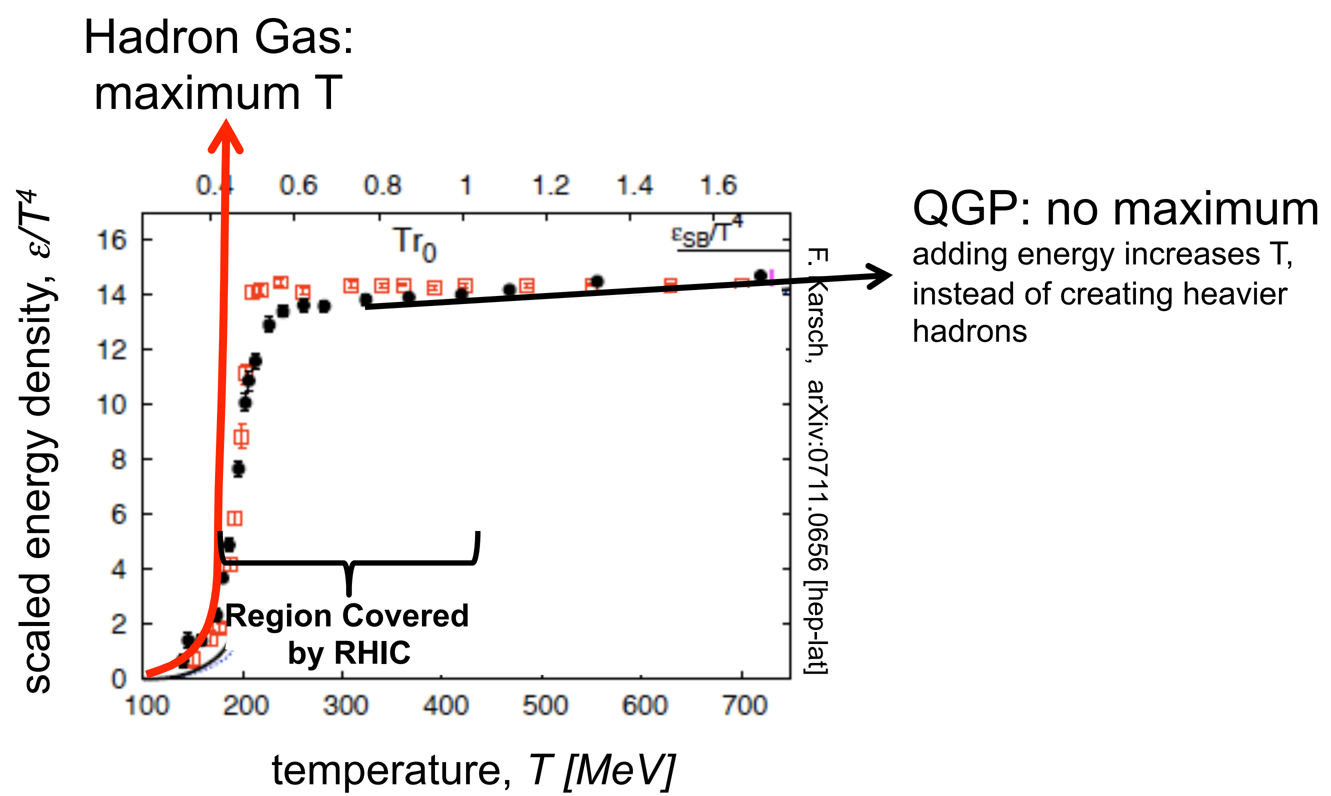
Flow at Lower RHIC Energies

Paul Sorensen (BNL)

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP above a critical T: ε/T^4 (∝ # degrees-of-freedom) plateaus when quarks and gluons become the relevant degrees of freedom



The region around the transition is the most interesting, not the asymptotic limit

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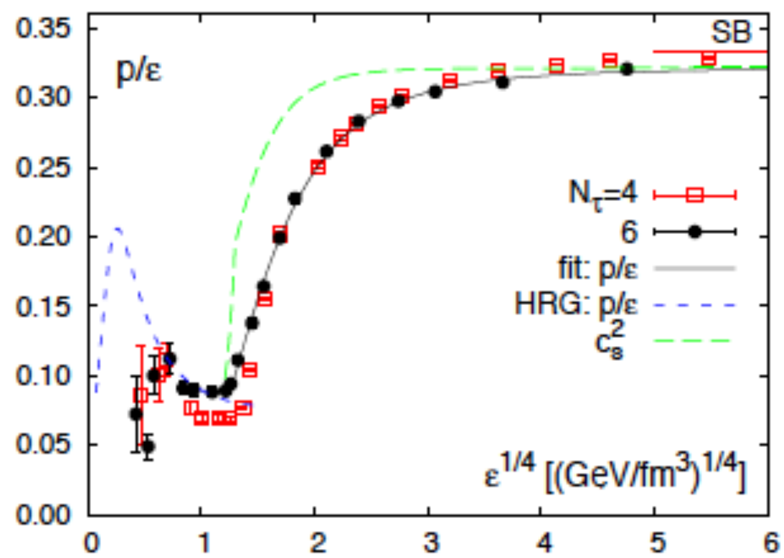


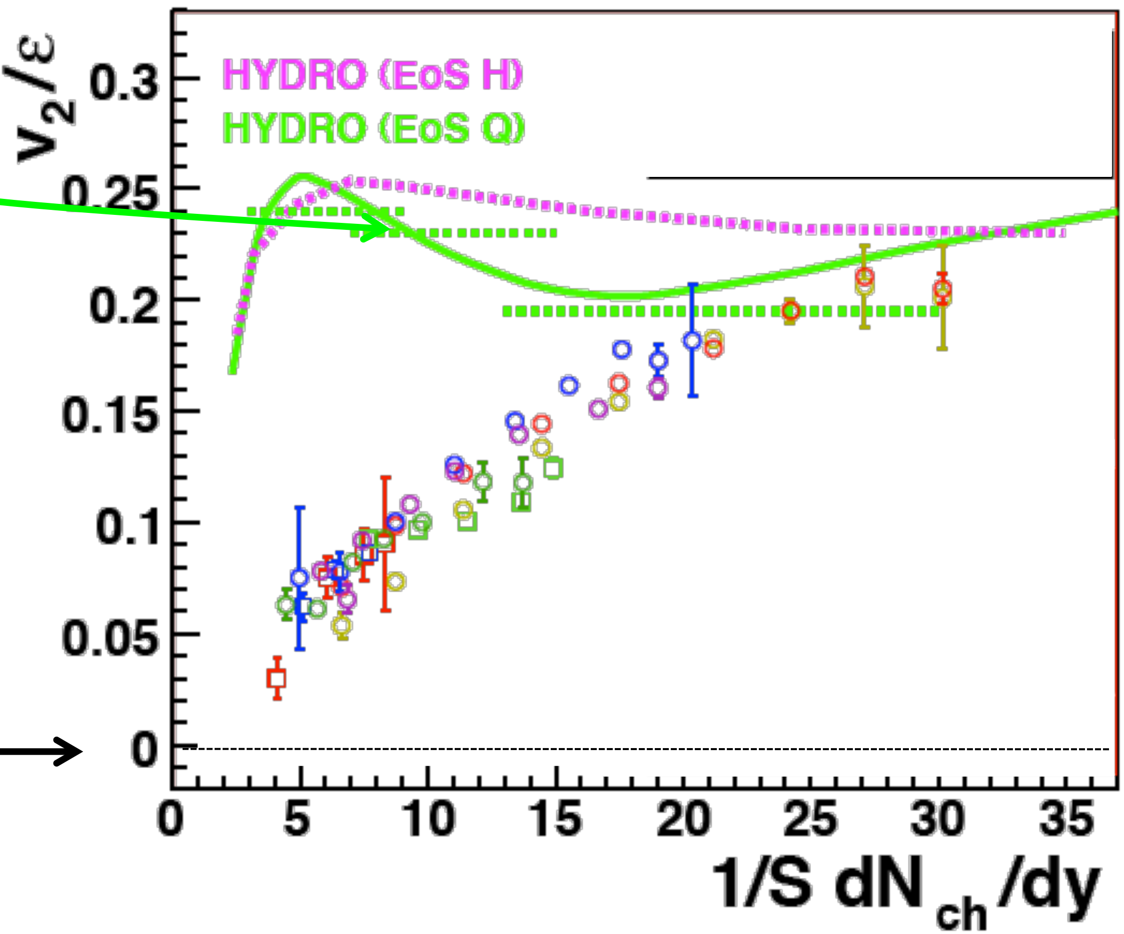
The region around the transition will exhibit significant changes in pressure. Can we study these?

Conversion of Initial Spatial Distortion

S. Voloshin, J.Phys.G34:S883-886,2007

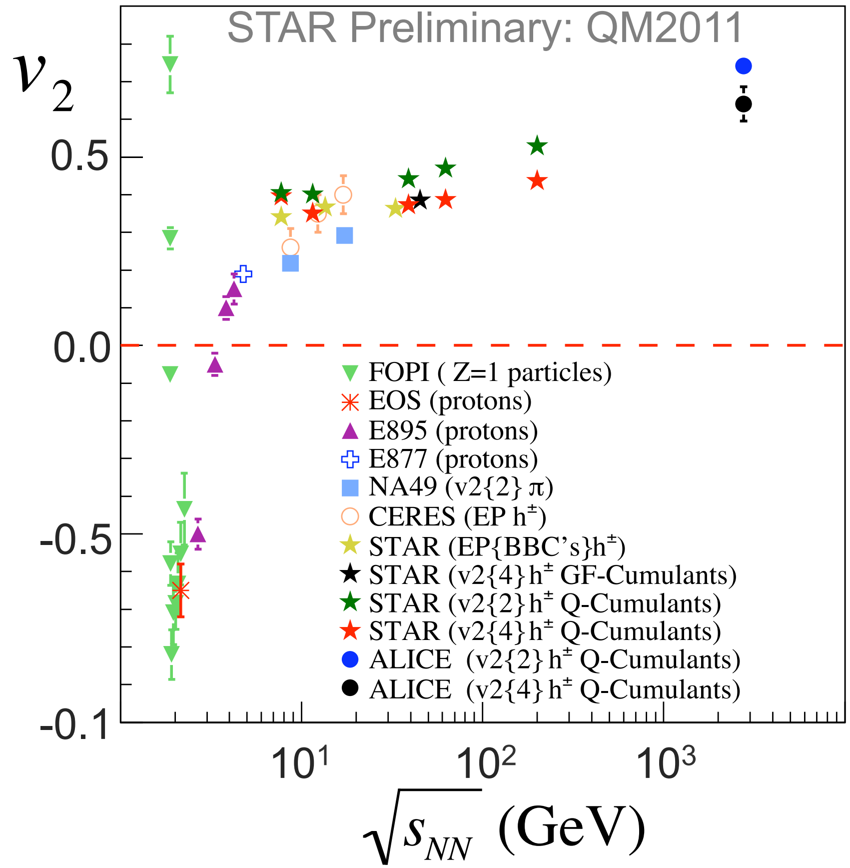
zero mean-free-path limit

Ballistic expansion



The strategy is to study quantities related to pressure vs something related to energy density

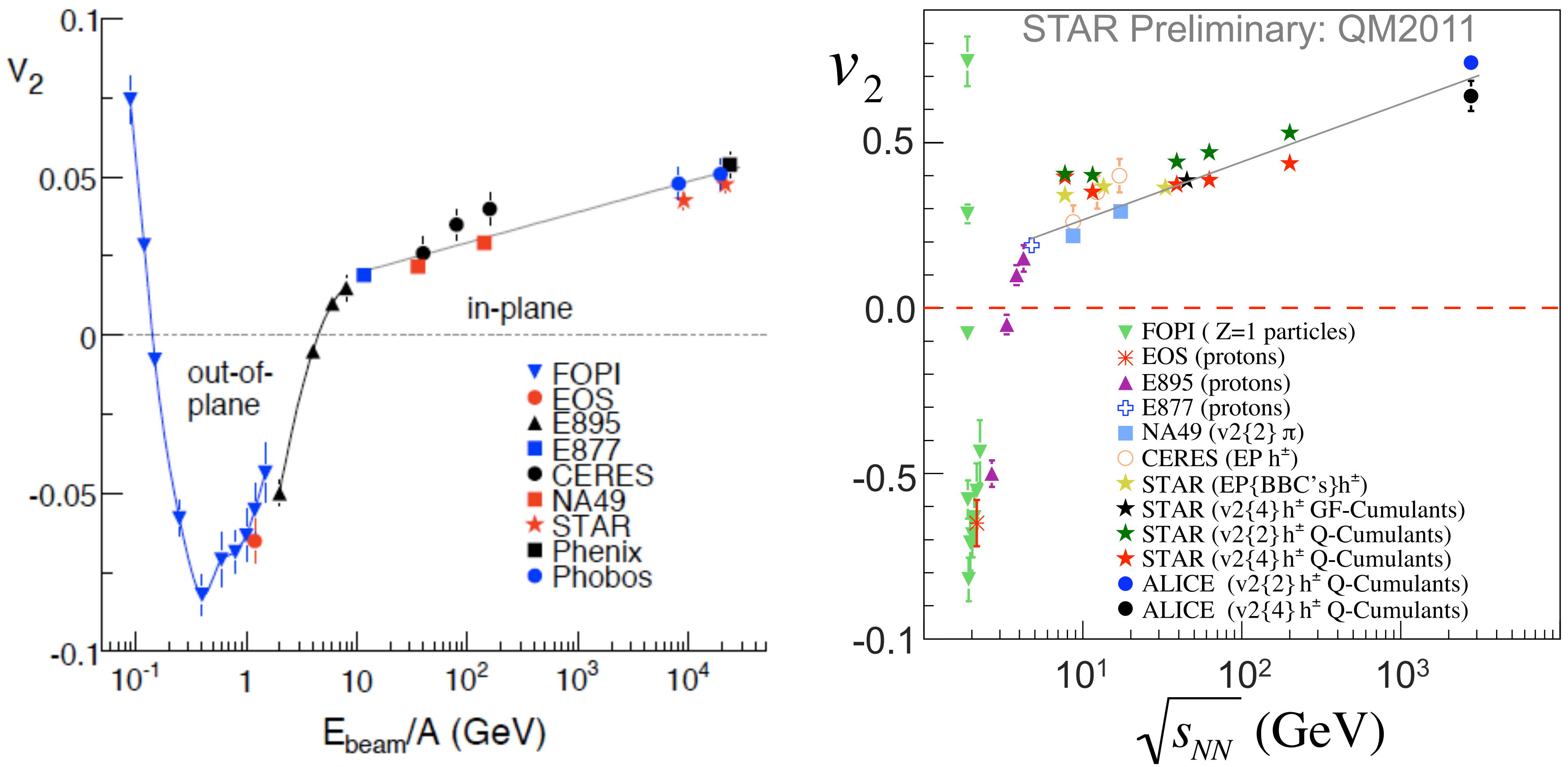
v_2 Over Three Orders of Magnitude



RHIC covers exactly the range where softening is expected

STAR data on $v_2\{2\}$ and $v_2\{4\}$ follows smooth trends but better systematics may reveal more detail…

v_2 Over Three Orders of Magnitude



RHIC covers exactly the range where softening is expected

Log linear curve does not describe new data; Old compilation was a hodge-podge of techniques, PIDs, and acceptances

Difference between $v_2\{2\}$ and $v_2\{4\}$

In the presence of fluctuations

$$v_n\{2\}^2 = \langle v_n \rangle^2 + \sigma_{v_n}^2$$

$$v_n\{4\}^4 = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle$$

$$= \langle v_n \rangle^4 - 2\langle v_n^2 \rangle \sigma_{v_n}^2 - 4\langle v_n \rangle \mu_3 - \mu_4 + 2\sigma_{v_n}^4$$

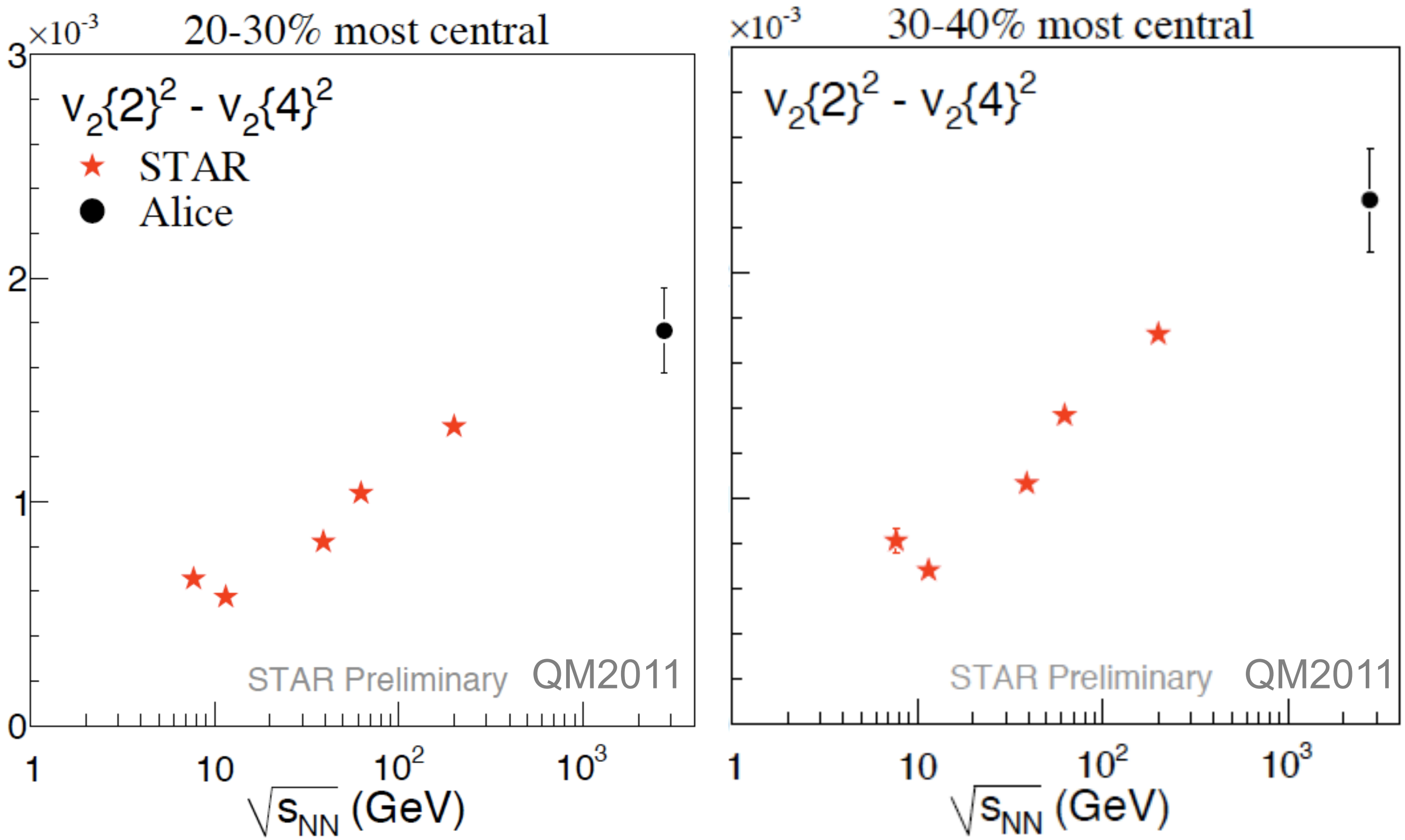
The difference between $v_2\{2\}$ and $v_2\{4\}$ measures fluctuations.

H. Kowalski, T. Lappi and R. Venugopalan, Phys.Rev.Lett. 100:022303

Does the initial pressure convert this lumpiness into v_n fluctuations? How does the initial pressure change with energy?

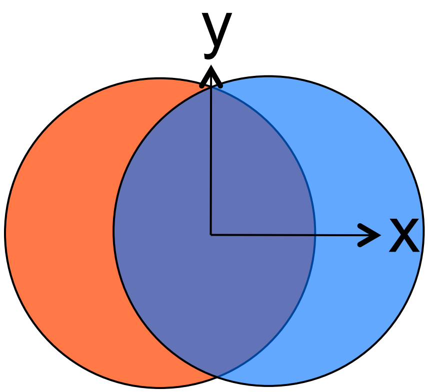
v_2 Fluctuations vs Beam Energy

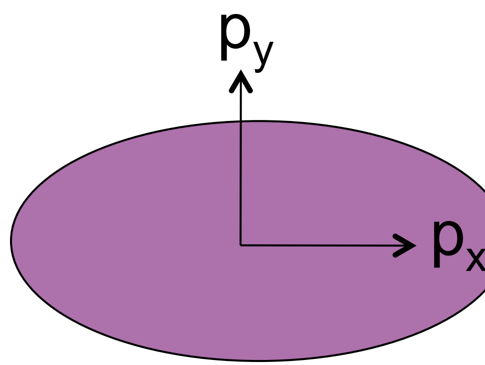
Difference goes approximately as $2(\sigma_{v2}^2)$

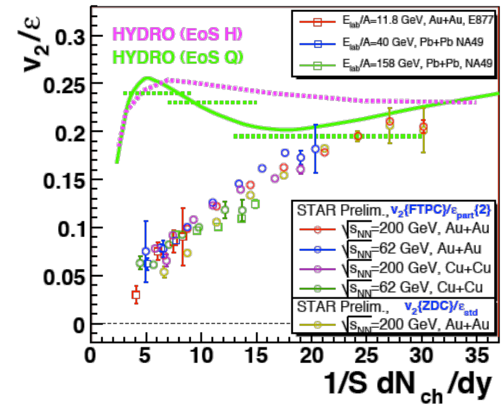


Excitation function of fluctuations shows striking increase: perhaps indicating an increase in early pressure

From v_2 to v_n: and what we learn

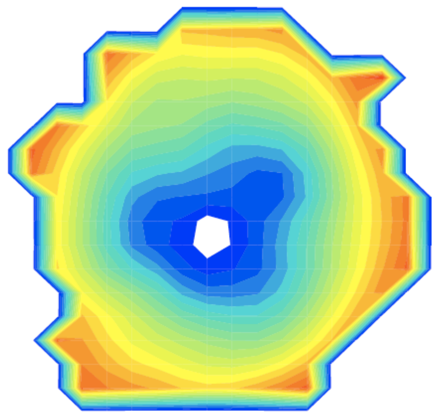




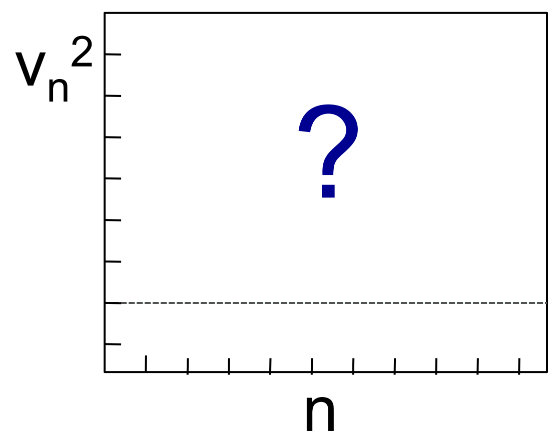


$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303



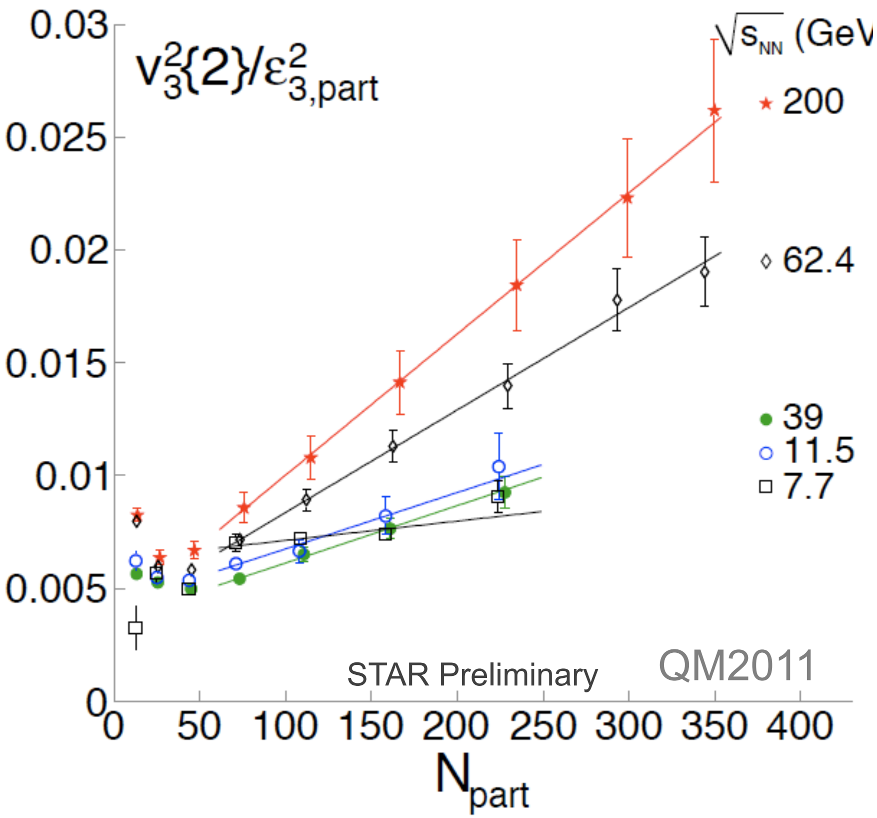
K. Werner, Iu. Karpenko, K. Mikhailov, T. Pierog, arXiv:11043269

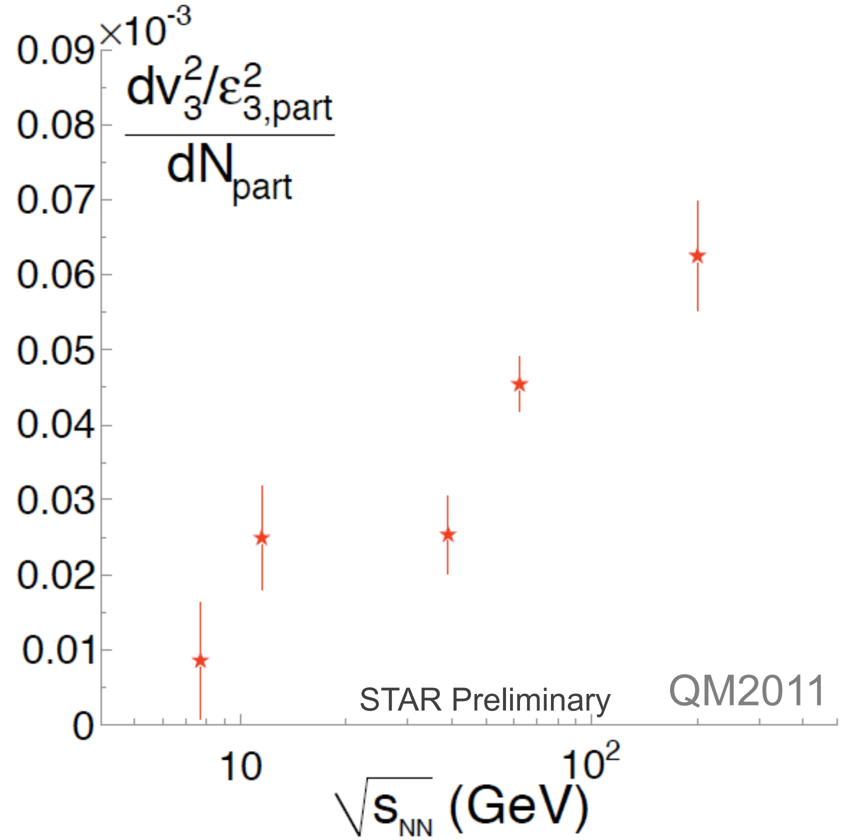


Fluctuations imply odd terms aren't necessarily zero and v_n^2 vs. n will provide information about the system like lifetime, viscosity, etc.

A.P. Mishra, R. K. Mohapatra, P. S. Saumia, A. M. Srivastava, Phys. Rev. C77: 064902, 2008
P. Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010

v_3 fluctuations vs Beam Energy



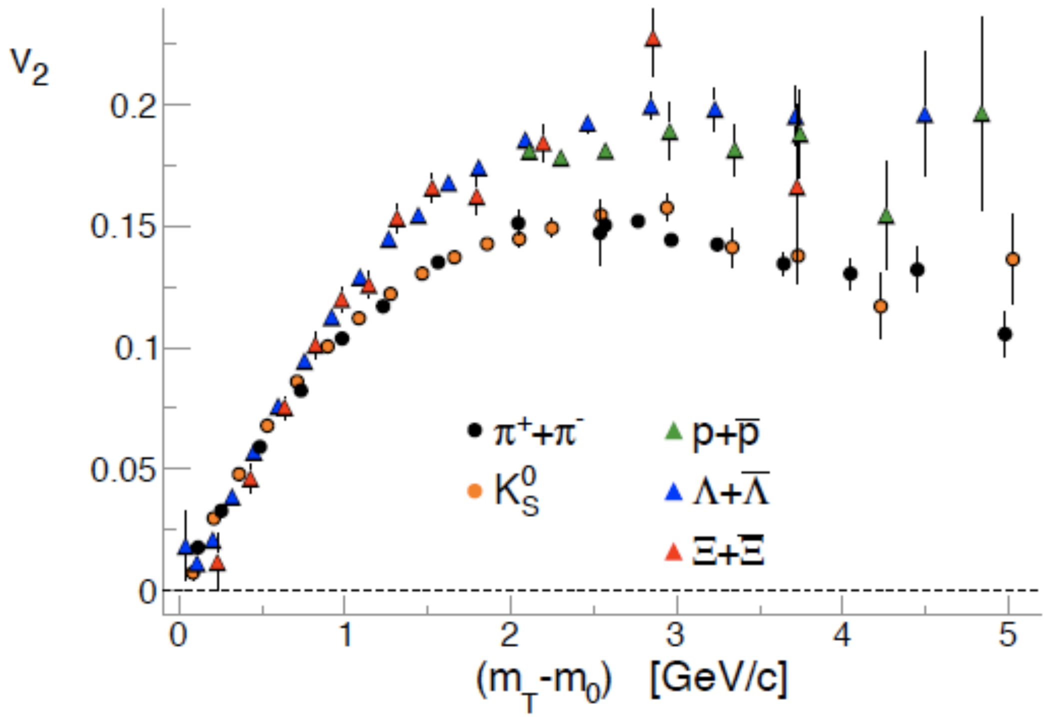


Analysis based on Q-Cumulants for all charges and -1<η<1 (still contains BEC peak)

$v_3^2/\varepsilon^2_{3,part}$ follows a simple trend with N_{part}

Slope of $v_3^2/\varepsilon^2_{3,part}$ is increasing with beam energy; similar to $v_2^2\{2\}-v_2^2\{4\}$

Quark Number Scaling at Full Energy

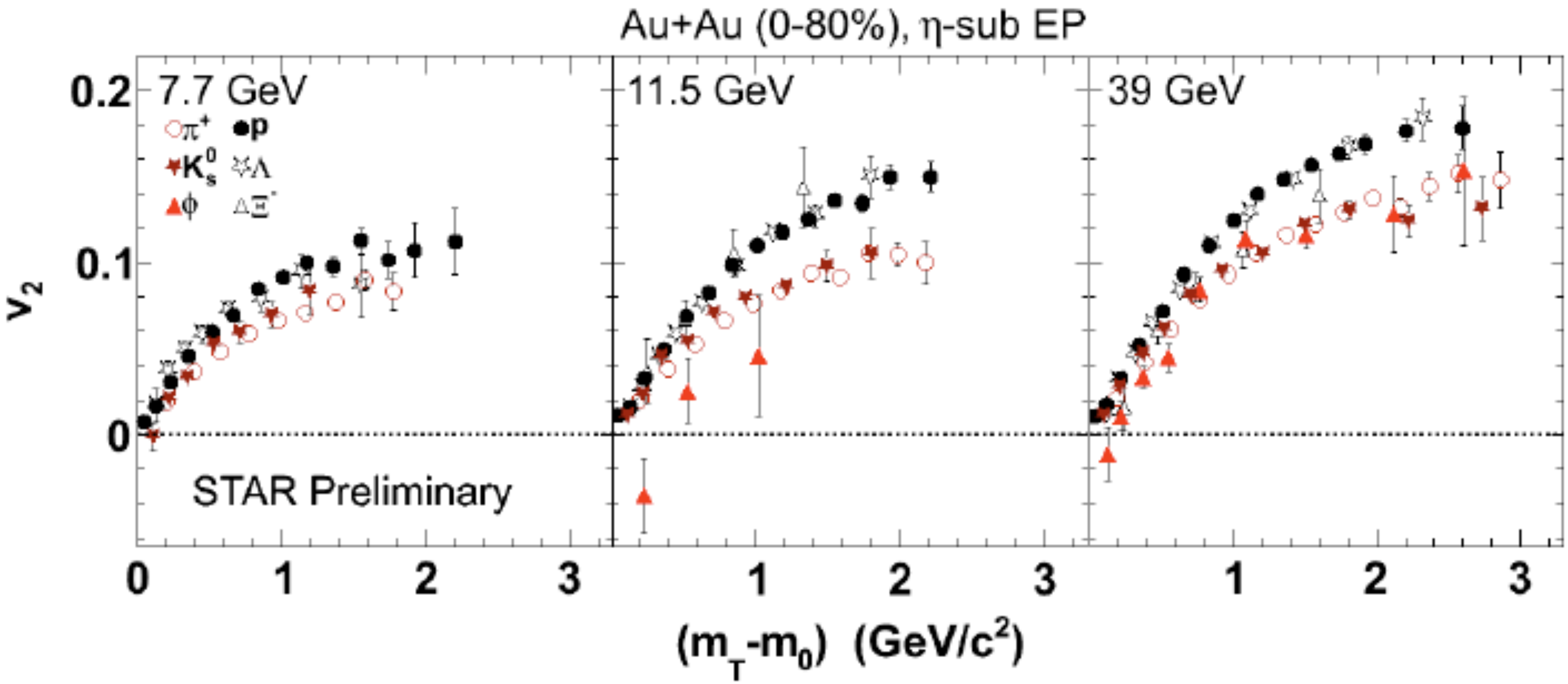


NCQ scaling and meson/baryon splitting: thought to arise from coalescence of dressed constituent quarks.

Interpretation implies v_2 was developed in a QGP phase: breakdown could signal dominance of a hadronic phase.

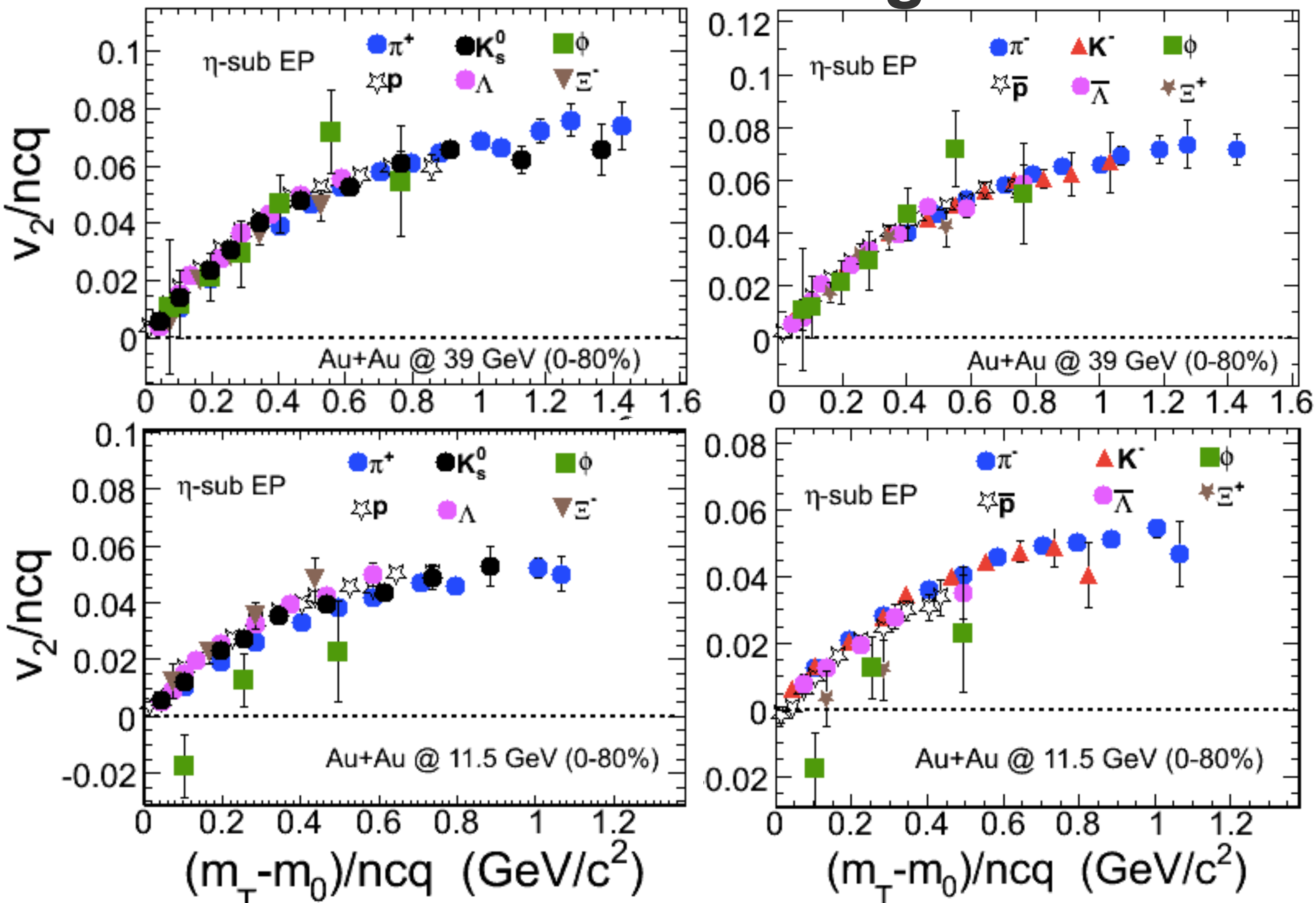
What do we see at the energies where fluctuations seem to decrease?

NCQ Scaling



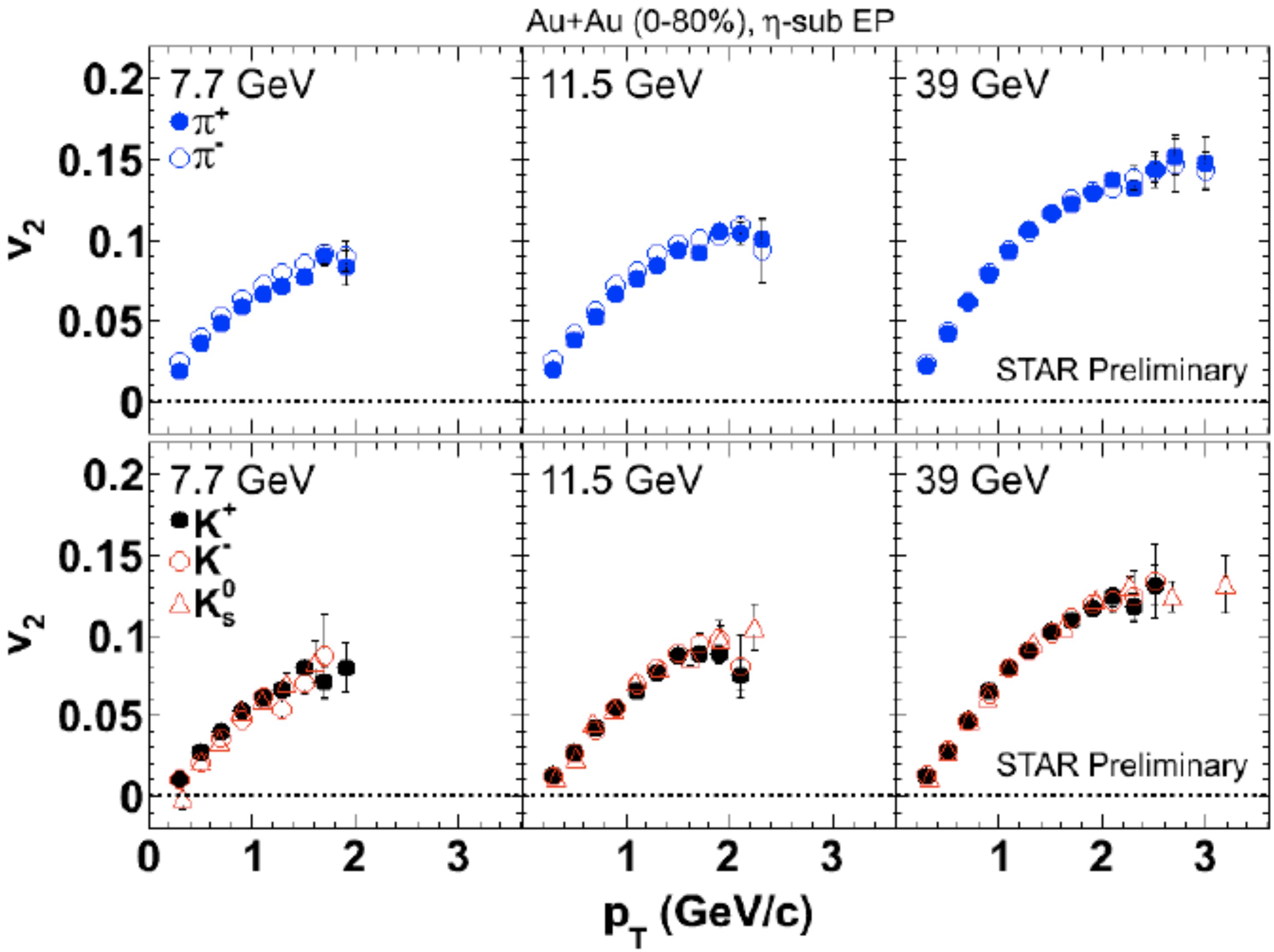
- Meson baryon seperation persists down to 11.5 GeV
- Splitting is not as clear at 7.7 GeV
- The φ-meson v_2 may fall off trend from other hadrons at 11.5 GeV (2.6σ)

NCQ Scaling



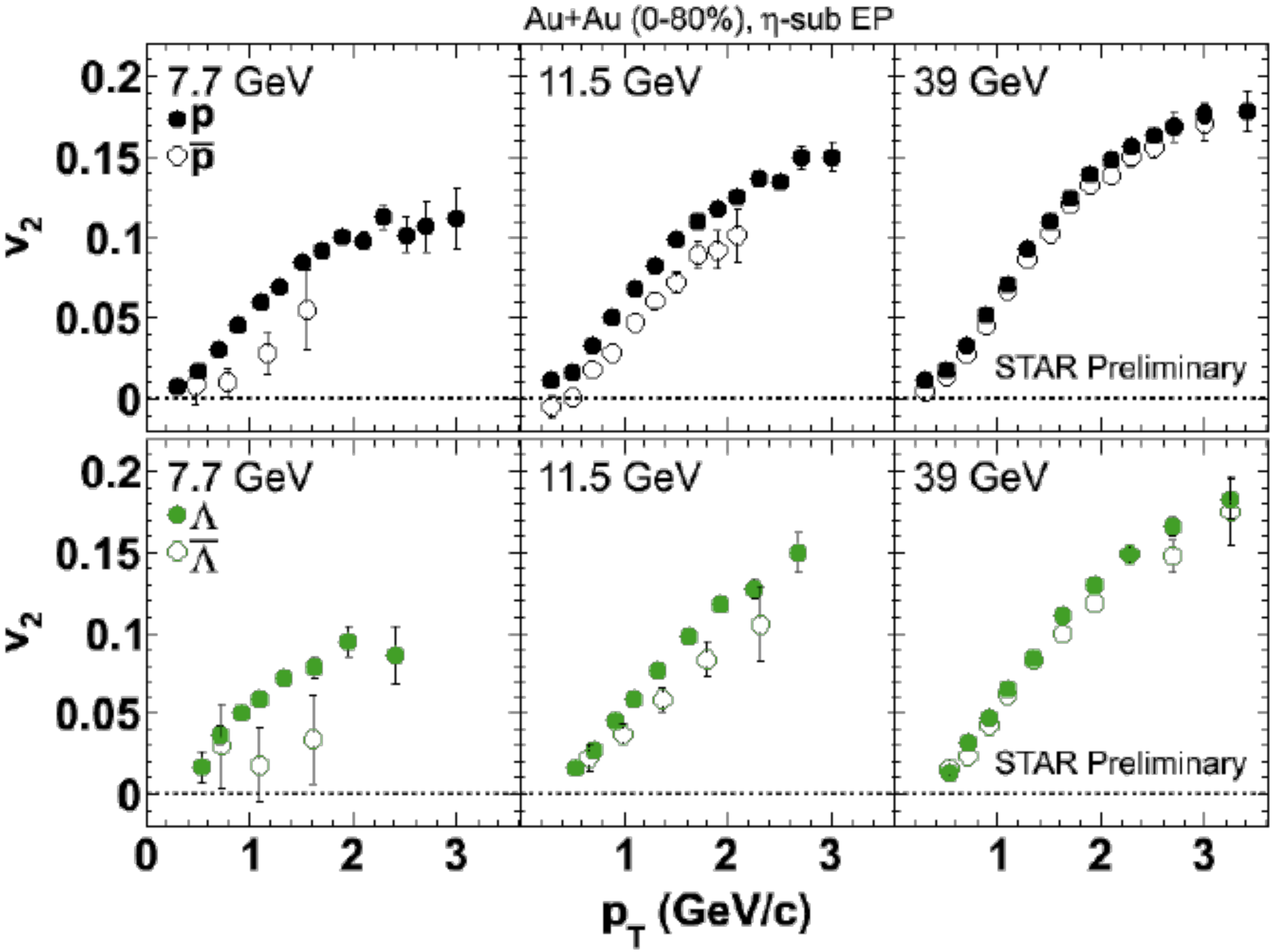
- The φ-meson v_2 may fall off trend from other hadrons at 11.5 GeV
- A 2.6σ effect

Particle/Antiparticle Dependence



Low energy data also show a particle/antiparticle dependence

Particle/Antiparticle Dependence



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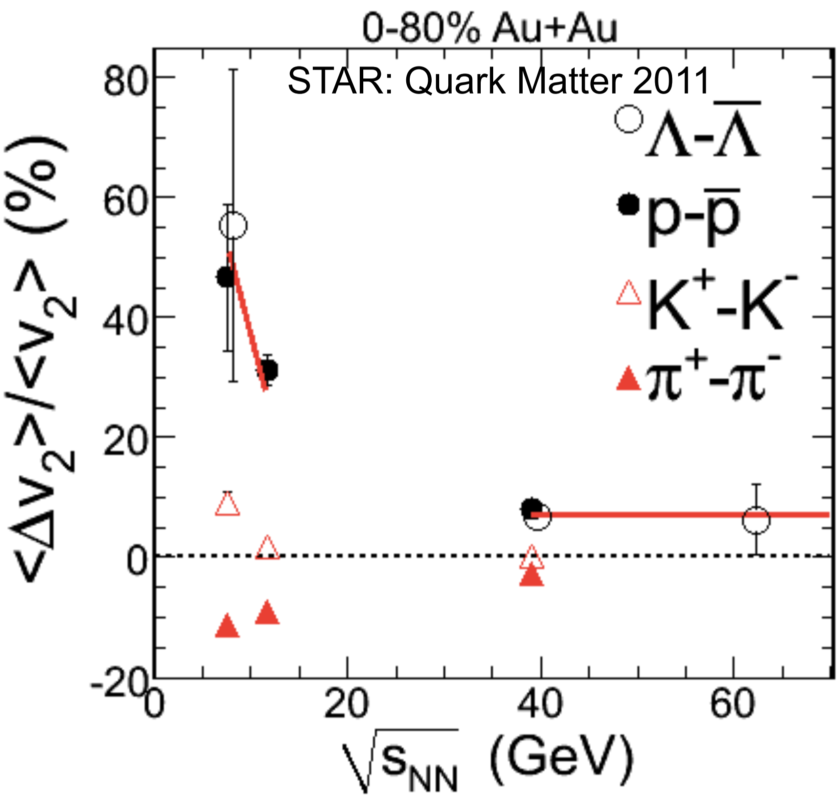


At $\sqrt{s_{NN}}$ ≤ *11.5 GeV:*
- v_2(baryon) > v_2(anti-baryon)
- $v_2(\pi^+) < v_2(\pi^-)$
- $v_2(K^-) < v_2(K^+)$

Dominance of hadronic interactions? Chiral Magnetic effects? Are there any other possibilities?

Mixing In Transported Quarks

What if quarks from beam rapidity, have a larger v_2 than produced quarks?

$\sqrt{s_{NN}}$	X_{u^T}	X_{d^T}
6.41 GeV	0.57	0.63
8.86 GeV	0.50	0.55

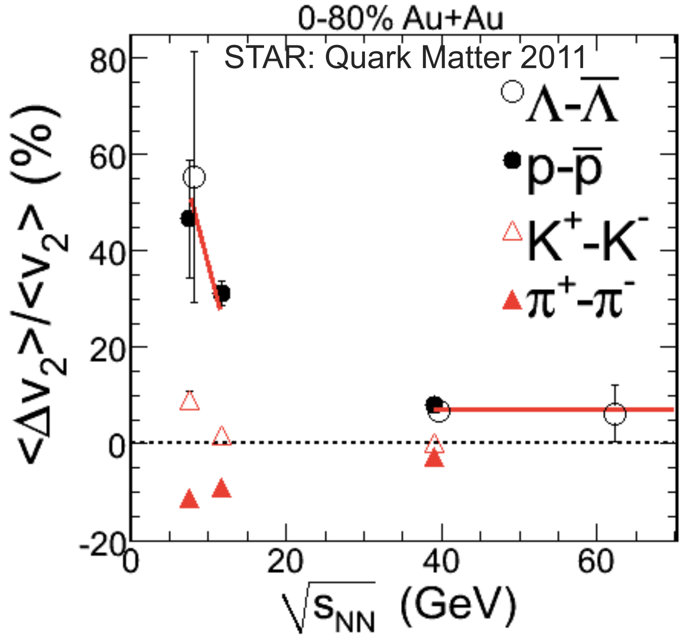
Fraction of mid-rapidity u and d quarks that were transported from the incoming nuclei

$$v_2^h(p_T) = \frac{1}{n}\sum_{i=1}^{n}\left[X_{q_i^T} v_2^{q_i^T}(p_T/n) + \left(1 - X_{q_i^T}\right) v_2^{q_i^P}(p_T/n)\right]$$

Let's assume coalescence still works but now with two samples of quarks

$$v_2\left[\pi^- = d\bar{u}\right] > v_2\left[\pi^+ = u\bar{d}\right]$$
$$v_2\left[K^+ = u\bar{s}\right] > v_2\left[K^- = \bar{u}s\right]$$
$$v_2\left[p = uud\right] > v_2\left[\bar{p} = \bar{u}\bar{u}\bar{d}\right]$$
$$v_2\left[\Lambda = uds\right] > v_2\left[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}\right]$$
$$v_2\left[p = uud\right] > v_2\left[\Lambda = uds\right]$$

Then we find the following relationship between species



Conclusions

RHIC covers the most interesting thermodynamic region of the QCD EOS

RHIC's range and flexibility make it ideal for carrying out scans of energy, system-size, and system geometry

- Pb+Pb (doubly magic spherical nuclei)

what we should use at RHIC from her on out

- U+U (highly deformed prolate spheroids)
- Cu+Pb (spherical but imbalanced)

Data from RHIC remain at the forefront of the field: showing interesting features that call for further study

- changing particle-type systematics at low energy
- sharp variation in signatures of v_n fluctuations