Probe the partonic/hadronic matter with elliptic flow in STAR Beam Energy Scan

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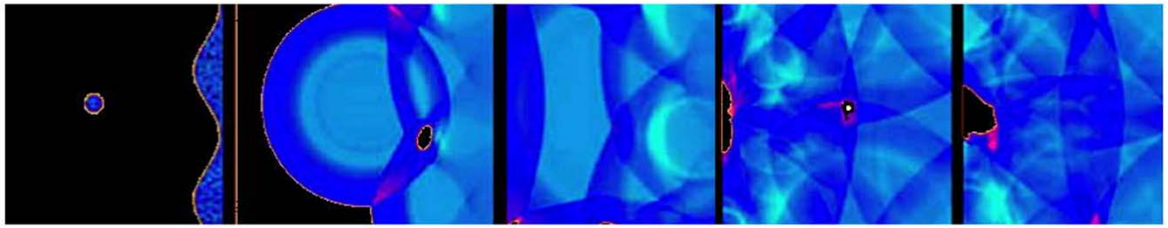
For the STAR Collaboration

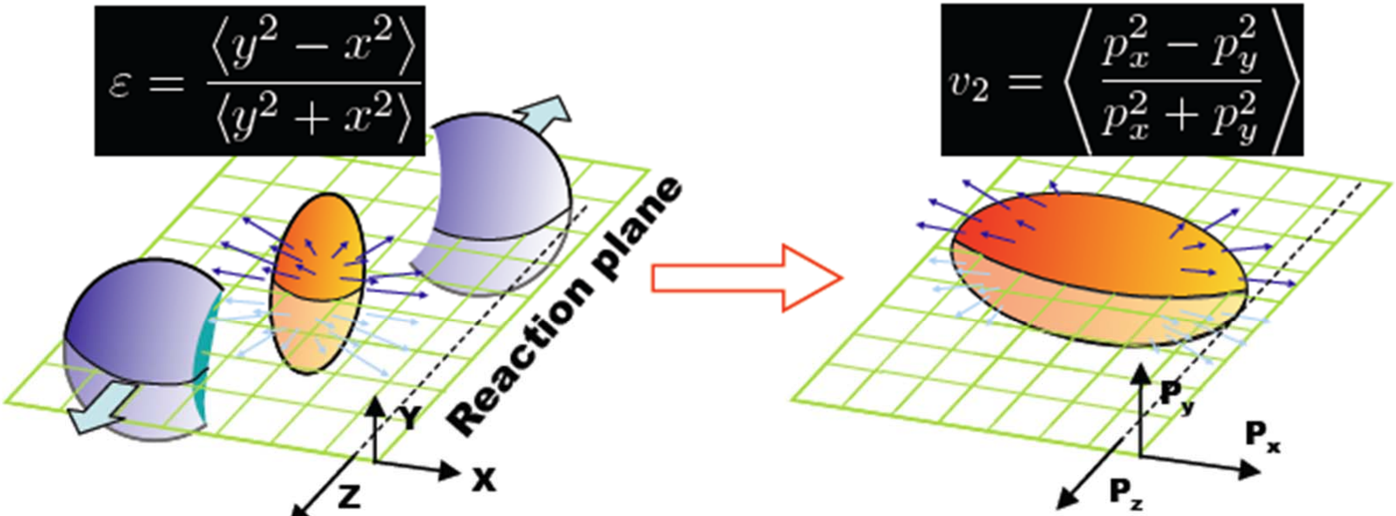


28th Winter Workshop on Nuclear Dynamics
Dorado del Mar, Puerto Rico

Outline

- Introduction and motivation
- STAR detector and data analysis
- Elliptic flow (v_2) results and discussions
- Summary and outlook

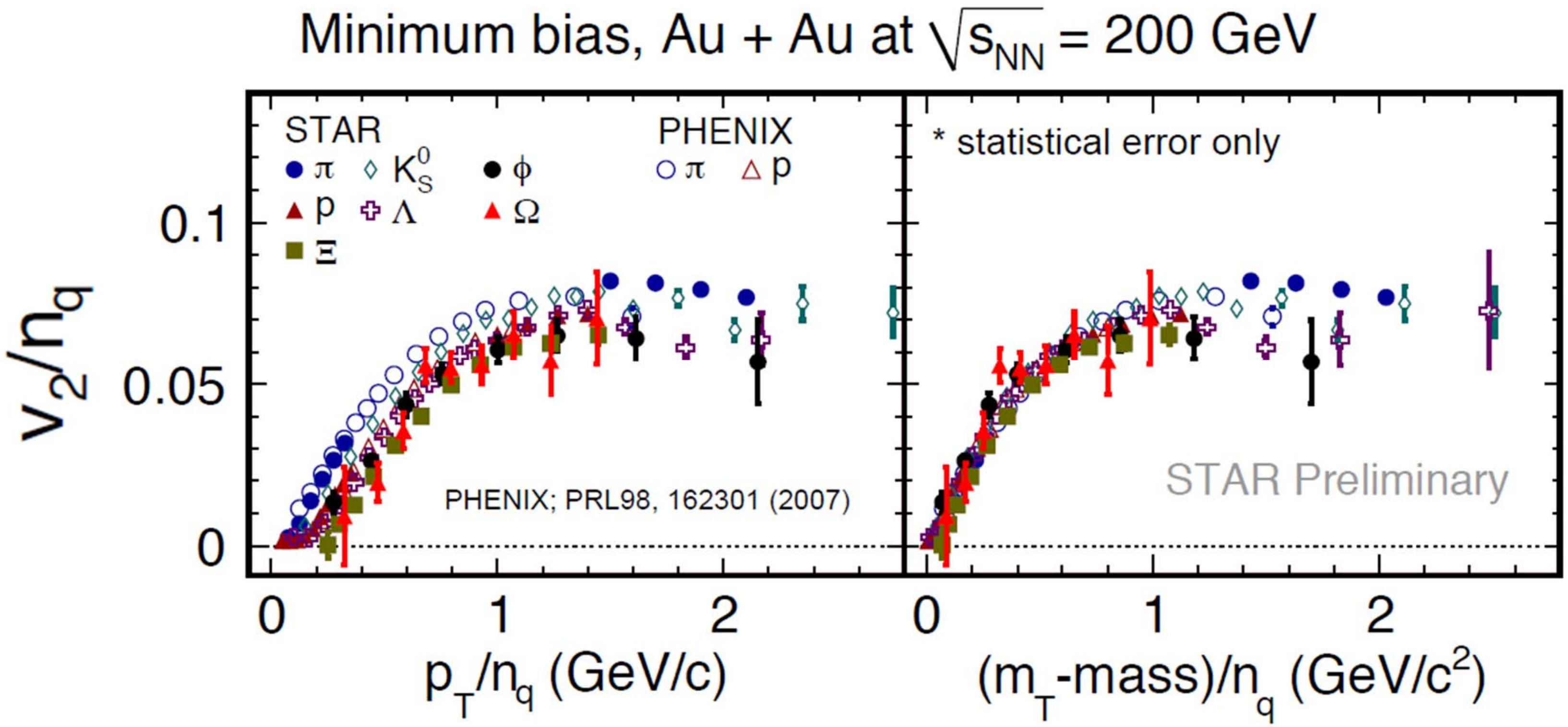
Introduction to elliptic flow



$$\frac{dN}{d(\phi - \Psi)} \propto 1 + 2v_1 \cos(\phi - \Psi) + \boxed{2v_2 \cos(2\phi - 2\Psi)} + \ldots$$

- **Elliptic flow:** initial spatial anisotropy → final momentum anisotropy
  - ✓ Characterized by v_2 coefficient of Fourier expansion of azimuthal particle distribution with respect to the reaction plane
- **Probe to the early collision dynamics**
  - ✓ Conversion efficiency depends on degrees of thermalization, equation of state, **degrees of freedom (partonic/hadronic),** …

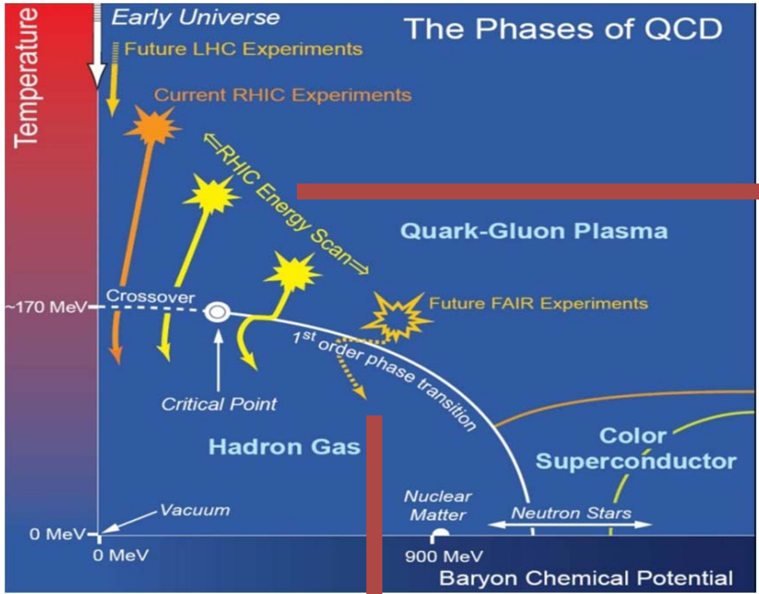
Partonic collectivity at RHIC top energy



- ➢ Number-of-quark (NCQ) scaling approximately works at intermediate p_T (2—5 GeV/c)
- ➢ Similar v_2 of multi-strange particles (ϕ, Ω) as light hadrons, **collectivity is developed at partonic stage**
- ➢ **Partonic degree of freedom → Deconfinement!**

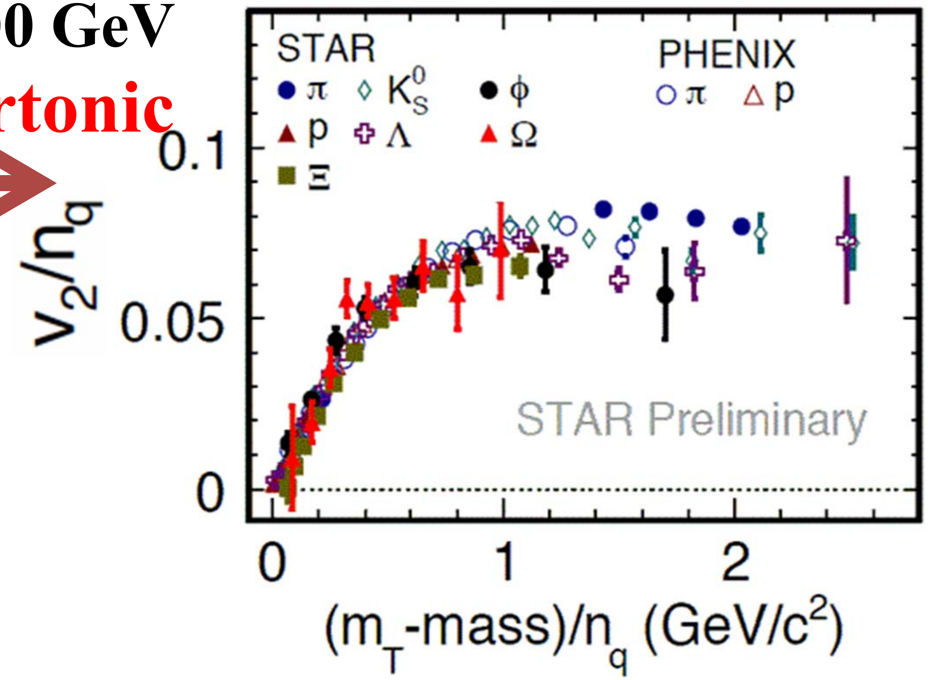
STAR, Phys. Rev. Lett. 99, 112301 (2007); Nucl. Phys. A 830, 187c (2009)

“Turn off” QGP signal at lower energy?



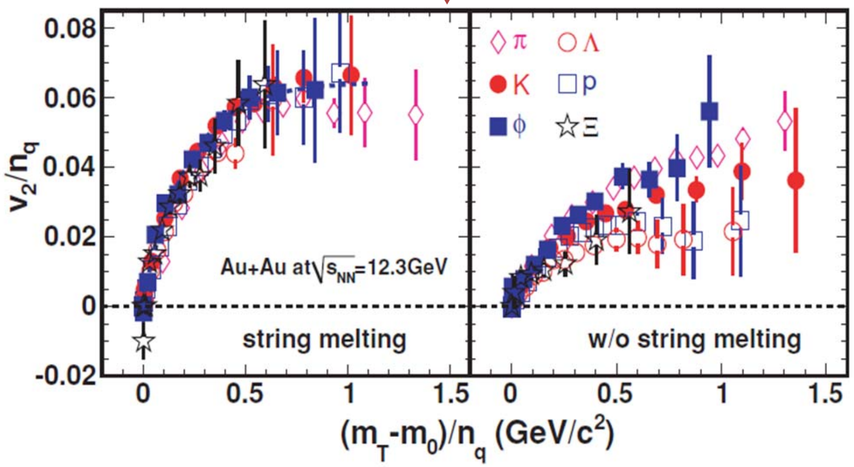
200 GeV

partonic



AMPT model

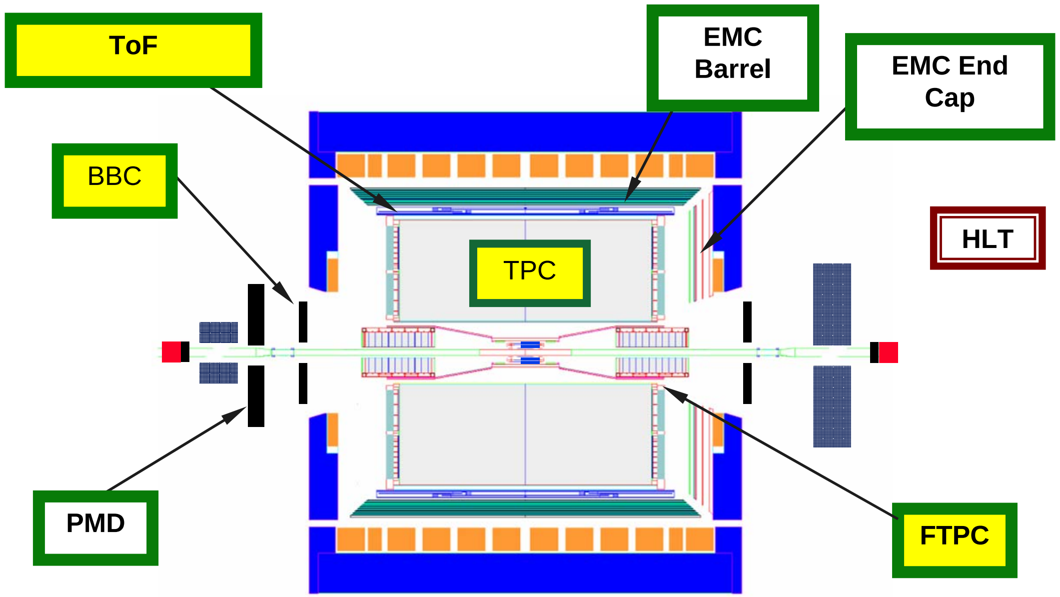
hadronic

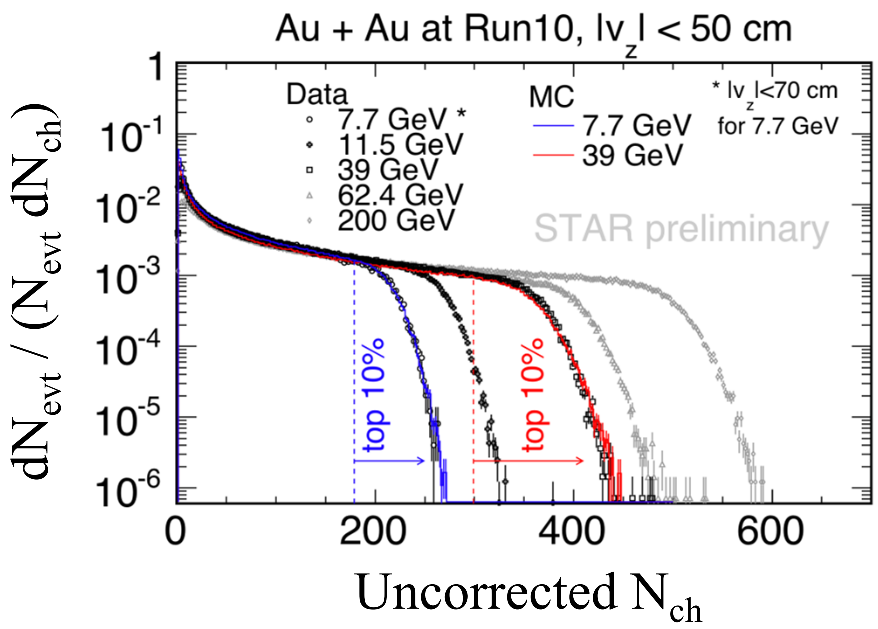


Phys. Rev. C 79, 067901 (2009); J. Phys. G 36, 064022 (2009); J. Phys. G 37, 094029 (2010)

- ✓ Au+Au 200 GeV, NCQ scaling, large ϕ(Ω) v_2, **partonic degree of freedom dominates**
- ✓ Lower energy, hadronic dominates, NCQ scaling may break, small ϕ(Ω) v_2
- ✓ Probe the partonic/hadronic matter with elliptic flow

Beam Energy Scan at STAR

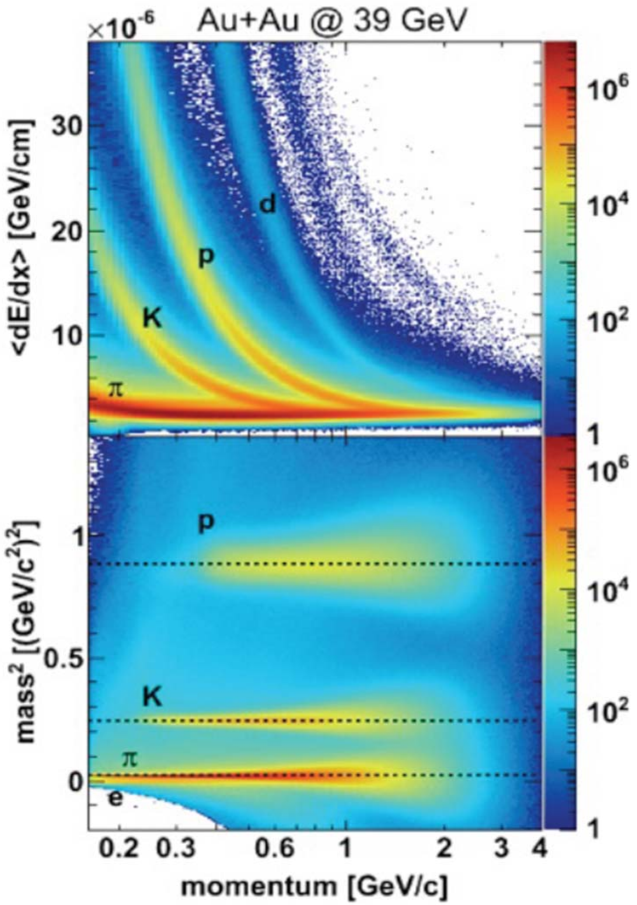


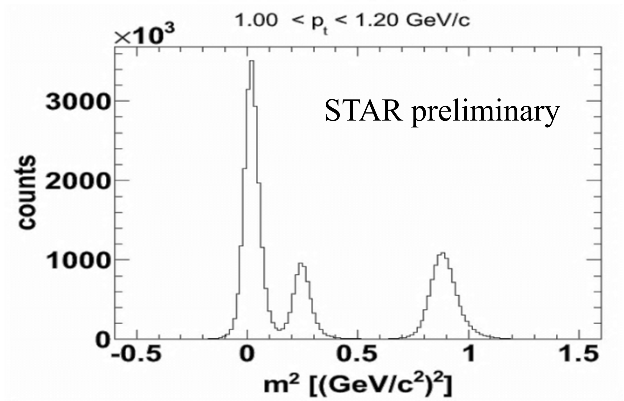


- Collisions: Au+Au
- Collisions centrality from uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$

$\sqrt{s_{NN}}$ (GeV)	Good MB events in Million
5.0	
7.7	~ 4 M
11.5	~ 12 M
19.6	~ 36 M
27	~ 70 M
39	~ 130 M
62.4	~ 67 M

Particle identification and v_2 analysis





- **Time projection chamber (TPC)**
  full azimuth, $|\eta| < 1$
  dE/dx v.s. momentum

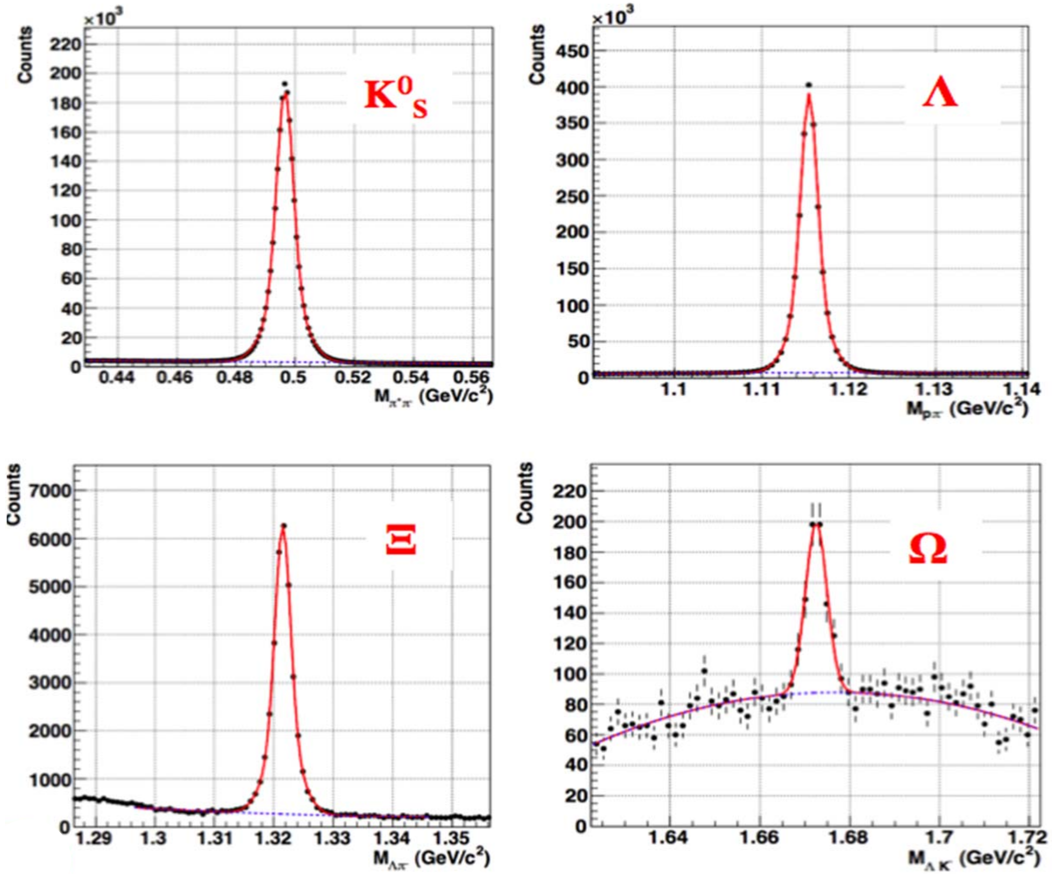
- **Barrel Time-Of-Flight (TOF)**
  full azimuth, $|\eta| < 1$
  Particle flight time
  Clean separation of K, π up to $p_T = 1.6$ GeV/c

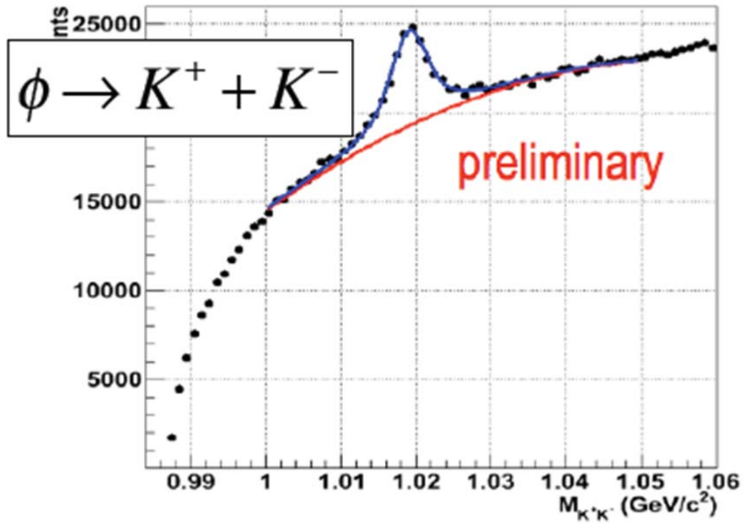
- $v_2 = < \frac{\cos(2\varphi - 2\psi_2)}{R} >$
  R: event plane resolution

- **TPC η-sub event plane for PID v_2 analysis,** non-flow effects reduced

η-sub event plane method: STAR, Phys. Rev. C **77,** 054901 (2008)

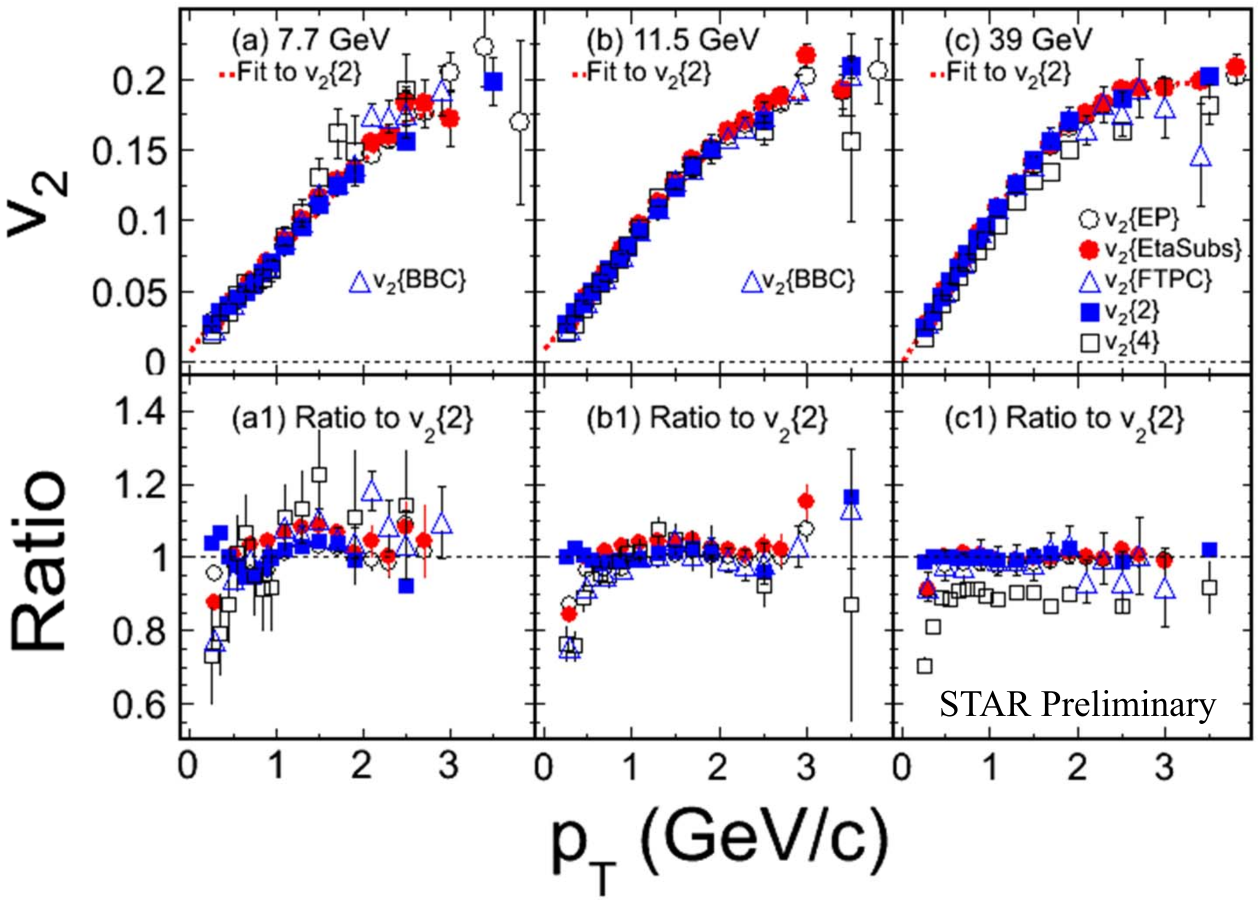
Particle reconstruction





- dE/dx+TOF: π, K, p and $\phi \rightarrow K^+ + K^-$(invariant mass)
- S/B of ϕ meson significantly improved with additional TOF PID
- Weak decay particles (K^0_S, Λ, Ξ, Ω), secondary vertex + invariant mass

v_2 of charged hadrons @ 7.7, 11.5, 39 GeV

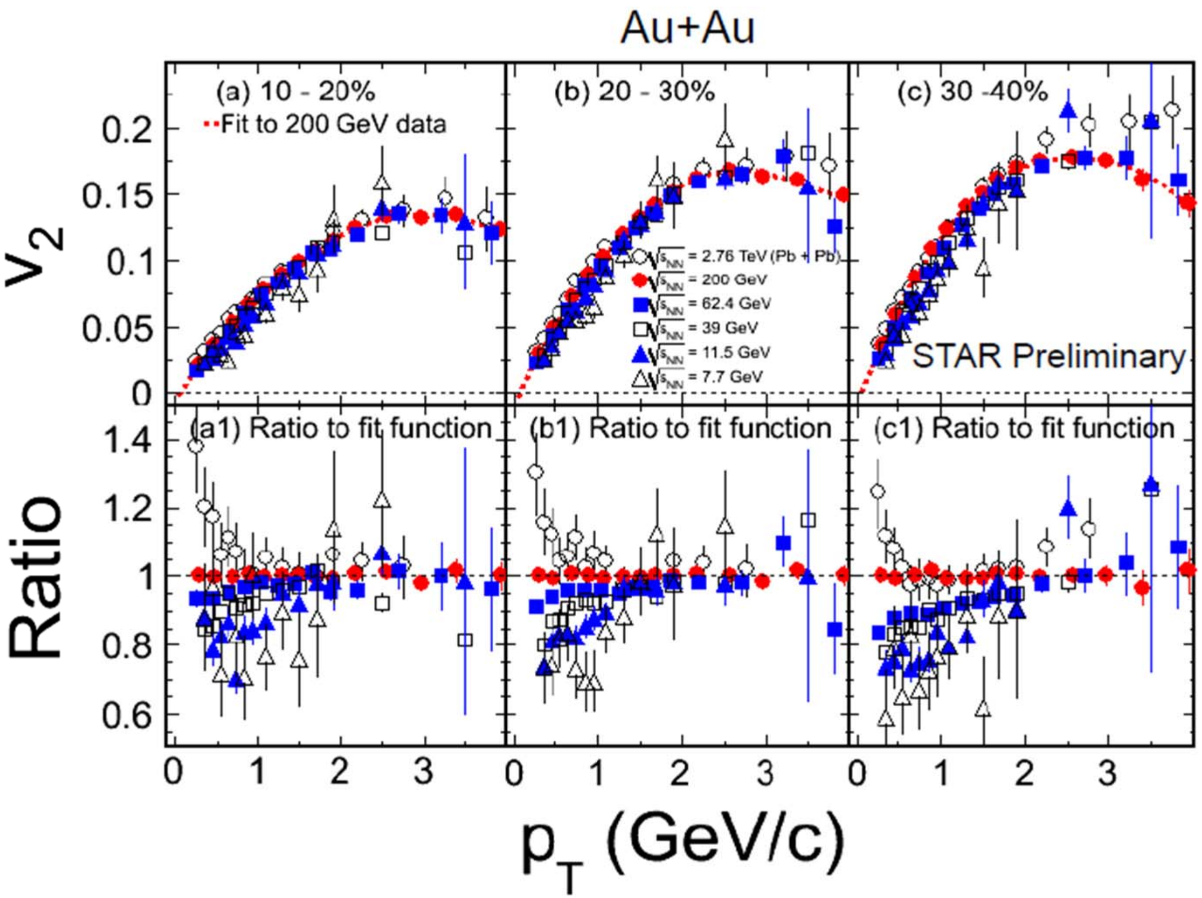


- Different event plane detectors
  TPC (| η |<1)
  FTPC (2.5<| η |<4)
  BBC (3.3<| η |<5)
- Different v_2 analysis method event plane, cumulant method
- Overall, good agreement

- **7.7, 11.5 GeV: less difference between $v_2\{2\}$ and $v_2\{4\}$ → non-flow, fluctuations**

STAR, CPOD 2011

v_2 of charged hadrons @ 7.7 – 2760 GeV



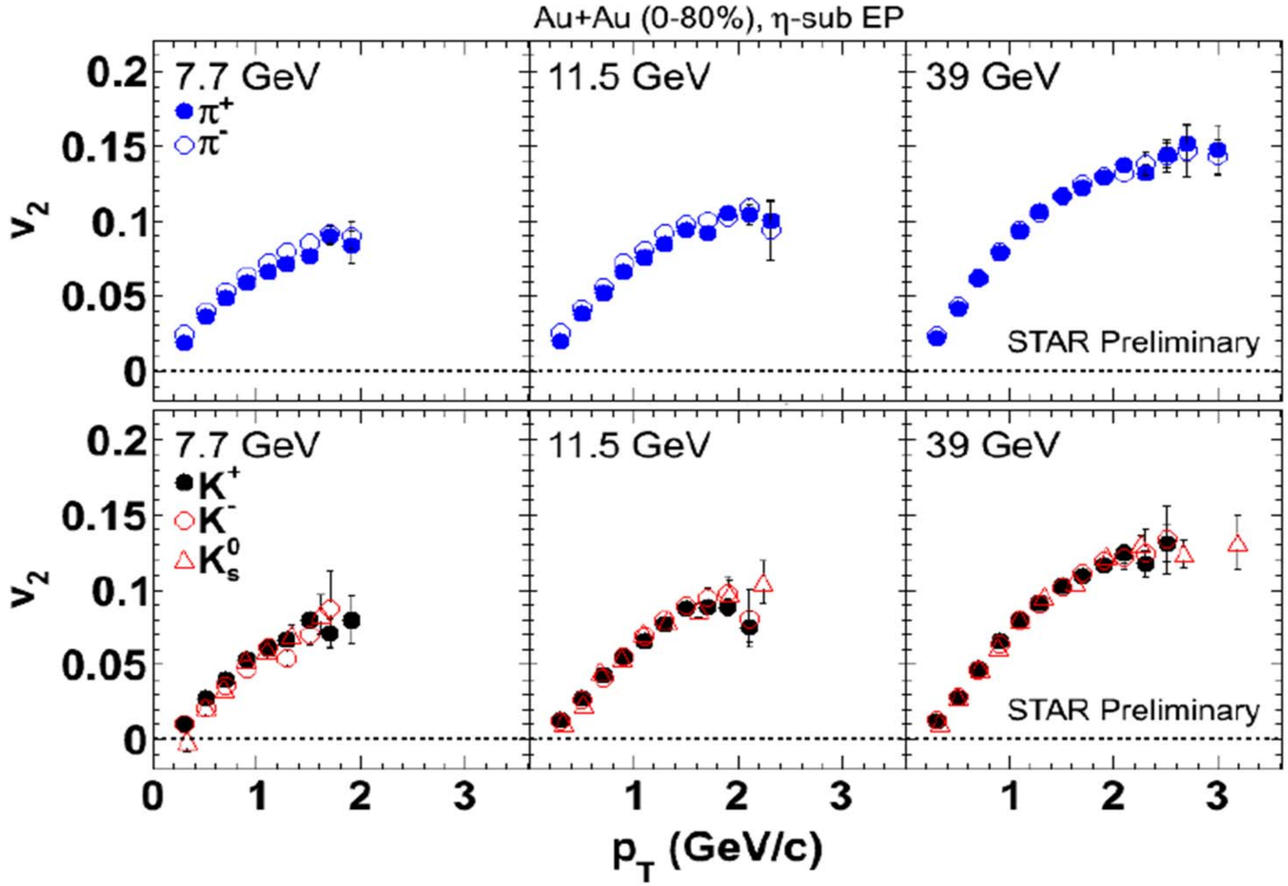
- Comparison of differential $v_2(p_T)$ over 2.6 orders of magnitudes in energy

  2760/7.7 ~ 360

- **Similar $v_2(p_T)$ shape**
  p_T = 2 - 4 GeV/c: almost same $v_2(p_T)$
  Differences increase at low p_T

STAR, CPOD 2011
ALICE, Phys. Rev. Lett. 105 (2010) 252302

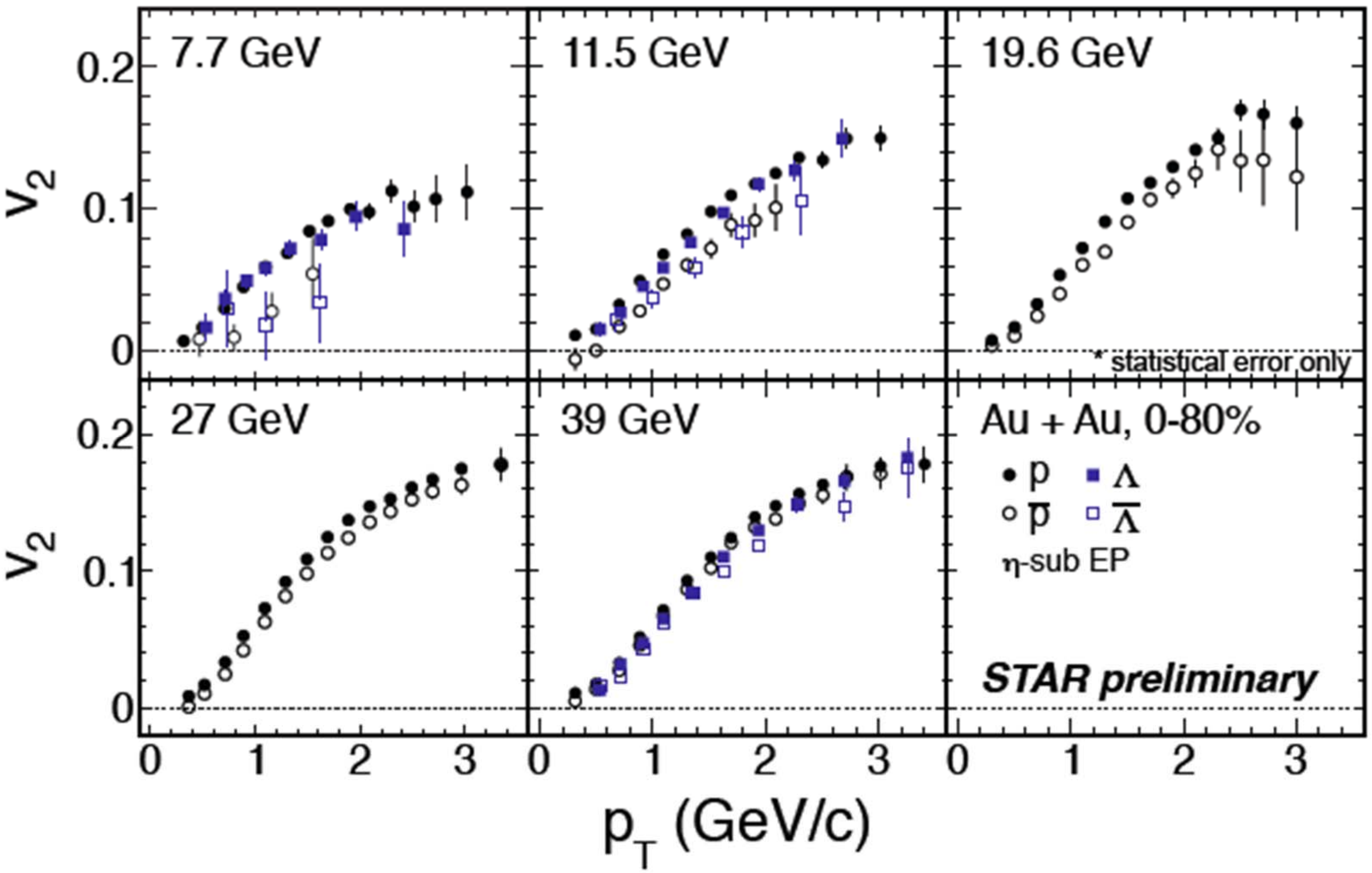
Particle and anti-particle v_2 (π and K)



- π: $v_2(\pi^-) \sim v_2(\pi^+)$ @ 39 GeV
  $v_2(\pi^-) > v_2(\pi^+)$ @ 7.7 and 11.5 GeV
- K: $v_2(K^+) \sim v_2(K^-)$ @ 11.5 and 39 GeV
  $v_2(K^+) > v_2(K^-)$ @ 7.7 GeV

STAR, CPOD 2011

Particle and anti-particle v_2 (Proton and Λ)

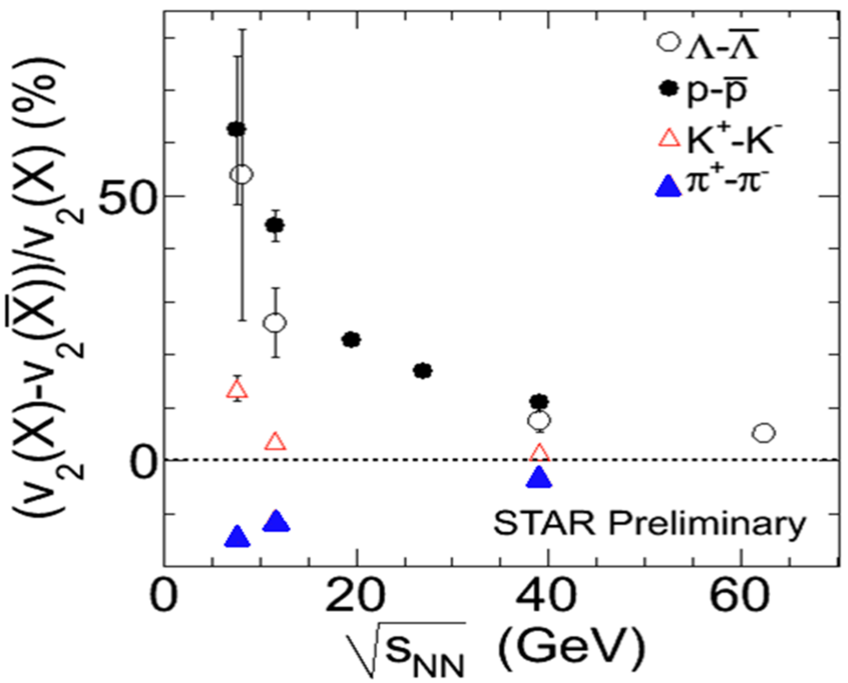


- **Proton: v_2(proton) > v_2(anti-proton)**
  Difference increases with decreasing energy
- **Λ: similar behavior**

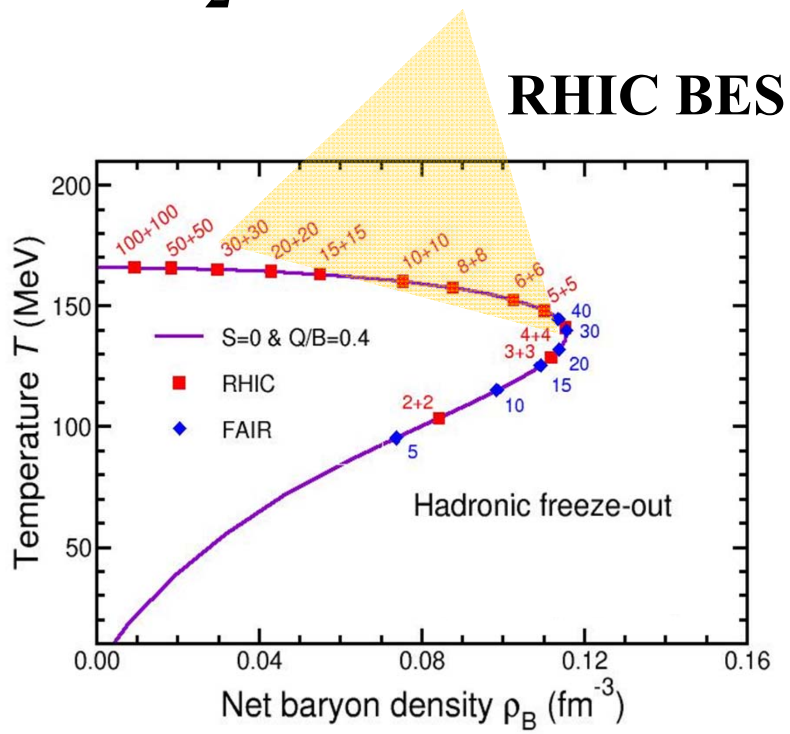
STAR, CPOD 2011

Particle and anti-particle v_2 difference

STAR, CPOD 2011



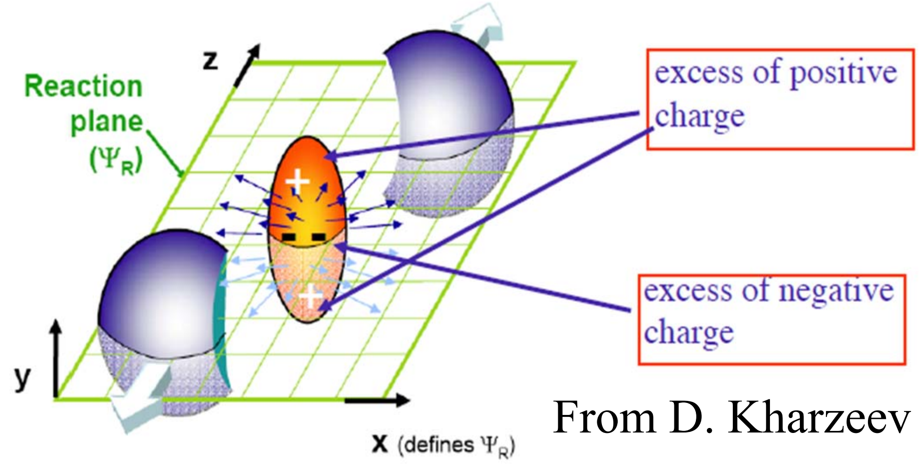
RHIC BES



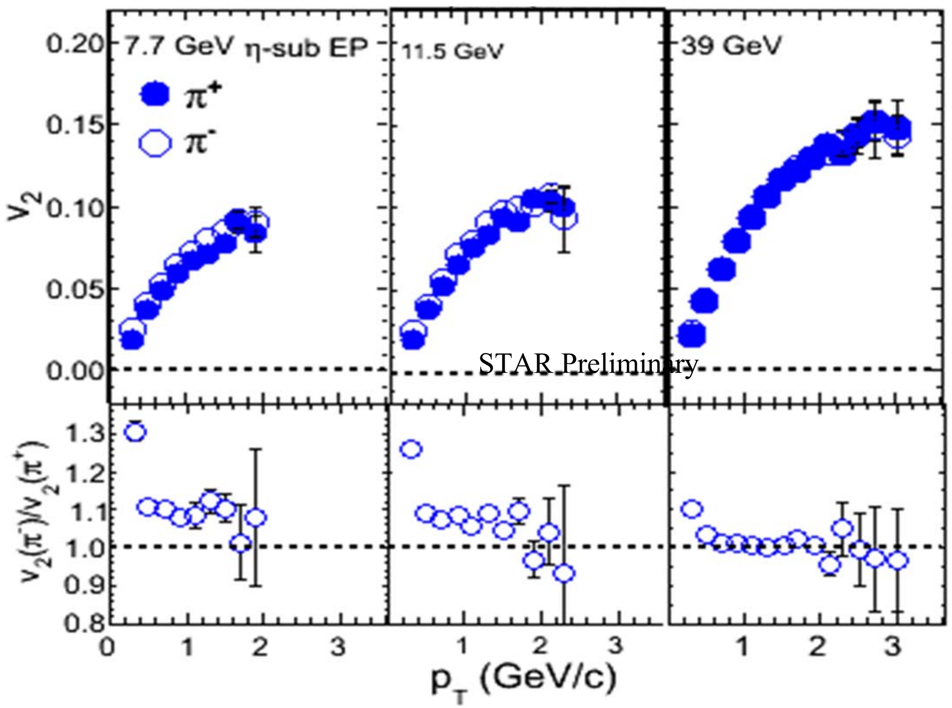
J. Randrup et al., Phys. Rev. C 74 (2006) 047901

- Baryon and anti-baryon v_2 differences: ~10% at higher energies increase dramatically @ 7.7 and 11.5 GeV
- **NCQ scaling between particles and antiparticles is broken at lower energies**
- Chiral magnetic wave? Baryon transport? Hadronic potential? Hadronic interactions dominant?

Electric quadrupole moment of QGP?



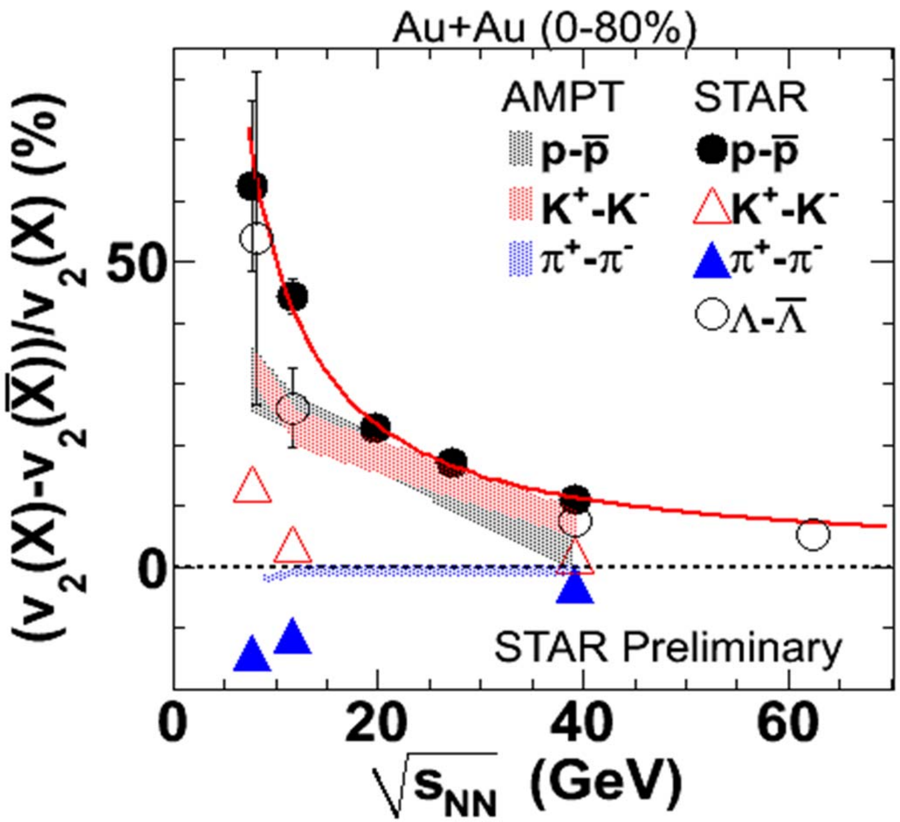
From D. Kharzeev



Y. Burnier et al., Phys. Rev. Lett. 107, 052303 (2011)

- Chiral Magnetic Wave (CMW): interplay of chiral magnetic effect and chiral separation effect
- **CMW induces a static electric quadrupole moment of QGP at finite baryon density**
- Elliptic flow of positive hadrons < negative ones **$v_2(\pi^+) < v_2(\pi^-)$,** calculated difference at $\sqrt{s} = 11$ GeV ~ up to 30% depending on the lifetime of the magnetic field
- **Data: difference ~ 10% at 11.5 GeV**
- Hongwei Ke's talk, "*Charge asymmetry dependency of π^+/π^- elliptic flow in Au+Au collisions at 200 GeV*", Apr. 12, 11:00 AM

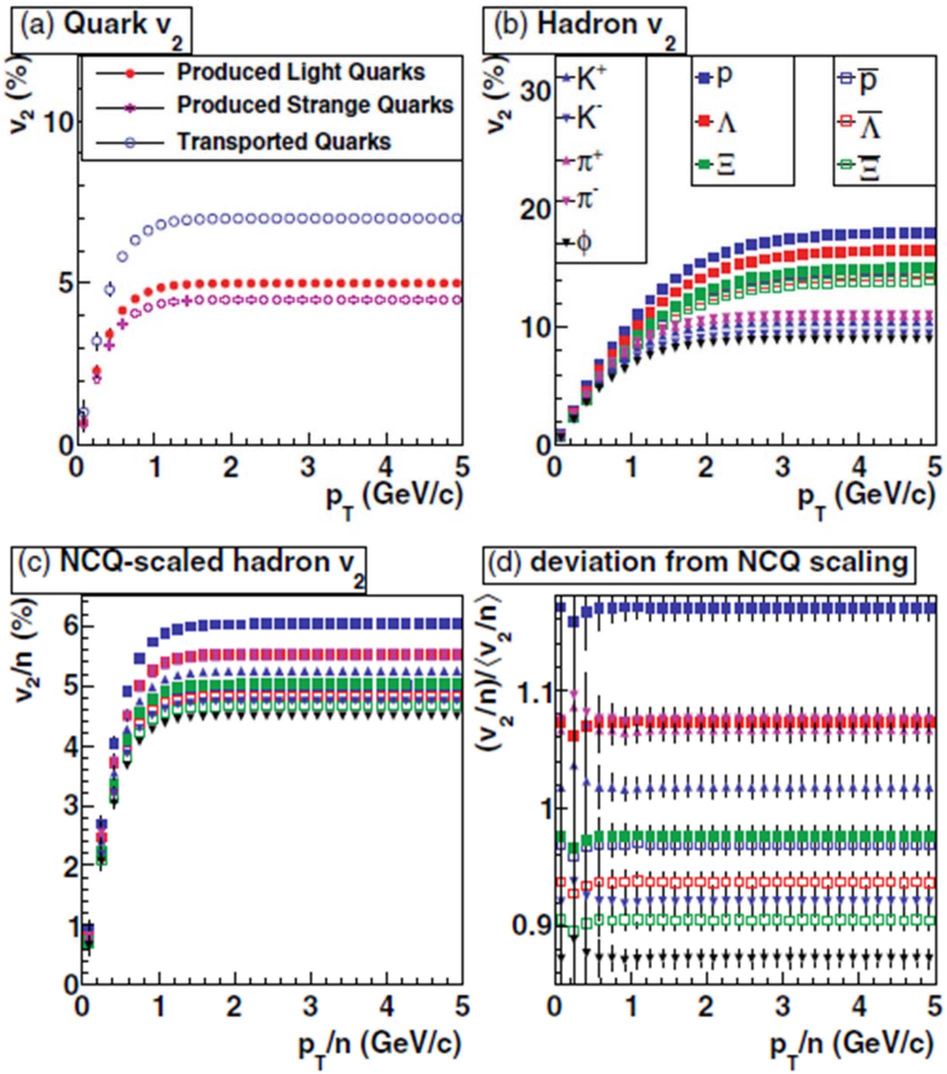
Hadronic potential?



- AMPT model including **the mean-field potentials in the hadronic phase leads to a splitting of the elliptic flows of particles and their antiparticles**
- Trend is the same as in our data
- The magnitude is inconsistent at 7.7 and 11.5 GeV

J. Xu et al., arXiv:1201.3391

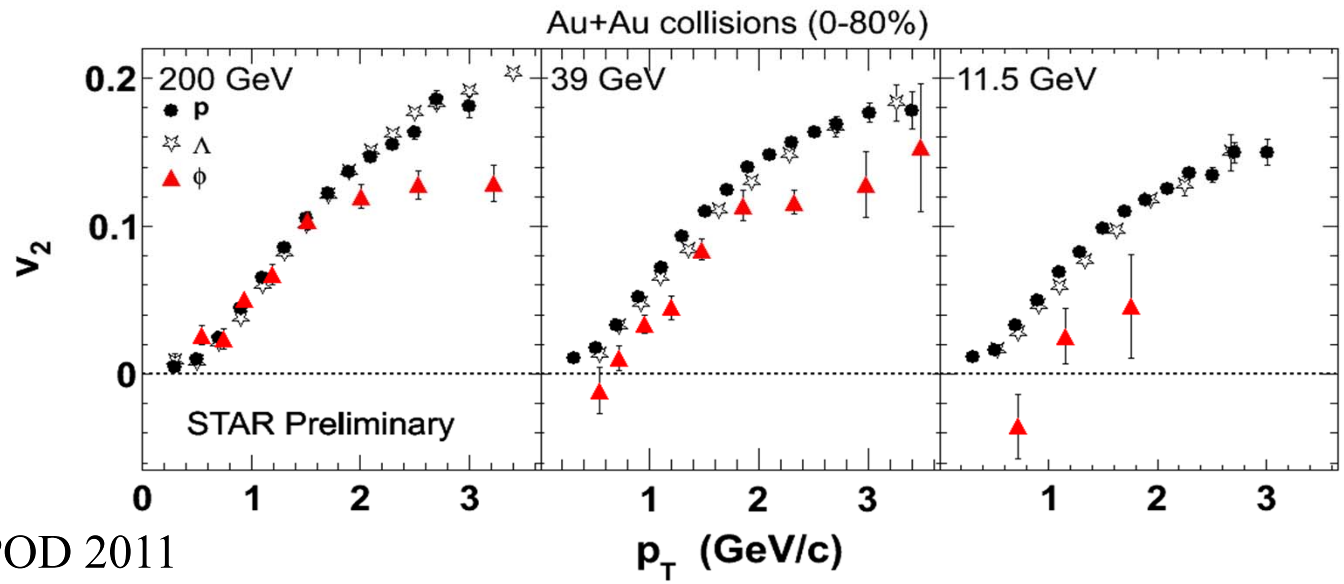
Baryon transport?



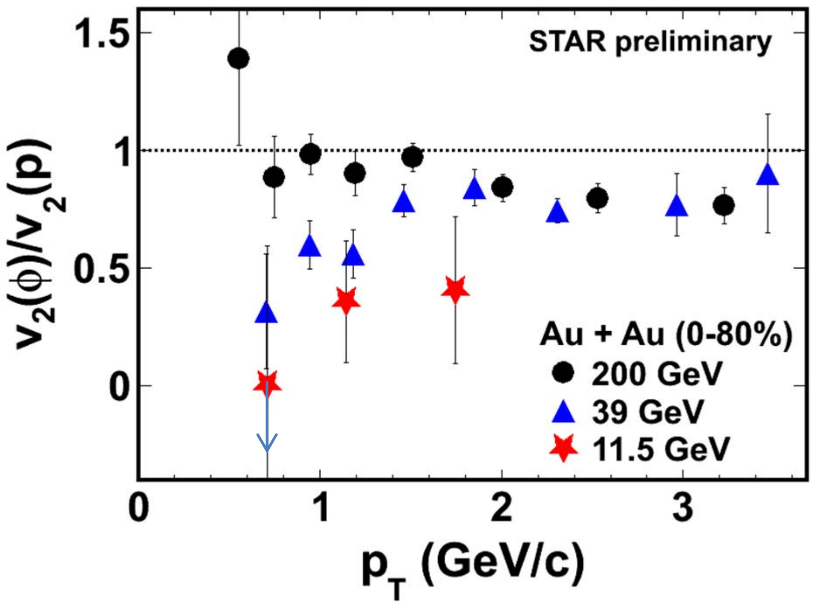
- Quark coalescence assumed
- **v_2(transported quarks) > v_2(produced light quarks) > v_2(produced strange quarks)**
- $v_2(\pi^-) > v_2(\pi^+)$
  $v_2(K^+) > v_2(K^-)$
  $v_2(p) > v_2(\bar{p})$
  $v_2(\Lambda) > v_2(\bar{\Lambda})$
  Qualitatively consistent with data
- Weak p_T dependence
- **Small ϕ meson v_2**

J.C. Dunlop, M.A. Lisa, & P. Sorensen, Phys. Rev. C 84, 044914 (2011)

ϕ ($s\bar{s}$) meson v_2



STAR, CPOD 2011



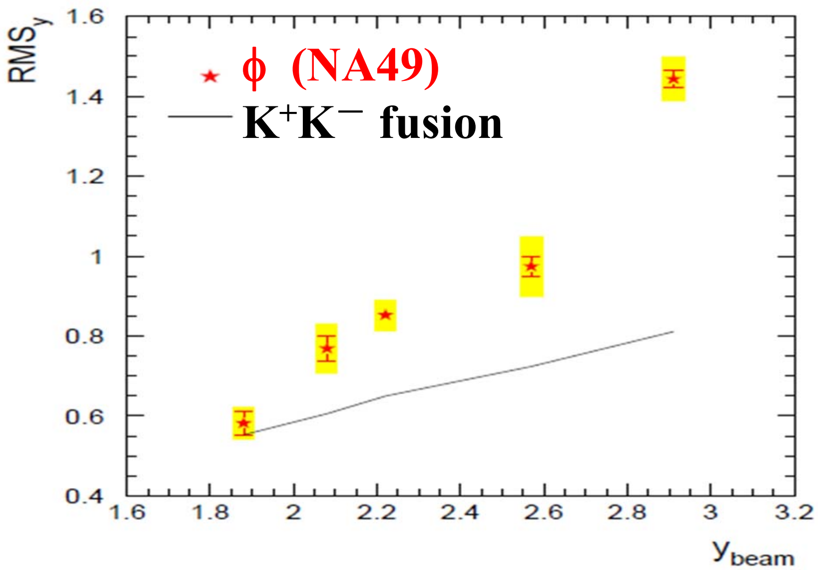
- Mass: proton ~ ϕ ~ Λ
  Similar v_2 at low p_T due to mass ordering in Au+Au 200 GeV
- At low p_T, $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies
  → **strange quark collectivity becomes weaker relative to light quarks**

200 GeV: TPC full event plane; 11.5 and 39 GeV, TPC η-sub event plane; statistical error only

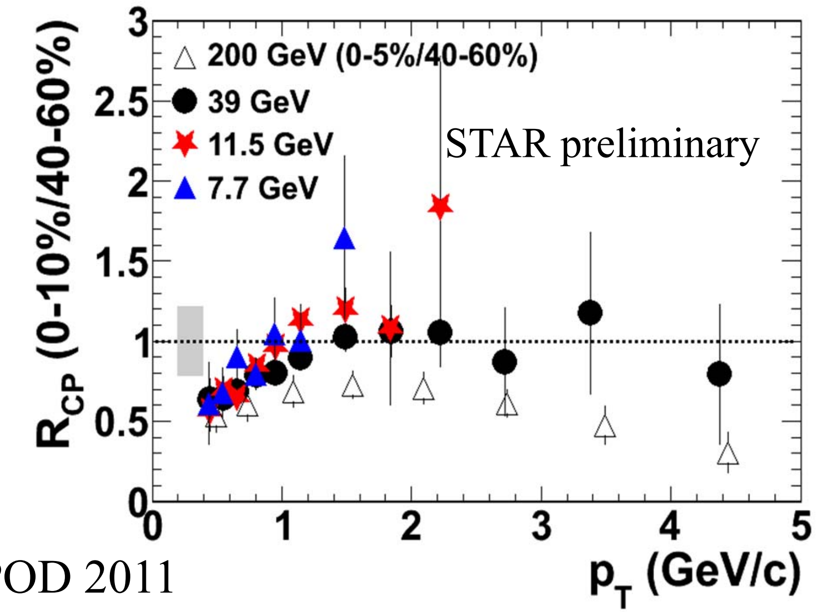
More about ϕ meson

- K^+K^- is not the main production channel in our interested region
- ϕ meson has small hadronic cross section. σ(ϕN) ~ 10 mb
- **Small ϕ v_2 at hadronic phase expected**
- ϕ meson R_{CP}(0-10%/40-60%) consistent with unity at 39 GeV, **no suppression**
- **Decreasing partonic effect with decreasing beam energies**

$\sigma_{\rho N} \sim 3\ \sigma_{\phi N}$
$\sigma_{\pi N} \sim 2.6\ \sigma_{\phi N}$
$\sigma_{KN} \sim 2.1\ \sigma_{\phi N}$
$\sigma_{\Lambda N} \sim 3.5\ \sigma_{\phi N}$
$\sigma_{NN} \sim 4\ \sigma_{\phi N}$



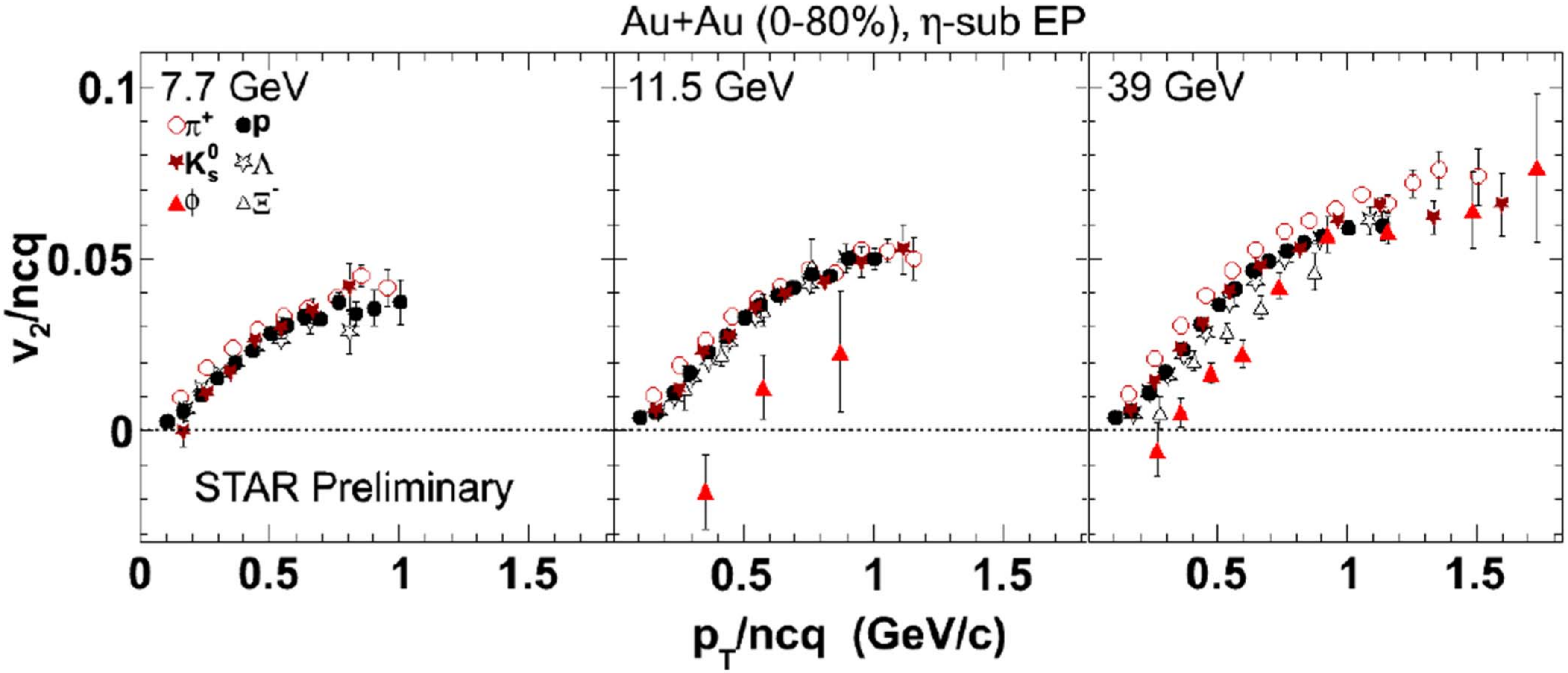
√s (GeV) 6.3 → 17.3



STAR, CPOD 2011

B. Mohanty and N. Xu, J. Phys. G 36 (2009) 064022
NA49, Phys. Rev. C 78 (2008) 044907

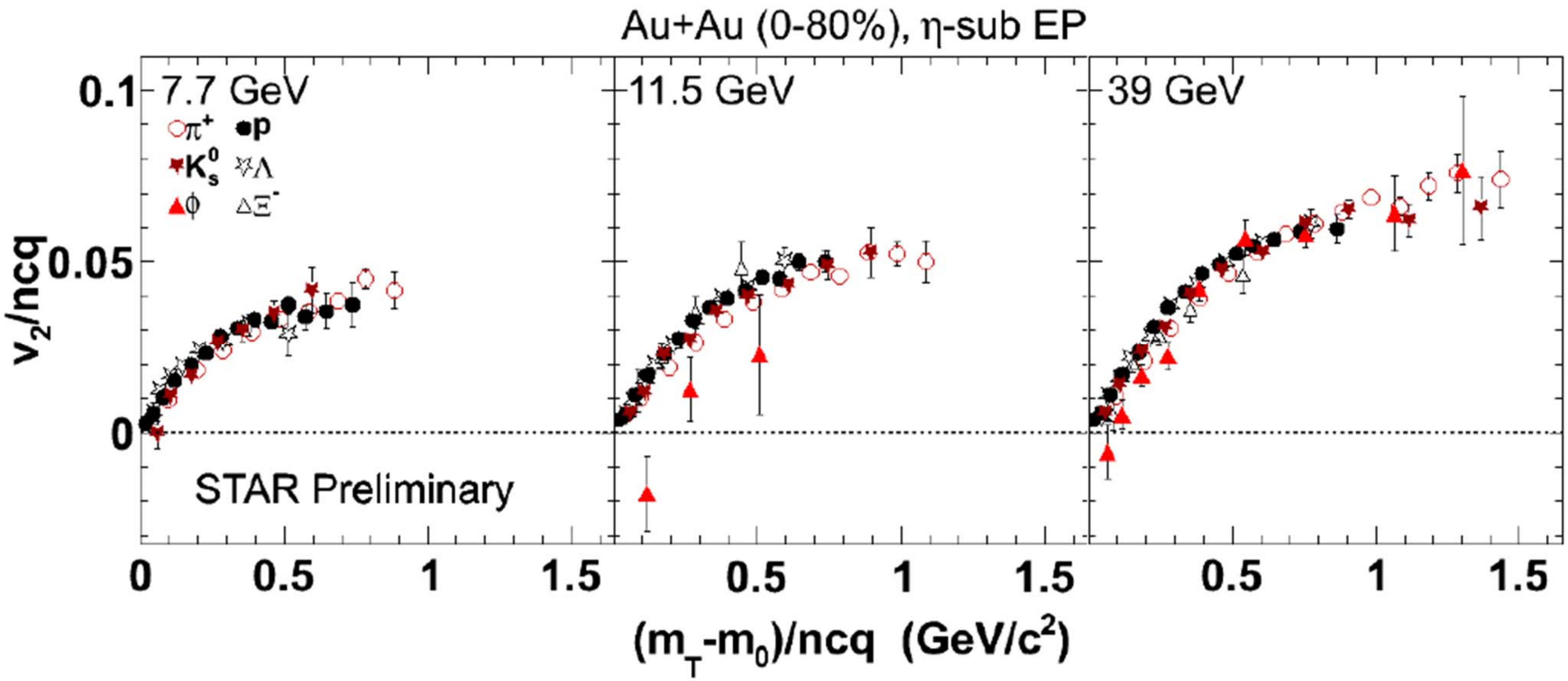
NCQ scaling test – v_2/n_q v.s. p_T/n_q



- π^+, $K^0{}_S$, p, Λ and Ξ^- approximately follow one common curve
- **φ-mesons @ 11.5 GeV does not follow the trend of other hadrons. Mean deviation from pion distribution: 2.6 σ**

STAR, CPOD 2011

NCQ scaling test – v_2/n_q v.s. $(m_T-m_0)/n_q$



- π^+, $K^0{}_S$, p, Λ and Ξ^- approximately follow one common curve
- **φ-mesons @ 11.5 GeV does not follow the trend of other hadrons.**

STAR, CPOD 2011

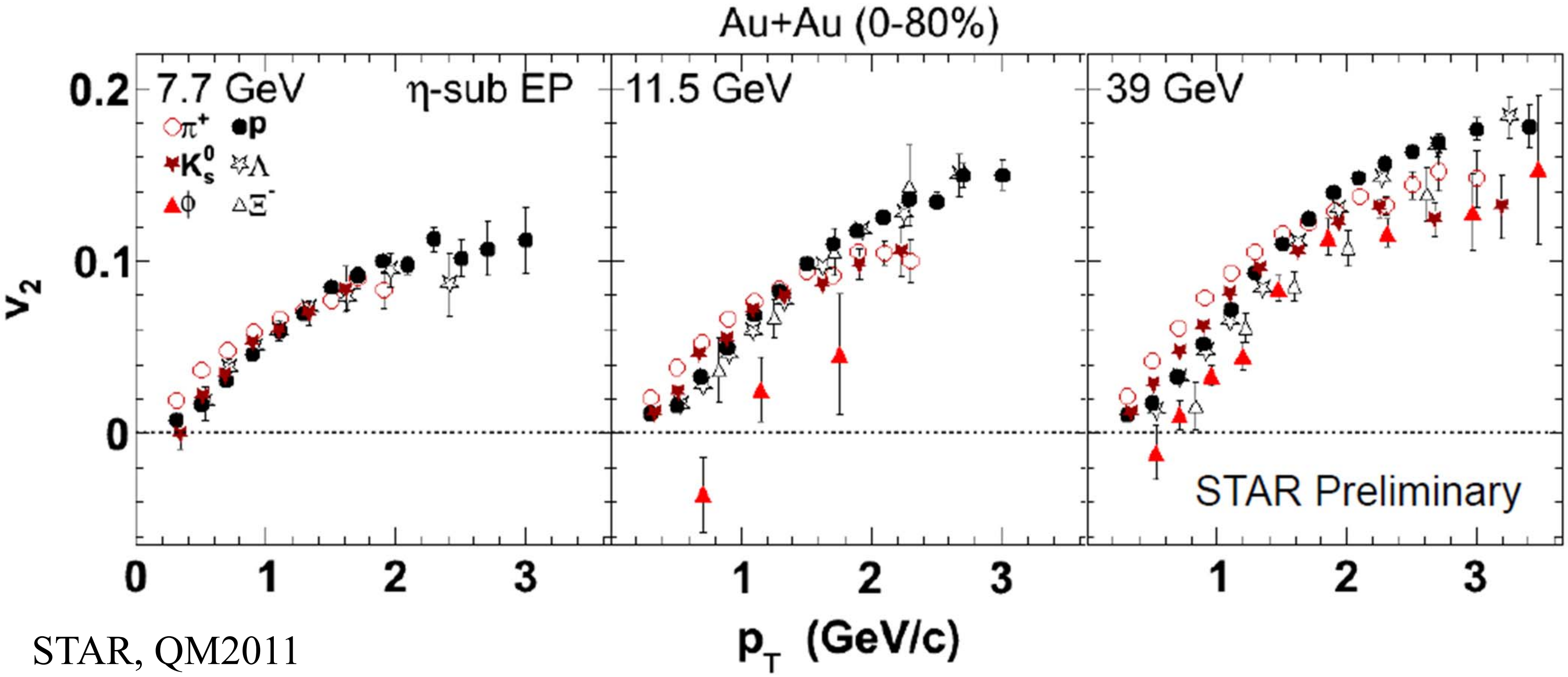
Summary and outlook

- Charged hadrons: consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for $p_T = 2$ - 4 GeV/c, differences increase at low p_T
- Relative difference of v_2 between particles and antiparticles increase with decreasing beam energies
  → **NCQ-scaling between particles and anti-particles is broken at lower energies**

  Chiral magnetic wave? Baryon transport? Hadronic potential?
- $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies at low p_T
  → **strange quark collectivity becomes weaker relative to light quarks**
- Results at 19.6, 27 and 62.4 GeV are in preparation

Backup

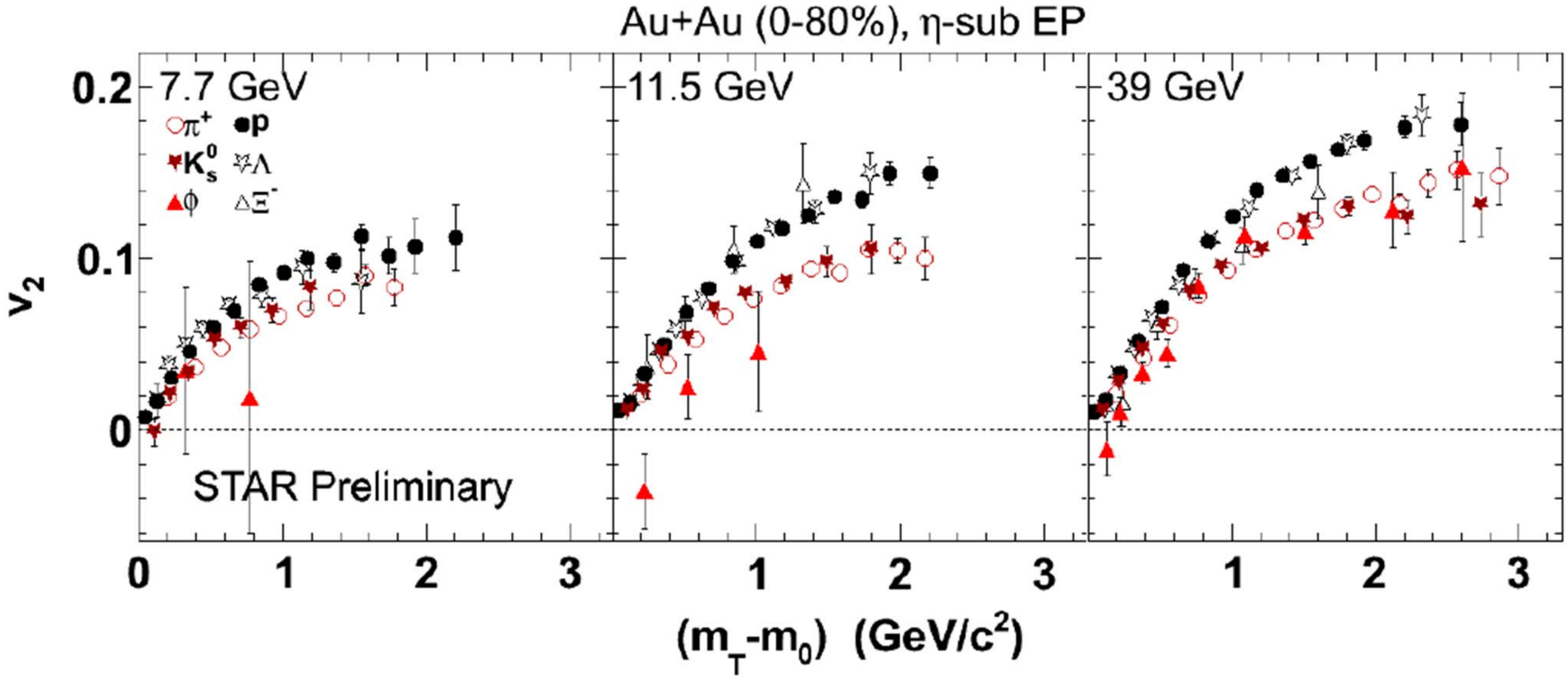
Identified hadrons v_2 v.s. p_T



STAR, QM2011

- Mass ordering holds at low p_T, except for ϕ-mesons
- **ϕ-mesons v_2 @ 11.5 GeV is small compared to other hadrons**

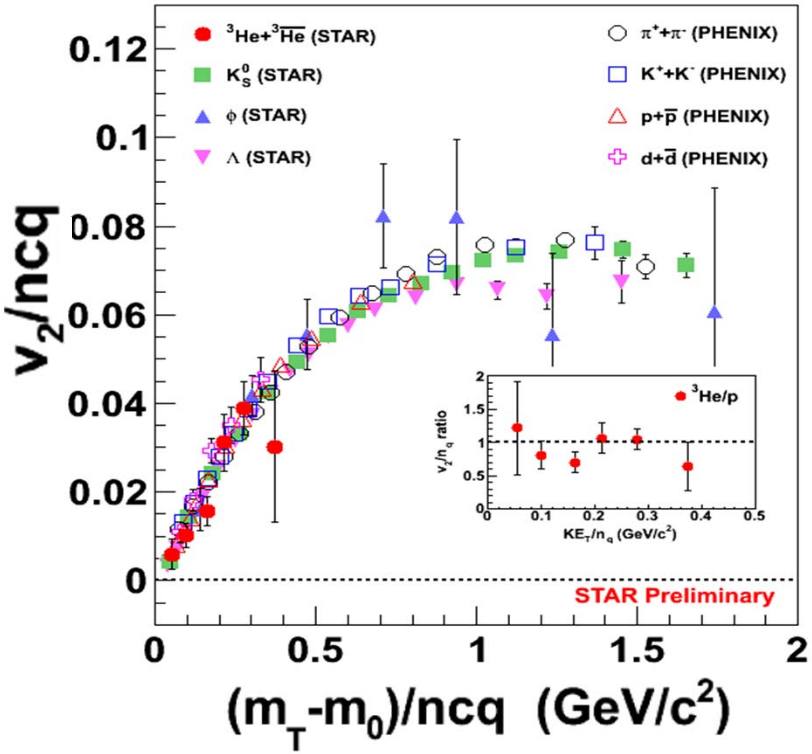
v_2 v.s. m_T - m_0



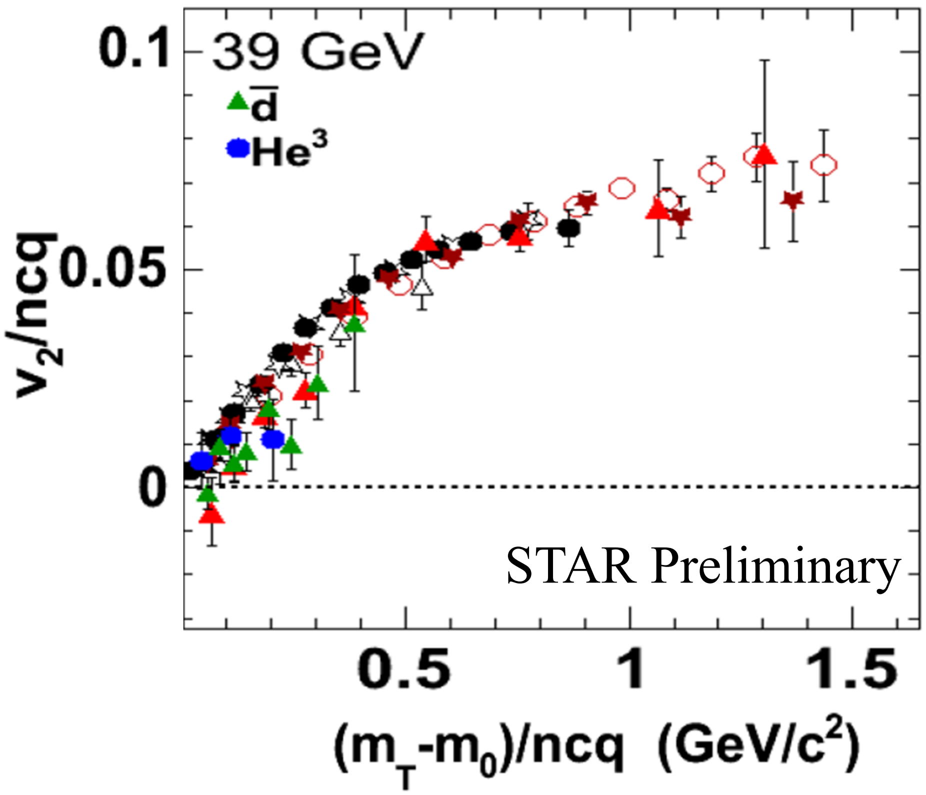
- Meson ↔ Baryon splitting for particles @ 11.5 and 39 GeV
  Splitting is smaller @ 7.7 GeV
- **ϕ-mesons @ 11.5 GeV show a different trend**

Light nuclei v_2

Au+Au 200 GeV



Au+Au 39 GeV

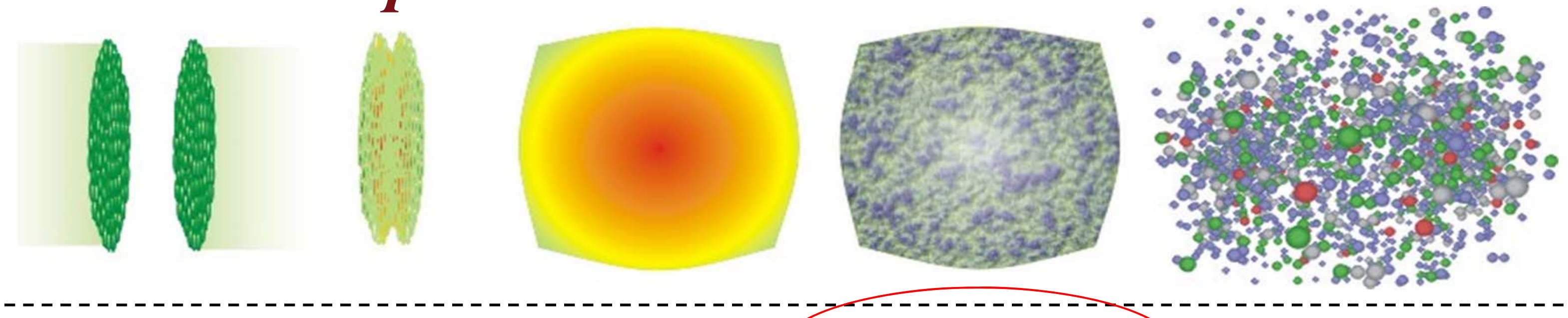


STAR, C. Jena, ICPAQGP 2010

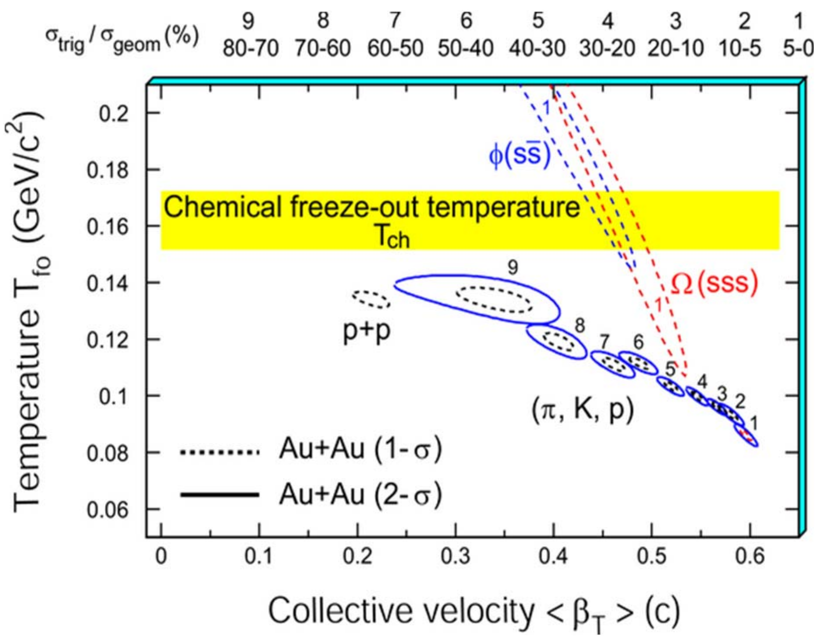
- **Light nuclei can be used to study nucleon coalescence**
- Currently only ~10% of total statistics @ 39 GeV in light nuclei analysis

Why NCQ scaling may break at hadronic phase?

partonic *hadronic*



J/ψ Ω, φ π, K, p time



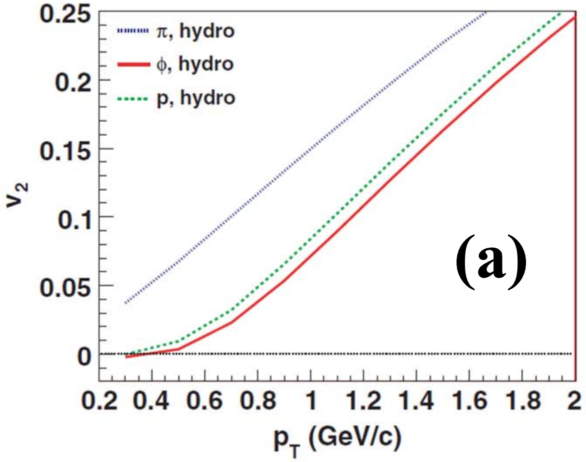
Multi-strange hadrons

- Small hadronic cross sections, freeze-out early
- **Small v_2 at hadronic stage**
- **NCQ scaling may break in hadronic dominated phase**

STAR, Nucl. Phys. A 757 (2005) 102

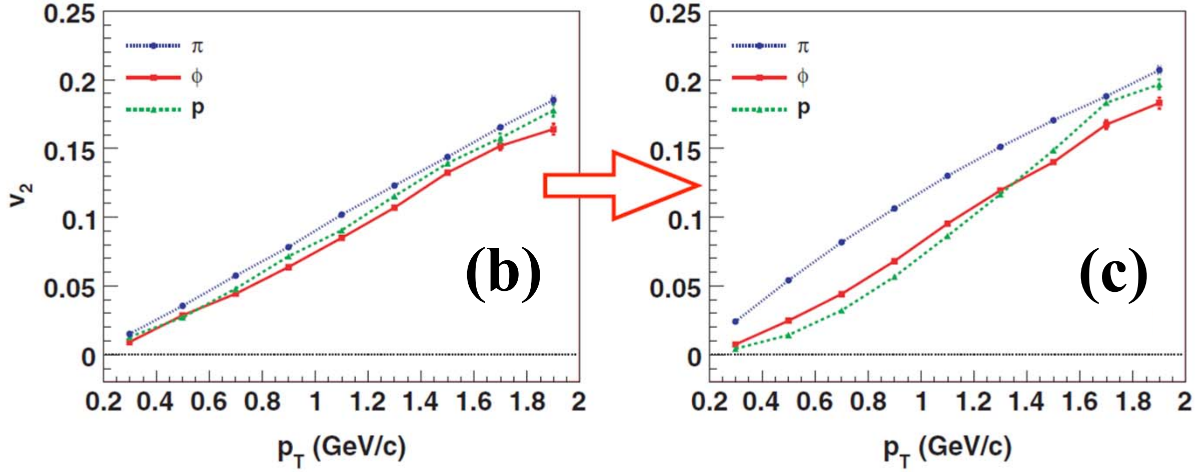
Mass ordering violation for ϕ meson v_2?

at kinetic freeze-out



Ideal hydro

at chemical freeze-out **at kinetic freeze-out**



Ideal hydro
+ hadron cascade

T. Hirano et al.,
Phys. Rev. **C**77, 044909 (2008)

- (a) **ideal hydro: mass ordering for ϕ meson v_2**
  (c) **ideal hydro + hadronic rescatterings: violation of mass ordering for ϕ meson v_2** due to small hadronic cross section of ϕ
- **Comparison of ϕ meson v_2 to proton v_2 is useful for understanding the effect of the hadronic phase**