Flow in the RHIC Beam Energy Scan from STAR

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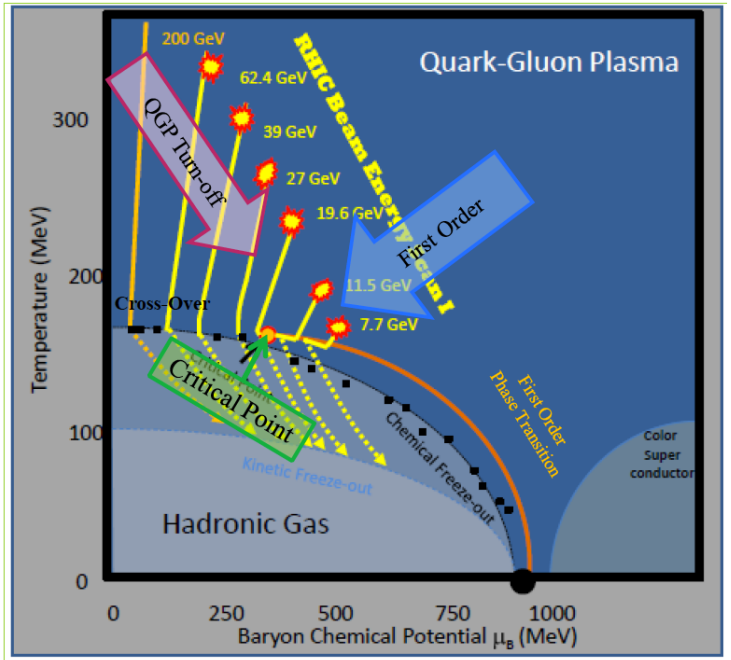
The Beam Energy Scan at RHIC

Methods to study the QCD phase space:

- QGP at high T and/or μ_B
  → R_{AA}, NCQ scaling of v_2,...
- We expect from QCD lattice calculations a cross over at high energies
- First order phase transition?
  → Azimuthal HBT, v_1 analyses
- Critical point?
  → Fluctuation analyses (net-protons)
- Hadron gas phase at low T and/or μ_B

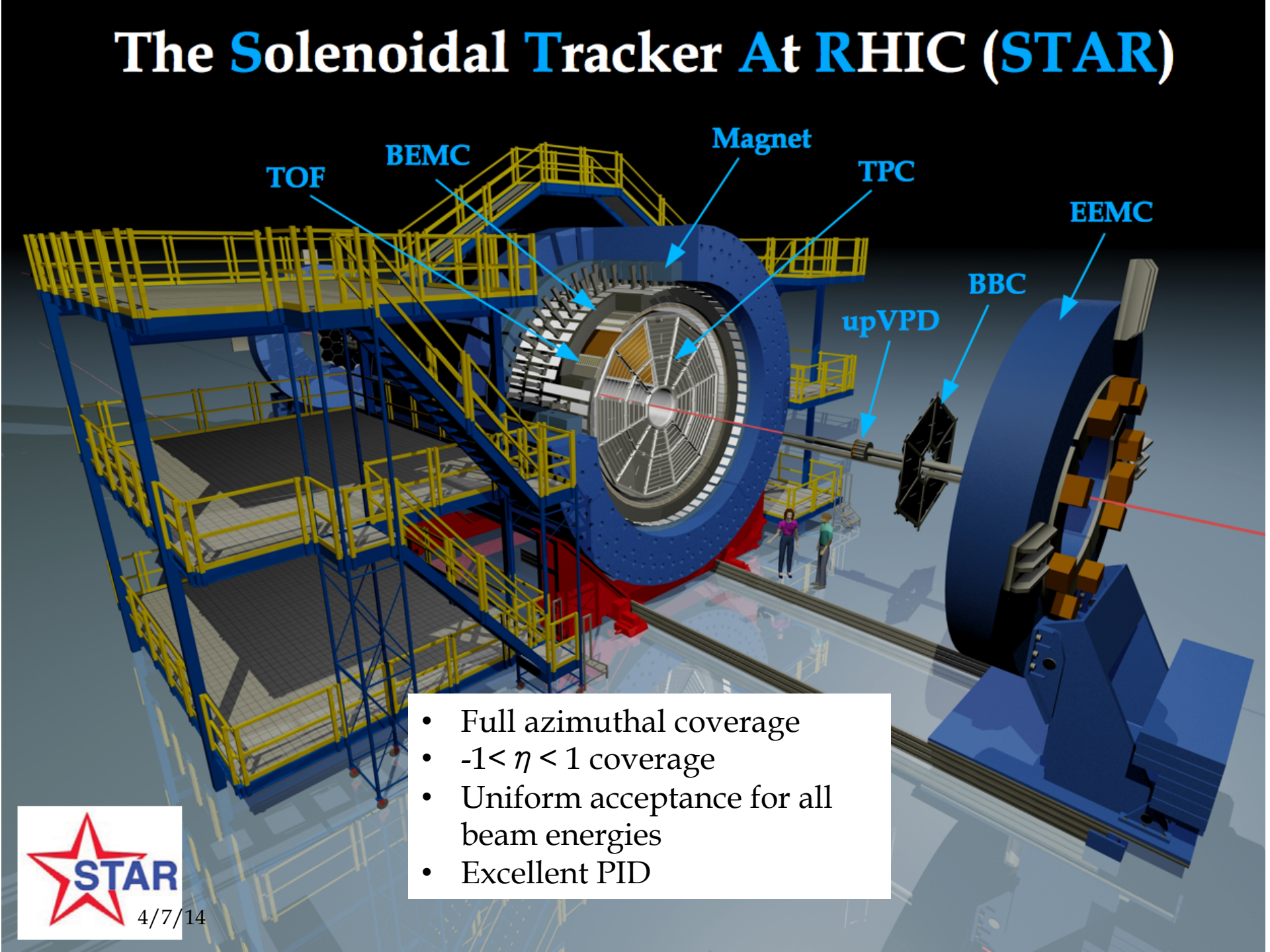
Initial state fluctuation
→ v_3 analysis



$\sqrt{s_{NN}}$ (GeV)	MB Events in 10^6
7.7	4.3
11.5	11.7
19.6	35.8
27	70.4
39	130.4
62.4	67.3

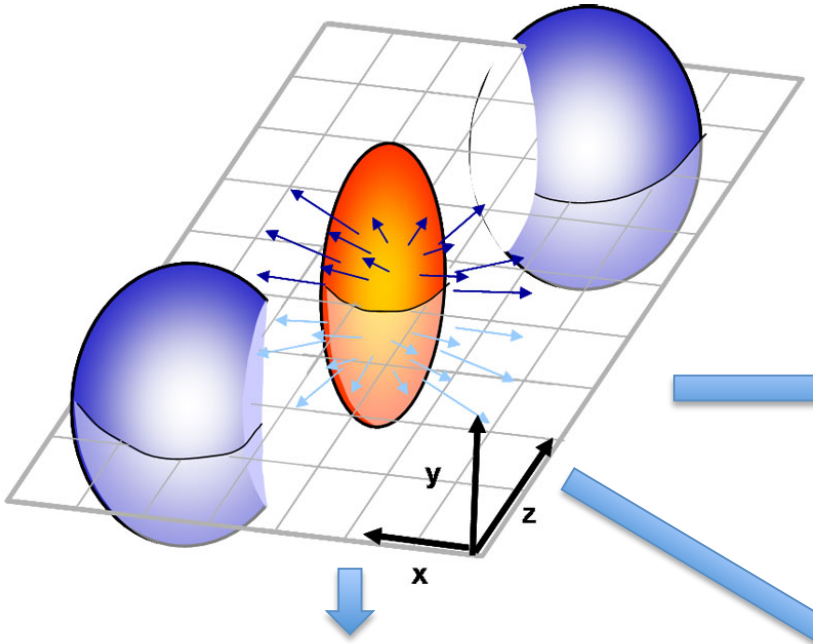
*Au+Au minimum bias events at STAR usable for analysis

The Solenoidal Tracker At RHIC (STAR)

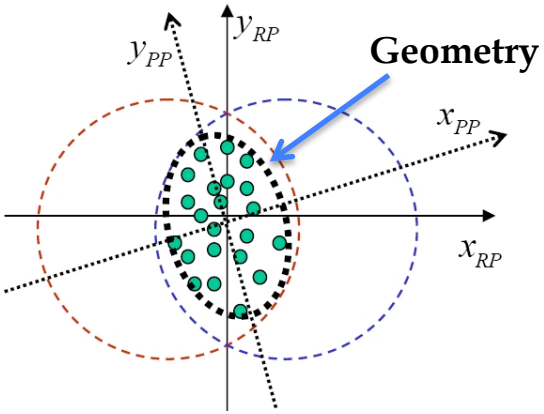


- Full azimuthal coverage
- $-1 < \eta < 1$ coverage
- Uniform acceptance for all beam energies
- Excellent PID

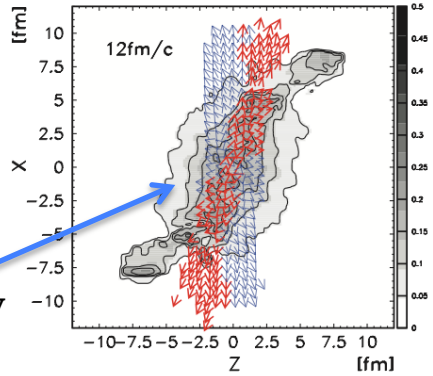
Introduction of Flow



$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left[n\left(\phi-\Psi_R\right)\right]\right)$$

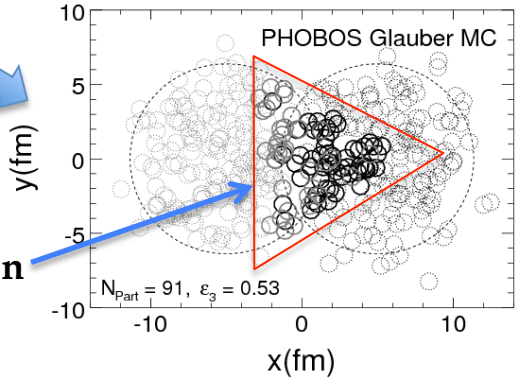


elliptic flow (v_2)



Compressibility

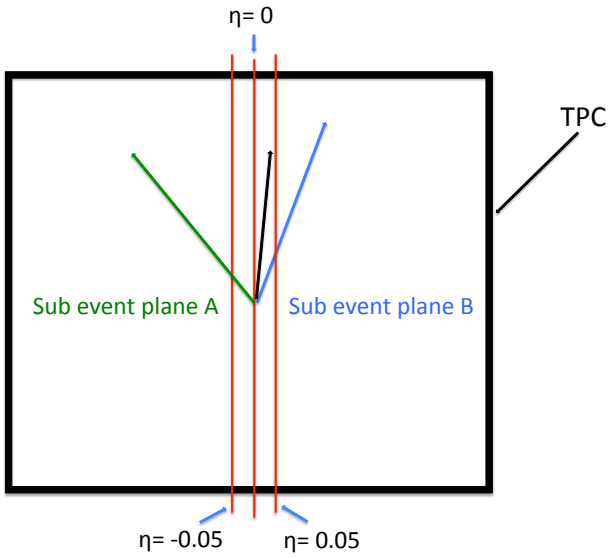
directed flow (v_1)



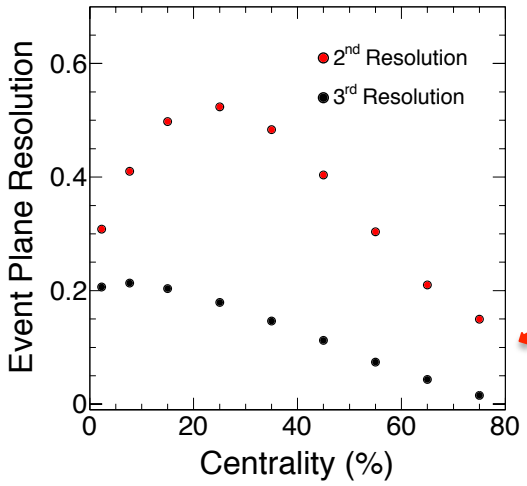
Fluctuation

triangular flow (v_3)

Event Plane Reconstruction



- Standard Event Plane Method
- η_{sub} Method with η_{gap} = +/- 0.05

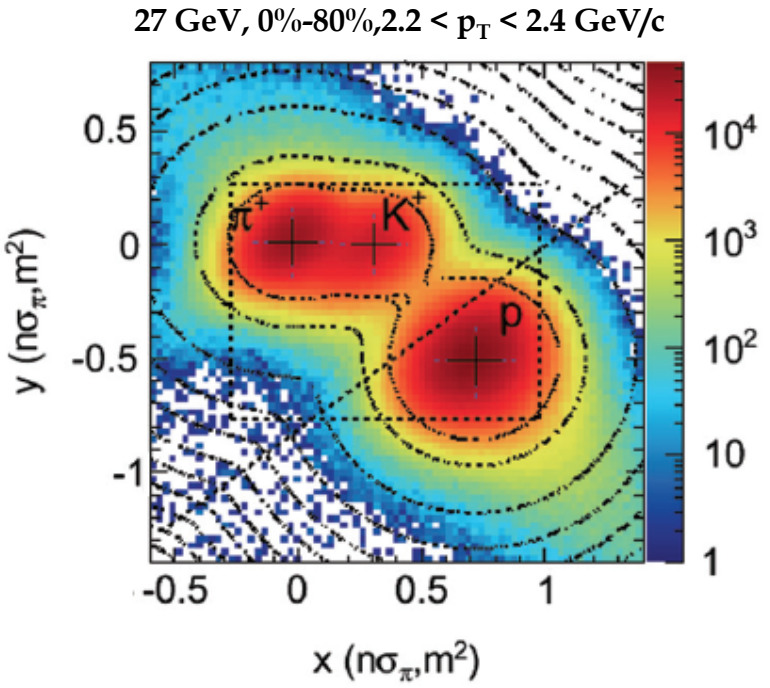


Event plane resolution:

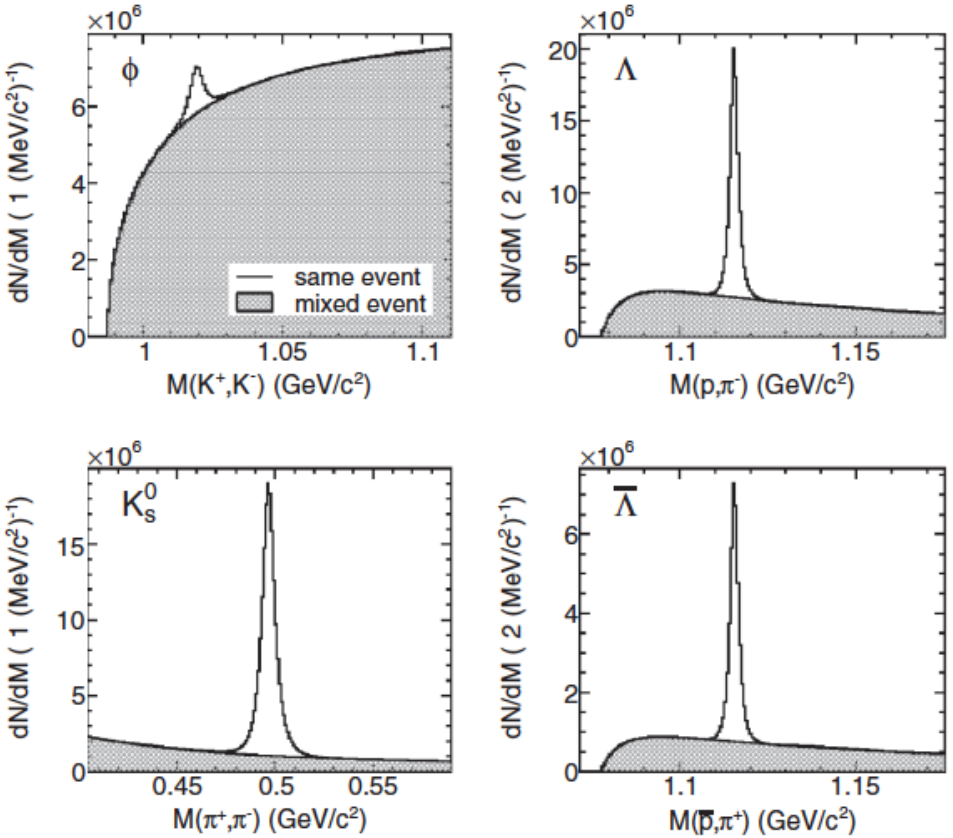
$$\text{res}_n = \sqrt{\left\langle \cos\left[n\left(\Psi_n^{East} - \Psi_n^{West} \right) \right] \right\rangle}$$

Phys. Rev. C 58, 1671 (1998)

Particle Identification

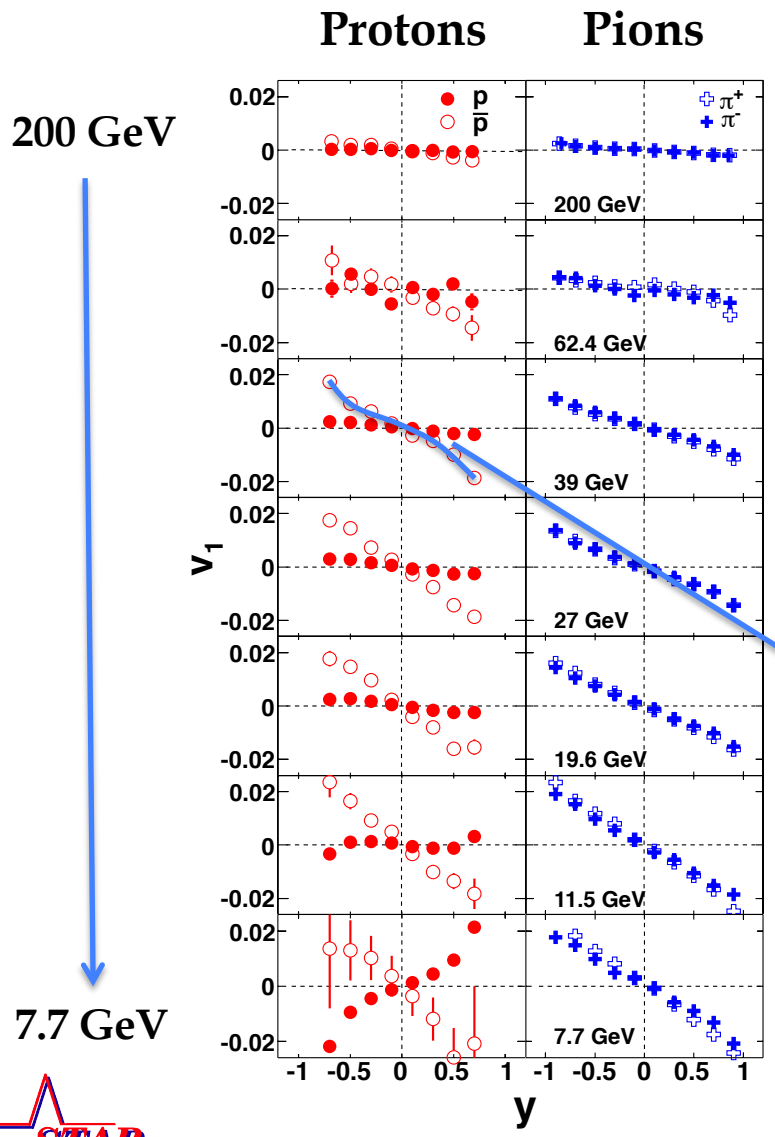


Phys. Rev. C 88, 014902(2013)



- Full time-of-flight detector for beam energy scan
  → 2D particle identification with dE/dx from TPC and m^2 from ToF
  → Better PID at low p_T region
- Short life time particle reconstruction via invariant mass method
  → Great signal to background ratio

v_1: Rapidity Dependence

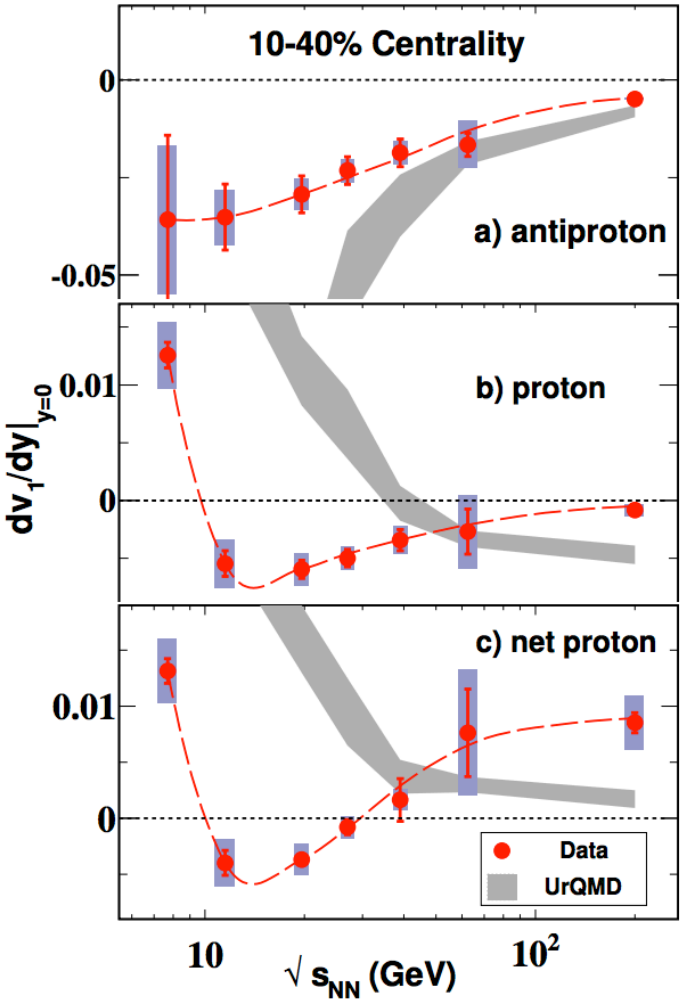


- Anti-symmetric at y=0 for pions and protons
- $v_1(y)$ for π^+ and π^- have small differences at 11.5 and 7.7 GeV
- $v_1(y)$ for protons and anti-protons have a large difference at 7.7-62.4 GeV
  → difference between transport baryon and produced baryon?
  → $[v_1(y)]_p = r(y)[v_1(y)]_{\bar{p}} + [1-r(y)][v_1(y)]_{net-p}$

Slope: $dv_1/dy\,|_{y=0}$

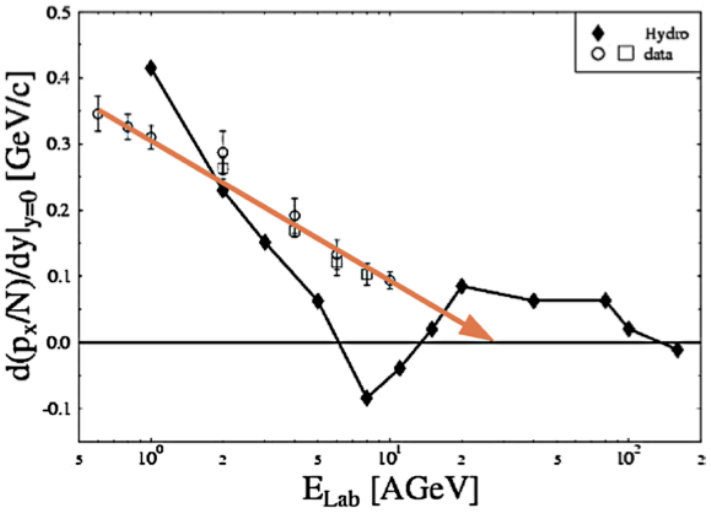
arXiv:1401.3043, accepted by PRL

v_1: Slope ($dv_1/dy|_{y=0}$) as a function of Beam Energy



➢ **The dashed curves are a smooth fit to guide the eye**

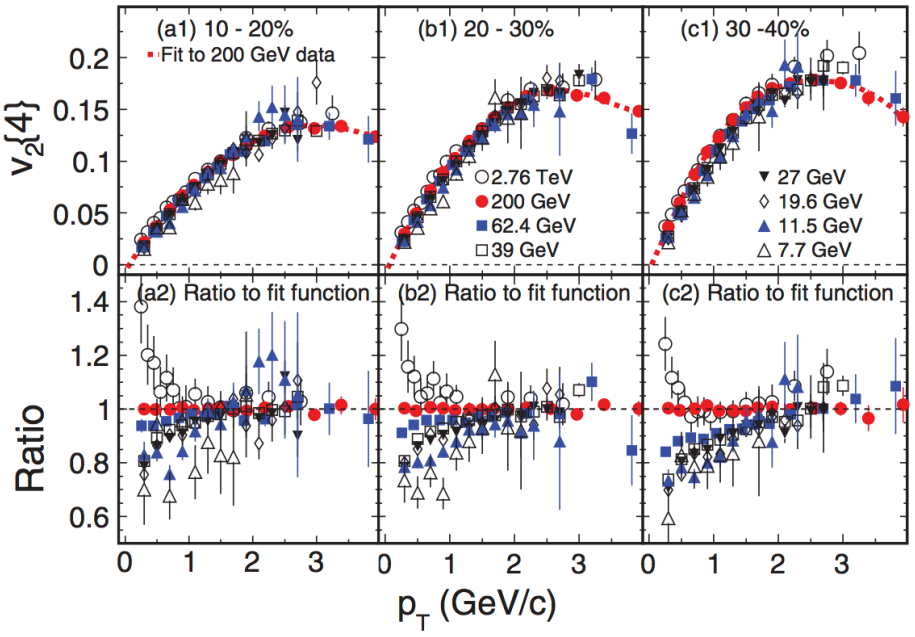
arXiv:1401.3043, accepted by PRL



H. Stoecker, Nucl. Phys. A 750, 121 (2005)

- A minimum near 11.5-19.6 GeV for protons and net protons
  → Possible signatures for the softest point of the EoS
- UrQMD cannot reproduce this trend
- The sign of net proton $v_1(y)$ changes twice between 7.7 and 39 GeV

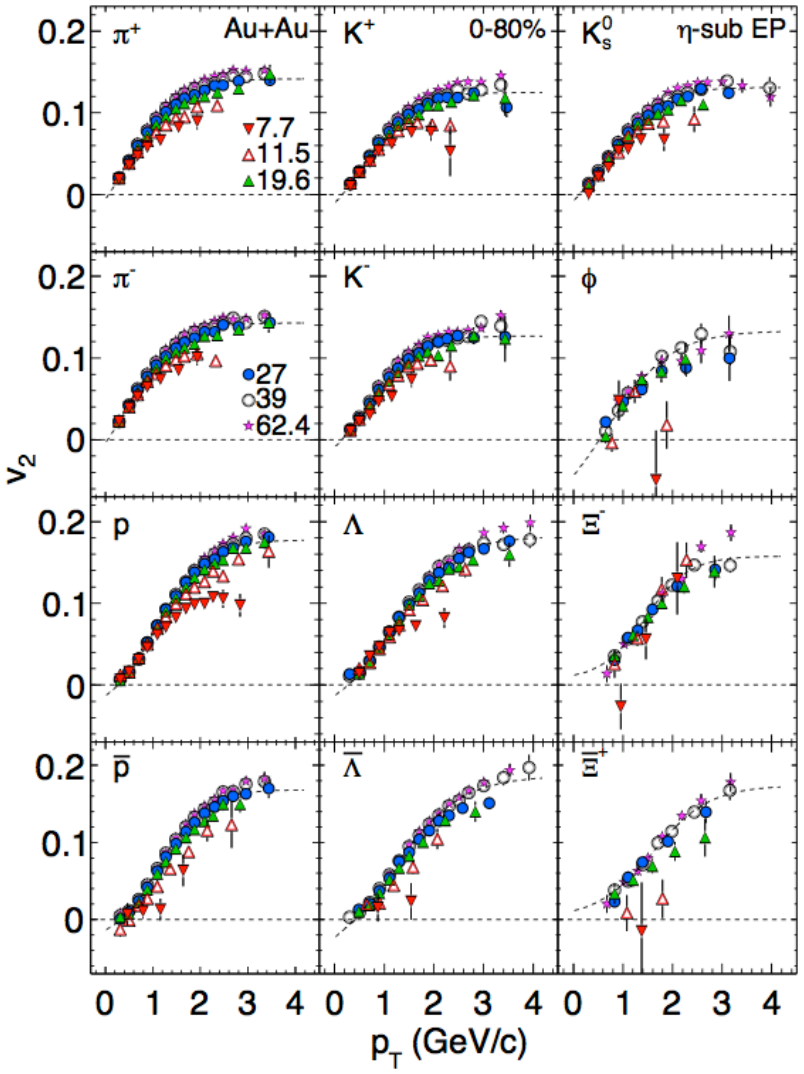
v_2: Charged Hadrons



STAR: Phys.Rev. C86, 054908 (2012)
ALICE: Phys. Rev. Lett. 105, 252302 (2010)

- $v_2\{4\}$ cumulant method → insensitive to non-flow
- General shape and magnitude of $v_2\{4\}(p_T)$ is similar for all energies between 7.7 GeV – 2.76 TeV
- In detail: at $p_T < 2$ GeV/c the $v_2\{4\}$ increases with increasing $\sqrt{s_{NN}}$
- Large collectivity?
- Baseline measurement for identified particle v_2

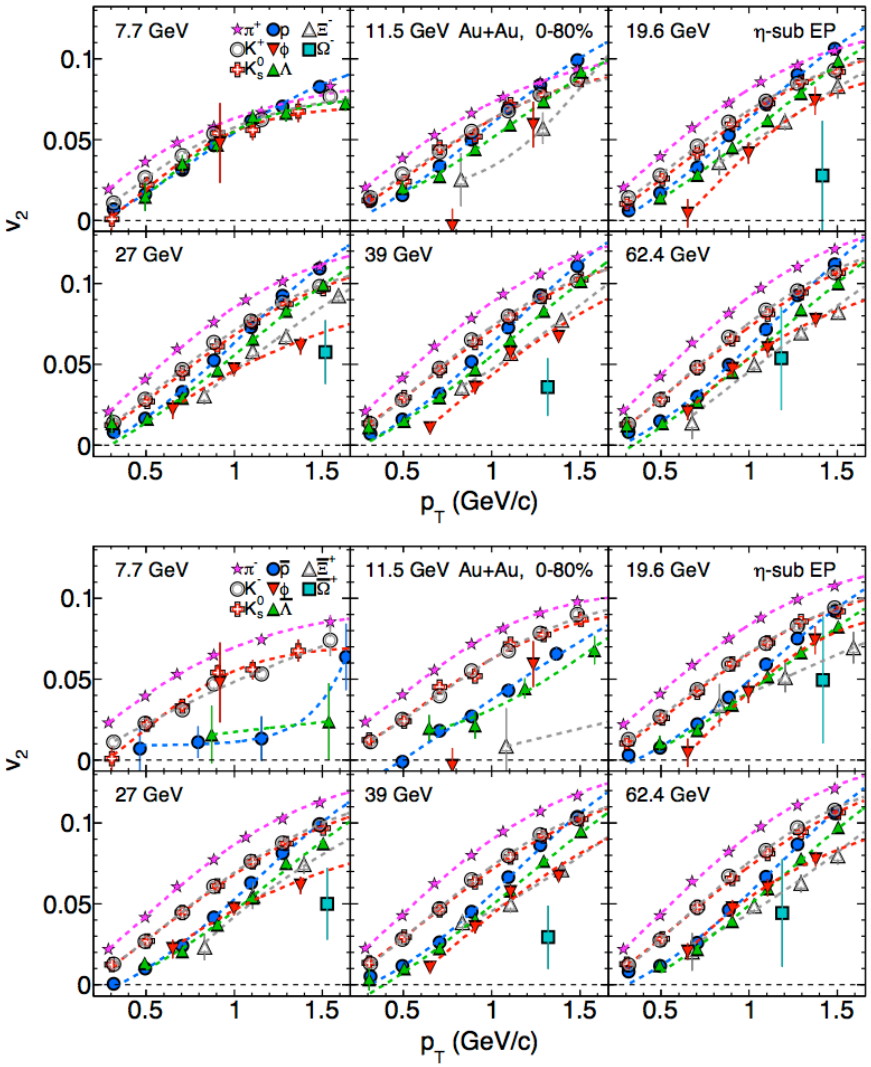
v_2: Identified Particles



Phys. Rev. C 88, 014902(2013)

- v_2 up to p_T = 4 GeV/c
- v_2 is increasing with beam energy
- Particle mixture
  → Pions dominant at 200 GeV
  → Protons dominant at 7.7 GeV

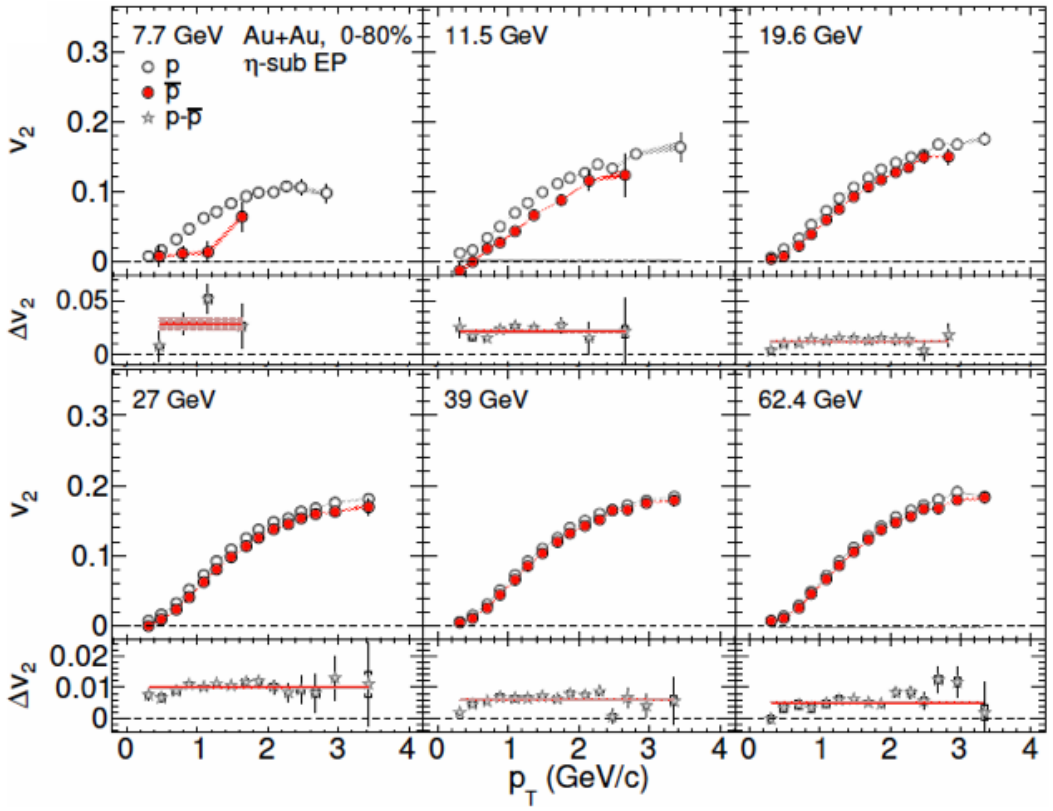
v_2: Mass Ordering



- Mass ordering at low p_T region at all energies due to radial flow
- $p_{T,radial} \sim m_0 < \beta >$
- The splitting between particle species is increasing with increasing energies for particles
- The splitting between particle species is almost constant for anti-particles

Phys. Rev. C 88, 014902(2013)

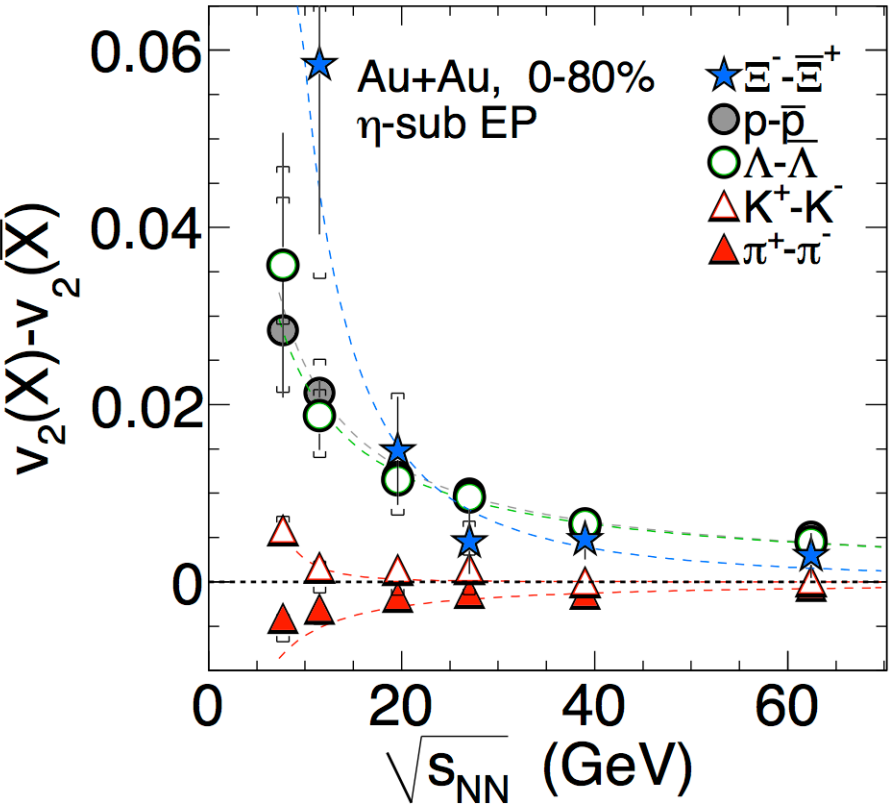
v_2: Protons and anti-Protons



- Difference in v_2 between protons and anti-protons is constant as a function of p_T
- Δv_2 is increasing with decreasing energy

Phys. Rev. C 88, 014902 (2013)

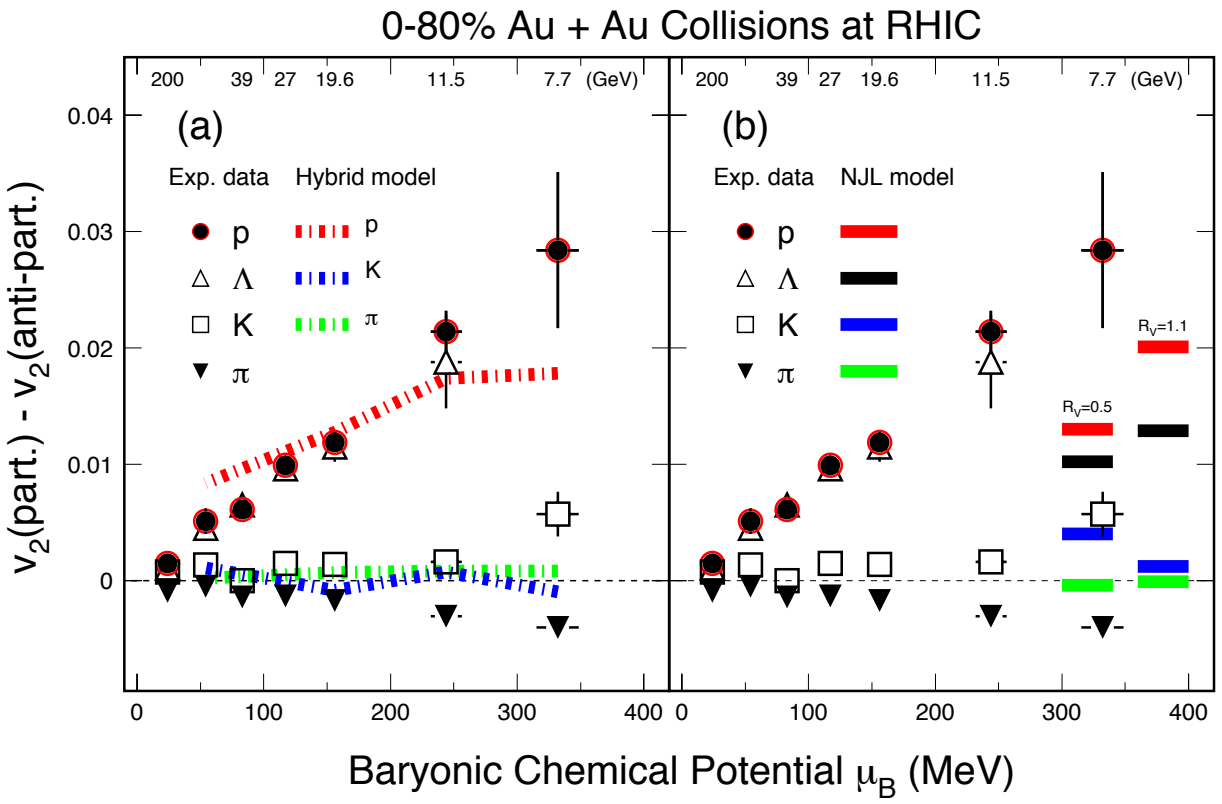
v_2: Difference between Particles and anti-Particles



Phys. Rev. Lett. 110, 142301 (2013)

- Beam energy dependent difference in $v_2(p_T)$ between particles and anti-particles is observed
- Particles and anti-particles are no longer consistent with the single Number-of-Constituent Quark scaling

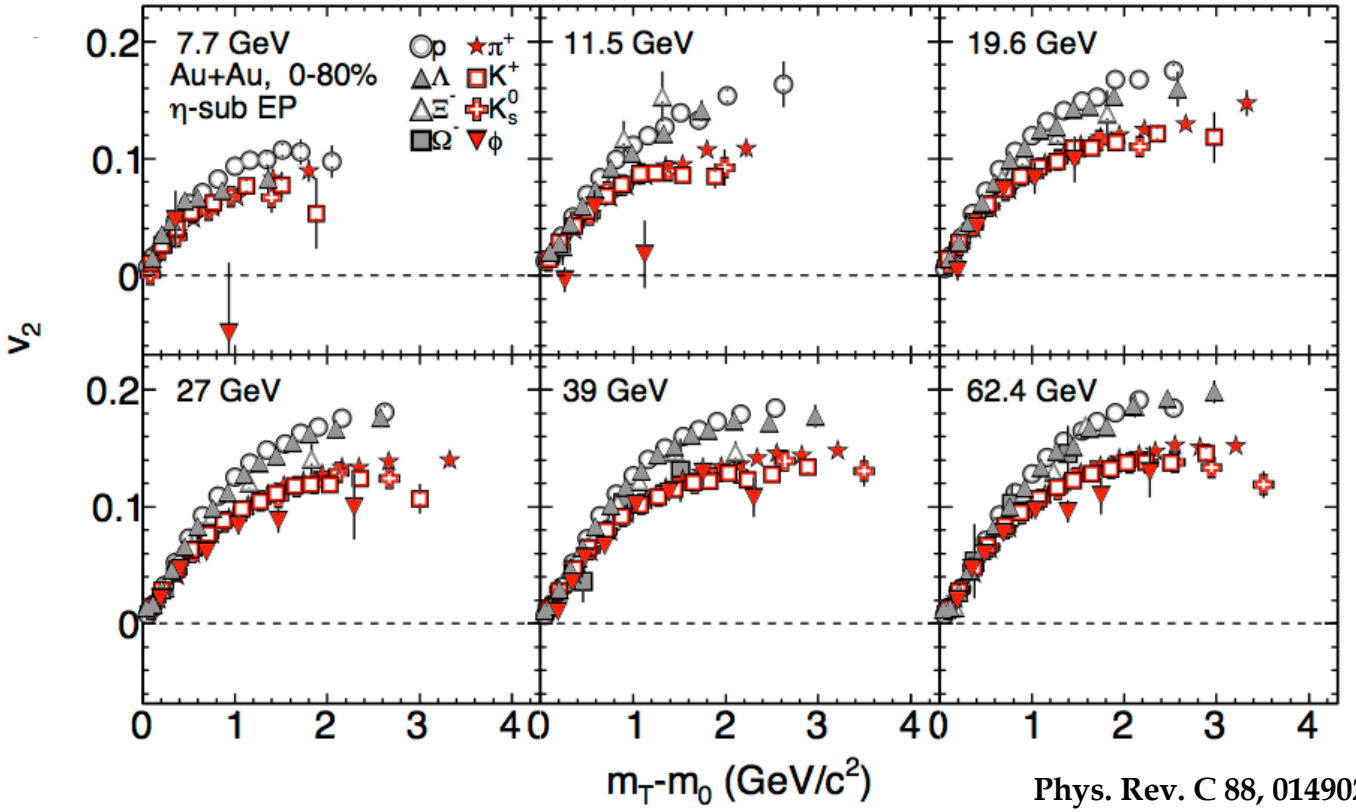
v_2: Theory Comparison



Phys. Rev. C 86, 044903 **Phys. Rev. Lett. 112, 012301**

- Hybrid model: The added baryon stopping can explain the difference
- Nambu-Jona-Lasinio (NJL): Using vector mean-field potential, repulsive for quarks, attractive for anti-quarks

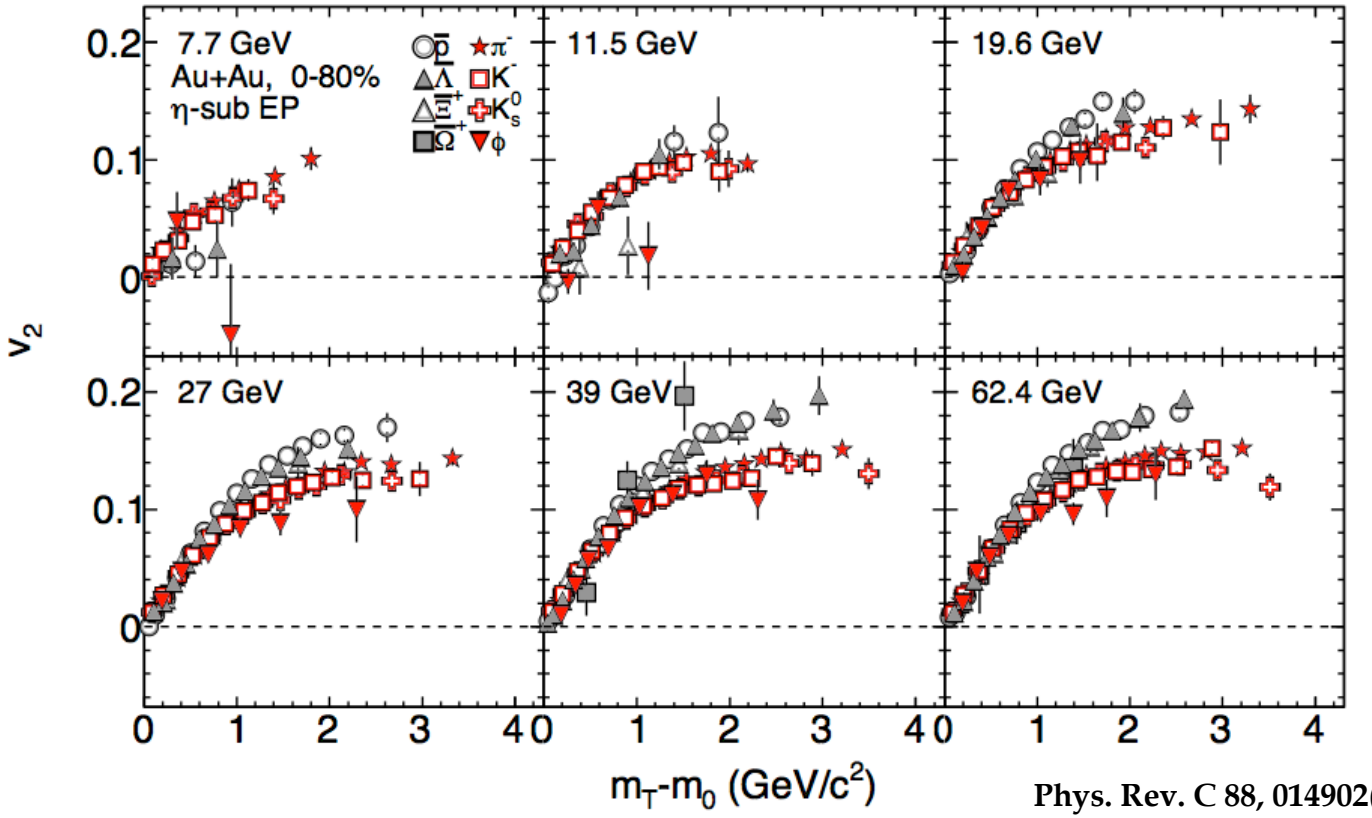
v_2: Meson and Baryon Splitting Particles



Phys. Rev. C 88, 014902(2013)

- Meson and baryon splitting at intermediate p_T region at all energies
- More statistics needed (BES II)

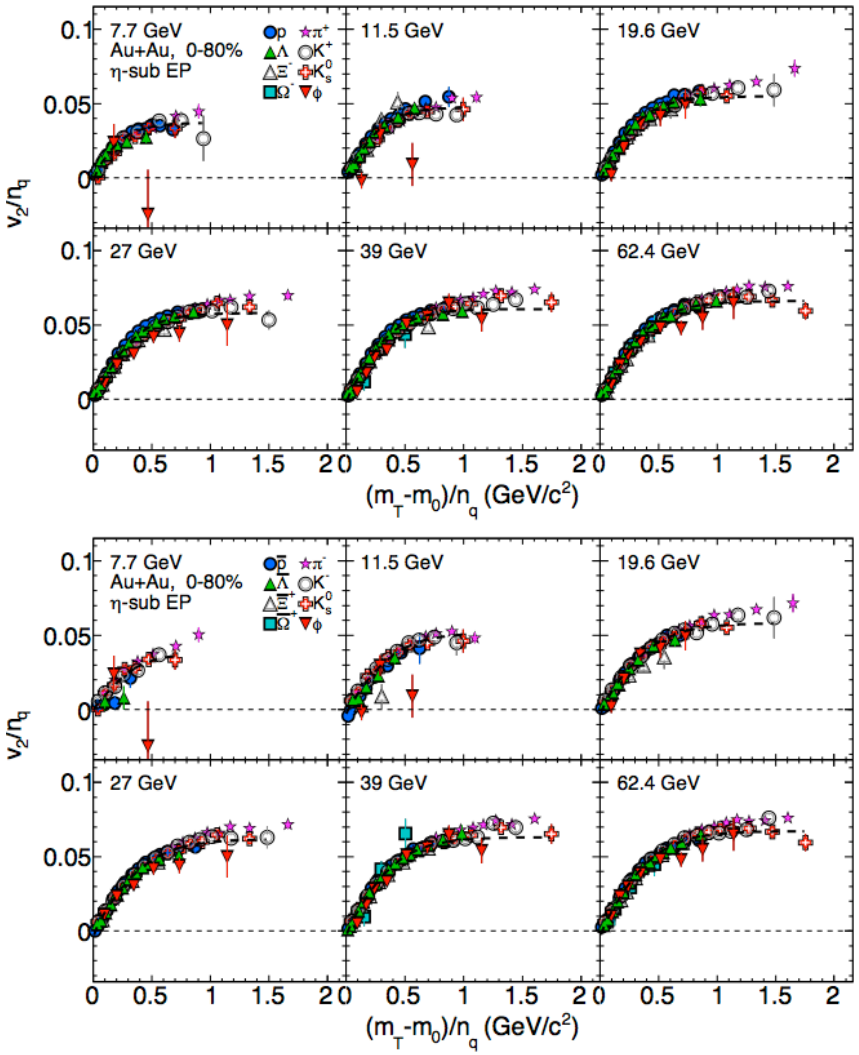
v_2: Meson and Baryon Splitting anti-Particles



Phys. Rev. C 88, 014902(2013)

- Meson and baryon splitting at intermediate p_T region down to 19.6 GeV
- More statistics needed (BES II)

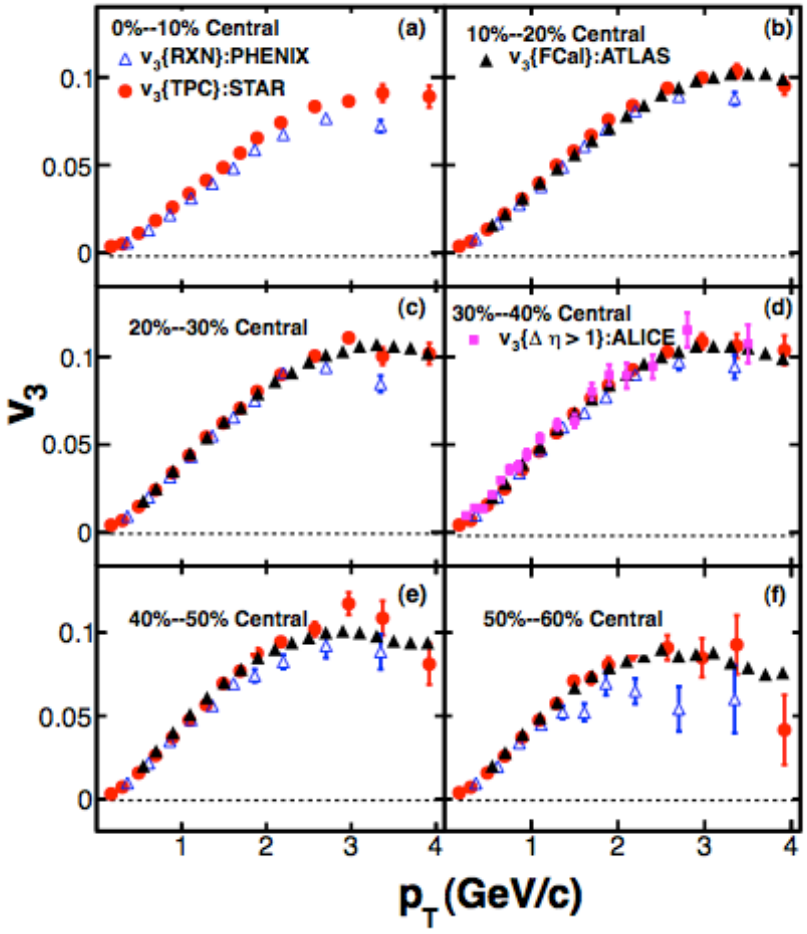
v_2: Number-of-Constituent Quark Scaling



Phys. Rev. C 88, 014902(2013)

- NCQ scaling holds for particles and anti-particles separately at all beam energies
  → need more data at low beam energy ($\sqrt{s_{NN}}$ < 19.6 GeV)

v_3: Charged Hadron at 200 GeV



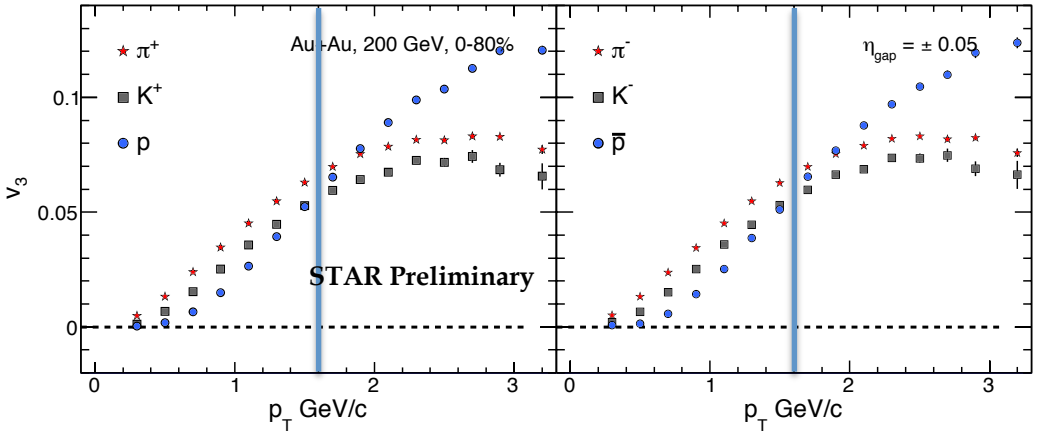
Phys. Rev. C 88 (2013) 014904

- Agreement is good not only between RHIC experiments, but also between RHIC and LHC experiments. This is surprising because of the somewhat different $\Delta\eta$ ranges.
- Detail study need to be done
  ➔Identified particle v_3

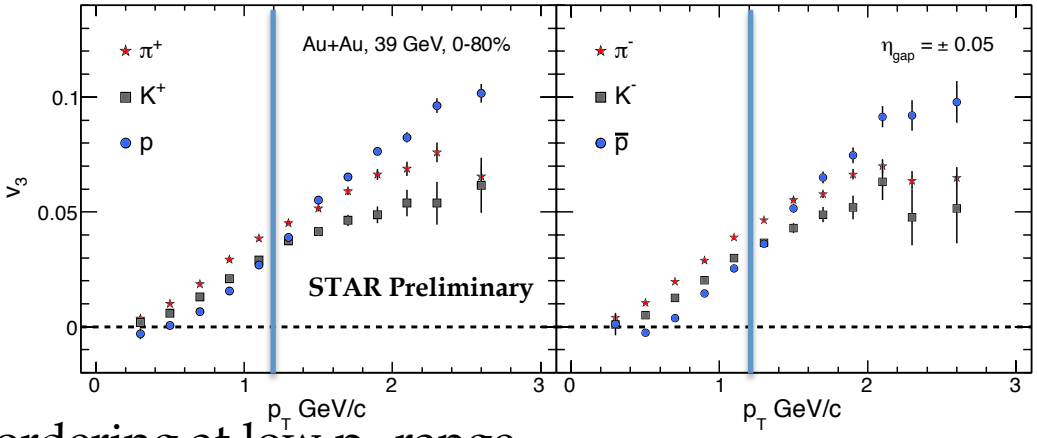
	$\lvert\eta\rvert$	$\langle\Delta\eta\rangle$
STAR	<1.0	0.63
PHENIX	<0.35	≈1.9
ALICE	<0.8	>1.0
ATLAS	<2.5	>0.8

v_3: p_T Dependence

200 GeV



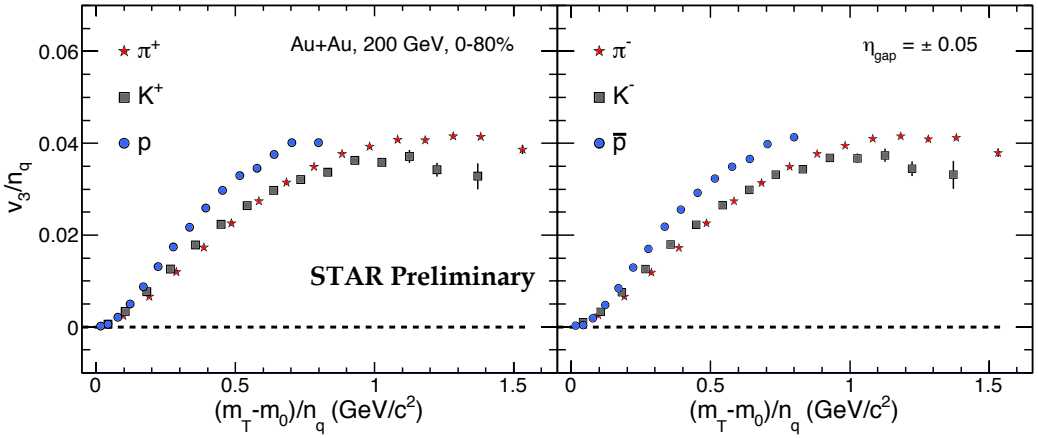
39 GeV



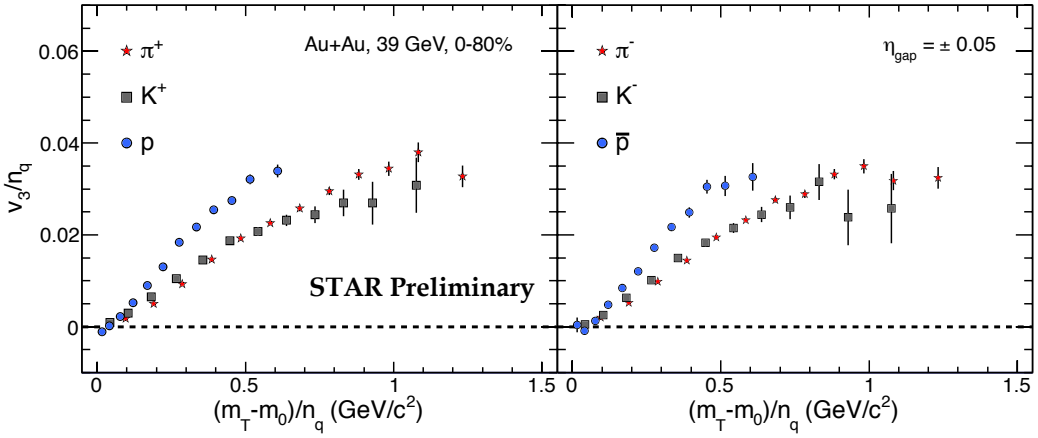
- Mass ordering at low p_T range
- Baryon and meson splitting at intermediate p_T range (2-3 GeV/c)?
  → Need more particle species to investigate
- Similar property as v_2

v_3: NCQ Scaling

200 GeV



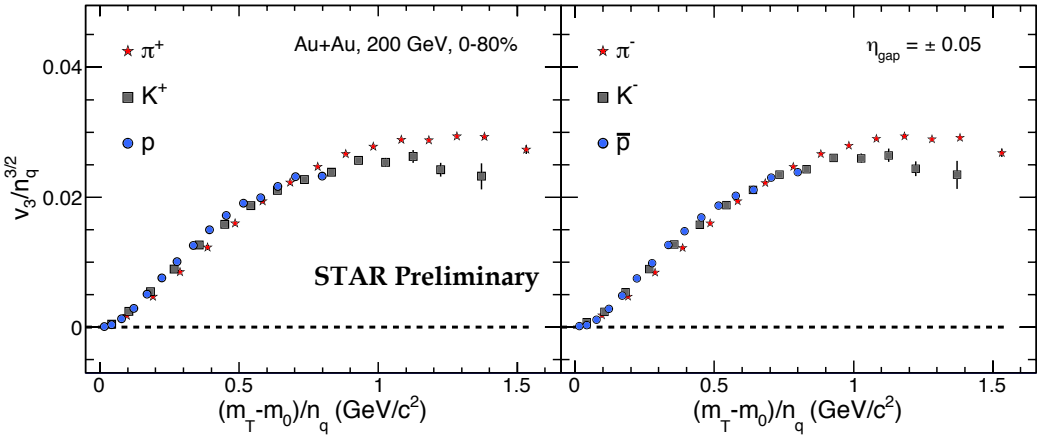
39 GeV



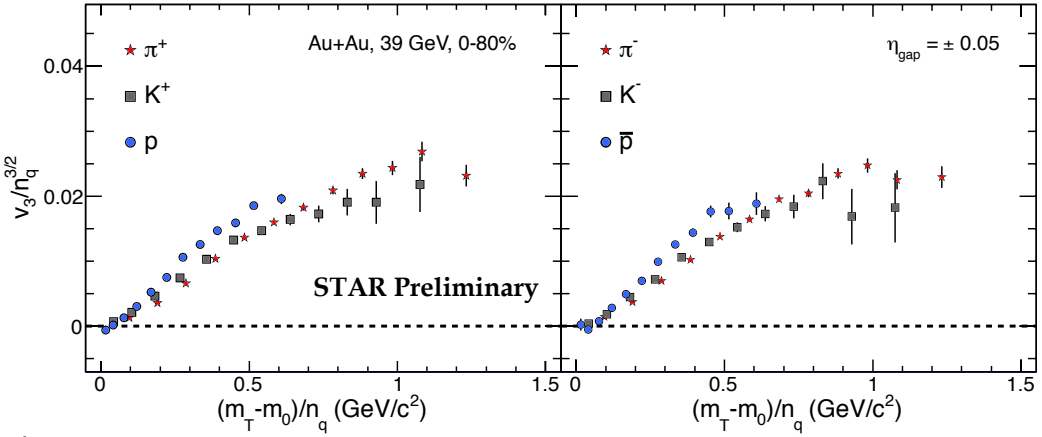
- no scaling observed at 200 (up to 0.8 GeV/c^2) and 39 GeV (up to 0.6 GeV/c^2)
- More particle species are needed to investigate the NCQ scaling

v_3: NCQ ($n_q^{3/2}$) Scaling

200 GeV



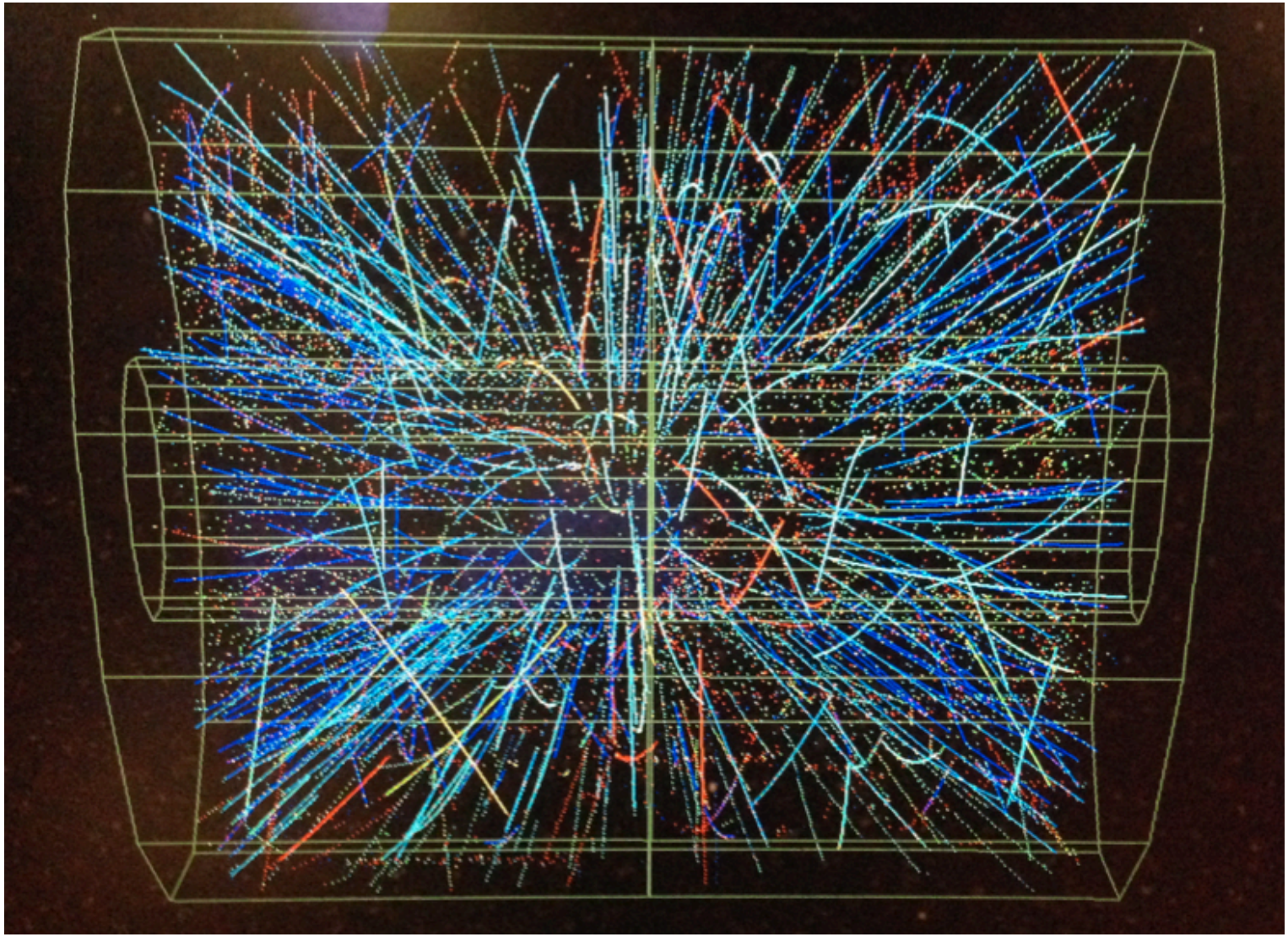
39 GeV



- NCQ ($n_q^{3/2}$) scaling observed at 200 (0.5-0.8 GeV/c^2) but not at 39 GeV (up to 0.6 GeV/c^2)
- $v_n \sim n_q^{n/2}$

J. Phys. G: Nucl. Part. Phys. 38 (2011) 124048

14.5 GeV from Year 2014



Summary

- v_1: A minimum of $dv_1/dy|_{y=0}$ near 11.5-19.6 GeV for proton and net proton

  → Possible signatures for the softest point of the EoS
- v_2 and v_3: Mass ordering at low p_T region

  → Radial flow
- v_2 and v_3: Meson and baryon splitting at intermediate p_T region (down to 19.6 GeV)

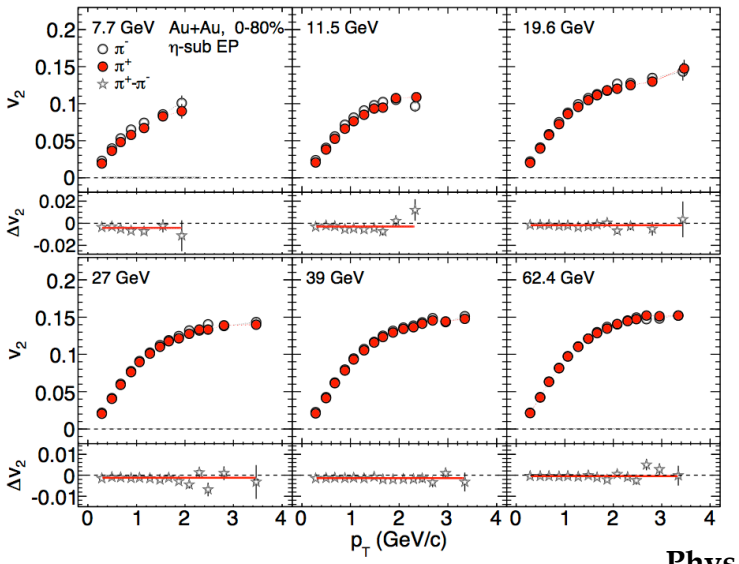
  → Partonic collectivity
- NCQ scaling for v_2: Holds for particles and anti-particles separately

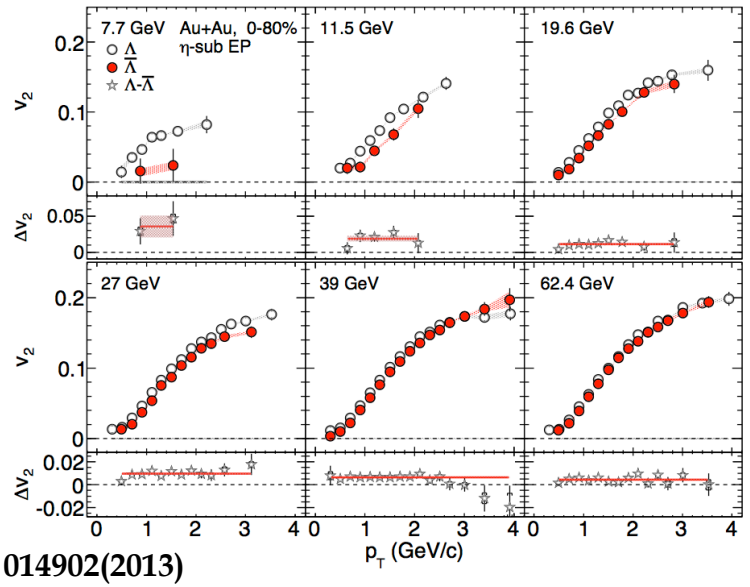
  → need more data at low beam energy ($\sqrt{s_{NN}}$ < 19.6 GeV)
- NCQ scaling for v_3: Need more particle species and more data

  → BES II
- A good dataset at $\sqrt{s_{NN}}$ = 14.5 GeV was collected in the presently ongoing Year-14

Backup

v_2: particles and anti-particles





Phys. Rev. C 88, 014902(2013)