How to study the location of the critical point in the phase diagram of nuclear matter with the event generator EPOS 4?

Johannès JAHAN (Ph.D. student) - Subatech / CNRS / Nantes University

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Under the supervision of:
Klaus WERNER - Subatech / Nantes University
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My work takes place in the context of high energy particle collisions. In particular, I use an event generator (EPOS) to simulate heavy-ion collisions (HIC) and compare my results mainly to:

- **Au + Au** collisions with center-of-mass energy $\sqrt{s_{NN}} = 7.7 - 200$ GeV/A
- **Pb + Pb** collisions with center-of-mass energy $\sqrt{s_{NN}} = 2.76 - 5.02$ TeV/A

1 collision

≡

kinetic energy of 3 to 2000 flying mosquitoes in a $10^{-15}$ m size object!
Little Big-Bangs

But *why* do we perform such heavy-ion collisions? ...to *recreate the Big-Bang*!

Analogy between the Big-Bang and HIC (*U. W. Heinz, 2013*)

We want to understand how the fundamental interactions work at very high energy scales.

We will focus in particular on the *strong interaction*, and more especially on the state of matter once created at the early stages of the Universe: the *Quark-Gluon Plasma (QGP)*.

This boiling nuclear matter made of *deconfined quarks and gluons* that can move freely (while *usually bounded into hadrons*) can be recreated in HIC!
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Event generators are programs made to compute models in order to simulate every step of a collision (e.g. PYTHIA, HIJING++...).

**Advantages**: - perfect detector, as final-state particles are all listed (no uncertainties)
- dynamical approach

*(indeed, there’s always a shadow in the picture: one has to be careful on the applicability, and phenomenological approaches generally requires parametrisation)*
What is EPOS?

Event generators are programs made to compute models in order to simulate every step of a collision (e.g. PYTHIA, HIJING++...).

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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 (PBGRT), unifying Parton model and Gribov-Regge theory by solving inconsistencies of both models.

Can simulate with the same formalism any type of collision consistently:

\[ e^{+/-} + e^{+/-} \quad e^{+/-} + p \quad p + p \quad p + A \quad A + A \]
Primary interactions treated with PBGRT
Exchange of multiple Pomerons in parallel

Core-corona separation
Those ladders are formed by strings, or color flux tubes
(q − g − ... − g − \overline{q} chains)
with ”kinks” due to transverse gluons.

(K. Werner, 2018)

(K. Werner et al., 2000)
Primary interactions treated with PBGRT
Exchange of multiple Pomerons in parallel

⇒ can be seen as parton ladders which are cut (particle production) or uncut (\(\sigma\) calculation)

(\(\equiv\) *Multiple Parton Interaction*)

Core-corona separation
Those ladders are formed by strings, or color flux tubes (\(q - g - \ldots - g - \bar{q}\) chains) with ”kinks” due to tranverse gluons.

In HIC (but not only !), many strings may overlap, so we can separate :

- **core** = high string density region (\(> \varepsilon_c\))
- **corona** = escaping segments (with high \(p_T\)) (\(< \varepsilon_c\))
Medium evolution, hadronisation and re-scattering

**Core evolution**
Viscous 3D+1 relativistic hydrodynamics expansion

+ Hadronisation of the medium via Cooper-Frye procedure

(MADAI collaboration)

**Corona evolution**
Strings evolution following dynamics of gauge invariant Lagrangian

+ String fragmentation to produce hadrons

⇓

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

kinetic freeze-out (no more elastic scatterings)

⇓

Final state particle
As an important part of my Ph.D., I am involved in the development of EPOS 4, a new version planned to be released publicly in late 2021 / early 2022.

In order to help and improve the validation process of this new version before its release, I’ve been working on:

1. searching for experimental data of basic observables (like $p_T$ spectra, production yields of particles...) and writing the corresponding analyses
   ⇒ mandatory for validation of the new EPOS version
2. adding the HepMC output format to enable EPOS usage with RIVET
   ⇒ makes it more user-friendly
   + integrating RIVET to the online EPOS analysis framework
   ⇒ provides huge and constantly growing library of data and analyses
   + fastens the validation process
What is RIVET?

Robust Independant Validation of Experiment and Theory

Software based on C++ libraries, installed with different packages:

- **YODA**: Python libraries and classes used for analyses and histogramming
- **HepMC**: simulations recording and reading for analyses
- **Fastjet**: recombination algorithms, mainly used for jet analyses

**Purpose**: offer a simple and standardised tool to automatise comparison between event generators simulations and experimental data

```
rivet EG_DATA.hepmc -a ANALYSIS_NAME -p CALIB_NAME.yoda -o OUTPUT_FILE.yoda
```
Robust Independant Validation of Experiment and Theory

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RIVET contains many analyses based on publications from many different experiments (experimental results included), and develops thanks to contributions from the users community (experimentalists & theoreticians).

**Advantages**:
- provides huge and constantly growing library of data and analyses
- easy to handle (a lot of documentation + helpful reactive developers)
- don’t have to ”think about” the analysis details anymore

⇒ RIVET is a very useful tool for us!
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Quantum Chromodynamics phase diagram and critical point

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

- **Theoretically**: use models & theories to make predictions \((T_c, \mu_{BC})\) or to extract information from measurements \((T & \mu_B\) of a collision, viscosity of the QGP...)

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

**Question(s) of interest**: is there a 1\(^{\text{st}}\) order phase transition and a critical endpoint (CEP) between QGP and hadronic gas phases? If yes, where?
Susceptibilities

To answer this question, many tools can be used, among which are the **susceptibilities**, which quantify how an extensive property of a system changes under the variation of an intensive property.

In a grand-canonical ensemble (GCE), a formalism often used to describe HIC, they are **theoretically defined** as derivatives of the partition function $Z(T, V, \mu)$:

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

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

2$^{\text{nd}}$ order baryonic susceptibility as a function of $T$ and $\mu_B$

*(P. Parotto et al., 2020)*
In a more convenient and understandable way, susceptibilities can be written as a function of the net-charge cumulants \((N_{B,Q,S} = n_{B,Q,S} - n_{B,Q,S})\).

They represent in fact event-by-event fluctuations of the considered net charges, and can be linked to the statistical moments of their distributions.

Also, in order to get rid of volume and temperature factors, as they cannot be measured directly in experiments, ratios are often used.

### 2\textsuperscript{nd} order susceptibilities for X/Y = B, Q, S

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

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

\[
\chi_X^2 = \frac{1}{VT^3} \sigma_X^2 = \frac{\langle N_X^2 \rangle - \langle N_X \rangle^2}{VT^3}
\]

### Ratios

\[
C_{BS} = \frac{\sigma_{BS}^{11}}{\sigma_S^2} \quad C_{QB} = \frac{\sigma_{QB}^{11}}{\sigma_B^2} \quad C_{QS} = \frac{\sigma_{QS}^{11}}{\sigma_S^2}
\]
Experimental results

\textbf{STAR collaboration} measured, for $N_Q$, $N_{protons}$ and $N_{kaons}$ (proxies for $N_B$ and $N_S$) in a restrained phase space ($|\eta| < 0.5 + 0.4 < p_T < 1.6$ GeV/c):

$$
\begin{pmatrix}
\sigma^2_Q \\ 
\sigma^1_{Q,p} \\ 
\sigma^2_p \\ 
\sigma^1_{p,k} \\ 
\sigma^2_k
\end{pmatrix}
$$

vs $<N_{part}>$ ($\chi^{B,Q,S}_{11,2}$ proxies)
STAR collaboration measured, for $N_Q$, $N_{protons}$ and $N_{kaons}$ (proxies for $N_B$ and $N_S$) in a restrained phase space ($|\eta| < 0.5$ + $0.4 < p_T < 1.6$ GeV/c):

$$\begin{pmatrix}
\sigma_Q^2 & \sigma_{Q,p}^{11} \\
\sigma_{p,k}^{11} & \sigma_k^2
\end{pmatrix} \text{ vs } <N_{part}> (\chi_{11,2}^{B,Q,S} \text{ proxies})$$

- Koch ratios $C_{Qp,Qk,pk}$ (proxies for $C_{QB,QS,BS}$)
  - as a function of $\langle N_{part} \rangle$
  - as a function of $\sqrt{s_{NN}}$
Recent feature: inclusion of a new EoS containing CEP + 1st order phase transition.

However, the hydrodynamic evolution of the core in EPOS (macroscopic quantities) does not include fluctuations: susceptibilities are NOT expected to be sensitive to any possible CEP within the hydro phase

⇒ search for signatures of CEP impossible with EPOS by construction?

Recent work with EPOS (see M. Stefaniak’s thesis) showed almost no differences between new and old EoS

In fact, in EPOS, we expect that most of the fluctuations come from initial conditions, hadronisation process and/or hadronic cascades. (may even dominate the fluctuations of phase transition we are seeking...)

Then, what we plan to do is

1. comparing cumulants before & after UrQMD (+ with STAR results), to see the impact of hadronic cascades on the susceptibilities
Furthermore, the choice of grand-canonical ensemble to describe heavy-ion collisions is questionable (taken from M. Nahrgang’s talk):

In a GCE, the system is:
- in thermal equilibrium (=long-lived)
- in equilibrium with a particle heat bath
- static

The system created in a HIC is:
- short-lived
- inhomogeneous
- highly dynamical

Hence, we also include in our plan

2. comparing cumulants after decays for micro (new standard in EPOS 4) & grand canonical (= classical Cooper-Frye procedure) with STAR results, to see the impact of hadronisation on the susceptibilities
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Au+Au @ $\sqrt{s_{NN}} = 200$ GeV/A

Results from recent EPOS 4 version (3 months-old) compared with STAR data

⇒ As expected for $\sigma_{11,2}^{11}$ (Sahar et al.), no difference w/wo CBWE correction

- EPOS reproduces qualitatively well the $N_{part}$ dependence of variances
- pretty good estimation of $\sigma_Q^2$ + $\sigma_Q^{11}$ & $\sigma_k^{11}$ for peripheral collisions

- EPOS fails to describe quantitatively $\sigma_p^2$ and $\sigma_k^2$
  → particle production
- fails to reproduce properly the $N_{part}$ dependence of covariances, especially $\sigma_p^{11}$ (no dependence?)
  → check the feed-down
Last results

Hadronic species multiplicity

Why does particle production should be checked?

Simply because amplitudes of these 2nd order cumulants are directly linked to the net-multiplicities 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:

$$\sigma_{X^1 Y}^{11} = \langle N'_X . N'_Y \rangle - \langle N'_X \rangle \langle N'_Y \rangle$$

$$= \langle c_X N_X . c_Y N_Y \rangle - \langle c_X N_X \rangle \langle c_Y N_Y \rangle$$

$$= c_X c_Y \langle N_X . N_Y \rangle - c_X \langle N_X \rangle c_Y \langle N_Y \rangle$$
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\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
$$

Then

$$
\sigma'_{11}^{XY} = (c_X . c_Y) \times \sigma_{11}^{XY} \quad \text{and} \quad \sigma_X^{2} = (c_X)^{2} \times \sigma_{XY}^{11}
$$
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Summary & Outlook

**Main research goal**: use last version of EPOS 4 study the impact of hadronisation and hadronic cascades on 2\textsuperscript{nd} order susceptibilities of $B, Q, S$, using STAR proxies and best proxies proposed by C. Ratti \textit{et al.} through BES

**Status**:

1. compare EPOS results with STAR measured proxies:
   - $\sqrt{s_{NN}} = 200$ GeV/A:
     - OK qualitatively for variances, even almost quantitatively covariances fall for central collisions
     - $\Rightarrow$ finish EPOS 4 validation ($\approx$ OK @ 200 GeV/A $\rightarrow$ go to lower energies)
     - $\rightarrow$ check results for other energies in order to check the energy dependence

2. implement the best proxies from C. Ratti \textit{et al.} (see backup slides)
3. compare results from different hadronisation processes
4. compare results before and after hadronic cascades
5. take a look at higher order cumulants and ratios (skewness, kurtosis...) ?
Thanks for your attention!

NO GOD NO PLEASE NO QUESTIONS

Noooooooooooooooooooooo

... just kidding of course 😊
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)
- microcanonical decay of the core

+ development of EPOS-HQ for heavy flavour observables

Stay tuned! More papers to come...
PBGRT - The motivations

**Parton model**
Mainly used for inclusive cross-section calculations

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**Gribov-Regge theory**
EFT for Multiple *Pomeron* Interaction

(K. Werner et al., 2000)

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**Problems:**
- can only calculate cross-section for hard processes → not suitable alone for HIC

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**Solution:** merge both into a formalism treating consistently hard and soft scattering

⇒ Parton-based Gribov-Regge Theory!
Main principle of PBGRT

In the PBGRT, an elementary interaction is modeled as a *Pomeron*.

- **Soft process** ($Q^2 < 1 \text{ GeV}$): mainly elastic scatterings, parametrised T-matrix (Regge poles)

- **Hard process** ($Q^2 > 1 \text{ GeV}$): pQCD applicable, computed T-matrix (DGLAP equation)

- **Semi-hard process** ($Q^2 > 1 \text{ GeV}$ $q_{\text{sea}}/\bar{q}_{\text{sea}}/g$): using both previous formalisms
C. Ratti et al.: breakdown of hadronic species contributions to susceptibilities, studied from lQCD + HRG model calculations (gas of non-interacting hadrons and resonances in a box)
C. Ratti et al.: breakdown of hadronic species contributions to susceptibilities, studied from lQCD + HRG model calculations (gas of non-interacting hadrons and resonances in a box) ⇒ best proxies for ratios (so potentially the most sensitive ones)

\[ C_{BS} = \frac{\chi^{BS}_{11}}{\chi^{S}_{2}} = \frac{\sigma^2_{\Lambda} + 2\sigma^2_{\Xi} + 3\sigma^2_{\Omega}}{\sigma^2_{\Lambda} + 4\sigma^2_{\Xi} + 9\sigma^2_{\Omega} + \sigma^2_{k}} \left( = \frac{\sigma^{11}_{pk}}{\sigma^2_{k}} \right)_{\text{STAR}} \]

or \[ = \frac{\sigma^2_{\Lambda}}{\sigma^2_{k} + \sigma^2_{\Lambda}} \] (easier to measure experimentally !)

\[ C_{QS} = \frac{\chi^{QS}_{11}}{\chi^{S}_{2}} = \frac{1}{2} \cdot \frac{\sigma^2_{k}}{\sigma^2_{k} + \sigma^2_{\Lambda}} \left( = \frac{\sigma^{11}_{Qk}}{\sigma^2_{k}} \right)_{\text{STAR}} \]
Lattice QCD + Hadron Resonance Gas model

C. Ratti et al.:

- breakdown of hadronic species contributions to susceptibilities, studied from lQCD + HRG model calculations (gas of non-interacting hadrons and resonances in a box)
  - best proxies for ratios (so potentially the most sensitive ones)
  - results depending on $\sqrt{s}$ + kinematic cuts compared with STAR data

$$C_{BS} = \frac{\chi^{BS}_{11}}{\chi^{S}_{2}} = \frac{\sigma^2_\Lambda + 2\sigma^2_\Xi + 3\sigma^2_\Omega}{\sigma^2_\Lambda + 4\sigma^2_\Xi + 9\sigma^2_\Omega + \sigma^2_k} \left( \frac{\sigma^1_{pk}}{\sigma^2_k} \right)_{\text{STAR}}$$

or

$$C_{QS} = \frac{\chi^{QS}_{11}}{\chi^{S}_{2}} = \frac{1}{2} \cdot \frac{\sigma^2_k}{\sigma^2_k + \sigma^2_\Lambda} \left( \frac{\sigma^1_{Qk}}{\sigma^2_k} \right)_{\text{STAR}}$$

... and what about event generators?
Backup slides

Hadron Resonance Gas Model (summarised from C. Ratti 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:

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

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

$$\chi^{BQS}_{ijk}(T,\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S) = \sum_{\alpha} (P_{R\rightarrow p})^l \times B^i_p Q^j_p S^k_p \times I^R_l(T,\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S)$$

with:

- $l = i + j + k$
- $P_{R\rightarrow p} = \sum_{\alpha} N^\alpha_{R\rightarrow p} \times n^R_{p,\alpha}$: $\langle n_p \rangle$ produced in process $\alpha$ by each resonance $R$
- $B^i_p, Q^j_p, S^k_p$: quantum numbers of particle specie $p$
- $I^R_l(T,\hat{\mu}_B,Q,S) = \frac{\partial^l}{\partial \hat{\mu}_R^l} \left[ \frac{1}{VT^3} \sum_R \ln(\mathcal{Z}_R) \right] \quad (\hat{\mu}_R = \hat{\mu}_B \cdot B_R + \hat{\mu}_Q \cdot Q_R + \hat{\mu}_S \cdot S_R)$
When plotting whatever moment $\sigma^{i,j}$ vs $N_{\text{part}}$, one induces trivial fluctuations due to the volume variation of the system: this is the CBWE.

In fact, for a certain centrality bin considered (and even for a single $N_{\text{part}}$ value), there will be volume variations in the collisions ($\leftrightarrow$ different final-state multiplicities) that will contribute to $\sigma^{11,2}_{p,Q,k}$ without being "real fluctuations" (the one we are seeking).

To minimise this effect, STAR collaboration measure $\sigma^{11,2}_{p,Q,k}$ vs $N_{\text{ch}}$ for each centrality bin considered, and calculate the corresponding weighted mean value:

$$\sigma_{c} = \sum_{i} \frac{n_{i} \times \sigma_{i}}{n_{c}}$$

- $n_{i}$: the number of events for the multiplicity bin $i$
- $n_{c}$: the number of events in the centrality bin $c$
When plotting whatever moment $\sigma_{i,j}$ vs $N_{part}$, one induces trivial fluctuations due to the volume variation of the system: this is the CBWE.

In fact, for a certain centrality bin considered (and even for a single $N_{part}$ value), there will be volume variations in the collisions (↔ different final-state multiplicities) that will contribute to $\sigma_{p,Q,k}^{11,2}$ without being "real fluctuations" (the one we are seeking).

⇒ Our method (faster & easier): calculate $\sigma_{p,Q,k}^{11,2}$ vs $N_{ch}$, and then convert $N_{ch} \rightarrow N_{part}$ from the $< N_{part} >$ vs $N_{ch}$ distribution.

\begin{align*}
\sigma_{Q}^{2} & \quad 0.4 < p_T < 1.6 \text{ GeV (}|\eta| < 0.5) \\
N_{part} & \quad 0.5 < |\eta| < 1
\end{align*}