What experiments tell us about thermalization at RHIC ?

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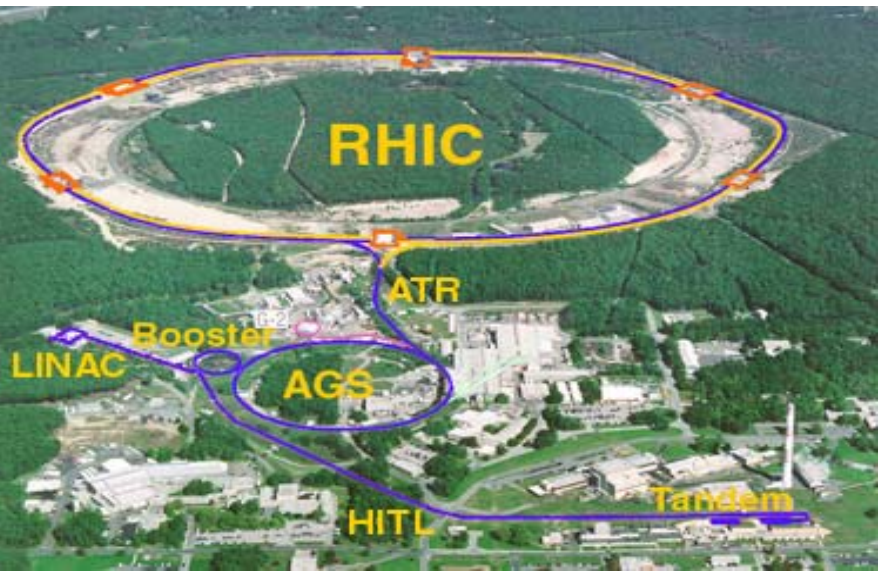


Info comes from:

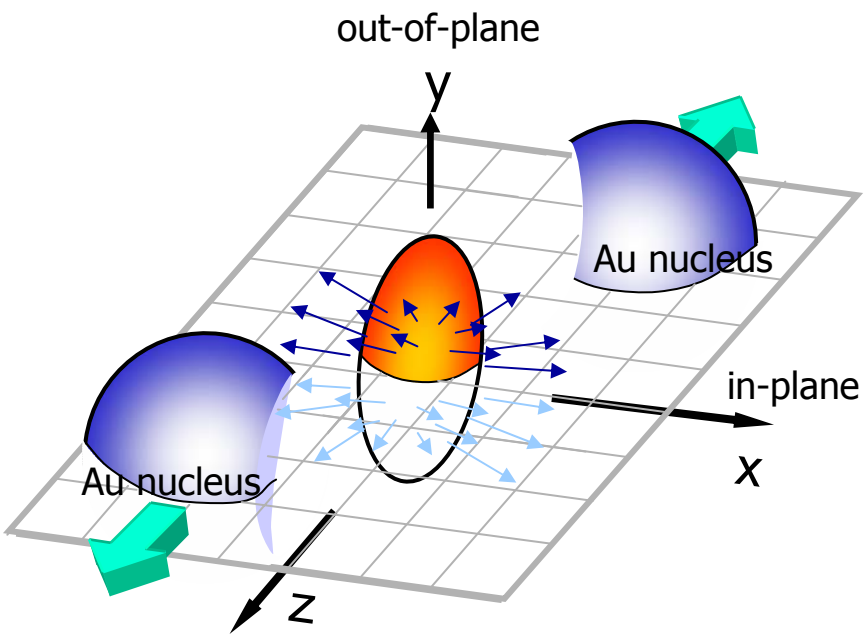
- V_2 / quark – partonic collectivity
- V_2 of non-photonic electrons –

  Heavy flavor collectivity = >

  Light flavor thermalization
- Away-side jets

are we there yet ?

Event anisotropies -> Flow



Non-central Collisions

The initial spatial anisotropy evolves (via interactions and density gradients) into a momentum space anisotropy

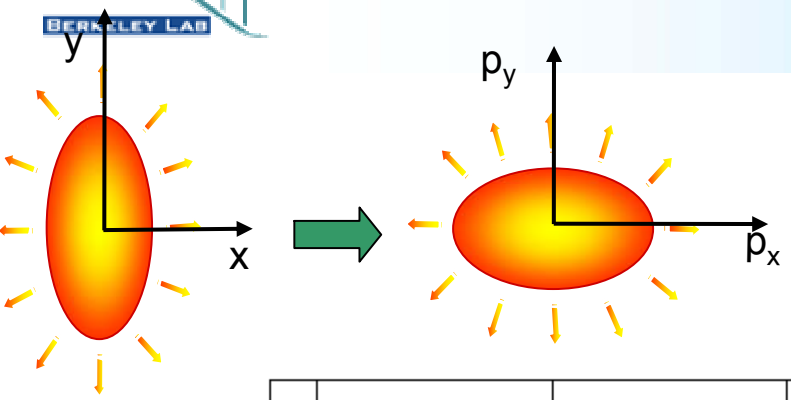
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\Delta\varphi\right)\right)$$

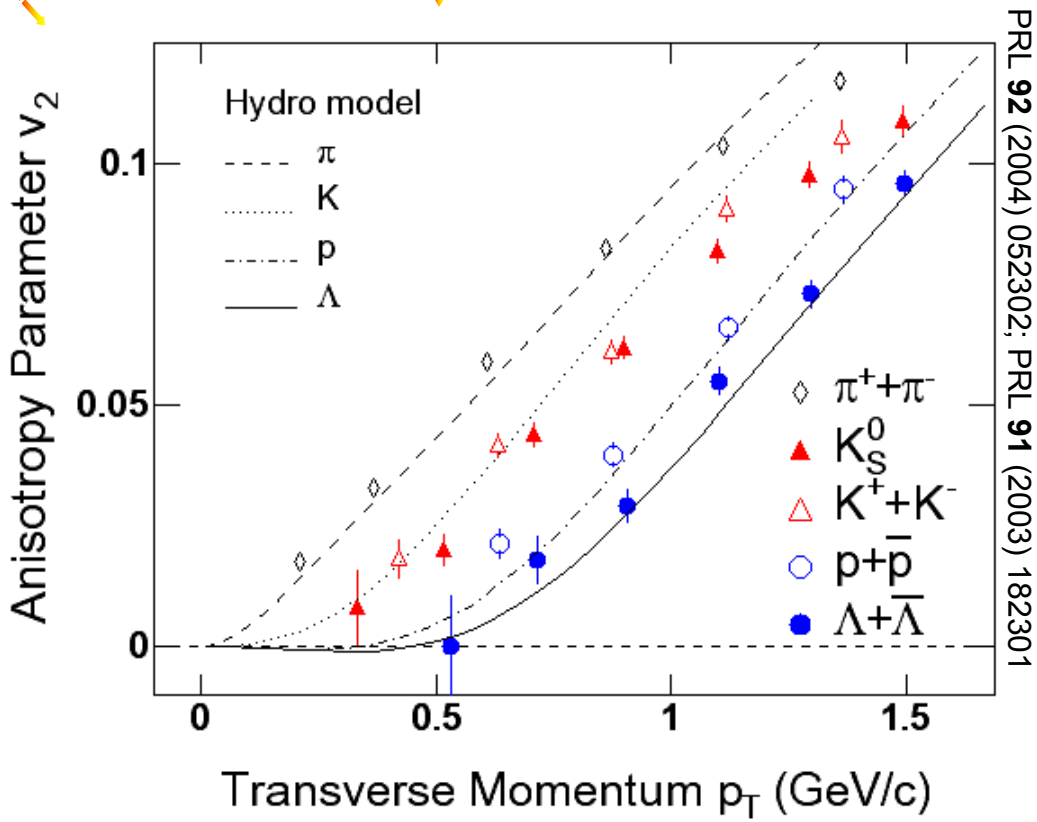
v_0 "radial flow", v_1 "directed flow"

v_2 "elliptic flow" (largest).

Azimuthal space-momentum anisotropy: a self quenching probe of early interactions

Elliptic Flow v_2

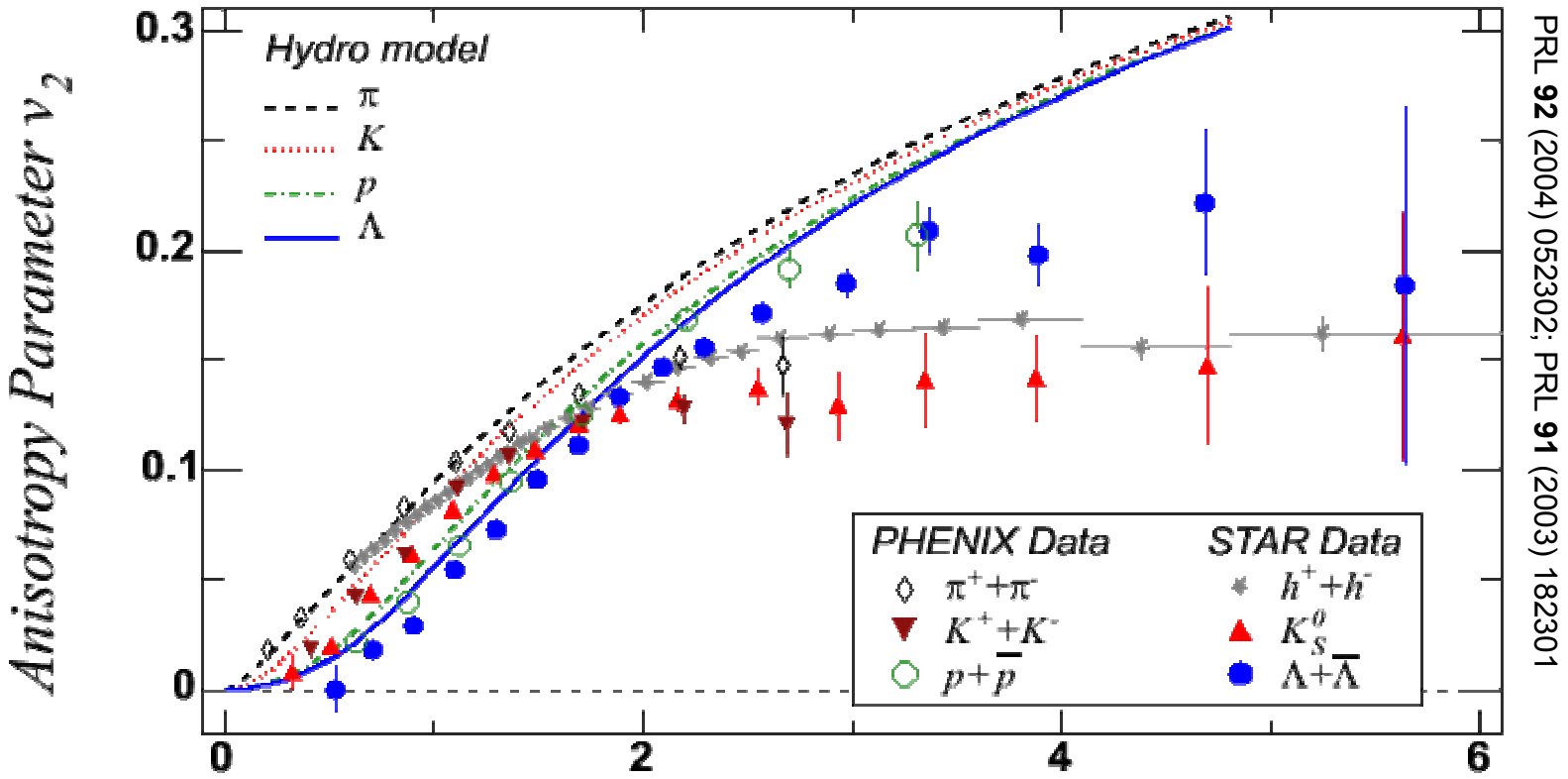




-hydro works:
amount of v_2 (spatial anisotropy) indicates early thermalization
-m_T dependence:
common v_T field
-soft (QGP) EOS favored:
sub-hadronic DOF

Efficiency of conversion of spatial anisotropy to momentum anisotropy depends on the medium

v_2 vs. p_T



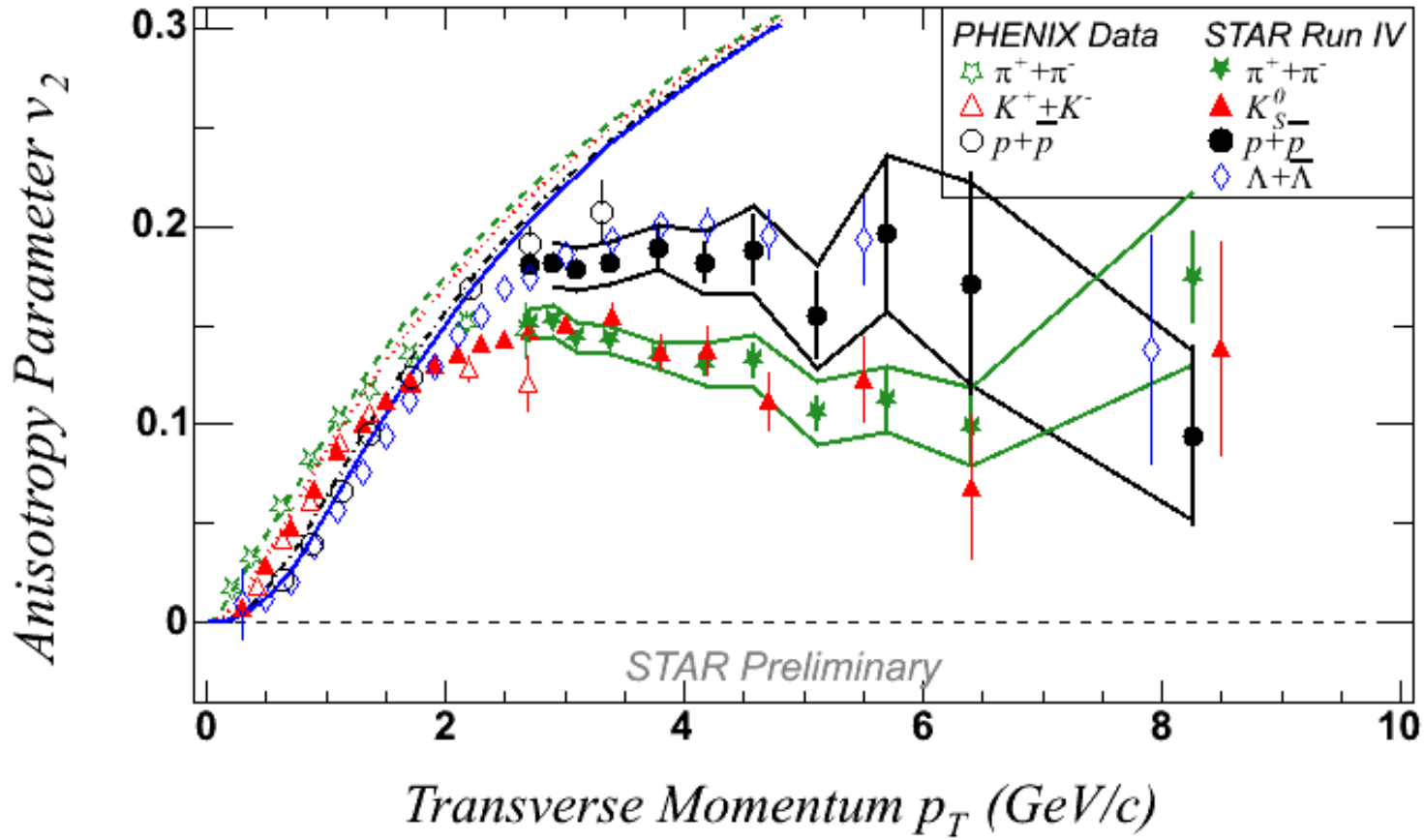
PRL **92** (2004) 052302; PRL **91** (2003) 182301

Hydro calculations break-down 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?

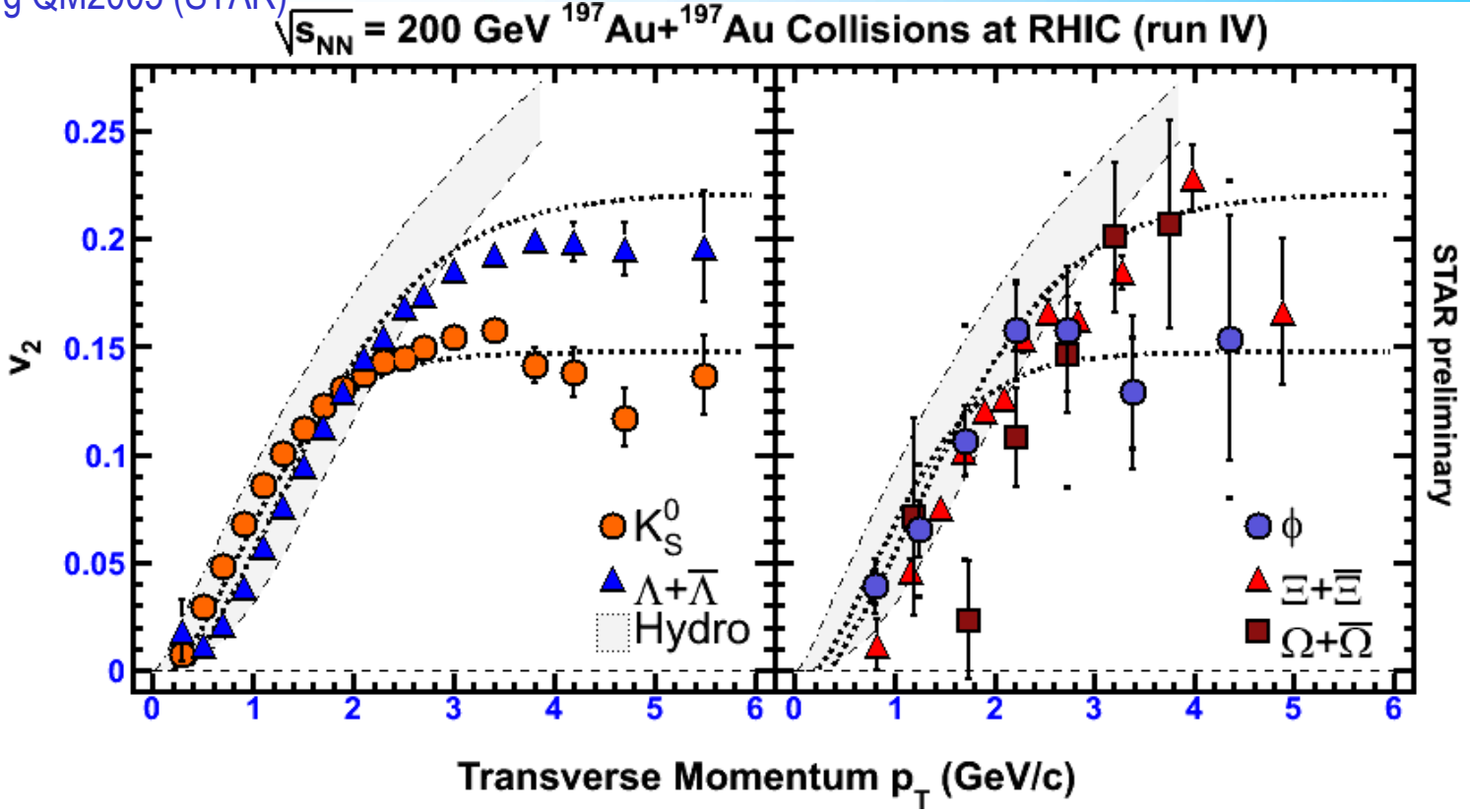
Extended p_T

Year 4 data gives RHIC higher statistics and greater coverage for identified particle v_2

Oldenburg, Srensen QM2005 (STAR)



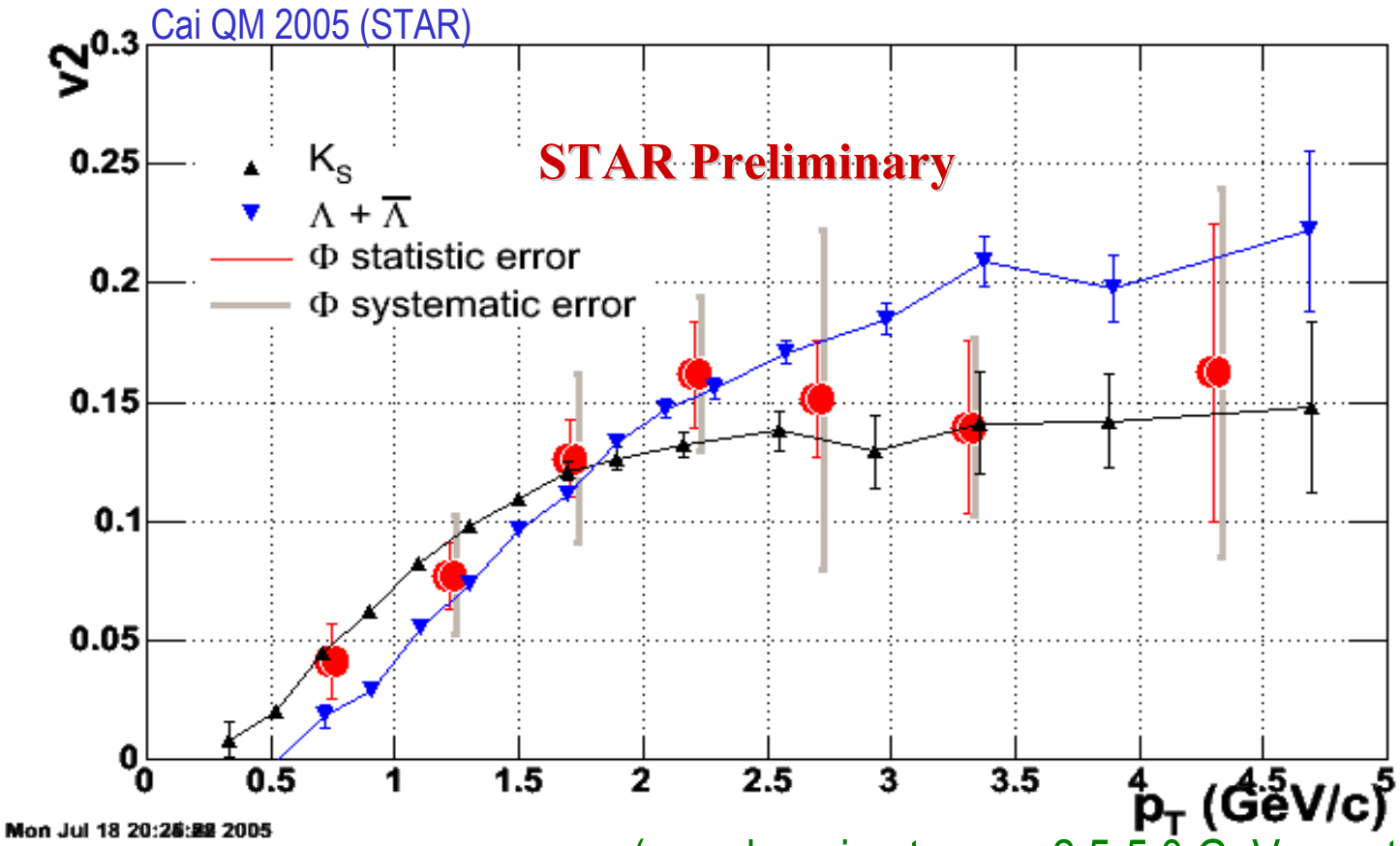
multi-strange hadrons



even ϕ(ss) and Ω(sss) have large v_2 values and follow baryon vs. meson systematics

(in)dependence of v_2 on hadronic σ or flavor/mass ⟶ consistent with the creation of v_2 on partonic level, before hadron formation.

ϕ flows as strongly as other mesons

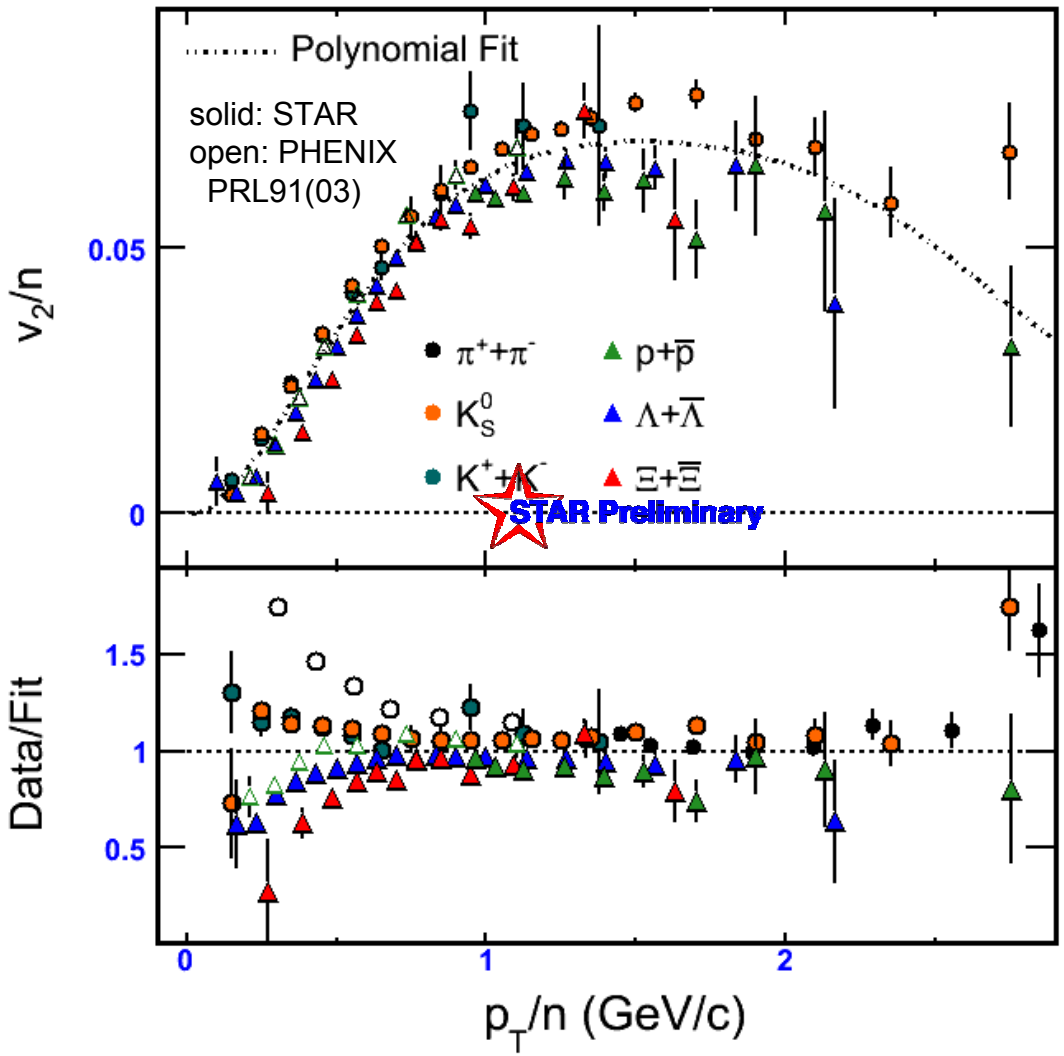


(error bars in pt range 2.5-5.0 GeV are still large)

Collective flow is generated during the partonic stage !

constituent quark scaling

Wang, Oldenburg, QM 2005 (STAR)



- v_2 appears to scale with number of constituent quarks for $p_T/n > 0.6$ GeV/c.

-quark coalescence.

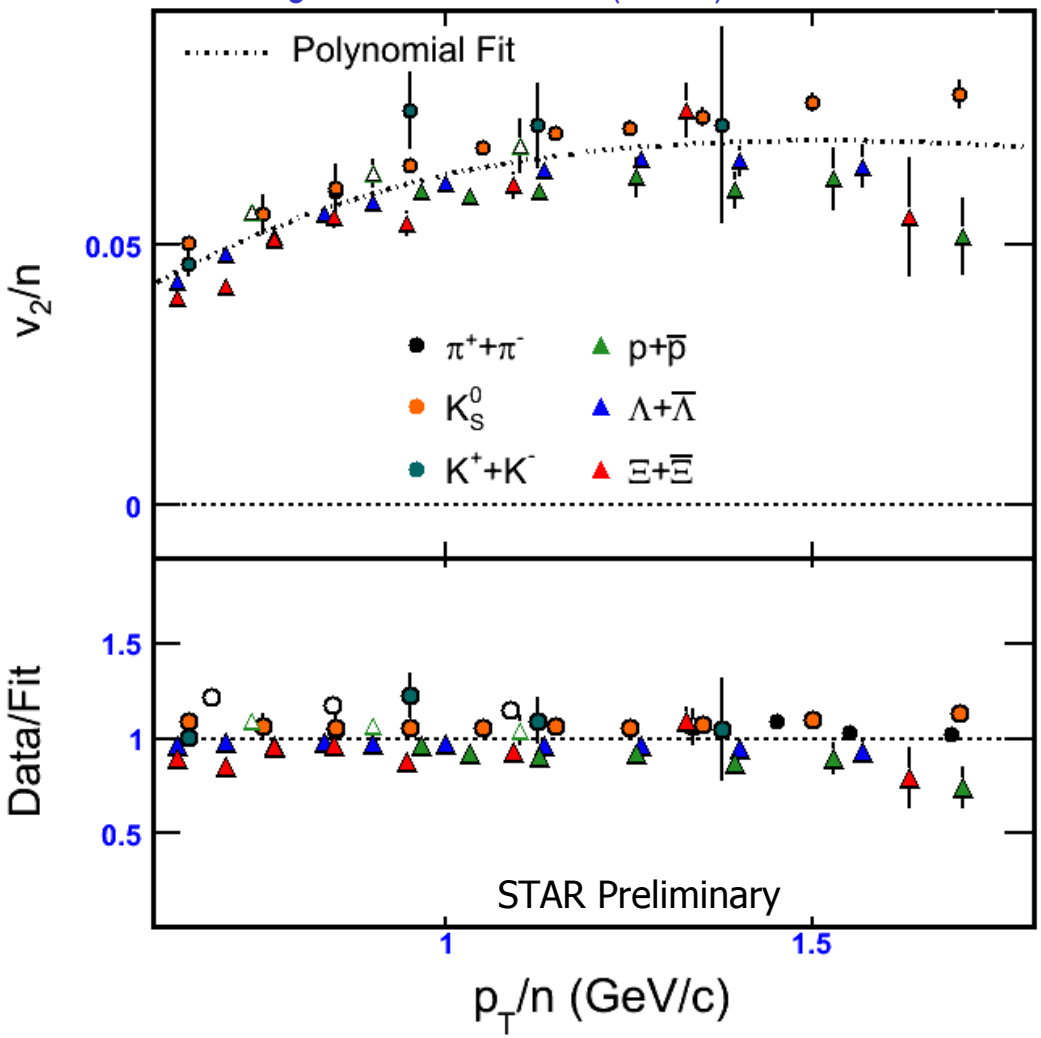
Pions deviate: may be due to resonance decays

constituent quark DOF !

???:
gluons not present at hadronization ?

a closer look

Oldenburg, Srensen QM2005 (STAR)



but

jet fragmentation contribution + spatial correlations can spoil the scaling of v2/n:

D. Molnar nucl-th/0406066

work in progress ….

if hydro works …

Partonic collectivity observed experimentally

and

- observed substantial signal related to flow
- resulting from large pressure gradient
- assuming hydro: THERMALIZATION

If hydro o.k.

thermalization

V_2 of $p,\pi,K,\phi,\Lambda,\Omega,\Xi$, ...

flow - common velocity field

Charm as a probe to test early thermalization

Why Charm ?

Heavy !!

Charm quarks created at early stage of HIC
→ total yields scaled by N_{bin}

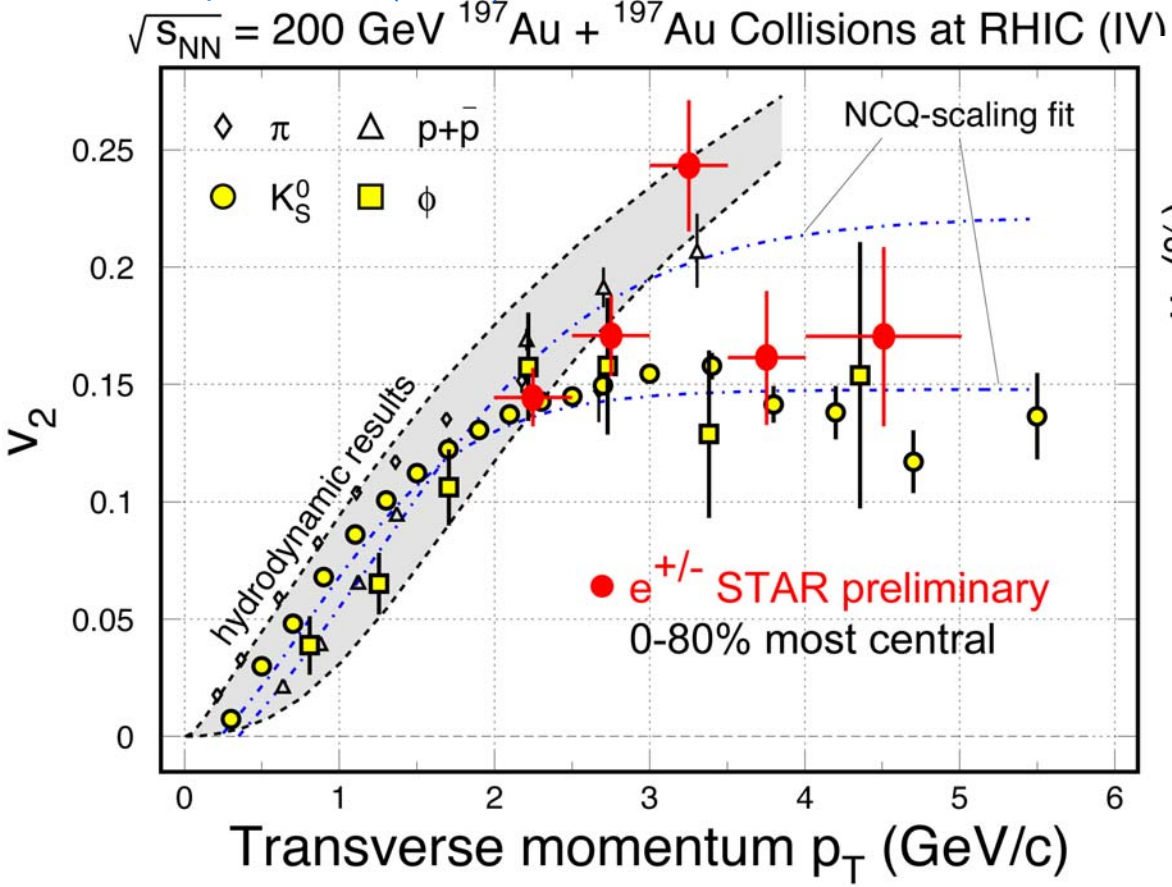
Sensitive to the partonic rescatterings

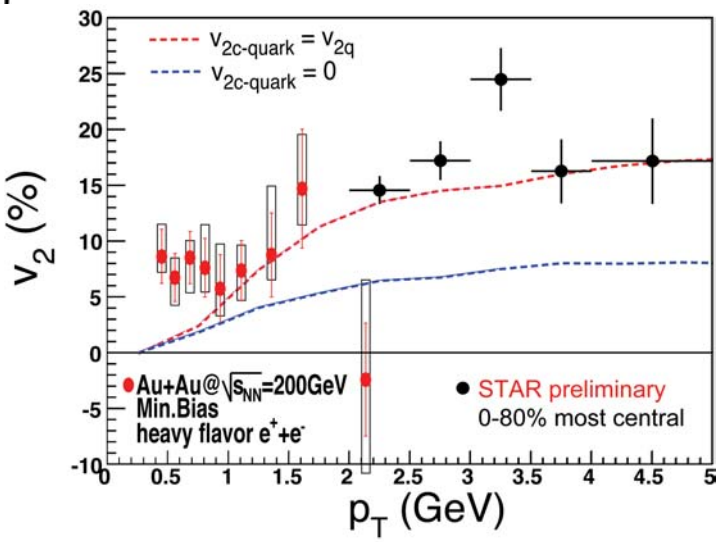
Collectivity, flow
→ light flavor thermalization

Heavy flavor collectivity ⟶ light flavor thermalization

Charm v_2

Laue, Dunlop QM 2005 (STAR)

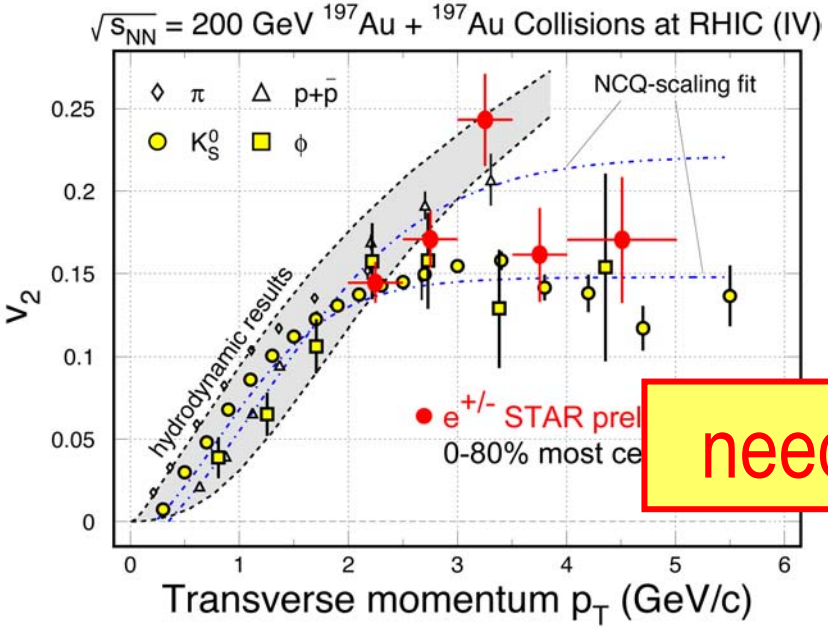




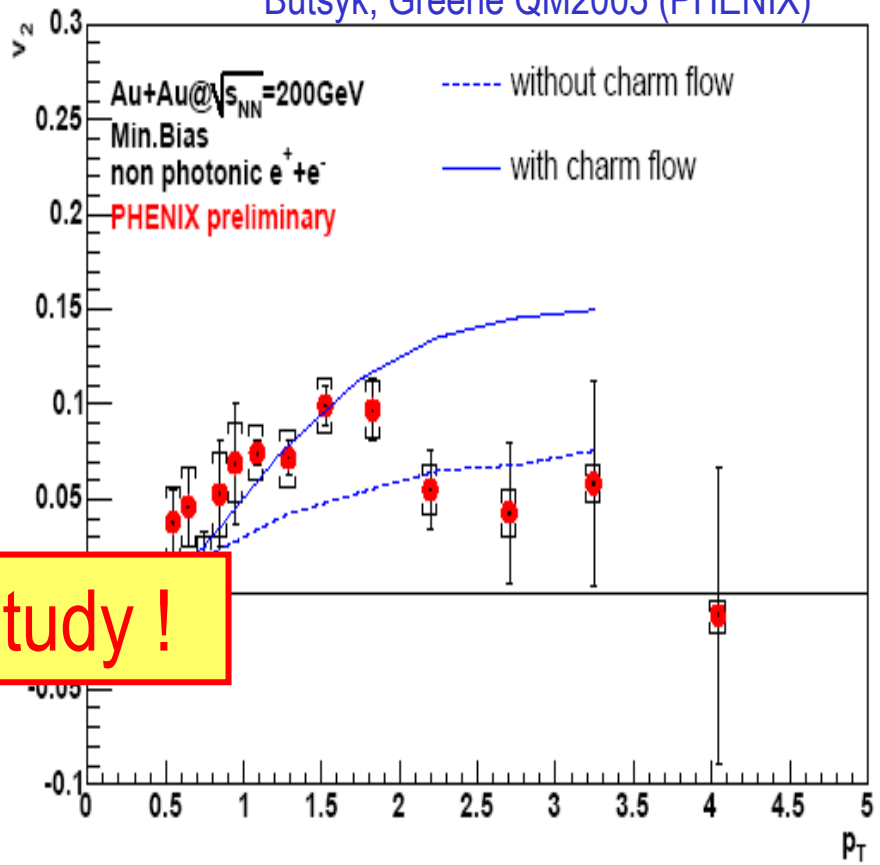
- flow for non-photonic electrons is non-zero ! => heavy flavor collectivity
- favors scenario in which charm quark flows as light quarks
- strong coupling of charm quark to the medium

before and after QM 2005

Laue, Dunlop at QM2005 (STAR)



Butsyk, Greene QM2005 (PHENIX)



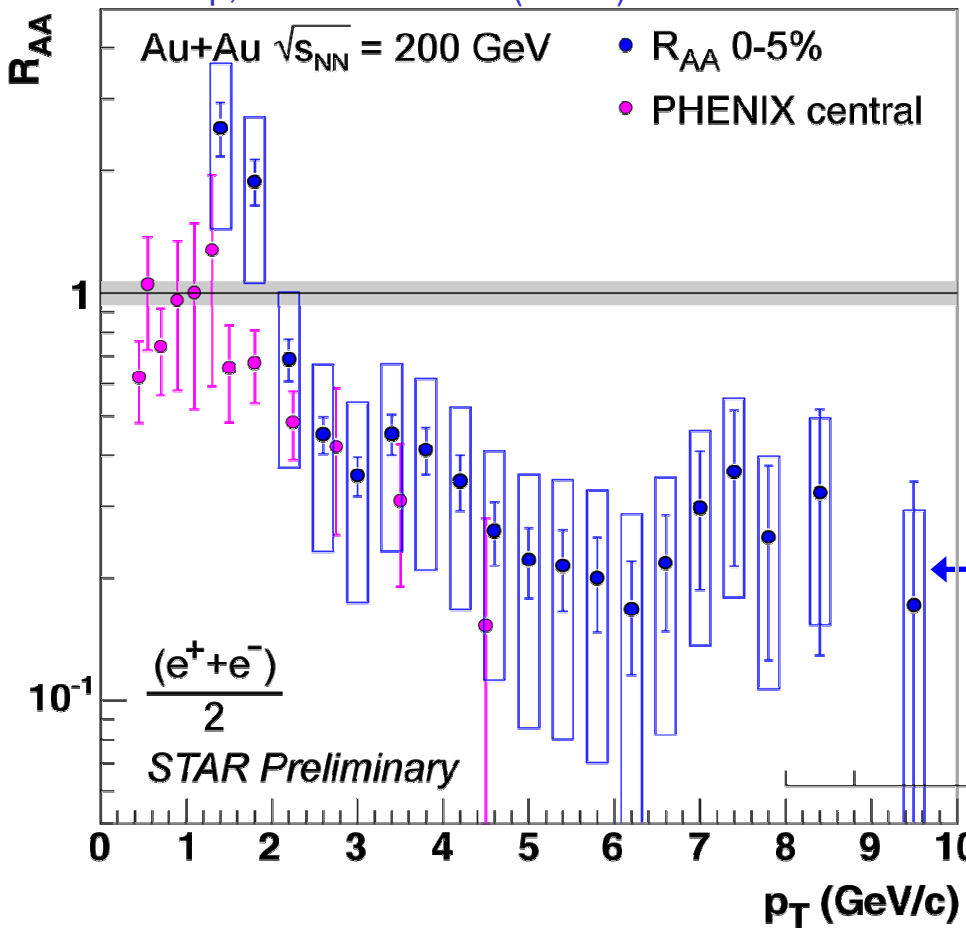
needs study !

Experimental data do not agree at $2<p_T(e)<5$ GeV/c!

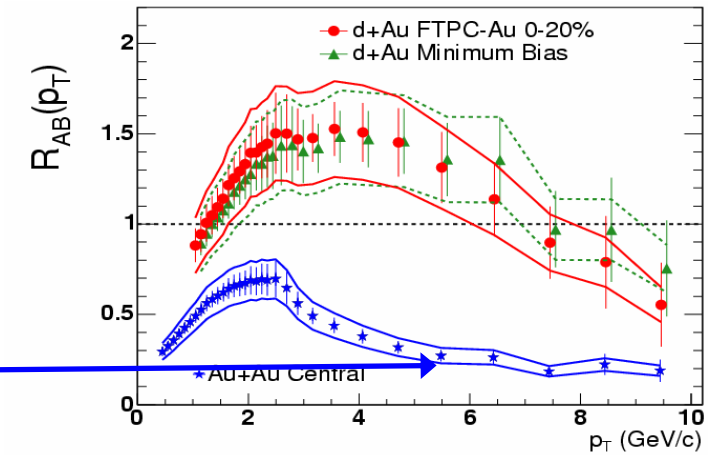
$v_2(e)$ favors non-zero $v_2(c)$

Heavy Flavor R_{AA}

Dunlop, Bielcik QM 2005 (STAR)



Charged Hadron R_{AA}



Clear evidence of strong interactions between heavy and the hot/dense medium!

- **STAR and PHENIX experiments agree!**
- **Clear evidence of large heavy quark energy loss!**

but difference in pp (2x) ?

(J.Nagle, yesterday's talk)

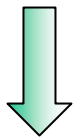
What did we learn from charm study ?

Before any physics conclusion, experimental data must agree!

Non-photonic electrons arise primarily from c and b.

Large charm suppression and flow at intermediate p_T :

- ***v_2(e) favors non-zero v_2(c) !?***
- ***R_{AA}(e) $\approx$ R_{AA}(h) !?***

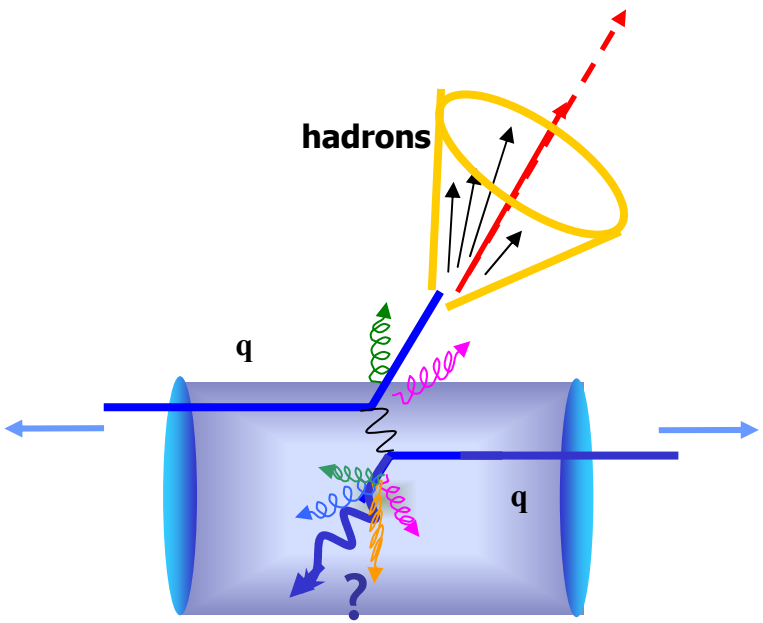


if confirmed

Heavy flavor collectivity!
Light flavor thermalization!
@RHIC

jets and thermalization…

forget Hydro ! look at data, model independent experimental results …



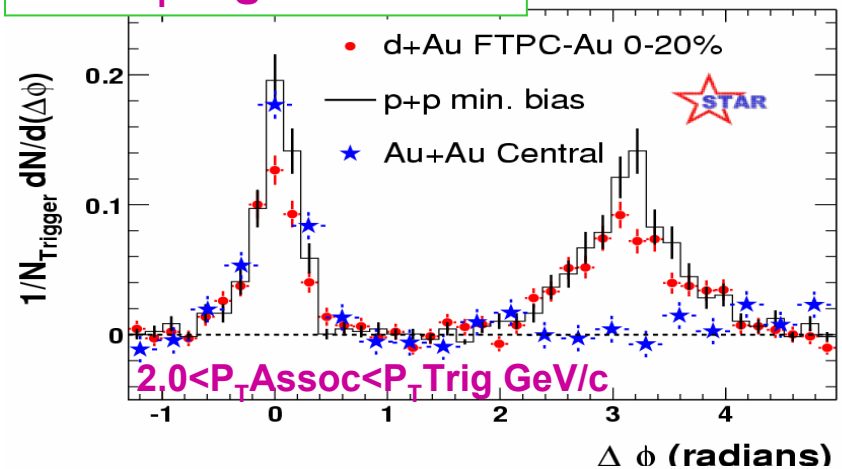
how medium responds to jets ?

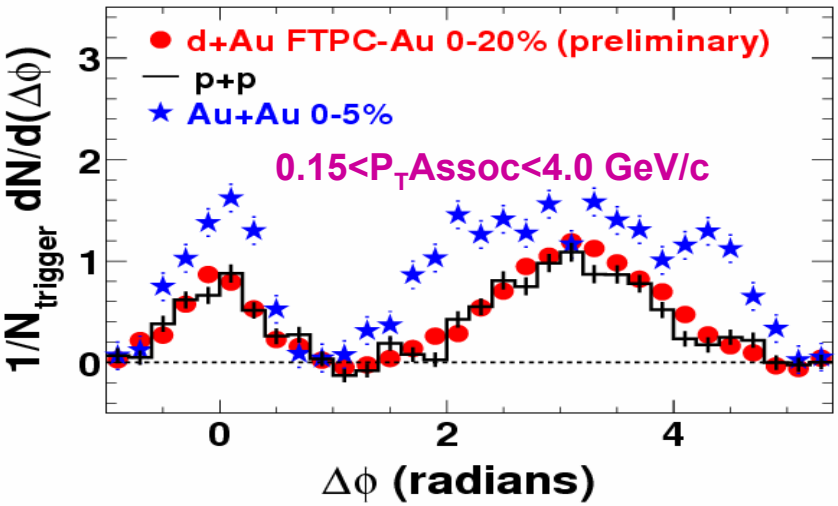
di-jets = way to study medium

Au+Au, pp and d+Au

J.Adams et al., PRL 91 (2003) 072304

4.0<P_TTrig<6.0 GeV/c





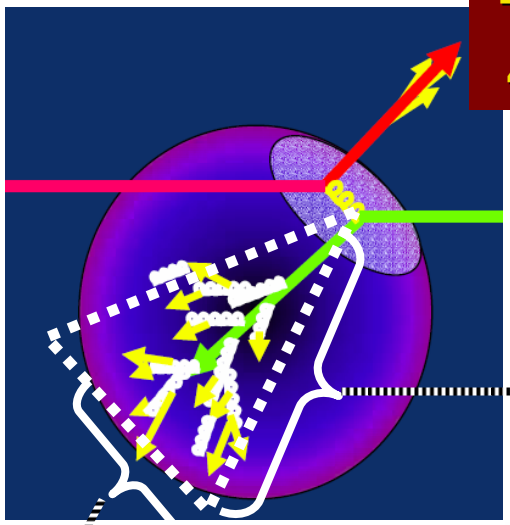
- d+Au and pp similar
  - Implies jet suppression not an initial nuclear effect.
- Au+Au suppressed on away side for higher associated p_T

away side peak is back !

to understand quenching – go beyond leading hadrons

Jet remnants (thermalization)

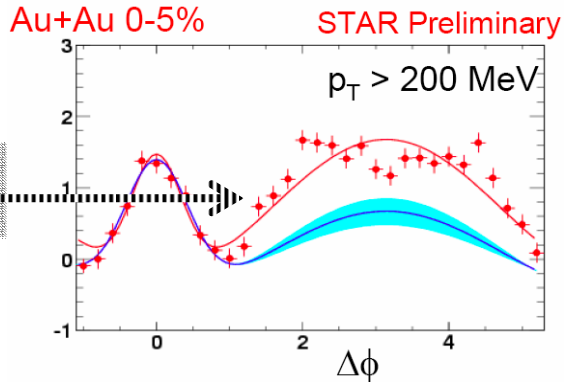
What happens to a hard probe that traverses a colored medium?

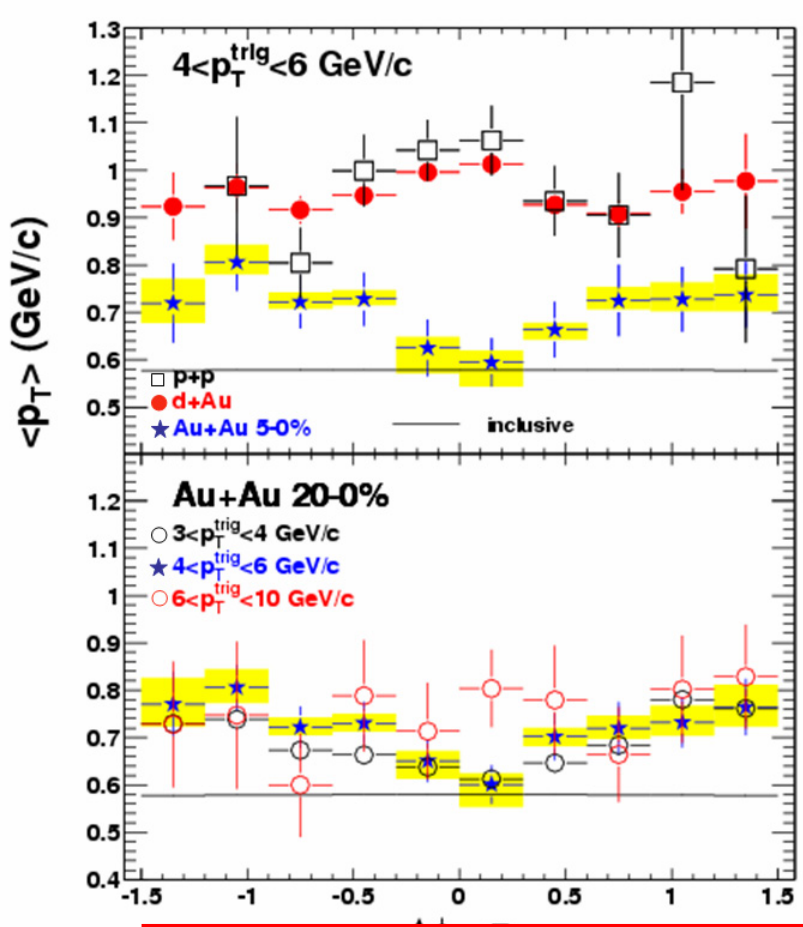


Trigger p_T: 4–6 GeV/c

SOFTENING

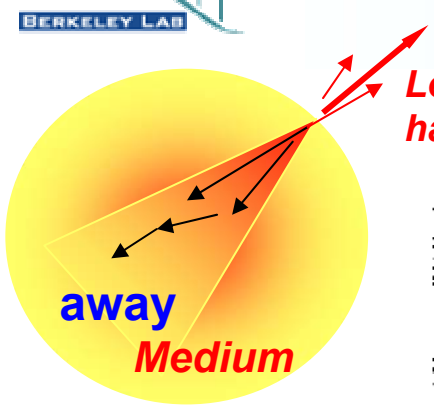
BROADENING



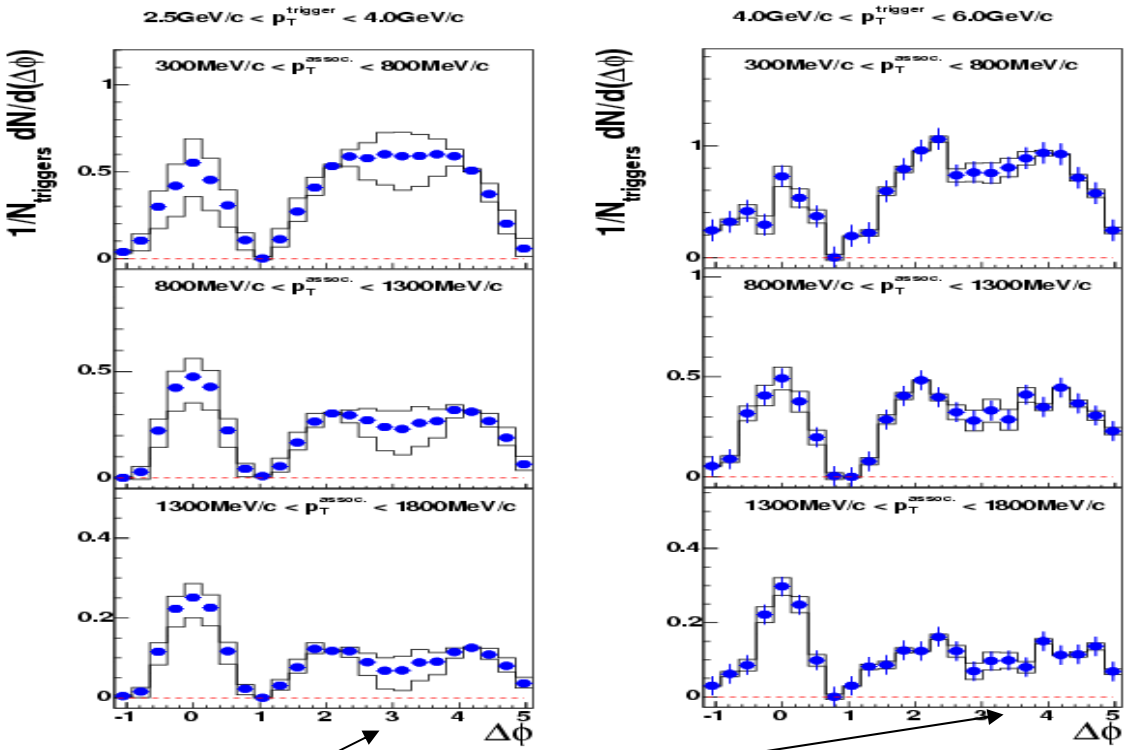


Thermalization !?

Surprise !

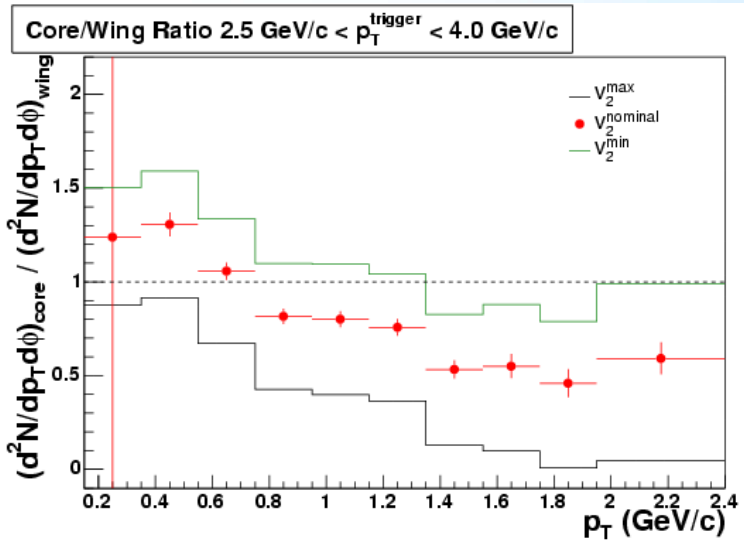


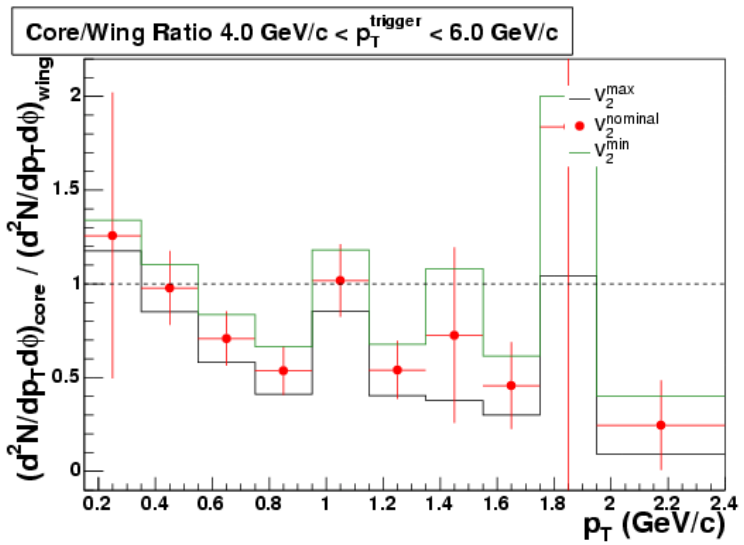
M.Horner QM2005 poster (STAR)



Expected: jet center hardest, especially if we increase associated p_t , but data shows depletion in this region

Study of away-side jets as function of p_t





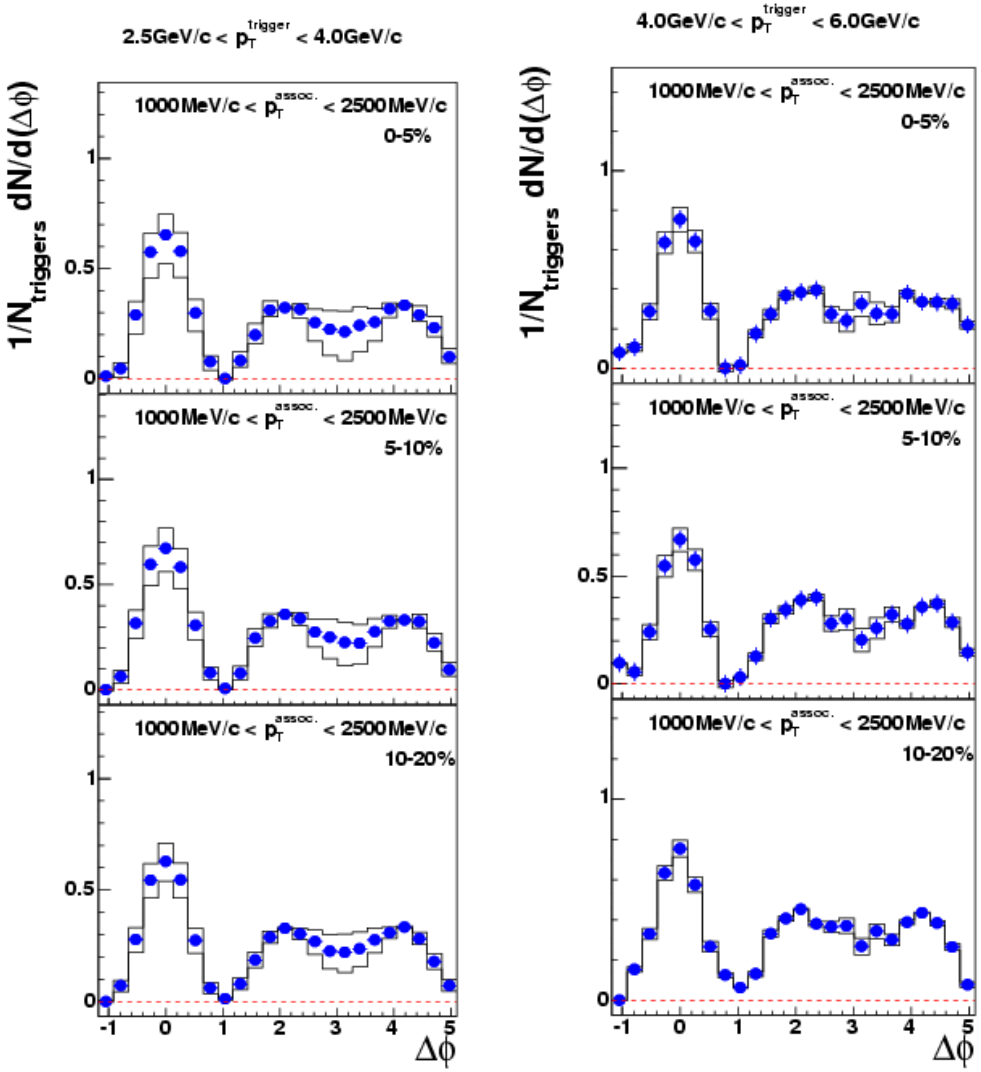
M.Horner QM2005 poster (STAR)

wing: $97.5^0 < |\Delta\Phi| < 120^0$

core: $157.5^0 < |\Delta\Phi| < 180^0$

ratio of yields in core and wing as function of associated pt shows that excess in the core diminish relative to the wing as associated pt increases

dependence on centrality

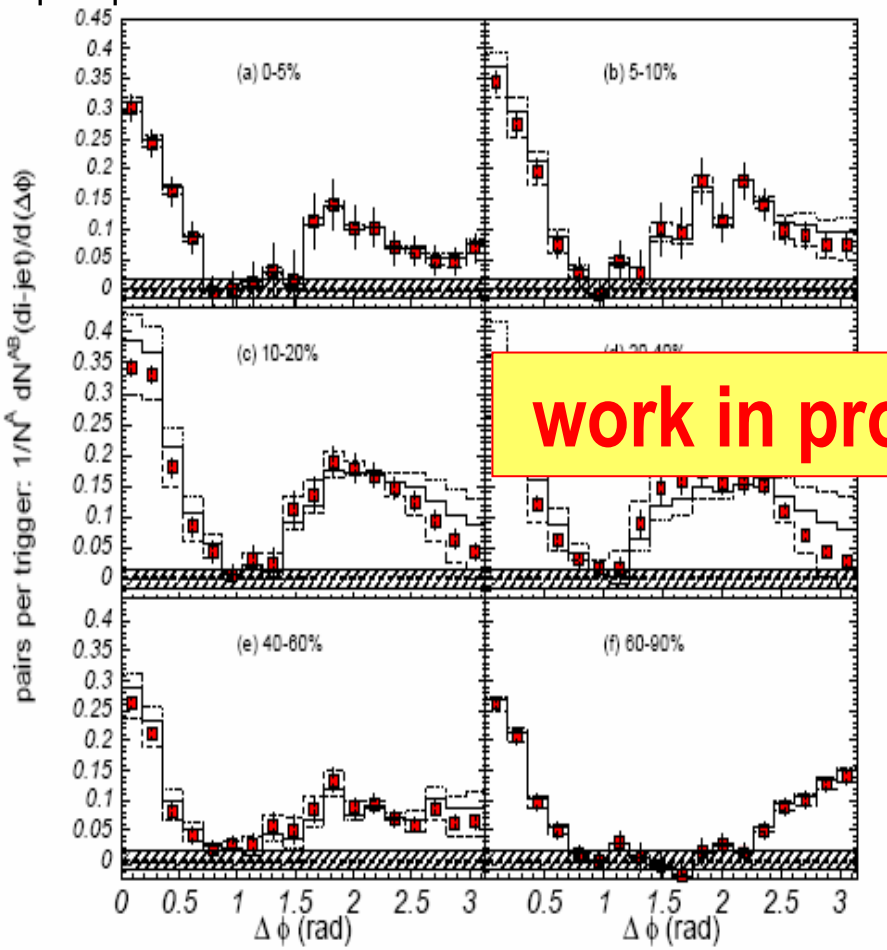


M.Horner QM2005 poster (STAR)

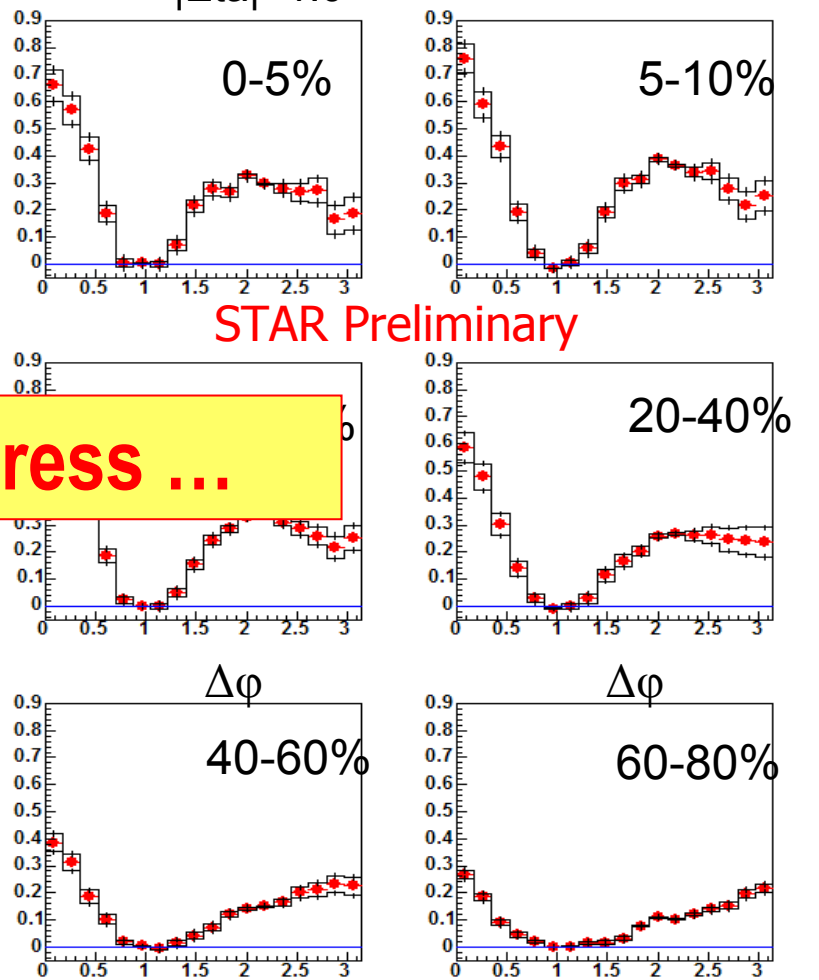
correlated yields and shapes are very similar over the centrality range 0-20 %

PHENIX vs STAR @QM2005

PHENIX data: background subtracted
trigger p_T =2.5-4.0 GeV/c,
associated p_T =1.0-2.5 GeV/c
|Eta|<0.35



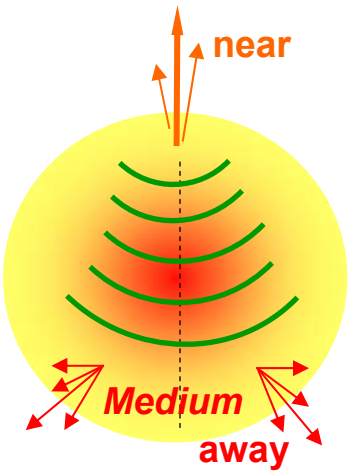
STAR data: background subtracted
trigger p_T =2.5-4 GeV/c,
associated p_T =1.0-2.5 GeV/c
|Eta|<1.0



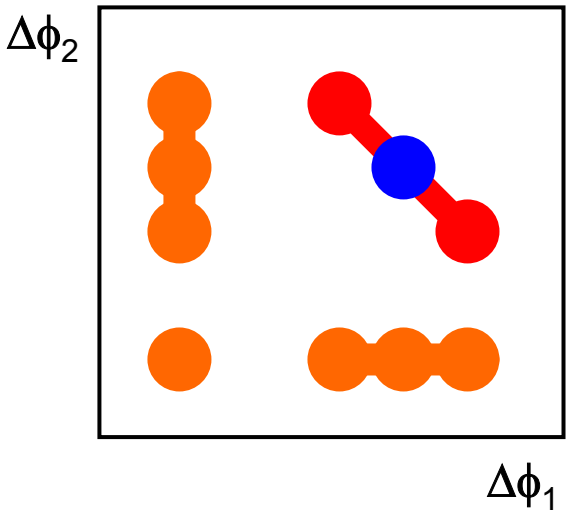
work in progress …

Three-particle correlations

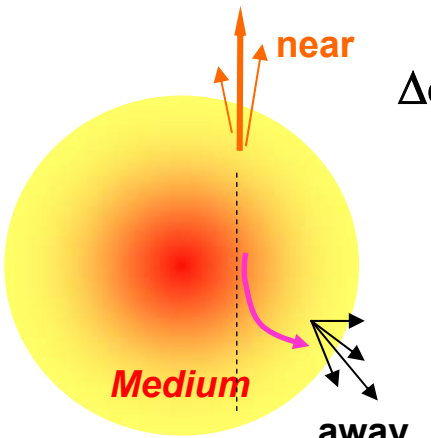
Ulery, Wang QM 2005 (STAR)



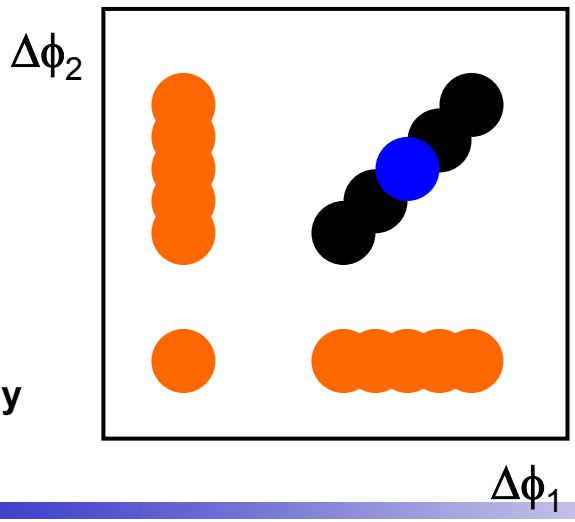
Conical flow



– **Conical flow**: associated particles may appear on opposite sides of $\Delta\varphi = \pi$



Deflected jets



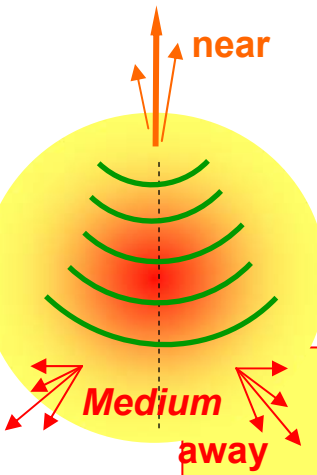
– **Deflected jets**: associated particles on the same side of $\Delta\varphi = \pi$

Casalderrey-Solana, Shuryak and Teaney, hep-ph/0411315
Stocker, NP A750, 121
Ruppert and Muller, PL B618, 123

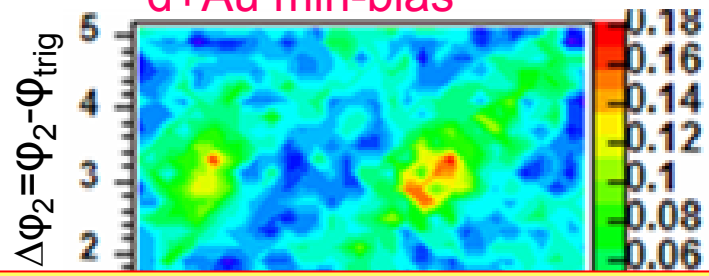
Three-particle correlations in d+Au and Au+Au

Ulery, Wang QM 2005 (STAR)

p_T^{trig}=3-4, p_T^{assoc}=1-2 GeV/c
2-particle corr, bg, v2 subtracted



Conical flow



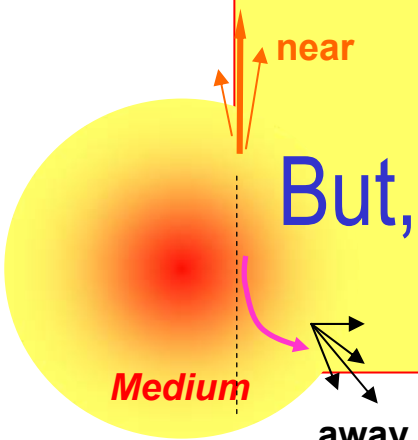
Difference in Au+Au average signal per radian^2:

center – corner =
0.3 ± 0.3 (stat) ± 0.4 (syst)

center – cone =
2σ = 0.3 (stat) ± 0.8 (syst)

STAR - no PHENIX - yes

to conical flow



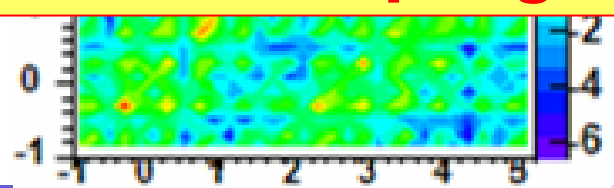
Deflected jets

Elongated along diagonal: k_T effect? deflected jets?

But, experiments show different stuff

- **work in progress**

Distinctive features of conical flow are not seen in present data with these p_T windows.



experimental situation for today

So far the picture is consistent !

Measurements show:

1. elliptic flow $\Leftrightarrow$ large number of initial interactions, collective behavior amongst partons (particularly from Φ and Ω v_2)
2. high p_T suppression $\Leftrightarrow$ initial density, partons lose energy in a hadronic or partonic medium
3. non-photonic electron v_2 $\Leftrightarrow$ interactions copious enough for
4. the u-, d-, and s-quarks to be in a QGP state
5. $\langle p_T \rangle$ of the away side associated particles $\Leftrightarrow$ even hard probes start to become thermalized in the medium.

do we see thermalization … ?

Thanks !