Chasing the Unicorn: RHIC and the QGP

Unicorn = fantastic and mythical beast!

RHIC = Relativistic Heavy Ion Collider @ Brookhaven Natl. Lab (BNL):
collide large nuclei at high energies (also: SPS & LHC @ CERN)

QGP = Quark Gluon Plasma =
New *state* of hadronic matter, in
thermodynamic *equilibrium* at temperature $T \neq 0$

Q: Has RHIC made the QGP?

1. Hot hadrons and the QGP

2. QGP from the Lattice.

3. "Gluon stuff" @ RHIC:
   the (high-pt) tail wags the (low-pt) body of the Unicorn

A: *Some* new *kind* of matter has been created

Hadronic Zoo, units

Hadronic particles = strongly interacting = *baryons & mesons*

baryons: proton & neutron   mass = 940 MeV (MeV = 10^6 eV)
≈ 1 GeV

mesons: pions $\pi^{\pm}, \pi^{0}$ mass π ≈ 140 MeV

All hadrons interact by pion exchange => fund. length: $1/m_\pi$ = 1 fermi (fm)
fund. time scale = 1 fm/c

Less familiar: strange baryons: Λ (1120), Σ (1190), Ω (1680)
strange mesons: 4 Kaons $(K^{\pm}, K^{0}, \overline{K}^{0})$ (540) & η (550)

Many others: higher spin, other "flavors"....

Quark Model: *all* hadrons composed of quarks.

Quark Zoo: 2, 3, 5(!) quarks

Previous: *up, down, & strange flavors* of quarks = u, d & s

π, K, η *very* light = "spin waves" of (approx.) *chiral symmetry*

mass up & down quarks << mass strange quark

mesons = $\overline{q}q$ q = u, d, or s.   π = u&d   K = (u or d) & s

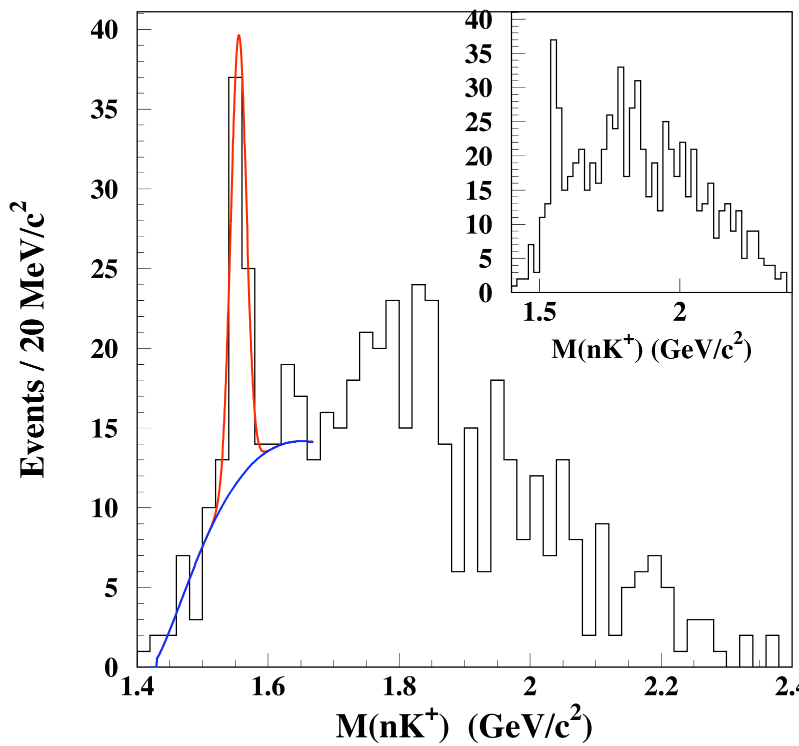
baryons = qqq n,p = u,d's; Λ = 2(u,d)&s; Σ = (u,d)& ss; Ω = sss.

New: "penta-quarks" = $qqqq\overline{q}$

Θ^+ = $udd\overline{s}$ (Diakonov, Petrov, Polyakov)

CLAS @ JLAB: mass = 1550 ± 10 MeV.   8 σ! =>

width < 26 MeV! => *really* narrow



Quark & Gluons = QCD: asymptotic freedom

Global symmetries familiar. E.g., spherical symmetry = SO(3).

Local symmetry: at *each* point, *arbitrary* rotations in "internal" space.

Need new degrees of freedom: non-Abelian gauge fields = gluons.

QCD = SU(3) gluons + quarks. 3 of SU(3) = # colors.

Remember: at critical point in *four* dimensions, coupling vanishes
logarithmically at *small* momentum = *large* distances.

QCD = asymptotically free = exact converse to 4-dim. critical pt.
QCD coupling constant vanishes
logarithmically at *high* momentum = *short* distances.

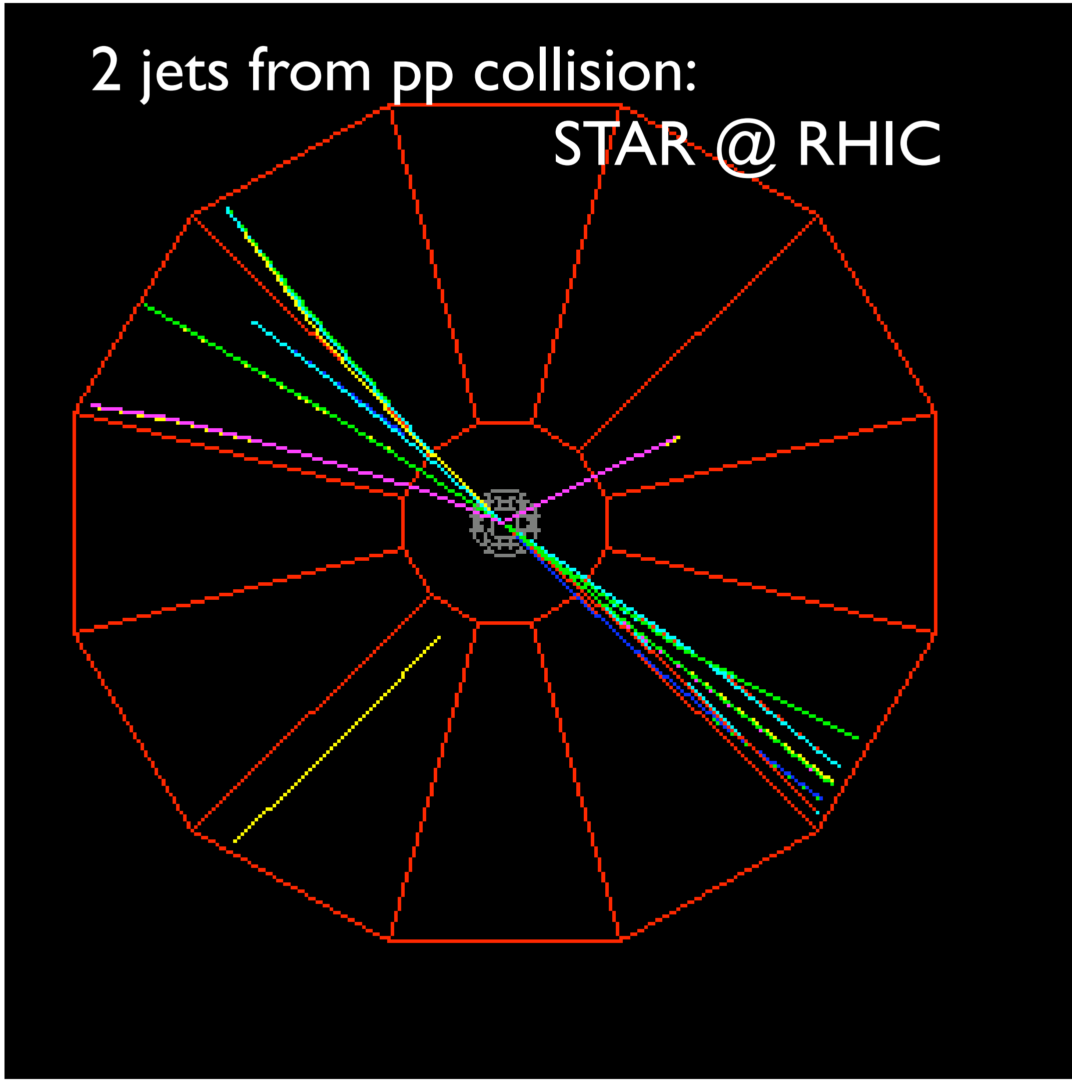
('t Hooft) Gross & Wilczek, Politzer...

Jets: "seeing" quarks and gluons in QCD

Confinement => qks & gluons *permanently* bound into hadrons at *large* distances!

Asymptotic freedom => "see" quarks & gluons as "jets" = sprays of particles (see =>) quark or gluon => mesons & baryons.

Can compute jets perturbatively in weak coupling.



Note: given a jet in one direction, there *must* be another jet in the backward direction.

QCD & chiral phase transition

In broken phase, (approx.) "spin waves"
= (almost massless) pions, K's, η

up & down quarks: "flavor" symmetry = $SU_L(2) \times SU_R(2) = O(4)$

& strange quark: = $SU_L(3) \times SU_R(3)$

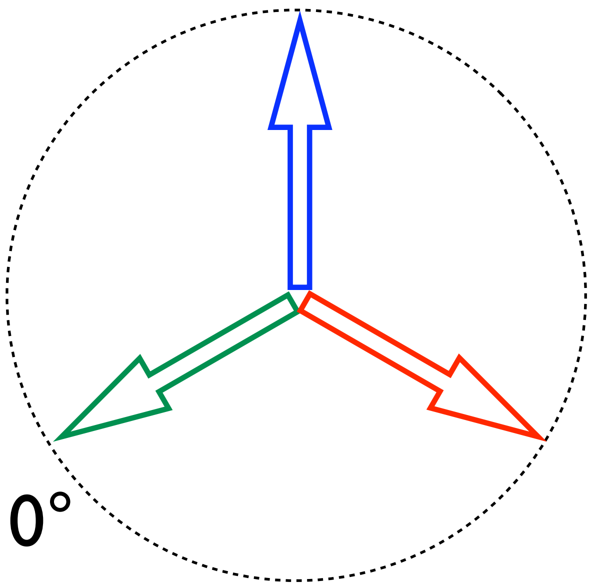
Heat QCD at some temperature ~ pion mass

Chiral symmetry ~ magnet:
broken at low temperature
restored at temperature for chiral phase transition, T_ch

(What about η' from extra axial U(1)? Instantons....
Could dramatically affect transition properties with *light* quarks.)

Gluons and a three state model

Confinement: gluons => individual quarks don't exist, only
nucleons & mesons.
= type of *three* state (Potts) model.



For a given state, assume a transformation:
for *each* quark, rotate by 120°.

With three quarks, rotate by 3 x 120°= 360° = 0°
=> baryons *invariant*

Anti-quark => rotation by -120°. Mesons +120° -120° = 0°
=> mesons *invariant*

Global Z(3) symmetry in local SU(3). 't Hooft '79.

Confinement => only *invariant* states exist.

Confinement & Ordering

Confinement => all states *invariant* under Z(3) rotations.

Valid at zero temperature, for some range of temp.'s

Asymptotic freedom => coupling constant vanishes as T=> ∞,

=> ideal gas at T=∞ => *NO* confinement.

So, there must exist a deconfining phase transition @ some T_d

Above T_d, ok to have system with 1, 2, 3... quarks (anti-quarks)

In terms of Z(3) model, "deconfinement" =>

Z(3) spins order at *high,* not *low,* temperature!

Order of Phase Transitions

For QCD, *both* Z(3) and chiral symmetries are *approximate*.

Relationship between deconfining and chiral transitions?

Guess: Strongly First Order Transition(s)?

"of course" hadrons ≠ quarks & gluons!

Deconfining transition (NO quarks): cubic invariant is Z(3) symmetric: ℓ^3

first order deconfining transition (Svetitsky & Yaffe).

colors => ∞: first order deconfining transition.

Two massless flavors: O(4) sym. => second order chiral transition

three massless flavors: *cubic* invariant $\det(\Phi)$ => first order chiral trans.

if axial U(1) restored: first order chiral transition for 2 & 3 flavors (RDP & Wilczek)

The “Unicorn”:

Quark-Gluon Plasma =

Deconfined,
Chirally Symmetric “Phase”
at nonzero temperature

But how to compute
properties of the QGP?

QGP on the Lattice

Lattice: compute from *first* principles as lattice spacing a=>0. 2004:

Only gluons (no qks, pure gauge): present methods close to a=0!

T_d ~ 270 ± 10 MeV
Weakly first order deconfining trans. (Some masses ↓ by ~10).

Non-perturbative QGP from T_d => 3 T_d. *No* "of course"

QCD: present methods *not* close to a=0. *All* results tentative.

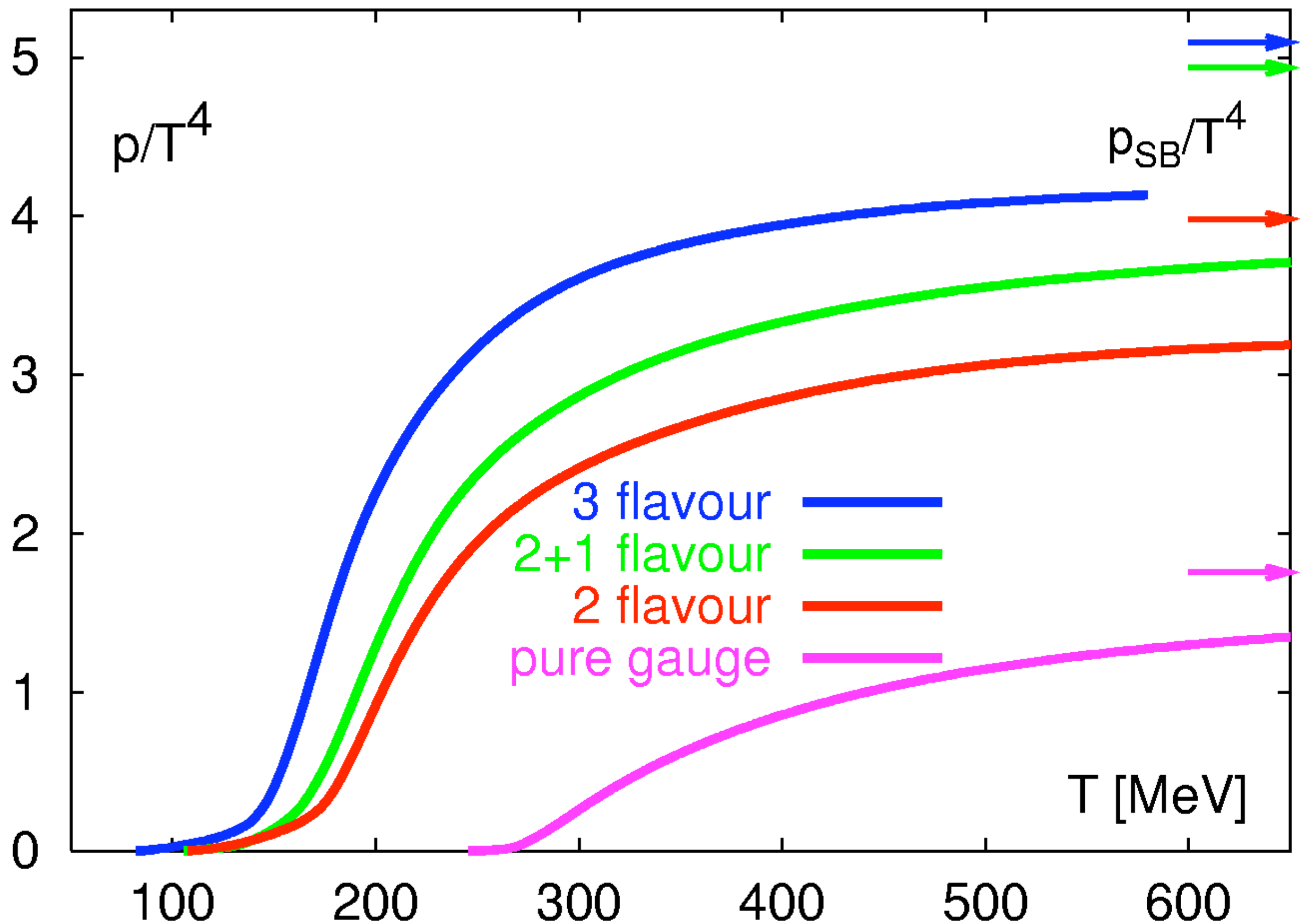
T_c ~ 175 ± ? MeV
Only *one* transition (chiral = deconfining)

Order? Crossover today, tomorrow?
"Flavor independence": pressure *with* qks ~ with*out* qks.

Lattice: pressure vs temp., pure glue to QCD

p(T)=pressure. Asymptotic freedom => p/T^4 = const. as T → ∞

p/T^4↑



<=ideal gas: QCD = 2+1 qk fl.'s & gluons

<=ideal gas: just gluons

T(MeV)=>

↑Tc ~ 270: pure gauge

↑Tc ~ 175: QCD = 2+1 flavors qks & gluons

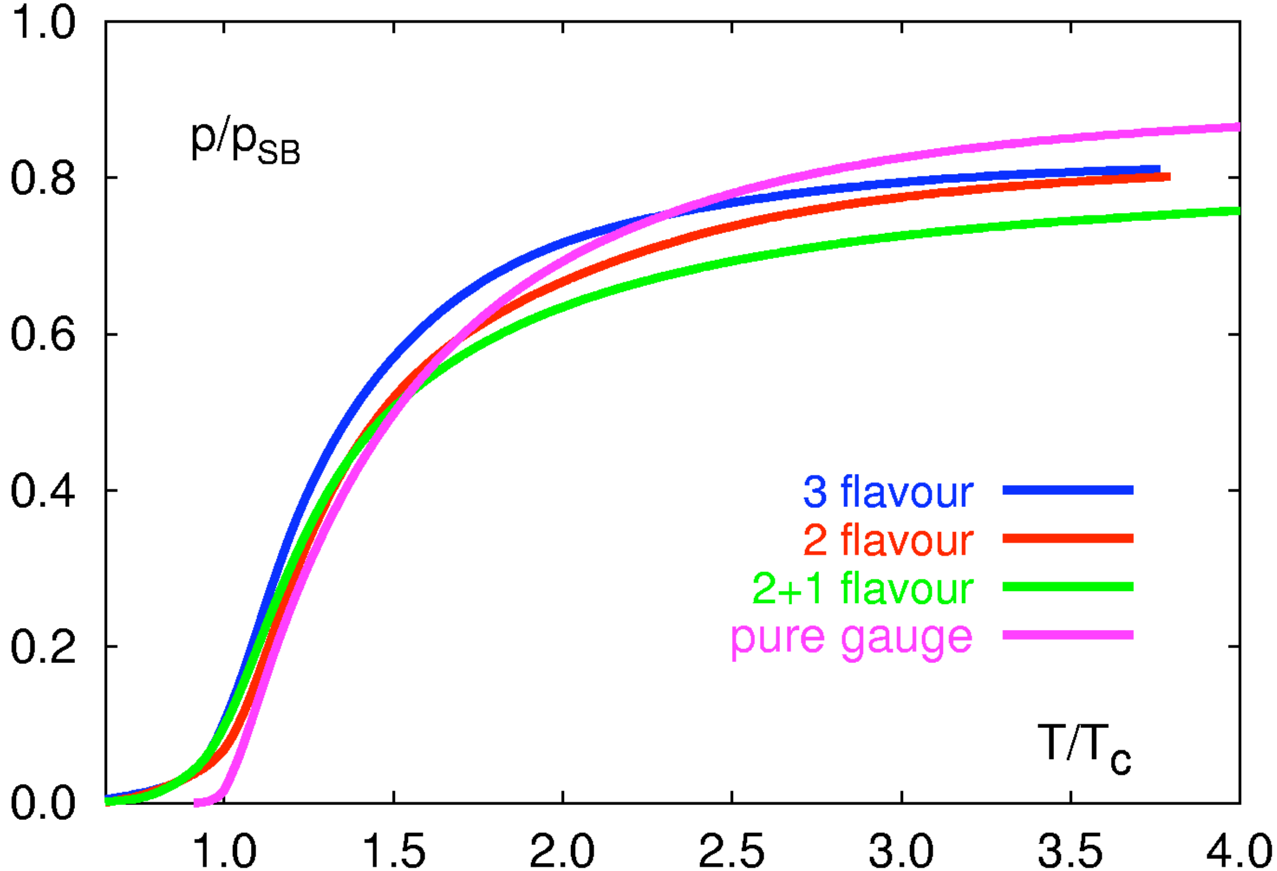
Lattice: "Flavor Independence"

Lattice finds *amazing* property: properly scaled, pressure *with* quarks like that *without*: *Bielefeld.*

$$\frac{p}{p_{ideal}}\left(\frac{T}{T_c}\right) \approx universal$$

1.0=>

pressure/
ideal gas↑

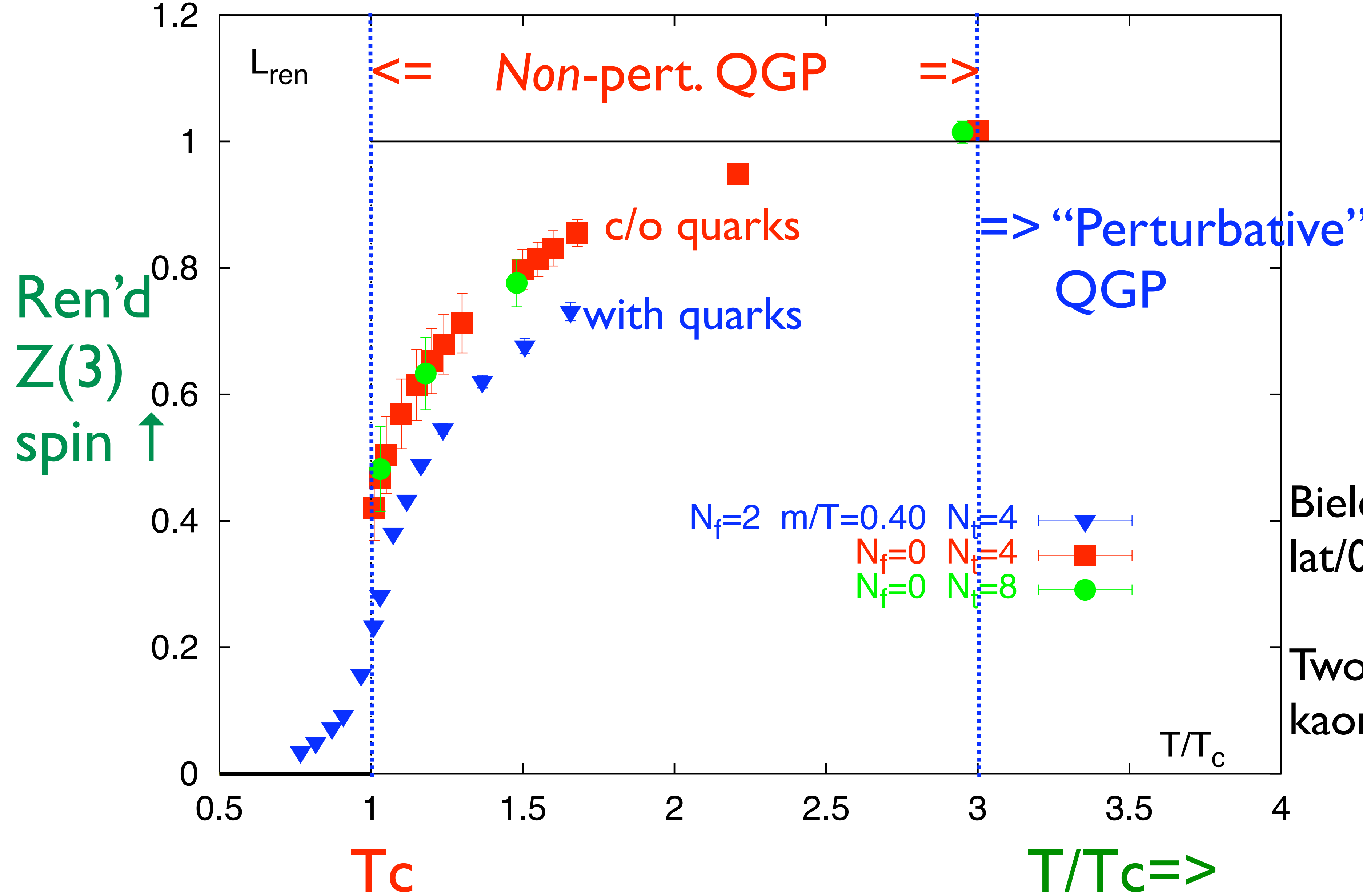


=> pressure *dominated* by *gluons?*

T/Tc=>

Non-pert. QGP for Tc => ~ 3 Tc

(Ren.'d) Z(3) spin for pure glue (c/o qks) & with quarks.
Z(3) spin ~1 in pert. thy; loop far from one=> *NON-pert. plasma.*



Bielefeld:
lat/0312015

Two flavors,
kaon masses

The QGP Exists!
Hunting for the "Unicorn" in Heavy Ion Collisions

"Unicorn" & the QGP: Scott, Stock, Gyulassy...

Hunters = experimentalists, "all theorists are dogs..."

Why collide big nuclei at high energies?

One can collide:

pp: protons on protons. Benchmark for "ordinary" strong int.'s

AA: nucleus with atomic number A on same.

dA: deuteron (N+P) on nucleus. Serves as another check.

Why AA? Baryons are like hard spheres, so nuclear size $\sim A^{1/3}$

Biggest: Pb (lead) or Au (gold), A ~ 200 => r_A ~ 7.

Transverse radius of nucleus $\sim A^{2/3}$ => trans. size ~ 50 x proton.

A ~ 200 close to A $\rightarrow \infty$ $=$ *infinite* nuclear matter?

AA collisions at high energy: where?

High energy >> mass. Particles accelerated in rings.
Either: one ring hitting a *fixed target,* or
collider: two rings, with particles in opposite directions. Collider higher energies

Machines	Total energy/nucleon	Type
SPS @ CERN	5 => 17 GeV	(fixed target)
**** RHIC @ BNL	20, 130, 200 GeV	(collider, > 2000)
LHC @ CERN	5500 GeV = 5.5 TeV	(collider, > 2007)
SIS200 @ GSI	2 => 6 GeV	(fixed target, > 2010)

SPS = Super Proton Synchotron: CERN @ Geneva, Switzerland.
RHIC = Relativistic Heavy Ion Collider: BNL @ Long Island, NY.
LHC = Large Hadron Collider.
SIS = SchwerIonenSynchrotron: GSI @ Darmstadt, Germany.

Essentials of AA collisions

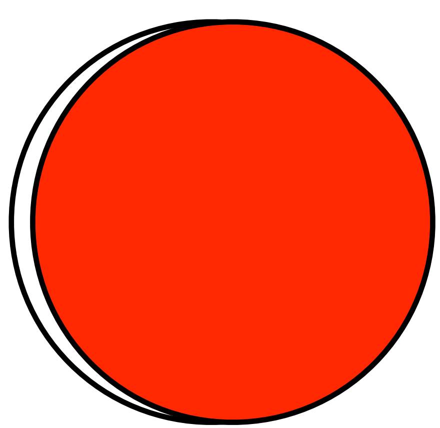
At energies >> mass, nuclei *slam* through each other.

Particles very different *along* beam direction, vs. *transverse* to beam.

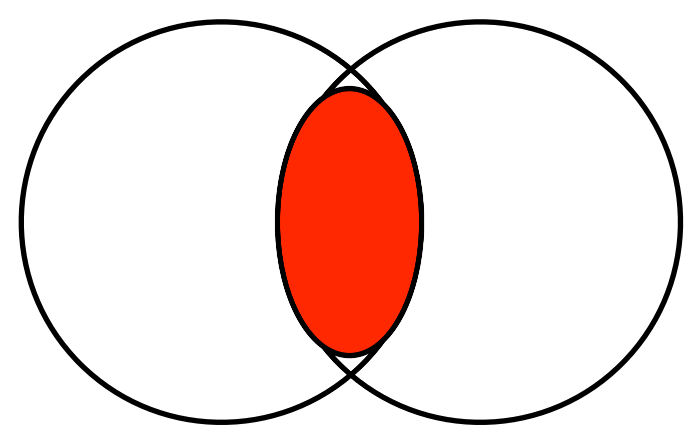
In collider: *ignore* along beam; look *just* perpendicular to beam
"central" or zero rapidity (rapidity ~ velocity along beam.)
90° to beam => few baryons => most likely to see nonzero temp.

Consider distribution of particles *only* in transverse momentum, p_t
Most particles at $p_t = 0$, fall off with increasing p_t. Thermal?

Central:
Maximum Overlap



Peripheral=>
"Almond" of overlap region



Typical Heavy Ion Event @ RHIC

Experiments @ RHIC:

"Big" expts: ~ 400 people
STAR & PHENIX

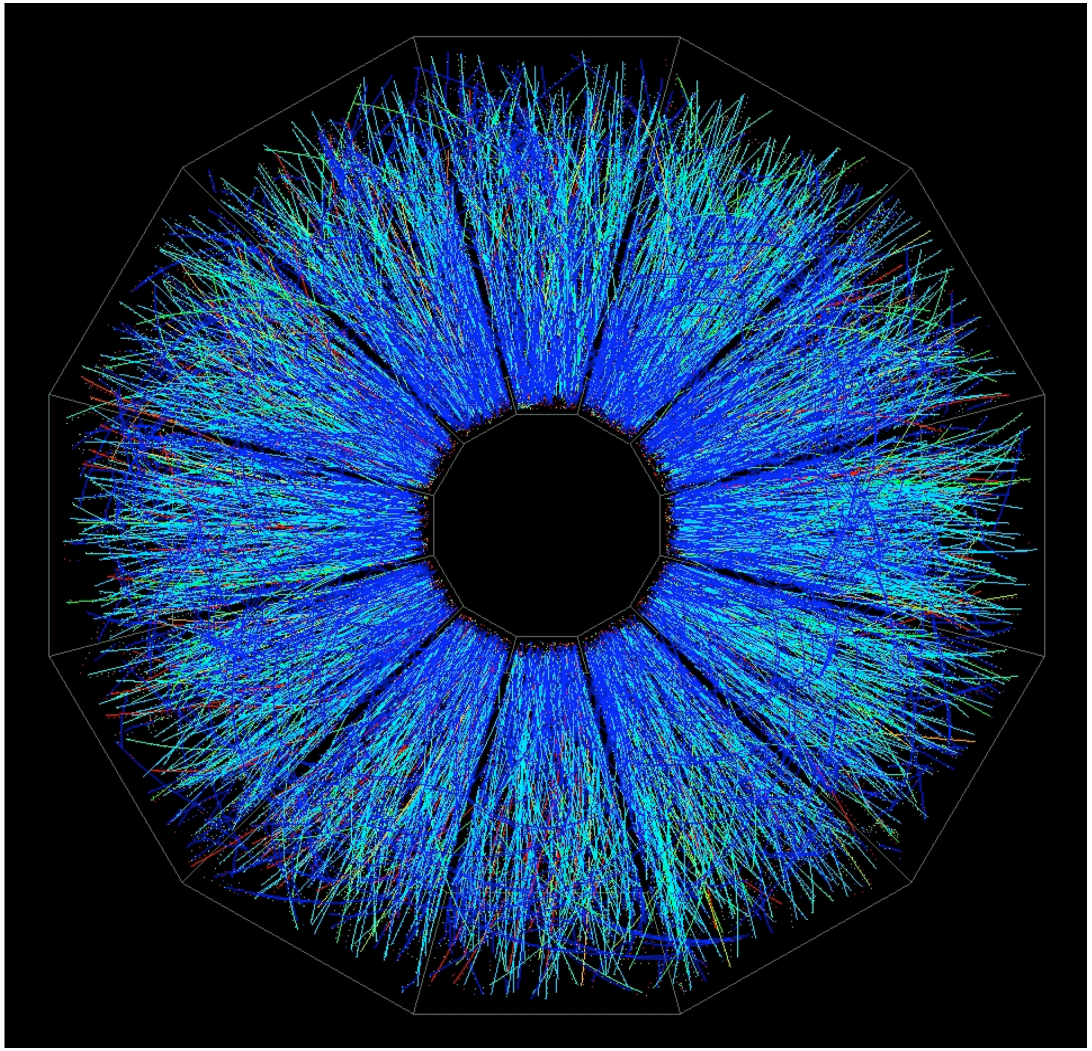
"Small" expts.: ~ 50 people
PHOBOS & BRAHMS

Note: total # particles ~
total # experimentalists
~ log(total energy)

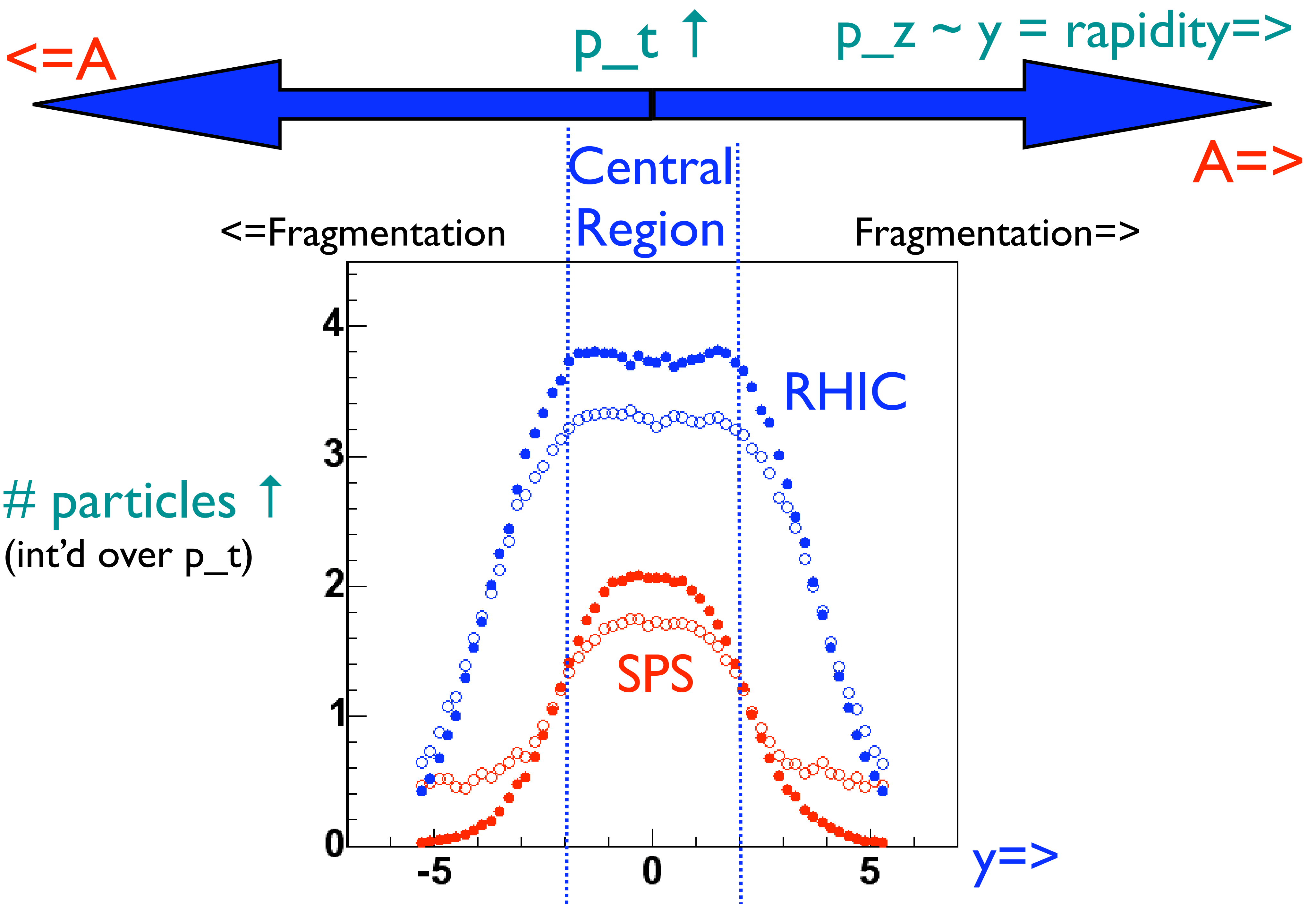
theorists
~ log(log(total energy)).

Need hunters more than dogs...

Total # particles(/unit rapidity)
~ 900↓



Particle # vs velocity along beam @ collider



Body of the "Unicorn":

Majority of particles, peaked about zero transverse momentum; ~1% relative abundance by p_t ~ 2 GeV.

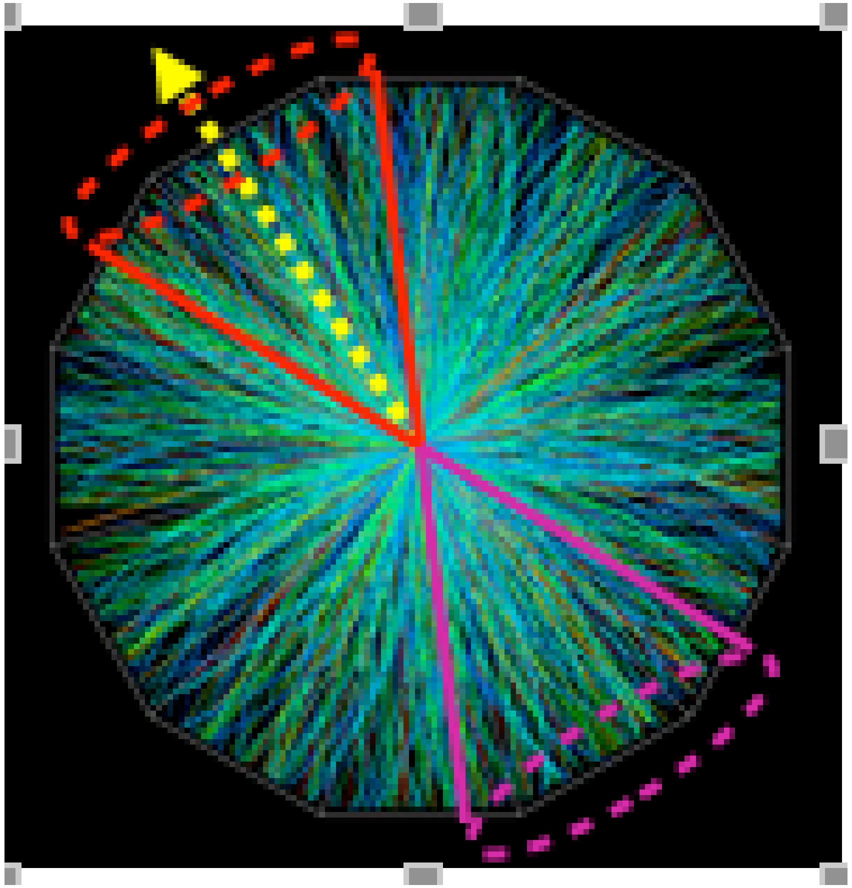
Tail of the "Unicorn":

Look at particles at *high* momentum, p_t > 2 GeV, to probe the body.

The Tail wags the (Dog) Unicorn

"Jets" in central AA collisions

pp collisions: ~ 4 particles/unit rapidity, vs 900 in central AA.
Hence cannot see *individual* jets in AA.



Can construct statistical measures.

p_t = momentum transverse to beam

Trigger on "hard" particle,
p_t: 4 => 6 GeV

Given a jet in one direction, there *must* be *something* in the opposite direction.

Look for the "away" side jet, p_t > 2 GeV. (mass proton ~ 1 GeV)

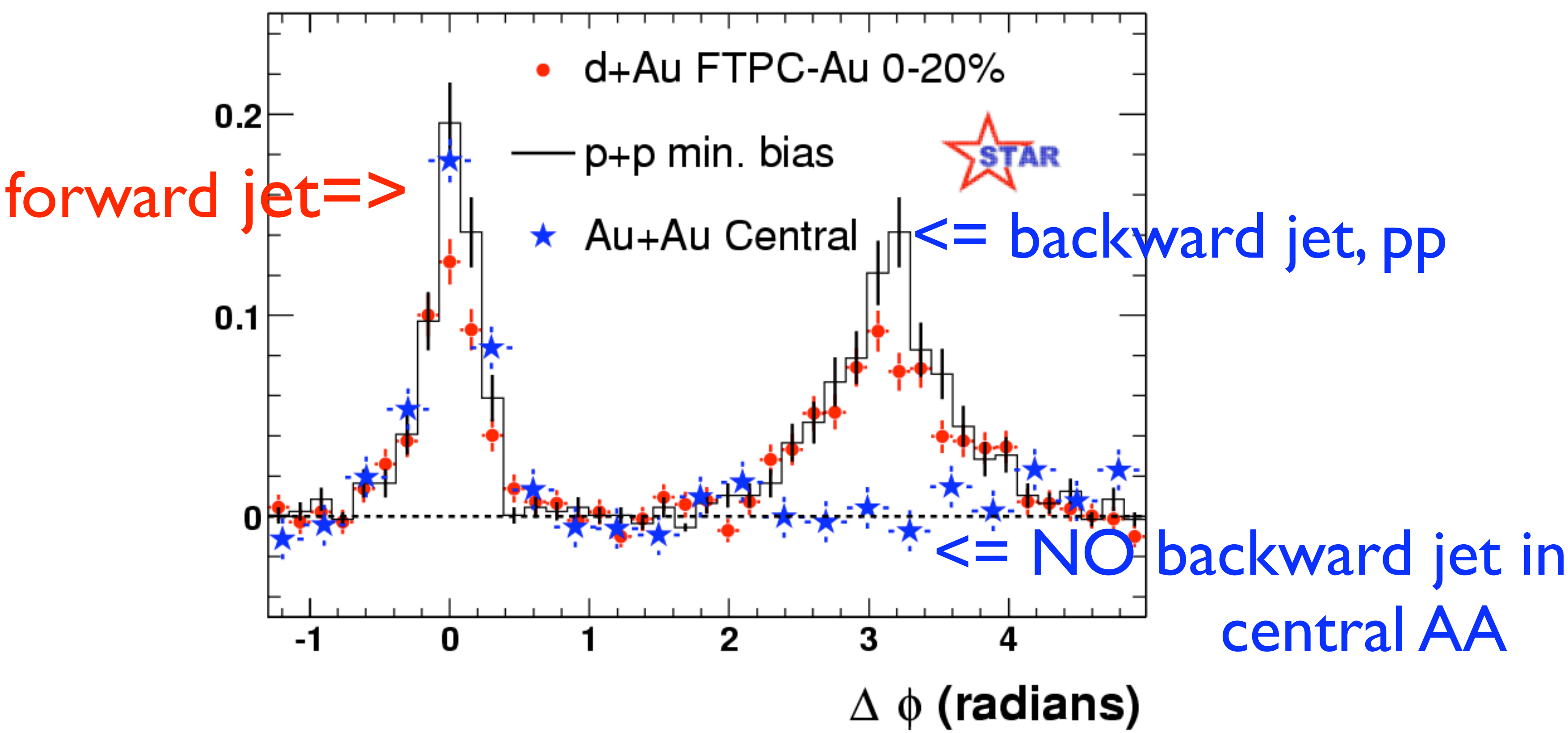
Central AA collisions "eat" jets!

In pp or dAu collisions, *clearly* see away side jet.

In central Au-Au, away side jet *gone: "stuff" in central AA "eats" jets!*

Fast jet tends to lose energy by many soft scatterings off "stuff".

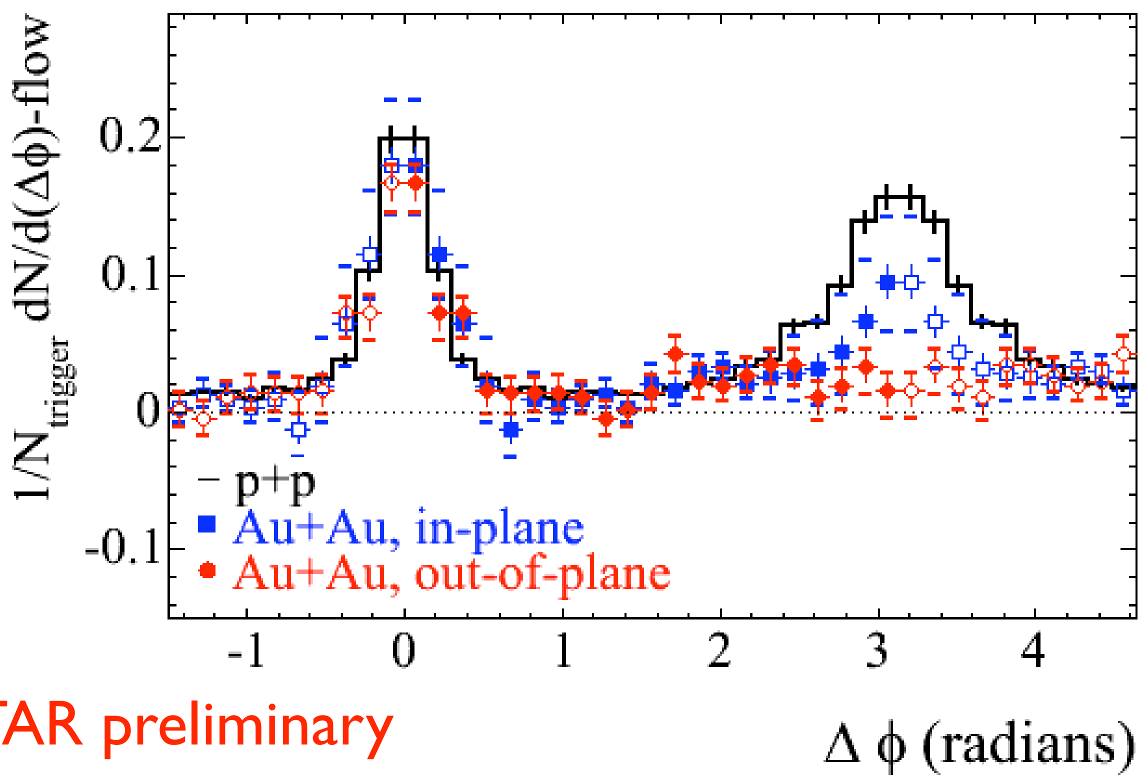
Adams *et al.*, Phys. Rev. Let. 91 (2003)



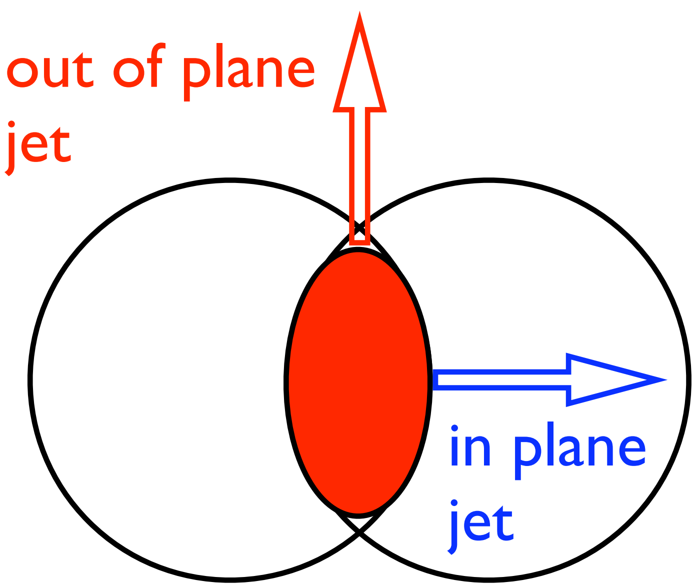
Peripherhal Coll.'s: *Geometrical* Test that AA *Eats* Jets

Peripheral collisions, "stuff" forms "almond": a jet travels farther through the almond, out of the reaction plane, than in the plane.

Exp.'y: backward jet more strongly suppressed *out* of plane than *in* plane => *geometrical* test that central AA *"eats"* jets



STAR preliminary



peripheral collision ↑
almond = "stuff"

Central AA: high p_t jets give low p_t remains!

Trigger on all particles, p_t > .15 GeV.

Backward jet: high p_t suppressed, low p_t enhanced.

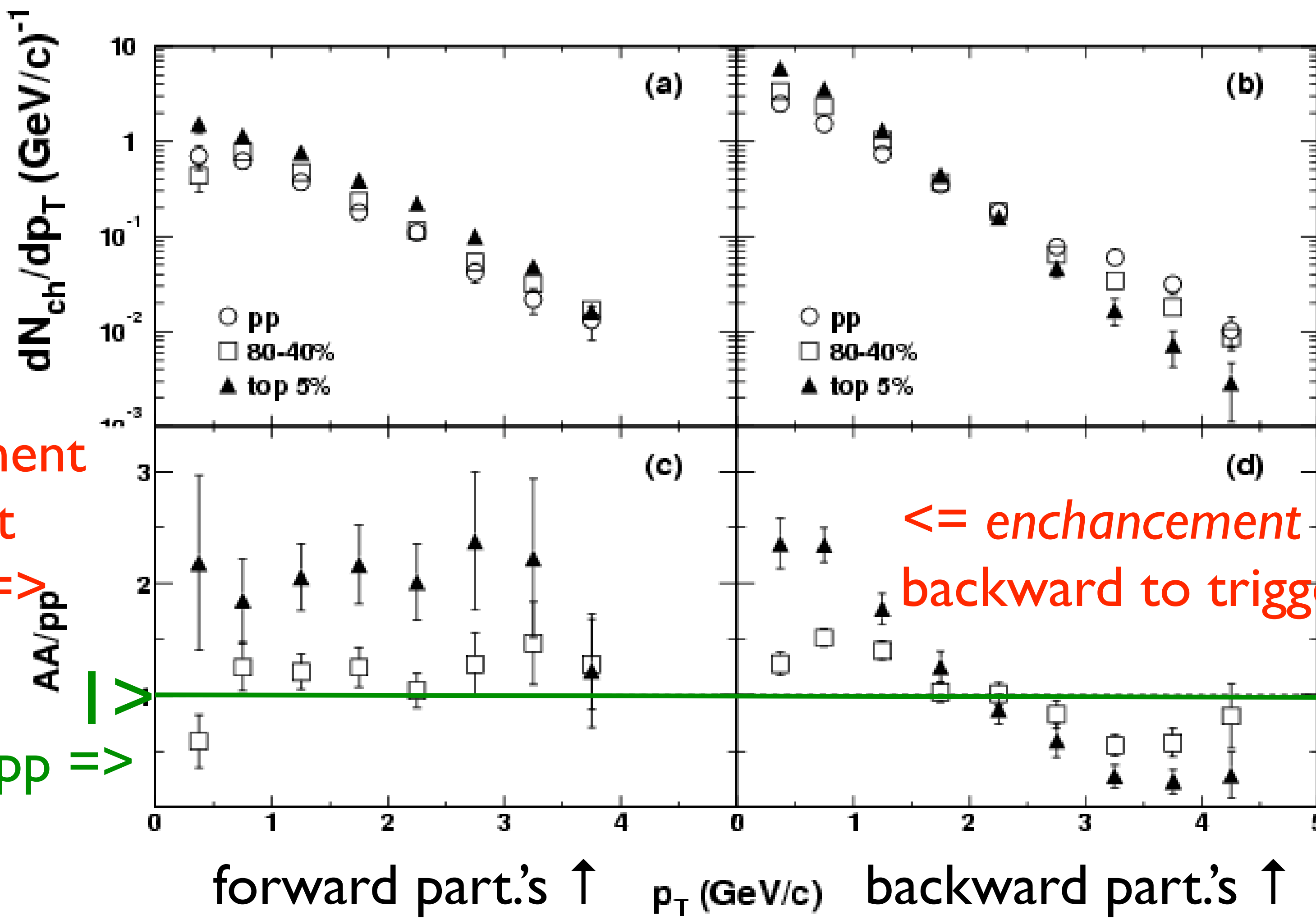
"Stuff" in central AA slows fast particle down.

Forward jet: enhanced at low momentum: "stuff" dragged along!

raw => spectra

enhancement at low p_t *along* jet =>

ratio, AA/pp =>



STAR prelim.

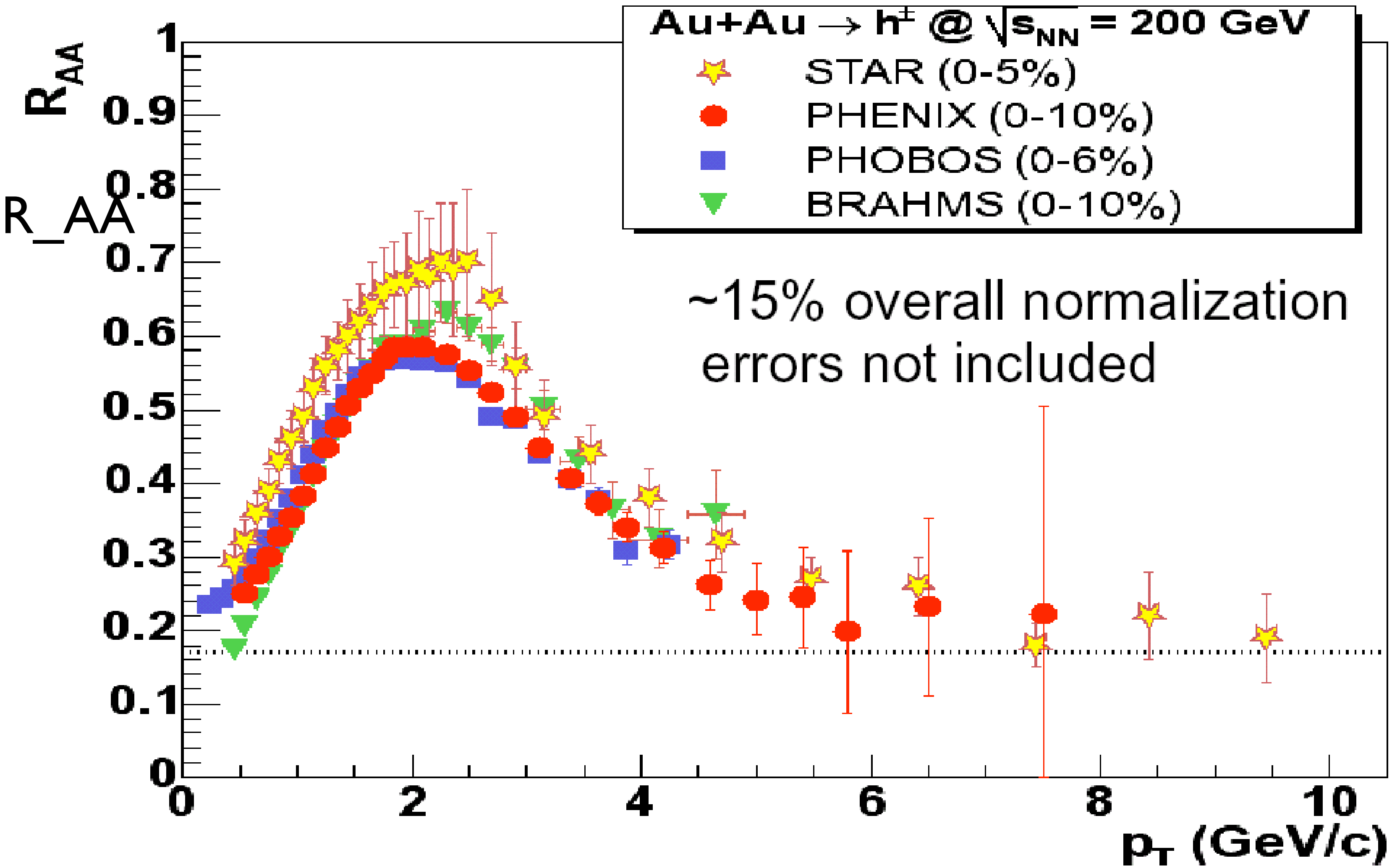
AA=pp

<=*suppression* at high p_t backward

Clear Experimental Signal of "Stuff": R_AA

Compare *central* AA spectra to pp spectra, esp. "hard" pt > 2 GeV:

R_AA = # particles at a *given* p_t, in central AA collision/
(# part's at the *same* p_t in pp, *central rapidity* x A^{4/3})



R_AA => *suppression* of hard particles in AA, vs pp.

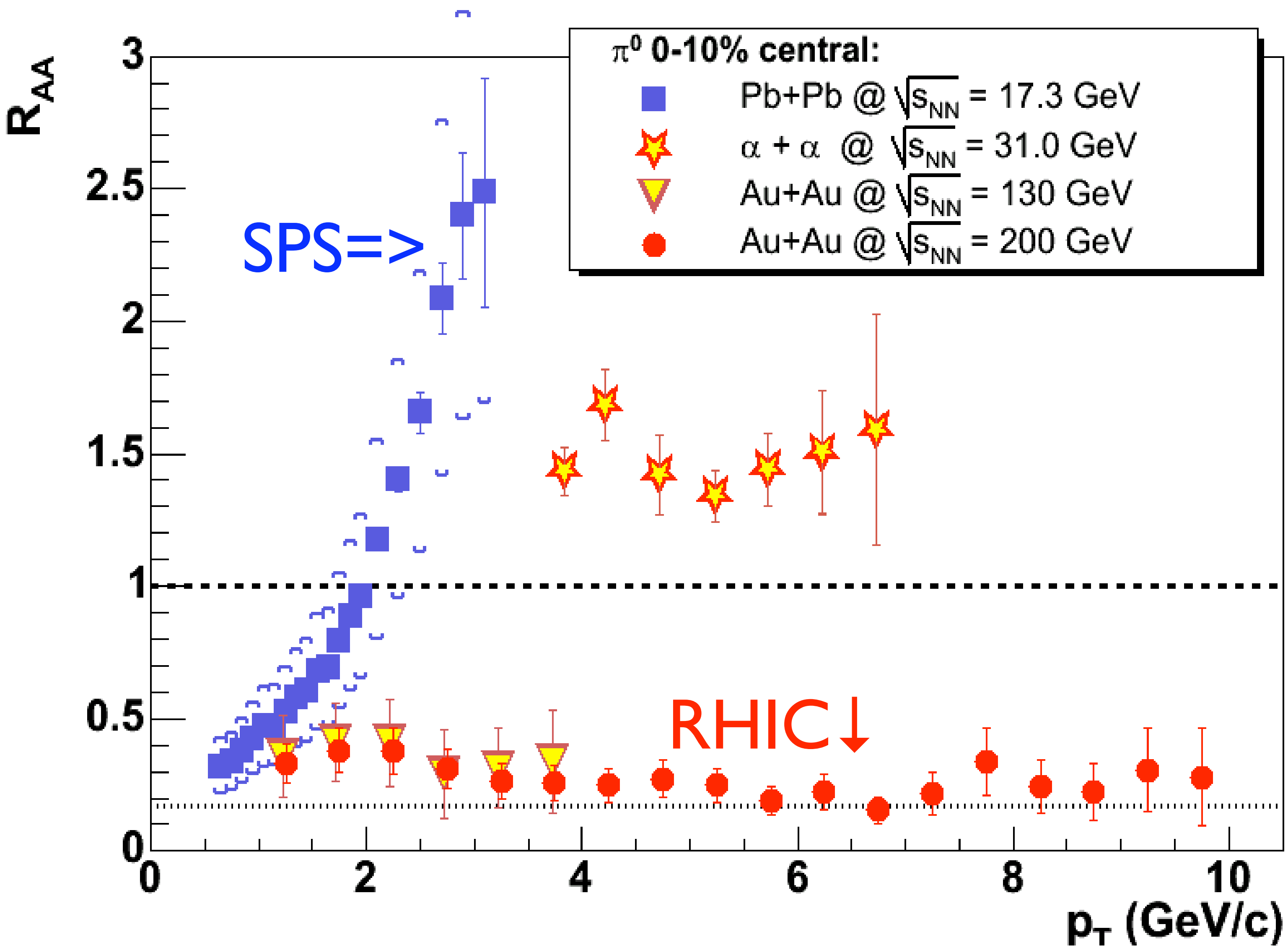
p_t > 6 GeV, ~ *constant* suppression.

R_AA: *Enchancement* @ SPS, *Suppression* @ RHIC

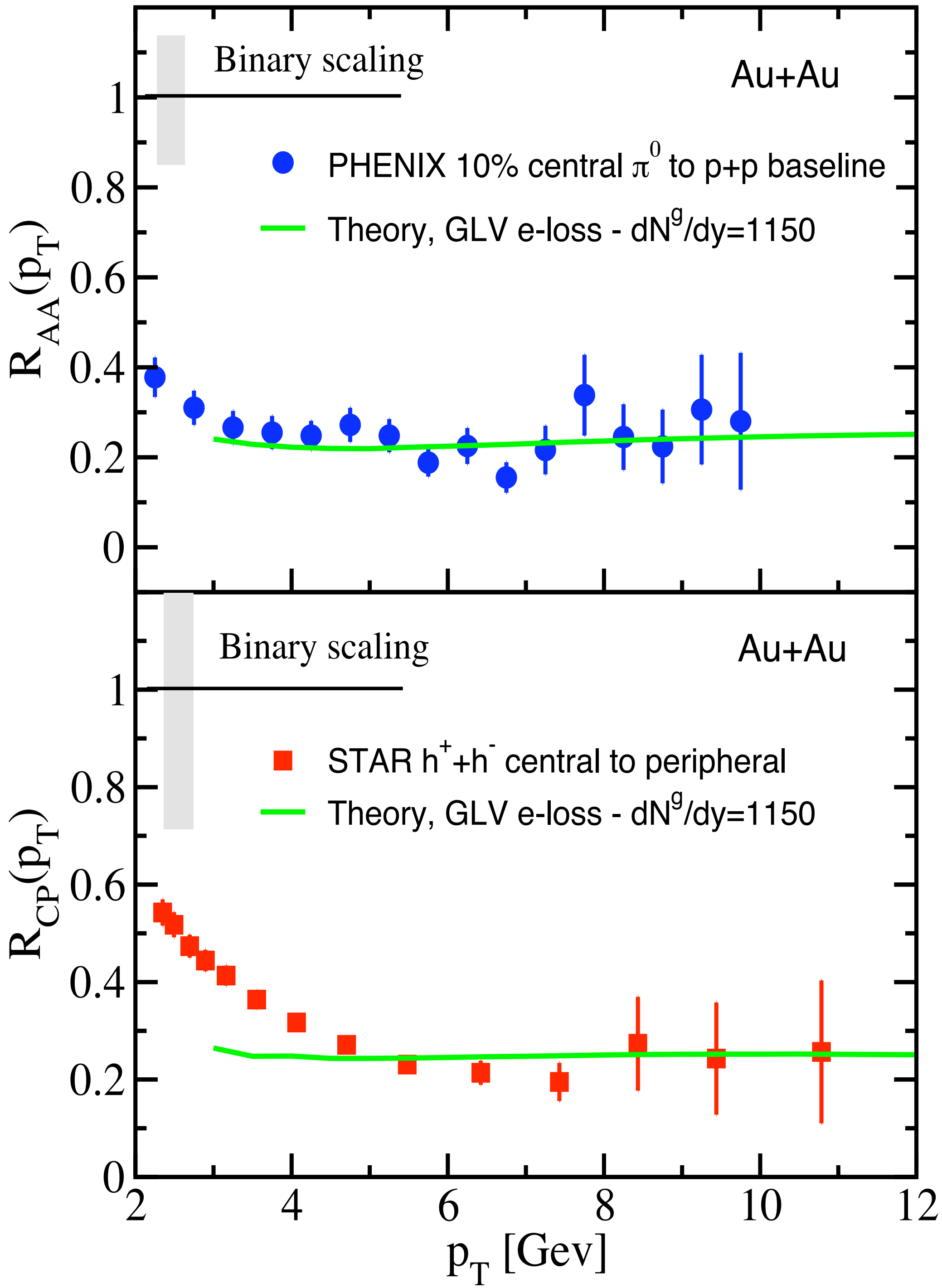
Effect most dramatic for π^0's. SPS: R_AA ~ 2.5 @ 3 GeV. "Cronin"

RHIC: R_AA ~ 0.2 @ 3 GeV.

RHIC: Supp. from *energy loss* - *"stuff"* slows fast particles down.



R_AA: Qualitative Agreement with "Energy Loss"



Energy Loss: A fast particle going through a thermal bath loses energy:
Landau, Pomeranchuk, Migdal '50's
Gyulassy, X.N. Wang, Vitev...Baier, Dokshitzer, Mueller, Schiff, Zakharov

<= Gyulassy & Vitev: *conspiracy* to give *flat* R_AA @ RHIC.

Need to add "Cronin", shadowing...

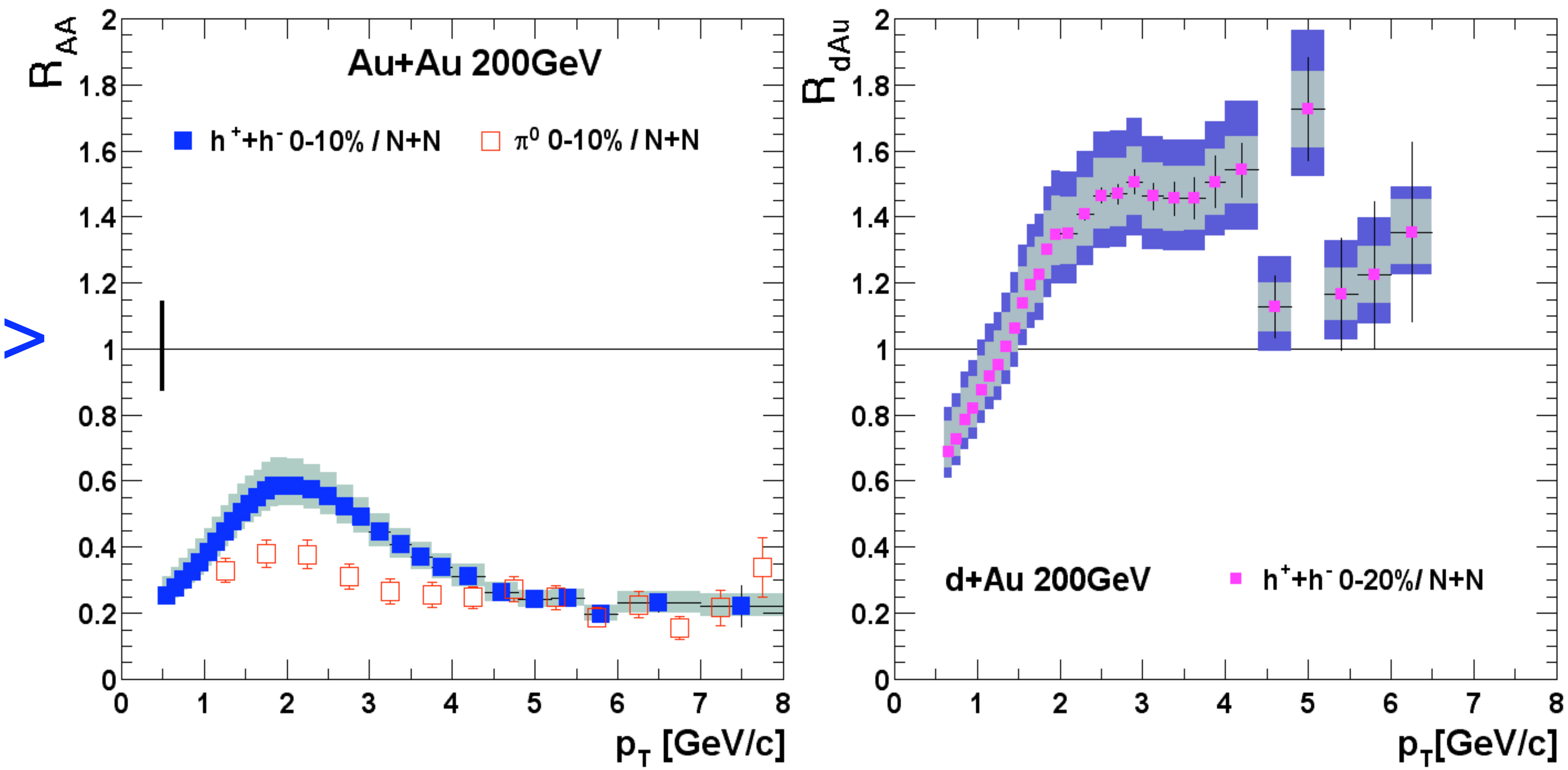
Is "flat" R_AA for π^0's special to RHIC? Will be interesting @ LHC!
When does R_AA => 1?

R_AA *final* state effect: *not* seen in R_dA

R_dA: like R_AA, but for dA/pp. *Central rapidity (y=0):*
"Cronin" enhancement in dA, vs suppression in AA.

NO "color glass" suppression. McLerran, Venugopalan, Kharzeev, Iancu...

AA=>



<=dA

Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

Where to find the Color Glass: dA, by the *proton*

Fragmentation region: like looking in the rest frame.
Incident projectile gets Lorentz contracted:

proton fragmentation region

nuclear fragmentation region

Nuclear frag. region: proton contracted. Study *final* state effects

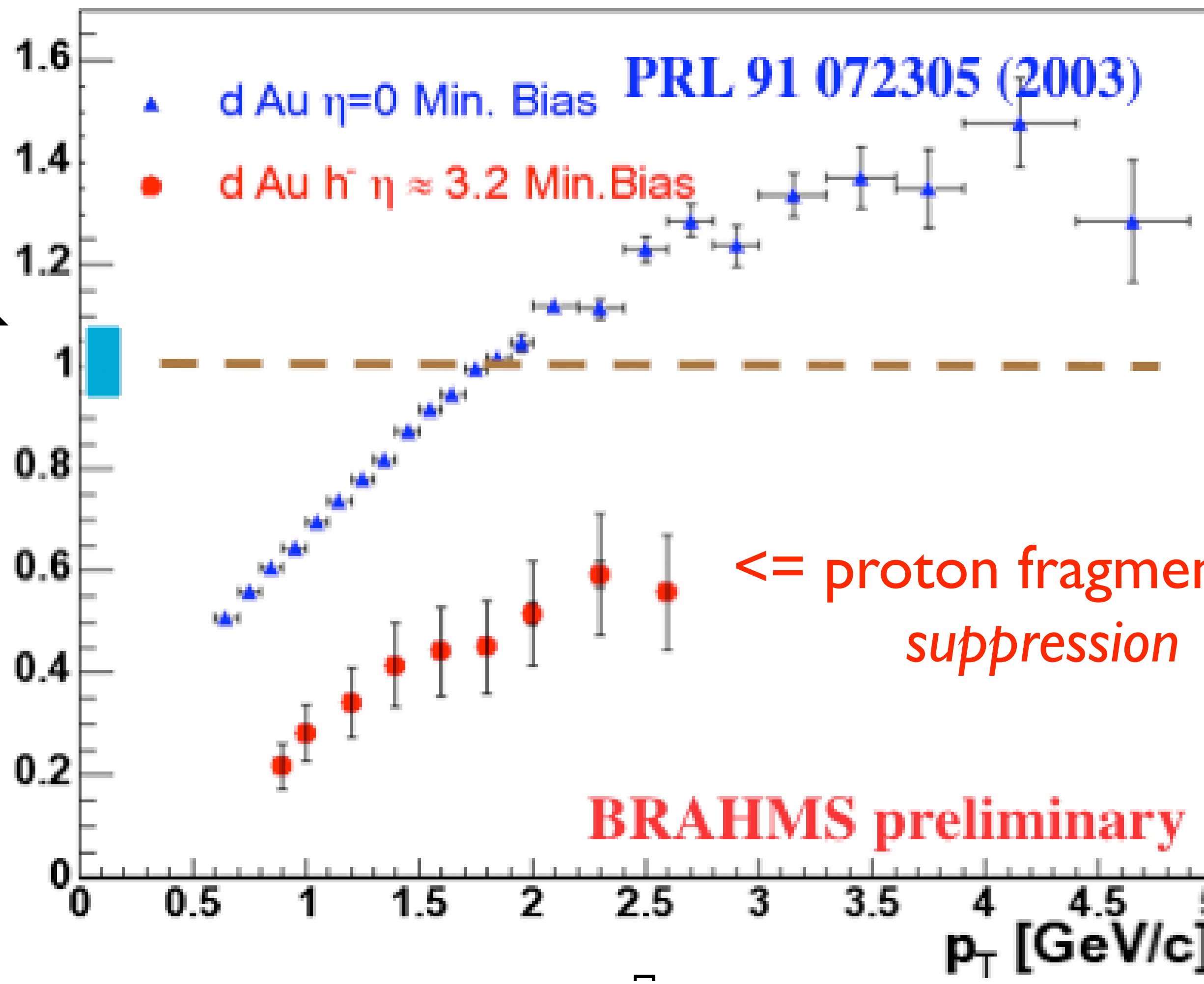
Proton frag. region: study *initial* state effects
(Dumitru & Jalilian-Marian, Gelis...)
Scatter valence quarks off classical (gluon) field=>π^+/π^- asymmetry

dA, by the proton: *suppresion!*

BRAHMS in dA, *enhancement* @ central rapidity (per. to beam)
suppression @ proton frag. region. (along beam)

Supports color glass initial state.

R_dA↑



<= central rapidity:
enhancement

<= proton fragmentation region:
suppression

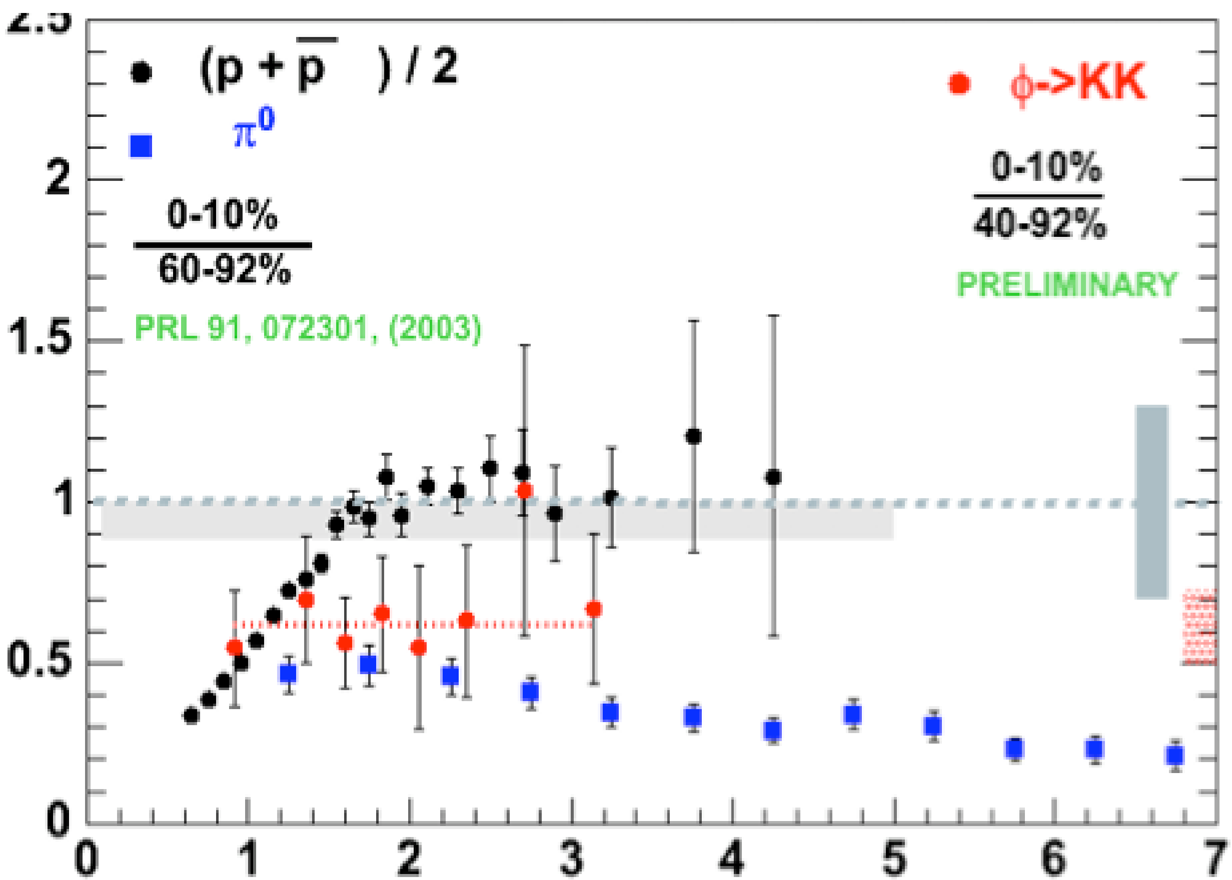
Central AA: at p_t 2=>6 GeV , *no* baryon supp.

R_CP: ratio for # particles at given p_t, for central to peripheral collisions
Behaves like R_AA, easier to get data.

Find: *baryons* not suppressed for pt: 2=> 6 GeV, *mesons* are.

Mesons suppressed => “stuff” is *gluonic.*

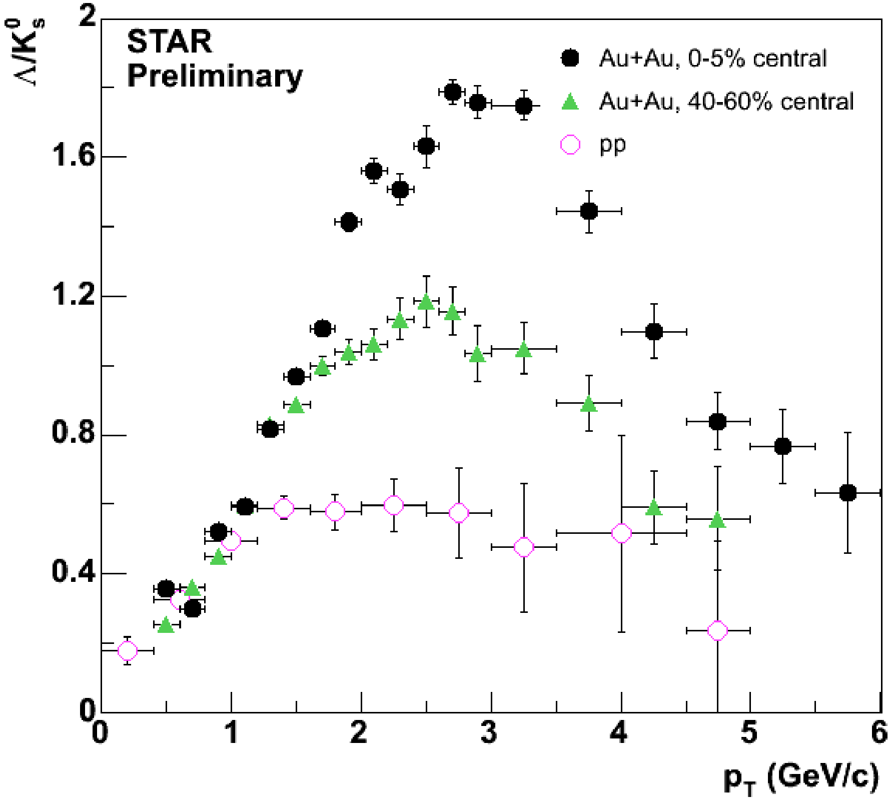
R_CP↑



PHENIX

p_t (GeV)=>

Baryon "*bump*" at p_t: 2 => 6 GeV



Central AA: *baryon "bump" at p_t: 2 => 6 GeV*

Baryon/meson ratio enhanced by ~3 in central AA vs pp. First seen in p/π.

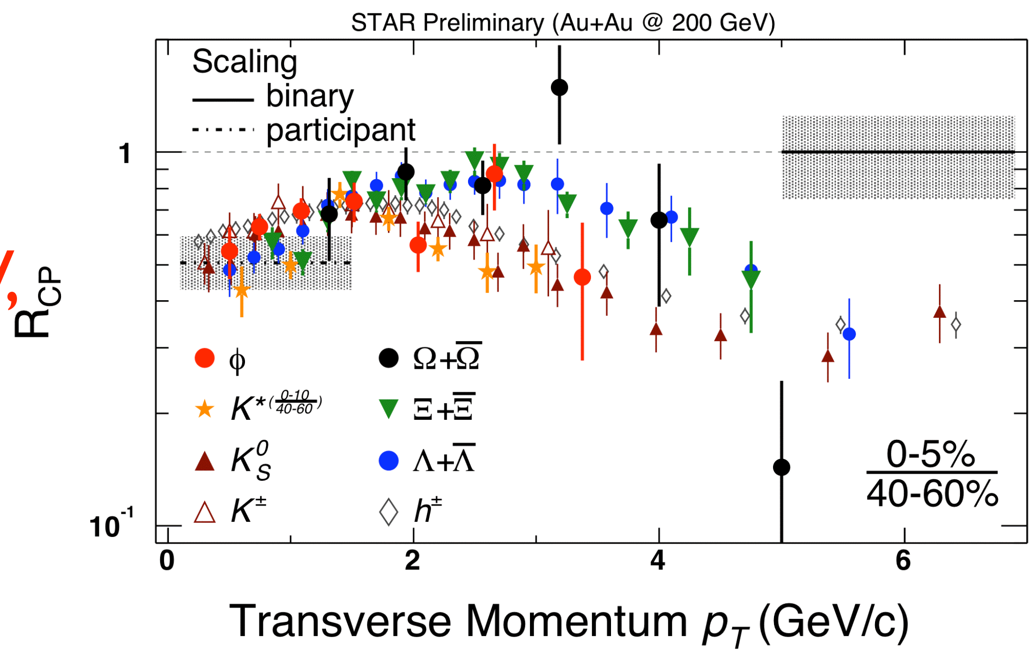
<= Λ/K ratio: bump peaks at ~ 3 GeV.

Above p_t = 6 GeV, ratios like pp.

R_CP vs particle species =>

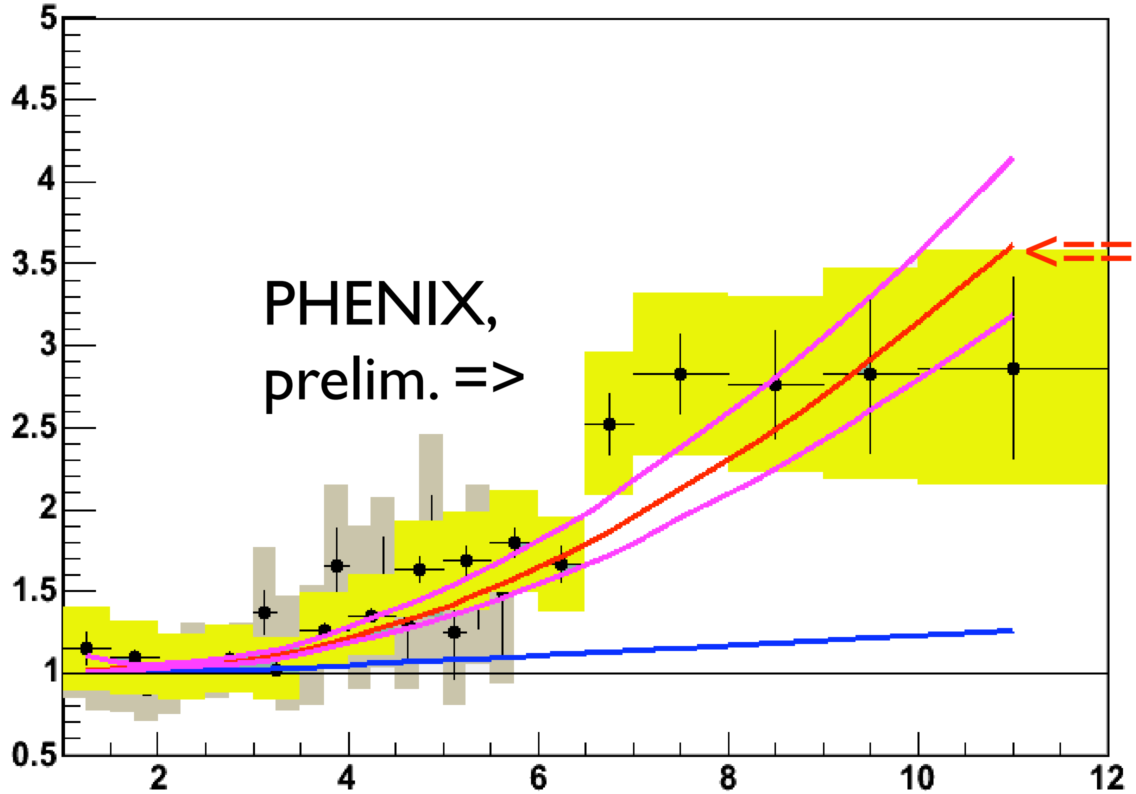
All particles suppressed > 6 GeV, R_CP ~ 0.2.

=> *Gluon "stuff"* supp.'s mesons, generates baryon "bump"



Direct photons @ RHIC!

Direct photons: easily escape, so probe initial state. *Without* pion suppression, *very* hard to measure (true at SPS). *With* observed suppression of π^0’s, measurable. Reasonable agreement at p_t ~ 10 GeV with Next to Leading Order QCD calculation, = pp times # binary collisions.



The “body” of the unicorn: soft p_t < 2 GeV

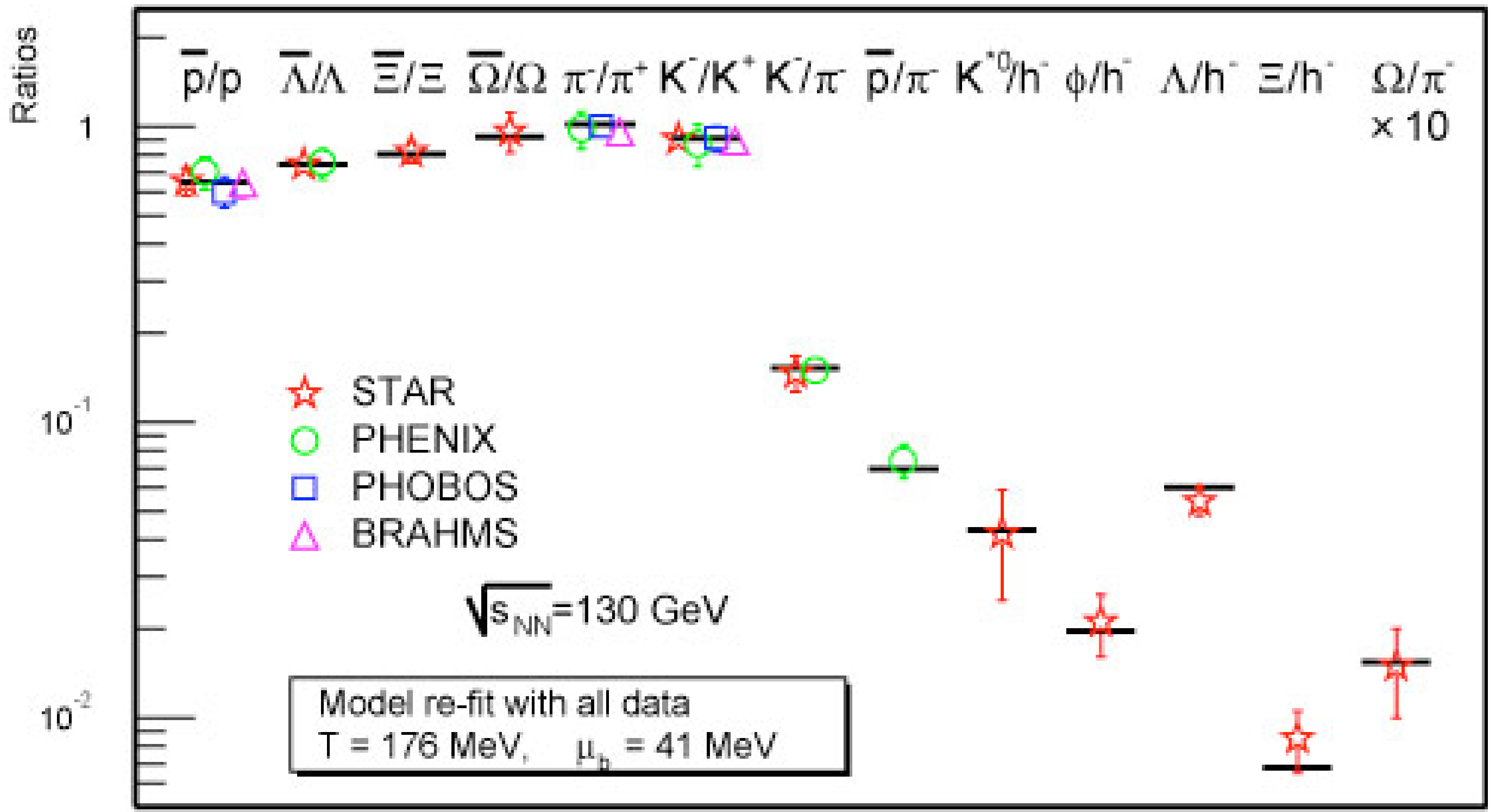
Particles peaked about zero (transverse) momentum
Tc ~ 200 MeV: *expect* thermal to p_t ~ 2 GeV.
Thousands of particles, hydrodynamics should be ok...

“dog”=>

<=unicorn

Total Chemical Ratios *Appear* in Thermal Equilibrium

$$T_{ch} = 175\ MeV$$



Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

OVERALL chemical abundances *well* fit with T_ch = 175 MeV, μ_baryon ~ 0
(Becattini, Braun-Munziger, Letessier, Rafelski, Redlich, Stachel, Tounsi...)

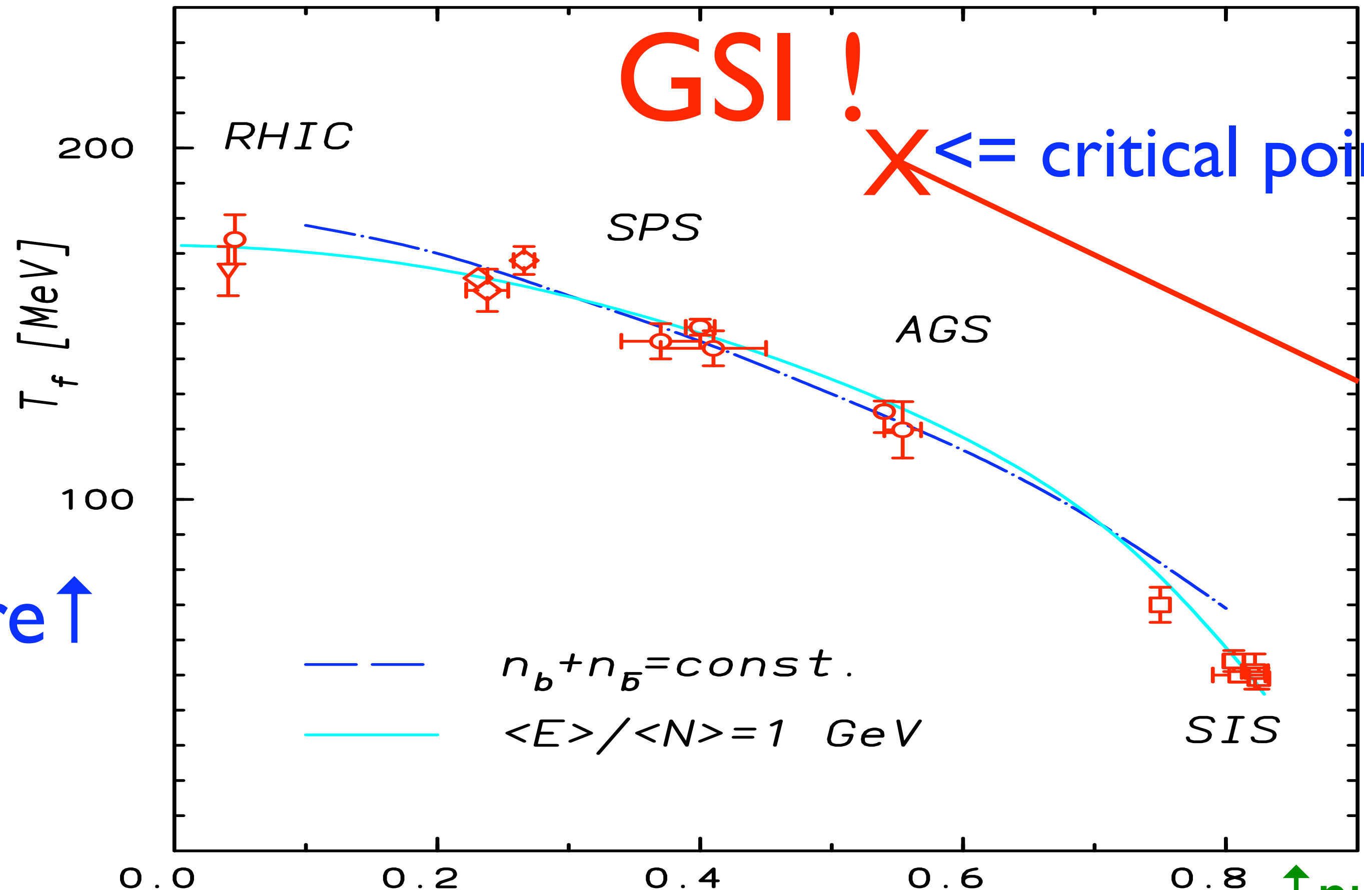
N.B.: even for multi-strange baryons, with relative abundances ~.1% of pions.

Exact critical point in plane of T & μ

Similar fits also work at lower energies. Need baryon chemical potential, μ.

(Apparent) T_ch in pA, pp - *everywhere!* => *NOT* conclusive.

N.B.: in T-μ plane, expect *exact* critical point - GSI?



Temperature↑

μ= baryon chem. pot. => μ_B^f [GeV]

↑nuclear matter

p_t Spectra *Appear* In Thermal Equi. ~ *Hydrodyamics*

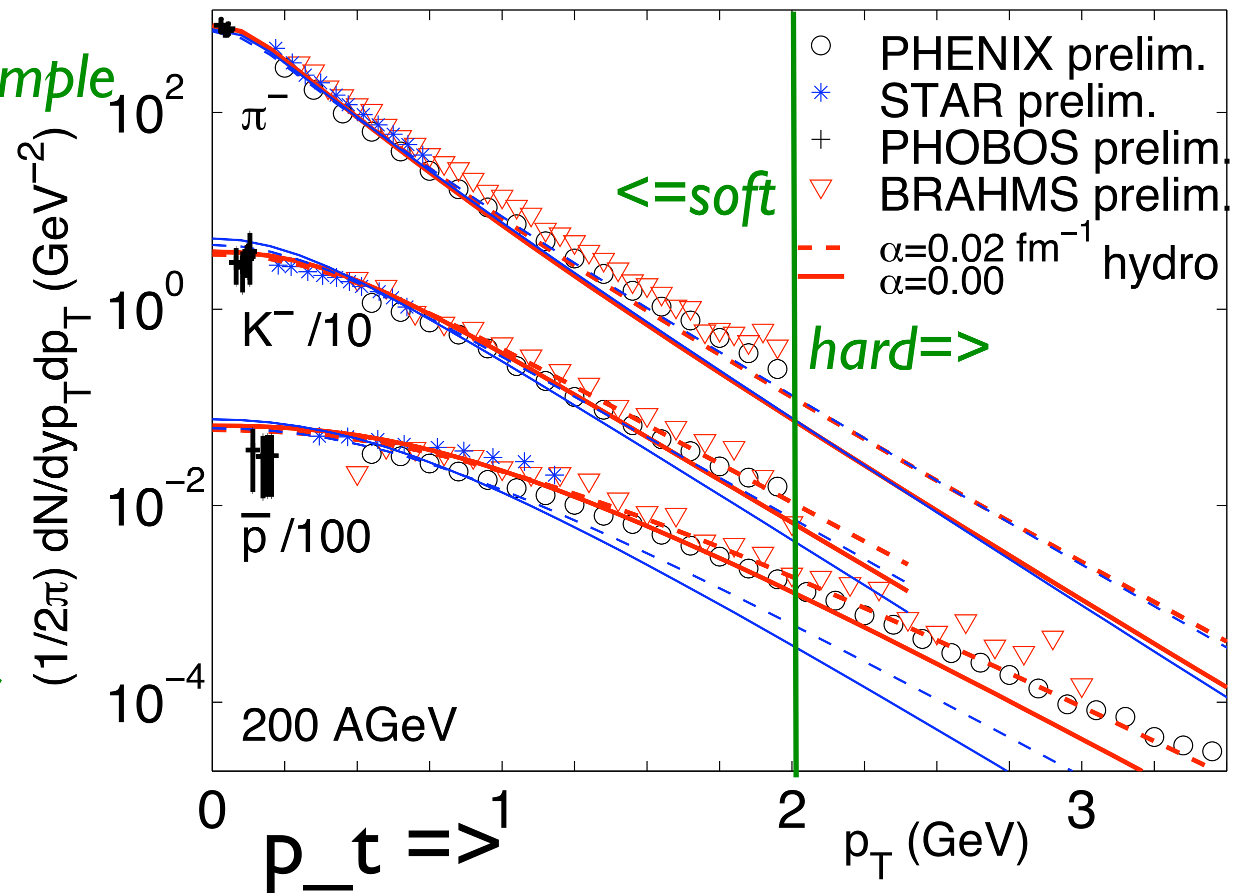
$T_{kin} \approx 100 MeV (\ll T_{ch}!)$ *Local* Boost Velocity $\beta \sim .7c$

Hydro. gives good description for most particles, at low p_t< 1GeV.

Assumes initial conditions: starts
above Tc in thermal equilibrium, *simple*
Equation of State (1st order!)
Ideal hydro.: NO viscosity...

Large local boost velocity β~ .7 c.
Spectra of heavy particles "turn over" at low p_t. β=β(radius).

RHIC: first clear evidence for boost velocity: big!
Also: "Blast-wave"

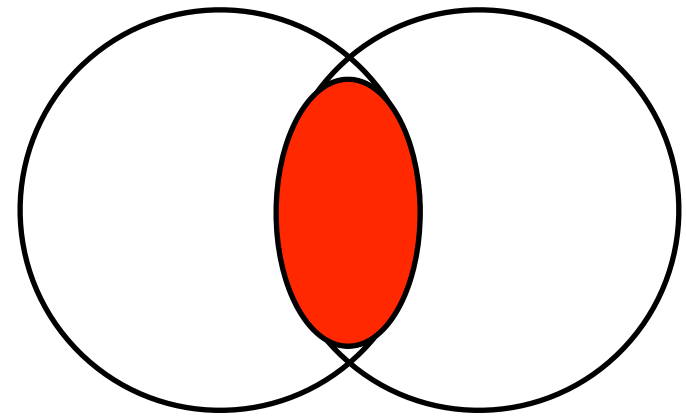


Hydro *needs* to assume applicable from *very* early times, .6 fm/c!

Heinz, Hirano, Kolb, Rapp, Shuryak, Teaney, Tomasik... (above Heinz & Kolb)

Success of Hydro.: v2 = Elliptical Flow

Peripheral Coll.'s: Start with system which is anisotropic in momentum space. Exp.'y, compute how *spatial* anistropy => *momentum* anistropy. (Ollitrault, Borghini)



$$v_2 = \langle cos(2\phi) \rangle \ , \ \tan\phi = p_y/p_x$$

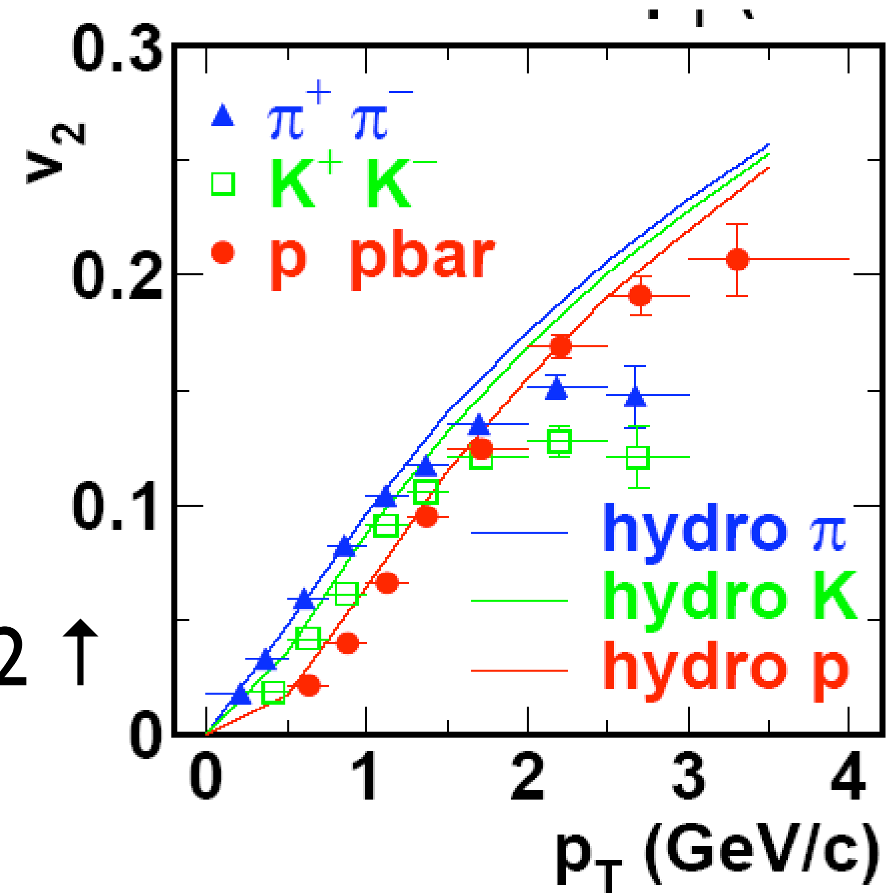
$\uparrow y$

$\rightarrow x$

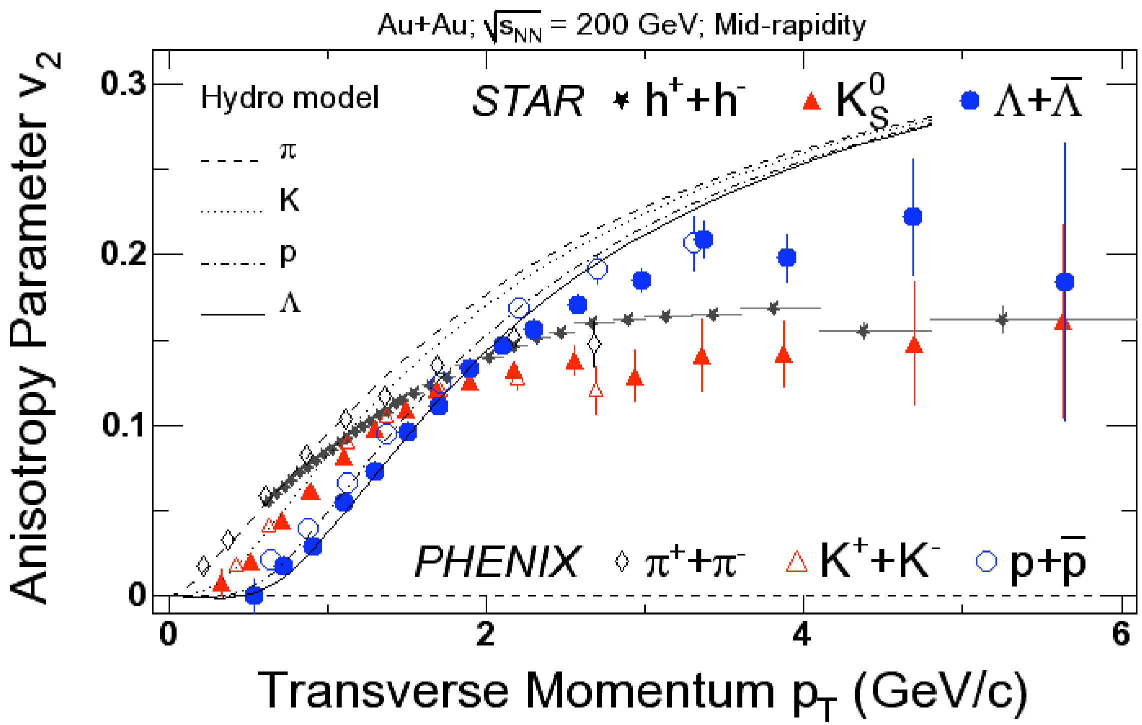
v2 => collective behavior:
there is "stuff", and it sticks.

Hydro works for v2 @ RHIC, not SPS.

v_2 ↑

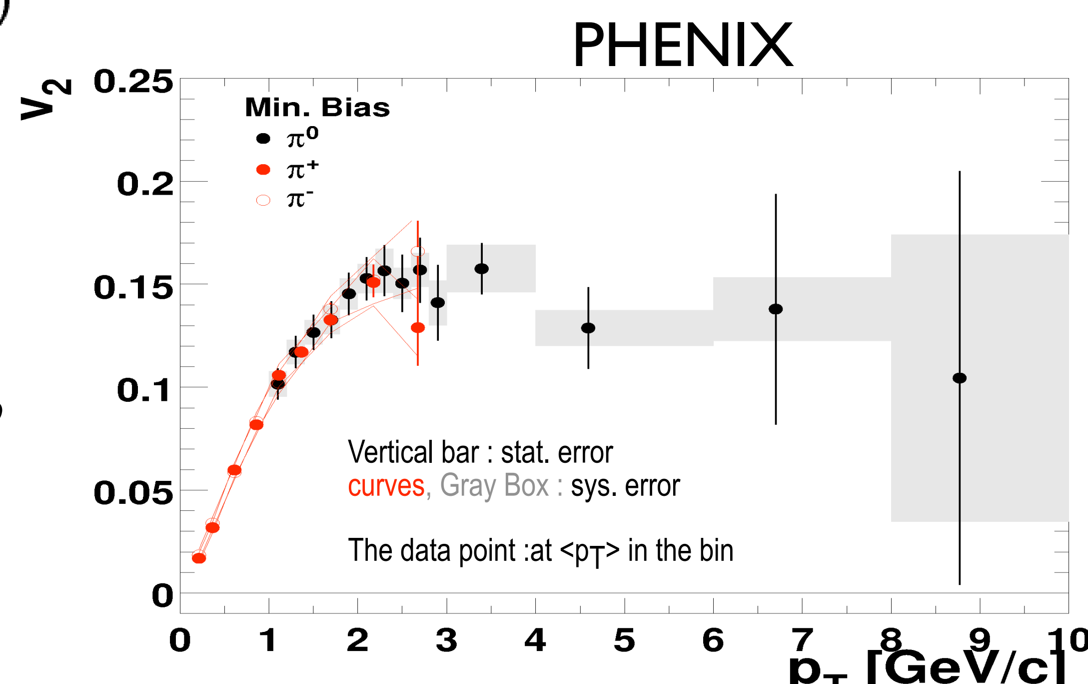


At Low p_t < 1 GeV, Hydro. works for *All* Particles



<= Hydro works for v_2 to p_t ~ 1 GeV for π's, K's, p's, Λ's…. *everything.*

For *all* particles, v_2 *flat* for p_t > 1 GeV => 10 GeV - ?!

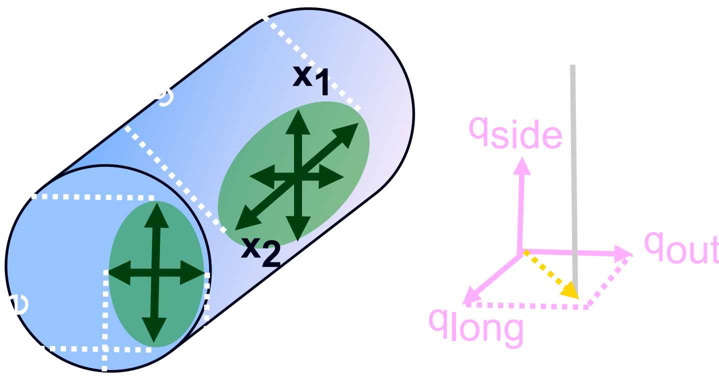


Is v_2 at p_t>1 GeV measuring collective flow, or jet-jet correlations?
Apparently: true collective flow.

So why flat?

HBT Radii: Hydro *Fails*. *"Blast Wave"* Works

Hanbury-Brown-Twiss: two-particle correlations for identical particles
Sizes at freezeout. *Three* directions, Bertsch & Pratt, Heinz, Tomasik+...
along beam R_long., along line of sight R_out, perpendicular R_side.



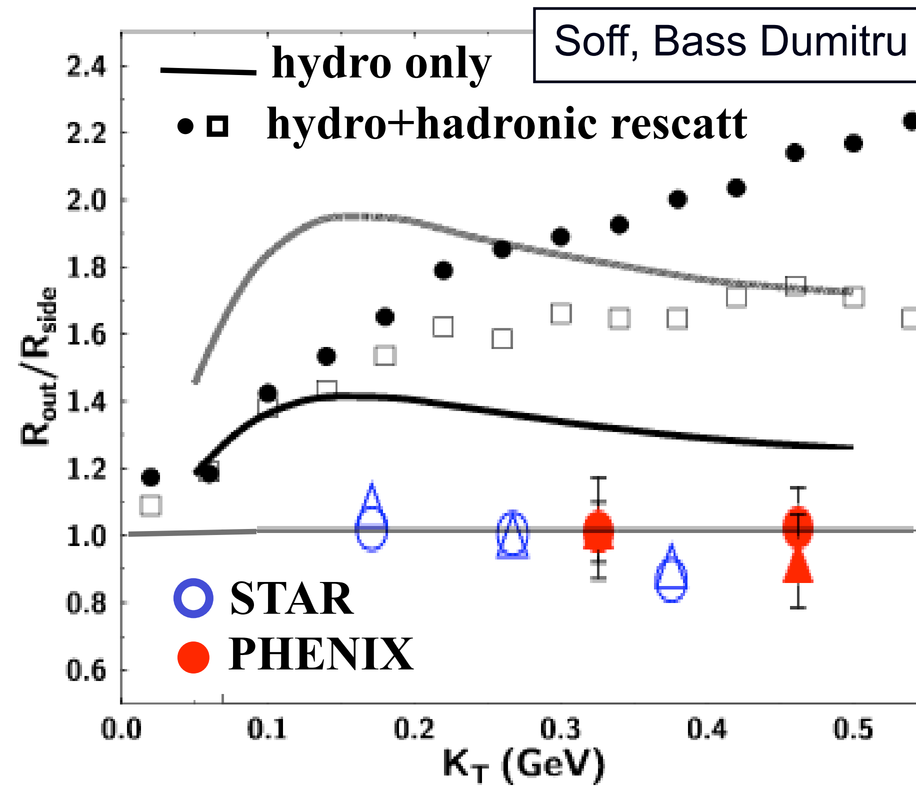
$$C(p_1,p_2) = \frac{N(p_1,p_2)}{N(p_1)N(p_2)}$$
$$= 1 + \lambda \exp(-R^2(p_1-p_2)^2)$$

Hydro: R_out/R_side > 1,
increases with p_t.

Exp.: R_out/R_side ~ 1,
decreases with p_t!

Hydro: R_long, R_out too big.

Peripheral coll.'s: azimuthally Asym. HBT



HBT radii ~ *same* in pp, dA, and AA!

Can also measure HBT in pp, dA...

Ratios behave ~ *same* with p_t!

Can fit HBT radii to "blast wave"
= *fit* not fundamental model.

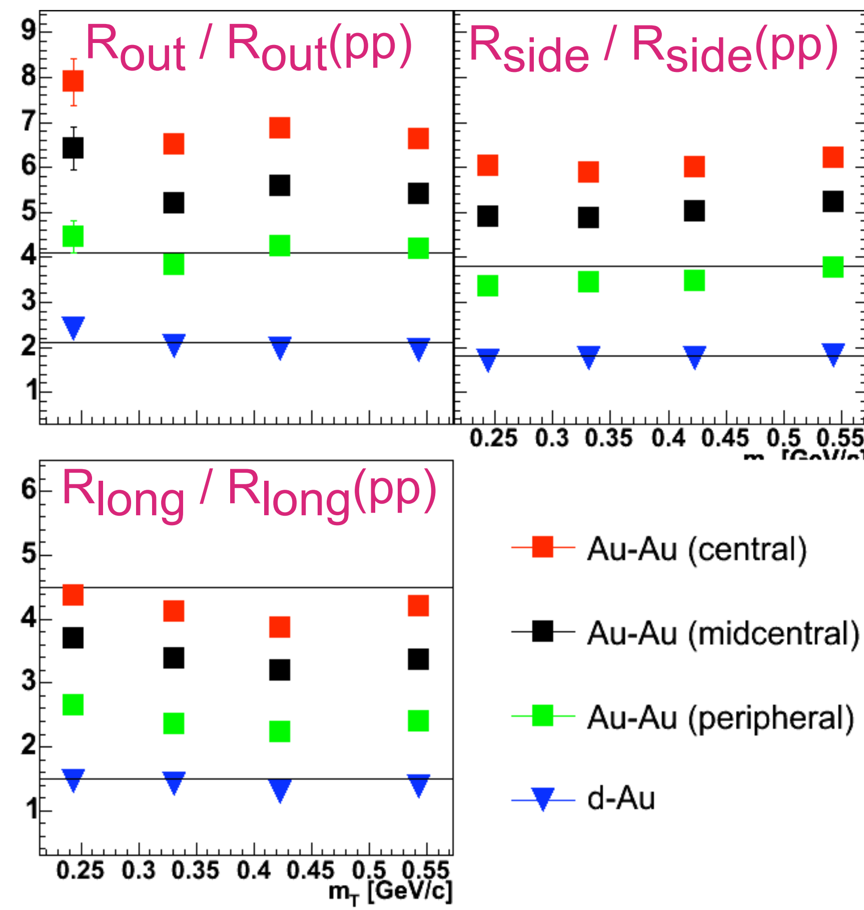
Blast wave suggests:
lifetime ~ 8-9 fm/c, emission ~ 2 fm/c

(No big times from strong 1st order!)

Space-time history "exploding shell"

HBT => *universal* hadronization?

Fluctuations (p_t...) *NOT* same in pp, dA, AA....



m_t ~ p_t=>

STAR prelim.

Has RHIC found (tamed) the "Unicorn" = QGP?

New final state effects:

R_AA

Suppression of backward jets

Also: new initial state effects,
BRAHMS:Color Glass in forward dA

Exp.'y: for the unicorn of central AA,
the high p_t "tail" wags the
low p_t "body"

HBT? Space-time evolution of the body?
Precise measure of thermal equilibriation?

Perhaps: it is a different beast....
But its still a *NEW* beast!

“A possible eureka.”