

Gearing up for GSI/FAIR: State-of-the-art simulations of dense baryonic matter

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September 25th 2026, EMMI Workshop on Light Ion Collisions

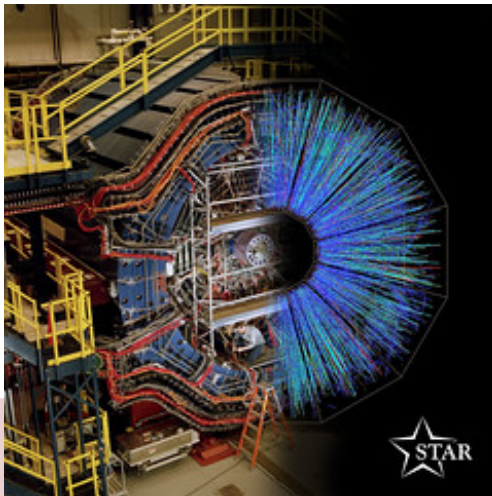
Outline

- Heavy-Ion Collisions at Low Beam Energies
- Transport Approaches
 - Degrees of freedom, potentials
 - Equation of state of nuclear matter
 - Strings and rope formation -> strangeness
- Hybrid Approaches
 - Dynamical Initial Conditions
 - Phase transition signatures?
 - Dileptons and net proton fluctuations
- Experimental Status of CBM at FAIR

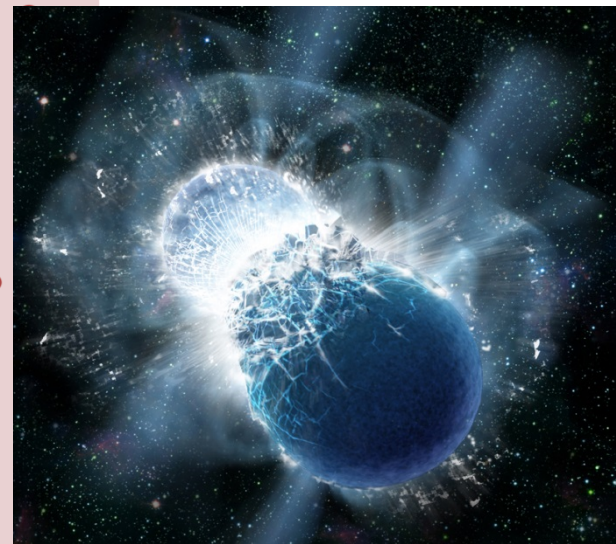
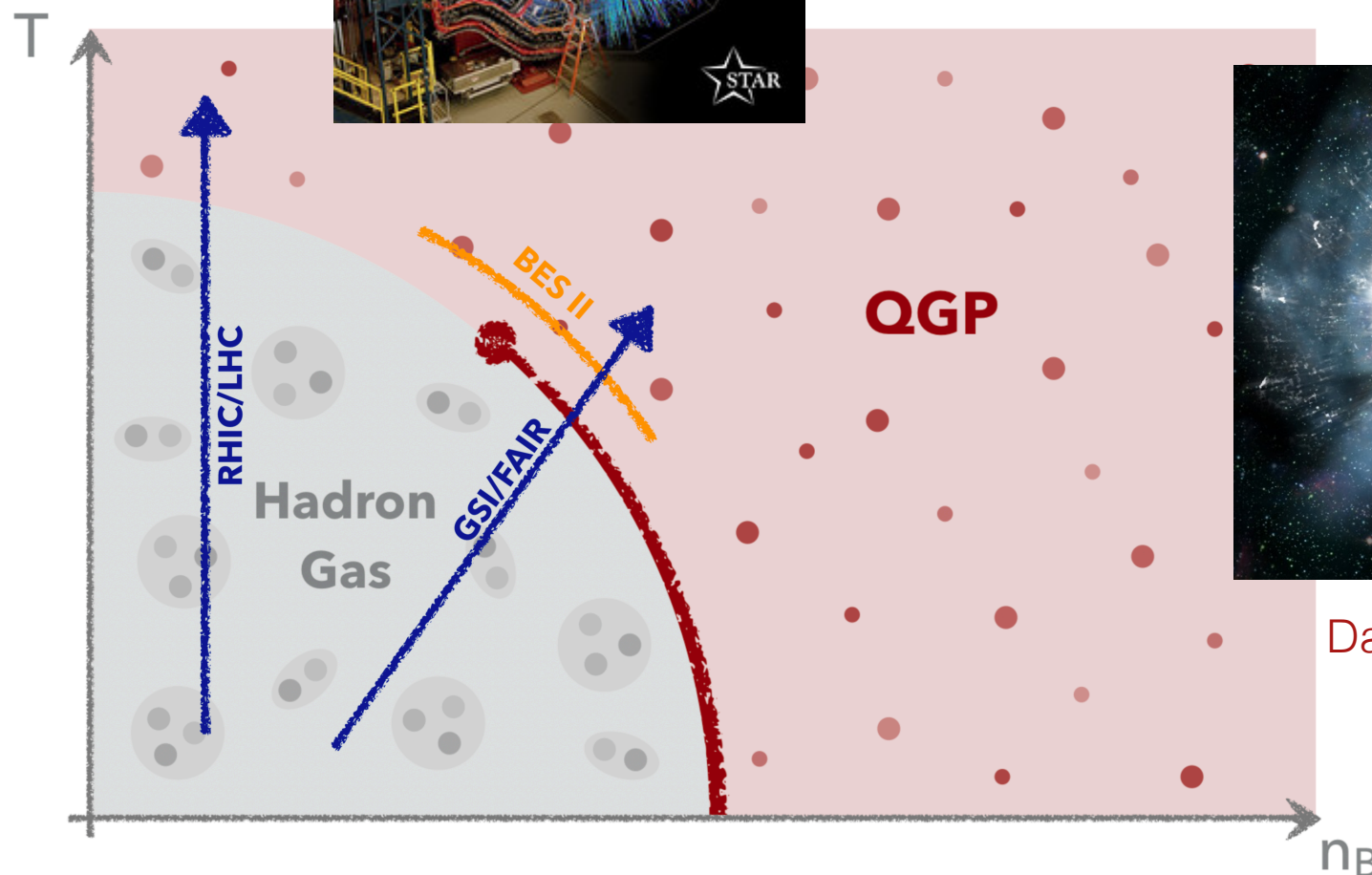
The QCD Phase Diagram

- **Main goals** of heavy-ion research:

STAR experiment at RHIC



- What are the relevant degrees of freedom at high densities?
- Phase transition, critical endpoint?
- Properties of neutron star mergers?

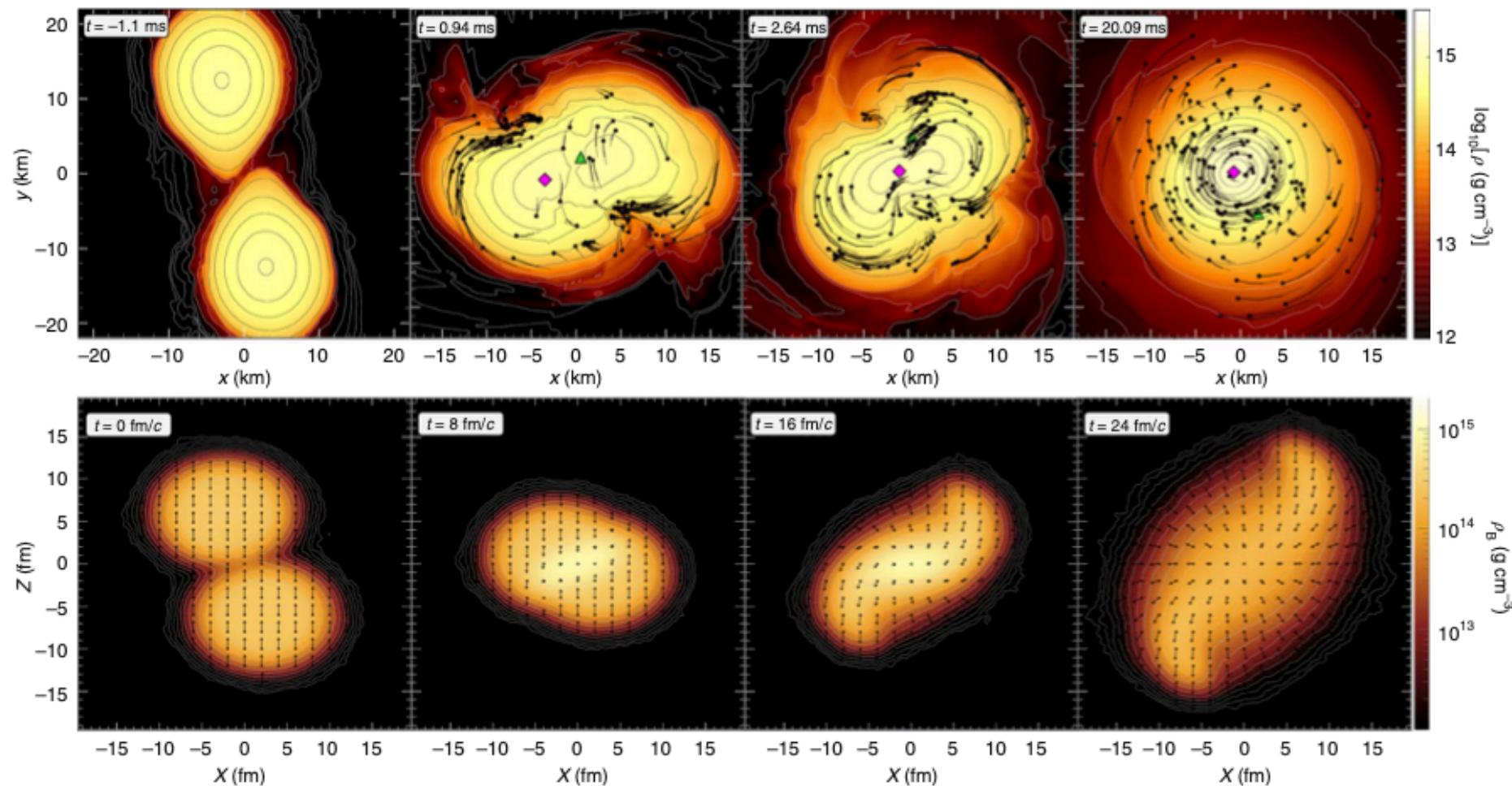


Relevant for neutron
star mergers as
detected by
gravitational waves
(GW170817)

Dana Berry, SkyWorks Digital, Inc

Matter at Extreme Densities

- 18 orders of magnitude in scales, still similar temperature up to ~ 80 MeV and densities up to 2-4 times nuclear ground state density



- Binary neutron star mergers: First detected events are GW170817, GW19042
 - Heavy-ion collisions: Ongoing experiments: RHIC-BES, NA61, HADES, FAIR Phase-0
- HADES collaboration, Nature Physics 15, 1040-1045 (2019)

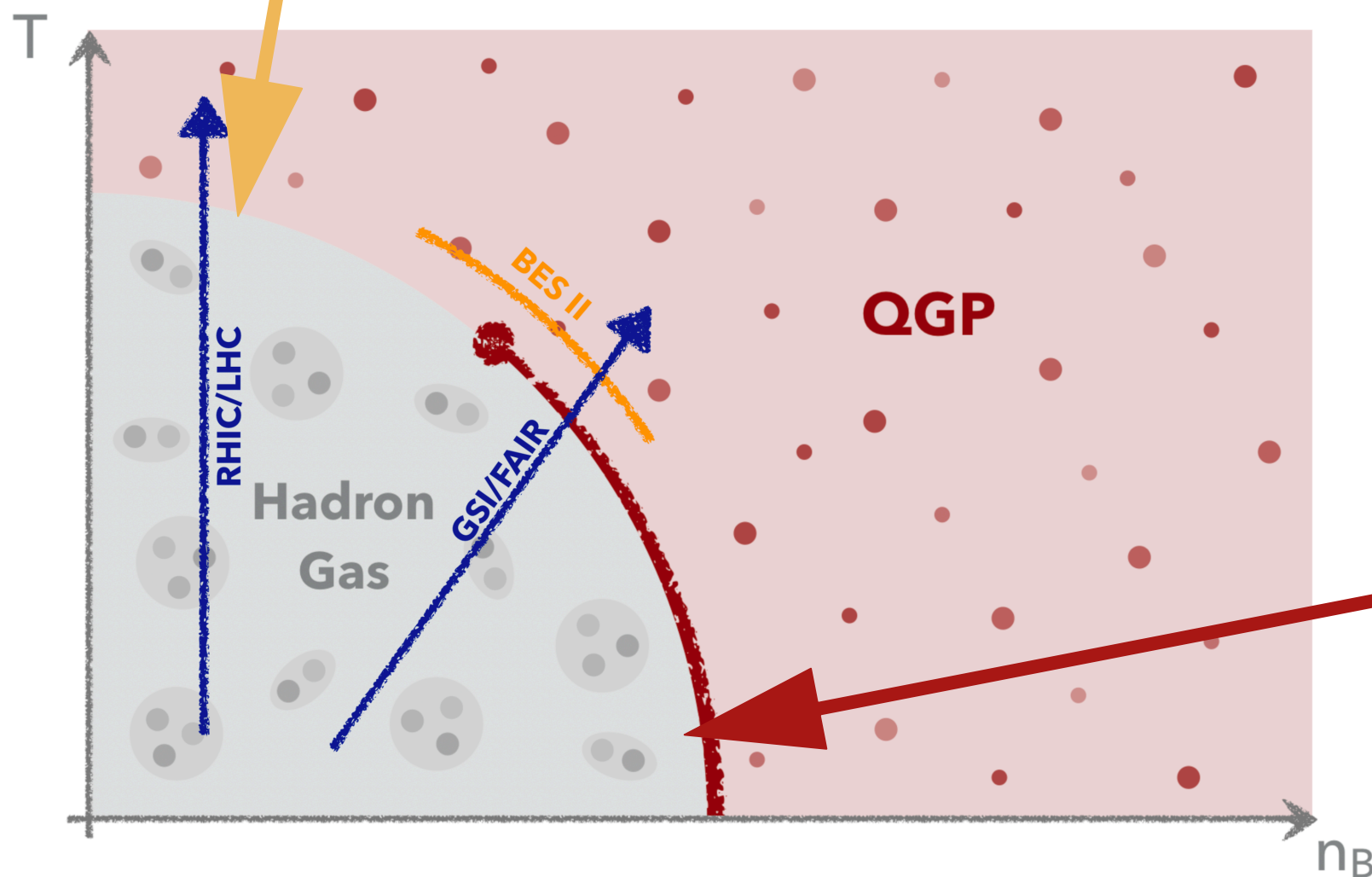
Dynamical Description

Standard approach at high energies

- Non-equilibrium initial evolution
- Viscous hydrodynamics
- Hadronic rescattering

- **Status:** Two regimes with well-established approaches
- Intermediate regime requires appropriate description

- Low beam energies probe limits of applicability of fluid dynamics as small systems



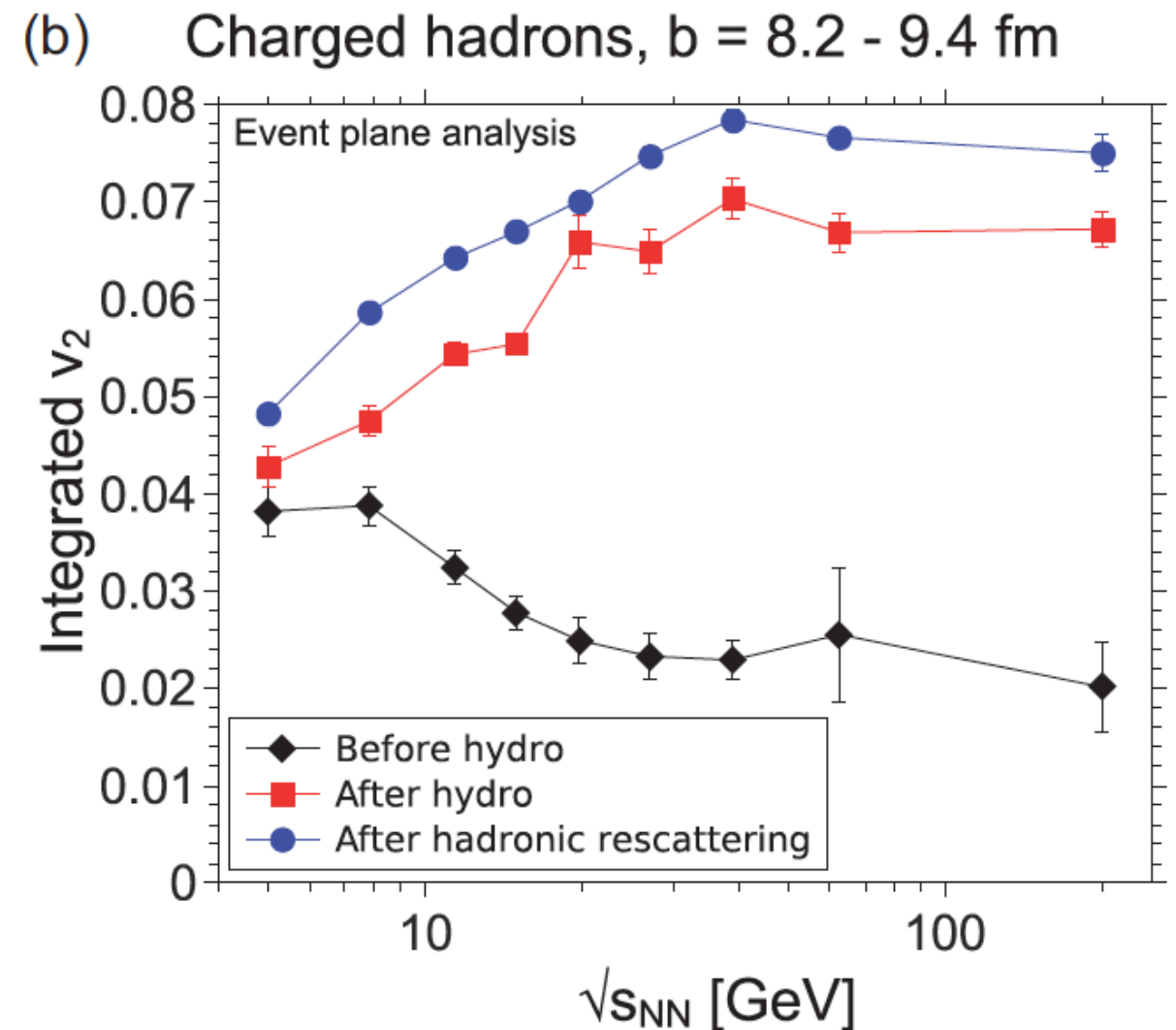
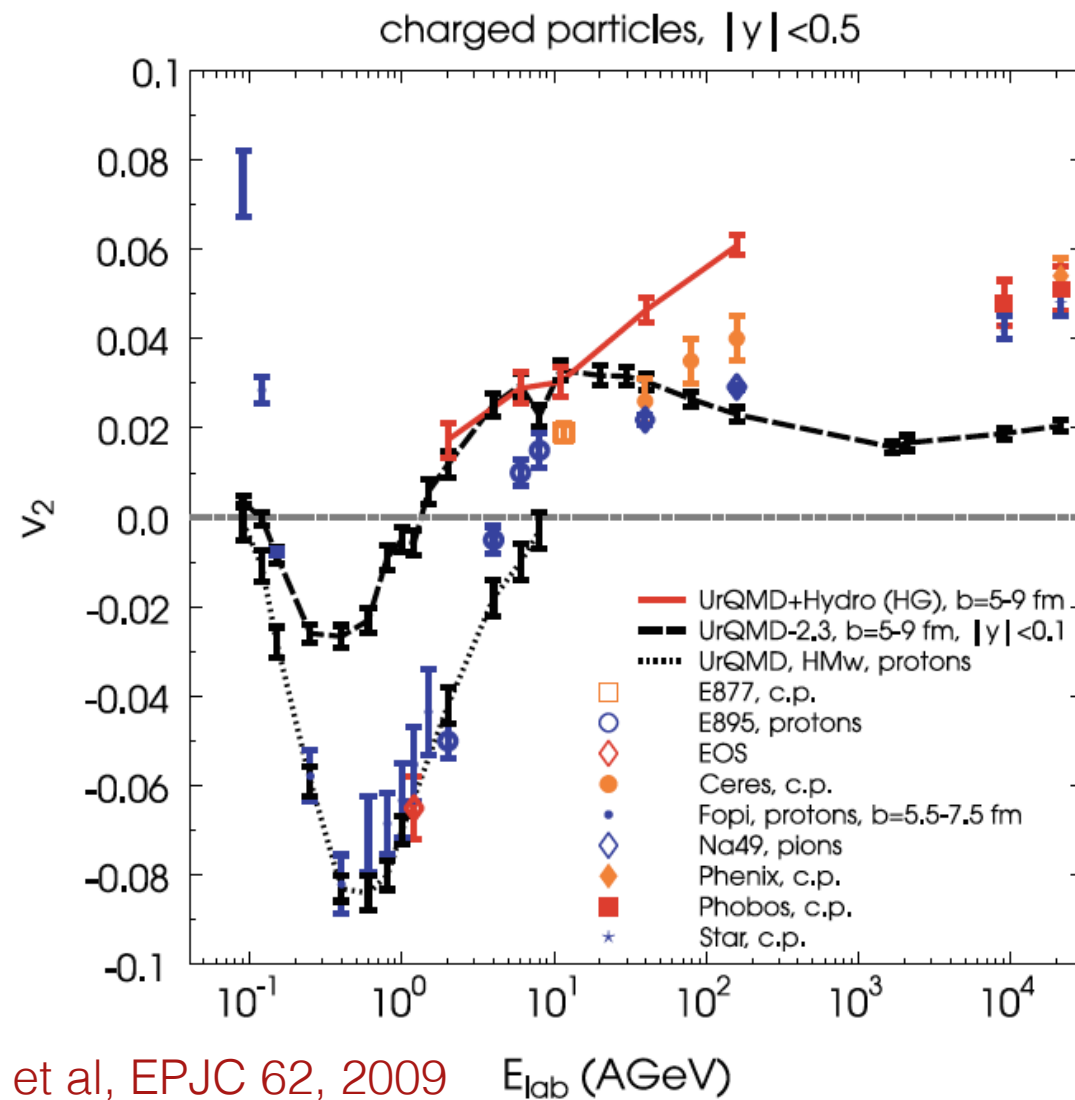
Standard approach at low beam energies

- Hadronic transport approaches
- Resonance dynamics
- Nuclear potentials

Elliptic Flow Excitation Function

- Low energies require mean field potentials

J. Auvinen and HP, PRC 88, 2013

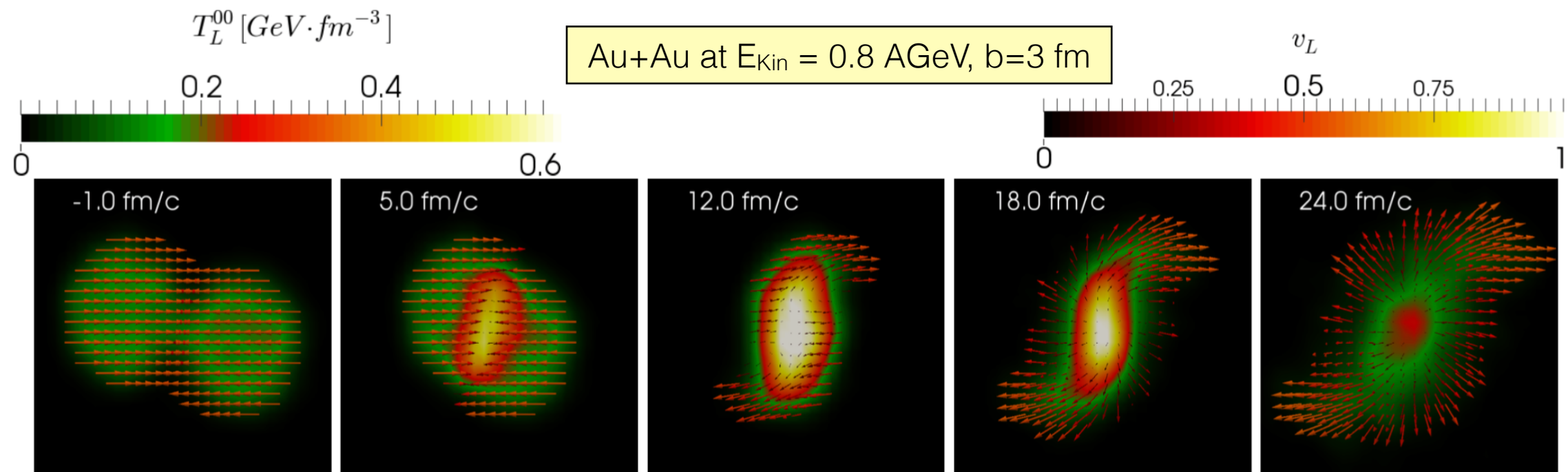


- High energies are well described by hybrid approaches
- Transition region in between

Transport Approaches

Transport Approaches

- Hadronic transport approach (SMASH, UrQMD, GiBUU):
 - Includes all mesons and baryons up to ~ 2 GeV
 - Binary interactions: Inelastic collisions through resonance/string excitation and decay
 - Boltzmann equation: $p^\mu \partial_\mu f_i(x, p) + m_i F^\alpha \partial_\alpha^p f_i(x, p) = C_{\text{coll}}^i$
 - PHQMD includes treatment of light nuclei production and their interactions



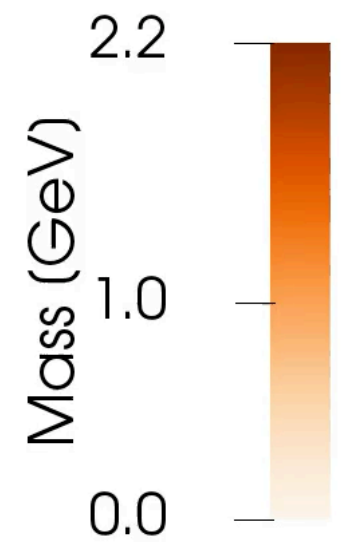
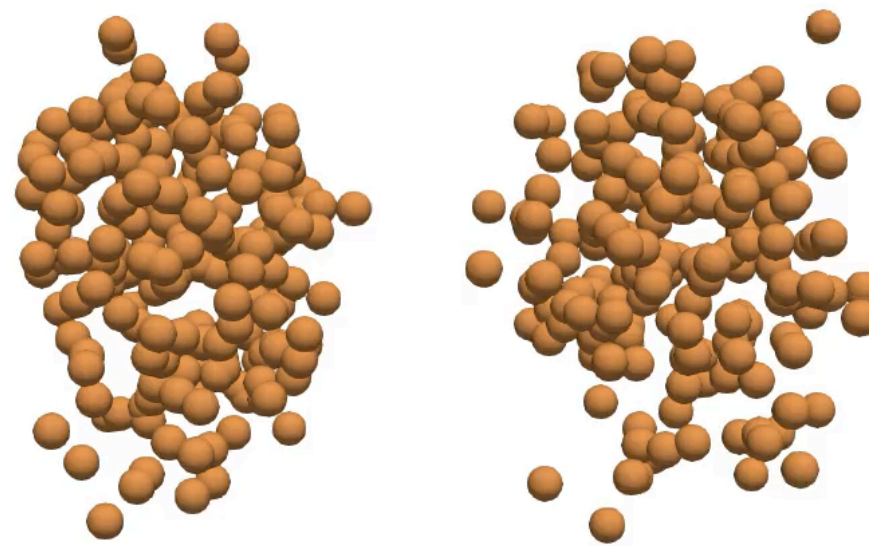
J. Weil et al, PRC 94 (2016)

Example for GSI Energy

Au+Au at $E_{\text{kin}} = 1.23A \text{ GeV}$

Impact: 0.0 fm

Time: -4 fm



<https://cloud.itp.uni-frankfurt.de/s/YJb9zEfzwqXmwgp>

Degrees of Freedom

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

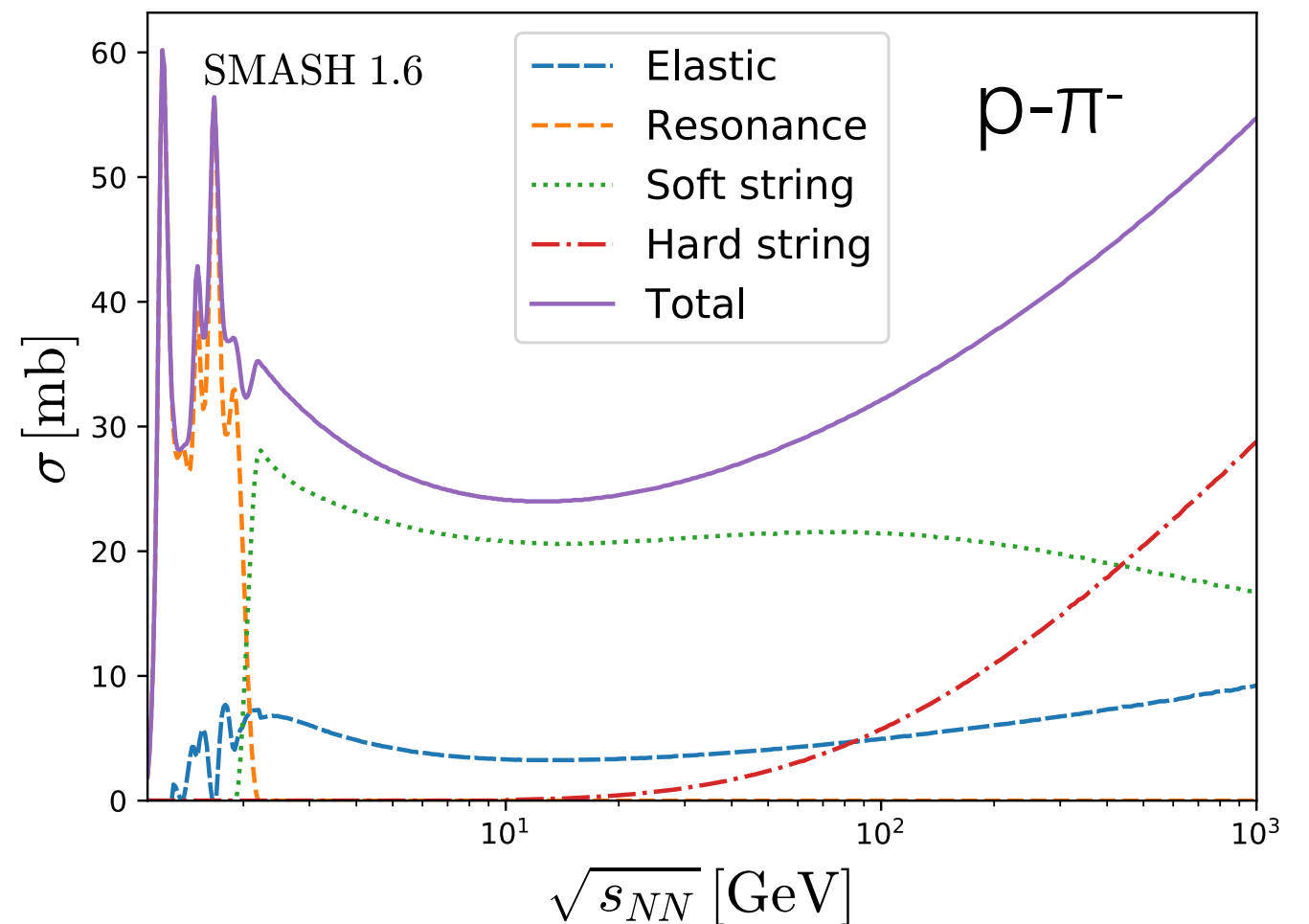
► Perturbative treatment of photons and dileptons

► Isospin symmetry

- Mesons and baryons according to particle data group
- Isospin multiplets and anti-particles are included

Cross-Sections

- High energy cross-section is dominated by string excitation and fragmentation while low energy cross-sections are treated via resonances
- Soft strings
 - Pythia is only employed for fragmentation
 - Single-diffractive, double diffractive and non-diffractive processes
- Hard strings
 - Fully treated by Pythia
 - All species mapped to pions and nucleons

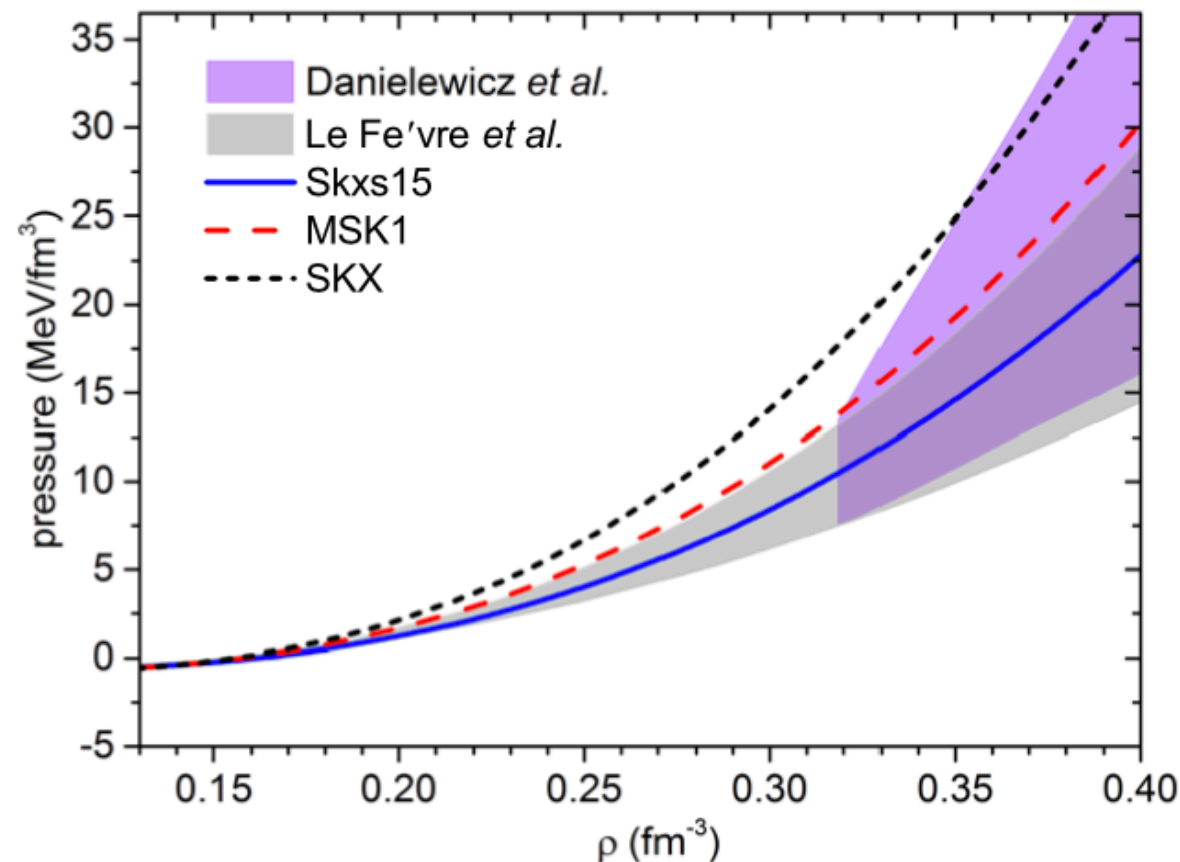


J. Mohs, S. Ryu and HE, *J.Phys.G* 47 (2020)

Equation of State of Nuclear Matter

Nuclear Matter Equation of State

- ‚Danielewicz constraint‘ and newer constraints -> varying mean field parameters to fit flow observables best



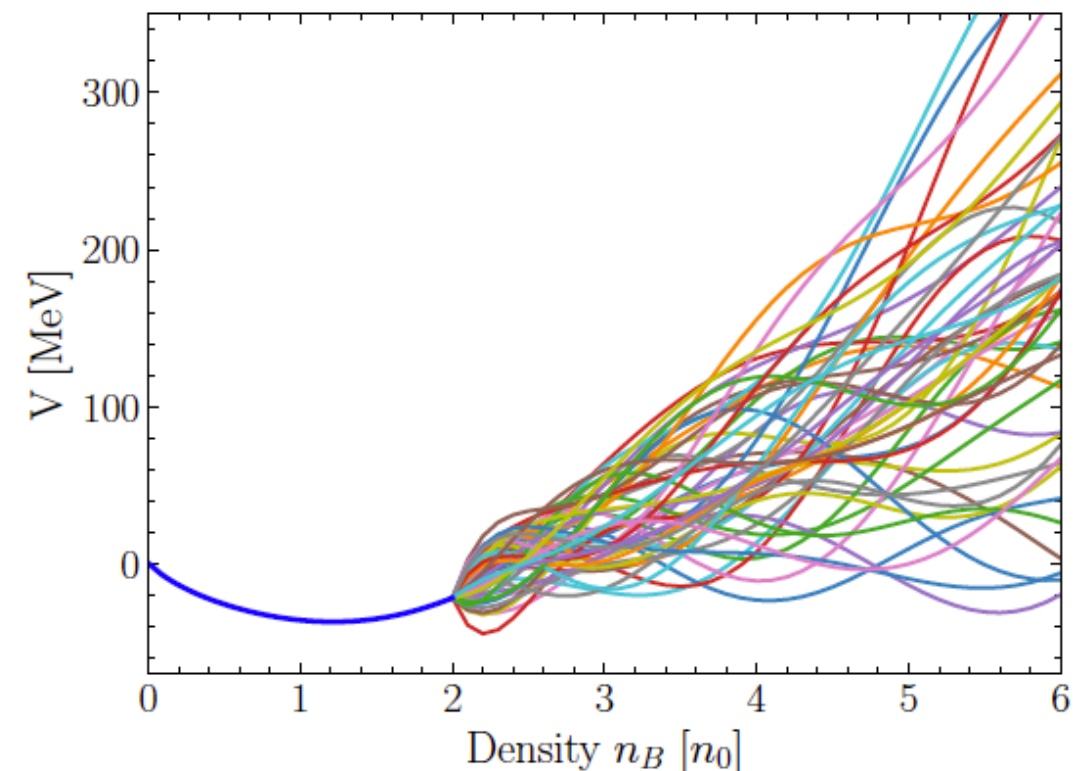
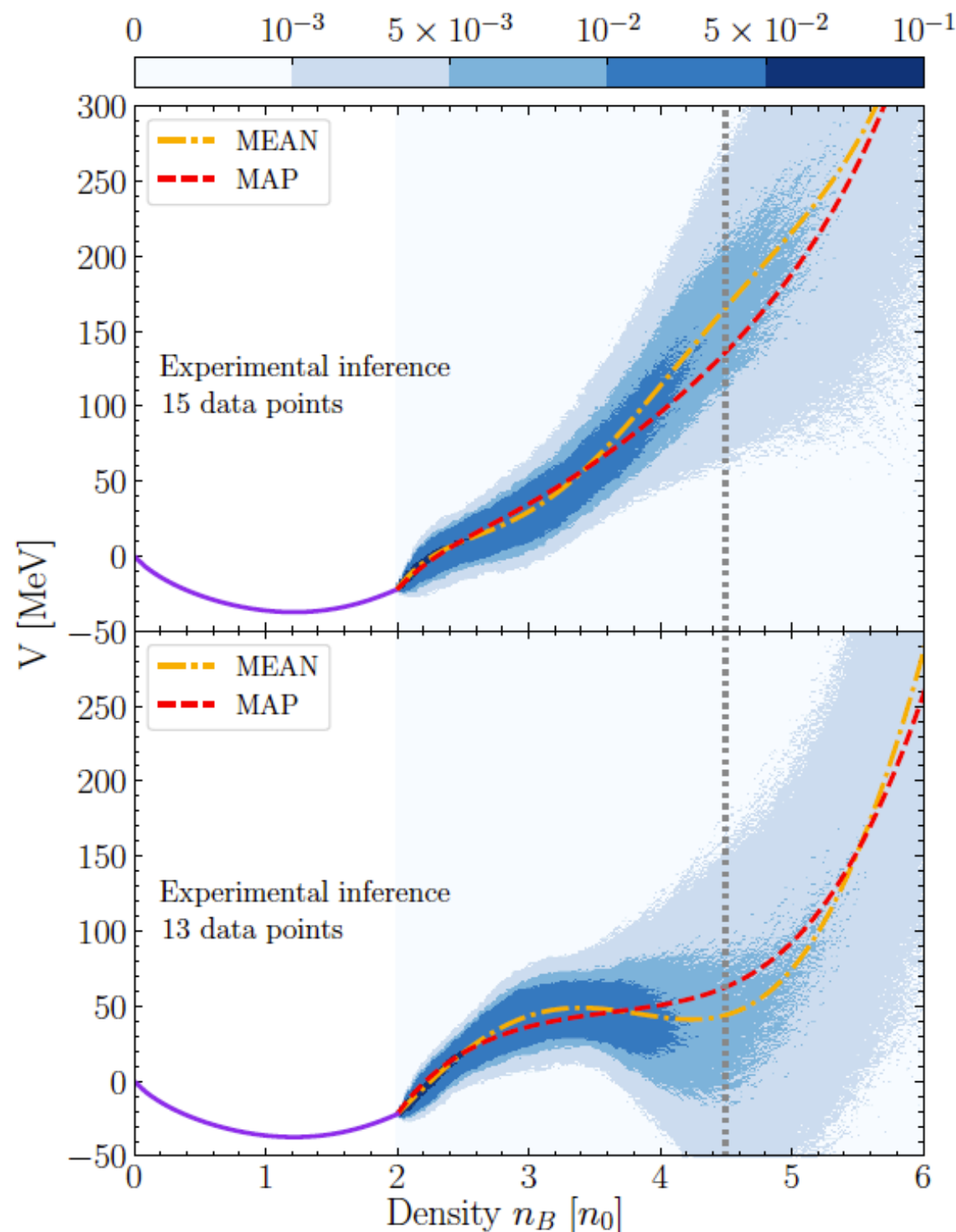
Y. Wang et al, arXiv:1804.04293
A. Hombach et al, Eur.Phys.J.A 5 (1999)
Show importance of resonances

- Open issues: Results are dependent on details of transport code and in particular mean field properties, e.g. BUU vs QMD, cluster formation, form of the potential...

TMEP collaboration, e.g. Prog.Part.Nucl.Phys. 125 (2022)

Bayesian Constraints

- Chiral mean field in UrQMD allows to vary equation of state -> Bayesian analysis is performed and indicates dependence on which observables are used
- Mean transverse mass and elliptic flow from $\sqrt{s_{NN}} = 3-9$ GeV

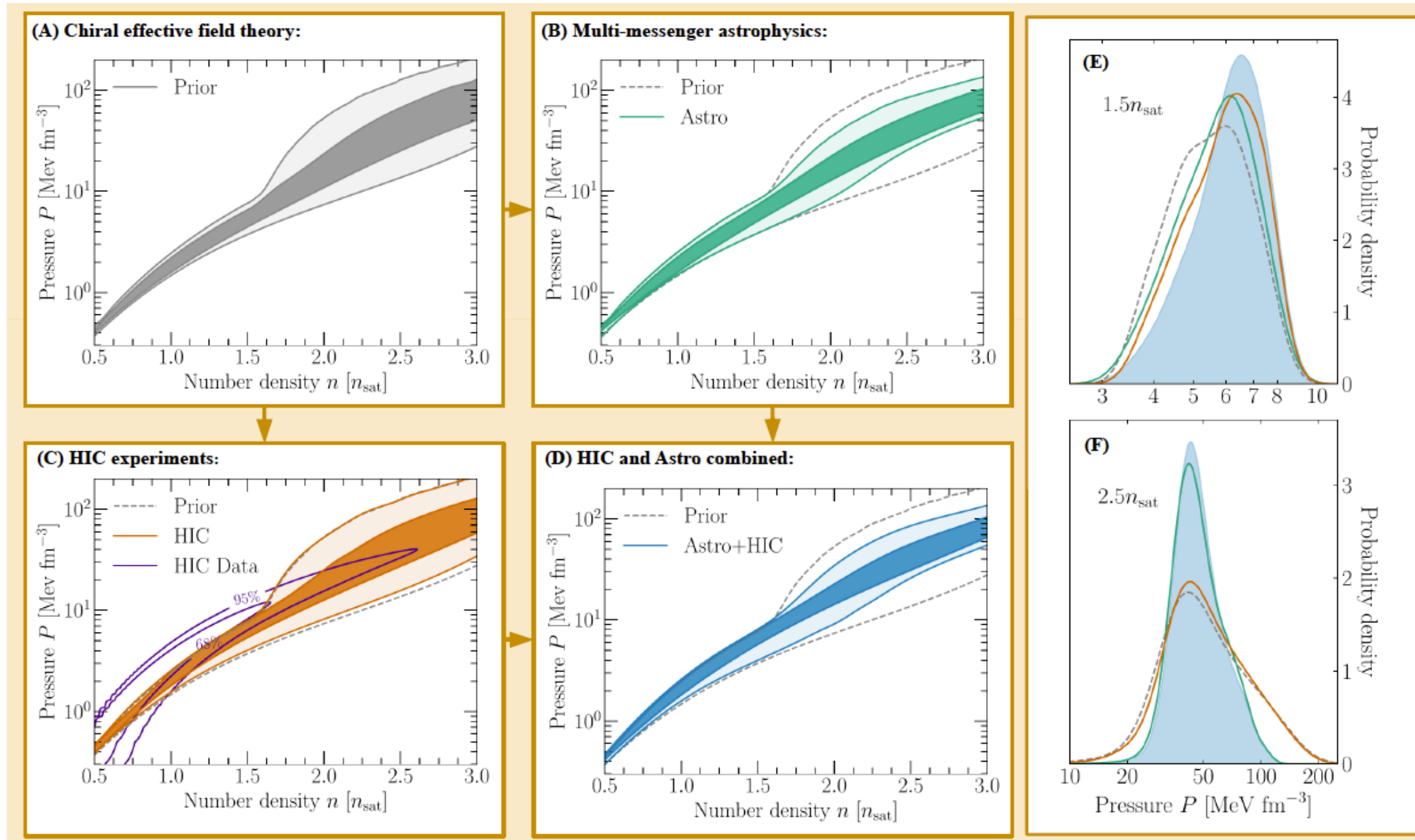


M. Omana Kuttan et al., PRL 131, 2023

Combining with Astrophysics

- Combination of analysis of heavy-ion data and astrophysical constraints

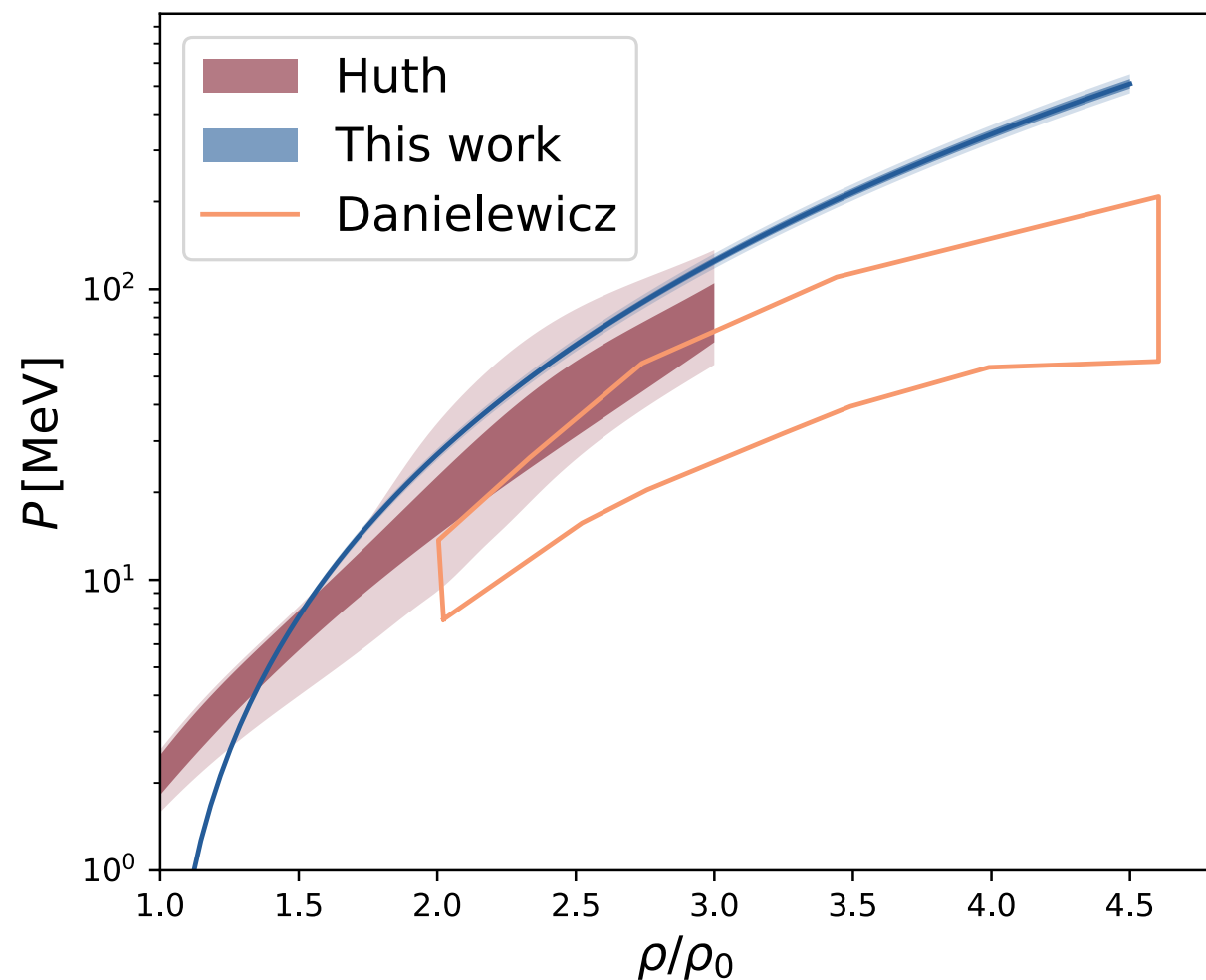
S. Huth et al., Nature 606, 2022



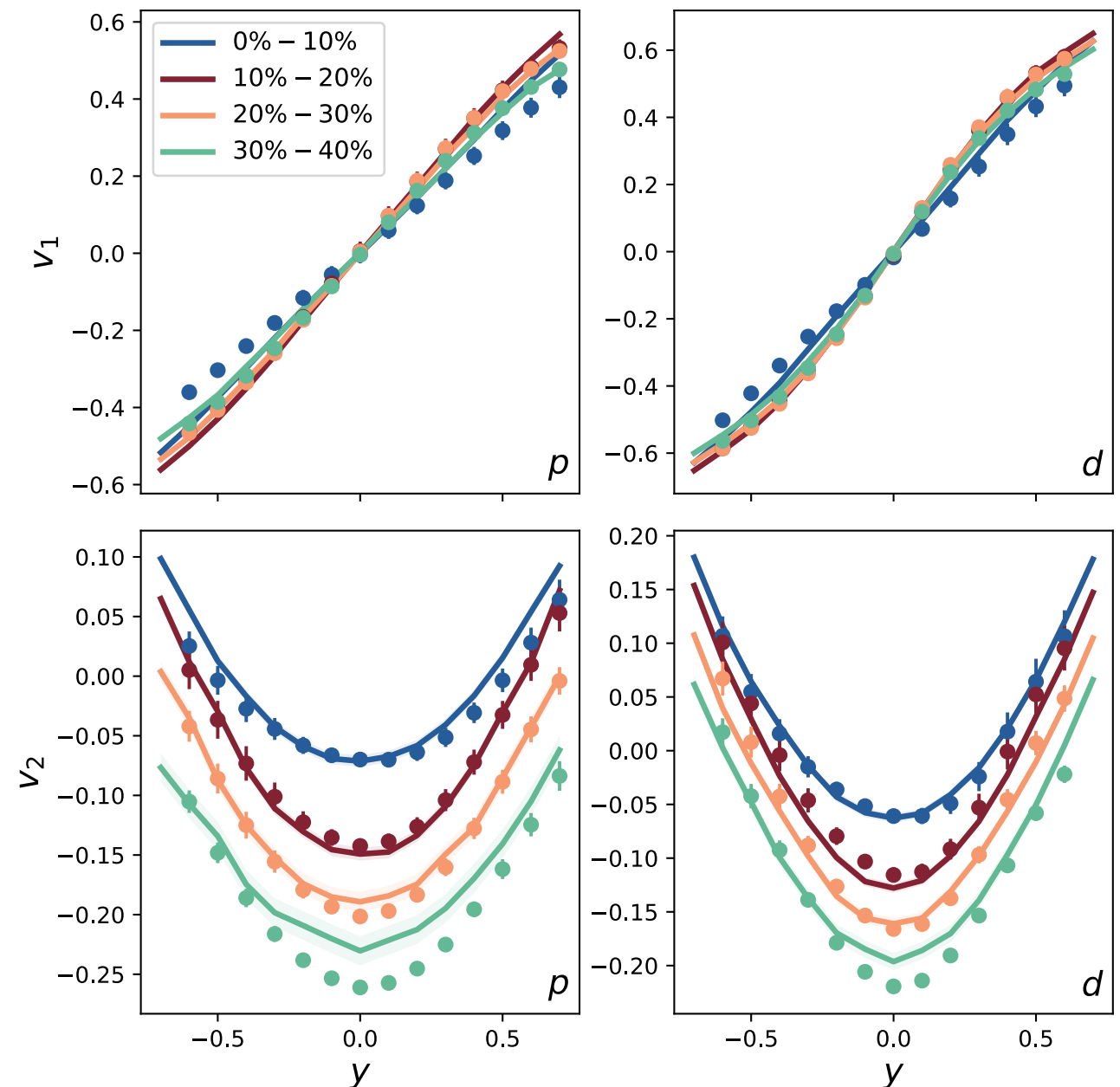
- Dependence of results on prior based on chiral effective field theory

Bayesian Analysis with HADES Data

- Comparing the maximum of the posterior distribution to data



J. Mohs, S. Spies, HE, PRC 112 (2025)

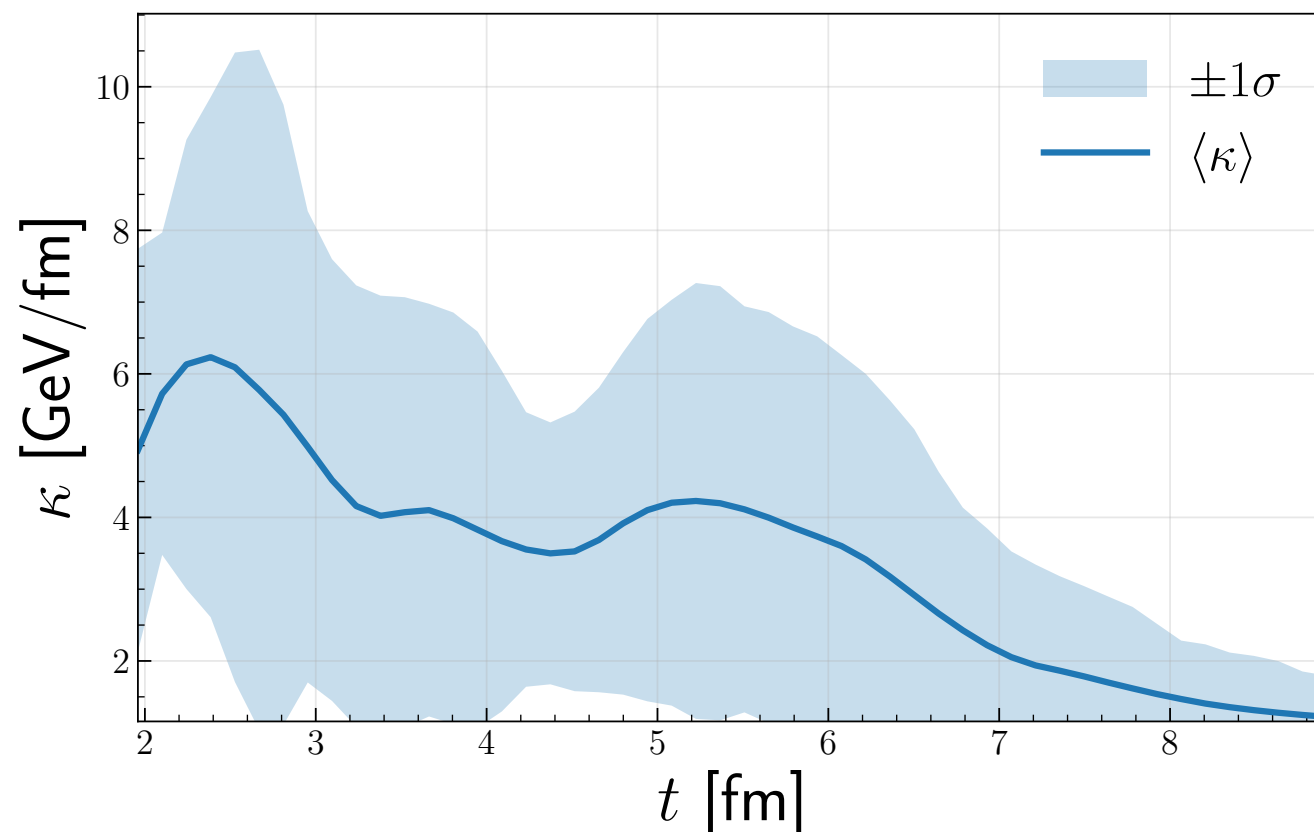


- Not all data perfectly reproduced but good agreement overall
The pion and kaon yields also agree with HADES measurements

Strings and Rope Formation

Towards Collectivity

- Introducing rope formation in a non-equilibrium transport approach
- Does one reach the same level of collectivity as in a hybrid approach?
- Idea: Overlapping strings lead to larger string tension following the Angantyr+Ropes approach

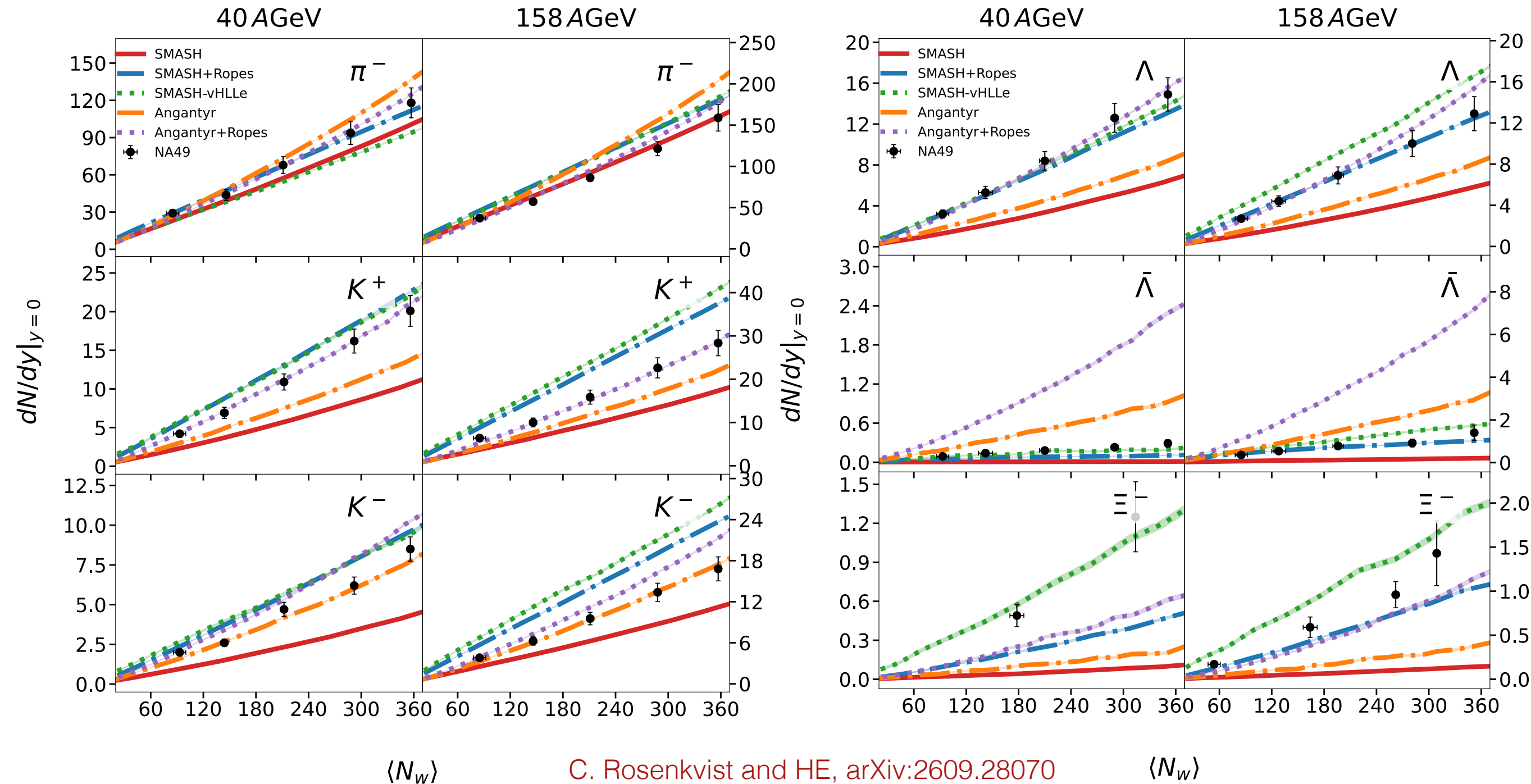


- Mean string tension over time in a Pb+Pb collision in SMASH at $\sqrt{s_{\text{NN}}} = 17.3$ GeV (default is 1 GeV)

C. Rosenkvist and HE, arXiv:2609.28070

Strangeness Production

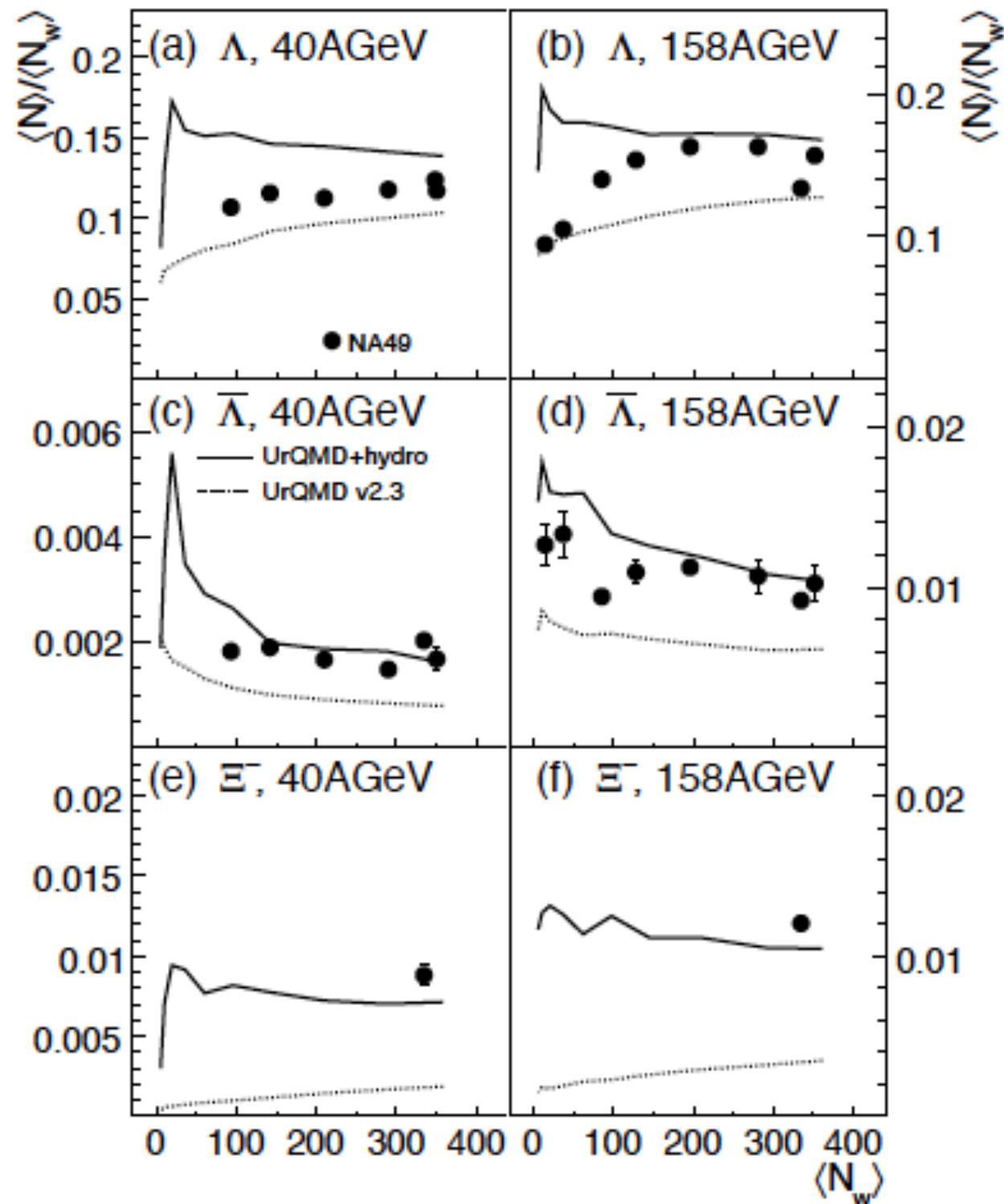
- Ropes mechanism enhances strangeness production



C. Rosenkvist and HE, arXiv:2609.28070

- Ropes lead to similar results as full hybrid approach

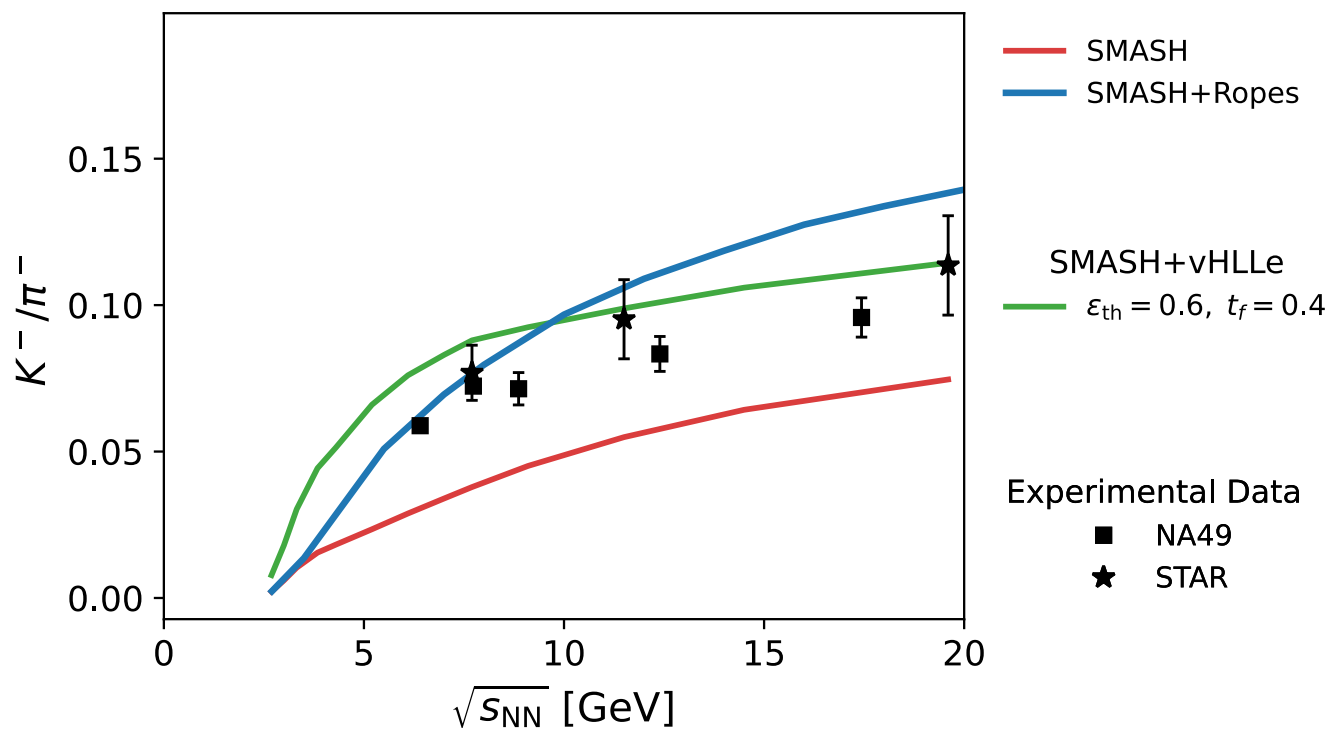
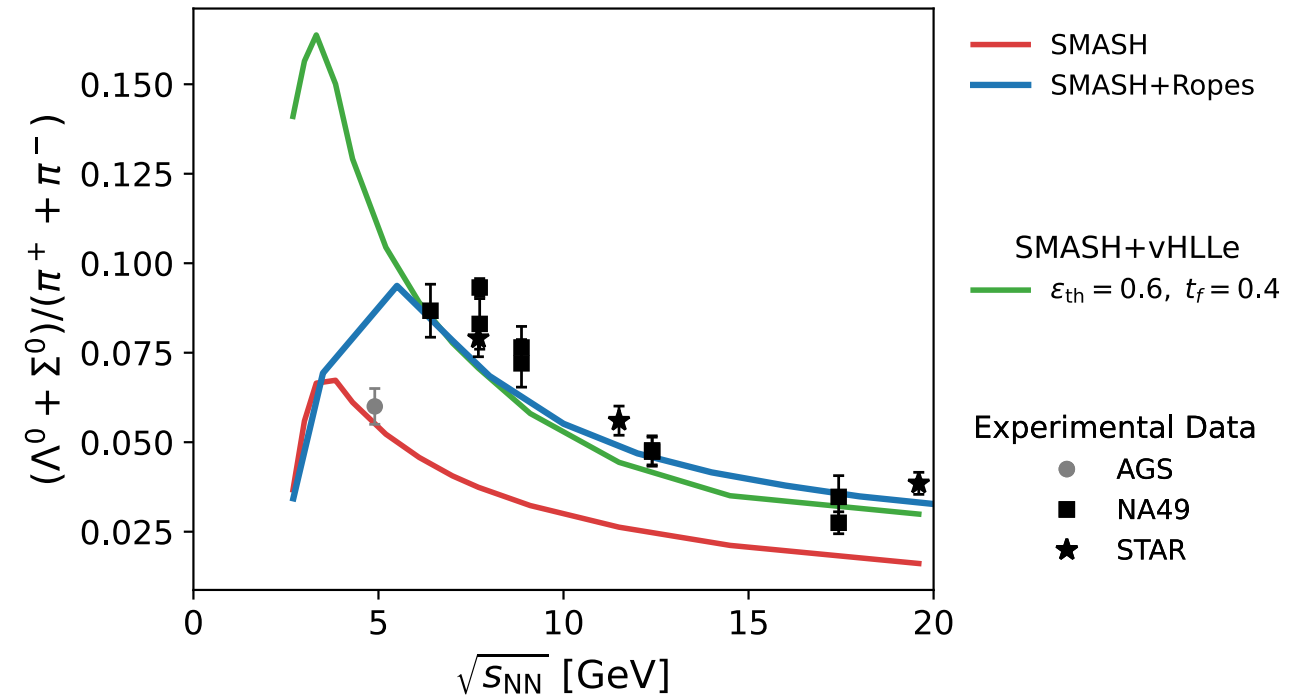
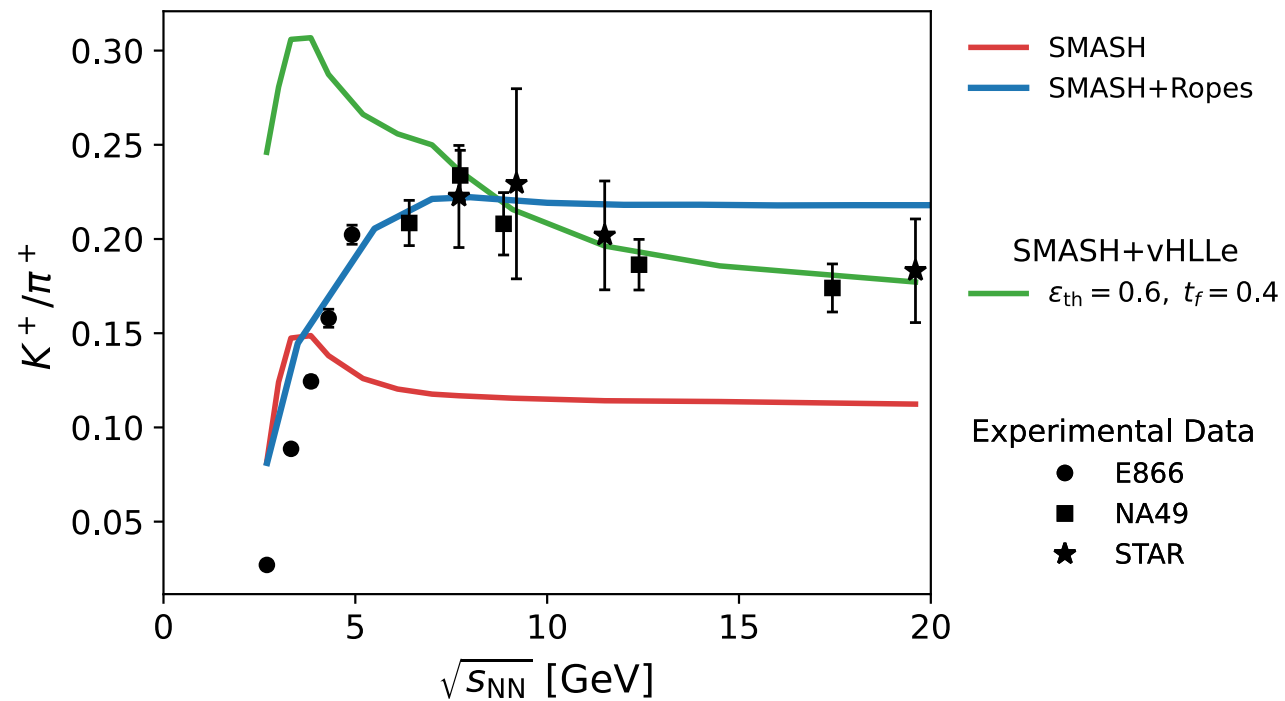
Similar Trends seen before



- In particular multi-strange baryons are sensitive to hot and dense stage
- Measurements of rare species is one of the goals for CBM at FAIR
- Sensitivity to the equation of state is expected

HP et al, PRC 80, 2009

Excitation Function



- Rope formation interpolates between pure transport and hybrid approach as a function of beam energy

C. Rosenkvist and HE, arXiv:2609.28070

Hybrid Approaches

SMASH-vHLL E Hybrid Approach

- Modular hybrid approach for intermediate and high energy heavy-ion collisions
- Open source and public

SMASH

- Hadronic transport approach
- Initial conditions

+

vHLL E

- 3+1 D viscous hydrodynamics (event-by-event)
- Cornelius routine for hypersurface

+

smash-hadron-sampler

- Cooper-Frye sampler
- Particlization of fluid elements

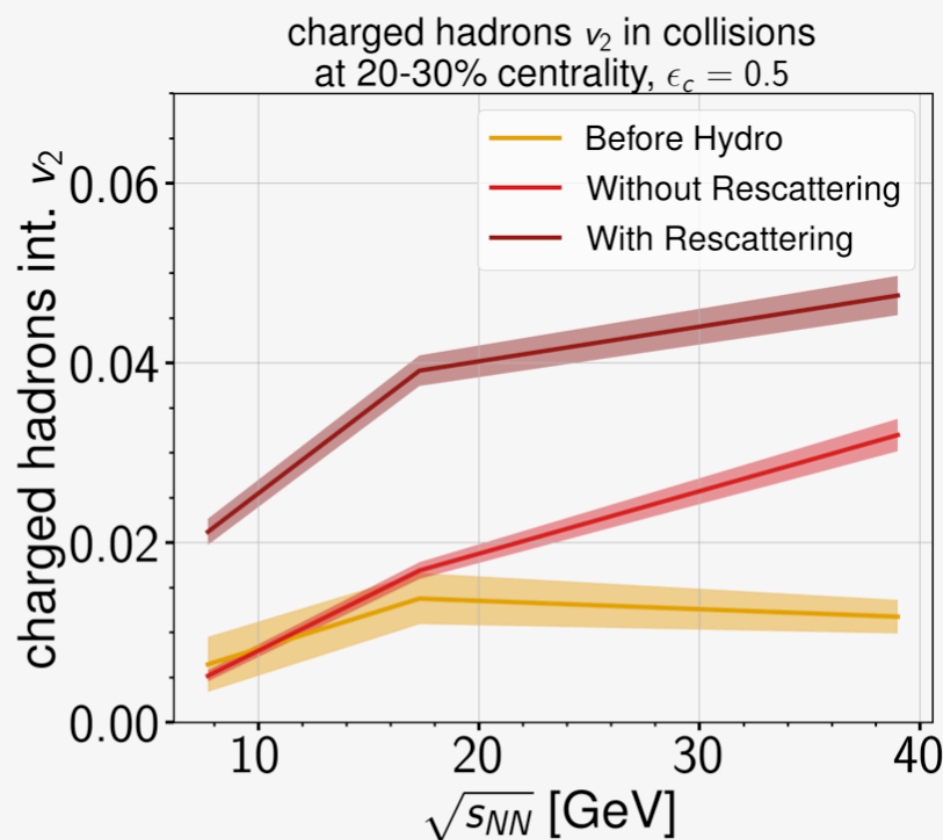
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SMASH

- Hadronic transport approach
- Evolution of hadronic rescattering

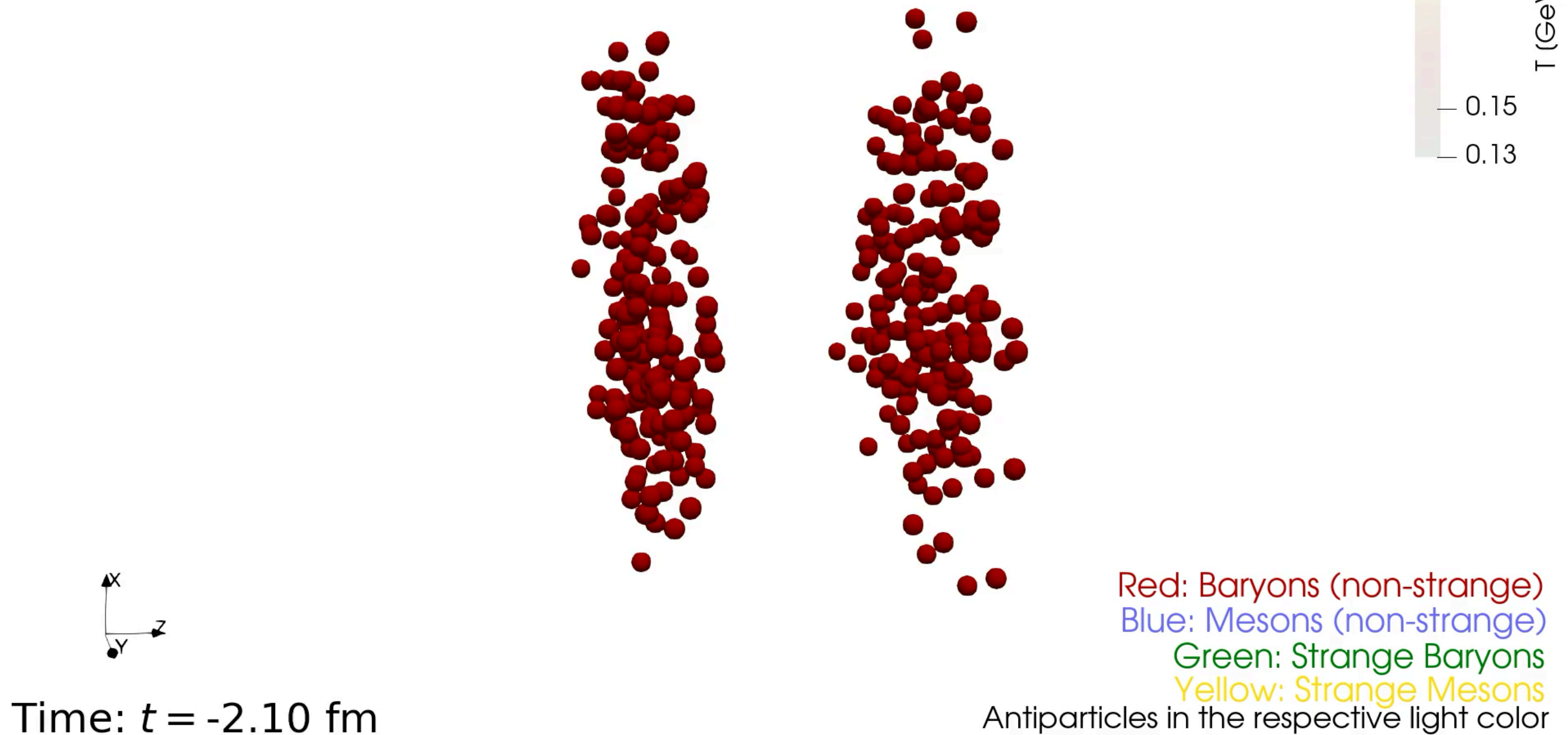
A. Schäfer et al., Eur.Phys.J.A 58 (2022)
 Huovinen et al.: Eur. Phys. J A 48 (2012)
 Karpenko et al.: PRC 91, 064901 (2015)
 Karpenko et al.: Comput. Phys. Commun. 185 (2014)

<https://github.com/smash-transport/smash-vhll e-hybrid>



Hybrid Visualization

SMASH-vHLE-Hybrid
Au-Au @ $\sqrt{s_{NN}} = 7.7$ GeV, $b = 0$ fm



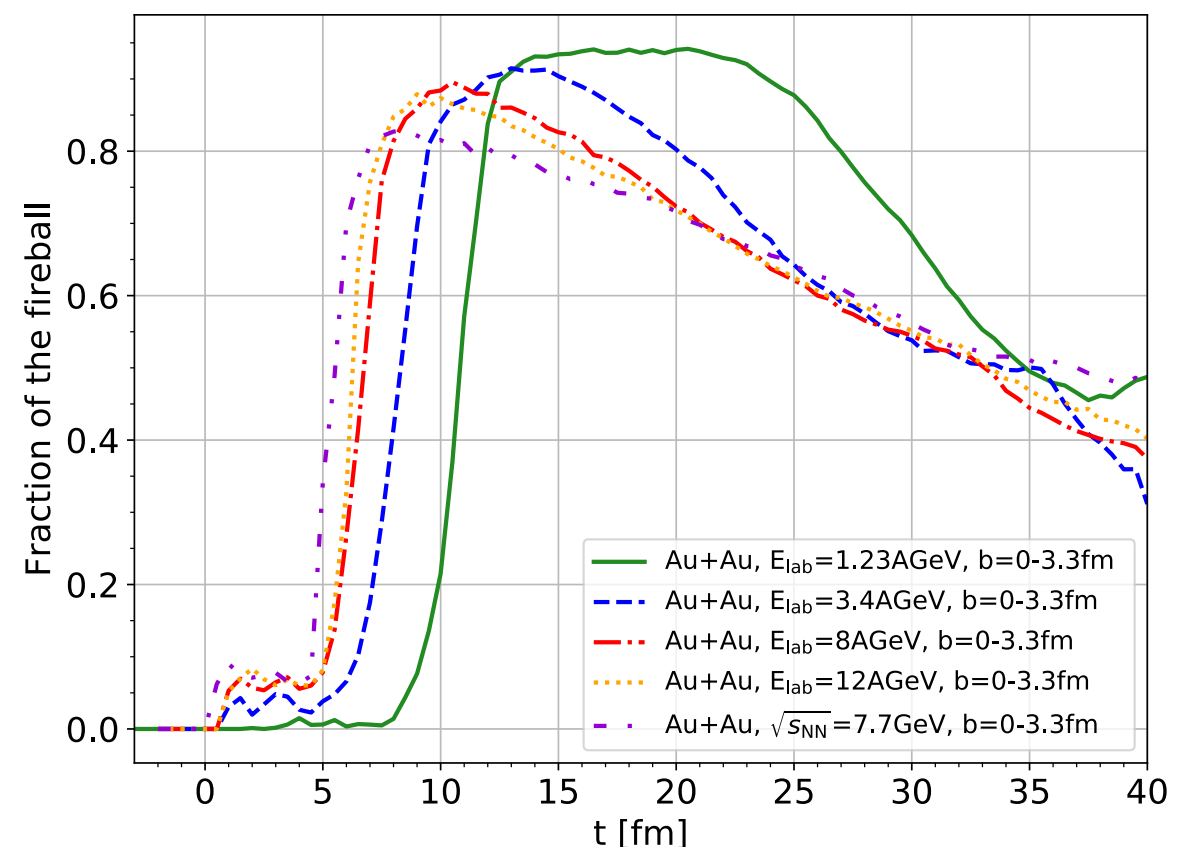
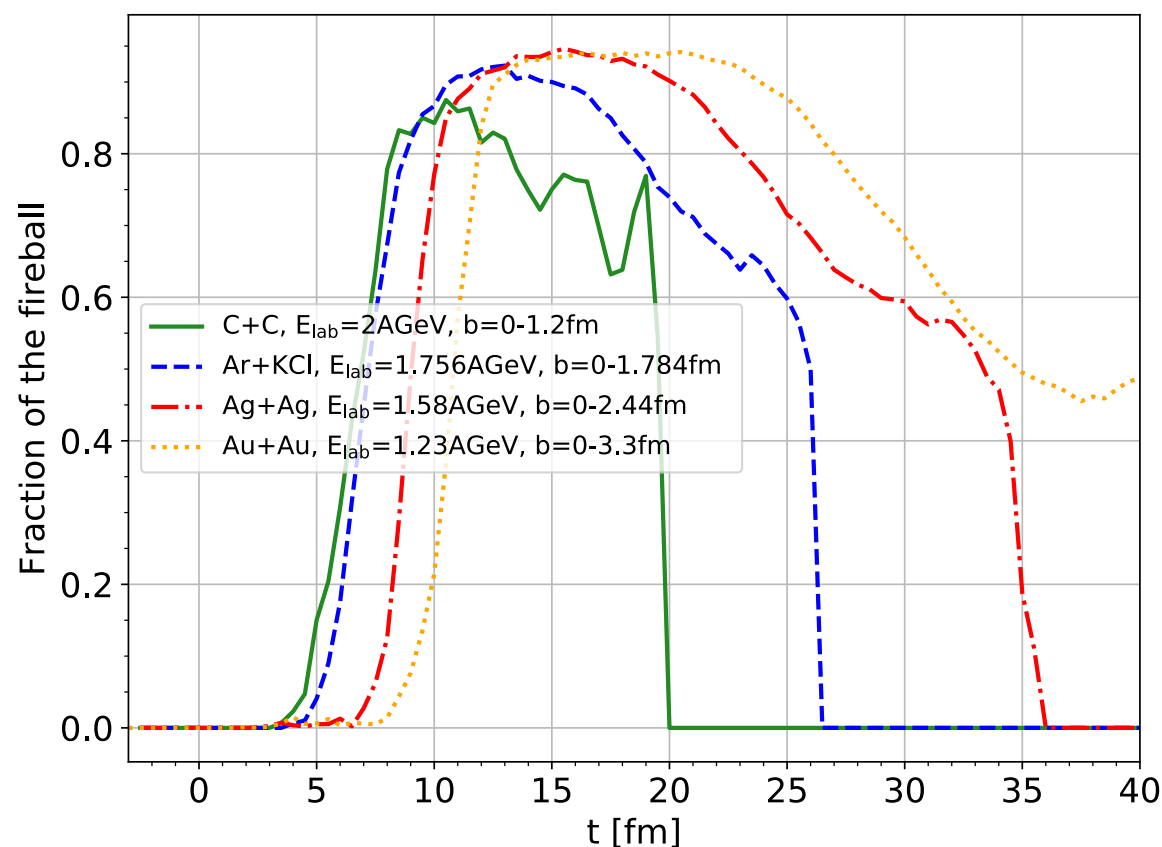
<https://cloud.itp.uni-frankfurt.de/s/8HWkFt8i8yJWbWT>

Dynamical Fluidization

Local Equilibrium

- Percentage of fireball close to local equilibrium in different collision systems (left) and in Au+Au collisions at different beam energies (right)

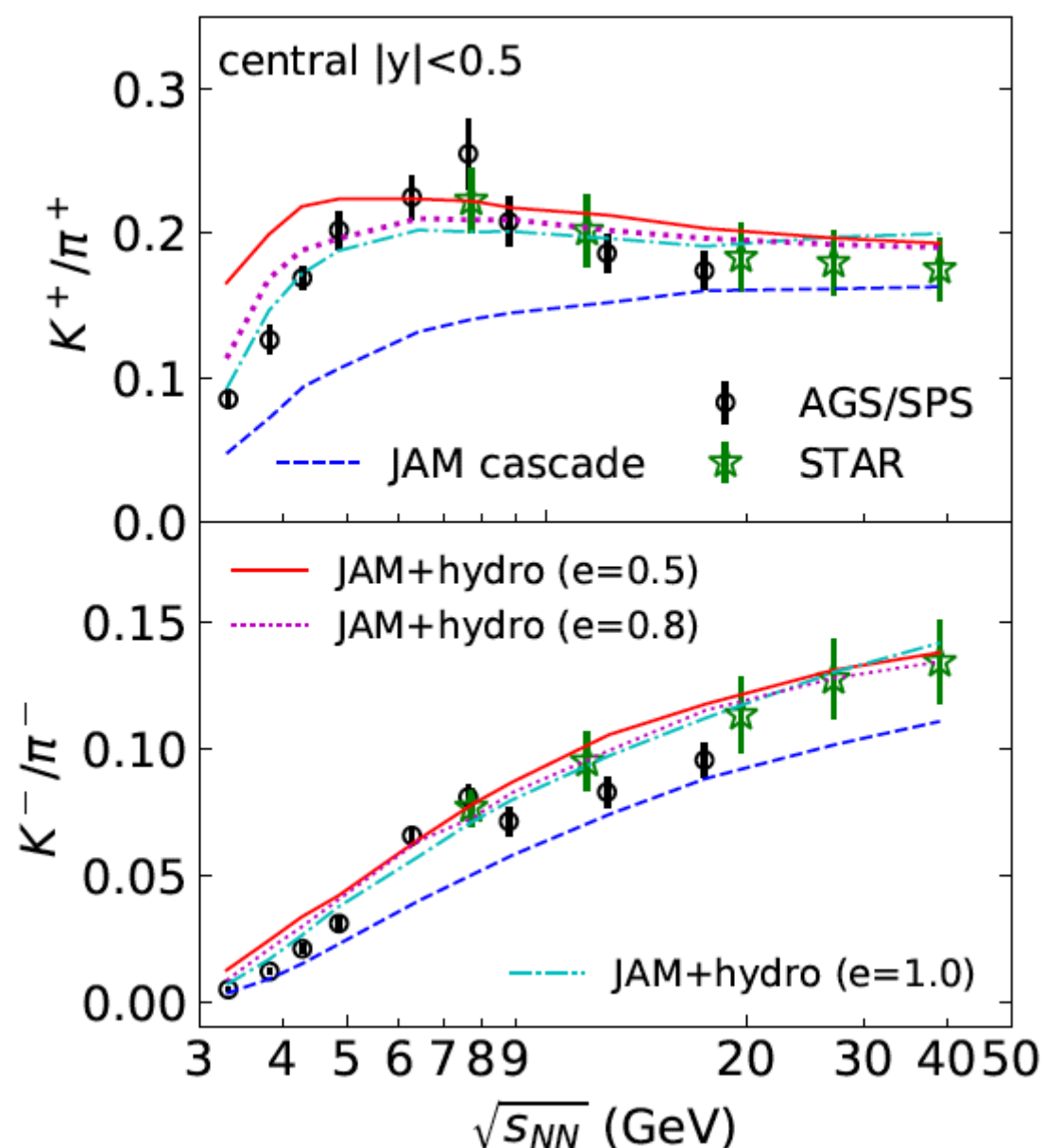
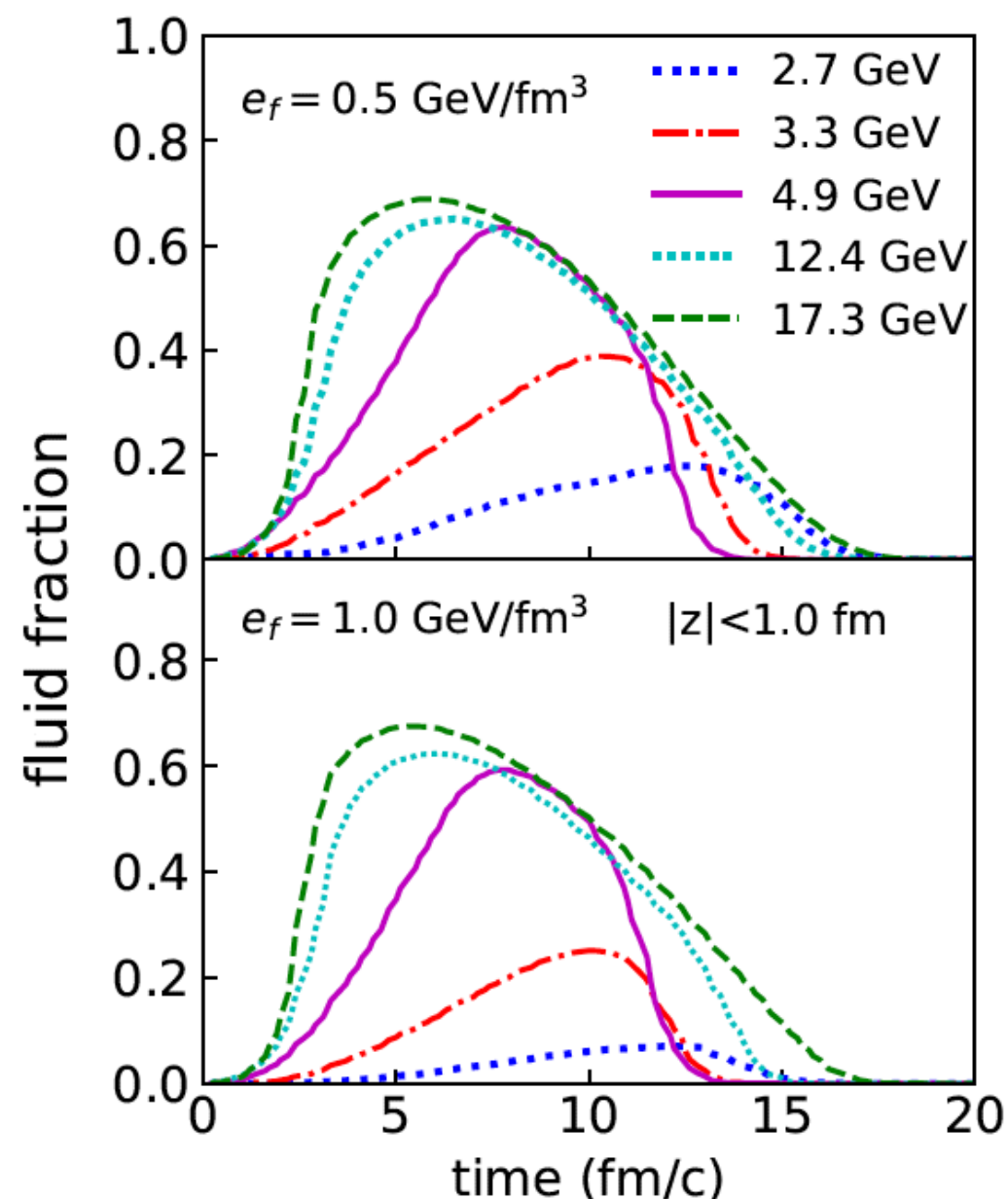
$$X, Y < 0.3 \text{ and } \varepsilon > 1 \text{ MeV/fm}^3$$



- Calculation within coarse-grained SMASH hadronic transport approach by investigating properties of $T_{\mu\nu}$

G. Inghirami and H. Elfner, EPJC 82 (2022)

JAM+Fluid Dynamics

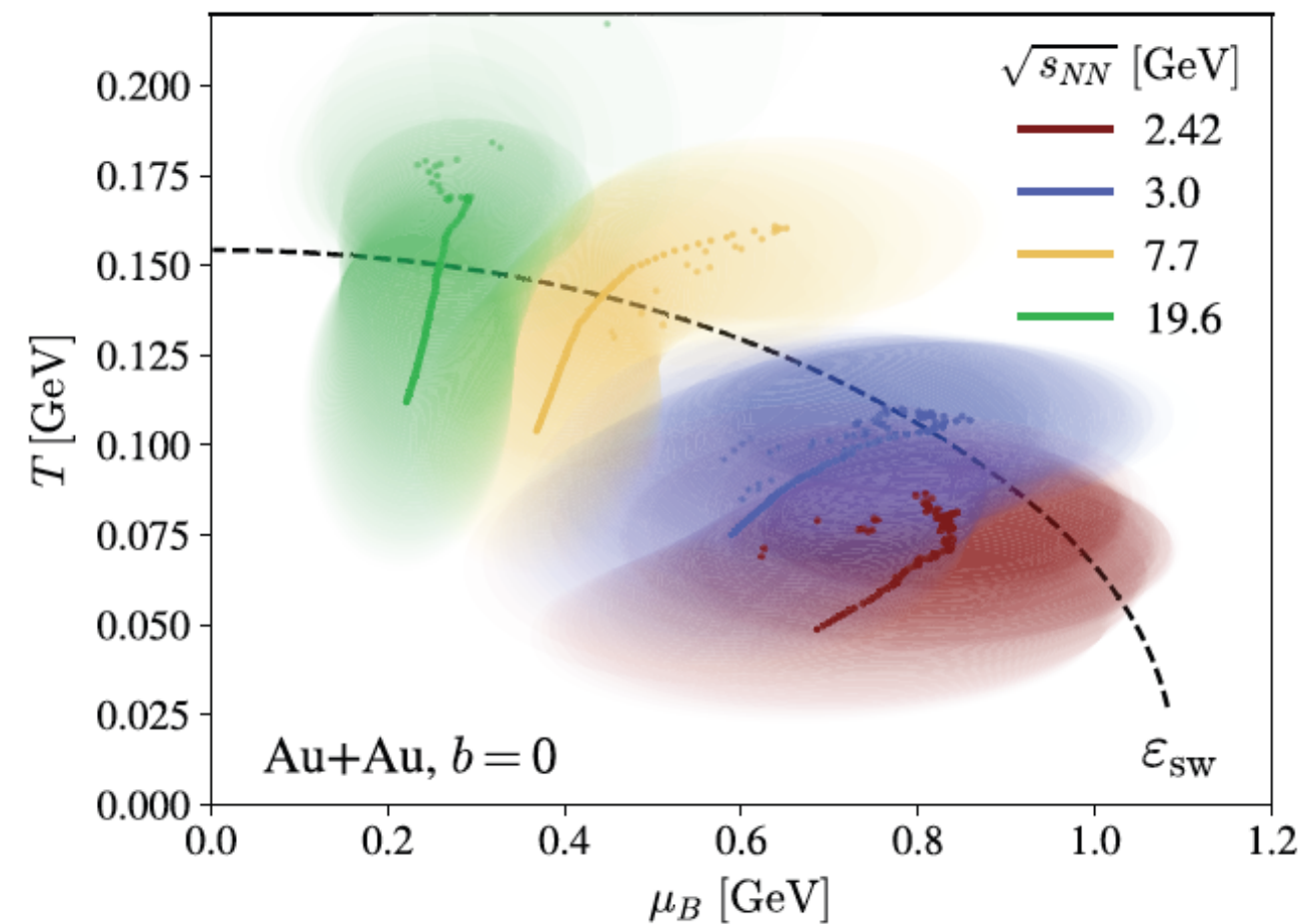
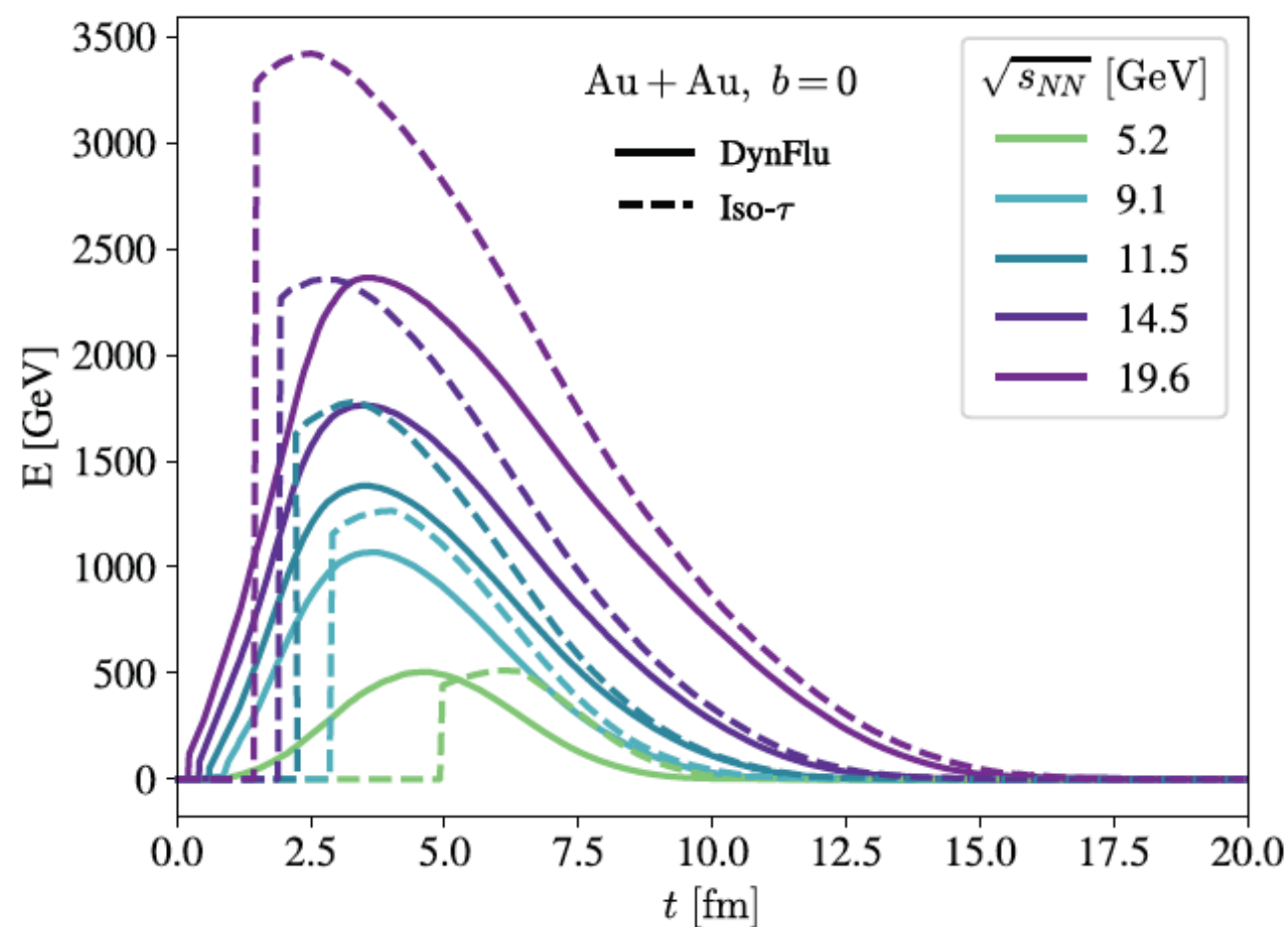


- Energy density based decision of fluid formation
- Strangeness production is enhanced

Y. Akamatsu et al, PRC 98, 2018

SMASH-vHLLC Hybrid

- SMASH particles are converted to fluid when the cells get to high enough energy density
- Allows to apply hybrid approach down to ~ 1 GeV/nucleon
- Phase transition can be controlled within hydrodynamics

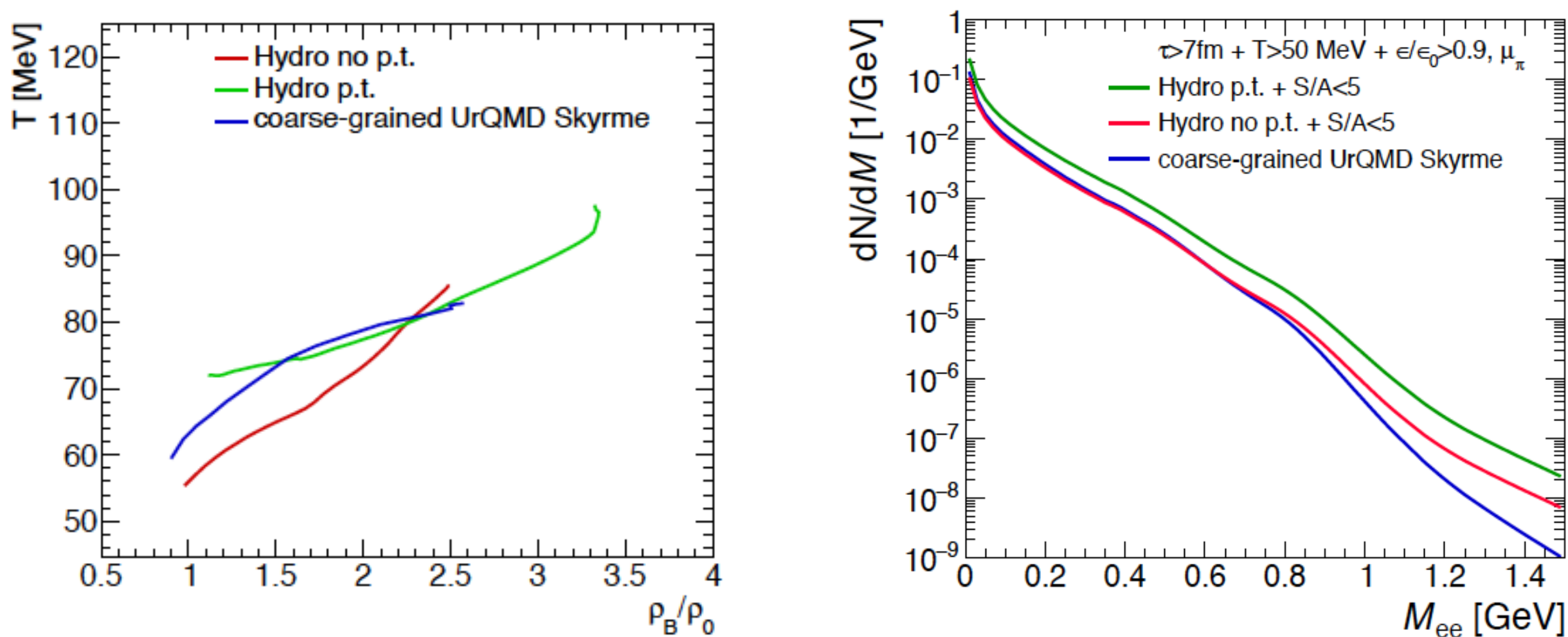


R. Góes-Hirayama et al, PRC 113, 2026

Phase Transition Signatures

Dilepton Emission

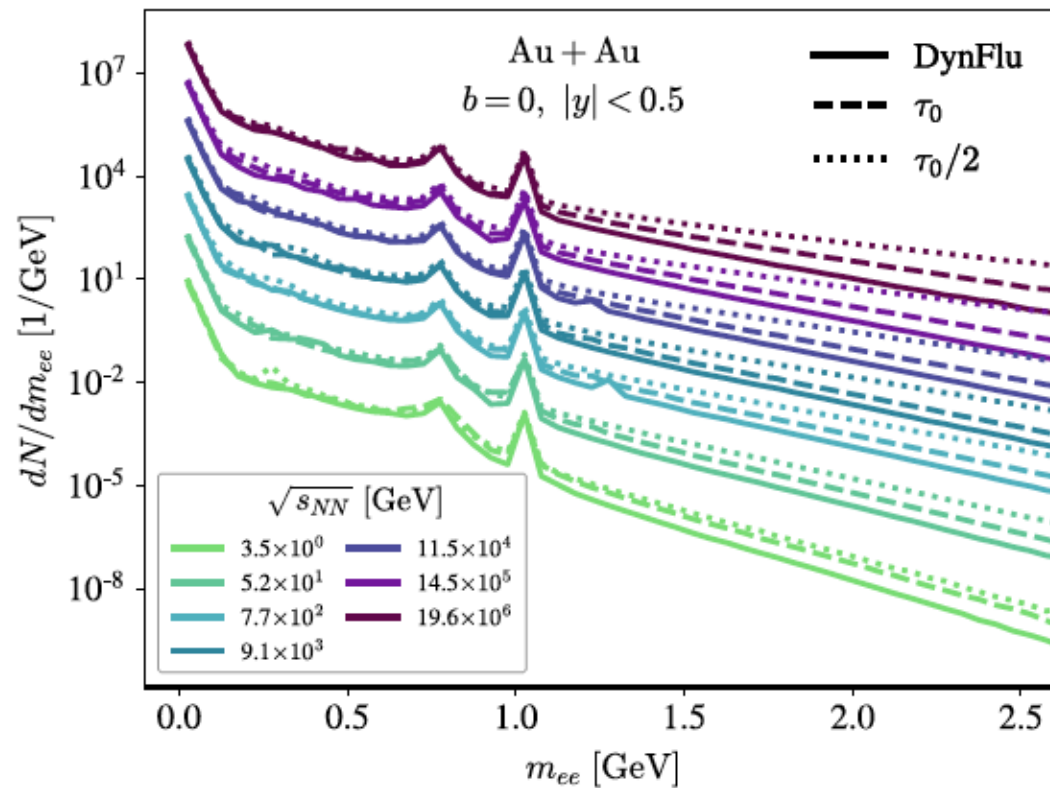
- Coarse-grained UrQMD compared to UrQMD hybrid approach with and without first order transition



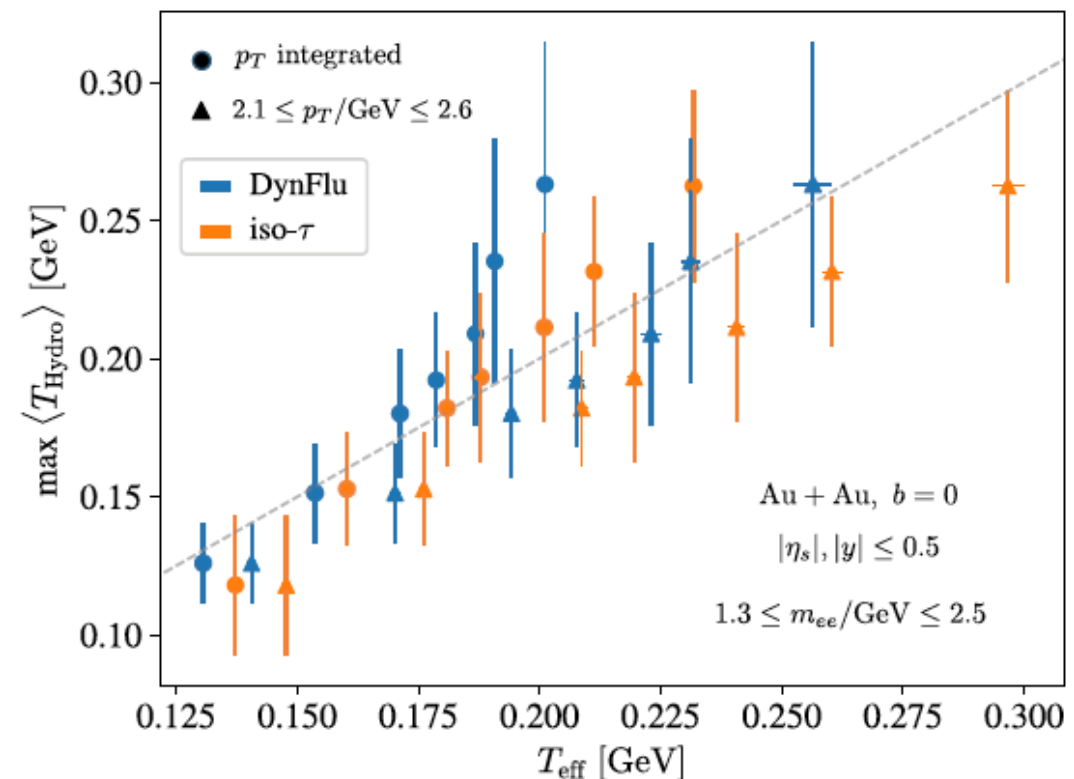
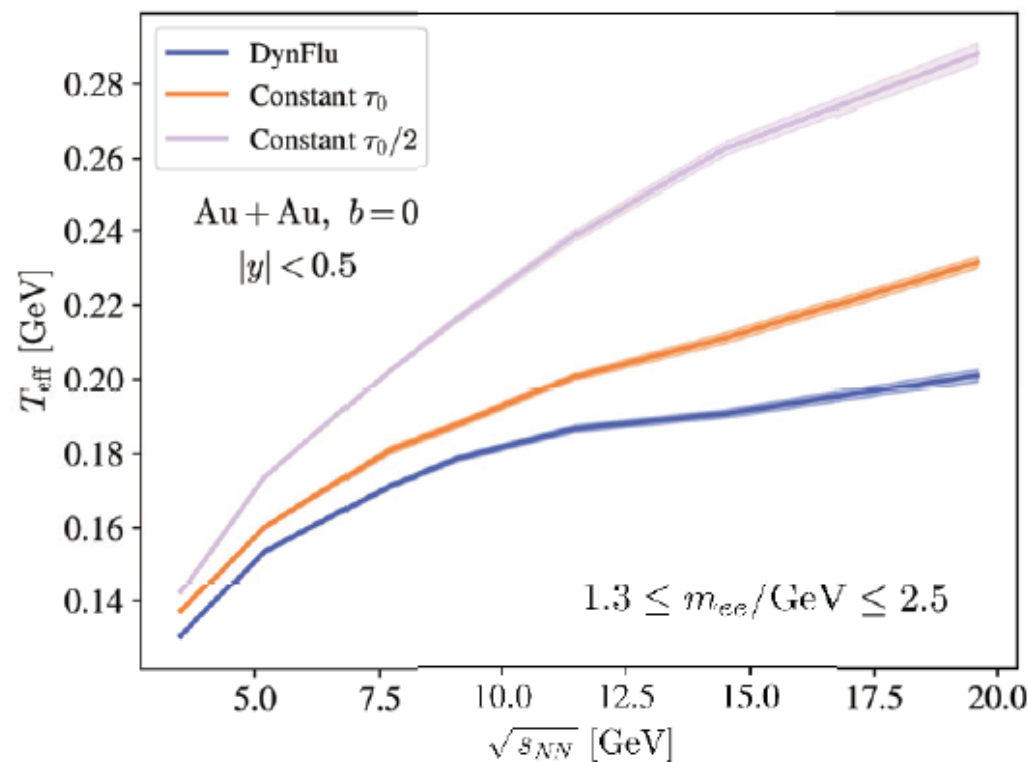
- Dilepton emission is enhanced due to latent heat

F. Seck et al, PRC 106, 2022

Dileptons as Thermometer



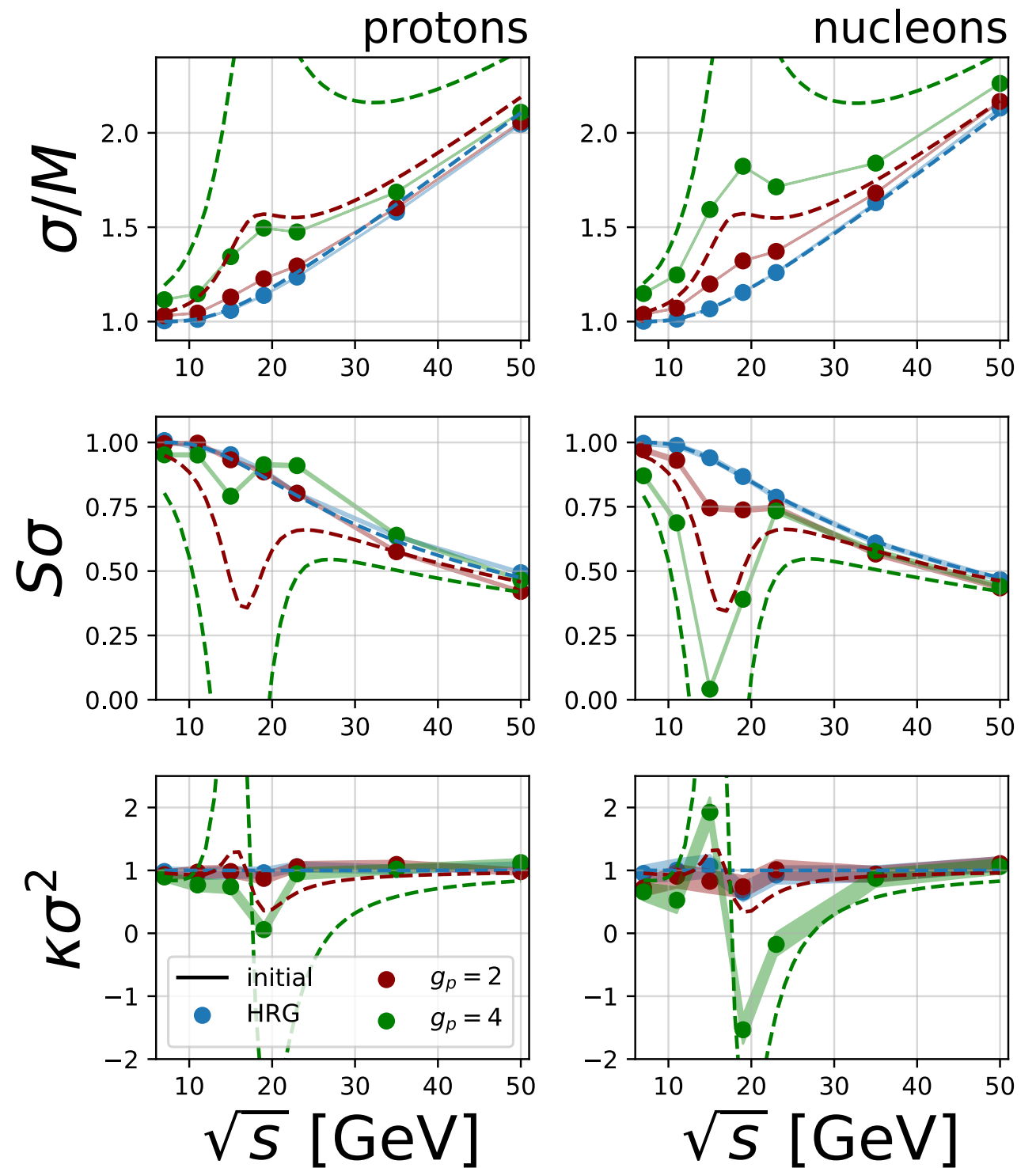
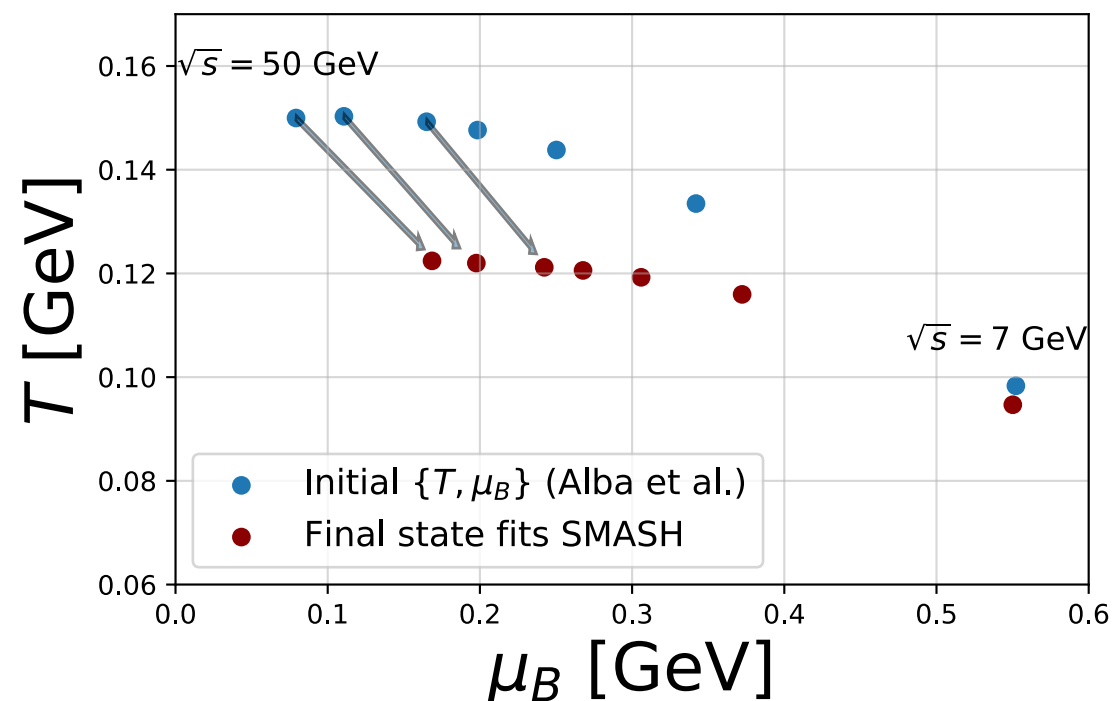
- Dilepton production is sensitive to initial conditions
- Effective temperature tracks maximum temperature of fireball



Survival of Critical Fluctuations

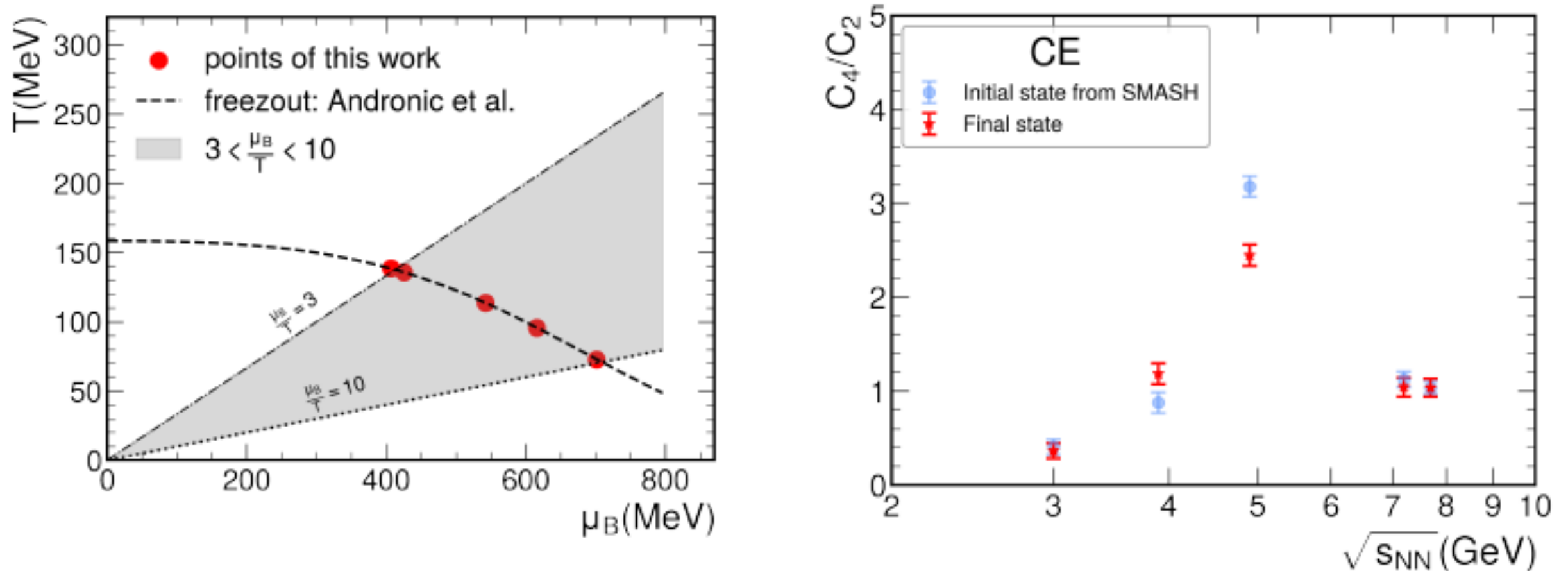
J. Hammelmann et al, PRC 110 (2024)

- Plugging critical fluctuations in an expanding sphere with full SMASH hadronic dynamics
- Signal survives, if coupling strong enough



Hadronic Rescattering Effect

FRG input from W.-J. Fu et al, PRD 111 (2015) in SMASH, Q. Lin et al, arXiv:2608.28299



- Cumulant ratio as a function of beam energy from FRG calculations
- Rescattering reduces height of the peak but leaves structure in place

Gearing up for FAIR

Construction Site FAIR



GSI, D. Fehrenz

- SIS-100 tunnel is ready
- Many buildings for experiments are ready as well
- First beam time with SIS-100 expected in 2028-2030

CBM at FAIR

Visualization of CBM at FAIR

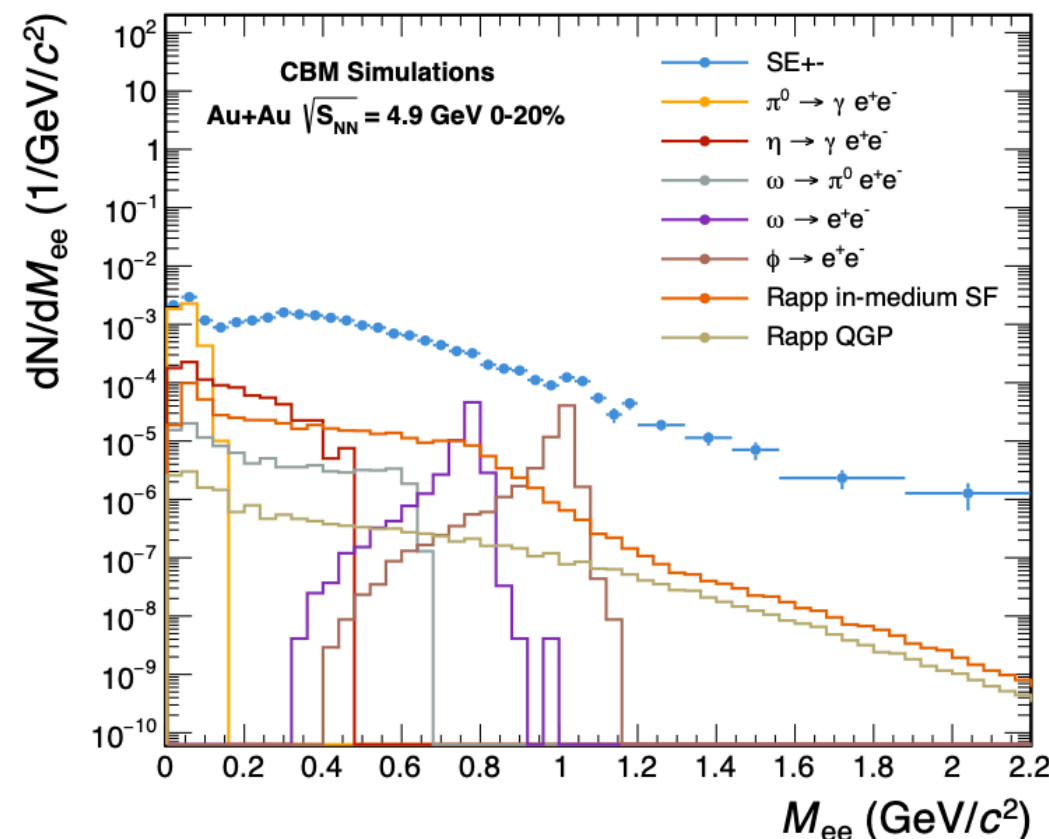


- Fixed Target Experiment at high densities
- Very high luminosity -> rare observables and high statistics

Latest Developments

- CBM White paper:
 - multi-strange hadron production and their flow coefficients,
 - high-order net-baryon cumulants
 - dileptons
 - production of double-strange hypernuclei

CBM collaboration, arXiv:2606.16395



- QCD at FAIR initiative

White paper: Hadron Physics Opportunities at FAIR

- Pion and proton beams to study elementary reaction properties
- From baseline to medium modifications

J. Messchendorp et al, arXiv:2512.15986

Summary

- Low beam energies provide access to high baryon densities
- Critical endpoint and first order transition to QGP expected in that energy regime
- Theoretical models are being developed based on transport or as hybrid approaches
- Excitation functions provide interesting information on amount of collectivity
- Dileptons and net baryon fluctuations are interesting observables
- CBM at FAIR will start data taking within the next years
- Theory support is needed to extract full information