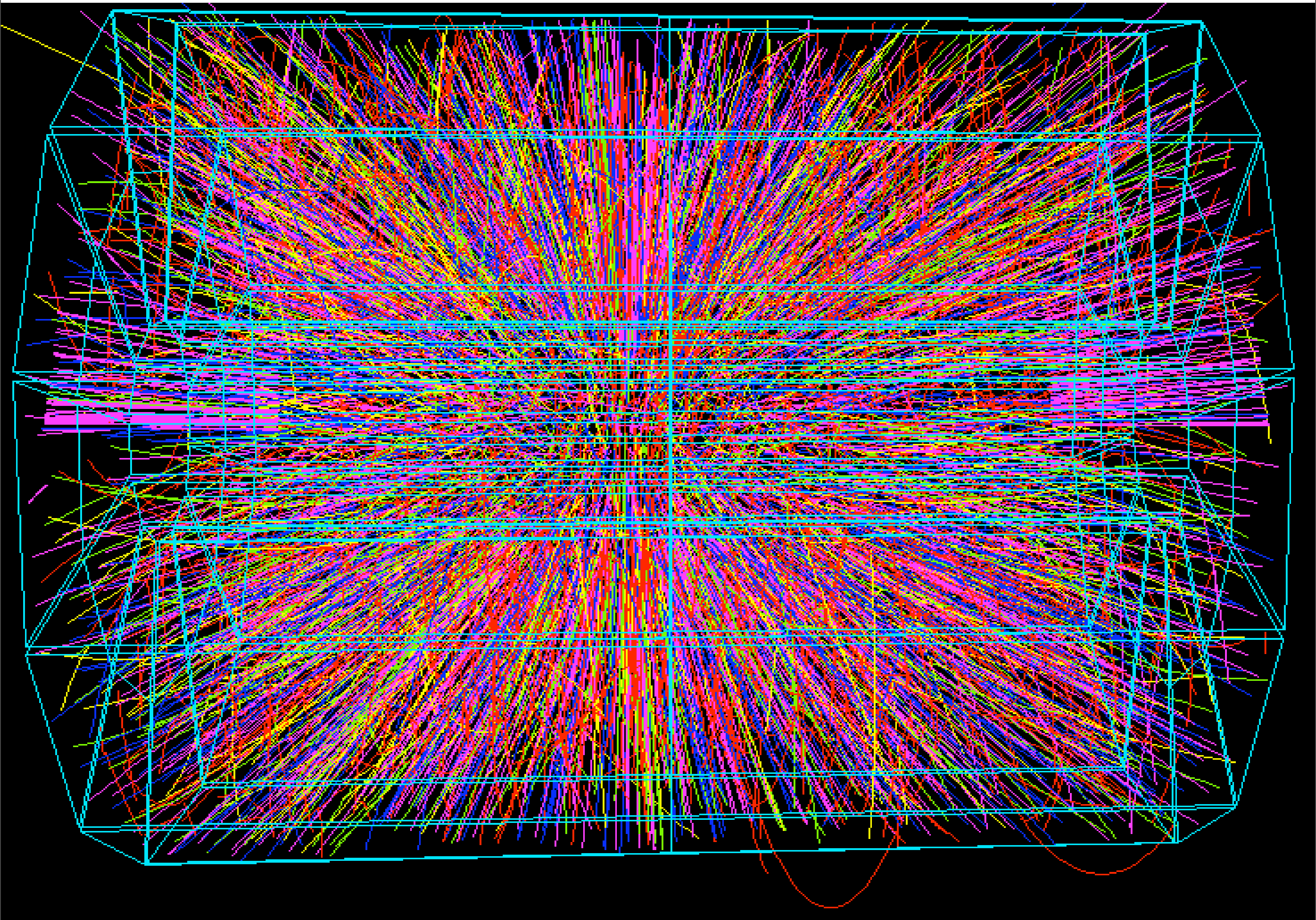


Heavy Ions at RHIC: an Experimental Cornucopia

Collisions of heavy ions at high energies:

AGS at Brookhaven, SPS at CERN

Relativistic Heavy Ion Collider (RHIC) at Brookhaven

Large Hadron Collider (LHC) at CERN

Wealth of results: for large nuclei, with atomic number A ~ 200,

"Central" AA collisions are *very* unlike A * proton-proton collision

Several *robust* signals for new "stuff": but *what* stuff?

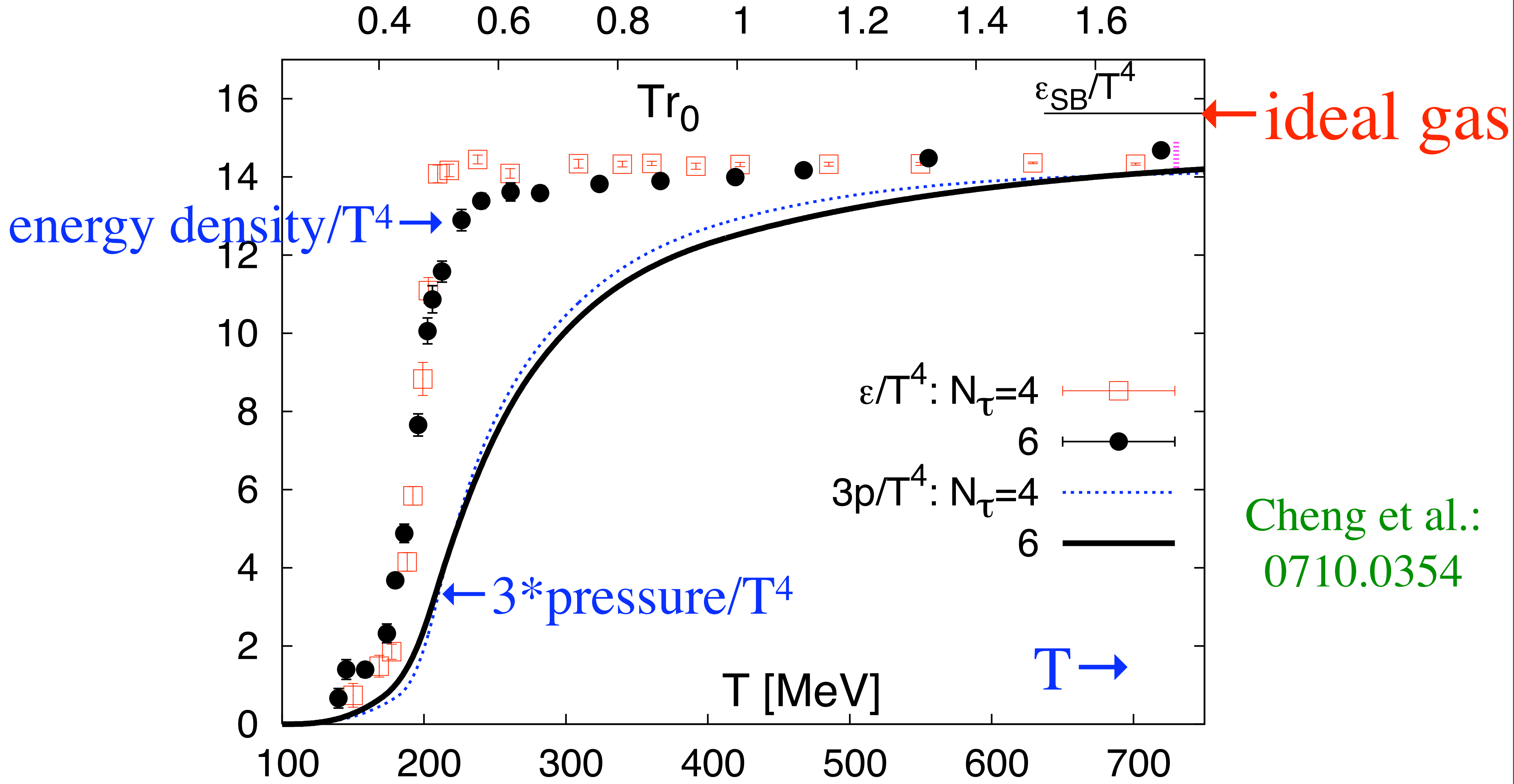
A Quark-Gluon Plasma (QGP)? *Not* the QGP we expected...

Golden age for *experimental* HE Nuclear Physics

Theorists awash in data, a "horn of plenty" =>

Lattice simulations *essential*

Lattice: Quark-Gluon Plasma, in equilibrium



Lattice simulations at temperature T: "T_c" ~ 150 - 200 MeV. (C. DeTar, Monday)

No true phase transition, only crossover.

Equilibrium thermodynamics is *not* all one needs! (H. Meyer, following)

Outline

Basics of Heavy Ion Collisions: central plateau, peripheral collisions

SPS: J/ψ suppression, excess dileptons

RHIC:

Soft particles: hydrodynamics & "elliptic flow" => *small* shear viscosity
Hard particles: R_{AA} & "jet" suppression
Electromagnetic signals: J/ψ suppression, excess dileptons & photons

Clear evidence for collective behavior of "stuff".

But: Heavy quarks "flow", "suppressed" ~ *same* as light quarks: *weird*

Not a perturbative QGP: maybe a "s"QGP?
"s" = strong: AdS/CFT and QCD
"s" = semi: partial deconfinement

The sQGP at the LHC?

Hunt for the Quark Gluon Plasma

QGP as a “Unicorn”. Experimentalists as hunters,
so (in *this* field), “All theorists are...”

Basics of Heavy Ion Collisions at High Energies

Central plateau in rapidity

Central vs. peripheral collisions

AA collisions at high energies

Collide:

AA, nuclei on nuclei. Atomic # "A": 60 => 200, Cu -> Au. "Hot" nuclei.

pp, protons on protons. Benchmark for "ordinary" QCD.

dA, deuteron on nucleus. QCD in "cold" nuclei

Why AA? A ~ 200, linear size $A^{1/3} \sim 6$. Transverse area $A^{2/3} \sim 36$.

Total energy in the center of mass, per nucleon, $\sqrt{s}/A = \sqrt{s_{NN}}$

AGS@BNL => 5 GeV

SPS @ CERN 5 => 17 GeV

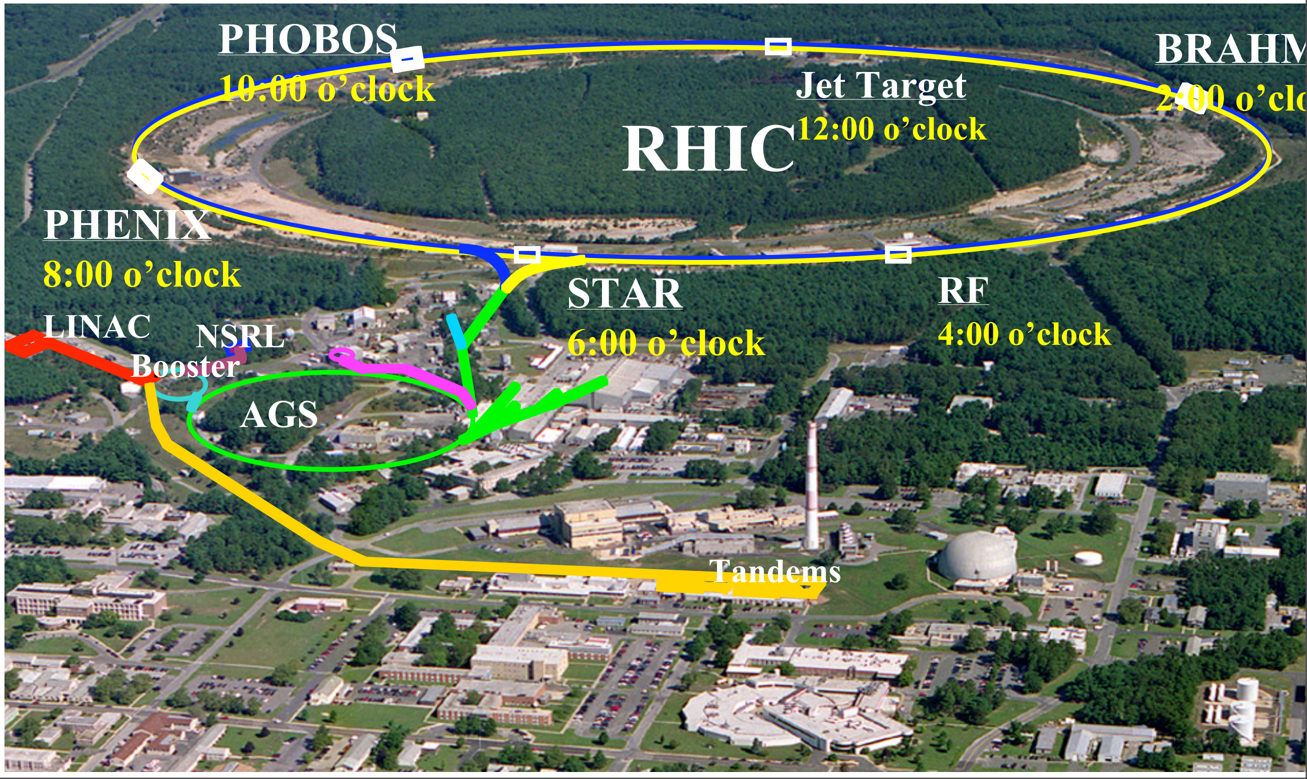
RHIC @ BNL 20 => 200 GeV

LHC @ CERN 5500 GeV

AGS, SPS Fixed Target

RHIC, LHC Colliders

LHC > '09



Geometry of AA collisions, "central plateau"

Momenta of produced particles: along beam, p_z; transverse to beam, p_t

At high energy, no "stopping": original nuclei go *down* beam pipe, at *large* $\pm p_z$

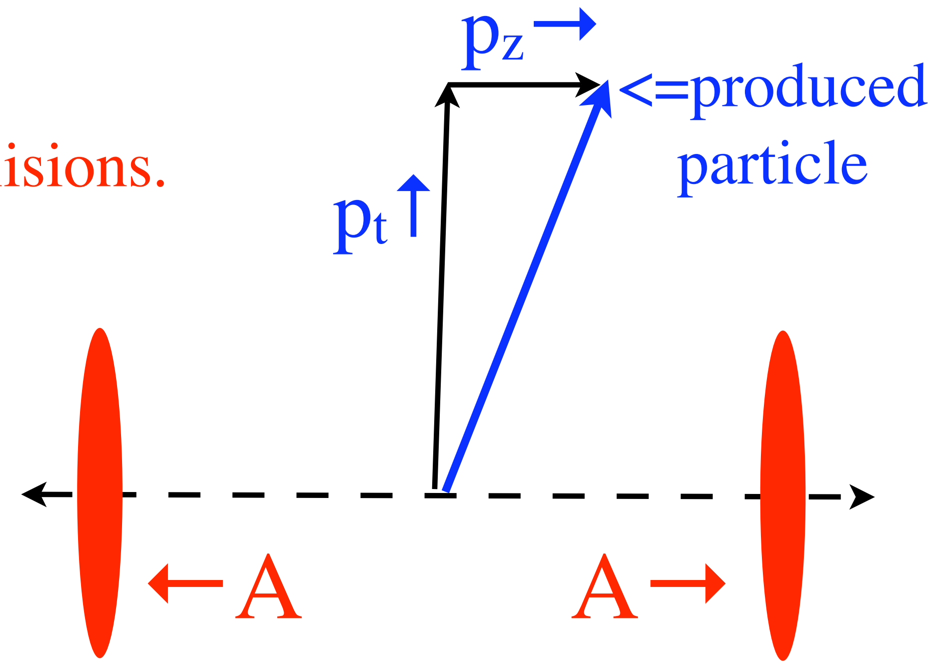
Instead of p_z, use rapidity $y = 1/2 \log((E+p_z)/(E-p_z))$

For pp collisions at high $\sqrt{s}$: # particles, etc.
~ constant in y about zero rapidity, y = 0: "central plateau"

(Collider: $y = p_z = 0$ is 90° to beam)

Bjorken '83: look at central plateau in AA collisions.

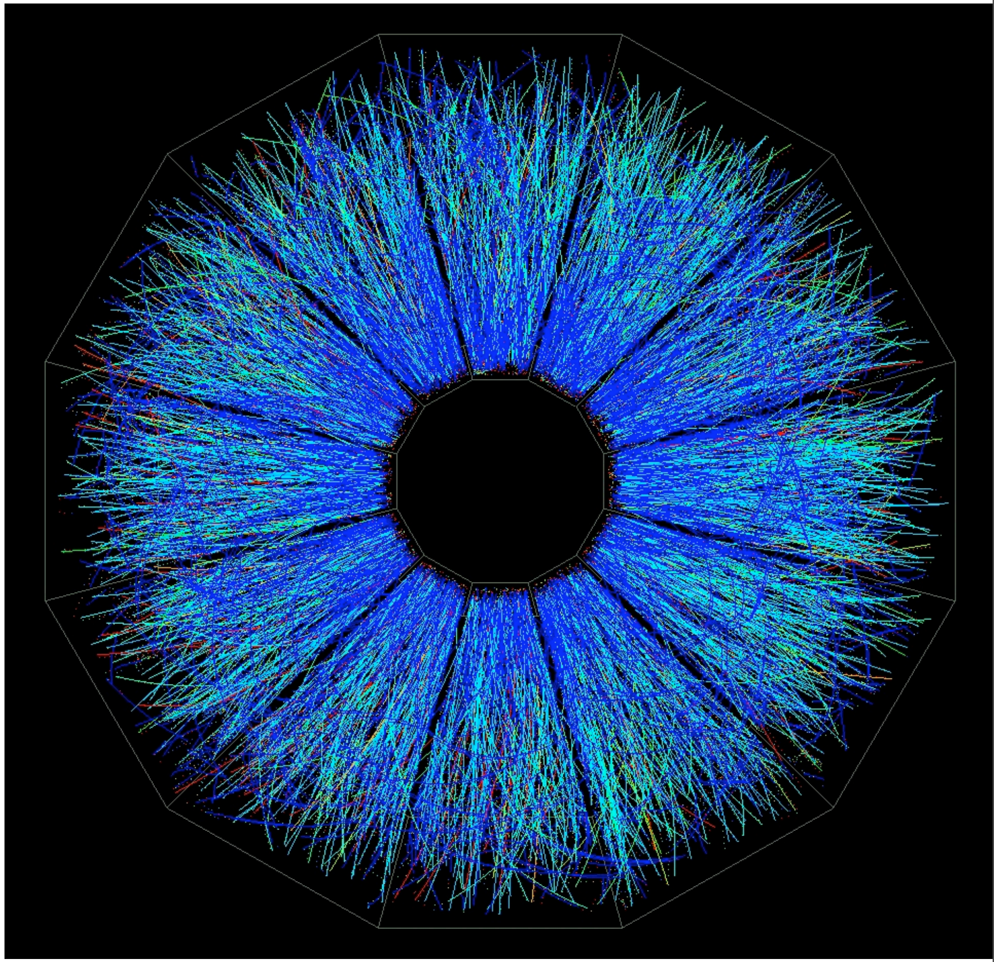
Central plateau ~ *free* of incident baryons.
=> most likely to be at nonzero temperature,
zero (quark) density.



Au-Au collisions @ RHIC: *low* multiplicity

Total # particles/unit rapidity ~ 900 (A ~ 200)

~ 1.30 × A × (# particles/unit y) in pp
Not much entropy generated.



Experiments @ RHIC:
“Big”: ~ 400 people.
STAR & PHENIX
“Small”: ~ 50 people.
PHOBOS & BRAHMS

total # particles ~ total # experimentalists
~ log(total energy)
# theorists ~ log(log(total energy)).
(Need hunters more than...)

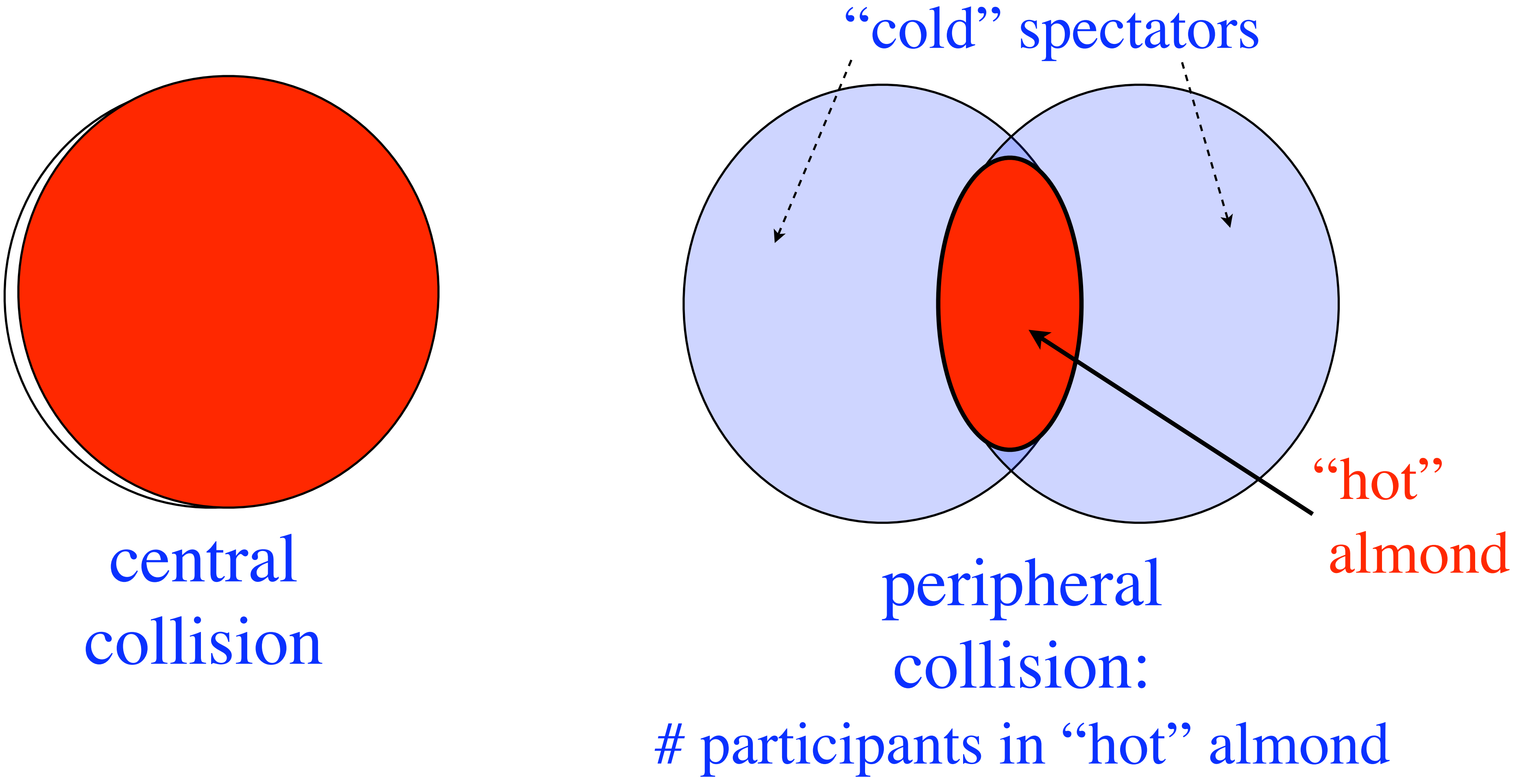
Narrow central plateau first arises at RHIC:
dN/dy and <p_t> constant over ± .5 in y, out of ± 5.0 (STAR & BRAHMS)

Central vs peripheral collisions

Nuclei overlap completely: central collision (Beam *into* the plane)

Nuclei overlap partially ("almond"): peripheral collision

Exp.'y, can determine # *participants* when > 100; maximum 400 for A ~ 200



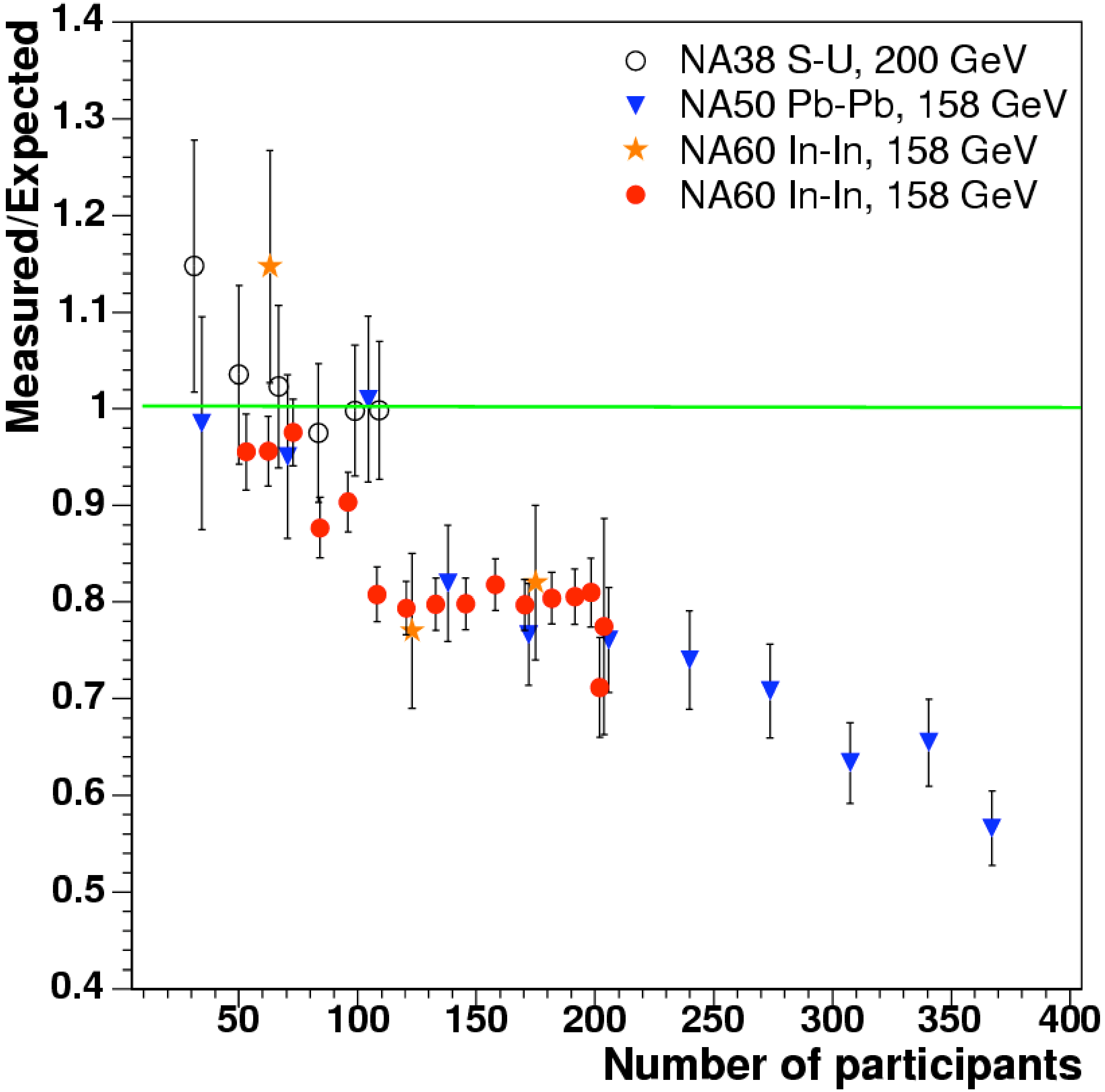
AA collisions at SPS: J/ψ suppression, dileptons

SPS: NA50, NA60 J/ψ suppression

J/ψ measured/ expected↑

J/ψ suppressed when "number of participants" is > 100.

J/ψ can be suppressed by "hadronic" co-movers, but requires *high* density.



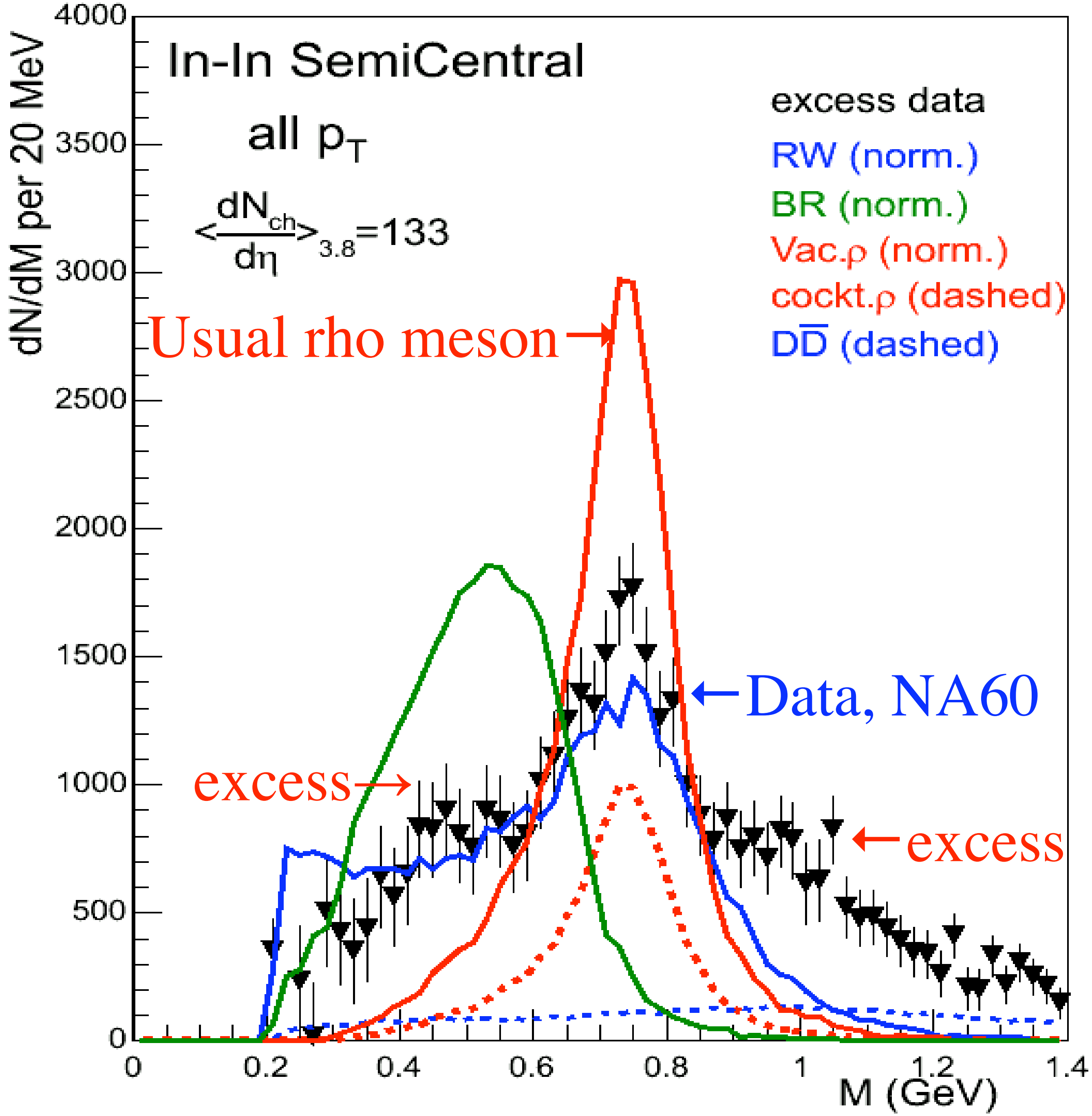
participants →

SPS: Dileptons from NA60

NA60: excess in dileptons both below, and above, the ρ meson.

Central peak of the ρ meson is *not* shifted.

Thermal broadening of ρ meson?



RHIC: Soft particles

Most particles at *small* momenta, $p_t < 2$ GeV.

Body of the "Unicorn"

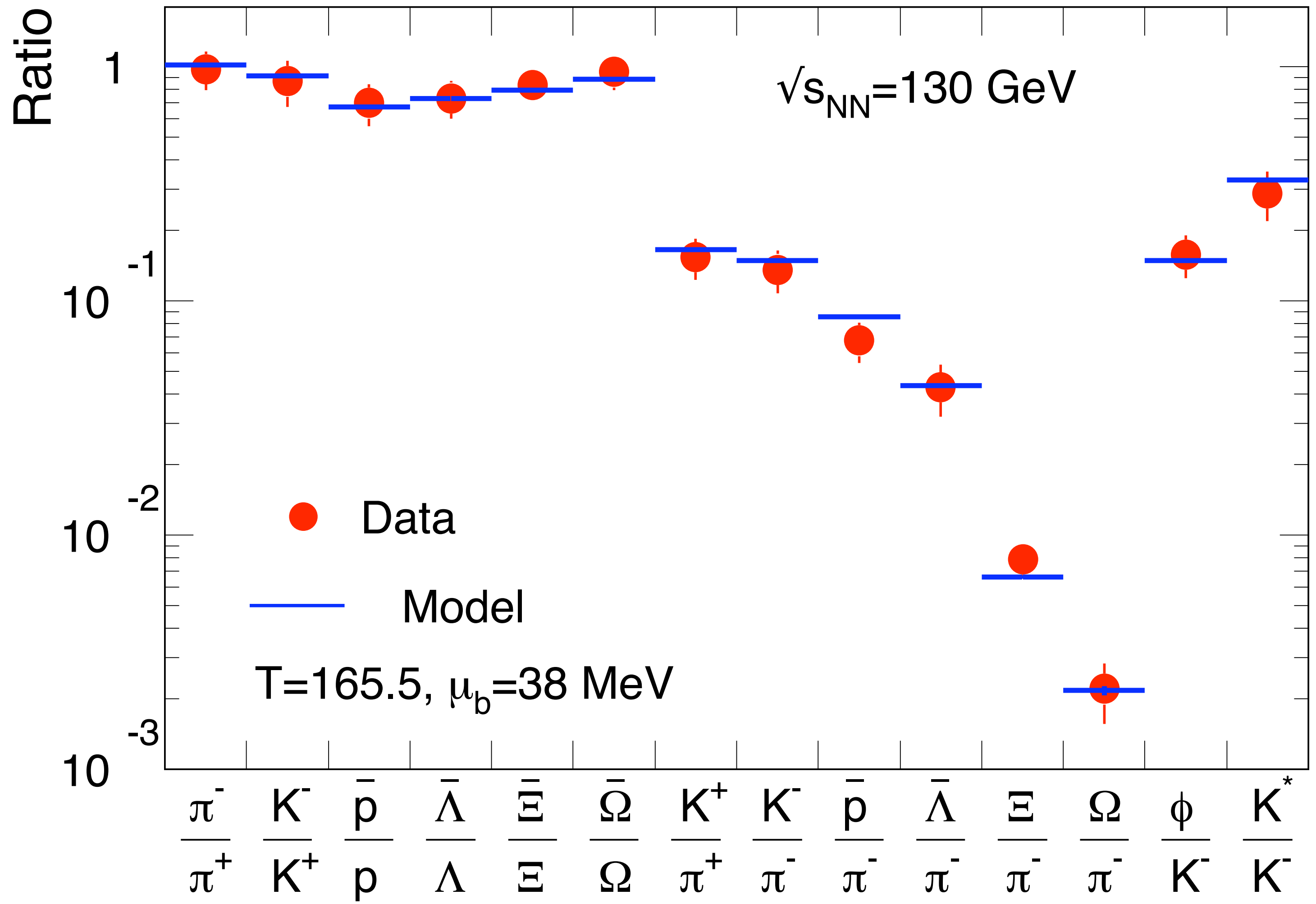
Chemical equilibrium?

Hydrodynamics & elliptical "flow"

Small shear viscosity

Heavy quarks "flow" ~ *same* as light quarks!

Total abundances: chemical equilibrium?



Andronic,
Braun-Munziger,
&
Stachel
nucl-th/0511071

χ^2/# d.o.f. = 4.1/11

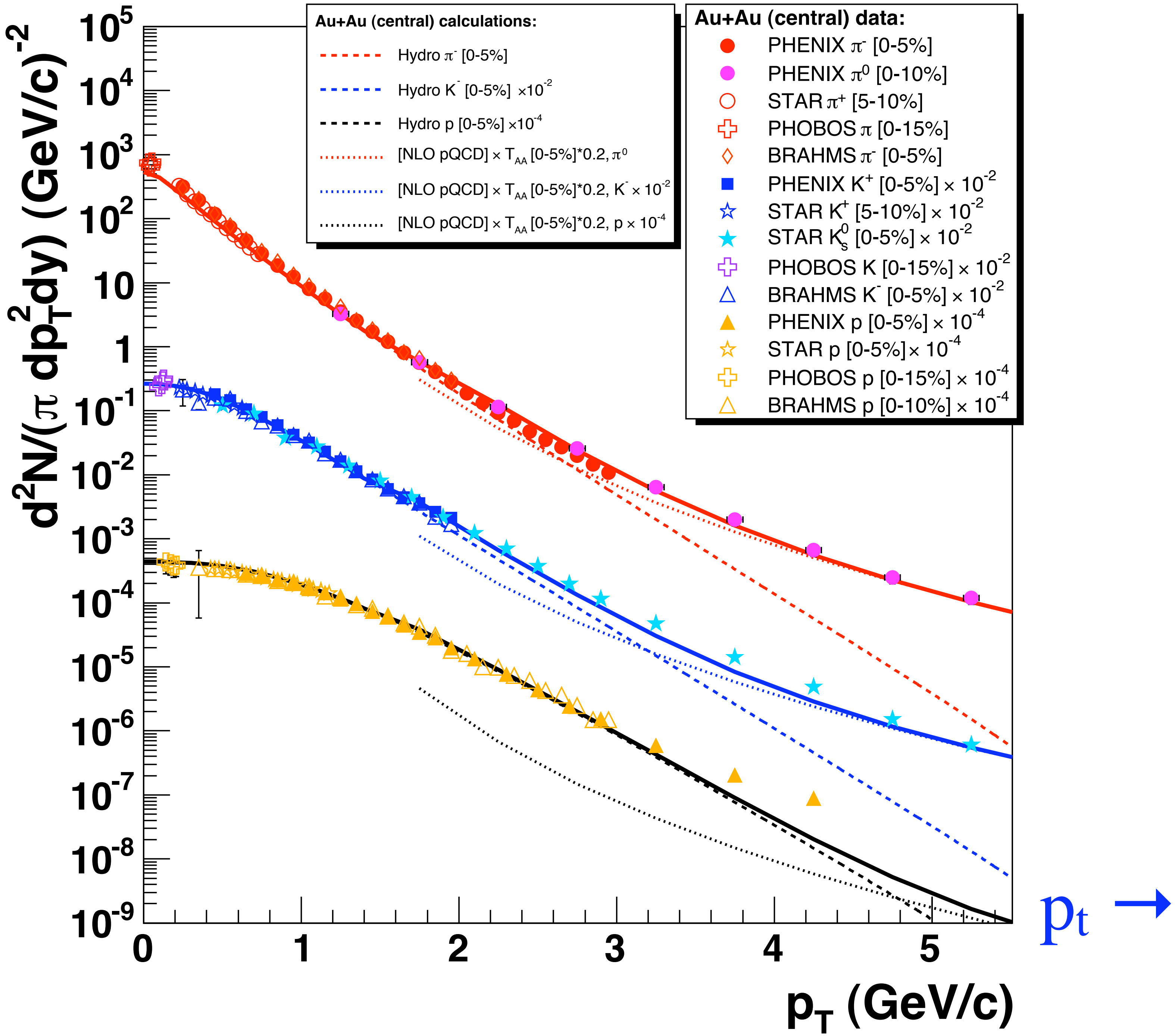
Overall abundances well fit with : $T_{chemical}$ = 165 MeV, μ_{baryon} = 38 MeV

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

Not proof of chemical equilibriation. *BUT:* amazingly efficient summary of data!

Includes strange particles, *unlike* pp, e^+e^-....

Single particle spectra



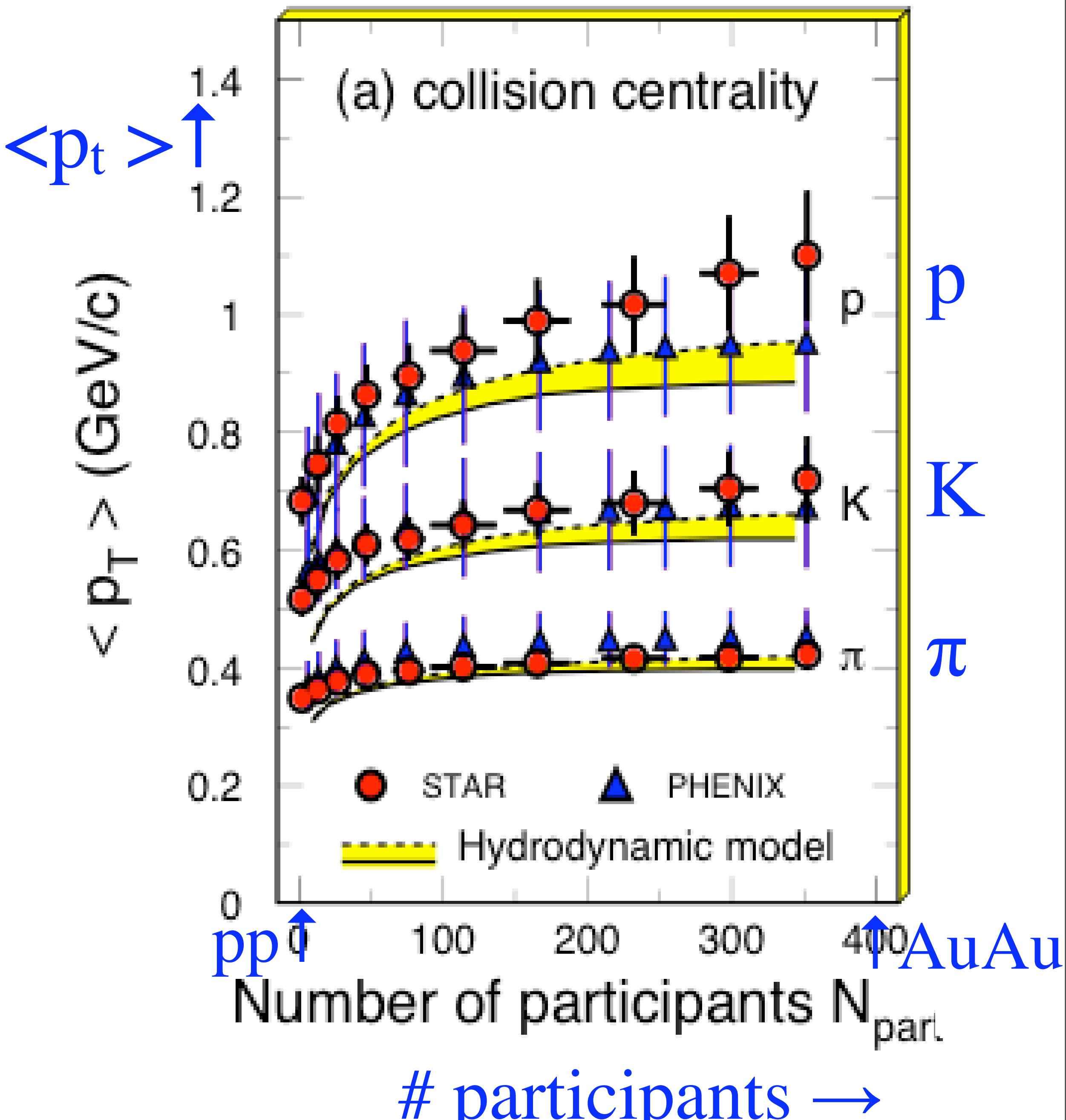
Mean transverse momenta & "radial flow"

Mean transverse momenta, $<p_t>$:
from pp (left) to AuAu (right),
@ 200 GeV

Large increases in $<p_t>$ for kaons, protons.

Due to radial flow of "medium", with radial velocity v/c ~ 0.6: heavy particles flow more easily.

Pion $<p_t>$, ~ same in pp and AA. *Odd*.



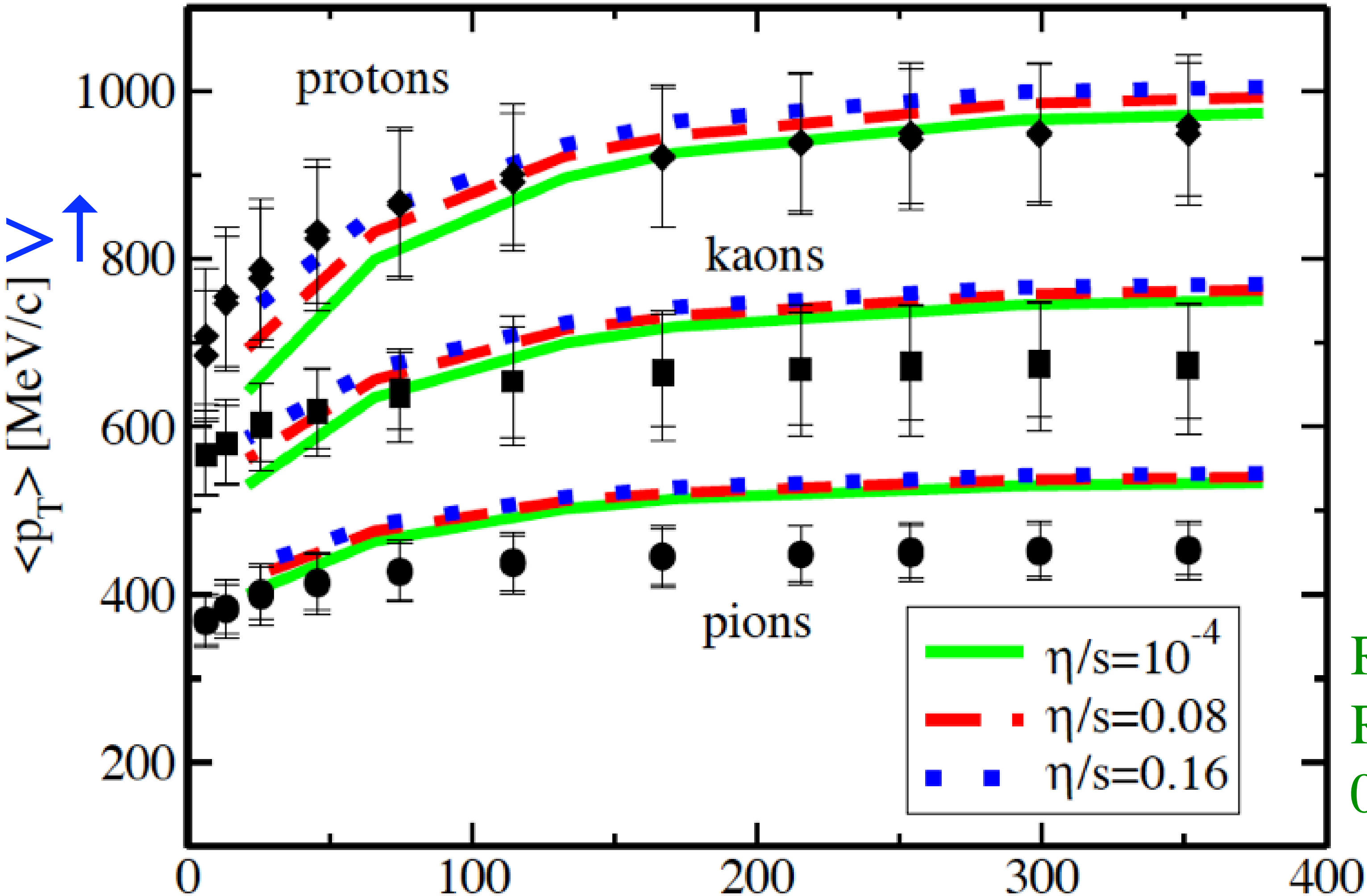
Hydrodynamics: single particle spectra

Large # particles, so hydrodynamics reasonable.

Non-ideal hydro. : depends upon η/s = shear viscosity/entropy.

Not very restrictive for <p_t>. Hydro. still gives too big <p_t> for pions.

<p_t >↑



p

K

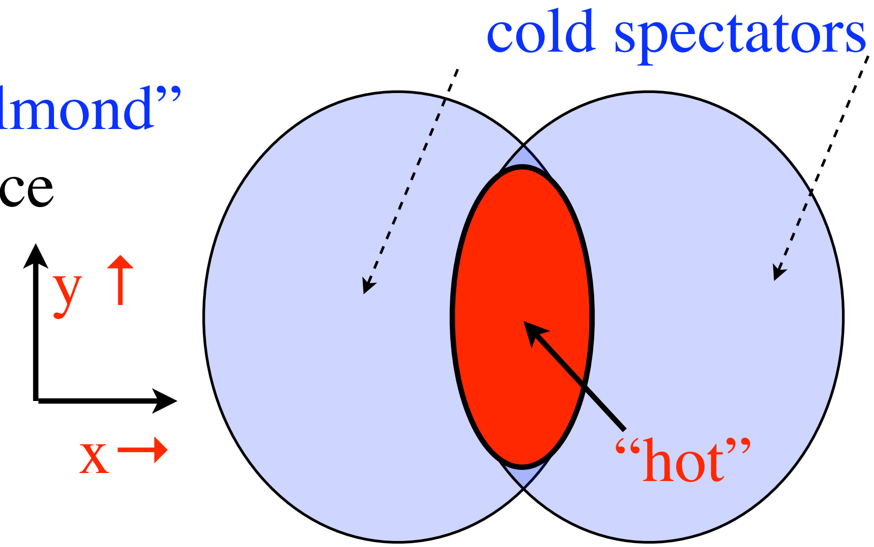
π

Romatschke & Romatschke 0706.1522

participants →

“Elliptic Flow”

For peripheral collisions, overlap region is “almond” in coordinate space, sphere in momentum space



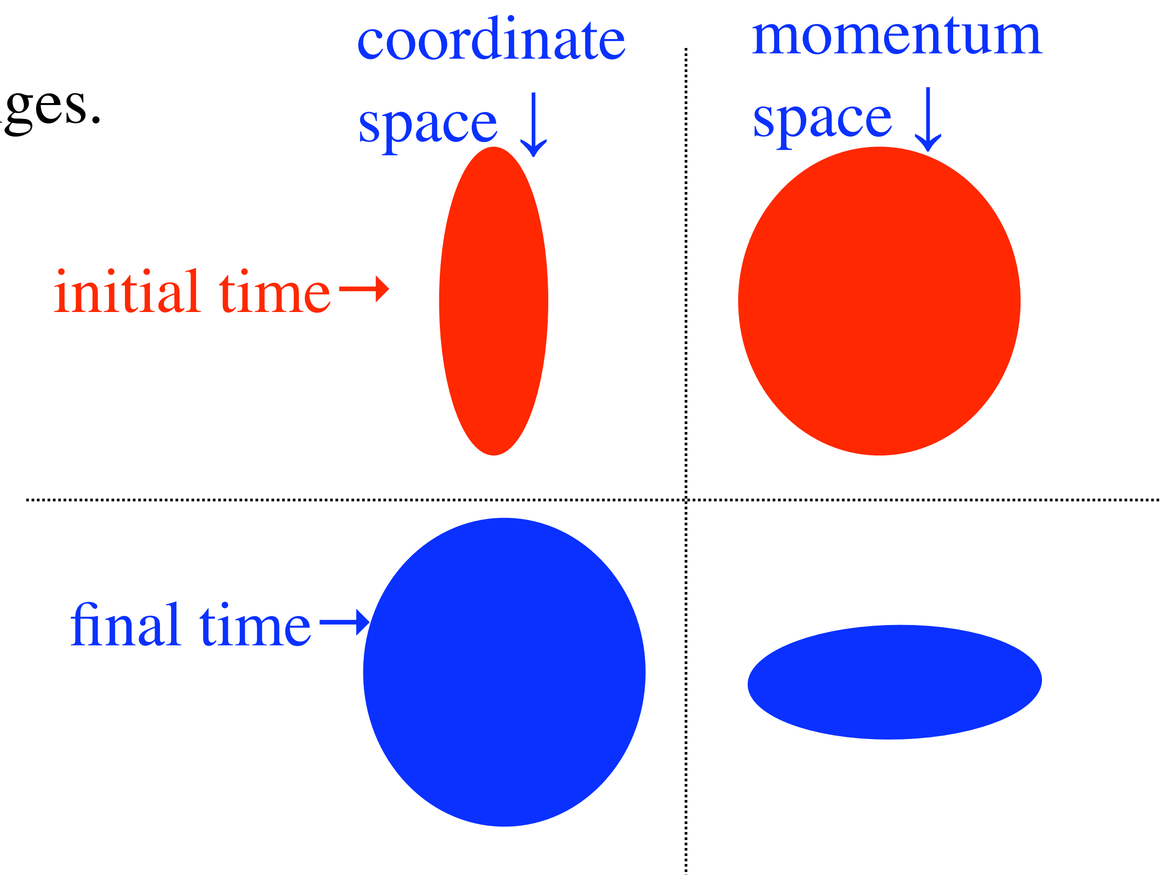
So start with spatial anistropy,

$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle x^2 + y^2 \rangle}$$

If particles free stream, nothing changes.

If collective effects present, end up with sphere in coordinate space, almond in momentum space: “elliptic flow”

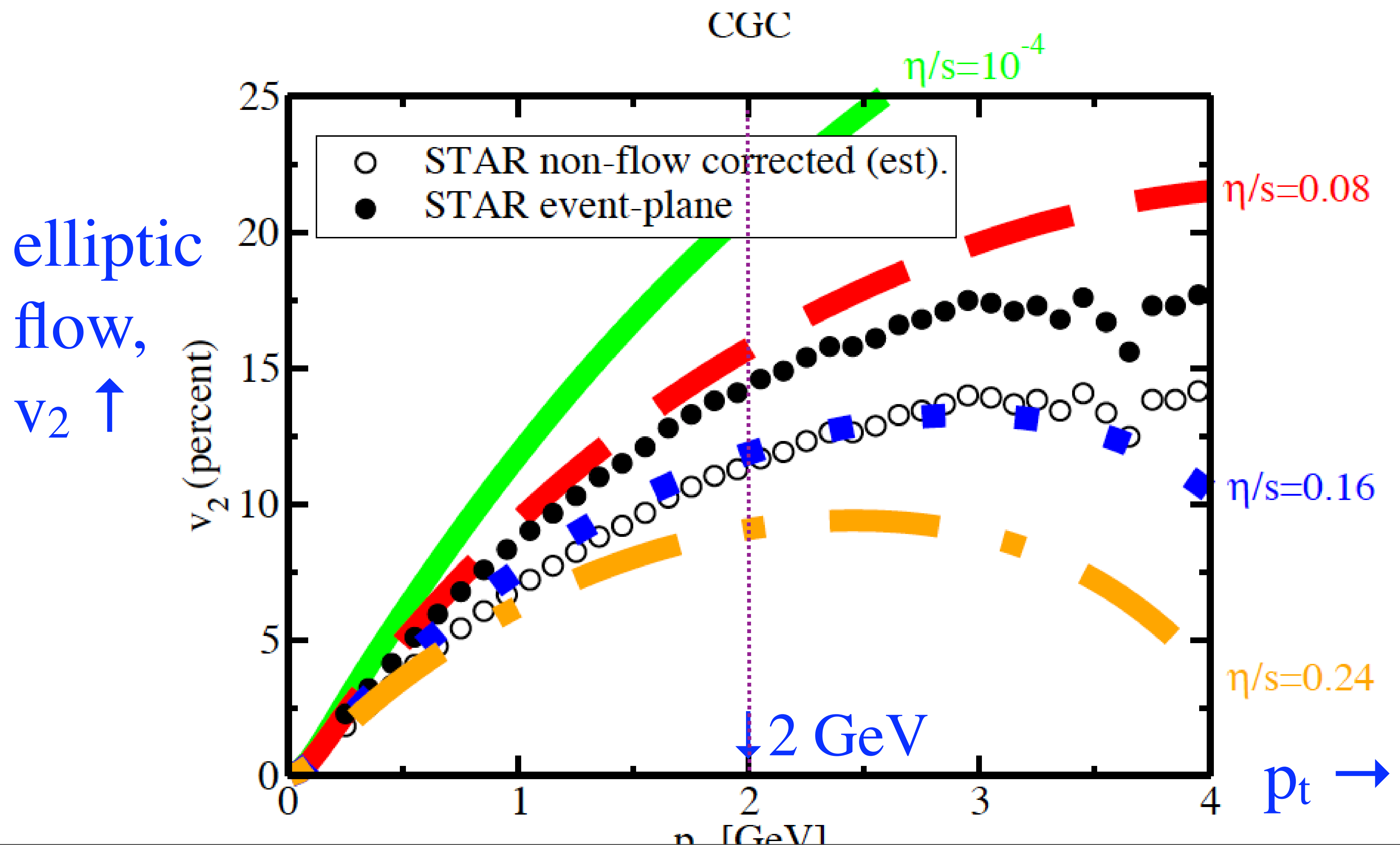
$$v_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



Elliptic flow: bound on η/s

Elliptic flow *strongly* constrains η/s = shear viscosity/entropy.

η/s = 0.1 ± 0.1 (theory) ± 0.1 (exp.)   Luzum & Romatschke 0804.4015



Elliptic flow: SPS to RHIC (*LHC?*)

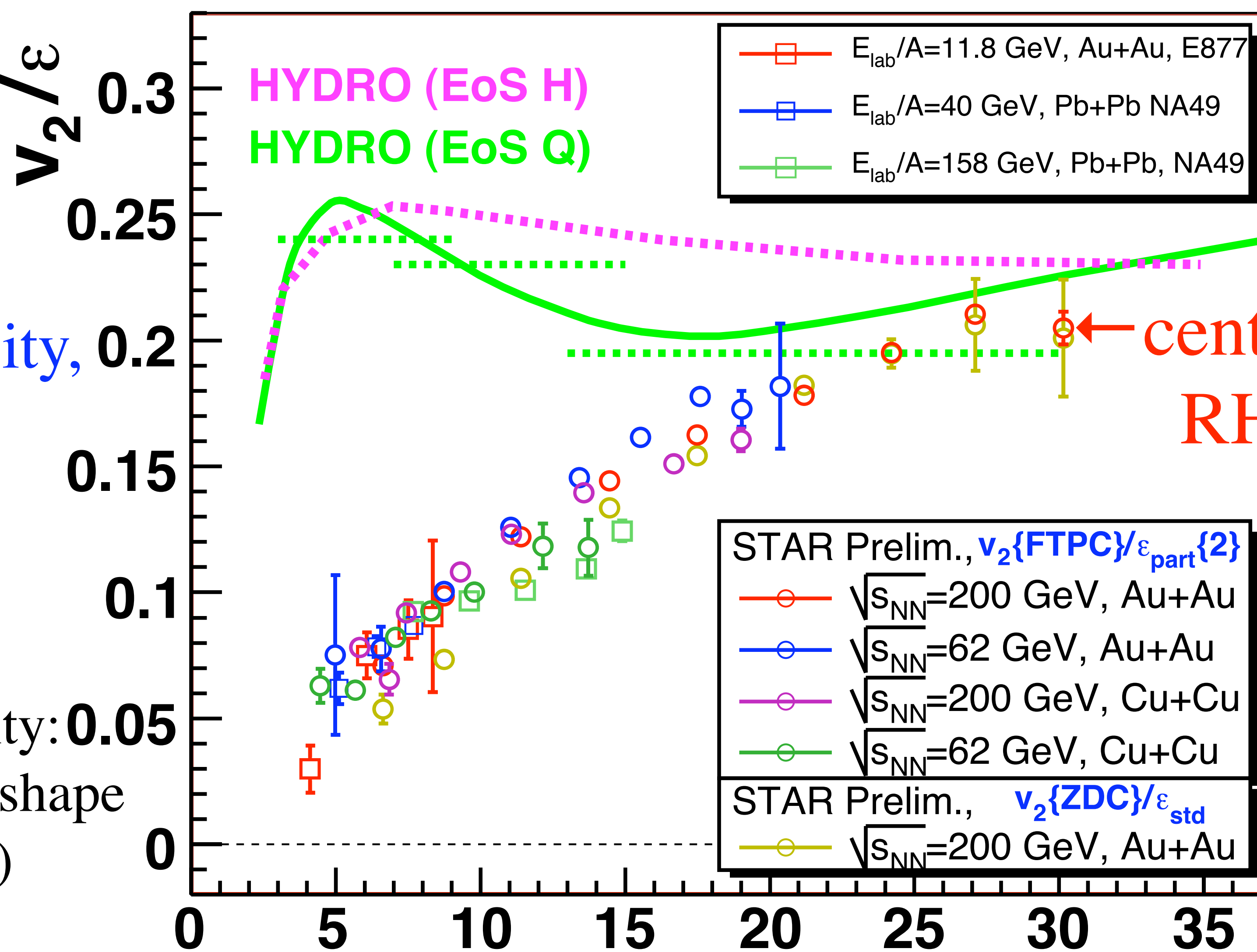
Central AA at RHIC: good fit to v_2 with ideal hydrodynamics

Does *not* work at lower energies. Song & Heinz 0805.1756

Below: energies AGS, SPS, RHIC. A ~ 60, 200. *Where is LHC?*

elliptic flow/ eccentricity, v_2/ε ↑

(eccentricity: "almond" shape of overlap)



← *LHC?*

ideal ← hydro

← central AA, RHIC

multiplicity/ transverse area →

RHIC and the "most perfect fluid on earth"

Experimental bound on η/s appears valid.

Order of magnitude smaller than *any* non-relativistic system.

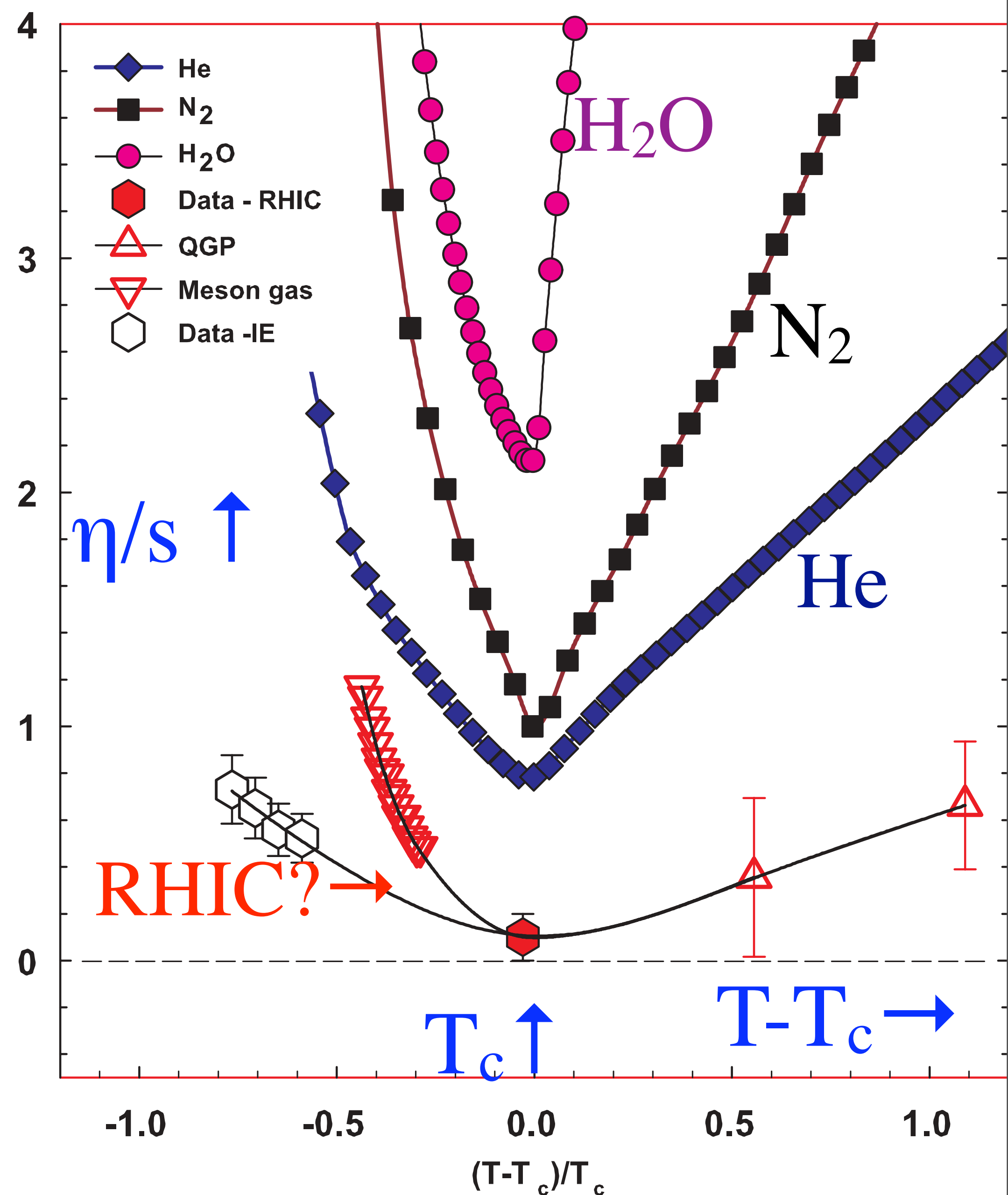
Close to conjectured bound from $\mathcal{N} = 4$ SU(∞)?

$$\left.\frac{\eta}{s}\right|_{\rm SUSY} \sim \frac{1}{4\pi}$$

Exp. value is ~ 10 *smaller* than in perturbation theory,

$$\left.\frac{\eta}{s}\right|_{\rm pert.} \sim \frac{1}{\alpha_s^2} \sim 1.0$$

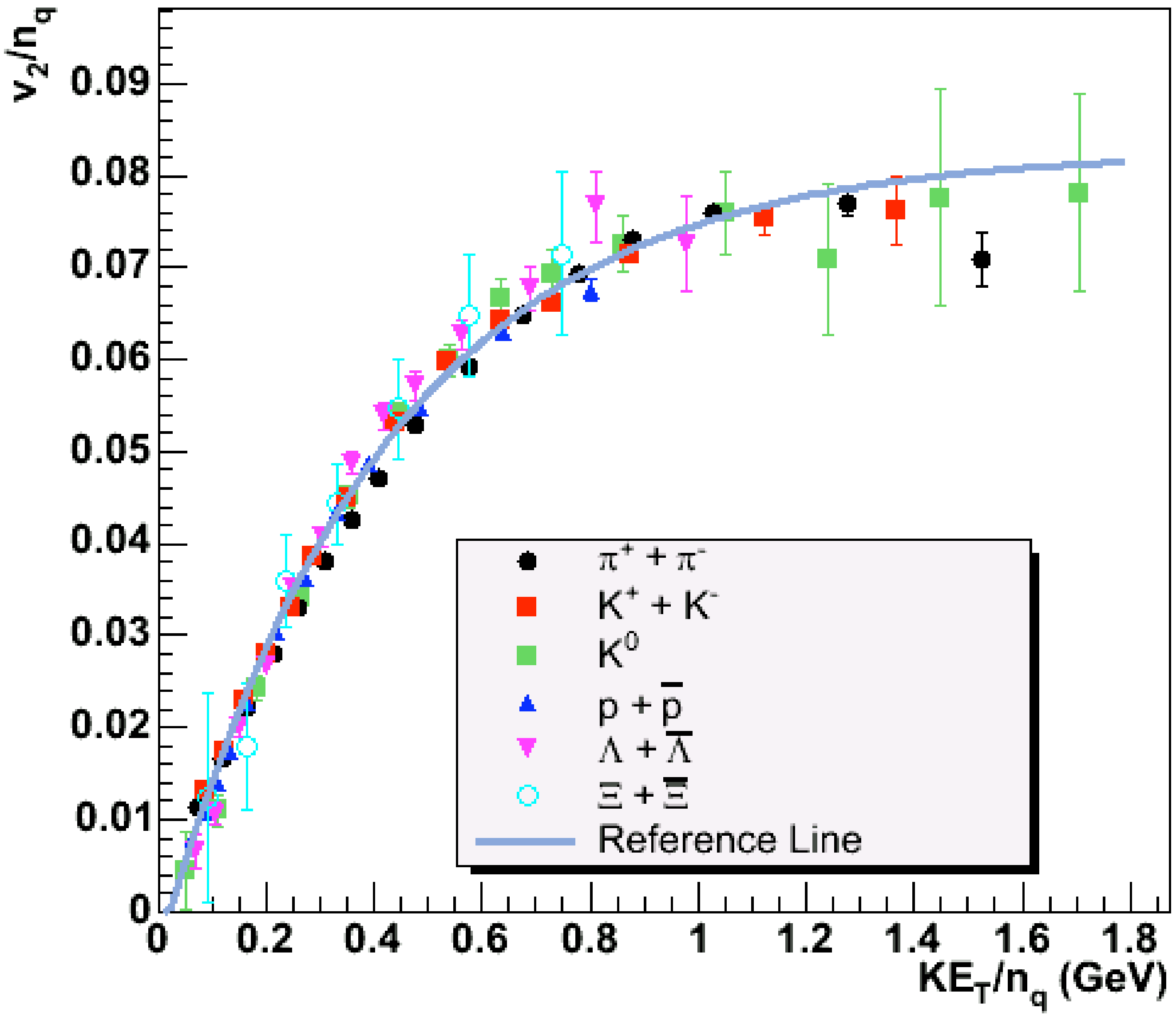
Evidence of *strong* coupling near T_c?



Universal curve for elliptical flow

Exp.y, elliptical flow/# quarks satisfies a *universal* scaling, with respect to transverse *kinetic* energy/ # quarks (kinetic?)

elliptic flow/ # quarks v_2/n_q ↑



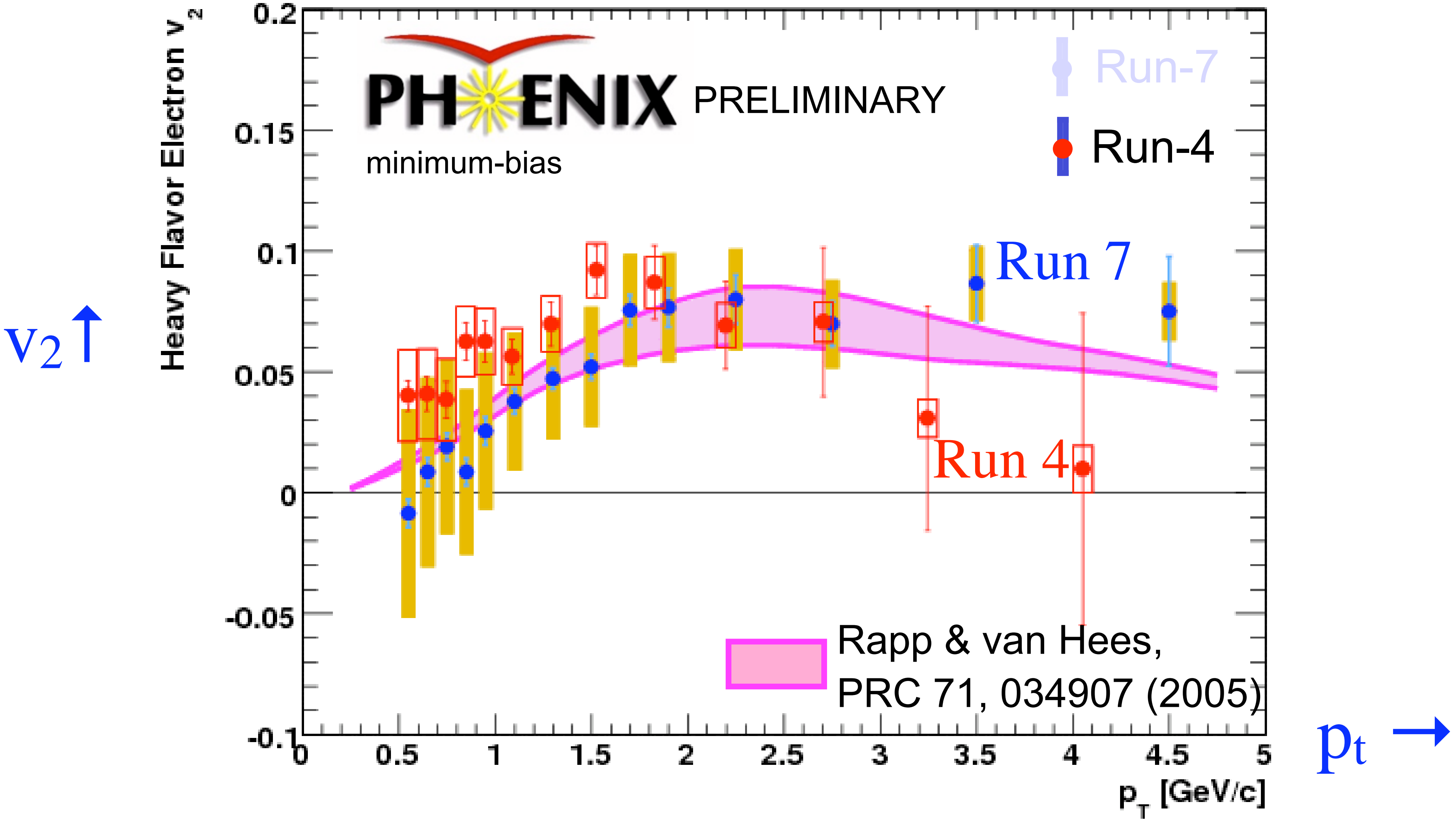
KE_{tr}/n_q →

Elliptic flow even for *charm* quarks

Look at charm quarks through single electrons.

Find *large* elliptic flow: *no* suppression due to large mass.

Heavy quarks "flow" ~ *same* as light quarks! *Weird.*



RHIC: Hard particles

Hard particles, p_t > 2 GeV ("jets")

"Tail" of the Unicorn

R_{AA} & jet suppression

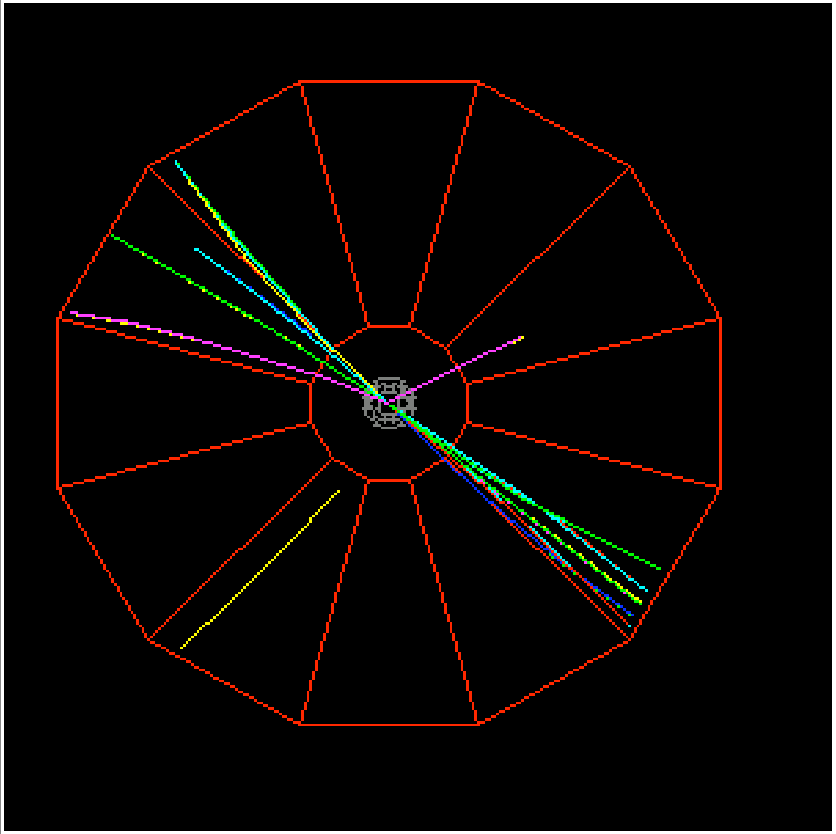
Geometrical tests of jet suppression

Conical emission of jets

Heavy quarks "suppressed" ~ *same* as light!

"Ridge" in rapidity

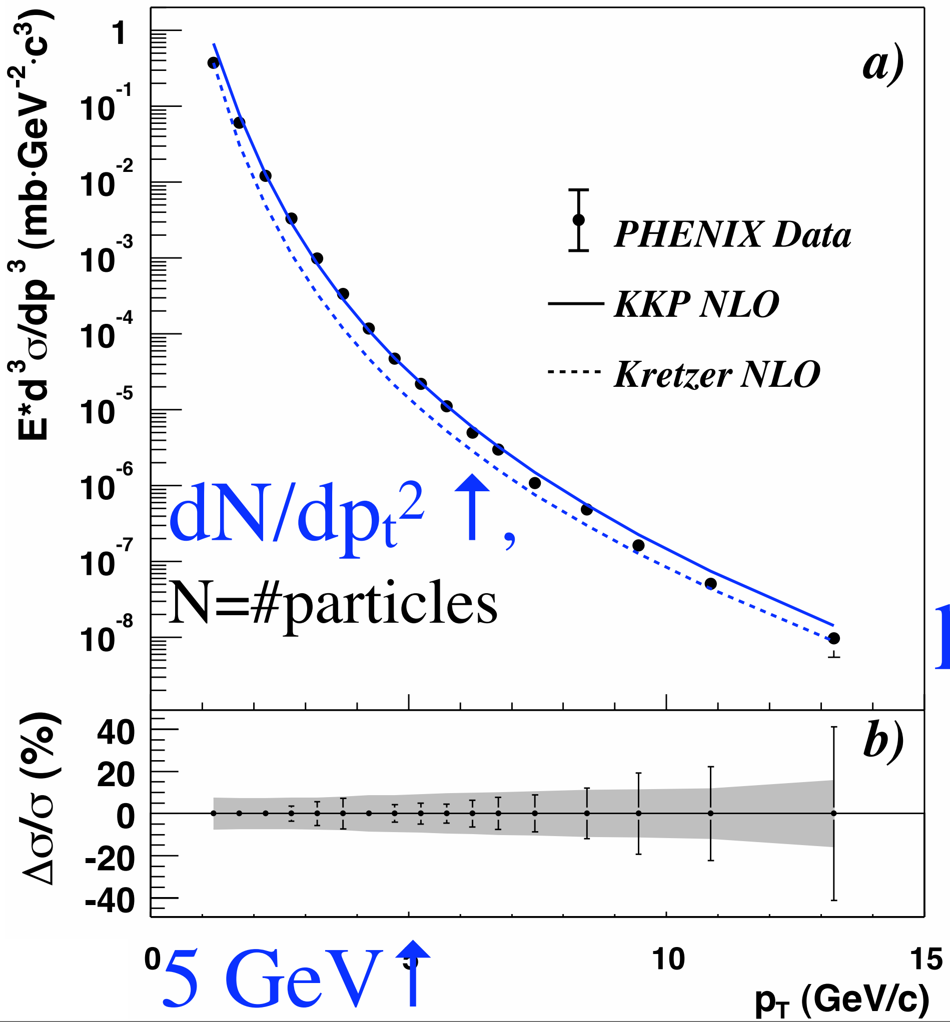
Jets at RHIC, pp and AA



← At RHIC, clearly see jets in pp collisions.

For each jet, there is always an away side jet.

Can compute perturbatively at high p_t ↓



dN/dp_t^2 ↑, N=#particles

p_t →

5 GeV ↑

In AA collisions, how to pick out jets, over a background with *high* multiplicity?

Need *statistical* measures.

R_{AA} and jet suppression

For any species:

$$R_{AA}(p_t) = \frac{\#\text{ particles central AA}}{A^2\ \#\text{ particles pp}}$$

A^2: # hard collisions.

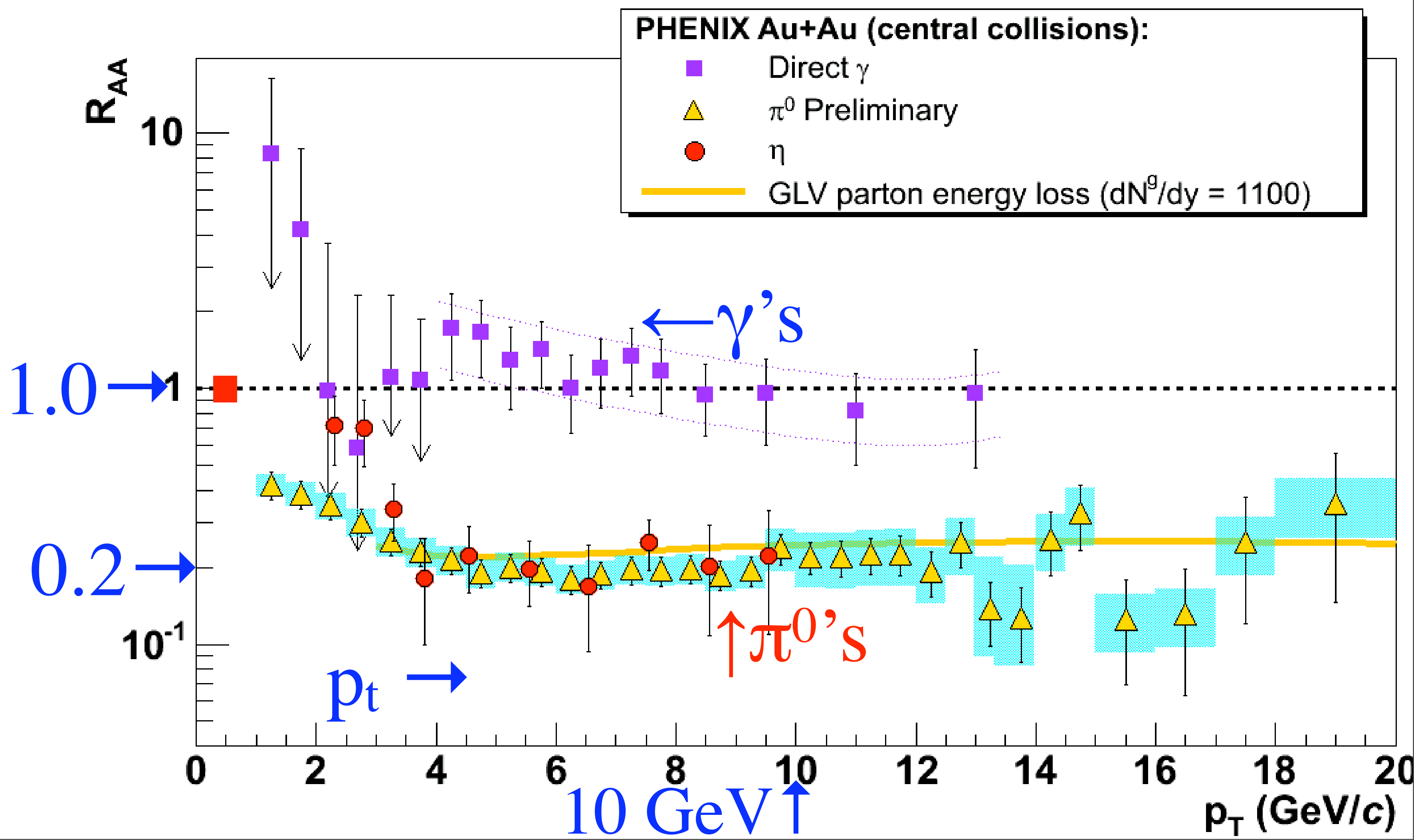
For γ's, $R_{AA} \sim 1.0$, $p_t > 2$ GeV.

For π^0's, $R_{AA} \sim 0.2$, $p_t : 4 \rightarrow 20$ GeV. As if jets emitted *only* from surface!

R_{AA}: ↑

A=200,

$\sqrt{s}$=200 GeV



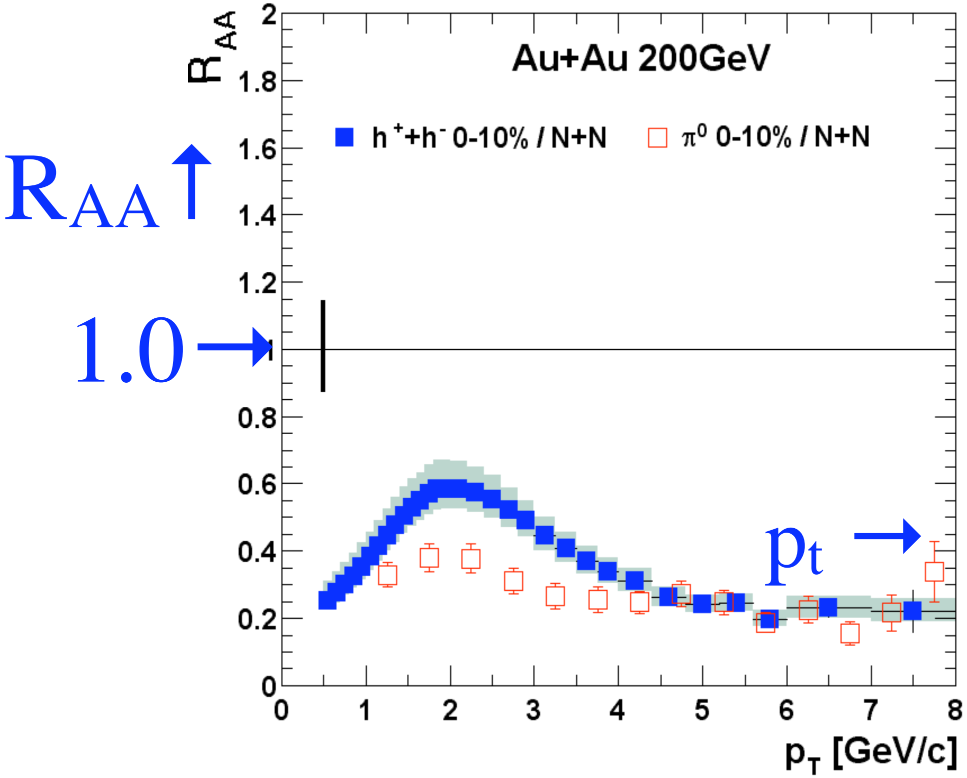
R_{AA} final state effect: *not* in R_{dA}

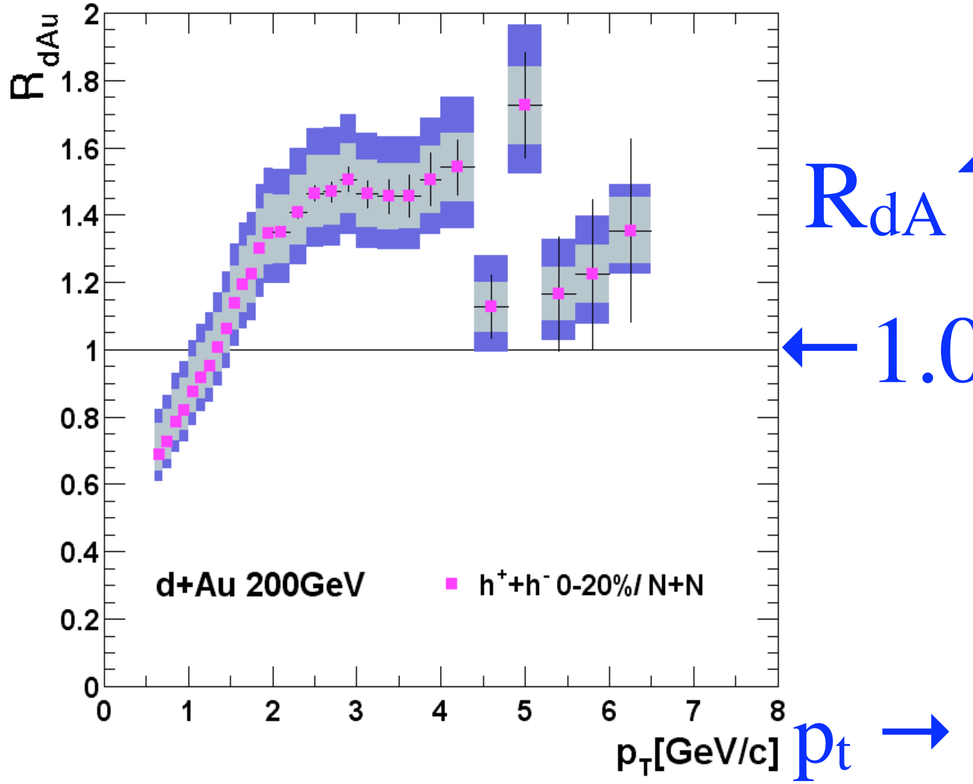
For dA coll.'s: R_{dA} ~ # particles in dA/(2A # pp). At zero rapidity:

dA: *enhancement*, from initial state (Cronin) effect ($R_{dA} \rightarrow 1$, $p_t > 8$ GeV)

AA: *suppression* => *final* state effect

Suppression in dA in d-fragmentation regime: Color Glass





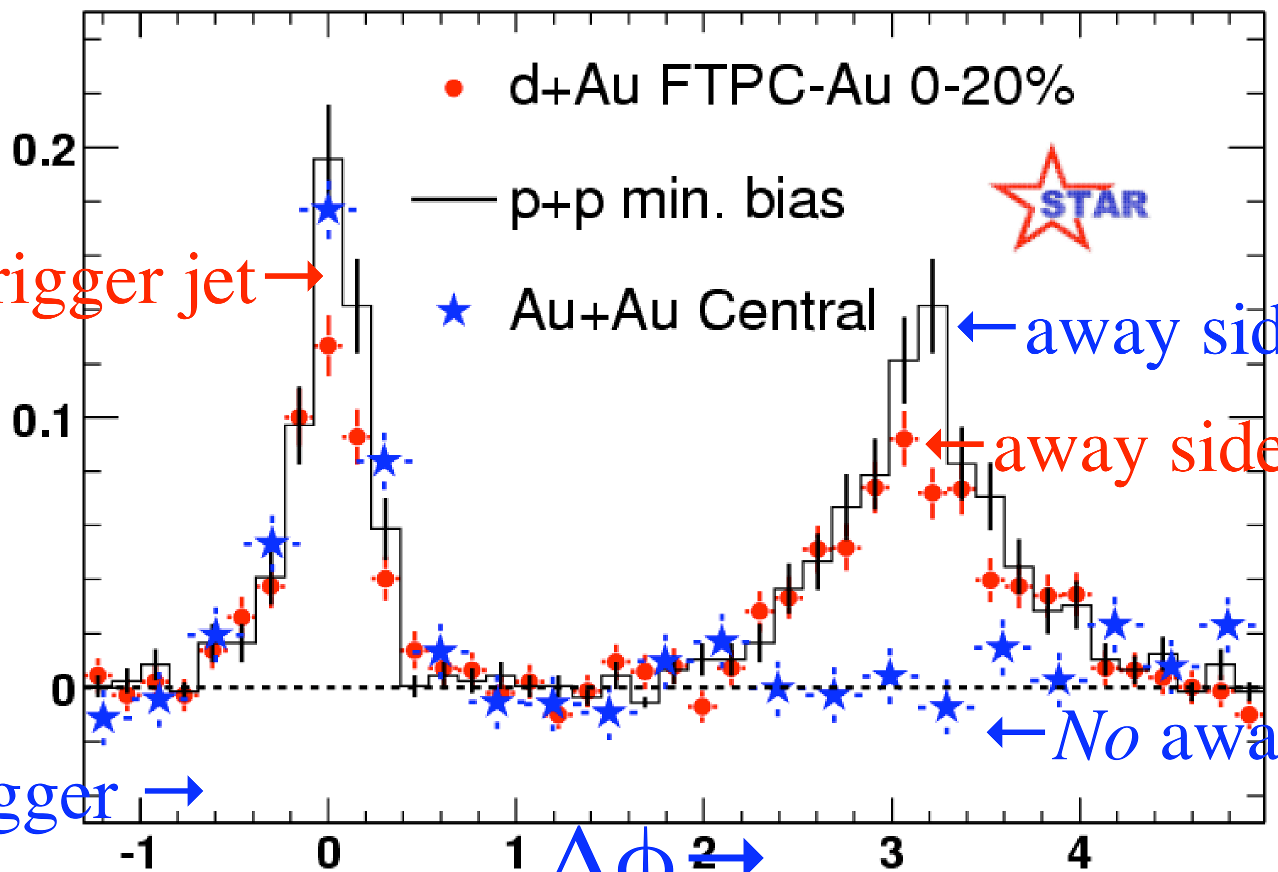
Suppression in AA ↑ Enhancement in dA ↑

Central AA collisions "eat" jets!

Another statistical measure of jets: angular correlations.

Trigger on hard jet, p_t: 4 → 6 GeV. Look for away side jet, $p_t > 2$ GeV

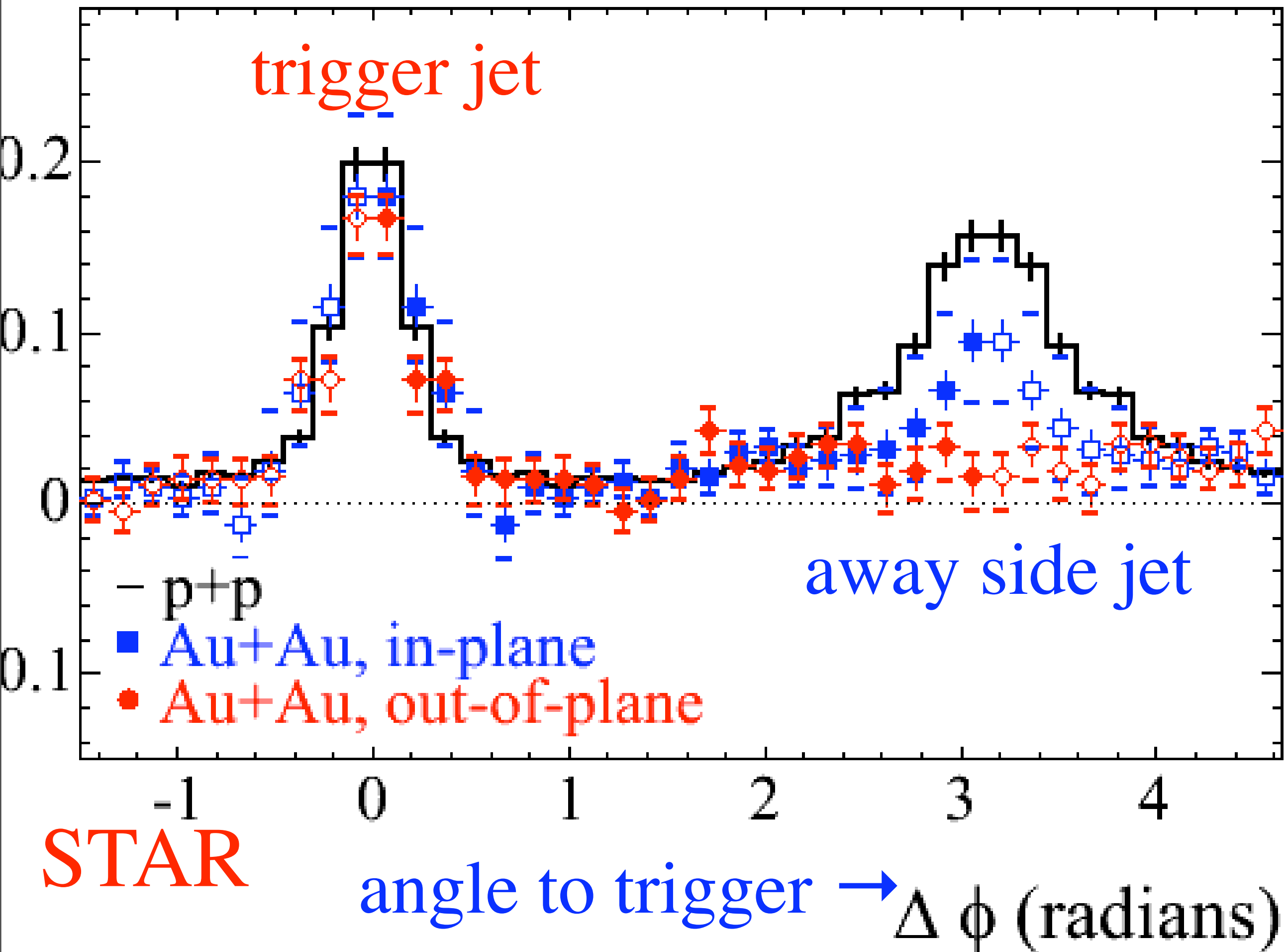
In pp or dAu collisions, *clearly* see away side jet.
In central Au-Au, away side jet gone: *"stuff" in central AA "eats" jets*

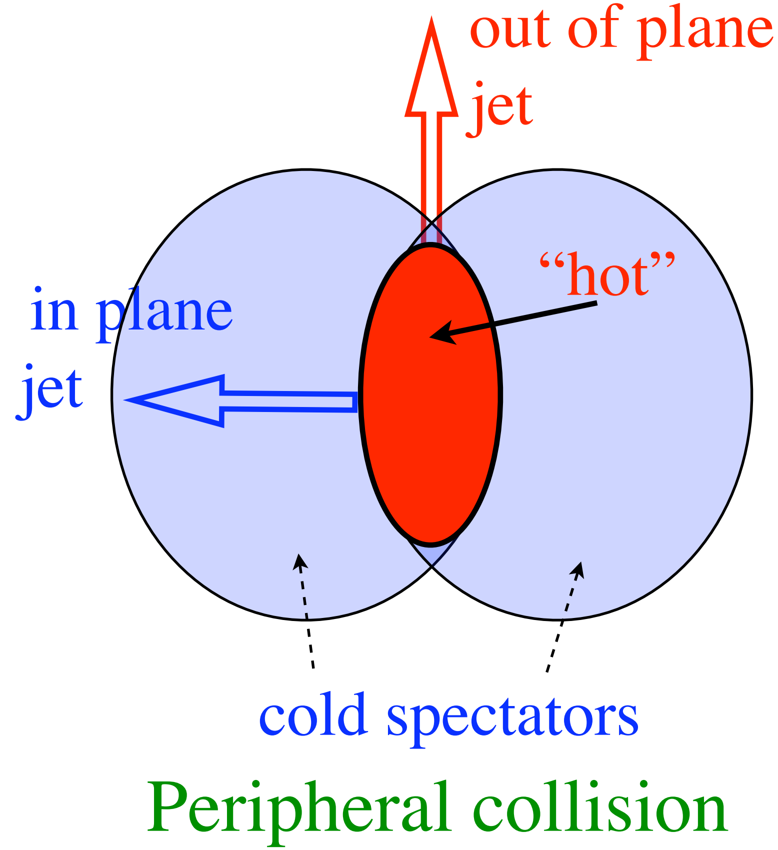


Geometrical test of jet suppression

Peripheral collisions: " hot stuff" forms "almond". In vs. out of reaction plane
Out: more "hot stuff". *In*: less hot stuff, more cold nuclear matter

Exp.'y: away side jet more strongly suppressed *out* of plane than *in* plane



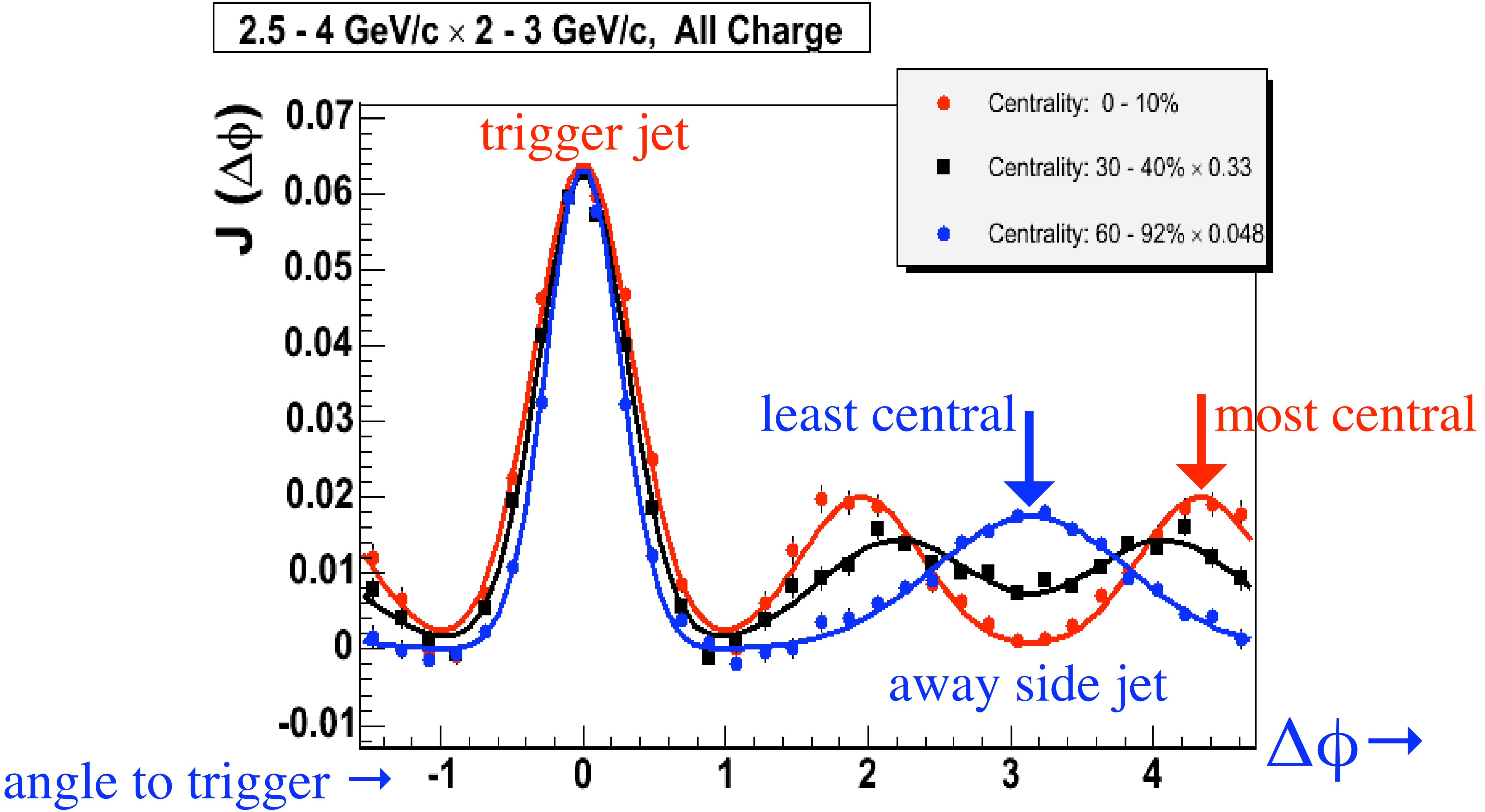


AA collisions: conical emission of away side jet

PHENIX: shape of away side jet is modified in central AA collisions

Trigger: 2.5 - 4 GeV. Away side: 2-3 GeV.

Confirmed by 3 particle correlations. Mach Cone or Cerenkov radiation?

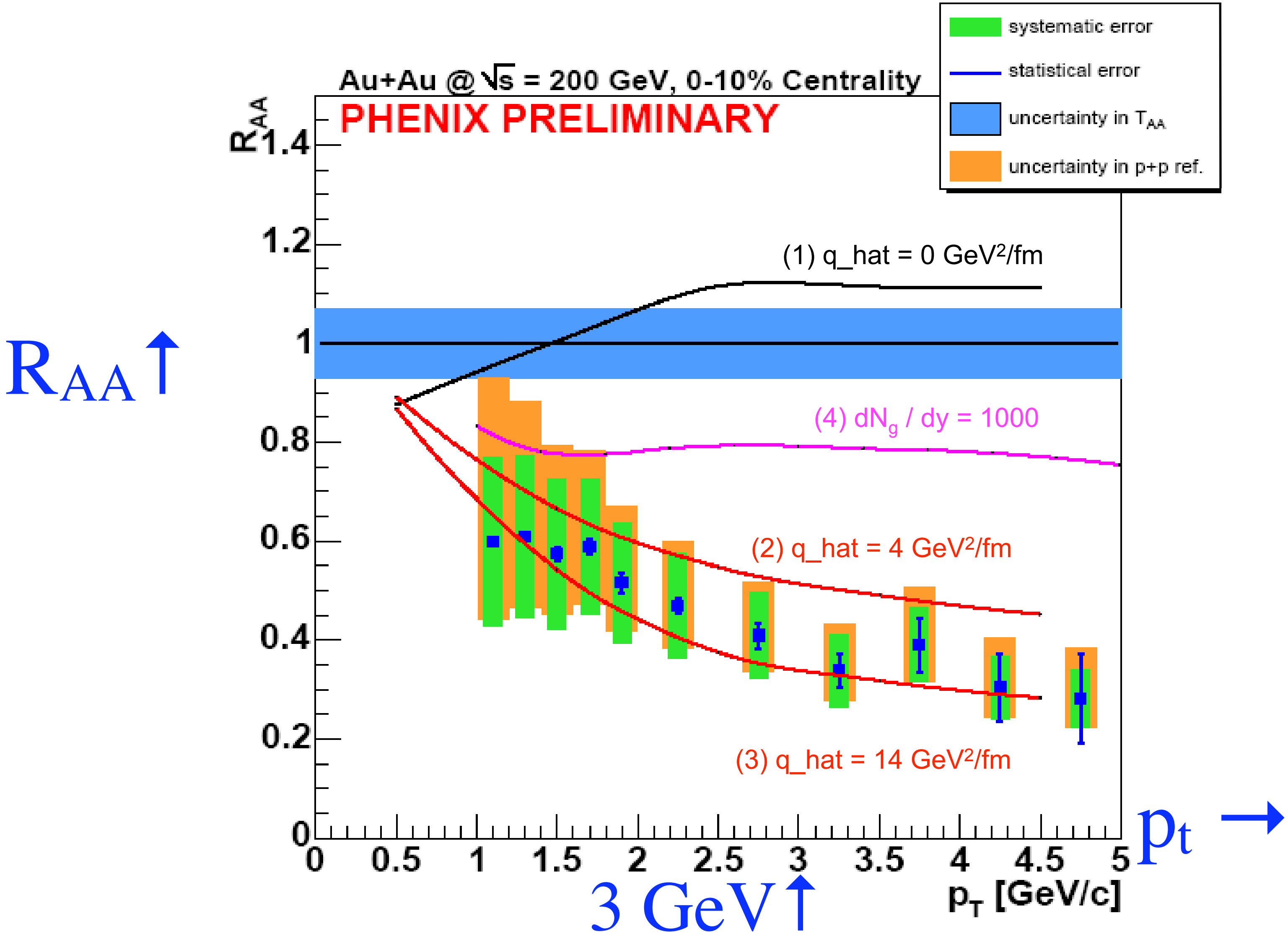


Suppression of heavy quarks ~ light.

PHENIX: direct e⁻'s from decay of heavy quarks

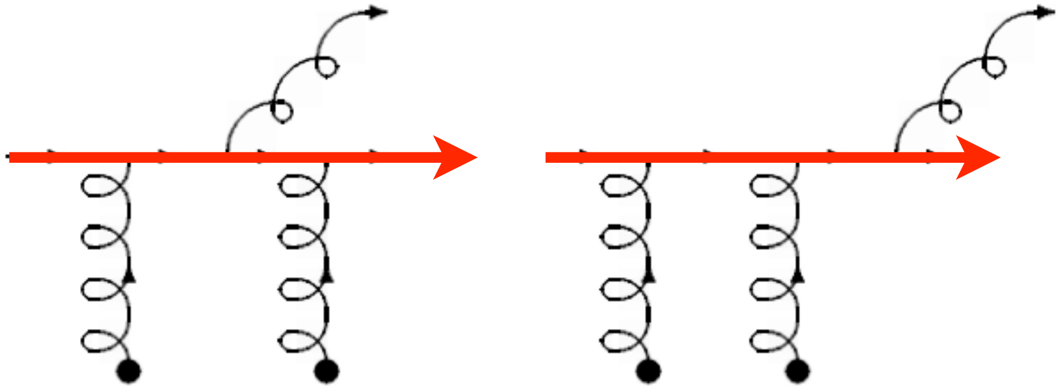
R_{AA} charm quarks ~ light quarks! But T/m_{charm} ~ 1/8: not *less* suppression?

Appears true even for *bottom* quarks: ~ *same* suppression. *Weird*.



Theory of jet suppression: energy loss?

Fast quark (or gluon) emits radiation,
scatters off of thermal bath.
Landau-Pomeranchuk-Migdal effect

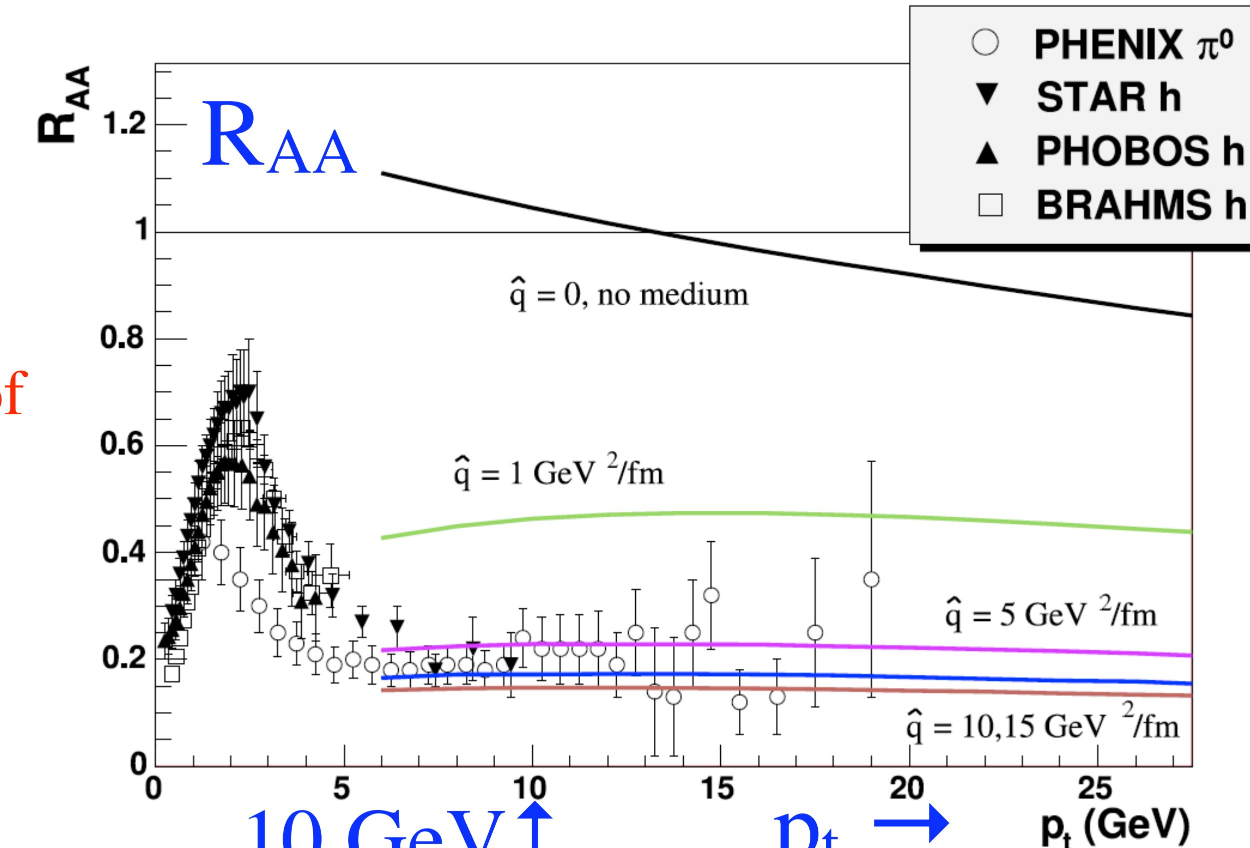


Parametrized by one number.
theorists disagree:
"weak" coupling ~ 2 GeV^2/fm
or "strong" ~ 15 GeV^2/fm?

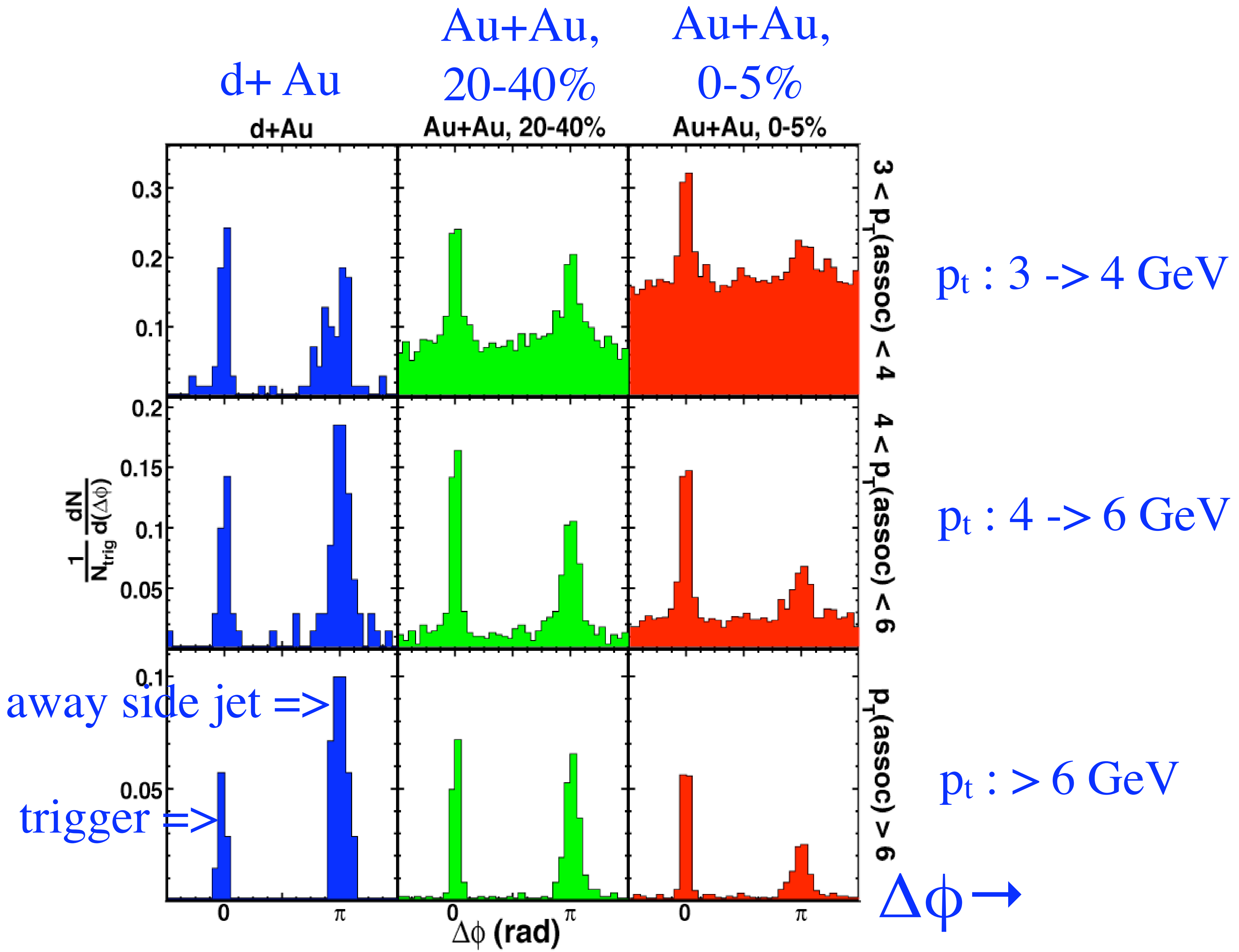
Why R_{AA} *flat* above 5 GeV?

Difficult to explain suppression of
heavy quarks ~ light quarks.

Maybe *not* energy loss?



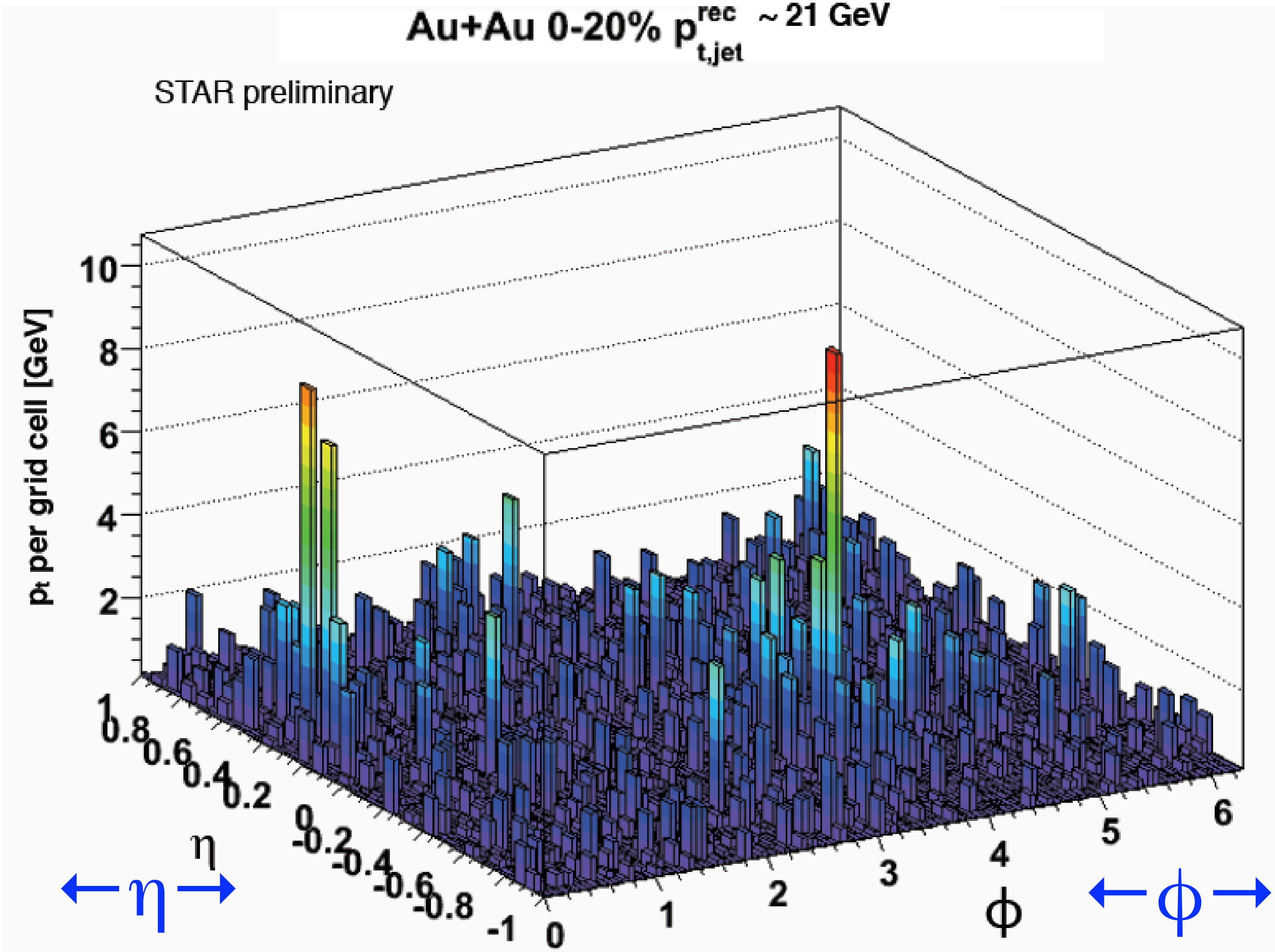
Jets "punch through" at high p_t



True jets at high p_t

STAR: central Au+Au, 0-20%, p_t ~ 21 GeV: lego plot

Many more jets at LHC: ALICE, CMS, ATLAS!



"Ridge" in rapidity

Shape of trigger jet modified in central AA:

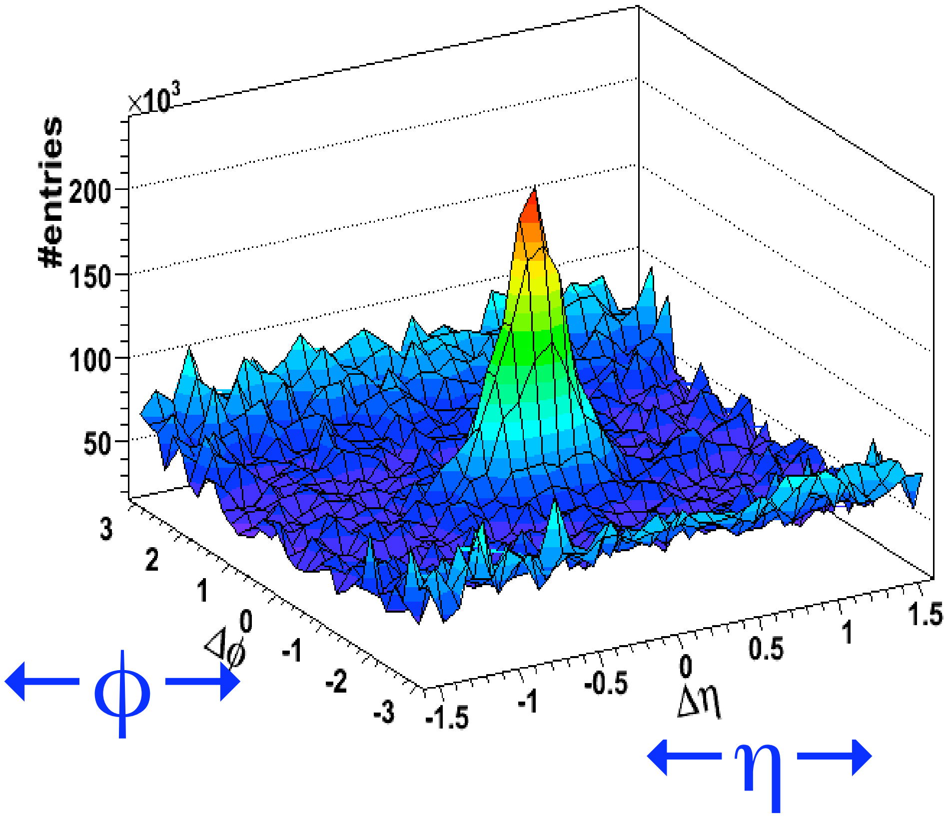
Trigger on hard particle, p_t: 3-6 GeV;

look at soft particles, $p_t > 2$ GeV, in *same* direction.

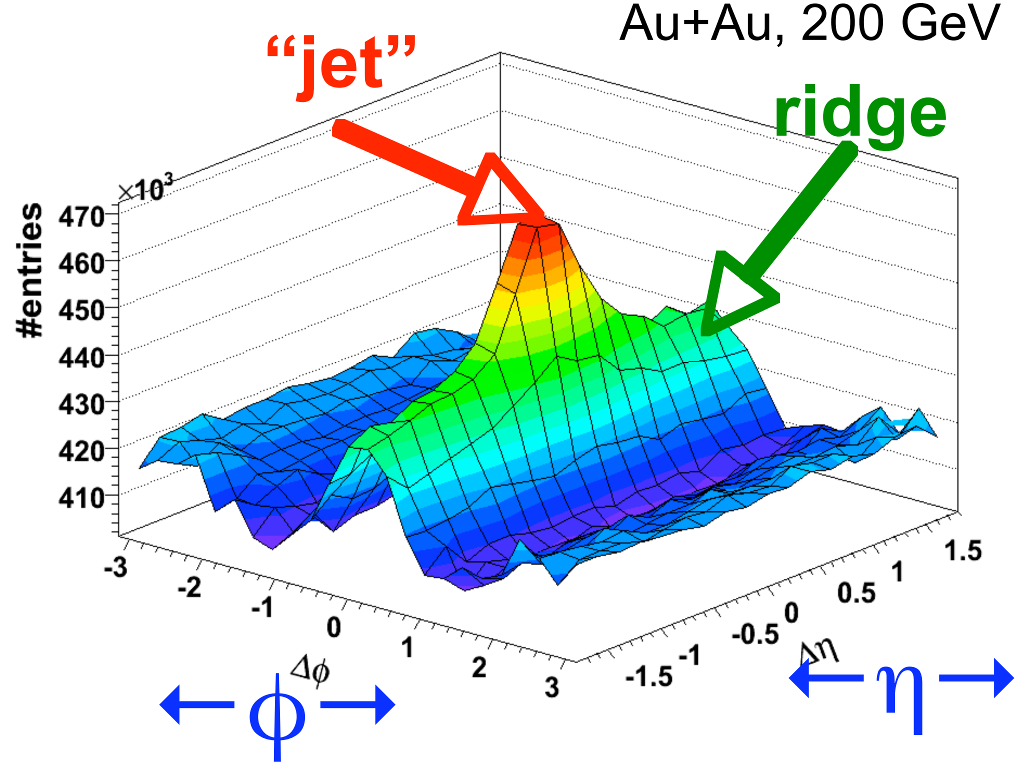
In pp, or d+Au, 1 unit of rapidity. In central AA, *much* wider, 4 units of rapidity.

Not wider in transverse angle.

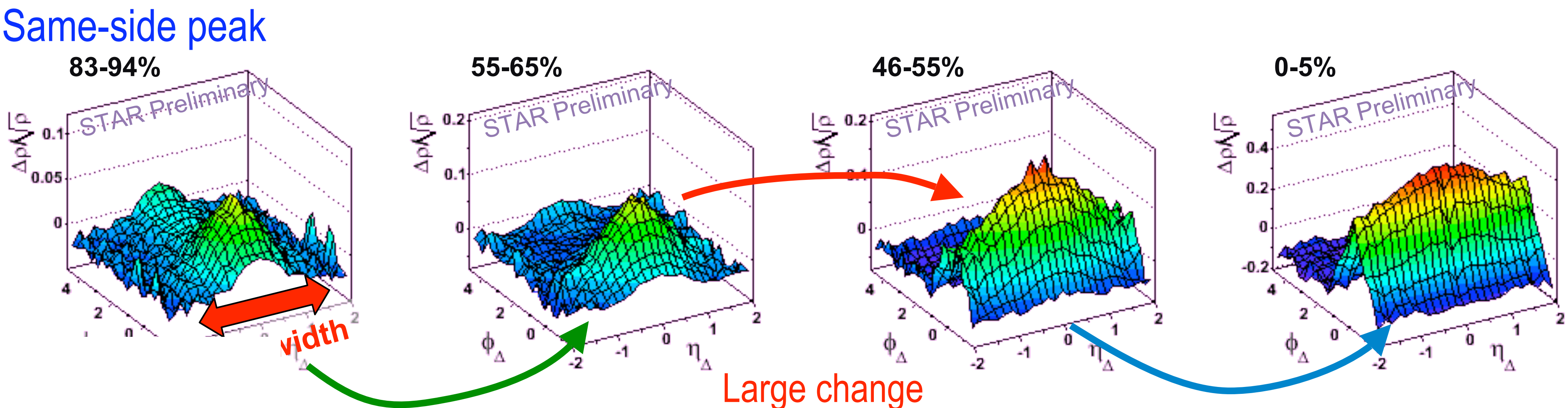
d+Au



Au+Au



"Ridge" vs # participants: sharp change



Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

Smaller change from transition to most central

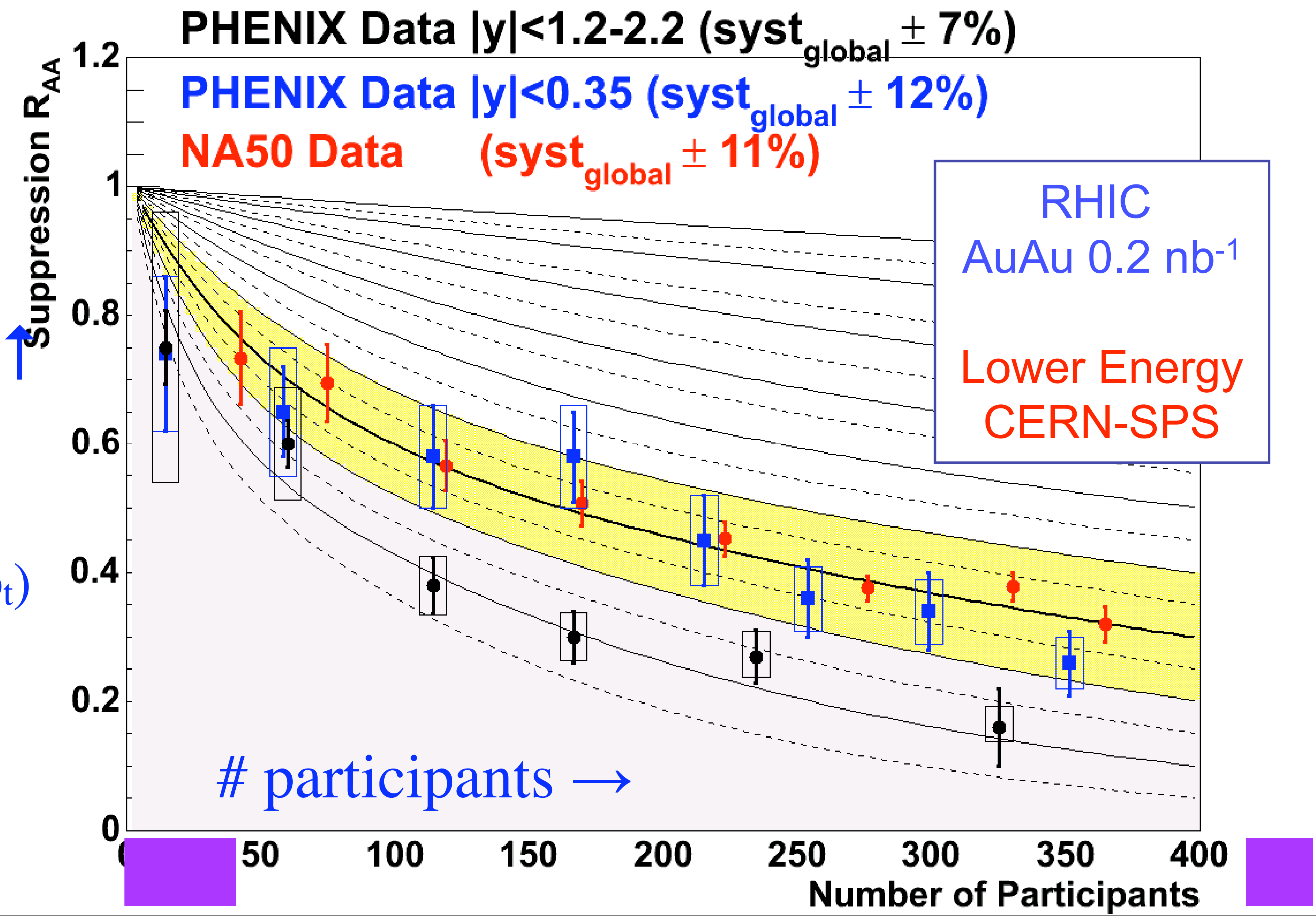
Electromagnetic Signals: J/ψ's, excess dileptons, photons

J/ψ suppression at RHIC ~ SPS

Using R_{AA} (integrated over p_t) vs # participants,
J/ψ suppression ~ SPS (y=0)   Suppression *greater* at nonzero rapidity.

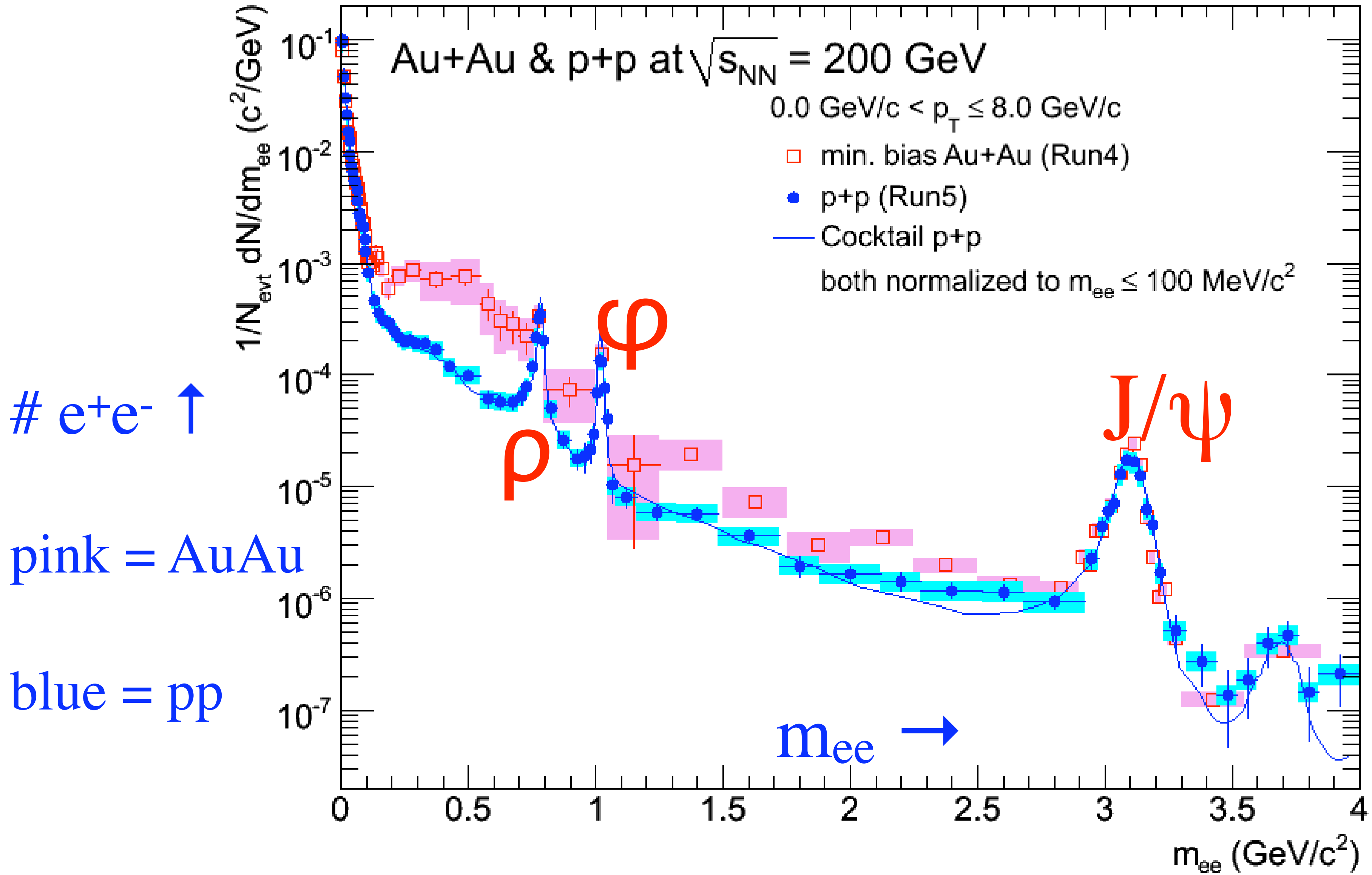
R_{AA} ↑

(int'd over p_t)

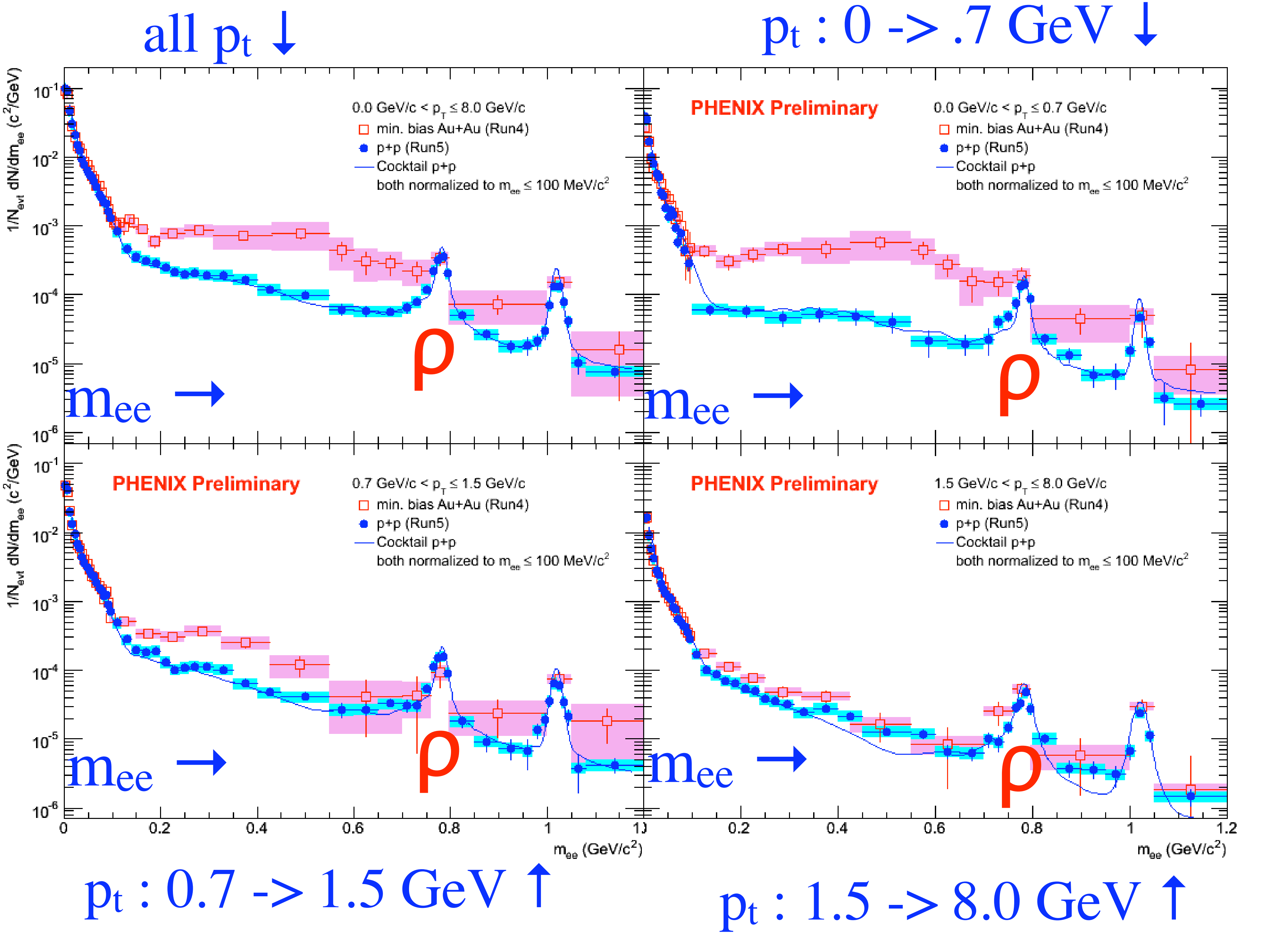


Dileptons: excess below the ρ

PHENIX: as at SPS, significant excess in dielectrons below the ρ meson.



Dilepton excess at *low* p_t

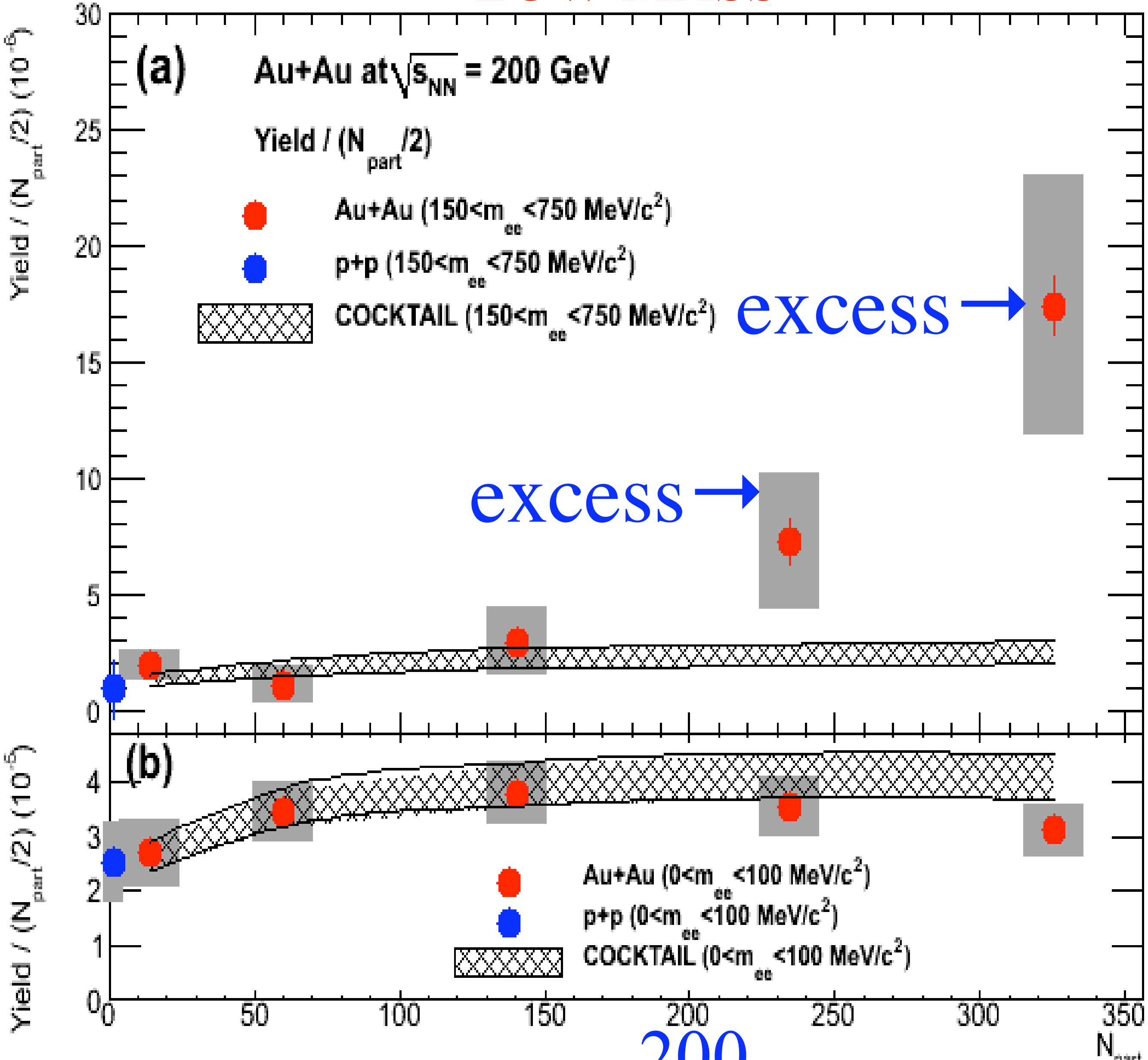


Dilepton excess *only* for central collisions

LOW MASS

Yield in e^+e^- ↑

AA vs "cocktail" from pp



excess →

excess →

200

participants →

Excess for thermal photons

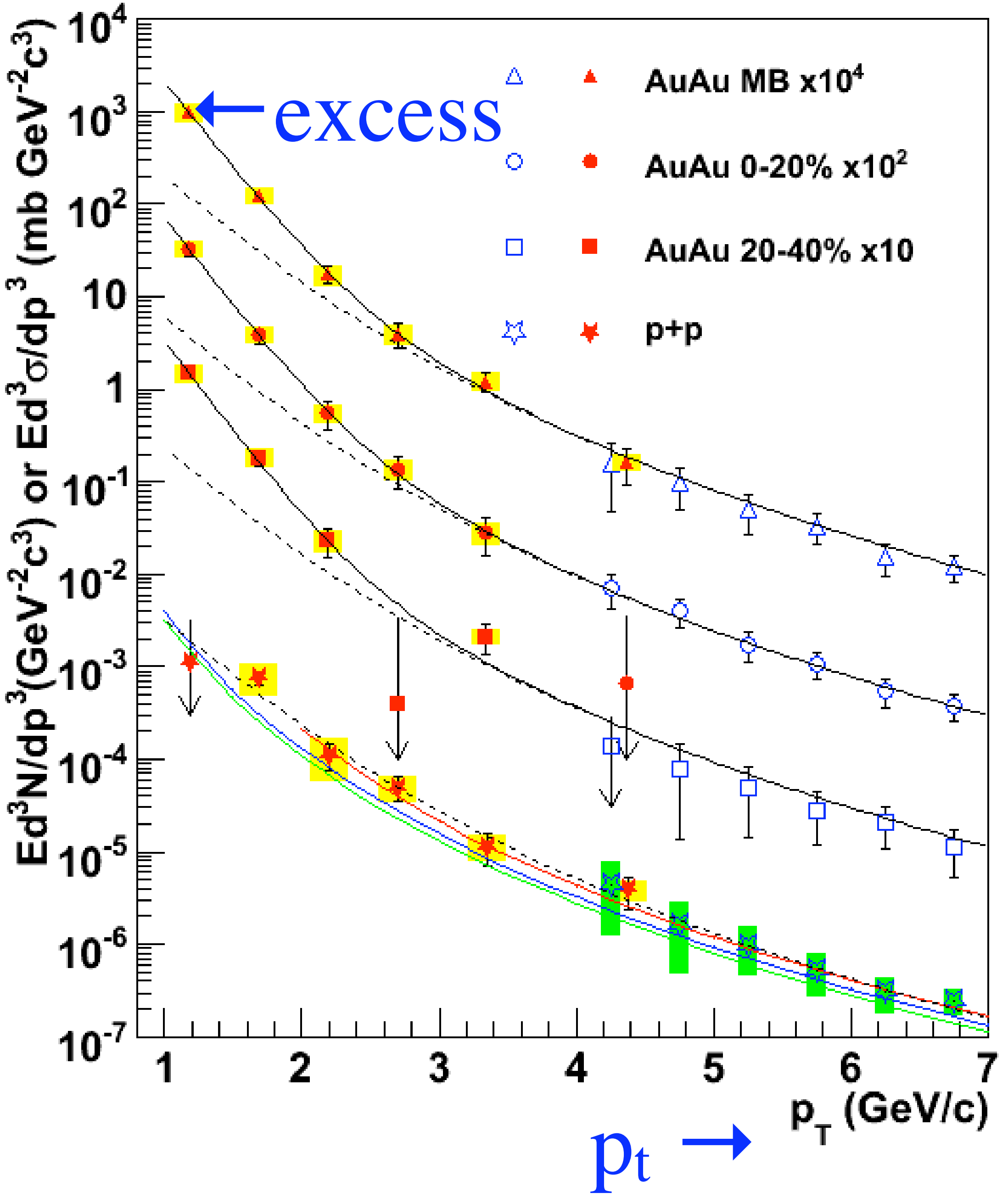
PHENIX, 0804.4168:

Look at low mass e^+e^- to get direct photons via internal conversion.

Find large excess for p_t:1 - 3 GeV, fit to exponential

T ~ 221 MeV

± 23 (stat) ± 18 (syst.)



RHIC and the “s”QGP

Heavy quarks “flow”, “suppressed” ~ *same* as light quarks?

Weird. Does *not* follow in a perturbative QGP. An “s”QGP?

How big is the QCD coupling near T_c?

Perhaps RHIC: T_c ~ 200 MeV -> ? How big is $\alpha_s(T_c)$?

$$\alpha_s(T) = \frac{\#}{\log(c\,T/\Lambda_{QCD})}$$

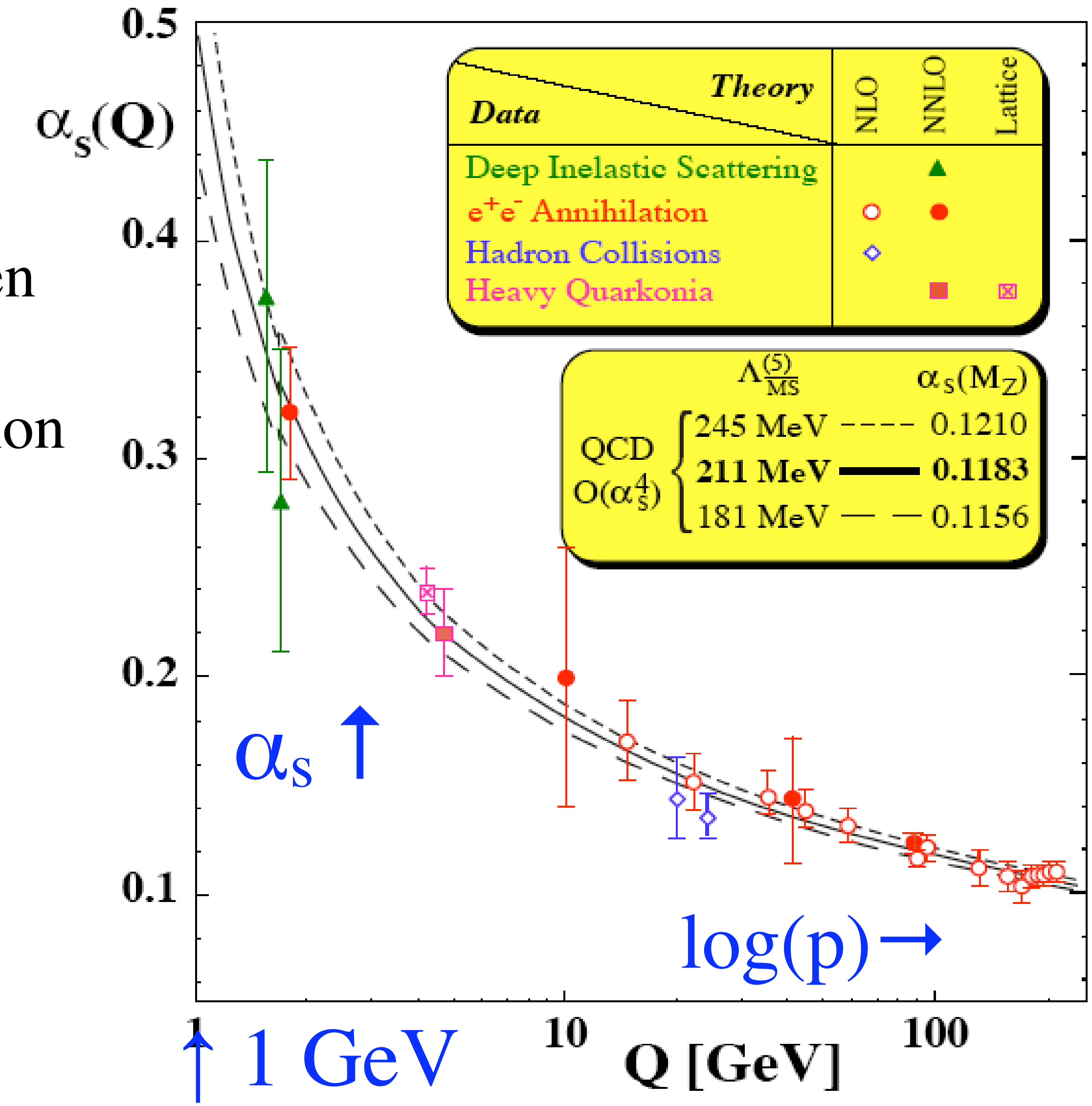
Assume α_s big (non-perturbative) when
cT < 1 GeV
"c" = constant from two loop calculation

c ~ 1: $\alpha_s(T_c)$ *big*

= "*strong*" QGP near T_c

c > 2 π: $\alpha_s(T_c)$ *moderate*

= "*semi*" QGP near T_c

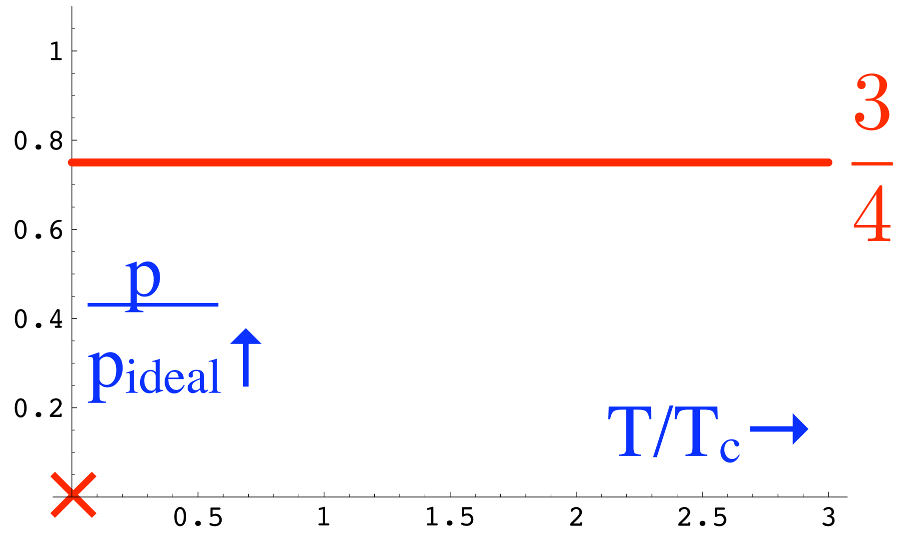


"Strong" QGP and AdS/CFT

If coupling big, maybe close to infinite:
compute for $\mathcal{N} = 4$ SU(∞), infinite α_s
using AdS/CFT (Maldacena) (E. Katz, Wed.)

Often easier for $\alpha_s = \infty$ than $\alpha_s \approx 0$.

Pressure = 3/4 ideal gas.   CFT => *flat* with T.



Kovtun, Son, Starinets: 0704.0240
Universal lower bound?

$$\frac{\eta}{s} = \frac{\text{shear viscosity}}{\text{entropy}} = \frac{1}{4\pi}$$

Many other quantities computed: heavy quark energy loss, saturation...

Can modify theory to fit pressure down to T_c:
Gubser & Nellore 0804.0434; Gursoy et al. 0804.0899; Evans & Threlfall 0805.0956.

Still, η/s remains *constant*! *Prediction* of AdS/CFT.

"Semi" QGP and Polyakov loops

For pressure, in 3-dim. effective thy., "c" > 2π , $\alpha_s(T_c) \sim 0.3$: *moderate*!

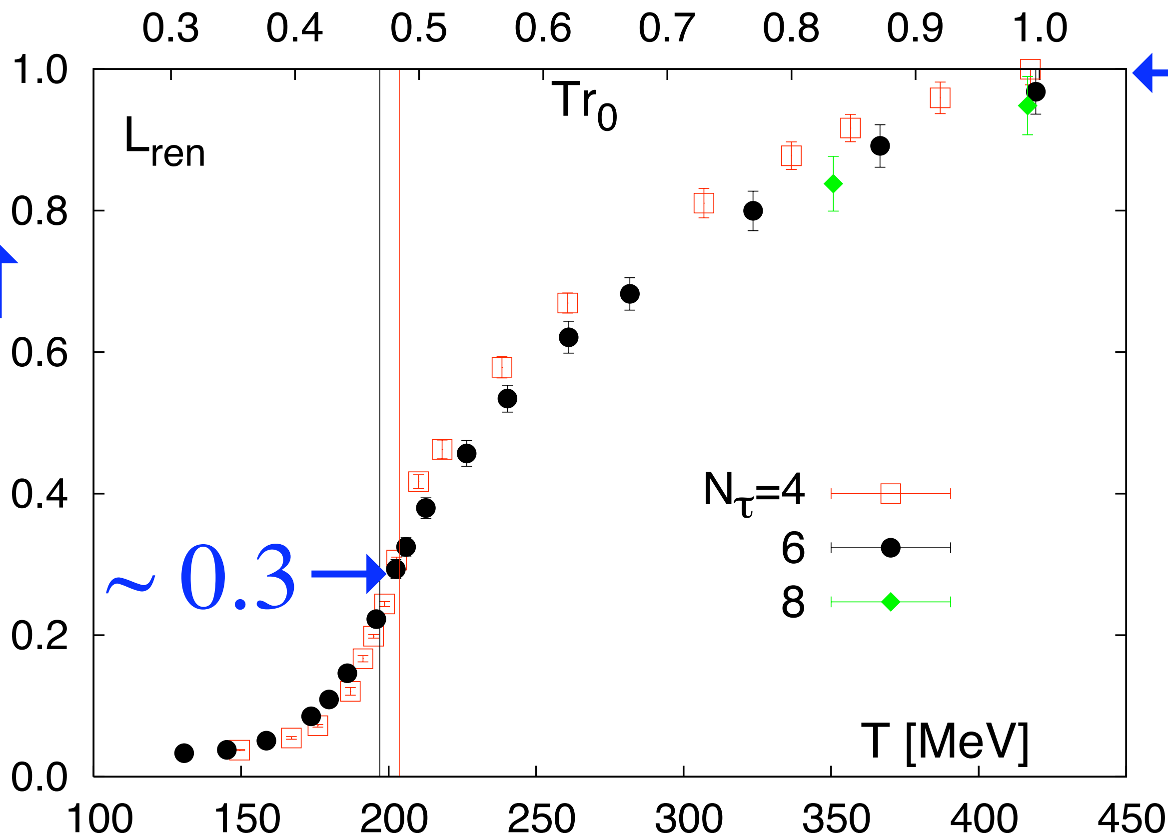
(Laine & Schröder: hep-ph/0503061) So why phase transition?

"semi"-QGP: phase with *partial* deconfinement near T_c

Measure on lattice through *renormalized* Polyakov loop

Triplet loop ↑

Renormalized,
SU(3) gauge
with quarks



← 1.0

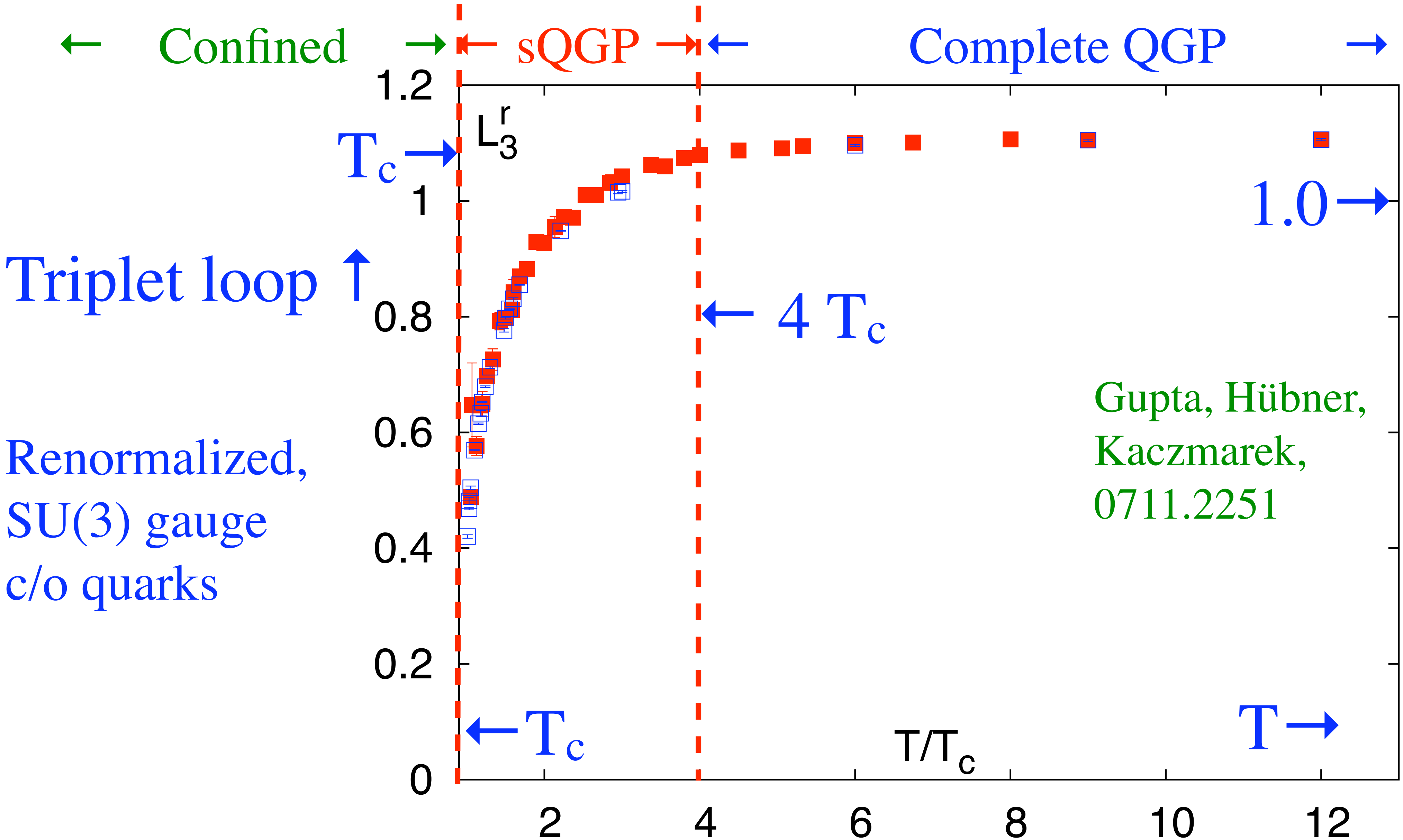
Cheng et al,
0710.0354

T →

T_c ↑

Semi- and complete QGP in pure SU(3)

Semi-QGP, T: $T_c \rightarrow \sim 4\, T_c$. Complete QGP: $T > 4\, T_c$



From RHIC to the LHC

Assume: RHIC probes region *above* T_c

LHC probes to temp.s ~*twice* as big

"strong" QGP: LHC ~ RHIC (majority)

$\alpha_s(T)$ big at T_c, stays big at 2 T_c : η/s stays *small*

No large increase in multiplicity

Nearly ideal hydro. works, large elliptic flow

"semi" QGP: LHC ≠ RHIC (*distinct* minority)

LHC starts initially in the complete QGP,

then cools through semi-QGP

Large *decrease* in η/s, $2\,T_c \rightarrow T_c$

(Y. Hidaka & RDP 0803.0453)

Large η/s for $T > 2\,T_c$: *increased* multiplicity

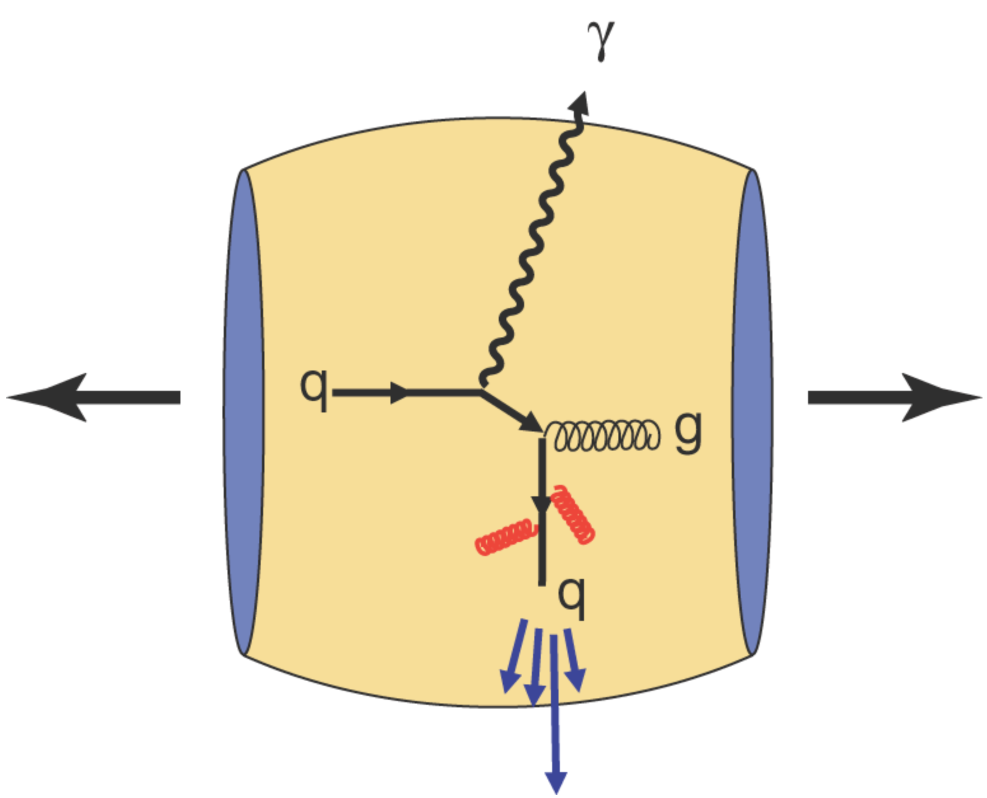
Hydro.? Elliptic flow not as large as ~ ideal.

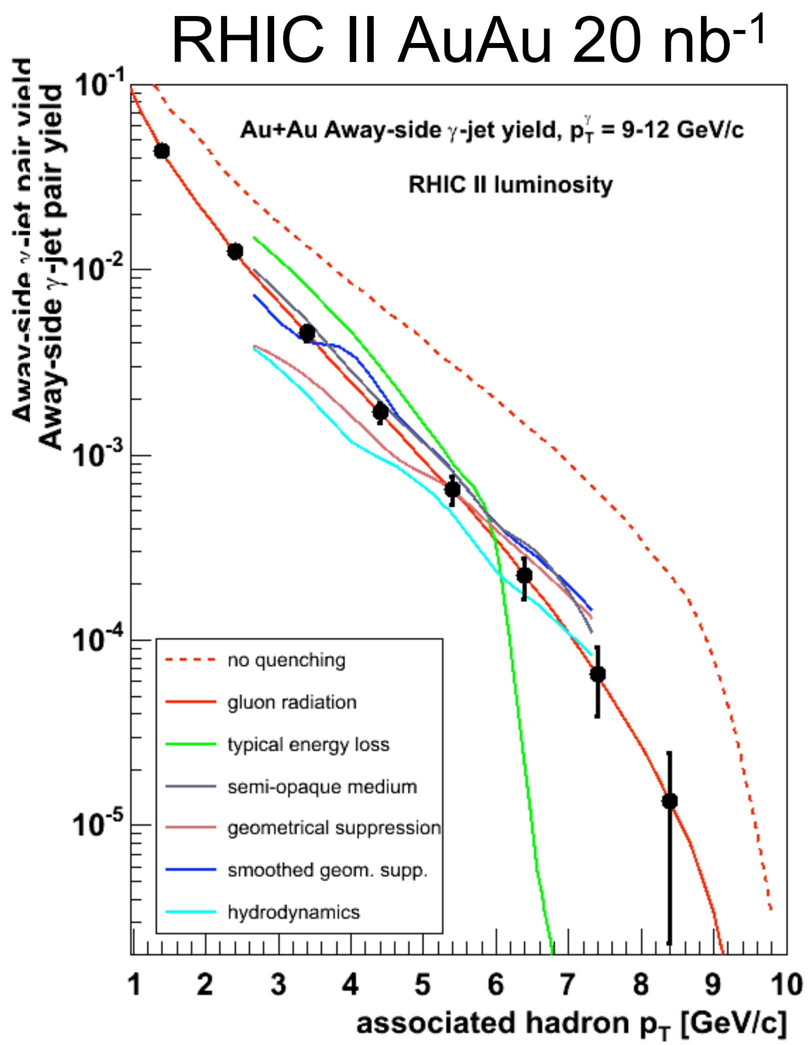
We'll know soon!

"A possible eureka."

Upgrade to RHIC II: Gamma + Jet

Luminosity upgrade (RHIC II) allows one to study gamma + jet:
pin down energy loss!





Definition of Cornucopia

1. A goat's horn overflowing with fruit, flowers, and grain, signifying prosperity. Also called horn of plenty.

2. Greek Mythology: The horn of the goat that suckled Zeus, which broke off and became filled with fruit. In folklore, it became full of whatever its owner desired.

3. A cone-shaped ornament or receptacle.

4. An overflowing store; an abundance:
a cornucopia of experimental opportunities.

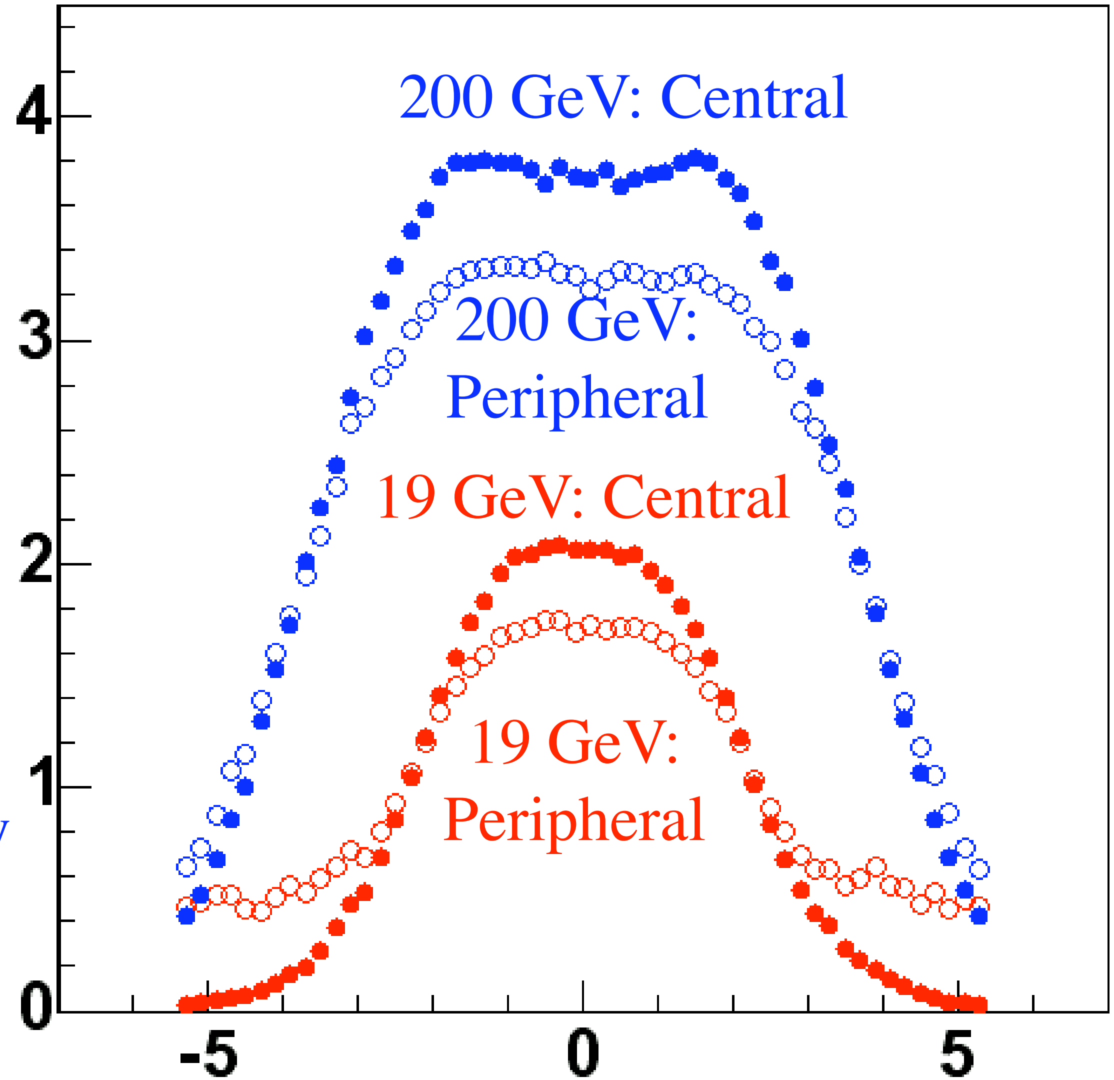
(Narrow) central plateau at RHIC

No big surprises in multiplicity at RHIC, moderate increase from SPS.
c/o particle ID, use η = pseudo-rapidity below: broad central plateau?
With particle ID (y = rapidity), *narrow* central plateau first arises at RHIC
STAR, BRAHMS: dN/dy and <p_t> constant over ± .5 in y, out of ± 5.0.

dN/dη/ ↑

Total multiplicity,
particles
/"# participants"

No particle ID,
η=*pseudo*-rapidity



200 GeV, RHIC
900 particles
/unit η

19 GeV, SPS
600 particles
/unit η

η→

Hydro and mean p_t for strange particles?

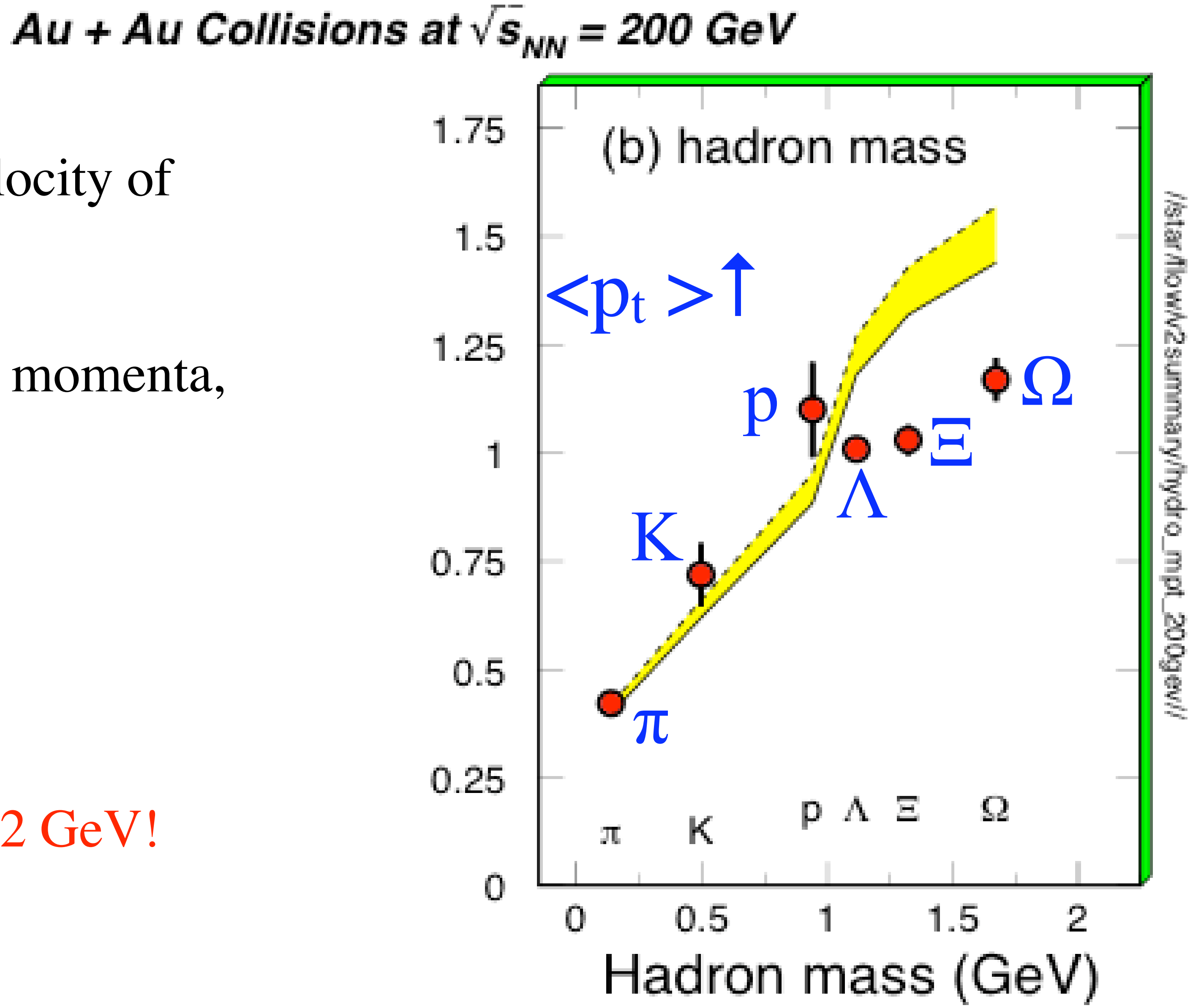
Hydrodynamics:
particles travel with velocity of rest frame, v/c ~ 0.6

Hence mean transverse momenta, $\langle p_t \rangle \sim$ mass * v/c

Valid for π, K, p

But heavier particles:
Λ, Ξ, and even Ω have ~ constant $\langle p_t \rangle \sim$ 1 - 1.2 GeV!

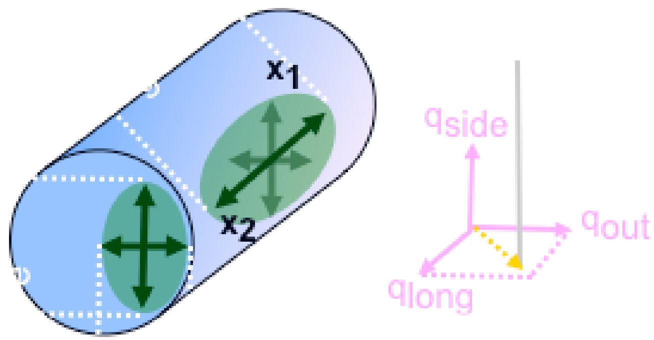
Odd.



HBT radii: collisions "*explosive*"

Hanbury-Brown-Twiss: two-particle correlations of identical particles
= sizes at freezeout. Three directions:
along beam R_{long}, along line of sight R_{out}, perpendicular R_{side}.

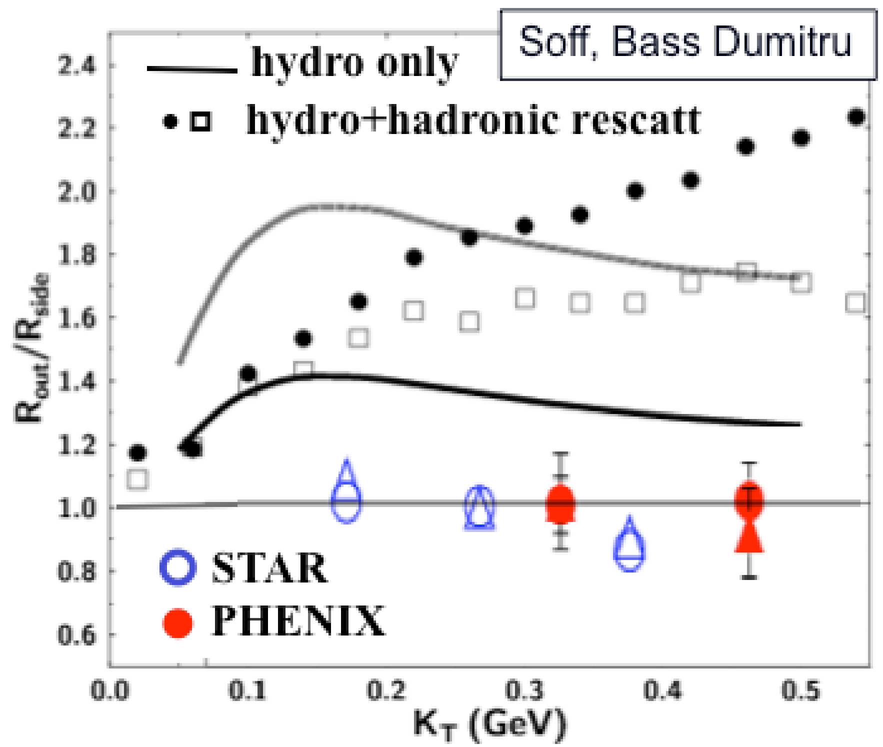
$$C(p_1, p_2) = N(p_1, p_2)/(N(p_1)N(p_2))$$
$$= 1 + \lambda \exp(-R^2_{HBT}(p_1 - p_2)^2)$$



Hydro.: $R_{out}/R_{side} > 1$, *increases* with p_t
("burning log")
Exp.: $R_{out}/R_{side} \sim 1.0$, *flat* with p_t

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

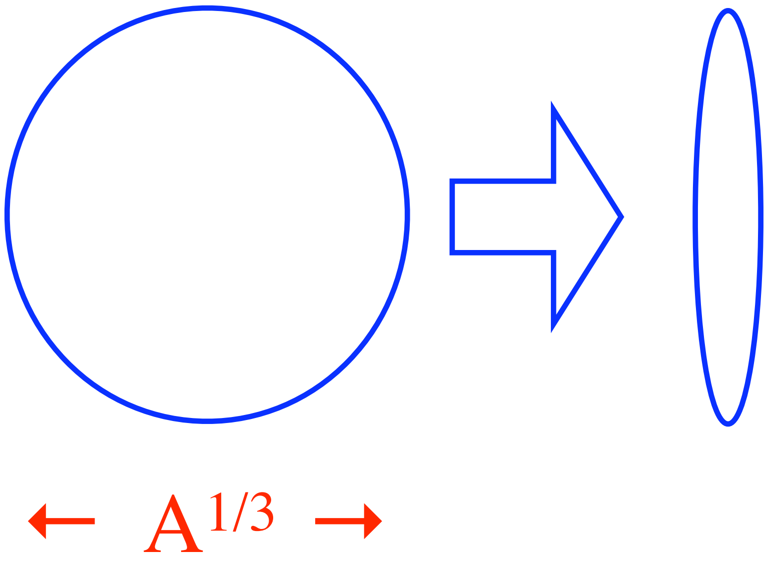
HBT "explosive": blast wave works:
Space-time history shell with
lifetime ~ 8-9 fm/c, emission ~ 2 fm/c



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

Initial State of AA collisions: Color Glass

Incident nucleus Lorentz contracted at high energy,



color charge bigger by $A^{1/3}$

$A \to \infty$: semi-classical methods, dominated by gluons at small x: "Color Glass"
Iancu & Venugopalan, hep-ph/0303204

"Saturation momentum"

$$Q_s^2 \sim \left(\frac{A}{x} \right)^{1/3}$$

Initial State Color Glass. *Final* State?

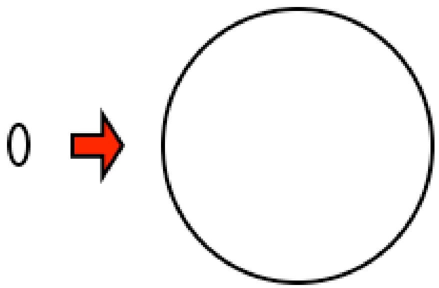
Also: Saturation momentum Q_s function of rapidity...

Predictions for pA...

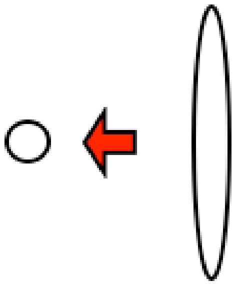
Color Glass suppression: in dA, by the deuteron

Fragmentation region ~ rest frame. Incident projectile Lorentz contracted:

nuclear frag.=>



proton frag.=>



Nuclear fragmentation region: proton contracted. Study final state effects

Proton fragmentation region: study initial state effects

BRAHMS in dA:

enhancement @ zero rapidity

suppression @ proton frag. region.

Supports color glass initial state.

Need to study all rapidities.

R_dA: