Impact of hadronisation process and hadronic cascades on the 2^{nd} order net-charge cumulants studied through the BES with EPOS 4

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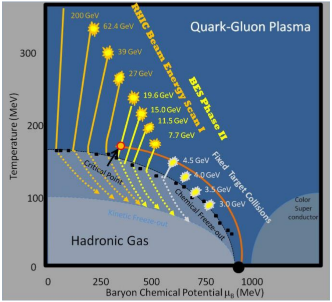
Quantum ChromoDynamics phase diagram and critical point

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 1^{st} order phase transition and a critical endpoint (CEP) between QGP and hadronic gas phases ? If yes, where ?

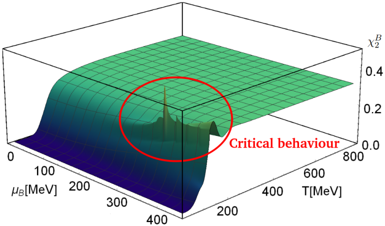
From susceptibilities...

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

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

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



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

(P. Parotto et al., 2020)

...to net-charge cumulants

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.

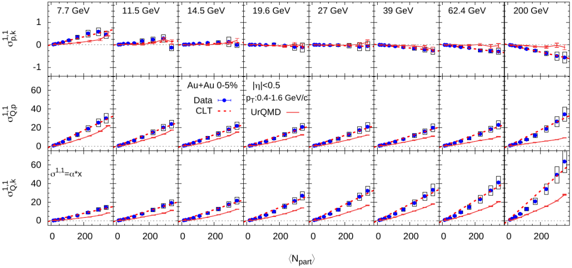
Ratios

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

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) :

- $\begin{pmatrix} \sigma^2_Q & \sigma^{11}_{Q,p} & \sigma^{11}_{Q,k} \\ \text{"} & \sigma^2_p & \sigma^{11}_{p,k} \\ \text{"} & \text{"} & \sigma^2_k \end{pmatrix}$ vs $< N_{part} >$ ($\chi^{B,Q,S}_{11,2}$ proxies)



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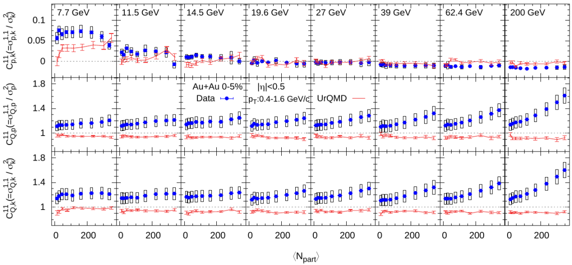
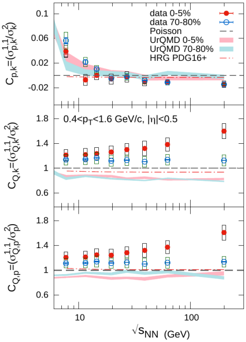
- Koch ratios $C_{Qp,Qk,pk}$ (proxies for $C_{QB,QS,BS}$)
  - as a function of $\langle N_{part} \rangle$
  - as a function of $\sqrt{s_{NN}}$





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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. EPOS, PYTHIA, HIJING++...).

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

(indeed, there are some caveats : one has to be careful on the applicability, and phenomenological approaches generally requires parametrisation)

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 :

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

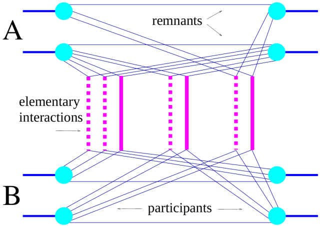
Initial conditions & core-corona procedure

Primary interactions treated with PBGRT

Exchange of multiple Pomerons in parallel

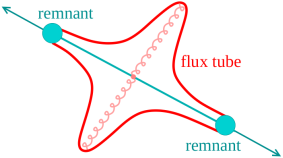
$\Rightarrow$ can be seen as parton ladders which are cut (particle production) or uncut (σ calculation)

(= Multiple Parton Interaction)



Schematic representation of a collision

(K. Werner et al., 2000)



A simple interaction within the PBGRT

(K. Werner, 2018)

Core-corona separation

Those ladders are formed by strings, or color flux tubes ($q - g - \dots - g - \overline{q}$ chains) with "kinks" due to tranverse gluons.

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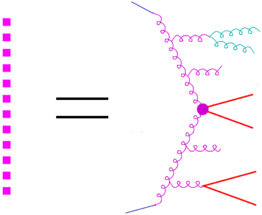


Diagrammatic view of a cut ladder

(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) ($<\varepsilon_c$)

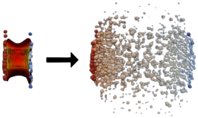
Medium evolution, hadronisation and re-scattering

Core evolution

Viscous 3D+1 hydrodynamics expansion based on a cross-over transition Equation of State (EoS)

+

Hadronisation of the medium via Cooper-Frye procedure



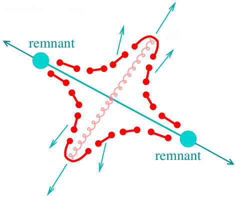
(MADAI collaboration)

Corona evolution

Strings evolution following dynamics of gauge invariant Lagrangian

+

String fragmentation to produce hadrons



$\Downarrow$

Re-scatterings between formed hadrons with the UrQMD model until chemical freeze-out then kinetic freeze-out

$\Downarrow$

$\boxed{\text{Final state particle}}$

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 last year's slides of Maria Stefaniak)* 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 thermal fluctuations if there are...)

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 cumulants

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 hadronisation of the core via <u>microcanonical</u> decay & <u>grand-canonical</u> Cooper-Frye *(= new EPOS 4 standard & old classical procedure),* to see the impact of hadronisation on the cumulants

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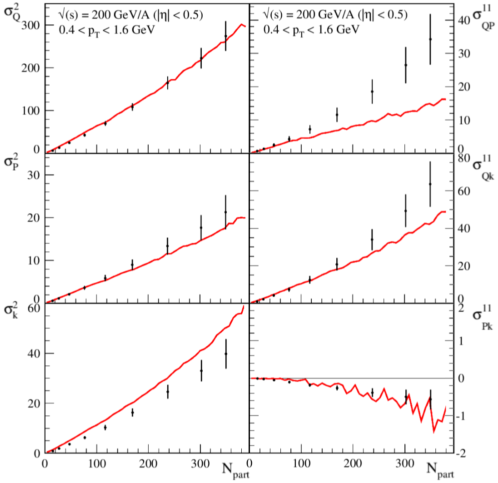
Comparison with data

1.8 Million events from recent EPOS 4 version (—) compared with **STAR** data (•)



- EPOS reproduces **qualitatively well** the centrality dependence for **all** variances and covariances
- **Quantitative agreement** for σ_Q^2, σ_p^2, and even σ_{Pk}^{11} *(where UrQMD fails)*

- EPOS fails to reproduce properly the N_{part} dependence of covariances

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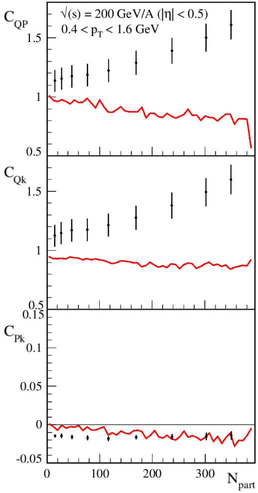


- EPOS reproduces **qualitatively well** the centrality dependence for **all** variances and covariances
- **Quantitative agreement** for σ^2_Q, σ^2_p, and even σ^{11}_{Pk} *(where UrQMD fails)*

- EPOS fails to reproduce properly the N_{part} dependence of covariances

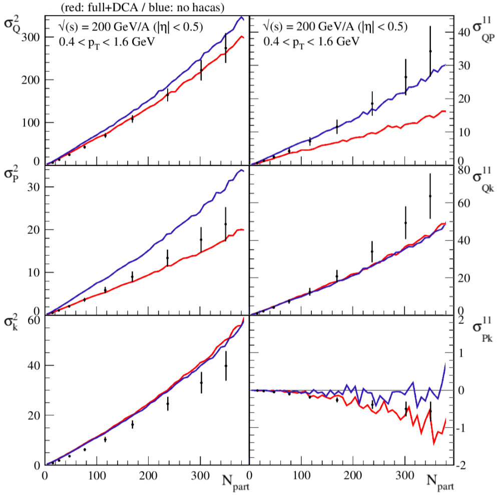
$\Downarrow$

- EPOS reproduces the anti-correlation of *p* and *K* for most of the centralities

- No excess of correlation for C_{Qp} & C_{Qk} *(even decrease of correlation for C_{Qp})* $\rightarrow$ check the resonances ?

Impact of hadronic cascades

1.8 Million events from recent EPOS 4 version (—) compared with **STAR** data (●)



- Significant decrease of σ^2_Q, σ^2_p, σ^{11}_{Qp}

+ slight increase of σ^2_k due to hadronic cascade
  $\Rightarrow$ baryon annihilation

- Despite a hydrodynamical evolution of the core, the σ^{11}_{pk} signal seems to emerge from hadronic phase exclusively
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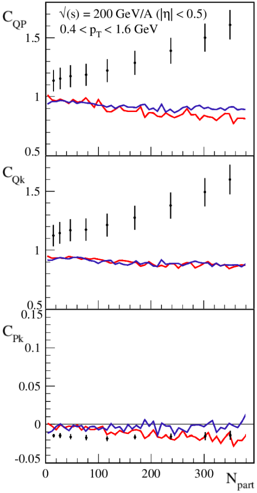

- Significant decrease of σ_Q^2, σ_p^2, σ_{Qp}^{11}

+ slight increase of σ_k^2 due to hadronic cascade
  ⇒ baryon annihilation

- Despite a hydrodynamical evolution of the core, the σ_{pk}^{11} signal seems to emerge from hadronic phase exclusively
  ⇒ lack of fluctuations in the hydro

Very few impact *(if not none)* of the hadronic cascade on the cumulant ratios

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Summary & Outlook

Main research goal : to use last version of EPOS 4 study the impact of hadronisation and hadronic cascades on 2^{nd} order cumulants of B, Q, S, using STAR proxies

Status :

1. compare EPOS results with STAR measured proxies
2. compare results before and after hadronic cascades
   - $\sqrt{s_{NN}} = 200$ GeV/A :

   EPOS does a good quantitative job for predicting variances and σ^{11}_{Qp}, but sees no excess correlations of net-Q with net-p and net-K

   No impact seen from hadronic cascade on the cumulant ratios

   $\Rightarrow$ scan lower BES energies down to 7.7 GeV/A
3. compare results from different hadronisation processes
4. test the sensitivity of enhanced proxies which include Λ (+ Ξ, Ω) proposed by C. Ratti *et al.*

Thanks for your attention !

All questions, 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)
- microcanonical decay of the core

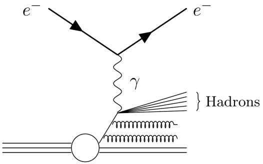
+ development of EPOS-HQ for heavy flavour observables

Stay tuned ! More papers to come...

PBGRT - The motivations

Parton model

Mainly used for inclusive cross-section calculations



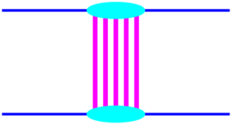
Deep Inelastic Scattering

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 :

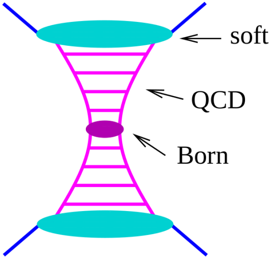
- energy conserved for particle production but NOT for cross-section calculations
- although multiple scattering approach, all interactions are not treated equally

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



Centrality bin width effect (CBWE)

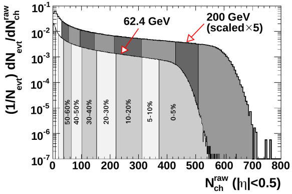
When plotting whatever moment $\sigma^{i,j}$ vs N_{part}, one induces trivial fluctuations due to the volume variation of the system : this is the CBWE.

In fact, for a certain centrality bin considered *(and even for a single N_{part} value)*, there will be volume variations in the collisions *($\leftrightarrow$ 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_{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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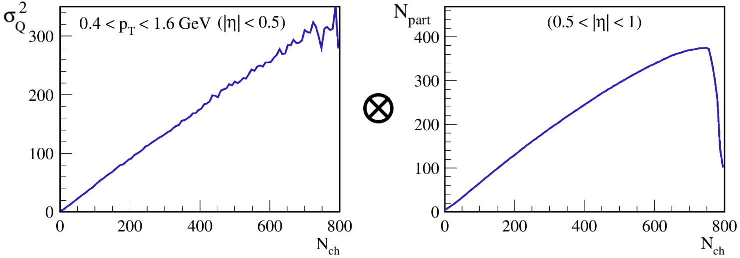
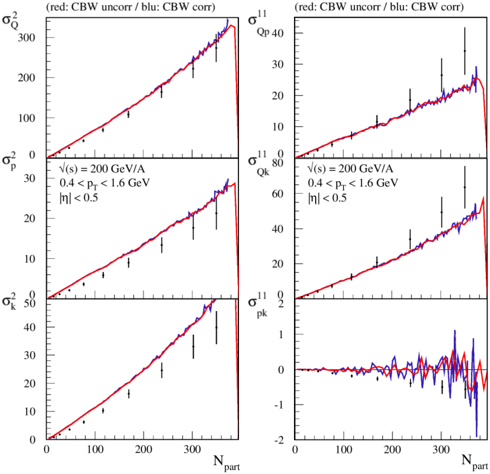
$\Rightarrow$ **Our method** (faster & easier) : calculate $\sigma^{11,2}_{p,Q,k}$ vs N_{ch}, and then convert $N_{ch} \rightarrow N_{part}$ from the $< N_{part} >$ vs N_{ch} distribution



Centrality bin-width correction

Firsts results from EPOS 4 *(June 2021)* compared with **STAR** data



$\Rightarrow$ As expected for $\sigma^{11,2}$ in Au+Au collisions @ 200GeV/A (see paper from Sahar *et al.* and more recent STAR paper), no difference w/wo CBW correction

Results from lattice QCD + Hadron Resonance Gas model

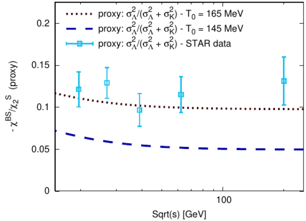
C. Ratti *et al.* :

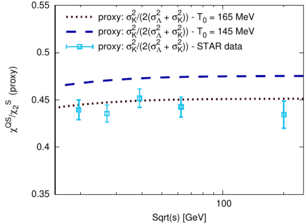
- breakdown of hadronic species contributions to susceptibilities, studied from lQCD + HRG model calculations *(gas of non-interacting hadrons and resonances in a box)*
  - ⇒ enhanced proxies for ratios (potentially more sensitive ones)
  - ⇒ results depending on $\sqrt{s}$ + kinematic cuts compared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

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

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

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





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