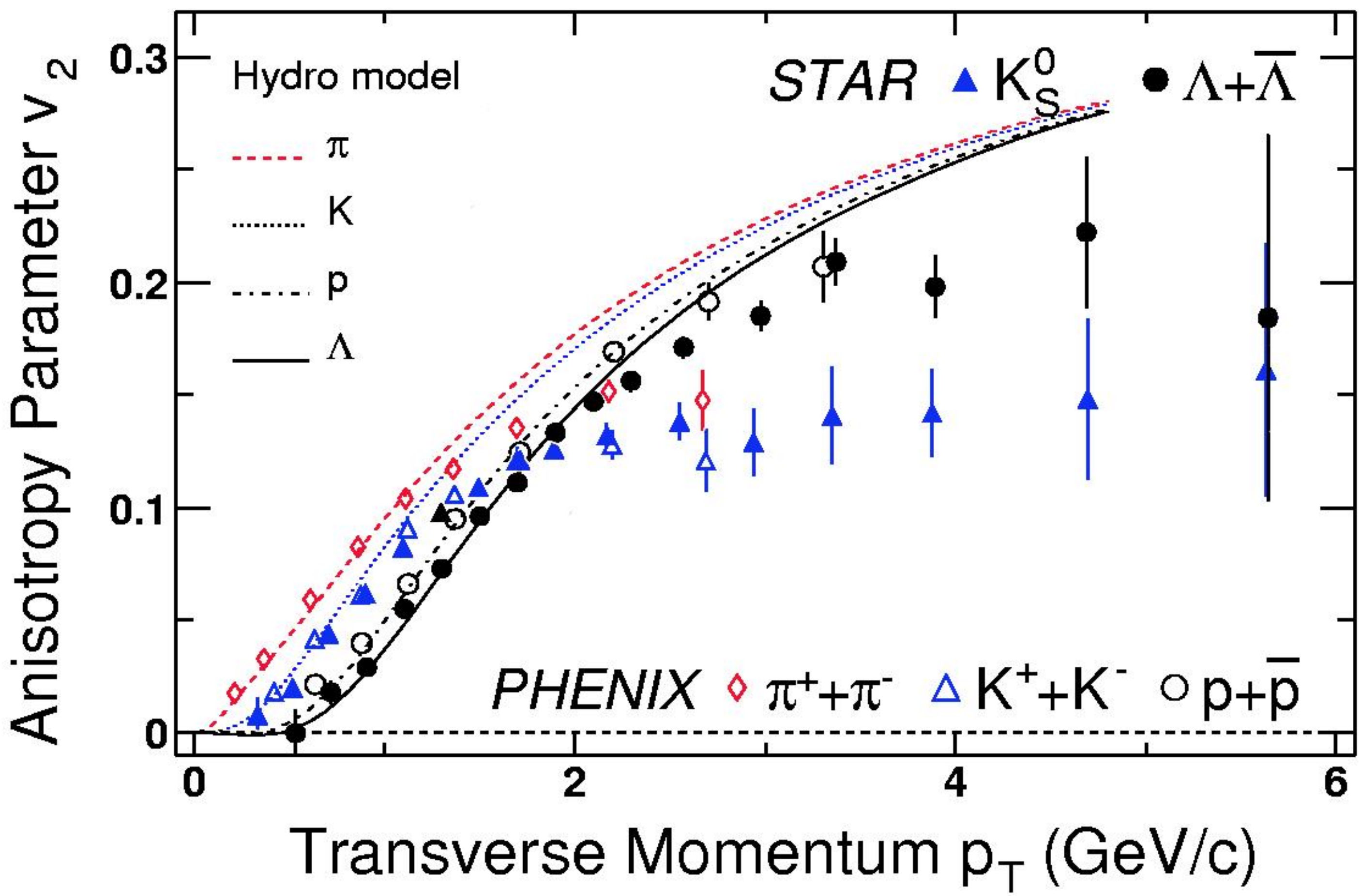
Baryon puzzle: hadronization in heavy-ion collisions

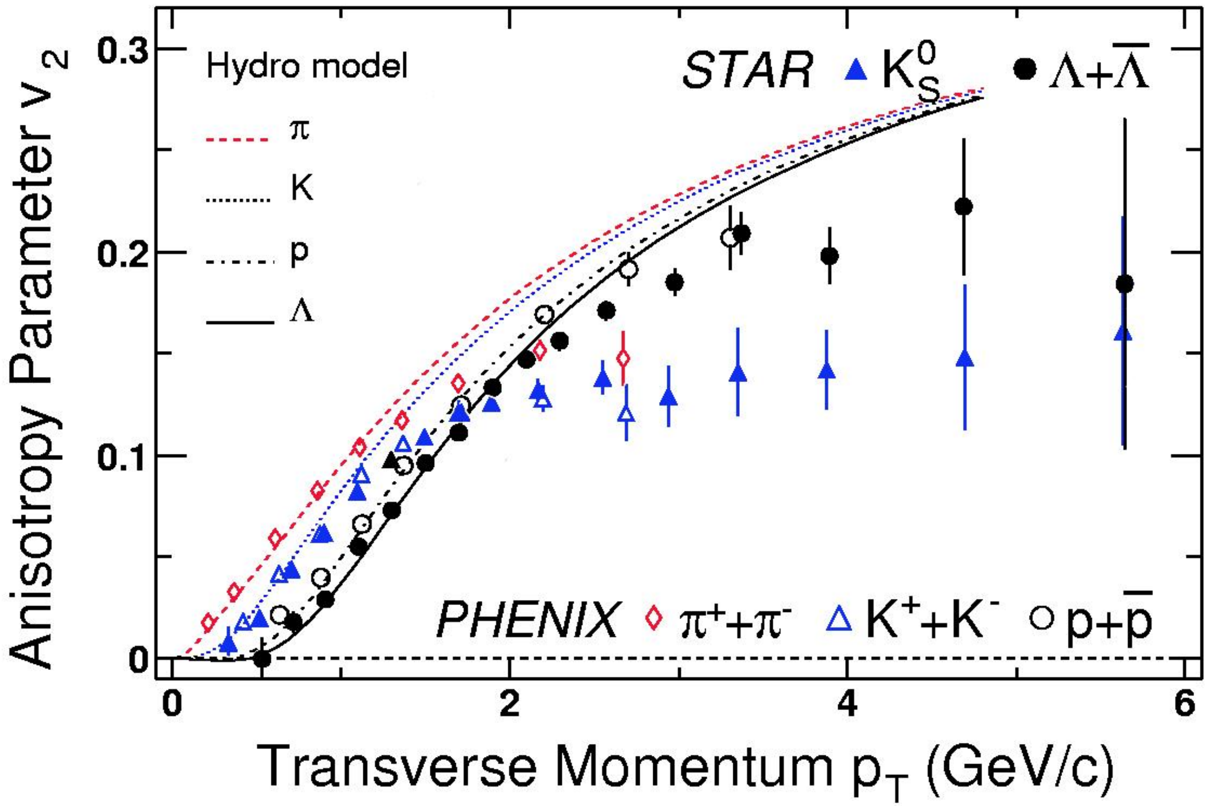
- We discussed particle spectra, radial and elliptic flow, jet quenching
- Today, let's take a closer look at the data to discover
  - The "baryon puzzle"

Elliptic Flow of identified particles



At low p_T hydro works remarkably well. Deviation from hydro above ~ 1-2 GeV/c

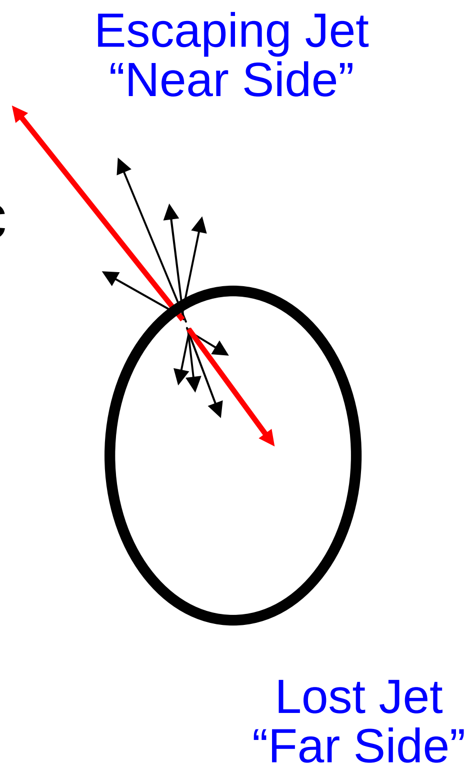
What causes the azimuthal asymmetry at high p_T ?

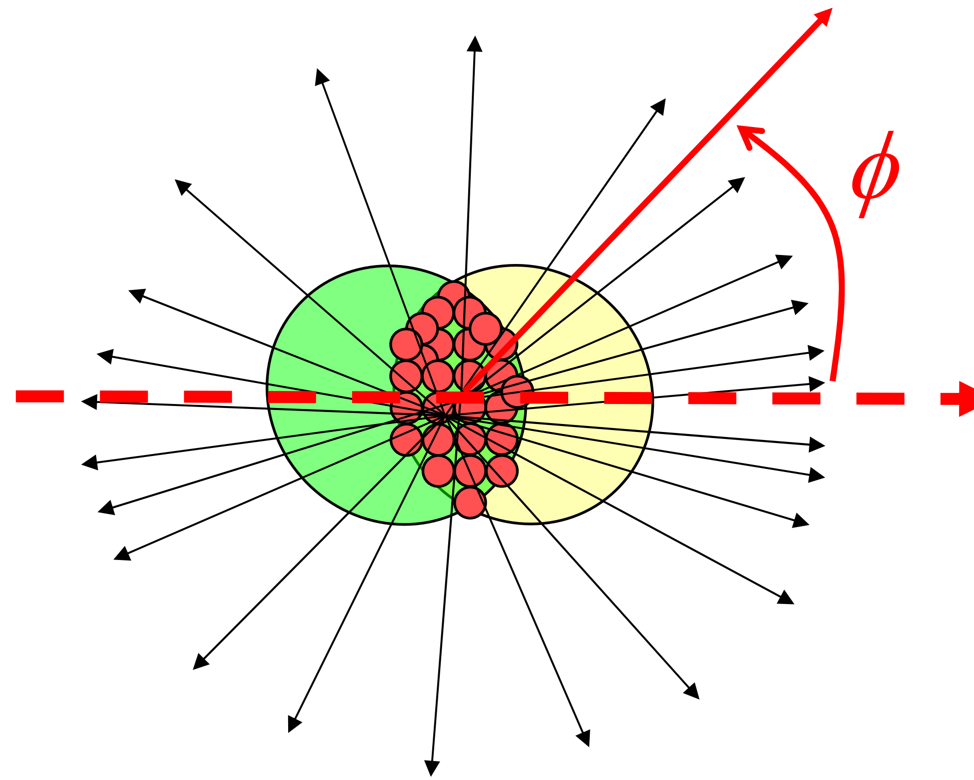


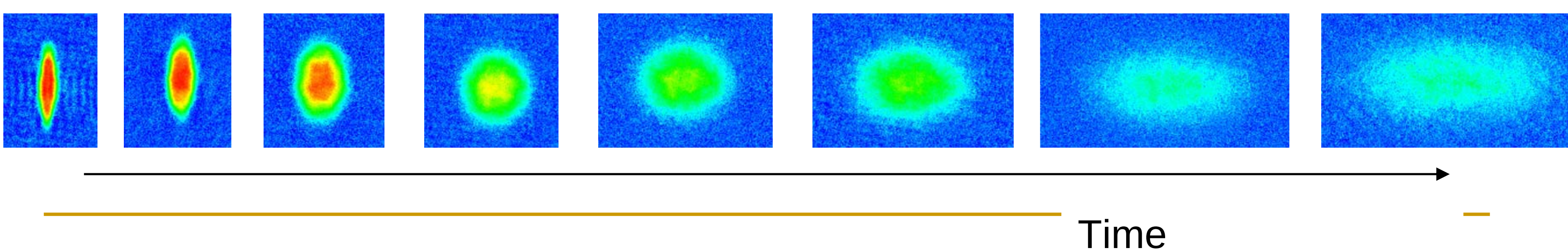
Hint: it is not pressure moving the bulk medium.

Back to back jets (di-jets) and flow

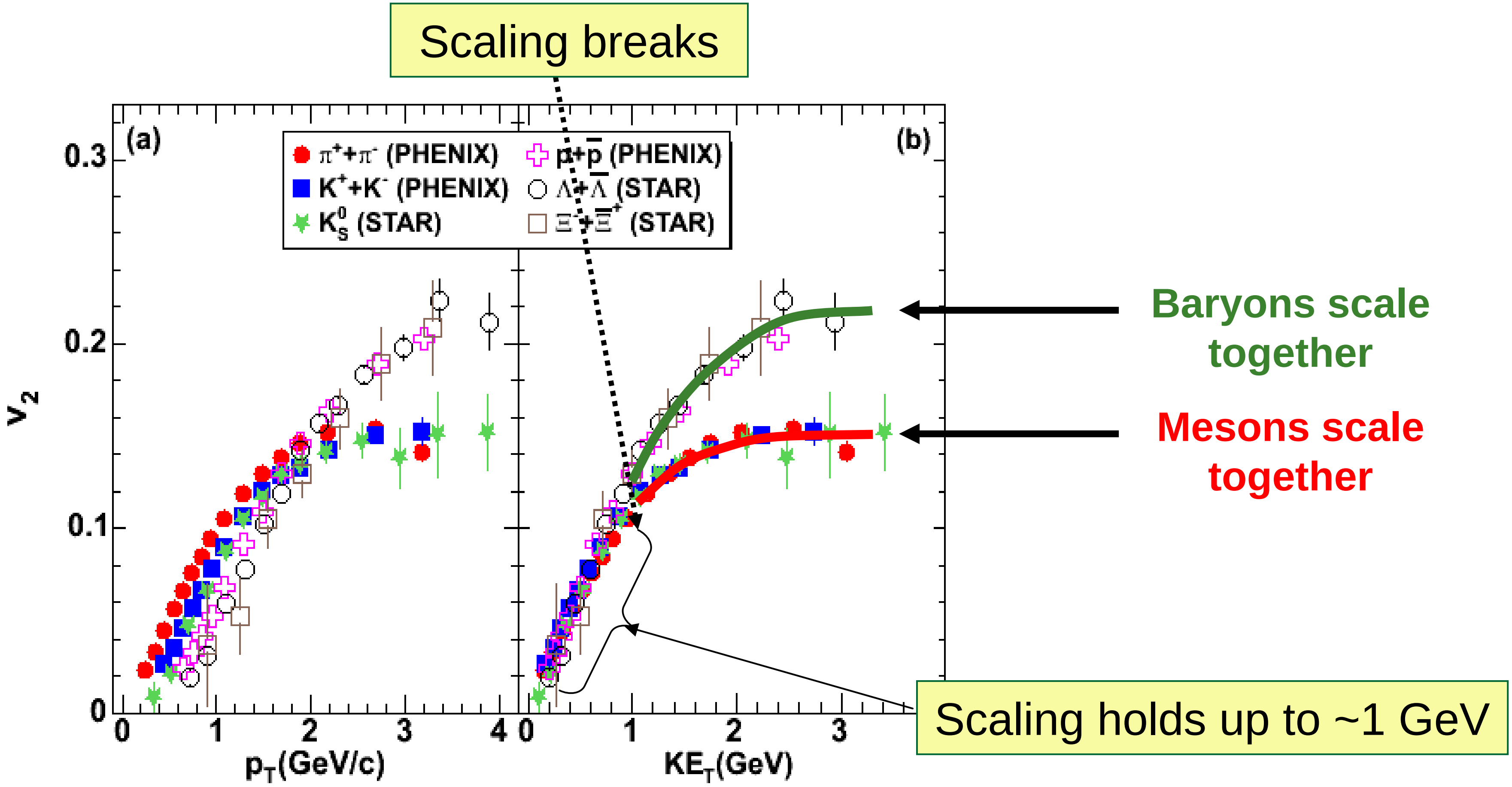
Tomographic information on the medium





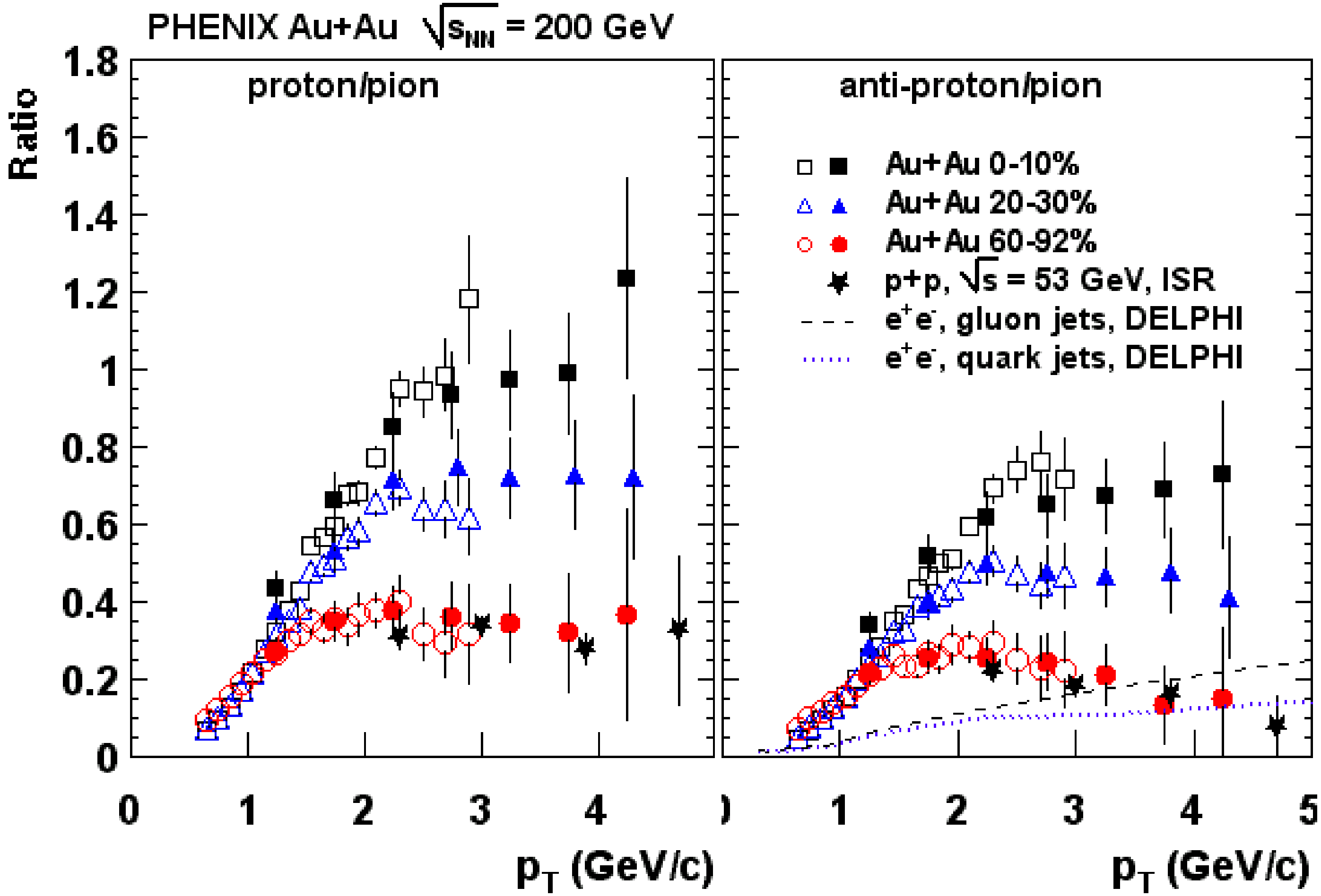


Test for hydro scaling in azimuthal asymmetry

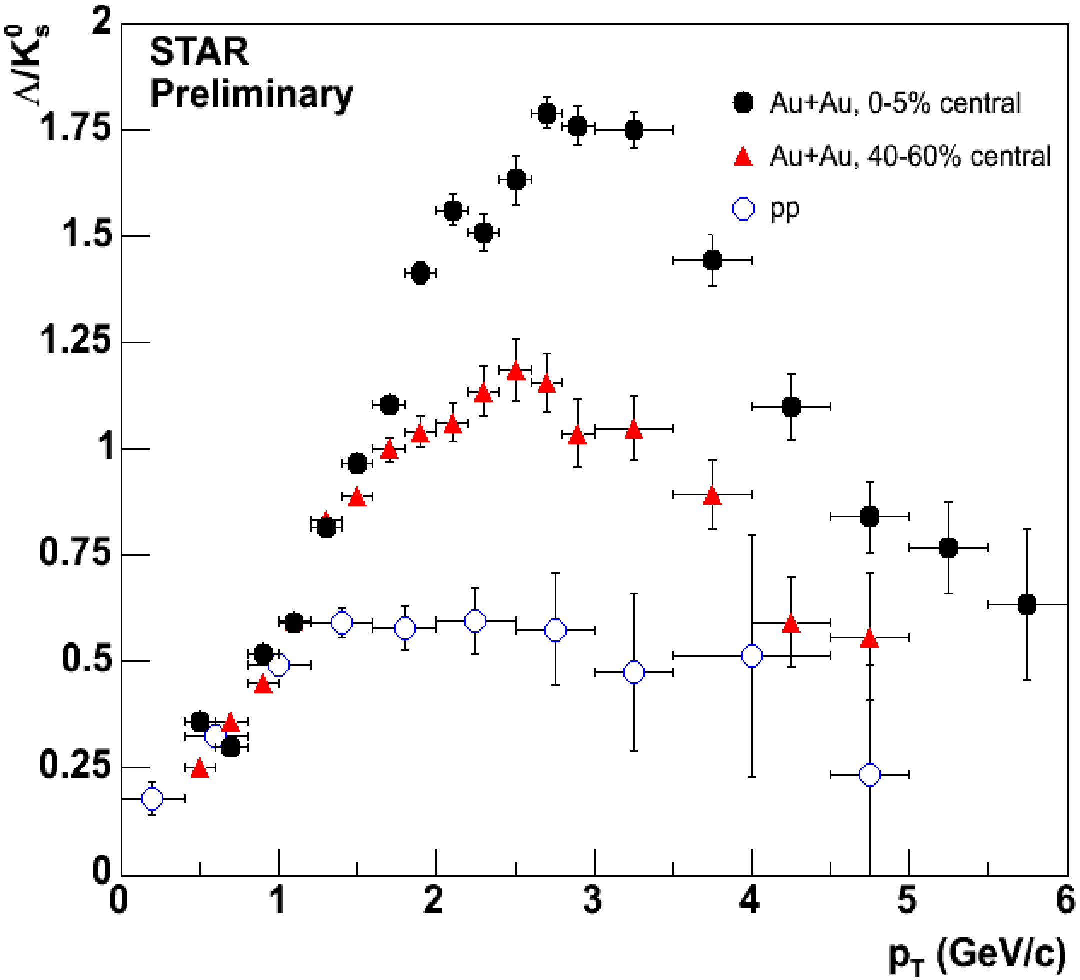


- Something unusual is going on with the baryons
  - Parton energy loss followed by fragmentation would produce the same asymmetry for all types of particles (baryons and mesons, heavy and light)
  - The baryon azimuthal asymmetry at high-p_T is too large to be explained by jet quenching
  - It is not explained by hydro either: at high-p_T the mass doesn’t play a role – all particles should have the same v2

There are too many baryons at high-p_T in central AuAu collisions

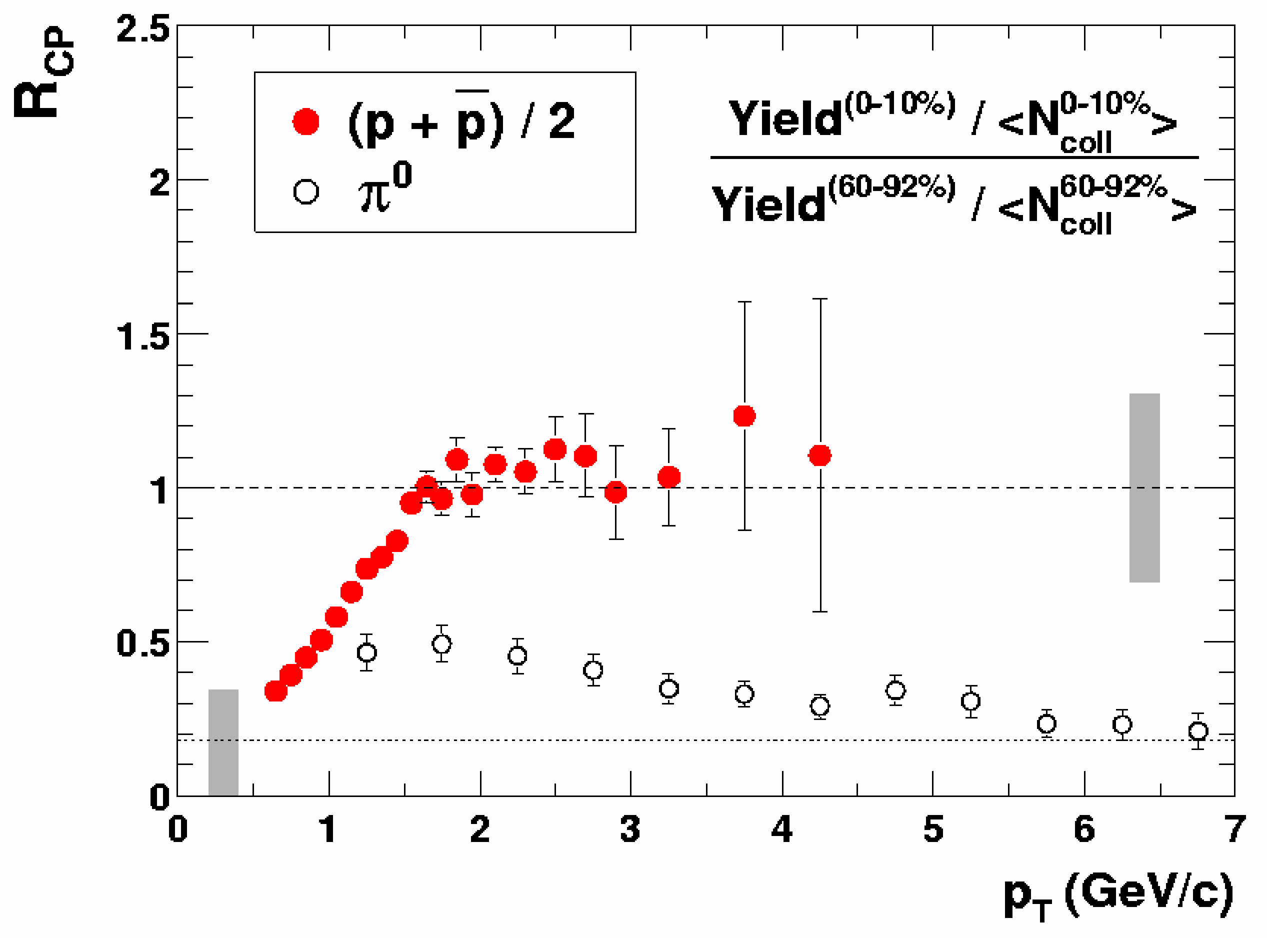


Baryon/meson ratios for strange particles



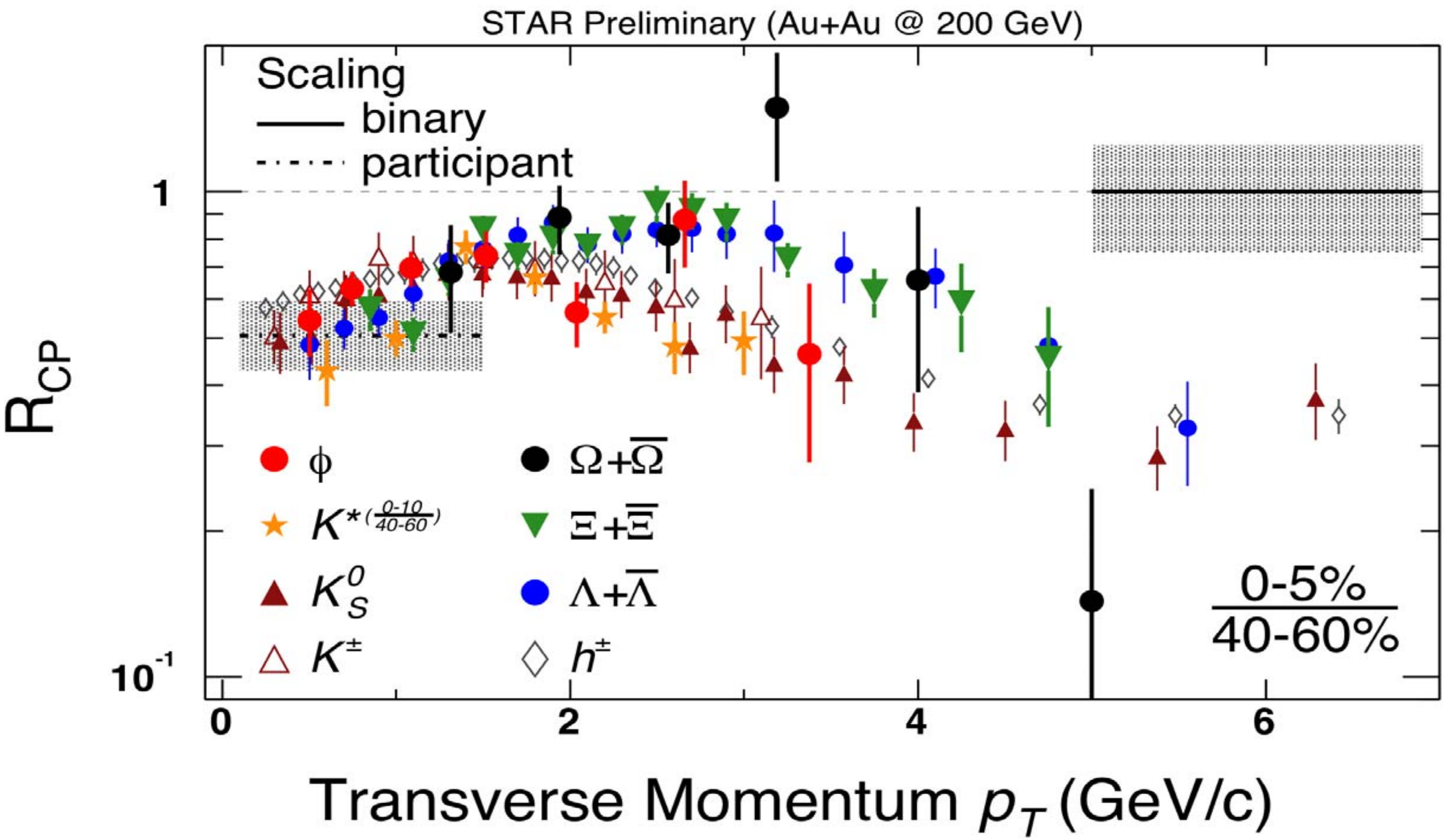
Also show baryon excess in central AuAu collisions.

Baryon puzzle at high-p_T



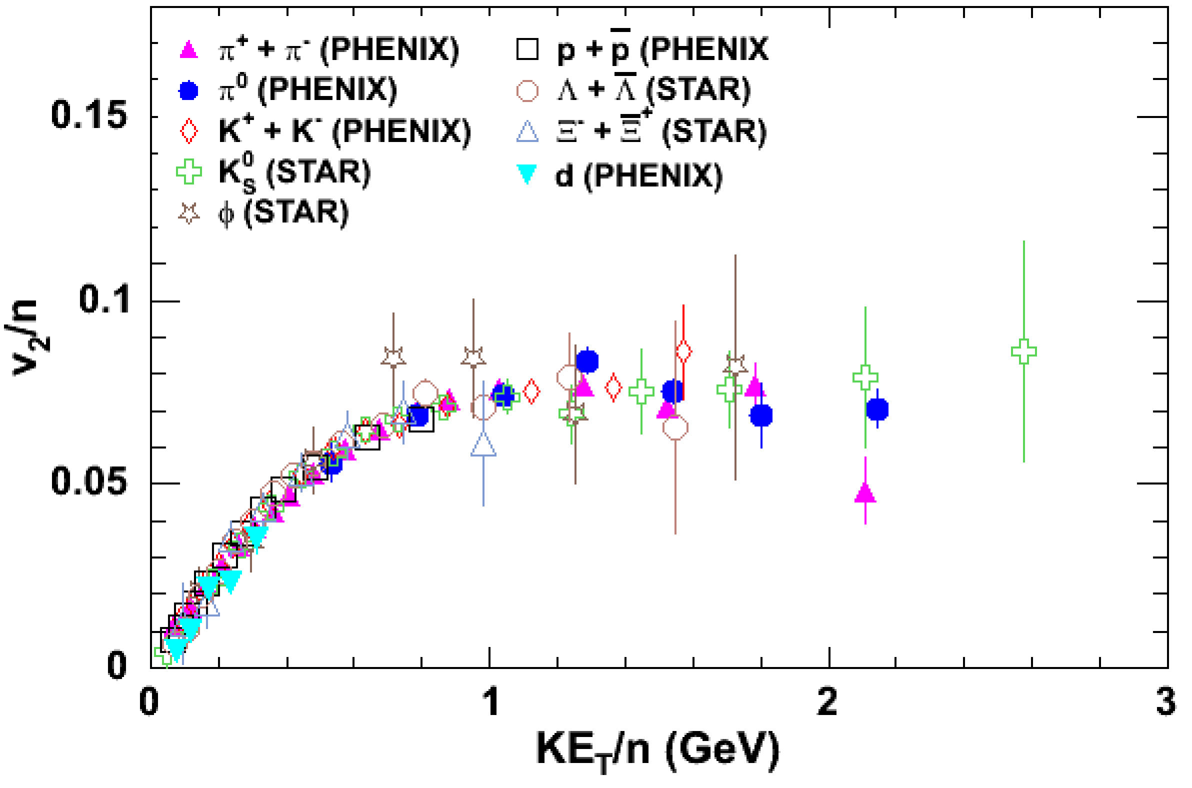
No apparent suppression for protons and anti-protons

Adding more particles: test for mass effects



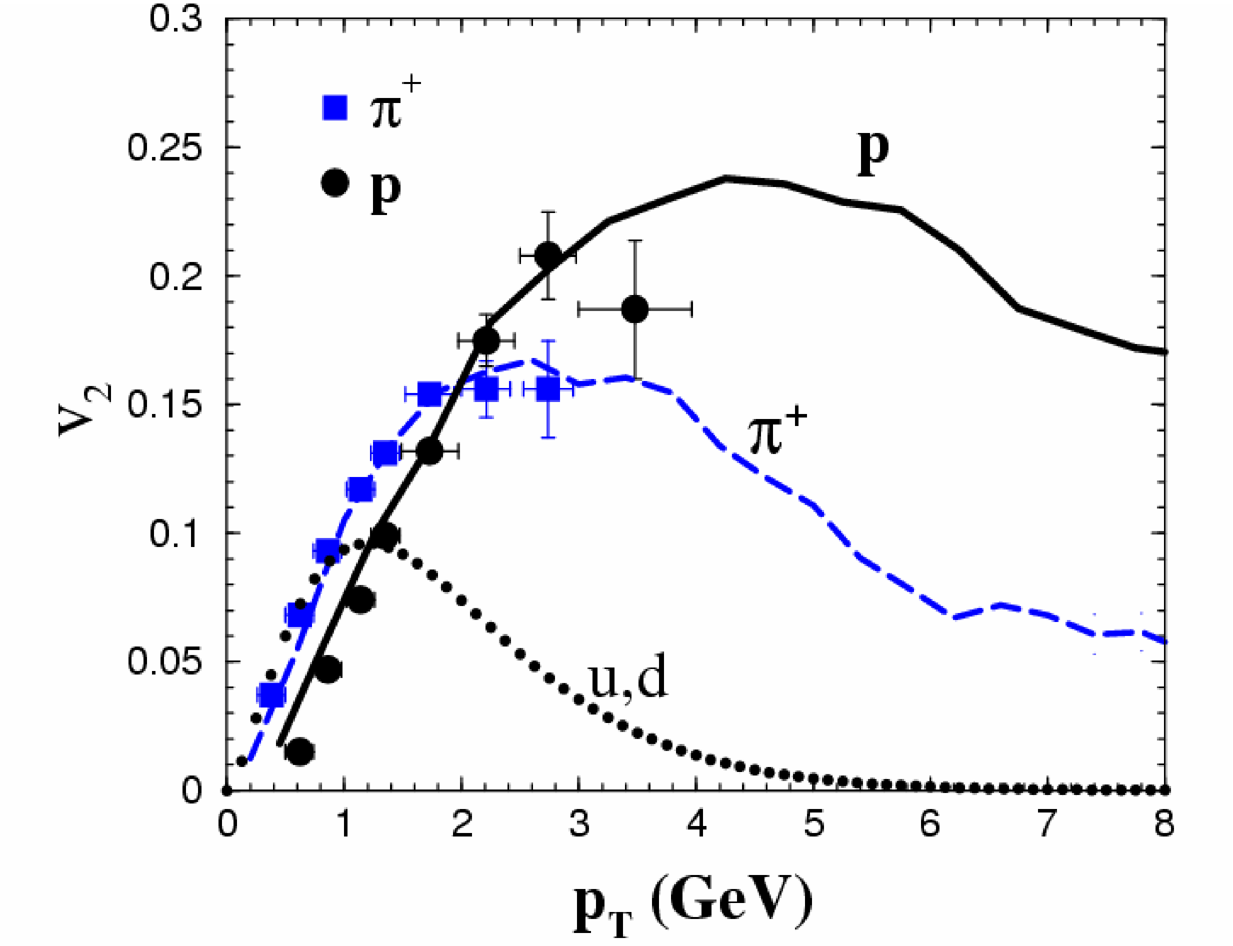
We see dependence on # of quarks, not mass !

So let's scale v_2 with # of quarks



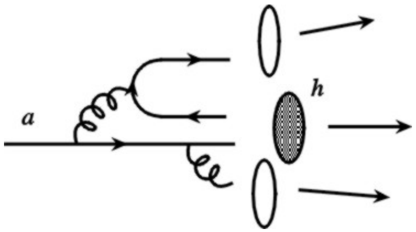
Hints to partonic flow !

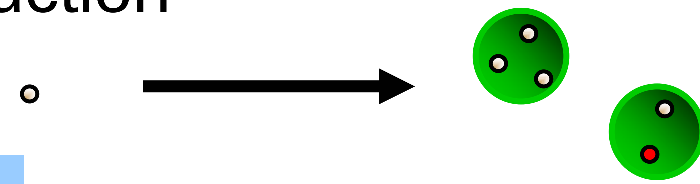
Quark flow and quark recombination



Hadronization at high-p_T :Fragmentation

- E.g. measure hadrons produced in e^+e^-
- Single parton has to hadronize = fragmentation
  - Radiation of gluons + pair production

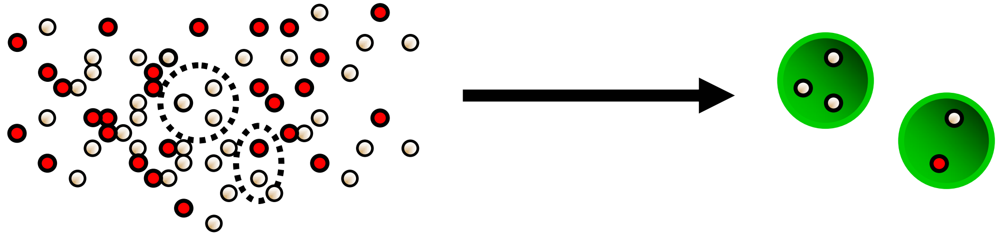




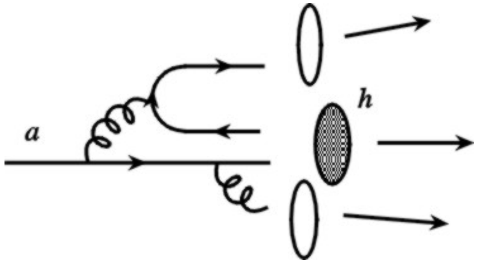
- Factorization: $$\sigma_h = \sum_p \sigma_p \otimes D_{p \to h}$$
  - Holds for $Q^2 \to \infty$

Dense Parton Systems

- Fragmentation = limit of hadronization for very dilute systems (parton density $\rightarrow$ 0)
- What happens in the opposite limit (thermalized phase of partons just above T_c)?
  - No perturbative scale in the problem ($T \approx \Lambda_{\mathrm{QCD}}$)
- Naively: recombine partons



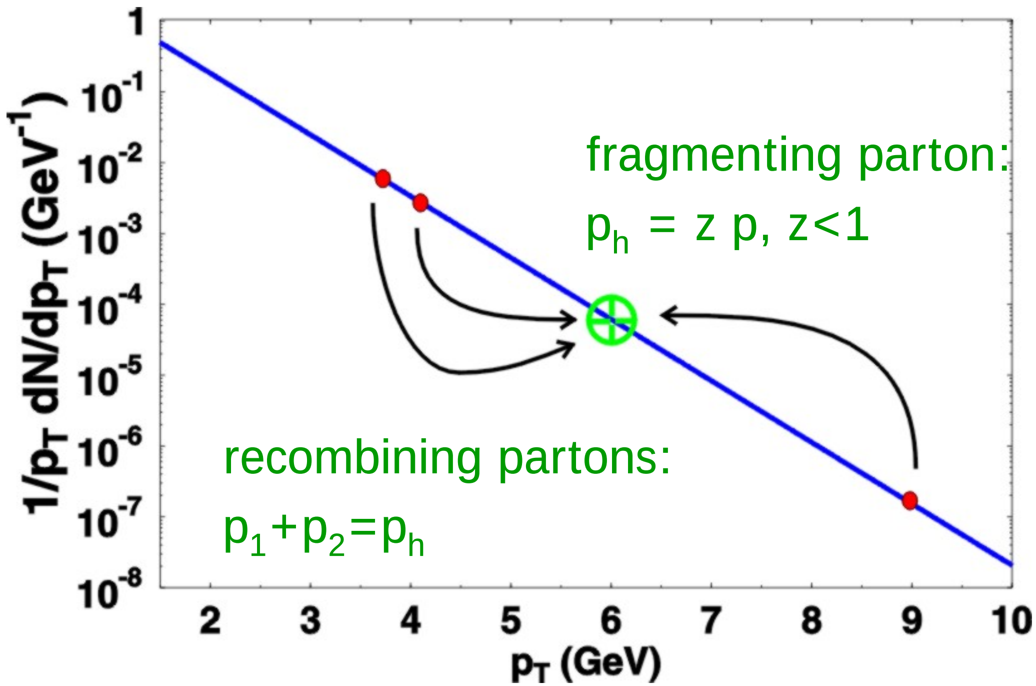
Recombination Concept: favors baryons at high-p_T

Fragmentation: 

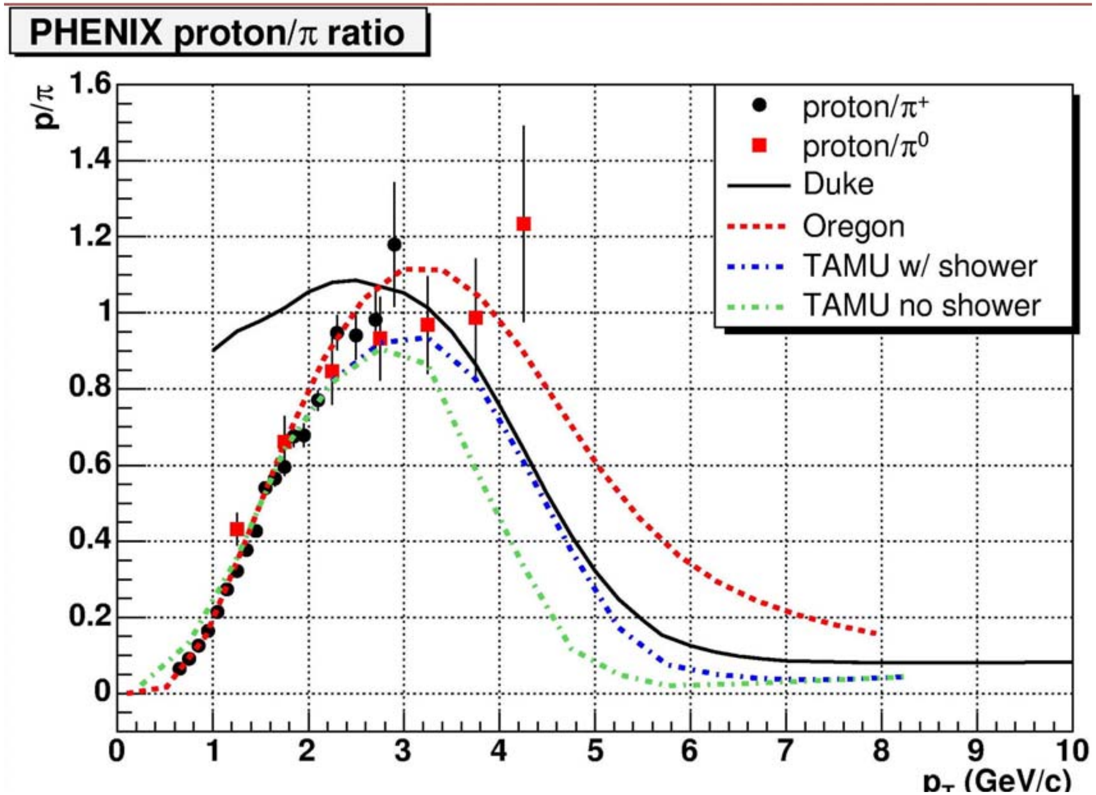
$$E\frac{dN_h}{d^3P}=\int_0^1 \frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)}D_{\alpha\to h}(z)$$

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

➢ understand behavior of protons!



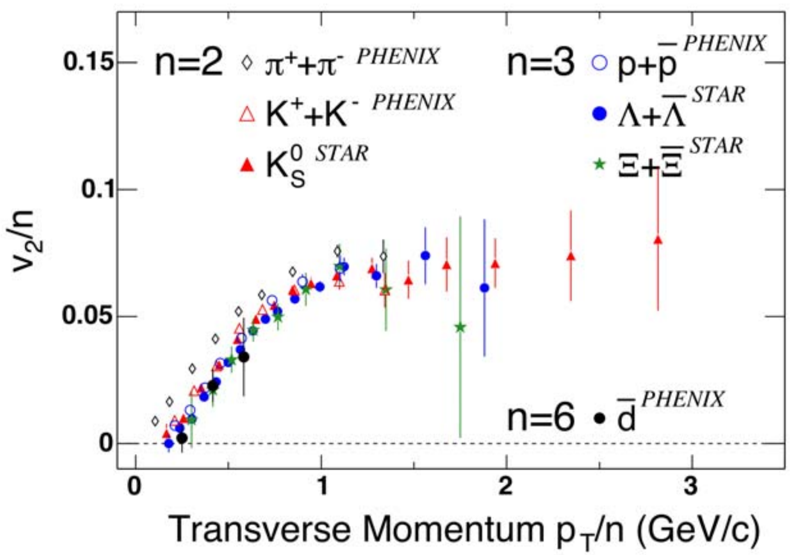
Recombination Models: p/π ratio

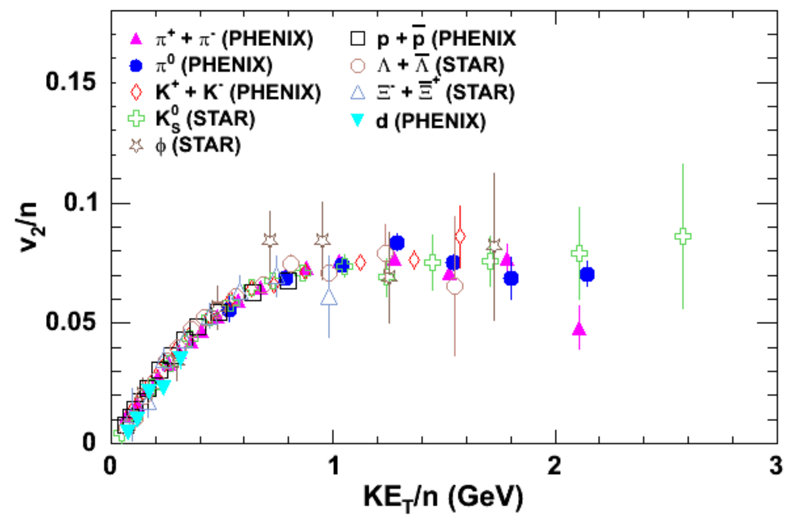


- Duke:
  - Pure thermal reco.
- Oregon:
  - Fragmentation itself is recast as a recombination process. HI collision simply adds extra thermal quarks during the process.
- TAMU:
  - Jets and also feeddown from resonances.

Recombination and elliptic flow

$$v_2^M(p_t) = 2v_2^p\left(\frac{p_t}{2}\right) \quad \text{and} \quad v_2^B(p_t) = 3v_2^p\left(\frac{p_t}{3}\right)$$





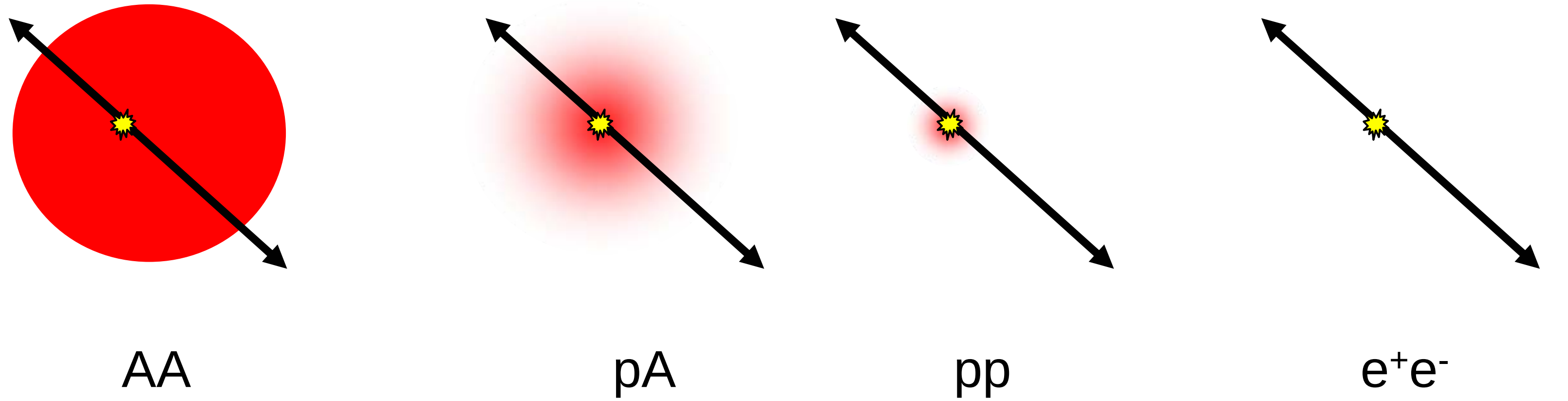
Recombination summary

- Recombination is a very simple model to describe a very complex process (hadronization)
- And it does a remarkable job in describing v2, baryon/meson ratios and high-p_T suppression
- Recombination from a thermalized quark distribution means QGP
- Partonic elliptic flow reveals that the degrees of freedom are NOT hadrons

- But not all data is consistent with reco from thermalized quark distribution: e.g. – jet correlation measurements reveal that both baryons and mesons show correlations (i.e. at least one quark was correlated with the jet axis and came from fragmentation)
- Does this spoil the QGP hypothesis ? – No, because the bulk medium still looks thermalized. Just a few fragmentation partons at high-p_T which are not thermalized (as expected)

Do we need QGP for recombination to work?

- No, not really: just a certain parton density
- Fragmentation is very ineffective for baryons!
- It might just be easier to pick up soft partons instead of creating them, even in cold nuclear matter.



Recombination in d+Au?

- Yields of protons and pions can be explained in a picture containing fragmentation and soft/hard recombination.
  - Hwa and Yang:

PHENIX measurement in dAu collisions