The elliptic flow of identified hadrons v.s. $\sqrt{s_{NN}}$ in Au + Au collisions at STAR

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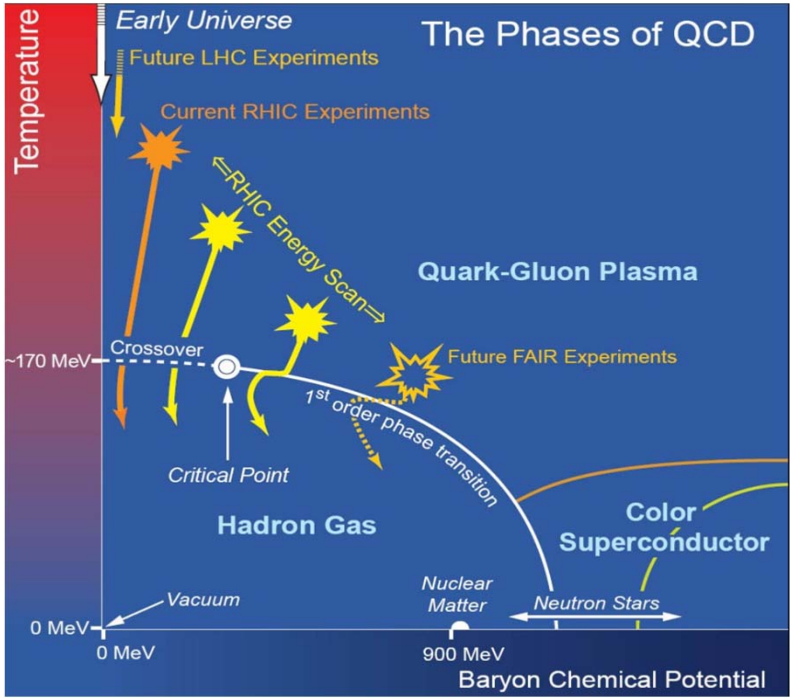
For the STAR Collaboration

- QCD phase transition and elliptic flow
- Elliptic flow (v_2) results and discussions
- Summary and outlook

Motivation



- **NCQ scaling of elliptic flow (v_2) for multi-strange hadrons**

→ Partonic degree of freedom

- **Characterize different phases**

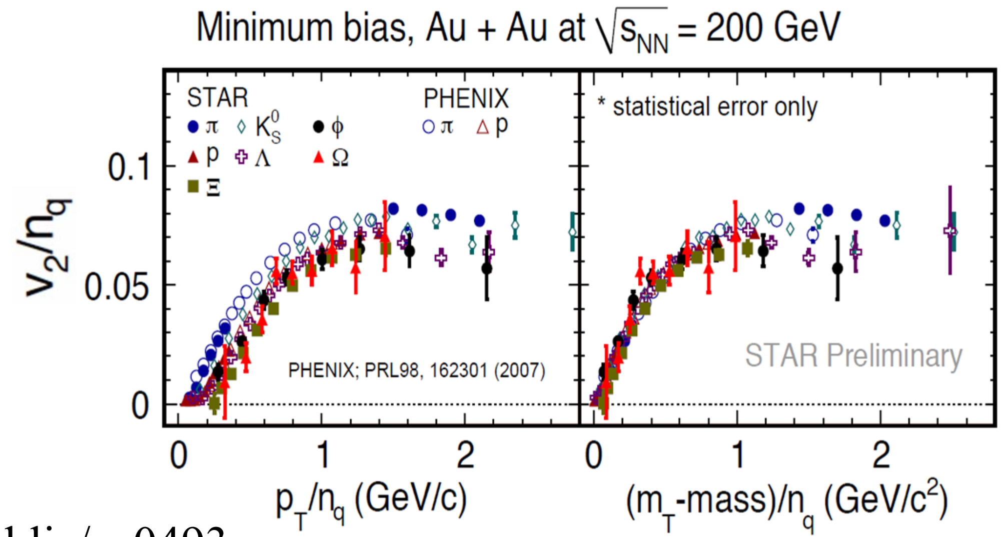
→ Partonic dominate: NCQ scaling
Hadronic dominate: small v_2 of multi-strange hadrons, NCQ scaling may break

Beam Energy Scan at RHIC

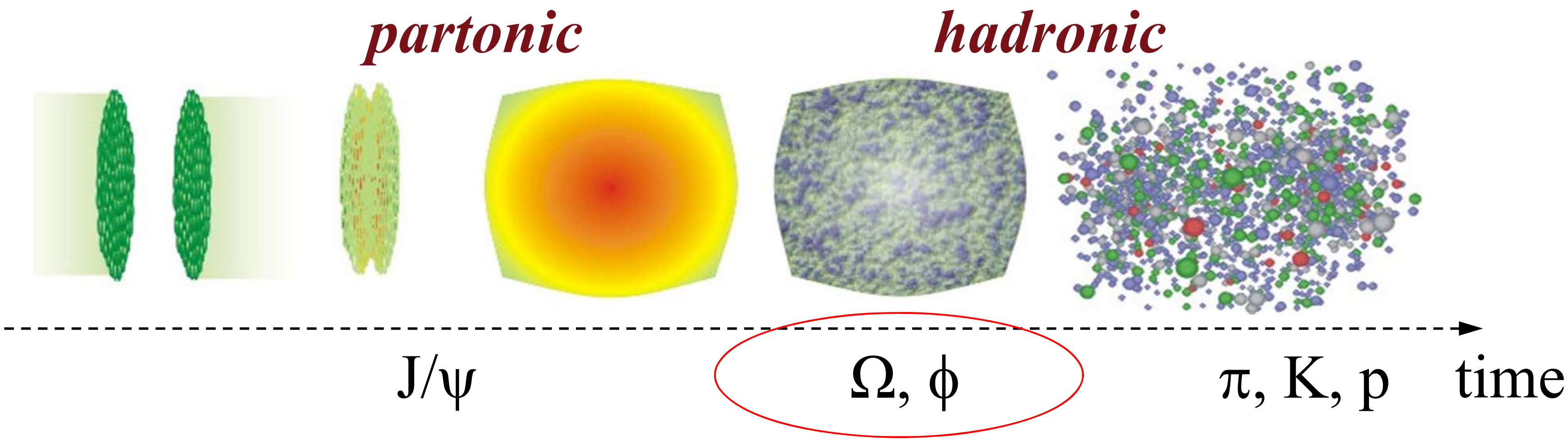
Search for signals of phase boundary

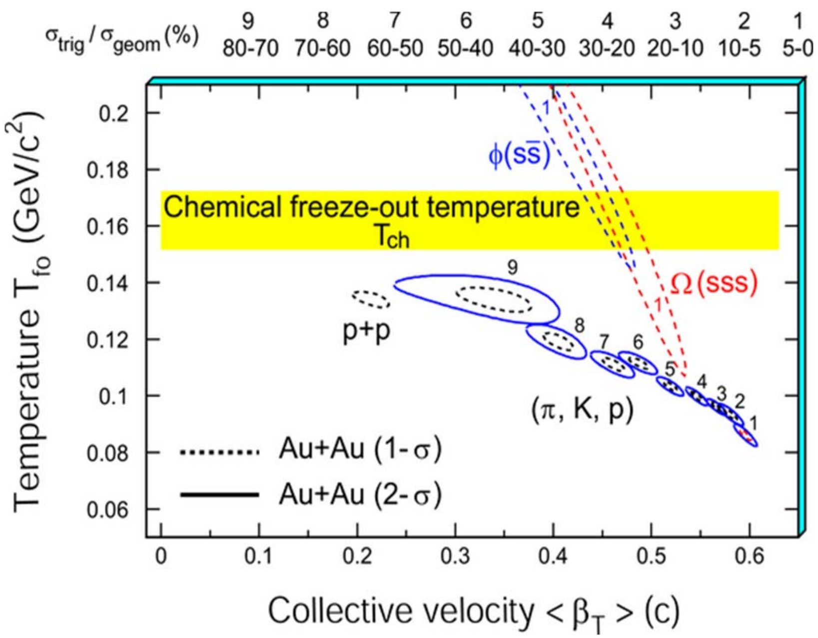
Search for QCD critical point

STAR, Phys. Rev. Lett. 92 (2004) 052302
STAR, Phys. Rev. Lett. 99 (2007) 112301
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493



Why NCQ scaling may break at hadronic phase?



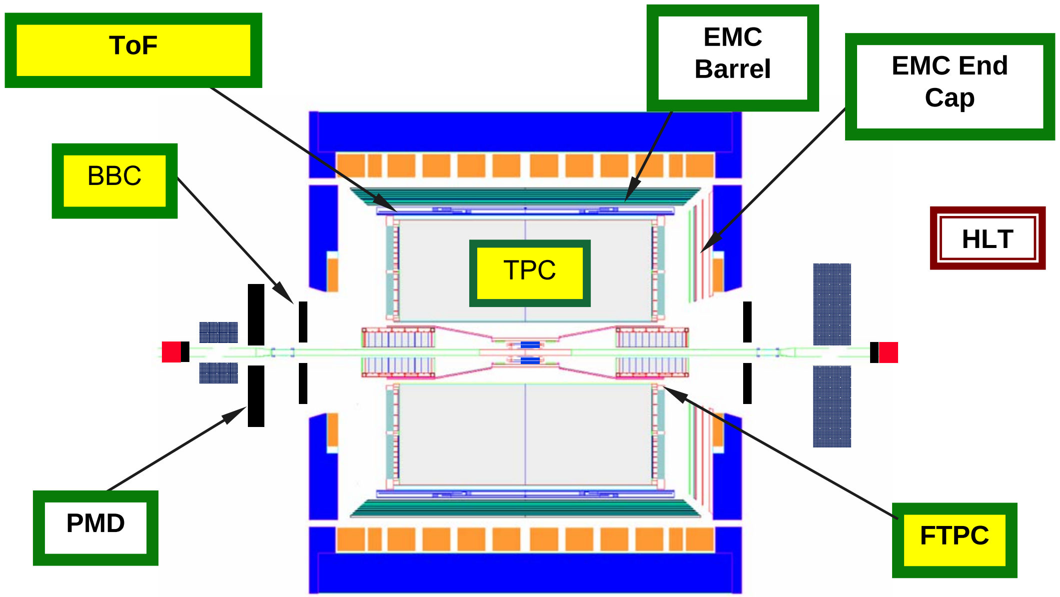


Multi-strange hadrons

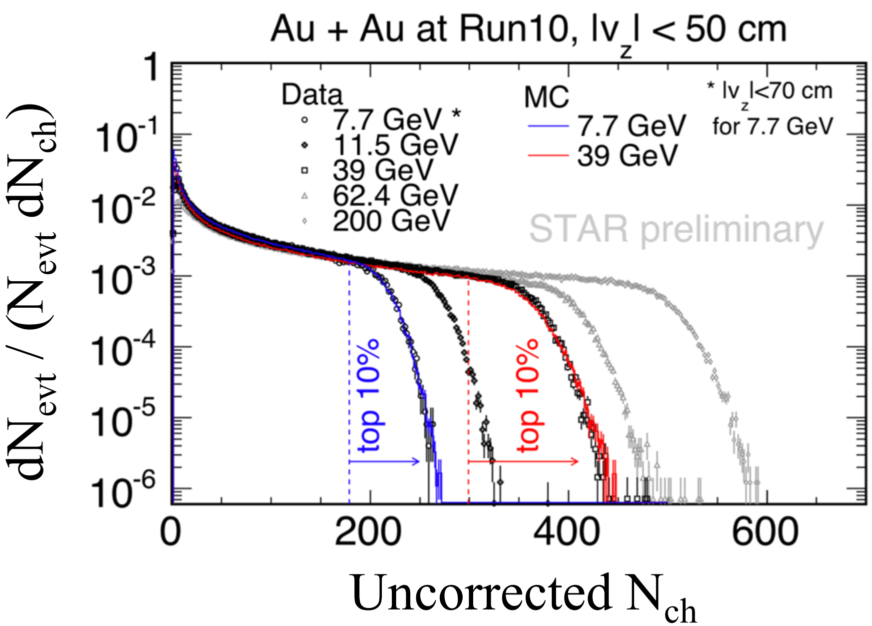
- Small hadronic cross sections, freeze-out early
- **Small v_2 at hadronic stage**
- **NCQ scaling may break in hadronic dominated phase**

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

Detector settings during STAR BES 2010-2011

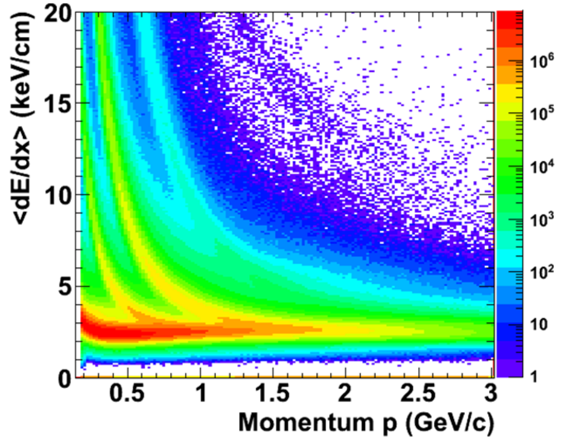


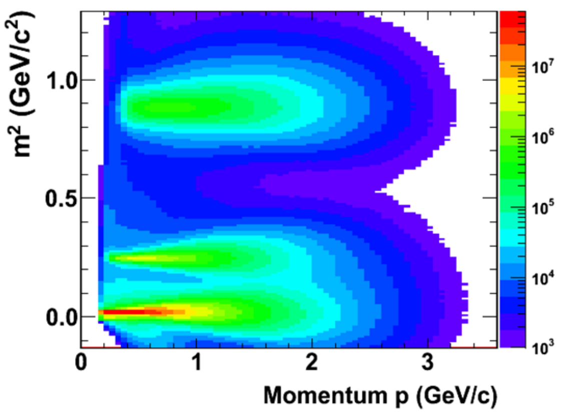
- Collisions: Au+Au
- High Level Trigger
  Online collision vertex selection, reject beam pipe events

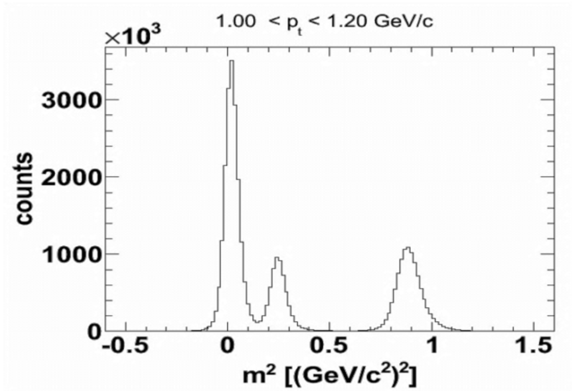


$\sqrt{s_{NN}}$ (GeV)	Good MB events in Million
5.0	
7.7	~ 5
11.5	~ 11
19.6	~ 17
27	Expected ~ 150
39	~ 170

Particle identification and v_2 analysis

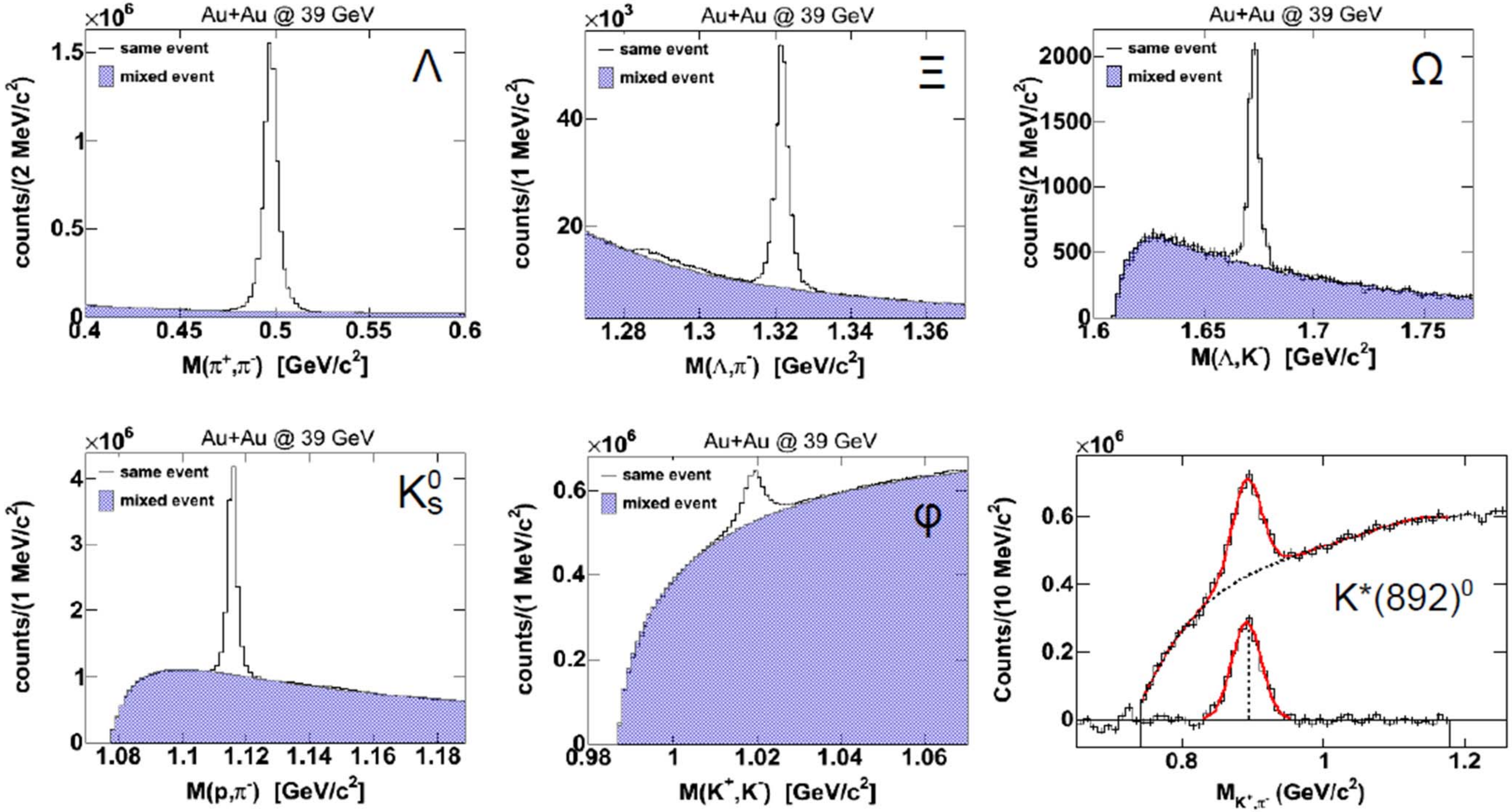






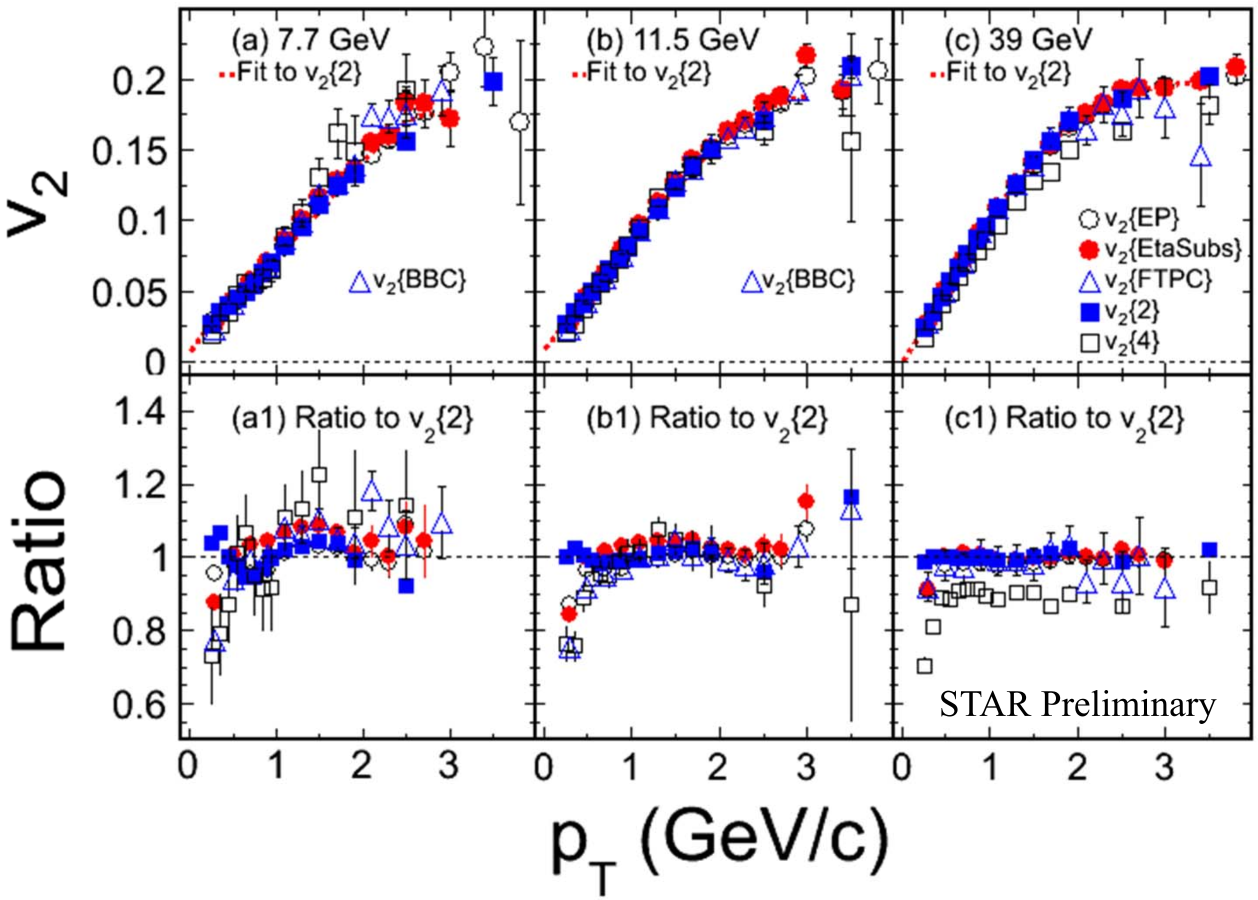
- **Time projection chamber (TPC)**
  full azimuth, $|\eta| < 1$
  dE/dx v.s. momentum
  secondary vertex finder for K^0_s, Λ
- **Barrel Time-Of-Flight (TOF)**
  full azimuth, $|\eta| < 1$
  Particle flight time
  Clean separation of K, π up to $p_T = 1.6$ GeV/c
- Collisions centrality from
  uncorrected $dN_{ch}/d\eta$ in $|\eta| < 0.5$
- $v_2 = \langle \cos 2(\varphi - \psi_R)/Res \rangle$
- **TPC η-sub event plane for PID flow**
  Non-flow effect reduced

Particle reconstruction



- S/B of resonances [ϕ and K*0(892)] significantly improved with additional TOF PID

v_2 of charged hadrons @ 7.7, 11.5, 39 GeV

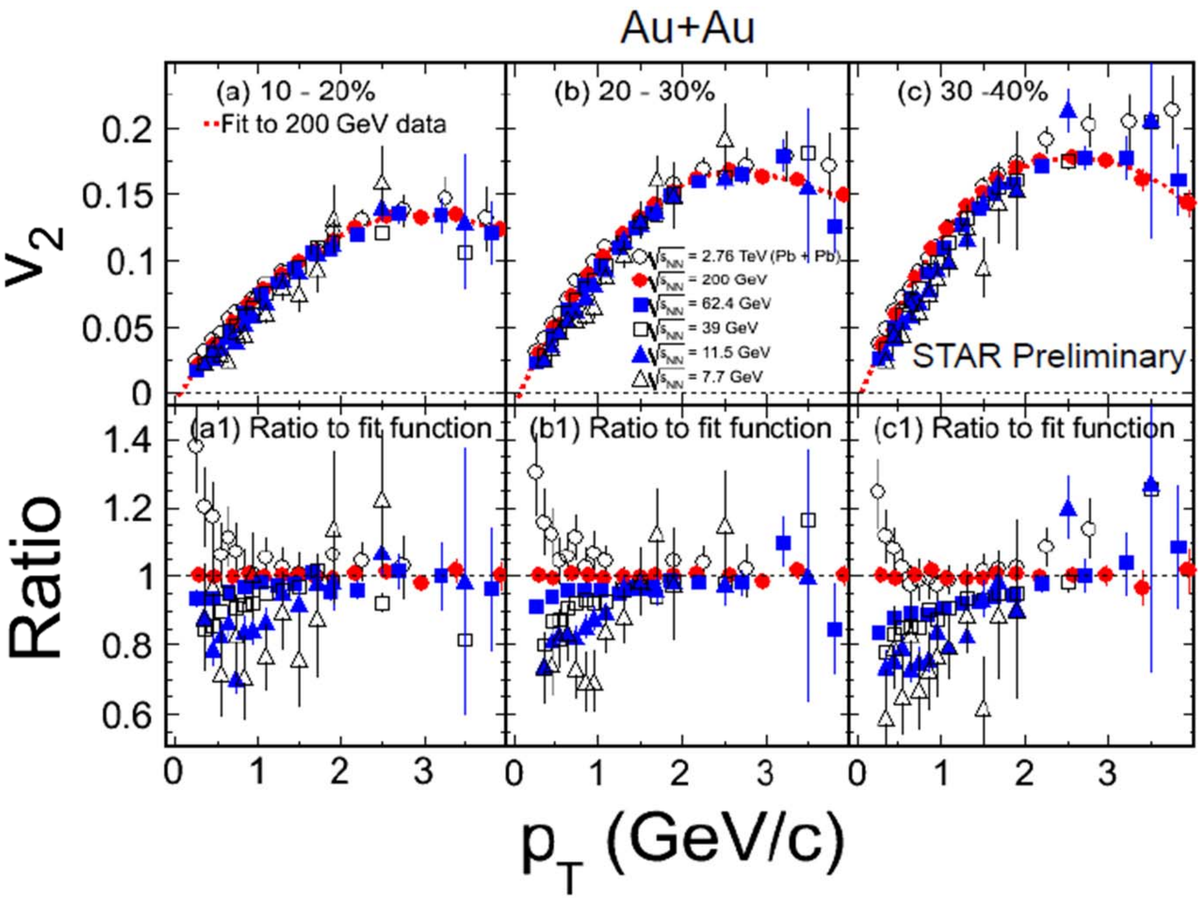


- Different event plane detector
  TPC (| η |<1)
  FTPC (2.5<| η |<4)
  BBC (3.3<| η |<5)
- Different v_2 analysis method
  EP, cumulant method
- Overall, good agreement

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

STAR, M. Mitrovski, S. Shi, QM2011 poster

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

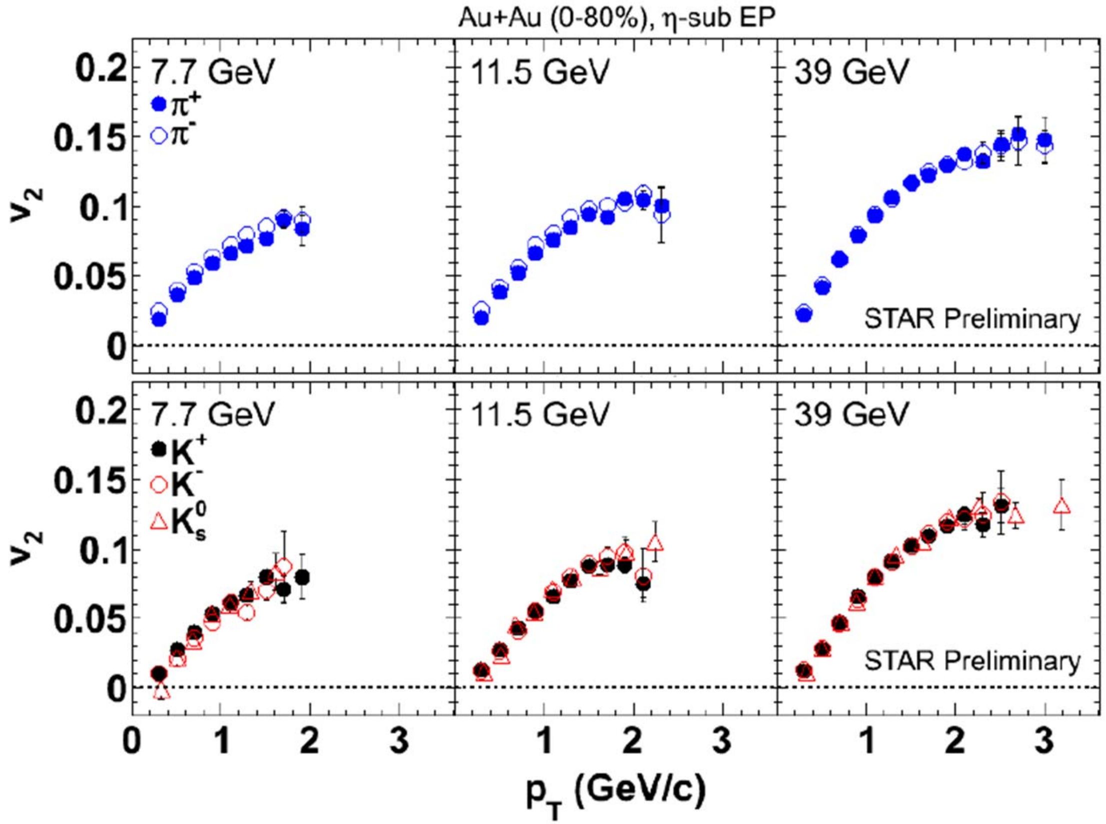
- **Similar $v_2(p_T)$ shape**

  p_T = 2 - 4 GeV/c: almost same $v_2(p_T)$

  Differences increase at low p_T

STAR, M. Mitrovski, S. Shi, QM2011 poster
ALICE, Phys. Rev. Lett. 105 (2010) 252302

Particle and anti-particle v_2 (π and K)

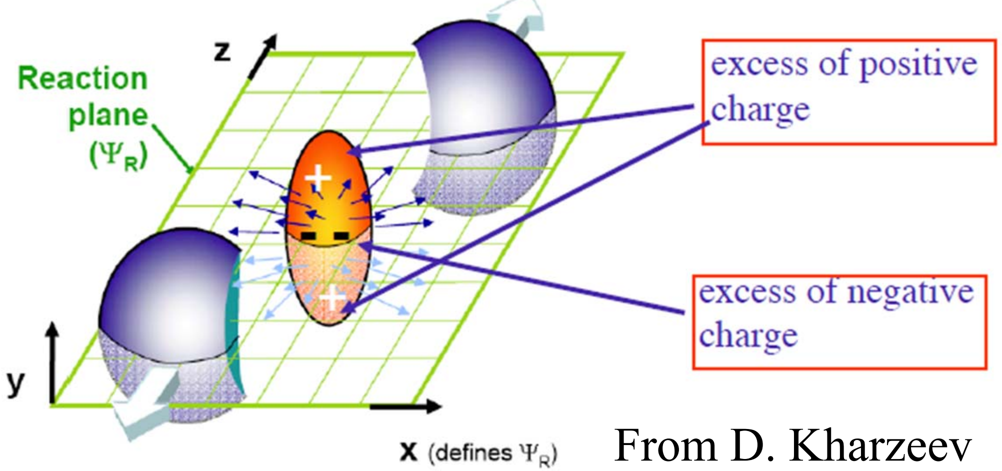


- Coulomb repulsion of π^+? Resonances? Chiral Magnetic Wave?
- K^- absorption? Associated production?

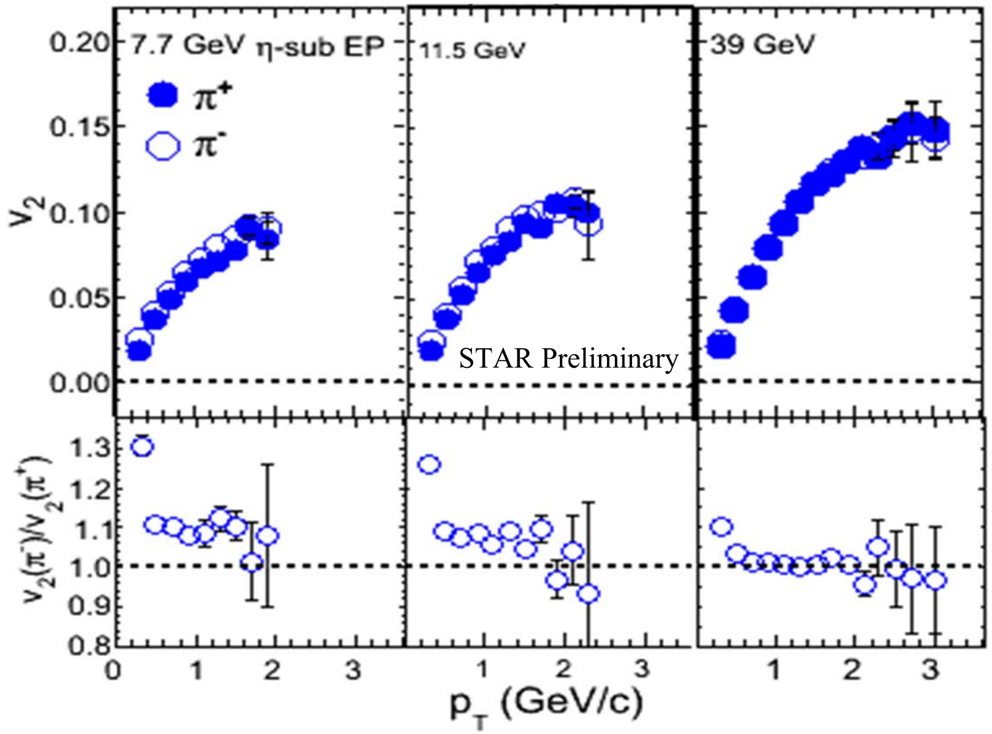
- π: $v_2(\pi^-) \sim v_2(\pi^+)$ @ 39 GeV
  $v_2(\pi^-) > v_2(\pi^+)$ @ 7.7 and 11.5 GeV
- K: $v_2(K^+) \sim v_2(K^-)$ @ 11.5 and 39 GeV
  $v_2(K^+) > v_2(K^-)$ @ 7.7 GeV

STAR, A. Schmah, QM2011

Electric quadrupole moment of QGP?



From D. Kharzeev

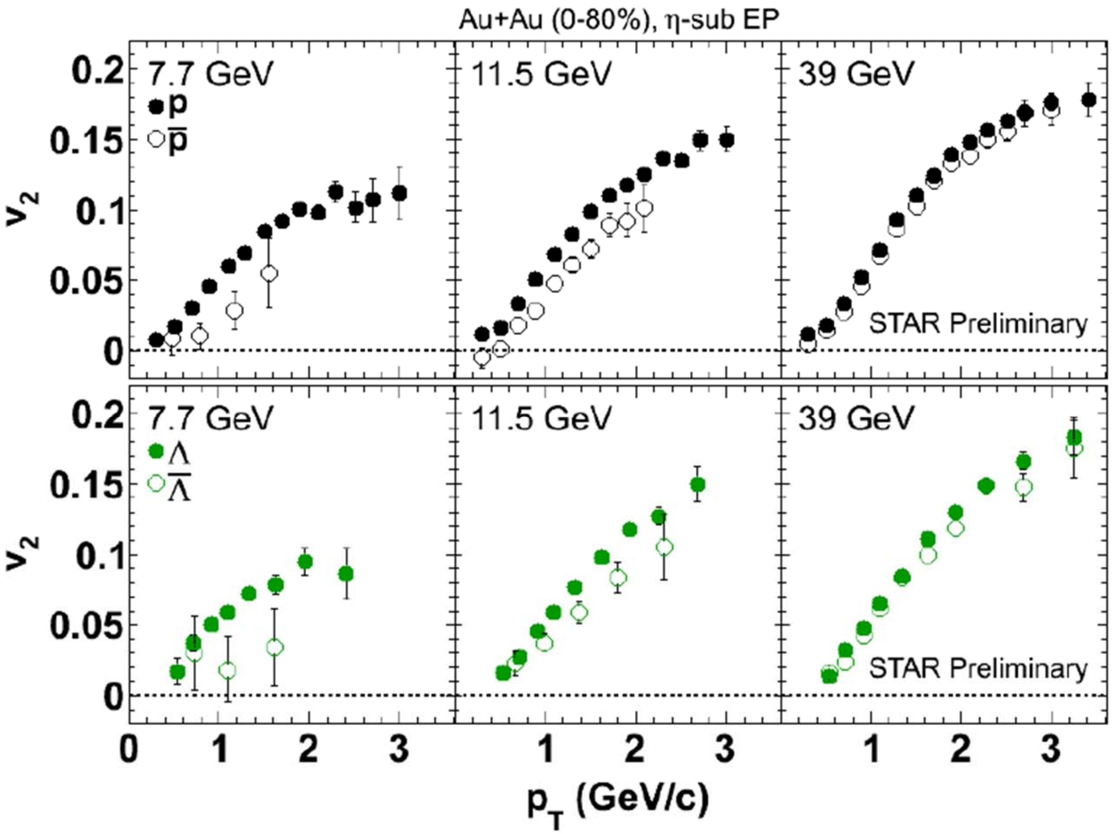


- Chiral Magnetic Wave: interplay of CME and CSE
- CMW induces a static electric quadrupole moment of QGP at finite baryon density
- Elliptic flow of positive hadrons < negative ones **$v_2(\pi^+) < v_2(\pi^-)$, calculated difference at $\sqrt{s}$ = 11 GeV ~ up to 30%**
- **Data: difference ~ 10% at 11.5 GeV**

STAR, B. Mohanty, D. Gangadharan, QM2011

Y. Burnier et al., arXiv:1103.1307

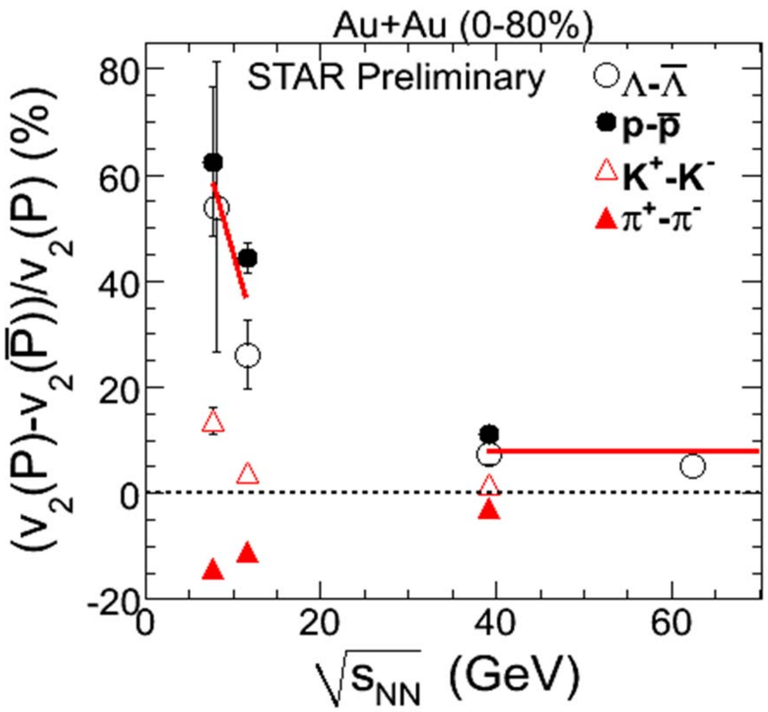
Particle and anti-particle v_2 (Proton and Λ)



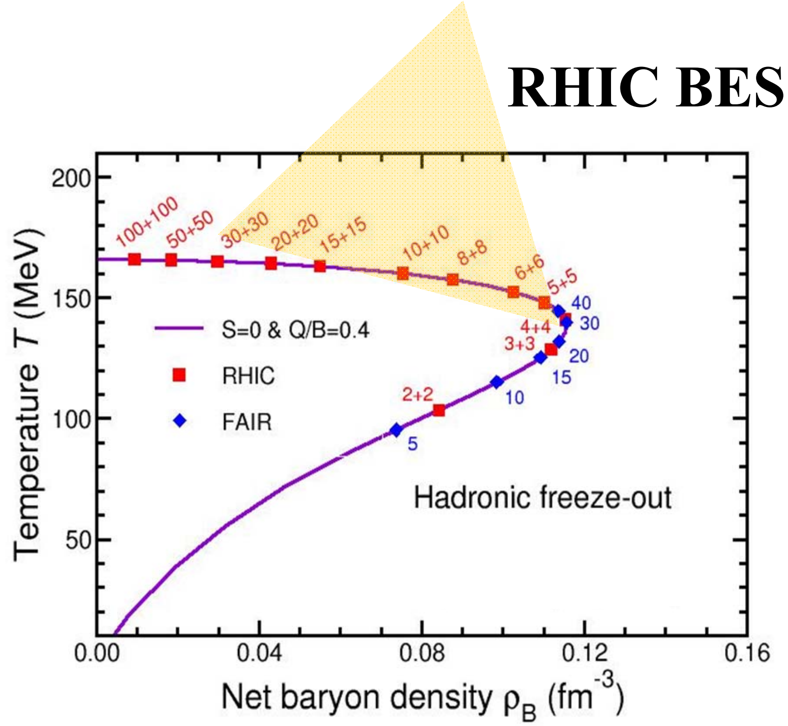
- **Proton: v_2(proton) > v_2(anti-proton) at three energies Difference increases with decreasing energy**
- **Λ: similar behavior**

STAR, A. Schmah, QM2011

Particle and anti-particle v_2 difference



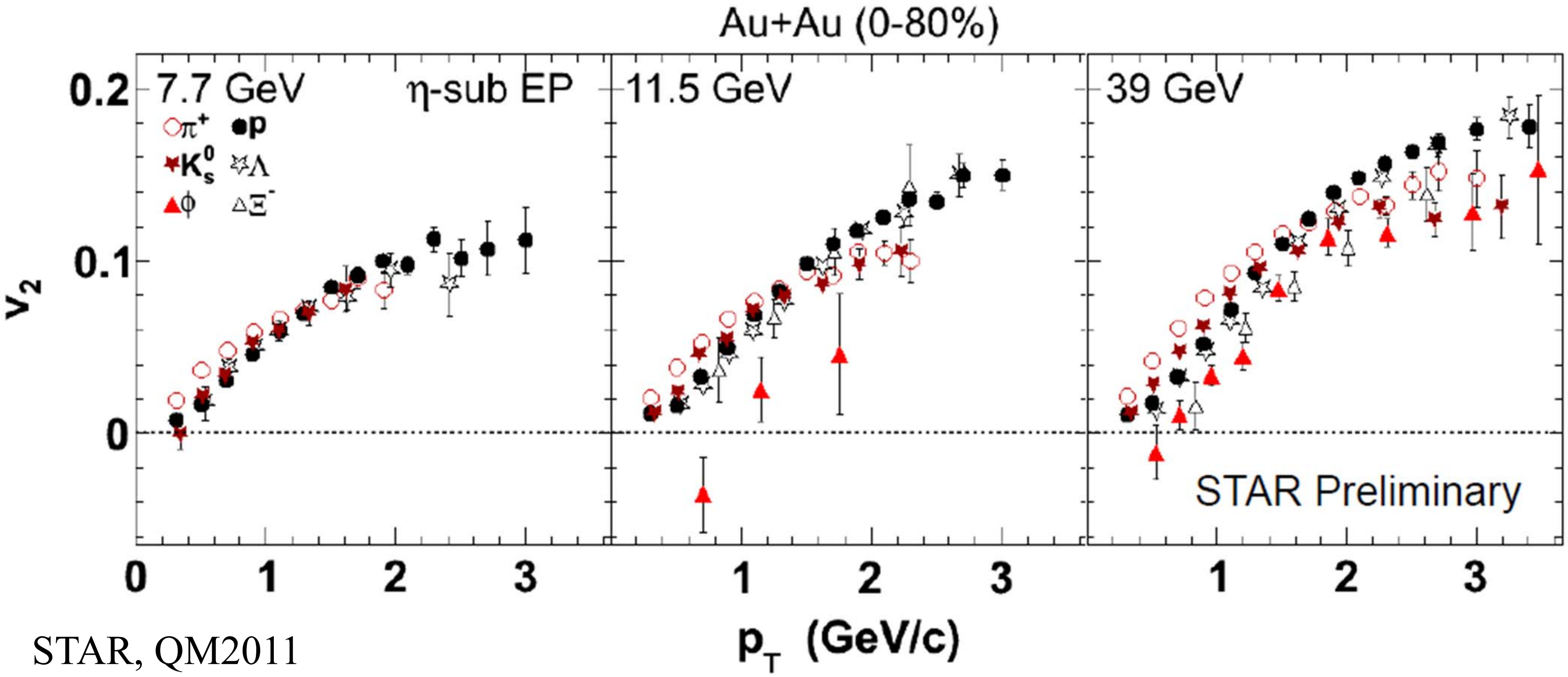
STAR, A. Schmah, QM2011



J. Randrup & J. Cleymans, 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
- Baryon transport to mid-rapidity? absorption in hadronic environment?
- **NCQ scaling between particles and antiparticles is broken at 11.5 and 7.7 GeV**

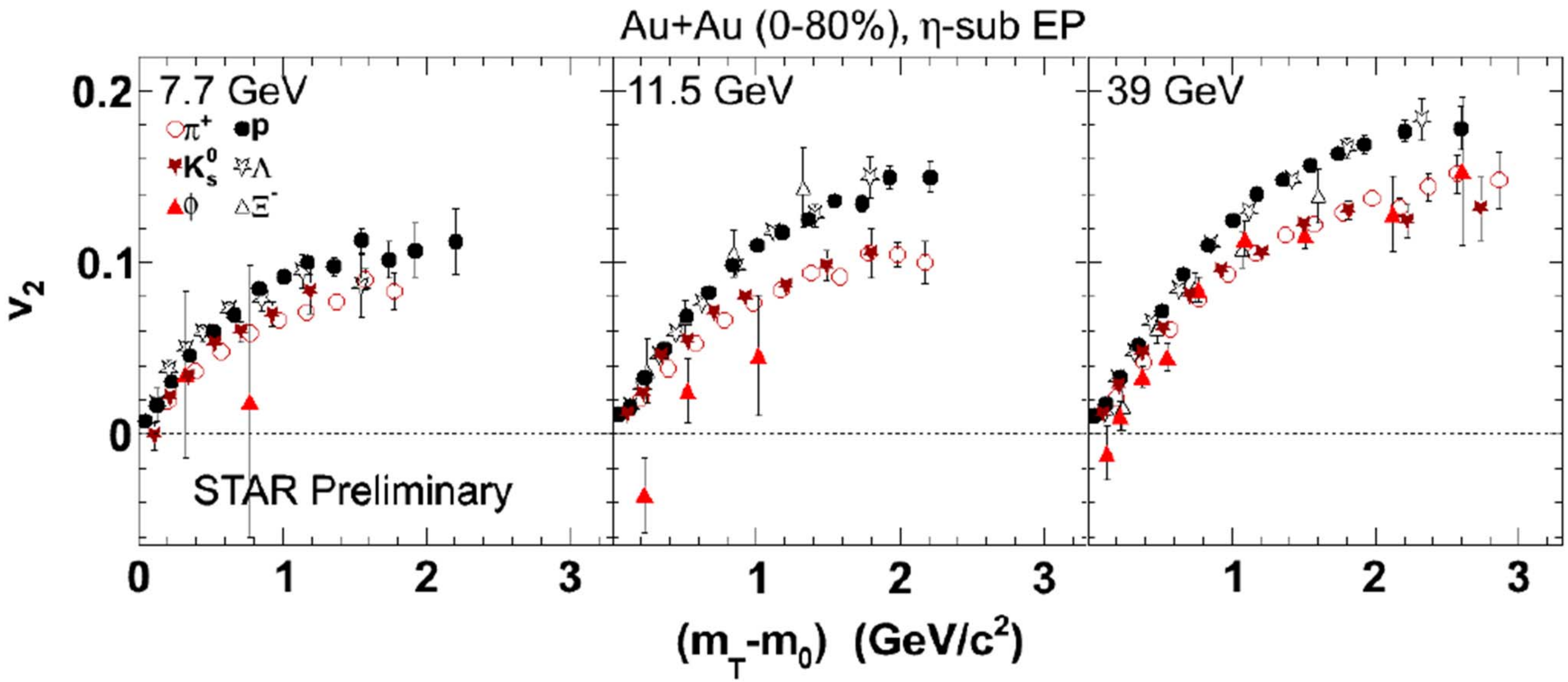
Identified hadrons v_2 v.s. p_T



STAR, QM2011

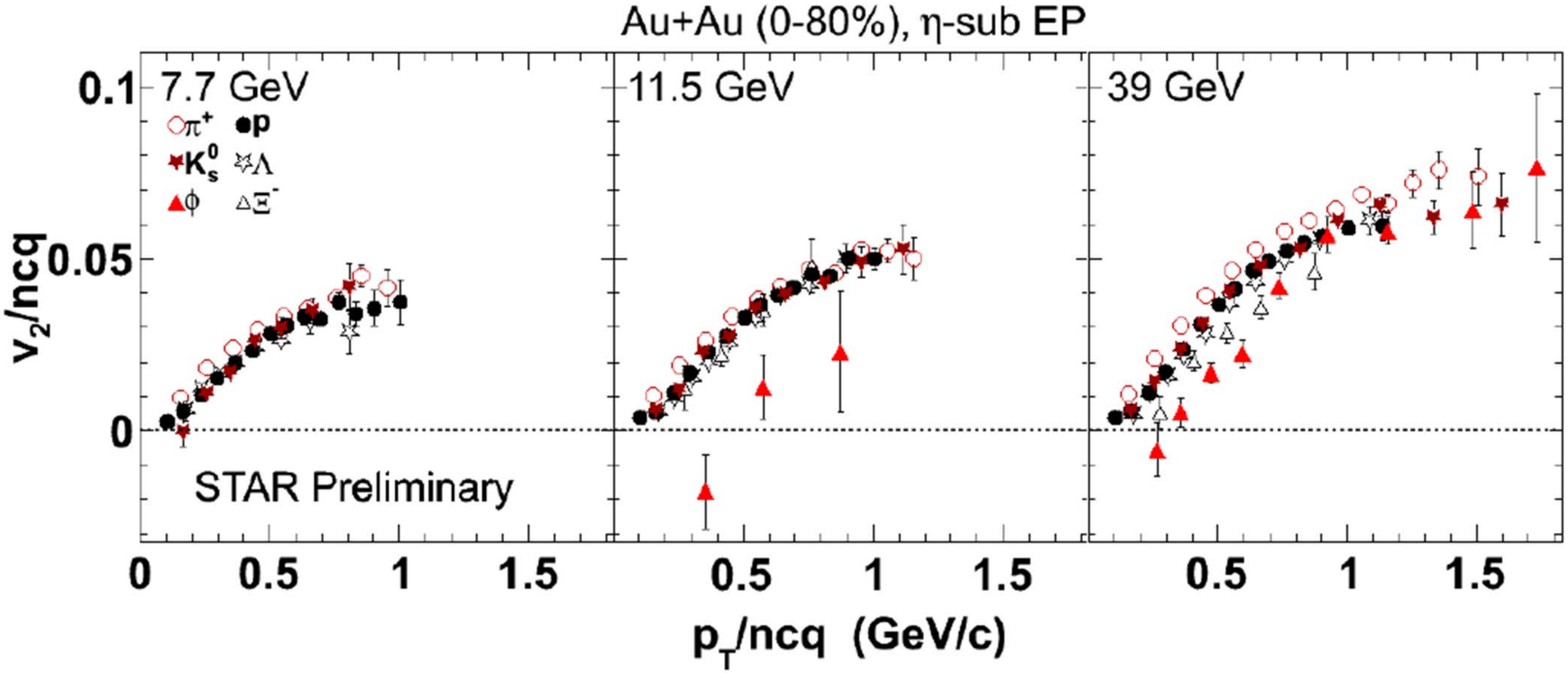
- Mass ordering holds at low p_T, except for ϕ-mesons
- **ϕ-mesons v_2 @ 11.5 GeV is small compared to other hadrons**

v_2 v.s. m_T - m_0



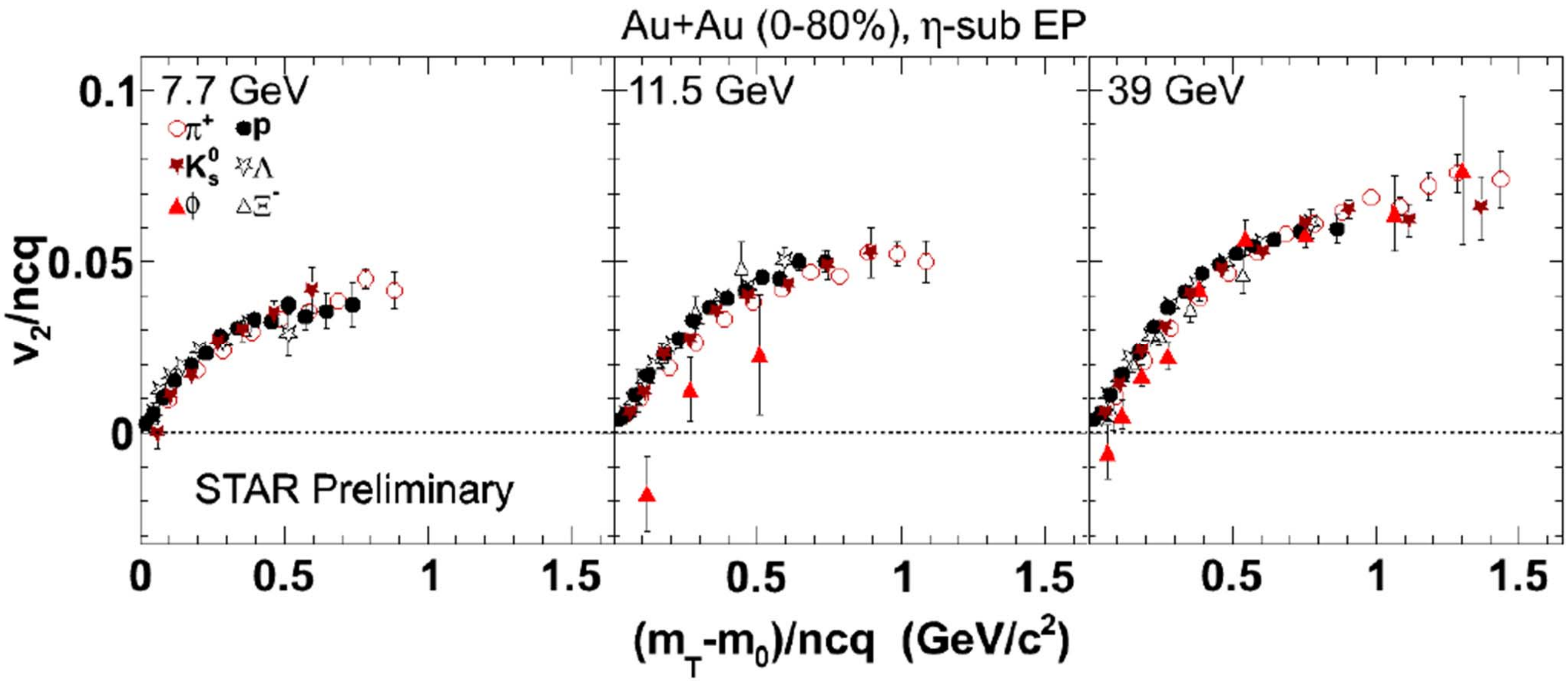
- Meson ↔ Baryon splitting for particles @ 11.5 and 39 GeV
  Splitting is smaller @ 7.7 GeV
- **φ-mesons @ 11.5 GeV show a different trend**

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



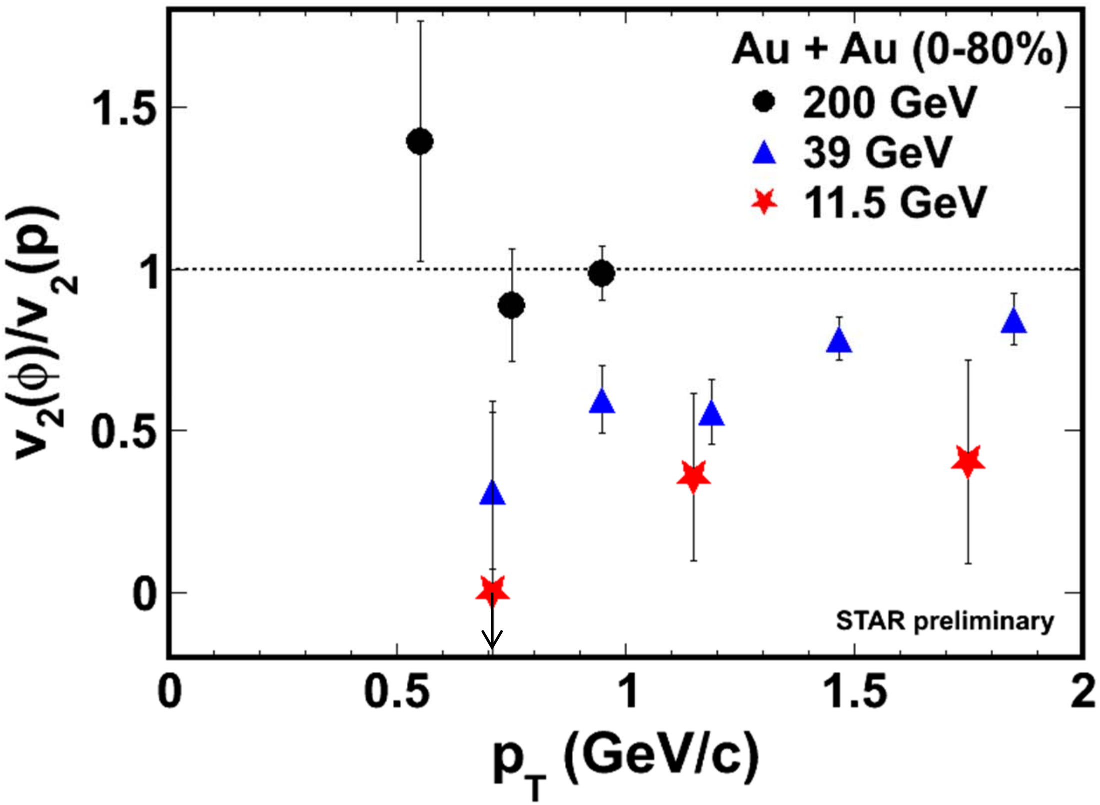
- π^+, $K^0{}_S$, p, Λ and Ξ^- approximately follow one common curve
- **φ-mesons @ 11.5 GeV does not follow the trend of other hadrons. Mean deviation from pion distribution: 0.02±0.008 (→ 2.5 σ)**

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.**

$v_2(\phi)$ / v_2(proton)



- $\sqrt{s}$ = 200 GeV, $v_2(\phi) \sim v_2(p)$ at low p_T (mass ordering)
- **The ratio $v_2(\phi)/v_2(p)$ at low p_T decreases with decreasing beam energies**

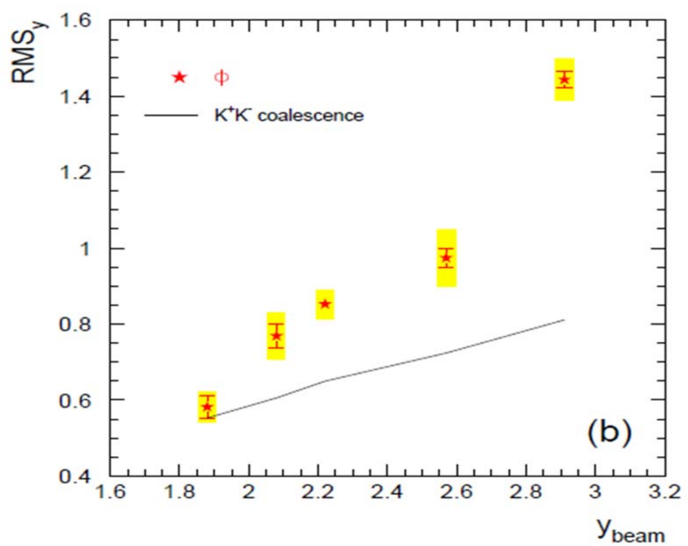
Why $\phi(s\bar{s})$ is special?

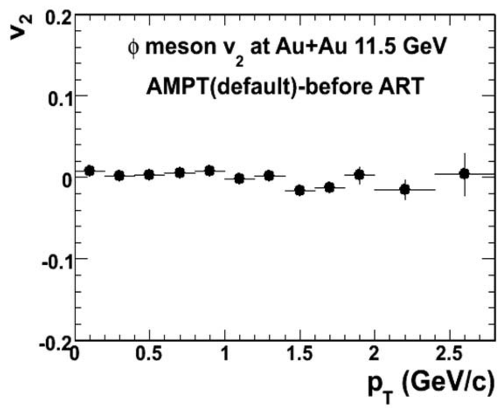
- K^+K^- is not the main production channel in our interested region
- ϕ meson $v_2 \sim 0$, if only from string fragmentation
- ϕ meson has small hadronic cross section. $\sigma(\phi N) \sim 10$ mb
- **Small ϕ v_2 at hadronic phase**
- **ϕ meson v_2 indicates collectivity contribution from partonic interactions decreases with decrease in center of mass energy**

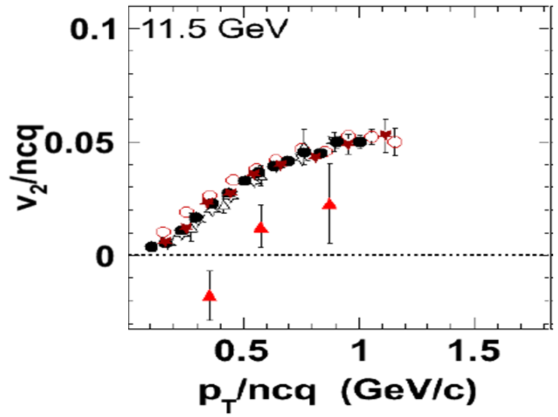
$\sigma_{\rho N} \sim 3\ \sigma_{\phi N}$ $\quad \sigma_{\Lambda N} \sim 3.5\ \sigma_{\phi N}$

$\sigma_{\pi N} \sim 2.6\ \sigma_{\phi N}$ $\quad \sigma_{NN} \sim 4\ \sigma_{\phi N}$

$\sigma_{KN} \sim 2.1\ \sigma_{\phi N}$







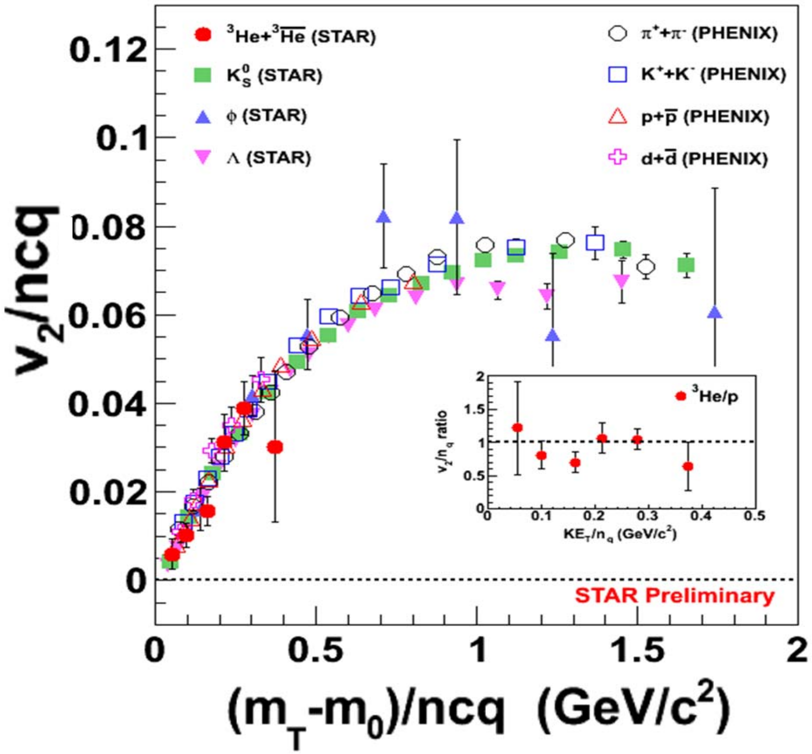
$\sqrt{s}$ (GeV) 6.3 → 17.3

B. Mohanty and N. Xu, J. Phys. G 36 (2009) 064022

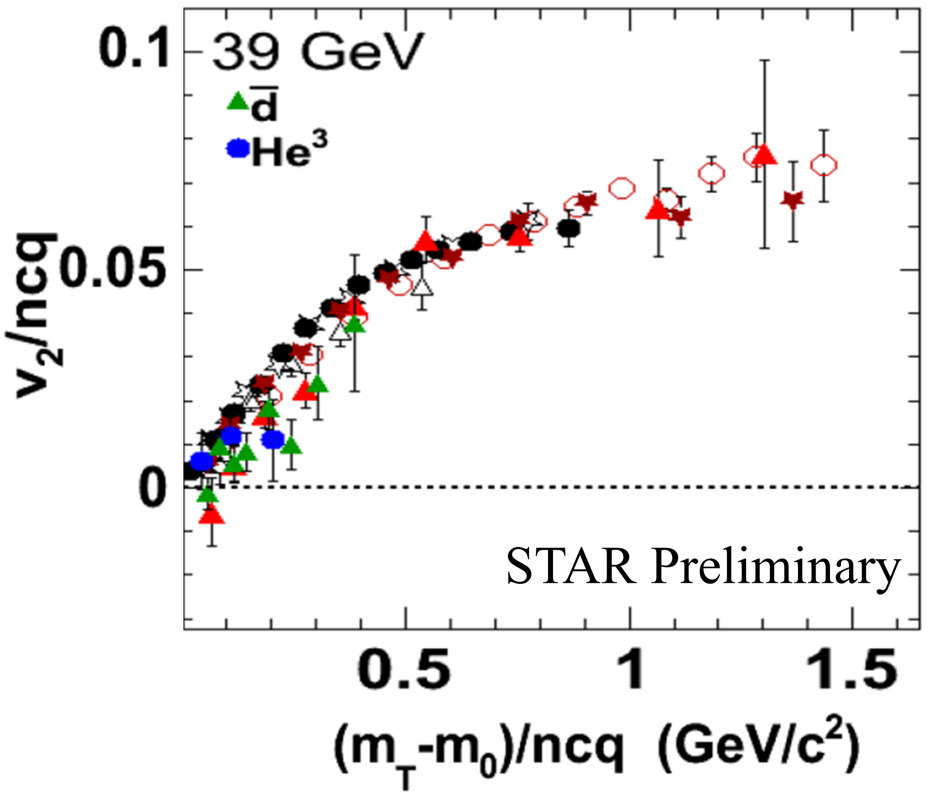
NA49, Phys. Rev. C 78 (2008) 044907

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

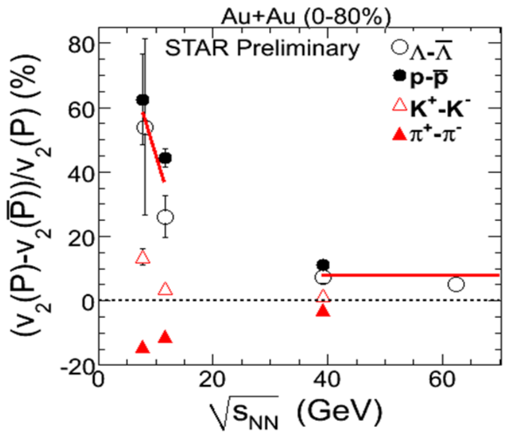
Summary and outlook

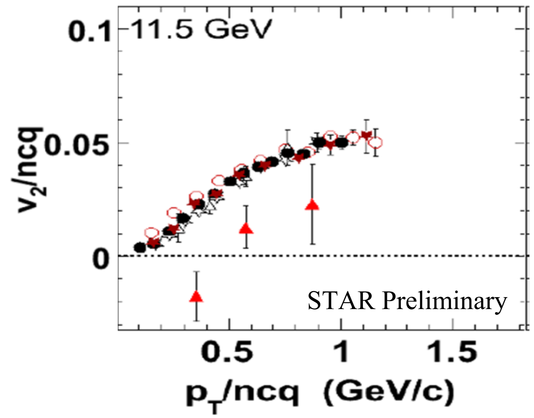
- STAR preliminary v_2 results in $\sqrt{s}$ = 7.7, 11.5 and 39 GeV Au+Au collisions have been presented

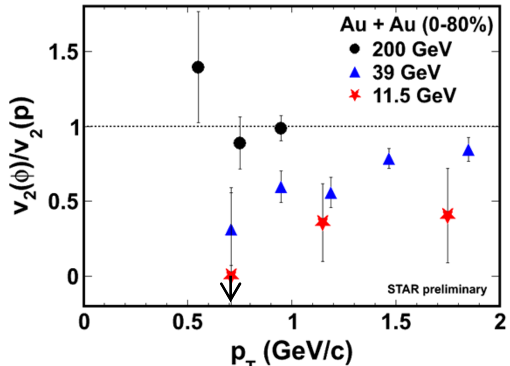
- NCQ-scaling between particles and anti-particles is broken @ 11.5 and 7.7 GeV

- ϕ meson v_2 falls off the trend from other hadrons at 11.5 GeV → **indicates collectivity contribution from partonic interactions decreases with decrease in center of mass energy**

- Outlook
  19.6 GeV data is under processing, 27 GeV data will be taken at the end of Run 2011



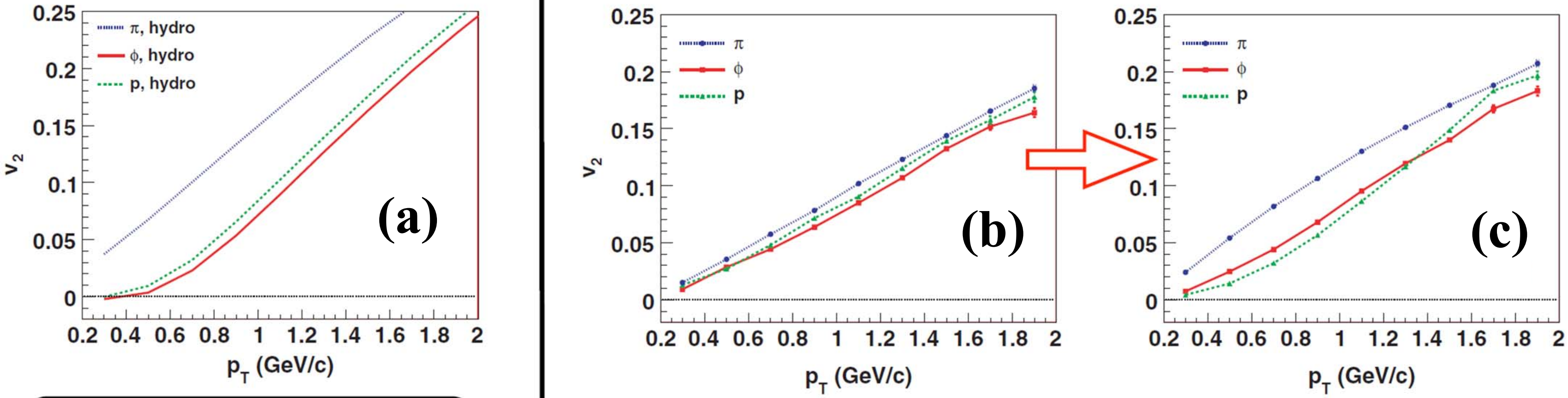




Backup

Mass ordering violation for ϕ meson v_2?

at kinetic freeze-out | at chemical freeze-out | at kinetic freeze-out



Ideal hydro

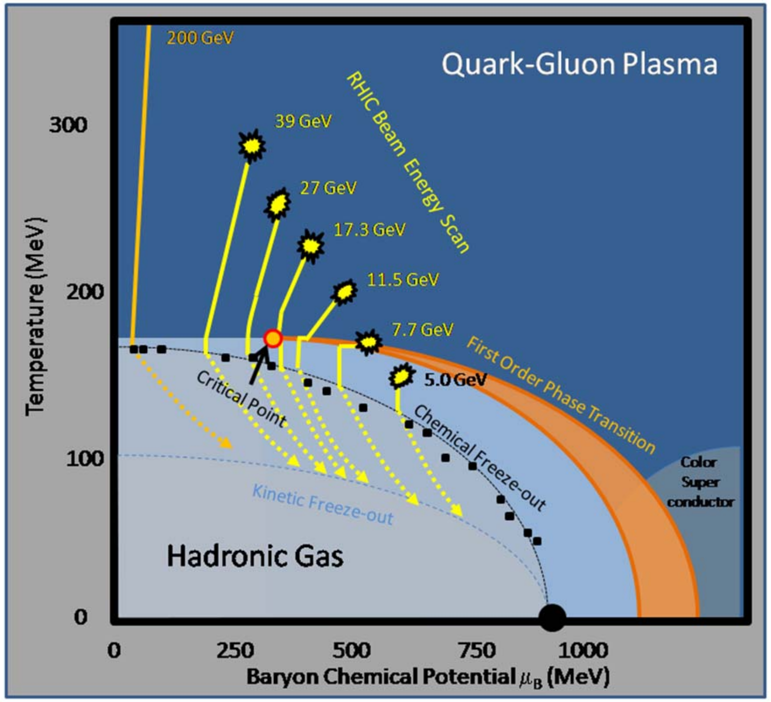
Ideal hydro
+ hadron cascade

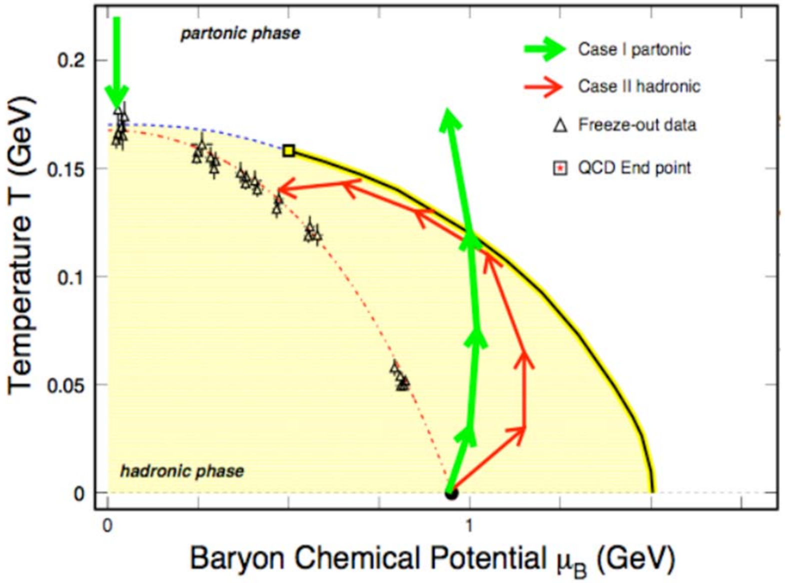
T. Hirano et al.,
Phys. Rev. **C**77, 044909 (2008)

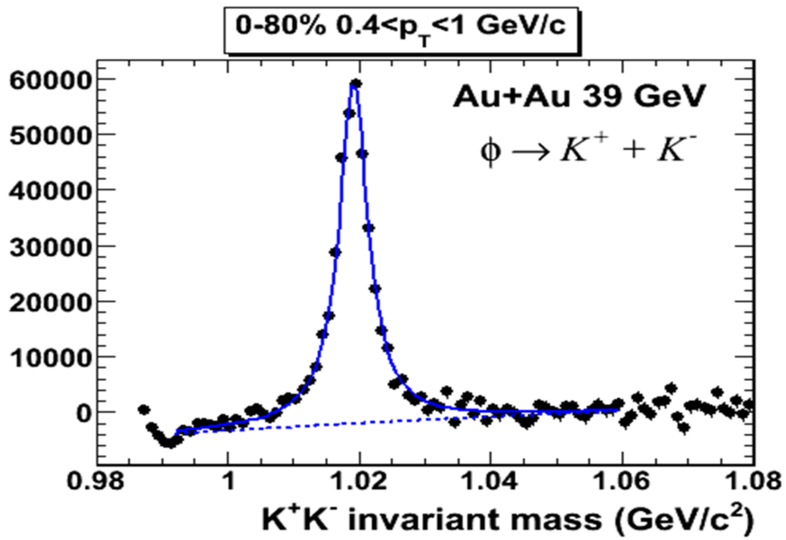
- (a) **ideal hydro: mass ordering for ϕ meson v_2**
  (c) **ideal hydro + hadronic rescatterings: violation of mass ordering for ϕ meson v_2** due to small hadronic cross section of ϕ
- **Comparison of ϕ meson v_2 to proton v_2 is useful for understanding the effect of the hadronic phase**

Outlook ─ Beam Energy Scan at STAR

Mapping QCD phase diagram with multi-strange hadrons v_2







Nu Xu et al., SQM 2009 presentation