The UrQMD transport model and its applications

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Most interesting results

- Listen to the talk of

- Tom Reichert (Tuesday) – Thermal model or not?!
- Jan Steinheimer (Wednesday) – Hyper clusters!

Motivation

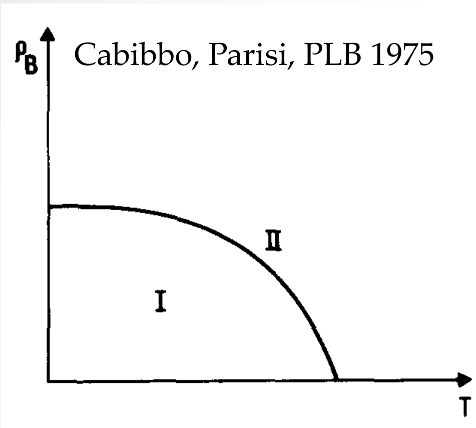
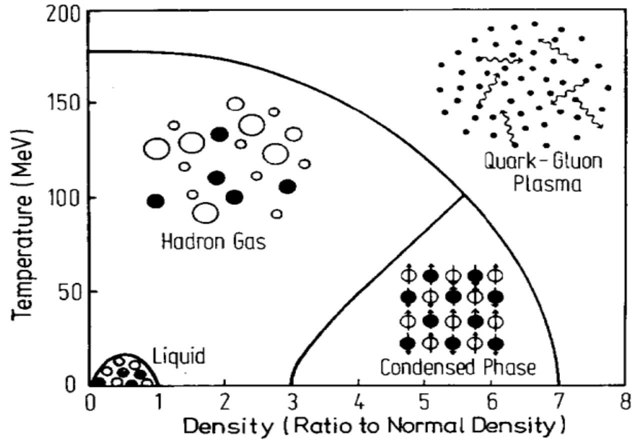
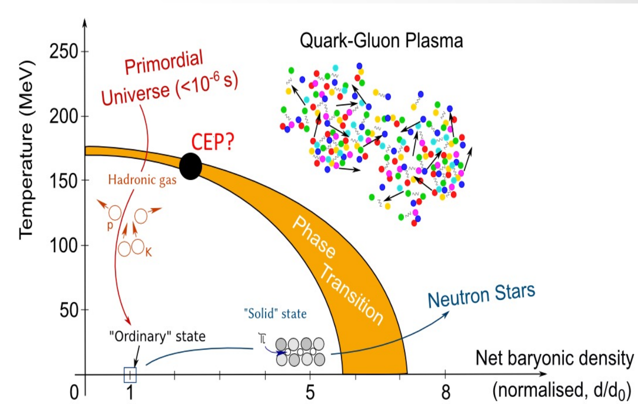


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.



W. Greiner, PR 1986



A. Maire, CERN, 2015

- Learn about phase structure of QCD
- Explore strangeness, fluctuations, leptons, clusters, spectra, flow, fluctuations, correlations,…
- Unfortunately we do not have QCD in box → simulations
- Unfortunately modelling a phase transition is still not fully possible

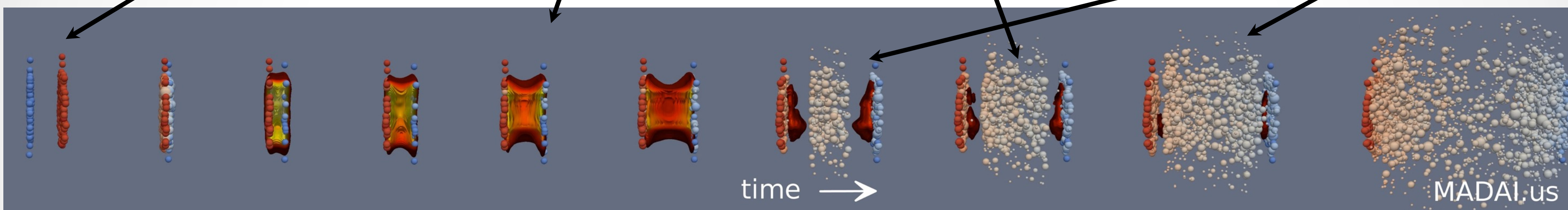
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Cluster emissions vs. formation



$1x\ 10^{-23}$ s

10×10^{-23} s

30×10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics/ Particle dynamics → Hadron Transport

At high energies hybrid approaches are very successful for the description of the dynamics

Figure adapted from H. Elfner, arXiv:1404.1763

Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Hadron cascade (standard mode)

- Based on the propagation of hadrons
- Rescattering among hadrons is fully included
- String excitation/decay (LUND picture/PYTHIA) at higher energies
- Provides a solution of the relativistic n-body transport eq.:

  $$p^{\mu} \cdot \partial_{\mu} f_i(x^{\nu}, p^{\nu}) = \mathcal{C}_i$$

  The collision term C includes more than 100 hadrons
- "*Standard Reference*" for low and intermediate energy hadron and nucleus interactions

M. Bleicher et al, J.Phys. G25 (1999) 1859-1896

List of included particles

nucleon	Δ	Λ	Σ	Ξ	Ω
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1192}	Ξ_{1317}	Ω_{1672}
N_{1440}	Δ_{1600}	Λ_{1405}	Σ_{1385}	Ξ_{1530}	
N_{1520}	Δ_{1620}	Λ_{1520}	Σ_{1660}	Ξ_{1690}	
N_{1535}	Δ_{1700}	Λ_{1600}	Σ_{1670}	Ξ_{1820}	
N_{1650}	Δ_{1900}	Λ_{1670}	Σ_{1775}	Ξ_{1950}	
N_{1675}	Δ_{1905}	Λ_{1690}	Σ_{1790}	Ξ_{2025}	
N_{1680}	Δ_{1910}	Λ_{1800}	Σ_{1915}		
N_{1700}	Δ_{1920}	Λ_{1810}	Σ_{1940}		
N_{1710}	Δ_{1930}	Λ_{1820}	Σ_{2030}		
N_{1720}	Δ_{1950}	Λ_{1830}			
N_{1900}		Λ_{1890}			
N_{1990}		Λ_{2100}			
N_{2080}		Λ_{2110}			
N_{2190}					
N_{2200}					
N_{2250}					

0^{-+}	1^{--}	0^{++}	1^{++}
π	ρ	a_0	a_1
K	K^*	K_0^*	K_1^*
η	ω	f_0	f_1
η'	ϕ	f_0^*	f_1'
1^{+-}	2^{++}	$(1^{--})^*$	$(1^{--})^{**}$
b_1	a_2	ρ_{1450}	ρ_{1700}
K_1	K_2^*	K_{1410}^*	K_{1680}^*
h_1	f_2	ω_{1420}	ω_{1662}
h_1'	f_2'	ϕ_{1680}	ϕ_{1900}

- Binary interactions between all implemented particles are treated
- Cross sections are taken from data or models
- Resonances are implemented in Breit-Wigner form
- No in-medium modifications

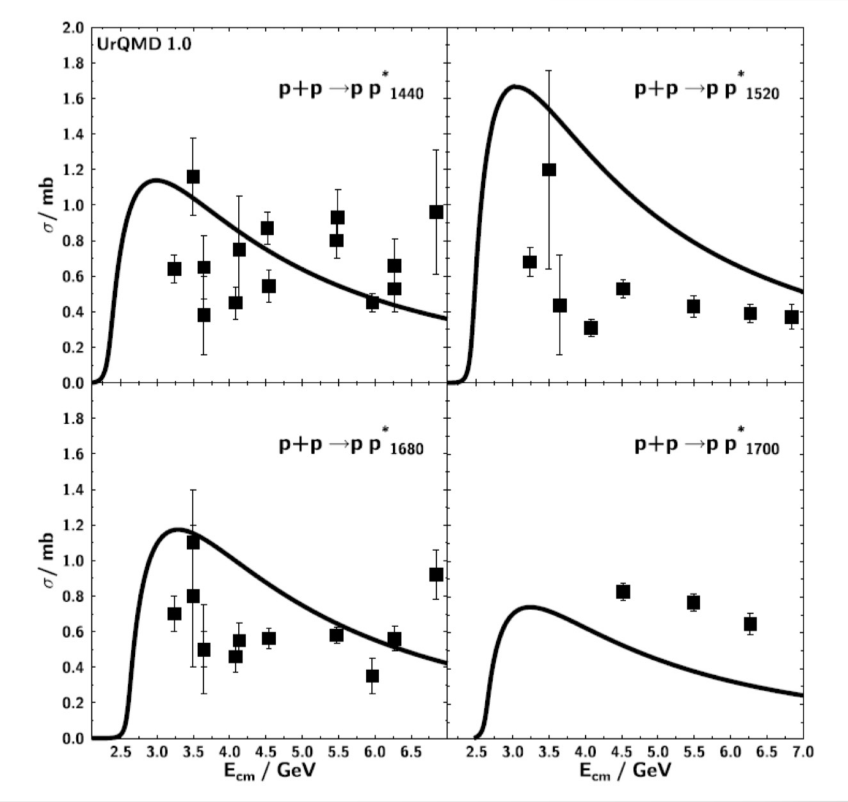
Baryon-baryon scattering cross section

- Phase space x matrix element:

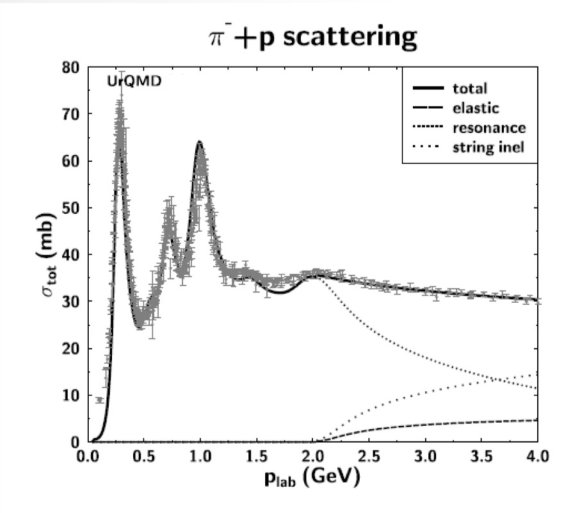
$$\sigma_{tot}^{BB}(\sqrt{s}) \propto (2S_D+1)(2S_E+1)\frac{\langle p_{D,E}\rangle}{\langle p_{A,C}\rangle}\frac{1}{s}|\mathcal{M}|^2$$

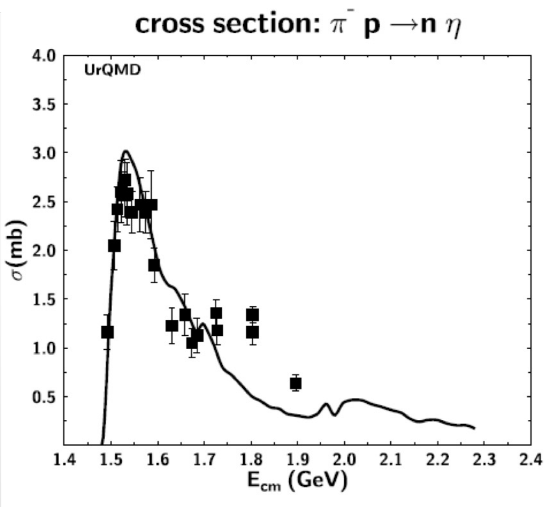
- Matrix element is fitted to data for groups of resonance channels
- Detailed balance is fulfilled for the inverse reaction:

$$\sigma(y \to x)\, p_y^2\, g_y = \sigma(x \to y)\, p_x^2\, g_x$$



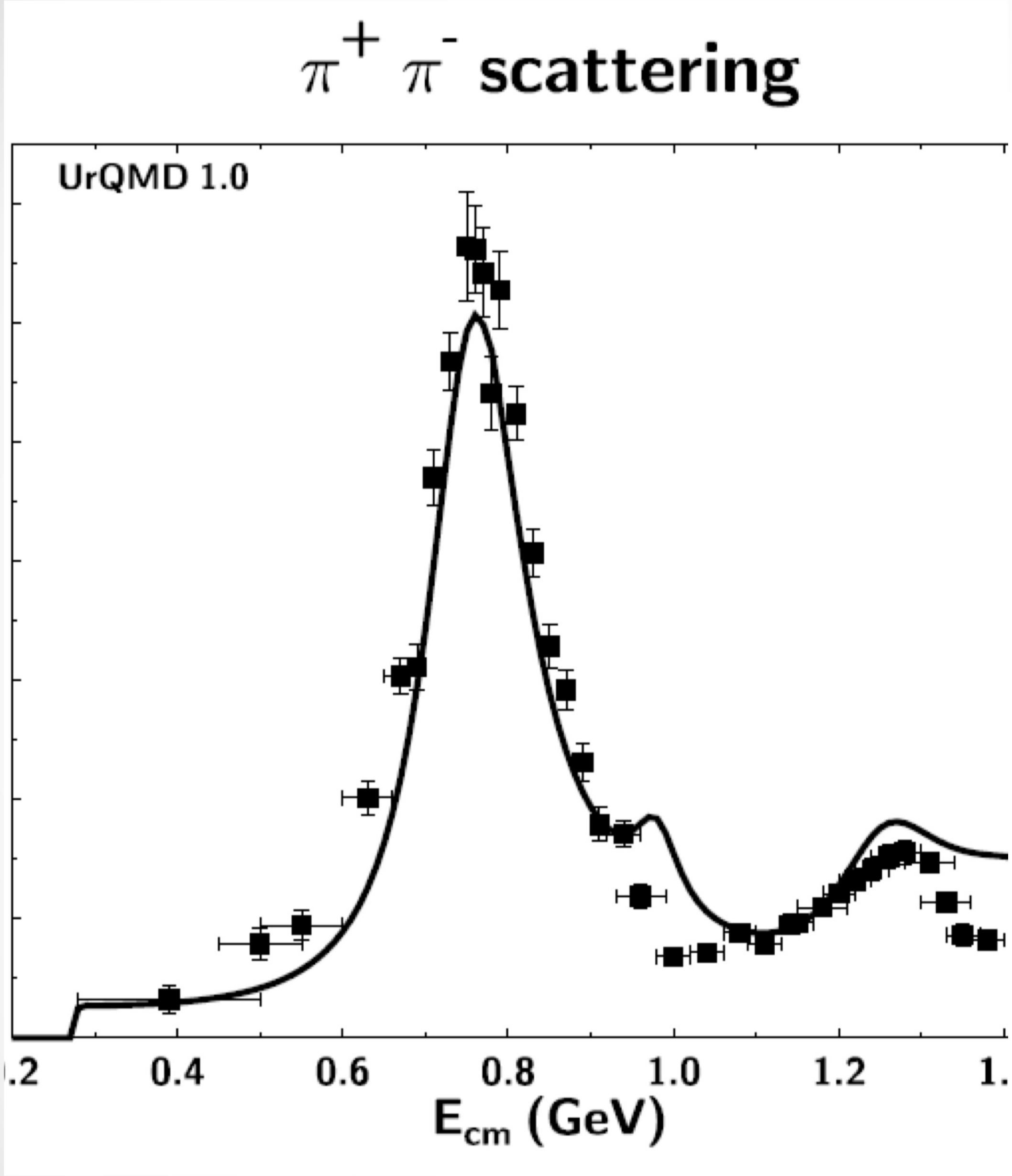
Meson-baryon scattering cross section (resonances)





resonance	mass	width	$N\gamma$	$N\pi$	$N\eta$	$N\omega$	$N\varrho$	$N\pi\pi$	$\Delta_{1232}\pi$	$N^*_{1440}\pi$	ΛK
N^*_{1440}	1.440	200		0.70				0.05	0.25		
N^*_{1520}	1.520	125		0.60				0.15	0.25		
N^*_{1535}	1.535	150	0.001	0.55	0.35			0.05		0.05	
N^*_{1650}	1.650	150		0.65	0.05			0.05	0.10	0.05	0.10
N^*_{1675}	1.675	140		0.45					0.55		
N^*_{1680}	1.680	120		0.65				0.20	0.15		
N^*_{1700}	1.700	100		0.10	0.05		0.05	0.45	0.35		
N^*_{1710}	1.710	110		0.15	0.20		0.05	0.20	0.20	0.10	0.10
N^*_{1720}	1.720	150		0.15			0.25	0.45	0.10		0.05
N^*_{1900}	1.870	500		0.35		0.55	0.05		0.05		
N^*_{1990}	1.990	550		0.05			0.15	0.25	0.30	0.15	0.10
N^*_{2080}	2.040	250		0.60	0.05		0.25	0.05	0.05		
N^*_{2190}	2.190	550		0.35			0.30	0.15	0.15	0.05	
N^*_{2220}	2.220	550		0.35			0.25	0.20	0.20		
N^*_{2250}	2.250	470		0.30			0.25	0.20	0.20	0.05	
Δ_{1232}	1.232	115.	0.01	1.00							
Δ^*_{1600}	1.700	200		0.15					0.55	0.30	
Δ^*_{1620}	1.675	180		0.25					0.60	0.15	
Δ^*_{1700}	1.750	300		0.20			0.10		0.55	0.15	
Δ^*_{1900}	1.850	240		0.30			0.15		0.30	0.25	
Δ^*_{1905}	1.880	280		0.20			0.60		0.10	0.10	
Δ^*_{1910}	1.900	250		0.35			0.40		0.15	0.10	
Δ^*_{1920}	1.920	150		0.15			0.30		0.30	0.25	
Δ^*_{1930}	1.930	250		0.20			0.25		0.25	0.30	
Δ^*_{1950}	1.950	250	0.01	0.45			0.15		0.20	0.20	

$$\sigma^{MB}_{tot}(\sqrt{s}) = \sum_{R=\Delta,N^*} \langle j_B, m_B, j_M, m_M \| J_R, M_R \rangle \frac{2S_R+1}{(2S_B+1)(2S_M+1)} \times \frac{\pi}{p^2_{cm}} \frac{\Gamma_{R\rightarrow MB}\Gamma_{tot}}{(M_R-\sqrt{s})^2+\Gamma^2_{tot}/4} ,$$

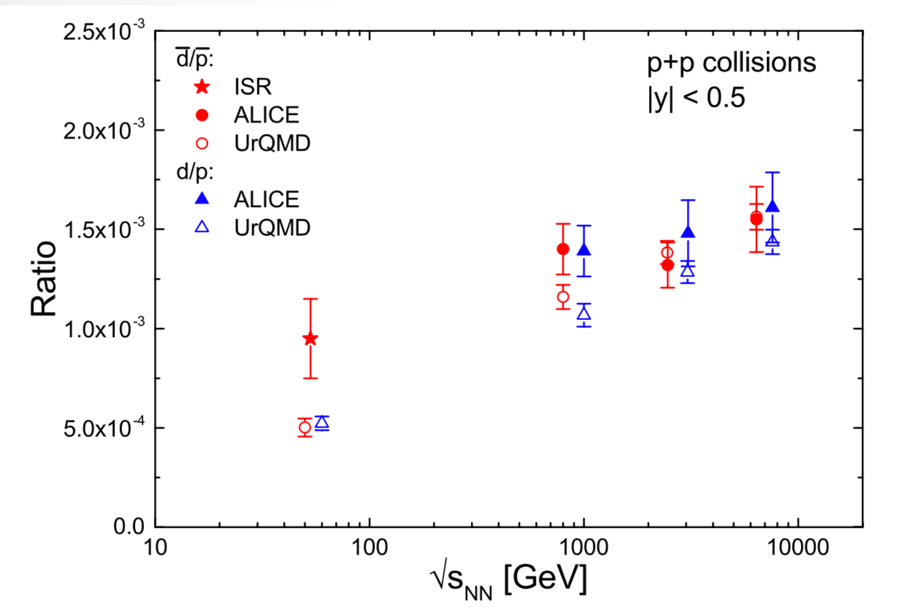


Meson-meson scattering

- Meson-meson scattering in the resonance region is treated in analogy to the meson-baryon scattering
- At higher energies, also t-channel excitation is taken into account

Proton-proton collisions

Deuteron (anti-deuteron): ratios



Absolute yields

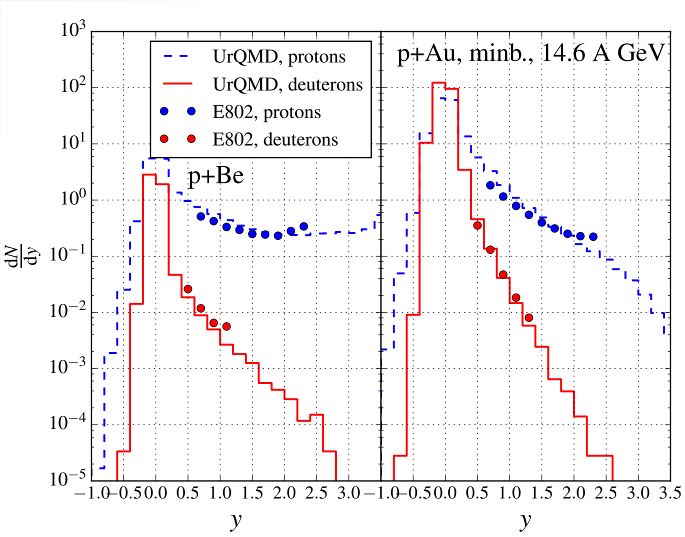
	$\sqrt{s_{NN}}$(TeV)	dN/dy	
		ALICE	UrQMD
	0.9	$(1.12\pm0.09\pm0.09)\times10^{-4}$	$(0.96\pm0.05)\times10^{-4}$
d	2.76	$(1.53\pm0.05\pm0.13)\times10^{-4}$	$(1.47\pm0.06)\times10^{-4}$
	7	$(2.02\pm0.02\pm0.17)\times10^{-4}$	$(2.05\pm0.09)\times10^{-4}$
	0.9	$(1.11\pm0.10\pm0.09)\times10^{-4}$	$(1.00\pm0.05)\times10^{-4}$
$\bar{d}$	2.76	$(1.37\pm0.04\pm0.12)\times10^{-4}$	$(1.55\pm0.07)\times10^{-4}$
	7	$(1.92\pm0.02\pm0.15)\times10^{-4}$	$(2.22\pm0.09)\times10^{-4}$

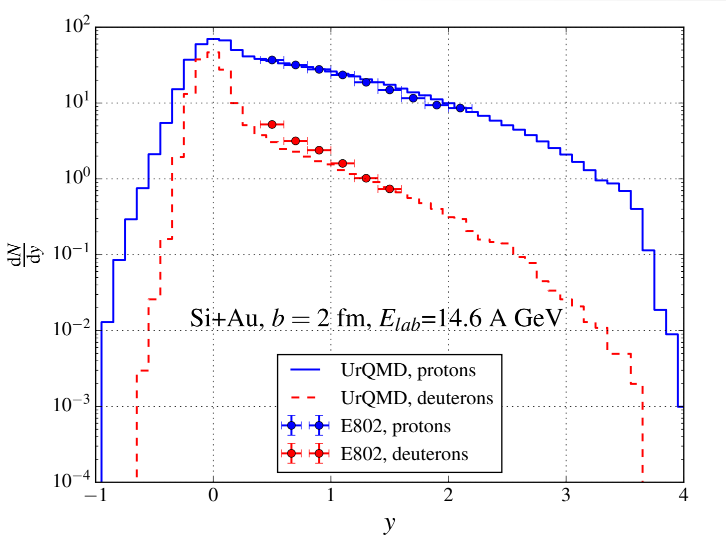
Good description even of pp by coalescence

Absolute yields in line with ALICE data

S. Sombun, M. Bleicher et al, *Phys.Rev.C* 99 (2019) 1, 014901

Comparison to low energy data (small systems)





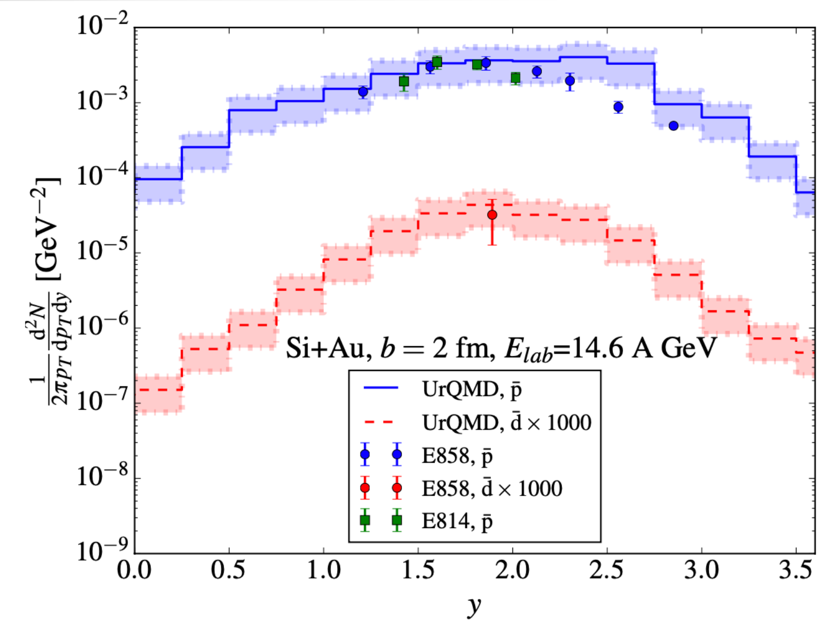
Proton and deuteron rapidity distribution in p+Be, p+Au reaction at E_{lab}=14.6 AGeV

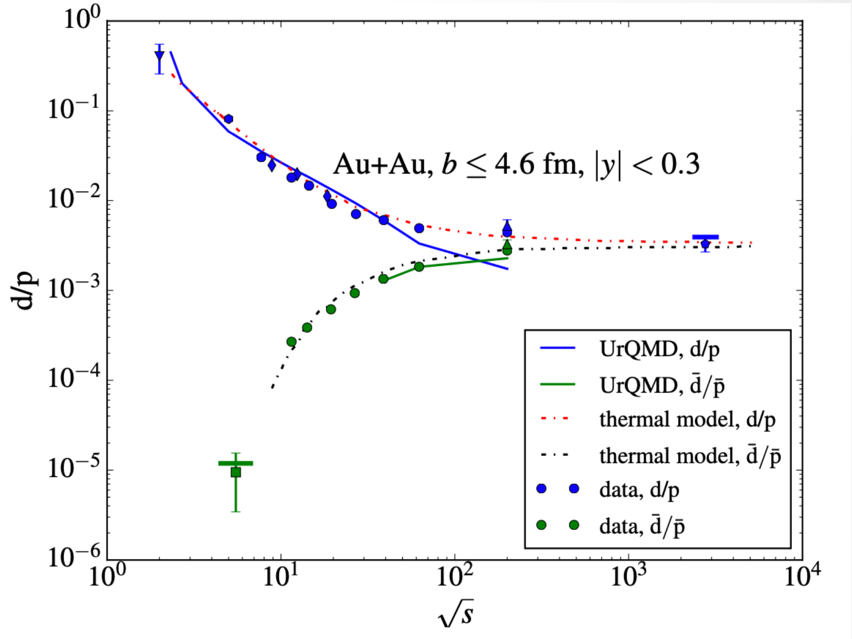
Proton and deuteron rapidity distribution for Si+Au reactions at E_{lab}=14.6 AGeV

- Baryon energy loss in line with data at low energies

S. Sombun, M. Bleicher et al, *Phys.Rev.C* 99 (2019) 1, 014901

Side remark on anti-deuterons





Anti-proton and anti-deuteron rapidity distribution for Si+Au reactions at E_{lab}=14.6 AGeV

d/p and anti-d/anti-p ratios as function of energy, UrQMD vs data vs thermal model

- Substantial amount of anti-deuteron production even near threshold
- Relevance for dark matter…

S. Sombun, M. Bleicher et al, *Phys.Rev.C* 99 (2019) 1, 014901

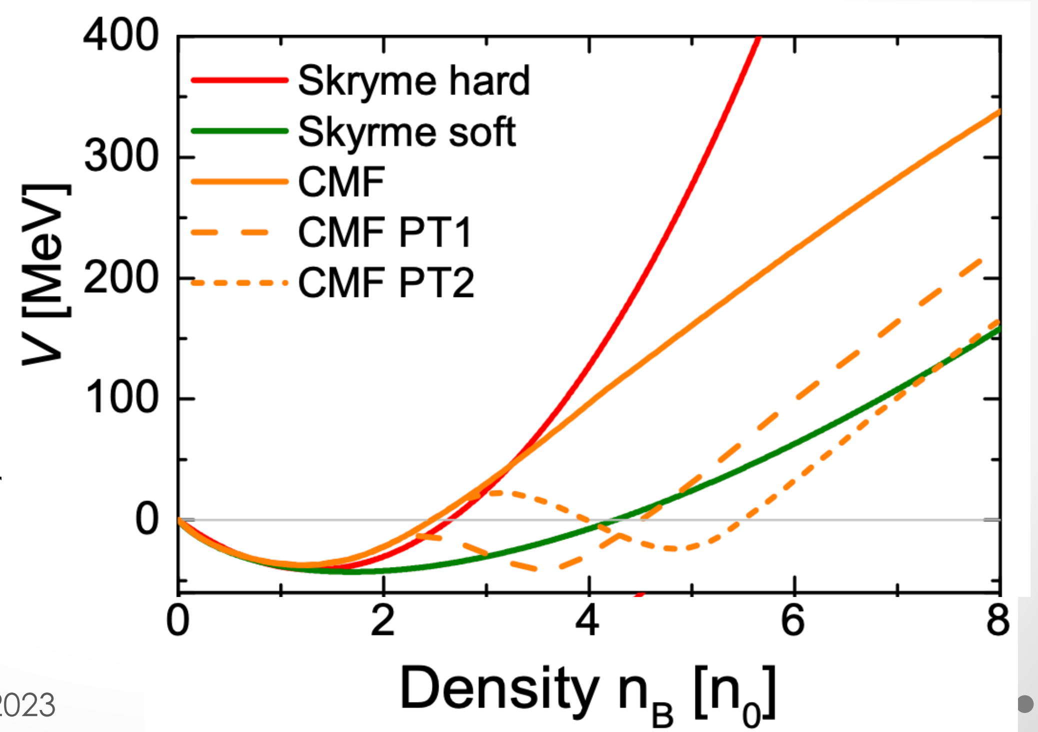
Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Potential mode calculations (RHIC-BES energies):

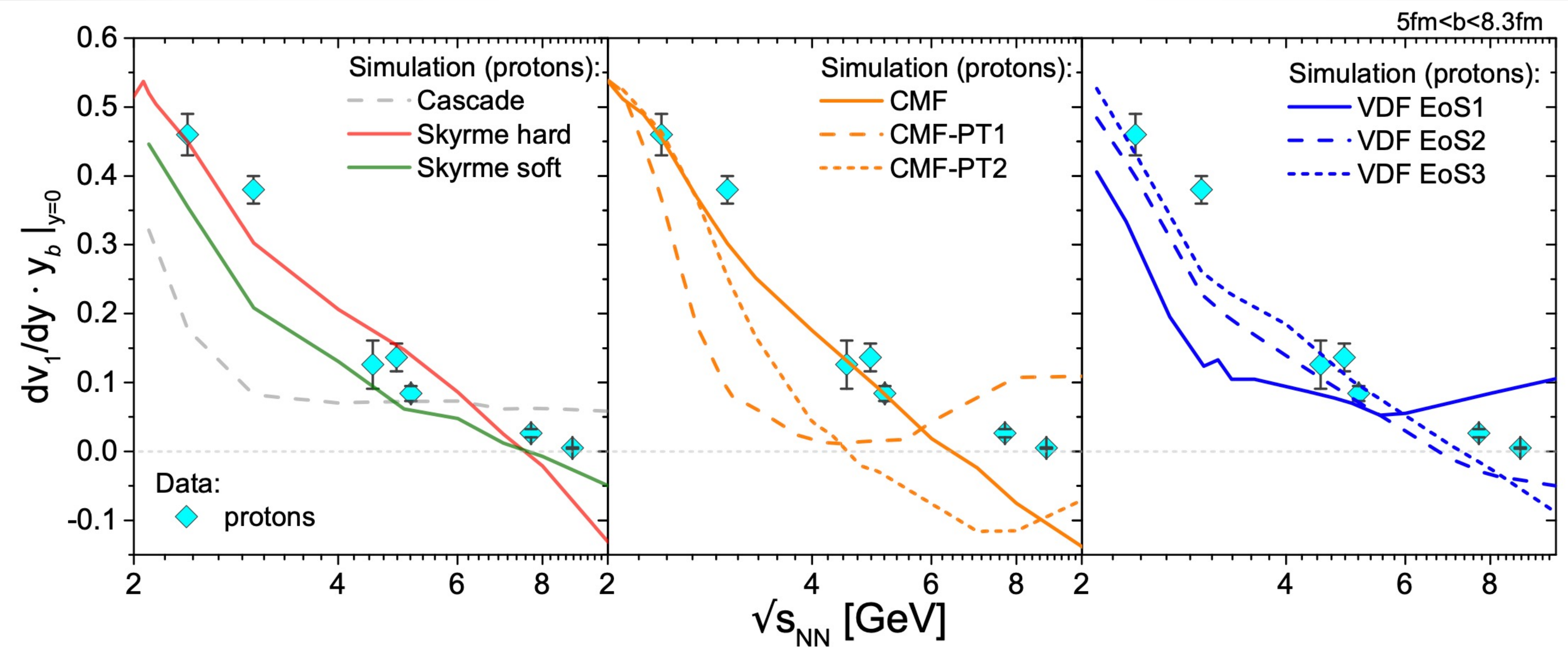
- Cascade calculation can be supplemented by hadronic potentials – standard: hard/soft Skyrme type

- Other potentials mimicking a phase transition are also possible.

Steinheimer, Moronenko, Sorenser
Nara, Koch Bleicher,
Eur.Phys.J.C 82 (2022) 911



Studying effects of the phase transition



- Inclusion of different potentials (including those mimicking a phase transition or cross over) allows to make prediction of effects

Steinheimer, Moronenko, Sorensen, Nara, Koch Bleicher, *Eur.Phys.J.C* 82 (2022) 911

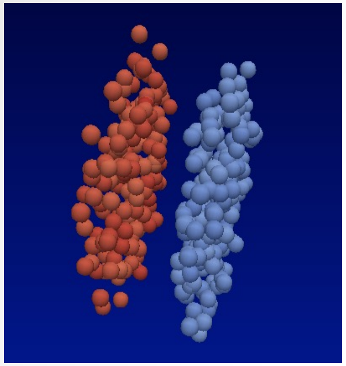
Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

Hybrid mode calculations (RHIC and LHC energies)

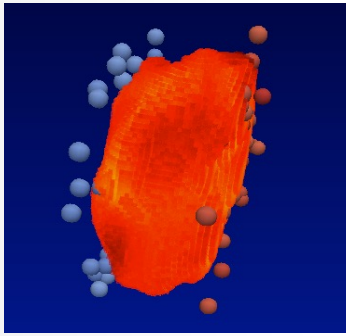
- At energies above 100 GeV (CM-energy) the early intermediate state should not be modeled by strings and particles alone
- To take the local equilibration and the phase transition to a QGP into account, a hydrodynamic phase is introduced
- This is known as hybrid model (Boltzmann+hydrodynamics), hybrid models have become the standard at RHIC and LHC energies

Petersen, Steinheimer, Burau, Bleicher et al, Phys.Rev. C78 (2008) 044901

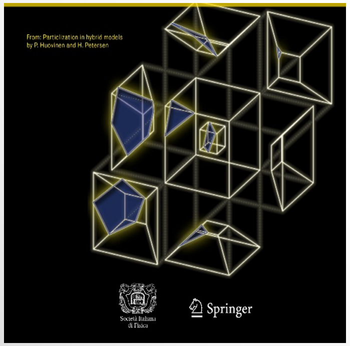
Option: Hybrid model



- Initial State:
  - Initialization of two nuclei
  - Non-equilibrium hadron-string dynamics
  - Initial state fluctuations are included naturally



- 3+1d Hydro +EoS:
  - **SHASTA** ideal relativistic fluid dynamics
  - Net baryon density is explicitly propagated
  - Equation of state at finit μ_B



- Final State:
  - Hypersurface at constant energy density
  - Hadronic rescattering and resonance decays within UrQMD

H.Petersen, M. Bleicher et al, PRC78 (2008) 044901

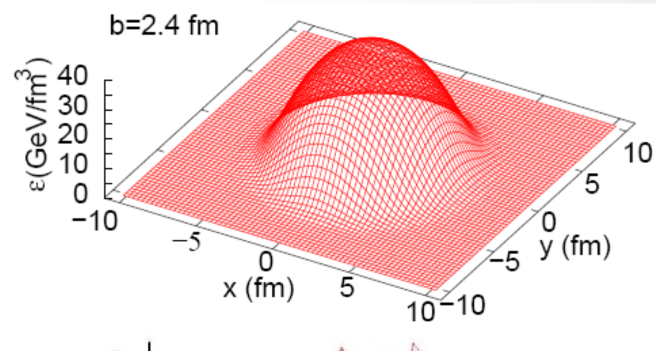
Initial State

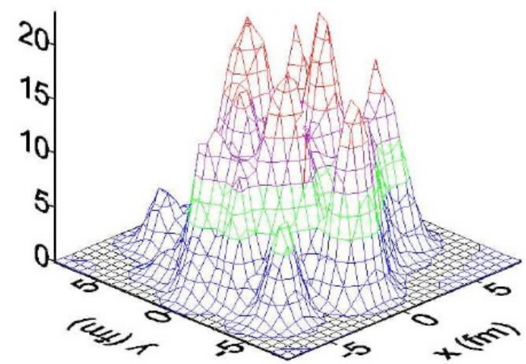
- Contracted nuclei have passed through each other

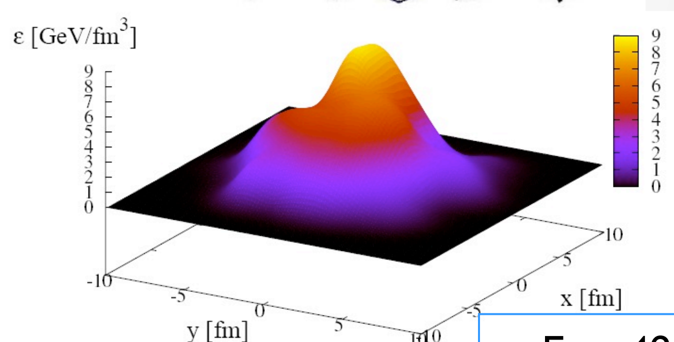
$$t_{start} = \frac{2R}{\gamma v}$$

  - Energy is deposited
  - Baryon currents have separated
- Energy-, momentum- and baryon number densities are mapped onto the hydro grid
- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade

(J.Steinheimer et al., PRC 77,034901,2008)







E_{lab}=40 AGeV
b=0 fm

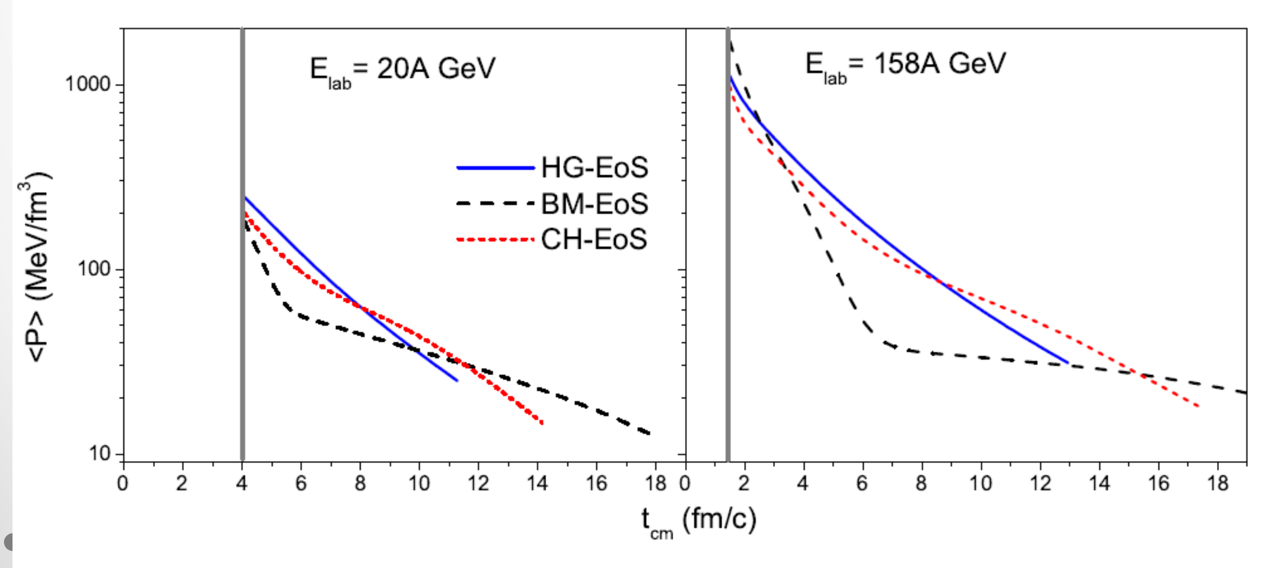
(nucl-th/0607018, nucl-th/0511021)

Equations of State

Ideal relativistic one fluid dynamics:

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu (n u^\mu) = 0$$

- HG: **Hadron gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- CH: **Chiral EoS** from quark-meson model with first order transition and critical endpoint
- BM: **Bag Model EoS** with a strong first order phase transition between QGP and hadronic phase



D. Rischke et al., NPA 595, 346, 1995,

D. Zschiesche et al., PLB 547, 7, 2002

Papazoglou et al., PRC 59, 411, 1999

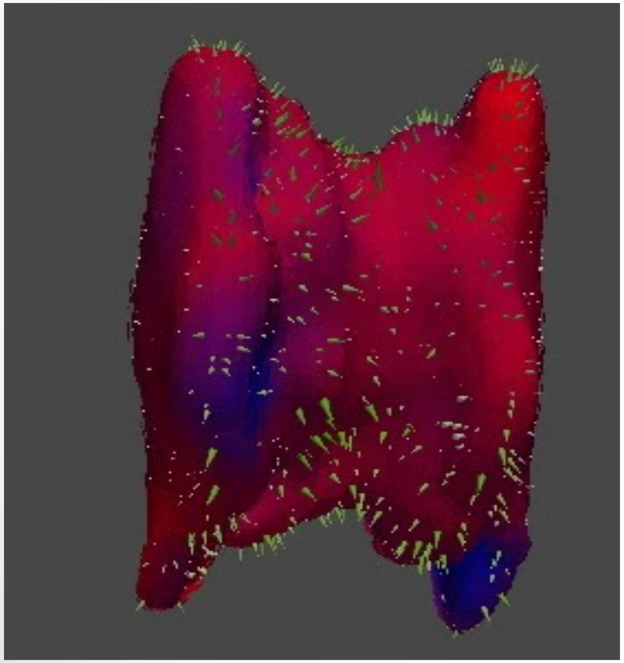
J. Steinheimer, et al., J. Phys. G38 (2011) 035001

Hadronization, Particlization, Decoupling

Experiments observe **finite number** of hadrons in detectors

Hadronization controlled by the equation of state

Sampling of particles according to **Cooper-Frye** equation:
-Respect **conservation laws**, maybe even locally?
-Introduces fluctuations on its own



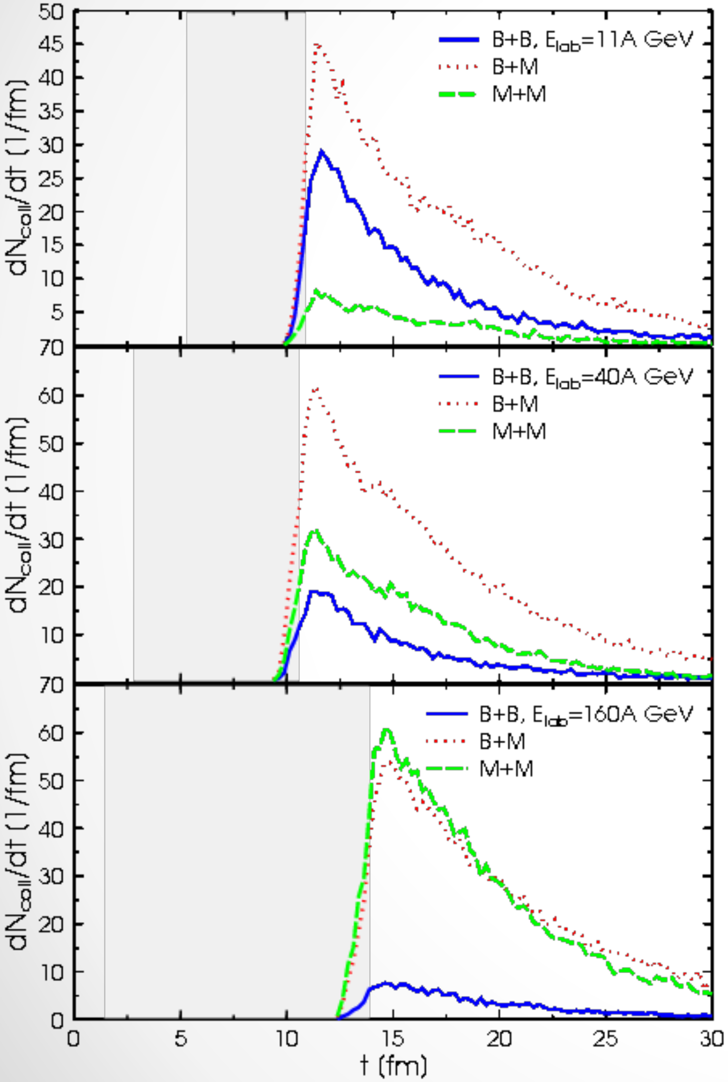
$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

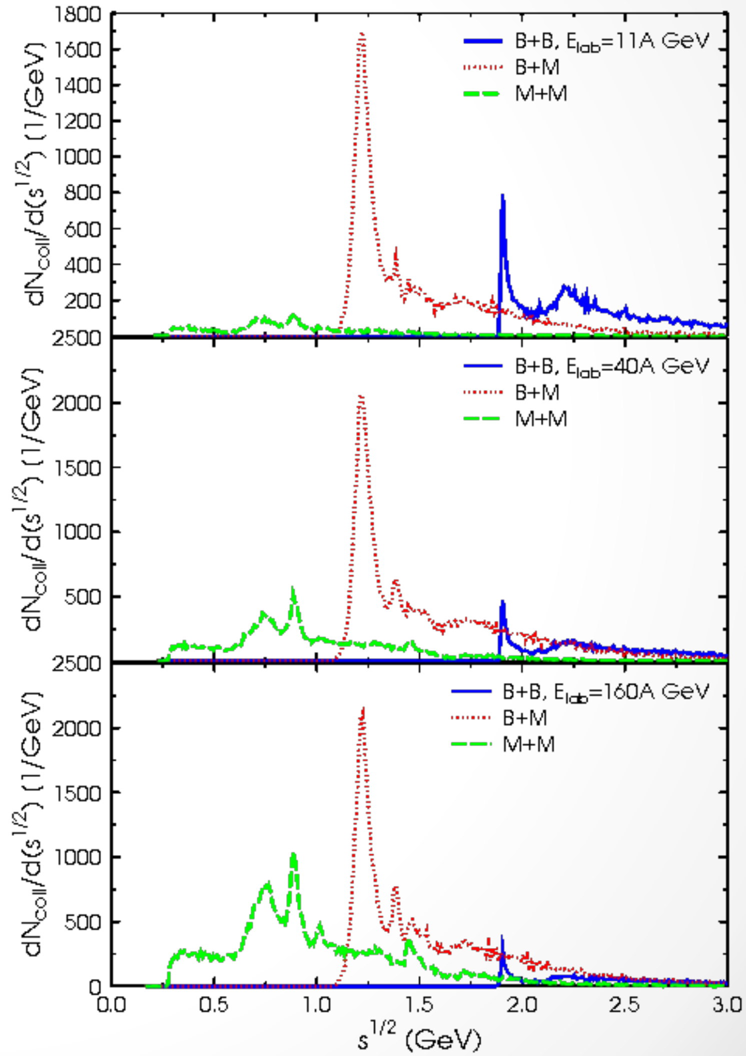
→ Yields 4-momenta, 4-positions of hadrons on the hypersurface

→ Final propagation
Relativistic transport equation $(p^\mu \partial_\mu)f = I_{coll}$

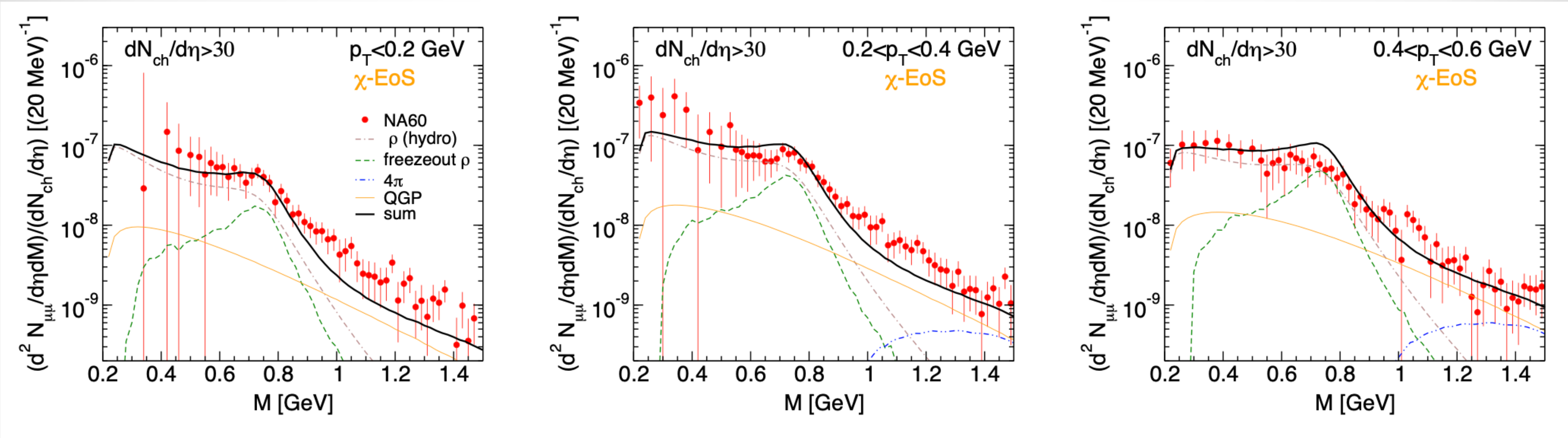
Sophisticated 3D hypersurface finder to resolve interesting structures in event-by-event simulations
Petersen, Huovinen, arXiv:1206.3371

Final State Interactions (after Hydro)





Dileptons from hybrid approaches



- Using in-medium dilepton rates, a hydrodynamic evolution with a chiral EoS, and late stage hadron dynamics
- Allows for a full description of the dilepton yields at SPS energies

Santini, Steinheimer, Bleicher, et al, Phys.Rev.C 84 (2011) 014901

Summary

- Transport models are good tools to describe the dynamics of matter in heavy ion collisions
- UrQMD 3.5 has different modes to allow for the inclusion of various different physics scenarios
- These scenarios can be systematically tested and allow for predictions/analysis of a broad spectrum of observables