Particle production at low, intermediate and high p_T:

What we're learning about heavy-ion collisions, and hadronization of bulk partonic matter from measurements of identified particle production.

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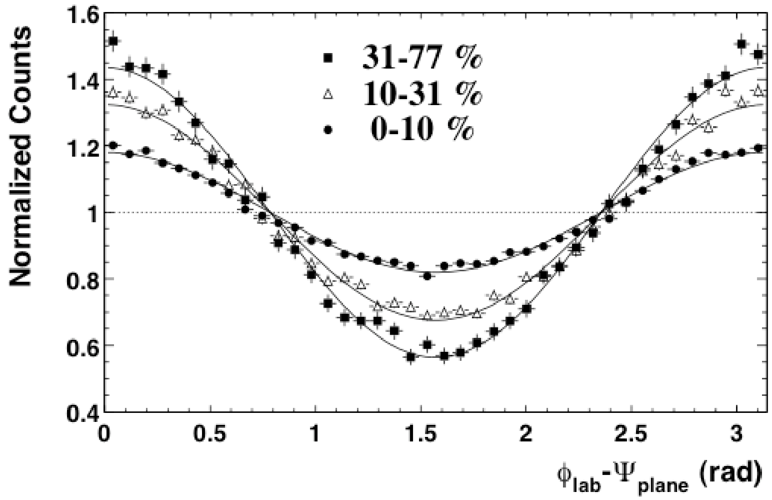
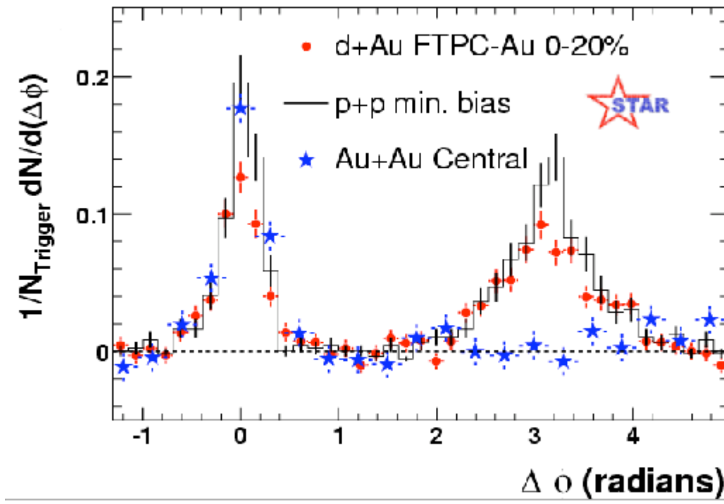
STAR

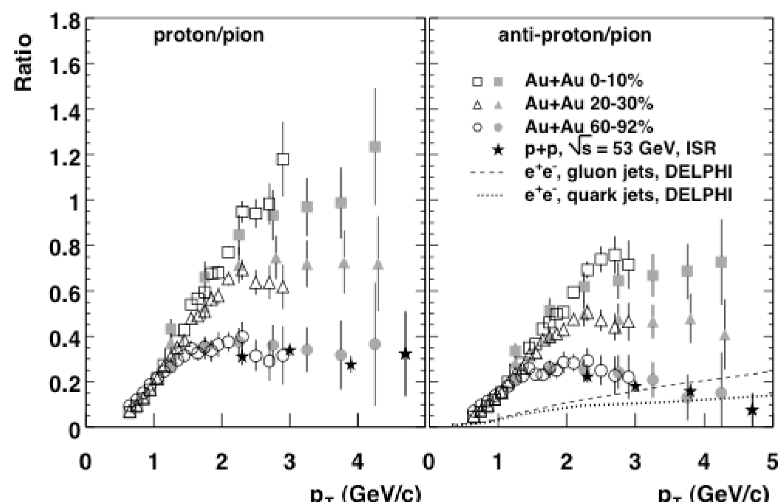
Key features of Au+Au collisions



1) Azimuthal Anisotropy: *near the hydrodynamic coordinate-to-momentum conversion limit*



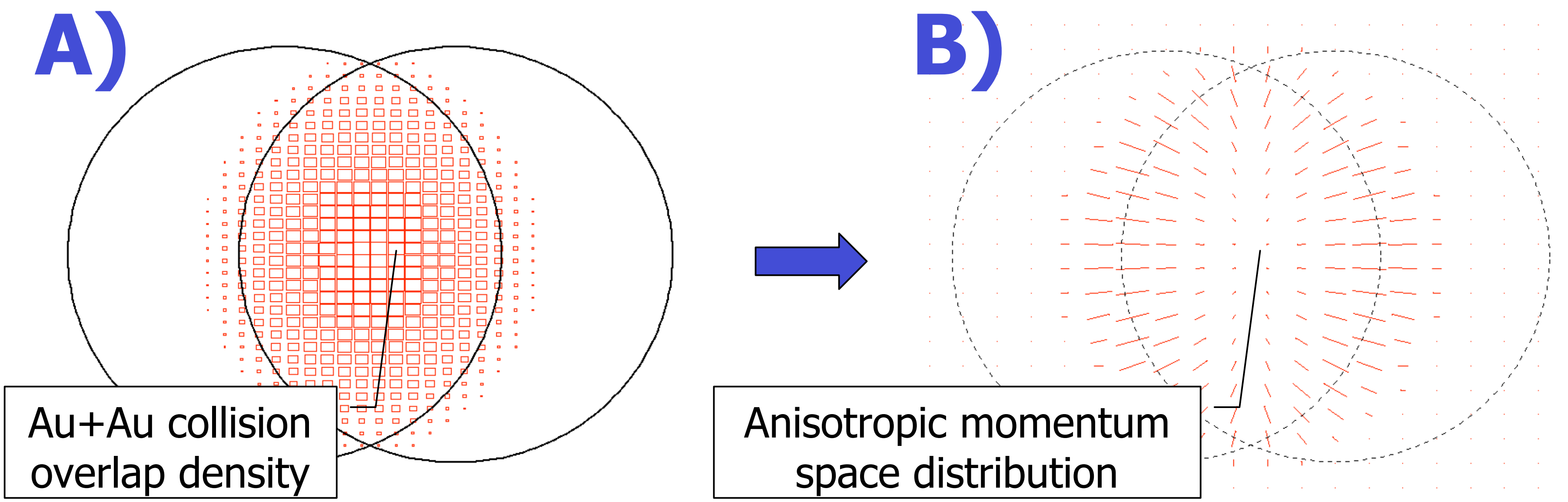
2) Suppression of high p_T yields with reduced away-side jet-like correlations



3) Large Baryon/Meson ratio

WE PRESENT: measurements of K_S and □ production in central and peripheral collisions and their azimuthal anisotropy in the transverse plane (mid-rapidity).

Azimuthal anisotropy parameters

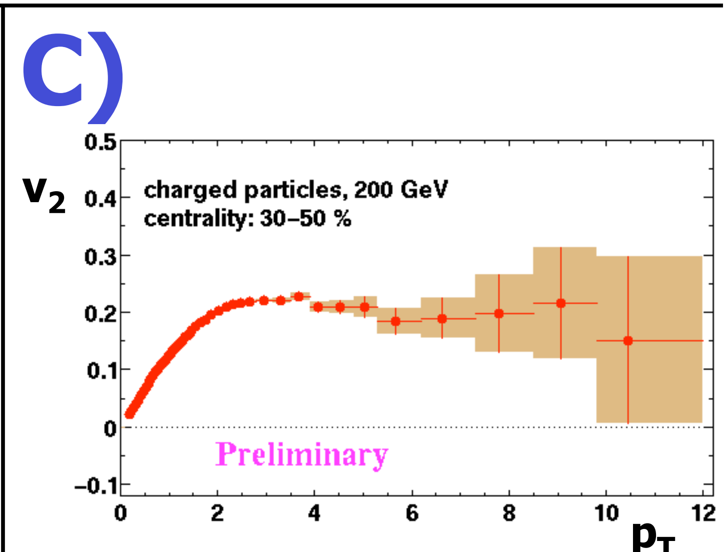


A) Coordinate space anisotropy $\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

B) Momentum space anisotropies

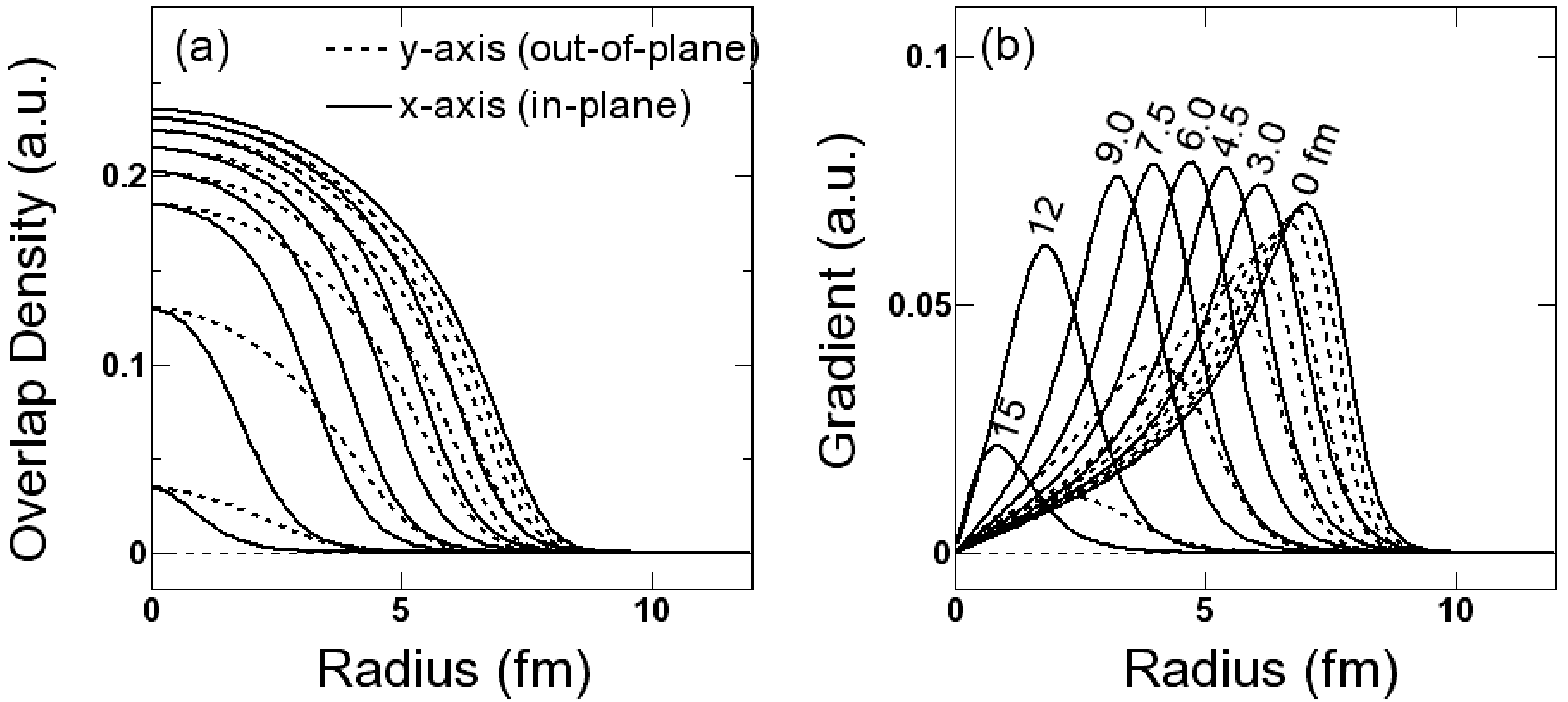
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_{n=1} 2v_n \cos\left[n\left(\phi - \Psi_r\right)\right]\right]$$

C) "Elliptic Flow" $v_2 = \langle \cos\left[2\left(\phi - \Psi_r\right)\right] \rangle$



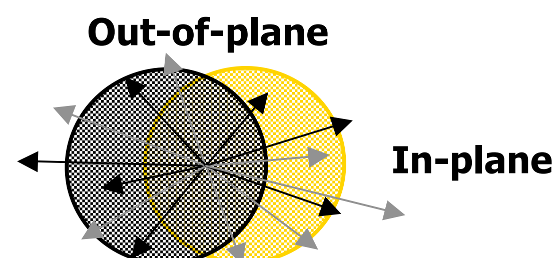
Pressure gradients and v_2:

Self-quenching sensitive to early stage (hydro picture).



- Collision overlap density from Woods-Saxon/Wounded-Nucleon

- If a pressure is established, it should be anisotropic in the transverse plane.



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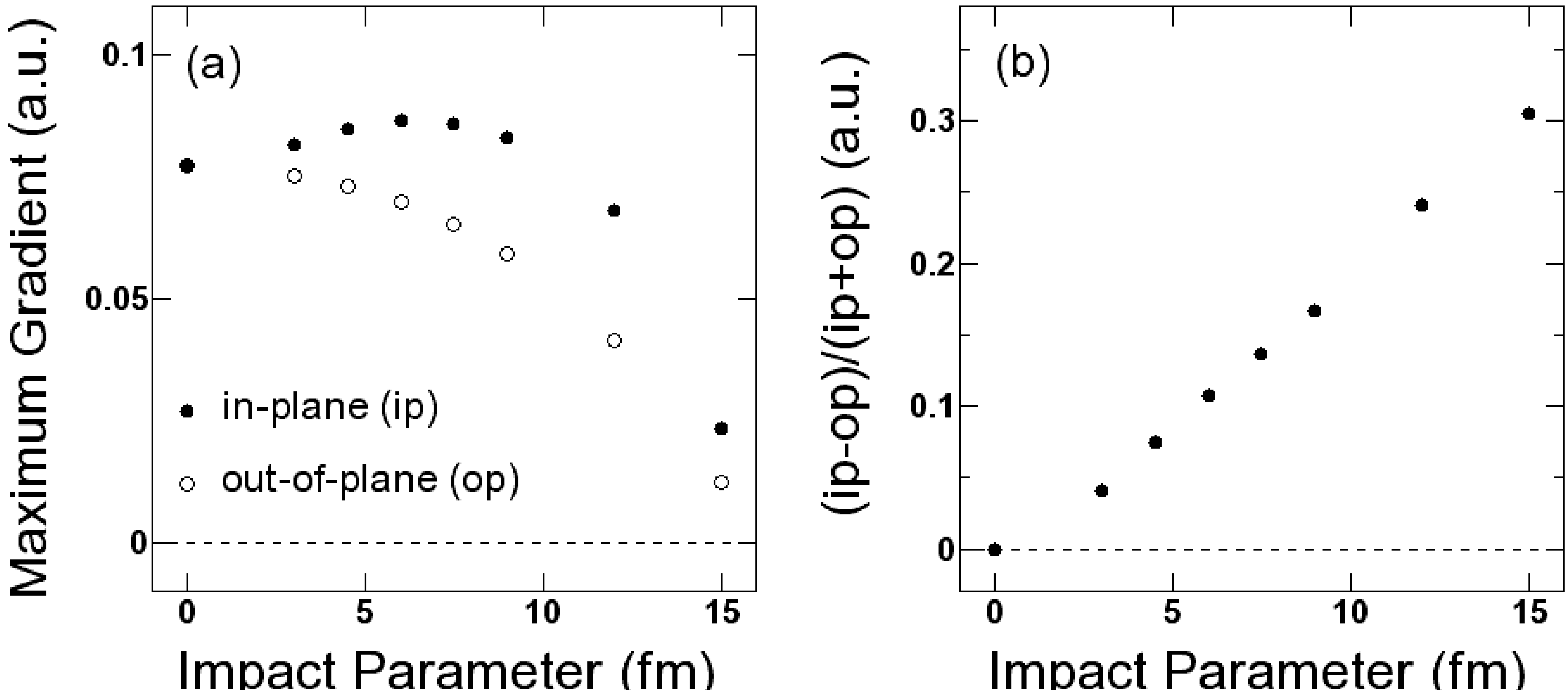
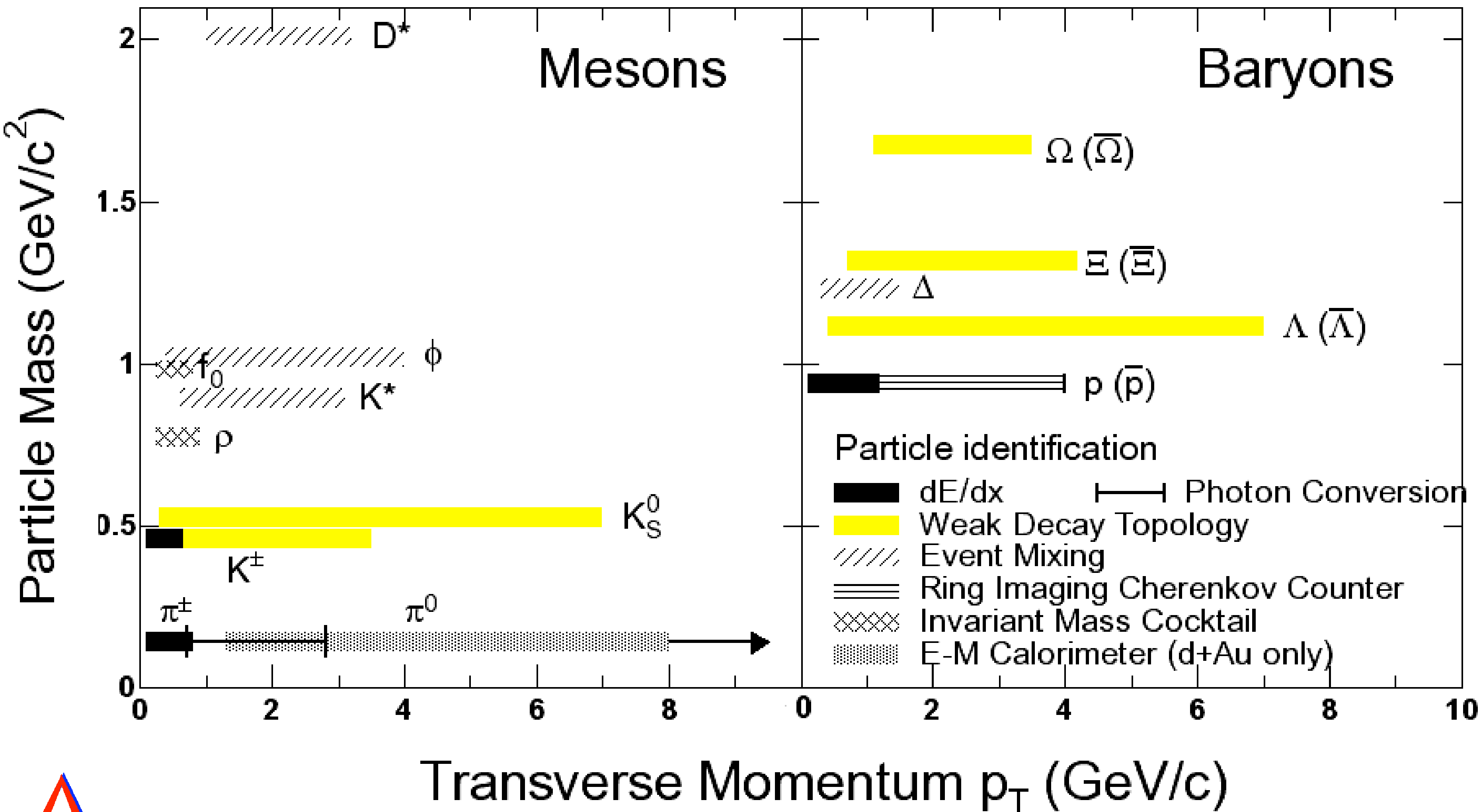
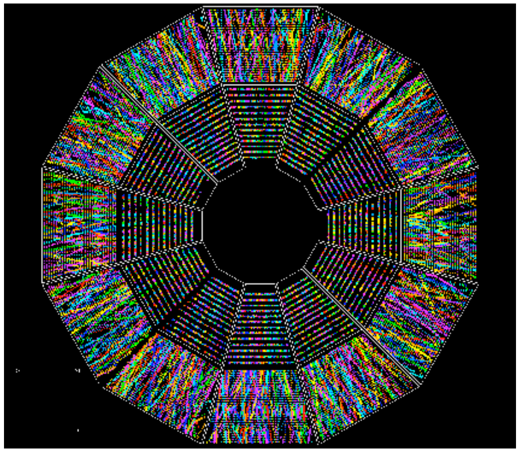


- Initial conditions only: initial pressure gradient assumed proportional to initial density gradient.

- Fewer interactions will reduce the peripheral anisotropy.

STAR particle identification





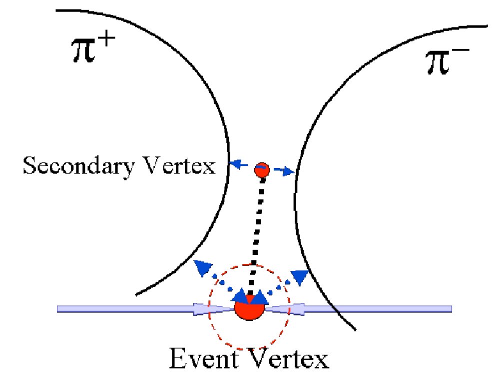
The decays:

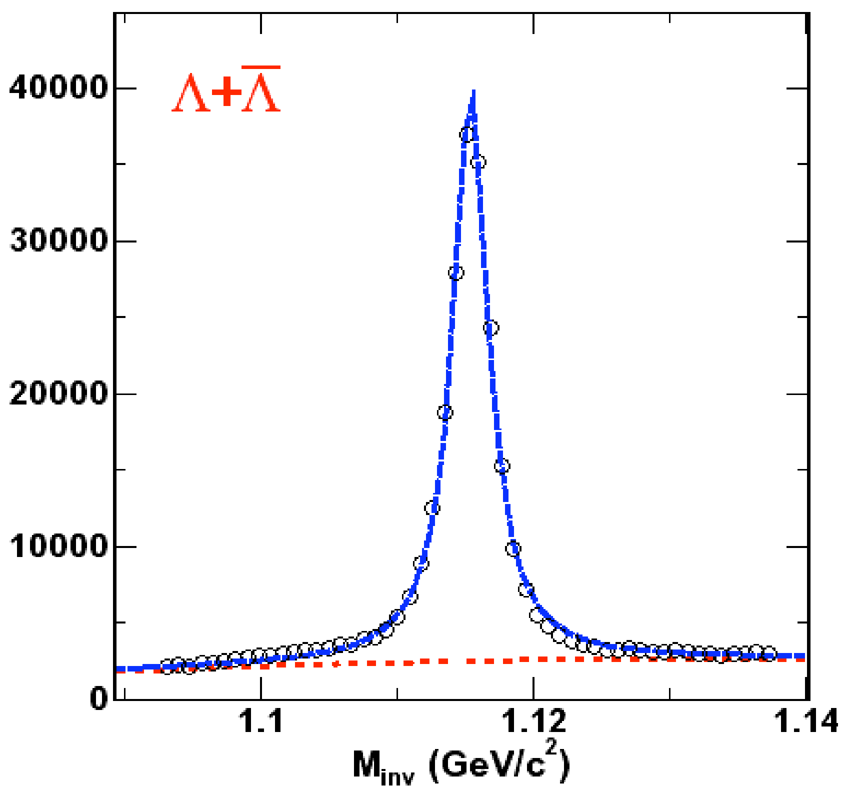
$K_S \rightarrow \pi^+\pi^-$ ($\Gamma_i/\Gamma \approx$ 69%)

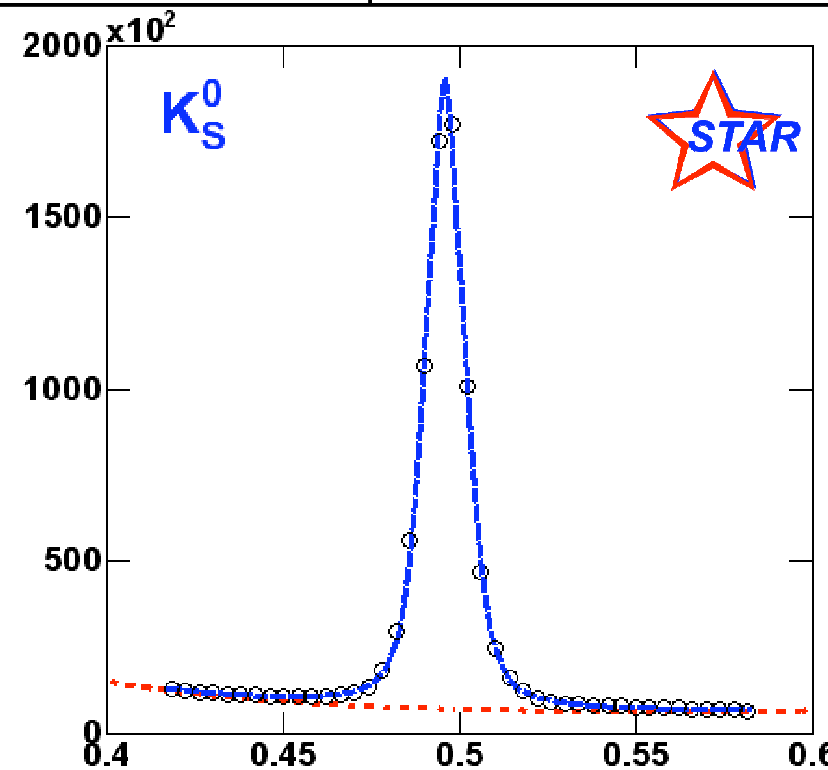
and

$\Lambda \rightarrow p\pi^-$ ($\Gamma_i/\Gamma \approx$ 64%)

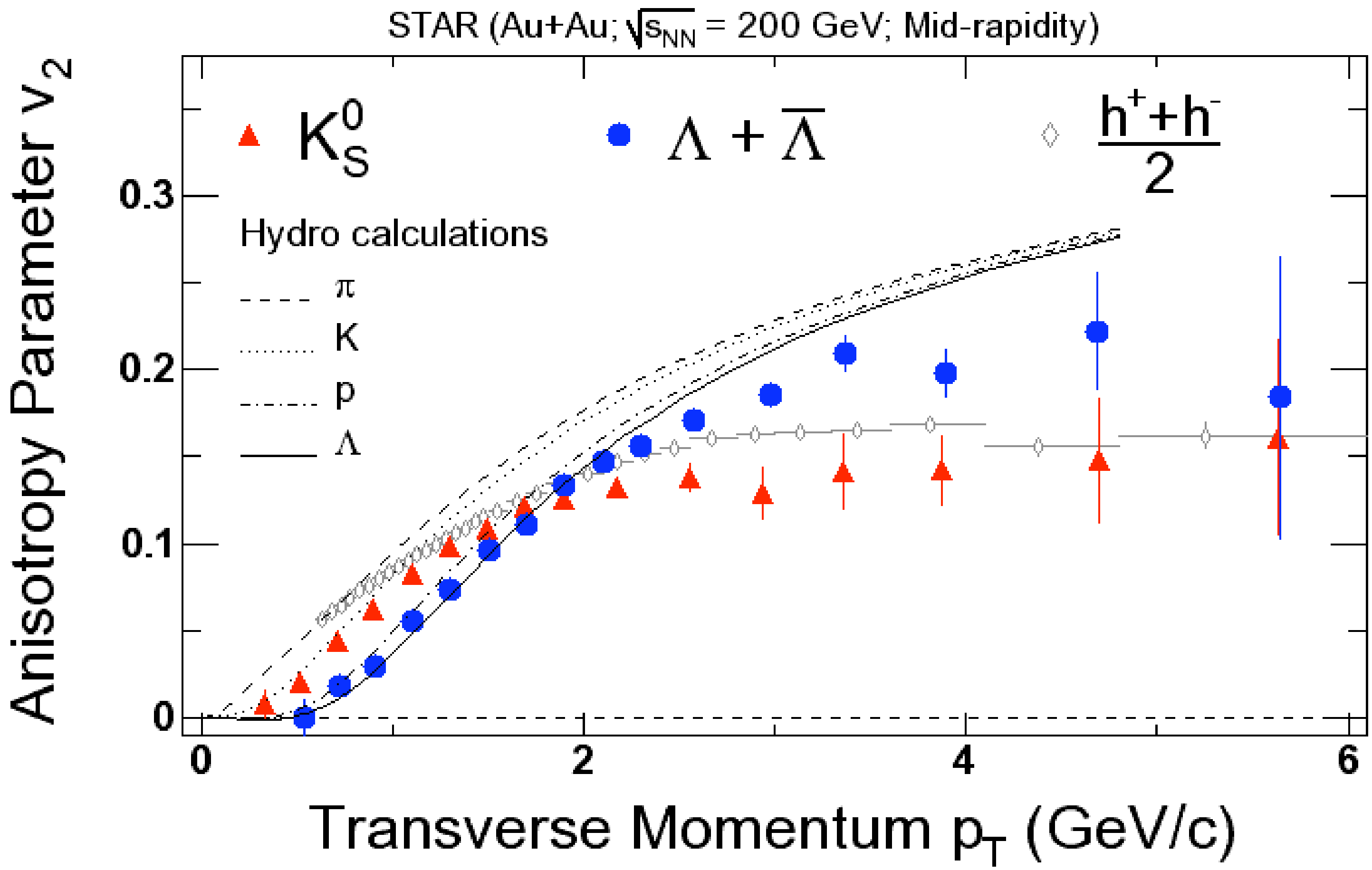
are reconstructed in the TPC using code developed by Hui Long from UCLA.







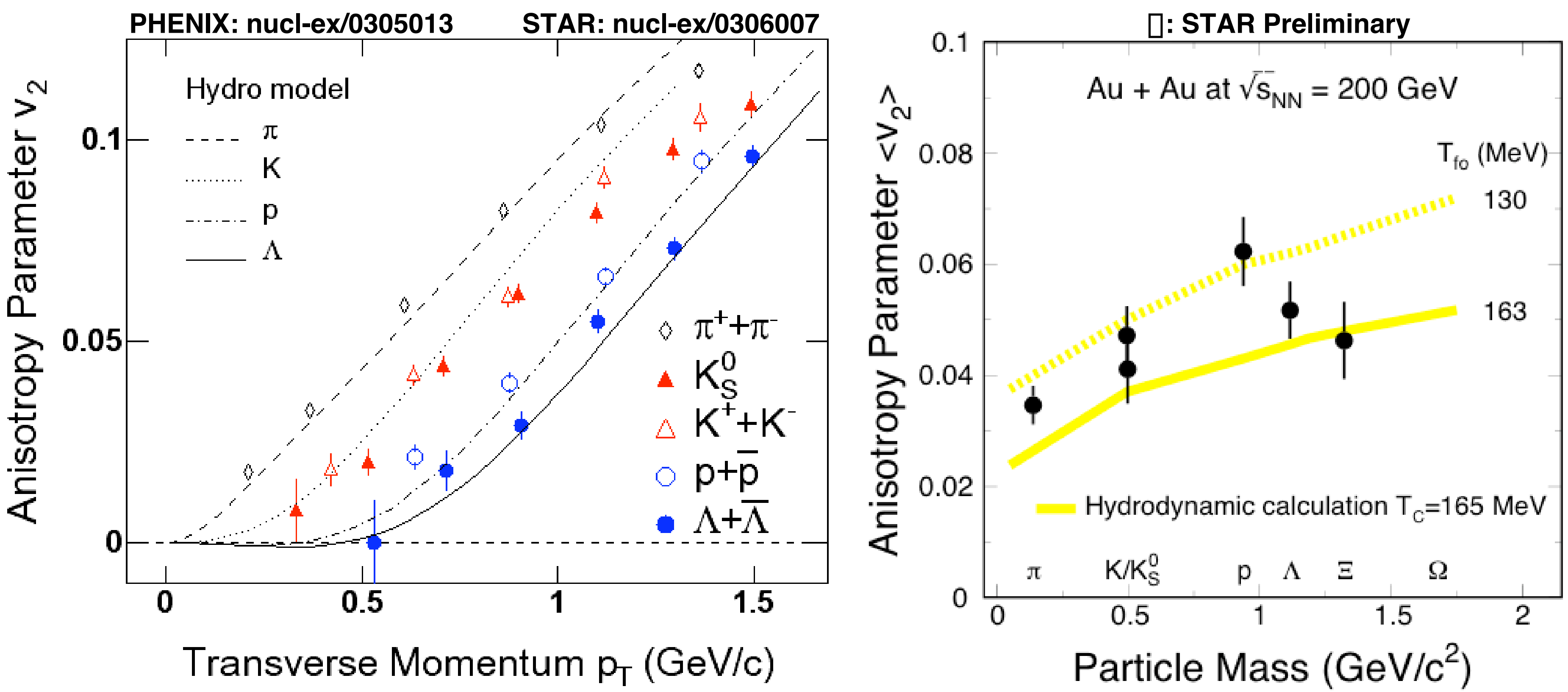
Min-bias identified particle v_2 at 200 GeV



•v_2 appears to saturate at ~0.13 for K_S and ~0.20 for with the saturation setting in at different p_T.

•Conversion of coordinate to momentum anisotropy: at or near the hydrodynamic limit (zero path length/totally opaque).

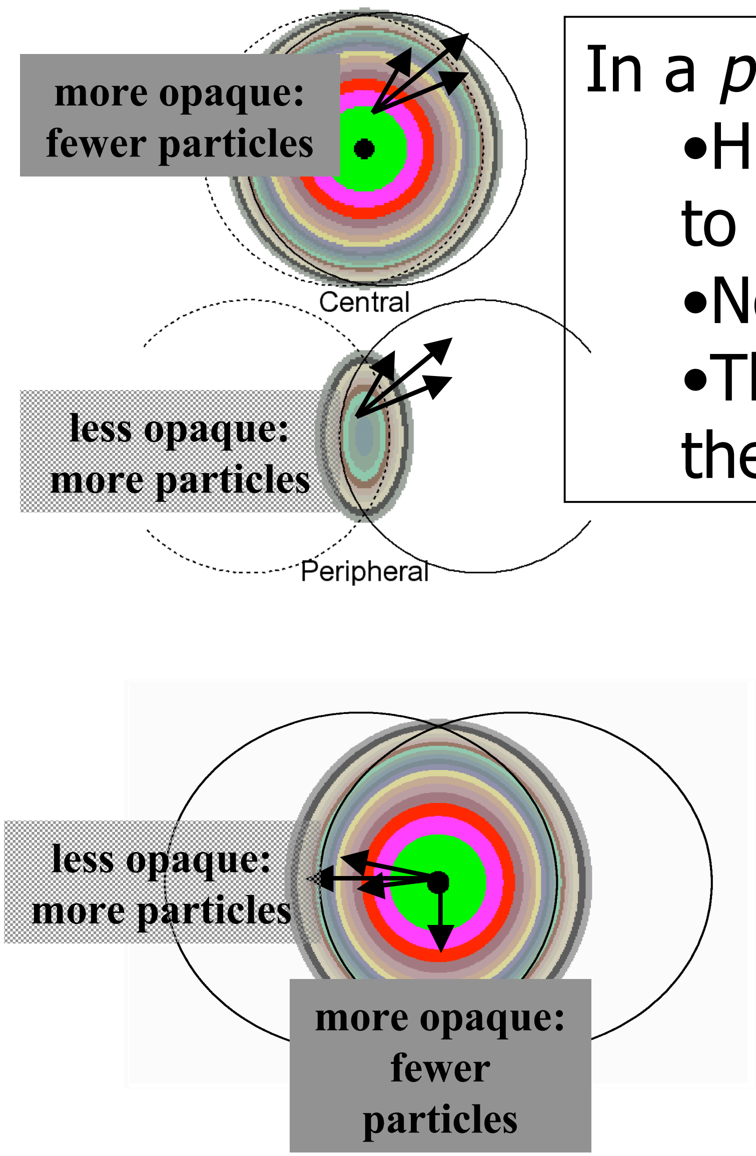
Identified particle v_2 at low p_T



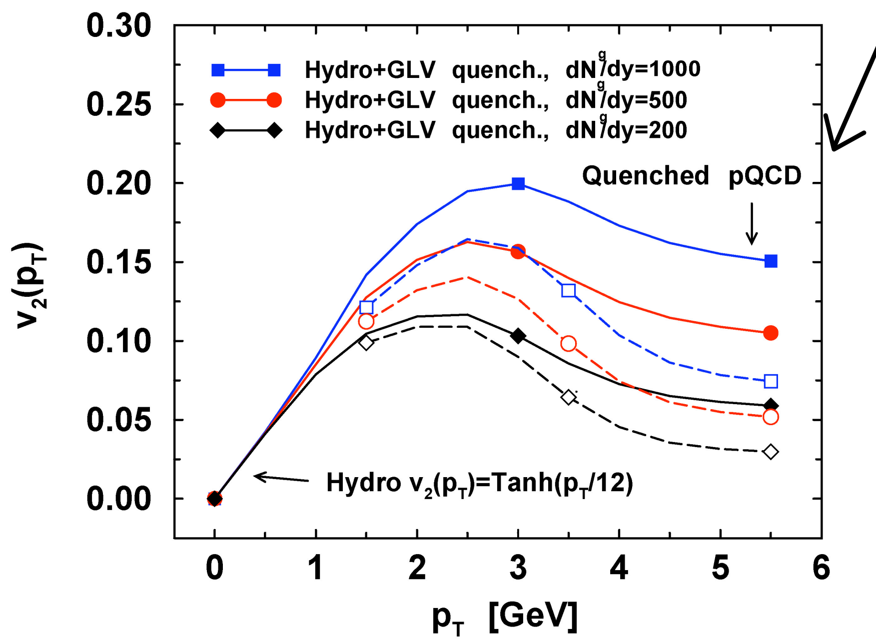
•Hydro models assuming local thermal equilibrium describe the species dependence of v_2 well.

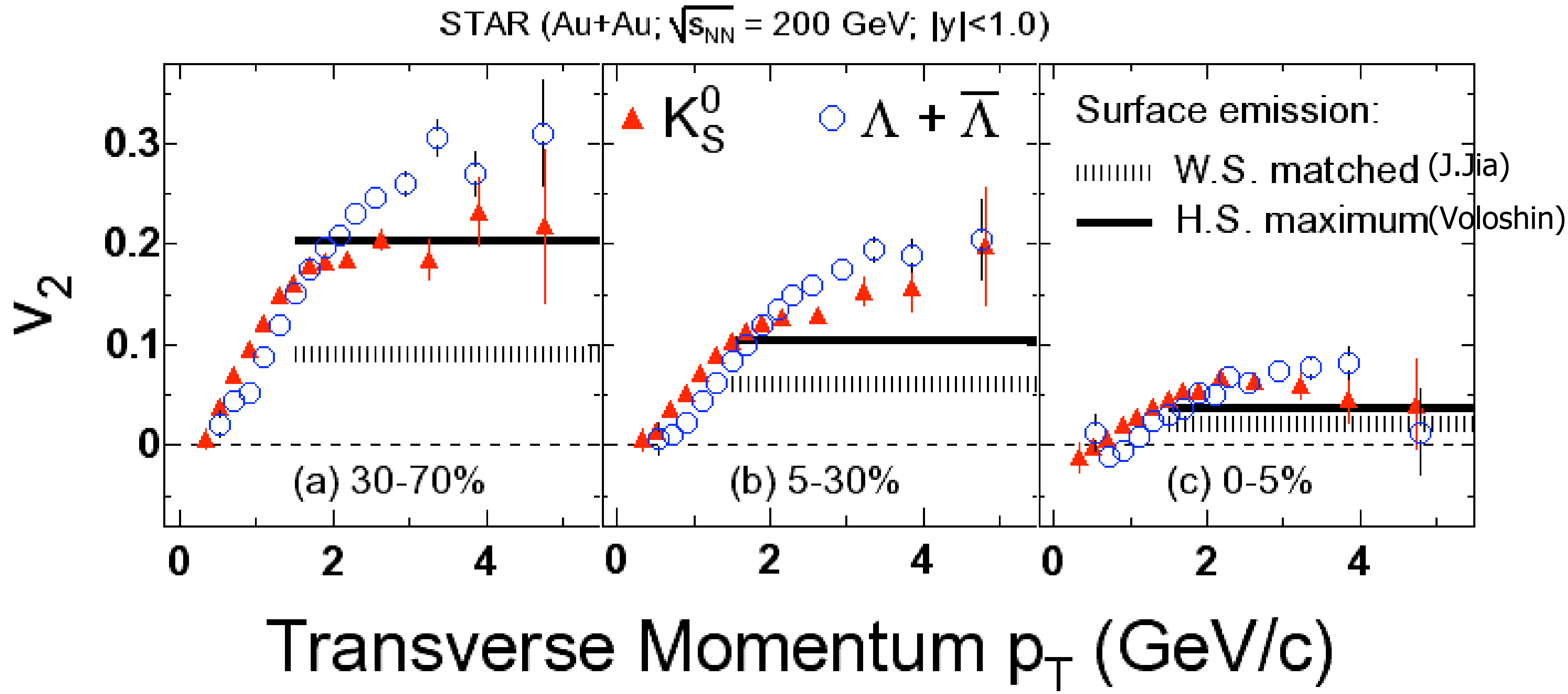
•Increase of integrated v_2 with mass is indicative of significant collective motion.

High p_T v_2:
Energy loss and surface emission?

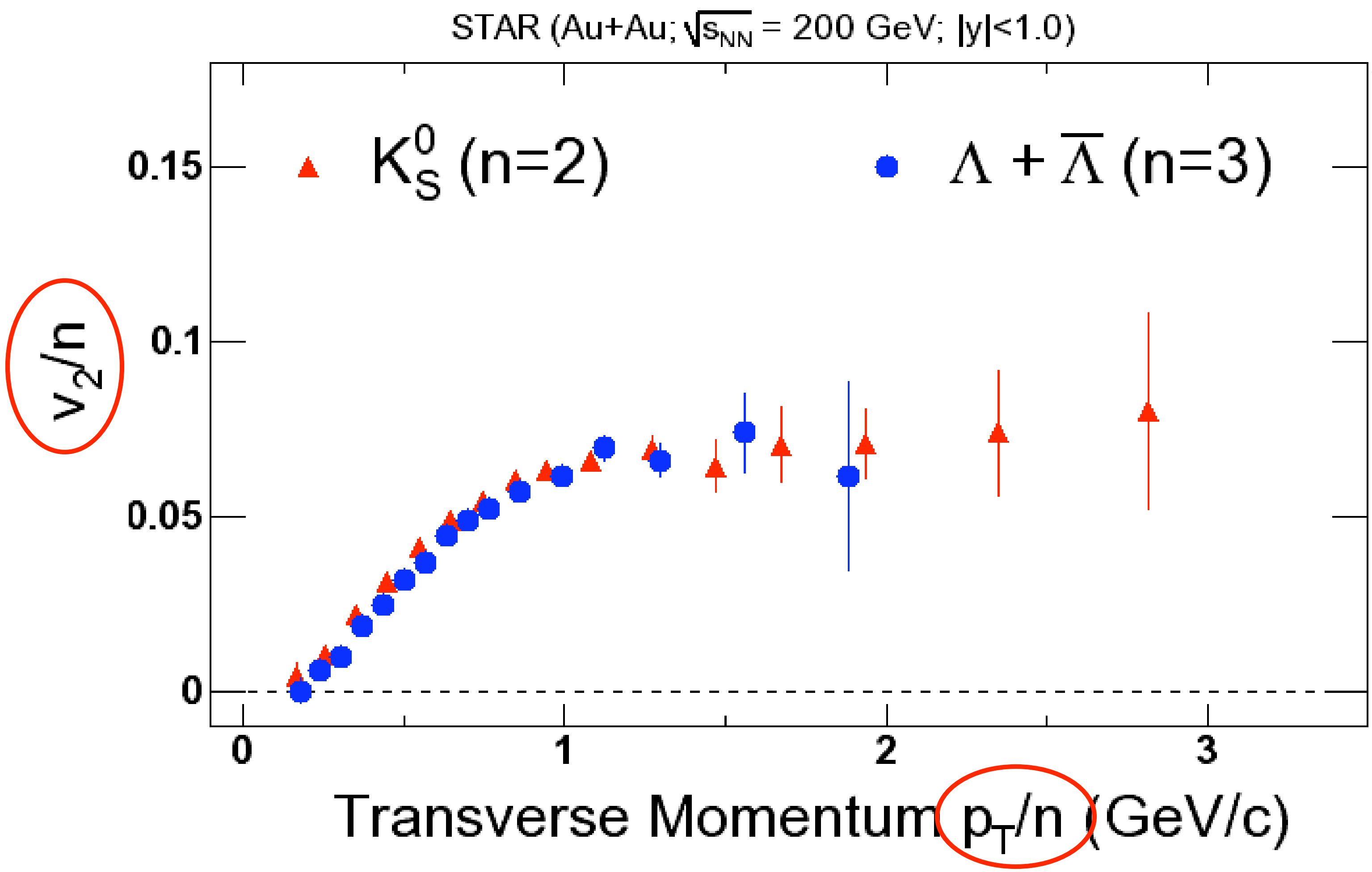


In a *partonic dE/dx* scenario:
- High p_T central yields suppressed relative to scaled peripheral yields: $R_{CP}<1$.
- Non-zero v_2 expected at high p_T.
- The magnitude of the suppression and the anisotropy are coupled.





- A particle dependence and saturation in all three centrality intervals.
- Hard-sphere, infinite-opacity limit for surface emission can’t reach the measured v_2 v_2 requires a dynamic expansion of strongly interacting matter.

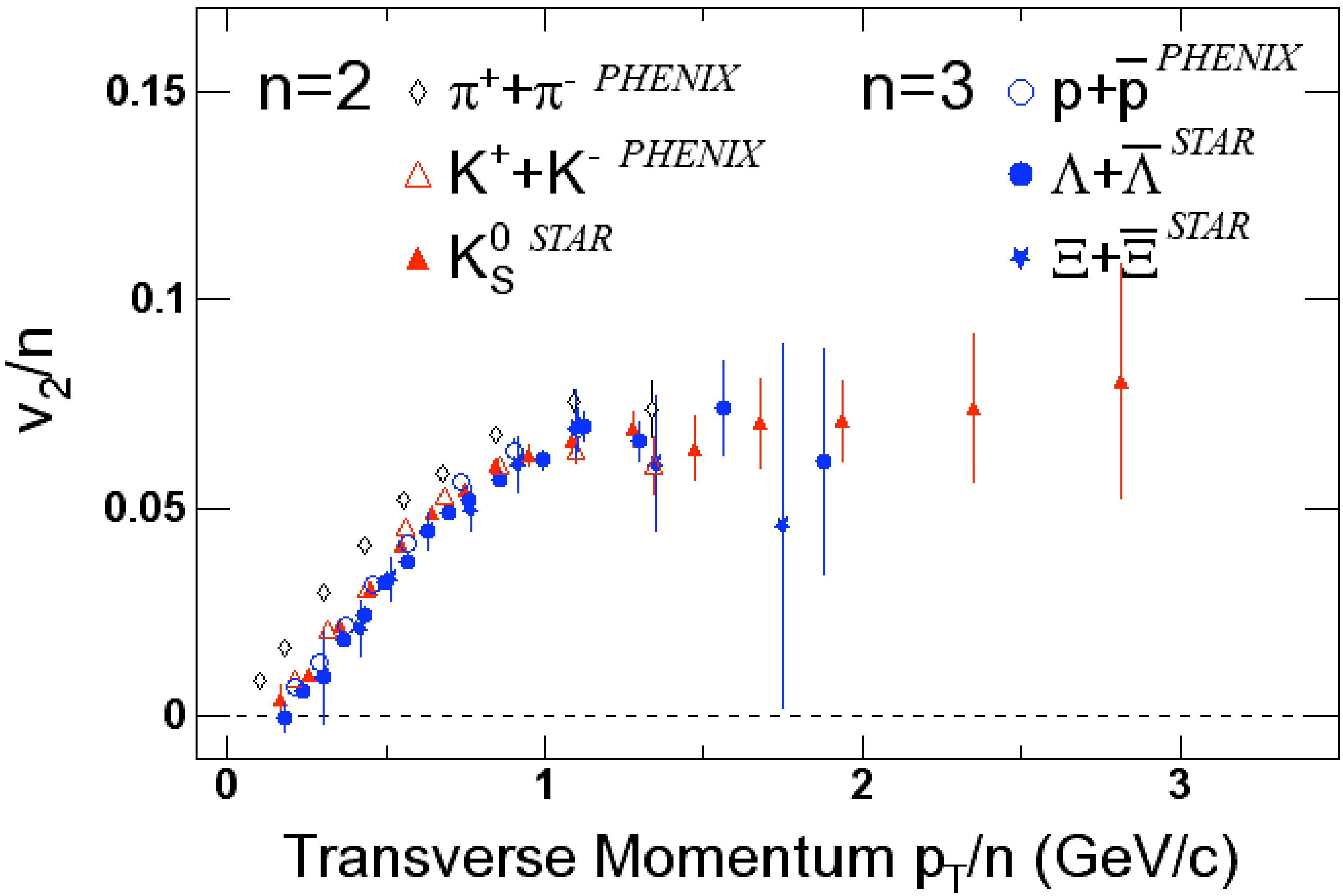


For hadron formation by coalescence of co-moving partons

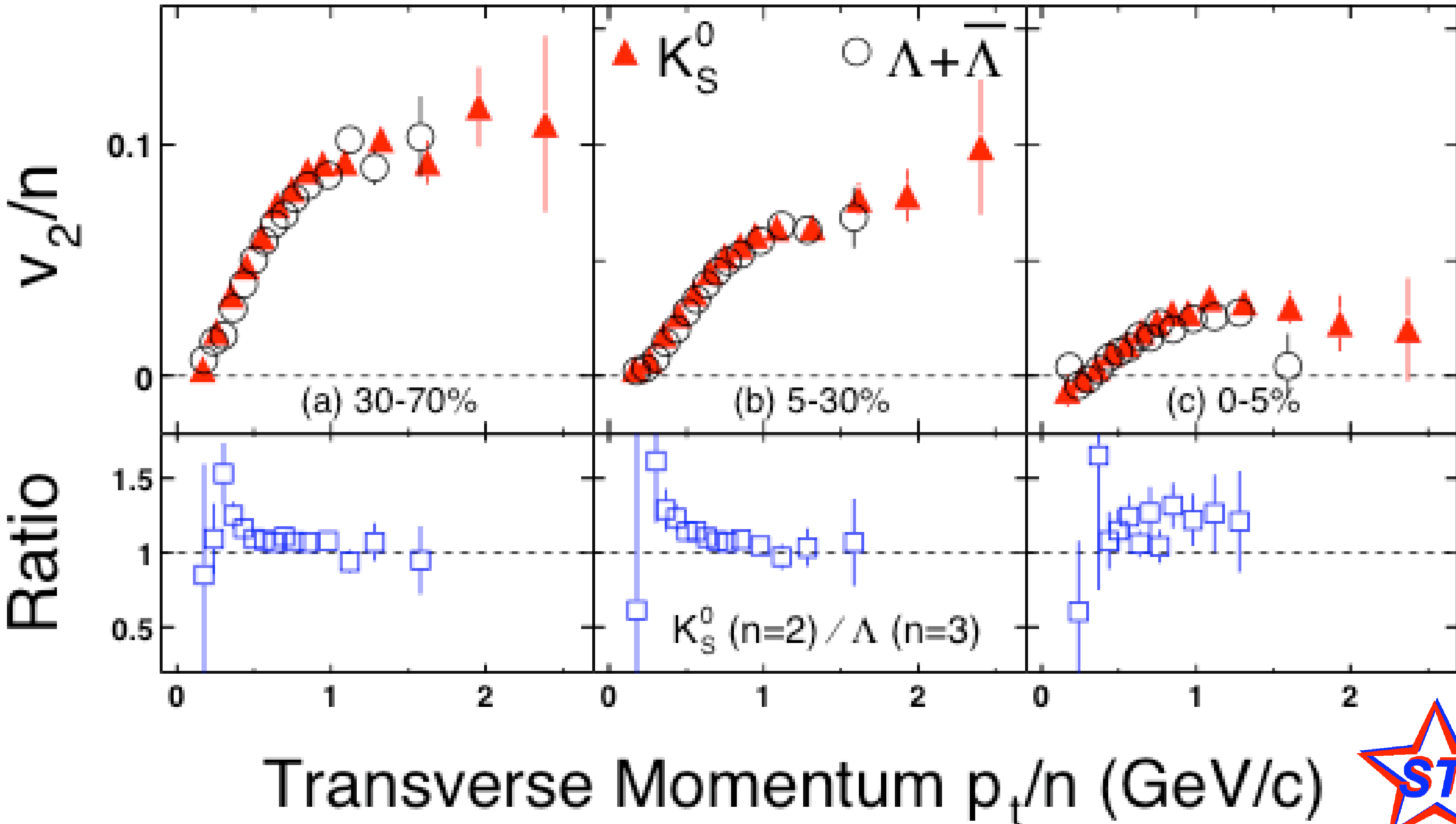
$$v_2^{meson}(p_T) \approx 2 \cdot v_2^{quark}(p_T/2)$$

$$v_2^{baryon}(p_T) \approx 3 \cdot v_2^{quark}(p_T/3)$$

In this scenario we can infer the value of the parton v_2 in the relevant p_T region (~7%).



Scaling works with kaons, protons, lambdas and Xis. Pions may be problematic.



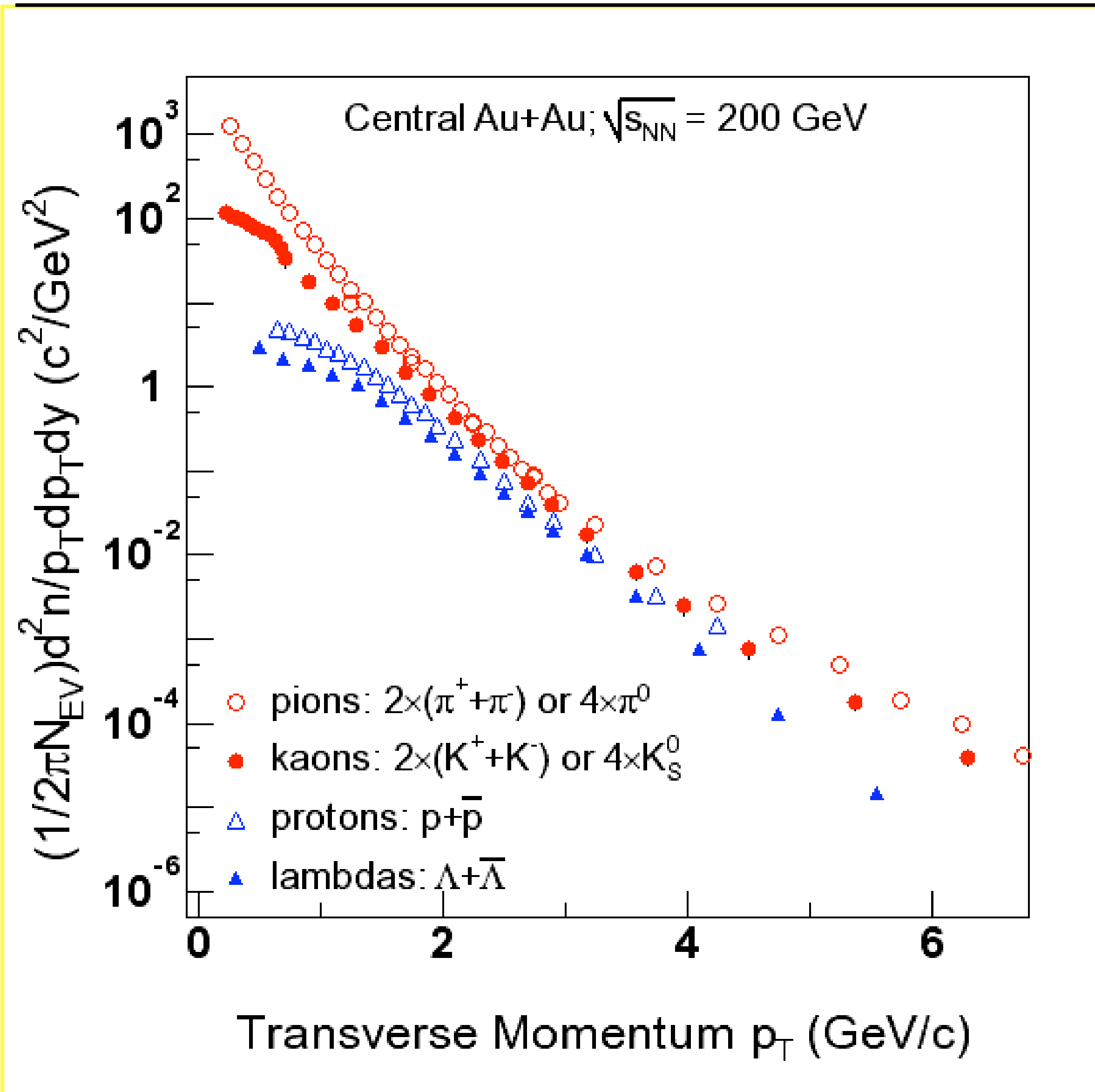
Scaling Breakdown Lower limit: $p_T/n<0.6$ GeV/c[2]

Upper limit: undetermined*

*R_{CP} suggest a breakdown for $p_T/n>1.7$ GeV/c[2]

Particle spectra:

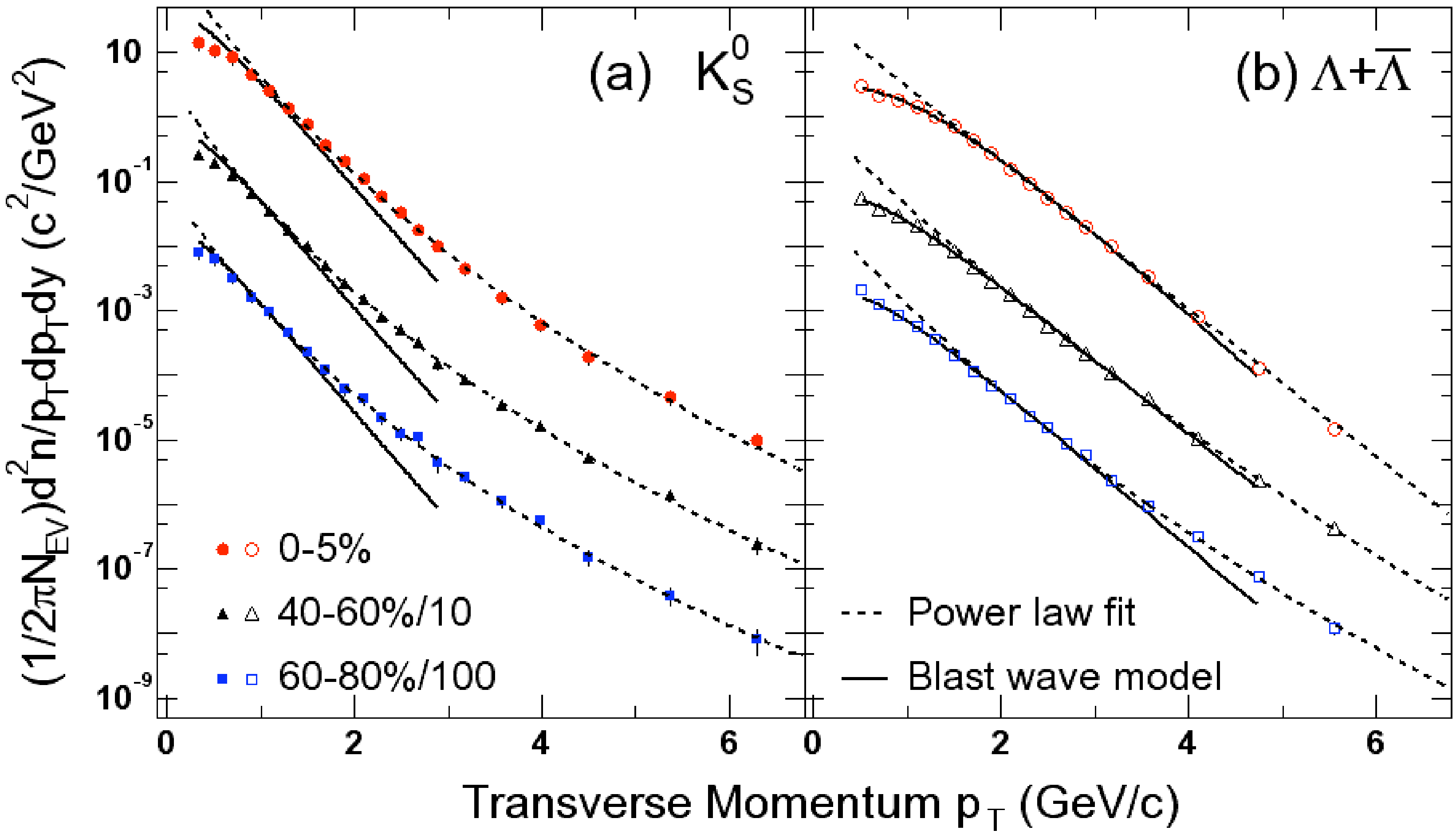
Baryon enhancement at intermediate p_T.



- Two component shape evident in kaon and pion spectra.
- The pion and kaon shape change occur at similarly small p_T (near 1.5 GeV/c).
- For proton and □ the spectra don't exhibit such a two-component shape.

Two component spectra fits:

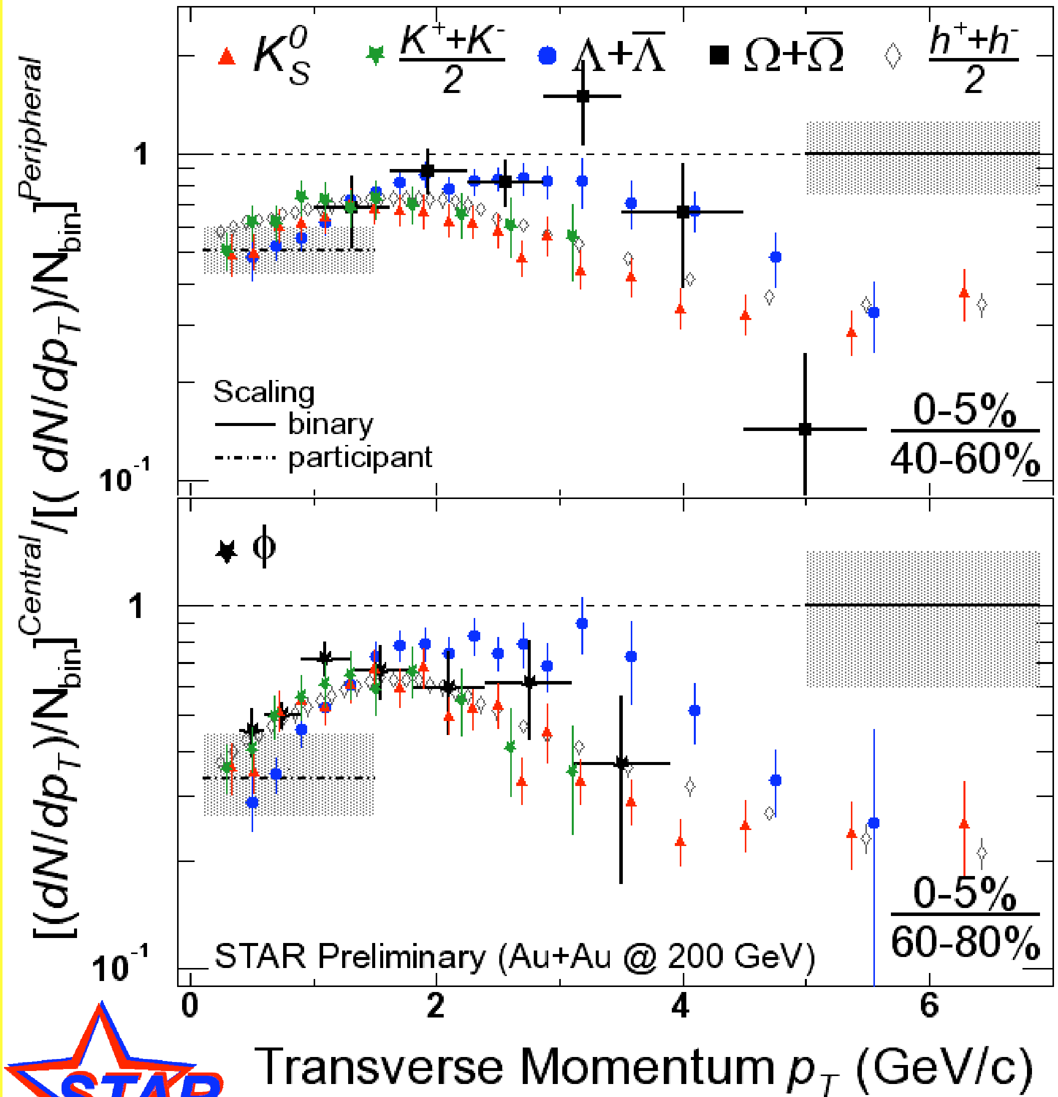
Hydrodynamic inspired model and pQCD power-law.



The crossover from a soft to hard shape is species dependent:

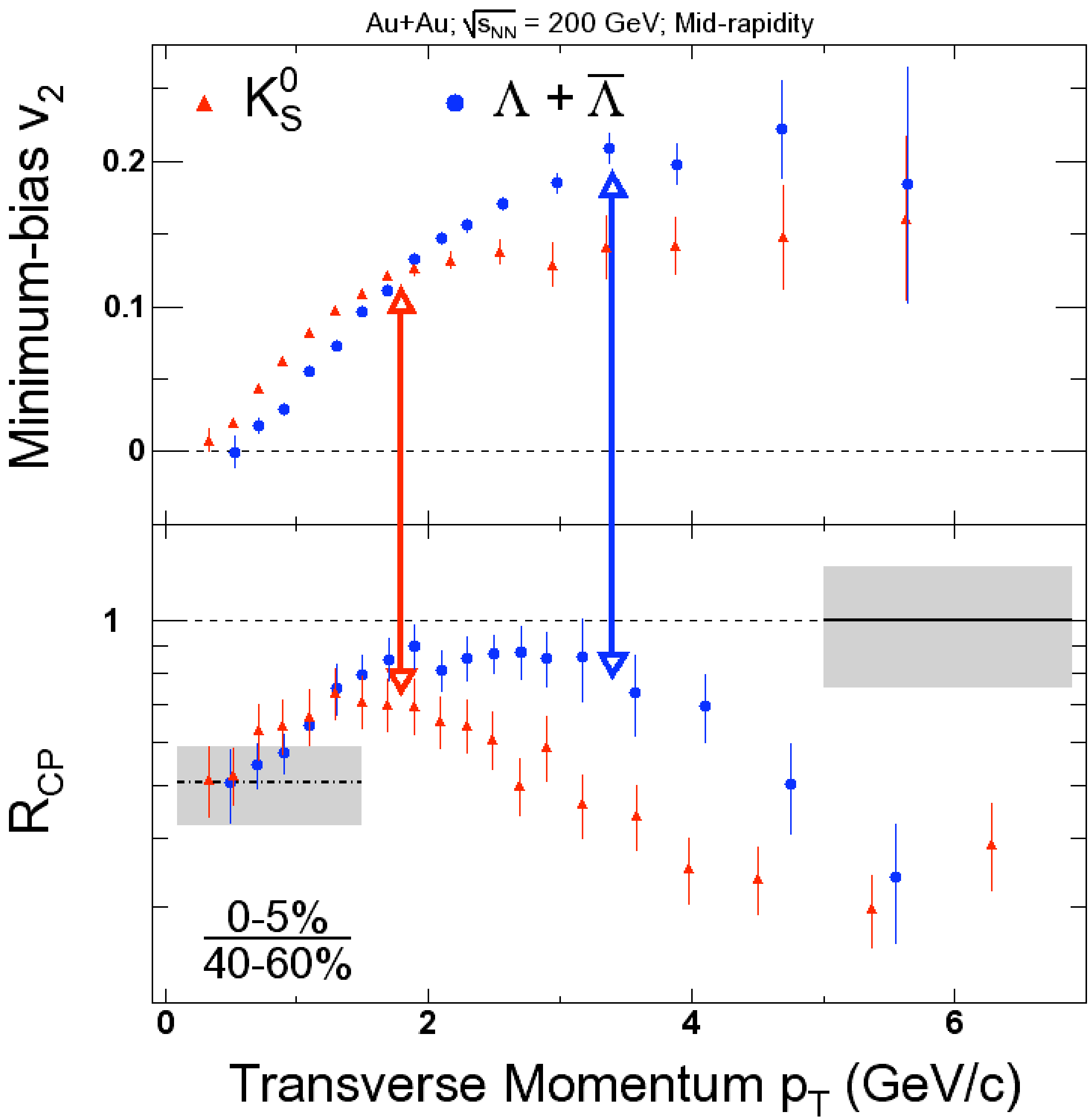
$p_{T,cross}$(kaon) ≈1.5 GeV/c, **$p_{T,cross}$(□) ≈ 3–4 GeV/c ?**

System size dependence: R_{CP}



- Total yield in central collisions suppressed w.r.t. scaled peripheral collisions.
- At intermediate p_T however, the baryon yields are increasing more quickly with centrality than meson yields.
- The □, K_S, and inclusive yields have the same suppression near 5 GeV/c.

The p_T Scale of R_{AA} and v_2 for K_S and



The saturation of v_2 and fall of R_{CP} are correlated.

In a scenario with partonic energy loss followed by unmodified fragmentation, a larger v_2 would be associated with a smaller R_{CP}.

At intermediate p_T: species dependence contradicts a simple partonic energy loss and unmodified fragmentation picture.

Observations of const. quark number dependence:

- A two-component p_T spectra (exponential and power-law tail):
  - –with $p_{T,cross}$(kaon) ≈ $p_{T,cross}$(pion) ≈ 1–2 GeV/c.
  - –and $p_{T,cross}$(□) ≈ $p_{T,cross}$(proton) ≈ 3–4 GeV/c.
- Particle-type dependent nuclear modification at intermediate p_T:
  - –with R_{CP}(kaon) ≈ R_{CP}(□) ≤ 0.65.
  - –and R_{CP}(□) ≈ R_{CP}(□) ≈ R_{CP}(proton) ≤ 0.95.
- Particle-type dependent elliptic flow:
  - –with most hadrons having the same $v_2/n(p_T/n)$ for p_T above ~1 GeV/c.
- Large baryon to meson ratio (□/K_S and p/pion).

Const. quark no. dependence

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These observations:

- ***Provide insight into the environments influence on hadron formation.***
- ***Provide information on the characteristics of the partonic state.***

Further investigation/confirmation is still needed.

An extensive phenomenological study of identified particle yields and v_2 verses system-size can shed light on hadron formation (long-term/high-impact RHIC project)

Acknowledgment of contributors

- Javier Castillo
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- Kai Schweda
- Christophe Suire
- Eugene Yamamoto

Four steps to final hadronic distributions (perturbative)

- Production of fast partons from hard scattering.
  - Blind to final hadron species.
- Propagation and interaction within the partonic medium.
  - Blind to final hadron species (caveat gluon vs quark).
  - Strong interaction of color charged objects.
- Hadronization of the parton.
- Propagation and interaction within the hadronic medium.

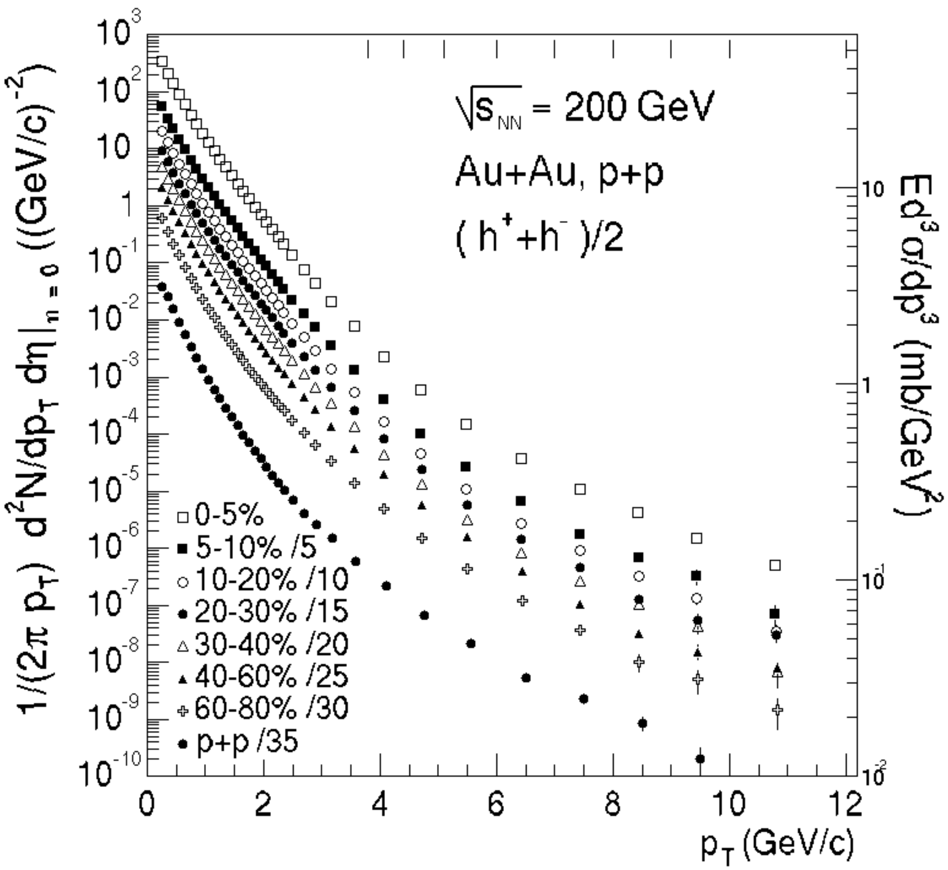
How do we disentangle the partonic and hadronic effects?

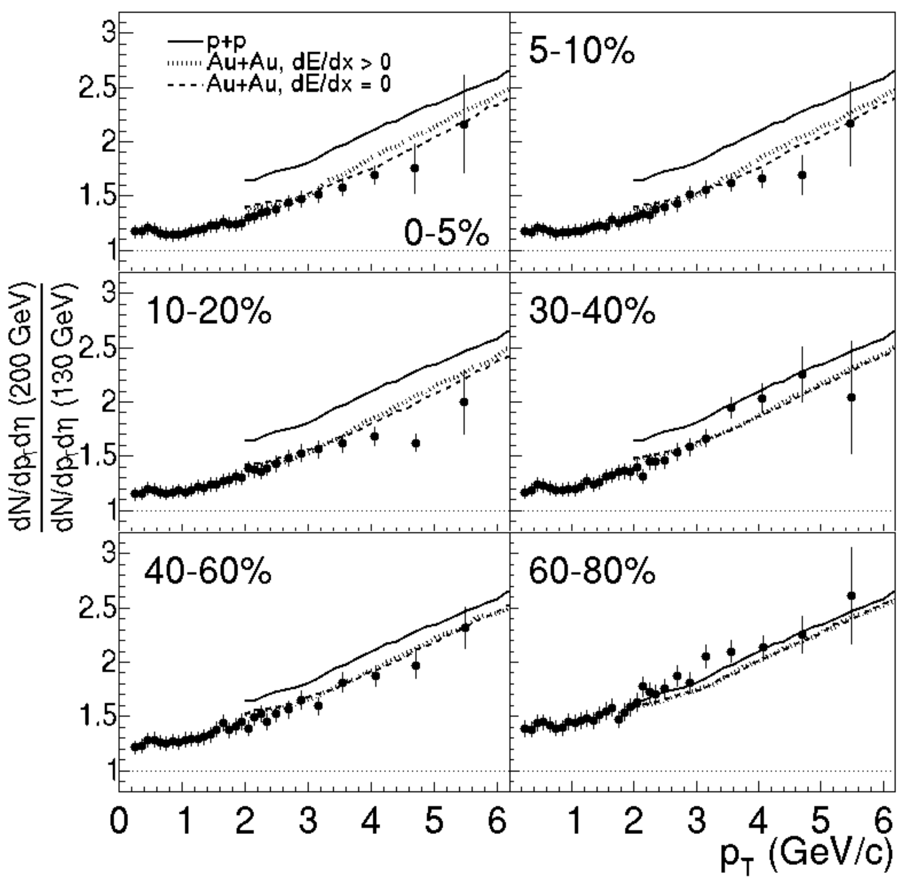
Disentangling partonic/hadronic

$$E_h \frac{d\sigma_h}{d^3p_h} = \sum_a \int_0^1 \frac{dz}{z^2} D_{a\to h}(z) E_a \frac{d\sigma_a}{d^3p_a}$$

- In a *dE/dx* scenario: the larger _ v_2 contradicts the smaller _ suppression.
  - Changing the partonic distributions or rescaling *z* affects all hadron species in the same way (gluon/quark jets?)
- The hadronization process is a crucial step:
  - The p_T-scale seems to be set by constituent-quark-number not mass (can we measure a flavor dependence).
- Particles with small hadronic x-sections (*i.e.* _, _, _) will help disentangle partonic/hadronic interactions:
  - Measure v_2 and R_{CP} for _ and _ up to p_T=7 GeV/c.
  - Conduct a system size scan to study the variation

Why would anyone believe jets and dE/dx at 2-5 GeV/c





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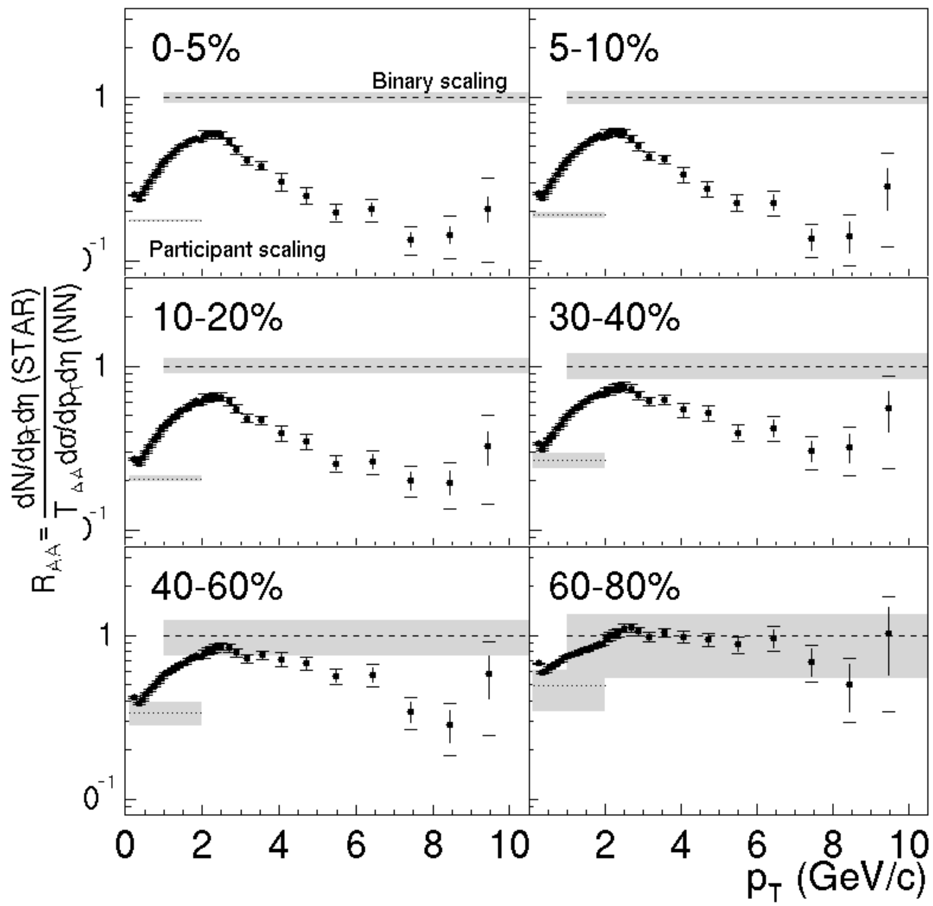
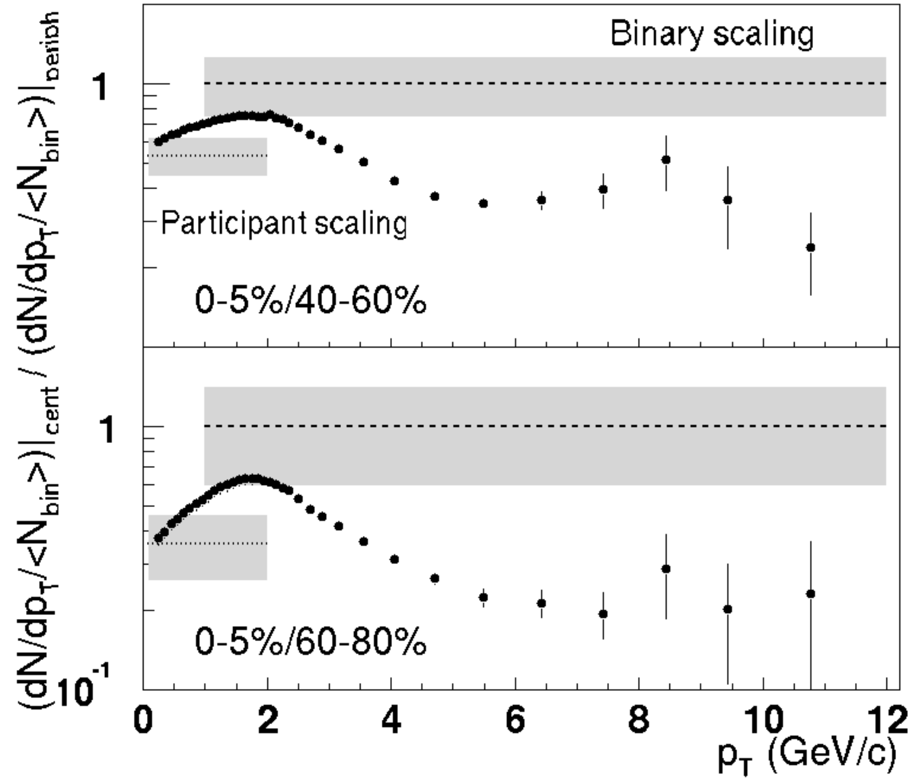
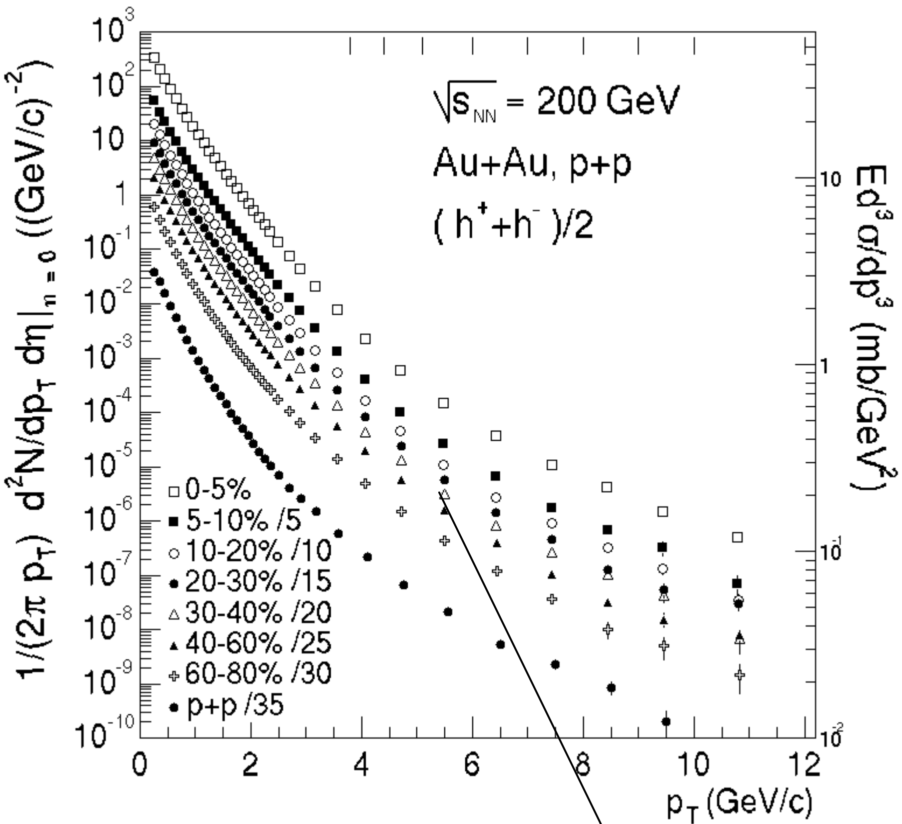


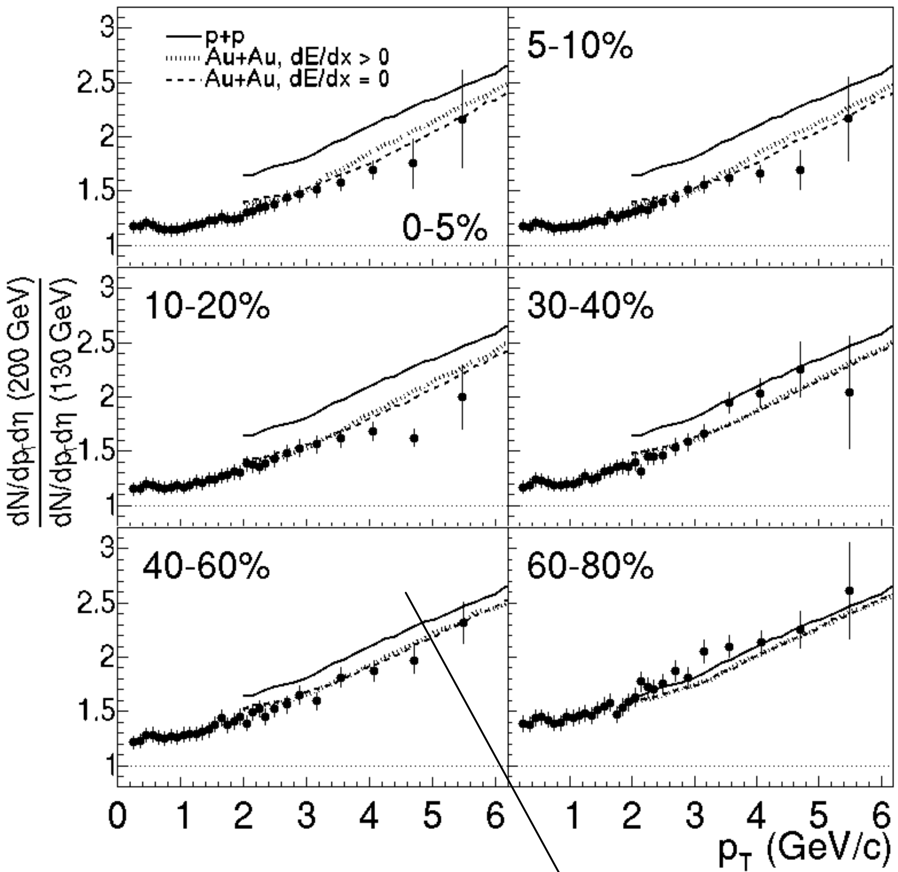


Why not believe jets and dE/dx at 2-5 GeV/c



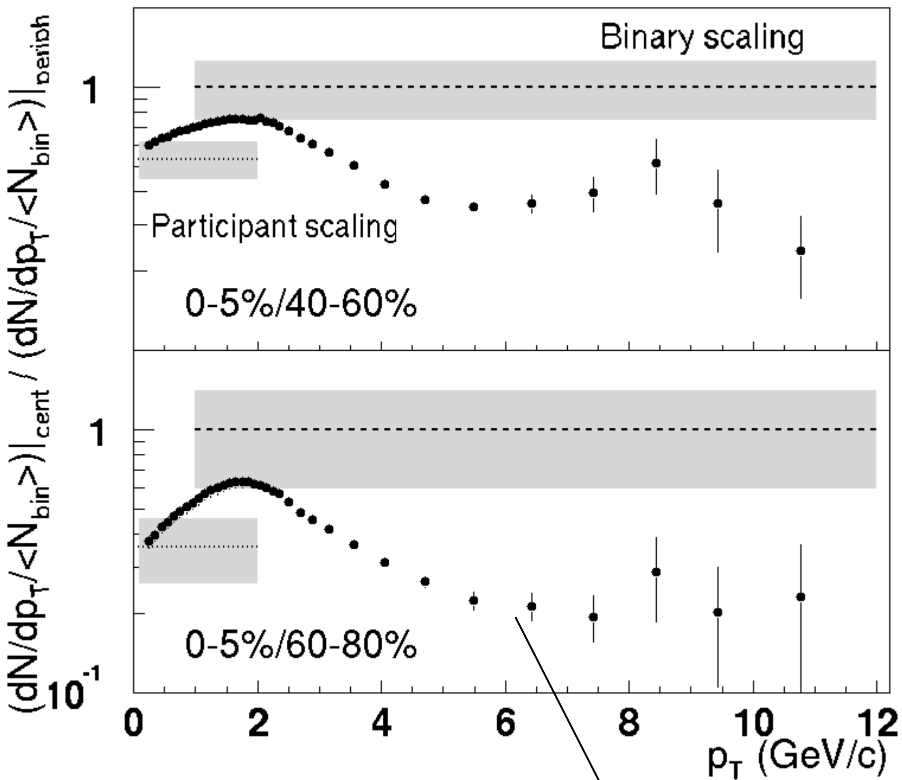
We know the spectra at 2-5 GeV/c is a complicated superposition of soft and hard identified spectra (Baryon/Meson).

Why not believe jets and dE/dx at 2-5 GeV/c



Still doesn't provide a strong constraint. Further study will help. Too much room for unconstrained modifications.

Why not believe jets and dE/dx at 2-5 GeV/c



Again: we know for 2-5 GeV/c there is a complicated superposition between identified spectra.