Measurements of azimuthal anisotropy for high p_T charged hadrons at $\sqrt{s_{NN}}$ = 200GeV in Au+Au at RHIC-PHENIX

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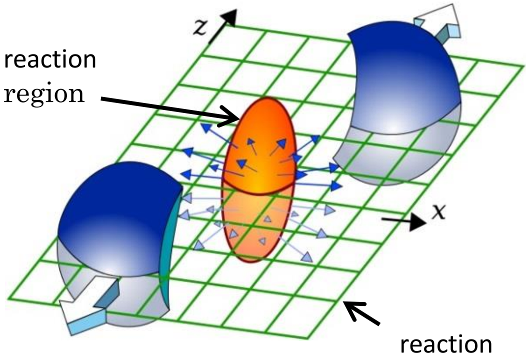
Motivation

We would like to investigate
the energy loss mechanism of QGP,
which is one of the important
properties of QGP.

Introduction
(Why azimuthal anisotropy at high p_T?)



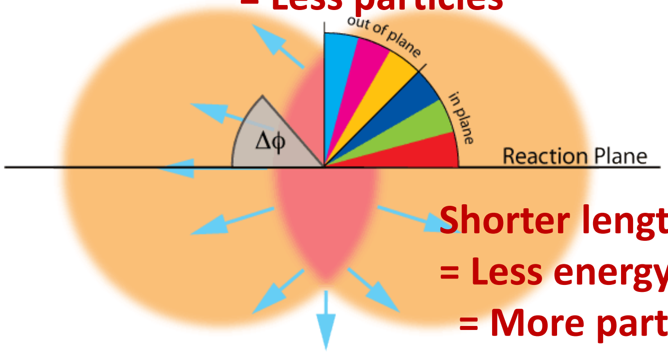
At non-central collisions, the reaction region (QGP) is an ellipse because nuclei have a certain size.

The high p_T particles will traverse different path lengths in the QGP, depending on azimuthal angles of emitting particles .

The amount of the energy loss is different depending on azimuthal angle.

The yield with pT is modified.

Longer length
= More energy loss
= Less particles

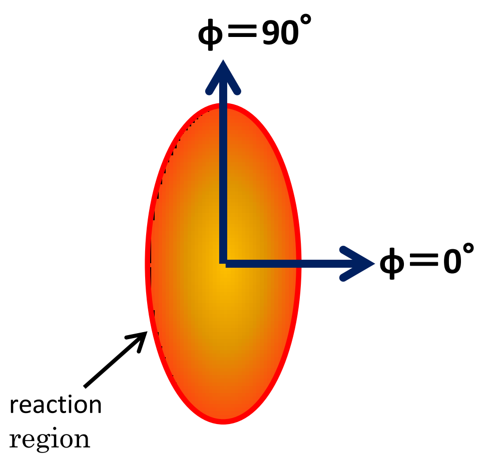


Shorter length
= Less energy loss
= More particles

What v_2 ?

$$\frac{dN(\phi)}{d\phi} \propto 1 + 2v_2 \cos 2\phi$$

v_2 is the coefficient of the second term of Fourier expansion of azimuthal distribution measured with respect to reaction plane.



↓

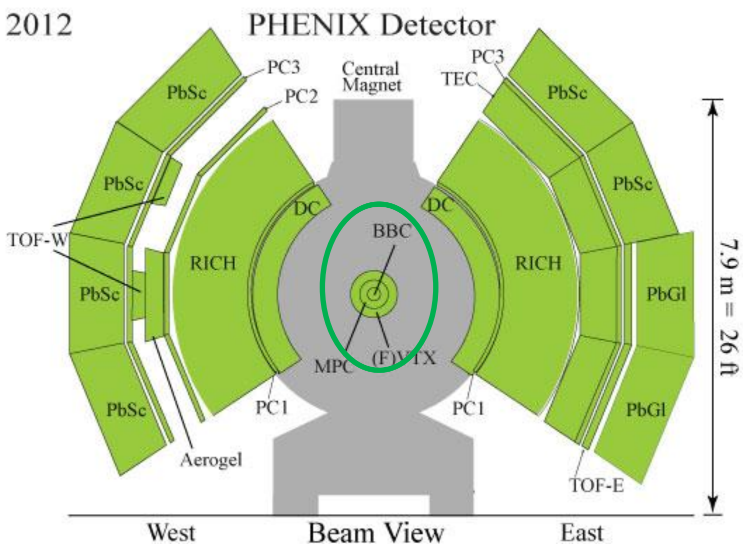
v_2 shows the relative yield difference of ϕ=90° to ϕ=0°.

We can study the energy loss mechanism of QGP by investigating v_2 in detail by measuring and comparing with various shapes of reaction regions.

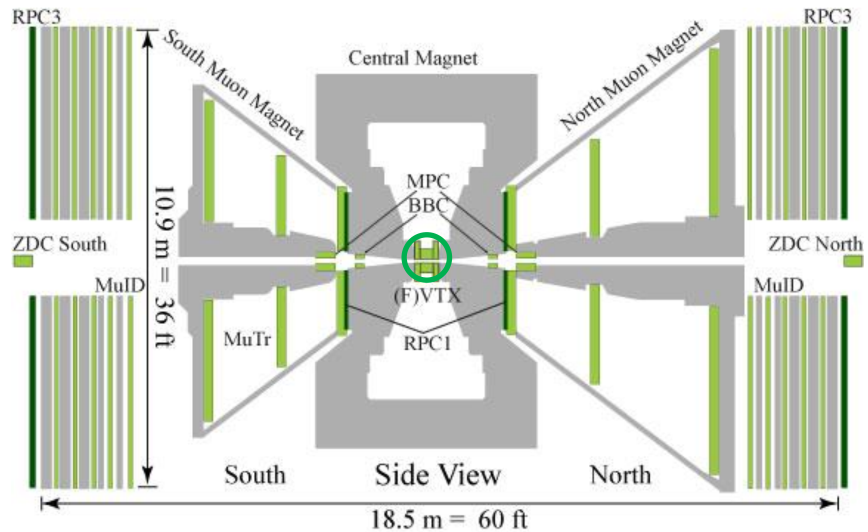
PHENIX experiment

It is one of the international joint experiments at Brookhaven National Laboratory（BNL）.

Vertical with the beam axis



Parallel with the beam axis



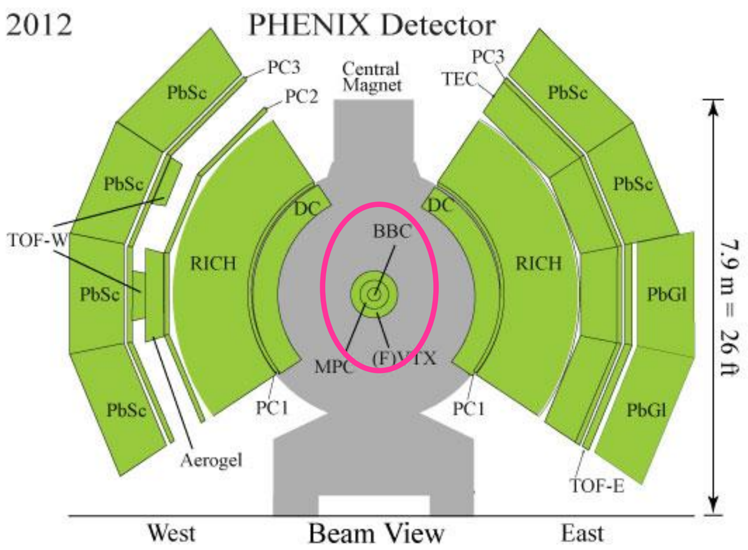
VTX

- precise tracking

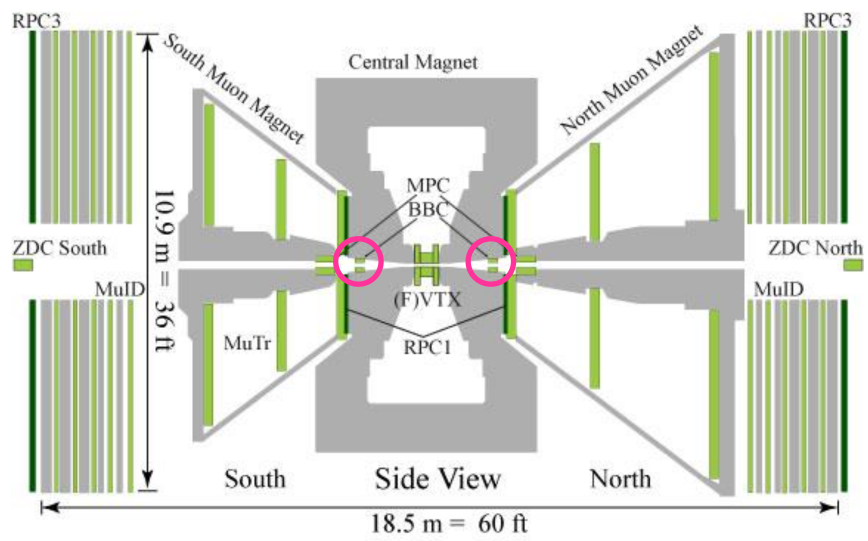
PHENIX experiment

It is one of the international joint experiments at Brookhaven National Laboratory（BNL）.

Vertical with the beam axis



Parallel with the beam axis

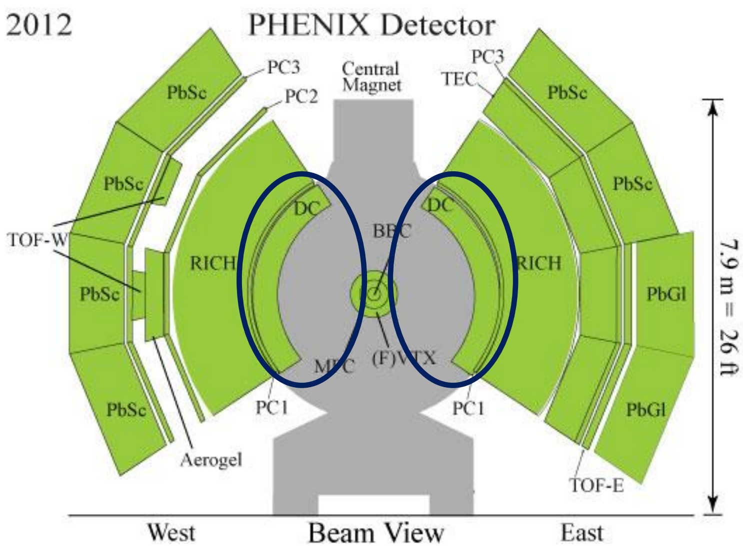


Beam Beam Counter (BBC)
- vertex position,
  centrality, reaction plane

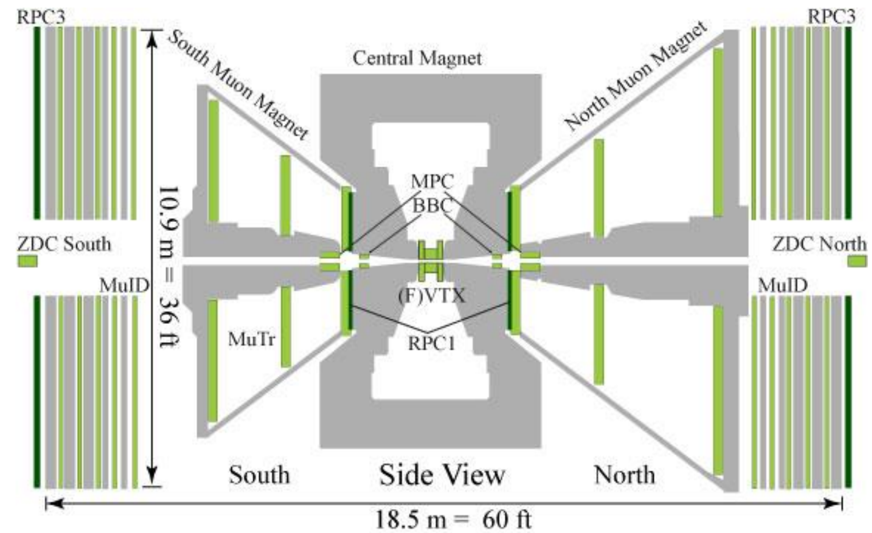
PHENIX experiment

It is one of the international joint experiments at Brookhaven National Laboratory（BNL）.

Vertical with the beam axis



Parallel with the beam axis

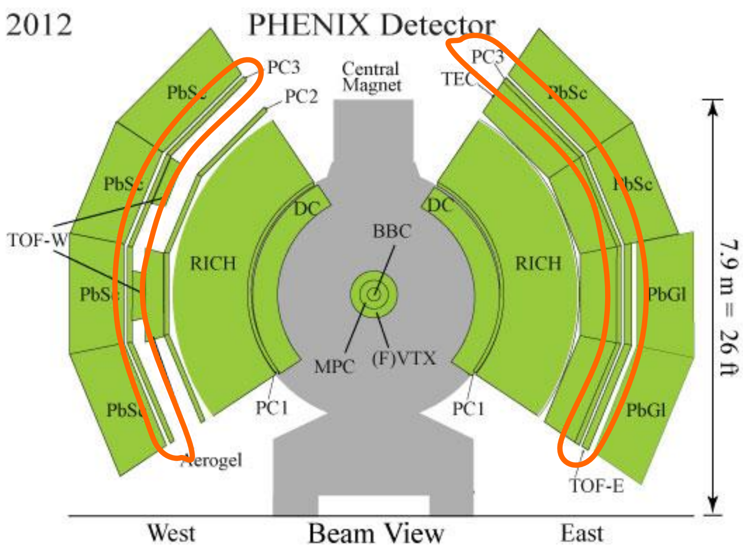


Drift Chamber (DC)
 - momentum, tracking

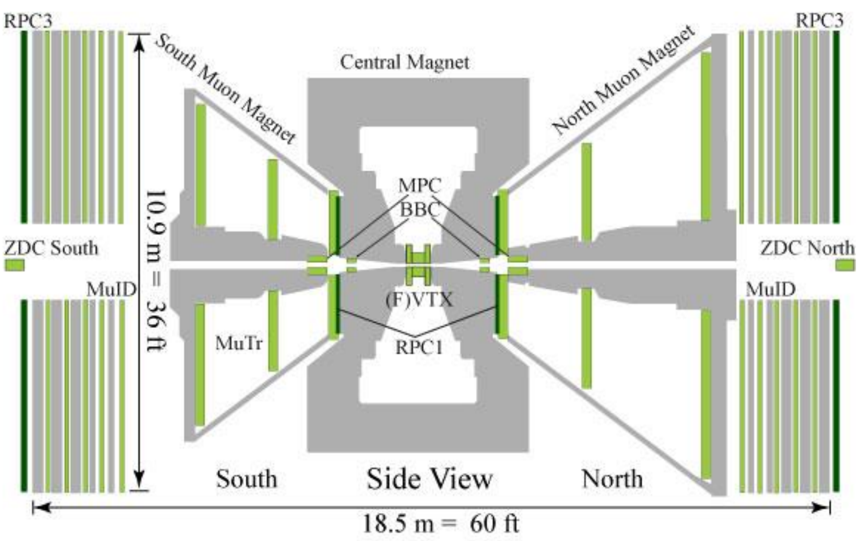
PHENIX experiment

It is one of the international joint experiments at Brookhaven National Laboratory（BNL）.

Vertical with the beam axis



Parallel with the beam axis

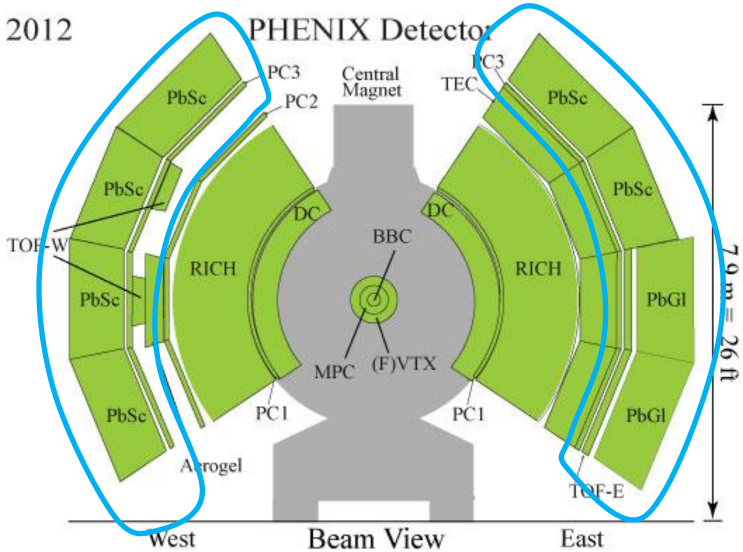


Pad Chamber 3 (PC3)
- tracking

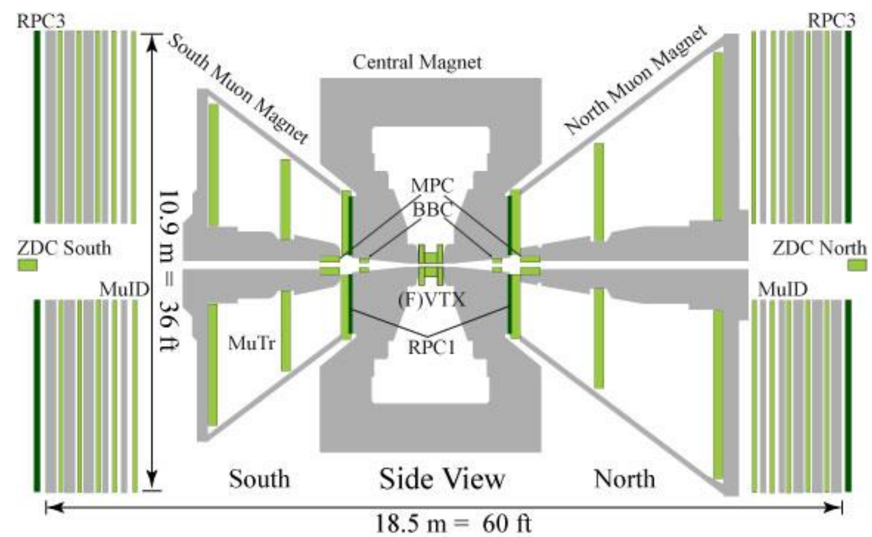
PHENIX experiment

It is one of the international joint experiments at Brookhaven National Laboratory（BNL）.

Vertical with the beam axis



Parallel with the beam axis



EMCal (PbSc, PbGl)
- deposit energy, position

We measure v_2 by using these detectors.

How to analyze

1. Track selection (two methods)

2. Reaction plane measurements
   - Reaction plane determination

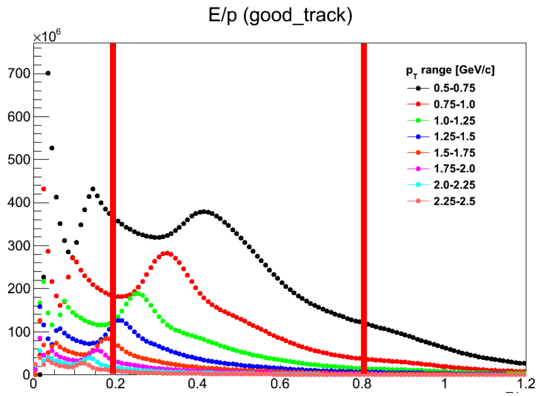
Track selection

It is important for v_2 measurement at high p_T to reduce background tracks and improve S/N.
We tried two different methods to reduce background.

E/p cut

E : Energy measured by EMCal
p : momentum measured by DC

Entry



E/p

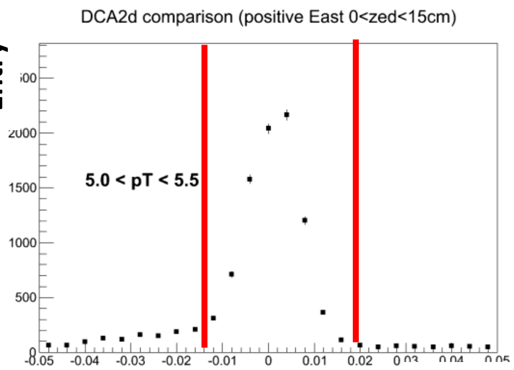
The range used

More statistic

DCA cut

DCA : Distances of closest approach

Entry



DCA2d

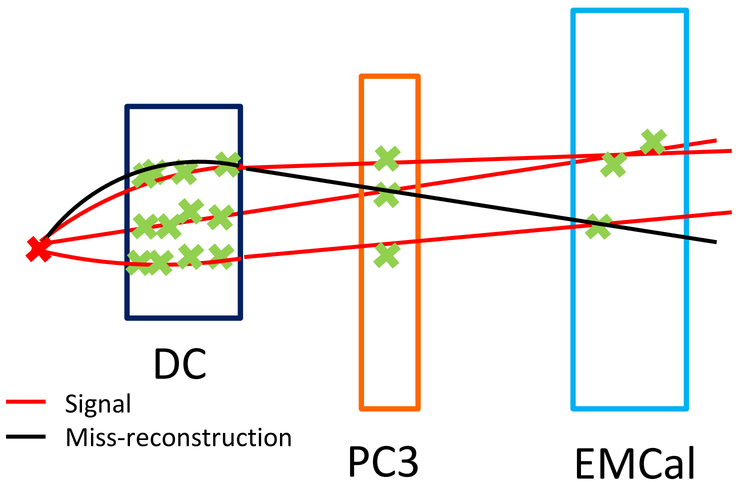
The range used

Less back ground

Details are shown in following pages.

Track selection (E/p cut)

E : Energy measured by EMCal
p : momentum measured by DC



In PHENIX, there are many hit points and they make miss-reconstructed tracks. Features of the miss-reconstructed tracks are p is random but E is small.

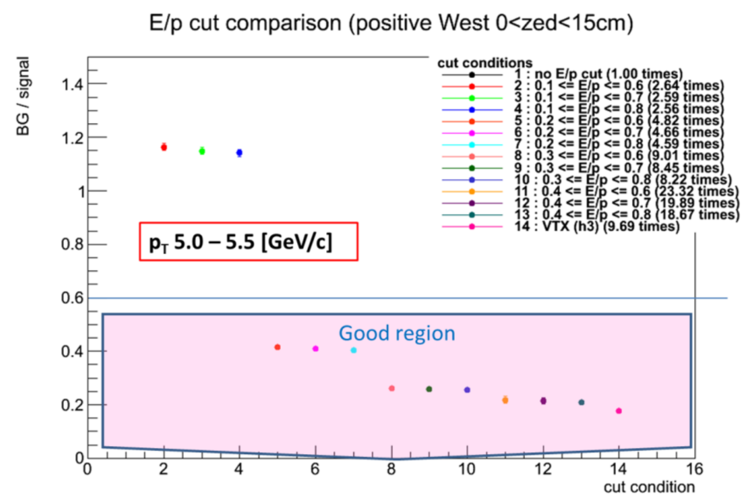
Back Ground

- Miss-reconstruction
- Decayed particles

E/p << 1

- Electron

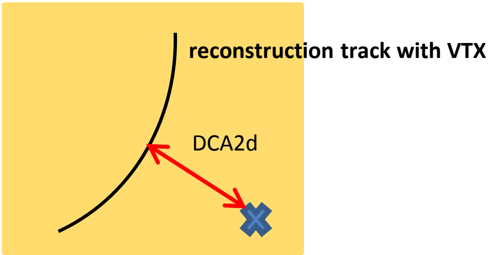
E/p ~ 1

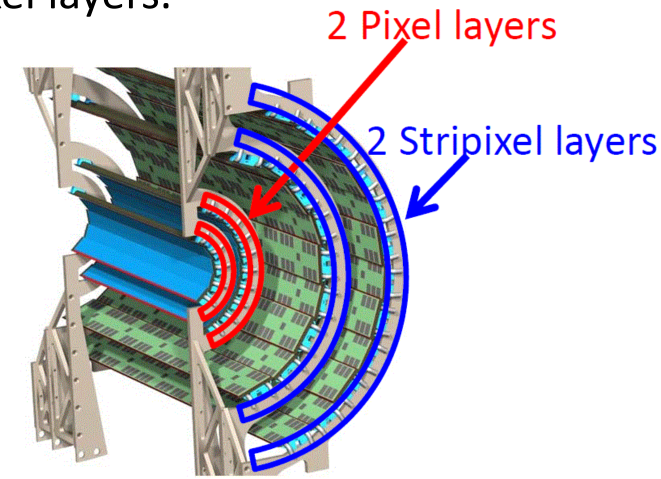


The range used is 0.2 <= E/p <= 0.8

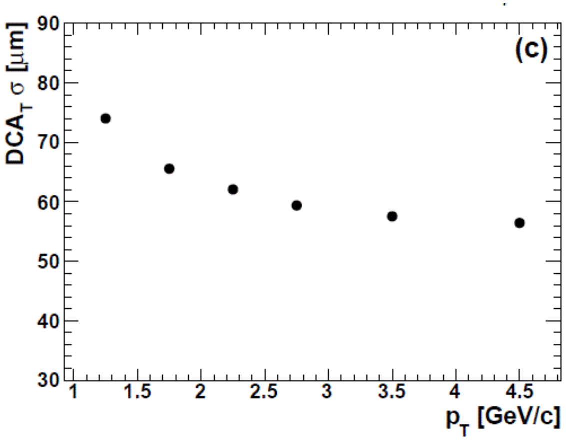
Track selection (DCA cut)

VTX is made of two Pixel layers and two Stripixel layers.





DCA (Distance of Closest Approach)
: Distances between reconstruction track with VTX and vertex point.



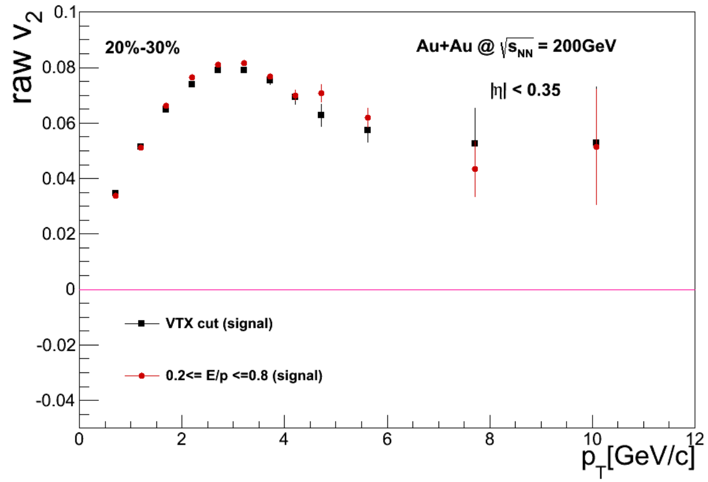
PRC 93, 034904

Resolution σ = 60[μm] (p_T > 2[GeV/c])

Hadrons come from vertex point, so DCA is small.
VTX can reject the background tracks with the good DCA resolution !

Comparison of two methods

$$v_2^{raw}(measured) = \frac{N_S}{N_T} v_2^{raw}(signal) + \frac{N_B}{N_T} v_2^{raw}(BG)$$



raw v_2 by the two methods are consistent.

We will show v_2 by E/p cut method from next page.

Reaction plane determination

Reaction plane method

$$v_2 = \frac{< \cos 2(\phi - \Psi_2) >}{reaction\_plane\_resolution}$$

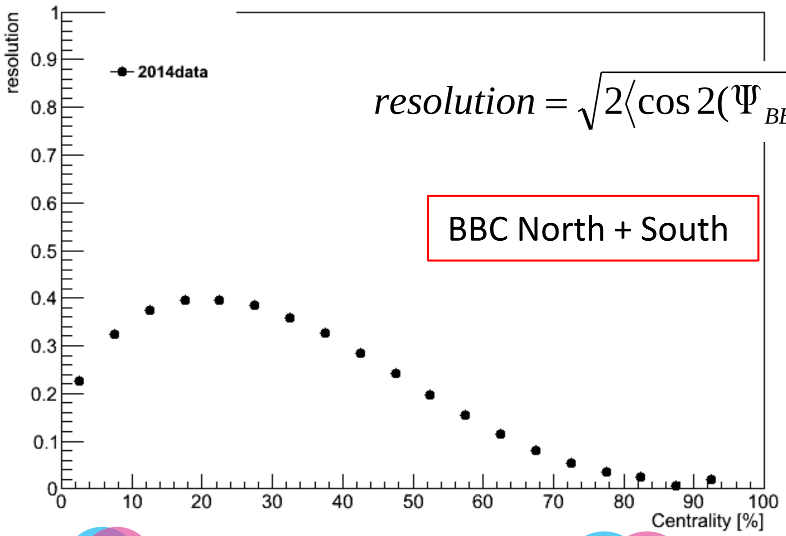
$\phi - \Psi_2$: azimuth from reaction plane

ϕ : track -> track selection

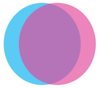
Ψ_2 : RP -> RP measurement

Reaction plane resolution vs. centrality

$$resolution = \sqrt{2\langle \cos 2(\Psi_{BBCN} - \Psi_{BBCS}) \rangle}$$

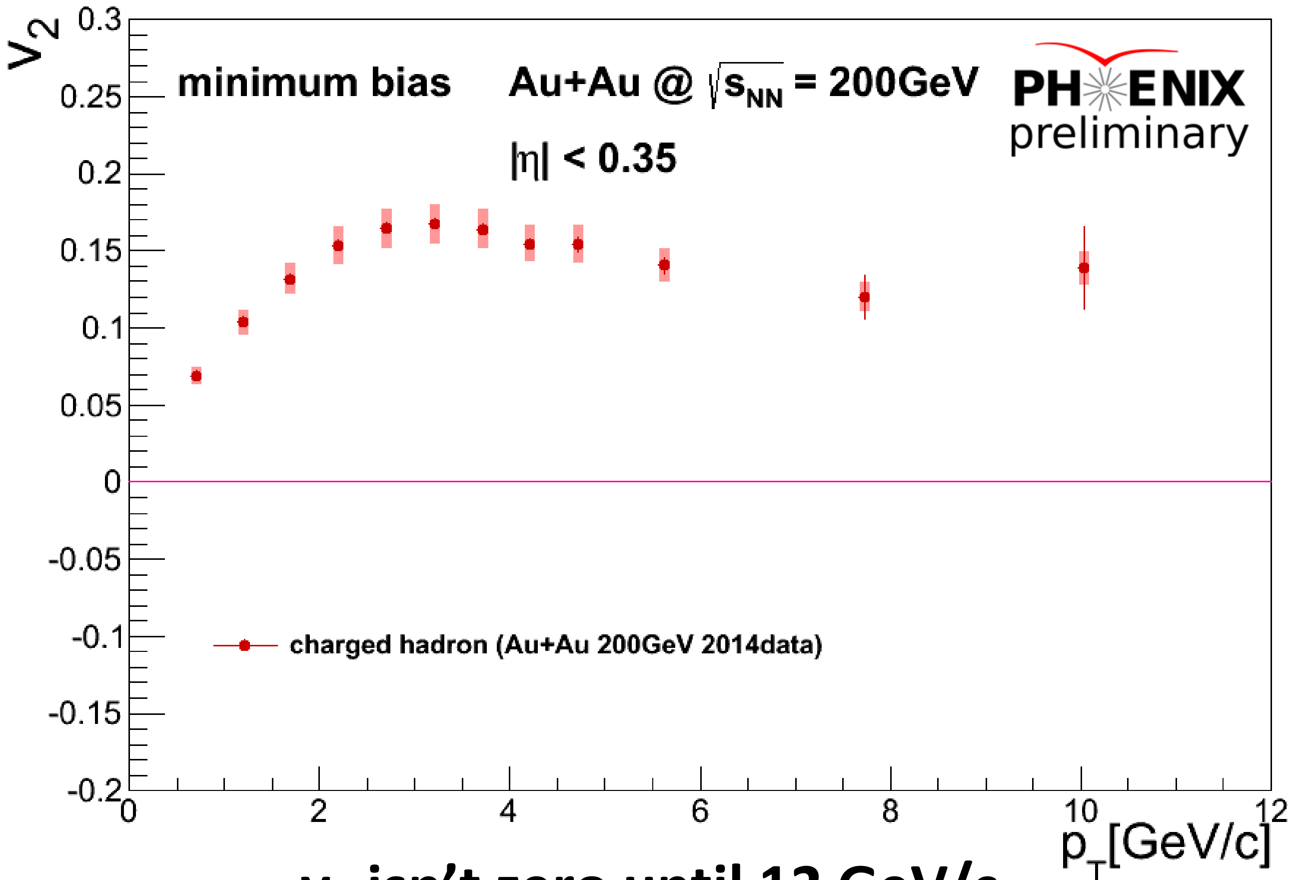


We use reaction plane azimuth (Ψ_{BBCN} , Ψ_{BBCS}) by BBC-North and BBC-Soutn.



v_2 (minimum bias)

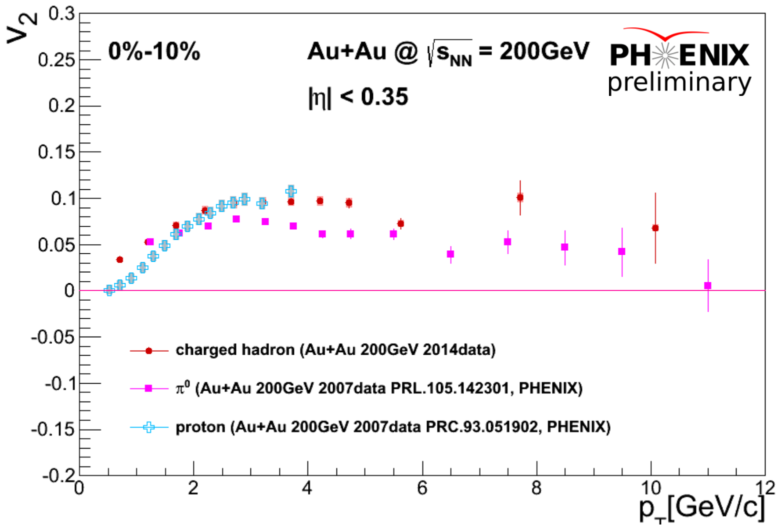
result

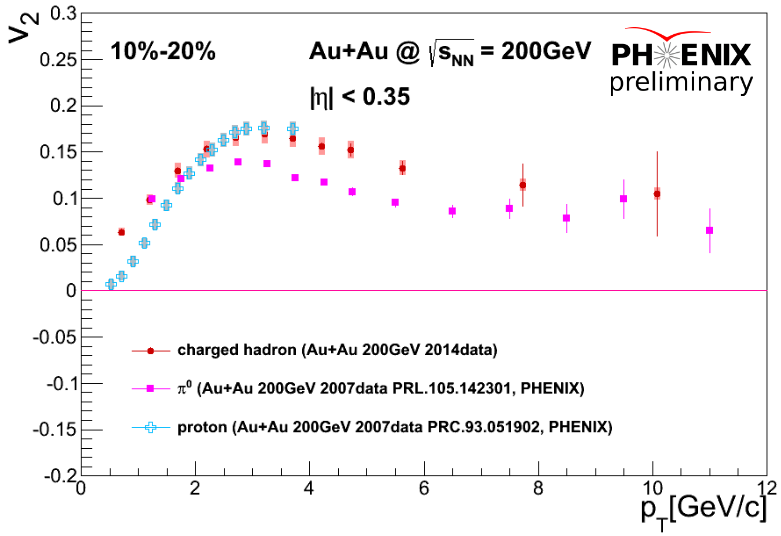


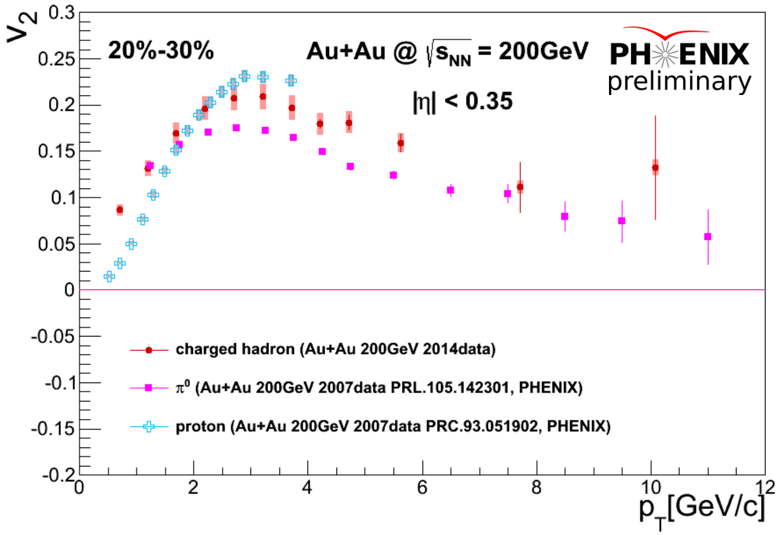
v_2 isn't zero until 12 GeV/c.

v_2 (centrality dependence)

result







There is a difference in v2 between charged hadrons and neutral pions for pT < 7GeV/c.

The difference becomes smaller as going to peripheral collisions: qualitatively consistent with baryon anomaly seen in most central collisions.

Summary

Track cut

We try two different cut methods to reduce background tracks.

- we select E/p cut method for v_2 measurements because of the statistical advantage.

Reaction Plane

We measure reaction plane.

We obtain reaction plane resolution.

v_2 results

We obtain charged hadron v_2 in $0 < p_T < 12$ [GeV/c]

- v_2 is not zero until $p_T = 12$ GeV/c.

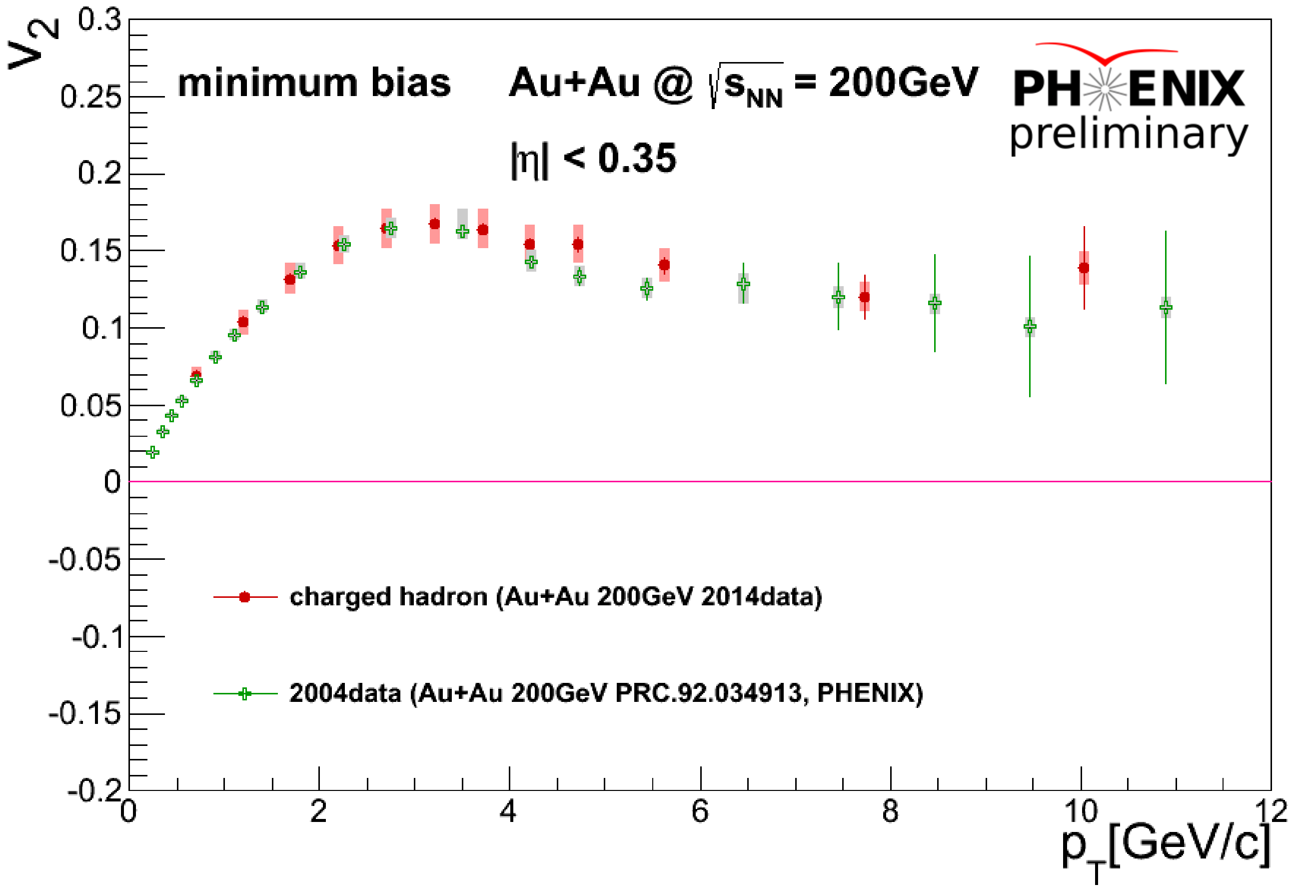
In centrality 0-10%, 10-20% and 20-30%, there is a difference in v_2 between charged hadrons and neutral pions for $p_T < 7$GeV/c.

Next to do

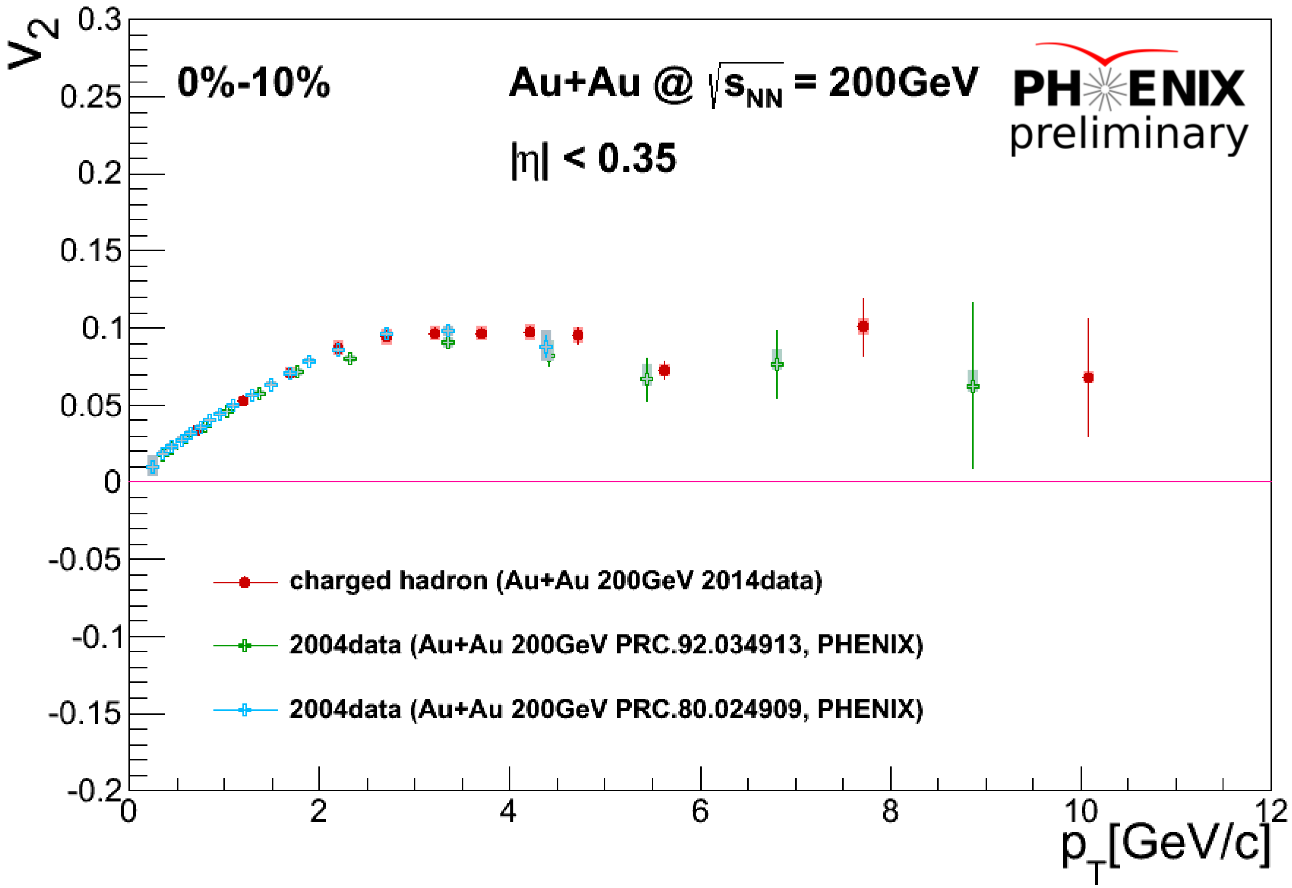
2014 data will increase 4 times larger. So I would like to measure peripheral centrality v_2.

Back up

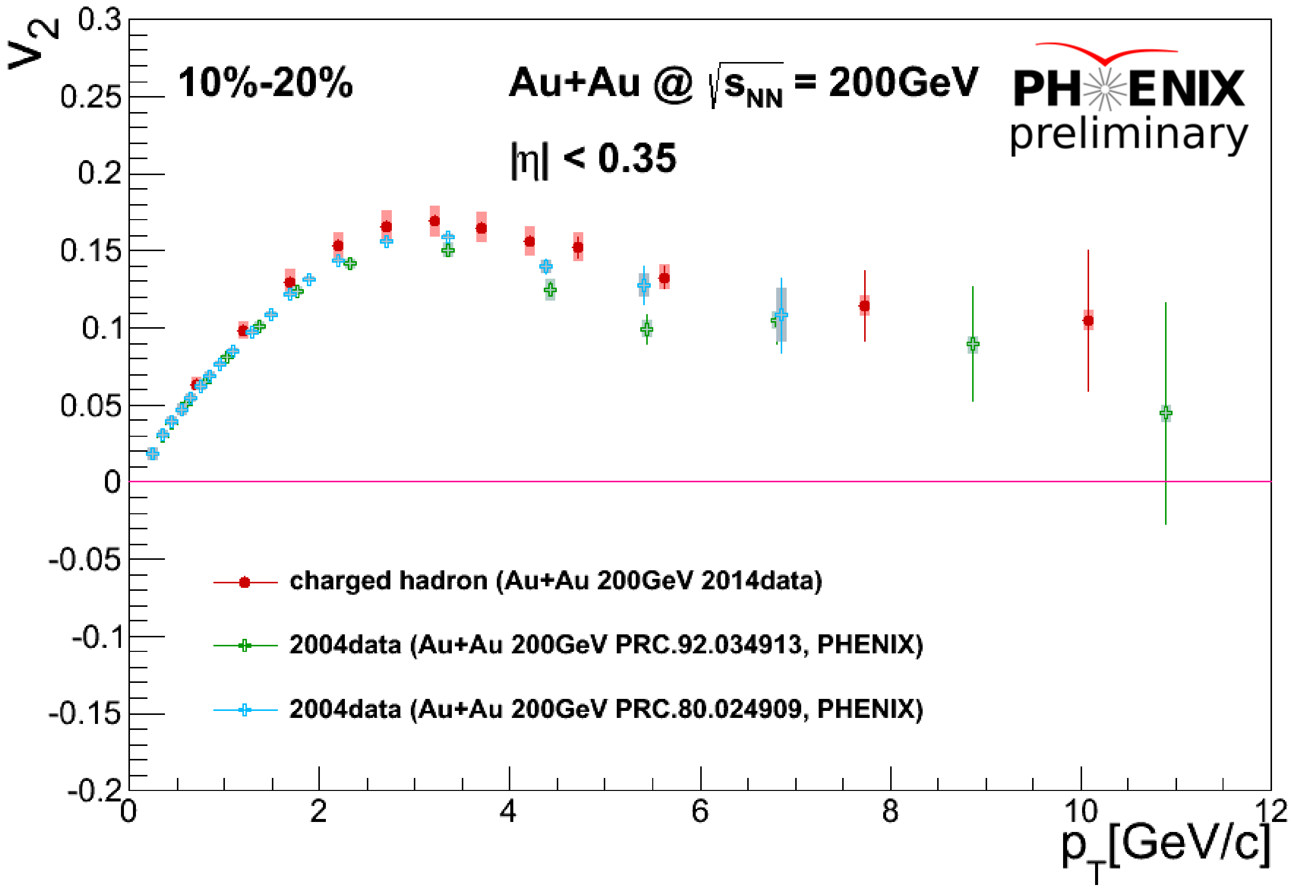
Comparison of New & Old PHENIX Results



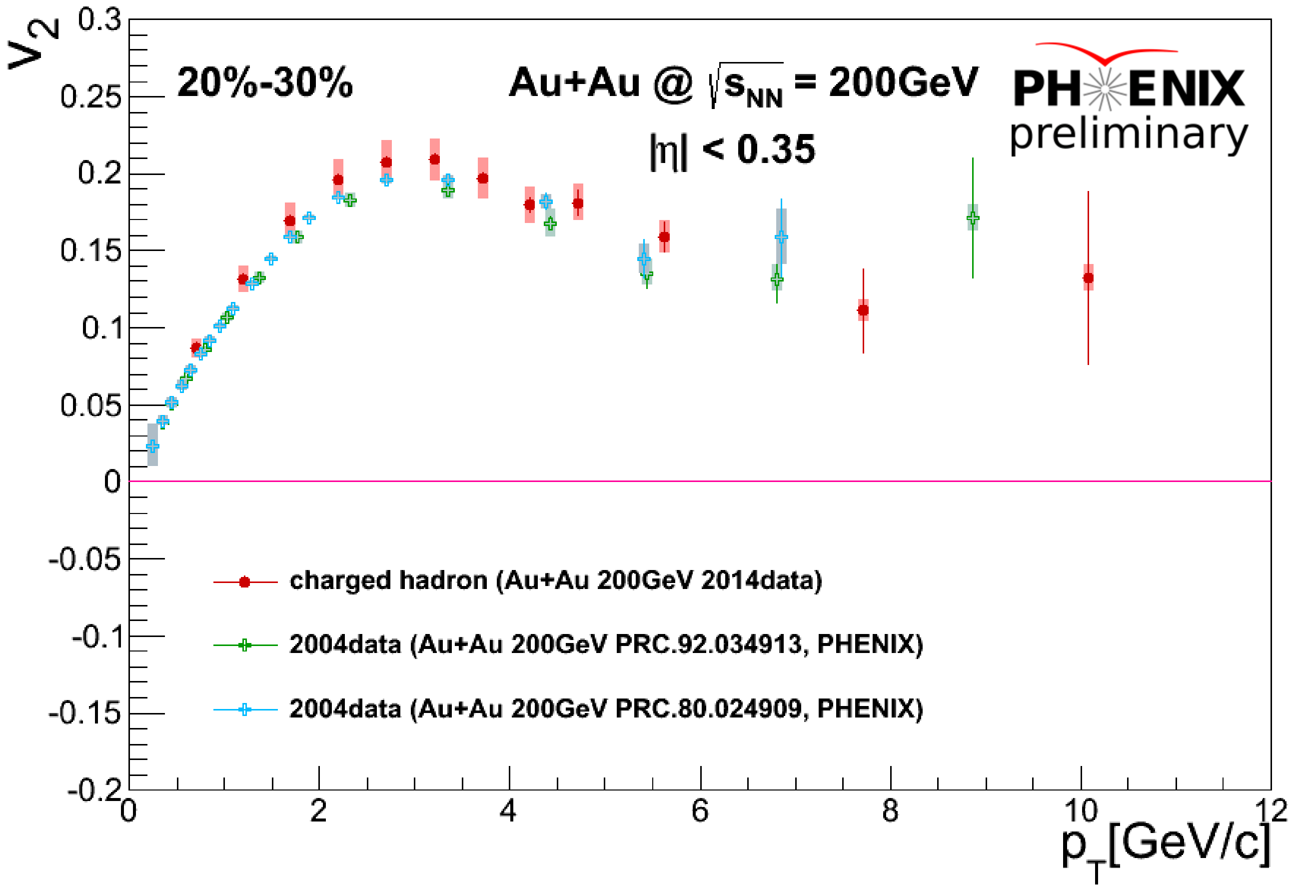
Comparison of New & Old PHENIX Results



Comparison of New & Old PHENIX Results



Comparison of New & Old PHENIX Results



π^0 systematic error

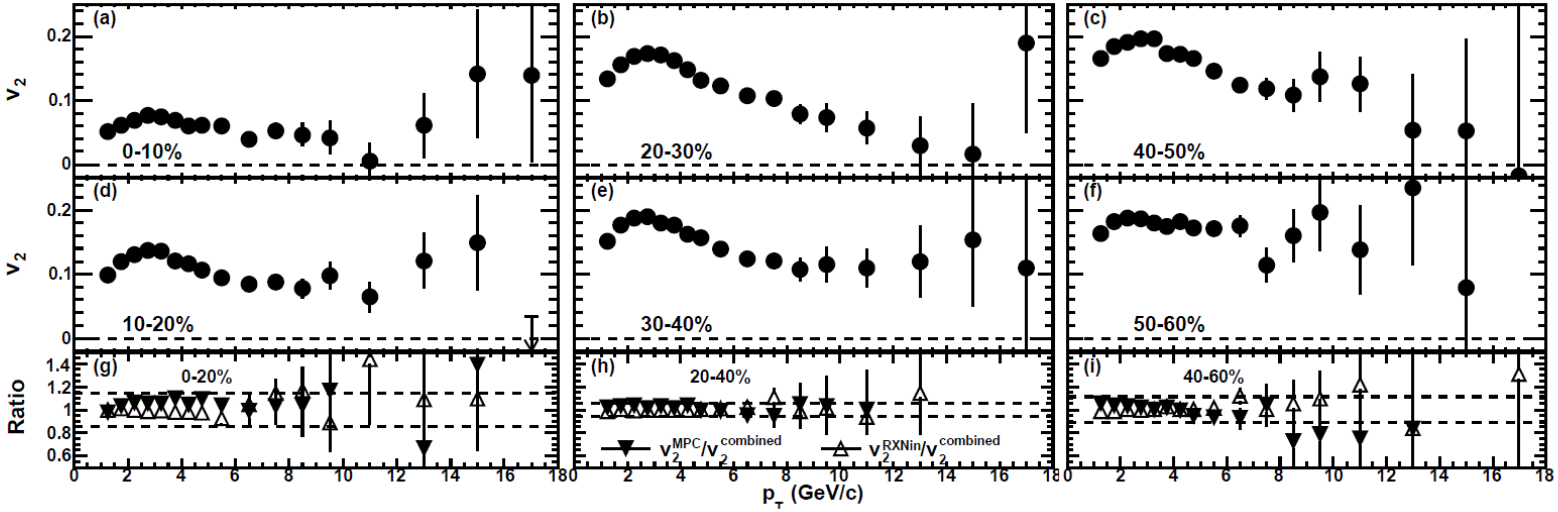
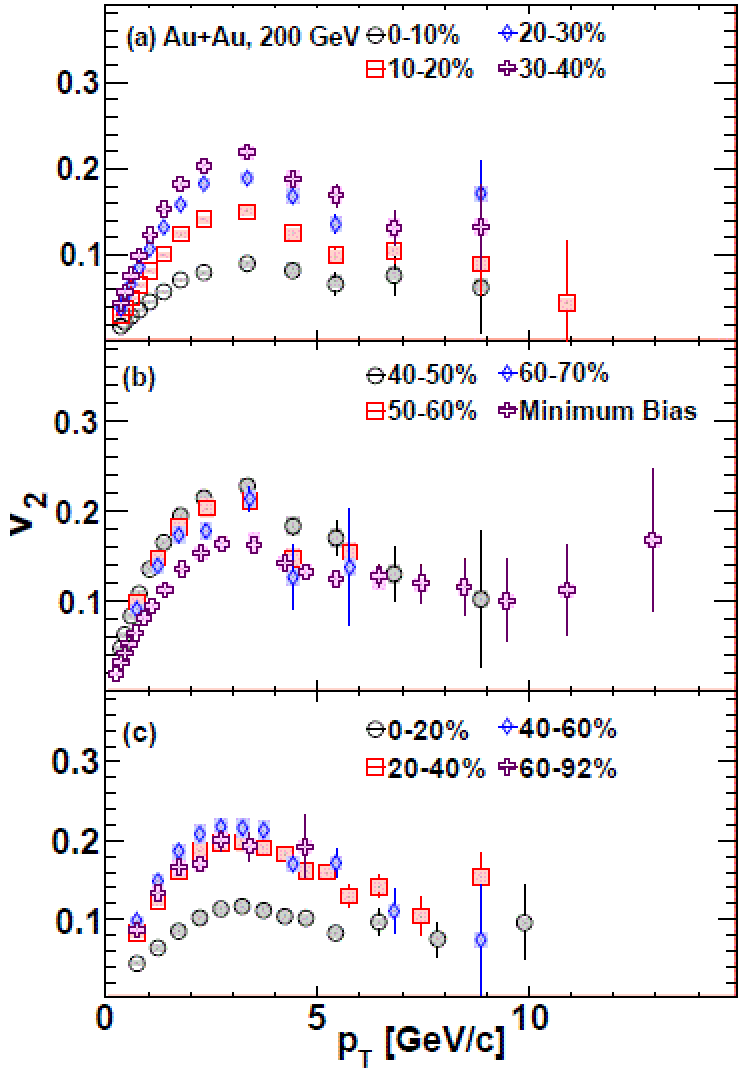


FIG. 1: (a)-(f): π^0 v_2 using reaction plane determined with MPC and RXN_{in} combined as a function of p_T for different centralities. (g)-(i): ratios of v_2 measured separately using MPC (solid triangles) and RXN_{in} (open triangles) to combined result; the dashed lines indicate the systematic error.

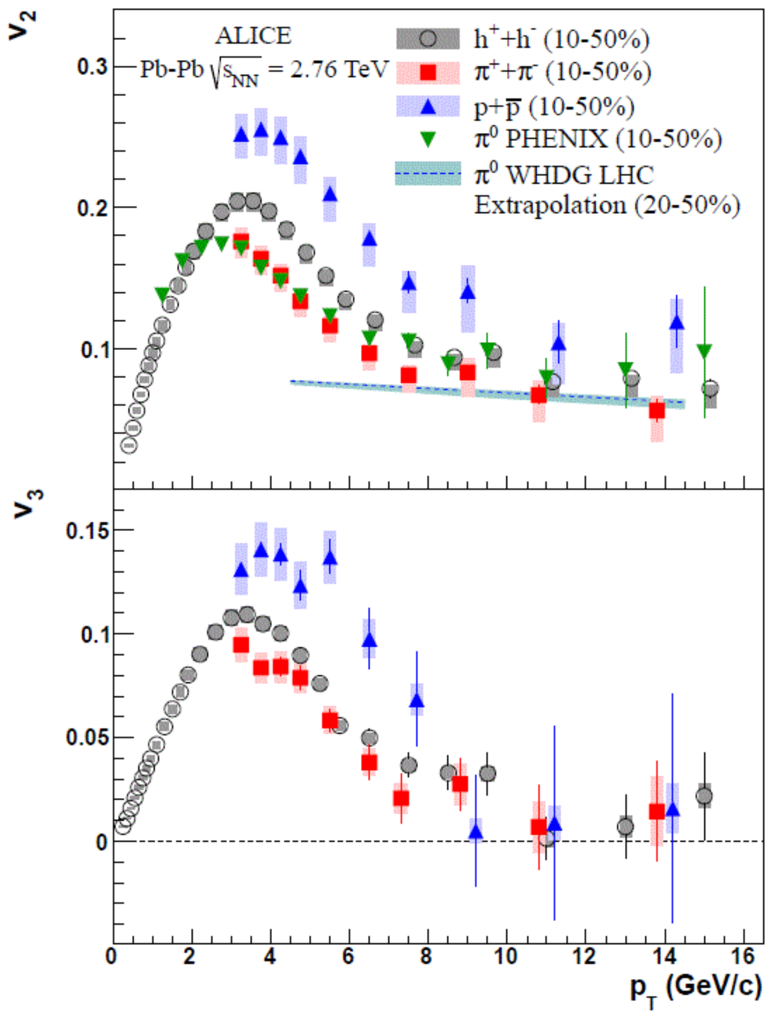


PHENIX results

2004data

PhysRevC.92.034913

http://arxiv.org/pdf/1412.1043v2.pdf



an ALICE result at a different of $\sqrt{s_{NN}}$

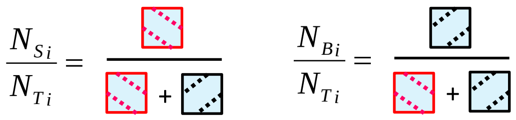
https://arxiv.org/pdf/1205.5761v3.pdf

Least-square method

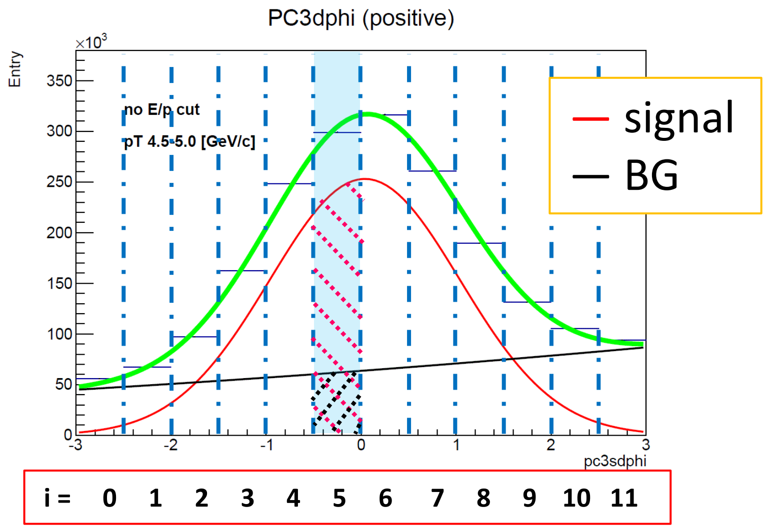
$$v_2(measured)_i = \frac{N_{Si}}{N_{Ti}} v_2(signal) + \frac{N_{Bi}}{N_{Ti}} v_2(BG)$$

v_2(measured) is made of v_2(signal) and v_2(BG).
It is assumed that v_2(signal) and v_2(BG) are constants in PC3sdphi range(i = 0 ~ 12).

1. we get $v_2(\text{measured})_i$, N_{Si}, N_{Bi} and N_{Ti} in each range.



Entry vs. PC3sdphi



2. we calculate v_2(signal) and v_2(BG) by Least-square method.
   - please see the details in back up pages.

Least-square method

$$v_2 = \frac{N_S}{N_T} v_2(signal) + \frac{N_B}{N_T} v_2(BG)$$

Change characters

$$-c = xa + yb$$

Least-square method by all range (i = 0 ~ 5)

$$\sum_i \frac{(ax_i + by_i + c_i)^2}{\sigma_{ci}^{\ 2}} = f(a,b)$$

Differentiate for least values

$$\frac{\partial f}{\partial a} = \sum_i \frac{ax_i(ax_i + by_i + c_i)}{\sigma_{ci}^{\ 2}} = 0$$

$$\frac{\partial f}{\partial b} = \sum_i \frac{by_i(ax_i + by_i + c_i)}{\sigma_{ci}^{\ 2}} = 0$$

Get a and b by coalition

$$a = \frac{\sum \frac{y^2}{\sigma_c^{\ 2}}}{\sum \frac{y^2}{\sigma_c^{\ 2}} \sum \frac{x^2}{\sigma_c^{\ 2}} - (\sum \frac{xy}{\sigma_c^{\ 2}})^2} \left\{ \frac{\sum \frac{cy}{\sigma_c^{\ 2}} \sum \frac{xy}{\sigma_c^{\ 2}}}{\sum \frac{y^2}{\sigma_c^{\ 2}}} - \sum \frac{cx}{\sigma_c^{\ 2}} \right\} = v_2(signal)$$

$$b = \frac{\sum \frac{x^2}{\sigma_c^{\ 2}}}{\sum \frac{y^2}{\sigma_c^{\ 2}} \sum \frac{x^2}{\sigma_c^{\ 2}} - (\sum \frac{xy}{\sigma_c^{\ 2}})^2} \left\{ \frac{\sum \frac{cx}{\sigma_c^{\ 2}} \sum \frac{xy}{\sigma_c^{\ 2}}}{\sum \frac{x^2}{\sigma_c^{\ 2}}} - \sum \frac{cy}{\sigma_c^{\ 2}} \right\} = v_2(BG)$$

Statistical error

fitting error of Least-square method

$$\Delta a_f$$

$$\boxed{\Delta a = \Delta a_f}$$

Error（fitting error of Least-square method）

$$a = \frac{\sum \frac{y_i^2}{\sigma_{ci}^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \{ \frac{\sum \frac{c_i y_i}{\sigma_{ci}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2}} - \sum \frac{c_i x_i}{\sigma_{ci}^2} \} \tag{7.1}$$

$$= \frac{\sum \frac{c_i y_i}{\sigma_{ci}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} - \sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{c_i x_i}{\sigma_{ci}^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.2}$$

$$= \frac{\sum \frac{x_i y_i}{\sigma_{ci}^2} (\frac{c_0 y_0}{\sigma_{c0}^2} + \frac{c_1 y_1}{\sigma_{c1}^2} + \cdots) - \sum \frac{y_i^2}{\sigma_{ci}^2} (\frac{c_0 y_0}{\sigma_{c0}^2} + \frac{c_1 y_1}{\sigma_{c1}^2} + \cdots)}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.3}$$

$$= \frac{(\frac{y_0}{\sigma_{c0}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} - \frac{x_0}{\sigma_{c0}^2} \sum \frac{y_i^2}{\sigma_{ci}^2}) c_0 + (\frac{y_1}{\sigma_{c1}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} - \frac{x_1}{\sigma_{c1}^2} \sum \frac{y_i^2}{\sigma_{ci}^2}) c_1 + \cdots}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.4}$$

Partial differential (7.5)

$$\Delta a_f = \frac{\sqrt{(\frac{y_0}{\sigma_{c0}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} - \frac{x_0}{\sigma_{c0}^2} \sum \frac{y_i^2}{\sigma_{ci}^2})^2 \sigma_{c0}^2 + (\frac{y_1}{\sigma_{c1}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} - \frac{x_1}{\sigma_{c1}^2} \sum \frac{y_i^2}{\sigma_{ci}^2})^2 \sigma_{c1}^2 + \cdots}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.6}$$

$$= \frac{\sqrt{(\frac{y_0^2}{\sigma_{c0}^4} (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2 - 2 \frac{y_0}{\sigma_{c0}^2} \frac{x_0}{\sigma_{c0}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} \sum \frac{y_i^2}{\sigma_{ci}^2} + \frac{x_0^2}{\sigma_{c0}^4} (\sum \frac{y_i^2}{\sigma_{ci}^2})^2) \sigma_{c0}^2 + \cdots}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.7}$$

$$= \frac{\sqrt{(\frac{y_0^2}{\sigma_{c0}^2} (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2 - 2 \frac{y_0}{\sigma_{c0}} \frac{x_0}{\sigma_{c0}} \sum \frac{x_i y_i}{\sigma_{ci}^2} \sum \frac{y_i^2}{\sigma_{ci}^2} + \frac{x_0^2}{\sigma_{c0}^2} (\sum \frac{y_i^2}{\sigma_{ci}^2})^2) + \cdots}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.8}$$

$$= \frac{\sqrt{\sum \frac{y_i^2}{\sigma_{ci}^2} (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2 - 2 \sum \frac{y_i x_i}{\sigma_{ci}^2} \sum \frac{x_i y_i}{\sigma_{ci}^2} \sum \frac{y_i^2}{\sigma_{ci}^2} + \sum \frac{x_i^2}{\sigma_{ci}^2} (\sum \frac{y_i^2}{\sigma_{ci}^2})^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.9}$$

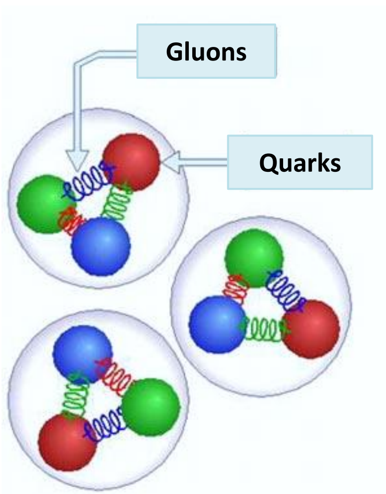
$$= \frac{\sqrt{- \sum \frac{y_i^2}{\sigma_{ci}^2} (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2 + \sum \frac{x_i^2}{\sigma_{ci}^2} (\sum \frac{y_i^2}{\sigma_{ci}^2})^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.10}$$

$$= \frac{\sqrt{\sum \frac{y_i^2}{\sigma_{ci}^2} (\sum \frac{x_i^2}{\sigma_{ci}^2} \sum \frac{y_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2)}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2} \tag{7.11}$$

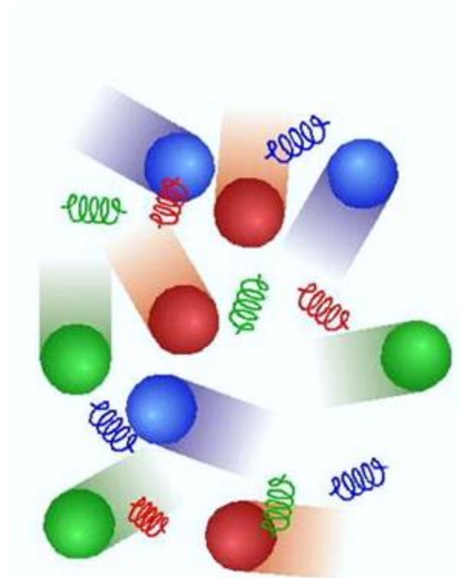
$$= \sqrt{\frac{\sum \frac{y_i^2}{\sigma_{ci}^2}}{\sum \frac{y_i^2}{\sigma_{ci}^2} \sum \frac{x_i^2}{\sigma_{ci}^2} - (\sum \frac{x_i y_i}{\sigma_{ci}^2})^2}} \tag{7.12}$$

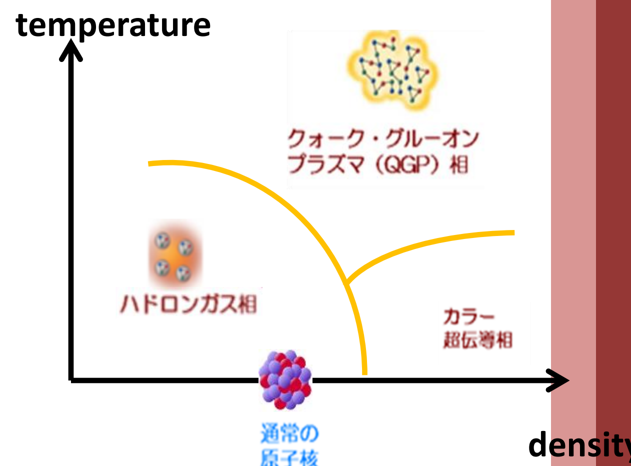
QGP

QGP (quark-gluon-plasma) is a state in which in a few μ seconds immediately after the big bang, quarks and gluons aren't bind as nucleons.



High temperature density





考えられている、相の状態の様子

Quarks and gluons are bind as nucleons.

Quarks and gluons aren't bind as nucleons.
＝QGP

QGP can be made by using high energy heavy ion collision, because matter can reach high temperature of QGP!