Formation of a Quark-Gluon-Plasma : understanding the energy and system size dependence

Sophys Gabriel

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Seminar Plenary at JINR - Dubna - 03 September

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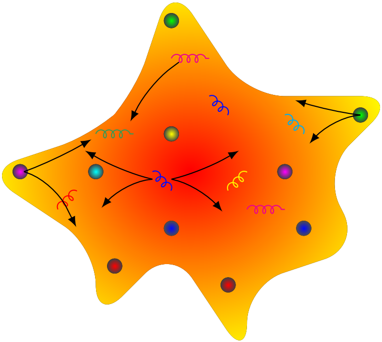
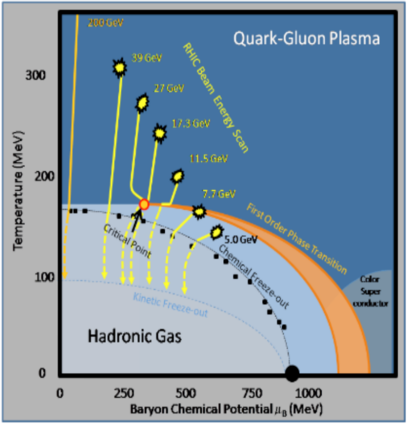
Context : QGP



- Quark-Gluon Plasma (QGP)
- **Partons are deconfined**
- QGP life-time : 10^{-21} s, size : 10^{-15} m ⇒ cannot study directly the QGP
- QGP formated in Heavy Ion collisions at accelerators
- Can we see an energy or system size dependence to create a QGP?

BES program: Dependence on Energy



STAR collaboration : arXiv:1007.2613

BES program

- At RHIC in Brookhaven National Laboratory
- Gold-Gold Collisions

Three Goals

- Find evidence of a phase transition ?
- Find critical point ?
- Evolution with $\sqrt{s_{NN}}$ of the medium ?

Small system: Dependence on system size

A new problematic of small system? A recent aspect of heavy ion physics

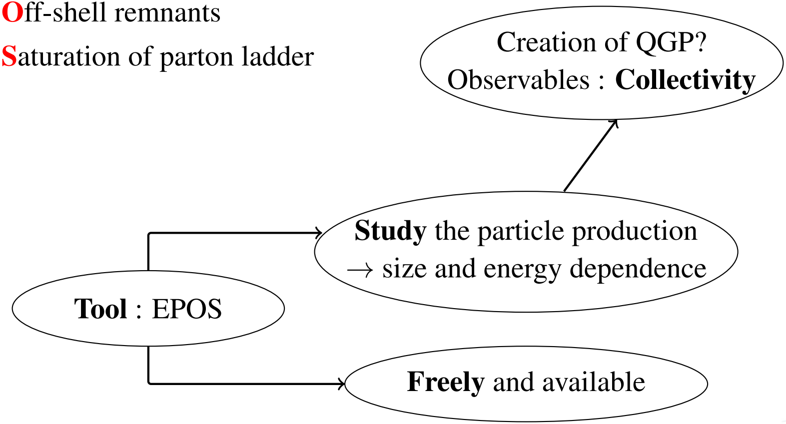
- The name "small systems" appeared at LHC Run I, it is now a **session at Quark Matter**
- A nonofficial translation could be ”*system a priori too small to show characteristics of heavy ion physics and however in which we observe them, at least some* ”. **Caveats** "*a priori too small*" is not defined ..
- ”A priori small” refers to system size: protons in initial stage with sometimes a **final state looking like a large system**, at least for charged particle multiplicity

pp/pA/AA at the same multiplicity have same behavior, role of geometry?
How is done the transition from small to large?

Introduction

Event generator : **EPOS**

- **E**nergy conserving quantum mechanical multiple scattering approach
- based on **P**artons, partons ladders, strings
- **O**ff-shell remnants
- **S**aturation of parton ladder



Creation of QGP?
Observables : **Collectivity**

Study the particle production
→ size and energy dependence

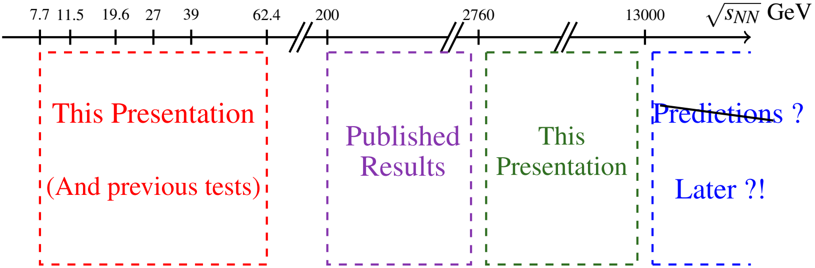
Tool : EPOS

Freely and available

Introduction

When do we use EPOS ?

Model for very high energy.



This Presentation

(And previous tests)

Published Results

This Presentation

~~Predictions~~ ?

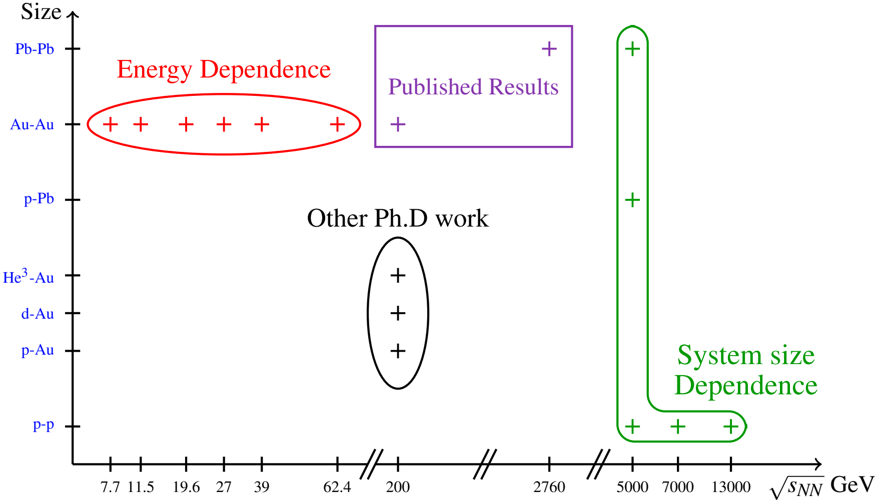
Later ?!

BES energies

LHC Run II

Do we really have a “collectively expanding plasma” in all systems, big (PbPb) and small (pp), at high energies and low energies?

Introduction



Contents

Event generator : EPOS

How do we construct one event ?

Universal Model for all collisions

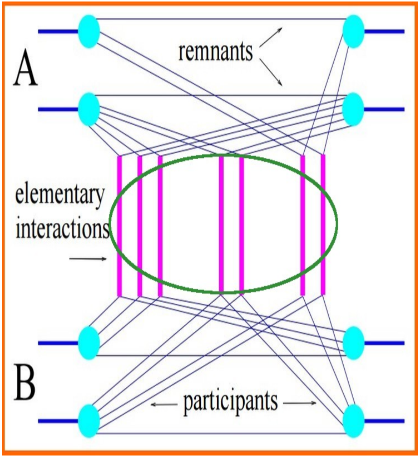
Same procedure applies, based on several stages :

1. Initial Conditions
2. Core-Corona Approach
3. Viscous hydrodynamic expansion
4. Statistical hadronization
5. Final state hadronic cascade

Event Generator : EPOS

Parton-Based-Gribov-Regge-Theory (PBGRT)

1. Initial Conditions
2. Core-Corona Approach



H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog and K. Werner, Phys. Rept. **350**, 93 (2001)

- Interaction between partons is : **Pomeron** : treated by Quantum Field Theory
- Energy conserved by partonic participants and remnants

Pomeron

Event Generator : EPOS

Parton-Based-Gribov-Regge-Theory (PBGRT)

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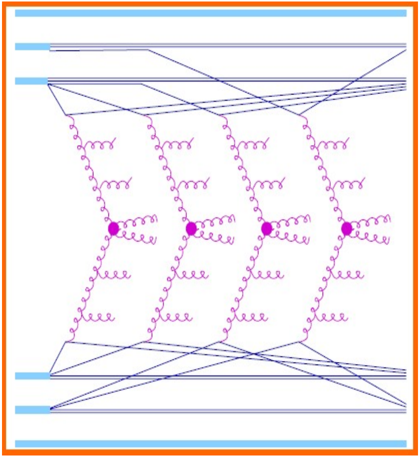

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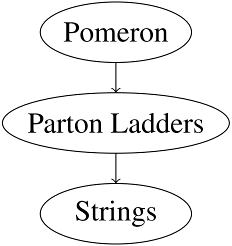


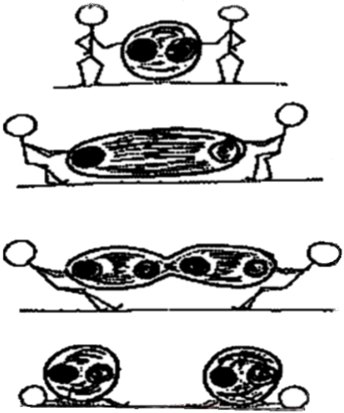
Pomeron

Parton Ladders

Strings

Strings ?

String Model : A phenomenological model of hadronization

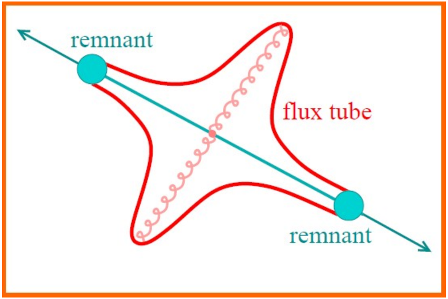


- String without mass and without color between two partons
- **Potential proportional to length**
- **When the potential is sufficient → one pair of quark-antiquark is created : Schwinger Mechanism**

Core-Corona Evolution

One Lund string for one scattering

Few scatterings → we *can* treat **independently** each string



GDRE2012, Nantes, Jul 2012, Klaus WERNER, Subatech, Nantes

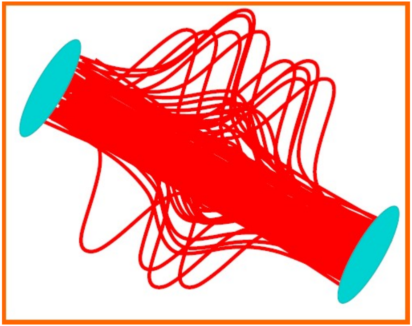
More scatterings ⇒

Core-Corona Evolution

One Lund string for one scattering

A lot of scatterings → we **cannot** treat *independently* each string

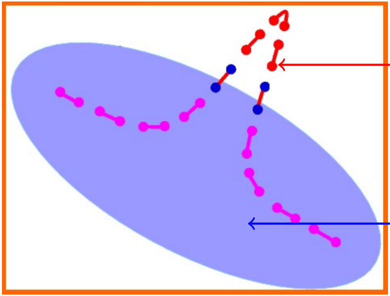
We can observe a different string densities



B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1

Core-Corona Evolution

High density : we use hydrodynamics → the Core is treated as fluid.
Low density : we do nothing → Corona becomes hadrons !



Corona : high p_t
classical evolution

Core : high density
Hydrodynamic evolution

B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1

Unified Approach

1. Initial Conditions
2. Core-Corona Approach
3. Hydrodynamical expansion

Core-Corona Approach

Using hydrodynamic → the **Core is treated as fluid**.

Corona becomes Jet ⇒ Later Hadrons !

Hydrodynamical expansion

Core evolves with respect to the equation of relativistic viscous hydrodynamics

Local energy momentum :

$$\partial_\mu T^{\mu\nu} = 0 \qquad \nu = 0, \cdots, 3$$

and the conservation of net charges,

$$\partial N_k^\mu = 0, \qquad k = B, S, Q$$

with B, S and Q reffering to baryon number, strangeness and electric charge

Unified Approach

1. Initial Conditions
2. Core-Corona Approach
3. Hydrodynamical expansion
4. Statistical Hadronization
5. Hadronic cascade

Statistical Hadronization

Core-Matter makes hadronization
Defined by a constant temperature T_H
Procedure of Cooper-Frye

K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, arXiv:1010.0400, Phys. Rev. C 83, 044915 (2011)

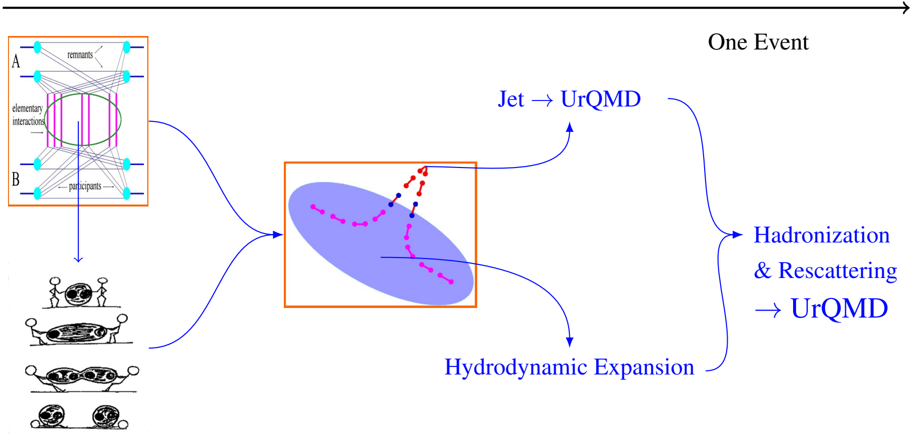
Hadronic Cascade

Hadron density still big → hadron-hadron rescatterings
Use **UrQMD Model**

M. Bleicher et al., J. Phys. G25 (1999) 1859

H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C78 (2008) 044901

Unified Approach



One Event

Jet → UrQMD

Hydrodynamic Expansion

Hadronization
& Rescattering
→ UrQMD

Contents

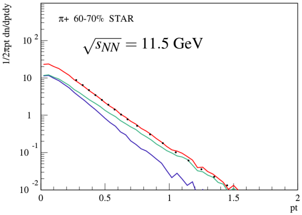
pt Spectra

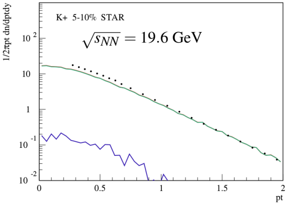
Au-Au collisions

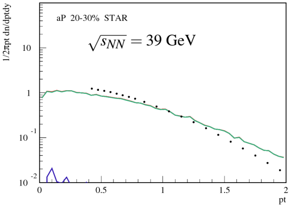
$$p_T = \sqrt{p_x^2 + p_y^2}$$

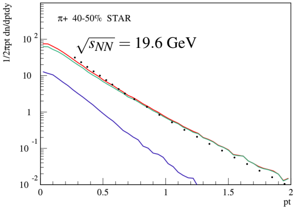
$\approx$ 1M events

🟥 Full
🟩 Core
🟦 Corona









- The slope is slightly different
- Big part of core (fluid) even at low energies!
- Not enough core at low p_T, and too much core at high p_T

Description of used observable

Anisotropic flow

A way of characterizing the various patterns of anisotropic flow is to use a Fourier expansion of the particle distribution function:

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi - \psi_{RP})\right]\right)$$

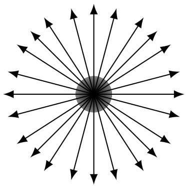
E: energy of the particle ; p: momentum ; pt: transverse momentum ; ϕ: azimuthal angle ; y: rapidity ; ψ_{RP}: reaction plane angle.

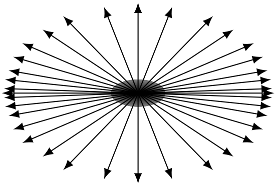
Anisotropic Flow : (n=1: Directed Flow , n=2: Elliptic Flow)

$$\boxed{v_n(pt,y) = \langle \cos\left[n\left(\phi(pt,y) - \psi_{RP}\right)\right]\rangle}$$

Anisotropic Flow

Anisotropy $\neq$ Isotropy





- Elementary Collisions: **Isotropy** of particle production

  $v_2 = 0$: Elliptic Flow

- A-A Collisions: **Anisotropy** of particles production

  $v_2 > 0$

- Something more than elementary processes
- Complex observable with different methods to calculate it

Event plane method

Eta-Sub : Event Plane Method

Event Flow vector (projection of azimuthal angle):

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) = Q_n \cos(n\Psi_n)$$
$$Q_{n,y} = \sum_i w_i \sin(n\phi_i) = Q_n \sin(n\Psi_n)$$

The sum goes over all particles i used in ***the event plane calculation***.
ϕ_i and w_i are the lab azimuthal angle and weight for particle i

Where Ψ_n is **the event plane angle**:

$$\Psi_n = \frac{1}{n} \tan^{-1}\left(\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right)$$

Anisotropic flow

Eta-Sub : Event Plane Method

$$v_n^{\text{obs}}(p_T, y) = \langle \cos[n(\phi_i - \Psi_n)] \rangle$$

Average over all particles in all events with their azimuthal angles ϕ_i in a given rapidity and p_T momentum space.

Anisotropic flow

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Average over all particles in all events with their azimuthal angles ϕ_i in a given rapidity and p_T momentum space.

The final flow coefficients are : $\boxed{v_n = \frac{v_n^{\text{obs}}}{\mathscr{R}_n}}$

Anisotropic flow

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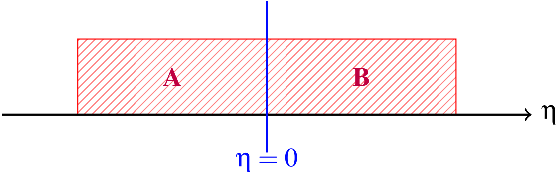
Eta-sub method : two planes defined by negative (A) and positive (B) pseudorapidity with ≈ equal multiplicity used to reduce nonflow effects:

$$\mathscr{R}_{n,sub} = \sqrt{\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$



Anisotropic flow

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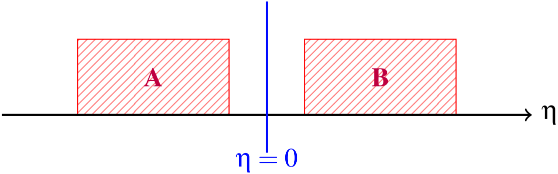

Anisotropic flow

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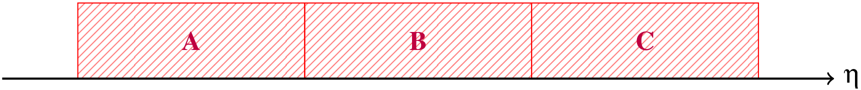
$$v_n^{\text{obs}}(p_T, y) = \langle \cos[n(\phi_i - \Psi_n)] \rangle$$

The final flow coefficients are : $\boxed{v_n = \dfrac{v_n^{\text{obs}}}{\mathscr{R}_n}}$

Three planes :

$$\mathscr{R}_n = \sqrt{\frac{\langle \cos[n(\Psi_n^A - \Psi_n^B))\rangle \times \langle \cos[n(\Psi_n^A - \Psi_n^C))\rangle}{\langle \cos[n(\Psi_n^B - \Psi_n^C))\rangle]}}$$



Anisotropic flow

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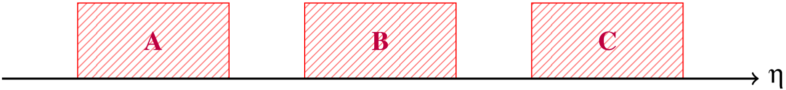


Results: Event plane

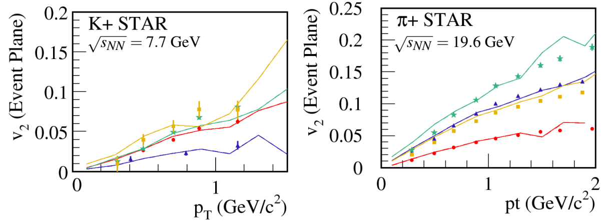
Au-Au collisions

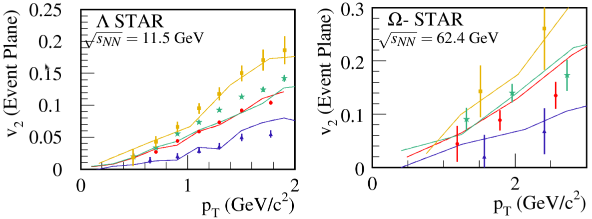
$$p_T = \sqrt{p_x^2 + p_y^2}$$

●	0-80%	▲	0-10 %
■	40-80 %	★	10-40 %

Mesons

$\approx$ 50K events



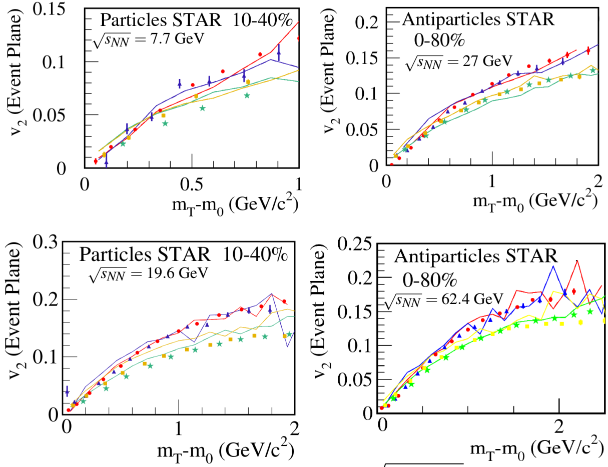


Baryons

- v_2 vs p_t reveals little anisotropy for all energies
- EPOS approximatively reproduces results for all energies for several centralities

Separation Baryons - Mesons

Au-Au collisions



● proton p (uud)
▲ lambda Λ (dus)
■ kaon K^+ (us)
★ pion π^+ (ud)

- Contributions [to v_2] from particles and antiparticles reproduced for different centrality regions

$$m_T - m_0 = \sqrt{p_T^2 + m_0^2} - m_0$$

$\approx$ 50K events

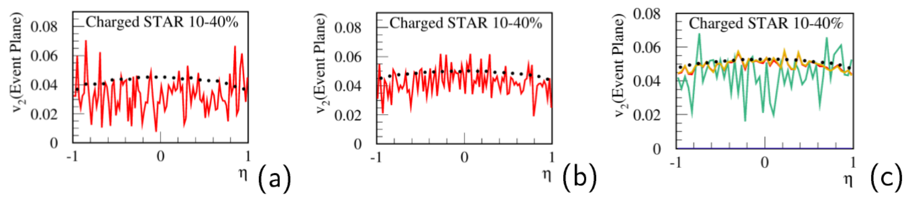
Results:Event Plane Method

Au-Au collisions

$$\eta = \frac{1}{2}\ln\left(\frac{p+p_z}{p-p_z}\right)$$

Full
Core
Corona

v_2 vs Pseudorapidity at EPOS 3.210



At energy collisions : $\sqrt{s_{NN}} = 7.7, 11, 39$ **GeV** with ≈ 30K events
Seems easier to reproduce experimental data when energy increases

STAR Collaboration (Adamczyck, L. et al.) Phys. Rev. C 86, 054908 (2012)

Cumulants Method

A. Bilandzic, R. Snellings, and S. Voloshin Phys. Rev. C 83, 044913 – Published 26 April 2011

Q-Cumulant → Recent Method to calculate cumulants → **one loop over data**
Faster and unbiased contrary to the previous cumulants method

Flow vector : $Q_n = \sum_{i=1}^{M} e^{in\phi_i}$ $\quad \langle 2 \rangle \equiv \langle e^{in(\phi_1 - \phi_2)} \rangle \quad \langle 4 \rangle \equiv \langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle$

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Procedure to create cumulants by direct calculations :

1. Decompose azimuthal correlations into expressions like $|Q_n|^2, |Q_n|^4$ ... in terms of $\langle 2 \rangle, \langle 4 \rangle$ ...
2. Solve system of coupled equations for multi-particle scattering in same harmonic $\langle 2 \rangle, \langle 4 \rangle$ ...
3. Create $\langle\langle 2 \rangle\rangle, \langle\langle 4 \rangle\rangle$, average on all events, taking in account weights of event
4. Create Cumulants with terms of $\langle\langle 2 \rangle\rangle, \langle\langle 4 \rangle\rangle$ etc ...

Ex :

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

Reduce the contribution of nonflow effects

Cumulants Method

A. Bilandzic, R. Snellings, and S. Voloshin Phys. Rev. C 83, 044913 – Published 26 April 2011

Cumulant coefficients

Cumulants for reference flow :

$$c_n\{2\} = \langle\langle 2\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\times\langle\langle 2\rangle\rangle^2$$

Reference flow or integrated flow :

$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

Reference Flow : v_2 vs multiplicity or vs centrality

Cumulants for differential flow :

$$d_n\{2\} = \langle\langle 2'\rangle\rangle$$
$$d_n\{4\} = \langle\langle 4'\rangle\rangle - 2\times\langle\langle 2'\rangle\rangle\langle\langle 2\rangle\rangle$$

Differential flow :

$$v'_n\{2\} = d_n\{2\}/\sqrt{c_n\{2\}}$$
$$v'_n\{4\} = -d_n\{4\}/(-c_n\{4\})^{3/4}$$

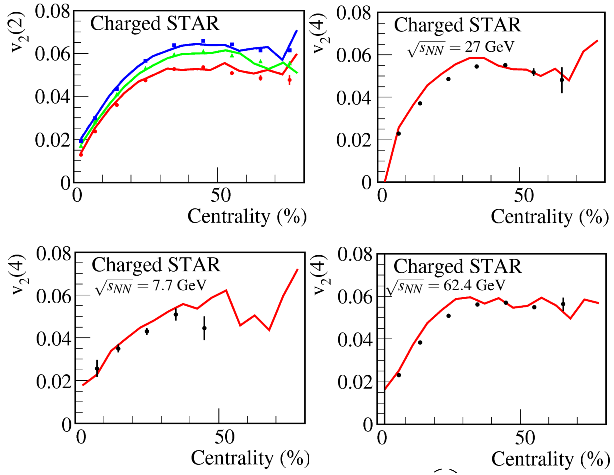
Differential Flow : v_2 vs p_t or vs η

Results Cumulants Method

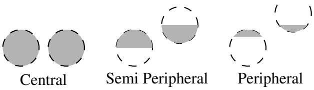
Au-Au collisions

$\approx$ 50K events

● $\sqrt{s_{NN}} = 7.7$ GeV
▲ $\sqrt{s_{NN}} = 19.6$ GeV
■ $\sqrt{s_{NN}} = 62.4$ GeV



- Good reproduction of results for cumulants methods for $v_2\{2\}$ and $v_2\{4\}$ for each energy



Energy Dependence

Conclusion

- Do not reproduce p_t spectra at low energies
- Core contributes stronger than corona at all energies
- Implementation of event plane and cumulant methods in EPOS
- Reproduce integrated and differencial flow for all energies
- No energy dependence see at BES energies
- Same behavior for all energies

Our scenario of an hydrodynamical expansion, based on initial conditions from our Gribov-Regge approach, is supported

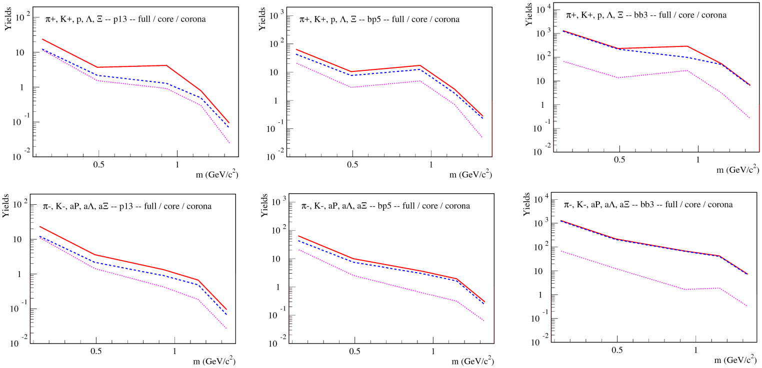
Contents

Yields

Theoretical test

How the fluid contributes for each type of collisions?

— Full
- - - Core
⋯ Corona



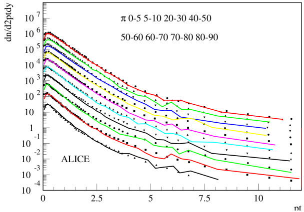
- same trend of full-core-corona contributions
- core part contributes stronger than corona part
- core part stronger for big system sizes

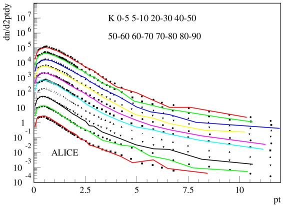
pt spectra

Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

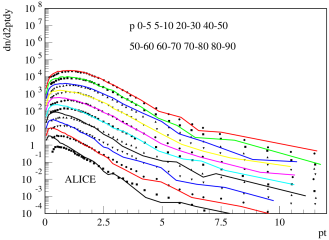
$$p_T = \sqrt{p_x^2 + p_y^2}$$

$\approx$ 250K events





- Good reproduction for each multiplicity class

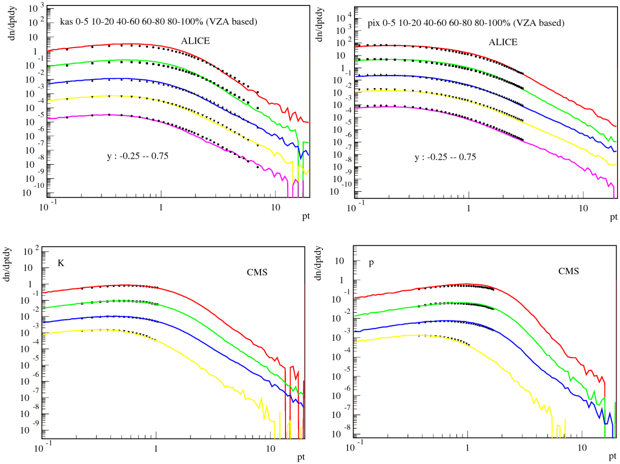


Spectra

p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$\approx$ 500K events



- EPOS approximatively reproduces results for distributions in p_T

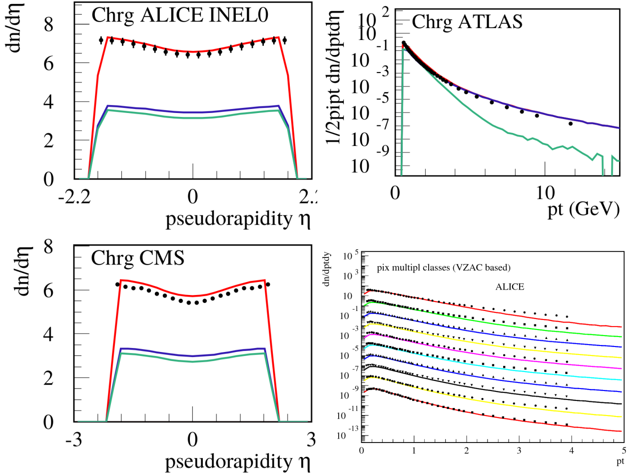
Spectra

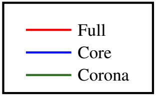
pp collisions at $\sqrt{s_{NN}} = 13$ TeV

$$p_T = \sqrt{p_x^2 + p_y^2}$$

≈ 1M events

$$\eta = \frac{1}{2} \ln\left(\frac{|p|+p_z}{|p|-p_z}\right)$$



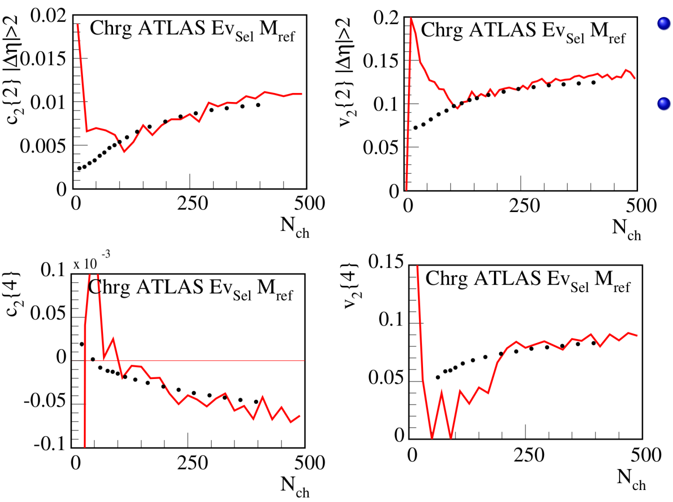


- EPOS approximatively reproduces results for distributions in p_T or η

Anisotropic flow: cumulant

≈ 240K events

Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

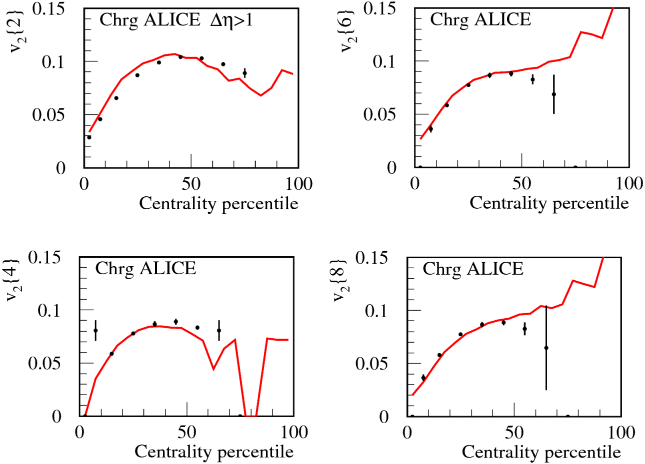


- No reproduction at low multiplicity
- Reproduction at high multiplicity (or central collisions)

Anisotropic flow: cumulant

Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

$\approx$ 240K events

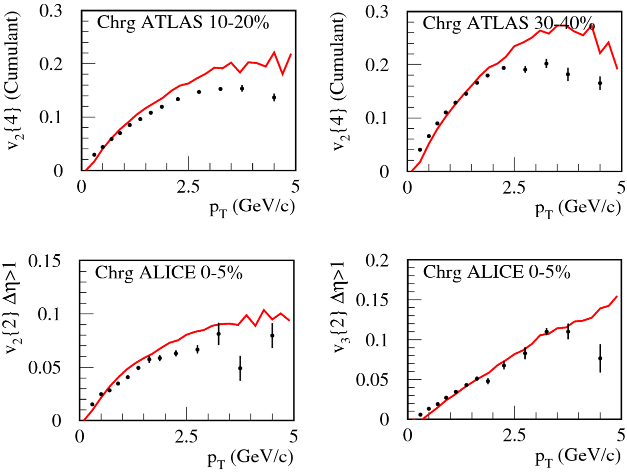


- No reproduction at low multiplicity
- Reproduction at high multiplicity (or central collisions)
- Same conclusion than v_n vs multiplicity

Anisotropic flow: cumulant

$\approx$ 240K events

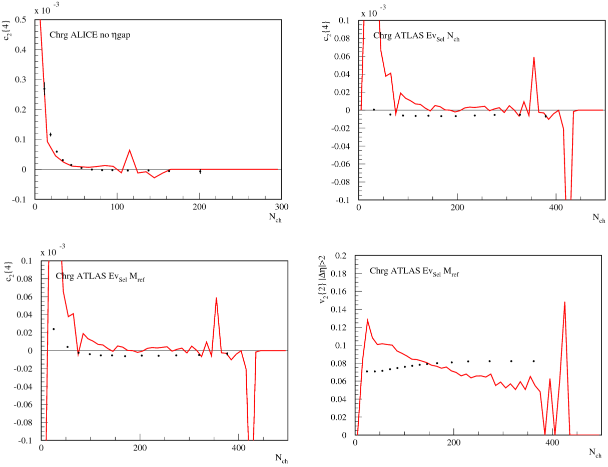
Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV



- Reproduction at high multiplicity (or central collisions)
- Seems difficult to reproduce data at high p_t: hydro model
- Same conclusion than v_n vs mult

Anisotropic flow: cumulant

p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



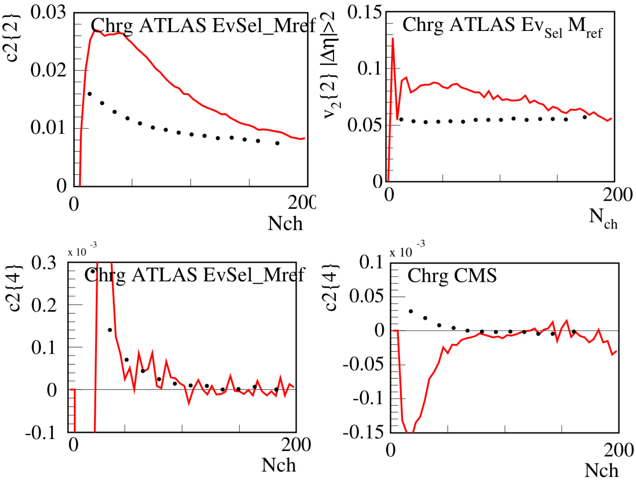
≈ 500K events

- almost agreement at high multiplicity but do not reproduce anisotropic observables
- $c_2\{4\}$ seems higher than 0, collectivity not related to the fluid?!!?

Anisotropic flow: cumulant

pp collisions at $\sqrt{s_{NN}} = 13$ TeV

$\approx$ 1M events



- at high multiplicity, EPOS seems more adapted to reproduce data
- But we do not reproduce anisotropic observables

Conclusion

- **EPOS part**

Use EPOS at different energy ranges to moving forward its release
Implementation of **event plane** and the **cumulant** methods with or without pseudorapidity gap.

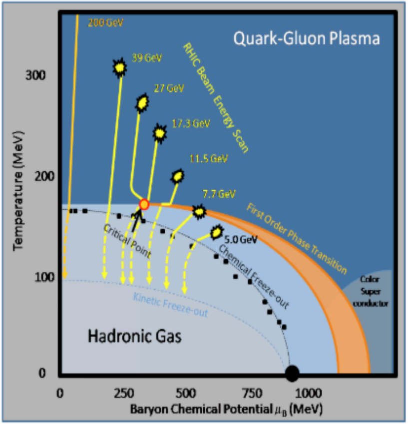
- **Energy dependence**

Good data reproduction for anisotropic observables: **a collectively expanding plasma** seems exist at these energies.
No Good data reproduction for pt spectra, first time that we use EPOS at these energies, *work in progress*.

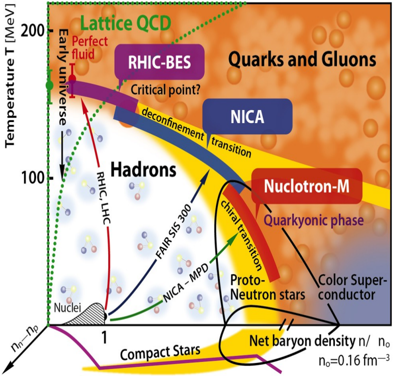
- **System Size dependence**

Confirmation of the utilisation of EPOS for high multiplicity **Pb-Pb** collisions.
Good reproduction of spectra observables for each system size with high core contribution but not for anisotropic observables.
Work on *size of initial* fluid to solve the problem of anisotropy for pp collisions

BES and NICA program



STAR collaboration: arXiv:1007.2613



http://nica.jinr.ru/physics.php

Both programs study physics at $\mu \neq 0$:

- anisotropic flow
- strange particles production
- yield & spectra ..

Try to work on Nica energies?

Thank you for your attention !

Core Corona separation

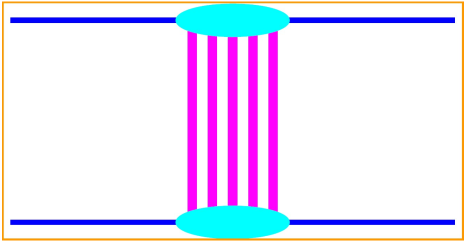
The core corona separation start by the identification of string fragments in core or corona depending of critical density ρ_0. However, some string fragments of bulk matter can escape the plasma depending of their transverse momenta. To know exaclty which fragments escape, we compute:

$$p^t_{new} = p_t - f_{Eloss} \int_\gamma \rho \, dL \tag{1}$$

where γ is the trajectory of the segment and f_{Eloss} a model parameter using some interpolation. The p_t^{new} can be positive or negative, if the new p_t is positive, the string fragments can escape the bulk matter and can be identify as a corona fragment. In the other case ($p^t_{new} < 0$), the segment cannot escape the plasma, therefore it contributes to the core.

Gribov-Regge Theory and Pomeron

Effective Field Theory
Elementary interaction → Pomeron exchange
Pomeron : Quantum numbers of vacuum
Vladimir Gribov in ≈ 1960



Elastic Amplitude : $T(s,t) \approx i s^{\alpha_0 + \alpha' t}$

Collectivity in small system ?

What is collectivity ? ⇒ A lot of definitions !

My definition : **multiple particles are correlated across rapidity or pseudorapidity due to a common origin**.

Why do we care? : learn about : medium (transport), initial state (saturation), and microscopic processes (MPI,strings, parton ladders ...)

We want to find collectivity by measure of multiparticles correlations :

$$\underbrace{\begin{array}{llll} v_2\{2\} & \leqslant v_2\{4\} & \approx v_2\{6\} & \approx v_2\{8\} \\ c_2\{2\} > 0 & , c_2\{4\} < 0 & , c_2\{6\} > 0 & , c_2\{8\} < 0 \end{array}}_{\text{measure in small system ?}}$$

- Learn about the medium (transport)
- Learn about the initial state (saturation)
- Small and dilute system: chance to learn about microscopic processes (MPI, strings, parton ladders ...)

Elliptic Flow

Differential Flow

Definitions of vectors p and q :

For particles labeled as POI :

$$p_n \equiv \sum_{i=1}^{m_p} e^{in\Psi_i}$$

For particles labeled as **both** POI and REP :

$$q_n \equiv \sum_{i=1}^{m_q} e^{in\Psi_i}$$

Average of two- and four-particles azimuthal correlations :

$$\langle 2' \rangle = \frac{\mathscr{R}\left[p_n Q_n^*\right] - m_q}{m_p M - m_q} \qquad \langle 4' \rangle \propto \mathscr{R}\left[p_n Q_n Q_n^* Q_n^*\right] + \mathscr{R}\left[q_n Q_n^*\right] \ldots$$

Hydrodynamic equations

Based on the four-momenta of string segments, we compute the energy momentum tensor and the flavor flow vector at some position x (at $\tau = \tau_0$) as :

$$T^{\mu\nu} = \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i)$$

$$N_q^\mu(x) = \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i g(x - x_i)$$

where q = u,d,s

arXiv:1312.1233v1 [nucl-th] 4 Dec 2013

Elliptic Flow

Event Weight

Event Average :

$$\langle\langle 2\rangle\rangle = \frac{\sum\limits_{events} (W_{\langle 2\rangle})_i \langle 2\rangle_i}{\sum\limits_{events} (W_{\langle 2\rangle})_i} \qquad \langle\langle 4\rangle\rangle = \frac{\sum\limits_{events} (W_{\langle 4\rangle})_i \langle 4\rangle_i}{\sum\limits_{events} (W_{\langle 4\rangle})_i}$$

$$\langle\langle 2'\rangle\rangle = \frac{\sum\limits_{events} (w_{\langle 2'\rangle})_i \langle 2'\rangle_i}{\sum\limits_{events} (w_{\langle 2'\rangle})_i} \qquad \langle\langle 4'\rangle\rangle = \frac{\sum\limits_{events} (w_{\langle 4'\rangle})_i \langle 4'\rangle_i}{\sum\limits_{events} (w_{\langle 4'\rangle})_i}$$

Definition of weights :

$$W_2 = M(M-1) \qquad W_4 = M(M-1)(M-2)(M-3)$$

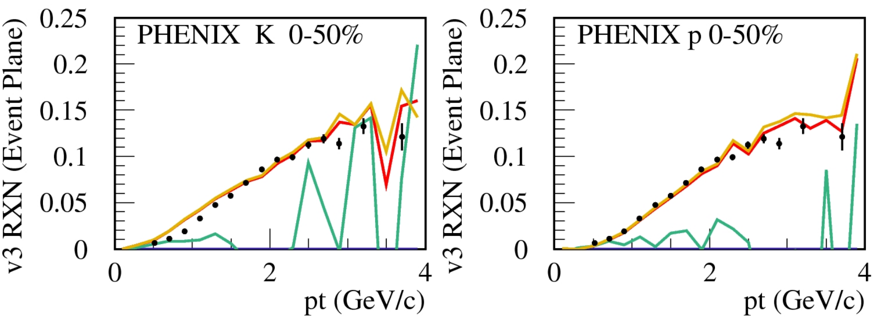
$$w_{2'} = m_p M - m_q \qquad w_{4'} = (m_p M - 3m_q)(M-1)(M-2)$$

Results

Event Plane Method

$$p_t = \sqrt{p_x^2 + p_y^2}$$

v_3 vs p_t at EPOS 3.210



At energy collisions : $\sqrt{s_{NN}} = 200$ **GeV** with 287300 events

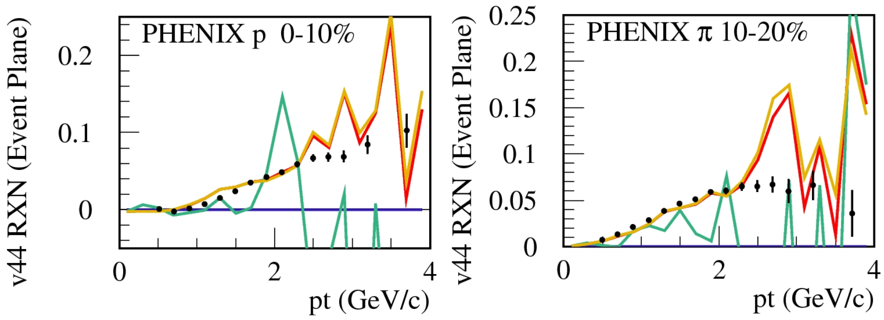
PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 93, 051902 – 2016

Results

Event Plane Method

$$p_t = \sqrt{p_x^2 + p_y^2}$$

v_4 vs p_t at EPOS 3.210



At energy collisions $\sqrt{s_{NN}} = 200$ **GeV** with 287300 events

PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 93, 051902 – 2016