A Unicorn at RHIC: the (s)QGP

At *very* high temperatures, expect hadrons (QCD) behaves qualitatively different:
new type of matter, Quark Gluon Plasma (QGP).

To see experimentally, collide heavy ions (AA) at high energies:

Relativistic Heavy Ion Collider, RHIC at Brookhaven; SPS & LHC at CERN.

Today:

Theory of the QGP, especially numerical "experiments" on a lattice

RHIC: Suppression of jets in AA collisions. Robust signal of new physics.

Non central collisions exhibit strong "flow"

Even heavy ("charm") quarks are suppressed, flow!

Not a perturbative QGP, instead "sQGP" (s?)

"Most perfect fluid on earth"?

Theory of Ads/CFT: hot "QCD" at infinite coupling.

Theorists all agog about a *wealth* of experimental data.

Myths can come true, but maybe not the ones you expect...

QCD: Quantum ChromoDynamics

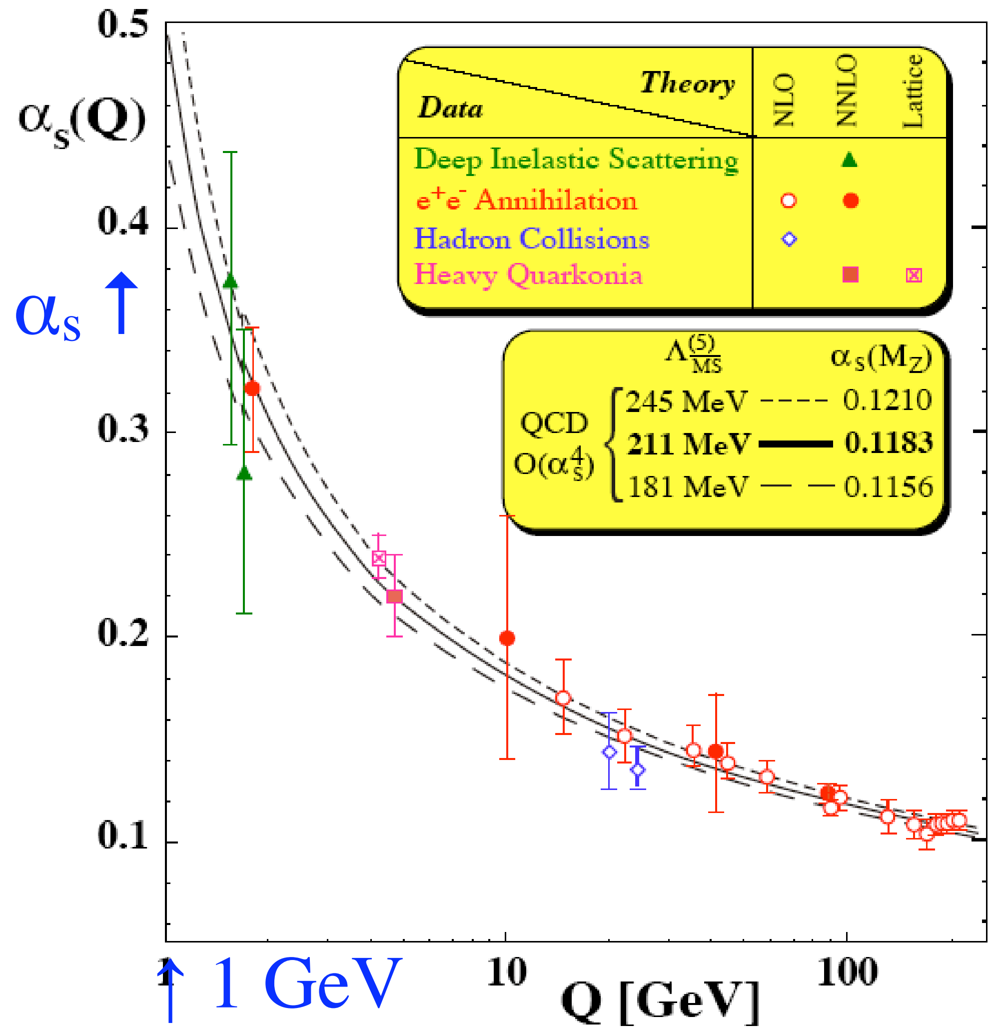
Gluons: spin-1, three colors, local SU(3) symmetry. Classically, *no* mass scale.
One dimensionless coupling, α_s, which “runs”with momentum.
Theory *uniquely* specified by value of α_s at *one* (finite) momentum.
Asymptotically Free (AF): α_s *vanishes* at *infinite* momenta

$$\alpha_s(p) \sim \#/\log(p) \ , \ p \to \infty$$

Perturbative > 1-2 GeV
powers of $\alpha_s \sim 1/\log(p)$
Non-perturbative < 1-2 GeV:
powers of (non-pert. mass)$^2/p^2$

AF => *ideal* gas at *infinite* temperature.
Natural to normalize to ideal gas values.

Quarks: six “flavors”, coupled to glue
Light: up, down (u,d). Kinda: strange (s)
Heavy: charm (c), bottom, top.



QCD & Confinement

Non-perturbative effects => confinement. *Only color singlets observable.*

Quark + anti-quark = meson.

Very light: pions ($\overline{u}d$ ...), 140 MeV. kaons, ($\overline{u}s$ ...), 490 MeV

= Spin waves of global ("chiral") symmetry for light quarks, u, d, & s.

Three quarks = baryon.

Neutrons, protons (ddu, uud), 940 MeV; also strange (uds ...), 1-2 GeV

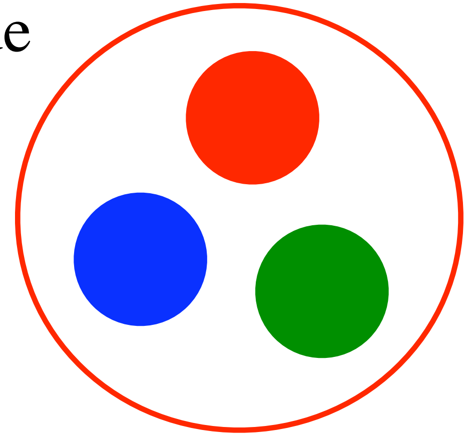
Charm mesons, J/Psi, ($\overline{c}c$) 3.1 GeV. *Glueballs?*

One model: MIT bag. Confine quarks & gluons inside bag =>

Costs Bag constant B ~ $(200\ \text{MeV})^4$; ~ perturbative inside

Dynamics of bag? Surface has *zero* width

Spectrum OK, ~ non-relativistic quark model



Large N Expansion

Instead of SU(3) color, consider SU(N). Claim: N=3 is “near” infinite N!

Gluons: SU(N) matrix, so # ~ N^2-1. Quarks: SU(N) vector, so # ~ N.

=> large N exp. is dominated by glue.

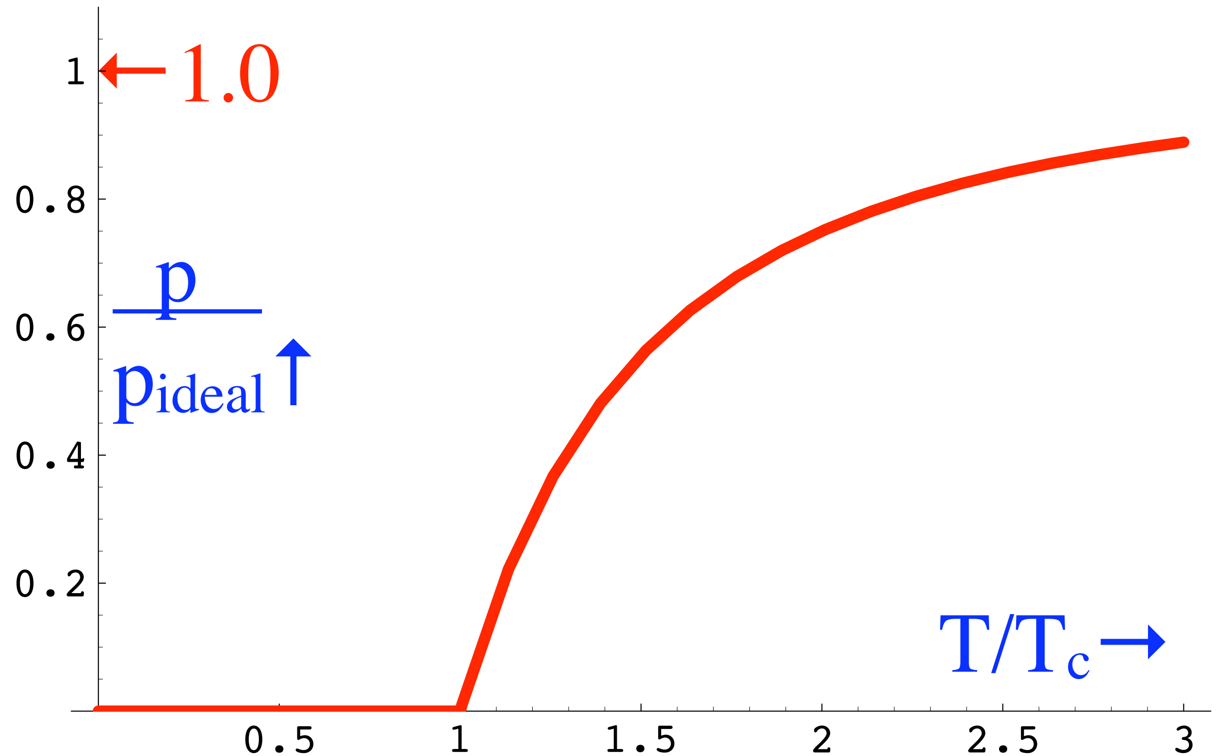
AF => *ideal* gas of ~ N^2 gluons at T = ∞. Presumably for all $T > T_c$

Confinement => only color singlets, so # hadrons ~ 1 for $T < T_c$

At *infinite* N:
pressure/(ideal gas pressure)
is an *order parameter:*

Ratio = 0 below T_c (~$1/N^2$) ,
≠ 0 above T_c , → 1 as T→∞.

Possible form for this ratio =>



Numerical "experiments": the lattice

How to compute non-perturbatively? Put QCD on a lattice, with spacing "a".

In QCD, AF + renormalization group => *unique* answer as a→0, continuum limit

Approximate ∞-dim. integral by finite dim.: "Monte Carlo"

In practice: need to "improve" to control lattice effects ~ a^2, etc.

For pure gauge (*no* quarks) near continuum limit from mid-'90's!

Compute equilibrium thermodynamics: pressure(temperature) = p(T)

Lattices: 6-8 steps in time, 24-32 in space => $8\ 32^3\ 8 = 10^6$ dim. integral

With dynamical quarks, much harder: today, *not* near continuum for light quarks

Quarks non-local, difficult to treat (global!) "chiral" symmetry of light quarks

Today: only $T \neq 0$, *not* dense quarks at T=0

With quarks: *orders* of magnitude more difficult

BIG calculations done on BIG machines...

To the right: "QCDOC", QCD on a chip

RIKEN/BNL: 12,000 nodes, 20 teraflops...

Lattice: SU(3) gluons deconfine

Confined phase at T=0: only "glueballs". *Lightest* glueball 1.5 GeV

Deconfinement at $T_c \sim 270$MeV ± 10% *Small* relative to glueball masses.

Pressure *very* small below T_c: *very* much like large N!

MIT bag model does *not* work $p_{\rm MIT}(T) = \# T^4 - B$

"Fuzzy" bag does:

$$p_{\rm fuzzy}(T) = \#(T^4 - T_c^2\, T^2)$$

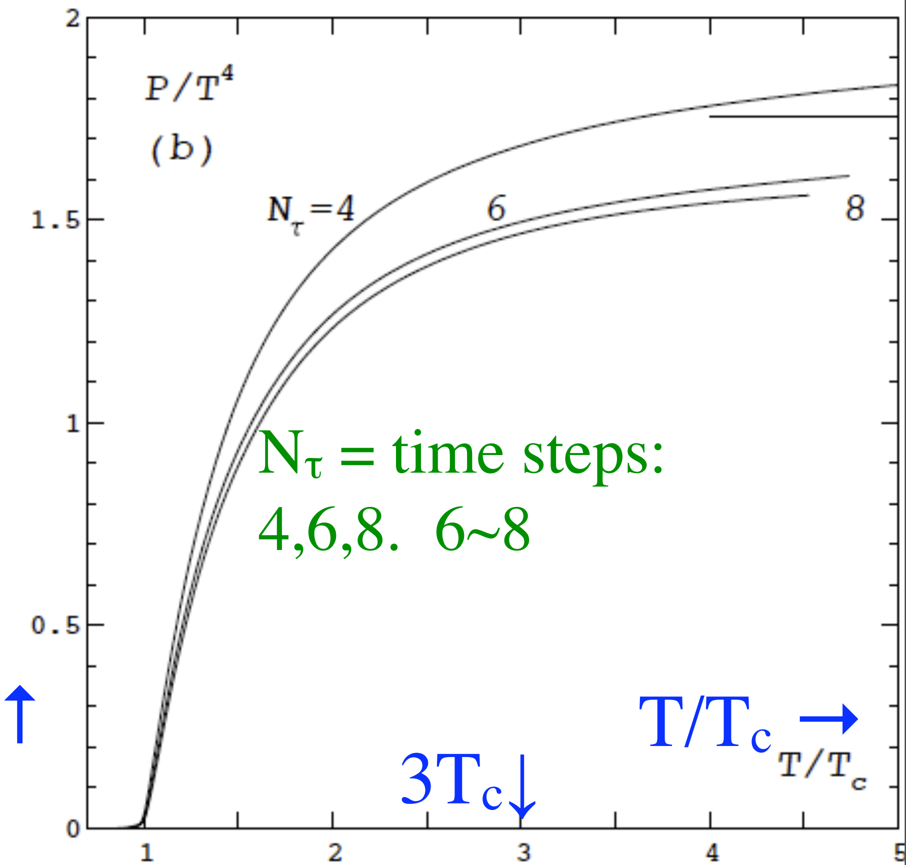
= 90% of ideal gas => T^4 ~ perturbative

Term ~ T^2 non-pert. power law correction

Transition weakly first order

~ Z(3) Potts model

$p(T)/T^4$↑



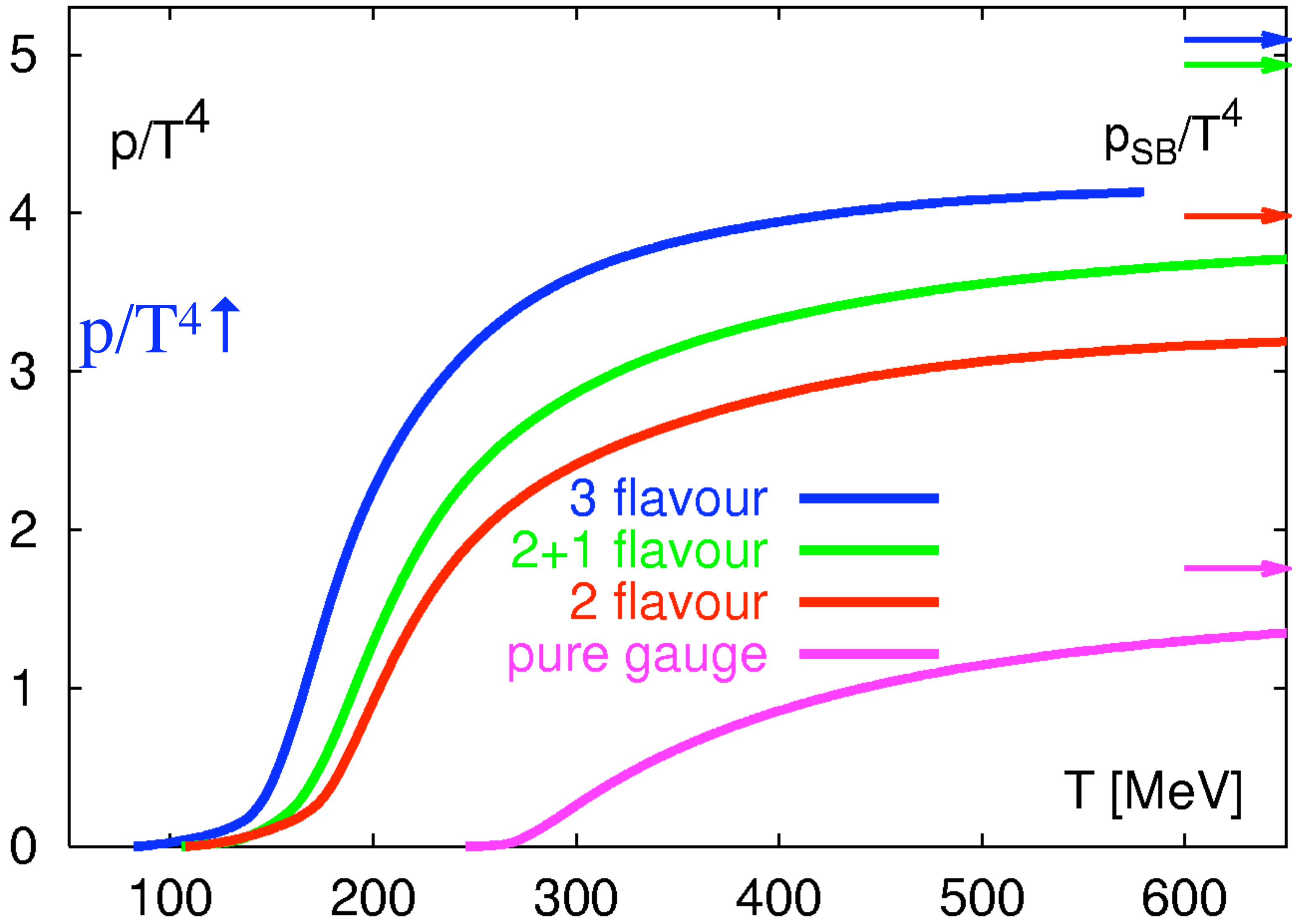
Lattice: QCD, with quarks

Adding quarks: ideal gas value increases by ~ 3

"T_c" decreases. Today: ~ 190 MeV ± ? 1st order transition washed out, *crossover*.

Pressure nonzero < T_c : from pions, kaons..., masses ~ T_c

Pressure within 20% of ideal by ~ 3 × T_c. Different behavior?



←ideal gas: QCD

←ideal gas: pure glue

T→

Lattice thermo.: QCD & "flavor independence"

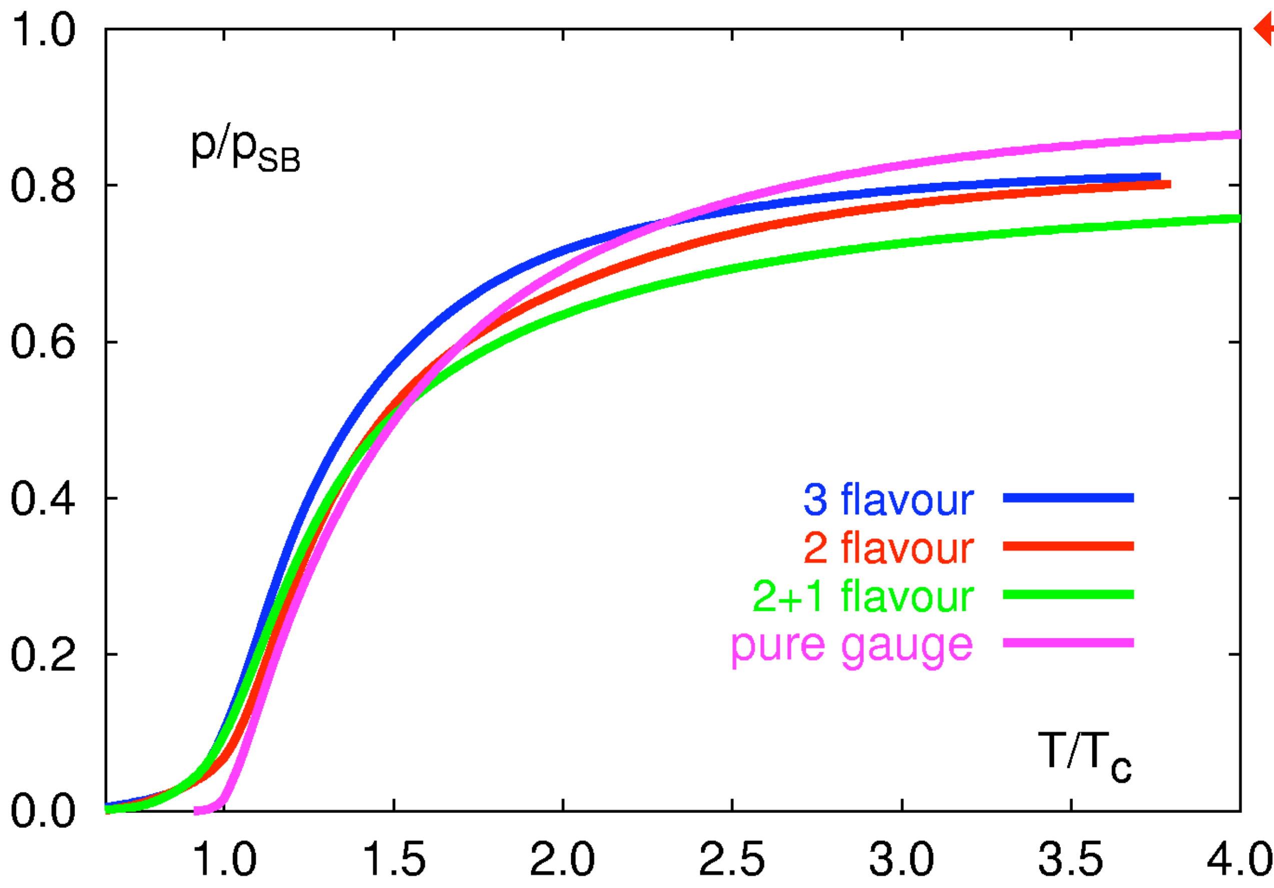
Bielefeld: properly scaled, ≈ *universal* pressure
Transition dominated by deconfinement

$$\frac{p}{p_{ideal}}\left(\frac{T}{T_c}\right) \approx \text{const.}$$

In *all* cases so far, chiral symmetry restored at *same* T_c as deconfinement: *why?*

Is transition from confined phase, directly to nearly ideal QGP?

$\dfrac{p(T)}{p_{ideal}(T)}$ ↑



←1.0

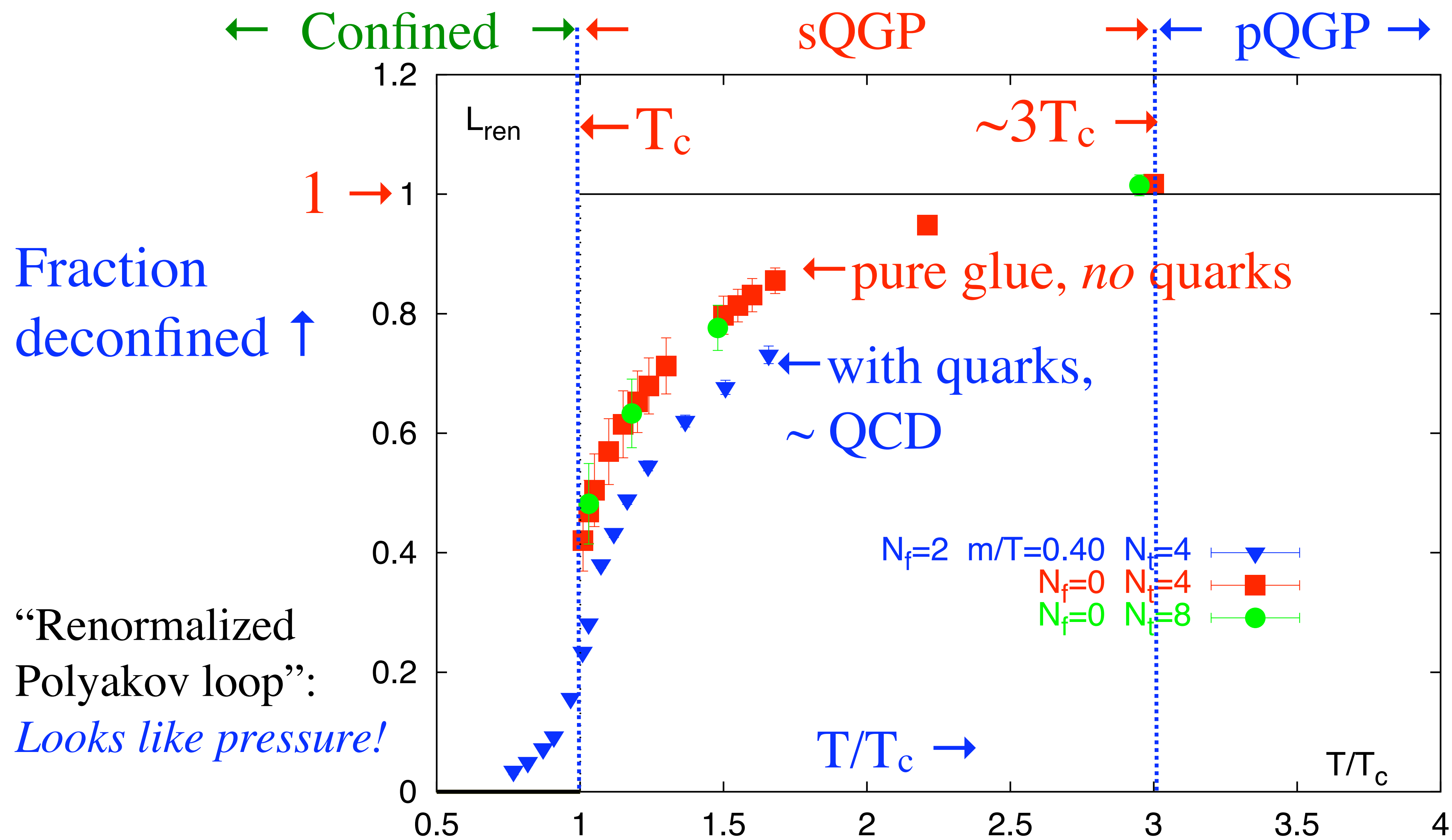
T/T_c→

Partially deconfined, T_c to ~ 3 T_c: "sQGP"

On lattice, can measure *fraction of deconfinement*

T > 3 T_c : fraction ~ 1, => ~ perturbative QGP

T_c → 3 T_c : fraction < 1, partially deconfined. "sQGP" (s?)



The “sQGP”: *not* strong coupling

“Helsinki Dogma”: resum pert. thy. to 4 loop order. *Fails* below ~ 3 T_c

Sure! Coupling big below 3 T_c !

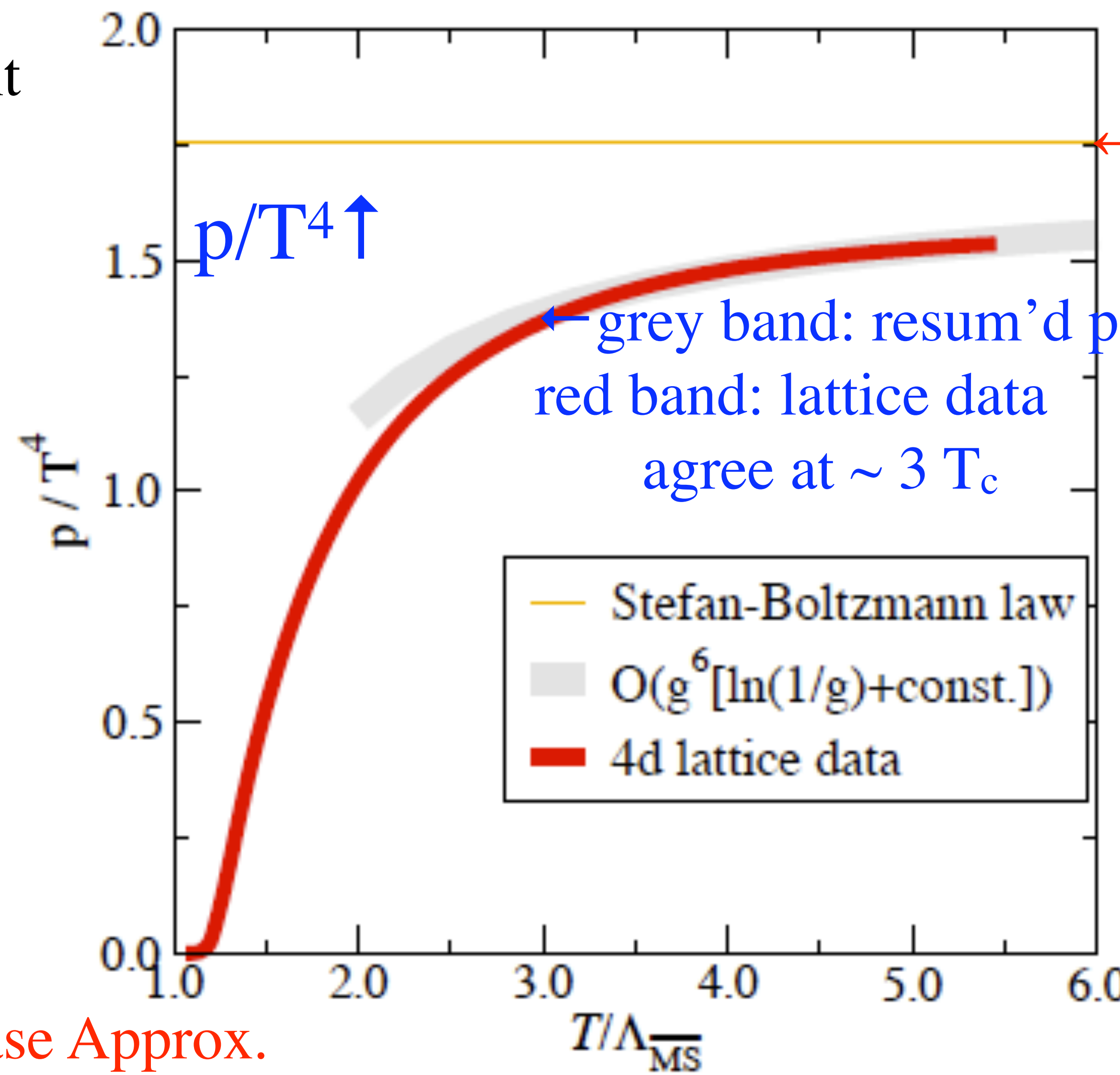
No! While deconfinement only partial at T_c, *coupling moderate*

$\alpha_s(9T_c) \sim \alpha_s(1.6\ \text{GeV})$!

So what *is* “sQGP”, T_c to ~ 3 T_c?

Semiclassical, dominated by solitons.

Eventually - NaRPA: Non-abelian Random Phase Approx.



←ideal gas: pure glue

Hunting for the "Unicorn" in Heavy Ion Collisions

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

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

AA collisions at high energies

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

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

pA, proton (or deuteron) on nucleus. Another check: QCD in "cold" nuclei

Why AA? Baryons are like hard spheres, so for A: 60 - 200,

transverse size $A^{2/3}$: 15 - 35 × proton. Big nuclei are big!

Total energy in the center of mass, $E_{cm} = \sqrt{s}$ (GeV); per nucleon, $\sqrt{s}/A = \sqrt{s_{NN}}$.

SPS @ CERN	5 => 17 GeV
RHIC @ BNL	20 => 200 GeV
LHC @ CERN	5500 GeV
SIS @ GSI	2 => 6 GeV

SPS, SIS Fixed Target

RHIC, LHC Colliders

LHC > '08

SIS @ GSI, Darmstadt > '12

Geometry of AA collisions at high energy

At *high* energies: nuclei Lorentz contracted along beam (15 fermi => 0.3 fermi)

AF => nuclei don't stop, pass through each other.

Collider: lab = center of mass frame

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

Baryons in original nuclei go down beam pipe, at large $\pm\, p_z$

For pp collisions: particles ~ constant for some range in p_z about $p_z = 0$:

"rapidity plateau" (rapidity ~ p_z; boost invariance)

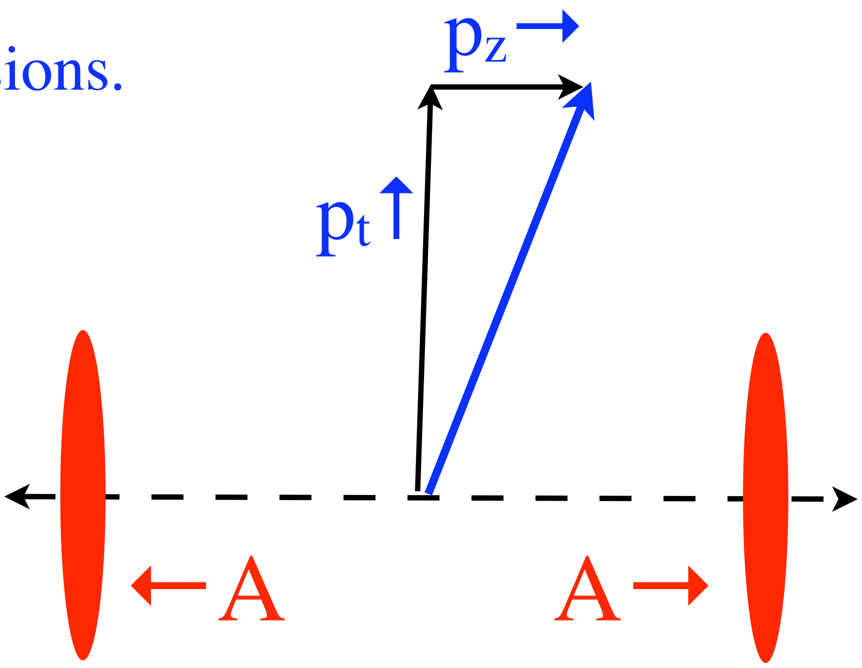
Bjorken: look at rapidity plateau in AA collisions.

Rapidity plateau ~ *free* of incident baryons.

=> most likely to be at nonzero temperature,

zero (quark) density.

Collider: central plateau 90° to beam



Typical Au-Au collision @ RHIC

Experiments @ RHIC:

“Big”: ~ 400 people. STAR & PHENIX

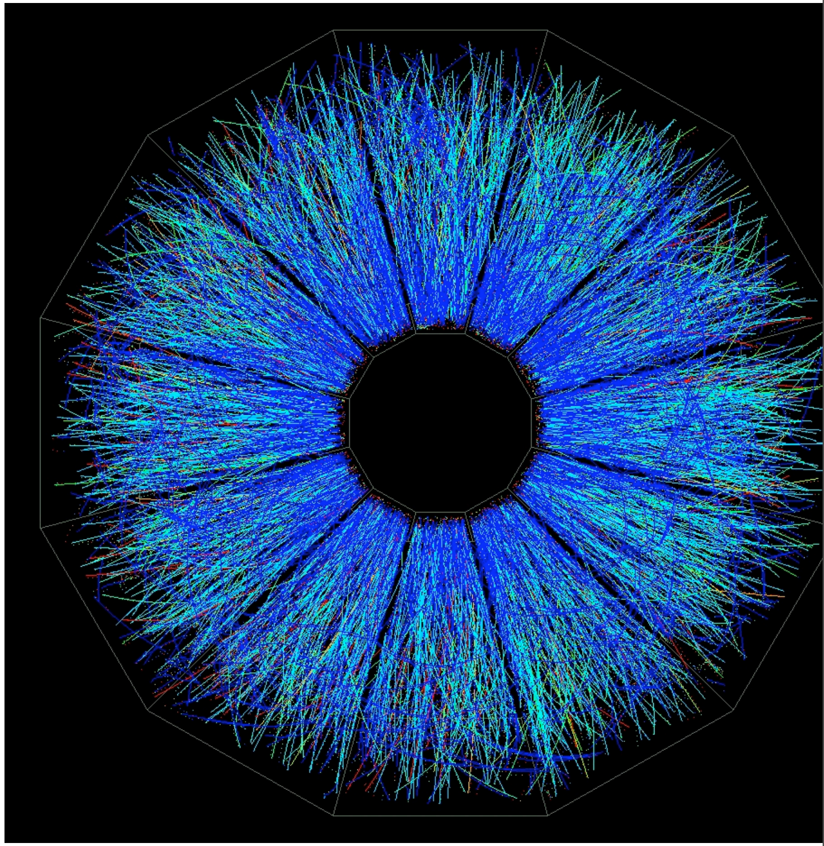
“Small”: ~ 50 people. PHOBOS & BRAHMS

No surprises in total multiplicity; ~ 1.3 A × pp:

total # particles ~ ~ log(total energy)

~total # experimentalists

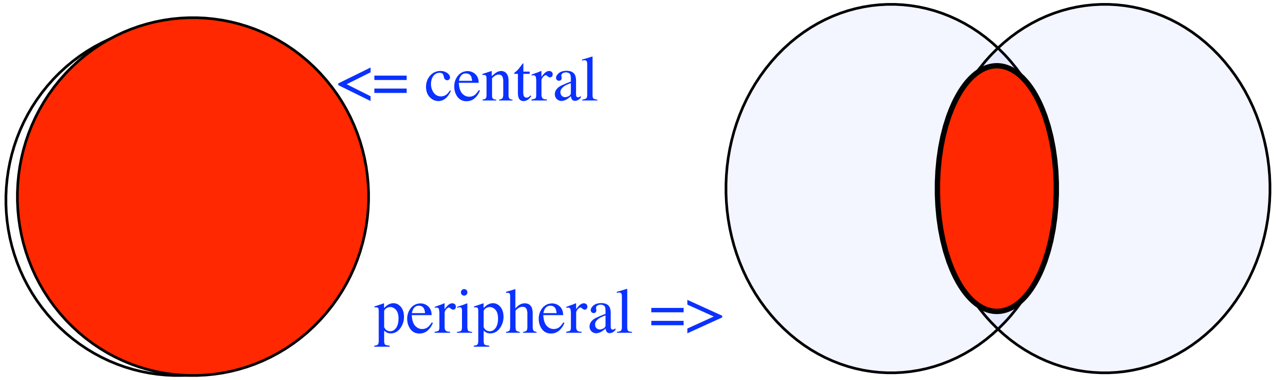
theorists ~ log(log(total energy)).



Need hunters more than dogs...

Total # particles/unit rapidity ~900↑

Also: can exp.’y measure how much nuclei overlap in transverse plane



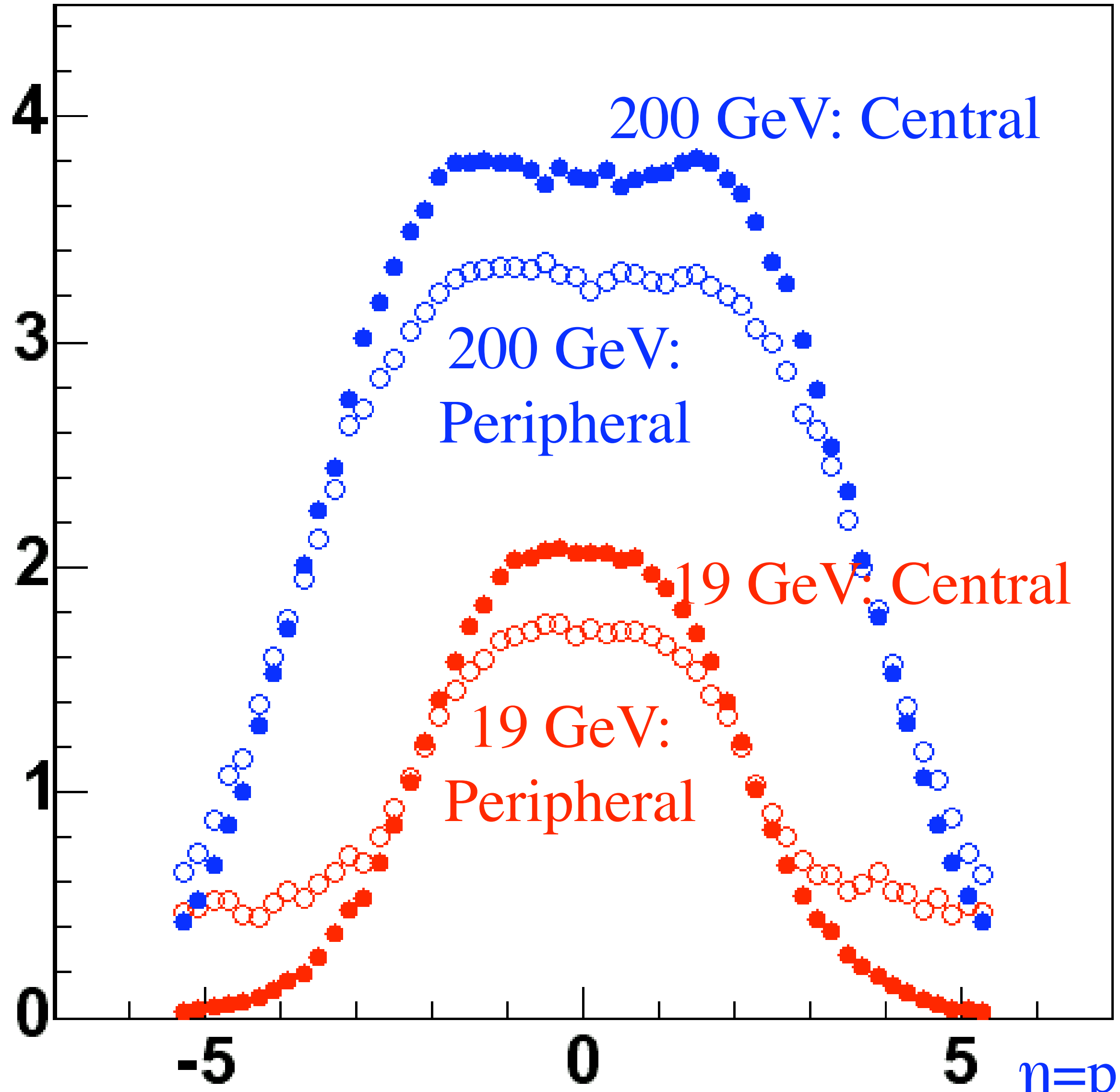
Overall multiplicity: slow growth

dN/dη/ ↑

N = # particles

η=”pseudo”-rapidity (no particle ID)

/ by # “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.

Rapidity plateau ± .5 (out of ± 5.0) for dN/dy (y = true rapidity)

The Tail Wags the (Dog) Unicorn

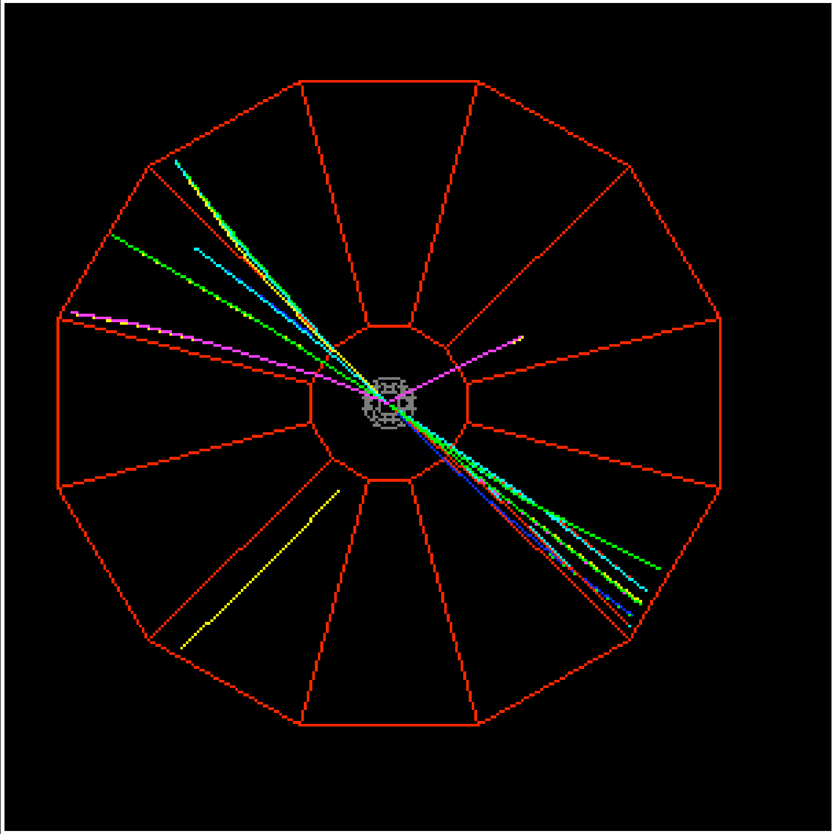
Body of the “Unicorn”:

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.

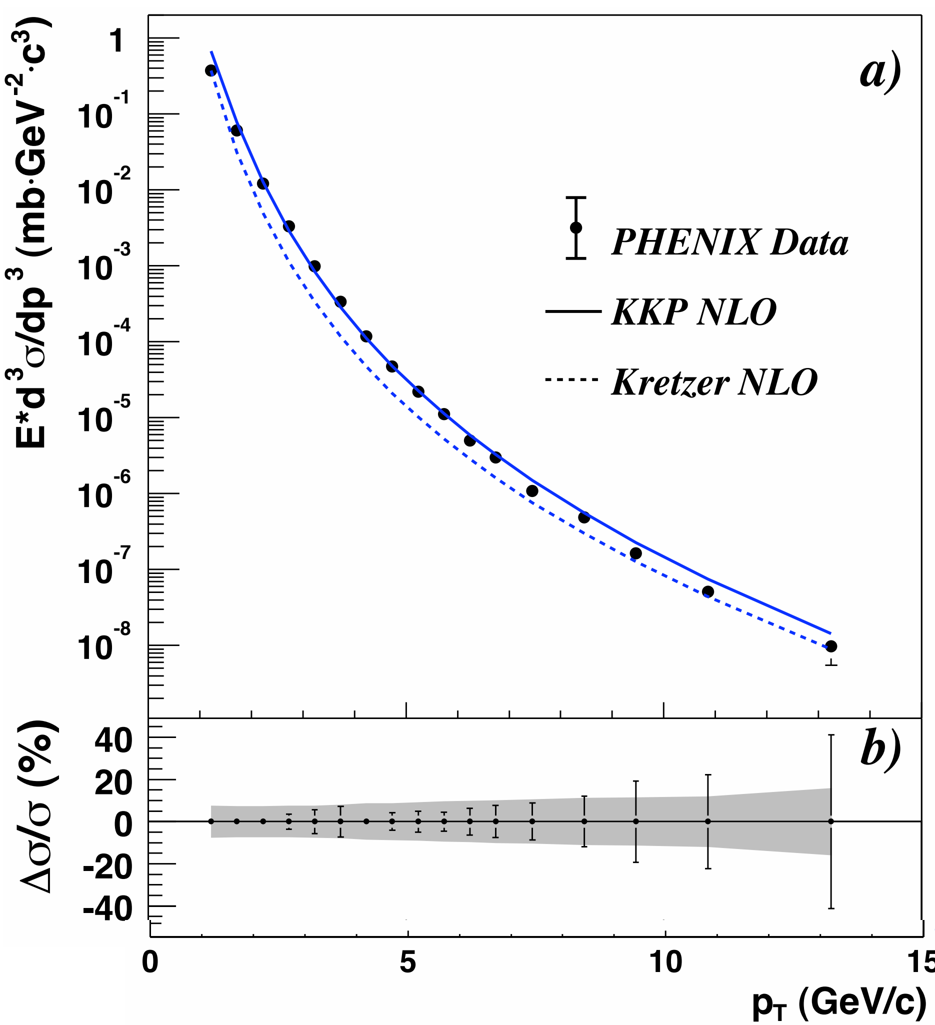
Jets: “seeing” quarks and gluons in QCD



At high transverse momentum (p_t), instead of hadrons, have ~ quarks & gluons: *jets*.

<= 2 jets from pp collision at RHIC.

By momentum conservation,
for each jet, there is a backward jet.



In pp coll.’s, jets can be computed for large p_t, down to p_t ~ 1 GeV.

Jets *rare*: particles at p_t ~ 2 GeV ~ .1 % of total!

p_t →

Look at jets in AA

"R_{AA}": *robust* signal of new physics

R_{AA}= for a given p_t, # particles central AA/($A^{4/3}$ # particles pp)

For π^0's, p_t : 2 -> 20 GeV, R_{AA} ~ 0.2. As if jets emitted *only* from surface!

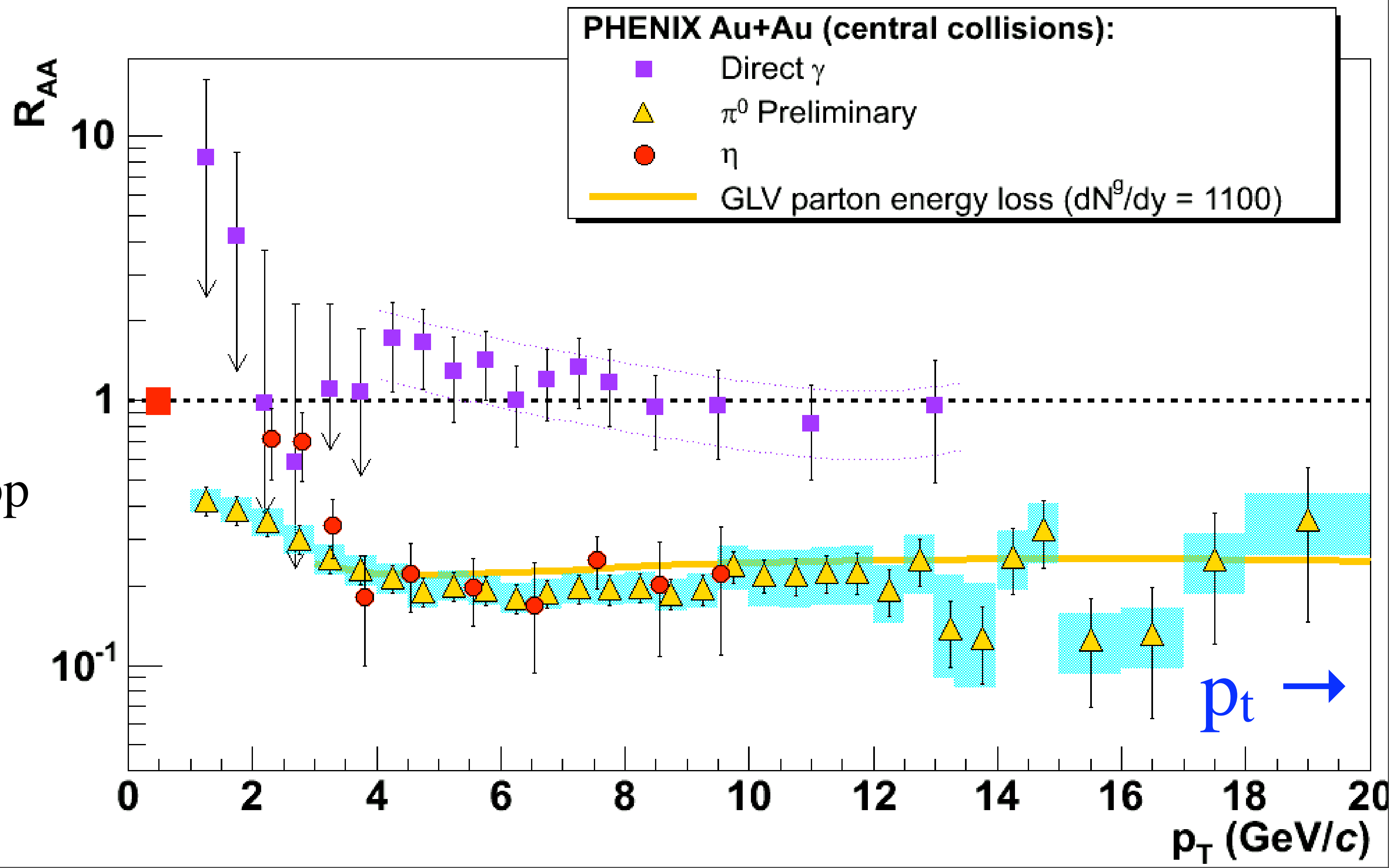
Due to "energy loss" in thermal medium?

$A^{4/3}$: *experimentally*: for γ's, R_{AA} ~ 1.0 π^0's "eaten", γ's not

R_{AA}: ↑

particles
central AA/
particles pp

A=200 =>



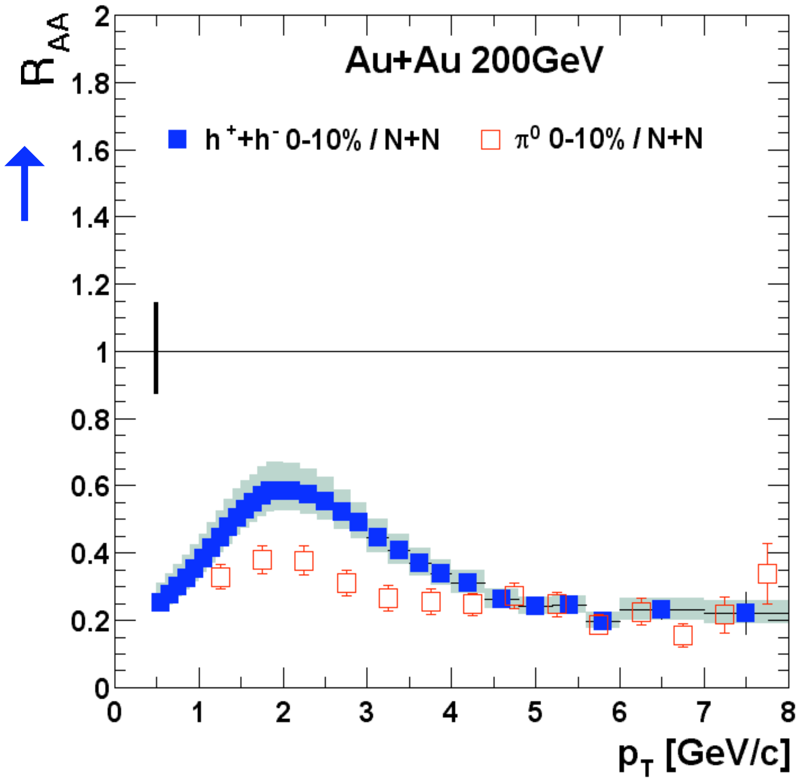
R_{AA} final state effect: *not* in R_{dA}

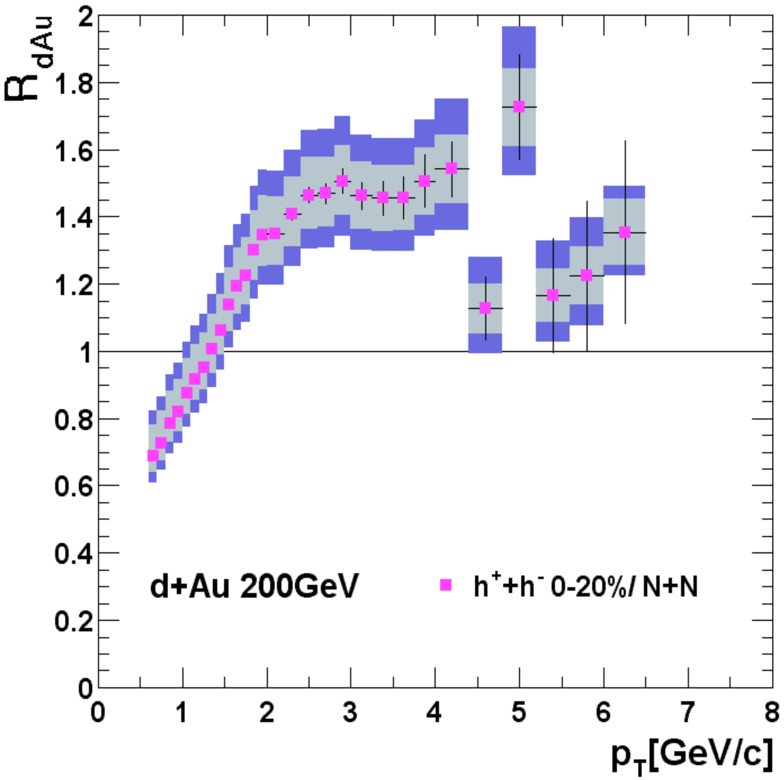
R_{dA}: like R_{AA}, but for dA coll.'s/pp coll.'s. At zero rapidity:

dA: *enhancement*, from initial state "Cronin" effect (=> 1 @ p_t > 8 GeV)

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

R_{AA} ↑





R_{dA} ↑

p_t →

Suppression in AA ↑

R_AA ~ 0.4 @ 3 GeV

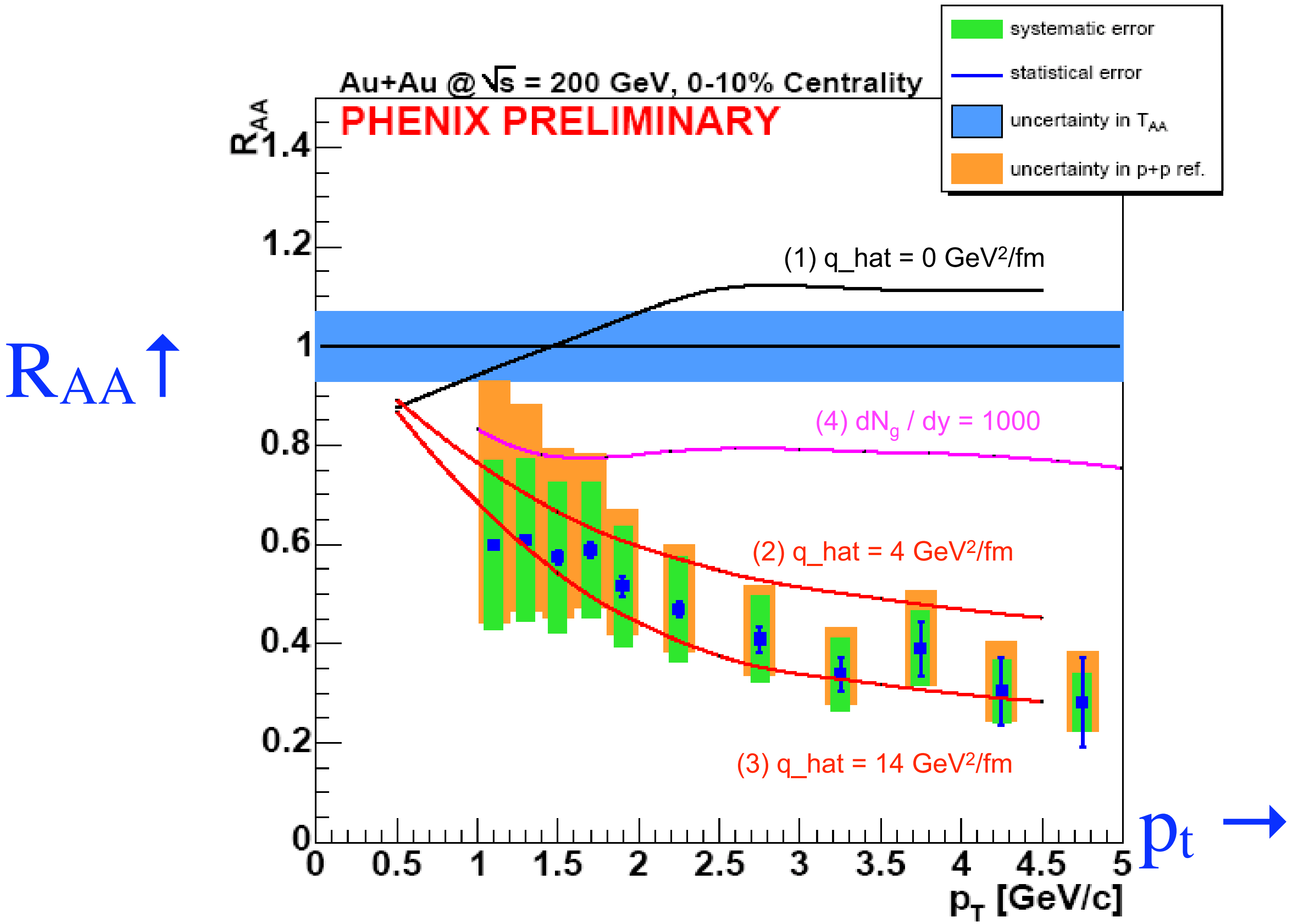
Enhancement in dA ↑

R_dA ~ 1.4 @ 3 GeV

R_{AA} for heavy quarks: also suppressed!

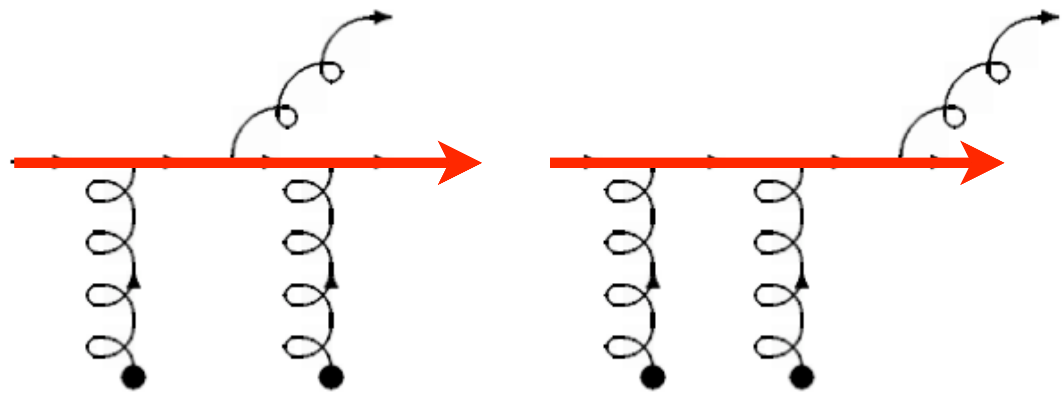
PHENIX: R_{AA} for charm quarks ~ light quarks!

Theoretically? Heavy quarks should feel medium less by T/m ~ 1/10 for charm. No sign of that!



Theory of R_{AA} : energy loss

Fast quark (or gluon) emits radiation, scatters off of thermal bath.



Like QED, but qualitatively different in QCD: emitted gluon emits more gluons, etc.

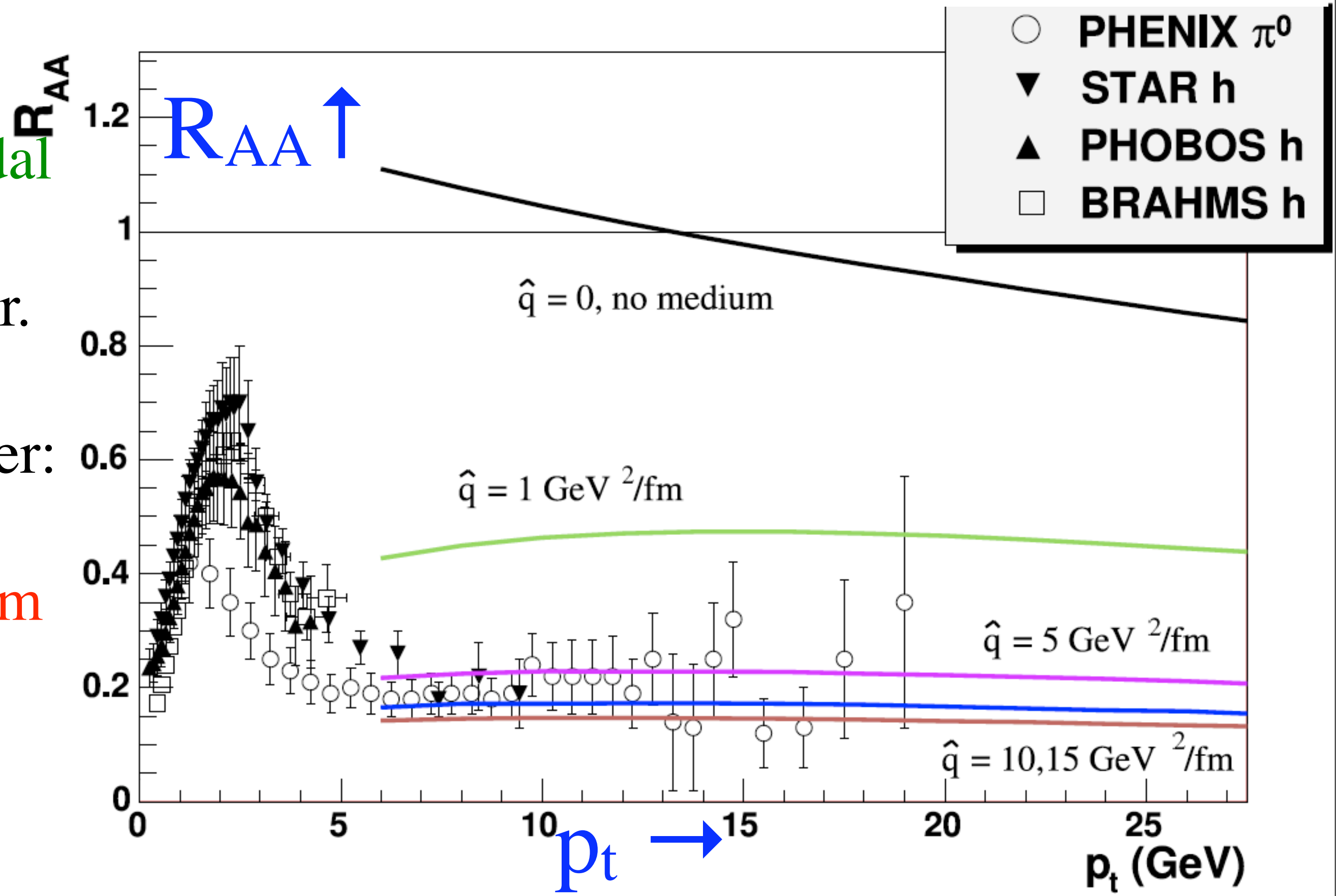
Involves LPM: Landau-Pomeranchuk-Migdal

Parametrized by one number.

Theorists disagree on number:

“weak” coupling ~2 GeV^2/fm

or “strong” ~15 GeV^2/fm?



Central AA collisions “eat” jets!

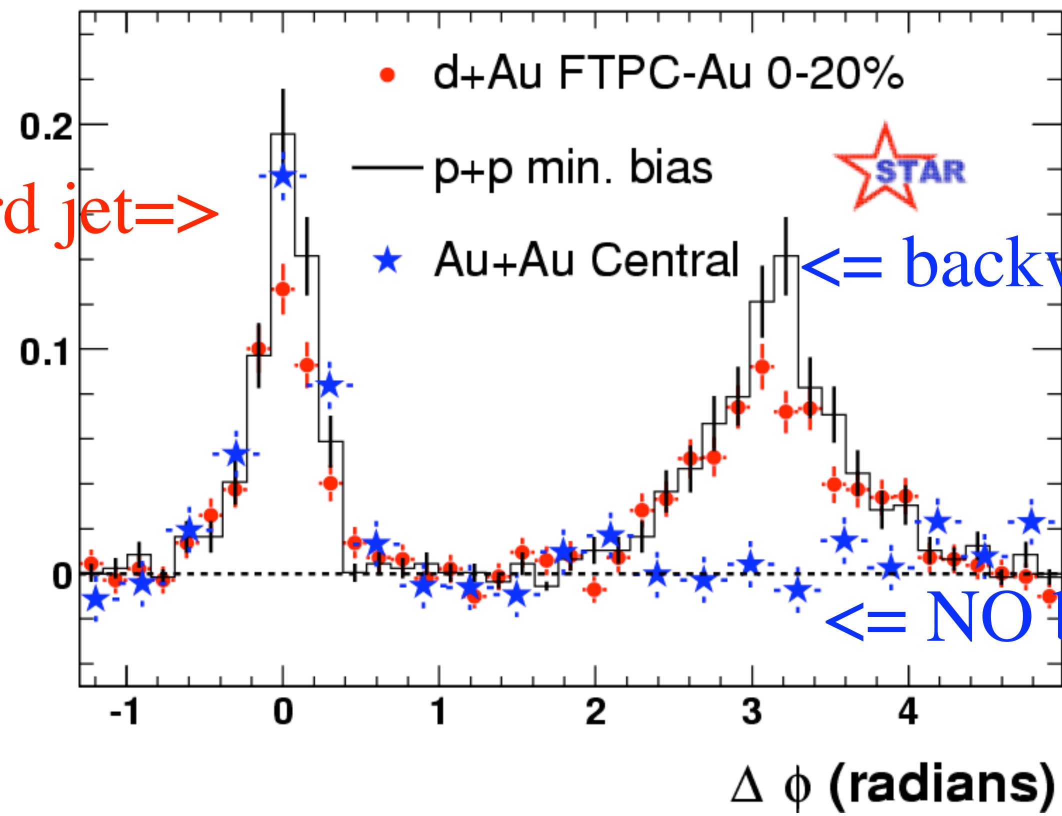
Unlike pp, in central AA, cannot trigger on individual jets. Can:

Trigger on “hard” particle, 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!*

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



forward jet=>

<= backward jet, pp

<= NO backward jet in central AA

Peripheral coll.'s: more jets eaten *out* of plane

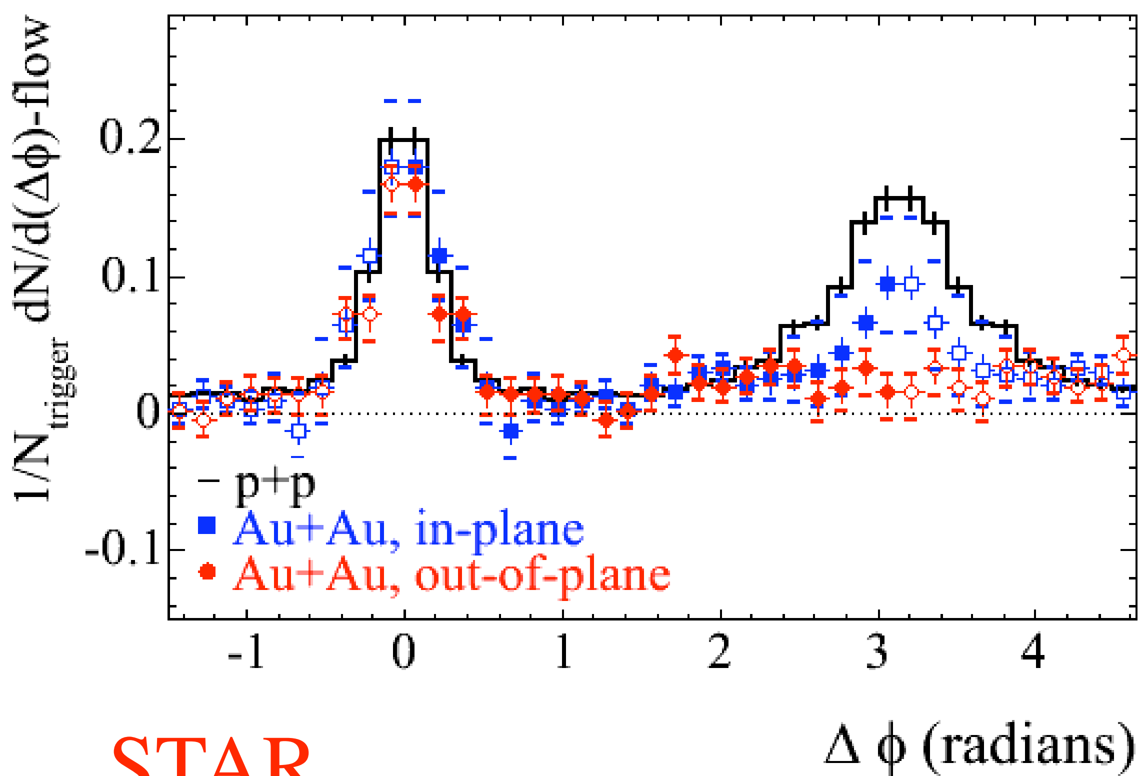
Peripheral collisions: " hot stuff" forms "almond":

Out of the reaction plane: more "hot stuff" than *in* plane

In the reaction plane, less hot stuff, but more cold nuclear matter

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

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



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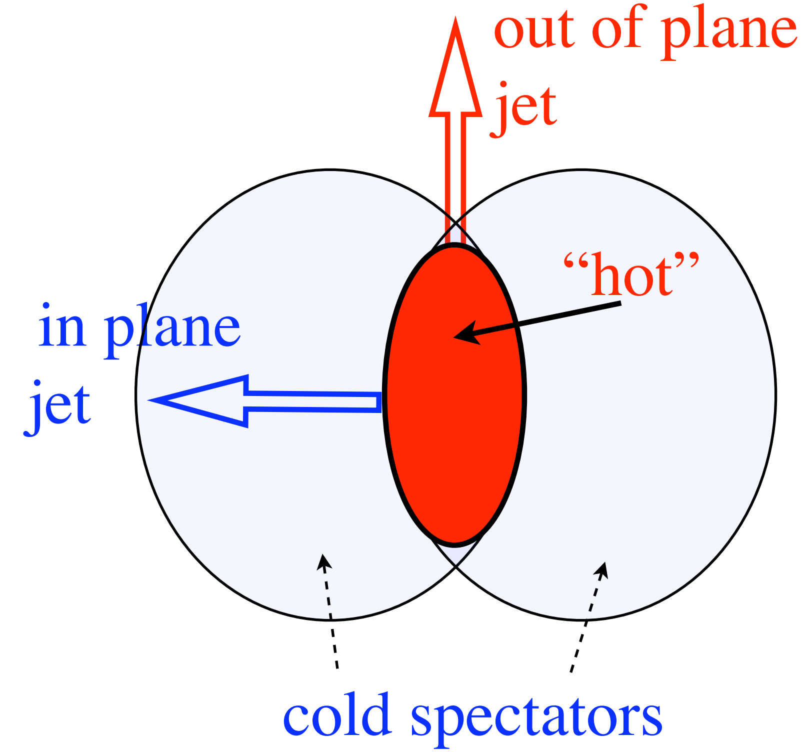
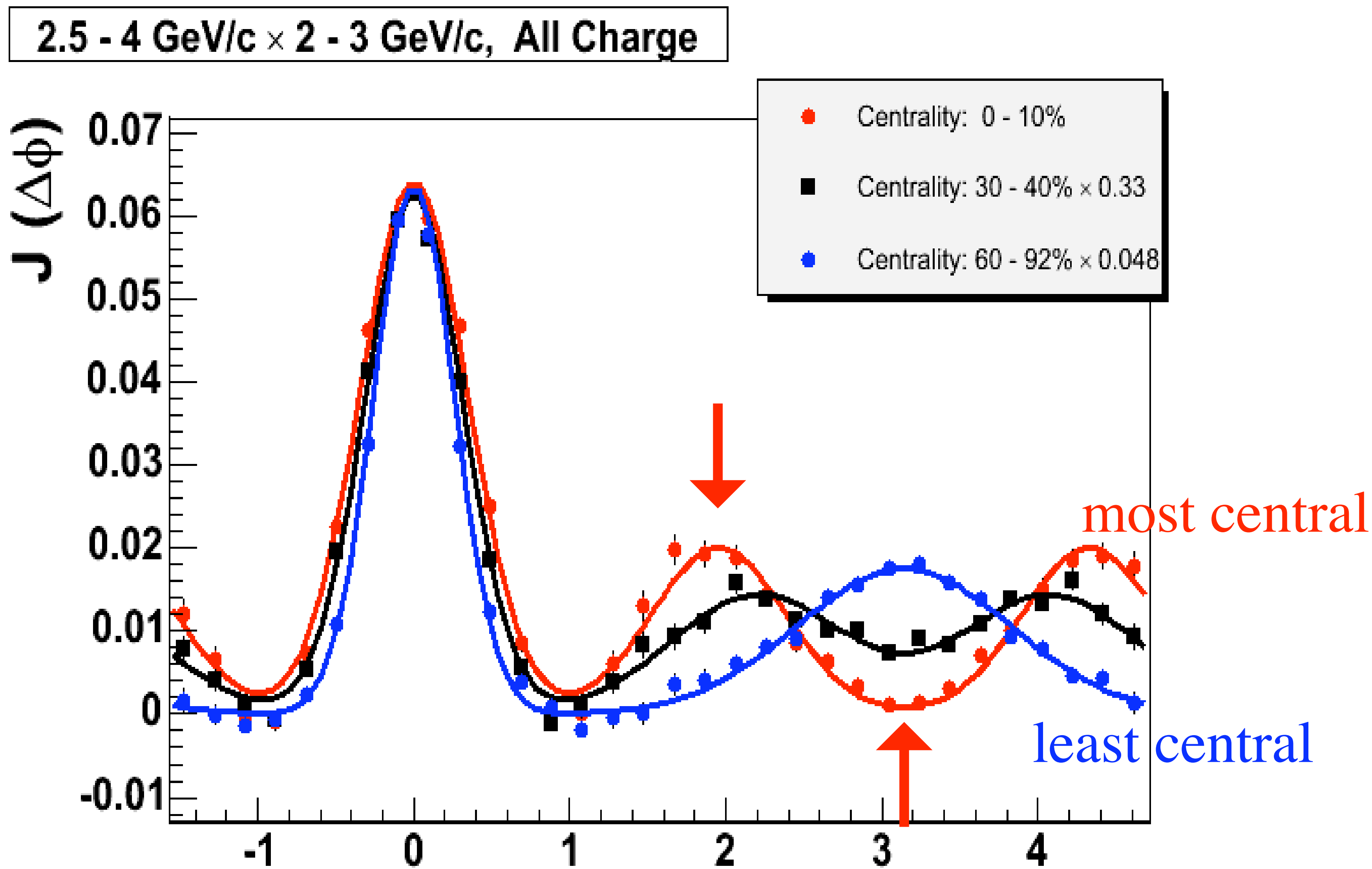


Peripheral collision

AA collisions modifies jet shapes

PHENIX: shape of away side jet appears to be modified by “stuff”:

Mach cone or Cerenkov radiation?



The Body of the Unicorn: the sQGP

Particles peaked about zero transverse momentum

T_c ~ 200 MeV: expect thermal to p_t ~ 2 GeV.

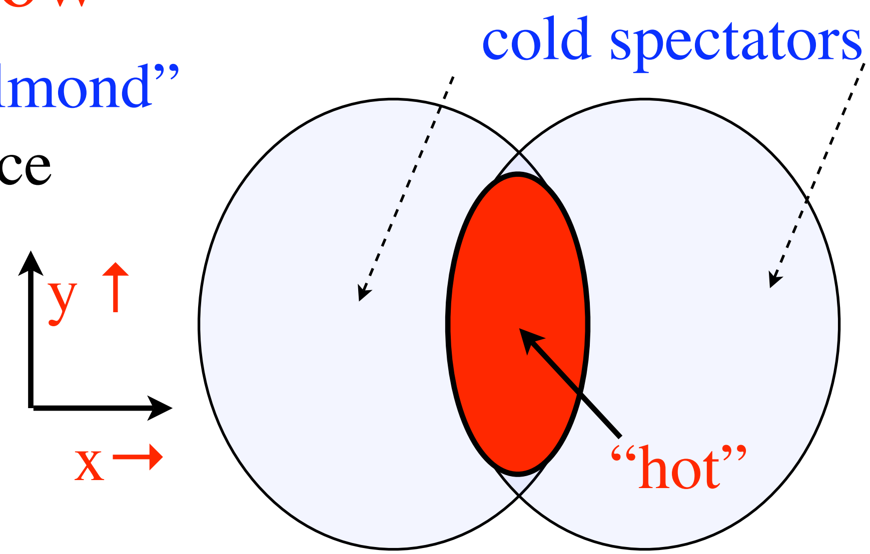
Thousands of particles, maybe hydrodynamics ok?

me→

←Unicorn

“Elliptic Flow”

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

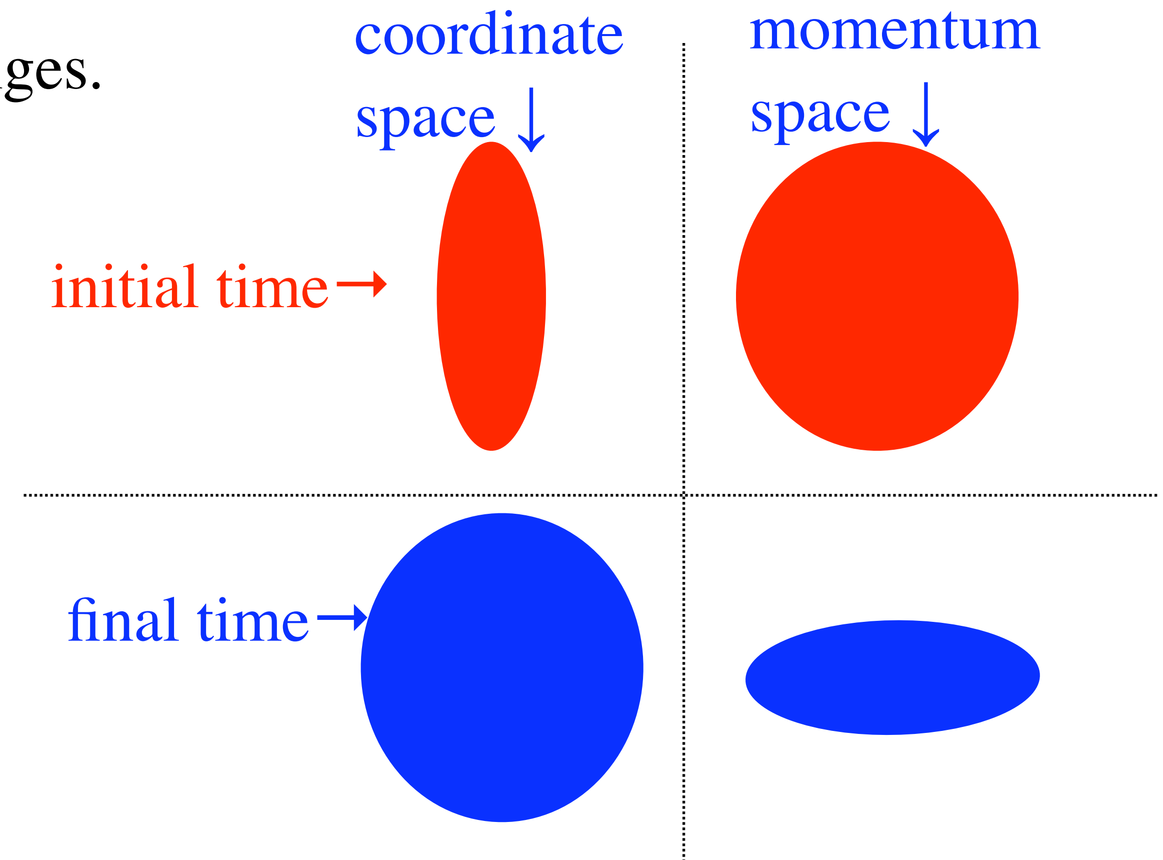


So start with spatial anistropy,

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

If particles free stream, nothing changes.

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



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

"Most perfect fluid on earth"

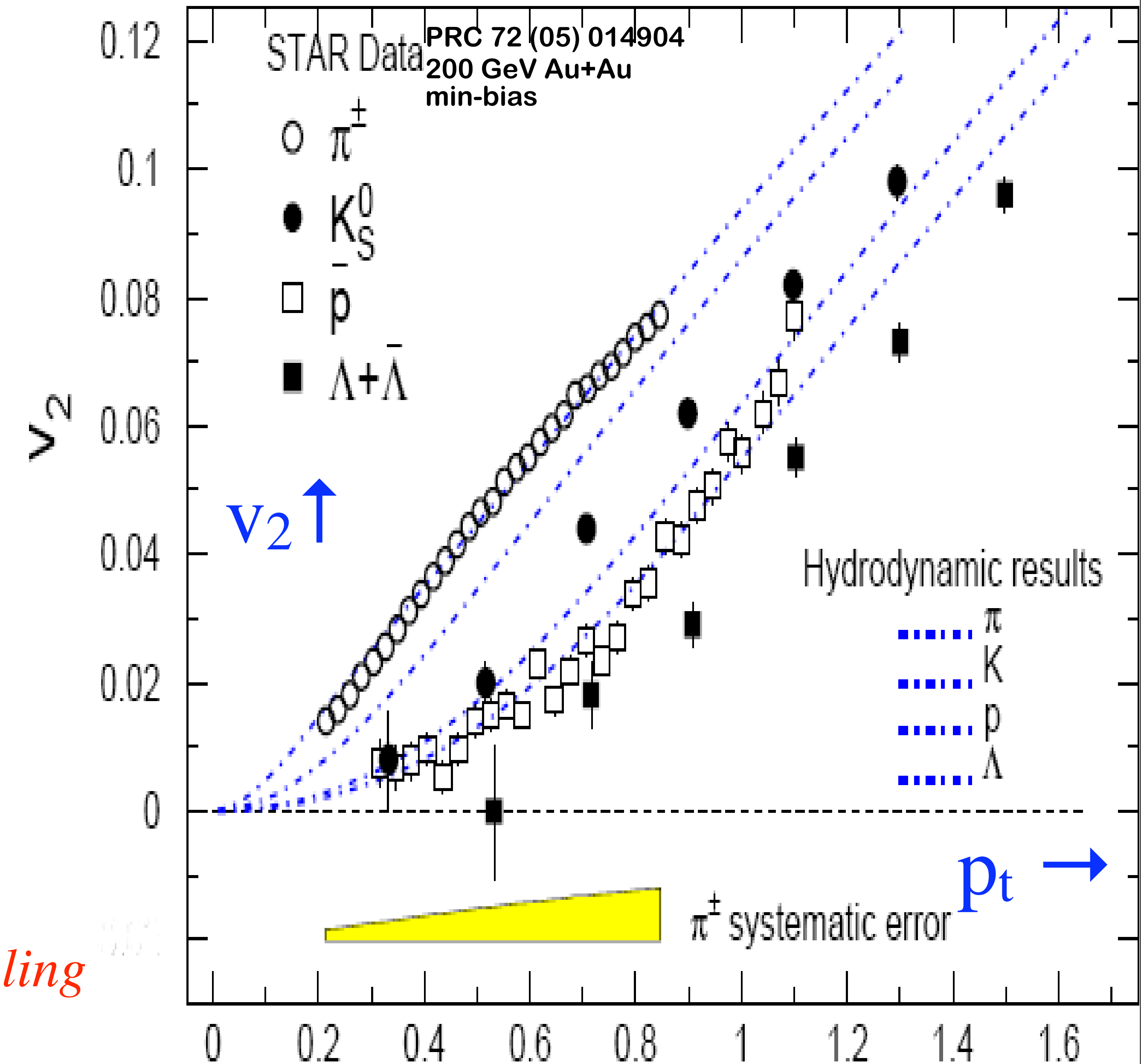
Try *ideal* hydrodynamics: large # particles

Bag Equation of State.
Zero viscosity in QGP phase
Large viscosity in
  hadronic "afterburner"
Short inital time (tune)

"Good" fit to π's, K's, p's.

So far: *no* bound on
viscosity in QGP.
Viscous, relativistic hydro.
very hard.

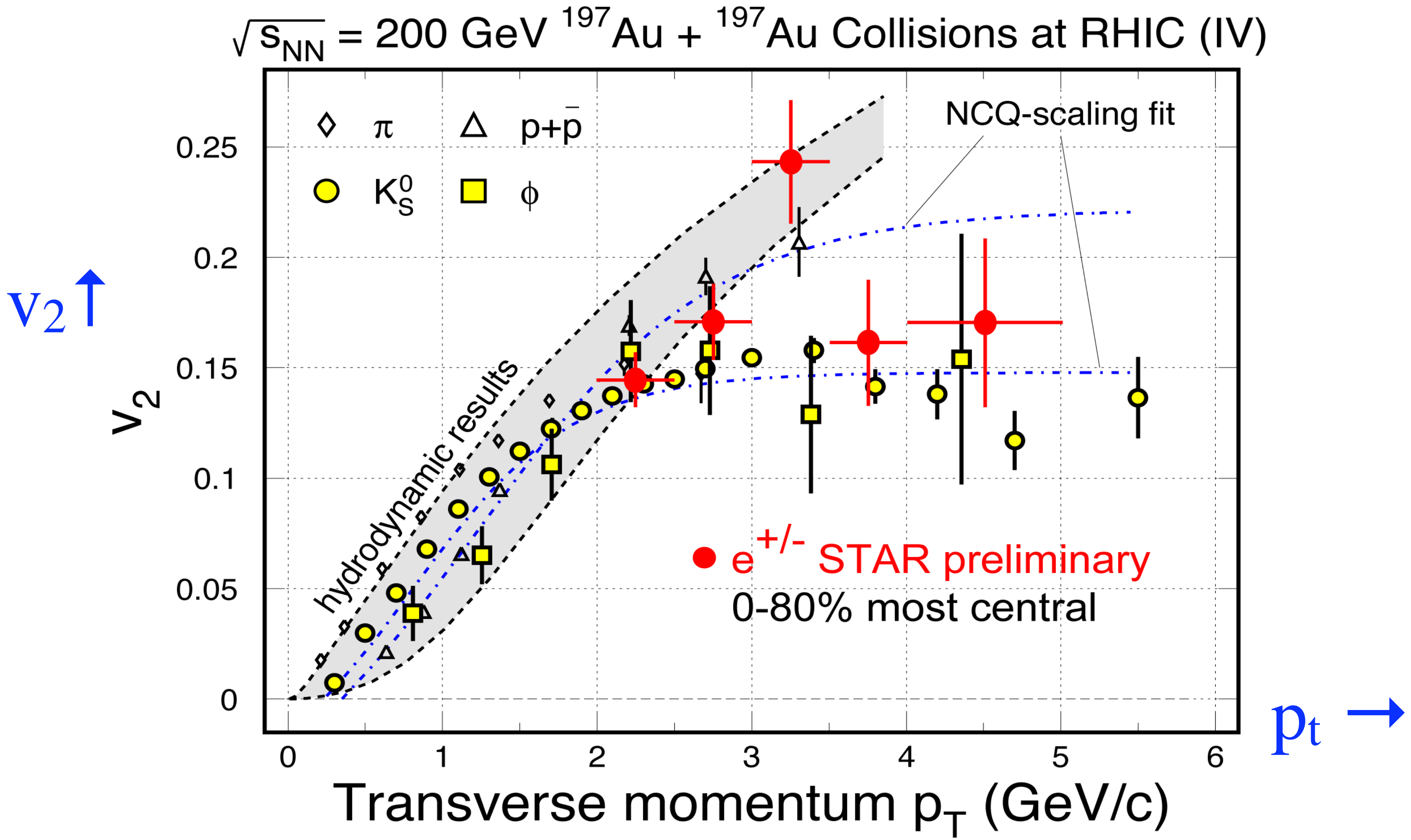
Viscosity ~ 1/cross section: so
small viscosity =>strong coupling
in sQGP?



Even charm quarks flow

Look at charm quarks through single electrons. See large elliptic flow.

No suppression due to large mass. Experimental evidence for “sQGP”.

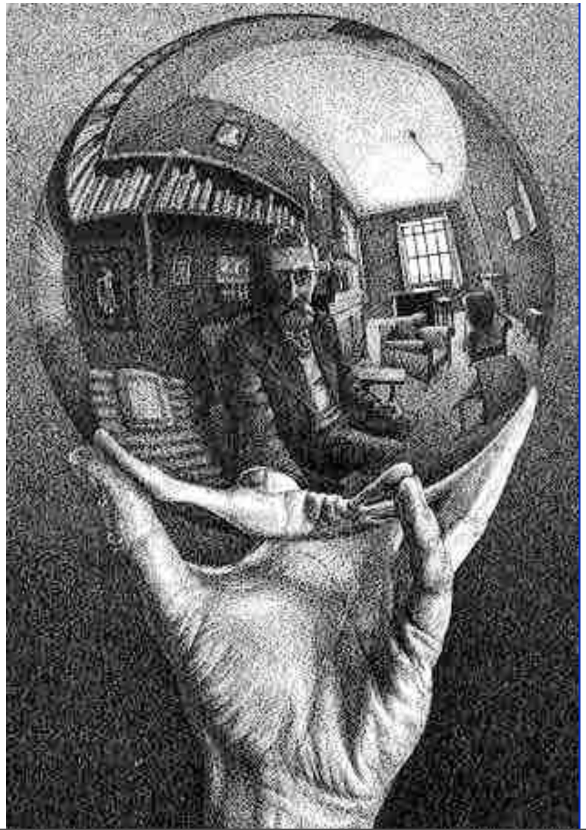


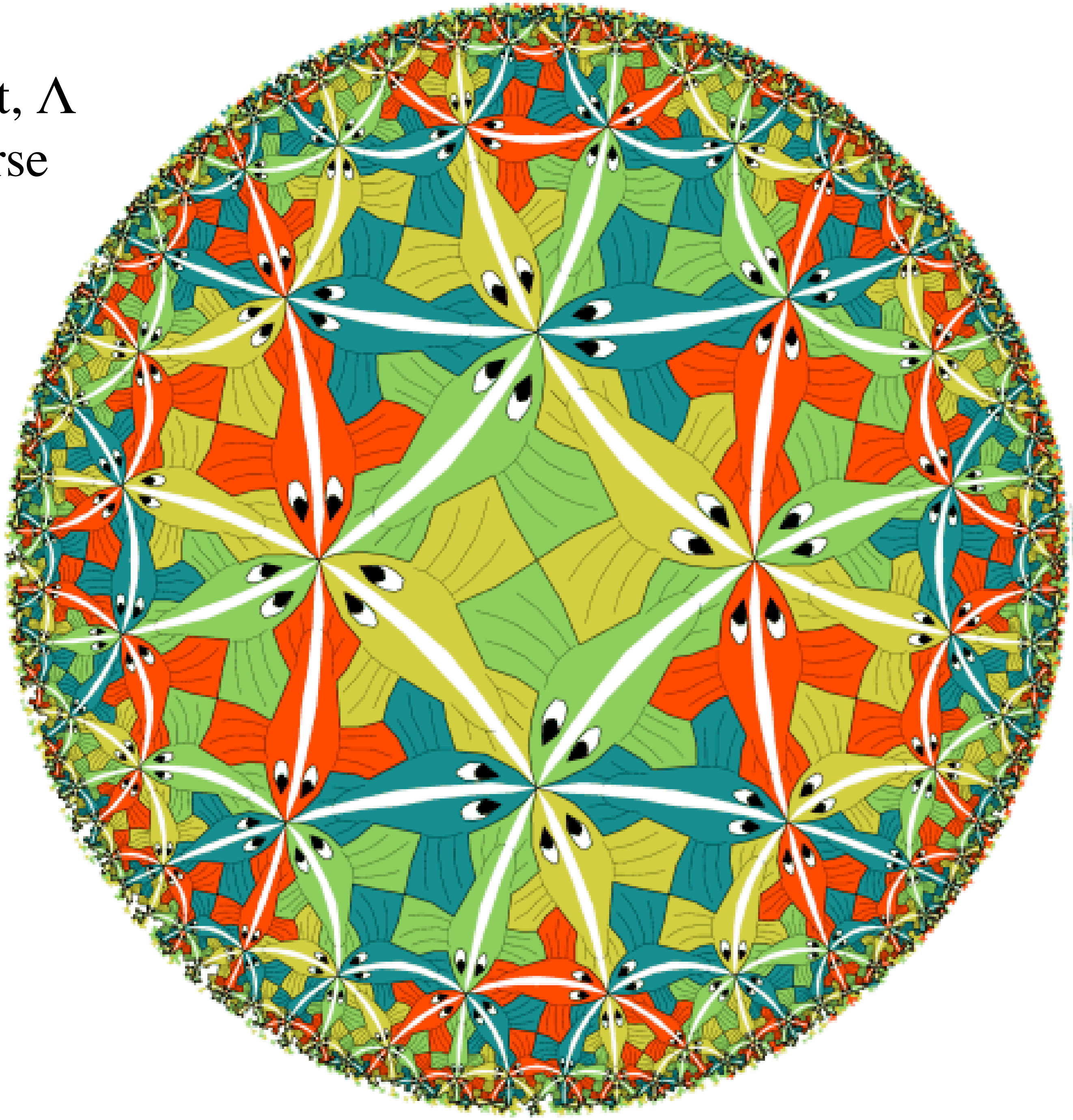
AdS: Anti de Sitter space

De Sitter space: Gravity with positive cosmological constant, Λ
Accelerated, expanding universe

Anti de Sitter: $\Lambda < 0$

Spatial cross section of AdS = hyperbolic space





M. K. Escher, courtesy of J. Maldacena

AdS/CFT Duality

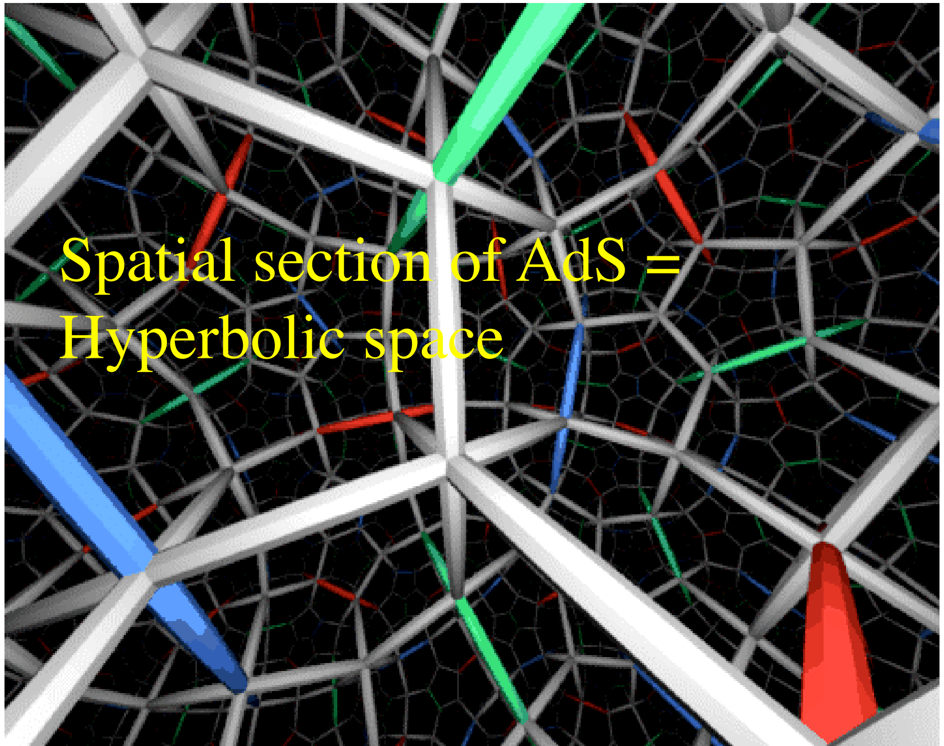
Most supersymmetric QCD: "$\mathcal{N} = 4$" SUSY for SU(N) gluons: 4 supercharges.
Gluons (spin 1) + 4 spin 1/2 + 6 spin 0, all adjoint rep. No quarks.

One dimensionless coupling, α_s, but does *not* run! Extraordinary theory:
No mass scale, both classically *and* quantum mechanically!
Conformal Field Theory (CFT). Probably exactly soluble.

Maldacena's Conjecture: $\mathcal{N} = 4$ SU(∞) *dual* to string theory on AdS_5 x S^5
AdS_5 (AdS in 5 dimensions) + S^5 (five sphere)
= Type IIB string in 10 dim.'s

AdS/CFT duality: Strong coupling in one theory is weak coupling in the other.

So *strong* coupling for $\mathcal{N} = 4$ SU(∞), $\alpha_s = \infty$ same as *weak* coupling on AdS_5 x S^5.
Weak coupling string theory = *classical* supergravity!

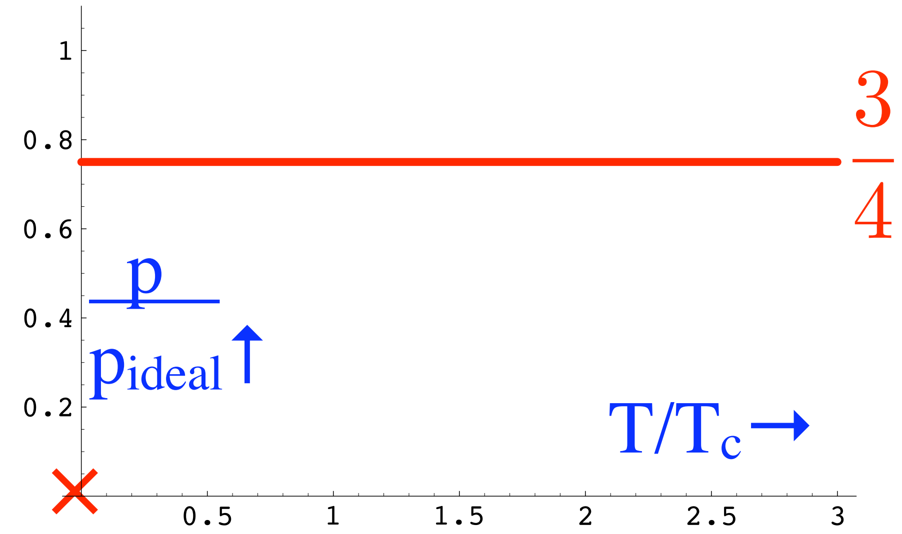


AdS/CFT at T ≠ 0: "Most perfect fluid"

If one can compute with AdS/CFT,
often easier for $\alpha_s = \infty$ than $\alpha_s \approx 0$!

Results for $\mathcal{N} = 4$ SU(∞), infinite α_s :

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



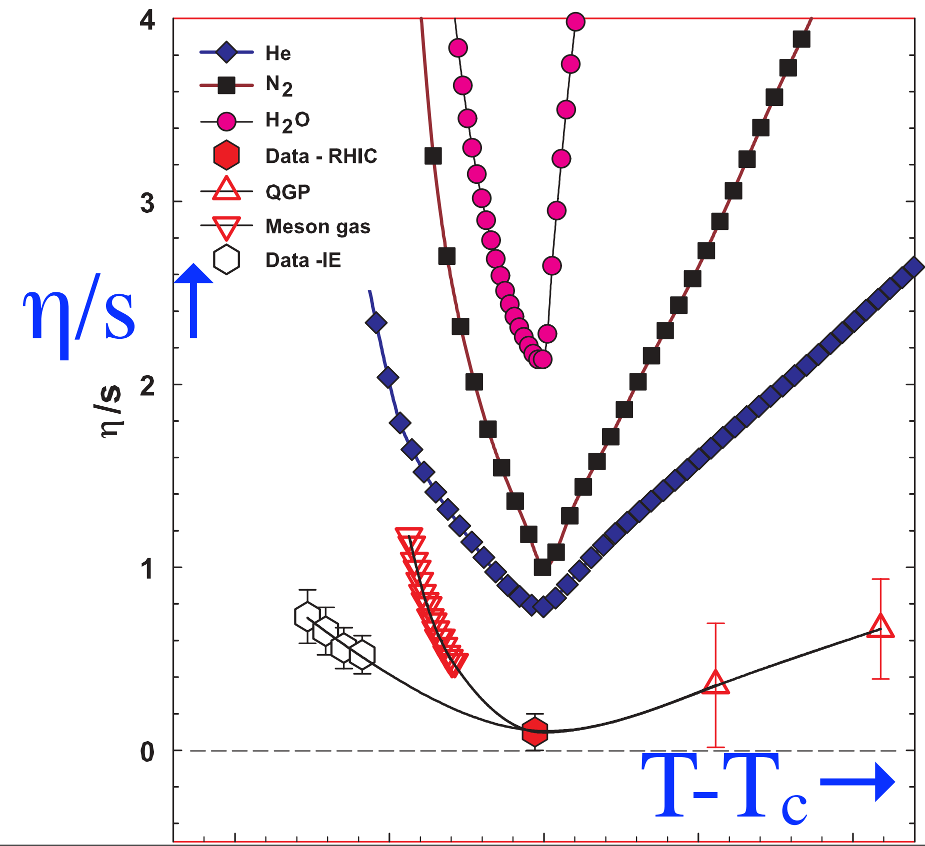
Not only equi., but also transport properties!

η/s = viscosity/entropy = $1/(4\,\pi)$

Universal lower bound?

Perhaps. $\eta \sim 1/\alpha_s^2$ for $\alpha_s \approx 0$

In many systems, η/s has a minimum
near T_c. Maybe in the sQGP?



Shootout in the Unicorn Corral!

At RHIC, central AA ≠ A (pp) collsions

"Tail wags the Unicorn"

Clearest signal from "high" pt:

R_{AA}, jet suppression...

Body of the Unicorn: sQGP

Two packs of fighting dogs (aka theorists):

Strong coupling! AdS/CFT rules!

Weak coupling:

need lattice for equilibrium thermo.

need to extend to non-equi.: NaRPA!

Nothing better than a good dog fight...

"A possible eureka."