Collectivity in High-Energy Nuclear Collisions at RHIC and LHC

Workshop on QCD Thermodynamics
in High-Energy Collisions
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College of Physical Science and Technology
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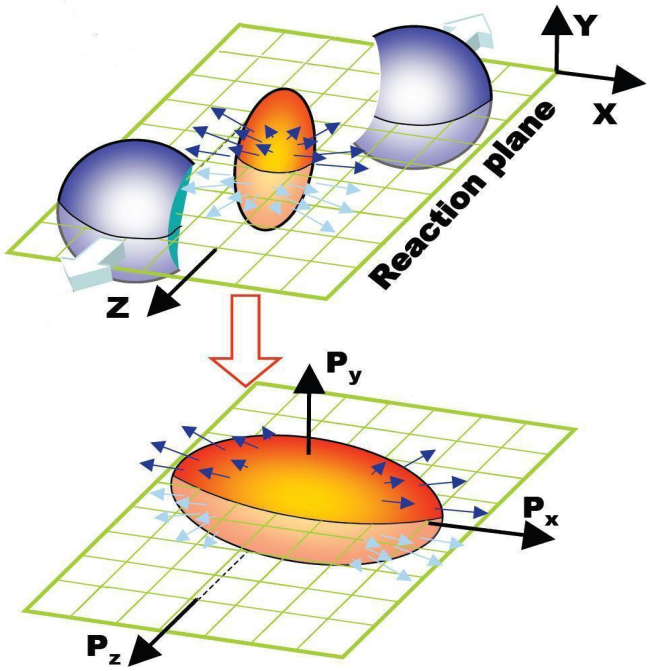
Outline

- Introduction
- Multi-strange hadron and ϕ meson flow
- Comparison to hydro
- Number of constitute quark scaling
- Energy dependence
- Summary

Elliptic Flow (v_2)

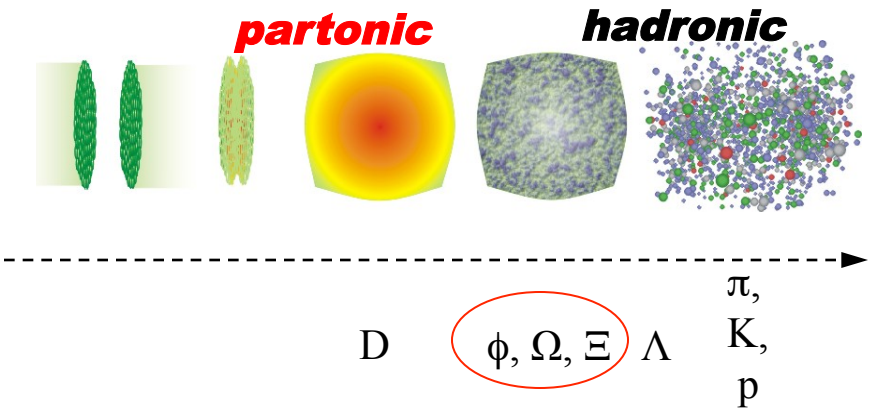


$$\varepsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >} \Rightarrow v_2 = < \cos 2\varphi >, \quad \varphi = \tan^{-1}(\frac{p_y}{p_x})$$

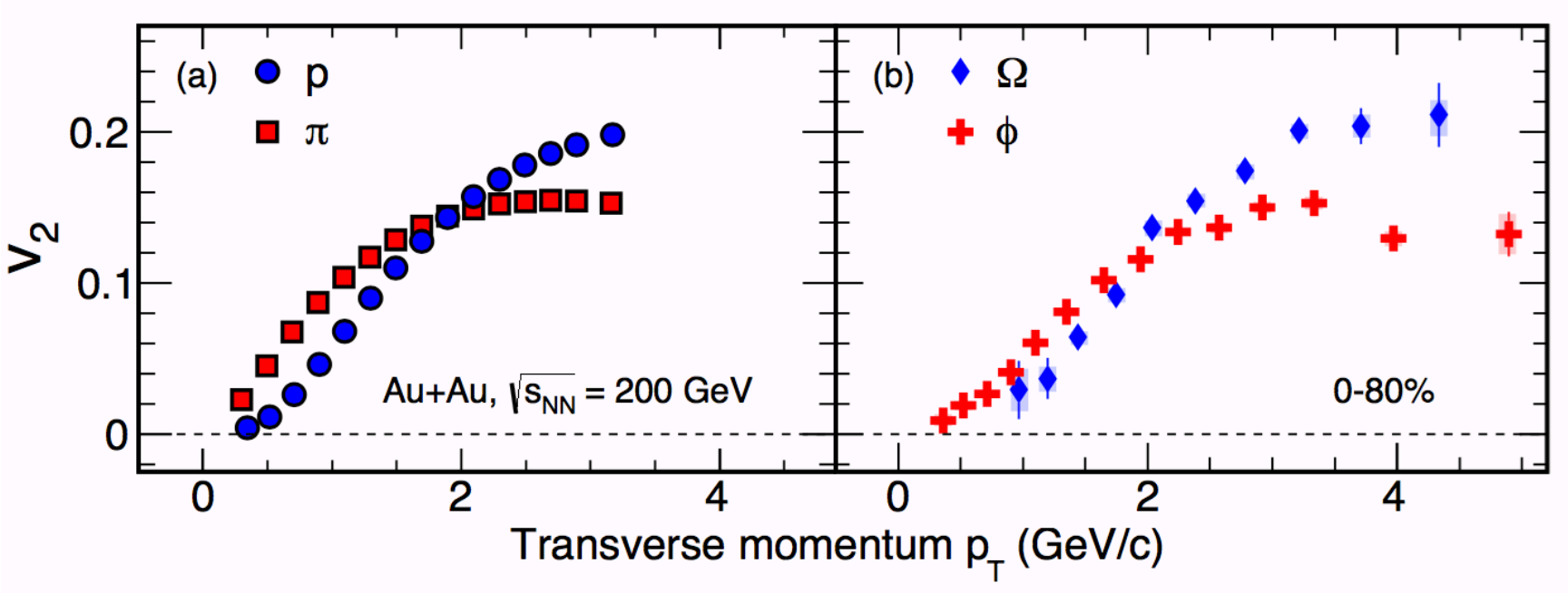
- **Elliptic flow =>**
- Initial spatial anisotropy (eccentricity ε)
  - ->Final momentum anisotropy v_2
    - ➔ Interactions among constituents
      - Sensitive to degree of thermalization
- Self-quenching with time
  - Sensitive to the early stages of the system evolution
- **Multi-strange hadrons and ϕ meson =>**

  Less sensitive to late hadronic rescattering

Probe of the early (partonic) stage of the collision.



Partonic Collectivity

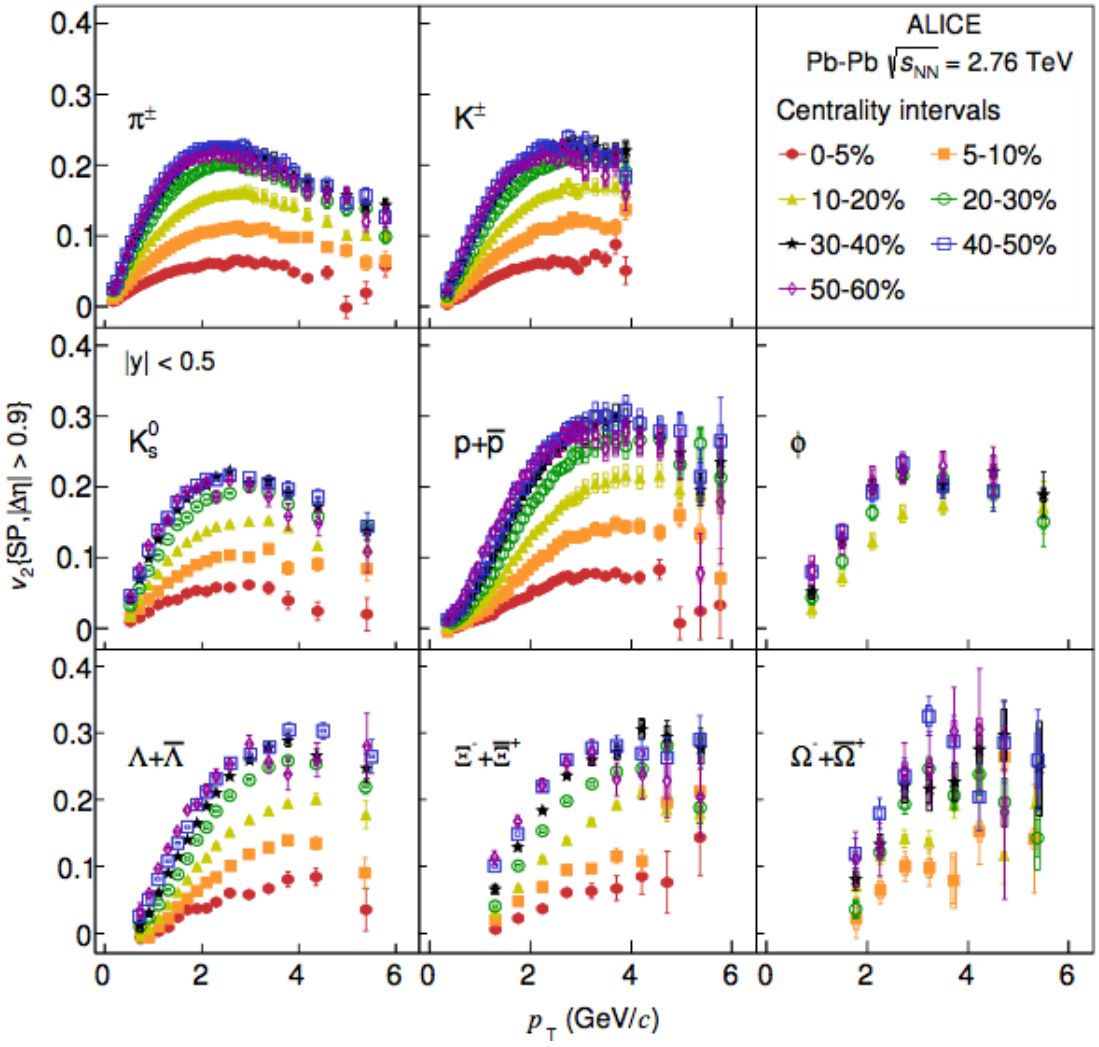


SQM2015, arxiv:1507.05247

- **Mass ordering when p_T < 2 GeV/c**
- **Baryon/meson splitting when 2 < p_T < 5 GeV/c**

High precision data prove that Ω follows the baryon/meson splitting.
First time!

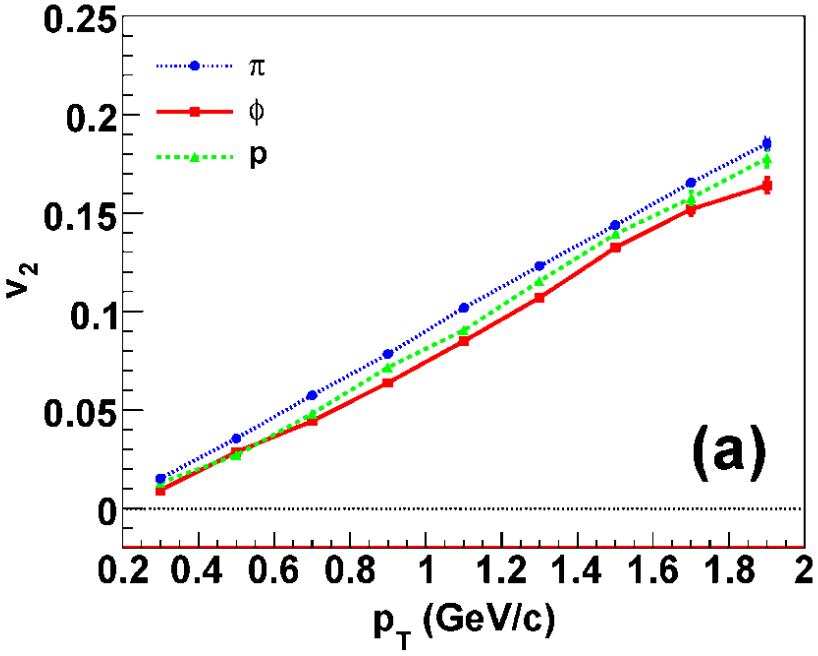
Partonic Collectivity



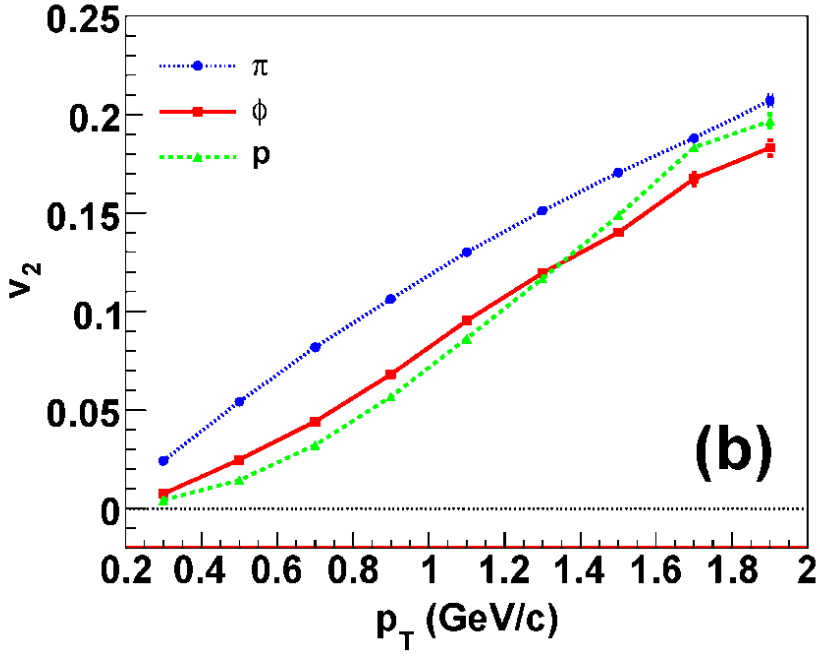
Significant flow signals for multi-strange hadrons

JHEP06(2015)190

Mass Ordering for ϕ-mesons



Before hadronic rescattering

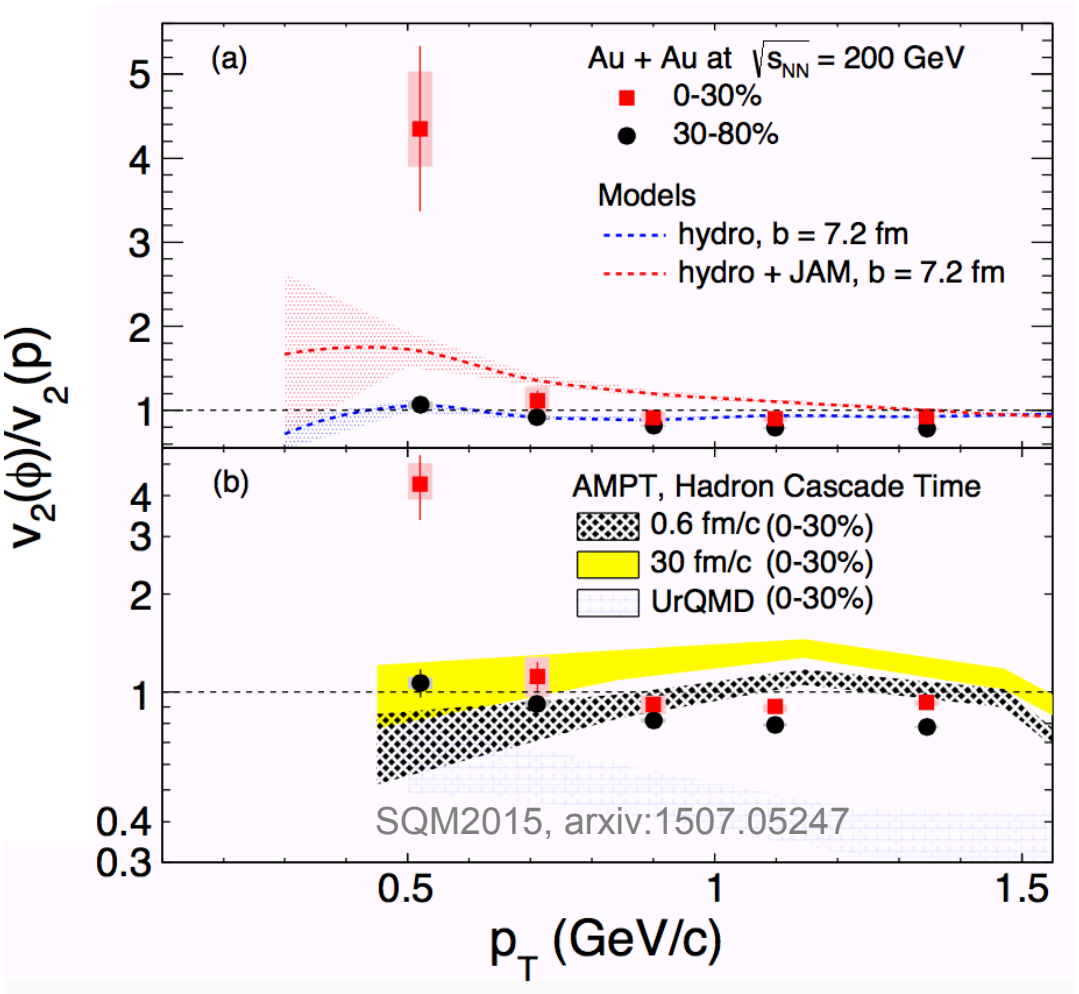


After hadronic rescattering

T. Hirano et al., ; PRC77, 044909 (2008)

- **Ideal hydro + hadron cascade**
- **Small hadron cross section + hadronic rescattering effect on v_2**
  Mass ϕ > mass p ➔ $v_2(\phi) > v_2(p)$
  ➔ ***Break mass ordering for ϕ meson***

$v_2(\phi)$ versus $v_2(p)$

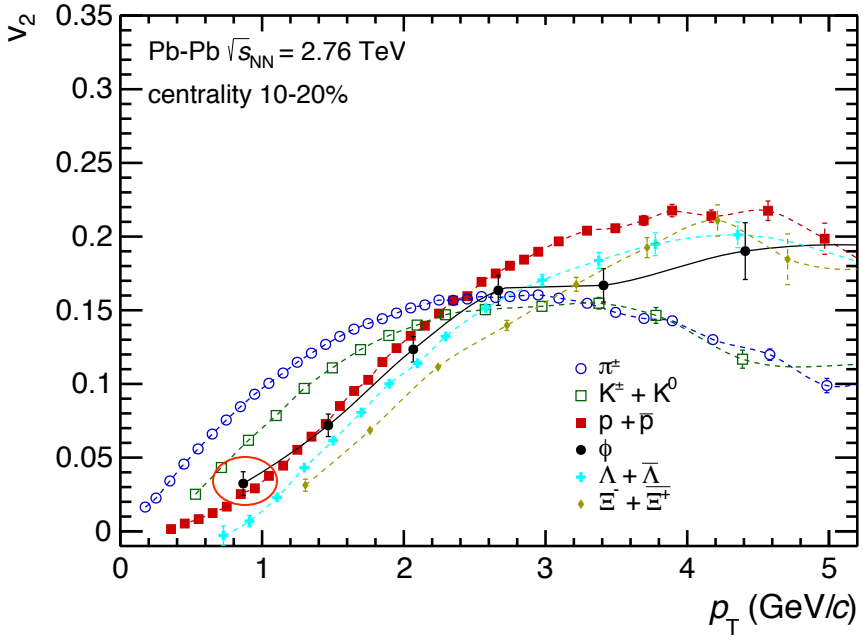


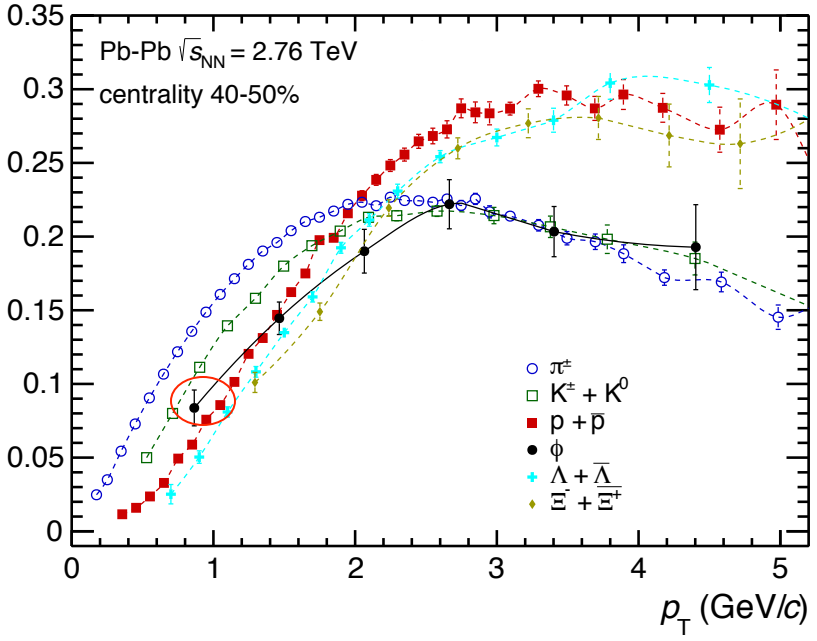
- **Model study indicates with increasing hadronic cascade time (more hadronic re-scattering), the $v_2(\phi)/v_2(p)$ ratio increases**

- **The ratio $v_2(\phi)/v_2(p)$ Is $4.35 \pm 0.98 \pm^{0.66}_{0.45}$ at p_T = 0.52 GeV/c in 0-30% ->**

Possibly due to the effect of late hadronic interactions on the proton v_2

$v_2(\phi)$ versus $v_2(p)$





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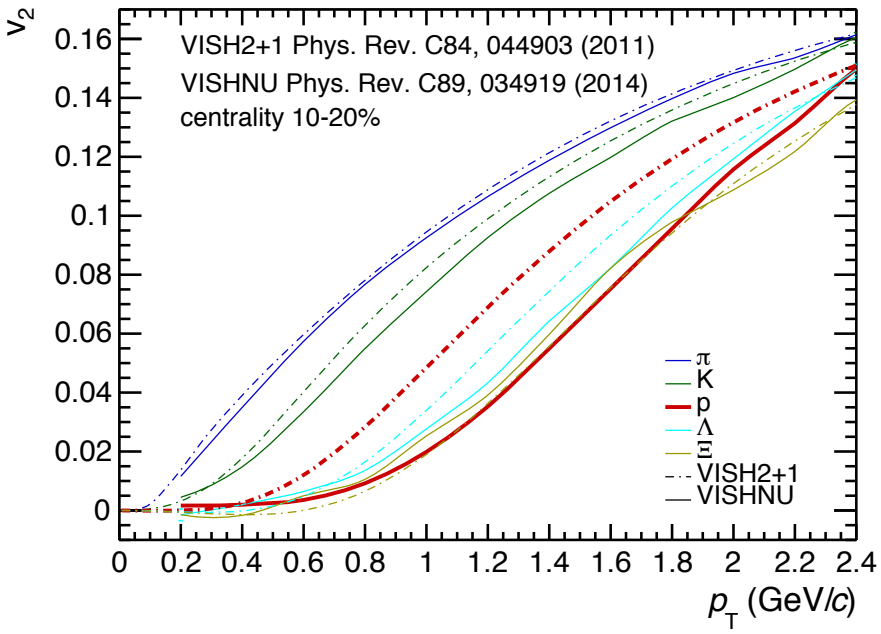
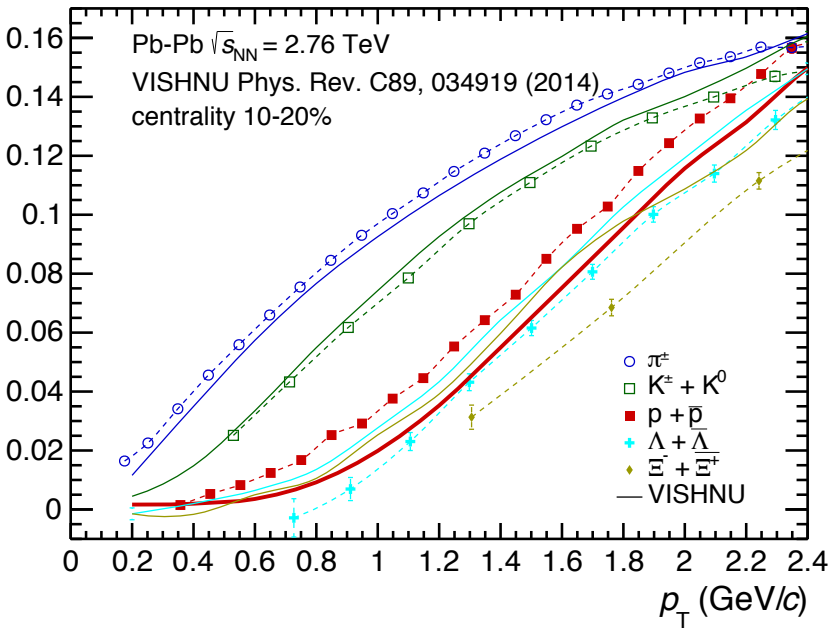
- **There is an indication that the ϕ meson v_2 is larger than the proton v_2 for the lowest p_T bin.**
- **Currently the uncertainties are too large**

Comparison to Hydro





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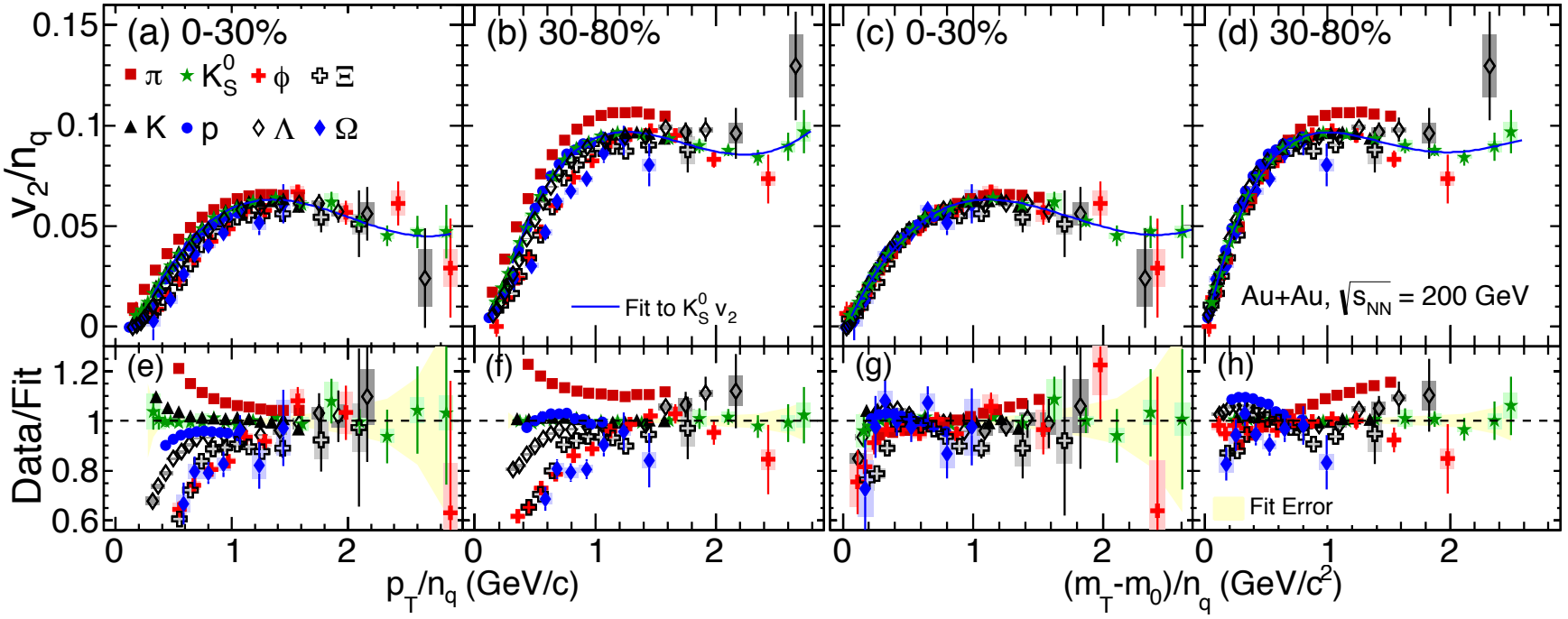
- **Hydro calculations fail to reproduce the baryon v_2 data -> indicates the contributions from the hadronic phase are not understood yet**

NCQ Scaling - RHIC

arxiv:1507.05247

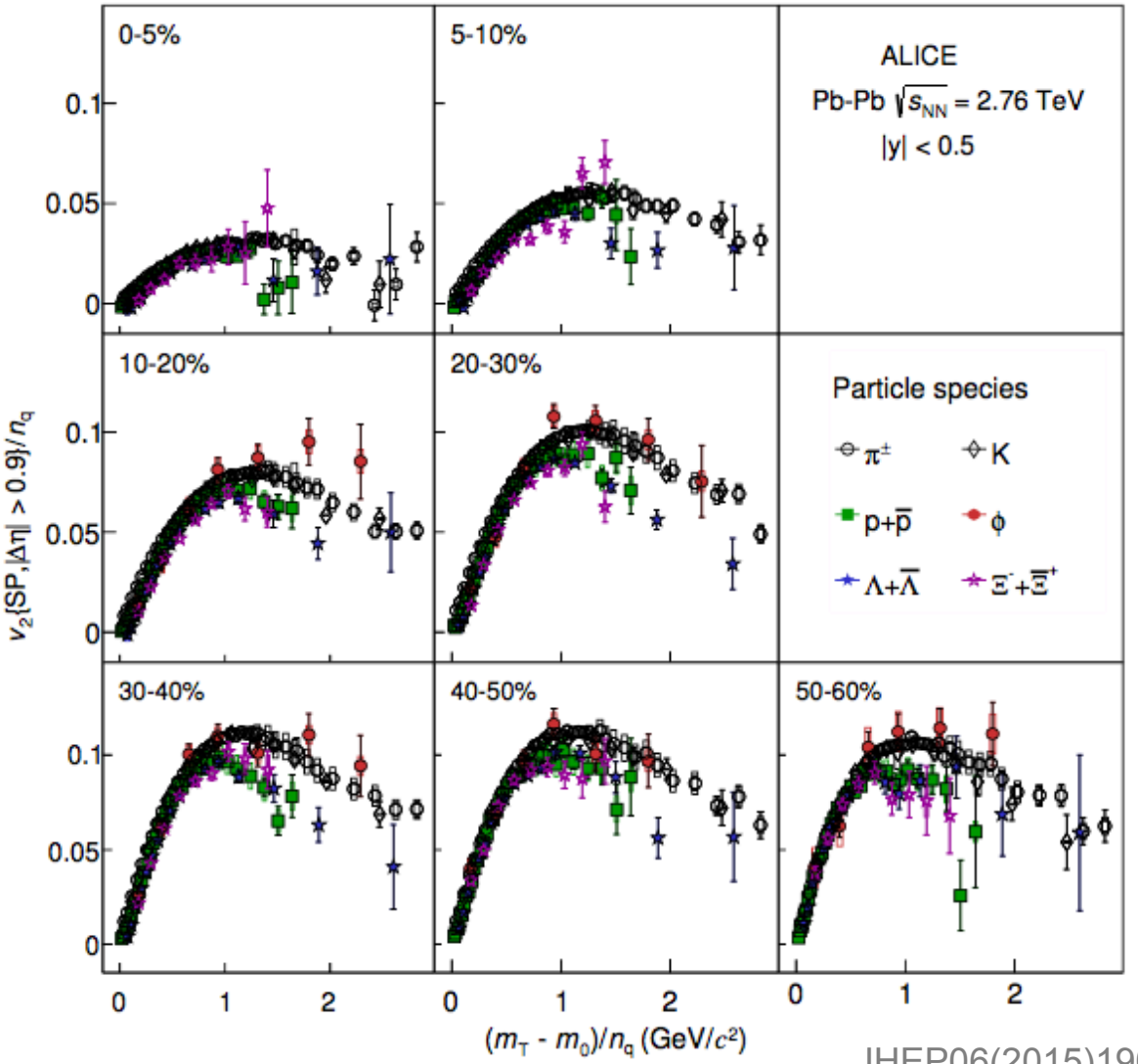


Deviation from the K^0_S fit line in the range $(m_T - m_0)/n_q > 0.8$ GeV/c^2 for 0-30% and 30-80% centrality.

Particle	Deviation	
	0-30% centrality	30-80% centrality
ϕ	2.7±2.6(stat.)±1.8(sys.)%	1.2±1.3(stat.)±0.6(sys.)%
Λ	4.3±0.8(stat.)±0.2(sys.)%	1.5±0.7(stat.)±0.2(sys.)%
Ξ	11.3±2.3(stat.)±1.4(sys.)%	8.5±2.0(stat.)±0.5(sys.)%
Ω	10.1±8.4(stat.)±5.3(sys.)%	7.0±6.0(stat.)±1.5(sys.)%

- **NCQ scaling holds within 10%**

NCQ Scaling - LHC



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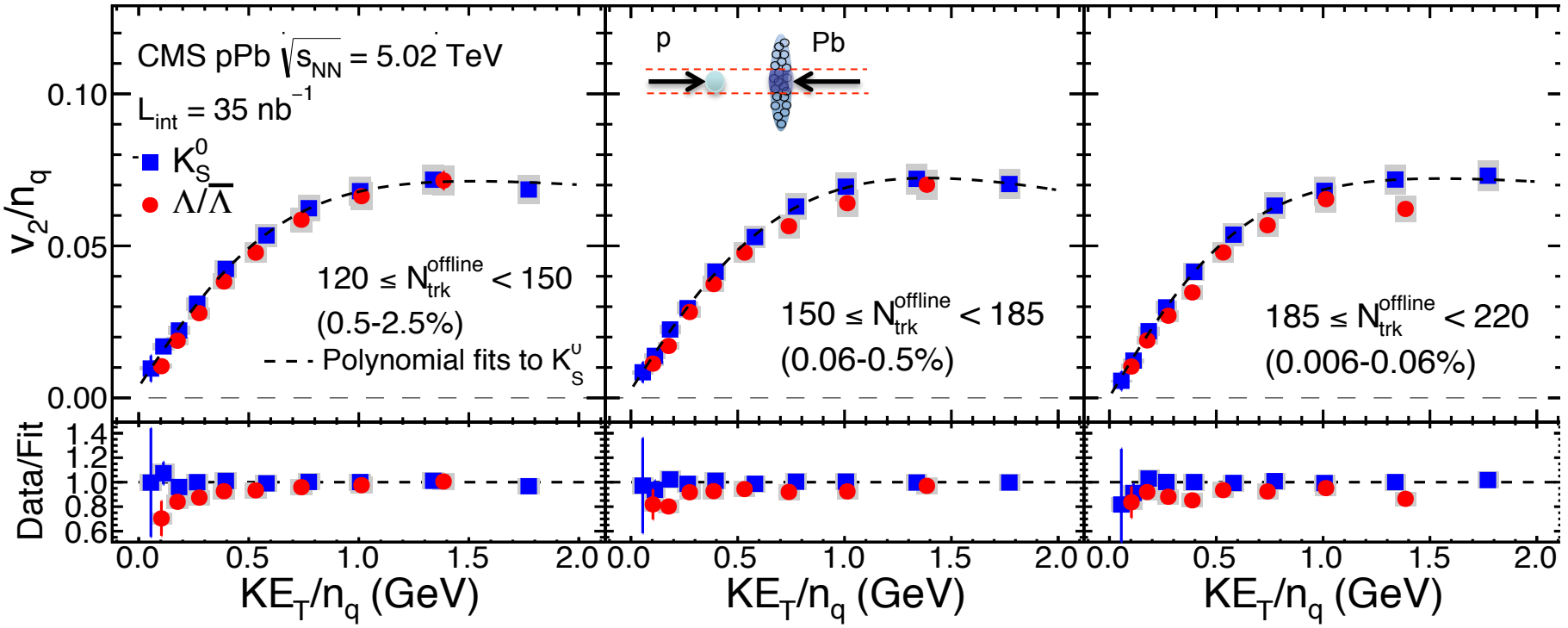
- **The deviation from the NCQ scaling at the level of +/-20%**
- **Better NCQ scaling at RHIC -> indicates coalescence is the dominant hadronization mechanism at RHIC in the intermediate p_T range**

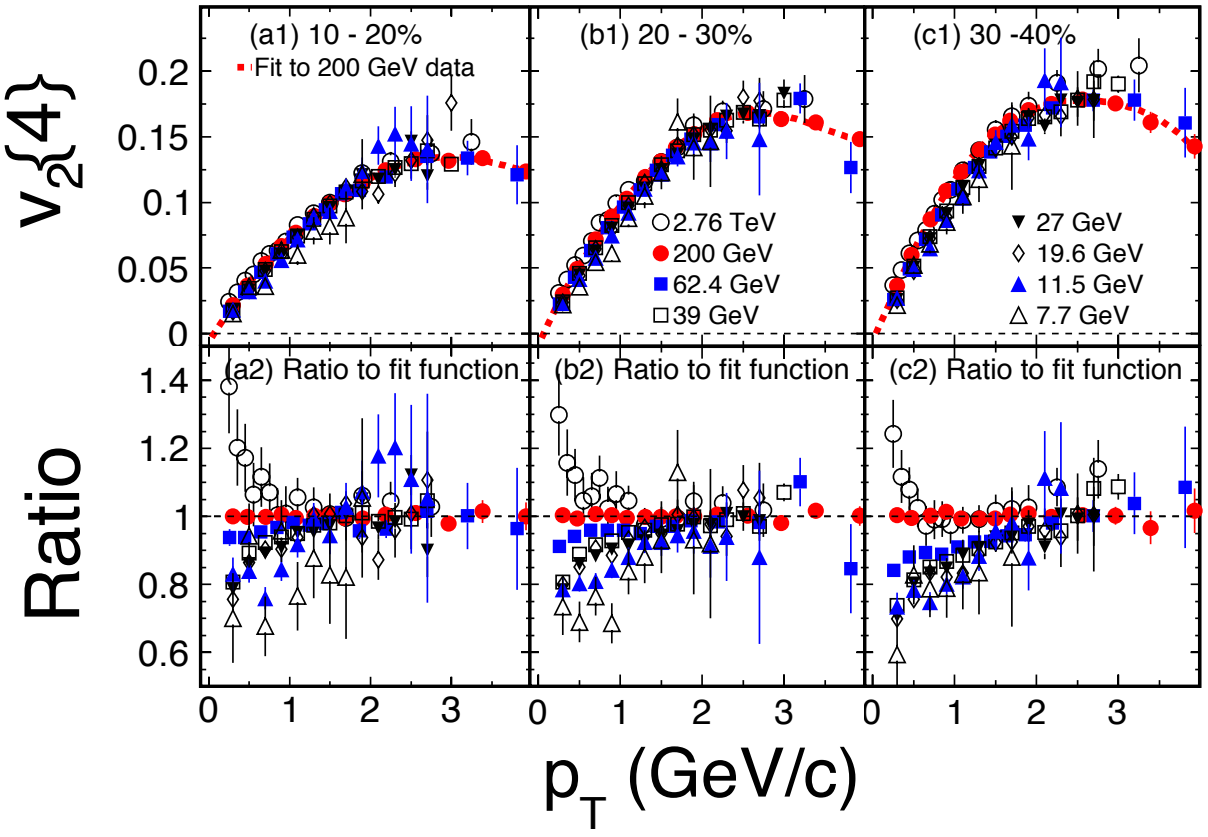
NCQ Scaling - pPb

SQM2015, PLB 7 42 (2015) 200



- **NCQ scaling observed for K_S^0 and Λ v_2**
- **Partonic collectivity at small colliding system?**

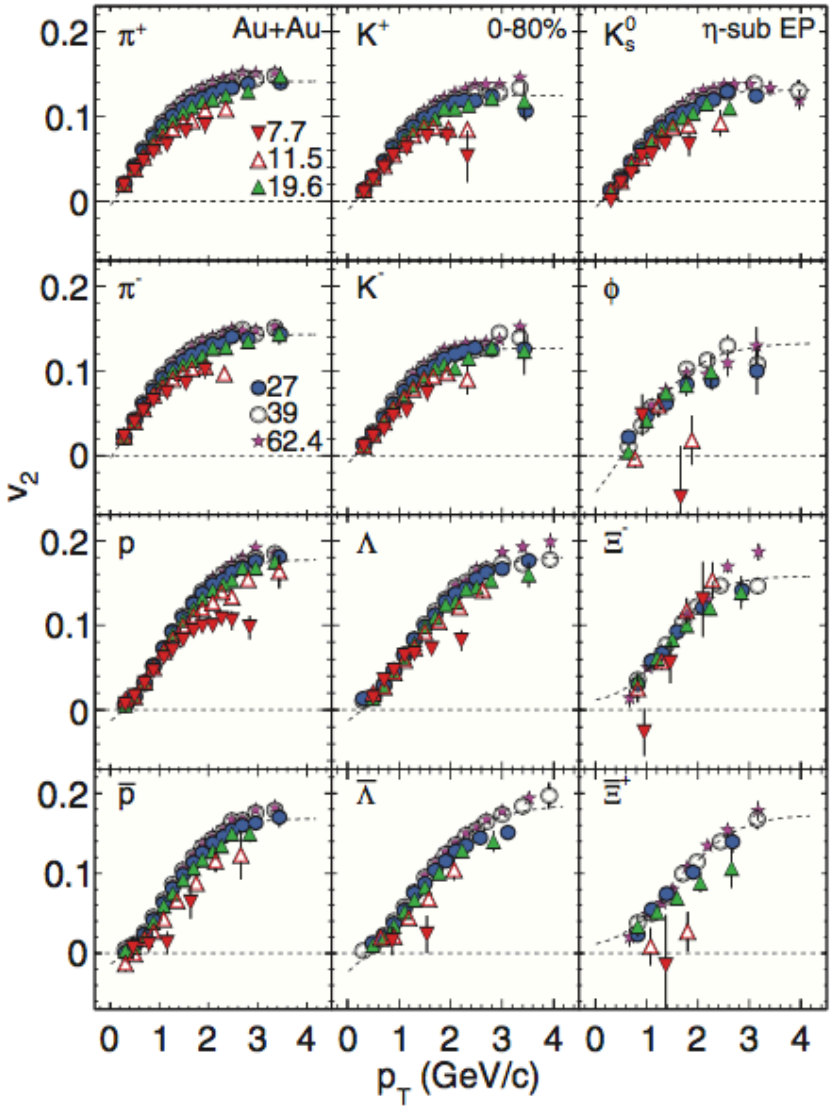
Energy Dependence



- **$v_2\{4\}$ results**
- Three centrality bins
- **Consistent $v_2(p_T)$ from 7.7 GeV to 2.76 TeV for p_T > 2 GeV/c**
- **p_T< 2GeV/*c***
- The v_2 values rise with increasing collision energy -> Large collectivity? Particle composition?

STAR: Phys. Rev. C 86, 054908 (2012)
ALICE: Phys. Rev. Lett. 105, 252302 (2010)

Energy Dependence

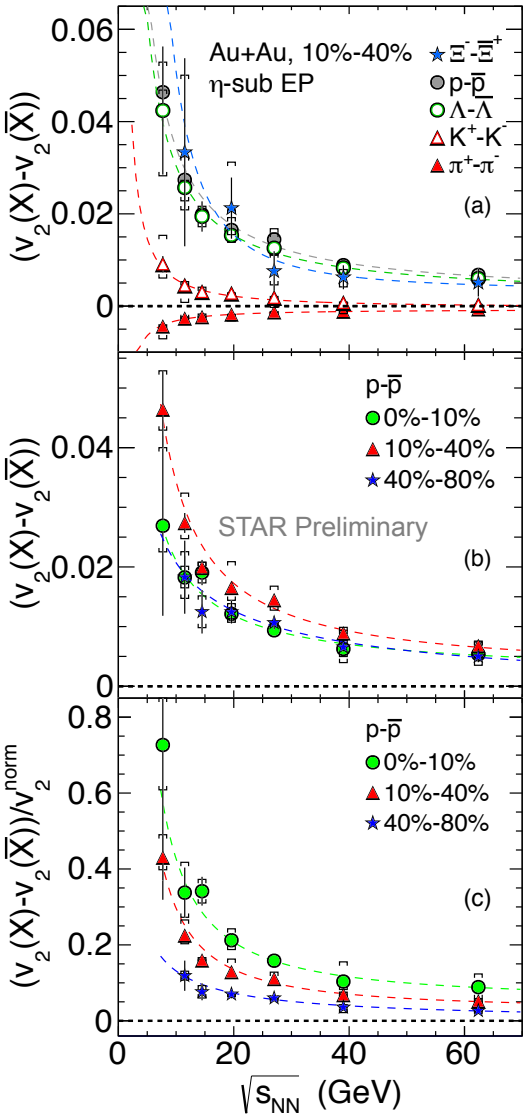


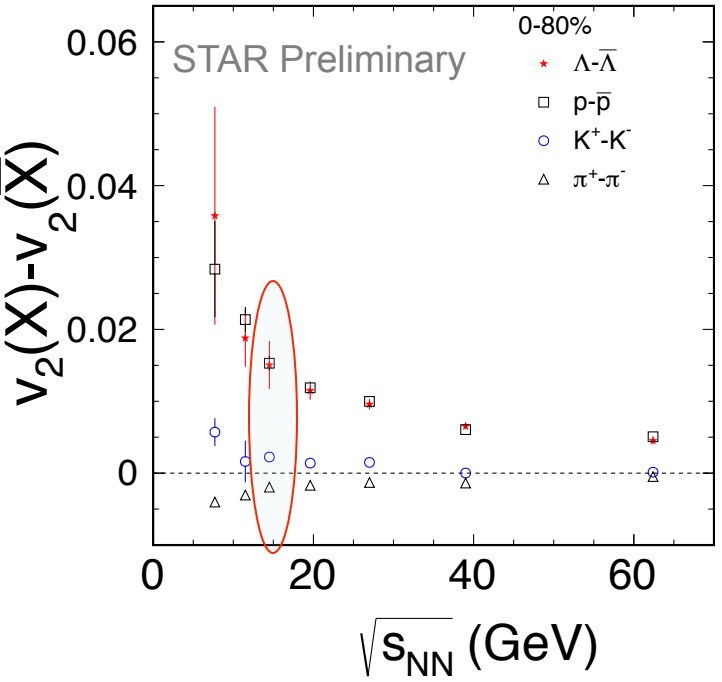
STAR: Phys. Rev. C 88, 014902 (2013)

- **Similar $v_2(p_T)$ shape for PID**
- **A more realistic theoretical approach required**

  such as three-dimensional viscous hydro + hadronic phase with a consistent EOS at nonzero baryon chemical potential

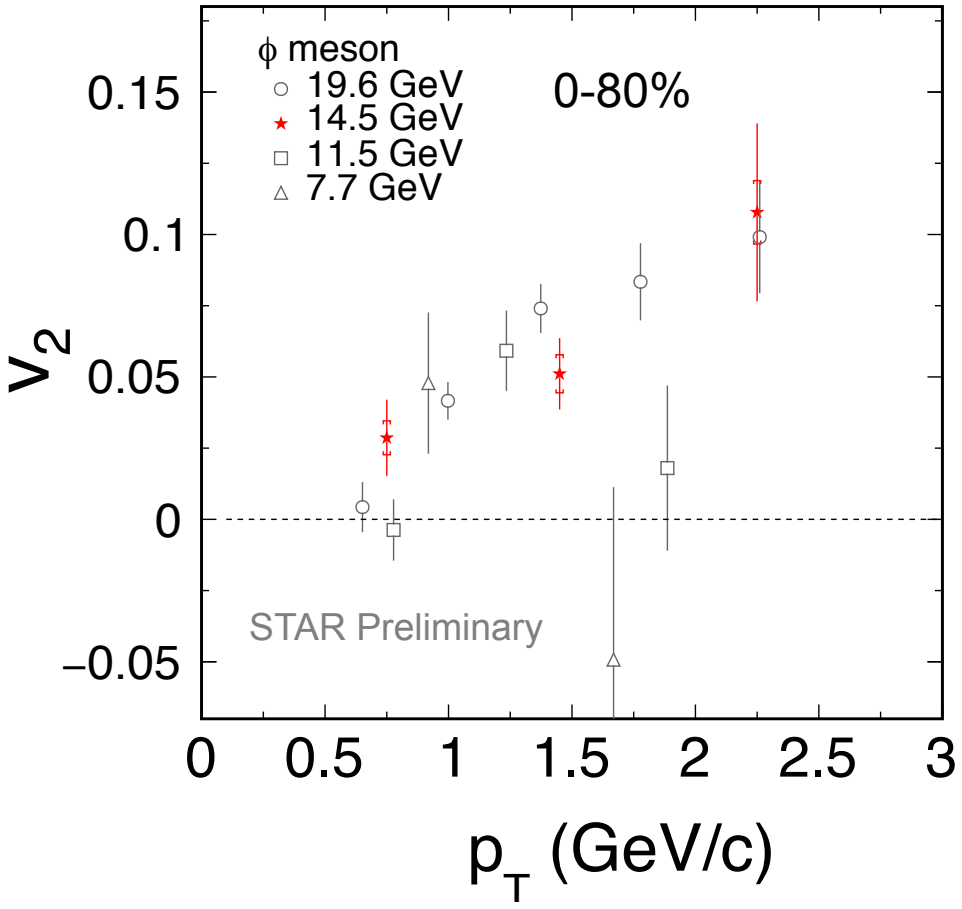
Particle vs. Anti-particle





- **Significant difference of baryon and anti-baryon v_2 observed**
- **New data from 14.5 GeV fit the energy dependency curve**

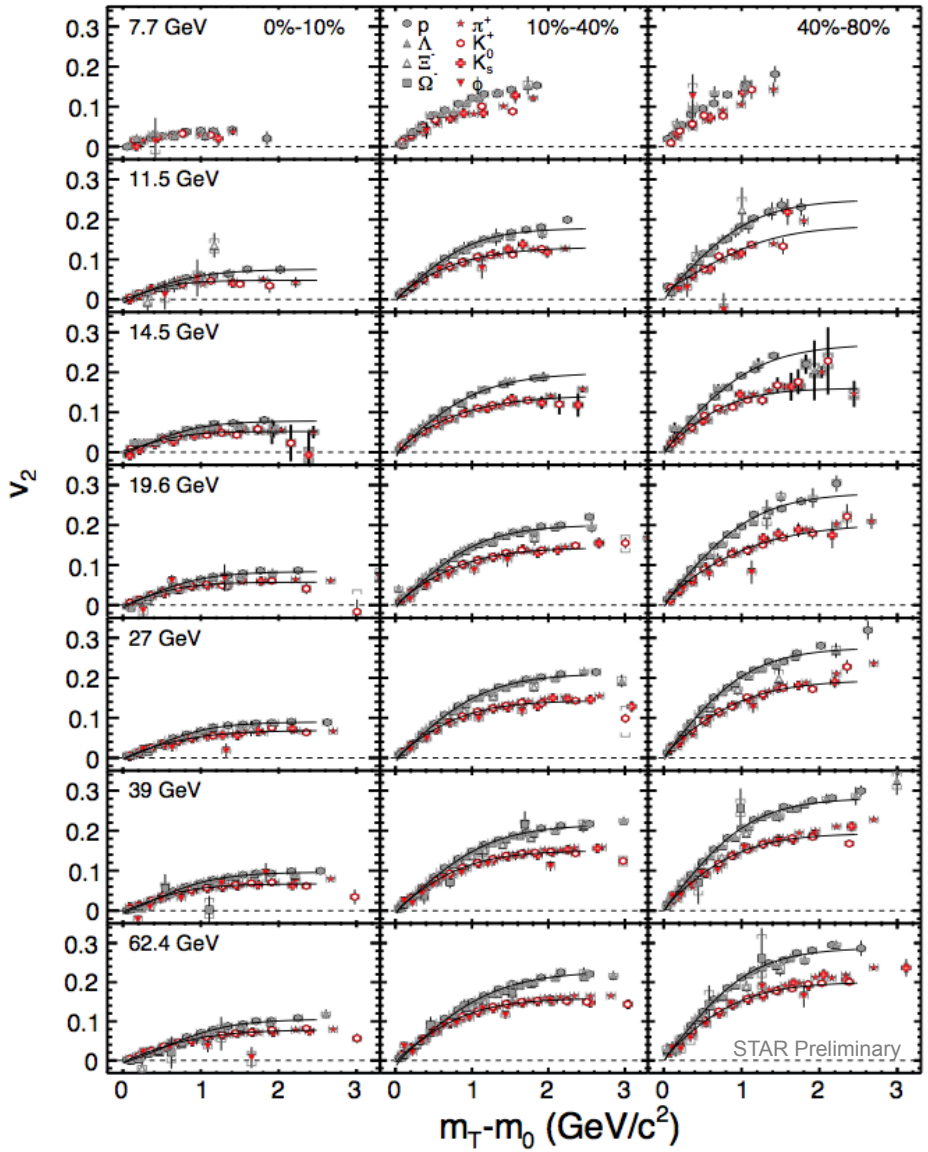
ϕ Meson v_2



Sizable ϕ meson v_2: comparable to 19.6 GeV

High statistics and more energies below 20 GeV needed!

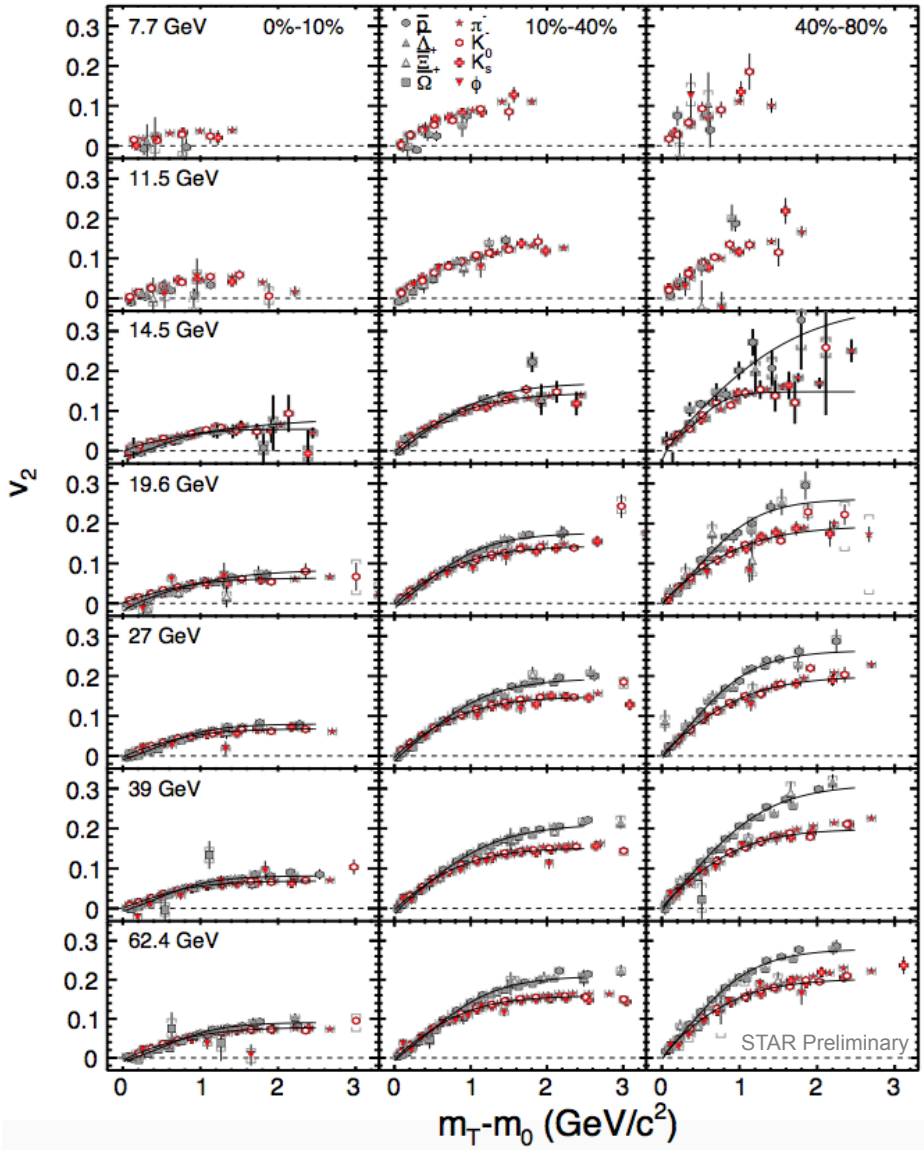
Baryon/Meson Separation



A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.

At 7.7 GeV we are limited by the statistics number of events.

Baryon/Meson Separation



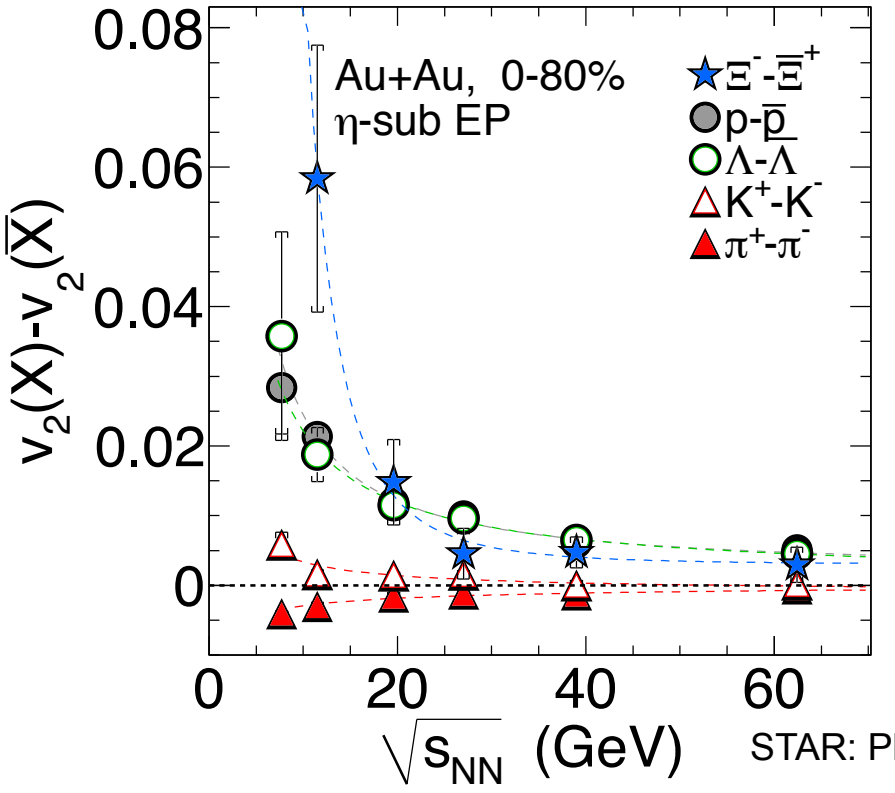
The splitting between baryons and mesons is observed significant for all energies above 14.5 GeV and also at 14.5 GeV for 40%–80%.

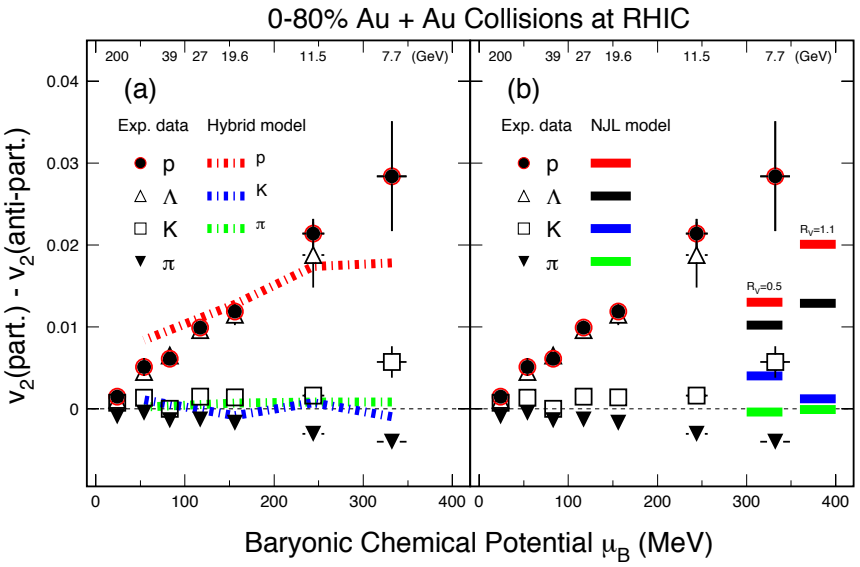
For these energies below 11.5 GeV, we are limited by the number of events.

Summary

- **Multi-strange hadron v_2 -> *Partonic collectivity***
- **Comparison to hydro -> *Contributions from the hadronic phase are not understood***
- **NCQ scaling-> *Hadronization mechanism***
- **Energy dependence-> *Similar $v_2(p_T)$ shape from 7.7 - 2760 GeV***
- **Beam Energy Scan program-> *Explore the QCD phase structure***

Particle vs. Anti-particle v_2





STAR: Phys. Rev. Lett. **110** (2013) 142301

- The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks
- Model comparison
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent

J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(2013); J. Xu, et al., PRL112, 012301(2014)