UNIVERSITÉ DE NANTES

Subatech

cnrs GDR Groupement de recherche
QCD Chromodynamique quantique

Study of 2nd order susceptibilities with EPOS event generator

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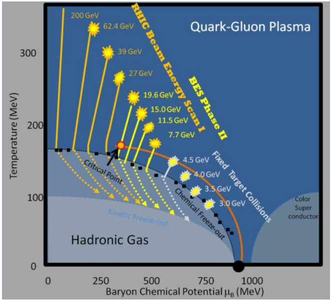
QCD phase diagram and CEP

Since the QGP has been observed (indirectly), efforts has been made to learn about its properties, and to map the QCD phase diagram.

- **Theoretically :** use models & theories to make predictions (T_C, μ_{B_C}) or to extract information from measurements (T, μ_B, η/s...)

- **Experimentally :** exploration of QCD phase diagram thanks to the Beam Energy Scan (BES) program, measurements of observables of interest



D. Cebra, 2013

Question(s) of interest : is there a 1st order phase transition and a critical endpoint between QGP and hadronic gas phases ? If yes, where ?

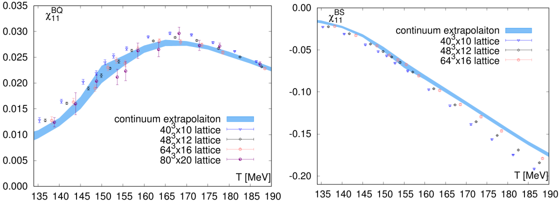
Susceptibilities

To answer this question, there are many tools that can be used, among which are the **susceptibilities**.

In a grand-canonical ensemble, to what a heavy-ion collision can be compared to, they are defined as derivatives of the partition function Z :

$$\chi_{i,j}^{X,Y} = \frac{1}{VT^3} \cdot \left[\frac{\partial^{i+j} Z(T,V,\mu)}{(\partial \hat{\mu}_X)^i (\partial \hat{\mu}_Y)^j} \right]_{\mu_{X,Y}=0} \qquad (\hat{\mu} = \frac{\mu}{T})$$

As we are searching for radical changes in the state of nuclear matter, i.e. phase transition, these derivatives of Z should reveal them.



R. Bellwied et al., 2019

Susceptibilities

In a more convenient and understandable way, susceptibilities can be written as a function of the net-charge cumulants ($N_X = n_X - n_{\overline{X}}$).
They represent in fact event-by-event fluctuations of the considered net charges.

2^{nd} order susceptibilities for B, Q, S

Linked to the (co)variances of the considered charges :

$$\chi_{11}^{XY} = \frac{1}{VT^3}\sigma_{XY}^{11} = \frac{\langle N_X N_Y\rangle - \langle N_X\rangle\langle N_Y\rangle}{VT^3}$$

$$\chi_2^X = \frac{1}{VT^3}\sigma_X^2 = \frac{\langle {N_X}^2\rangle - \langle N_X\rangle^2}{VT^3}$$

Also, in order to have observables independent from volume or temperature, which cannot be measured directly in experiments, ratios are often used.

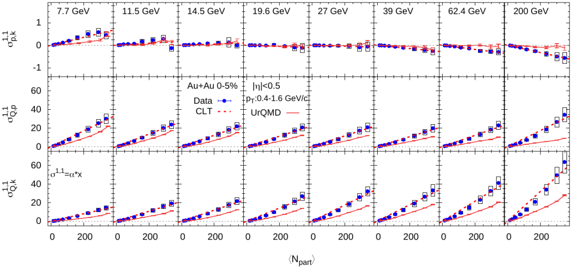
Ratios

$$C_{BS} = \frac{\sigma_{BS}^{11}}{\sigma_S^2} \qquad C_{QB} = \frac{\sigma_{QB}^{11}}{\sigma_B^2} \qquad C_{QS} = \frac{\sigma_{QS}^{11}}{\sigma_S^2}$$

Experimental results

STAR collaboration measured (for particles with $|\eta| < 0.5$ + $0.4 < p_T < 1.6$ GeV/c) :

- (co)variances $\sigma^{11,2}_{p,Q,k}$ (proxies for $\chi^{B,Q,S}_{11,2}$)
  - as a function of the η-window
  - as a function of $\langle N_{part} \rangle$



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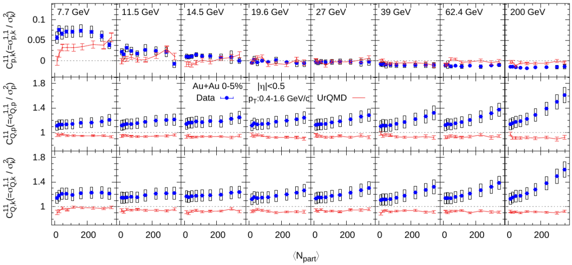
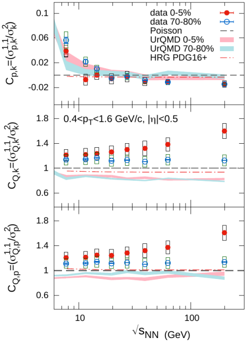
  - as a function of the η-window
  - as a function of $\langle N_{part} \rangle$
- Koch ratios $C_{Qp,Qk,pk}$ (proxies for $C_{QB,QS,BS}$)
  - as a function of $\langle N_{part} \rangle$
  - as a function of $\sqrt{s_{NN}}$





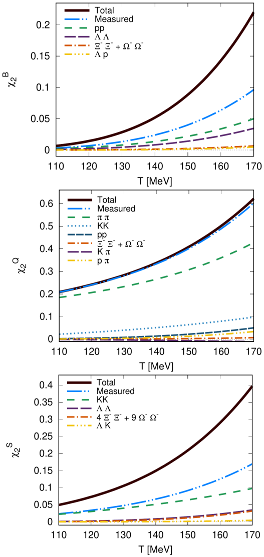
Lattice QCD + HRG model

R. Bellwied *et al.* :

- breakdown of hadronic species contributions to susceptibilities, using Hadron Resonance Gas model
  ⇒ best proxies for ratios
  (so potentially the most sensitive ones)

$$C_{QS} = \frac{\chi_{11}^{QS}}{\chi_2^S} = \frac{1}{2} \cdot \frac{\sigma_K^2}{\sigma_K^2 + \sigma_\Lambda^2}$$

$$C_{BS} = \frac{\chi_{11}^{BS}}{\chi_2^S} = \frac{\sigma_\Lambda^2}{\sigma_K^2 + \sigma_\Lambda^2}$$



Lattice QCD + HRG model

R. Bellwied *et al.* :

- breakdown of hadronic species contributions to susceptibilities, using Hadron Resonance Gas model

  $\Rightarrow$ best proxies for ratios
  (so potentially the most sensitive ones)

  $\Rightarrow$ results depending on $\sqrt{s}$ + kinematic cuts compared with STAR data

$$C_{QS} = \frac{\chi_{11}^{QS}}{\chi_2^S} = \frac{1}{2} \cdot \frac{\sigma_K^2}{\sigma_K^2 + \sigma_\Lambda^2}$$

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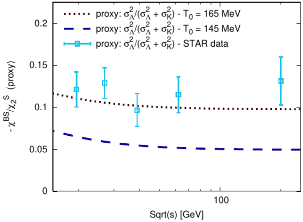

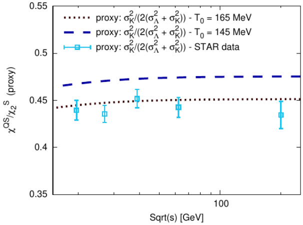

... and what about event generators ?

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EPOS

Event generators are programs made to compute models and simulate every steps of a collision (e.g. EPOS, PYTHIA, HIJING++...).

Advantage : perfect detector, as final-state particles are all listed (no uncertainties)

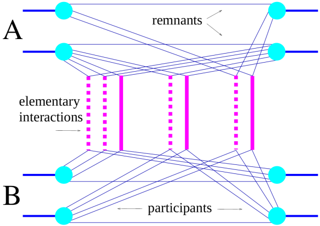
Energy conserving quantum mechanical approach, based on
Partons, parton ladders, strings,
Off-shell remnants, and
Saturation of parton ladders

Event generator based on Parton-Based Gribov-Regge Theory, which unifies Parton model and Gribov-Regge theory by solving inconsistencies of both models.

Can simulate any type of collision :

$e^{+/-} + e^{+/-}$ $e^{+/-} + p$ $p + p$ $p + A$ $A + A$

Initial conditions

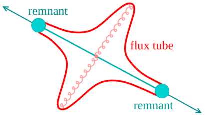


K. Werner et al., 2000

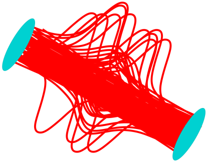
Primary interactions treated with PBGRT

exchange of multiple Pomerons in parallel

$\rightarrow$ can be seen as cut (particle production) or uncut (σ calculation) parton ladders



$\times\ N_{int}\ =$



K. Werner, 2018

Core-corona separation

- Core = high string density region
- Corona = escaping segments (with high p_T)

Medium evolution, hadronisation and re-scattering

Core evolution

Viscous 3D+1 hydrodynamics expansion based on a cross-over transition EoS
+
Hadronisation of the medium via Cooper-Frye procedure

Corona evolution

Strings evolution following dynamics of gauge invariant Lagrangian
+
String fragmentation to produce hadrons

$\Downarrow$

Re-scatterings between formed hadrons with UrQMD model until
chemical freeze-out (no more inelastic scatterings)
kinetic freeze-out (no more elastic scatterings)

$\Downarrow$

Final state particle

What we can (not) study with EPOS

The hydrodynamic evolution of the core in EPOS does not include fluctuations : susceptibilities are NOT sensitive to any possible CEP

$\Rightarrow$ search for signatures of CEP impossible with EPOS by construction !

In fact, in EPOS, all the fluctuations are coming from initial conditions, hadronisation process and/or hadronic cascades.

Hence, what we plan to do is to

study the impact of hadronisation and hadronic cascades on the susceptibilities

by comparing susceptibilities :

- from **micro-canonical** & **grand-canonical** decays
- from **before** & **after** UrQMD

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Koch ratios vs energy

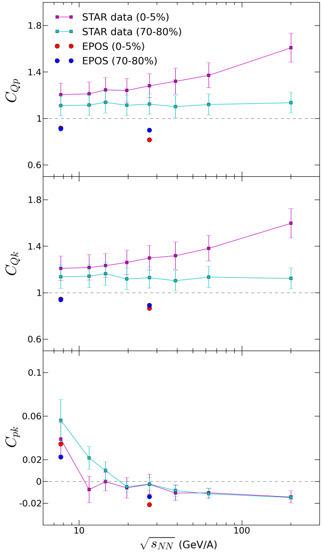
Results from **EPOS 4** with BEST EoS, with $T_c = 155$ MeV and $\mu_{B_C} = 350$ MeV *(cf. recent presentation from M. Stefaniak for more details)*

!!! CAUTION : β version of EPOS 4 !!!
→ just started parametrisation for LHC data

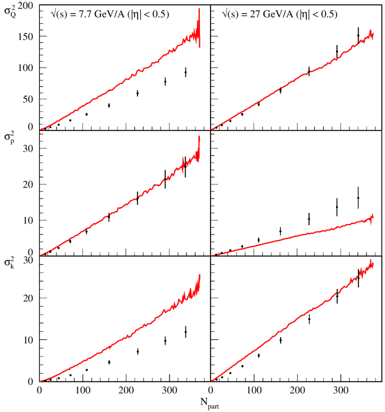
(+ only 2 energies tested yet)

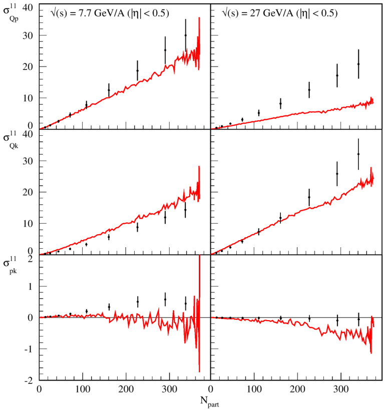
⇒ EPOS underestimate ratios

Let's check in details...



(Co)variances vs Npart





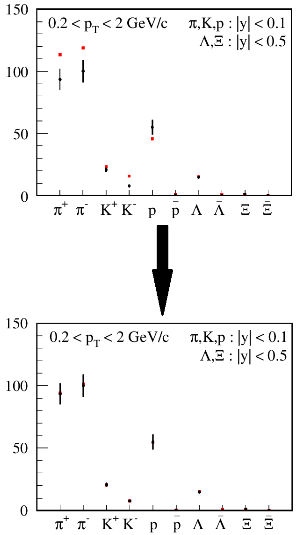
Qualitatively √

- EPOS general behaviour ≡ **STAR** data
- globally same variation trends w energy

Quantitatively X

- few EPOS results match with **STAR** data
- too much / not enough variation

Hadronic species multiplicity

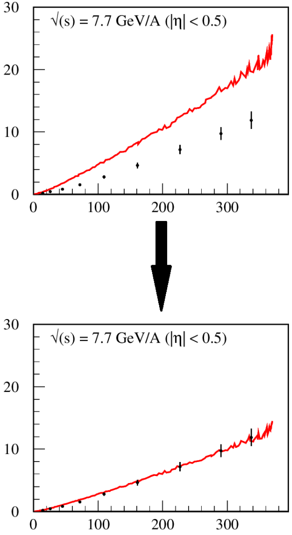


In fact, discrepancies for these 2nd order cumulants are directly linked to the multiplicity of the considered species.

Indeed, if we multiply net particle numbers N_X and N_Y by factors c_X and c_Y, we get :

$$\begin{aligned}\sigma'^{11}_{XY} &= \langle N'_X . N'_Y \rangle - \langle N'_X \rangle \langle N'_Y \rangle \\ &= \langle c_X N_X . c_Y N_Y \rangle - \langle c_X N_X \rangle \langle c_Y N_Y \rangle \\ &= c_X c_Y \langle N_X . N_Y \rangle - c_X \langle N_X \rangle c_Y \langle N_Y \rangle\end{aligned}$$

Hadronic species multiplicity



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Then

$$\boxed{\sigma'^{11}_{XY} = (c_X.c_Y)\times\sigma^{11}_{XY}}$$

and similarly

$$\boxed{\sigma'^{2}_{X} = (c_X)^2\times\sigma^{11}_{XY}}$$

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Summary & outlook

Plan : use last version of EPOS 4 study the impact of hadronisation and hadronic cascades on 2nd order susceptibilities of B, Q, S.

In particular : compare values of STAR proxies and best proxies proposed by R. Bellwied *et al.* before and after hadronic cascades
+ compare them for different hadronisation processes (grand-canonical / microcanonical)

Status :

1. compare EPOS results with STAR measured proxies :
   OK qualitatively, NOT OK quantitatively
   BUT "works" technically, even without any RHIC data matching test yet
   ⇒ finish EPOS 4 parametrisation + add proxies from R. Bellwied *et al.*
   → investigate particle production (yields, dN/dy vs N_{part}...)
   → check results for other energies to see better the global tendency
2. compare results before and after UrQMD
3. compare results from different hadronisation processes
4. take a look at higher order cumulants and ratios (skewness, kurtosis...) ?

Thanks for your attention !

Time for questions

Every comments or suggestions are welcome ☺

A bit more about EPOS...

More references about EPOS :

- primary interactions & hydrodynamics in EPOS
- hydrodynamics in EPOS
- heavy flavors in EPOS
- jet-fluid interaction in EPOS

Recent developments for EPOS 4 :

- parton saturation (see also here)
- factorisation
- BEST equation of state inclusion

Stay tuned ! More papers to come...

Hadron Resonance Gas Model (summarised from **R. Bellwied *et al.***)

It assumes that a gas of interacting hadrons in ground states can be described by a gas of non-interacting hadrons and resonances.
One can then re-write partition function, allowing to consider kinematic cuts simply by changing the phase space integration :

$$\ln(\mathscr{Z}_R) = \eta_R \frac{V.d_R}{2\pi^2 T^3} \int_0^\infty p^2.dp.\ln\left(1 - \eta_R.z_R.e^{-\varepsilon_R/T}\right)$$

Hence, with such assumption, one can decompose susceptibilities as a function of hadronic species :

$$\chi_{ijk}^{BQS}(T,\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S) = \sum_R \sum_{i\in stable} (P_{R\to p})^l \times B_p^i Q_p^j S_p^k \times I_l^R(T,\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S)$$

with :

- $l = i + j + k$
- $P_{R\to p} = \sum_\alpha N_{R\to p}^\alpha \times n_{p,\alpha}^R$: $\langle n_p \rangle$ produced in process α by each resonance R
- B_p^i, Q_p^j, S_p^k : quantum numbers of particle specie p
- $I_l^R(T,\hat{\mu}_{B,Q,S}) = \frac{\partial^l}{\partial \hat{\mu}_R^l}\left[\frac{1}{VT^3}\sum_R \ln(\mathscr{Z}_R)\right]$ $(\hat{\mu}_R = \hat{\mu}_B.B_R + \hat{\mu}_Q.Q_R + \hat{\mu}_S.S_R)$