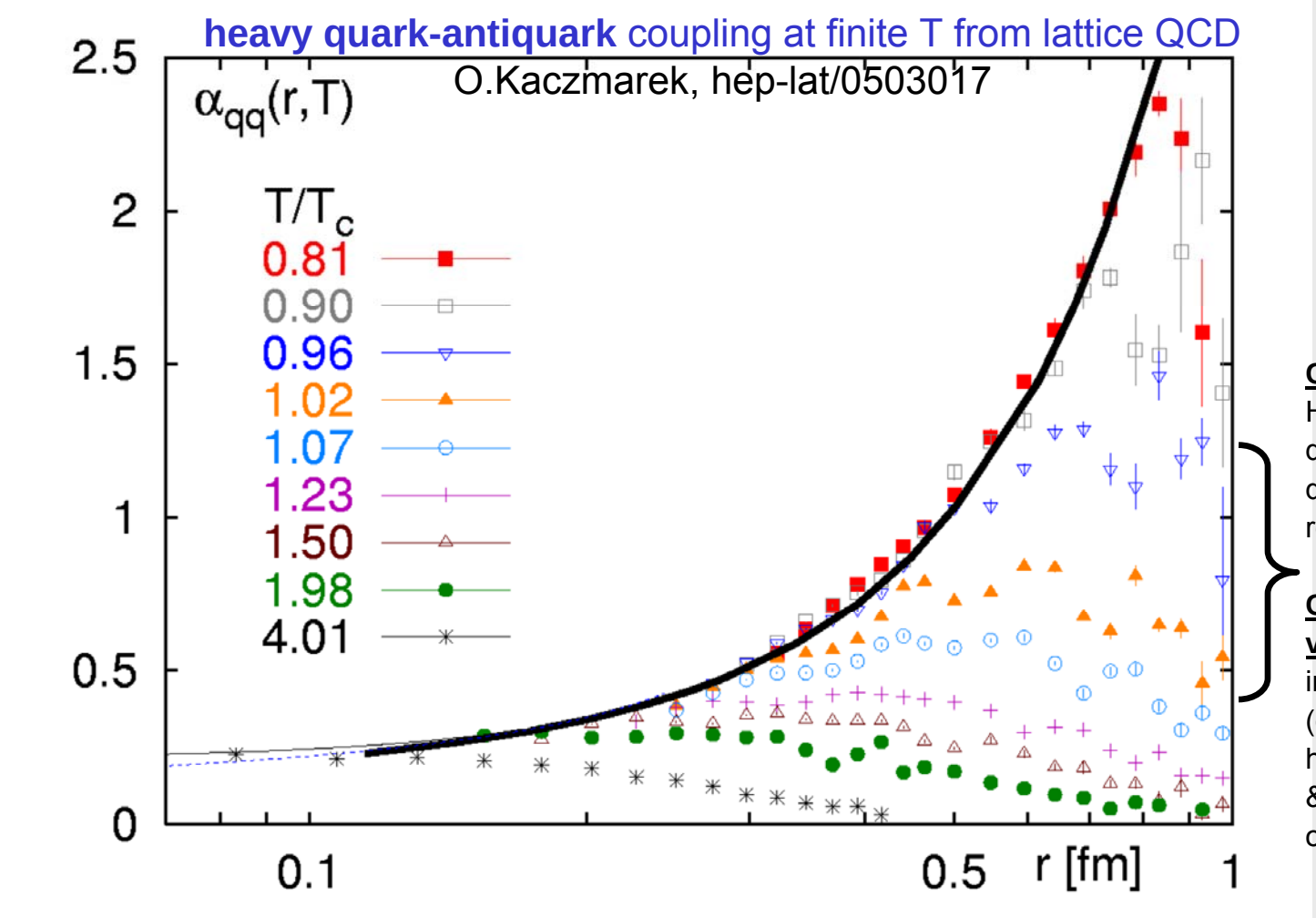
Exploring the Quark-Gluon Plasma at RHIC & LHC – Today's Perspective

Modifications to α_s



high Q^2 low Q^2

Constituents - Hadrons, dressed quarks, quasi-hadrons, resonances?

Coupling strength varies investigates (de-)confinement, hadronization, & intermediate objects.

Modifications to α_s

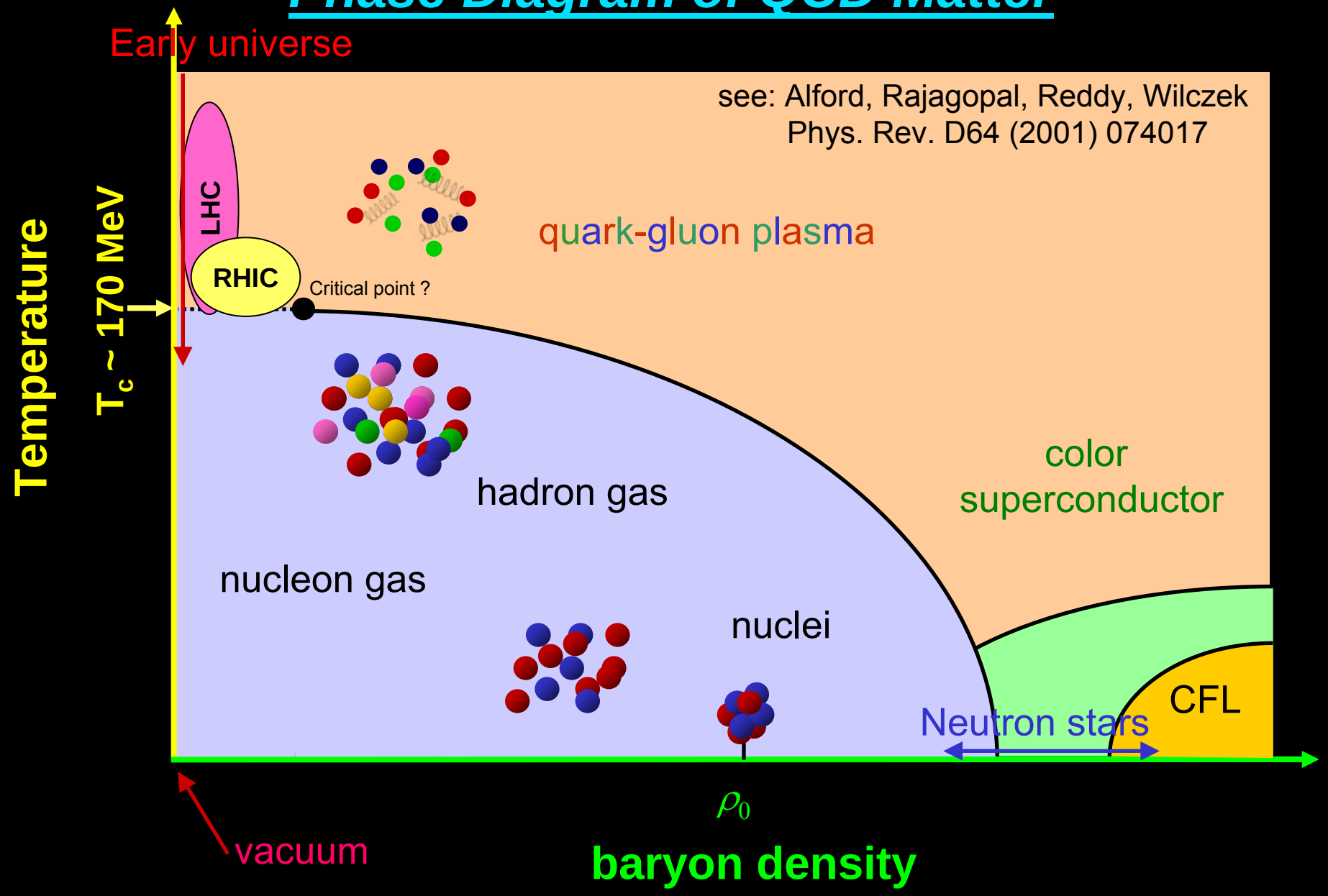
Nobel Prize 2005

D. Gross
H.D. Politzer
F. Wilczek

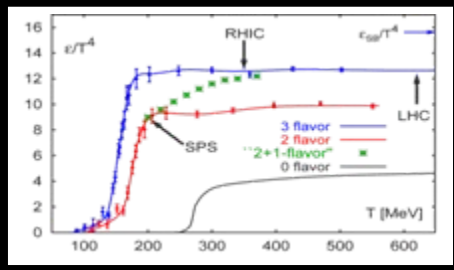
QCD Asymptotic Freedom (1973)

"Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today…since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted…to form a quark-gluon plasma."
David Gross, Nobel Lecture (RMP 05)

Phase Diagram of QCD Matter



Quark-Gluon Plasma (Soup)



Standard Model → Lattice Gauge Calculations predict QCD Deconfinement phase transition at $T_c \sim 175$ MeV ($\varepsilon_c \sim 0.5$ GeV / fm^3)

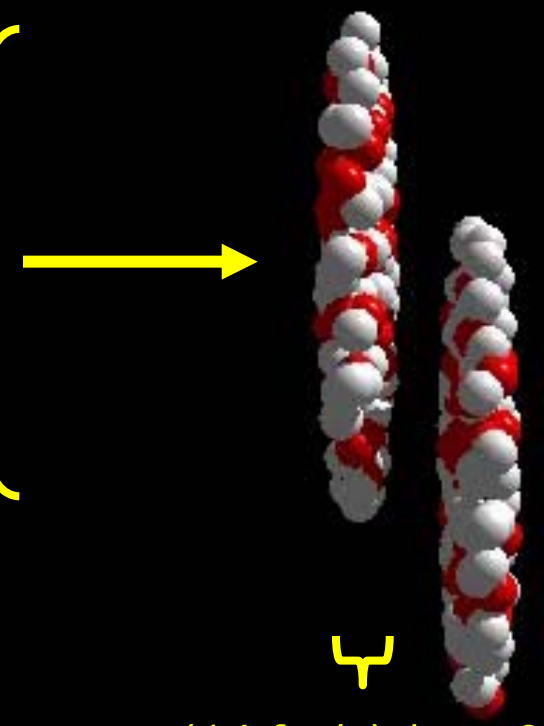
Cosmology → Quark-hadron phase transition in early Universe

- Can we make the primordial quark-gluon soup in the lab?
- Establish properties of QCD at high T (and density?)

Ultra-Relativistic Heavy Ion Collisions

Interaction of Au nuclei complete
in $\tau \leq$ few tenths fm/c

Gold nucleus
diameter = 14 fm



γ = 100
(Lorenz contracted)

τ = (14 fm/c) / γ ~ 0.1 fm/c

General Orientation

Hadron (baryons, mesons) masses ~ 1 GeV

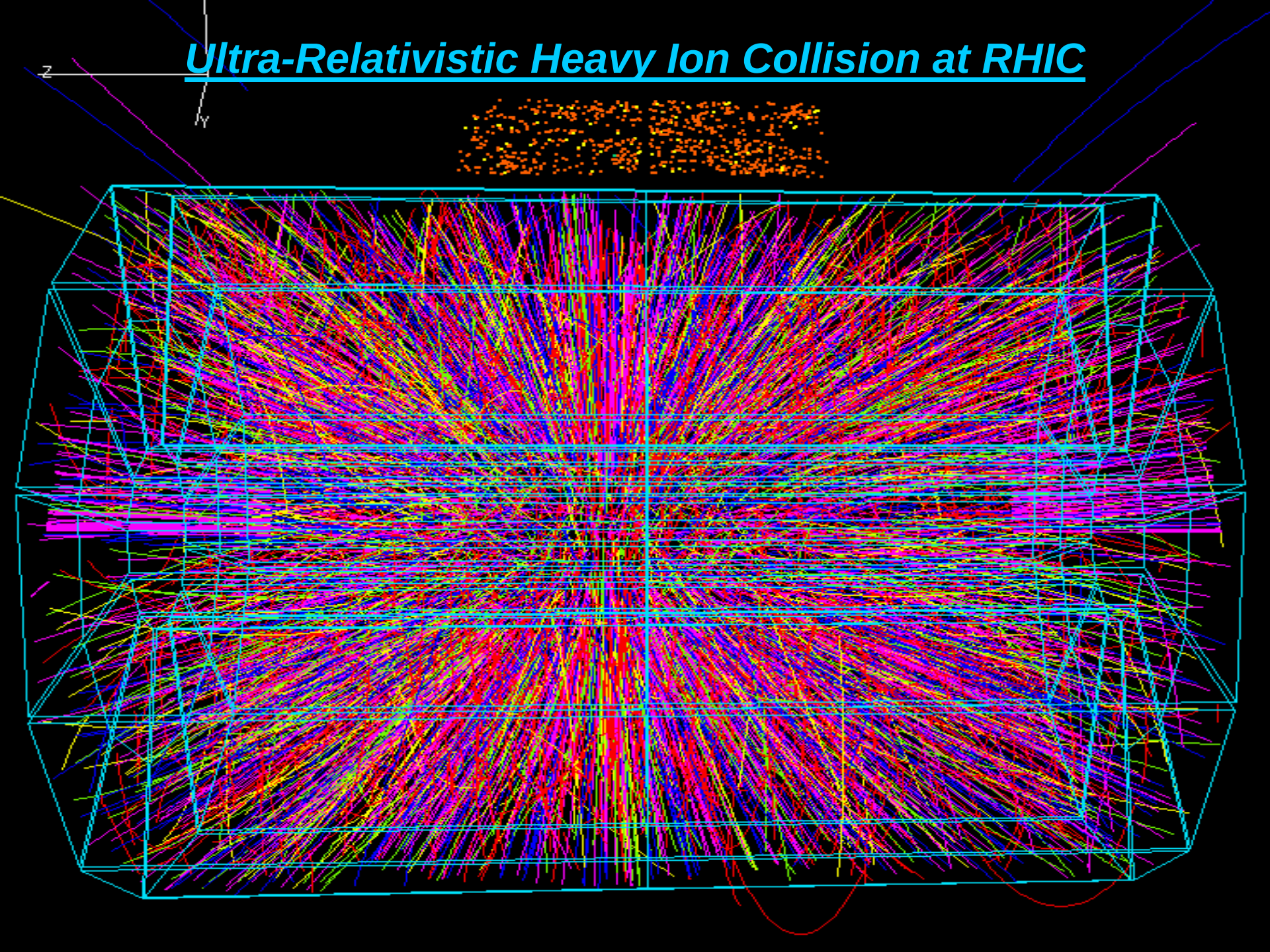
Hadron sizes ~ 10^{-15} meters (1 fm ≡ 1 fermi)

RHIC Collisions

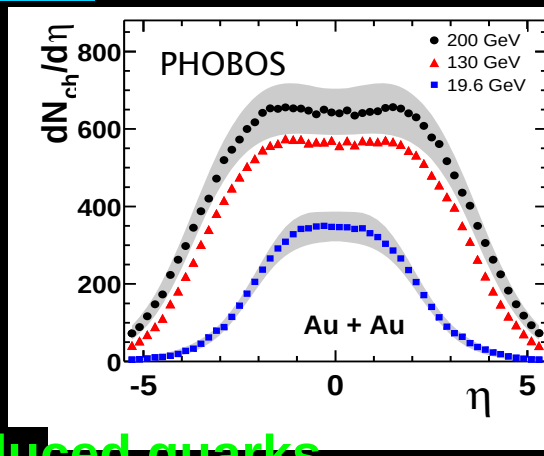
E_{cm} = 200 GeV/nn-pair

Total E_{cm} = 40 TeV

Ultra-Relativistic Heavy Ion Collision at RHIC



On the "First Day" (at RHIC)



Initial Observations:

Large produced particle multiplicities

ed. - "less than expected! → gluon-saturation?" → CGC?

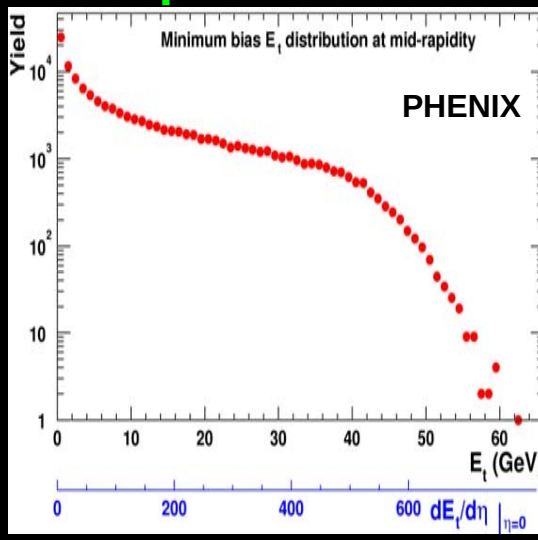
→ $dn_{ch}/d\eta\,|_{\eta=0}$ = 670, N_{total} ~ 7500

> 15,000 $q + \bar{q}$ in final state, > 92% are produced quarks

Large energy densities ($dn/d\eta$, $dE_T/d\eta$)

→ $\varepsilon \geq 5$ GeV/fm^3 $\varepsilon \geq 5 - 15\ \varepsilon_{critical}$

$30 - 100$ x nuclear density



Large collective flow

ed. - "completely unexpected!"

→ Due to large early pressure gradients, energy & gluon densities

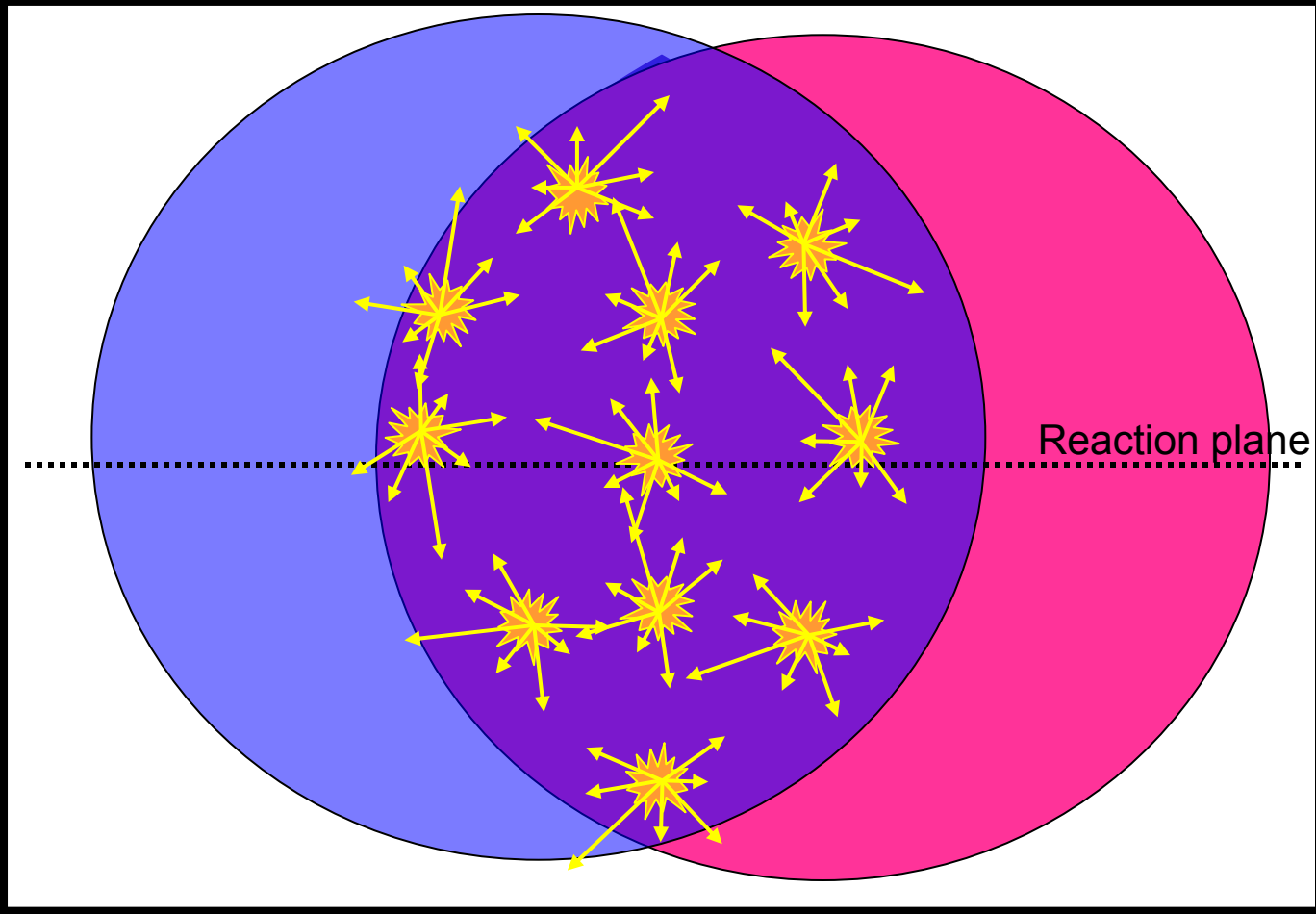
→ Requires hydrodynamics and quark-gluon equation of state

Quark flow & coalescence → constituent quark degrees of freedom!

How do RHIC Collisions Evolve?

1) Superposition of independent p+p:

momenta random
relative to reaction plane



$\vec{b}$

How do RHIC Collisions Evolve?

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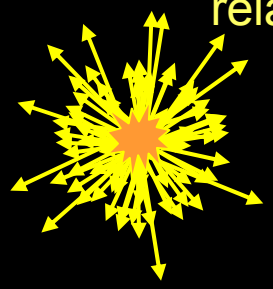
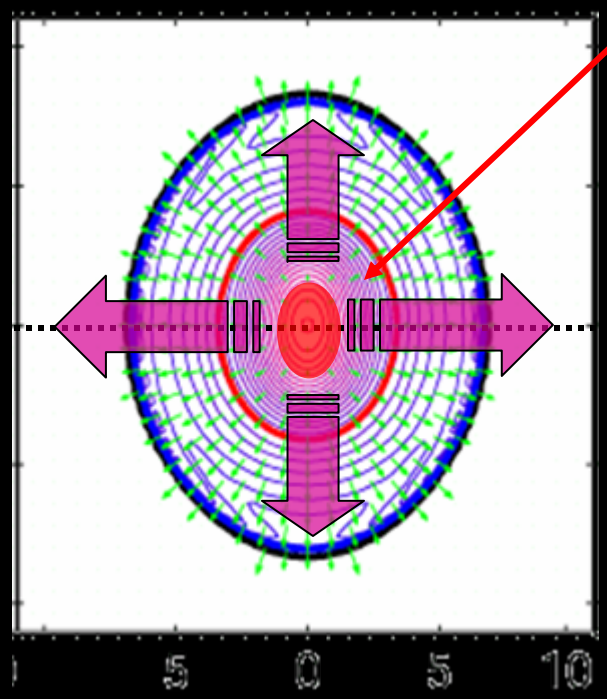
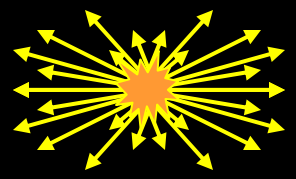


High density
pressure
at center



2) Evolution as a **bulk system**

Pressure gradients (larger in-plane)
push bulk "out" → flow"



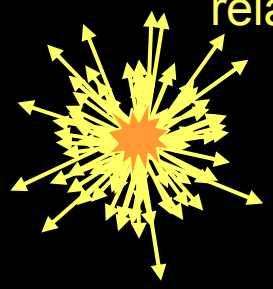
more, faster particles
seen in-plane

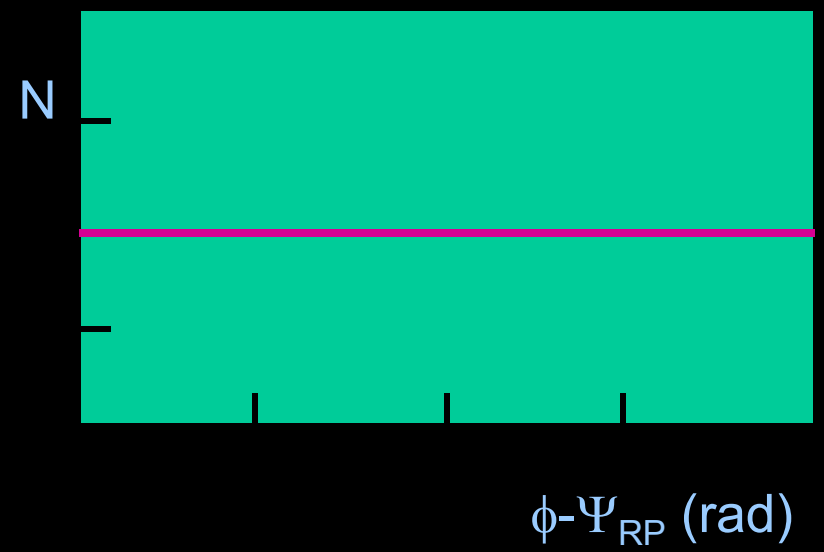
"zero" pressure
in surrounding vacuum

Azimuthal Angular Distributions

1) Superposition of independent p+p:

momenta random
relative to reaction plane





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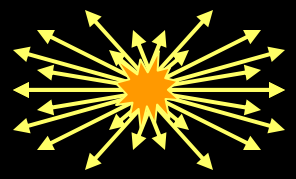

more, faster particles
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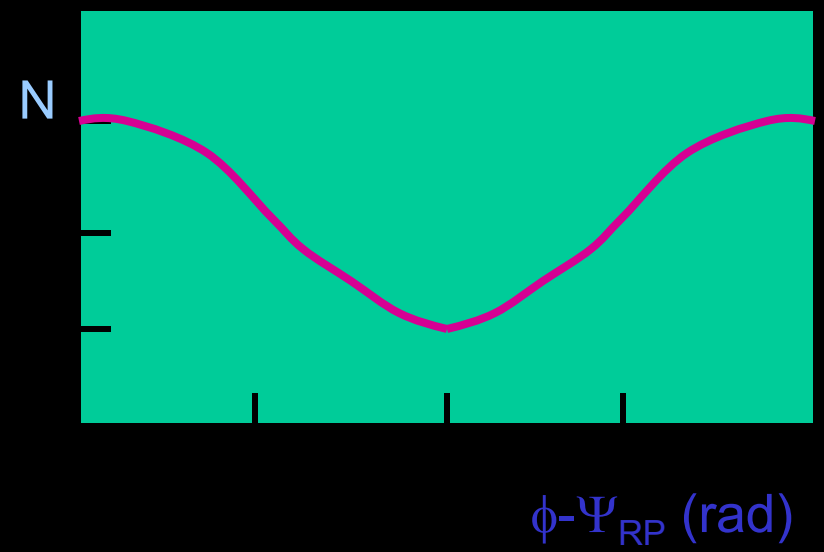
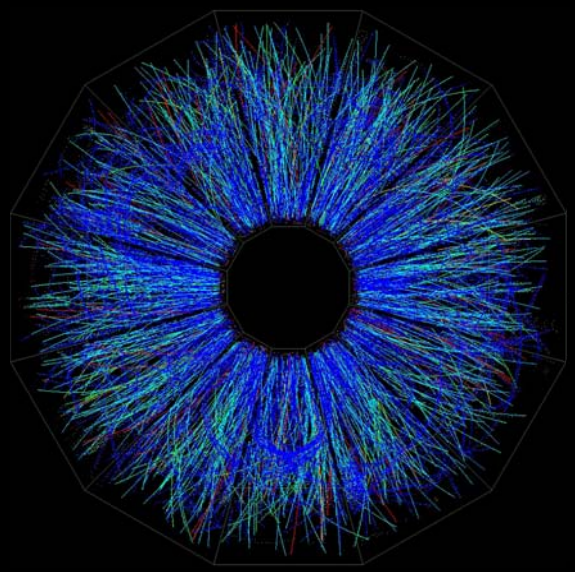
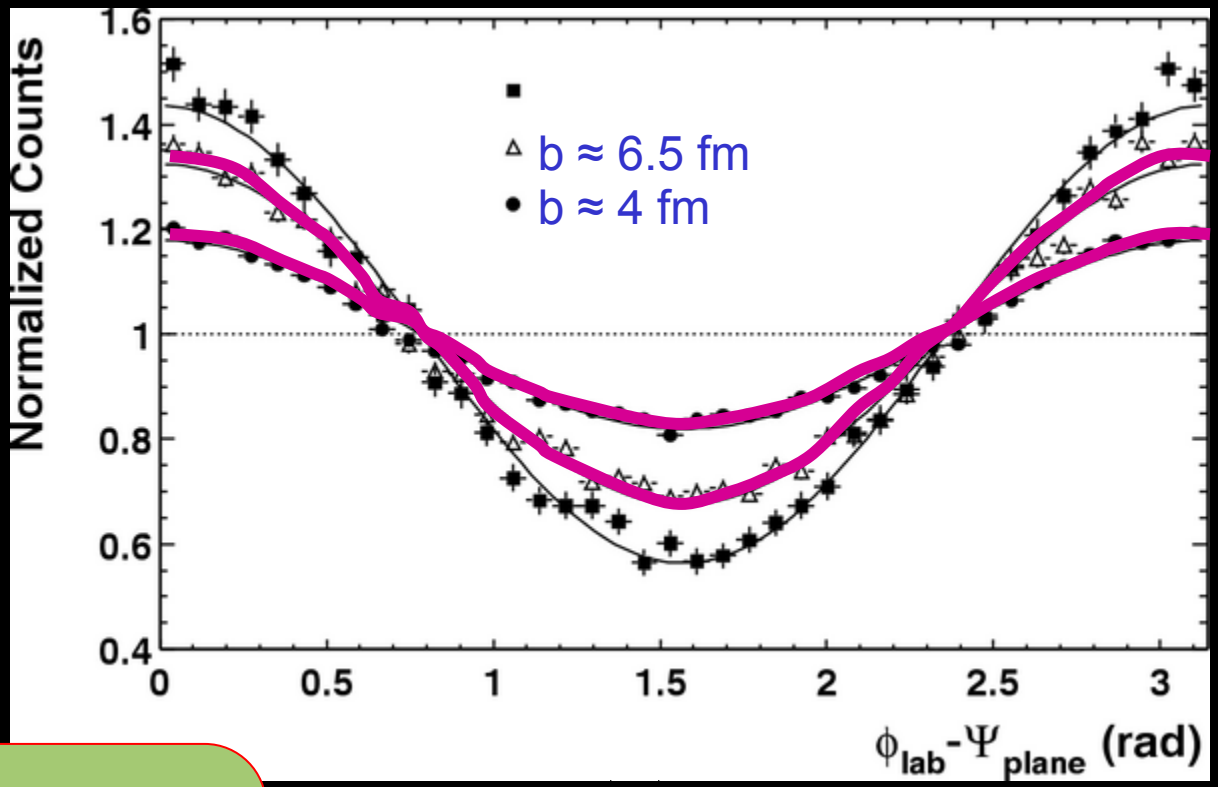


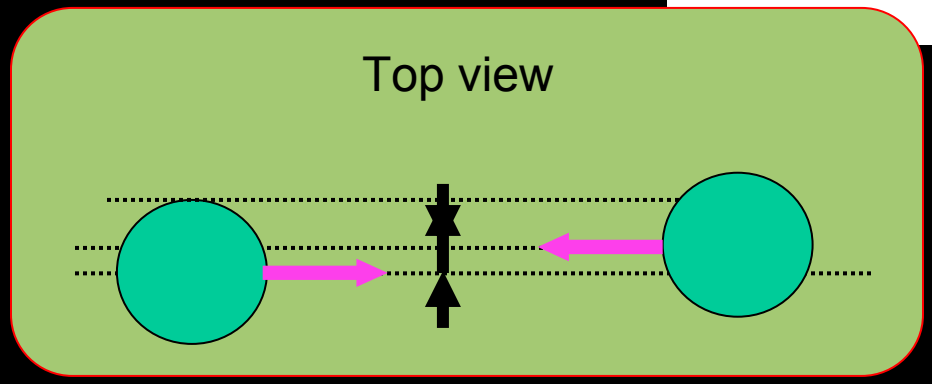
On the First Day at RHIC - Azimuthal Distributions

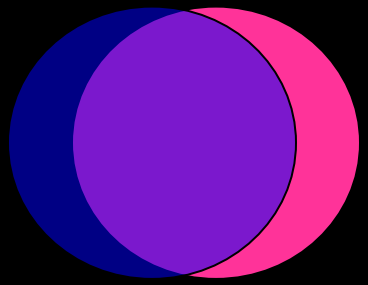


"central" collisions

STAR, PRL**90** 032301 (2003)

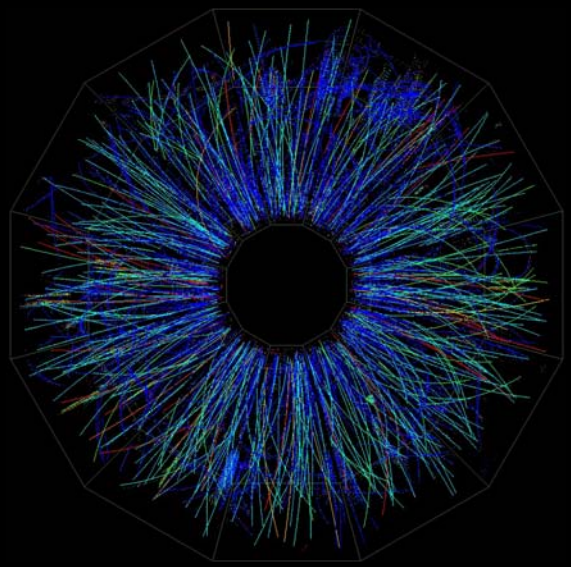






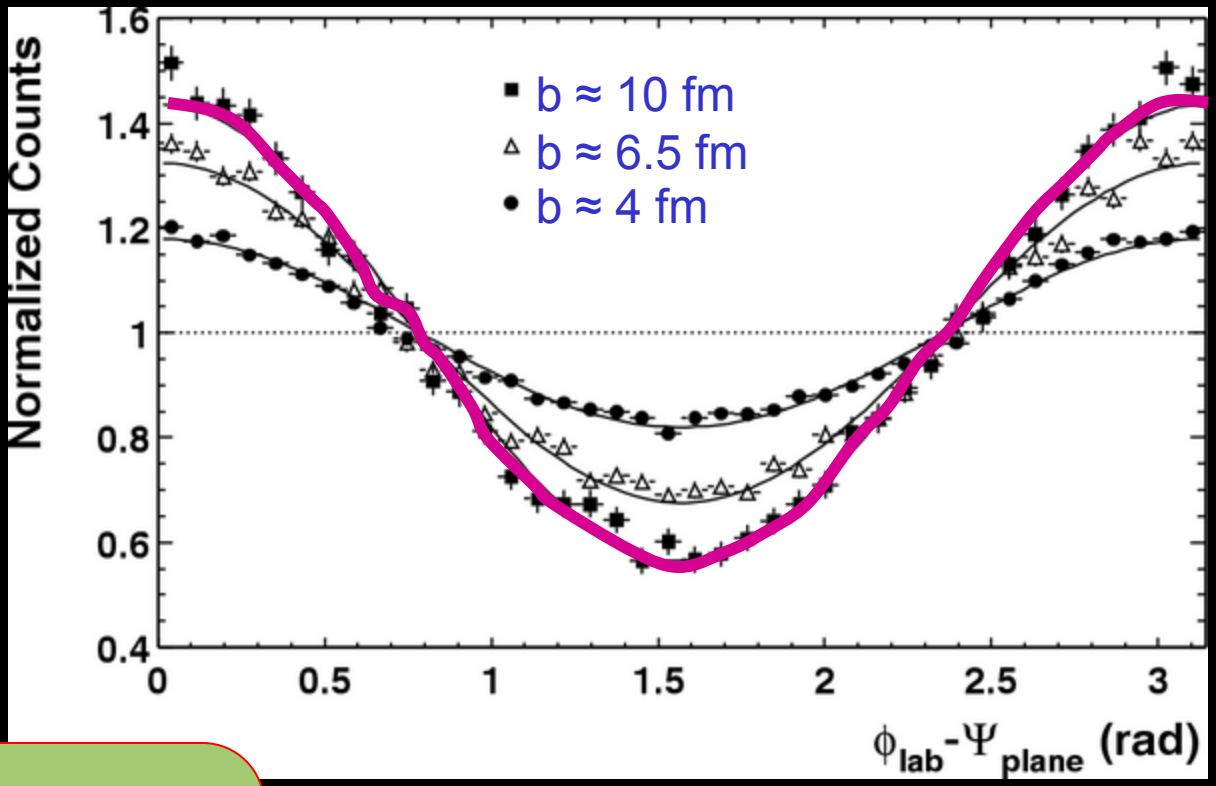
Beams-eye view

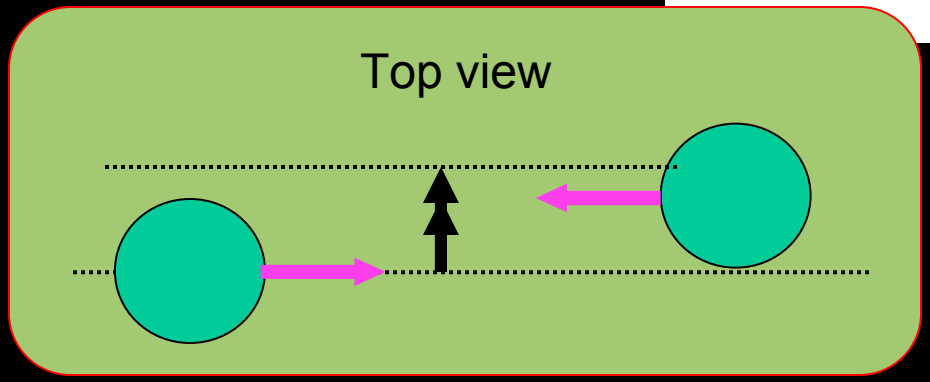
On the First Day at RHIC - Azimuthal Distributions

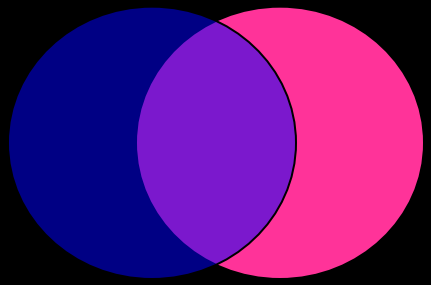


peripheral collisions

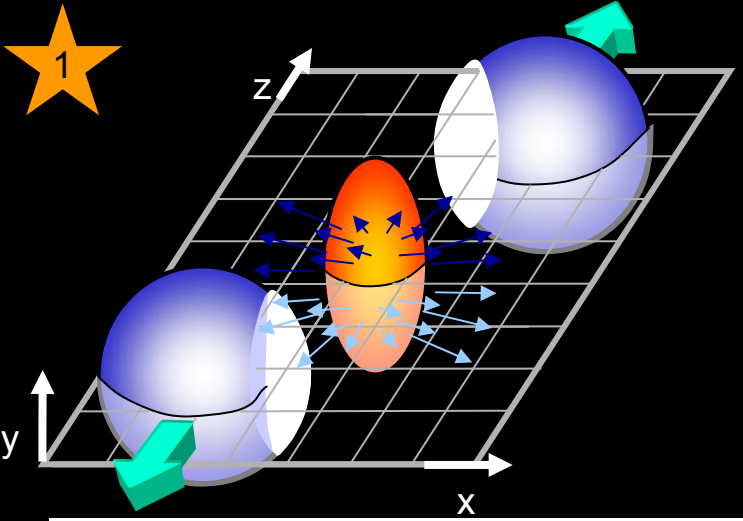
STAR, PRL**90** 032301 (2003)







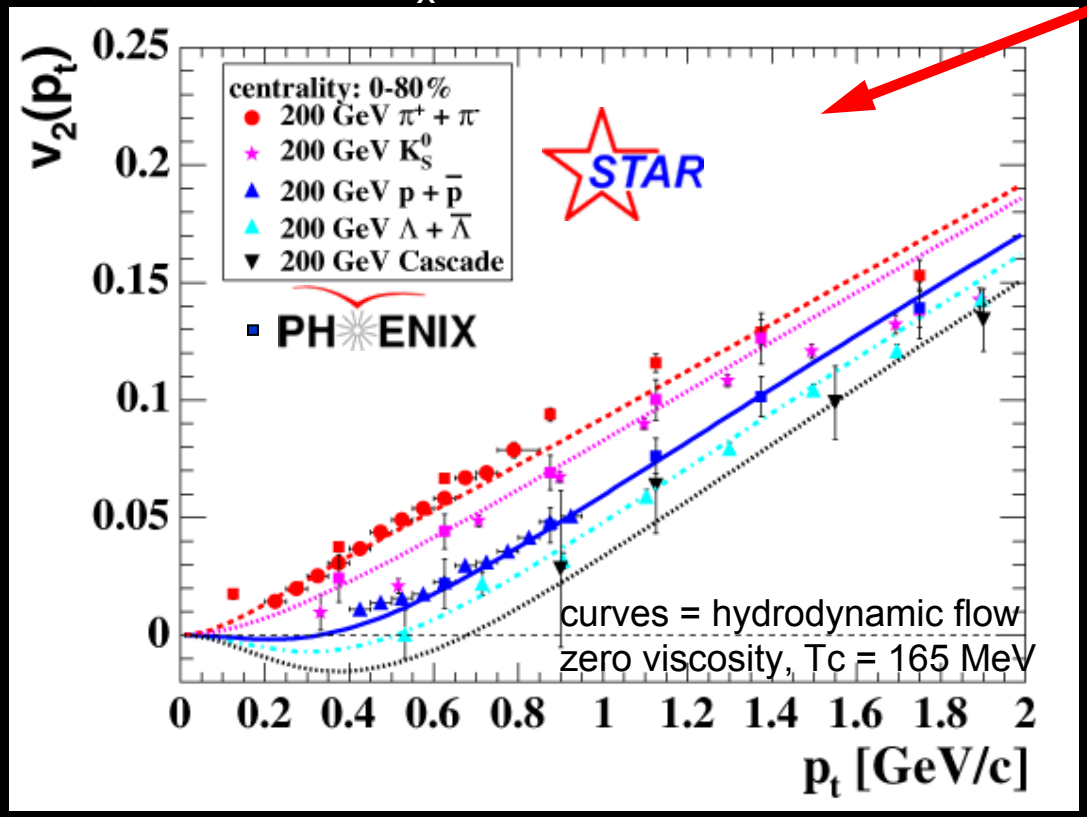
Beams-eye view



Elliptic Flow Saturates Hydrodynamic Limit

- Azimuthal asymmetry of charged particles:

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$



Mass dependence of v_2

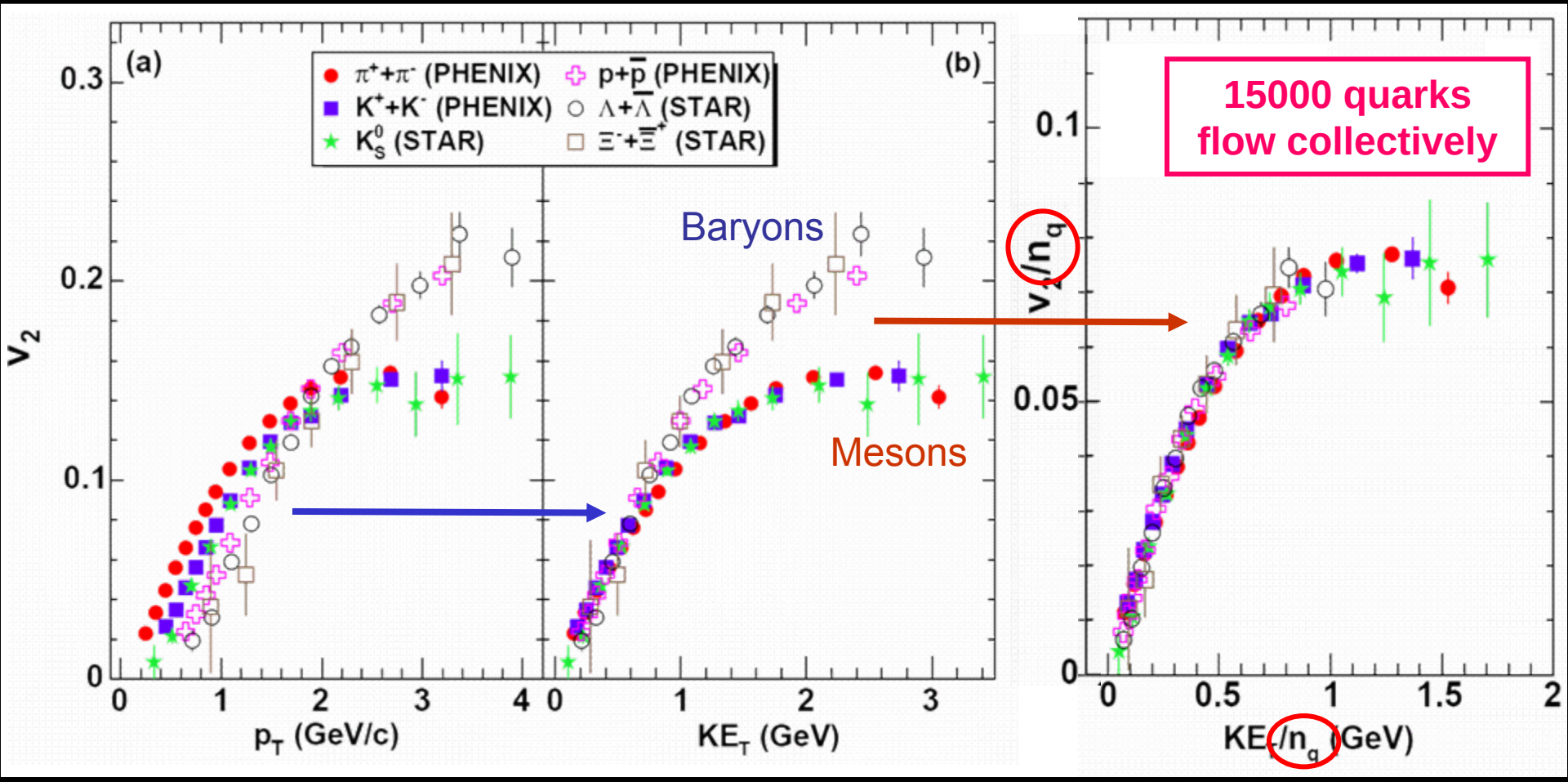
Requires -

- Early thermalization (0.6 fm/c)
- Ideal hydrodynamics (zero viscosity) → "nearly perfect fluid"
- $\varepsilon \sim 25$ GeV/fm^3 (>> $\varepsilon_{critical}$)
- Quark-Gluon Equ. of State

Identified Hadron Elliptic Flow Complicated

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons

$$d^2n/dp_T d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi)$$



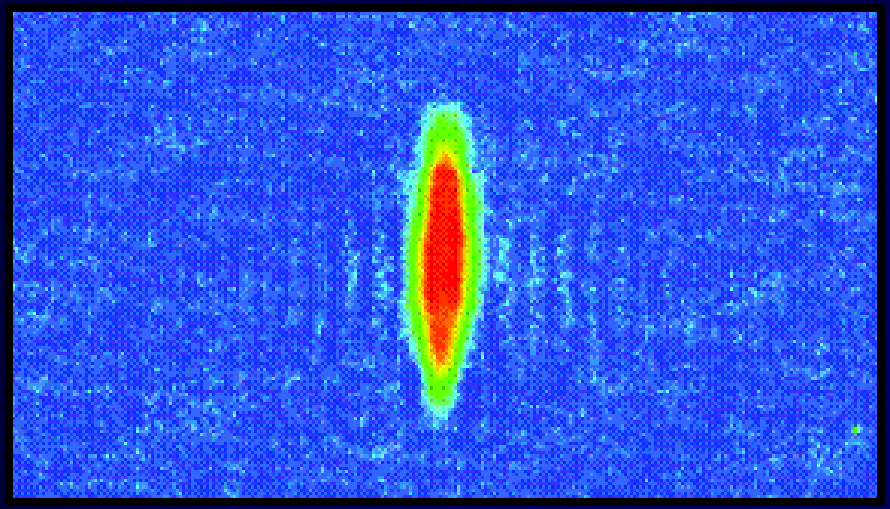
If the flow established at quark level, it is predicted to be *simple* →

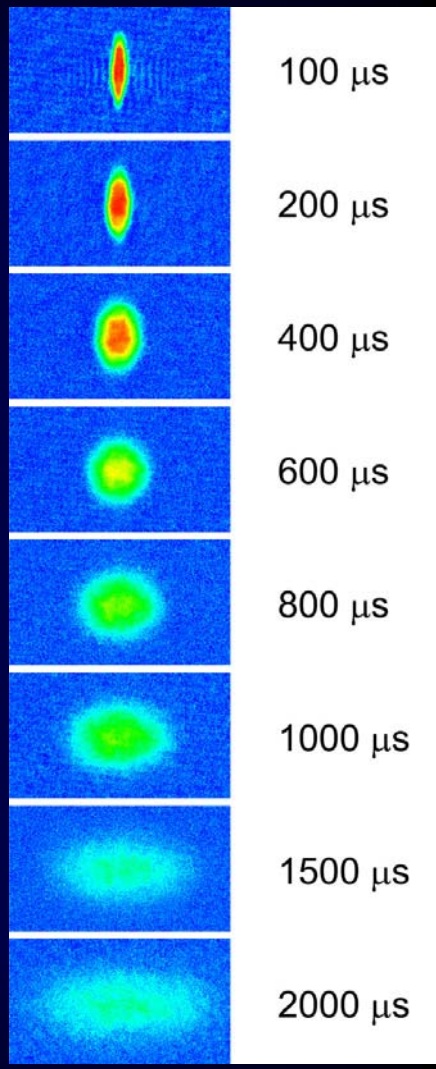
$KE_T \rightarrow KE_T / n_q$, $v_2 \rightarrow v_2 / n_q$, n_q = (2, 3 quarks) for (meson, baryon)

If baryons and mesons form
from independently flowing quarks
then
quarks are deconfined
for a brief moment (~ 10^{-23} s), then hadronization!

Universality of Classical Strongly-Coupled Systems?

Transport in gases of strongly-coupled atoms





K.M. O'Hara et al
Science 298 (2002) 2179

RHIC fluid behaves like this –

a strongly coupled fluid.

Universality of classical strongly-coupled systems?

→ Atoms, sQGP, ……. AdS/CFT……

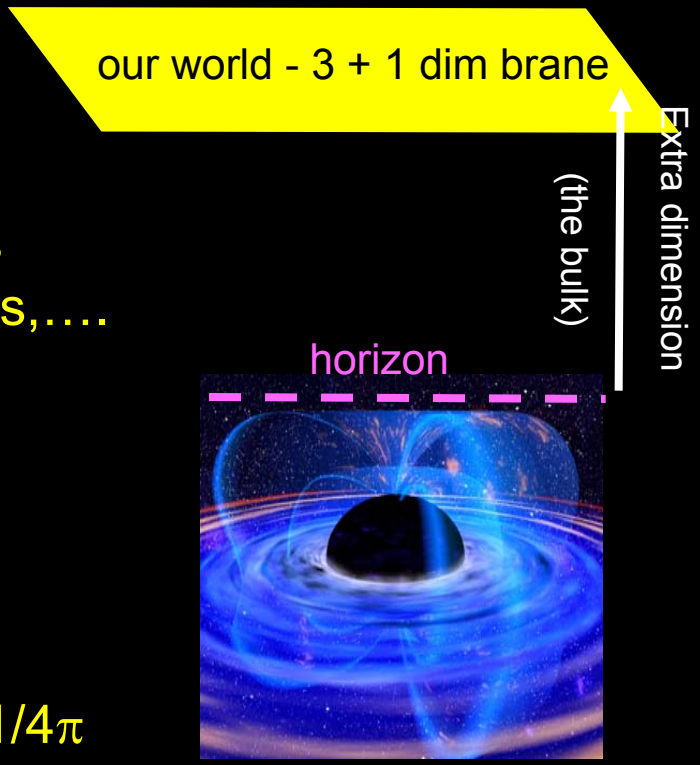
AdS_5/CFT – a 5D Correspondence of 4D Systems

PRL 94, 111601 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]
[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
(Received 20 December 2004; published 22 March 2005)

- Analogy between black hole physics and equilibrium thermodynamics
- Solutions possess hydrodynamic characteristics Similar to fluids – viscosity, diffusion constants,….



MULTIPLICITY

Entropy ↔ Black Hole Surface Area

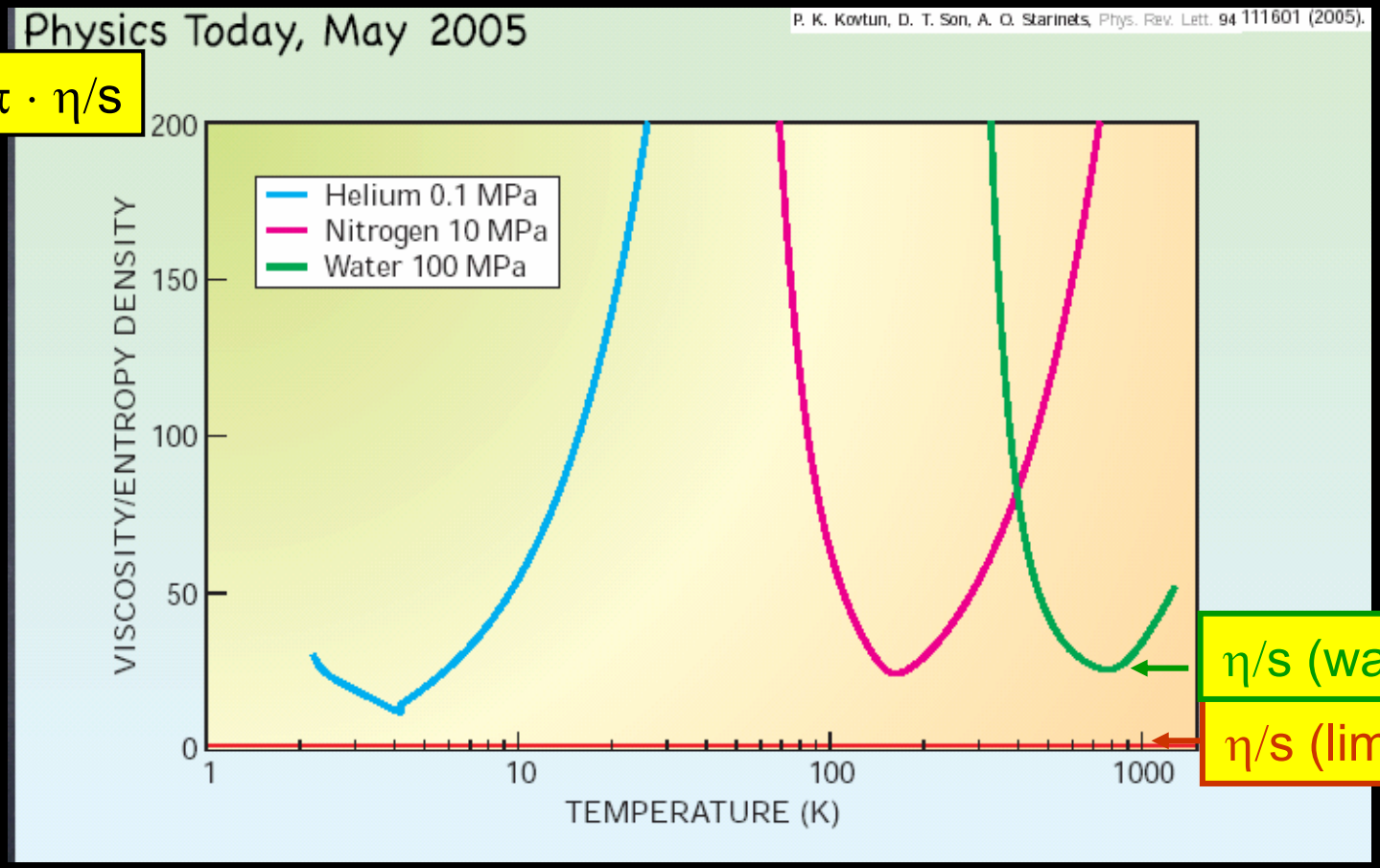
DISSIPATION

Viscosity ↔ Graviton Absorption

Use strongly coupled N=4 SUSY YM theory.

Derive a quantum lower viscosity bound: $\eta/s > 1/4\pi$

Ultra-low (Shear)Viscosity Fluids



QGP

T = 2 x 10^{12} K

Quantum lower viscosity bound: $\eta/s > 1/4\pi$ (Kovtun, Son, Starinets)

From strongly coupled *N* = 4 SUSY YM theory.

2-d Rel Hydro describes STAR v_2 data with $\eta/s \leq 0.1$ near lower bound!

"The RHIC fluid may be the
least viscous fluid ever seen"

The American Institute of Physics
announced the RHIC quark-gluon liquid
as the top physics story of 2005!

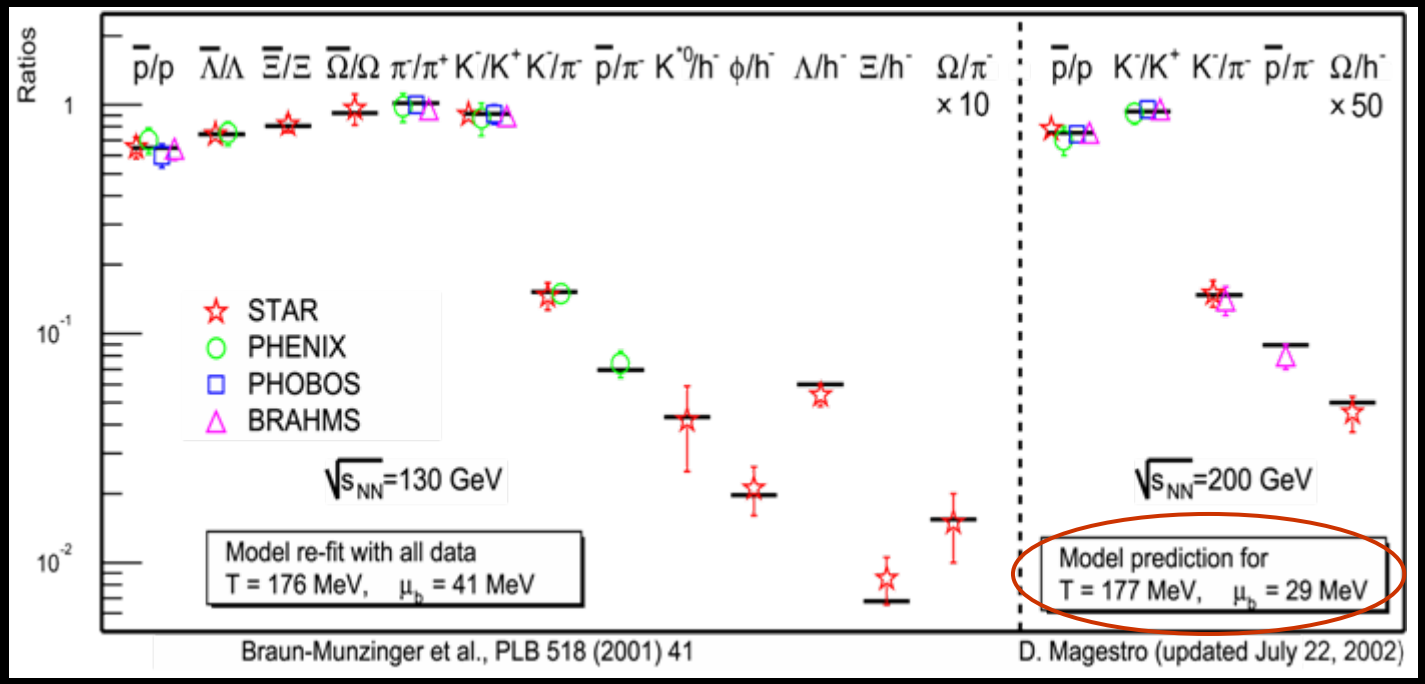
see http://www.aip.org/pnu/2005/

It Flows - Is It Really Thermalized?

"Chemical" equilibration (particle yields & ratios):

Particles yields represent equilibrium abundances

→ universal hadronization temperature



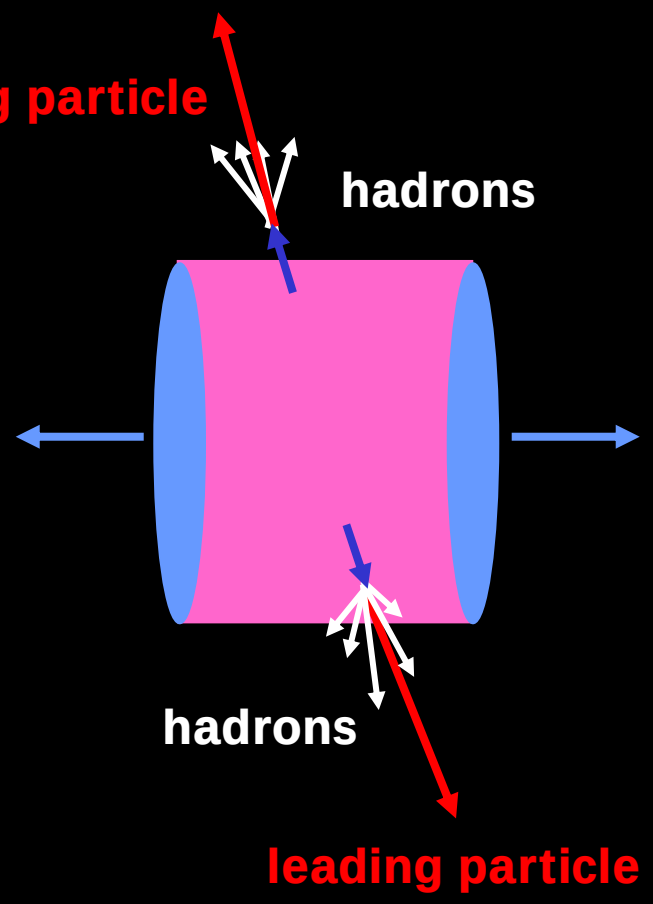
Small net baryon density (K^+/K^-, $\bar{B}/B$ ratios) → μ_B ~ 25 - 40 MeV

Chemical Freezeout Conditions → T = 177 MeV, μ_B = 29 MeV → T ~ $T_{critical}$ (QCD)

Particles are thermally distributed and flow collectively, at universal hadronization temperature T = 177 MeV!

On the "Second" Day (~ Year) at RHIC

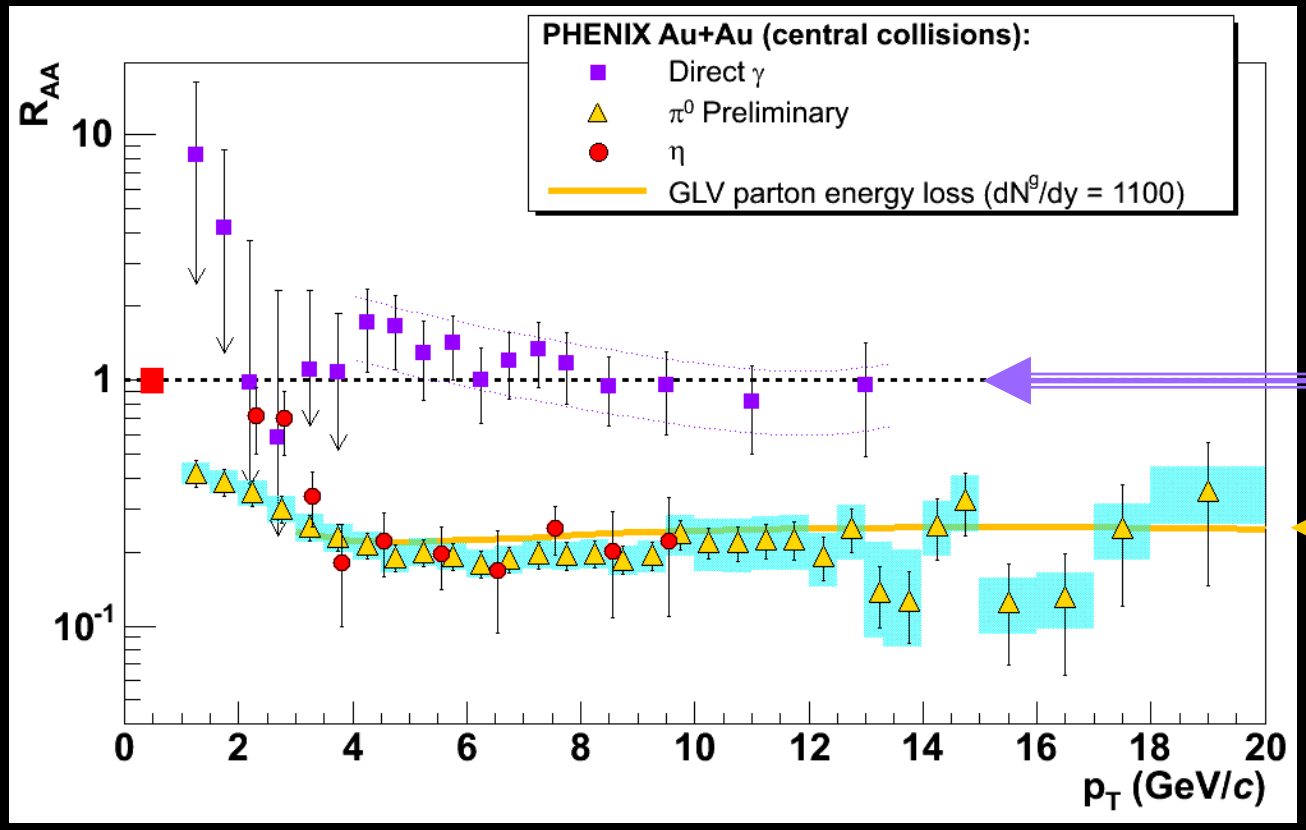
Probing Hot QCD Matter with Hard-Scattered Probes



→ parton energy loss: modification of jets and leading particles & jet-correlations

High Momentum Hadrons Suppressed - Photons Not

Deviations from binary scaling of hard collisions: $R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$



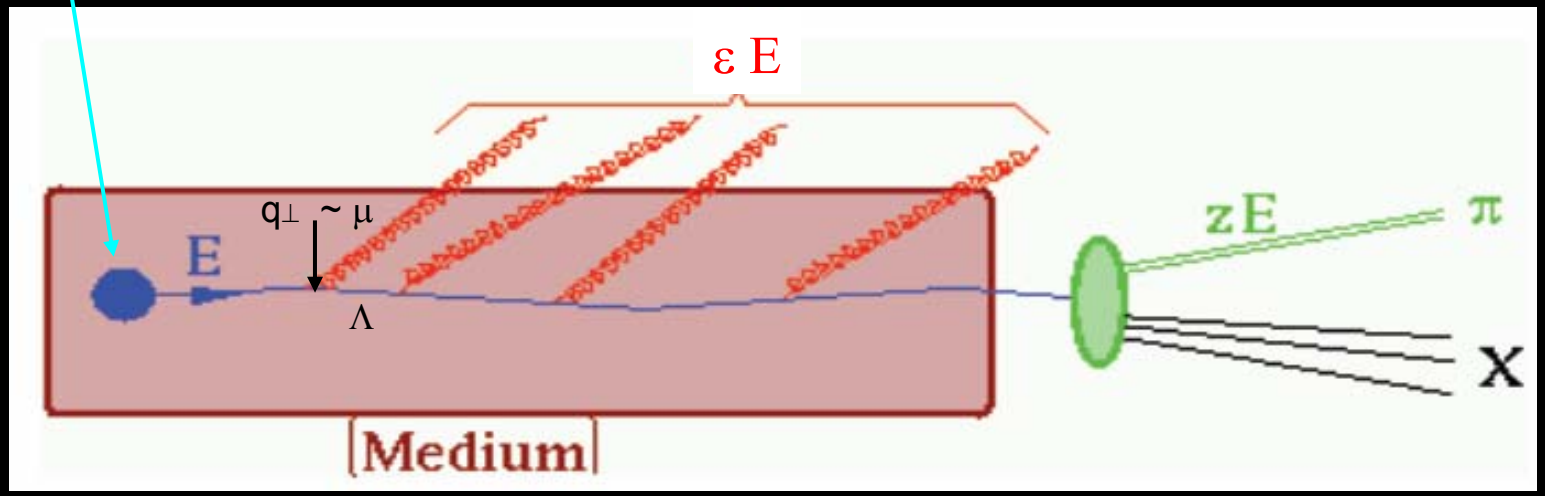
Photons

Hadrons factor 4 – 5 suppression

Dynamical Origin of High p_T Hadron Suppression?

How does parton lose energy?

What happens to the radiation?



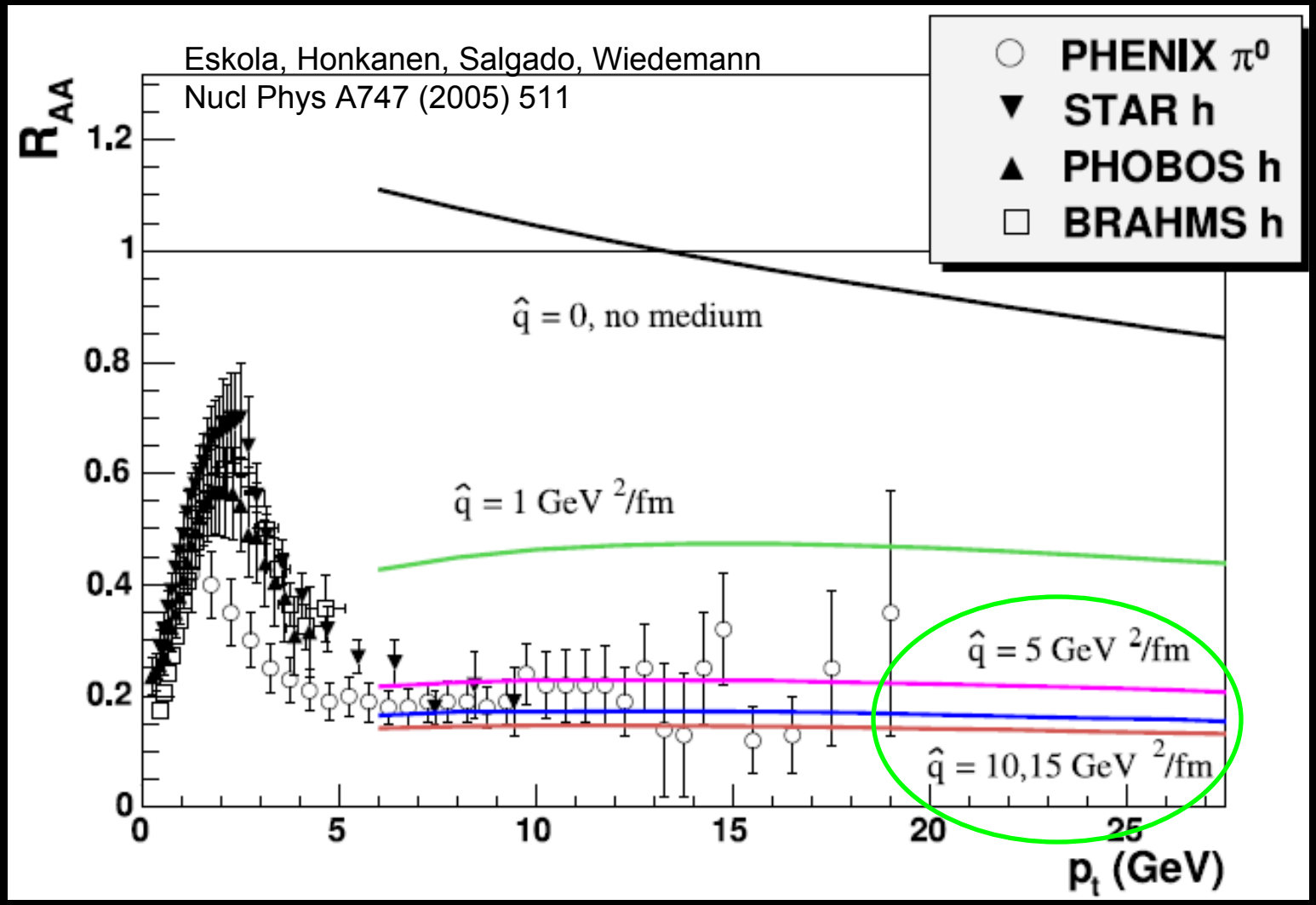
What is the dependence on the type of parton?

For collisional energy loss what about recoil energy?

$$\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$$

One parameterization of energy loss $\rightarrow$ $\hat{q} = \mu^2 / \Lambda$

$\hat{q}$ Parameterization of Parton Energy Loss

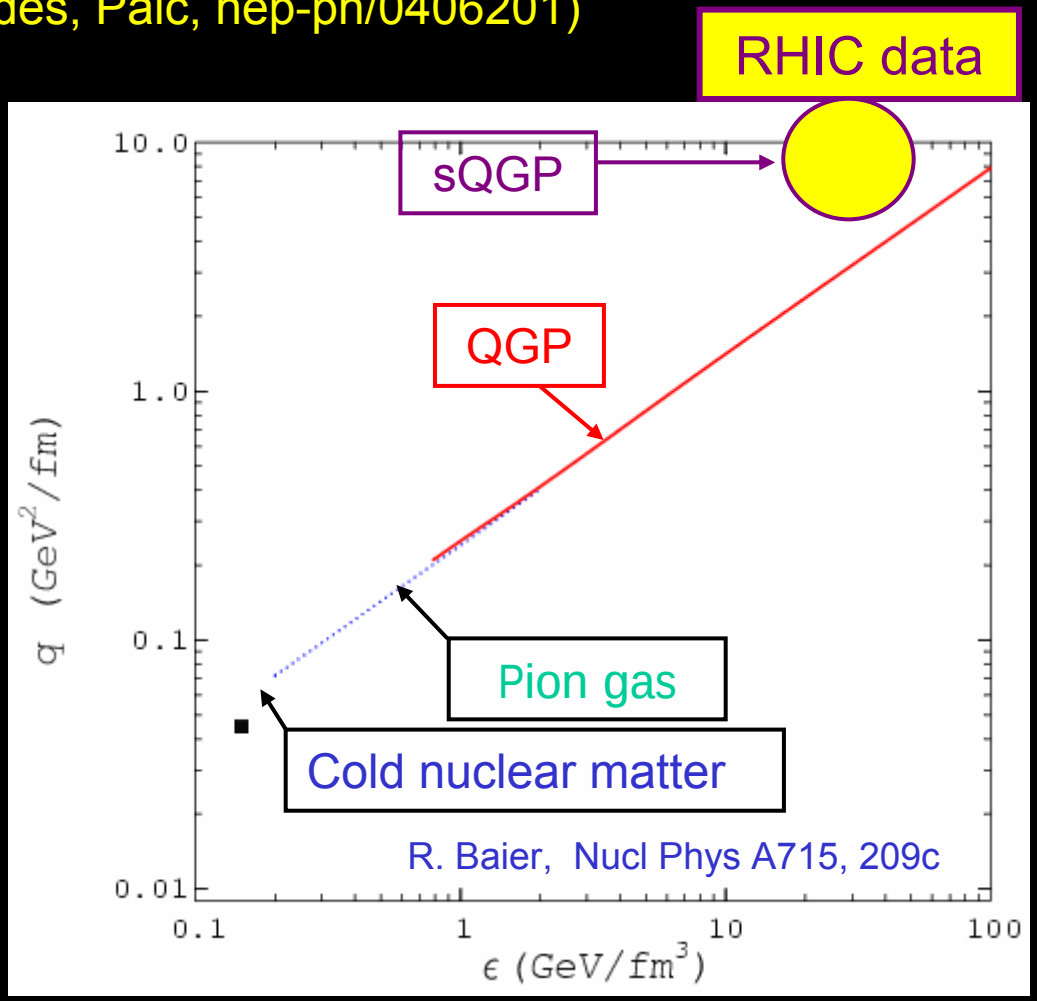


$\hat{q}$ = 5 – 15 GeV^2 / fm from RHIC R_{AA} Data

Interpretation of the Parton Energy Loss

Energy loss requires large $\langle \hat{q} \rangle \approx 5 - 15\ \mathrm{GeV}^2/\mathrm{fm}$

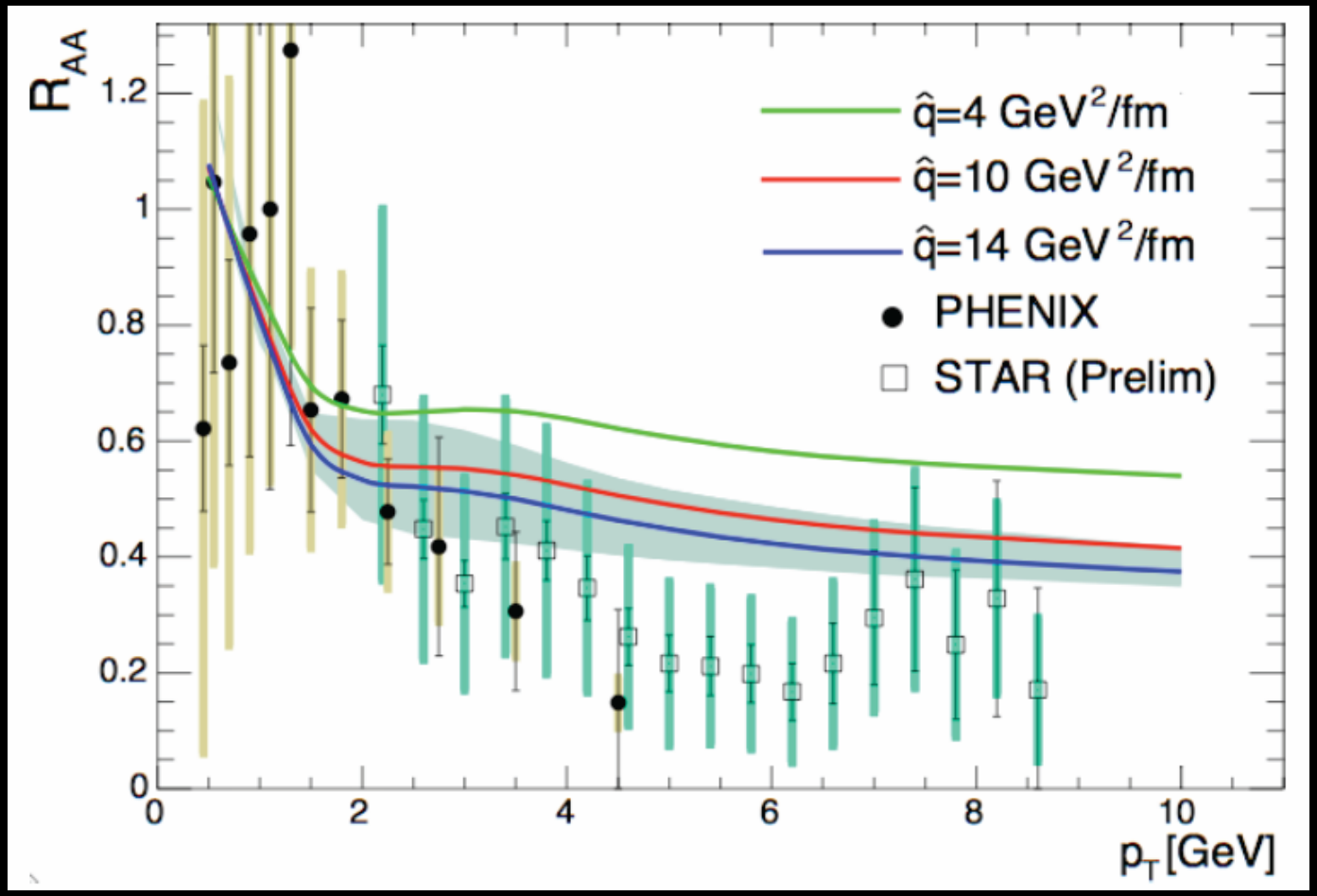
(also : Dainese, Loizides, Paic, hep-ph/0406201)



Heavy Quark Suppression

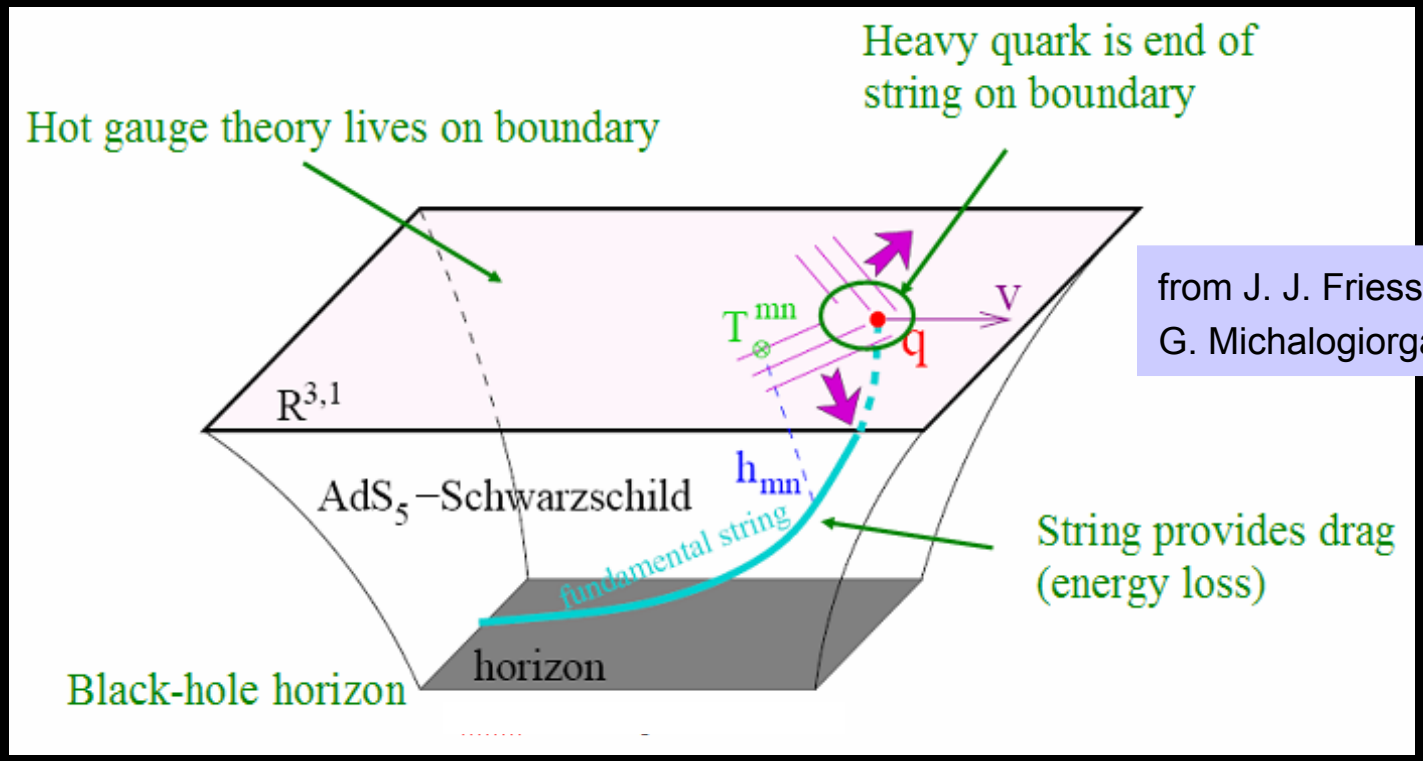
- Using fixed order next-to-leading log (FONL) cross sections for charm and beauty

Armesto, Cacciari, Dainese, Salgado, Wiedemann, PLB637:362, 2006



Insufficient suppression from theoretical models!

AdS_5/CFT *Again! - Initial Results on Jet Quenching*



from J. J. Friess, S. S. Gubser and G. Michalogiorgakis,arXiv:hep-th/0605292.

Calculating the Jet Quenching Parameter from AdS/CFT

Hong Liu,[1] Krishna Rajagopal,[1,2] and Urs Achim Wiedemann[3,4]

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[2] *Nuclear Science Division, MS 70R319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, University of Stony Brook, NY 11794, USA*
[4] *RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*

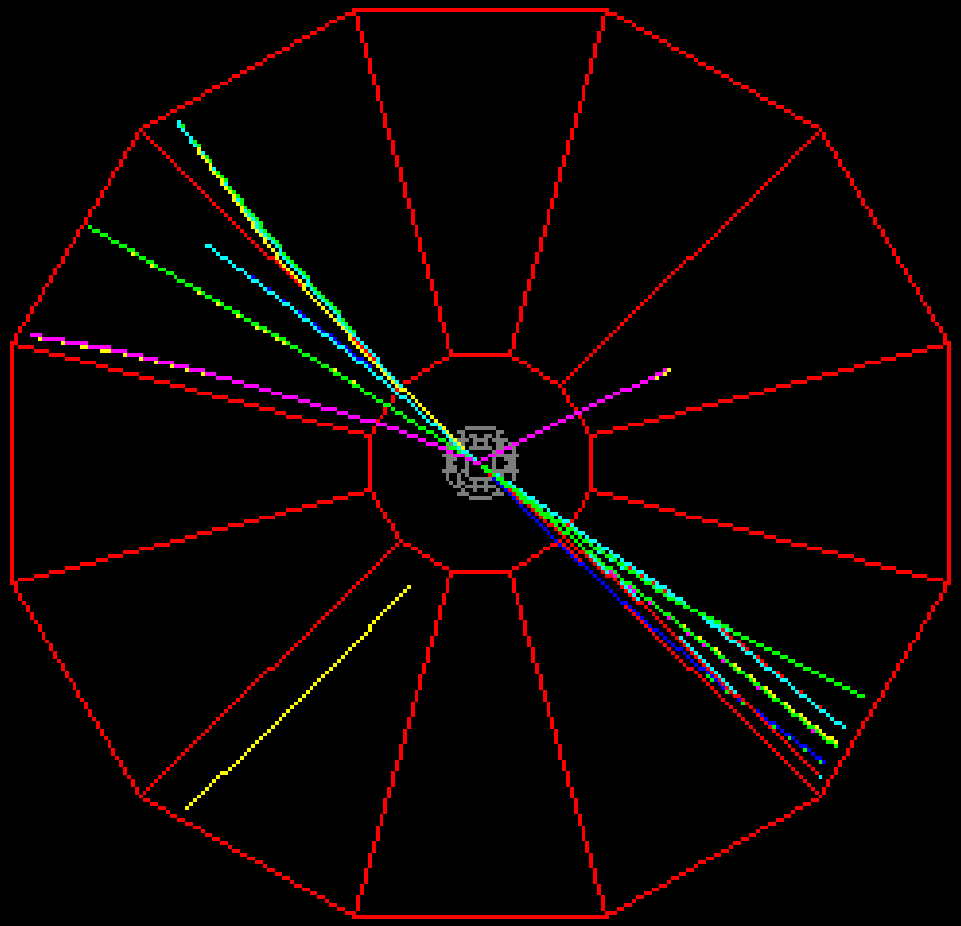
(Dated: May 16, 2006)

H. Liu, K. Rajagopal and U. A. Wiedemann, arXiv:hep-ph/0605178, recent PRL

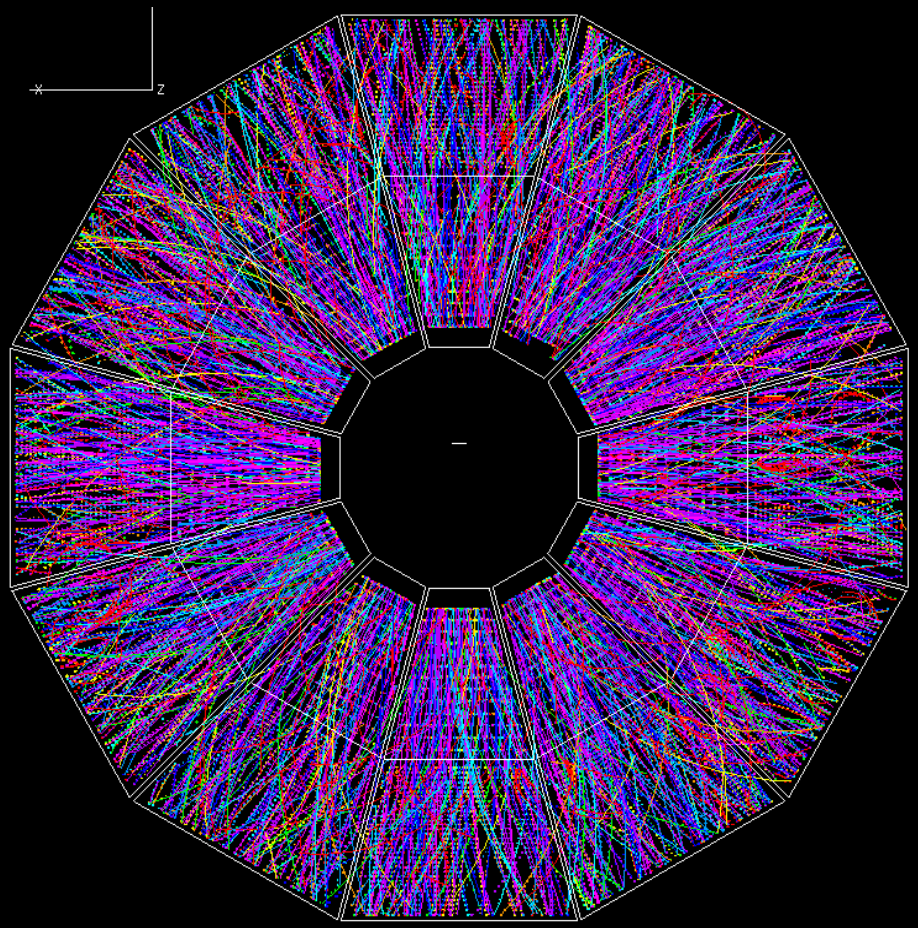
transition, we shall use $\lambda = 6\pi$ to make estimates. From (15), we find $\hat{q}$ =3.2, 7.5, 14.7 GeV^2/fm for T = 300, 400, 500 MeV. In a heavy ion collision, $\hat{q}$ decreases with time τ as the hot fluid expands and cools. The time-averaged $\hat{q}$ which has been determined in comparison with RHIC data is $\bar{\hat{q}} \equiv \frac{2}{(L^-)^2}\int_{\tau_0}^{\tau_0+L^-} \tau\,\hat{q}(\tau)\,d\tau$, found to be of order 10 GeV^2/fm [4, 5]. If we assume a one-

Hard Scattering (Jets) as a Probe of Dense Matter II

STAR p + p → jet event



STAR Au+Au (jet?) event

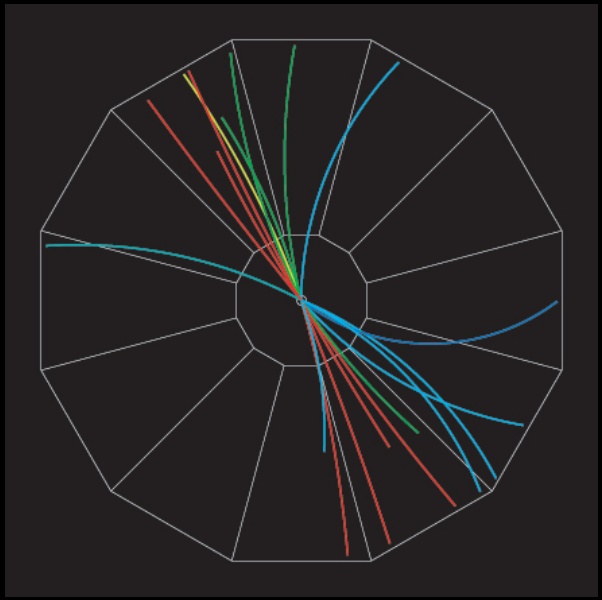


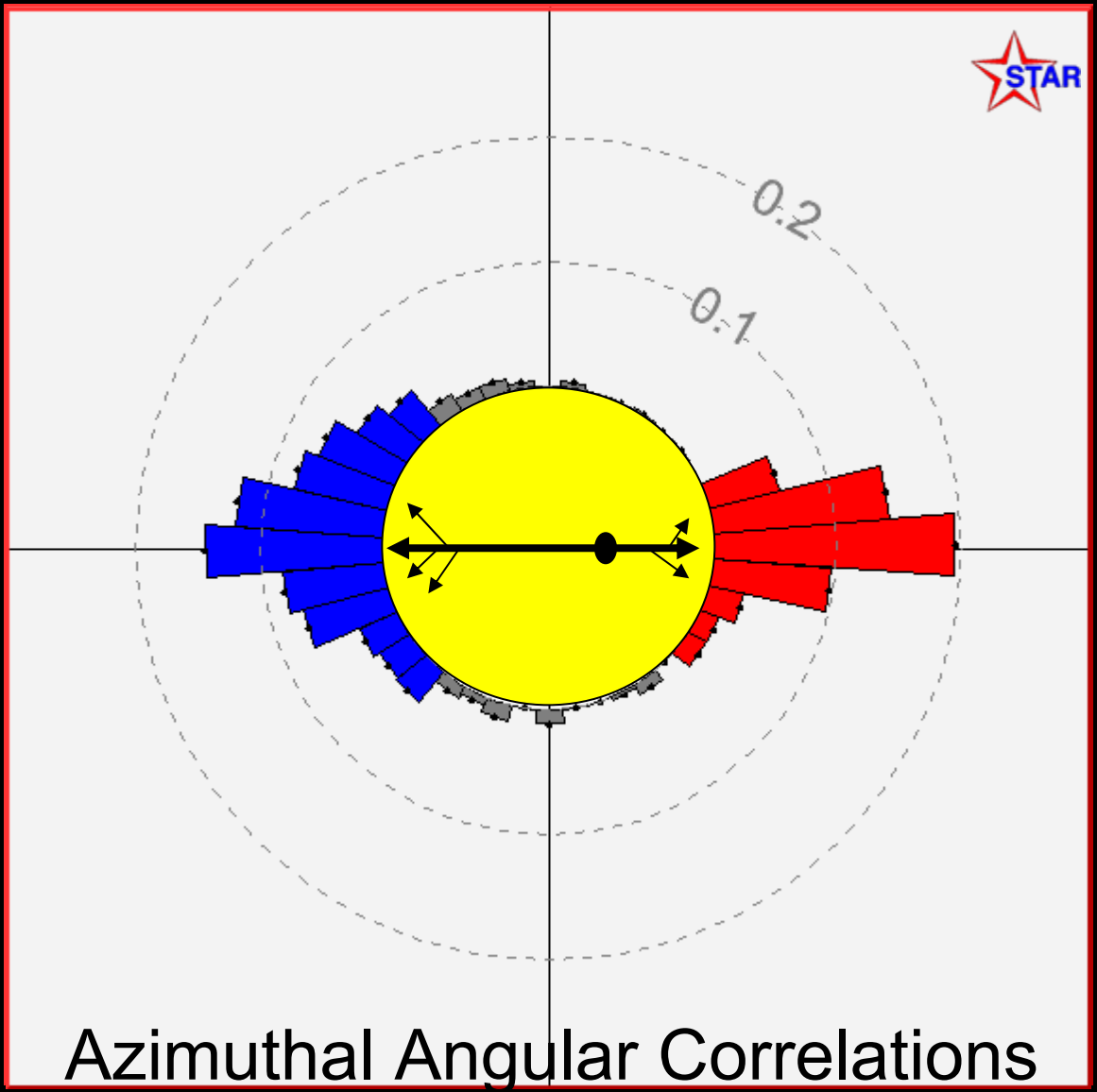
Can we see jets in high energy Au+Au?

Where Does the Energy Go?

Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

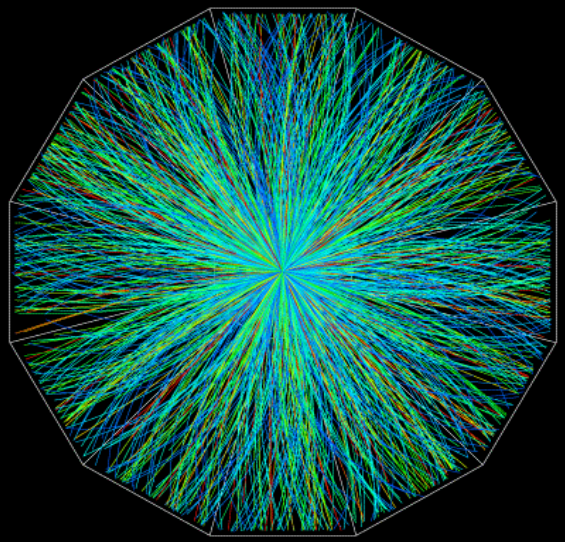


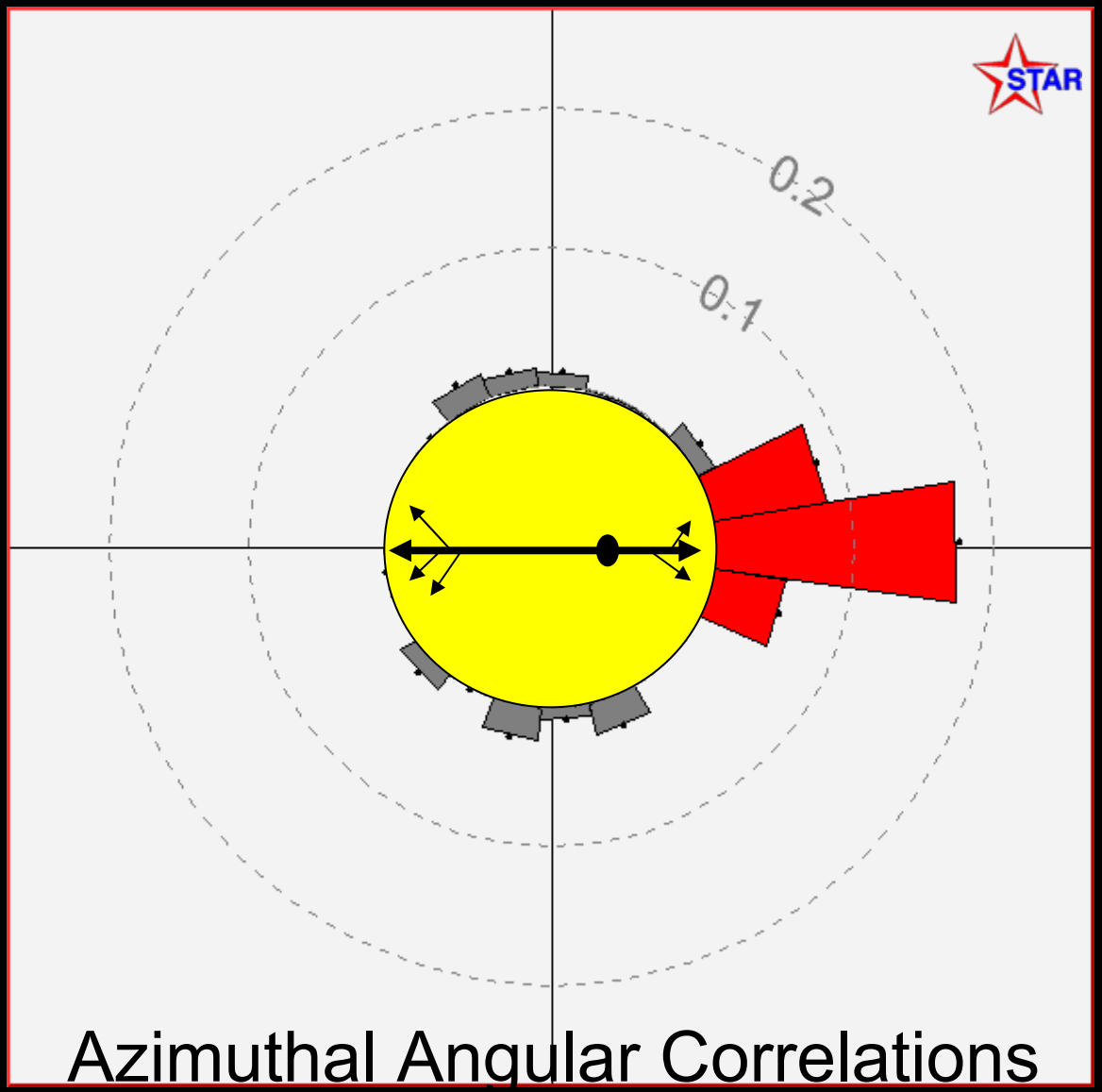


Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet disappears for particles $p_T > 2$ GeV

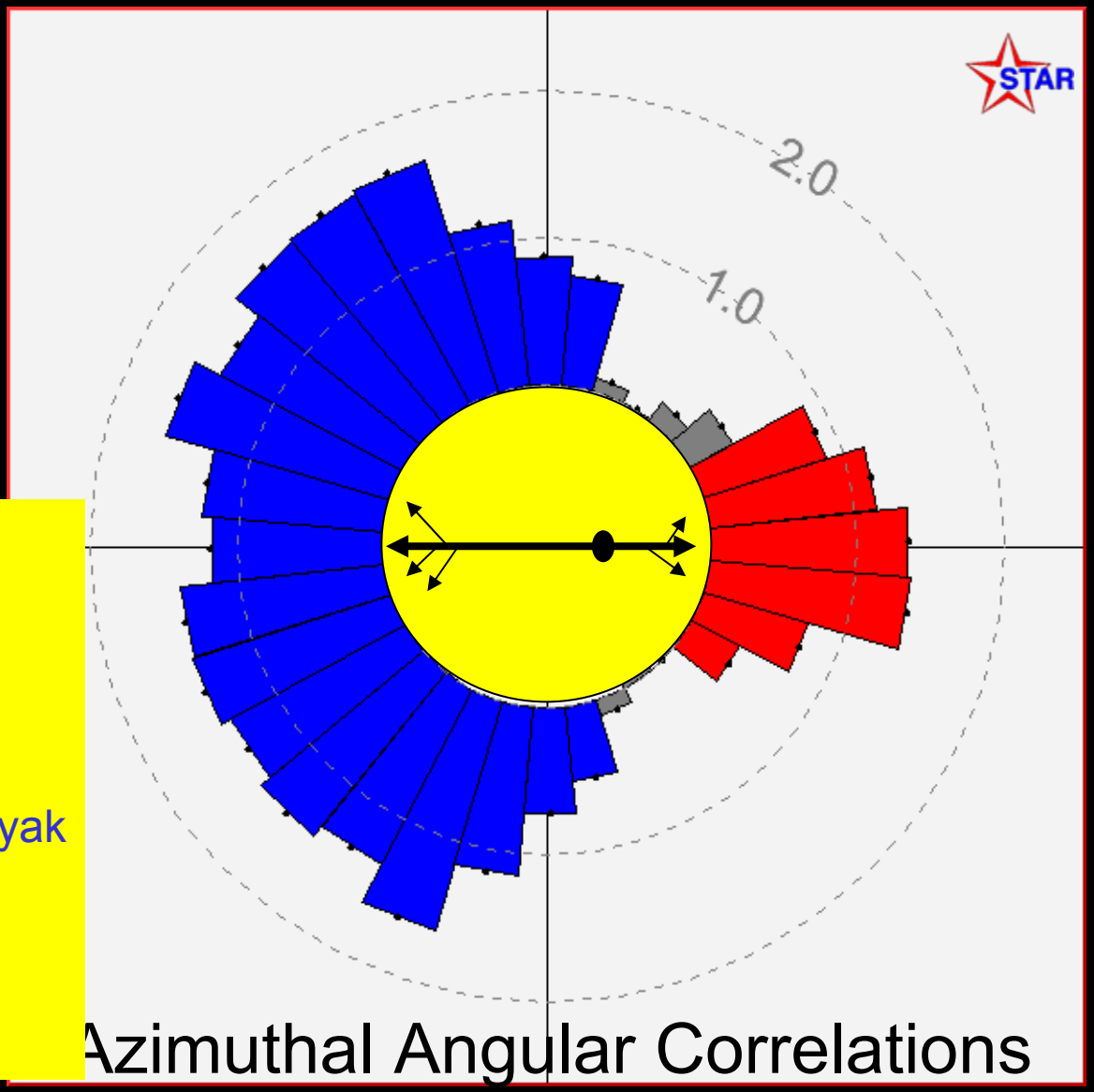




Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet reappears in particles $p_T > 200$ MeV



Color wakes?

J. Ruppert & B. Müller

Mach cone from sonic boom?

H. Stoecker

J. Casalderrey-Solana & E. Shuryak

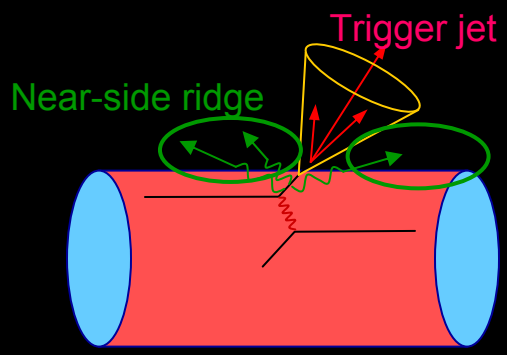
Cherenkov-like gluon radiation?

I. Dremin

A. Majumder, X.-N. Wang

Lost energy of away-side jet is redistributed to rather large angles!

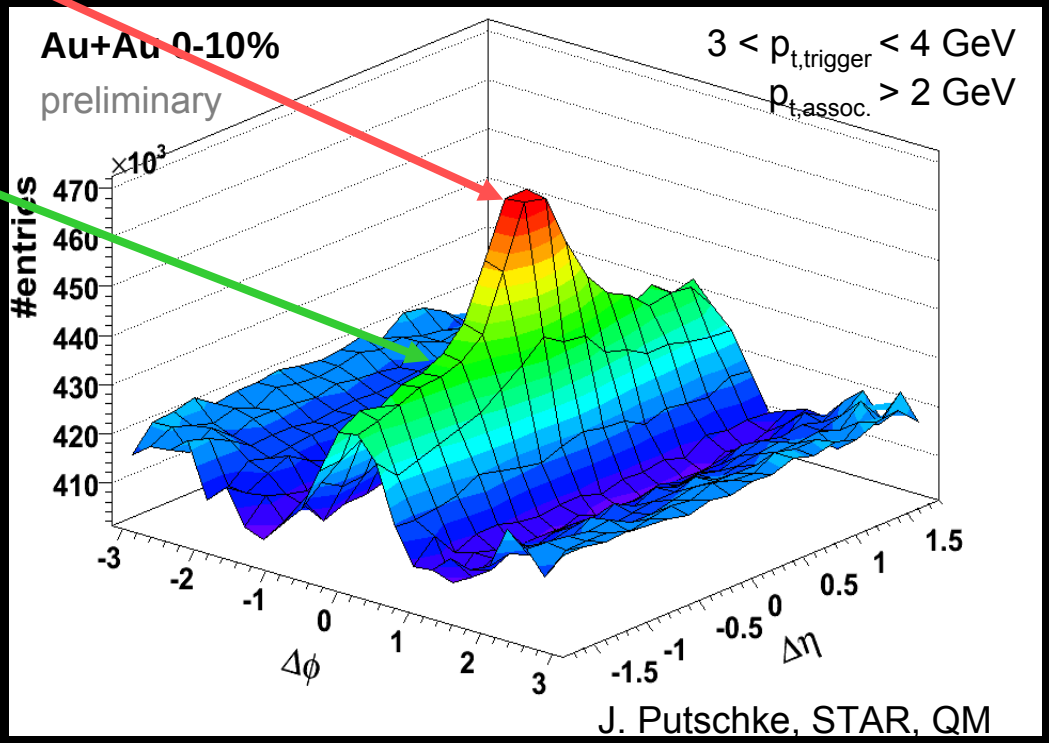
A Near-side "Ridge" Appears!



Di-hadron correlations

Trigger Jet (near-side)

Near-side ridge



Jets: scale with # of binary collisions

Ridge: exists to highest p_T (trig) → correlated with jets

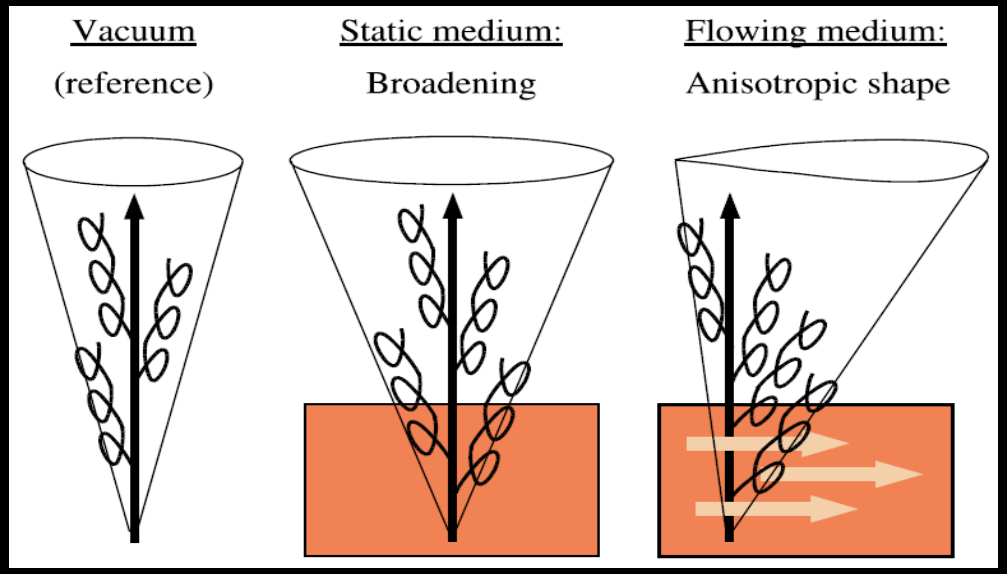
But ridge spectra same as medium ('bulk-like', seen for mesons/baryons)

→ thermal spectra + flow origin? or jet-heating?

Possible "Ridge" Mechanisms So Far

References to proposed explanations so far:

- Radiated gluons, broadened by
  - Longitudinal flow, Armesto et al, PRL 93 (2004)
  - Color magnetic fields, Majumder et al, hep-ph/0611035
- Medium heating + recombination, Chiu & Hwa PRC72, 034903
- Radial flow + trigger particle bias, Voloshin nucl-th/0312065, N.P. A749, 287
- Initial parton scatter + Jet-medium interactions, C.Y. Wong, hep-ph/07072385



The suppression of high p_T hadrons and the quenching of jets indicates the presence of a high density, strongly-coupled colored medium. !

Conclusions about a QGP at RHIC (for reference)

- Large $\varepsilon > \varepsilon_c$ ($T > T_c$) system – QCD vacuum "melts" – NOT hadrons
- Thermalized system of quarks and gluons – NOT just q & g scattering

  Large elliptic & radial flow $\rightarrow$ fluid flow ("perfect"!)

  Heavy quark (charm) flow (not shown)

  Particle ratios fit by thermal model $\rightarrow$ $T = 177$ MeV ~ T_c (lattice QCD)
- System governed by quark & gluon Equation of State – NOT hadronic

  Flow depends upon particle (constituent quark & gluon) masses

  $\rightarrow$ QGP EoS,, quark coalescence
- Deconfined system of quarks and gluons – NOT hadrons

  Flow already at quark level, charmonium suppression (tbd)
- NOT a Weakly-interacting QGP (predicted by Lattice QCD)

  Strongly interacting quarks and gluons $\rightarrow$ ….degrees of freedom (tbd)
- Strongly-interacting QGP (NOT predicted by Lattice QCD)

  Suppression of high p_T hadrons, away-side jet quenched

  Large opacity (energy loss) $\rightarrow$ extreme gluon/energy densities

  $\rightarrow$ strongly-interacting QGP (sQGP)

Future!

Geneva with Large Hadron Collider Superimposed

Starts in Spring 2008

Simple Expectations - Heavy Ion Physics at the LHC

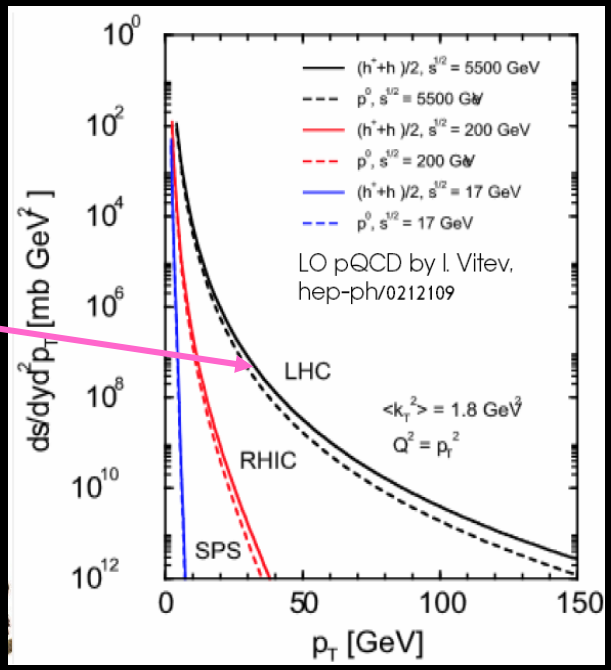
	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	factor 28
t_{form} (fm/c)	1	0.2	0.1	shorter
T / T_c	1.1	1.9	3.0 - 4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤ 2	2-4	> 10	longer-lived

Significant increase in hard scattering yields at LHC:

- jets & large p_T processes

- σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

- σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)



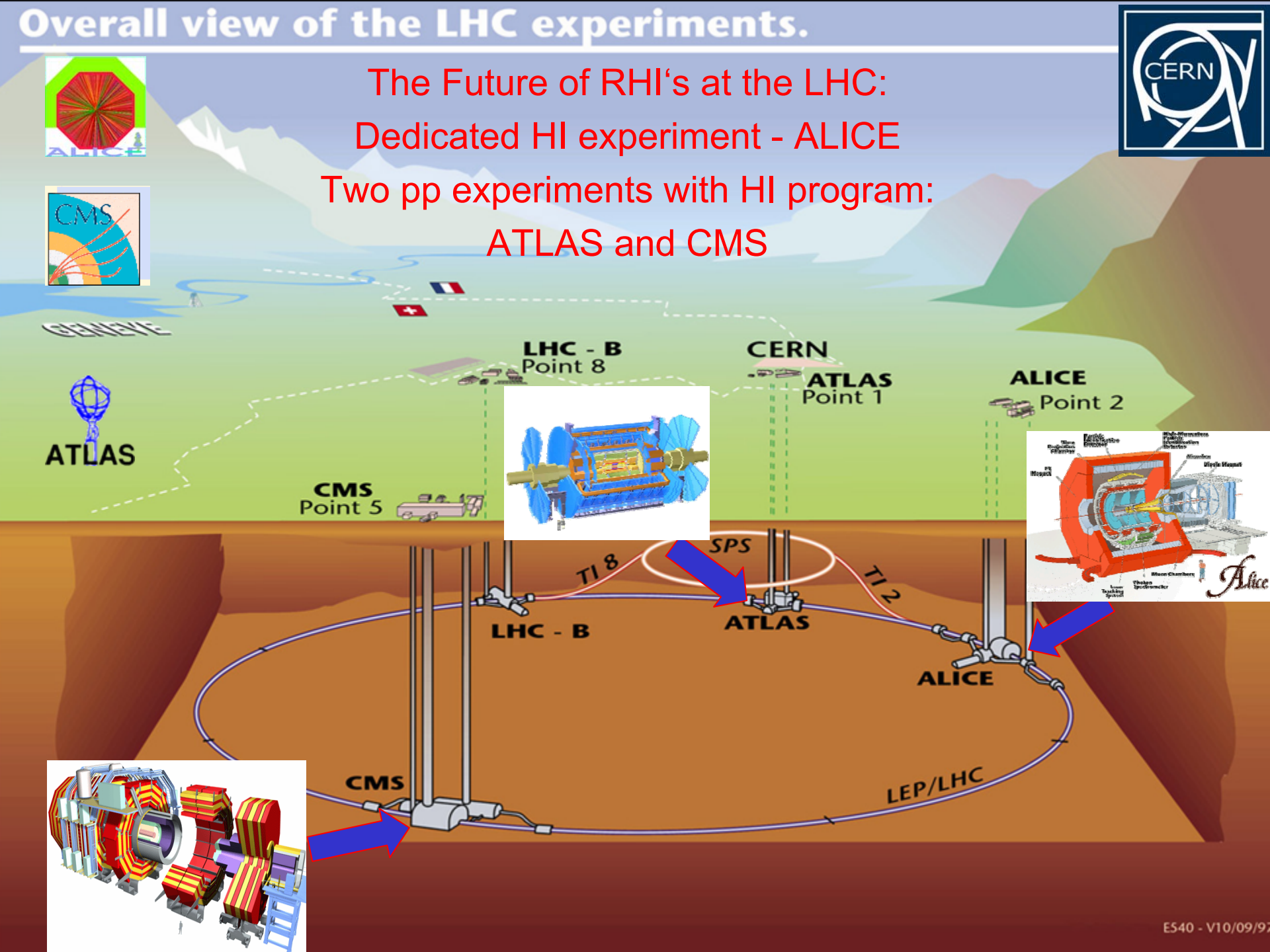
Overall view of the LHC experiments.

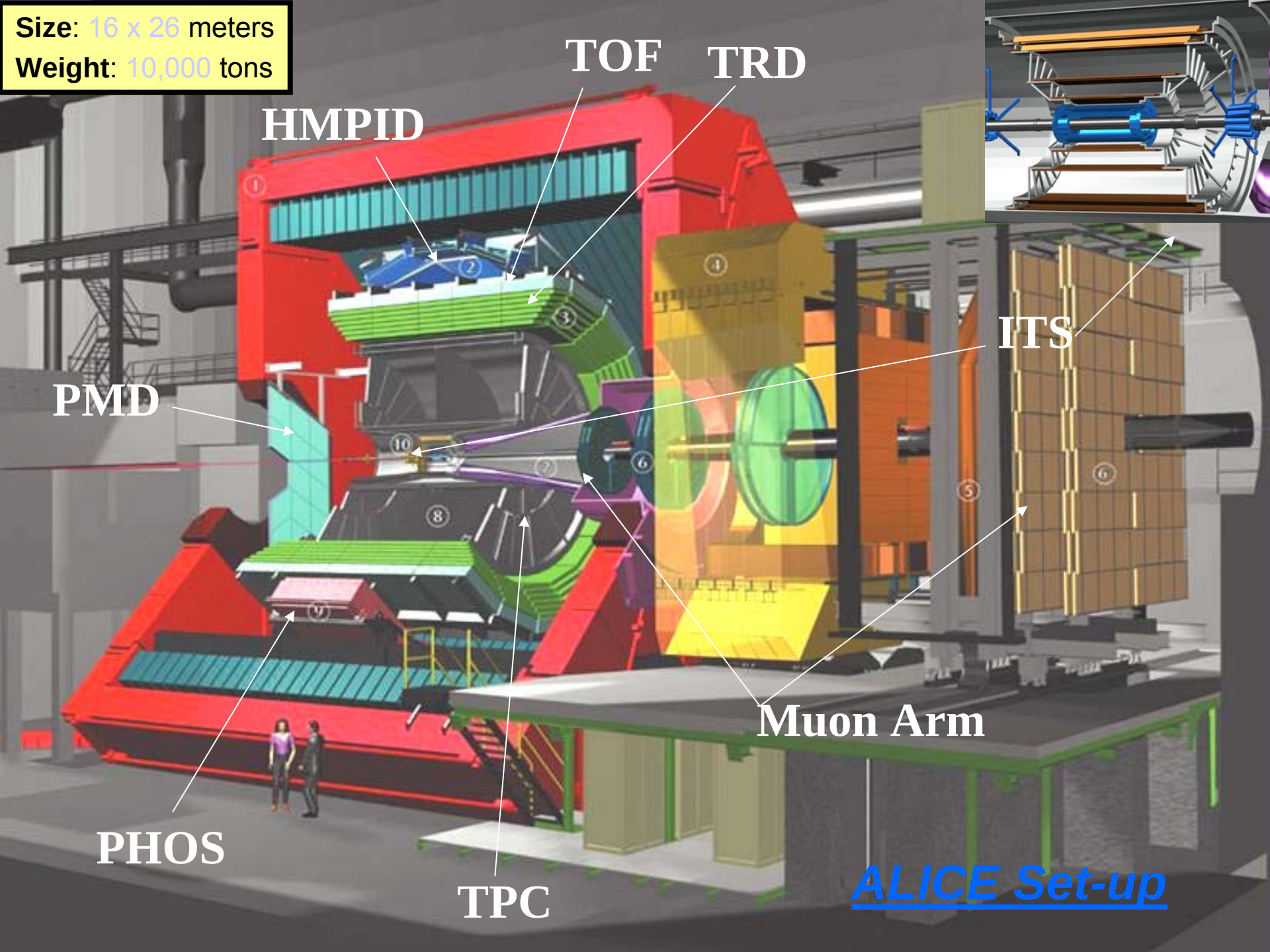
The Future of RHI's at the LHC:

Dedicated HI experiment - ALICE

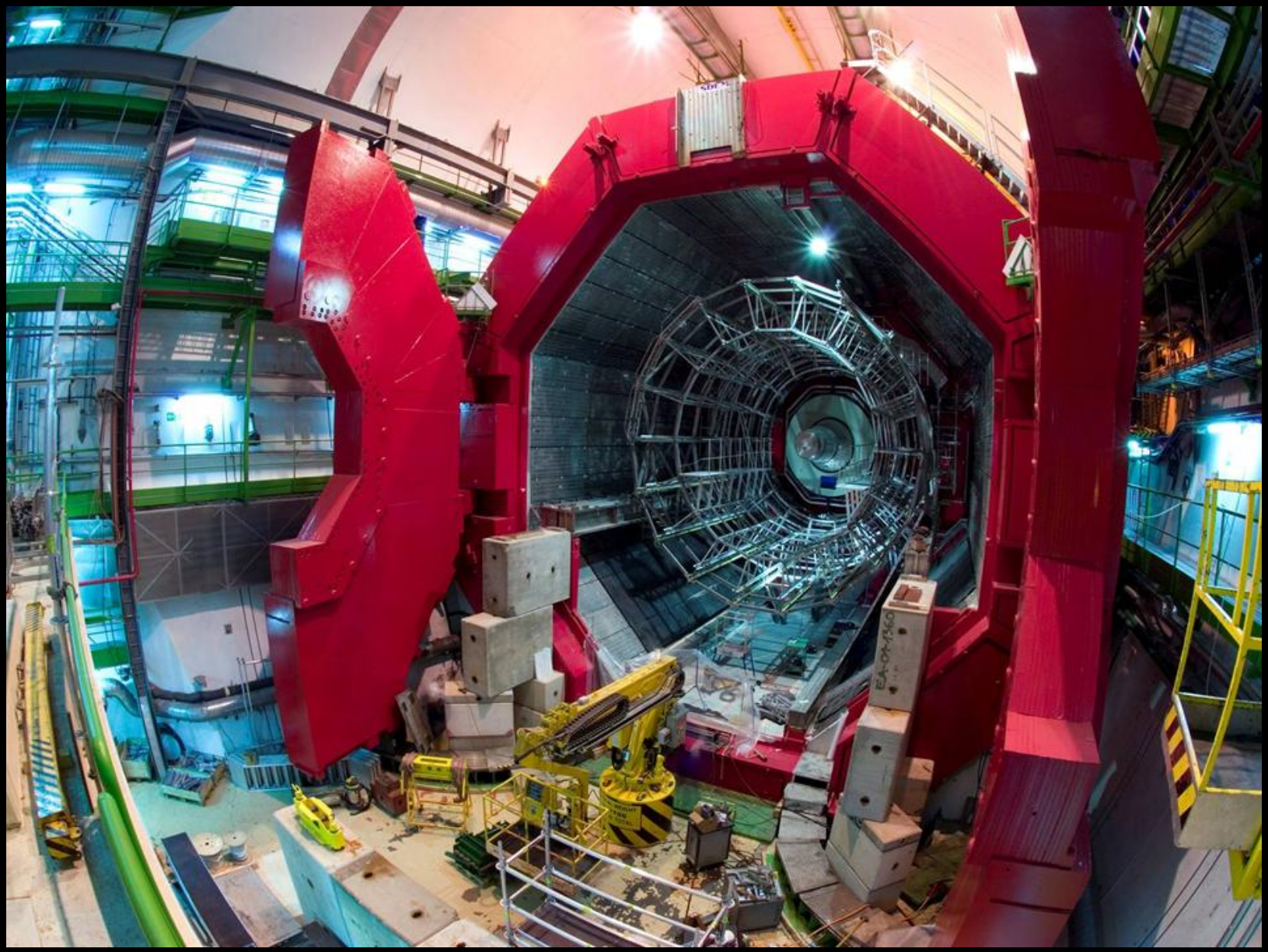
Two pp experiments with HI program:

ATLAS and CMS

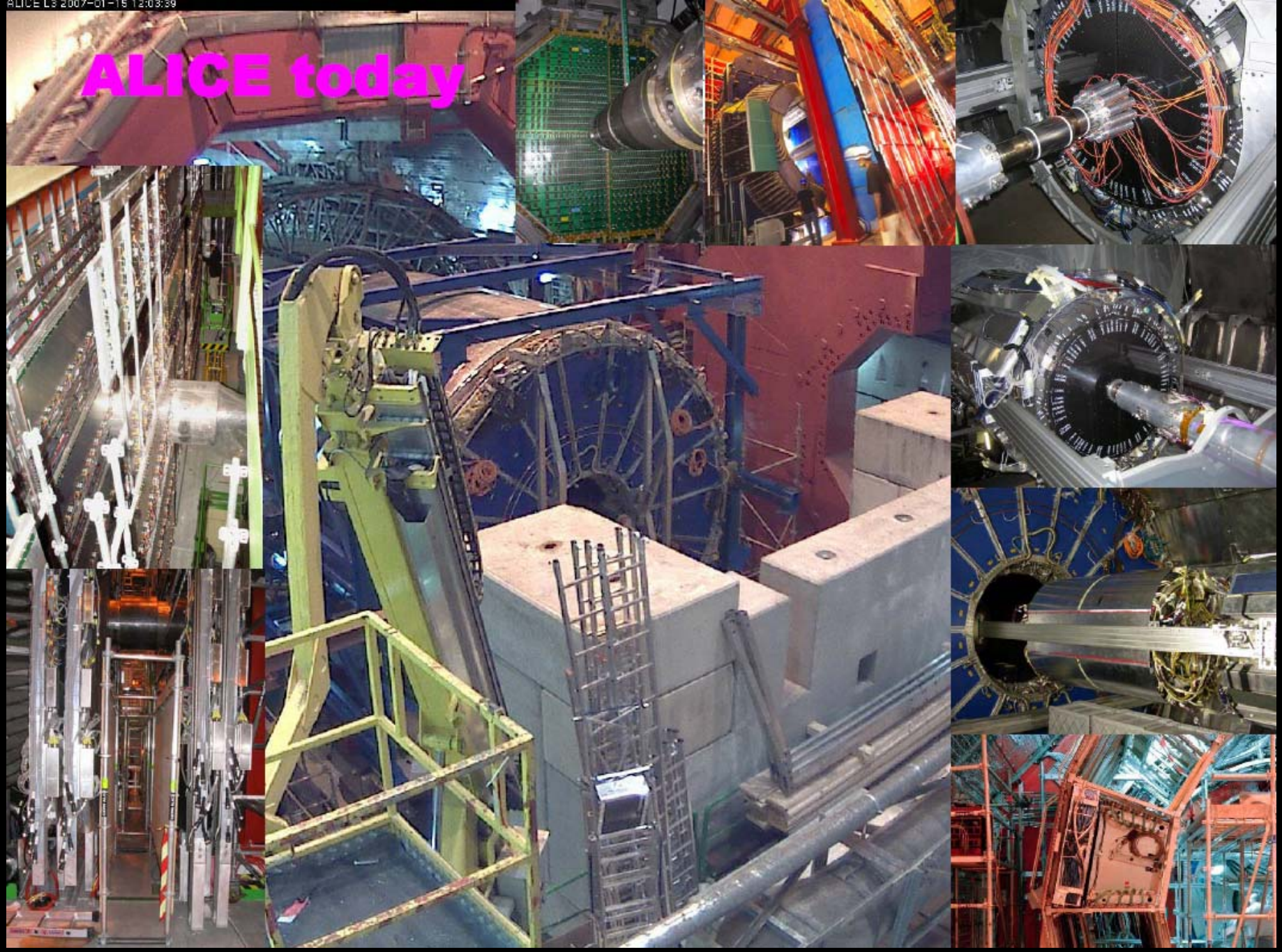



Size: 16 x 26 meters
Weight: 10,000 tons
TOF
TRD
HMPID
ITS
PMD
Muon Arm
PHOS
TPC
ALICE Set-up

A View of ALICE Before Detector Installation



ALICE today



The Quark-Gluon Plasma at RHIC & LHC – Today's Perspective

So far at RHIC:

Elliptic Flow	→	Near-perfect Fluid
High p_T Suppression	→	Strongly-coupled QGP
Jet Quenching	→	Strongly-coupled QGP
Away-side of jet	→	Energy dissipation/propagation in medium
		Medium properties?
Near-side Ridge	→	Something new, unresolved
		Heating of the system
		Longitudinal expansion?
		Initial parton distributions?
		Initial parton bremsstrahlung + flow?

RHIC and LHC:

Cover 2 – 3 decades of energy ($\sqrt{s_{NN}}$ ~ 20 GeV – 5.5 TeV)

What are the properties of hot QCD in this temperature range (T ~ 150 – 600 MeV)?

The Quark-Gluon Plasma at RHIC & LHC – Today's Perspective

At LHC:

Is the QCD phase diagram feature-less at 1 – 4 T_c?

What happens as we go up in T (e.g. coupling)?

Are there new phenomena?

What's the range of theoretical validities (non-pQCD, pQCD, strings)?

Measure/understand parton energy loss at the fundamental level

Establish flavor (gluon and quark mass) dependence

Use jets and/or photons to establish hard-scattered parton energy

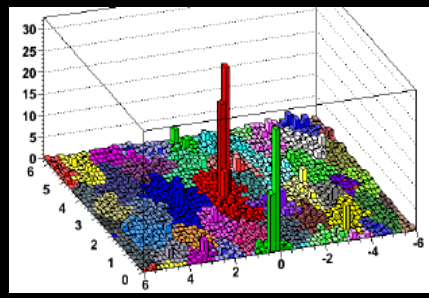
Jet modifications - longitudinal & transverse "heating"

Medium response to jet-heating (near- and away-side)

Measure/use open charm and beauty decays (also as jet-tags)

$c\bar{c}$ and $b\bar{b}$ states (T_i, screening/suppression, enhancement?)

Direct Photon Radiation?



Developments in theory (lattice, hydro, parton E-loss, string theory…)

"the next frontier!"

Special Thanks for Contributions to This Presentation!!

Miklos Gyulassy

Peter Jacobs

Mike Lisa

Thomas Ullrich

Urs Wiedemann