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SMR.1508 - 18

SUMMER SCHOOL ON PARTICLE PHYSICS

16 June - 4 July 2003

QDC PHASE TRANSITIONS

Lectures I & II

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THE CONDENSED MATTER PHYSICS OF QCD

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ICTP Summer School
June 2003

My lectures will fall roughly into two halves. The title just given applies literally to the 2nd half, and metaphorically to the 1st half. More literal titles for 1st half:

USING LITTLE BANG
EXPERIMENTS TO STUDY
THE STUFF OF THE BIG BANG

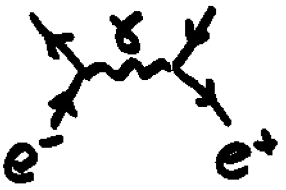
or...

FROM THE QCD PHASE DIAGRAM
TO HEAVY ION COLLISIONS
AND BACK

WHAT IS QCD?

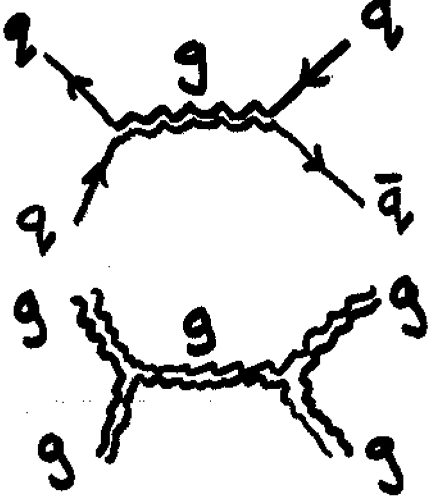
Its Lagrangian suggests it is a theory of quarks and gluons, not too different from QED which is a theory of electrons and photons:

QED



e^-: charge -1
γ: neutral

QCD



q: charge r, g or b
gluons: also colored.

Quarks come in six flavors:

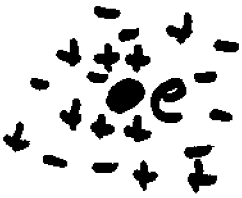
Flavor	Mass (MeV)	
u	5	light. treat as massles to first approx.
d	10	
s	100	← middleweight
c	1500	too heavy to play a role in this talk
b	5000	
t	175000	

ASYMPTOTIC FREEDOM

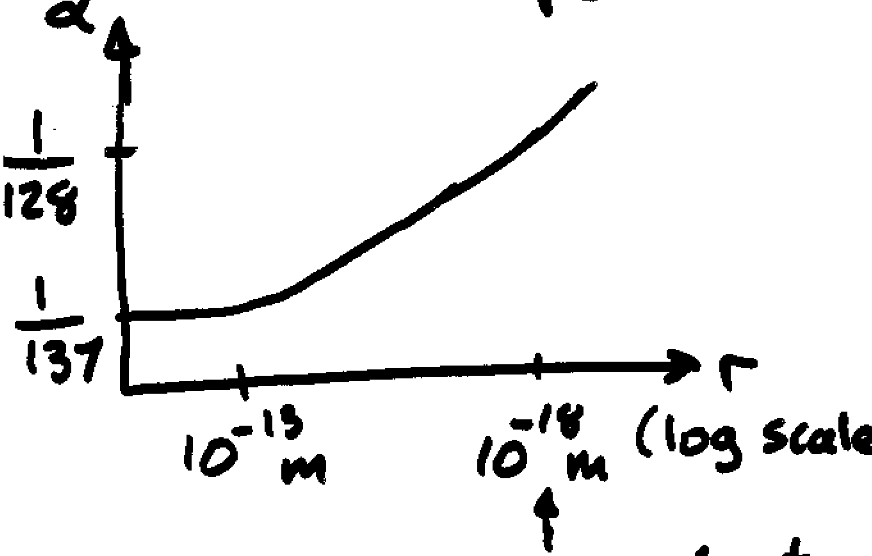
Gross, Wilczek, Politzer (1973)

In quantum field theory, the vacuum is a medium which can screen charge.

QED



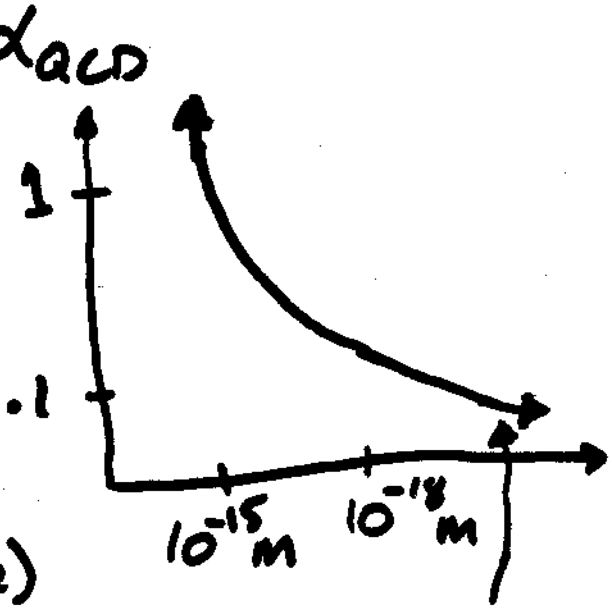
α: Force between electrons ~ $\frac{\alpha(r)}{r^2}$



experiments at CERN

Coupling "constants" not constant. Depend on scale at which you probe.

QCD



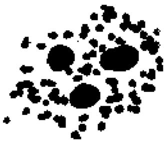
asymptotic freedom, or anti-screening.

(That's why Friedman, Kendall, Taylor were able to see weakly interacting quarks.)

WHAT DOES QCD DESCRIBE?

It is an experimental fact that in the world around us, quarks and gluons occur only in colorless packages:

Protons, neutrons,...



Pions, kaons,....

These hadrons are the quasiparticles of the QCD vacuum.

They, in turn, make up everything from nuclei to neutron stars, and thus most of the mass of you and me.

Why no colored quasiparticles?

- would disturb vacuum out to ∞, and $\therefore$ have ∞ mass.
- NB: growth of $\alpha(r)$ with r $\Rightarrow$ force between colored objects does not fall off with distance.
- their absence confirmed by direct calculation. (Lattice gauge theory.)

NB: hadrons are heavy. $m_{proton} = 938$ MeV
$m_{u+u+d} \cong 20$ MeV

WHAT IS QCD?

A theory of quarks and gluons ....

WHAT DOES QCD DESCRIBE?

Colorless, heavy, hadrons...

Hadrons are the (rather complicated) quasi-particles of the QCD vacuum.

The vacuum, whose excitations are the hadrons, is therefore quite a nontrivial [confinement; chiral symmetry breaking; strong coupling; ...] phase of the theory.

BUT: QCD is asymptotically free ....

DO OTHER (SIMPLER?) PHASES EXIST?

Do other phases exist whose quasiparticles look more like the quarks and gluons of the QCD Lagrangian? And look more like phases familiar from QED?

Asymptotic freedom: quarks and gluons weakly interacting

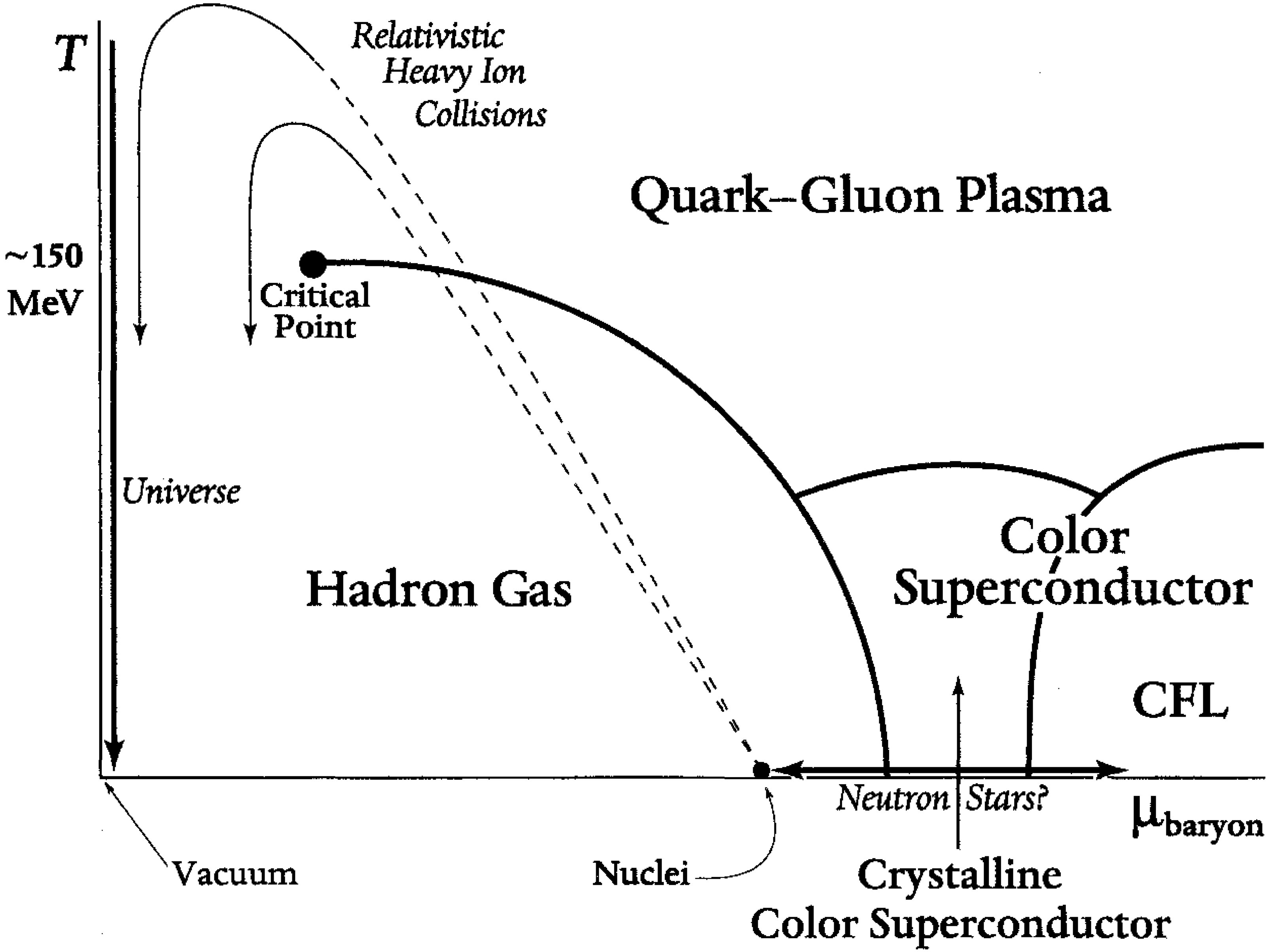
i) when close together

ii) when interact at large momentum.

Suggests look at high density or high temperature.

NB: condensed matter physics teaches us that phases may be far from simple even for α as small as $\frac{1}{137}$.

EXPLORING *the* PHASES *of* QCD

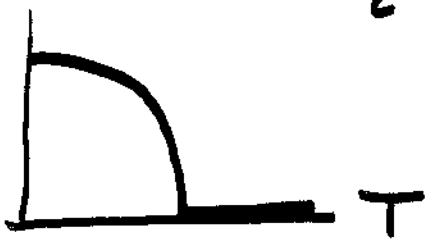


PHASE TRANSITIONS

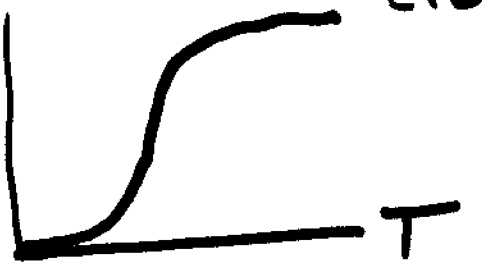
i) Look for an order parameter.
- zero on one side of transition, non-zero on the other

ii) - change in symmetry?

1st order: thermodynamic quantitities discontinuous
- latent heat; bubbles
- eg: boiling water



2nd order: continuous, but not smooth.
- long wavelength fluctuation
- no length scale at T_c
- eg: Curie transition



Crossover: smooth. No order parameter. No change in symmetry.
eg: ionization of a gas

SECOND ORDER PHASE TRANSITIONS

Physics is scale invariant at $T=T_c$.

$\Rightarrow$ fluctuations on all length scales.

$\Rightarrow$ coarsen your microscope, and the world looks the same.

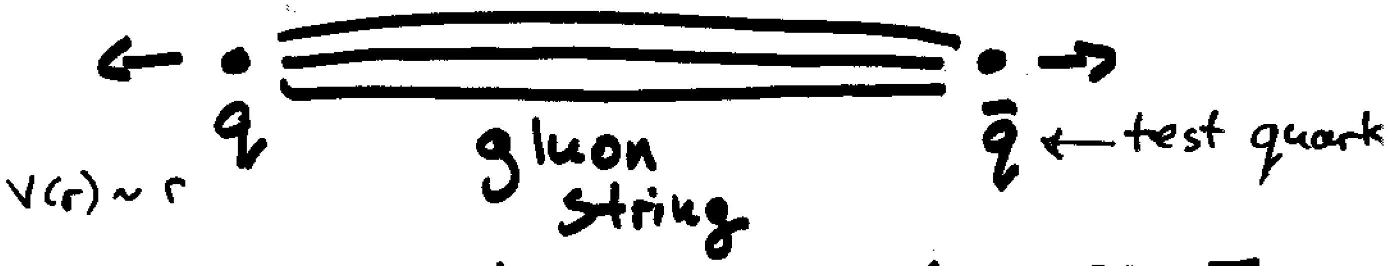
(fancy way to say this: you are at an infrared fixed point of the renormalization group.)

$\Rightarrow$ long wavelength physics independent of microscopic physics - UNIVERSAL.

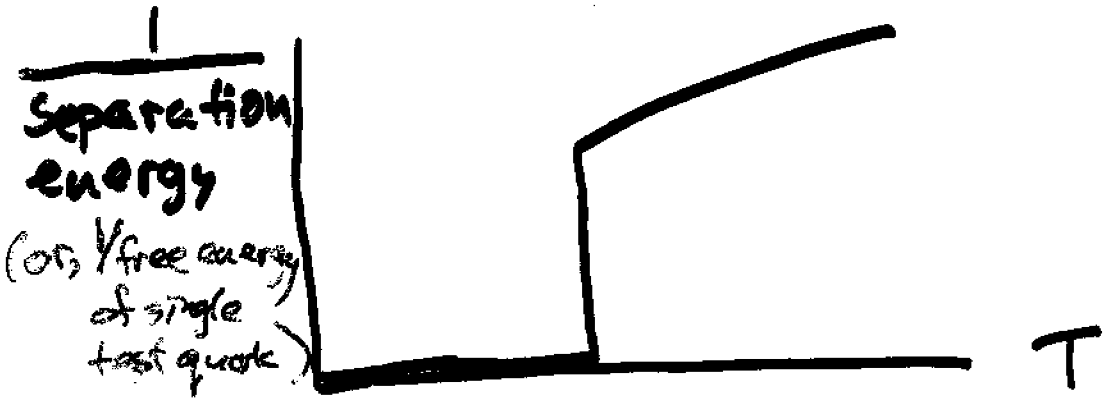
$\Rightarrow$ many microscopic theories → same long wavelength physics.

DECONFINEMENT

i) Without dynamical quarks.
(eg pair creation forbidden.)



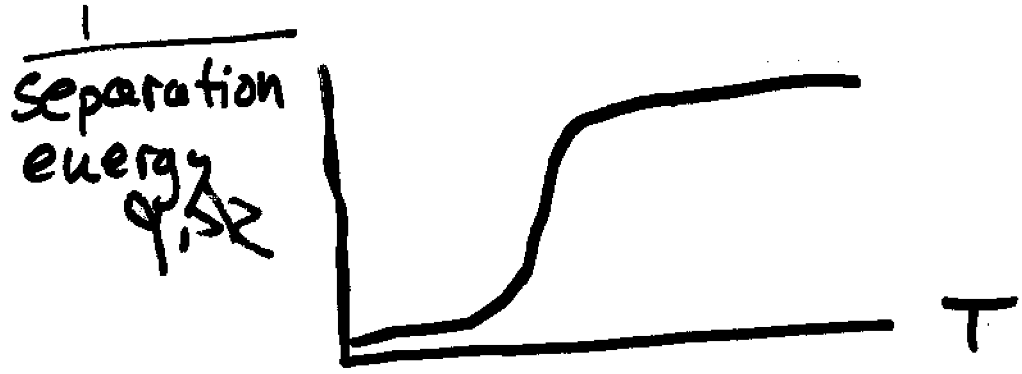
T=0: Energy to separate TEST
q + $\bar{q}$ = ∞



So QCD with no quarks has a 1st order deconfinement transition

ii) Add dynamical quarks

- if you pull two test quarks apart, you make a pair.
- theory is confining at $T=0$, but what used to be an order parameter is no longe



No order parameter is known for a deconfinement transition in QCD with quarks. BUT .....

CHIRAL SYMMETRY

There is another qualitative difference between $T \ll T_c$ and $T \gg T_c$, associated with a qualitative feature of the QCD vacuum.

$$\mathcal{L}_{QCD} = \sum_i \bar{q}_L^i \, i\not{\partial} \, q_L^i + \sum_i \bar{q}_R^i \, i\not{\partial} \, q_R^i$$

$$+ \mathcal{L}_{\text{gluons only}}$$

i is a flavor index. $i = u, d$ (2 massless flavors, for now.)

$\mathcal{L}_{QCD}$ is symmetric under:

$$SU(2)_L \times SU(2)_R$$

but: predictions of this symmetry <u>fail</u>.

eg predicts 4 pions and only 3 exist.

RESOLUTION: $\mathcal{L}$ invariant, but $|0\rangle$ not:

$$\langle 0 | \bar{q}_L^i \, q_R^j | 0 \rangle \neq 0$$

$$= \sigma \mathbb{1}^{ij} + i \vec{\pi} \cdot \vec{\tau}^{ij}$$

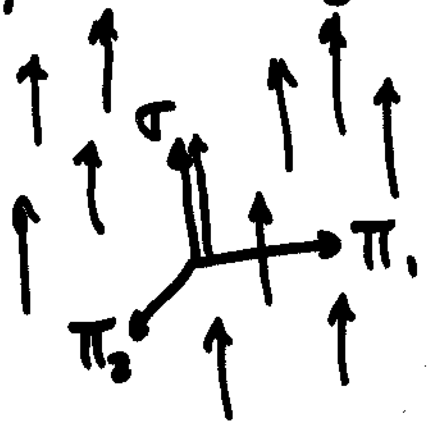
- only symmetric under $SU(2)_{L+R}$
- can point in one of four directions
  ie: $\bar{u}u, \bar{d}d, \bar{u}d, \bar{d}u$ or: $\sigma, \pi^1, \pi^2, \pi^3$

CHIRAL SYMMETRY BREAKING....

(for now, $m_u = m_d = 0$; $m_s = \infty$)

The QCD vacuum (the $\bar{q}q$ pairs therein) is ordered in flavor space.

$\langle \bar{q}_L q_R \rangle \neq 0$ condensate "picks a direction" among 4 previously equivalent options.



- called σ-direction.
- points in same direction everywhere.

$\langle \sigma \rangle \neq 0$ $\langle \vec{\pi} \rangle = 0$

Could have pointed any direction. ∴ waves in which direction of ↑ undulates associated with massless pions.

(Goldstone's theorem)

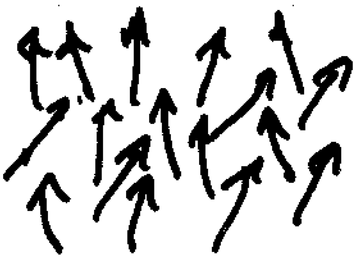
$m_\pi = 140$ MeV. Lightest hadron.

($m_\pi \neq 0 \leftrightarrow m_q \neq 0$)

NB: Heaviness of other hadrons (eg p, n) can be seen as due to their interaction with (disturbance of) condensate.

... CHIRAL SYMMETRY RESTORATION

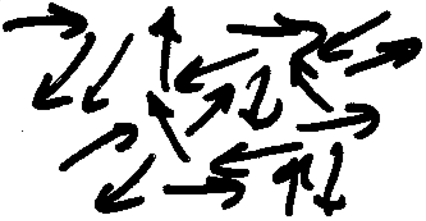
$T \neq 0$



"waves on the condensate", but $\langle \bar{q}q \rangle$ still nonzero. Still a preferred direction. Symmetry still broken.

a.k.a. a gas of pions

T ABOVE SOME T_c...



Entropy wins over order. "Condensate scrambled." Disordered. $\langle \bar{q}q \rangle \to 0$

All directions equivalent.

... CHIRAL SYMMETRY RESTORED

What is T_c? Lattice calculations indicate $T_c \sim 140 - 190$ MeV

$\sim 2 \times 10^{12}$ Kelvin

THE QCD PHASE TRANSITION

$T \ll T_c$	$T \gg T_c$
hadrons confinement	plasma of quarks and gluons, which is weakly interacting for $T \to \infty$.

(associated with change in symmetry if $m_{\text{all quarks}} \to \infty$)

chiral symmetry spontaneously broken	chiral symmetry restored

(associated with change in symmetry if $m_{\text{2 or more quarks}} \to 0$)

$T_c \sim$ ~~140-190~~ MeV

165-180

MEAN FIELD ANALYSIS OF χ. PHASE TRANS.

- ignoring fluctuations;

$$\langle \bar{q}_L^i q_R^j \rangle = \sigma \mathbb{1}^{ij} + i\, \vec{\pi} \cdot \vec{\tau}^{ij}$$

combine σ and $\vec{\pi}$ into $\phi^i \equiv (\sigma, \vec{\pi})$

- For $m_q = 0$, QCD Lagrangian chirally symmetric

$$\Rightarrow V_{eff} \sim a(T)\, \phi_i \phi^i + b(T) \left[\phi_i \phi^i\right]^2 + \dots$$

T_c is the T at which $a(T_c) = 0$.

So, write $a(T) \sim a_0 (T - T_c)$ & $b(T) \sim b_0$ $[b_0 > 0]$

For $\underline{T > T_c}$: $\left[\phi_i \phi^i\right]^{1/2} = 0$

For $\underline{T < T_c}$: $\left[\phi_i \phi^i\right]^{1/2} \sim \left(\frac{a_0}{b_0}\right)^{1/2} (T_c - T)^{1/2}$

→ $|\phi_i| \neq 0$ must pick a direction in i-spa

at $T \simeq T_c$, $m_\sigma = 0$ → breaks chiral symmetry. $m_\pi = 0$
(call the chosen direction σ)

- Effect of $m_q \neq 0$? $m_q(\bar{u}u + \bar{d}d) \sim m_q \sigma$
  - explicit symmetry breaking

$$V \sim -\epsilon \sigma + a(T)\, \phi_i \phi^i + b(T) \left[\phi_i \phi^i\right]^2$$

- $|\phi_i|$ in σ direction. Small but nonzero even for $T \gg T_c$. And, for $T < T_c$, $m_\pi^2 \sim \epsilon \neq 0$.

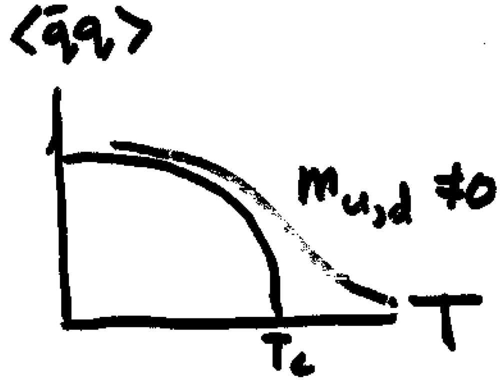
How do fluctuations change the predictions of mean field theory?

APPLICATION OF UNIVERSALITY

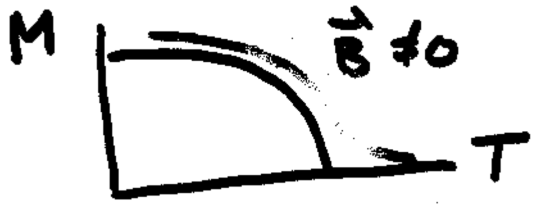
QCD near T_c ↔ 4-component magnet near its T_c.

↑

Has 2nd order transition.



←



Calulations tested in expt, at least for 3-component magnets.

$\langle\bar{q}q\rangle \sim (T_c - T)^{\beta}$ at $m_{u,d} = 0$

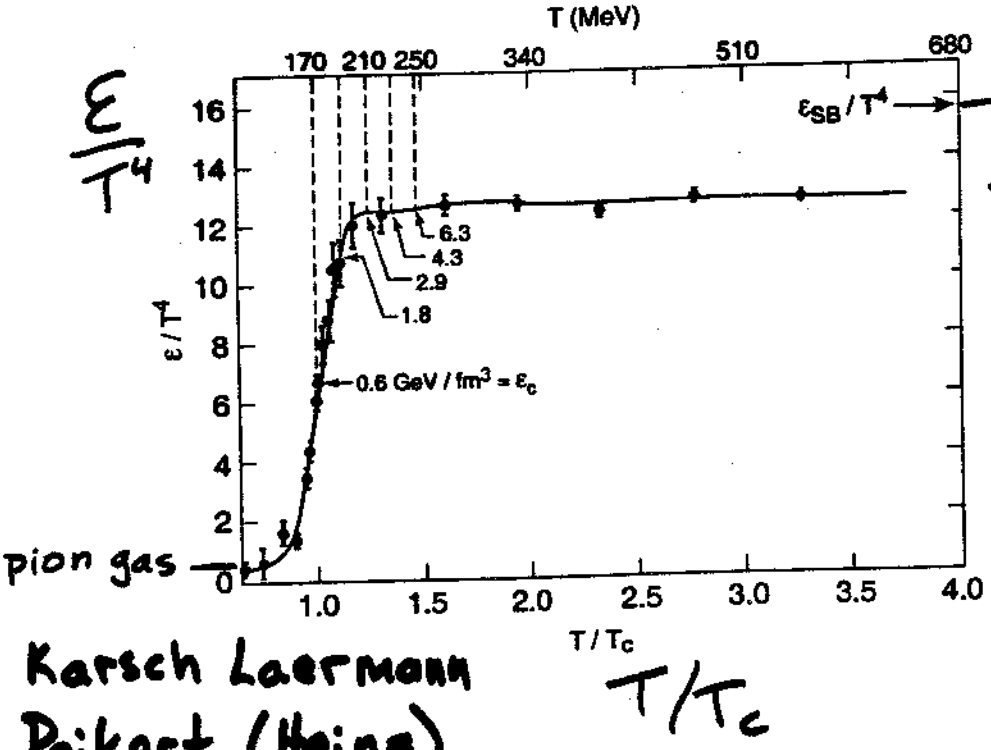
$\beta = .383 \pm .005$

$\langle\bar{q}q\rangle \sim (m_{u,d})^{1/\delta}$ at $T = T_c$

$1/\delta = .208 \pm .001$

These predictions from magnets for QCD being tested by simulation of quarks and gluons on worlds biggest computers.

T(MeV), assuming $T_c = 170$ MeV.
(estimate is $140 < T_c < 190$)



— ideal QGP

DECONFINEMEN

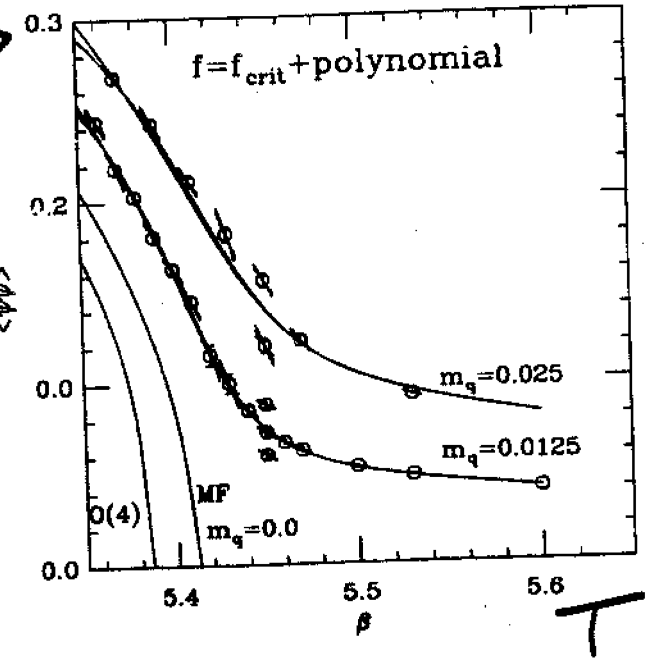
(IONIZING
THE
HADRONS)

Karsch Laermann Peikert (Heine)

&

$\langle \bar\psi \psi \rangle$

Blum DeTar MILC collab.



(funny units)

CHIRAL
SYMMETRY
RESTORATION
(MELTING THE
VACUUM)

ON THE
LATTICE

$N_f = 2$
$m_q \neq 0$
∴ smooth crossover

WHAT ABOUT THE STRANGE QUARK?

$m_s = \infty$: 2nd order → crossover

$m_s = 0$: 1st order. (Lattice calculations and ren. group calculations agree.)

QUESTION

For m_s as in nature, is transition 1st order or 2nd order?
(→ crossover)

Lattice calculations suggest not 1st order, but still controversial.

ONE GOAL FOR REMAINDER OF TALK:

Suggest how to answer this question EXPERIMENTALLY.

Experiments (unlike lattice calculations or cosmology) have nonzero baryon density...

ASIDE: 1st order QCD transition upsets big bang nucleosynthesis, making it inconsistent with cosmological data.
($\exists$ caveats)

COSMOLOGICAL CONSEQUENCES ?

Nobody has proposed a signature of a 2nd order QCD transition in the early universe.

BUT

- A first order transition screws up big bang nucleosynthesis.
- This is inconsistent with the data.

⇒ not 1st order.

This is consistent with what we have seen previously.

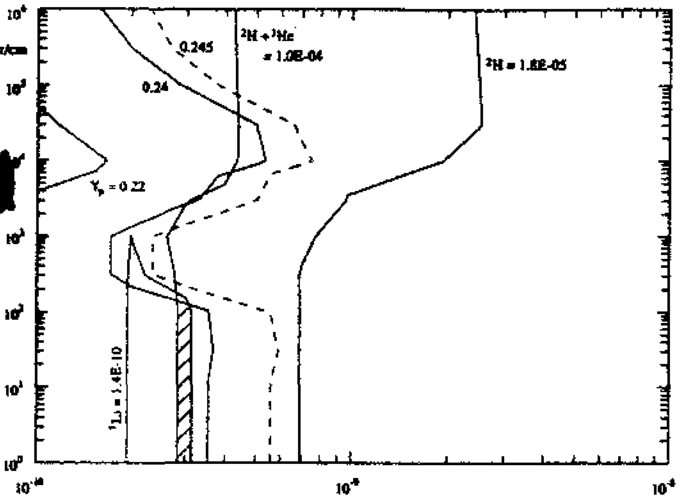
Thomas et al

r - bubble spacing

horizon (10 km)

BBN affected

wash out by diffusion



n_B/s

FIG. 2a

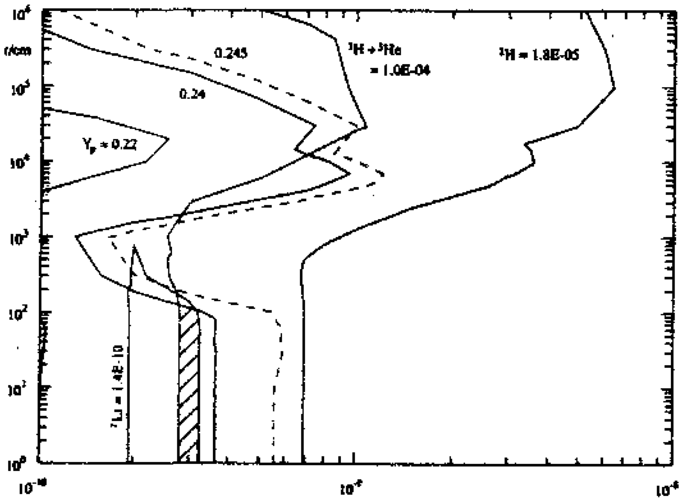


FIG. 2b

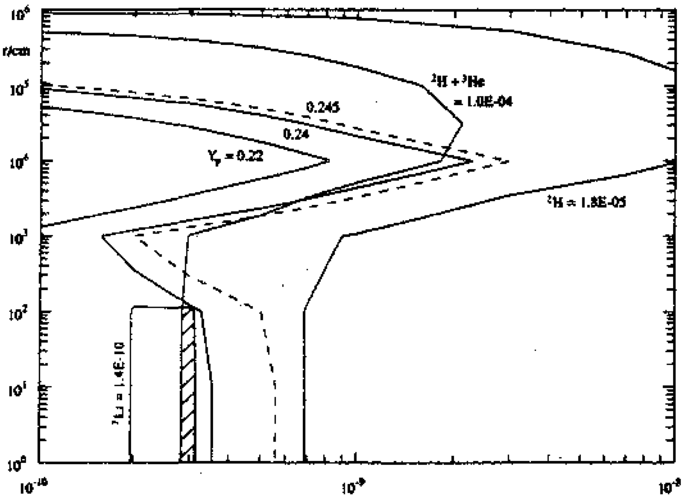
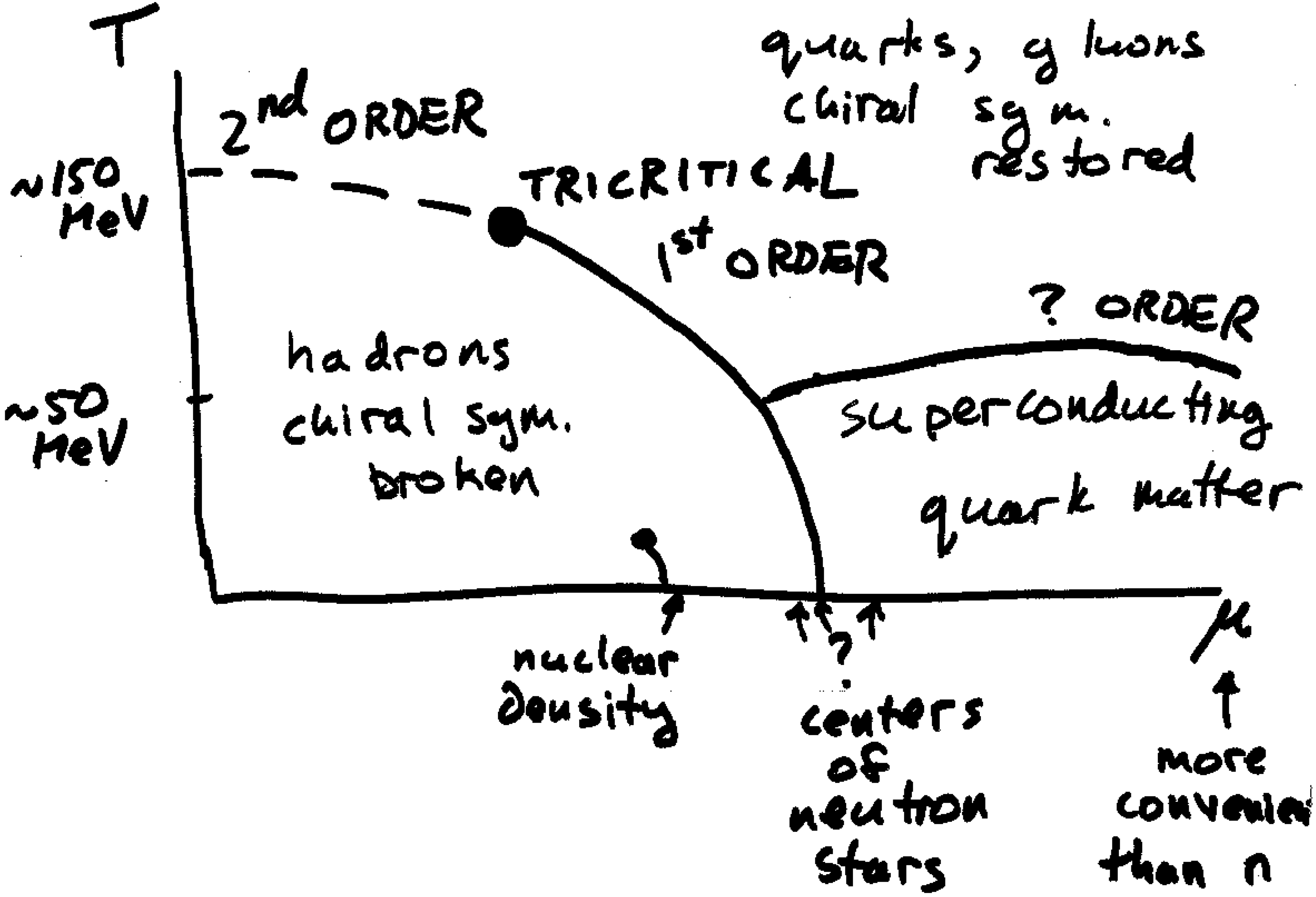


FIG. 2c

FIG. 2—(*a*) Limits on r and η due to the light element abundances, for $R = 100$. Curves show the most generous limits for $f_v = 1/8$ and $f_v = 1/64$, and represent the following abundances: $^2H/H = 1.8 \times 10^{-5}$, $(^2H + {}^3He)/H = 1.0 \times 10^{-4}$, $^7Li/H = 1.4 \times 10^{-10}$, $Y_p = 0.22, 0.24$. The dashed curve is for $Y_p = 0.245$. The hatched area shows the region allowed by the light element abundances. (*b*) Same as Fig. 2*a*, but for $R = 1000$. (*c*) Same as Fig. 2*a*, but for $R = 10^6$, $f_v = 1/64$.

THE QCD PHASE DIAGRAM

i) $m_u = m_d = 0 \qquad m_s = \infty$



Alford KR Wilczek

Rapp Schaefer Shuryak Velkovsky

Berges KR

Halasz Jackson Shrock Stephanov Verbaarschot

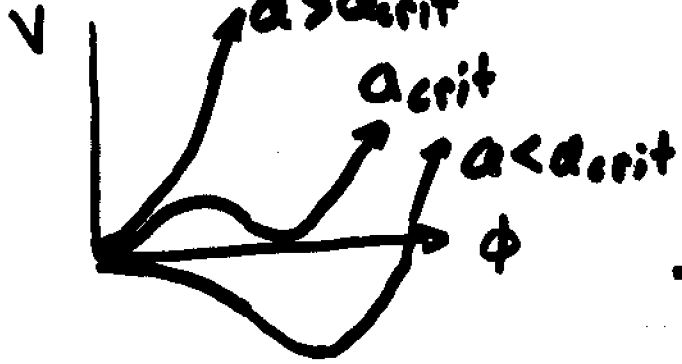
UNDERSTANDING THE TRICRITICAL POINT

Near tricritical point, 3-D effective theory with

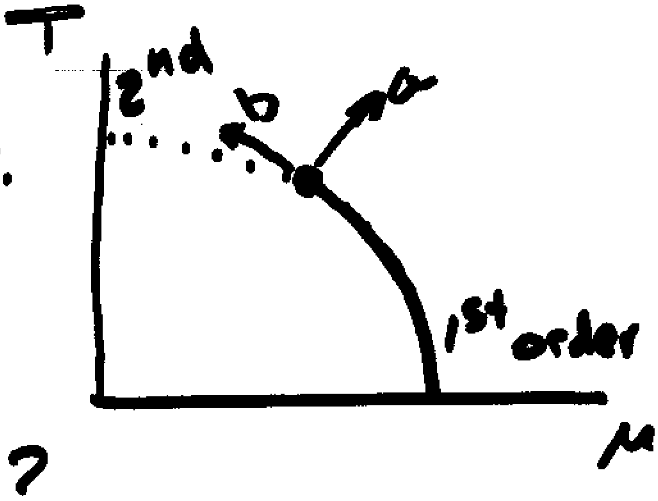
$$V \sim a(\mu,T)\,\phi^2 + b(\mu,T)\,\phi^4 + c(\mu,T)\,\phi^6$$

<u>$b>0$</u> : 2nd order as before [$c>0$]

<u>$b<0$</u> : <u>1st order</u> phase transition at some $a<0$.



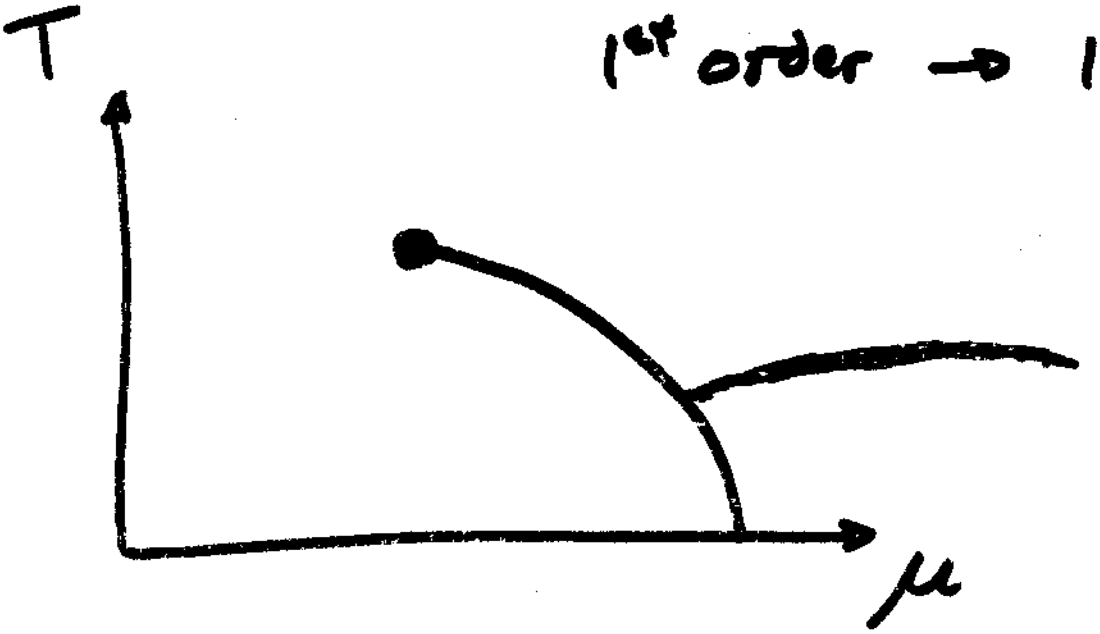
<u>$a=b=0$</u>: tricritical point.



- Effect of fluctuations?
  in ϕ^6 theory in $d=3$, fluctuations only lead to log corrections. Mean field critical exponents correct
- $M_q \neq 0$ → term linear in ϕ.

$m_{u,d} \neq 0$

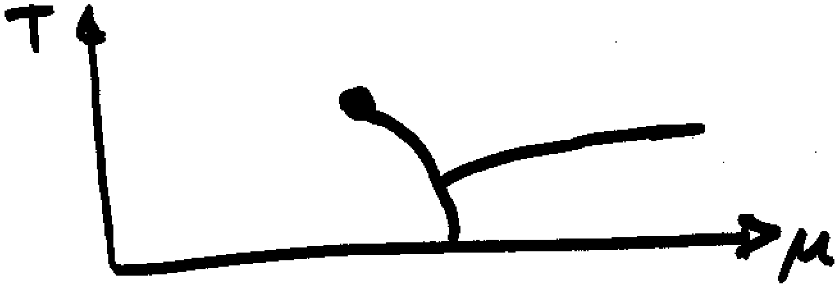
2nd order → crossover
Tricritical → 2nd order
1st order → 1st order



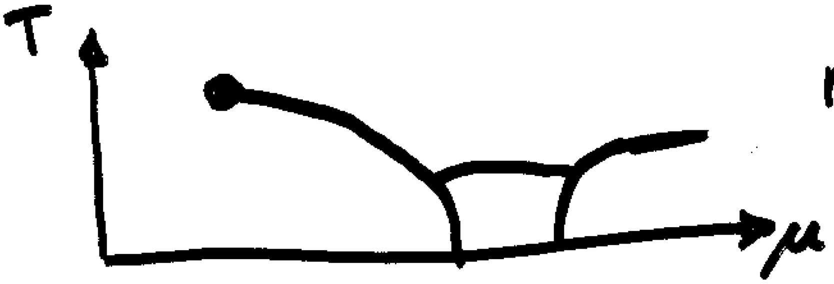
At ● : $m_\pi \neq 0$ (because of $m_{u,d} \neq 0$)
$m_\sigma = 0$

3D Ising model universality class
eg liquid-gas critical point

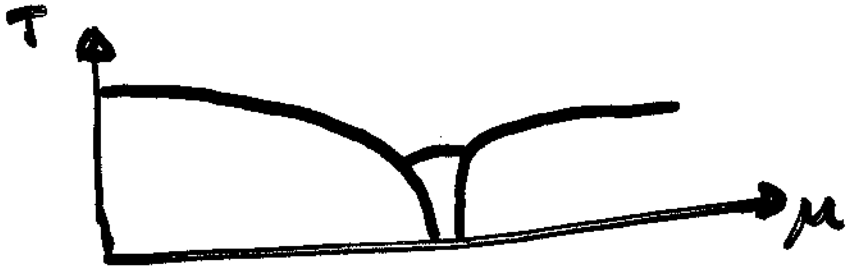
WHAT ABOUT THE STRANGE QUARK?



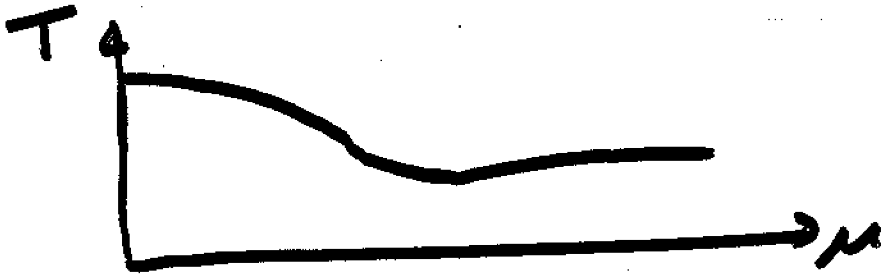
$m_s = \infty$



$m_s \sim$ physical ?



$m_s <$ physical



$m_s = 0$

Effects of reducing m_s:

i) ● sucked to the left

ii) funny business at large μ. (WAIT)

If experiments were to detect signatures of ●, learn that cosmological phase transition *not* first order, ie crossover.

$T \neq 0$; $\mu = 0$

- vertical axis
- We know a lot from lattice QCD. eg →
- QCD describes a transition

FROM	TO
gas of hadrons	plasma of quarks and gluons
with chiral symmetry badly broken	with chiral sym. almost restored.

- $T_c \simeq 175 \pm 15$ MeV
- The transition is a smooth crossover, like ionization of a gas, occurring in a narrow range of T

IF $m_s \gtrsim \frac{1}{5} m_s^{\text{physical}}$, and is in natur

NB: In world with $m_u = m_d = m_s$, crossover if $m_q \gtrsim \frac{1}{15} m_s^{\text{physical}}$

Bielefel
[illegible]

THE DIFFICULTY WITH DENSITY

Why are we still asking basic questions about QCD at high μ, low T, like "what is symmetry of ground ~~state~~?"

NO LATTICE CALCULATIONS

$\mu \neq 0 \rightarrow$ complex Euclidean action
→ sign problem that makes difficulty of standard Monte Carlo $\sim e^{V}$.

Equally nasty sign problems can be solved in simpler systems. Chandrasekharan Wiese

Sign problem may also be evaded:

- at small V, small μ/T Fodor Katz; Hands Karsch et al
- calculate at $\mathrm{Im}\,\mu$; continue observables. Works at $\mu/T < \pi/3$. V can be large. de Forcrand Philipsen; d'Elia Lombardo

→ may be used to locate critical point.

- modify the theory. (color superconductivi studied on lattice for NJL & QCD w̄ $N_c=2$ Hands et al Kogut et al

NO EVASION POSSIBLE FOR QCD at $\mu \gg T$

- use smallness of g at $\mu \to \infty$
- use models at accessible μ.

$T \neq 0$; $\mu \neq 0$; μ/T NOT LARGE

- regime explored by heavy ion collisions
- very recently, we are starting to learn about this regime from lattice calculations that rely on smallness of μ/T to keep fermion sign problem under control.
- these methods may be used to locate the....

CRITICAL POINT, a 2nd order point in the phase diagram where a line of 1st order transitions ends. (Location is sensitive to quark masses. Moves leftward as masses ↓.)

THREE NEW LATTICE METHODS

① Reweighting. Fodor + Katz

Want physics at ⓐ $\equiv (\mu, T_a)$.

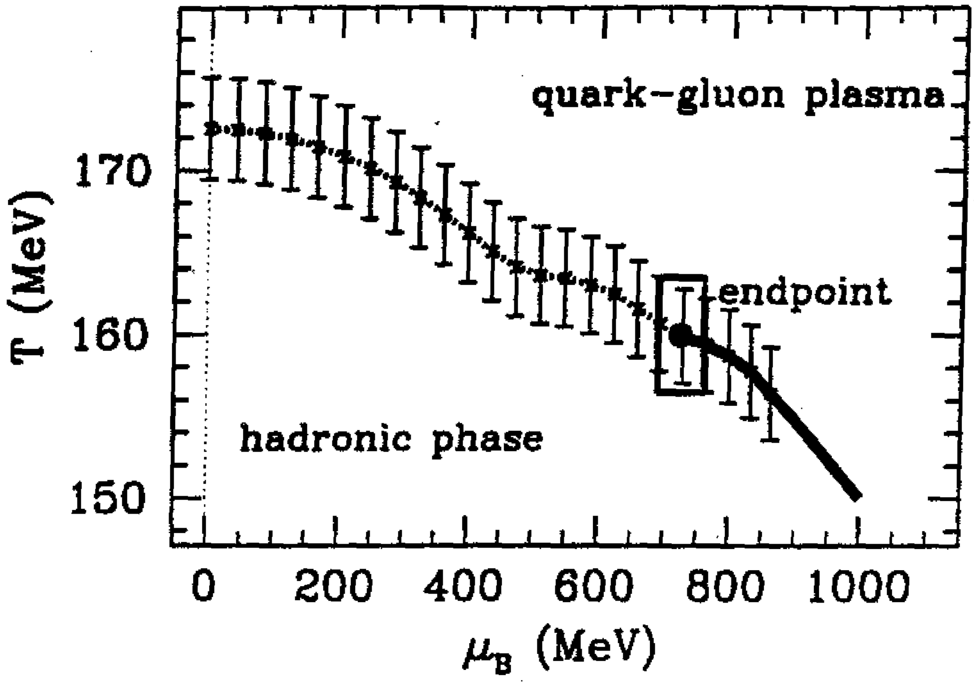
Simulate at ⓑ $\equiv (0, T_b)$, and "reweight": lump difference betw physics at ⓑ and ⓐ into observables.

$$\text{Difficulty} \sim \exp\left[\frac{|F_{ⓑ} - F_{ⓐ}|V}{T}\right]$$

F+K choose T_b to minimize $\mathcal{D}$.

BUT: cannot use method at large volumes.

Fodor+Katz



- $T_{\text{crossover}}(\mu)$ quite flat.
- Claim to locate end point!

  CAVEATS: $V = 4^3, 6^3, 8^3$ is small.

  (makes me wonder how they located end point so accurately.)

  - recall: <u>can't</u> go to $V \to \infty$
  - no continuum extrapolation yet
  - light quarks not light enough (⇒ end point too far right)

② Continue from imaginary μ.

de Forcrand + Philipsen

Simulate at $\mu = i\mu_I$; calculate

$T_c(\mu_I)$; Taylor expand:

$$= c_0 + c_2 \mu_I^2 + c_4 \mu_I^4 + \ldots$$

- valid for $\frac{\mu_I}{T} < \frac{\pi}{3}$. (ask Owe)
- Good luck!! $c_4, c_6, \ldots$ terms all small over this range.
- ∴ boldly continue:

$$T_c(\mu) = c_0 - c_2 \mu^2 + \ldots$$

- valid for $\mu/T < \pi/3 \rightarrow \mu_B \lesssim 500$ MeV
- $\mu_{RHIC} \sim 45$ MeV ; $\mu_{SPS} \sim 250$ MeV ; $\mu_{AGS} \sim 500$ MeV
- so far, done at fairly small volume. No obstacle to $V \to \infty$. (Unlike Fodor + Katz's method.)
- order of transition can be studied via how T_c changes with V.
  → search for critical point

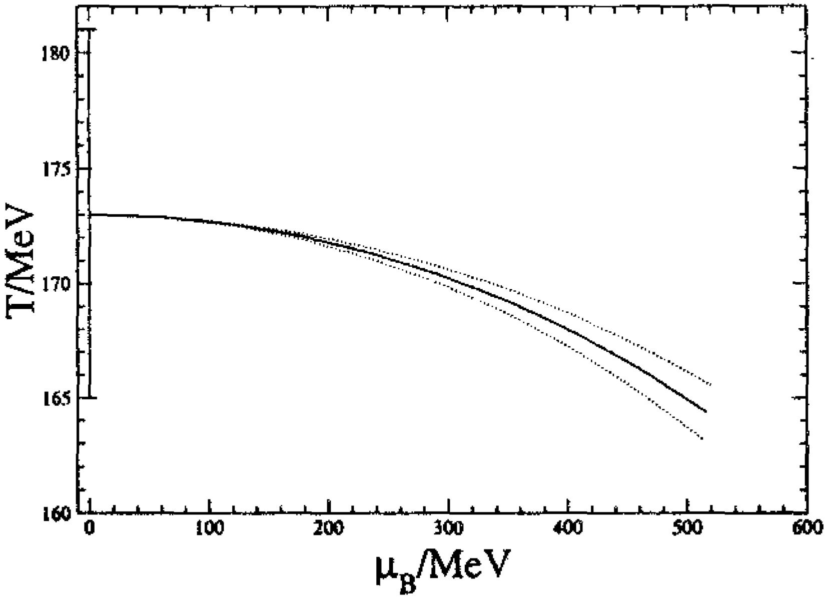


Figure 10: *Location of the deconfinement transition corresponding to the first fit in Table 1. The error bar gives the uncertainty in $T_c(0)$ used to set the scale, the dotted lines reflect the error on c_1 from Table 1.*

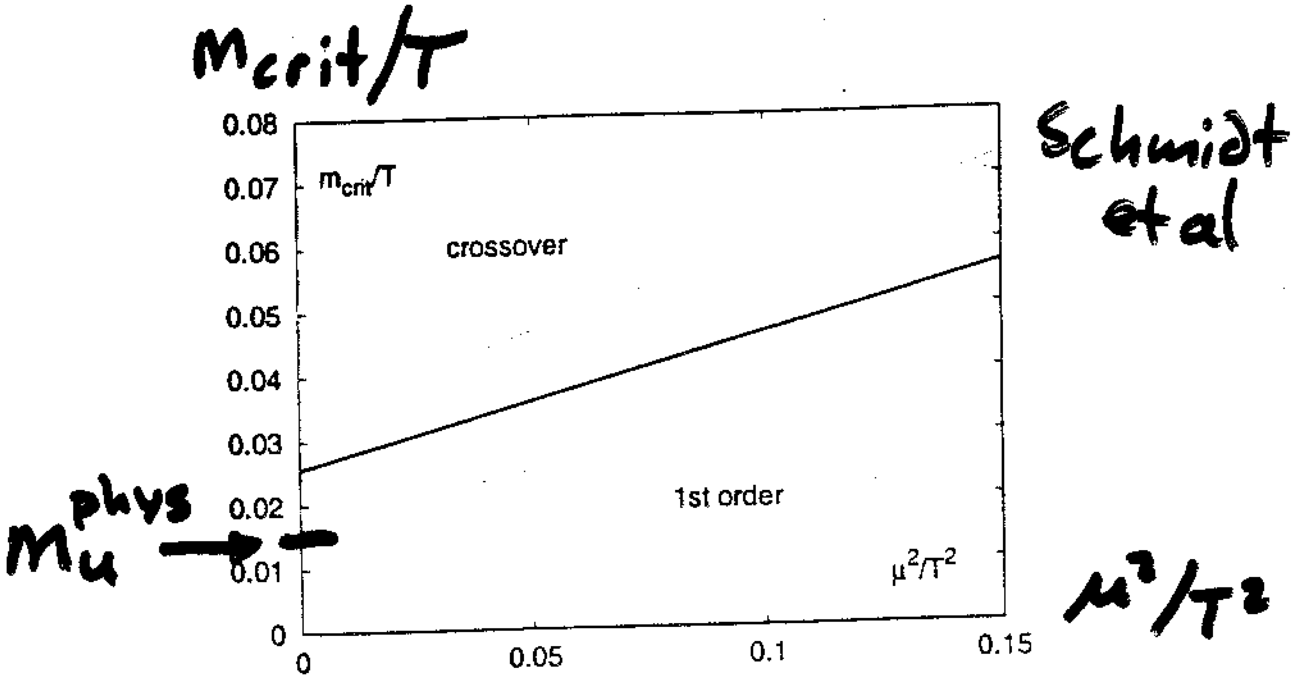
$T_c(\mu_B)$ agrees quantitatively with Fodor + Katz. "Flatness confirmed"

de Forcrand
Philipsen

③ Calculate $\frac{\partial}{\partial\mu^2}\left[\cdots\right]\Big|_{\mu=0}$.

Allton Ejiri Hands Karczmarek Karsch Laermann Schmidt
("Bielefeld-Swansea")

- $\frac{\partial}{\partial\mu^2}T_c$ agrees with Fodor+Katz, Philipsen + deForcran



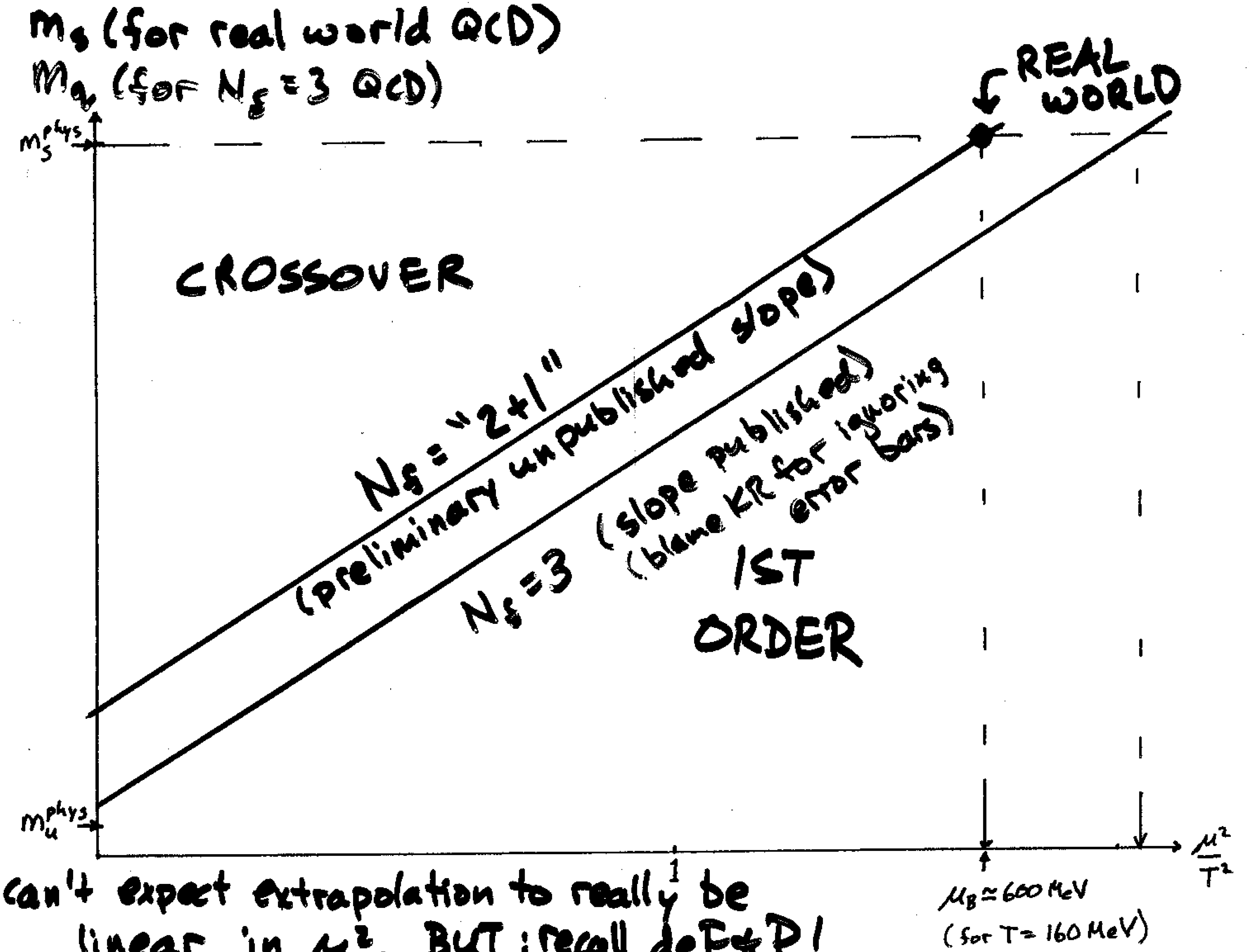
Schmidt et al

- $\frac{\partial}{\partial\mu^2}\left[\begin{array}{l} m_q \text{ at which transition} \\ \text{goes from 1st order to} \\ \text{crossover.}\end{array}\right]$,

  in this figure for $m_s = m_u = m_d = m_q$

- For fun, let's extrapolate ....

  (Thanks to Schmidt for help; apologies to him for extrapolating ....)



Can't expect extrapolation to really be linear in μ^2. BUT: recall deF+P!

LOCATING THE CRITICAL POINT

- Best guess at present is that critical point has μ_B somewhere around 600 MeV.
- error estimates uncertain and large. (Not at all like calculating Tc. Yet.)
- progress is all of a sudden occurring very rapidly....

WHAT DO I WANT TO LEARN FROM HEAVY ION COLLISIONS?

i) Where is ●? (If ● found, tells us transition is crossover on vertical axis.)
This is one example of how to use h.i.c. to map the transition region of the diagram. $\exists$ others.

ii) Measure physical properties of QGP phase, as far above T_c as possible. There is (or need be) no sharp line between QGP + hadrons. CF: ionization of a gas.
As there, we want to measure physical properties which are expected to be very different for $T \gg T_c$ vs $T \ll T_c$.
I will describe one example.

HEAVY ION COLLISIONS:
A BRIEF INTRODUCTION

- A picture worth 1000 words →
- Sequence of events:
  - i) collision leaves lots of gluons + quarks at mid-rapidity
  - ii) scattering → thermalization (?) - must be tested experimentally
  - iii) hot fireball expands, cools, following some track on phase diagram
  - iv) "Freezeout": after which hadrons (mostly pions) fly outwards into detector. [Much evidence from SPS suggests final state at freezeout is hadron gas with ~ equilibrated momenta.]
- What does higher collision energy buy?
  - i) higher initial T, we hope
  - ii) lower baryon #/entropy ⇒ lower μ
  - iii) NOT higher freezeout T

4 CLASSES OF ANALYSES / SIGNATURES

① MULTIPLICITY. Determined by how many partons released in initial stage of collision, and also to some (small ?) extent by how thermalization occurs, but not by what happens later.

Tells you more about dynamics of hadron collisions and about wave function of incident hadrons than it does about properties of hot quark matter.

- Analyses of centrality- and collision-energy-dependence of multiplicity using <u>only</u> physics of wave function of incident nuclei ("saturation setting in earlier in nuclei than in nucleon") have been surprisingly successful.

PHENIX
PHOBOS
STAR
BRAHMS

⇒ not an interesting signature for our purposes

② Characterize <u>hadrons at freezeout</u> in as many ways as you can:

- ratios, spectra, two-particle correlations..
- learn about T, μ, expansion velocity, degree of equilibration, ... <u>at freezeout</u>.
- Done in great detail @SPS + @RHIC
- one example: [PHOBOS, PHENIX, STAR, BRAHMS]

  $\sqrt{s} = 130\,\mathrm{GeV}$: $\bar{p}/p \sim .65 \rightarrow \mu_B \sim 40\,\mathrm{MeV}$

  $\sqrt{s} = 200\,\mathrm{GeV}$: $\bar{p}/p \sim .75 \rightarrow \mu_B \sim 30\,\mathrm{MeV}$

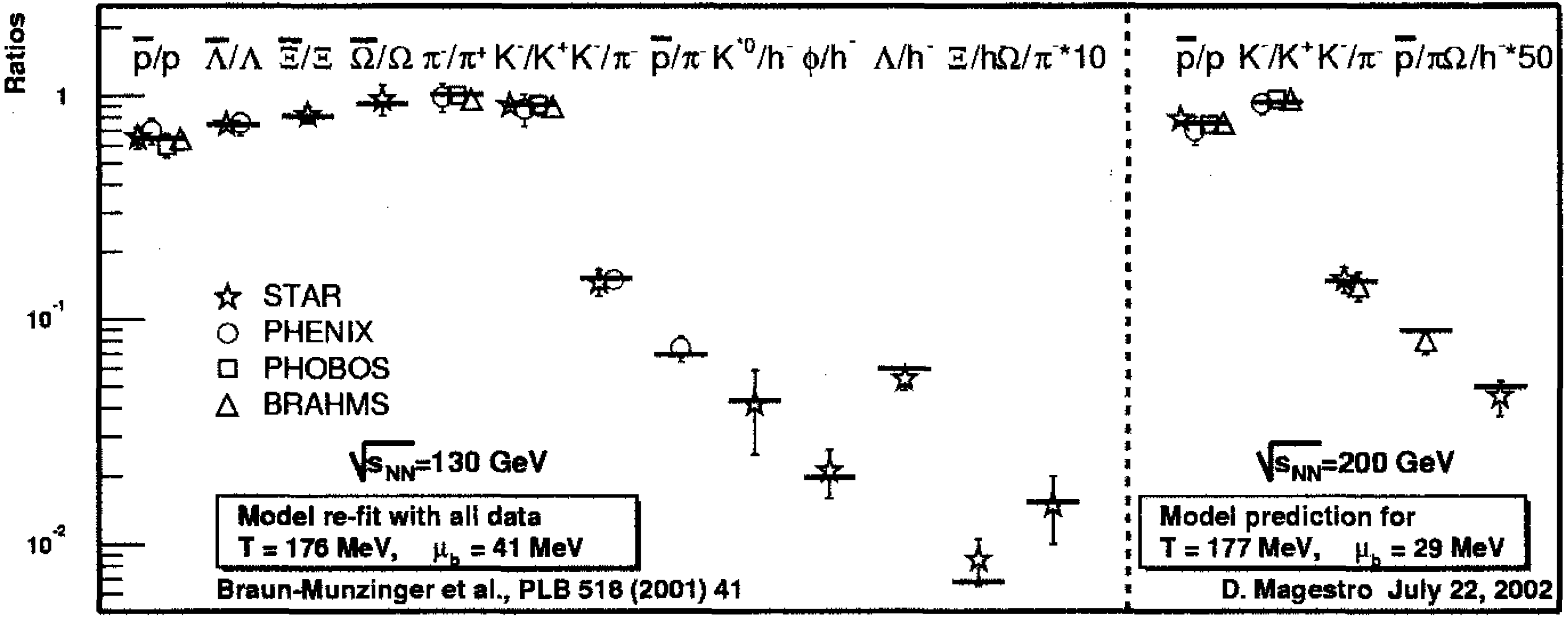
  cf: $\bar{p}/p \sim .1 \rightarrow \mu_B \sim 250\,\mathrm{MeV}$ at SPS
- Also, from spectra,

  $T_{\substack{\text{momentum}\\ \text{freezeout}}} \sim 100 - 110\,\mathrm{MeV}$ (cf 120 @SPS)

  $\langle v_{\text{expansion}} \rangle \sim .6 - .7$ (cf .4 - .5 @ SPS)
- These observables tell you where on the phase diagram freezeout occurs
- And, they are a prerequisite to....

$\sqrt{s} = 130$ (200) @ RHIC. Fit many ratios → freezeout at $\mu_B = 41$ (29) MeV

More evidence for equilibrated final state



Braun-Munzinger et al., PLB 518 (2001) 41

D. Magestro July 22, 2002

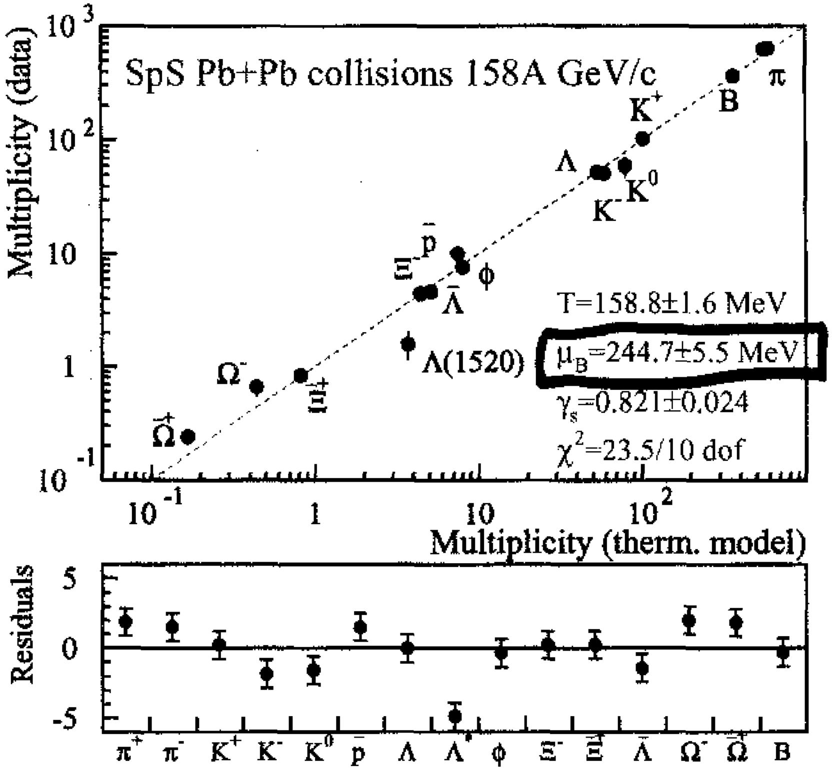
Observed hadron ratios in agreement with thermal ratios!
T(chemical freeze-out) ~ 175 MeV

from talk by B. Jacak

$\sqrt{s}=17$ @SPS. Fit to many ratios $\rightarrow \mu_B = 245 \pm 6$ MeV

Particle yields at 158 *A*GeV (fixed target)

All total yields measured by NA49, including final results for K, π and new preliminary Ω, fitted by F. Becattini



All multiplicities scaled to 5% centrality, using the ratio of pion multiplicities (factor 1.08 for 10%, 1.38 for 20%)

Hadron gas fit with partial strangeness saturation describes multiplicities over several orders of magnitude

Chemical freeze–out in the T–μ_B plane

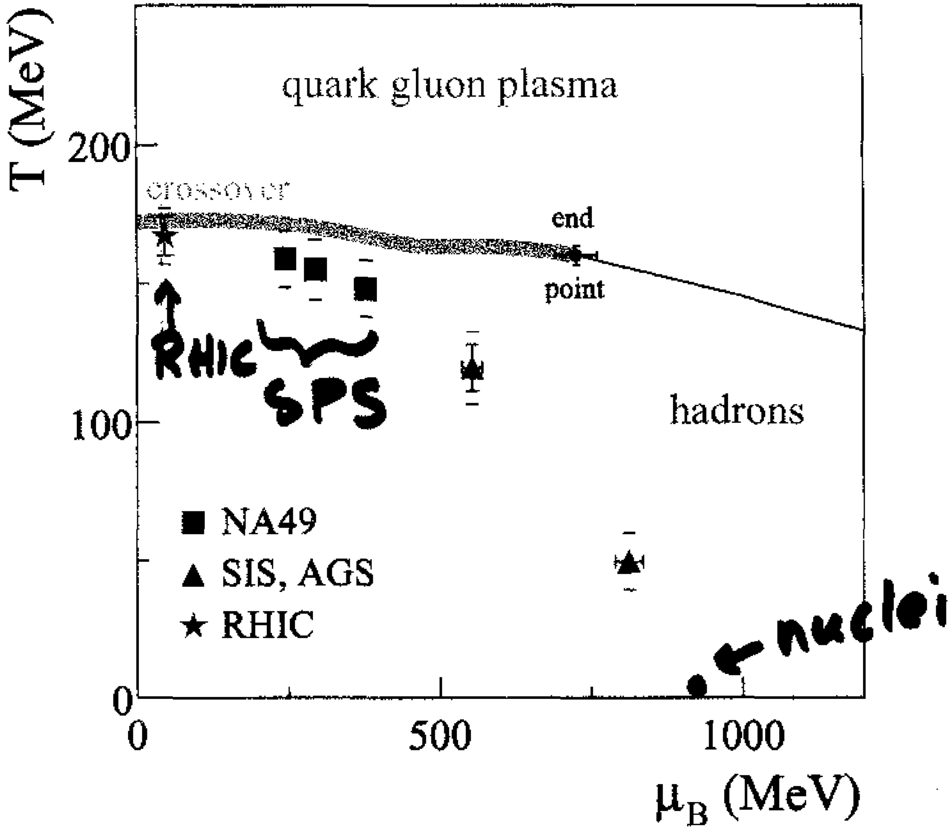
40 and 80 *A*GeV yields also fitted

	40 *A*GeV	80 *A*GeV	158 *A*GeV
T (MeV)	148 ± 2	155 ± 4	159 ± 2
μ_B (MeV)	377 ± 7	294 ± 15	244.5 ± 4.7
γ_S	0.75 ± 0.02	0.72 ± 0.03	0.82 ± 0.02
χ^2/NDF	14.8/4	10.4/4	23.5 / 11

$\sqrt{s}$: 9 12 17

fits by F. Becattini

- Freeze–out parameters on a (relatively) smooth curve
- Curve approaches phase boundary in the SPS energy range
- Even at RHIC, the parameters do not enter QGP–phase



Cross–over line from Z. Fodor, S.D. Katz hep–lat/0204029

③ SIGNATURES THAT TEACH YOU ABOUT THE PHASE TRANSITION

One (of several) examples:

SEARCHING FOR THE CRITICAL POINT

- gaussian event-by-event fluctuations of specific observables, calculable in magnitude, predicted to occur in those collisions that pass near the critical point as they cool.
  Stephanov KR Shuryak; Berdnikov KR; Stephanov
- vary μ by varying collision energies, and search for enhancement of these specific fluctuations in some window in $\sqrt{s}$, ie in μ.
- NA49, CERES analyzing data taken at $\sqrt{s} = 9, 12, 17$ GeV. Results expected in July.
  $\mu \sim 400 \to 250$ KeV
- RHIC expts. will extend search to lower μ.

By varying (ie lowering) its energy, CERN can look for ●, the END POIN of line of 1st order transitions.

<u>2nd order</u> ⇒ universal predictions (Berges, KR; HJSSV; Stephanov, KR, Shuryak)

Want signatures which are like critical opalescence in the sense that they rely on long wavelength fluctuation occurring only near ●.

Look for fluctuations in appropriate observables (constructed from # & $\vec{p}$ of pions) turn on, and then turn off, as ● is approached and then passed. (SRS)

CERN can find ● if $\mu_\bullet \gtrsim 250$ MeV

RHIC can find ● if $\mu_\bullet \lesssim 250$ MeV

↑ all 4 experiments can play a role.

SIGNATURES

(Stephanov, KR, Shuryak)

NA49 & CERES (at CERN SPS) and STAR (at RHIC) can measure $\langle p_T \rangle$ of pions in *one* event, and hence can measure event-by-event fluctuations. → FIG

Data consistent with Gaussian.

$\Uparrow$ (but not $\Downarrow$)

Thermodynamic fluctuations;
Freezeout from equilibrated hadronic gas.

ASIDE: Data severely constrain various *non*-eqbm possibilities, eg DCC. (NA49)

A far-from-eqbm chiral transition
→ Disoriented Chiral Condensate (large-λ π-wav
→ large $n_{\pi^0}/n_{\pi^{+/-}}$ fluctuations
at *low* p_T.

→ non-Gaussian e.-by-e. fluctuations
of $\langle p_T \rangle$ of charged pions.

NOT SEEN. This extends WA98's null result from direct search for $n_{\pi^0}/n_{\pi^{+-}}$ fluctuations

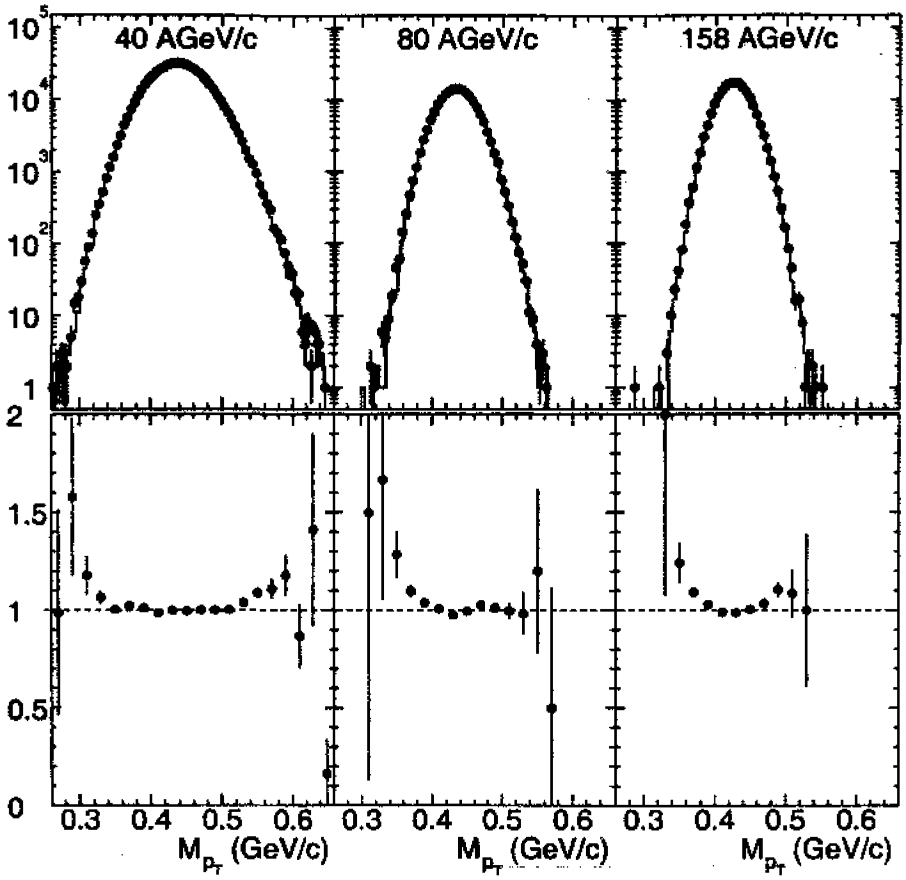
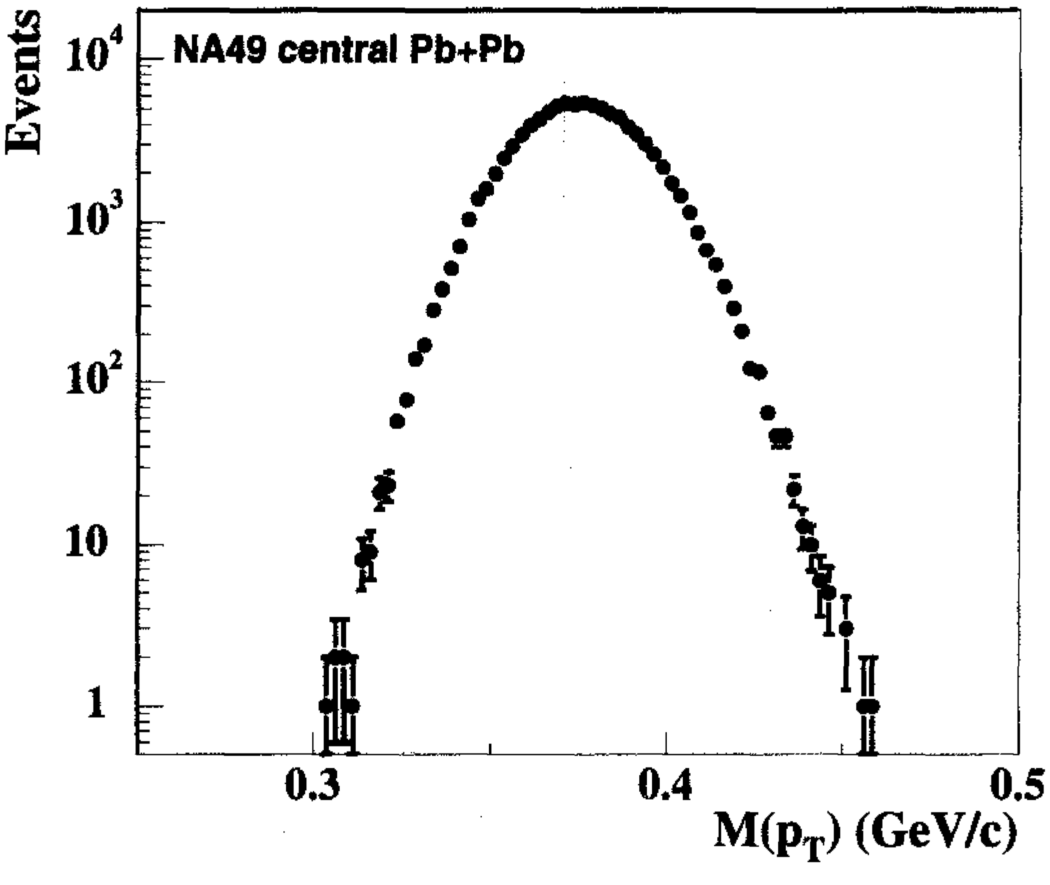


Fig. 3. Top : Event-by-event mean p_T distributions in the 6.5% most central events at 40, 80, and 158 A GeV/c. Circles show the distributions of data events, solid lines indicate the mixed events. Bottom: Ratio between the distributions of data events and mixed events for 40, 80, and 158 A GeV/c.

obtained by event mixing. The mixed events are constructed from particle momenta randomly chosen from data events of the same centrality class. Only one particle per measured event is used for a given mixed event, and the multiplicity distribution of mixed events is generated by sampling that of the data events. We calculated Σ_{p_T} and Φ_{p_T} for the mixed event samples and found them to be consistent with zero within statistical errors at all three beam energies.

The mixed event mean p_T distributions exhibit a Gamma distribution shape [23]. The subtle but clearly significant differences between the data and mixed event distributions are emphasized in Fig. 3 (bottom), where the ratio of the two is shown. The real event distributions are slightly wider, indicating a small but finite non-statistical contribution to the mean p_T fluctuations at all three energies. A preliminary account of these results was presented in [24].

CERES nucl-ex/0305002



NA49 central Pb+Pb
Events
10^4
10^3
10^2
10
1
0.3
0.4
0.5
$M(p_T)$ (GeV/c)

ANALYSIS OF WIDTH

$$F \equiv \frac{\langle N\rangle^{1/2}\,(\Delta\langle p_T\rangle)_{ebe}}{(\Delta p_T)_{\text{inclusive}}} \sim \frac{\text{width of real e.b.e. dist}}{\text{width of mixed event dist.}}$$

THEORY: (Gazdzicki, Mrowczynski, SRS, NA49)

Equilibrium __non__ critical fluctuations

$$\Rightarrow F = \underset{\substack{\nearrow\\ \text{classical}\\ \text{ideal gas}}}{1} + \underset{\substack{\uparrow\\ \text{Bose}}}{(\sim 2\%)} - \underset{\substack{\nearrow\\ \text{energy}\\ \text{conservation}\\ \text{in a finite}\\ \text{system}}}{(\sim 1\%)} - \underset{\substack{\uparrow\\ \text{experimental}\\ \text{effects}\\ \text{(track}\\ \text{resolution)}}}{(\sim (1\text{-}2)\%)}$$

Effects of correlations introduced by resonance decays and by fluctuation in flow velocity are < 1%.

So, freezeout from equilibrated hadron gas __NOT__ near critical point

$\Rightarrow$ F within 1 or 2% of 1, and no interesting dependence on $\sqrt{s}$.

DATA CONSISTENT WITH THIS.....

CERES uses a variable $\Sigma_{p_T} \sim \frac{1}{2}(F-1)$

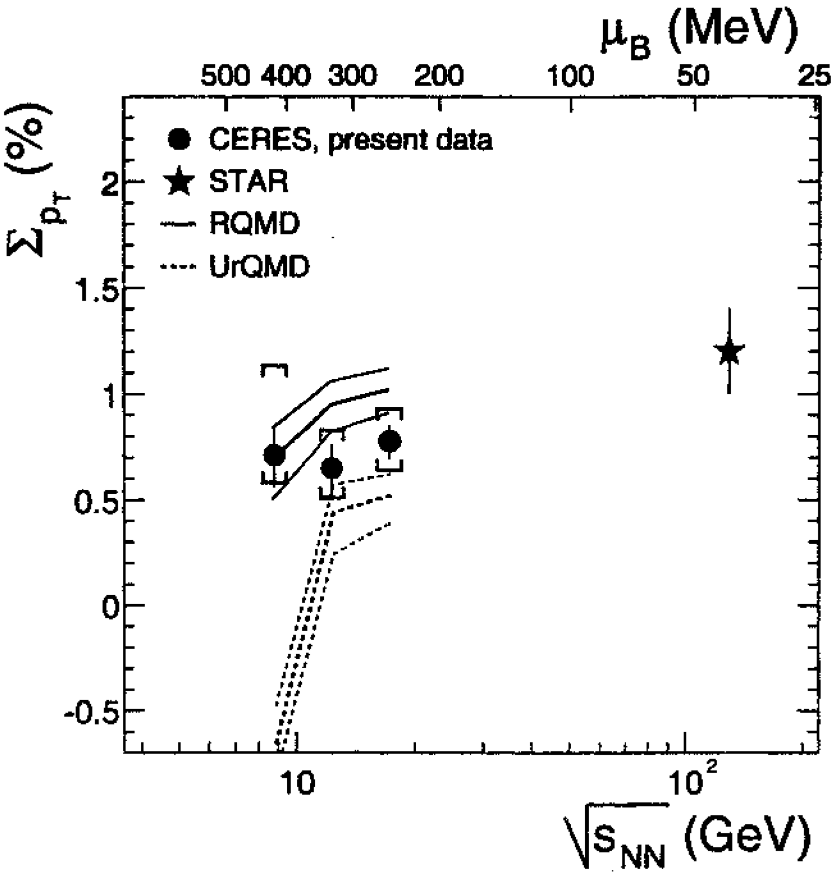


Fig. 10. The fluctuation measure Σ_{p_T} as function of $\sqrt{s_{NN}}$ and of μ_B at chemical freeze-out [30]. The full circles show CERES results (after SRC removal) in central events at 40, 80, and 158 A GeV/c. The brackets indicate the systematic errors. Also shown is the STAR result [31] at $\sqrt{s_{NN}} = 130$ GeV which is not corrected for SRC. Results and statistical errors from RQMD and URQMD calculations (with rescattering) are indicated as solid and dashed lines, respectively.

the critical point of the QCD phase diagram. At SPS energies and for the finite rapidity acceptance window of the CERES experiment, the fluctuations should reach values of about 2%, i.e. more than three times larger than observed in the present data[3]. Most important, no indication for a non-monotonic behaviour as function of the beam energy has been observed. This suggests that the critical point may not be located in the μ_B regime below 450 MeV.

The results from RQMD and URQMD show rough agreement with the data, except for the URQMD calculation at 40 A GeV/c where Σ_{p_T} is negative (see Fig. 10). We note that a positive value of $\Sigma_{p_T} = 0.38^{+0.17}_{-0.48}\%$ is obtained from

---

[3] The predicted fluctuations in the measure $\sqrt{F} = 1.1$ in [13] corresponds to about 2% in Σ_{p_T} in the CERES acceptance [33].

CERES nucl-ex/0305002

EFFECT OF CRITICAL FLUCTUATIONS

Experimenters do NOT measure (SRS) value of order parameter itself.

Must calculate effects of critical fluctuations of $\langle\sigma\rangle$ on momenta of pions.

RESULT:

$$F = 1 + (\sim .05)\left(\frac{\xi_\sigma}{3\,\mathrm{fm}}\Big|_{\text{freezeout}} \right)^2$$

$\Rightarrow$ increase in width of Gaussian could easily be > 10× present statistical error, which is ±.002.

∃ MORE SENSITIVE OBSERVABLES

Ie F_{soft}, constructed from 10% softest pions, can easily be increased by 50% for $\xi_\sigma \sim 3$ fm.

WHY DOES ξ_σ NOT GROW >> ~3 fm?

Finite time spent by cooling plasma in critical region. Estimate that $\xi_\sigma \not> 3$ fm is surprisingly robust. (Berdnikov + KR)

WANTED: (and coming)

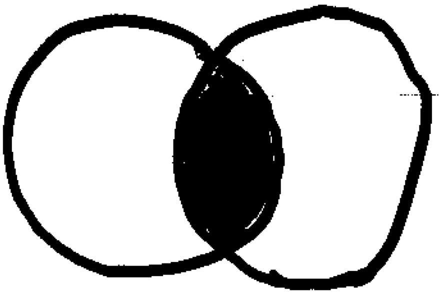
- mid-rapidity NA49 data, to check CERES' results
- data from runs in Fall 2002 at CERN SPS at $\sqrt{s} = 4, 6$
  $\rightarrow$ higher μ.
  ⌈NB: $\sqrt{s} = 4$ may yield $\mu_B \sim 600$ MeV, which is close to where VERY CRUDE lattice calculations suggest to look.⌋
- Also wanted: RHIC data for $\sqrt{s} = 20 \rightarrow 130$, & 200.

④ SIGNATURES THAT ALLOW YOU TO MEASURE PROPERTIES OF HOT QUARK-GLUON PLASMA

- the goal of RHIC experiments
- not a "yes/no question" since transition likely a crossover at small μ. Goal is to measure properties that can be compared to theory, thus teaching us about phase diagram.
- I will describe two (related) examples.
  - "elliptic flow"
  - "jet quenching"

ELLIPTIC FLOW

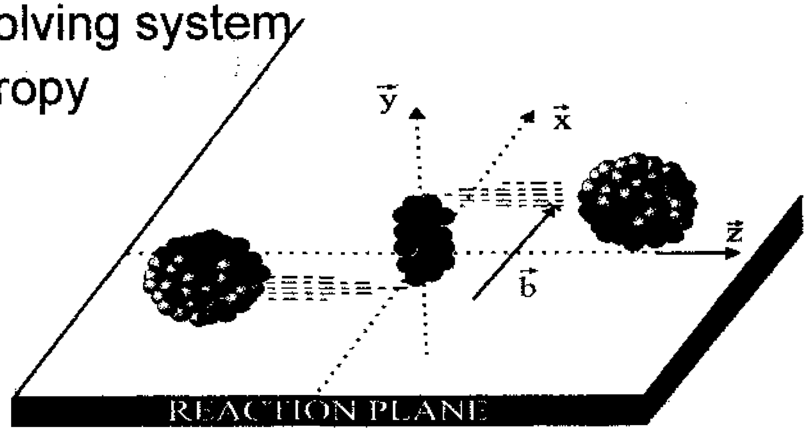
- a signature indicating extent of early equilibration.
- related to pressure. ⌈Not as simple as "a measurement of the pressure", but that's the core idea.⌋
- look at non-central collisions:



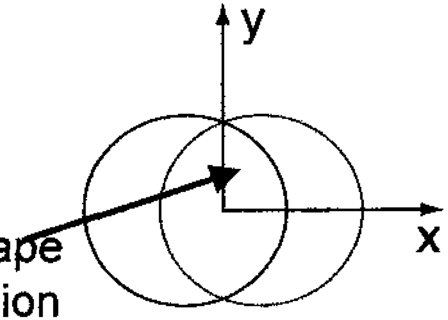
  - if no rescattering ("sum of lots of independent p-p") then final state momenta uniformly distributed in azimuth ϕ.
  - rescattering → equilibration → pressu
    - pressure gradients → collective flow
    - turns position anisotropy into momentum anisotropy.

Early state? a barometer called "elliptic flow"

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system
spatial anisotropy → momentum anisotropy

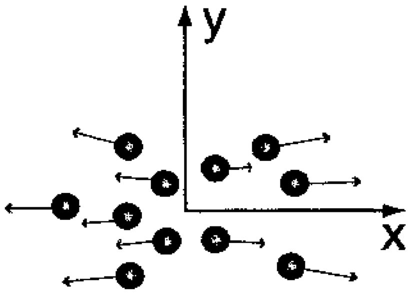


v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

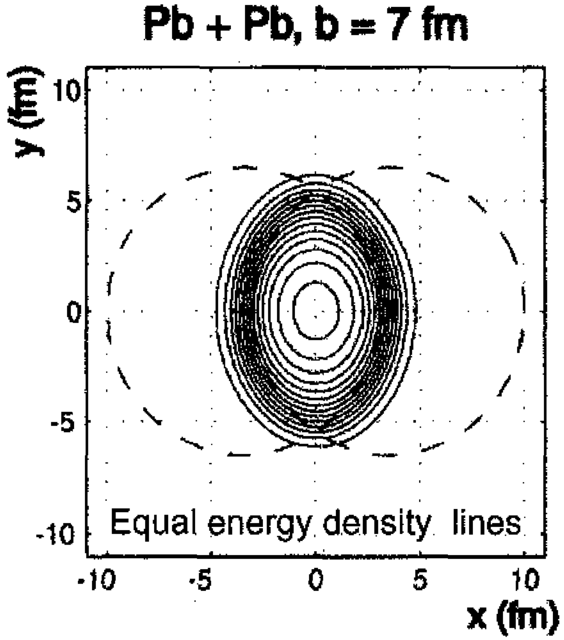
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



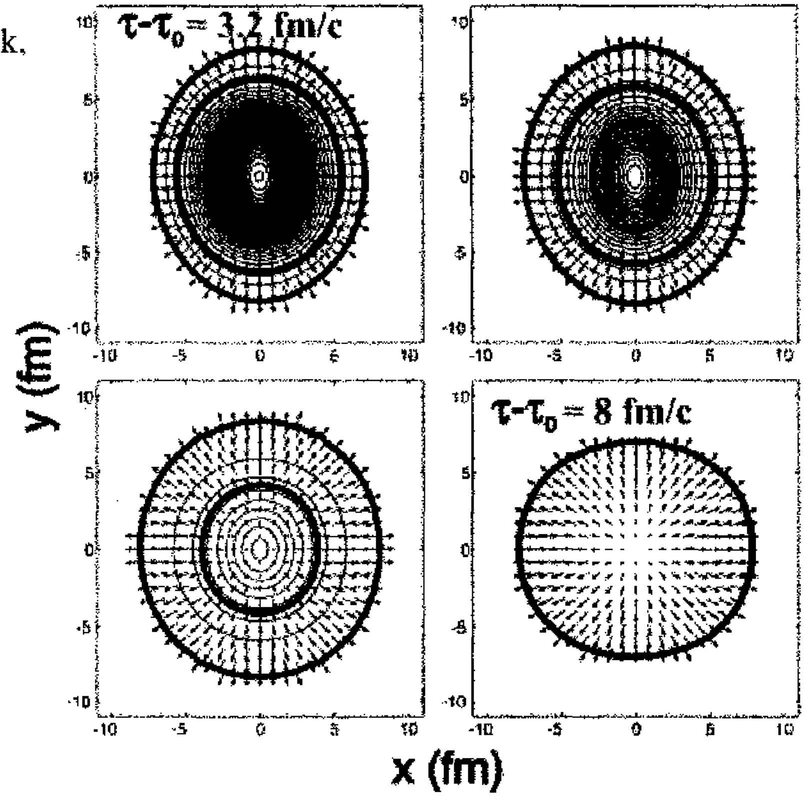
$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \mathrm{atan}\frac{p_y}{p_x}$$

- $v_2 = \frac{1}{2}$ means twice as many $\rightleftarrows$ as $\uparrow\downarrow$.

Hydro Calculation of Elliptic Flow



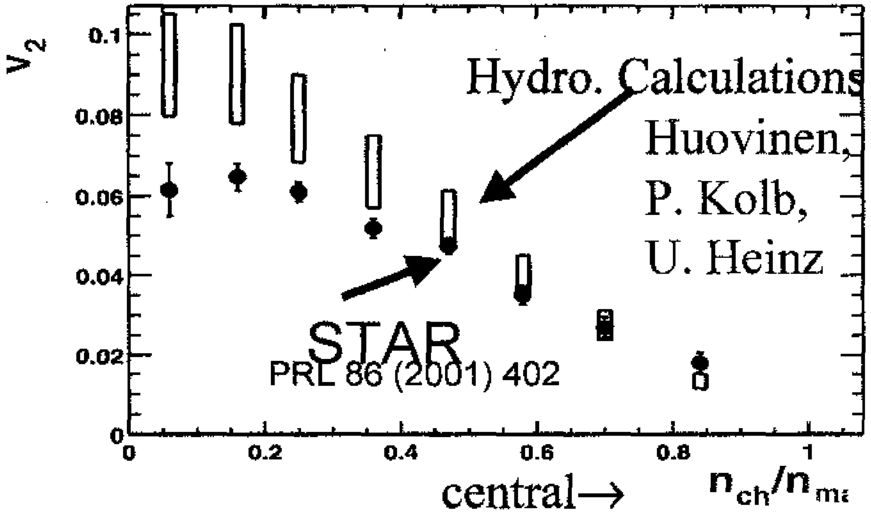
P. Kolb, J. Sollfrank, and U. Heinz



- Elliptic flow observable sensitive to early evolution of system
- Large v_2 is an indication of early thermalization

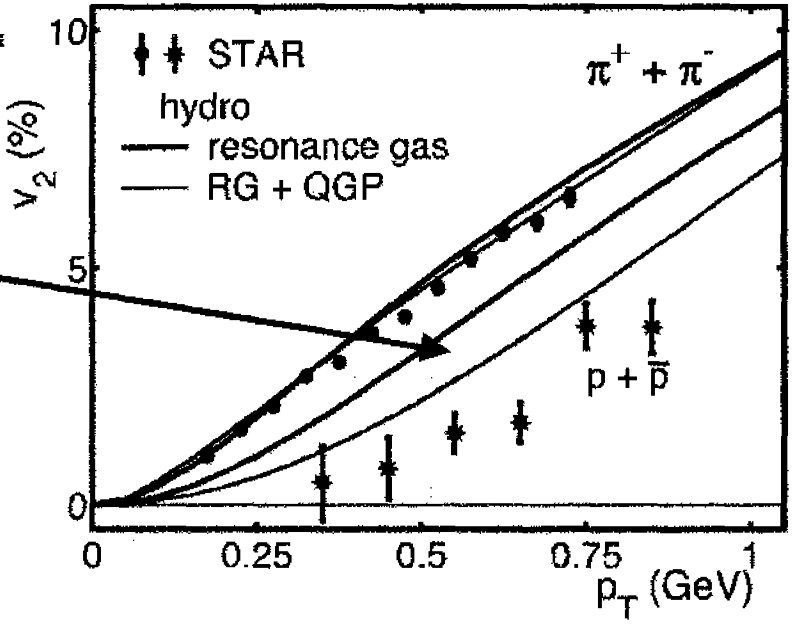
cf superposition of p-p collisions, for which $v_2 \approx 0$.

v_2 predicted by hydrodynamics



pressure buildup → explosion
happens fast →
early equilibration !

Hydro can reproduce magnitude of elliptic flow for π, p. BUT *must add QGP to hadronic EOS!!*

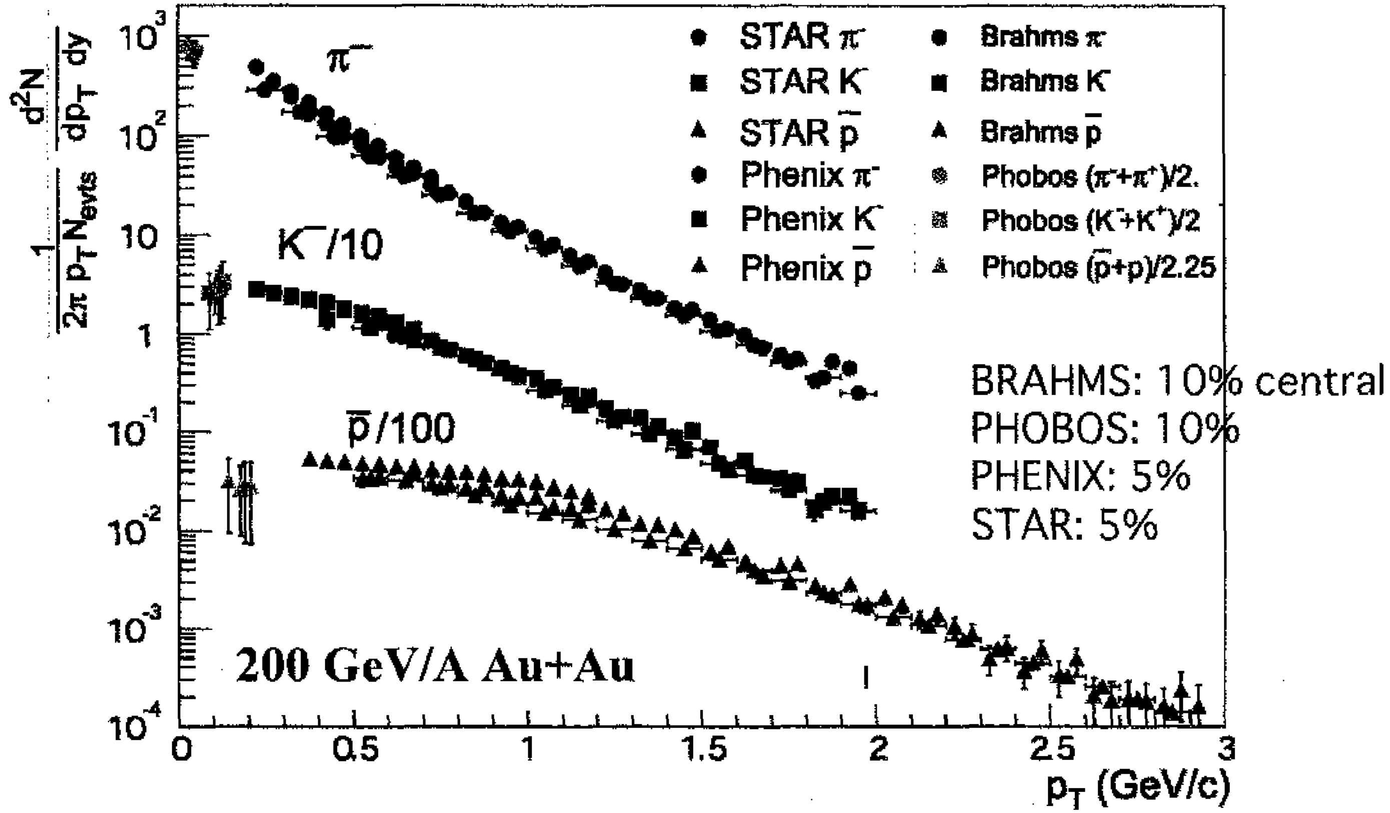


Similar conclusion reached by CM Ko, et al., Kapusta, et al., Bleicher, et al., among others…

talk by B. Jacak

- hydro calculations based on <u>assumption</u> of local equilibrium
- hydro has never agreed with data before RHIC. (At SPS, $v_2^{data} \sim \frac{1}{2} v_2^{hydro}$)
- at RHIC, hydro does good job of describing both spectra → and v_2, except at most peripheral, where it has to fail.
- Success of hydro description of V_2 means rescattering/equilibration/pressure ie "hydro begins to apply", <u>EARLY</u>, before free streaming circularizes 0. By $\tau \sim 0.6 - 1$ fm, according to Heinz.
- Challenge to theory: how can equilibration occur so quickly?

Hadron p_T spectra – all 4 experiments!



BRAHMS: 10% central
PHOBOS: 10%
PHENIX: 5%
STAR: 5%

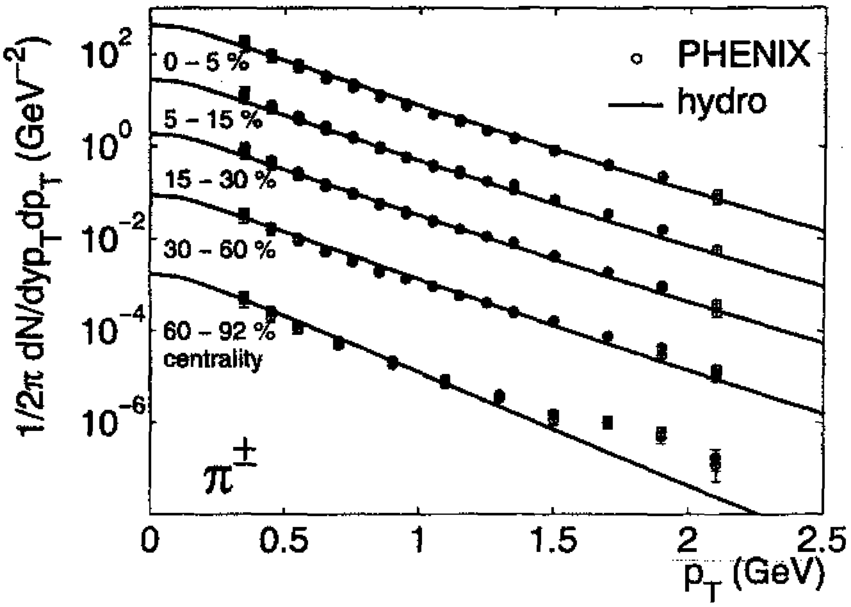
Protons show velocity boost ⊥ to beam.

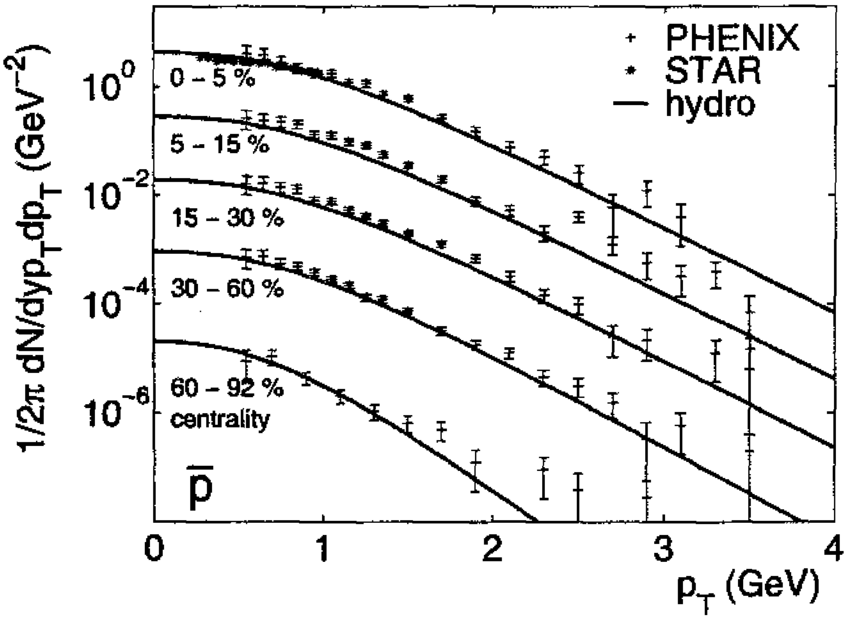
Expect if pressure build-up due to rescattering

Data well fit with: T_{fo} = 110-120 MeV & $\langle\beta_t\rangle$ = 0.5-0.6

Pion and antiproton p_T spectra for various centralities

Heinz and Kolb, NPA702,269 (2002)





- Nice fit up to $b \approx 10$ fm and $p_T \approx 3$ GeV

- timescale for equilibration has been calculated from first principles using perturbative QCD for collisions with $\sqrt{s} \to \infty$.

  Baier Dokshitzer Mueller Son

- not under control at RHIC energies (too low!), but if you apply their result anyway, find $t_{eqbm} \sim 5$ fm. Baier at QM

- qualitative lesson from data is that equilibration is faster than perturbative.

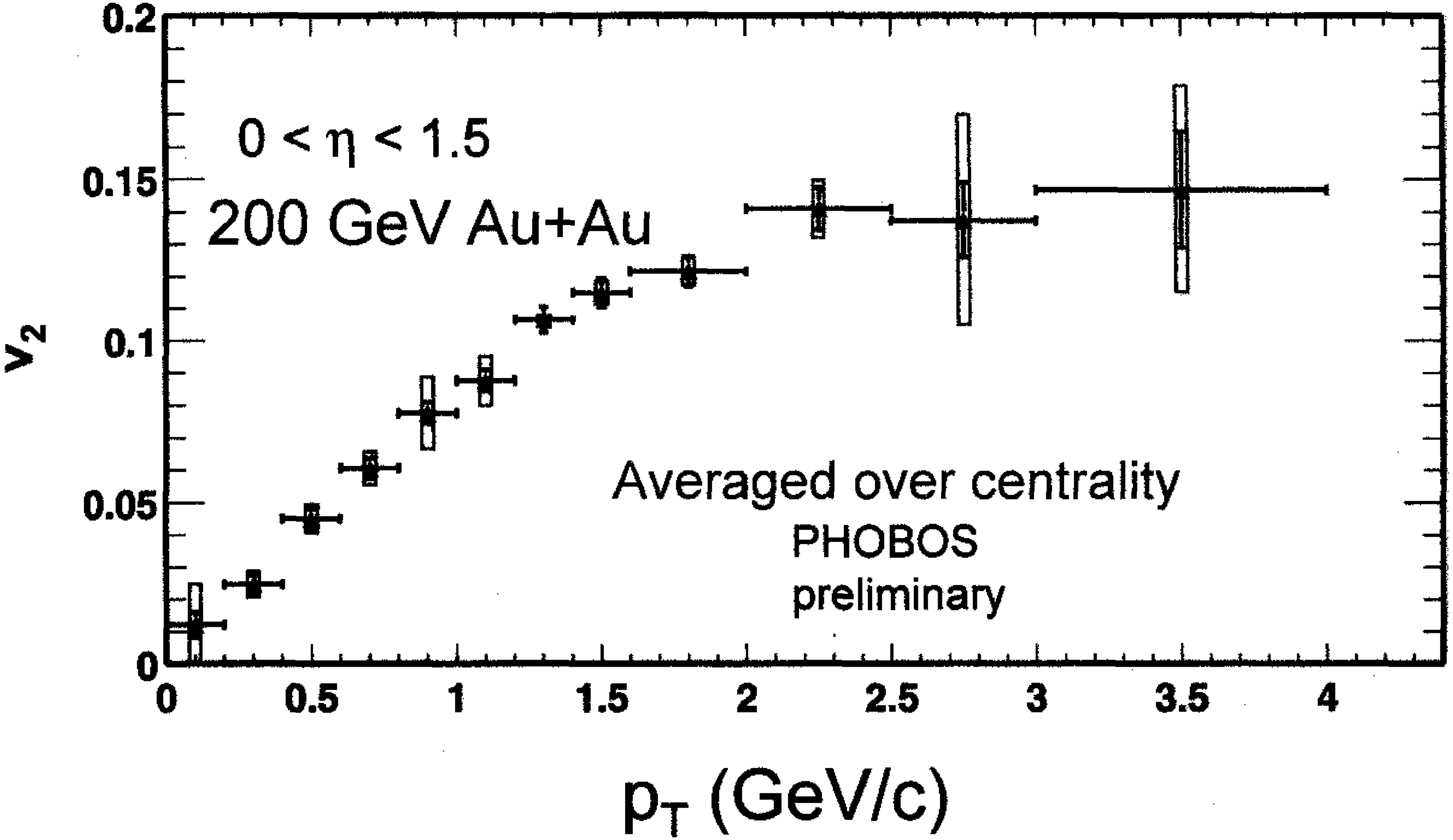
- Good! If t_{eqbm} were 5 fm or longer, RHIC would teach us less about hot QGP. (Would equilibrate at lower T.)

v_2 vs. p_T

- Expect that for $p_T >$ ____ , particles come from initial hard scatterings, not from the exploding QGP.
- hydro should fail at high p_T.
- should v_2 drop back to zero ??
  - NO, we shall see in a bit....
  - need new way to understand v_2 at high p_T....

- First, though, an at first seemingly unrelated high p_T story: "jet quenching".

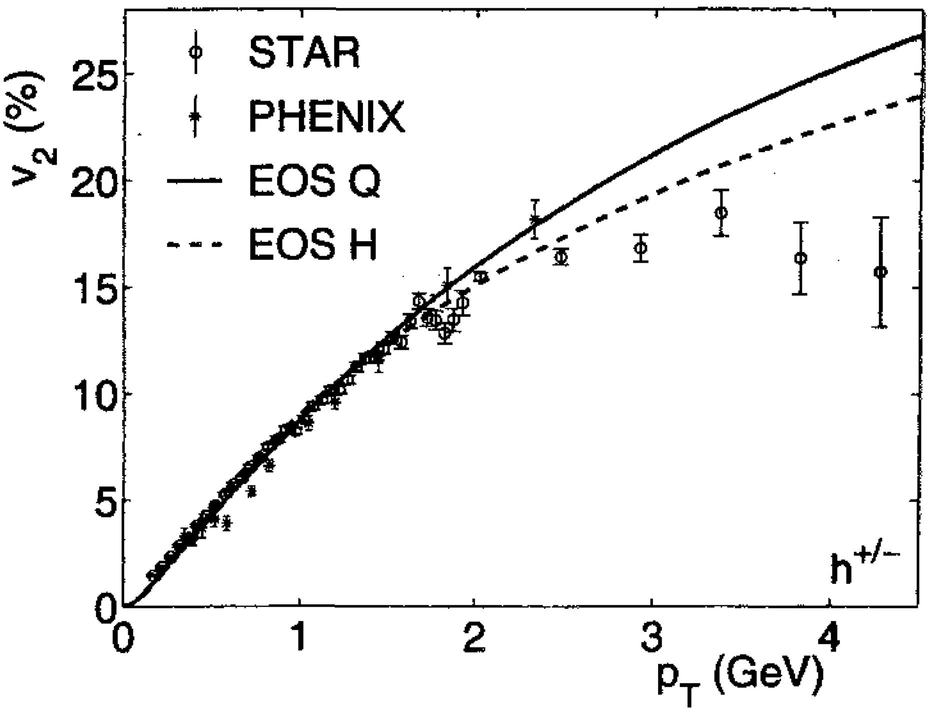
v_2 vs p_T (200 GeV)



$v_2(p_T)$ in minimum bias collisions

Heinz and Kolb: hep-ph/0204061

Charged hadrons:

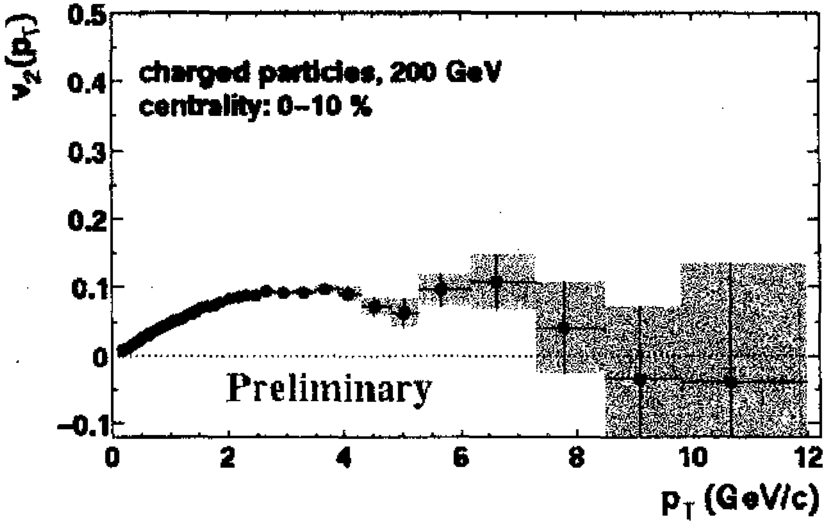


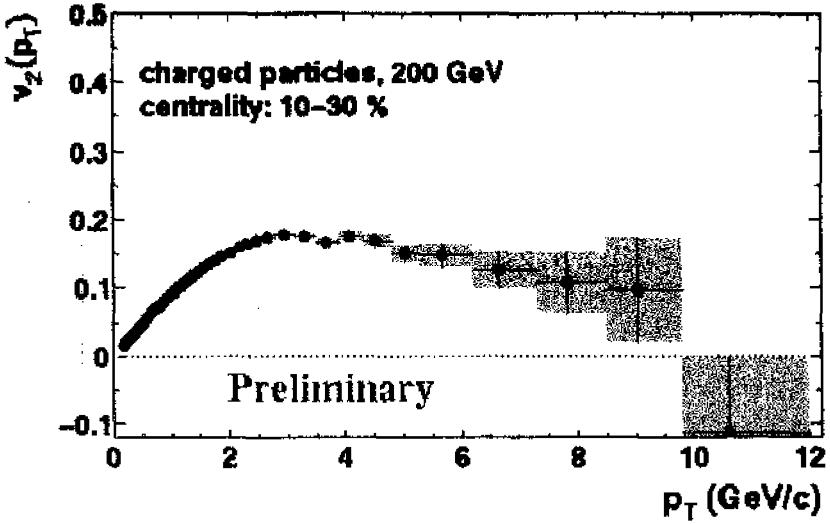
- data reproduced at low p_T, deviates above 1.5–2 GeV/c

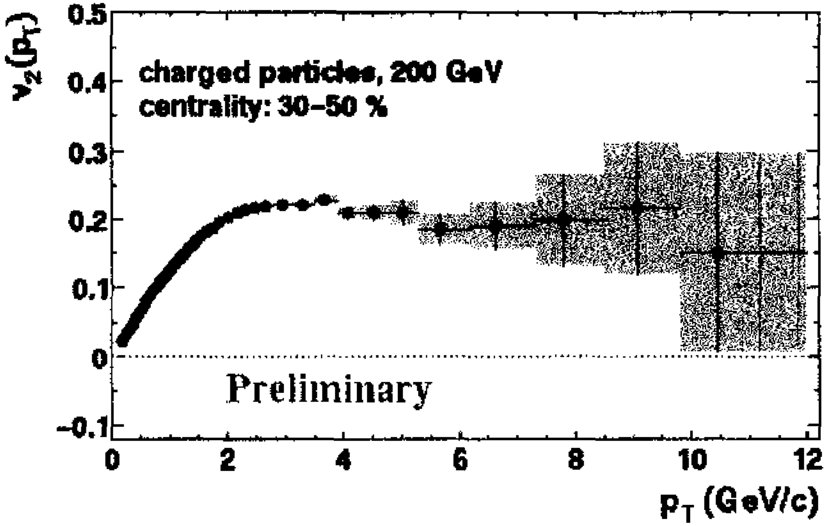
$p_T \lesssim 2$GeV : particles from the exploding QGP; well-described hydrodynamically

$p_T \gtrsim 2$GeV : particles from initial hard scatterings, not described by hydro

$v_2(p_T)$ up to 12 GeV/c





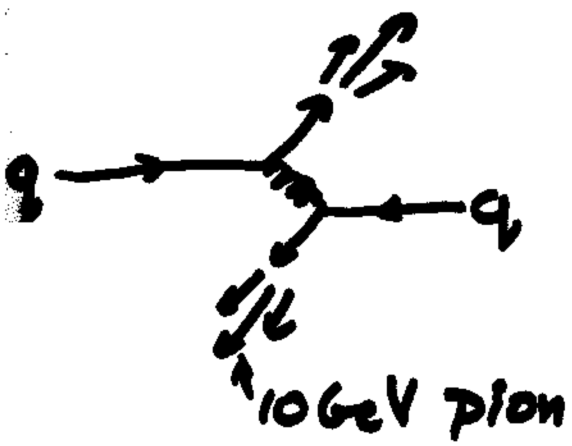


- Statistical errors only

- Finite v_2 up to 12 GeV/c in mid-peripheral bin

ENERGY LOSS

p-p collision vs. Au-Au collision



- Expect fewer high P_T pions in Au-Au than in superposition of p-p.
- For high P_T parton, $T_{[illegible]} \gg T_c$, $\frac{dE}{dx}$ calculable from first principles.

  Baier Dokshitzer Mueller Peigné Schiff Zakharov...
  Gyulassy Wang....
- For QGP with $T \sim 250$ MeV (not really $\gg T_c$) expect $\frac{dE}{dx} \sim 5-10$ GeV/fm
- For cold nuclear matter, $\frac{dE}{dx} \sim 0.5$ GeV/fm

  (BDMS; also, Wang et al's analysis of Hermes data.)

- For an equilibrated QGP, $\frac{dE}{dx}$ is a measure of μ^2/λ.

  μ : inverse Debye length. (density)$^{1/3}$

  λ : ~~inverse~~ transport mean free path

- BUT: seeing large dE/dx does NOT imply equilibration. In essence, dE/dx measures number density of colored objects.
- Energy loss looked for and not seen at SPS.
- Has it been seen at RHIC?

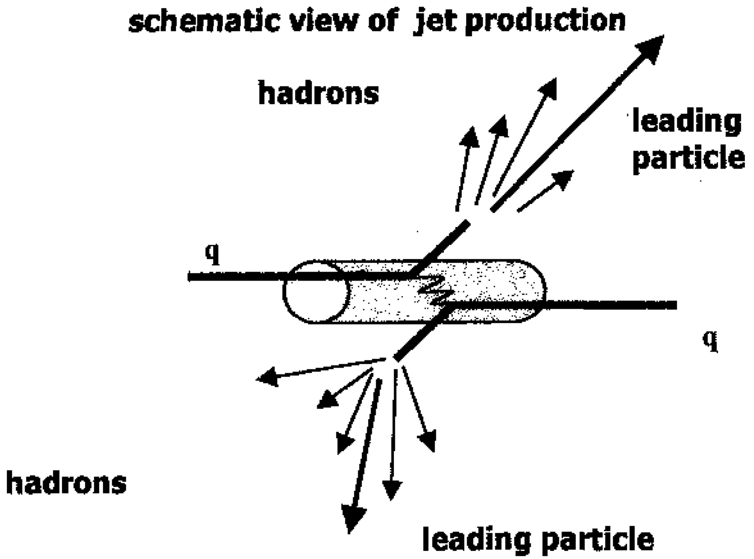
SUMMARY

- hard pions must come from *initial* hard scatterings.
  - thermal probability (eg $e^{-\frac{5\,\mathrm{GeV}}{200\,\mathrm{MeV}}}$) negligible
- energy loss small at SPS
  - $\Rightarrow$ hadronic matter at late times at RHIC has little effect
- if seen, allows us to measure a characteristic property of quark-gluon plasma.
- will need to compare p-A $\leftrightarrow$ A-A and different energies, to turn effect on & off, to fully understand
- theoretical progress also mandatory
  - better modelling (expansion)
  - calculate μ, λ
  - calculation of $\frac{dE}{dx}$ which is valid at lower T, E ???

a unique probe for physics of hot medium

Probe: Jets from hard scattered quarks

Observed via fast leading particles or azimuthal correlations between the leading particles



But, before they create jets, the scattered quarks radiate energy (~ GeV/fm) in the colored medium

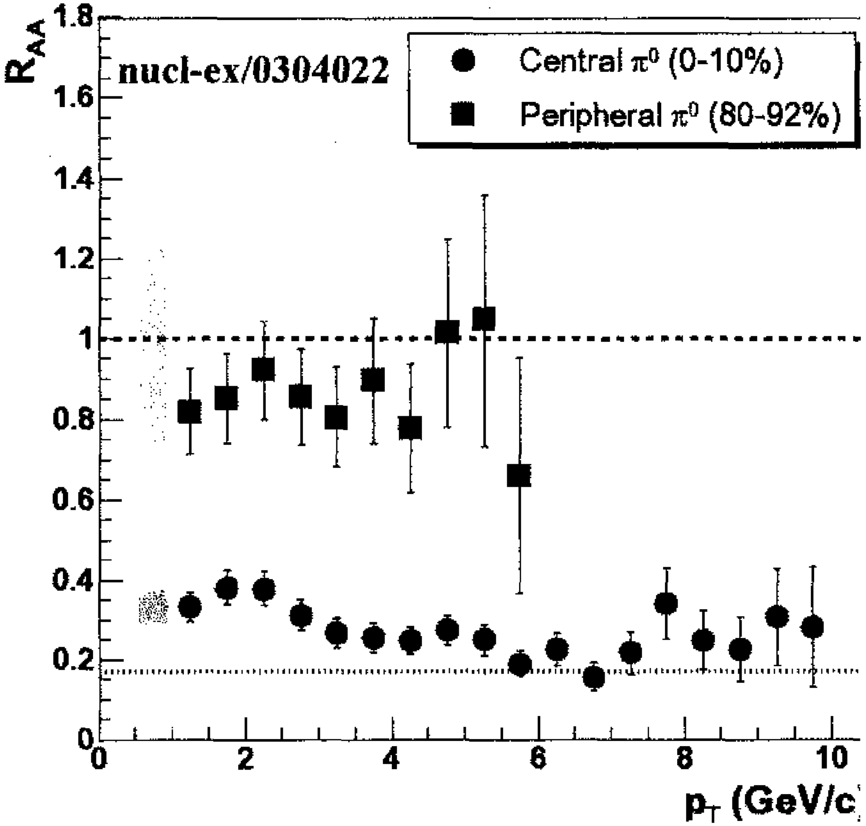
→decreases their momentum (fewer high p_T particles)
→"kills" jet partner on other side
→ "jet quenching"

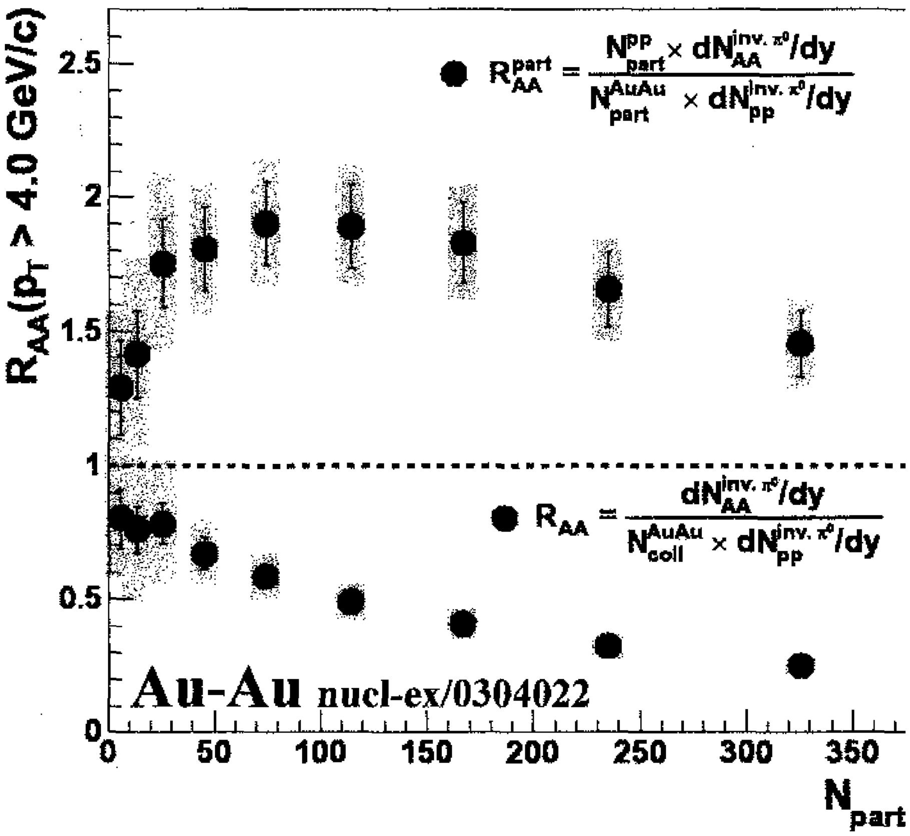
talk by B. Jacak

Au-Au ÷s = 200 GeV: high p_T suppression!

$$R_{AA} = \frac{\text{Yield}_{AuAu}/\langle N_{binary}\rangle_{AuAu}}{\text{Yield}_{pp}}$$

$$R_{AA}^{part} = \frac{\text{Yield}_{AuAu}/\langle N_{part}\rangle_{AuAu}}{\text{Yield}_{pp}/2}$$



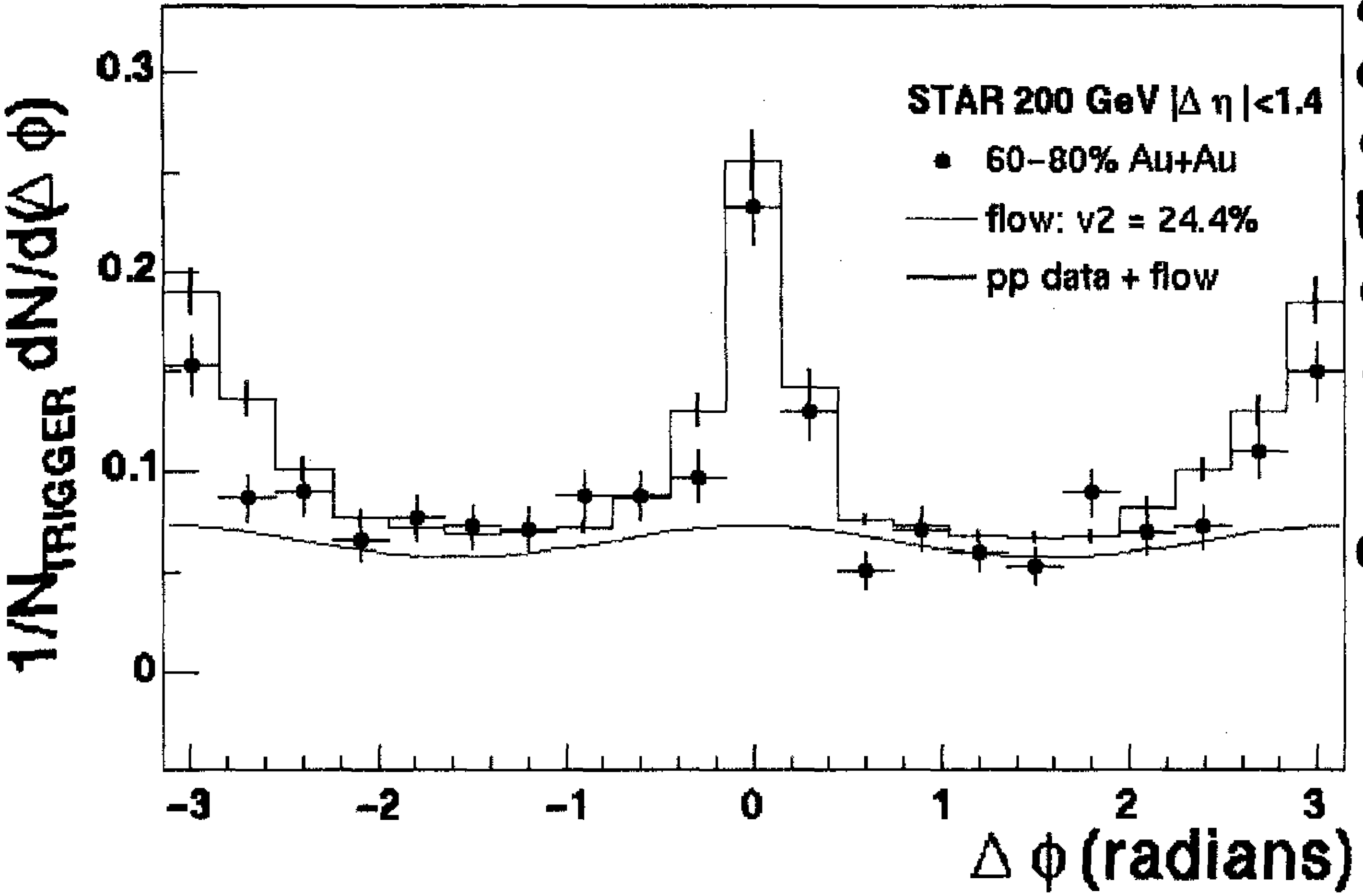


SEEING JETS, AND MISSING JETS

- arguably most interesting single result at Quark Matter 2002
- makes idea of energy loss *much* more tangible

Peripheral Au+Au data vs. pp+flow

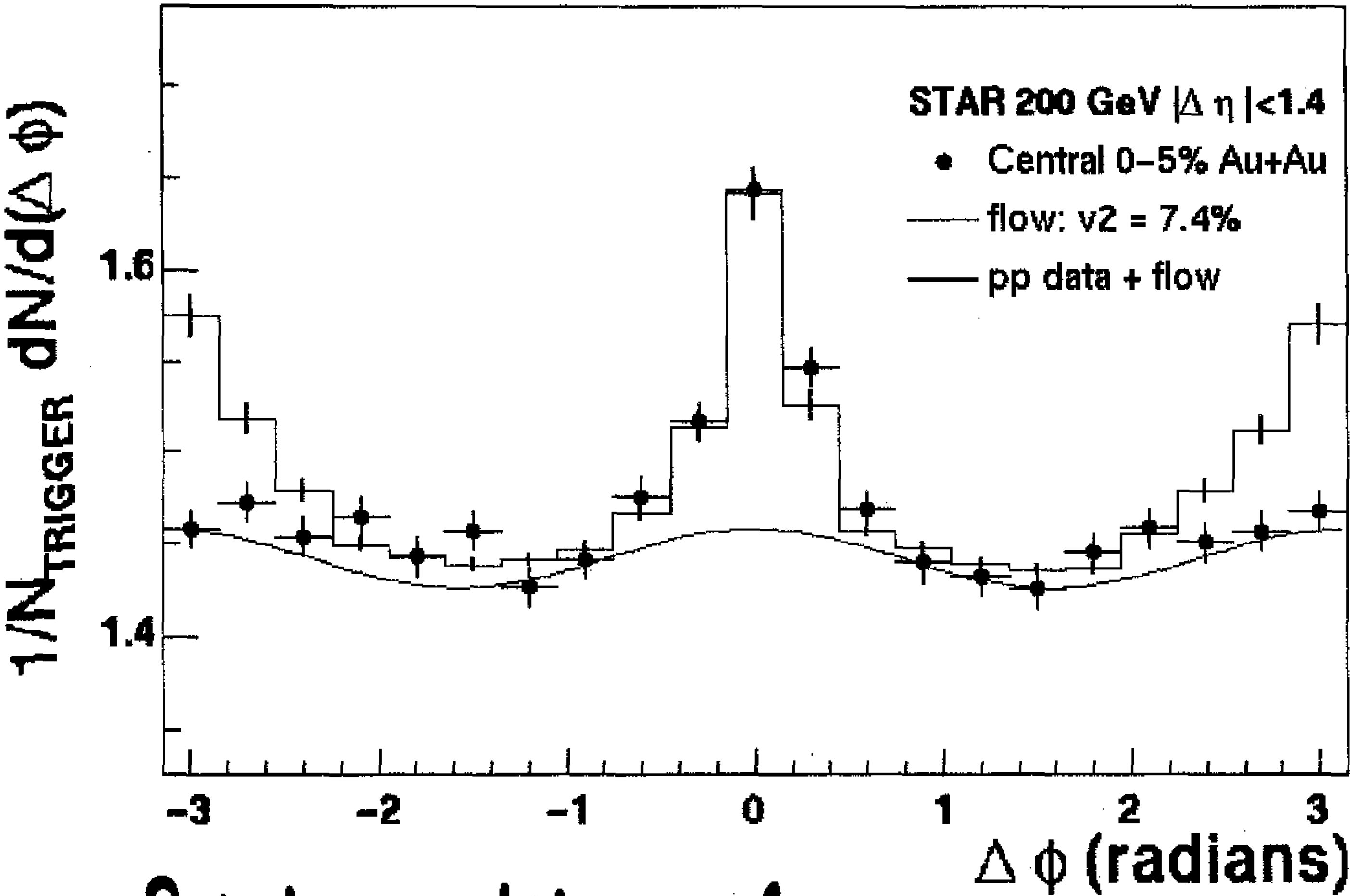
$$C_2(Au+Au) = C_2(p+p) + A*(1+2v_2^2\cos(2\Delta\phi))$$



angular correlation of $P_T > 2$ GeV particles with a trigger particle with $P_T > 4$.

Central Au+Au data vs. pp+flow

$$C_2(Au+Au) = C_2(p+p) + A^*(1+2v_2^2\cos(2\Delta\phi))$$



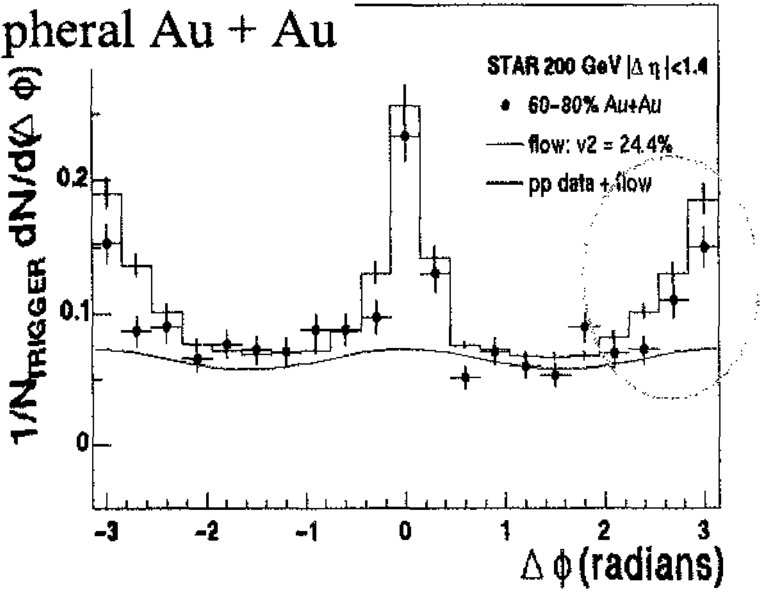
- shape of jet you triggered on as in p-p.

- counter-jet at 180° gone!

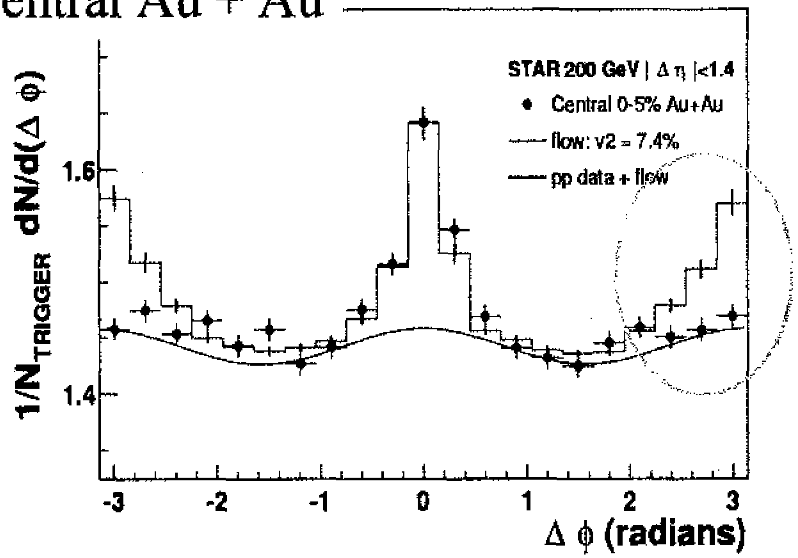
jet correlations: Au+Au vs p+p

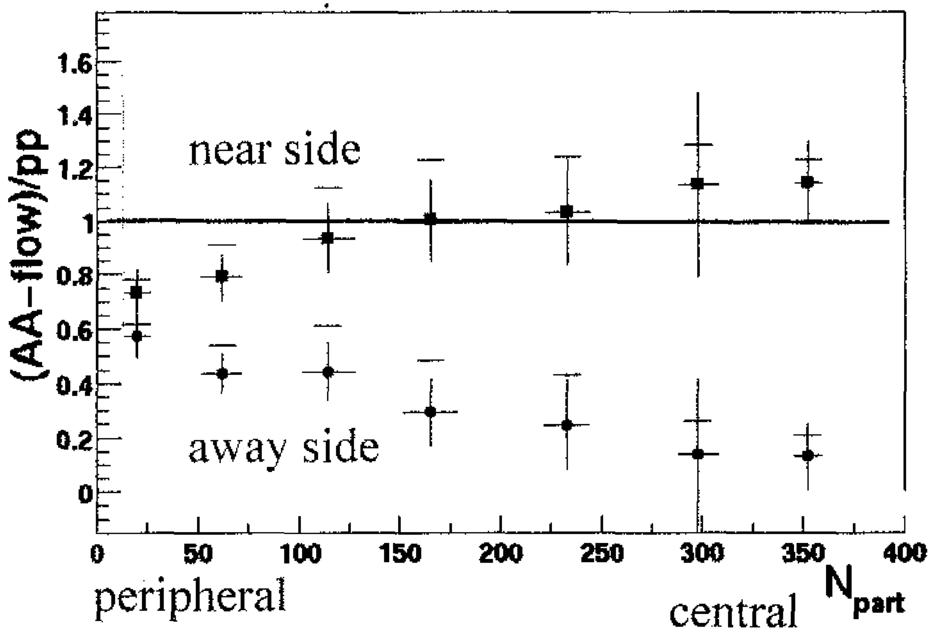
STAR PRL 90, 082302 (2003)

Peripheral Au + Au



Central Au + Au

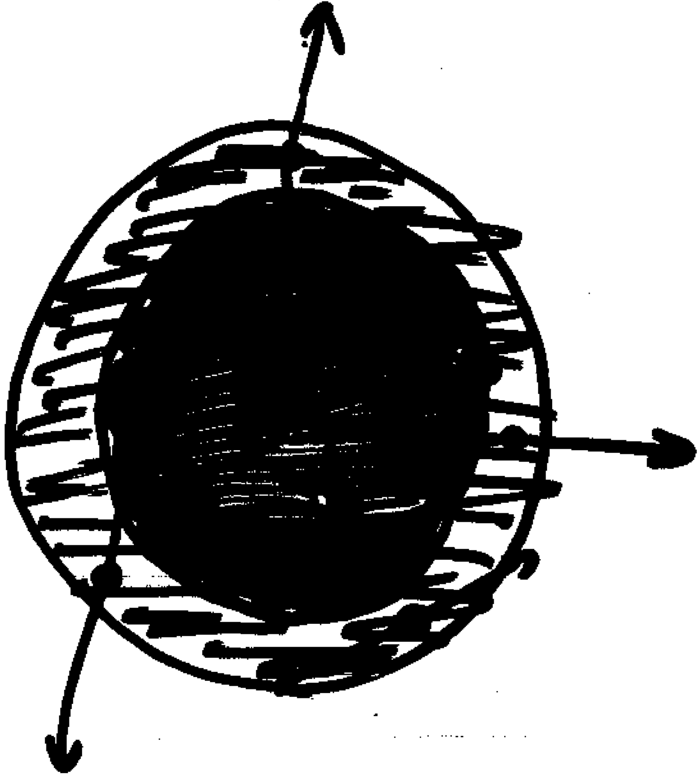




Back-to-back jets are suppressed in central collisions!

JET QUENCHING

- the picture suggested is:



- High p_T particles detected all come from hard scatterings occurring near the surface, and only from the outward jet.
- Ingoing, and interior, jets quenched.
- Should see <u>some</u> back to back jets.

CORROBORATION (INDIRECT)

- Centrality dependence of quenching of counter-jet and of π^0's similar
- PHOBOS observes that quenching of charged hadrons is enough to turn the expected $N_{part}^{4/3}$ dependence on centrality for particles produced in hard scattering into data $\sim N_{part}^{1}$

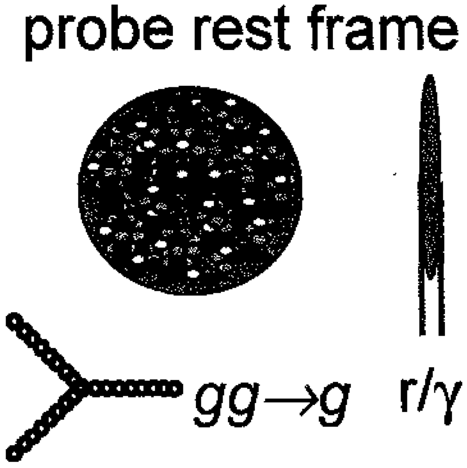
$$\frac{N_{part}}{N_{part}^{4/3}} \sim \frac{\text{surface}}{\text{volume}} \; !$$

Suppression: an initial state effect?

- **Gluon Saturation (color glass condensate)**

Wavefunction of low x gluons overlap; the self-coupling gluons fuse, saturating the density of gluons in the initial state. ***(gets N_{ch} right!)***

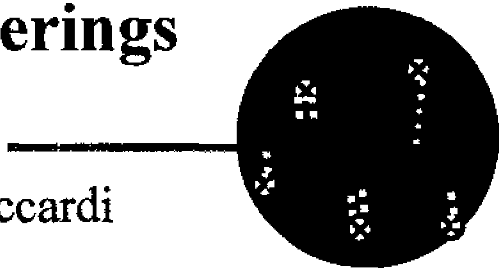
Gribov, Levin, Ryshkin, Mueller, Qiu, Kharzeev, McLerran, Venugopalan, Balitsky, Kovchegov, Kovner, Iancu ...



$\sqrt{\quad}$ $R_{dAu} \sim 0.5$

D.Kharzeev et al., hep-ph/0210033

- **Multiple elastic scatterings (Cronin effect)**



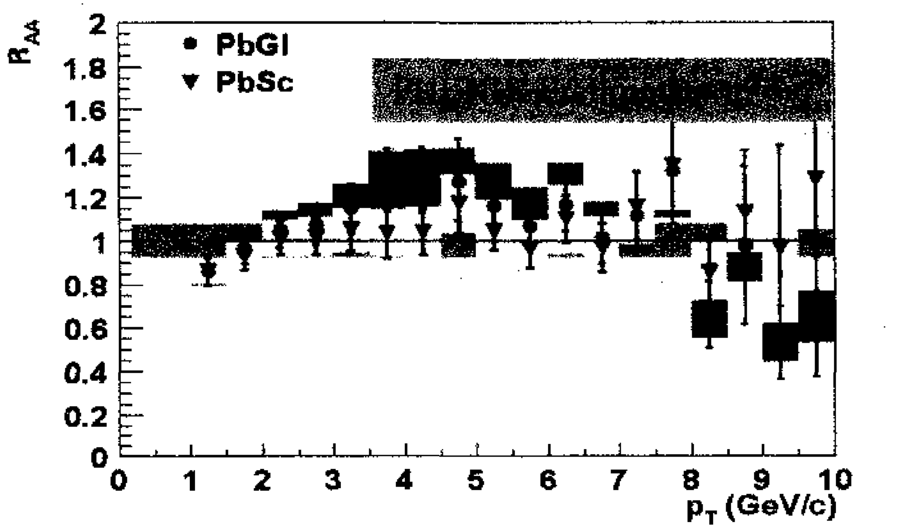
Broaden p_T :

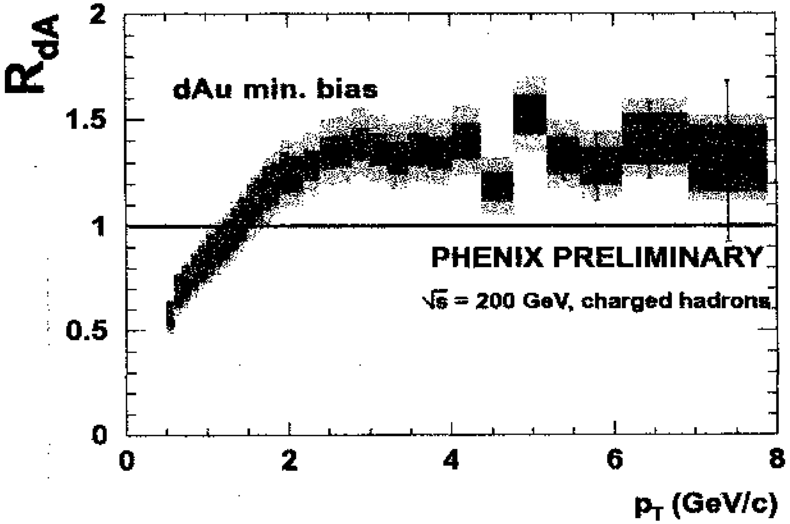
Wang, Kopeliovich, Levai, Accardi

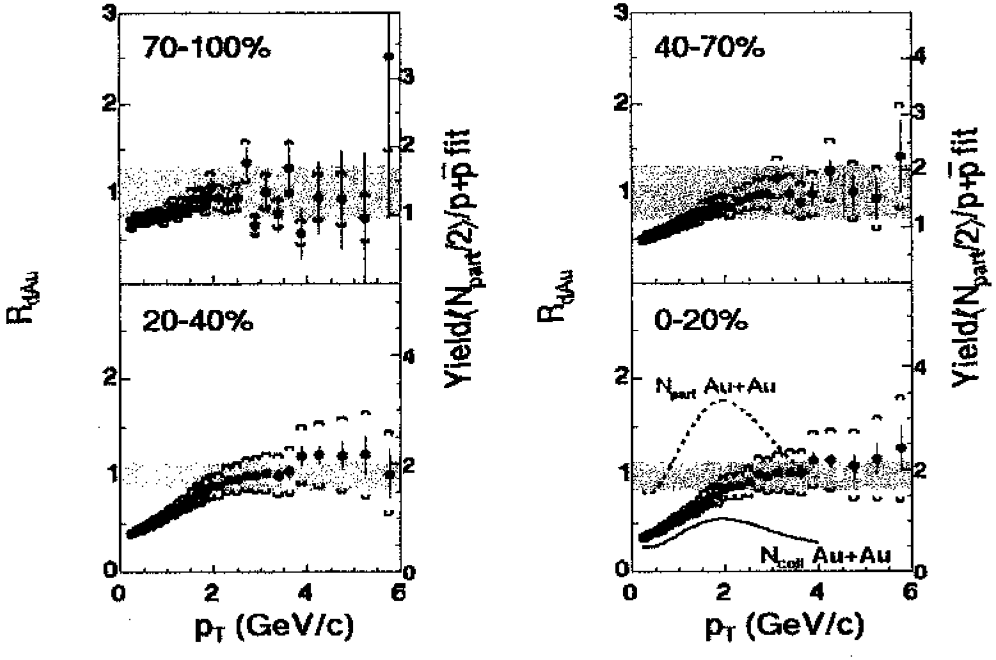
- **Nuclear shadowing**

talk by B. Jacak

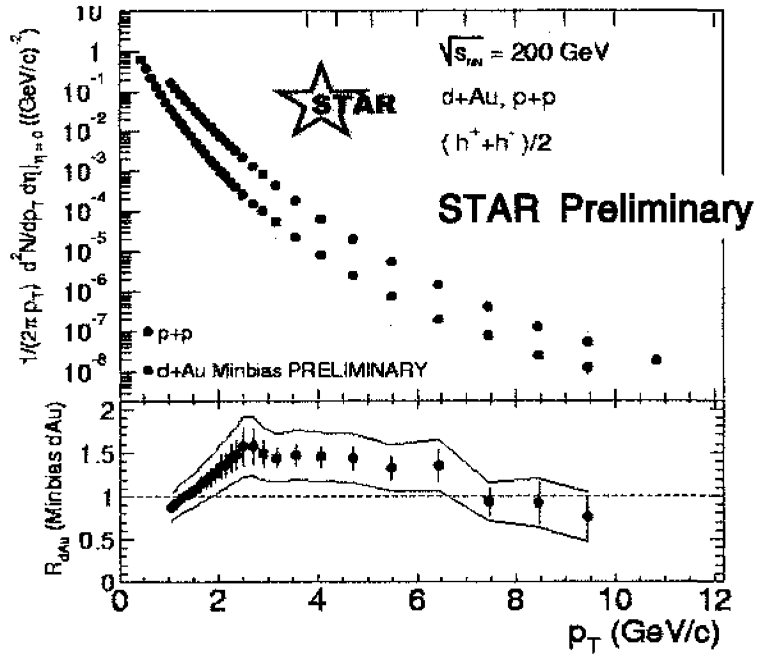
Experiments show NO suppression in d+Au!







PHOBOS Preliminary

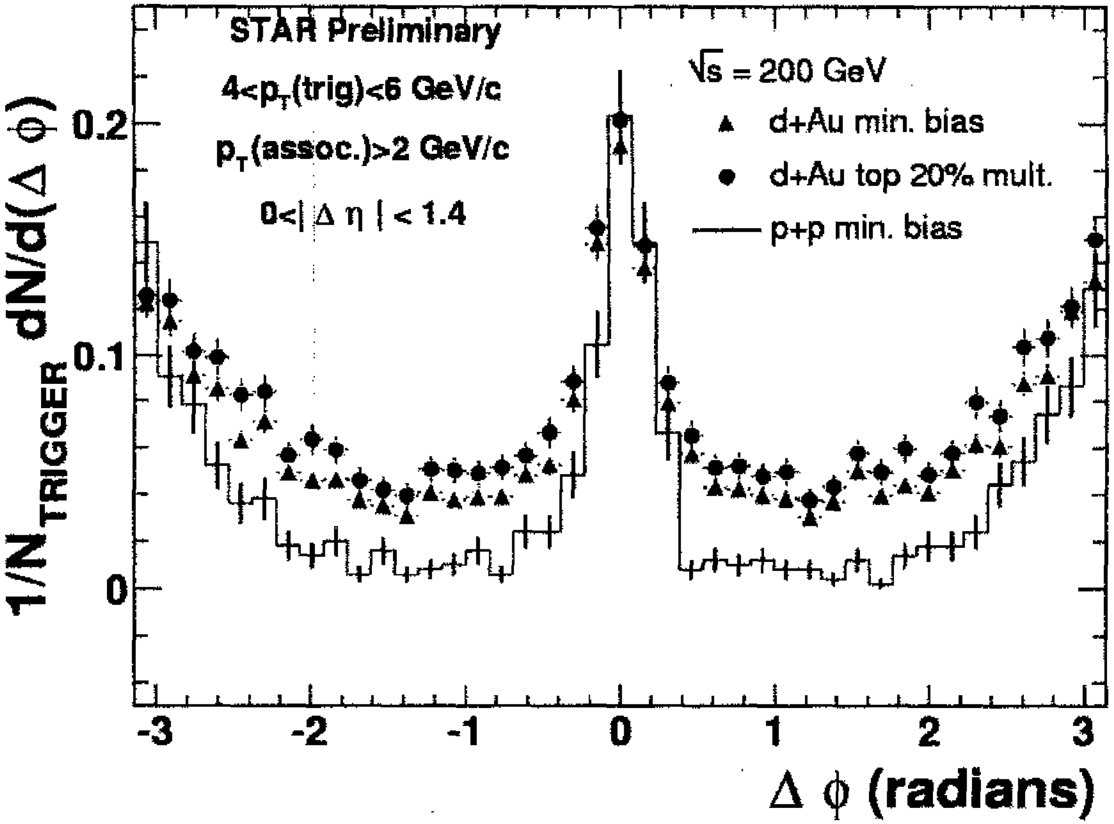


Back-to-back jets observed in d+Au

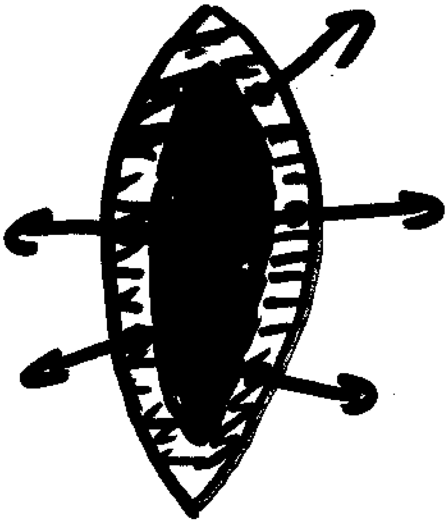
- jet pair production also looks independent of N_{coll}

- observe no (big) suppression!

- probably some jet broadening due to initial multiple scattering…

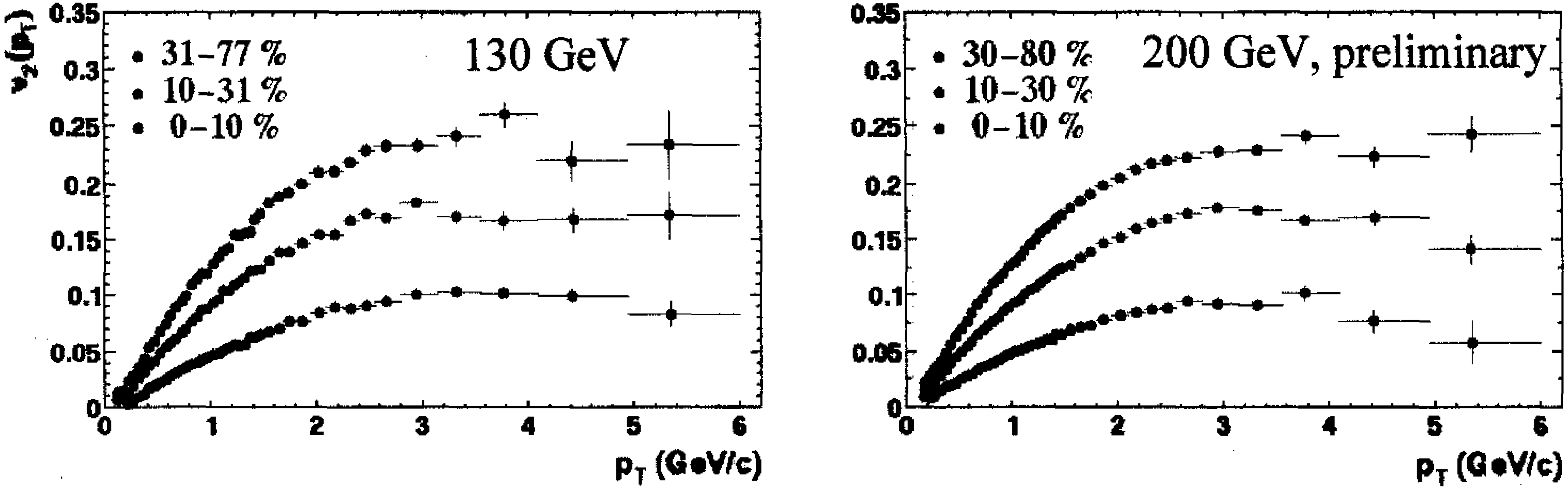


BACK TO V_2 AT HIGH P_T

- 

- If all high P_T particles <u>emitted from surface</u>, expect a V_2 anisotropy which is geometric! Shuryak

Centrality dependence of $v_2(p_T)$

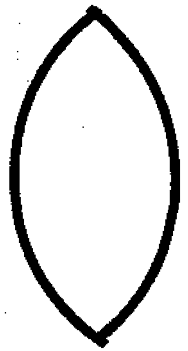


- v_2 saturates for p_T>3 GeV/c for all centralities at both energies
- Indication of geometric origin?

Depends on geometry but not on p_T, $\sqrt{s}$.

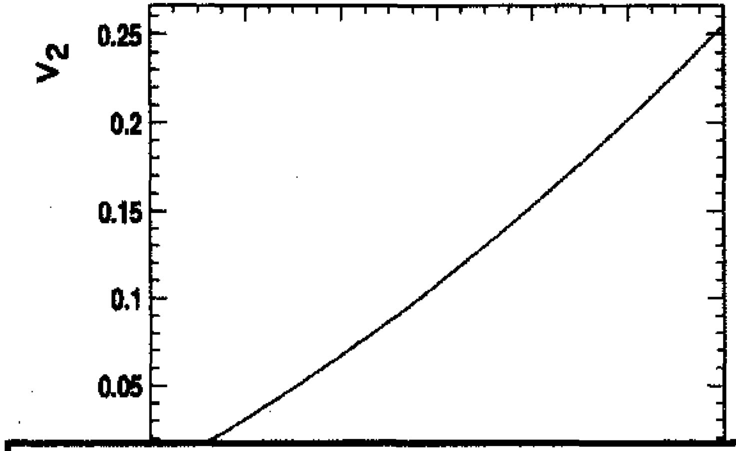
v2 max due to jet quenching (absorption)

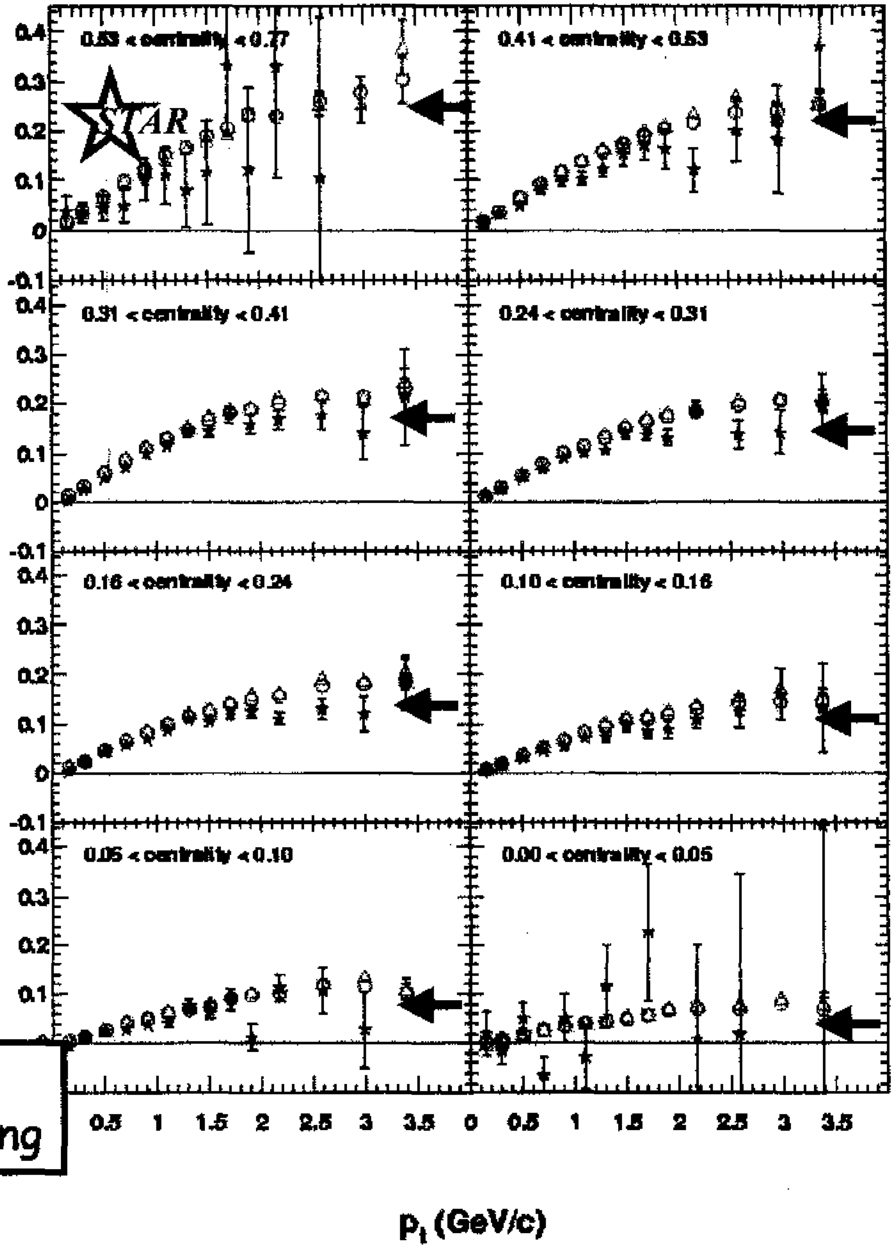
E. Shuryak, nucl-th/0112042



$$\boxed{v_{2,\max} = \frac{\sin(2\alpha)}{6\alpha};}$$

$$\cos(\alpha) = b/(2R)$$





Observed anisotropy at high p_t is close to maximum possible due to the jet quenching

WHAT NEXT? IMPLICATIONS?

loss of counter jet, ie "surface emission at high p_T" <u>not</u> predicted

need to do p-A (or d-A) collisions as a control ✓✓

Measure "penetration depth" (ie thickness of region from which particles escape) as function of p_T

- by seeing some away-side jets
- by deviation of v_2 from geometric prediction
- different ways of measuring this "mean free path" should agree

- At higher p_T, see away-side jets reemerge, and v_2 fall to zero. (This may have to wait for LHC??)

- this beautiful experimental discovery implies greater energy loss – i.e. shorter mean free path – than predicted by perturbative QCD.
- in qualitative agreement with the conclusion (from v_2 data) that thermalization is more rapid than in perturbative QCD.
- the "non-asymptotic quark-gluon plasma being studied at RHIC is more like a "quark-gluon liquid." Short mean free path. Low viscosity.
- challenge to theory is to make these implications more quantitative.
- at $T \sim 2T_c$, we know from lattice that P/T^4 is within 15% of that for ideal QGP; and yet, we now see, mean free path short. Need a calculation of viscosity...

3. JACAK's conclusions

- Rapid equilibration!
  Strong pressure gradients, hydrodynamics works
- *EOS is <u>not</u> hadronic*
- The hot matter is "sticky" – it absorbs energy
  See energy loss, disappearance of back-to-back jets
  d+Au data says: *final state*, not initial state effect

- So, the stuff is dense, hot, and ~ equilibrated
  Is it quark gluon plasma? *Sure looks like it to me…*

- OK, then where's the New York Times?
  J/Ψ suppression or not? *Next run*
  T_{initial}? *direct photon analysis underway by PHENIX*

MOST THOUGHT-PROVOKING RHIC DATA

Goal of RHIC: create matter above the crossover + study its properties.

- Large azimuthal anisotropy v_2 in non-central collisions, well-described for $p_T \lesssim 2\text{GeV}$ by <u>ideal</u> hydrodynamics.

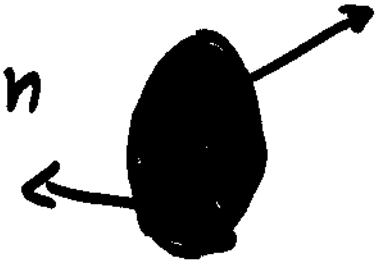
  → <u>ear</u>ly rescattering + equilibration, by $t \sim 0.6 - 1.0$ fm.

  – shorter mean free path + lower viscosity than in pQCD.

in pQCD, mfp $\sim \frac{1}{\alpha^2 T}$ and equil. takes ~ 5fm (?)

- For $p_T \gtrsim 2\text{GeV}$, $v_2 \sim$ geometric $\left(\begin{matrix}\text{indep of}\\ p_T, \sqrt{s}\end{matrix}\right)$
- Missing away-side jets

  → Surface emission



→ short m.f.p. even at larger p_T.

IMPLICATIONS? • need non-pert calc of η.

- $\frac{\eta}{\epsilon+P} \sim \frac{1}{T}$ in strongly coupled N=4 SUSY QCD (Son + Starinets, using AdS/CFT)

  → $\eta <$ perterbative. mfp $\sim \frac{1}{T}$. could this be relevant?!?!

Have the RHIC experiments discovered the

QUARK-GLUON LIQUID

?

(In a plasma, mfp $\gg \frac{1}{T}$, and quasiparticle ~~lifetimes~~ widths $\ll$ " masses.

In a liquid, the $\gg$ and $\ll$ are $\sim$.)

NB: for T large enough, pQCD works, mfp $\sim \frac{1}{\alpha^2 T}$, and the QGL becomes a QGP.

GOOD QUESTIONS ARE VALUABLE

WHERE IS ● ?

- answering it would allow transition region of QCD phase diagram to be mapped with confidence
- data just taken at lower energies (SPS) and higher energy (RHIC) allow us to search....

HOW MUCH ENERGY DO HARD QUARKS LOSE AT RHIC?

- since QGP not bounded by sharp line, need an operational definition. This may provide one.
- probes a property of hot quarks and gluons which can be calculated from QCD from first principles, at higher T.
- very interesting preliminary data from RHIC. Stay tuned....

EXPLORATION OF QCD PHASE DIAGRAM IS UNDERWAY

WHERE ARE WE GOING?

- Lattice & expt both making progress in hunting the critical point ...

v_2 : early equilibration. Tells us we're on the phase diagram early, and thus high. Use to constrain P.

Jet quenching: striking new phenom-enon.

Ties in to v_2 at high P_T.

Need pA control expt.

Use to measure energy density $\mathcal{E}$.

How can we measure/constrain T?

Photons? Dileptons? (Rates of emission calculable from 1st principles at high T.)

Test lattice calculations of P/T^4 & $\mathcal{E}/T^4$!

Can $c\bar{c}$ bind to form J/ψ? Expect NO.

" $b\bar{b}$ " " " Υ? Expect yes at RHIC.

(expectations based on lattice calculation)

(RHIC data in future.)

What is going on with HBT? A puzzle in current RHIC data. Will teach us about freeze-out