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

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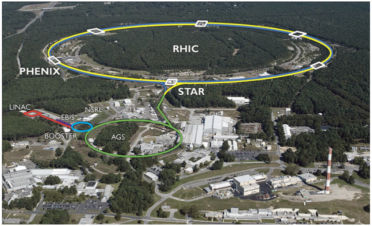
Heavy-ion collisions

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



RHIC facility

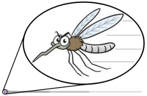
Pb + Pb collisions with center-of-mass energy $\sqrt{s_{NN}} = 2.76 - 5.02$ TeV/A

LHC facility

1 collision

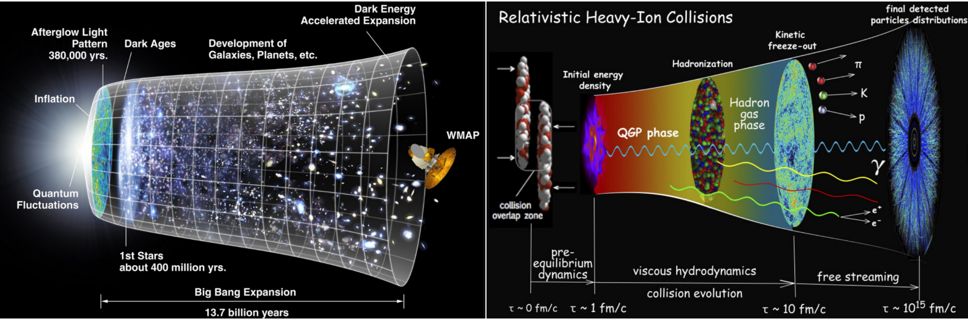
$\equiv$

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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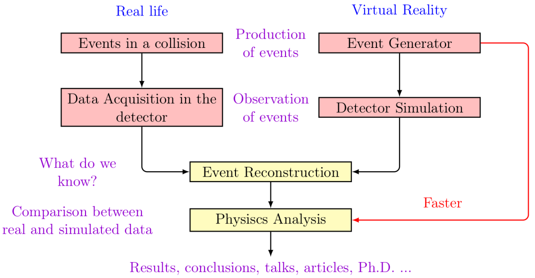
What is EPOS ?

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)*



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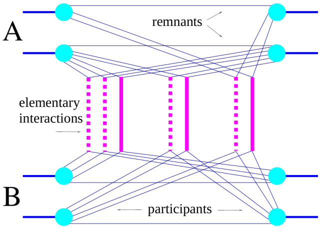
Energy conserving quantum mechanical approach, based on
Partons, parton ladders, strings,
Off-shell remnants, and
Saturation of parton ladders

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 :

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

Initial conditions & core-corona procedure

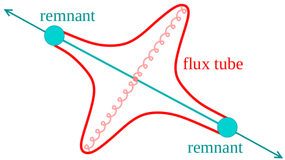


Schematic representation of a collision

(K. Werner et al., 2000)

Primary interactions treated with PBGRT

Exchange of multiple Pomerons in parallel



A simple interaction within the PBGRT

(K. Werner, 2018)

Core-corona separation

Those ladders are formed by strings, or color flux tubes

($q - g - ... - g - \overline{q}$ chains)

with "kinks" due to tranverse gluons.

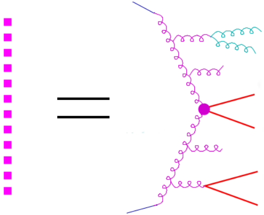
Initial conditions & core-corona procedure

Primary interactions treated with PBGRT

Exchange of multiple Pomerons in parallel

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

($=$ *Multiple Parton Interaction)*



Diagrammatic view of a cut ladder

(K. Werner et al., 2016)

Multiple interactions within the PBGRT

(K. Werner, 2018)

Core-corona separation

Those ladders are formed by strings, or color flux tubes ($q - g - ... - g - \overline{q}$ 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) ($< \varepsilon_c$)

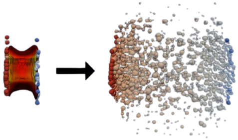
Medium evolution, hadronisation and re-scattering

Core evolution

Viscous 3D+1 relativistic hydrodynamics expansion

+

Hadronisation of the medium via Cooper-Frye procedure



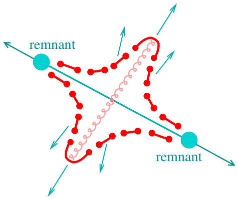
(MADAI collaboration)

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

Toward the next public release : **EPOS 4**

As an important part of my Ph.D., I am involved in the development of **EPOS 4**, a new version planed 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
   $\Rightarrow$ **mandatory for validation of the new EPOS version**
2. adding the HepMC output format to enable **EPOS** usage with **RIVET**
   $\Rightarrow$ **makes it more user-friendly**

   + integrating RIVET to the online EPOS analysis framework
   $\Rightarrow$ **provides huge and constantly growing library of data and analyses**
   + fastens the validation process

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

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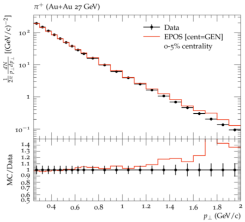
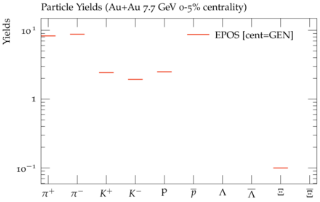
rivet EG_DATA.hepmc -a ANALYSIS_NAME -p CALIB_NAME.yoda -o OUTPUT_FILE.yoda
```





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

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

$\Rightarrow$ **RIVET is a very useful tool for us !**

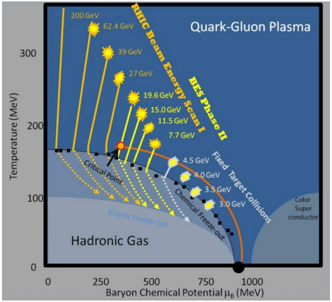
Contents

Quantum ChromoDynamics phase diagram and critical point

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 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...)



Phase diagram of nuclear matter

(D. Cebra, 2013)

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

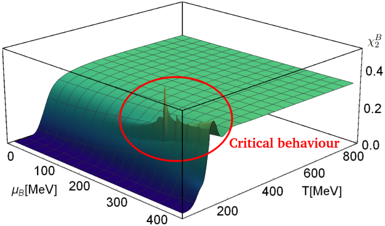
Susceptibilities

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 $Z(T,V,\mu)$:

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

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



2[nd] order baryonic susceptibility as a function of T and μ_B

(P. Parotto et al., 2020)

Susceptibilities

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

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

2^{nd} order susceptibilities for $X/Y = B,Q,S$

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

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

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

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

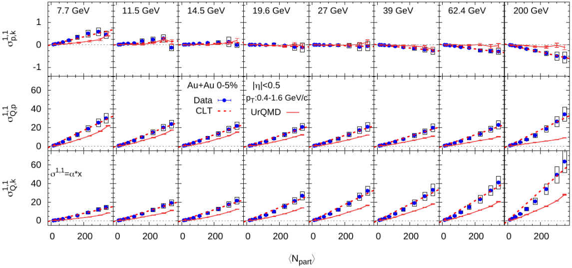
Ratios

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

Experimental results

STAR collaboration measured, for 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) :

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



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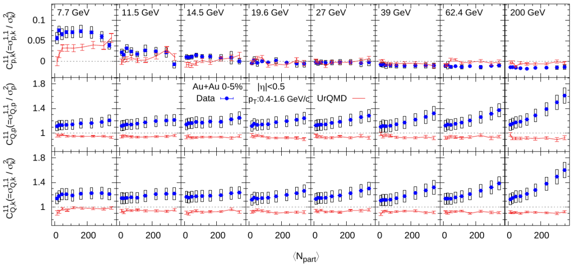
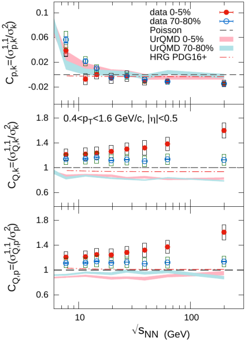
- $\begin{pmatrix} \sigma^2_Q & \sigma^{11}_{Q,p} & \sigma^{11}_{Q,k} \\ '' & \sigma^2_p & \sigma^{11}_{p,k} \\ '' & '' & \sigma^2_k \end{pmatrix}$ vs $< N_{part} >$ ($\chi^{B,Q,S}_{11,2}$ proxies)
- Koch ratios $C_{Qp,Qk,pk}$ (proxies for $C_{QB,QS,BS}$)
  - as a function of $\langle N_{part} \rangle$
  - as a function of $\sqrt{s_{NN}}$





What we can(not) study with EPOS

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

$\Rightarrow$ 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

What we can(not) study with EPOS

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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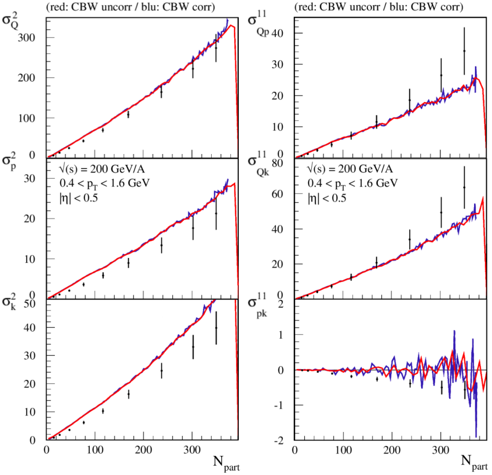
Au+Au @ $\sqrt{s_{NN}} = 200$ GeV/A

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

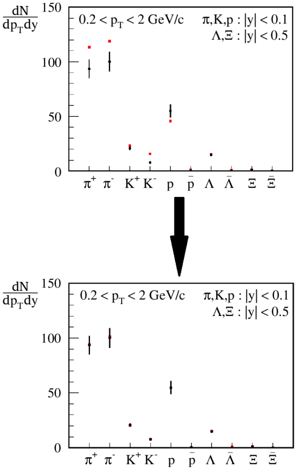


⇒ As expected for $\sigma^{11,2}$ (Sahar *et al.*), no difference w/wo CBWE correction

- EPOS reproduces qualitatively well the N_{part} dependence of variances
- pretty good estimation of σ^2_Q + σ^{11}_{Qp} & σ^{11}_{Qk} for peripheral collisions

- EPOS fails to describe quantitatively σ^2_p and σ^2_k
  → particle production
- fails to reproduce properly the N_{part} dependence of covariances, especially σ^{11}_{pk} *(no dependence ?)*
  → check the feed-down

Hadronic species multiplicity



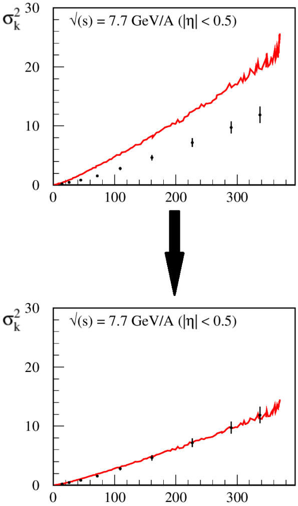
Why does particle production should be checked ?

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 :

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

Hadronic species multiplicity



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Then

$$\boxed{\sigma'^{11}_{XY} = (c_X.c_Y)\times\sigma^{11}_{XY}} \quad \text{and} \quad \boxed{\sigma'^{2}_{X} = (c_X)^2\times\sigma^{11}_{XY}}$$

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Summary & Outlook

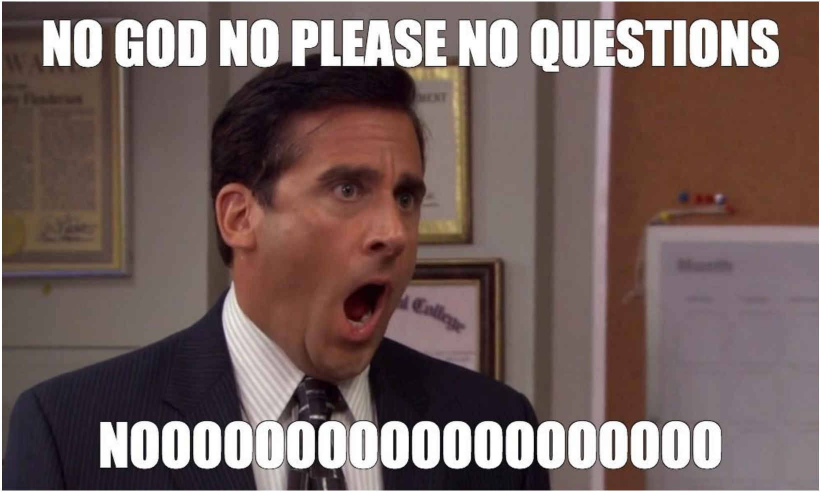
Main research goal : use last version of EPOS 4 study the impact of hadronisation and hadronic cascades on 2nd order susceptibilities of B, Q, S, using STAR proxies and best proxies proposed by C. Ratti *et al.* through BES

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 *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 !



... 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

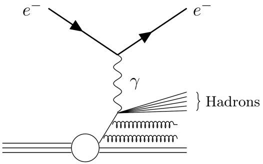
+ development of EPOS-HQ for heavy flavour observables

Stay tuned ! More papers to come...

PBGRT - The motivations

Parton model

Mainly used for inclusive cross-section calculations



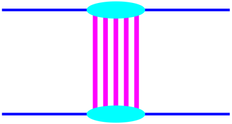
Deep Inelastic Scattering

Problems :

- can only calculate cross-section for hard processes $\rightarrow$ not suitable alone for HIC

Gribov-Regge theory

EFT for Multiple *Pomeron* Interaction



(K. Werner et al., 2000)

Inconsistencies :

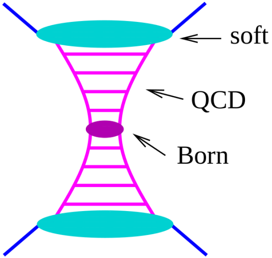
- energy conserved for particle production but NOT for cross-section calculations
- although multiple scattering approach, all interactions are not treated equally

Solution : merge both into a formalism treating consistently hard and soft scattering $\Rightarrow$ Parton-based Gribov-Regge Theory !

Main principle of PBGRT

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

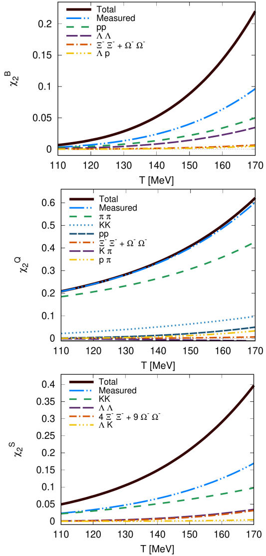
- **Soft process ($Q^2 < 1$ GeV) :** mainly elastic scatterings, parametrised T-matrix (Regge poles)
- **Hard process ($Q^2 > 1$ GeV) :** pQCD applicable, computed T-matrix (DGLAP equation)
- **Semi-hard process ($Q^2 > 1$ GeV $q_{sea}/\overline{q}_{sea}/g$) :** using both previous formalisms



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)*



Lattice QCD + Hadron Resonance Gas model

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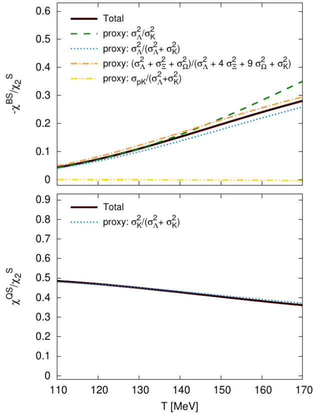
  - $\Rightarrow$ best proxies for ratios (so potentially the most sensitive ones)



$$C_{BS} = \frac{\chi^{BS}_{11}}{\chi^S_2} = \frac{\sigma^2_\Lambda + 2\sigma^2_\Xi + 3\sigma^2_\Omega}{\sigma^2_\Lambda + 4\sigma^2_\Xi + 9\sigma^2_\Omega + \sigma^2_k} \quad \left(= \frac{\sigma^{11}_{pk}}{\sigma^2_k} \right)_{STAR}$$

$$or \quad = \frac{\sigma^2_\Lambda}{\sigma^2_k + \sigma^2_\Lambda}$$ *(easier to measure experimentally !)*

$$C_{QS} = \frac{\chi^{QS}_{11}}{\chi^S_2} = \frac{1}{2} \cdot \frac{\sigma^2_k}{\sigma^2_k + \sigma^2_\Lambda} \quad \left(= \frac{\sigma^{11}_{Qk}}{\sigma^2_k} \right)_{STAR}$$

Lattice QCD + Hadron Resonance Gas model

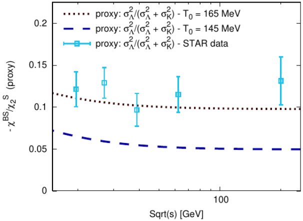
C. Ratti *et al.* :

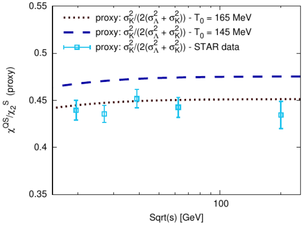
- breakdown of hadronic species contributions to susceptibilities, studied from lQCD + HRG model calculations *(gas of non-interacting hadrons and resonances in a box)*
  - ⇒ best proxies for ratios (so potentially the most sensitive ones)
  - ⇒ results depending on $\sqrt{s}$ + kinematic cuts compared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

$$C_{BS} = \frac{\chi_{11}^{BS}}{\chi_2^S} = \frac{\sigma_\Lambda^2 + 2\sigma_\Xi^2 + 3\sigma_\Omega^2}{\sigma_\Lambda^2 + 4\sigma_\Xi^2 + 9\sigma_\Omega^2 + \sigma_k^2} \quad \left(= \frac{\sigma_{pk}^{11}}{\sigma_k^2} \right)_{STAR}$$

$$or \quad = \frac{\sigma_\Lambda^2}{\sigma_k^2 + \sigma_\Lambda^2} \quad \textit{(easier to measure experimentally !)}$$

$$C_{QS} = \frac{\chi_{11}^{QS}}{\chi_2^S} = \frac{1}{2} \cdot \frac{\sigma_k^2}{\sigma_k^2 + \sigma_\Lambda^2} \quad \left(= \frac{\sigma_{Qk}^{11}}{\sigma_k^2} \right)_{STAR}$$





... and what about event generators ?

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 :

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

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
- $I_l^R(T,\hat{\mu}_{B,Q,S}) = \frac{\partial^l}{\partial \hat{\mu}_R^l}\left[\frac{1}{VT^3}\sum_R \ln(\mathscr{Z}_R)\right]$ $(\hat{\mu}_R = \hat{\mu}_B.B_R + \hat{\mu}_Q.Q_R + \hat{\mu}_S.S_R)$

Centrality bin width effect (CBWE)

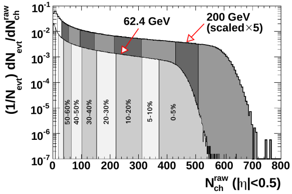
When plotting whatever moment $\sigma^{i,j}$ vs N_{part}, one induces trivial fluctuations due to the volume variation of the system : this is the CBWE.

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 $\sigma^{11,2}_{p,Q,k}$ without being "real fluctuations" (the one we are seeking).

To minimise this effect, STAR collaboration measure $\sigma^{11,2}_{p,Q,k}$ vs N_{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



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