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. QCD @ nonzero temp.: what is the QGP?

2. The QGP on the Lattice: numerical "experiment"

3. Experiments at RHIC: evidence for "gluon stuff" -
the (high-pt) tail wags the (low-pt) body of the Unicorn

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

Symmetries of QCD: Chiral Symmetry

Like a magnet: *broken* at low temperature,
restored at some finite temperature.

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

with strange: $SU_L(3) \times SU_R(3)$

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

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

Deconfinement as a *Global* Z(3) Symmetry

Multiply each quark by a constant phase:

$$q \to e^{2\pi i/3} q \quad , \quad \overline{q} \to e^{-2\pi i/3} \overline{q}$$

Mesons and baryons don't change:

$$\overline{q}q \to \overline{q}q \quad , \quad qqq \to (e^{2\pi i/3})^3 qqq = qqq$$

but q, qq, etc, are not. Could use exp(- 2 π i/3), too = Z(3) symmetry.

Z(3) spin = *Polyakov loop*
= *propagator* "test" quark =>

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

= (trace) color Aharonov-Bohm phase.

Only valid in a pure gauge theory, without dynamical quarks.
In QCD, is the Z(3) symmetry approximate?

Deconfinement & Polyakov Loops

't Hooft: part of *local* SU(3) is *global* Z(3) $\ell \rightarrow e^{2\pi i/3}\ell$

At T=0, confinement => *quarks don't propagate* => *UN*broken Z(3) symmetry

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

As T→∞, by *asymptotic freedom*, g^2 small, pert. thy. ok, => loop is near one (x3).
=> deconfined phase in which quarks propagate:

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

Deconf. *opposite* to spins: Z(3) broken at *high*, and not *low*, temp.

Order of Phase Transitions

Relation between deconfining and chiral transitions? 1 or 2 trans.'s?

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

Strongly First Order Transition(s)?

"Of course"! Hadrons ≠ Quarks & Gluons.

Limits:

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

first order deconfining trans. (Svetitsky & Yaffe).

colors => ∞: first order deconf.'g trans.

Chiral transition: two massless flavors: O(4) sym. $\det(\Phi)$ => *second order chiral trans.*

three massless flavors: *cubic* invariant => *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.
But how close is the lattice (today) to the continuum limit, a=0?

"Pure" gauge (no dynamical quarks): present methods close to a=0!

QCD: present methods *not* close to a=0. *All* results tentative.
Very hard to put *global* chiral symmetry on lattice!

View: lattice simulations as (another) experiment... What it has told us to date

Pure gauge: T_d ~ 270 ± 10 MeV.
Weakly first order deconfining trans.
Non-perturbative QGP from T_d => 3 T_d. NO "Of Course"

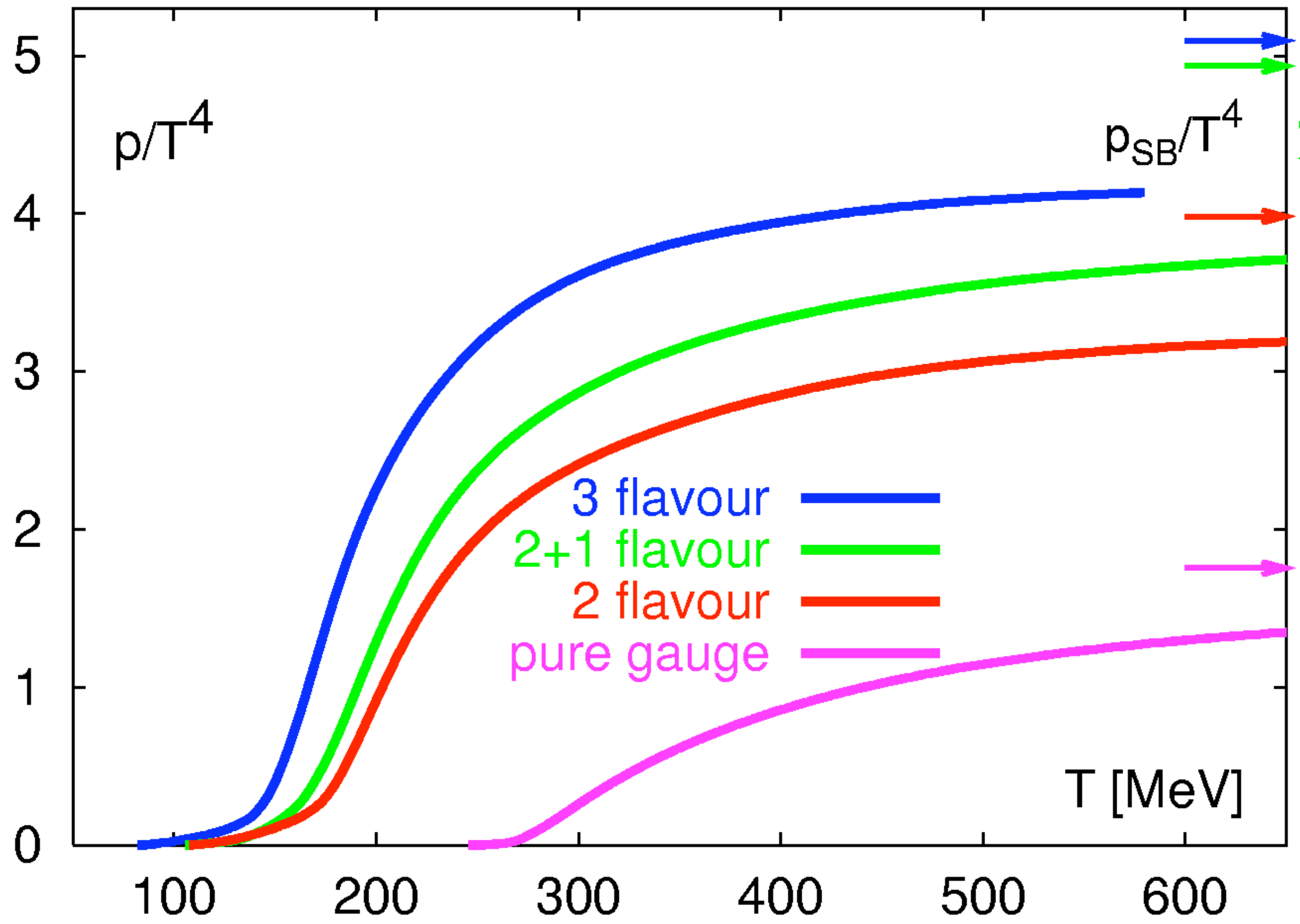
With quarks: T_c ~ 175 ± ? MeV
Order? Crossover today.
Only *one* transition (chiral = deconfining)
"Flavor independence": pressure with qks like that without qks.

Lattice: Pressure vs T, Different # Flavors

QCD:"2+1" flavors (up & down light, strange heavy): BIG changes

p=p(T)=pressure. Plot p/T^4, => constant as T → ∞ (asymp. freedom)

p/T^4↑



<=ideal gas: 2+1 flavors

<=ideal gas: pure gauge

↑Tc ~ 175: 2+1 flavors

T=>

↑Tc ~ 270: pure gauge

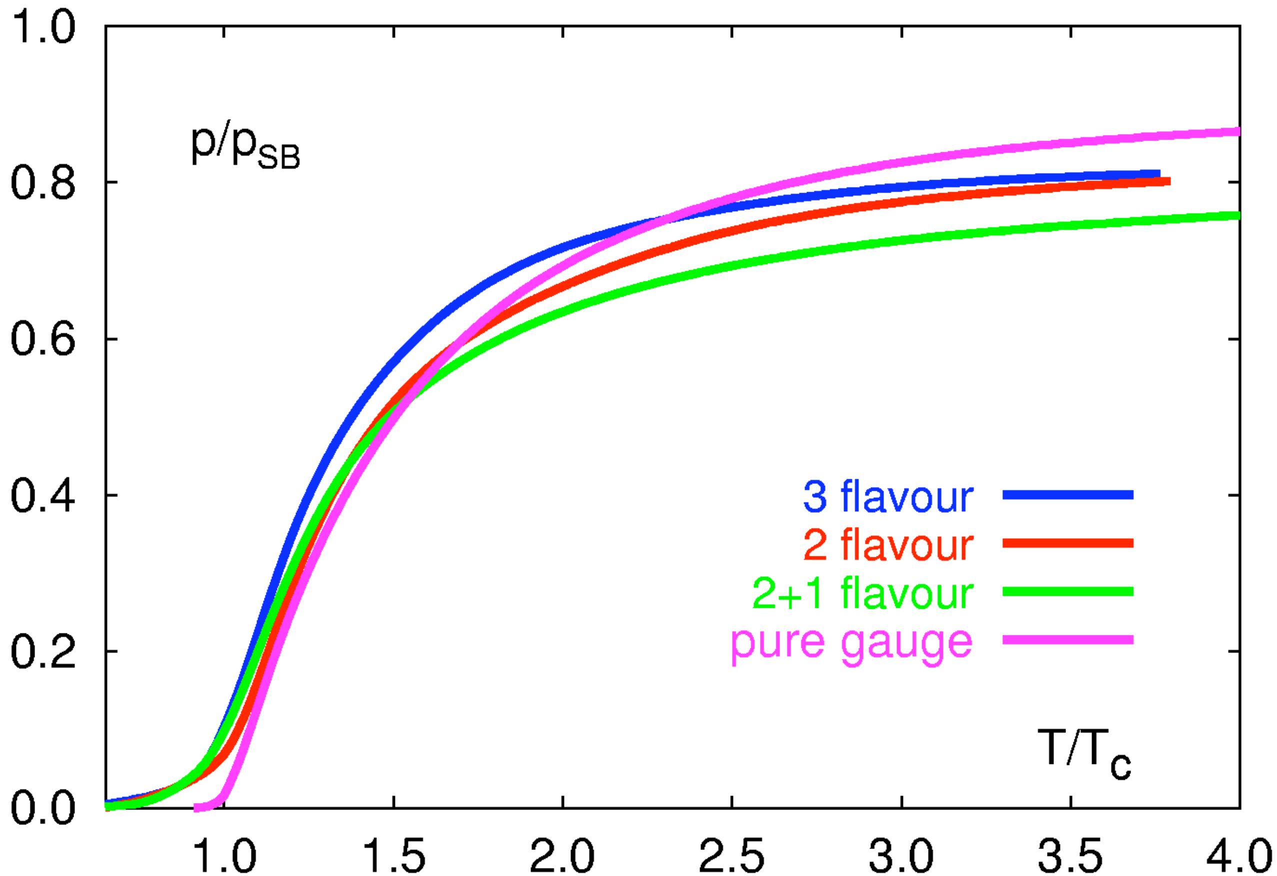
Lattice: "Flavor Independence"

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↑

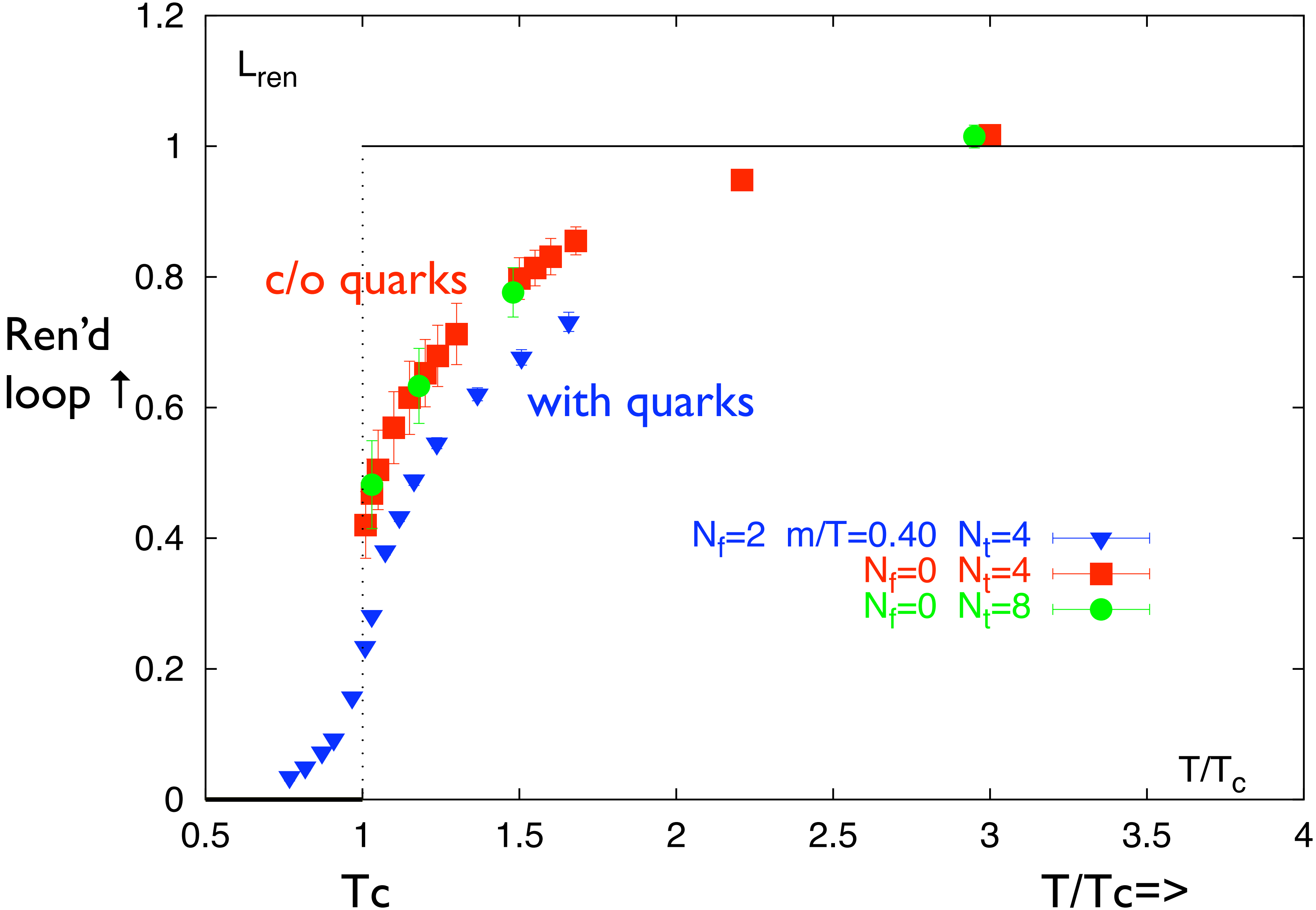


=> pressure *dominated by gluons?*

T/Tc=>

(Ren.'d) Polyakov Loop *with* Quarks ~ Pure Gauge

NON-pert. QGP from Tc => ~ 3 Tc (loop far from one)



Bielefeld: lat/0312015

Two flavors, kaon masses

Hunting for the "Unicorn": the Quark-Gluon Plasma, in Heavy Ion Collisions

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

Why do AA? *Big* Transverse Size.

pp: protons on protons. "Ordinary" hadronic collisions.

AA: nucleus with atomic number A on same.

pA: proton on a nucleus. At RHIC, often dA. Serves as test to tell pp from AA.

WHY AA? Nuclear size $r_A \sim A^{1/3}$

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 → ∞: *infinite* nuclear matter. A~200 close to ∞? Decide by *experiment.*

Colliders: Energy, Machines

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

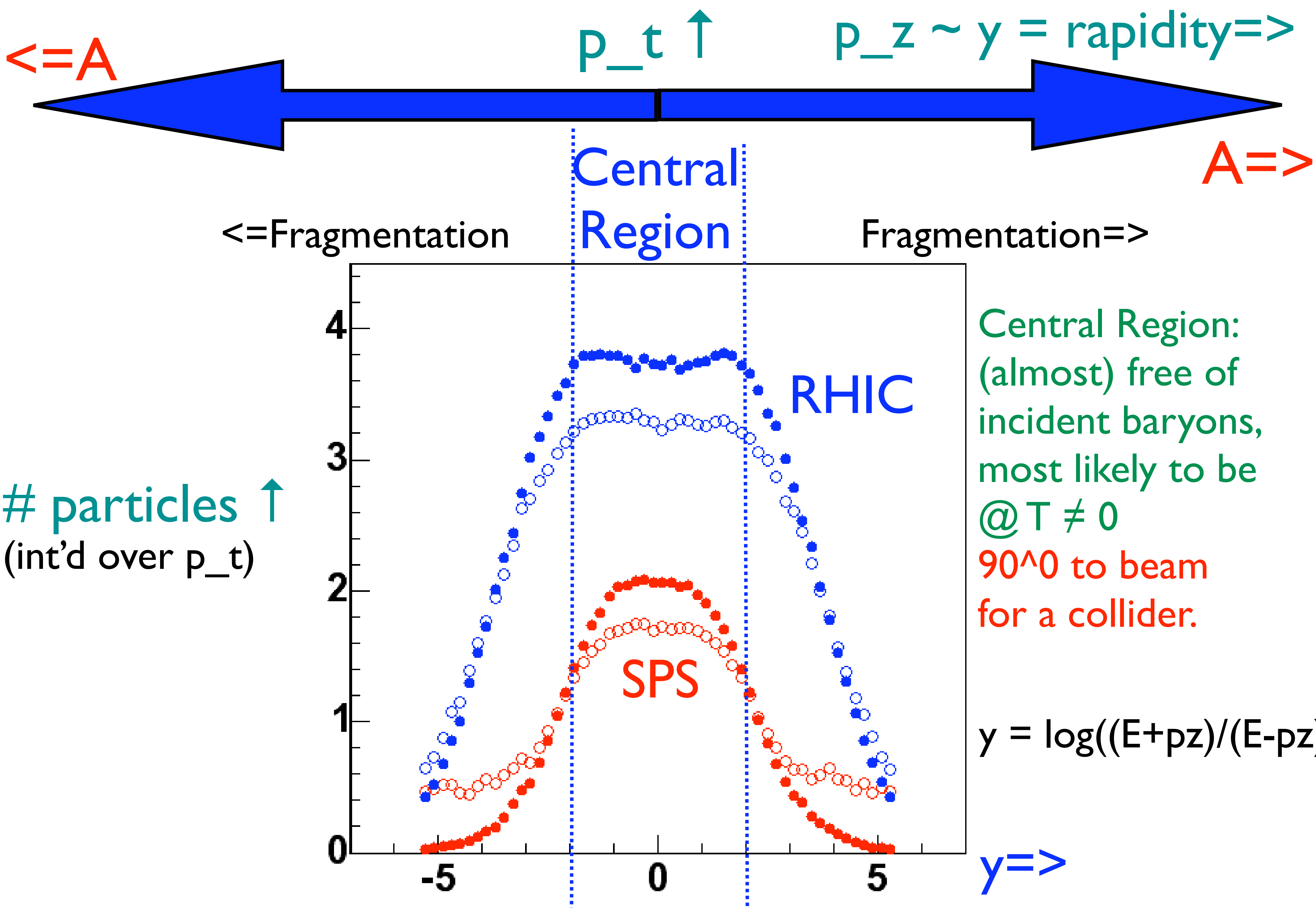
For AA collisions, energy *per* nucleon is $\sqrt{s}/A \equiv \sqrt{s_{NN}}$

Machines:

	$\sqrt{s}/A$	
SPS @ CERN:	5 => 17 GeV	(fixed target)
RHIC @ BNL:	20, 130, 200 GeV	(collider)
LHC @ CERN:	5500 GeV = 5.5 TeV	(collider, > 2007)

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

Relativistic Kinematics @ Collider

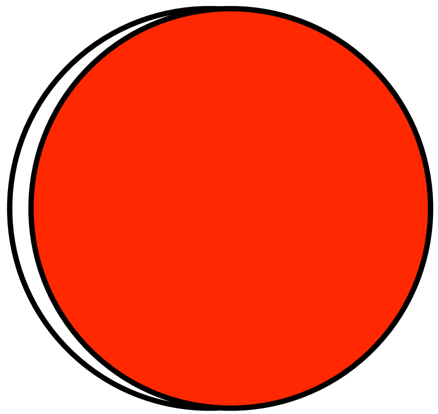


Central Region:
(almost) free of
incident baryons,
most likely to be
@ T ≠ 0
90^0 to beam
for a collider.

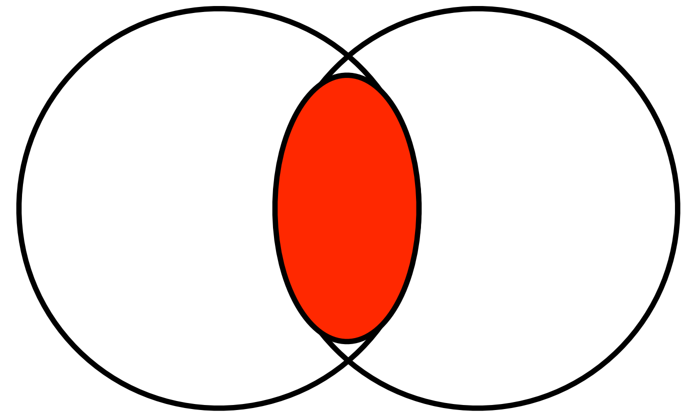
y = log((E+pz)/(E-pz))

AA collisions: Central vs Peripheral

Central:
Maximum Overlap



Peripheral=>
"Almond" of overlap region



Theoretically: would like to compare central AA from small to large A. Takes a lot of beam time. But running with given A, *automatically* measure peripheral collisions.

Exp. variable: # participants.

= 400 in central (= 200 + 200)

= 100 => 400 in peripheral (Glauber & other models; agree to 10%)

Typical Heavy Ion Event @ RHIC

Total # particles = 1000's.

Experiments @ RHIC:

STAR: big, 4 π coverage, y = ±2

PHENIX: big, elec.-mag.,y = ±2

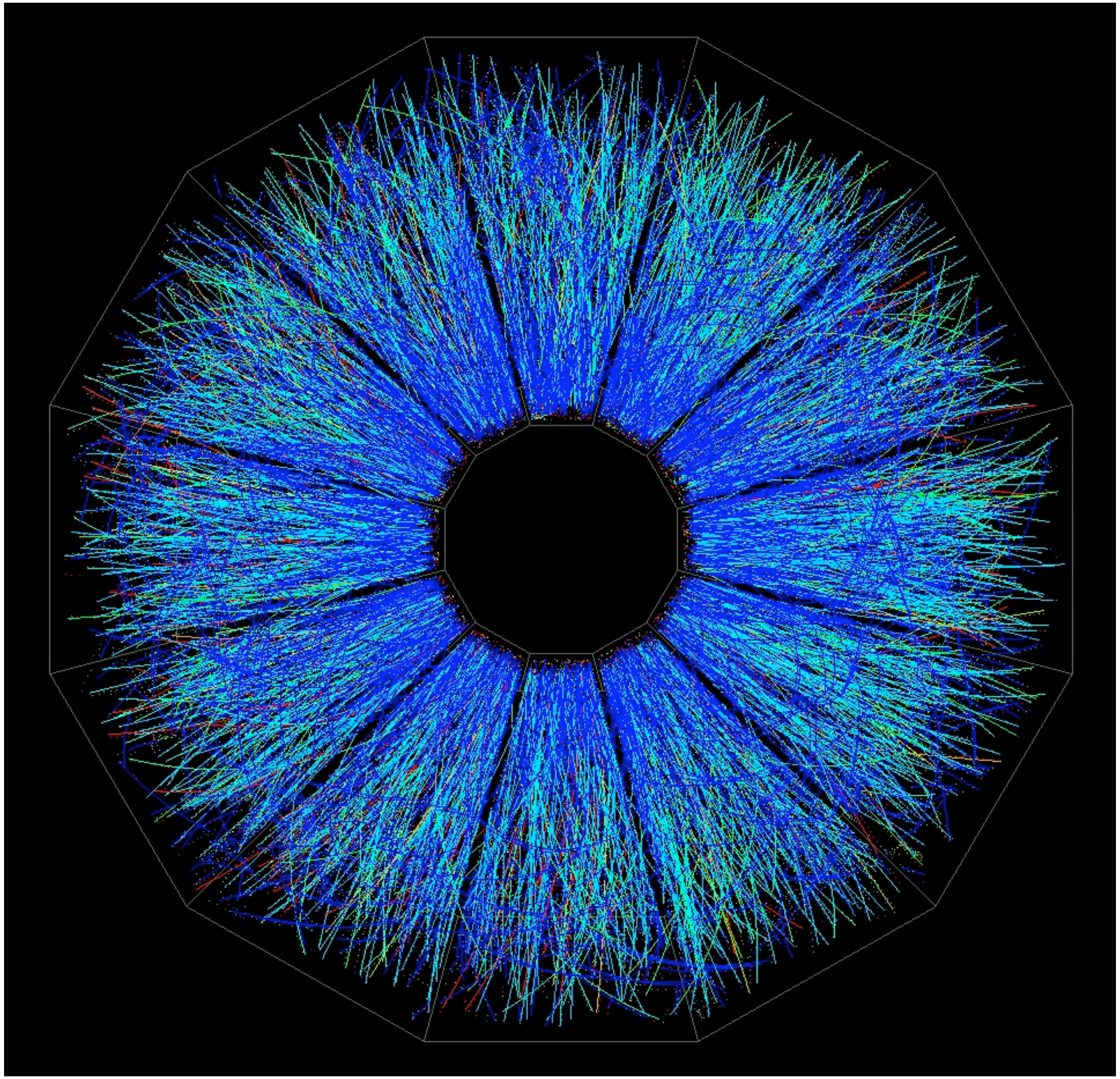
PHOBOS: small, all rapidity

BRAHMS: small, all rapidity

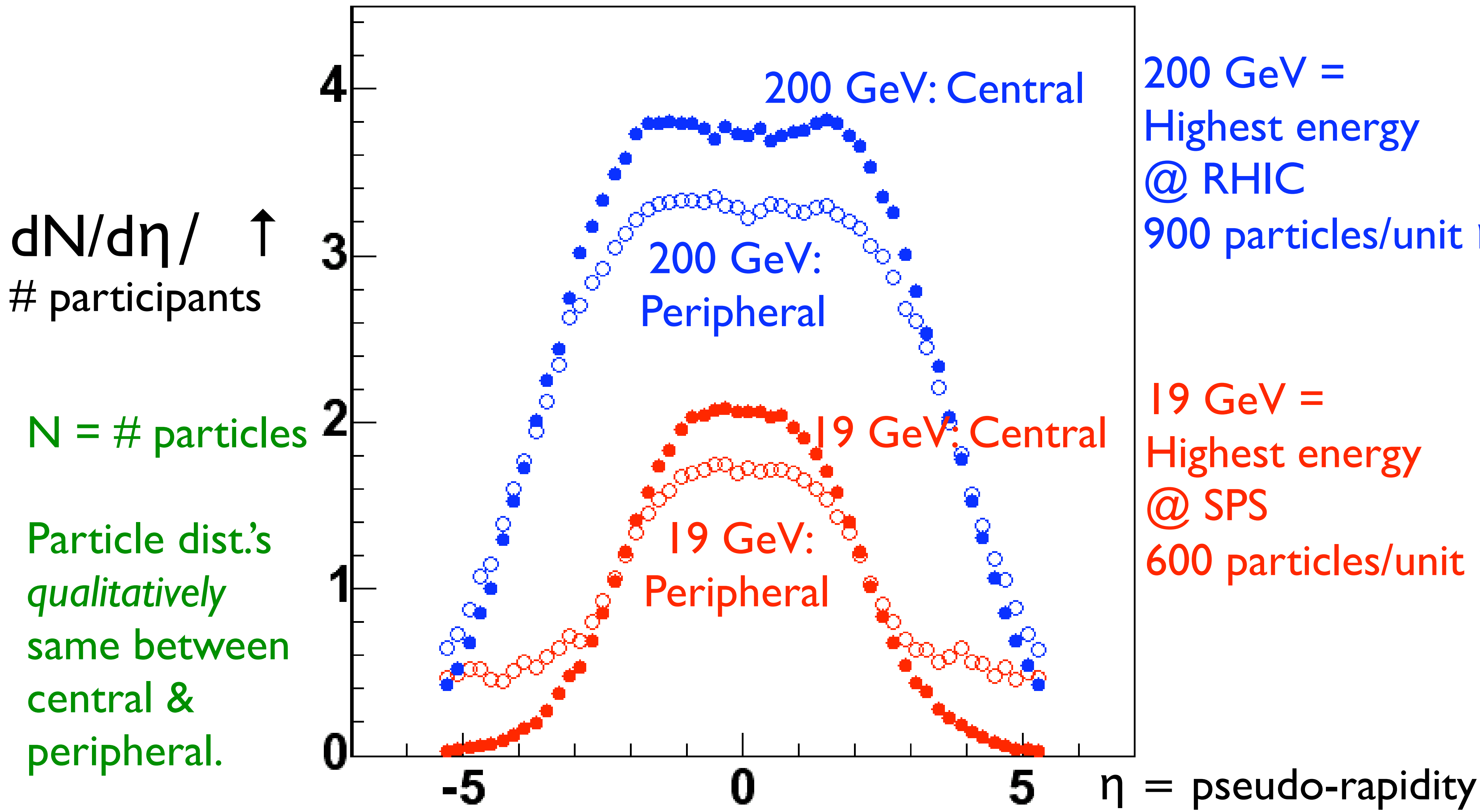
small = 50 exp.'s.

big = 400 experimentalists

400 ~ # part.'s/rapidity ~ log(s)?
theorists ~ log(log(s))?



Particle Distributions vs η, Energy: "Central Plateau" @ RHIC



N = # particles

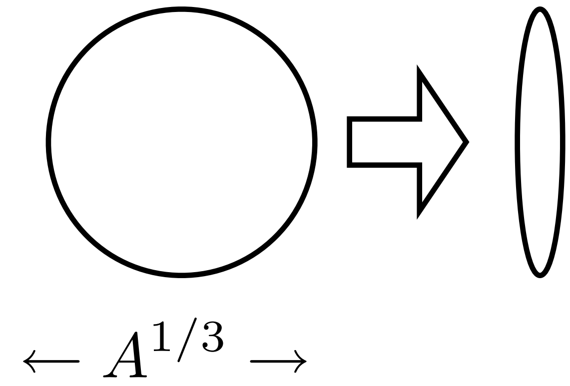
Particle dist.'s *qualitatively* same between central & peripheral.

200 GeV = Highest energy @ RHIC
900 particles/unit η

19 GeV = Highest energy @ SPS
600 particles/unit η

No surprises from overall multiplicity

Why do AA? "Saturation" as a Lorentz Boost



At high energies, incident nucleus is *Lorentz contracted.*
=> color charge of incident nucleus gets "squashed".

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

$A \rightarrow \infty$: can use *semi-classical* methods.

@ central rapidity, gluon *saturation* = Color Glass.

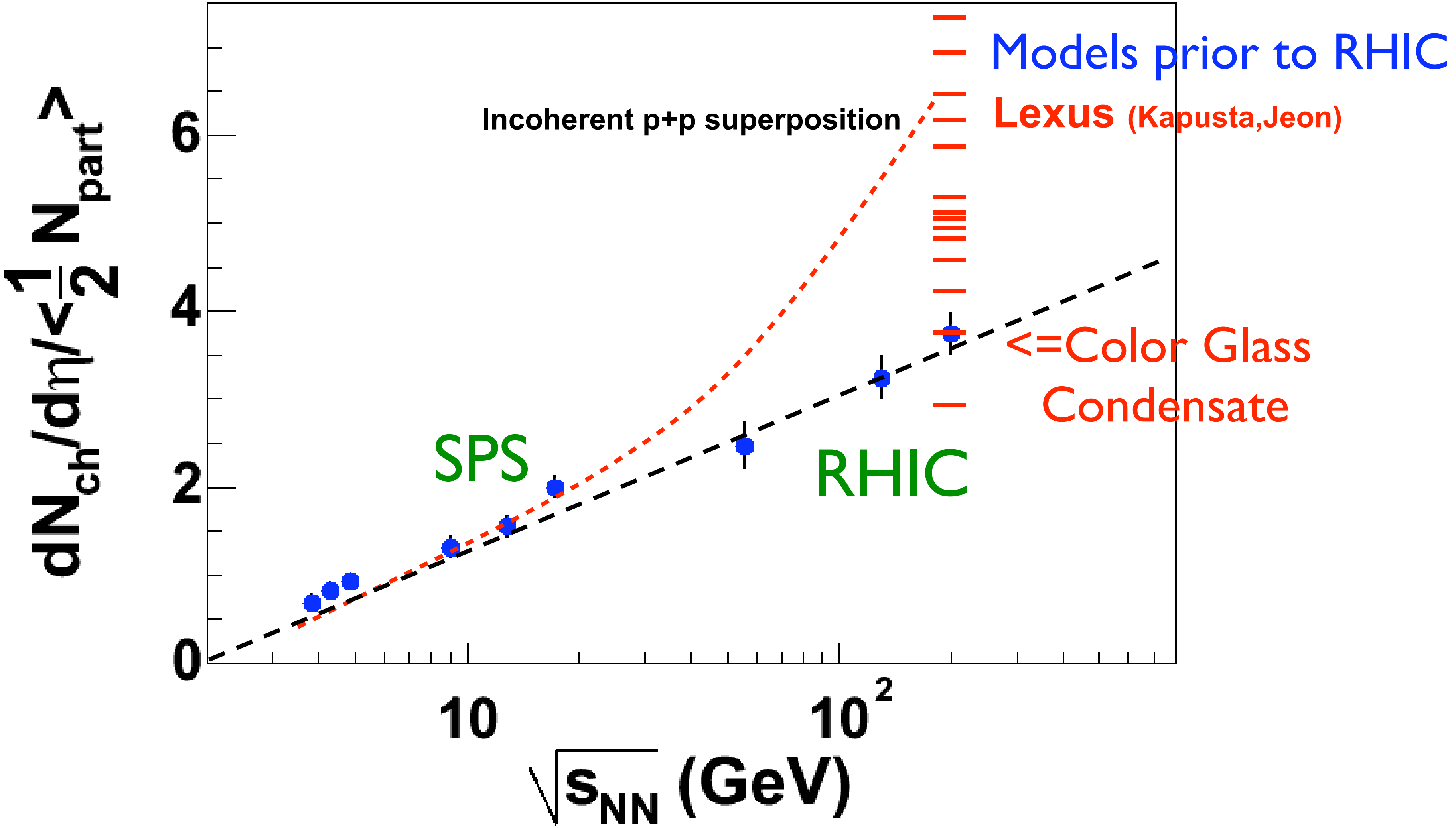
As semi-classical, predicts *logarithmic* growth in multiplicity:

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

First surprise from Day 1: NO big increase in multiplicity. Approx. log growth.

Also: expect avg. momentum to grow similarly $\langle p_t \rangle \sim \log(\sqrt{s}/A)$
(Krasnitz & Venugopalan)

Slow Growth in Multiplicity with Energy



Good fits to overall multiplicity, centrality dependence (Kharzeev, Levin, Nardi)

STAR: from 130 => 200 GeV, multiplicity increases by 14%,
but NO change in $\langle p_t \rangle$ ± 2%. Vs. > 7% increase from Color Glass!

Body of the "Unicorn":

Majority of particles, at small momenta
< 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

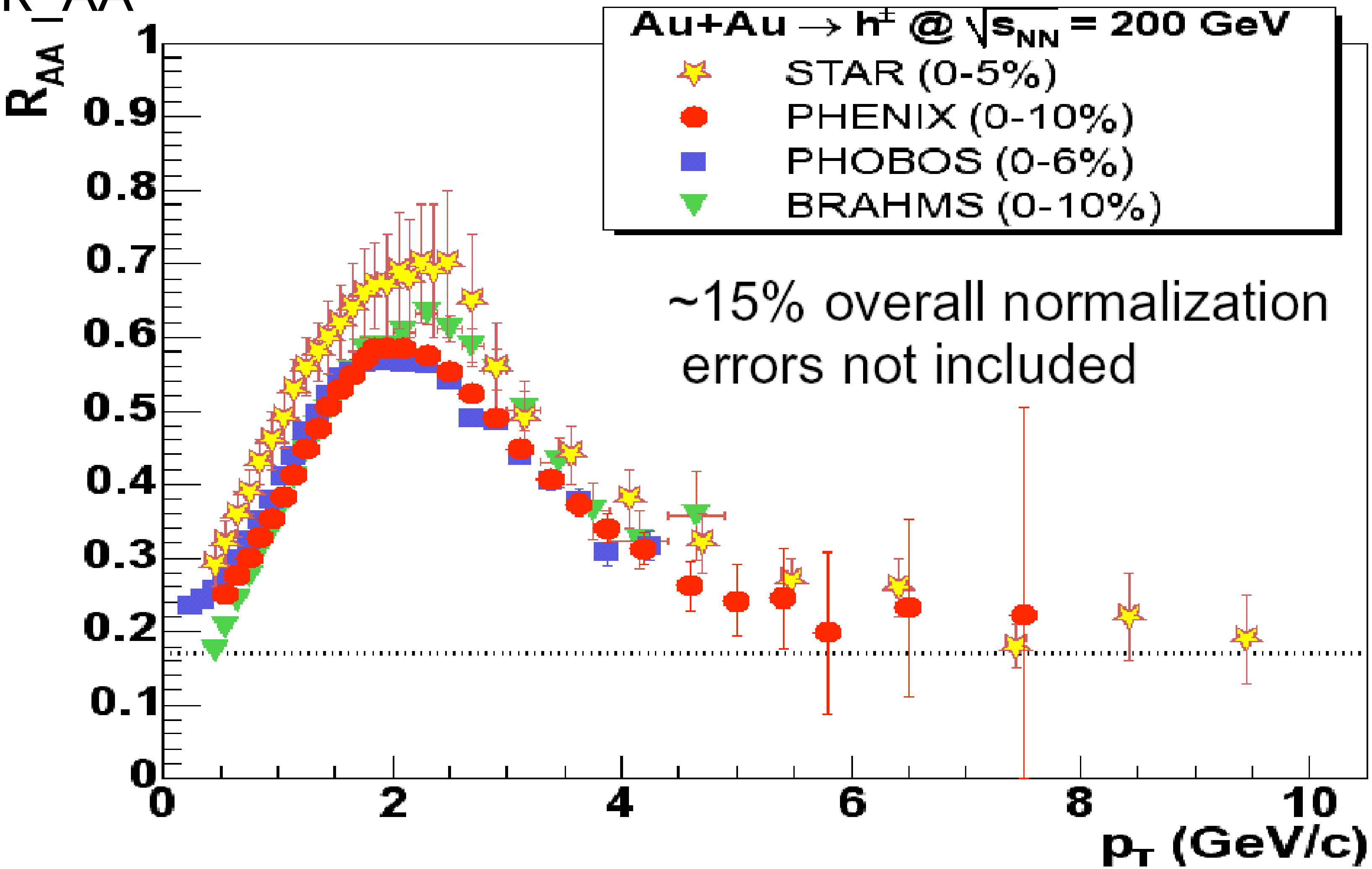
Clear Experimental Signal of "Stuff": R_AA

Compare spectra in AA to that in pp, especially for "hard" pt > 2 GeV:

From Day 1, "hard" spectra appear *steeper* in AA than pp => *fewer* particles.

R_AA = # particles at a *given* p_t, in central AA collision/ # particles at the *same* p_t in pp, *central rapidity*.

R_AA



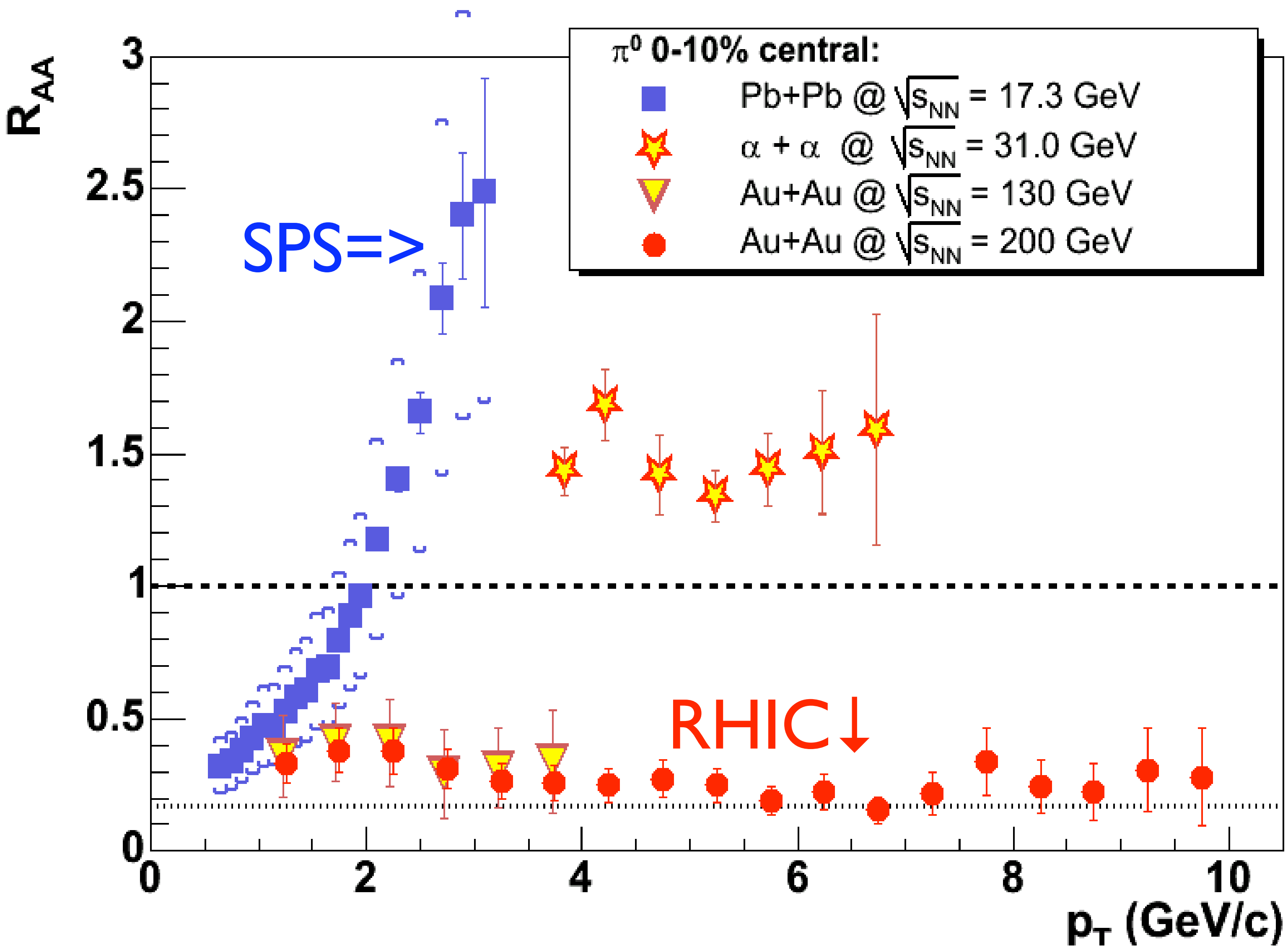
R_AA => *suppression* of hard particles in AA, vs pp.

For p_t> 6 GeV *all* particles suppressed.

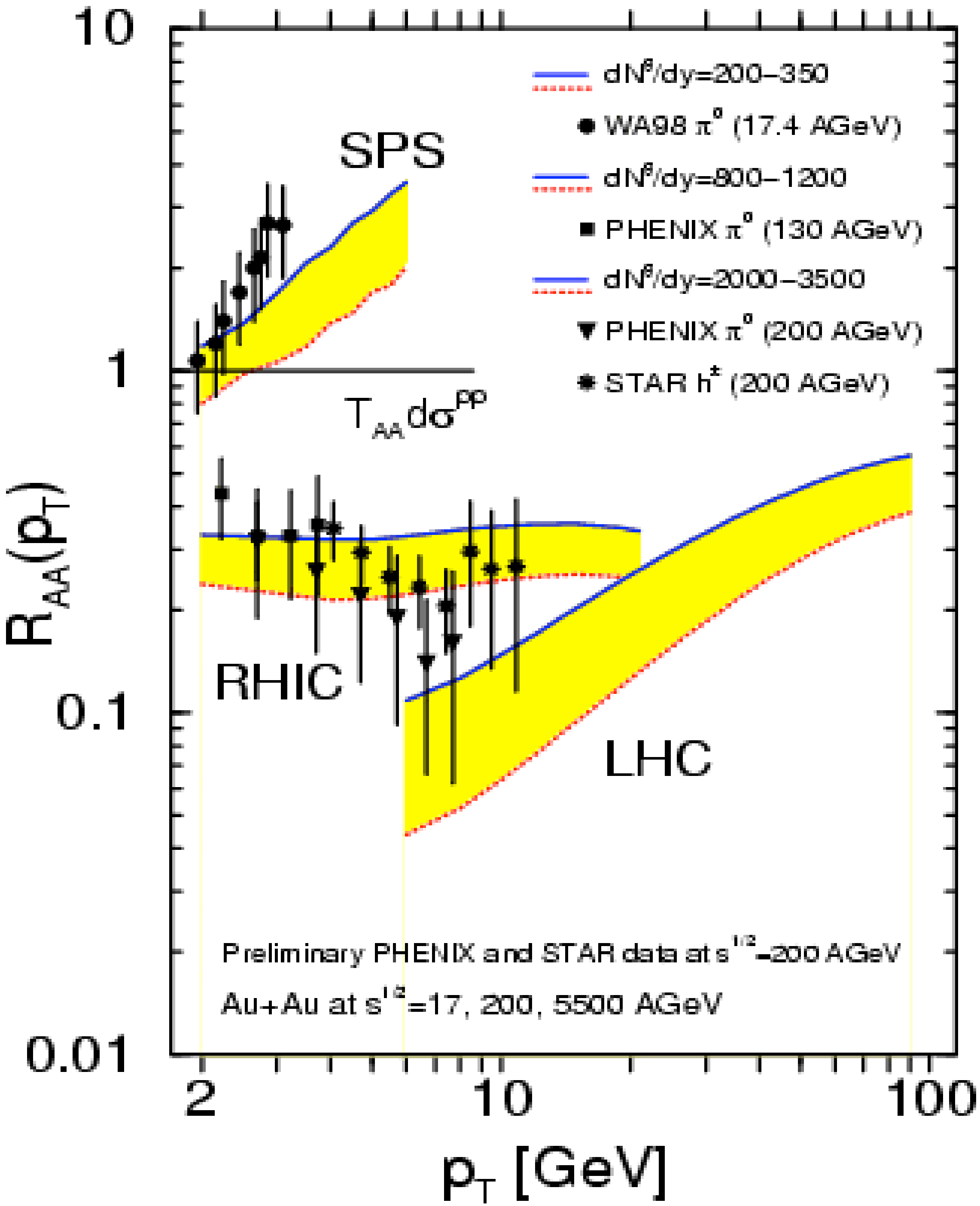
R_AA: *Enchancement* @ SPS, *Suppression* @ RHIC

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:
Gyulassy, X.N. Wang, Vitev...Baier, Dokshitzer, Mueller, Schiff, Zakharov

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

Need to add several effects, “Cronin”, energy loss, shadowing...

Is “flat” R_AA for π^0’s special to RHIC? Will be interesting @ LHC!

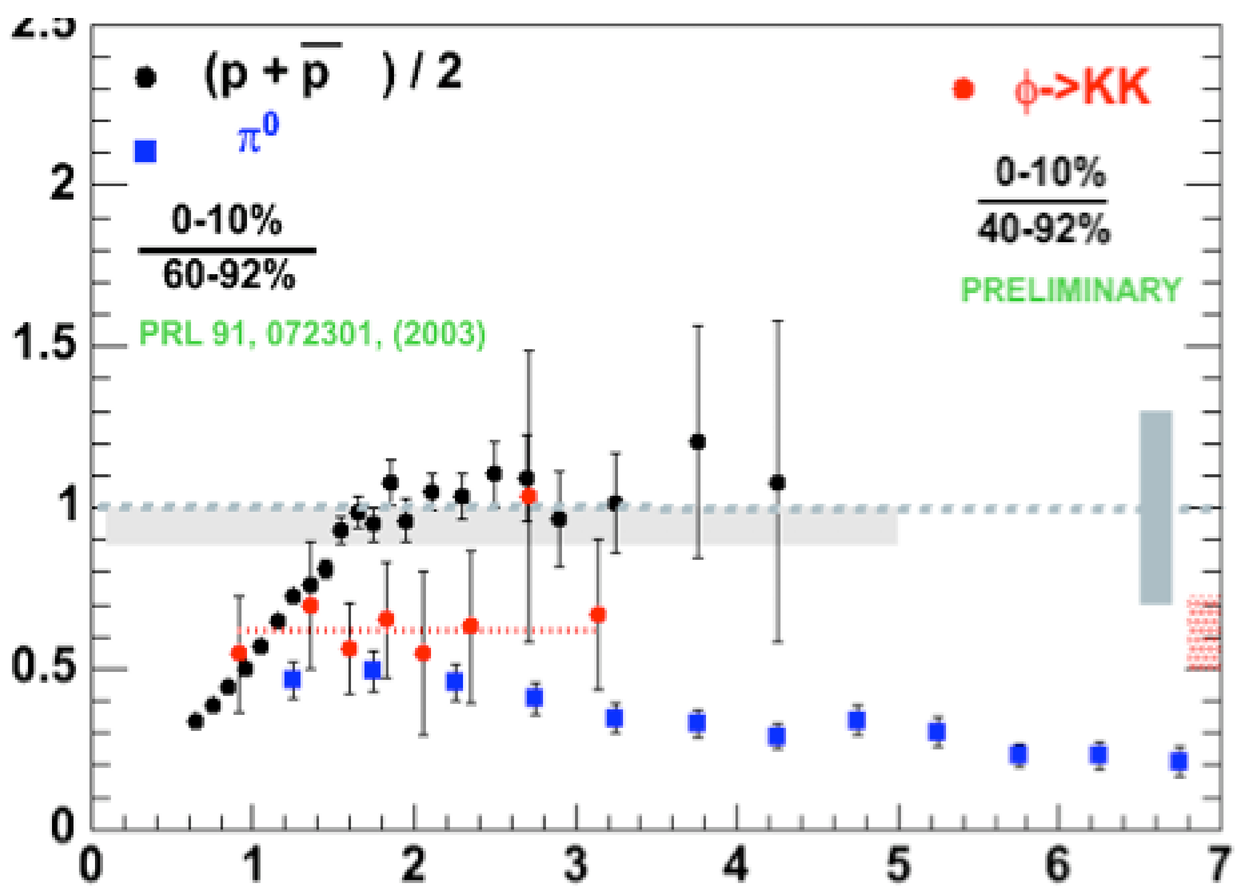
Central AA: at inter. p_t, *only* mesons suppressed

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.

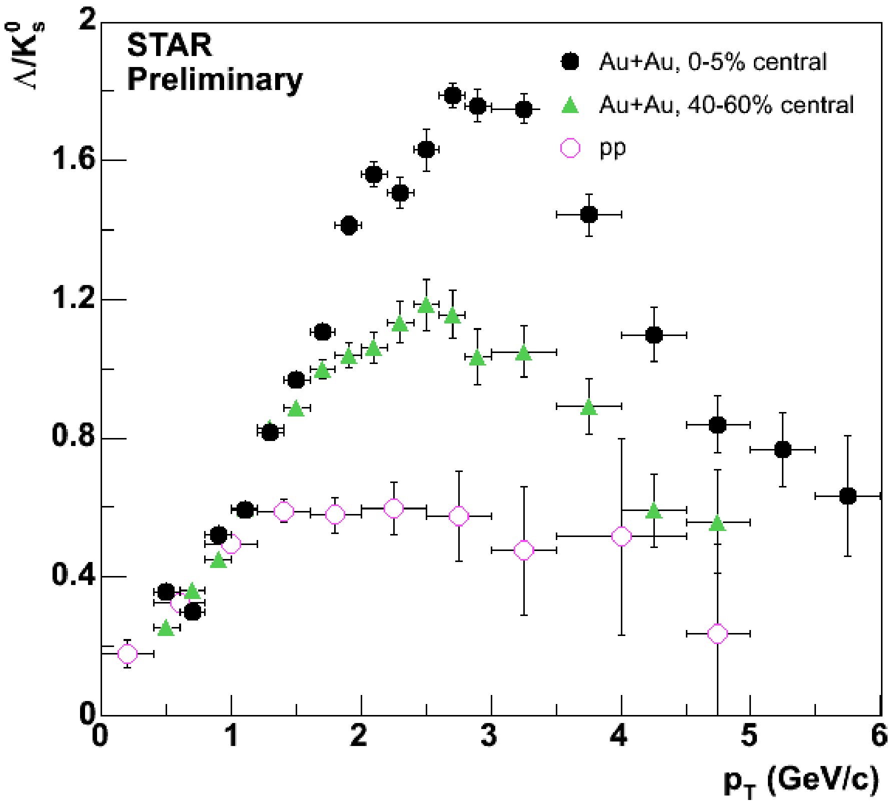
Mesons suppressed => "stuff" is *gluonic.*

R_CP↑



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.

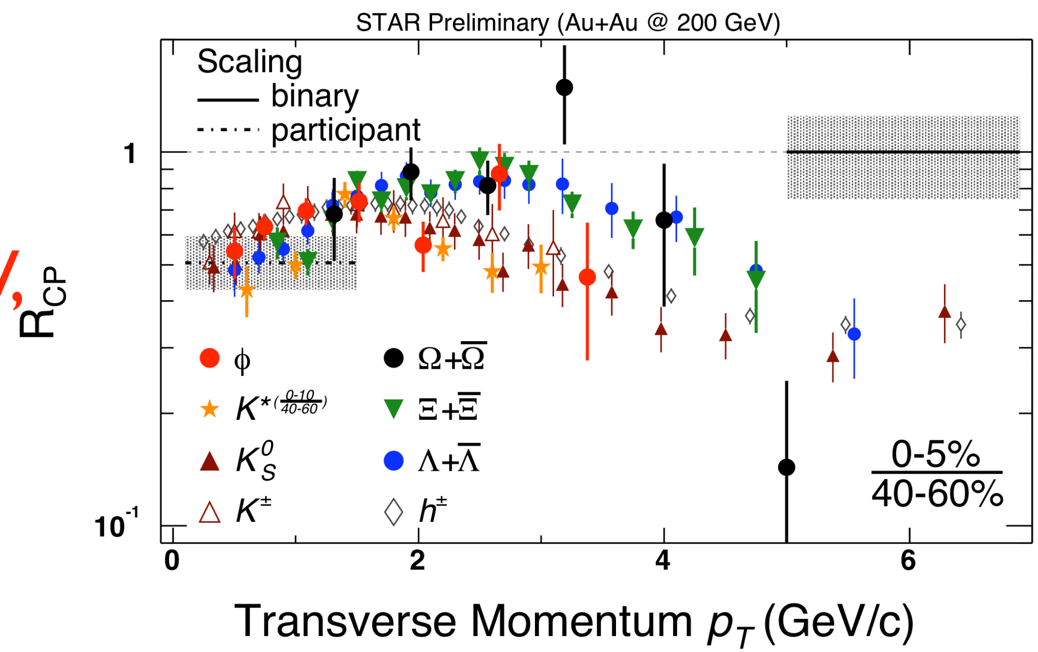
<= Λ/K ratio: bump peaks at ~ 3 GeV.

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"

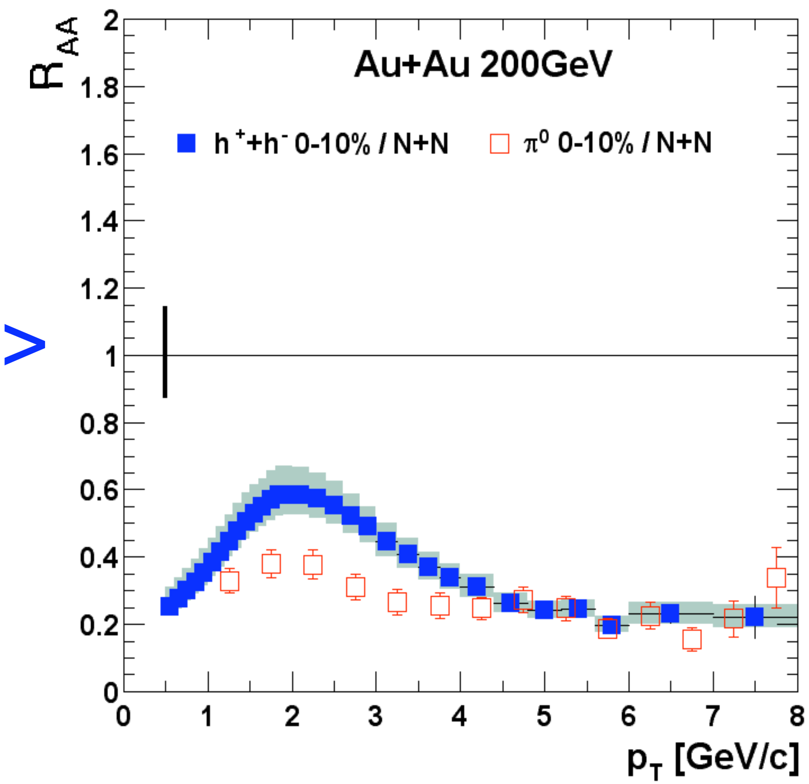


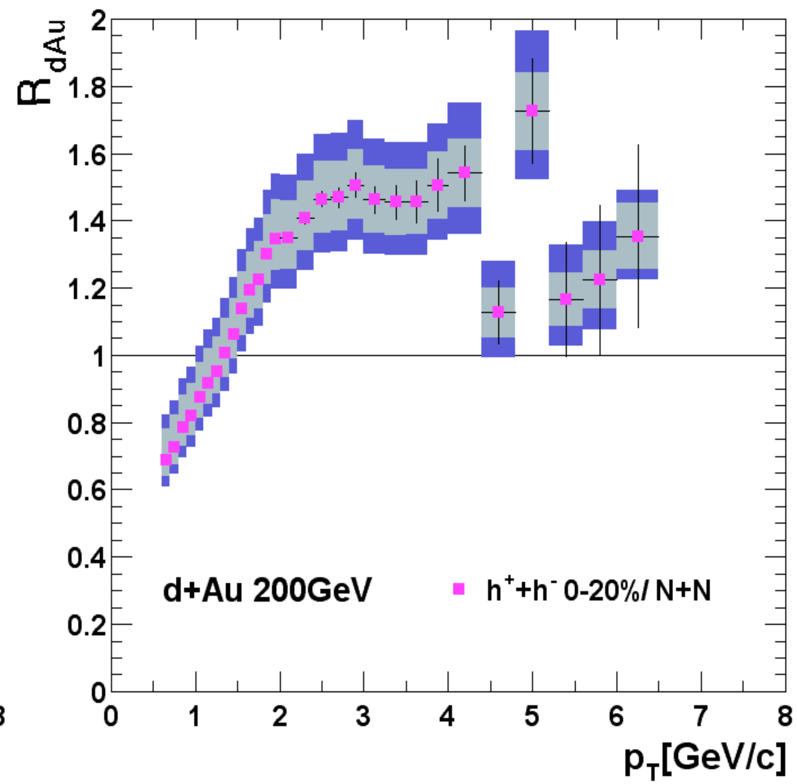
R_AA *Final* State Effect: *NOT* seen in R_dA

Look at R_dA, analogous ratio in dA collisions @ *central rapidity (y=0):*
find "Cronin" enhancement in dA, vs suppression in AA.

Color Glass (initial state effect) predicted suppression in dA, *not* seen.

AA=>





<=dA

Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

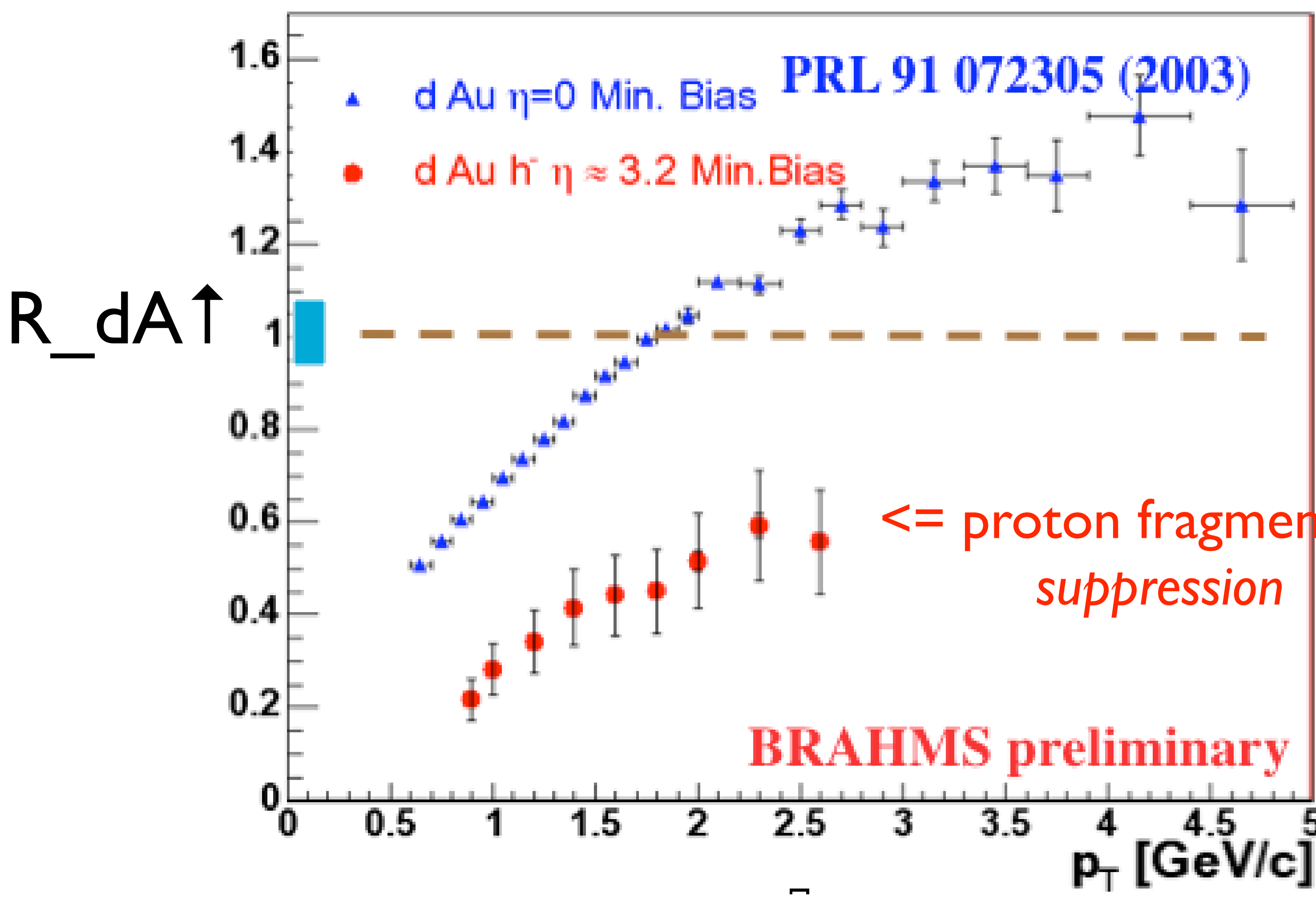
Where to find the Color Glass: dA, by the *proton*

dA: fragmentation region of nucleus tells one about *final* state effects.

frag. region of *proton:* in the proton rest frame, feels the large color charge of the incident nucleus => sensitive to *initial* state effects:

= *the* place to find the Color Glass (Dumitru, Gelis, Jalilian-Marian)

BRAHMS: in dA, *enhancement* @ y=0, *suppression* @ proton frag. region.

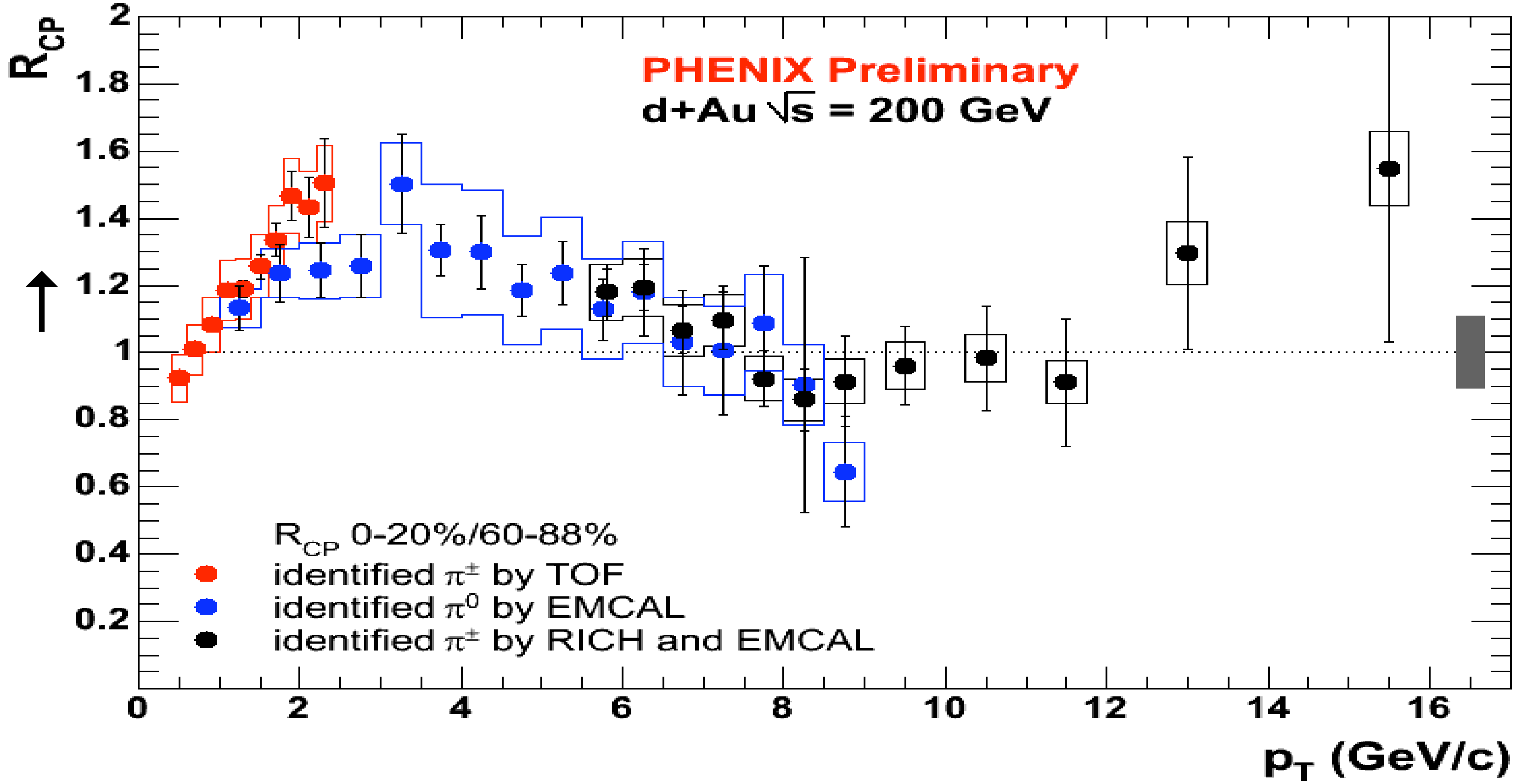


dA: No "Cronin" Enhancement at High p_t

At high p_t, *all* R's (R_AA & R_CP) should go to one.

In dA, seen in R_CP for p_t ~ 8 GeV.

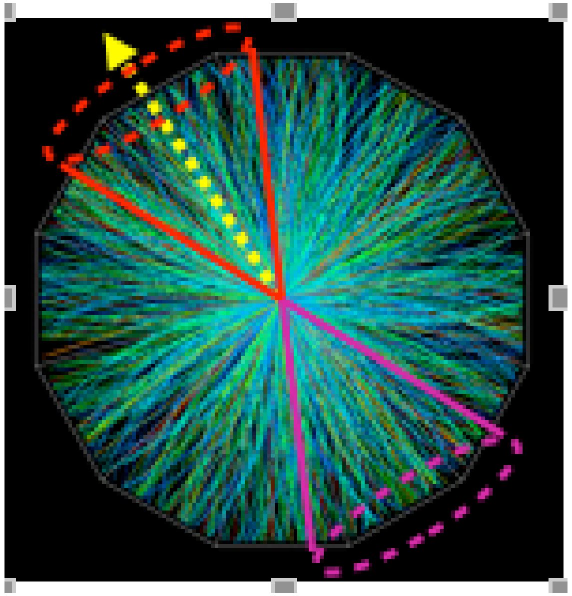
R_CP ↑



p_t=>

At what p_t does R_AA => 1? > 10 GeV!

The "Tail" of the Unicorn: Central AA "*Eats*" Jets

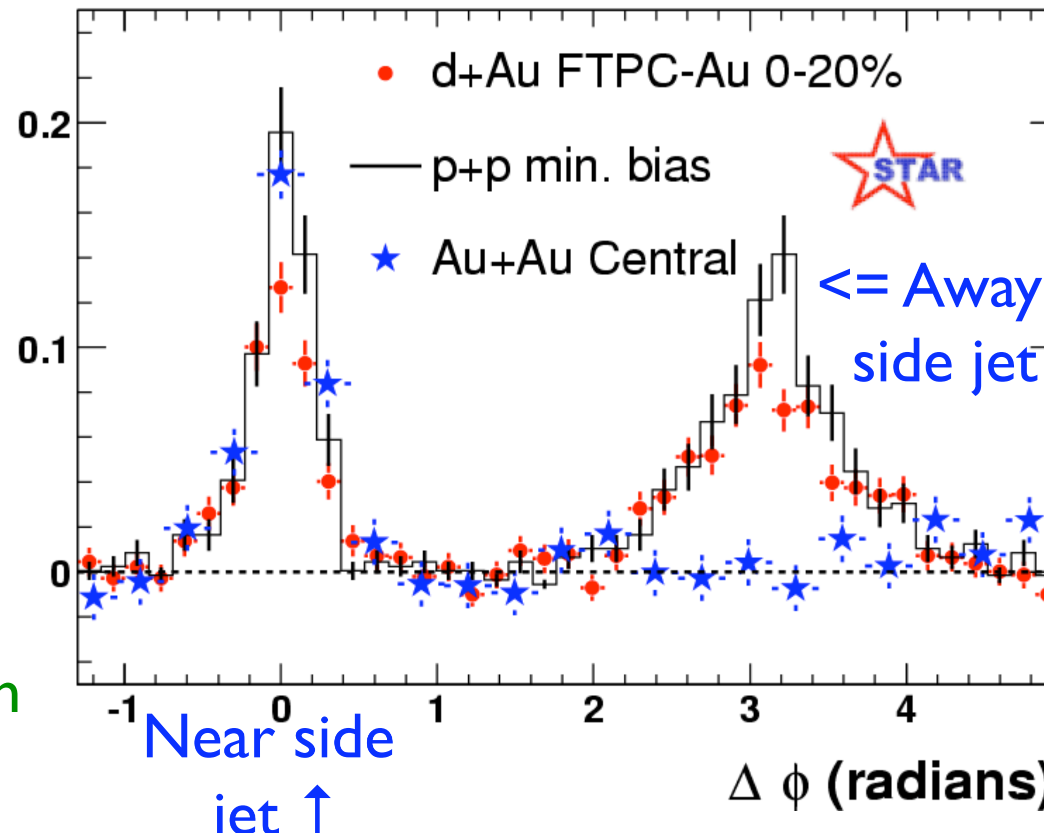


In pp collisions at √s = 130, 200 GeV, clearly see "jets": high energy quarks (& gluons) in each event.
<= "jet" in AA: cannot see on an event by event basis.
In AA, construct statistical measure: trigger on *hard* particle in one direction, look for for *associated* particle in the backward direction
forward: 6>p_t>4 GeV Adams *et al*., Phys. Rev. Let. 91 (2003)
back: p_t> 2

In pp & dA, *clearly* see "backward" peak in angular correlation => associated jet.

In central AA, backward peak is *gone: "stuff" in AA "eats" jets.*

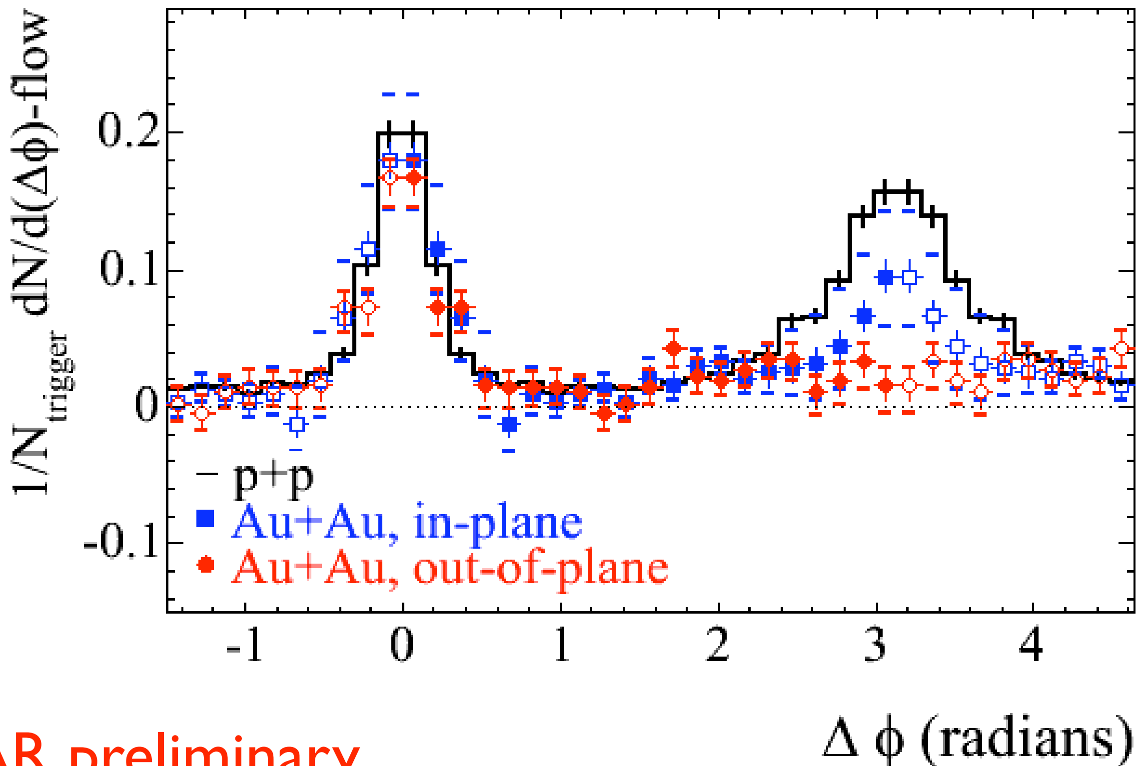
Central AA *really* "eats" the jet: essentially *nothing* at *hard* momentum in the backward direction.



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

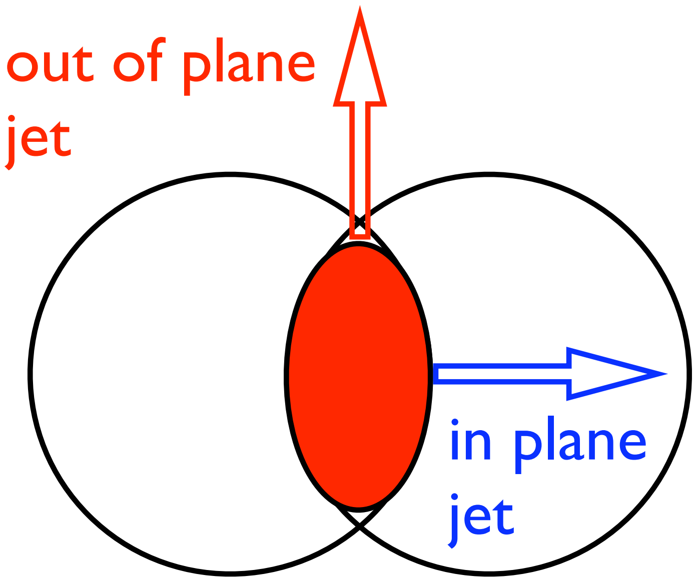
In peripheral collisions, "stuff" forms an "almond"; a jet has to travel farther through the almond, out of the reaction plane, than in the reaction plane.

=> *Geometrical* test that AA *"eats"* jets: backward jet more strongly suppressed out of plane than in plane!



STAR preliminary

Suppression larger out-of-plane



peripheral collision ↑

almond = "stuff"

Where does the Backward Jet go in AA?

As before, trigger on forward jet, 6> p_t > 4 GeV. But look at *all* particles, p_t > .15 GeV, in both forward and backward directions.

In direction opposite to jet, *suppressed* at high p_t (yes), & *enhanced* at low p_t.

In direction *along* jet, *more* particles at low p_t in central AA than pp.

=> "stuff" in central AA shifts backward jet to *low* momentum,

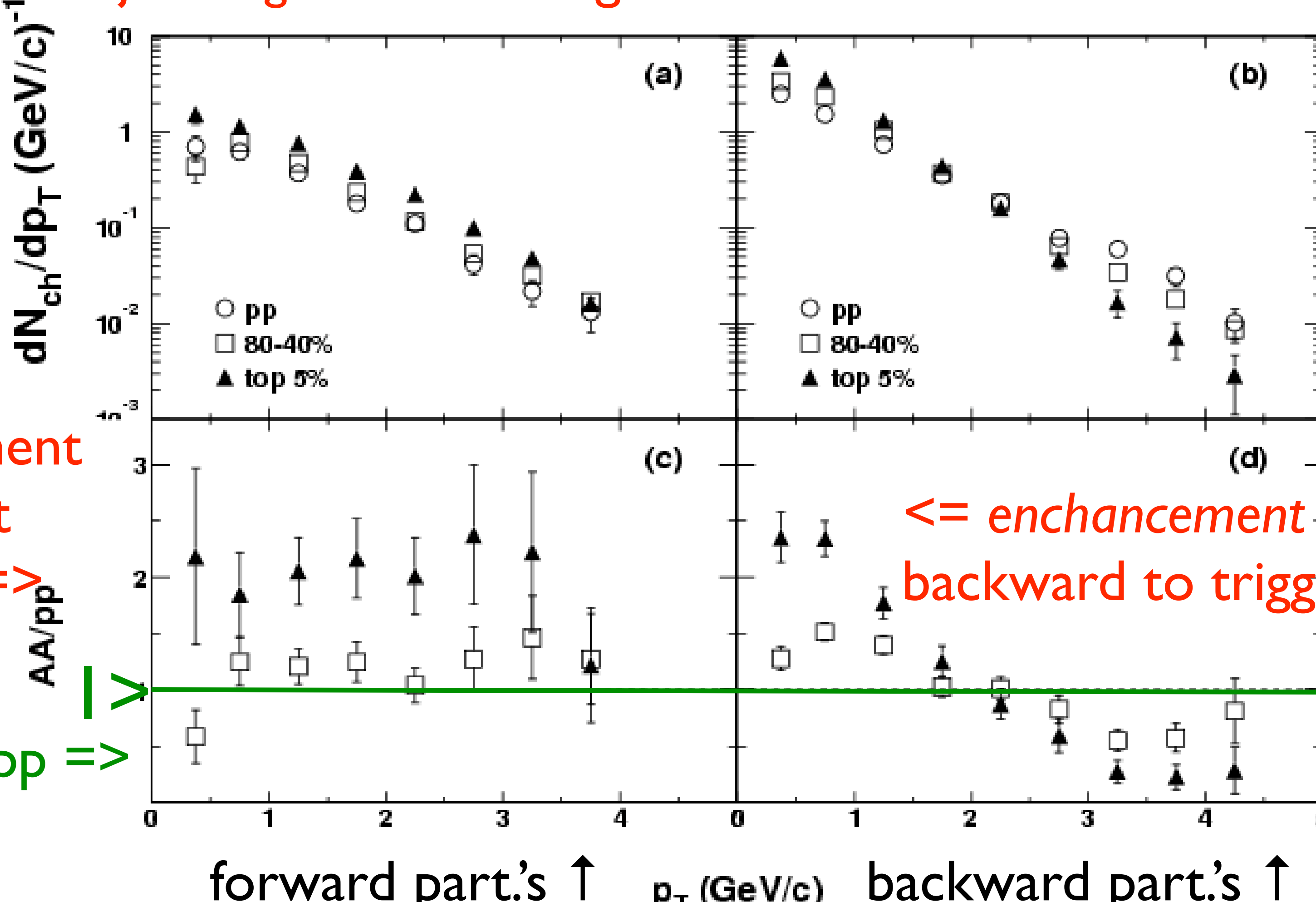
forward jet *drags* "stuff" along with it!

raw => spectra

enhancement at low p_t *along* jet =>

ratio, AA/pp =>

1 >



forward part.'s ↑ backward part.'s ↑

STAR prelim.

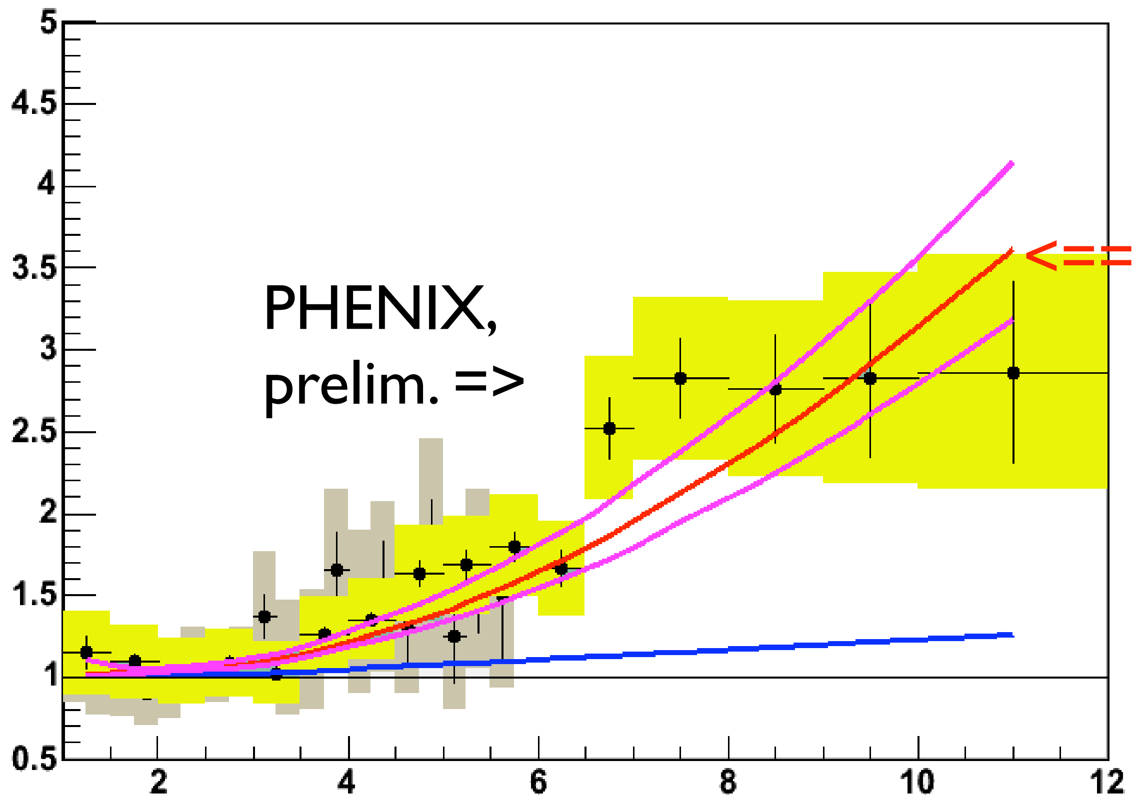
<= *enchancement* at low p_t backward to trigger jet

AA=pp

<=*suppression* at high p_t backward

Direct Photons Measured

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 $p_t \sim 10$ GeV with Next to Leading Order QCD calculation, = pp times # binary collisions.



<=== NLO QCD, Vogelsang...

<= signal c/o π suppression

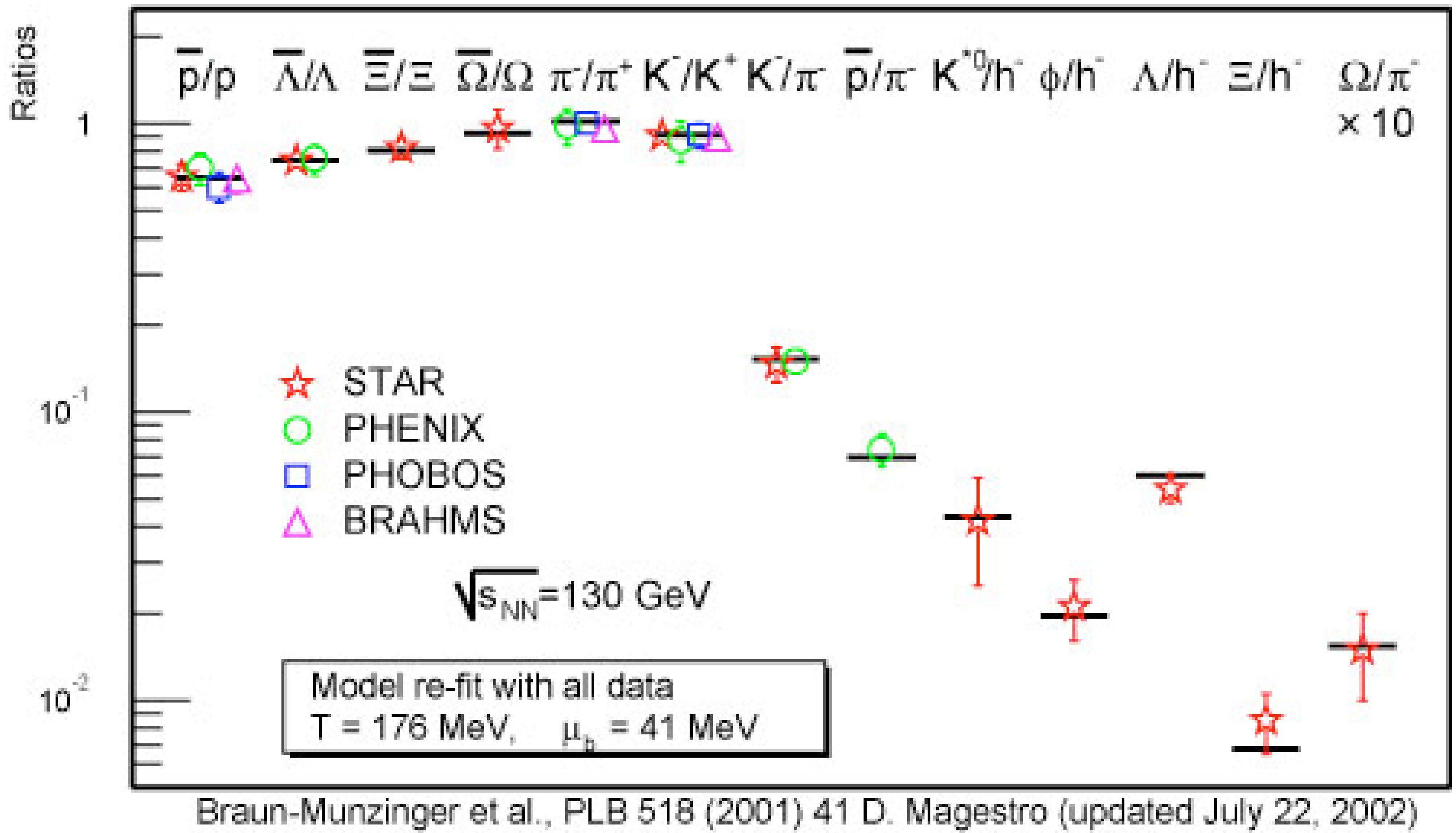
p_t (GeV)=> 10

The "Body" of the Unicorn: Soft Momenta, pt < 2 GeV

Most particles are at soft momentum.
With Tc ~ 200 MeV, *expect* thermal particle distributions to p_t ~ 2 GeV.
Thousands of particles, should be able to use hydrodynamics...

Total Chemical Ratios *Appear* in Thermal Equilibrium

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



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

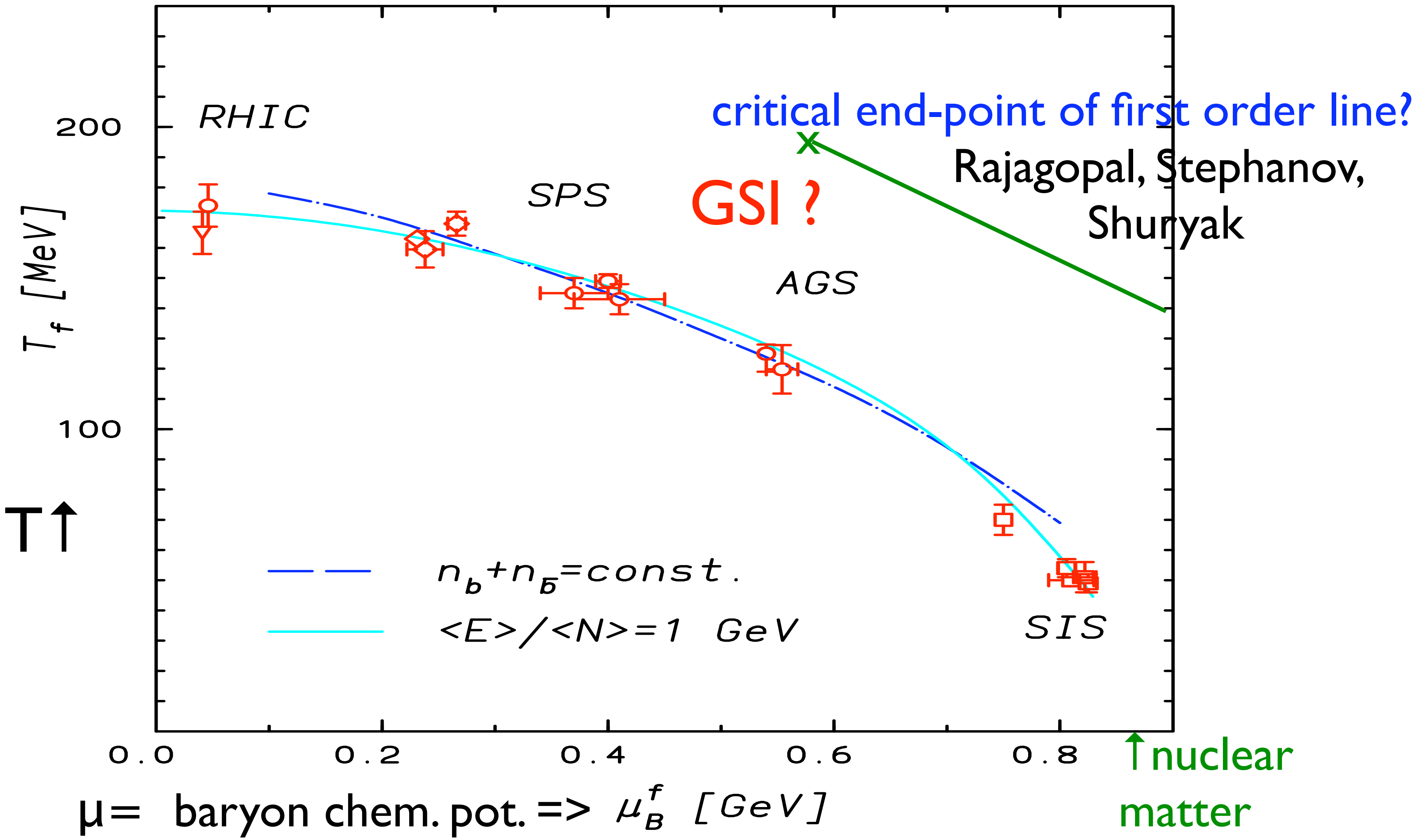
N.B.: even for multi-strange baryons, with relative abundances ~.1% of pions.

Chemical Ratios vs Energy in AA: T-μ plane

Similar fits for chemical abundances also work at lower energies. Baryons still present at y=0, so need to add baryon chemical potential, μ.

Find *line* in T-μ plane. Similar fits work for pA, pp - *everywhere!*

(With corr.'s for finite vol., canonical ensemble...) => *NOT* conclusive.



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

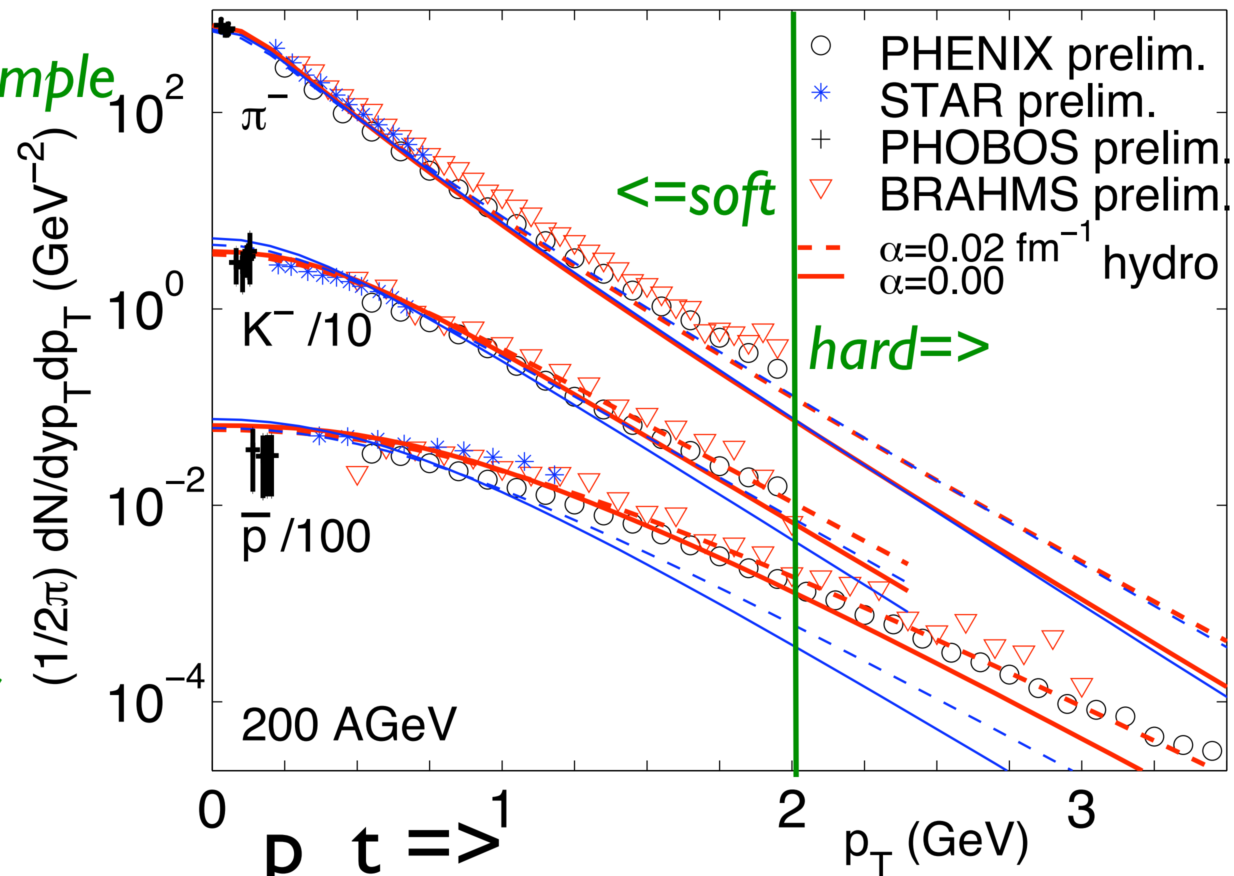
$T_{kin} \approx 100 MeV (\ll T_{ch}!)$ *Local* Boost Velocity $\beta \sim .7c$

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!
Direct fits similar: "Blast-wave"

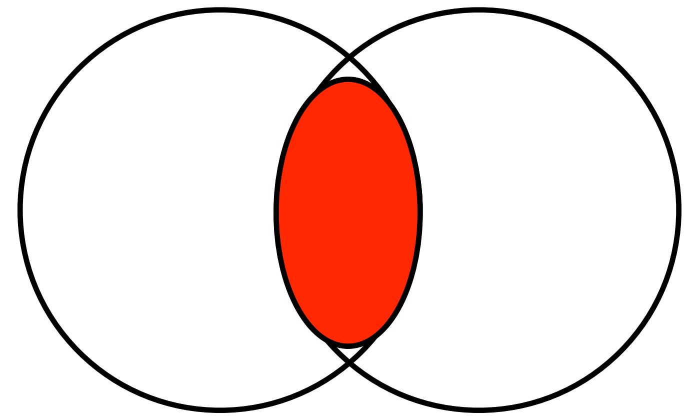


Hydro *needs* to assume applicable from *very* early times, .6 fm/c!

Heinz, Hirano, Kolb, Rapp, Shuryak, Teaney... (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)



$\uparrow y$

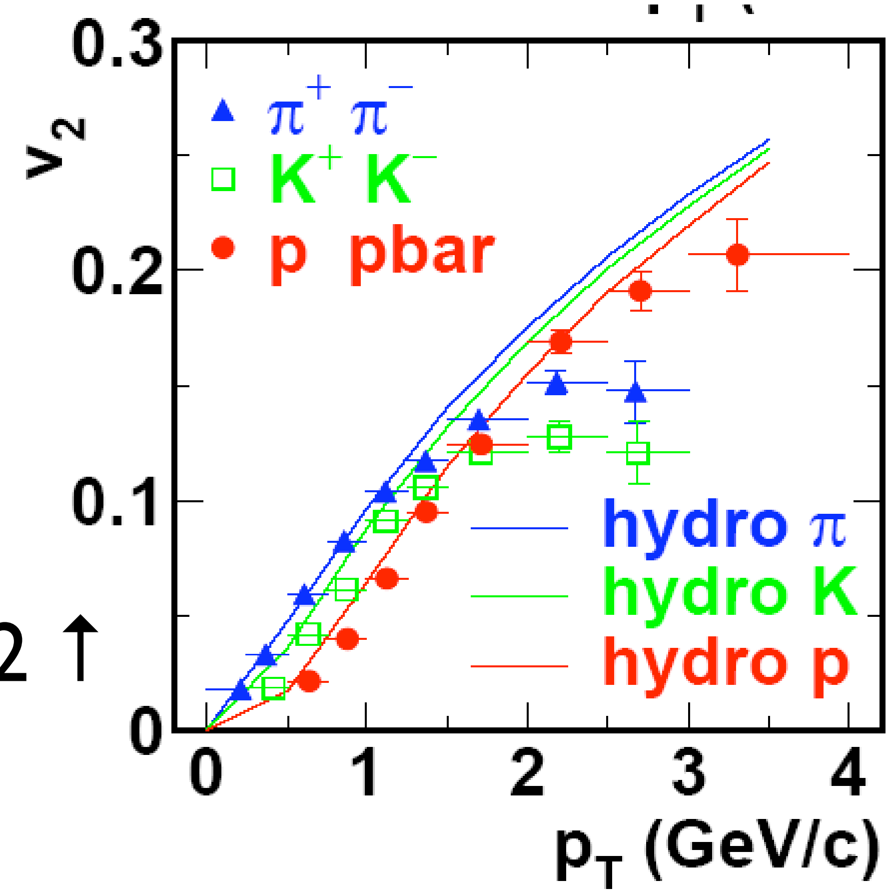
$\rightarrow x$

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

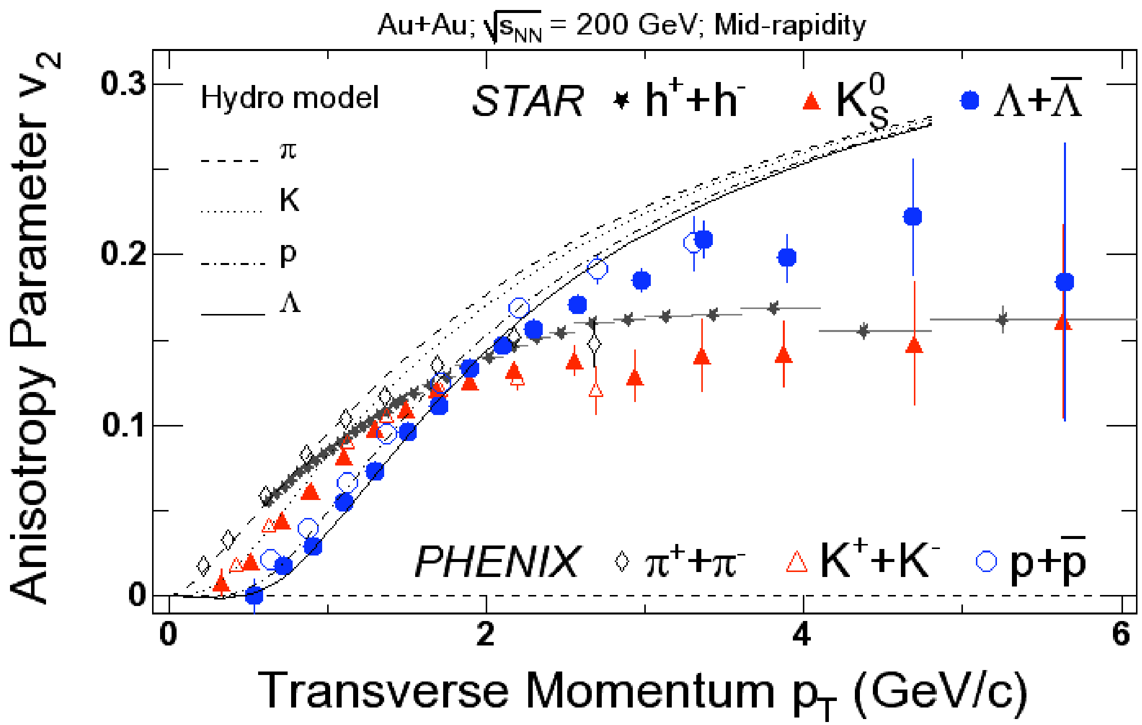
v2 => collective behavior:
there is "stuff", and it sticks.

Hydro works for v2 @ RHIC, not SPS.

v_2 ↑



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

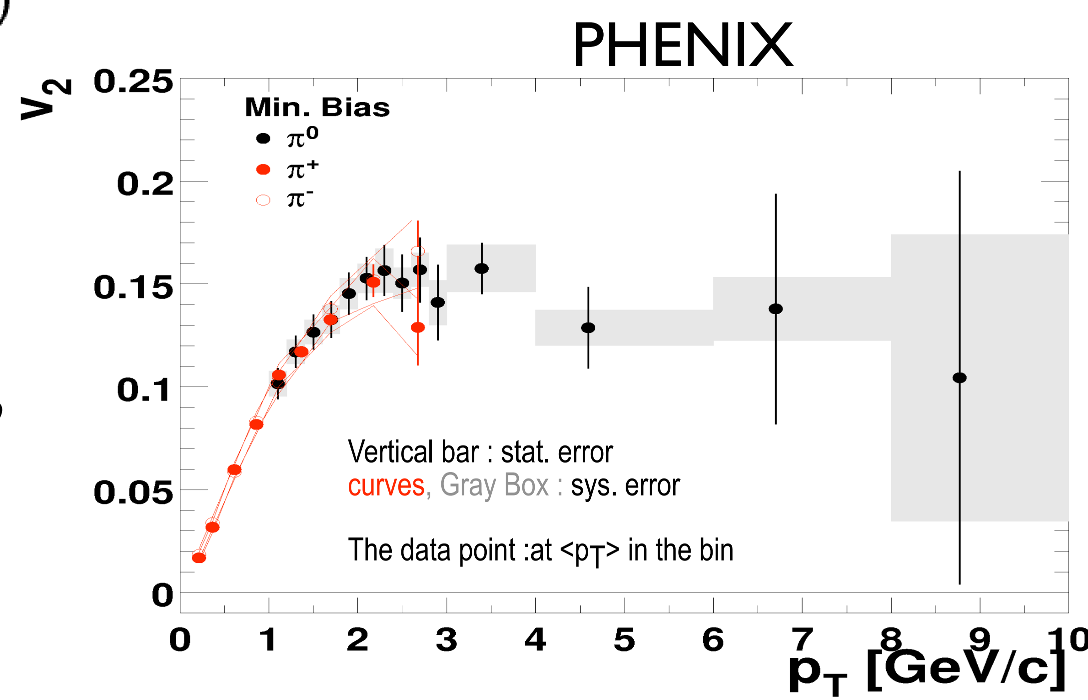


<= Hydro works for v_2
to p_t ~ 1 GeV for
π's, K's, p's, Λ's…. *everything.*

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

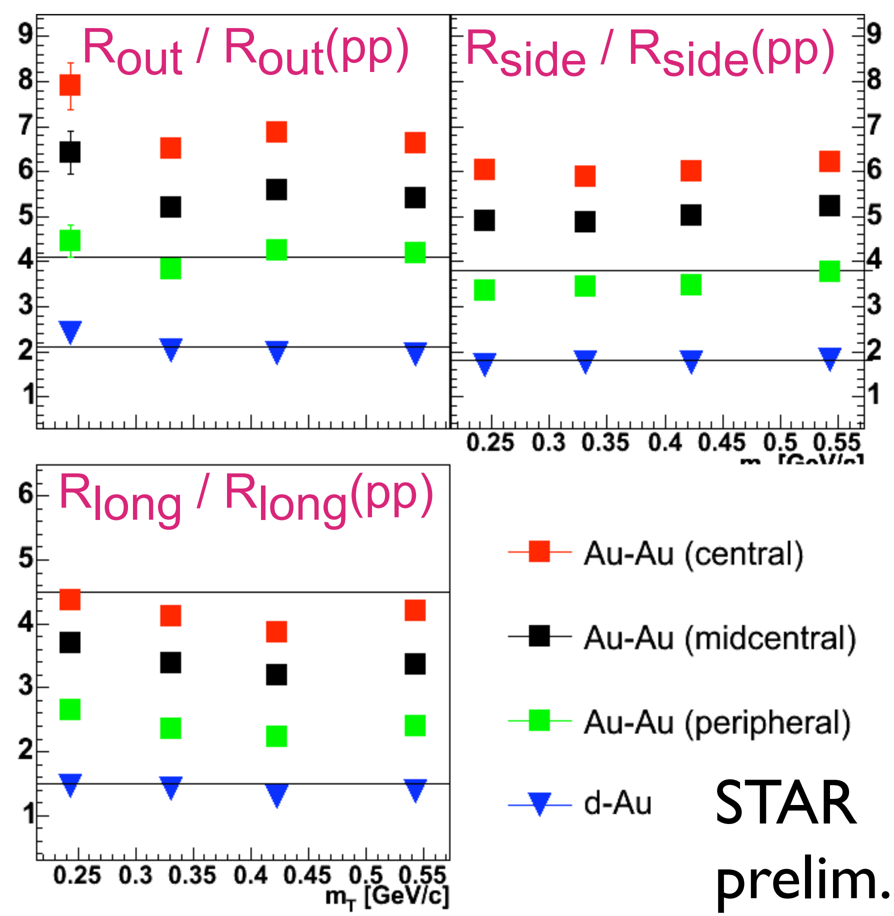
Hanbury-Brown-Twiss (HBT) radii: two-particle correlations for identical particles, used to determine size (as for stars). Typically: fall off like Gaussian.

Here: *three* directions for momentum of pion pair (Bertsch & Pratt).
HBT then gives three sizes: along beam (R_longitudinal), along line of sight (R_out), & perpendicular to light of sight (R_side).

Hydro: R_out/R_side > 1, *increases* with p_t.
Exp.: R_out/R_side ~ 1, *decreases* with p_t!

"Blast Wave" works: expanding shell.
Is a *fit*, not underlying space-time picture.

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



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

New final state effects:

R_{AA}

Suppression of backward jets

Also: new initial state effects,

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?

p_t fluctuations at *low* p_t

Perhaps: it is a different beast....

But its still a *NEW* beast!

"A possible eureka."