Dynamical Modeling of Heavy-Ion Reactions

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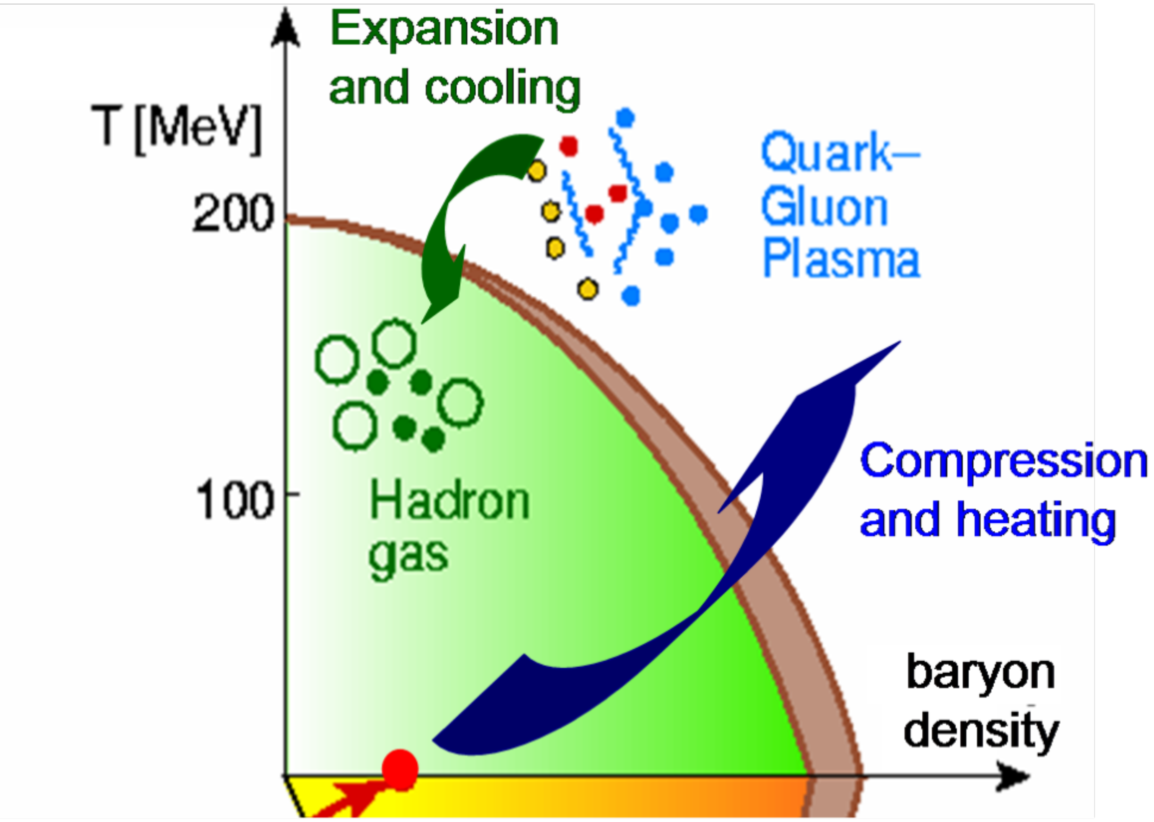
9.10.18, ISNET, Darmstadt

Outline

- QCD phase diagram
  - Goals of heavy-ion physics
  - ‚Standard model' for the dynamical evolution
  - Results of Bayesian analysis at high beam energies
  - Energy dependence of transport coefficients
- Hadronic transport approach, SMASH
  - Short overview of the main ingredients
  - Planned projects for Bayesian statistical analysis:
    - Properties of resonances for strangeness production
    - Equation of state of nuclear matter constrained by GSI-SIS data

The QCD Phase Diagram

- Main goals of heavy ion research

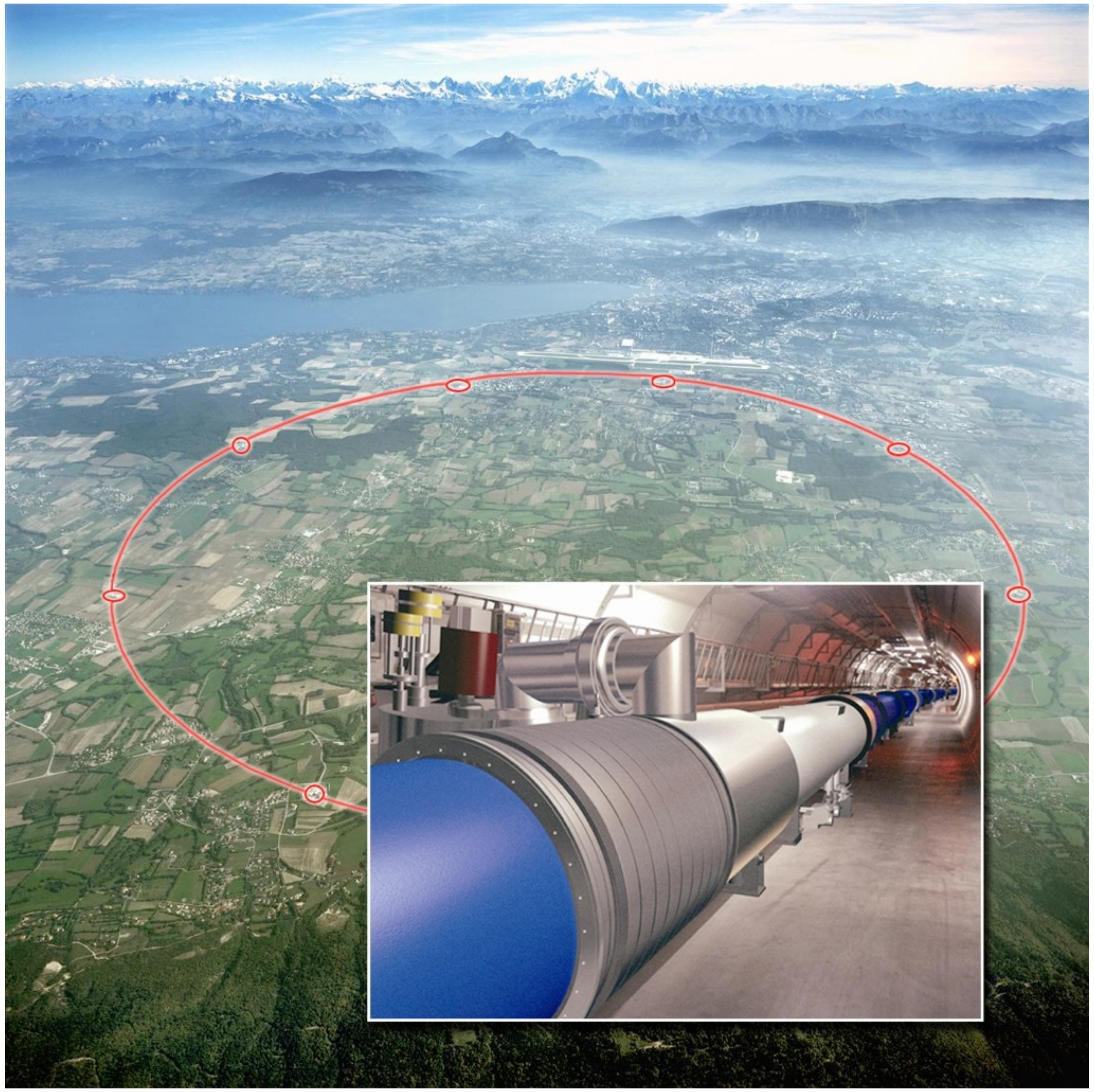


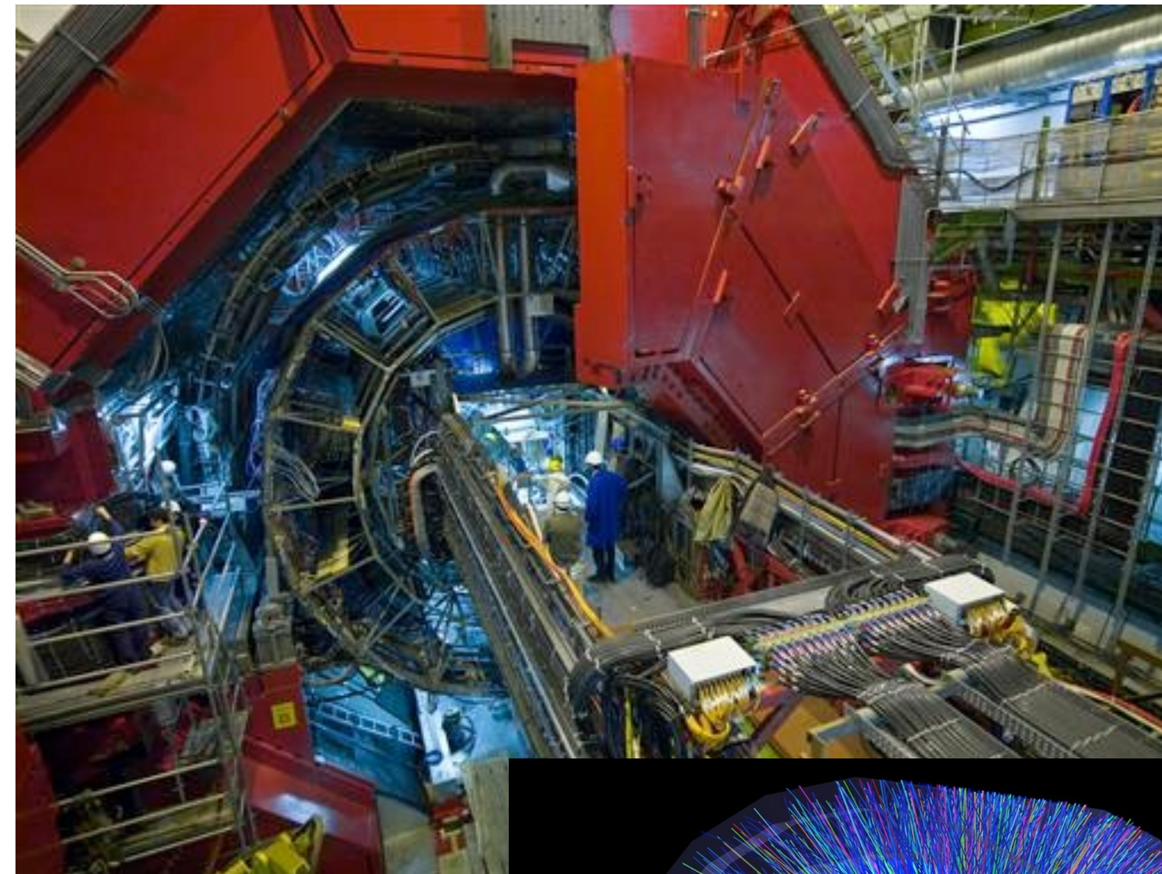
nuclei (n_B=0.14/fm^3)

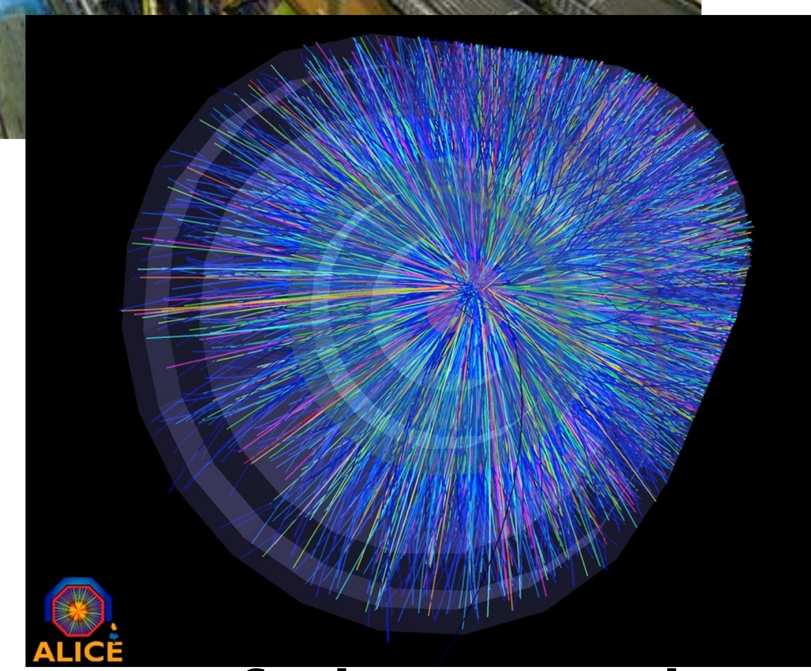
- **Questions** to be answered:
  - What is the temperature and the density? What are the relevant degrees of freedom?
  - Phase transition, critical point?
  - What are the transport properties? $(\eta/s)(T,\mu_B)$ and $(\zeta/s)(T,\mu_B)$

- Understand the structures in the phase diagram
- Investigate the properties of the quark-gluon plasma
- Collisions of heavy ions at different beam energies at LHC, RHIC and GSI provide experimental insights

Creating the QGP in the Lab

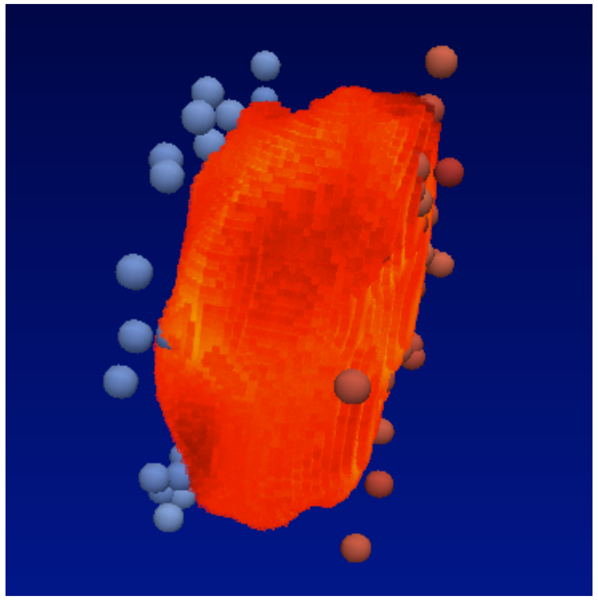




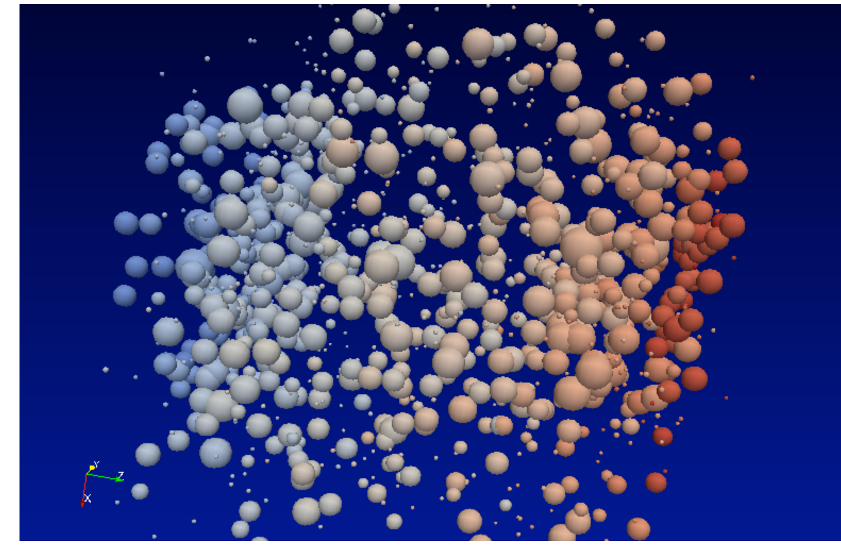


- ALICE at **Large Hadron Collider**, CERN
- How to find relics of the QGP in the traces of thousands of hadrons?

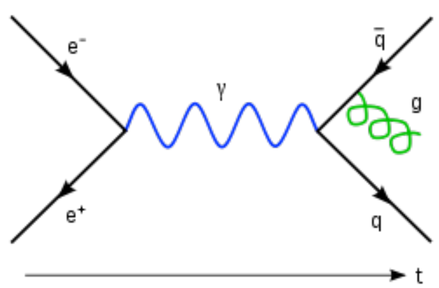
Theoretical Description



Dynamical description of heavy ion reactions

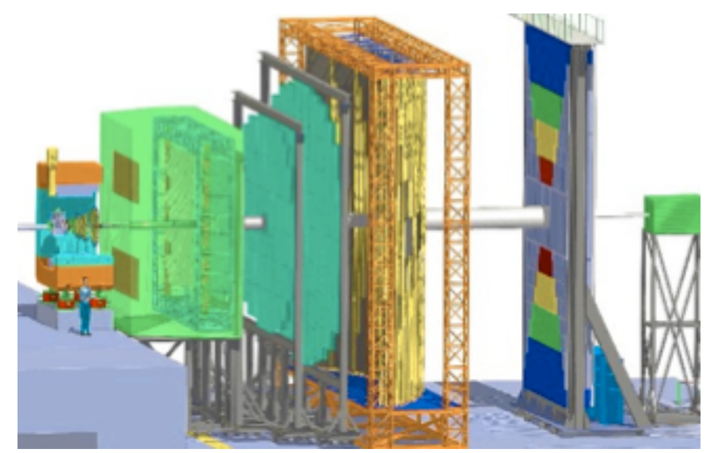


Fundamental field theory of strong interactions (QCD)



$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Measurements in the detector (CBM@FAIR)



- **Theoretical models** are essential to gain insights about the properties of the quark gluon plasma, since the short timescale and small volume do not allow for a direct observation

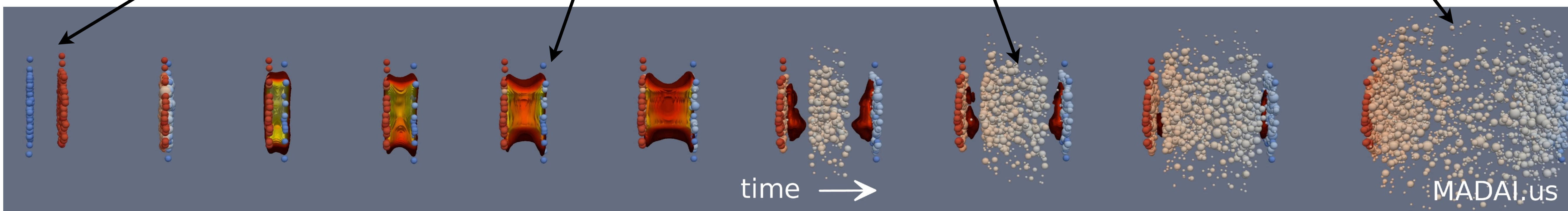
Time Evolution of Heavy Ion Collisions

Nuclei at 99 % speed of light

Quark Gluon Plasma

Hadronic Rescattering

Measurable Fragments in the detector



1×10^{-23} s

10×10^{-23} s

30×10^{-23} s

Nonequilibrium initial state dynamics → Relativistic Hydrodynamics → Hadron Transport

- Due to the short **time scale** of **10^{-22} seconds** and the tiny **volume $(10 \times 10^{-15}\text{m})^3$** the quark gluon plasma escapes direct detection

Dynamic description of heavy ion collisions has to capture all the stages of the reaction

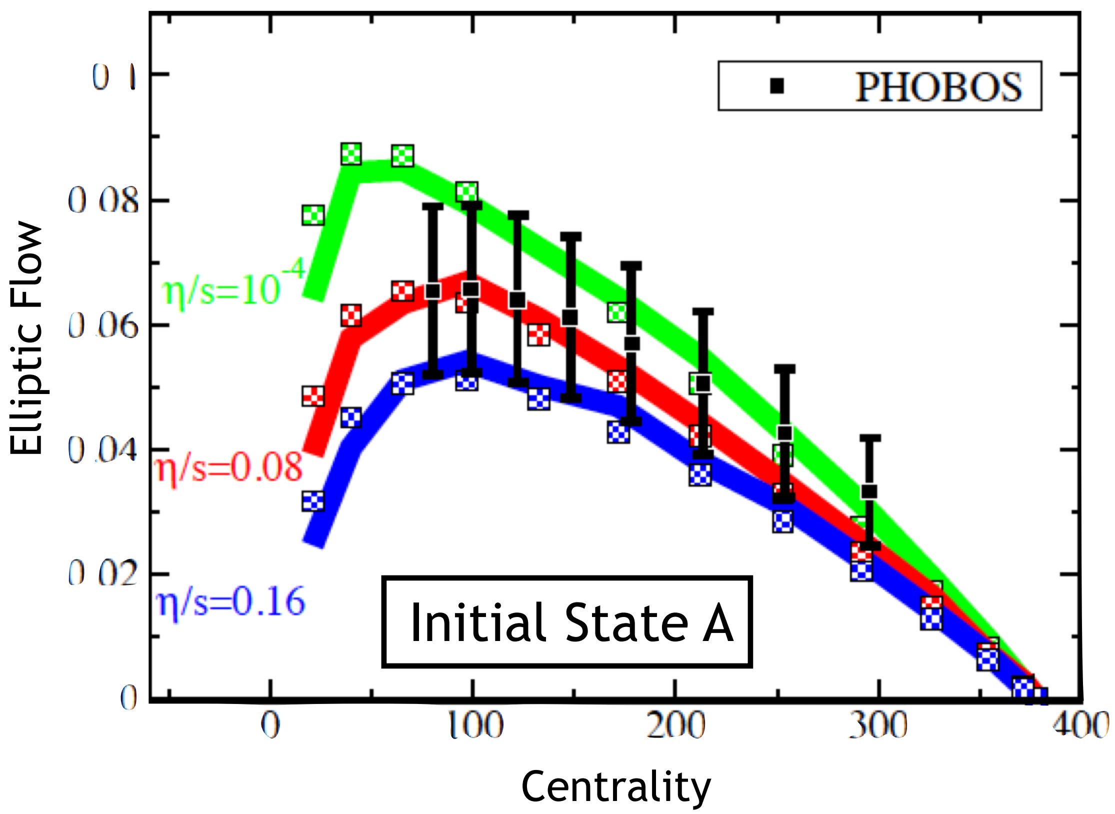
Quantifying QGP Properties

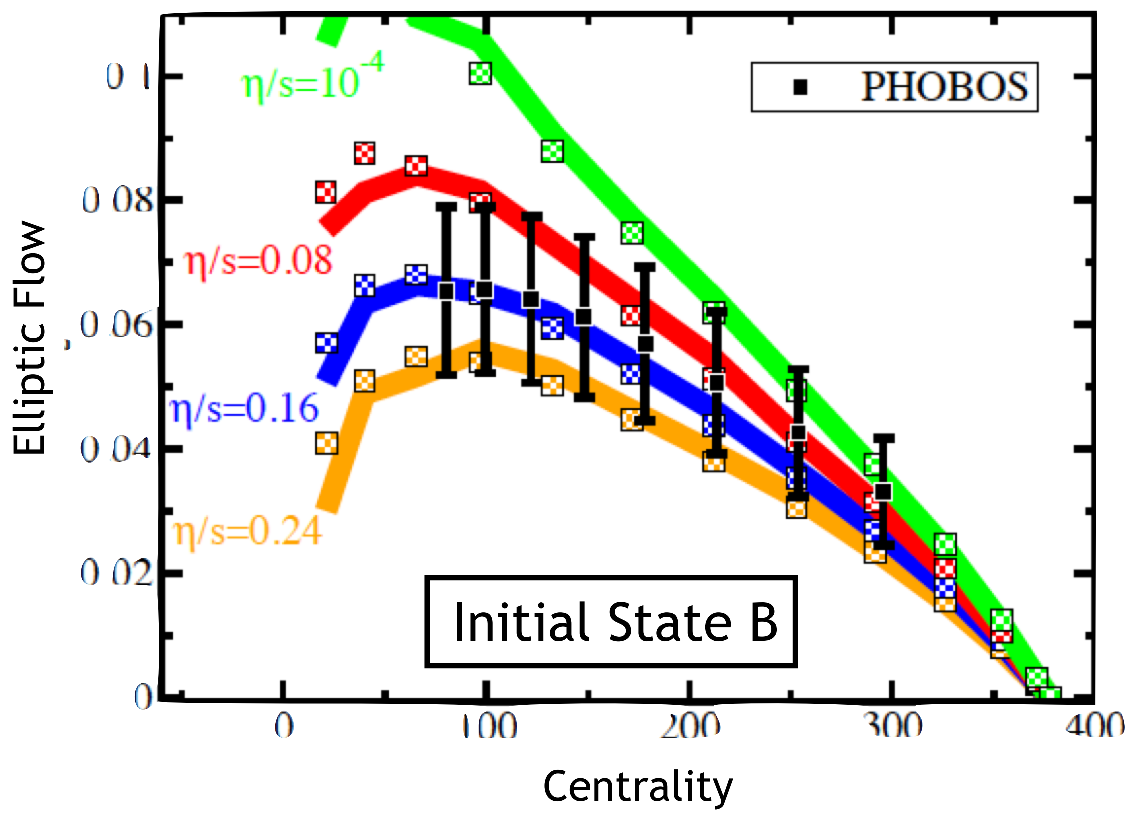
- Dynamical approaches have many parameters
- Sensitivities of interest are hidden in non-linear dependencies

Initial State
- Shape of the profile
- Starting time
- Fluctuations

Hydrodynamics
- Equation of state
- Min. viscosity
- Viscosity

Hadronic Transport
- Transition criterion
- Particle species
- Cross-sections





M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915

→ Multi-Parameter analysis of many observables

How to get more quantitative?

- **Qualitative** description of heavy ion reactions by hybrid approaches
- Dependence on **multitude** of parameters
- Huge amount of experimental **observables**
- How can we get **quantitative results** for quantities of interest, like viscosity, transition energy density, thermalization time,...?

M.A.D.A.I.
Modeling and Data Analysis Initiative

Modeling **a**nd **D**ata **A**nalysis **I**nitiative

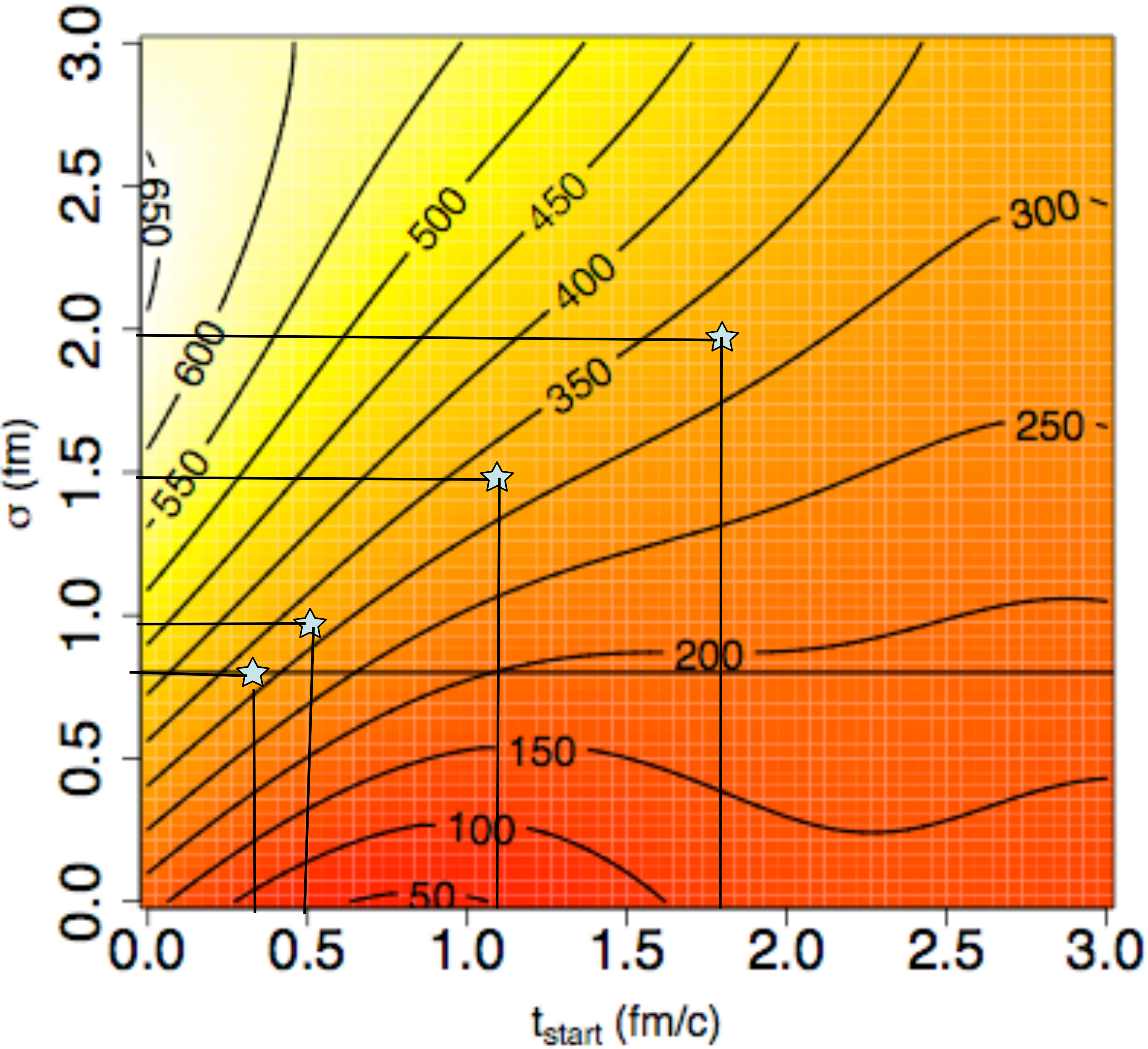
NSF Cyber discovery initiative ~2009-1015

- Different fields of science coping with **large data sets** and complicated dynamical models, e.g. meteorologists, galaxy cluster formation, heavy ion physics,..
- Develop **statistic** analysis tools for multi-parameter fit
- Apply new **visualization techniques** to dynamical simulation
- Extract **quantitative** statements from RHIC data

http://madai.us for examples

Parameter Sensitivity Tests

Initial Conditions parameter study in one specific hybrid approach



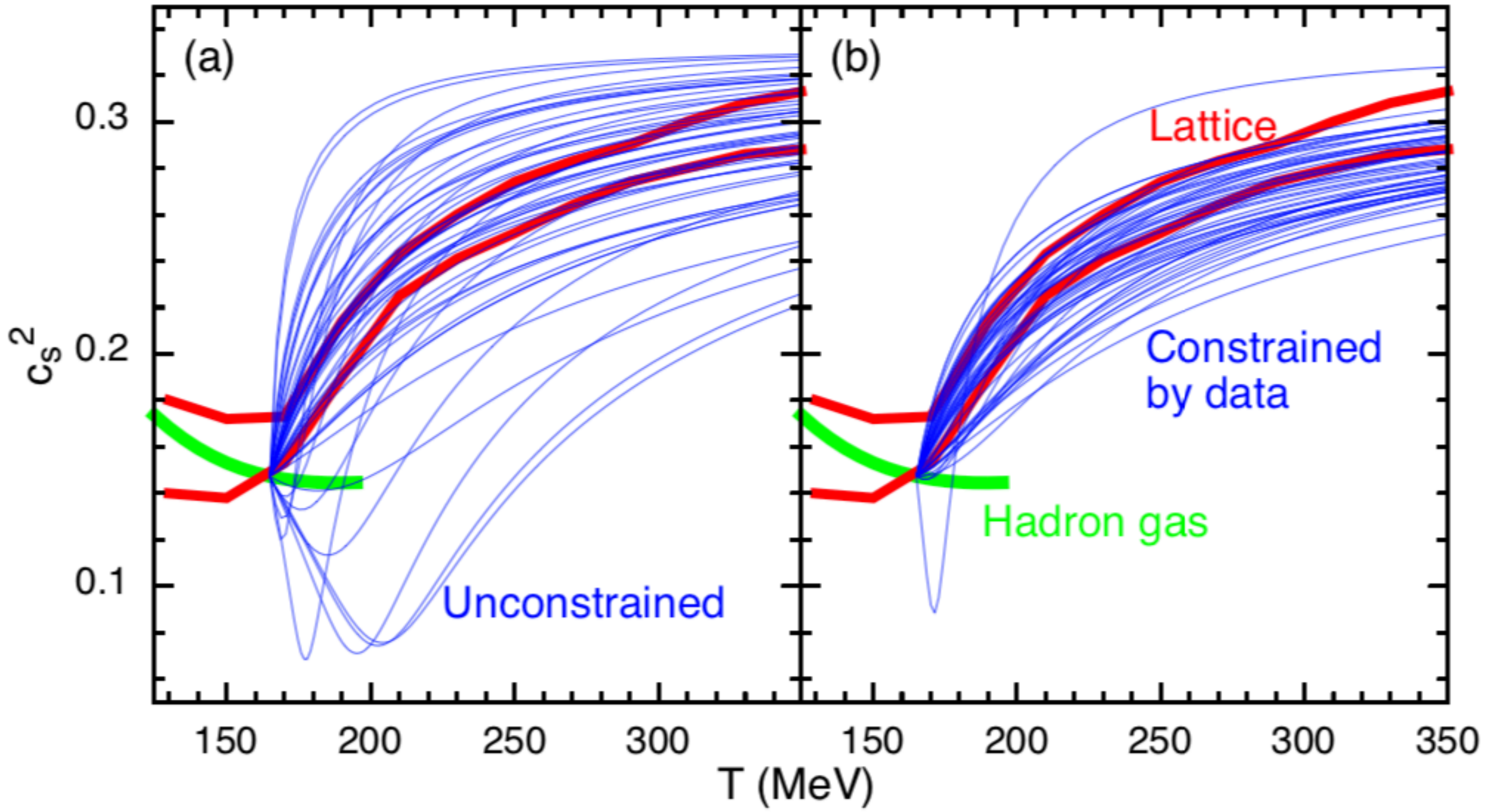
- Sophisticated statistical analysis
- **Emulator** predicts results of calculations for parameter sets by means of advanced statistics
- Number of pions in the t_{start}- σ plane

→ Determine reasonable **combinations** of parameters

H.P. et al, J.Phys.G G38 (2011) 045102

Equation of State

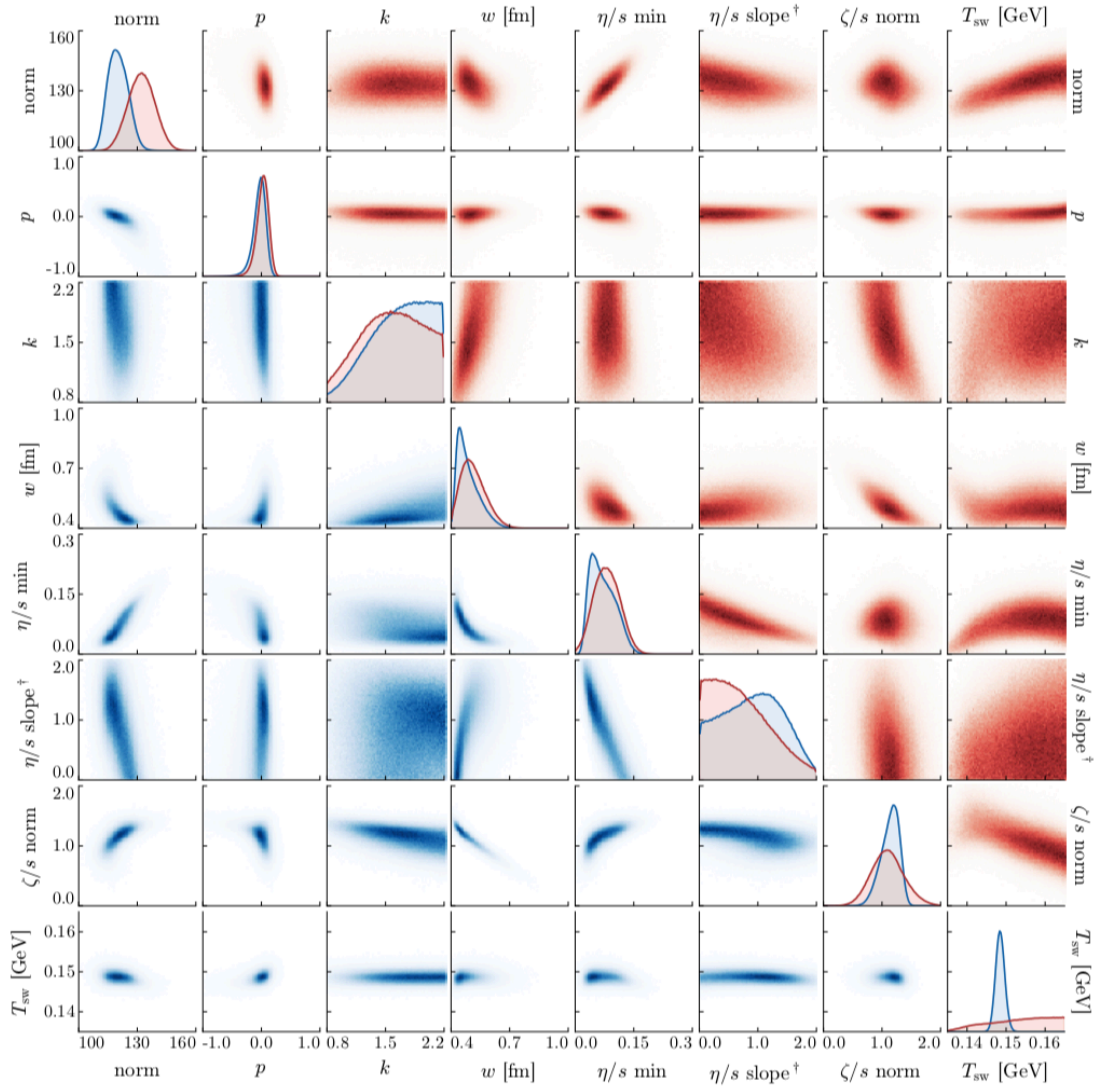
- Equation of state constrained by RHIC and LHC bulk observables matches lattice QCD result



S. Pratt et al, Phys.Rev.Lett. 114 (2015) 202301

- Experimental results provide statistical and systematic errors, what about theory?

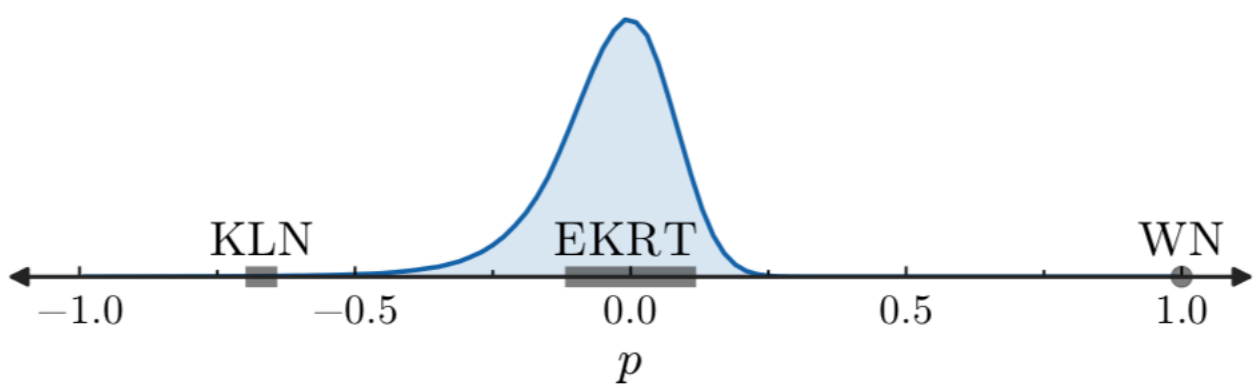
Multi-Parameter Analysis Posteriors

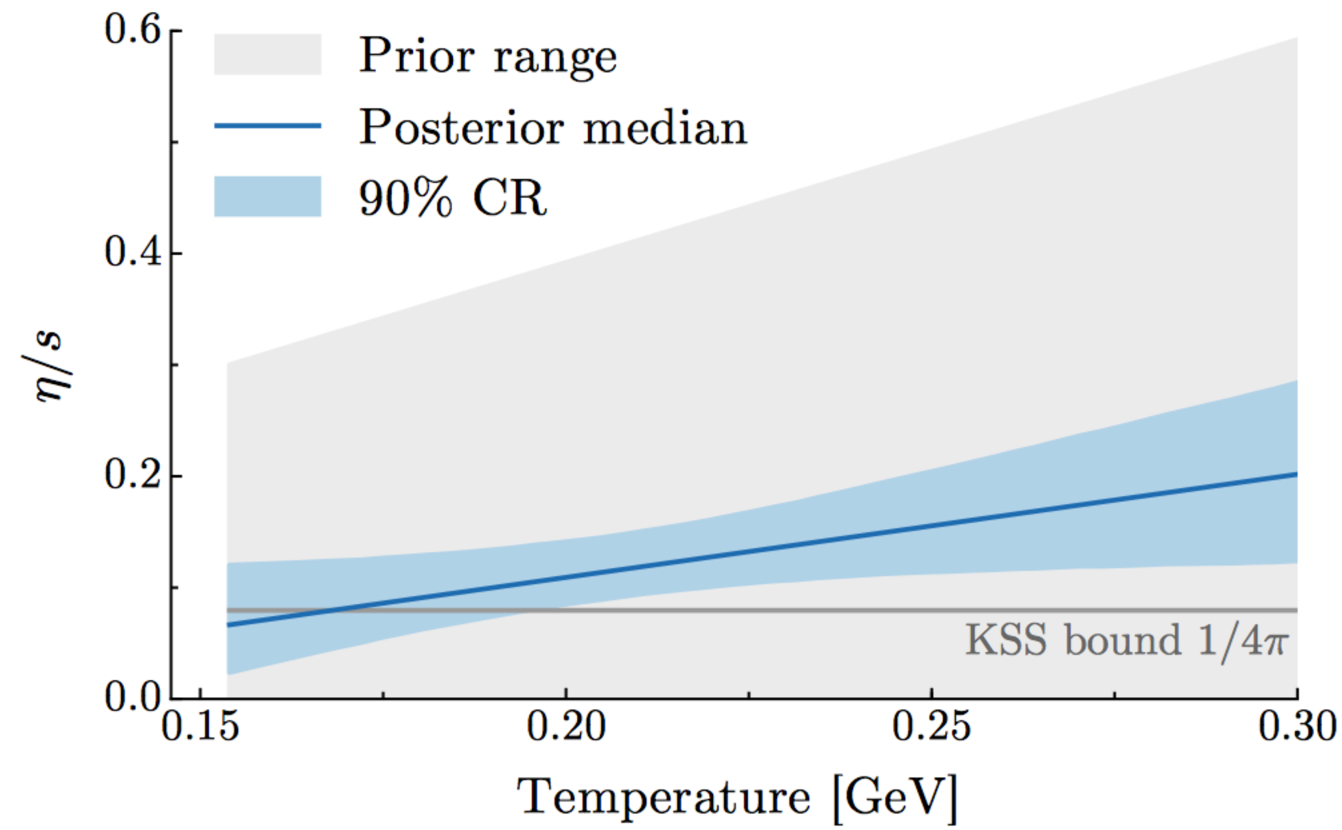


J. Bernhard et al, Phys.Rev. C94 (2016) no.2, 024907

Duke Bayesian Analysis

- Constraints on initial state and transport coefficients are provided with quantified uncertainties





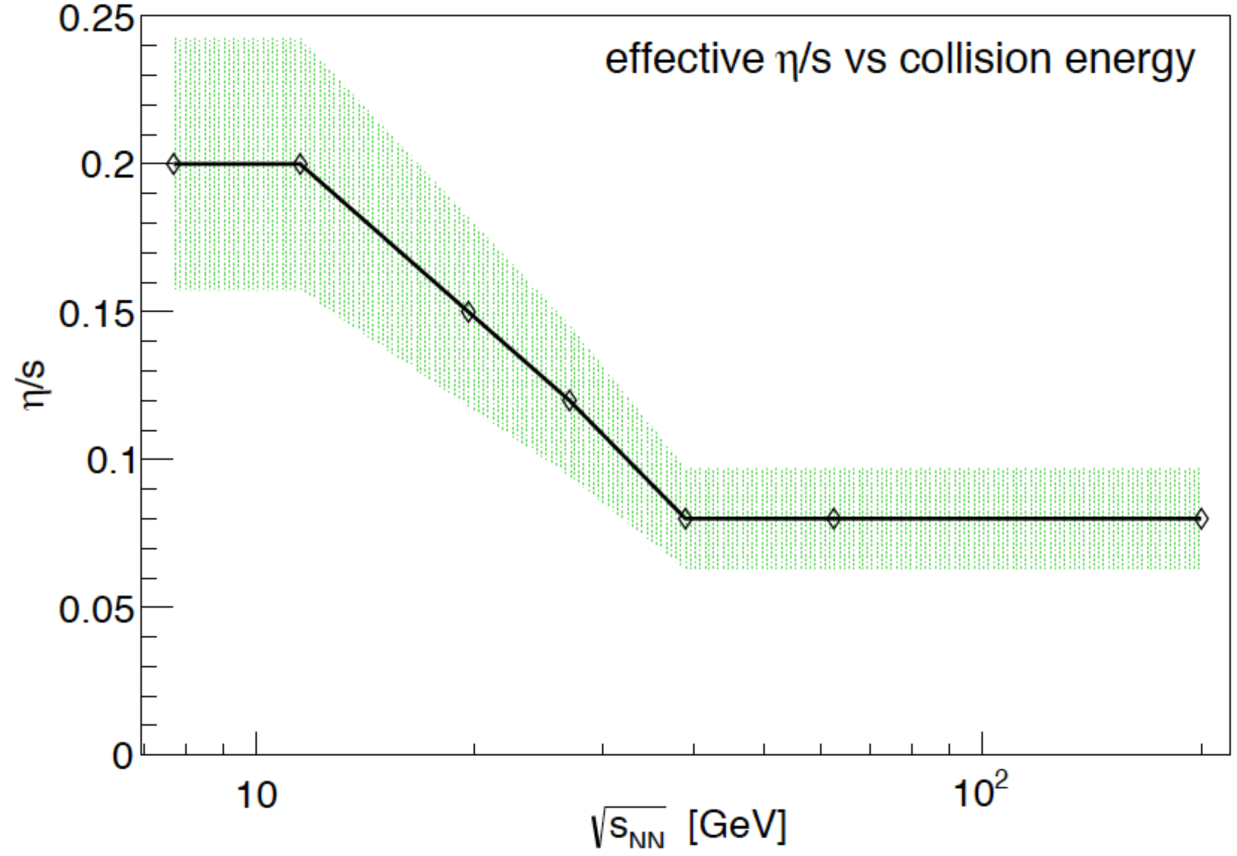
J. Bernhard et al, Phys.Rev. C94 (2016)

- Is this result confirmed within independent theoretical analysis? (different implementation of the same physics ingredients) -> Hint of systematic uncertainties..

η/s Energy Dependence

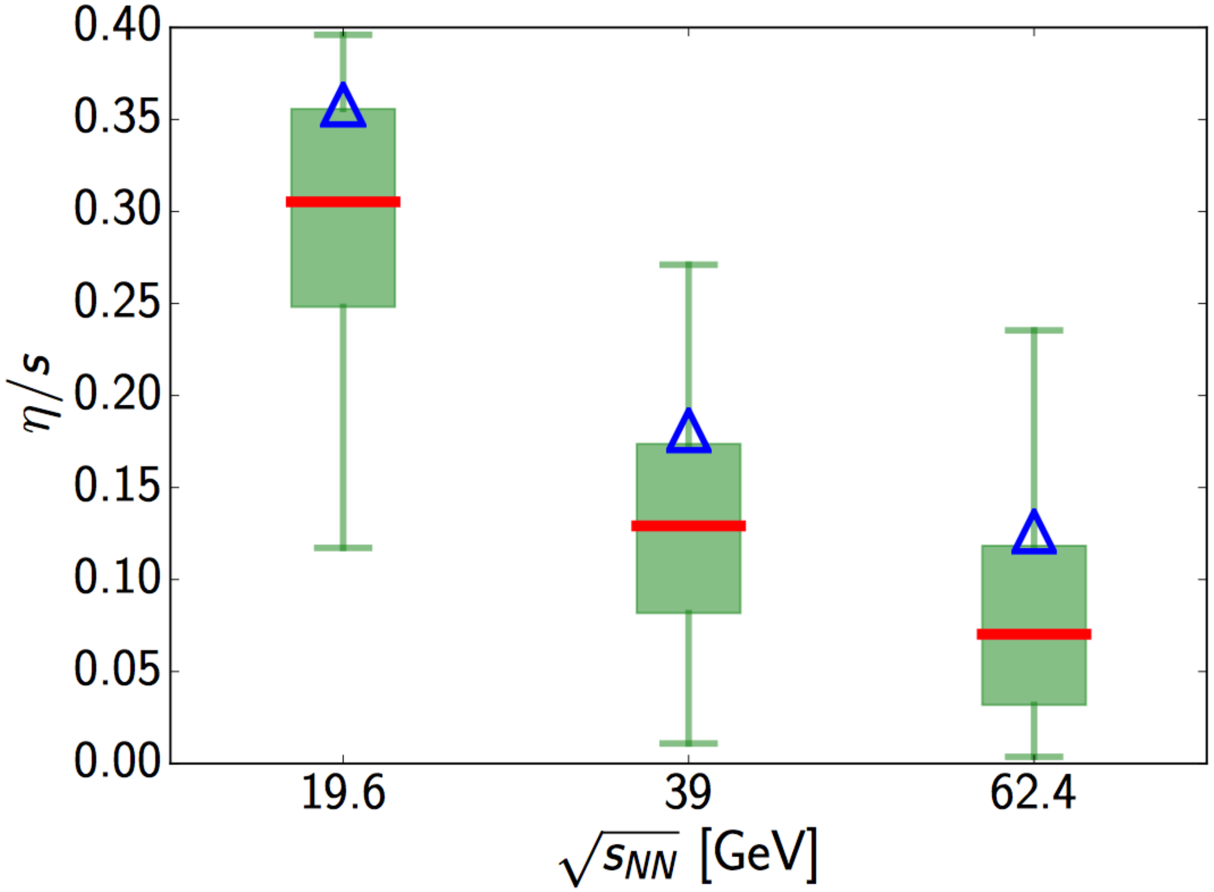
- Viscous UrQMD hybrid fitted to RHIC beam energy scan and SPS data allows to extract **effective** shear viscosity of the hydrodynamic stage

Analysis „by eye“



Y. Karpenko et al, Phys.Rev. C91 (2015)

Bayesian framework



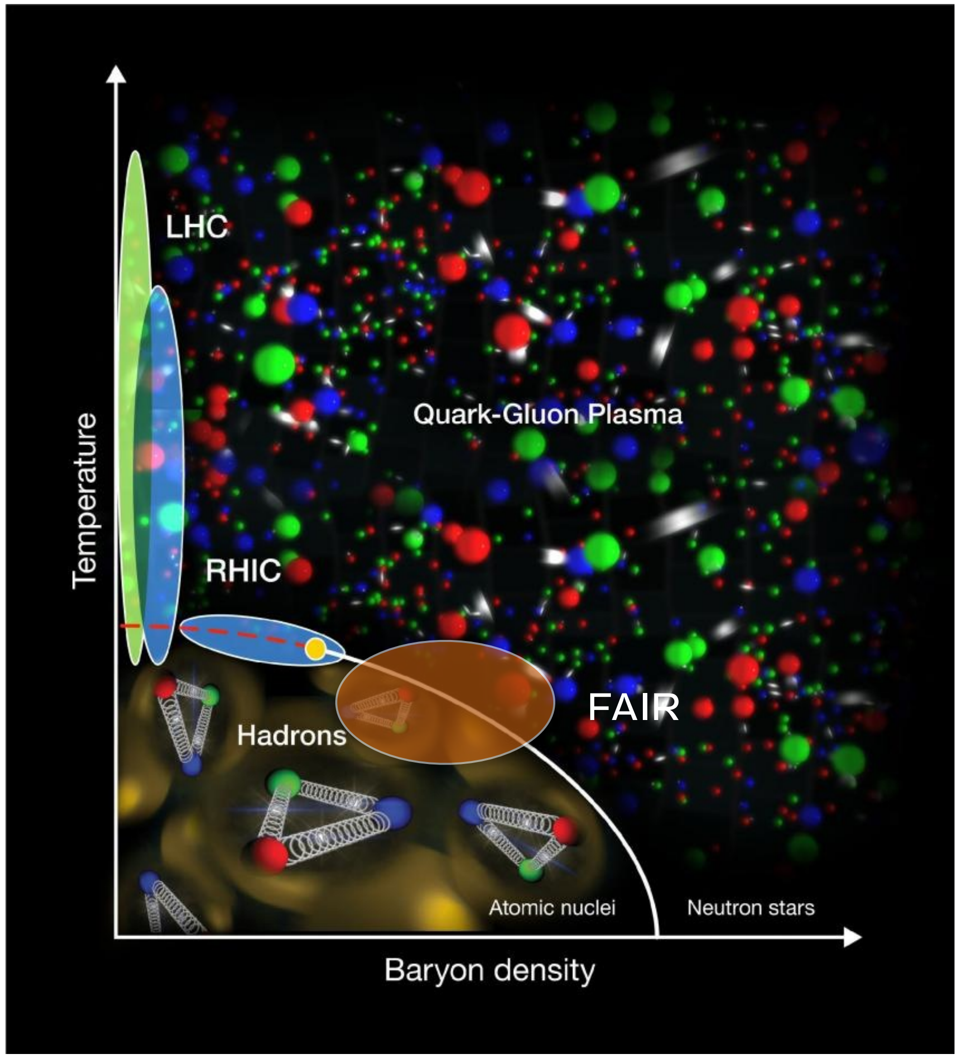
Auvinen et al., arXiv:1610.00590

- The heavy-ion community starts to appreciate the quantitative analysis -> NSF initiative JETSCAPE

JETSCAPE

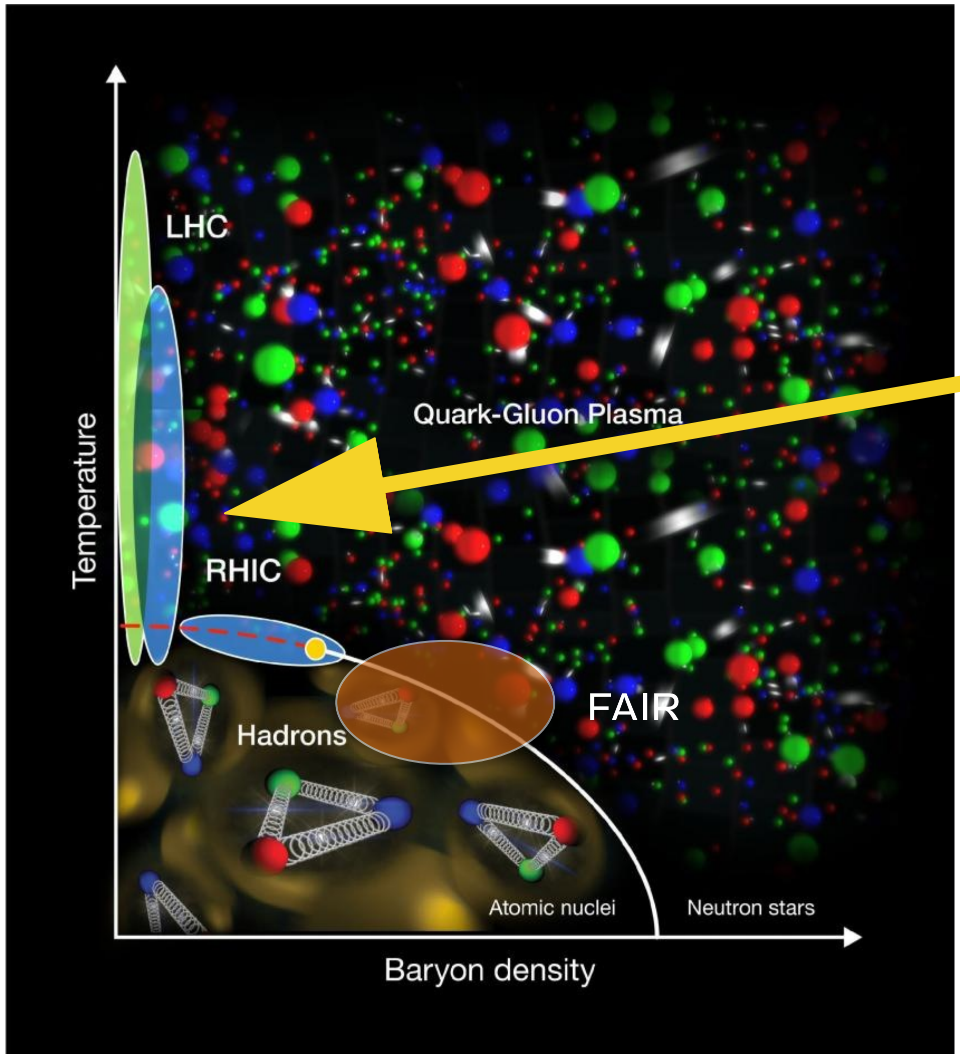
Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



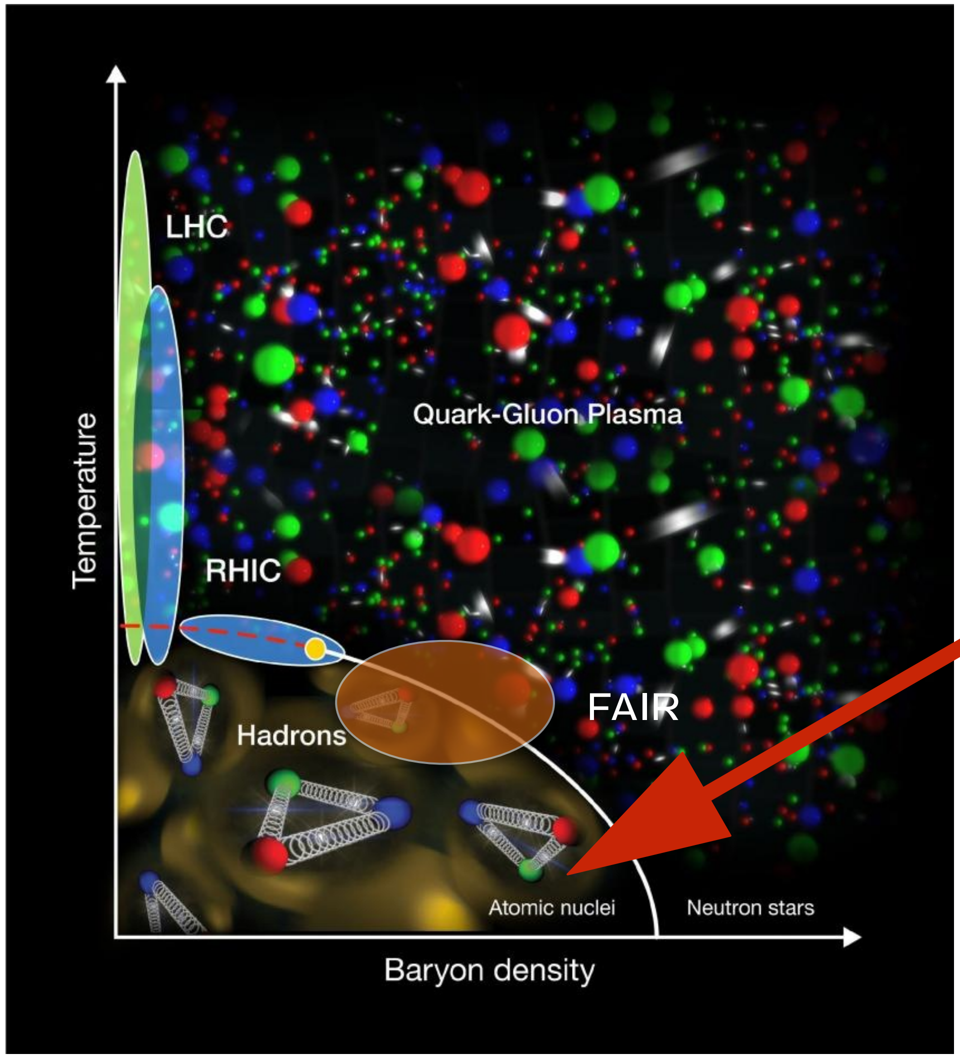
‚**Standard model**‘ at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+):

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

—> Refinement and Bayesian multi-parameter analysis

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



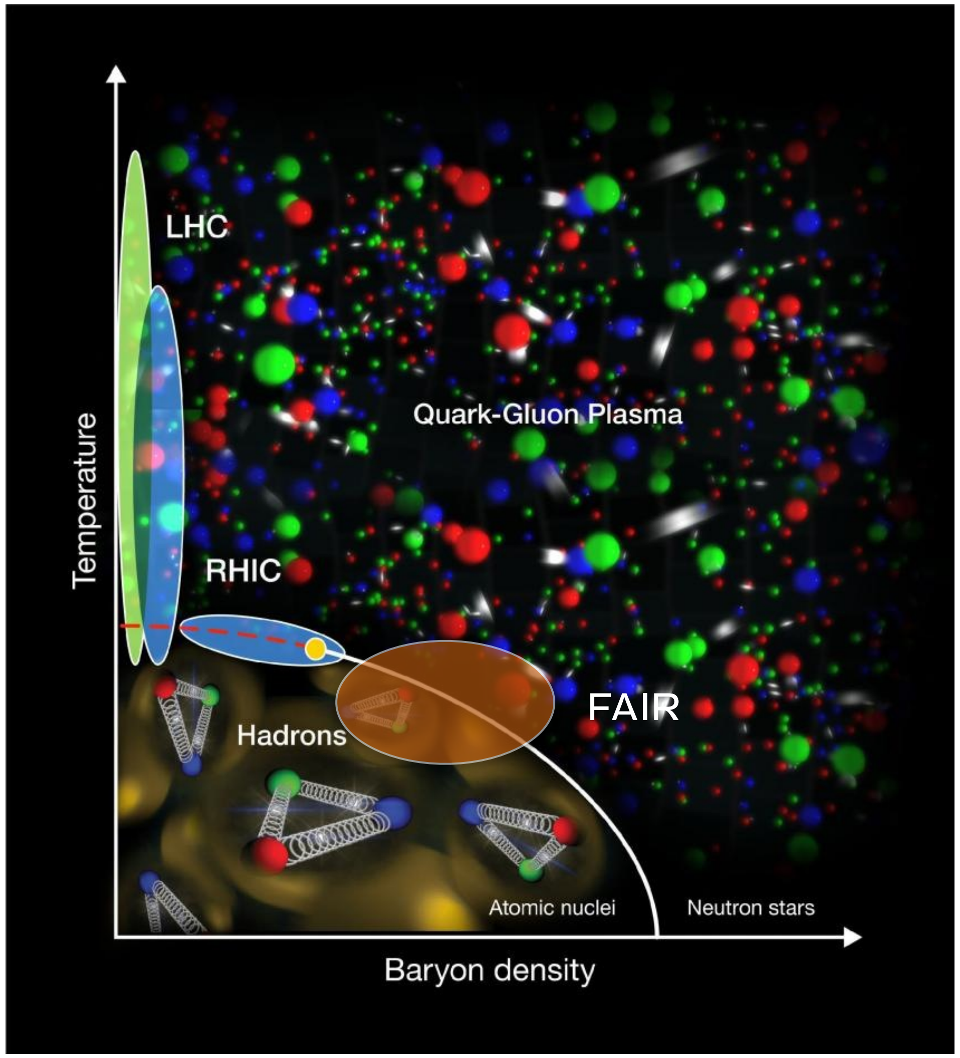
At very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV):

- **Hadronic** transport approaches
- Resonance dynamics
- Nuclear potentials

—> High density phase?
Multi-particle interactions?

Dynamical Description of Heavy Ion Collisions

- Two regimes with **well-established** approaches



‚Standard model' at high energies ($\sqrt{s_{\mathrm{NN}}}$ = 39 GeV-5.5 TeV+)

Hadron transport at very low beam energies ($\sqrt{s_{\mathrm{NN}}}$ < 3 GeV)

- In the intermediate energy region, more qualitative understanding is required, before statistical analysis is sensible

New Hadronic Transport Approach

- Hadronic transport approaches are successfully applied for the dynamical evolution of heavy ion collisions
- Hadronic **non-equilibrium** dynamics is crucial for
  - Full/partial evolution at **low**/ intermediate **beam energies**
  - Late stage **rescattering** at high beam energies (RHIC/LHC)

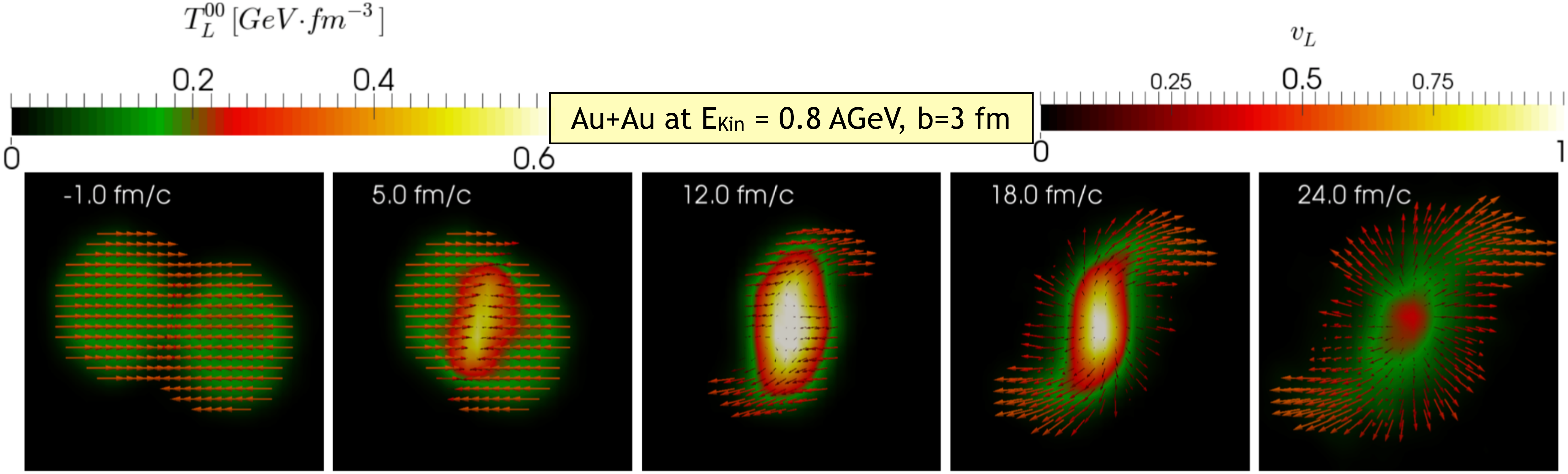
smash

- New experimental data for cross-sections and resonance properties is available (e.g. COSY, GSI-SIS18 pion beam etc)
- Philosophy: Flexible, modular approach condensing knowledge from existing approaches
- Goal: Baseline calculations with hadronic vacuum properties essential to identify phase transition

SMASH*

- Hadronic transport approach:
  – Includes all mesons and baryons up to ~2 GeV
  – Geometric collision criterion
  – Binary interactions: Inelastic collisions through resonance/string excitation and decay
  – Infrastructure: C++, Git, Redmine, Doxygen, (ROOT)

J. Weil et al, PRC 94 (2016)



* Simulating Many Accelerated Strongly-Interacting Hadrons

Degrees of Freedom

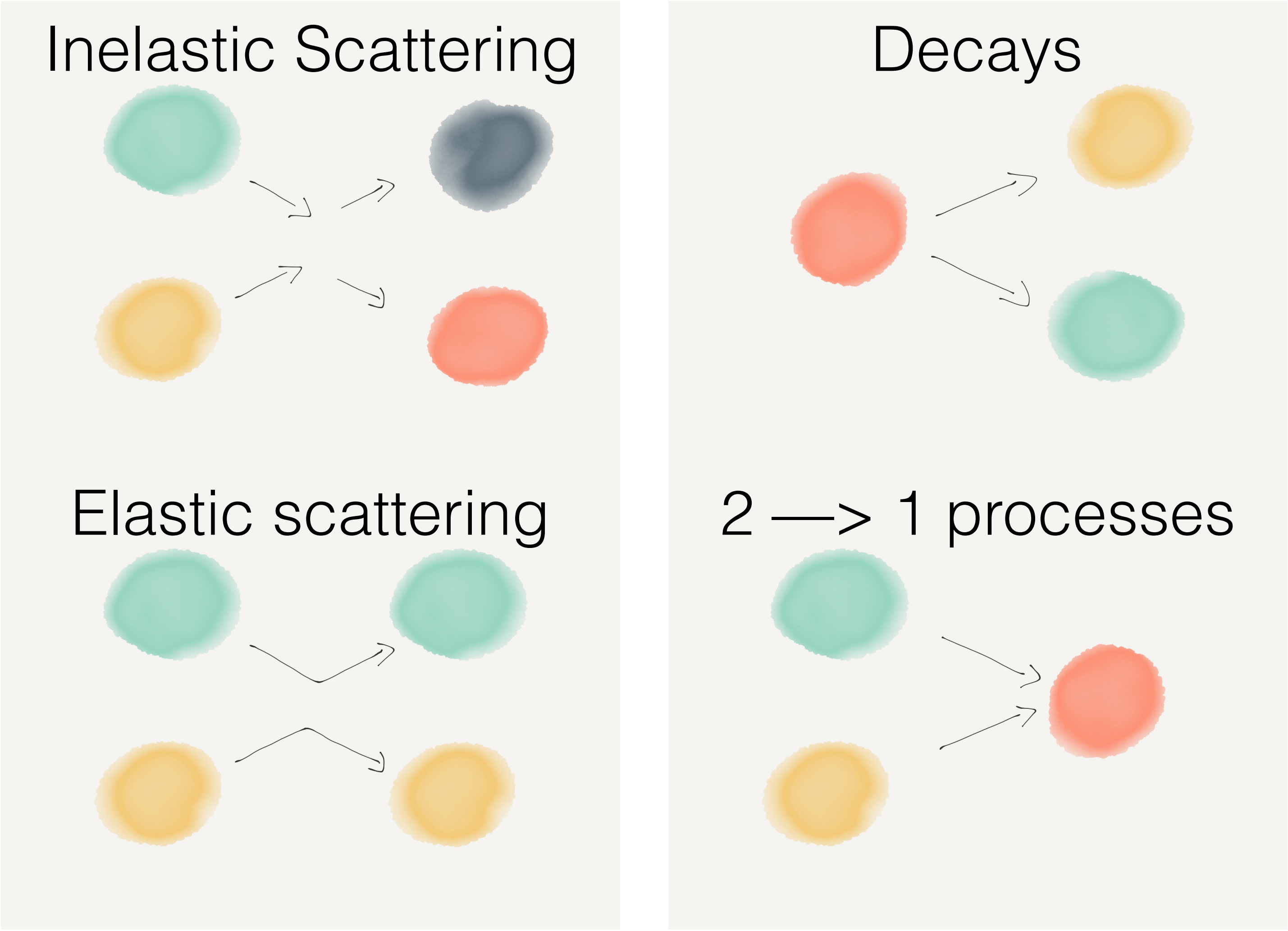
- Easily configurable by human-readable input files

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_{1905}	Λ_{1600}	Σ_{1670}	Ξ_{1820}			$f_{0\,1710}$	$f_{2\,2010}$		$K_{1\,1400}$
N_{1650}	Δ_{1910}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\,2300}$	$\phi_{3\,1850}$	K^*_{1410}
N_{1675}	Δ_{1920}	Λ_{1690}	Σ_{1775}	Ξ_{2030}		η'_{958}	$a_{0\,980}$	$f_{2\,2340}$		$K_0^*{}_{1430}$
N_{1680}	Δ_{1930}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\,1450}$		$a_{4\,2040}$	$K_2^*{}_{1430}$
N_{1700}	Δ_{1950}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\,1285}$		K^*_{1680}
N_{1710}		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_{2080}		Λ_{2350}				ρ_{1450}	$b_{1\,1235}$	$\pi_{1\,1600}$		
N_{2190}						ρ_{1700}				
N_{2220}							$a_{1\,1260}$	$\eta_{2\,1645}$		
N_{2250}						ω_{783}				
						ω_{1420}		$\omega_{3\,1670}$		
						ω_{1650}				

•Isospin symmetry
•Perturbative treatment of non-hadronic particles (photons, dileptons)

Collision Term

- In few GeV energy regime decay and excitation of resonances dominate hadronic cross section



- There are many (thousands) of unknown parameters that are hardly constrained by experimental data

Strangeness Production

K^+ production ($Y \in \{\Lambda, \Sigma\}$):

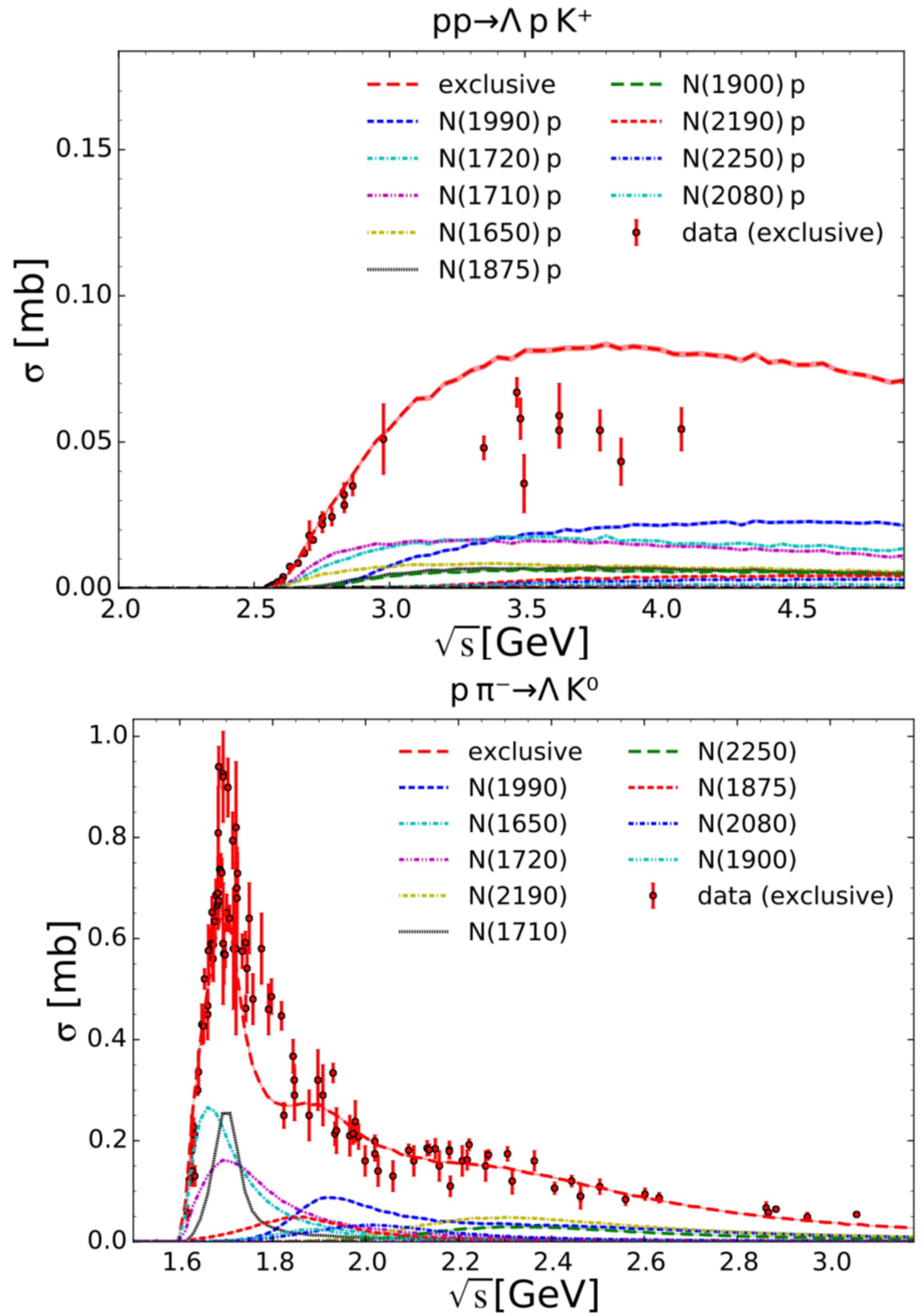
$$NN \to NN^*/\Delta^* \to NYK$$

K^- production:

$$NN \to N^*/\Delta^* ... \to Y ... \to Y^* ... \to \bar{K} ...$$
$$\pi Y \leftrightarrow \bar{K} N$$

resonance	branching ratio $N^* \to \Lambda K$ PDG	HADES	SMASH
$N(1650)$	$5-15\%$	$7\pm4\%$	4%
$N(1710)$	$5-25\%$	$15\pm10\%$	13%
$N(1720)$	$4-5\%$	$8\pm7\%$	5%
$N(1875)$	>0	$4\pm2\%$	2%
$N(1880)$		$2\pm1\%$	
$N(1895)$		$18\pm5\%$	
$N(1900)$	$2-20\%$	$5\pm5\%$	2%
$N(1990)$			2%
$N(2080)$			0.5%
$N(2190)$	$0.2-0.8\%$		0.8%
$N(2220)$			0
$N(2250)$			0.5%

- Find best fit ‚by eye' is tedious and complicated



V. Steinberg et al., arXiv:1809.03828

Idea #1: Bayesian Techniques

- Experimental data: 20-30 exclusive strangeness production cross-sections
- Parameters: ~10 branching ratios of nucleon resonances (other channels will be rescaled)
  - Definition of prior by requiring to fulfill PDG constraints and/or other observables like pion production
- Issues: heterogeneous, old data set
  - Interpretation of error bars, weighting of results?
- Deterministic results of the model -> direct MCMC run without emulator
  - Is 1 minute per step still feasible in a10-dimensional parameters space?
- Goal: Systematic uncertainty quantification for hyperon and kaon production

Collective Behaviour

- Potentials in SMASH
  - Basic Skyrme and symmetry potential

$$U_{\mathrm{Skyrme}} = \alpha(\rho/\rho_0) + \beta(\rho/\rho_0)^\tau \qquad U_{\mathrm{Symmetry}} = \pm 2 S_{\mathrm{Pot}} \frac{\rho_{I_3}}{\rho_0}$$

  - Describes interactions between nucleons, repulsive at high densities

	soft EoS	default EoS	hard EoS
α	-356.0 MeV	-209.2 MeV	-124.0 MeV
β	303.0 MeV	156.4 MeV	71.0 MeV
τ	1.17	1.35	2.00
κ	200 MeV	240 MeV	380 MeV

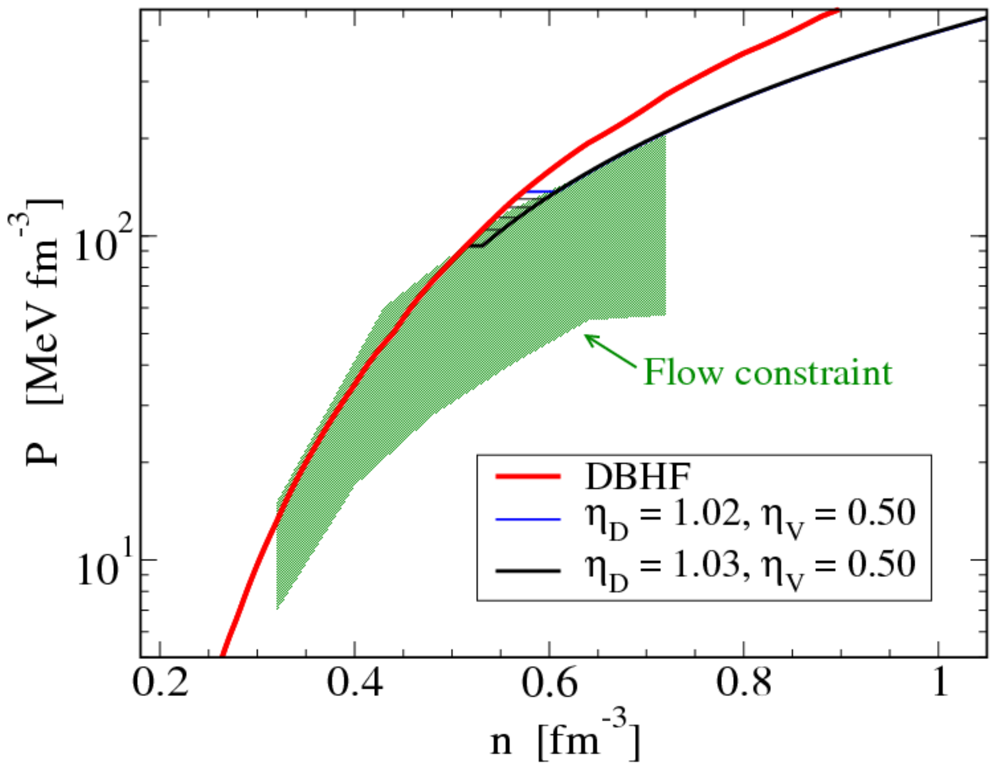
  - Default values according to recent transport code comparison

J. Xu et al., PRC 93 (2016)

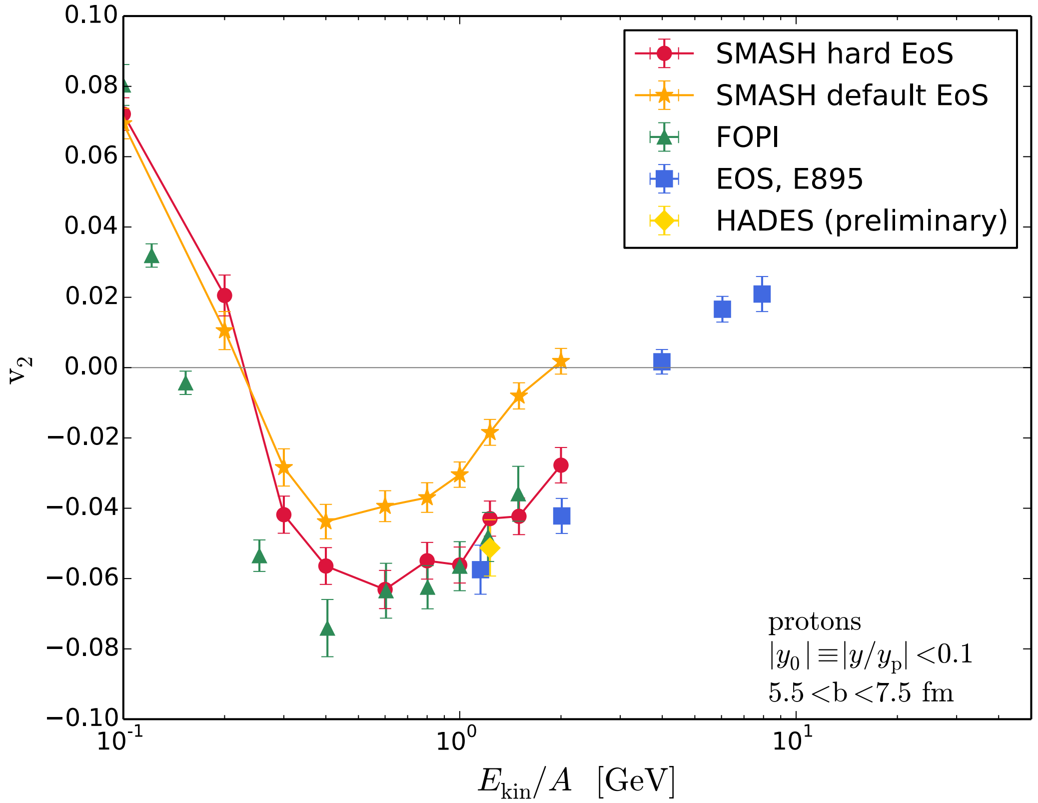
#2 Nuclear Matter Equation of State

- Measurements on collective flow of different species at different energies and systems are available

D. Blaschke et al, AIP Conf.Proc. 1068 (2008) 191-198



by Markus Mayer



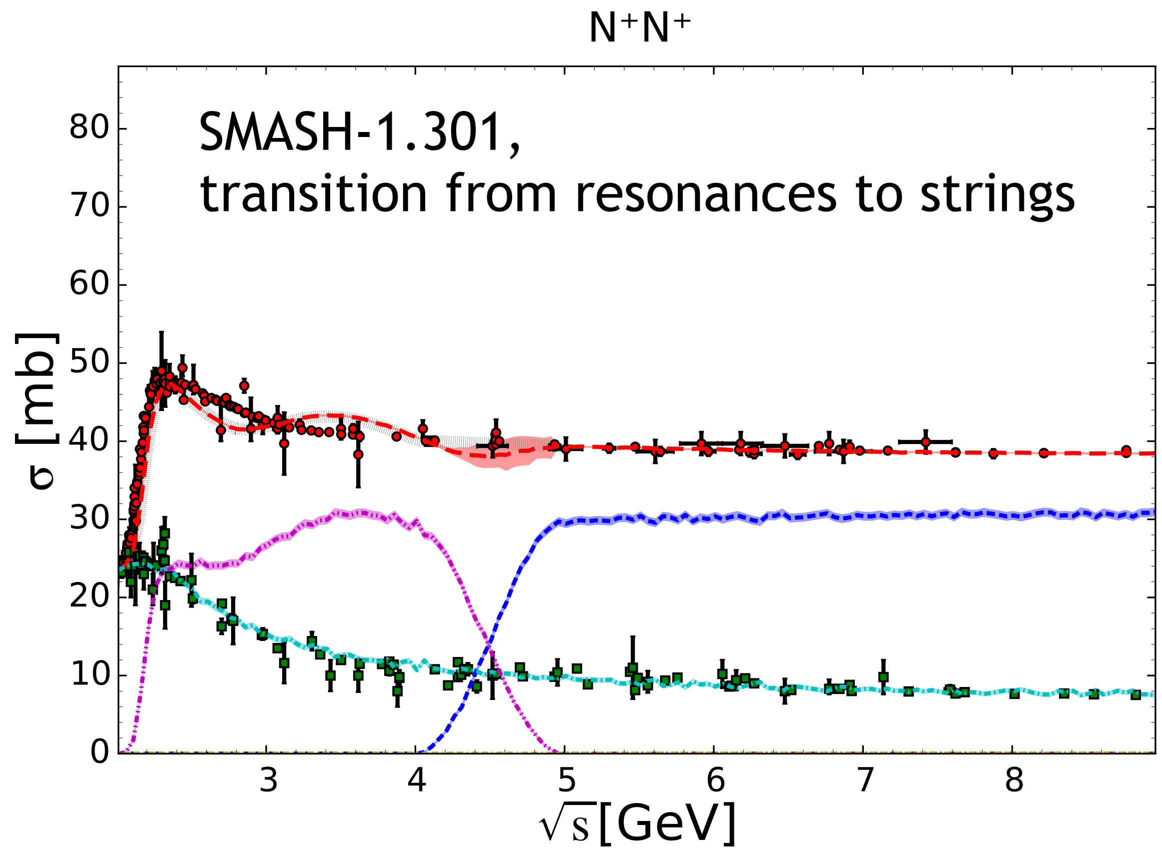
- Plan: Quantify systematic uncertainties by proper Bayesian analysis
- Repeat ‚Danielewicz constraint' with interplay of resonances and potentials

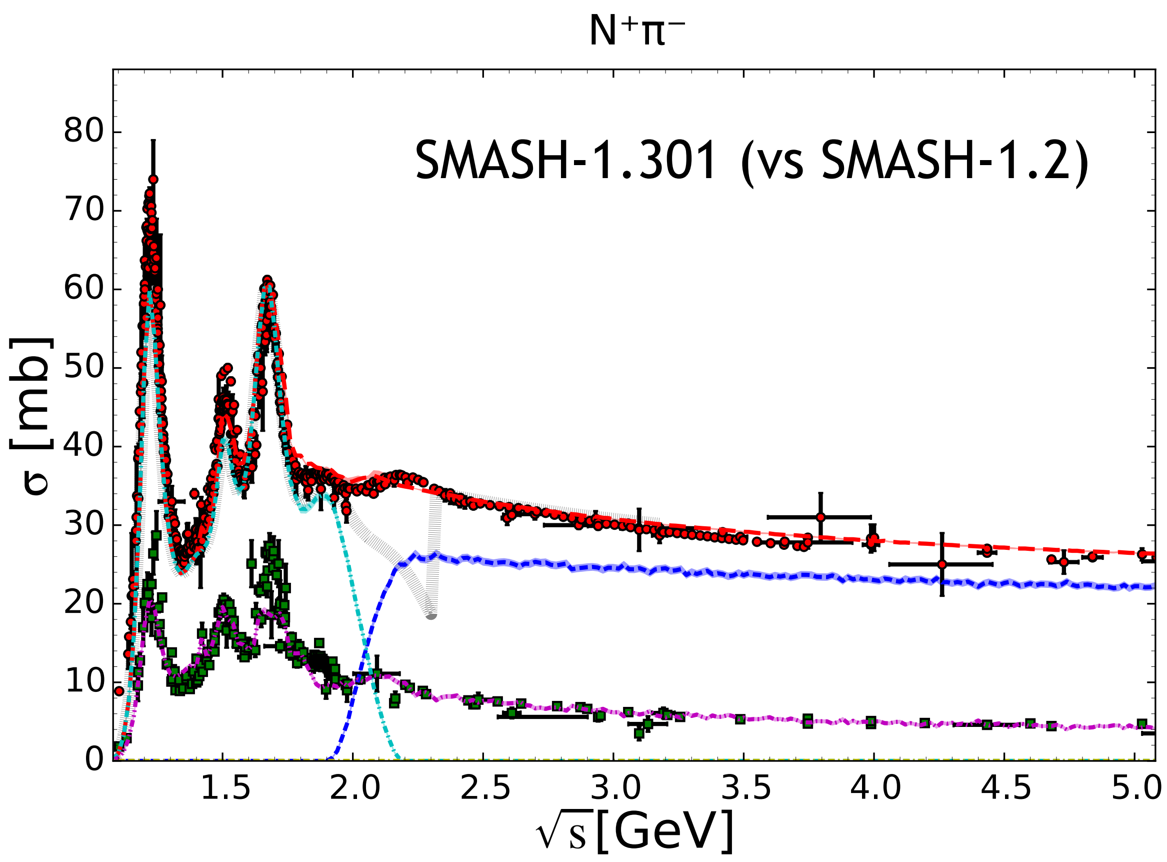
Summary

- The quark-gluon plasma is produced in high energy heavy-ion reactions
  - Dynamical modeling converges towards a ‚standard model' based on relativistic dissipative fluid dynamics and hadronic transport approaches
  - Promising results from first Bayesian analysis are available
- New hadronic transport approach SMASH
  - Applicable at low beam energies and for hadronic rescattering
  - 2 potential applications for Bayesian techniques:
    - Constraining branching ratios for strangeness production
    - Renew „Danielewicz constraint“ for nuclear matter equation of state

Backup

Elementary Cross Sections





- Total cross section for pp/pπ collisions
- Parametrized elastic cross section
- Many resonance contributions to inelastic cross section
- Reasonable description of experimental data
- Work in progress: Compare particle production from strings to pp data

J. Mohs and S. Ryu, in progress

Hybrid approaches

Transport

Microscopic description of the whole phase-space distribution

Non-equilibrium evolution based on the Boltzmann equation

$$\left(p^{\mu}\partial_{\mu}\right)f = I_{coll}$$

Partonic or hadronic degrees of freedom

Cross-sections are calculable using different techniques

Phase transition?

Hydrodynamics

Macroscopic description

Local equilibrium is assumed

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

Propagation according to conservation laws

Equation of state is an explicit input

Boundary conditions: Breakdown of equilibrium assumptions?

- Combine the advantages of both approaches
- Successful description from initial to final state

General Setup

- Transport models provide an effective solution of the relativistic Boltzmann equation

$$p^\mu \partial_\mu f_i(x,p) + m_i F^\alpha \partial^p_\alpha f_i(x,p) = C^i_{\text{coll}}$$

- Particles represented by Gaussian wave packets
- Geometric collision criterion

$$d_{\text{trans}} < d_{\text{int}} = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}} \qquad d^2_{\text{trans}} = (\vec{r_a} - \vec{r_b})^2 - \frac{((\vec{r_a} - \vec{r_b}) \cdot (\vec{p_a} - \vec{p_b}))^2}{(\vec{p_a} - \vec{p_b})^2}$$

- Test particle method

$$\sigma \mapsto \sigma \cdot N_{\text{test}}^{-1}$$

$$N \mapsto N \cdot N_{\text{test}}$$