Probing longitudinal dynamics in isobar collisions with a hybrid approach

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in collaboration with Iurii Karpenko and Hannah Elfner

AS, Iurii Karpenko, Xiang-Yu Wu, Jan Hammelmann, Hannah Elfner: arXiv: 2112.08724

Stiftung Polytechnische Gesellschaft Frankfurt am Main

CRC-TR 211 Strong-interaction matter under extreme conditions

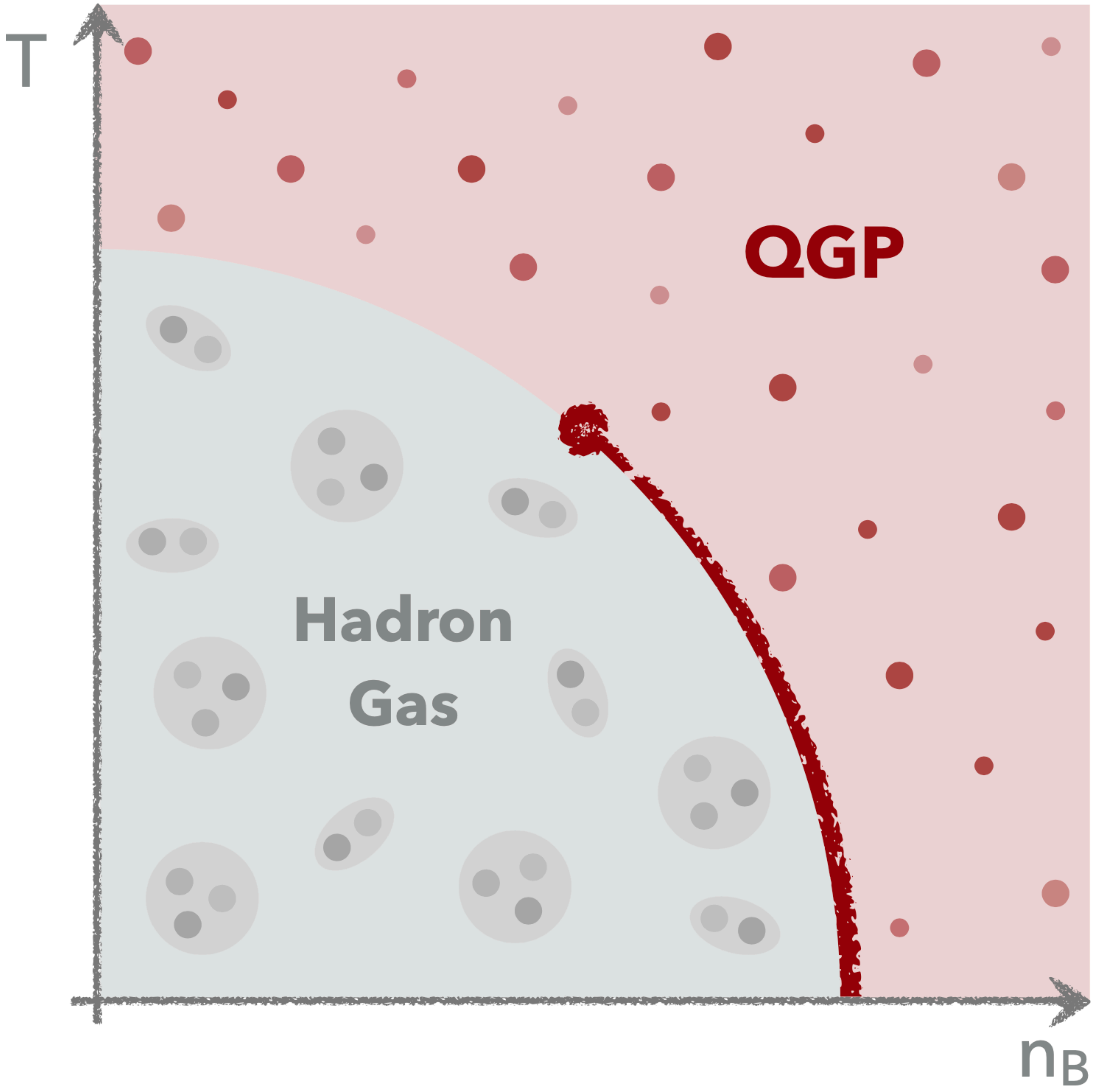
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

GSI

FIAS Frankfurt Institute for Advanced Studies

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

Exploring the QCD phase diagram



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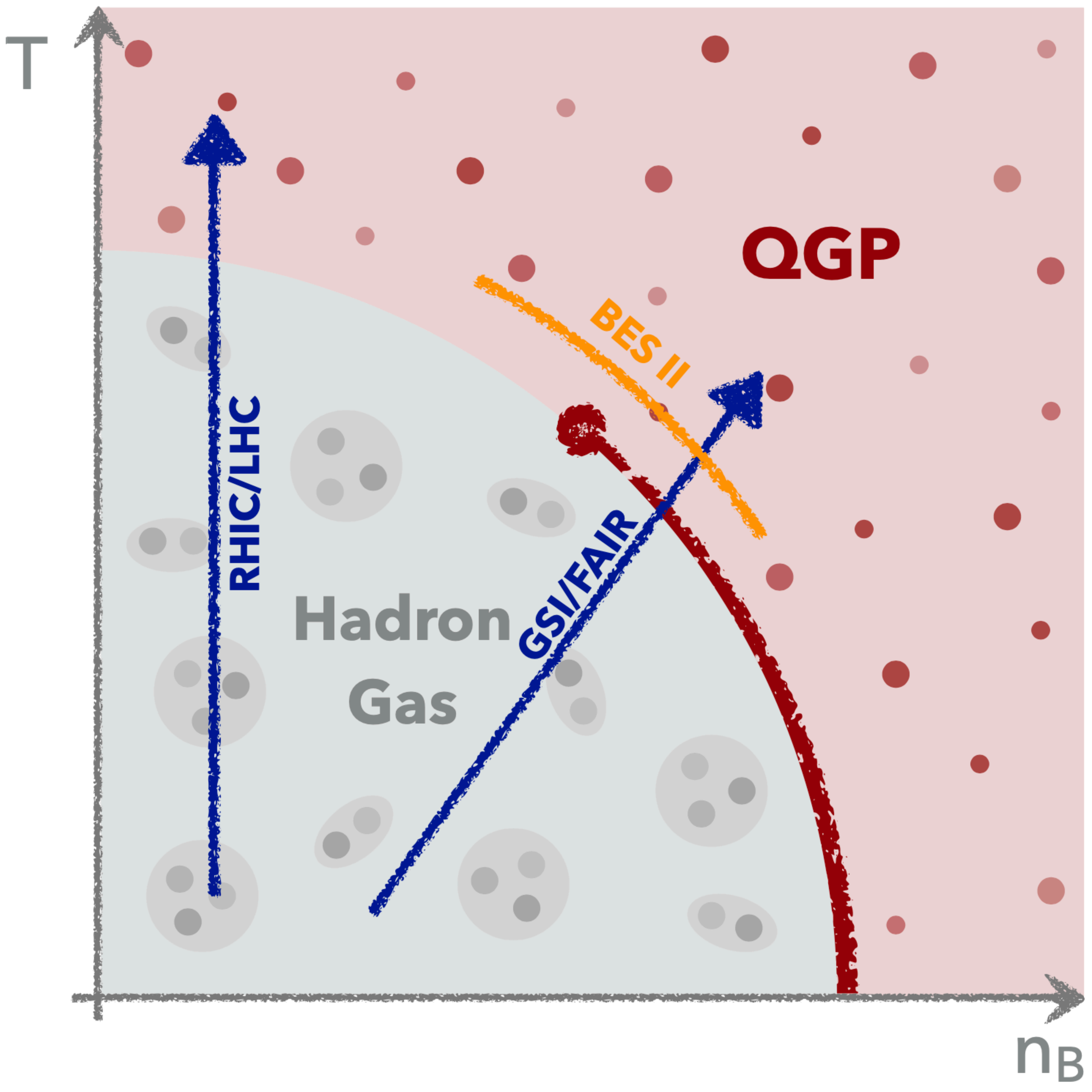
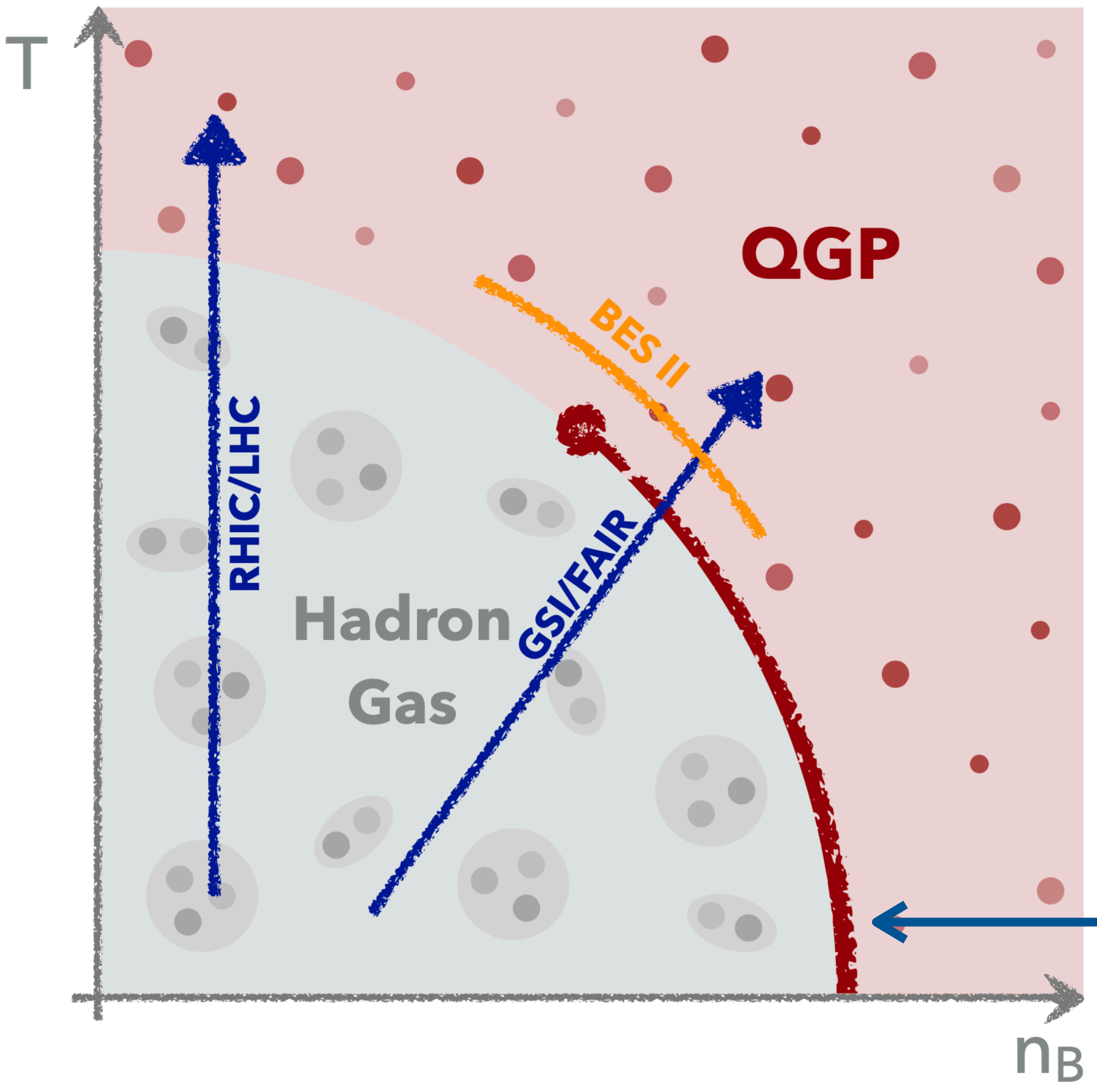
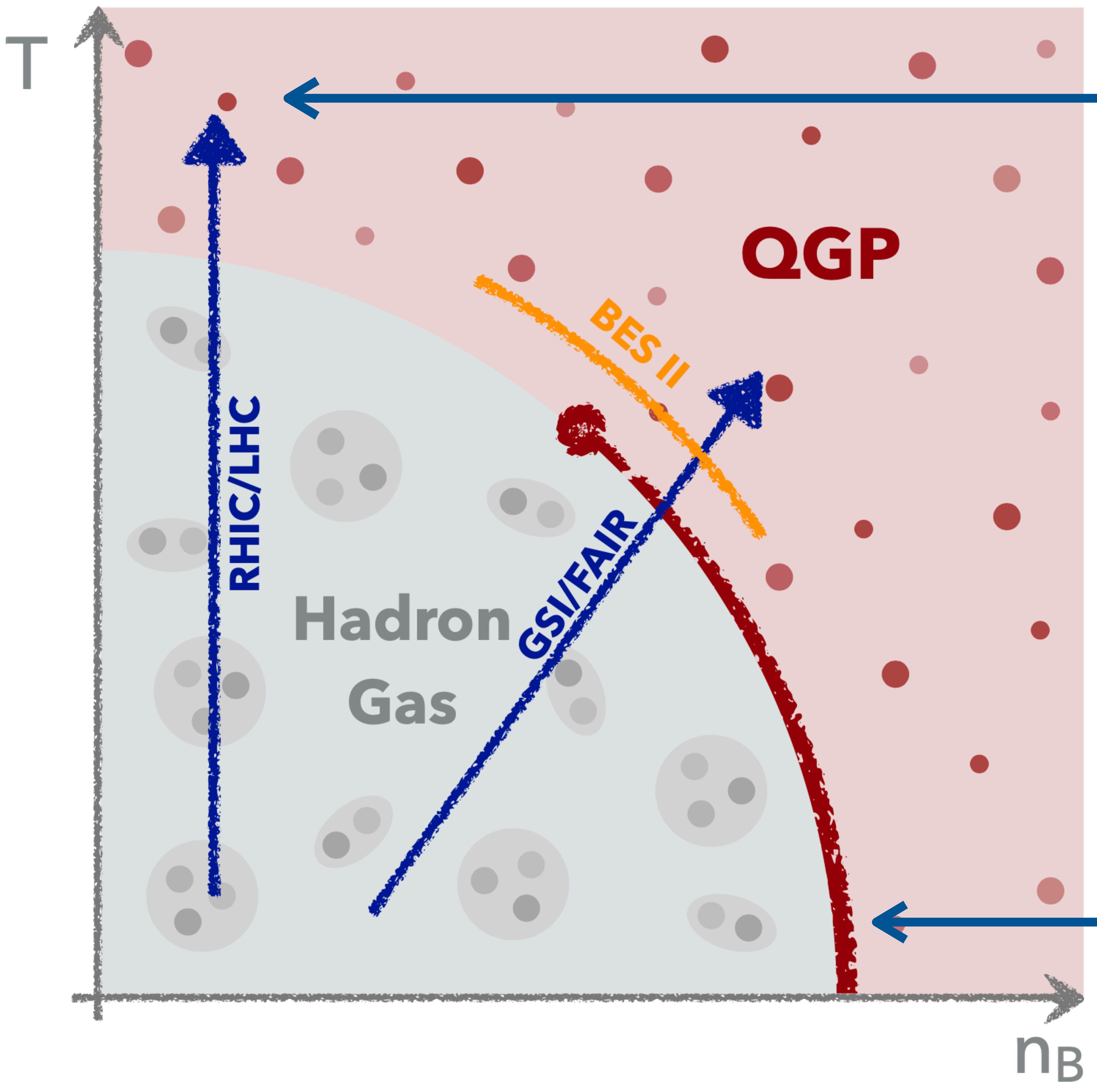


Exploring the QCD phase diagram



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

Exploring the QCD phase diagram



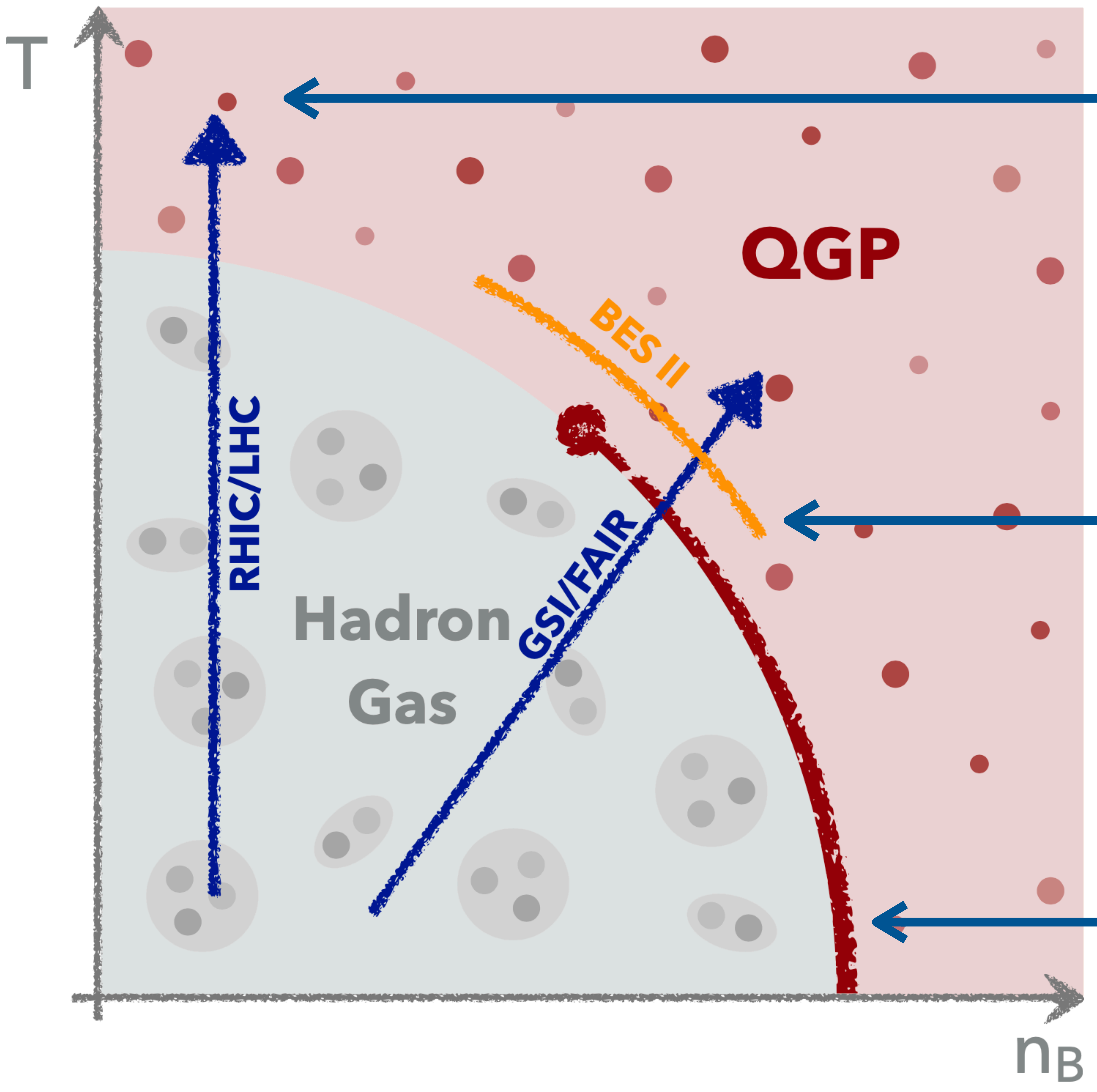
Standard description at high collision energies:

- 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

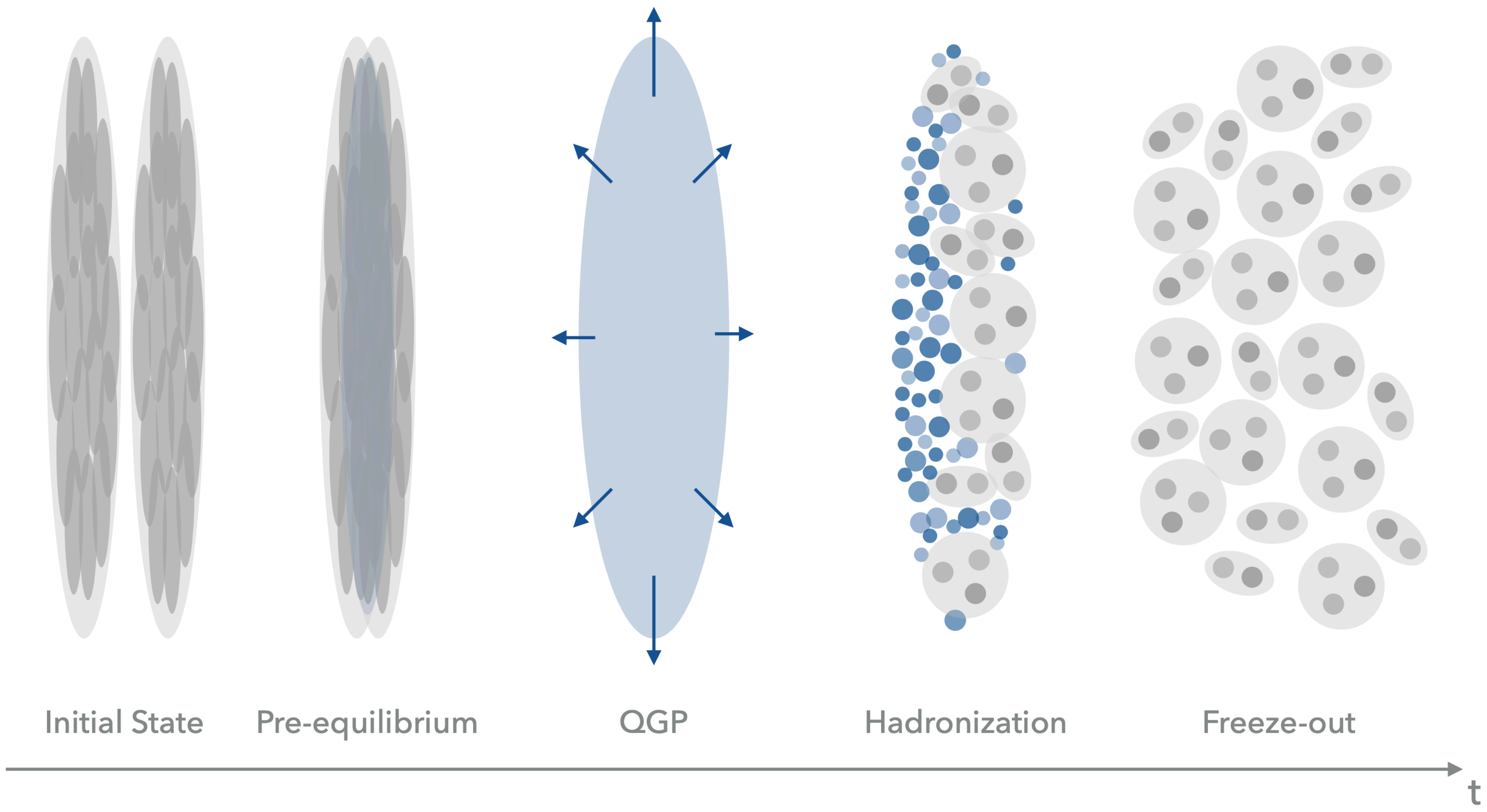
Standard description at intermediate collision energies:

- ?
- Intermediate collision energies remain a challenge
- Hybrid approaches with dynamical initial conditions?

Standard description at low collision energies:

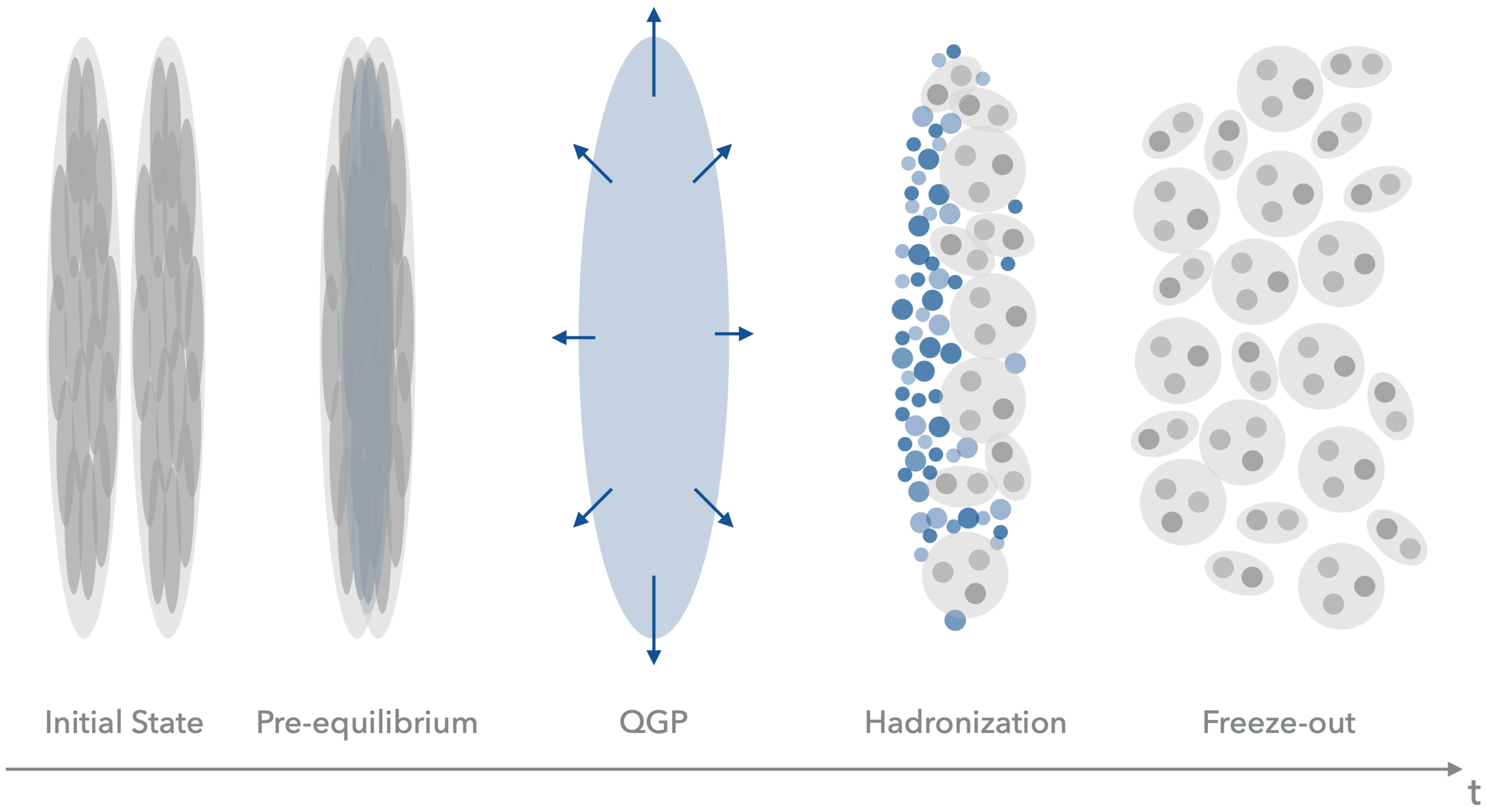
- Hadronic transport approaches
- Resonance dynamics and nuclear potentials

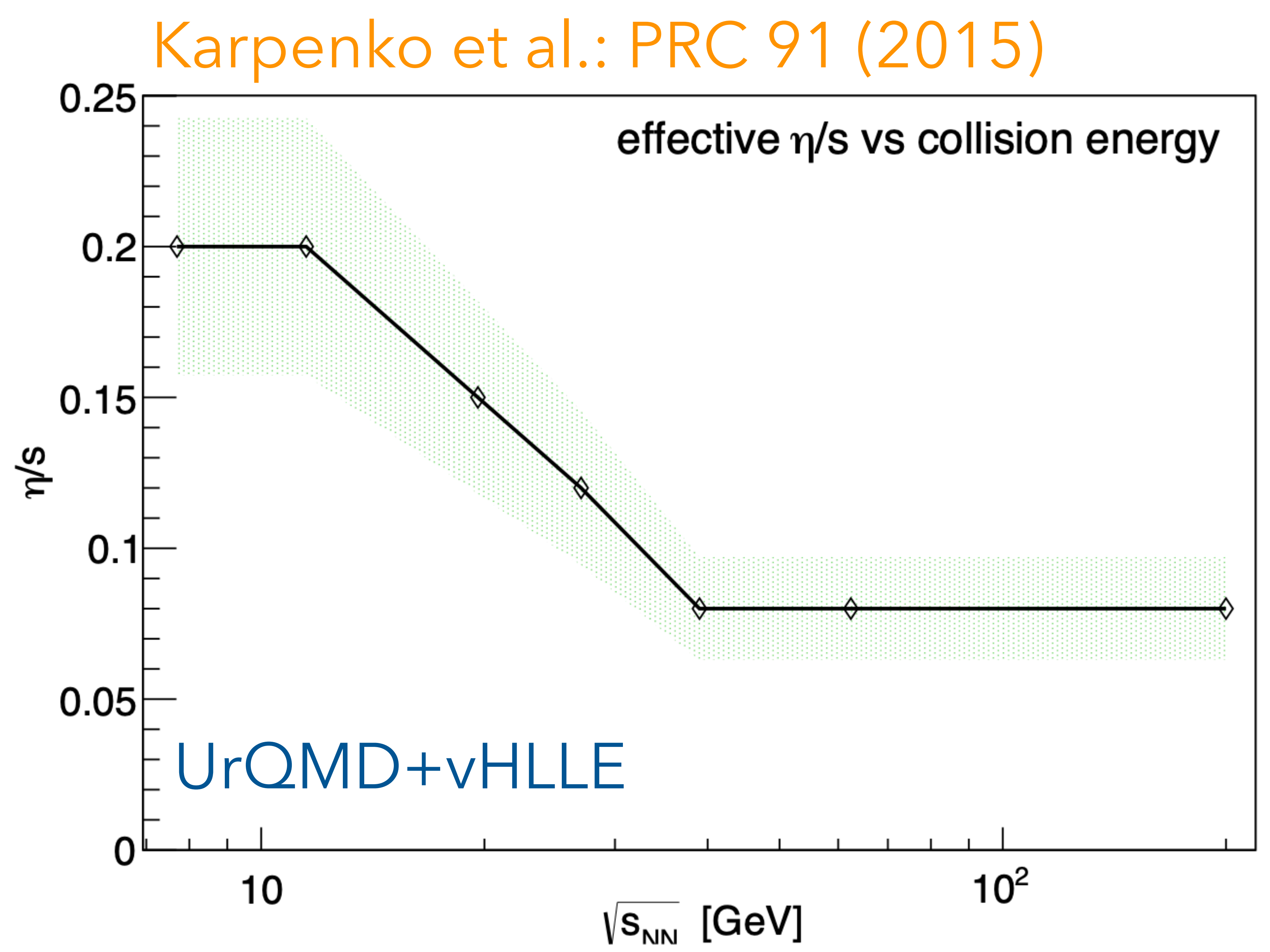
Hybrid Approaches at Intermediate Collision Energies



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 …

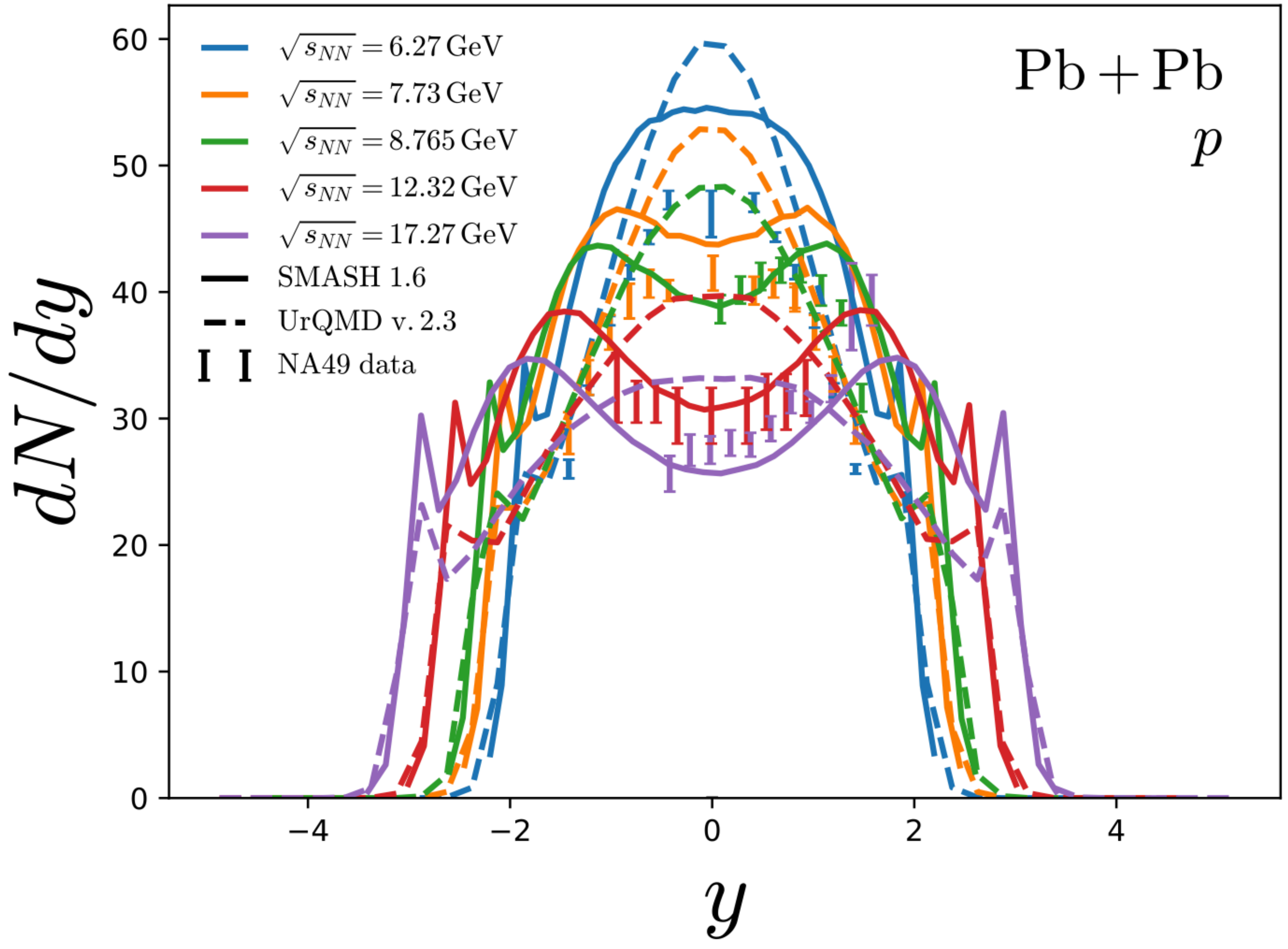
Karpenko et al.: PRC 91 (2015) Akamatsu et al.: PRC 98 (2018) Du et al.: Comp.Phys.Com. 251 (2020) Nandi et al.: PRC 102 (2020)

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

AS et al., arXiv: 2112.08724
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)

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

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	$\sqrt{s}$	η/s	$R_\perp$	R_η
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	0.5
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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

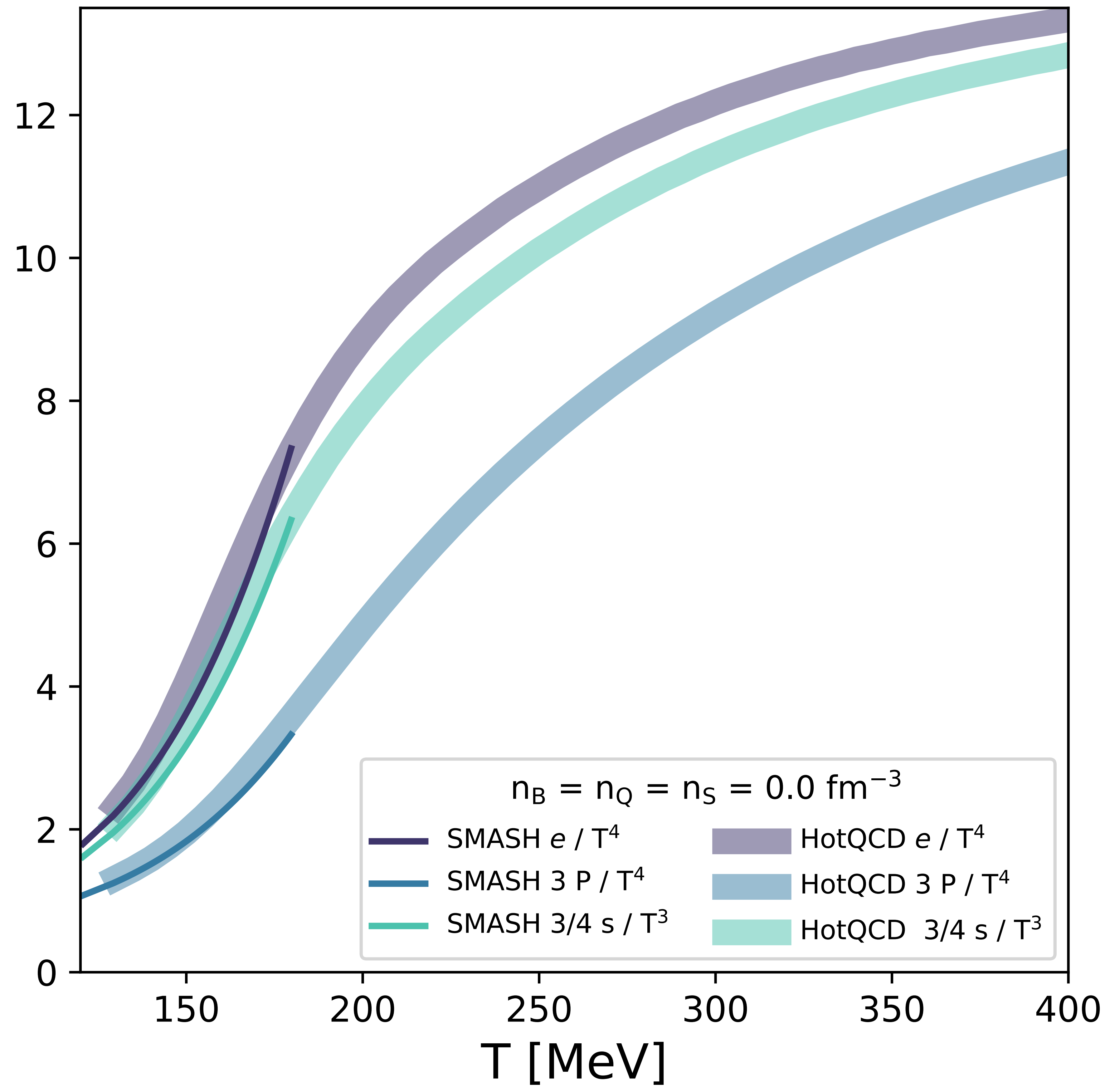
$R_\perp$, R_η: transverse and longitudinal smearing parameter

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

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: $(e, n_\mathrm{B}, n_\mathrm{Q}) \to (T, p, \mu_\mathrm{B}, \mu_\mathrm{Q}, \mu_\mathrm{S})$
- 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
- https://github.com/smash-transport/smash-HRG-EoS



AS et al., arXiv: 2109.08578

AS et al., arXiv: 2112.08724

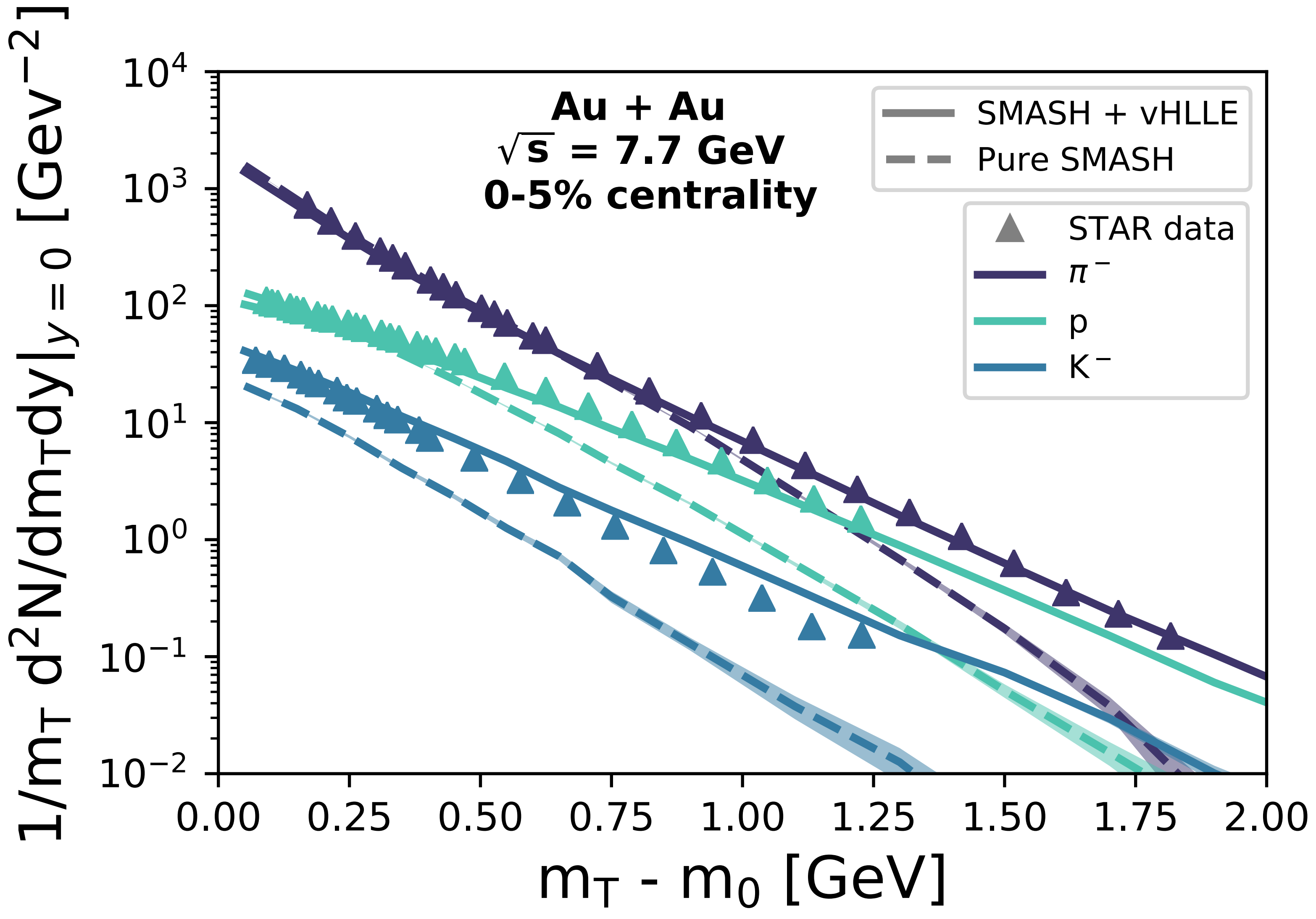
Bazavov et al.: PRD 90 (2014)

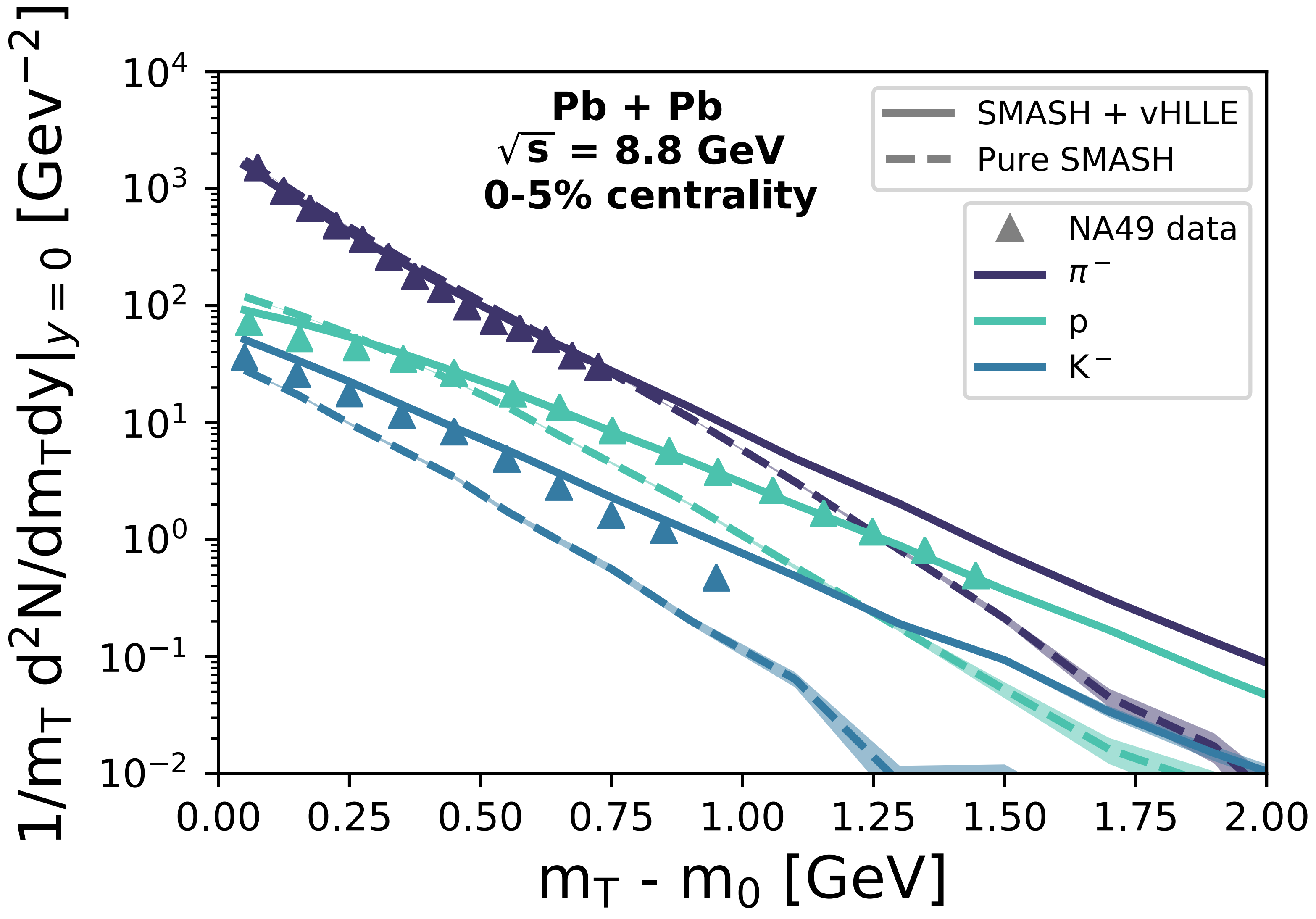
SMASH-vHLLE-hybrid vs. SMASH: dN/dy spectra

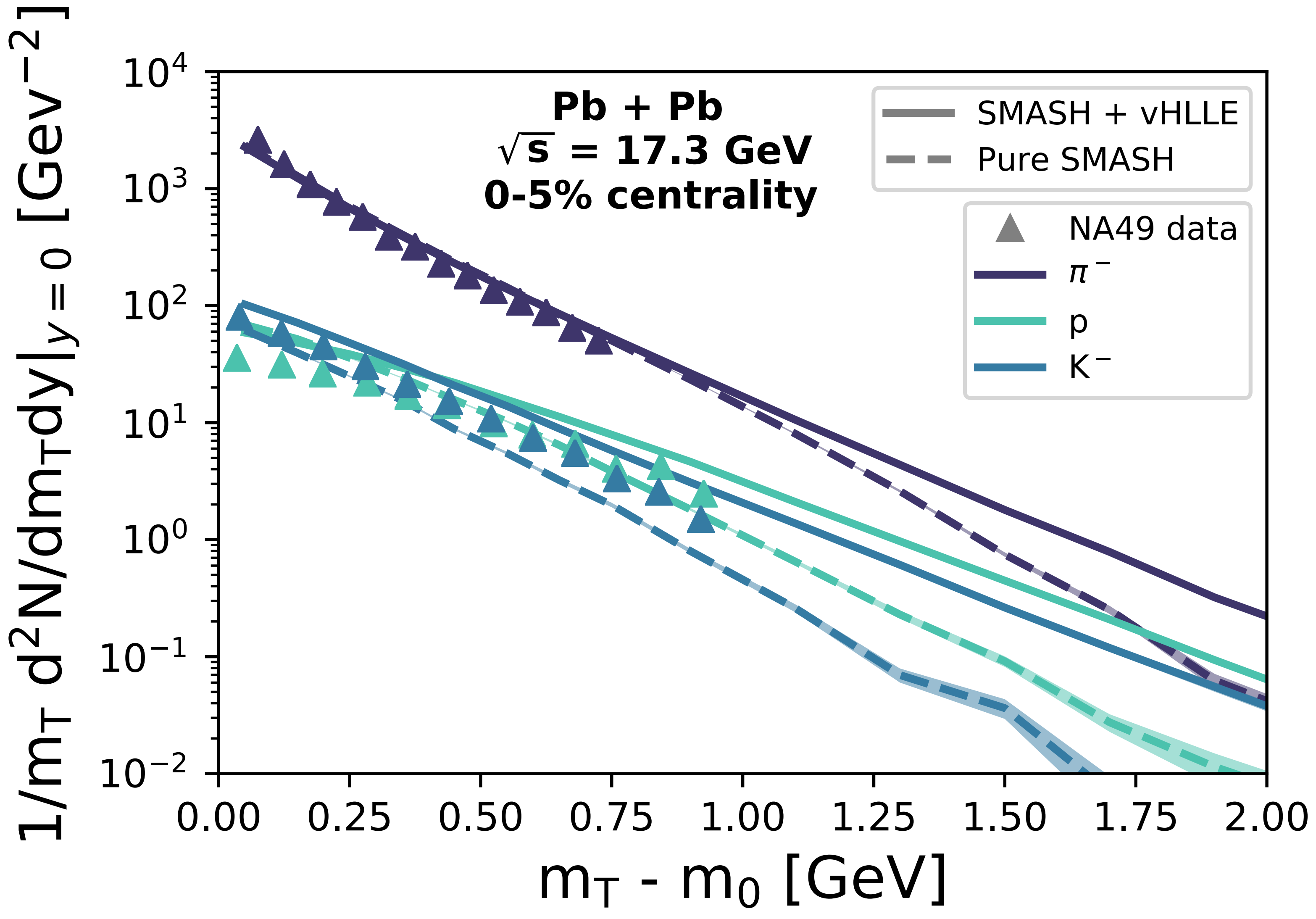
- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution …
  - -> Decreases pion production and enhances kaon production
  - -> Decreases width of proton rapidity distribution
  - -> Improves agreement with experimental data at intermediate collision energies

STAR Collaboration: Phys.Rev.C 96 (2017) AS et al., arXiv: 2112.08724 NA49 Collaboration: Phys.Rev.C 66 (2002)

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





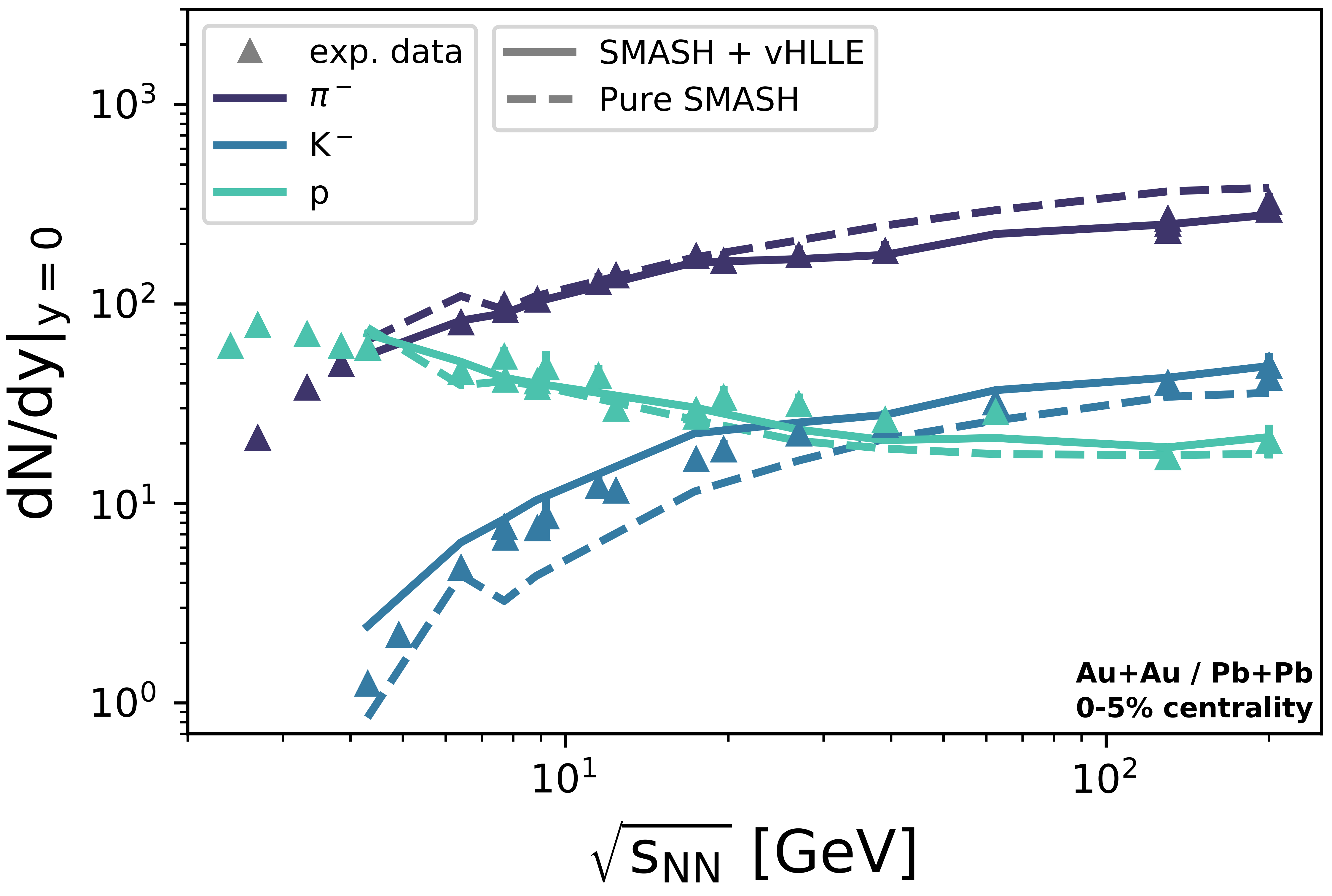


- Application of SMASH-vHLLE-hybrid instead of pure SMASH evolution ...
  - -> Hardens the midrapidity dN/dm_T spectra of pions, kaons and protons
  - -> Improves the agreement with experimental data at intermediate collision energies

STAR Collaboration: Phys.Rev.C 96 (2017)   AS et al., arXiv: 2112.08724   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

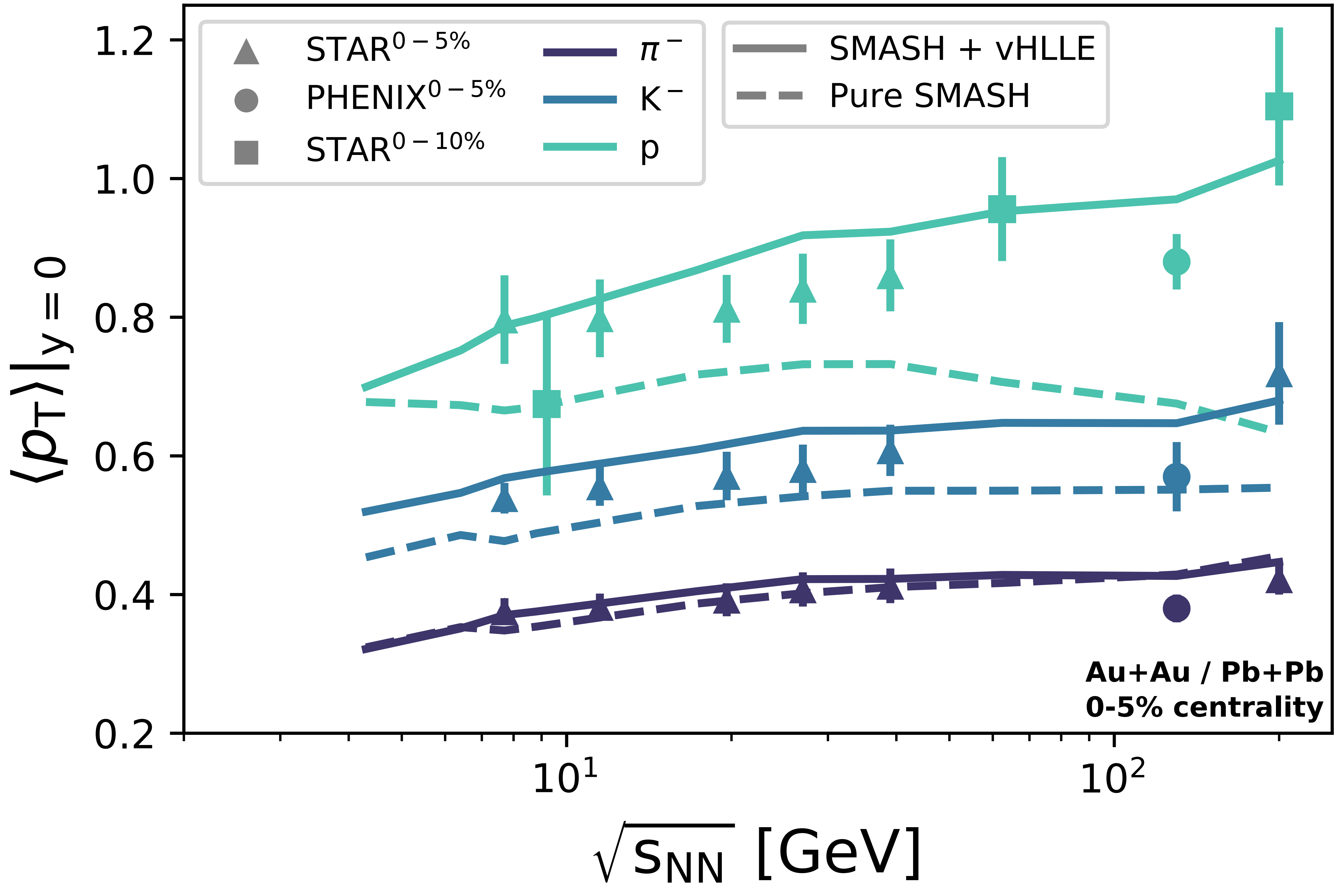


AS et al., arXiv: 2112.08724

E895: Phys.Rev.C 68 (2003) 054905
E866: Phys.Lett.B 490 (2000) 53-60
E895: Phys.Rev.Lett. 88 (2002) 102301
PHENIX: Phys.Rev.C 69 (2004) 024904
NA49: Phys.Rev.C 83 (2011) 014901
NA49: Phys.Rev.C 73 (2006) 044910
NA49: Phys.Rev.C 66 (2002) 054902
STAR: Phys.Rev.C 96 (2017) 4, 044904
STAR: Phys.Rev.C 81 (2010) 024911
STAR: Phys.Rev.Lett. 92 (2004) 112301
BRAHMS: J.Phys.G 30 (2004) S85-S92
BRAHMS: Nucl.Phys.A 715 (2003) 478-481

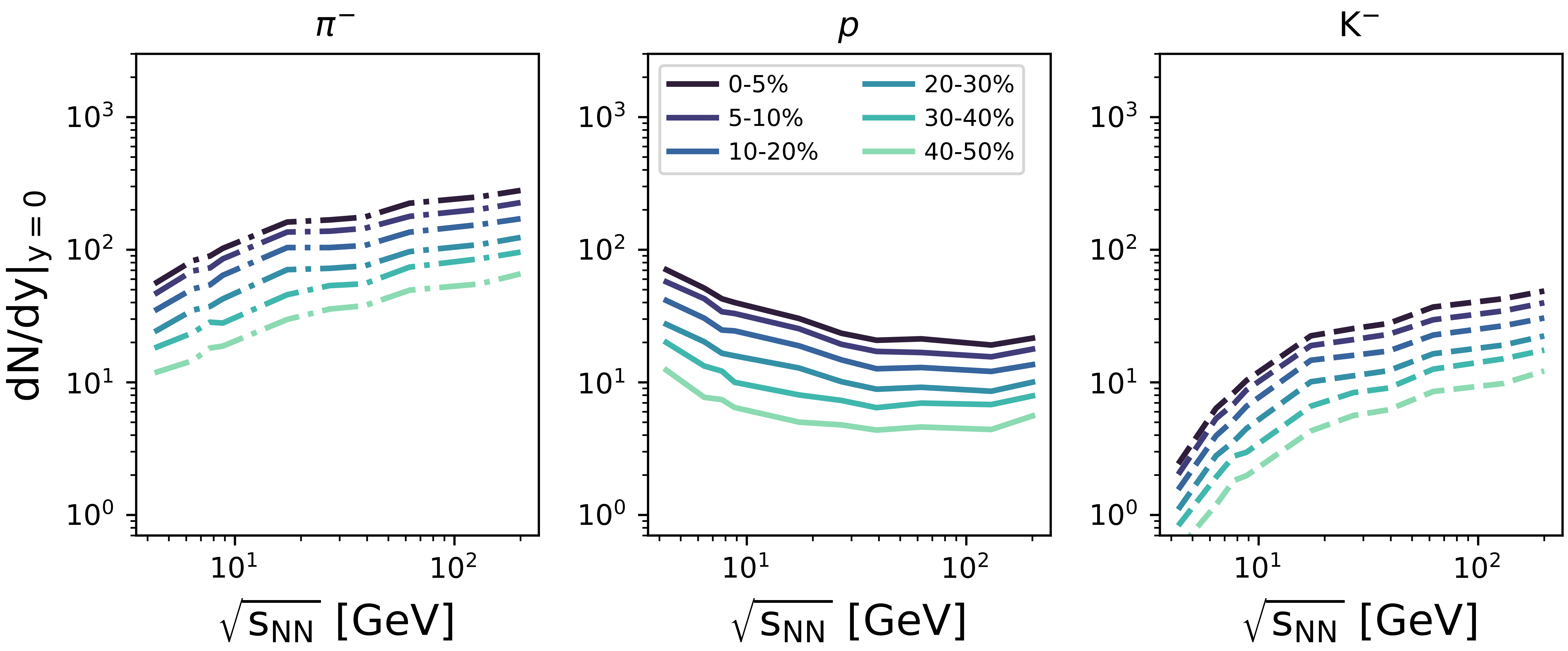
Excitation Function: <p_T>

- 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



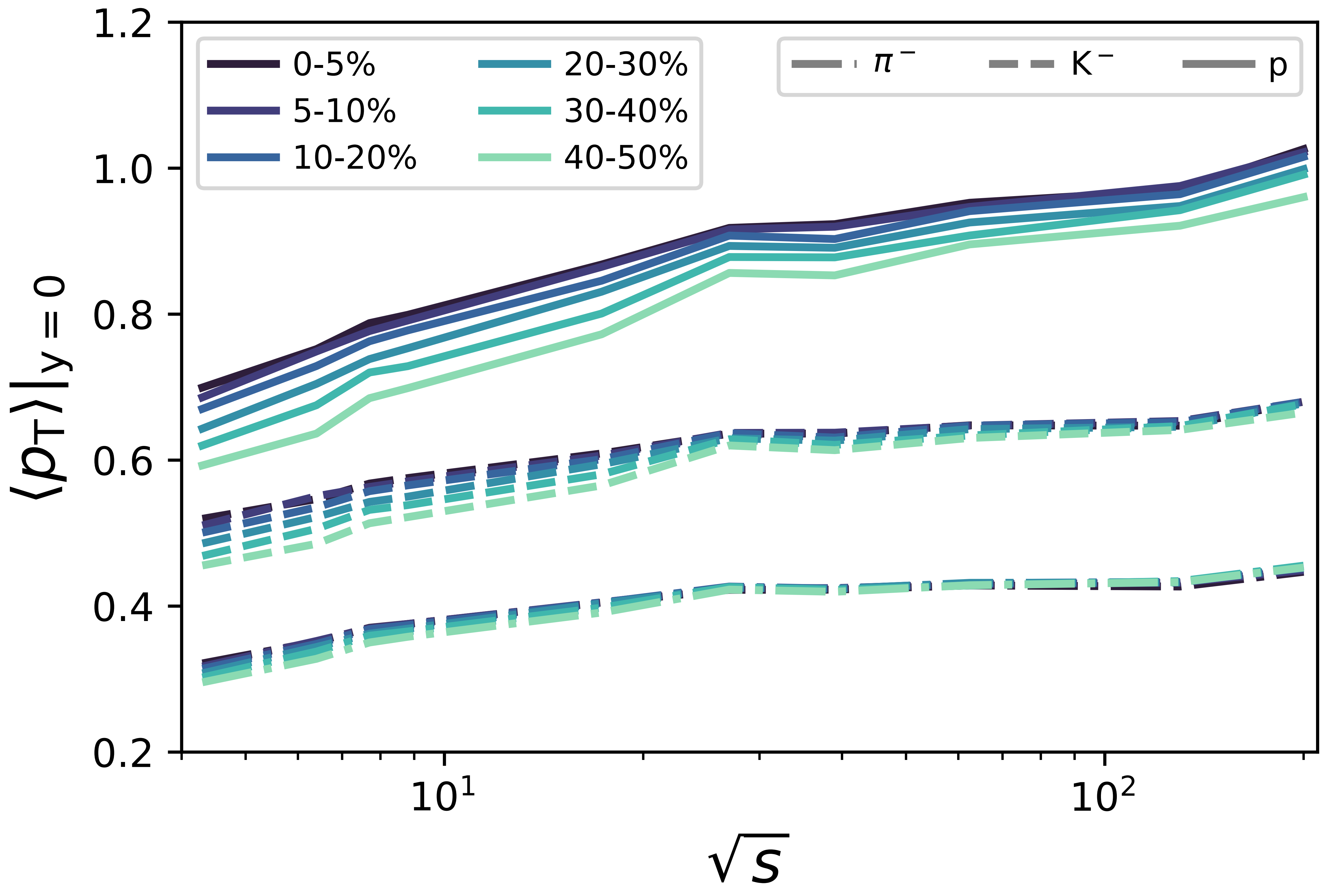
STAR: Phys.Rev.C 96 (2017) 4, 044904
PHENIX: Phys.Rev.C 69 (2004) 024904
AS et al., arXiv: 2112.08724
STAR: Phys.Rev.C 81 (2010) 024911
STAR: Phys.Rev.Lett. 92 (2004) 112301

Centrality dependence: $dN/dy|_{y=0}$ Excitation Function



- Mid-rapidity yield excitation function of pions, kaons, and protons between $\sqrt{s_{NN}}$ = 4.3 GeV and $\sqrt{s_{NN}}$ = 200.0 GeV for different centralities
- Centrality dependence is small, yield decreases continuously with rising centralities

Centrality dependence: <p_T> Excitation Function

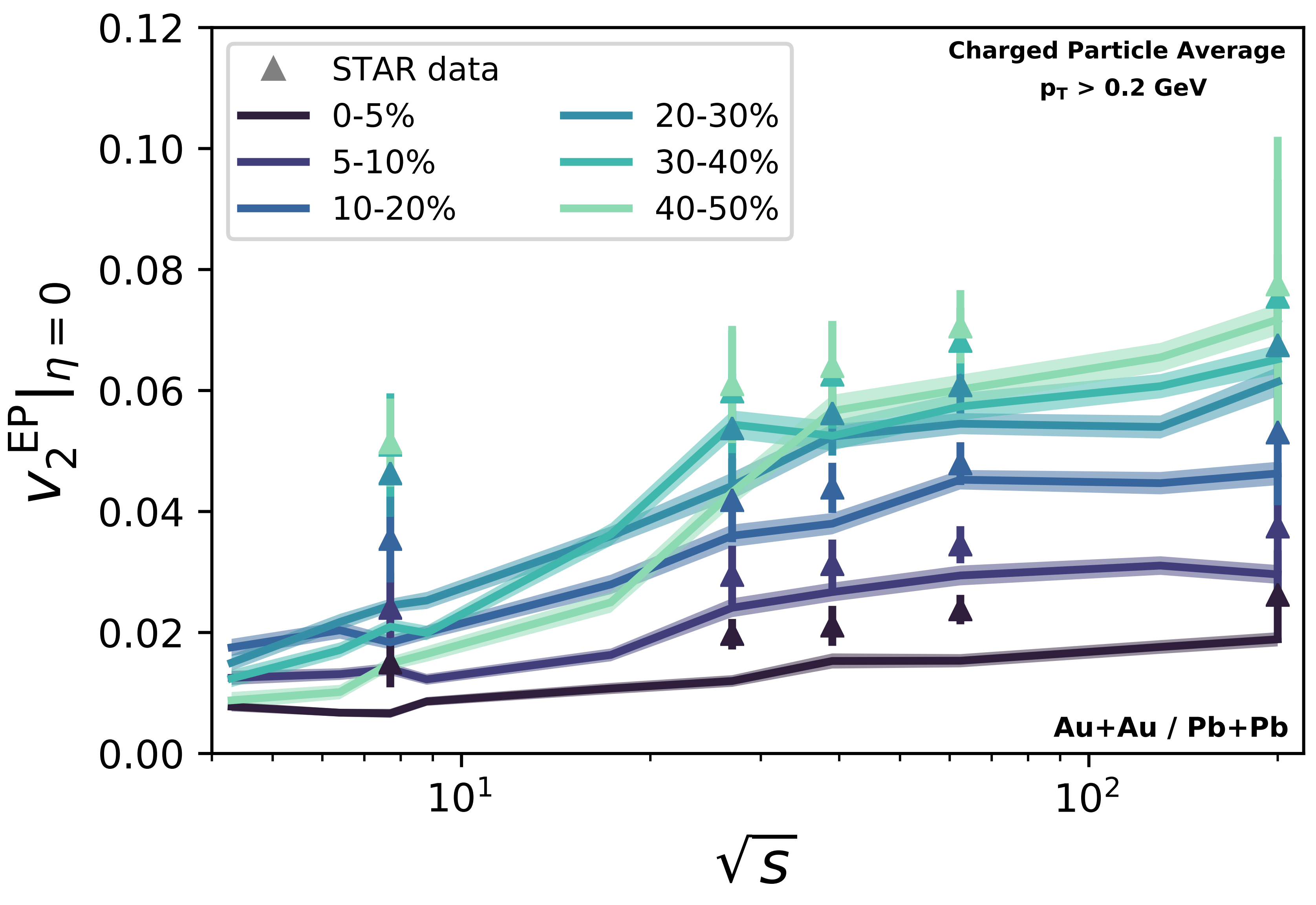


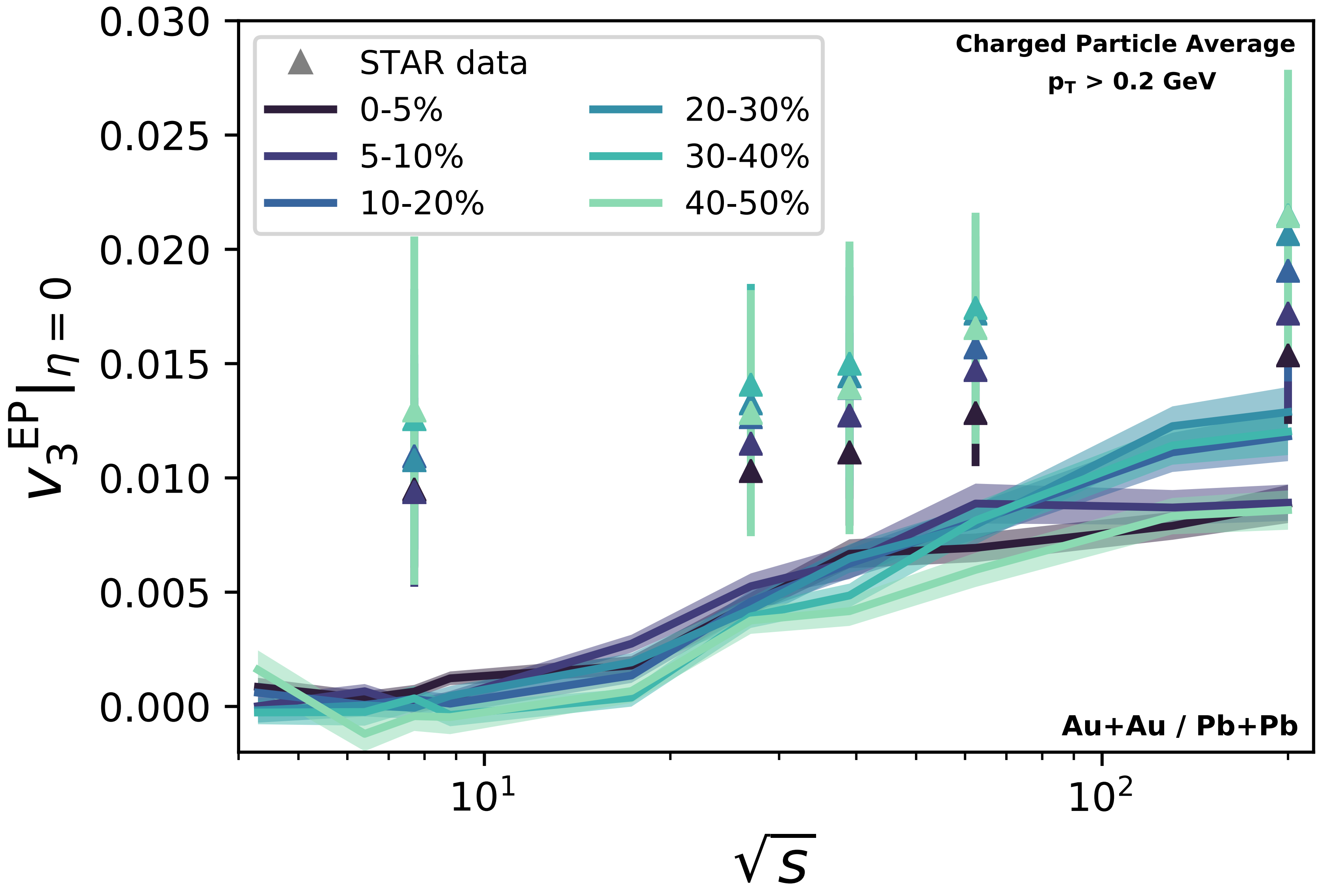
- Mean transverse momentum excitation function of pions, kaons and protons between $\sqrt{s_{NN}}$ = 4.3 GeV and $\sqrt{s_{NN}}$ = 200.0 GeV for different centralities
- Centrality dependence is generally small, but stronger at lower energies
- Kaons nearly unaffected, protons affected the most

AS et al., arXiv: 2112.08724

Excitation Function: Integrated v_2 and v_3

- Integrated v_2 and v_3 for charged particle average
- v_2: Good agreement with STAR data at high energies and in central collisions
- v_3: STAR data underestimated at all energies and centralities
- Potential explanation:
  - Too short lifetime of the hydrodynamical fireball
  - Initial state fluctuations washed out in smearing process





AS et al., arXiv: 2112.08724

STAR: Phys.Rev.C 98 (2018) 3, 034918

Employing the SMASH-vHLLE-hybrid in isobar collisions

Initial Conditions: Ruthenium and Zirconium in SMASH

Ruthenium

- Nuclear radius: r_0 = 5.085 fm
- Diffusiveness: d = 0.46 fm
- Saturation density: ρ_0 = 0.1604 fm^{-3}

Zirconium

- Nuclear radius: r_0 = 5.02 fm
- Diffusiveness: d = 0.46 fm
- Saturation density: ρ_0 = 0.1673 fm^{-3}

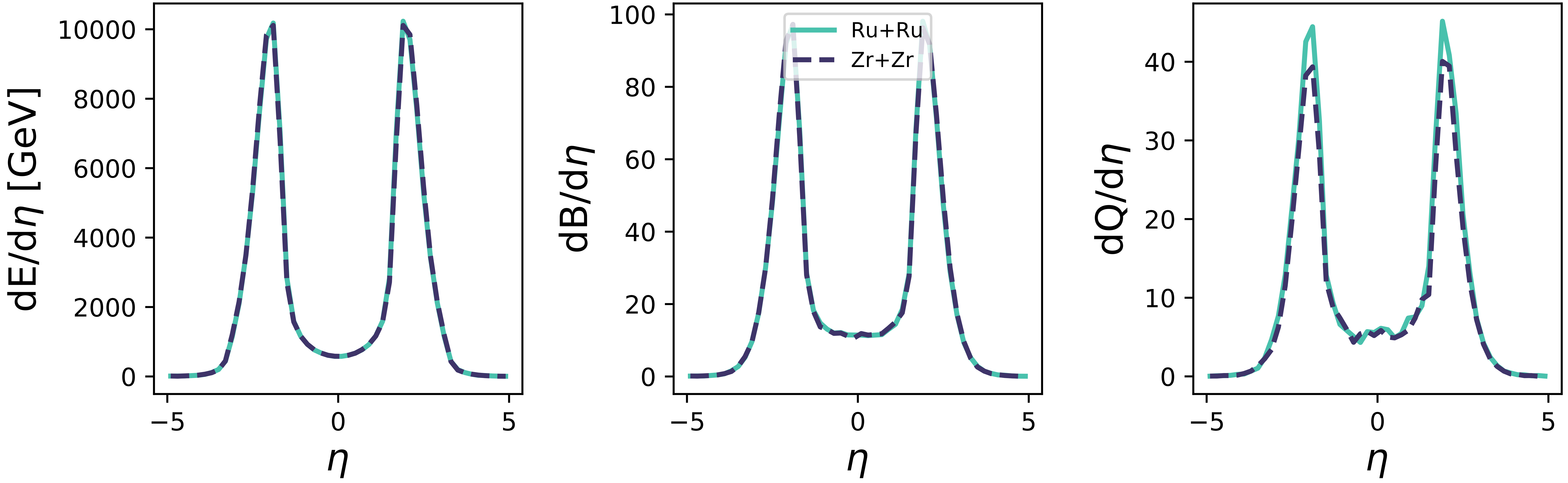
- Woods-Saxon distribution to initialize Nuclei:

$$\frac{\mathrm{d}N}{\mathrm{d}^3 r} = \frac{\rho_0}{\exp\left(\frac{r - r_0}{d}\right) + 1}$$

- Ruthenium and Zirconium are initialized with different radii and saturation densities

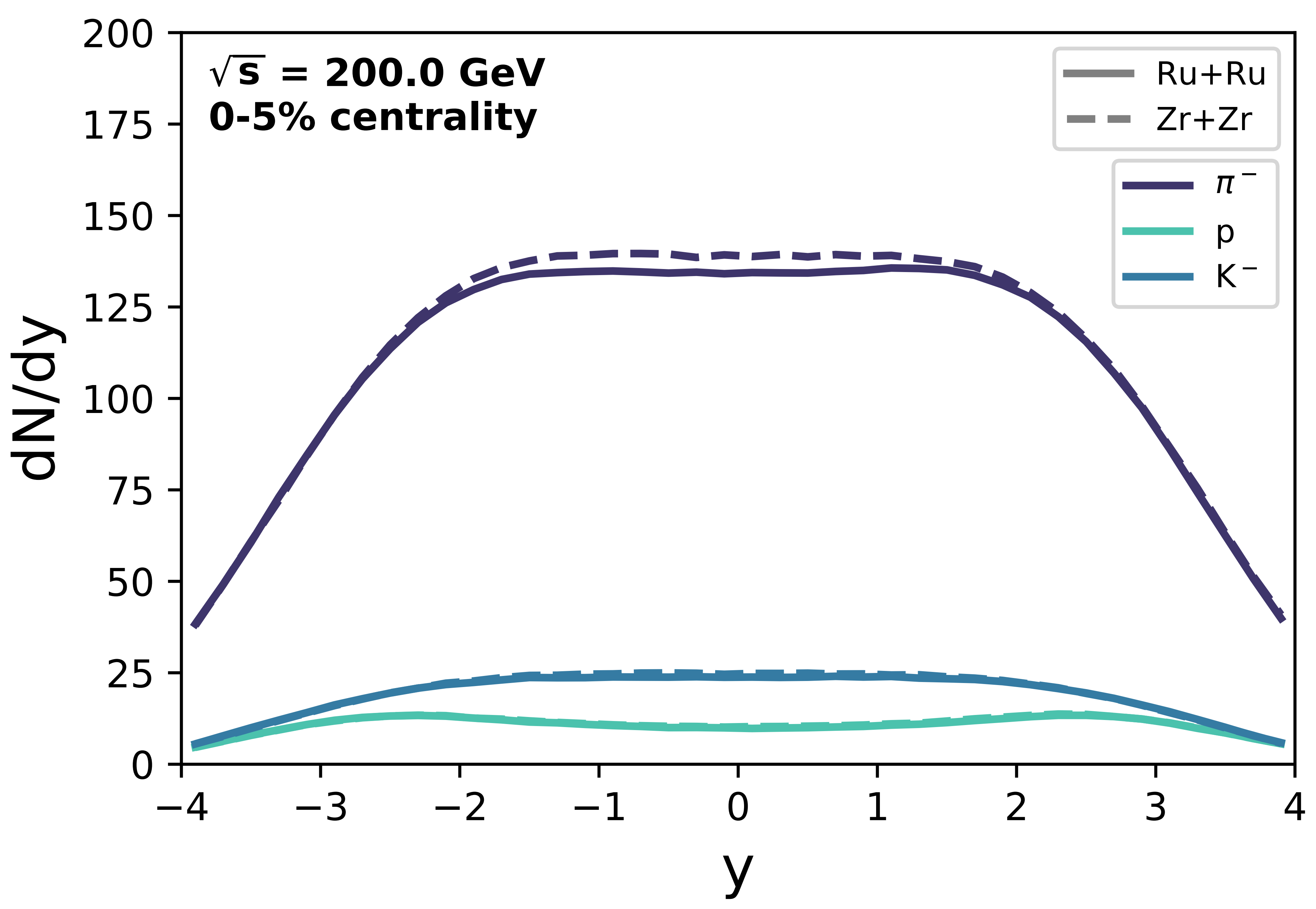
Weil et al.: PRC 94 (2016) and references therein

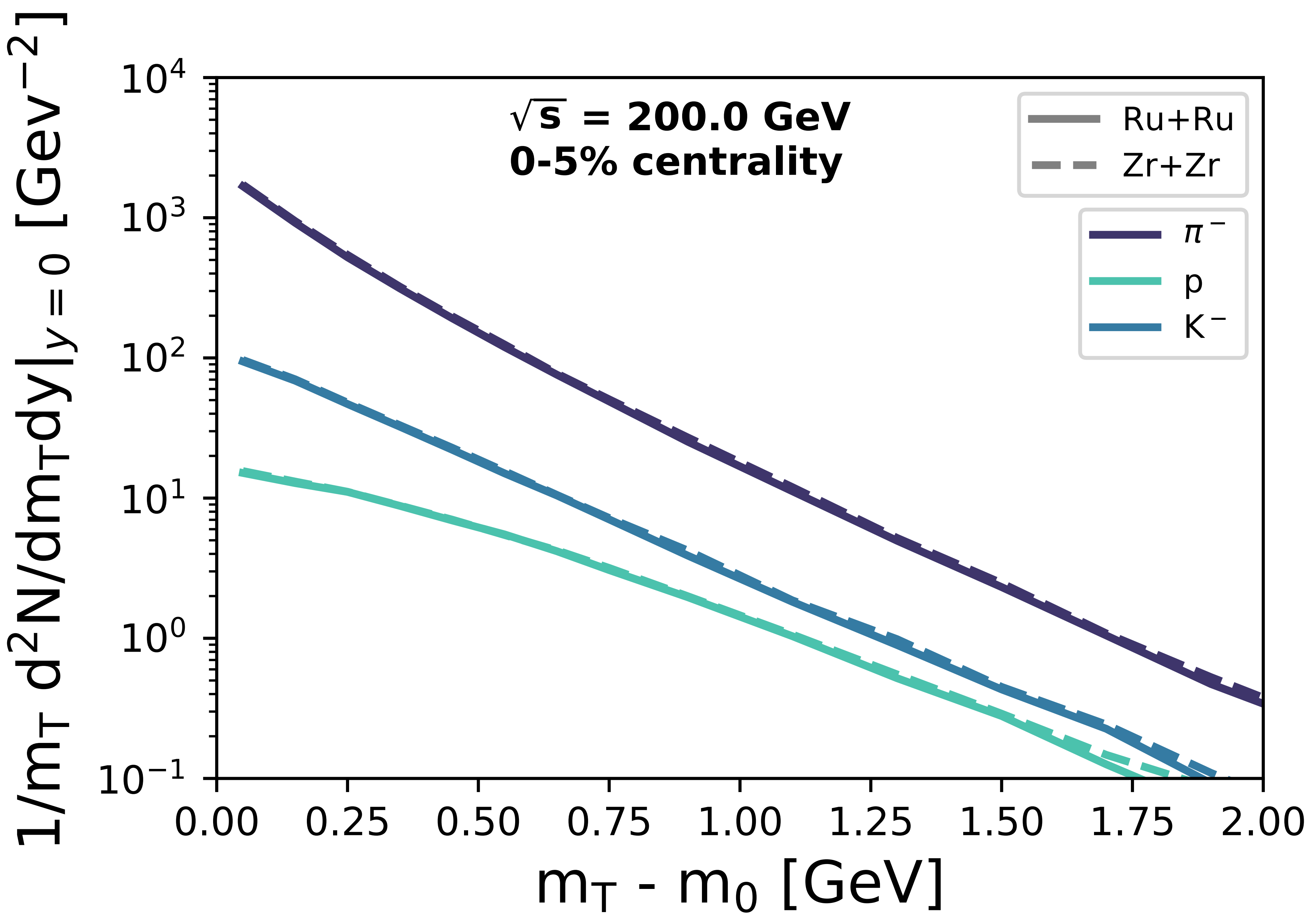
Initial Longitudinal Quantum Number Distribution at $\sqrt{s} = 200.0$ GeV



- Distribution of energy, baryon number, and electric charge as a function of the space-time rapidity
- Differences between Ru and Zr are negligible regarding E and B
- Difference in Q resulting from different numbers of protons clearly visible

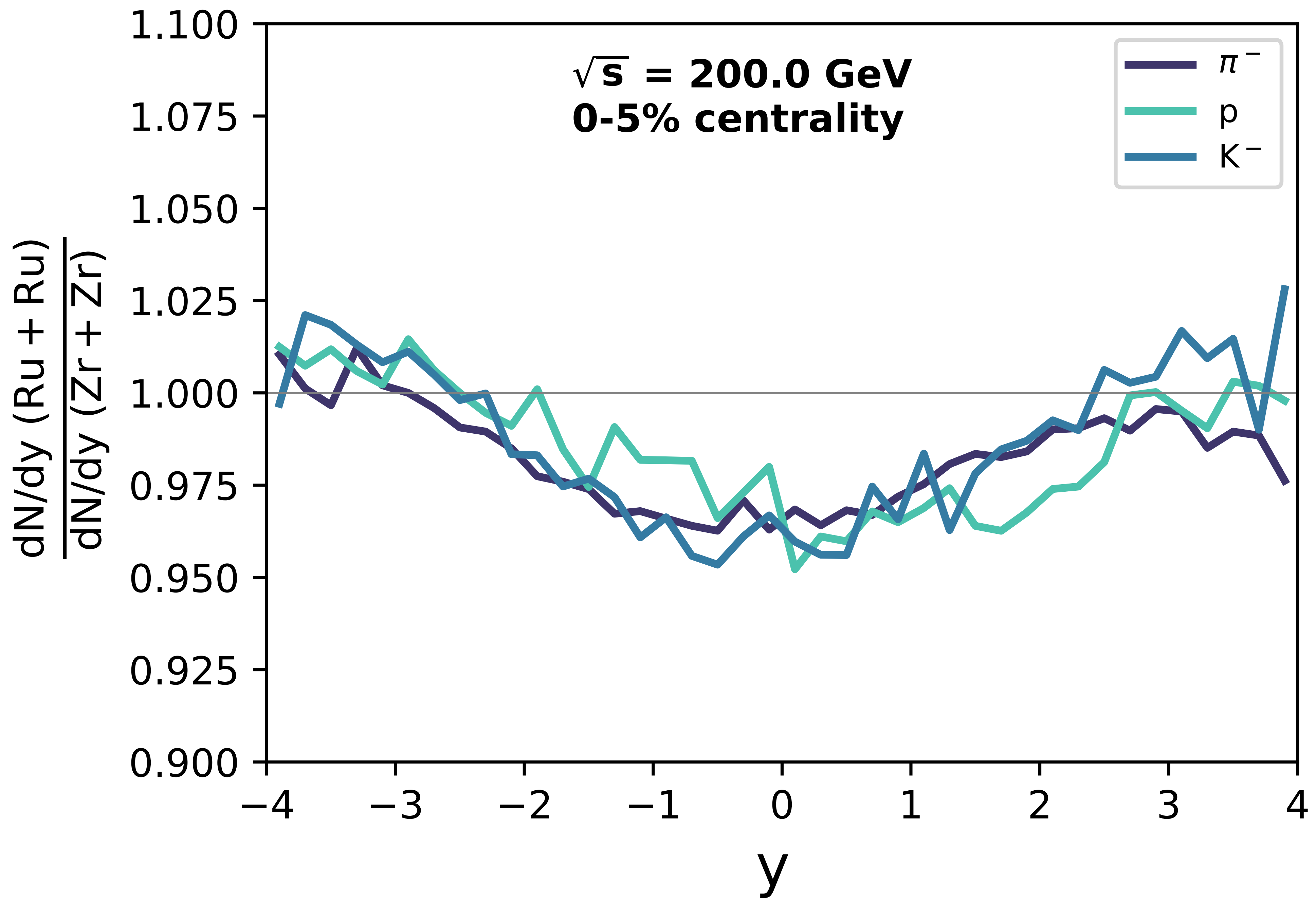
Ru+Ru and Zr+Zr spectra at $\sqrt{s}$ = 200 GeV

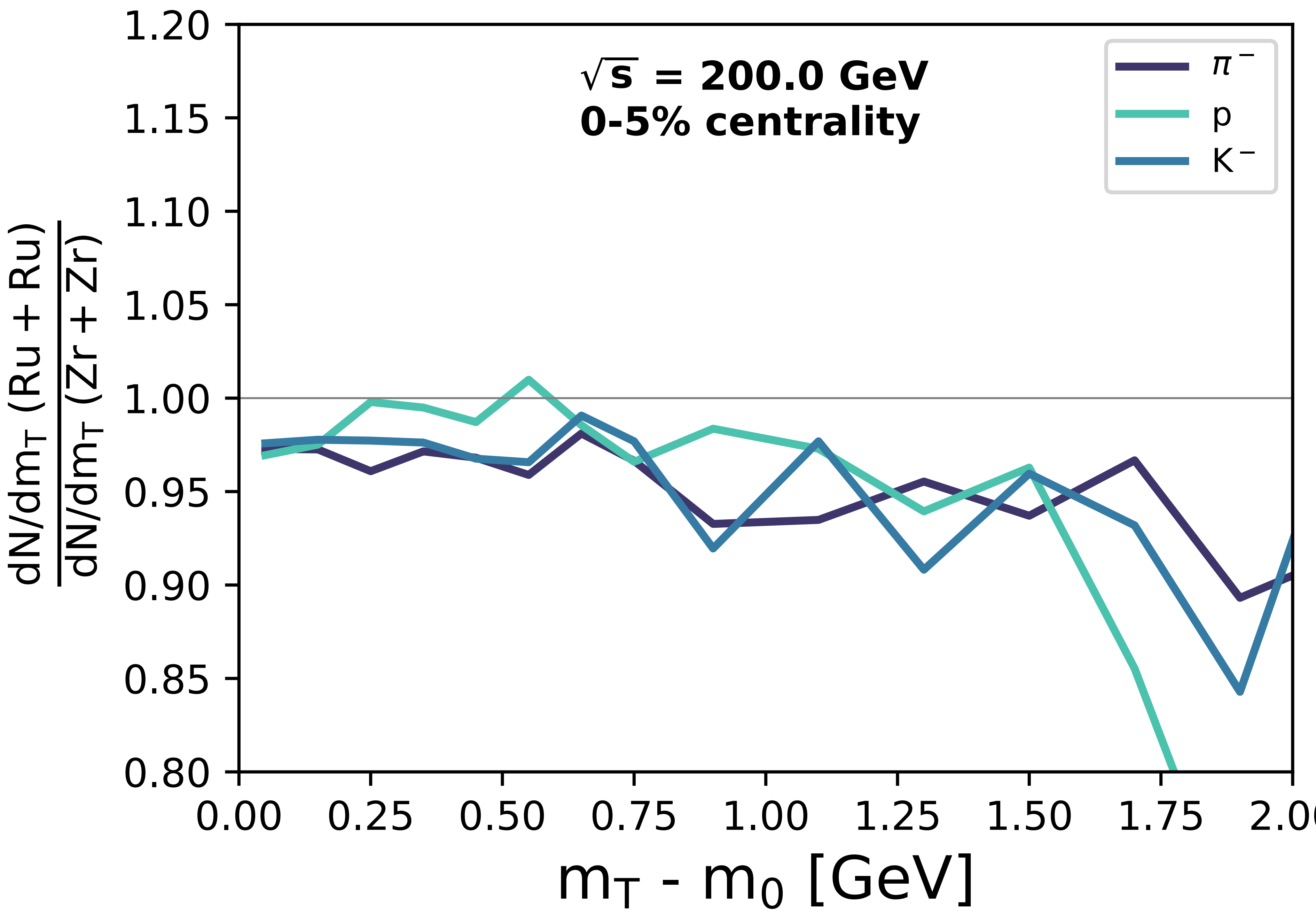




- Differences between the rapidity and transverse mass spectra of Ru+Ru collisions and Zr+Zr collisions can be observed at $\sqrt{s}$ = 200 GeV

Ratios: Ru+Ru/Zr+Zr spectra at $\sqrt{s} = 200$ GeV





- Yield at mid-rapidity is higher in Zr+Zr collisions than in Ru+Ru collisions, and vice versa at large rapidities
- Towards larger m_T, the dN/dm_T spectra of Zr+Zr collisions overpass those of Ru+Ru collisions
- Both observations hold for pions, protons, and kaons

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
- 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 $dN/dy|_{y=0}$, $\langle p_T \rangle$, v_2, and v_3 in decent agreement with experimental data
- Extension by more dynamical initial conditions constitutes next step to better capture dynamics at FAIR/NICA/NA61(SHINE) energies

- SMASH-vHLLE-hybrid employed to simulate Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}}$ = 200.0 GeV (sneak preview)

What next?

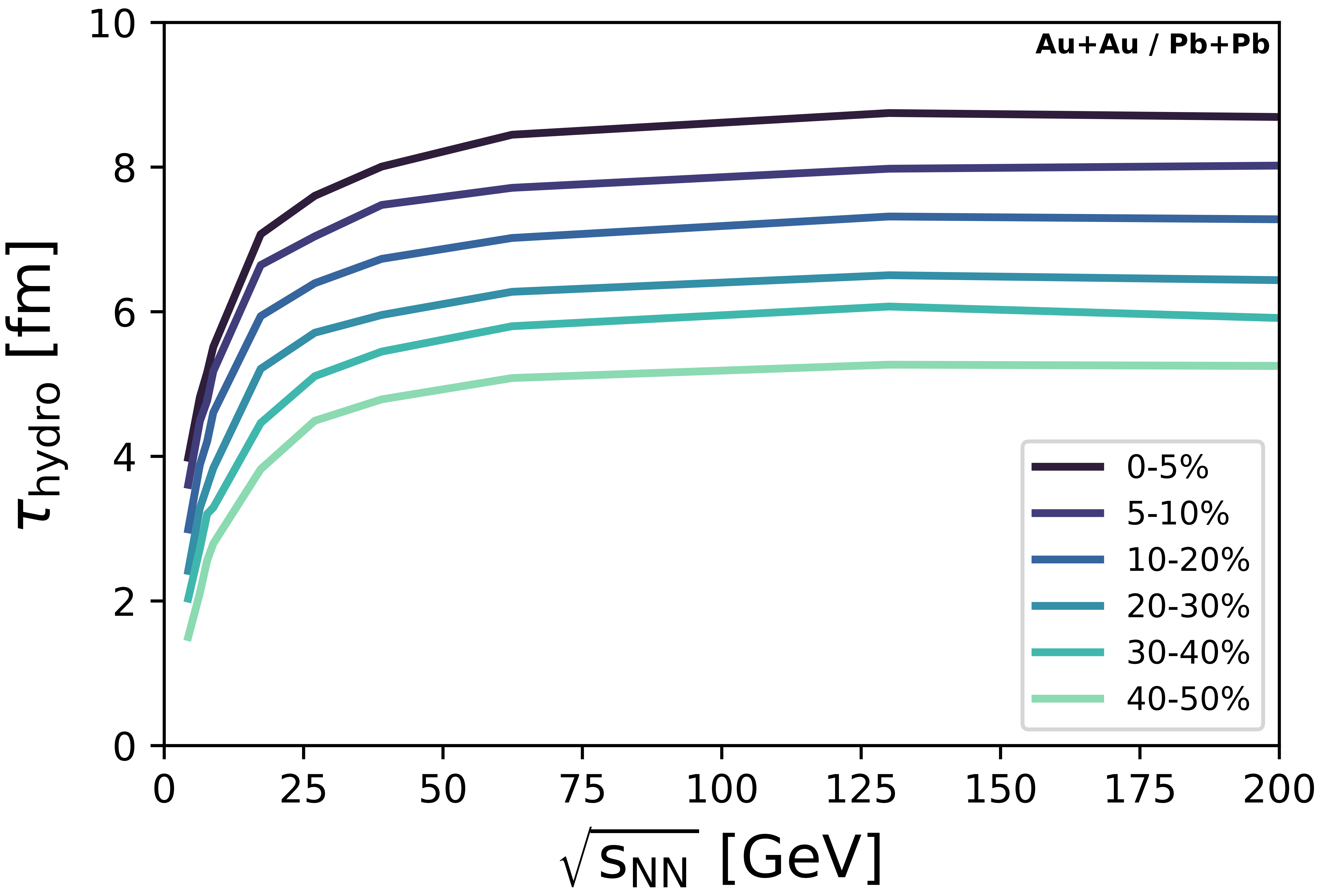
- Sneak preview at isobar results with the SMASH-vHLLE-hybrid is not enough
- Systematically study centrality dependence and collision energy dependence of a range of observables, e.g.:
  -> Yield
  -> Transverse momentum
  -> Anisotropic flow
- Make use of the *deformed nuclei* feature of SMASH in the initial state
  -> systematically study the impact of deformed Ru or Zr nuclei on final particle spectra
- Employ initial Ru and Zr configuration accounting for neutron skin (as in Hammelmann et al.: Phys.Rev.C 101 (2020) 6, 061901)

Stay Tuned!

https://github.com/smash-transport/smash-vhlle-hybrid

BACKUP

Lifetime of the hydrodynamical fireball



AS et al., arXiv: 2112.08724

Additional Feature: Deformed Nuclei

- Woods-Saxon distribution with angular dependent radius:

$$\frac{\mathrm{d}N}{\mathrm{d}^3r}\left(r,\theta,\varphi\right) = \frac{\rho_0}{\exp\left(\frac{r-r_0(\theta,\varphi)}{d}\right)+1}$$

where

$$r_0(\theta,\varphi) = r_0\left(1+\sum_{l=1}^{\infty}\sum_{m=-l}^{l}\beta_{lm}\,Y_{lm}\,(\theta,\varphi)\right)$$

- Assumption of azimuthal symmetry, hence m=0
- Consider parameters up to l=4
- β_{20} and β_{40} that control deformation

Ruthenium

β_{20} = 0.158

β_{40} = 0.0

Zirconium

Assumed to not be deformed

Weil et al.: PRC 94 (2016) and references therein

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

SMASH-vHLLE-hybrid

System	$\sqrt{s}$	η/s	$R_\perp$	R_η
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	0.5
Au + Au	39.0 GeV	0.08	1.0	0.3
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

UrQMD-vHLLE-hybrid

System	$\sqrt{s}$	η/s	$R_\perp$	R_η
Au + Au	7.7 GeV	0.2	1.4	0.5
Pb + Pb	8.8 GeV	0.2	1.4	0.5
Pb + Pb	17.3 GeV	0.15	1.4	0.5
Au + Au	27.0 GeV	0.12	1.0	0.5
Au + Au	39.0 GeV	0.08	1.0	0.7
Au + Au	62.4 GeV	0.08	1.0	0.7
Au + Au	130.0 GeV	-	-	-
Au + Au	200.0 GeV	0.08	1.0	1.0

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

http://smash-transport.github.io

SMASH

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

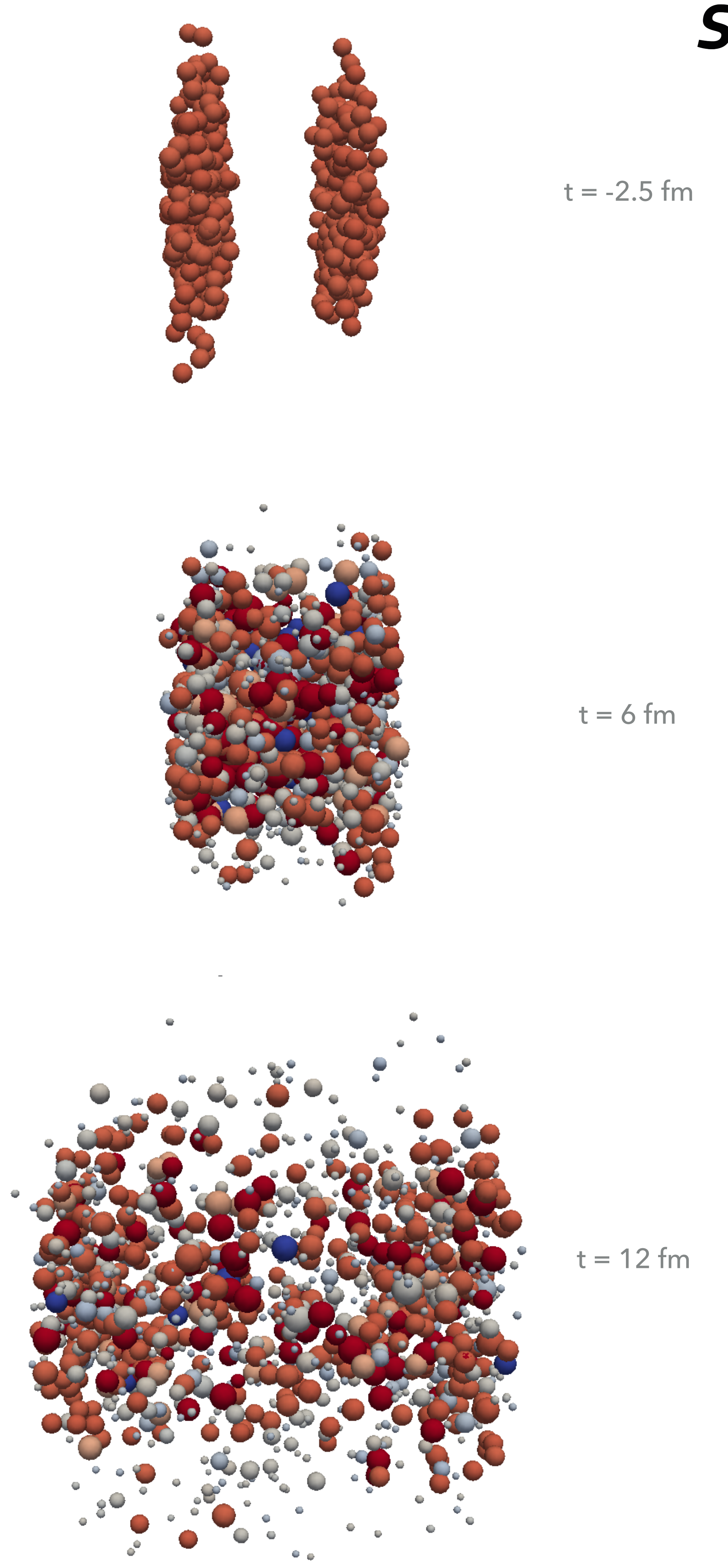
- Degrees of freedom:
  All well-established hadrons listed by the PDG up to mass of
  M ≈ 2.35 GeV

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



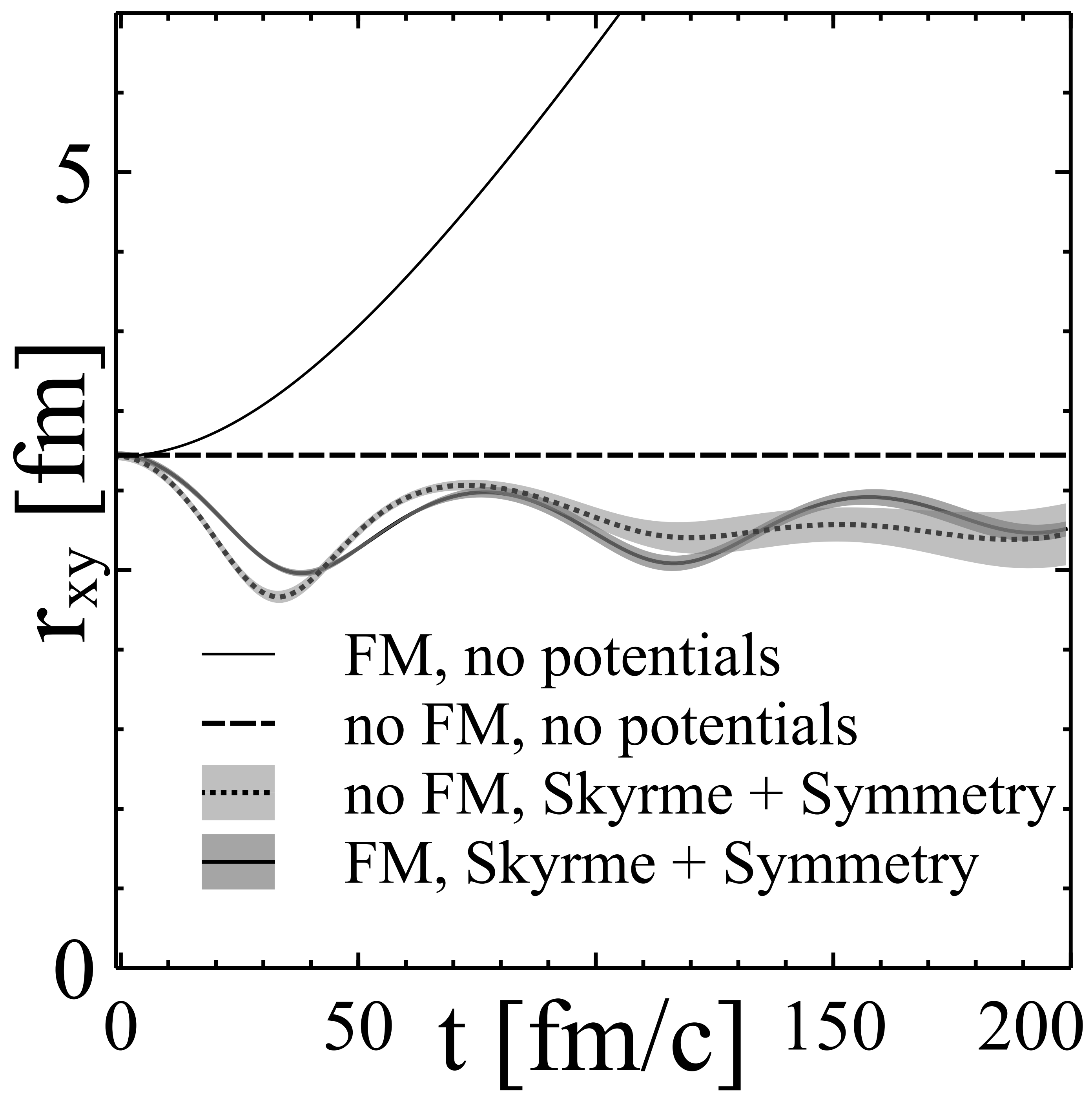
by J. Mohs

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
  - $\sigma \rightarrow \sigma / N_{test}$ $\quad$ $N \rightarrow N \cdot N_{test}$
- 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

N	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1321}	Ω^{-}_{1672}
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	Ω^{-}_{2250}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}	
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2030}	
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1950}	Λ_{1820}	Σ_{2030}		
N_{1720}		Λ_{1830}	Σ_{2250}		
N_{1875}		Λ_{1890}			
N_{1900}		Λ_{2100}			
N_{1990}		Λ_{2110}			
N_{2060}		Λ_{2350}			
N_{2080}					
N_{2100}					
N_{2120}					
N_{2190}					
N_{2220}					
N_{2250}					

As of SMASH-1.7

Unflavored				Strange
π_{138}	$f_{0\ 980}$	$f_{2\ 1275}$	$\pi_{2\ 1670}$	K_{494}
π_{1300}	$f_{0\ 1370}$	$f_2'{}_{1525}$		K^*_{892}
π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\rho_{3\ 1690}$	$K_{1\ 1270}$
	$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
η_{548}		$f_{2\ 2300}$	$\phi_{3\ 1850}$	K^*_{1410}
η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K_0^*{}_{1430}$
η_{1295}	$a_{0\ 1450}$		$a_{4\ 2040}$	$K_2^*{}_{1430}$
η_{1405}		$f_{1\ 1285}$		K^*_{1680}
η_{1475}	ϕ_{1019}	$f_{1\ 1420}$	$f_{4\ 2050}$	$K_{2\ 1770}$
	ϕ_{1680}			$K_3^*{}_{1780}$
σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
	$h_{1\ 1170}$			$K_4^*{}_{2045}$
ρ_{776}		$\pi_{1\ 1400}$		
ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
ρ_{1700}				
	$a_{1\ 1260}$	$\eta_{2\ 1645}$		
ω_{783}				
ω_{1420}		$\omega_{3\ 1670}$		
ω_{1650}				

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