Study of the energy and system size dependence of particle production in high energy collisions

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Rencontre QGP France, Etretat : 09 -12 October

Ph.D in Theory Group at Subatech

Introduction

Event generator : **EPOS**

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

Observables : **Collectivity**

Study the particle production
$\rightarrow$ size and energy dependence

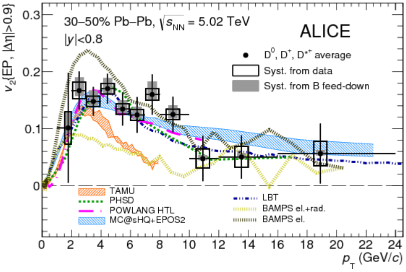
Tool : EPOS

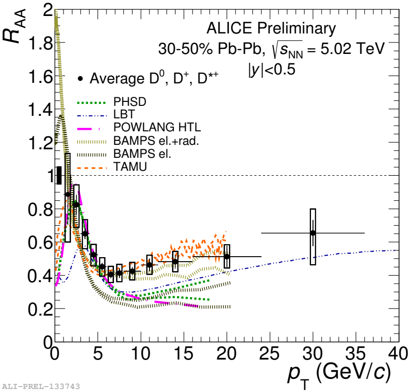
Freely and available

Introduction

Results on collectivity from models

Good agreements with experimental data for heavy quarks



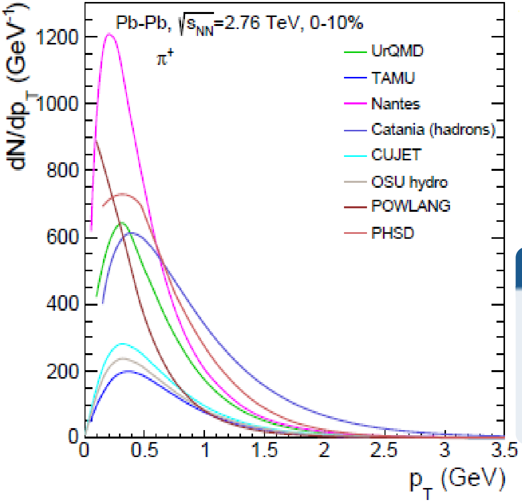


ALICE collaboration : arXiv:1707.01005

EPOS works !!

Introduction

Results on collectivity from models



EPOS works ?

But ! For light quarks :

- distributions at little p_t: no consensus between models

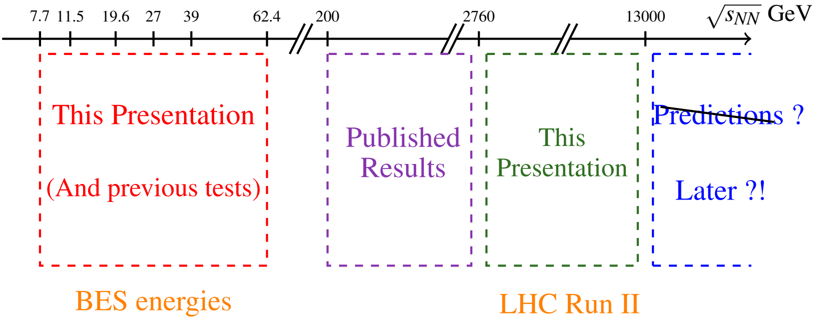
My contribution to EPOS

Investigation with EPOS for light quarks in a wide range of energy and corrected if necessary

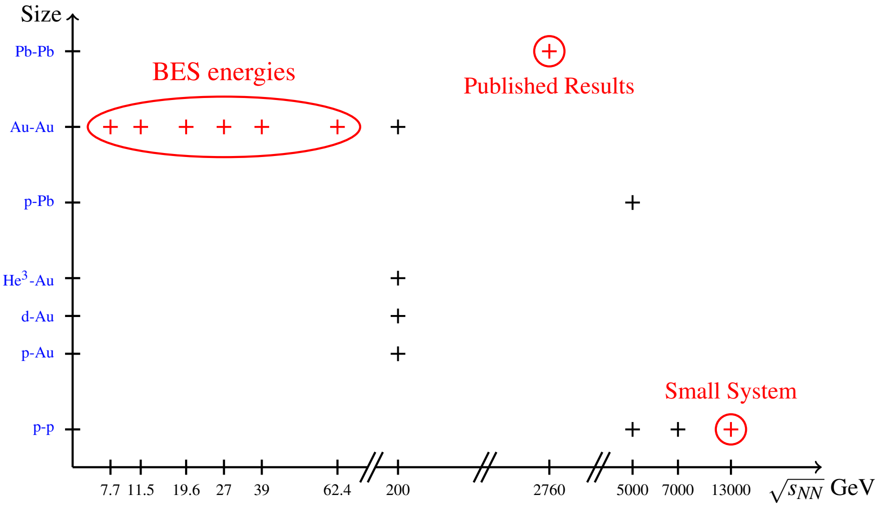
Introduction

When do we use EPOS ?

Model for very high energy.



Introduction



Contents

Event generator : EPOS

How do we construct one event ?

Universal Model for all collisions

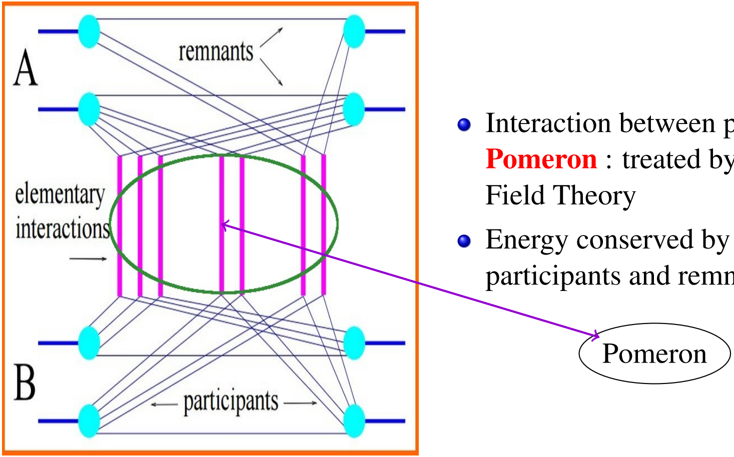
Same procedure applies, based on several stages :

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

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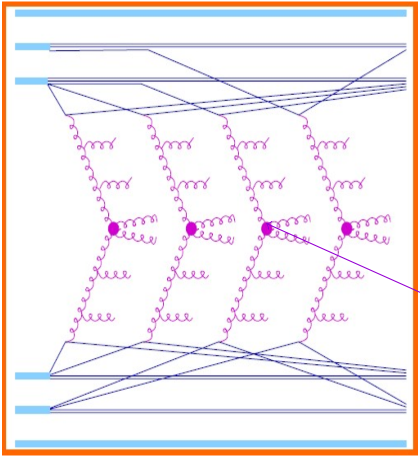

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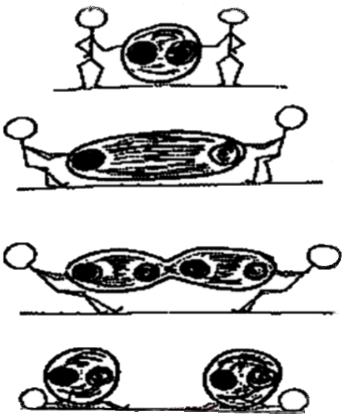
- Interaction between partons is : **Pomeron** : treated by Quantum Field Theory
- Energy conserved by partonic participants and remnants

Pomeron
↓
Parton Ladders
↓
Strings

1 Initial Conditions
2 Core-Corona Approach

Strings ?

Lund Model : A phenomenological model of hadronization

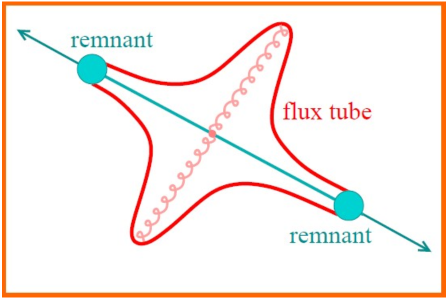


- String without mass and without color between two partons
- **Potential proportional to length**
- **When the potential is sufficient $\rightarrow$ one pair of quark-antiquark is created : Schwinger Mechanism**

Core-Corona Evolution

One Lund string for one scattering

Few scatterings $\rightarrow$ we *can* treat **independently** each string



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

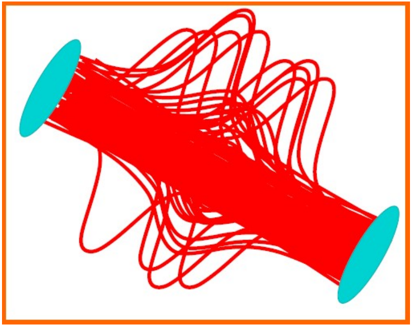
More scatterings $\Rightarrow$

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

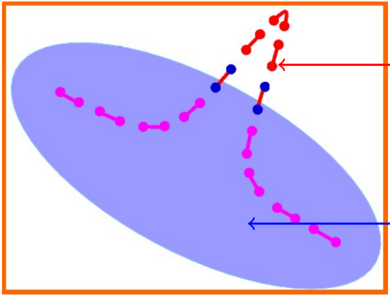


B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1

Core-Corona Evolution

1. Initial Conditions
2. Core-Corona Approach

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



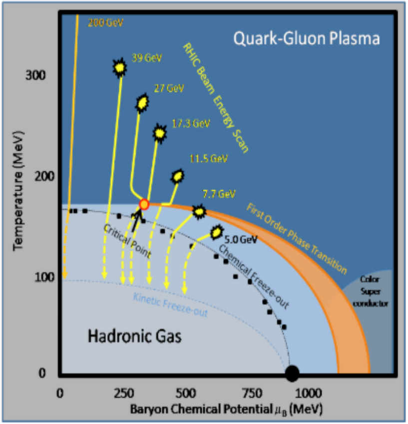
Corona : high p_t
classical evolution

Core : high density
Hydrodynamic evolution

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

Contents

BES program



STAR collaboration : arXiv:1007.2613

BES program

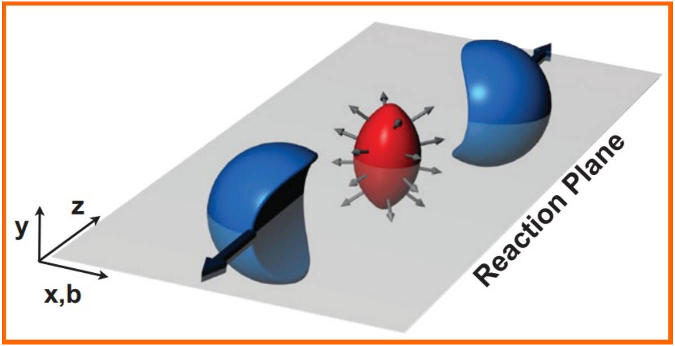
- At RHIC in Brookhaven National Laboratory
- Gold-Gold Collisions

Three Goals

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

Anisotropic Flow

Direct evidence of flow : anisotropy in particle momentum distributions correlated with the reaction plane.



R. Snellings, New J. Phys. **13** (2011) 055008

Anisotropic Flow

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

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

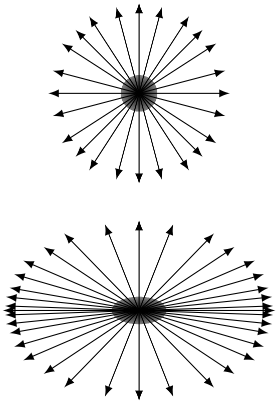
E : energy of the particle ; p : momentum ; pt : transverse momentum ; ϕ : azimuthal angle ; y : rapidity ; ψ_{RP} : reaction plane angle.

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

Elliptic Flow

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** :

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

Elliptic 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.

Elliptic Flow

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

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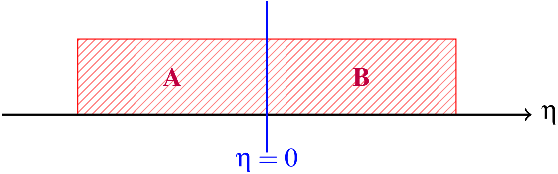
Eta-sub method : two planes defined by negative (A) and positive (B) pseudorapidity with ≈ equal multiplicity :

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



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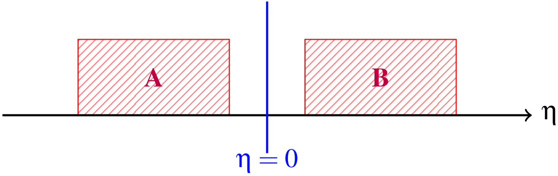

Elliptic Flow

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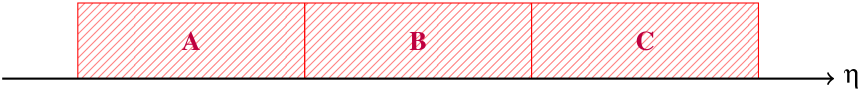
Three planes :

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



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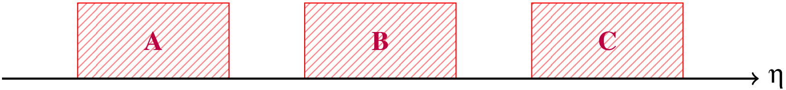


Results

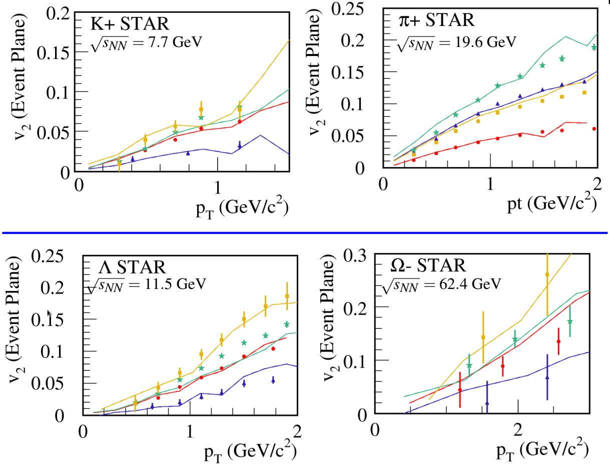
Au-Au collisions

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

$\approx$ 1M events

- 0-80%
- 0-10 %
- 40-80 %
- 10-40 %

Mesons

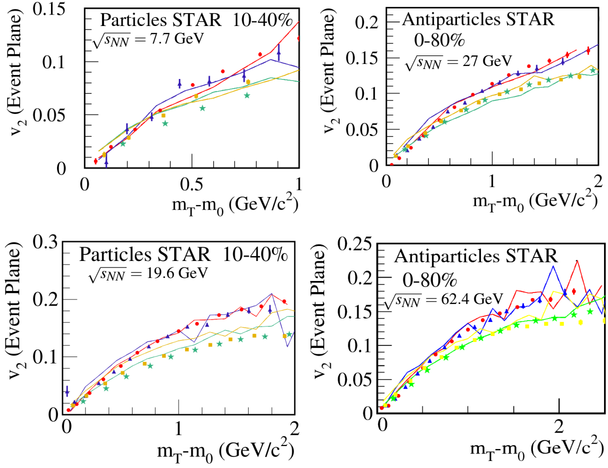


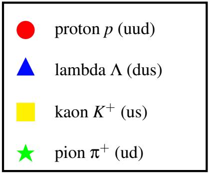
Baryons

- v_2 vs p_t reveals little anisotropy for each energy
- EPOS approximatively reproduces results for each energy for several centralities
- Curious because no work on EoS and size of initial fluid

Separation Baryons - Mesons

Au-Au collisions





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

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

⚠ Without modifications on EoS and size of initial fluid

$\approx$ 1M events

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

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 :

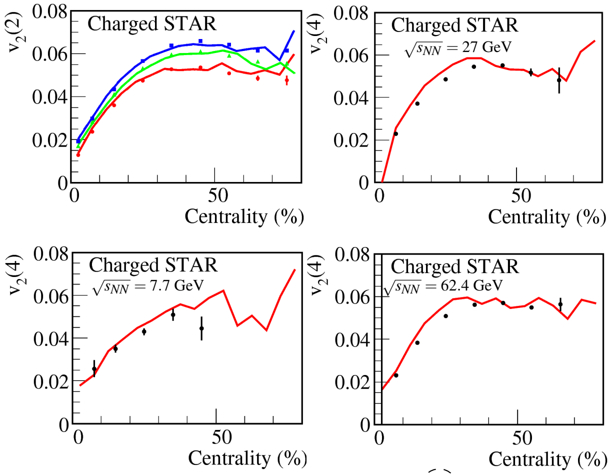
$$v'_n\{2\} = d_n\{2\}/\sqrt{c_n\{2\}}$$
$$v'_n\{4\} = -d_n\{4\}/(-c_n\{4\})^{3/4}$$

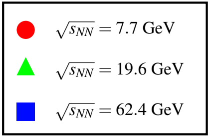
Differential Flow : v_2 vs p_t or vs η

Results

Au-Au collisions

$\approx$ 1M events





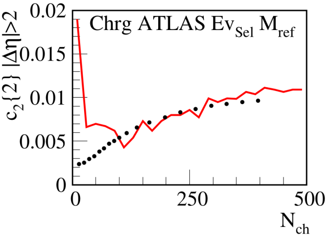
- Good reproduction of results for cumulants methods for $v_2\{2\}$ and $v_2\{4\}$ for each energy
- Little above data for $v_2\{4\}$ but must be corrected with corrections of EoS and size of initial system

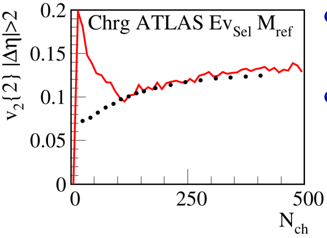
Contents

LHC energy

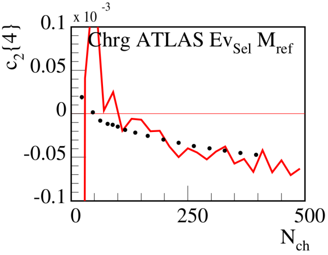
Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

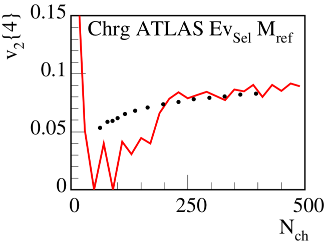
$\approx$ 240K events





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



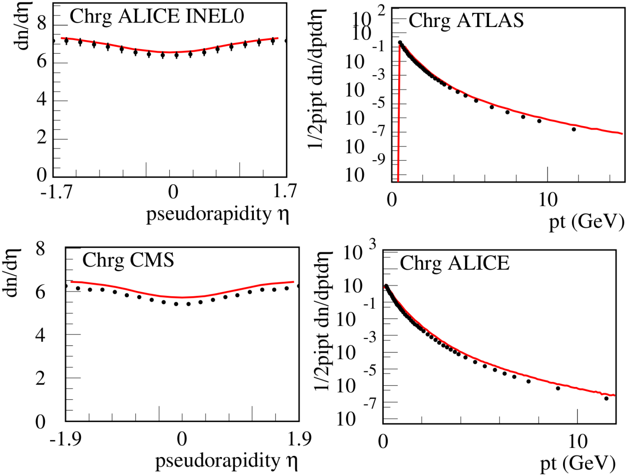


LHC energy

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

$$p_T = \sqrt{p_x^2 + p_y^2} \qquad \approx 1\text{M events}$$

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

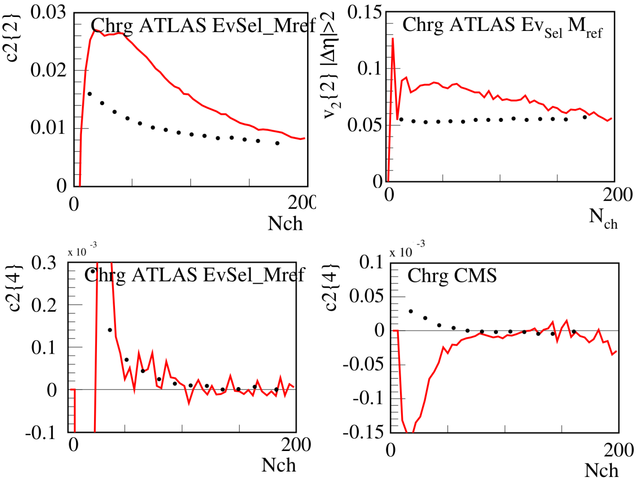


- EPOS approximatively reproduces results for distributions in p_T or η

LHC energy

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

$\approx$ 1M events



- But we do not reproduce anisotropic observables

Conclusion

- **EPOS part**

Implementation of **event plane** and the **cumulant** methods with or without pseudorapidity gap.

- **BES part**

First work with EPOS on BES energies

Good results but this is strange because we use the *LHC model* for RHIC energies. Need to investigate **EoS** and **initial density** of fluid $\Rightarrow$ planned on November with Yuriy Karpenko.

- **LHC part**

Confirmation of the utilisation of EPOS for **Pb-Pb** collisions and for **elementary** observables for **pp** collisions. Need work on the **size of initial** fluid to solve the problem of anisotropy for pp collisions

Thank you for your attention !

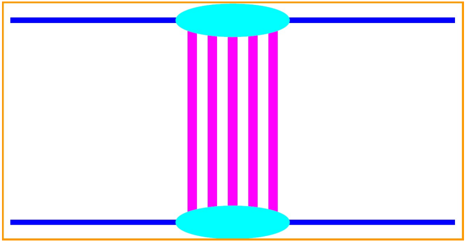
Gribov-Regge Theory and Pomeron

Effective Field Theory

Elementary interaction $\rightarrow$ 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 ...)

Unified Approach

Core-Corona Approach

Using hydrodynamic $\rightarrow$ the **Core is treated as fluid**.

Corona becomes Jet $\Rightarrow$ 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

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

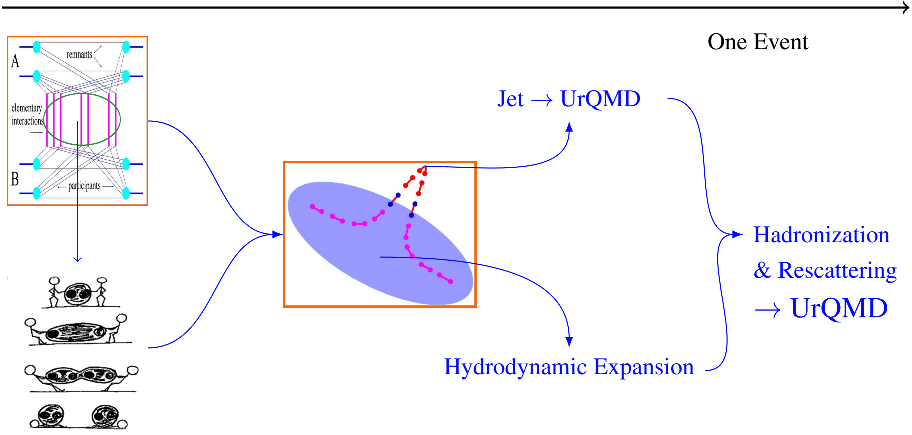
Hadron density still big $\rightarrow$ hadron-hadron rescatterings

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



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 :

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

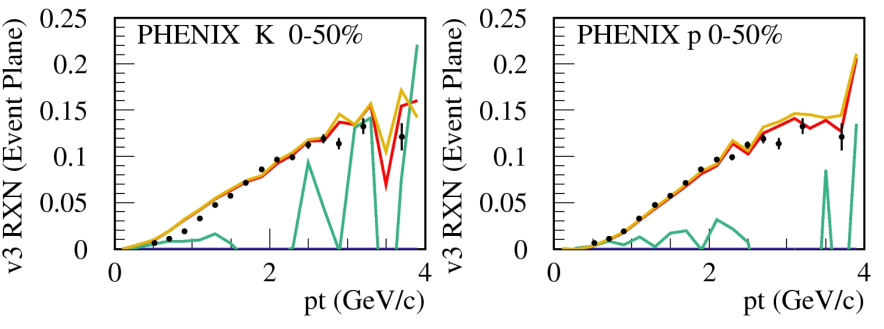
$$w_{2'} = m_p M - m_q \qquad w_{4'} = (m_p M - 3m_q)(M-1)(M-2)$$

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

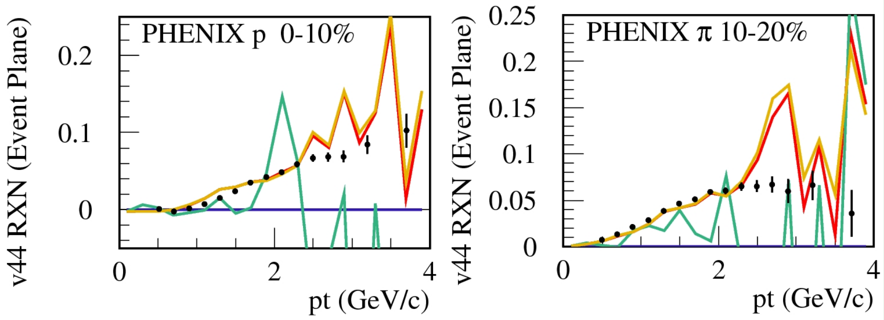
PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 93, 051902 – 2016

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

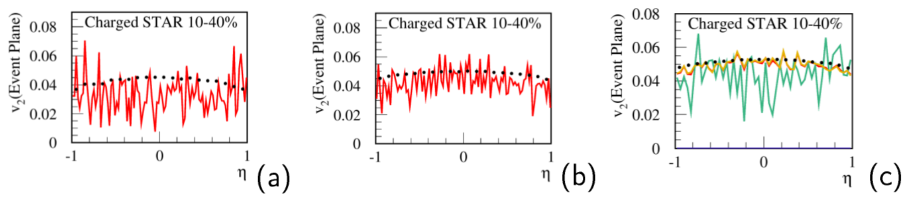
PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 93, 051902 – 2016

Results

Event Plane Method

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

v_2 vs Pseudorapidity at EPOS 3.210



At energy collisions : $\sqrt{s_{NN}} = 7.7, 11, 39$ **GeV** with $\approx$ 30K events

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