Measurement of Azimuthal Anisotropy and the QGP

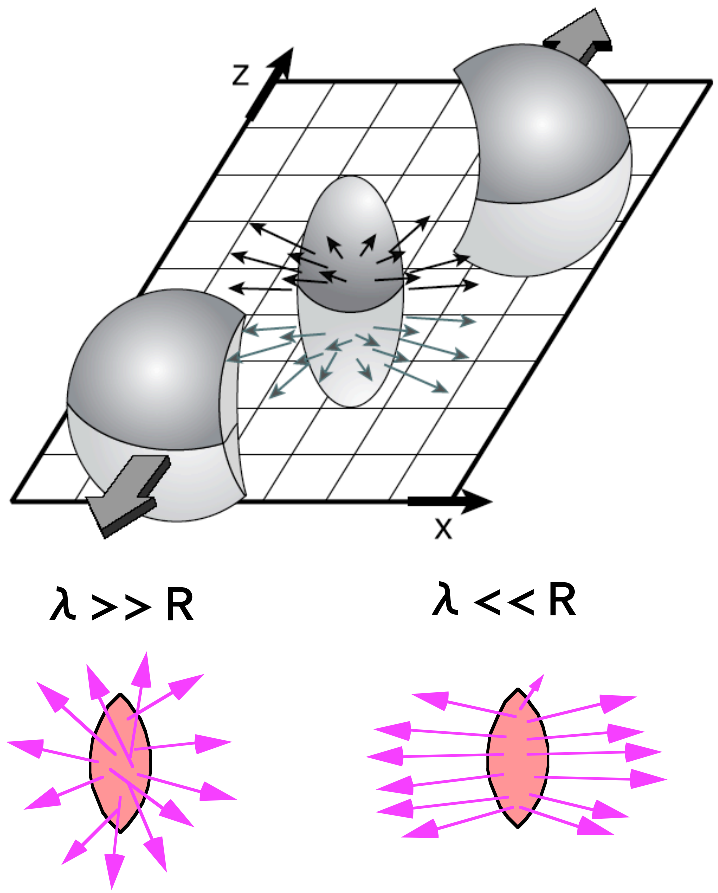
Yasuo MIAKE, Univ. of Tsukuba

i) What is azimuthal anisotropy
ii) How it is measured
iii) What is learned

Part 1

What is azimuthal anisotropy

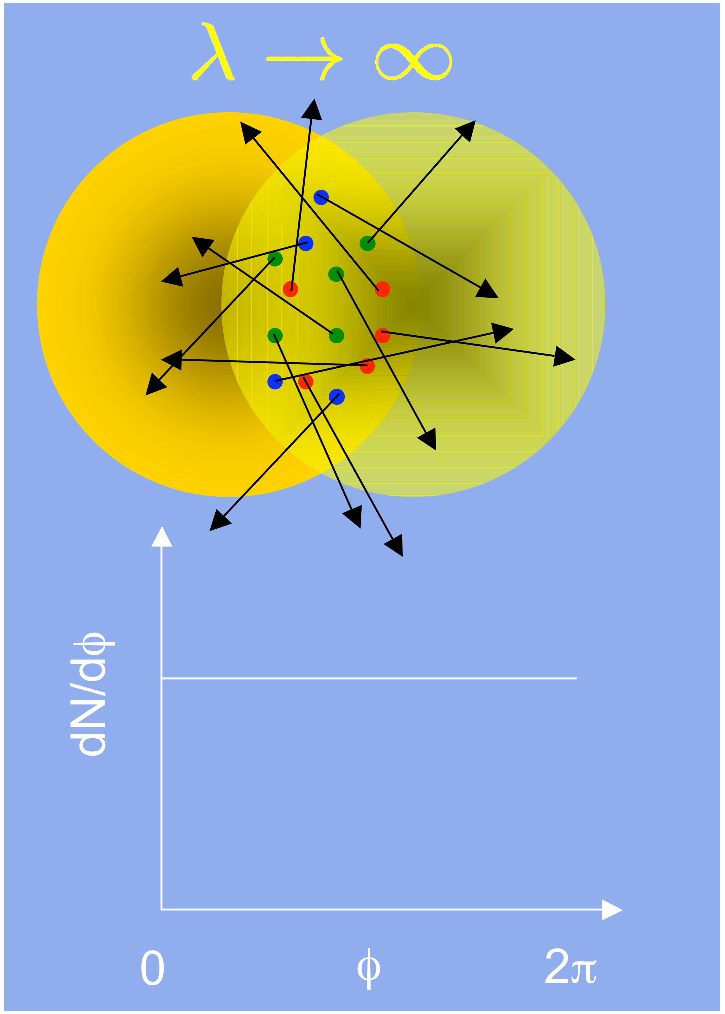
Azimuthal anisotropy

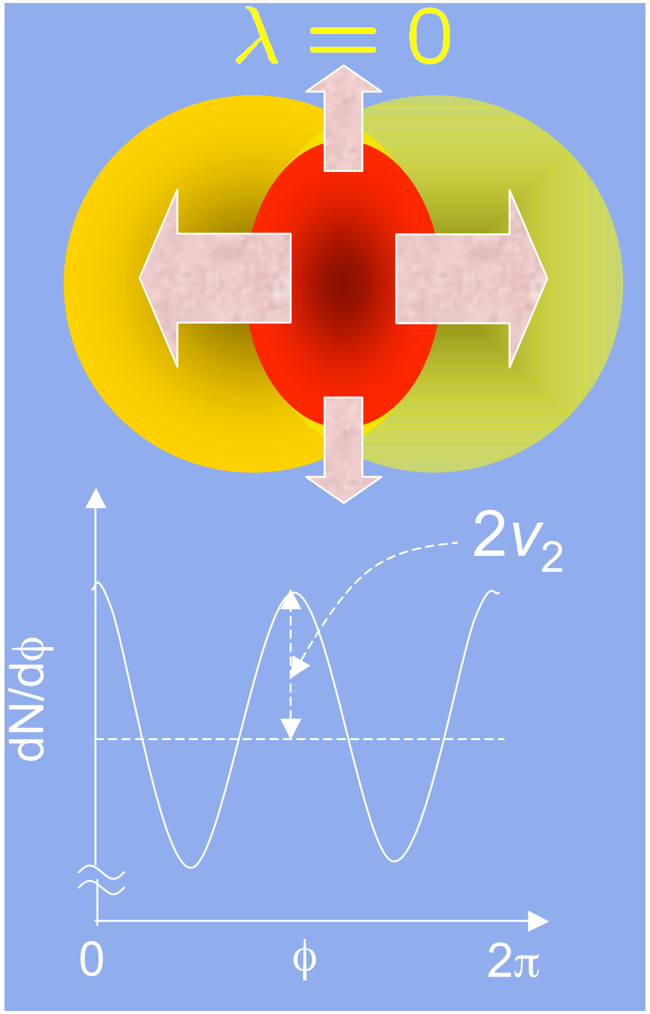


J.Y. Ollitrault, P.R.D48('93)1132

- In non-central col., participant has almond shape at initial stage.
  - ie., anisotropy in coordinate space
- Emission of particle in azimuth is influenced by λ & R relation.
  - *$\lambda >> R$; isotropic*
  - *$\lambda << R$; hydro.➔elliptic*
    - *Anisotropy of the coordinate space converted to that of the momentum space.*
- *Conversion of anisotropy from coordinate space to momentum space*

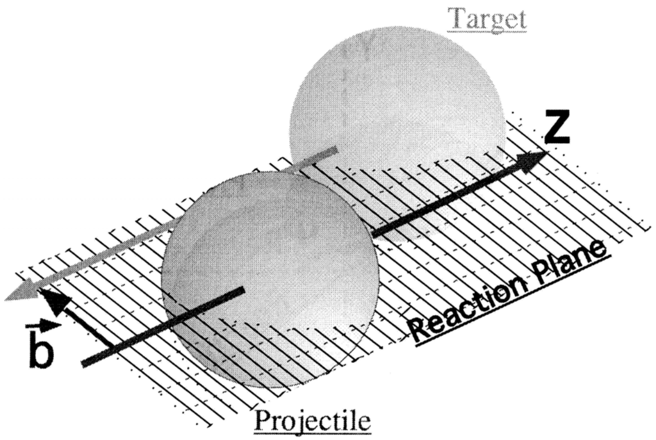
Azimuthal distr wrt reaction plane





- Evaluate as Fourier components

Evaluation with Fourier exp.

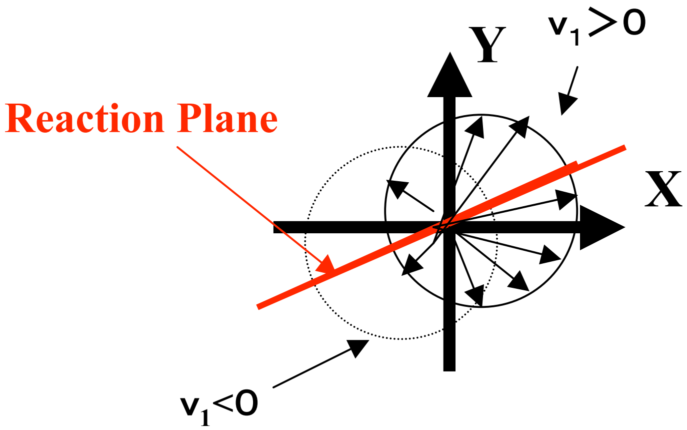


- Obtain azimuthal distributions w.r.t. the reaction plane.
- Evaluate the distribution with Fourier components

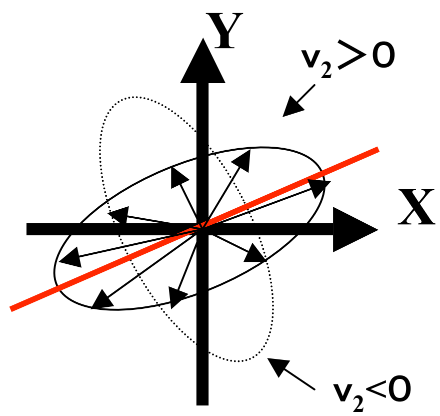
$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi_0) + 2v_2\cos(2(\phi - \Psi_0))\}$$

Fourier harmonics

1st harmonics
"Directed Emission"



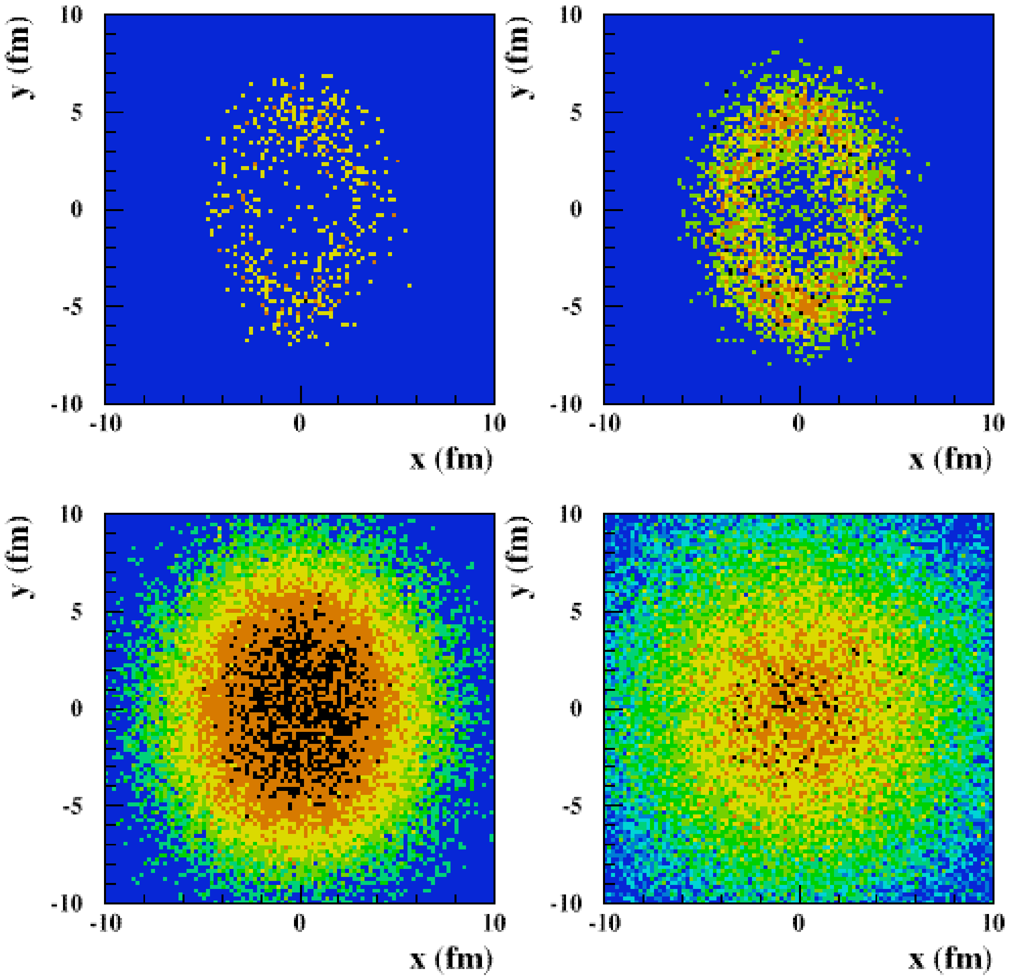
2nd harmonics
"Elliptic Emission"



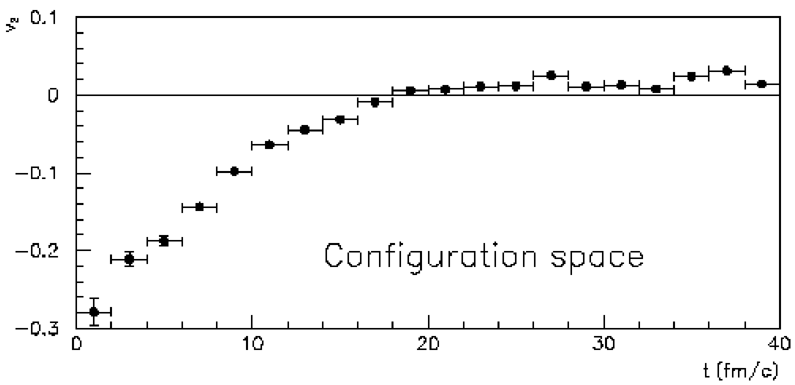
$$v_1 = \langle \cos(\phi - \Phi_R) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle \qquad v_2 = \langle \cos 2(\phi - \Phi_R) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Sensitivity to the early stage

RQMD



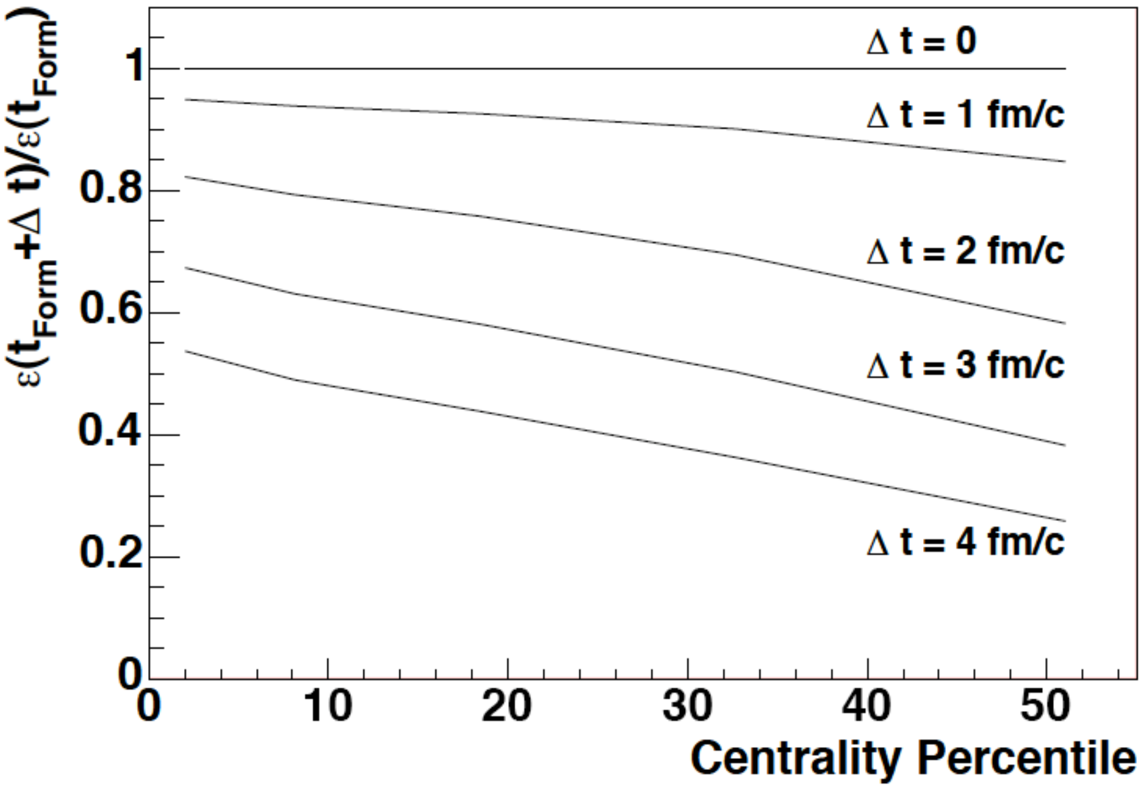
- Anisotropy in coordinate space disappears quickly
- Direct measure of the conversion mechanism



Y.Miake, KPS meeting at APCTP in Pohang, 2005

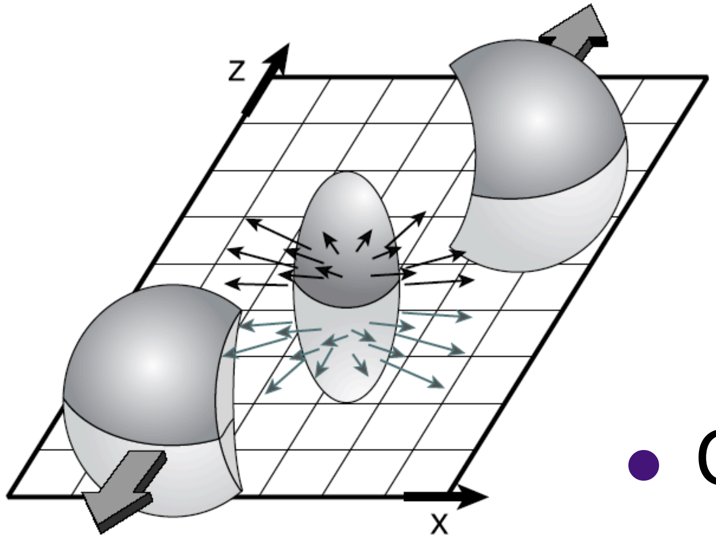
Expect Eccentricity to disappear quickly

Kolb et.al., PRC62(2000)054909



- Ratio of eccentricity after a time delay
  - Disappears quickly
  - ➔ v_2 senses early stage of collision

Reasons why I like v_2



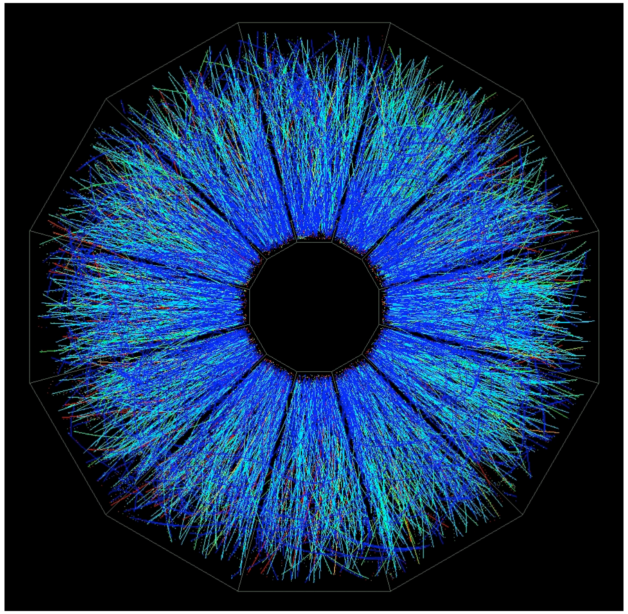
$$\varepsilon_{ecc} = \left\langle \frac{x^2 - y^2}{x^2 + y^2} \right\rangle \qquad v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

- Clear origin of the signal !
  - Geometry is clear
  - From eccentricity to v_2
  - Centrailty dependence gives good tests
- Sensitivity to the early stage of collisions !
  - Mean free path λ vs. R

Part 2

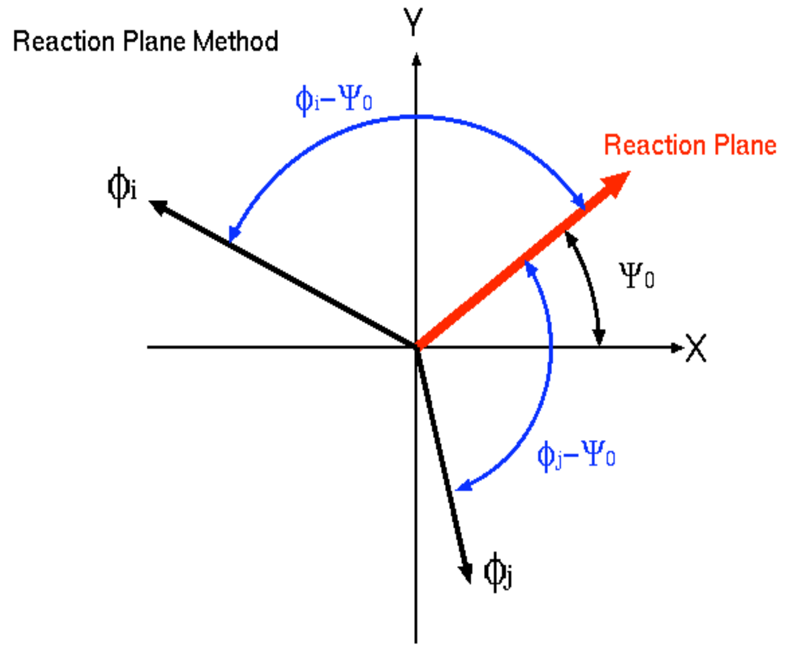
How it is measured

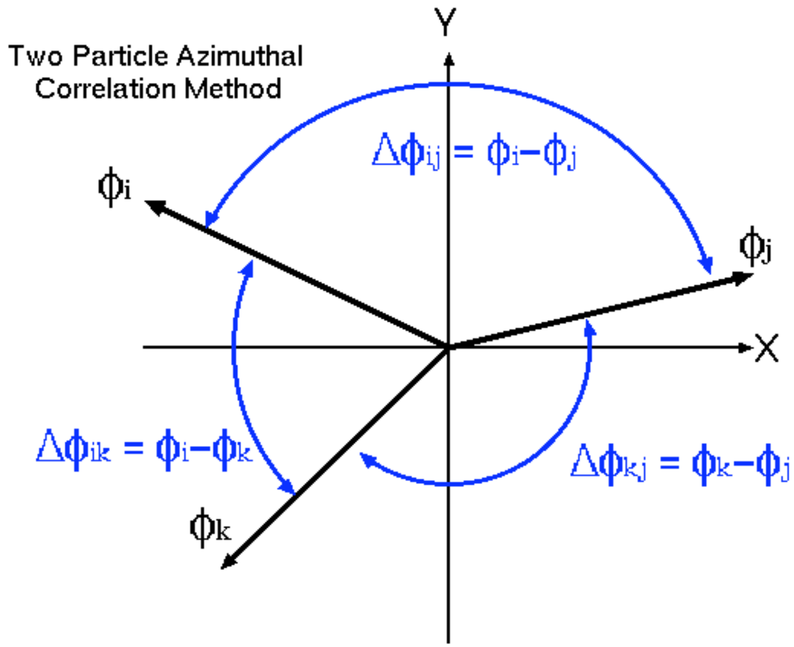
How it is analyzed



- Three methods;
  - Pairwise Method
  - Cumulant Method
  - Reaction Plane Method

Two Methods

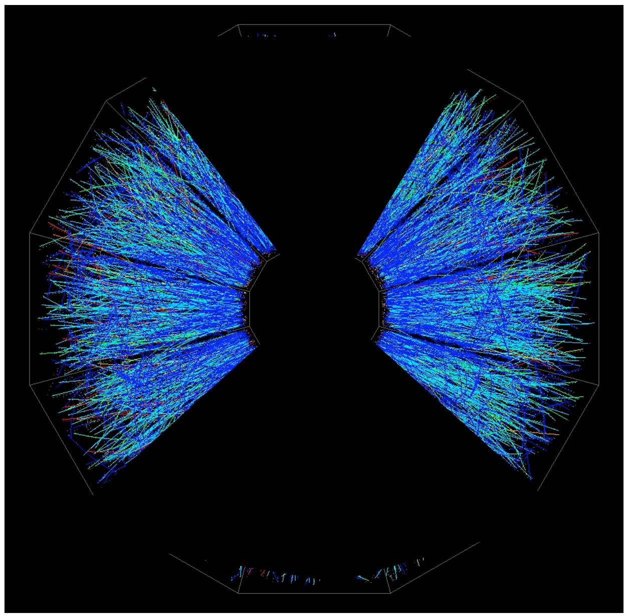


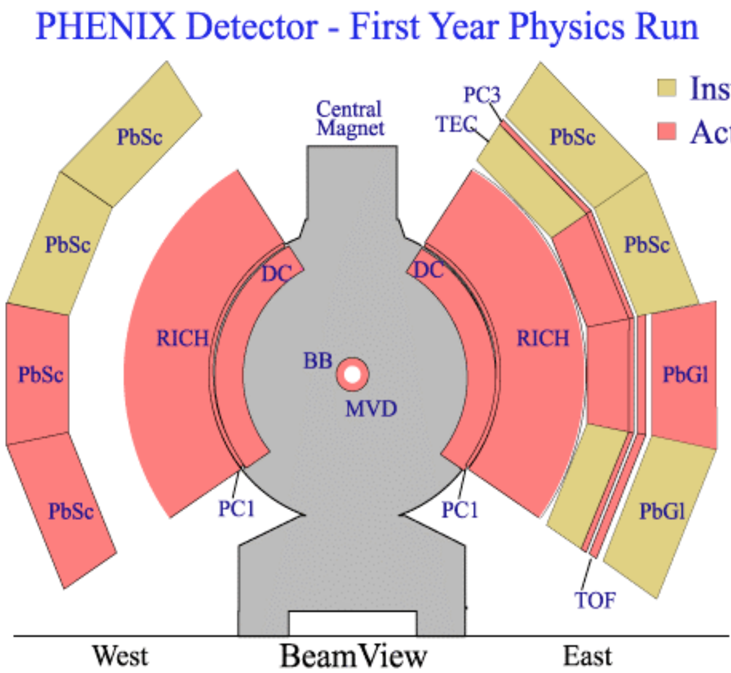


- Reaction Plane Method
  - Event by event determination of R.P.
  - Once the R.P. is established, easier to apply other particle species.
- Pairwise Method
  - No Reaction Plane.
  - Measure azimuthal corr. of all the pairs
  - Small effects ~v_2**2, but high statistics

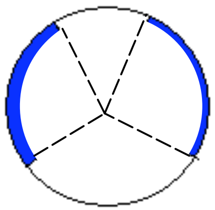
Analyze me

- PHENIX; non-uniform in azimuth
- How it works?





R. P. method & flattening corr.

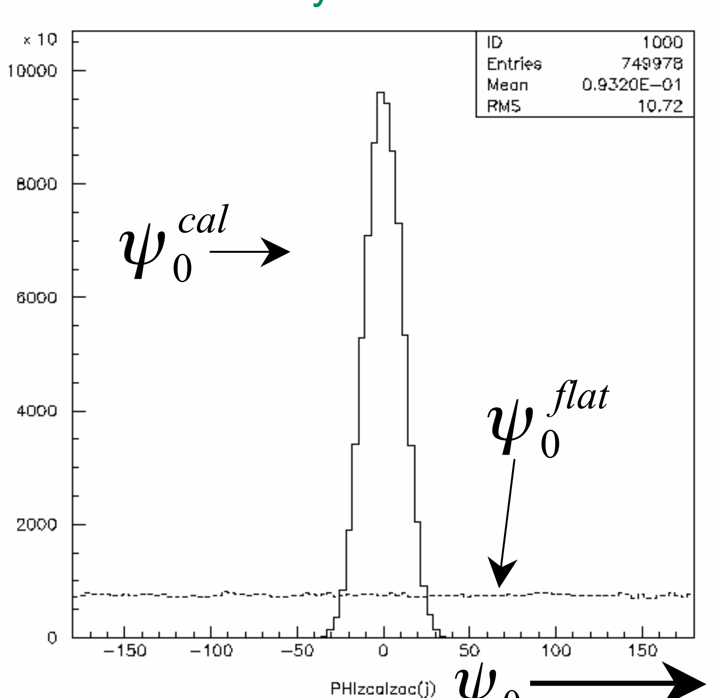


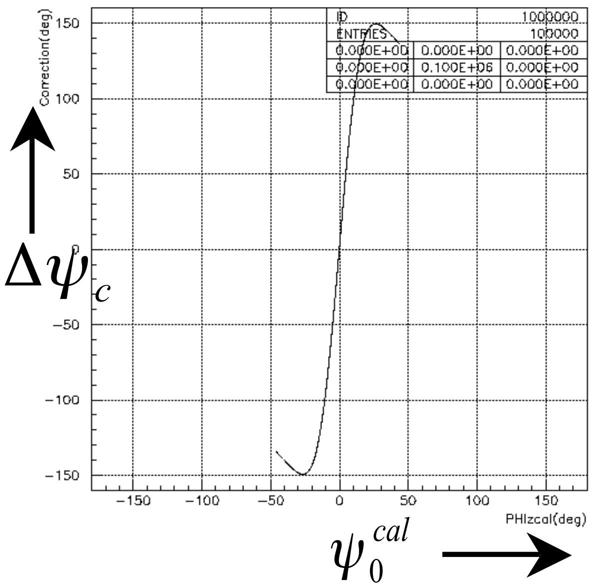
Azimuthal acceptance of PHENIX

$$\tan 2\psi_0^{cal} = \frac{\langle \sin 2\phi_I \rangle}{\langle \cos 2\phi_I \rangle}$$

- Determine azimuthal direction of R.P. every event
  - Define average of azimuthal angles of all the measured particles as R.P.
  - Most probable direction as R.P.
    - Artificial peak due to detector acceptance !
- Flattening the peak

Toy Simulation





$$\Delta\psi_c = \sum_n (A_n \cos(2n\psi_0^{cal}) + B_n \sin(2n\psi_0^{cal}))$$

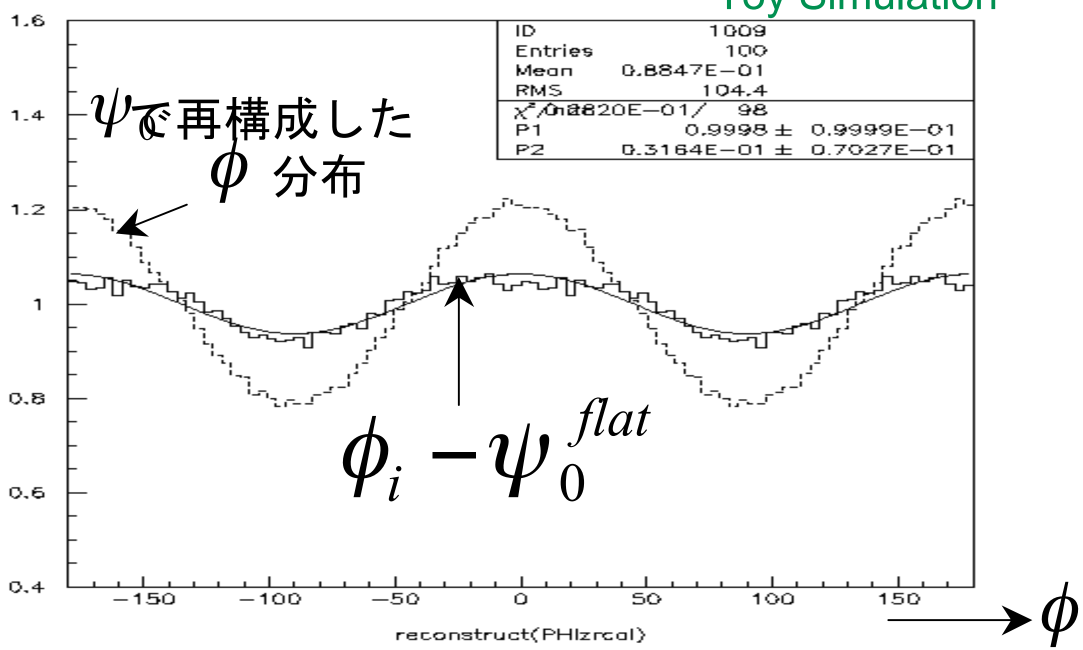
$$A_n = -\frac{2}{n}\langle \sin(2n\psi_0^{cal}) \rangle$$

$$B_n = \frac{2}{n}\langle \cos(2n\psi_0^{cal}) \rangle$$

$$\psi_0^{flat} = \psi_0^{cal} + \Delta\psi_c$$

Flattening corr. works for PHENIX

Toy Simulation



- Toy simulation assuming
  - PHENIX acceptance
  - v_1, v_2
  - multiplicity
- After resolution corr., v_2 can be reconstructed successfully
- It works!

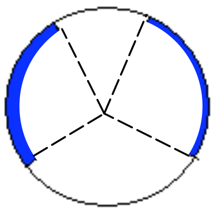
Resolution of R. P.

$$\left\langle \cos 2(\psi_0 - \psi_0^{flat}) \right\rangle = 0.309$$

$$v_2 = 0.1$$ ⇒ 解析 $$v_2 = \frac{v_2^{Fitting}}{\text{Resolution}} = 0.102 \pm 0.01$$

Ｈ１２・筑波大・卒業論文・進藤美紀

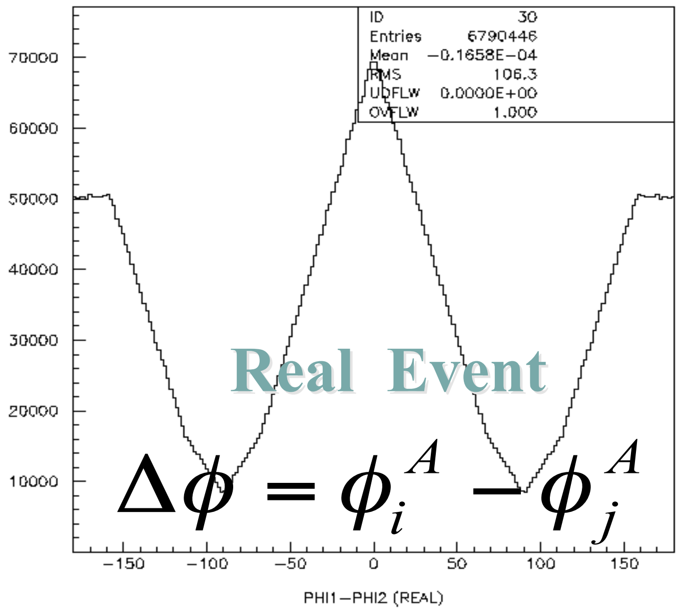
Pairwise Method & Acc. Corr.

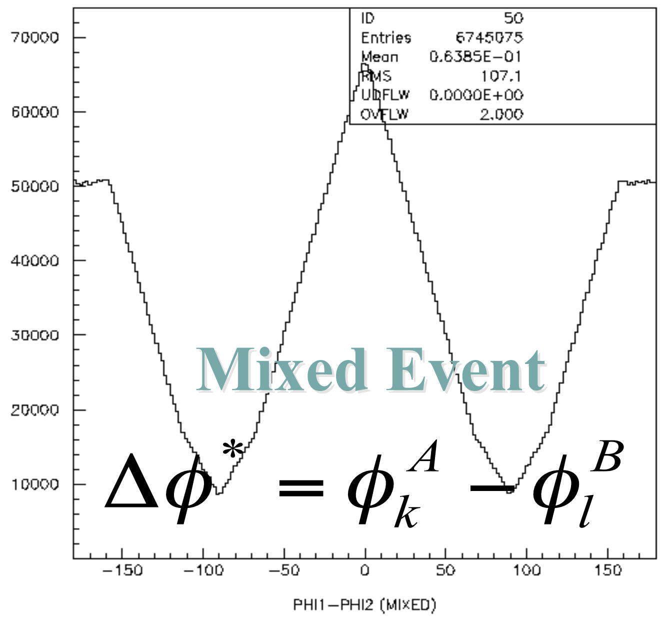


Azimuthal acceptance of PHENIX

- Azimuthal corr of all the measured particle pairs
  - Acceptance dominates the shape of distribution
- Effect of acceptance is evaluated by mixed event

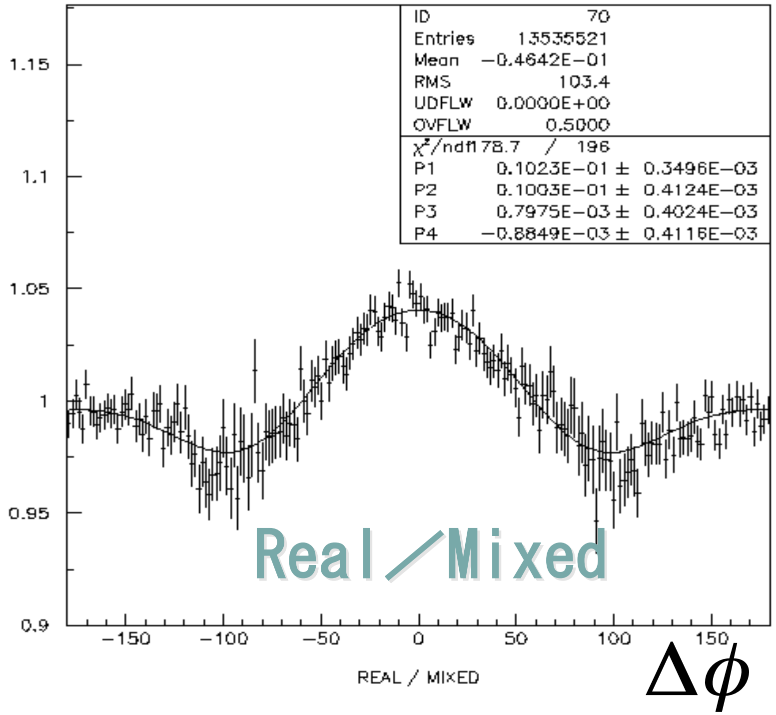
Toy Simulation





Ｈ１２・筑波大・卒業論文・進藤美紀

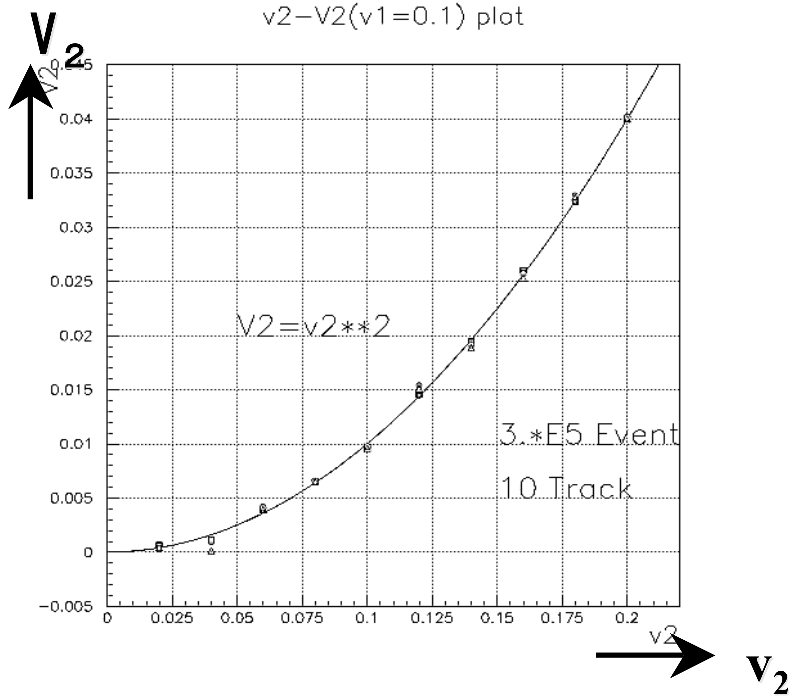
Pairwise method works!



$$V_2 = 0.100 \times 10^{-1} \pm 0.40 \times 10^{-3}$$

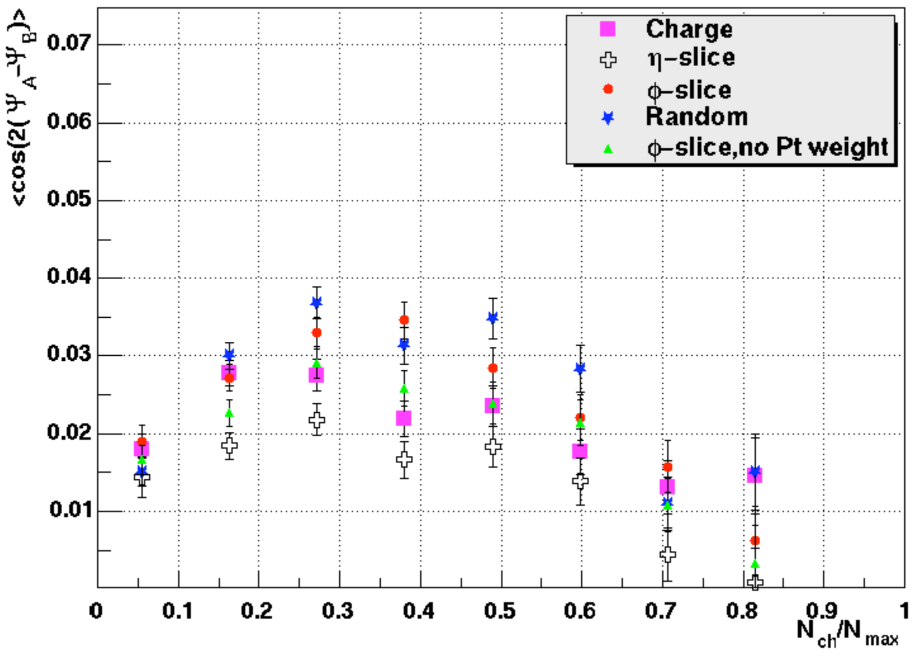
$$F(x) = F_0(1 + 2V_1 \cos x + 2V_2 \cos 2x)$$

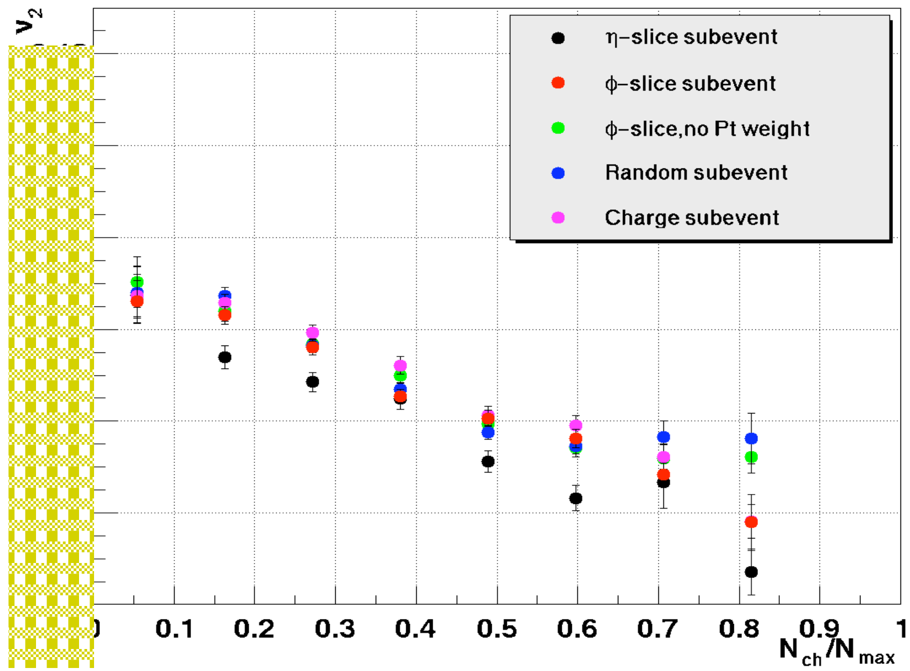
- Toy simulation assuming
  - PHENIX acceptance
  - v_1, v_2
  - multiplicity
- Observed anisotropy $= v_2$**2
- Good agreement with the input



Stability of results

Toy Analysis



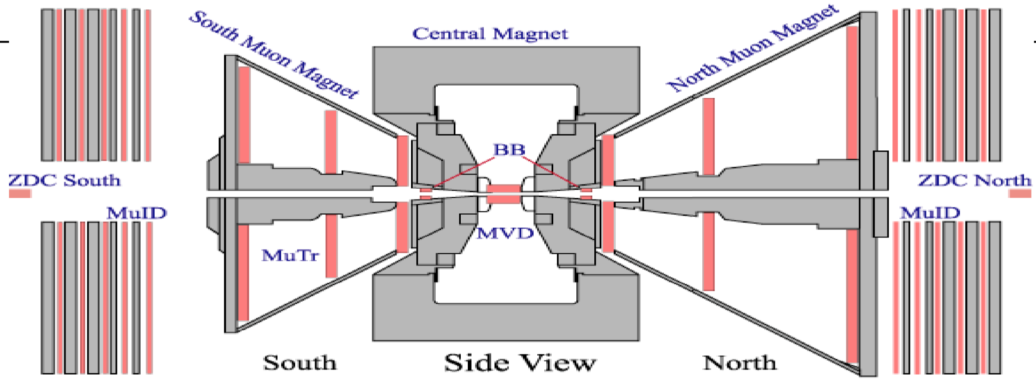


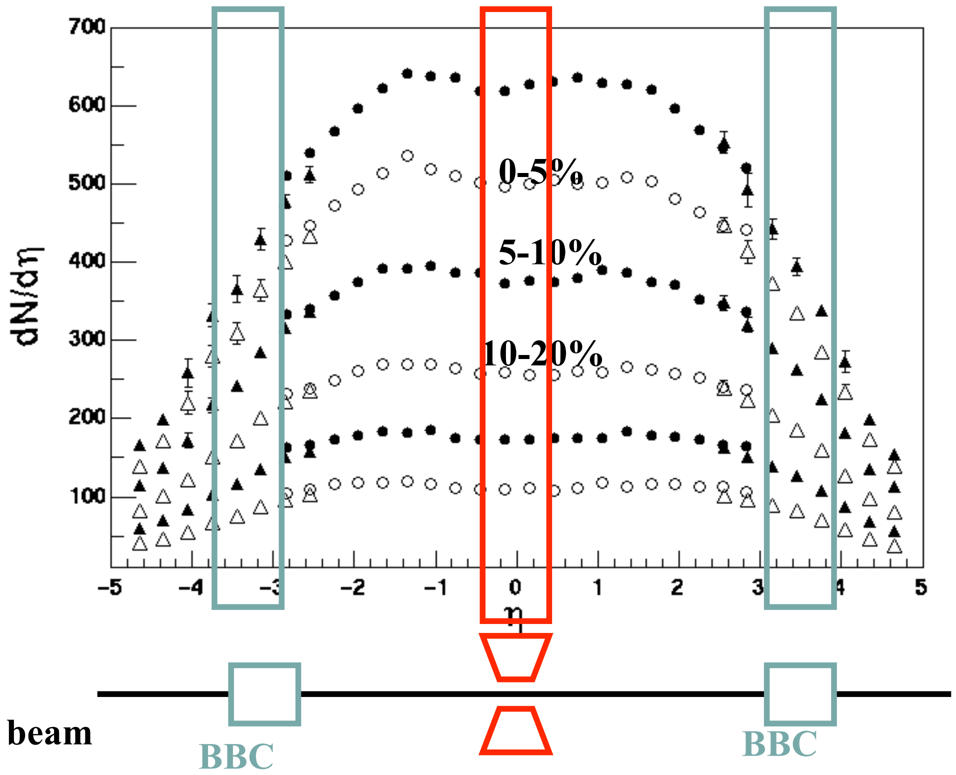
- With smaller acceptance, weaker effect observed.
  - Poorer resolution
- But, after resolution correction, consistent results obtained.

Conclusion of Toy model study

- Even with PHENIX acceptance, we obtain consistent results both from R.P. method and Pairwise method, if they are pure elliptic flow.
- We might get different results if there are
  - higher harmonics
  - non-flow effect such as HBT, particle decay, kinematical correlations
- Reliable determination of R.P. is more important !
  - avoid non-flow effect as much as possible
    - Take wide rapidity gap from central detector
      - ***→BBC as main R.P. detector***

Towards reliable R.P.



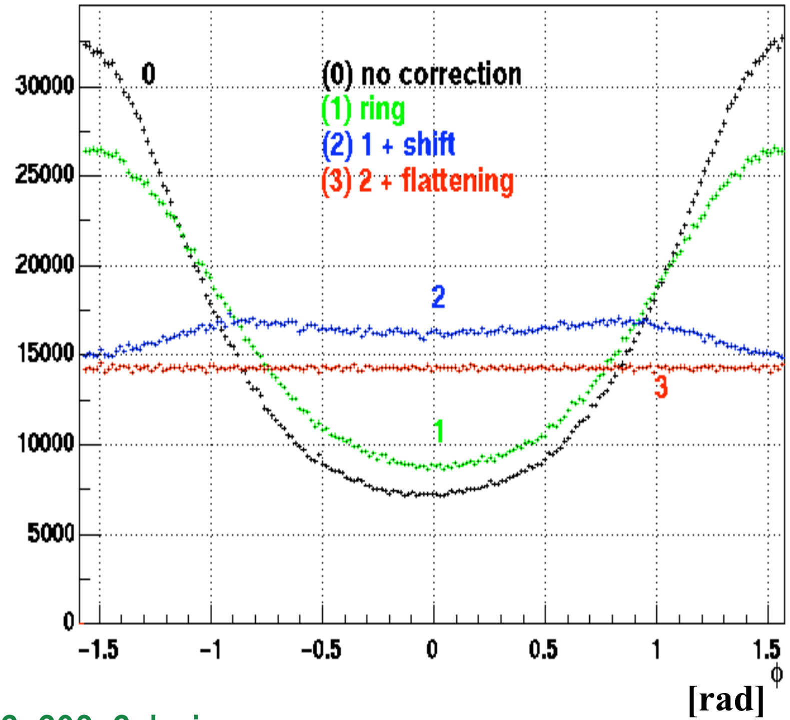


Beam Beam Counter (BBC)
$|\eta|$=3-4

- Wide rapidity gap from central detector
- Full Azmuthal Coverage
- Enough multiplicity for resolution

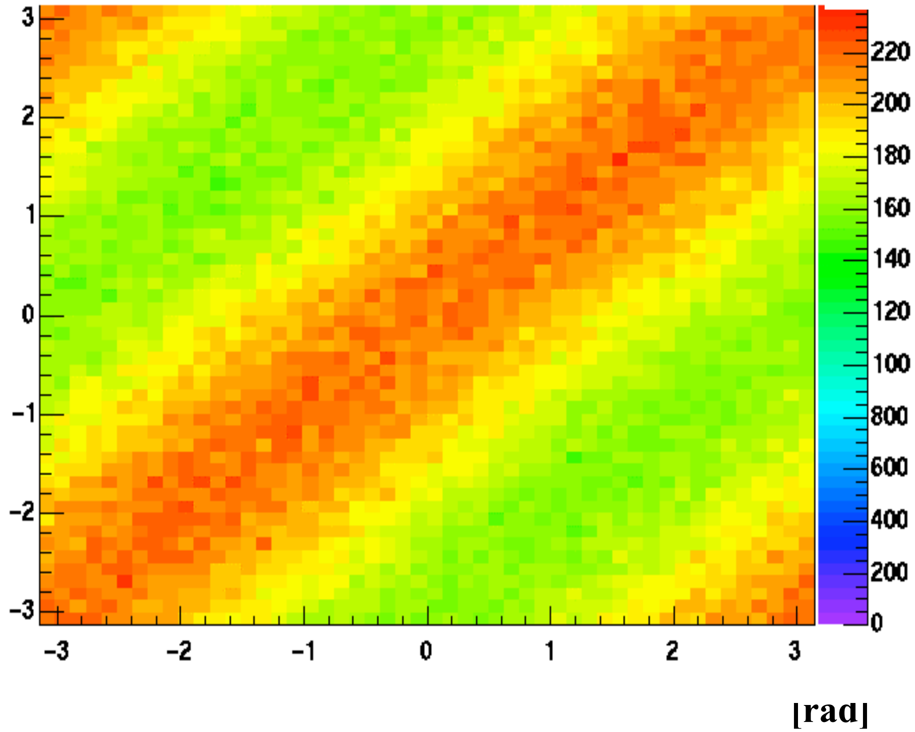
R.P. from BBC

Reaction plane distribution



Correlation of two reaction plane

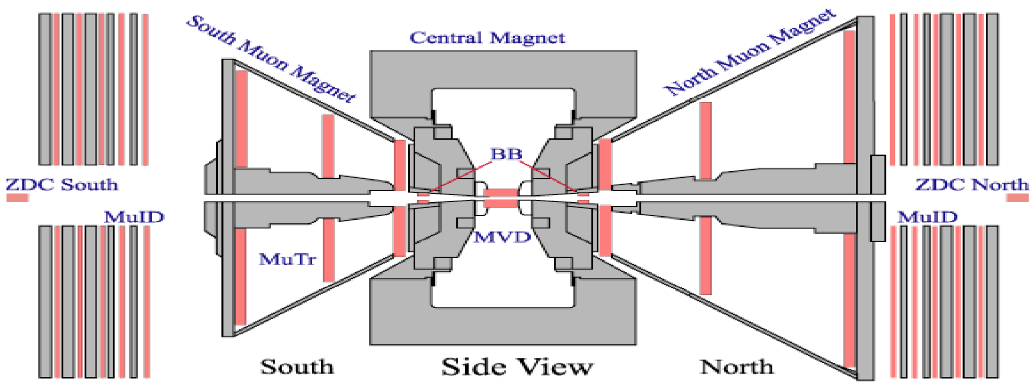
BBC north v.s south

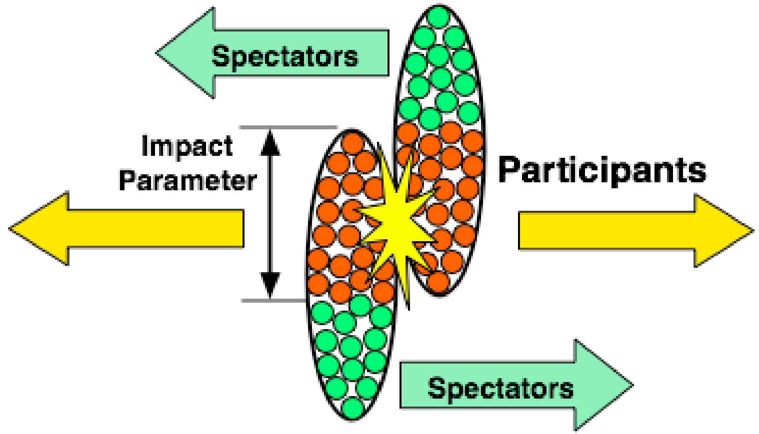


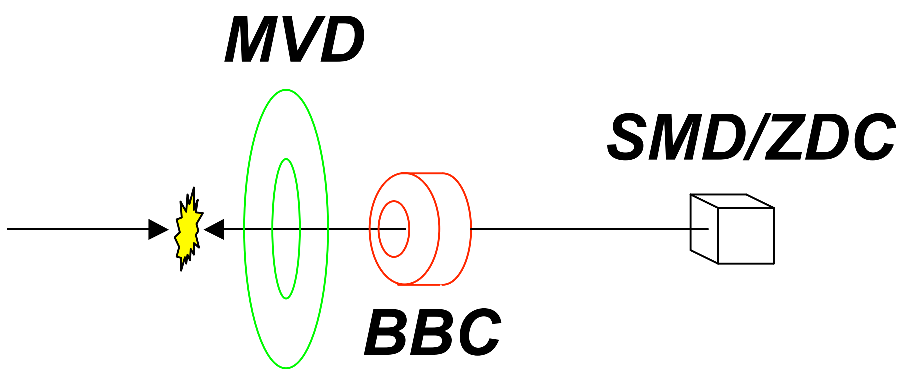
JPS-S02-Sakai

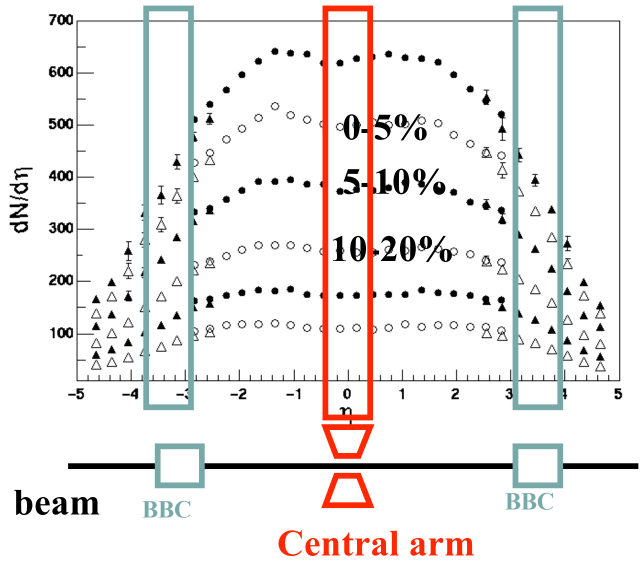
- Clear and consistent correlation among two BBC's.

Further R.P. studies



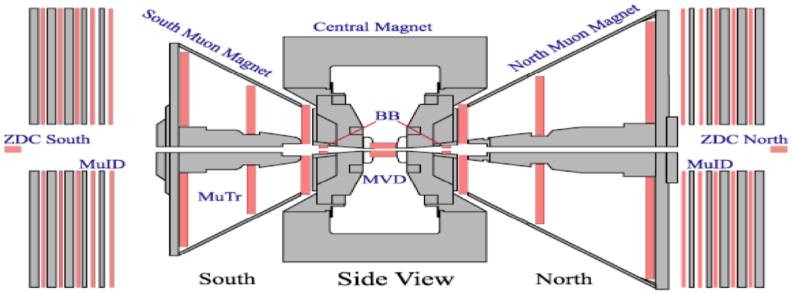




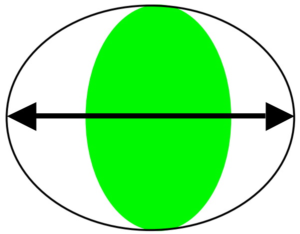


- To establish R.P., need to confirm global(whole event) correlations

R.P. from elliptic flow



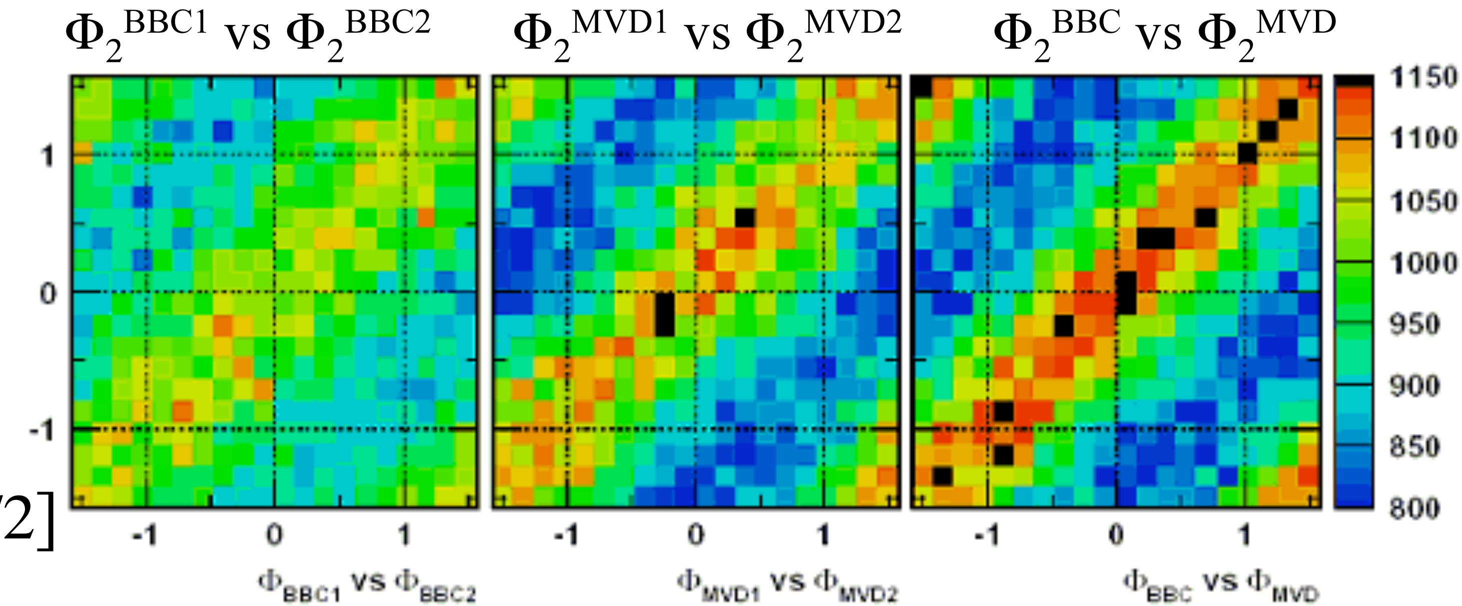
Phenix; S.Esumi JPS/DNP 2005



Participant Region

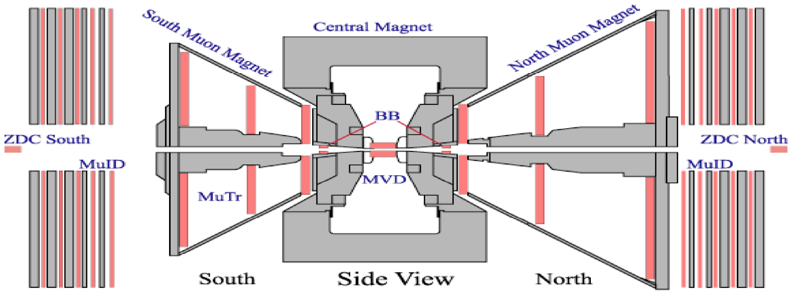
elliptic plane

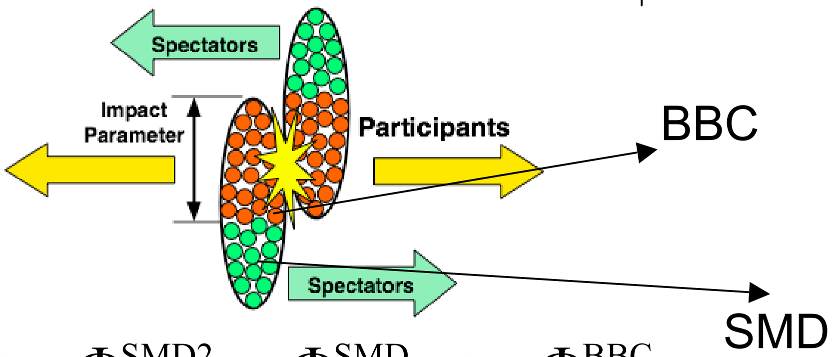
$[-\pi/2,\pi/2]$

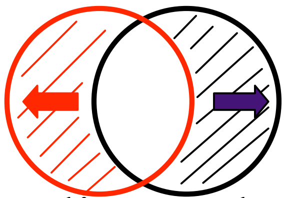


- Better resolution with MVD since wider acceptance
- Confirm clear event-wide correlations among detectors

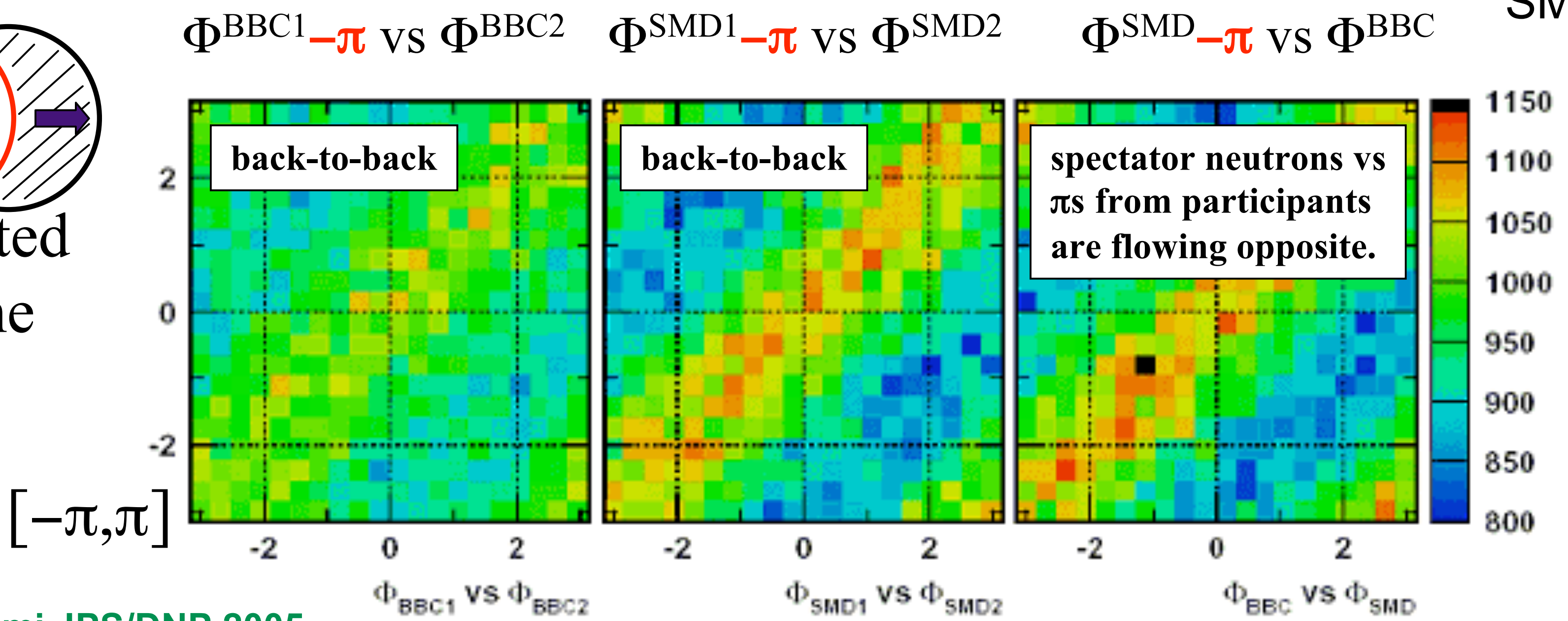
R.P. from directed flow







directed
plane

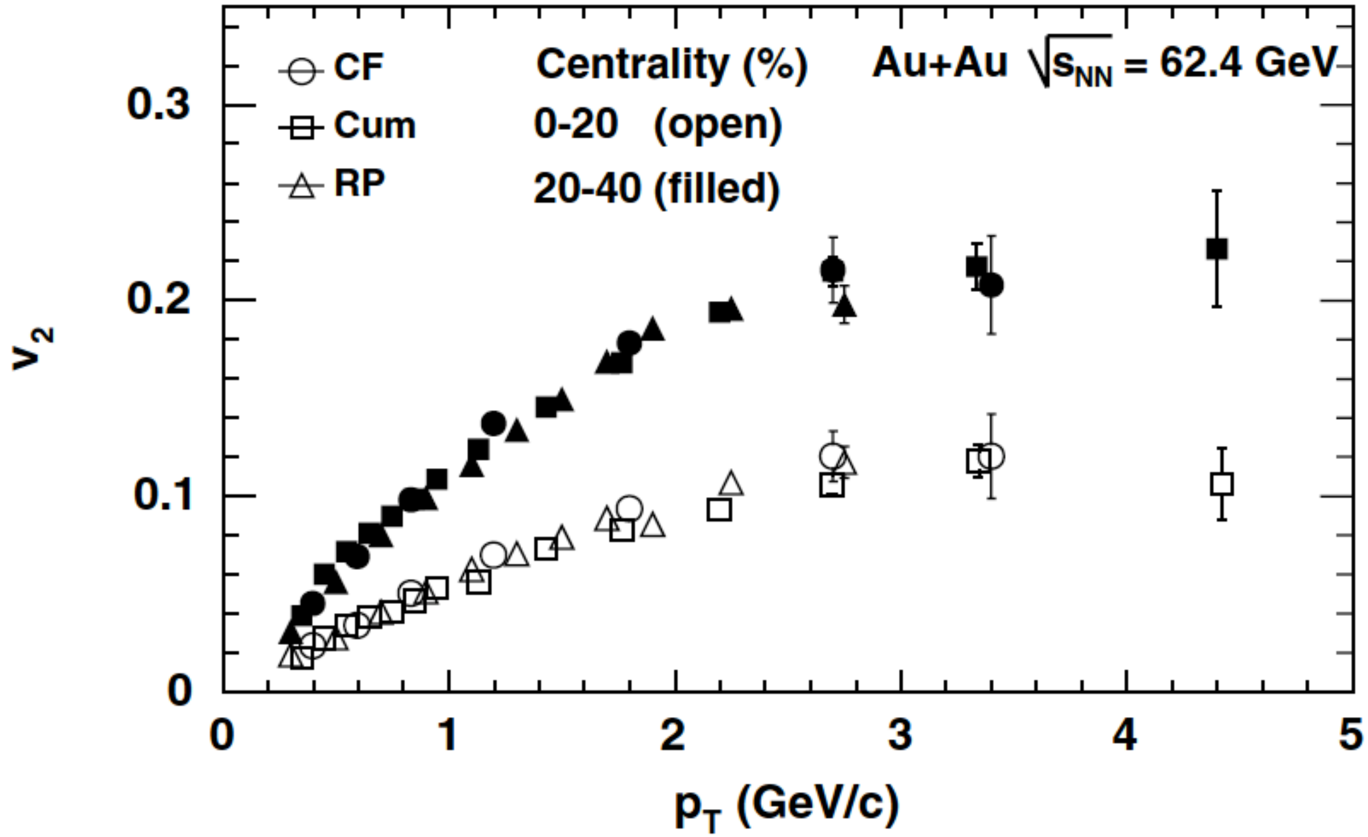


Phenix; S.Esumi JPS/DNP 2005

- Clear correlation between SMD(spect) and BBC(part) in v1
  - As seen at SPS, back-to-back corr of Neutrons and Pions.

Comparison of three methods

Phenix; P.R.L. 94, 232302(2005)

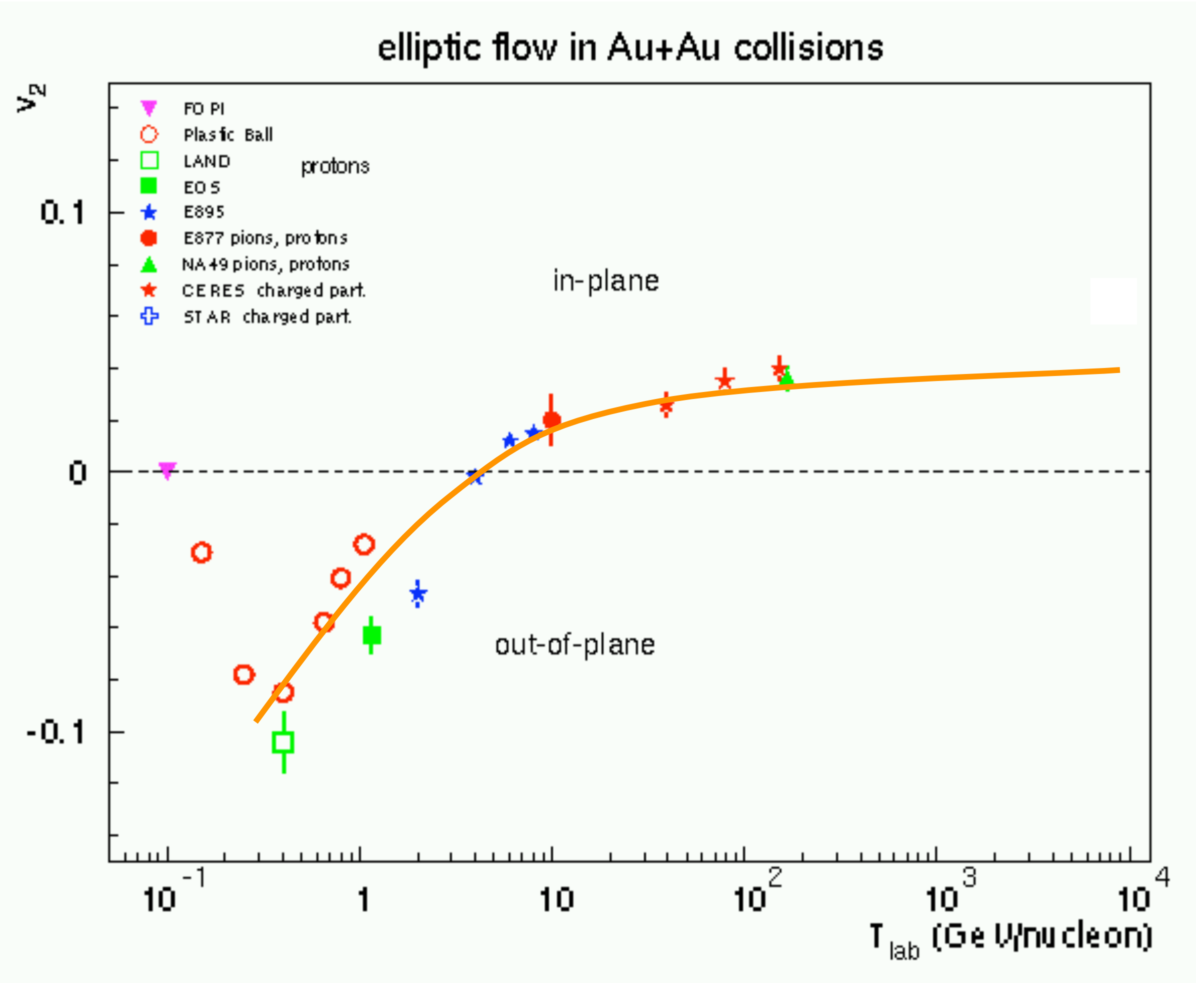


- Striking agreement (!) even with R.P. method.
  - No strong non-flow effect !?

Part 3

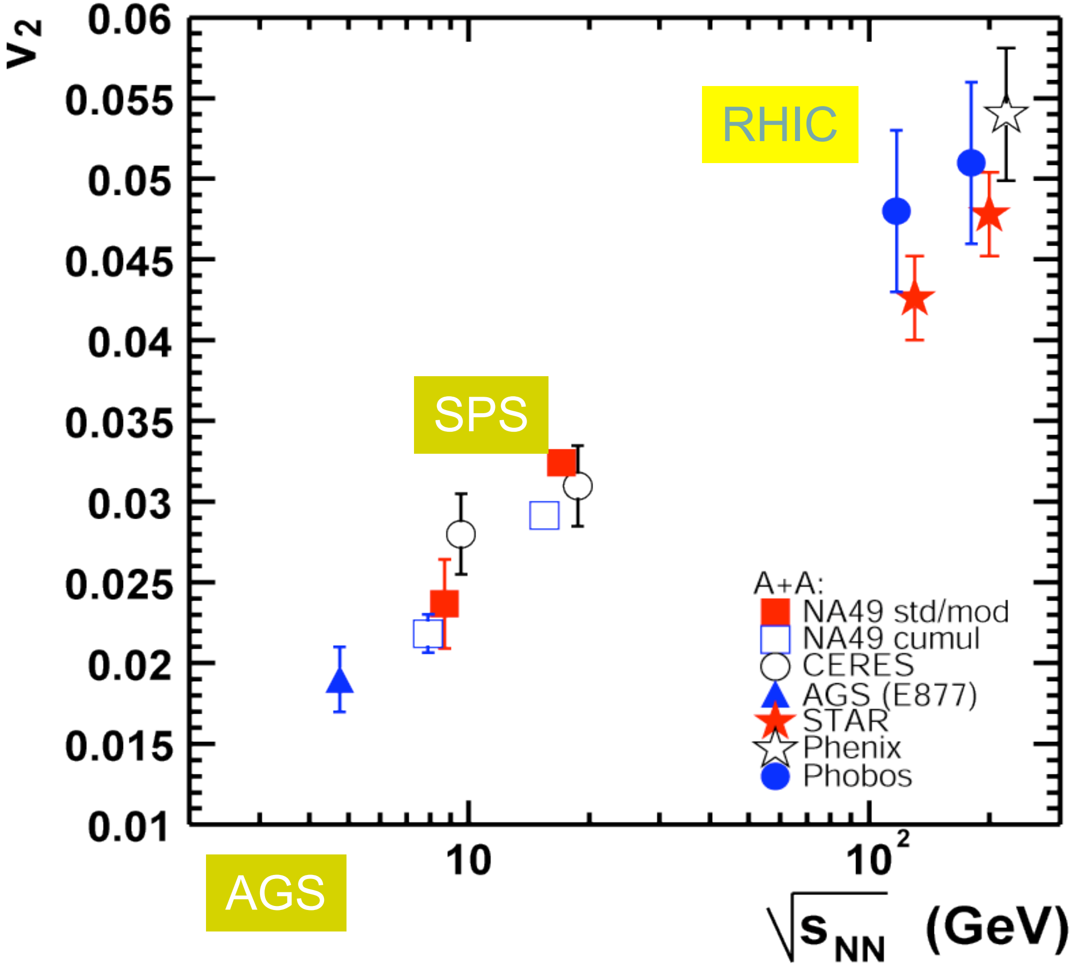
What is learned

What we expected before RHIC



- There is a tendency of saturation!?
- Hadron cascade predicts a few %.

Surprise !

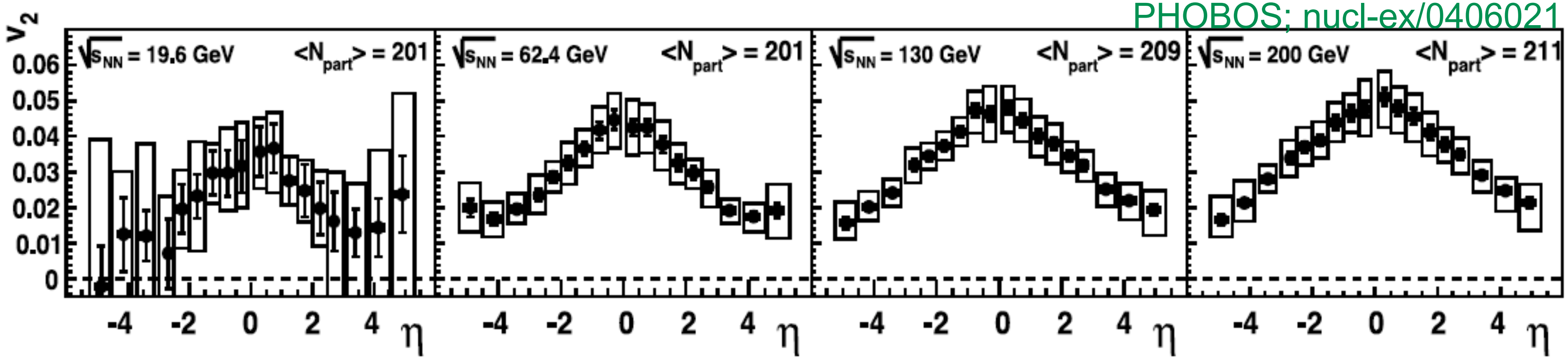


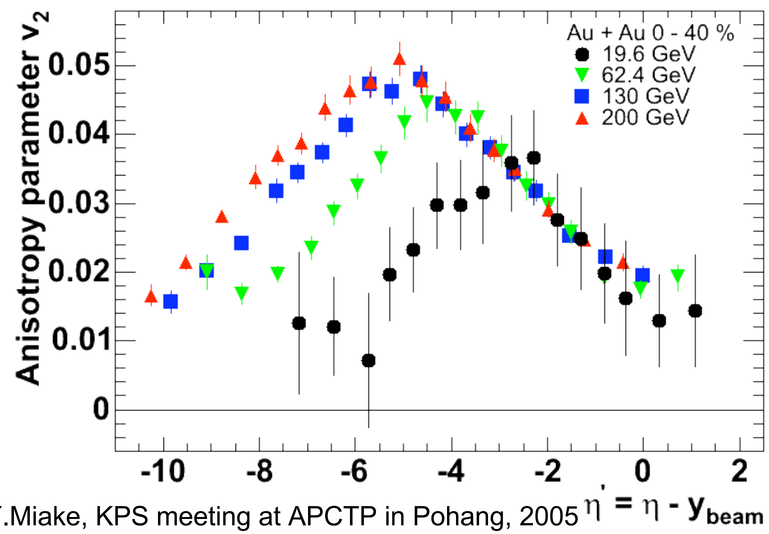
- Early compilation

Large azimuthal anisotropy

$$N(\phi) = N_0\{1 + 2v_1\cos(\phi - \Psi_0) + 2v_2\cos(2(\phi - \Psi_0))\}$$

PHOBOS; nucl-ex/0406021



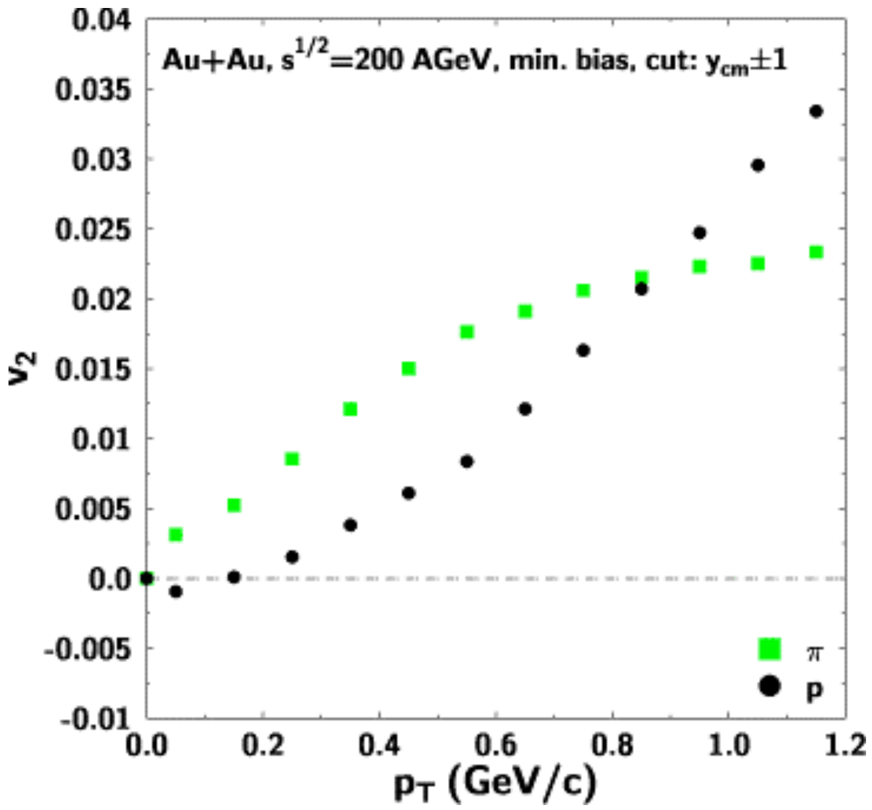


Y.Miake, KPS meeting at APCTP in Pohang, 2005

- Larger in higher energies.
  - Scaling w. η-y_{beam} !?
- As high as 5%

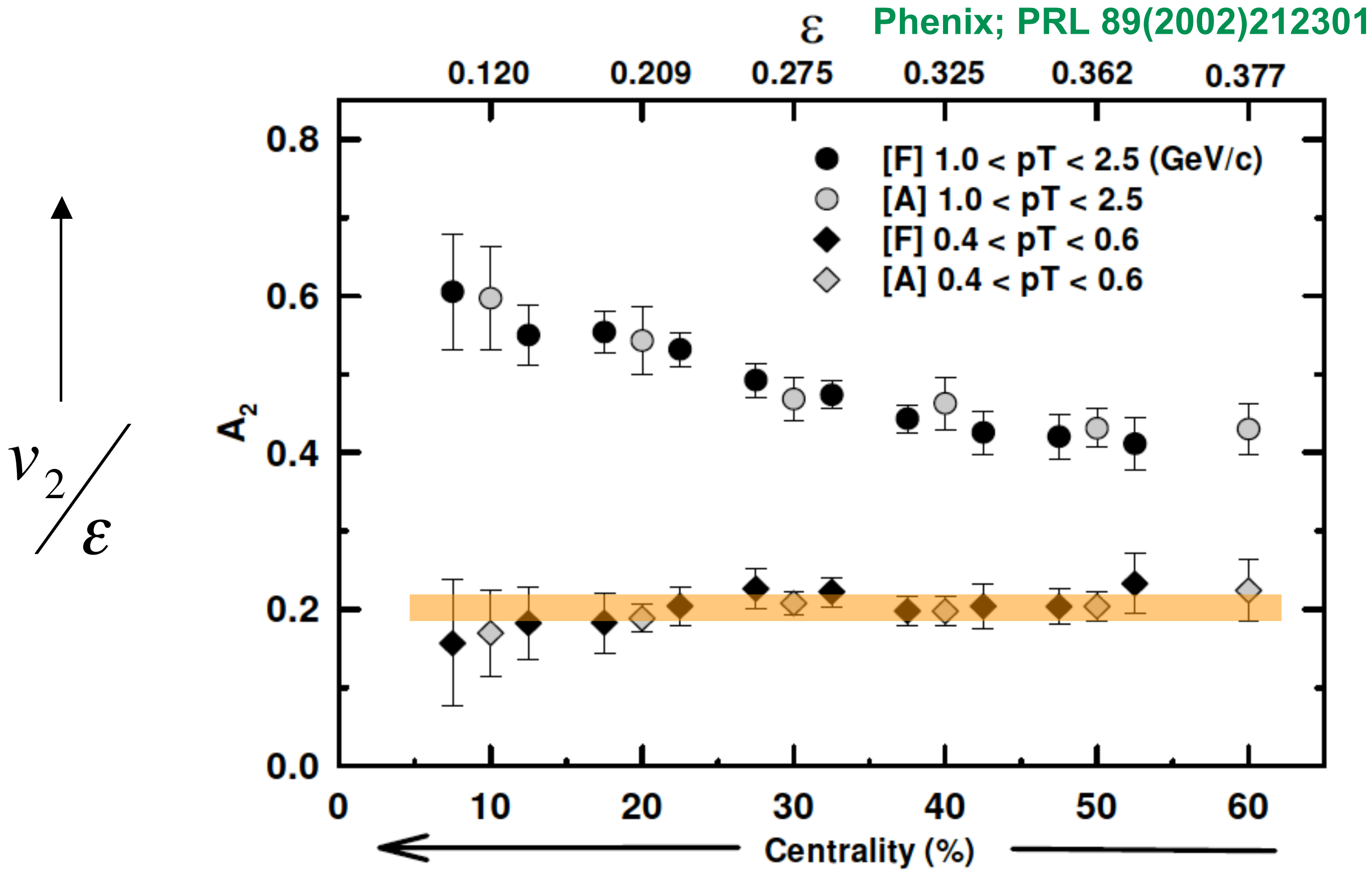
Failure of hadronic scenarios

M. Bleicher, H. Stocker Phys. Lett. B526 (2003) 309



- Hadronic scenario underestimates v_2 at RHIC.
  - $v_2 \sim 1 - 2\ \%$
- System thermalized early with the mechanism other than hadronic rescatterings.

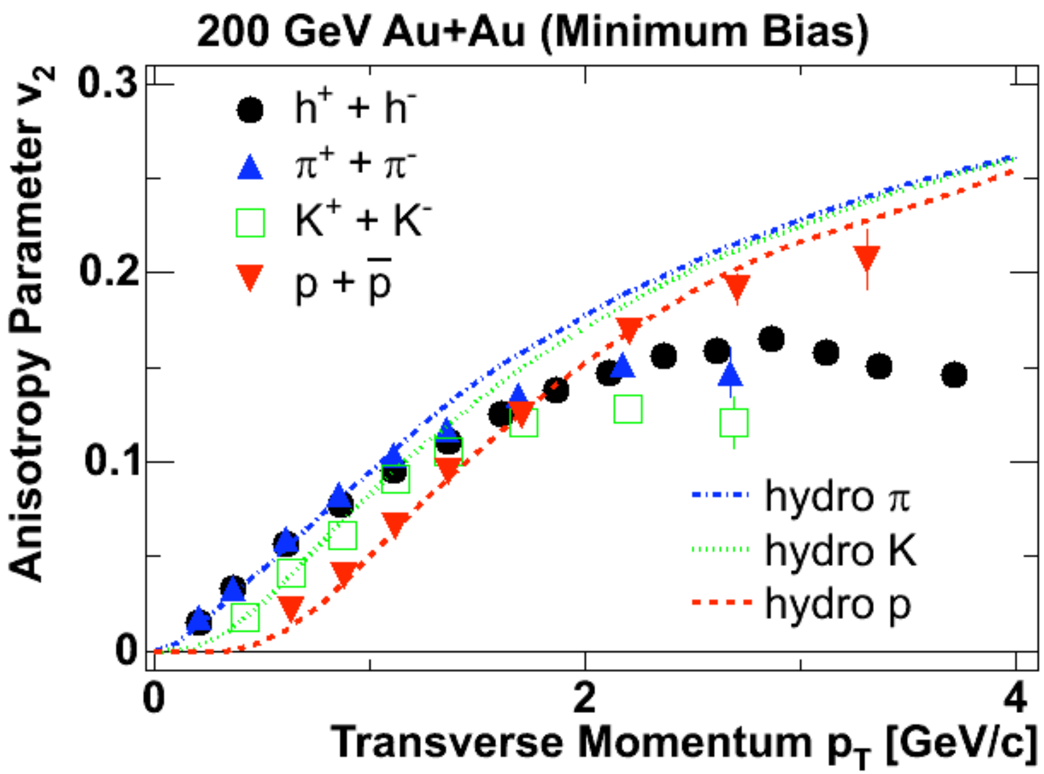
v_2 vs. Eccentricity



- At low pt region, the ratio stays ~constant
  - ➔Scaling with eccentricity shows v_2 builds up at early stage

Success of hydrodynamics

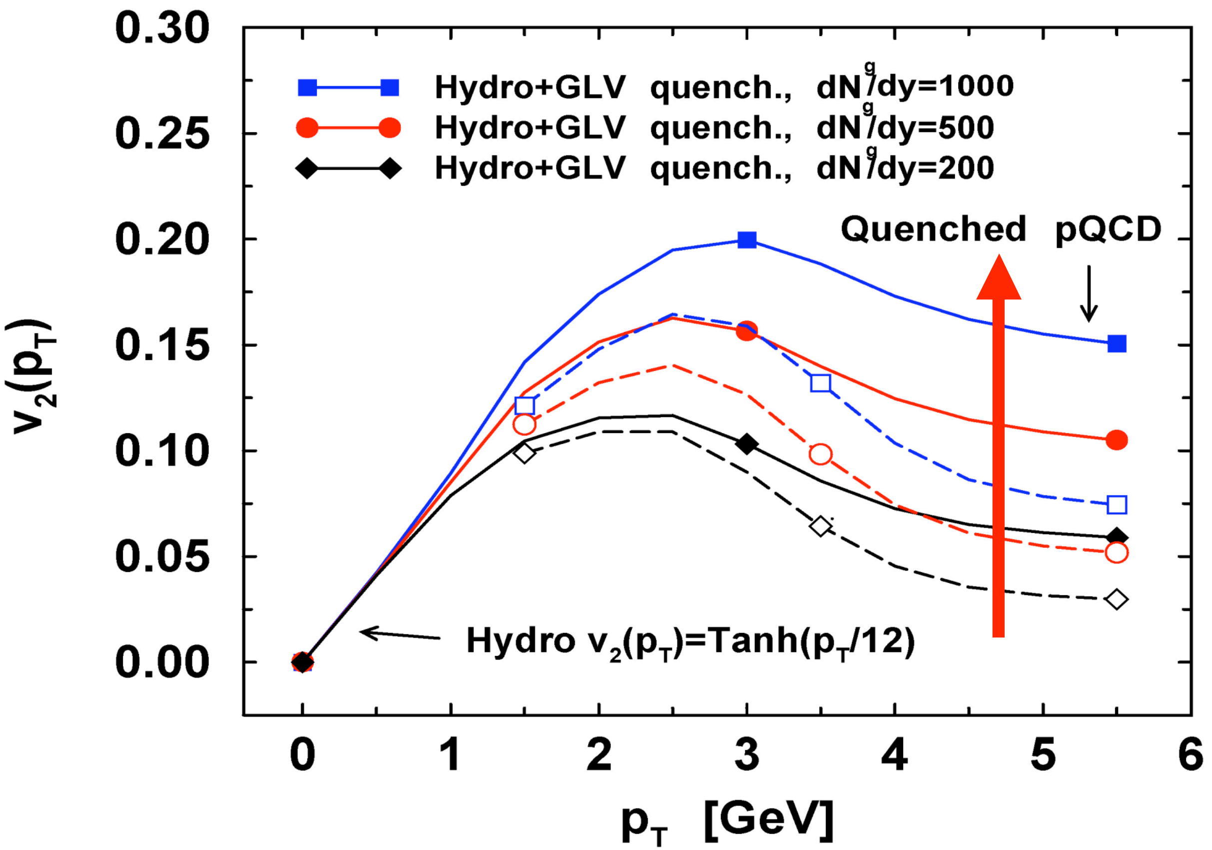
PHENIX : P.R.L. 91, 182301 (2003)

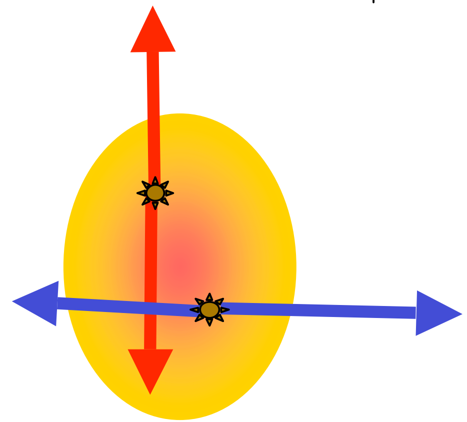


- Low pt region;
  - $v2(\pi) > v2(K) > v2(p)$
  - Good agreement with hydrodynamics
    - Very early thermalization (0.6 fm/c) required !
      - What brings the system thermalization in such a short time!
      - ➔Partonic degree of freedom
- Deviations from the hydro at higher pt (> 2 GeV/c);
  - $v2(\pi,K) < v2(p)$
    - Order Reversed !
    - Other mechanism?

Anisotropy at jet region

M. Gyulassy, I. Vitev and X.N. Wang, PRL 86 (2001) 2537



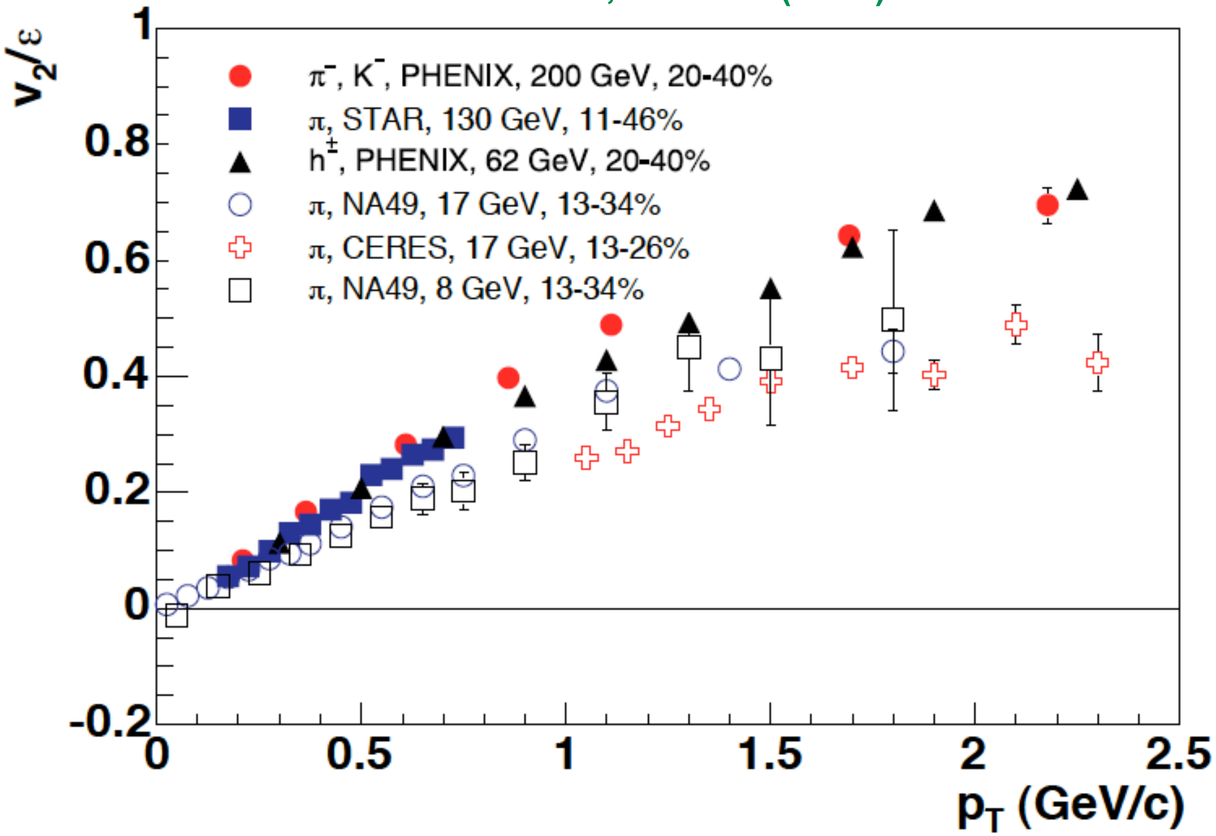


In higher gluon density, larger energy loss of partons

- Anisotropy at high pt caused by the parton energy loss.

What increases from SPS to RHIC

Phenix; NPA 757(2005)184

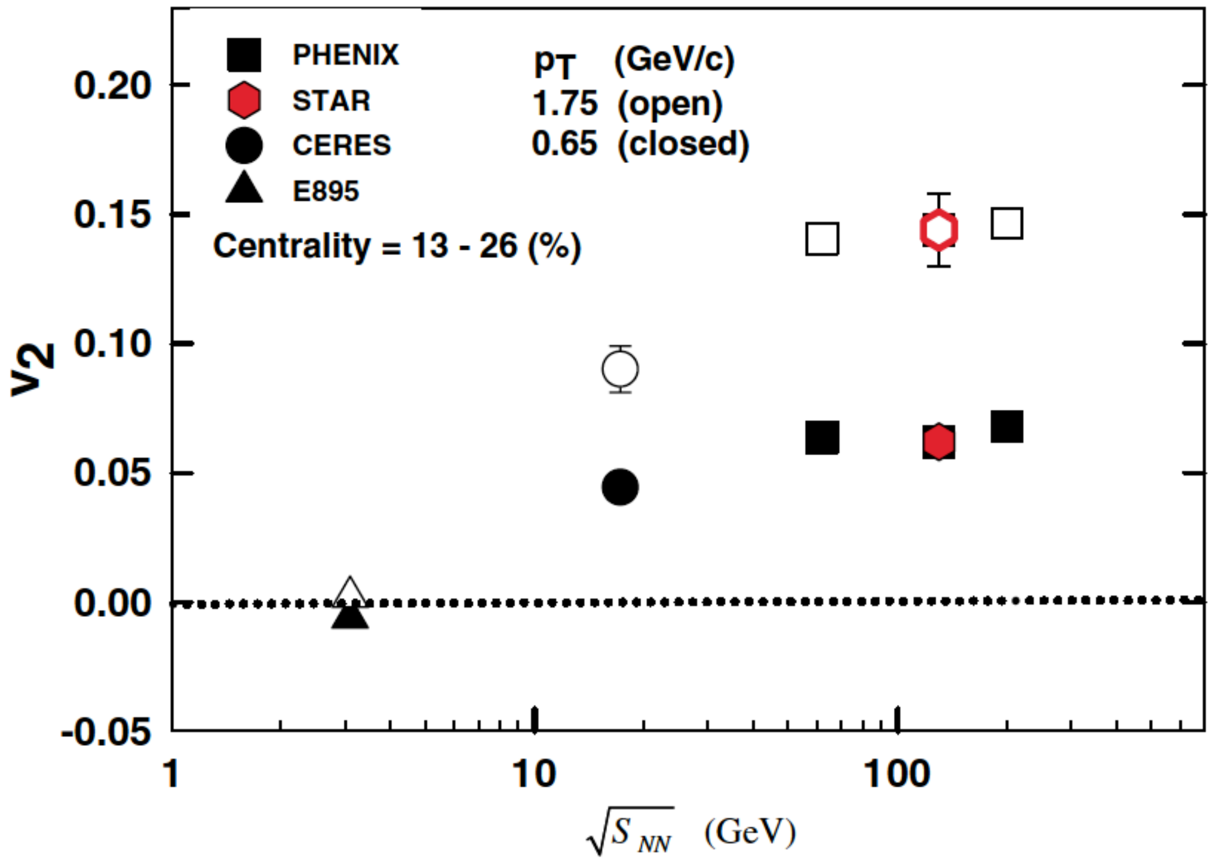


Filled ; RHIC
Open ; SPS

- How we compare RHIC and SPS data; pt-integrated-v_2?
  - Need to separete the effects; increase of <pT> and increase of v_2
  - pt integrated-v_2 includes the effect of increase of <pT>

Saturation of v_2 at the same pT

Phenix; P.R.L. 94, 232302(2005)

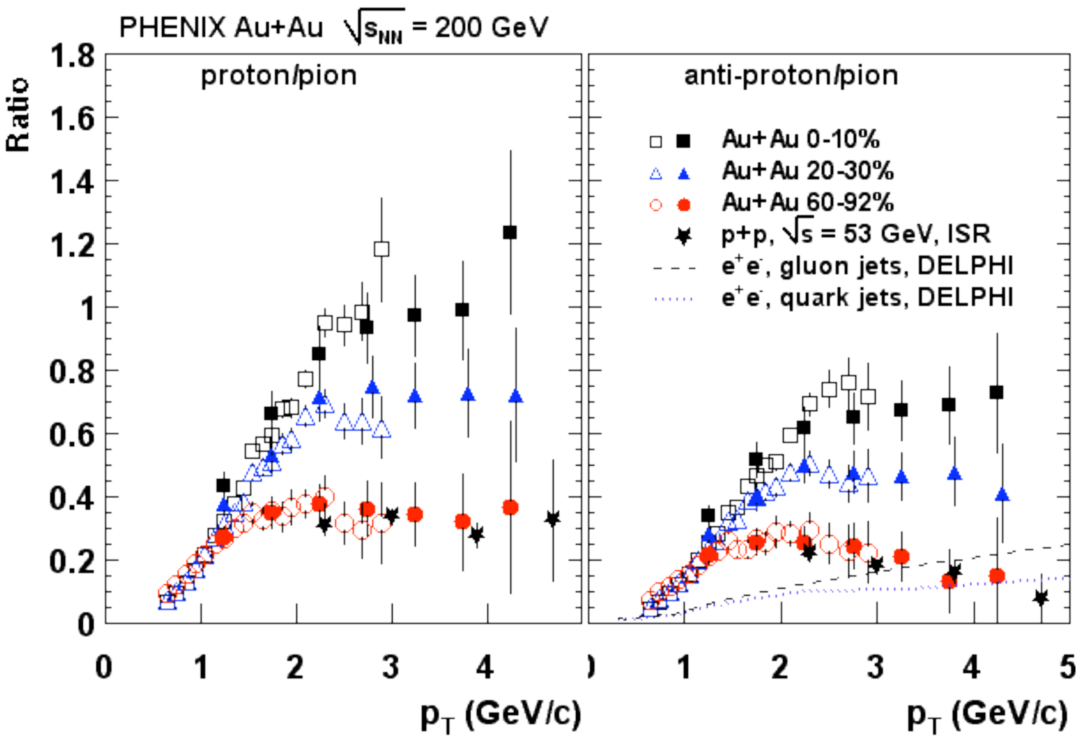


pT integrated-v_2 increases, since <pT> increases with energy.

- v_2 increases up to 62 GeV, then saturate.
  - May be indication of softening of EOS.

2nd surprise; baryon dominance

Phenix; P.R.L. 91(2003)172301



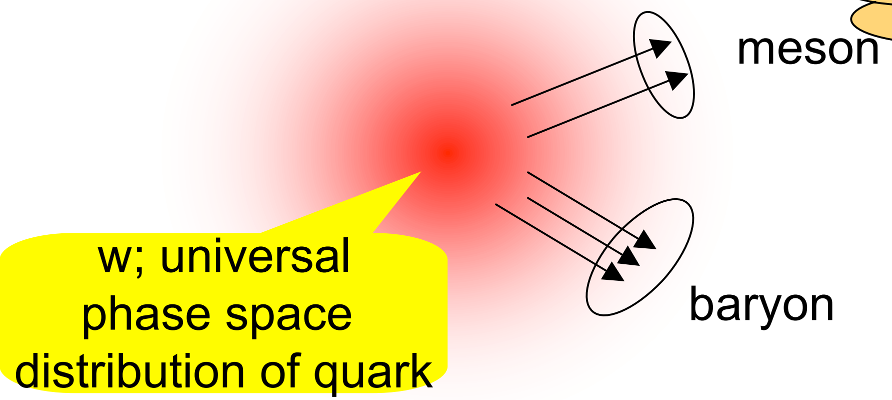
Thanks to high resolution Time-of flight detector

- We had many reasons to consider > 2GeV/c is the jet region.
- In peripheral, p/π ratio similar to those in ee/pp suggesting fragmentaton process.
  - Fragmentation process should show $n_p < n_\pi$ as seen in ee/pp.
- In central Au+Au, p/π ratio increases with centrality, suggesting other mechanism.

Quark Recombination Model (Quark Coalescence Model)

Quark recombination model

This process wins when the distribution is very steep



$$E\frac{d^3N_M}{d^3p} \approx C_M \cdot w^2(p_t/2), \quad E\frac{d^3N_B}{d^3p} \approx C_B \cdot w^3(p_t/3)$$

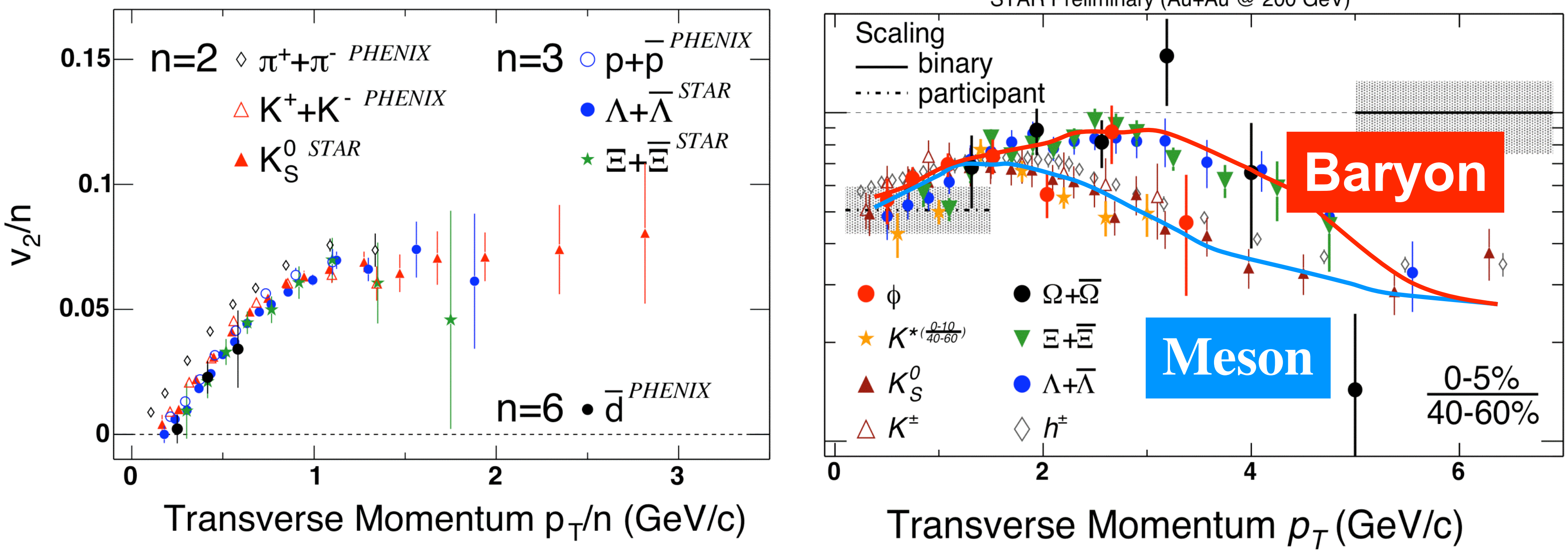
$$\frac{dN_M}{d\phi} \propto (1+2v_{2,q}\cos 2\phi)^2 \approx (1+4v_{2,q}\cos 2\phi) \qquad \frac{dN_B}{d\phi} \propto (1+2v_{2,q}\cos 2\phi)^3 \approx (1+6v_{2,q}\cos 2\phi)$$

$$v_{2,M} \approx 2v_{2,q}(p_t/2), \quad v_{2,B} \approx 3v_{2,q}(p_t/3)$$

- Other possible production mechanism of high pt hadrons than the frag.
- Quarks, anti-quarks combine to form mesons and baryons from universal quark distribution, *w*.
  - Mesons from 2 q with 1/2 of p_T, baryons from 3 q with 1/3 of p_T.
  - Bacause of the steep distr. of w, this process wins at mid-pt.
  - Characteristic scaling features expected.
  - *➔Quark number scaling*

Quark number scaling

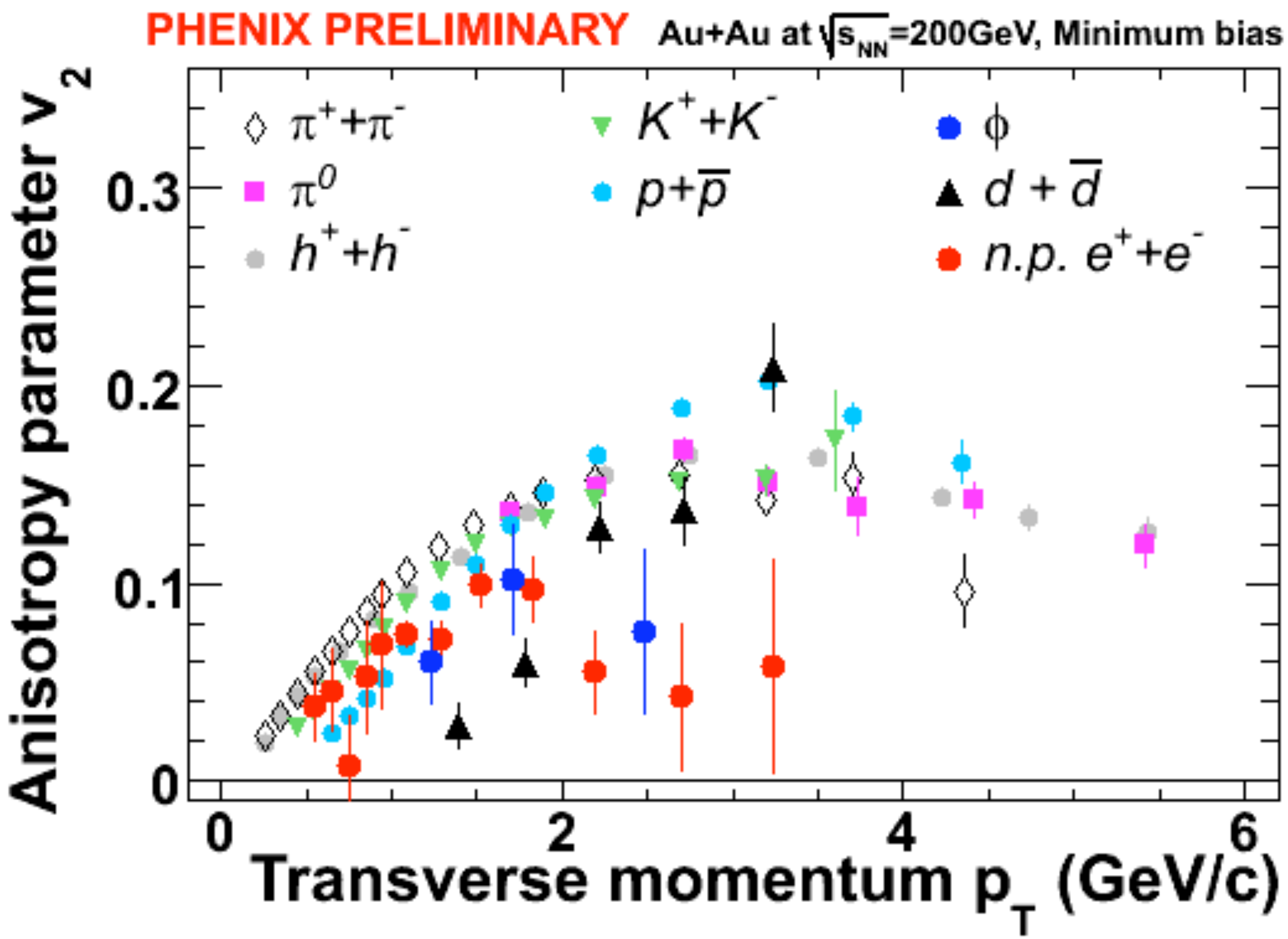
Presented by M. Lamont (QM04)



- Quark number scaling clearly observed in v_2.
- Distinct difference between Baryon Meson also seen in R_{CP}

Other particle species

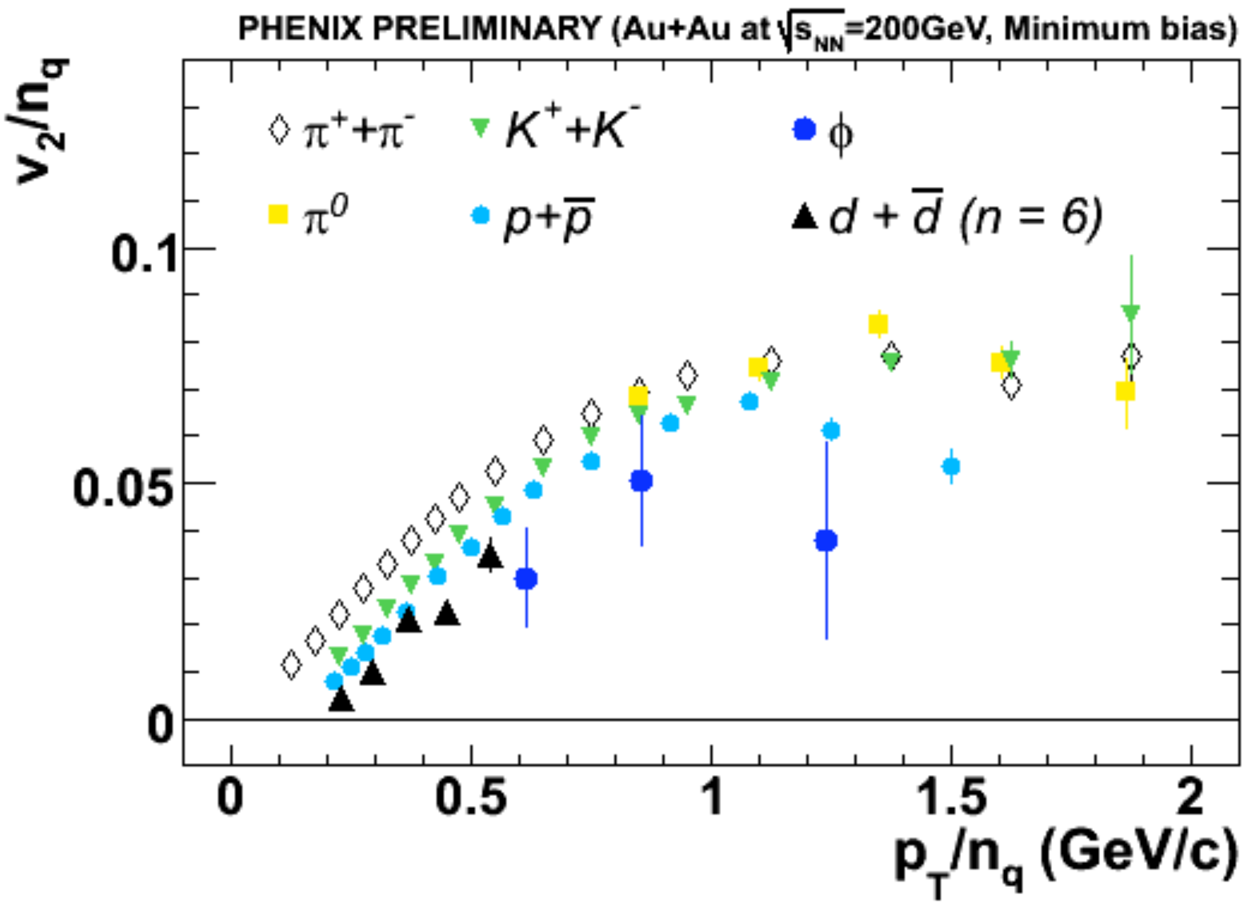
Phenix; H. Masui @ QM05



- Once the R.P. is established, the rest is easier.

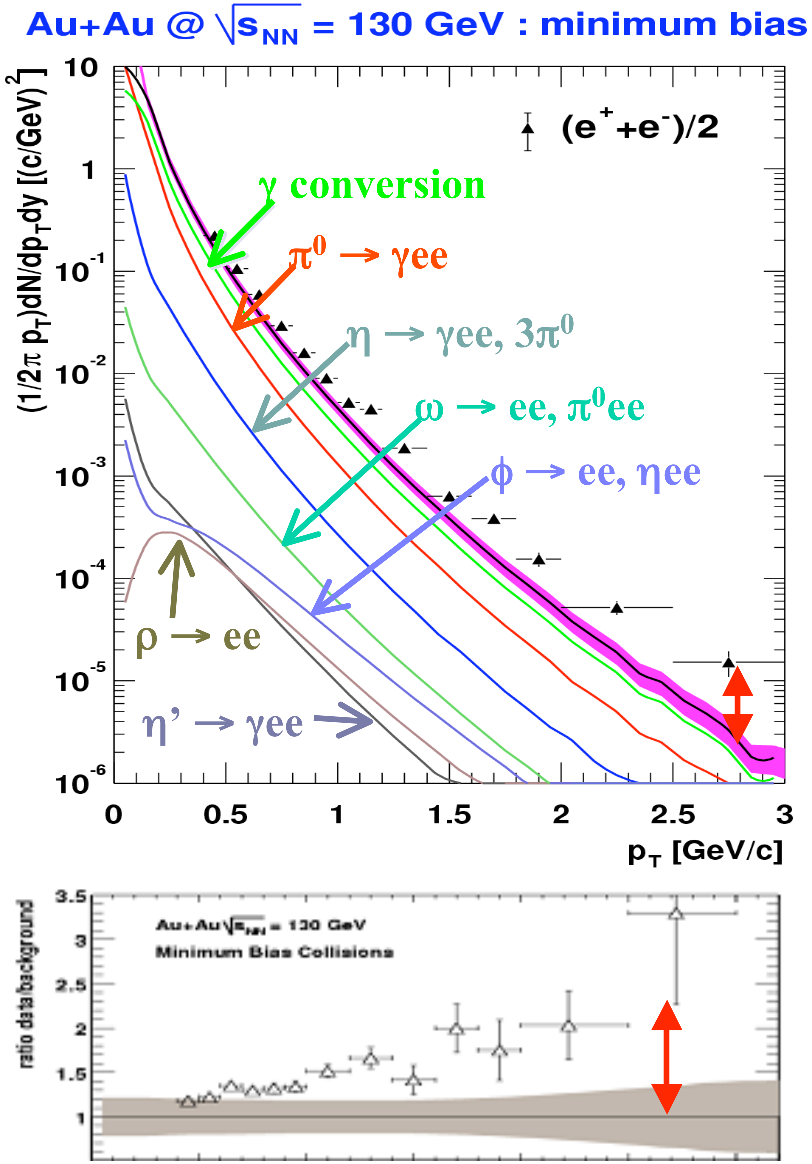
Quark Number Scaling

Phenix; H. Masui @ QM05



- Quark number scaling holds.
- Collectivity at partonic level.

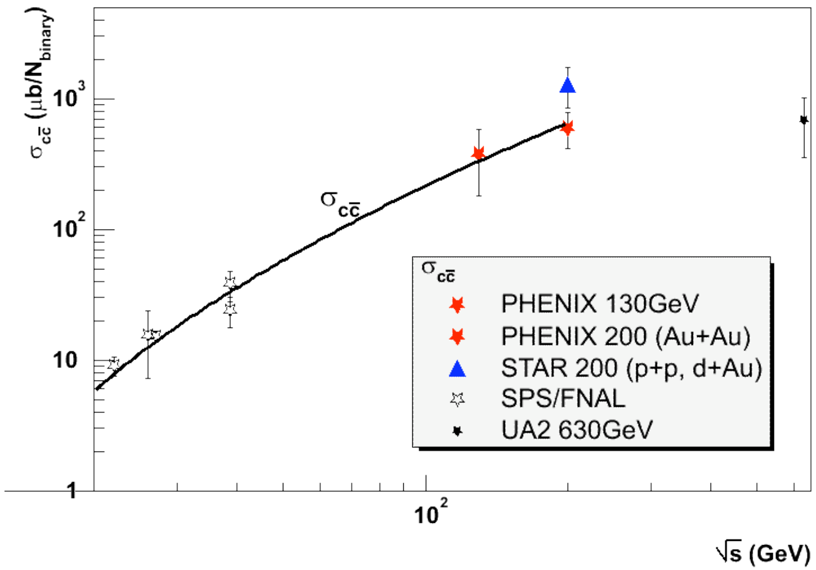
Electron and charm

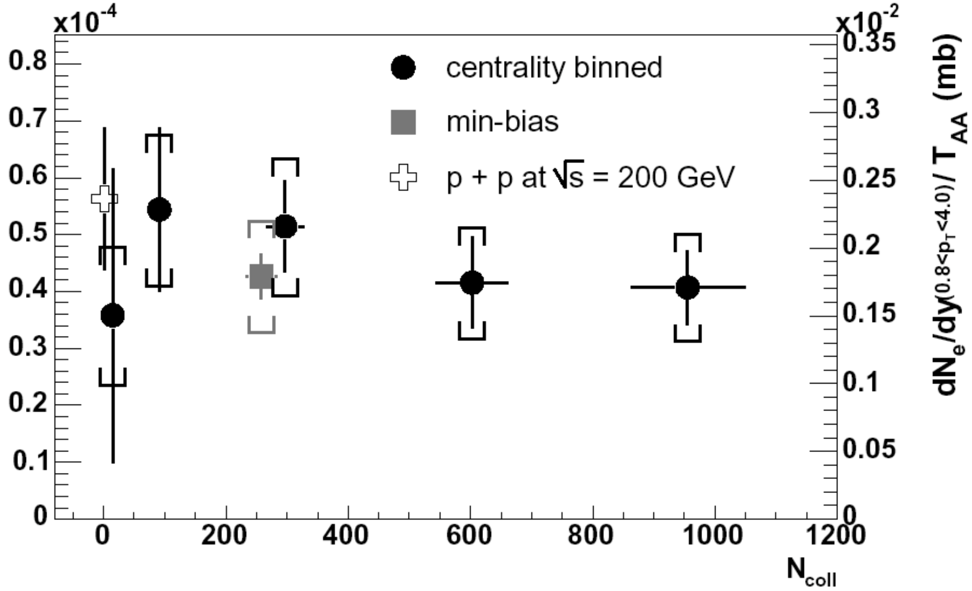


- Origins of electrons
  - "photonic"
    - Dalitz decays of $\pi 0, \eta, \rho, \omega$,
    - Photon conversions
  - "non-photonic"
    - Semi-leptonic decays of heavy flavored mesons
- Method of Analysis
  - Cocktail
  - Photon converter
- ➔Results are consistent with those photonic + charm decays.

Open charm production in AA

Phenix, PRL94(2005)082301

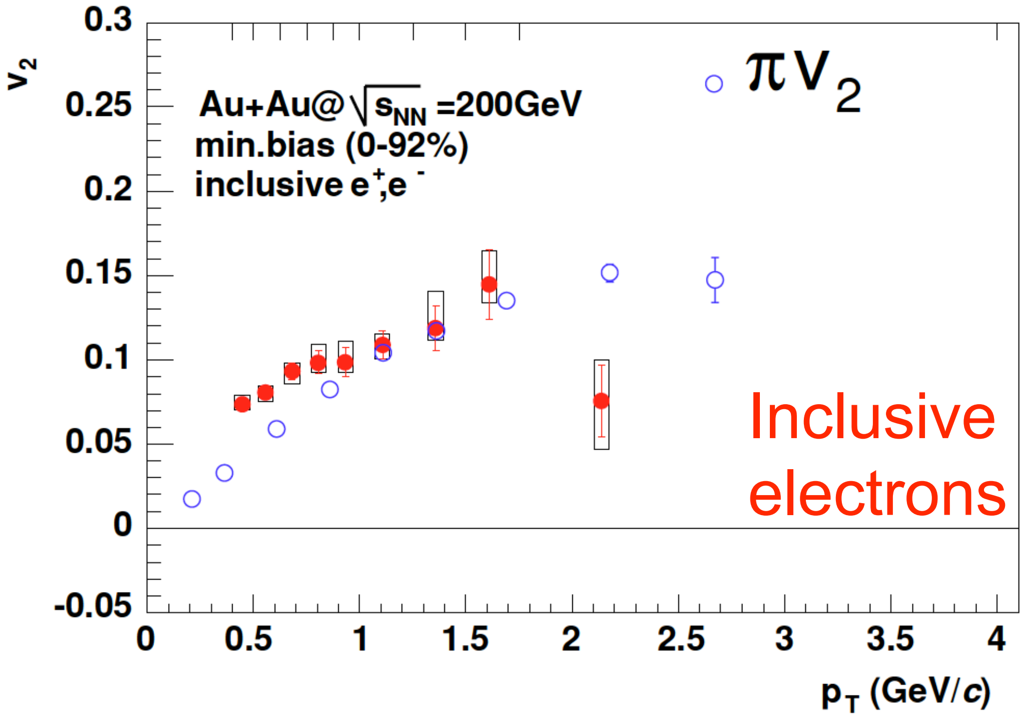




- consistent with $\sqrt{s}$ systematics and binary scaling.
- Centrality dependence shows N_{binary} scaling.
  - ➔support charm contribution

Info. of charm from electrons

Phenix, PRC72(2005)024901



- Measure v_2 of inclusive electrons
- Higher than pions in low pt.
  - Dalitz dominant.
- Lower in high pt?
  - Effect of charm?

$$N_e[1+2v_{2e}\cos 2\phi] = N_e^{\gamma}[1+2v_{2e}^{\gamma}\cos 2\phi] + N_e^{\text{non}-\gamma}[1+2v_{2e}^{\text{non}-\gamma}\cos 2\phi]$$

$$= (N_e^{\gamma}+N_e^{\text{non}-\gamma})[1+2\frac{N_e^{\gamma}v_{2e}^{\gamma}+N_e^{\text{non}-\gamma}v_{2e}^{\text{non}-\gamma}}{N_e^{\gamma}+N_e^{\text{non}-\gamma}}\cos 2\phi]$$

measured

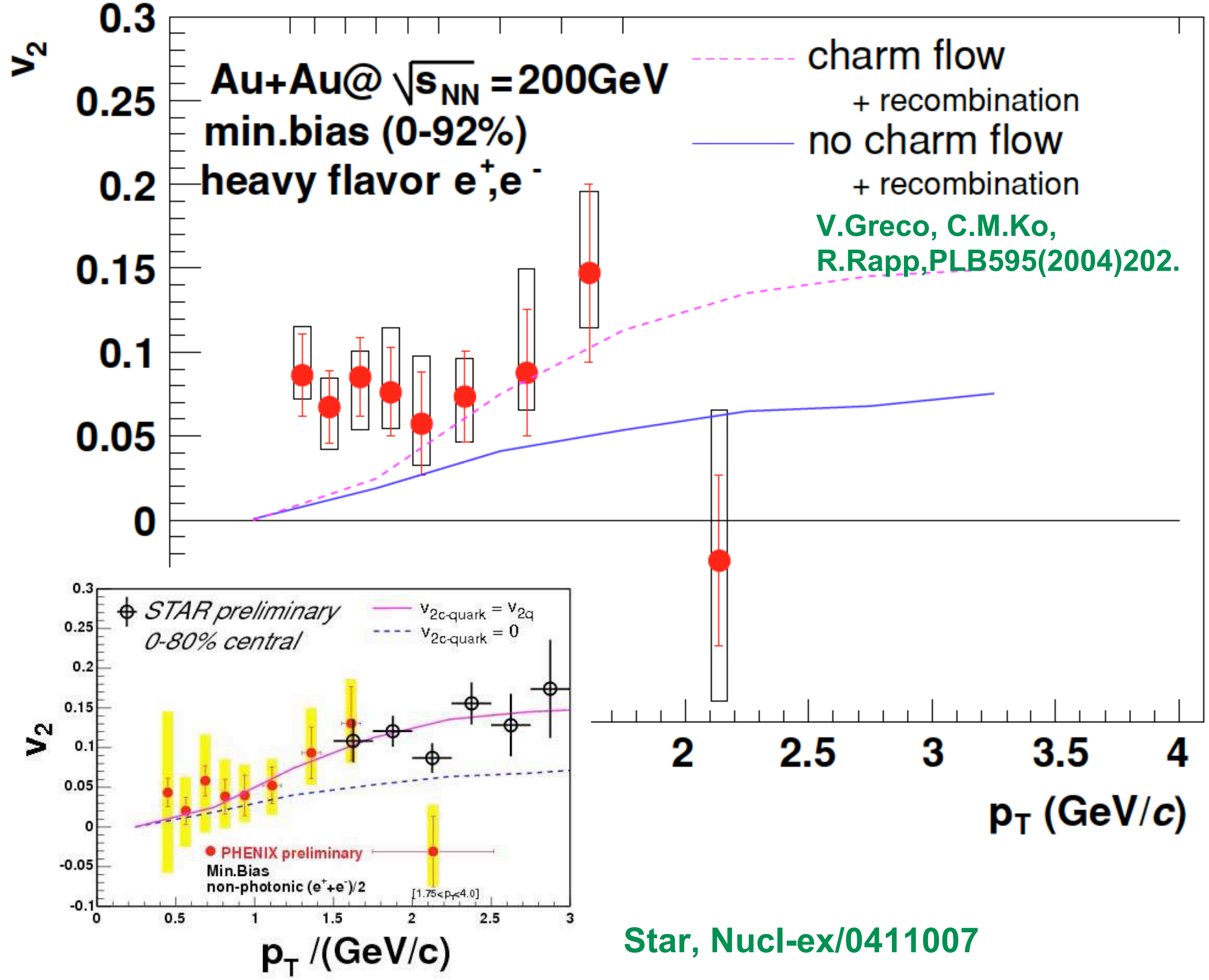
evaluated

known

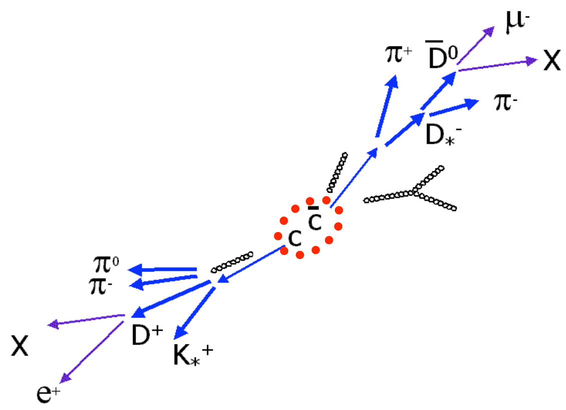
obtained!

Charm seems to flow!?

Phenix, PRC72(2005)024901



Star, Nucl-ex/0411007



- Data seem to favor flow of the charm.
- If so, thermalized & flowing charm supports quark-coalescence & formation of QGP.

Summary of my talk

- v_2 is fun!
  - Establishment of R.P. is great !
- v_2 is even useful !
  - Sensitive to the early stage of collisions
  - Thermalization as early as 0.6 fm/c
    - Large azimuthal anisotropy cannot be created with hadronic process.
  - Support the quark recombination model
    - Collectivity at parton level
    - Phenomenological, but universal quark distribution function!
    - ➔statistical description of quarks ➔QGP
- Much fun to come
  - Even charm seem to flow !

One more thing,

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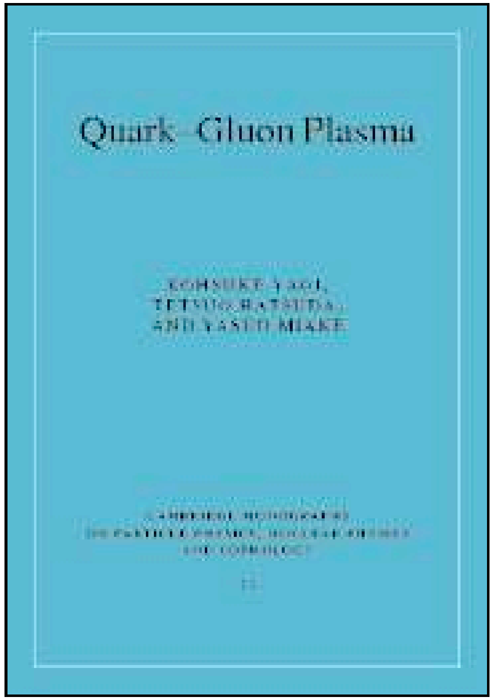

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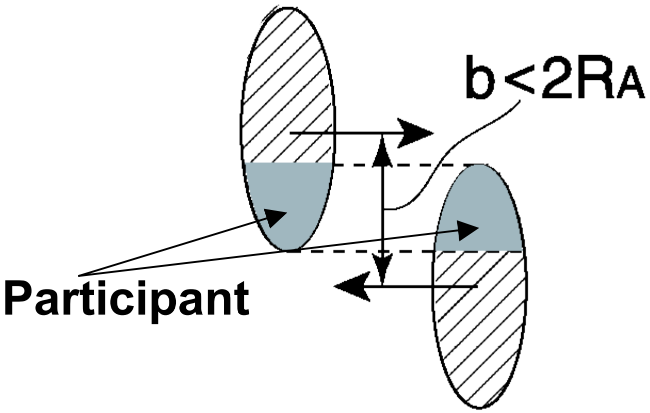
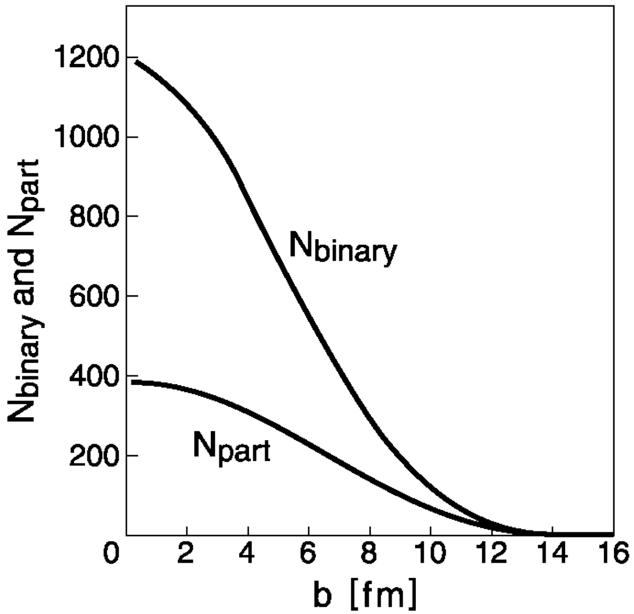
N_{part} vs N_{binary}





Y.Miake, KPS meeting at APCTP in Pohang, 2005

- Since nucleus is extended object, centrality of collision plays important role.
- For comparison with pp or dAu also for centrality study, we need scaling variables.
- N_{part};
  - # of participant nucleons
  - Particle production in hA is prop. to Npart, (Wounded-Nucleon Model)
- N_{binary};
  - # of binary nucleon-nucleon collisions
  - Pass through at high energy.
- Evaluation of N_{part} & N_{binary} by Glauber Model.

Measured vs Real correlation

$$\frac{dG}{d\phi} = \frac{G}{2\pi}\left(1 + \sum_{n=1}^{N} 2v_n \cos(n\phi)\right)$$

$$\phi = \phi_{lab} - \Psi_{real}$$

$$\frac{dG}{d\phi'} = \frac{G}{2\pi}\left(1 + \sum_{n=1}^{N} 2v'_n \cos(n\phi')\right)$$

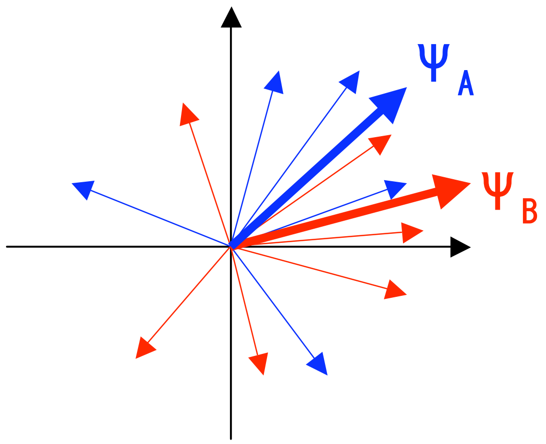
$$\phi' = \phi_{lab} - \Psi_{measured}$$

$$\begin{aligned}
v'_n &= \langle \cos(n\phi') \rangle \\
&= \langle \cos n(\phi_{lab} - \Psi_{real} - \Psi_{measured} + \Psi_{real}) \rangle \\
&= \langle \cos(n\phi)\cos(n(\Psi_{measured} - \Psi_{real})) \rangle + \langle sin(n\phi) sin(n(\Psi_{measured} - \Psi_{real})) \rangle \\
&= \langle G\cos(n\phi)\cos(n(\Psi_{measured} - \Psi_{real})) \rangle \\
&= v_n \langle \cos(n(\Psi_{measured} - \Psi_{real})) \rangle
\end{aligned}$$

$$\therefore v_n = \frac{v'_n}{\langle \cos(n(\Psi_{measured} - \Psi_{real})) \rangle}$$

$$v_{\mathrm{Real}} = \frac{v_{\mathrm{Measured}}}{\mathrm{R.P.\ Resolution}}$$

R.P. Resolution from sub-event



Ψ_A : R.P. angle of Sub-event A
Ψ_B : R.P. angle of Sub-event B

- Split 1 event to sub-event A and B randomly
- Determine R.P. in each sub-event ; Ψ_A Ψ_B

$$\langle \cos(n(\Psi_A - \Psi_B)) \rangle$$
$$= \langle \cos(n(\Psi_A - \Psi_{real}) \rangle \langle \cos(n(\Psi_B - \Psi_{real})) \rangle + (\sin - term)$$
$$= \langle \cos(n(\Psi_A - \Psi_{real}) \rangle \langle \cos(n(\Psi_B - \Psi_{real})) \rangle$$
$$\approx \left(\langle \cos(n(\Psi_A - \Psi_{real}) \rangle \right)^2$$