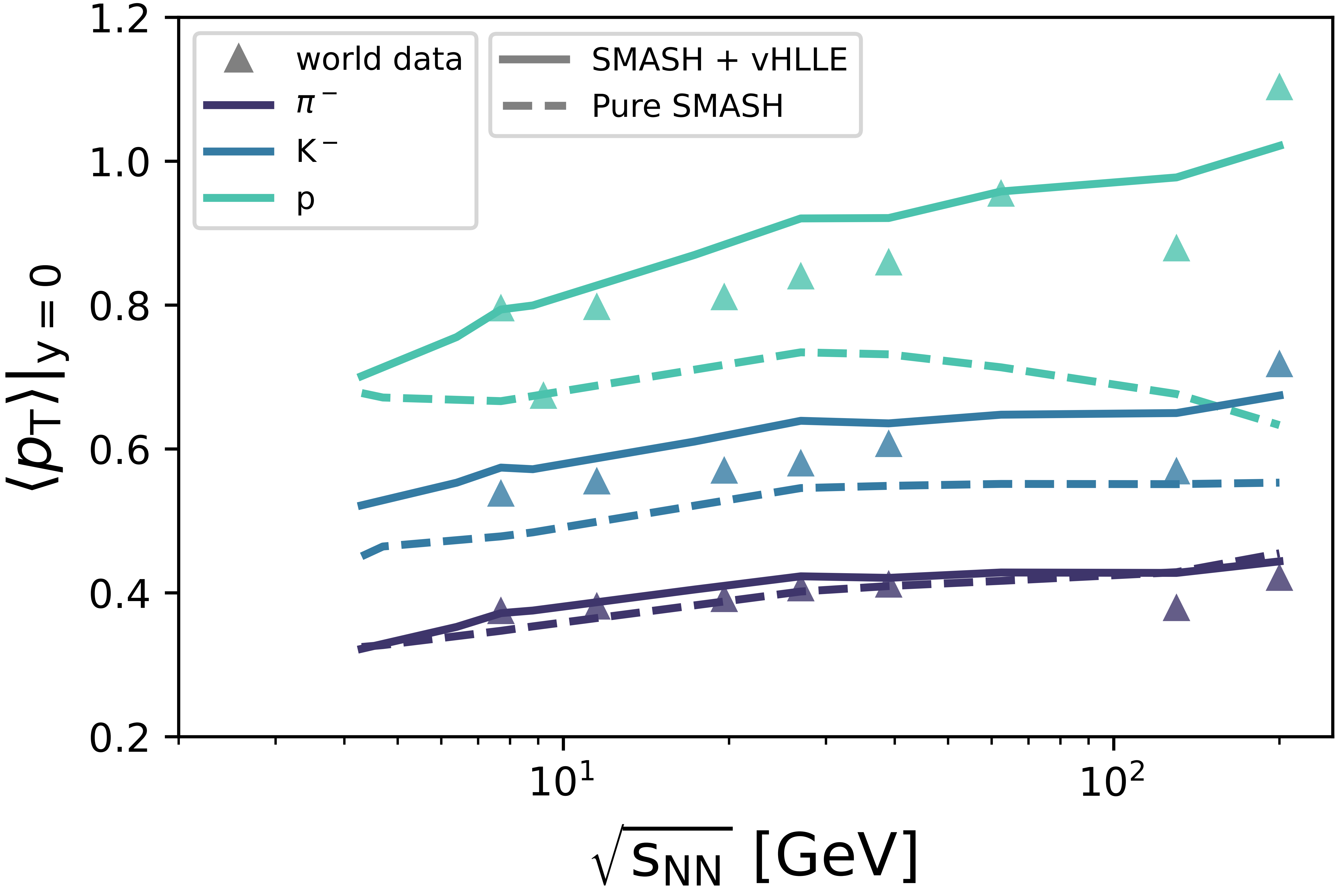
- Midrapidity yield excitation function of pions, kaons and protons between $\sqrt{s_{NN}}$ = 4.3 GeV and $\sqrt{s_{NN}}$ = 200.0 GeV
- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution improves the agreement with experimental data for pions and protons



Schäfer et al.: in preparation

Excitation function: <p_T>

- Mean transverse momentum excitation function of pions, kaons and protons between $\sqrt{s_{NN}}$ = 4.3 GeV and $\sqrt{s_{NN}}$ = 200.0 GeV
- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution improves the agreement with experimental data, especially for protons



Schäfer et al.: in preparation

The SMASH-vHLLE hybrid at RHIC/LHC energies

Oscar Garcia Montero, Fr. 10:45 AM:

“SMASH as an afterburner: Advances in the non-equilibrium hadronic evolution“

- SMASH-vHLLE-hybrid successfully applied in AuAu/PbPb collisions up to $\sqrt{s}$ = 5.02 TeV
- Study annihilation and regeneration of (anti-)protons and (anti-) baryons across a wide range of energies and centralities
- Stay tuned for tomorrow!

Garcia Montero et al.: 2107.08812

Summary

- Novel hybrid model for heavy-ion collisions at intermediate and high-energy collisions presented
  - Available at https://github.com/smash-transport/smash-vhlle-hybrid
- Different validations of the smash-vHLLE-hybrid successfully performed
- dN/dy and m_T spectra for protons, pions and kaons in good agreement with experimental data across a wide range of collision energies
- Excitation function for $dN/dy|_{y=0}$ and $\langle p_T \rangle$ in decent agreement with experimental data

Outlook

- Extension by more dynamical initial conditions
  - More accurate description of collisions at FAIR/NICA/NA61(SHINE) energies
- Investigate additional observables (anisotropic flow, horn, kink, step …)
- Systematically study the effects of different equations of state for the hydrodynamical evolution
- Extensions by electromagnetic probes: Study photon and dilepton production

And now? Where can I get it?

SMASH-vHLLE-hybrid and all submodules are open-source and publicly available on Github:

- SMASH-vHLLE-hybrid: https://github.com/smash-transport/smash-vhlle-hybrid
- SMASH: https://github.com/smash-transport/smash
- vHLLE: https://github.com/yukarpenko/vhlle
- vHLLE: https://github.com/yukarpenko/vhlle_params
- SMASH hadron sampler: https://github.com/smash-transport/smash-hadron-sampler

BACKUP

Smearing Parameters: SMASH-vHLLE-hybrid vs. UrQMD-vHLLE-hybrid

SMASH-vHLLE-hybrid

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UrQMD-vHLLE-hybrid

System	$\sqrt{s}$	η/s	$R_\perp$	R_η
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Pb + Pb	8.8 GeV	0.2	1.4	0.5
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SMASH

Weil et al.: Phys. Rev. C 94 (2016)

- Simulating Many Accelerated Strongly-interacting Hadrons
- Description of low-energy heavy-ion collisions (GSI-FAIR energies) and late, dilute stages of high-energy heavy-ion collisions
- Open source C++ project developed with modern tools (git, doxygen, continuous integration, ...)
- Goal:
  Standard reference with hadronic vacuum properties

smash

http://smash-transport.github.io

SMASH

Weil et al.: Phys. Rev. C 94 (2016)

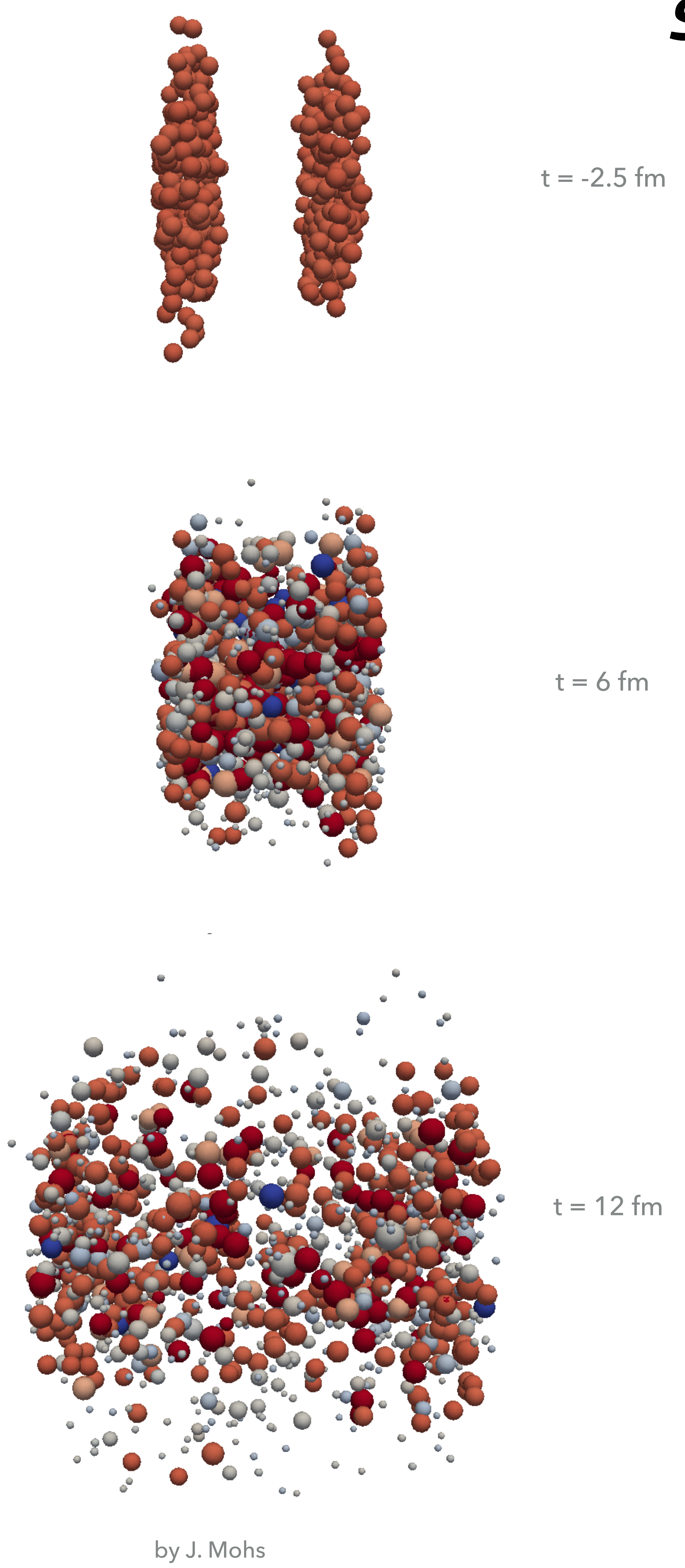
- Degrees of freedom:
  All well-established hadrons listed by the PDG up to mass of
  M ≈ 2.35 GeV

- Effective solution of relativistic Boltzmann equation

$$p_\mu \, \partial^\mu f + m \, \partial_{p_\mu} (F^\mu f) \;=\; C(f)$$

- Collision integral modeled through formations and decays of hadronic resonances

- Geometric collision criterion: $d_{\mathrm{coll}} < \sqrt{\frac{\sigma_{\mathrm{tot}}}{\pi}}$

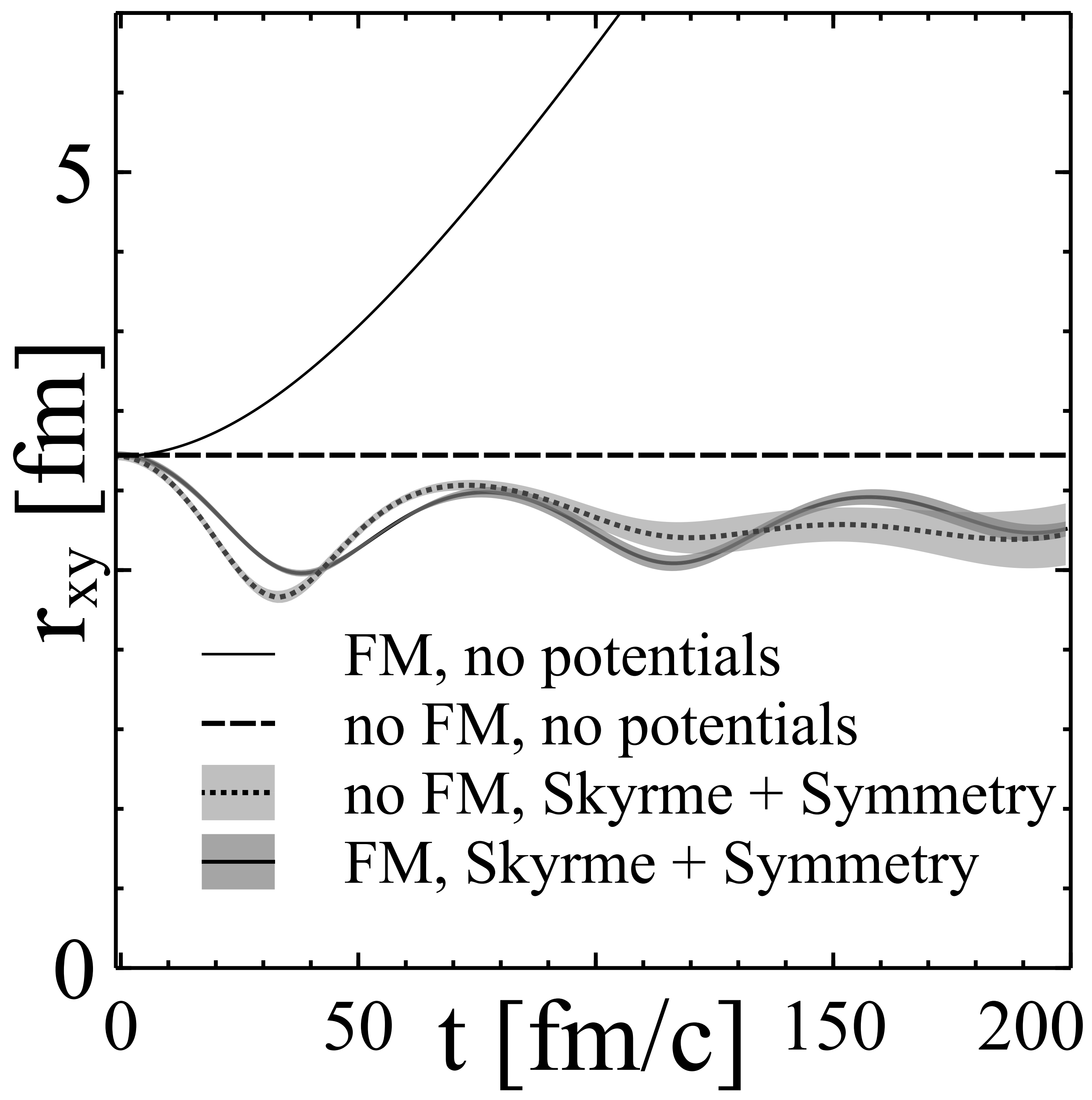


Pb-Pb @ E_{lab} = 40 AGeV

SMASH

Weil et al.: Phys. Rev. C 94 (2016)

- Conservation of Detailed Balance:
  - Multi-particle decays modeled by intermediate resonances
- Test particle method for mean-field potentials
  - $\sigma \rightarrow \sigma / N_{test}$ $N \rightarrow N \cdot N_{test}$
- String fragmentation by means of Pythia in high-energy region
- Photons and dileptons produced perturbatively
- Analysis Suite:
  - http://theory.gsi.de/~smash/analysis_suite/current/
  - https://github.com/smash-transport/smash-analysis



SMASH Degrees of Freedom

smash

N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^{-}_{1672}	π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^{-}_{2250}	π_{1300}	$f_{0\ 1370}$	$f_{2\ 1525}'$		K^{*}_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^{*}_{1410}
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_{0}^{*}{}_{1430}$
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_{2}^{*}{}_{1430}$
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\ 1285}$		K^{*}_{1680}
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}			η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
N_{1720}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K_{3}^{*}{}_{1780}$
N_{1875}		Λ_{1890}				σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
N_{1900}		Λ_{2100}					$h_{1\ 1170}$			$K_{4}^{*}{}_{2045}$
N_{1990}		Λ_{2110}				ρ_{776}		$\pi_{1\ 1400}$		
N_{2060}		Λ_{2350}				ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
N_{2080}						ρ_{1700}				
N_{2100}							$a_{1\ 1260}$	$\eta_{2\ 1645}$		
N_{2120}						ω_{783}				
N_{2190}						ω_{1420}		$\omega_{3\ 1670}$		
N_{2220}						ω_{1650}				
N_{2250}										

As of SMASH-1.7

- + corresponding antiparticles
- Perturbative treatment of photons and dileptons
- Isospin symmetry