Baryon and strangeness diffusion and their cross-talk as a function of temperature in a hadronic transport approach

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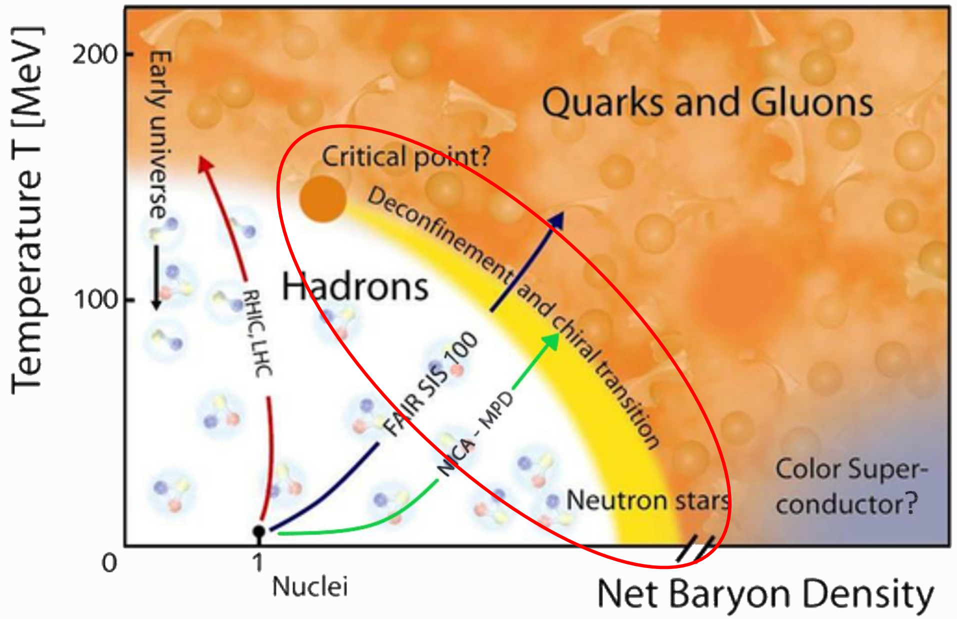
Introduction

Motivation

- Heavy-ion collisions performed to investigate QCD phase diagram
  - Finding expected 1st order phase transition and critical point



- After QGP phase: hadronization
- Low-energy heavy-ion collisions: hadron gas

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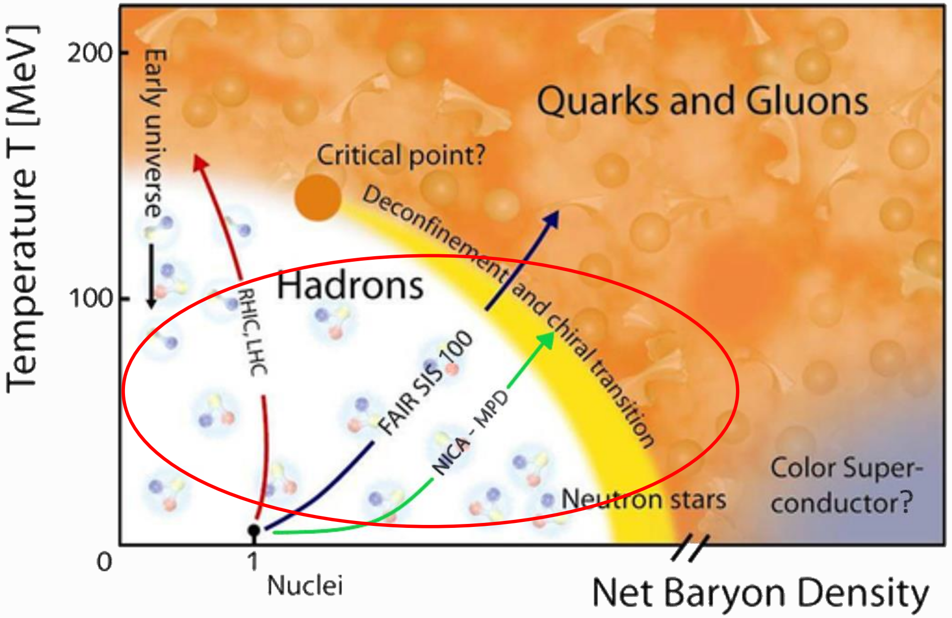
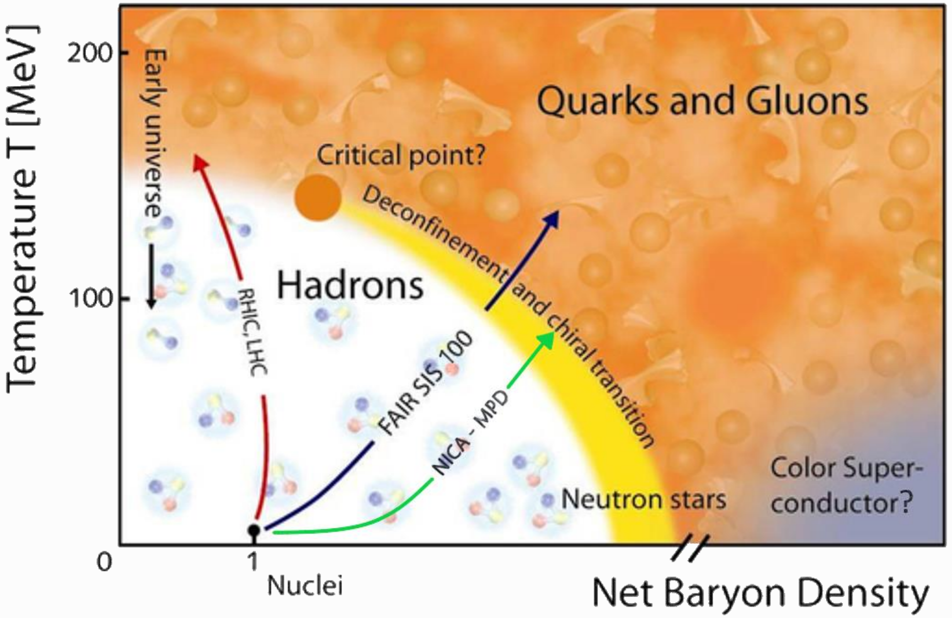
  - Finding expected 1st order phase transition and critical point



- After QGP phase: hadronization
- Low-energy heavy-ion collisions: only hadron gas

Motivation

- Low-energy heavy-ion collisions:
  - RHIC BES program @ BNL
  - FAIR @ GSI
  - NICA @ JINR
- Hydrodynamic and transport approaches (or hybrids)
  - UrQMD
  - BAMPS
  - PHSD
  - SMASH
  - …



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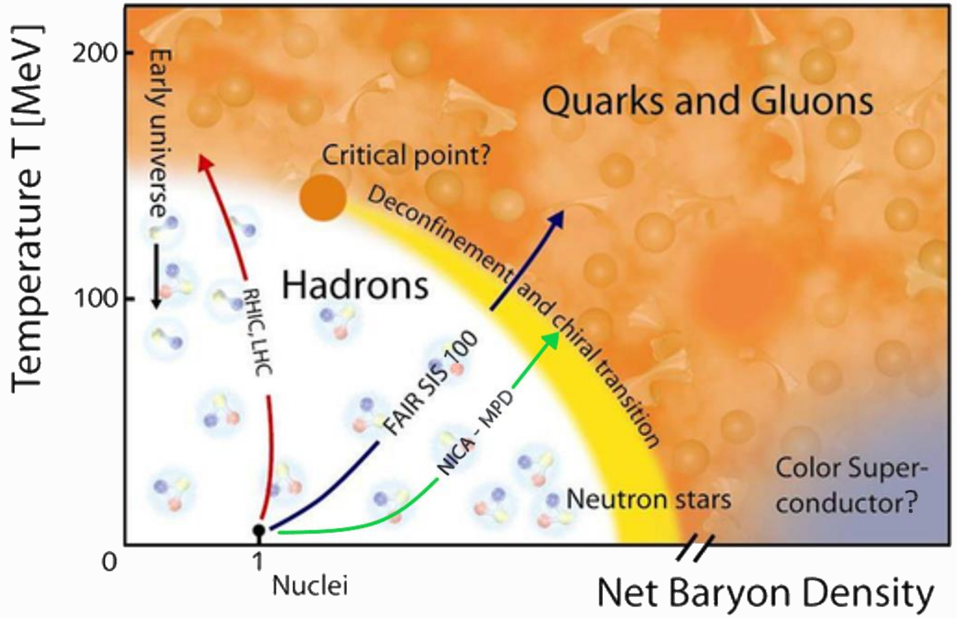
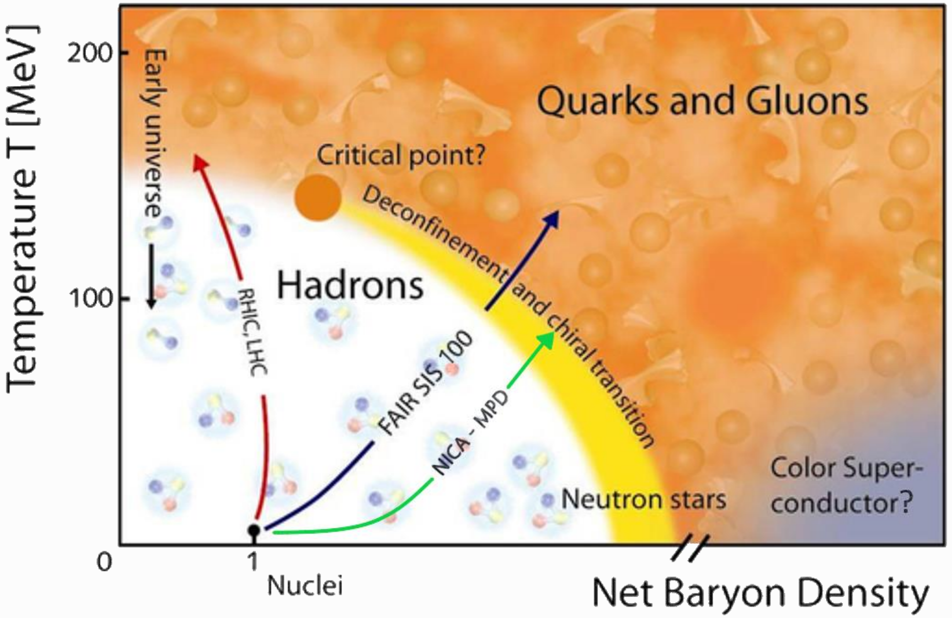


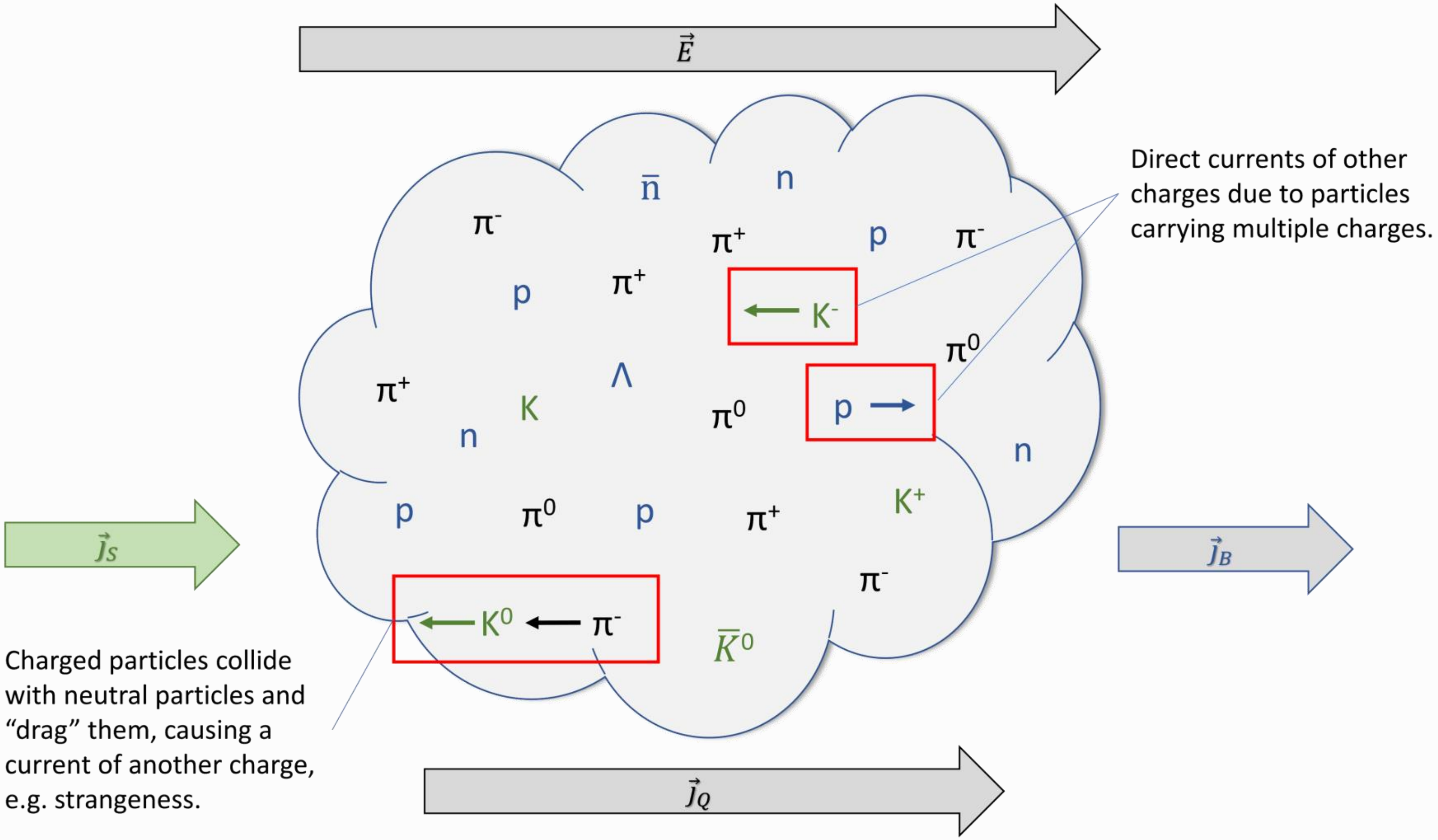
Motivation

- Linear response transport coefficients can be used to characterize hadronic matter
  - Shear and bulk viscosities: η, ζ
  - Conductivities / diffusion coefficients related to baryon, electric and strangeness charge: σ_{ij}, κ_{ij}

$$\underbrace{\vec{J}_k}_{\text{current}} = \underbrace{\nu_k}_{\text{transport coefficient}} \underbrace{\vec{X}_k}_{\text{gradient}}$$



Charge diffusion



Charge diffusion

- Diffusion processes associated with conserved currents (B,Q,S) do not occur independently from each other

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

charged current

diffusion coefficient matrix (symmetric)
$\kappa_{ij} = \sigma_{ij}/T$

gradients of charged thermal potentials
$\alpha_i = \mu_i/T$

Goals

- Calculate full diffusion coefficient matrix of the hadron gas using SMASH -> specifically, baryon and strangeness related coefficients

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

- Compare results to previous calculations by J.-B. Rose (SMASH) and kinetic theory by M. Greif & J. Fotakis *et.al.*

The model: SMASH

SMASH (Simulating Many Accelerated Strongly-interacting Hadrons)

- Hadronic transport approach using an effective solution of the relativistic Boltzmann equation:

$$p^{\mu}\partial_{\mu}f_a(\vec{x},\vec{p},t) + m_a F^{\alpha}\partial_{\alpha}^{p} f_a(\vec{x},\vec{p},t) = C_a^{coll}$$

- Geometric collision criterion:

$$d_{trans} < d_{int} = \sqrt{\frac{\sigma_{tot}}{\pi}}$$

- Spectral functions of resonances are described by relativistic Breit-Wigner functions, with resonance life-time $\tau = 1/\Gamma(m)$

SMASH (Simulating Many Accelerated Strongly-interacting Hadrons)

- Elastic collision via resonances, fully parametrized cross-sections, or scaled from πp cross-sections using the Additive Quark Model
- Inelastic 2 -> 2 processes:
  - $NN \leftrightarrow NR$
  - $NN \leftrightarrow \Delta R$
  - $KN \leftrightarrow KN$
  - $KN \leftrightarrow K\Delta$
  - $KN \leftrightarrow \pi\Upsilon,\quad \Upsilon = \{\Lambda, \Sigma, \Xi\}$
- Processes that violate detailed balance are turned off, e.g. string excitations

SMASH – Infinite matter simulations

- 3D cube with periodic boundary conditions
- Initialized with temperature T and chemical potentials μ_i with $i = \{B, Q, S\}$ → thermal momenta and multiplicities:

$$N_a = g_a \frac{VT^3}{2\pi^2} \exp\left(\frac{\sum_i \mu_a^i q_a^i}{T}\right) \left(\frac{m_a}{T}\right)^2 K_2\left(\frac{m_a}{T}\right)$$

Isospin degeneracy of particle species a

- All chemical potentials are set to 0 in this work

Degrees of freedom

DOF: Simplified hadron gas ($\sigma = 30\ \mathrm{mb}$)

N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
$\boldsymbol{N_{938}}$	$\boldsymbol{\Delta_{1232}}$	$\boldsymbol{\Lambda_{1116}}$	Σ_{1189}	Ξ_{1318}	Ω_{1672}	$\boldsymbol{\pi_{138}}$	$f_{0\ 980}$	$f_{2\ 1276}$	$\rho_{3\ 1690}$	$\boldsymbol{K_{494}}$
N_{1440}	Δ_{1620}	Λ_{1405}	Σ_{1385}	Ξ_{1533}	Ω_{2252}	π_{1300}	$f_{0\ 1370}$	$f'_{2\ 1525}$		K^*_{892}
N_{1520}	Δ_{1700}	Λ_{1520}	Σ_{1660}	Ξ_{1690}		π_{1800}	$f_{0\ 1500}$	$f_{2\ 1950}$	$\phi_{3\ 1850}$	$K_{1\ 1270}$
N_{1535}	Δ_{1900}	Λ_{1600}	Σ_{1670}	Ξ_{1823}			$f_{0\ 1710}$	$f_{2\ 2010}$		$K_{1\ 1400}$
N_{1650}	Δ_{1905}	Λ_{1670}	Σ_{1750}	Ξ_{1950}		η_{548}		$f_{2\ 2300}$	$a_{4\ 2040}$	K^*_{1420}
N_{1675}	Δ_{1910}	Λ_{1690}	Σ_{1775}	Ξ_{2025}		η'_{958}	$a_{0\ 980}$	$f_{2\ 2340}$		$K^*_{0\ 1430}$
N_{1680}	Δ_{1920}	Λ_{1800}	Σ_{1915}			η_{1295}	$a_{0\ 1450}$		$f_{4\ 2050}$	$K^*_{2\ 1430}$
N_{1700}	Δ_{1930}	Λ_{1810}	Σ_{1940}			η_{1405}		$f_{1\ 1285}$		K^*_{1680}
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N_{1875}		Λ_{1830}	Σ_{2250}				ϕ_{1680}			$K^*_{3\ 1780}$
N_{1880}		Λ_{1890}				σ_{800}		$a_{2\ 1320}$		$K_{2\ 1820}$
N_{1895}		Λ_{2100}					$h_{1\ 1170}$			$K^*_{4\ 2045}$
N_{1900}		Λ_{2110}				ρ_{776}		$\pi_{1\ 1400}$		
N_{1990}		Λ_{2350}				ρ_{1450}	$b_{1\ 1235}$	$\pi_{1\ 1600}$		
N_{2060}						ρ_{1700}				
N_{2080}							$a_{1\ 1260}$	$\eta_{2\ 1645}$		
N_{2100}						ω_{783}				
N_{2120}						ω_{1420}		$\omega_{3\ 1670}$		
N_{2190}						ω_{1650}				
N_{2220}								$\pi_{2\ 1670}$		
N_{2250}										

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DOF: Simple hadron gas with resonances

N	Δ	Λ	Σ	Ξ	Ω	Unflavored				Strange
N_{938}	Δ_{1232}	Λ_{1116}	Σ_{1189}	Ξ_{1318}	Ω_{1672}	π_{138}	$f_{0\,980}$	$f_{2\,1276}$	$\rho_{3\,1690}$	K_{494}
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DOF: Full hadron gas

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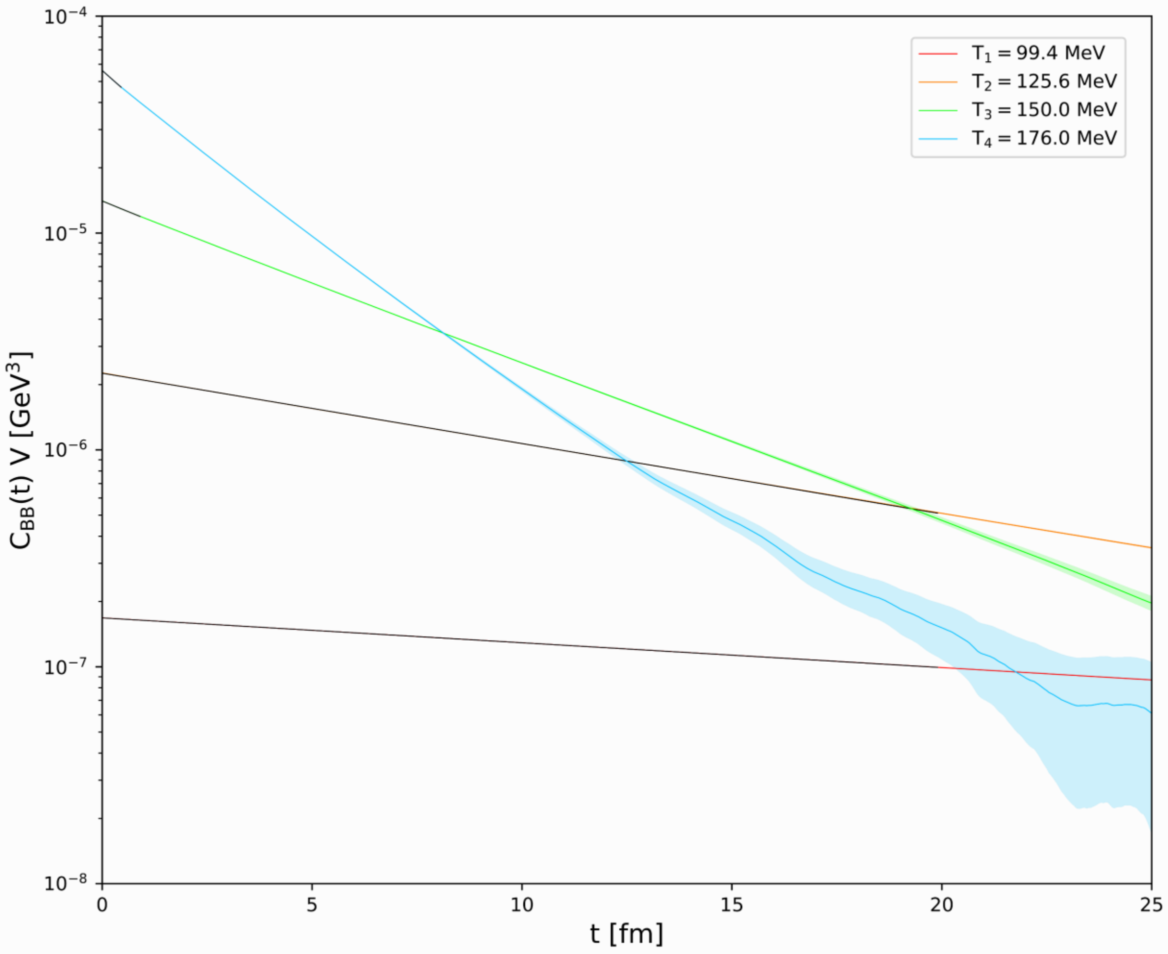
Methods

Linear response theory + Green-Kubo

- Allows to describe transport coefficients by equilibrium state correlation functions $(i,j = \{B,Q,S\})$:

$$C_x^{ij}(t) \equiv \left\langle J_x^i(t) J_x^j(0) \right\rangle$$
$$= \frac{1}{V}\frac{\kappa^{ij}}{\tau}\exp\left(-\frac{t}{\tau^{ij}}\right)$$
$$= C_x^{ij}(0) \cdot \exp\left(-\frac{t}{\tau^{ij}}\right)$$



Equilibrium of the hadron gas

- After initialization, a box is not in chemical or thermal equilibrium, e.g. due to Poissonian sampling of particles, initializations at pole masses, etc.

- Chemical and thermal equilibrium of a hadron gas is reached if:
  - steady state in terms of its chemical composition and momentum distribution is achieved
  - the temperature saturates at a constant value

$$\frac{\mathrm{d}\,N_a}{\mathrm{d}\,p} \propto p_a^2 \exp\left(-\frac{\sqrt{p_a^2+m_a^2}-\sum_k \mu_a^k q_a^k}{T}\right)$$

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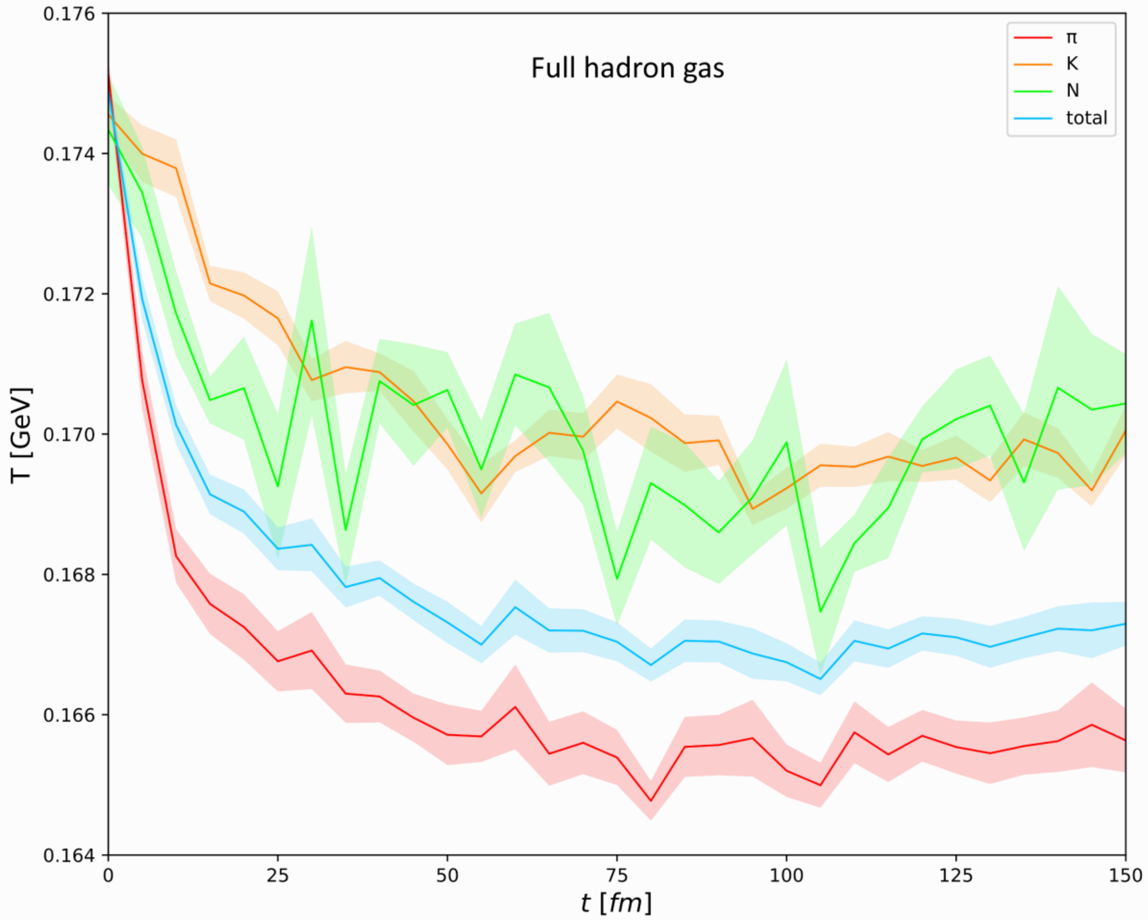
Equilibrium of the hadron gas

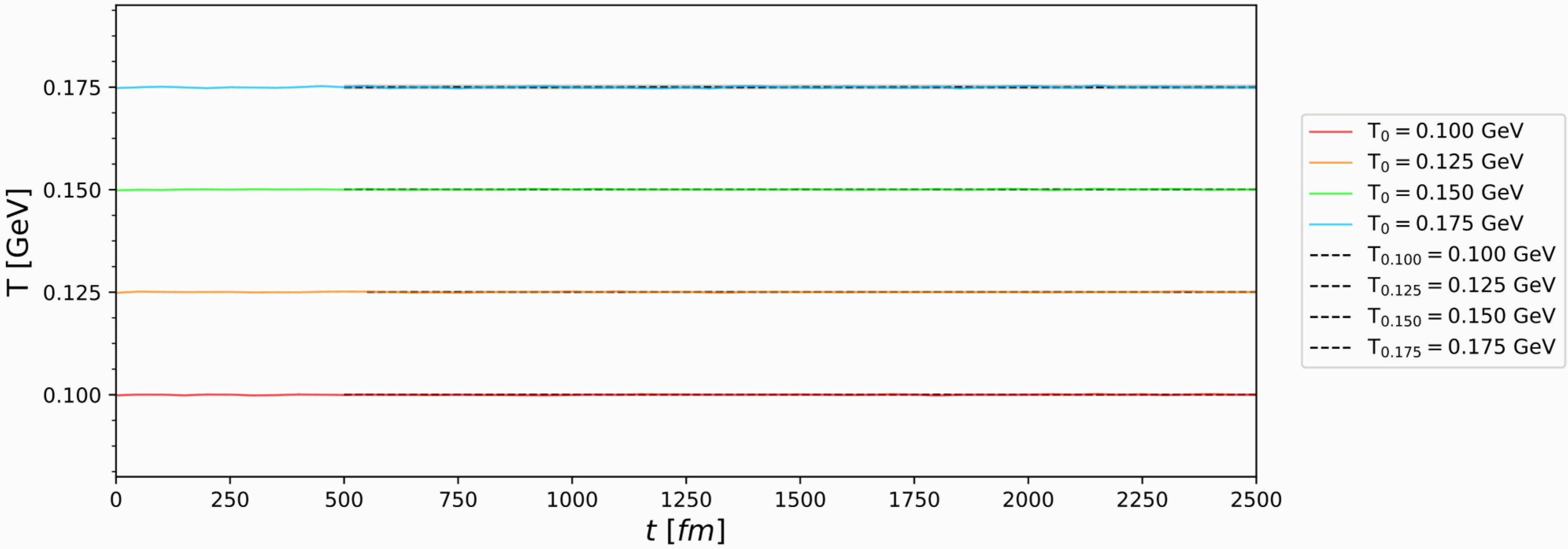
- Thermal equilibrium is reached after chemical, so monitoring the temperature is sufficient
- Temperature differs for different particle species
- Weighted average of most abundant particles:

  pions + kaons + nucleons

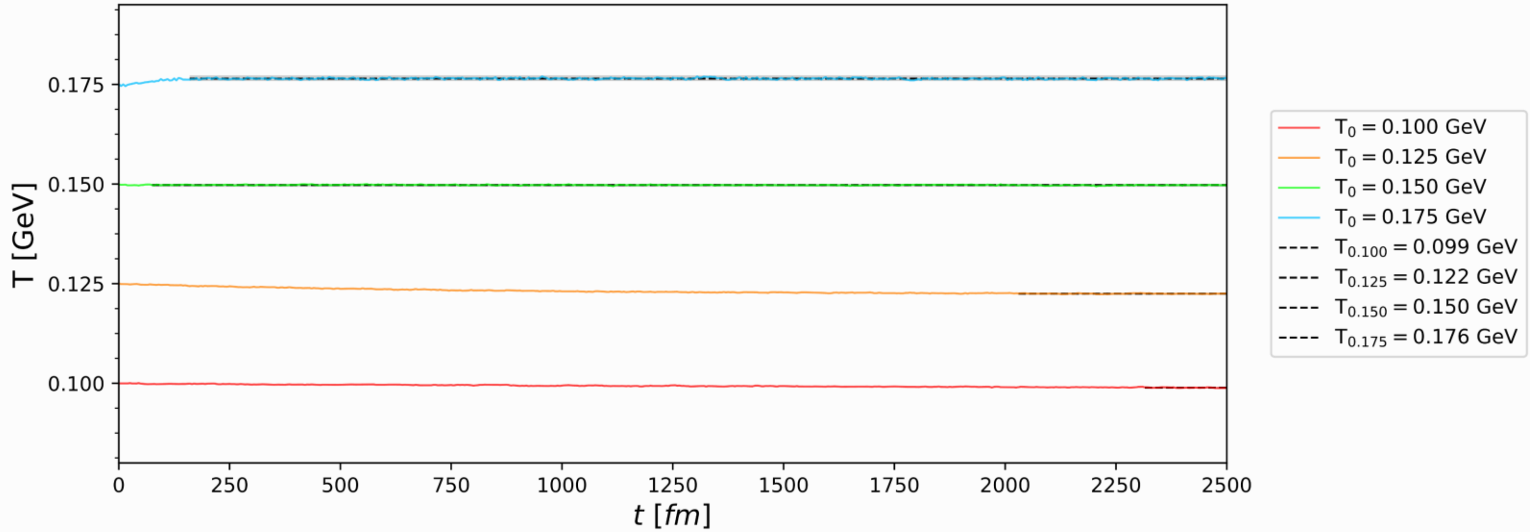


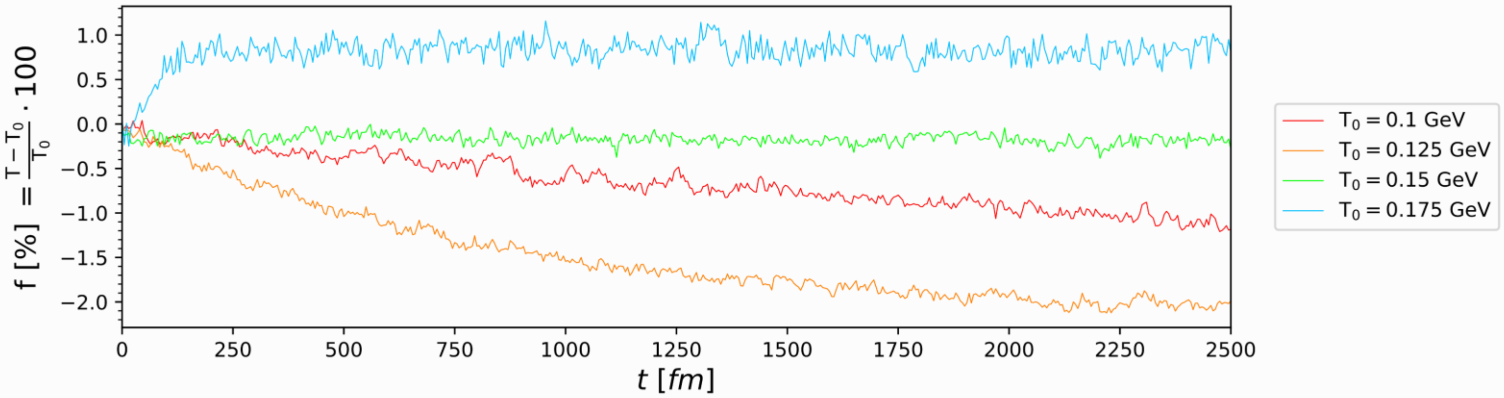
Results

Temperature: Simplified hadron gas

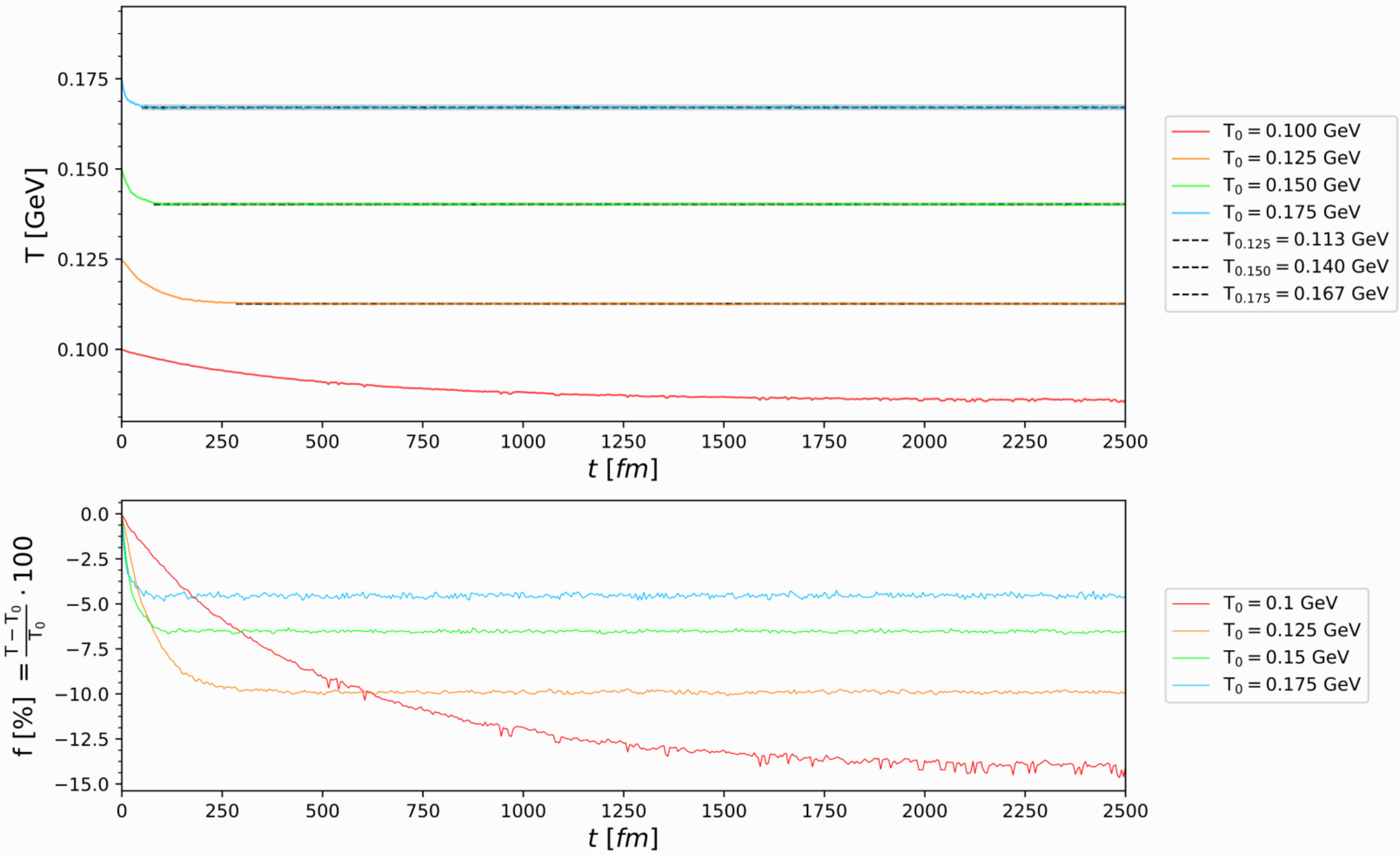


Temperature: Simple hadron gas with resonances





Temperature: Full hadron gas



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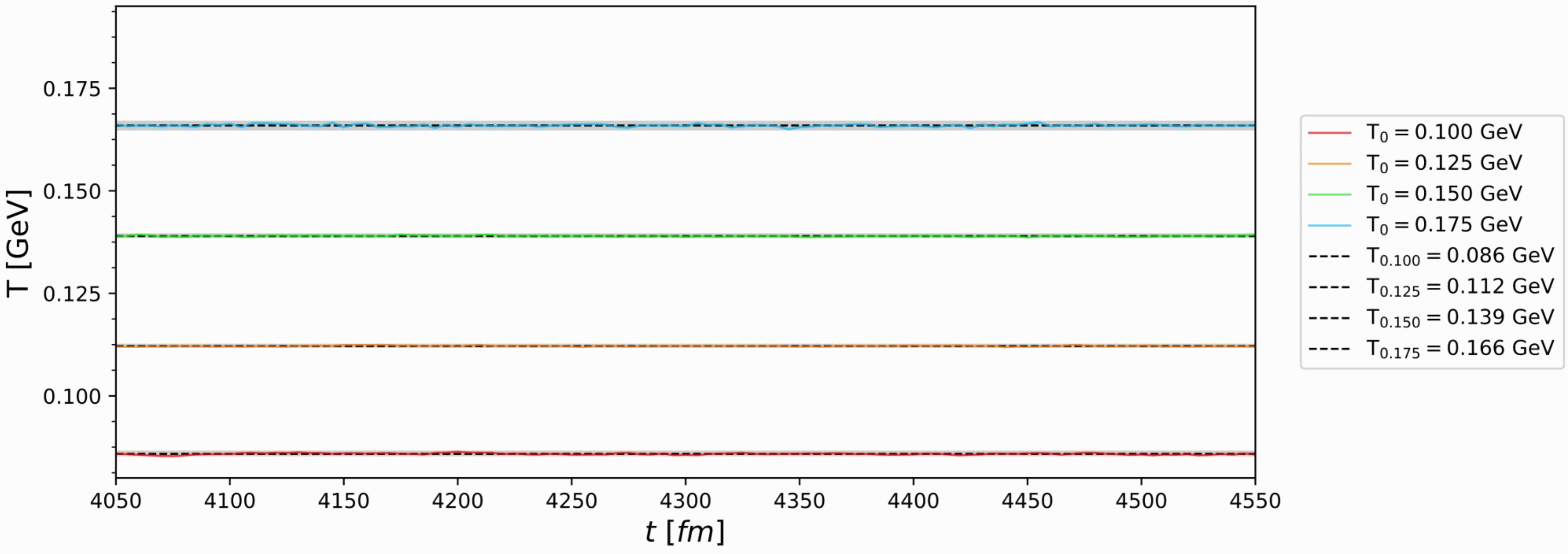


Correlation functions in SMASH

- SMASH provides full phase space information of each particle at every time step

$$J_i^\mu(t) = \frac{1}{V}\sum_{a=1}^{N} q_i^a \frac{p_a^\mu(t)}{p_a^0(t)} \qquad q_i^a = \{B^a, Q^a, S^a\}$$

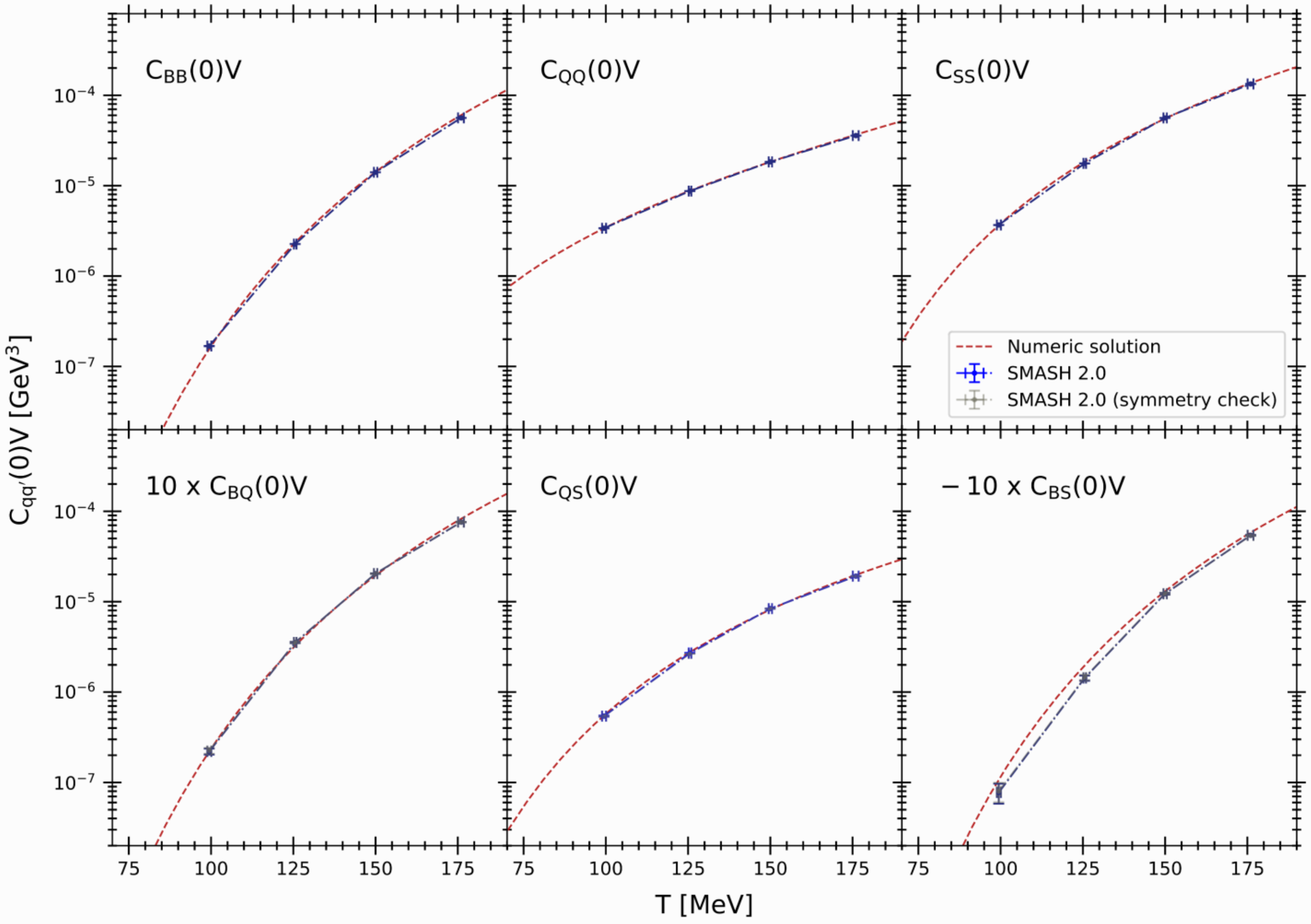
- Correlation function:

$$C(t) = \langle J(0)\, J(u\Delta t)\rangle = \lim_{K\to\infty} \frac{1}{K-u}\sum_{s=0}^{K-u} J(s\Delta t)\, J(s\Delta t + u\Delta t)$$

Total number of considered time steps

K=8000, Δt=0.05 fm

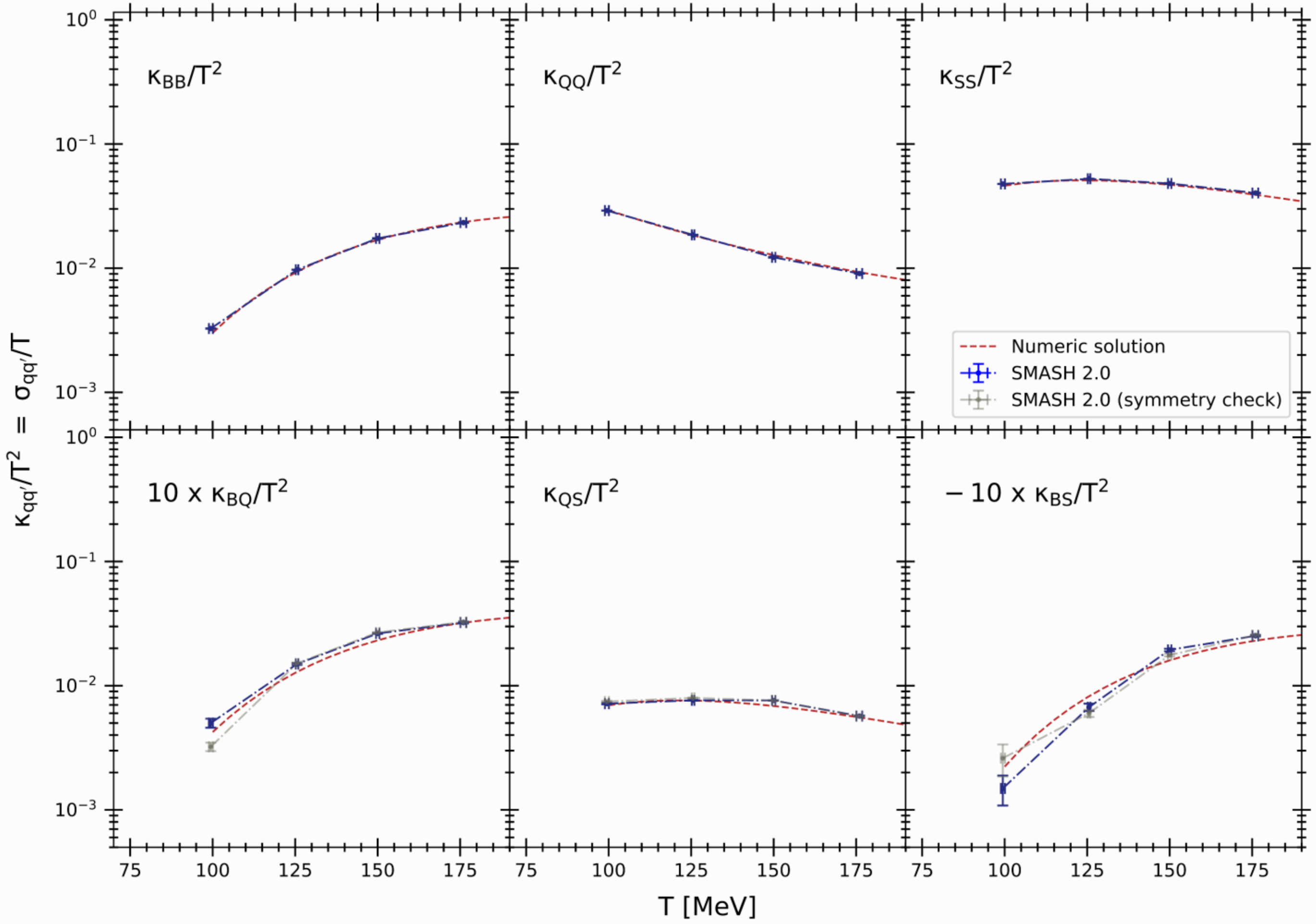
C(0)V: Simplified hadron gas



$$C_{ij}(t) = C_{ij}(0) \cdot \exp\left(-\frac{t}{\tau_{ij}}\right)$$

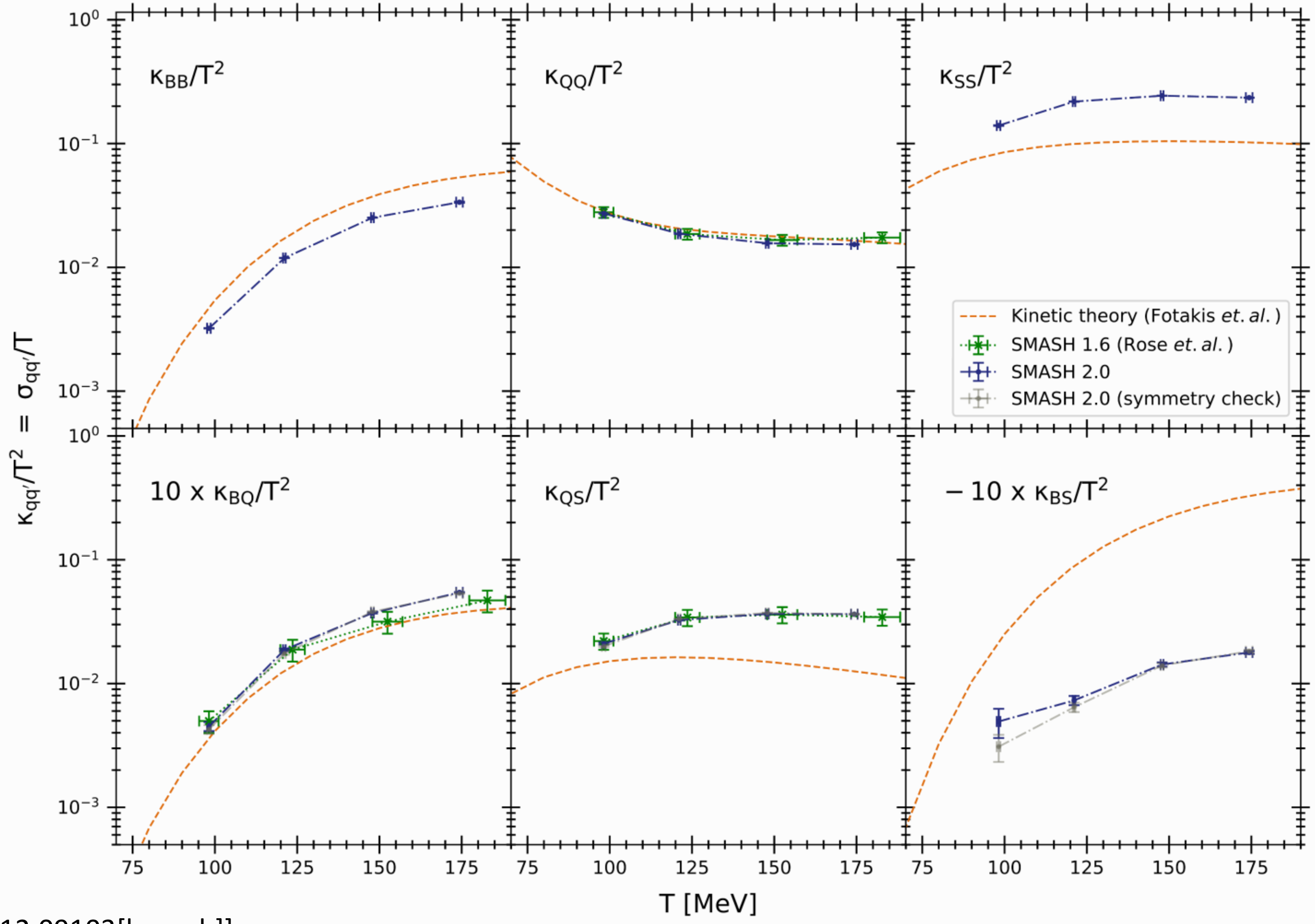
$$\kappa_{ij}(t) = C_{ij}(0)V \cdot \tau_{ij}$$

Diffusion: Simplified hadron gas



- Differences of symmetric quantities serve as an estimation for a systematical error
- All coefficients approximately of the same order of magnitude
- Larger errors for κ_{BQ} and κ_{BS} at lower T

Diffusion: Simple hadron gas with resonances



[arXiv:1912.09103[hep-ph]]

- Data compared to kinetic theory that uses a hadron gas of different chemical composition with more degrees of freedom
- κ_{QQ} and κ_{BQ} similar to kinetic theory due to contributing particles

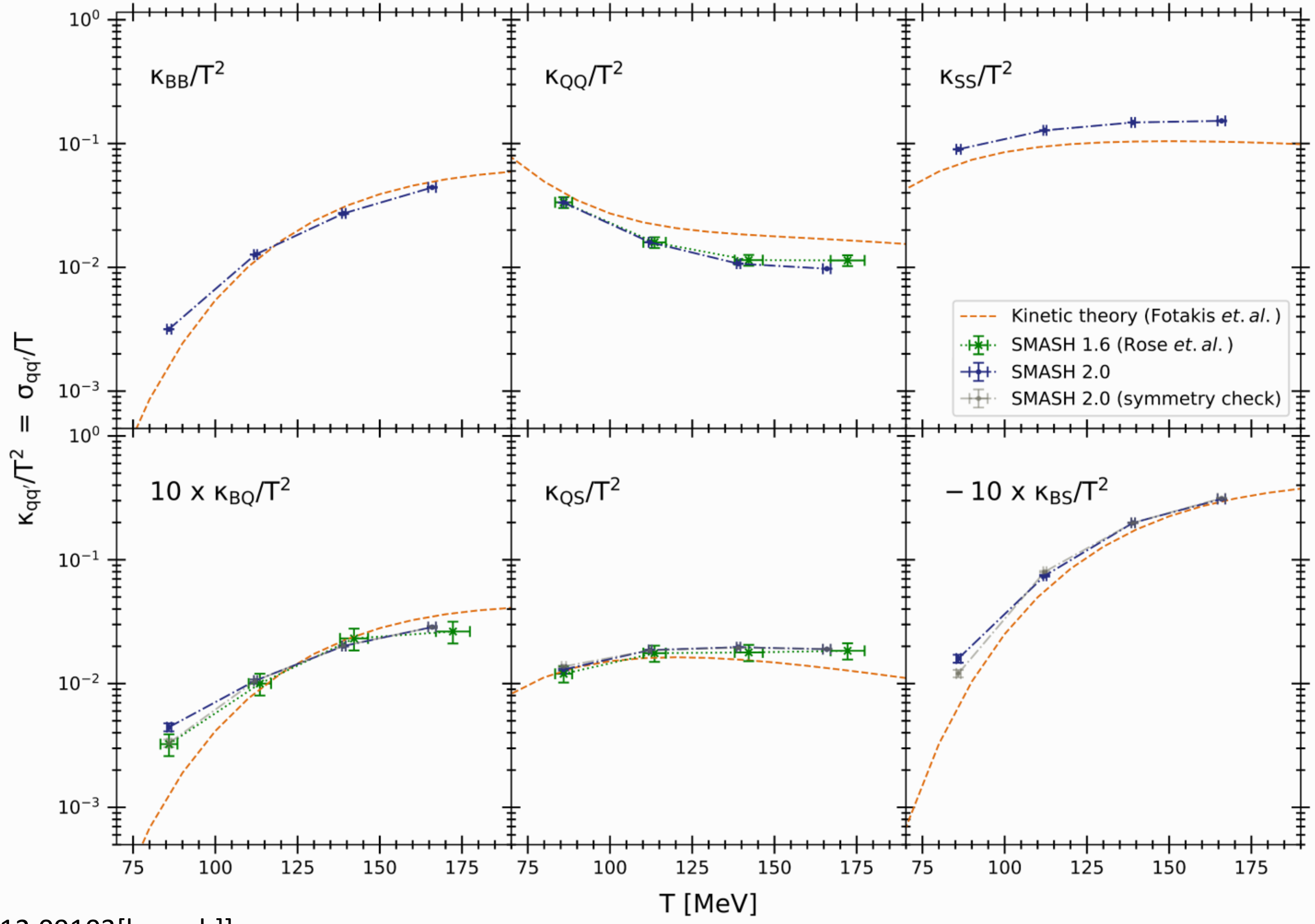
Kinetic theory: Composition

Particle	M_0 [GeV]	g
π	0.138	3
K	0.494	4
N	0.938	4
Λ	1.116	2
Σ^0	1.193	2
Σ^+	1.189	2
Σ^-	1.197	2

- No resonances, only parametrized, energy-dependent or constant cross-sections
- Addition of Σ baryons that can carry all three conserved charges (B,Q,S)

[arXiv:1912.09103[hep-ph]]

Diffusion: Full hadron gas



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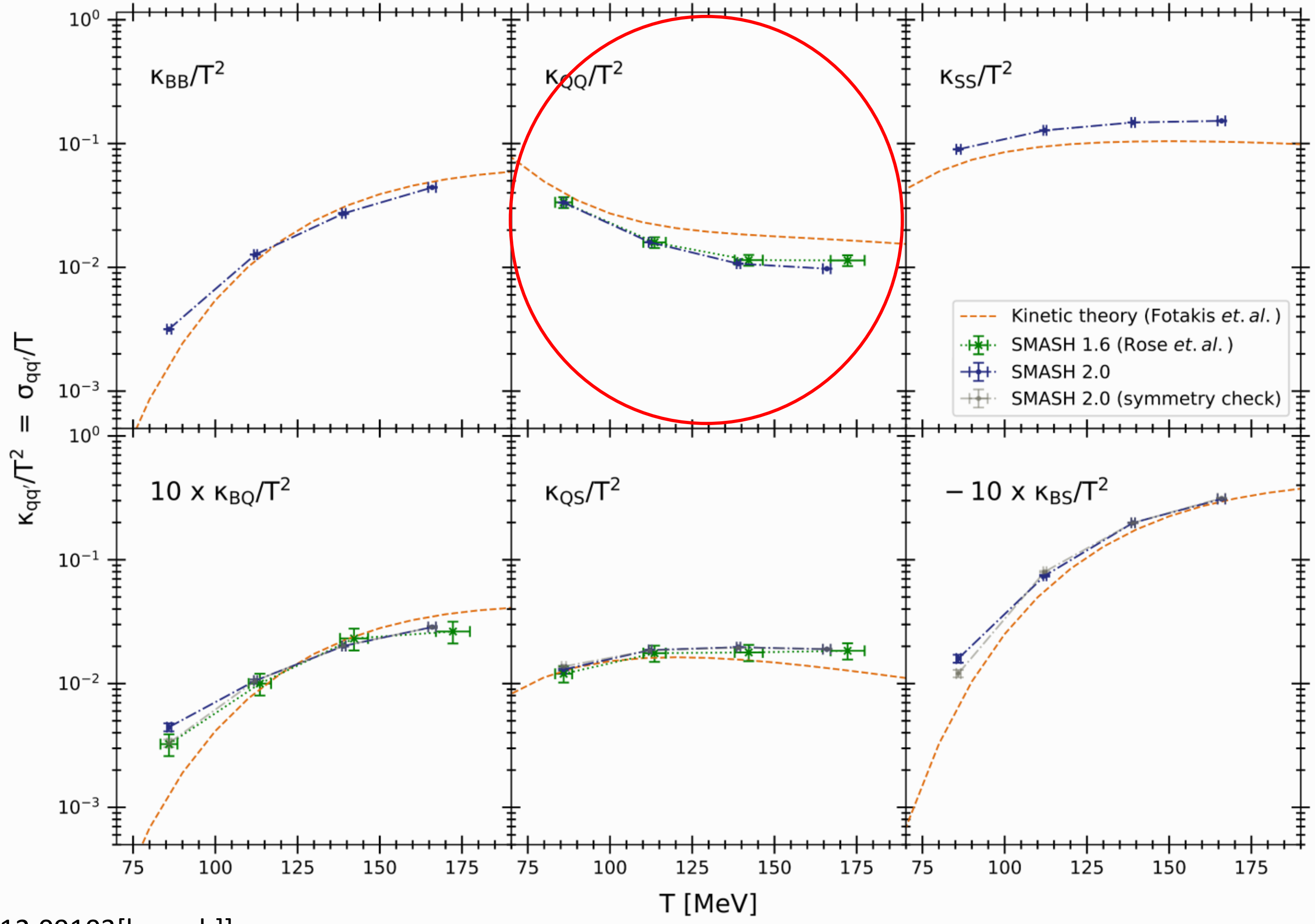
- Large contribution from the Σ baryon
- κ_{BS} errors smaller due to more contributing particles
- Kinetic theory gives good approximation of data, even though a simpler system was used

Diffusion: Full hadron gas



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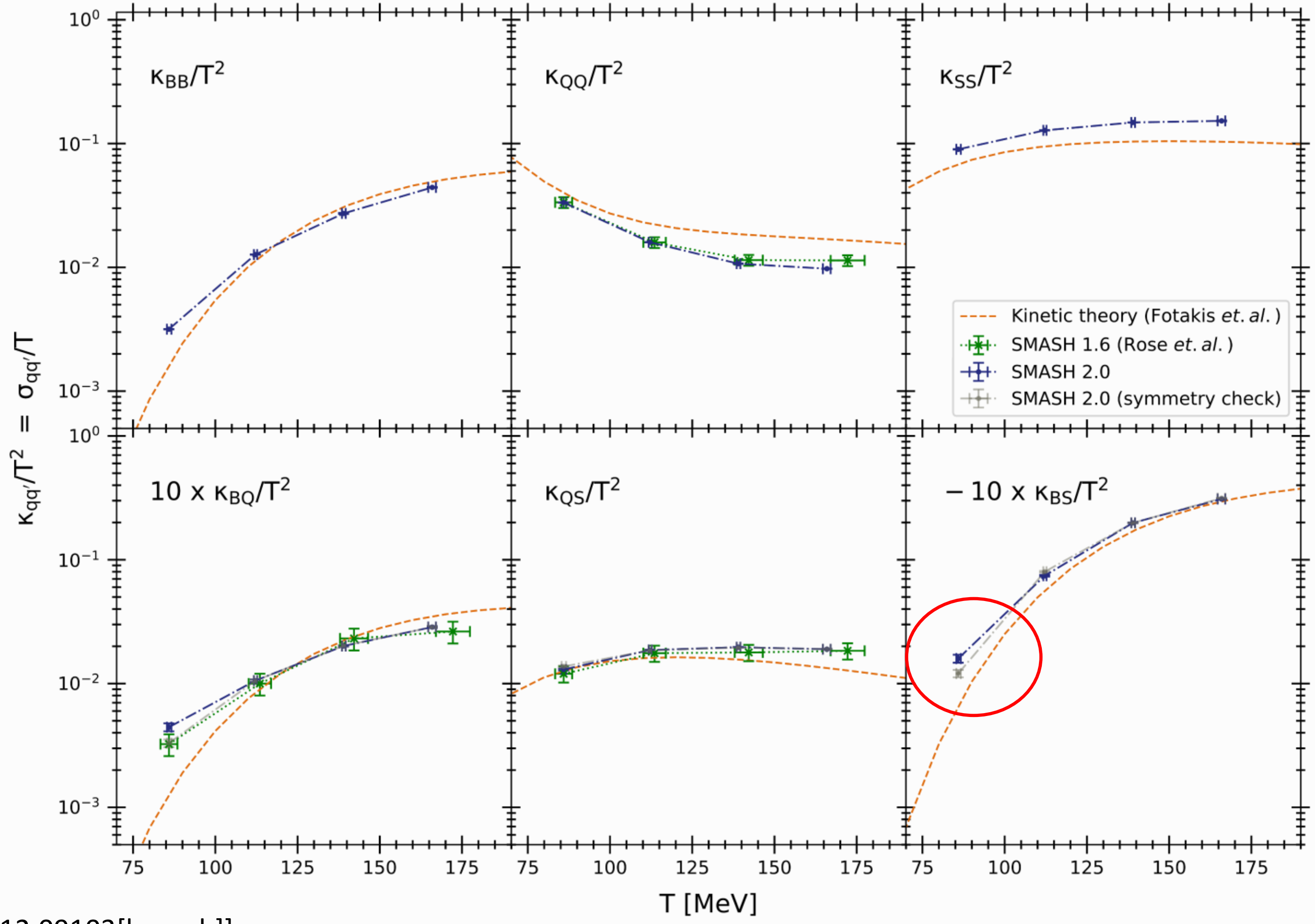

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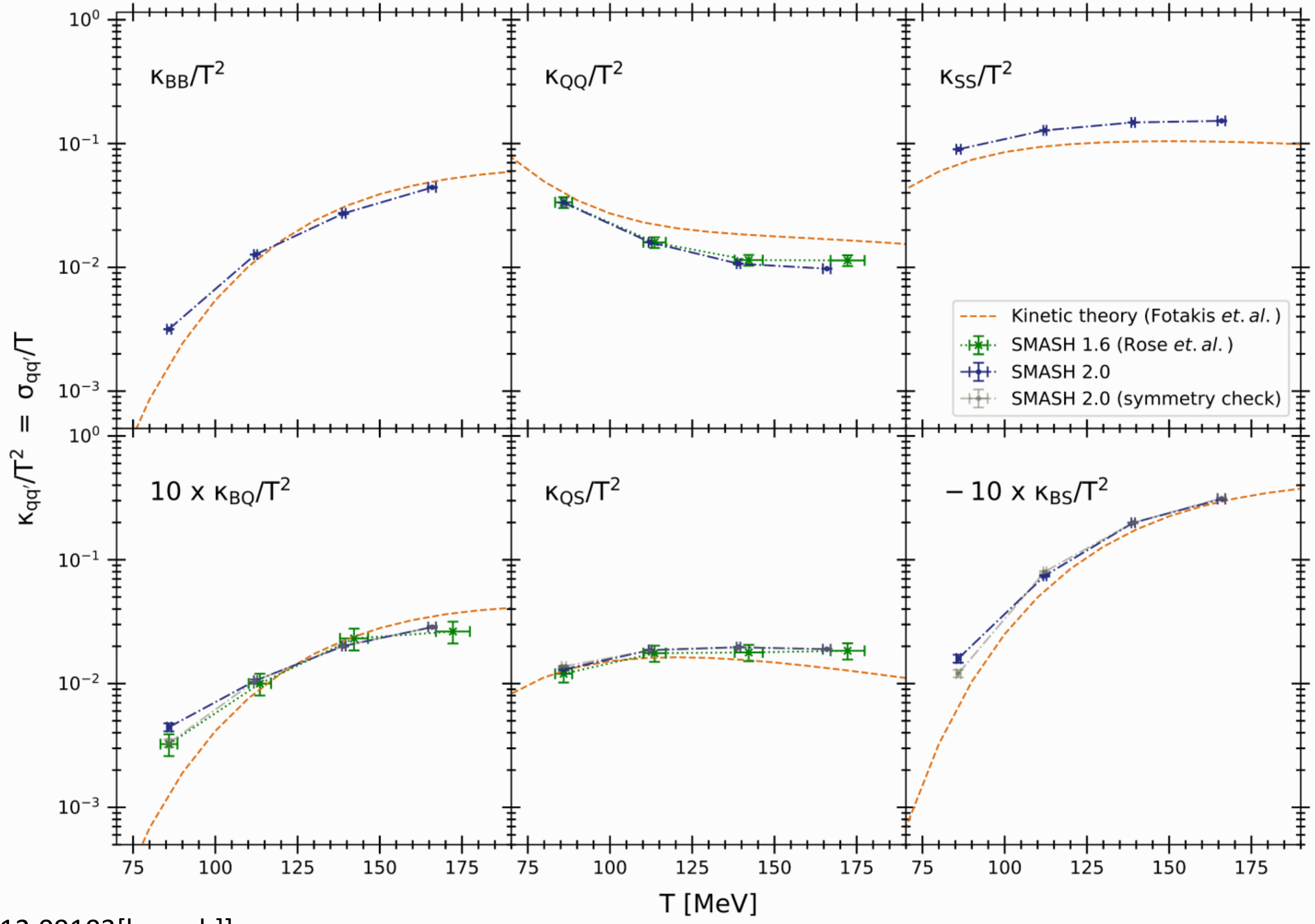

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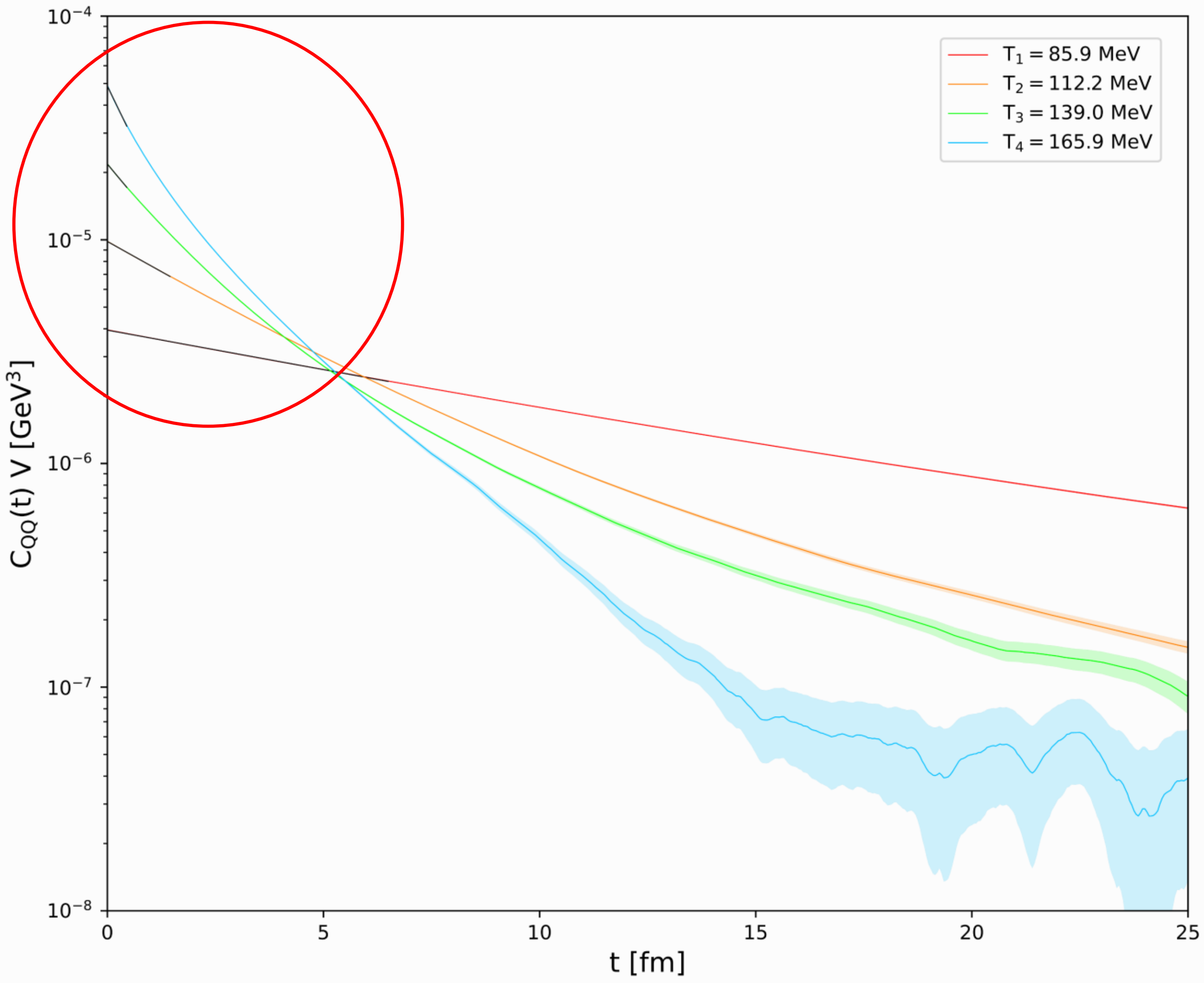
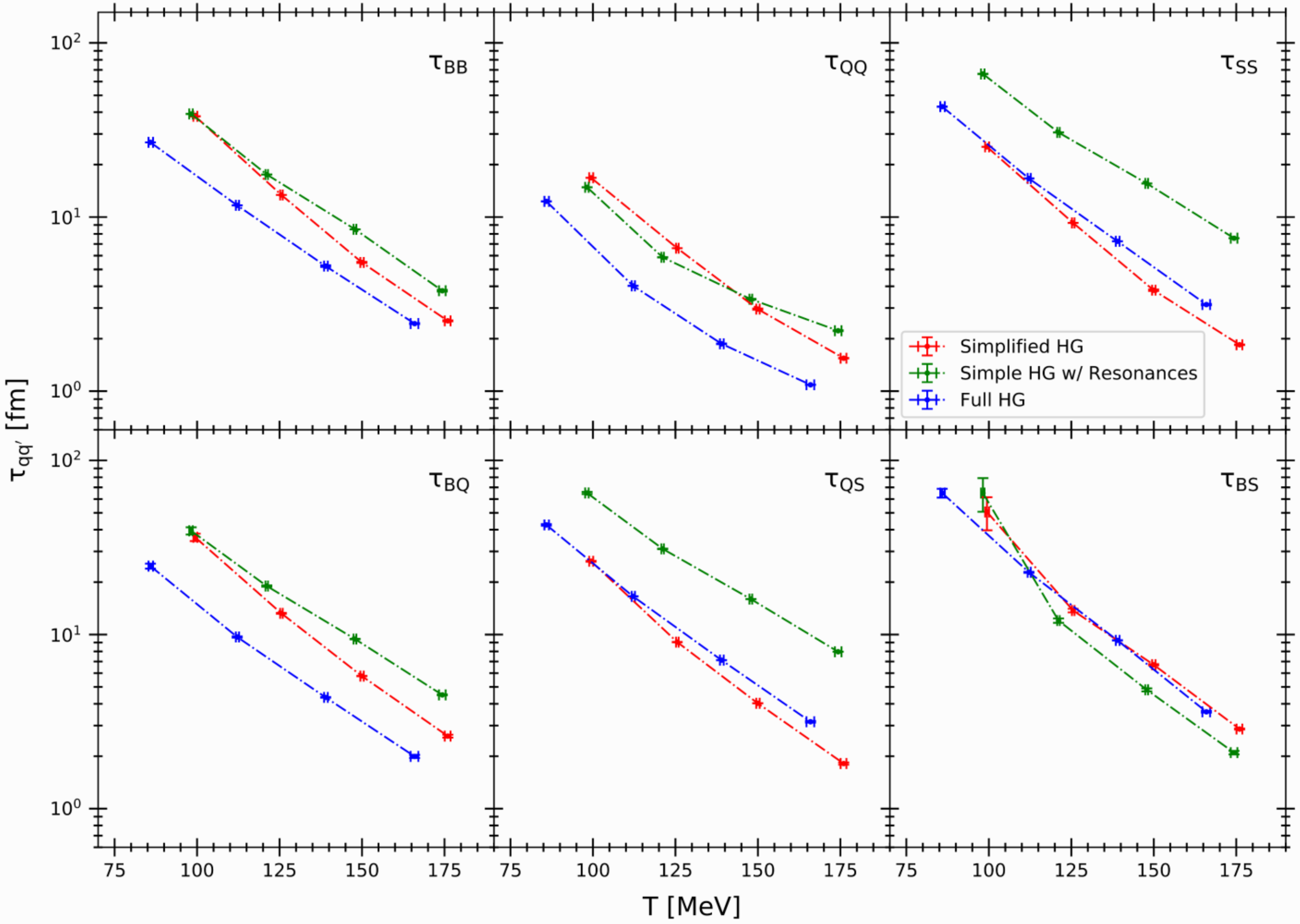
Breakdown of the exponential ansatz



- System very dense at high temperatures

$$C^{ij}(t) \neq C^{ij}(0) \cdot \exp\left(-\frac{t}{\tau}\right)$$

Relaxation times



- Time it takes for system to get back to equilibrium after perturbation
- Potential overestimation of contribution in the simplified hadron gas due to fixed cross-sections

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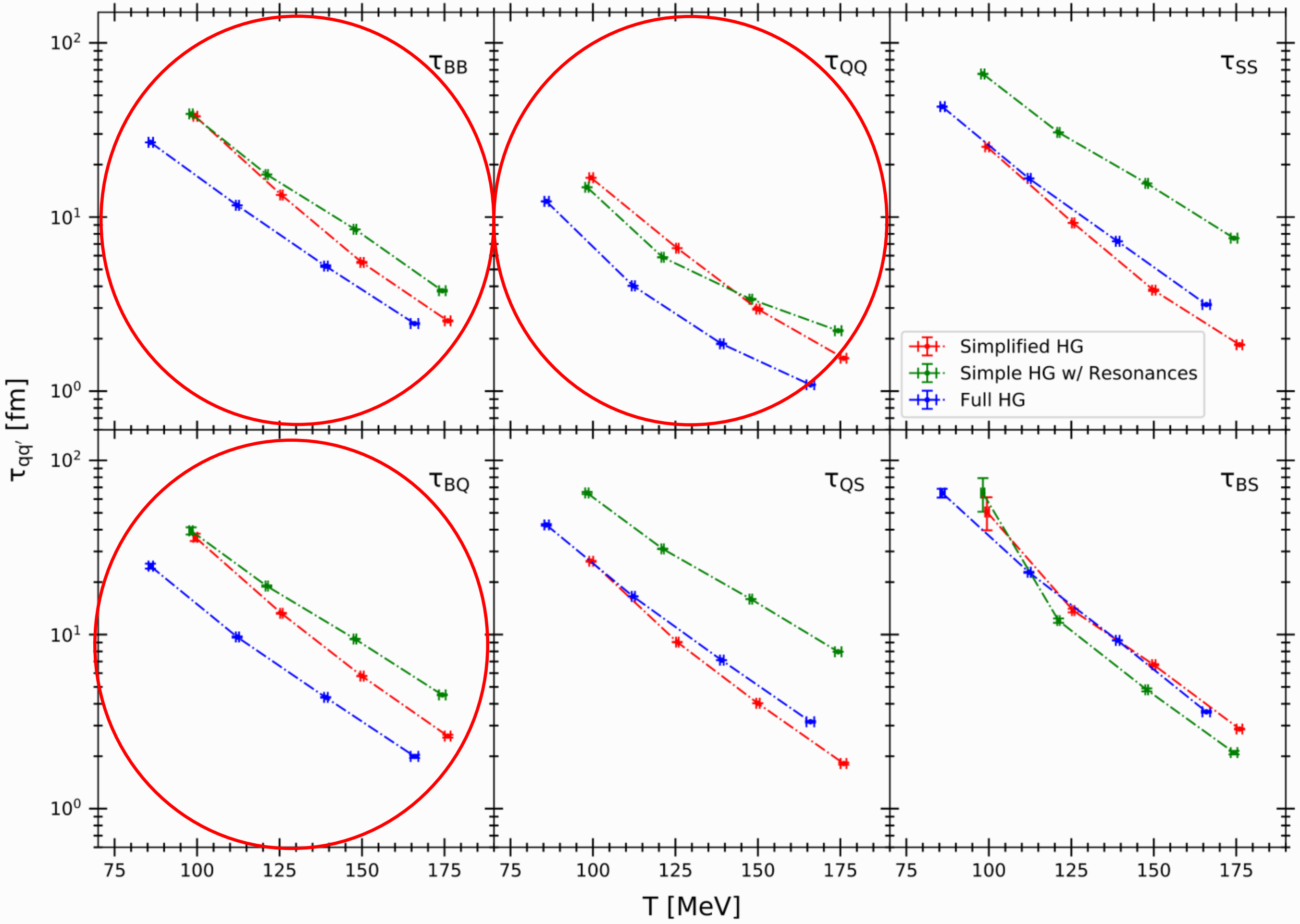

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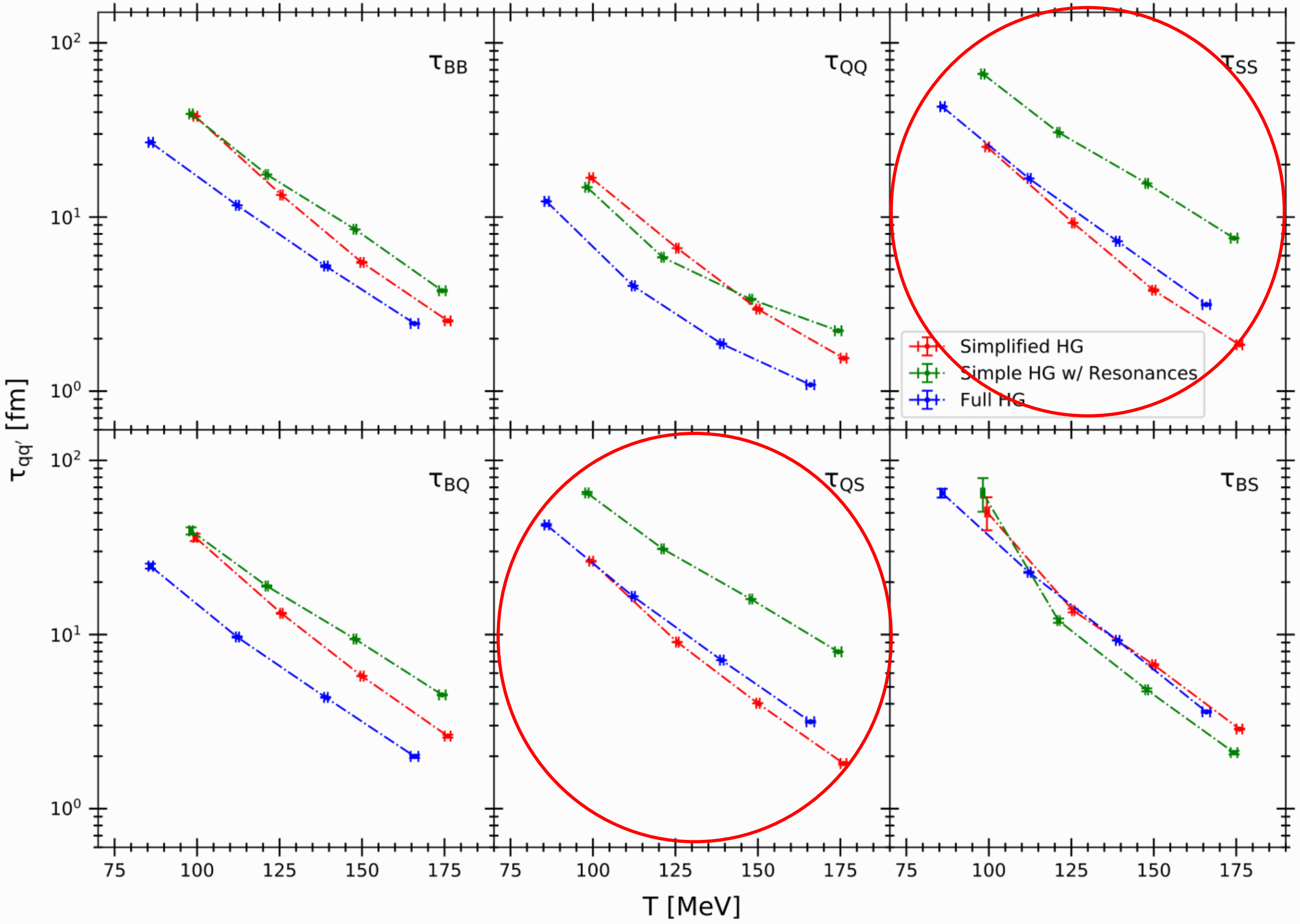
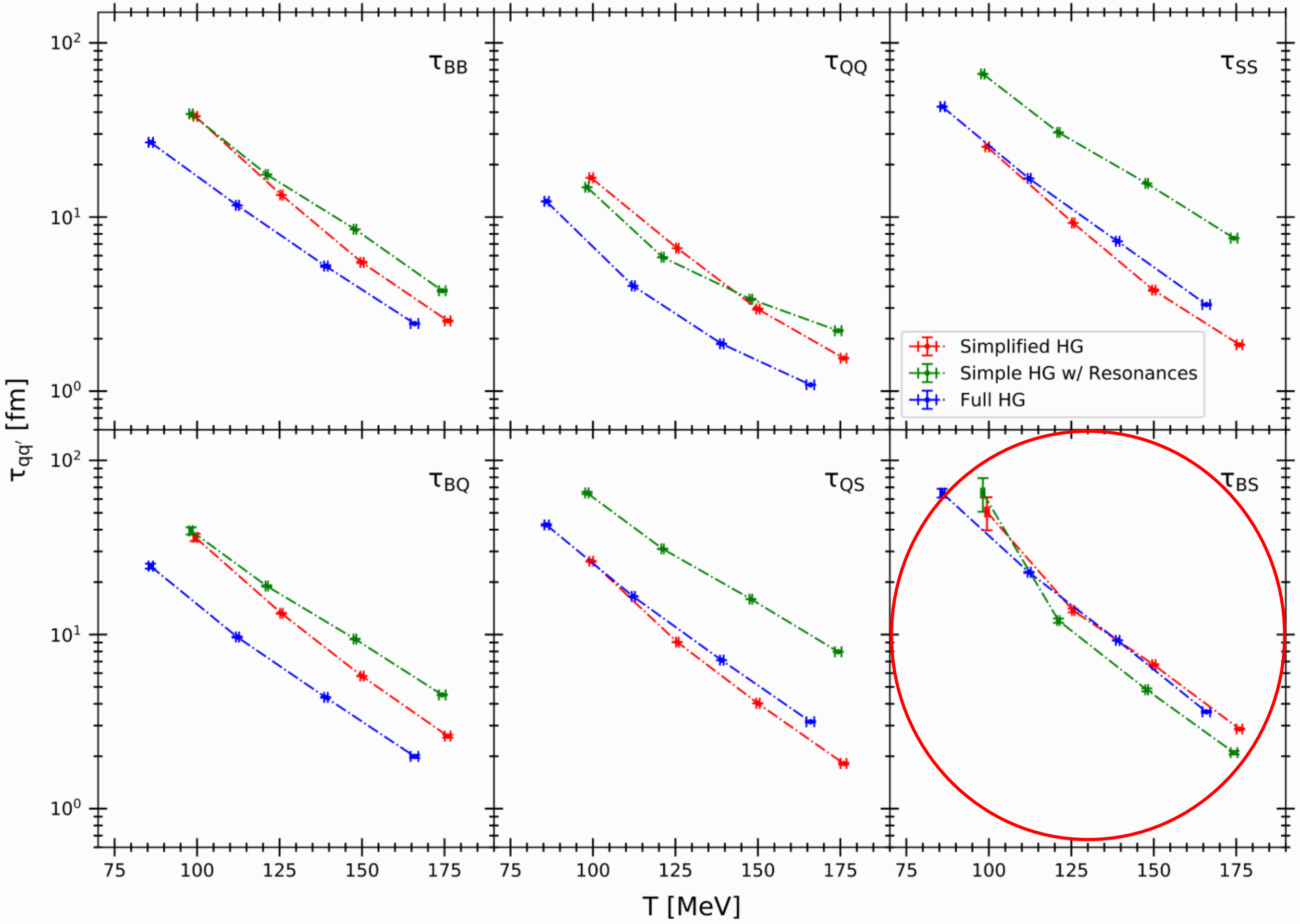
Relaxation times



- Time it takes for system to get back to equilibrium after perturbation
- Potential overestimation of contribution in the simplified hadron gas due to fixed cross-sections

Relaxation times



- Time it takes for system to get back to equilibrium after perturbation
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Conclusion

Summary

- Transport diffusion coefficients as a function of temperature for three hadron gases of different chemical composition have been calculated with SMASH
- Diffusion coefficients are sensitive to an increasing number of degrees of freedom
- Increasing the degrees of freedom has a larger effect on simpler systems than on systems that already have many different particle species
- Kinetic theory calculations from Fotakis *et.al.* serve as a good first approximation of the full hadron gas in SMASH

Outlook

- Investigation of all diffusion coefficients using SMASH at finite baryon, electric and strangeness chemical potentials
- Calculations take very long for complex systems, even longer with finite chemical potentials -> using already equilibrated systems for sampling more data
- Exponential ansatz breaks down -> potentially needing to find other methods for calculation
- QGP calculations have to be compared to those of the hadron gas in the region of the expected phase transition
- Hydrodynamic calculations with diffusion coefficients from SMASH as input

Backup Slides

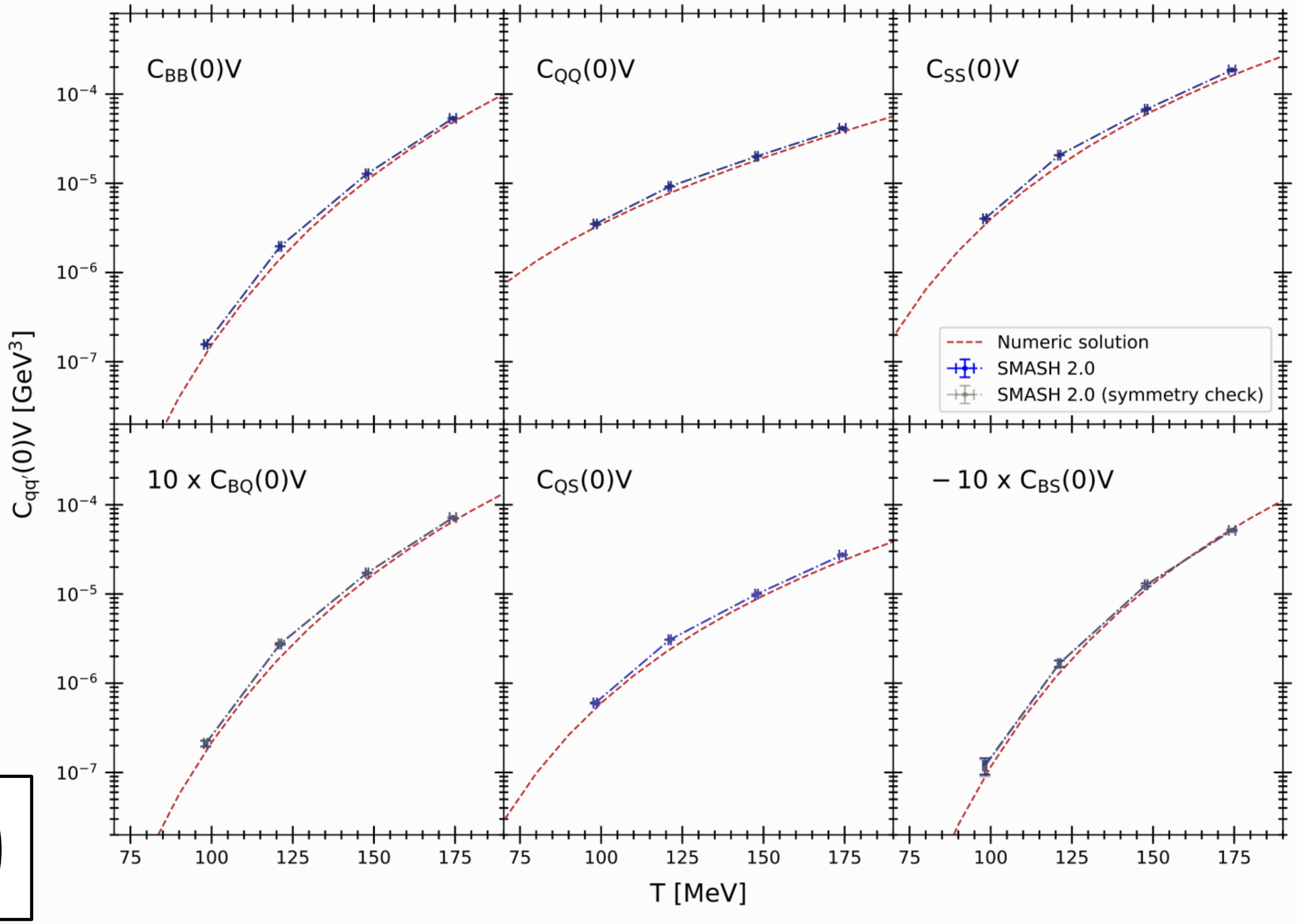
Name	Mass $[\mathrm{MeV}/c^2]$	Spin	Degeneracy	Baryon Number	Electric Charge	Strangeness
π^+	138	0	1	0	$+e$	0
π^-	138	0	1	0	$-e$	0
π^0	138	0	1	0	0	0
K^+	496	0	1	0	$+e$	$+1$
K^-	496	0	1	0	$-e$	-1
K^0	496	0	1	0	0	$+1$
$\bar{K}^0$	496	0	1	0	0	-1
p	938	$1/2$	2	$+1$	$+e$	0
$\bar{p}$	938	$1/2$	2	-1	$+e$	0
n	938	$1/2$	2	$+1$	0	0
$\bar{n}$	938	$1/2$	2	-1	0	0
Λ^0	1116	$1/2$	2	$+1$	0	-1
$\bar{\Lambda}^0$	1116	$1/2$	2	-1	0	$+1$
Σ^0	1193	$1/2$	2	$+1$	0	-1
$\bar{\Sigma}^0$	1193	$1/2$	2	-1	0	$+1$
Σ^+	1189	$1/2$	2	$+1$	$+e$	-1
$\bar{\Sigma}^+$	1189	$1/2$	2	-1	$-e$	$+1$
Σ^-	1197	$1/2$	2	$+1$	$-e$	-1
$\bar{\Sigma}^-$	1197	$1/2$	2	-1	$+e$	$+1$

[arXiv:1912.09103[hep-ph]]

	π^+	π^-	π^0	K^+	K^-	K^0	$\bar{K}^0$	p	n	$\bar{p}$	$\bar{n}$	Λ^0	$\bar{\Lambda}^0$	Σ^0	$\bar{\Sigma}^0$	Σ^+	$\bar{\Sigma}^+$	Σ^-	$\bar{\Sigma}^-$
π^+	10	res	res	10	10	res	10	res	10	10	res	23.1	23.1	5	5	5	5	5	5
π^-		10	res	res	10	10	res	res	res	res	10	23.1	23.1	5	5	5	5	5	5
π^0			5	res	10	res	res	res	res	res	res	23.1	23.1	5	5	5	5	5	5
K^+				10	10	10	50	res	10	20	10	18.5	18.5	3	3	3	3	3	3
K^-					10	50	10	res	res	6	10	18.5	18.5	3	3	3	3	3	3
K^0						10	50	6	6	20	20	18.5	18.5	3	3	3	3	3	3
$\bar{K}^0$							10	8	20	6	6	18.5	18.5	3	3	3	3	3	3
p								res	res	res	20	34.7	34.7	10	10	10	10	10	10
n									20	res	100	34.7	34.7	10	10	10	10	10	10
$\bar{p}$										10	10	34.7	34.7	10	10	10	10	10	10
$\bar{n}$											10	34.7	34.7	10	10	10	10	10	10
Λ^0												30	30	10	10	10	10	10	10
$\bar{\Lambda}^0$													30	10	10	10	10	10	10
Σ^0														10	10	10	10	10	10
$\bar{\Sigma}^0$															10	10	10	10	10
Σ^+																10	10	10	10
$\bar{\Sigma}^+$																	10	10	10
Σ^-																		10	10
$\bar{\Sigma}^-$																			10

[arXiv:1912.09103[hep-ph]]

C(0)V: Simple hadron gas with resonances



$$C_{ij}(t) = C_{ij}(0) \cdot \exp\left(-\frac{t}{\tau_{ij}}\right)$$

$$\kappa_{ij}(t) = C_{ij}(0)V \cdot \tau_{ij}$$