New Phases at RHIC: what's the "s" in the sQGP?

Theory:

At high temperature, hadrons (QCD) form new state of matter:

Quark Gluon Plasma (QGP). Near critical temperature: a "s"QGP?

Numerical "experiments" on a lattice: *semi*-QGP?

AdS/CFT duality: super-QCD and the *strong*-QGP?

Experiment:

Collide heavy ions at high energies: RHIC @ BNL; SPS & LHC @ CERN

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

Non central collisions exhibit strong "flow"

Even heavy quarks suppressed, "flow"

Not an ordinary QGP; "Most Perfect Fluid on Earth"?

Wealth of precise experimental data. Theorists agog.

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

QCD & Confinement

QCD (Quantum Chromo Dynamics): quarks and gluons carry *color*.

In vacuum: permanently bound - "*confined*" - into states without color.

Quarks are fermions, come in six "flavors"

Basic mass scale: GeV ~ 12 trillion degrees. GeV = 1000 MeV

Mesons: quark + anti-quark, color + anti-color cancel

Up, down, strange quarks => pions, kaons, eta, eta' + *many* others

Lightest hadrons: masses 140, 500, 550, 960 MeV.

Light because of "chiral" symmetry: up and down q's very light, strange kinda.

Charm, bottom, top quarks => J/Psi, Upsilon... Masses 3.1, 10... GeV

Baryons: three quarks. Color neutrality => three colors.

Up, down quarks => neutrons, protons. 940 MeV

Strange quarks => Lambda...Omega. 1-2 GeV

Symmetries of QCD

Why three colors?

Assume that for *each* quark, multiply by q -> z q, where $z = \exp(2 \pi i/3)$.

Since $z^3 = 1$, three quarks are *invariant* under this Z(3) symmetry.

QCD: Symmetries *local* SU(3), *global* Z(3) (Just like 3-state Potts model)

Quarks: spin 1/2, SU(3) vector. Carry Z(3) charge.

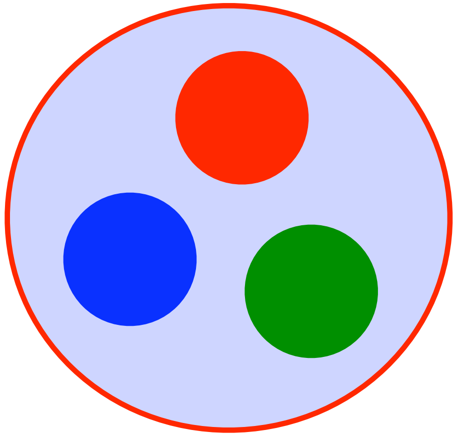
Gluons: spin 1, SU(3) matrix. $3^2 - 1 = 8$ types of gluons. Z(3) charge indirect.

Gluons interact with each other, quarks...*very* complicated!

Confinement related to “hidden” Z(3) symmetry.

“Easy” to see quarks, gluons more obscure.

One model: quarks & gluons confined inside MIT “bag” =>



QCD & Asymptotic Freedom

Unlike a photon, the 8 gluons in QCD interact with one another
Complicated at large distances, *very* simple at short distances (large momenta)

Asymptotically Free: QCD coupling, α_s, "runs", vanishes as momentum $k \to \infty$:

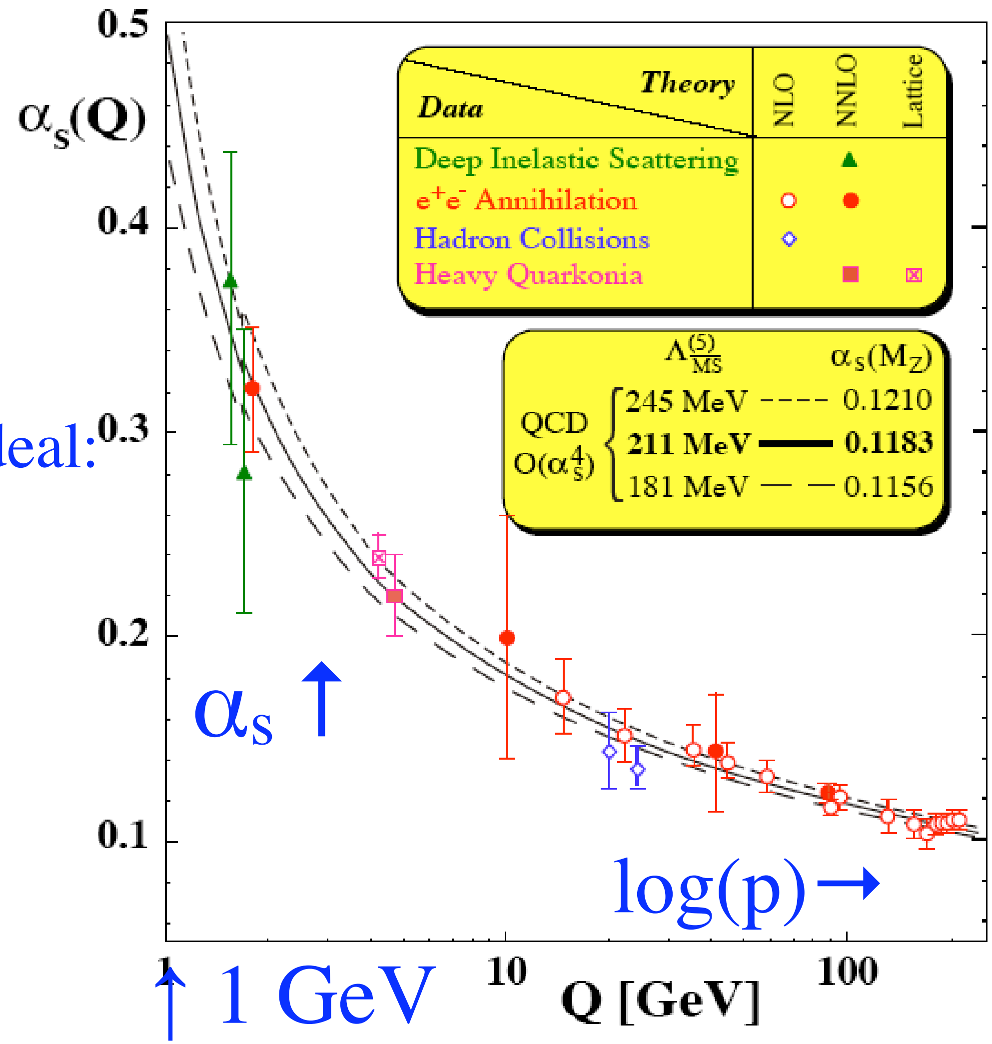
$$\alpha_s(k) \sim \#/\log(k)\ ,\ k \to \infty$$

Conversely, $\alpha_s(k)$ *increases* as momentum decreases (large distances). Experiment:

As temperature $T \to \infty$, pressure $p(T) \to$ ideal:

$$p_{ideal}(T) = \left(8 + \frac{7}{8} \cdot 18\right) \frac{\pi^2}{45}\, T^4$$

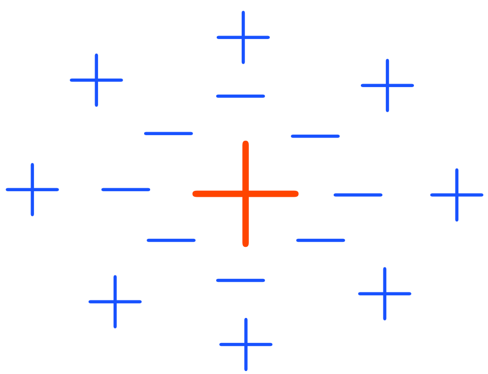
At *high* T, QCD forms *nearly* ideal Quark-Gluon Plasma, QGP: *deconfined*



Coulombic Plasmas, *partial* ionization

Ordinary matter (gas, liquid, solid) composed of electrically neutral objects.
"Fourth" state: plasma. No net charge, but charges *free* to move about.

Coulomb int. with test charge, **+**, *shielded* by free charges, **- +**, with density "n":



$$\frac{e^2}{r} \to e^{-m_{Debye} r}\,\frac{e^2}{r} \quad ; \quad m^2_{Debye} \sim \frac{e^2\, n}{T}$$

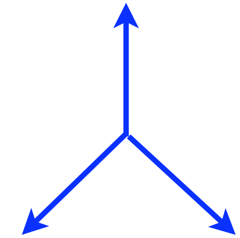
Ordinary matter: if *no* ionization, Coulomb int. remains 1/r, charge modified.

In plasma, distinguish between *complete* or *partial* ionization.

Interesting dynamics in regime with partial ionization. Hard to treat cleanly.

Z(3) charges in Gluonic Plasmas

QCD plasma: Coulomb int.'s + much more. Consider Z(3) charges:



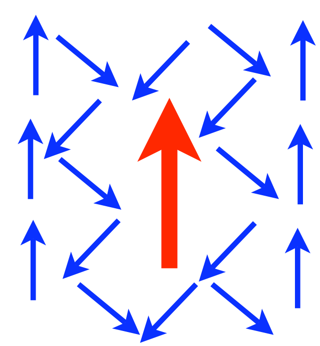
Use propagator of test quark, ~ "Polyakov Loop"

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

In purely gluonic plasma, *only* Polyakov Loops carry Z(3) charge. ('t Hooft)

Polyakov Loop ~ Z(3) magnetization of Potts model

Use Loop as probe of Z(3) test charge.



High temperature: g ~ 0, so Loop ~ 1. Debye screening.

Loop is order parameter for deconfinement!

Deconfinement in Gluonic Plasma

Zero temperature: confinement => Z(3) charge can't propagate.

<Loop> = 0: strict order parameter for confinement

Confined phase: *symmetric* phase of Z(3) spins
No ionization of Z(3) charge.

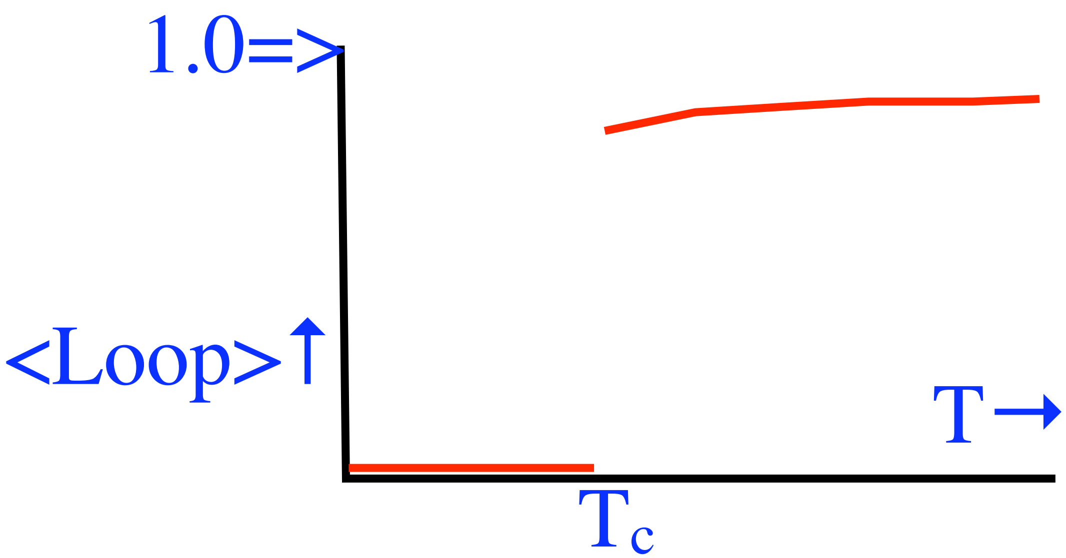
$T \to \infty$: test quark ~ free => <Loop> ~ 1; Z(3) charge *completely* ionized.

=> <Loop> *non*zero at some T_c = deconfinement transition temp.

Deconfined phase, $T > T_c$: *broken* phase of Z(3) spins.
Z(3) charge ionized.

How big is <Loop>(T_c^+)? At T_c^+, is ionization complete, or partial?

Ordinary or "Semi"-Gluonic Plasma?

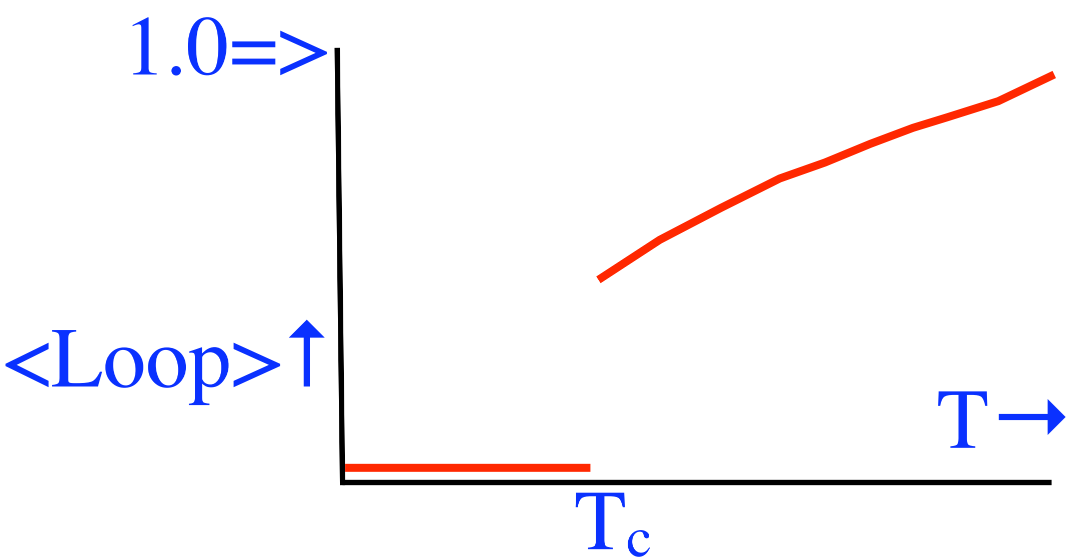


<Loop>(T_c^+) ~ 1:

complete ionization,
ordinary Gluonic Plasma,
for all $T > T_c^+$

<Loop>(T_c^+) < 1:

partial ionization at T_c^+



If <Loop>(# T_c) ~ 1

"Semi"-Gluonic Plasma,
T_c^+ to # T_c

Ordinary Gluonic Plasma,
$T >$ # T_c .

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 $a \rightarrow 0$, continuum limit

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

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

For pure glue near continuum limit from mid-'90's!

Compute equilibrium thermodynamics: pressure(temperature) = p(T), loop(s)

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

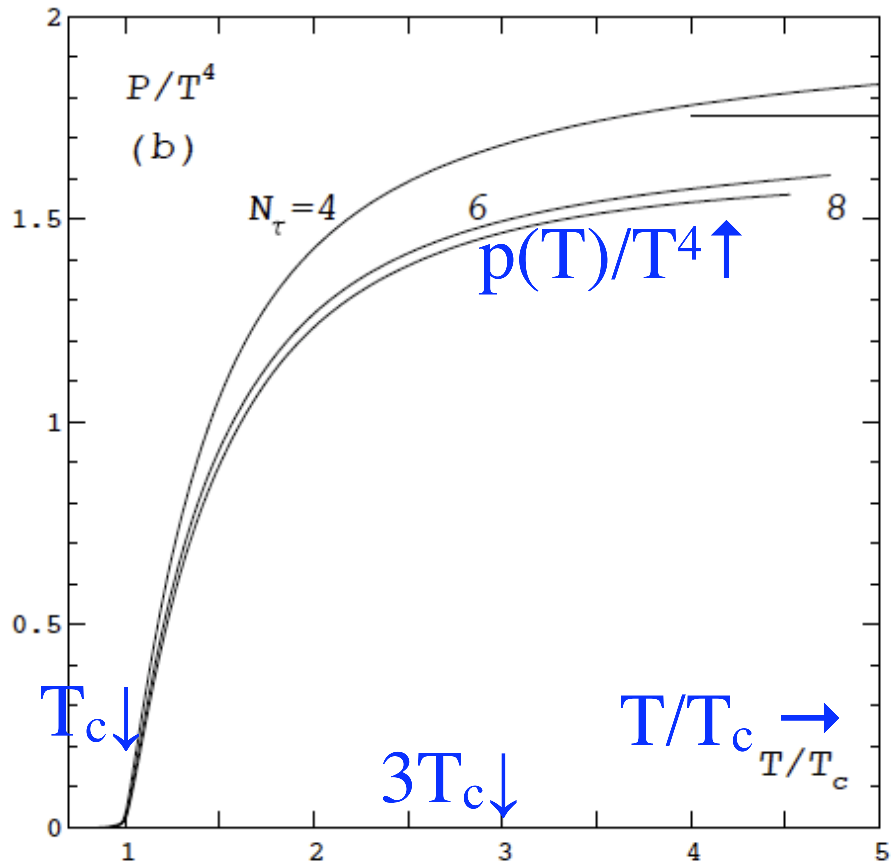
Quarks non-local, difficult to treat (global!)

"chiral" symmetry of light quarks

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

With quarks: *orders* of magnitude more difficult

Lattice: SU(3) gluonic plasma



N_τ = time steps: 4,6,8. 6~8

arXiv:hep-lat/9602007, Boyd et al

Lattice: SU(3) Gluonic Plasma (no quarks)

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, large above T_c (like large # colors)
Transition weakly first order (~ Z(3) Potts model)

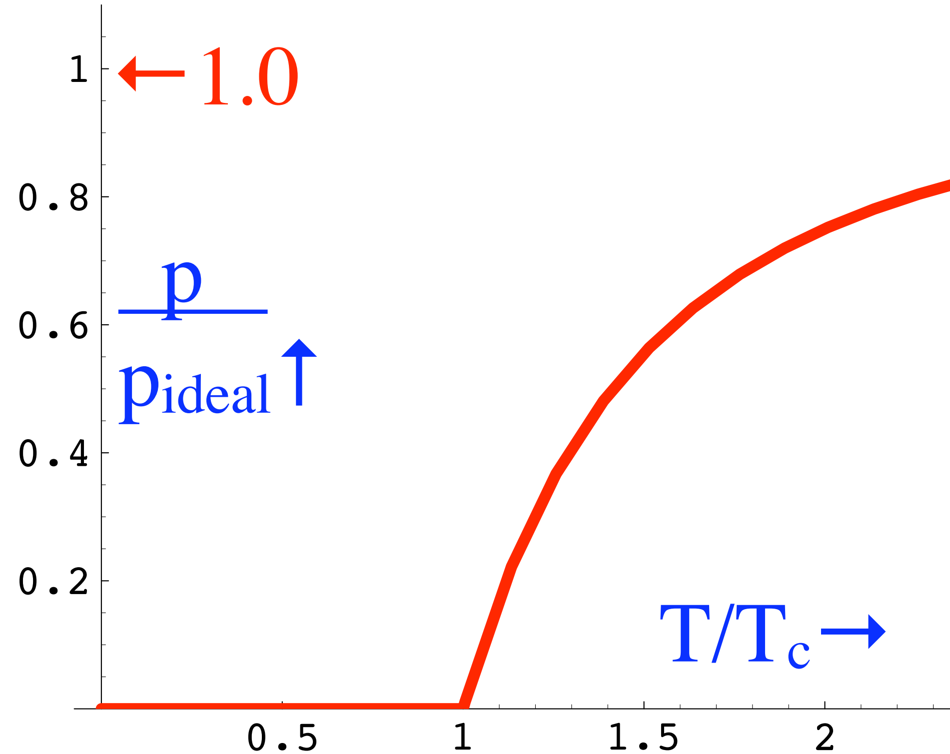
Pressure: MIT bag model does *not* work

$$p_{\rm MIT}(T) = \# T^4 - B$$

"Fuzzy" bag does:

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

~ T^4 perturbative: # ~ 0.9 ideal gas value
~ T^2 *non*-perturbative.
Pressure ~ 85% ideal by ~ 4 T_c



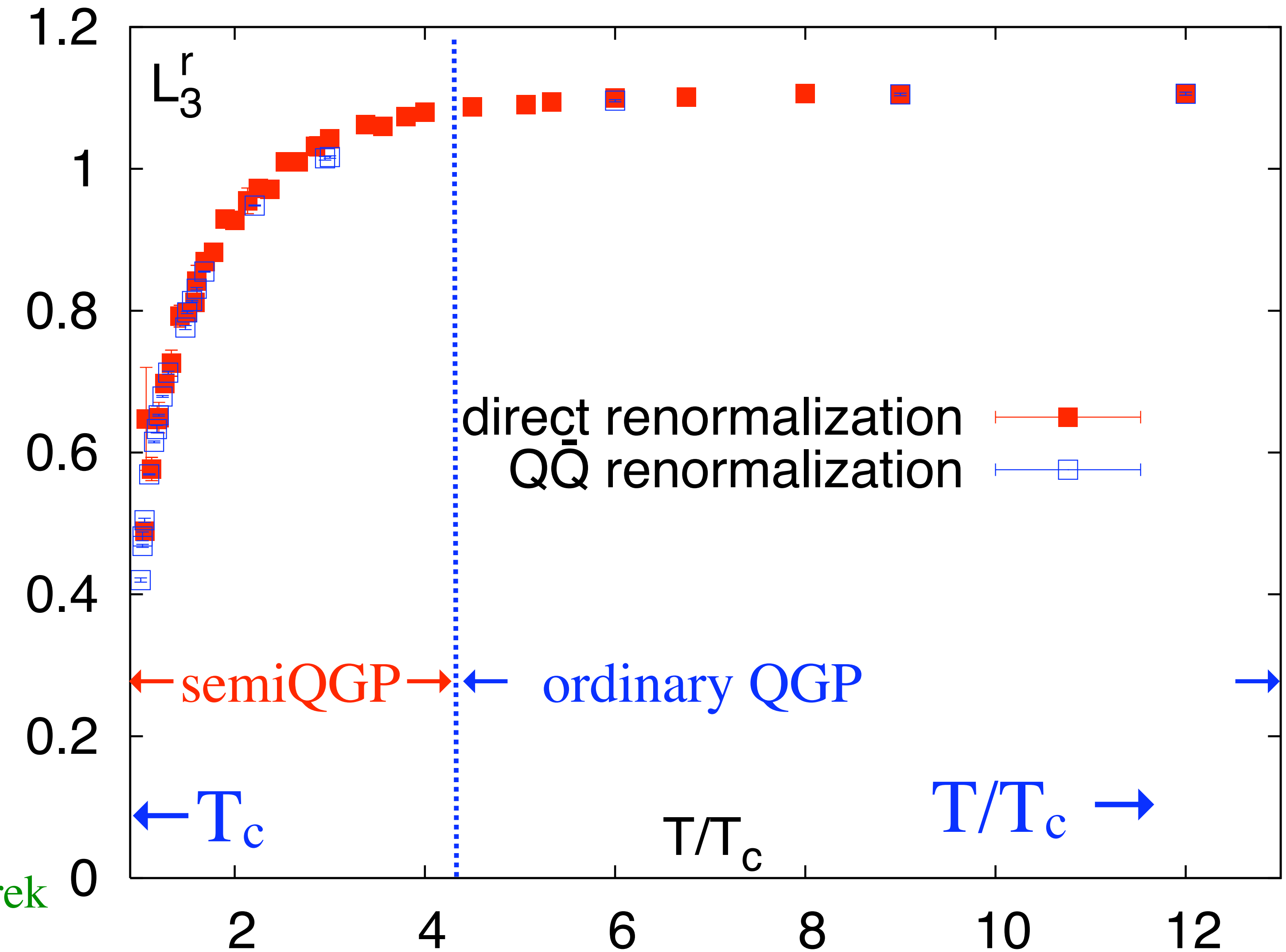
Lattice: SU(3) "Semi"-Gluonic Plasma

$T < T_c$: <Loop> = 0, confined phase.

<Loop>(T_c^+)~ 0.5 !   <Loop> < 1 for T_c to ~ 4 T_c : "semi"-Gluonic Plasma.

$T >\sim 4\, T_c$: ordinary QGP . Polyakov Loop ~ 1 (+ pert. corr.'s)

(Ren.d) Polyakov Loop ↑



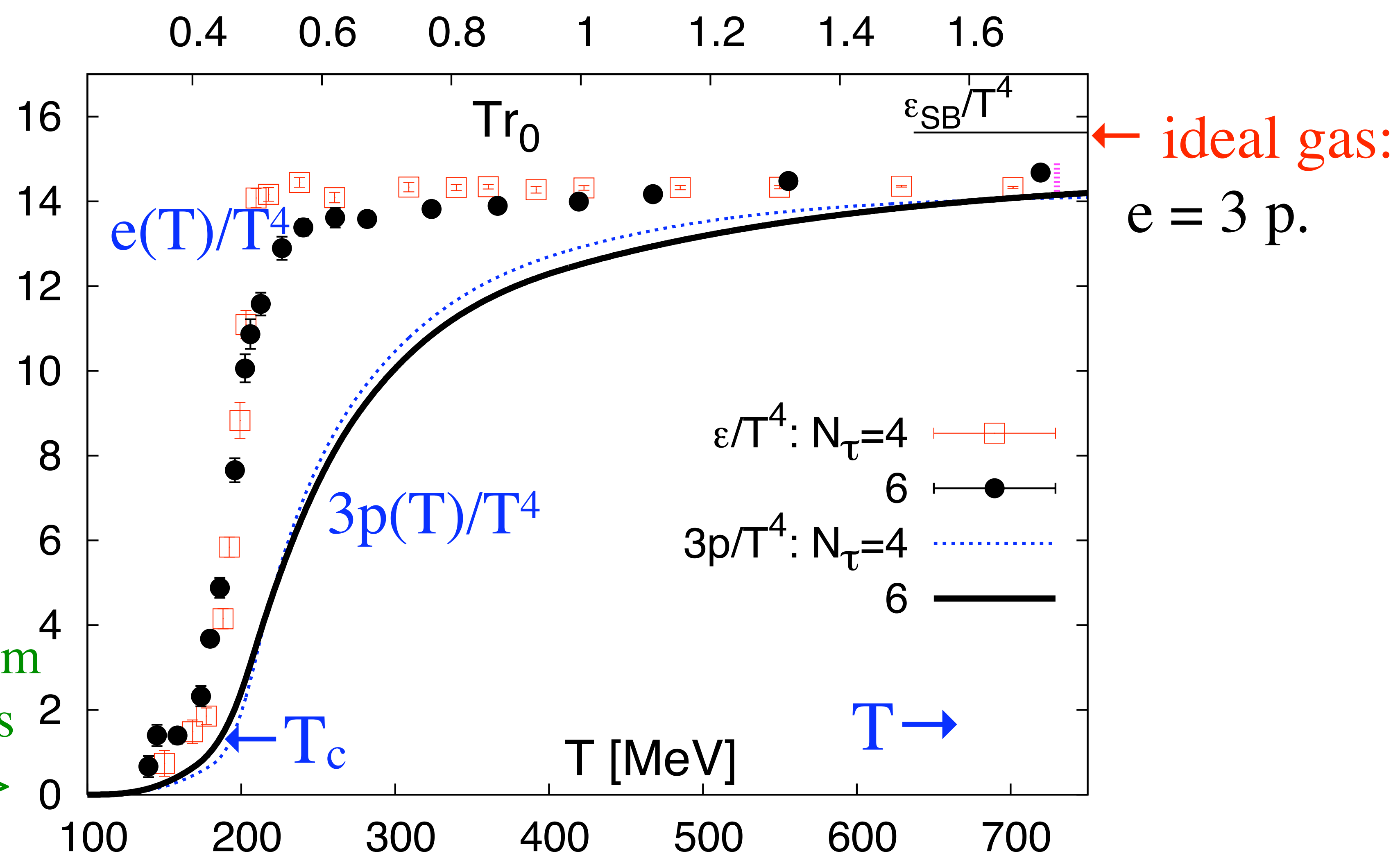
arXiv:0711.2251
Gupta, Hubner, Kaczmarek

Lattice: Quark-Gluon Plasma, “2+1” flavors

T_c ~ 190 MeV. Crossover, no true phase transition. Huge increase in pressure:

$$p(T) = c_{pert}T^4 - B_{fuzzy}T^2 - B_{MIT}$$

Energy density e(T), 3 x pressure(T), each/T^4. Pressure ~ 90% ideal by ~ $3T_c$.



arXiv:0710.0354
Cheng et al

Pressure from light mesons below T_c =>

Lattice: “Semi”-QGP, 2+1 flavors

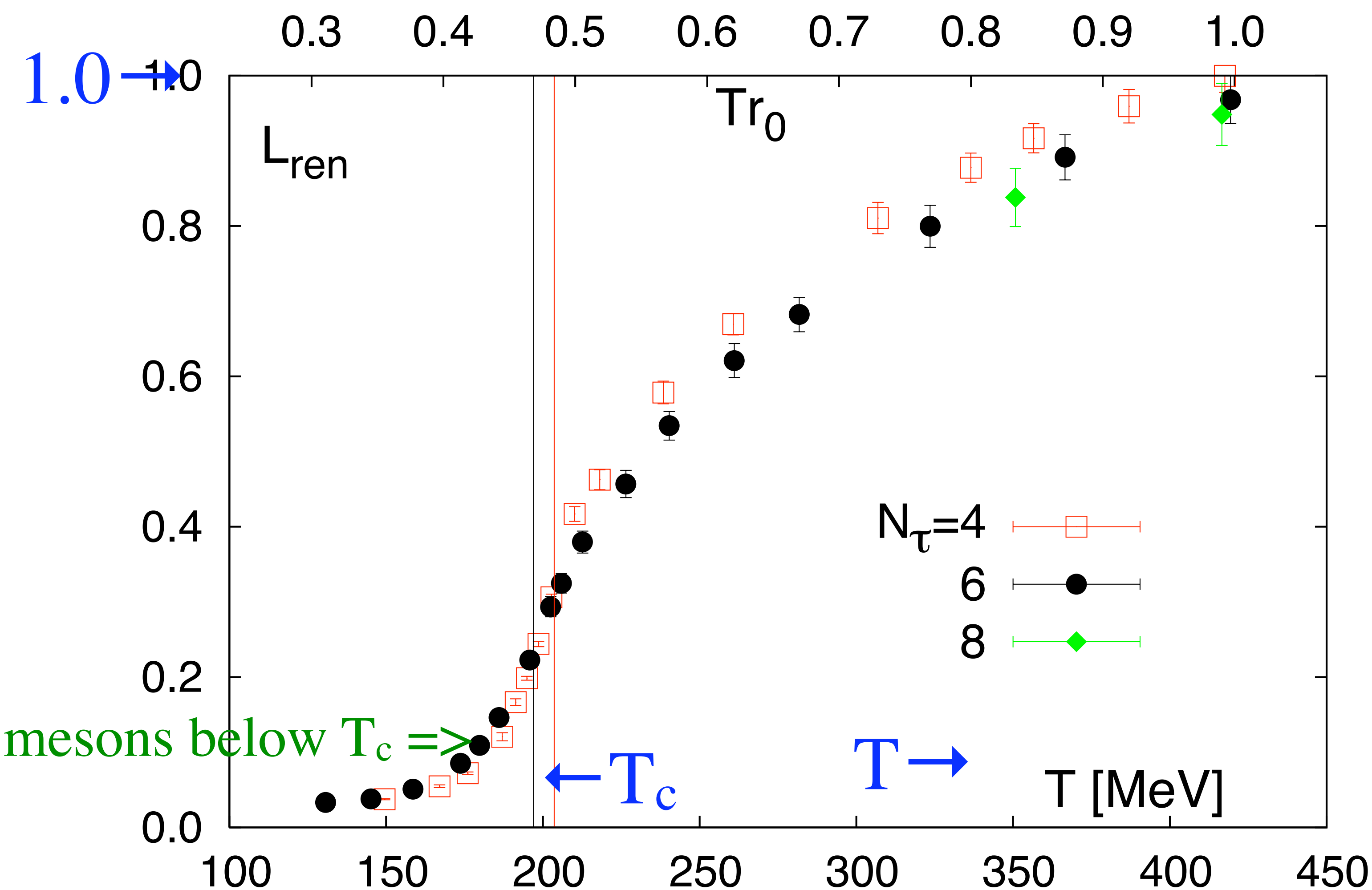
Quarks carry Z(3) charge, and so partially ionize QGP, even *below* T_c

Lattice: *Moderate* ionization below T_c. Loop ~ 0 below ~ 0.8 T_c .

<Loop>(T_c) ~ 0.3 . <Loop> ~ 1.0 at 2 T_c . Semi-QGP for 0.8 -> 2.0 T_c

arXiv:0710.0354, Cheng et al

(Ren.d)
Polyakov
Loop ↑



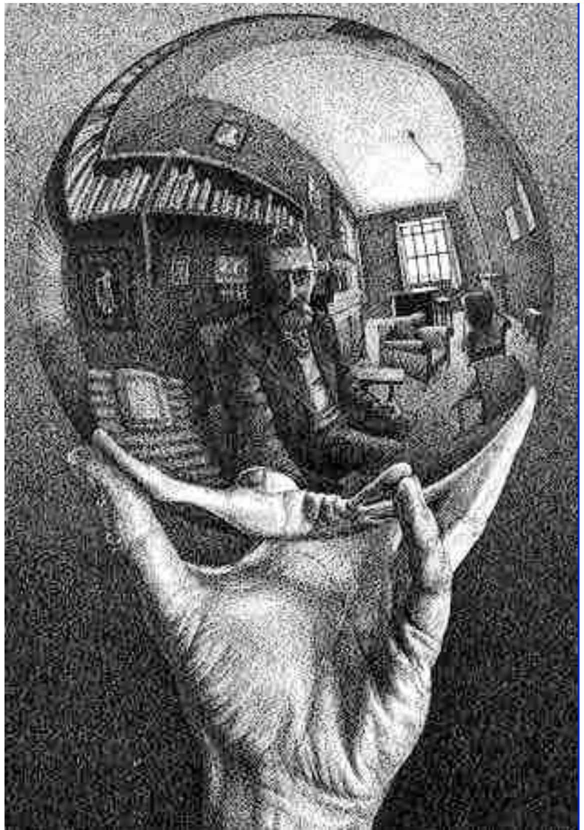
Ionization from light mesons below T_c =>

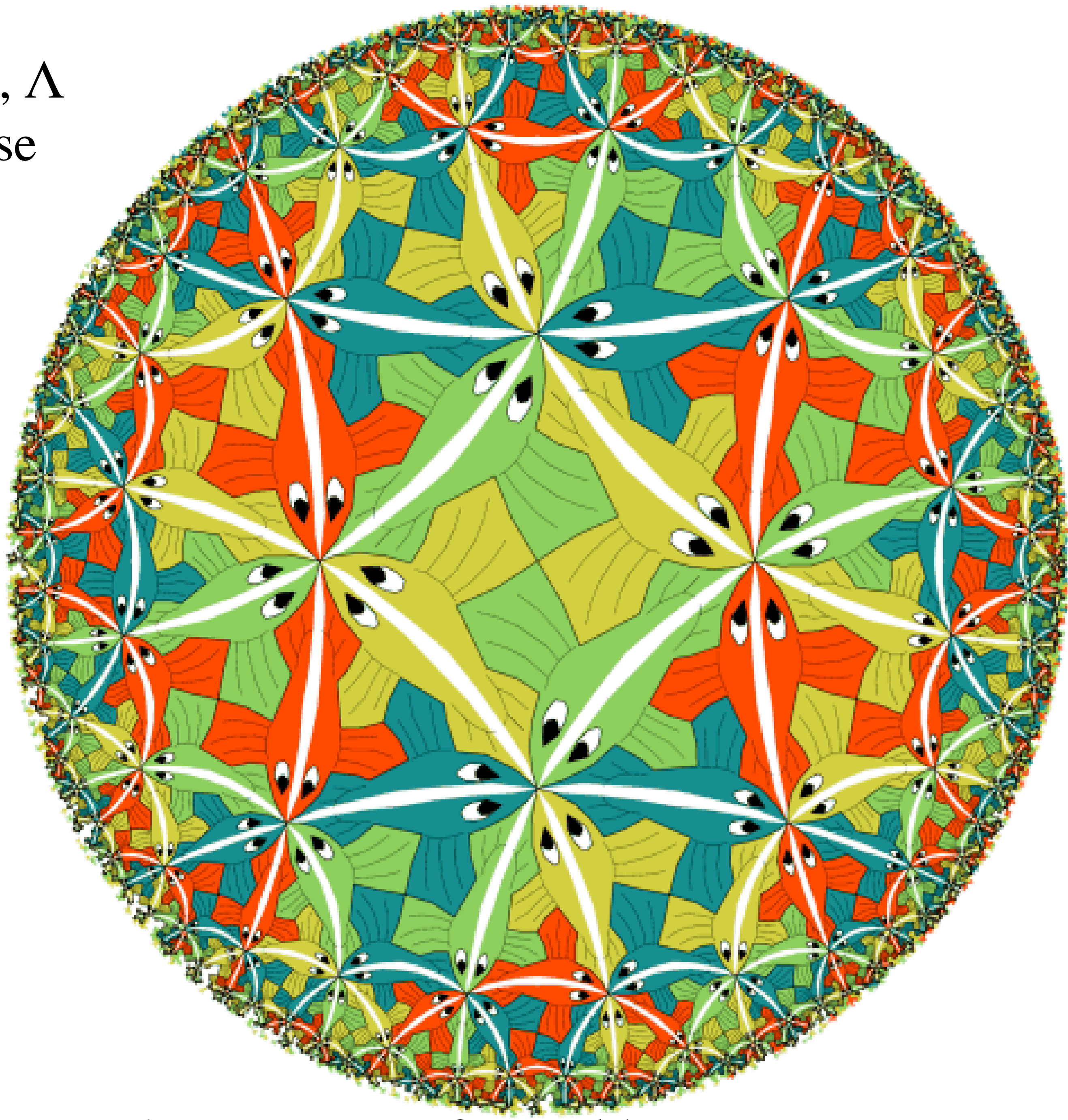
AdS: Anti de Sitter space

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 SU(N) matrices. 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

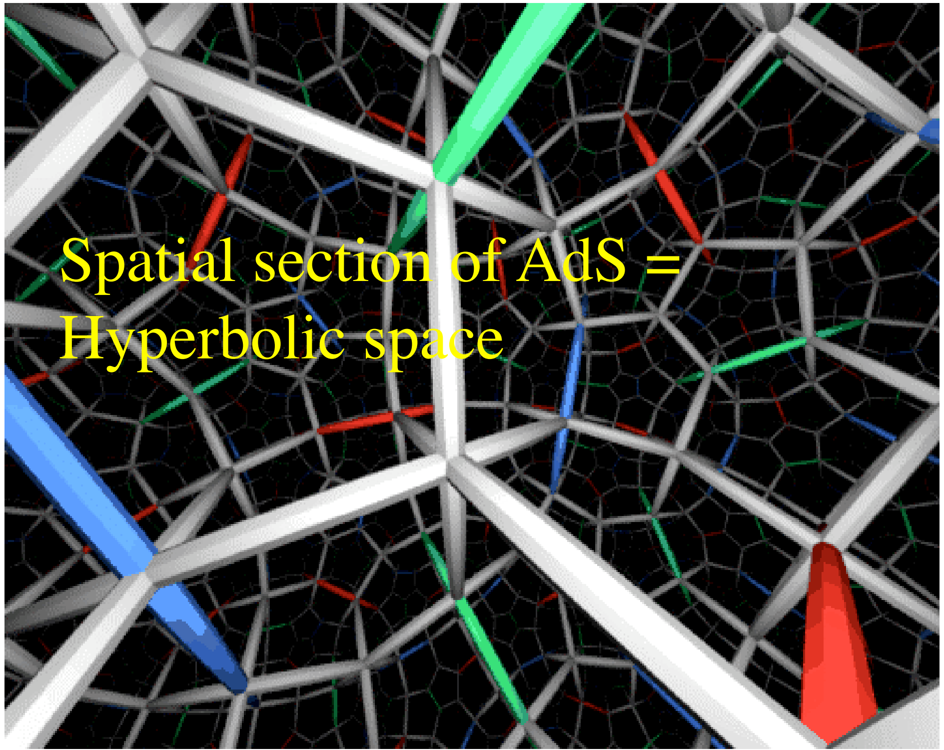
AdS_5 (AdS in 5 dimensions) + S^5 (five sphere)

= 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(∞) same as *weak* coupling on AdS_5 x S^5.

Weak coupling string theory = *classical* supergravity!



SUSY QCD and "strong"-QGP

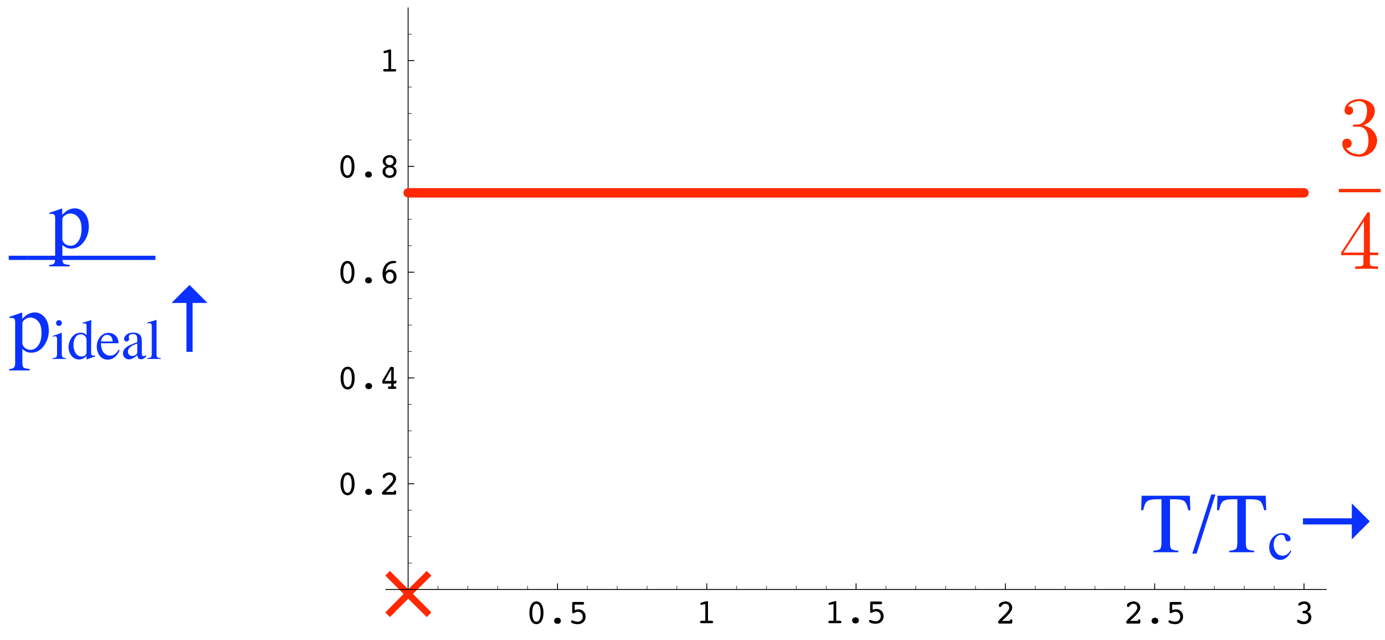
If one can compute with AdS/CFT, often easier for $\alpha_s = \infty$ than $\alpha_s \approx 0$!

Results for $\mathcal{N} = 4$ SU(∞), infinite α_s : pressure = 3/4 ideal.

Conformal field theory => p/T^4 flat with T.

Deconfined phase: heavy quark potential Coulombic. Polyakov Loop?

QCD (at 3 T_c): α_s is 300 x α_{em} in QED. So near T_c, take $\alpha_s = \infty$, "strong"-QGP



Shear viscosity in s-QGP

$\mathcal{N} = 4$ SU(∞), infinite α_s : Also transport properties: shear viscosity, η

η/s = viscosity/entropy = $1/(4\pi)$.   Universal bound?

arXiv:hep-th/0104066. Policastro, Son, Starinets

In non-relativistic QED plasmas,
η has a *minimum* in a dense regime,
"strongly coupled" plasma =>

Perhaps in strong-QGP?

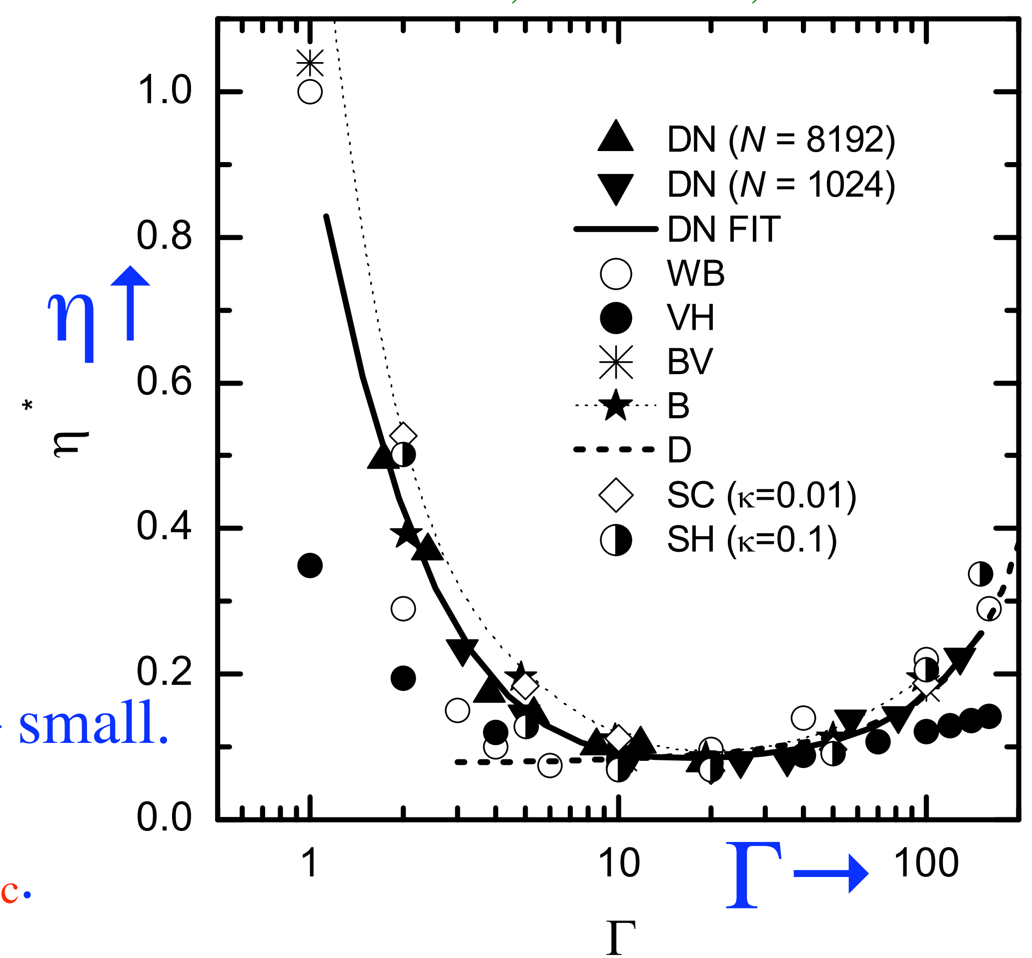
nucl-th/0701002, Mrowczynski & Thomas

In weak coupling, $\eta \sim T^3/\alpha_s^2$ for $\alpha_s \approx 0$.

Semi-QGP:

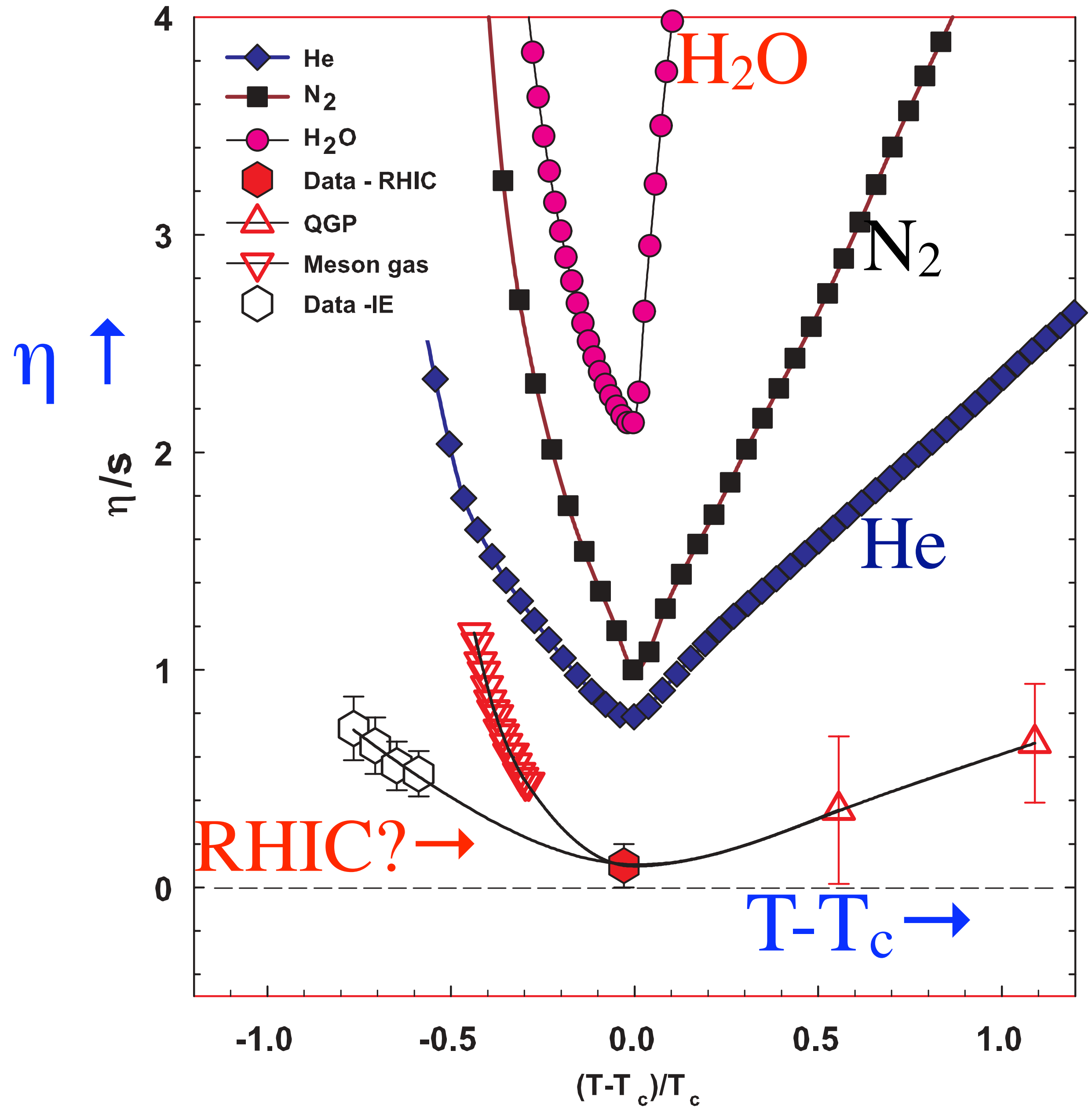
η *suppressed* by <Loop>^{2} when <Loop> small.
Minimum near T_c?
=> Large *increase* in η/s as T: T_c => 2 T_c.
Yoshimasa Hidaka & RDP '08.

arXiv:0710.5229,
Donko, Hartmann, Kalman



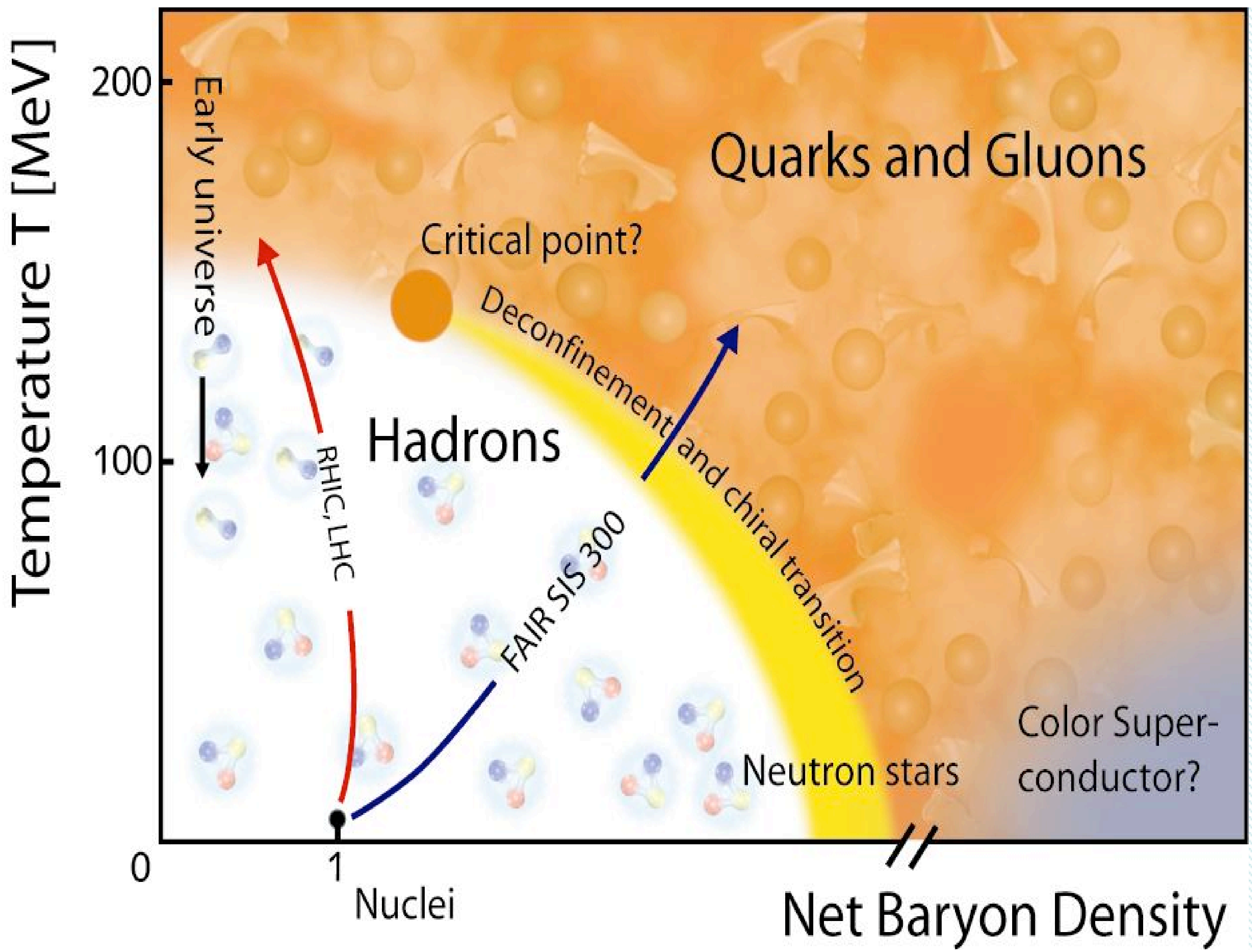
$$\Gamma \sim e^2 n^{1/3}/T$$

Minimum in η common



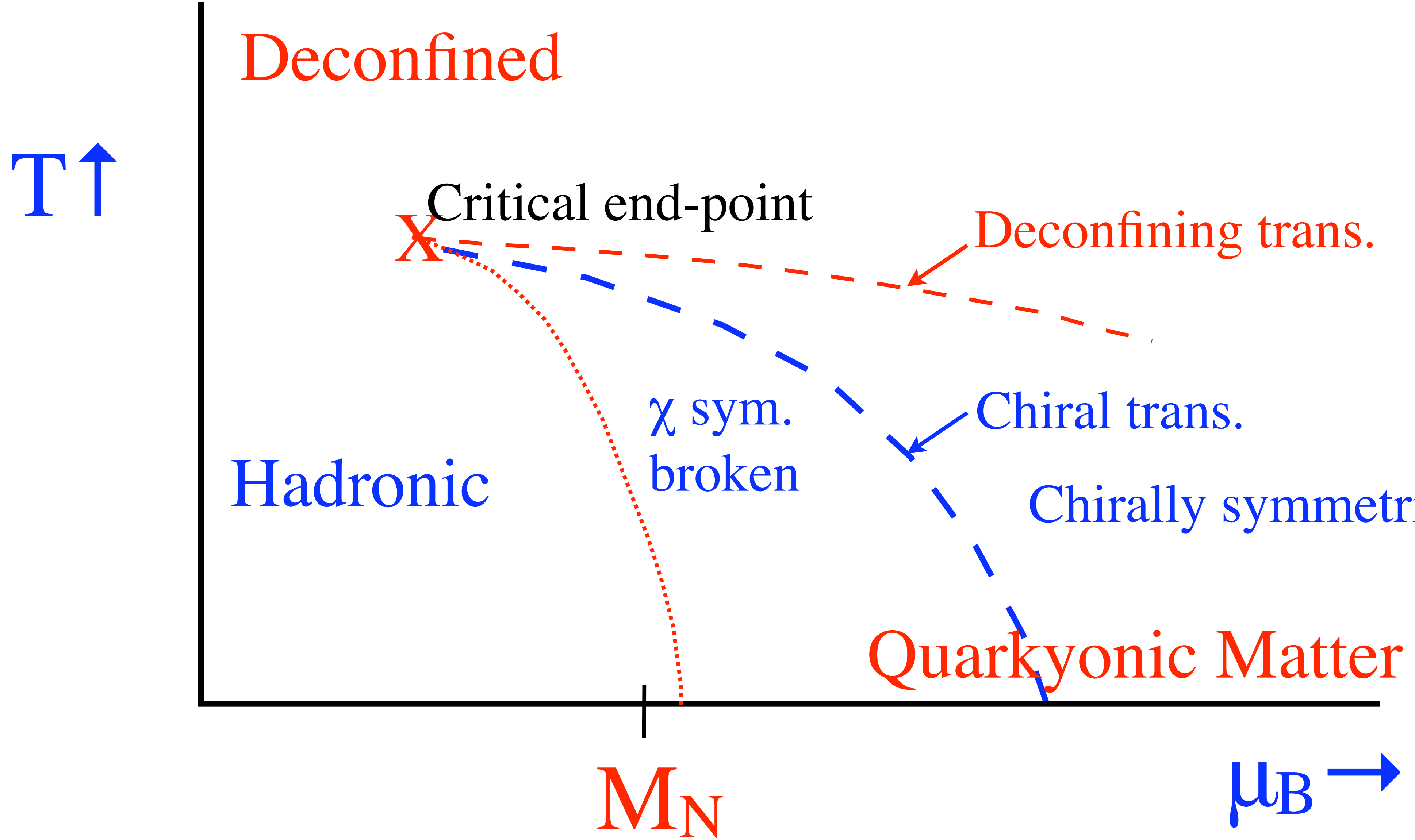
Usual phase diagram

In plane of T and baryon density: critical end point? Rajagopal, Shuryak, Stephanov



“Quarkyonic” matter

New phase diagram: novel behavior at low temperatures, high quark density: “Quarkyonic” matter: quarks in Fermi sea, but baryons at Fermi surface. Valid for infinite # colors - for QCD? McLerran and RDP ’07.



Hunting for the "Unicorn" in Heavy Ion Collisions

Unicorn = QGP. Hunters = experimentalists. 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)

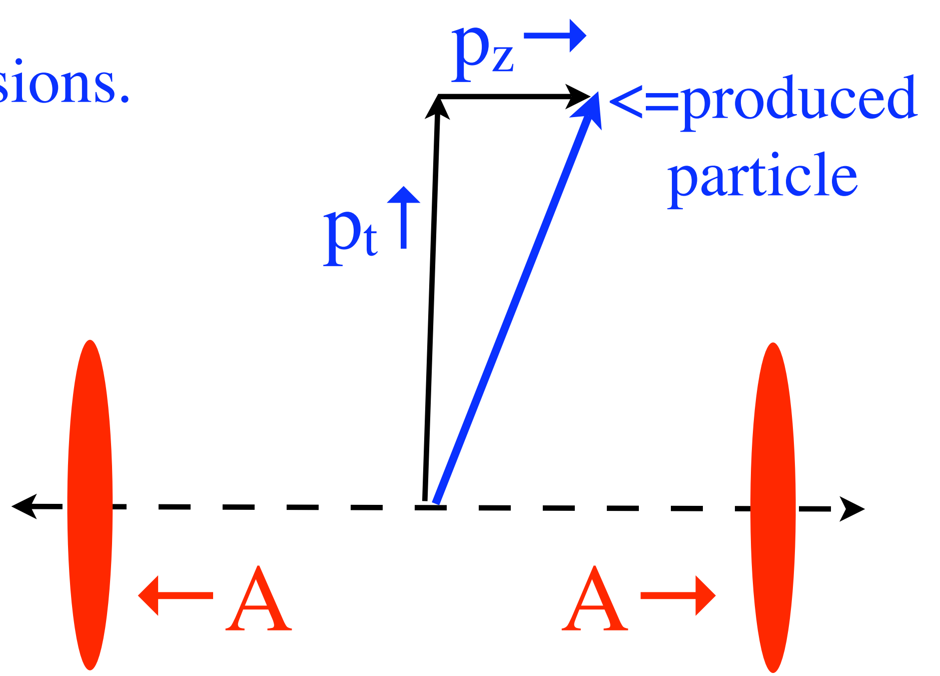
Bjorken: look at rapidity plateau in AA collisions.

Rapidity plateau ~ *free* of incident baryons.

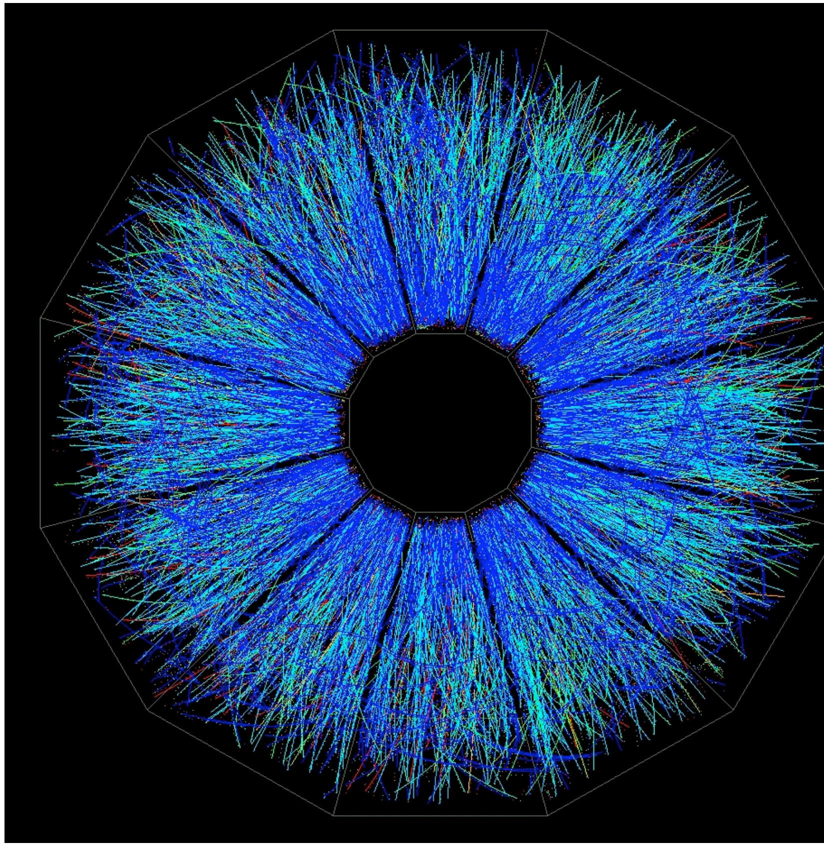
=> most likely to be at nonzero temperature,

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)

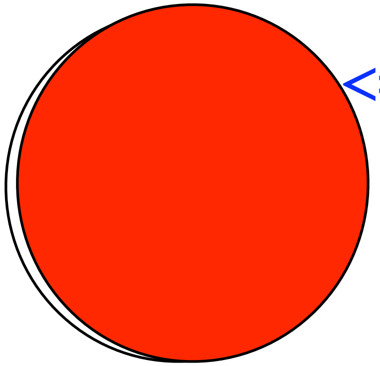
~total # experimentalists

theorists ~ log(log(total energy)).

Need hunters more than dogs...

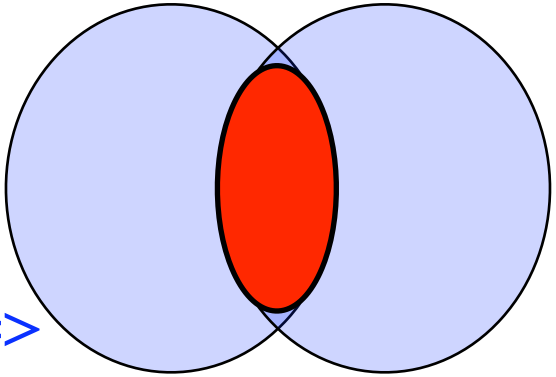
Total # particles/unit rapidity ~900↑

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



<= central

peripheral =>



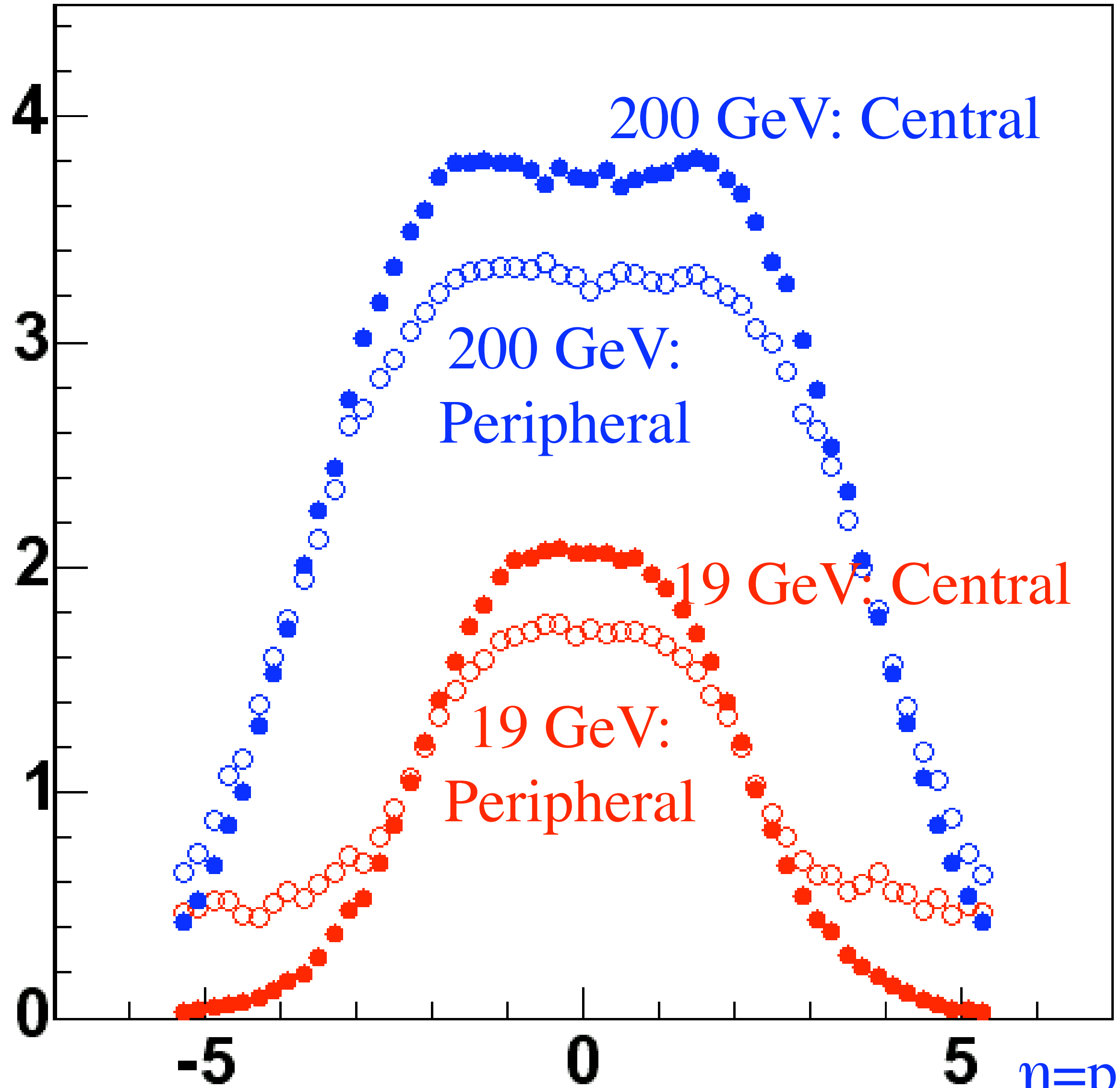
Overall multiplicity: slow growth

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":

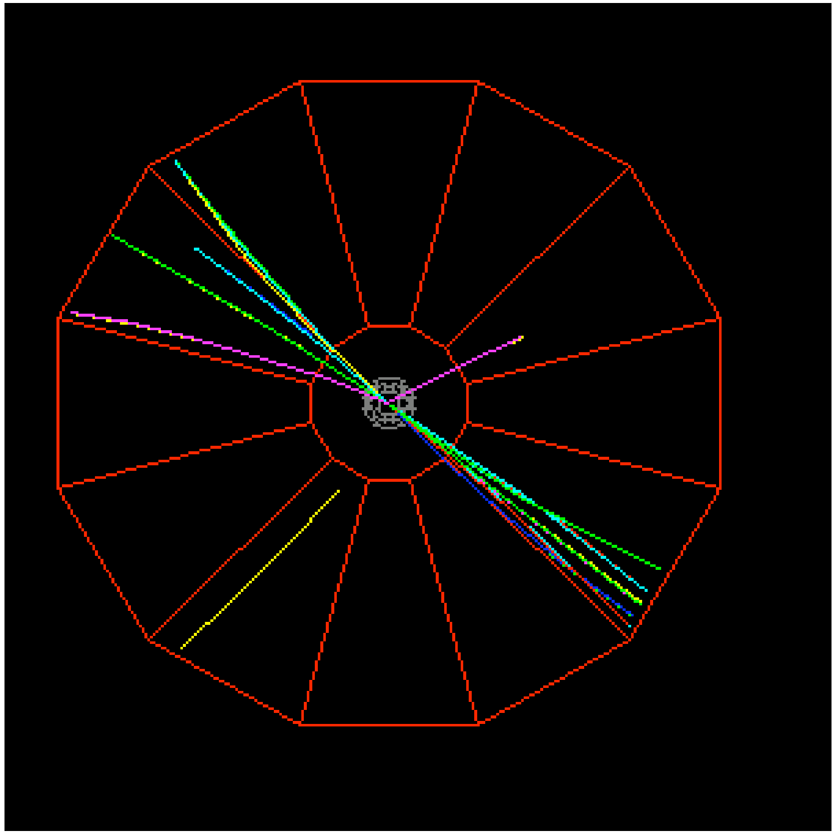
For T ~ 200 MeV,
majority of particles at *small* momenta,
$p_t < 2$ GeV.

Tail of the "Unicorn":

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

Concentrate on zero rapidity, 90^o to beam.

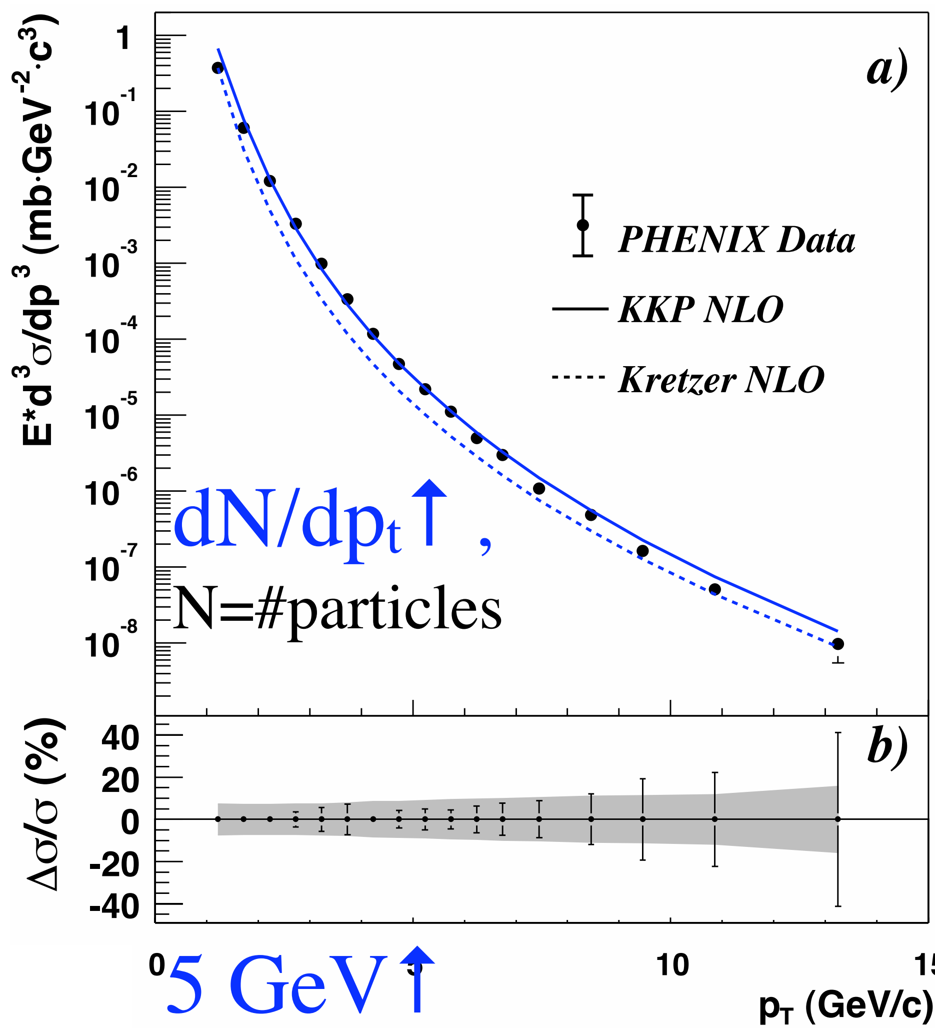
Jets: "seeing" quarks and gluons in QCD



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.



dN/dp_t↑ , N=#particles

p_t →

5 GeV↑

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!

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, $R_{AA} \sim 0.2$. As if jets emitted *only* from surface!

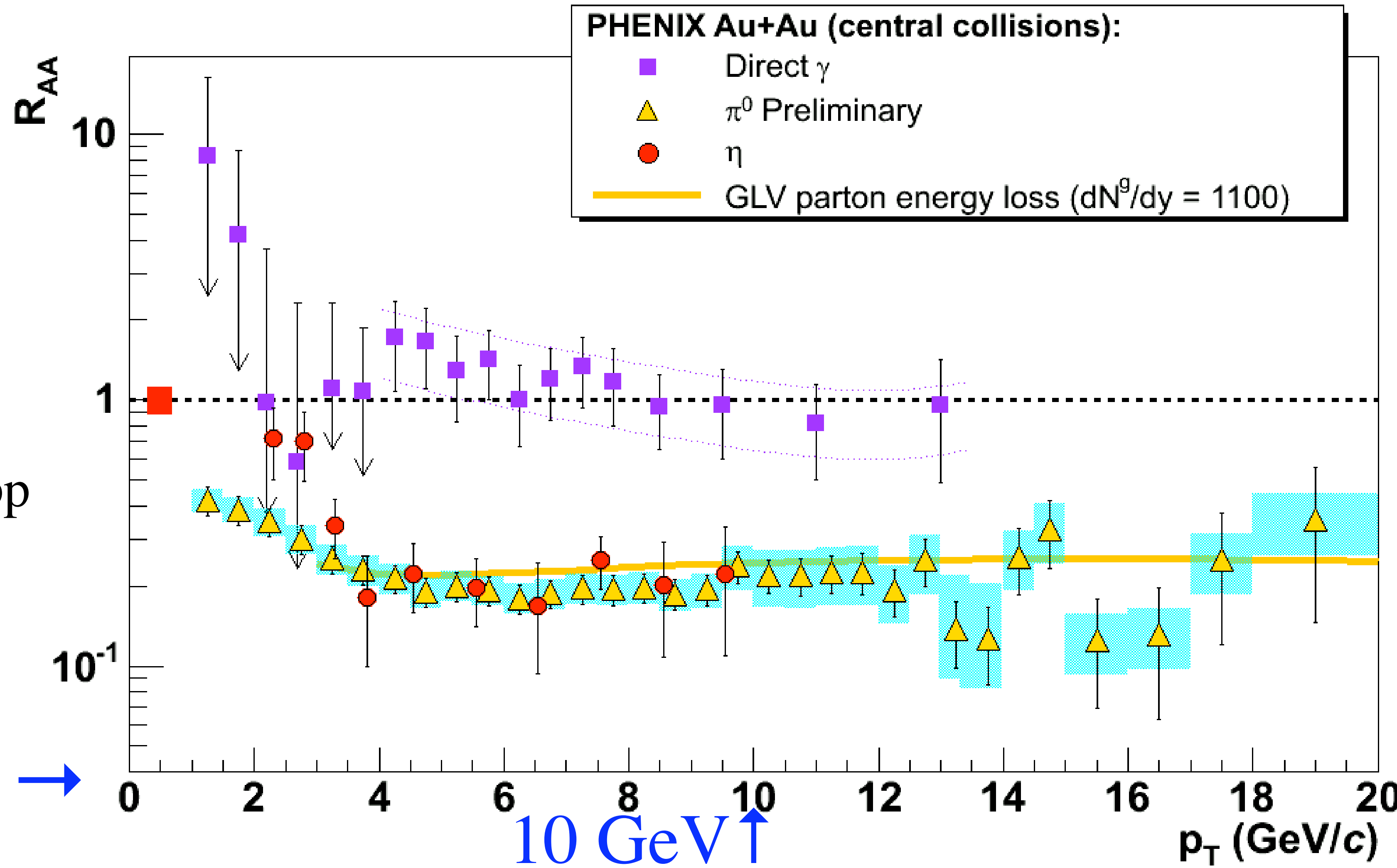
Due to "energy loss" in thermal medium?

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

R_{AA}: ↑

particles central AA/ # particles pp

A=200 =>



p_t →

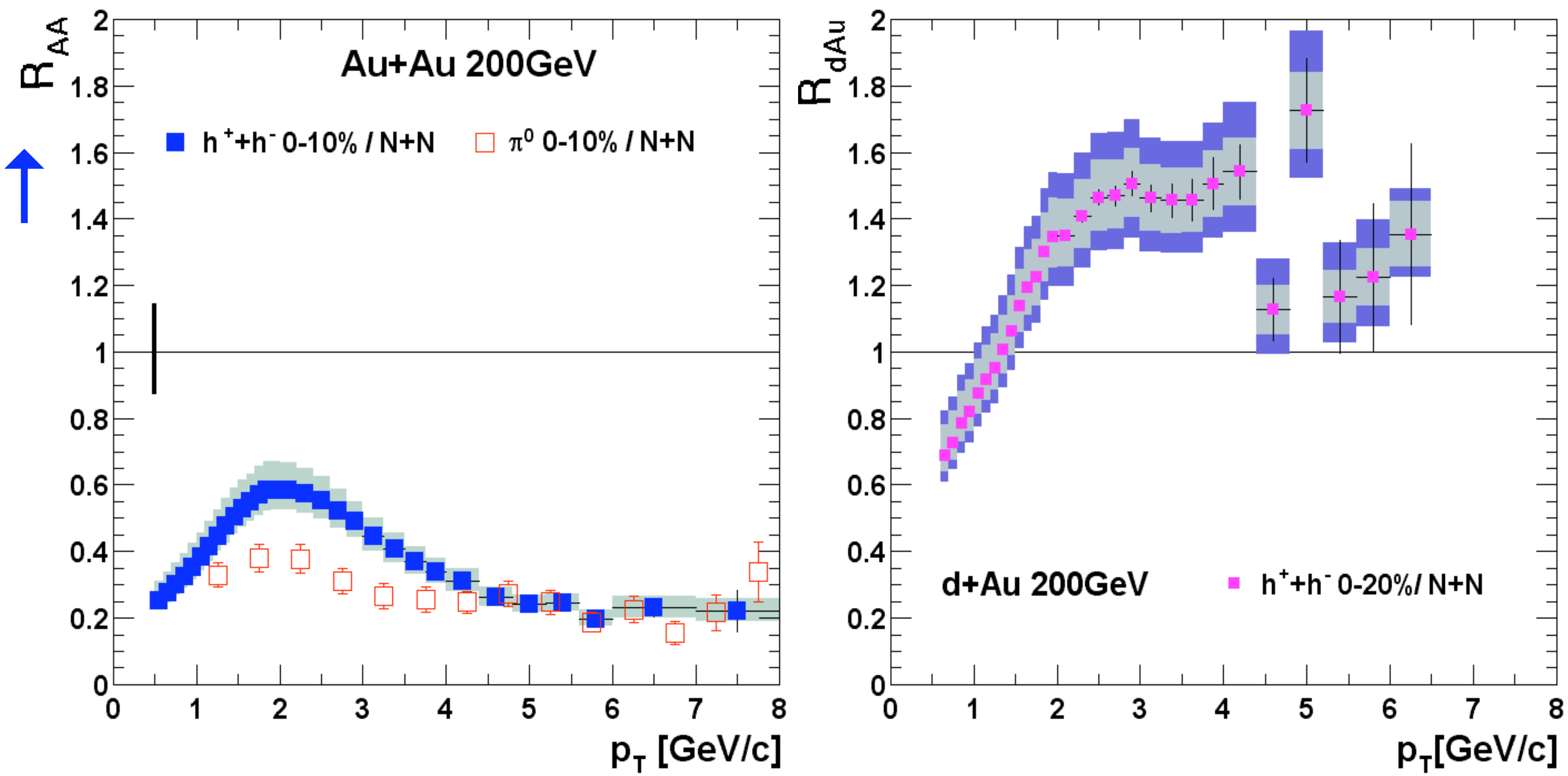
10 GeV↑

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 →

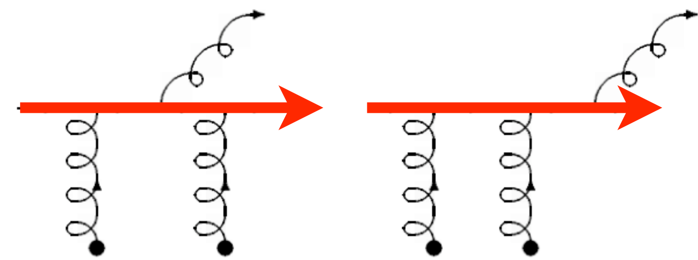
Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

Explanations of R_{AA}

“Energy loss”: fast particle emits radiation, scatters off of thermal bath.

Involves Landau-Pomeranchuk-Migdal effect



“strong”-QGP: large energy loss.

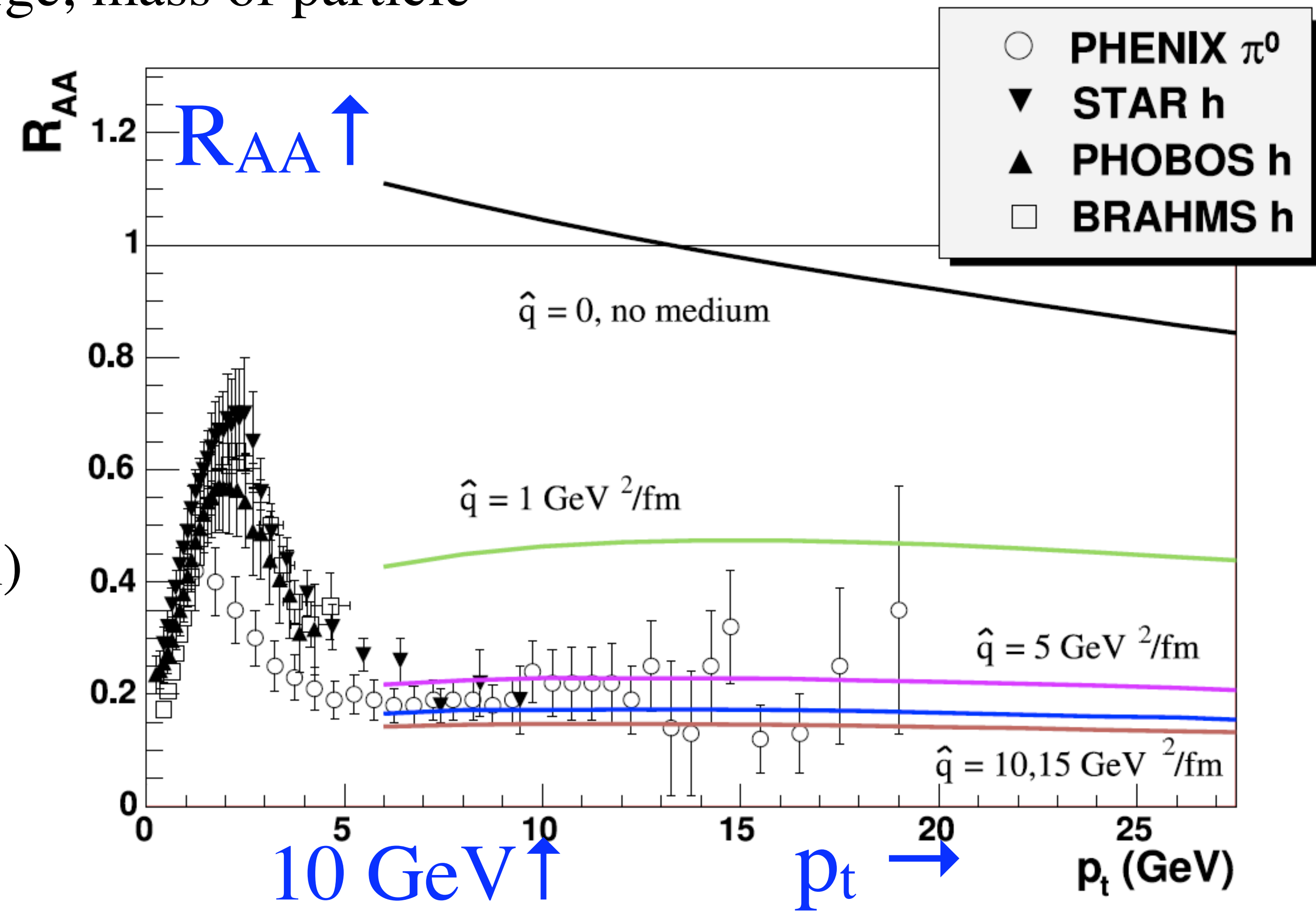
Details depend upon charge, mass of particle

“semi”-QGP:

propagator ~ loop,

small near T_c.

Details ~ independent of charge, mass of particle (assuming thermalization)



R_{AA} for heavy quarks: also suppressed!

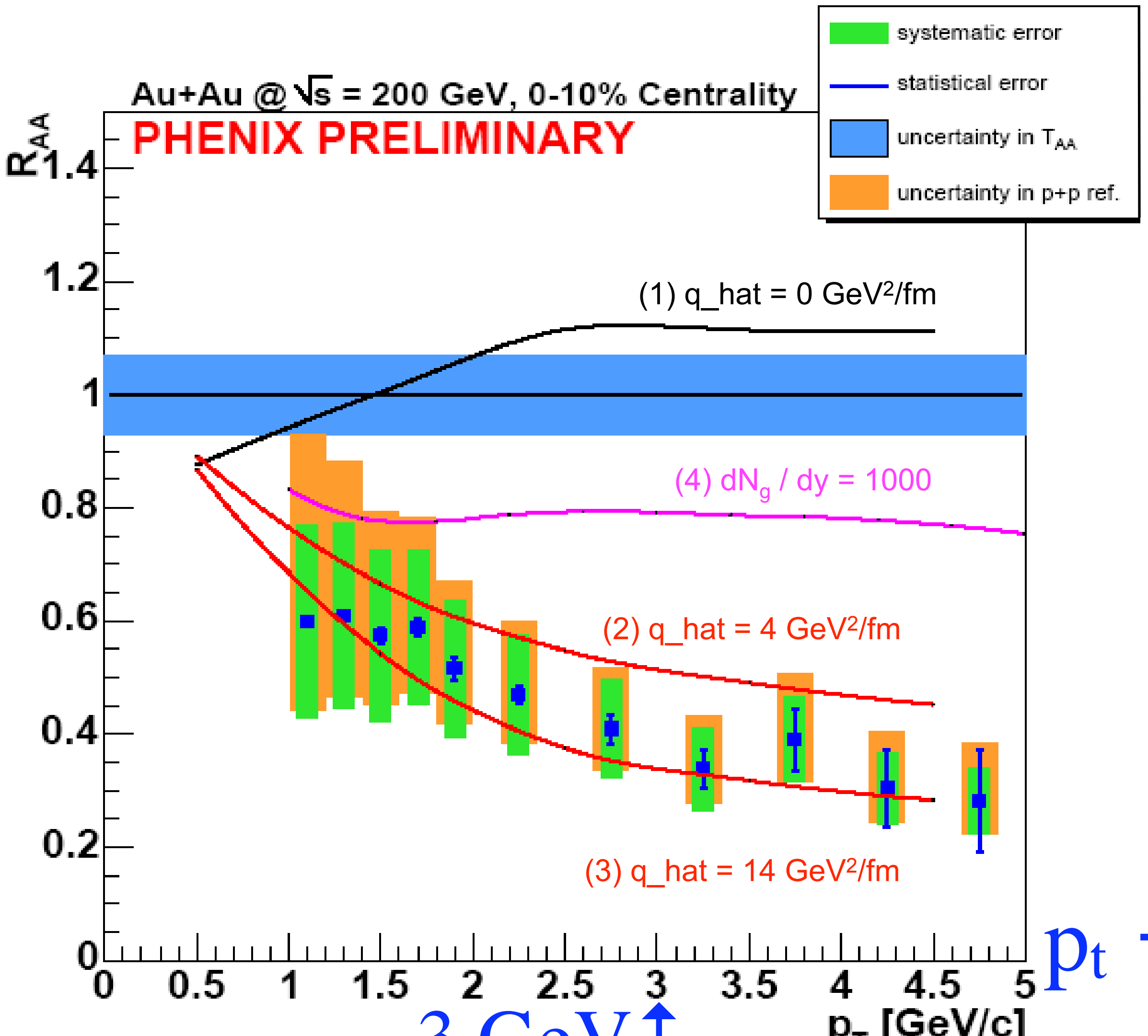
PHENIX: R_{AA} for charm quarks ~ light quarks!

Mass of charm quark m_{charm} ~ 1.5 GeV; T ~ 200 MeV.

Heavy quark less sensitive to medium by T/m_{charm} ~ 1/8. *No* sign of that!

Experimental evidence for "sQGP": heavy quarks ~ same as light!

R_{AA} ↑



p_t →

3 GeV ↑

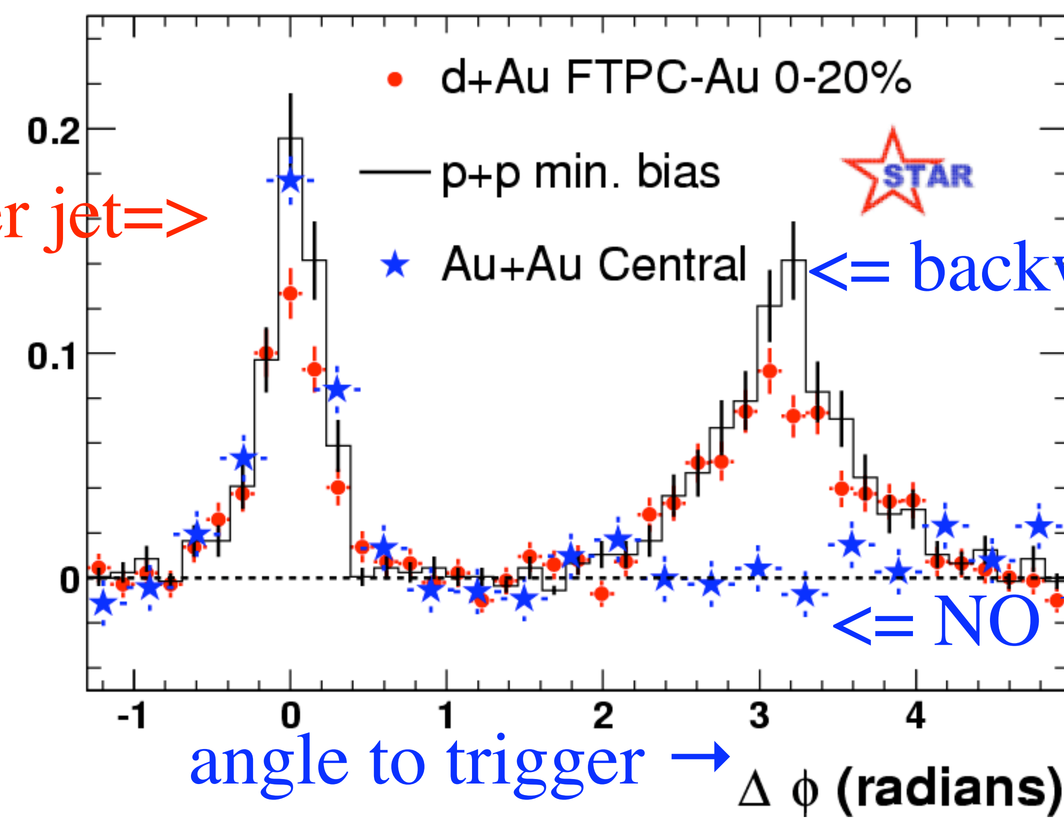
Central AA collisions “eat” jets!

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

Trigger on hard “jet”, p_t: 4 → 6 GeV. Look for backward “jet”, $p_t > 2$ GeV

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

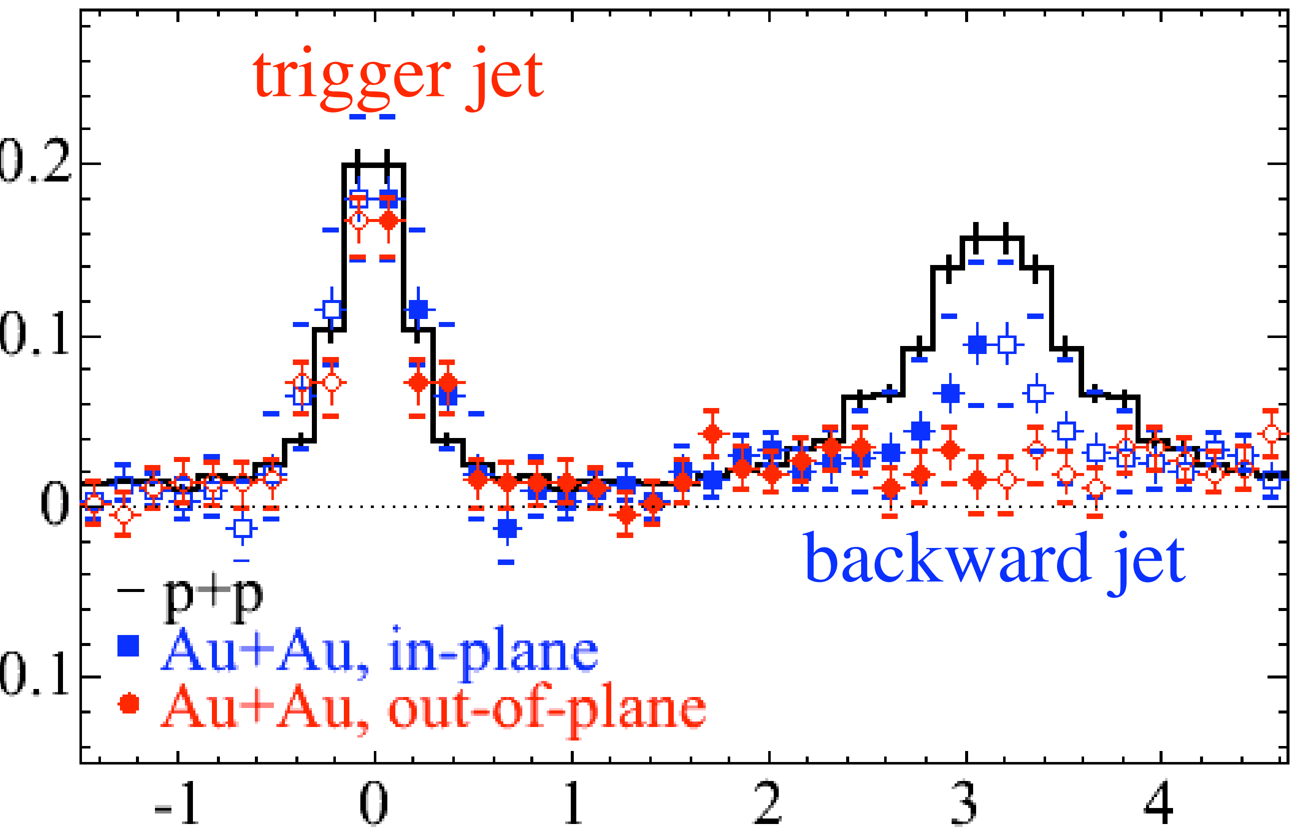
Adams *et al.*, Phys. Rev. Let. 91 (2003)



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

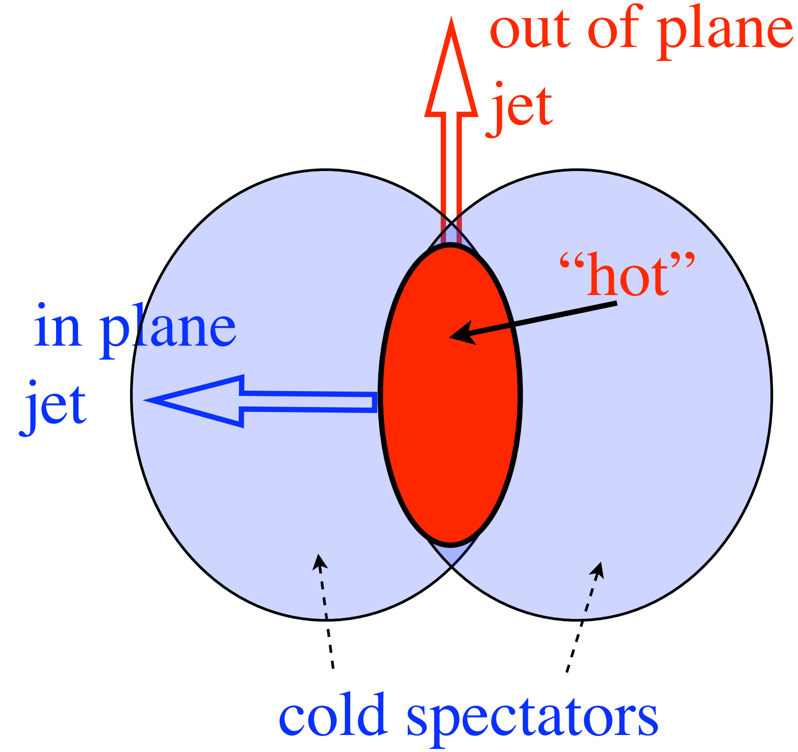
Peripheral collisions: " hot stuff" forms "almond". In vs. out of reaction plane
Out: more "hot stuff". *In*: less hot stuff, more cold nuclear matter

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



STAR

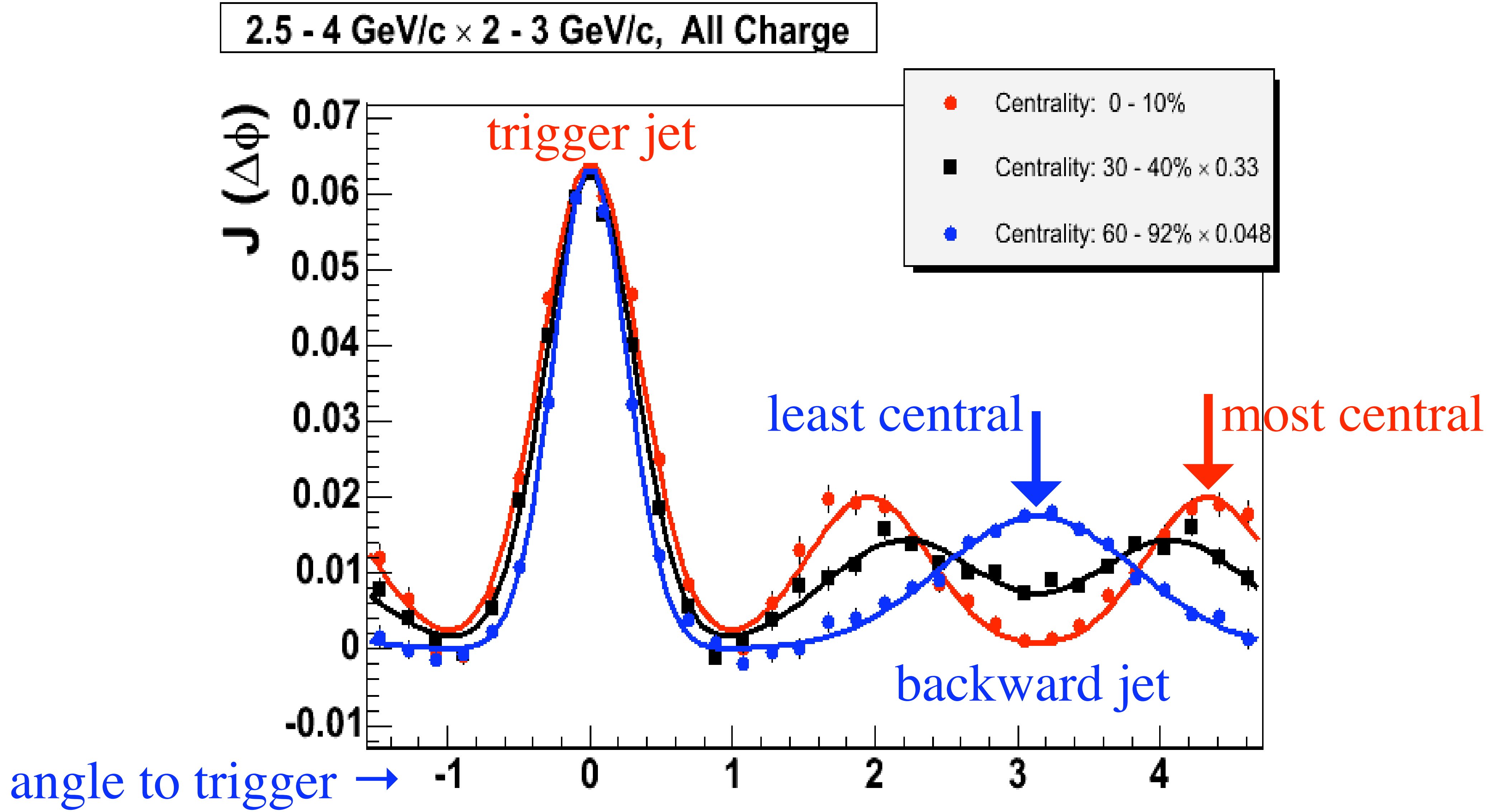
angle to trigger → Δ φ (radians)



Peripheral collision

AA collisions modifies jet shapes

PHENIX: shape of away side jet appears to be modified by “stuff”:
Mach cone or Cerenkov radiation in strong-QGP? semi-QGP?
Need to test with 3-particle correlations; appears real.



The Body of the Unicorn: the sQGP

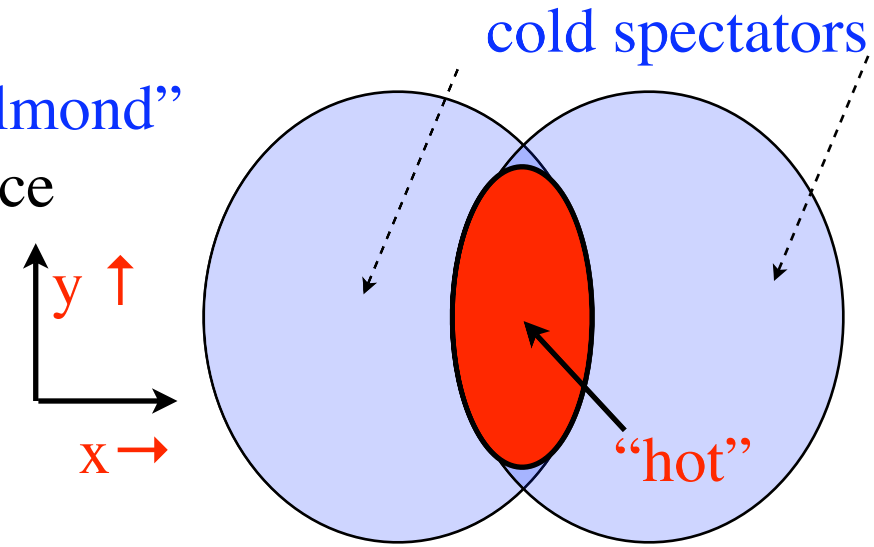
Particles peaked about zero transverse momentum

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

Thousands of particles: use hydrodynamics? “Most Perfect Fluid on Earth”

"Elliptic Flow"

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



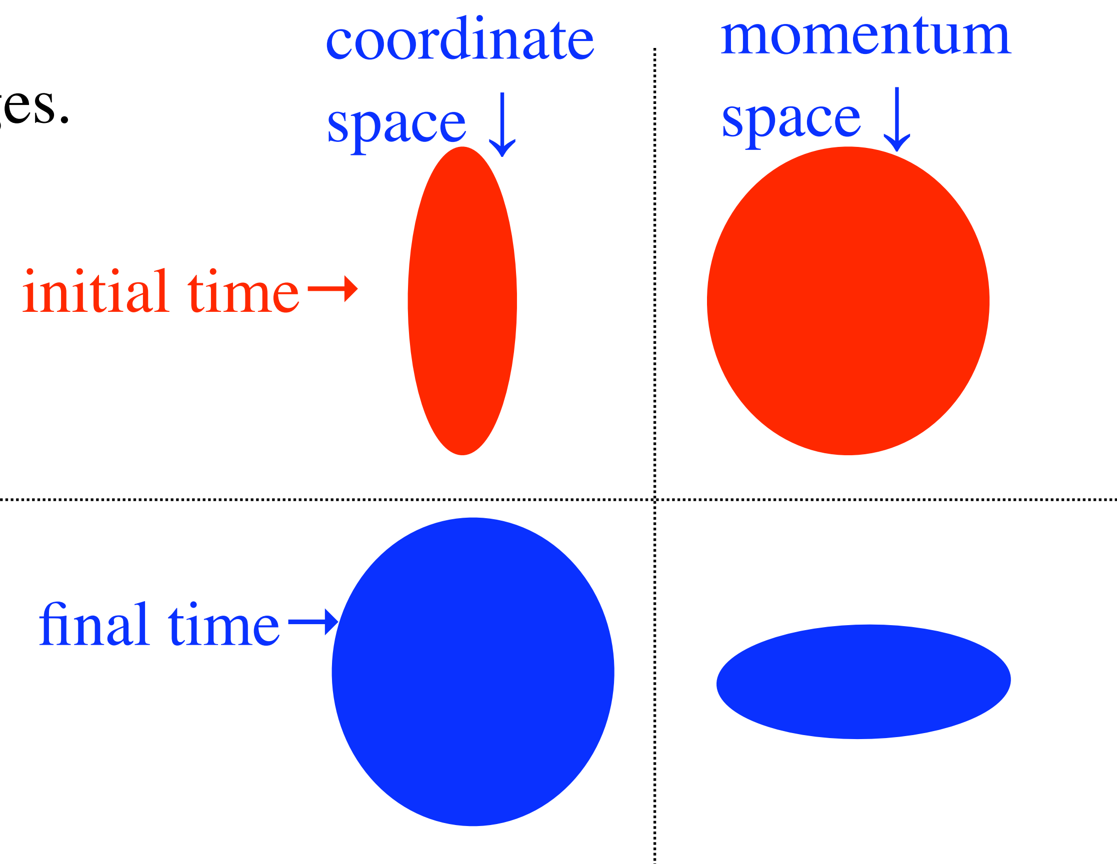
So start with spatial anistropy,

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

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”

Large # particles: try *ideal* hydrodynamics:

1. *Short* initial time (tune)   2. *MIT Bag* Equation of State

3. *Small* viscosity in QGP phase. 4. Hadronic “afterburner”: pions, K’s, p’s.

Good fit to π’s, K’s, p’s.... for *both* single particle spectra *and* v_2.

Need *small* viscosity.

Viscosity ~ 1/cross section:

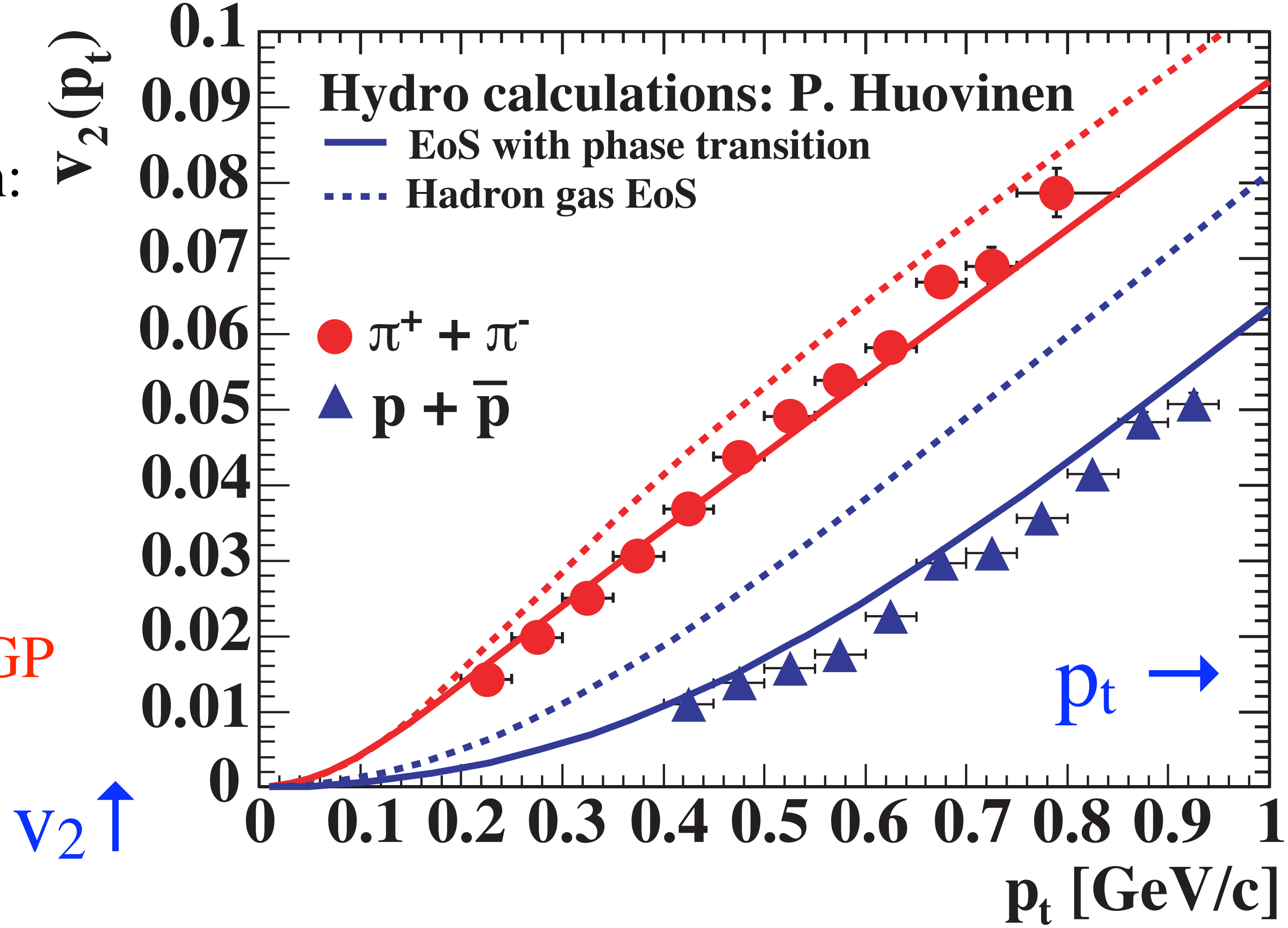
small viscosity =>

strong (coupling) QGP?

Gyulassy, Shuryak, Heinz,
Mrowczynski, Thoma...

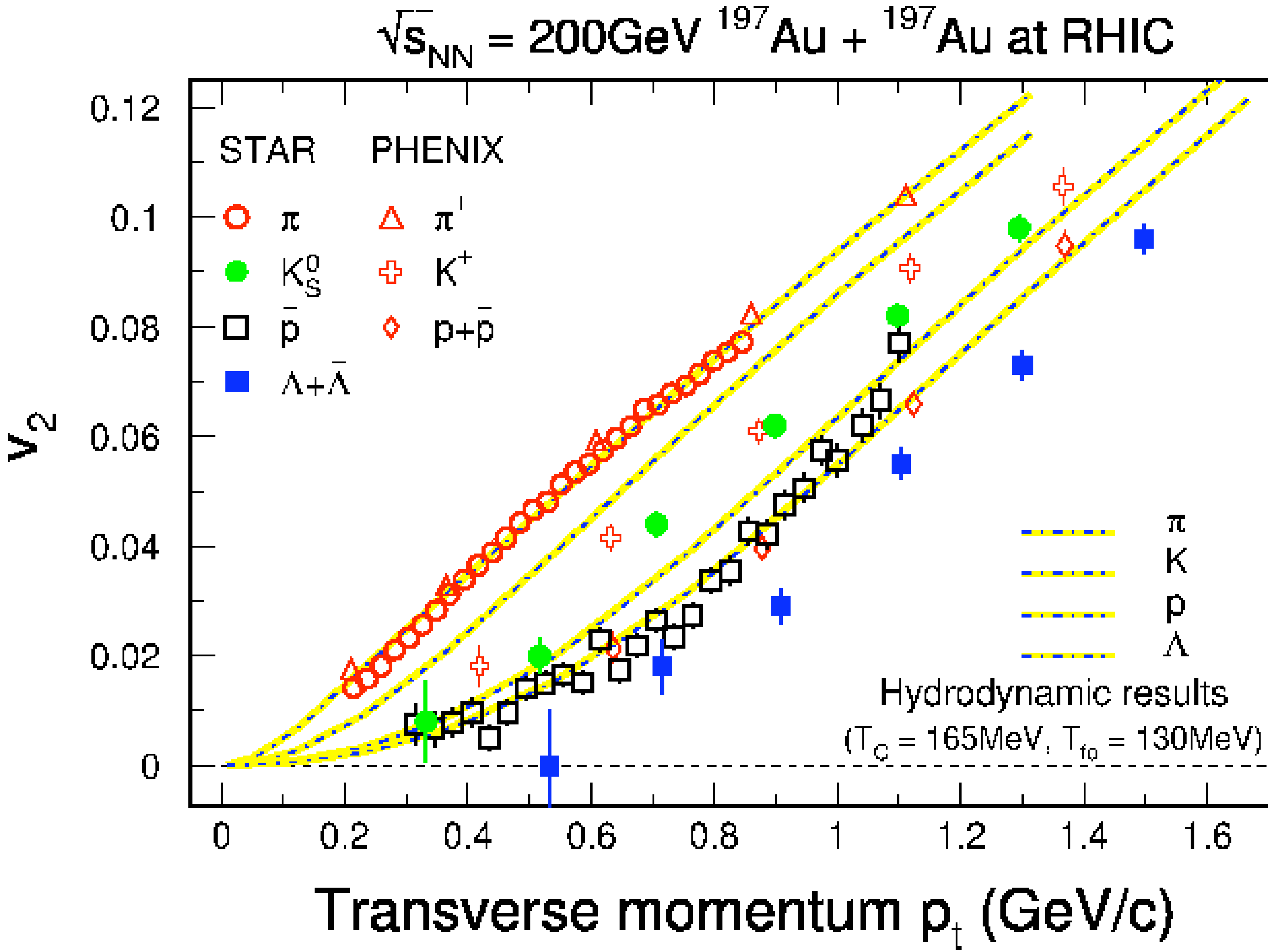
Small Polyakov loops =>
small viscosity in semi-QGP

Y. Hidaka & RDP ‘08



Strange Hydrodynamics, I

Hydrodynamic fits less dramatic for strange particles

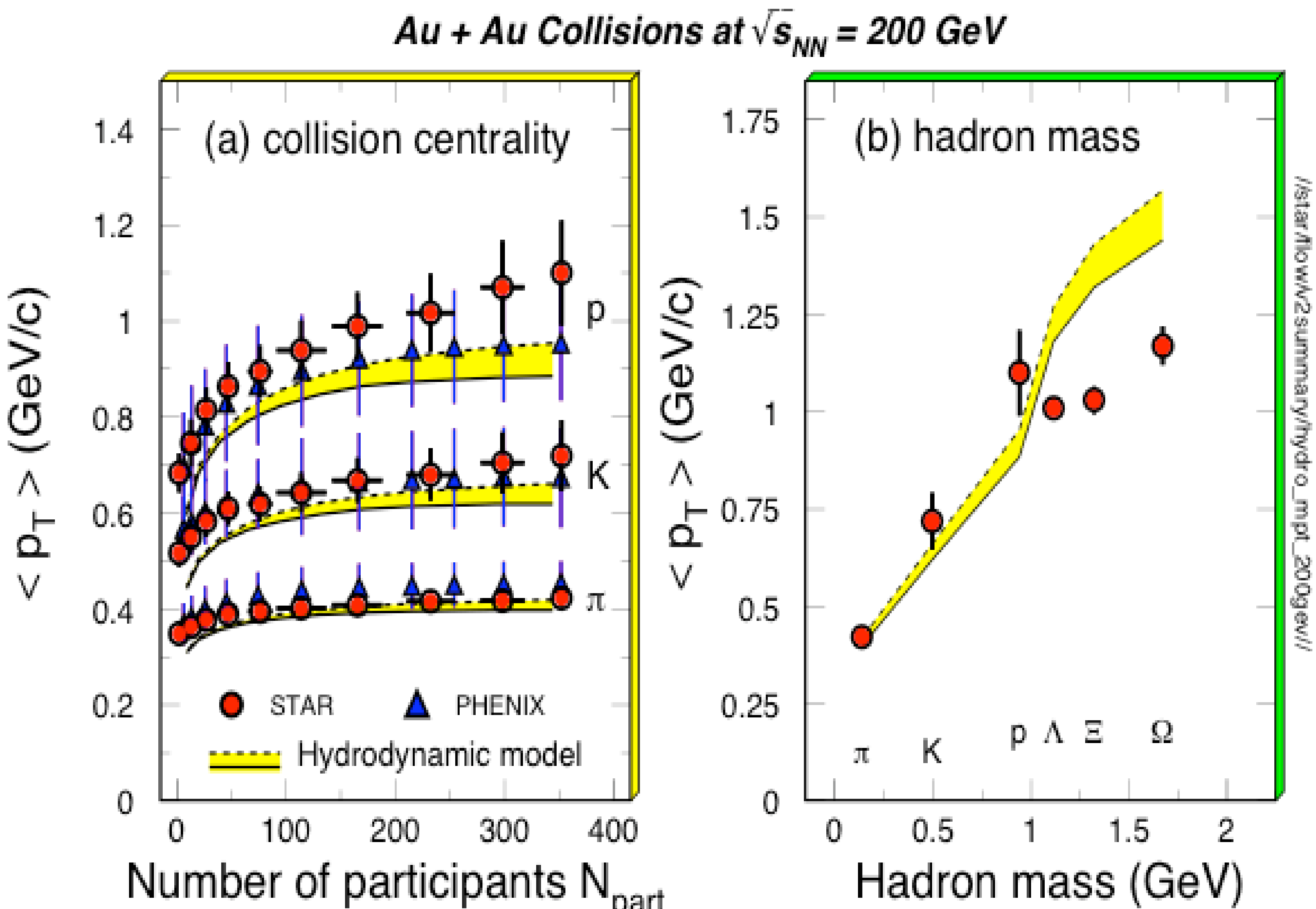


Strange Hydrodynamics, II

Strange particles? Hydro: $<p_t>$ ~ mass x (velocity of medium)

OK for π, K, p. But $<p_t>$ ~ 1 GeV for p, φ, Λ, Ξ, Ω!

Strange particles *don't* seem to flow with the medium. Why *constant* $<p_t>$?

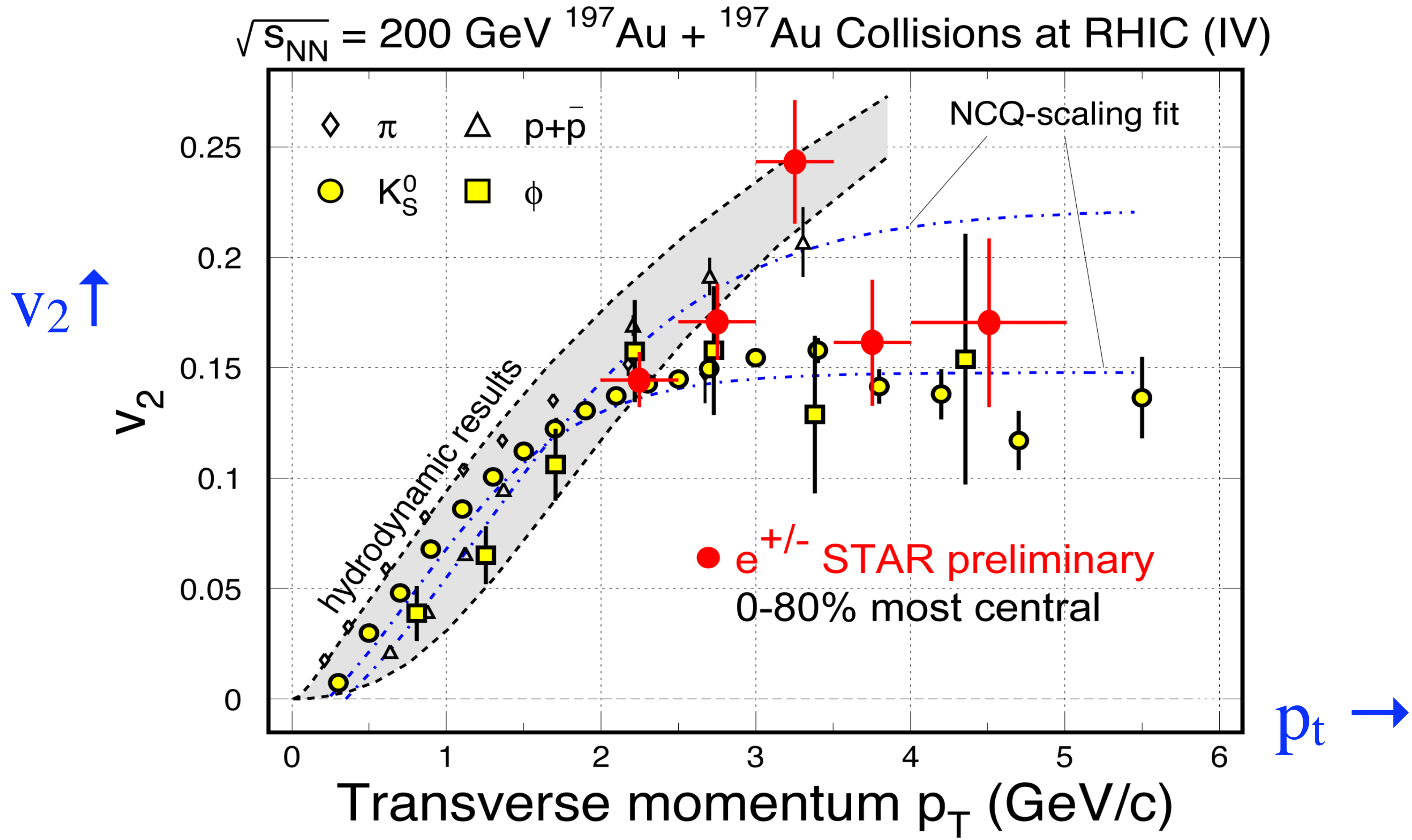


Even charm quarks flow

Look at charm quarks through single electrons.

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

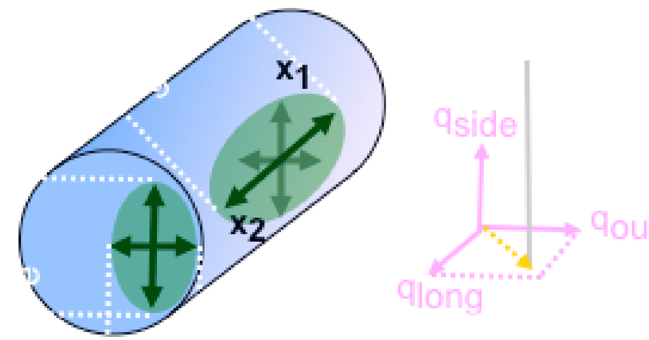
Experimental definition of “sQGP”: heavy quarks affected ~*same* as light quarks!



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}.

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

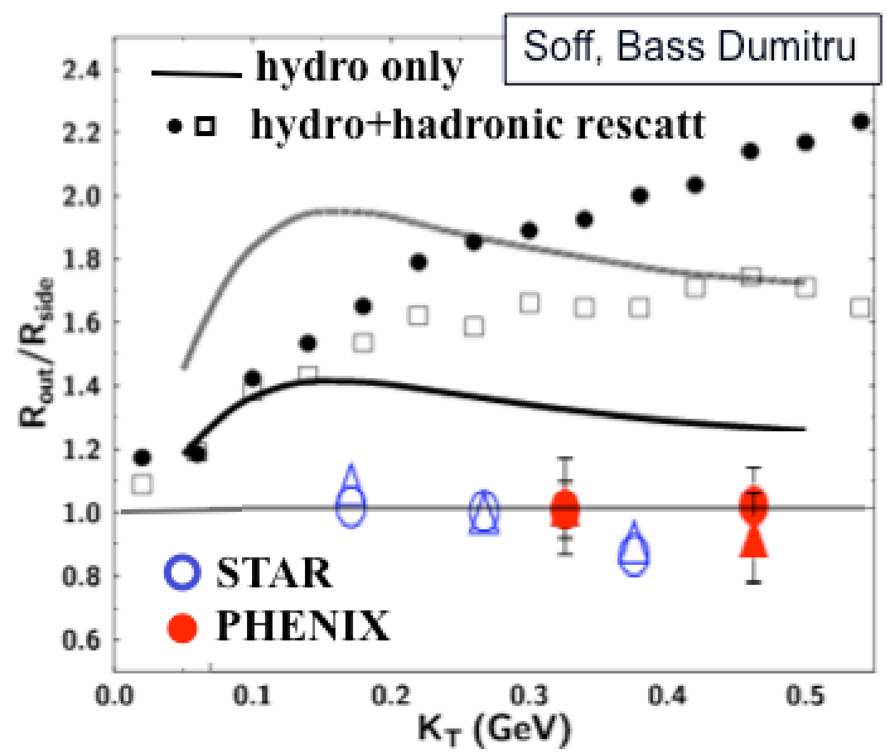


Hydro.: R_out/R_side > 1, *increases* with p_t
("burning log")
Exp.: R_out/R_side ~ 1.0, *flat* with p_t

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!



sQGP: from RHIC to LHC

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”

Assume RHIC near T_c, LHC well above.

“s” = strong. AdS/CFT rules!

No surprises from RHIC to LHC.

“s” = semi. Partial ionization of color.

Use lattice to construct effective theory

Qualitatively *new* behavior at LHC.

Nothing better than a good dog fight...

"A possible eureka."

From the SPS: NA60 and a "thermal" ϱ

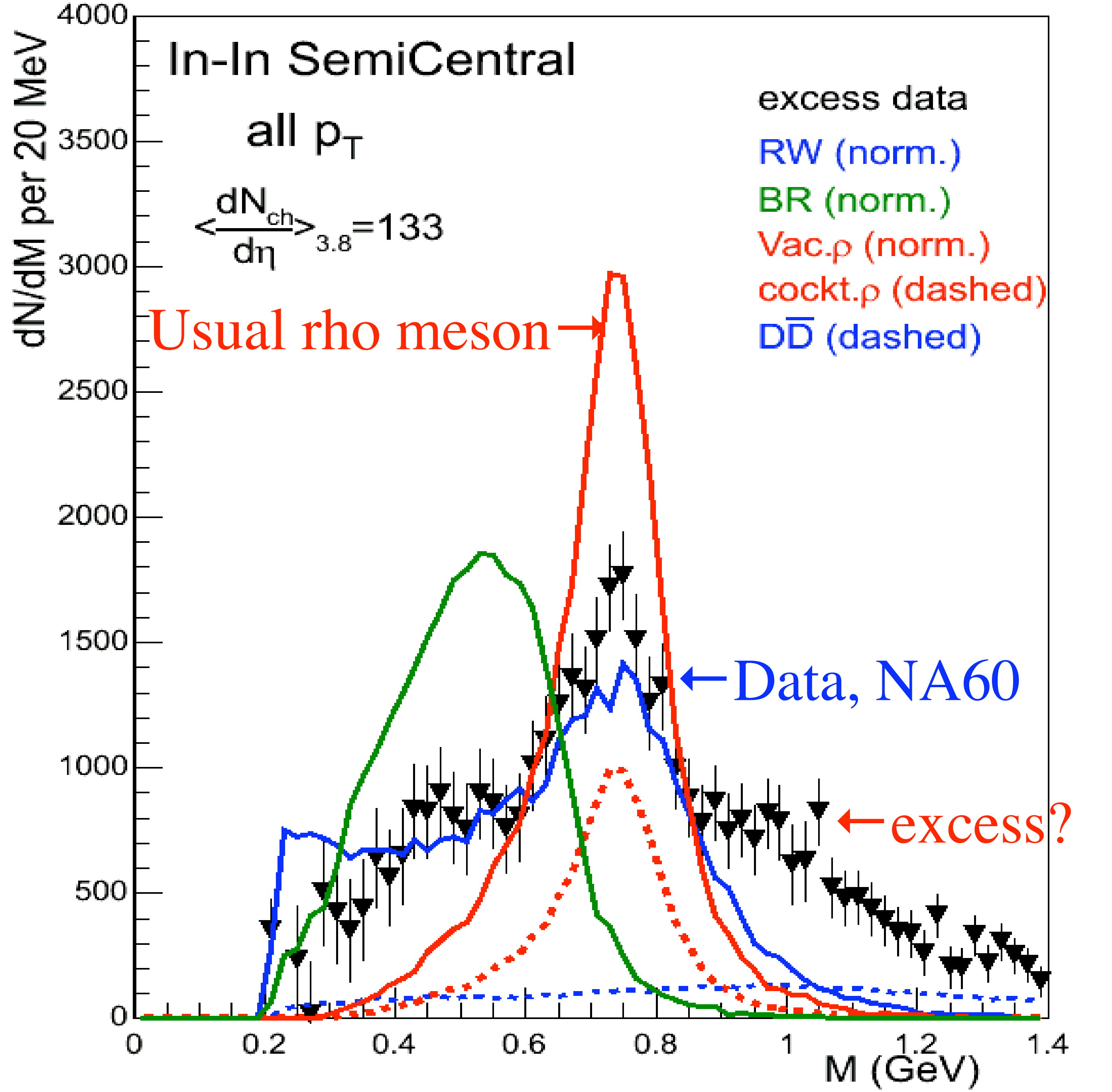
SPS = fixed target. Kinematics more awkward, but can generate many more events.

Example: electromagnetic signals, such as e^+e^- pairs.

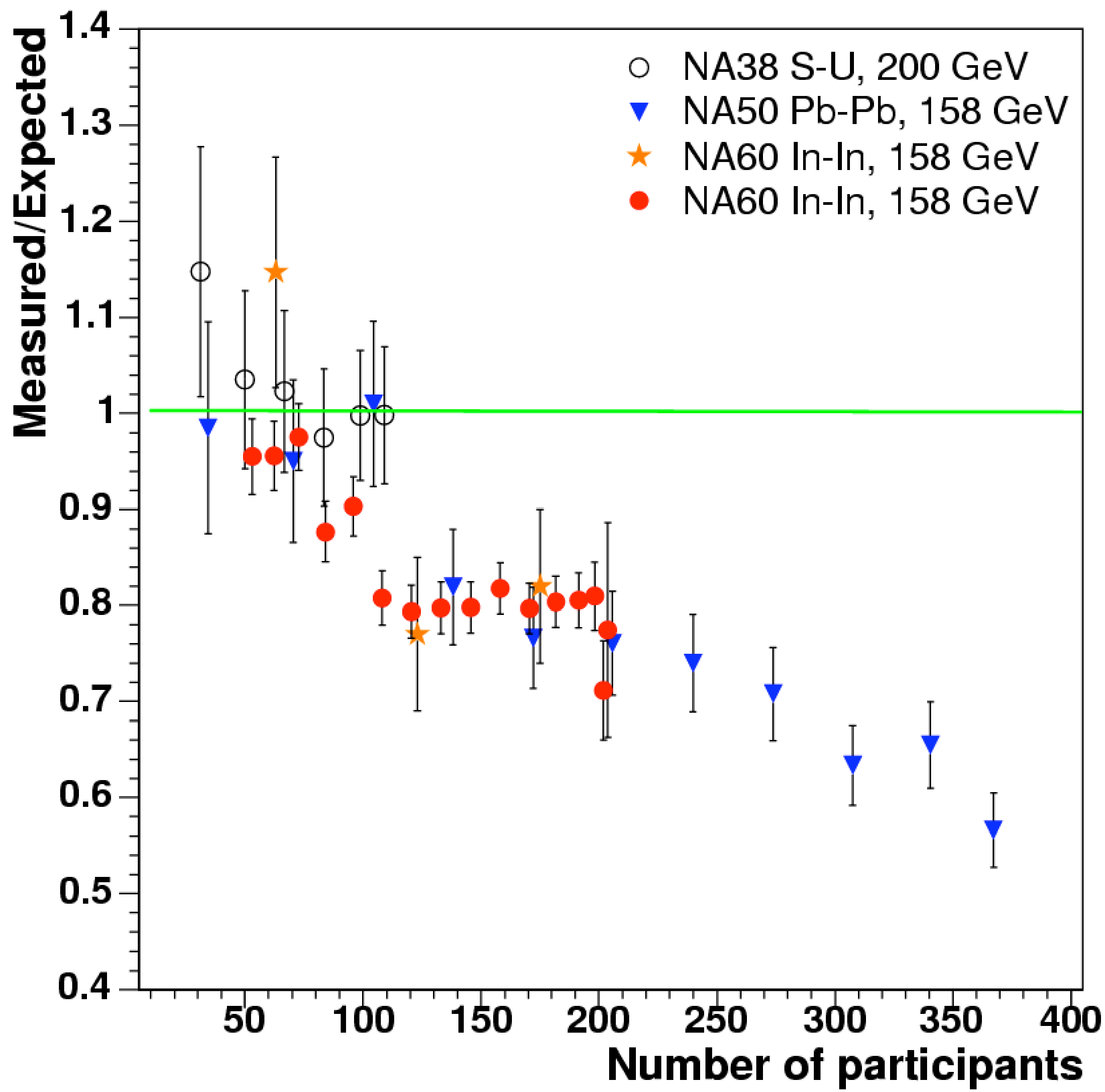
Look at "ϱ" meson, mass ~ 770 MeV. Decays directly to e^+e^-.

Find "thermal" ϱ: no shift in mass, thermal broadening.

Interesting excess *above* the ϱ?

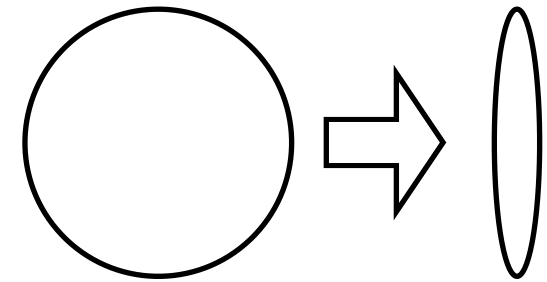


SPS: NA50, NA60 J/Psi suppression



consistent, # participants good variable

Why do AA? “Saturation” as a Lorentz Boost



$\leftarrow A^{1/3} \rightarrow$

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:

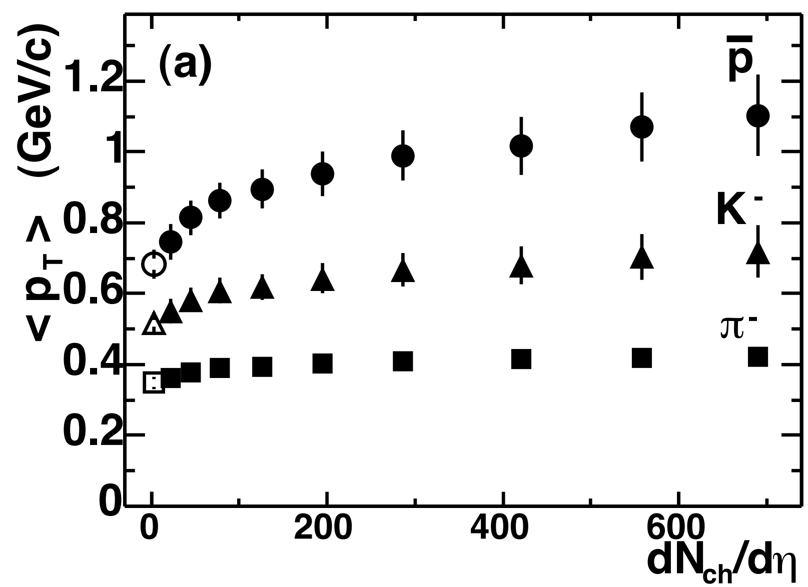
<p_t> ~ same for pions

<p_t> increases for K's, even more for p's!

=> CG not final state

Hydro: big "boost" velocity of medium.

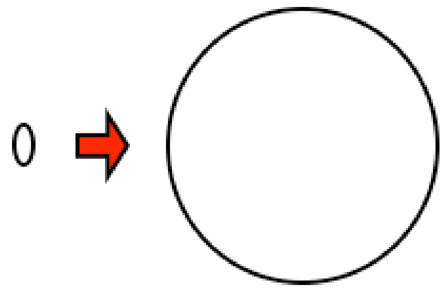
STAR, pp & AuAu, 200 GeV

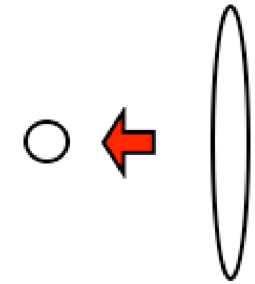


↑pp central AuAu ↑

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: