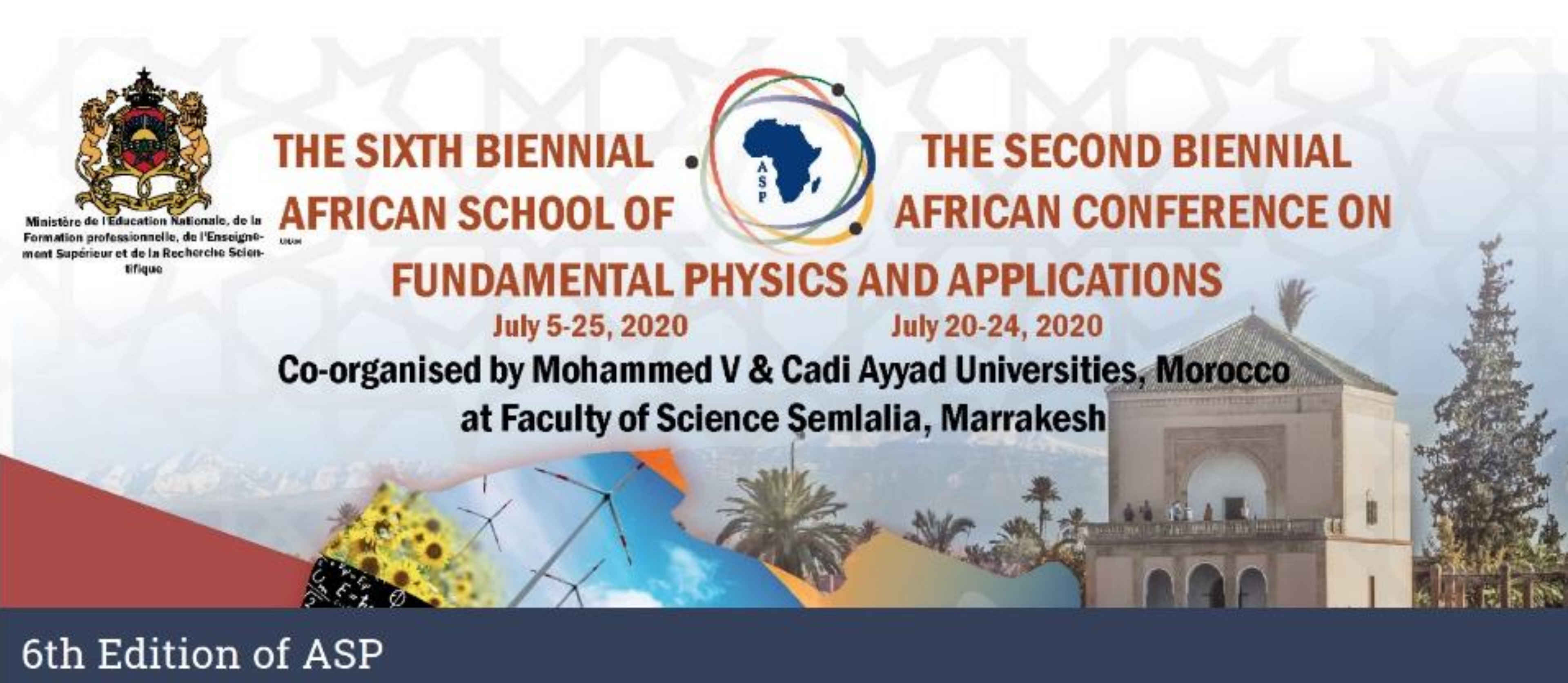


African School of

Fundamental Physics and Applications

Relativistic Heavy Ion Physics

Lecture 1:

Introduction to Relativistic Heavy Ion Physics

and Detectors Technology

Lecture 2:

QGP Discovery at RHIC (Signatures)

Future Projects and Opportunities

Lecture 1:

Introduction to Relativistic Heavy Ion Physics and Detectors Technology

Rachid Nouicer

Brookhaven National Laboratory, New York

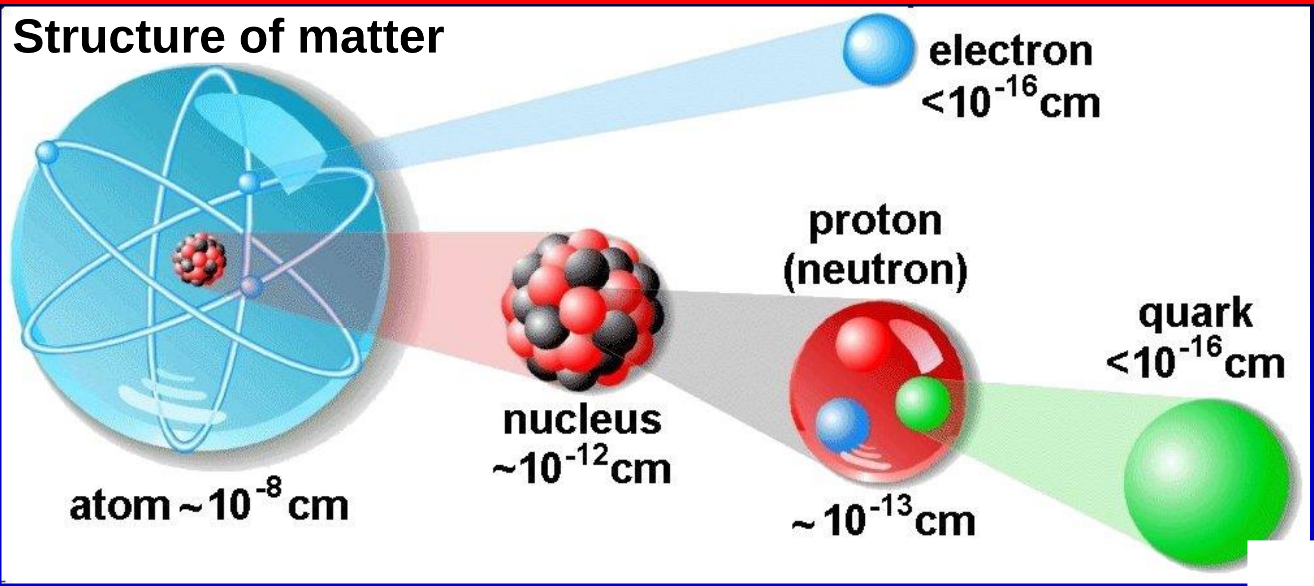
BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

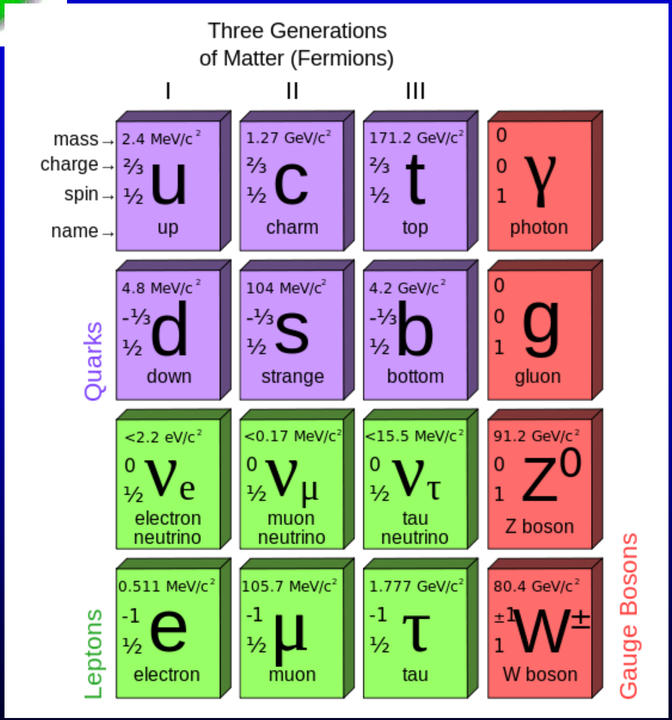
http://www.youtube.com/watch?v=xrL2ELkQOiE http://www.youtube.com/watch?v=xrL2ELkQOiE

Hadrons and Quarks



✓ The particles participating in the strong interaction, such as protons, neutrons (baryons) and pions (mesons), are called **hadrons.**

✓ We know (since at least 30 years) that protons, neutrons and the other hadrons are not elementary, but are made of **quarks:** elementary fermions with fractional charge subject to the strong interaction.



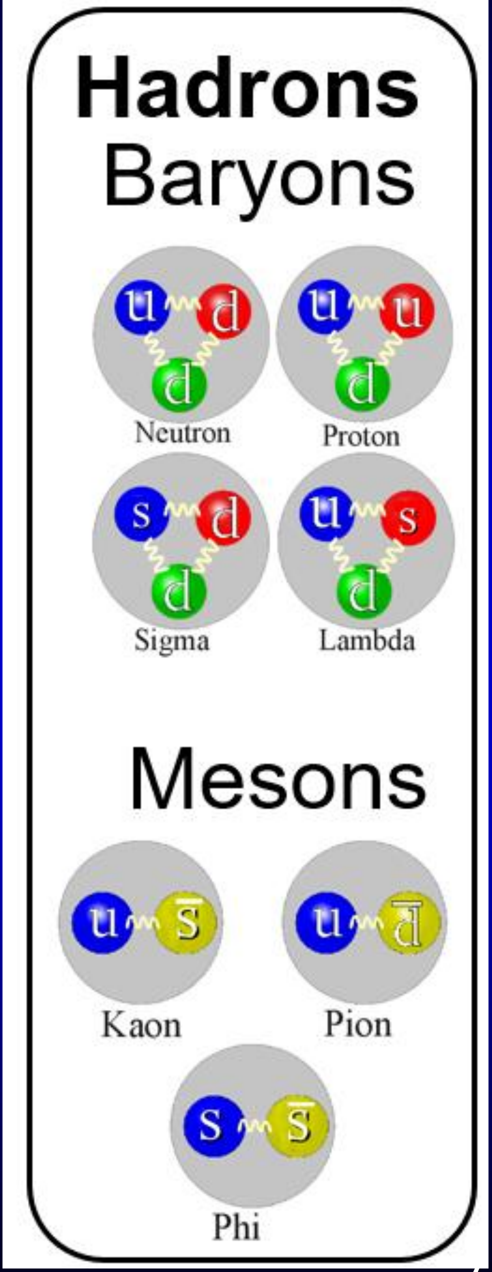
Quantum ChromoDynamics

✓ Quantum ChromoDynamics (QCD): theory of strong interactions:

– quarks carry a strong interaction charge (colour)
– color comes in three types, say **red**, **green** and **blue**
  ➢ antiquarks carry anticolor

– quarks interact among themselves via the exchange of the color field quanta (gluons)
  ➢ gluons themselves carry a color charge, unlike the photon in QED (Quantum Electro-Dynamics), which carries no electric charge

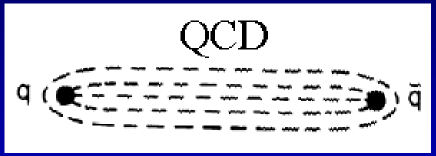
✓ All known hadron states are color singlets ("white")
– baryons: qqq states; mesons: $q\bar{q}$ states
– in particular, no free quark has ever been detected: quarks seem to be permanently confined within the hadrons

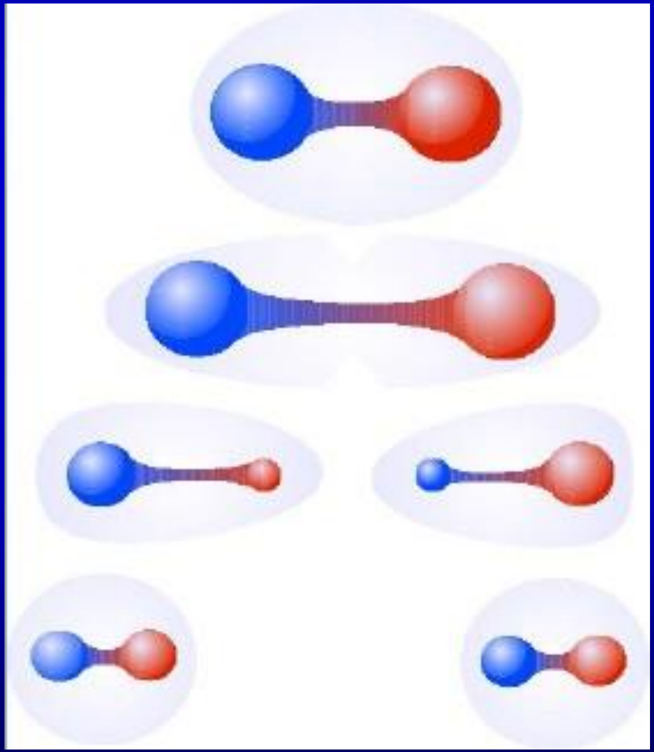


Strong Interaction: Confinement and String Breaking

✓ The interaction between color charges, and thus between quarks, is done through gluons. They have the particularity of carrying a color too and thus interacting with themselves! This is an important feature of the strong interaction that gives it its unique characteristics.

[voir D. Perkins, p.179]





✓ **In QCD, the field lines are compressed into a "flux tube" (or "string") of constant cross-section (~ fm²), leading to a long-distance potential which grows linearly with r:**

$$V_{long} = kr \quad \text{avec} \quad k \sim 1 GeV/fm$$

✓ If one tries to pull the string apart, when the energy stored in the string (kr) reaches the point where it is energetically favorable to create a $q\bar{q}$ pair, the string breaks. One ends up with two color-neutral strings (and eventually hadrons)

Essential Characteristic of QCD: Asymptotic Freedom

✓ QCD is "asymptotically free":

– the short distance potential is of the type:

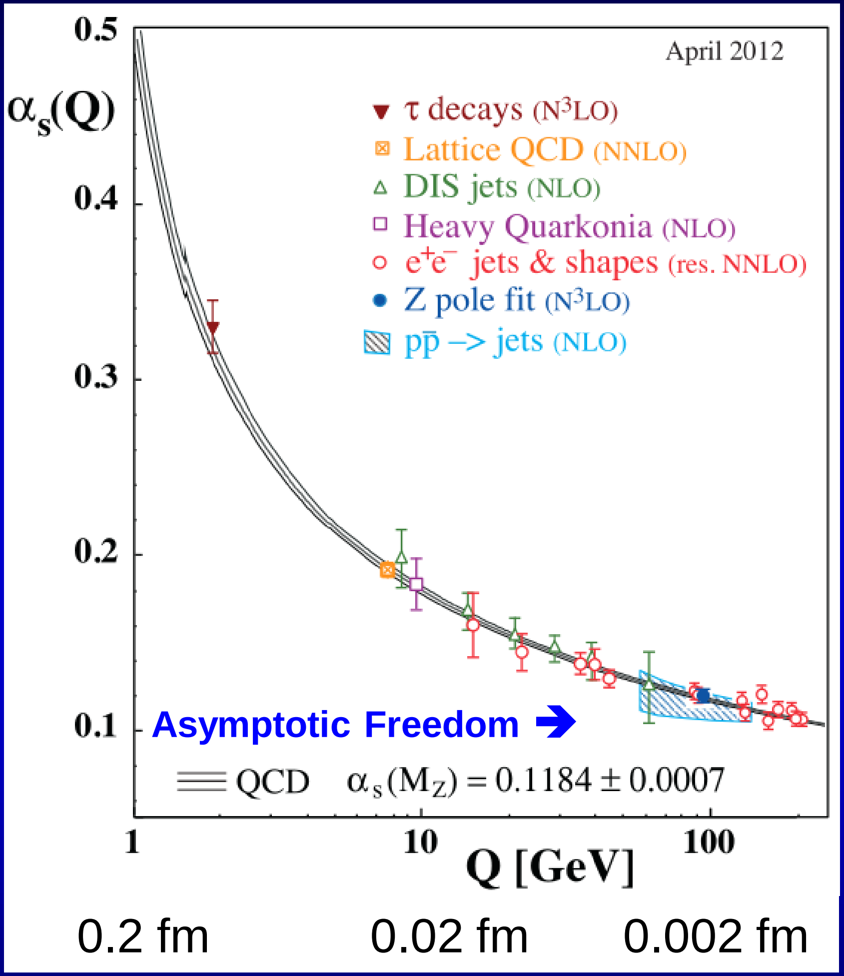
$$V_{short} = -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

[voir D. Perkins, p.172]

- the coupling constant is "running" with (depends on) r in such a way that

$$\lim_{r \to 0} \alpha_s(r) = 0$$

✓ Perturbation theory can be applied at short distance/high momentum transfer



$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2N_F)\log(\frac{Q^2}{\Lambda^2_{QCD}})} \sim \frac{1}{\log(\frac{Q^2}{\Lambda^2_{QCD}})} \quad \text{avec} \quad \Lambda_{QCD} = 0.2 \ \text{GeV}$$

Nobel Prize: 2004

The Nobel Prize in Physics 2004

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2004 "for the discovery of asymptotic freedom in the theory of the strong interaction" jointly to David J. Gross, H. David Politzer and Frank Wilczek

BACK

David J. Gross	H. David Politzer	Frank Wilczek
Kavli Institute for Theoretical Physics University of California, Santa Barbara, USA	California Institute of Technology (Caltech), Pasadena, USA	Massachusetts Institute of Technology (MIT), Cambridge, USA

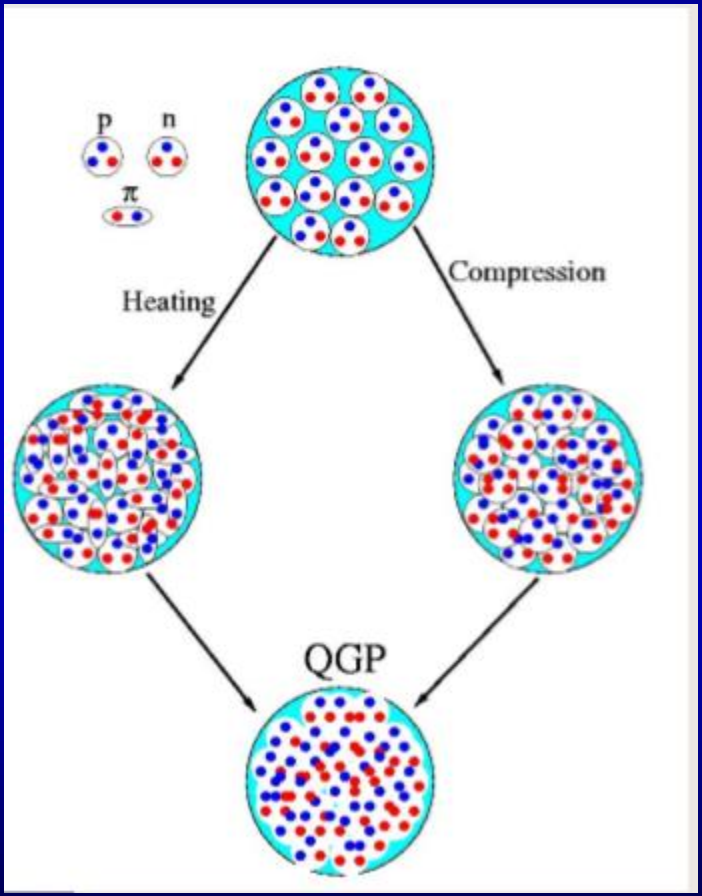
A good start ...
Frank Wilczek and David Politzer were barely 20 years old and still PhD students when their discovery of asymptotic freedom was published. These were their very first scientific publications!

A colourful connection

The scientists awarded this year's Nobel Prize in Physics have solved a mystery surrounding the strongest of nature's four fundamental forces. The three quarks within the proton can sometimes appear to be free, although no free quarks have ever been observed. The quarks have a quantum mechanical property called colour and interact with each other through the exchange of gluons - nature's glue.

Strong Interaction: Deconfinement …

✓ What if we compress/heat matter so much that the individual hadrons start to interpenetrate?

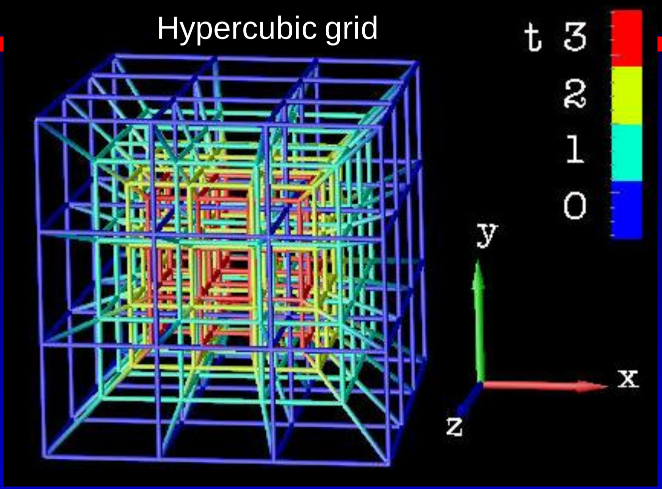


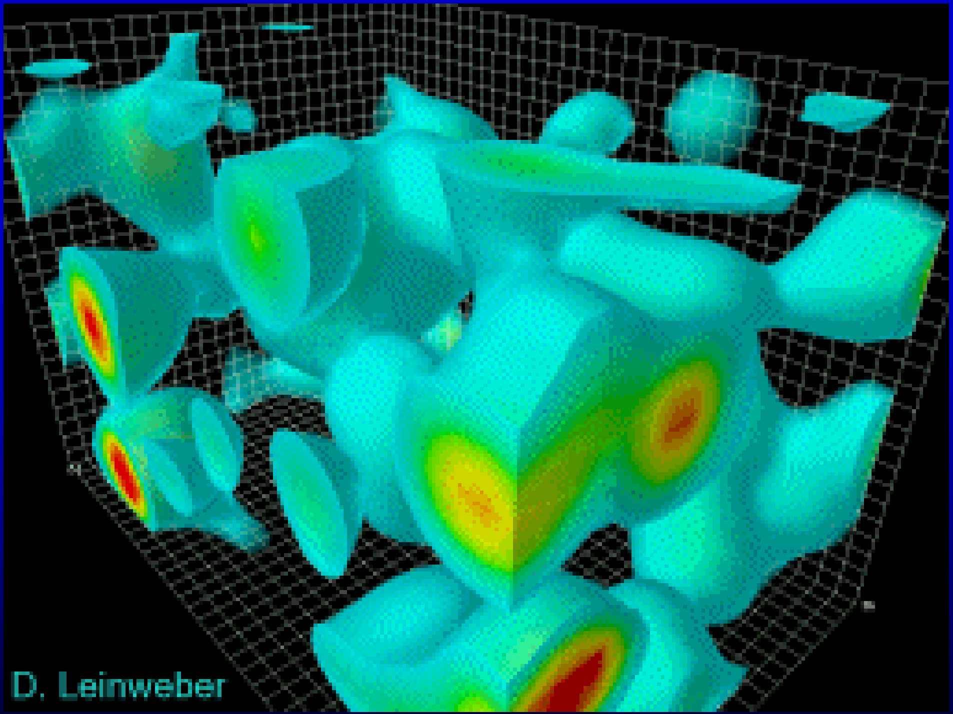
✓ Lattice QCD predicts that if a system of hadrons is brought to sufficiently large density and/or temperature a deconfinement phase transition should occur

✓ In the new phase, called Quark Gluon Plasma(QGP), quarks and gluons are no longer confined within individual hadrons, but are free to move around over a larger volume

Lattice QCD

In lattice QCD, non-perturbative problems are treated by discretization on a space-time lattice. As a result, ultraviolet (large momentum scale) divergencies can be avoided.



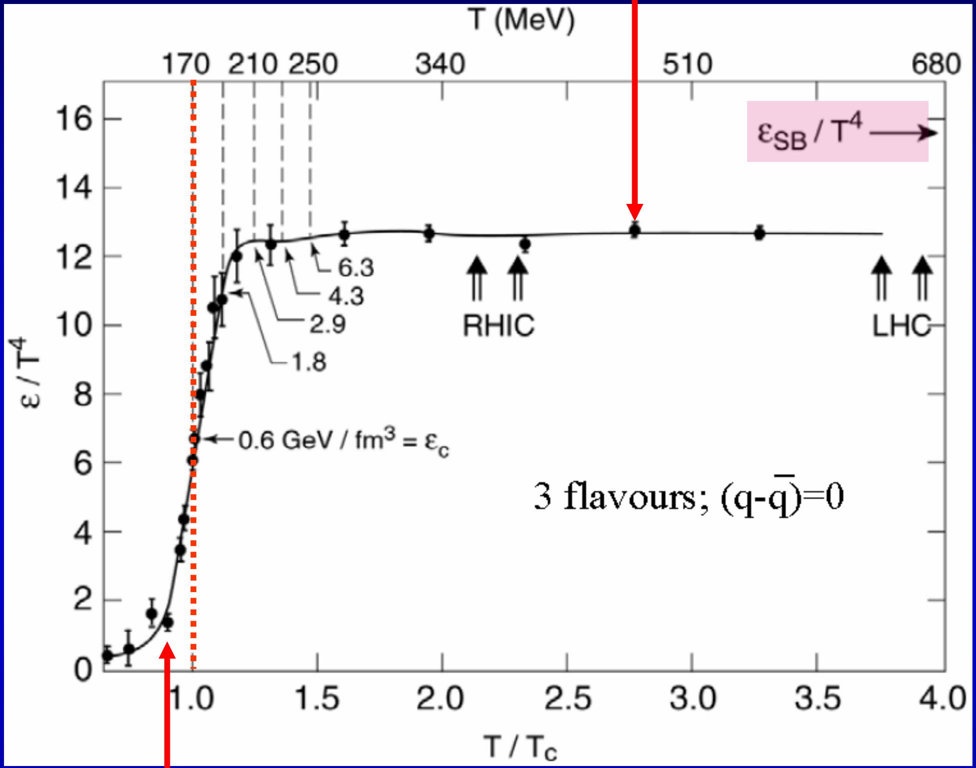


Lattice QCD Results

Stefan-Boltzmann for a gas of free particles

$$\frac{\epsilon}{T^4} = \nu \frac{\pi^2}{30} a$$

QGP = Quark-Gluon Plasma



Hadron gas

- ✓ zero baryon density, 3 flavours
- ✓ ε/T^4 changes rapidly around T_c
- ✓ T_c = 170 MeV

→ ε_c = 0.6 GeV/fm^3

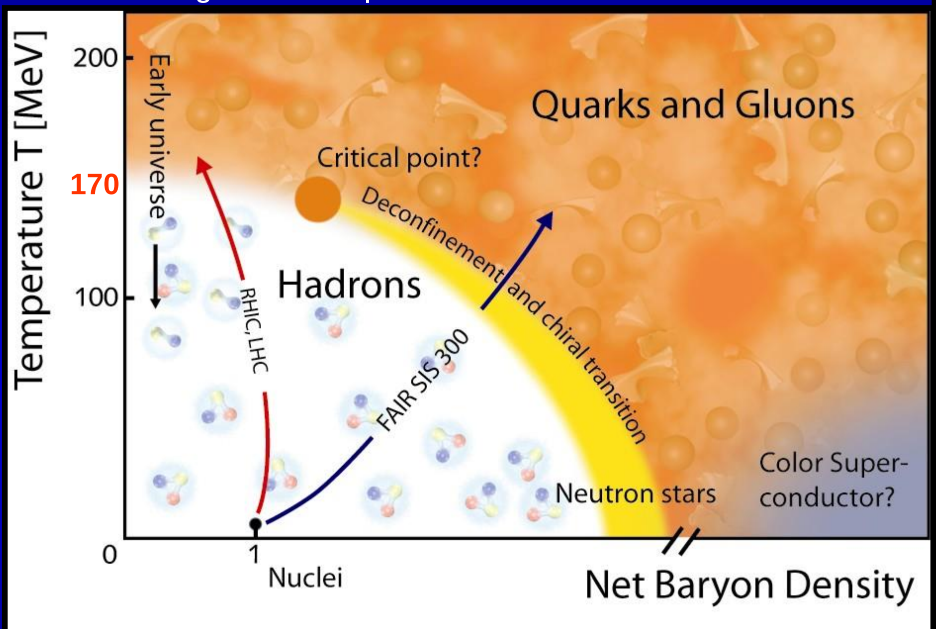
at T ~ 1.2 T_c the ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q, $\bar{q}$, g (ε_{SB})

But Scientific Goal : QCD Matter in Heavy Ion Collisions

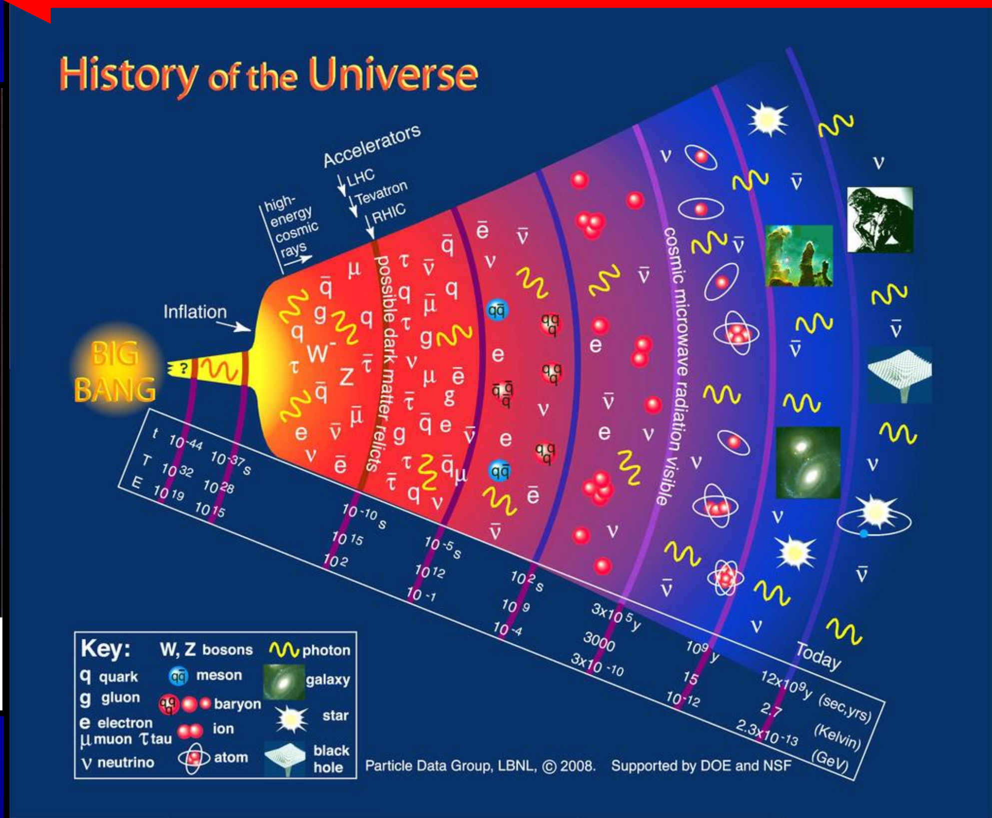
Heavy Ion Collisions (HIC) produce systems with high temperature/density

This allowed us to understand the first moments of the evolution of our universe and certain astrophysical phenomena

Diagramme de phase de la matière en interaction forte



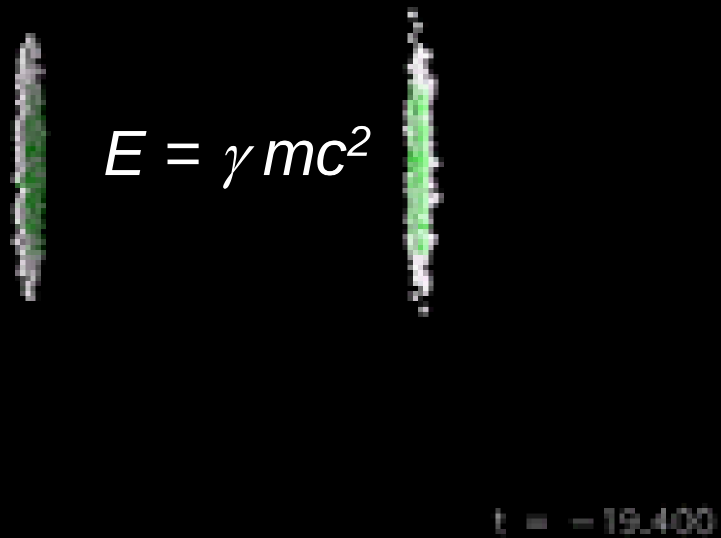
GSI : www.gsi.de



HICs allows us to study complex systems governed by QCD and understand the fundamental properties of matter.

Nucleus-Nucleus collisions

- ✓ How do we test this theory in the lab?
- ✓ How can we compress/heat matter to such cosmic energy densities?
- ✓ By colliding two heavy nuclei at ultrarelativistic energies we hope to be able to recreate, for a short time span (about 10^{-23}s, or a few fm/c) the appropriate conditions for deconfinement



$$E = \gamma mc^2$$

Lorentz Factor

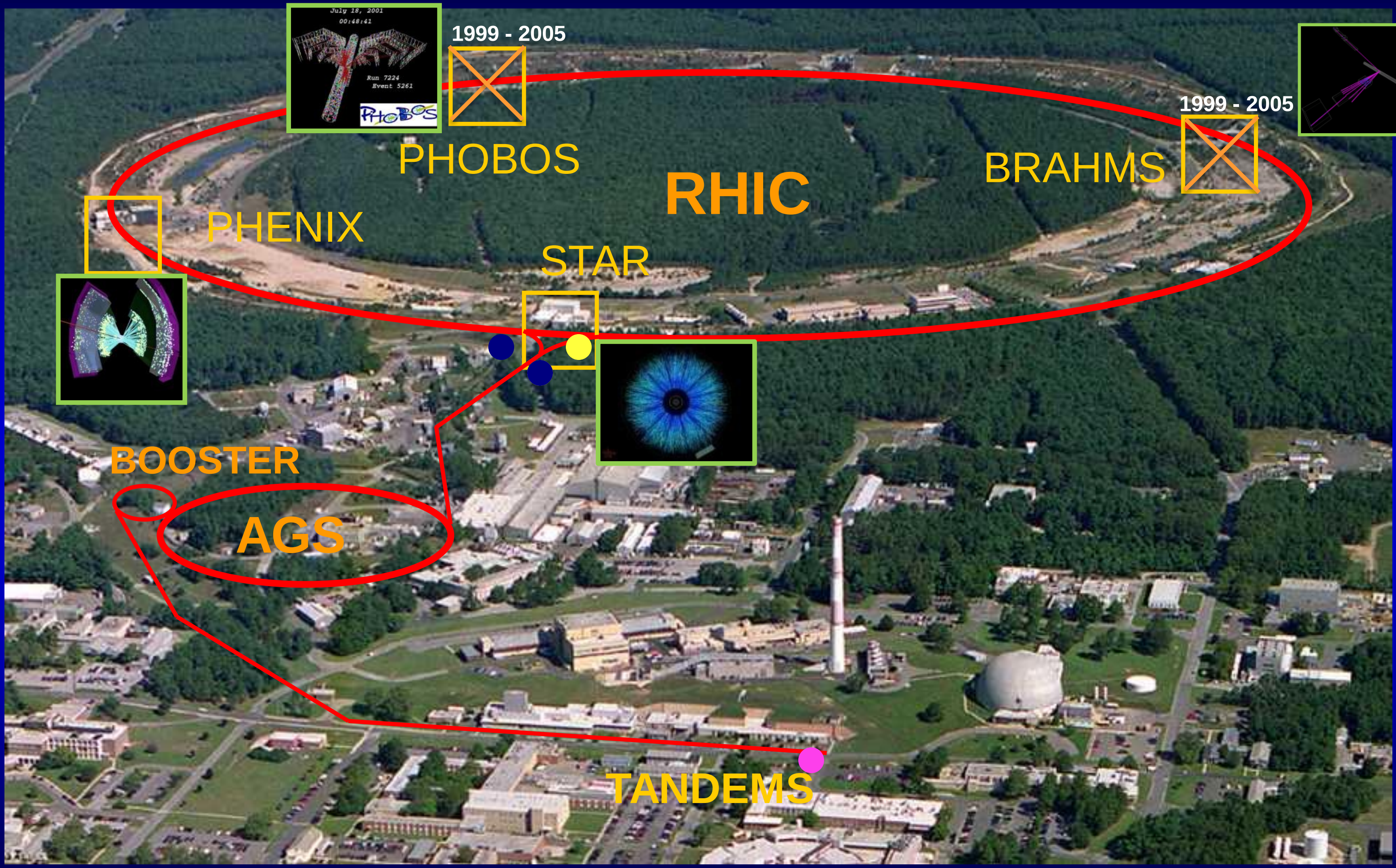
$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

γ = Lorentz factor

v = speed of moving observer

c = speed of light

First Collider in the world 2000: Relativistic Heavy Ion Collider (RHIC)



RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - 120 bunches/ring
  - 106 ns crossing time
- Capable of colliding ~any nuclear species on ~any other species
- Energy:
  - ➔ 500 GeV for p-p
  - ➔ 200 GeV for Au-Au (per N-N collision)
- Luminosity
  - Au-Au: 2×10^{26} cm^{-2} s^{-1}
  - p-p : 2×10^{32} cm^{-2} s^{-1} (***polarized***)

RHIC Amazing QCD Machine: Many Species and Many Energies!

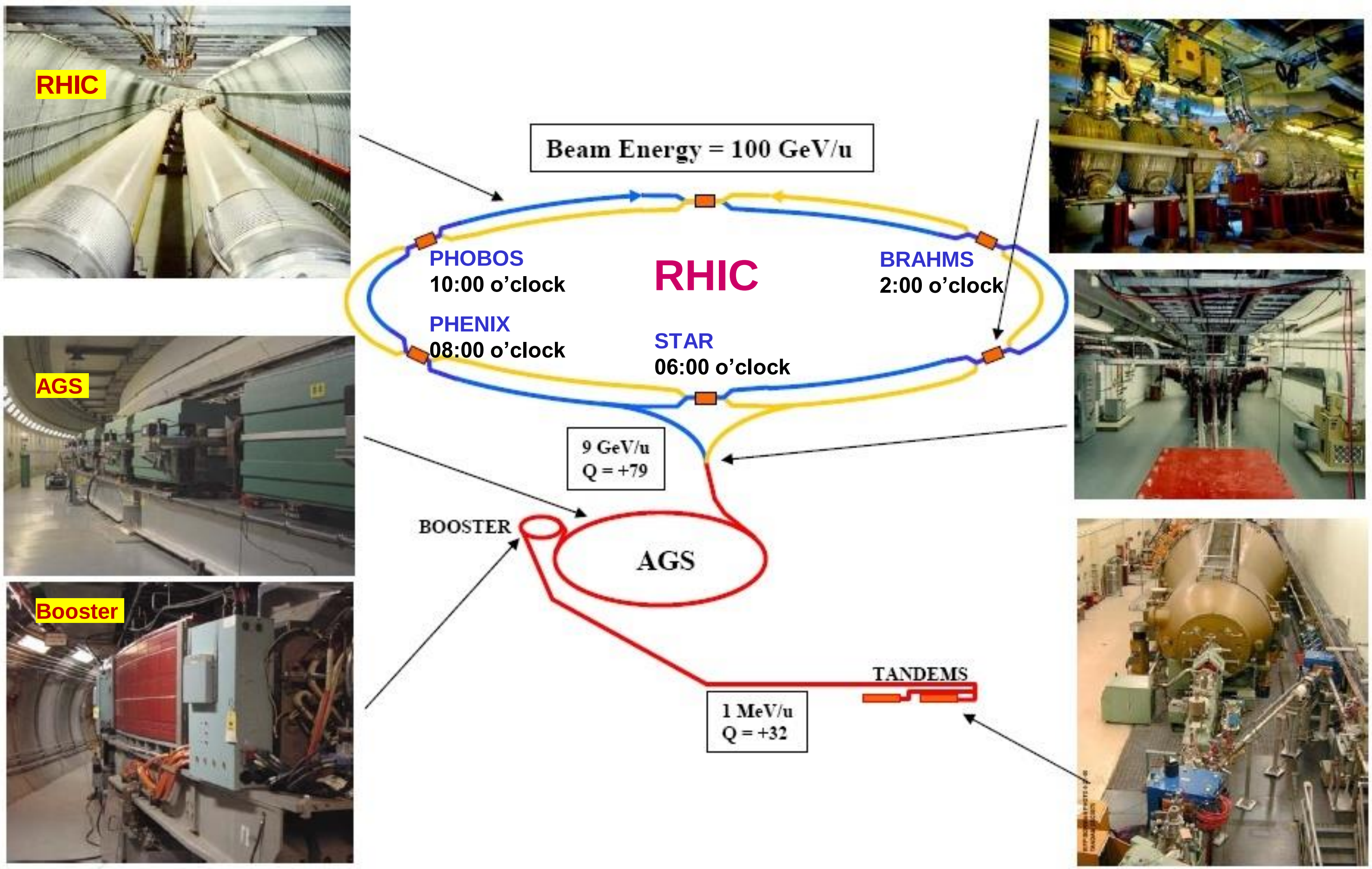
Run	Species	Total particle energy [GeV/nucleon]	total delivered Luminosity $[\mu b^{-1}]$
I (2000)	Au+Au Au+Au	56 130	< 0.001 20
II (2001/2002)	Au+Au Au+Au p+p	200 19.6 200	25.8 0.4 1.4×10^{-6}
III (2003)	d+Au p+p	200 200	73×10^{-3} 5.5×10^{-6}
IV(2004)	Au+Au Au+Au p+p	200 62.4 200	3.53×10^{-3} 67 7.1×10^{-6}
V (2005)	Cu+Cu Cu+Cu Cu+Cu p+p p+p	200 62.4 22.4 200 410	42.1×10^{-3} 1.5×10^{-3} 0.02×10^{-3} 29.5×10^{-6} 0.1×10^{-6}
VI (2006)	p+p p+p	200 62.4	88.6×10^{-6} 1.05×10^{-6}
VII (2007)	Au+Au Au+Au	200 9.2	7.25×10^{-3} Small
VIII (2008)	d+Au p+p Au+Au	200 200 9.6	437×10^{-3} 38.4×10^{-6} Small

Run	Species	Total particle energy [GeV/nucleon]	Total delivered luminosity $[\mu b^{-1}]$
IX (2009)	p+p +p	500 200	110×10^{-6} 114×10^{-6}
X (2010)	Au+Au Au+Au Au+Au Au+Au Au+Au	200 62.4 39 7.7 11.5	10.3×10^{-3} 544 206 4.23 7.8
XI (2011)	p+p Au+Au Au+Au Au+Au	500 19.6 200 27	166×10^{-6} 33.2 9.79×10^{-3} 63.1
XII (2012)	p+p p+p U+U Cu+Au	200 510 193 200	74×10^{-6} 283×10^{-6} 736 27×10^{-3}
XIII (2013)	p+p	510	1.04×10^{-9}
XIV (2014)	Au+Au Au+Au ^{3}He+Au	14.6 200 200	44.2 43.9×10^{-3} 134×10^{-3}
XV (2015)	p+p p+Au p+Al	200 200 200	282×10^{-6} 1.27×10^{-6} 3.97×10^{-6}
XVI (2016)	Au+Au d+Au d+Au d+Au d+Au	200 200 62.4 19.6 39	52.2×10^{-3} 46.1×10^{-3} 44.0×10^{-3} 7.2×10^{-3} 19.5×10^{-3}

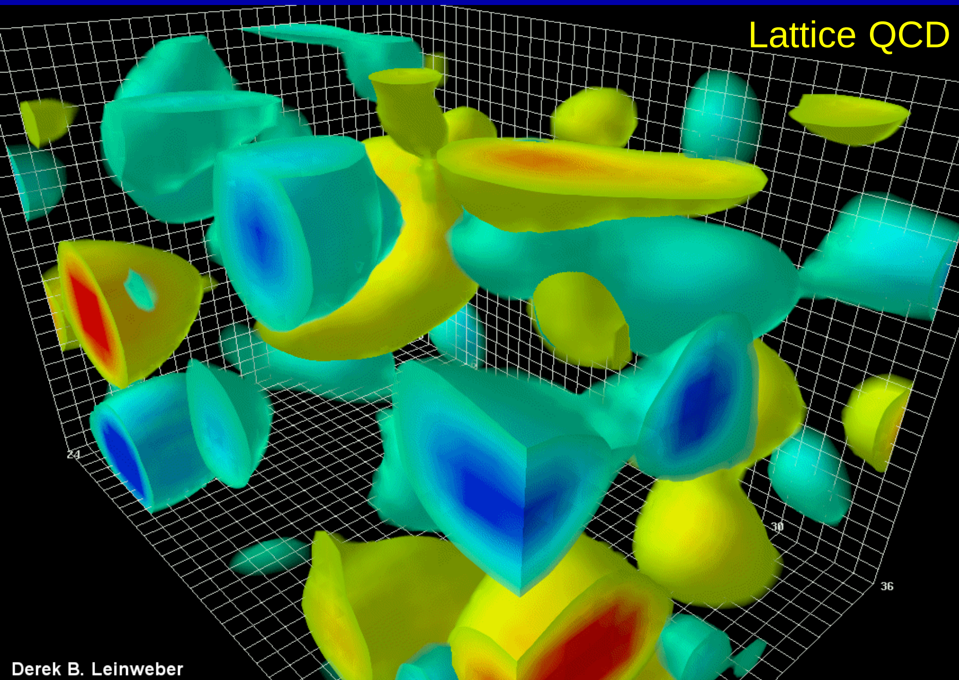
Relativistic Heavy Ion Collider (RHIC)

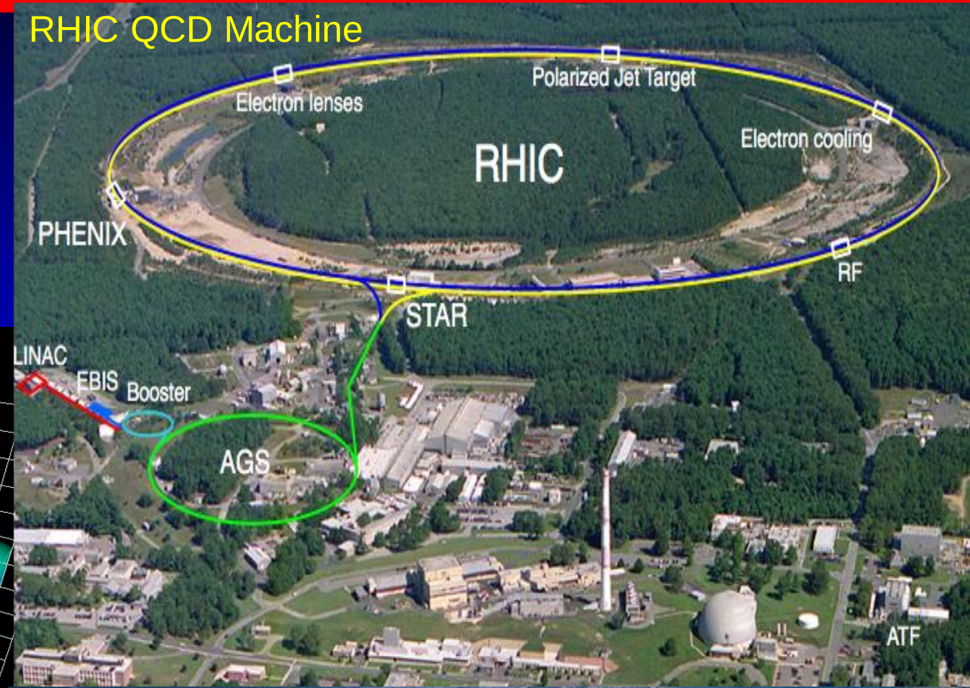
From Wikipedia, the free encyclopedia

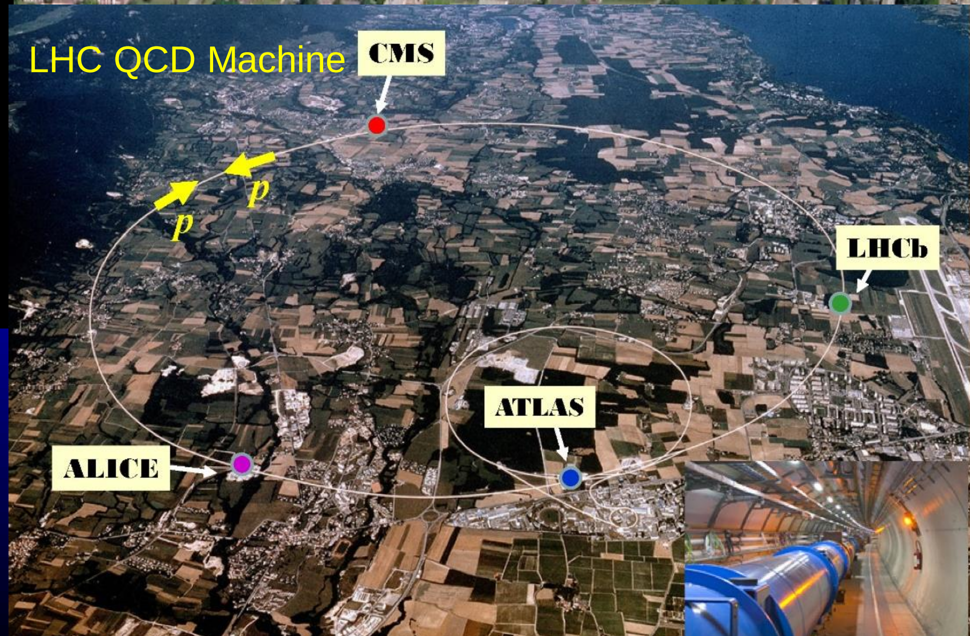
The **Relativistic Heavy Ion Collider** (**RHIC** /ˈrɪk/) is the first and one of only two operating heavy-ion colliders, and the only spin-polarized proton collider ever built. Located at Brookhaven National Laboratory (BNL) in Upton, New York, and used by an international team of researchers, it is the only operating particle collider in the US.[1][2][3] By using RHIC to collide ions traveling at relativistic speeds, physicists study the primordial form of matter that existed in the universe shortly after the Big Bang.[4][5] By colliding spin-polarized protons, the spin structure of the proton is explored.



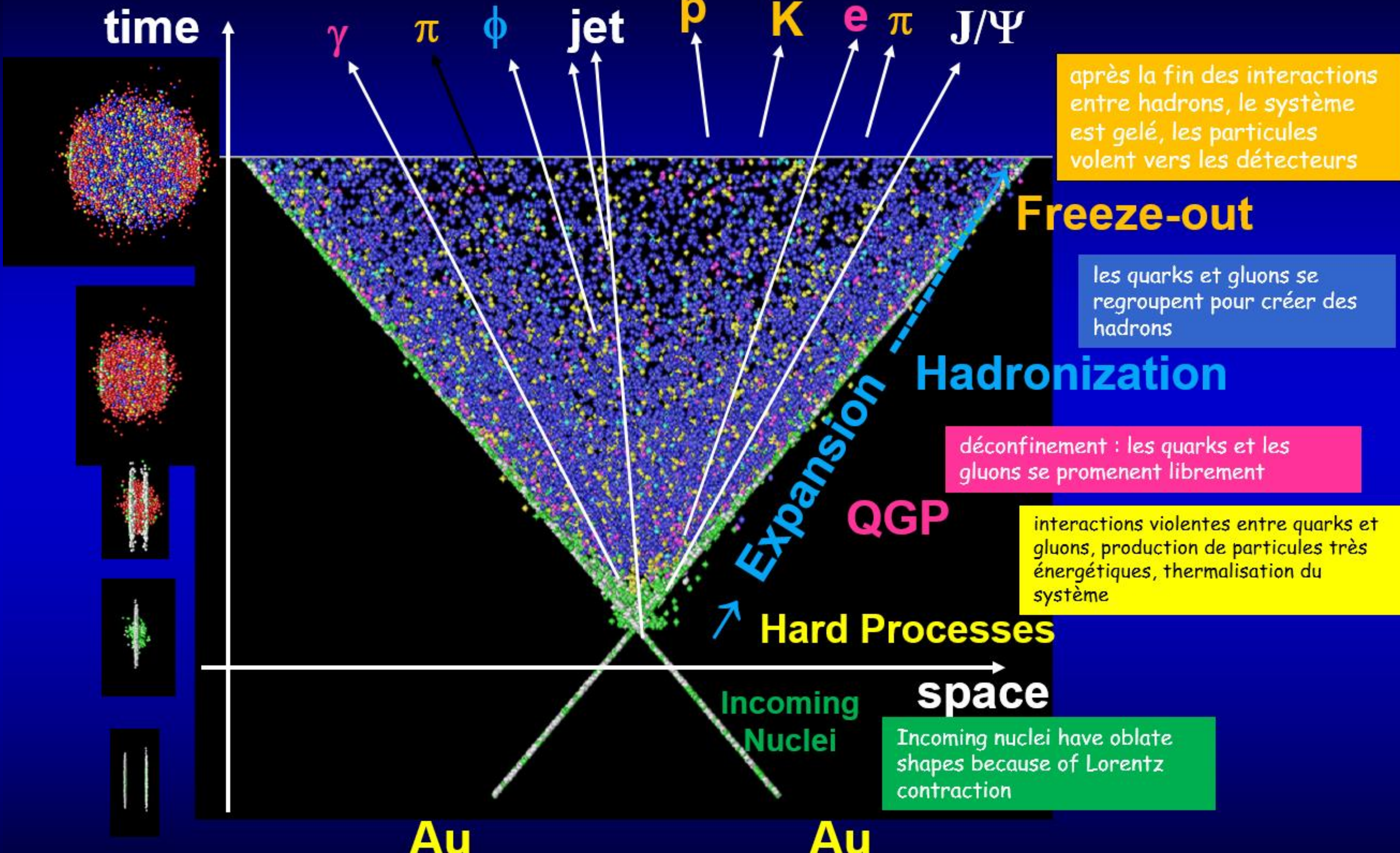
Heavy Ion Colliders: RHIC (2000…) and LHC (2010…)







Time Evolution of Heavy Ion Collisions (VNI)



- QGP Study Principle: the particles produced are used to probe the properties of the system formed during the collision

Charged Particle Multiplicity 4π Unique Measurements of PHOBOS Exp.

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November 20, 2007 Edition

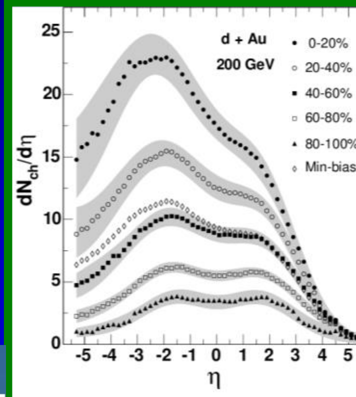
- Issue Summary / Events List
- Notes From the Associate Director
- System Size, Energy, Centrality and Pseudorapidity Dependence of Charged Particle Density in Nucleus-Nucleus Collisions at RHIC
- PHENIX Preparing for Run 8
- First Beam in Run 8

System Size, Energy, Centrality and Pseudorapidity Dependence of Charged Particle Density in Nucleus-Nucleus Collisions at RHIC

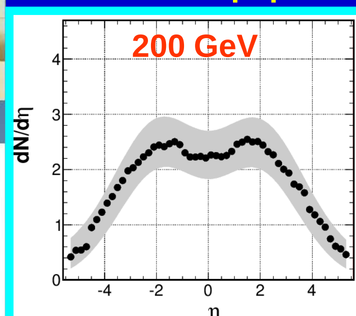
By Rachid Nouicer

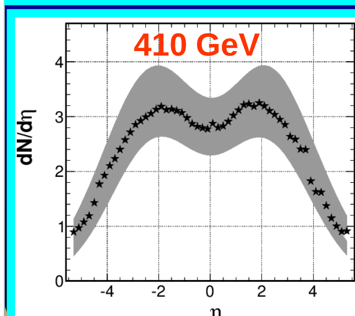
In ultrarelativistic heavy ion collisions, the charged particle multiplicities have been studied extensively because of the intrinsic interest in understanding the production mechanism. More recent interest comes in the context of searching for and studying new forms of matter that are

Collisions d+Au

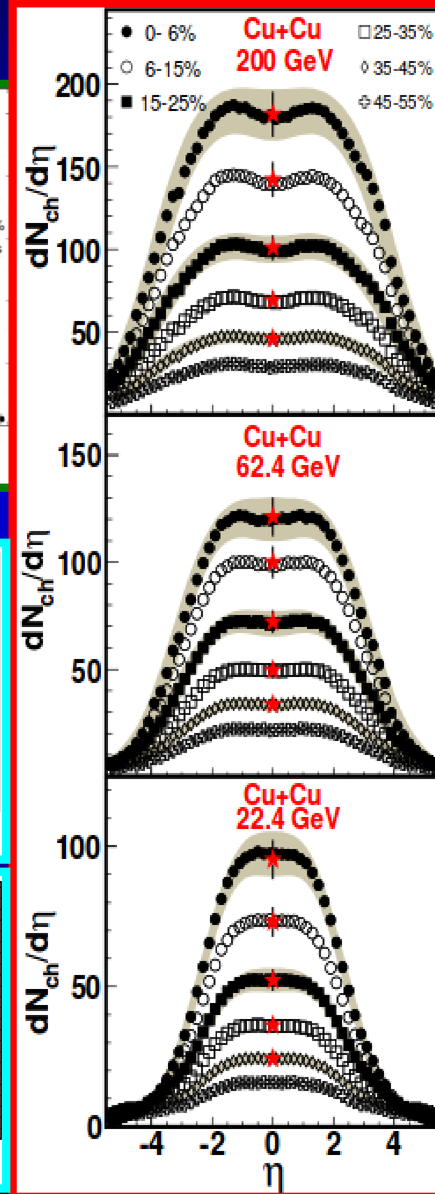


Collisions p+p

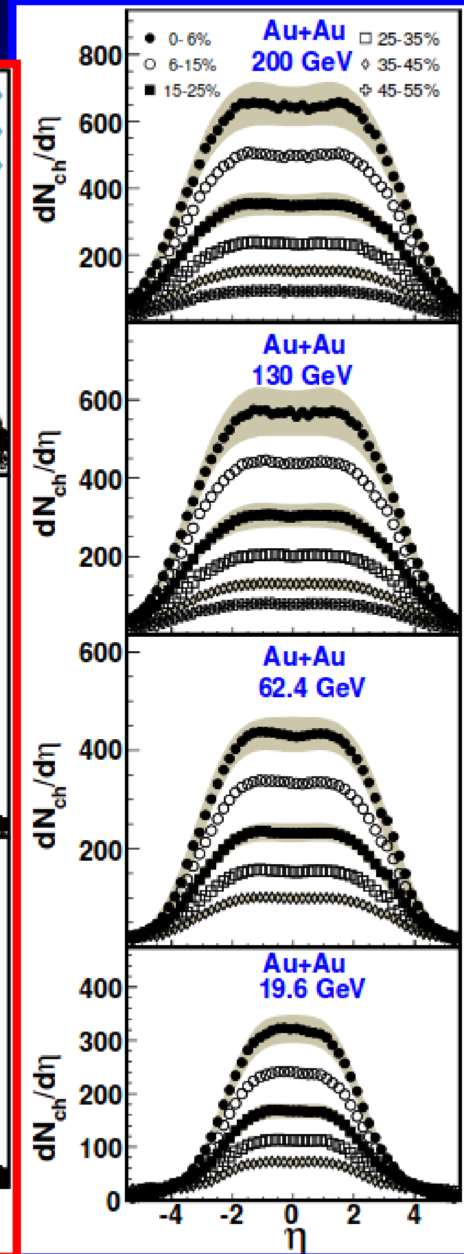




Collisions Cu+Cu



Collisions Au+Au



Globales Properties: What can we learn from Multiplicity of $h^{\pm}$?

Energy Density of Created Medium:

- Total N_{ch} ~ 5000 (Au+Au $\sqrt{s}$ = 200 GeV) ⇔ ~ 20 in p+p
- Relativistic Hydrodynamics and Bjorken Model (invariance ⇒ $\eta \sim 0$) :

$$\varepsilon = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau}\langle p_T \rangle \frac{3}{2}\frac{dN_{ch}}{d\eta}$$

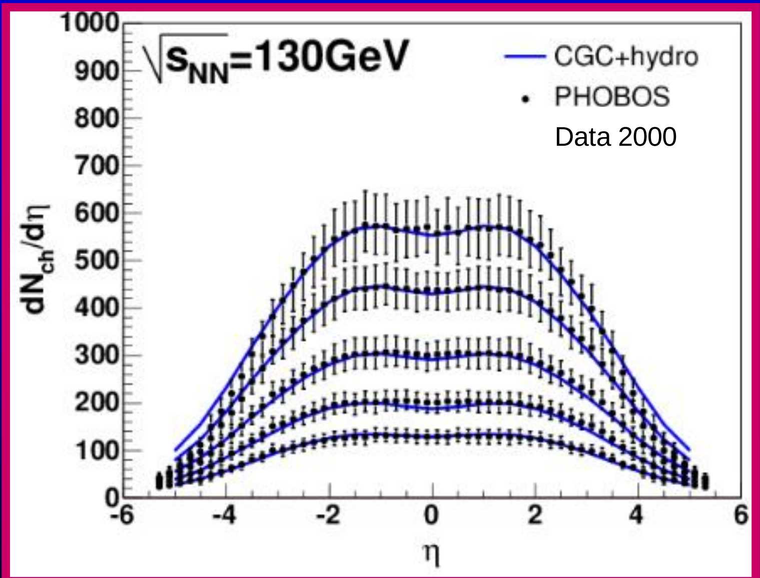
$(R \sim A^{1/3}, \tau = 1 \text{ fm/c})$

within these simplified hypotheses , energy density $\varepsilon \sim 5$ GeV/fm^3
⇒ Well above **critical energy density** ~1 GeV/fm^3 from LQCD

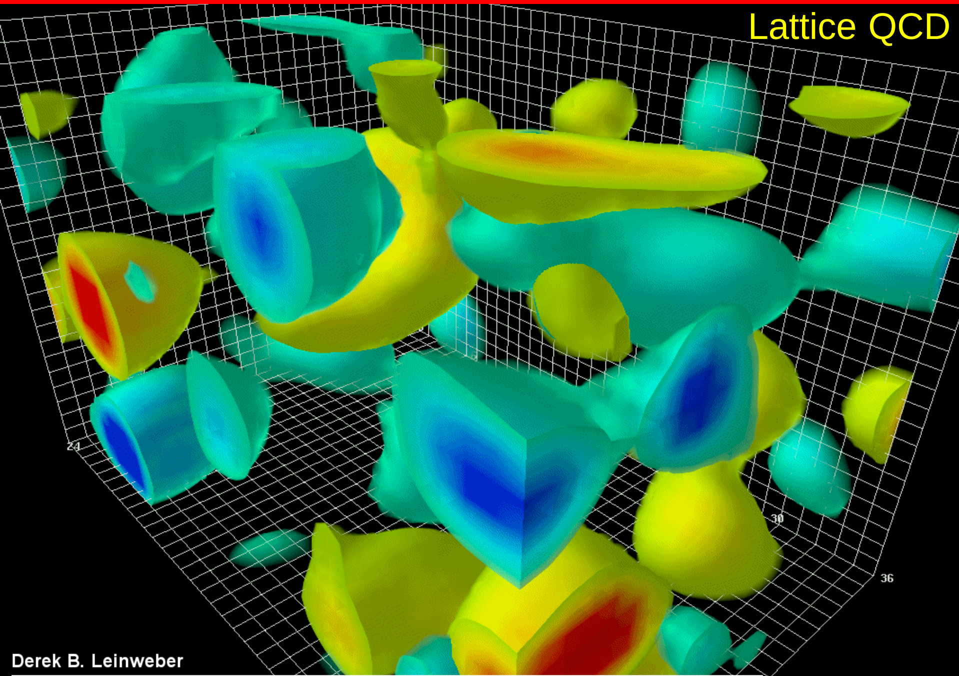
"New Forms of QCD Matter Discovered at RHIC"
Miklos Gyulassy and Larry Mclerran
Nucl.Phys.A750:30-63,2005

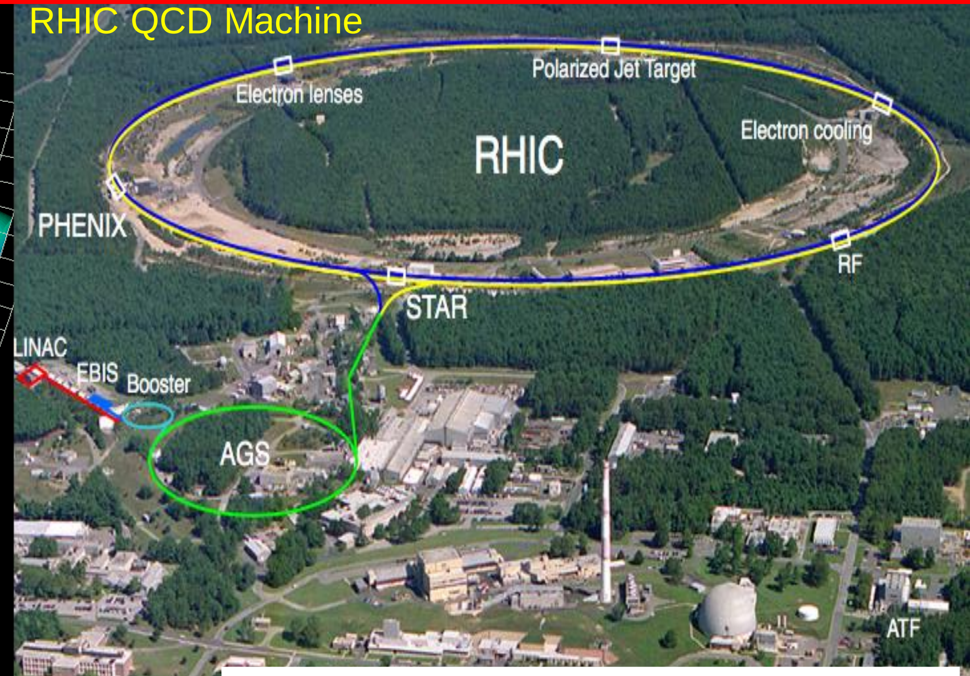
In this report, we discuss[14, 15] the evidence that at least one and possibly two new forms of QCD matter have been discovered at RHIC. We consider the Quark Gluon Plasma, which is a form of matter characterized by a thermal equilibrium density matrix of a system of quarks and gluons. We also consider the Color Glass Condensate (CGC), which is a form of matter characterized by a universal initial density matrix which describes high energy strongly interacting particles - including nuclei. The QGP is the incoherent thermal limit of QCD matter at high temperatures while the CGC is the coherent limit of QCD at high energies. Since the QGP has to be created at RHIC from the interaction of initial nuclear enhanced coherent chromo electric magnetic fields, both limiting forms of QCD matter need to be considered at RHIC.

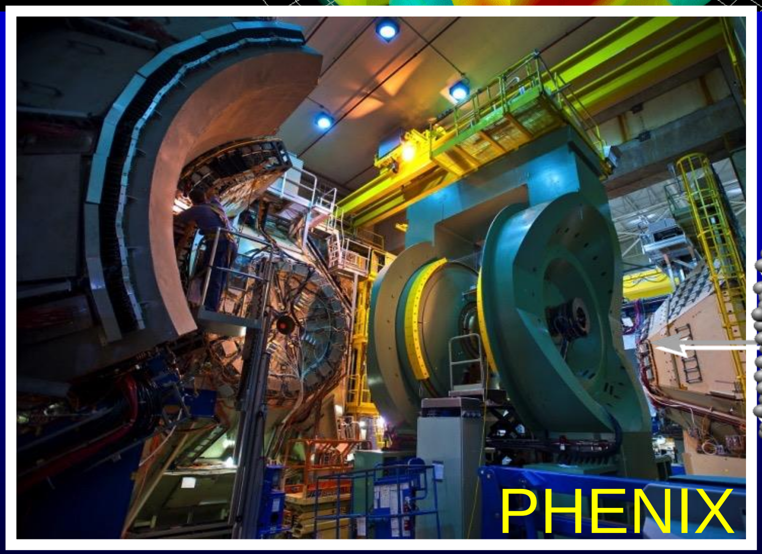
Modèle de Condensate de verre de couleur: nouvel état de la matière CGC

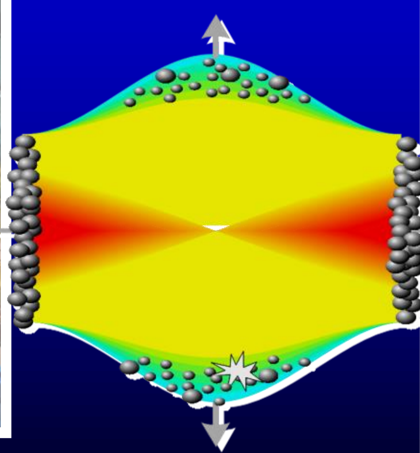


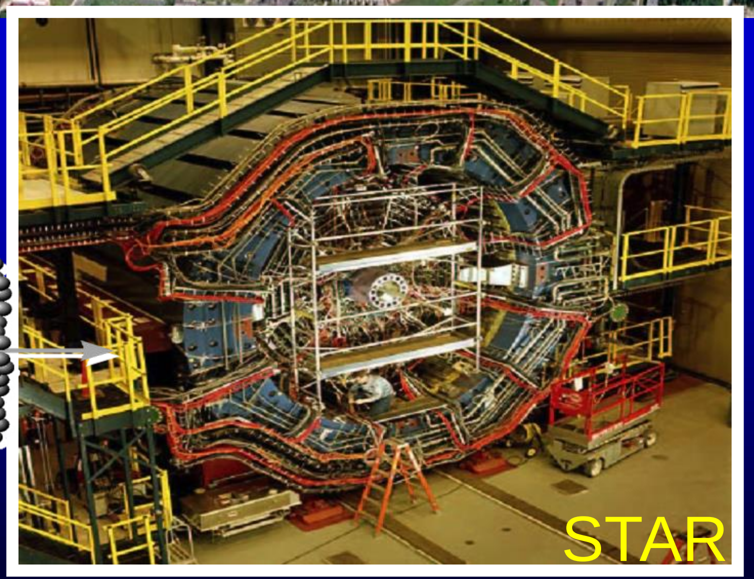
Two Big Experiments: PHENIX and STAR











PHENIX Detector

✪ **P**ioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment

- **2 central spectrometers**

  Photon, hadron, electron

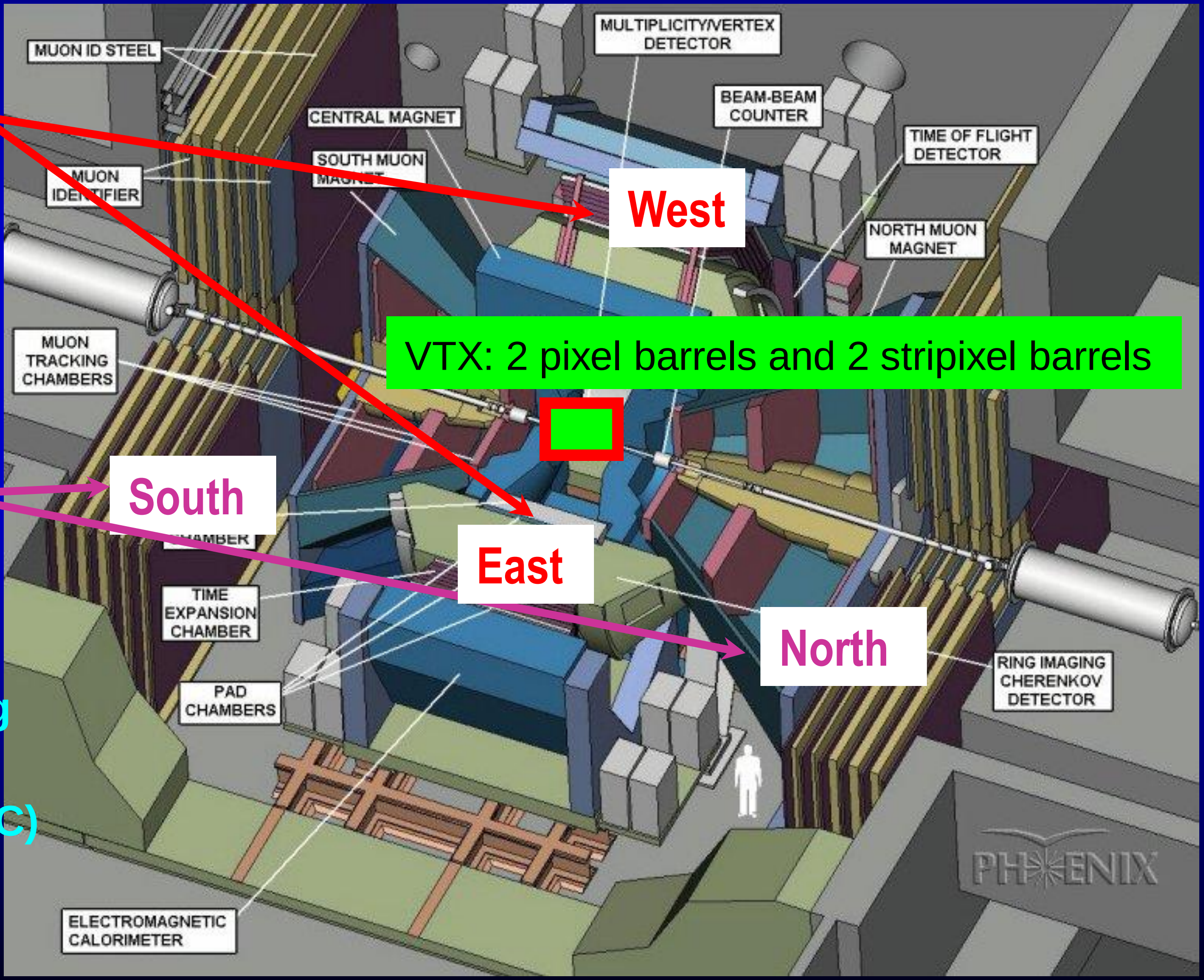
  $|\eta|<0.35$, $\Delta\phi=\pi$

- **2 forward spectrometers**

  μ detection

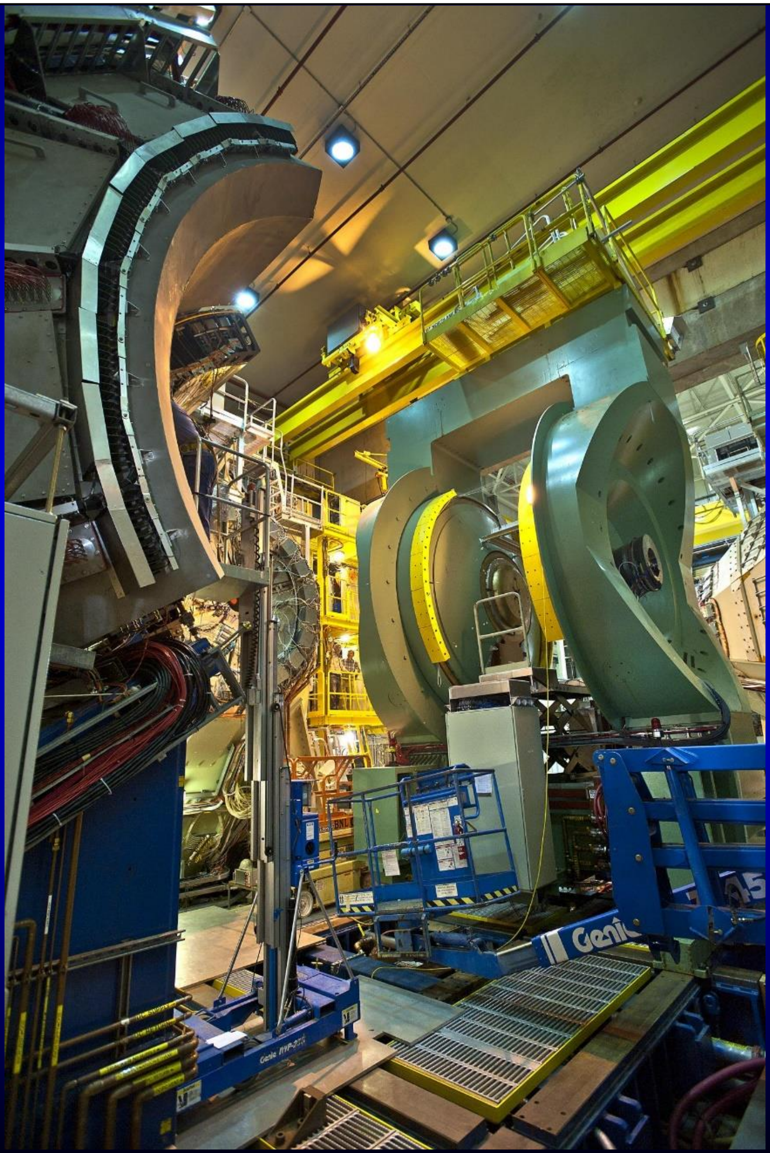
  $1.2<|\eta|<2.4$, 2π in ϕ

- **3 global detectors**
  - **Luminosity Monitoring (BBCN,BBCS)**
  - **Centrality (BBC vs ZDC)**
  - **Local polarimetery (ZDC & SMD)**



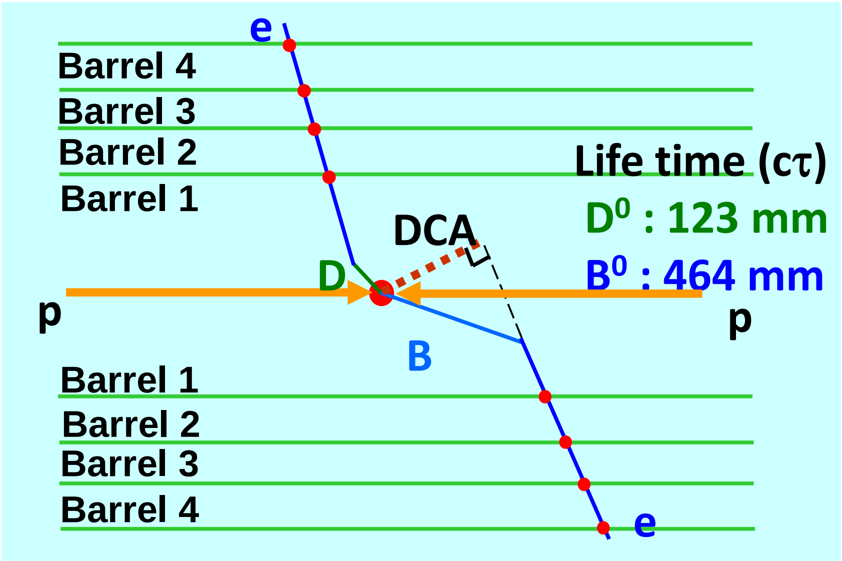
PHENIX Detector

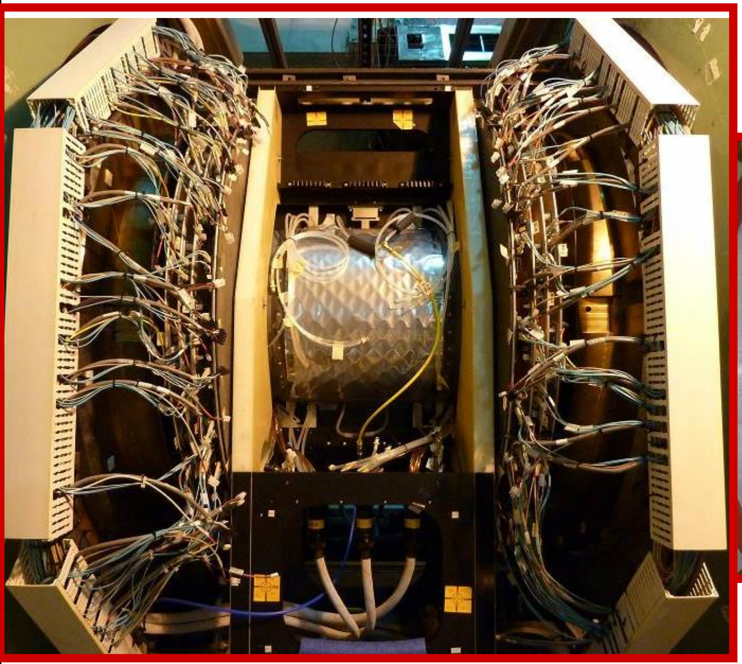
- **P**ioneering **H**igh **E**nergy **N**uclear **I**nteraction e**X**periment

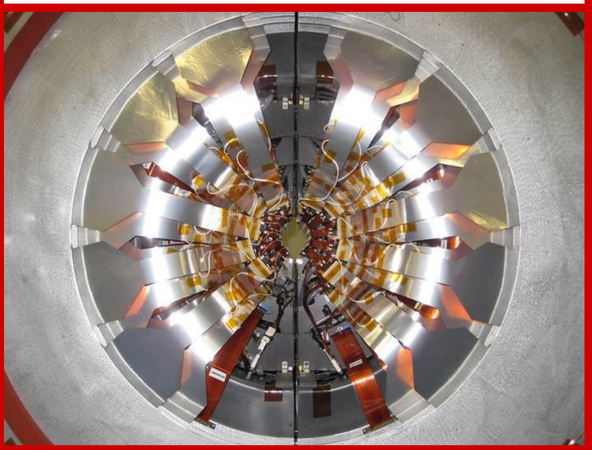


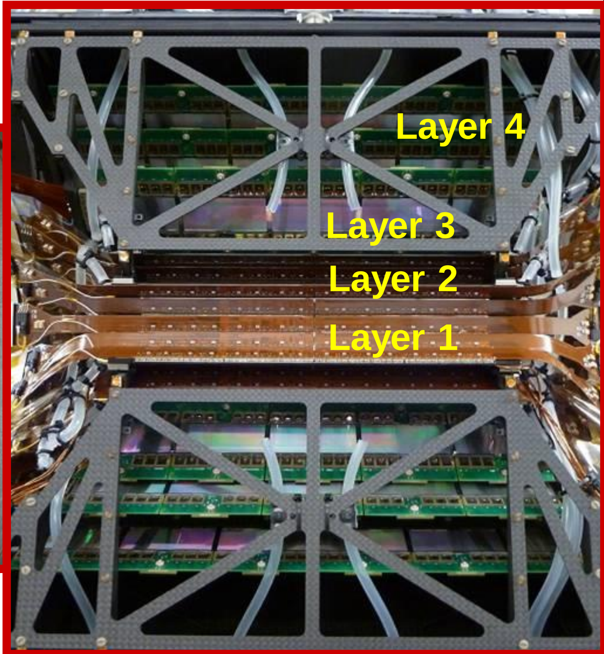
D → e^{HF} and B → e^{HF} with PHENIX Silicon Vertex Tracker (VTX)

To understand these medium effects in more detail it is imperative to directly measure the nuclear modification and flow of D- and B-mesons independently (c → e^{HF} and b → e^{HF}).



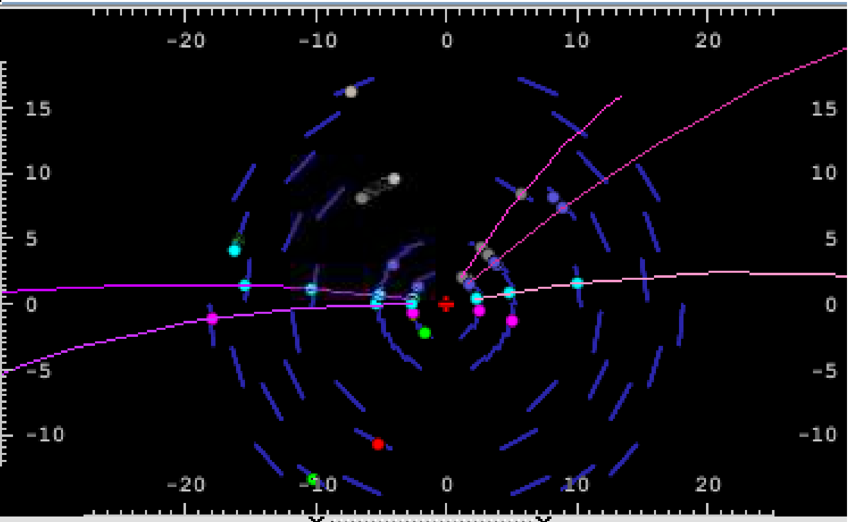




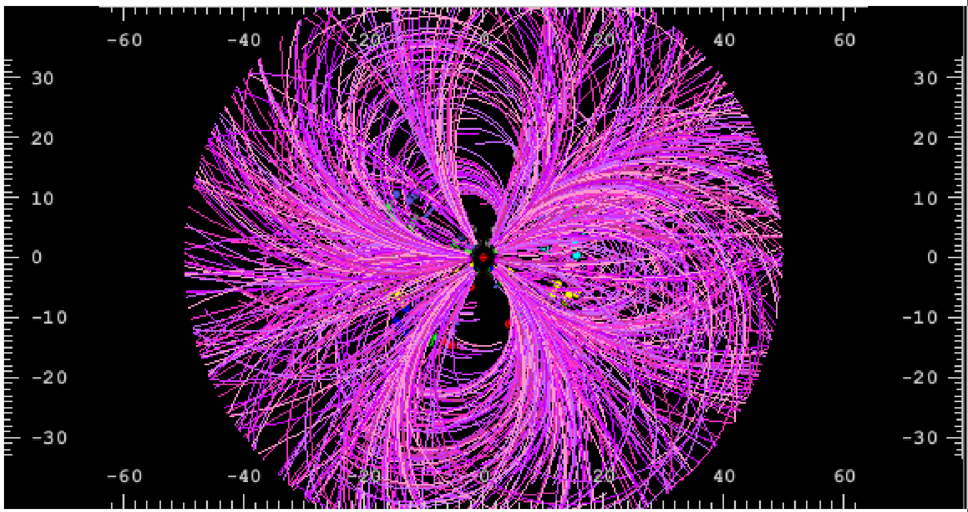


PHENIX-VTX at RHIC: Display of Single Event

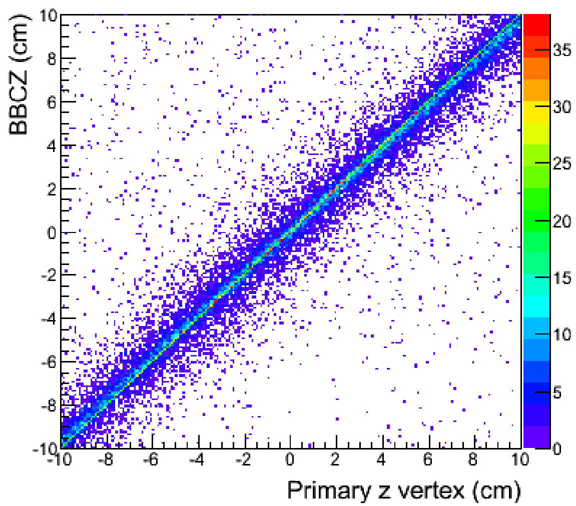
VTX RUN-12: p+p at 200 GeV



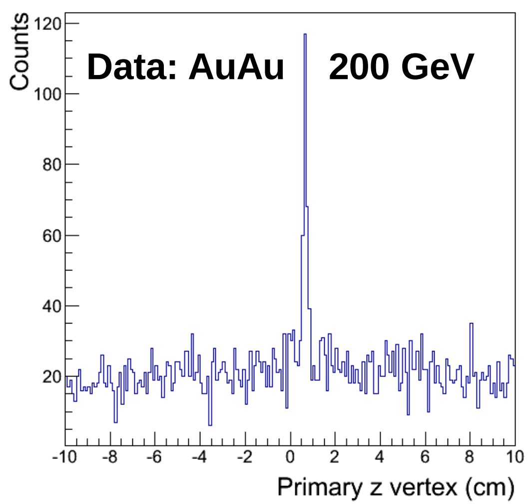
VTX RUN-11: Au+Au at 200 GeV



Primary Vertex: BBC vs VTX

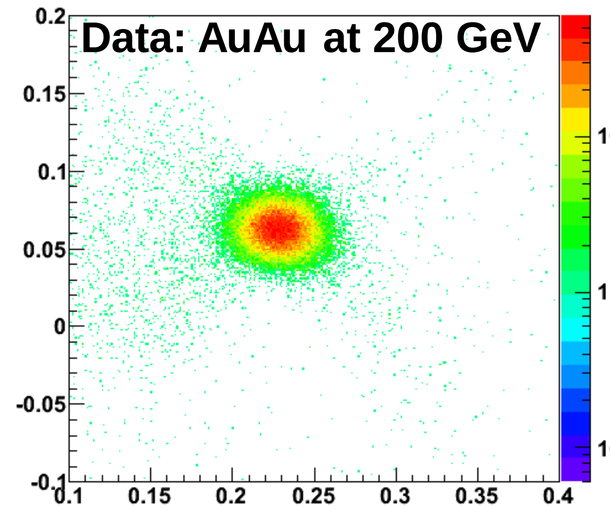


Primary vertex single event



Y vs X beam Size

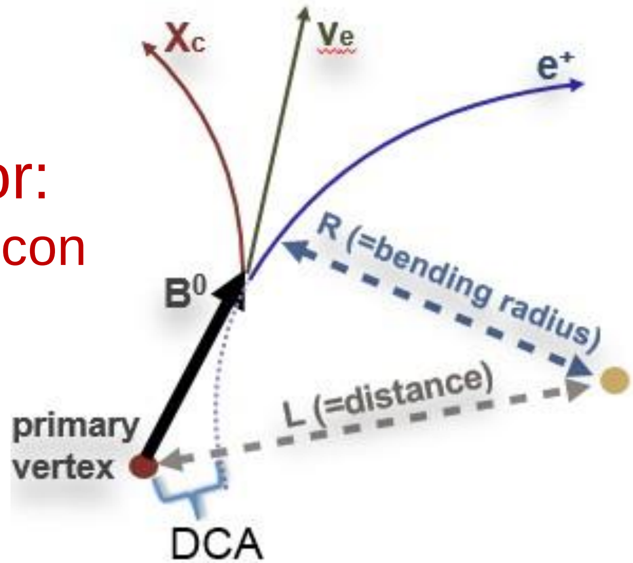
Beam size

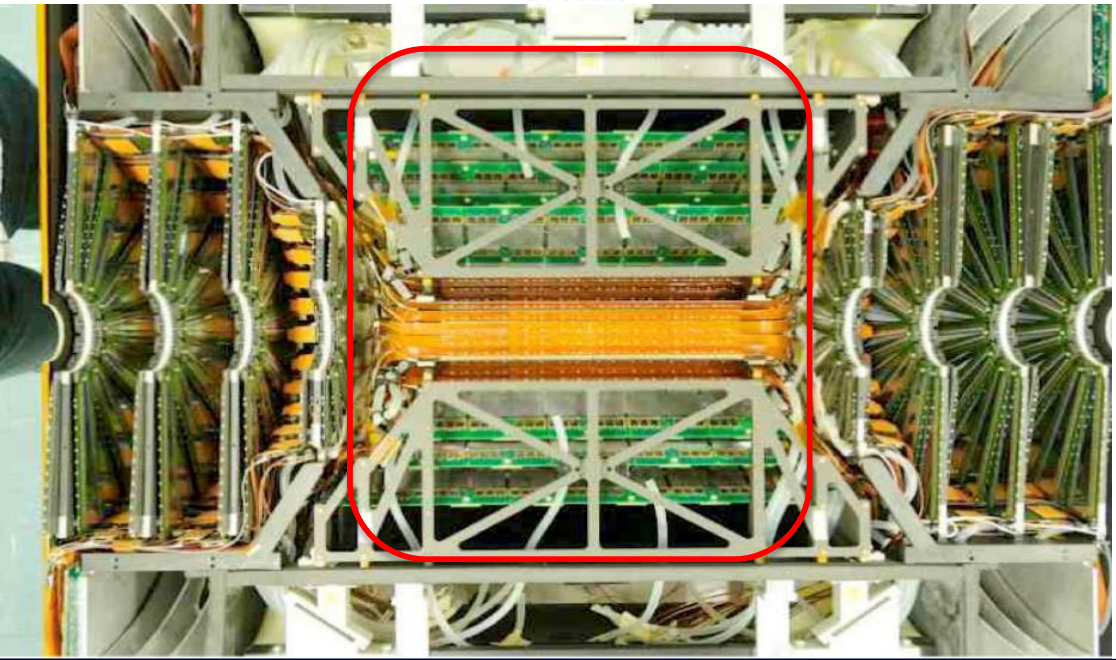


PHENIX Central Heavy Flavor Tracker (VTX)

VTX detector:

4 barrels of silicon





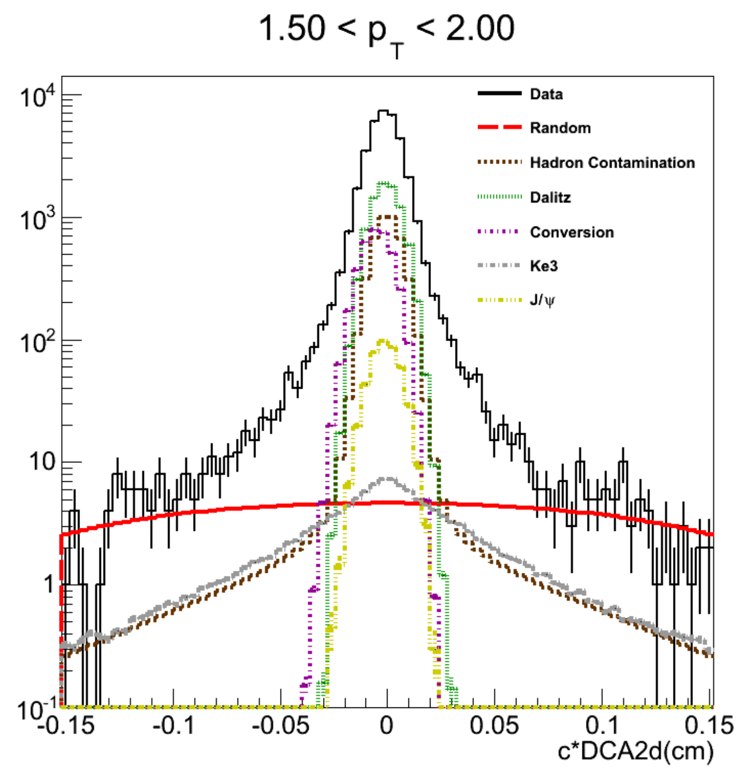
DCA_T Distributions: b/c separation

- VTX: |η | <1.2
  - Au+Au 200 GeV: DCA_T resolution ~ 60 μm

Life time (cτ)

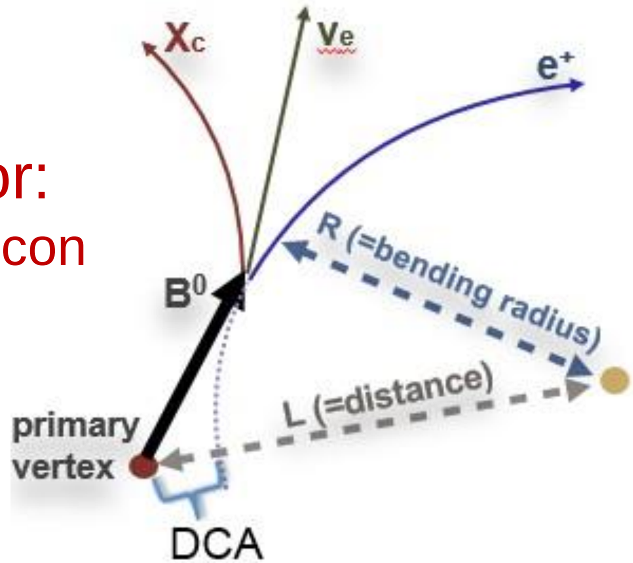
D^0 : 123 μm

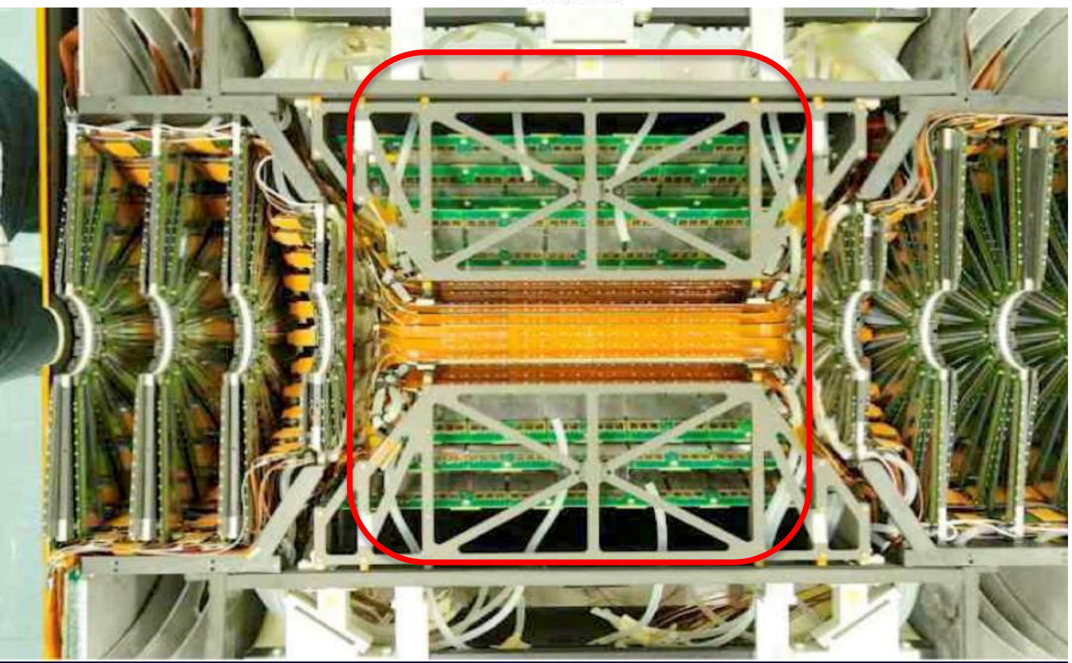
B^0 : 464 μm



PHENIX Central Heavy Flavor Tracker (VTX)

VTX detector:
4 barrels of silicon



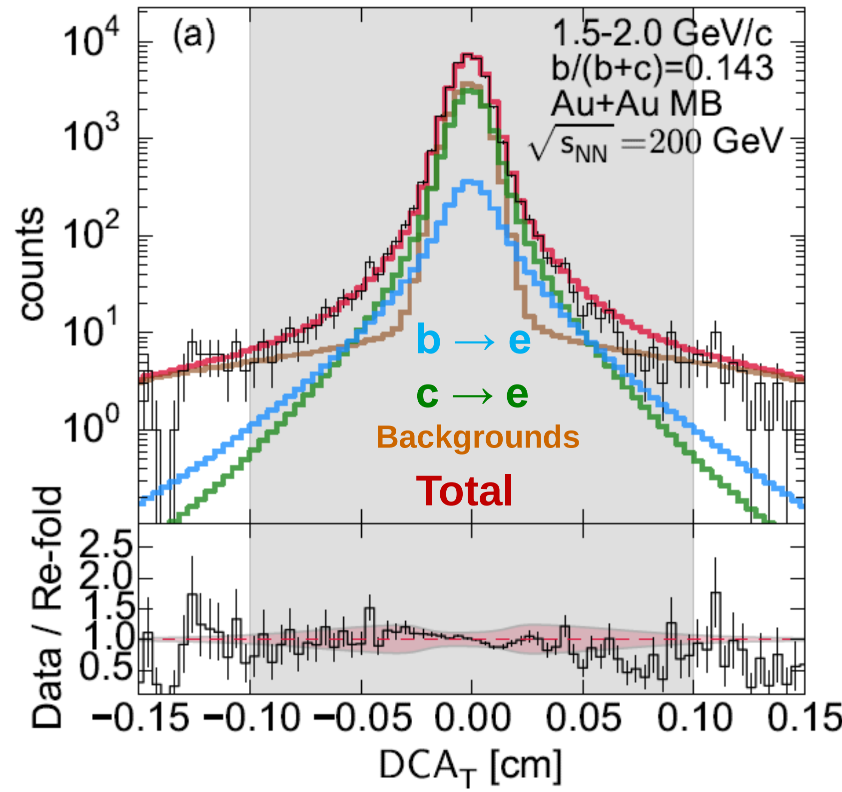


DCA_T Distributions: b/c separation

- VTX: $|\eta| < 1.2$
  - Au+Au 200 GeV: DCA_T resolution ~ 60 μm

Life time (cτ)
D^0 : 123 μm
B^0 : 464 μm

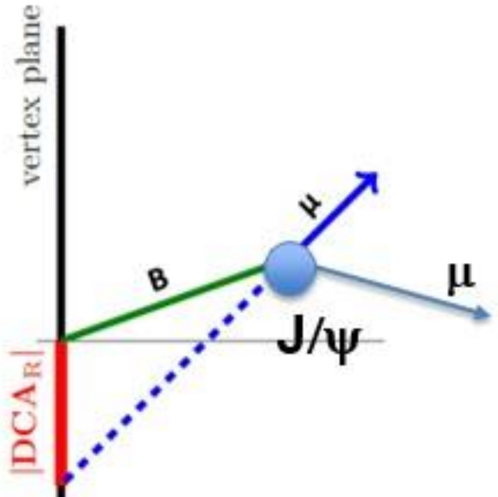
PHENIX: PRC **93**, 034904 (2016)



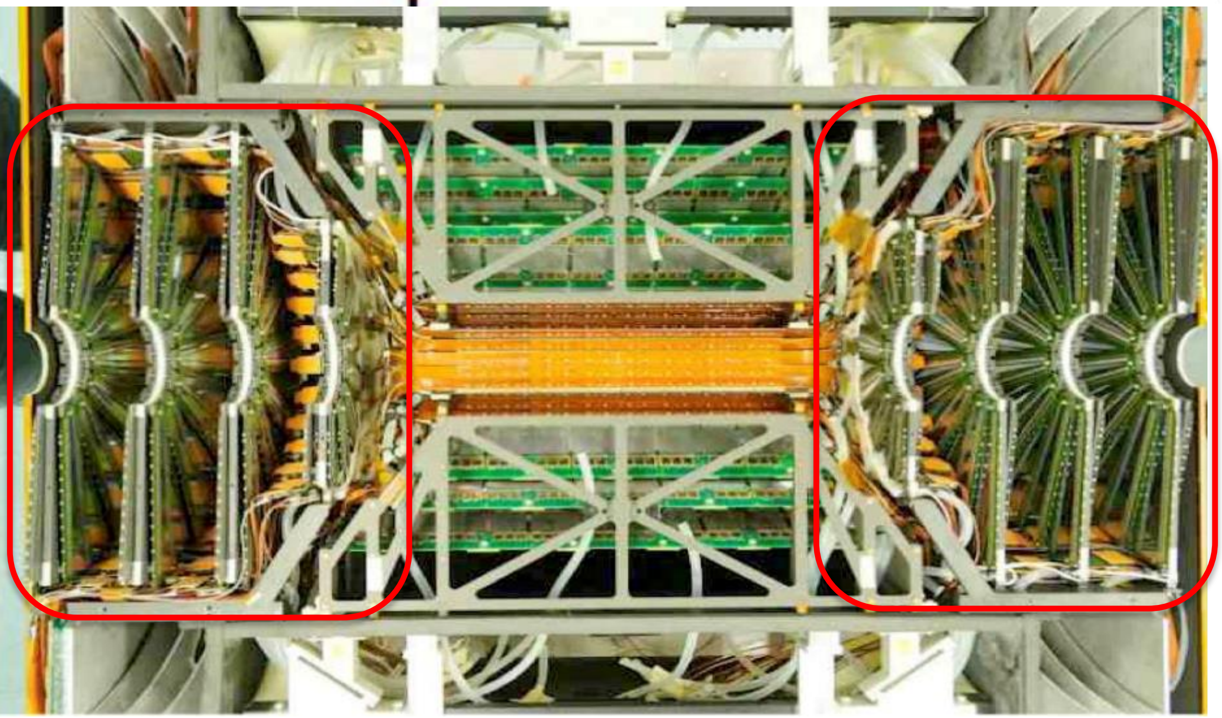
PHENIX Forward Heavy Flavor Tracker (FVTX)

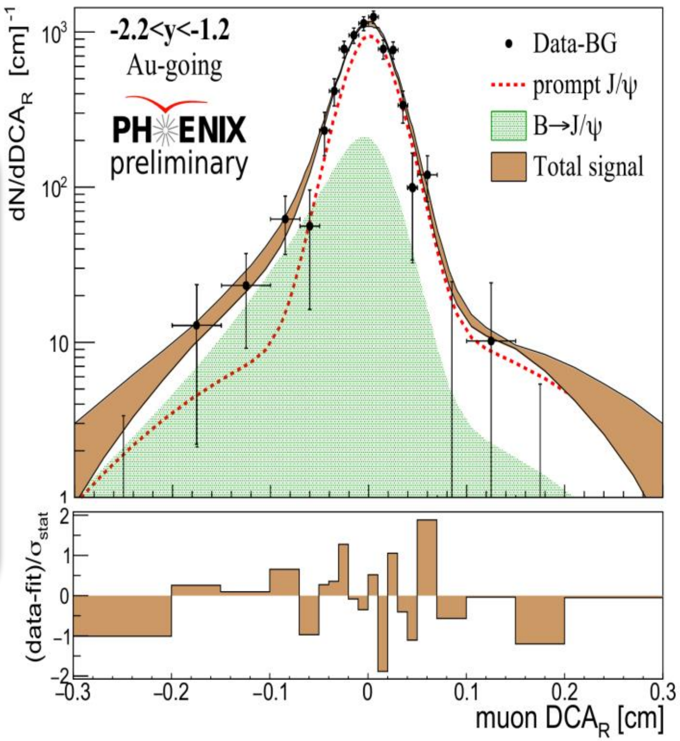
DCA_R Distributions: b/c separation

FVTX detector:

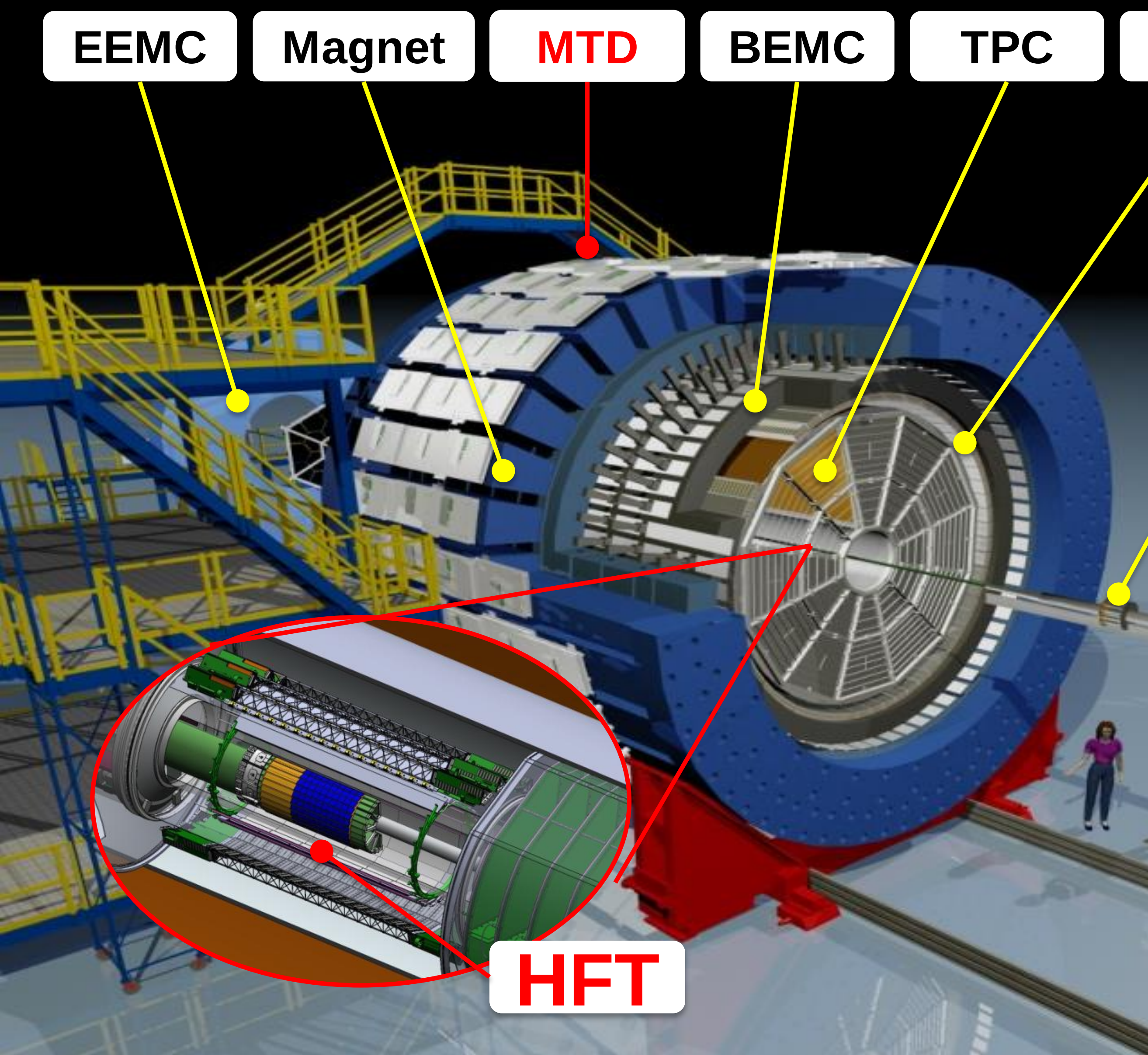


- FVTX:
- Forward rapidity - $1.2 < |\eta| < 2.2$
- Improved muon momentum resolution & precise tracking





STAR: Solenoidal Tracker At RHIC

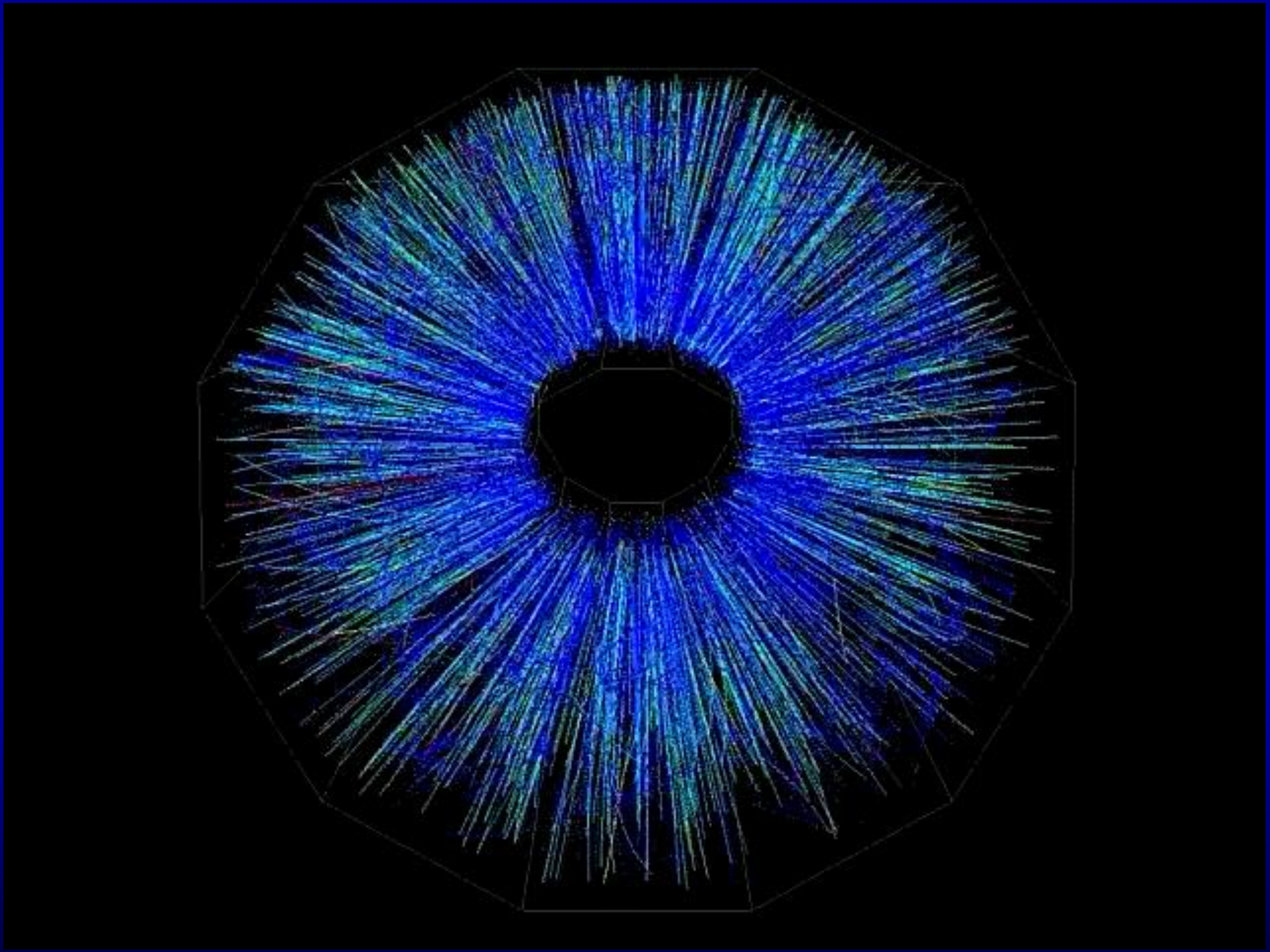


- **Tracking and PID (full 2π)**
  - TPC: $|\eta| < 1$
  - TOF: $|\eta| < 1$
  - BEMC: $|\eta| < 1$
  - EEMC: $1 < \eta < 2$
  - HFT (2014-2016): $|\eta| < 1$
  - MTD (2014+): $|\eta| < 0.5$
- **MB trigger and event plane reconstruction**
  - BBC: $3.3 < |\eta| < 5$
  - EPD (2018+): $2.1 < |\eta| < 5.1$
  - FMS: $2.5 < \eta < 4$
  - VPD: $4.2 < |\eta| < 5$
  - ZDC: $6.5 < |\eta| < 7.5$
- **On-going/future upgrades**
  - iTPC (2019+): $|\eta| < 1.5$
  - eTOF (2019+): $-1.6 < \eta < -1$
  - FCS (2021+): $2.5 < \eta < 4$
  - FTS (2021+): $2.5 < \eta < 4$

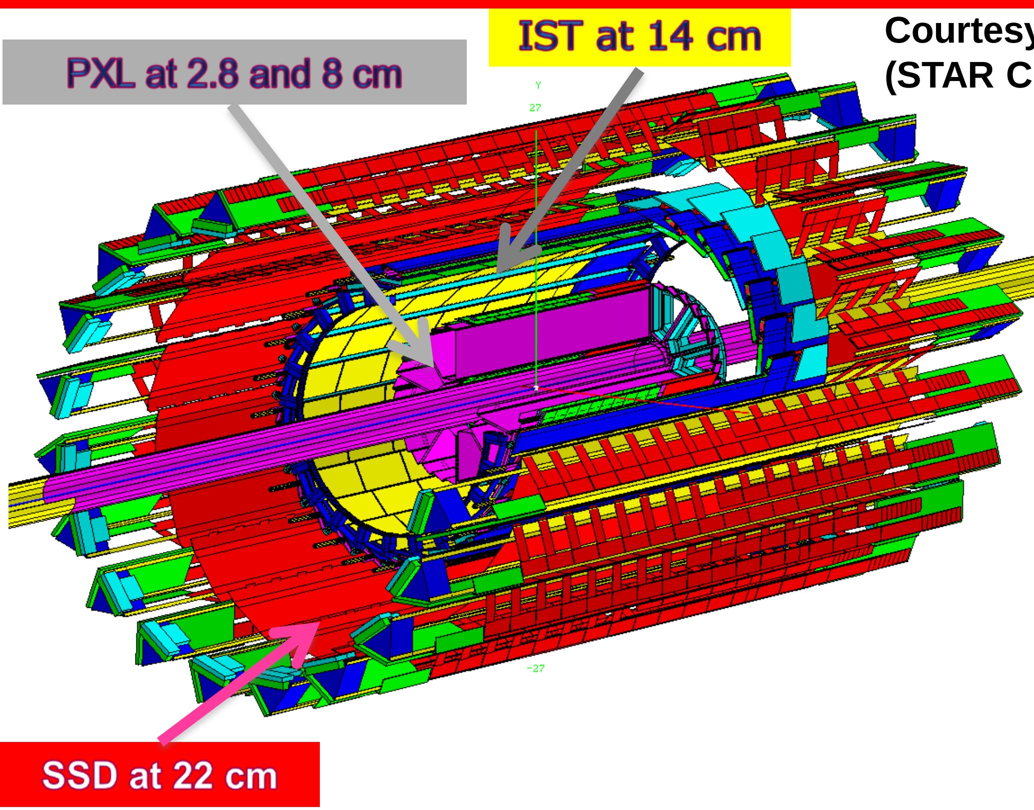
STAR: Solenoidal Tracker At RHIC

STAR: Solenoidal Tracker At RHIC

First Au+Au event recorded by STAR. Each line represents a particle recorded by the Time Projection Chamber (TPC).

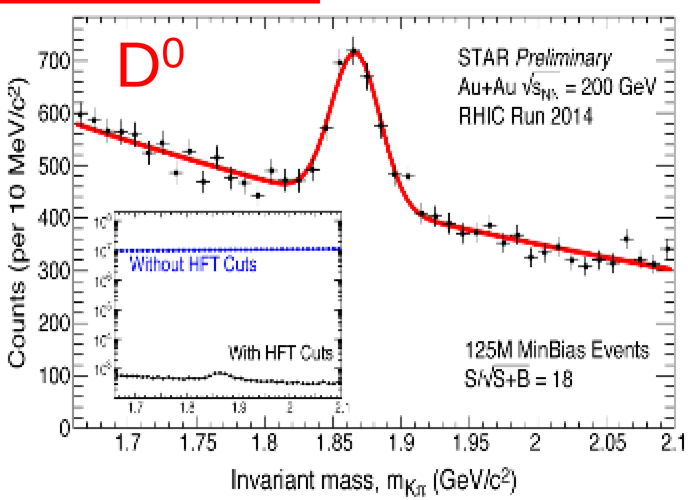


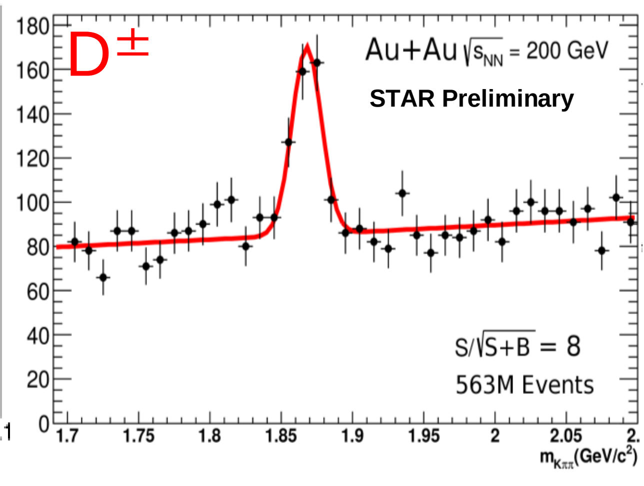
STAR Heavy Flavor Tracker (HFT)

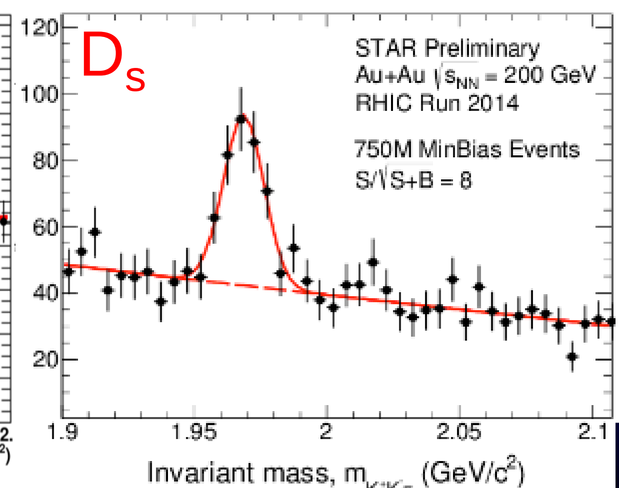


Courtesy of Zhenyu Ye (STAR Collaboration)

- First application of Monolithic Active Pixel Sensor technology in collider experiments. DCA resolution <50 μm for p_T= 750 MeV/c Kaon.
- Recorded about 3B Minimum Bias 200 GeV Au+Au events for D^0, $D^\pm$, D_s
- Results presented today are based on partial 2014 MB data.

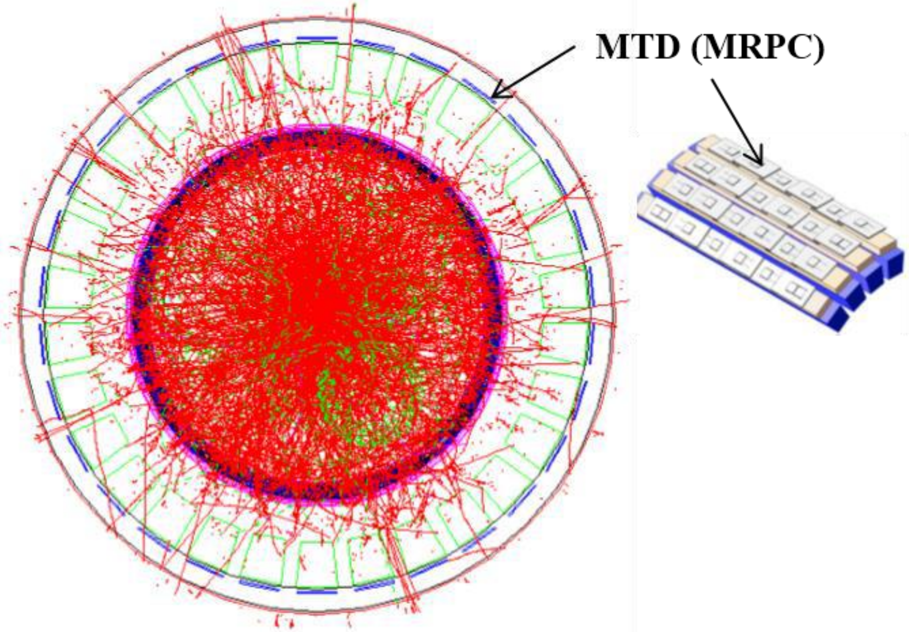






STAR Muon Telescope Detector (MTD)

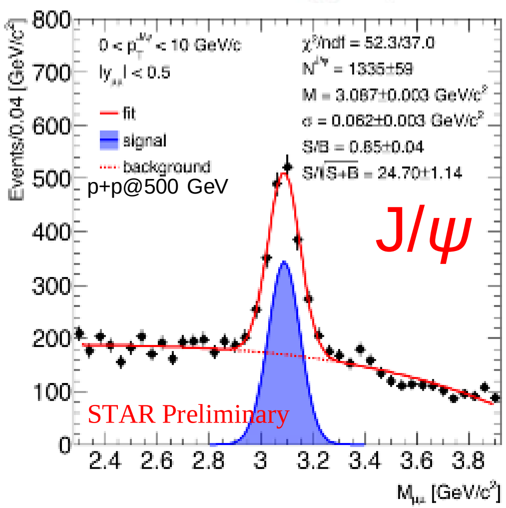
Courtesy of Zhenyu Ye
(STAR Collaboration)

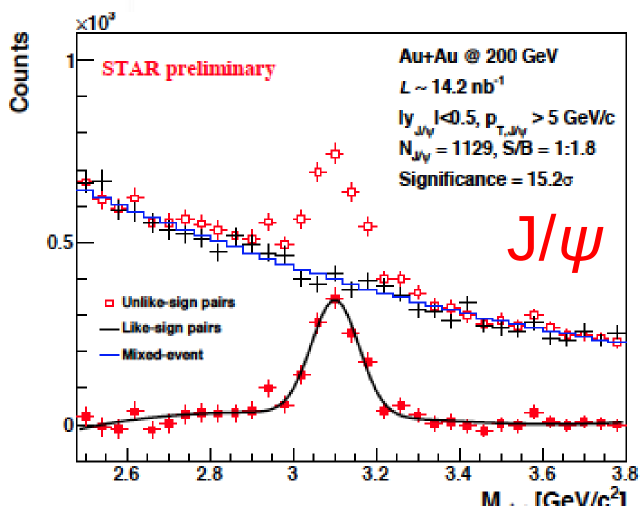


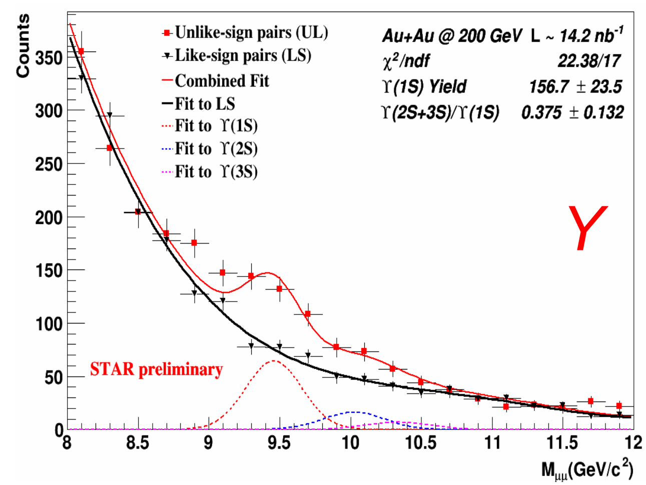
- Precise timing info (~100 ps) for $p_T > 1.2$ GeV/c; muon online triggering and offline identification.

- Recorded 28 pb^{-1}, 120 pb^{-1}, 400 nb^{-1} and 22 nb^{-1} dimuon-triggered 500 GeV p+p, 200 GeV p+p, p+Au and Au+Au data for J/ψ and Υ studies.

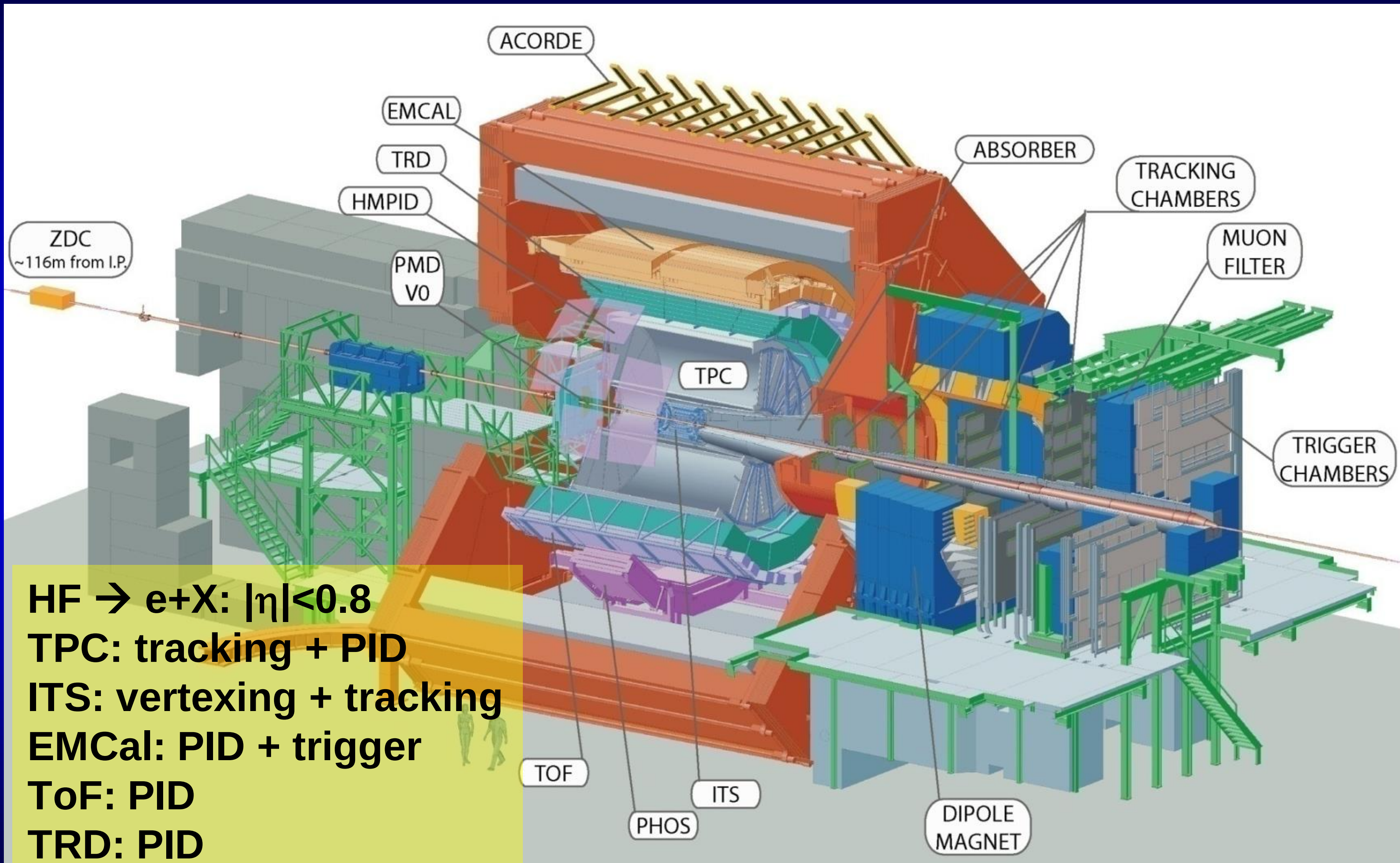
- Results presented today are based on 28 pb^{-1} p+p 500 GeV (63% MTD) and 14.2 nb^{-1} Au+Au 200 GeV data.





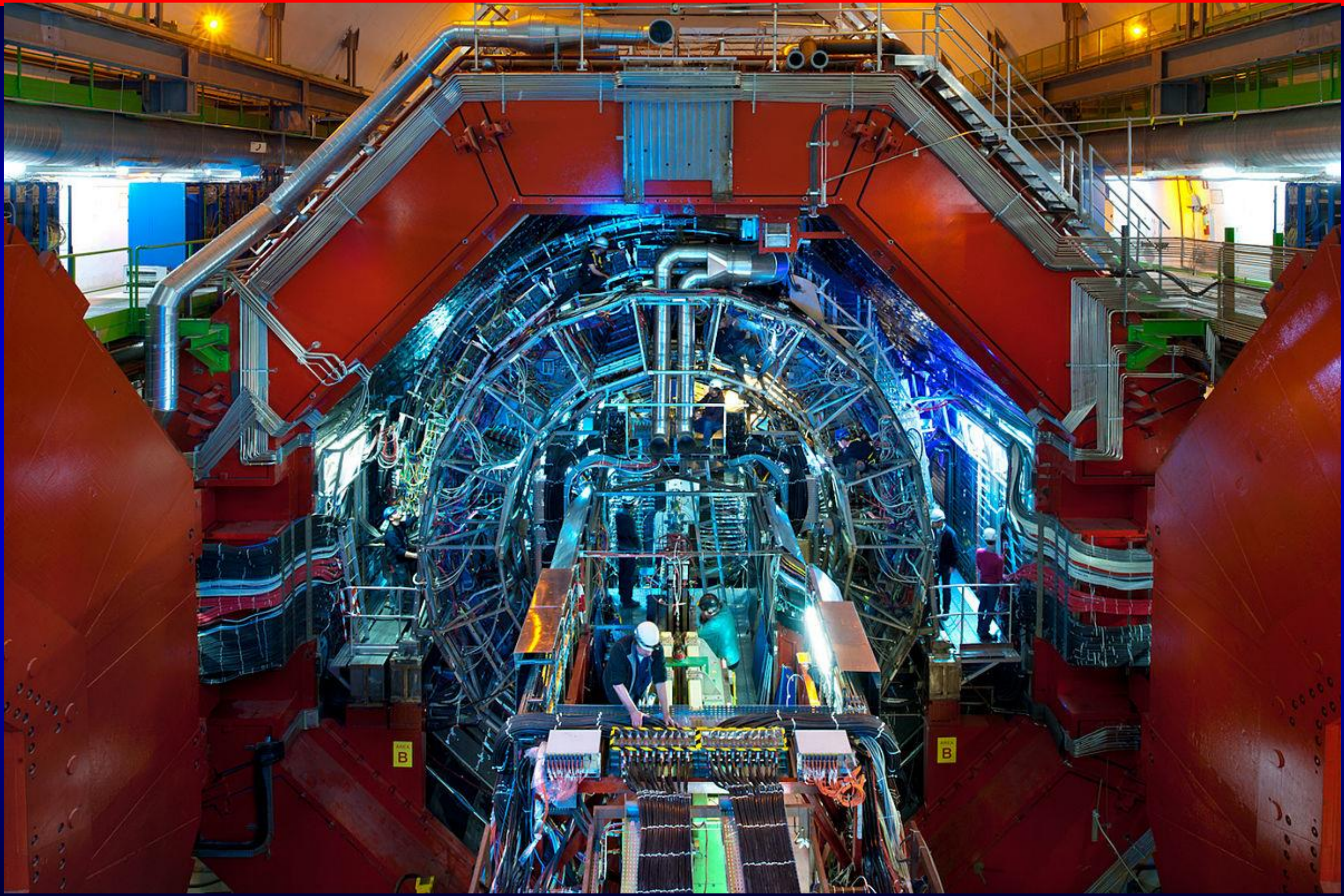


ALICE at LHC: A Large Ion Collider Experiment



HF → e+X: |η|<0.8
TPC: tracking + PID
ITS: vertexing + tracking
EMCal: PID + trigger
ToF: PID
TRD: PID

- ALICE at LHC: A Large Ion Collider Experiment



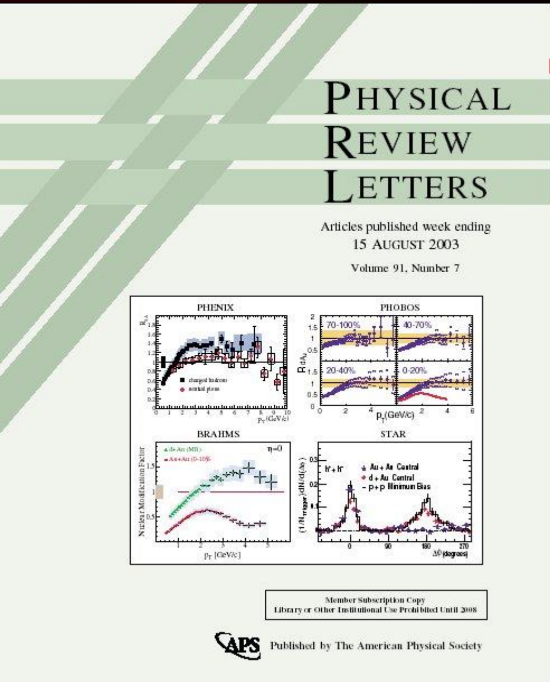
Relativistic Heavy Ion Physics

Highlight on Lecture 2

QGP Discovery at RHIC (Signatures)

Future Projects and Opportunities

RHIC Discoveries in the Press

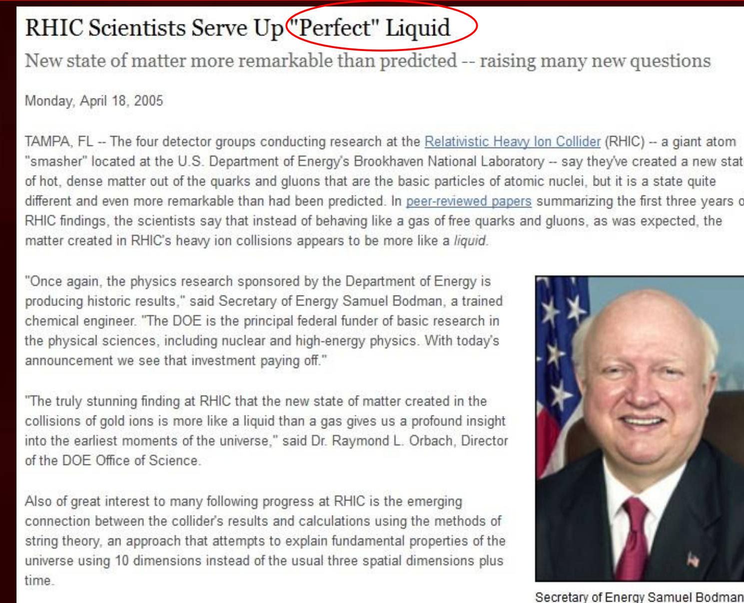


The Collaboration of the four experiments: PHENIX, BRAHMS, PHOBOS and STAR at RHIC

CONCLUDED

that strongly-interacting matter

has been created in most central Au+Au collisions at 200 GeV



RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

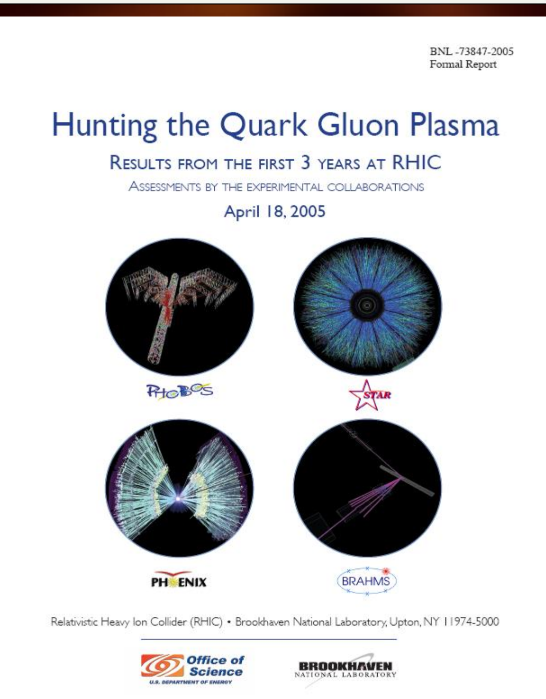
TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

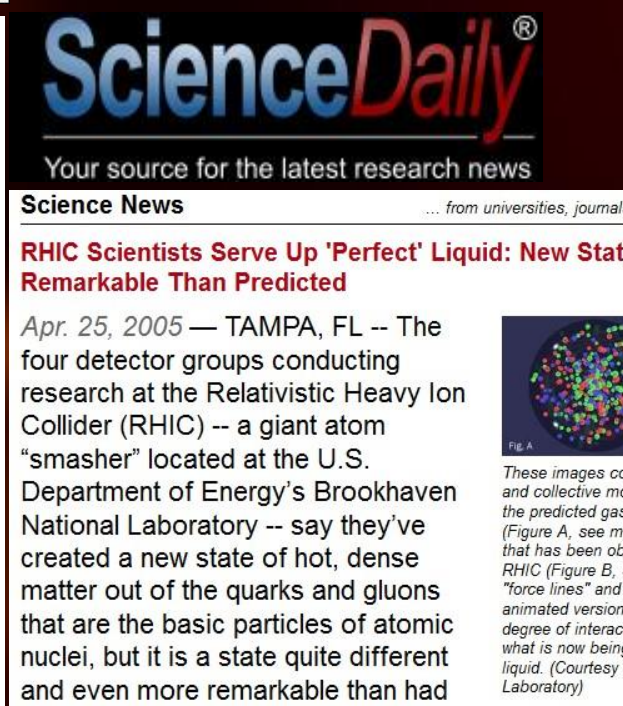
"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

Secretary of Energy Samuel Bodman





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RHIC Scientists Serve Up 'Perfect' Liquid: New State Remarkable Than Predicted

Apr. 25, 2005 — TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had

Fig. A

These images co and collective mo the predicted gas (Figure A, see mp that has been obs RHIC (Figure B, s "force lines" and animated version degree of interact what is now being liquid. (Courtesy Laboratory)

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CERN COURIER

May 6, 2005

RHIC groups serve up 'perfect' liquid

The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory have announced results indicating that they have observed a state of hot, dense matter that is more remarkable than had been predicted. In papers summarizing the first three years of RHIC findings, to be published simultaneously by the journal *Nuclear Physics A*, the four collaborations (BRAHMS, PHENIX, PHOBOS and STAR) say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter

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End of Lecture 1