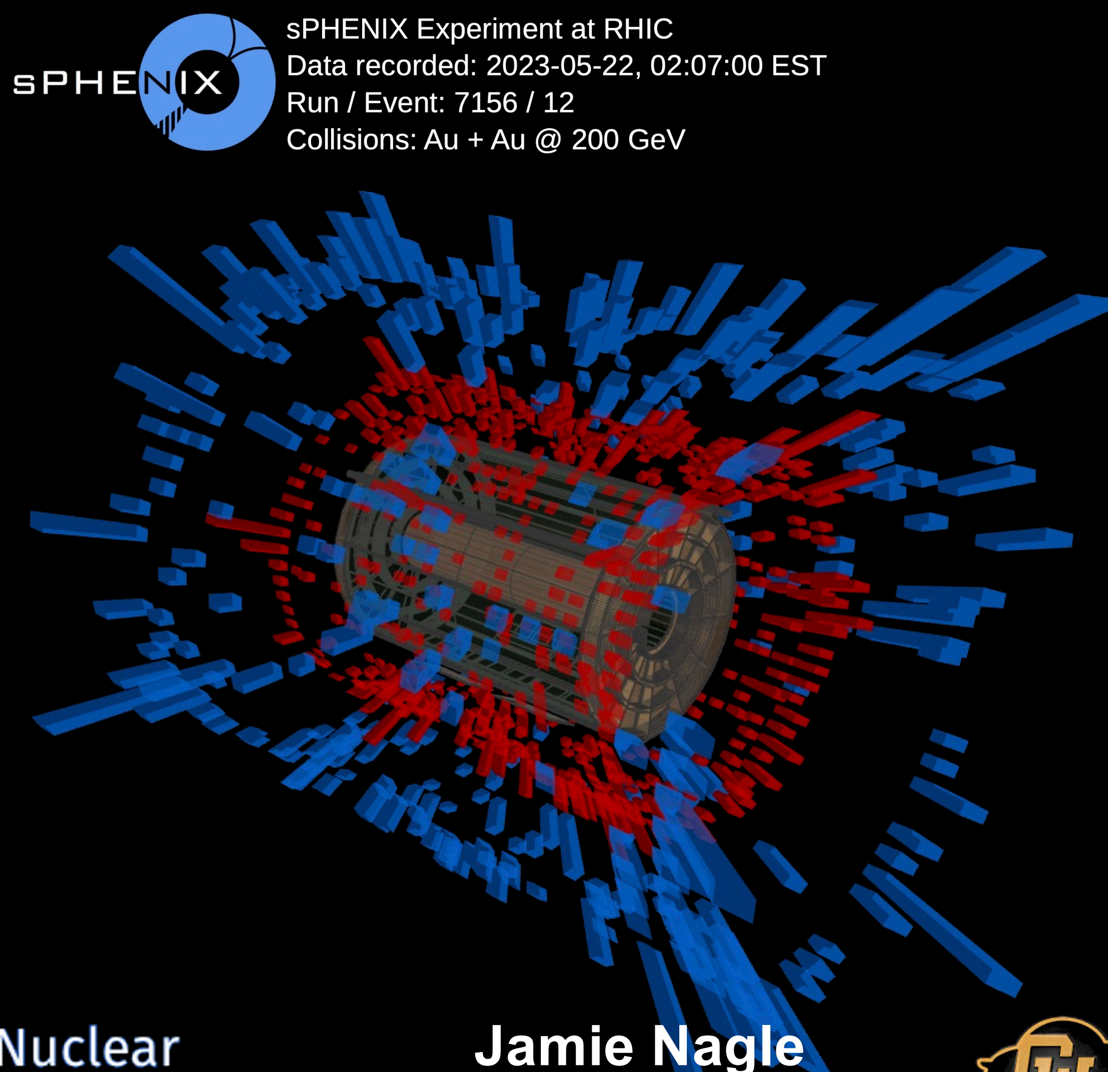
Lecture #1

A Pedestrian's Guide to Heavy Ion Physics



UC RIVERSIDE | 2023 National Nuclear Physics Summer School

Jamie Nagle
University of Colorado

Lecture Philosophy

- Less is more, i.e., not meant to be comprehensive
- Keep It Simple Stupid (KISS) principle…
- Even the experts often miss the big questions…
- Take away goals…

  - an appreciation for the science
  - excitement of the field
  - some details on experimental methods
  - open questions and opportunities for discovery by young people such as yourselves

Let me know if there are specific things you want to hear

Simplest Goals

Emergent Phenomena…

Collectivity…

What is the underlying origin?

For this flock of birds, it is all short-range interactions (amazing!)

Emergent Phenomena

Connection from the QCD Lagrangian to phenomena of confinement and asymptotic freedom was fundamental

Connection from QCD to the emergent phenomena of near perfect fluidity of the Quark-Gluon Plasma is just as fundamental

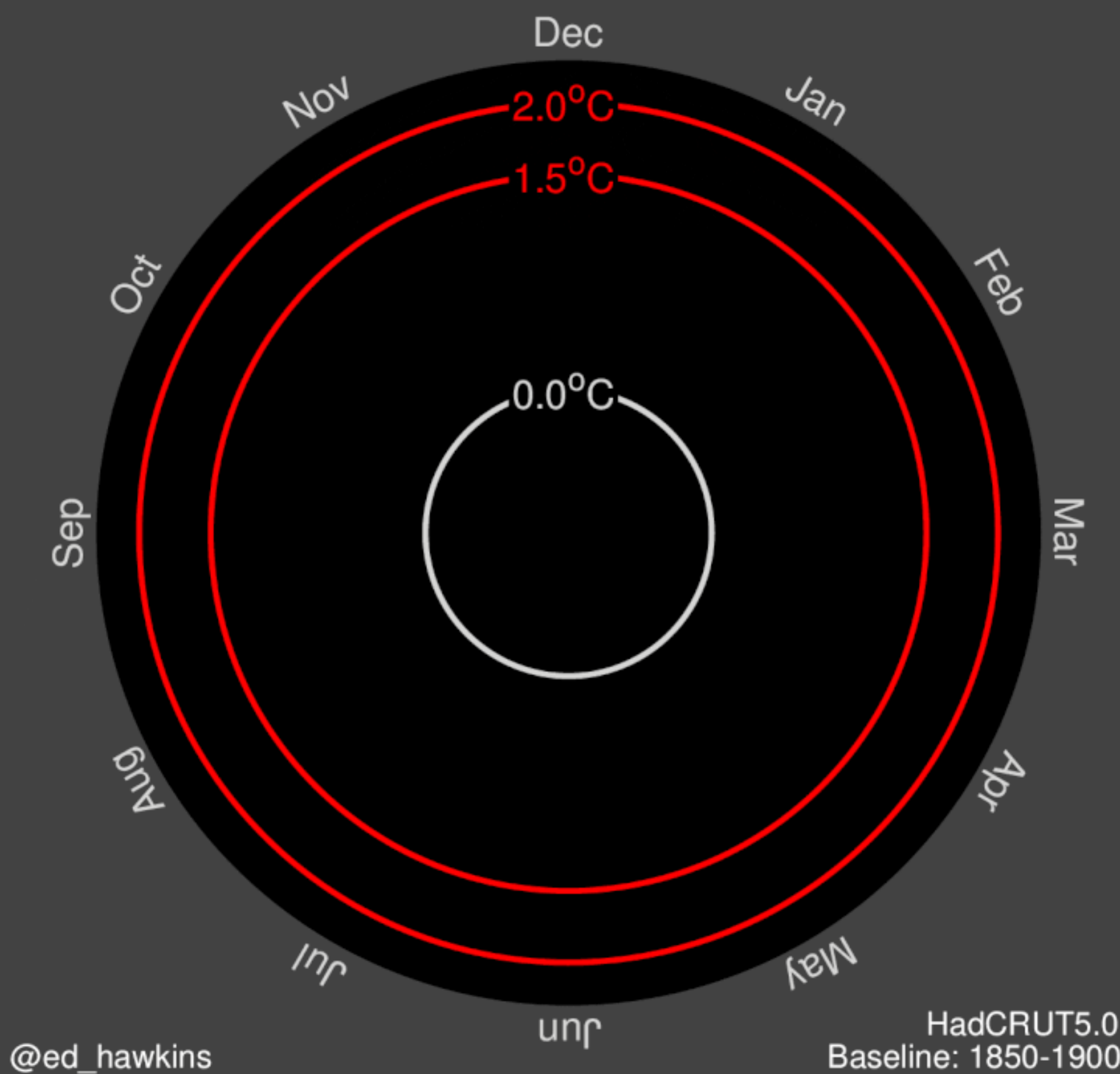
Perfect fluidity tells us the nature of the QGP,
more importantly we need to reconcile:

Most important discovery in field: perfect fluid

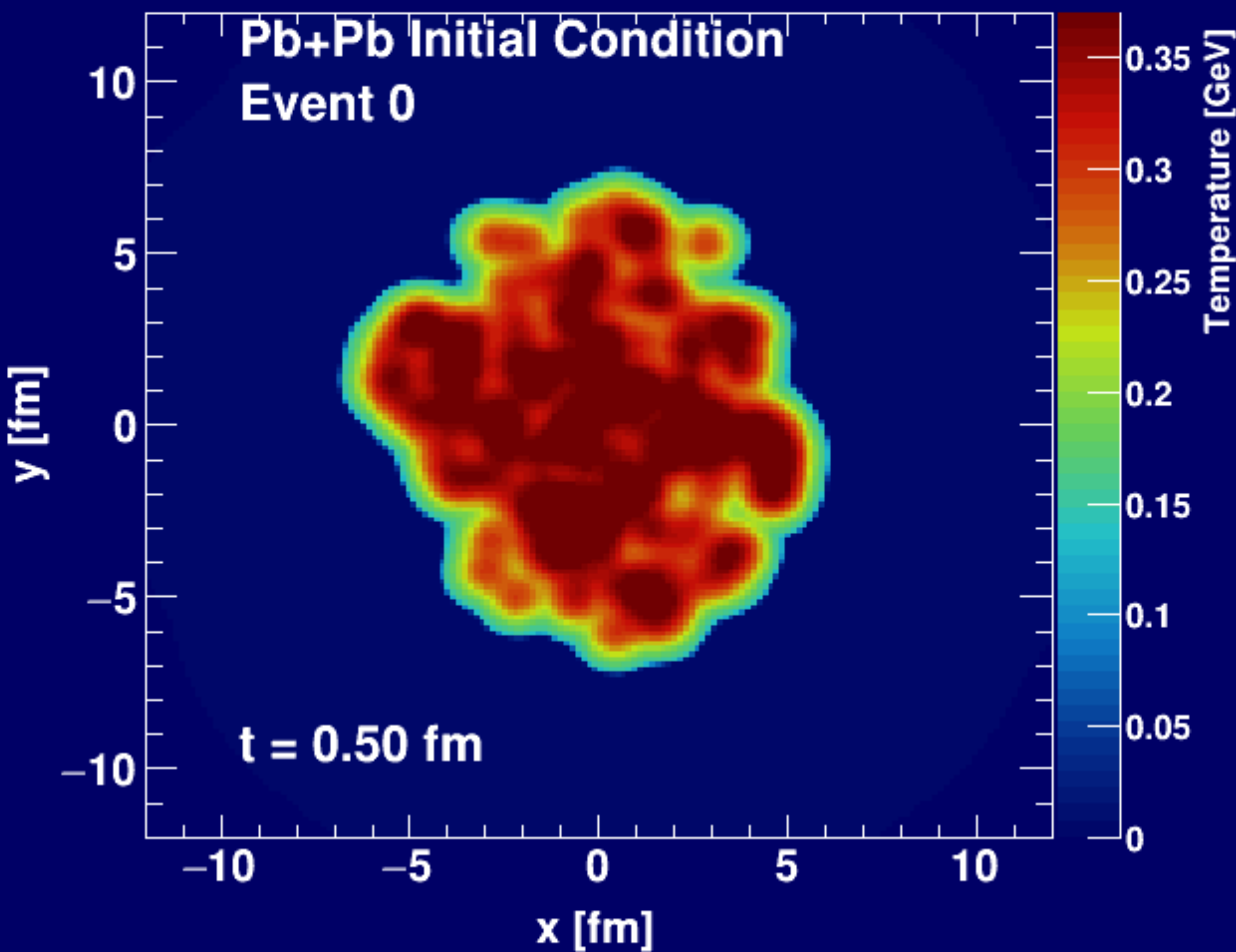
&

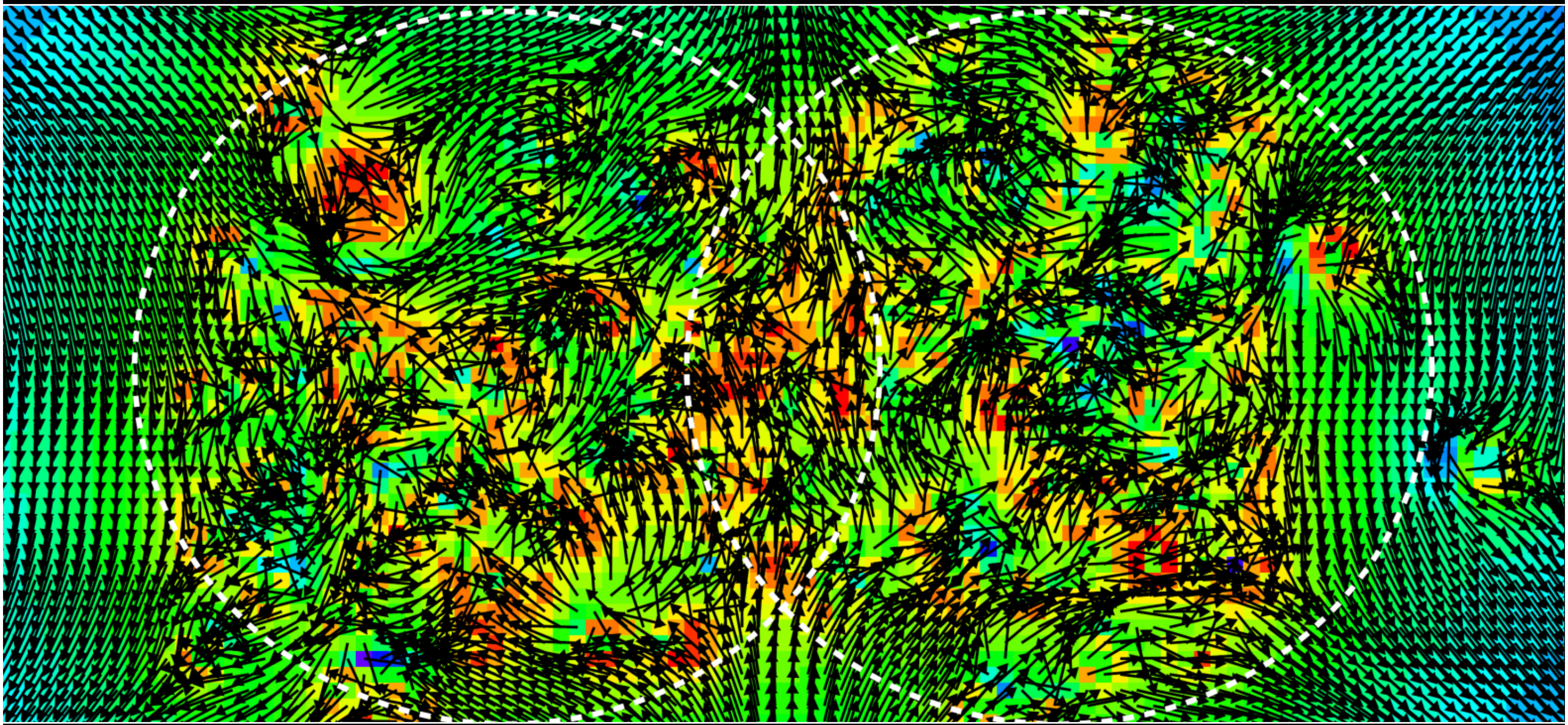
Crucial part of QCD: weak coupling at short distances

Global temperature change (1850-2020)



Jet Quenching Probes of QGP Fluid

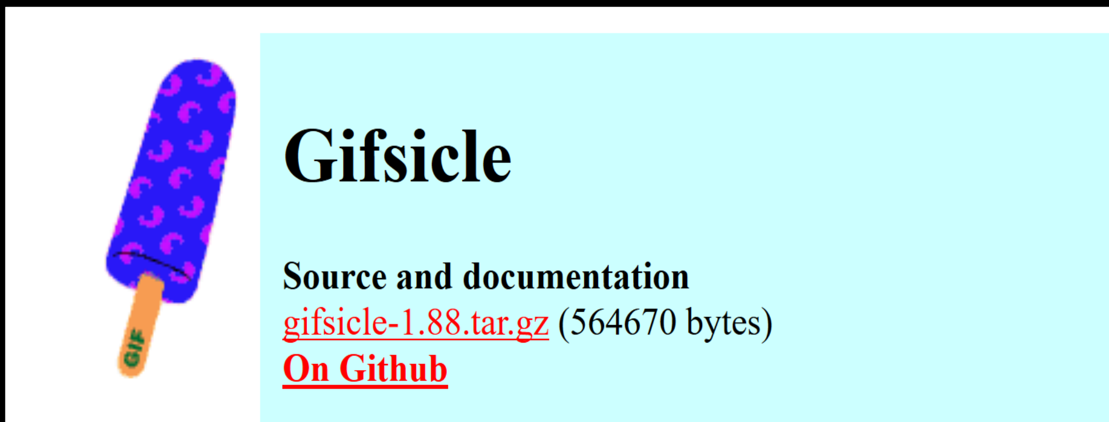




https://journals.aps.org/prc/abstract/10.1103/PhysRevC.96.024901

Easy Tools

https://www.lcdf.org/gifsicle/



Wild animations are distracting, but key visualizations stick with people.

Make your own!

Create your own ideas and borrow only selectively. The more important the talk, the more important it is to show your thoughts…

Data thief programs allow you to choose which data sets to show, re-fit your model, etc.

Side note to students…

1) Data visualization is very important

2) Leads to breakthroughs via more intuitive and physical picture

3) Most talks only get across 2-3 items that a given audience member will recall later

What take aways did you get from last week's lectures for example?

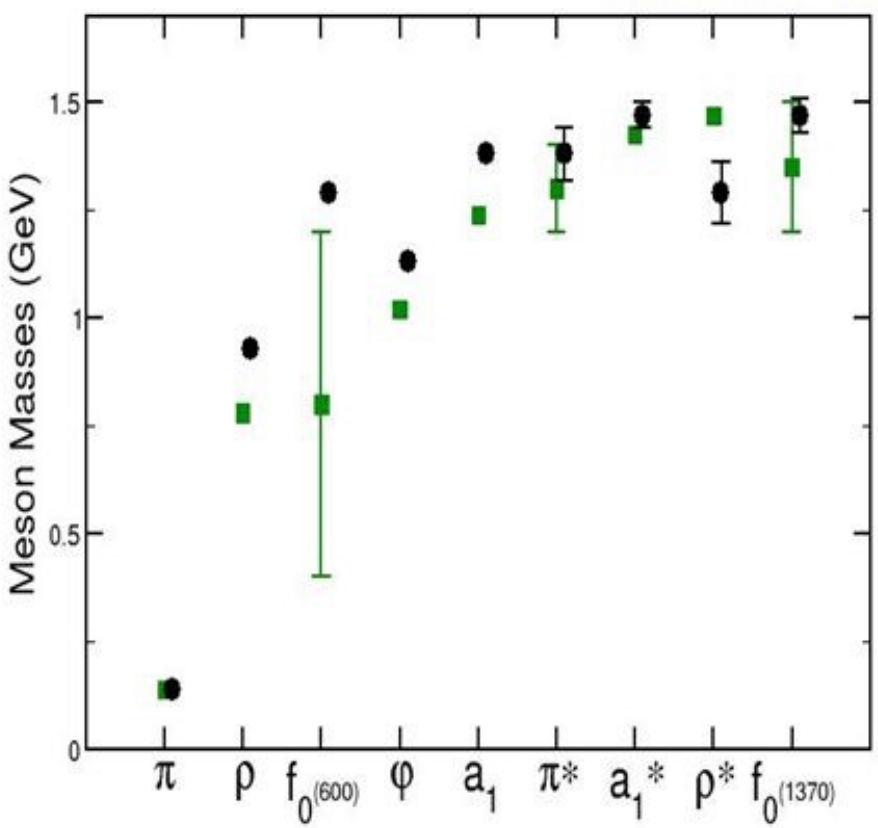
A Brief History of Time (in Heavy Ions)

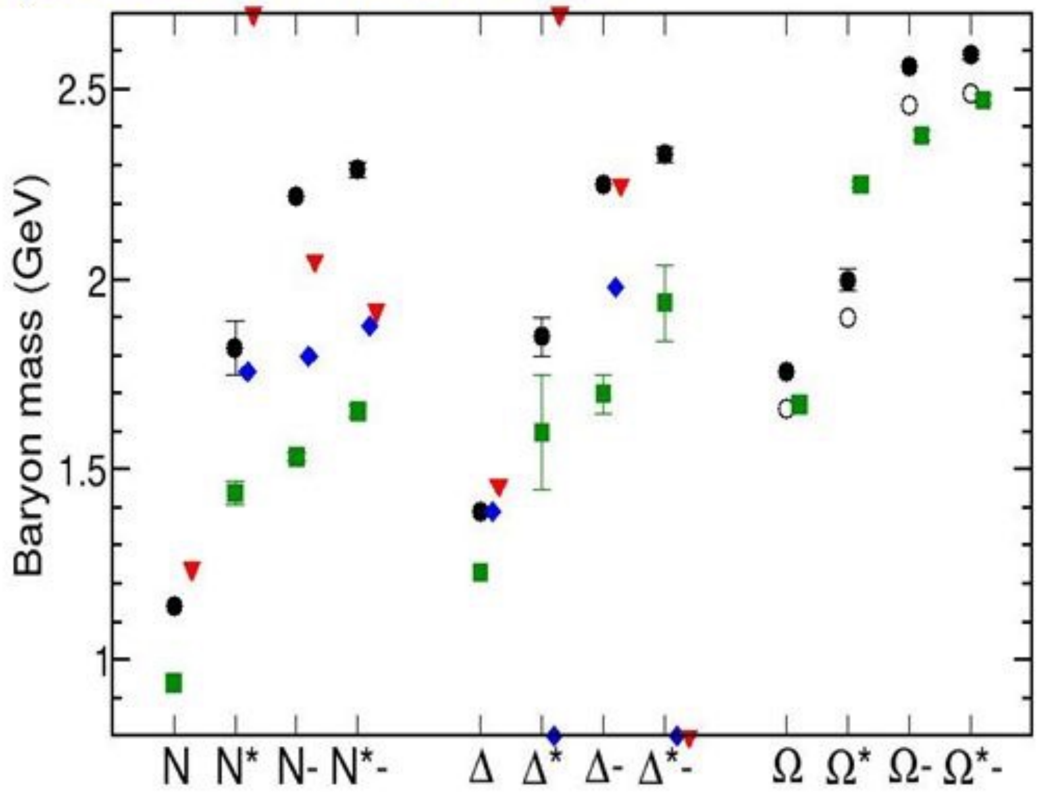
A long time ago in a galaxy far, far away....

History can be boring,
though often early in a new field is when the most basic questions are discussed openly.
Later people often focus too much on the latest details.

Start in 1950s → Hadron Zoo

Mesons **Baryons**





- More and more hadrons being discovered.
- Too many to be fundamental particles?
- Hadrons are strings (interesting history).

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

R. Hagedorn

CERN - Geneva

A B S T R A C T

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp(\frac{m}{T_o}).$$

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.

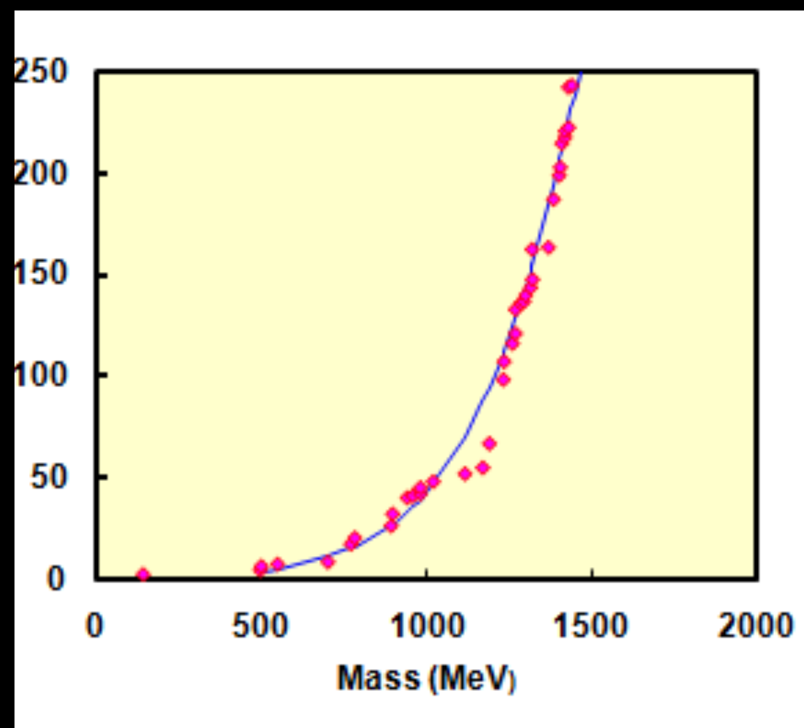
Another consequence is the prediction that the elastic amplitude $A(s,t)$ should decrease as $\sim \exp(-p_\perp / 2T_o)$ for any non-zero fixed scattering angle and $s \to \infty$.

For astrophysics the present theory puts some doubt on the neutron-star model for the interior of collapsing stars; at the same time it suggests a straightforward improvement.

http://cds.cern.ch/record/346206

Circa 1965 Hagedorn observed that these hadrons had an exponentially increasing density of states ρ(n)

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp(\frac{m}{T_o}).$$



Modern era compilation from PDG by Zajc

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

R. Hagedorn
CERN - Geneva

ABSTRACT

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

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For astrophysics the present theory puts some doubt on the neutron-star model for the interior of collapsing stars; at the same time it suggests a straightforward improvement.

Think about adding more and more energy to a system…

- Excite more states
- Give states more energy, i.e., a higher Temperature

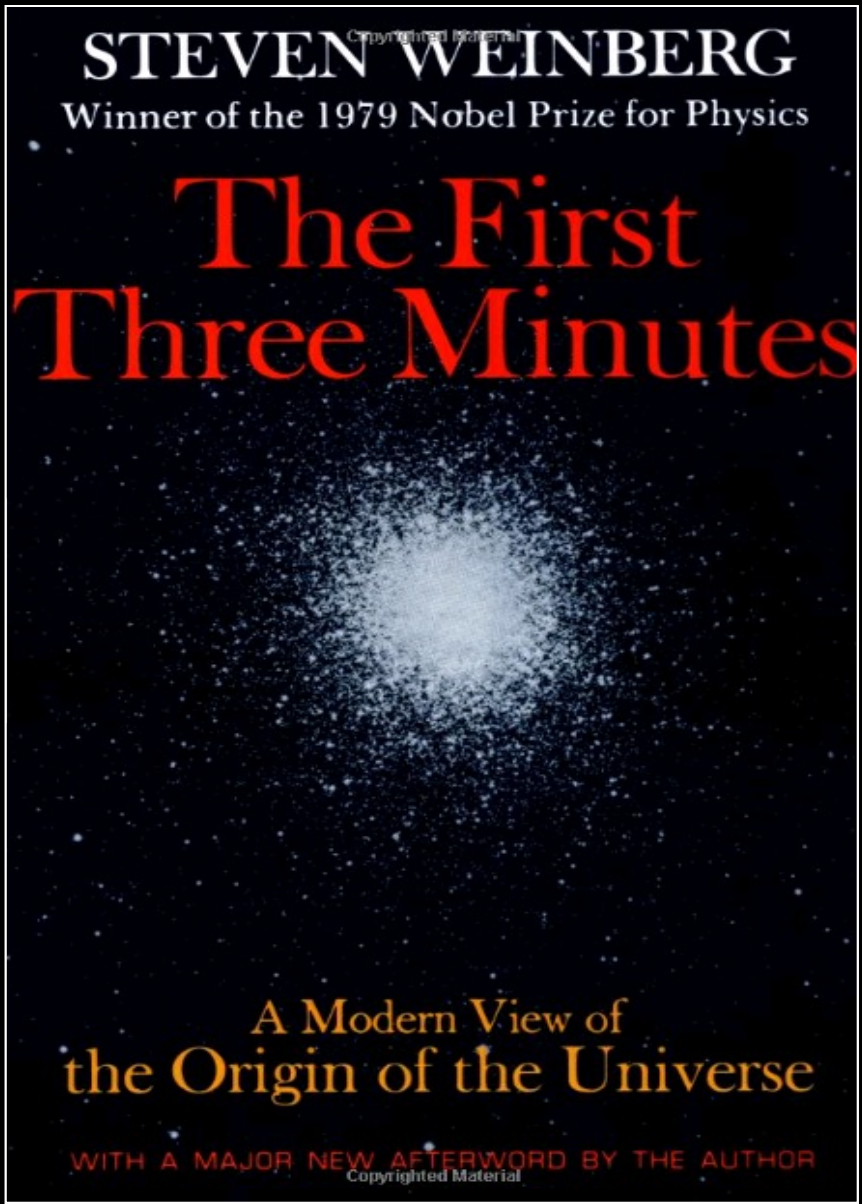
Equipartition Theorem

With exponentially increasing number of states, all the energy goes in to equally exciting these states, and not more energy per state.

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions.

"**Ultimate Temperature** in the Early Universe"

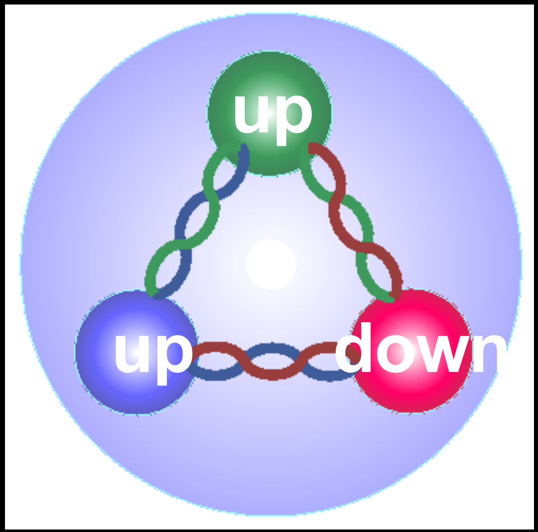
K. Huang & S. Weinberg, Phys Rev Lett 25, 1970.

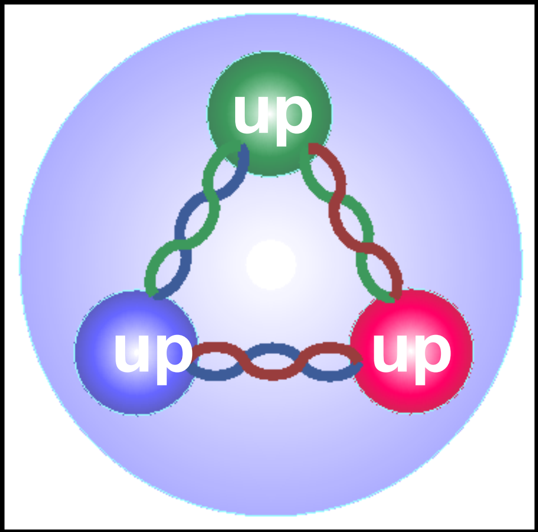


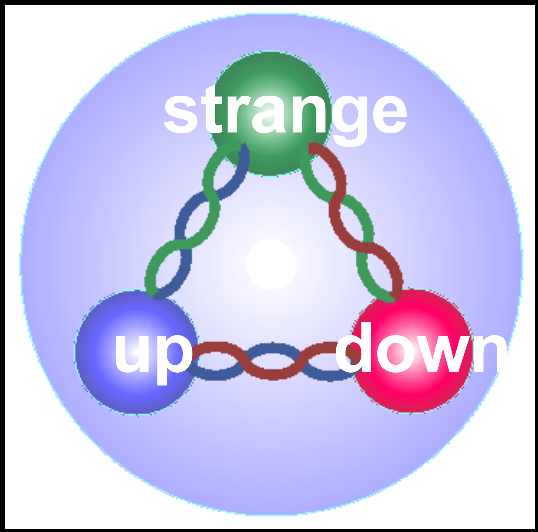
"…a veil, obscuring our view of the very beginning"

Steven Weinberg, *The First Three Minutes* (1977).

Quark Model







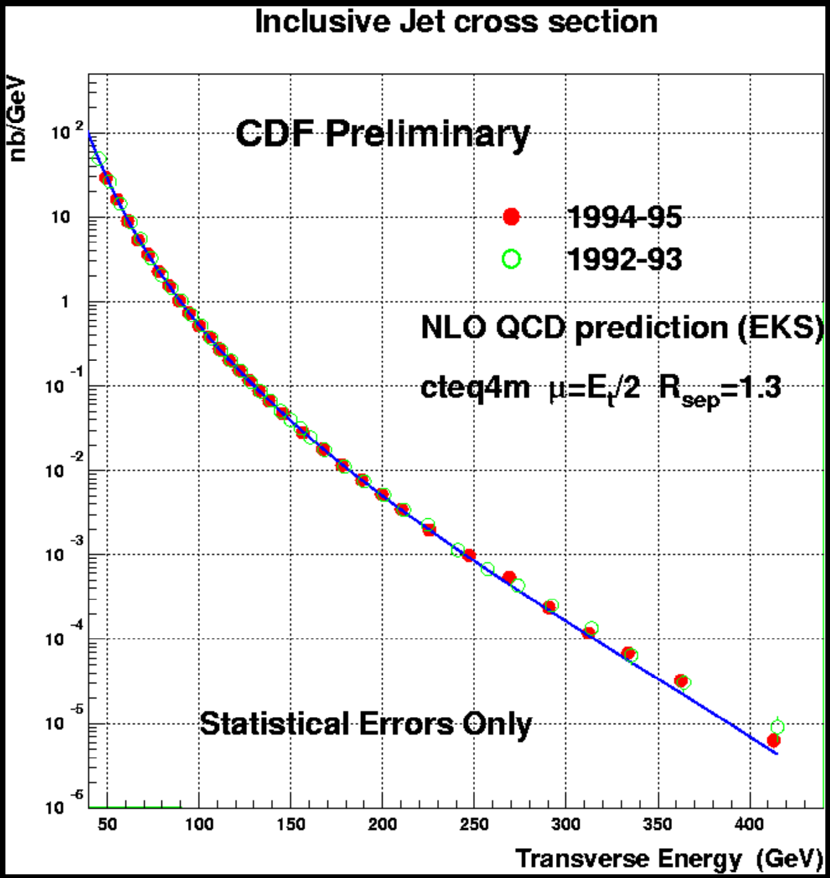
Proton Δ^{++} Λ

New degrees of freedom inside hadrons.

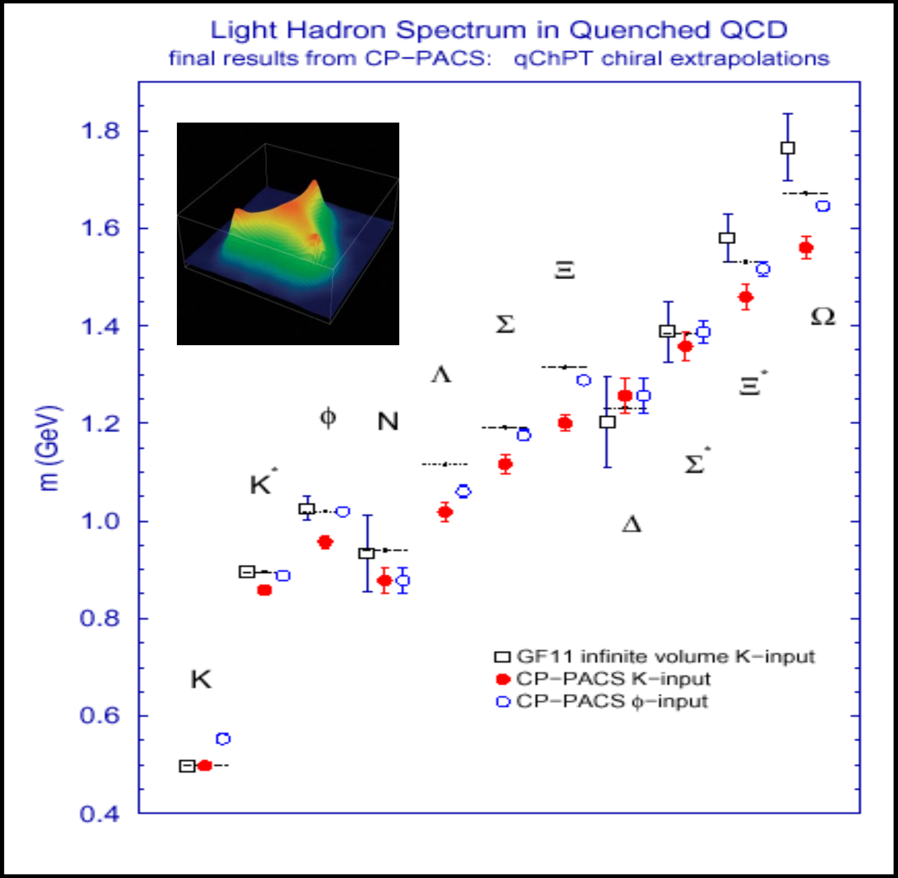
Rapidly people started to think about *Quark Matter* as being relevant at these very high temperatures.

We have strong evidence that QCD is the correct theory of the strong interaction

Perturbative Calculations



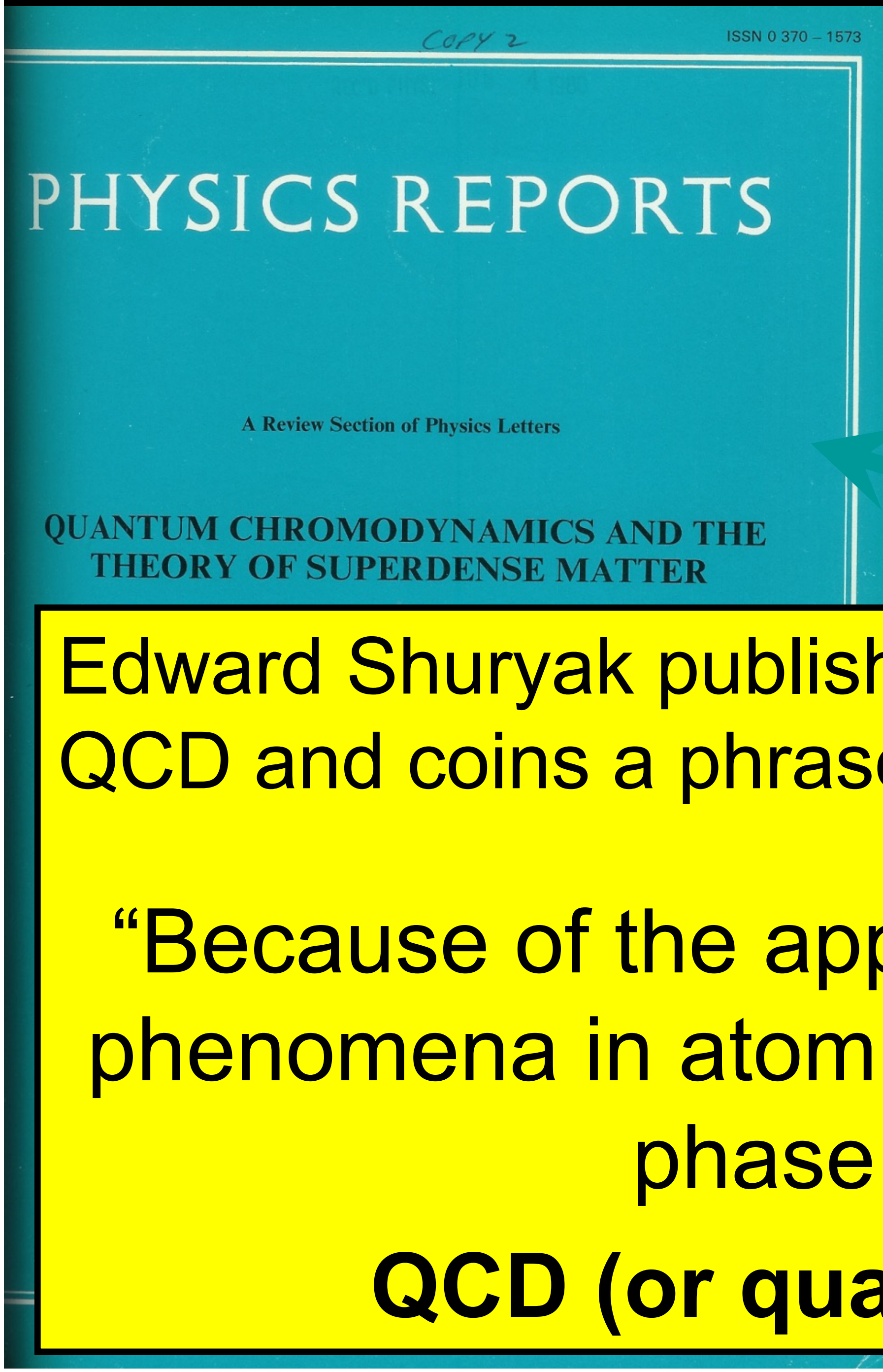
Lattice Calculations



The field is about understanding
emergent phenomena from QCD,
just like condensed matter physics from QED.

Quark-Gluon Plasma

Birth of a Name

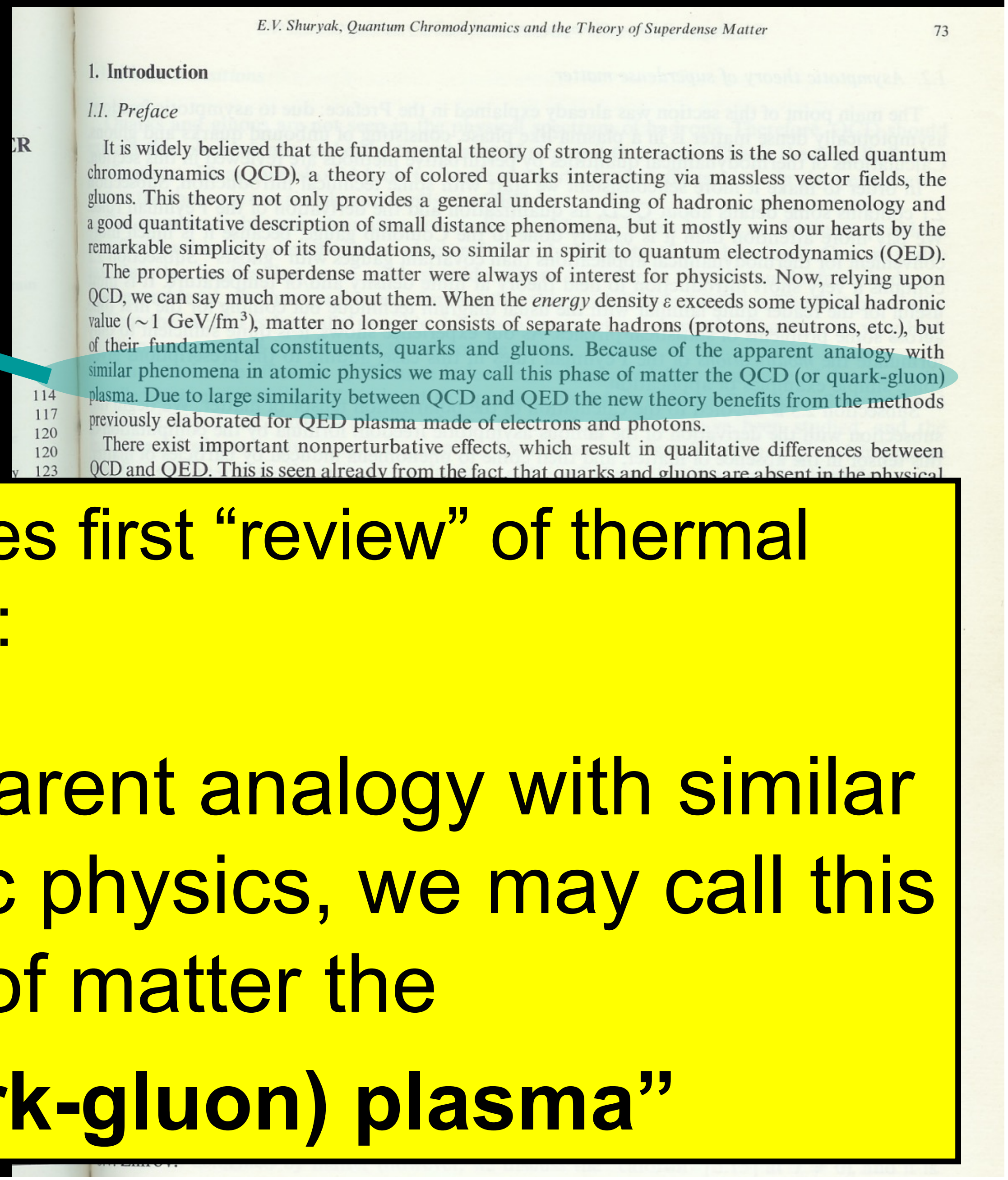


ISSN 0 370 – 1573

PHYSICS REPORTS

A Review Section of Physics Letters

QUANTUM CHROMODYNAMICS AND THE THEORY OF SUPERDENSE MATTER



1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact that quarks and gluons are absent in the physical

Edward Shuryak publishes first "review" of thermal QCD and coins a phrase:

"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the

QCD (or quark-gluon) plasma"

Melting the Hadrons

Can we melt the hadrons and liberate these quark and gluon degrees of freedom?

$$\varepsilon = g\frac{\pi^2}{30}T^4$$

Energy density for “g” massless d.o.f.

$$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$$

Hadronic Matter: quarks and gluons confined
For T ~ 200 MeV, 3 pions with spin=0

$$\varepsilon = \left\{2\cdot 8_g + \frac{7}{8}\cdot 2_s\cdot 2_a\cdot 2_f\cdot 3_c\right\}\frac{\pi^2}{30}T^4$$

Quark Gluon Matter:
8 gluons;
2 quark flavors, antiquarks,
2 spins, 3 colors

$$\varepsilon = 37\cdot\frac{\pi^2}{30}T^4$$

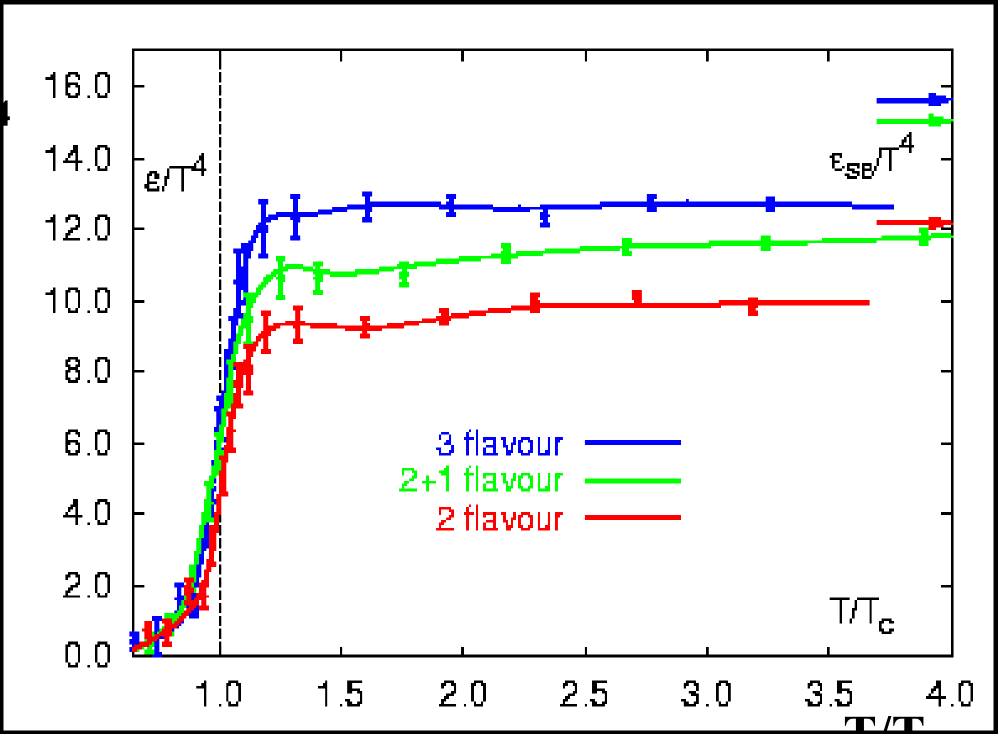
37 !

No Limiting Temperature

Lattice QCD calculations indicate that as one increases the energy input, it is very hard to move the temperature above approximately 170 MeV.

However, eventually the temperature does exceed the "limiting temperature" with a rapid jump in the effective degrees of freedom!

$$\varepsilon = g\frac{\pi^2}{30}T^4$$



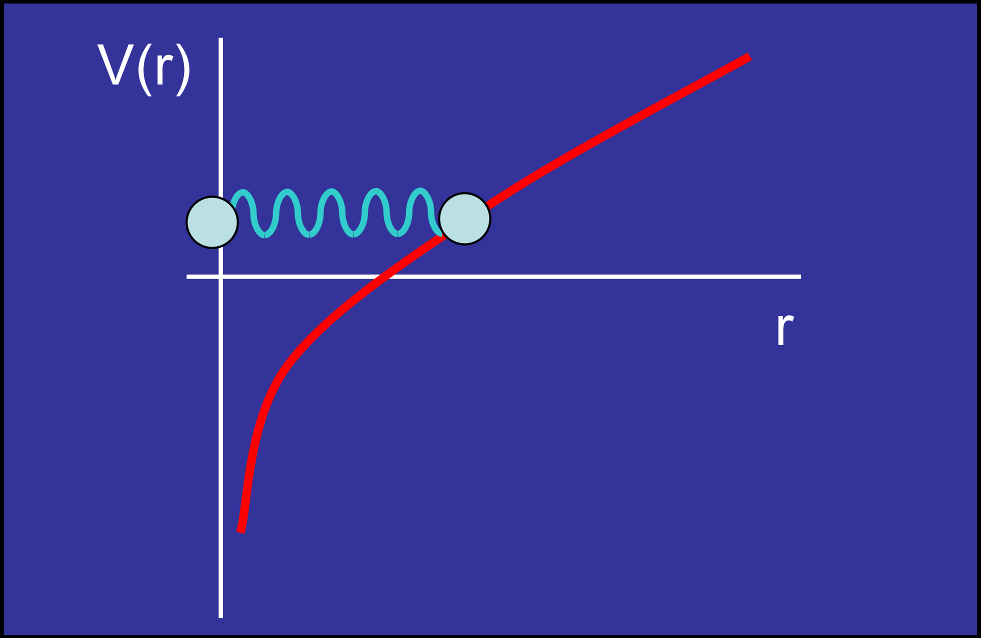
Question: why only 2 or 3 flavors?

Free Quarks?

No one has ever seen a free quark.

$$V = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

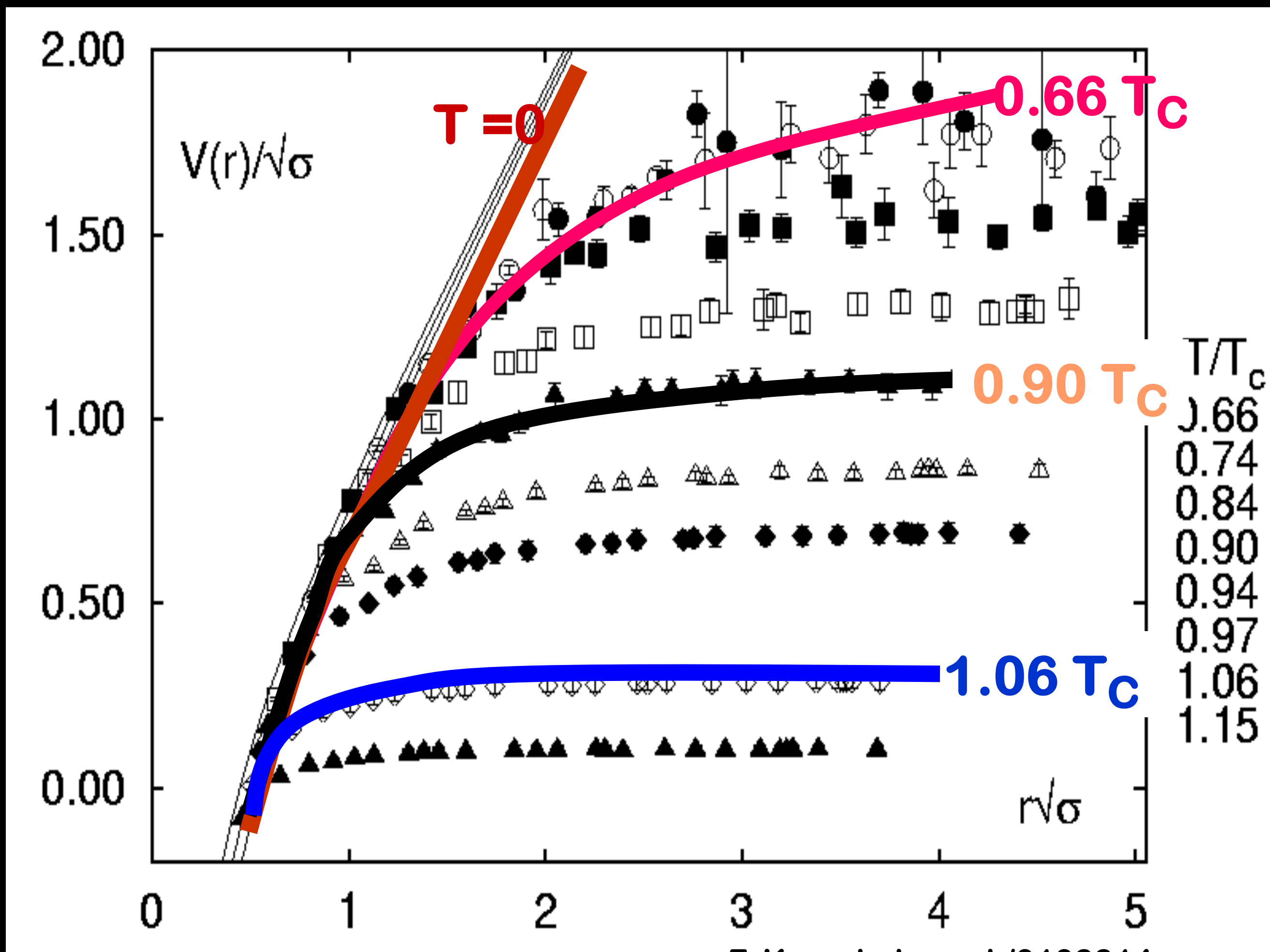
"Coulomb" "Confining"



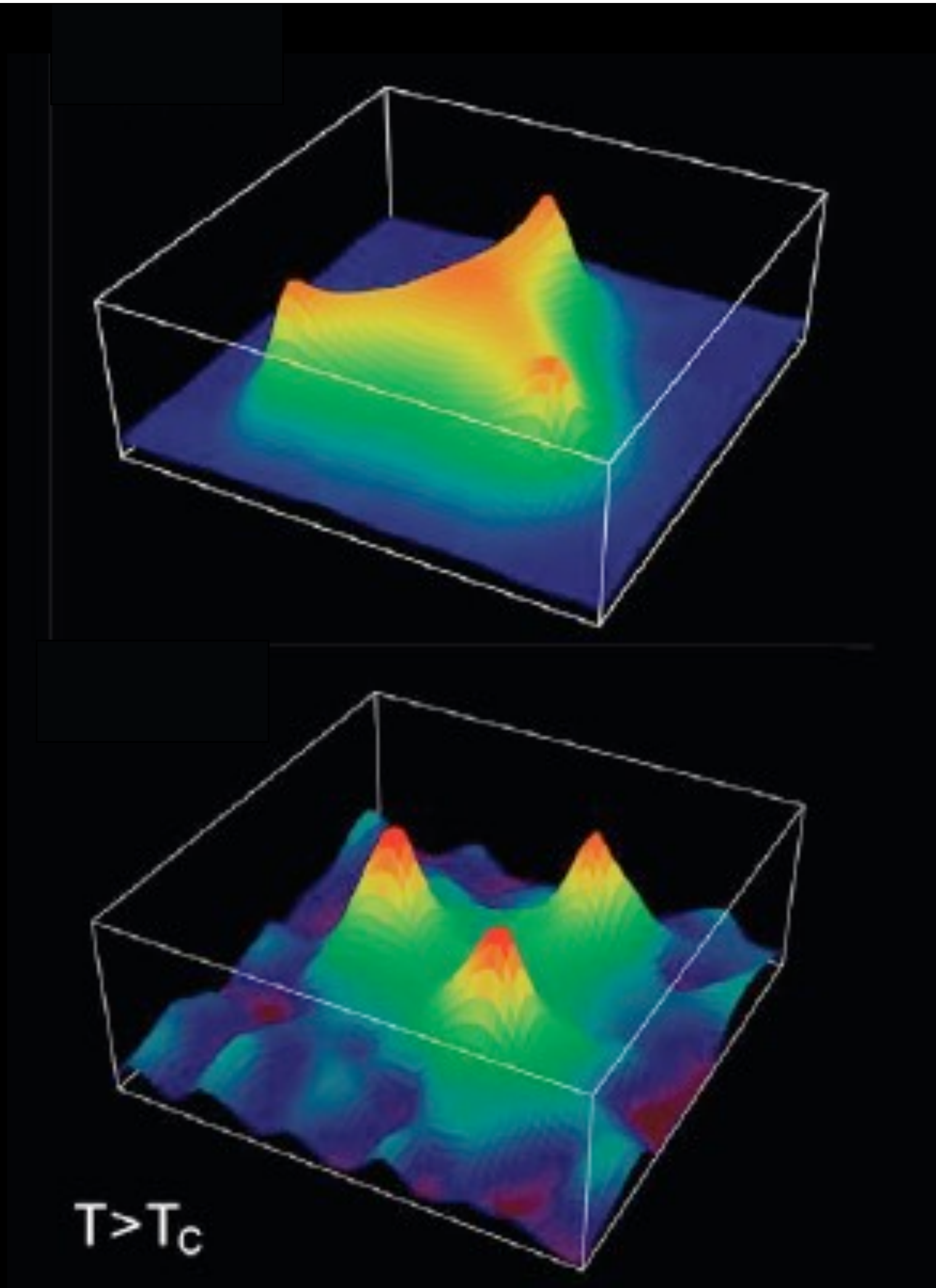
QCD is a "confining" gauge theory.

Lattice Thermodynamics

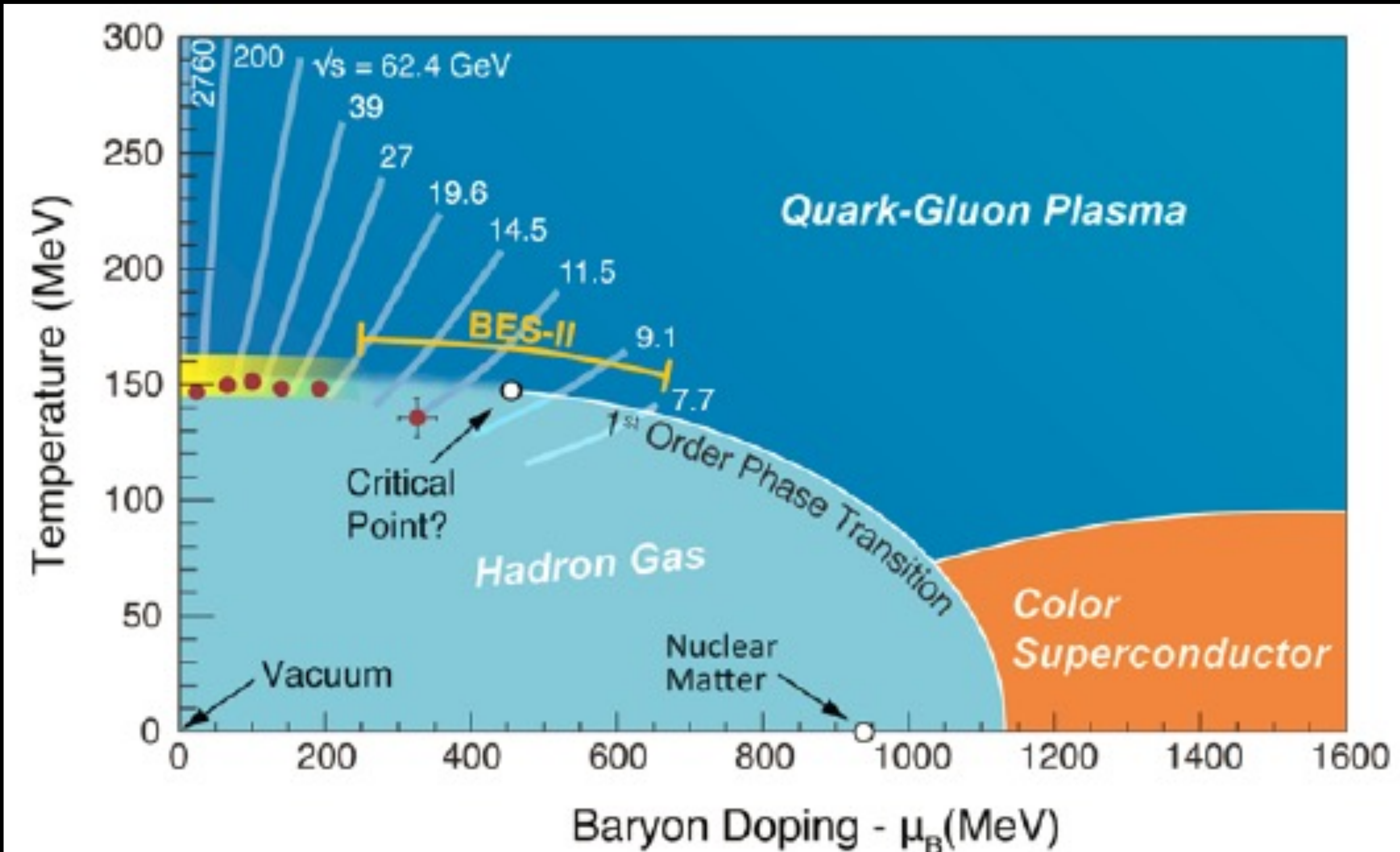
Lattice QCD (for heavy quarks as a test) show a screening of the long-range confining potential gradually as one passes the transition temperature.



F. Karsch, hep-ph/0103314


T>Tc

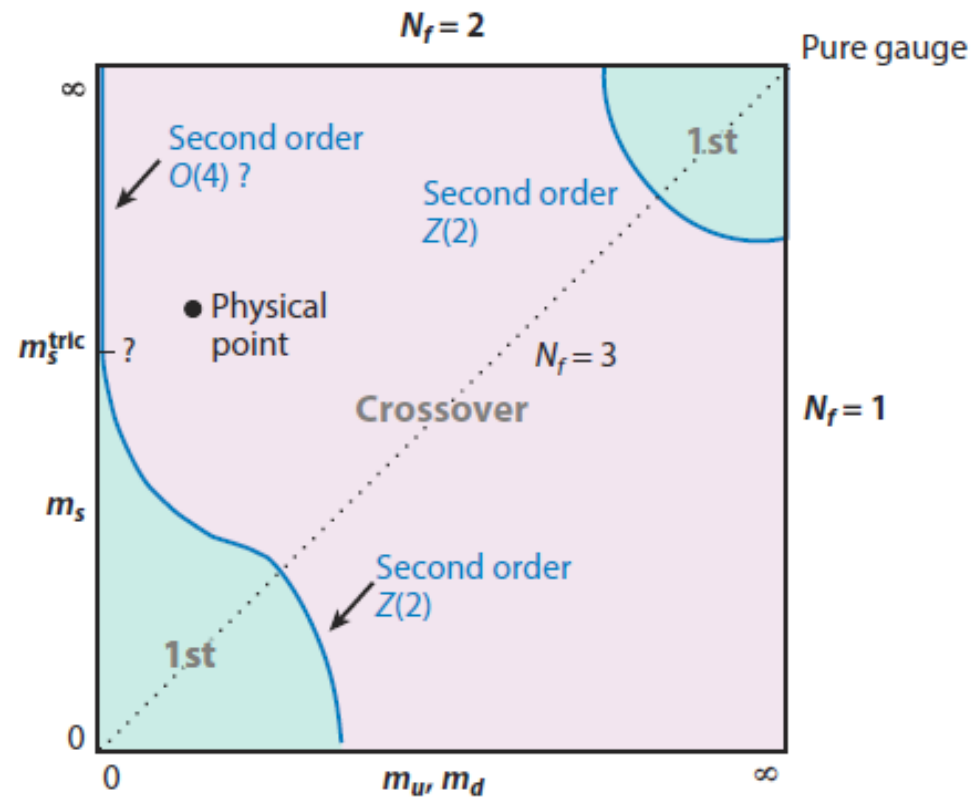
Phase Diagram of Nuclear Matter



Transition Order?

Pisarski and Wilczek, Phys.Rev.D ('84)

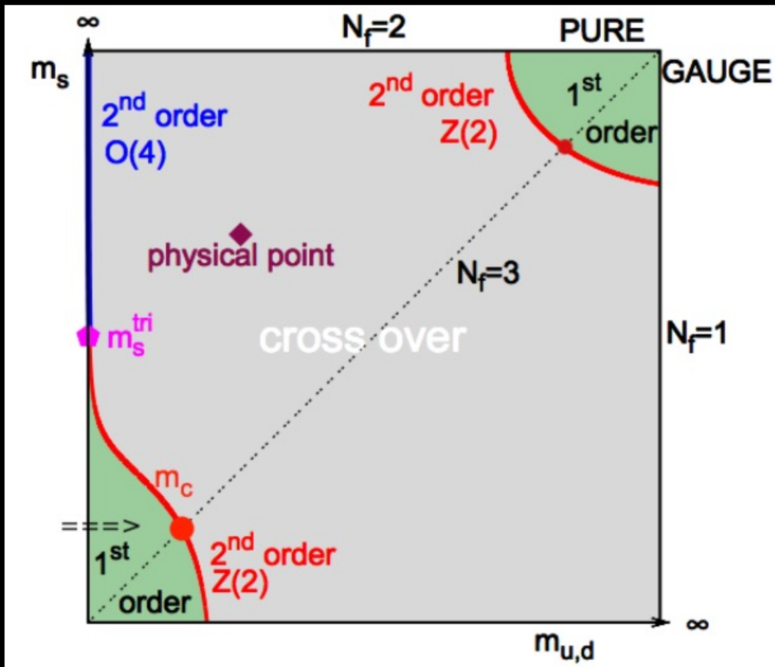
- N_f = 2 ($m_s = \infty$, $m_{u,d} = 0$)
  2nd order (O(4) universality)
- N_f = 3 ($m_s = 0$, $m_{u,d} = 0$)
  1st order (fluctuation/instanton induced)
- N_f = 2+1 ($m_s \gg m_{u,d} \neq 0$)
  1st order or crossover



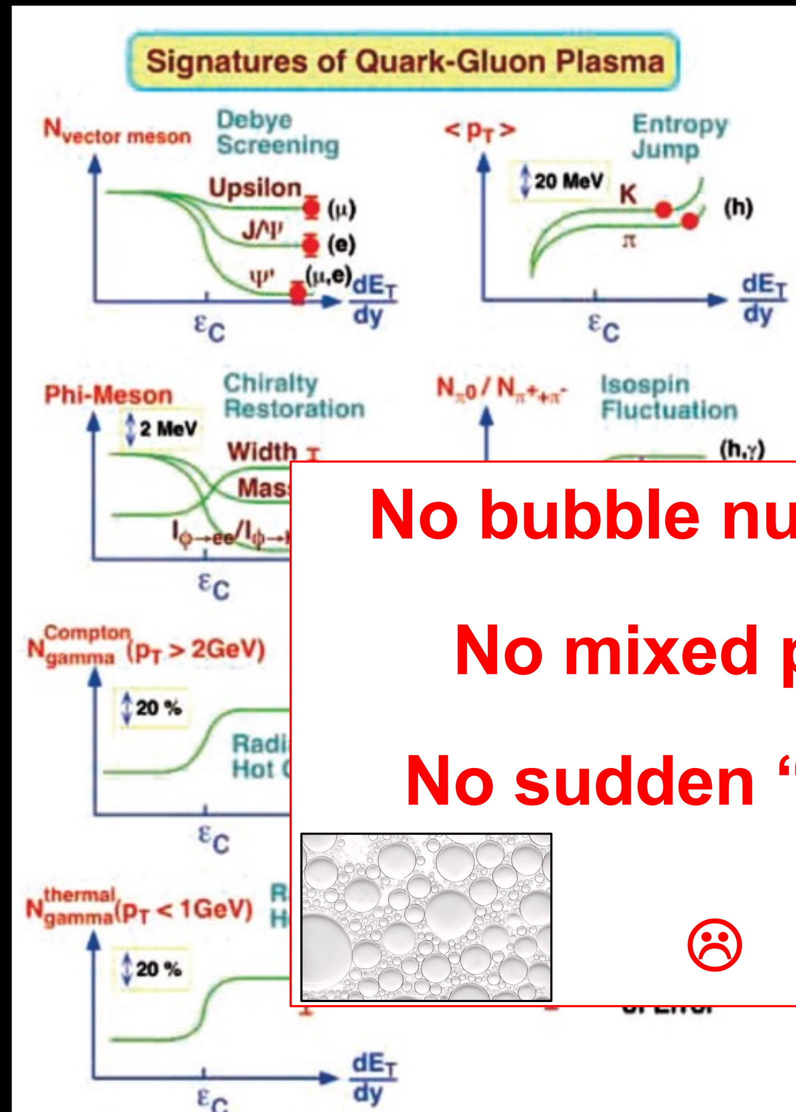
Lattice QCD results for a realistic strange quark mass indicate a smooth cross over transition for zero net baryon density

This has substantial implications.

Huge Paradigm Change in the Field (!)



When I started in the field in 1990 as an undergraduate student, for $\mu_B = 0$, many thought the QGP transition was 1^{st} order.

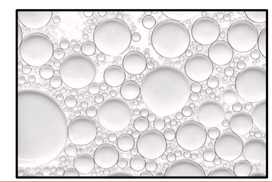


No bubble nucleation

No mixed phase

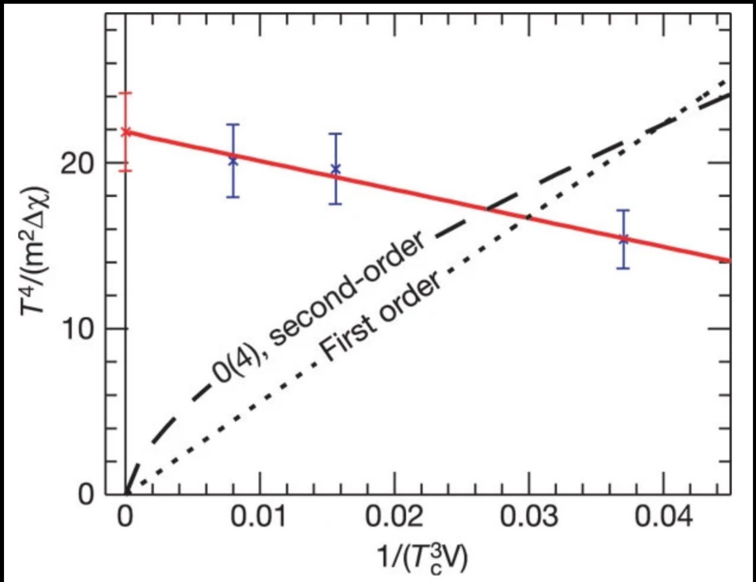
No sudden "onset"

☹



Shoji Nagamiya,
https://academic.oup.com/ptep/article/2015/3/03A101/1584228

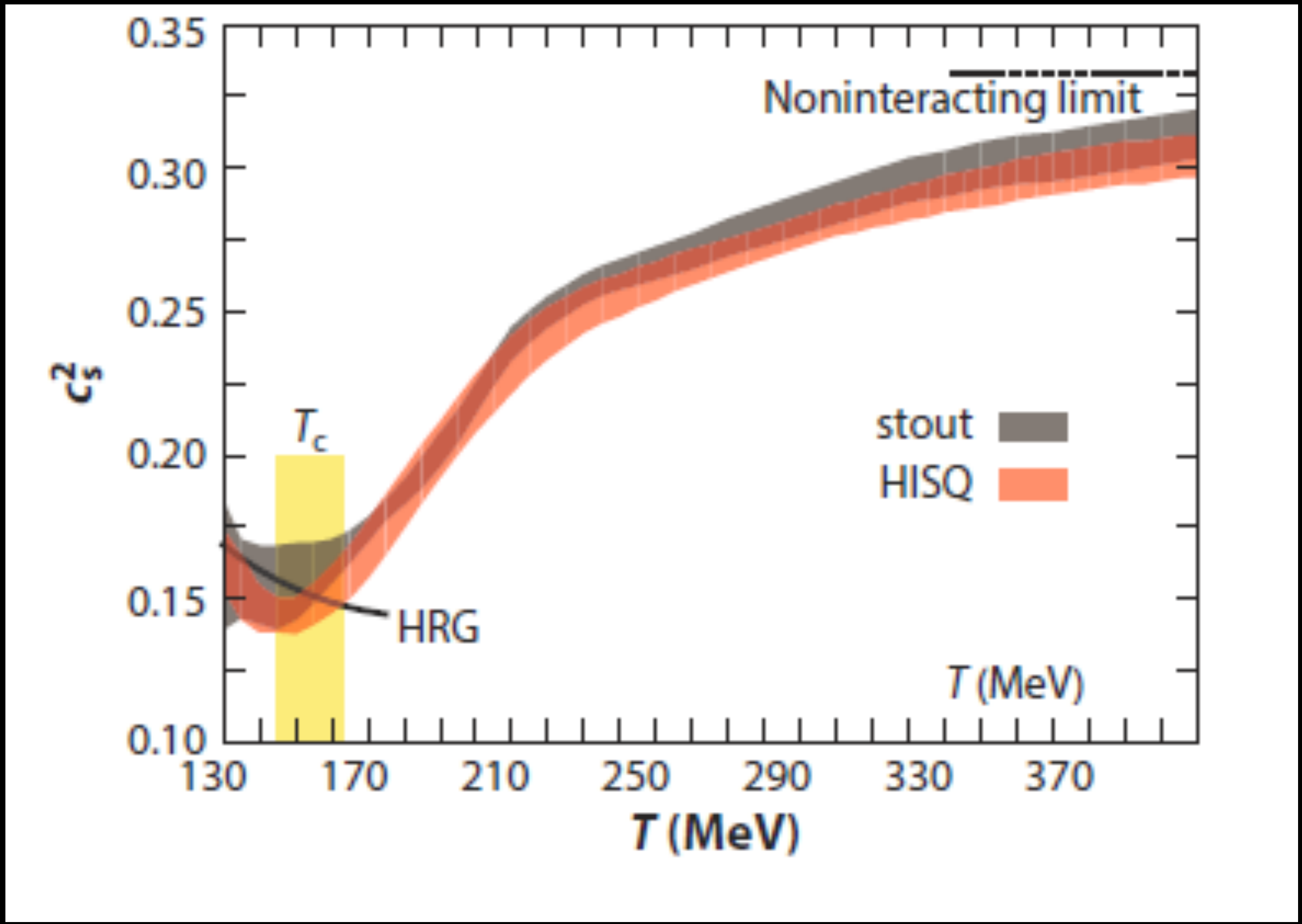
Smooth Crossovers are Cool Too!



"In a strong first-order phase transition the quark–gluon plasma supercools before bubbles of hadron gas are formed. These bubbles grow, collide and merge, during which gravitational waves could be produced[8]. Baryon-enriched nuggets could remain between the bubbles, contributing to dark matter. The hadronic phase is the initial condition for nucleosynthesis, so inhomogeneities in this phase could have a strong effect on nucleosynthesis[9]. As the first-order phase transition weakens, these effects become less pronounced. Our calculations provide strong evidence that the QCD transition is a crossover, and thus the above scenarios—and many others—are ruled out."

Lattice QCD, https://www.nature.com/articles/nature05120

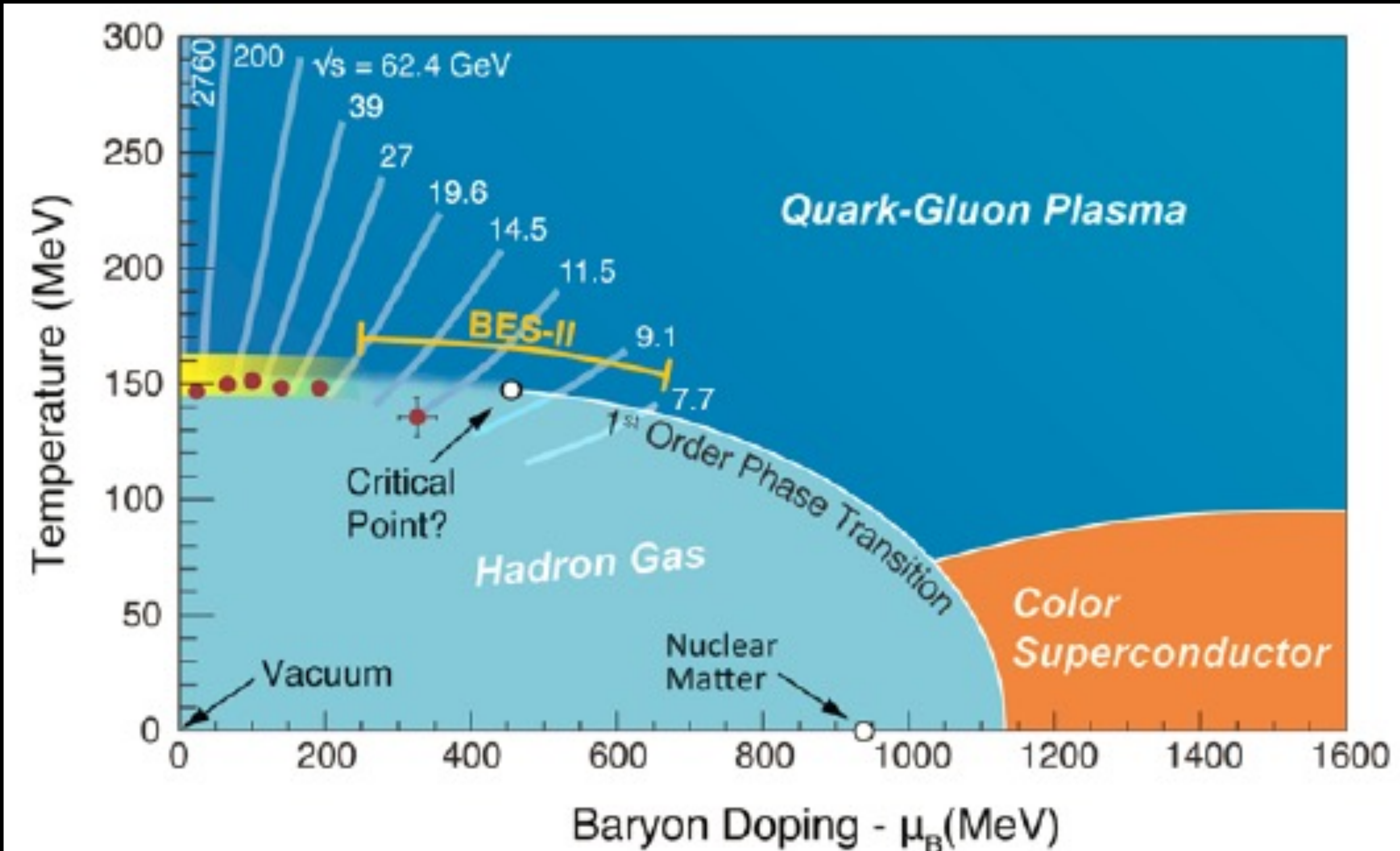
Speed of Sound



Speed of sound drops near transition ("soft point in EoS") and actually goes to zero in first order transition.

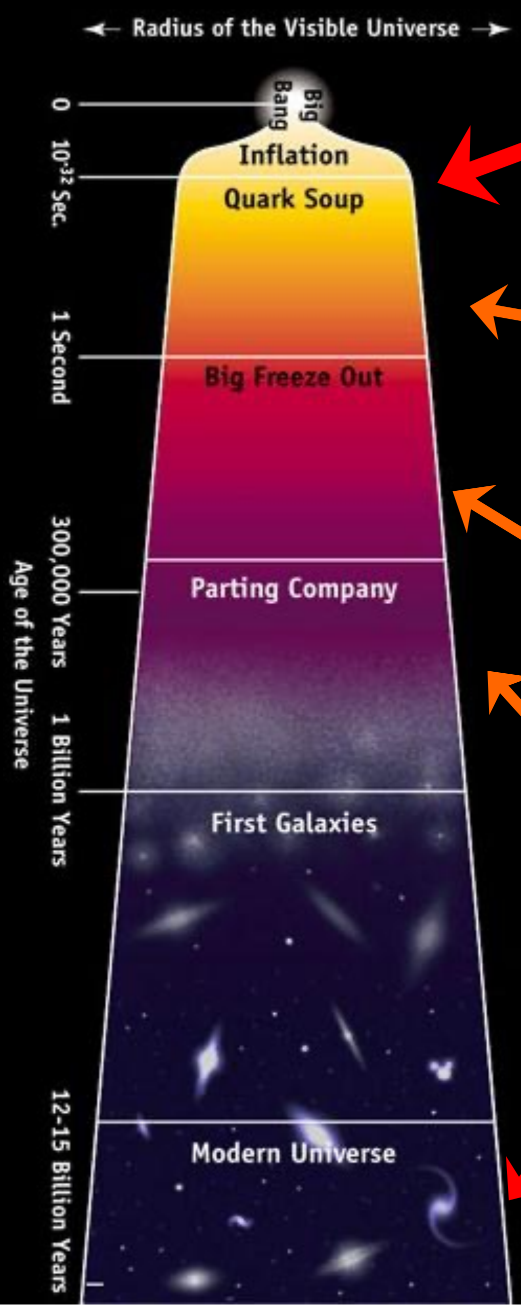
Sound wave transmits energy. In true mixed phase, all energy is absorbed into rearranging constituents.

Phase Diagram of Nuclear Matter



QGP
and
Cosmology

Brief History of Time



Too hot for quarks to bind!!!
Standard Model (N/P) Physics

Too hot for nuclei to bind
Nuclear/Particle (N/P) Physics

Nucleosynthesis builds nuclei up to He
Nuclear Force…Nuclear Physics

Universe too hot for electrons to bind
E-M…Atomic (Plasma) Physics

Today's Cold Universe
Gravity…Newtonian/General Relativity

Quark Gluon Plasma

Hadron Gas

E/M Plasma

Solid Liquid Gas

Annu. Rev. Nucl. Part. Sci. 2006. 56:441–500
doi: 10.1146/annurev.nucl.56.080805.140539

First published online as a Review in Advance on August 2, 2006

Phase Transitions in the Early and Present Universe

D. Boyanovsky,[1,2,3] H.J. de Vega,[3,2,1] and D.J. Schwarz[4]

Quark nuggets and strangelets

Inhomogeneous nucleosynthesis

Cold dark matter clumps

Damping of gravitational waves at the QCD transition

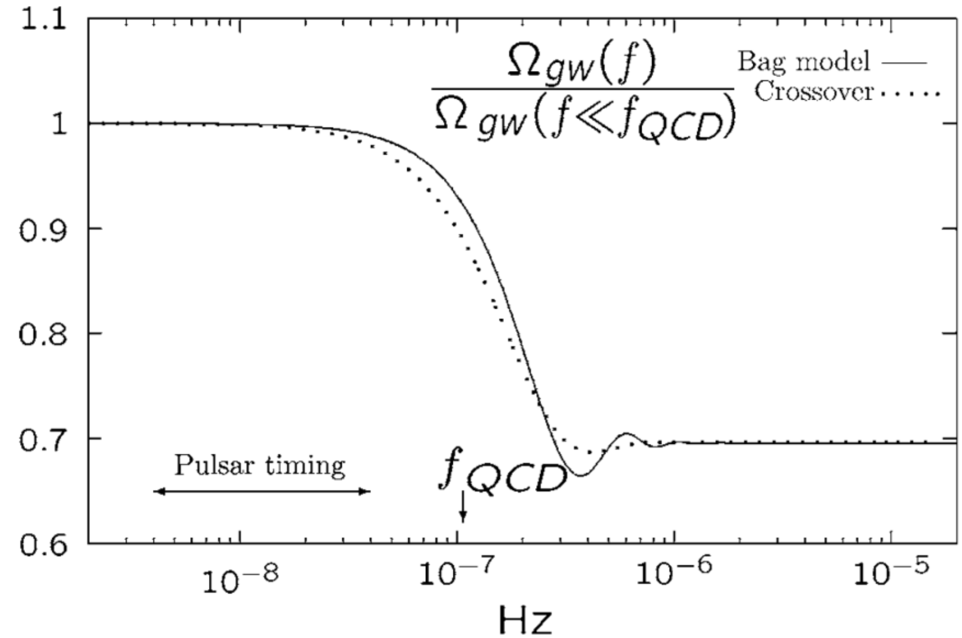


Figure 11 The modification of the energy density, per logarithmic frequency interval, of primordial gravitational waves from the QCD transition. Figure taken from Reference 107.

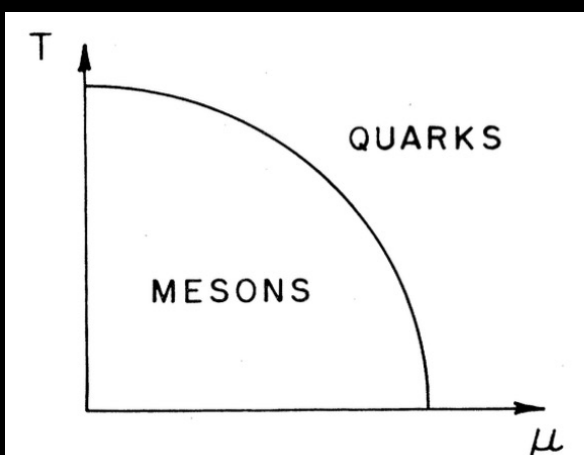
PHYSICAL REVIEW D VOLUME 30, NUMBER 2 15 JULY 1984

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.30.272
Over 4500 citations



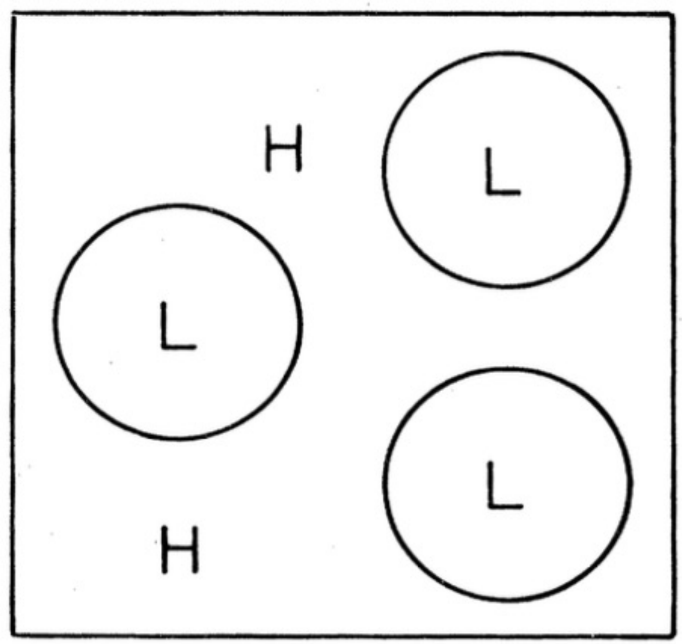


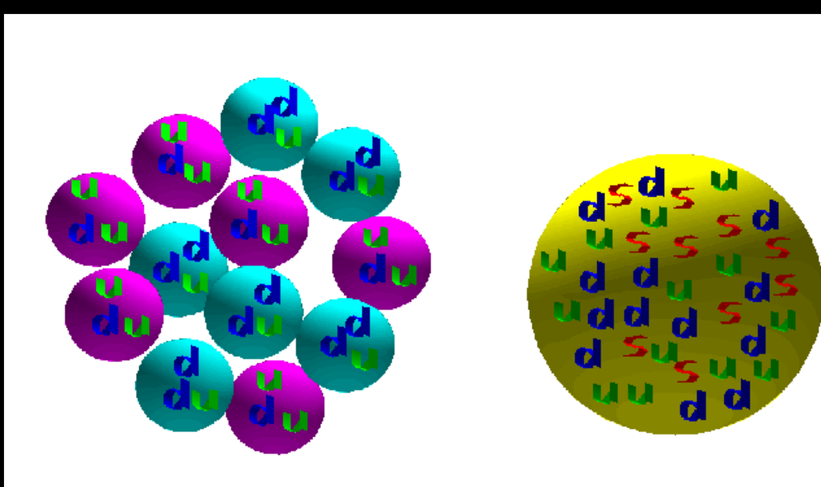
FIG. 1. Isolated expanding bubbles of low-temperature phase in the high-temperature phase.

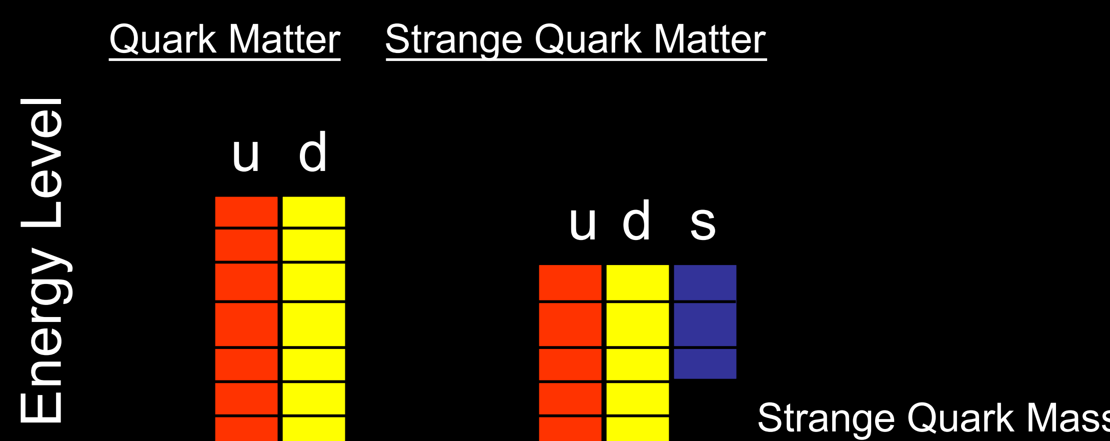
Strange Quark Matter

• Matter of roughly equal numbers of up, down and strange quarks.

• Strange Quark Matter could be more stable that Fe^{55} and thus be the ground state of nuclear matter.

• If stable, it could be a source of baryonic dark matter.

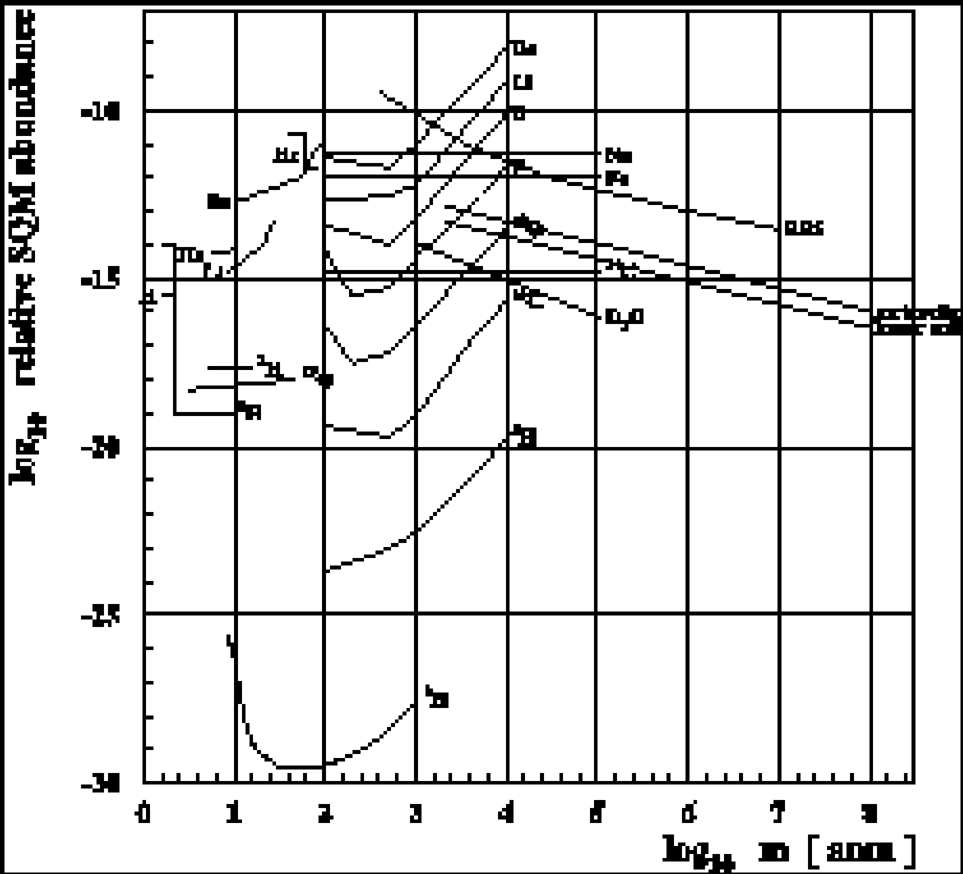


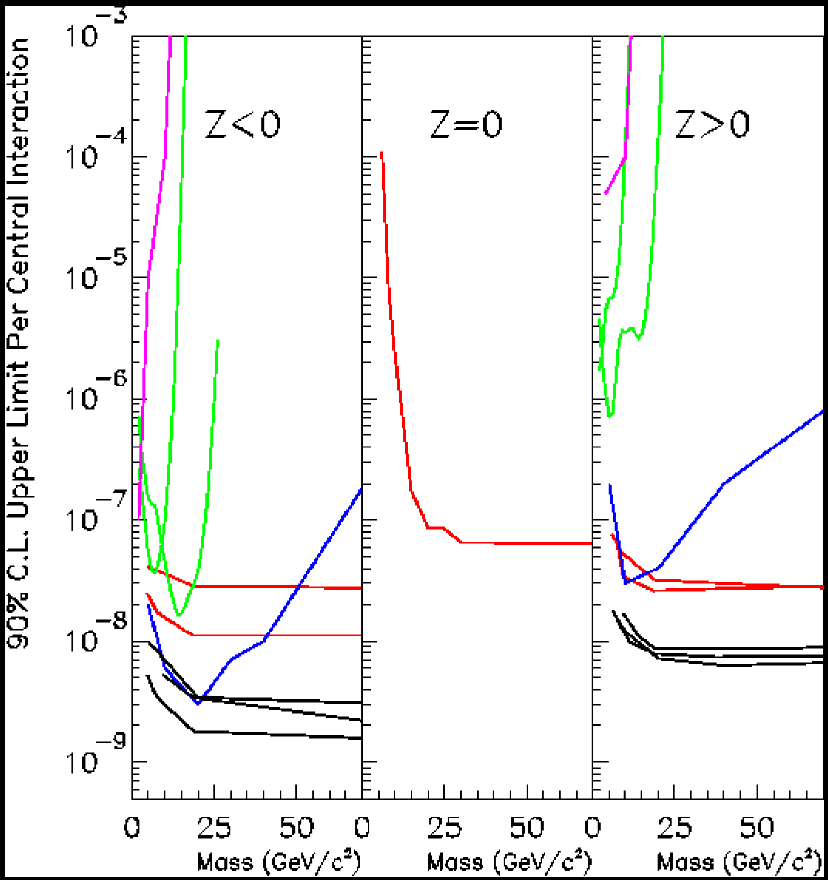


Creating Strangelets

• Many years later, SQM still theoretically allowed.

• Experiments searches in terrestrial matter and nuclear reactions for small A< 100 SQM have yielded null results.





LITTLEST NEUTRON STAR

Strange star: this bizarrely small neutron star may be made of quarks

Quarks all the way down

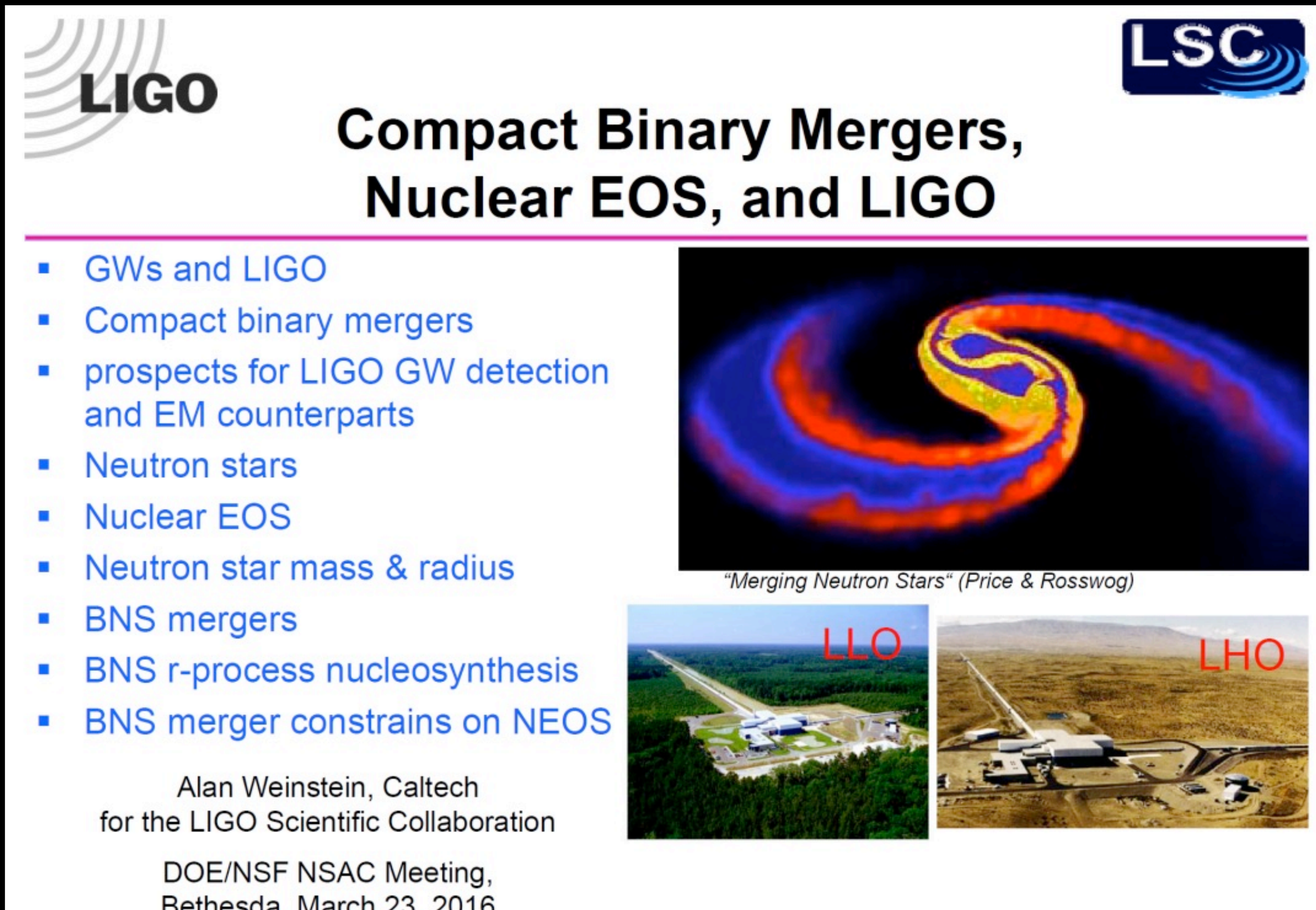
BY KIONA SMITH
OCT. 24, 2022

In the middle of the glowing gas cloud of a supernova remnant, about 8,000 light years away, sits the crushed heart of a dead star.

Astronomers recently discovered that this neutron star left behind by the **collapse and explosion of a supergiant** is now roughly 77 percent the mass of our Sun, packed into a sphere about 10 kilometers wide. That's a mind-bogglingly dense ball of matter — it's squished together so tightly that it doesn't even have room to be atoms, just neutrons. But as neutron stars go, it's weirdly lightweight. Figuring out why that's the case could reveal fascinating new details about exactly what happens when massive stars collapse and explode.

Neutron star physics via gravitational waves!

http://science.energy.gov/~/media/np/nsac/pdf/201603/Weinstein_LIGO_20160323.pdf

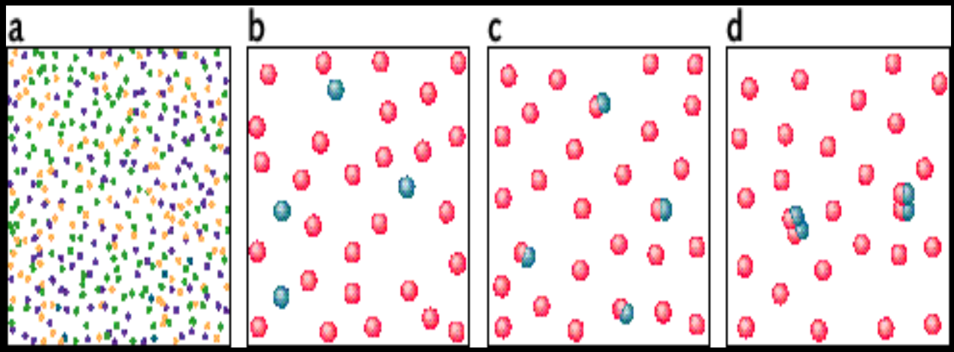


Supercooling and Bubbles

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.

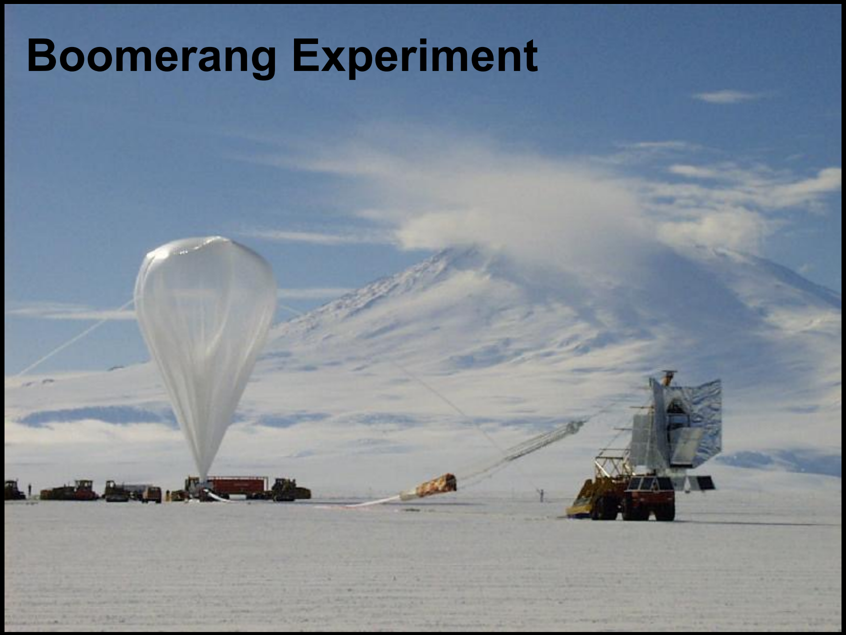


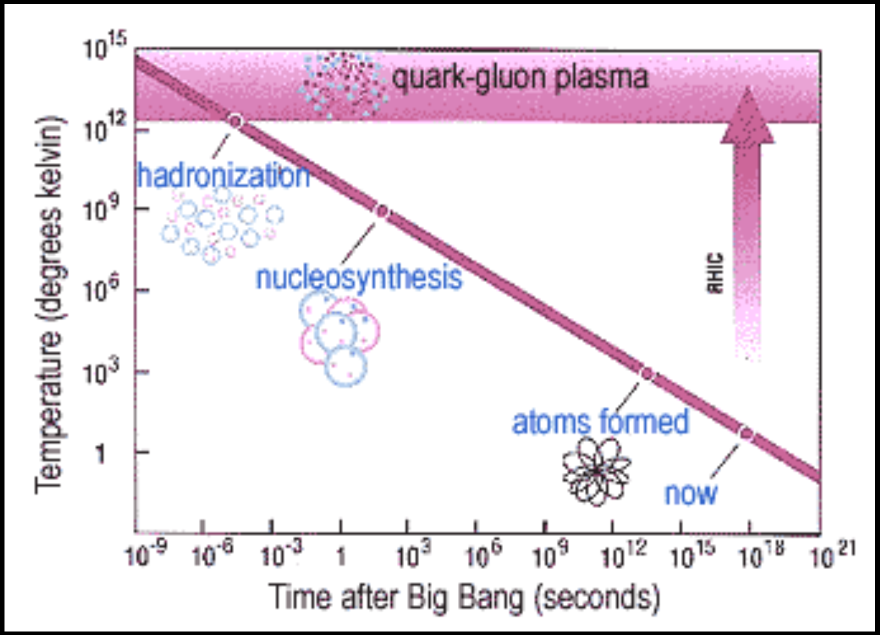
No BBN Problem

Physics Today, July 2001: Cosmic Microwave Background Observations

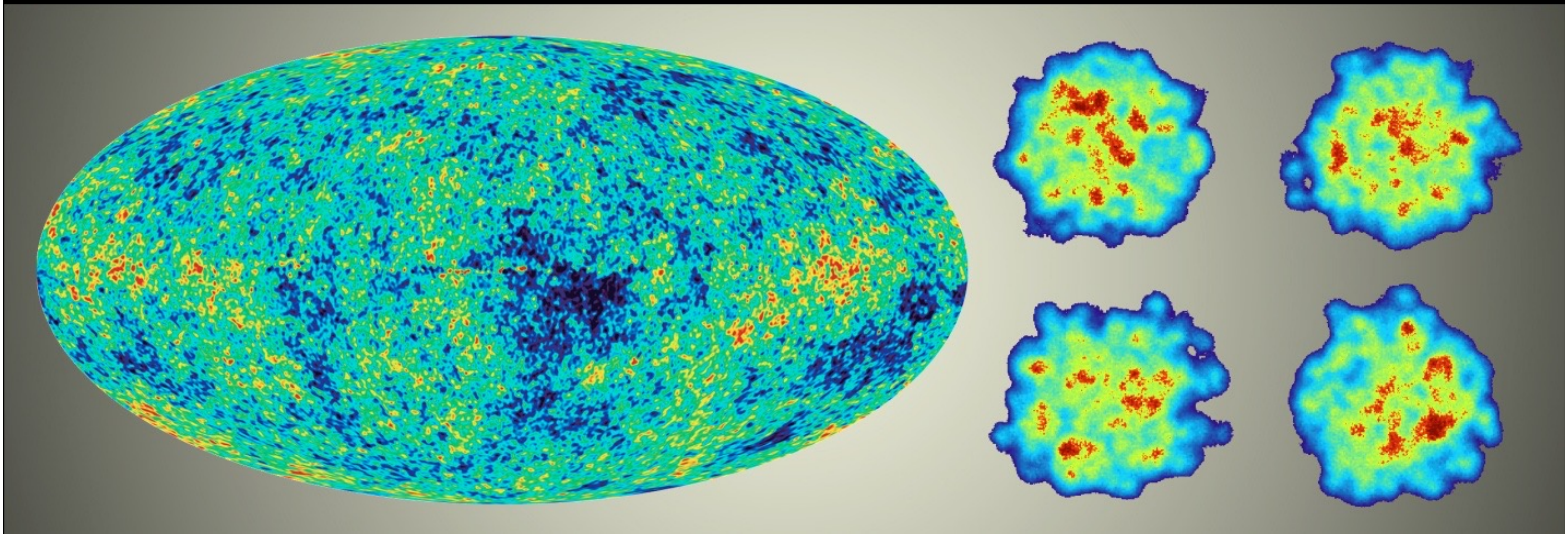
"The value deduced from the second harmonic in the acoustic oscillations for W_B=0.042 ± 0.008 (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."

In addition, Lattice QCD now confirms a smooth cross over transition.





Big Bang versus Little Bangs



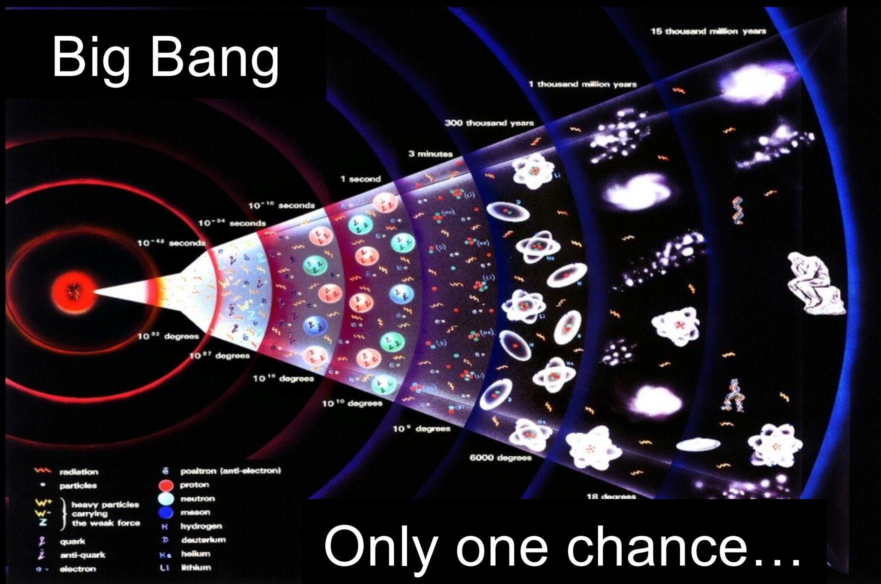
Universe Case:
Fluctuations pre-inflation…
and not impacted by QGP

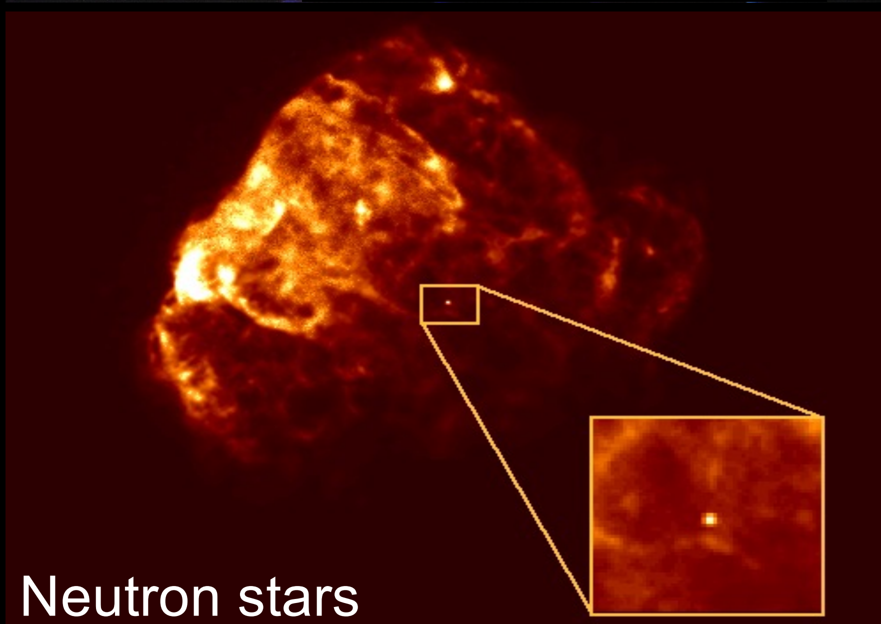
Heavy Ion Case:
QGP initial
condition
fluctuations

Study structures that survive to understand earlier epoch

Heavy Ion Experiments

How to Access This Physics?





Heavy Ion Machine History

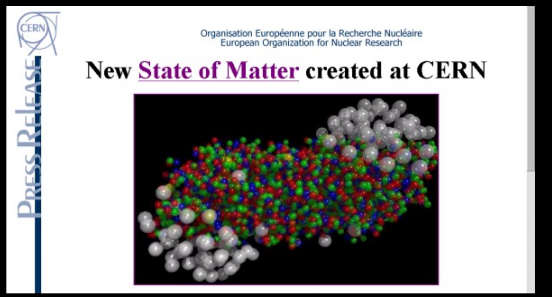
Bevalac-LBL and SIS-GSI fixed target
max. **2.2 GeV**

1992 Au-Au
AGS-BNL fixed target
max. **4.8 GeV**

E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 …

1994 Pb-Pb
SPS-CERN fixed target
max. **17.3 GeV**

NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, WA80/98, WA97, …



TEVATRON-FNAL (fixed target p-A)
max. **38.7 GeV**

2000 Au-Au
RHIC-BNL collider
max. **200.0 GeV**

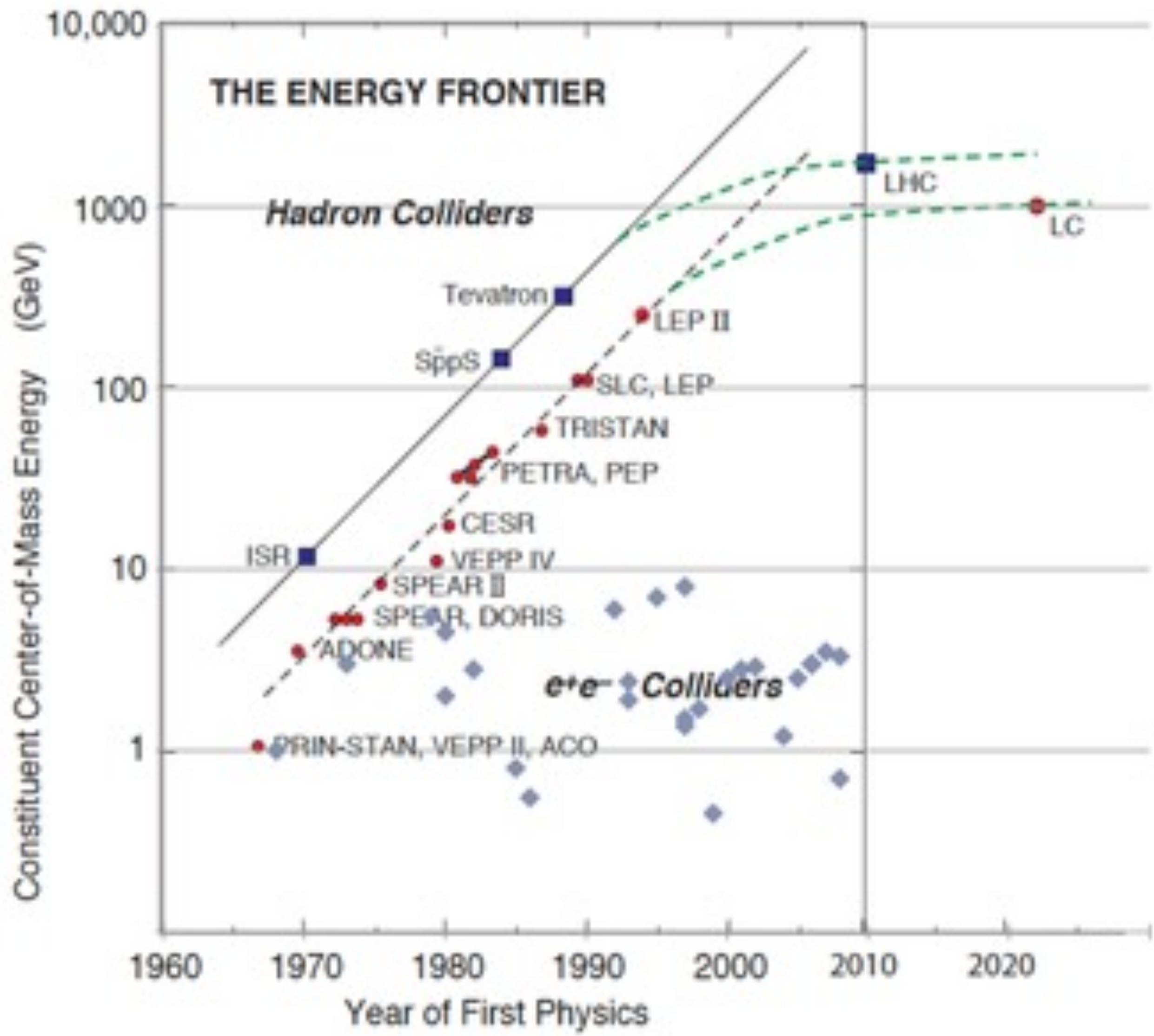
BRAHMS, PHENIX, PHOBOS, STAR, now sPHENIX

2010 Pb-Pb
LHC-CERN collider
max. **2760.0 GeV**
Now even higher

ALICE, ATLAS, CMS, LHCb (pA)

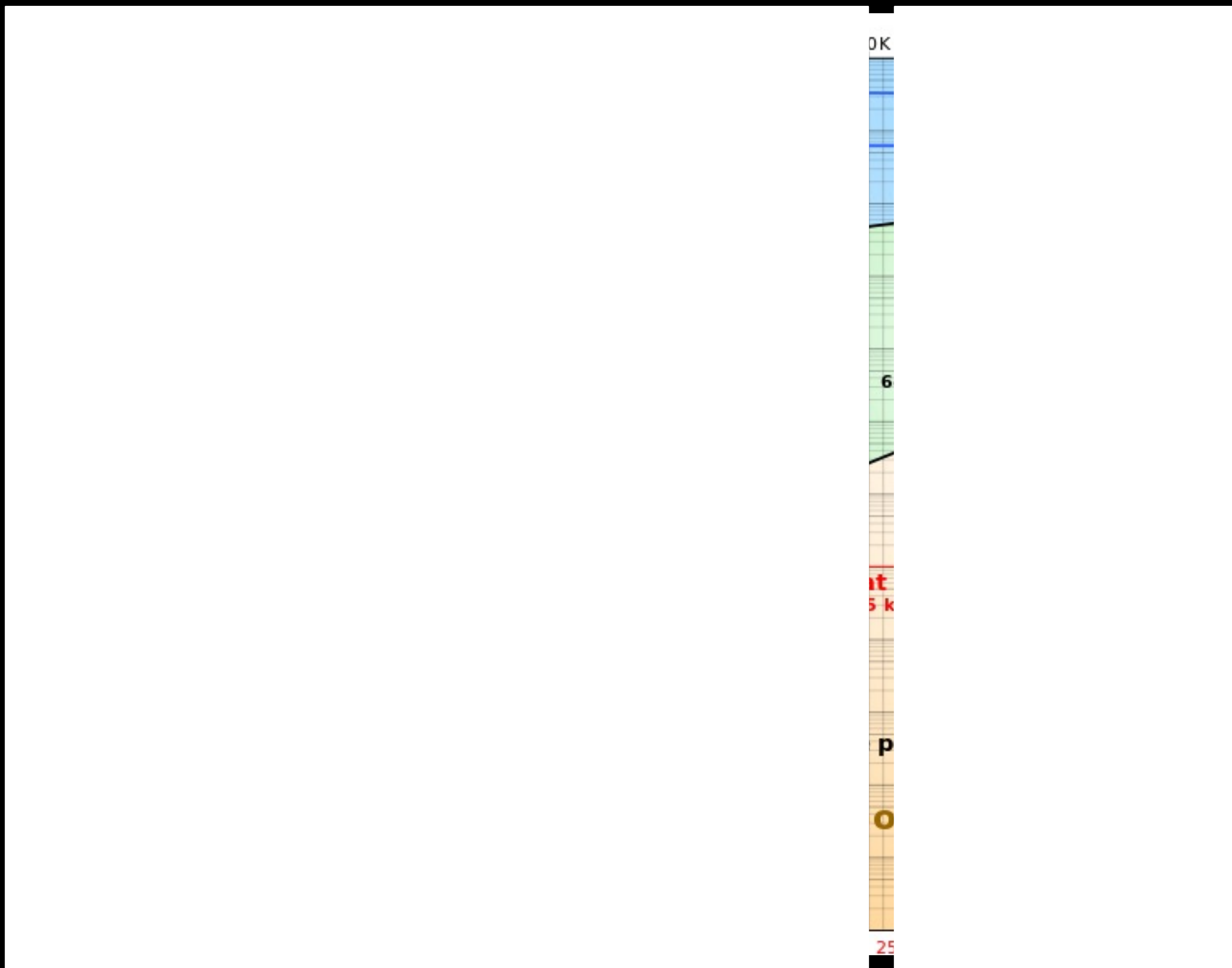
Particle Physics
the energy frontier

Machine with highest energy for point-like interactions dominates the world!

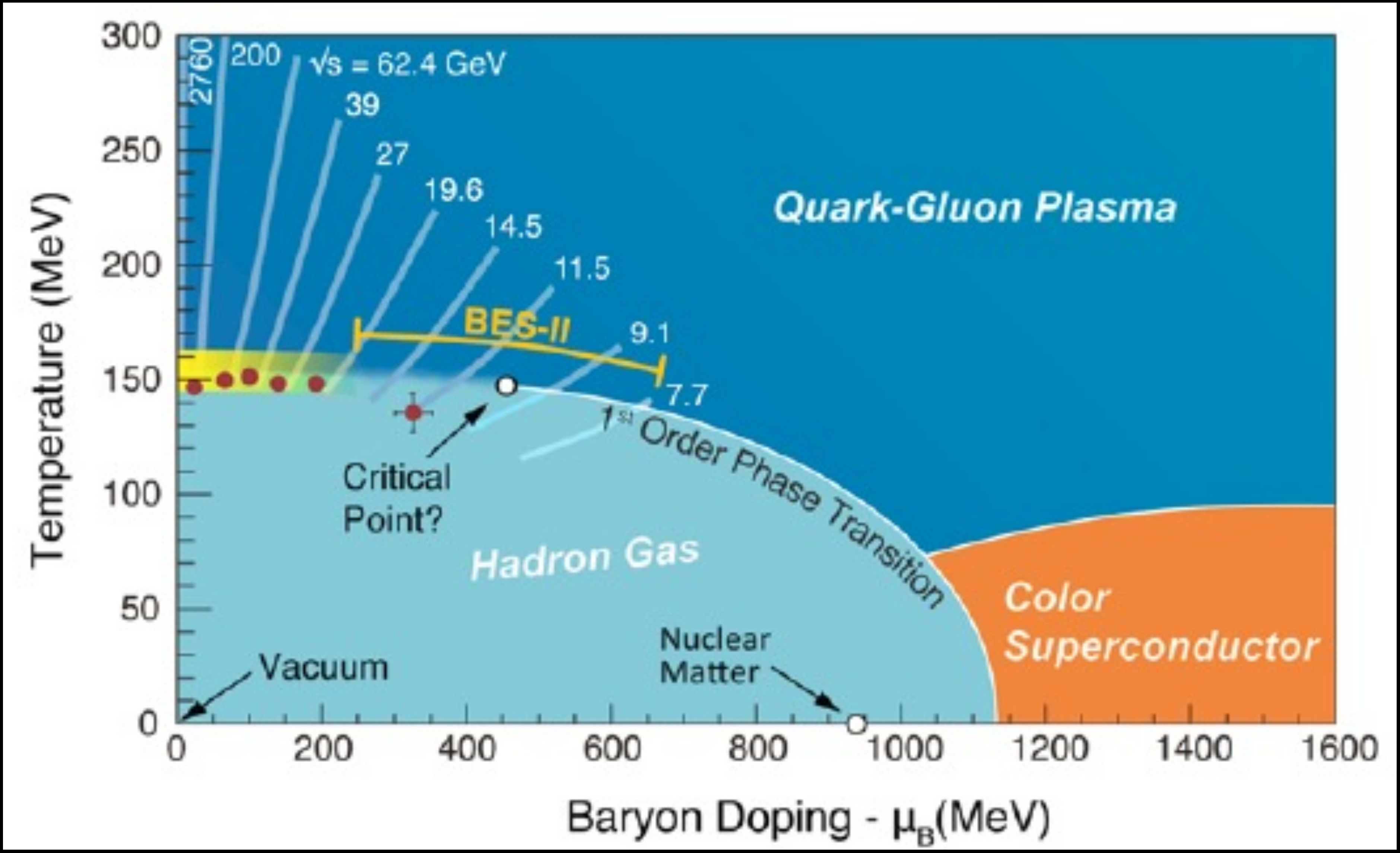


Nuclear Physics – studying a state of matter (thermodynamics, many-body physics) and how that emerges from underlying QCD theory

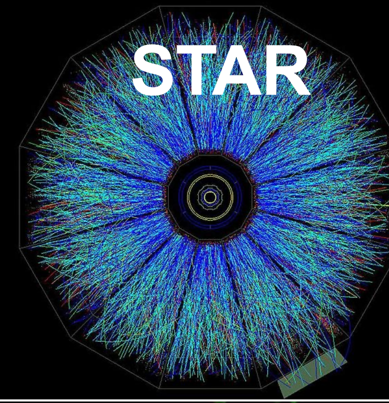
Think of mapping out a phase diagram with only one temperature?

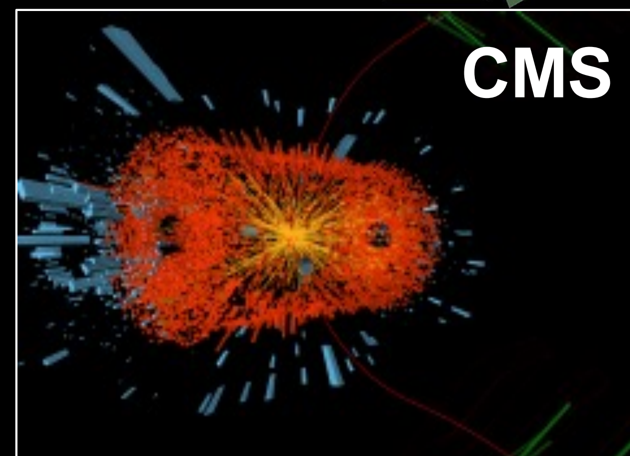


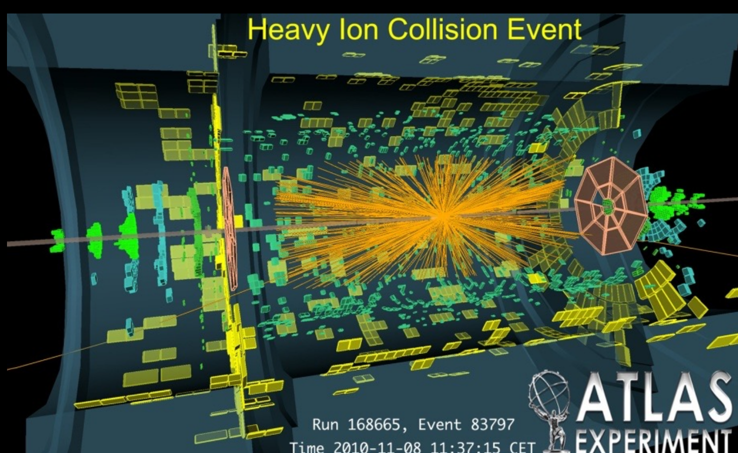
Phase Diagram of Nuclear Matter

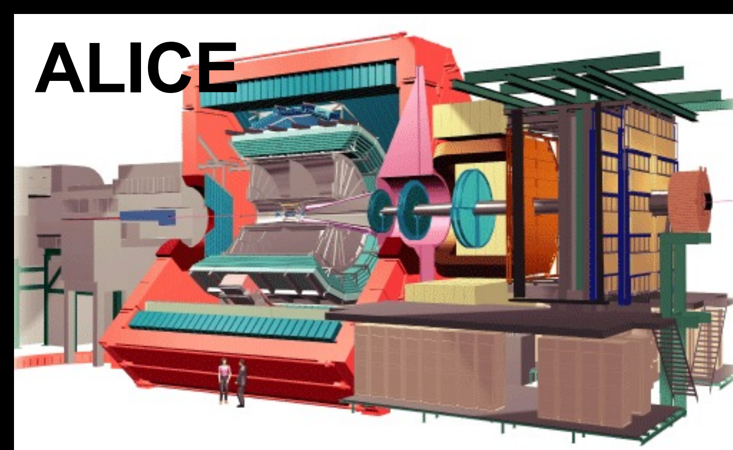


Experimental Tools









STAR

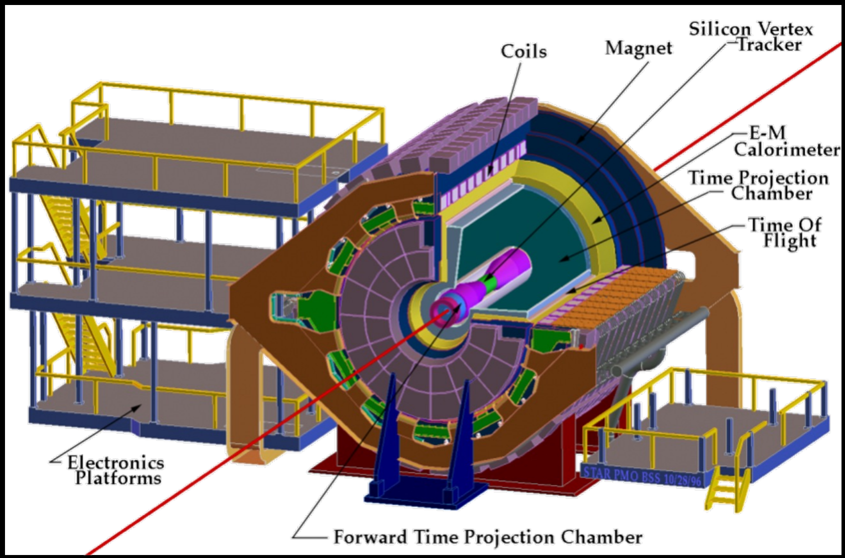
Hadronic Observables over a Large Acceptance
Event-by-Event Capabilities

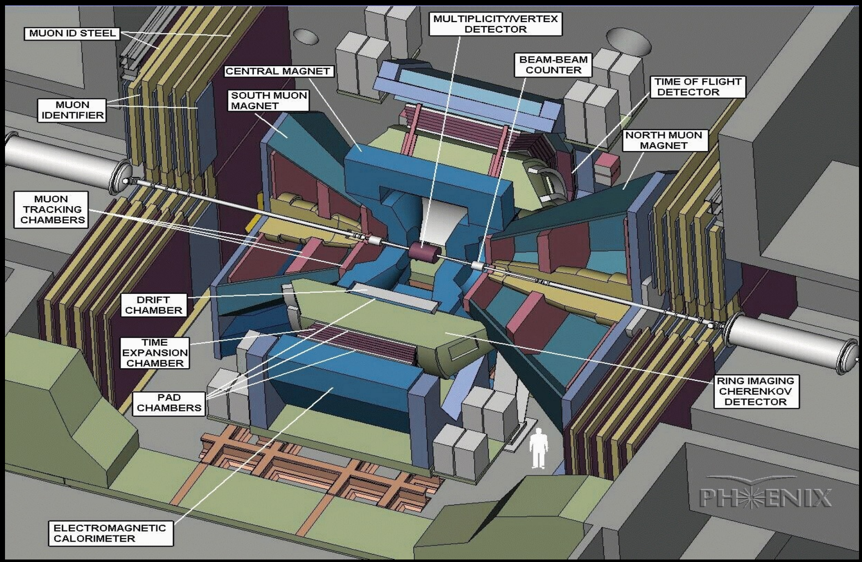
Solenoidal magnetic field
Large coverage Time-Projection Chamber
Silicon Tracking, RICH, EMC, TOF

PHENIX

Electrons, Muons, Photons and Hadrons Measurement Capabilities
Focus on Rare Probes: J/ψ, high-p_T

Two central spectrometers with tracking and electron/photon PID
Two forward muon spectrometers

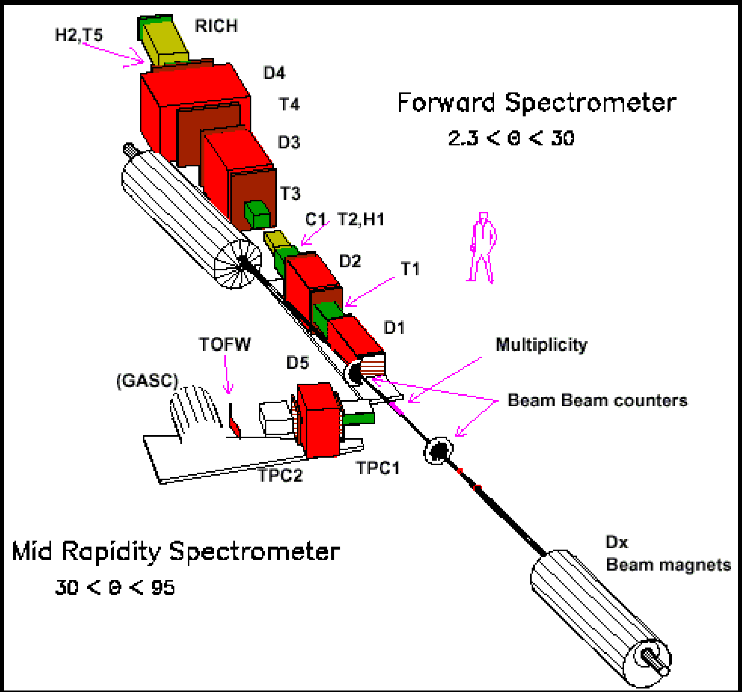




BRAHMS

Hadron PID over broad rapidity acceptance

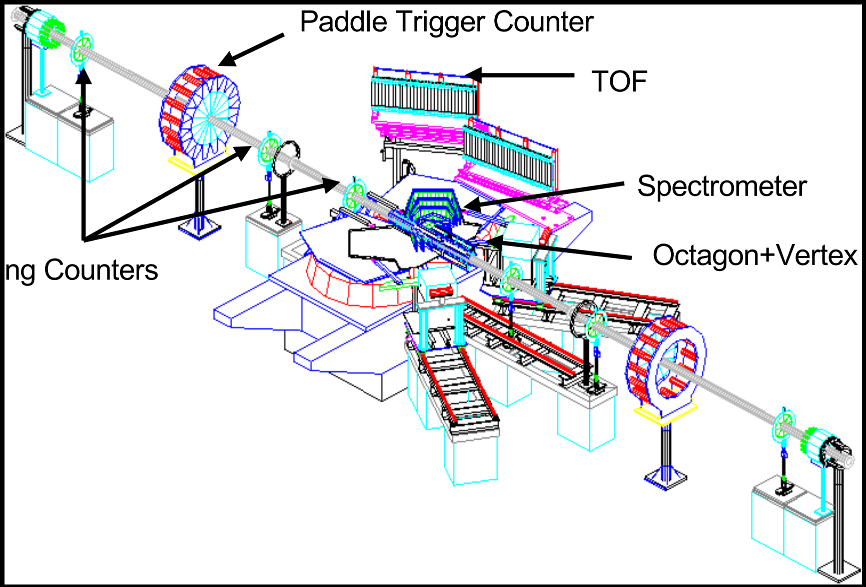
Two conventional beam line spectrometers
Magnets, Tracking Chambers, TOF, RICH



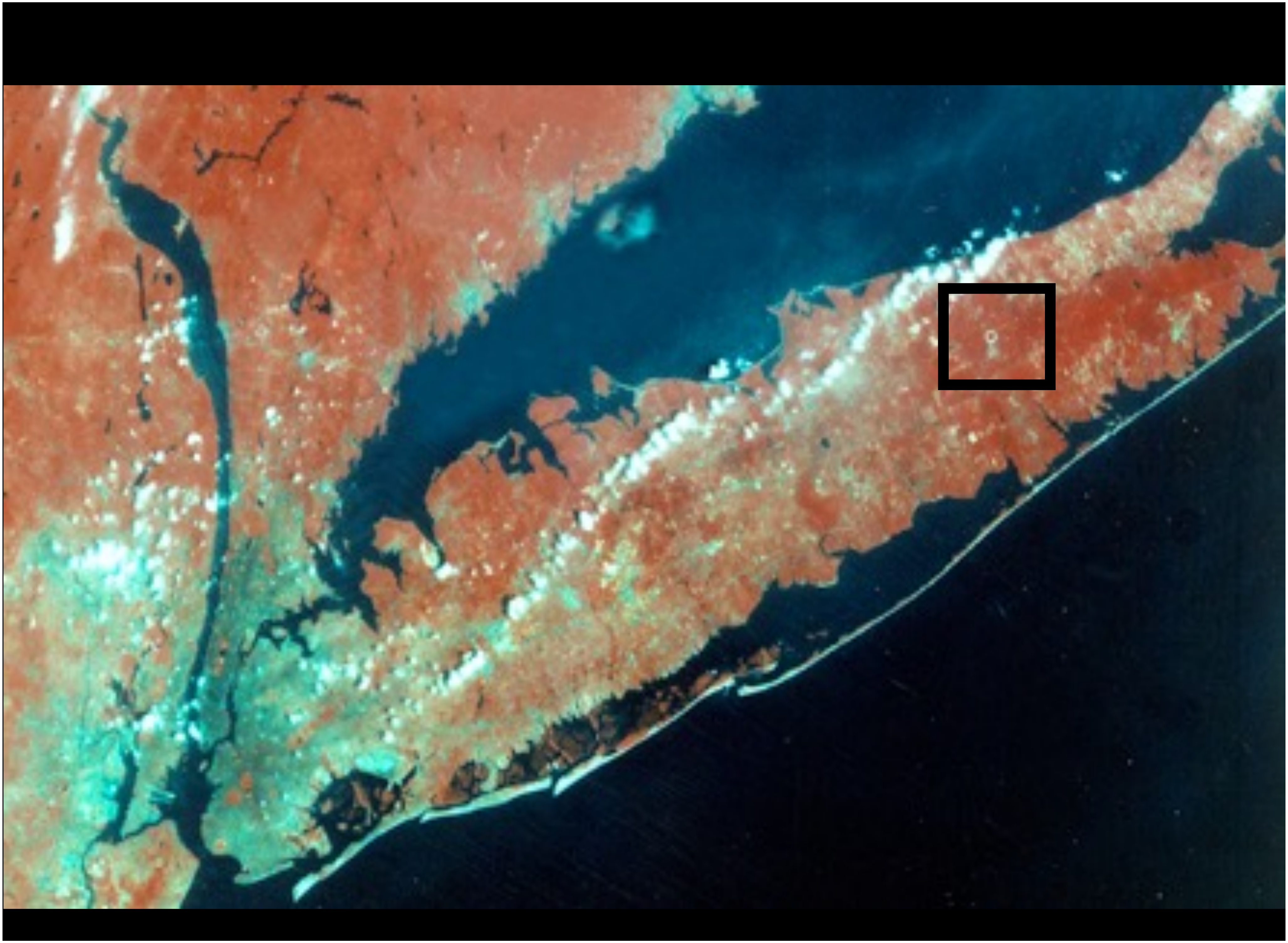
PHOBOS

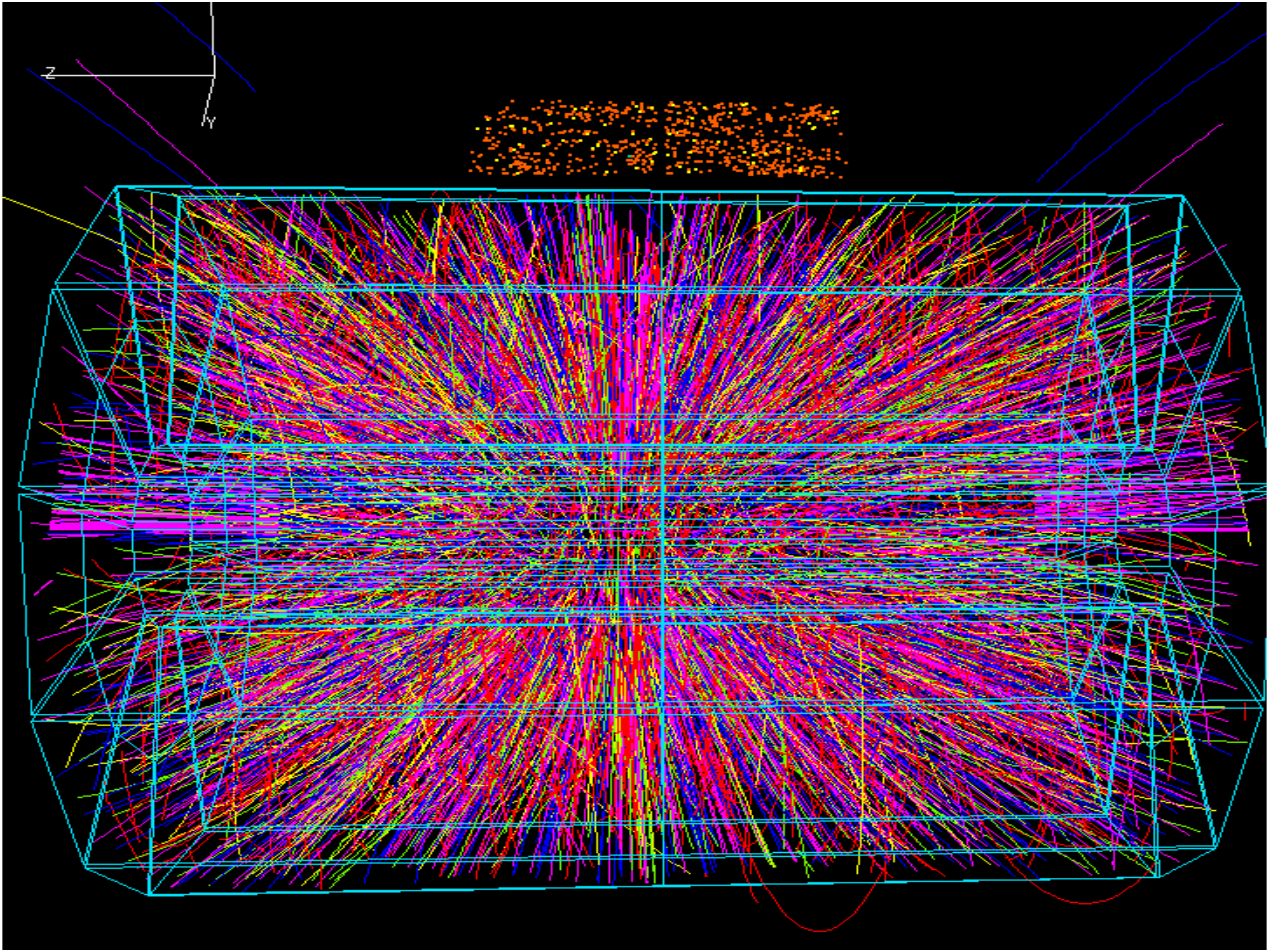
Charged Hadrons in Central Spectrometer
Nearly 4π coverage multiplicity counters

Silicon Multiplicity Rings
Magnetic field, Silicon Strips, TOF



Biggest contributions – intellectually independent thinking!




Z
Y

End of the World!

Can be dismissed with some basic General Relativity

$$R_S = {2GM}/{c^2} = 10^{-49}\, meters$$

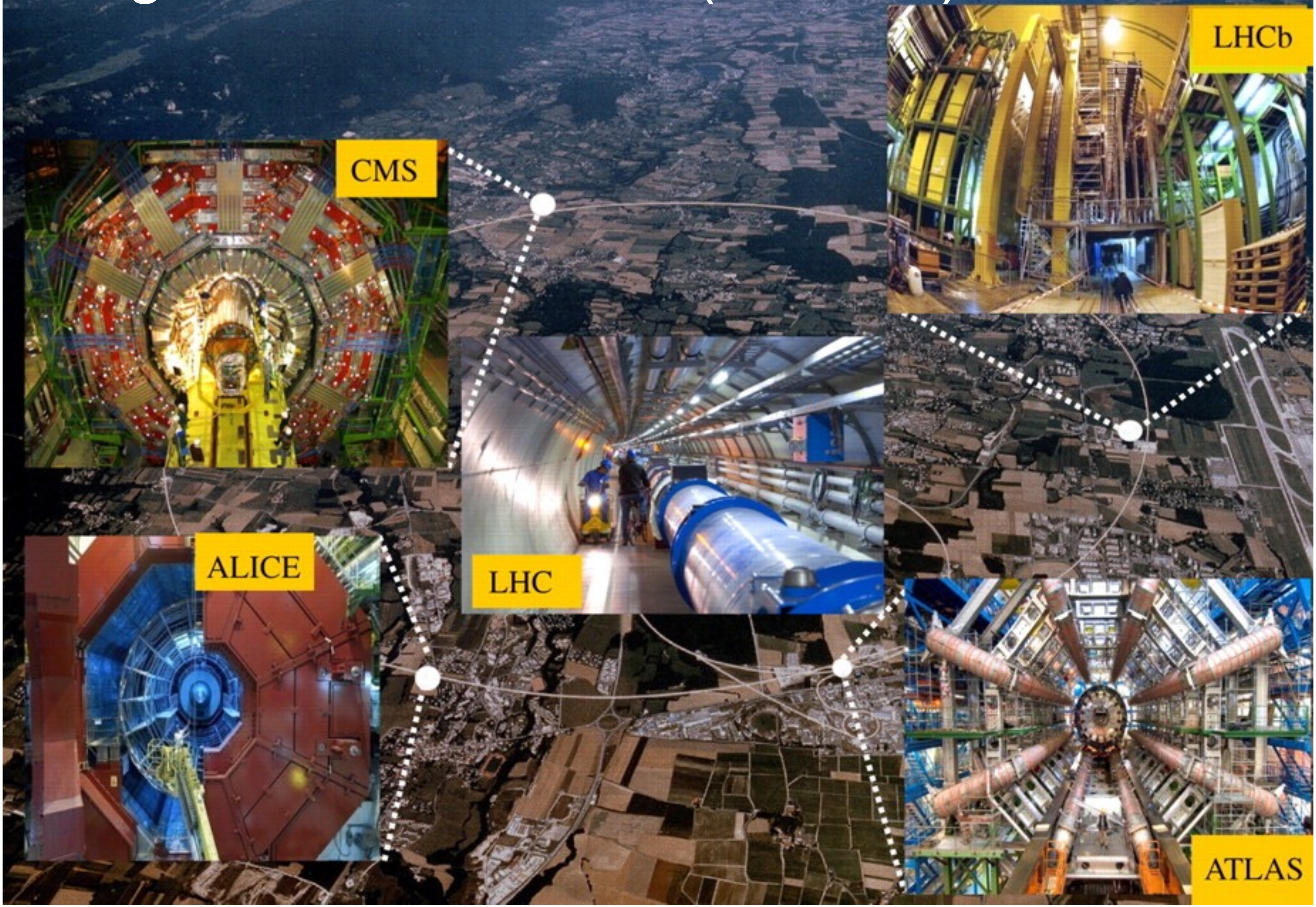
much less than Planck length !

$$R = 10^{-15}\, meters$$

Even if it could form, it would evaporate by Hawking Radiation in 10^{-83} seconds !

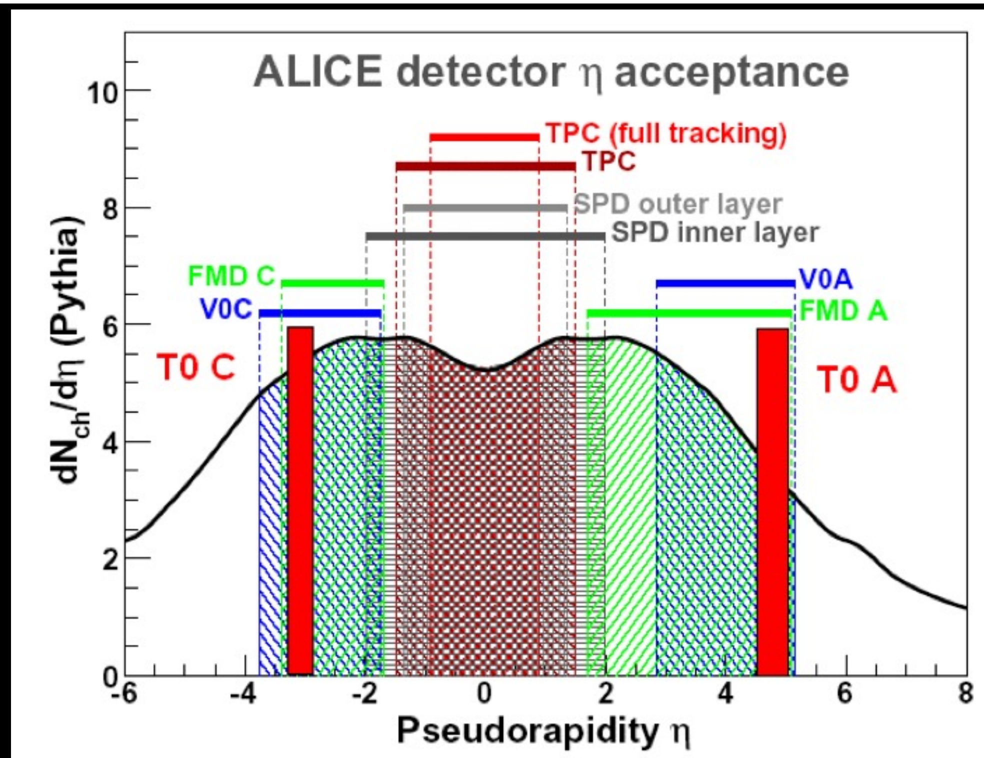
Also, concerns about SQM nuggets eating the earth

Large Hadron Collider (2010++)



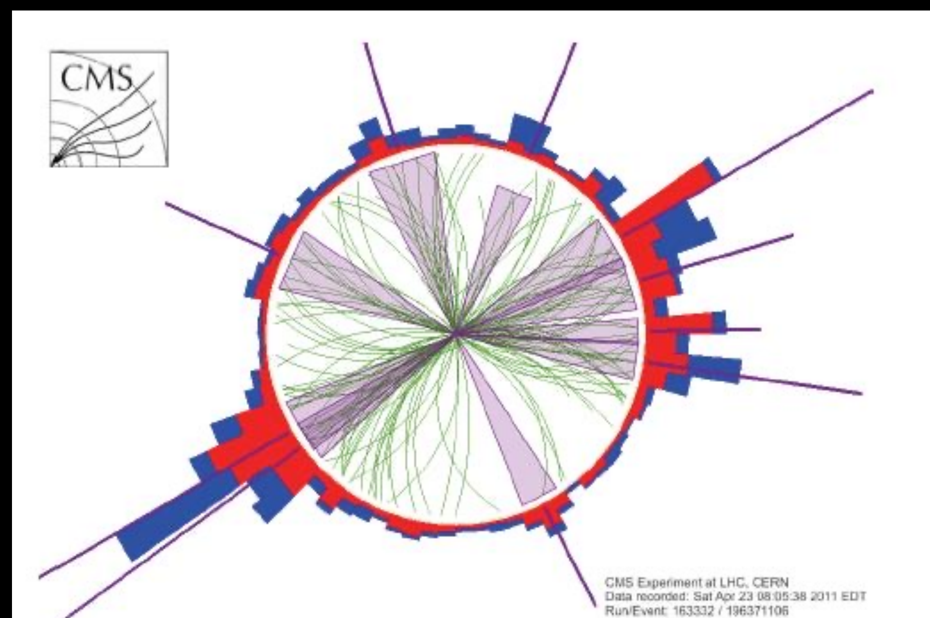
ALICE – dedicated heavy ion detector

Key advantages – particle identification, focused 1000+ people

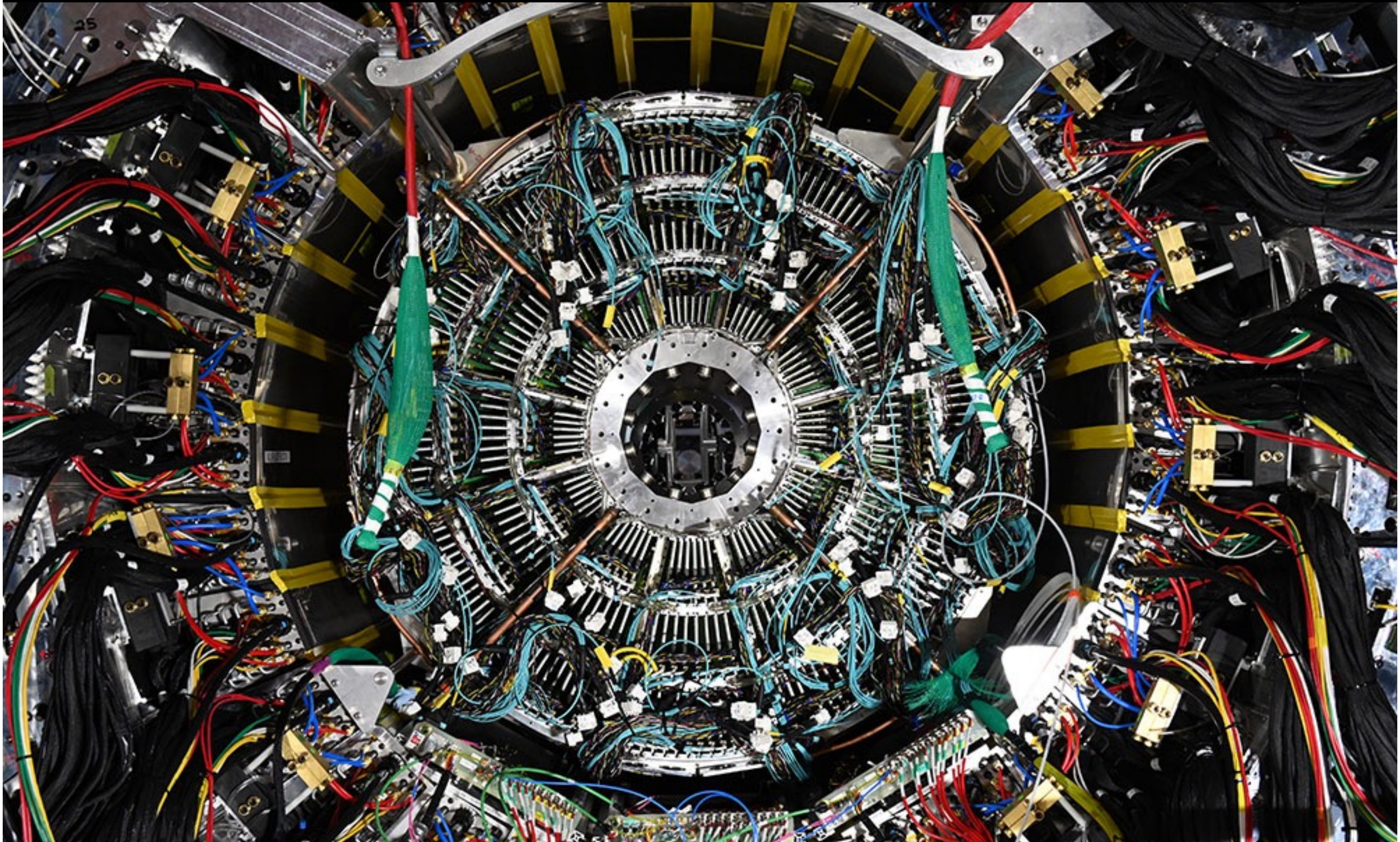


ATLAS & CMS –

full calorimetry, tracking, *different approaches and analysis philosophies*



sPHENIX – new collider detector at RHIC



More on sPHENIX later..

Lecture #2

Collision Dynamics

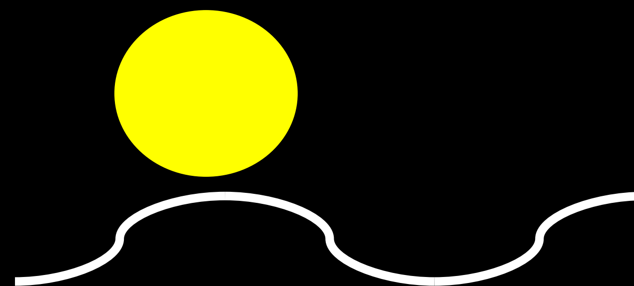
Structure of the Proton

See the whole proton

Momentum transfer

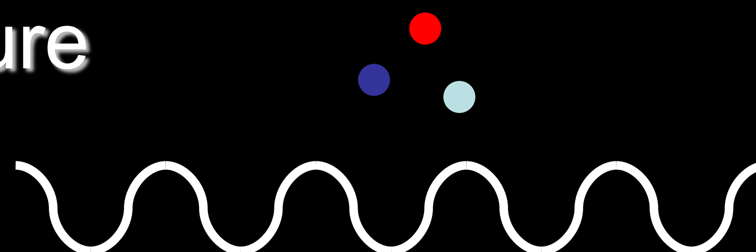
$Q^2 = 0.1\ \mathrm{GeV}^2$

Wavelength $\lambda = h/p$



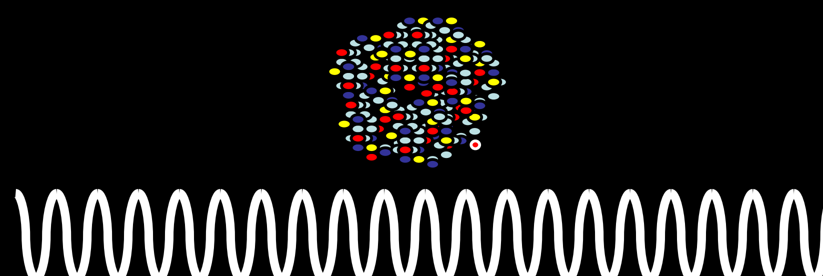
See the quark substructure

$Q^2 = 1.0\ \mathrm{GeV}^2$

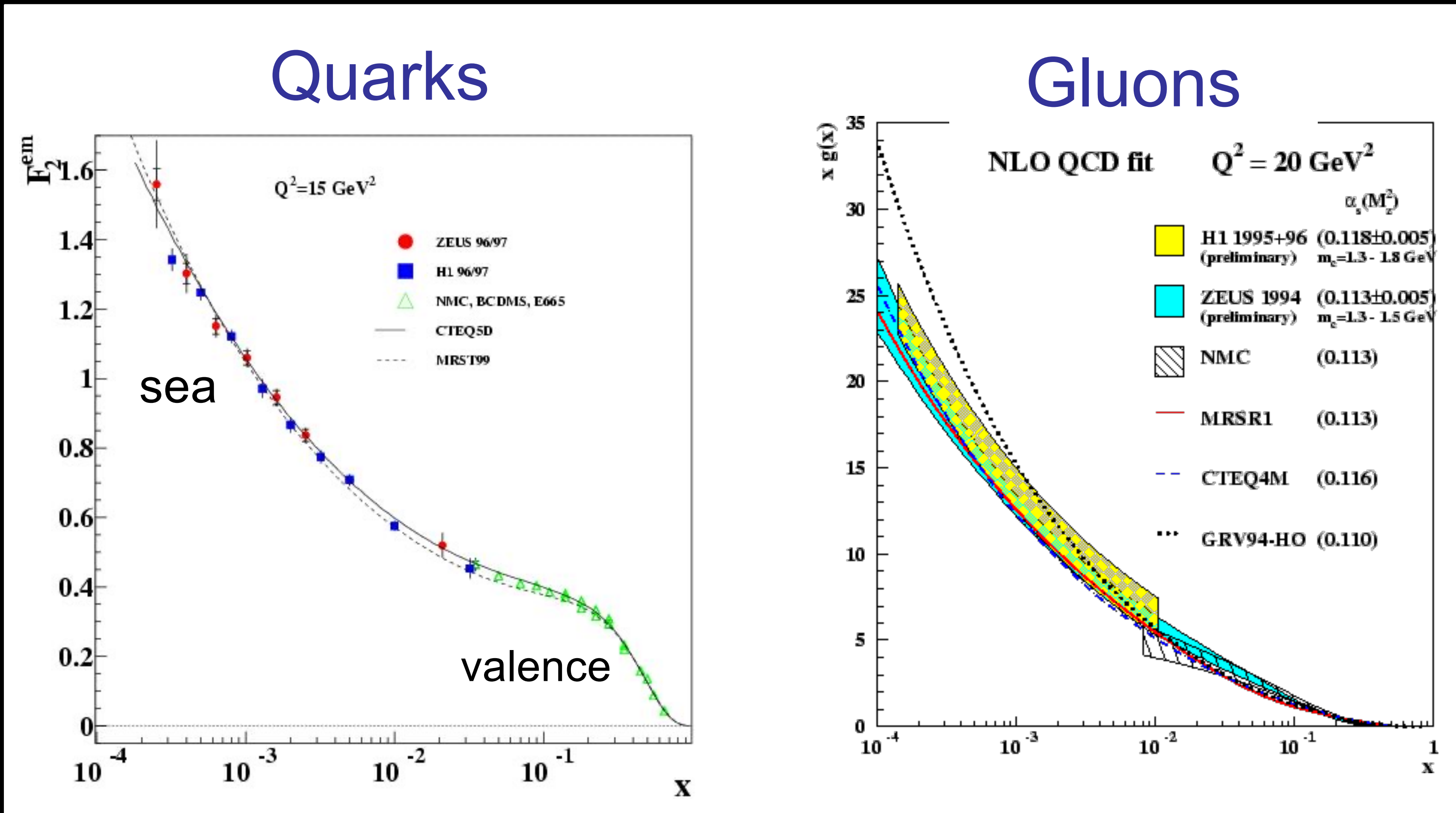


See many partons (quarks and gluons)

$Q^2 = 20.0\ \mathrm{GeV}^2$



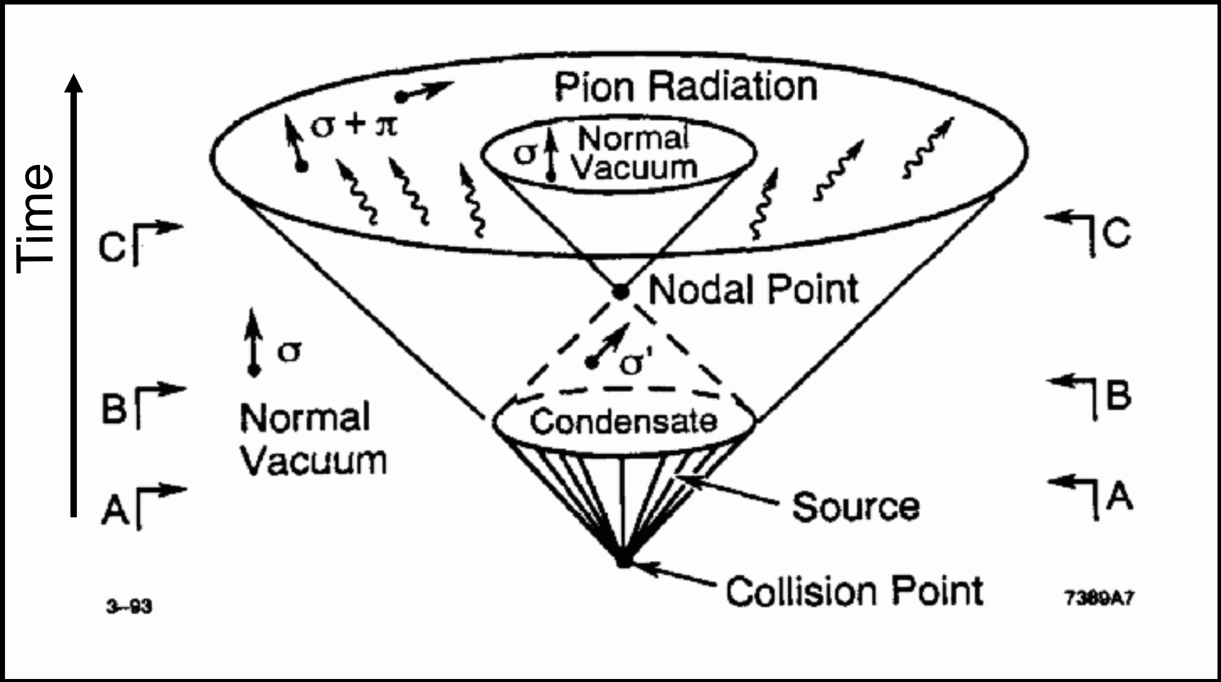
Parton Distribution Functions



- Structure functions rise rapidly at low-x
- More rapid for gluons than quarks
- Watch out for side-by-side plots with different vertical scales (left 1.7 and right 30!)

QGP in Proton+Proton Reactions?

Bjorken speculated that in the "interiors of large fireballs produced in very high-energy pp collisions; vacuum states of the strong interactions are produced with anomalous chiral order parameters."



http://www-minimax.fnal.gov/

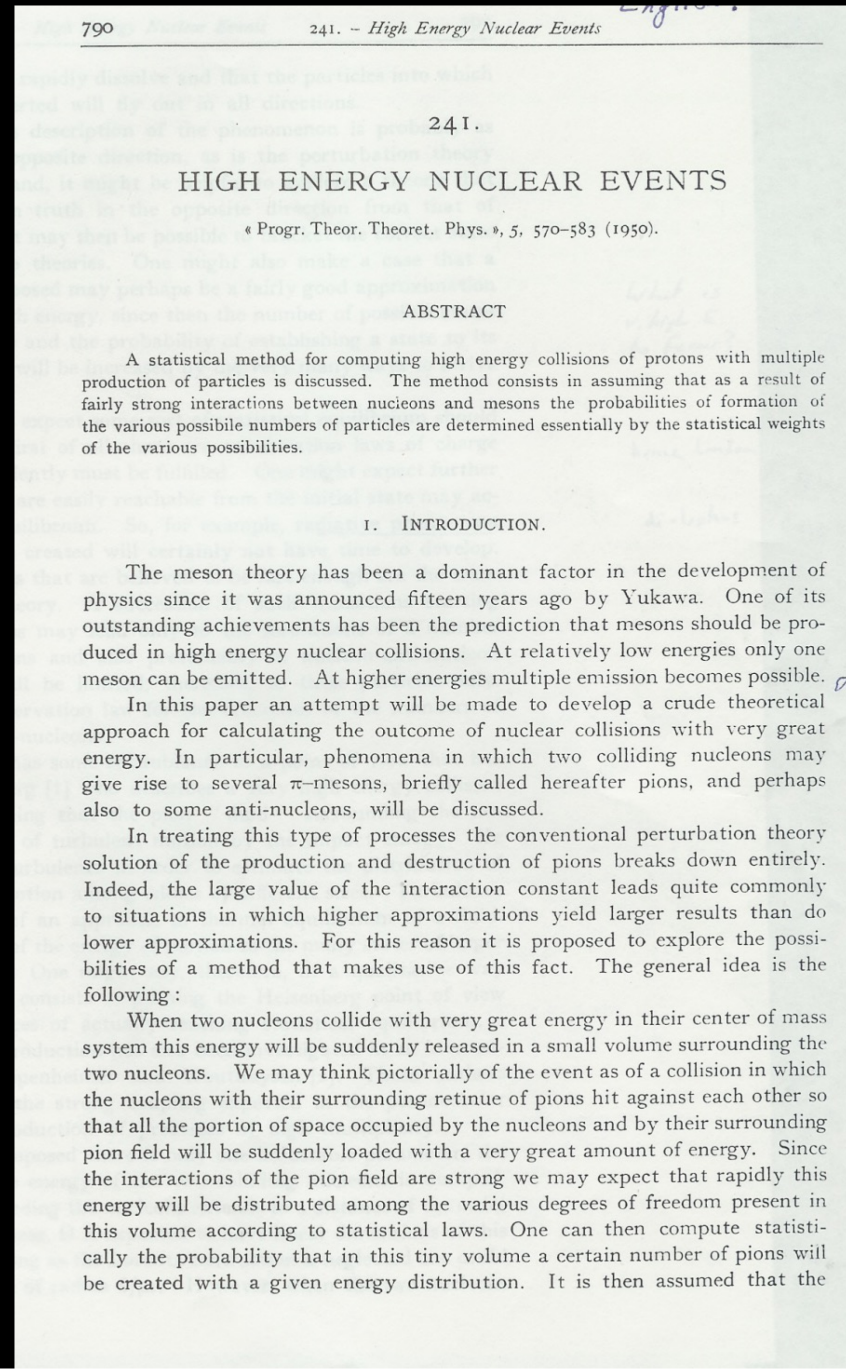
"Baked Alaska"

<u>Fermi (1950)</u>

"High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)

Groundwork for statistical approach to particle production in strong interactions:

> "Since the interactions of the pion field are *strong*, we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to <u>statistical laws</u>."



241.

HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several π–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

Landau (1955)

Significant extension of Fermi's approach

Considers fundamental roles of

- Hydrodynamic evolution
- Entropy

"The defects of Fermi's theory arise mainly because the expansion of the compound system is not correctly taken into account…(The) expansion of the system can be considered on the basis of relativistic hydrodynamics."

88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

1. Introduction

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of 10^9 eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume V in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume V in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, μ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume V will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \tag{1.1}$$

where M is the mass of a nucleon and E' the nucleon energy in the centre of mass system.

(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume V at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

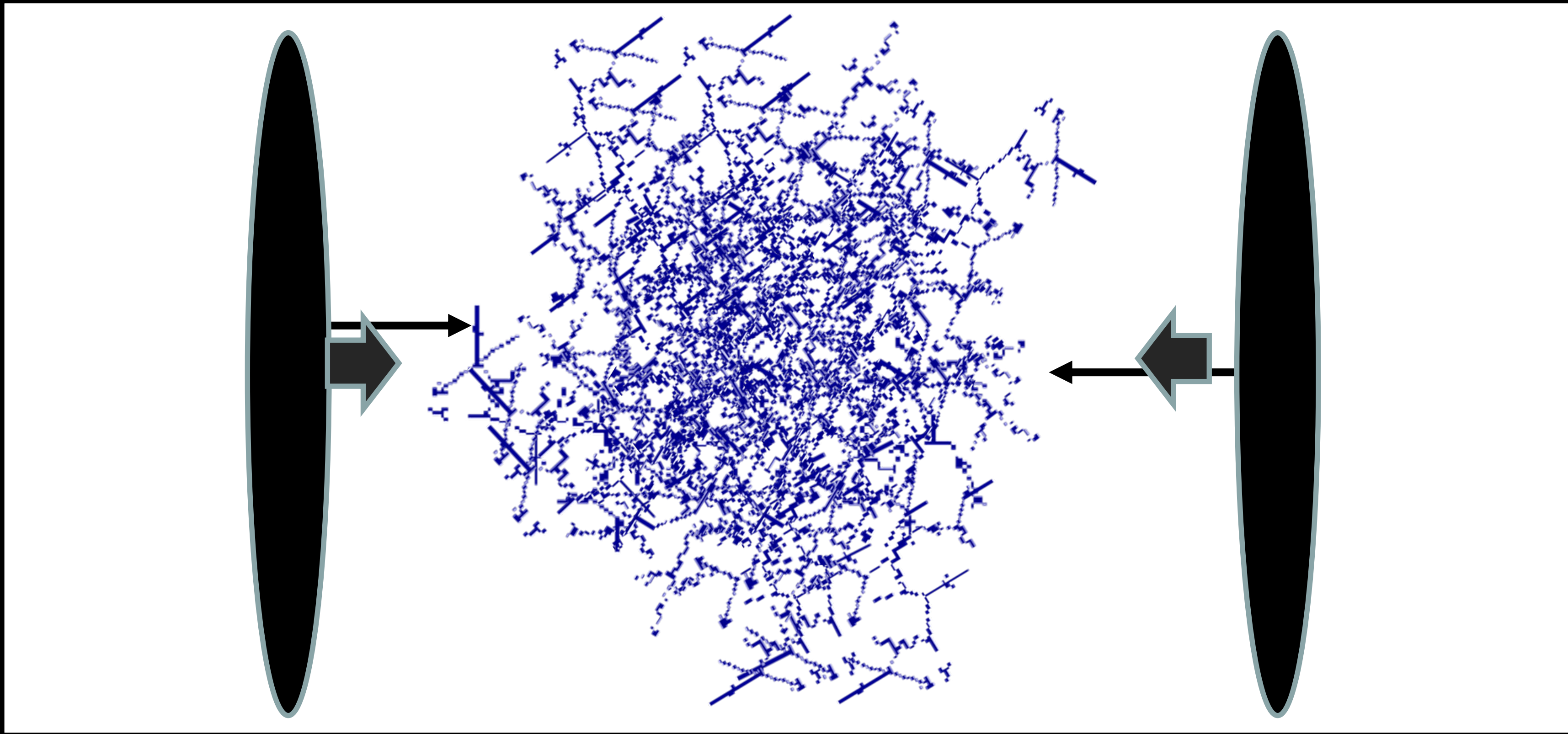
С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, **56**, 309 (1955).

S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, **3**, 15 (1956).

Why Heavy Ions?

- High energy density may be achieved in proton-proton collisions, but the partonic re-interaction time scale is only of order 1-3 fm/c
- It is difficult to select events with different geometries and avoid autocorrelations
- We will see that probes with long paths through the medium are key observables
- We should not rule out p+p reactions, but rather study the similarities and differences with A+A reactions -- spoiler alert: this is a big issue

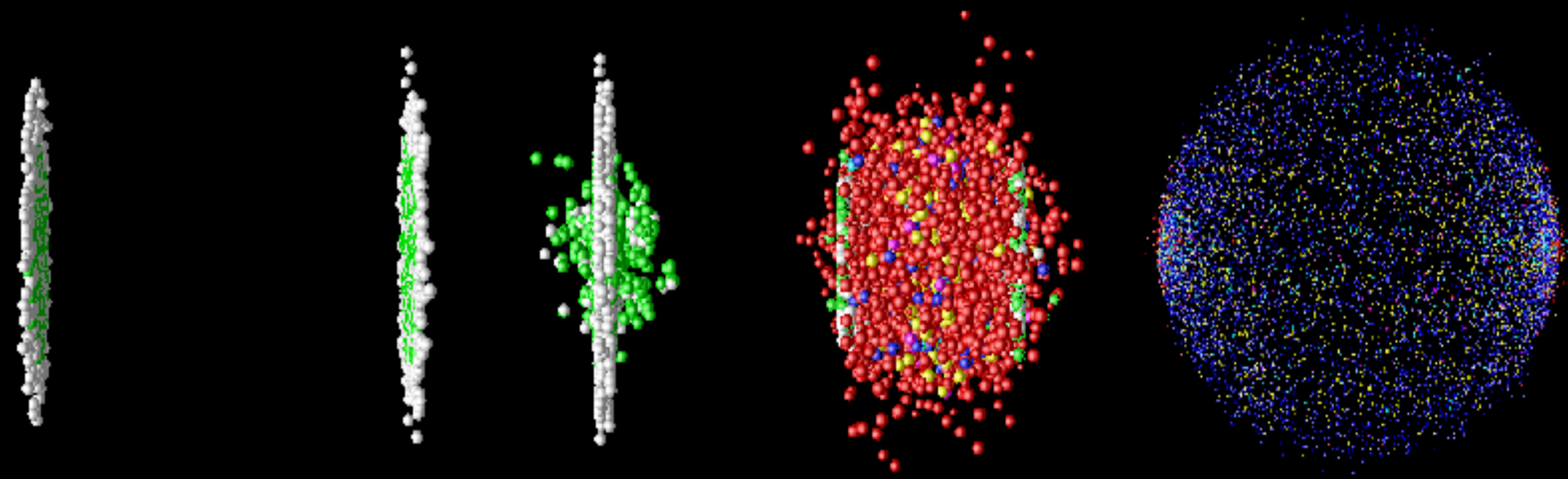
RHIC and LHC = Gluon Colliders



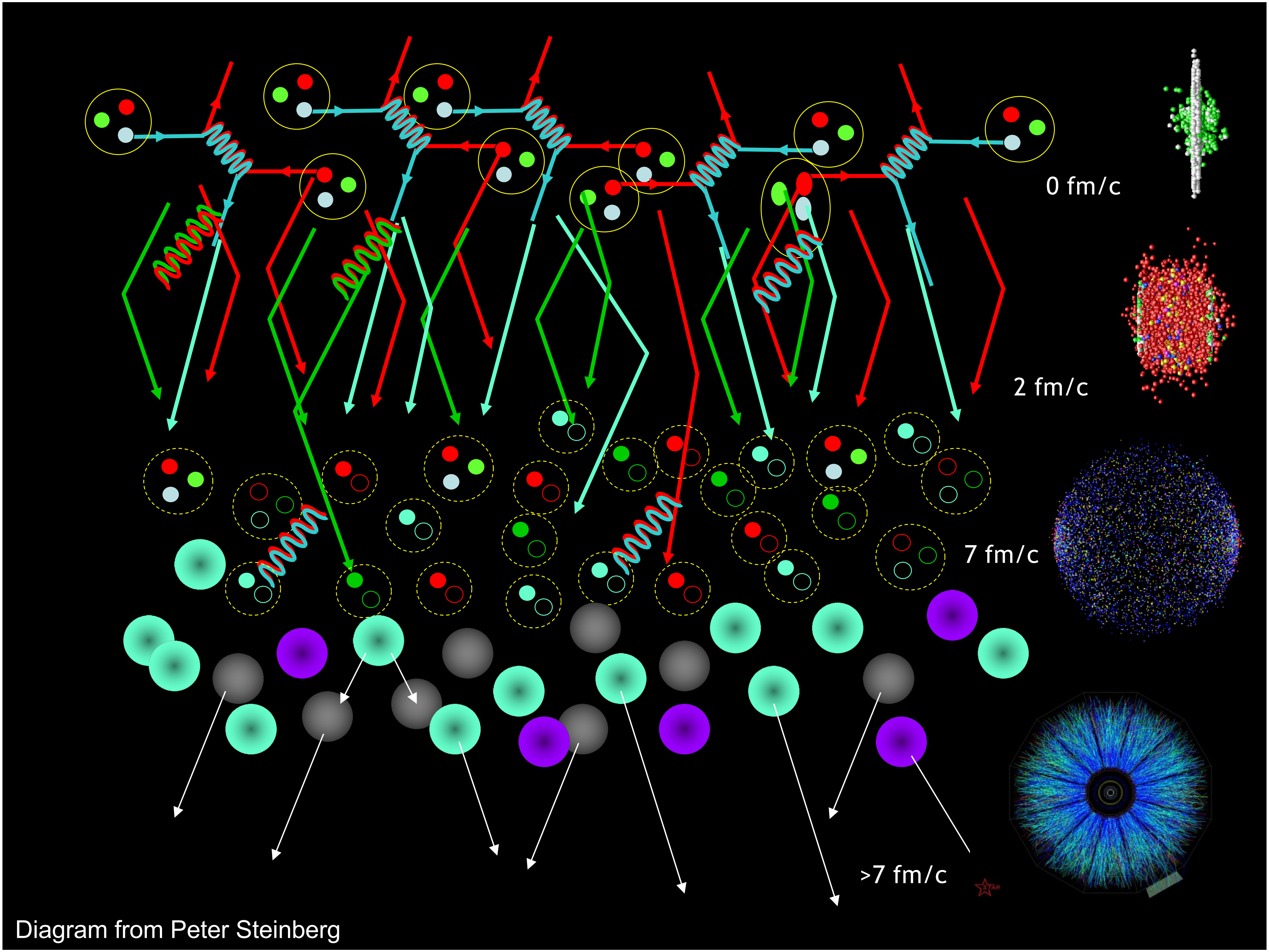
20,000 gluons, quarks, and antiquarks
are made physical in the laboratory !

What is the nature of this ensemble of partons?
New emergent phenomena?

Heavy Ion Time Evolution



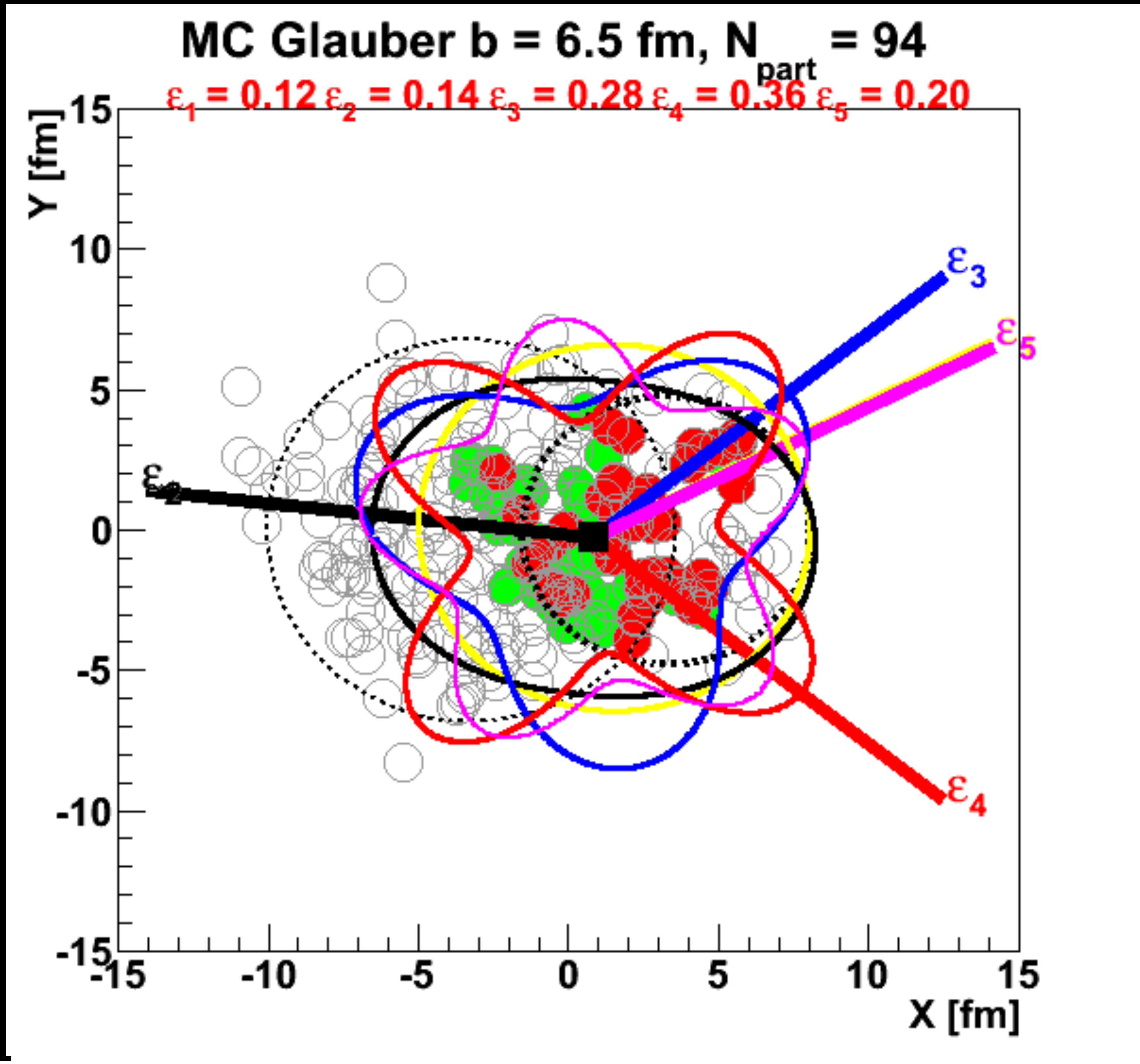
1. Initial Nuclei Collide
2. Partons are Freed from Nuclear Wavefunction
3. Partons interact and potentially form a Quark-Gluon Plasma
4. System expands and cools off
5. System Hadronizes and further Re-Scatters
6. Hadrons and Leptons stream towards our detectors


0 fm/c
2 fm/c
7 fm/c
>7 fm/c
Diagram from Peter Steinberg

Initial Conditions

Monte Carlo

Glauber Model and Characterization



https://tglaubermc.hepforge.org/

TGlauberMC is

- Home
- Subversion
- Tracker
- Wiki

TGlauberMC: A ROOT-based implementation of the PHOBOS Glauber Monte Carlo

Authors: Burak Alver (MIT), Mark Baker (BNL), Constantin Loizides (MIT), Peter Steinberg (BNL)
Brookhaven National Laboratory (BNL) & Massachusetts Institute of Technology (MIT)

"Glauber" models are used to calculate geometric quantities in the initial state of heavy ion collisions, such as impact parameter, number of participating nucleons and initial eccentricity. The four RHIC experiments have different methods for Glauber Model calculations, leading to similar results for various geometric observables. In this document, we describe an implementation of the Monte Carlo based Glauber Model calculation used by the PHOBOS experiment. The assumptions that go in the calculation are described. A user's guide, arXiv:0805.4411, is provided for running various calculations.

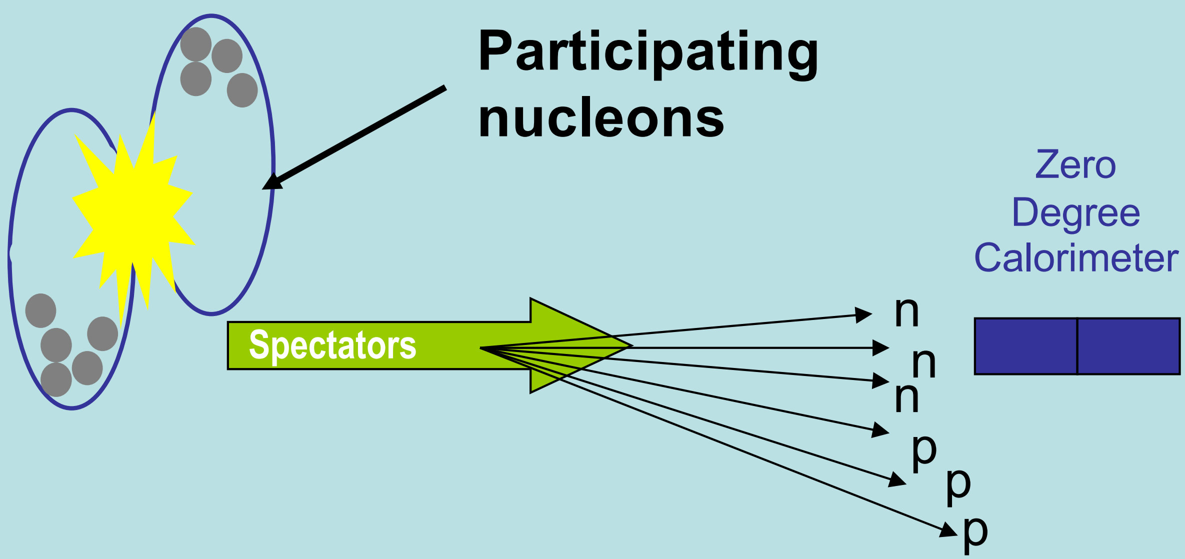
An **improved version (v2)** by C. Loizides (LBNL), J. Nagle (Colorado U.), P. Steinberg (BNL) is described in arXiv:1408.2549, which includes tritium, Helium-3, and Uranium, as well as the treatment of deformed nuclei and Glauber-Gribov fluctuations of the proton in p+A collisions.

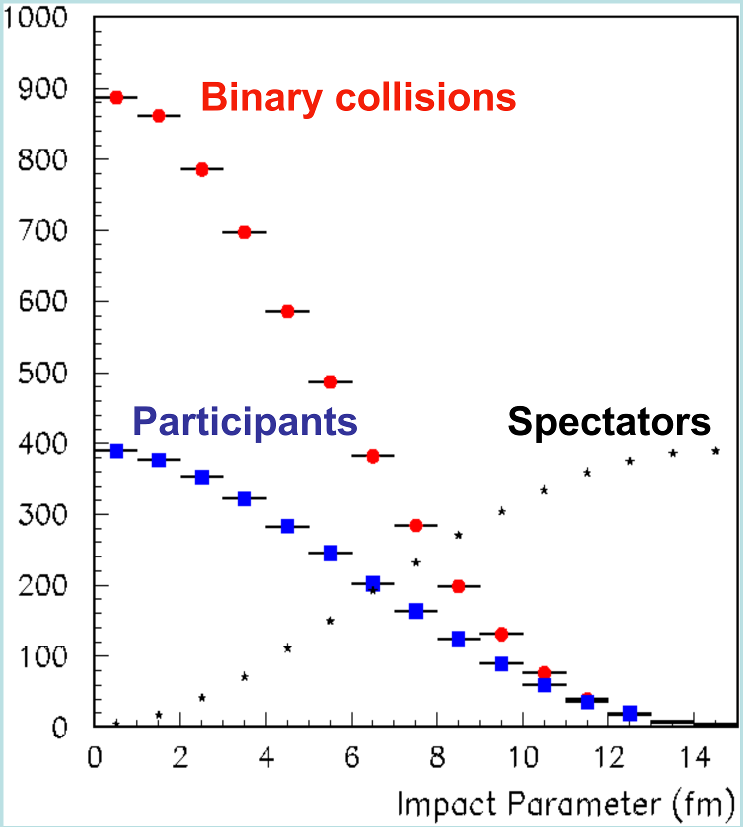
For the latest release see the TGlauberMC downloads page.

Click here to contact the authors with questions.

Collision Characterization

The impact parameter determines the number of nucleons that participate in the collision.





Participants = 2 x 197 - Spectators

Glauber Modeling in High-Energy Nuclear Collisions

Annual Review of Nuclear and Particle Science
Vol. 57: 205-243 (Volume publication date November 2007)
First published online as a Review in Advance on May 9, 2007
DOI: 10.1146/annurev.nucl.57.090506.123020

Michael L. Miller,[1] Klaus Reygers,[2] Stephen J. Sanders,[3] and Peter Steinberg[4]

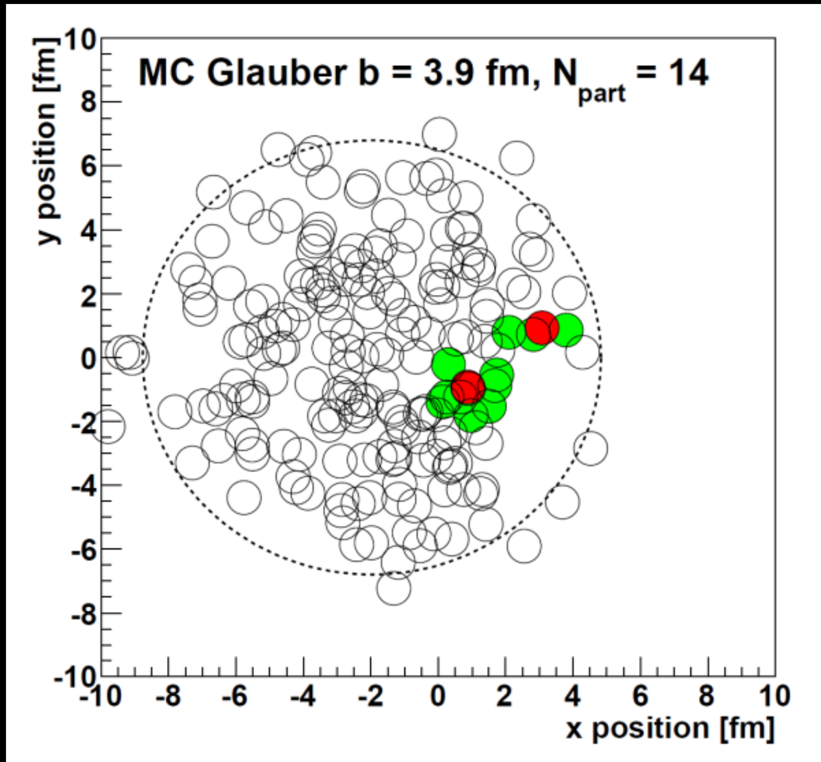
Relate experimental observables to averages from the Monte Carlo Glauber.

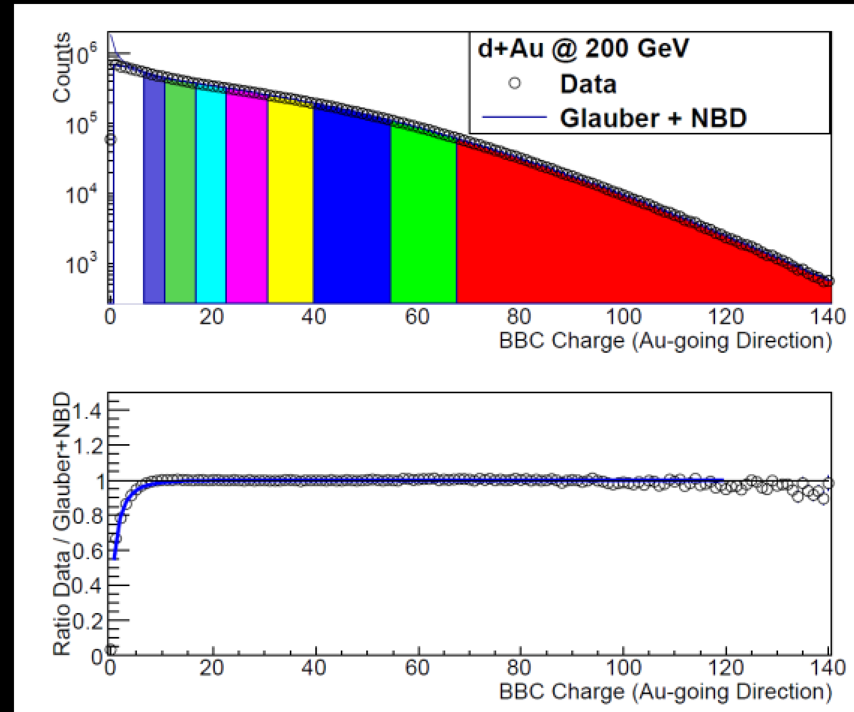
N_{coll} (binary collisions), N_{part} (participants), N_{spec} (spectators)
b (impact parameter), elliptical shape, orientation, overlap area,..

$$\varepsilon_n = \frac{\sqrt{\langle r^2 cos(n\phi)\rangle^2 + \langle r^2 sin(n\phi)\rangle^2}}{\langle r^2\rangle}$$

$$S = 4\pi\sqrt{\langle x^2\rangle\langle y^2\rangle - \langle xy\rangle^2}$$

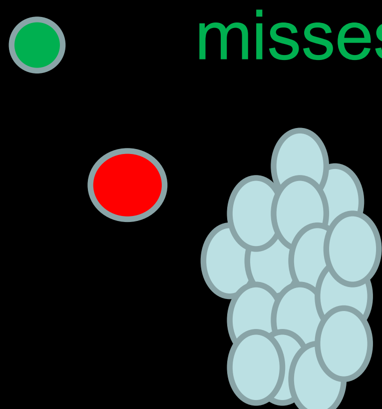
ALICE Centrality Paper – good resource
http://arxiv.org/abs/1301.4361

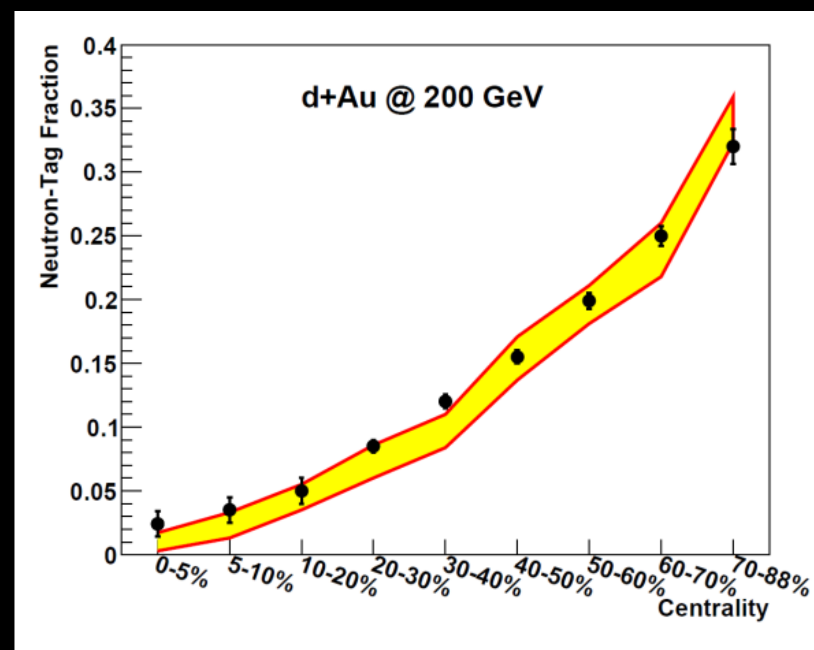




d+Au

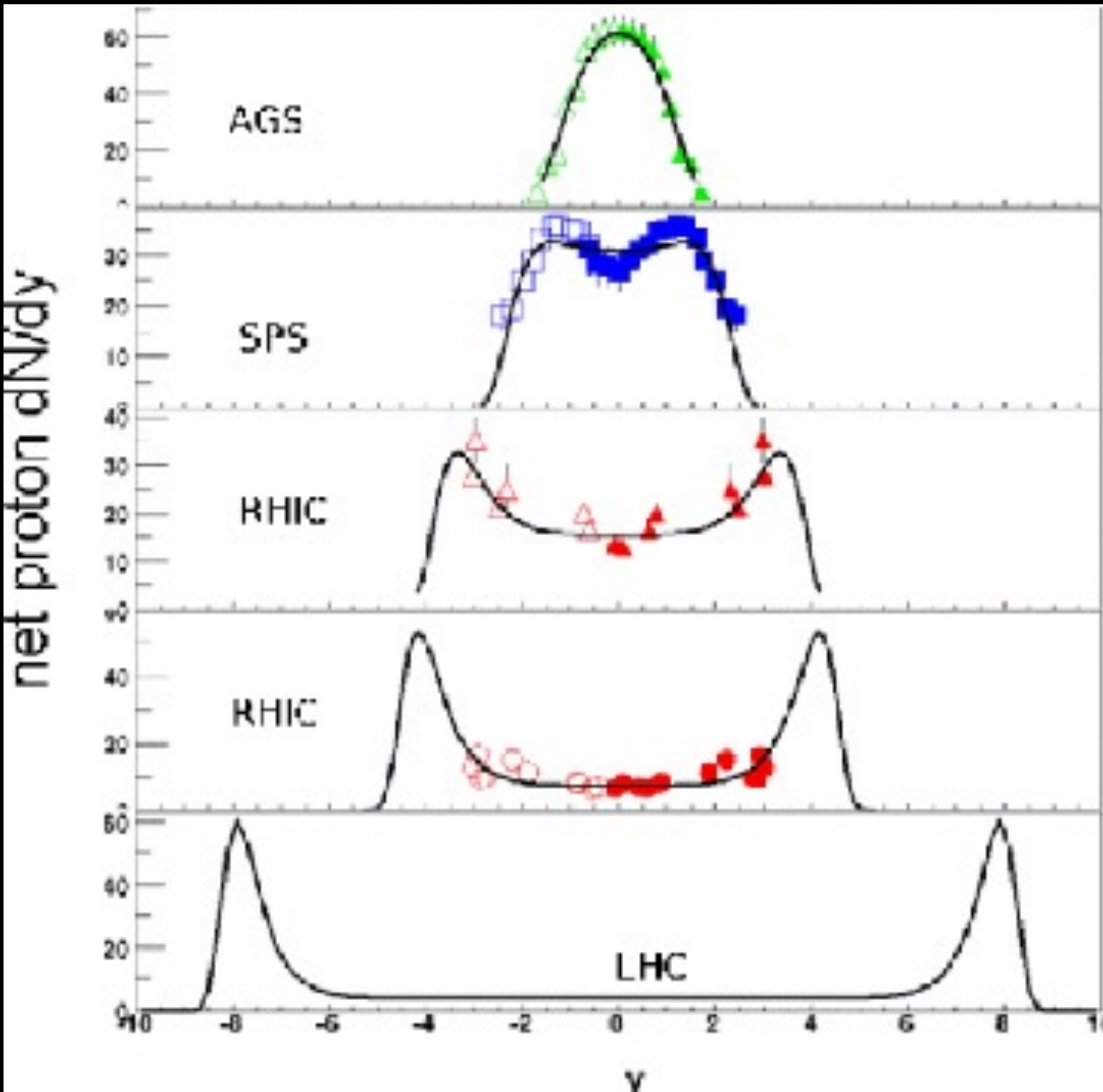
Sometimes the neutron misses





http://journals.aps.org/prc/abstract/10.1103/PhysRevC.90.034902

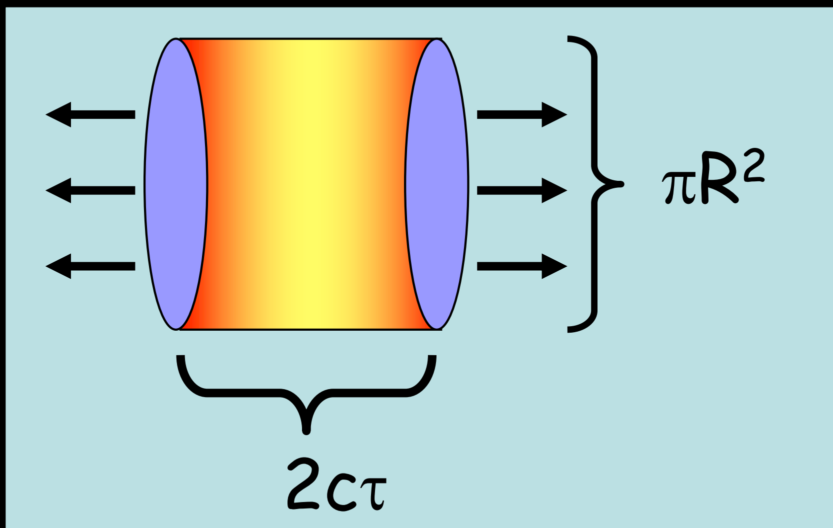
How much energy goes into QGP?

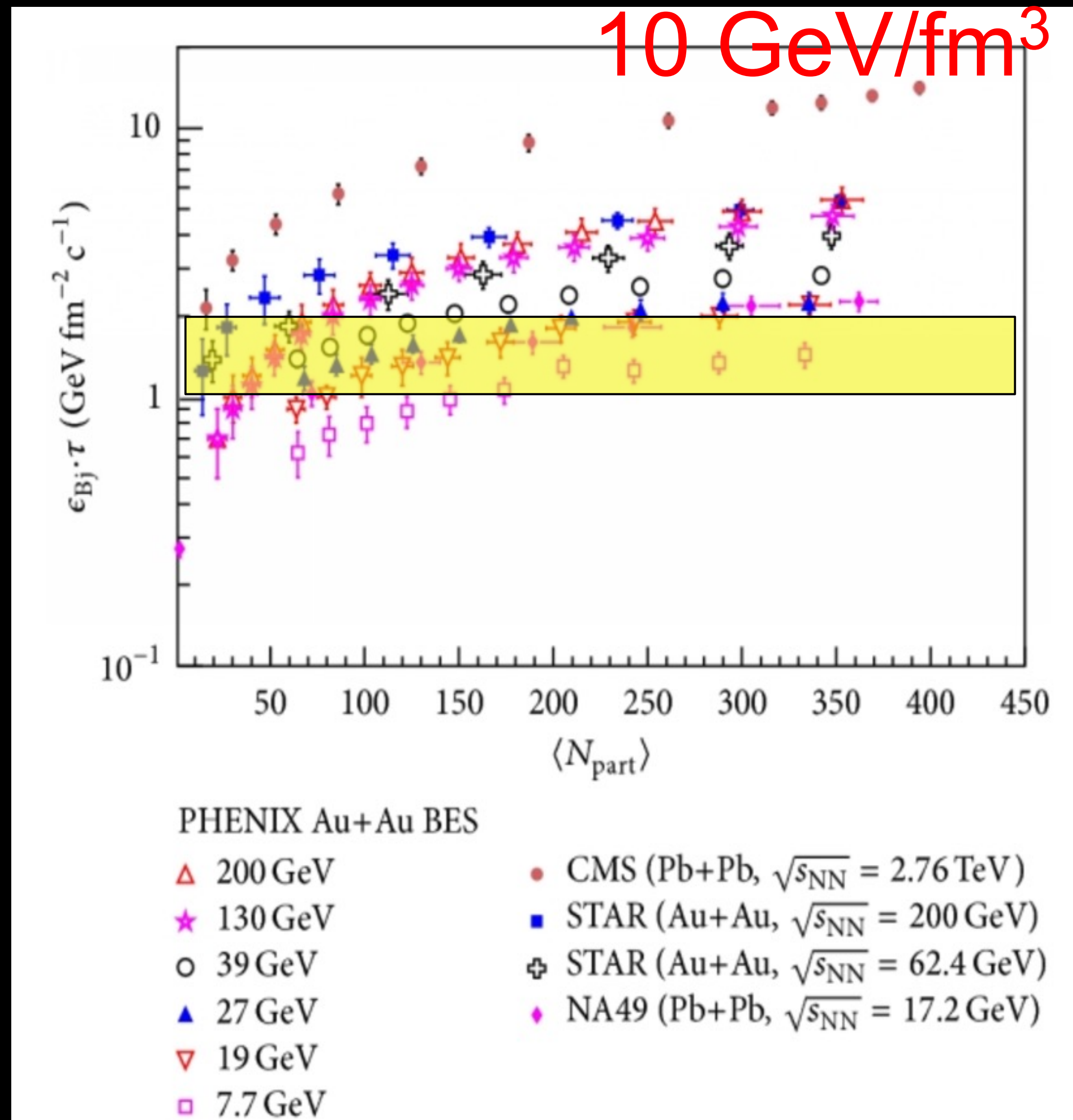


At RHIC out of a maximum energy of 39.4 TeV in central Gold+Gold reactions, **26 TeV** is made available for heating the system.

Bjorken Energy Density

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{2c\tau} \left(2 \frac{dE_T}{dy} \right)$$





Early energy density well above expected QGP transition

* Side note about errata or lack thereof…

Collision Dynamic Summary

- Depositing majority of kinetic energy into new medium
- Energy density appears above phase transition value, noting that it is a smooth crossover
- Energy is distributed into particle production statistically
- No sharp global feature distinct from smaller hadron collisions, but instead gradual changes

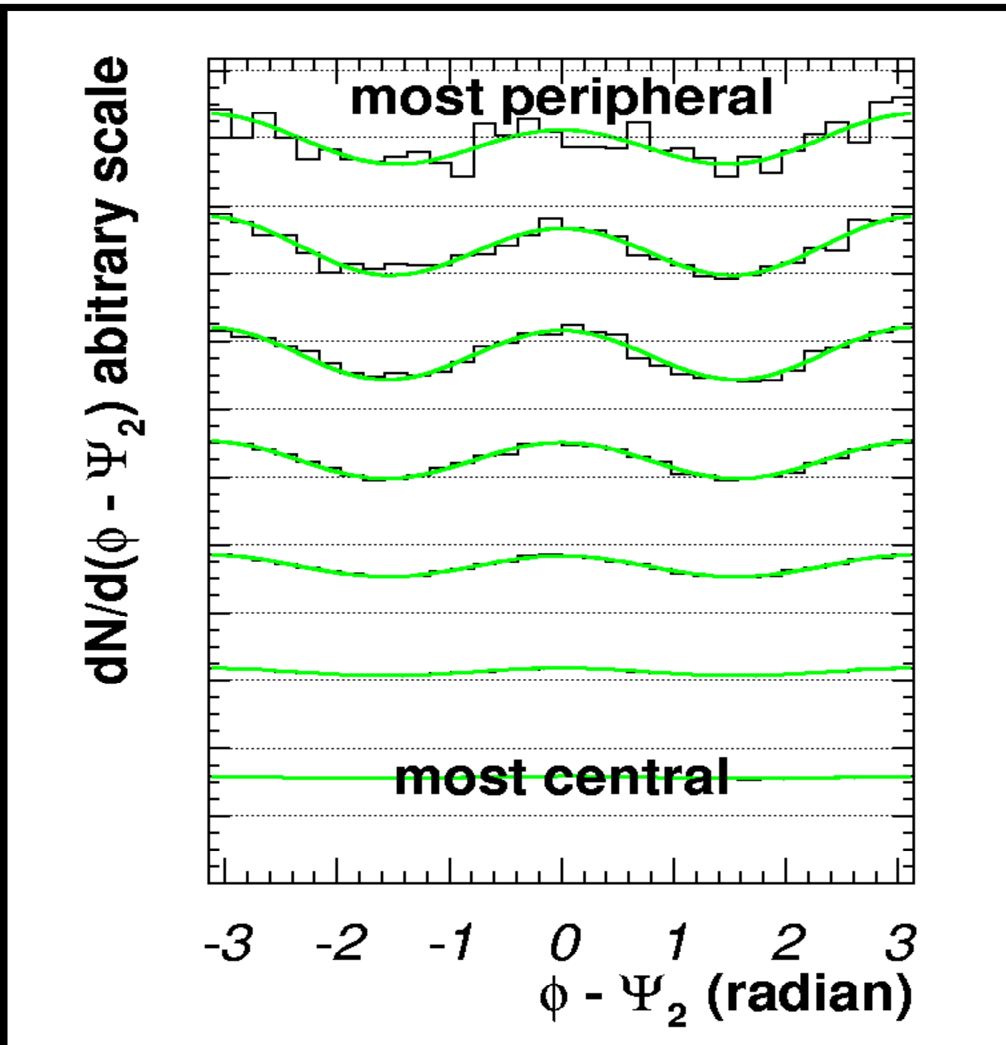
The Perfect Liquid

The Key Paradigm in the Field

What do we mean by Perfect?

What evidence is there?

Non-Central A+A Geometry



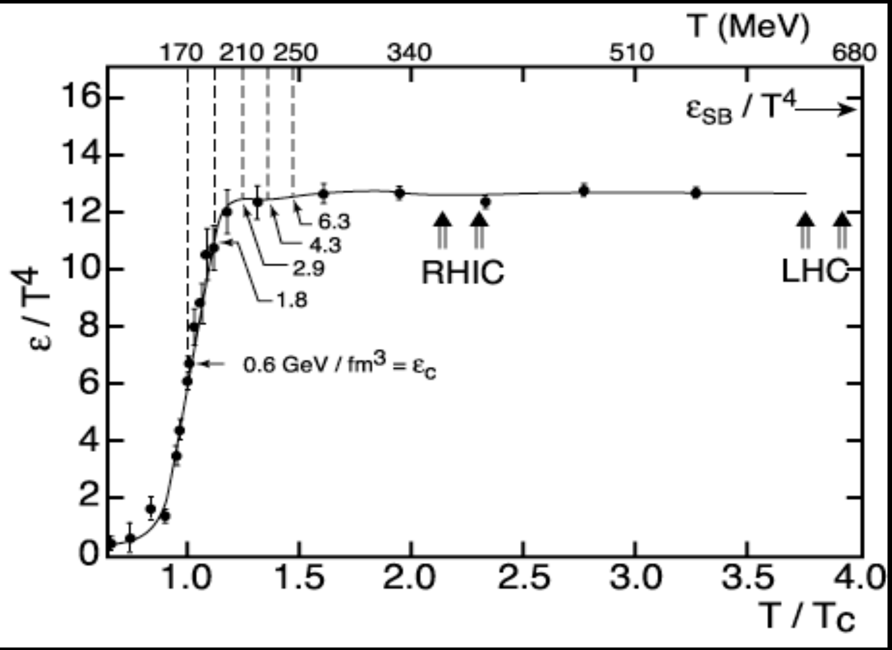
$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2v_2(p_T; b)\cos(2\varphi) + \ldots\right)$$

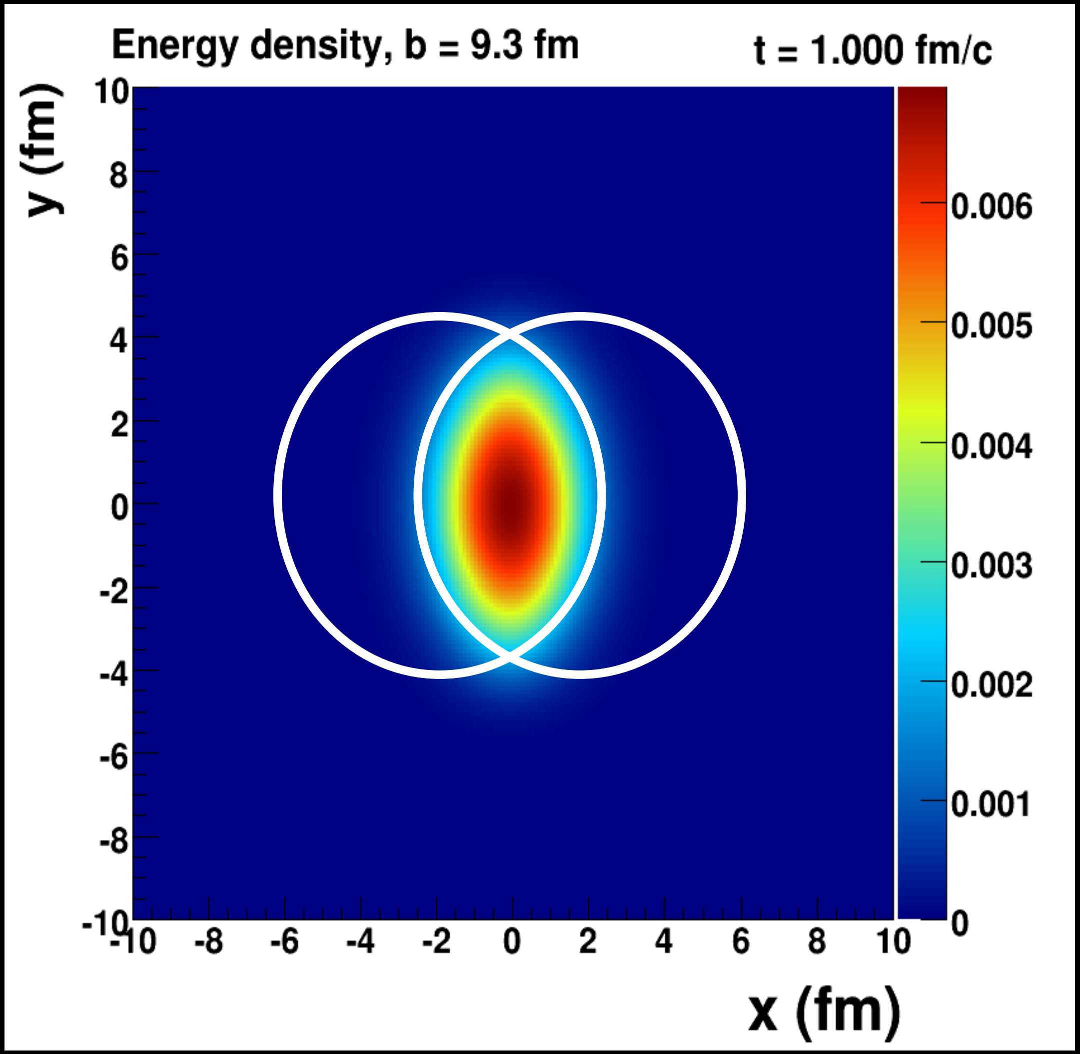
v_2 = "elliptic flow"

Ideal Hydrodynamics

Key Inputs:

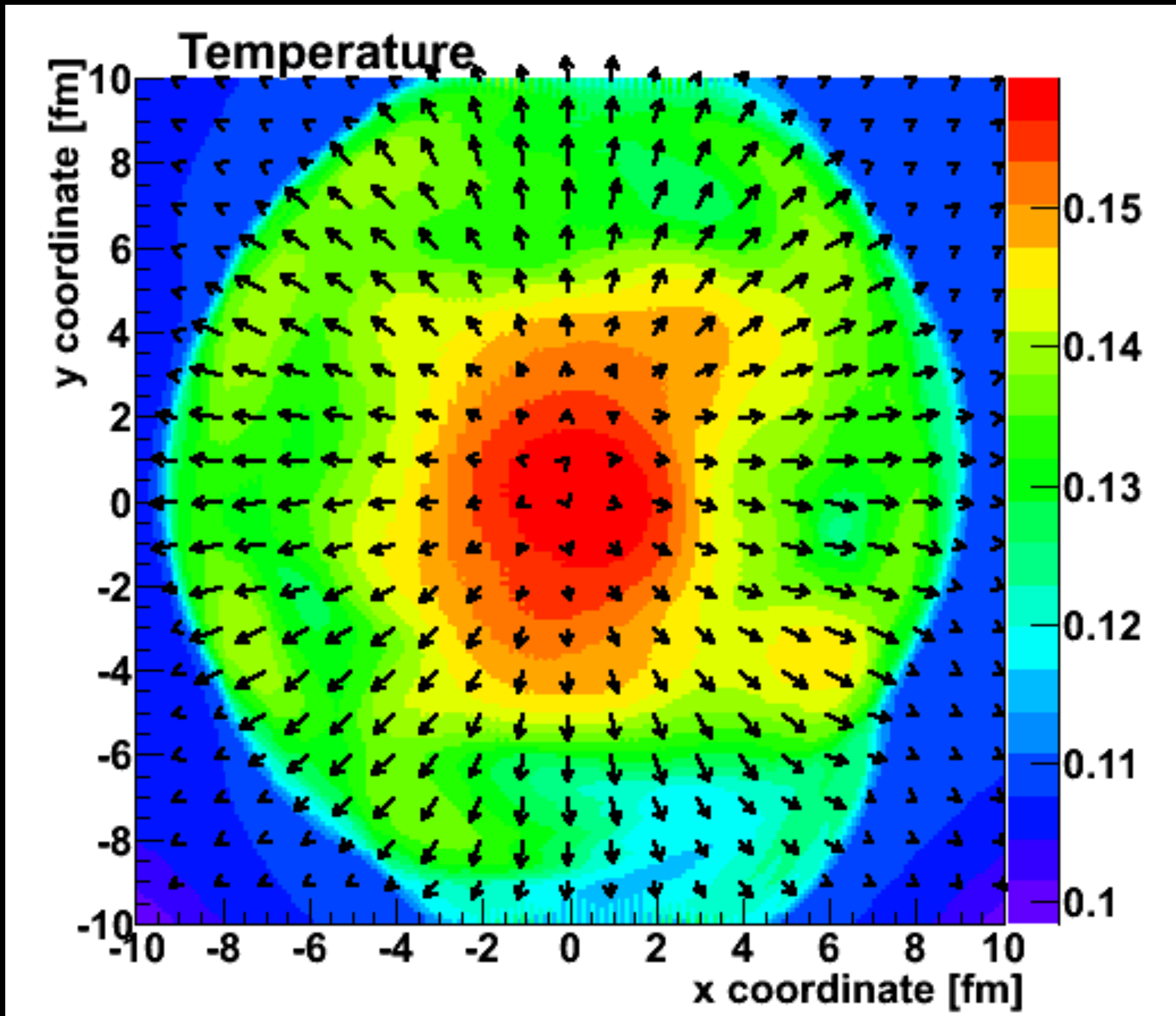
- Initial Geometry
- QCD Equation of State





Assumes early thermalization [not proven]
Assumes no dissipation (shear/bulk viscosity = 0)

Fluid cells "freeze-out" below T_{freeze}
Isotropic hadrons in cell rest frame, then boosted



Temperature Profile + Fluid Cell Velocity Vectors

Fluid → Hadrons

Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production

Fred Cooper and Graham Frye
Phys. Rev. D **10**, 186 – Published 1 July 1974

$$E\frac{dN}{d^3p} = \int_{\Sigma} d\Sigma_\mu p^\mu f(T, p_\mu u^\mu, \pi^{\mu\nu}) \,,$$

An important, but not often discussed, assumption in the calculations.

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.10.186

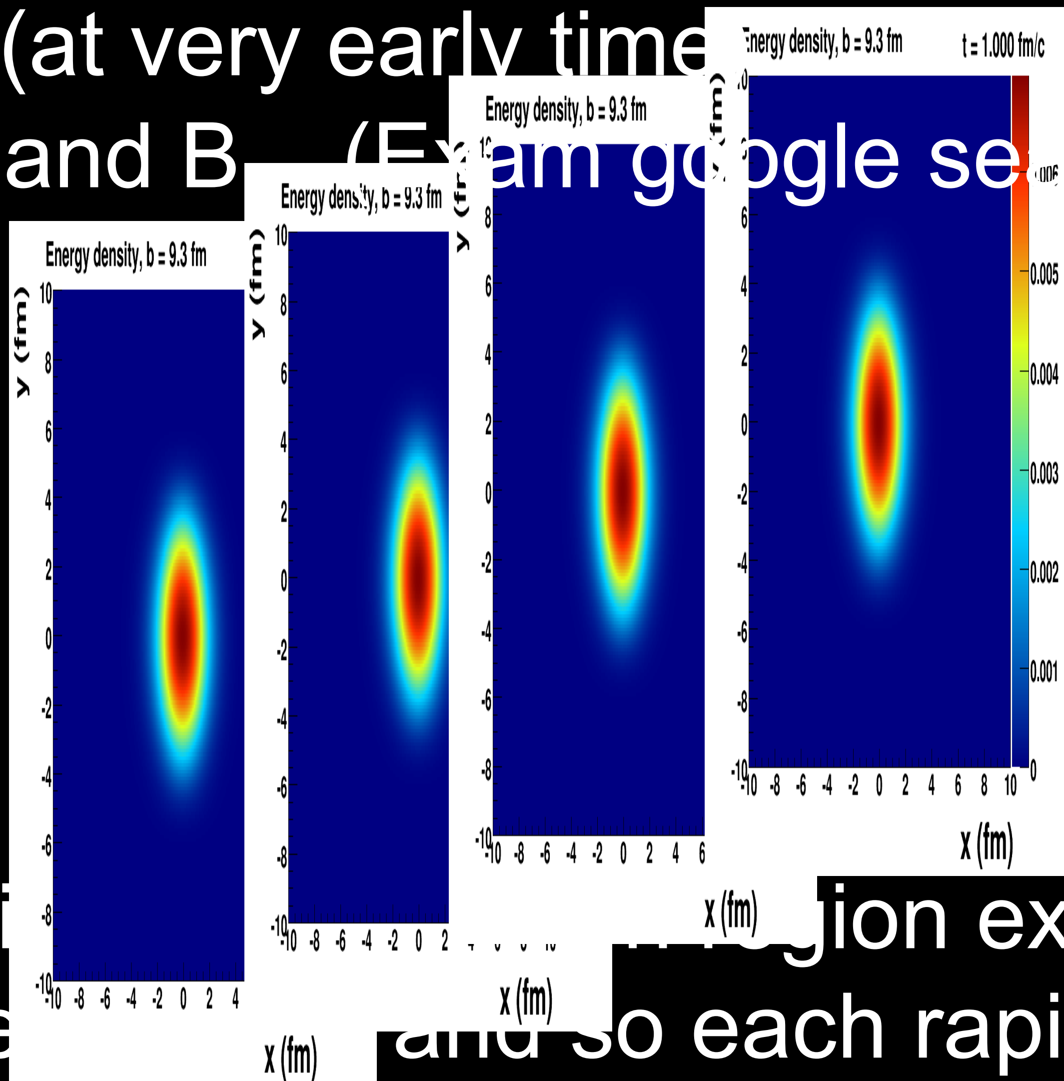
Two particles separated far in rapidity

Just like the Universe event horizon problem

A causes B (at very early time)

B causes A (at very early time

C causes A and B (Exam google search story)



Initial elli … region expands at the spee … and so each rapidity slice has approximately the same geometry.

Always Read the Original Material

PHYSICAL REVIEW D VOLUME 46, NUMBER 1 1 JULY 1992

Anisotropy as a signature of transverse collective flow

Jean-Yves Ollitrault
Service de Physique Théorique, Centre d'Études de Saclay, F-91191 Gif-sur-Yvette CEDEX, France
(Received 19 February 1992)

We show that anisotropies in transverse-momentum distributions provide an unambiguous signature of transverse collective flow in ultrarelativistic nucleus-nucleus collisions. We define a measure of the anisotropy from experimental observables. The anisotropy coming from collective effects is estimated quantitatively using a hydrodynamical model, and compared to the anisotropy originating from finite multiplicity fluctuations. We conclude that collective behavior could be seen in Pb-Pb collisions if a few hundred particle momenta were measured in a central event.

PACS number(s): 25.75.+r, 12.38.Mh, 24.60.Ky, 47.75.+f

Article
Zeitschrift für Physik C Particles and Fields
December 1996, Volume 70, Issue 4, pp 665-671

First online: 31 March 2014

Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions

S. Voloshin, Y. Zhang

Common problem – not reading the original references…

V = Voloshin (?)

How do experiments measure v2?

An entire lecture could be on these details…

http://journals.aps.org/prc/abstract/10.1103/PhysRevC.80.014904

PHYSICAL REVIEW C
covering nuclear physics

Highlights Recent Accepted Authors Referees Search Press About

Effect of flow fluctuations and nonflow on elliptic flow methods

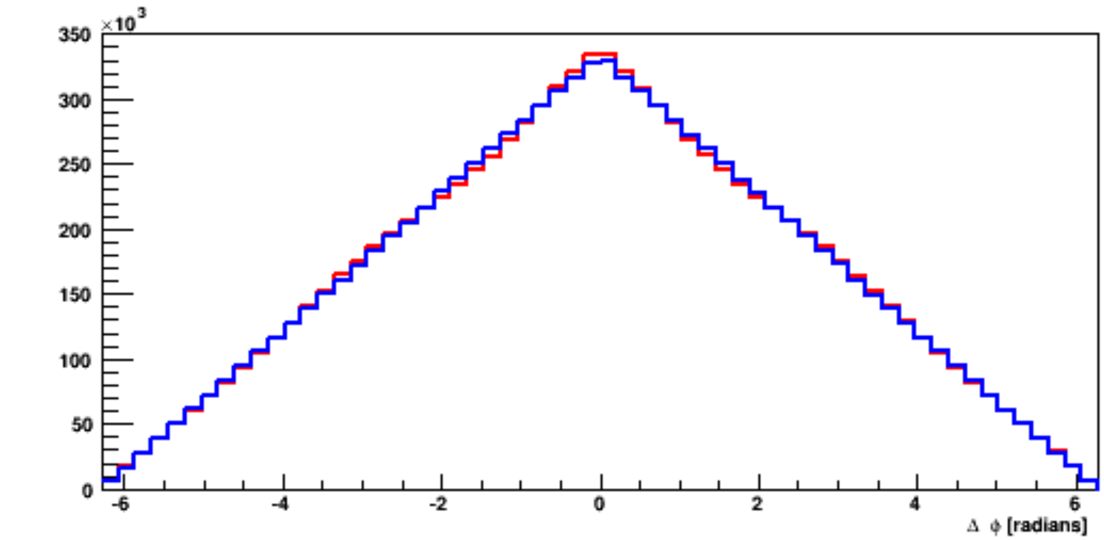
Jean-Yves Ollitrault, Arthur M. Poskanzer, and Sergei A. Voloshin
Phys. Rev. C **80**, 014904 – Published 10 July 2009

Short introduction to some experimental basics

Two Particle Correlations

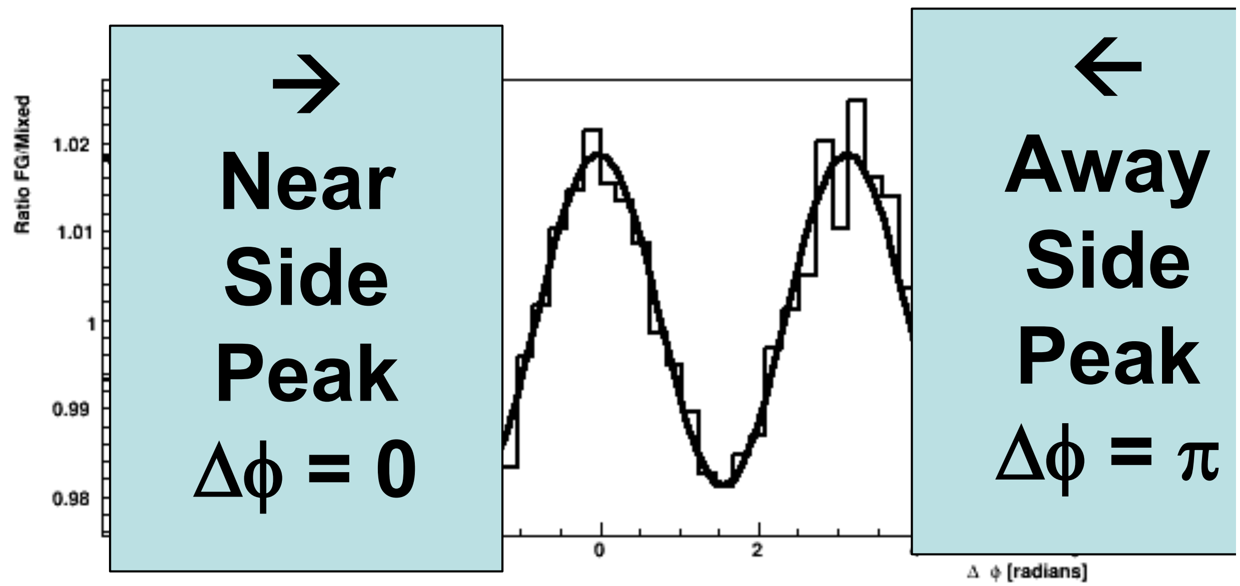
Two independent particles that come from a common source distribution $1 + 2v_2\cos[2(\phi-\psi_2)]$

Random Case



Resulting $\Delta\phi$ Distribution

Divide the two FG/BG



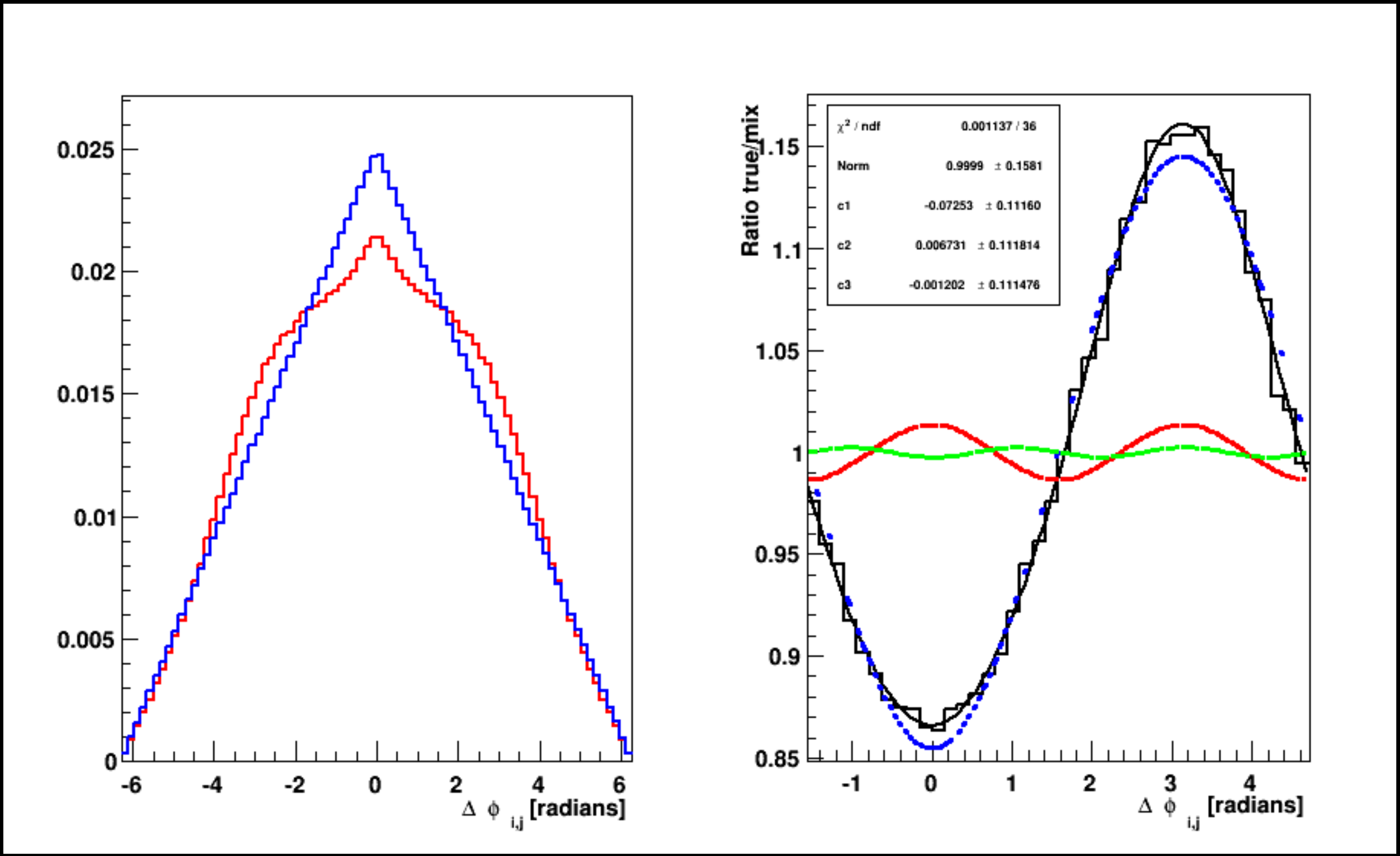
Near Side Peak $\Delta\phi = 0$

Away Side Peak $\Delta\phi = \pi$

Oscillation $1 + 2v_2^2 \cos(2\Delta\phi)$

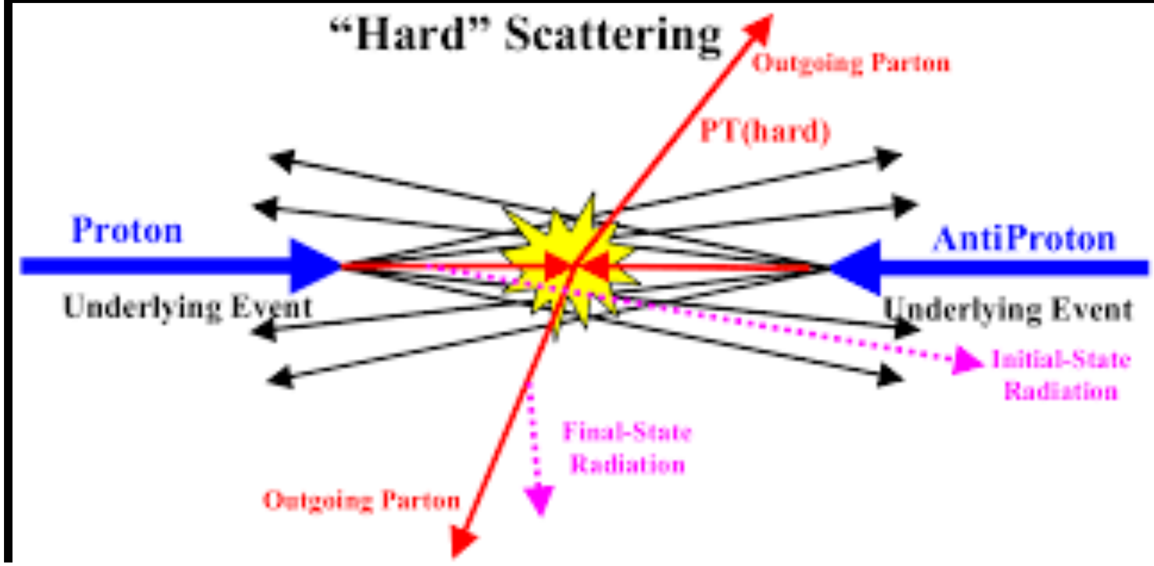
Complications and Other Contributions?

Momentum Conservation

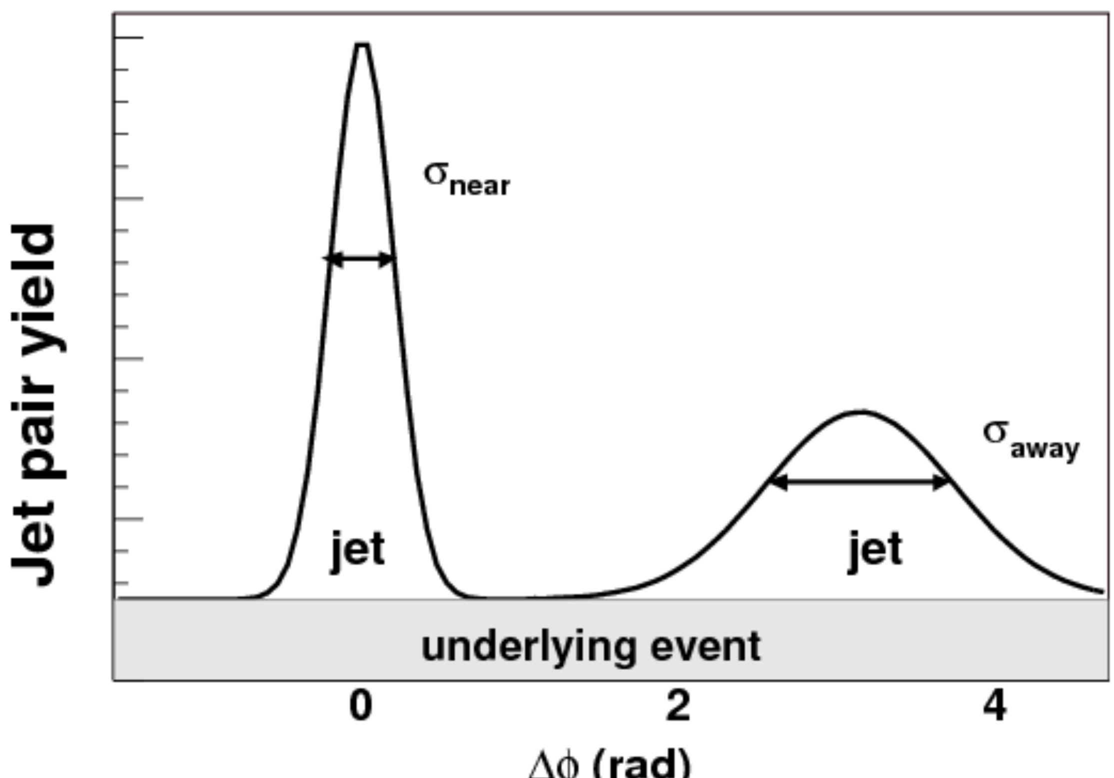


https://root.cern.ch/doc/master/classTGenPhaseSpace.html

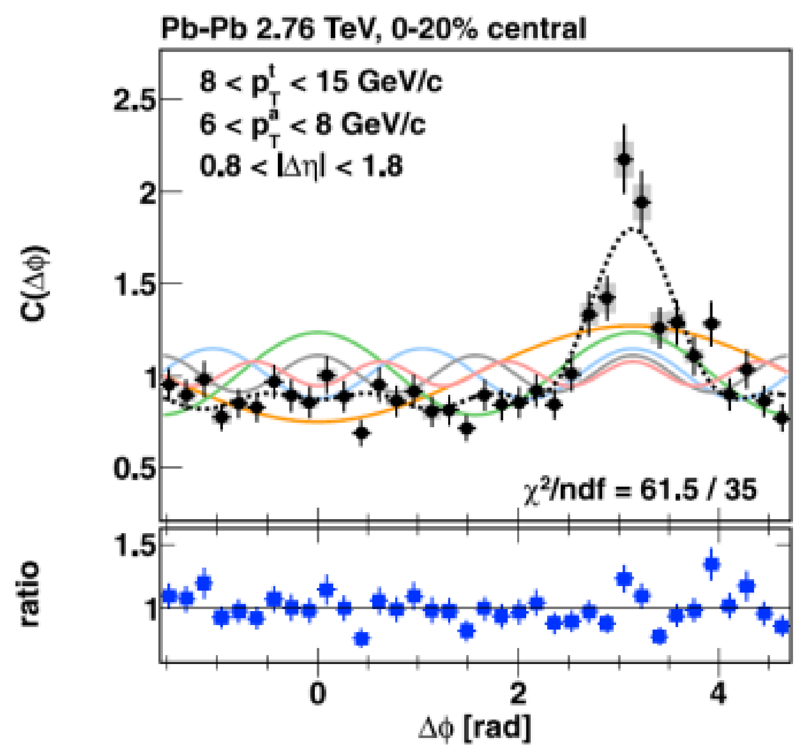
Jet Correlations



Multi-particle correlations – same jet, opposite jet, etc.

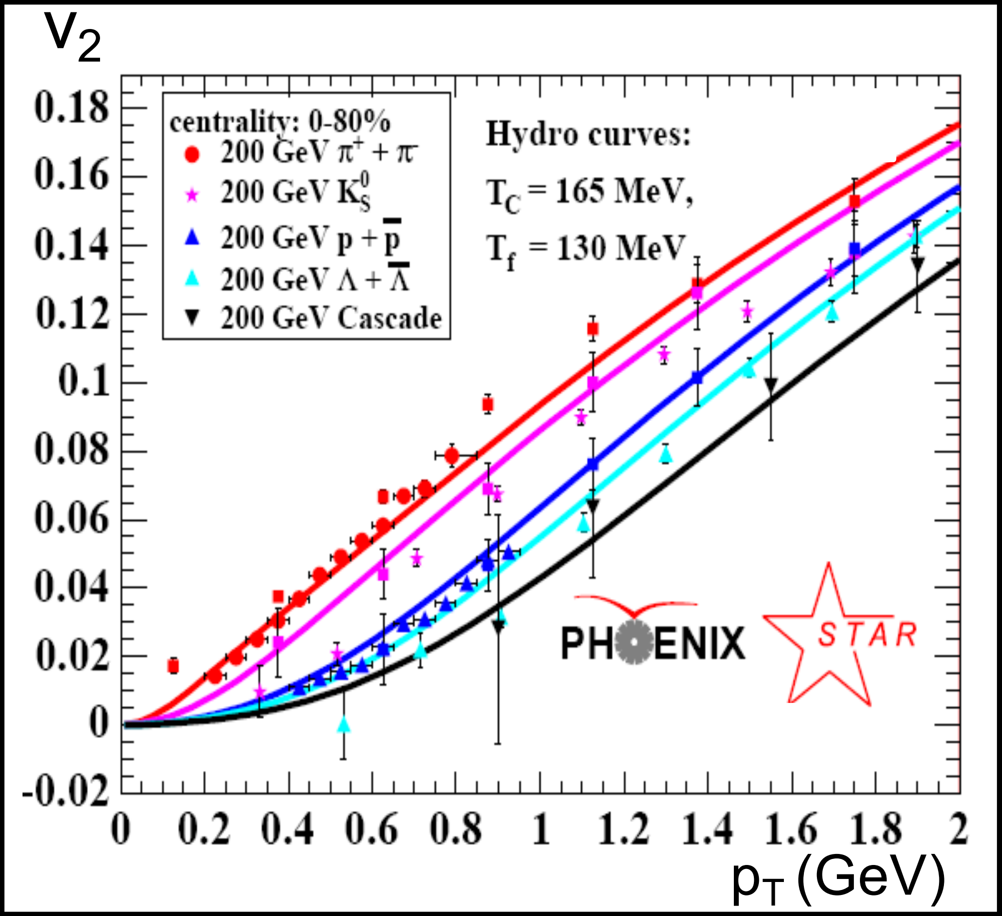


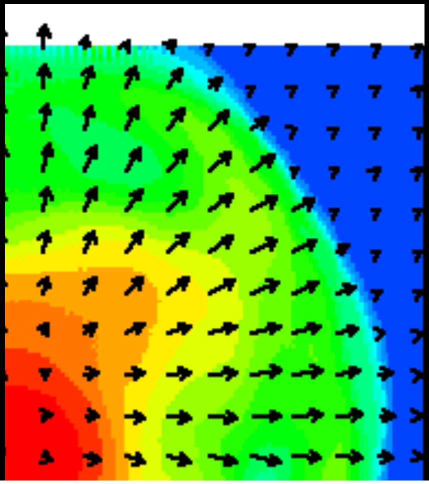
Require large pseudorapidity gap



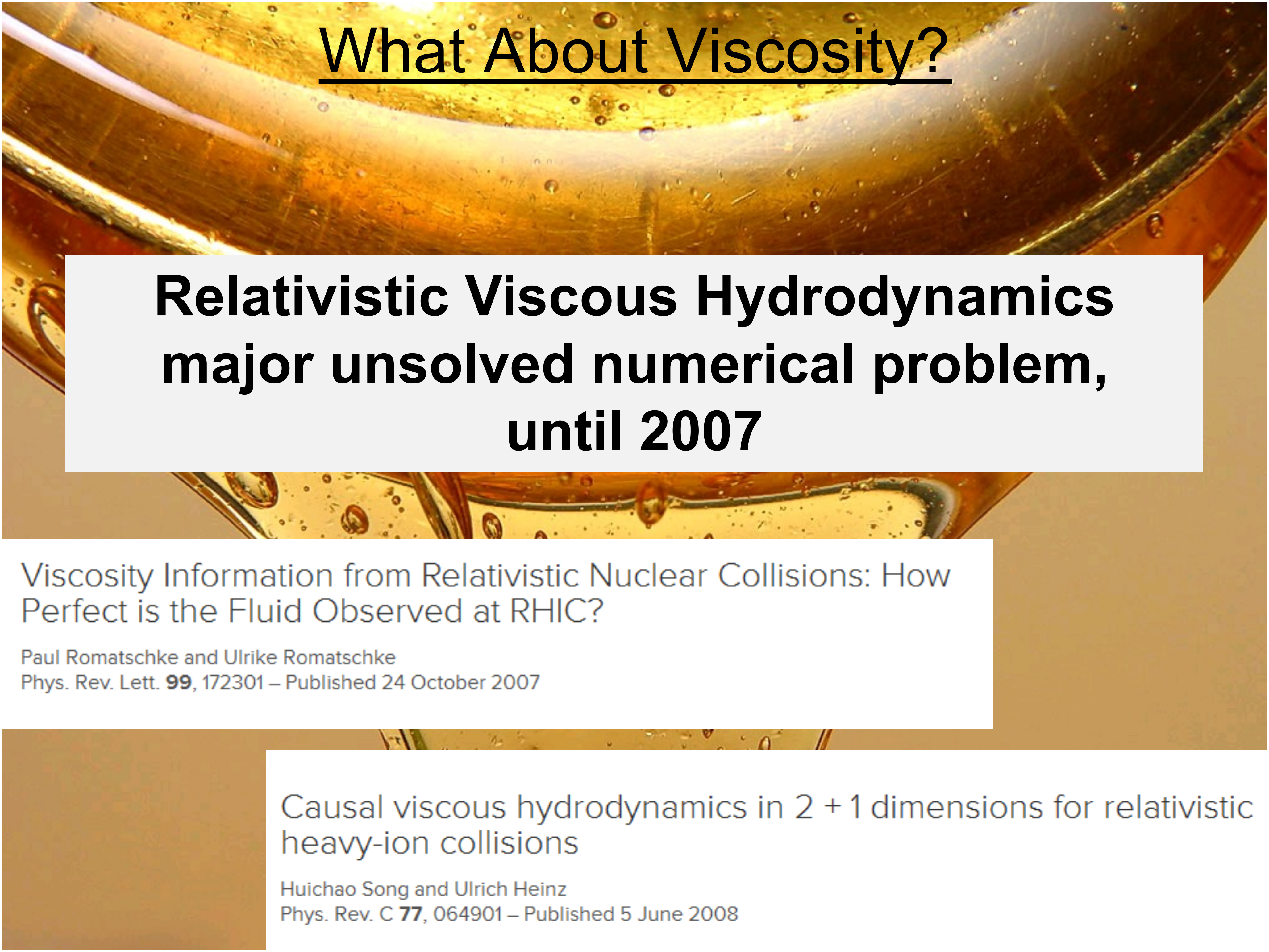
Perfect Fluidity Discovery - 2005

Agreement of ideal hydrodynamics with experimental data.





Heavier particles get a larger momentum boost from the fluid velocity and so heavier hadron v_2 pattern shifted to higher p_T.



What About Viscosity?

Relativistic Viscous Hydrodynamics major unsolved numerical problem, until 2007

Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?

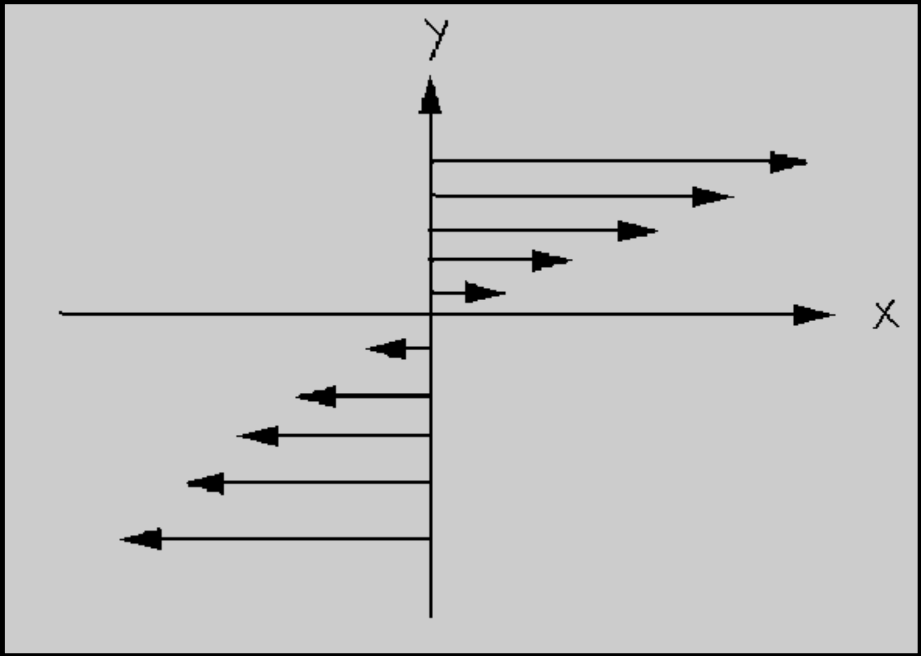
Paul Romatschke and Ulrike Romatschke
Phys. Rev. Lett. **99**, 172301 – Published 24 October 2007

Causal viscous hydrodynamics in 2 + 1 dimensions for relativistic heavy-ion collisions

Huichao Song and Ulrich Heinz
Phys. Rev. C **77**, 064901 – Published 5 June 2008

Shear Viscosity

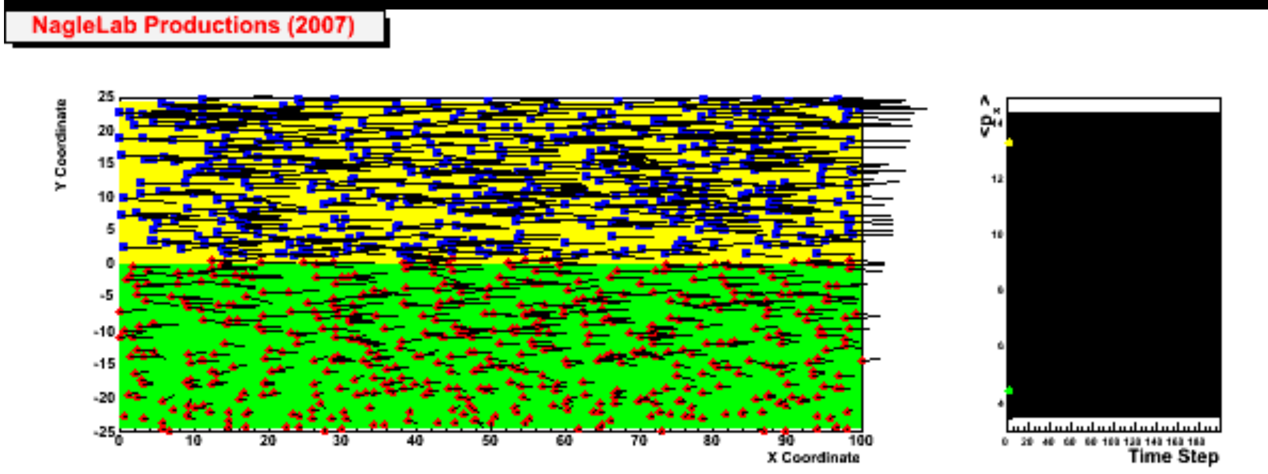
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



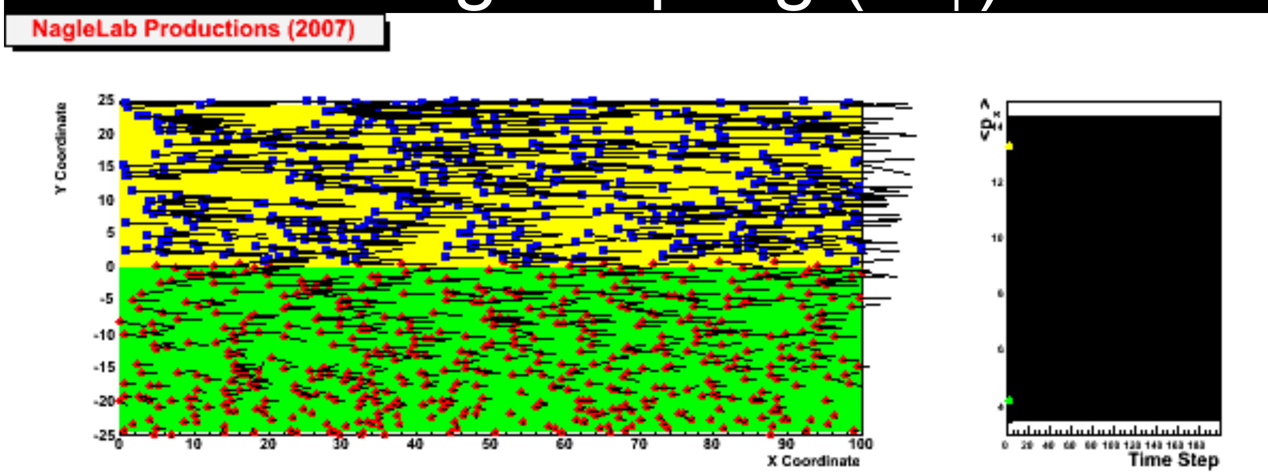
Viscosity Review

Honey – viscosity decreases at higher temperatures
viscosity increases with stronger coupling

Weak coupling (σ=0)



Strong coupling ($\sigma \uparrow$)



Inhibited diffusion

↓

Small viscosity

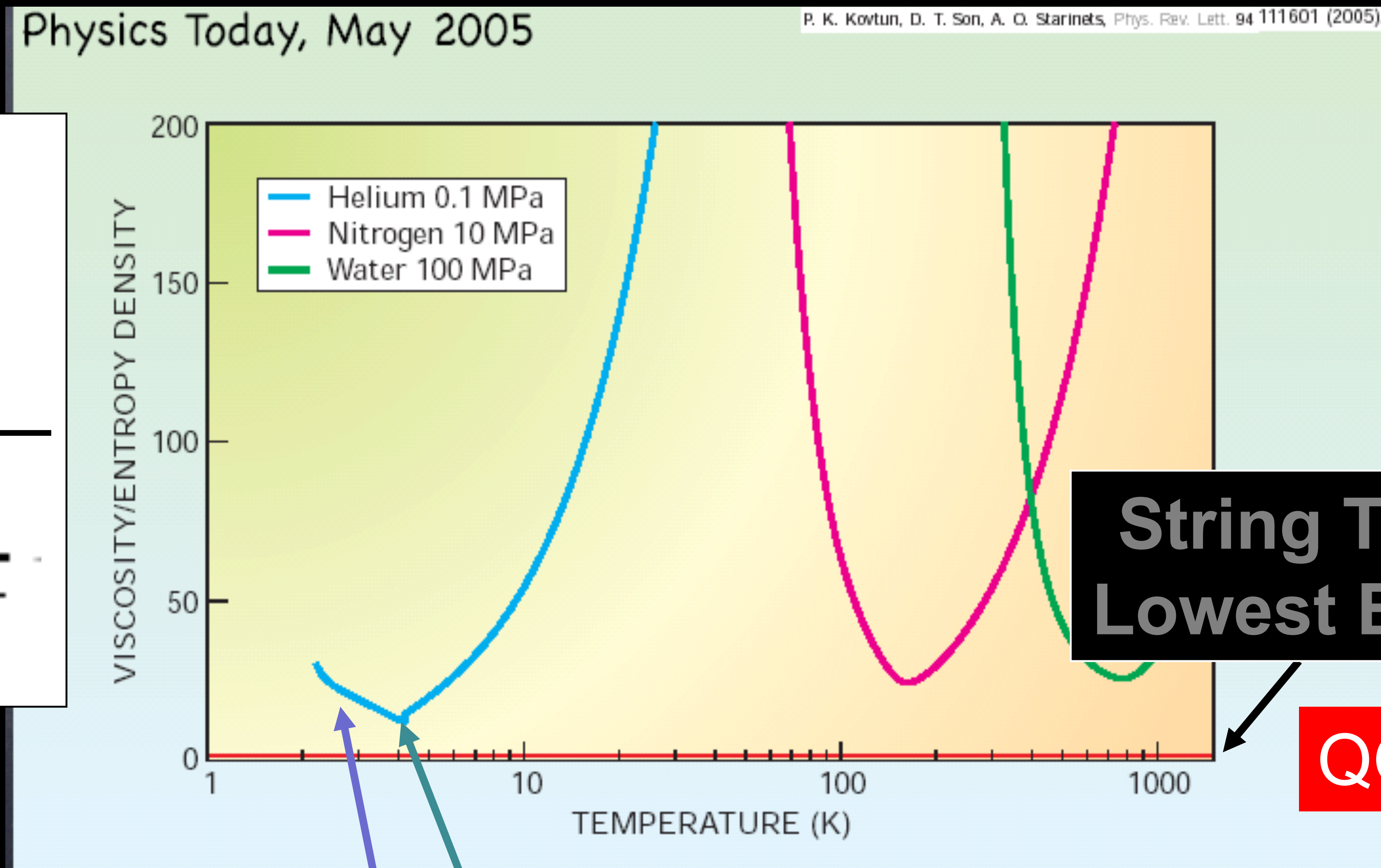
↓

Perfect fluid

↓

Strong Coupled QGP
(i.e. sQGP)

What is η/s for the Quark-Gluon Plasma



$$\frac{\eta / s}{1 / 4\pi}$$

String Theory Lowest Bound!

QGP?

Gas-Liquid Phase Transition

Superfluidity Transition

Lecture #3

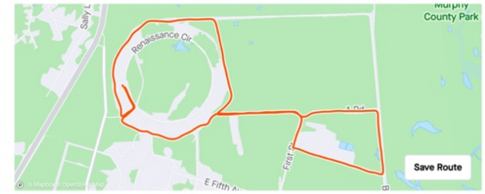
Work / Life Balance?

Distance 11.00 mi | Pace 9:01 /mi | Time 1h 39m

Distance 6.27 mi | Pace 9:34 /mi | Time 1h 0m

Distance 7.35 mi | Pace 9:15 /mi | Time 1h 8m

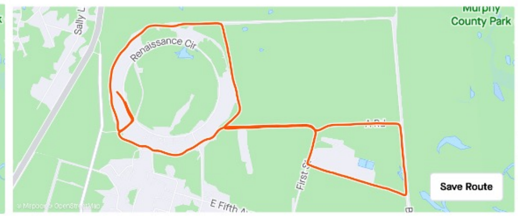
Distance 6.40 mi | Pace 9:13 /mi | Time 59m 0s



Distance 6.42 mi | Pace 10:19 /mi | Time 1h 6m

Distance 6.43 mi | Pace 9:38 /mi | Time 1h 1m | Achievements 1

Distance 6.34 mi | Pace 9:24 /mi | Time 59m 39s



Distance 13.11 mi | Pace 9:37 /mi | Time 2h 6m

100 miles+

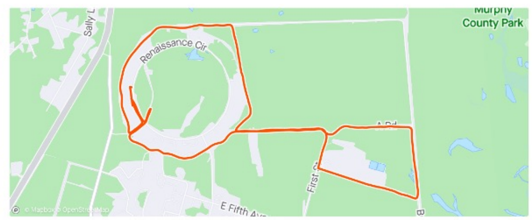
June 17 - July 3, 2023

6 box turtles

1 snapping turtle
2 snakes
1 racoon
innumerable groundhogs, turkeys, rabbits, deer, birds, bugs!

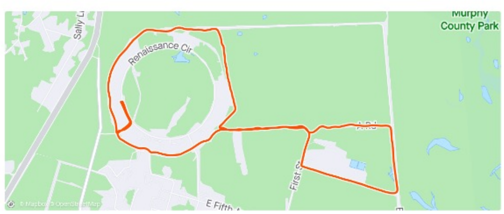
Distance 6.23 mi | Pace 9:50 /mi | Time 1h 1m

6.20 mi | 9:53 /mi | 1h 1m



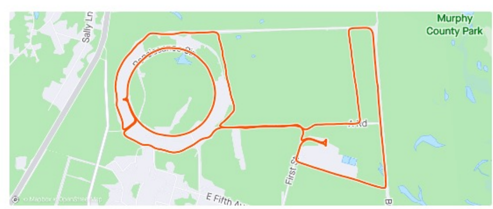
Distance 7.35 mi | Pace 9:35 /mi | Time 1h 10m

Distance 6.39 mi | Pace 9:22 /mi | Time 59m 52s



Distance 10.13 mi | Pace 8:56 /mi | Time 1h 30m | Achievements 1

Rochester St PR (7:12)

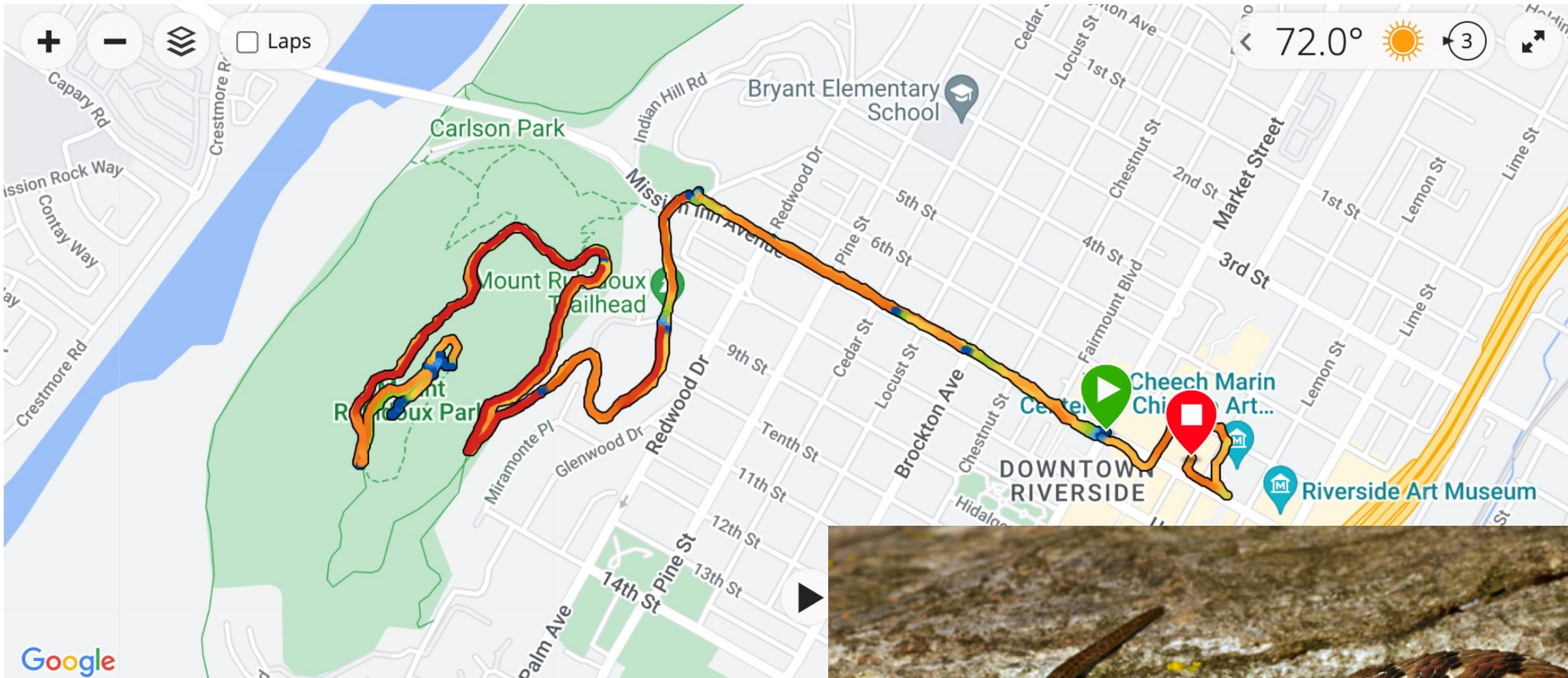


Distance 7.00 mi | Pace 9:26 /mi | Time 1h 6m

Riverside Running

Event: -- ▾   Event Type: Uncategorized ▾   Gear: Add

6.20 mi	1:02:00	10:00 /mi	508 ft	748 cal
Distance	Time	Avg Pace	Total Ascent	Calories

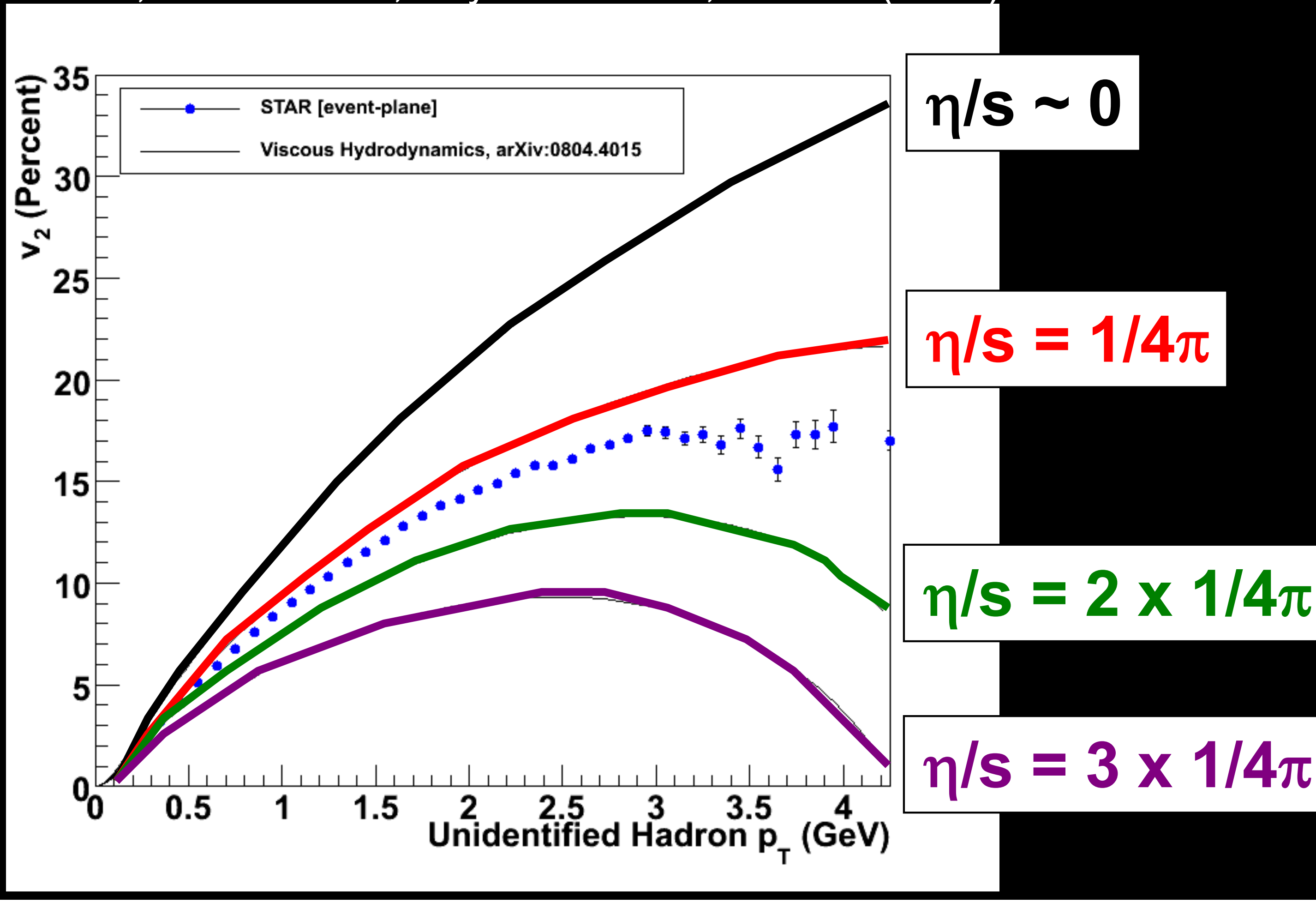


Perfect Fluid

How to Quantify QGP η/s?

Relativistic viscous hydrodynamics compared to data

Luzum, Romatschke, Phys. Rev. C78, 034915 (2008)

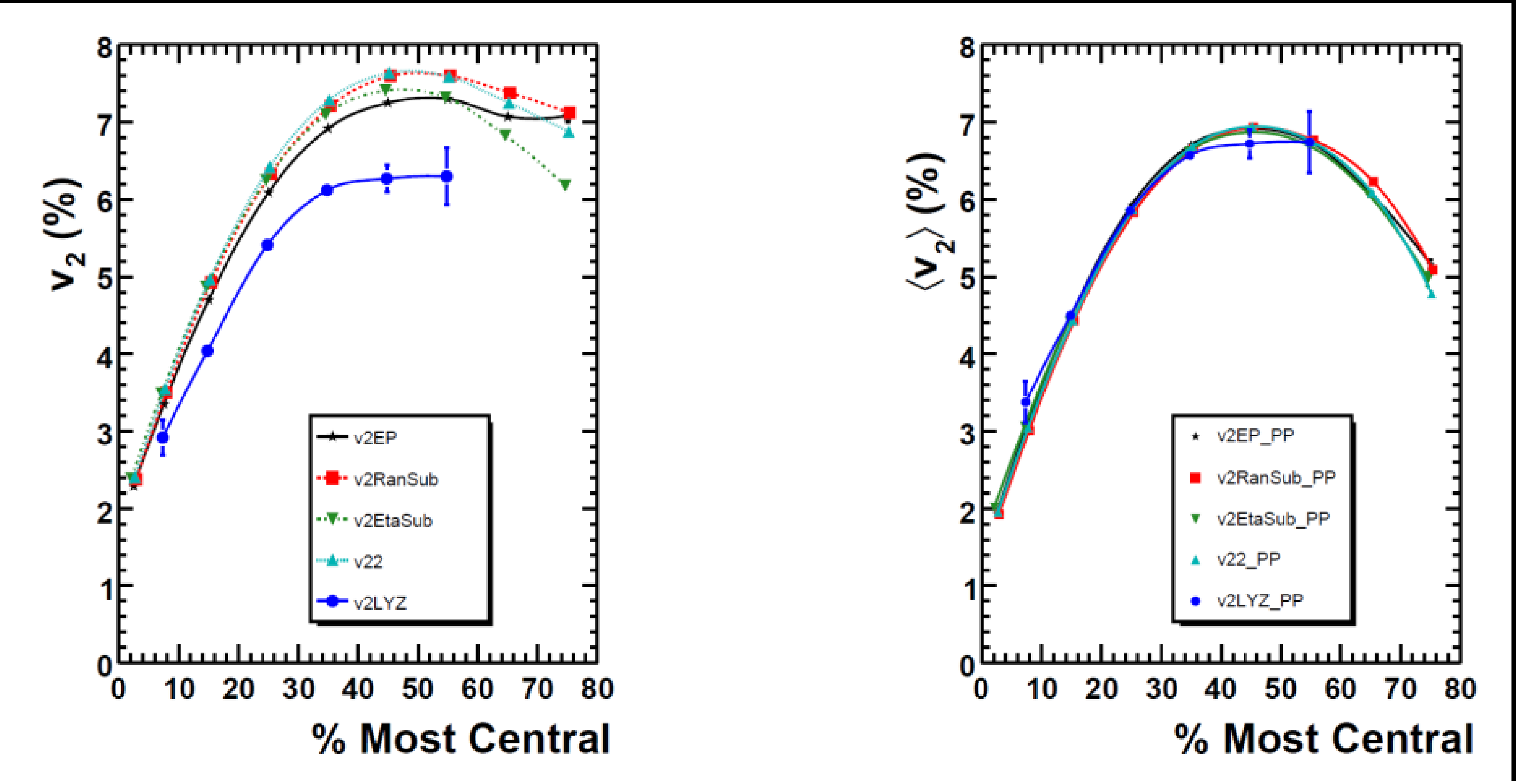


$$\left(\frac{\eta}{s}\right)\Big/\left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

What dominates the uncertainty?

$$\left(\frac{\eta}{s}\right) \Big/ \left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

At the time, different experimental flow methods gave different v_2 results. Now these differences are understood from non-flow contributions and fluctuations.

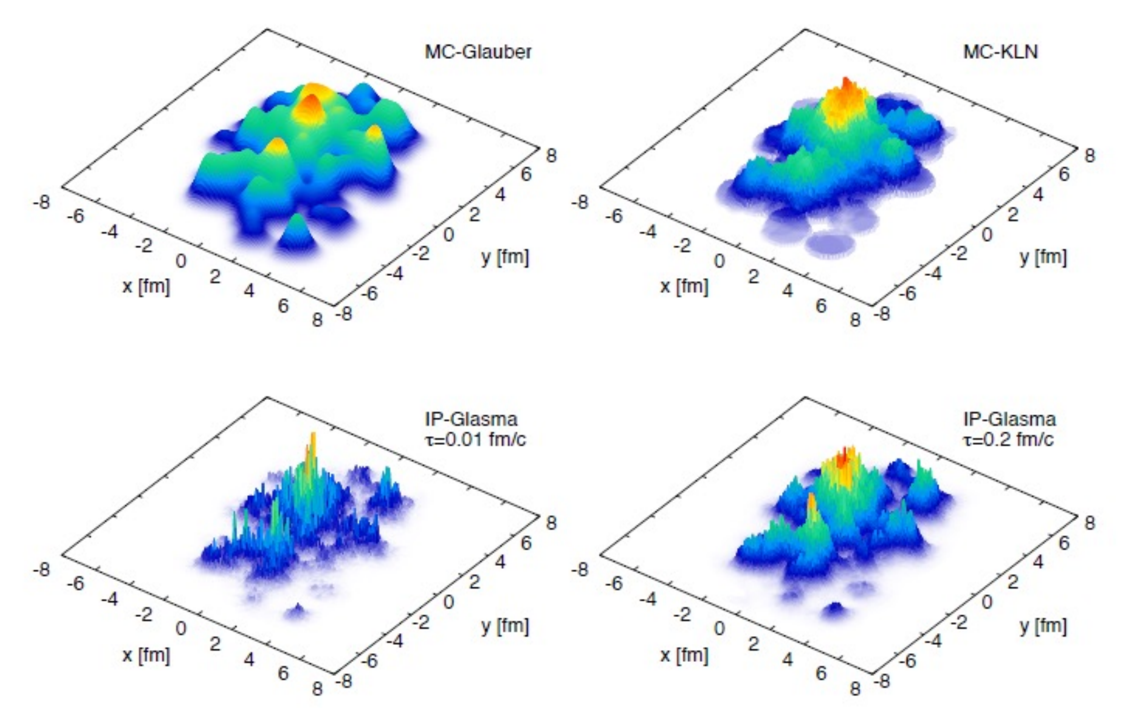


What dominates the uncertainty?

$$\left(\frac{\eta}{s}\right) \Big/ \left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

The v_2 you get out is directly related to the ε_2 of the initial geometry you put in.

Different initial geometry models yield 20% ε_2 differences resulting in 100% η/s differences.



Different models of the initial geometry.

Uncertainty by considering model A and model B.

Systematic Uncertainties

Systematic Errors

Joel Heinrich[1] and Louis Lyons[2]

[1]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104; email: heinrich@hep.upenn.edu

[2]Department of Physics, University of Oxford, Oxford OX1 3RH, United Kingdom; email: l.lyons@physics.ox.ac.uk

Not much help in many practical situations…

Example: Two model inputs give different results.

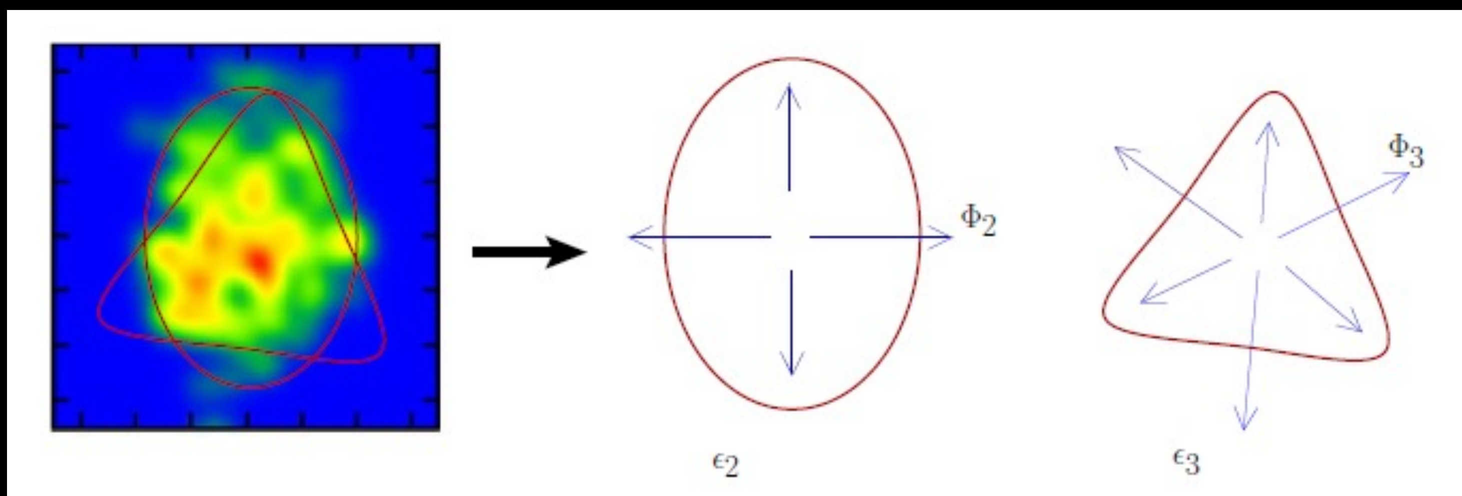
Uncertainty = 1 RMS = Difference / sqrt(12)
= Difference / 2
= Cannot determine

Alver and Roland Revolution 2010

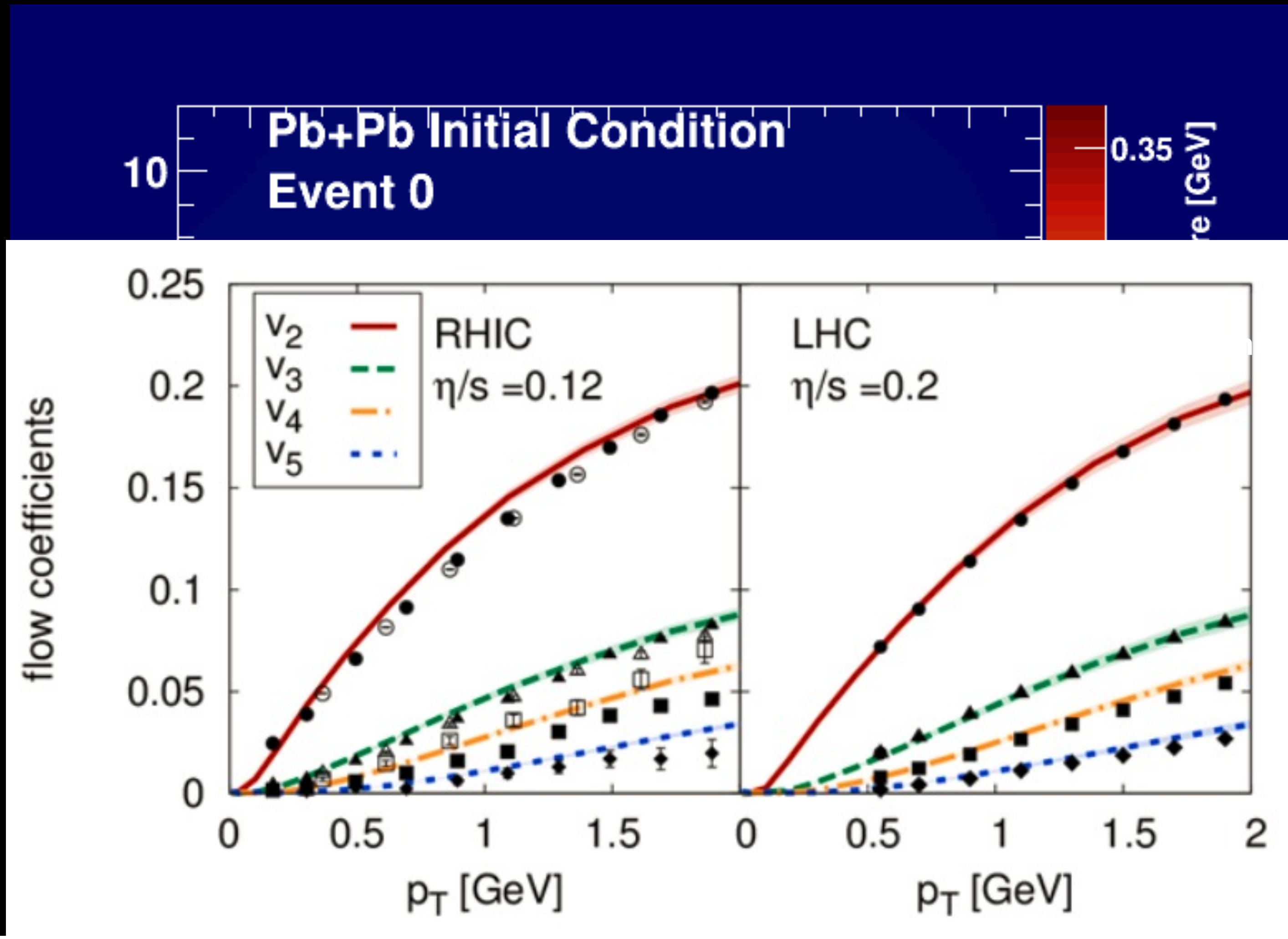
Collision-geometry fluctuations and triangular flow in heavy-ion collisions

B. Alver and G. Roland
Phys. Rev. C **81**, 054905 – Published 21 May 2010; Erratum Phys. Rev. C **82**, 039903 (2010)

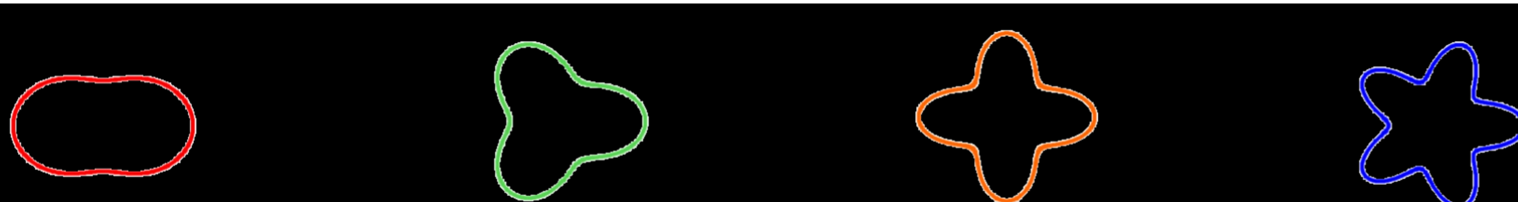
http://journals.aps.org/prc/abstract/10.1103/PhysRevC.81.054905



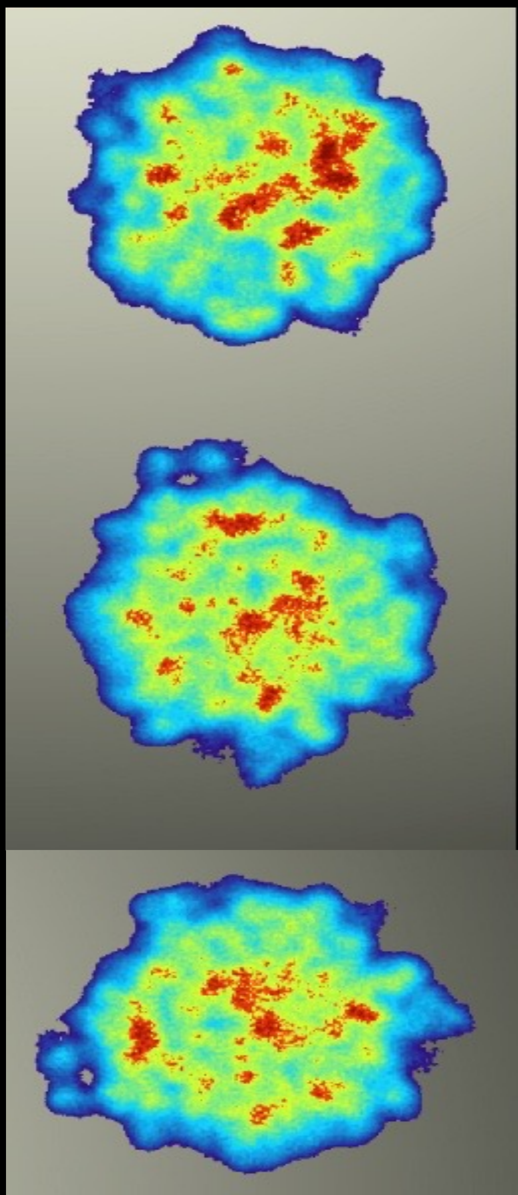
Fluctuations in geometry yield not only elliptical shapes, but triangular, quadrangular, etc.

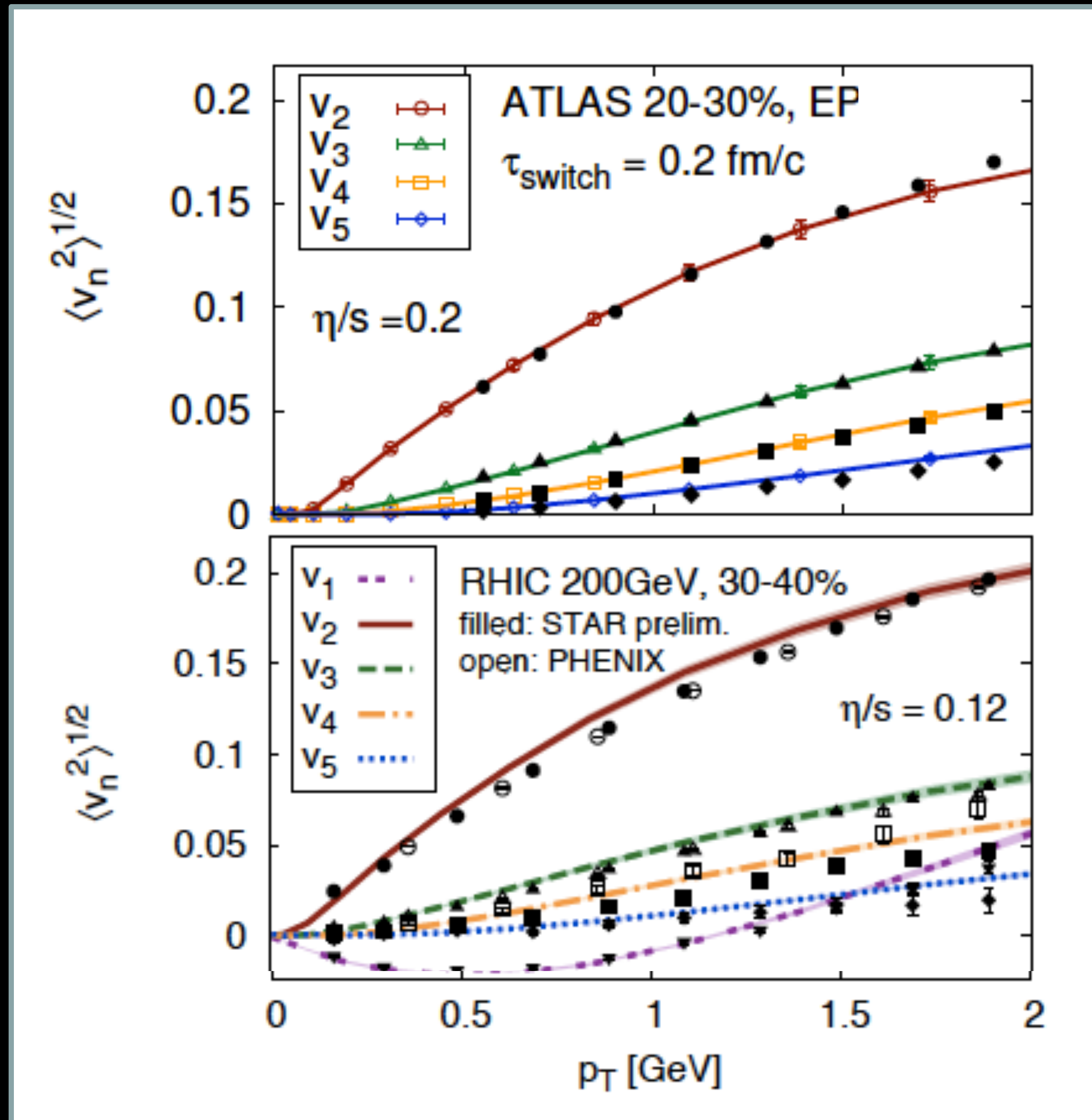


$$\frac{dN}{d\phi} = 1 + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + 2v_4 \cos[4(\phi - \Psi_4)] + 2v_5 \cos[5(\phi - \Psi_5)] + \ldots$$



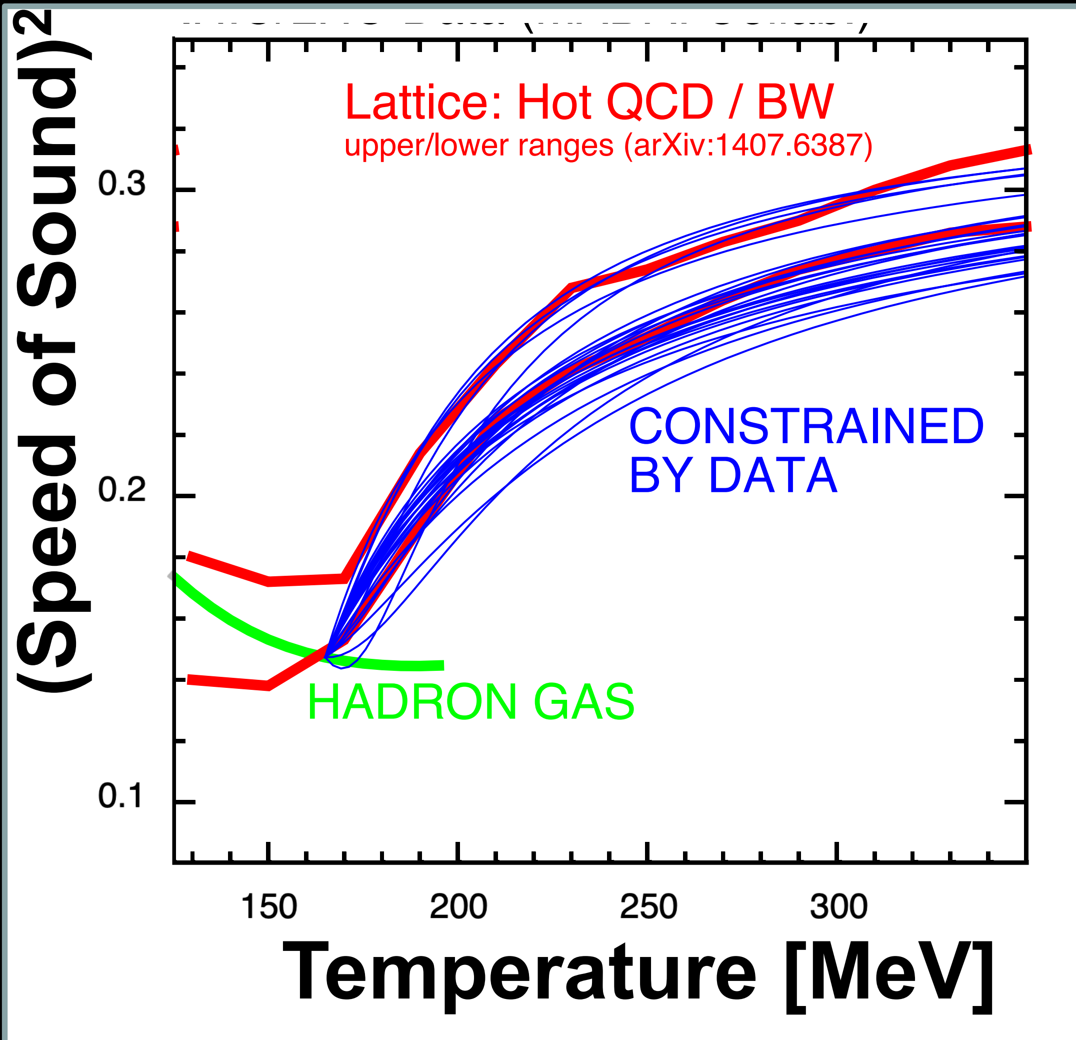
Detailed Fingerprint of Early Time





Calculation from Bjoern Schenke

Global Constraint Analysis

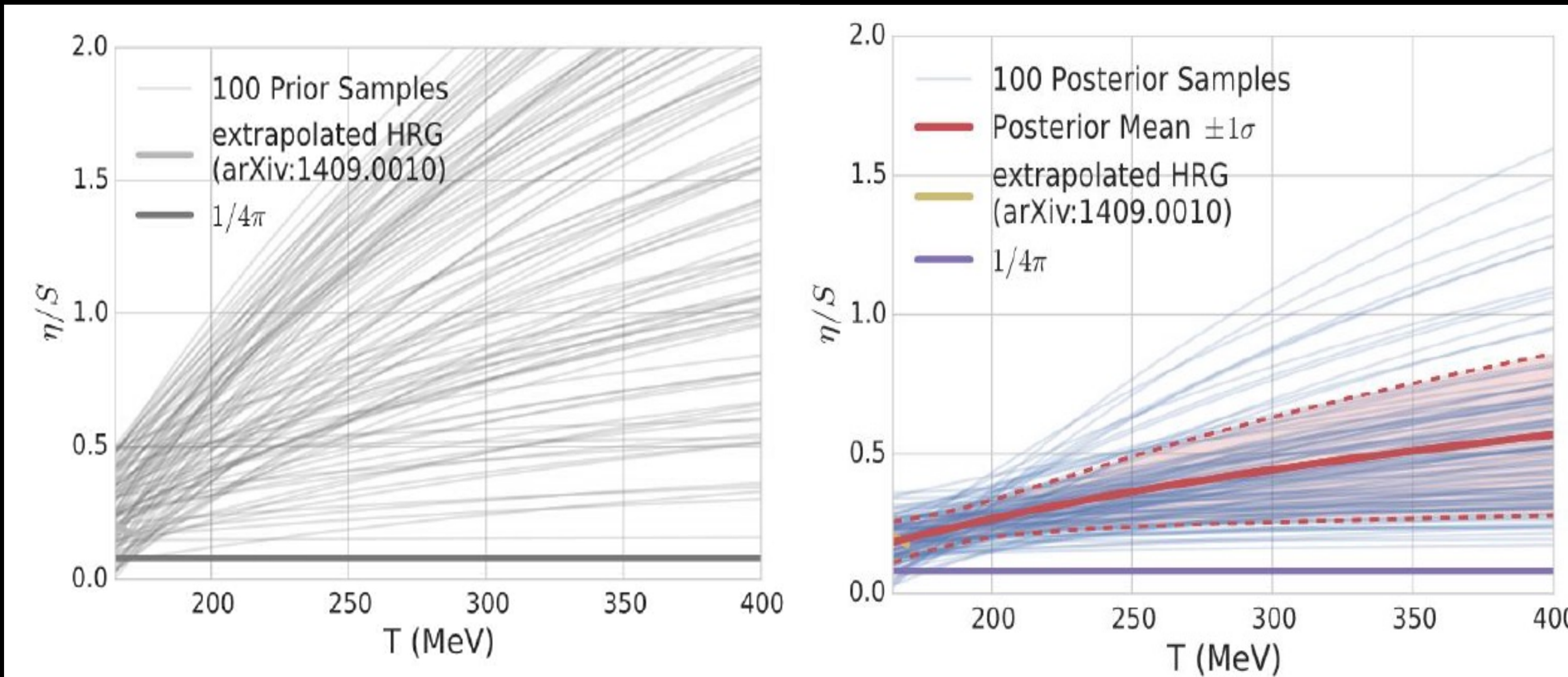


Global constraint methods using Bayesian sampling as done in Climate Modeling for example.

Includes particle spectra, elliptic flow, two-particle quantum correlations, …

Experimental confirmation of Lattice QCD Equation of State

Global Constraint Analysis



Expect η/s to increase at higher temperatures even just from running of α_s

Key lesson about when and when not to include scenarios (story of High Voltage Power Lines)…

Heavy Quarks

Why are heavy quarks so special?

QCD is flavor blind, so why are charm and beauty quarks interesting?

Very difficult to produce charm (beauty) quark-antiquark pairs via thermal production in the QGP

g+g → ccbar or bbbar

However, high energy gluons from the incoming nuclei can do the trick. Production dominated by "initial hard scattering" and perturbatively (pQCD) calculable even at low pT due to mass scale.

Cannot be destroyed via strong interaction with light quarks and gluons (i.e. QGP).

http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html

FONLL Heavy Quark Production

Calculate total or single inclusive differential cross sections for heavy quark production (charm or bottom) at ppbar or pp colliders, with cuts on p_T and y or eta. Non perturbative fragmentation into heavy hadrons and their subsequent decays into other final states (leptons, quarkonia, ...) can also be included.

NEWS:

- **09 Jan 2016** - Fixed bug (introduced on 23/12/2015) preventing correct selection of decay to electrons option
- **23 Dec 2015** - New interface, with responsive framework for mobile devices and option to email results. No change in physics results.
- **28 Sep 2015** - Modified smearing function used in integrations. Change in results should be well below 1%

Be sure to check the older news, as well as the list of bugs discovered so far. Feedback to matteo.cacciari@cern.ch is welcome.

Collider: LHC (pp, 13 TeV) [ptmax ≤ 300 GeV] **PDFs:** CTEQ6.6 **Perturbative order:** FONLL

Heavy quark: bottom **Hadronic final state:** bare quark **Further decay:** -

Cross section type: dsigma/dpt central prediction only ☐ Output all scales

☐ Include PDFs uncertainties

ptmin (GeV) 5

ptmax (GeV) 20

y(eta)min -1

y(eta)max 1

Change these defaults only if you know what you are doing.

Non-pert. FF: default

Non-pert. par. = default

☑ Use default N=5 moment

FF(c->D) = 1

BR(D->l) = 0.103

BR(B->l) = 0.1086

BR(B->D->l) = 0.096

BR(B->D) = 0.823

BR(B->D*) = 0.173

Alternative Fluid Probe:

Put a pebble in the stream and watch something out of equilibrium then equilibrate.

Charm Quark

Beauty Quark

“Does the Charm Flow at RHIC?”

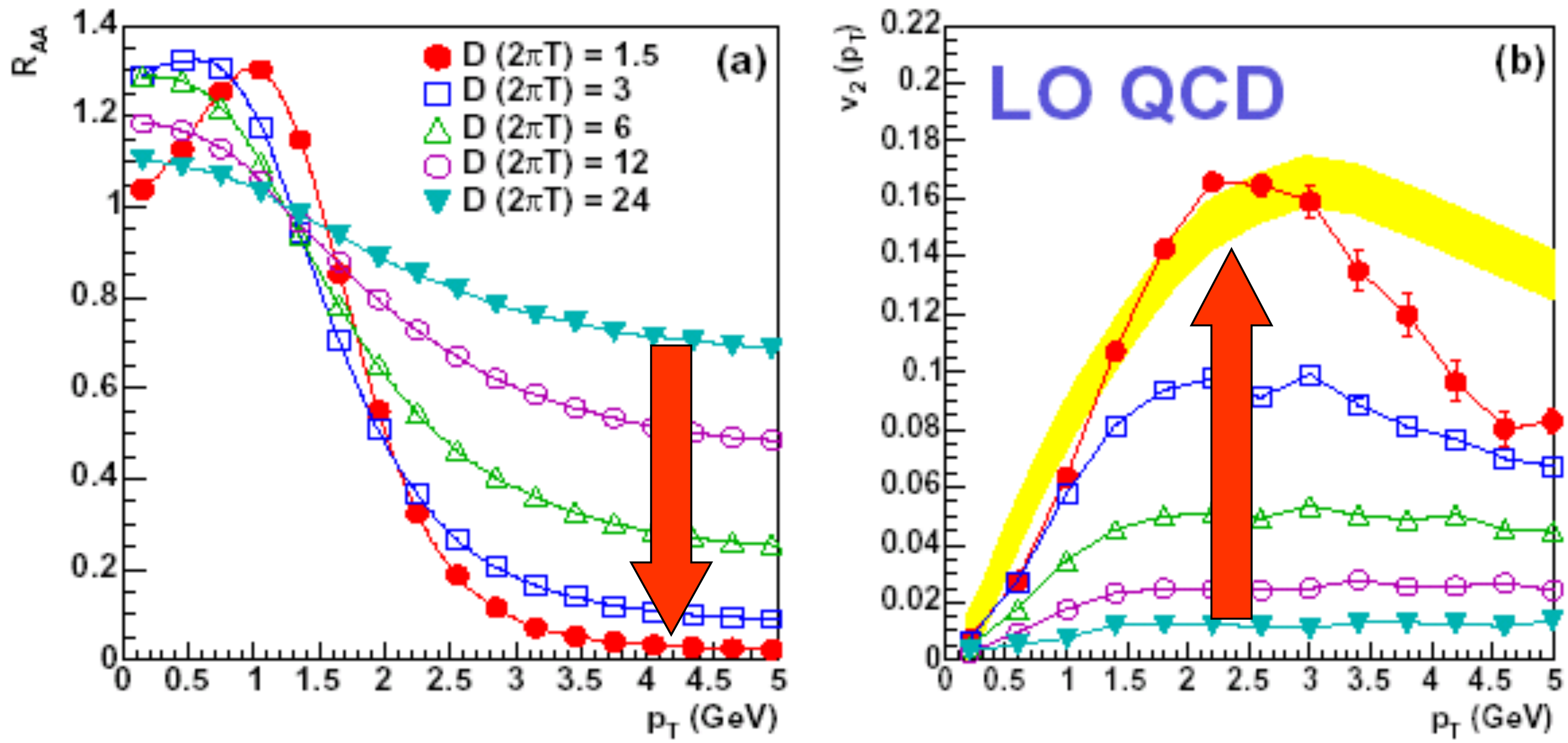
S. Batsouli, S. Kelly, M. Gyulassy (Columbia U.) , J.L. Nagle (Colorado U.) . Dec 2002. 11pp.
Published in **Phys.Lett.B557:26-32,2003**.
e-Print: **nucl-th/0212068**

At the time, many said this idea was “ridiculous”.

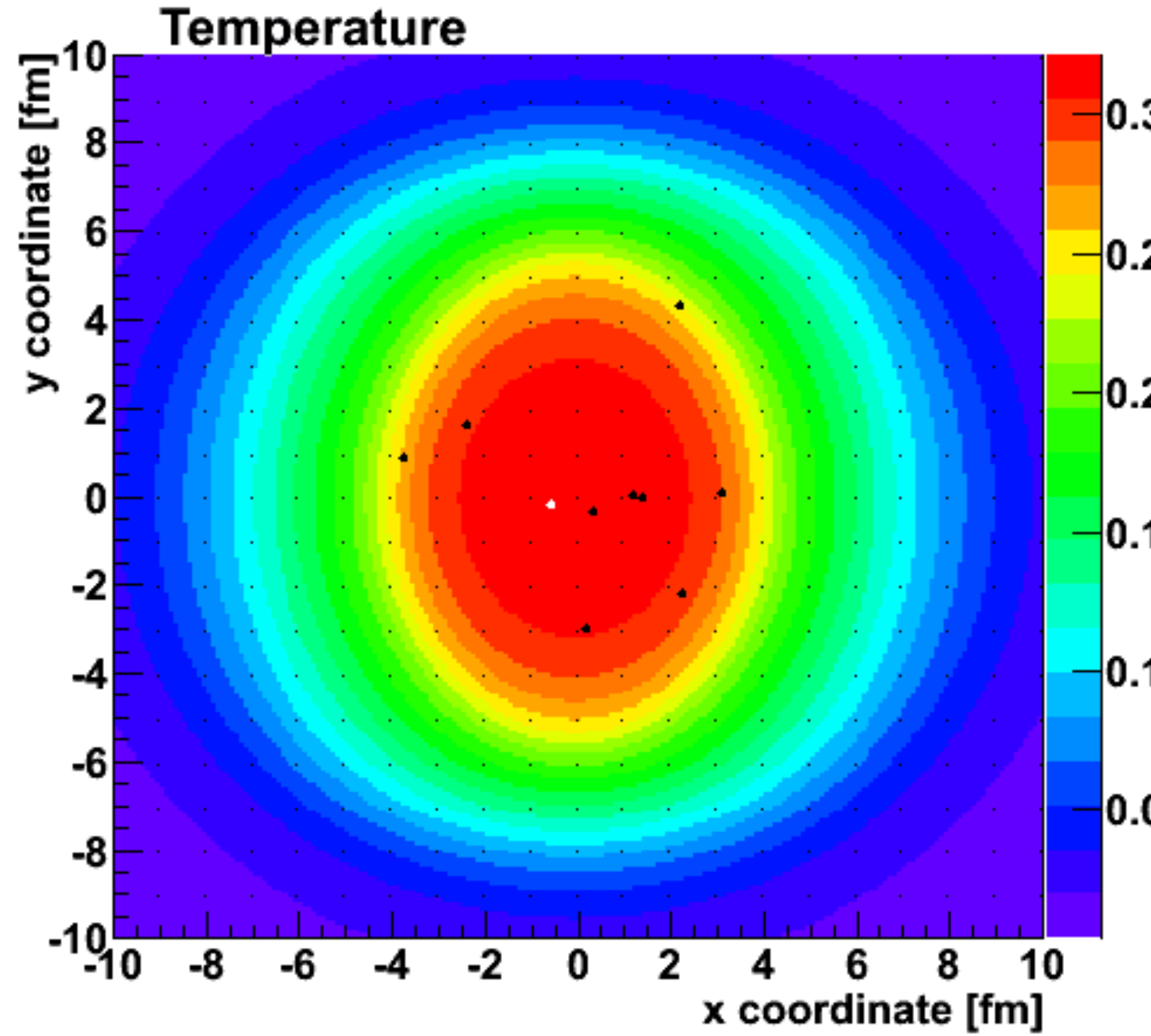
Langevin Model - Drag and Diffusion

$$\frac{dp_i}{dt} = \xi_i(t) - \eta_D p_i, \qquad \langle \xi_i(t)\xi_j(t')\rangle = \kappa\delta_{ij}\delta(t-t'). \quad (2)$$

Here η_D is a momentum drag coefficient and $\xi_i(t)$ delivers random momentum kicks that are uncorrelated in time.



Teaney and Moore
http://journals.aps.org/prc/abstract/10.1103/PhysRevC.71.064904

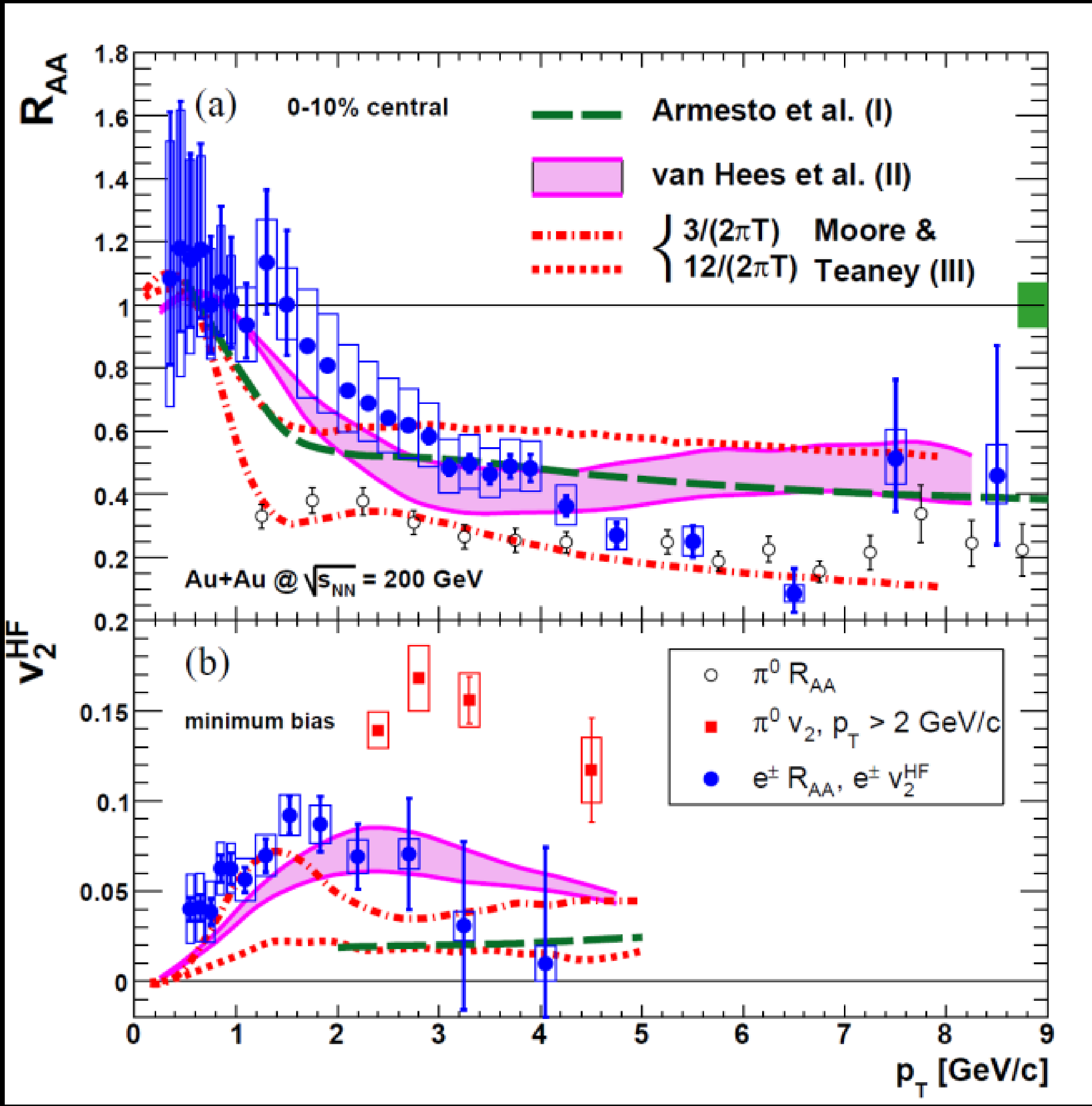


Temperature
y coordinate [fm]
x coordinate [fm]
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-8
-6
-4
-2
0
2
4
6
8
10
0.3
0.2
0.2
0.1
0.1
0.0

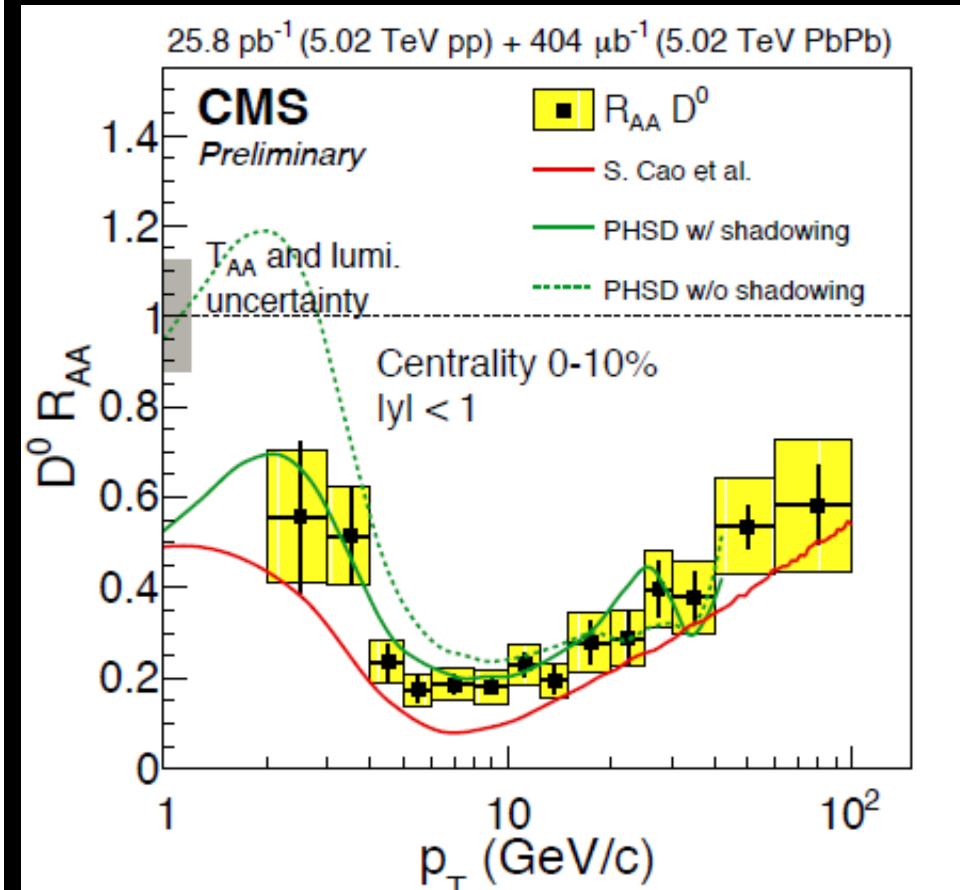
PHENIX Heavy Flavor Result

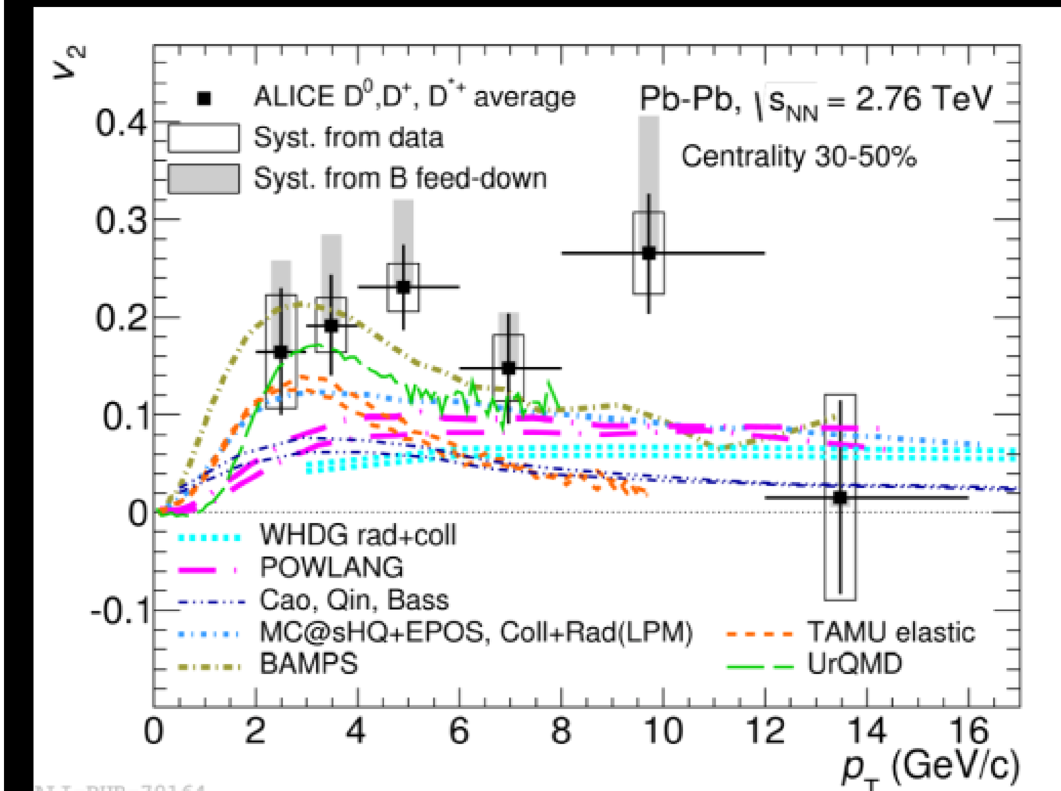
Charm quarks dragged and diffused in QGP suppresses high p_T hadrons ($R_{AA} \downarrow$)

And push generates "flow" ($v_2 \uparrow$)



Charm: Really moves with the medium

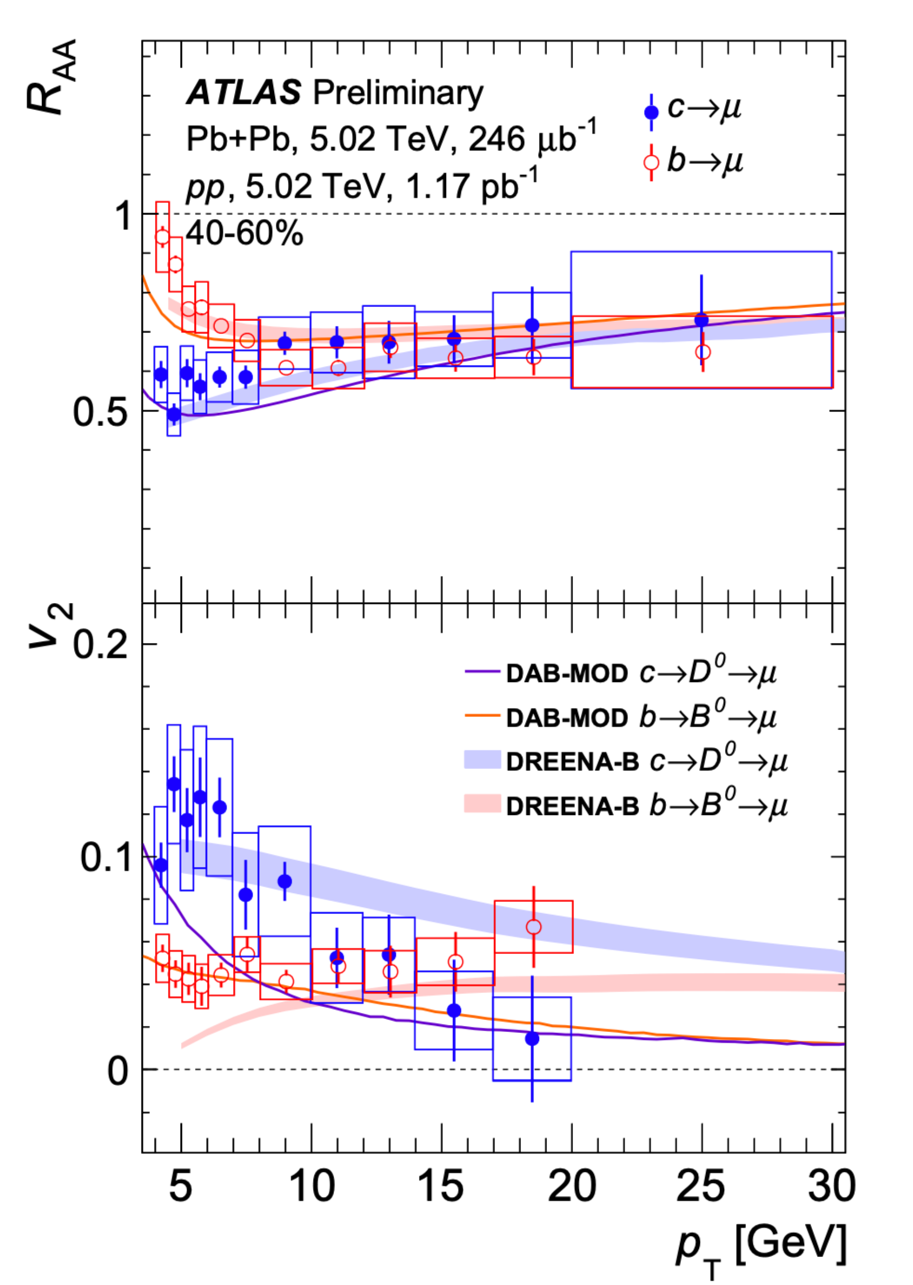




Lower momentum – drag and diffusion

Higher momentum – jet quenching energy loss

Bottom quarks are harder to push around



State-of-the-art calculations

DREENA-B (arXiv:1805.04786)

Dusan Zigic, Igor Salom, Jussi Auvinen, Marko Djordjevic, Magdalena Djordjevic

Dynamic energy loss in 1+1D expanding QCD medium

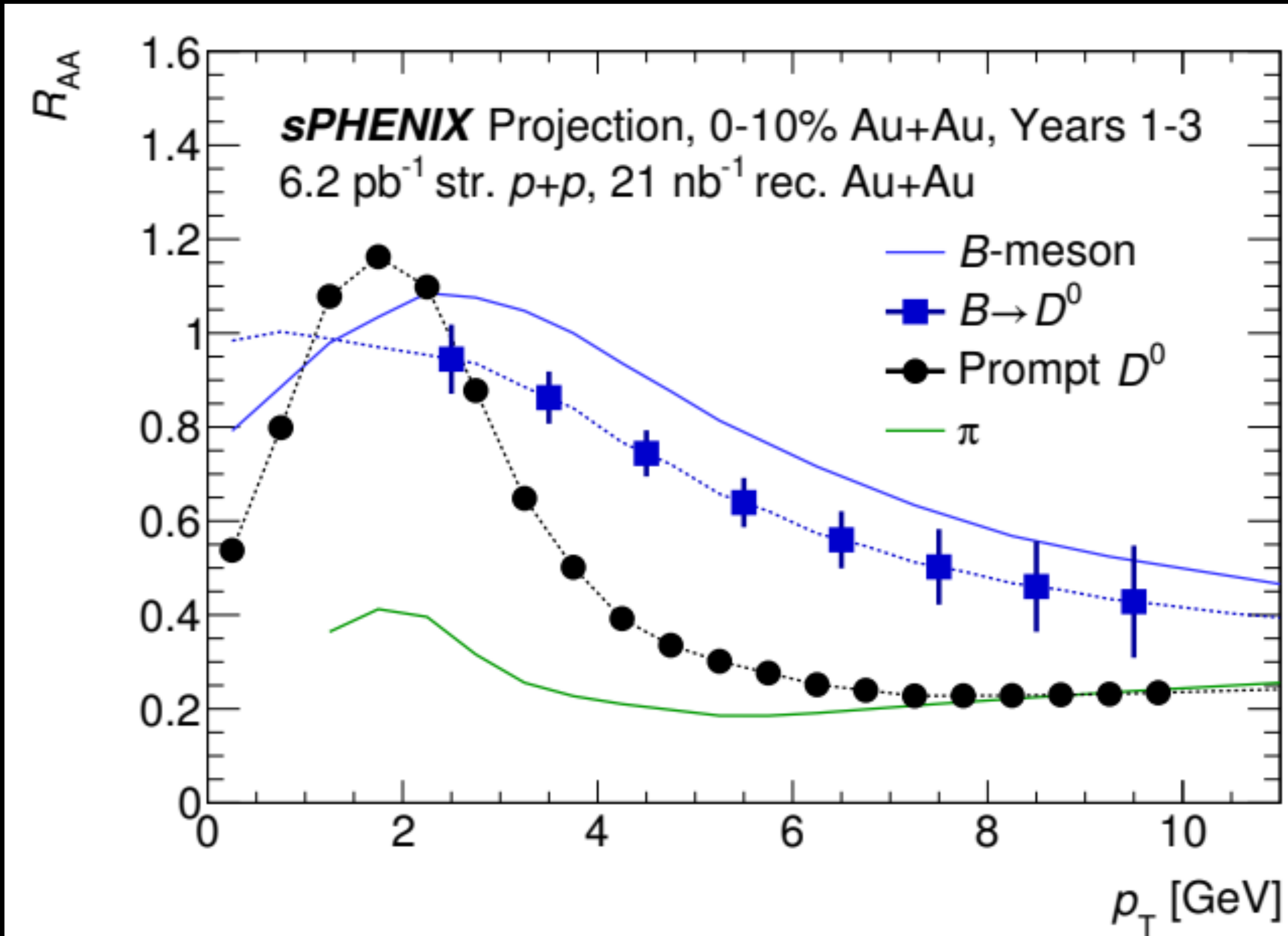
DAB-MOD (arXiv: 1906.10768)

Roland Katz, Caio A. G. Prado, Jacquelyn Noronha-Hostler, Jorge Noronha, Alexandre A. P. Suaide

2D+1 viscous hydrodynamic expansion with event-by-event fluctuations

Both match mass splitting in R_{AA} at low p_T
DREENA-B has closer match to elliptic flow v_2

It would be ideal to test both energy loss calculations on identical expanding QGP background
(challenge to the theorists)

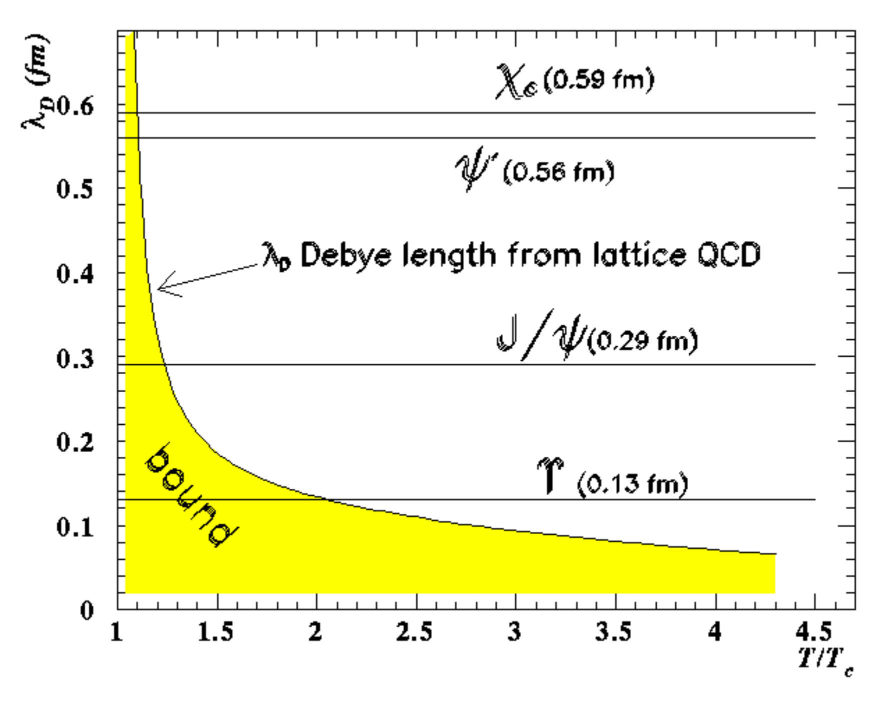


sPHENIX Projection, 0-10% Au+Au, Years 1-3
6.2 pb^{-1} str. p+p, 21 nb^{-1} rec. Au+Au
B-meson
$B\rightarrow D^0$
Prompt D^0
π
R_{AA}
p_T [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
2
4
6
8
10

Heavy Quarkonia

Screening Effects

Different states "melt" at different temperatures due to different binding energies.



The ψ' and χ_c melt below or at T_c

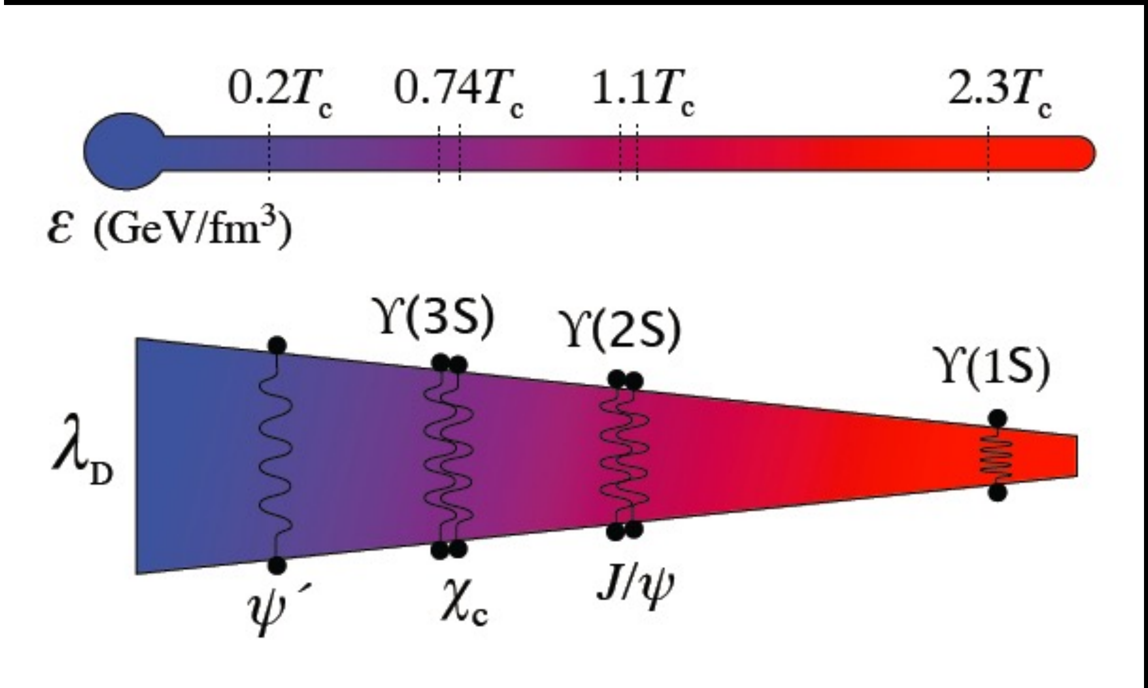
the **J/ψ** melts above T_c and

eventually the Υ(1s) melts.

state	J/ψ	χ_c	ψ'	Υ(1s)	χ_b	Υ(2s)	χ_b'	Υ(3s)
Mass [GeV}	3.096	3.415	3.686	9.46	9.859	10.023	10.232	10.355
B.E. [GeV]	0.64	0.2	0.05	1.1	0.67	0.54	0.31	0.2
T_d/T_c	---	0.74	0.15	---	---	0.93	0.83	0.74

hep-ph/0105234 - "indicate ψ' and the χ_c dissociate below the deconfinement point."

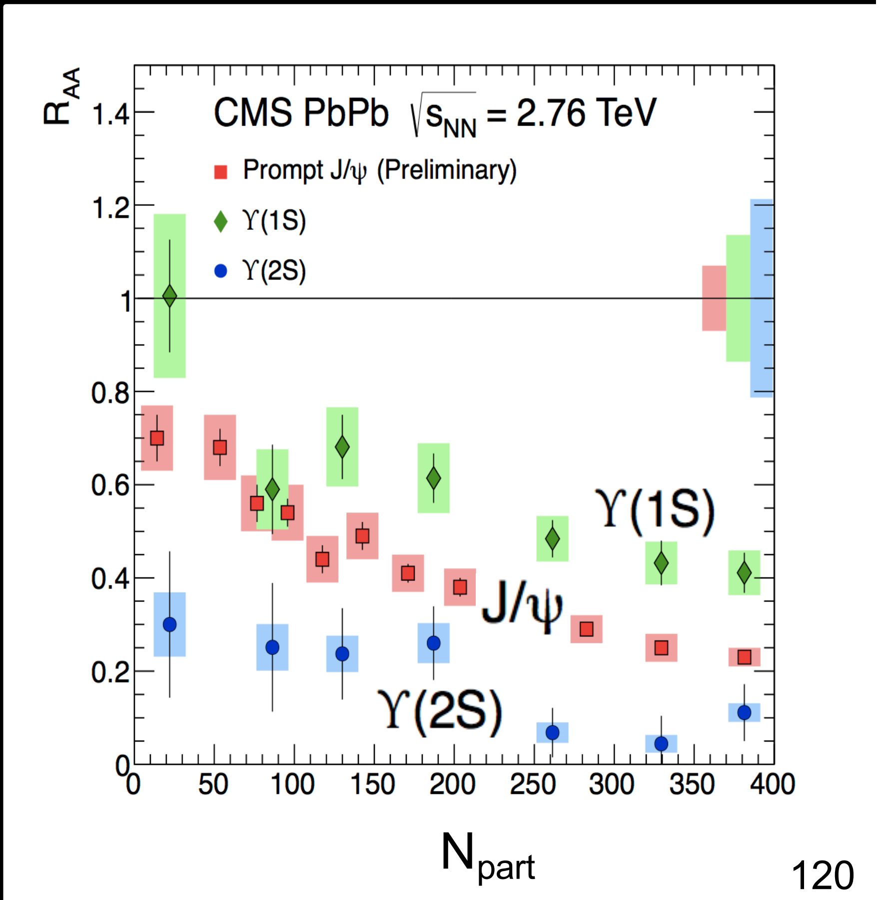
Quarkonia Thermometer



Many states constrains the temperature

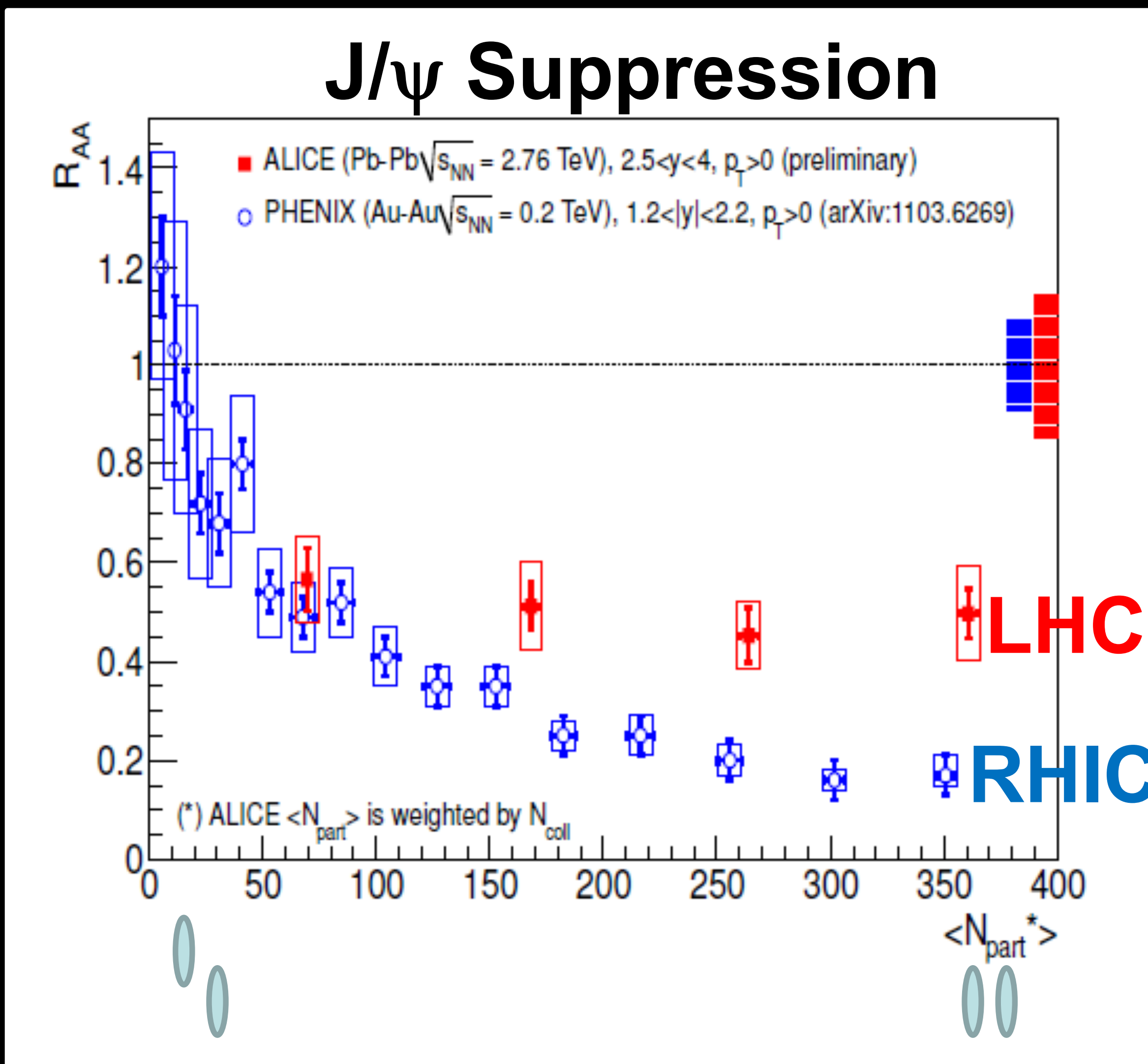
PHENIX, STAR, and CMS data consistent with *melting* of Υ(2s,3s)

Need more statistics



Quark recombination

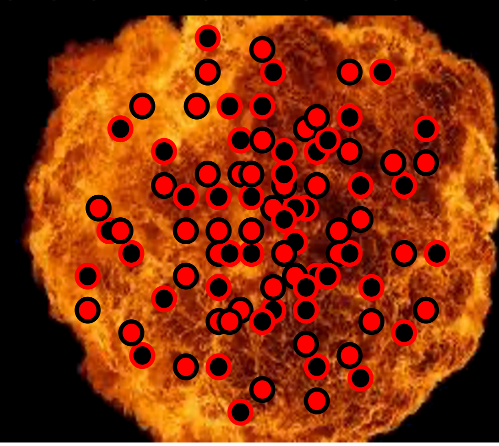
Bound states of $\bar{c}c$ and $\bar{b}b$ can be *Debye color screened* in the QGP as one increases the temperature (melting)



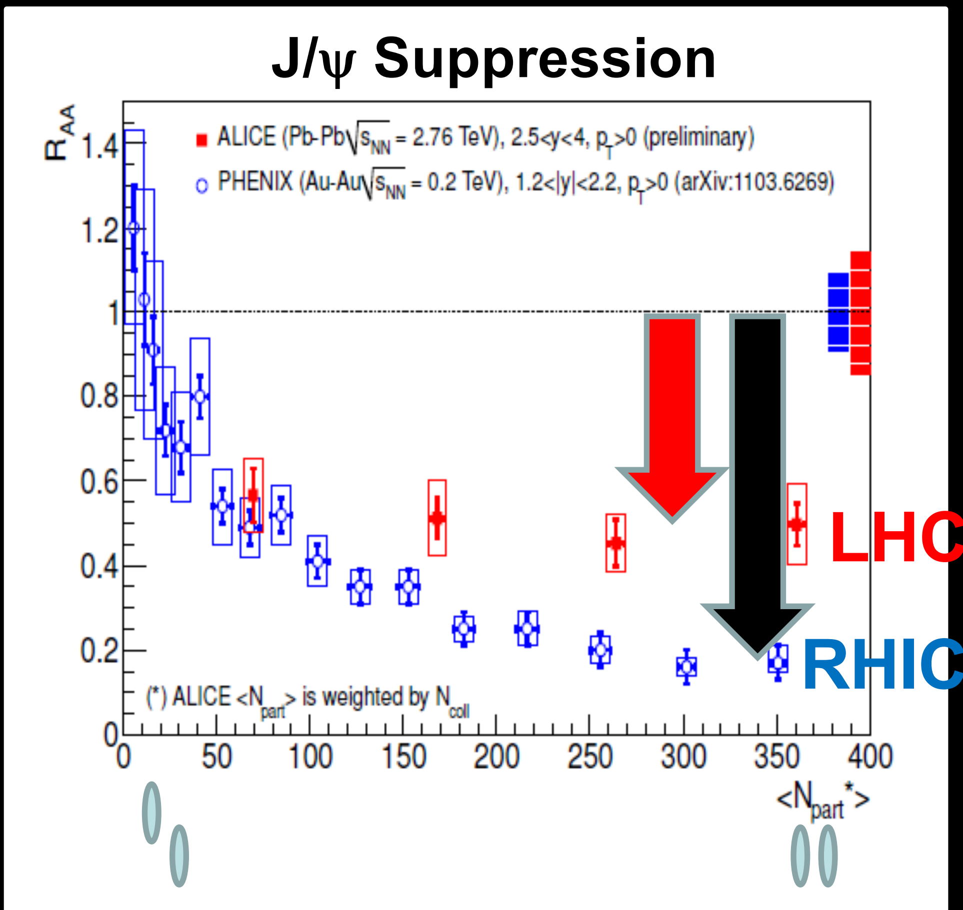
Bizarre twist

Less suppression at LHC with higher temperature.

Quark deconfinement and charm recombination at

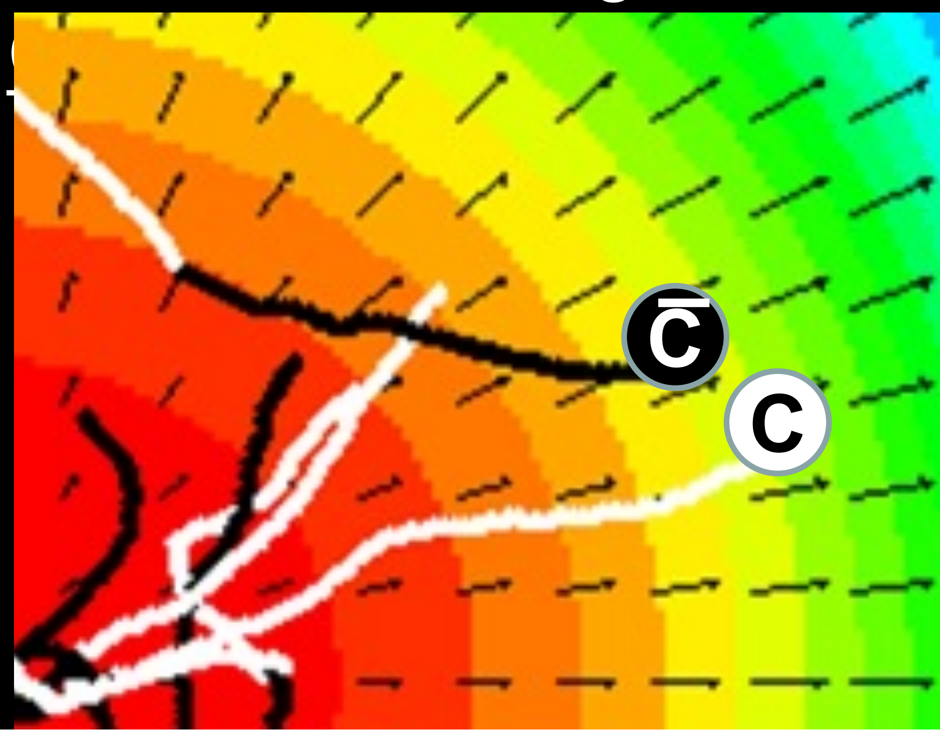


Heavy Quarkonia Recombination



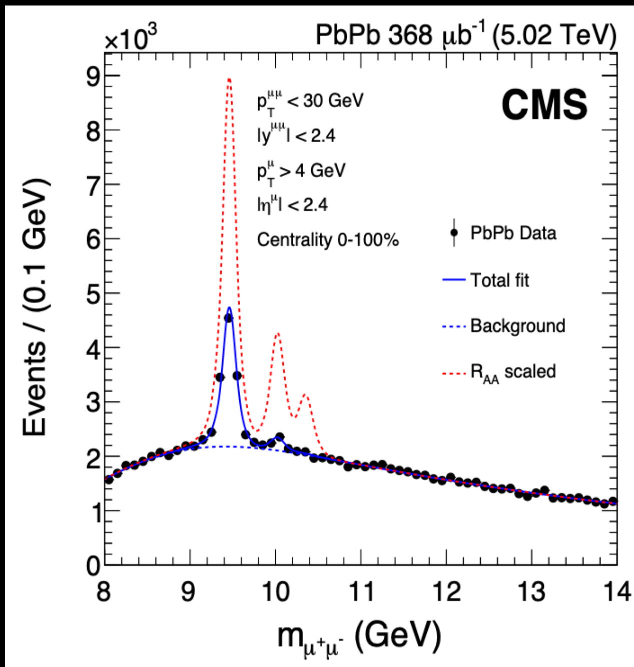
Less J/ψ suppression at LHC with higher temperature

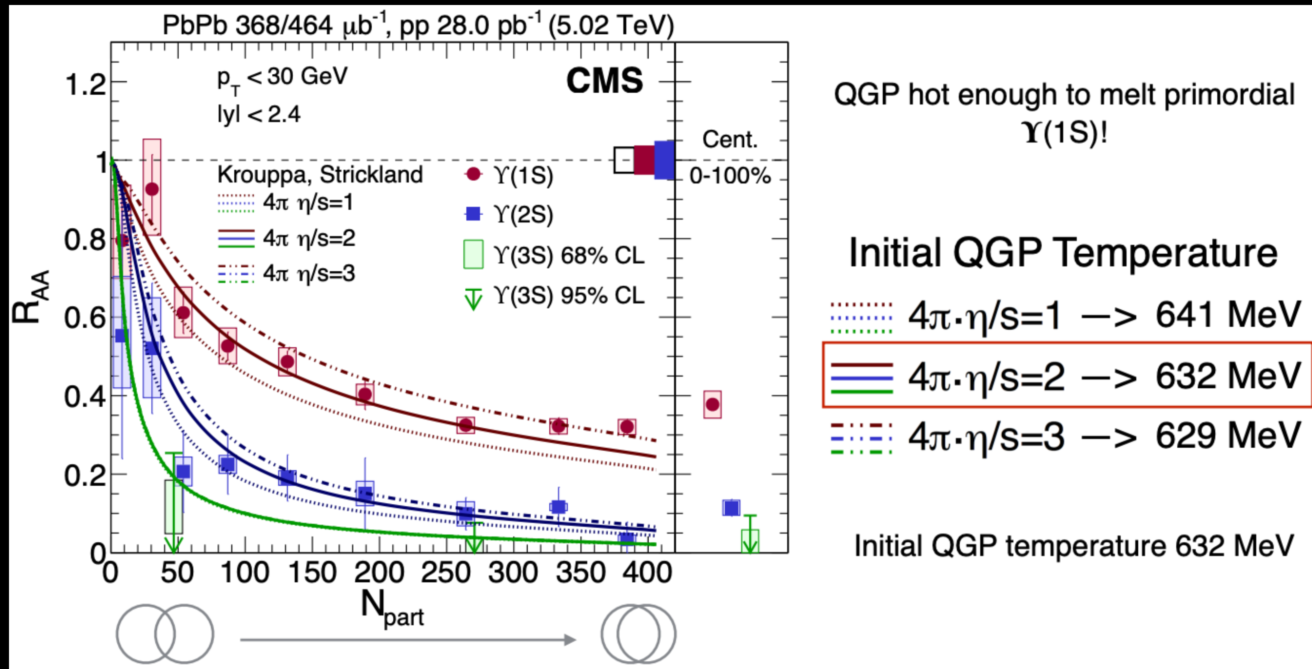
Charm recombination dominant effect, not screening.



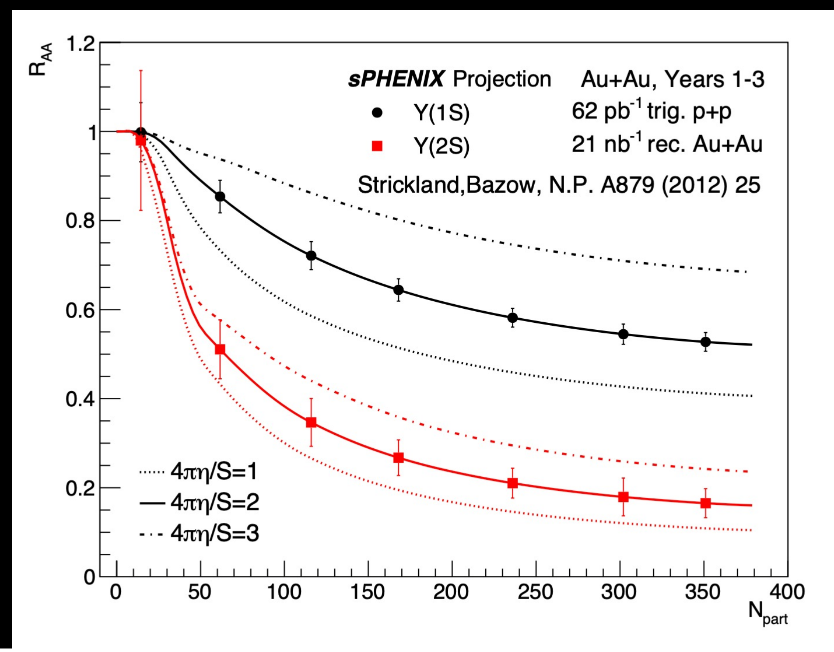
Look to Upsilons for Debye Screening, no recombination at RHIC

Upsilon sequential suppression



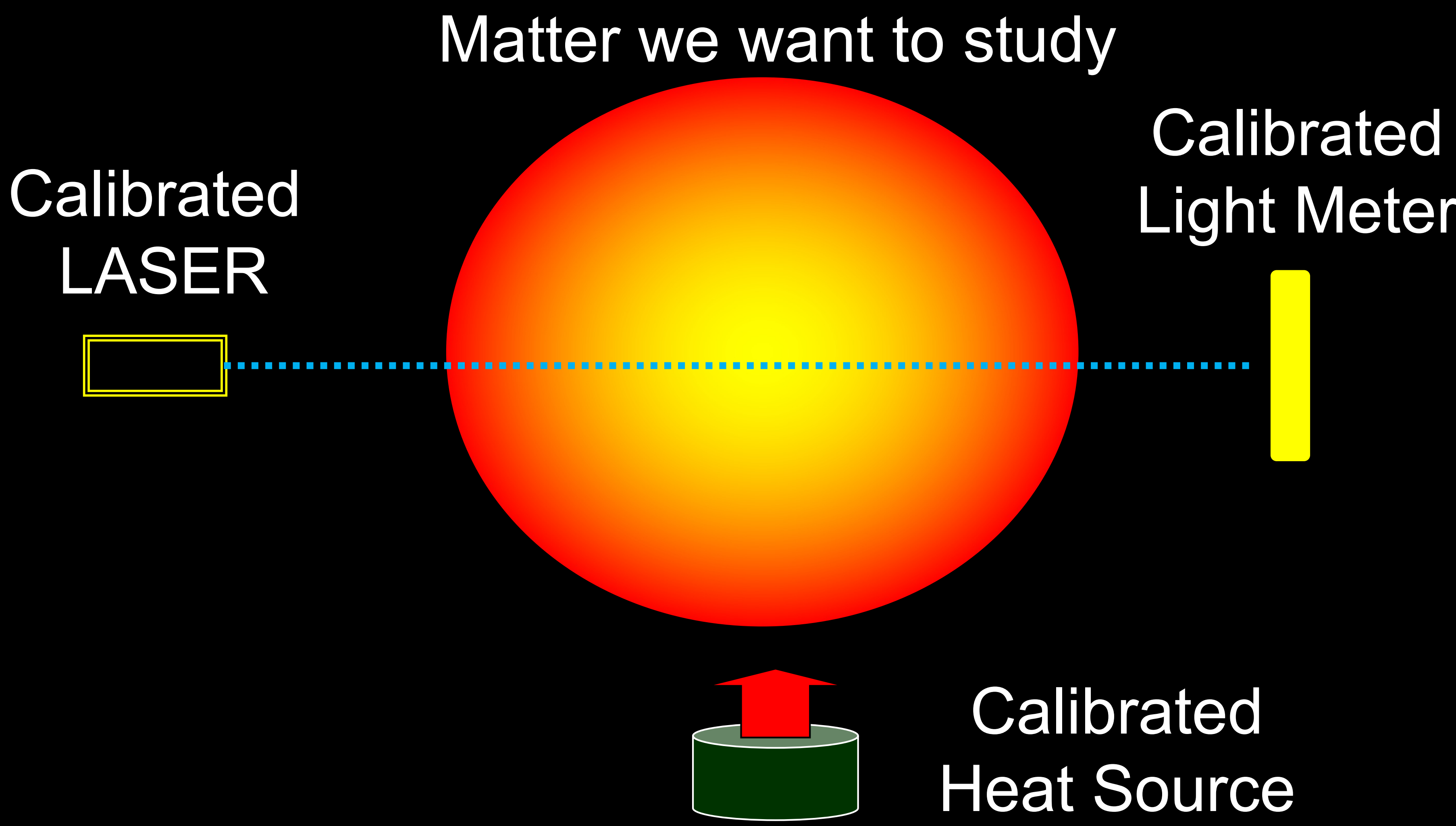


"Because the more excited states melt at lower temperatures, the sequential suppression is an excellent indicator of the temperature of the nuclear medium produced in PbPb collisions."

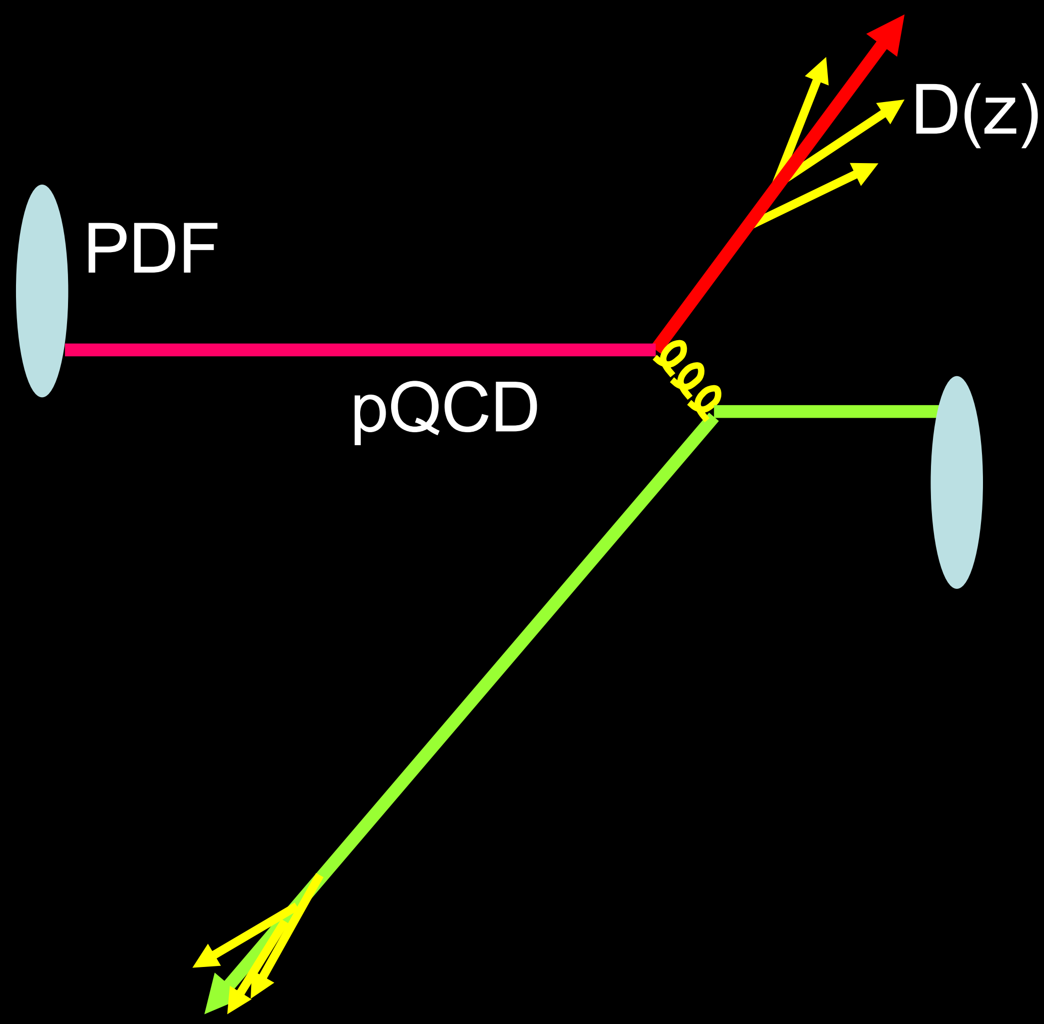


Jet Quenching

Probing the Matter



Autogenerated Quark "LASER"



Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

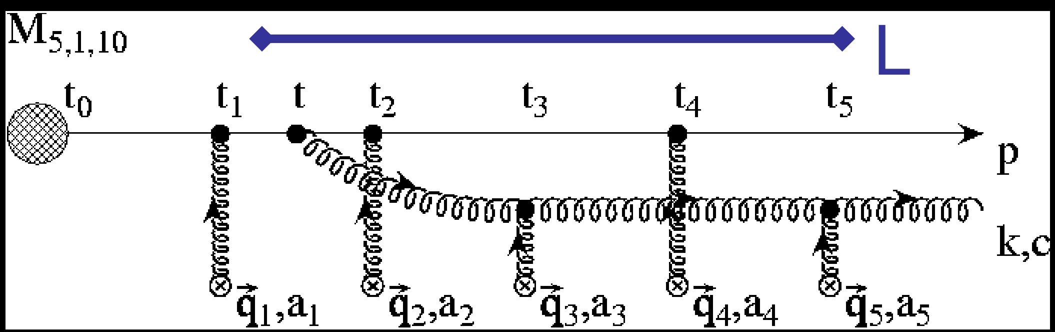
Abstract

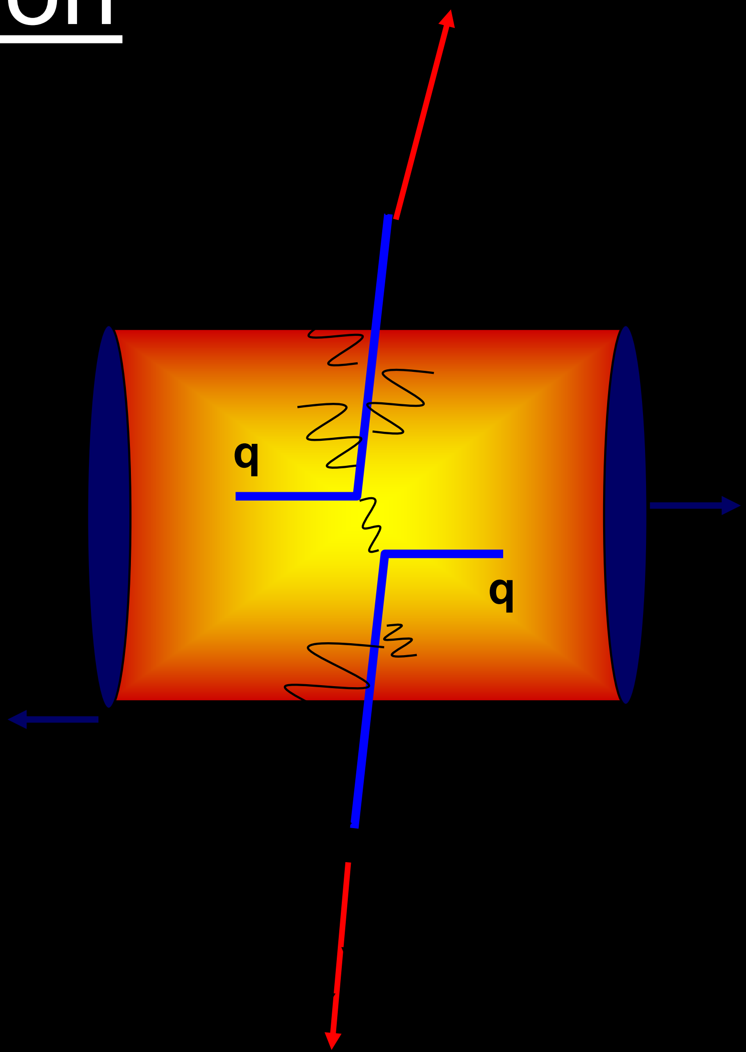
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Gluon Radiation

Partons are expected to lose energy via induced gluon radiation in traversing a dense partonic medium.

Coherence among these radiated gluons can lead to $\Delta E \; \alpha \; L^2$





Look for an effective modification in the jet fragmentation properties.

Baier, Dokshitzer, Mueller, Schiff, hep-ph/9907267
Gyulassy, Levai, Vitev, hep-pl/9907461
Wang, nucl-th/9812021
and many more…..

pQCD + Factorization + Universality

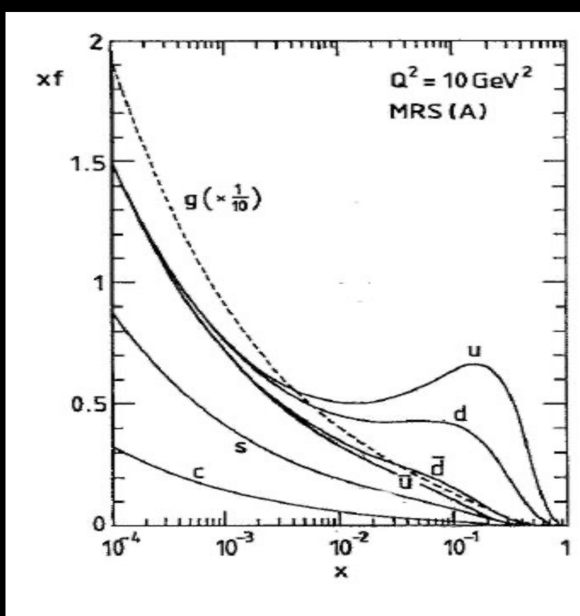
In heavy ion collisions we can calculate the yield of high p_T hadrons

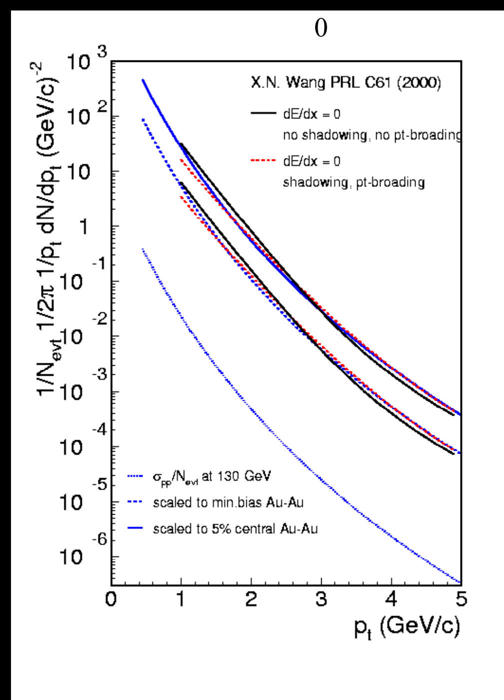
$$E_h \frac{d\sigma_h^{pp}}{d^3p} = K \sum_{abcd} \int dz_c\, dx_a\, dx_b \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} f(\mathbf{k}_{Ta}) f(\mathbf{k}_{Tb}) f_{a/p}(x_a, Q_a^2) f_{b/p}(x_b, Q_b^2)\, D_{h/c}(z_c, Q_c^2) \frac{\hat{s}}{\pi z_c^2} \frac{d\sigma^{(ab\to cd)}}{d\hat{t}} \delta(\hat{s}+\hat{u}+\hat{t})$$

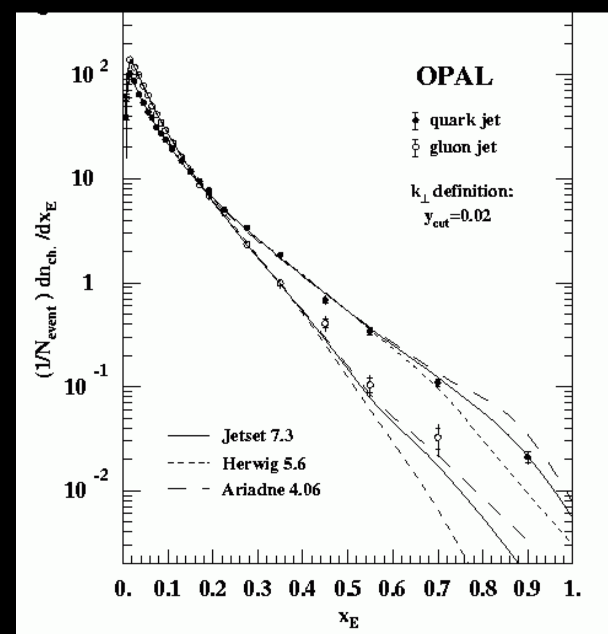
Flux of incoming partons (structure functions) from Deep Inelastic Scattering

Perturbative QCD

Fragmentation functions D(z) in order to relate jets to observed hadrons





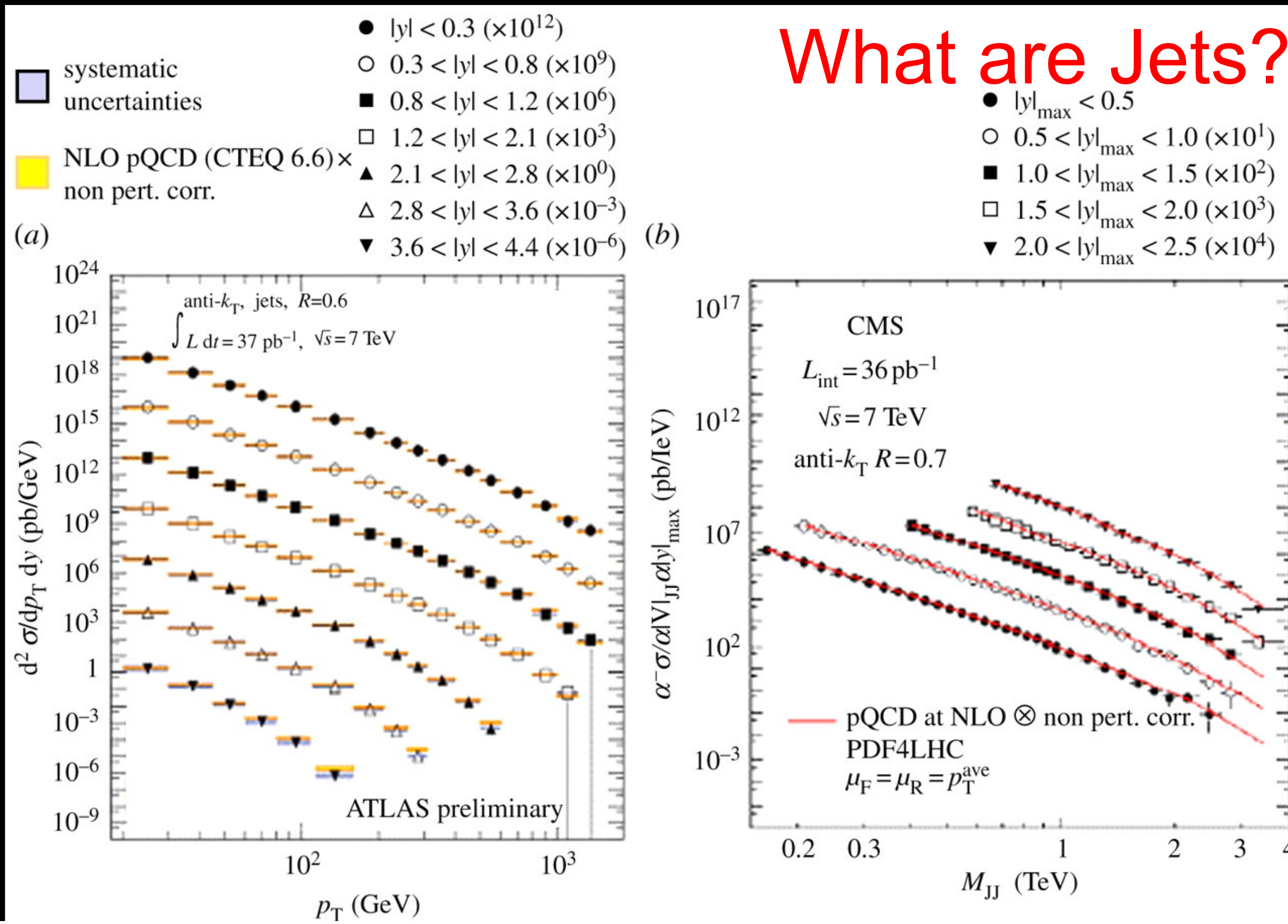


Calibrating Our Probes

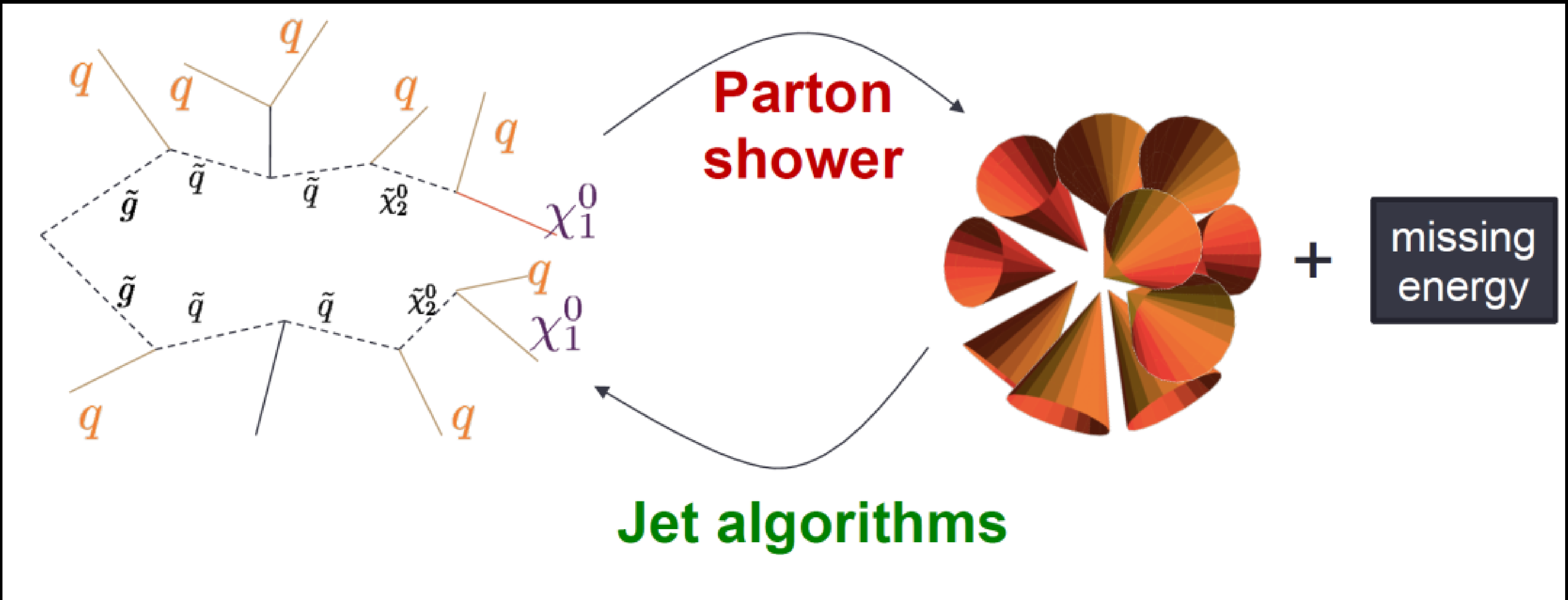
High energy probes are well described in proton-proton reactions by NLO Perturbative QCD.

Reconstructed Jets

What are Jets?



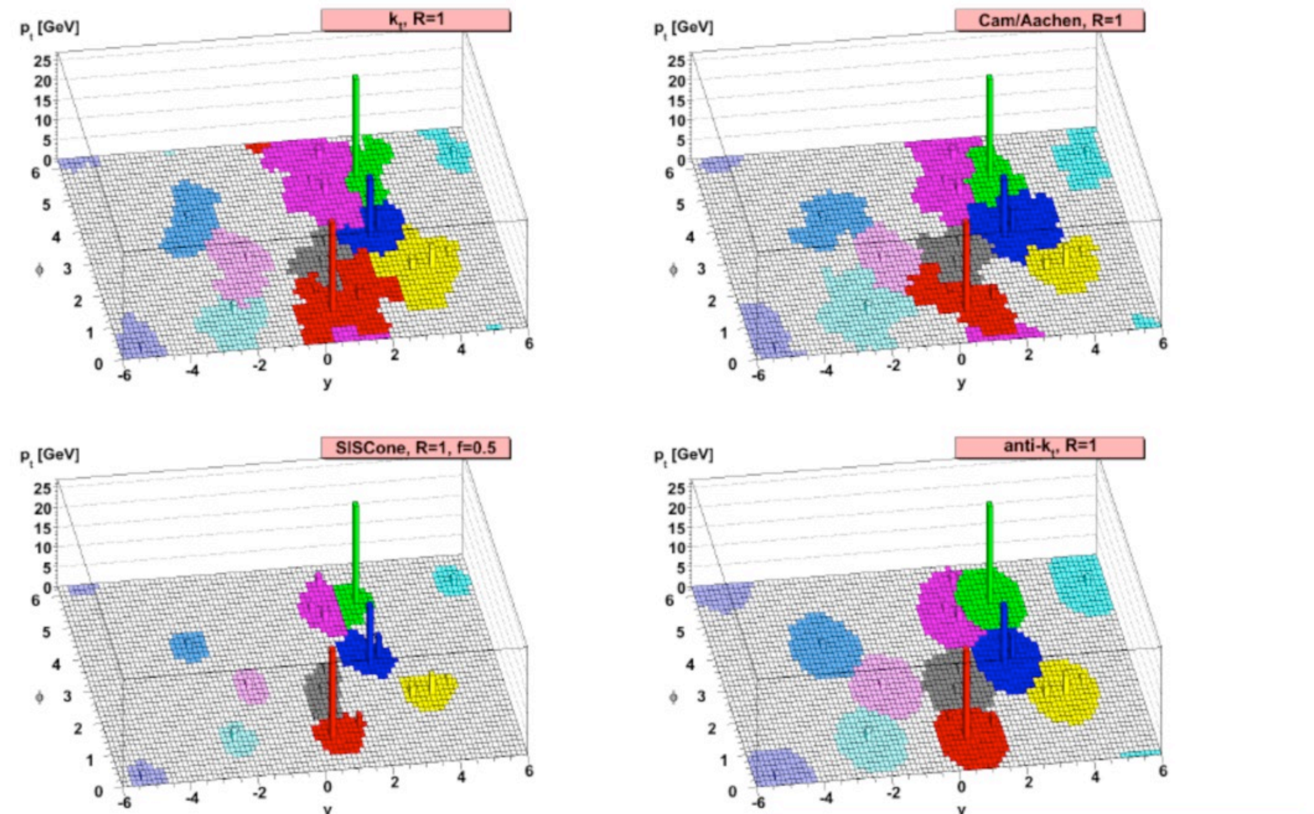
Jets-to-Parton Map



Jet algorithm sums the energy (typically in calorimeters) and can approximate catching an individual parton's energy.

Very useful in particle physics, but often used in a different way in heavy ion physics.

Jet Algorithms



Cacciari, Salam, Soyez JHEP 0804:063 (2008)

Different methods to "group" energies.

1. **The Anti-k(t) jet clustering algorithm**
   Matteo Cacciari, Gavin P. Salam (Paris, LPTHE), Gregory Soyez (Brookhaven). Feb 2008. 12 pp.
   Published in **JHEP 0804 (2008) 063**
   LPTHE-07-03
   DOI: 10.1088/1126-6708/2008/04/063
   e-Print: **arXiv:0802.1189 [hep-ph]** | PDF

   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service

   Detailed record - Cited by 3675 records 1000+

FastJet Code Publicly Available

http://fastjet.fr/

Home About Releases Quick start Manual Doxygen Tools Contrib FAQ

FastJet

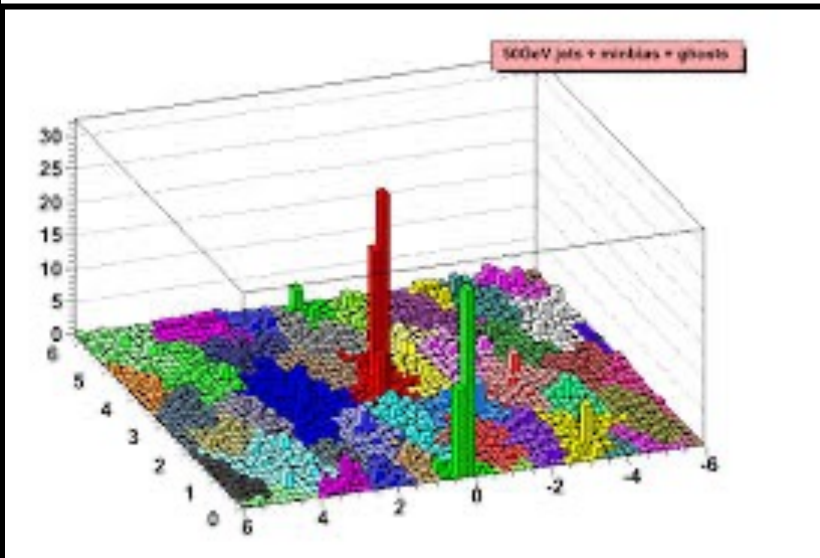
A software package for jet finding in pp and e^+e^- collisions. It includes fast native implementations of many sequential recombination clustering algorithms, plugins for access to a range of cone jet finders and tools for advanced jet manipulation.

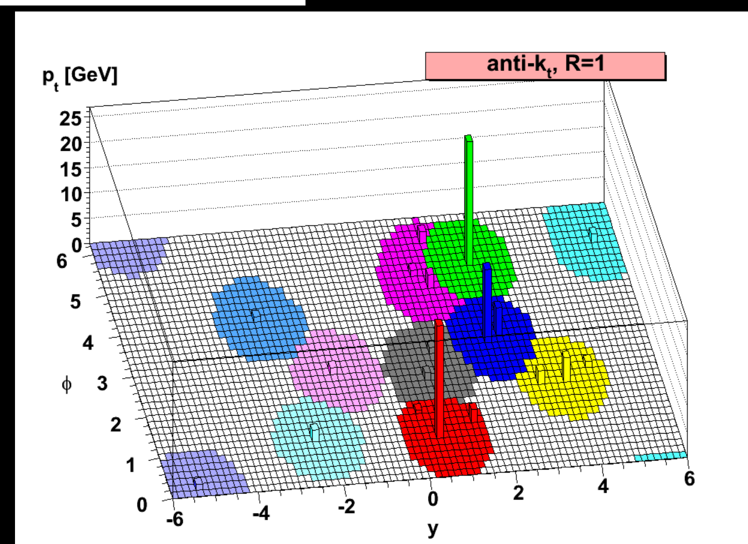
Release of FastJet 3.2.0, 17 March 2016 (release notes).
Its main new feature is that it exposes the N2Plain and N2Tiled strategies for 3rd-party clustering algorithms under the form of two new classes (NNFJN2Plain and NNFJN2Tiled), similar to NNH.
Download

Latest stable release of fjcore (v3.2.0), 17 March 2016
Lightweight access to the core FastJet functionality (PseudoJet, JetDefinition, ClusterSequence and Selector).
It consists of just two files, fjcore.hh and fjcore.cc, which can easily be included in 3rd party projects. Compile time: a few seconds. A fortran interface and basic examples are also included in the distribution. Download size: 74k.

Release of FastJet Contrib 1.024, 21 June 2016 *** NEW ***
A package of contributed add-ons to FastJet. This release brings

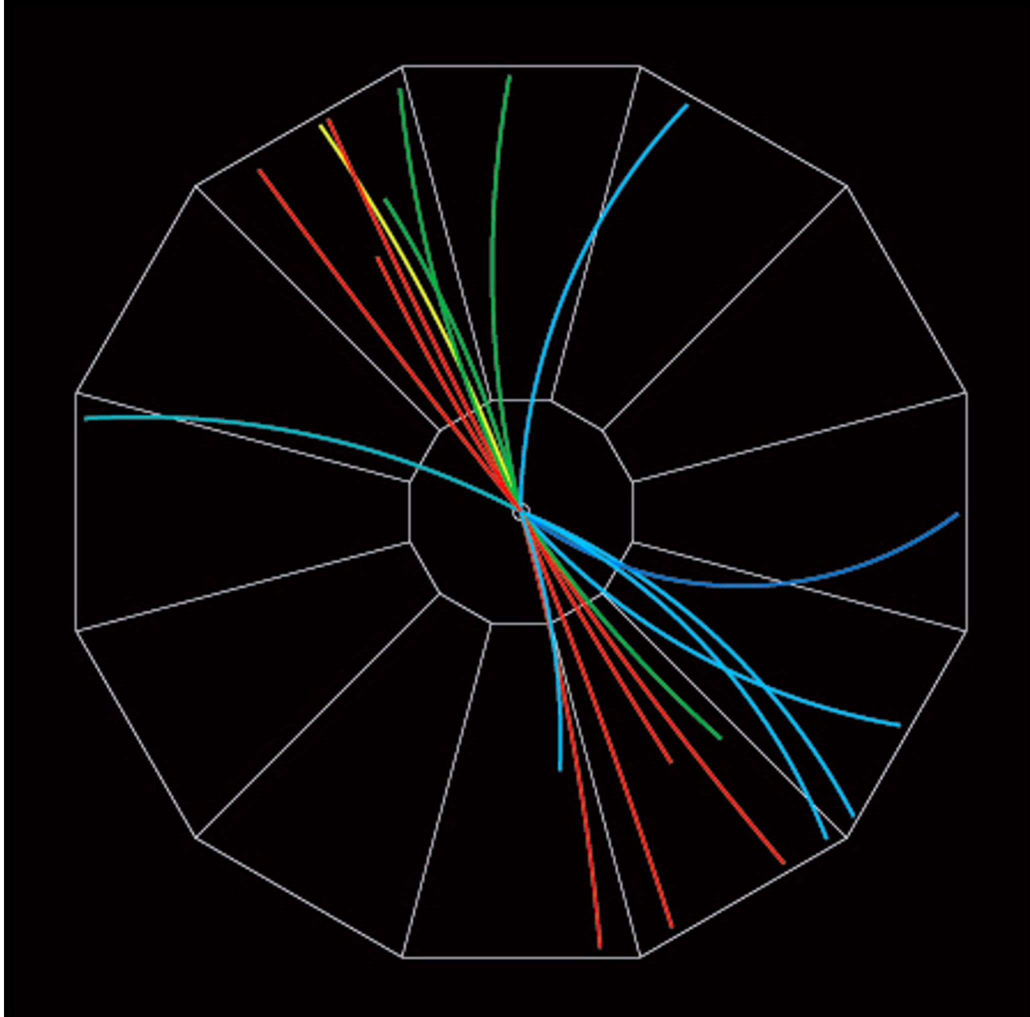
- update of Nsubjettiness to version 2.2.4 (fixed bug with multi-pass axes)
- update of VariableR to version 1.2.1 (fixed documentation and comments)

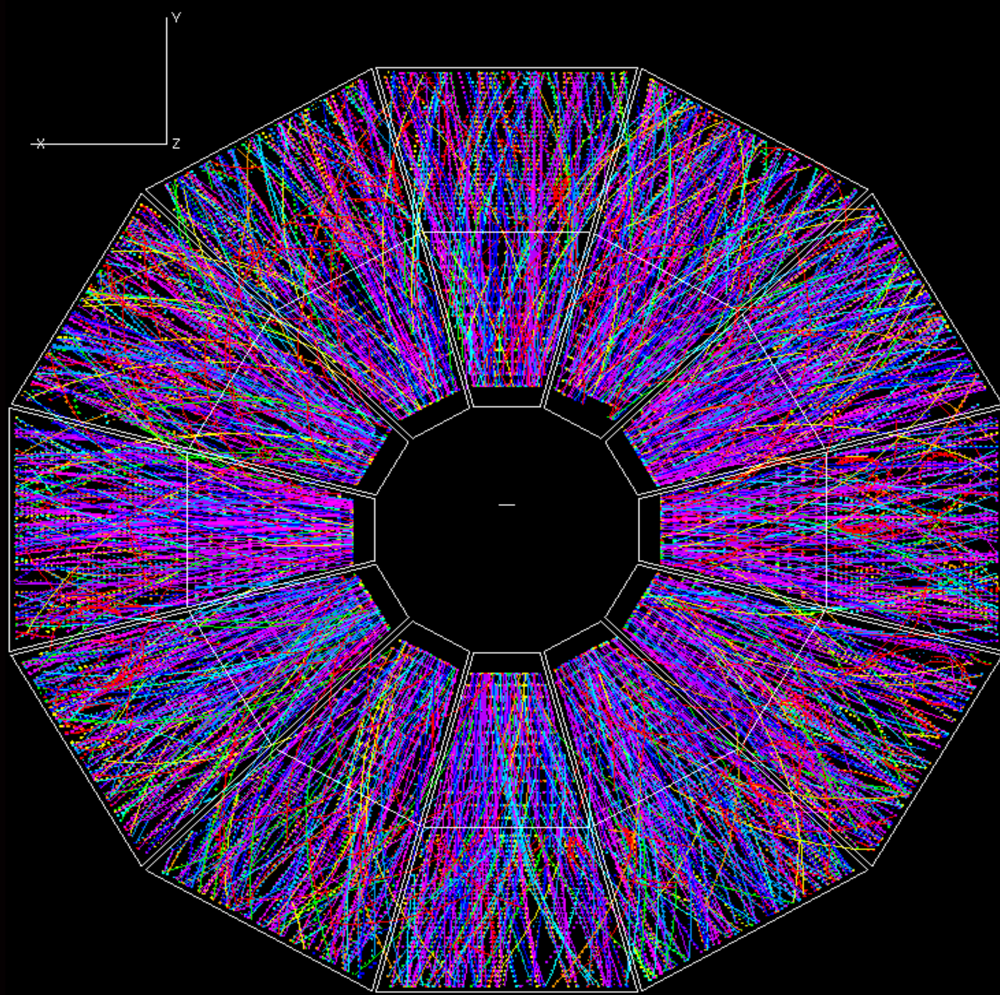




- R.D. Field, Applications of perturbative QCD A lot of detailed examples.
- R. K. Ellis, W. J. Stirling and B. R. Webber, QCD and Collider Physics
- CTEQ, Handbook of Perturbative QCD
- CTEQ website.
- John Collins, The Foundation of Perturbative QCD Includes a lot new development.
- Yu. L. Dokshitzer, V. A. Khoze, A. H. Mueller and S. I. Troyan, Basics of Perturbative QCD More advanced discussion on the small-x physics.

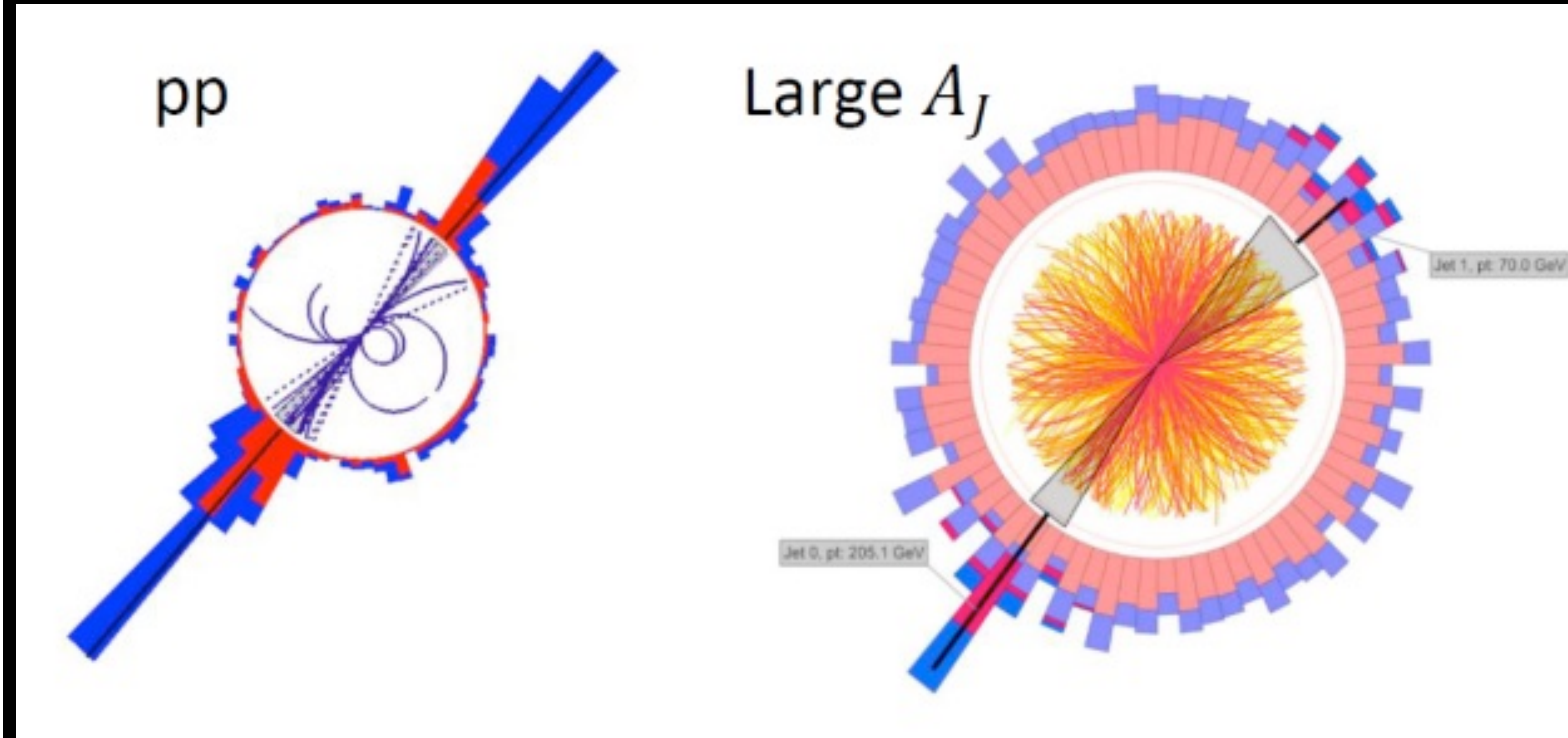
Jets in Heavy Ions





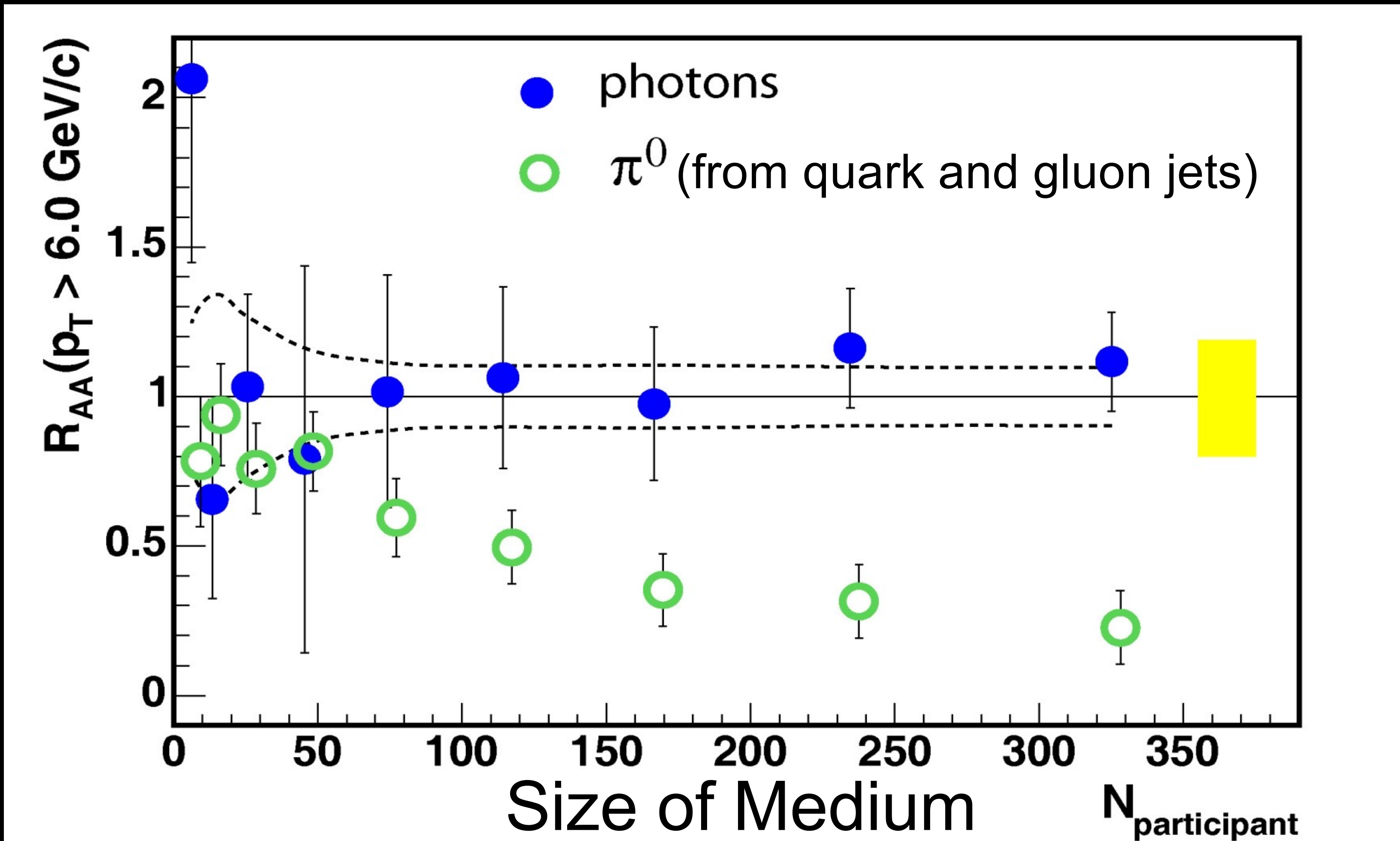
Start with single hadrons, then go to jets.

Much Higher Energy Jets at the LHC



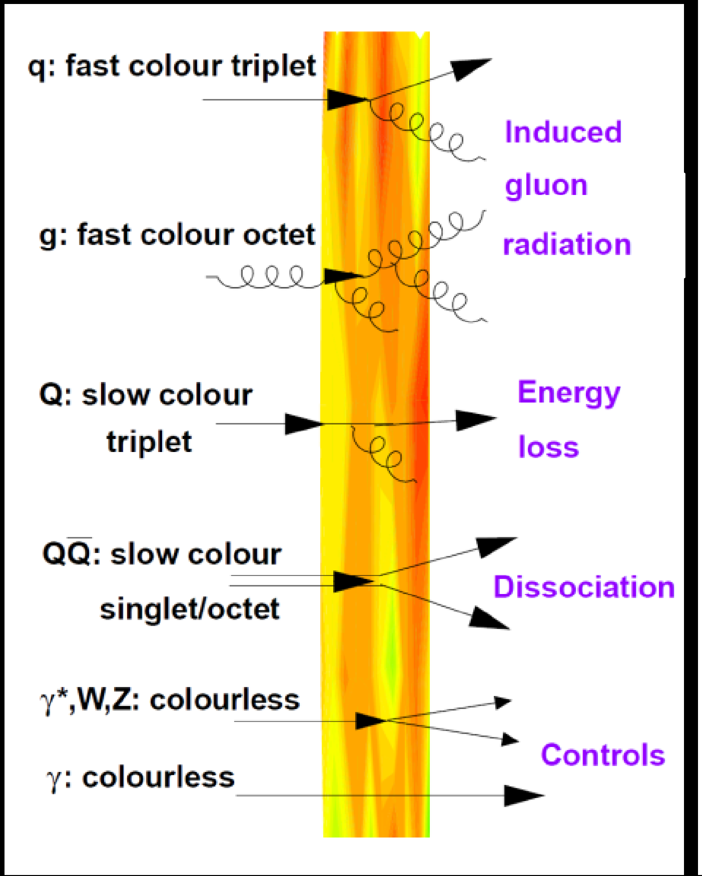
Nuclear Modification Factor

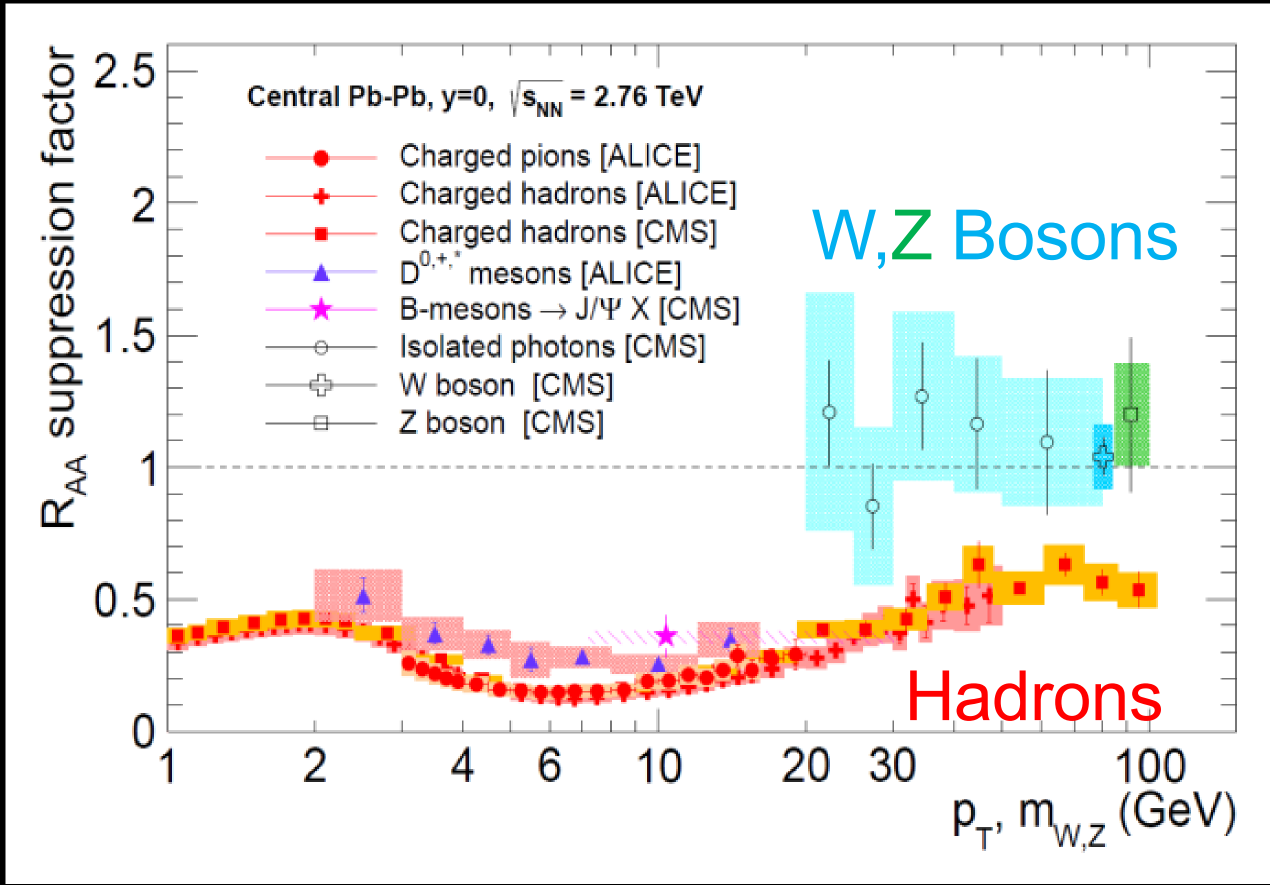
$$R_{AA}(p_T, y; b) = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \times d^2\sigma_{pp}/dydp_T} = \frac{\text{A+A yield}}{\text{Scaled p+p yield}}$$



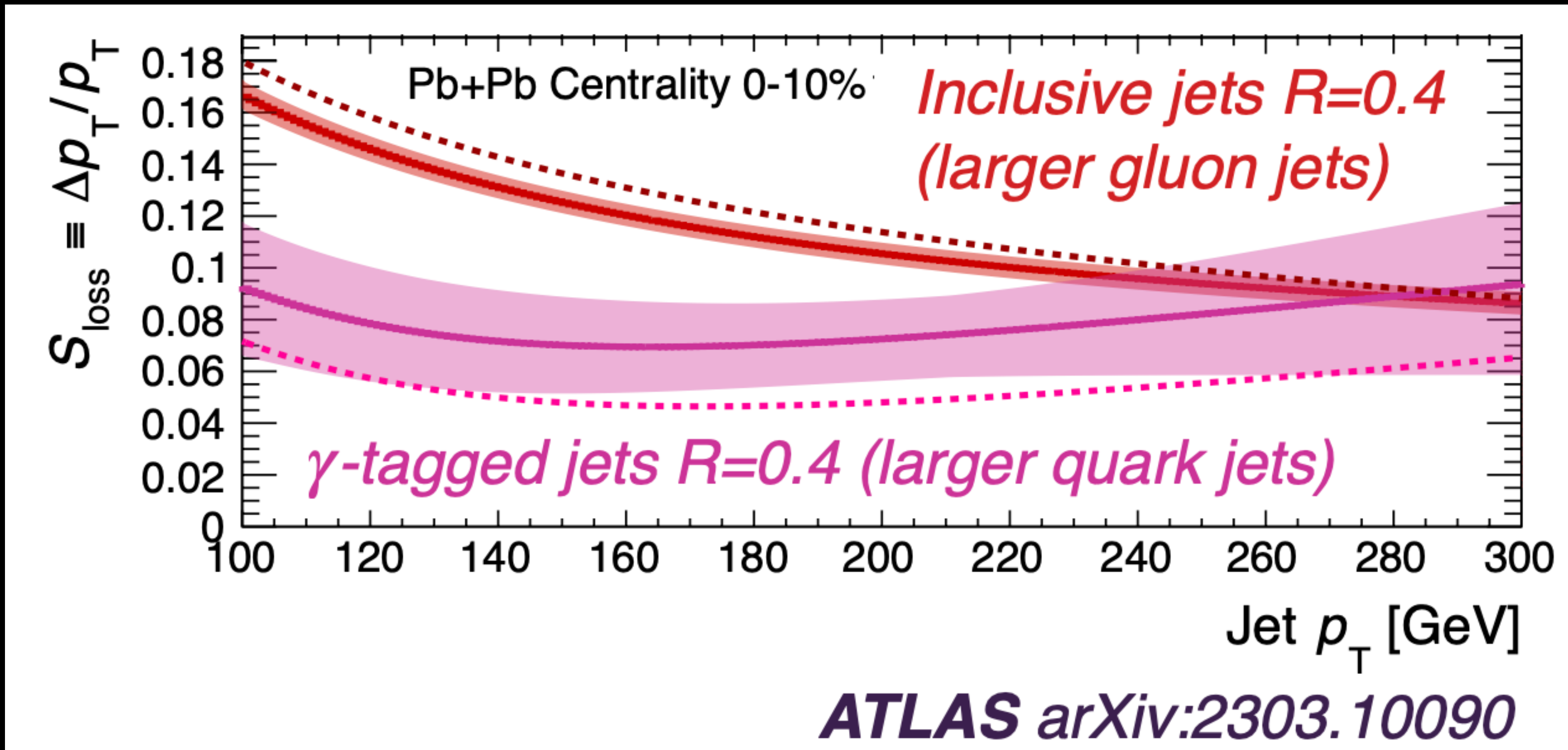
Photons unaffected by medium, pizeros suppressed

Probe expectations

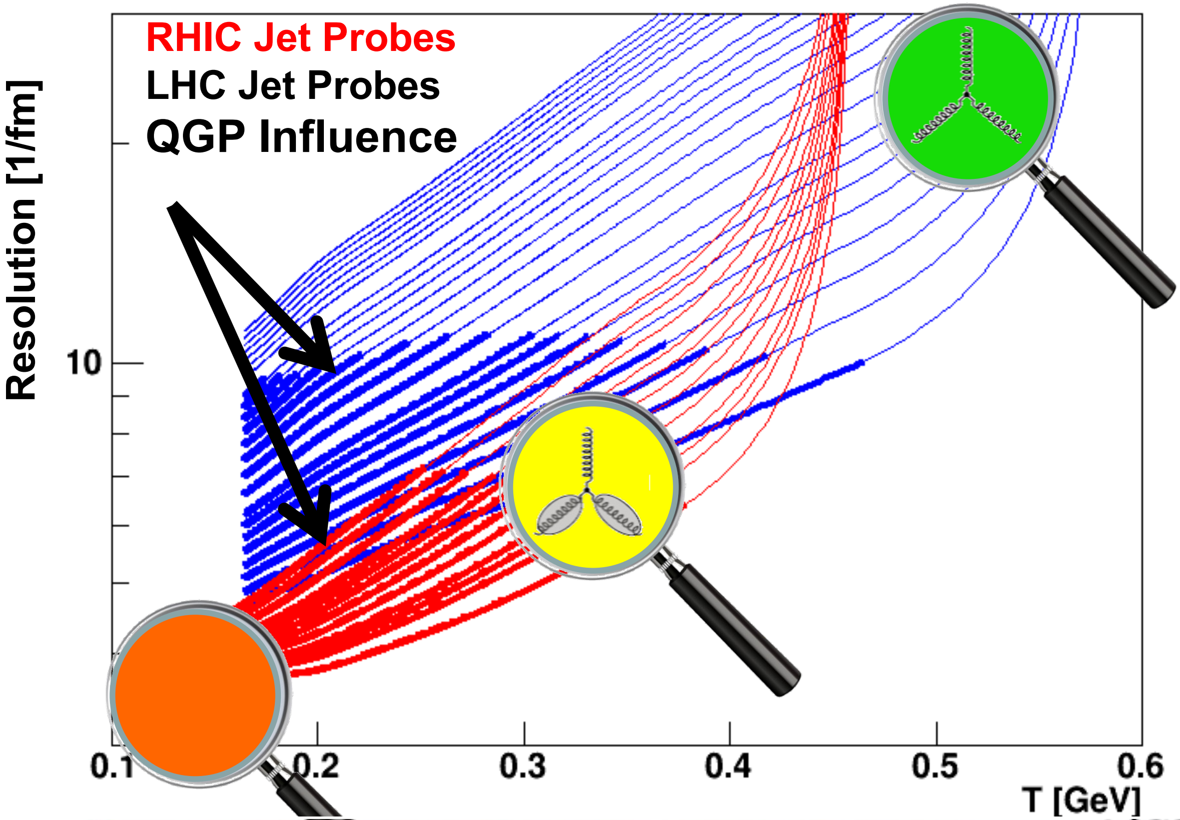


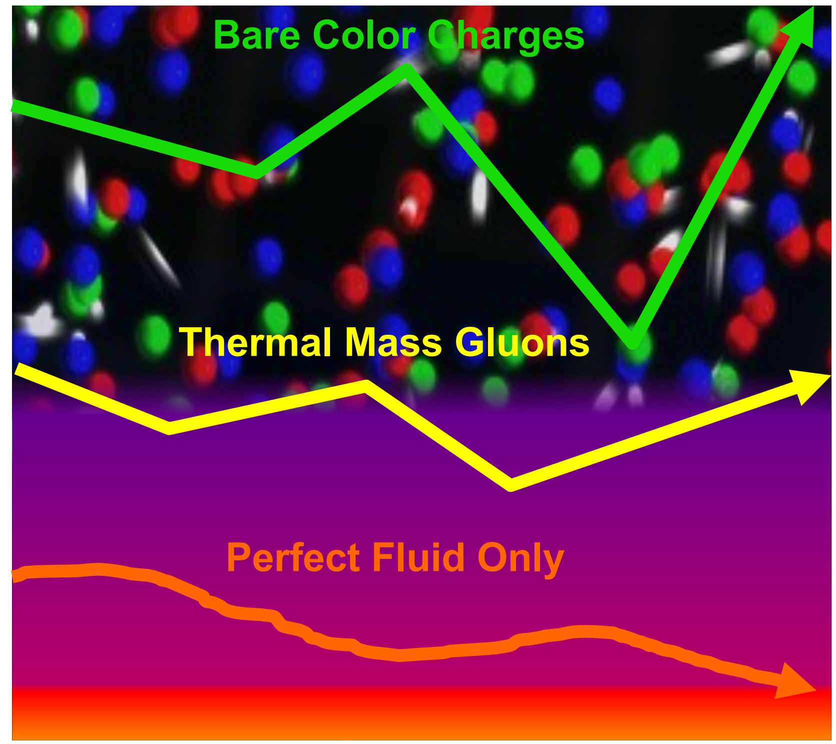


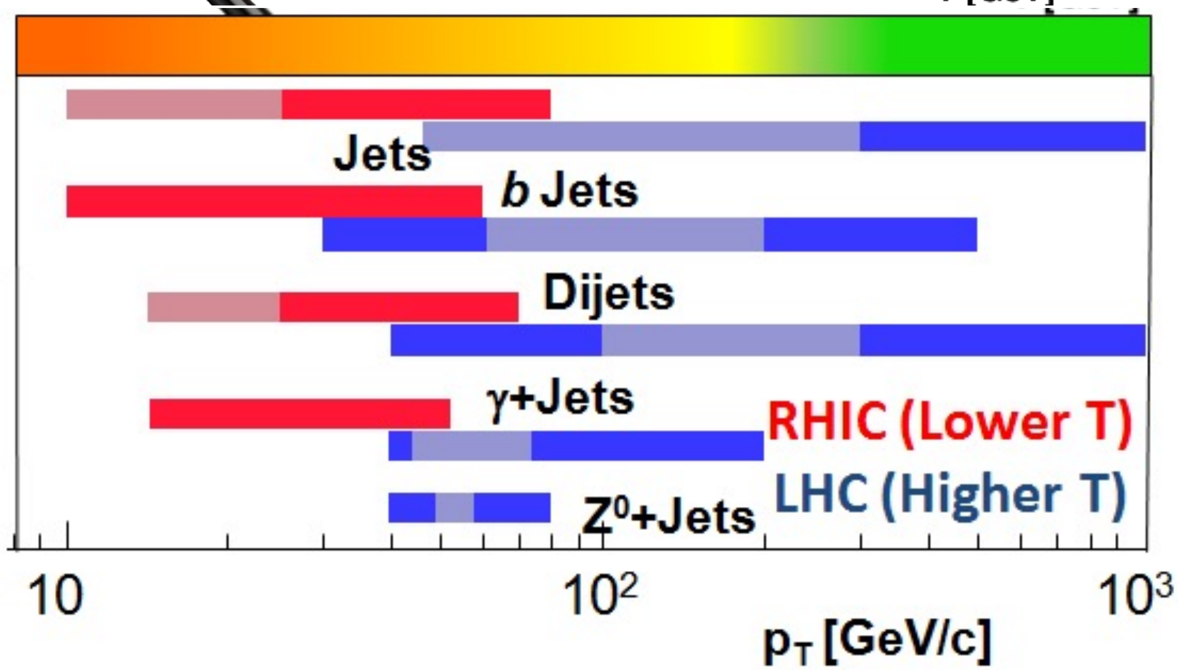
Quarks versus Gluons



$$\Delta E_{GLV} \approx \frac{9}{4}\alpha_s^3 \pi \, C_R \left(\frac{1}{\pi R^2} \frac{dN_g}{dy} \right) \left\{ \mathrm{Log} \frac{2E}{\mu^2 L} \right\} L(\phi)$$



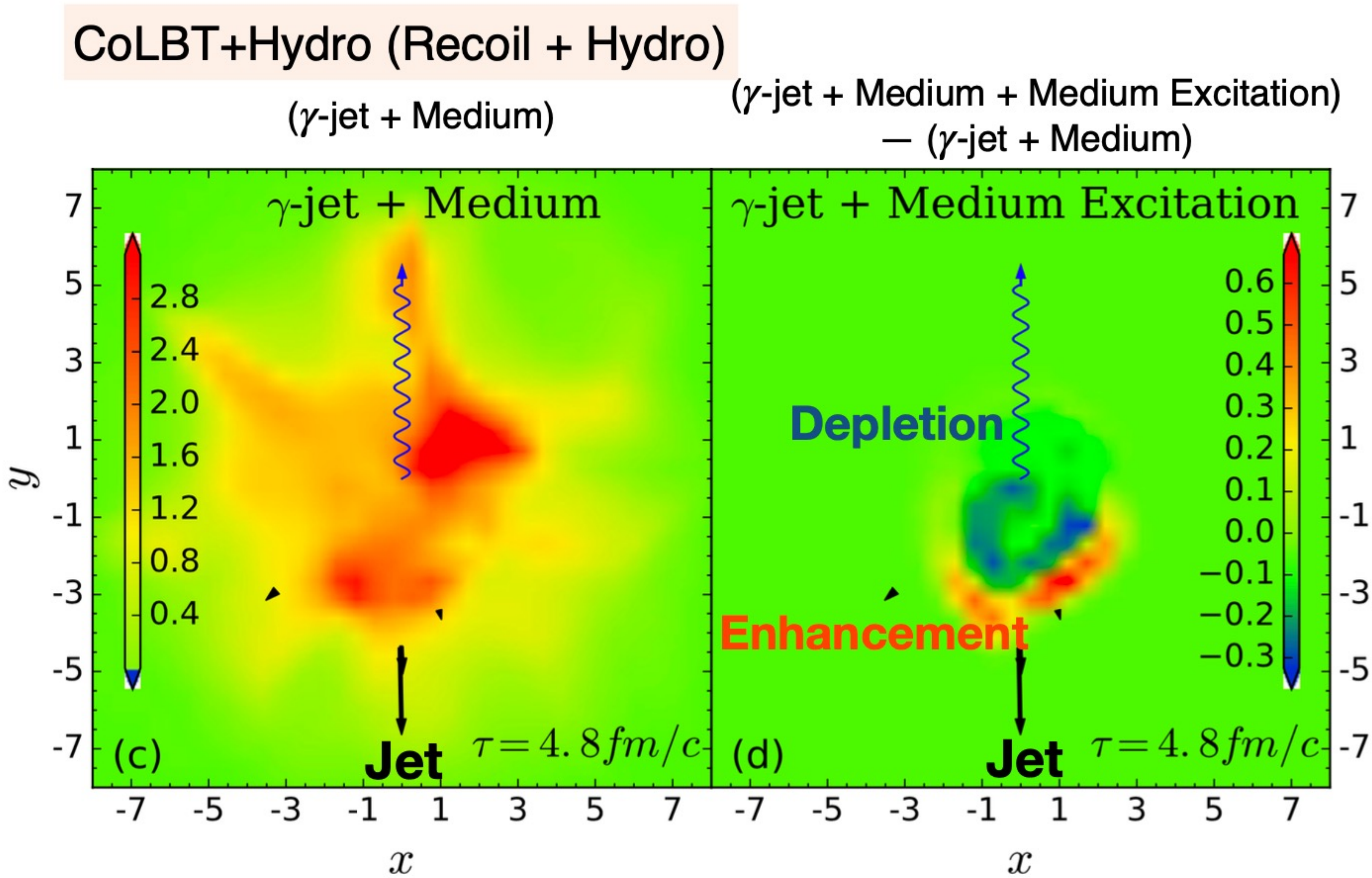




Critical microscope resolution at RHIC.

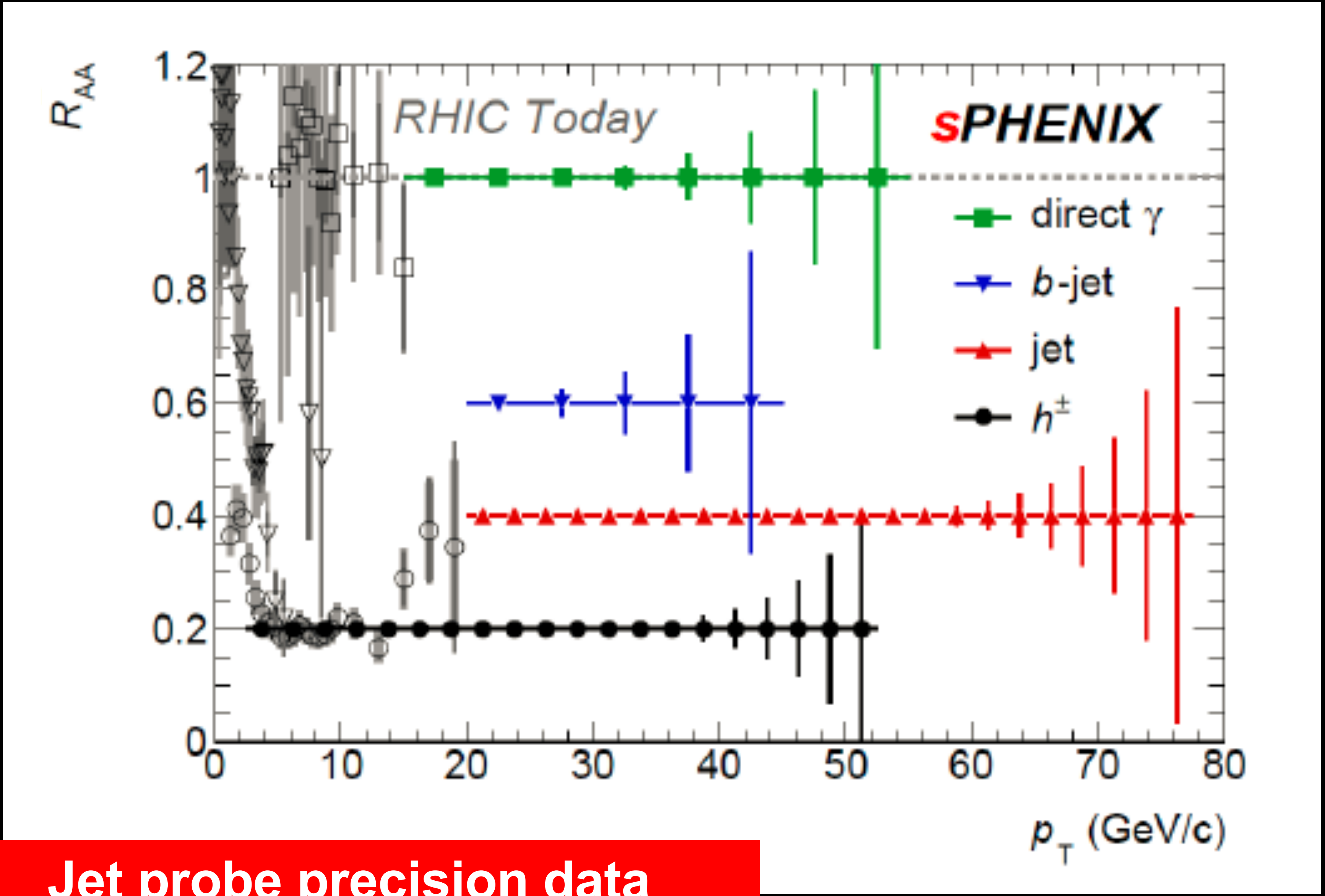
Also, overlap between RHIC and LHC for simultaneous description.

Does the fluid response to the energy input?



W. Chen et al. PLB 777 (2018) 86

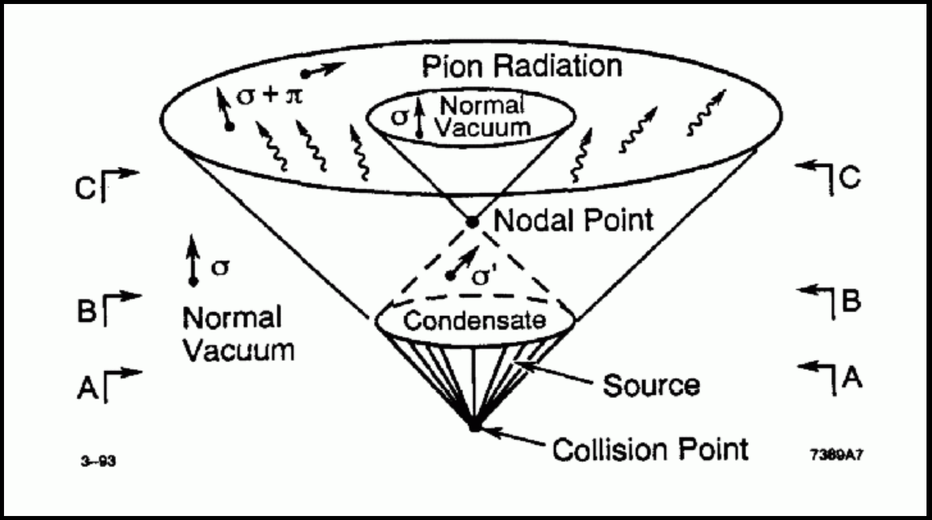
Precision Imaging of QGP Over Key Kinematics



Jet probe precision data
RHIC – 2023++
LHC – Run 3 + 4 statistics

Small QGP

Remember your History

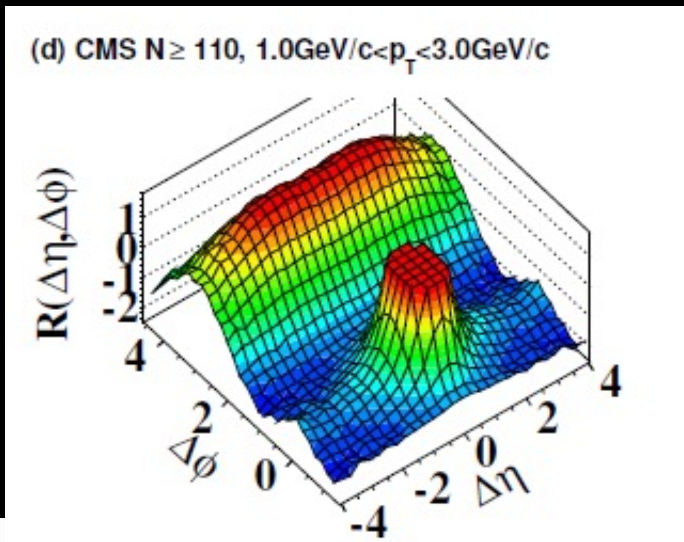


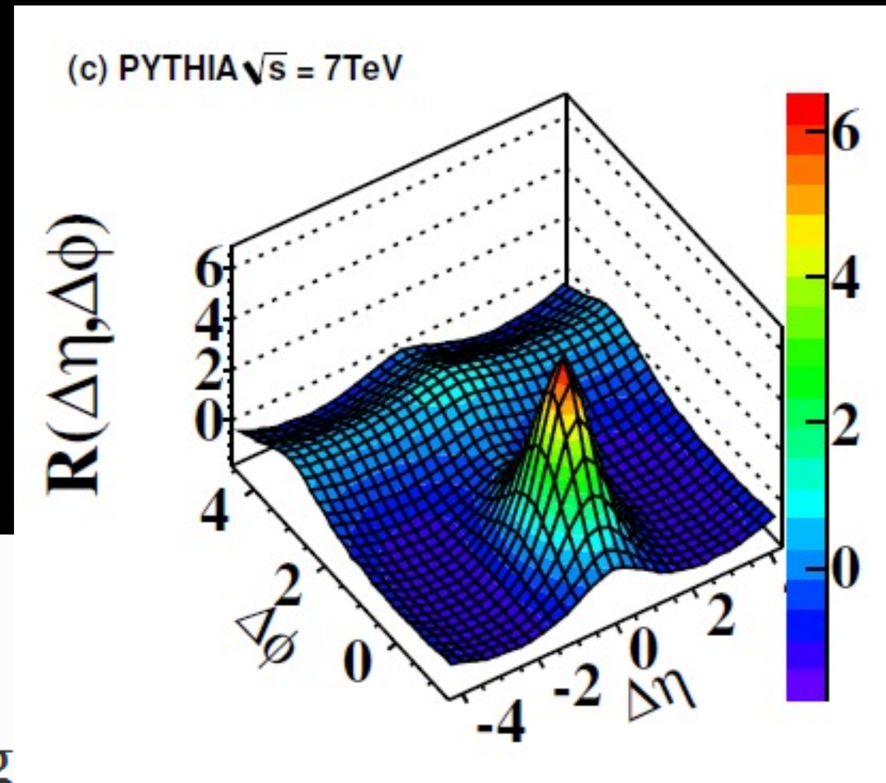
The idea about small QGP was somewhat lost, but maybe not for good scientific reasons.

No particles → think fields / disturbed vacuum

Maybe the small number of final state particles is just not relevant…

CMS Proton-Proton Hint





ics
September 2010, 2010:91

Observation of long-rang
correlations in proton-proton collisions at the LHC

The CMS collaboration, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V. M. Ghete, J. Hammer, S. Hänsel, C. Hartl … show 2150 more

Open Access | Article

First Online: 27 September 2010

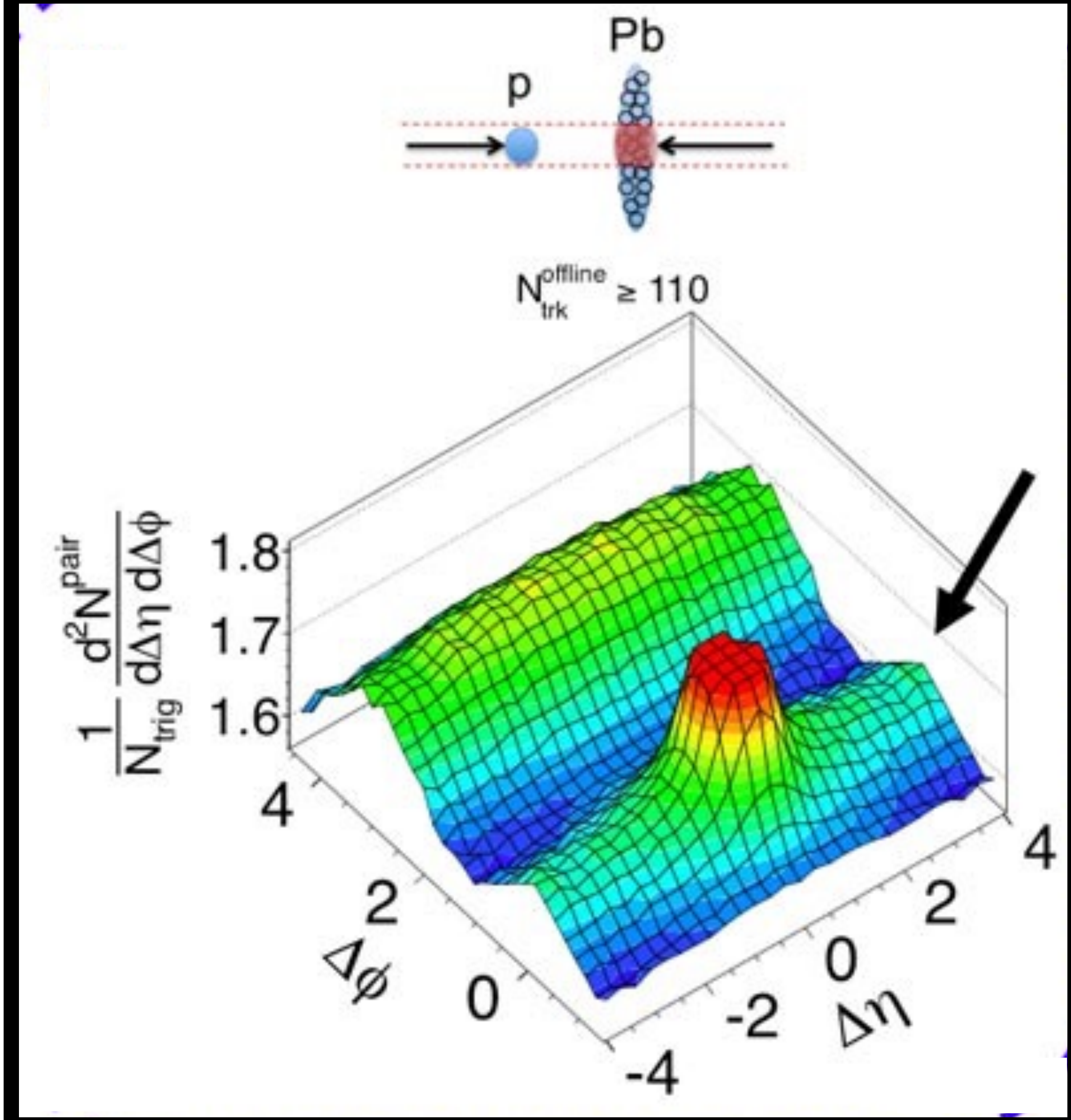
DOI: 10.1007/JHEP09(2010)091

Cite this article as:

The CMS collaboration et al. J. High Energ. Phys. (2010) 2010: 91. doi:10.1007/JHEP09(2010)091

http://link.springer.com/article/10.1007%2FJHEP09%282010%29091

Fall 2012 Revolution – p+Pb Collisions



- Very clear ridge
- Higher moments
- Particle dependence
- Cumulants

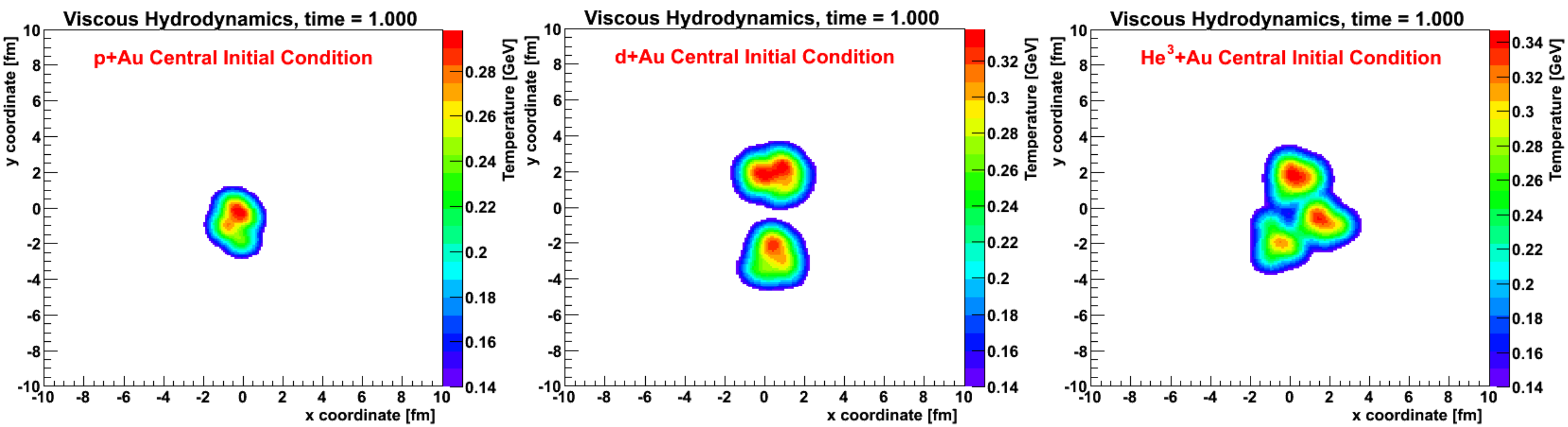
Almost every Pb+Pb collective flow signature by ALICE, ATLAS, CMS now seen in p+Pb!

Geometry Tests at RHIC

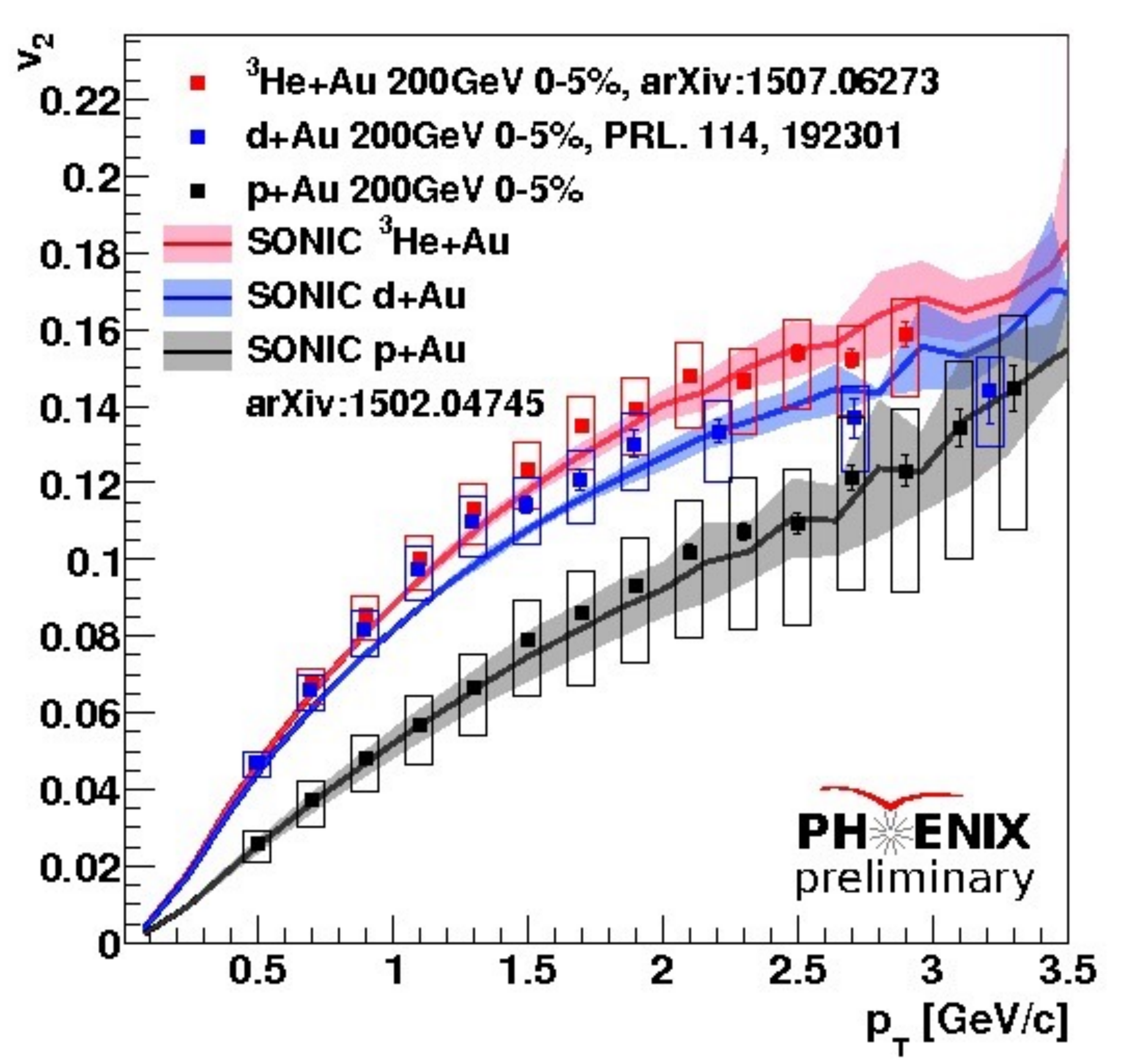
Exploiting Intrinsic Triangular Geometry in Relativistic ^{3}He + Au Collisions to Disentangle Medium Properties

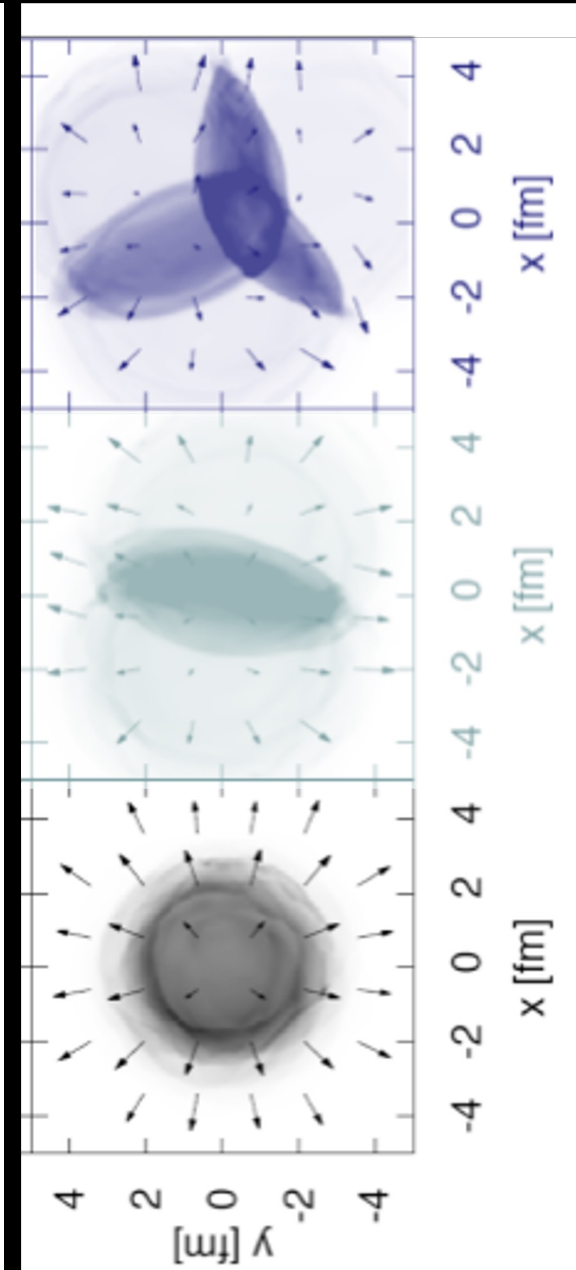
J. L. Nagle,[1,*] A. Adare,[1] S. Beckman,[1] T. Koblesky,[1] J. Orjuela Koop,[1] D. McGlinchey,[1] P. Romatschke,[1] J. Carlson,[2] J. E. Lynn,[2] and M. McCumber[2]
[1]*University of Colorado at Boulder, Boulder, Colorado 80309, USA*
[2]*Los Alamos National Laboratory,Los Alamos, New Mexico 87545, USA*
(Received 20 December 2013; revised manuscript received 27 June 2014; published 12 September 2014)

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301



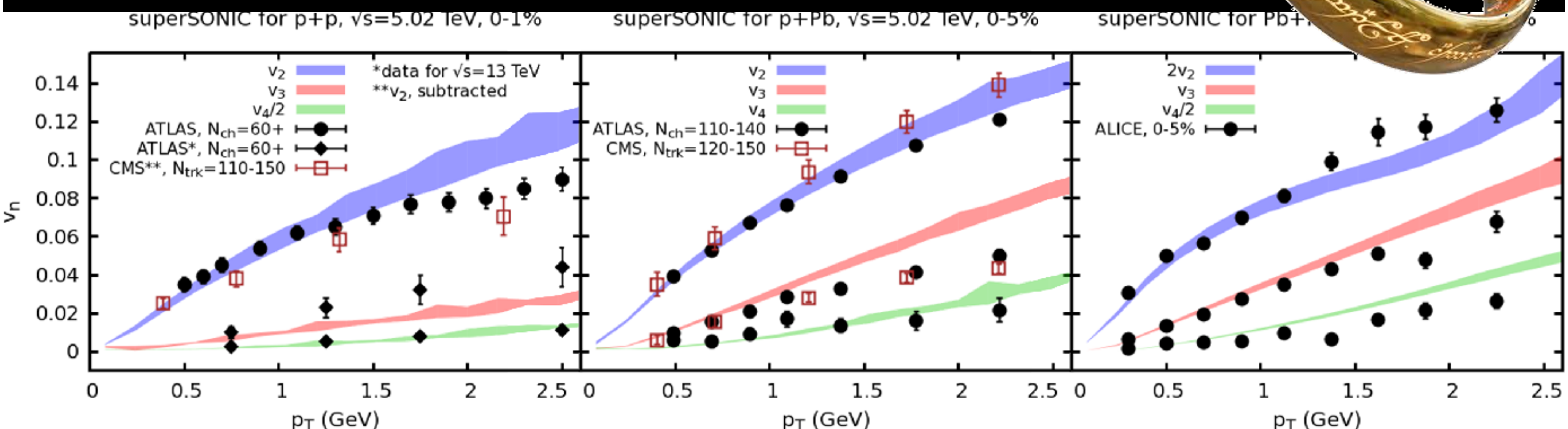
Glauber +Hydrodynamics+Cascade Predictions





Romatschke, Nagle et al. , http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.112301

One fluid to rule them all!



p+p　　　　p+Pb　　　　Pb+Pb

Has raised a lot of questions about the requirements for hydrodynamic behavior, equilibration, QGP droplet size..

The Future

New 2023 Long Range Plan being written now!

Well worth reading for young people…

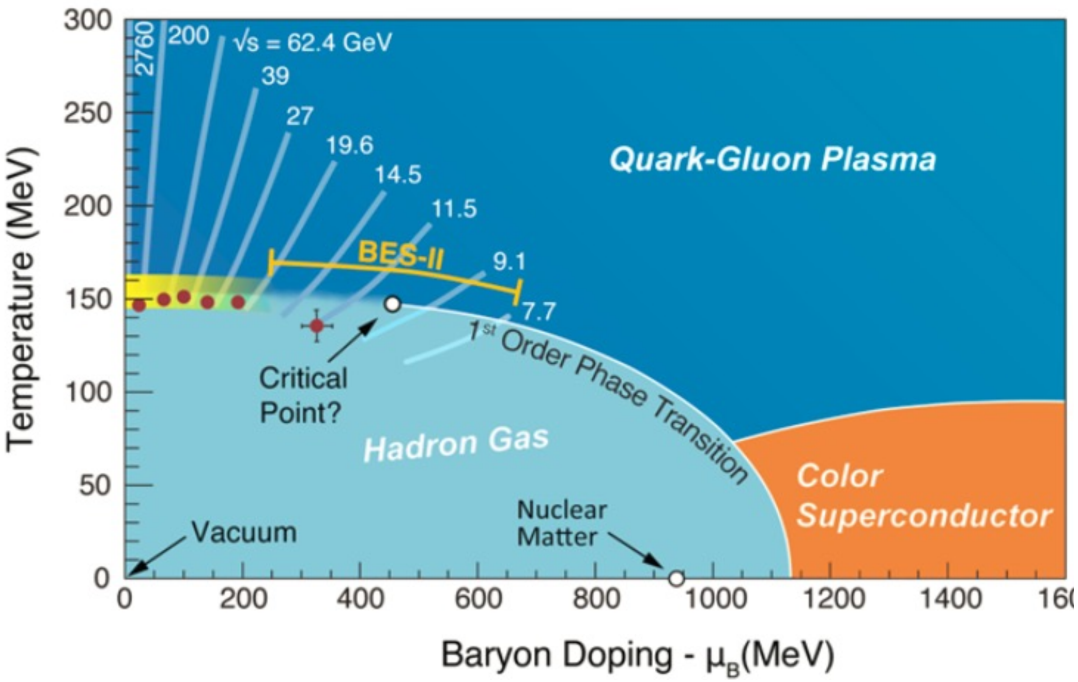
A roadmap for the future. Note that large \$0.5 - \$1.5B projects take 7-15 years at least.

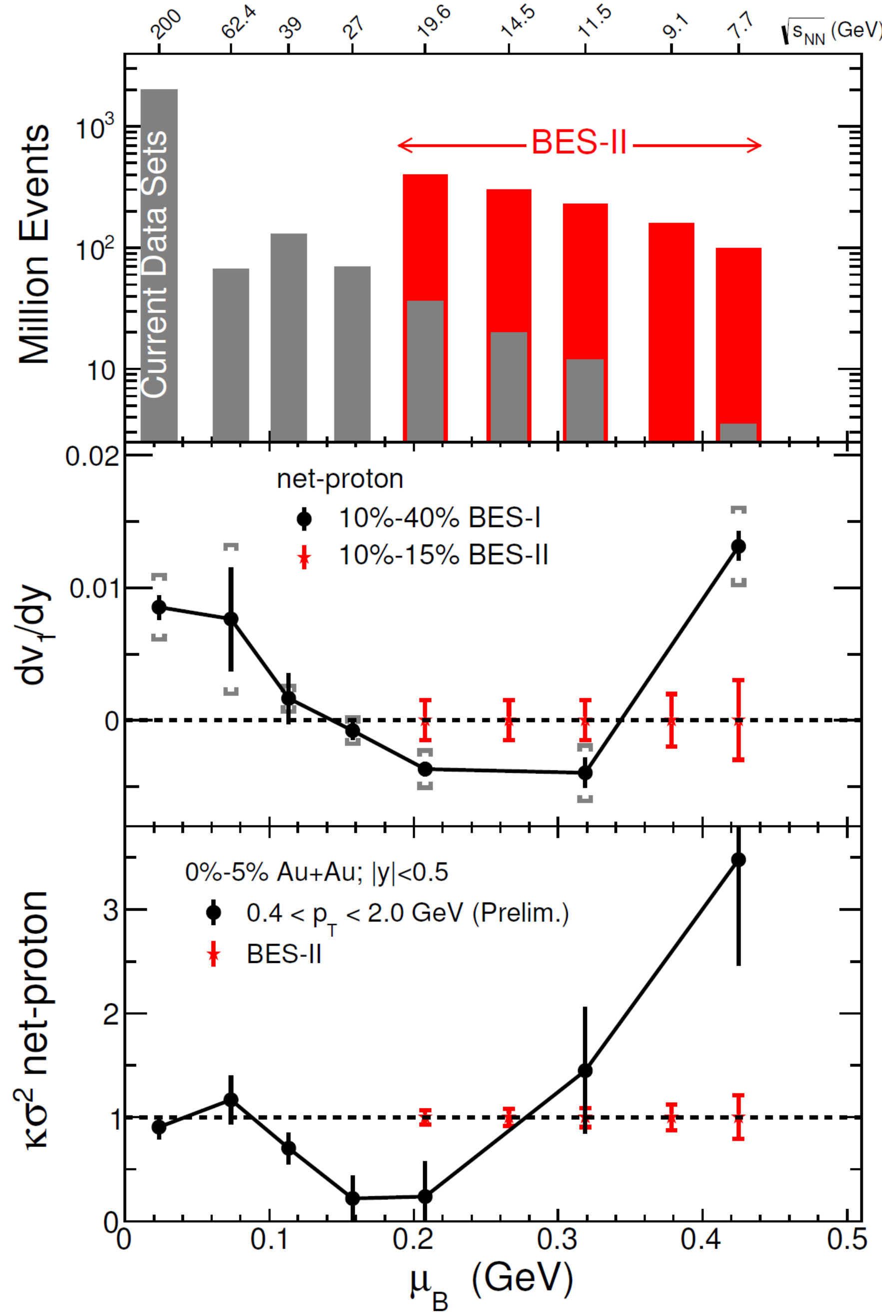
Capitalize on key investments.

Future facilities.

science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf

Beam Energy Scan – Phase II

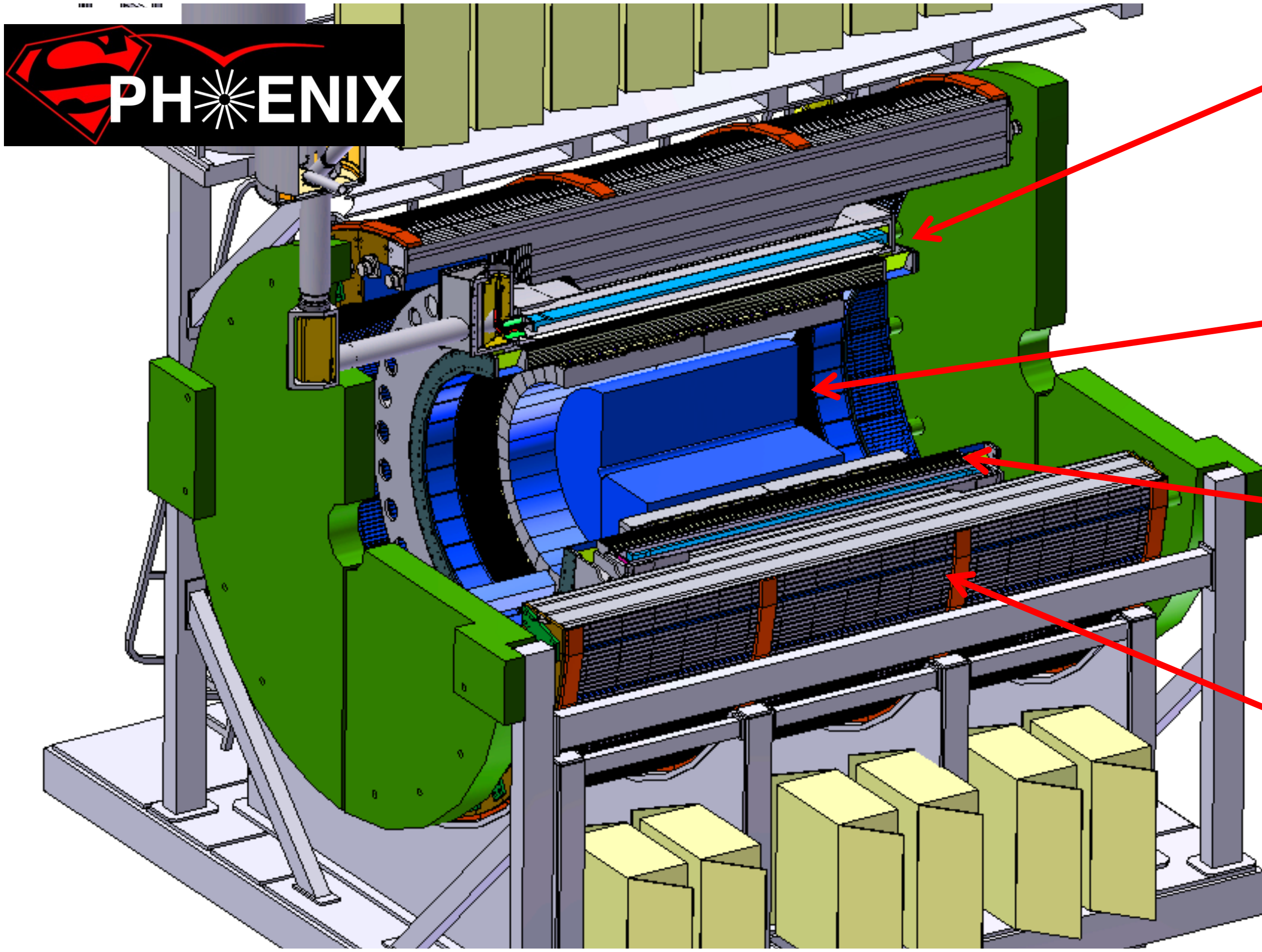




New precision in phase diagram mapping.

Data now collected by STAR experiment and analysis underway!

A New Detector at RHIC



BaBar Magnet 1.5 T

Coverage $|\eta| < 1.1$

All silicon tracking
Heavy flavor tagging

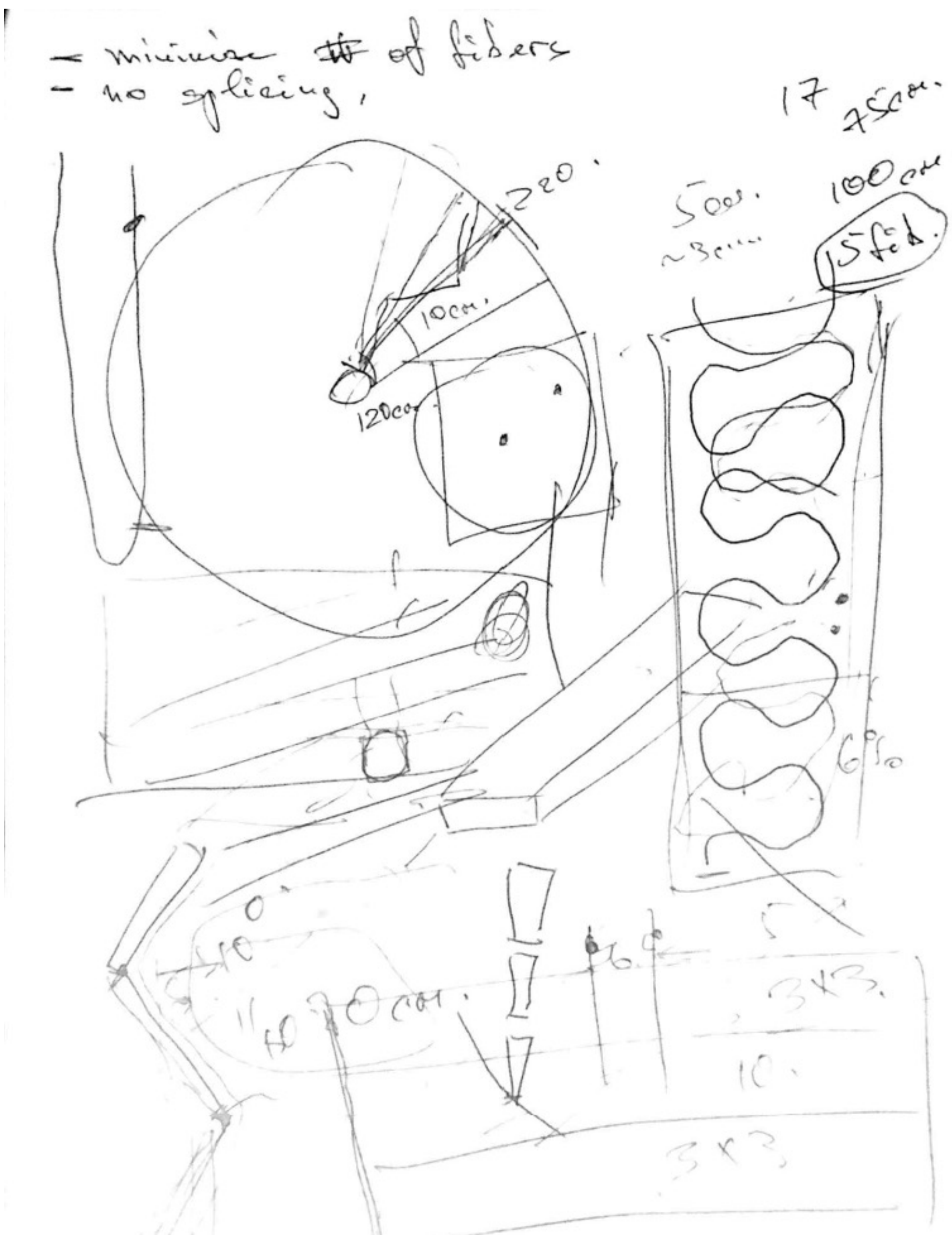
Electromagnetic
Calorimeter

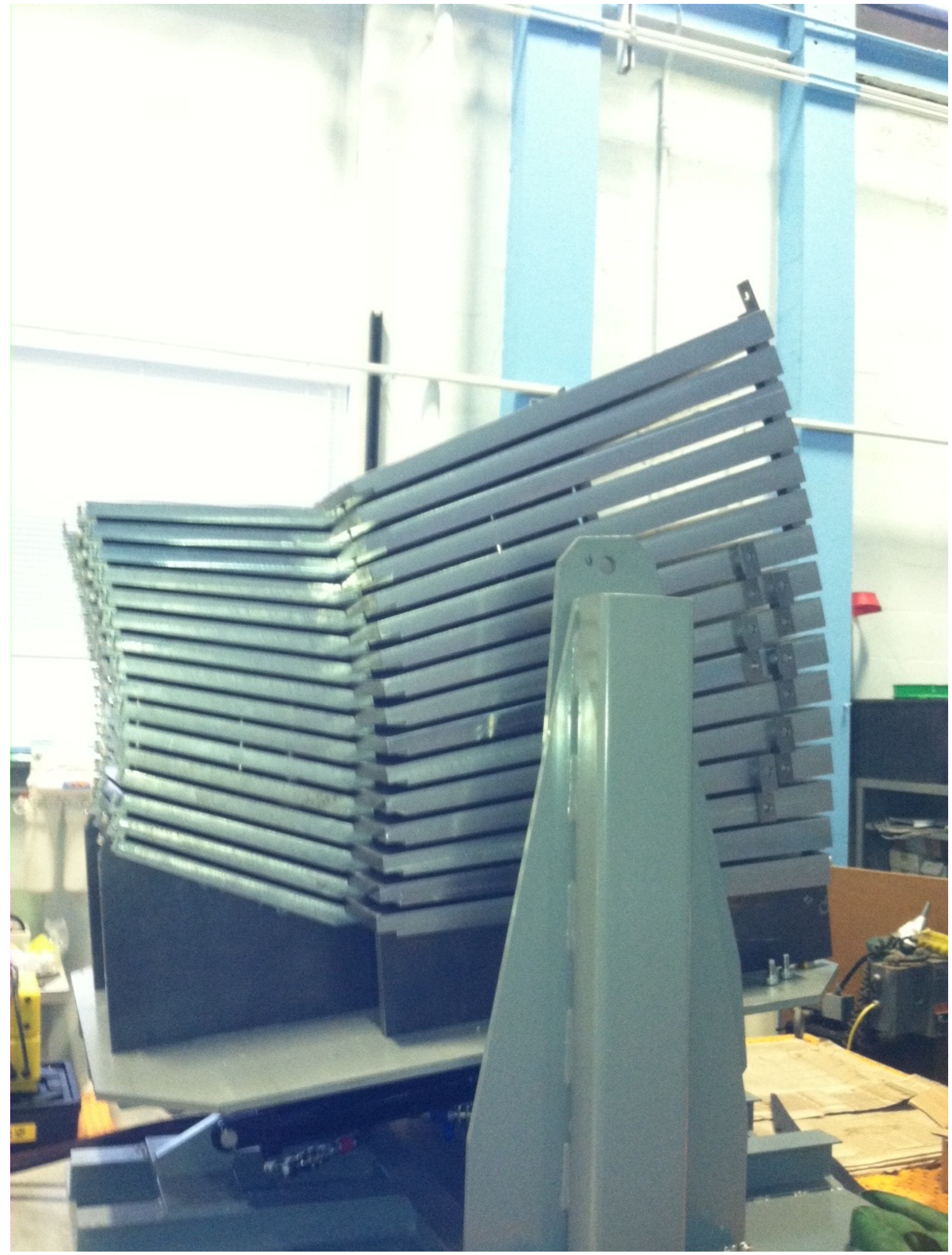
Hadronic
Calorimeter

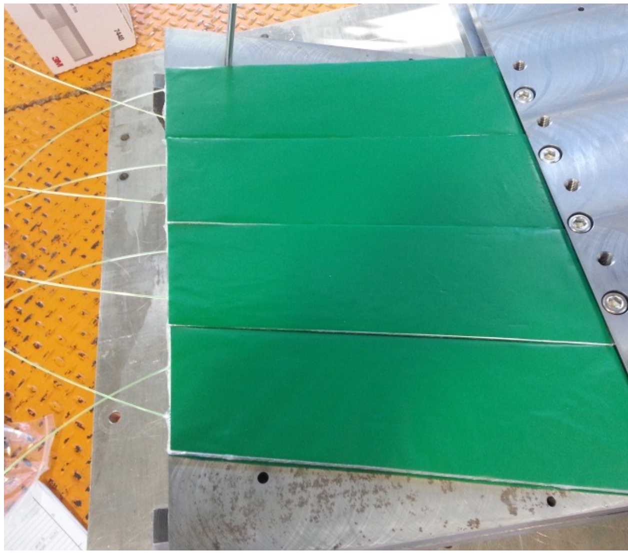
High data acquisition rate capability, 15 kHz

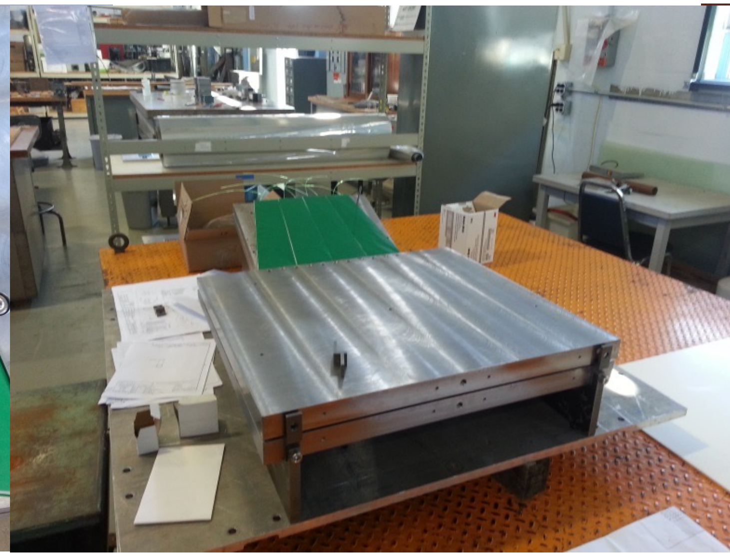
Sampling 0.6 trillion Au+Au interactions in one-year
Maximizing efficiency of RHIC running

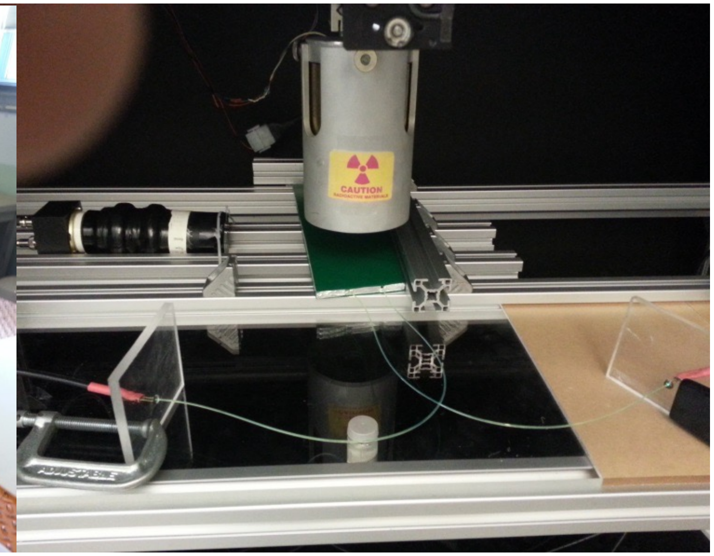
Napkin Drawing → Prototype → Detector → Physics

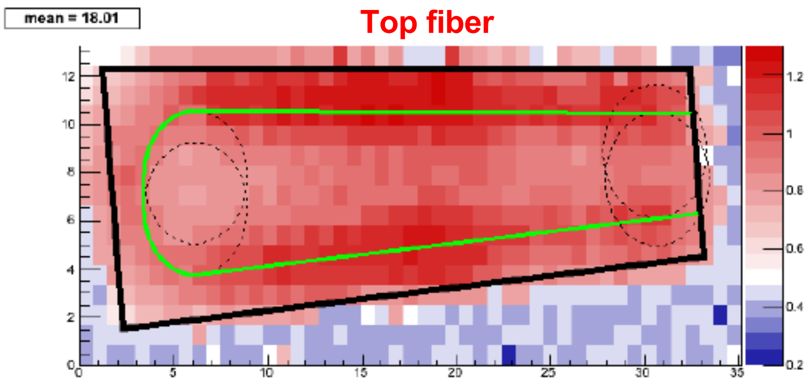


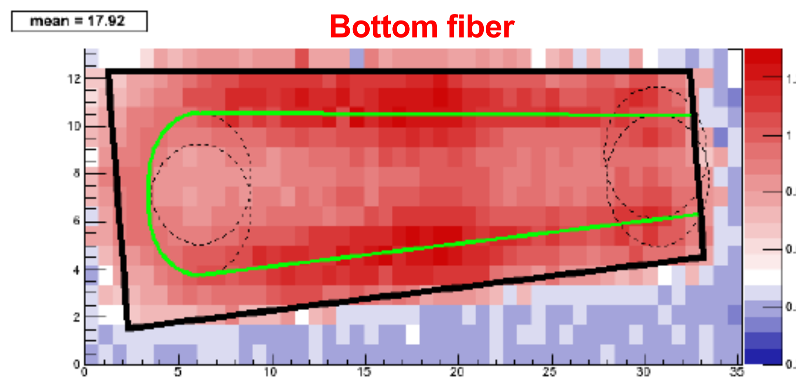


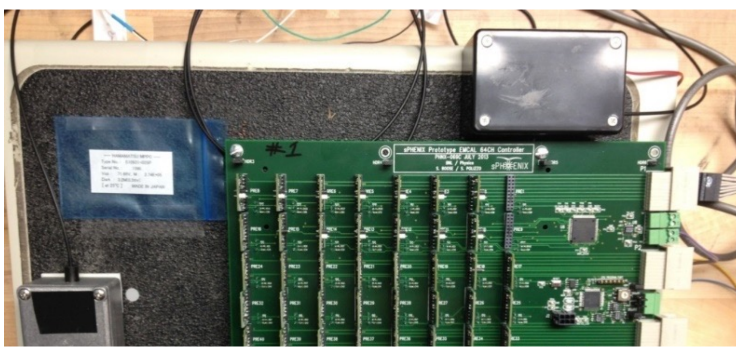


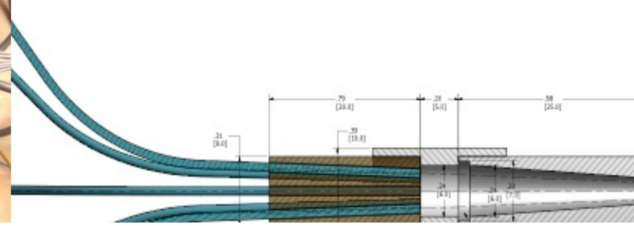




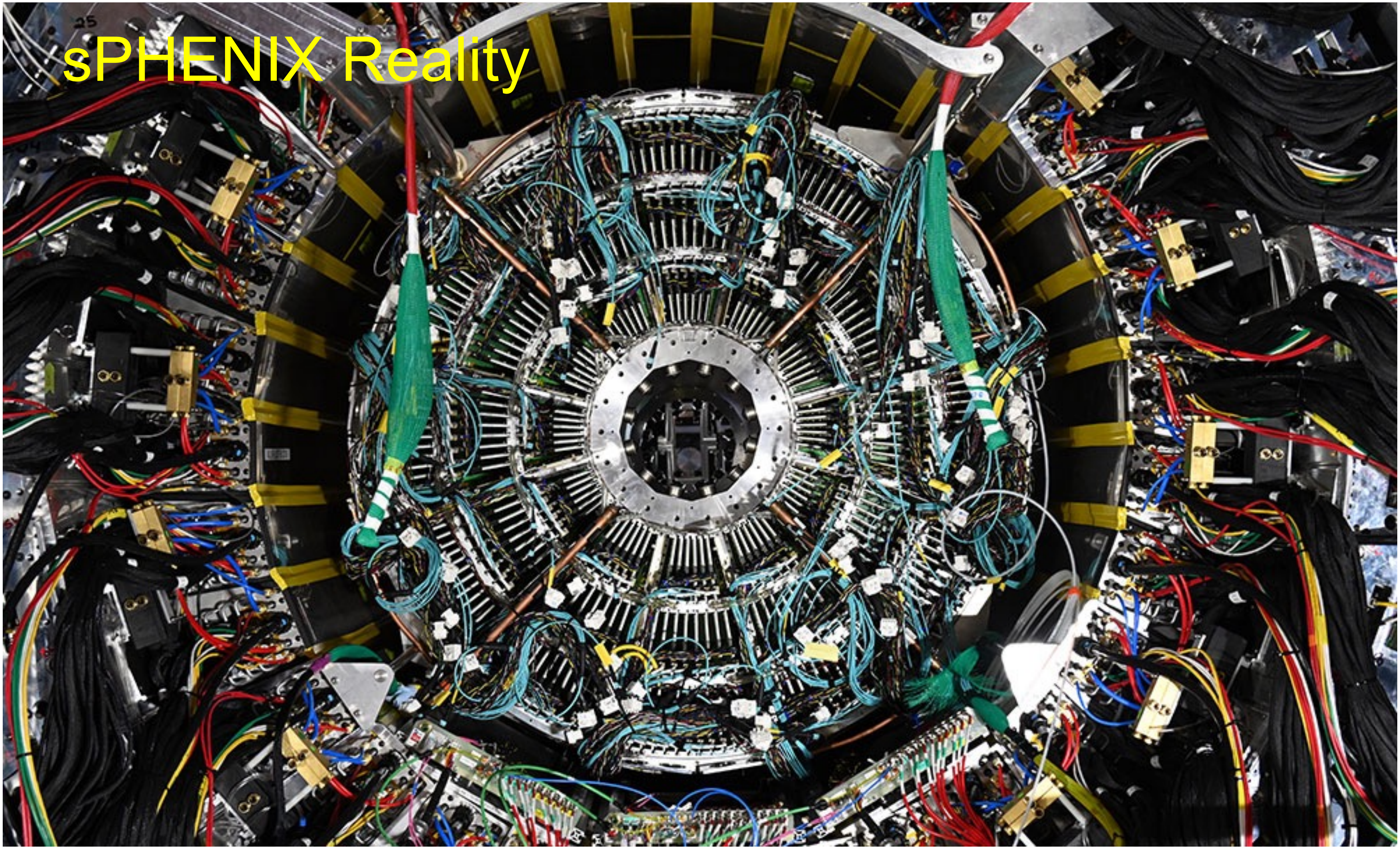






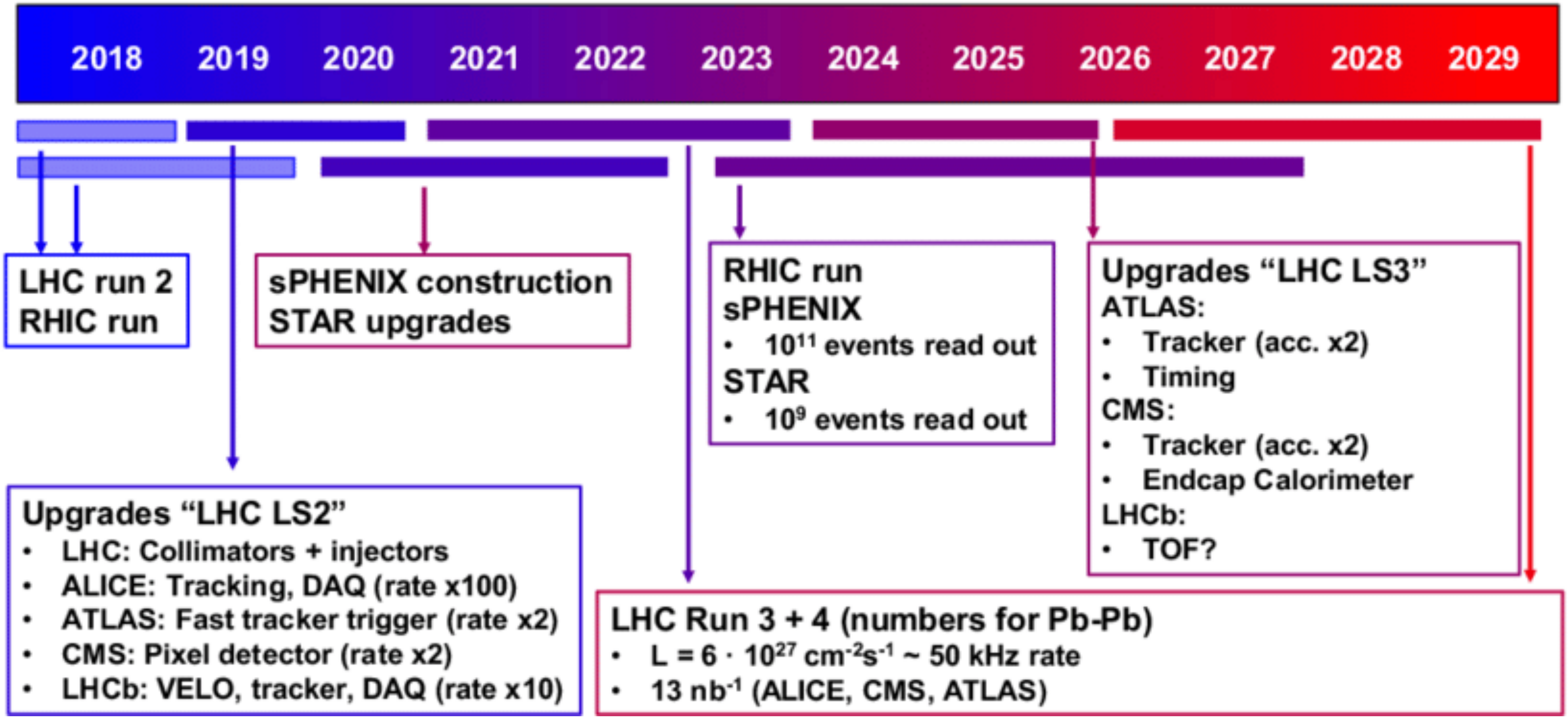


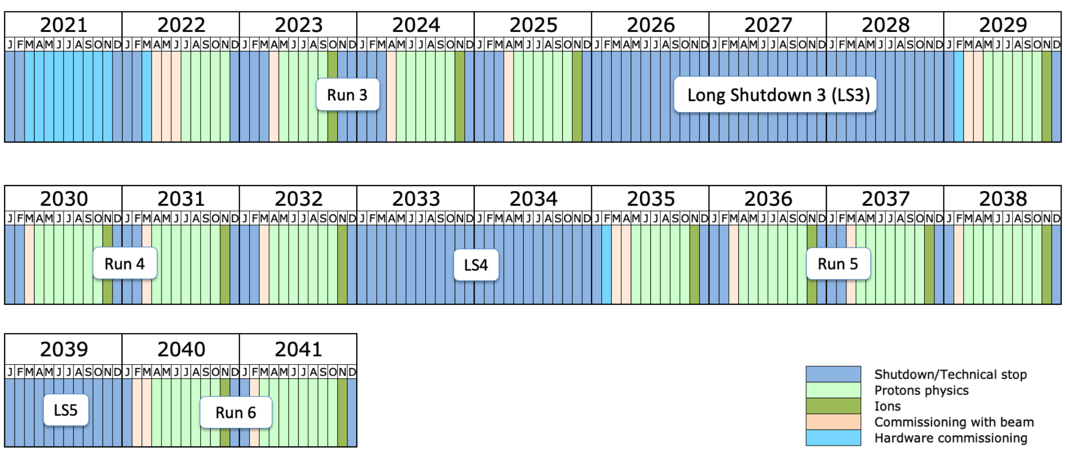
If you have the chance to get involved in hardware (even a little) it is well worth while.



Commissioning underway as I speak…


You must have
Scaffold User Safety
GL-SCAFFOLD
to use scaffold
on the box?



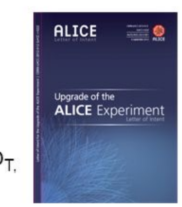


A Large Ion Collider Experiment

ALICE

ALICE Upgrade Overview

Planned for 2018 (LHC 2nd Long Shutdown)
("Upgrade of the ALICE Experiment", LoI, CERN-LHCC-2012-12)



Physics goals

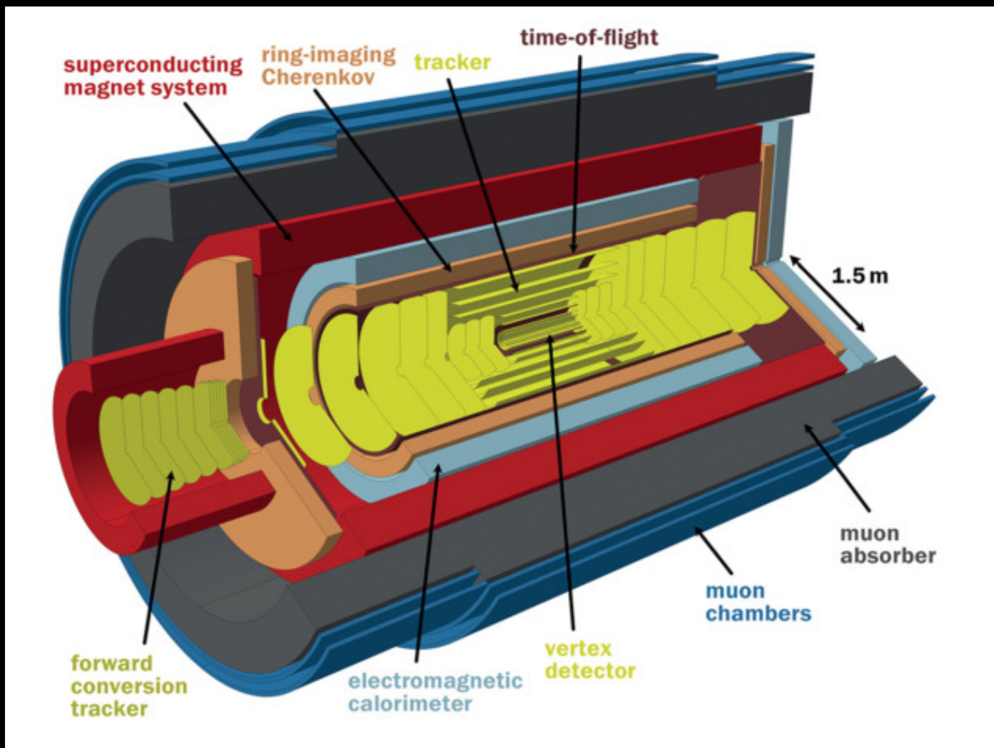
High precision measurements of rare probes at low p_T, which cannot be selected with a trigger, require a large sample of events recorded on tape

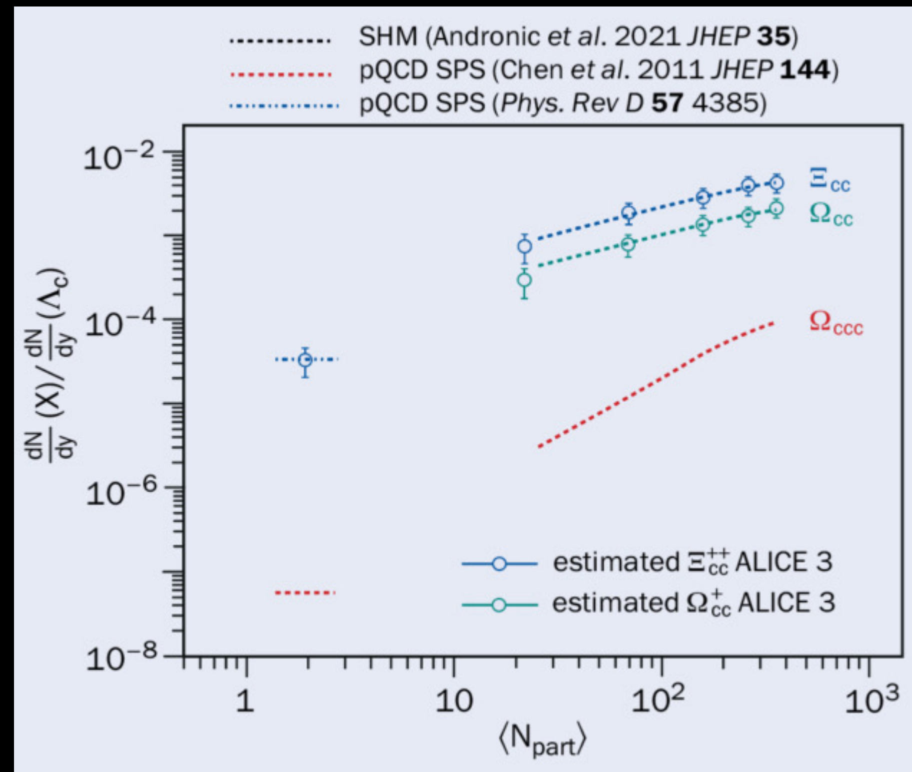
Target

- Pb-Pb recorded luminosity ≥ 10 nb^{-1} ➡ 8×10^{10} events
- pp (@5.5 Tev) recorded luminosity ≥ 6 pb^{-1} ➡ 1.4×10^{11} events

…and significant improvement of vertexing and tracking capabilities

Longer term… ALICE-3 Letter of Intent





https://cerncourier.com/a/alice-3-a-heavy-ion-detector-for-the-2030s/

Stay Curious