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 quarks are suppressed, flow!

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

"*Most Perfect Fluid on Earth*"

AdS/CFT duality: hot "Super 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

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

AF => *ideal* gas at *infinite* temperature.

Pressure: $p(T \rightarrow \infty) \sim \# T^4$, # = 8 × photon!

"Perturbative": > 1 GeV (= 1000 MeV)

Powers of $\alpha_s \sim 1/\log(p)$...

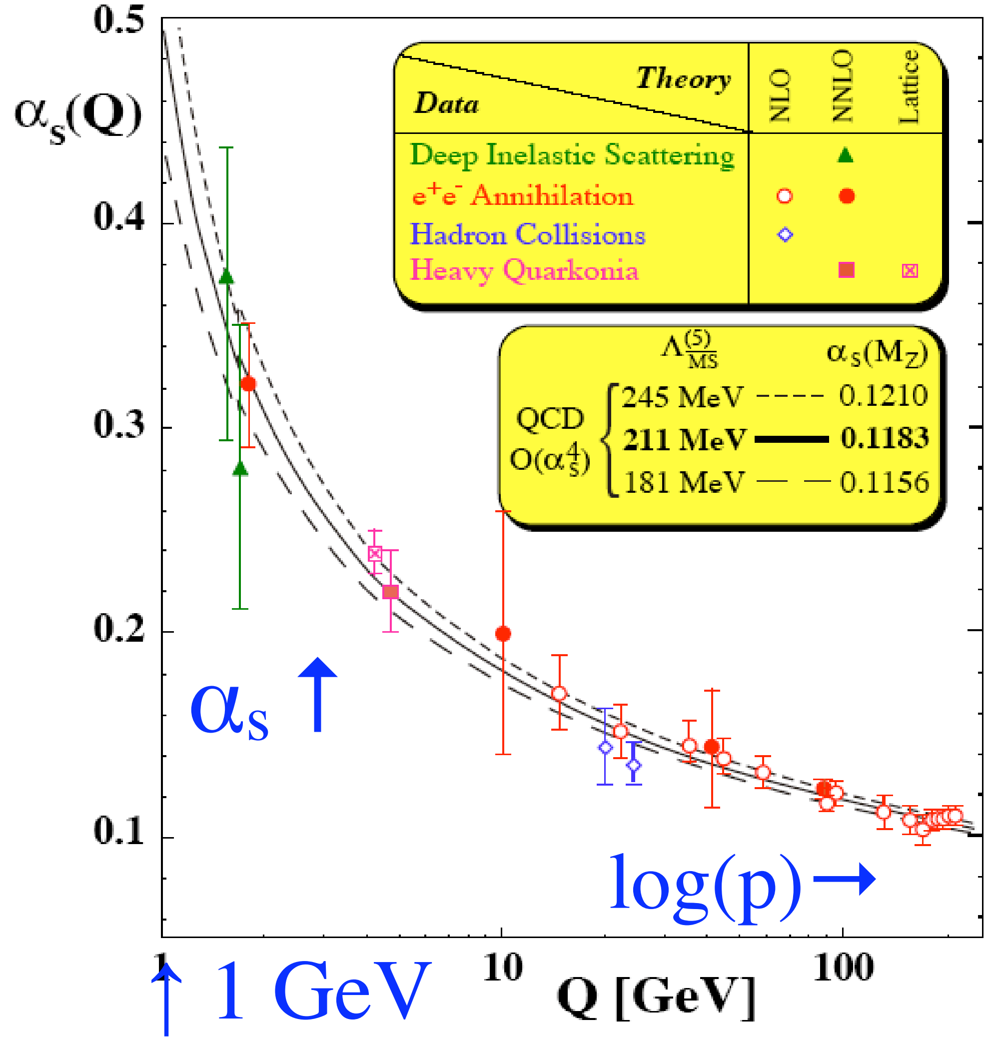
NON-perturbative: < 1 GeV

Powers of (*non*-pert. mass)$^2/p^2$

Quarks: six flavors, coupled to glue

"2+1" light: up (u), down (d) + strange (s)

Heavy: charm (c), bottom, top.



QCD & Confinement

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

Quark + anti-quark = meson.

Very light: pions ($\overline{u}d$ ...), mass = 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

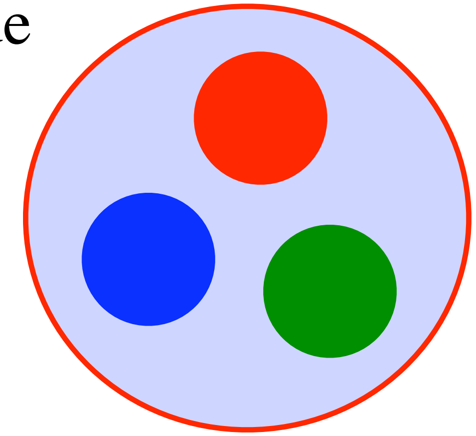
Charm mesons, J/Psi, ($\overline{c}c$) 3.1 GeV. *Glueballs? Where's the glue?*

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

Costs Bag constant B ~ (200 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*, # = N^2-1. Quarks: SU(N) *vector*, so # ~ N.

=> large N expansion is *dominated* by glue.

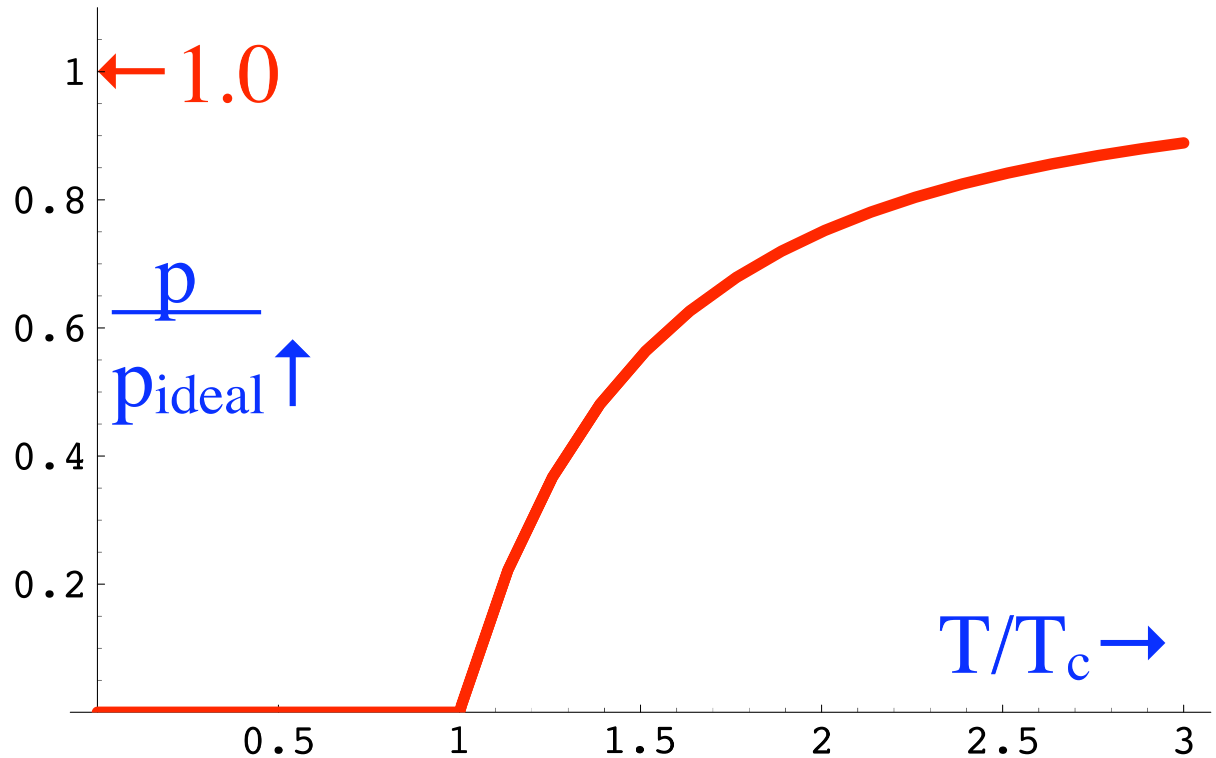
AF => *ideal* gas of ~ N^2 gluons at T = ∞. Pressure p(T) ~ N^2 for T > "T_c"

Confinement => only color singlets, # ~ 1. So p(T) ~ 1 for T < "T_c"

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

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

Possible form for this ratio =>
Like magnetization, in "reverse"



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 $a \to 0$, 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...

"QCDOC", QCD on a chip

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

Lattice: SU(3) gluons deconfine, $T_c \sim 270$ MeV

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

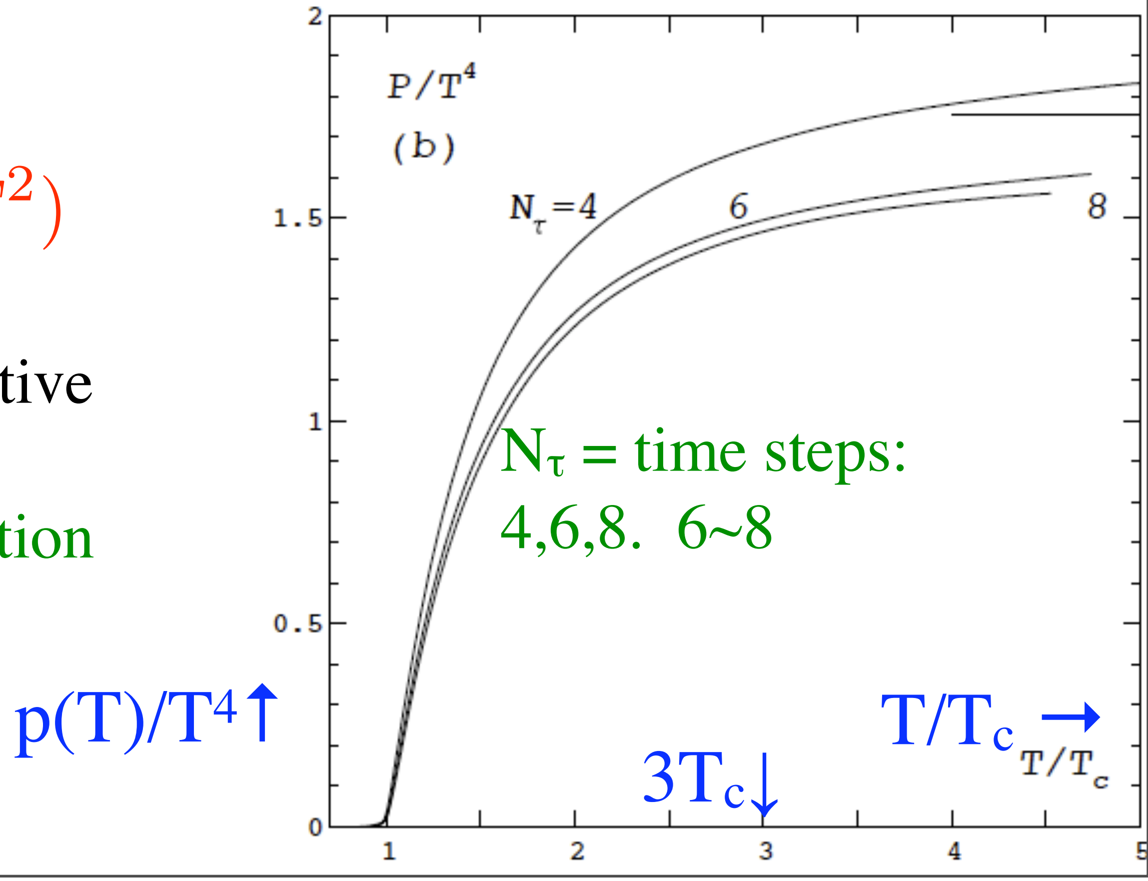
"Fuzzy" bag does:

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

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

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

Transition weakly first order
~ Z(3) Potts model



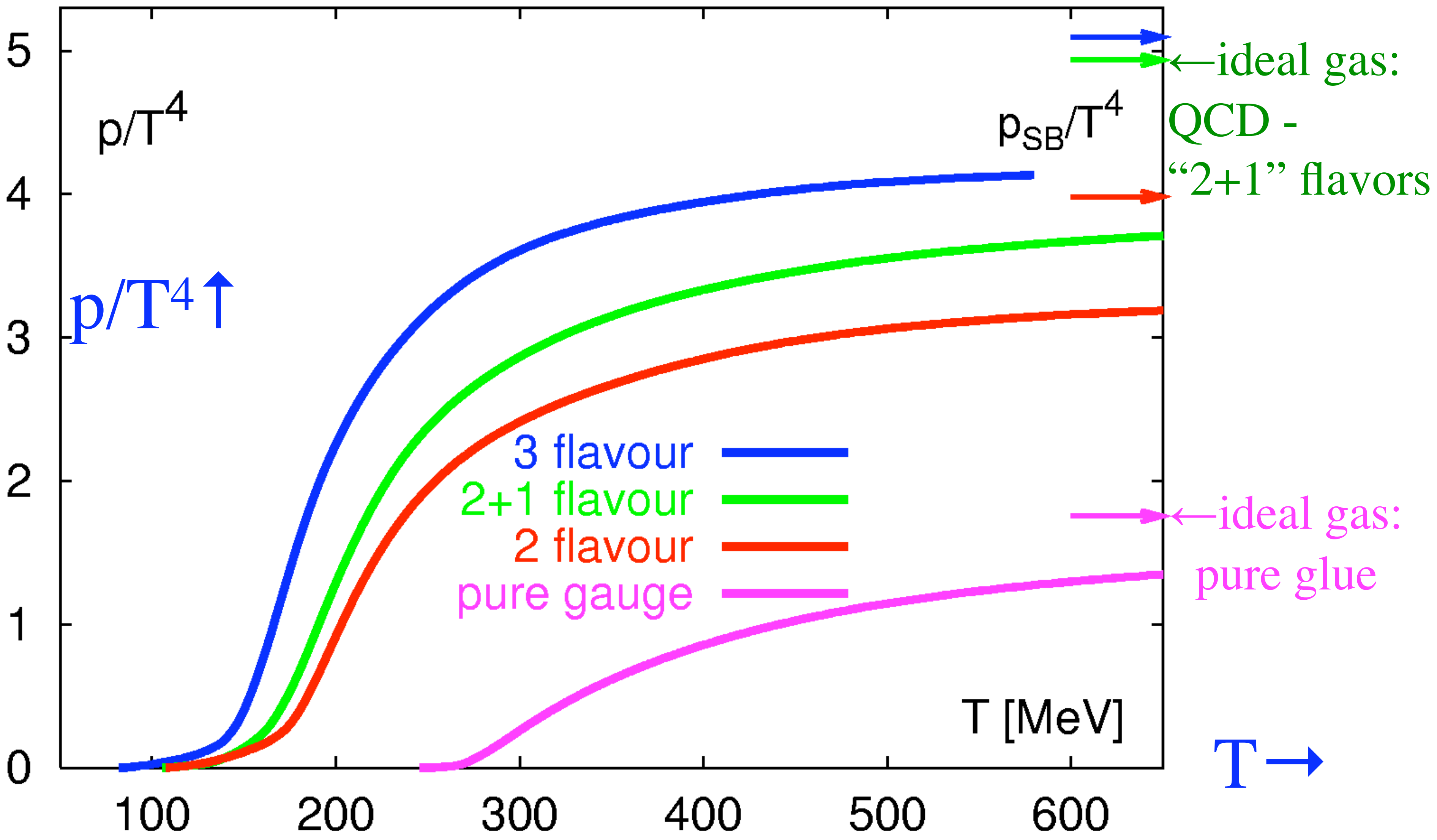
Lattice: QCD, with quarks: T_c ~ "175" MeV

Adding quarks: ideal gas value increases by ~ 3

"T_c" decreases. Today: ~ 175 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?



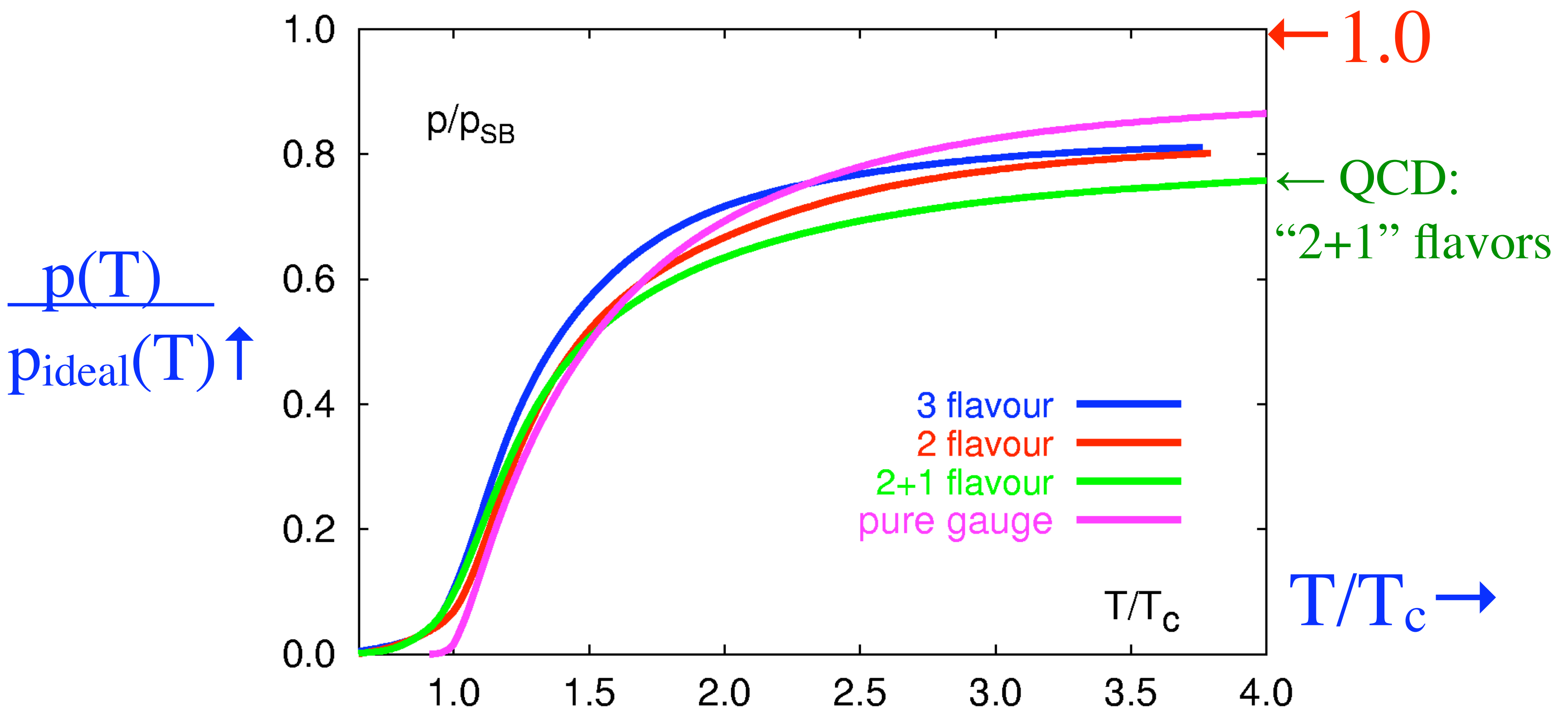
Lattice thermo.: QCD & “flavor independence”

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?*

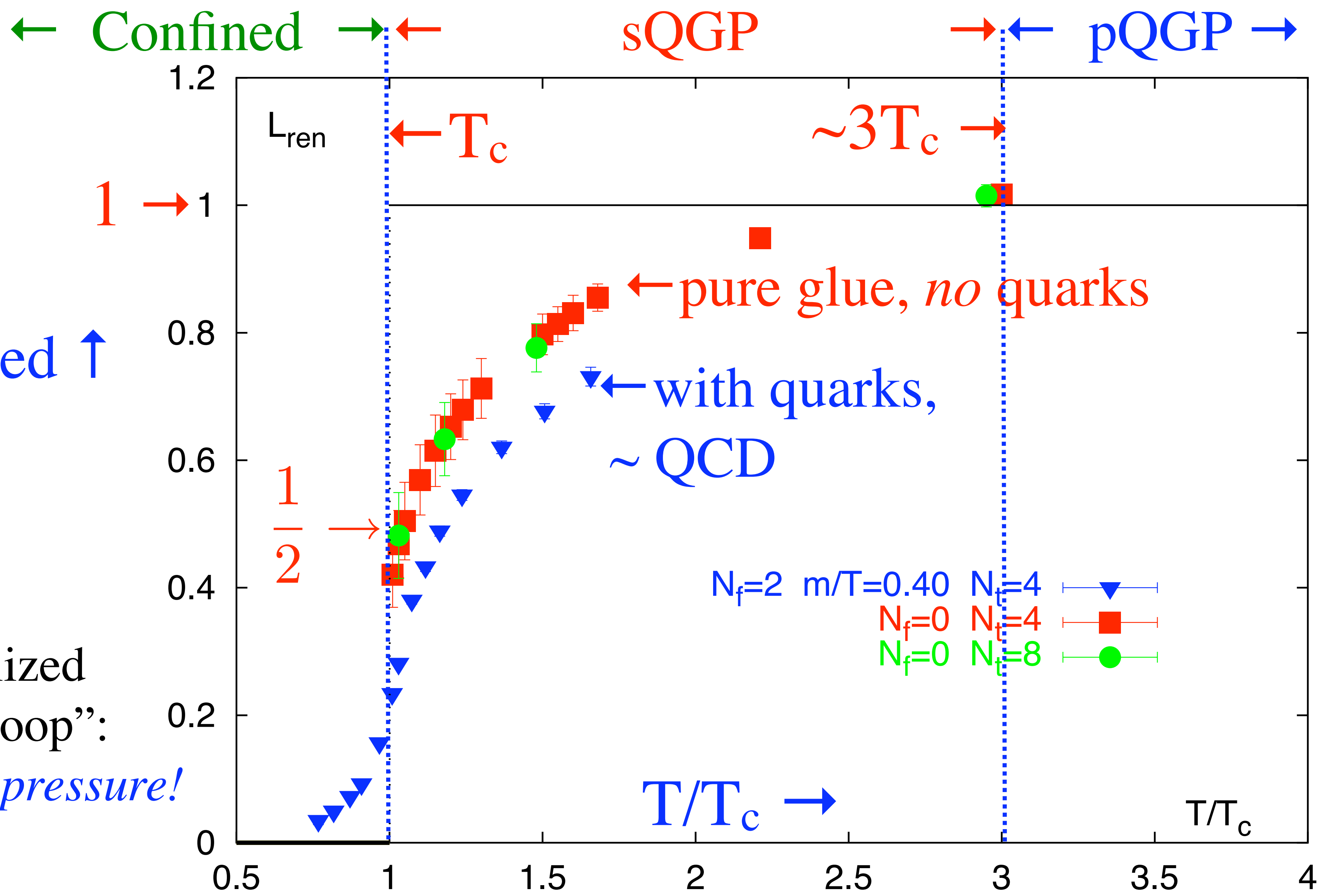
Is transition from confined phase, directly to nearly ideal QGP?



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

On lattice, can measure *fraction of deconfinement*

- $T > 3\ T_c$: fraction ~ 1, => ~ perturbative QGP, "pQGP"
- T: $T_c \rightarrow 3\ T_c$: fraction < 1, only *partially* deconfined: "sQGP" (s?)



Fraction deconfined ↑

"Renormalized Polyakov loop":
Looks like pressure!

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 ~ 500 MeV?

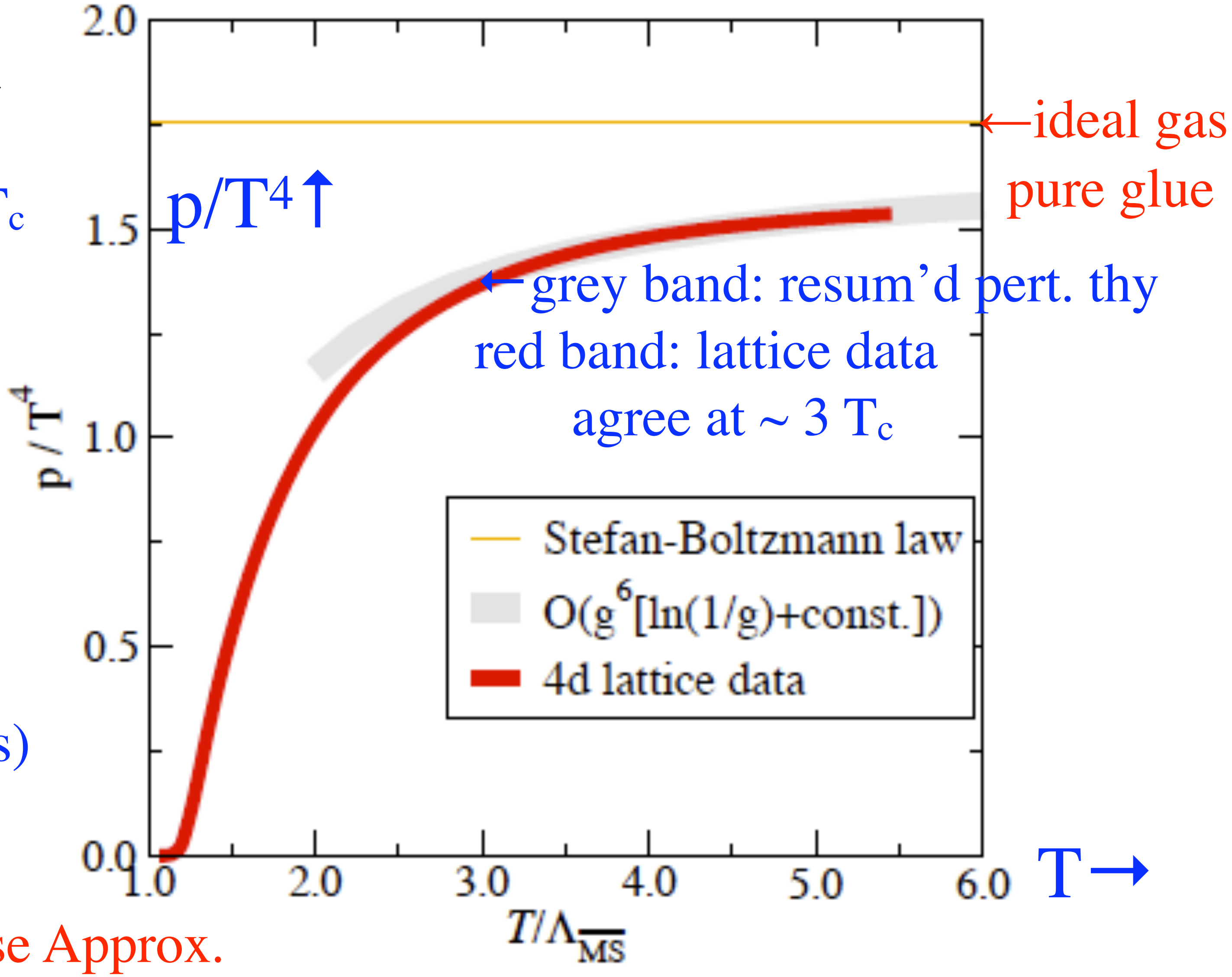
No! While deconfinement only partial at T_c, coupling *not* big, even at T_c

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

So what *is* “sQGP”, T_c to ~ 3 T_c?

Semiclassical, dominated by “solitons” (Wilson lines)

Eventually - NaRPA: Non-abelian Random Phase Approx.



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

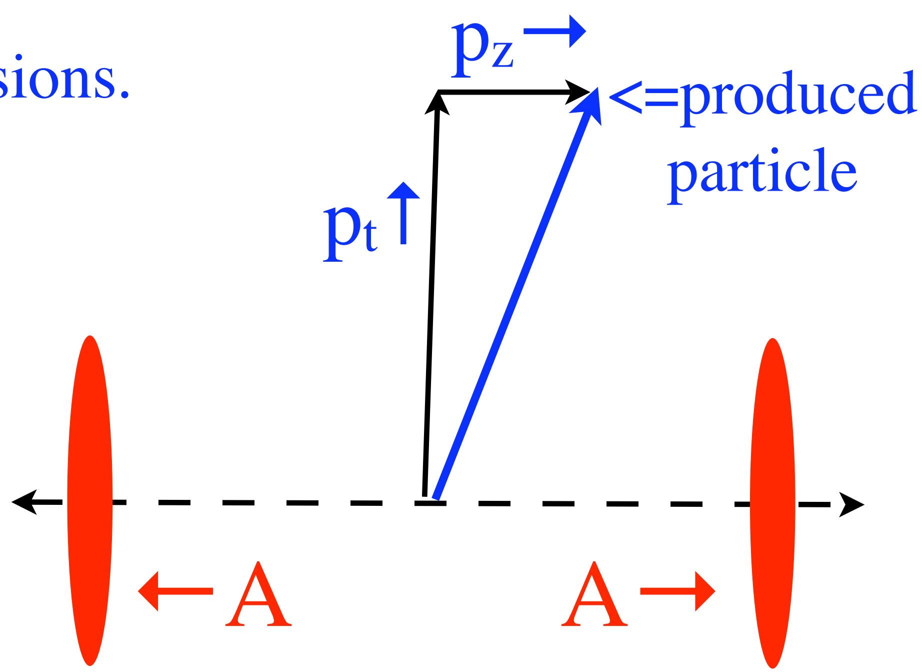
At *high* energies: nuclei Lorentz contracted along beam (15 fermi => 0.3 fermi)
  AF => nuclei don't stop, pass through each other.
  Collider: lab = center of mass frame
  Momenta of produced particles: along beam, p_z; transverse to beam, p_t
  Baryons in original nuclei go down beam pipe, at large $\pm\, p_z$

For pp collisions: particles ~ constant for some range in p_z about $p_z = 0$:
  "rapidity plateau" (rapidity ~ p_z; boost invariance)

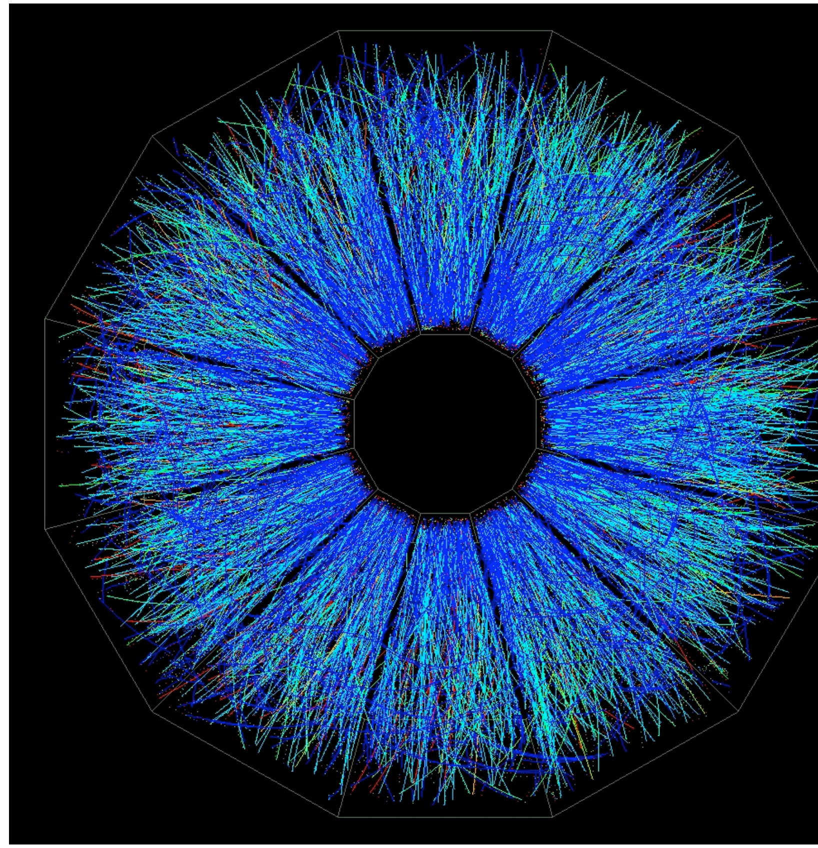
Bjorken: look at rapidity plateau in AA collisions.

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)

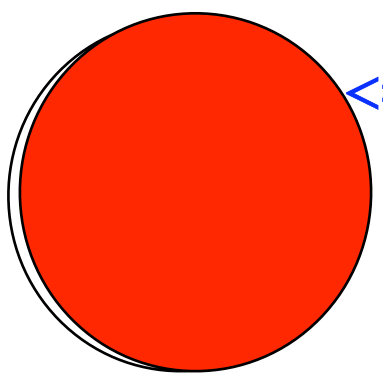
~total # experimentalists

theorists ~ log(log(total energy)).

Need hunters more than dogs...

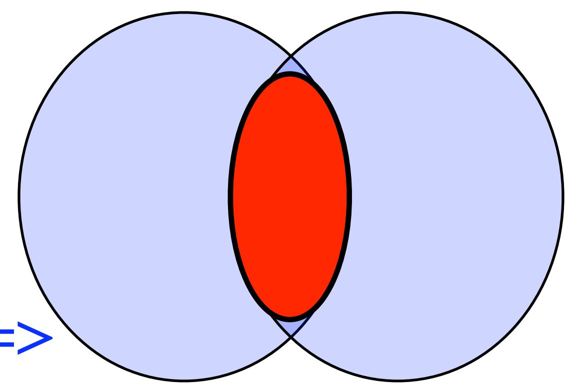
Total # particles/unit rapidity ~900↑

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



<= central

peripheral =>



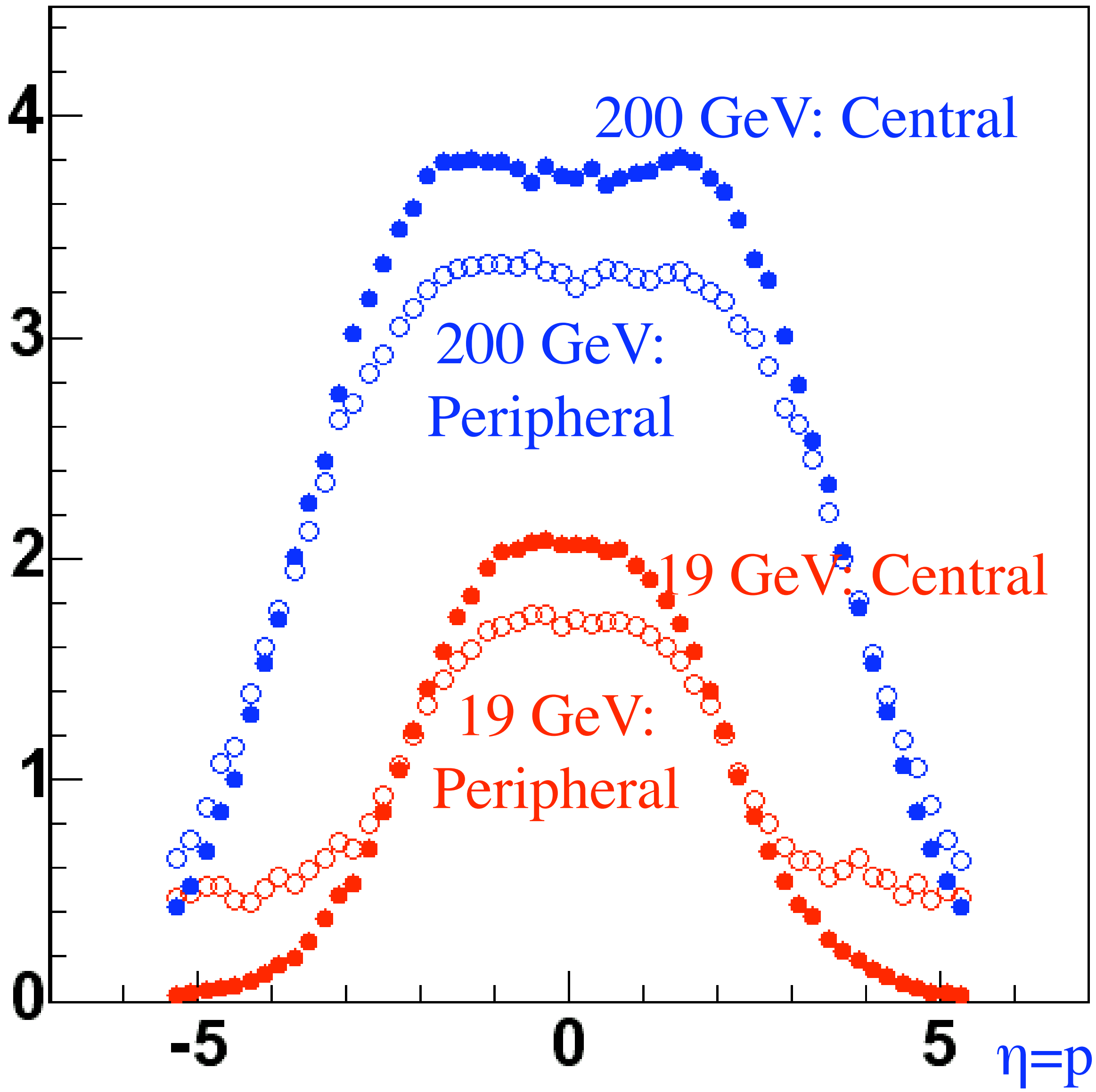
Overall multiplicity: slow growth

dN/dη/ ↑

N = # particles

η=”pseudo”-rapidity (no particle ID)

/ by # “participants”



η=pseudo-rapidity=>

200 GeV, RHIC
900 particles
/unit η

19 GeV, SPS
600 particles
/unit η

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":

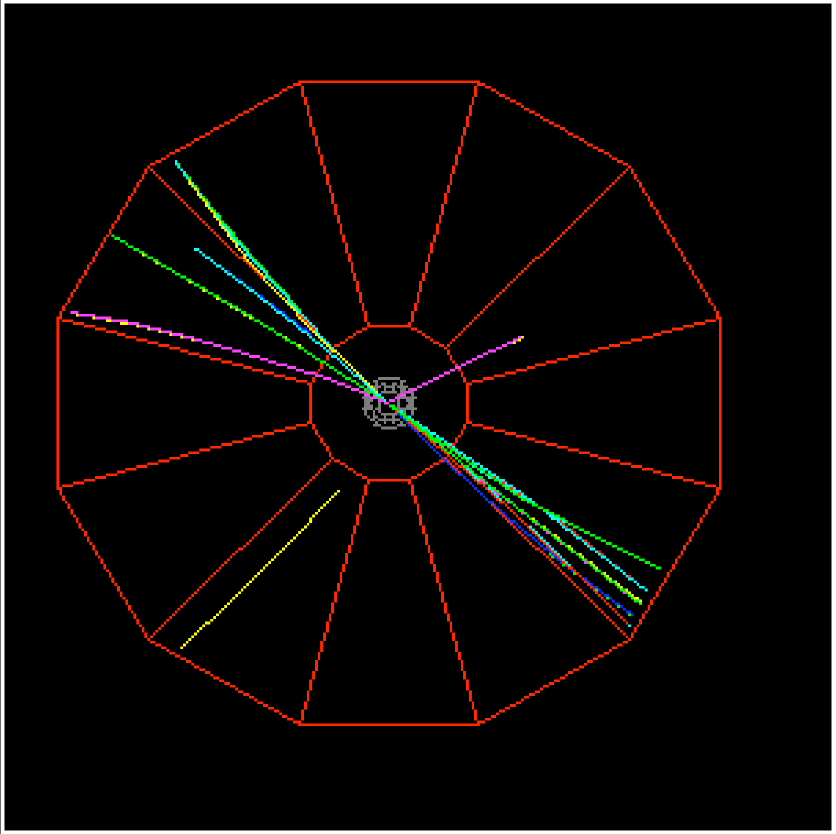
For T ~ 200 MeV,
majority of particles at *small* momenta,
$p_t < 2$ GeV.

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.

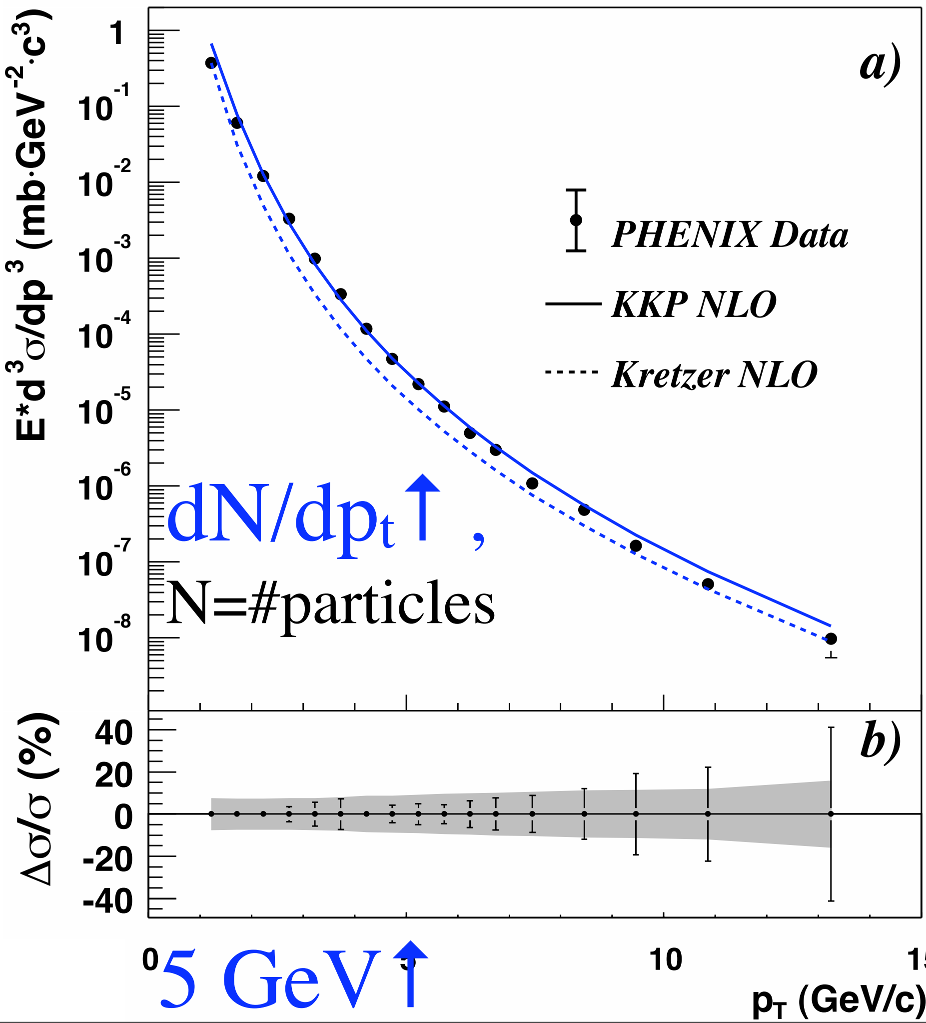
Jets: “seeing” quarks and gluons in QCD



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} ~ 0.2. As if jets emitted *only* from surface!

Due to "energy loss" in thermal medium?

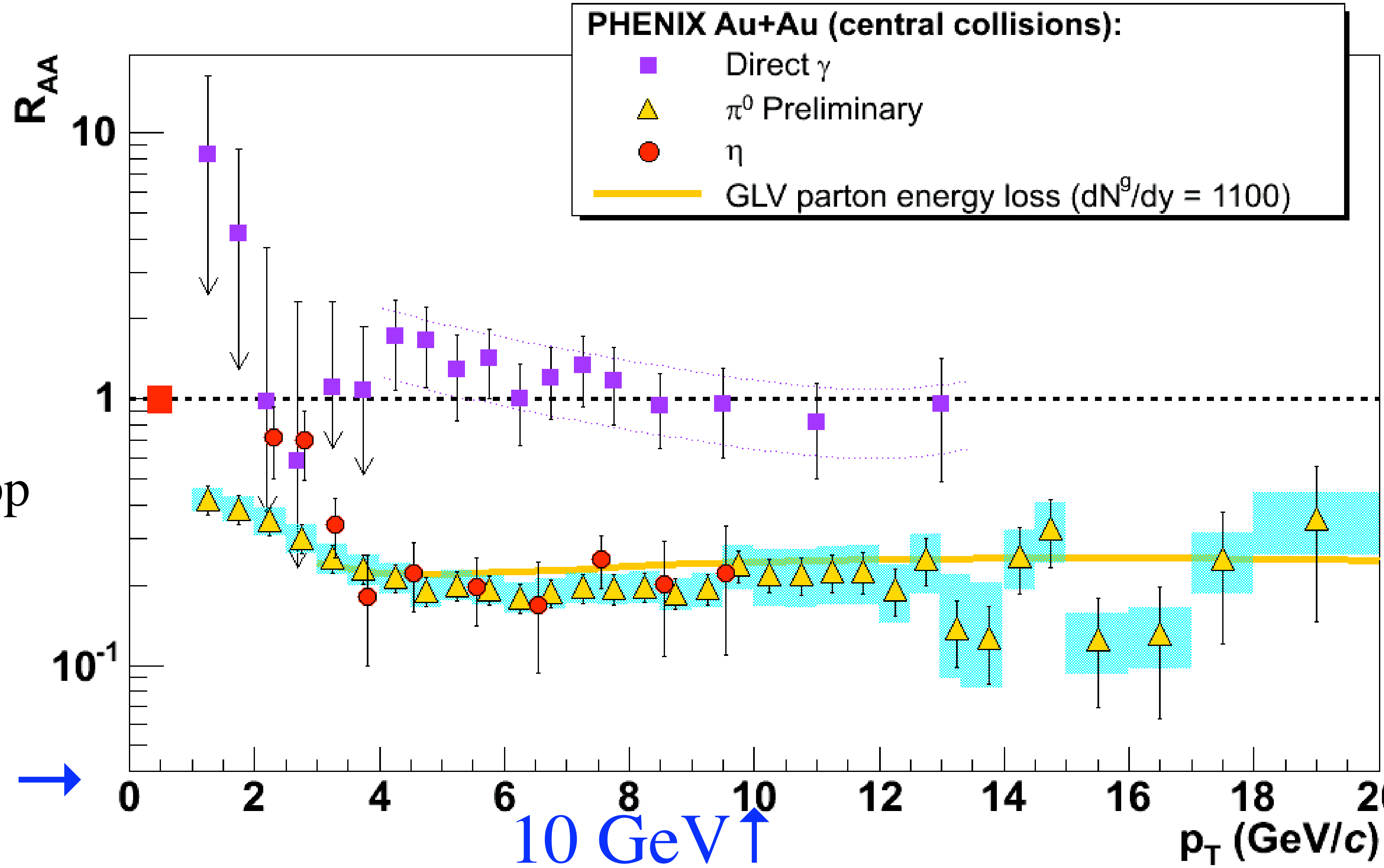
$A^{4/3}$: *experimentally*: for γ's, R_{AA} ~ 1.0 π^0's "eaten", γ's not

R_{AA}: ↑

particles central AA/ # particles pp

A=200 =>

p_t →



10 GeV↑

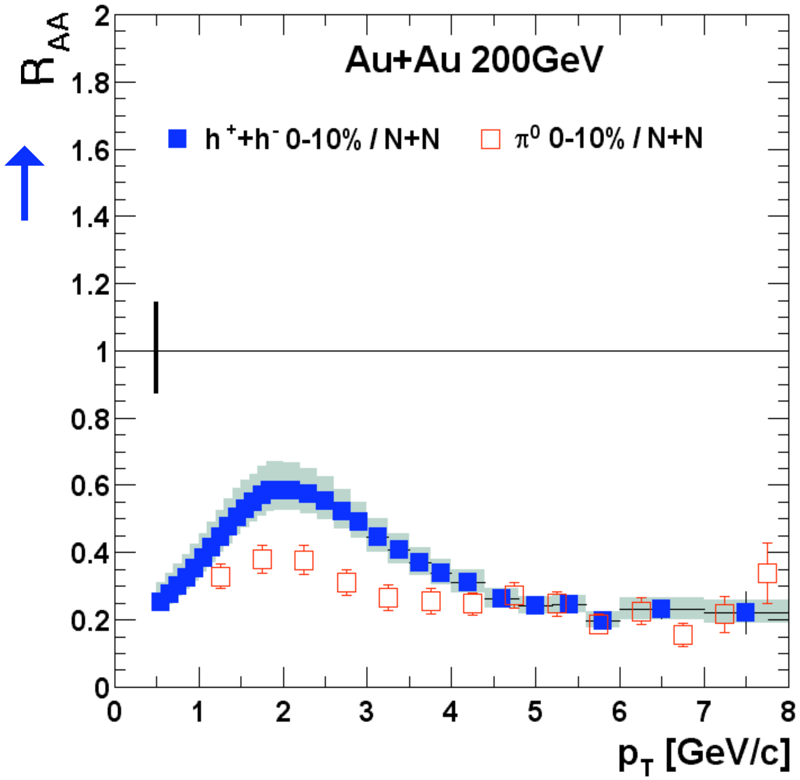
R_{AA} final state effect: *not* in R_{dA}

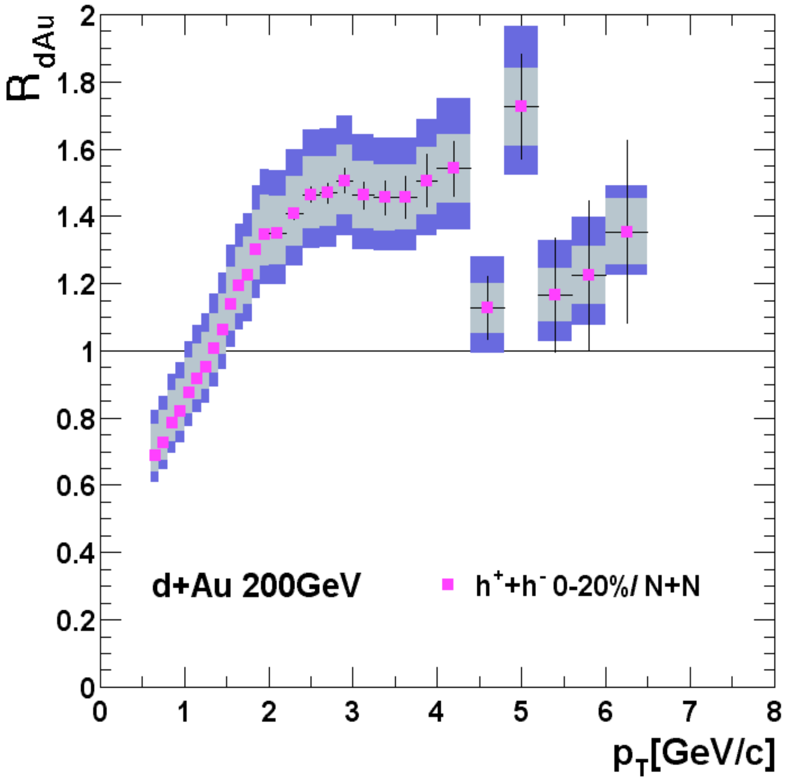
R_{dA}: like R_{AA}, but for dA coll.'s/pp coll.'s. At zero rapidity:

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

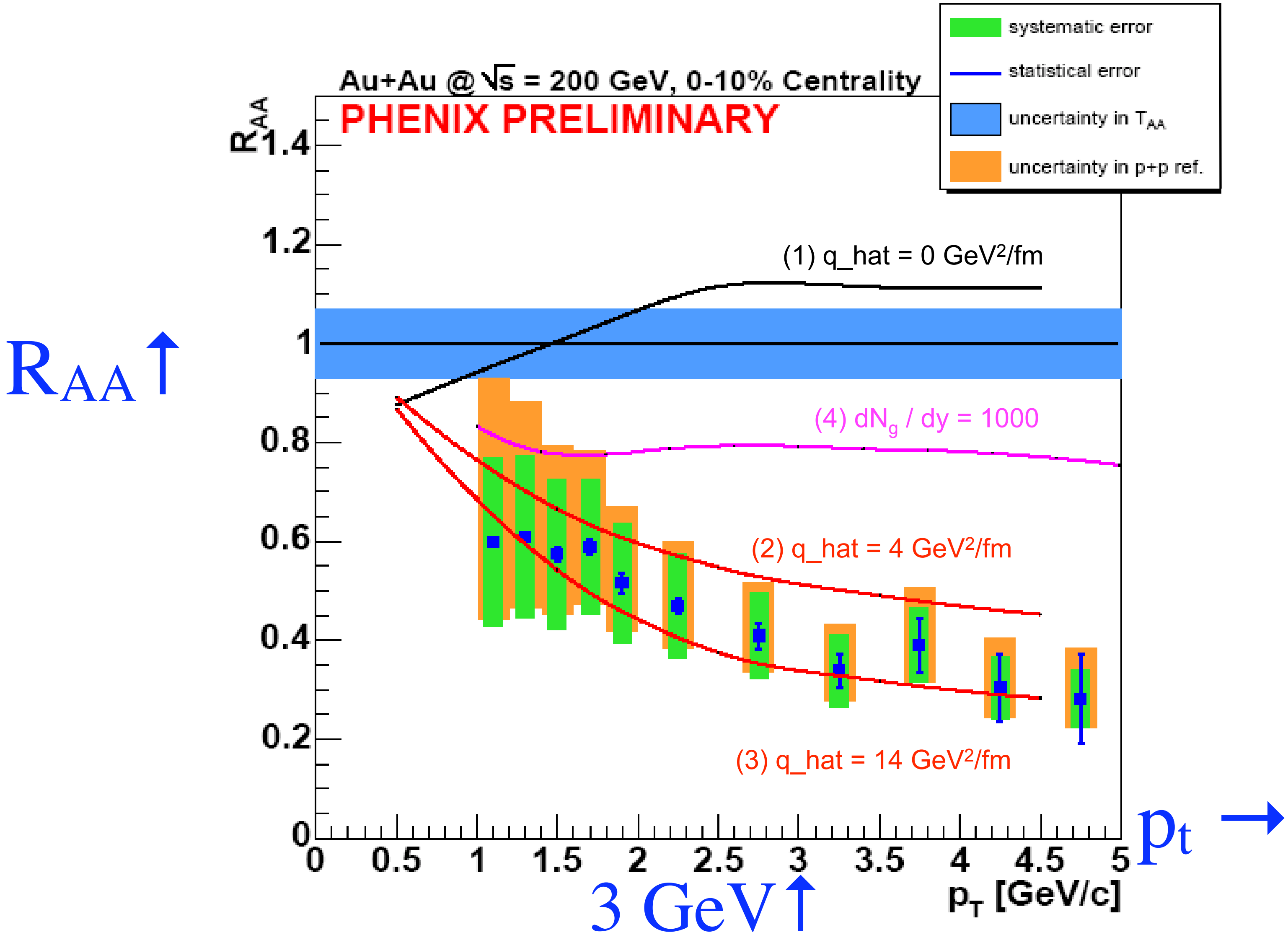
R_{AA} for heavy quarks: also suppressed!

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

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

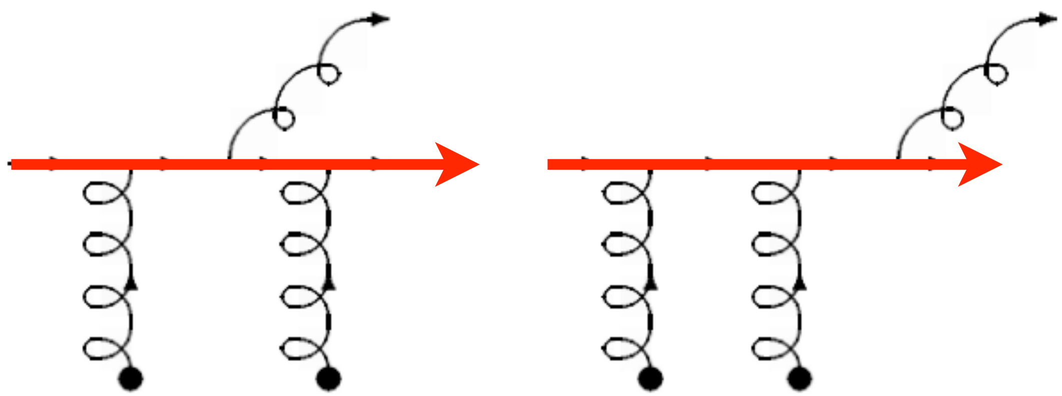
Heavy quark less sensitive to medium by T/m_{charm} ~ 1/8. *No* sign of that!

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



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.

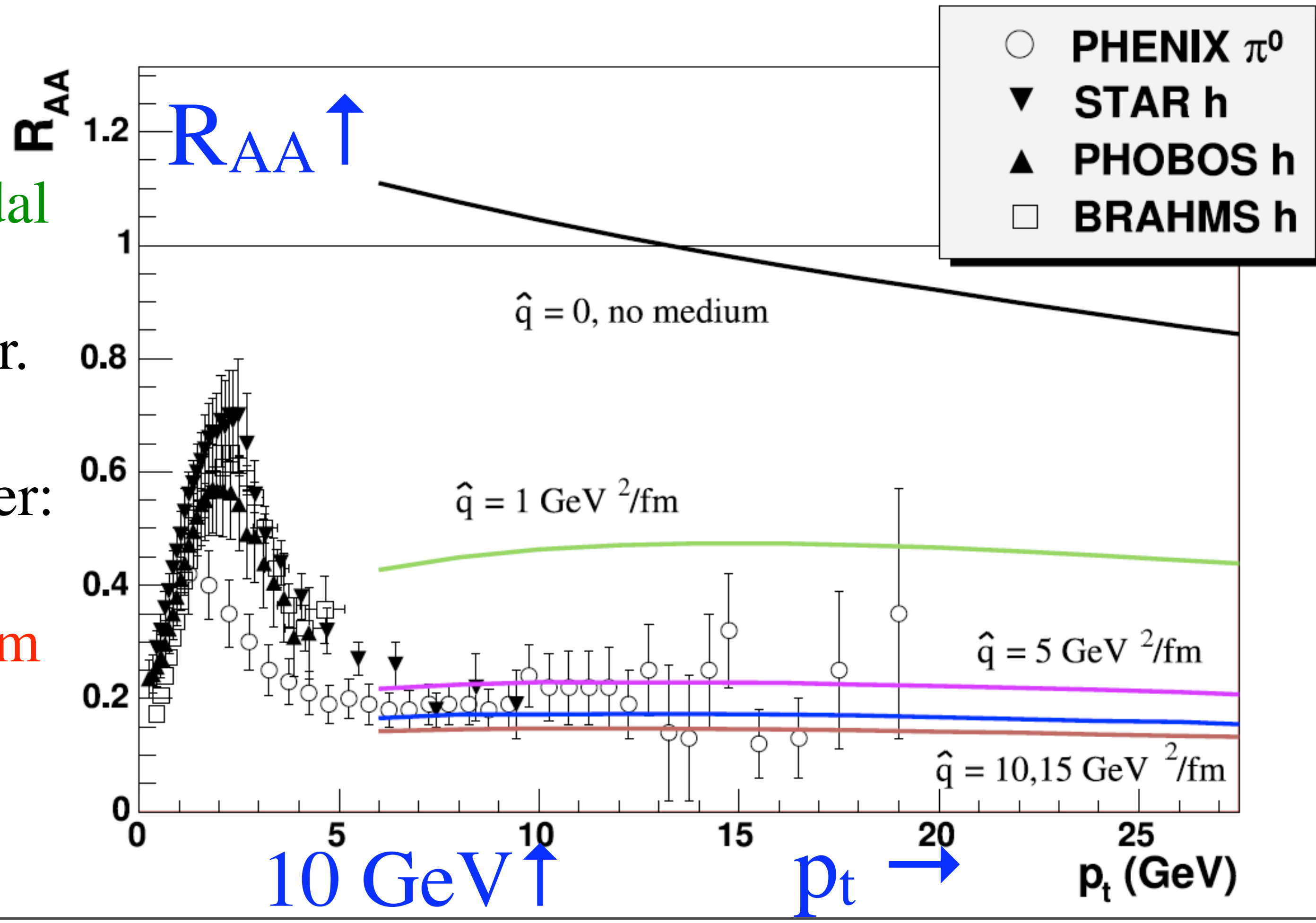
Involves LPM: Landau-Pomeranchuk-Migdal

Parametrized by one number.

Theorists disagree on number:

"weak" coupling ~2 GeV^2/fm

or "strong" ~15 GeV^2/fm?



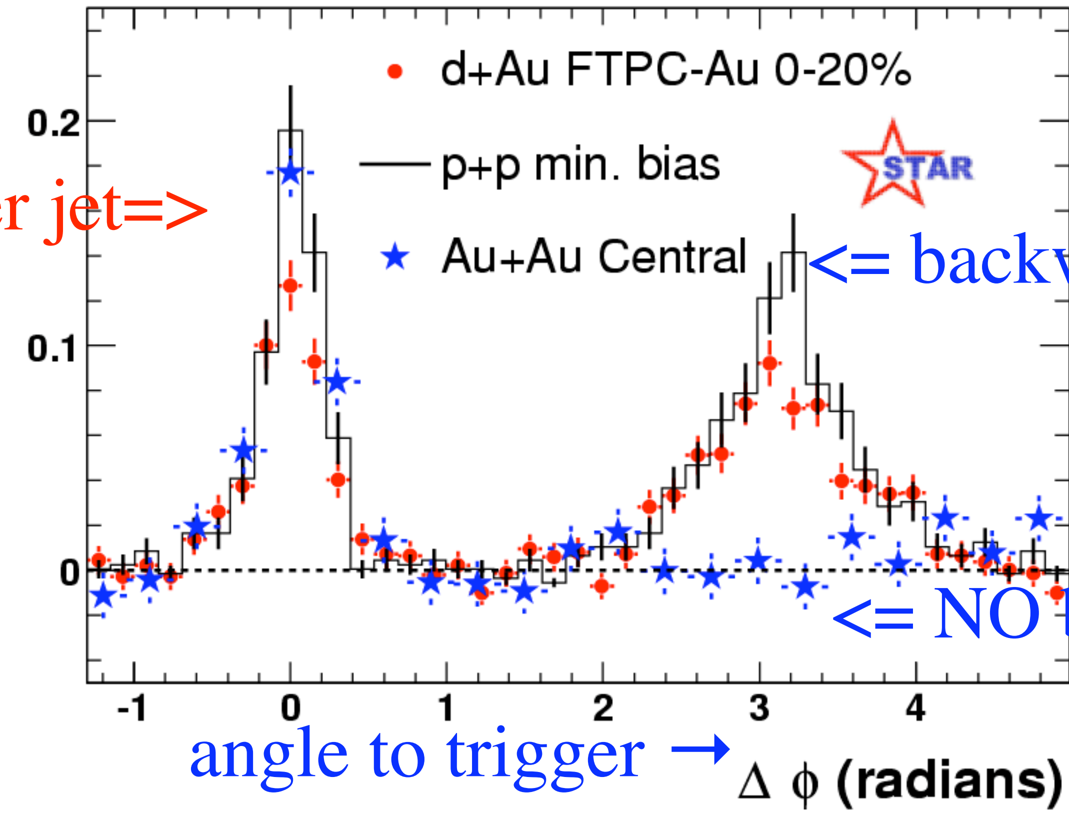
Central AA collisions "eat" jets!

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

Trigger on hard "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*

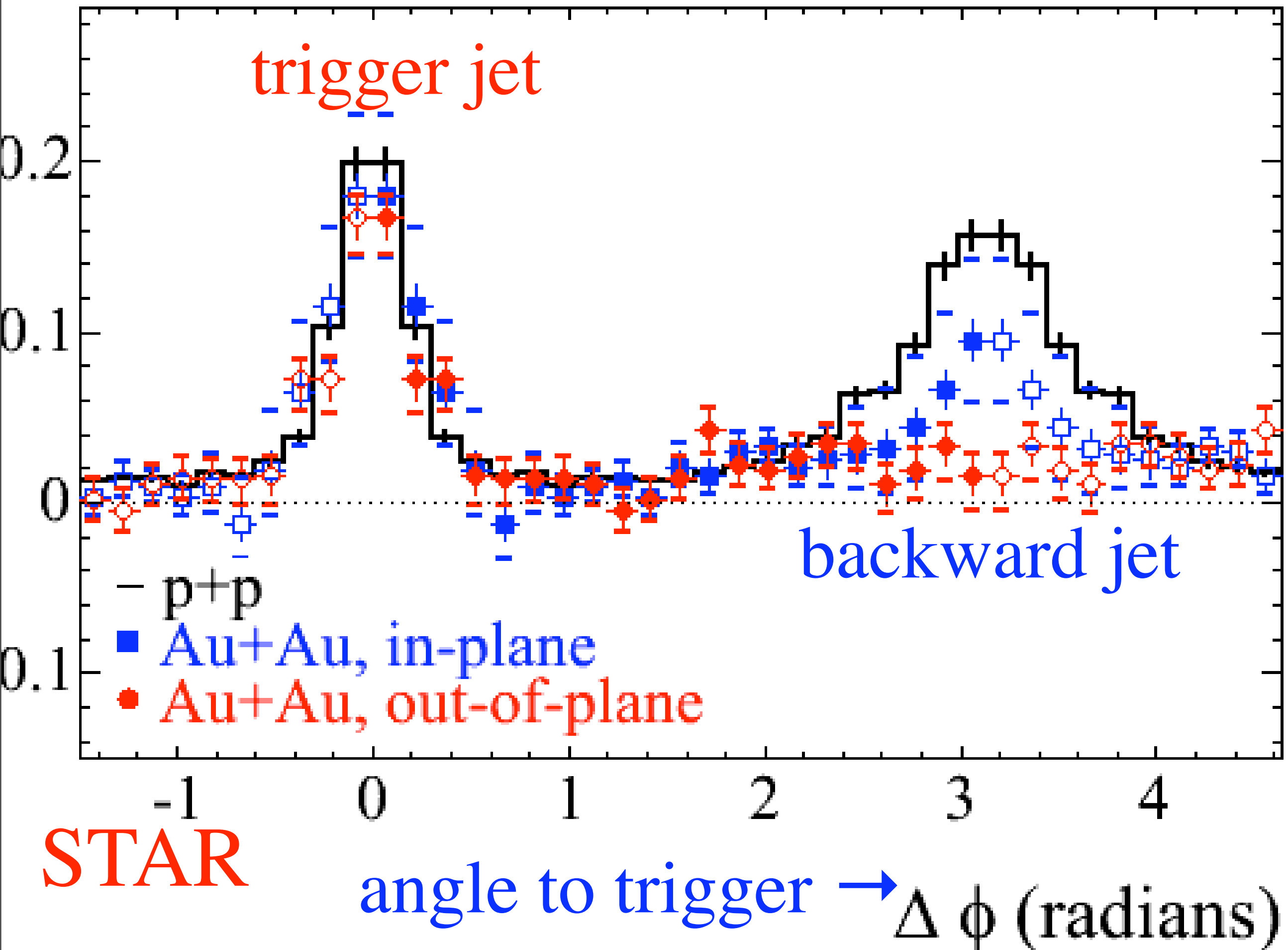
Adams *et al.*, Phys. Rev. Let. 91 (2003)

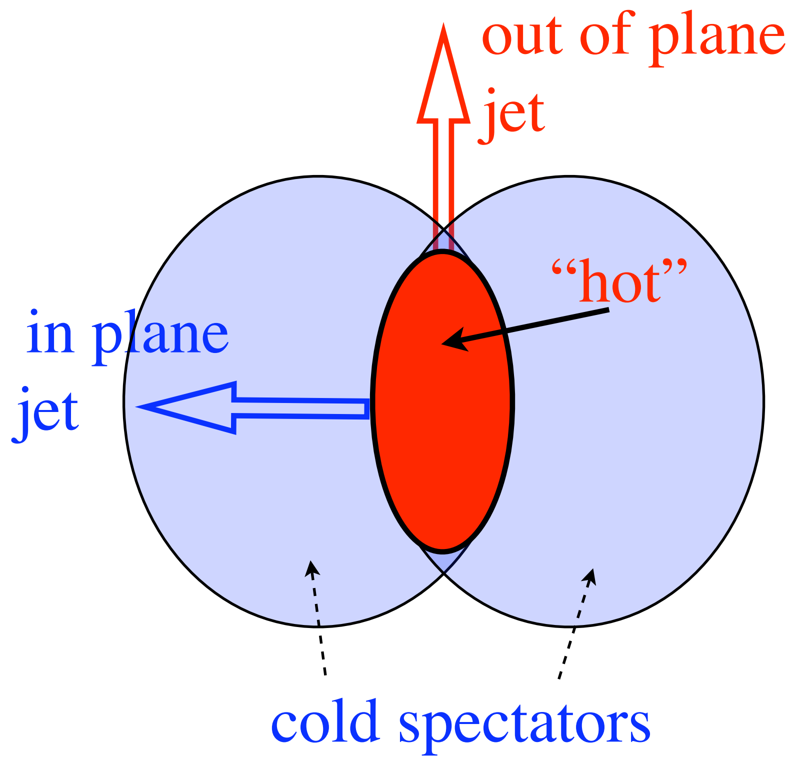


Peripheral coll.'s: more jets eaten *out* of plane

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



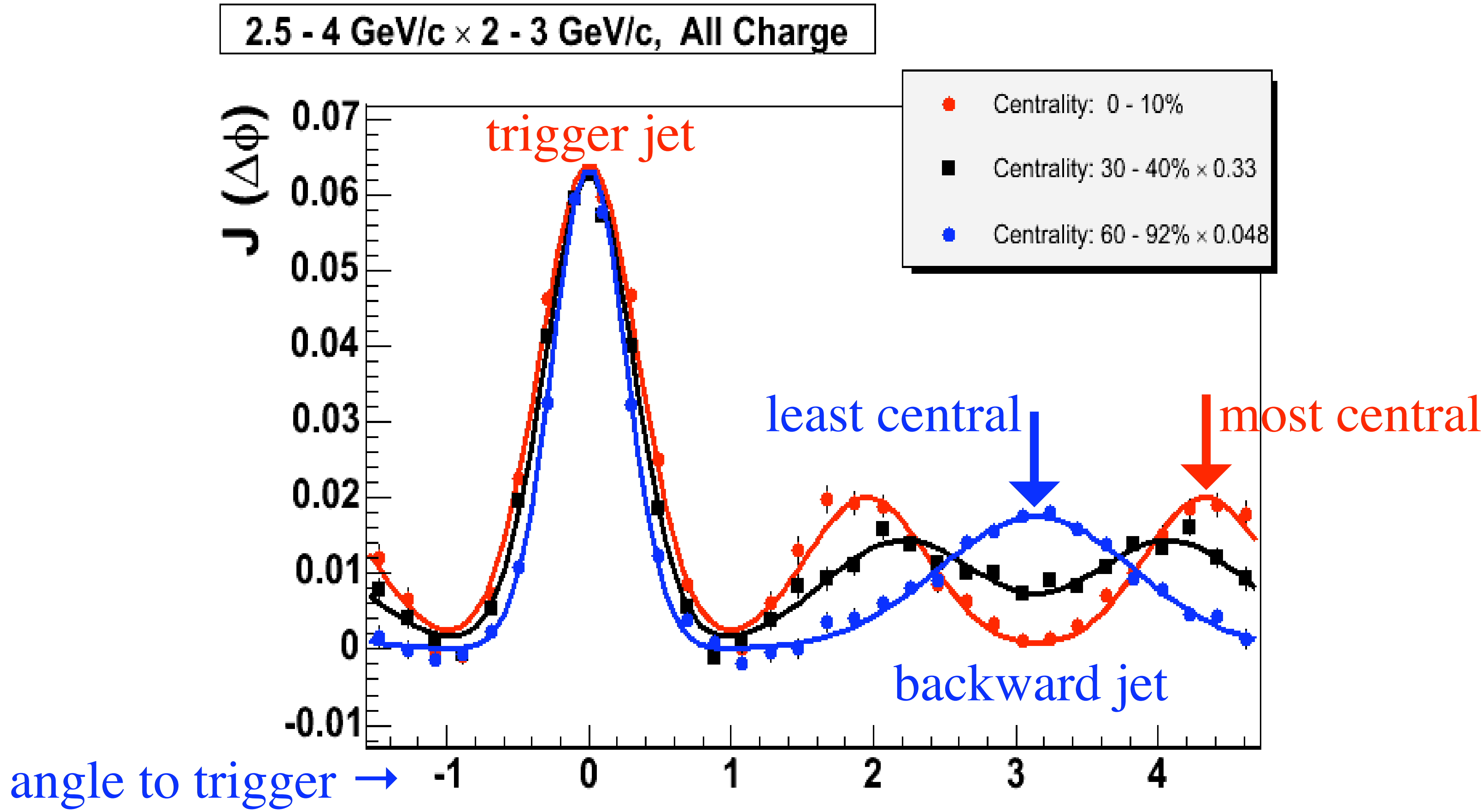


Peripheral collision

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.

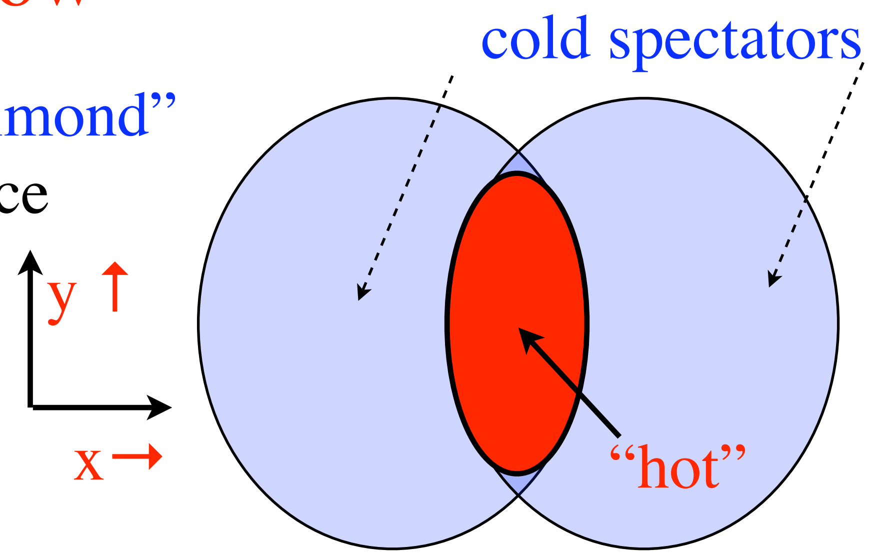
Thousands of particles: use hydrodynamics? "Most Perfect Fluid on Earth"

me→

←Unicorn

"Elliptic Flow"

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



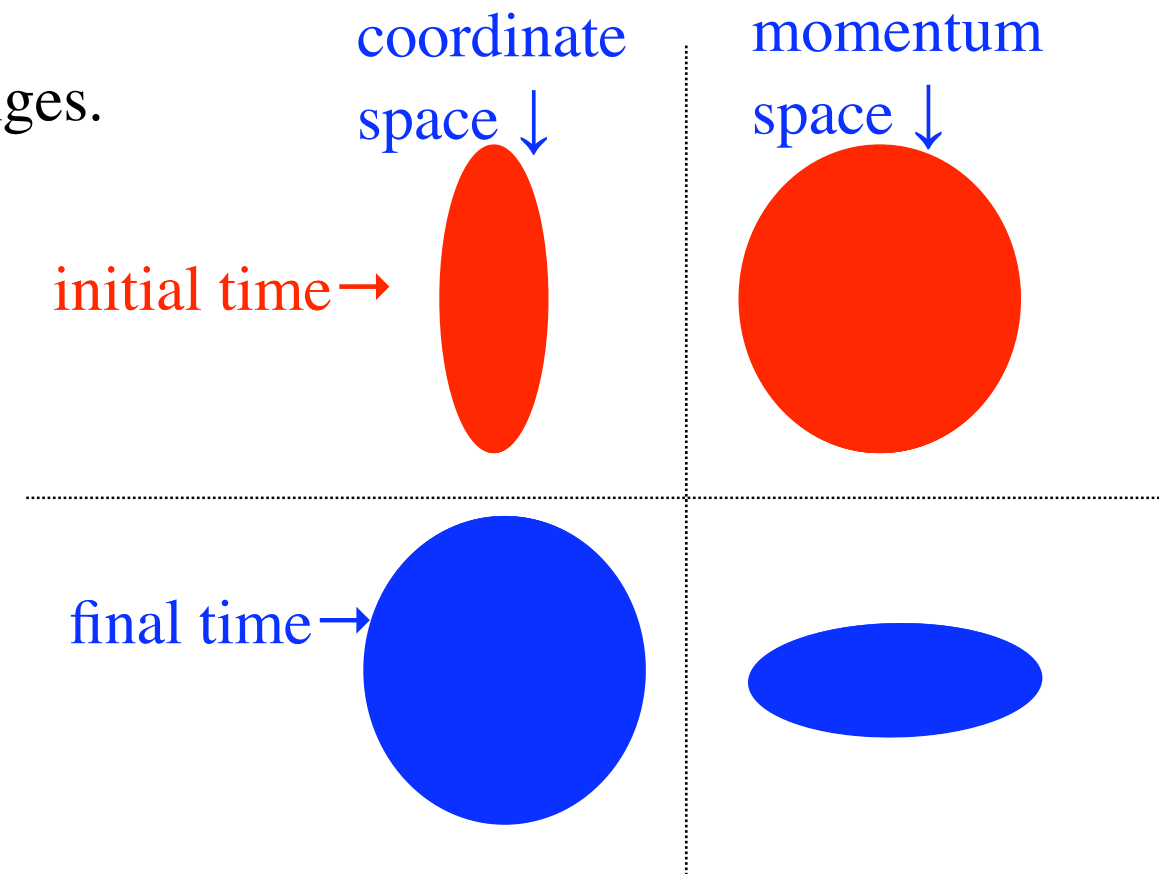
So start with spatial anistropy,

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

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"

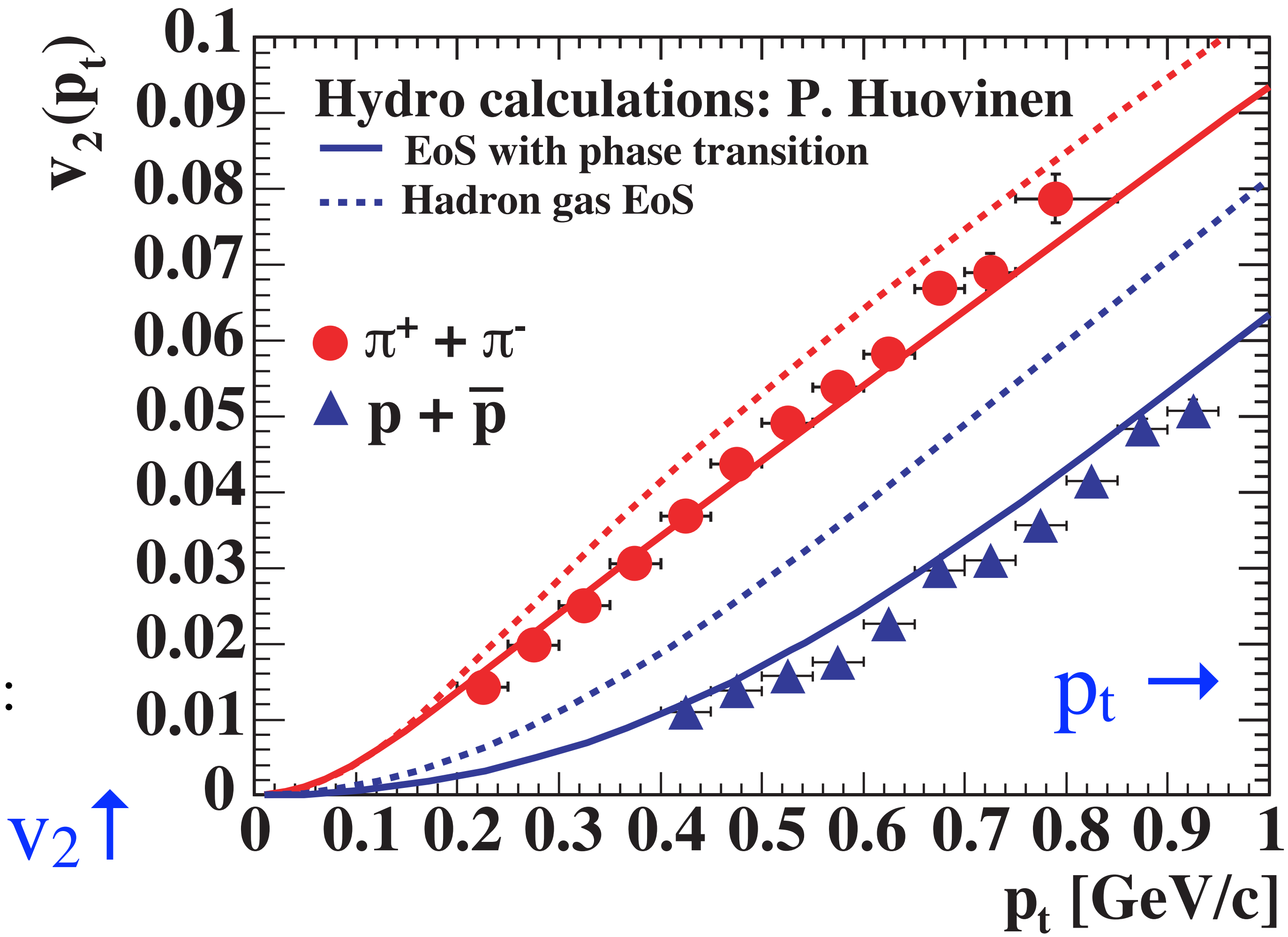
Large # particles: try *ideal* hydrodynamics:

1. *Short* initial time (tune) 2. *MIT Bag* Equation of State (not correct)
3. *Zero* viscosity in QGP phase
4. Hadronic "afterburner": ~ *large* hadronic viscosity

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

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

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



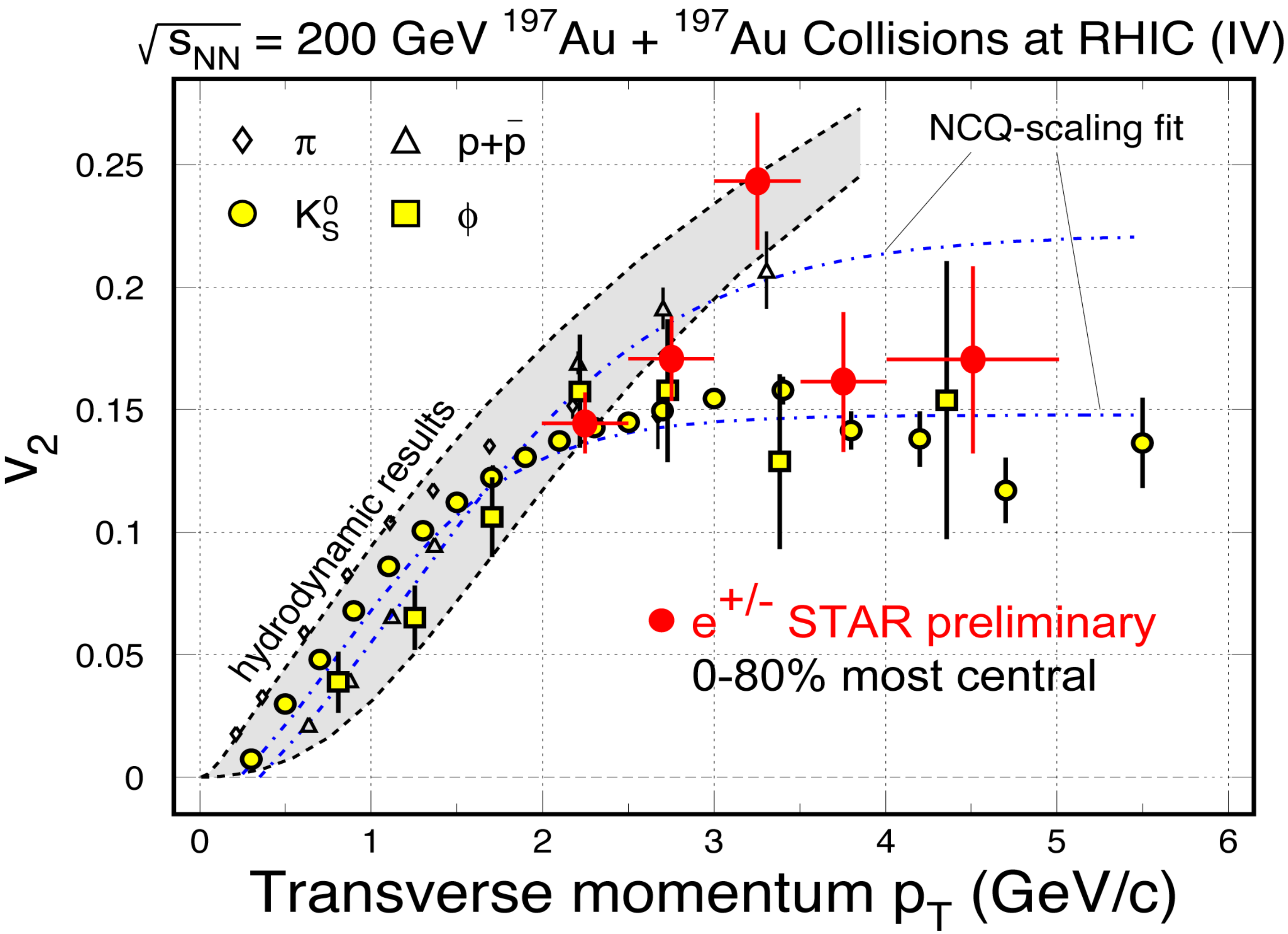
Even charm quarks flow

Look at charm quarks through single electrons.

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

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

$v_2 \uparrow$



$p_t \rightarrow$

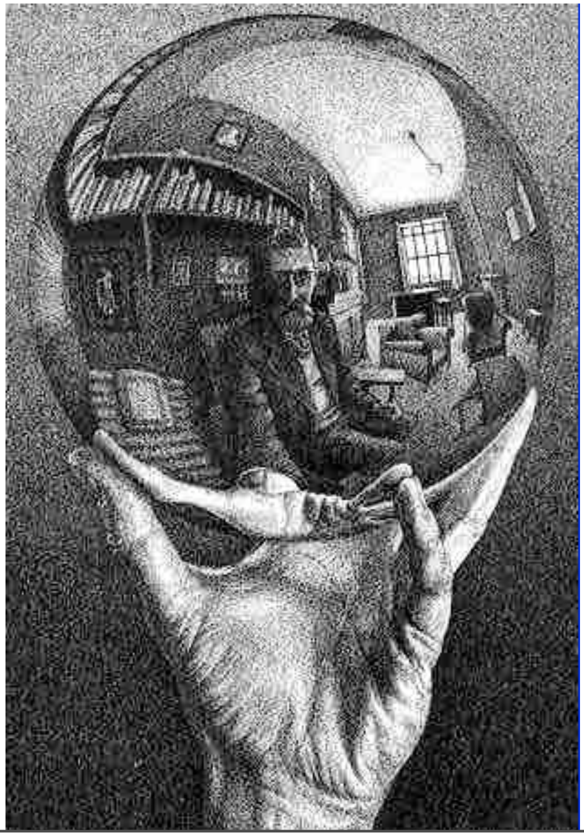
And now…

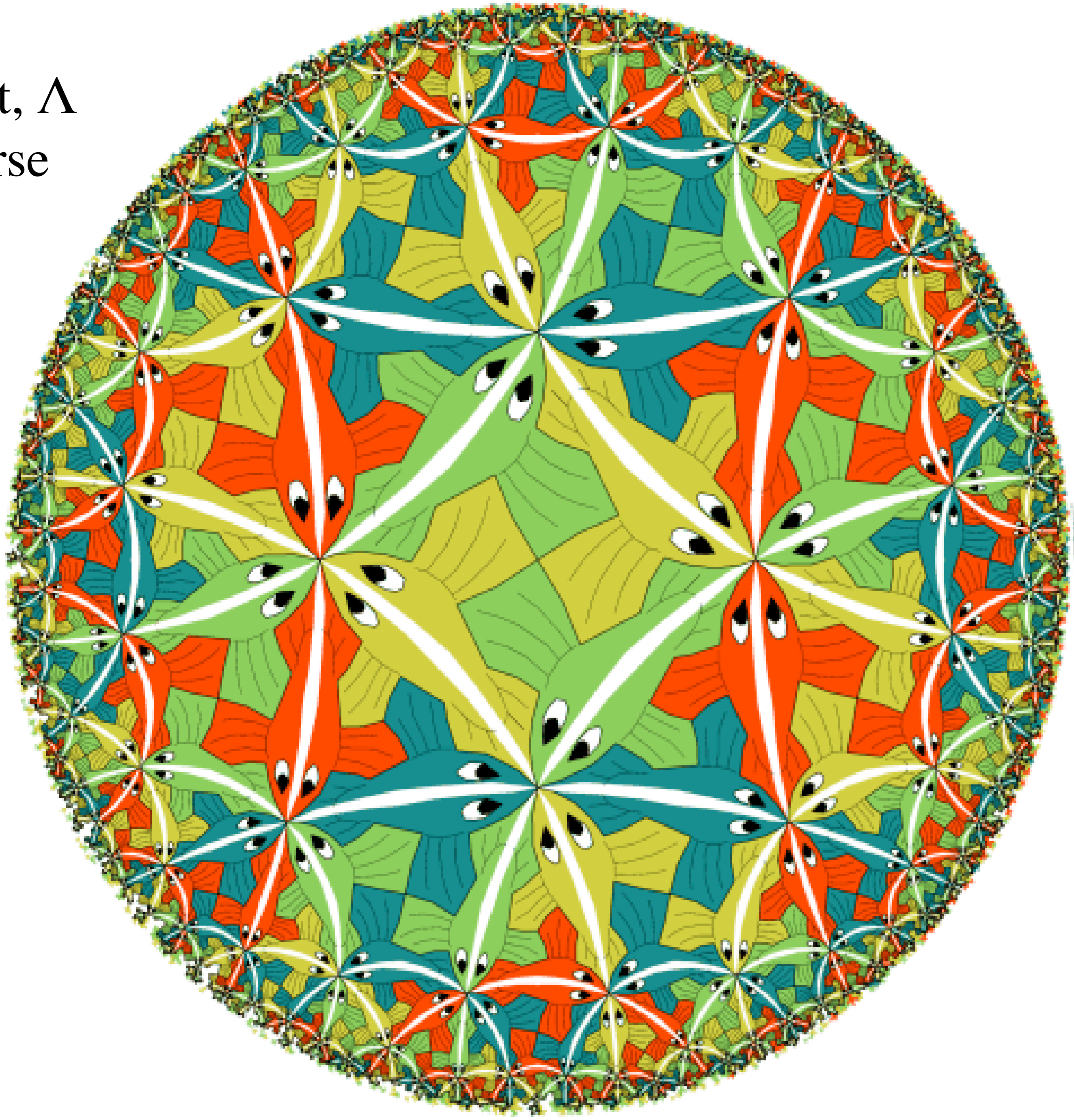
AdS: Anti de Sitter space

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:

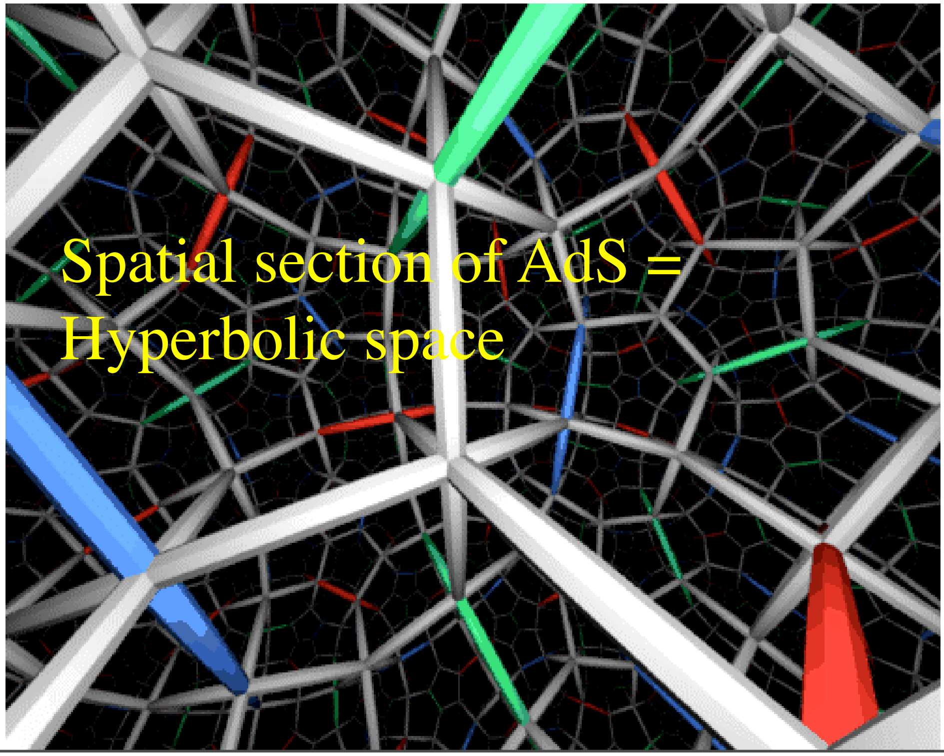
No mass scale, both classically *and* quantum mechanically!

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

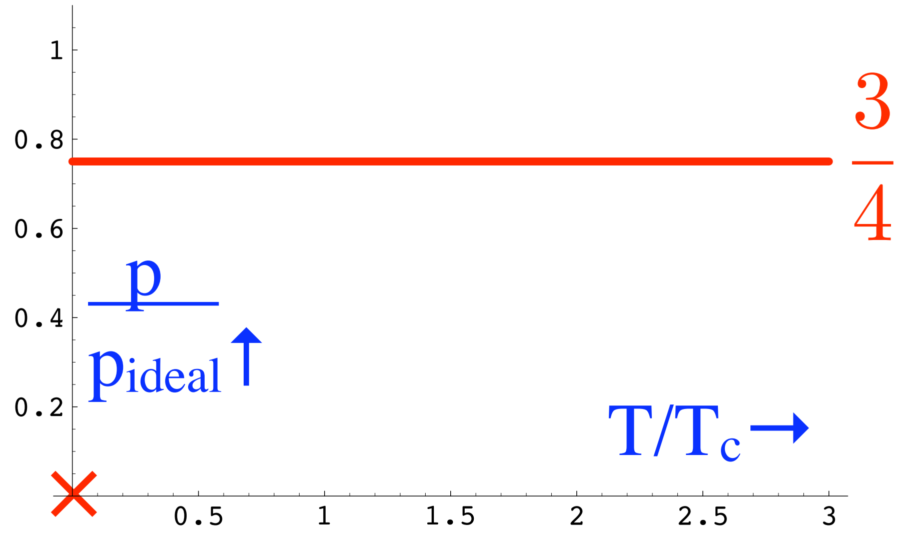
Weak coupling string theory = *classical* supergravity!

Thermal AdS/CFT: $\alpha_s = \infty$

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.



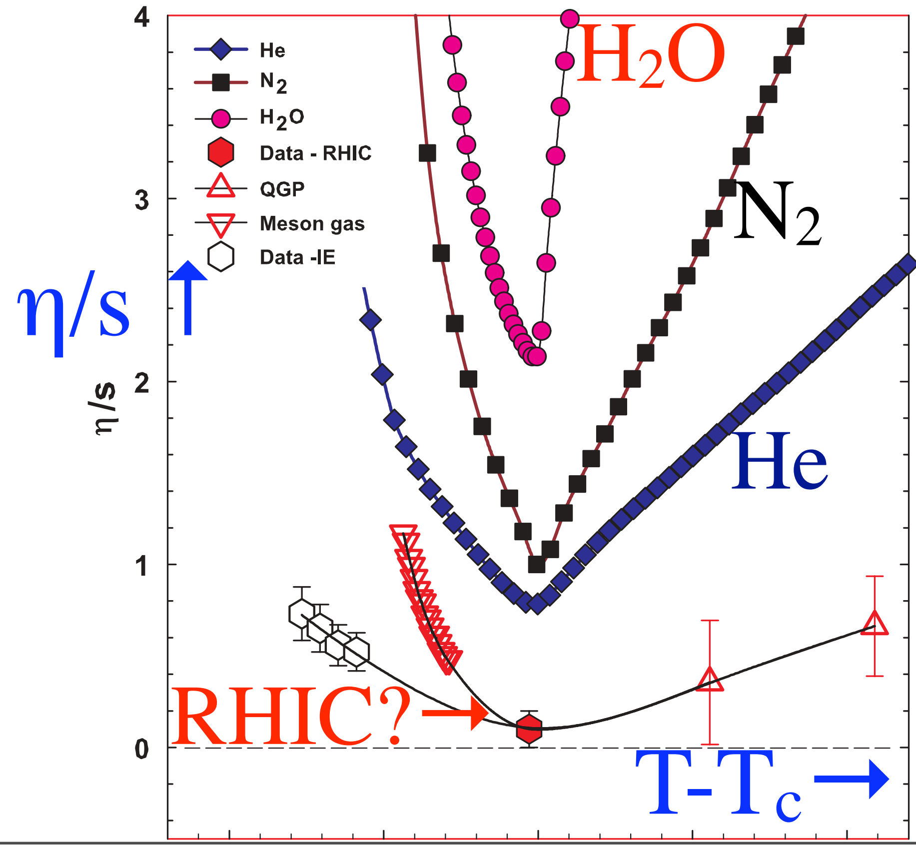
Not only equi., but also transport properties!

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."

From the SPS: NA60 and a "thermal" ϱ

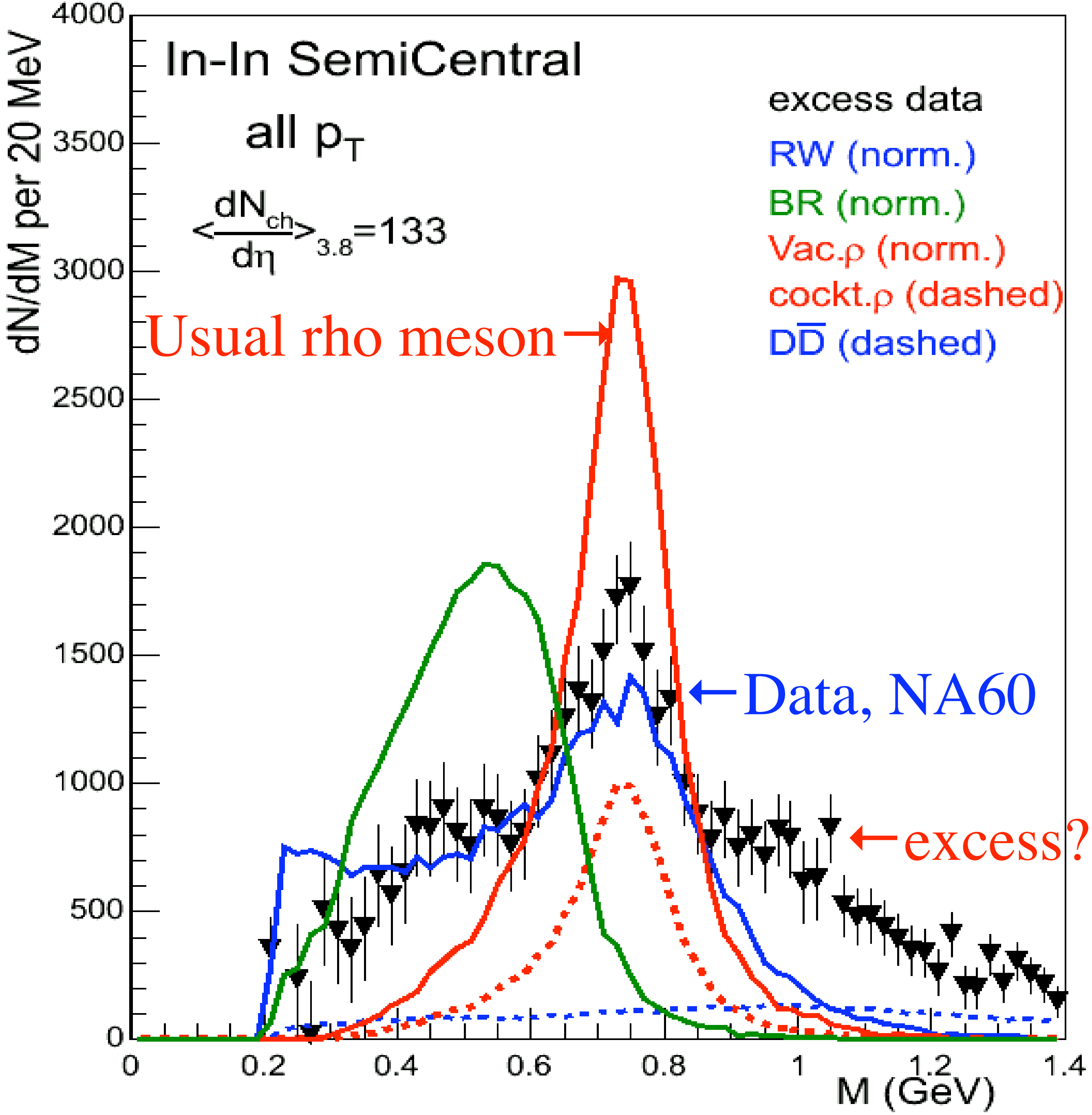
SPS = fixed target. Kinematics more awkward, but can generate many more events.

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

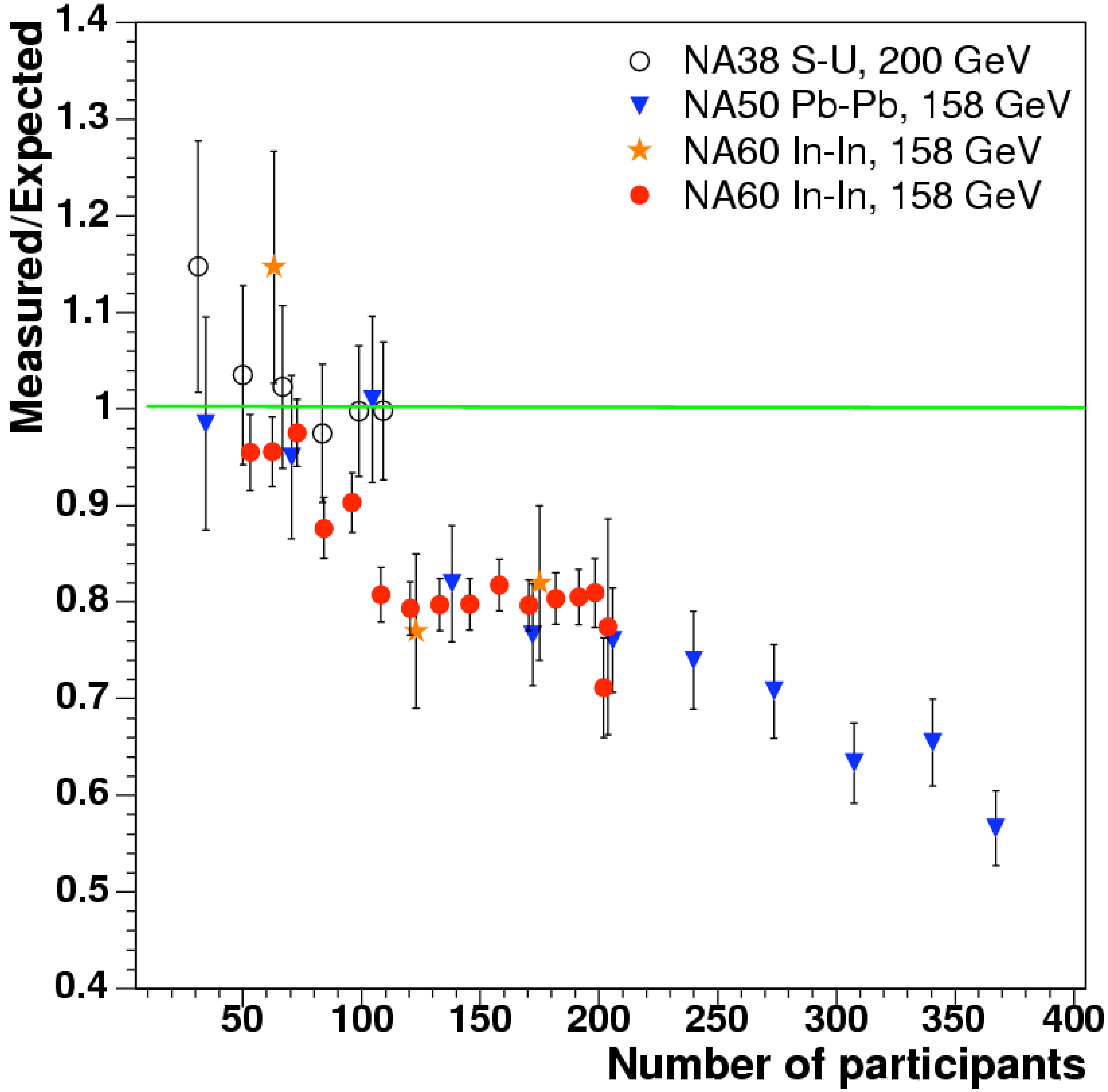
Look at "ϱ" meson, mass ~ 770 MeV. Decays directly to e^+e^- .

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

Interesting excess *above* the ϱ?



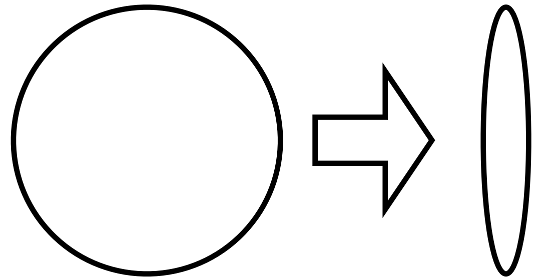
SPS: NA50, NA60 J/Psi suppression



consistent, # participants good variable

Why do AA? “Saturation” as a Lorentz Boost

Incident nucleus Lorentz contracted at high energy



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

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!

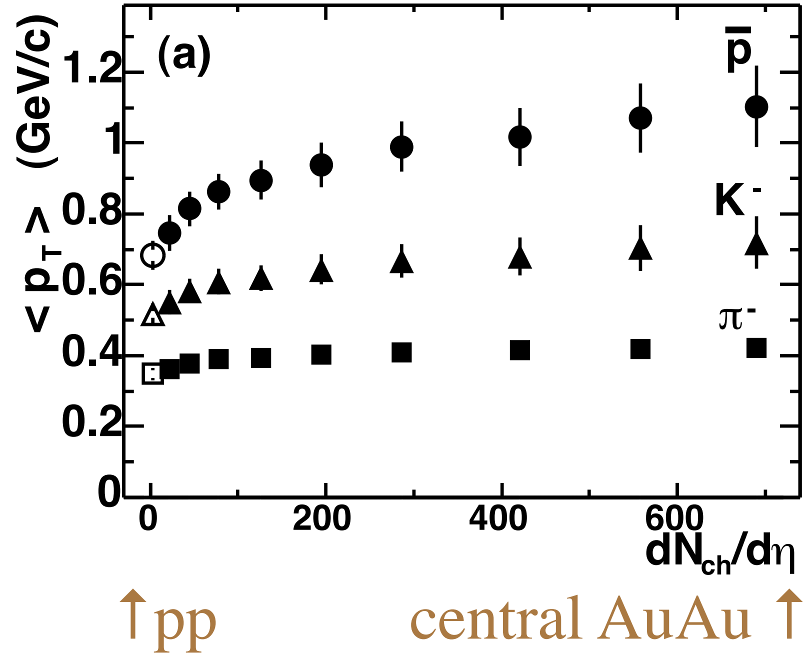
Color Glass, hydrodynamics... all predict <p_t> increases with mulitplicity!

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!

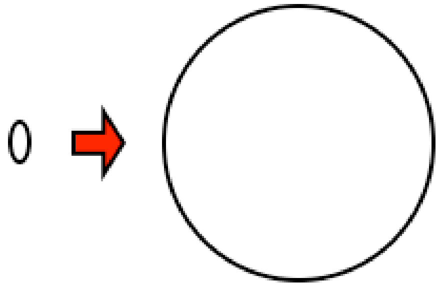
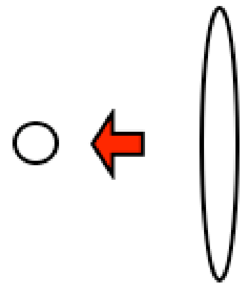
=> CG not final state
Hydro: big "boost" velocity of medium.

STAR, pp & AuAu, 200 GeV



Color Glass suppression: in dA, by the deuteron

Fragmentation region ~ rest frame. Incident projectile Lorentz contracted:

nuclear frag.=>    proton frag.=> 

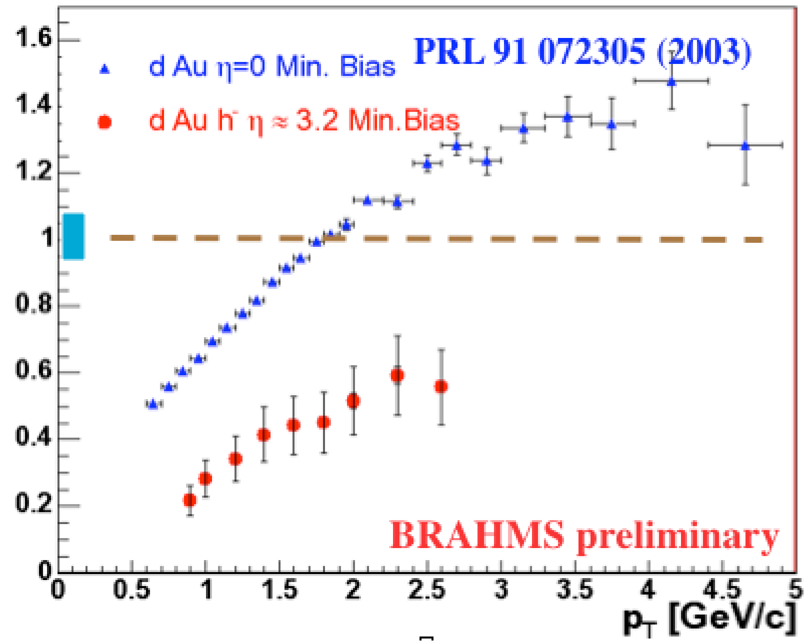
Nuclear fragmentation region: proton contracted. Study final state effects
Proton fragmentation region: study initial state effects

BRAHMS in dA:

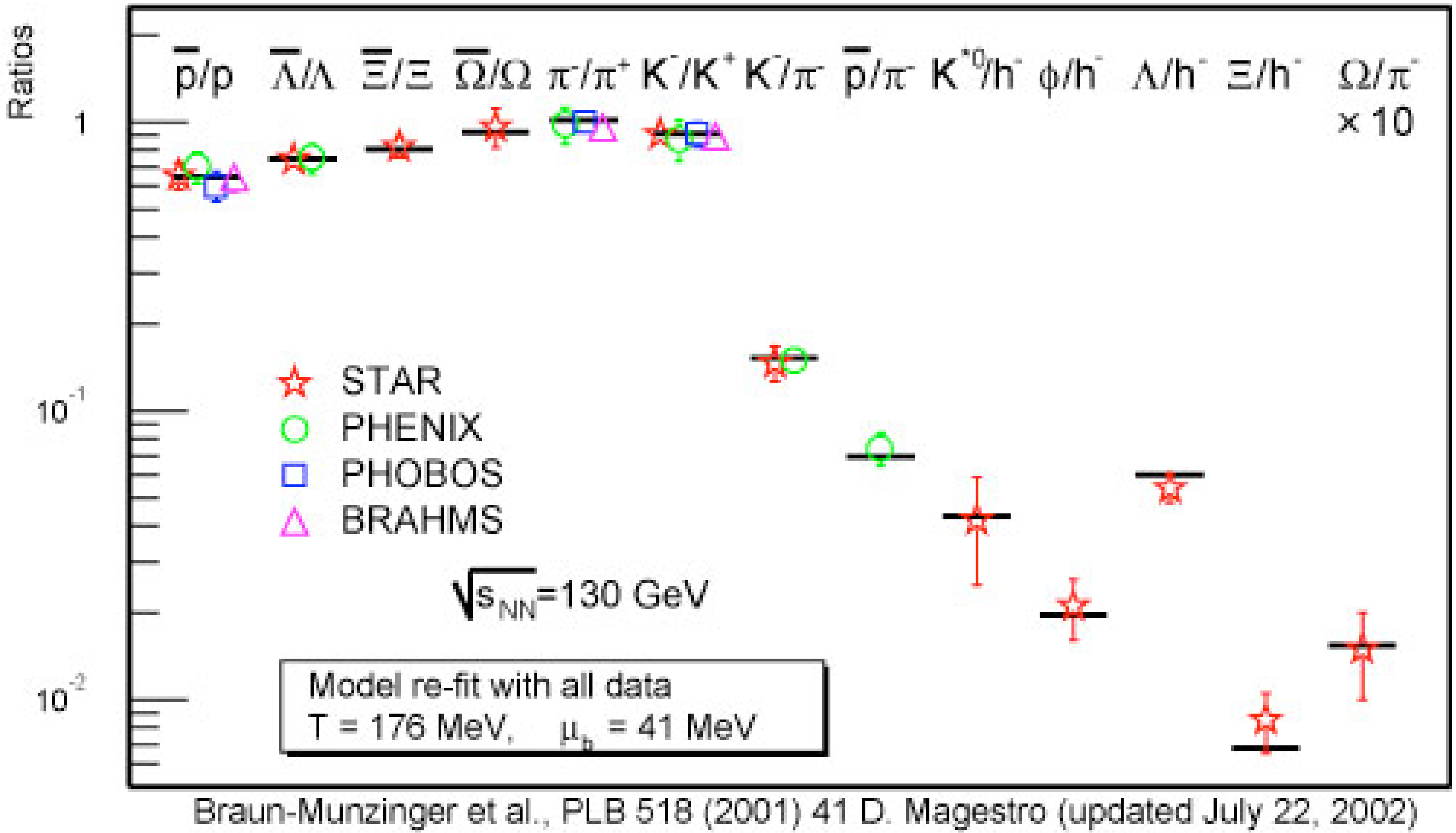
enhancement @ zero rapidity
suppression @ proton frag. region.

Supports color glass initial state.

Need to study all rapidities.

R_dA: 

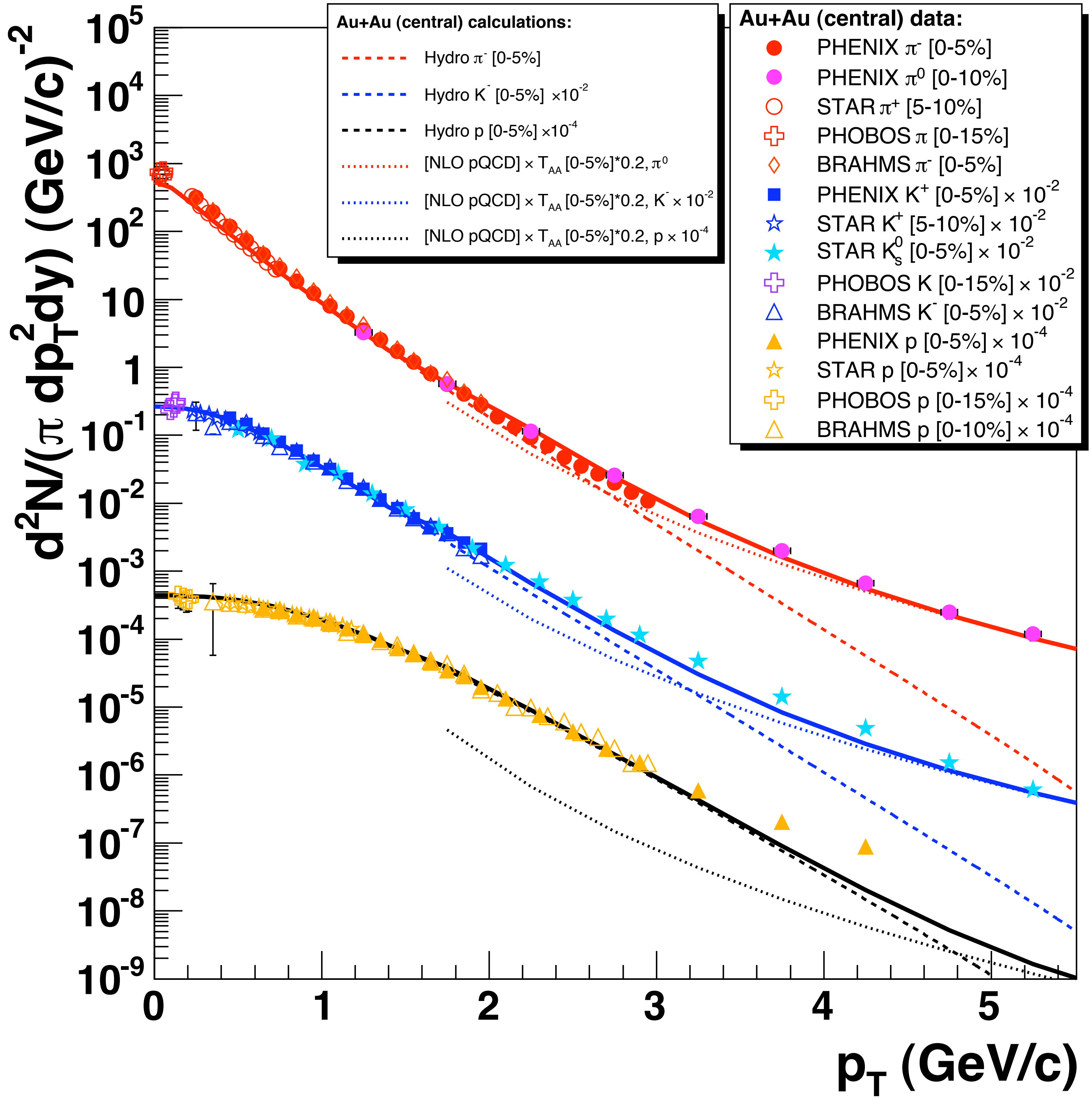
Total Chemical Ratios: $T_{chemical}$ ~ 160 MeV

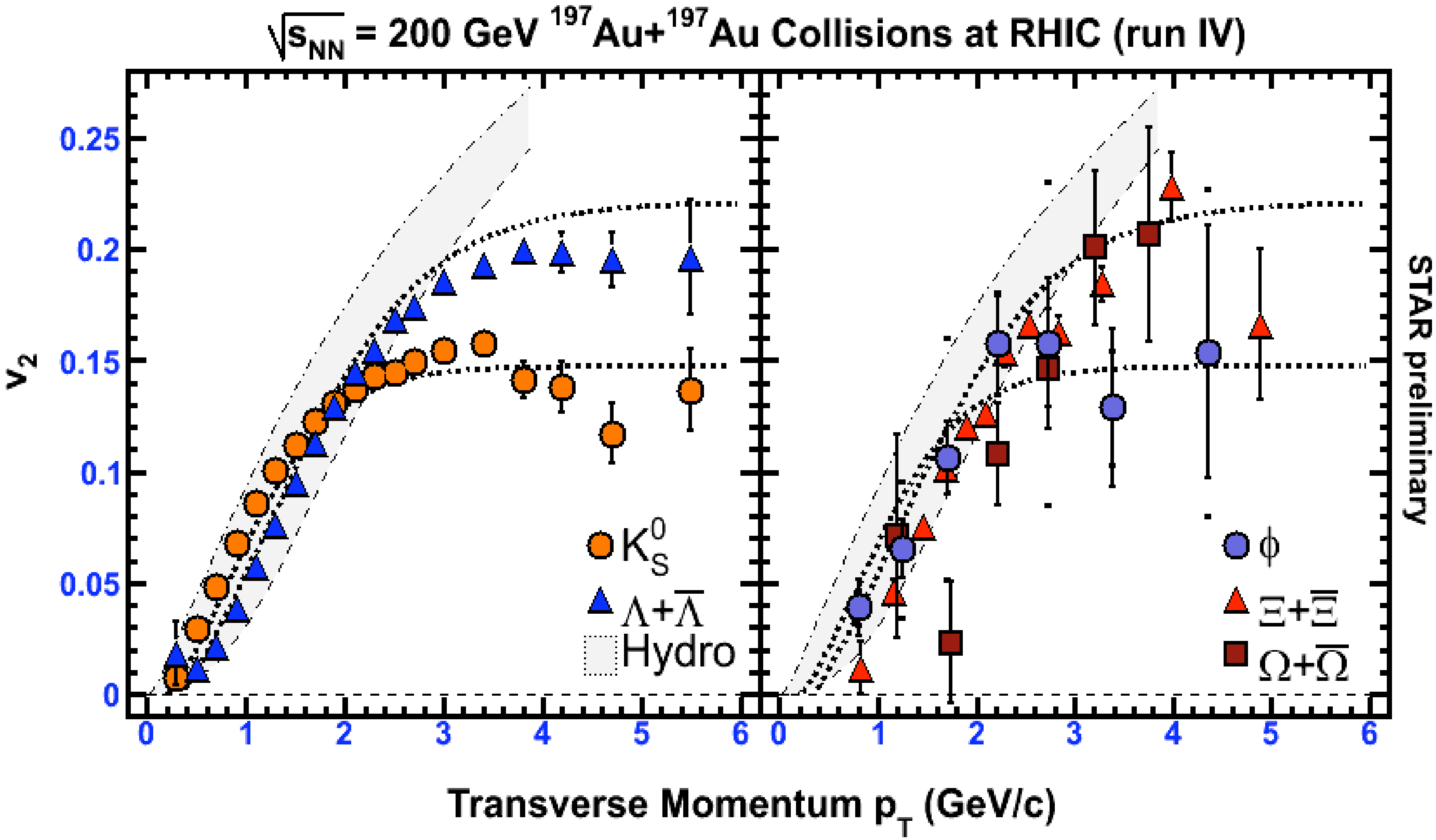


Overall chemical abundances for "long" lived states: well fit with

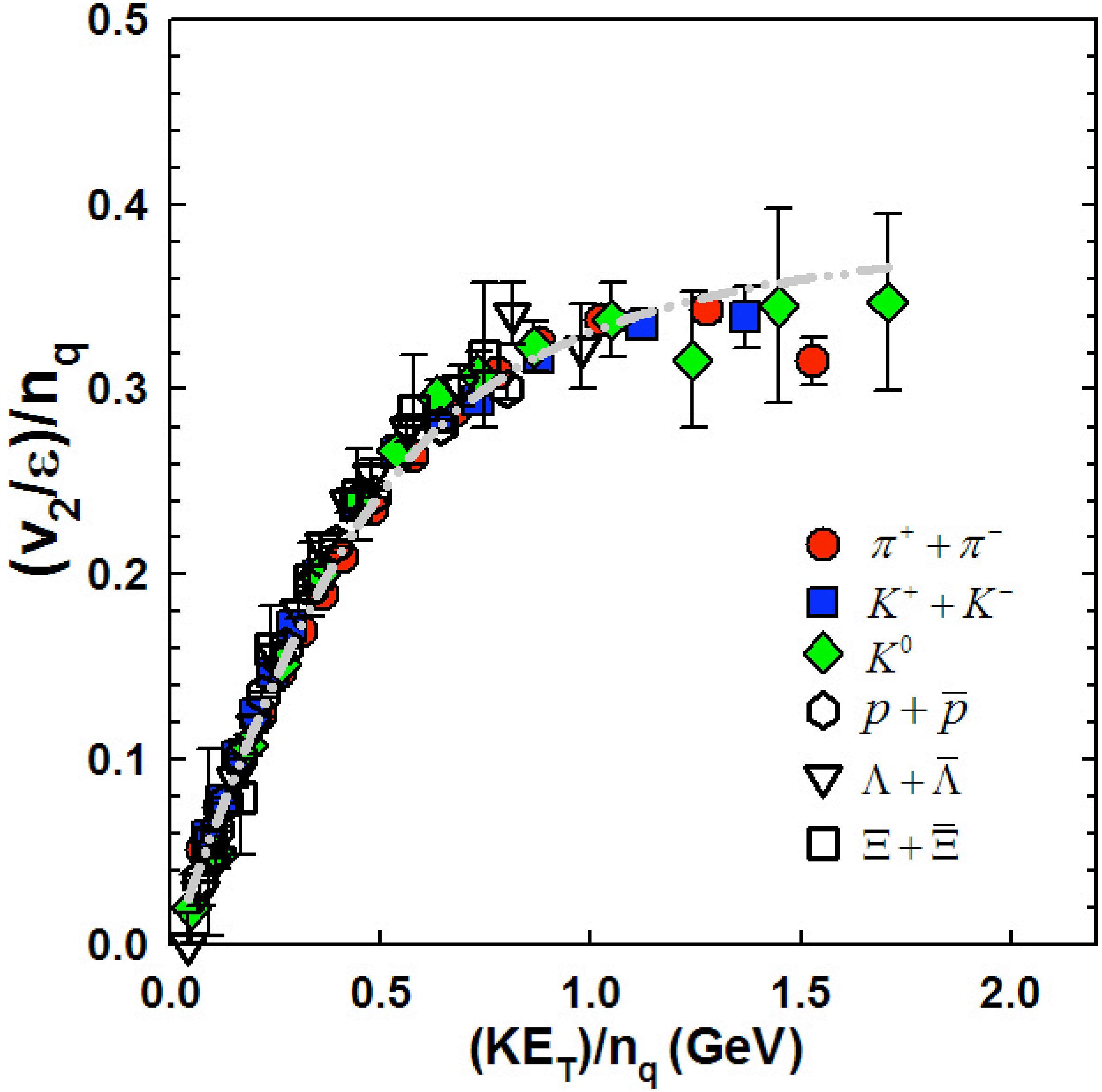
$T_{chemical}$ = 160 MeV, μ_{baryon} = 24 MeV

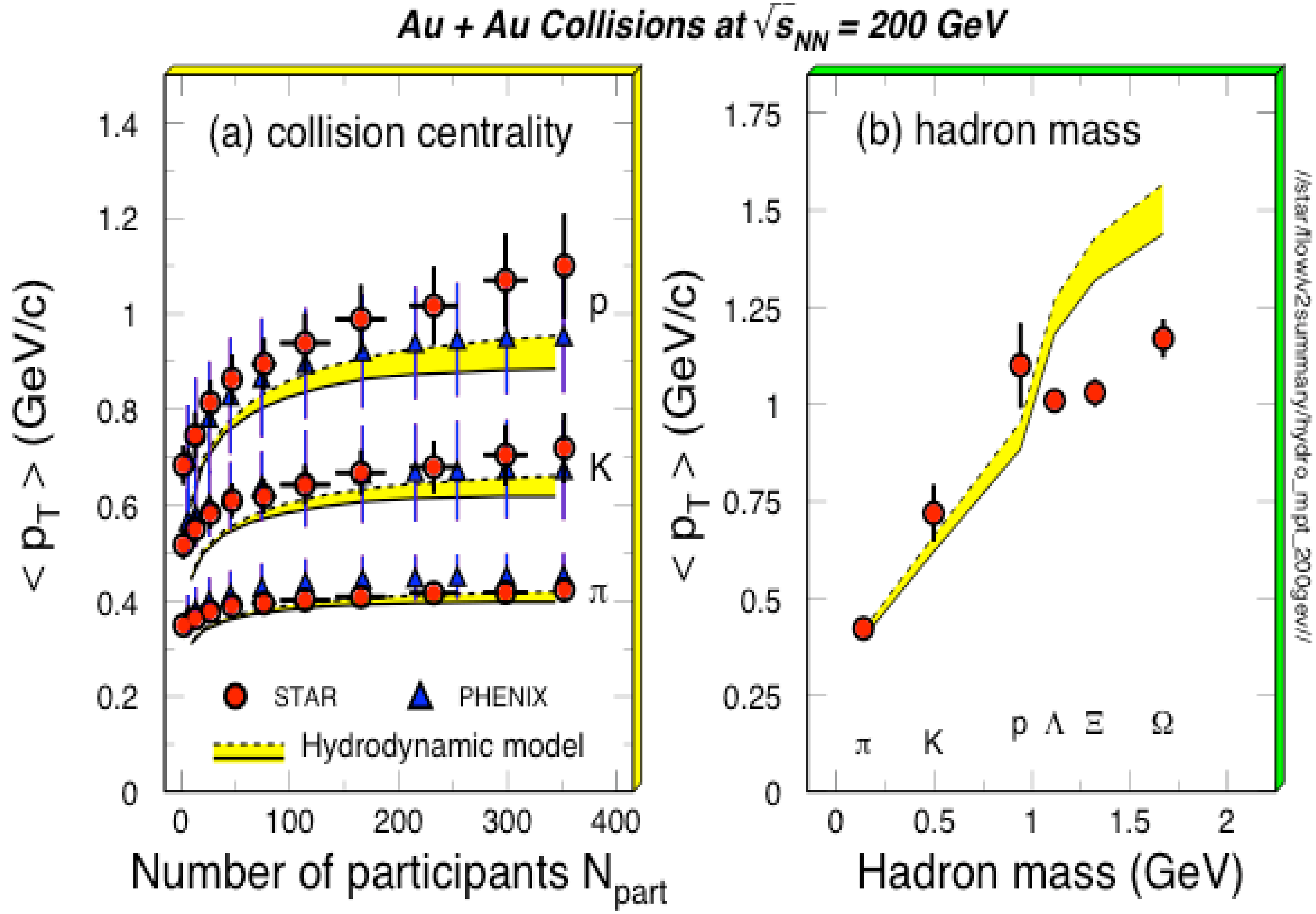
Not valid for "short" lived resonances: Δ, ϕ, K^*, Λ^*


Au+Au (central) calculations:
Hydro π⁻ [0-5%]
Hydro K⁻ [0-5%] ×10⁻²
Hydro p [0-5%] ×10⁻⁴
[NLO pQCD] × T_AA [0-5%]*0.2, π⁰
[NLO pQCD] × T_AA [0-5%]*0.2, K⁻ × 10⁻²
[NLO pQCD] × T_AA [0-5%]*0.2, p × 10⁻⁴
Au+Au (central) data:
PHENIX π⁻ [0-5%]
PHENIX π⁰ [0-10%]
STAR π⁺ [5-10%]
PHOBOS π [0-15%]
BRAHMS π⁻ [0-5%]
PHENIX K⁺ [0-5%] × 10⁻²
STAR K⁺ [5-10%] × 10⁻²
STAR K⁰_s [0-5%] × 10⁻²
PHOBOS K [0-15%] × 10⁻²
BRAHMS K⁻ [0-5%] × 10⁻²
PHENIX p [0-5%] × 10⁻⁴
STAR p [0-5%]× 10⁻⁴
PHOBOS p [0-15%] × 10⁻⁴
BRAHMS p [0-10%] × 10⁻⁴
d²N/(π dp_T²dy) (GeV/c)⁻²
p_T (GeV/c)



$\sqrt{s_{NN}}$ = 200 GeV ^{197}Au+^{197}Au Collisions at RHIC (run IV)
v_2
0.25
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6
K^0_S
$\Lambda+\overline{\Lambda}$
Hydro
ϕ
$\Xi+\overline{\Xi}$
$\Omega+\overline{\Omega}$
STAR preliminary
Transverse Momentum p_T (GeV/c)


0.0
0.1
0.2
0.3
0.4
0.5
0.0
0.5
1.0
1.5
2.0
$(v_2/\varepsilon)/n_q$
$(KE_T)/n_q$ (GeV)
$\pi^+ + \pi^-$
$K^+ + K^-$
K^0
$p + \bar{p}$
$\Lambda + \bar{\Lambda}$
$\Xi + \bar{\Xi}$

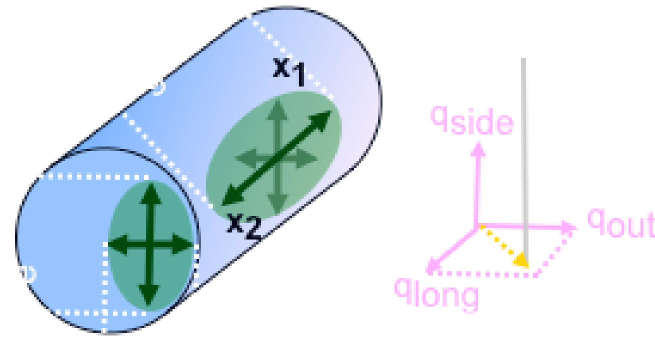


Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV
(a) collision centrality
(b) hadron mass
$< p_T >$ (GeV/c)
Number of participants N_{part}
Hadron mass (GeV)
STAR
PHENIX
Hydrodynamic model
p
K
π
π K p Λ Ξ Ω
//star/flow/v2summary/hydro_mpt_200gev//

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!