Results about elliptic flow with a unified approach at RHIC energies

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XIX GDRE WORKSHOP

Heavy Ions at Relativistic Energies - July 2017

Introduction

Unified Approach : **EPOS**

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

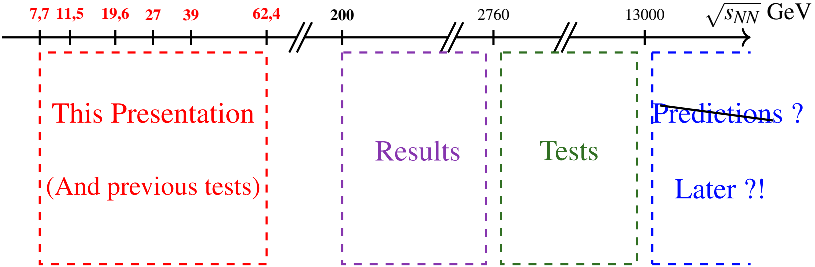
At the end of Ph D $\rightarrow$ open-diffusion of EPOS ?

Unified Approach

When do we use EPOS ?

Monte Carlo Method

Model for very high energy.



RHIC energies

Unified Approach

How we construct one event ?

Universal Model for all collisions

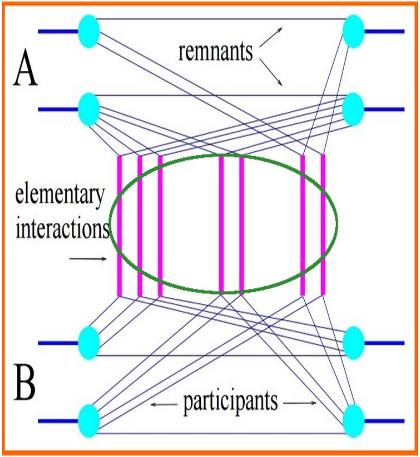
Same procedure applies, based on several stages :

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

Unified Approach

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

- Initial Conditions
- Core-Corona Approach
- Viscous hydrodynamic expansion
- Statistical hadronization
- Final state hadronic cascade



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

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

Unified Approach

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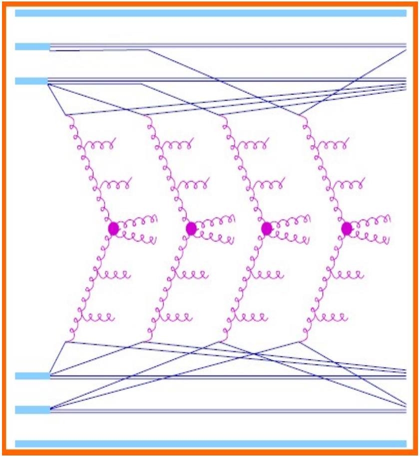

- Interaction between partons are : **Pomeron** : treated by Quantum Field Theory
- Energy conserved by participants and remnants partons
- Pomerons become Partons Ladders
- Partons Ladders become Strings

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

Unified Approach

Lund Model : A phenomenological model of hadronization

- Initial Conditions
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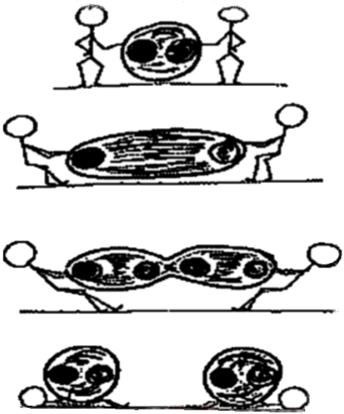

- String without mass and without color between two partons
- **Potential proportional to length**
- **When the potential is sufficient → one pair of quark-antiquark is created : Schwinger Mechanism**
- Use also at PYTHIA/JETSET

Unified Approach

- Initial Conditions
- Core-Corona Approach
- Viscous hydrodynamic expansion
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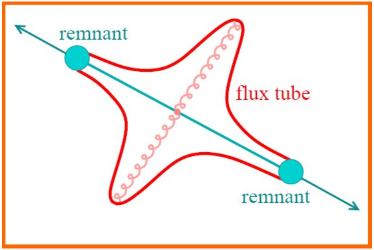
- Final state hadronic cascade

Core-Corona Approach

Using hydrodynamic → the Core is treated as fluid.

Corona becomes Jet ⇒ Later Hadrons !



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

More Scattering ⇒

Unified Approach

- Initial Conditions
- Core-Corona Approach
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Core-Corona Approach

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

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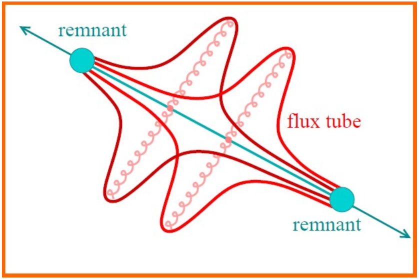

GDRE2012, Nantes, Jul 2012, Klaus WERNER, Subatech, Nantes

More Scattering $\Rightarrow$

Unified Approach

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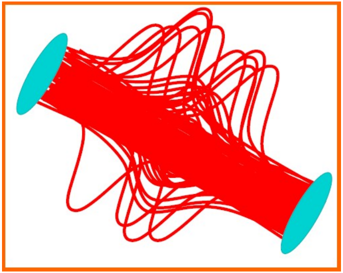

B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1

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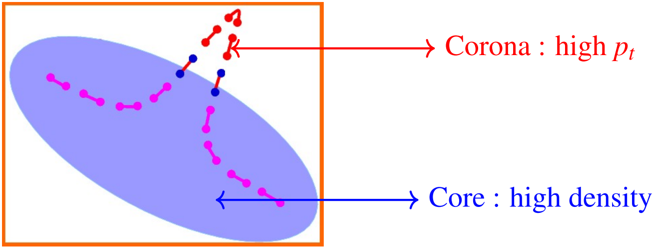

B. Guiot and K. Werner, J. Phys. Conf. Ser. **589** (2015) no.1

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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

- Initial Conditions
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- Final state 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

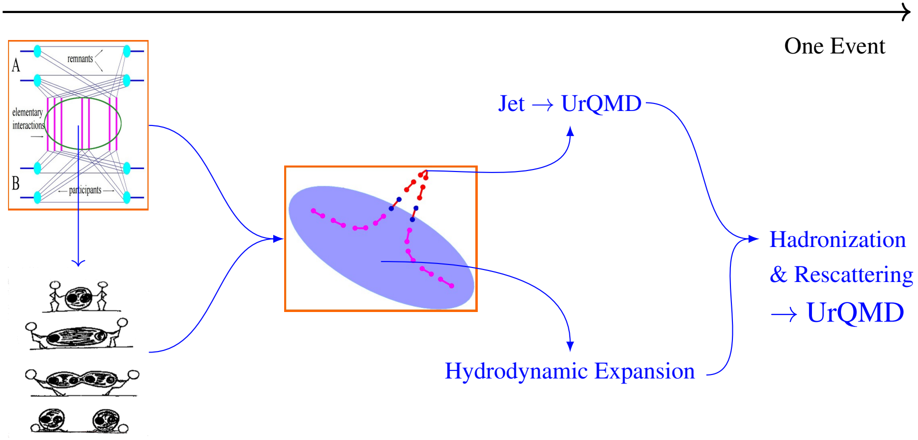
Hadron density still big $\rightarrow$ hadron-hadron rescatterings

Use **UrQMD Model**

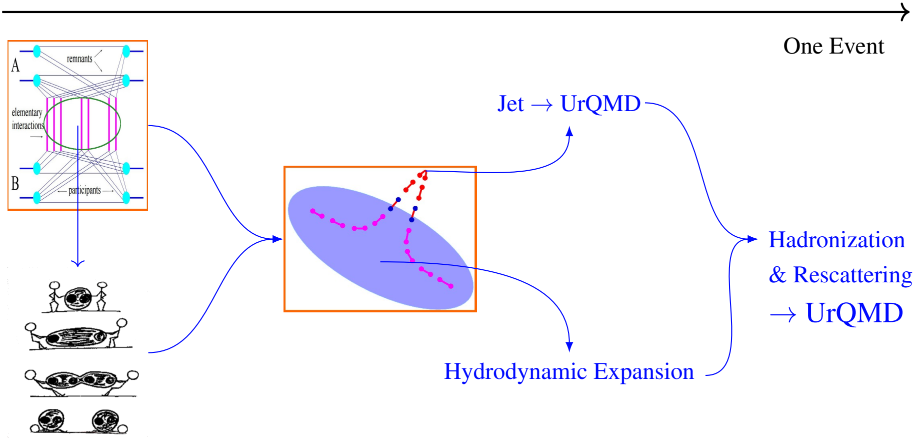
M. Bleicher et al., J. Phys. G25 (1999) 1859

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

Unified Approach



Unified Approach



Let's stop talking about EPOS now

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

Where Ψ_n **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 angle ϕ_i in a given rapidity and p_T momentum space.

Elliptic Flow

Eta-Sub : Event Plane Method

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

Elliptic Flow

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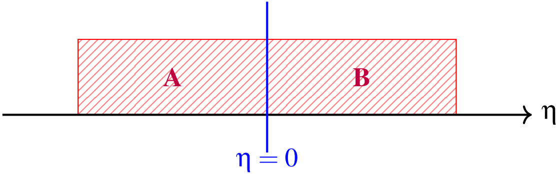
Eta-sub method : two planes defined by negative (A) and positive (B) pseudorapidity with ≈ equal multiplicity :

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



Elliptic Flow

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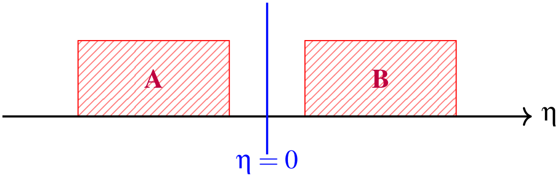


Elliptic Flow

Eta-Sub : Event Plane Method

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

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

Three planes :

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

Elliptic Flow

Eta-Sub : Event Plane Method

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

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

Three planes :

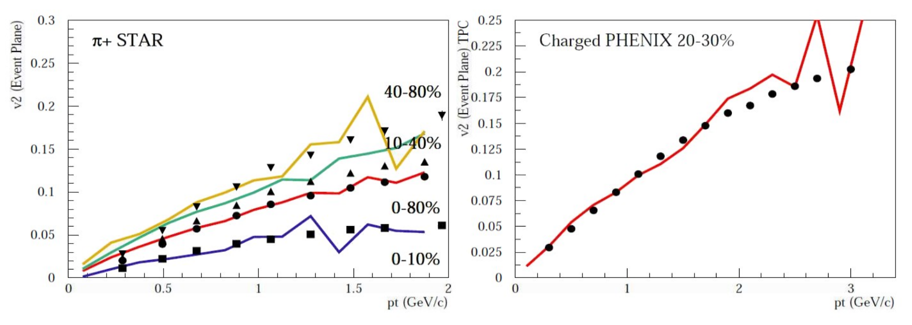
$$\mathscr{R}_n = \sqrt{\frac{\langle \cos[n(\Psi_n^A - \Psi_n^B)) \rangle \times \langle \cos[n(\Psi_n^A - \Psi_n^C)) \rangle}{\langle \cos[n(\Psi_n^B - \Psi_n^C)) \rangle]}}$$

Results

Event Plane Method

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

v_2 vs Transverse Momentum at EPOS 3.210



At energy collisions : $\sqrt{s_{NN}} = 19.6$ **GeV** with $\approx 120\,000$ events

STAR Collaboration (Adamczyck, L. et al.) Phys. Rev. C 88, 014902 (2013) and Phys. Rev. C 93, 014907 (2016)

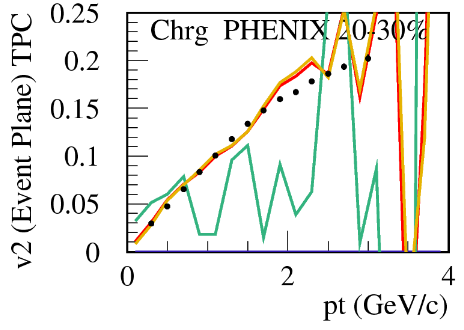
PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 86, 054908 – 2016

Results

Contribution of Core-Corona

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

v_2 vs Transverse Momentum at EPOS 3.210



Red - Full

Orange - Core

Green - Corona

At energy collisions : $\sqrt{s_{NN}} = 19.6$ **GeV** with $\approx 120\,000$ events

PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 86, 054908 – 2016

Results

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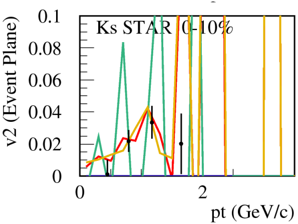

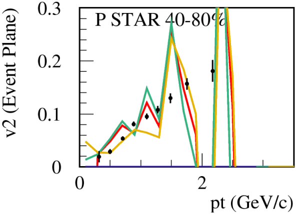

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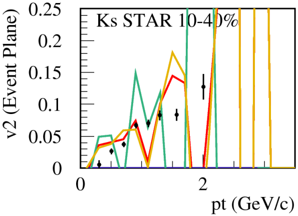
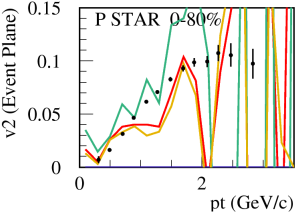




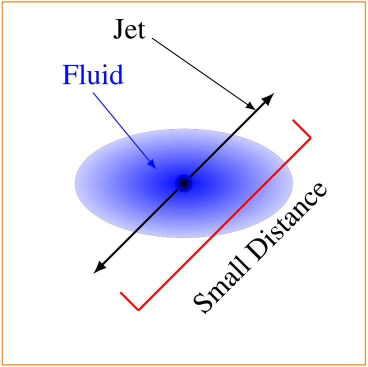
At energy collisions : $\sqrt{s_{NN}} = 7.7$ **GeV** with $\approx$ 30 000 events

PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 86, 054908 – 2016

Results

Contribution of corona ?

Why a big contribution of corona ?



Mesure of Anisotropy ?

Assumption !

Fluid too small ?

⇒ Jets very closed between them

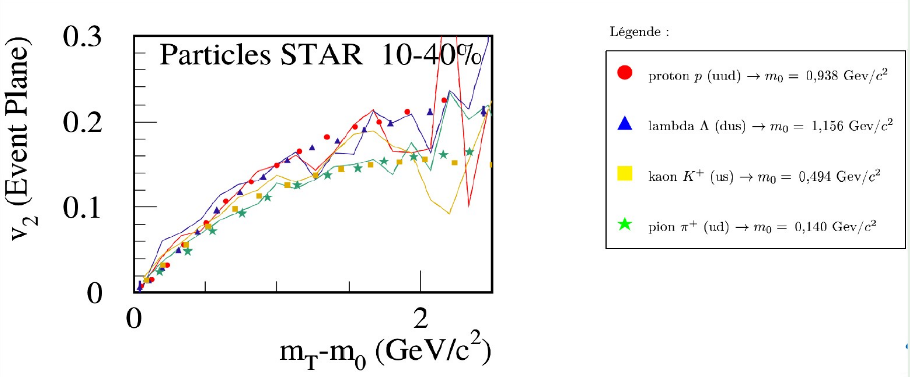
Anisotropy include jets ?

Results

Event Plane Method

$$m_t - m_0 = \sqrt{p_t^2 + m_0^2} - m_0$$

v_2 vs Reduce Mass Transverse at EPOS 3.210



At energy collisions : $\sqrt{s_{NN}} = 62.4$ **GeV** with 60 000 events

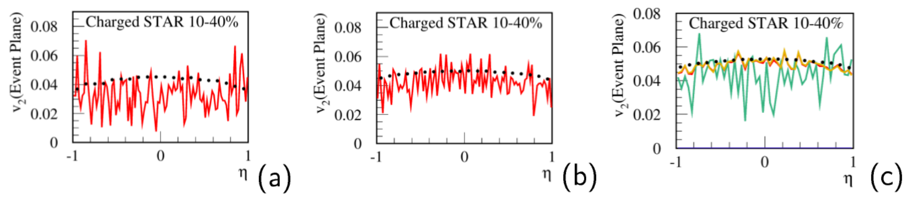
STAR Collaboration (Adamczyck, L. et al.) Phys. Rev. C 88, 014902 (2013)

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 ≈ 30 000 events

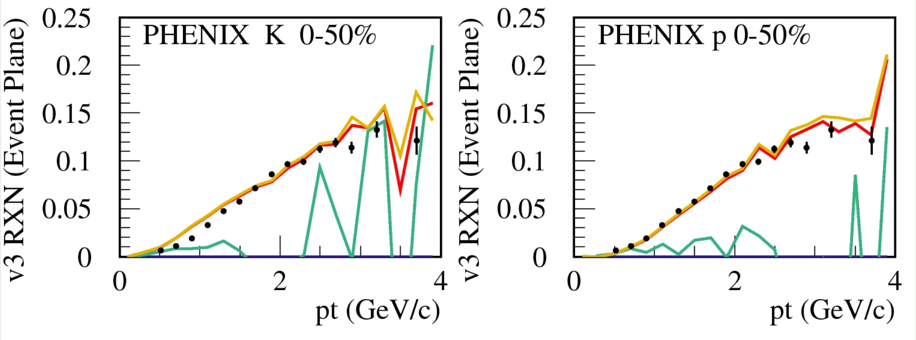
STAR Collaboration (Adamczyck, L. et al.) Phys. Rev. C 86, 054908 (2012)

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

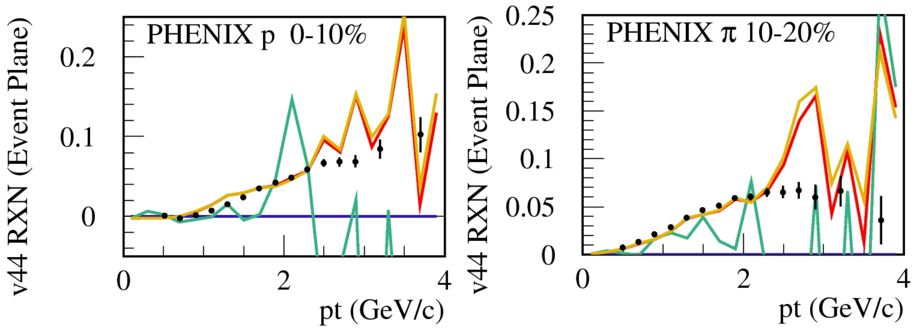
PHENIX Collaboration (A. Adare et al.) Phys. Rev. C 93, 051902 – 2016

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

Approach of Q-Cumulant

Procedure to create cumulants by directs calculations :

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

Cumulant Method

Q-Cumulant Method : Reference Flow

Q-Cumulant → Recent Method to calculate cumulants → **one loop over data**

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

$$\text{Flow vector : } Q_n = \sum_{i=1}^{M} e^{in\phi_i}$$

Azimuthal particles Correlations between 2 or 4 references particles (REP)

$$\langle 2 \rangle \equiv \langle e^{in(\phi_1 - \phi_2)} \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\langle 4 \rangle \equiv \langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle \propto |Q_n|^4 + |Q_{2n}|^2 - 2 \times \mathscr{R}|Q_{2n} Q_n^* Q_n^*| + \cdots$$

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 :

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

Elliptic Flow

Reference Flow

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 :

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

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 :

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

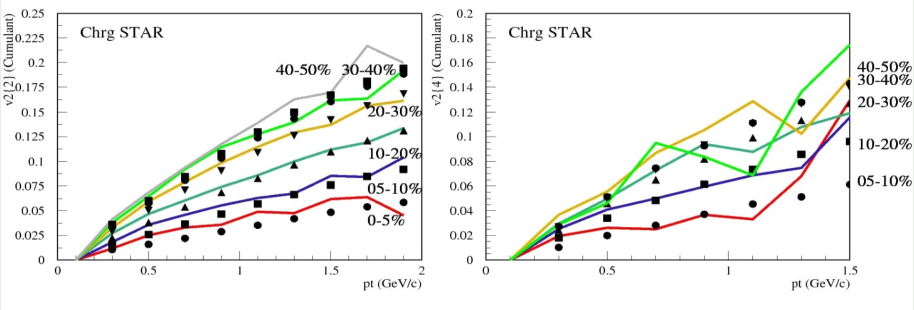
A. Bilandzic, R. Snellings, and S. Voloshin Phys. Rev. C 83, 044913 – Published 26 April 2011

Results

Cumulant Method

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

$v_2\{2\}$ and $v_2\{4\}$ vs Transverse Momentum at EPOS 3.210



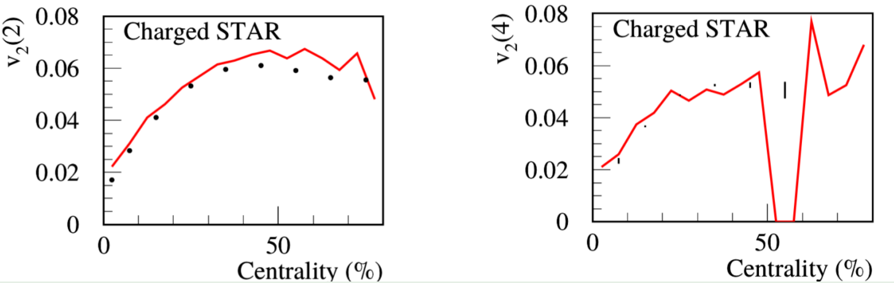
At energy collisions $\sqrt{s_{NN}} = 39$ **GeV** with ≈ 100 000 events

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

Results

Cumulant Method

$v_2\{2\}$ and $v_2\{4\}$ vs Centrality at EPOS 3.210



At energy collisions $\sqrt{s_{NN}} = 19.6$ **GeV** with ≈ 130 000 events

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

Conclusion

EPOS was created for **very high energy** with an application for multiple scattering

First Study[1] at BES energies ($\sqrt{s} = 7.7$ GeV at $\sqrt{s} = 62.4$ GeV) for v_2

We obtain good agreements with data !

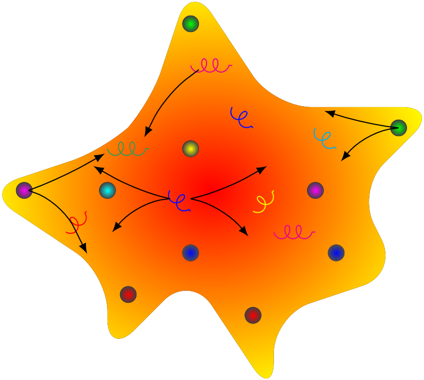
We create a **fluid** for each energy between 7.7 GeV at 200 GeV.
This **fluid** has a **big part** of elliptic flow since **19.6 GeV**, before the **corona** take **also a big part** $\rightarrow$ Must to do an investigation $\Rightarrow$ Look with **cumulants** if we obtain the same comportment.

Next step : Physics Investigation of result, look small system (like *pp*,*dg* at RHIC), go to the LHC energies
Start with pp at energy collision of 13 TeV.

[1] with M. Stefaniak

Thank you for your attention !

Context : QGP



- Quark-Gluon Plasma (QGP)
- **Partons are deconfined**
- QGP life-time : 10^{-21} s, size : 10^{-15} m $\Rightarrow$ cannot study directly the QGP
- Need theoretical models : **EPOS**

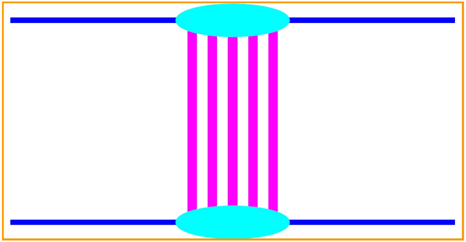
Gribov-Regge Theory and Pomeron

Effective Field Theory

Elementary interaction $\rightarrow$ Pomeron exchange

Pomeron : Quantum numbers of vacuum

Vladimir Gribov in $\approx$ 1960



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

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

Unified Approach

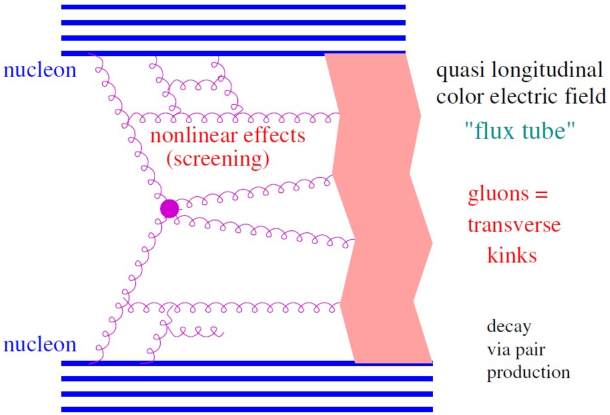
Initial Conditions : PBGRT to initialize collisions, Pomerons treated by partons ladders after by Lund string

Core-Corona Approach determines Jet and Quark Gluon Plasma

Viscous hydrodynamic expansion for the "core-matter"

Statistical Hadronization : Procedure of Cooper-Frye

Final state hadronic Cascade : Rescattering of products particle for the transport : UrQMD Model


nucleon
nonlinear effects
(screening)
nucleon
quasi longitudinal
color electric field
"flux tube"
gluons =
transverse
kinks
decay
via pair
production

Initial conditions. A Gribov-Regge multiple scattering approach is employed, where the elementary object (by definition called Pomeron) is a DGLAP parton ladder, using in addition a CGC motivated saturation scale for each Pomeron. The parton ladders are treated as classical relativistic (kinky) strings.

Core-corona approach. At some early proper time τ_0, one separates fluid (core) and escaping hadrons, including jet hadrons (corona), based on the momenta and the density of string segments. The corresponding energy-momentum tensor of the core part is transformed into an equilibrium one, needed to start the hydrodynamical evolution. This is based on the hypothesis that equilibration happens rapidly and affects essentially the space components of the energy-momentum tensor.

Viscous hydrodynamic expansion. Starting from the initial proper time τ_0, the core part of the system evolves according to the equations of relativistic viscous hydrodynamics. A cross-over equation-of-state is used, compatible with lattice QCD.

Statistical hadronization. The "core-matter" hadronizes on some hypersurface defined by a constant temperature T_H, where a so-called Cooper-Frye procedure is employed, using equilibrium hadron distributions.

Final state hadronic cascade. After hadronization, the hadron density is still big enough to allow hadron-hadron rescatterings. For this purpose, we use the UrQMD model.

We will present a "realistic" treatment of the hydrodynamic evolution of ultrarelativistic heavy ion collisions, based on the following features:

- ▷ initial conditions obtained from a flux tube approach (EPOS),
  - compatible with the string model used since many years for elementary collisions (electron-positron, proton proton),
  - and the color glass condensate picture;
- ▷ consideration of the possibility to have a (moderate) initial collective transverse flow;
- ▷ event-by-event procedure,
  - taking into the account the highly irregular space structure of single events,
  - leading to so-called ridge structures in two-particle correlations;
- ▷ core-corona separation, considering the fact that only a part of the matter thermalizes;

Data Comparison

RHIC at few energies : Q-Cumulant

Inclusive charged hadron elliptic flow in Au + Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 39 GeV

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **86** (2012) 054908

Measurements of the elliptic flow, v_2, of charged hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 19.6, 27, **39** GeV are presented.

Here, we compare at 39 GeV

We use the same method of STAR to compare Data and Results

Data Comparison

RHIC at few energies : Event Plane

Elliptic flow of identified hadrons in Au+Au collisions at
$\sqrt{s_{NN}} = 7.7 - 62.4$ GeV

L. Adamczyk *et al.* [STAR Collaboration], Phys. Rev. C **88** (2013) 014902

Measurements of the elliptic flow, v_2, of identified hadrons ($\pi^{\pm}, K^{\pm}, K_s^0, p, \overline{p}, \phi, \Lambda, \overline{\Lambda}, \Xi^-, \overline{\Xi}^+, \Omega^-, \overline{\Omega}^+$) in Au+Au collisions at $\sqrt{s_{NN}} =$ 7.7, 11.5, **19.6**, 27, 39 and 62.4 GeV are presented.

Here, we compare at 19.6 GeV

We use the same method of STAR to compare Data and Results

Elliptic Flow

Q-Cumulant Method : Reference Flow

Q-Cumulant $\rightarrow$ Recent Method to calculate cumulants $\rightarrow$ one loop over data

Correlations between 2 or 4 references particles (REP)

Elliptic Flow

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Flow vector : $Q_n = \sum_{i=1}^{M} e^{in\phi_i}$

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Correlations between 2 or 4 references particles (REP)

Flow vector : $Q_n = \sum_{i=1}^{M} e^{in\phi_i}$

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

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \times \mathscr{R}\left[Q_{2n} Q_n^* Q_n^*\right]}{M(M-1)(M-2)(M-3)} - 2\frac{2(M-2) \times |Q_n|^2 - M(M-3)}{M(M-1)(M-2)(M-3)}$$

Elliptic Flow

Event Weight

Event Average :

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

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

Definition of weights :

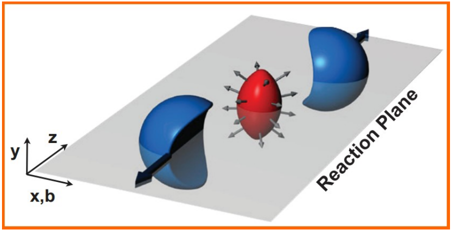
$$W_2 = M(M-1) \qquad W_4 = M(M-1)(M-2)(M-3)$$

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

Elliptic Flow

Anisotropic Flow

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



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

Elliptic Flow

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.

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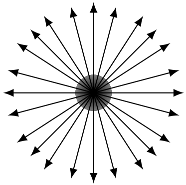
Anisotropic Flow : (n=1 : Directed Flow , n=2 : Elliptic Flow)

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

Anisotropic Flow

Anisotropy $\neq$ Isotropy

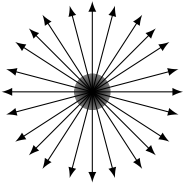


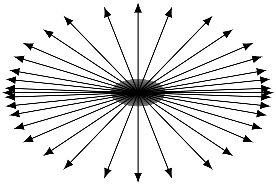
- Elementary Collisions : **Isotropy** of particles production

  $v_2 = 0$: Elliptic Flow

Anisotropic Flow

Anisotropy $\neq$ Isotropy





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

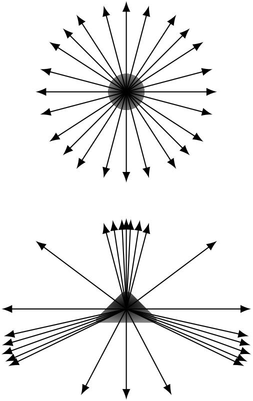
  $v_2 = 0$: Elliptic Flow

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

  $v_2 > 0$

Anisotropic Flow

Anisotropy $\neq$ Isotropy



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

  $v_2 = 0$: Elliptic Flow

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

  $v_2 > 0$

- $v_3 > 0$
- Something more than elementary processus : **QGP ?**