Impact of hadronic interactions and conservation laws on cumulants of conserved charges in a dynamical model

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arXiv: 2202.11417

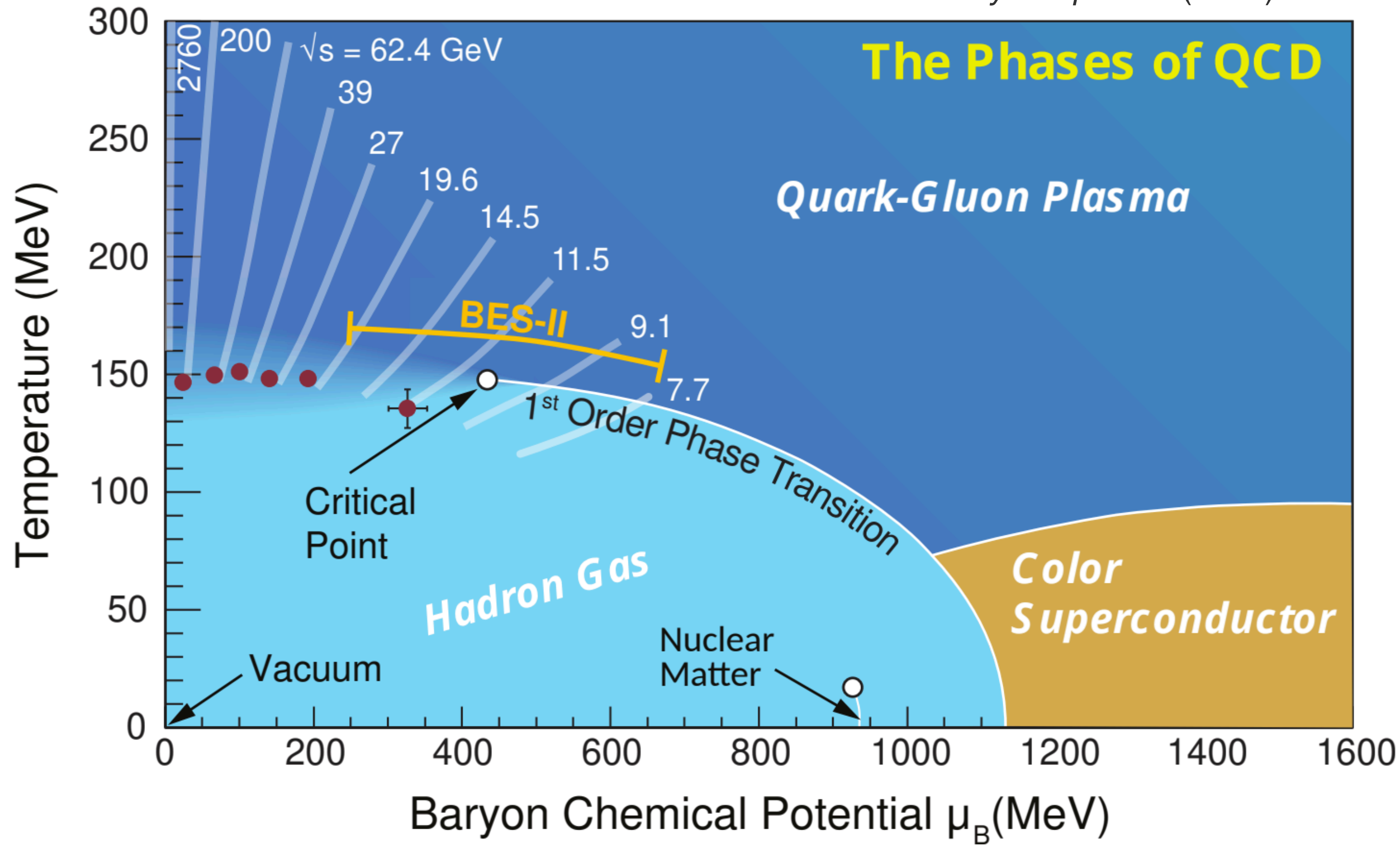
FIAS Frankfurt Institute for Advanced Studies

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

DFG Deutsche Forschungsgemeinschaft

Introduction

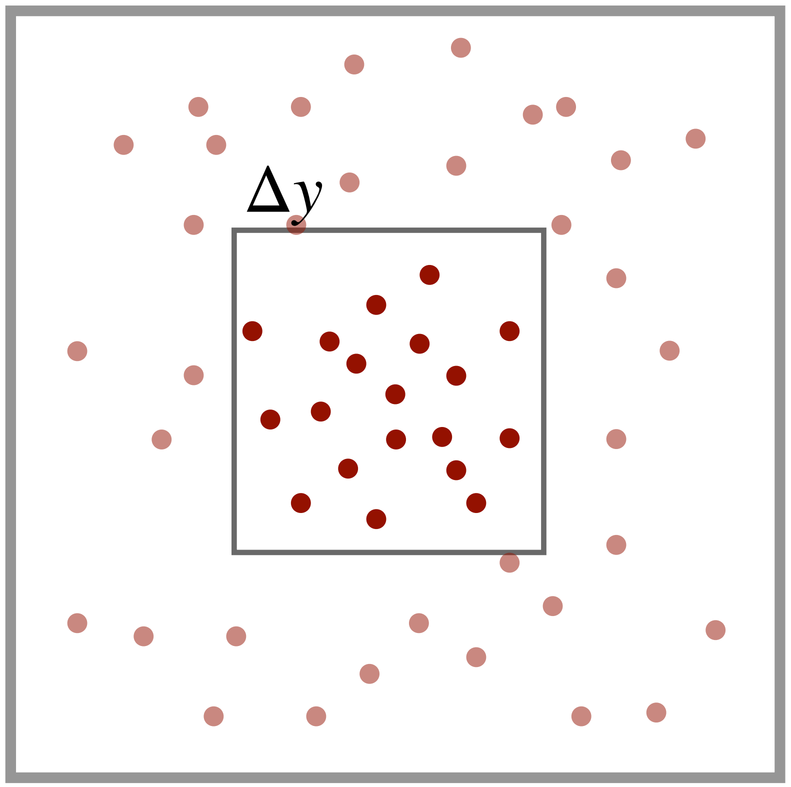
Bzdak et al. *Phys.Rept.* 853 (2020) 1-87



Explore the phase diagram of QCD by using heavy-ion collisions

Measure cumulants of conserved charges

Introduction



Signs of global charge conservation effects in measurements of heavy-ion collisions

Net protons are used as a proxy of the net baryon number fluctuations

Perform dynamical simulations to model the background signal

Model

Simulating **M**any **A**ccelerated **S**trongly-interacting **H**adrons (SMASH)
https://smash-transport.github.io/

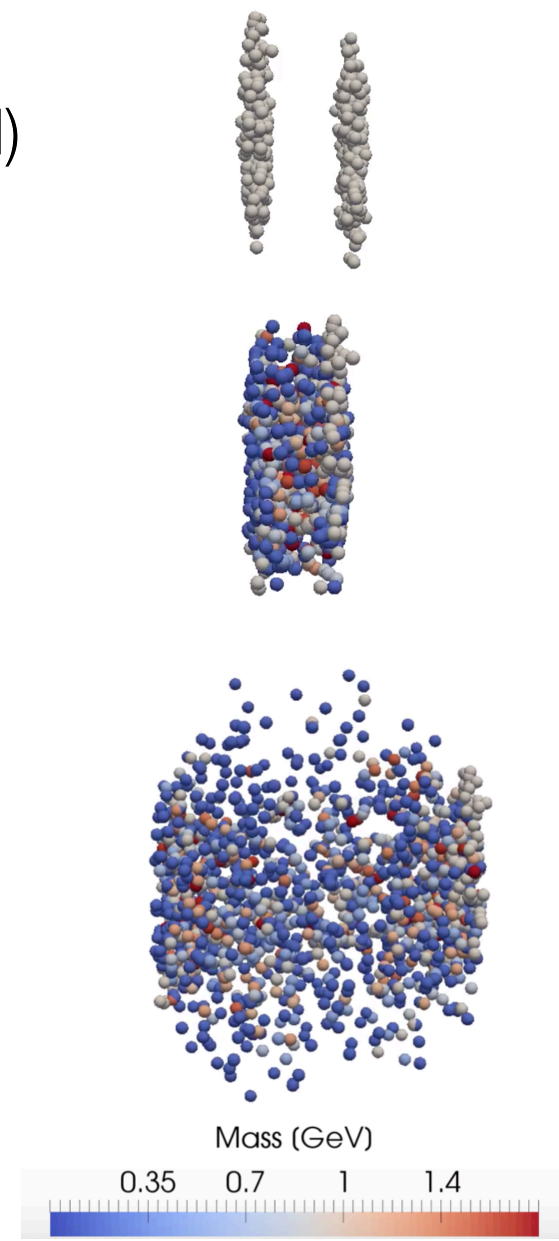
Uses a geometric collision criterion

$$\pi d_{\perp}^{2} < \sigma_{\mathrm{tot}}$$

Incorporates particles with masses up to $\sim 2\,\mathrm{GeV}$

Types of processes are:

- $2 \leftrightarrow 1$ resonance formation / decay
- $2 \leftrightarrow 2$ elastic / inelastic interactions
- String excitation (not used in this work)



Pb-Pb collision with 17.3 GeV center-of-mass energy (by J. Mohs)

Model

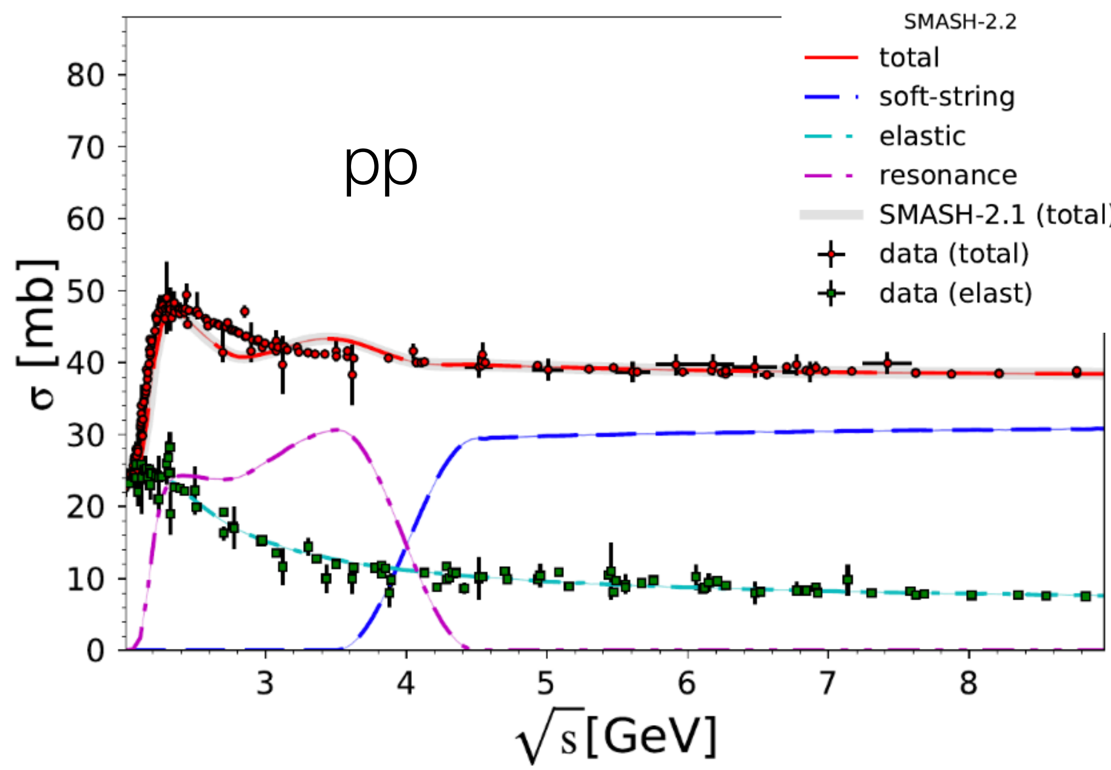
Degrees of freedom

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_{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}				

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

From A. Schaefer, see https://smash-transport.github.io/

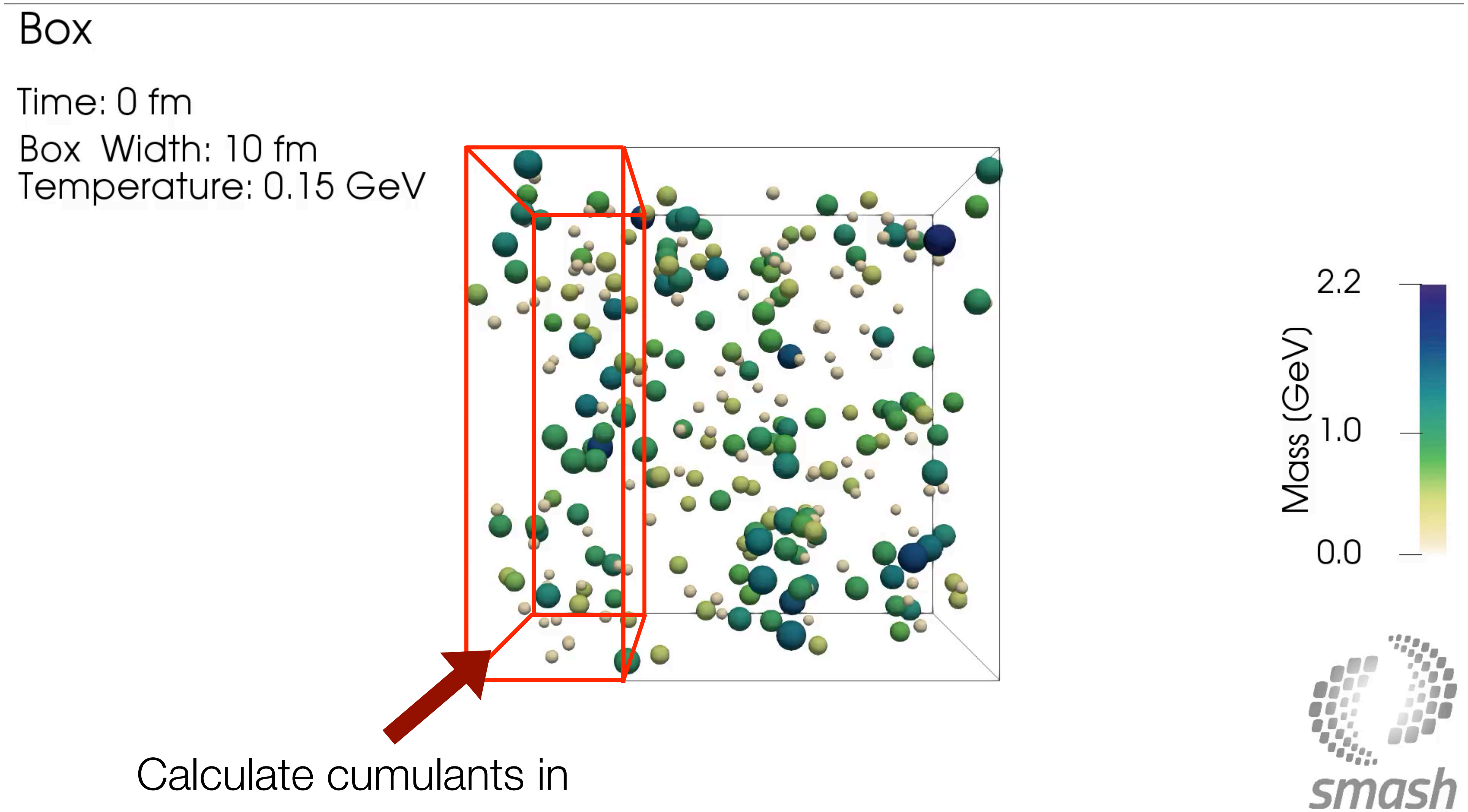
Cross section



https://theory.gsi.de/~smash/analysis_suite/SMASH-2.2/

Methodology

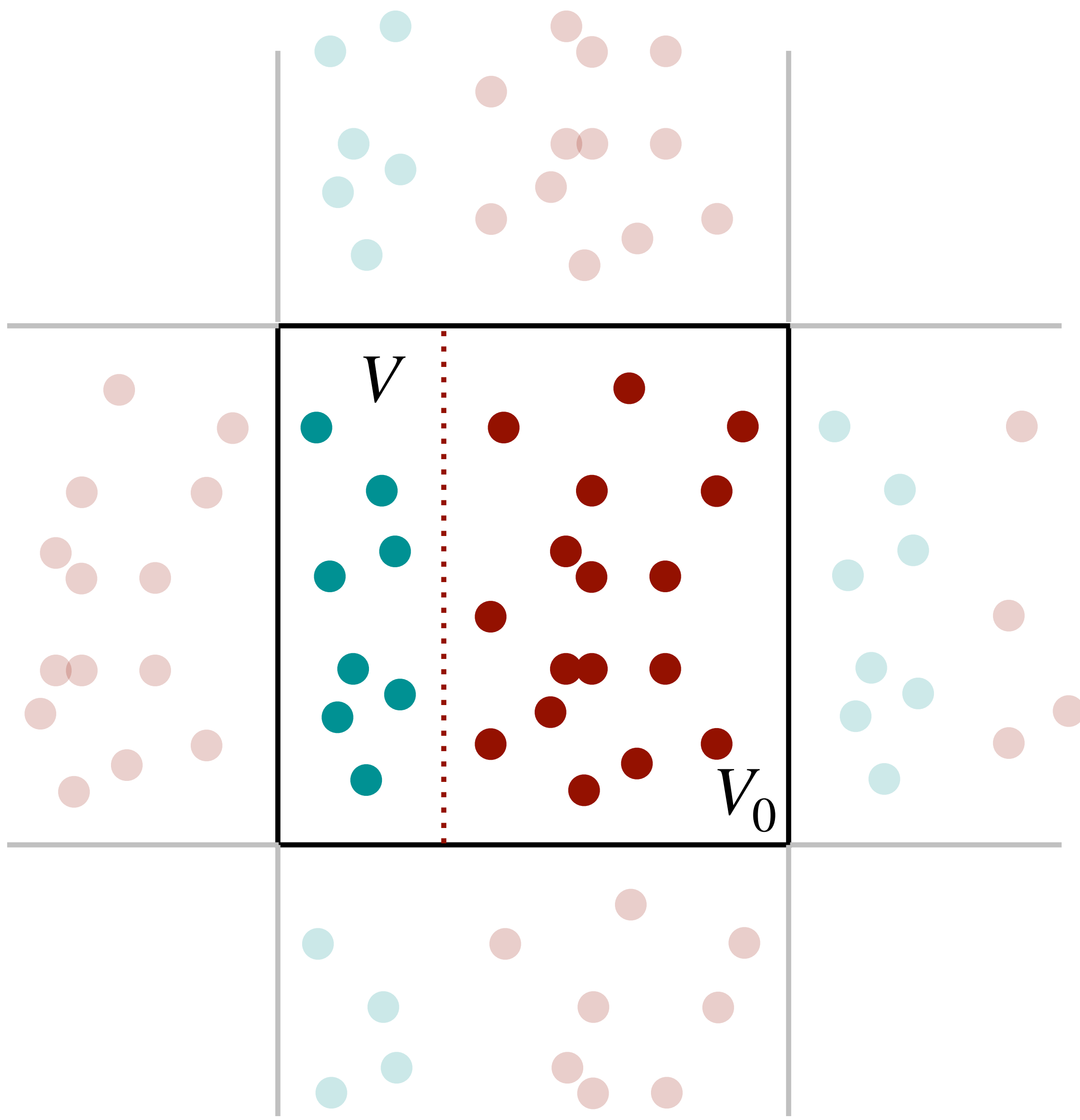
Initialization
Initialize a box event-by-event with the same number of particles with momenta according to the Boltzmann distribution



Calculate cumulants in this sub volume

https://smash-transport.github.io/

Methodology



Infinite matter simulation

Calculate cumulants of particle distributions as a function of the size of the subvolume $x = V/V_0$

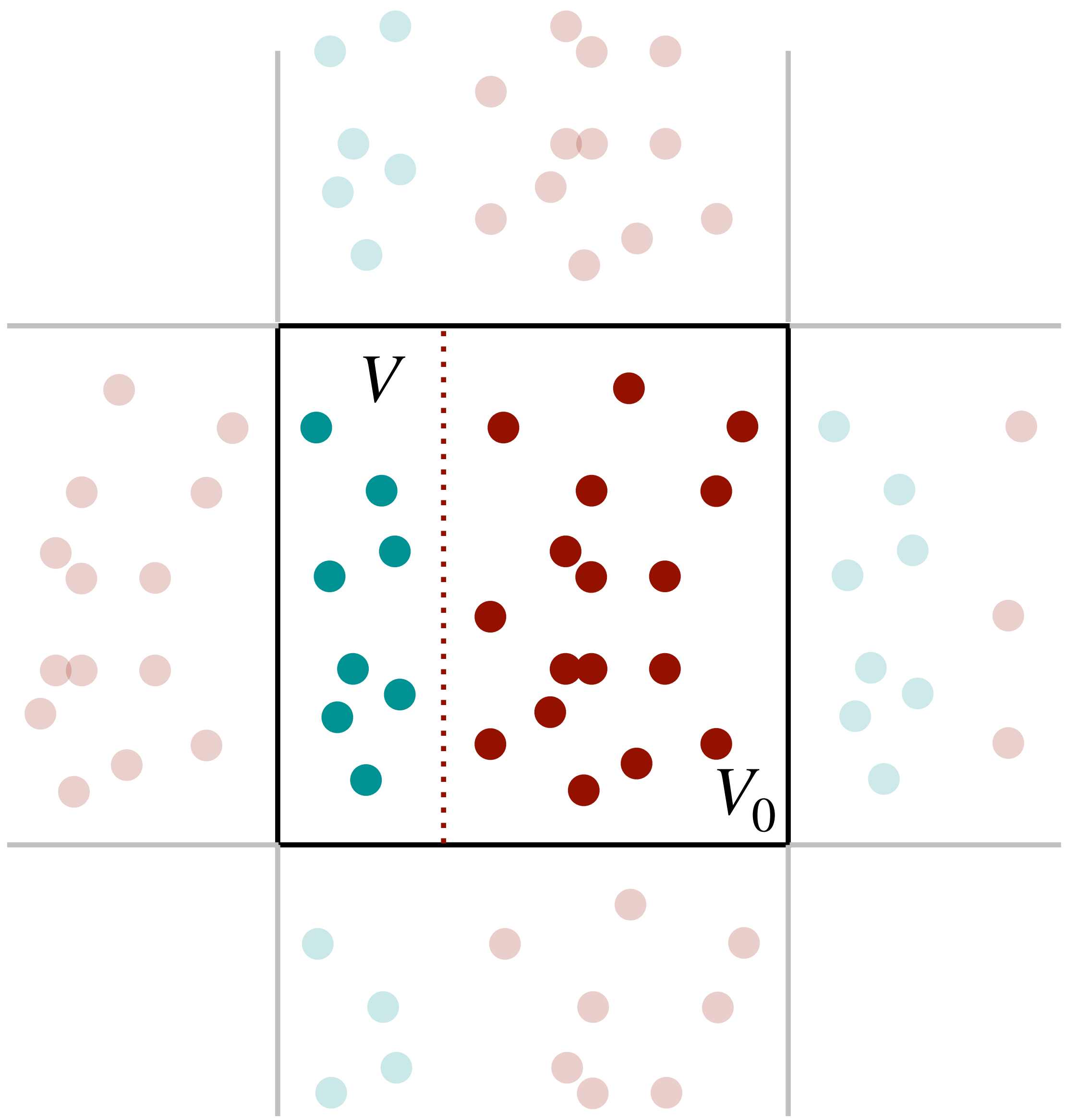
$$\omega = \frac{C_2}{C_1} = \frac{\langle(\delta N)^2\rangle}{\langle N\rangle}$$

$$S\sigma = \frac{C_3}{C_2} = \frac{\langle(\delta N)^3\rangle}{\langle(\delta N)^2\rangle}$$

$$\kappa\sigma^2 = \frac{C_4}{C_2} = \frac{\langle(\delta N)^4\rangle - 3\langle(\delta N)^2\rangle^2}{\langle(\delta N)^2\rangle}$$

Additionally study the effects of cuts on transverse momentum $0.4 < p_T < 2\,\mathrm{GeV}$

Methodology



Analytic Comparison

When the net charge number is conserved and the total charge number can fluctuate

$$P(n_+, n_-; x) = \sum_{N_+, N_-} P(N_+, N_-) \underbrace{B(N_+, n_+; x) B(N_-, n_-; x)}_{\text{Binomial distribution}}$$

$$P(N_+, N_-) = \underbrace{\delta(N_+ - N_- - Q)}_{\text{Net charge conservation}} \underbrace{P(N_{ch})}_{\text{Fluctuation of the total charge number}}$$

➡ Analytic expressions for cumulants as function of x

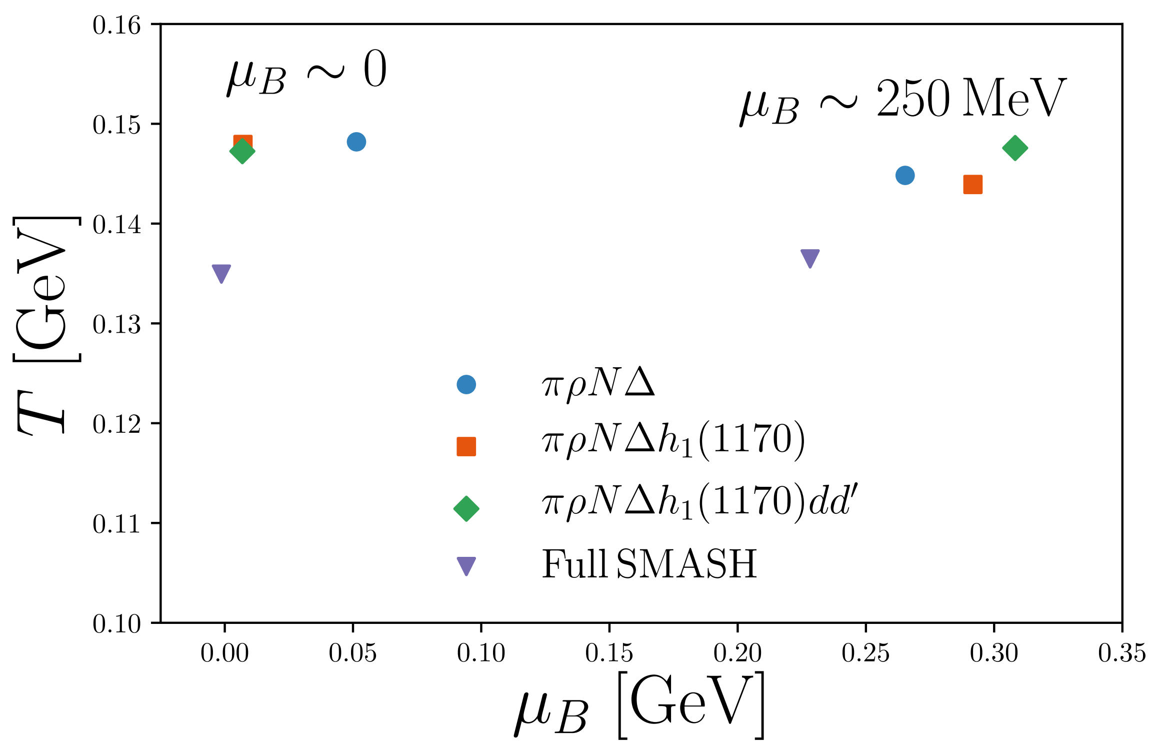
$$\omega = 1 - x$$

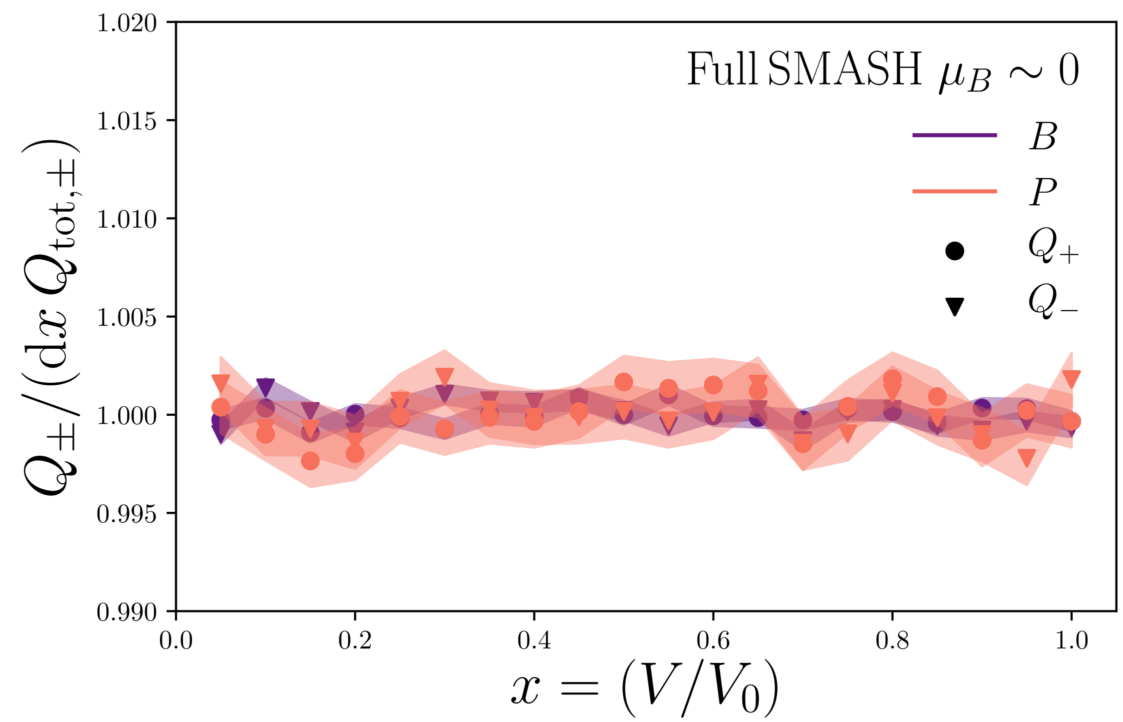
$$S\sigma = \frac{Q}{\langle N_{ch} \rangle}(1 - 2x)$$

$$\kappa\sigma^2 = 1 + 3x(1 - x)(\omega[N_{ch}] - 2)$$

For more details see *Phys.Rev.C* 101 (2020) 2, 024917

Methodology





- Thermal and chemical equilibrium as well as isotropic densities are a pre-requisite to perform these kind of calculations
- Temperature and baryon chemical potential are calculated assuming

$$dN/dp \sim \exp(-(\sqrt{\mathrm{p}^2+\mathrm{m}^2}-\mu_{\mathrm{B}})/\mathrm{T})$$

- The density is distributed isotropically in the system

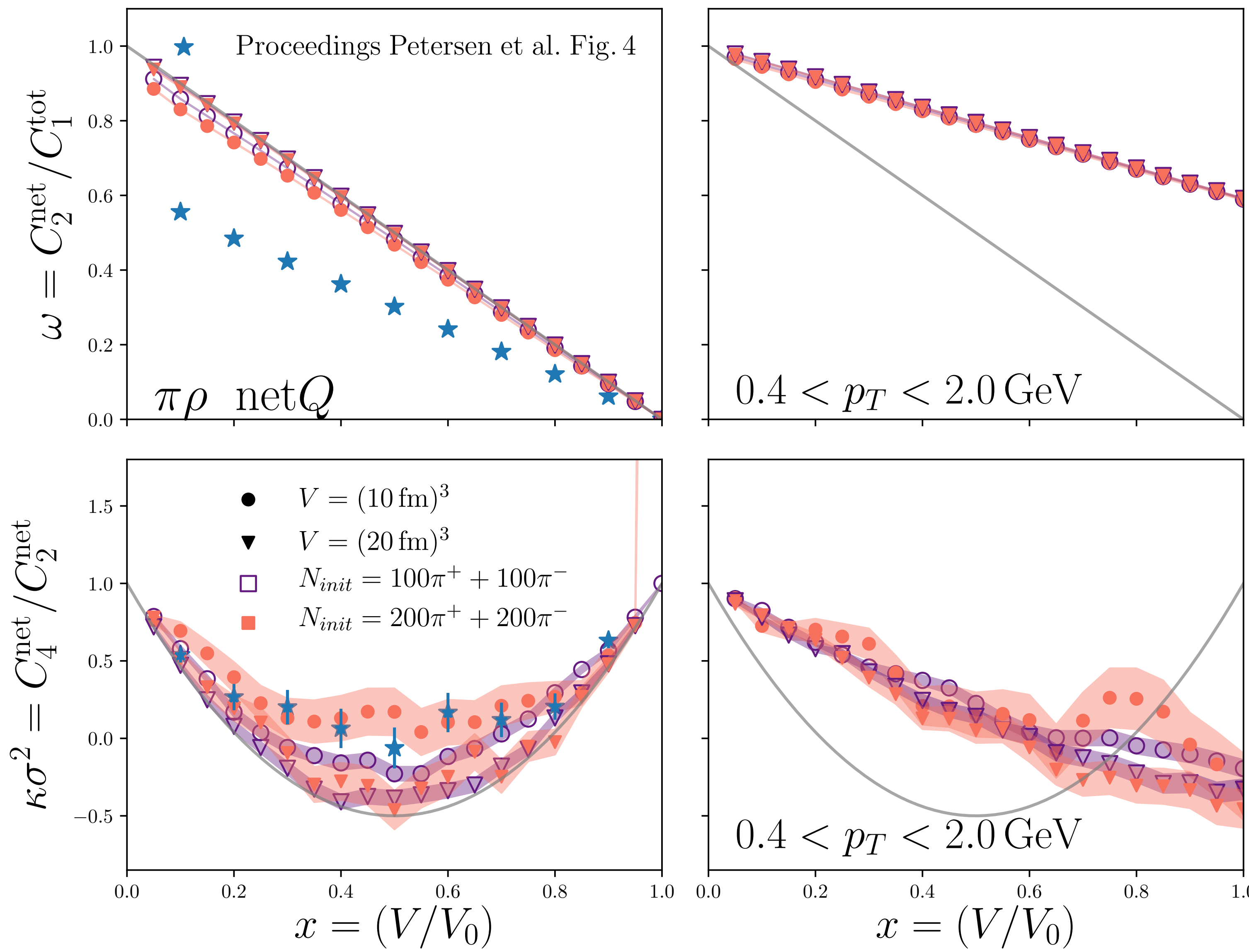
Test System

Simple $\pi\rho$ hadron gas interacting via an energy dependent cross section $\pi^{\pm}\pi^{\mp} \leftrightarrow \rho^0$

Cumulants follow lines of perfect conservation

Correlations are present within a cut in momentum space

$\kappa\sigma^2$ dependency on the charge density →total charge number fluctuation



Proceedings Petersen et al. *Nucl.Phys.A* 956 (2016) 336-339

Full Hadron Gas

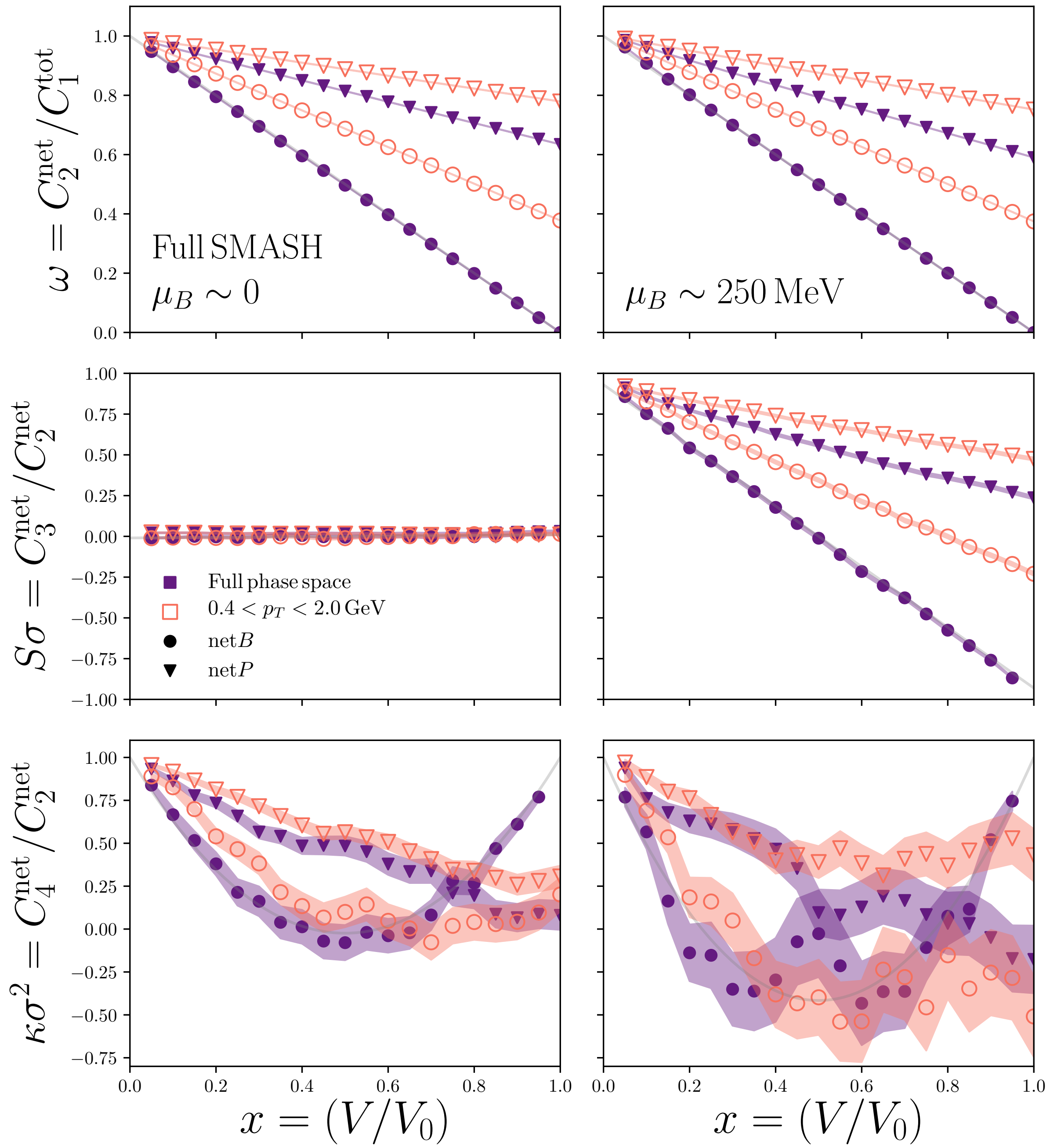
Full set of hadrons from SMASH with all possible interactions

Perform final decays after the dynamical evolution

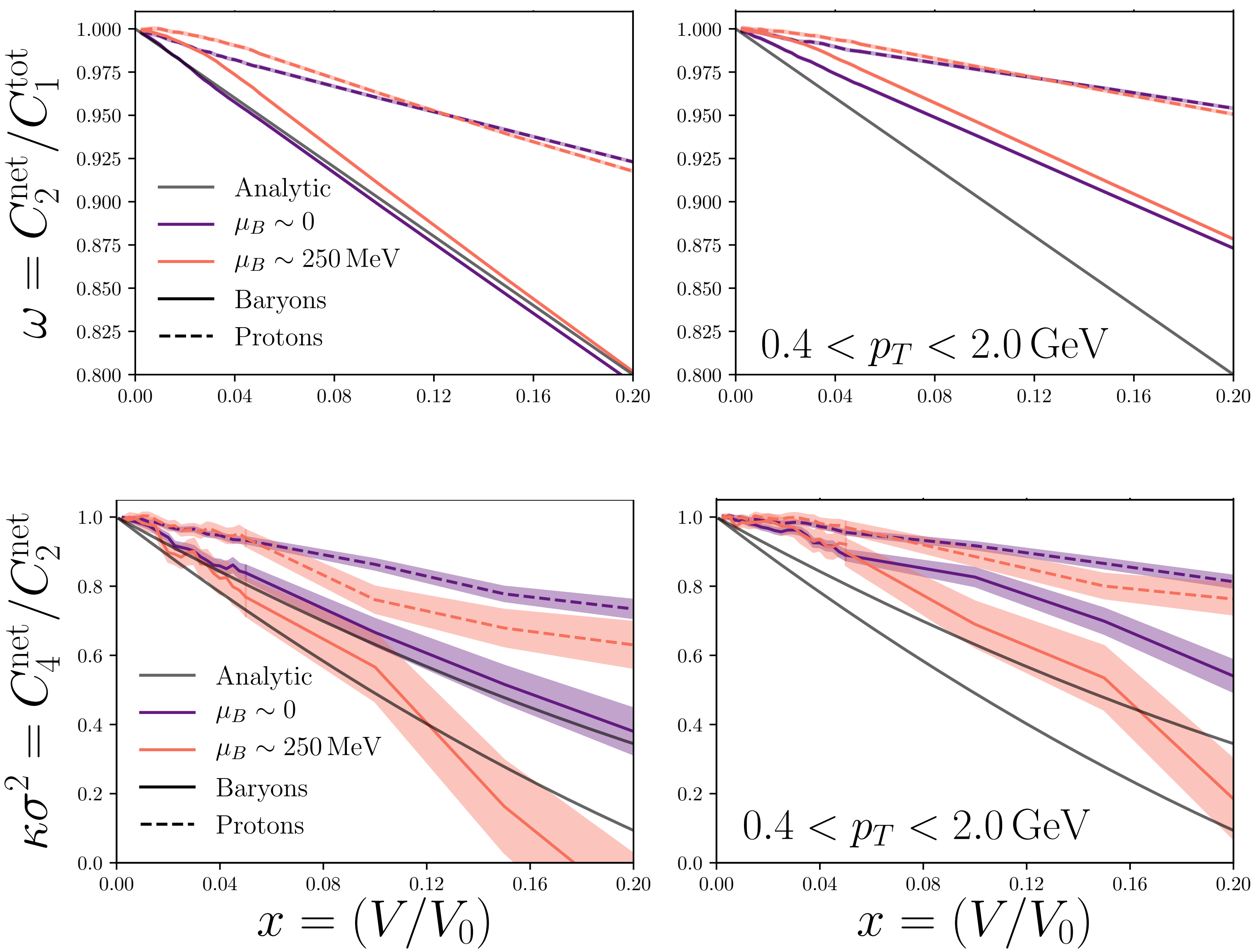
Possibility to extract $C_2[N_{ch}]$ for a realistic interacting hadron gas

Effects of conservation still present within the net-proton numbers

net baryons and net protons



Full Hadron Gas



In the limit $x \to 0$, $\omega/\kappa\sigma^2 \to 1$ (Poisson Limit)

For small volumes and large baryon chemical potentials, the cumulants don't strictly follow the analytic expressions

Mapping between protons and baryons

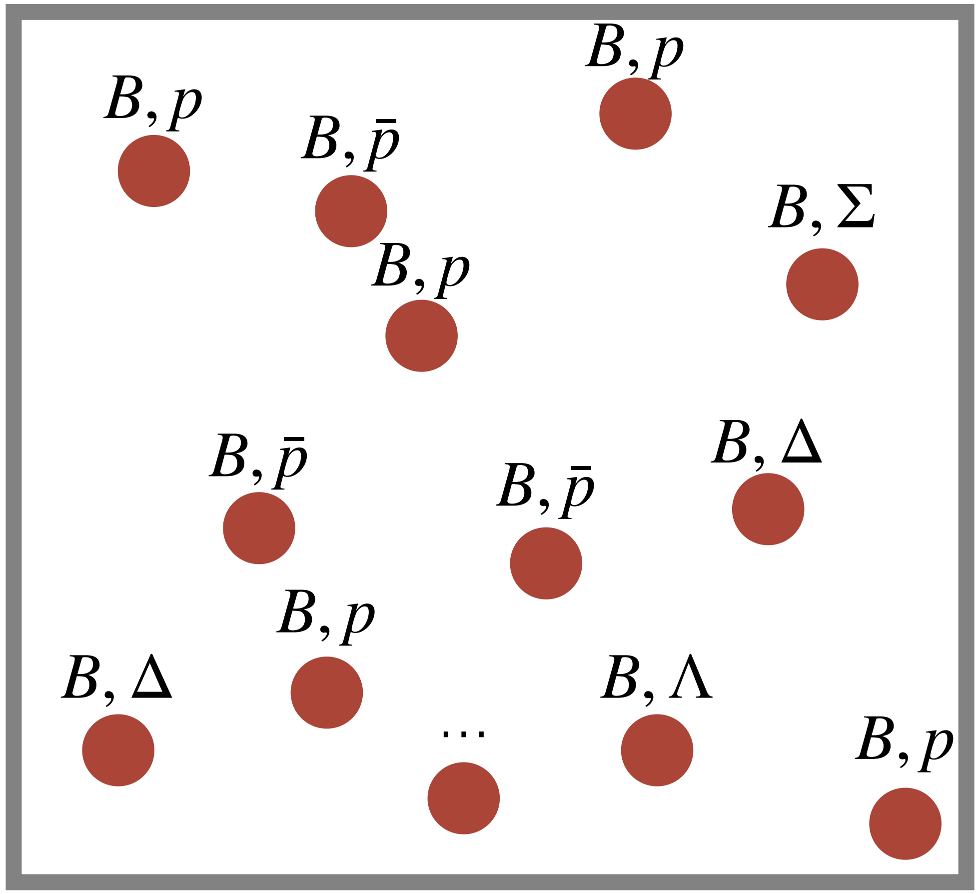
δB fluctuations are of interest, however only δP fluctuations are accessible

Is it possible to map fluctuations $\delta N_p \rightarrow \delta N_B$?

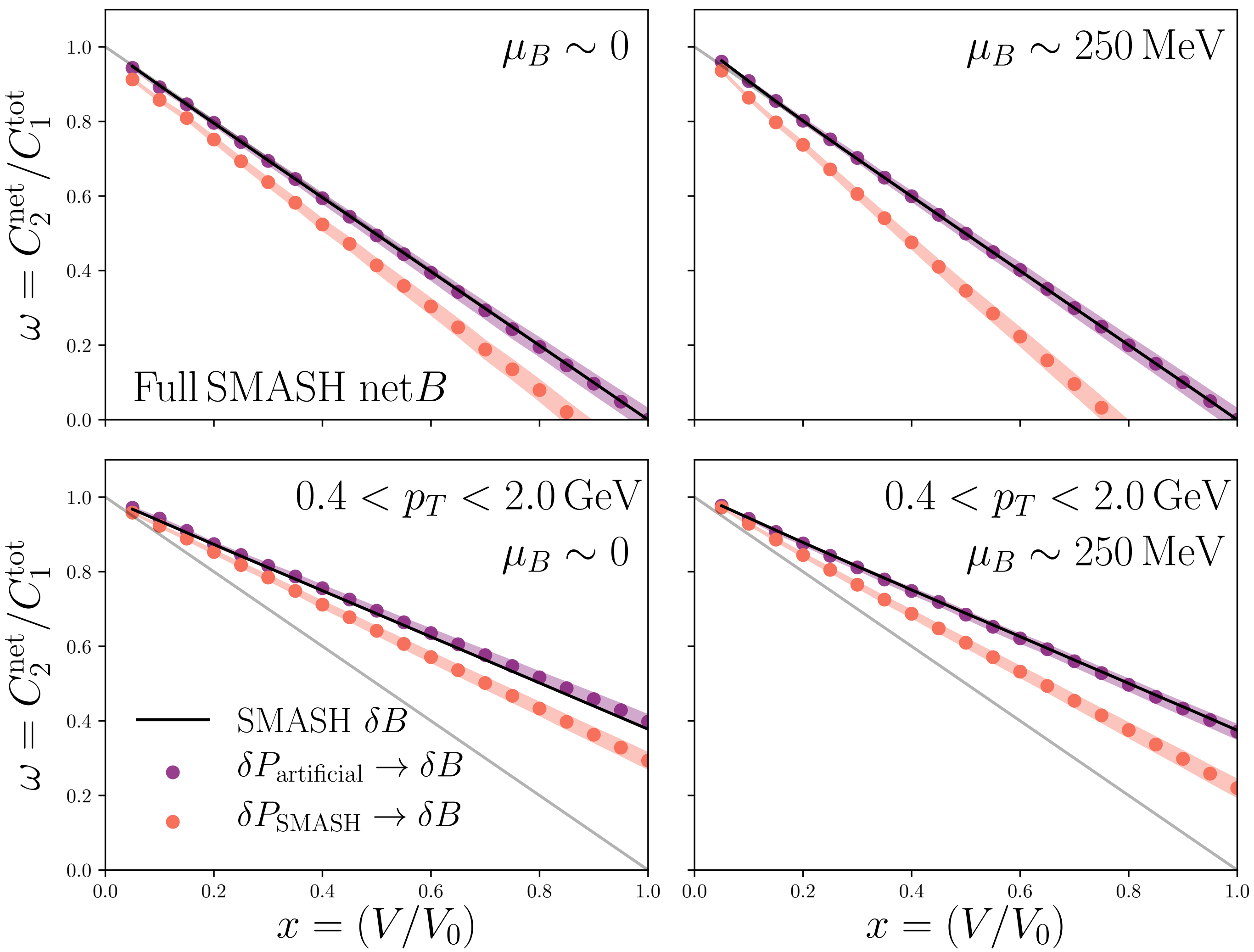
Mapping between proton and baryon number fluctuations $\delta P \leftrightarrow \delta B$

Kitazawa and Asakawa *Phys.Rev.C* 85 (2012) 021901

Based on binomial unfolding procedure input: Probability $p = \langle N_p \rangle / \langle N_B \rangle$



Mapping between protons and baryons



Dynamical correlations within the model limits the applicability in large acceptance regions

Dependency on the complexity of the system

Impact of deuteron formation

Build a relatively easy hadron gas such that the impact of deuterons can be extracted

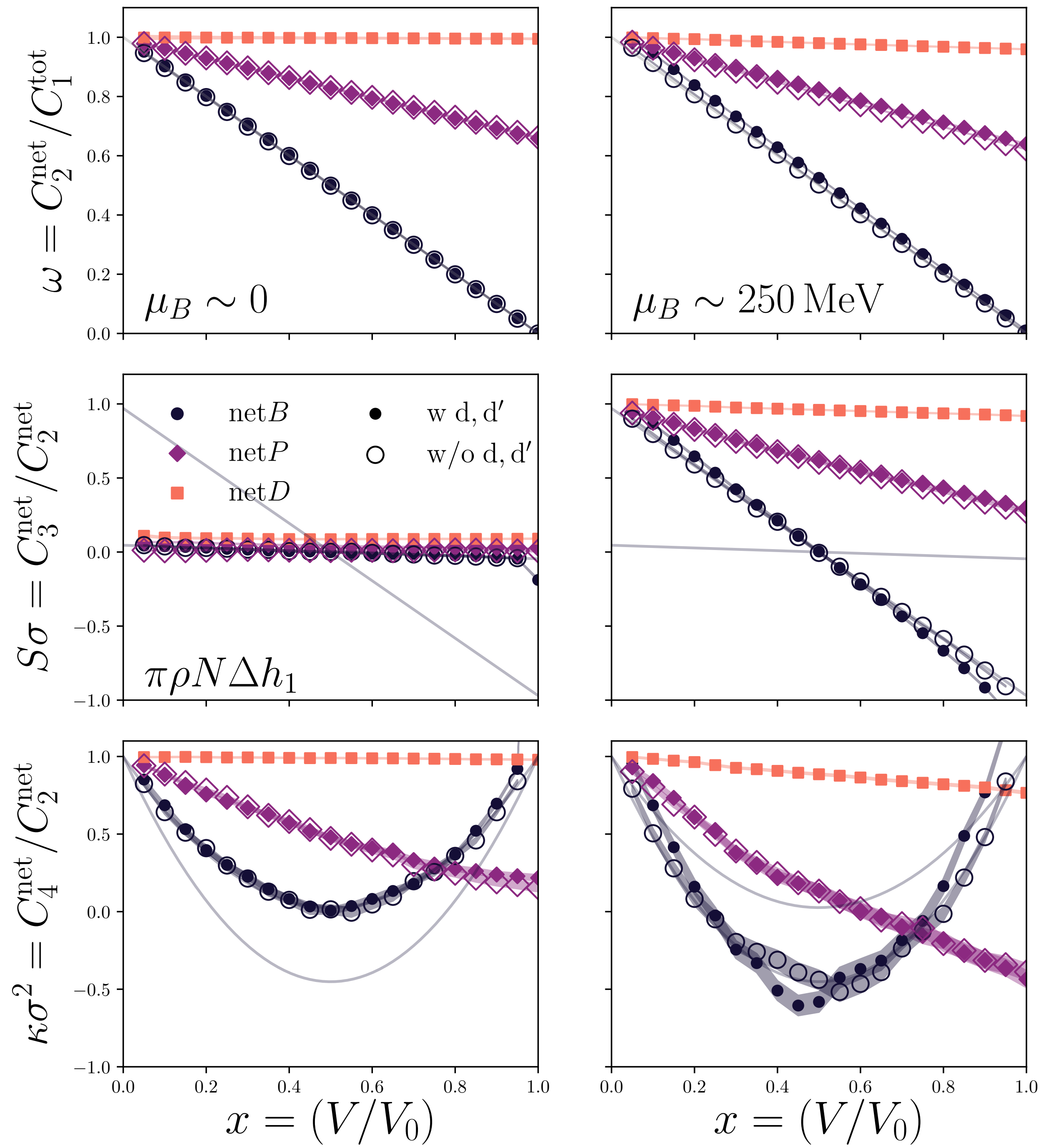
$\pi\, \rho\, h_1(1170)\, \Delta\, N\, d\, d'$

Deuteron formation on the basis of a fictional resonance *d'*

$pn \leftrightarrow d' \quad \pi d' \leftrightarrow \pi d \quad Nd' \leftrightarrow Nd$

Run system with and without deuterons and compare the fluctuations

Deuterons are almost not affected by conservation effects



Conclusion

Summary

Charge annihilation processes affect the kurtosis at large densities

At large baryon chemical potentials the scaled variance is modified in small volumes

Proton number fluctuations cannot be recovered at large acceptance regions from baryon number fluctuations due to dynamical correlations

Deuteron number has no large impact on conservation effect

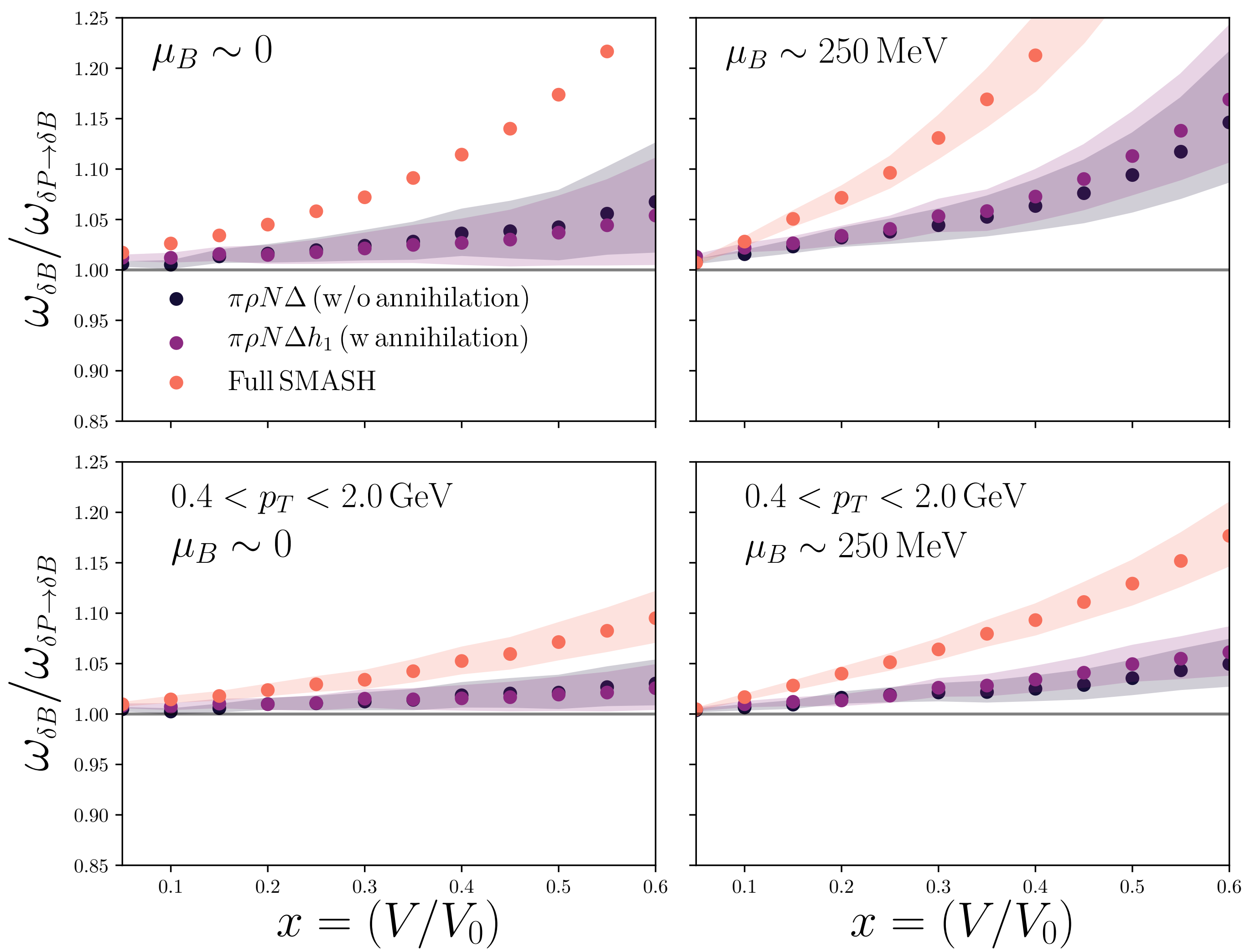
Outlook

Critical initial conditions in an expanding sphere

Impact of baryon annihilation and rescattering in more realistic scenarios

Backup

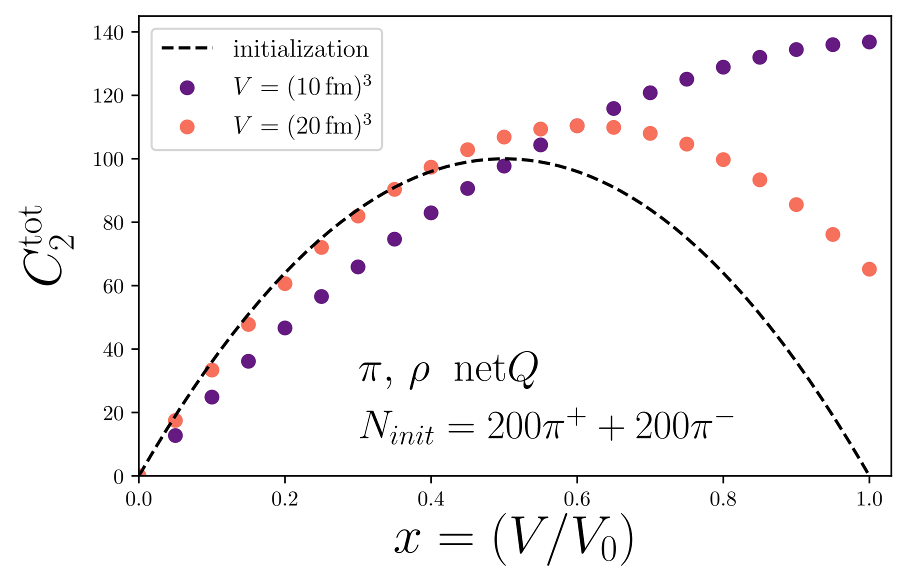
Mapping between protons and baryons



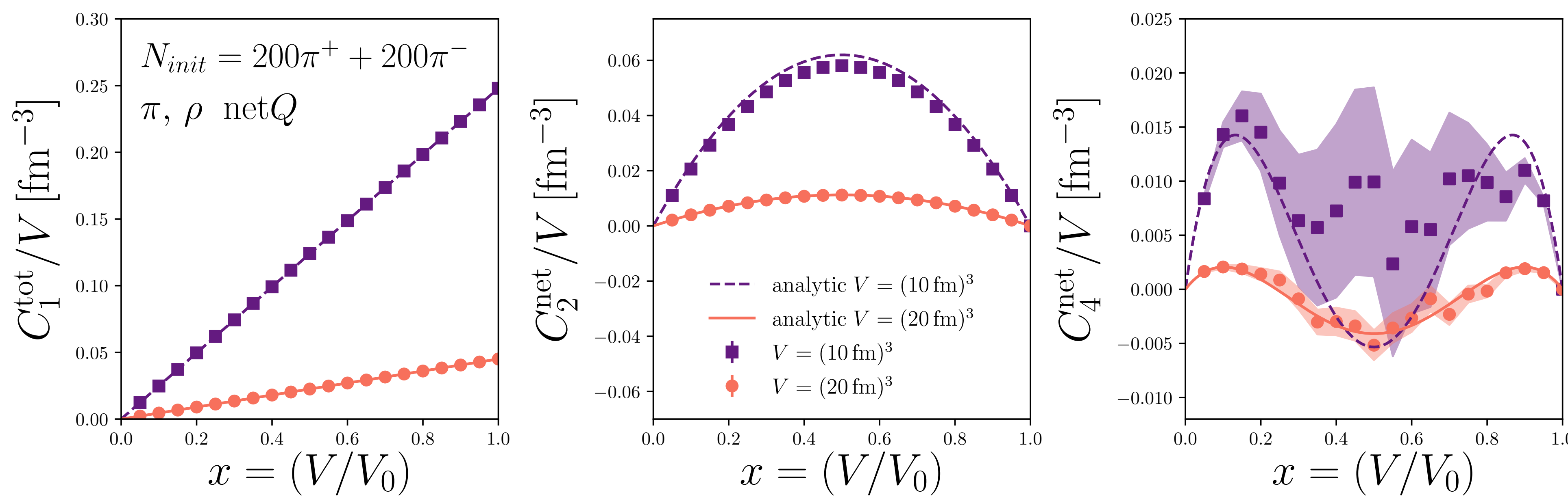
Dependence on the complexity of the system

Test System

Fluctuations of the total charge number $C_2[N_{ch}]$ becomes important at large densities



More charge annihilation processes (C_4 depends on $C_2[N_{ch}]$)



Fluctuations can be described by analytic formulas with the input of $\langle N_\pm \rangle$ and $C_2[N_{ch}]$