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. What is the QGP? Order parameters in QCD

2. : Numerical "experiment": QGP on the Lattice

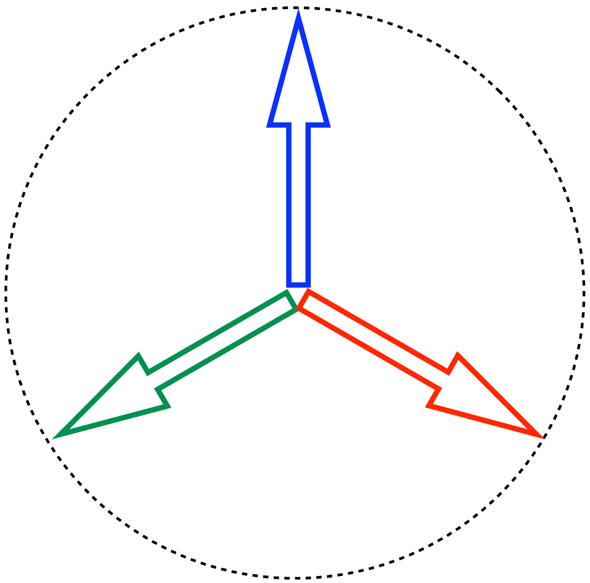
3. Experiment @ RHIC: "gluon stuff" & the QGP
   the (high-pt) tail wags the (low-pt) body of the Unicorn

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

Confinement and the "3 state way"

QCD: gluons confine => can't see single quarks (q), only
mesons, $\overline{q}q$, and baryons, qqq. = type of *three* state model.

Only 3 states allowed =>. for each quark, rotate by 120°; anti-quark, -120°.
Forms a group of Z(3): 0° = 360° => "clock" model



Single quarks, di-quarks... rotate, are not invariant

Z(3) invariant states have zero "triality":

mesons, +120° -120° = 0°.

baryons, 3 x 120°= 360° = 0°.

Confinement: only Z(3) invariant states exist.

Just like Z(3) spin, but *unbroken* at zero temperature.

't Hooft '79... Only valid with*out* dynamical quarks! (Need to know # quarks)

QCD: (at best) approximate Z(3) symmetry.

Deconfinement = Z(3) "breaking"

Z(3) "spin" = *Polyakov loop*
= (trace) color Aharonov-Bohm phase.

$$\ell = \frac{1}{3}\,\mathrm{tr}\,\mathcal{P}\exp\left(ig\int_0^{1/T} A_0\, d\tau\right)$$

= *propagator* "test" quark.

Confinement => symmetry unbroken
at zero, and so low, temperature:

$$\langle \ell \rangle = 0 \quad , \quad T < T_{deconf}$$

g = QCD coupling. Asymptotic freedom => theory free at infinite T
g^2(T) ~ 1/log(T) as T => ∞

=> Polyakov loop => 1 as T => ∞ : loop nonzero above some T

Deconfined phase: symmetry broken

$$\langle \ell \rangle \neq 0 \quad , \quad T > T_{deconf}$$

Deconfinement just like Z(3) spins, but symmetry broken at
high, instead of low, temperature

QCD & chiral symmetry

QCD: pions, kaons, eta, light. "2+1 flavors": almost Goldstone bosons of *approximate* SU(3)xSU(3) "chiral" symmetry: $\langle \overline{q} q \rangle \neq 0$ at T = 0.

SU(3)xSU(3) chiral symmetry type of "spin": restored *above* T_chiral > 0.

Two possible phase transitions: T_d(econfinement) & T_ch(iral)

Both gluonic Z(3) & chiral symmetries *approximate* in QCD

One or two transitions? Guess: one transition, *strongly* first order

No quarks, 3 colors: T_d first order (Svetitsky & Yaffe)

3 flavors massless quarks: T_ch first order (RDP & Wilczek)

2 flavors massless quarks, *heavy* η' @ T_ch: T_ch second order

" ", *light* η' " ": T_ch first order

The “Unicorn”:

Quark-Gluon Plasma =

Deconfined,
chirally symmetric “phase”
at nonzero temperature

But how to compute the properties of the QGP?

QGP on the Lattice

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

Only gluons (*no* quarks): present methods close to a=0!

T_d ~ 270 ± 10 MeV

Weakly first order deconfining trans. (Some masses ↓ by ~10).

Non-perturbative Gluon Plasma, T_d => 3 T_d. Pert. GP, 3T_d => ∞

QCD = "2+1" flavors quarks: now, *not* close to a=0. *All* results tentative.

T_c ~ 175 ± ? MeV

Only *one* transition (chiral = deconfining)

Order? '04: crossover, no true phase transition

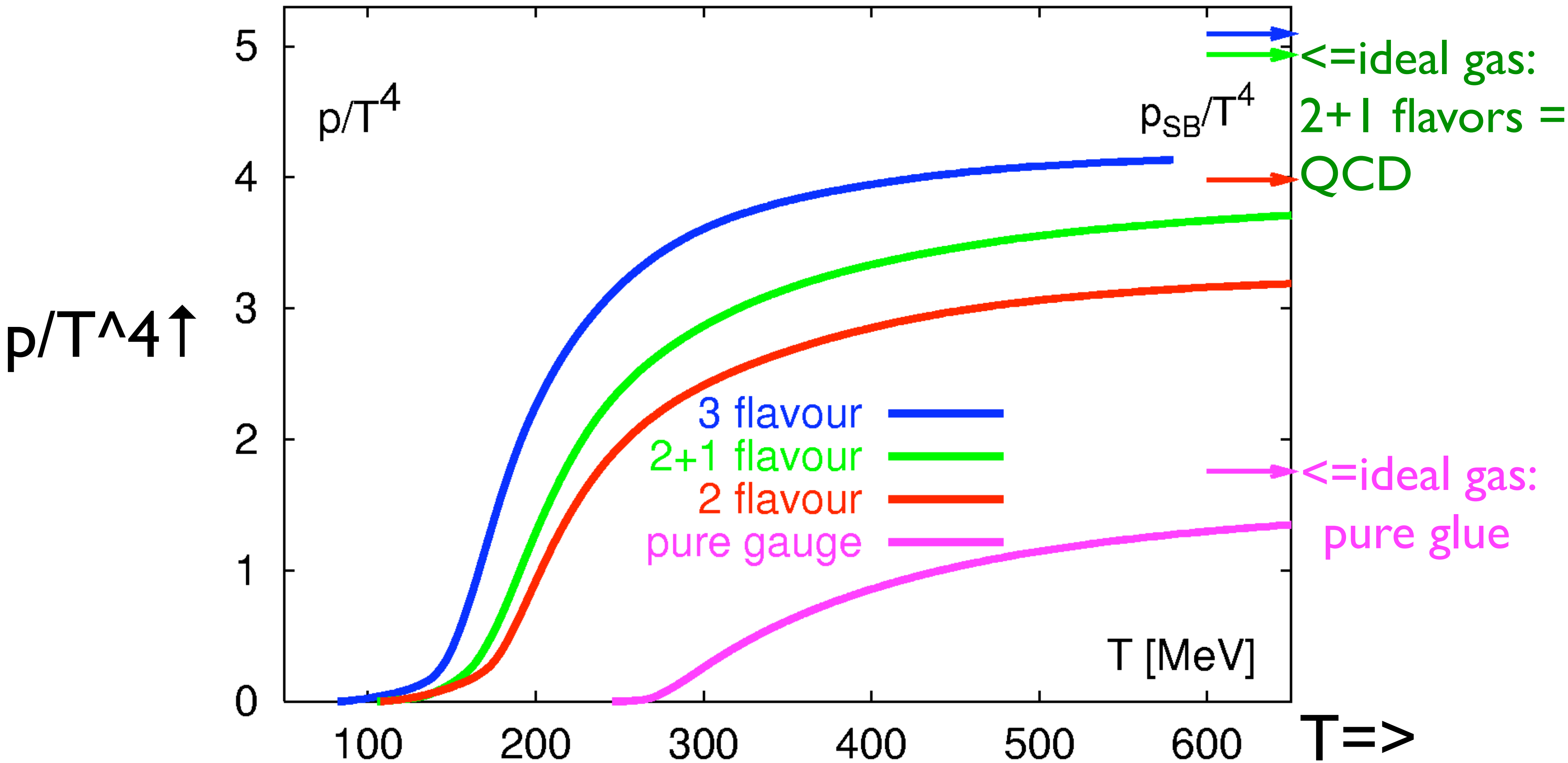
"Flavor independence": pressure *with* qks ~ with*out* qks.

Non-perturbative QGP from T_d => 3 T_d. Pert. QGP, 3T_d => ∞

Lattice QCD: pressure vs T

Asymptotic freedom => *ideal* gas of quarks & gluons at T = ∞

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



Pure glue: ↑T_d ~ 270. 1st order transition

QCD = 2+1 fl's: ↑T_ch ~ 175. No phase transition: "crossover"

Lattice QCD: "Flavor Independence"

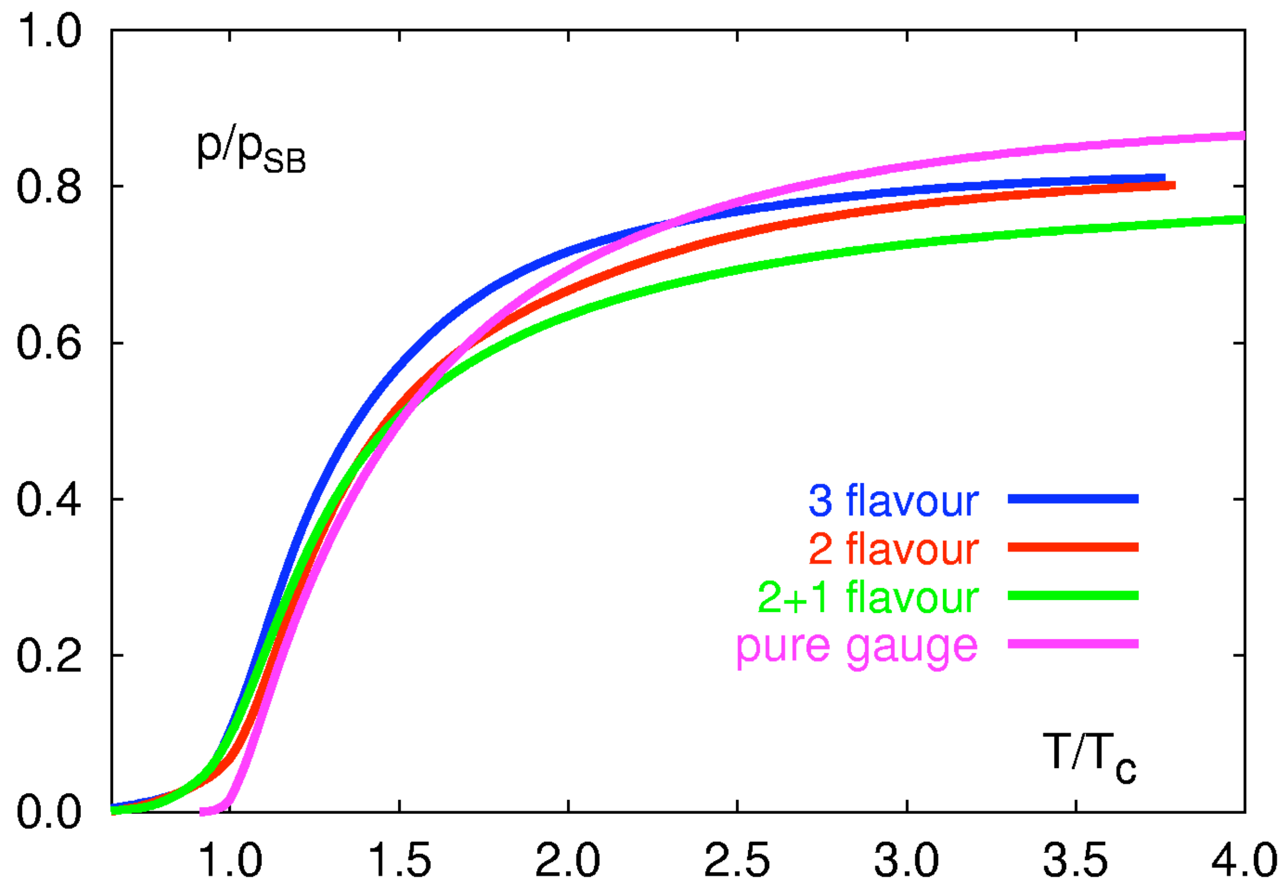
Lattice: properly scaled,

pressure *with* quarks ≈ *without:* Bielefeld.

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

=> transition *dominated* by deconfinement?

pressure/
ideal gas↑



<=1.0

T/T_d=>

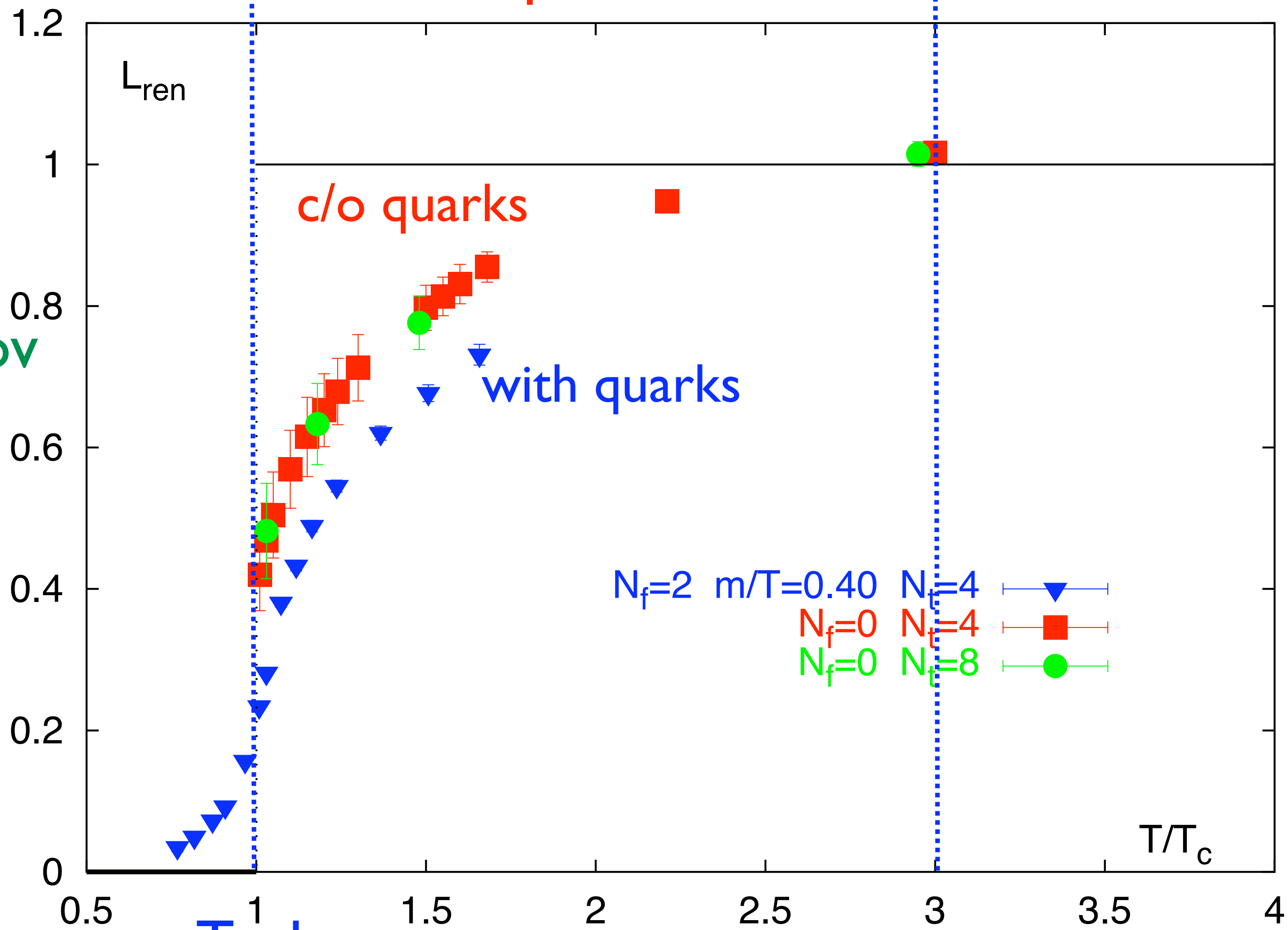
Non-perturbative QGP

Ren'd Polyakov loop: = 0 in confined phase, =1 in pert. thy

Lattice: Z(3) sym. approx in QCD. Loop only near 1 above 3 T_d

<= Confined =><= *Non*-pert. QGP =><= Pert. QGP =>

Ren'd Polyakov loop ↑



T_d

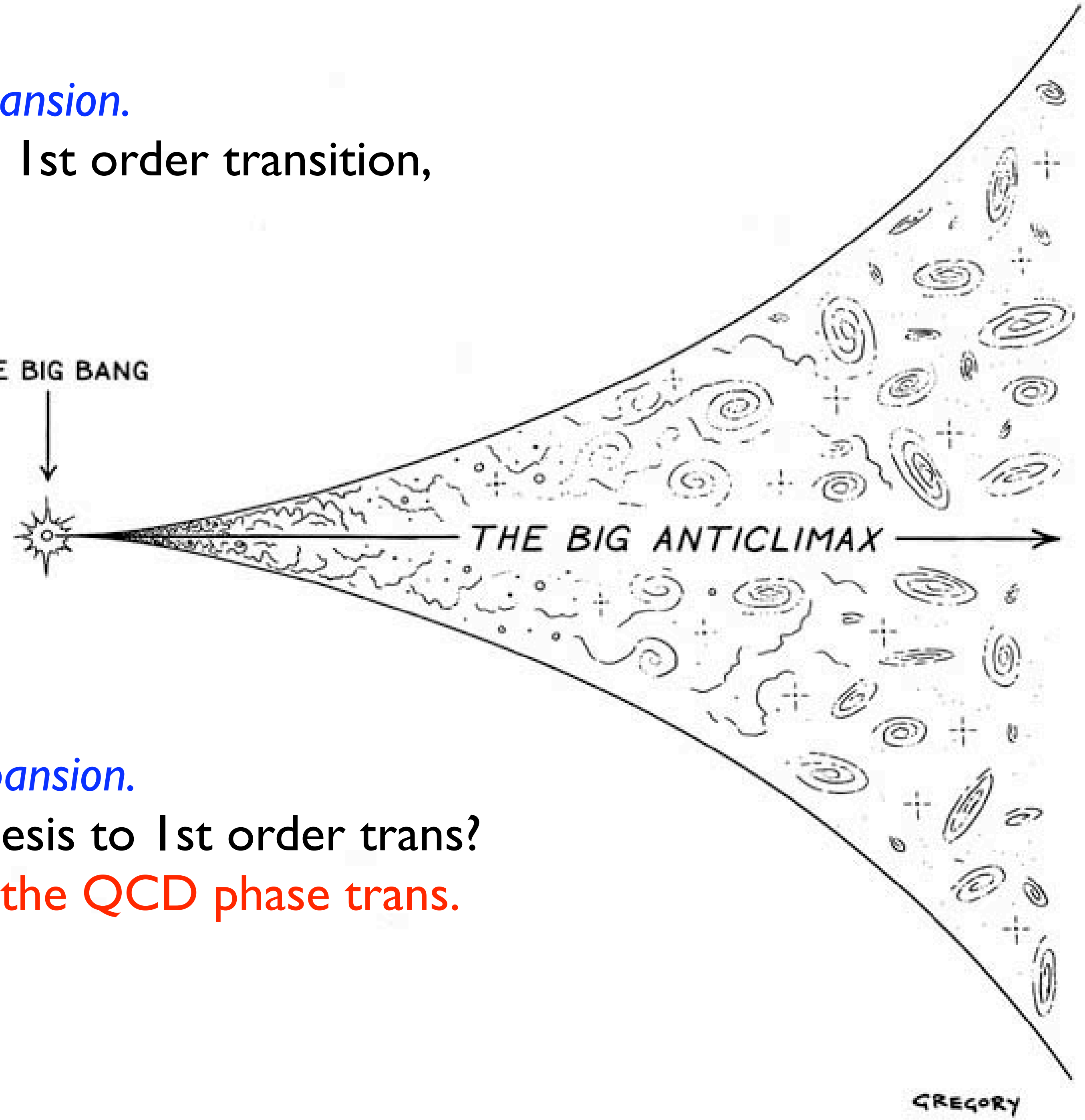
T/T_d=>

Bielefeld: lat/0312015

Two flavors, kaon masses

Early universe @ ~μsec: QCD phase transition

In AA collisions, *rapid expansion.*
Not sensitive to (weakly) 1st order transition,
indicated by lattice.



In early universe, *slow expansion.*
Sensitivity of nucleosynthesis to 1st order trans?
Goal for lattice: order of the QCD phase trans.
'04: crossover. '08?

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

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

Experimentalists = hunters, "all theorists are dogs..."

Why do AA? Big transverse size.

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?

Basic invariant: total energy in the center of mass, $E_{c.m.} \equiv \sqrt{s}$

For AA collisions, energy *per* nucleon is $\sqrt{s}/A \equiv \sqrt{s_{NN}}$

Machines	$\sqrt{s}/A$	
SPS @ CERN	5 => 17 GeV	fixed target
**** RHIC @ BNL	62, 130, 200 GeV	collider, > 2000
LHC @ CERN	5500 GeV = 5.5 TeV	collider, > 2007
SIS200 @ GSI	2 => 6 GeV	fixed target, > 2012

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

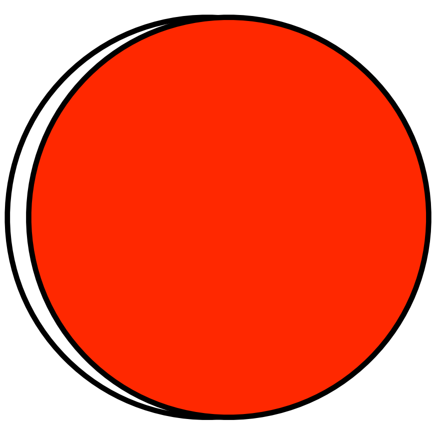
At energies >> mass, nuclei *slam* through each other.

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

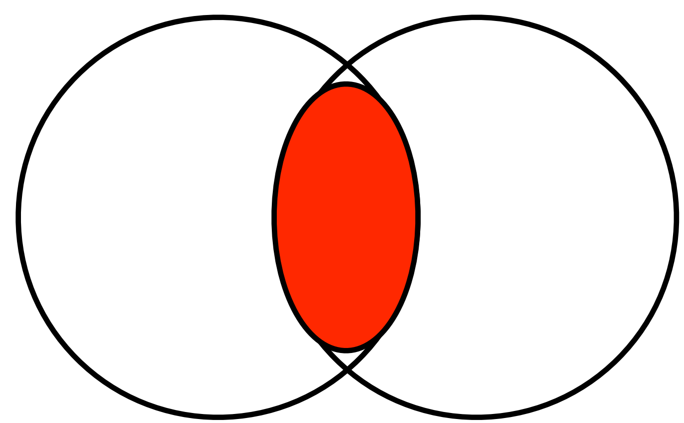
In collider: *ignore* along beam; look *just* perpendicular to beam
"central" or zero rapidity (rapidity ~ velocity along beam.)
90° to beam => few baryons => most likely to see nonzero temp.

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 Au-Au collision @ RHIC

Experiments @ RHIC:

"Big" expts: ~ 400 people
STAR & PHENIX

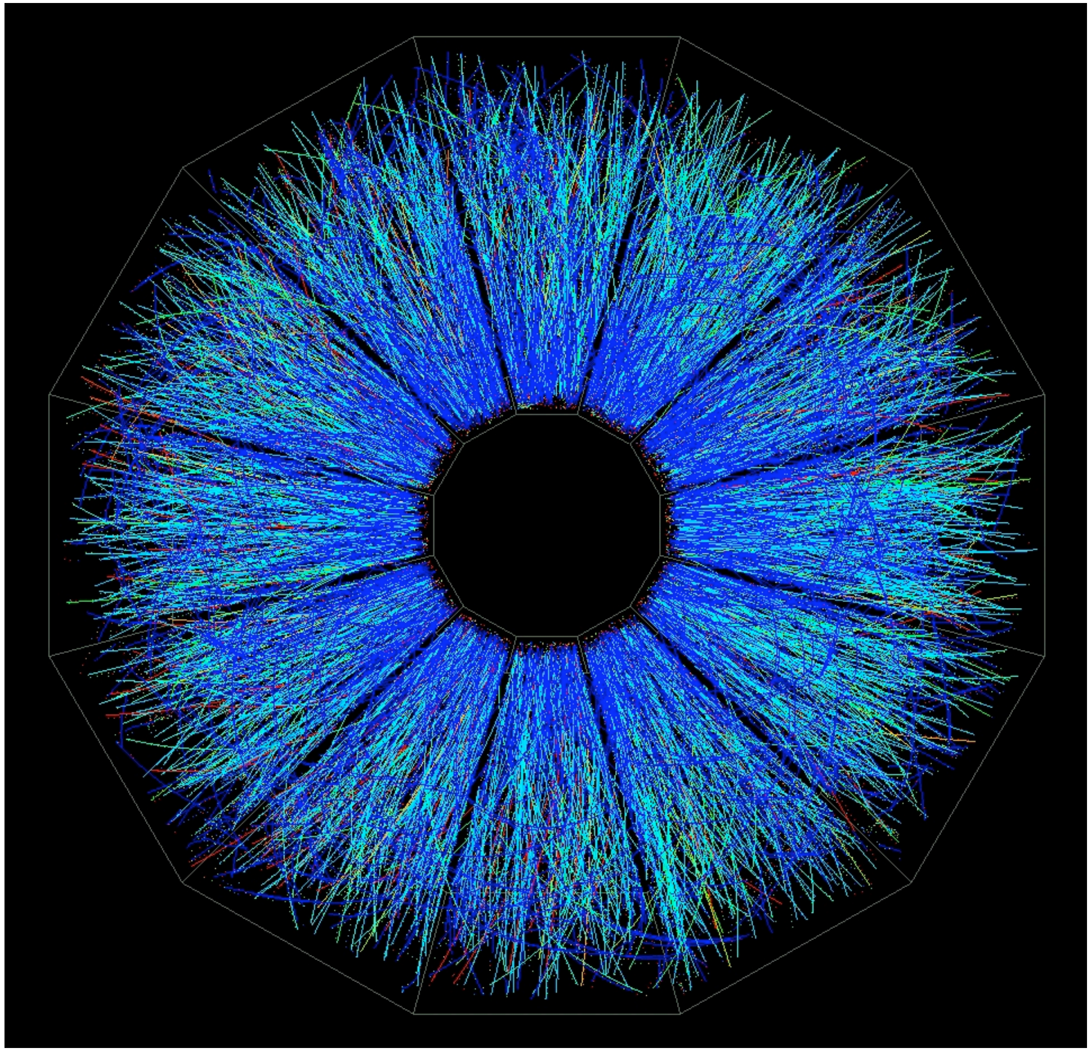
"Small" expts.: ~ 50 people
PHOBOS & BRAHMS

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

theorists
~ log(log(total energy)).

Need hunters more than dogs...

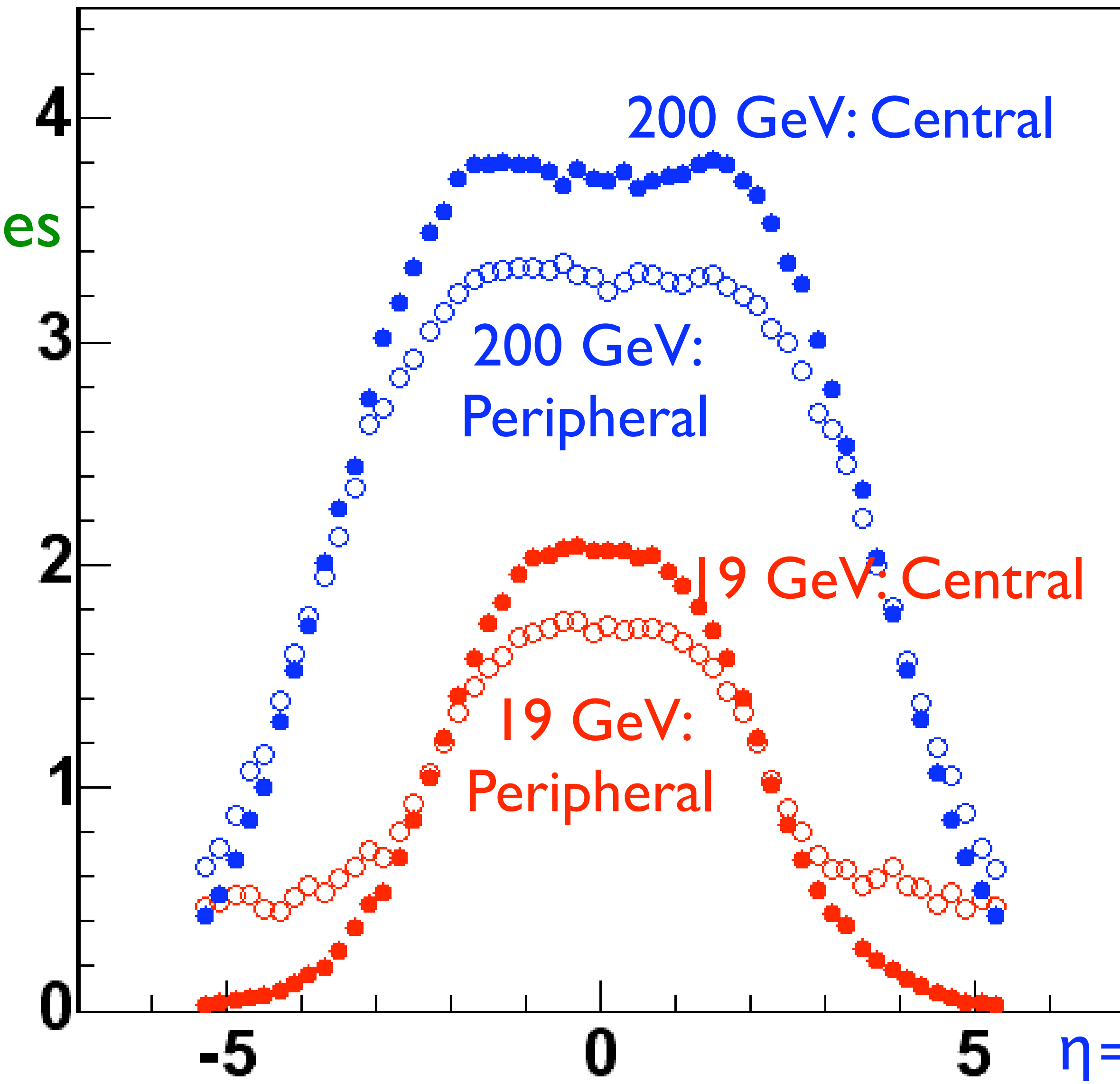
Total # particles(/unit rapidity)
~ 900↓



Overall multiplicity: *slow* growth, no big changes

N = # particles

dN/dη / ↑
participants



200 GeV @ RHIC
900 particles/unit η

19 GeV @ SPS
600 particles/unit η

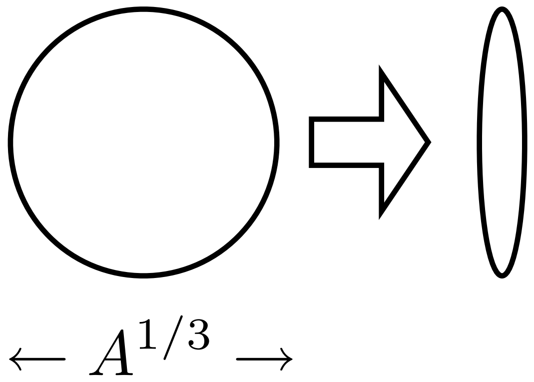
η=pseudo-rapidity=>

No big increases in multiplicity, as predicted by cascade models.

"Central Plateau", ± .5 for dN/dy of pions, appears.

Why do AA? "Saturation" as a Lorentz Boost

Incident nucleus *Lorentz contracted* at high energy



McLerran & Venugopalan: color charge bigger by $A^{1/3}$

$A \rightarrow \infty$: *semi-classical* methods, Color Glass

=> *Logarithmic* growth in multiplicity:

$$\frac{dN}{dy} \sim \frac{1}{g^2(\sqrt{s}/A)} \sim \log(\sqrt{s}/A)$$

Expect *at least* same rise in <p_t>.

Color Glass: "saturation momentum" function of energy, rapidity...

CG describes initial state. Final state?

Multiplicity, energy, & Color Glass

For example: compare central AuAu, 130 & 200 GeV:
All exp.'s: multiplicity increases by ~ 14% ± 2%.

Kharzeev, Levin, Nardi...: Color Glass gives good dN/dη with centrality....

But: STAR (alone) claims ratio of <p_t> = 1.02 ± 2% : ~ SAME!

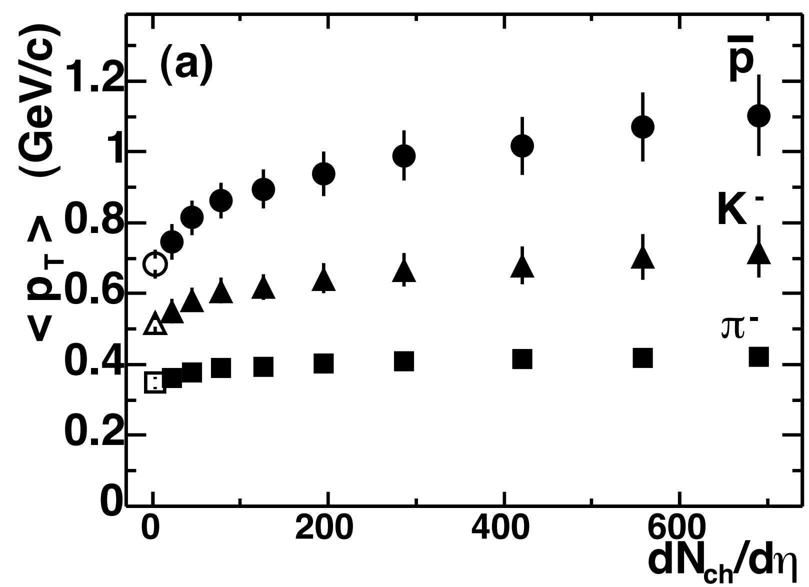
Color Glass, hydrodynamics... *all* predict <p_t> increases with mulitplicity!

From initial to final: "parton hadron duality":
one gluon => one pion

But from pp to central AuAu:
<p_t> ~ *same* for pions
<p_t> *increases* for K's, even more for p's!

=> CG not final state
Hydro: big "boost" velocity of medium.

STAR, pp & AuAu, 200 GeV



↑pp central AuAu ↑

Body of the "Unicorn":

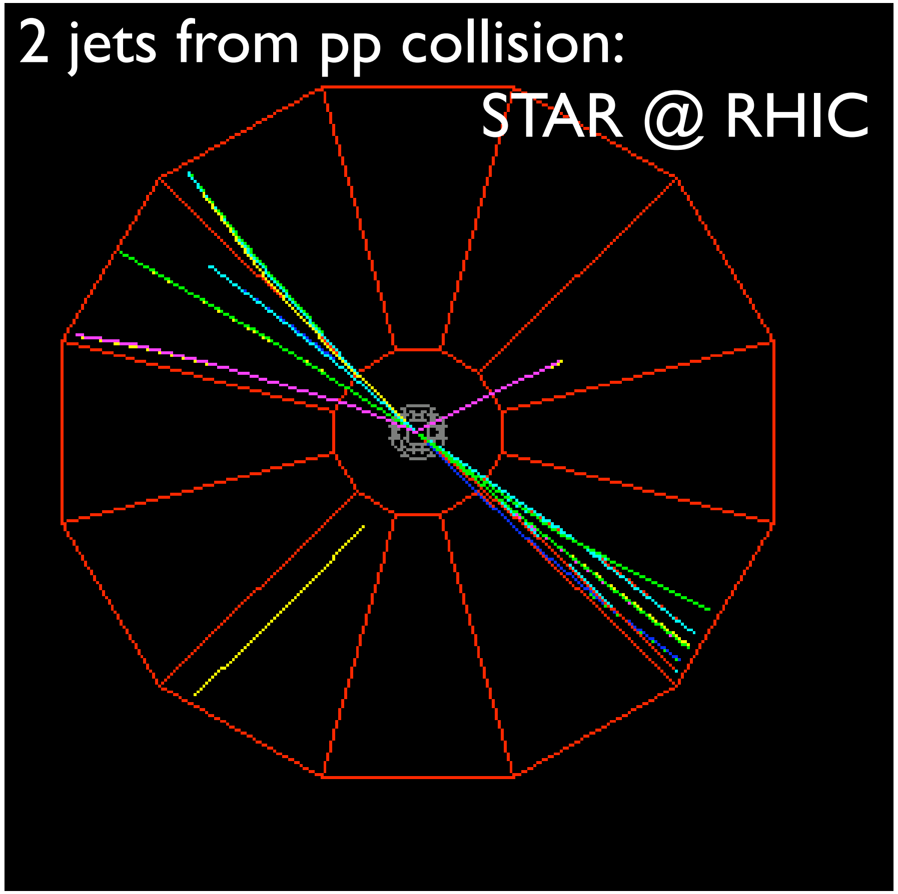
Majority of particles at small momenta $p_t < 2$ GeV.

Tail of the "Unicorn":

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

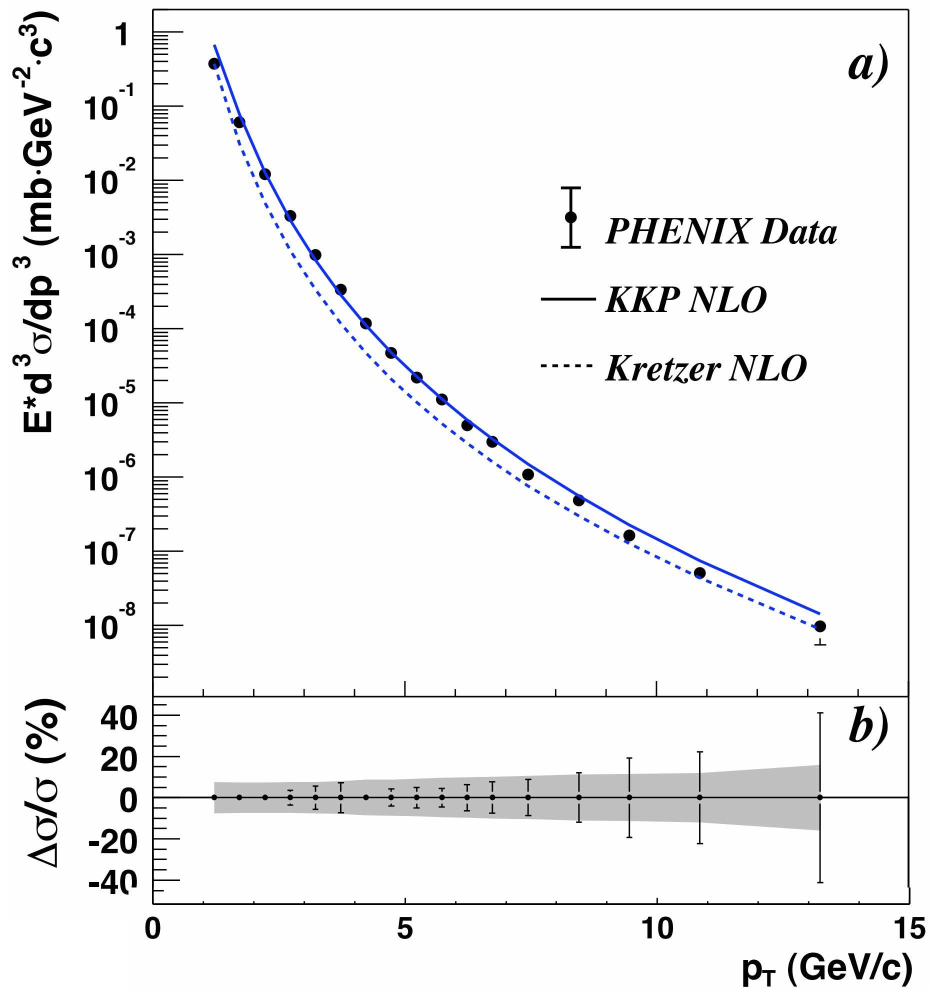
The Tail wags the (Dog) Unicorn

Jets: “seeing” quarks and gluons in QCD



Quarks & gluons => *jets*.
By momentum conservation,
for each jet, there is a backward jet.

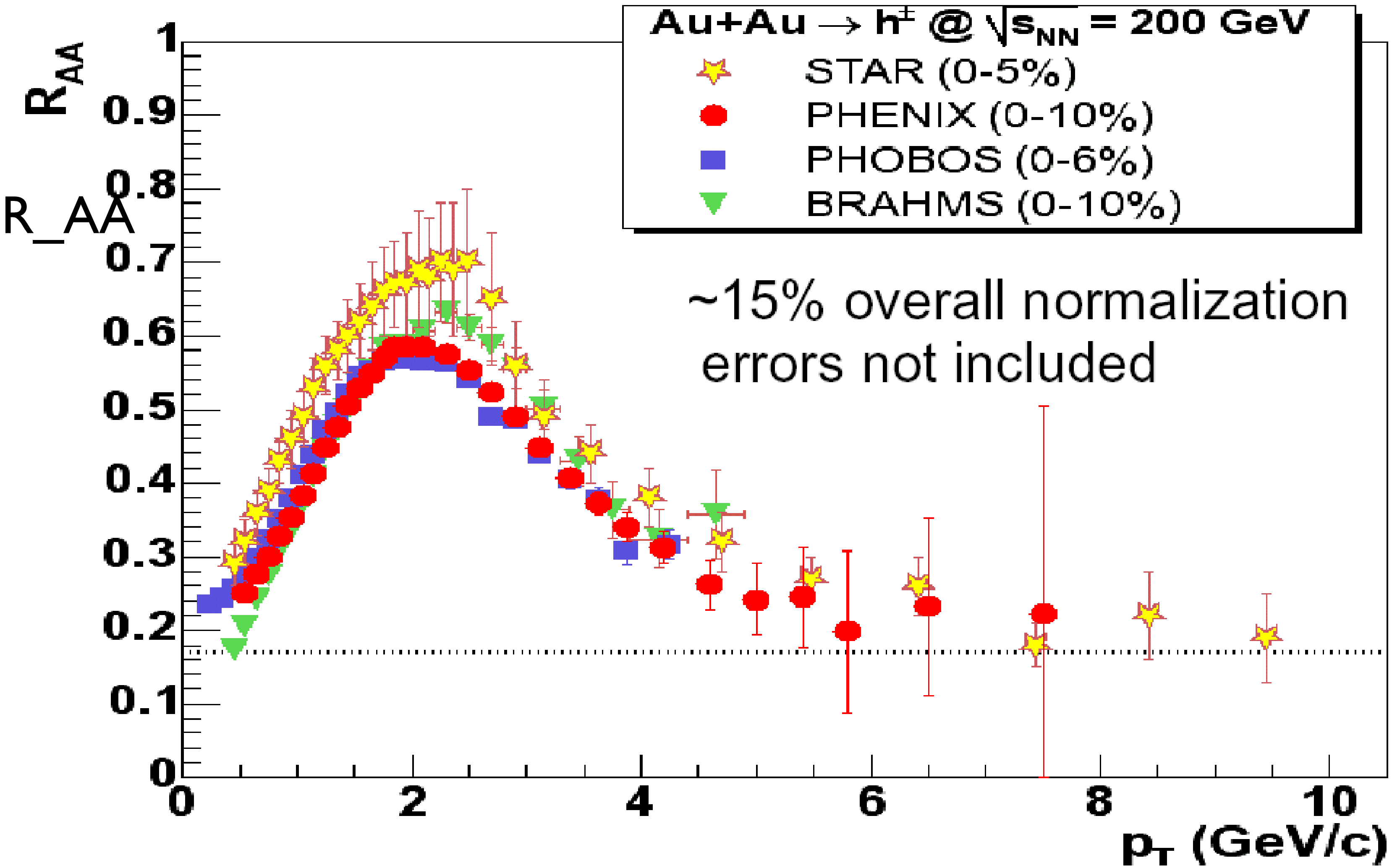
Jets can be computed at high energy
in pert. thy., down to ~ few GeV
Vogelsang et al =>



Clear Experimental Signal: R_AA

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

R_AA = # particles at a *given* p_t, in *central* AA/(# part's in pp times A^{4/3})
A^{4/3} ~ "hard" collisions



<= R_AA for all hadrons: *suppression* of hard particles in AA vs pp.

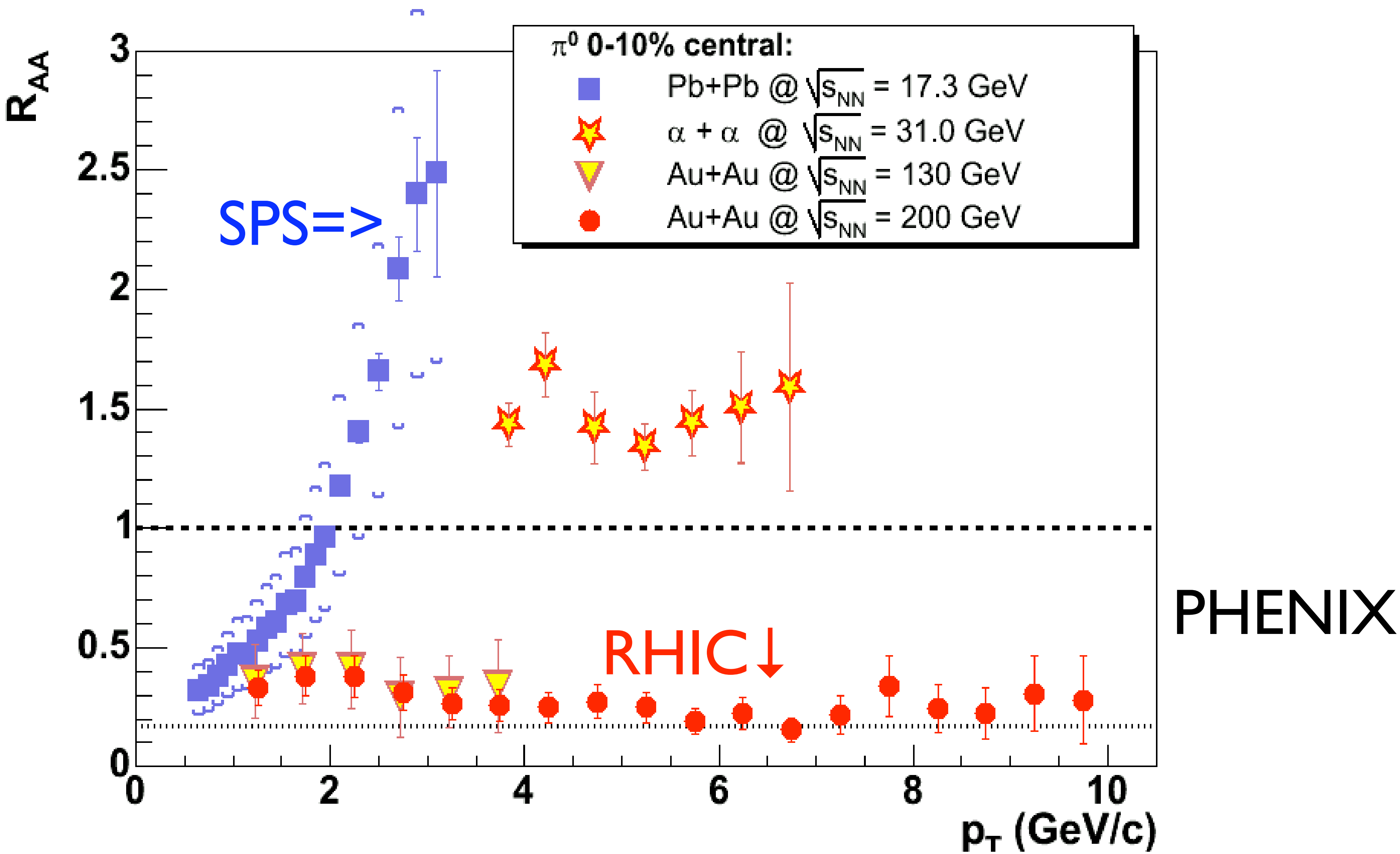
p_t > 6 GeV: ~ *constant* suppression @ 200 GeV

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

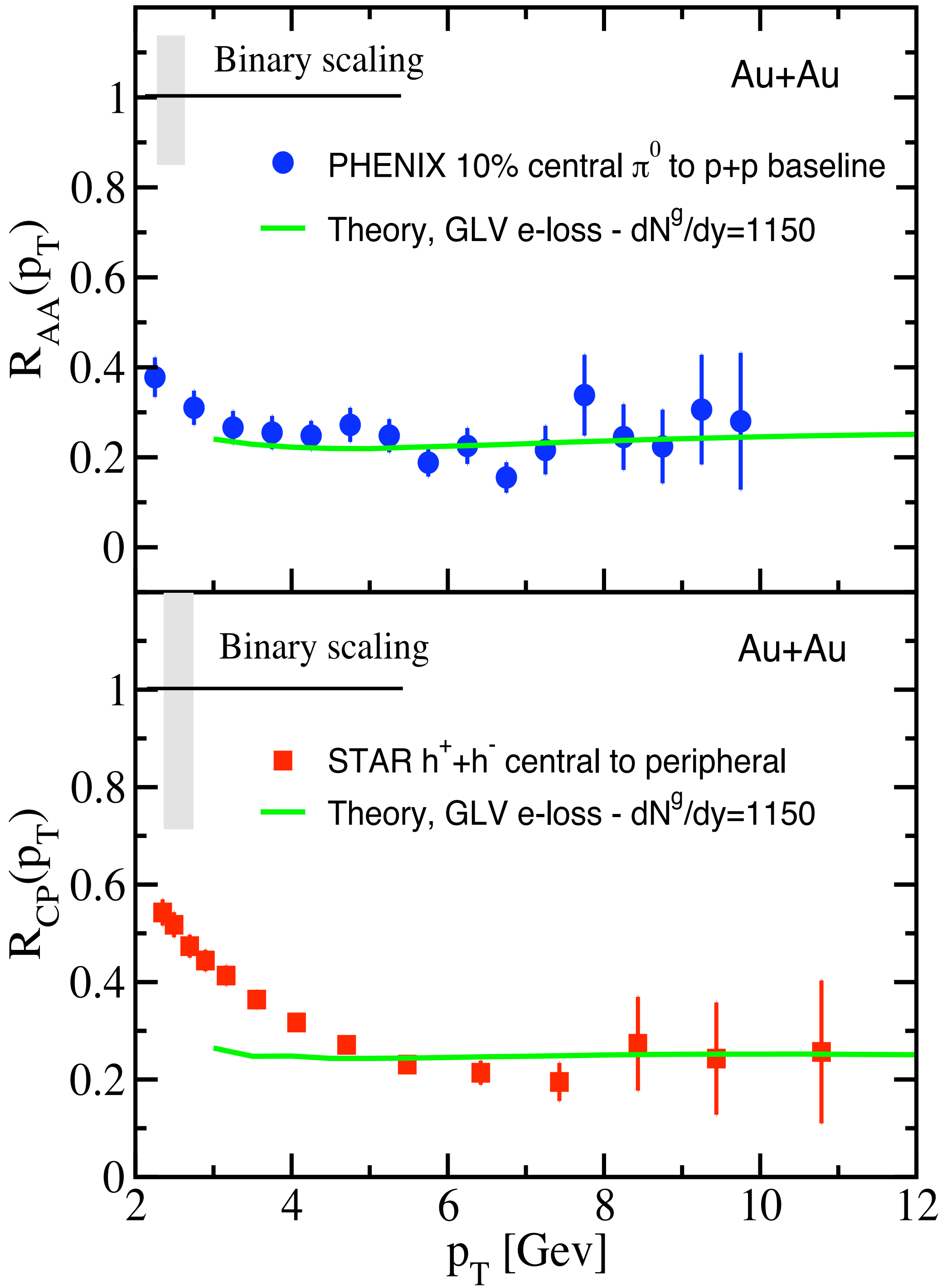
Effect most dramatic for π^0's. SPS: R_AA ~ 2.5 @ 3 GeV. "Cronin"

RHIC: R_AA ~ 0.2 @ 3 GeV.

RHIC: Suppression from *energy loss* in "*stuff*", which slows fast particles.



R_AA as 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
@ 130, 200 GeV

Need to add "Cronin", shadowing...

Why flat above 6 Gev?

When does R_AA => 1?

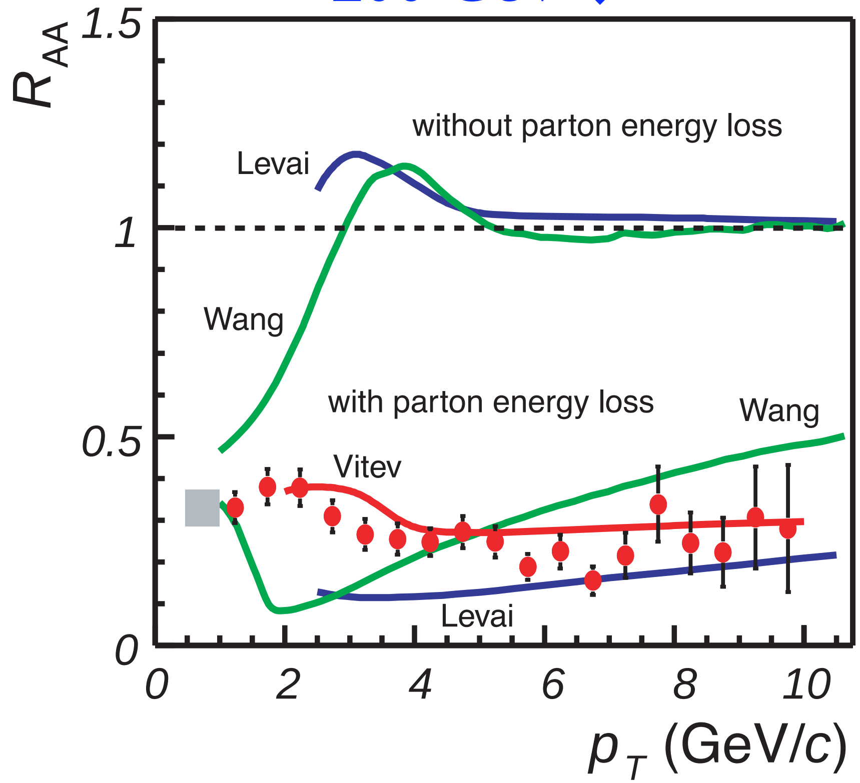
R_AA: strongly energy dependent

R_AA ~ same @ 130, 200 GeV. Run 4: ran at 62 GeV:

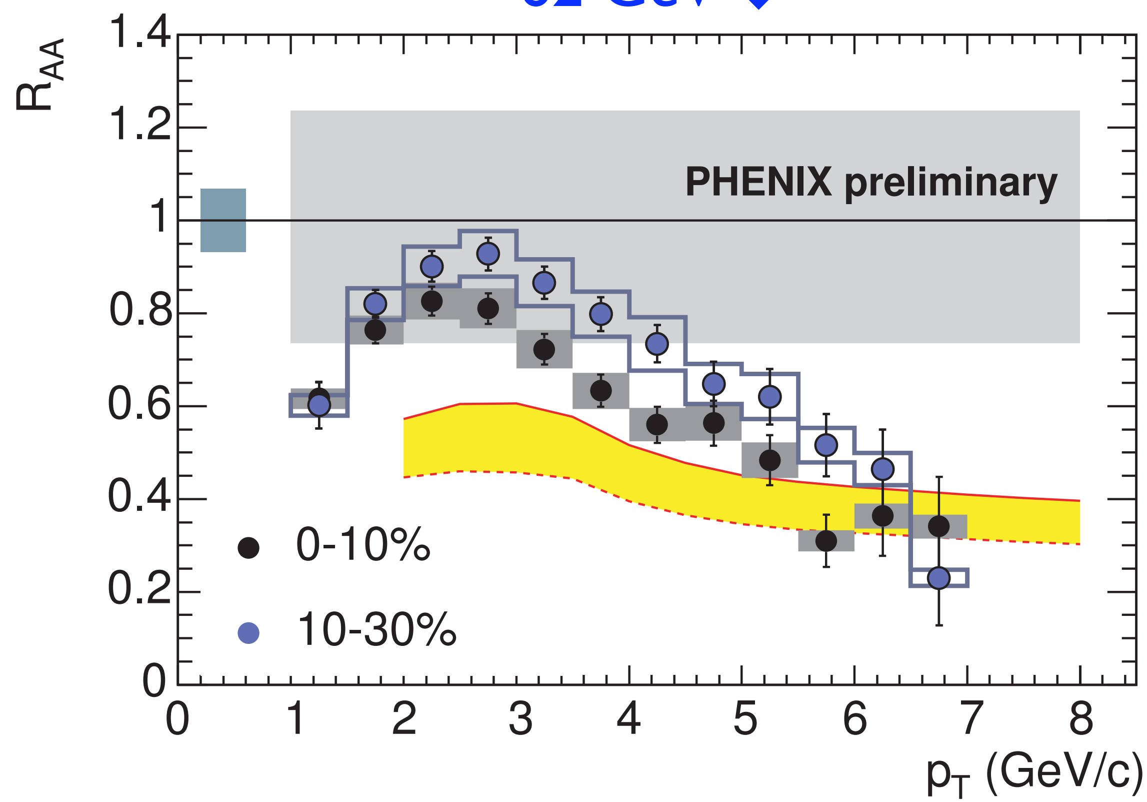
Big difference in R_AA! @ 62 GeV, ~2 bigger at p_t ~ 3 GeV than @ 130,200

R_AA (for neutral pions) strongly energy dependent

200 GeV ↓



62 GeV ↓

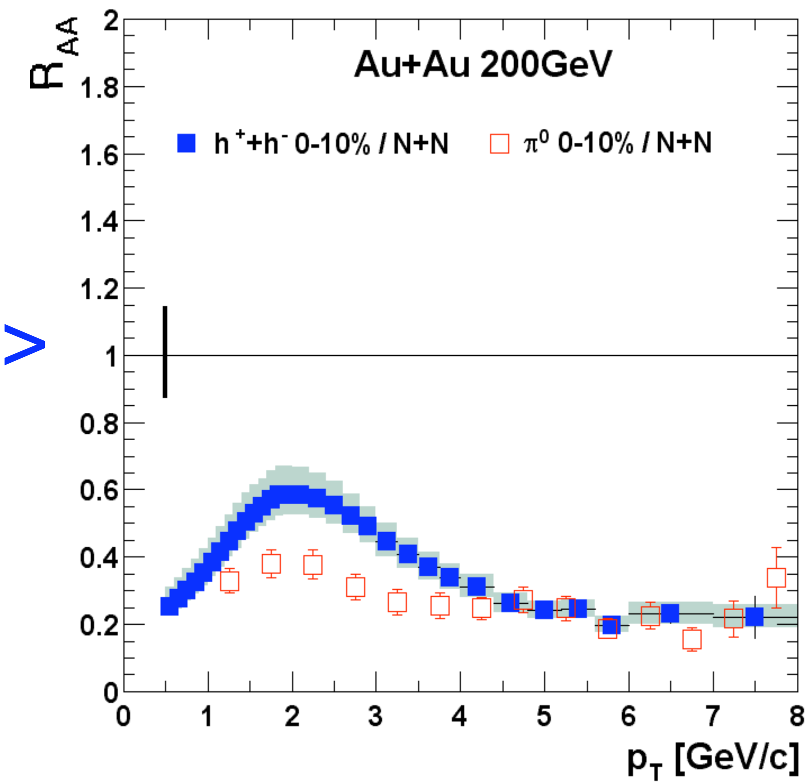


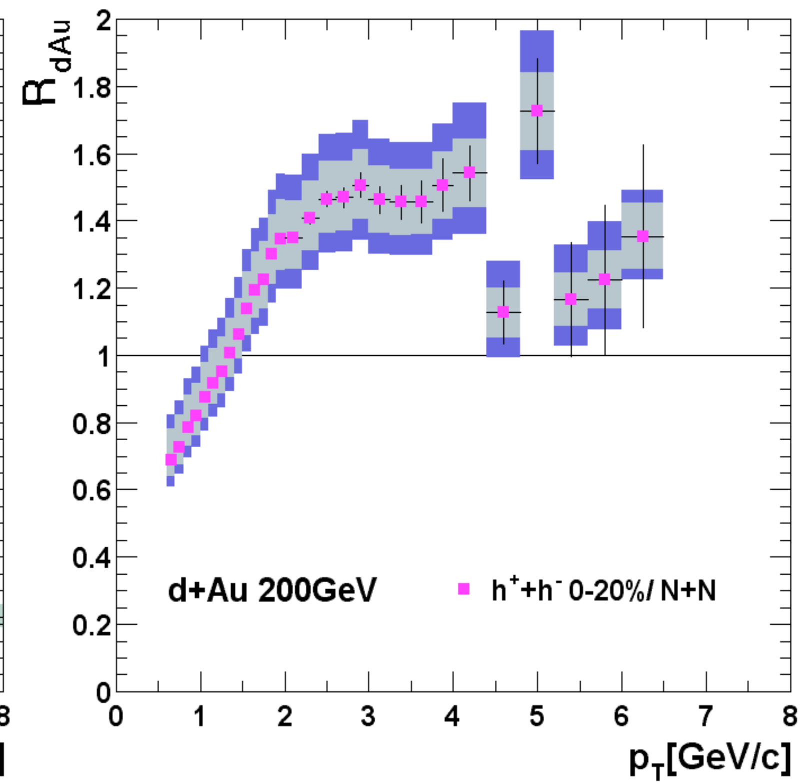
R_AA *final* state effect: *not* in R_dA @ central rap.

R_dA: like R_AA, but for dA/pp. *At central rapidity (y=0):*

dA: enhancement, from initial state "Cronin" effect (=> 1 @ p_t > 8 GeV)
AA: suppression, as *final* state effect (Color Glass predicted suppression in dA)

AA=>





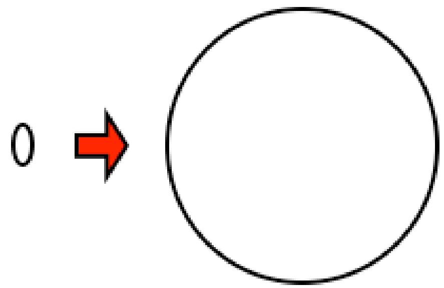
<=dA

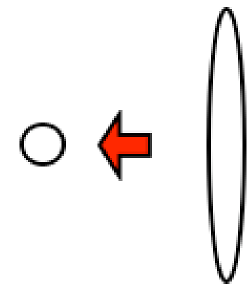
Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

Color Glass suppression: in dA, by the *deuteron*

Fragmentation region ~ rest frame. Incident projectile Lorentz contracted:

nucl. frag.=> 

proton frag.=> 

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

Proton frag. region: study *initial* state effects (Dumitru & Jalilian-Marian, Gelis...)

BRAHMS in dA:

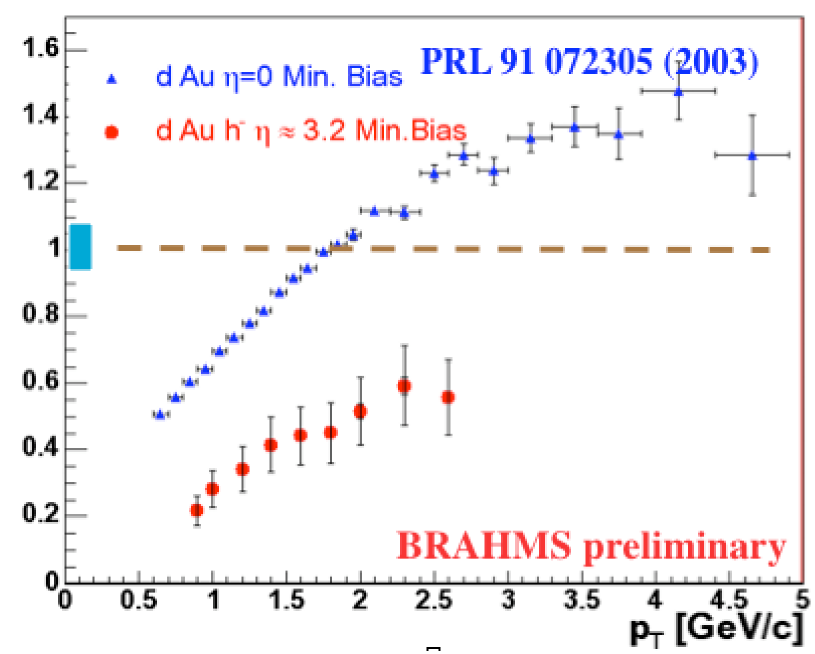
enhancement @ central rapidity

suppression @ proton frag. region.

Supports color glass initial state.

Need to study all rapidities.

R_dA:



Surprise! Baryon “bump” at moderate p_t

pp collisons @ 200 GeV: at p_t ~ 2 GeV, p/π ~ 0.1

central AuAu @ 200 GeV: at p_t ~ 2 GeV, p/π ~ 1.0: *increase by ~ 10!*

Baryon “bump” at moderate p_t: 2 => 6 GeV

Baryons at moderate p_t not suppressed as much as mesons:
explains difference in R_AA for total hadrons, versus pions

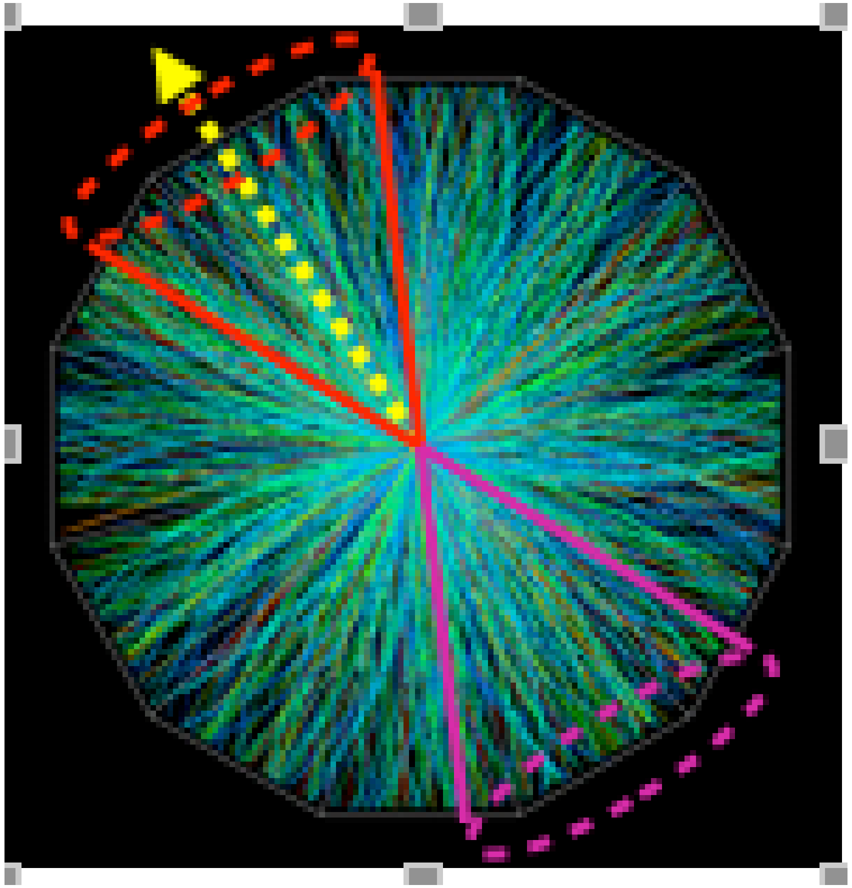
“Recombination”: quarks and anti-quarks coalesce into mesons, baryons.

Explains: difference in R_AA,
“elliptic flow” for baryons ~ 3/2 mesons at moderate p_t

But why do quarks and anti-quarks dominate (*only*) at moderate p_t?
Where do they come from? (Where did the gluons go?)

“Jets” in central AA collisions

pp collisions: ~ 4 particles/unit rapidity, vs 900 in central AA.



Hence hard to see *individual* jets in AA.

Can construct statistical measures.

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.

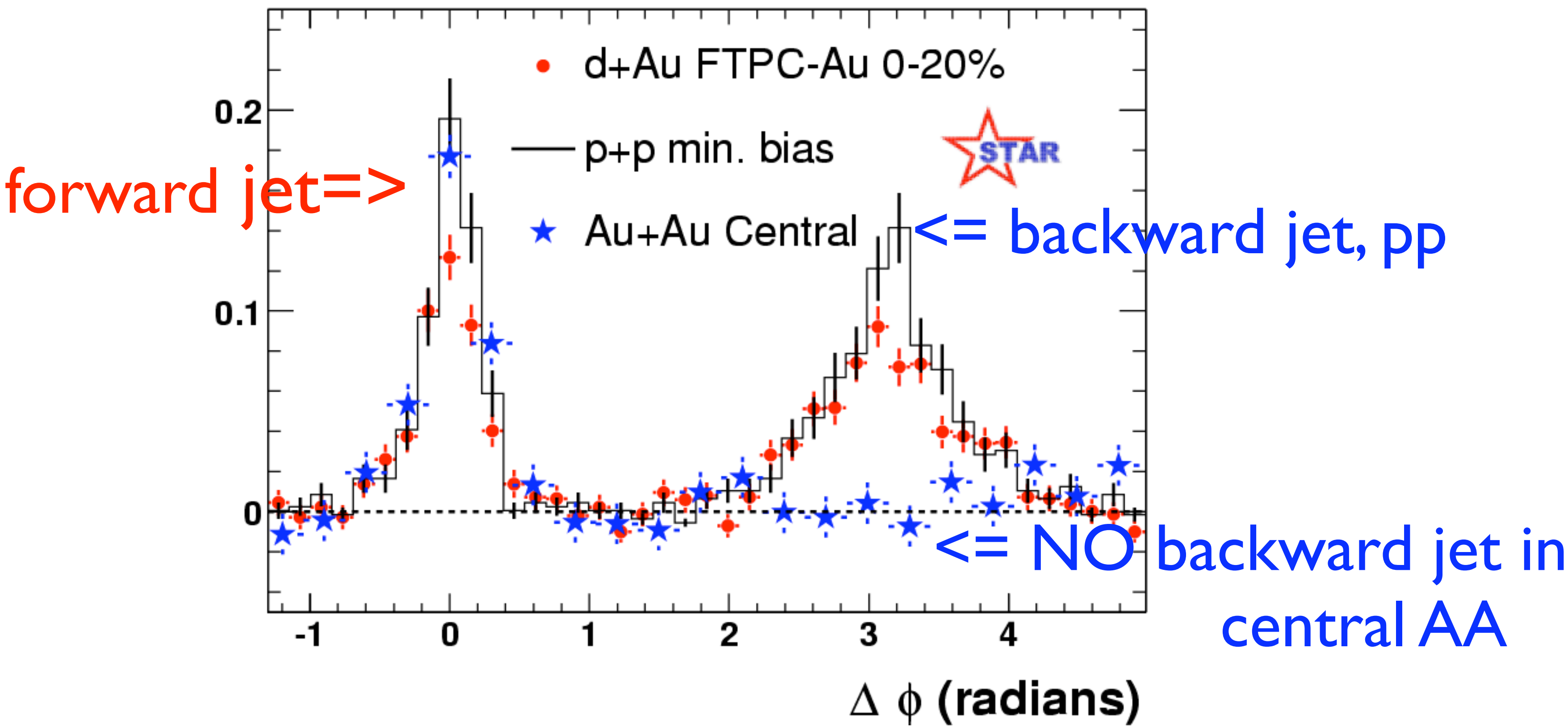
Central AA collisions "eat" jets!

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: prefer to *eat* jets out of plane

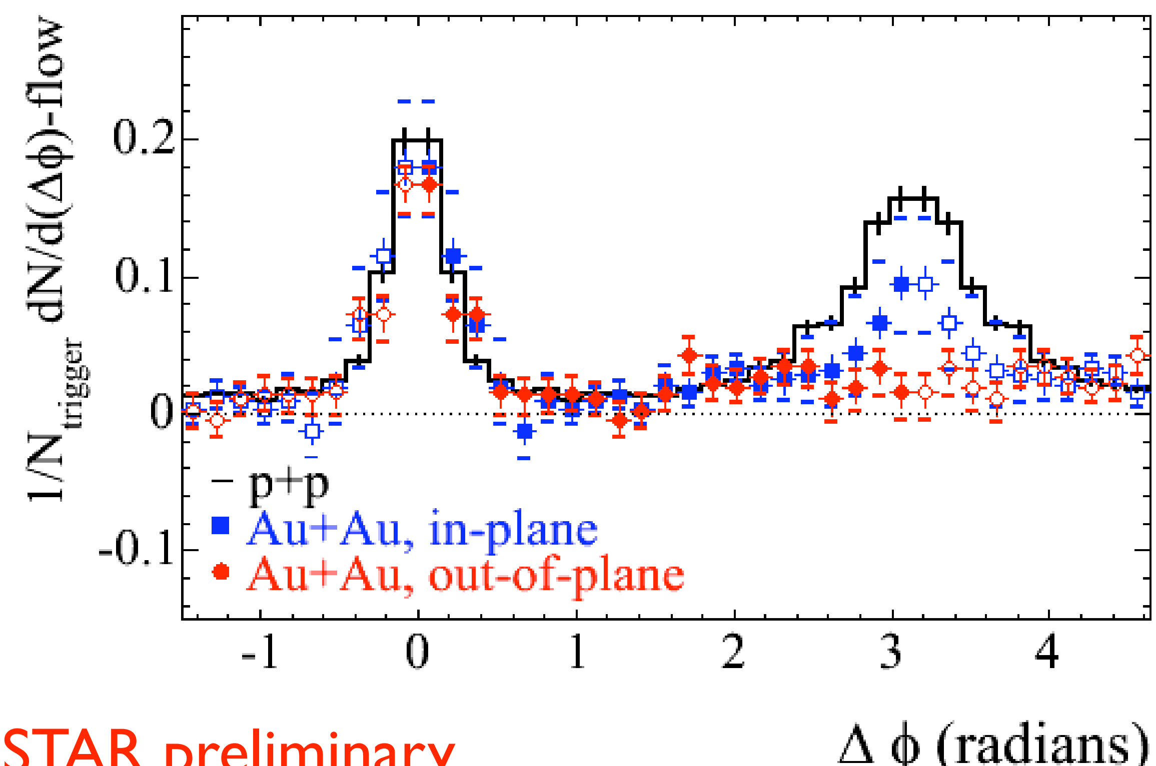
Peripheral collisions, "stuff" forms "almond":

more "stuff" out of the reaction plane, than in.

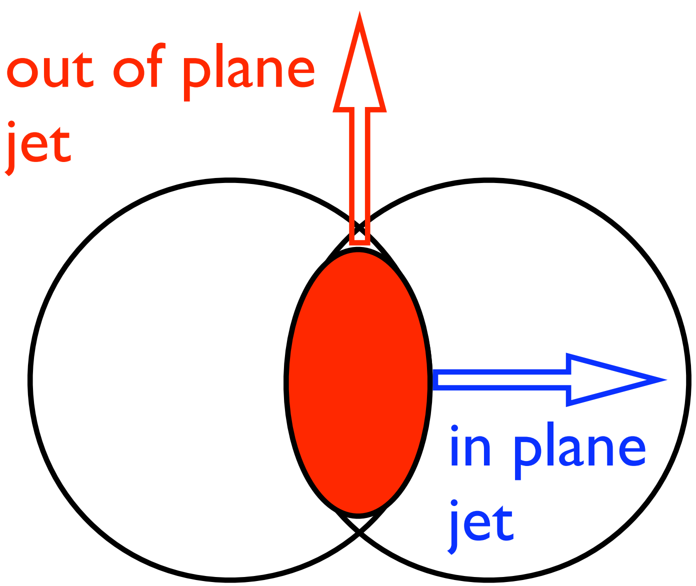
And: in the plane, not only less stuff, but *more* ordinary nuclear matter

Exp.'y: backward jet more strongly suppressed *out* of plane than *in* plane =>

geometrical test that central AA "*eats*" jets preferentially



STAR preliminary



peripheral collision ↑

almond = "stuff"

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

Particles peaked about zero transverse momentum

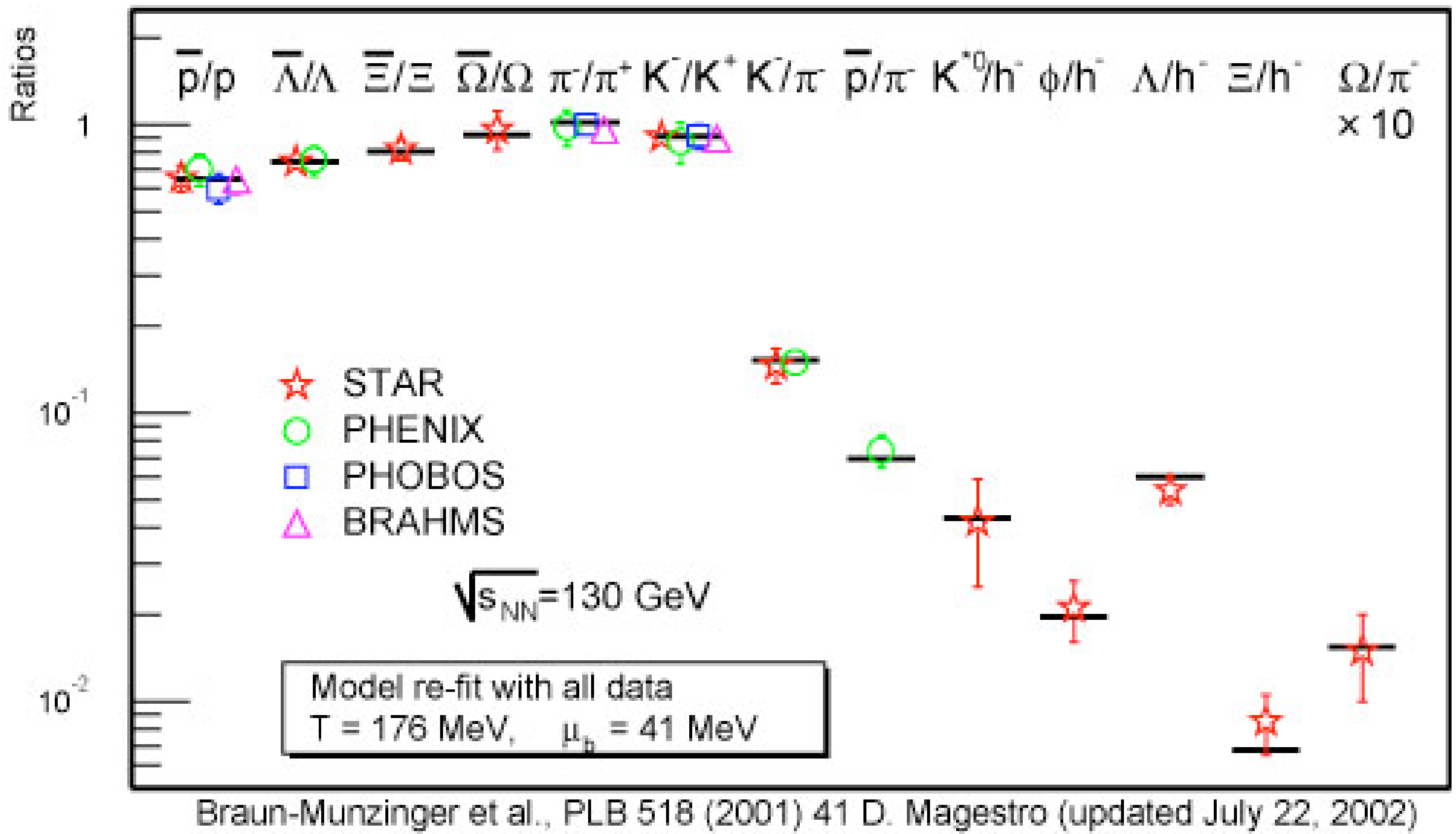
Tc ~ 200 MeV: *expect* thermal to p_t ~ 2 GeV.

Thousands of particles, hydrodynamics should be ok...

“dog”=>

<=unicorn

Total Chemical Ratios: T_chemical ~ 160 MeV



Overall chemical abundances for "long" lived states: *well* fit with

T_chemical = 160 MeV, μ_baryon = 24 MeV

Not valid for "short" lived resonances: Δ, φ, K*, Λ*

(Becattini, Braun-Munziger, Letessier, Rafelski, Redlich, Stachel...)

Hydrodynamics: *works* for soft spectra

Hydro.: *assumes* initial conditions: starts
above Tc in thermal equilibrium, *simple* Equation of State (1st order!)
~ *ideal* hydro. => ~ *no* viscosity... => *strongly* coupled theory

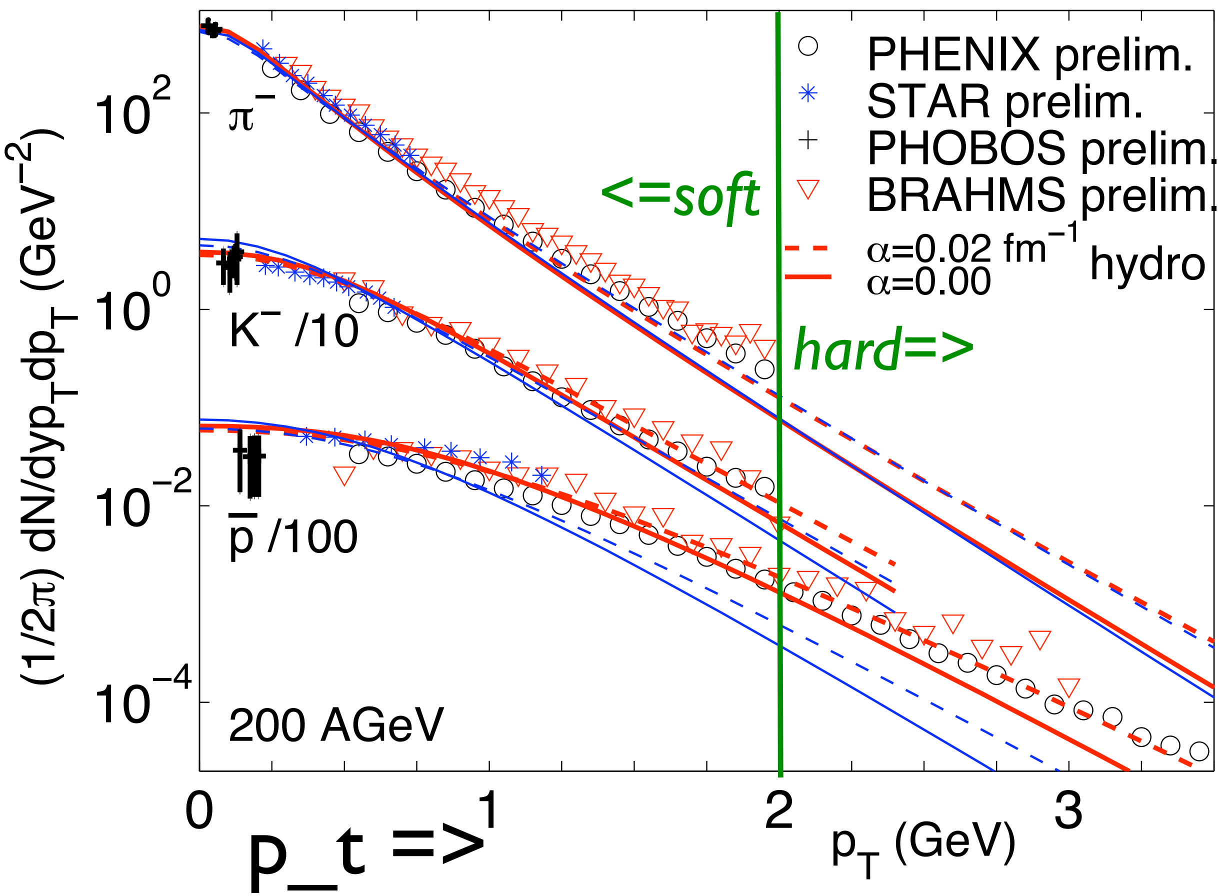
Fit to single particle spectra:
π, K, p's with:

T_freeze out = 100 MeV

Large "boost" velocity β~.7 c
(Spectra of heavy particles "turn over" at low p_t. β r-dep.)

But: need to start at .6 fm/c!

Multi-strange: higher T, lower β:
"partonic flow"?

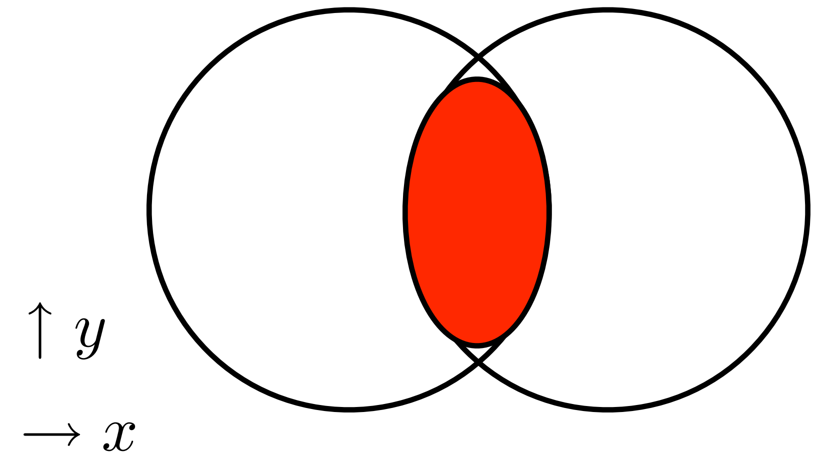


(above: Heinz & Kolb. Also: Hirano, Rapp, Shuryak, Teaney...)

Hydrodynamics: *works* for elliptical flow

Peripheral coll.'s: (Borghini, Ollitrault...)
spatial anistropy => *momentum* anistropy.

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

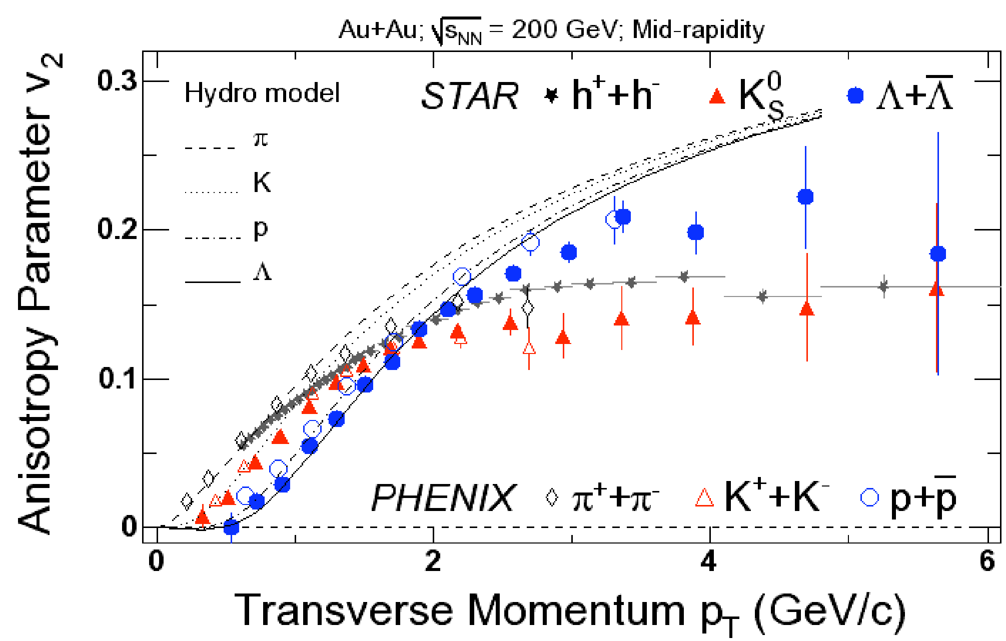


Ideal hydro. describes v_2 for all species to p_t ~ 2 GeV => *strong* collective behavior

p_t > 2 GeV: v_2 ~ # quarks
Agrees with recombination models
(Bass, Muller...)

But why *all* v_2 flat, p_t: 2 => 10 GeV - ?

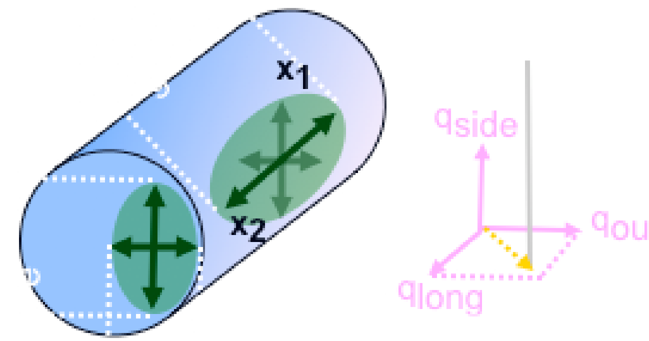
At high p_t, is v_2 collective effect, or some jet-jet correlation?



Hydro.: *fails* for HBT radii. “Blast wave” works

Hanbury-Brown-Twiss: two-particle corr.’s, identical particles
= *sizes at freezeout.* *three* directions (Bertsch, Pratt...):
along beam R_long, along line of sight R_out, perpendicular R_side.

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

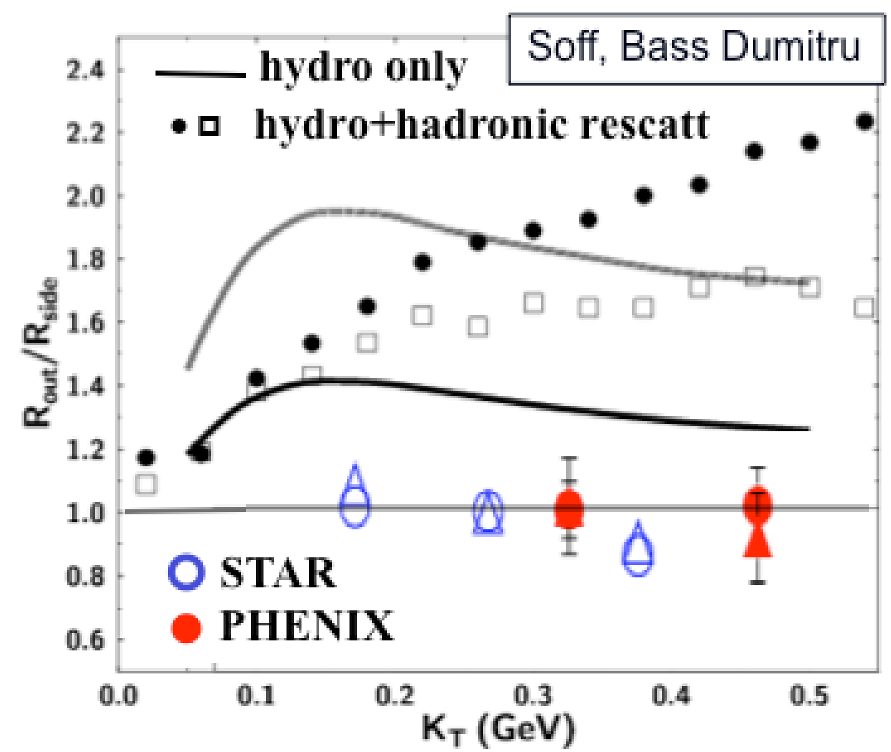


Hydro.: R_out/R_side > 1, *increases* with p_t
("burning log")
Exp.: R_out/R_side ~ 1.0, *flat* with p_t

Hydro. fails, badly, for HBT radii.
No big times from strong 1st order trans.!

HBT “explosive”: blast wave works:
Space-time history shell with
lifetime ~ 8-9 fm/c, emission ~ 2 fm/c

HBT: p_t dependence *same* in pp, dA, AA!



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

In central AA, new final state effects at high p_t ("tail"):

Suppression @ high p_t (/pp), R_AA
Baryon "bump" at moderate p_t
Backward jets "eaten"

In dA, new initial state effect:

suppression @ d frag. region = Color Glass?

In central AA, at low p_t ("body"):

chemical ratios in equilibrium
(Ideal) hydrodynamics works for:
single particles, elliptic flow, *not* HBT radii

~ Ideal hydro => *strongly* interacting system

No theory describes *all* features of the data. *None.*

Maybe its not the unicorn we expected, but it's still a new beast!

"A possible eureka."