



Elliptic Flow Measurements in Heavy-Ion Collisions at RHIC-STAR

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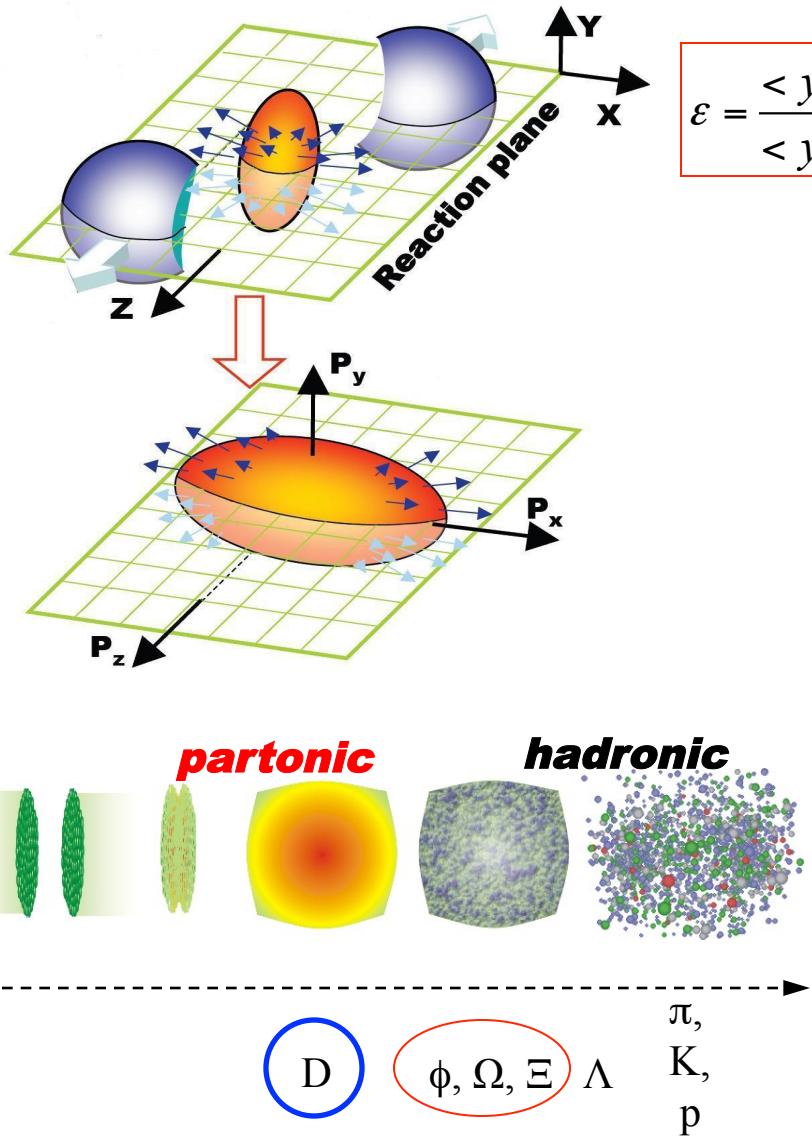
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Outline

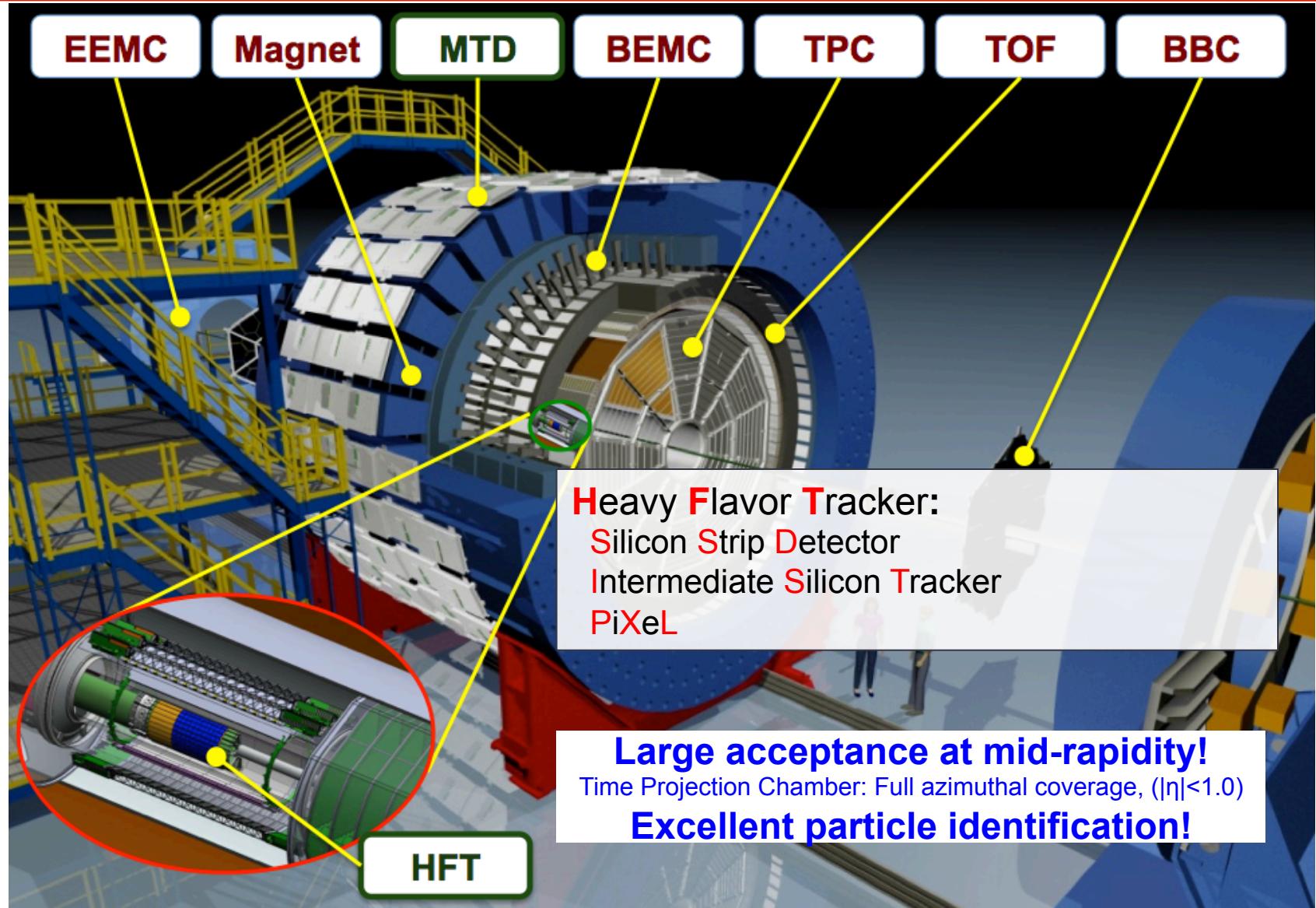
- **Introduction**
 - **Multi-strange hadron and ϕ meson flow**
 - **Heavy flavor flow**
 - **Number of constitute quark scaling**
 - **Beam energy scan**
 - **Summary**
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Elliptic Flow (v_2)

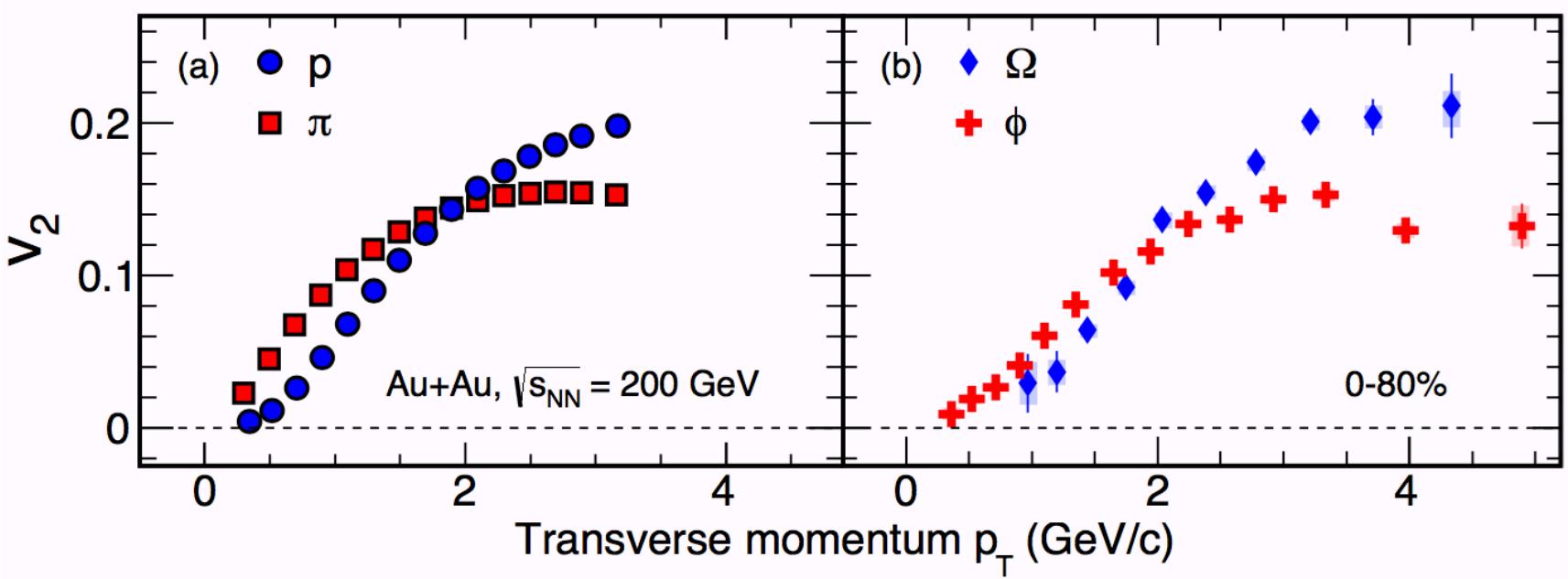


- **Elliptic flow =>**
- Initial spatial anisotropy $\epsilon \rightarrow$
Final momentum anisotropy v_2
➔ Interactions among constituents
- Self-quenching with time
 - Sensitive to the early stage of the system evolution
- **Multi-strange hadrons and ϕ meson**
Less sensitive to late hadronic interactions
- **Heavy flavor flow**
Extract medium properties from motion of heavy quarks in medium

STAR Detectors



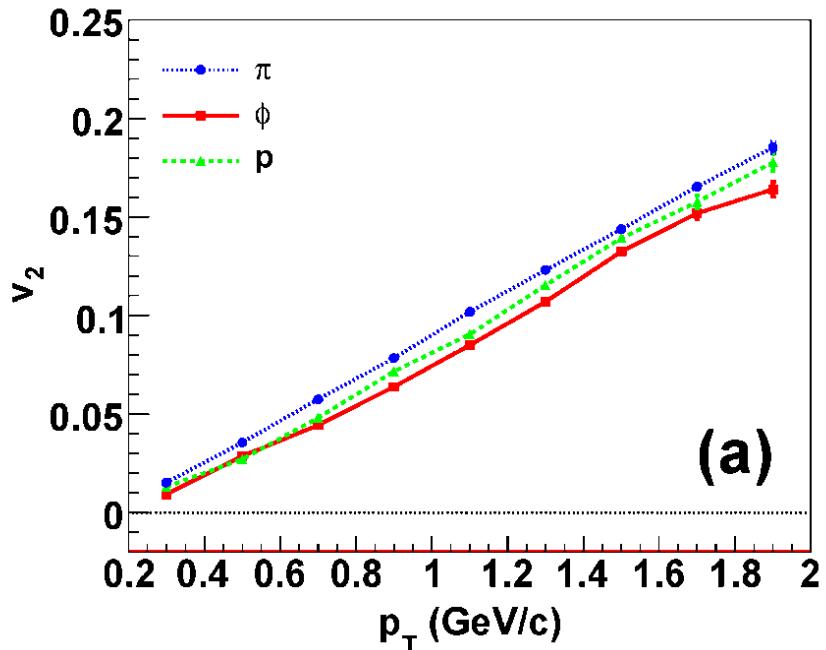
Partonic Collectivity



STAR: SQM2016, Phys. Rev. Lett. 116, 062301 (2016)

- 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!

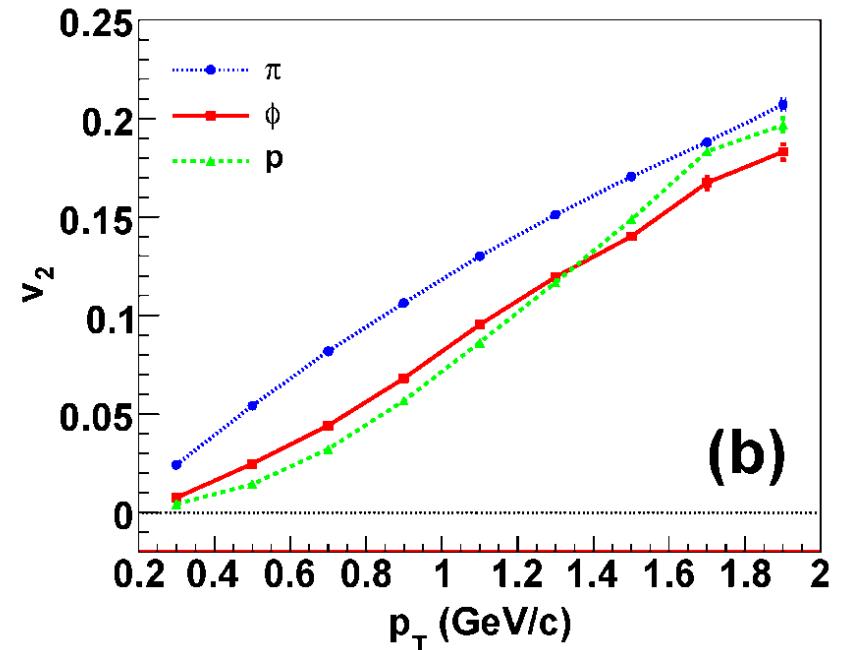
$v_2(\phi)$ versus $v_2(p)$



(a)

Before hadronic
rescattering

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



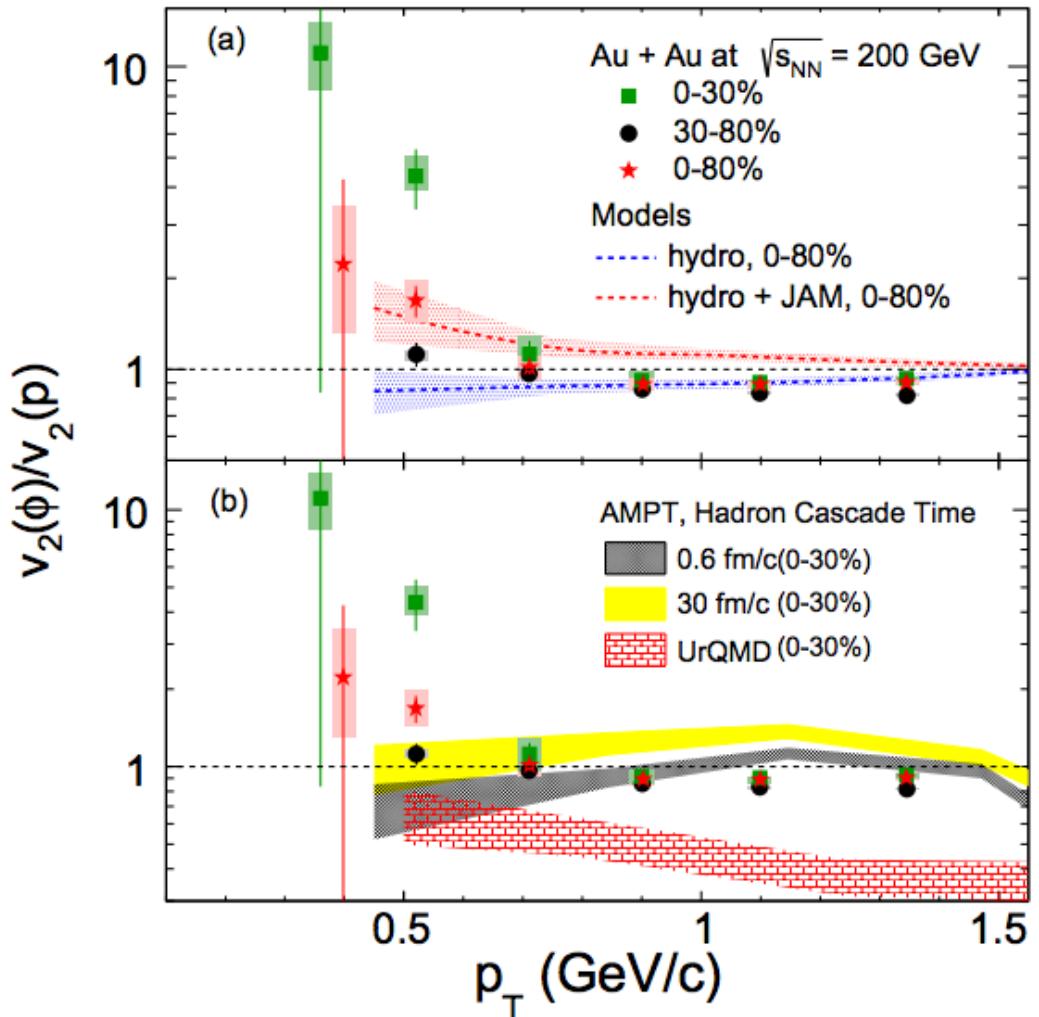
(b)

After hadronic
rescattering

- Ideal hydro + hadron cascade
- Small hadron cross section + hadronic rescattering effect on v_2
 $\text{Mass } \phi > \text{mass } p \rightarrow v_2(\phi) > v_2(p)$

→ Break mass ordering for ϕ meson

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

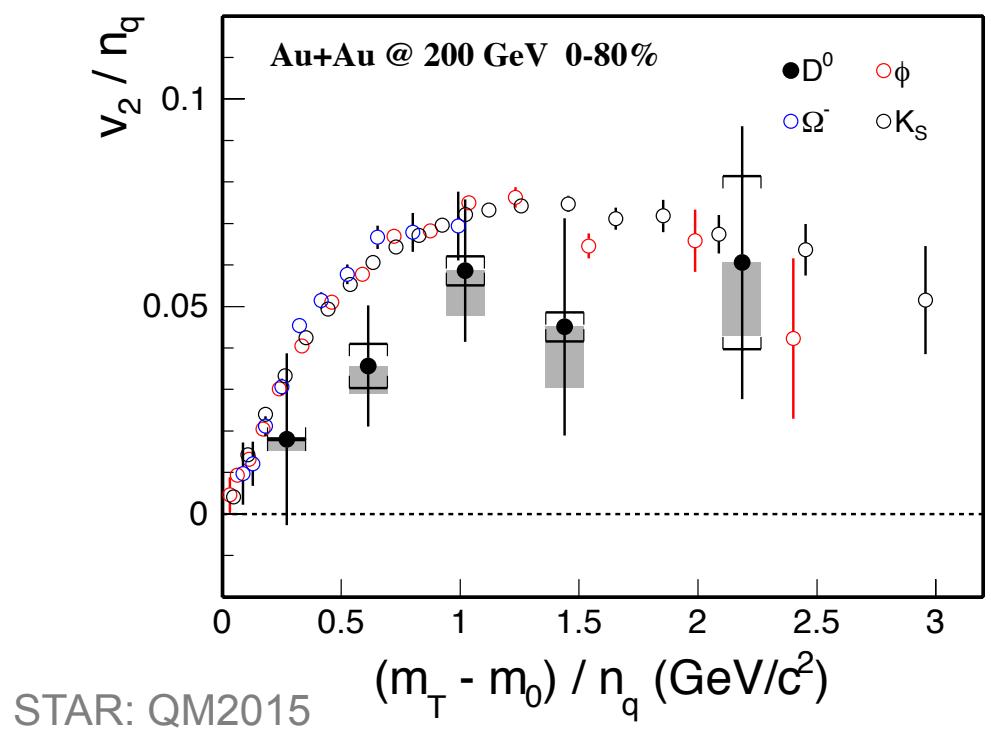
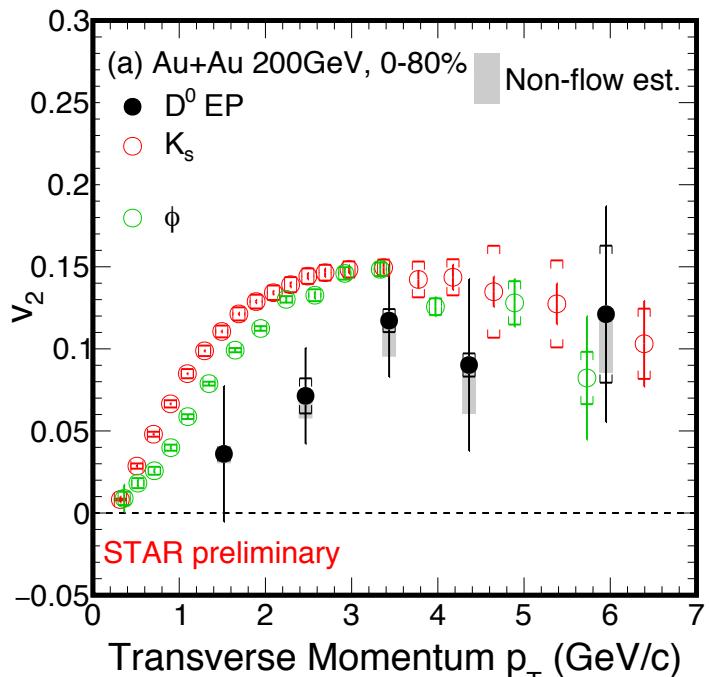


➤ Model study indicates with increasing hadronic cascade time (more hadronic re-scattering), the $v_2(\phi)/v_2(p)$ ratio increases

➤ The ratio $v_2(\phi)/v_2(p)$ is $4.35 \pm 0.98 \pm 0.66 \pm 0.45$ at $p_T = 0.52 \text{ GeV}/c$ in 0-30%
->
Possibly due to the effect of late hadronic interactions on the proton v_2

STAR: SQM2016, Phys. Rev. Lett. 116, 062301 (2016)

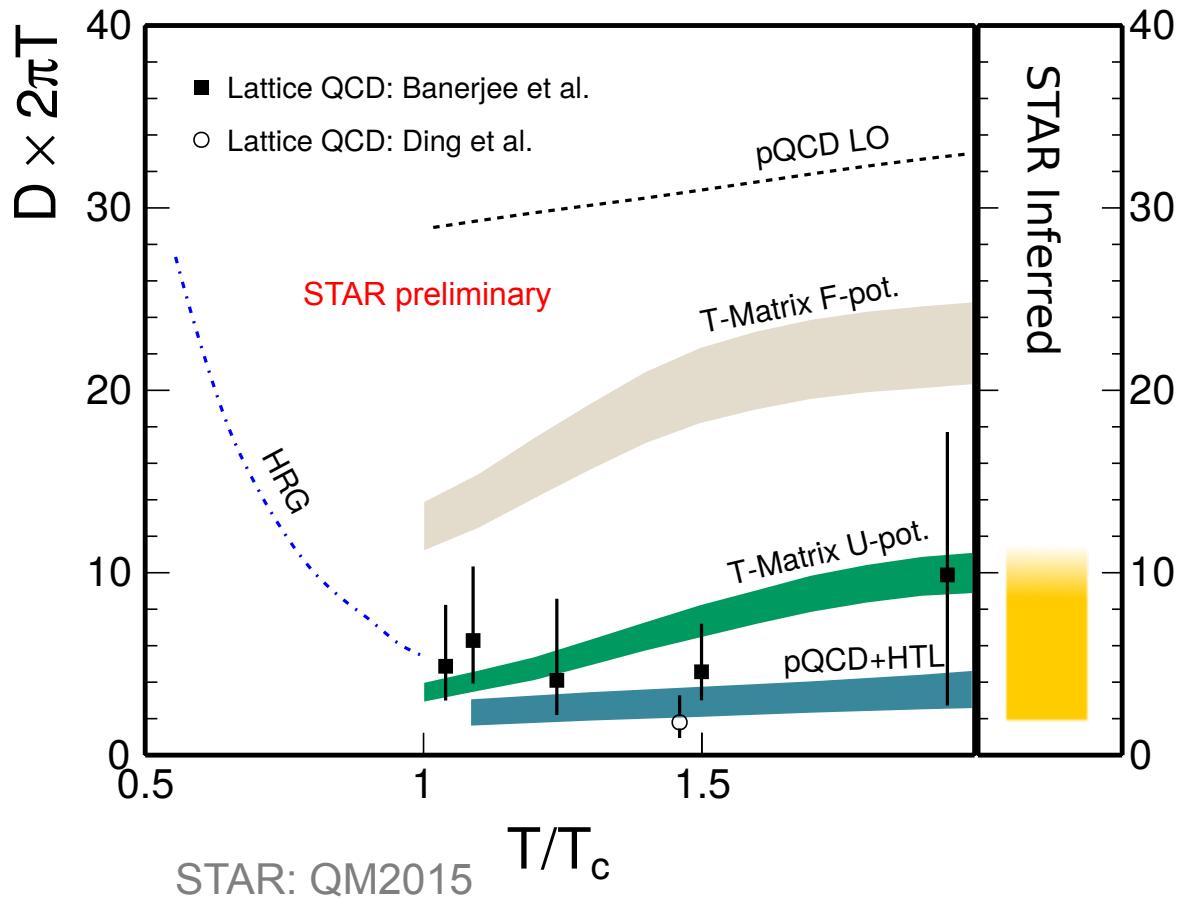
D Meson v_2 at RHIC



- Finite charm hadron v_2 at $p_T > 2$ GeV/c Thank Heavy Flavor Tracker!
- $v_2(D) < v_2(K_S, \phi)$ at $p_T < 3$ GeV/c
- v_2/n_q vs. $(m_T - m_0)/n_q$: indication of D meson lower than K_S, ϕ, Ω

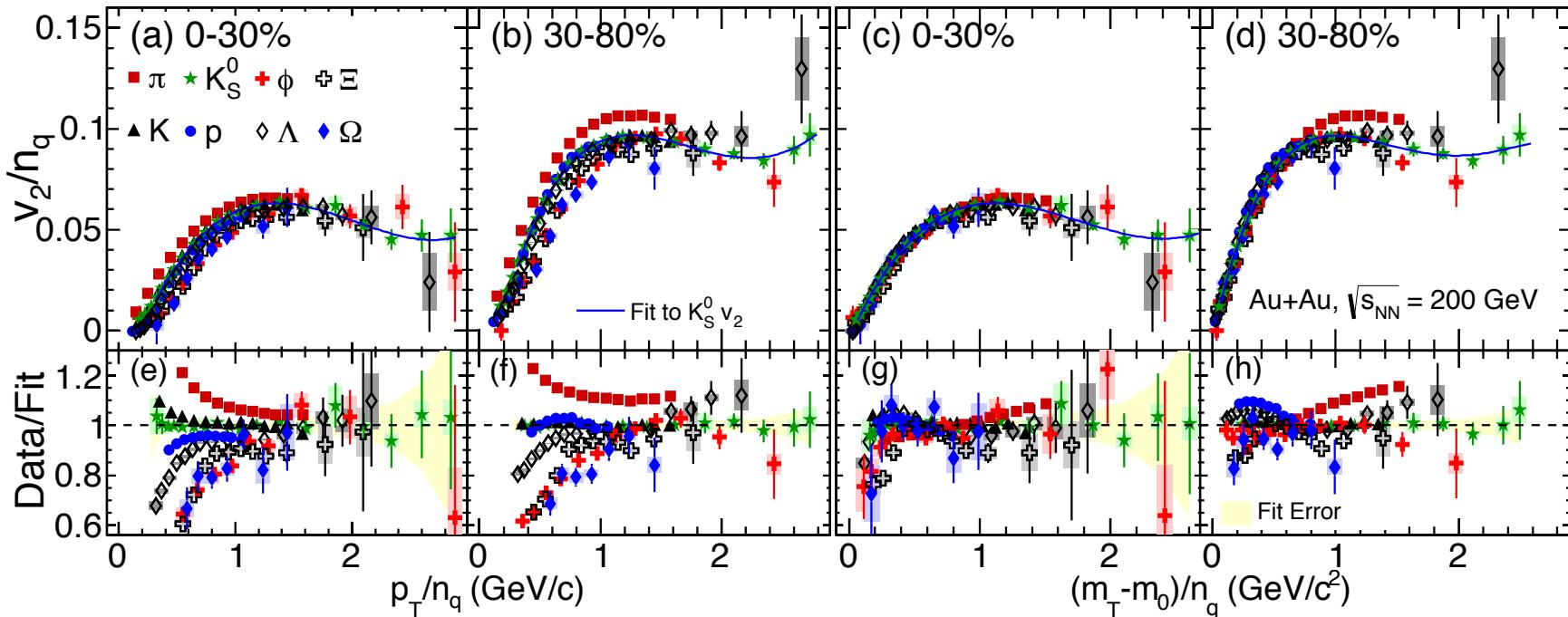
Charm quarks flow; smaller collectivity than light flavor

Diffusion Coefficient



- Compatible with models predicting a value of diff. coefficient between 2 - 10
- Lattice calculations are consistent with values inferred from data

NCQ Scaling - RHIC



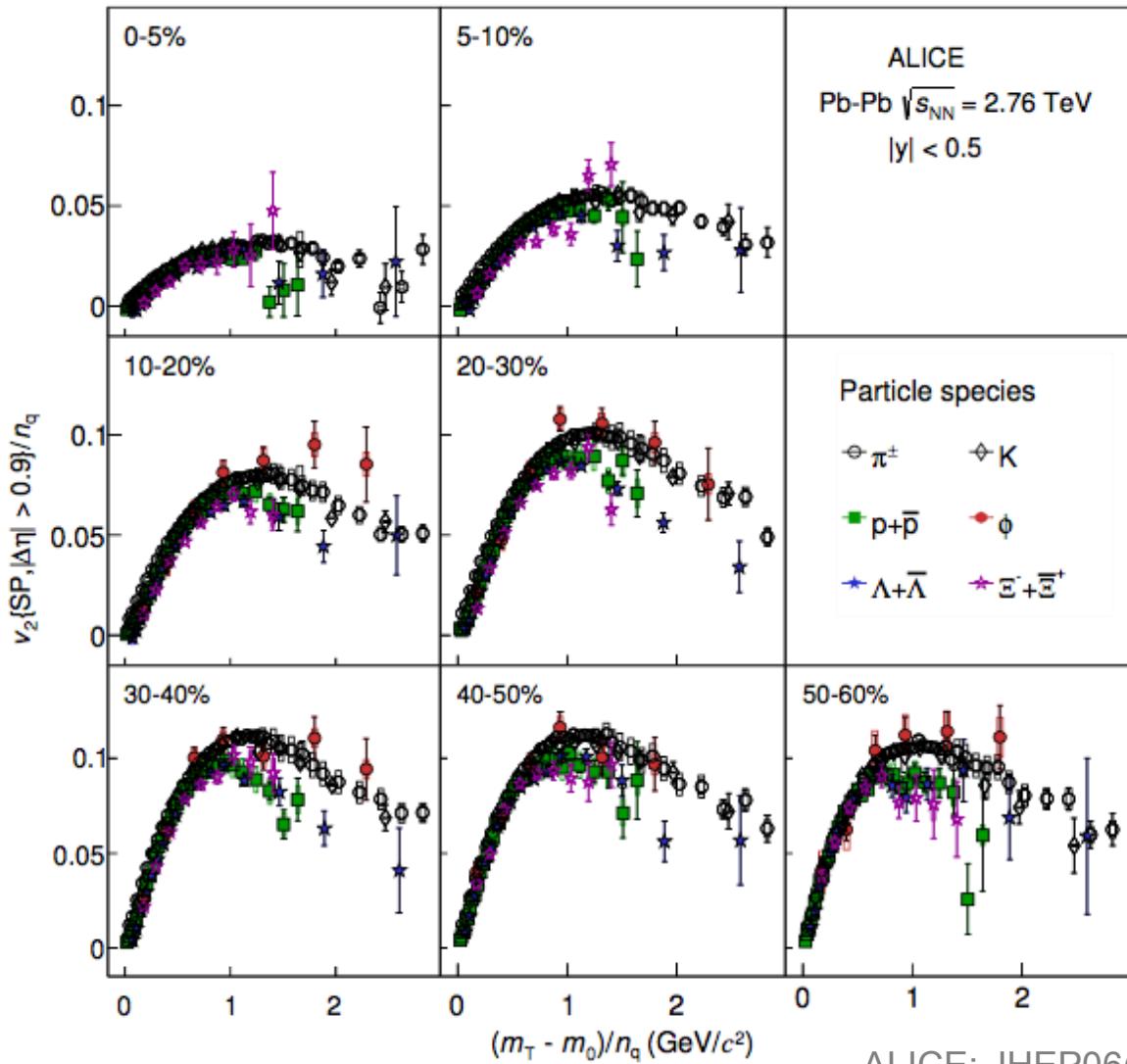
STAR: SQM2016, Phys. Rev. Lett. 116, 062301 (2016)

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

➤ NCQ scaling holds within 10%

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

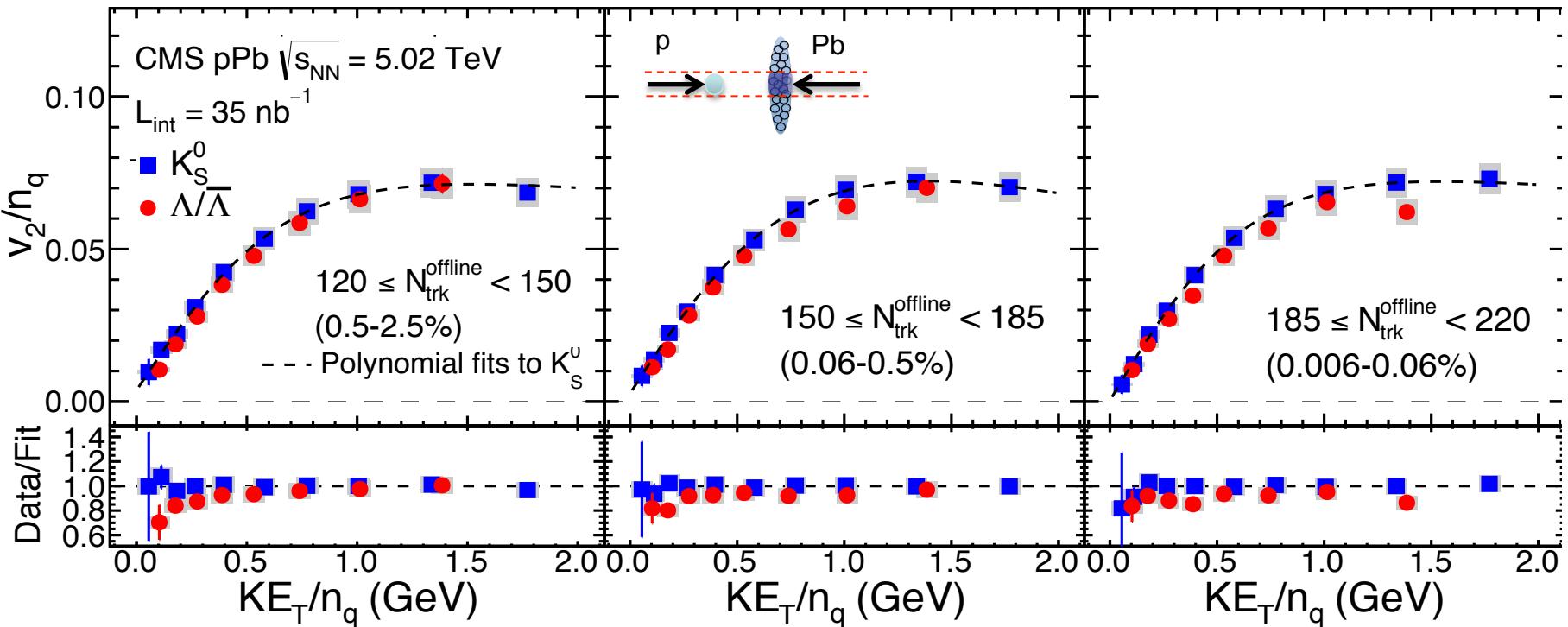
NCQ Scaling - LHC



- 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

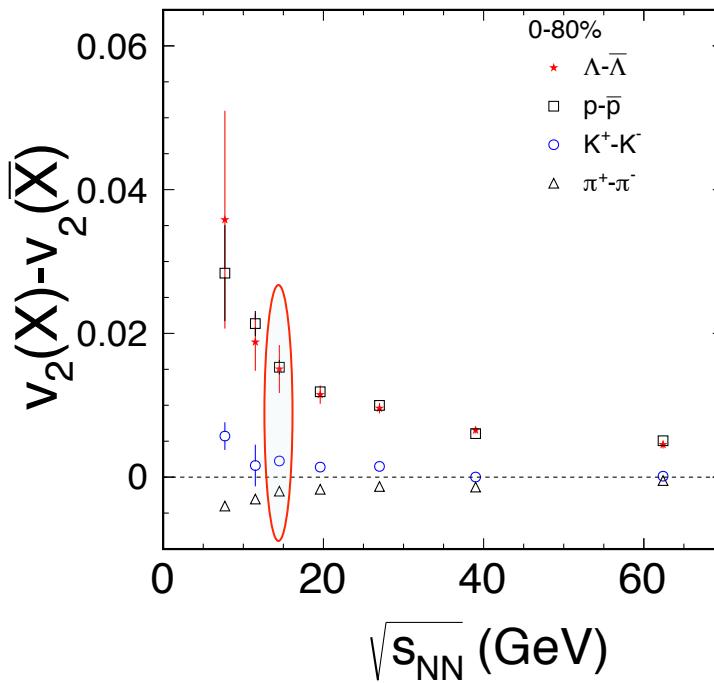
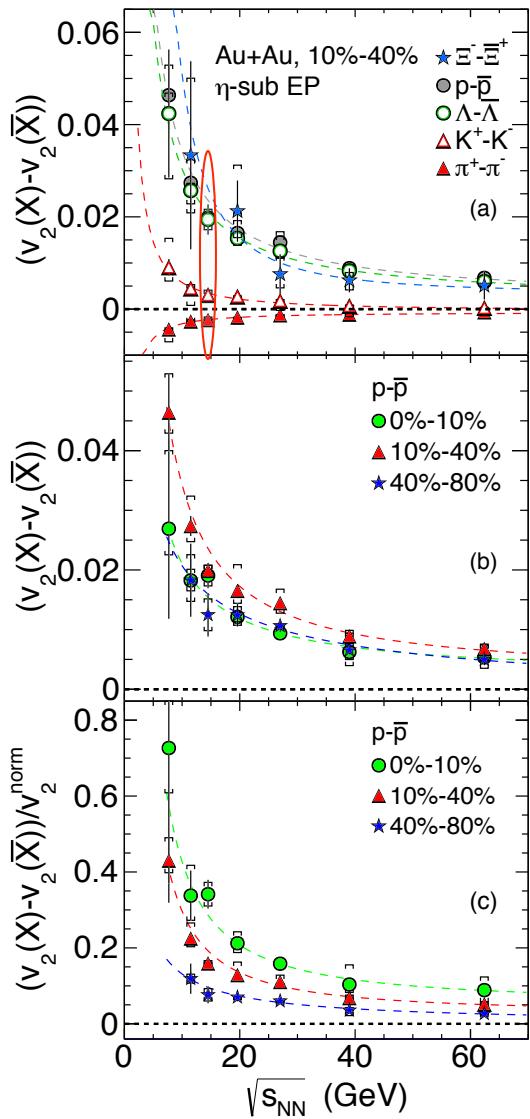
NCQ Scaling - pPb

CMS: SQM2015, PLB 742 (2015) 200



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

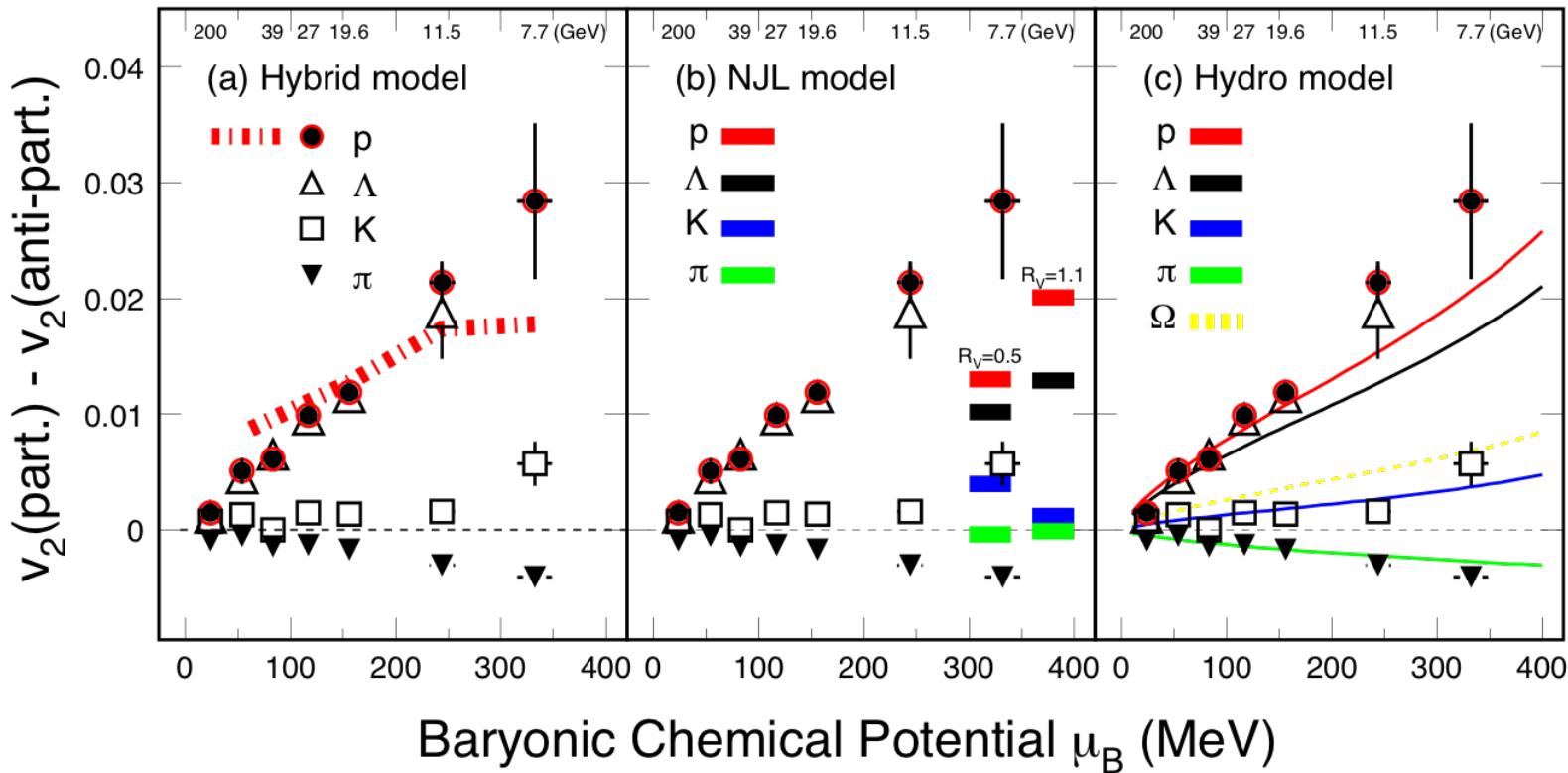
Particle vs. Anti-particle v_2



STAR: Phys. Rev. C 93, 014907(2016)

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

Particle vs. Anti-particle v_2



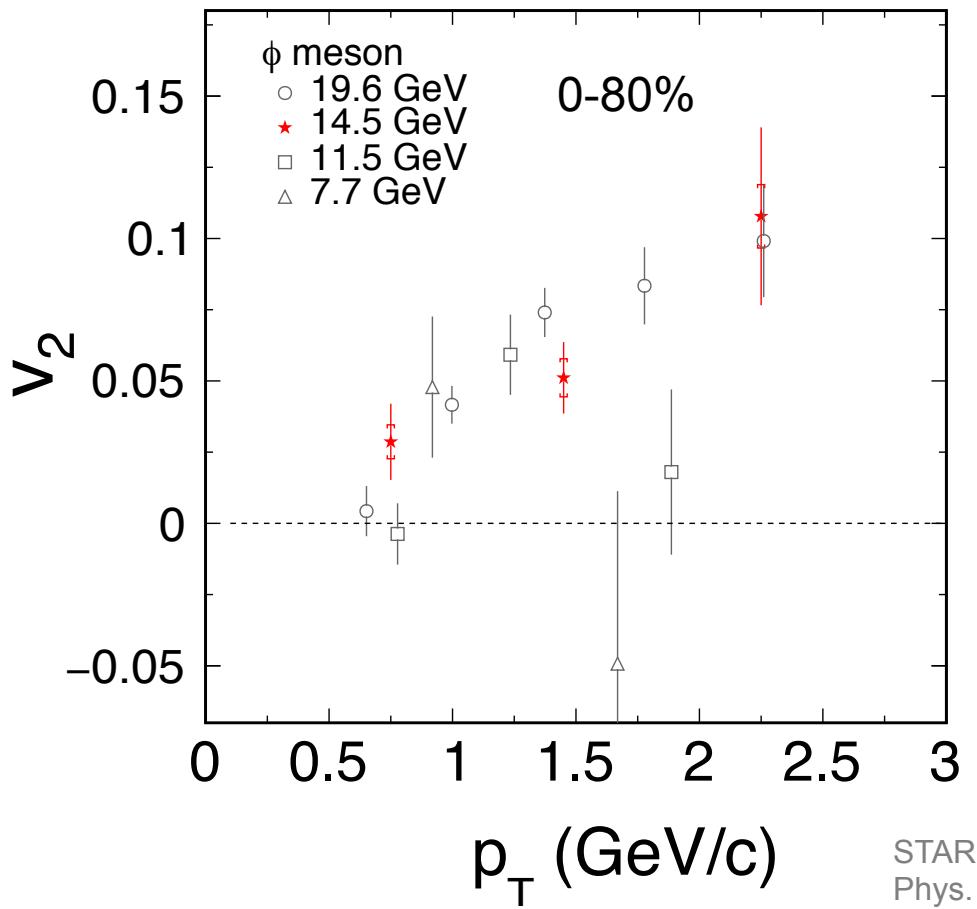
- The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks
- Model comparison

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

- Hydro + Transport (UrQMD): consistent with baryon data
- Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent
- Analytical hydrodynamic solution: $\Delta v_2^p > \Delta v_2^\Lambda > \Delta v_2^\Xi > \Delta v_2^\Omega$

J. Steinheimer et al., PRC86, 04902(2013); J. Xu et al., PRL112, 012301(2014); Y. Hatta et al., PRD92, 114010(2014)

ϕ Meson v_2

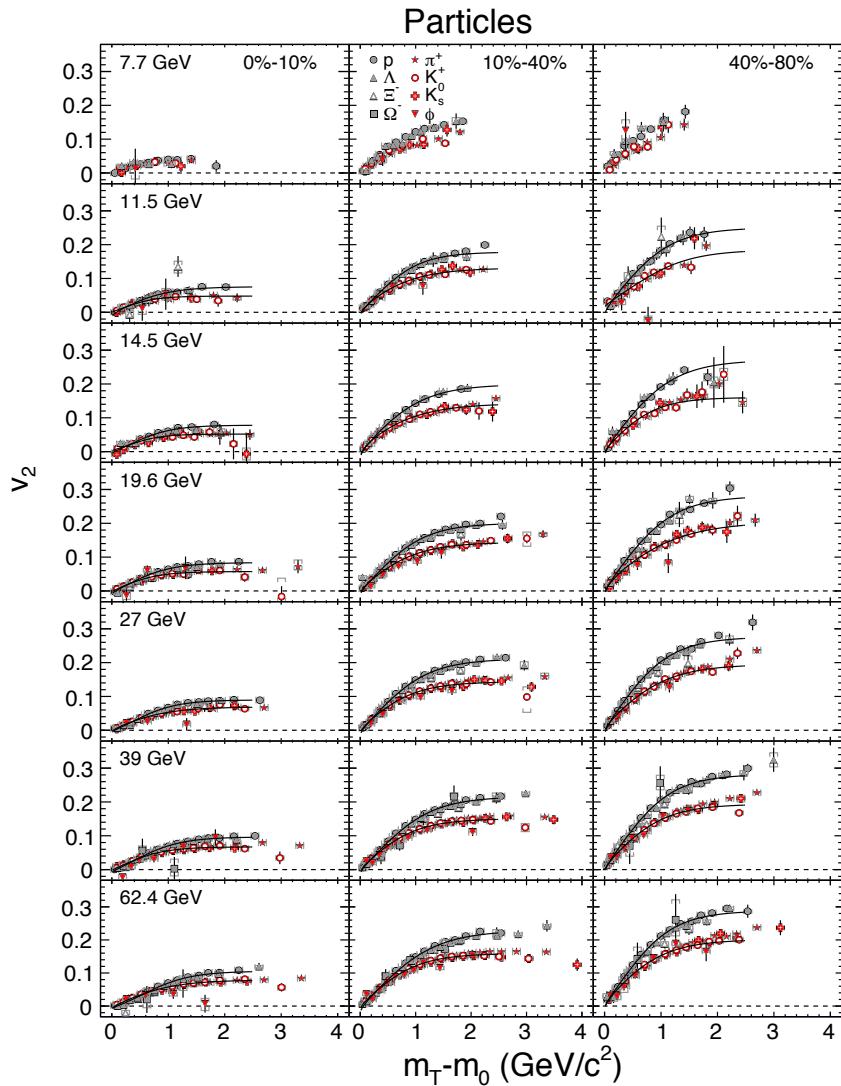


14.5 GeV: Sizable ϕ meson v_2 , comparable to 19.6 GeV

High statistics and more collision energies below 20 GeV needed!

STAR:
 Phys. Rev. C 93, 014907 (2016)
 Phys. Rev. C 88, 014902 (2013)

Baryon/Meson Separation

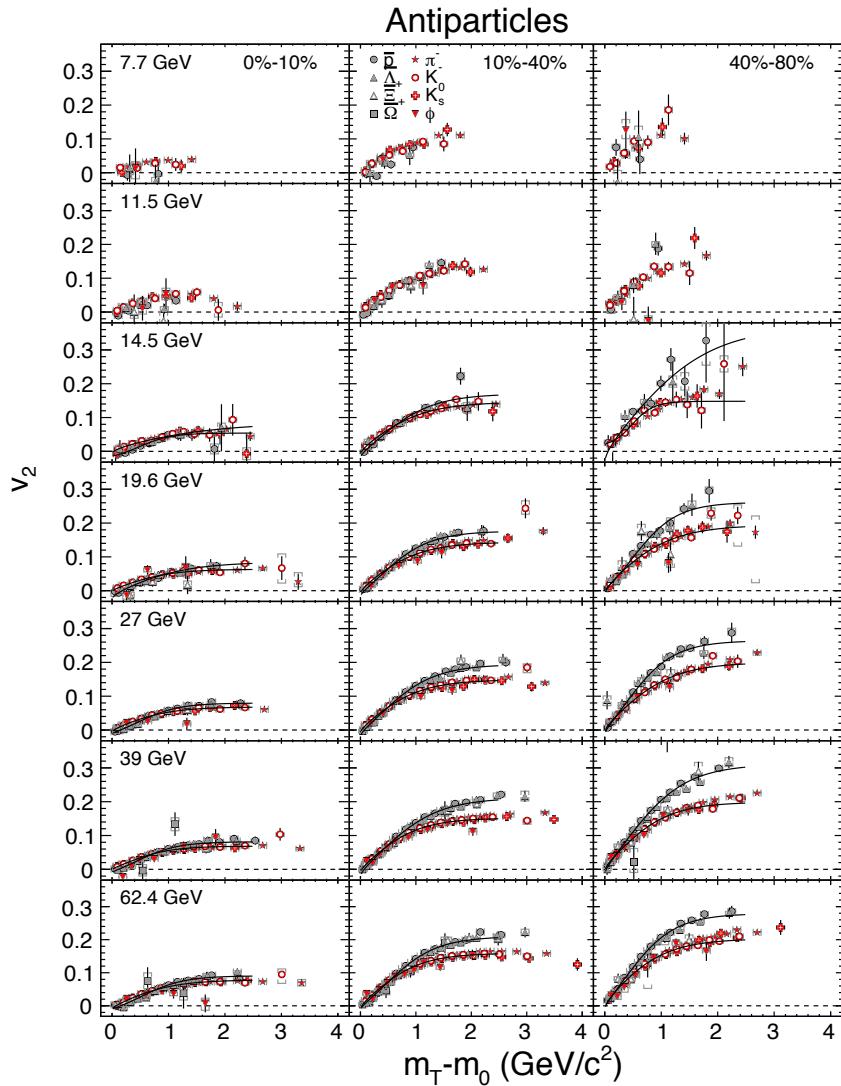


A splitting between baryons and mesons is observed at all energies except 7.7 GeV and all centralities.

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

STAR: Phys. Rev. C 93, 014907(2016)

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.

STAR: Phys. Rev. C 93, 014907(2016)



Summary

- Multi-strange hadron $v_2 \rightarrow$
Partonic collectivity
- D meson $v_2 \rightarrow$
Charm quarks flow
Inferred diffusion coefficient between 2 - 12
- NCQ scaling->
Hadronization mechanism
- Beam Energy Scan program->
Explore the QCD phase structure
Stay tuned for BES II