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# Sub-hadronic degrees of freedom in ultra-relativistic nuclear collisions: searching for de-confined quarks and gluons

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STAR

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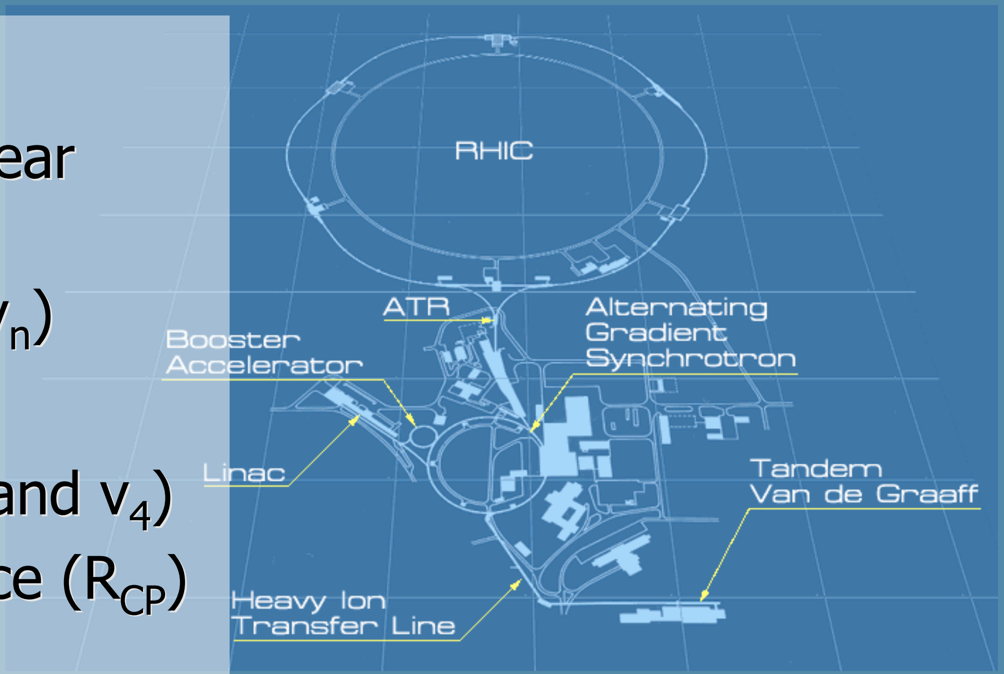
1) Introduction
   - Ultra-relativistic nuclear collisions
   - Event anisotropies ($v_n$)
2) Observations:
   - Anisotropic flow ($v_2$ and $v_4$)
   - Centrality dependence ($R_{CP}$)
   - Correlations
3) What's happening at intermediate $p_T$?
4) Conclusions



# Introduction

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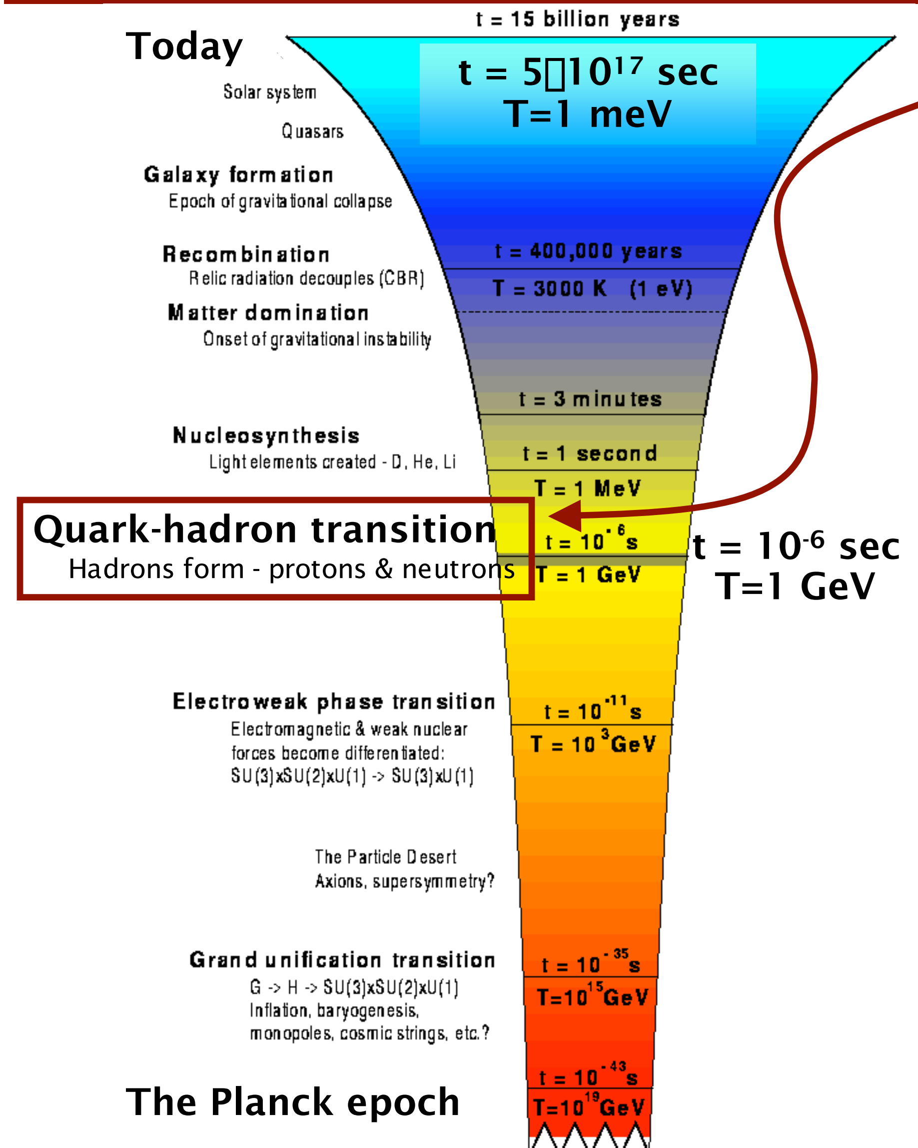
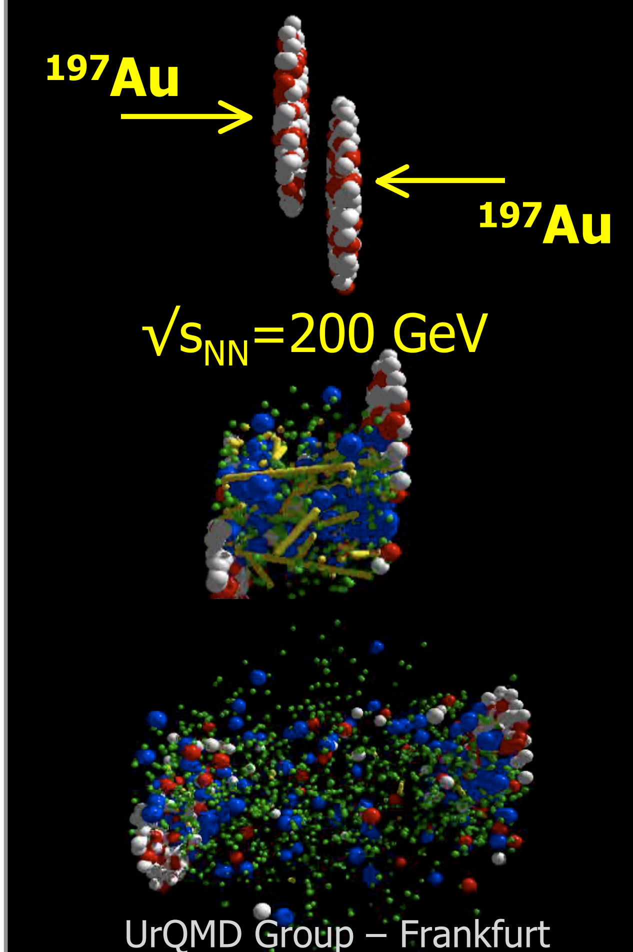
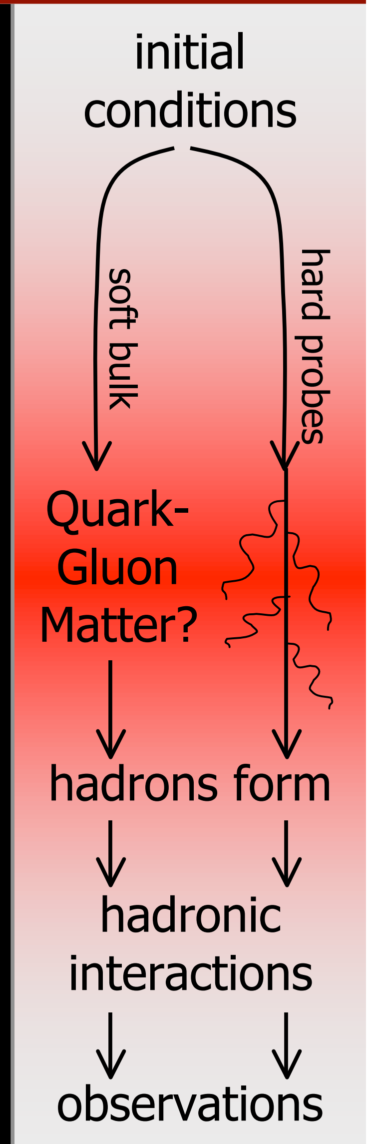


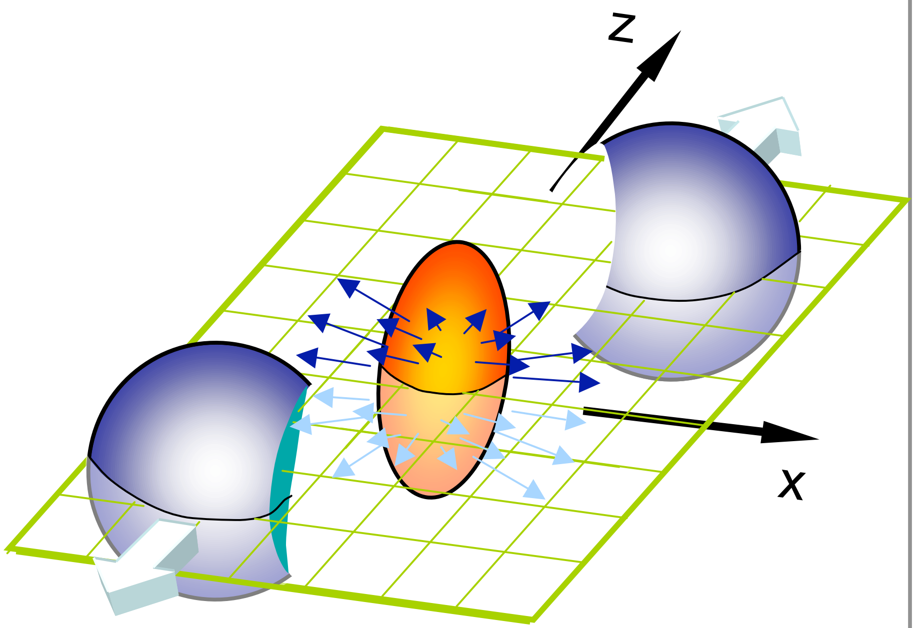

Nucleus-nucleus collisions may probe the physics of this quark-hadron transition



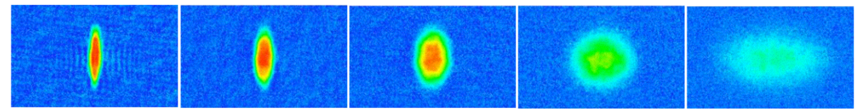



# Introduction

## EVENT ANISOTROPY: A UNIQUE OBSERVABLE



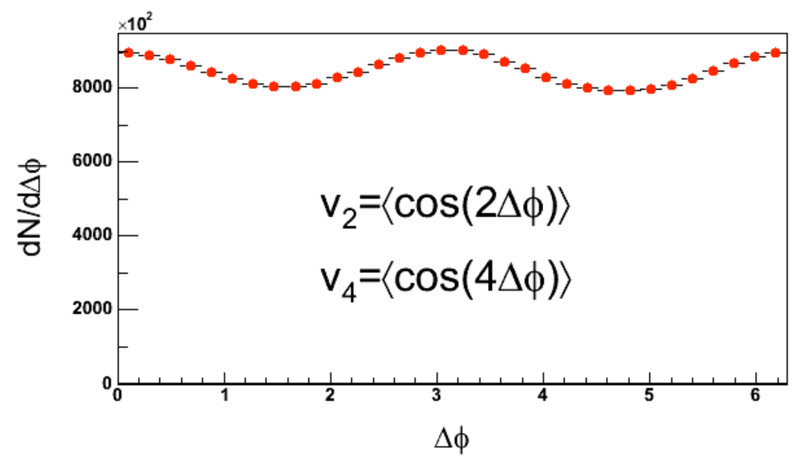

**Non-central Collisions**



The initial spatial anisotropy evolves into a momentum space anisotropy

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1} 2v_n \cos(n\phi)\right)$$

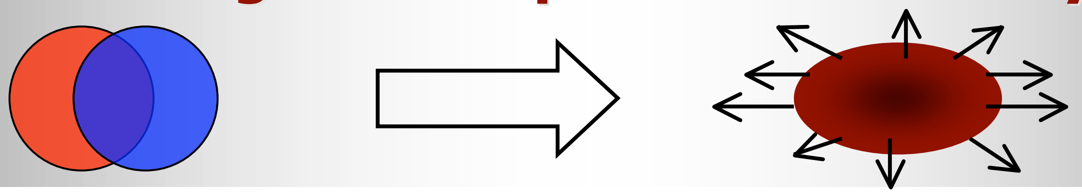
"Elliptic flow" $v_2$ is the largest harmonic

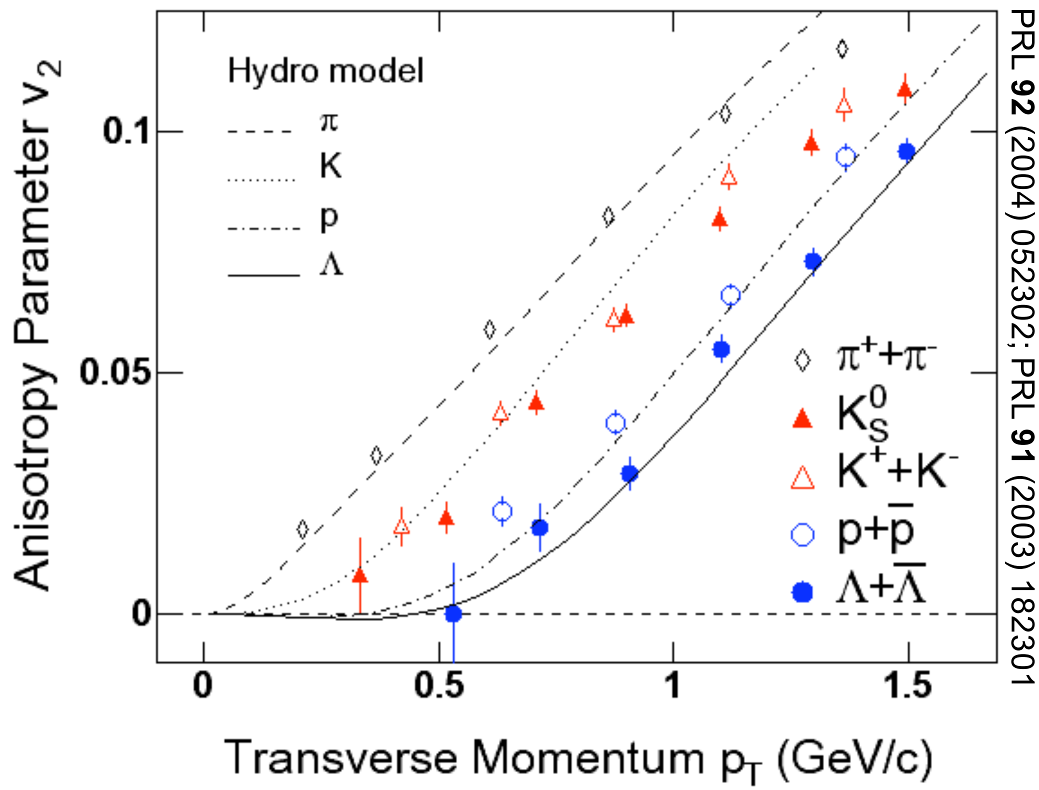


# Elliptic Flow $v_2$



**Does pressure convert spatial anisotropy to momentum anisotropy according to the equations of ideal hydrodynamics?**






Mass ordering for soft particles indicative of a common velocity.

Calculations are sensitive to the nature of the equation-of-state.

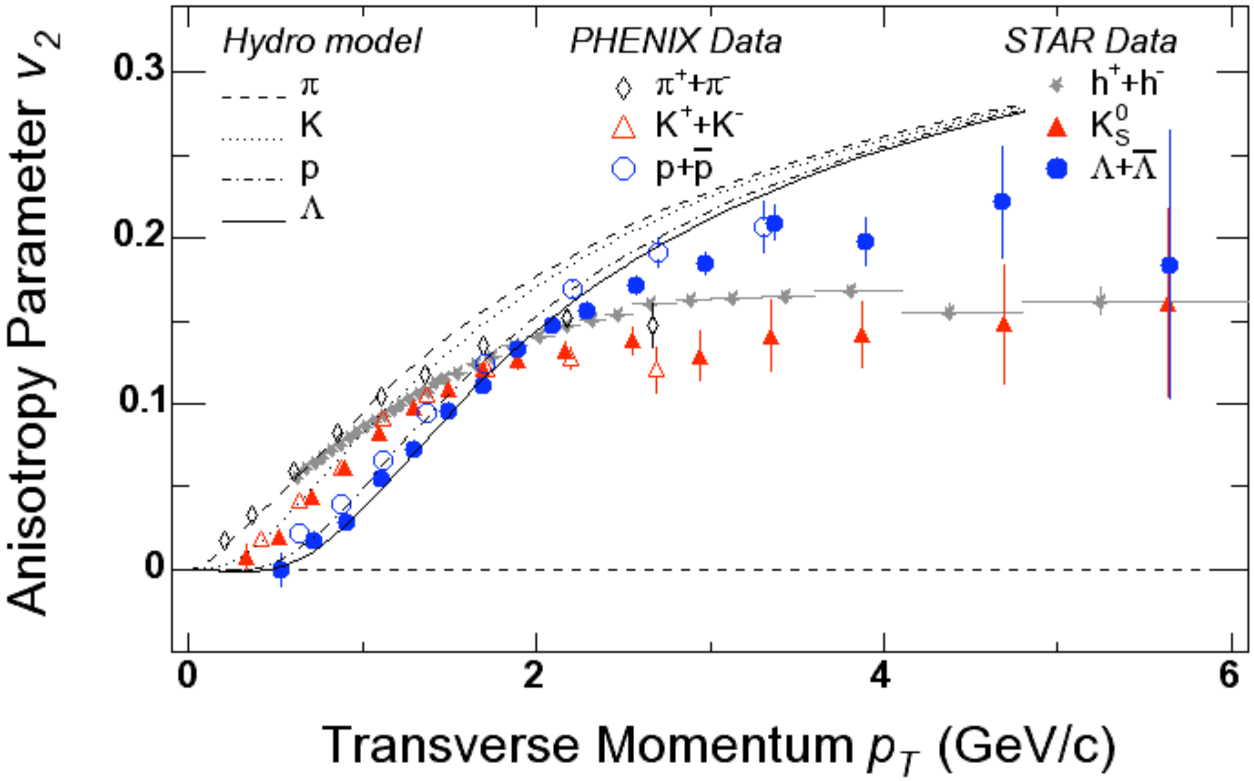
Consistent with the formation of locally equilibrated matter.

# Elliptic Flow $v_2$



**At higher $p_T$ the mass ordering breaks: with the momentum-anisotropy $v_2$ larger for baryons than mesons.**

PRL **92** (2004) 052302; PRL **91** (2003) 182301



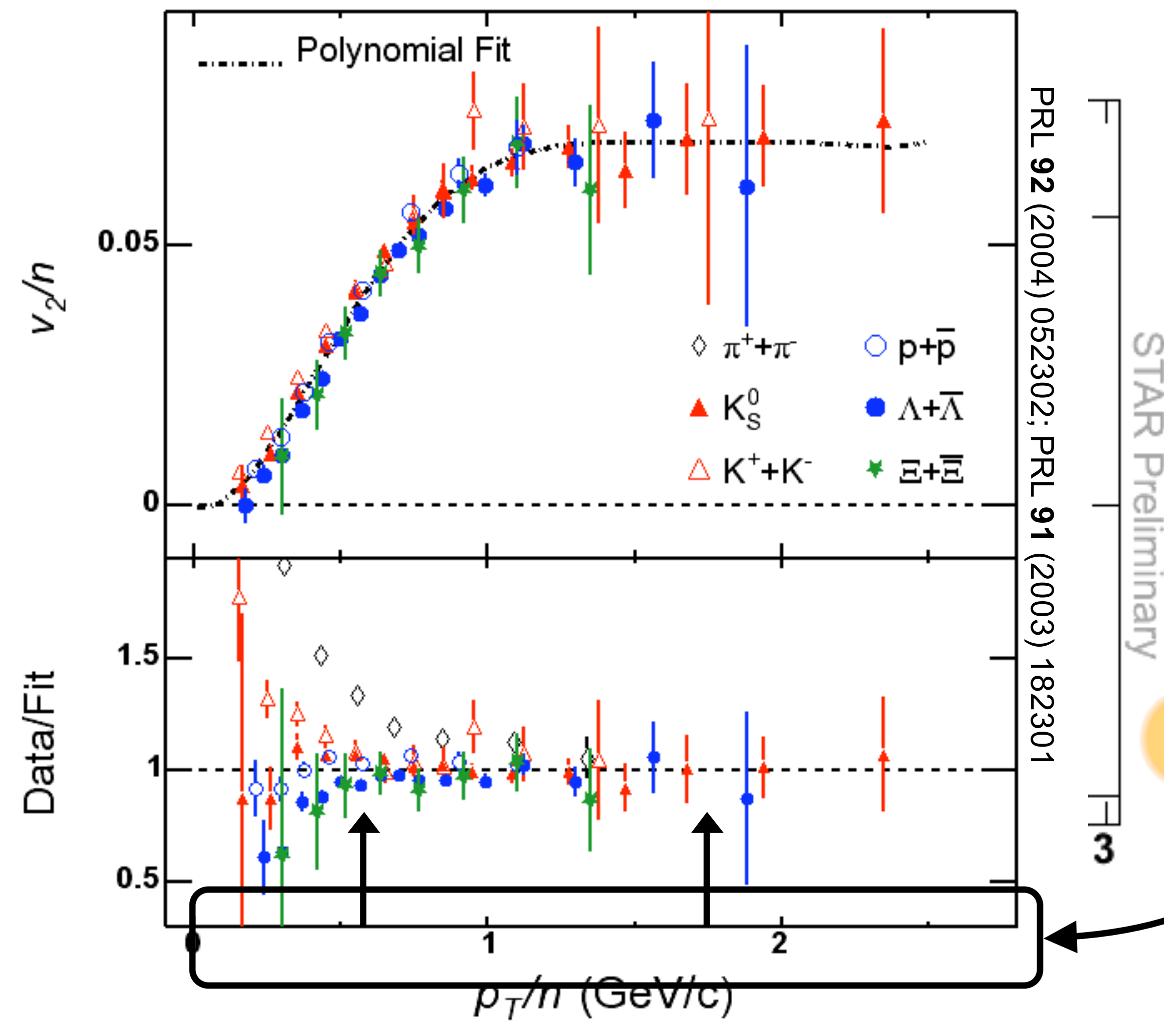

Data deviate from hydro at higher $p_T$ (as expected).

How is $v_2$ established at $p_T$ above 2 GeV/c?

Why is baryon $v_2$ so large; because of its mass or quark number?

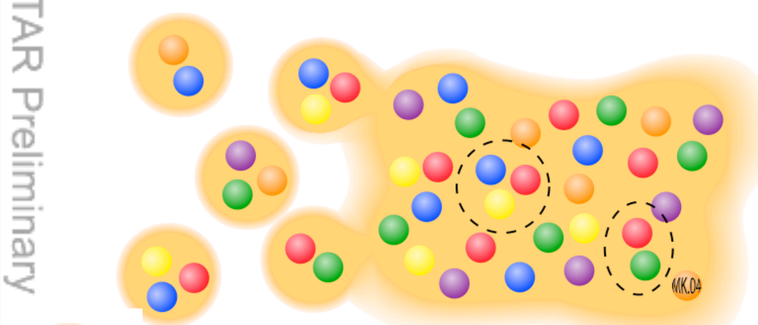
# Constituent-quark scaling






At intermediate $p_T$ $v_2$ appears to depend on quark-number

For $p_T/n > 0.6$ GeV/c, $v_2$ scales with the no. of constituent quarks n, as predicted for hadron formation by quark coalescence



$$v_2^{hadron}(p_T^{hadron}) \approx n v_2^{quark}(p_T^{quark})$$

$$p_T^{hadron} \approx n p_T^{quark}$$

Pions deviate: perhaps because they are goldstone bosons and do not acquire their mass from constituent quarks.

# Higher Harmonics

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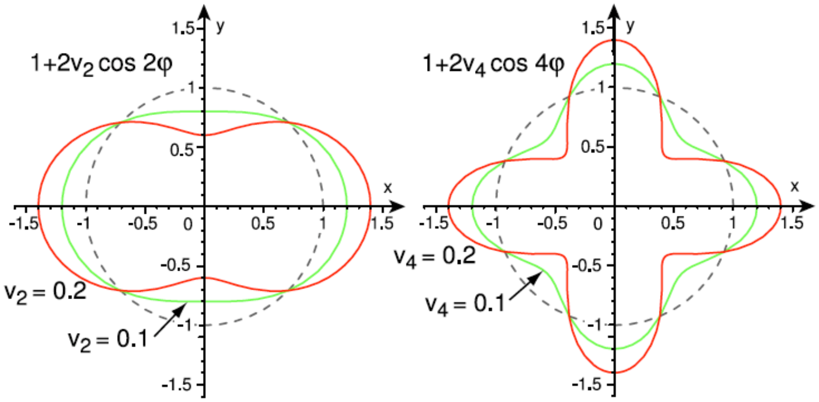
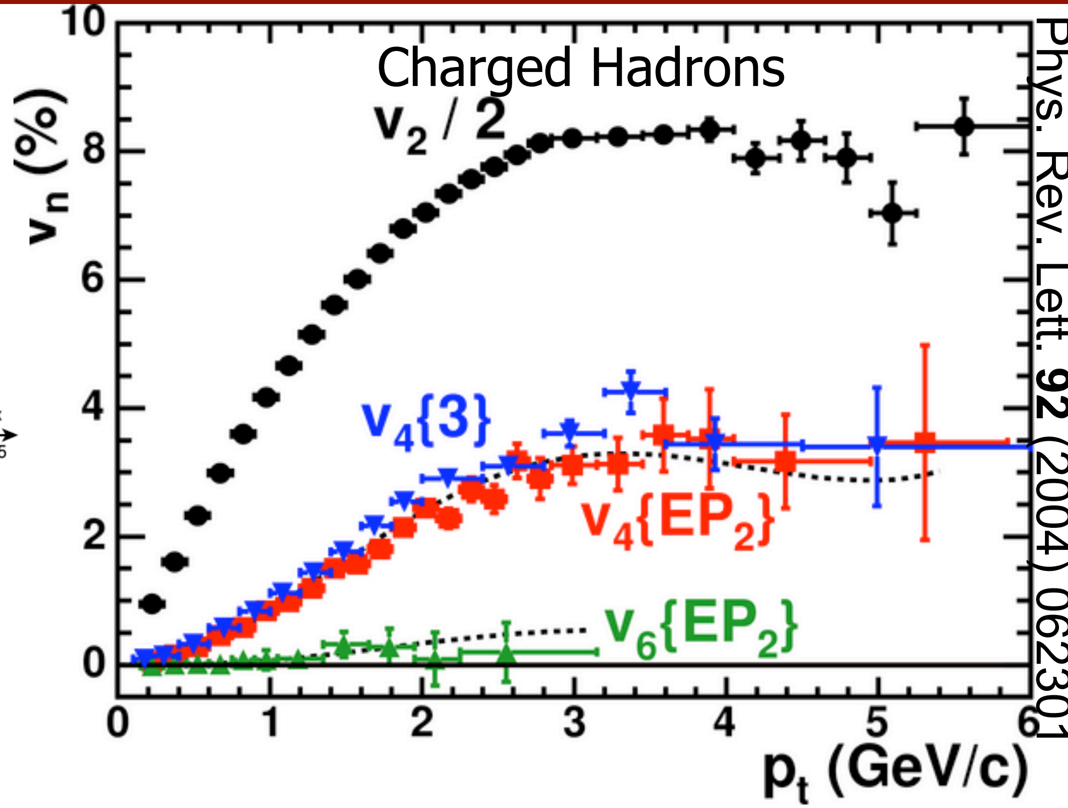
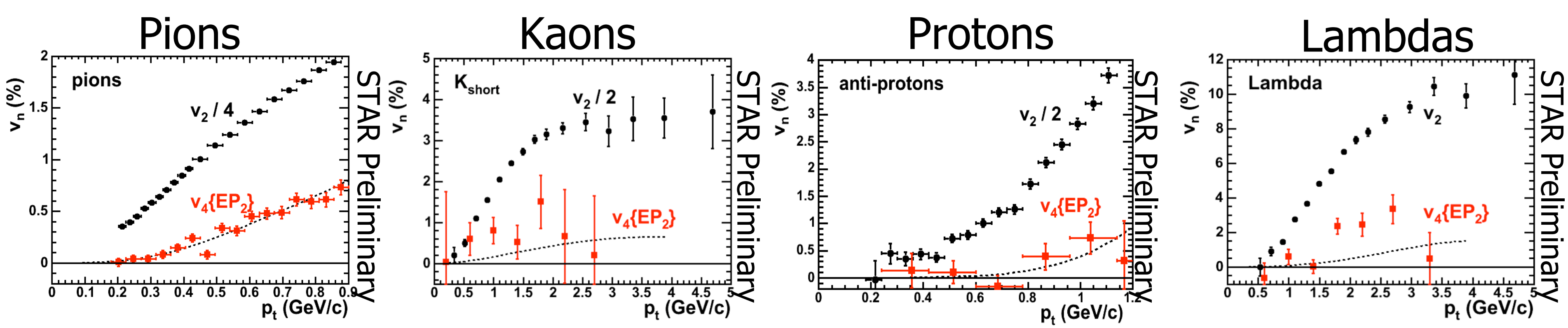
Another probe of the expansion dynamics




With better statistics at intermediate $p_T$ we can test constituent quark scaling for meson and baryon $v_4$.



# Another unique observable

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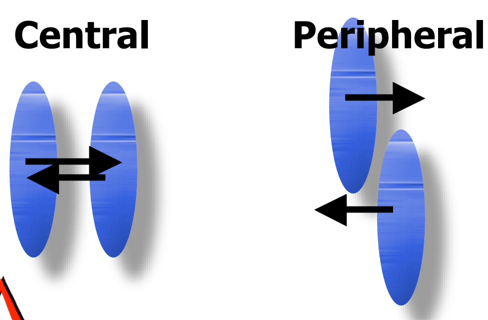
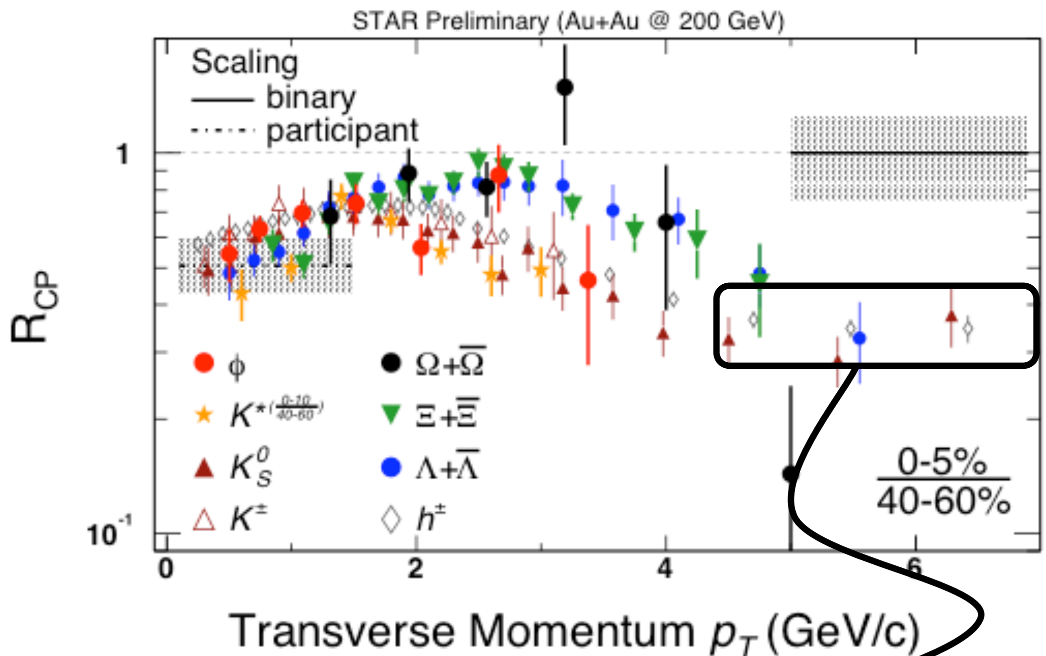
## CENTRALITY DEPENDENCE OF YIELDS

Spectra from head-on (central) collisions compared to spectra from grazing (peripheral) collisions:

$$R_{CP} = \frac{\left[d^2N/dp_T dy\right]^{central}}{\left[d^2N/dp_T dy\right]^{peripheral}} \frac{N_{coll}^{peripheral}}{N_{coll}^{central}}$$

scaled by the expected number of hard collisions $N_{coll}$. $R_{CP} = 1$ indicates scaling.

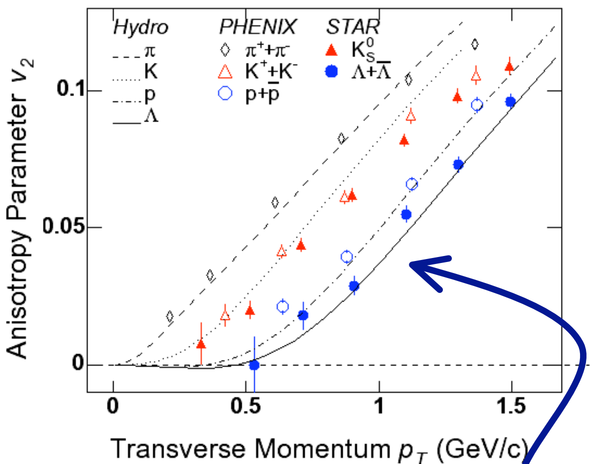


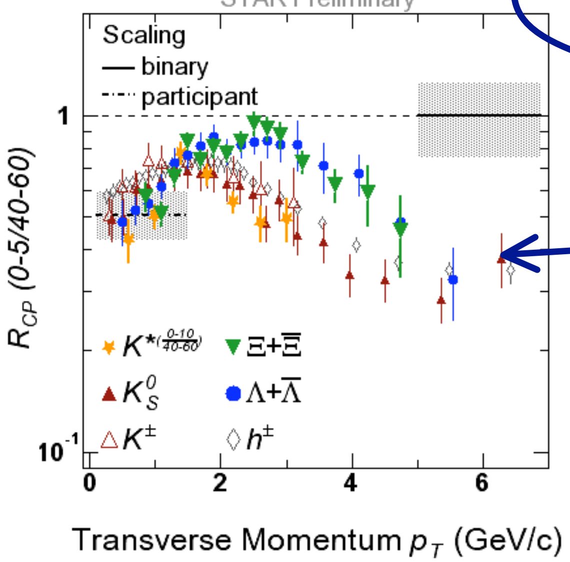



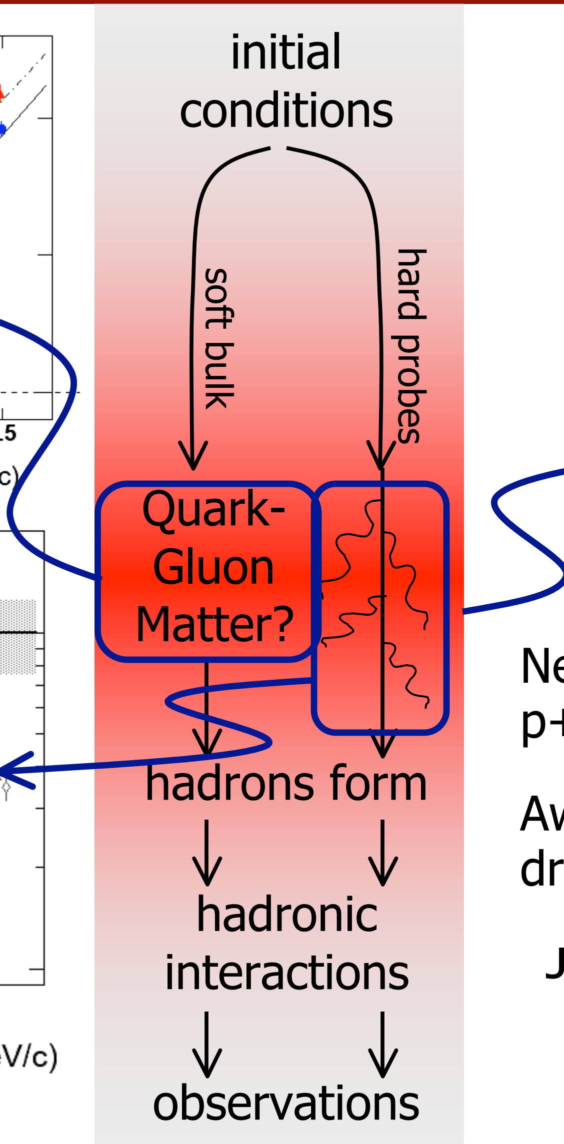

Factor of 5 suppression of yields!
Signature of jet-quenching

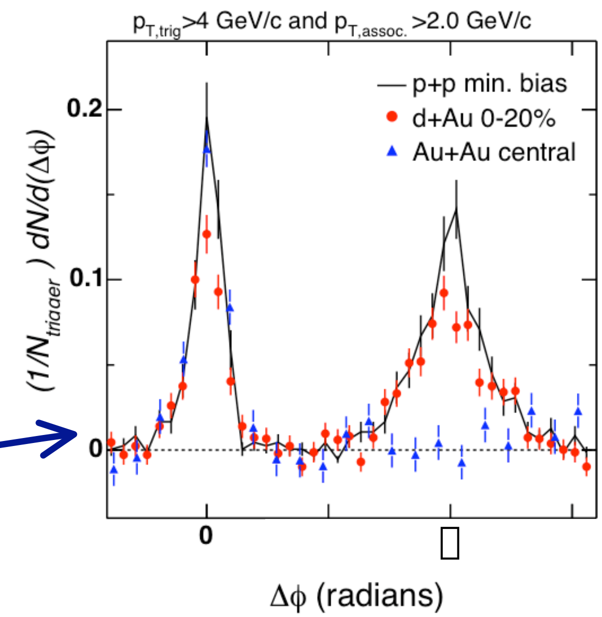
# 3rd piece of the puzzle





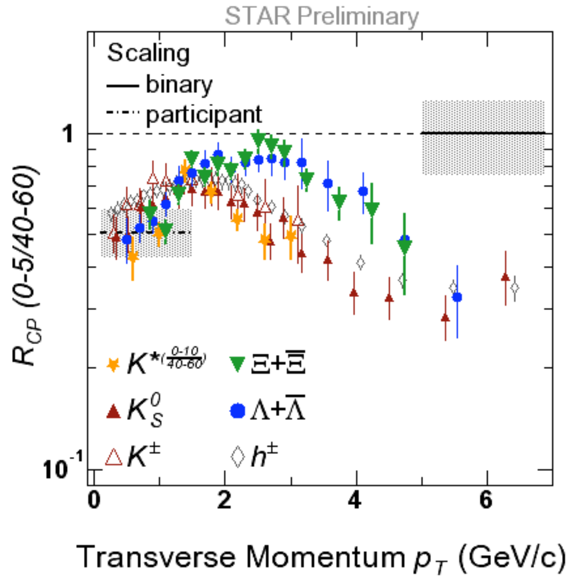



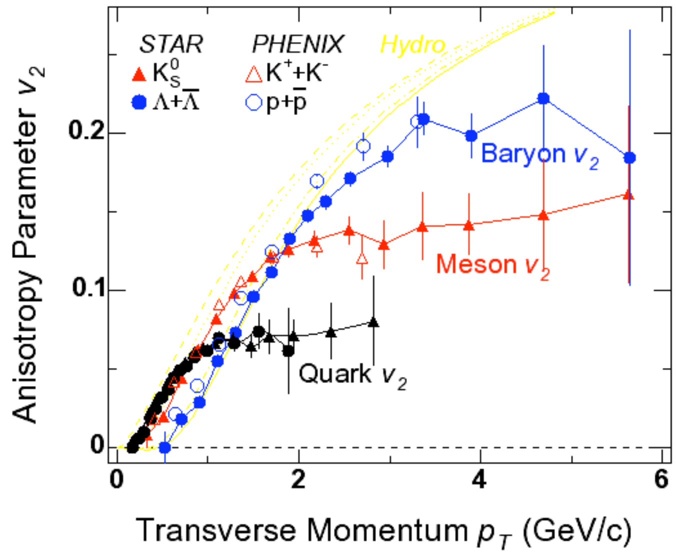

Near-side correlations are *"similar"* in p+p, d+Au, and Au+Au.

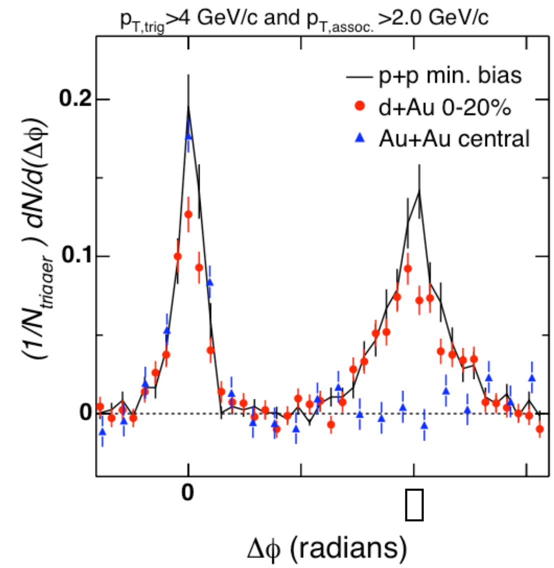
Away-side correlations in Au+Au are drastically different.

Jet quenching in dense matter: reduces high $p_T$ yields and back-to-back correlations

# What's happening at intermediate $p_T$?




$$\Delta p \Delta x \geq \hbar$$

- We are in the $p_T$ region to probe constituent-quark length scales and observe quark numbers dependencies.
- Recombination is one possible microscopic explanation of how the quark-number dependence arises.

# Hard Processes at Intermediate $p_T$?

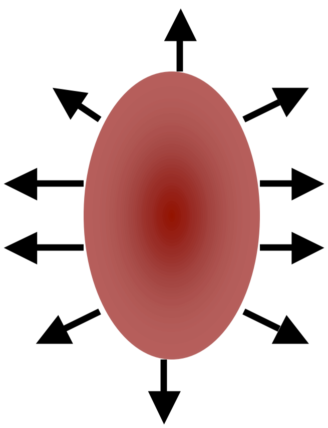


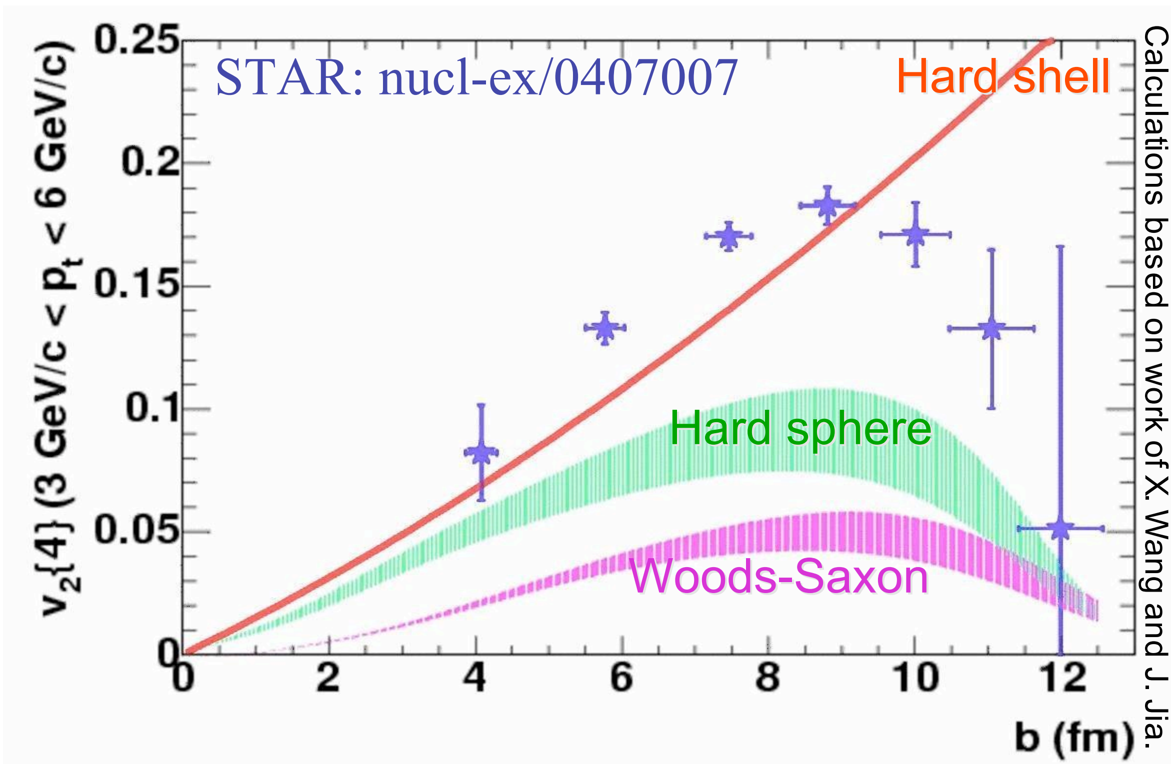
Anisotropy at intermediate $p_T$ is too large for any models that don't incorporate either hydrodynamics or recombination.

No mechanism has been proposed that can yield these $v_2$ values for hadrons produced predominantly from hard processes.

*Energy loss calculations may work for $v_2$ at higher $p_T$ but not here.

*Already shown by Shuryak at QM2001

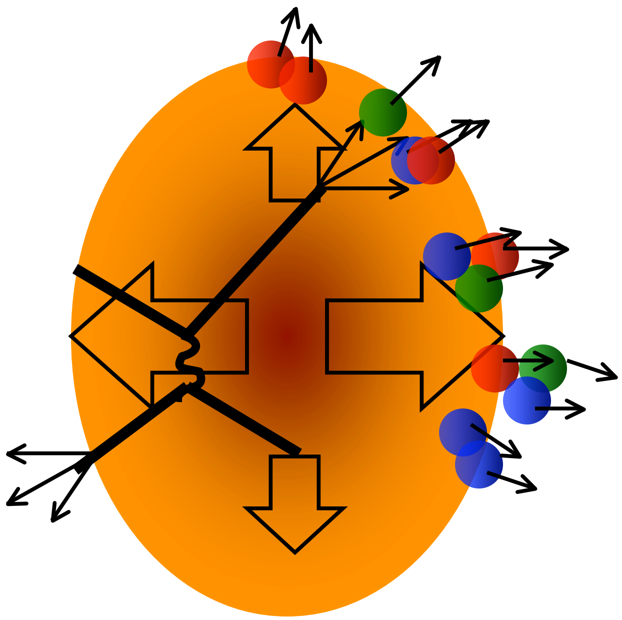




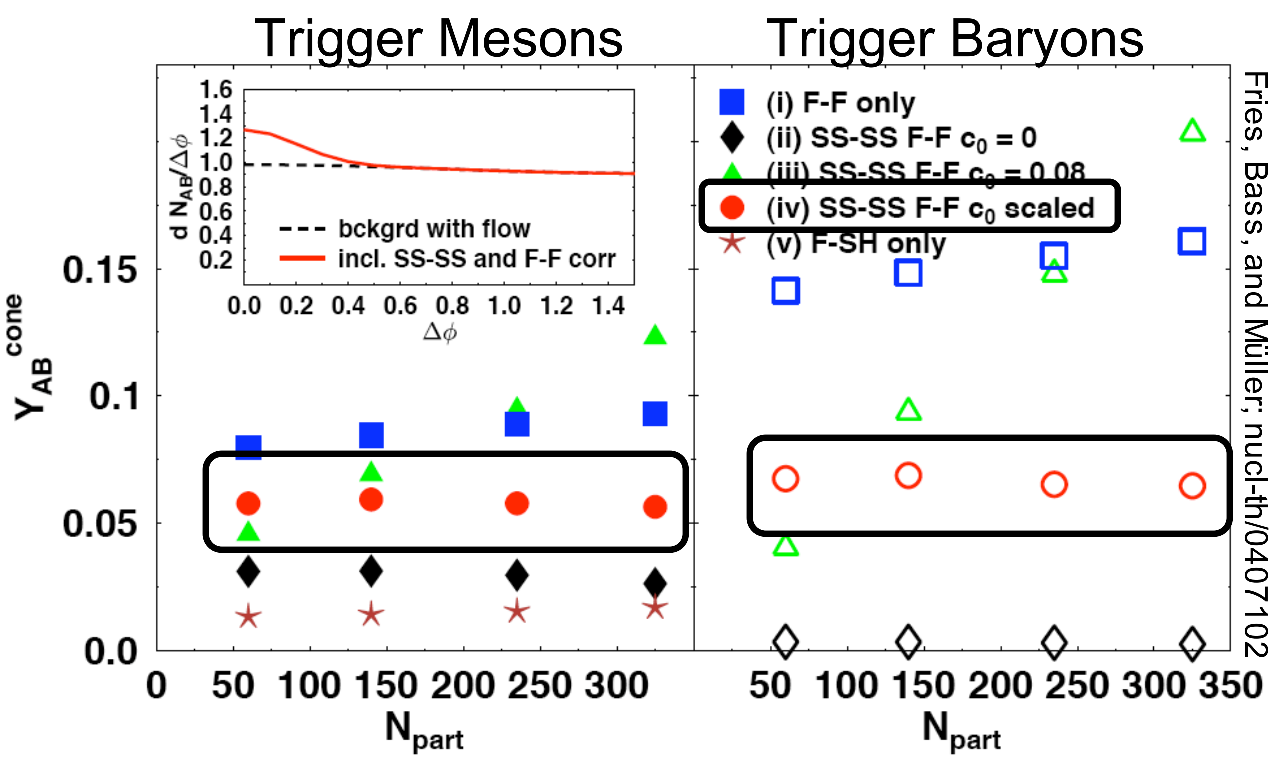
# "Jettiness" at Intermediate $p_T$



Perhaps correlations amongst constituent quarks that recombine can account for the correlations in Au+Au collisions.



Associated Yield



# Correlations: the odd man out?

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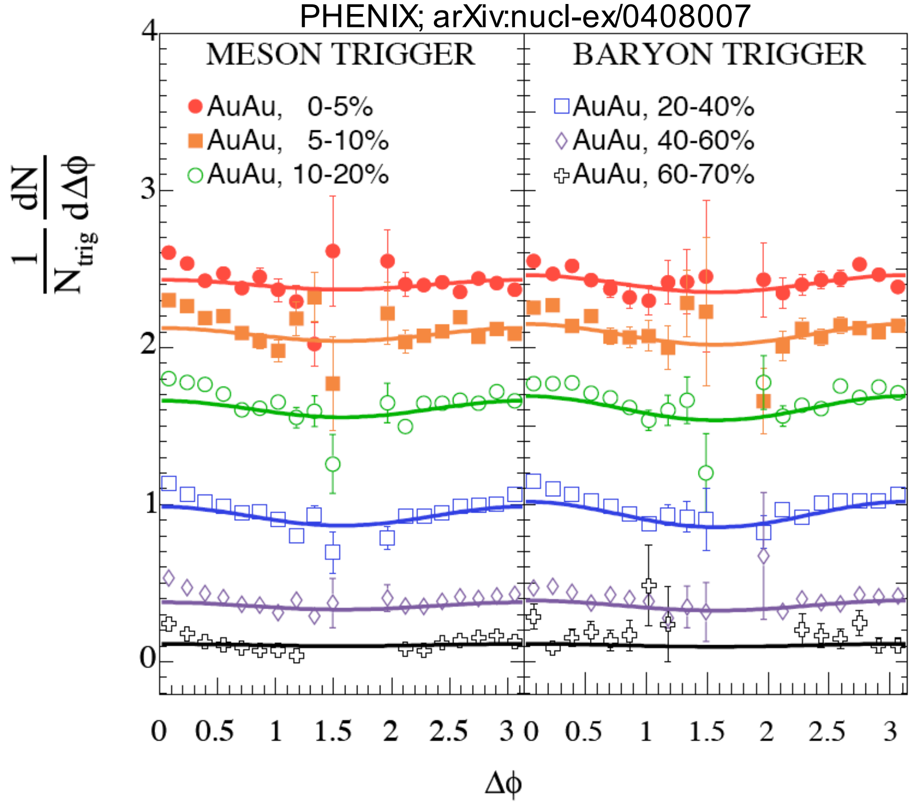
Observed correlations might be accommodated within the same picture that explains **less suppression of baryon yields AND a larger baryon $v_2$**?

PHENIX; arXiv:nucl-ex/0408007

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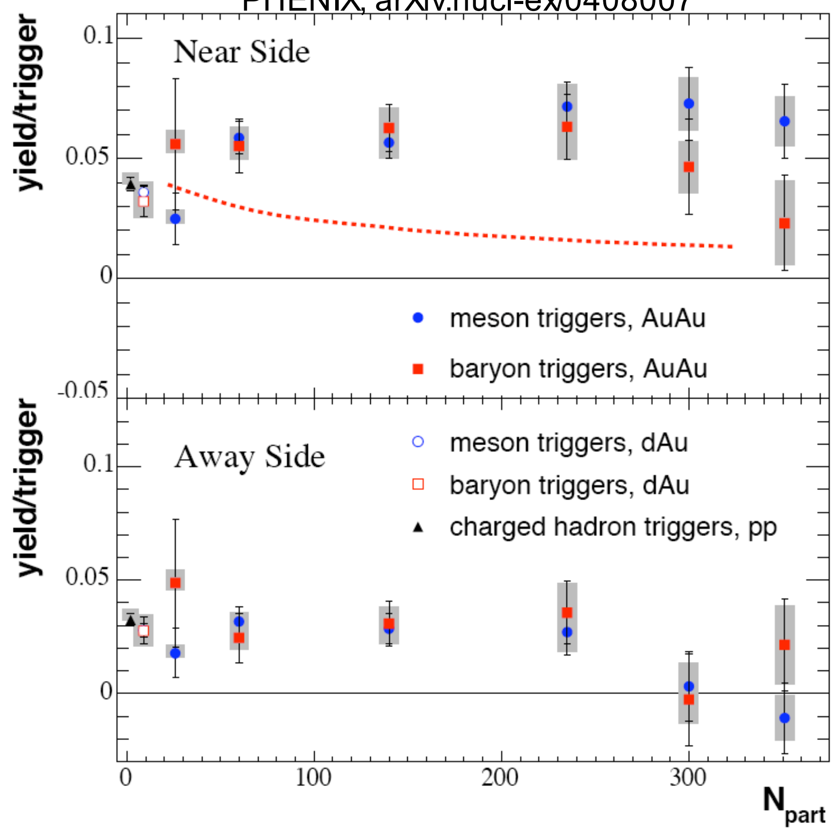
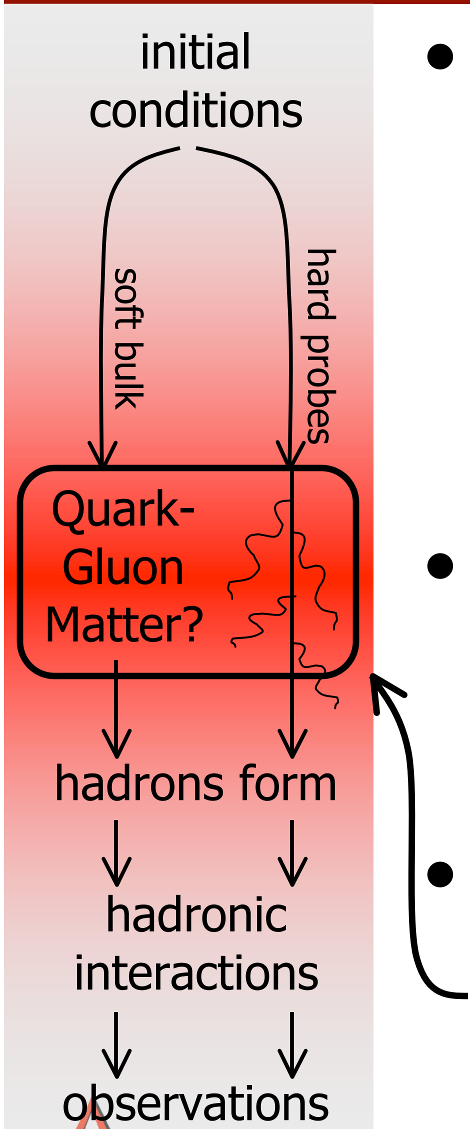


# Conclusions




- An apparent constituent-quark-number dependence arises in nuclear collisions:
  - most likely a manifestation of sub-hadronic degrees-of-freedom.
  - will demonstrate that coordinate- to momentum-space conversion happens before hadrons are formed.
  - the larger data set being analyzed will be conclusive.
- Baryon yields at intermediate $p_T$ are not suppressed ($R_{CP}$~1):
  - rules out available jet-quenching explanation of the large baryon $v_2$.
- So far, correlation measurements are difficult to interpret:
  - but they are likely to reveal how the non-hadronic "matter" and hard probes interact.

# Thanks!

-Paul Sorensen