Measurement of azimuthal anisotropy of hadrons in Au+Au collisions from a beam energy scan by the PHENIX experiment at RHIC.

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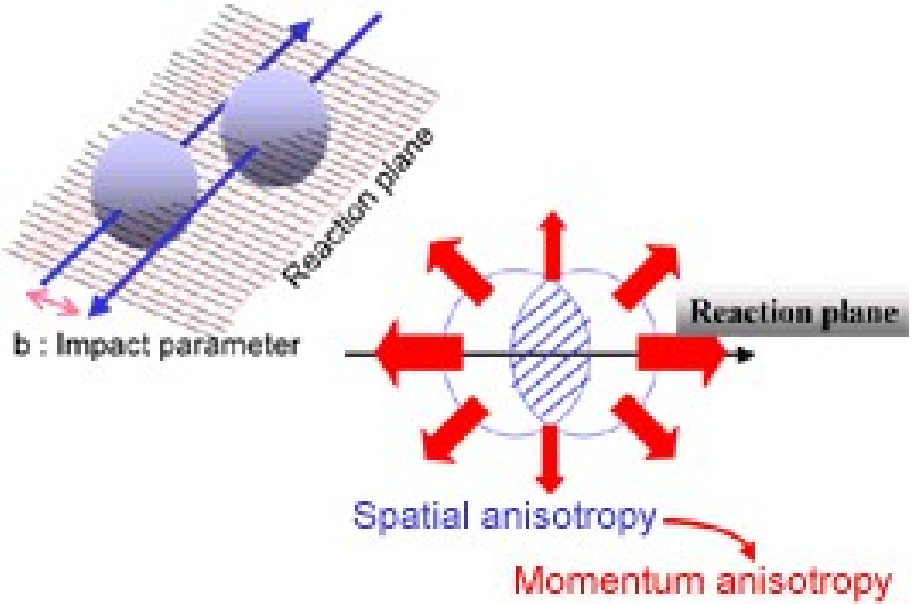
for the PHENIX collaboration

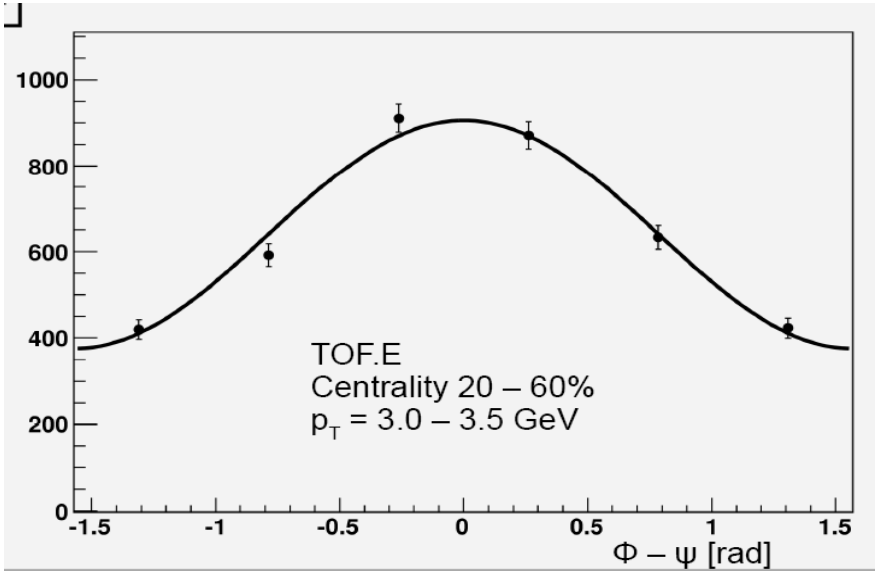
PHENIX

RIKEN

Computer
Center
in Japan

Azimuthal anisotropy



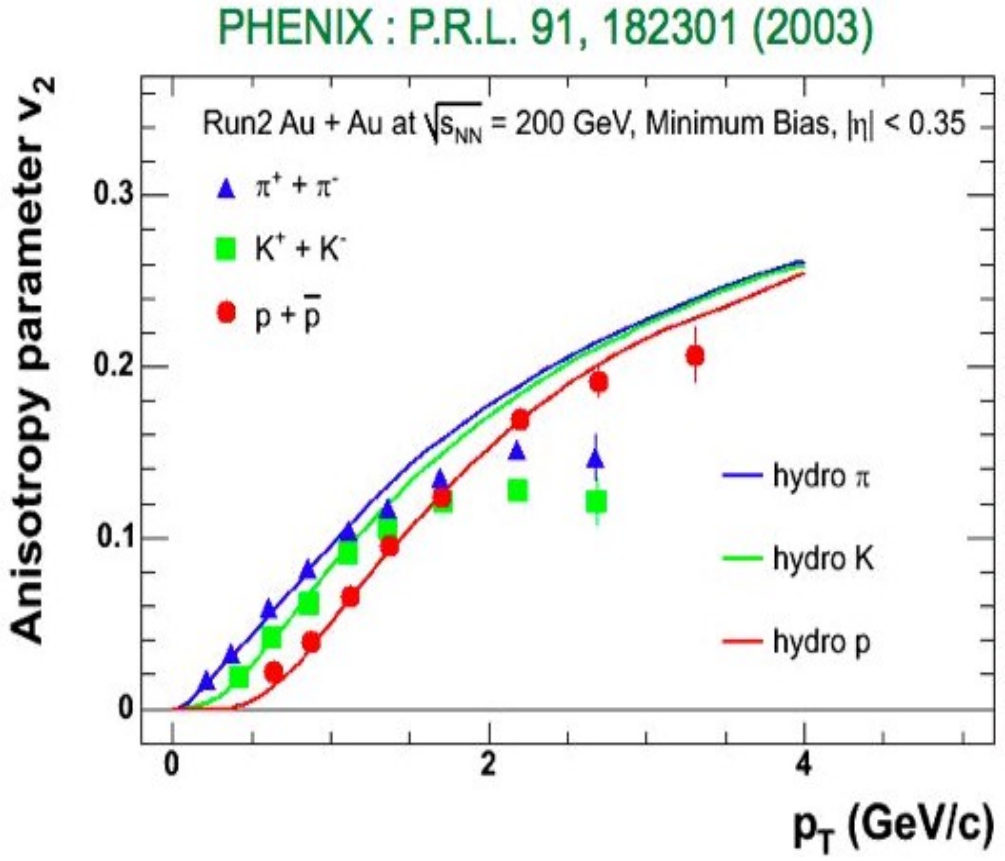


- Azimuthal anisotropy depends on initial kinematics
  - Elliptical particle emission angle distribution for non-central collision
- It is measured as 2nd term of Fourier series (v_2)

$$\frac{dN}{d\Phi} \propto 1 + 2\,v_2 \cos 2\left(\Phi - \Psi\right)$$

Ψ : reaction plane angle

Hydro-dynamics model

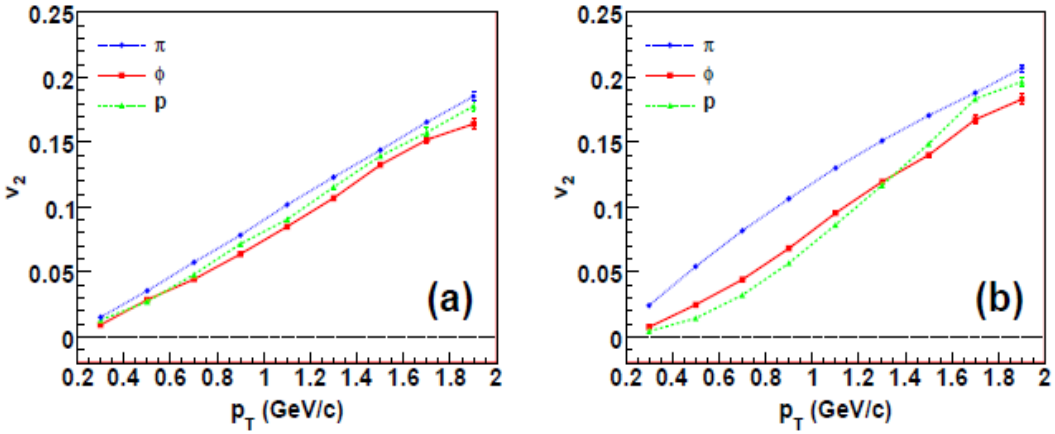


Large v_2 was observed in RHIC and it is agree with hydro-dynamical models.

Rapid thermalization and low viscosity are assumed in the model.

High resolution measurement of PID hadron v_2

- Comparison with rare particle.
  - Deuteron that is formed by p-n (or 6 quarks) should has higher v_2 than proton.
  - Φ meson has small cross section for hadron scattering. The mass is similar to proton or Λ rather than π or K.



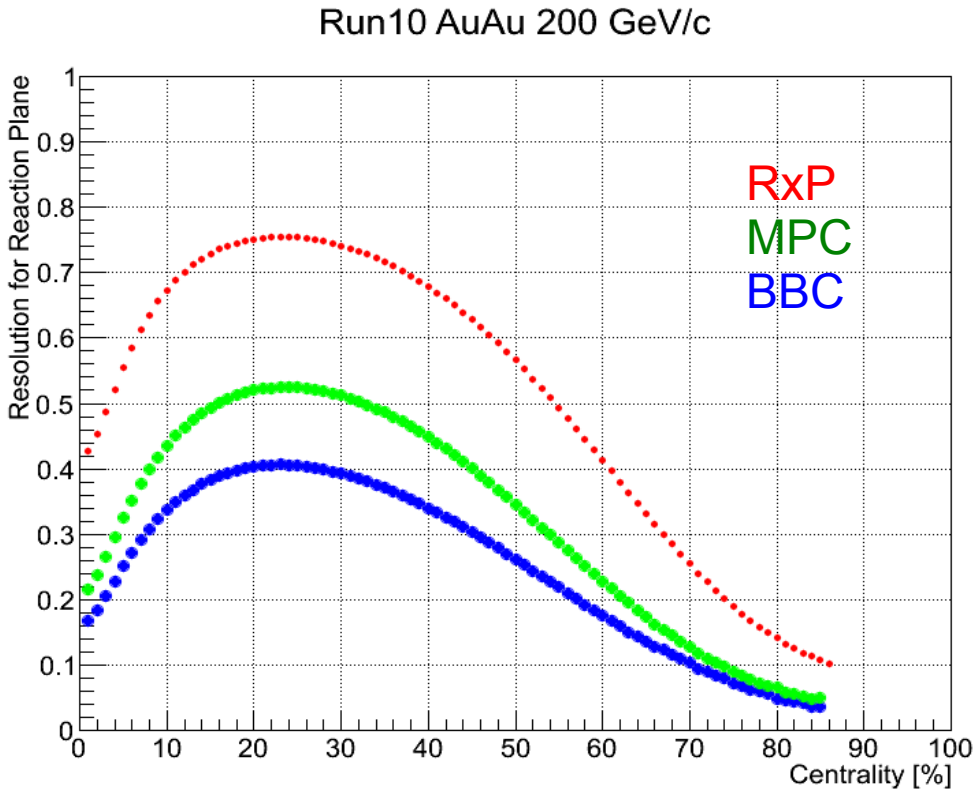
- Study for low energy collision

arXiv:0710.5795

- Study at high momentum range.

Reaction Plane Resolution

$$Res\,\Psi \equiv \left\langle \cos 2\left(\Psi_{real} - \Psi_{observe}\right)\right\rangle$$

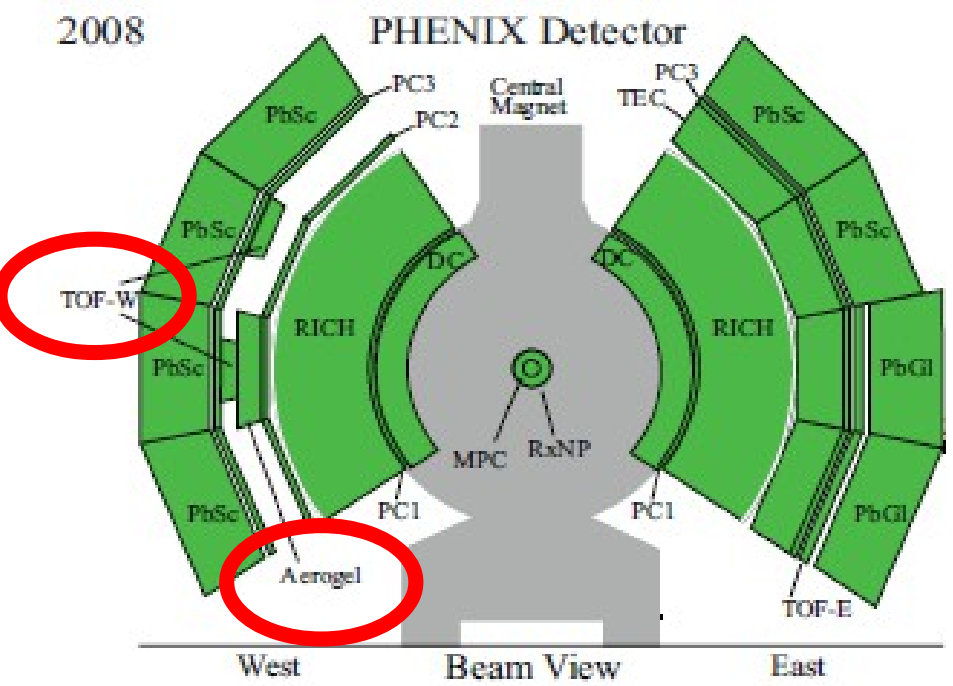


$$v_{2\,observe} = v_{2\,real} \times \left\langle \cos 2\left(\Psi_{real} - \Psi_{observe}\right)\right\rangle$$

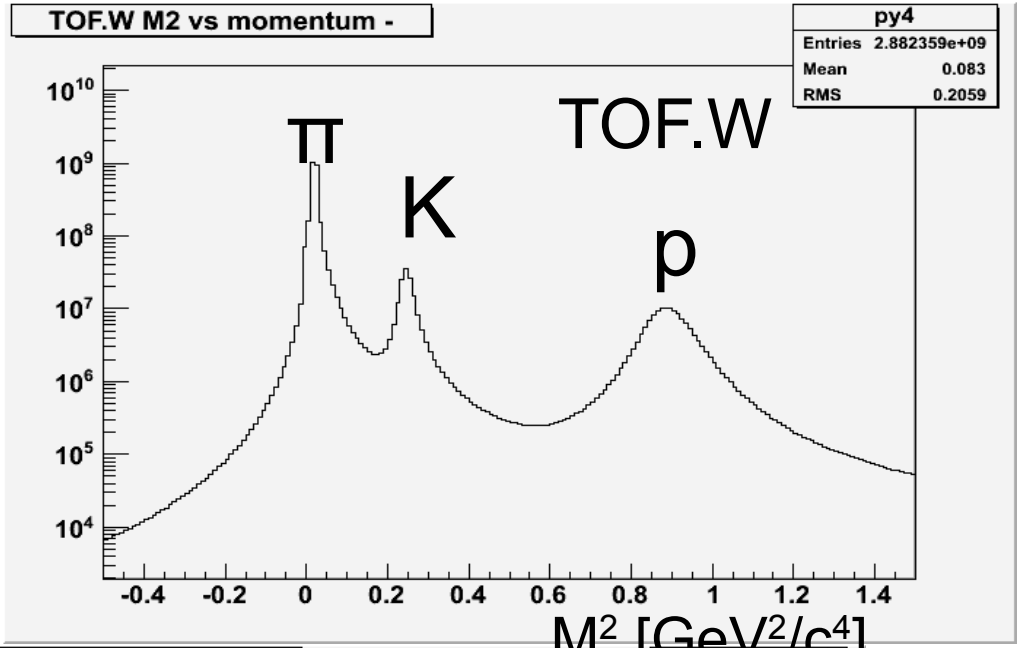
$$\delta v_2 \sim \frac{1}{\left\langle \cos 2\left(\Psi_{real} - \Psi_{observe}\right)\right\rangle} \times \frac{1}{\sqrt{N}}$$

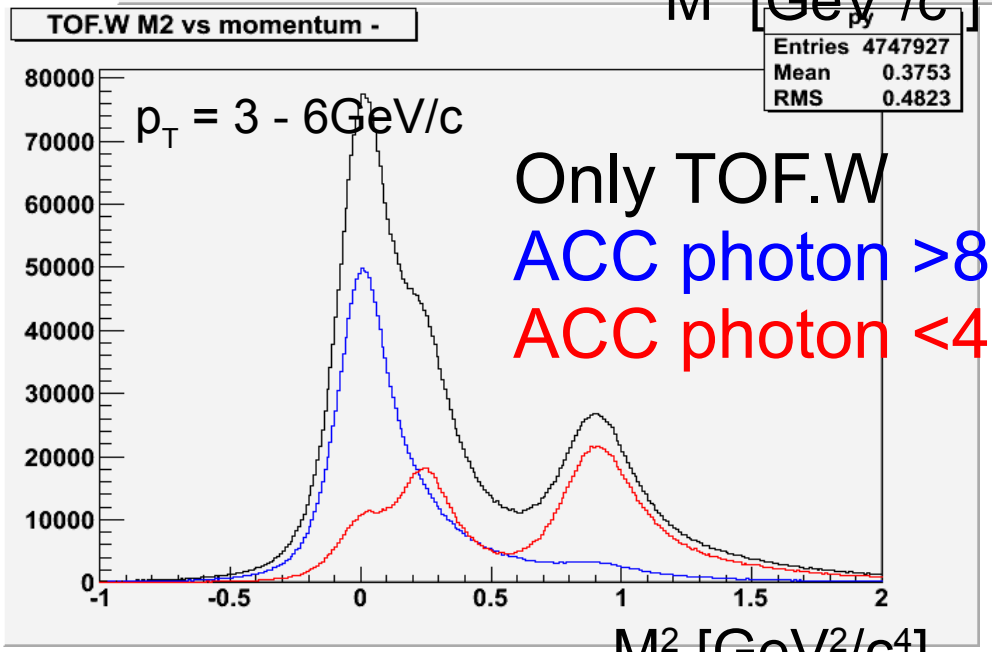
The observed v_2 is corrected by the correction factor $\langle \cos 2\Delta\Psi \rangle$.
The correction factor is called reaction plane resolution.

PID for π, K and proton

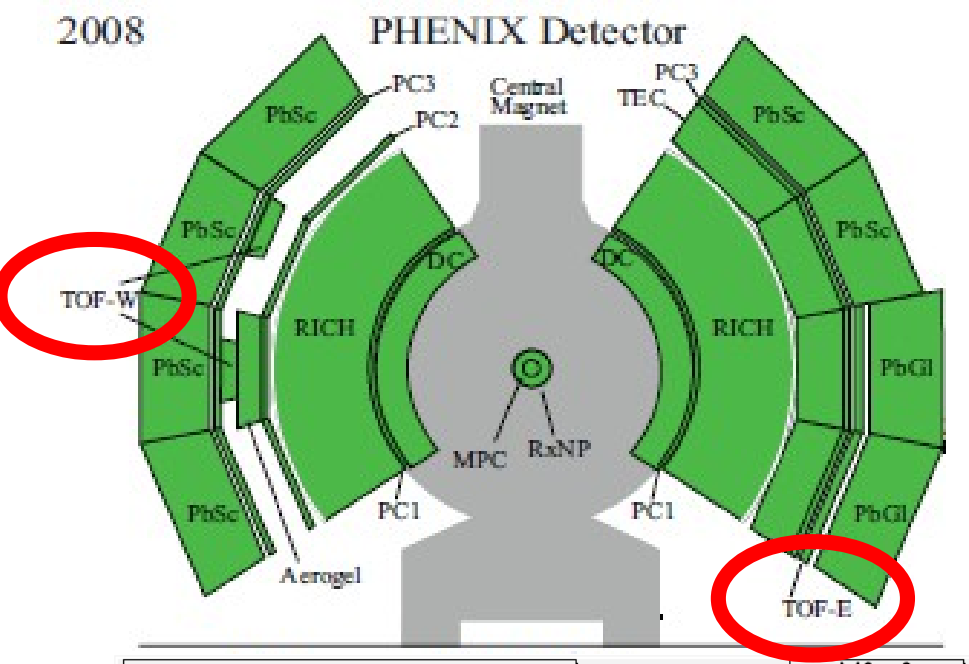


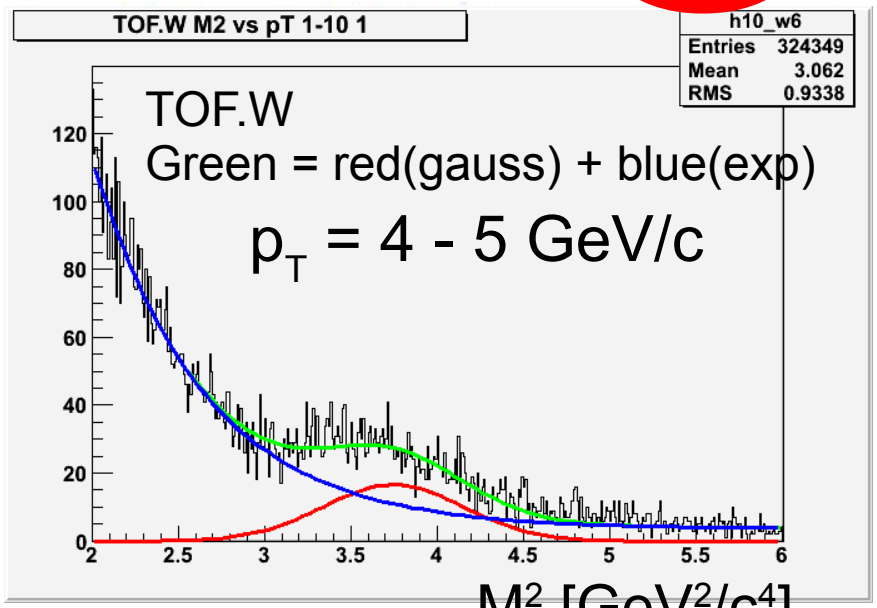
TOF.W was installed before Run7, too

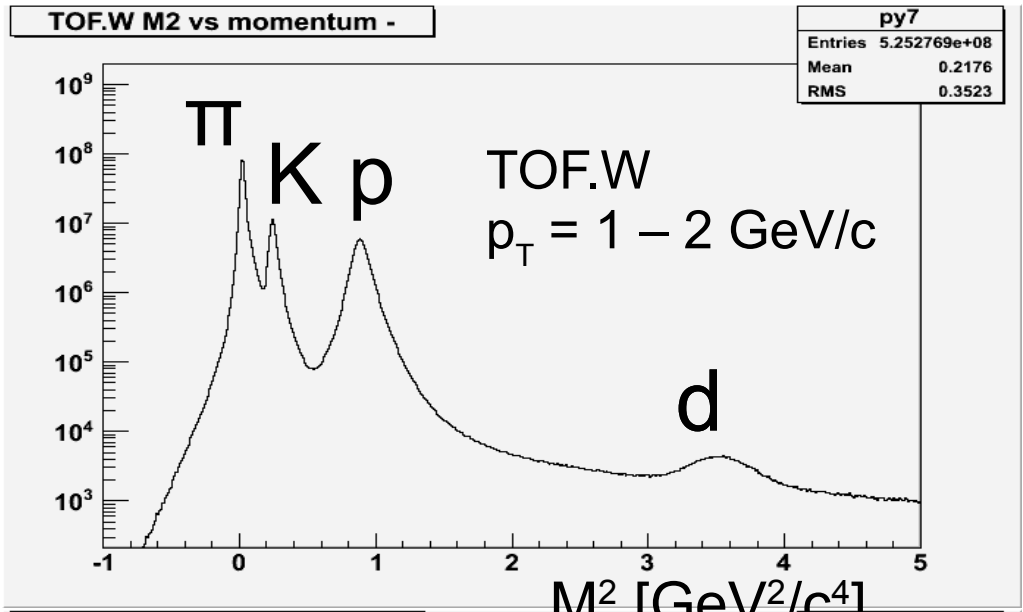


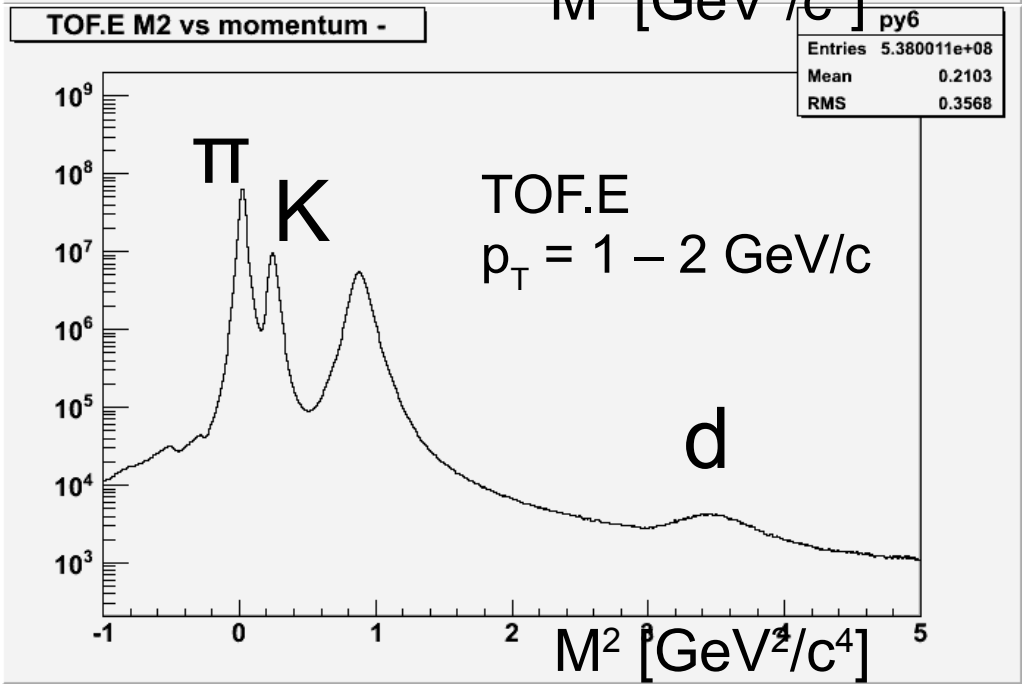


PID for deuteron

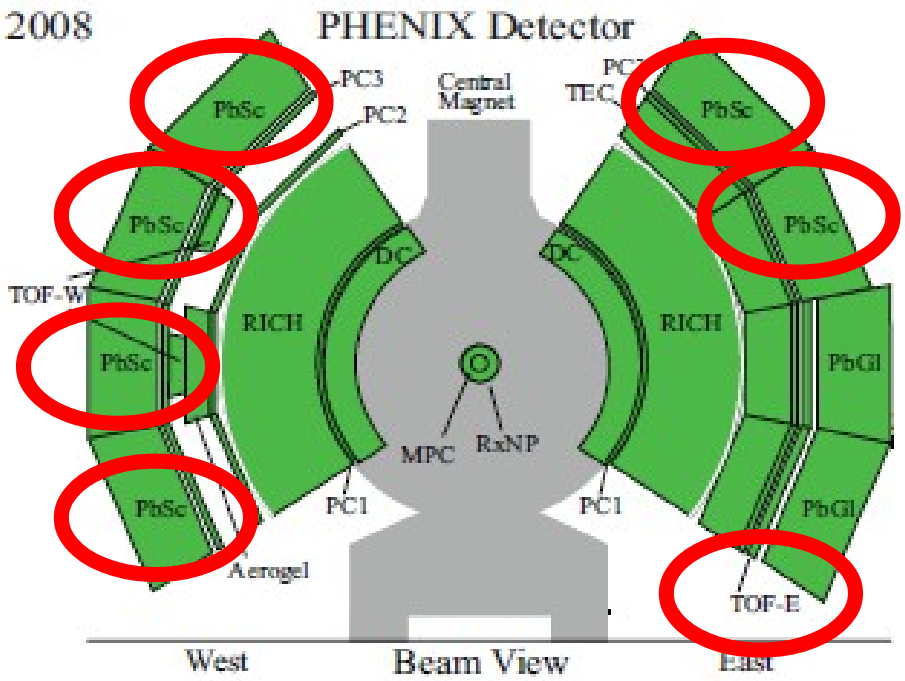


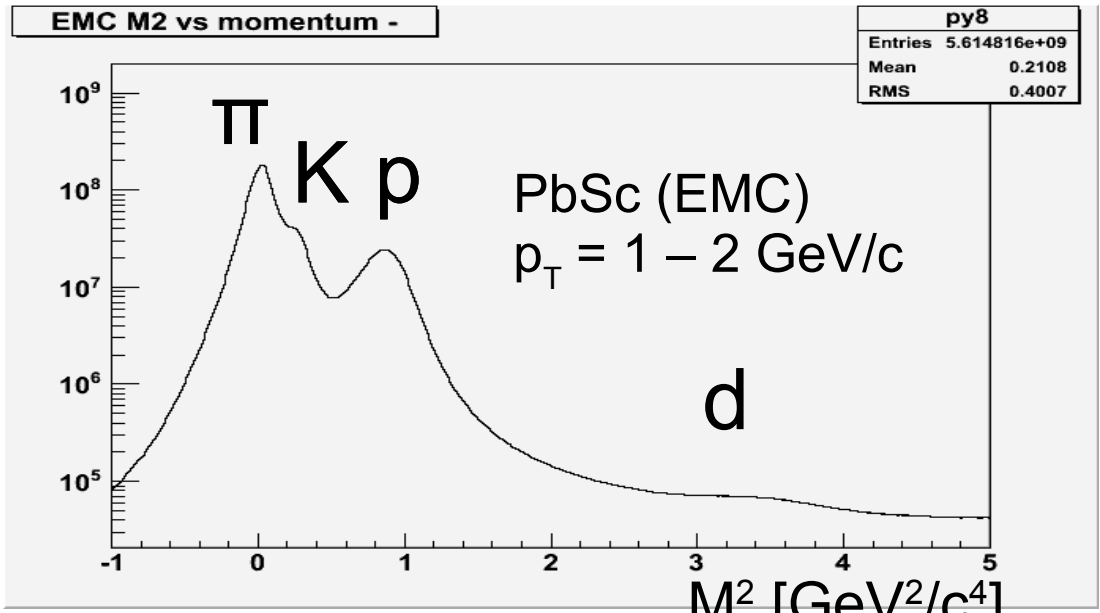


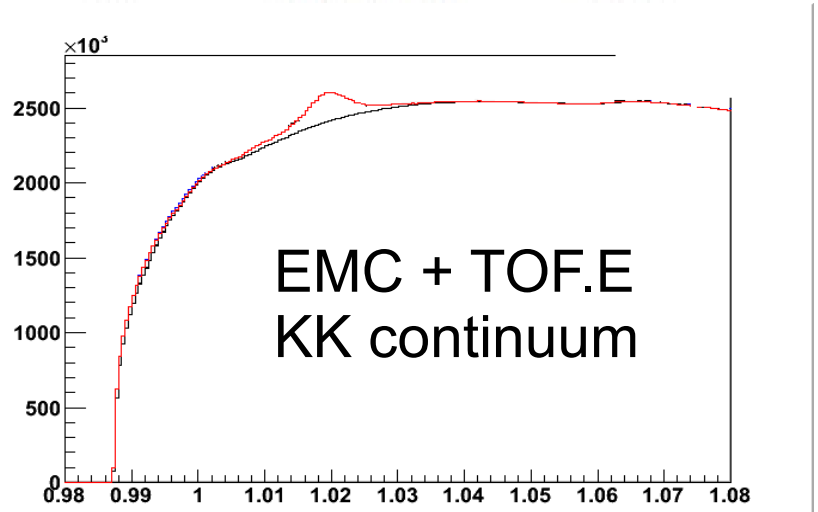


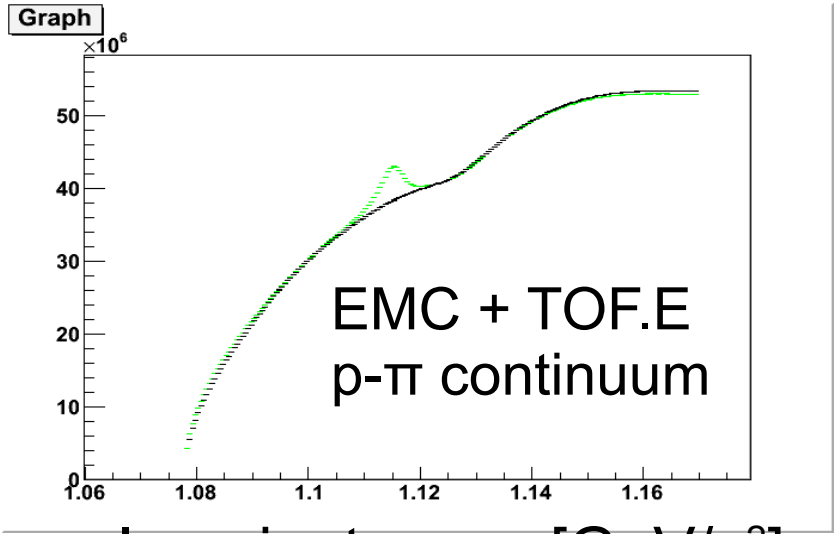


PID for Λ and Φ

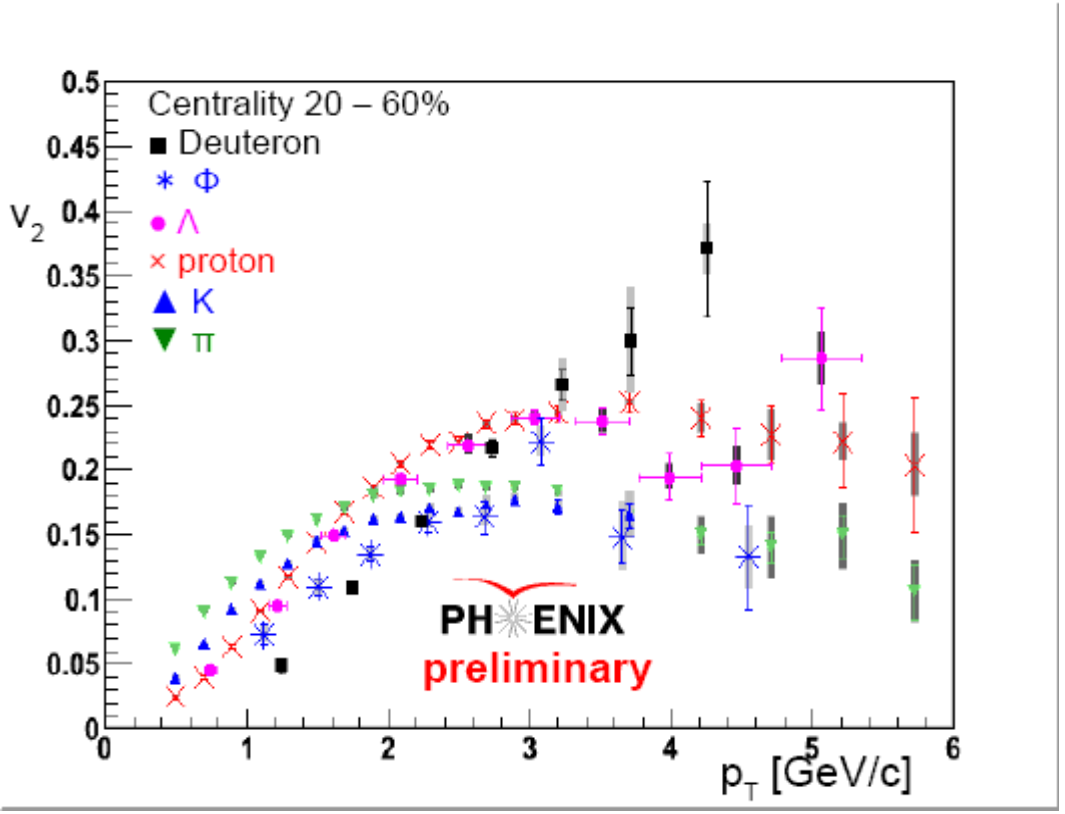






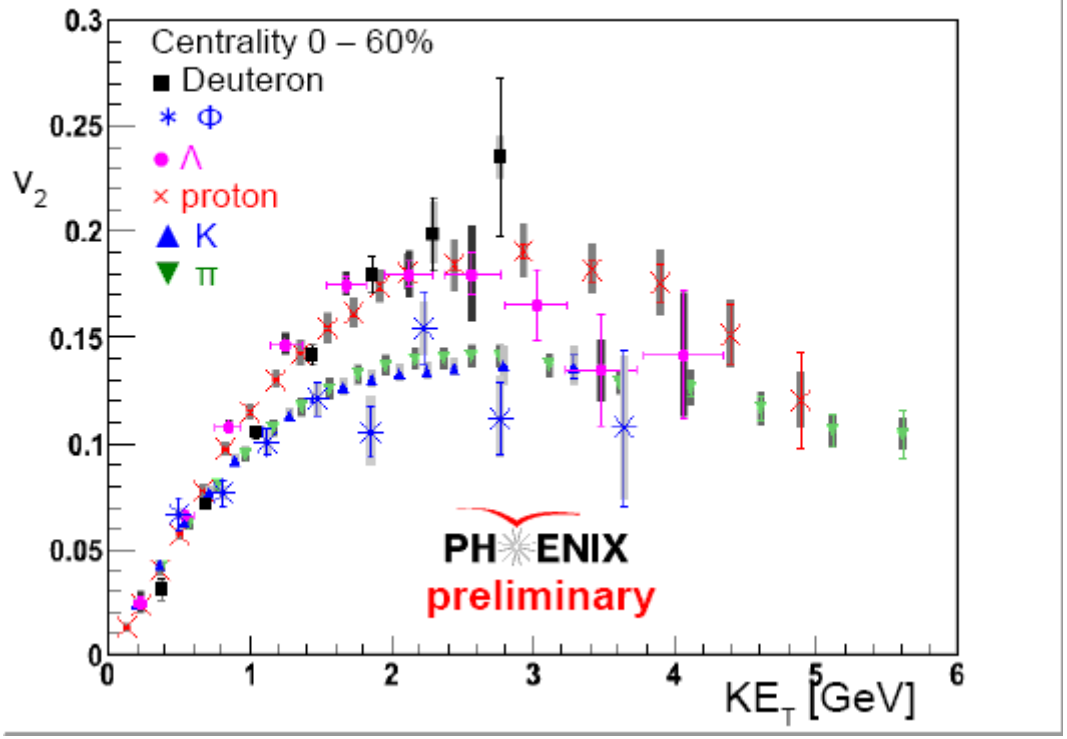


v_2 as p_T for 6 particles



- These are characteristic for each particle specie
- Heavy particle is shifted to high momentum
  - Collective flow
- Meson, baryon and Ion are deviated at p_T>2GeV/c
  - Quark coalescence

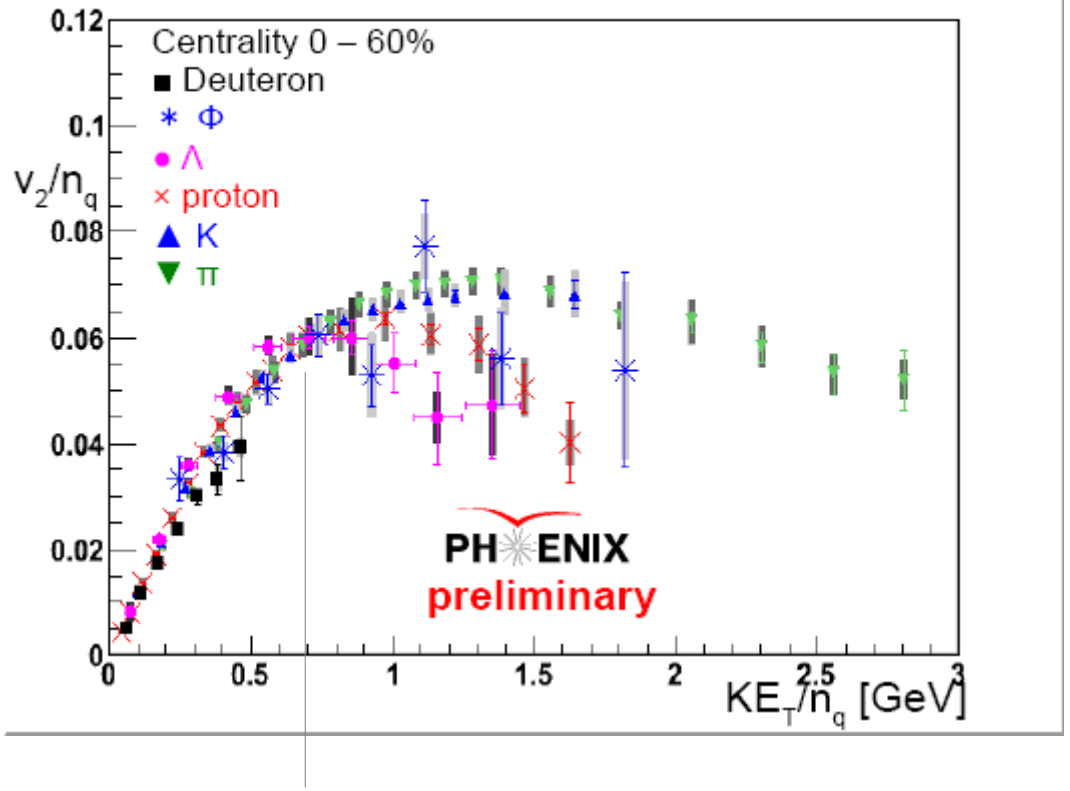
KE_T scaling



$$KE_T = M_T - M_0 = \sqrt{(M_0^2 + P_T^2)} - M_0$$

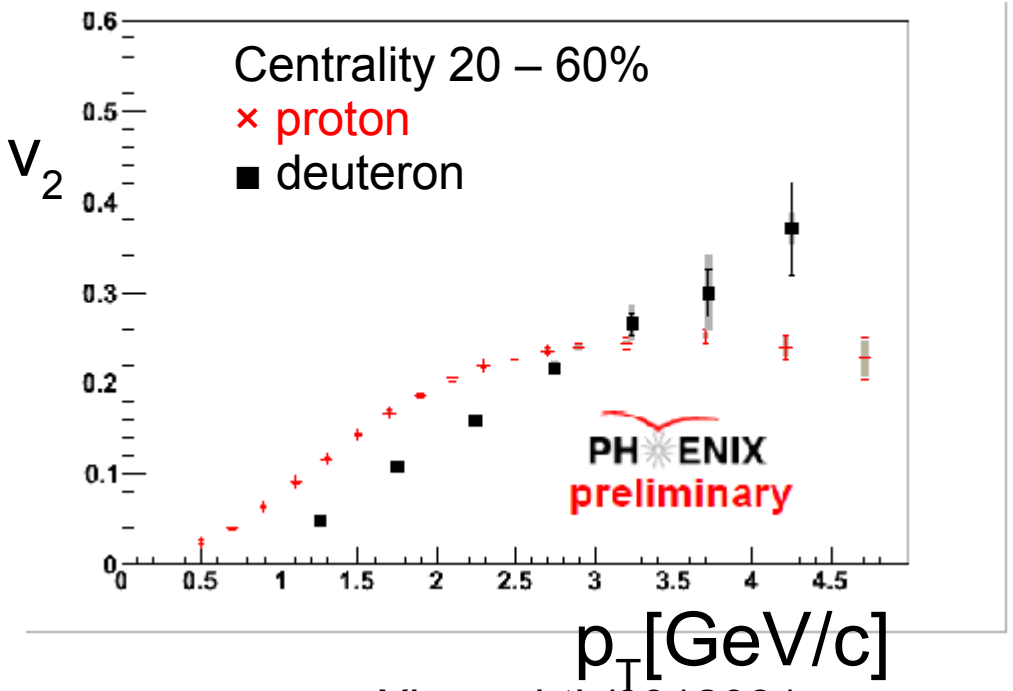
- The p_T shift depend on mass is described with KE_T
  - They are consistent separately for mesons or baryons.
- Meson line and baryon line approach at high KE_T.

Quark number and KE_T scaling

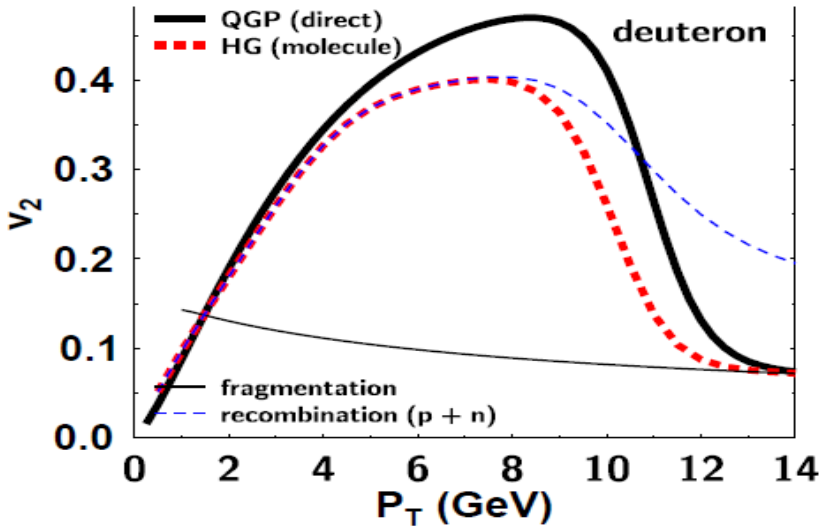


- Consistent for all particles with KE_T and number of constituent quark scaling at KE_T/n_q<0.7GeV.
  - Collective flow of quarks
- They deviate at high KE_T/n_q
  - This indicate a change of particle and v_2 production mechanism.

p-n combination

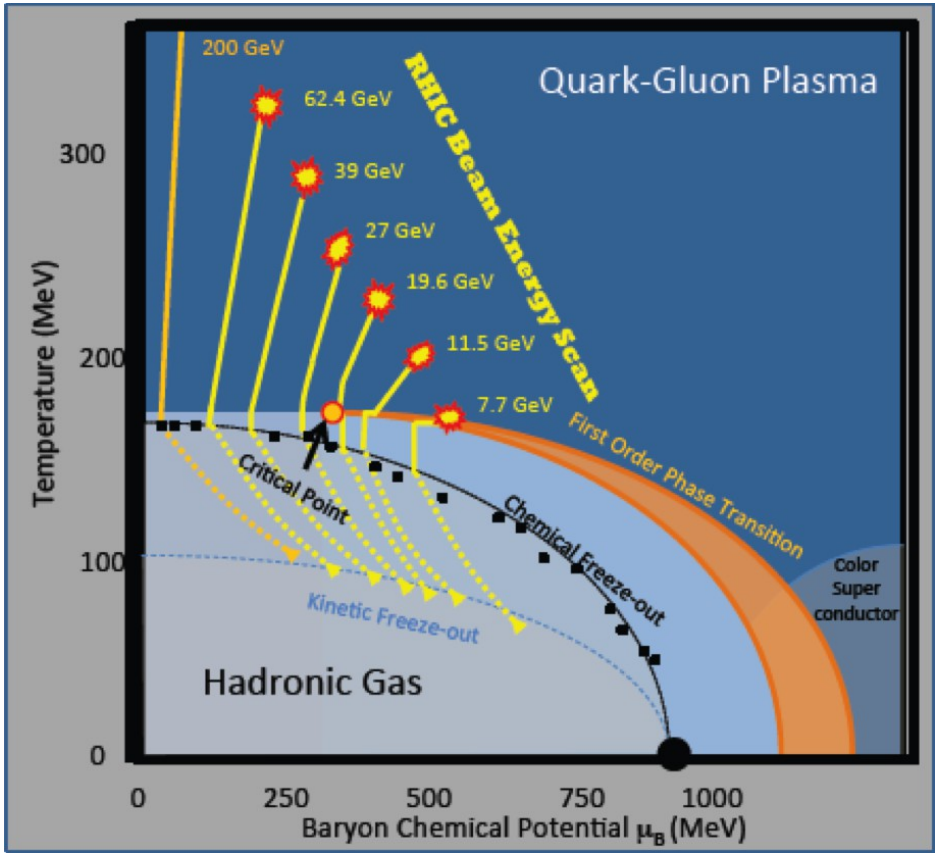


arXiv:nucl-th/0312081



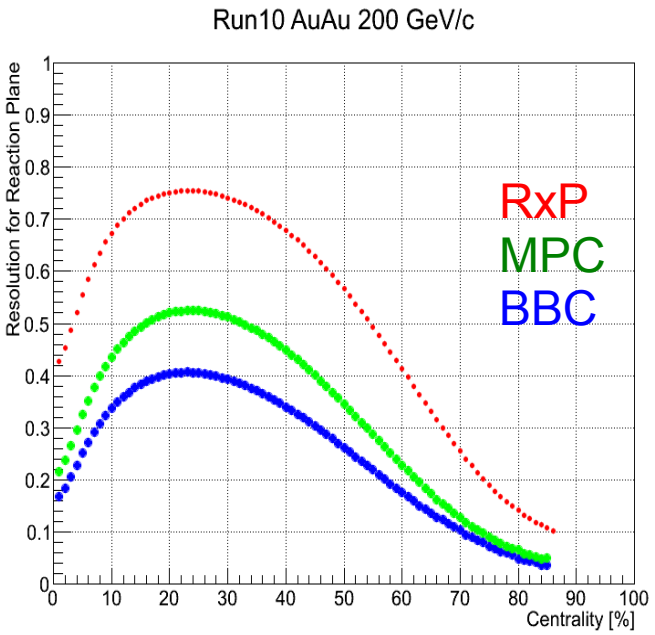
- The d v_2 is higher than p v_2 at p_T>3GeV/c.
- Succession of parton number scaling means p v_2 and n v_2 are very similar.
- Coalescence of p-n or 6 quarks?

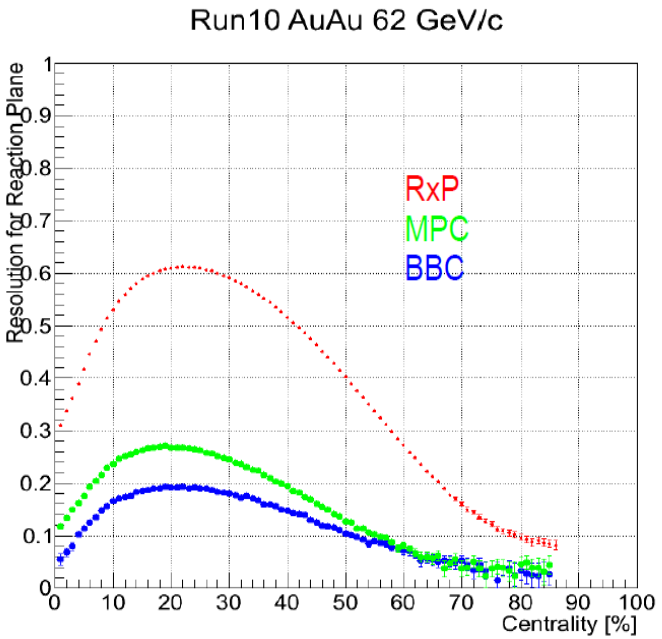
Beam energy scan with v_2 analysis

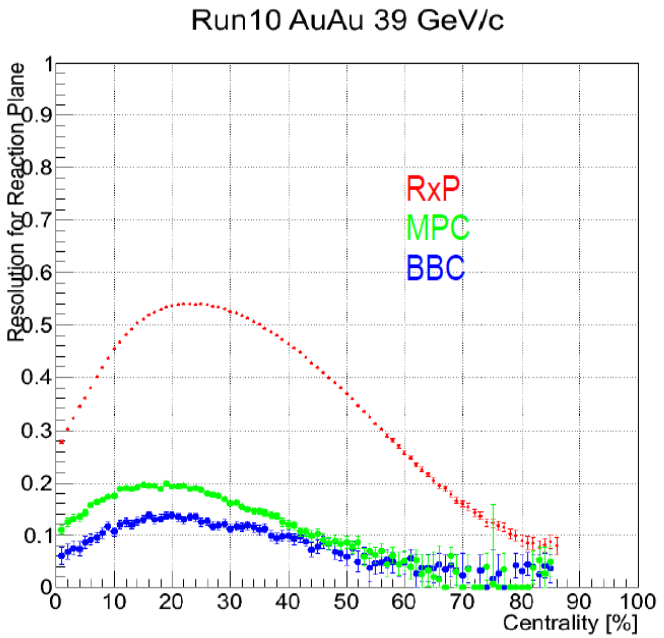


- Different regions of the QCD phase diagram.
- Brake of NCQ scaling
- Threshold of QGP
- Search the Critical point

Reaction Plane Resolution of PHENIX at low energy

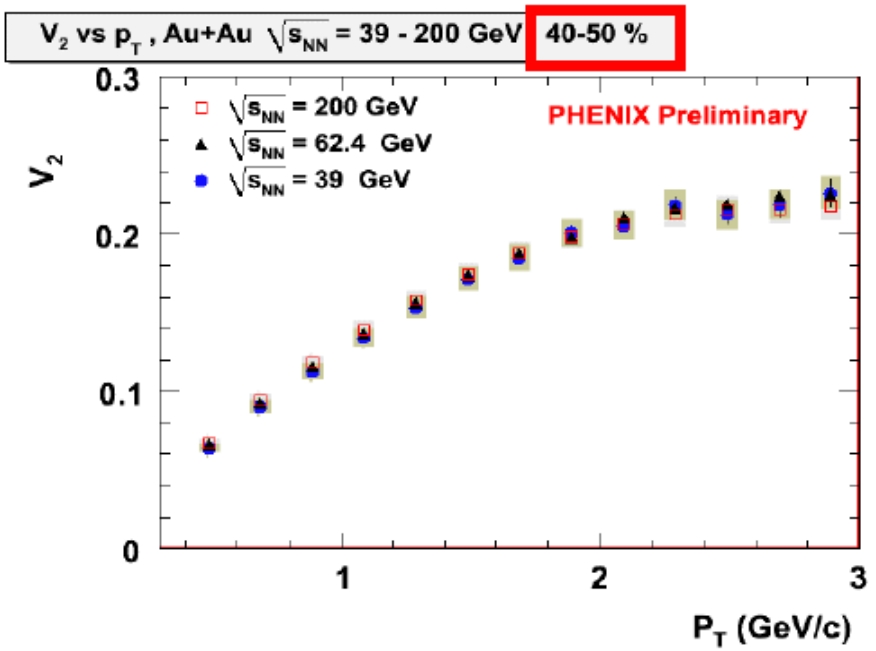


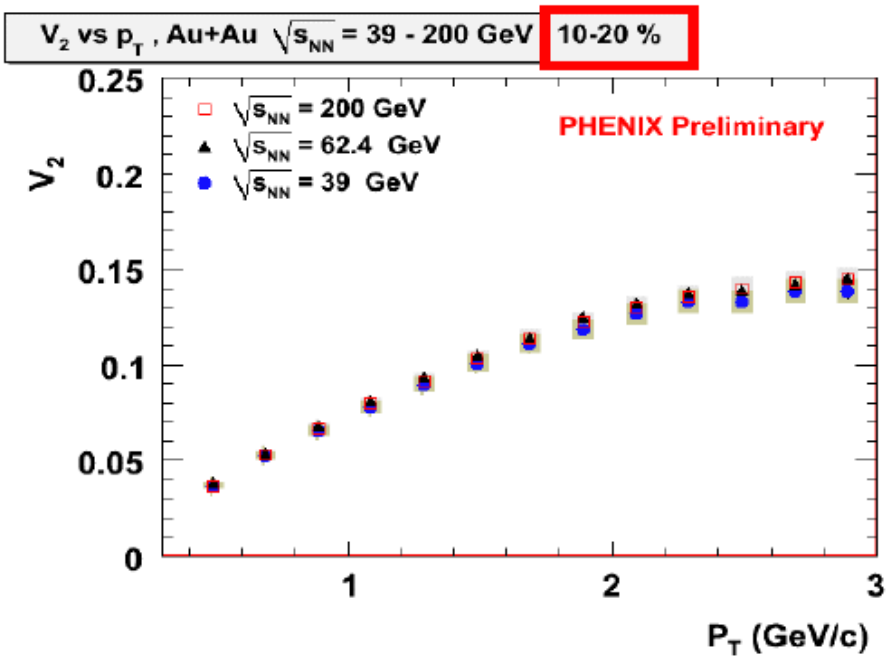




The high resolution of RxP allow the measurement of v_2 at low energy collision

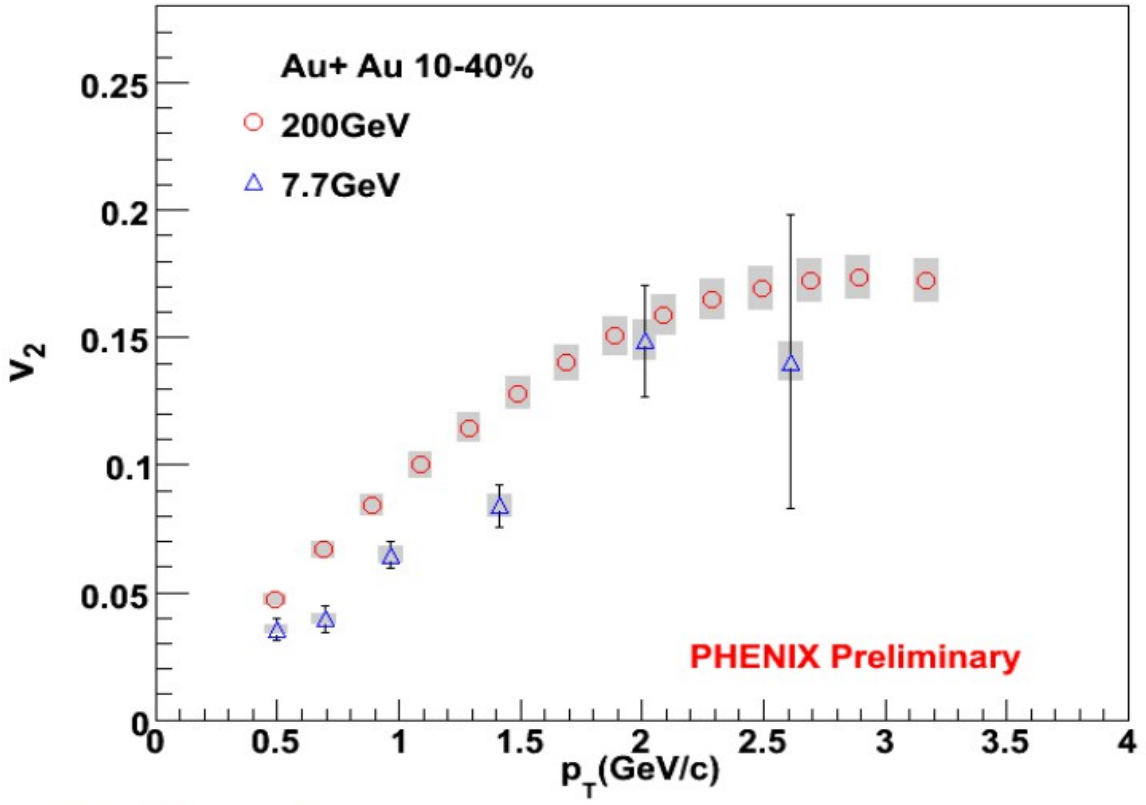
Charged hadron v_2 in $\sqrt{s_{NN}}$ = 39, 62, 200GeV





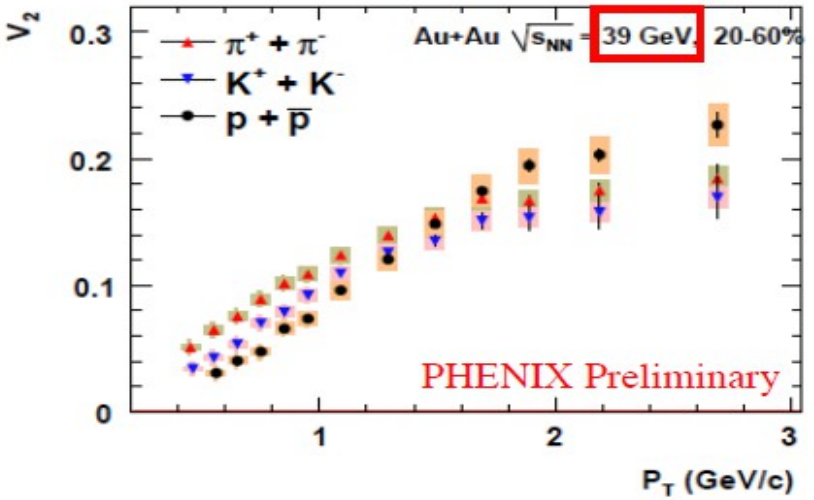
V_2 have no difference from 200GeV to 39GeV

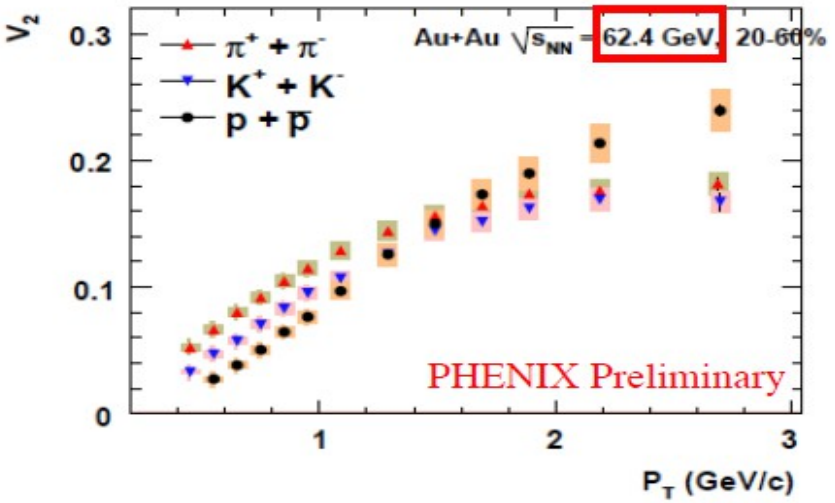
Charged hadron v_2 in $\sqrt{s_{NN}}$ = 7.7 GeV

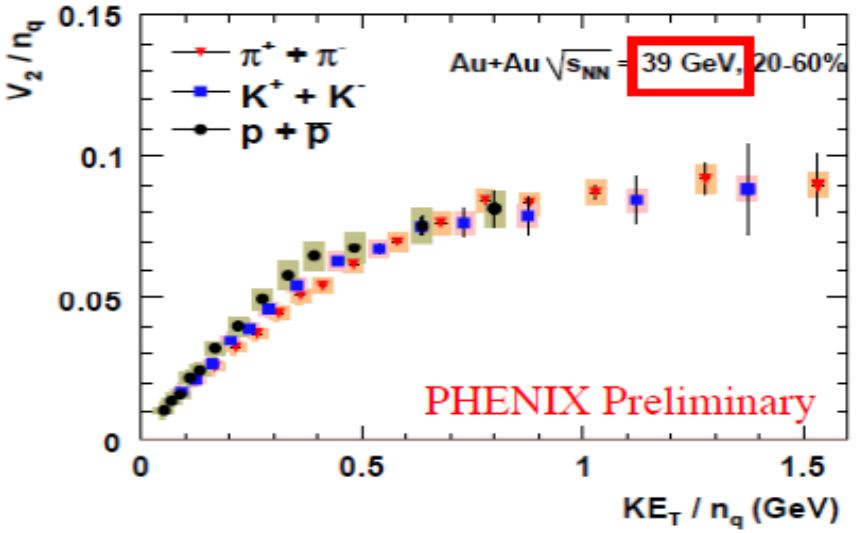


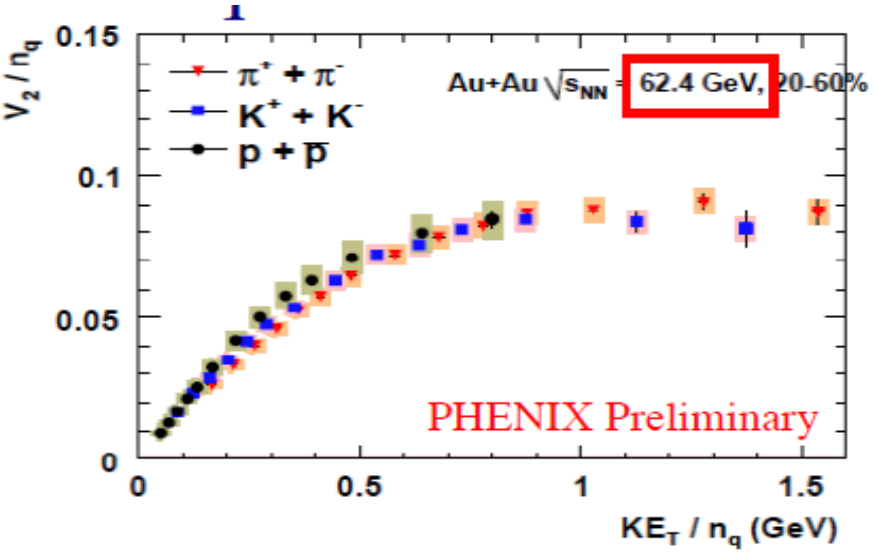
The magnitude of v2 at 7.7 GeV is significantly lower than the magnitudes at 39, 62 and 200 GeV

PID v_2 in $\sqrt{s_{NN}}$=39, 62 GeV



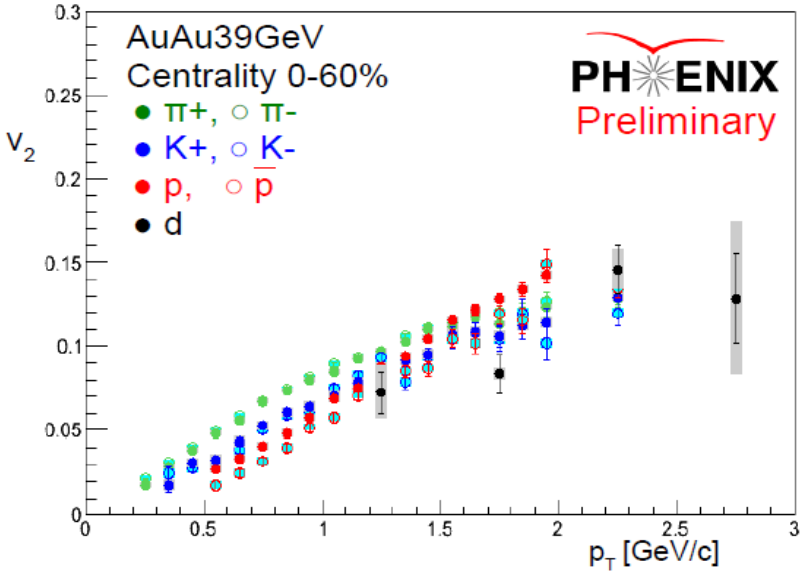


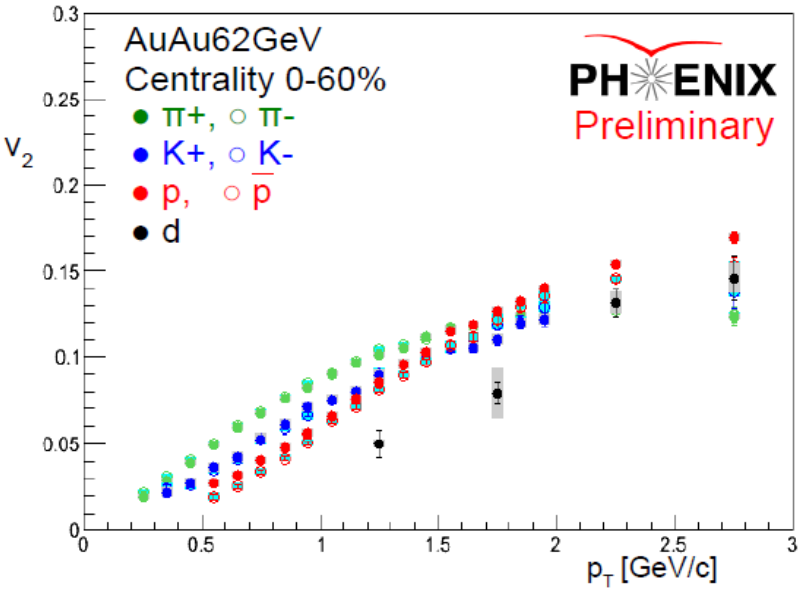


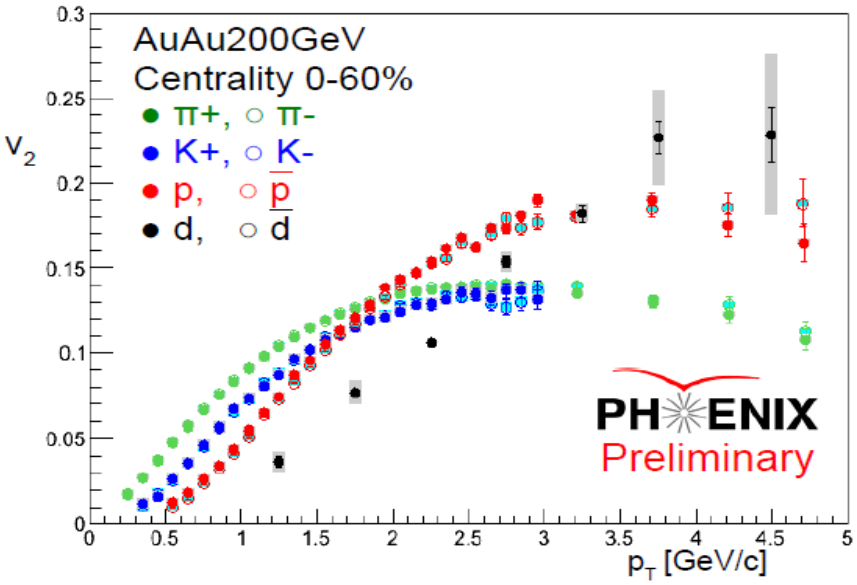


$p+\bar{p}$ is slightly large with n_q scaling

Charge separated PID v_2

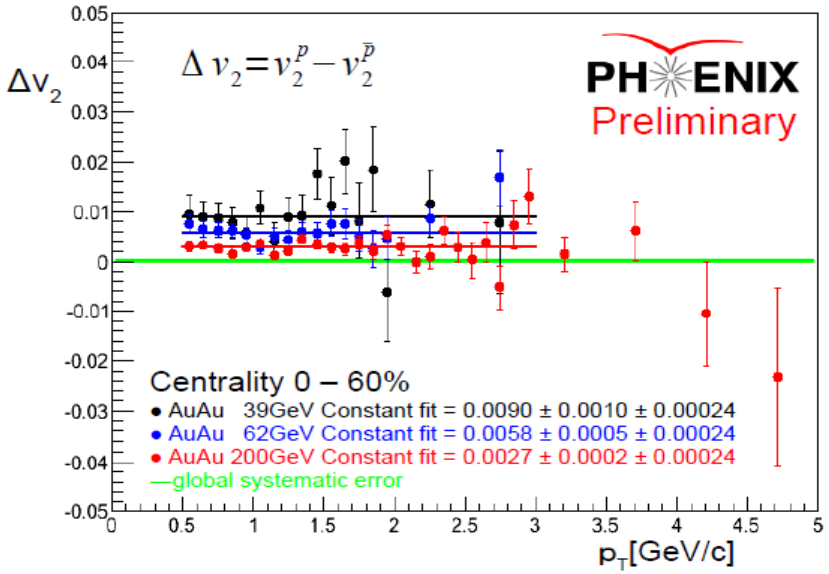




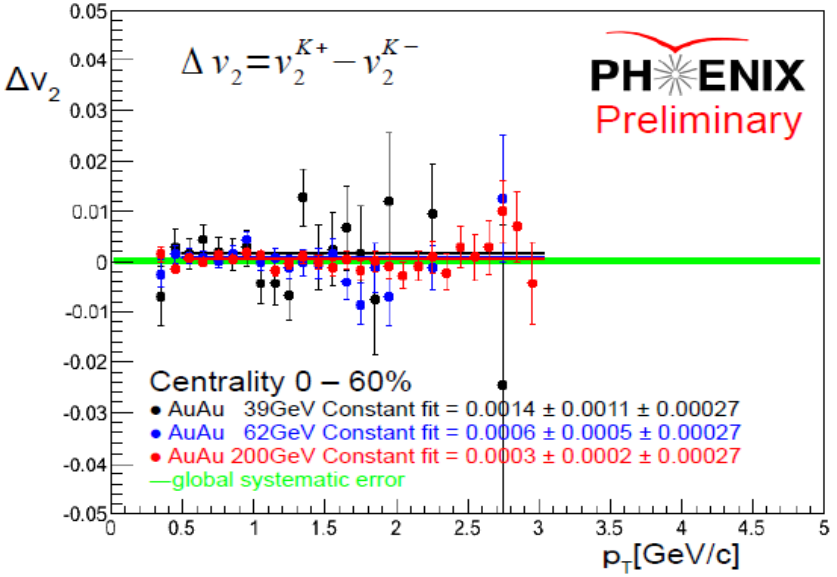


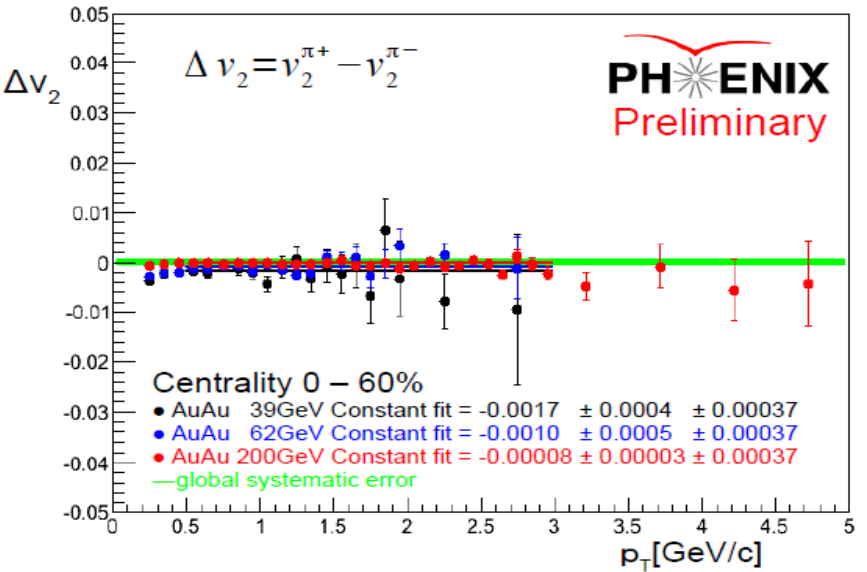
Proton have larger v_2 than that of anti-proton at low energy collision (39, 62GeV)

Difference v_2 between +/- charge

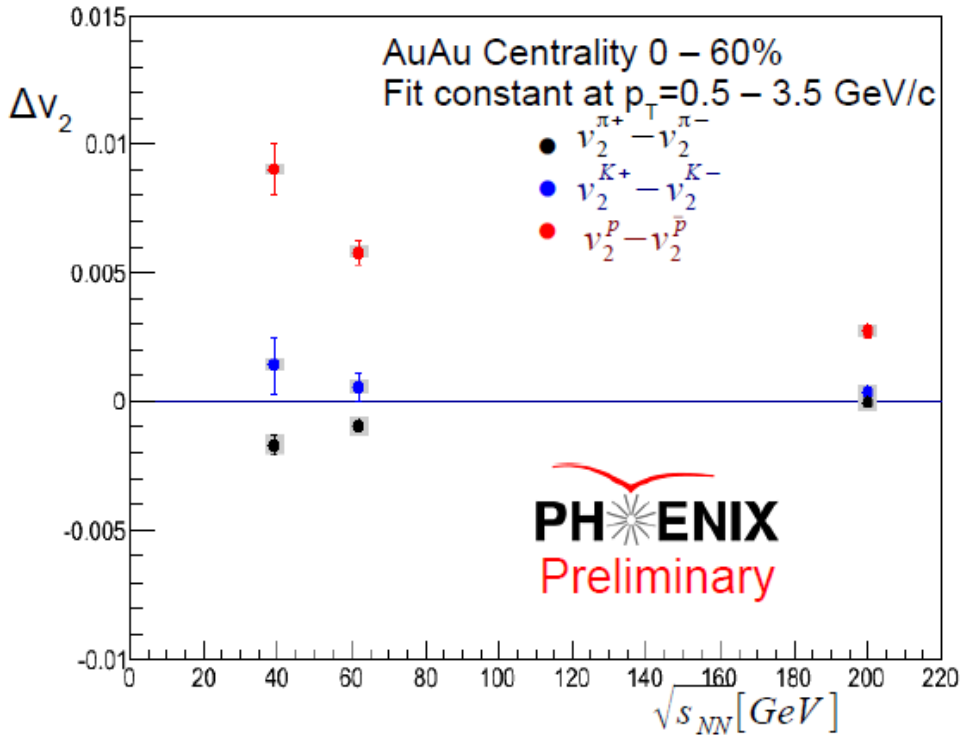


- Proton has larger v_2 than that of anti-proton at low energy collision
  - The v_2 difference is flat to momentum.





Δv_2 vs collision energy

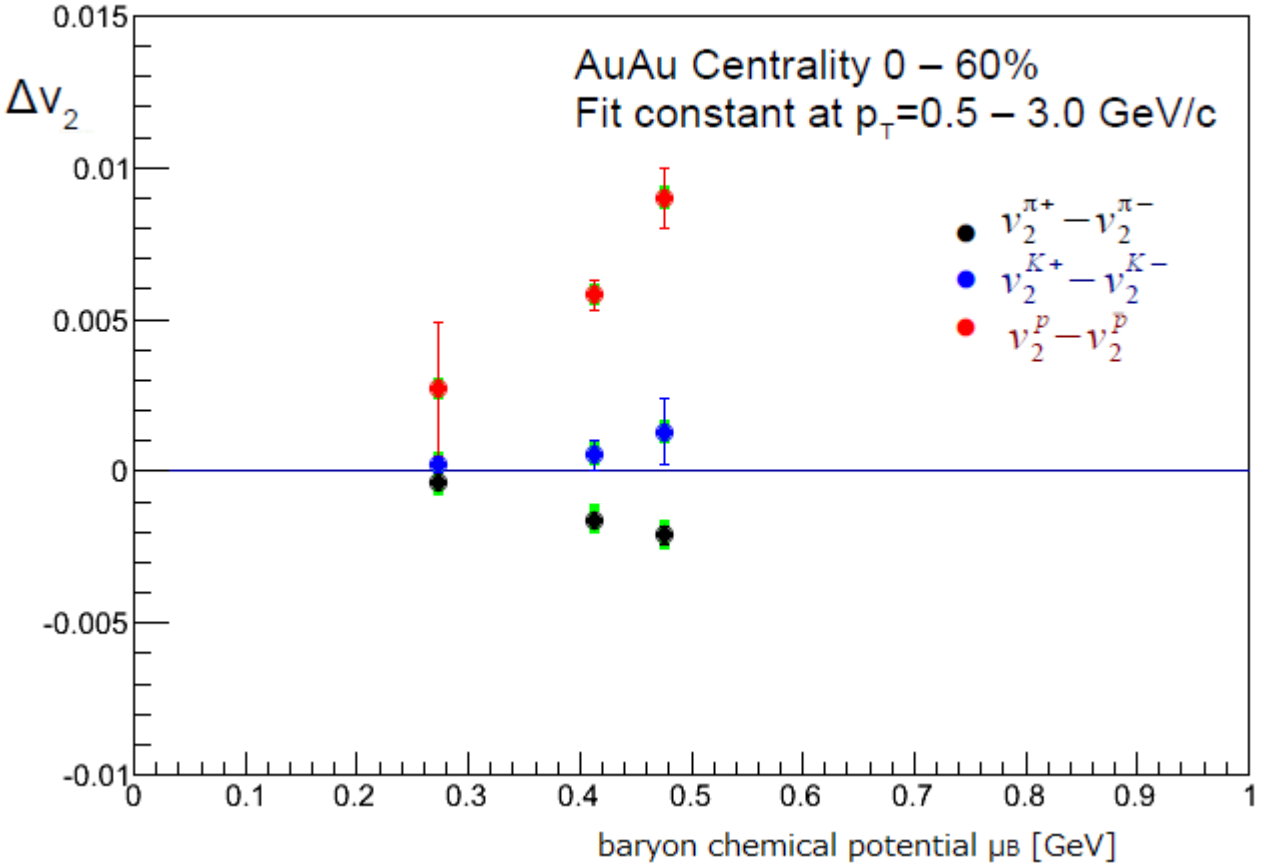


- p-$\bar{p}$ are deviated at low energy collision
  - The v_2 difference is flat to momentum.
- π- v_2 has slightly larger than π+
- K v_2 has no difference for +/- charge
- Annihilation effect with large net-baryon ratio ?

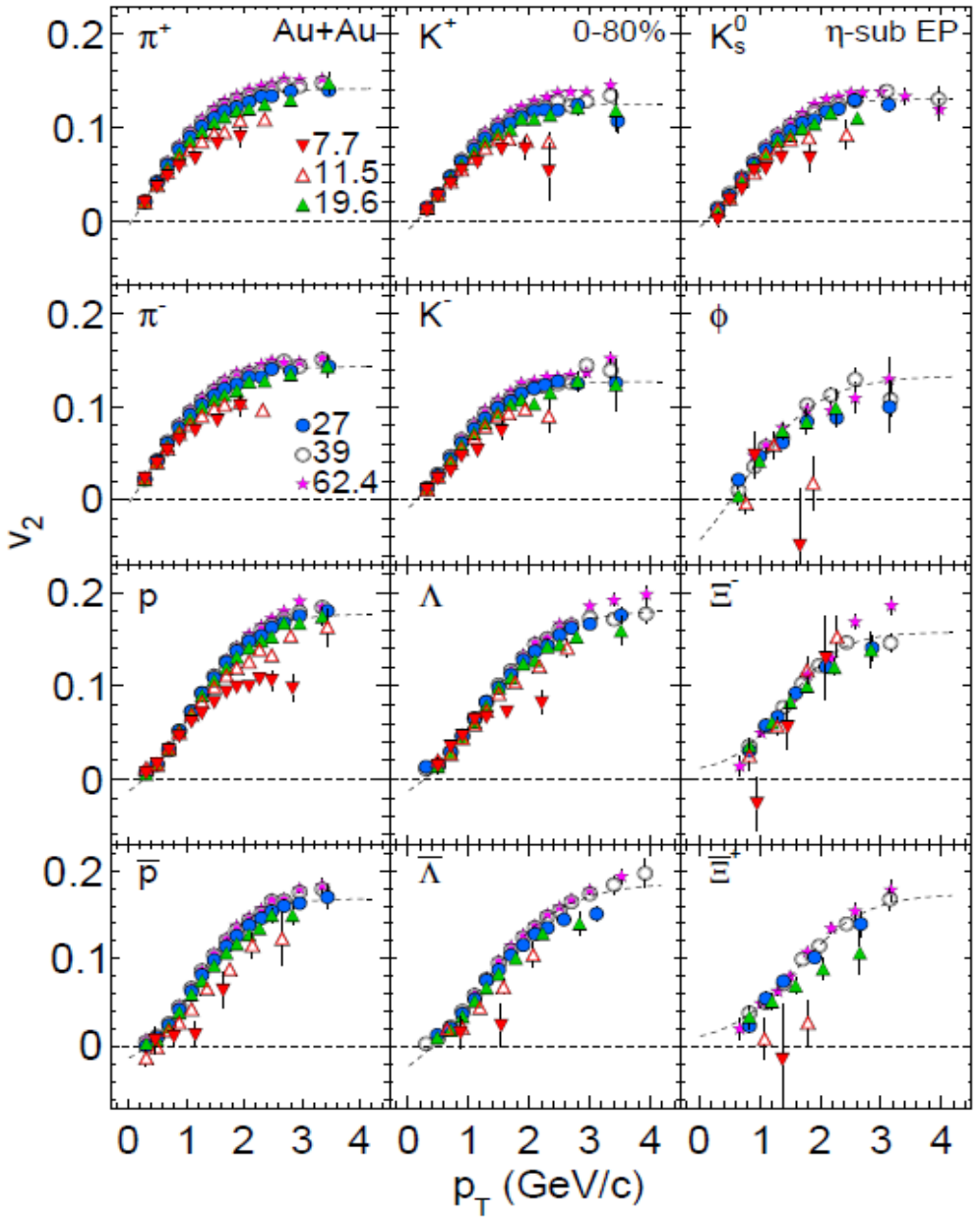
Summary

- V_2 of identified particles were measured at Au+Au $\sqrt{s_{NN}}$=200, 62 and 39GeV
- V_2 of all particles are consistent with number of constituent quark scaling at $\sqrt{s_{NN}}$=200GeV
  - Collective flow of quarks
- They are almost consistent at $\sqrt{s_{NN}}$=62 and 39GeV. But p v_2 is slightly large.
- Proton v_2 and anti-proton v_2 are deviated
  - The difference increases to low energy collision
  - The difference is flat to momentum.
  - π- v_2 has slightly larger than π+
  - K v_2 has no difference for +/- charge

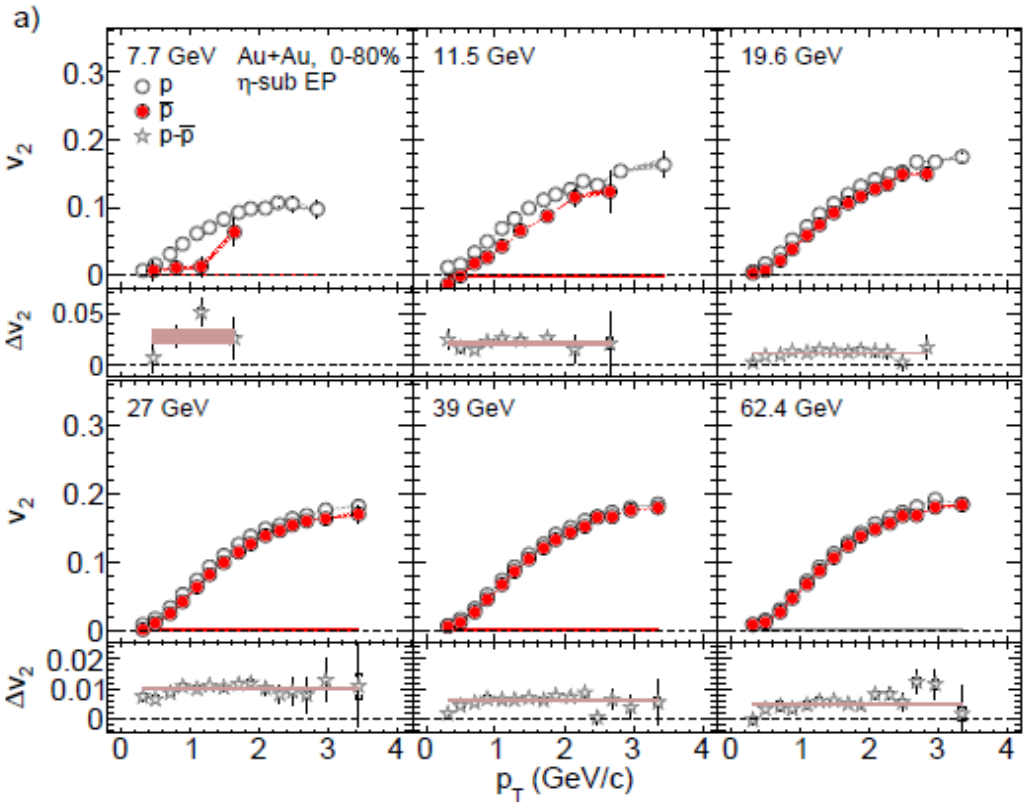
Backup


AuAu Centrality 0 – 60%
Fit constant at p_T=0.5 – 3.0 GeV/c
Δv_2
$v_2^{\pi+} - v_2^{\pi-}$
$v_2^{K+} - v_2^{K-}$
$v_2^{p} - v_2^{\bar{p}}$
0.015
0.01
0.005
0
-0.005
-0.01
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
baryon chemical potential μB [GeV]

RHIC-STAR



ArXiv:1301.2348v1



RHIC-STAR

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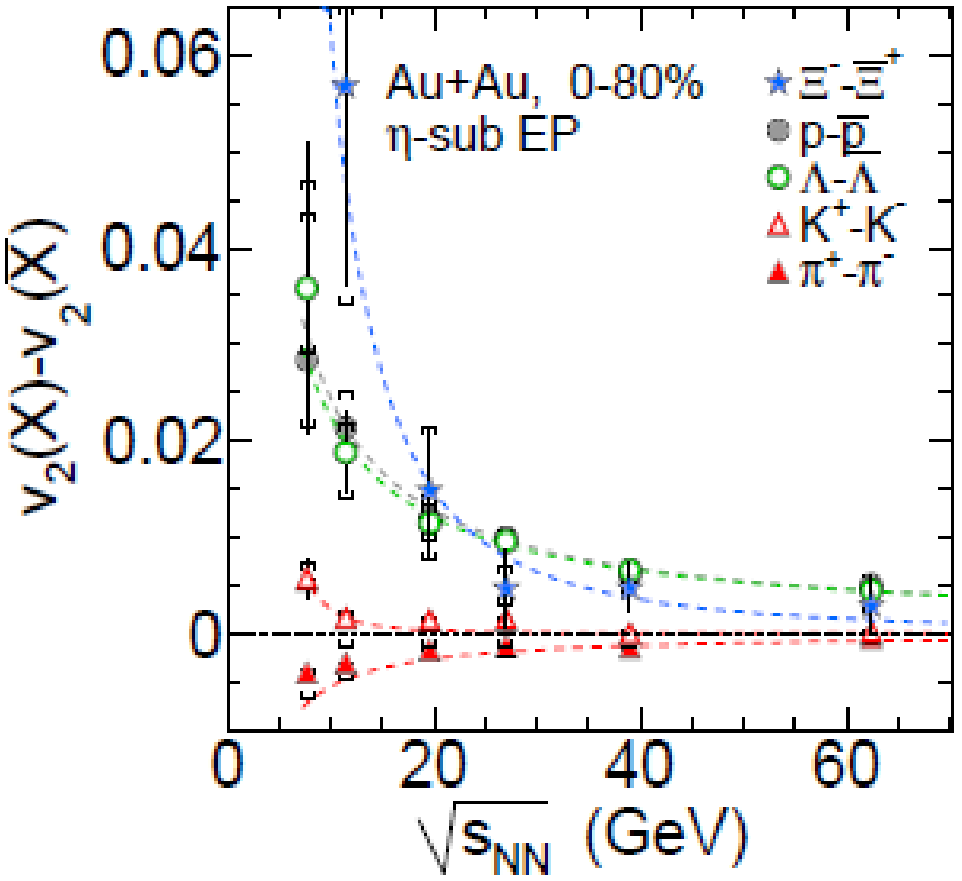
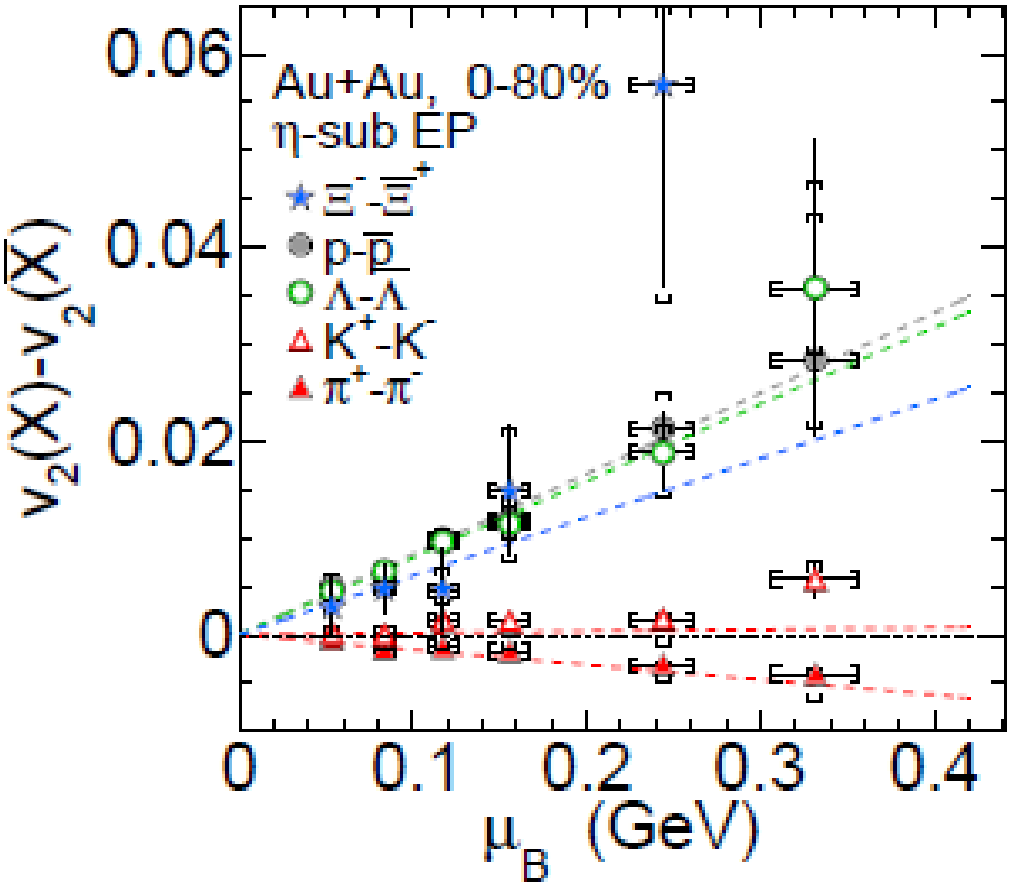
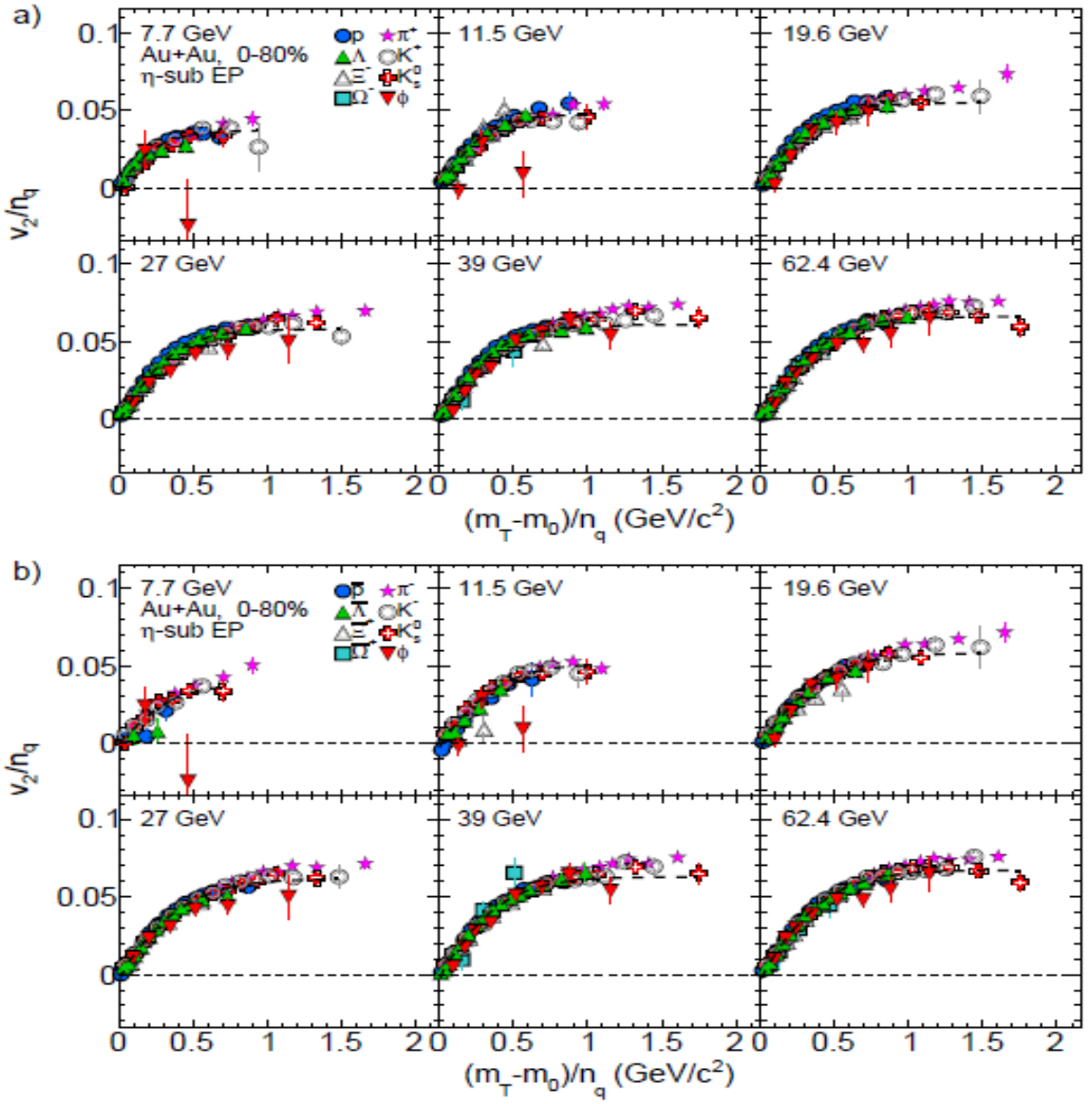


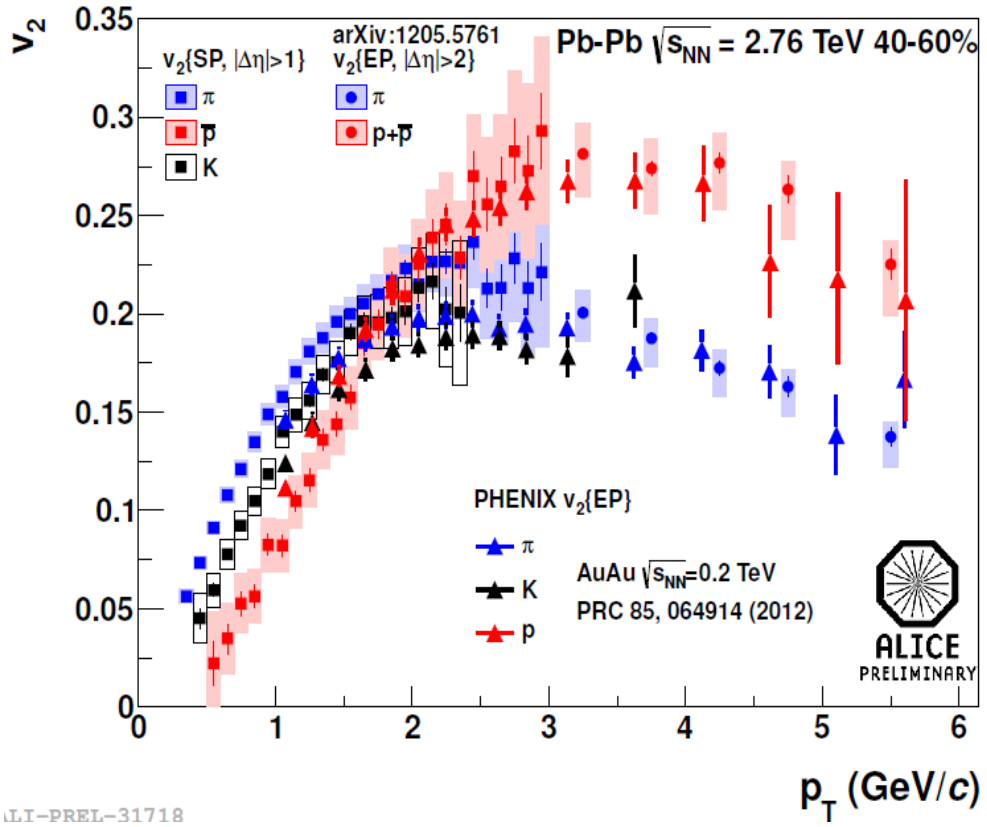


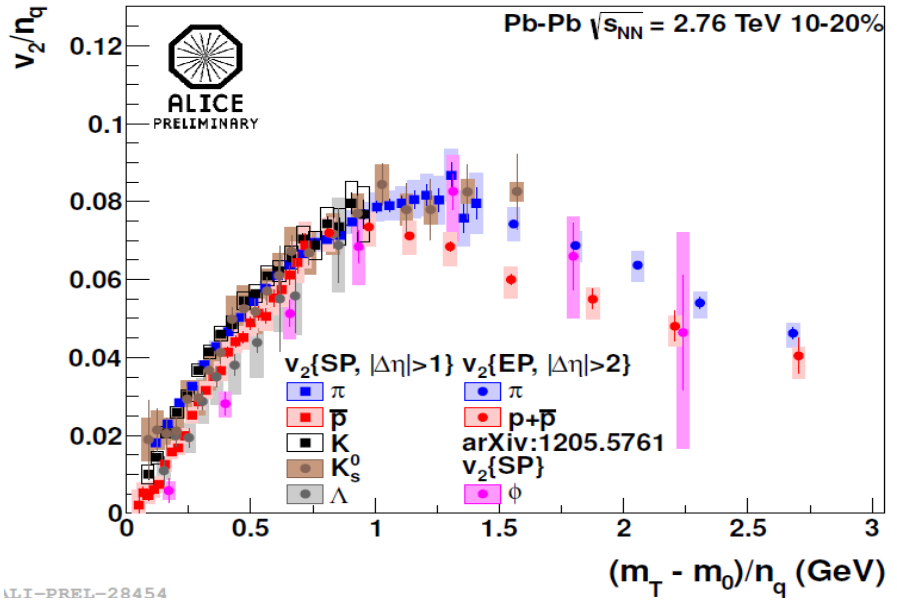
RHIC-STAR

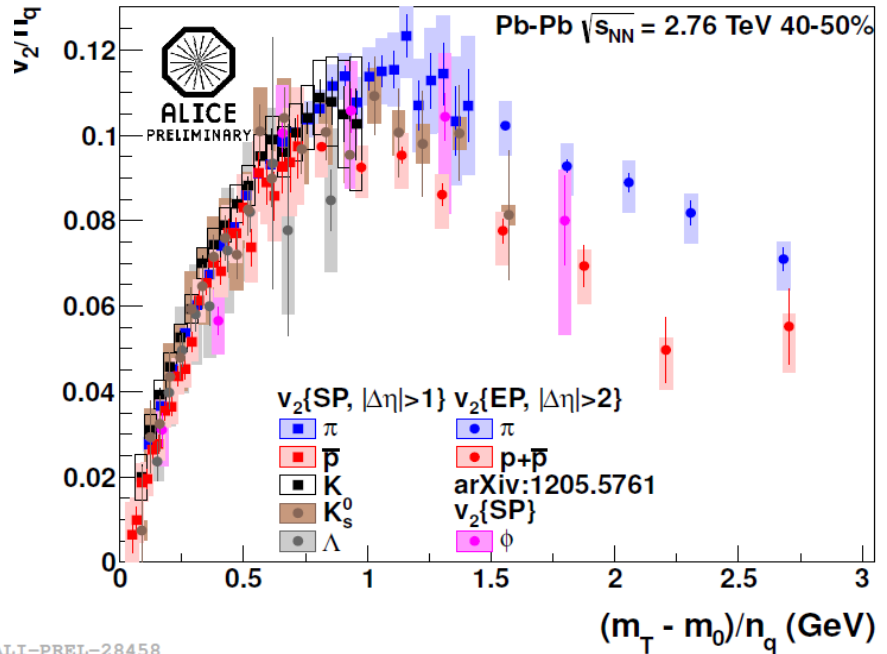
ArXiv:1301.2348v1



LHC-ALICE

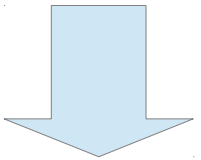

v2
arXiv:1205.5761
Pb-Pb √sNN = 2.76 TeV 40-60%
v2{SP, |Δη|>1}
v2{EP, |Δη|>2}
π
p̄
K
π
p+p̄
PHENIX v2{EP}
π
K
p
AuAu √sNN=0.2 TeV
PRC 85, 064914 (2012)
ALICE
PRELIMINARY
pT (GeV/c)
ALI-PREL-31718


v2/nq
Pb-Pb √sNN = 2.76 TeV 10-20%
ALICE
PRELIMINARY
v2{SP, |Δη|>1} v2{EP, |Δη|>2}
π
p̄
K
K0s
Λ
π
p+p̄
arXiv:1205.5761
v2{SP}
ϕ
(mT - m0)/nq (GeV)
ALI-PREL-28454


v2/nq
Pb-Pb √sNN = 2.76 TeV 40-50%
ALICE
PRELIMINARY
v2{SP, |Δη|>1} v2{EP, |Δη|>2}
π
p̄
K
K0s
Λ
π
p+p̄
arXiv:1205.5761
v2{SP}
ϕ
(mT - m0)/nq (GeV)
ALI-PREL-28458

Motivation of RP detector

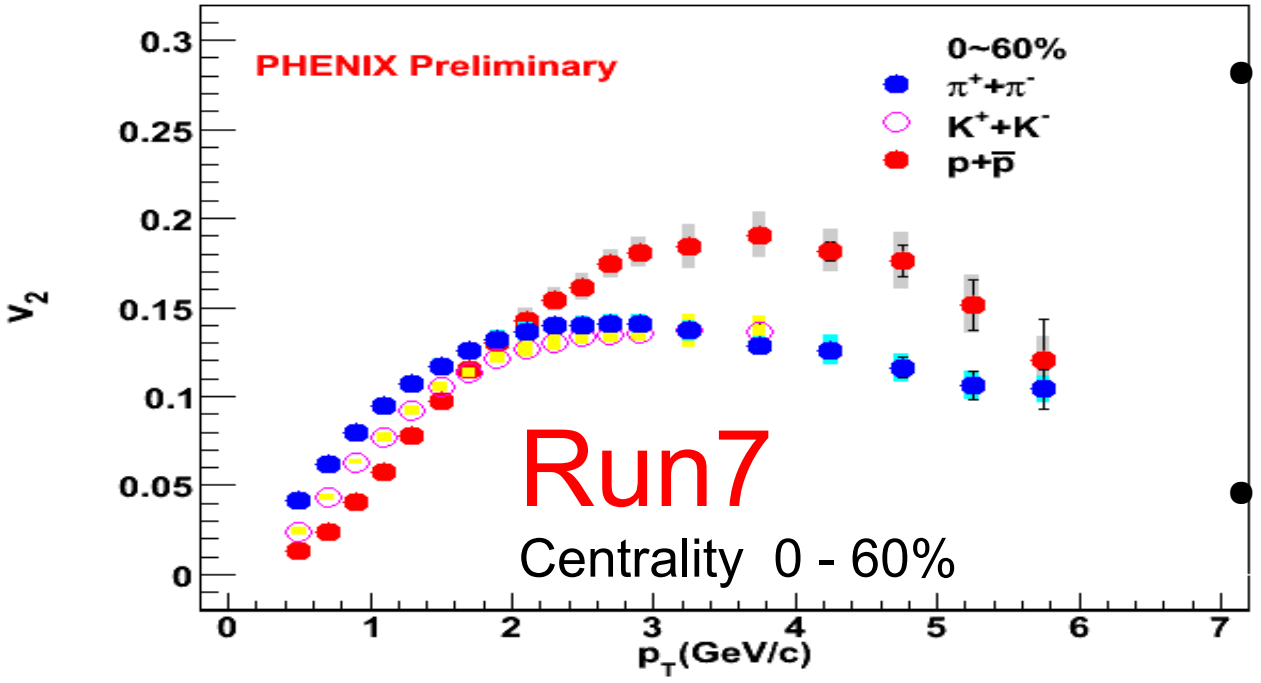
- Measurement of more precise v_2 is expected.
- Poor reaction plane resolution was a major limiting factor of PHENIX v_2 measurement of rare probes such as d, Φ.



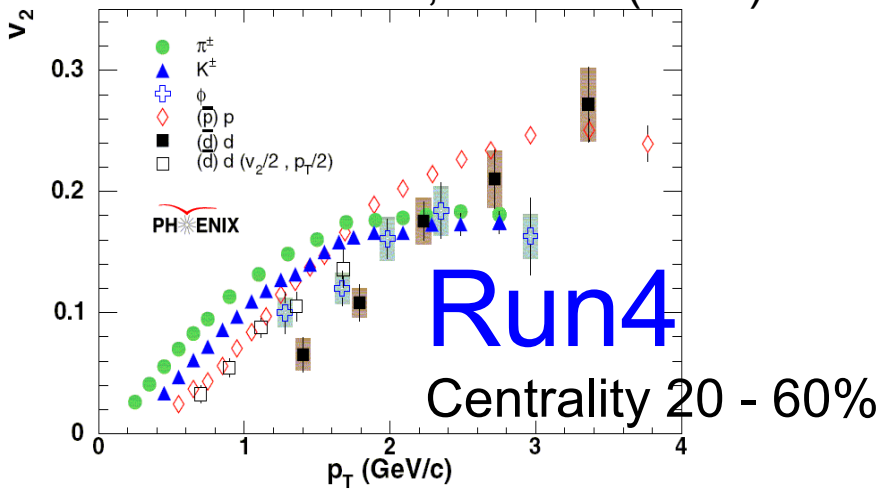
Reaction Plane Detector (RxP) has been constructed and installed to PHENIX in 2007.

- Reaction plane resolution of $\langle\cos 2\Delta\psi\rangle$ ~0.75 for minimum bias Au+Au collisions

v_2 on PHENIX-Run7

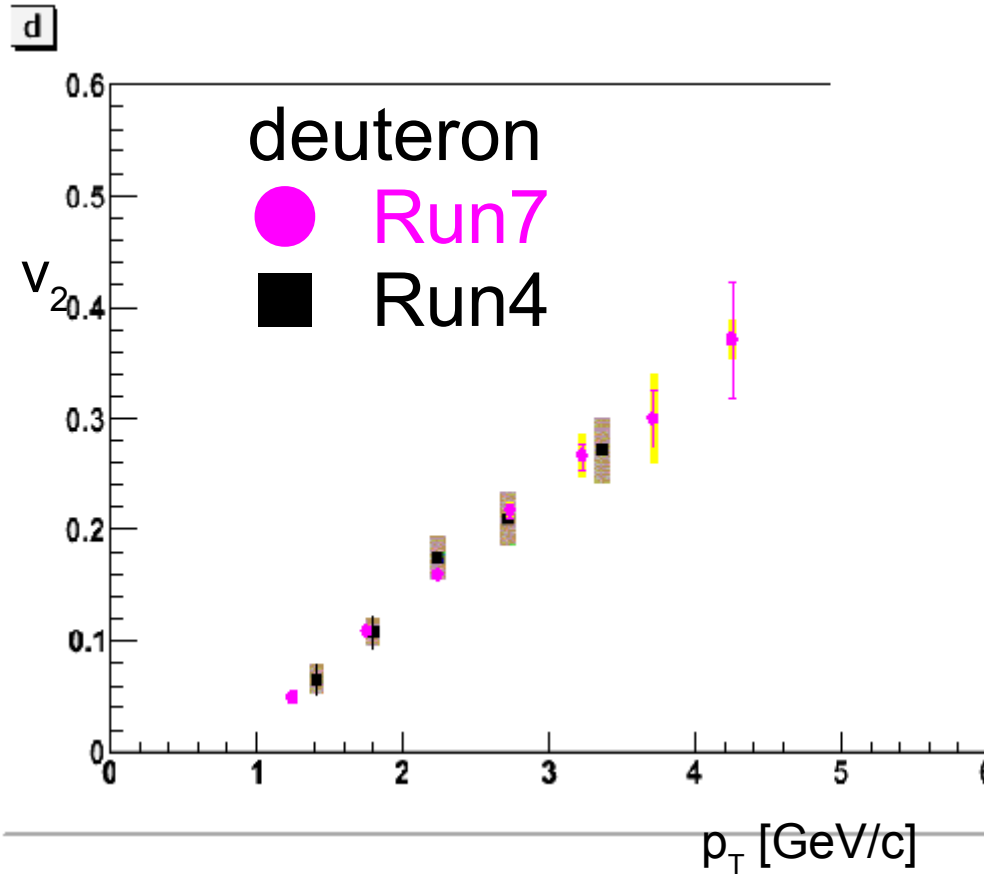


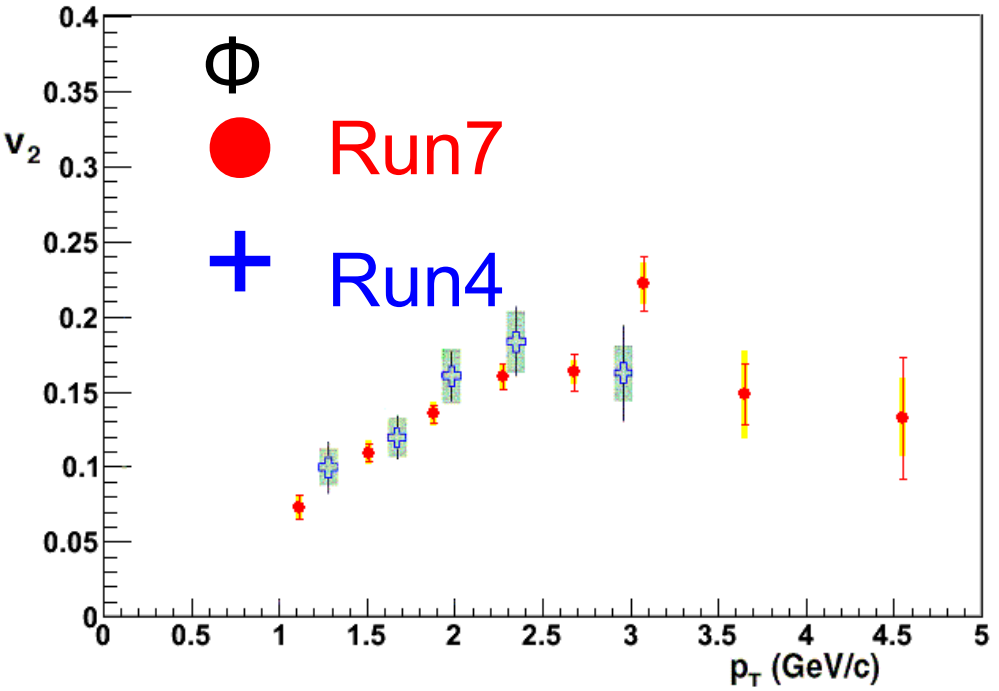
PHENIX. PRL. 99, 052301 (2007)



- Run7 have 2 times of RP resolution and 4 times of statistic from Run4.
- TOF.W and ACC work well, too.
- p_T range is extended to p_T = 6 GeV/c.

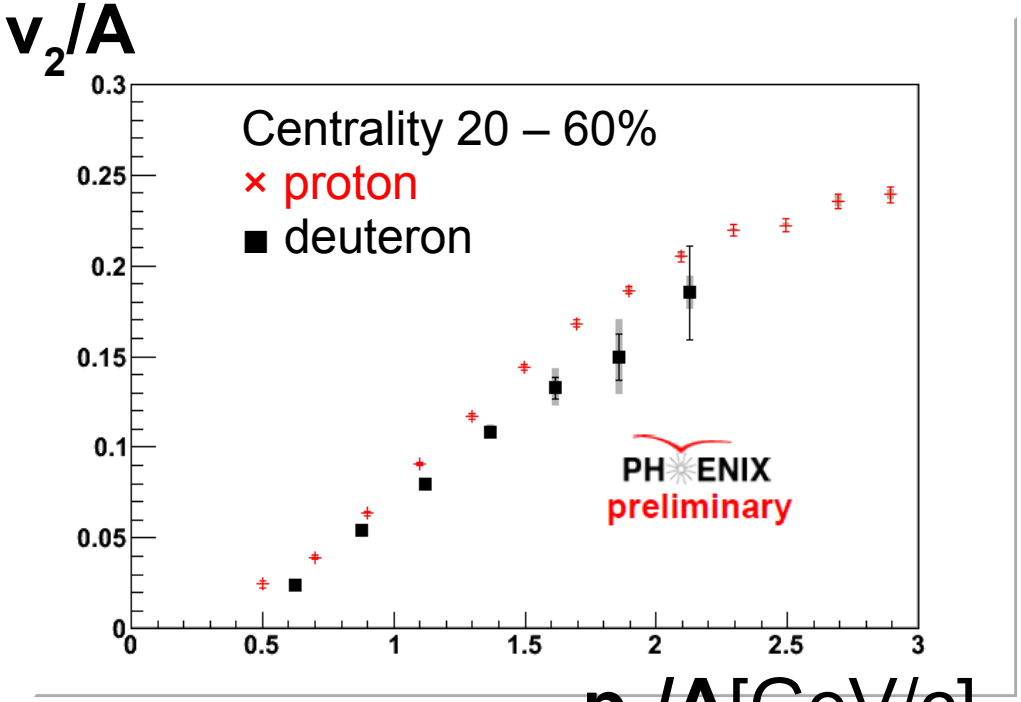
Comparison with last one

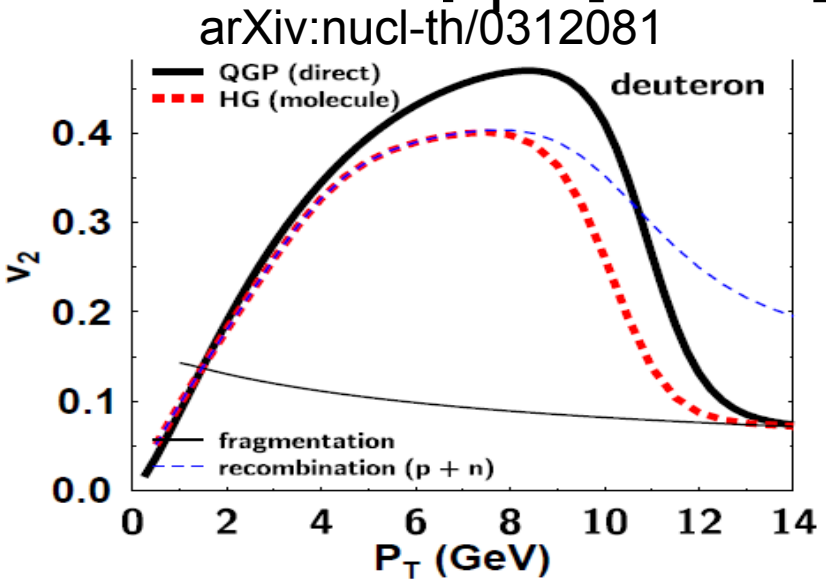




- p_T range is extended to p_T ~ 4.5 GeV/c.

Nucleon number scaling





$$v_2^d \sim 2\, v_2^p, \quad p_T^d \sim 2\, p_T^p$$

- The peak of d v_2 is expected at p_T=6GeV/c.
- D v_2 and p v_2 are very similar on p_T/A scaling.
- It means p v_2 and n v_2 are very similar.
- Coalescence of p-n or 6 quarks?