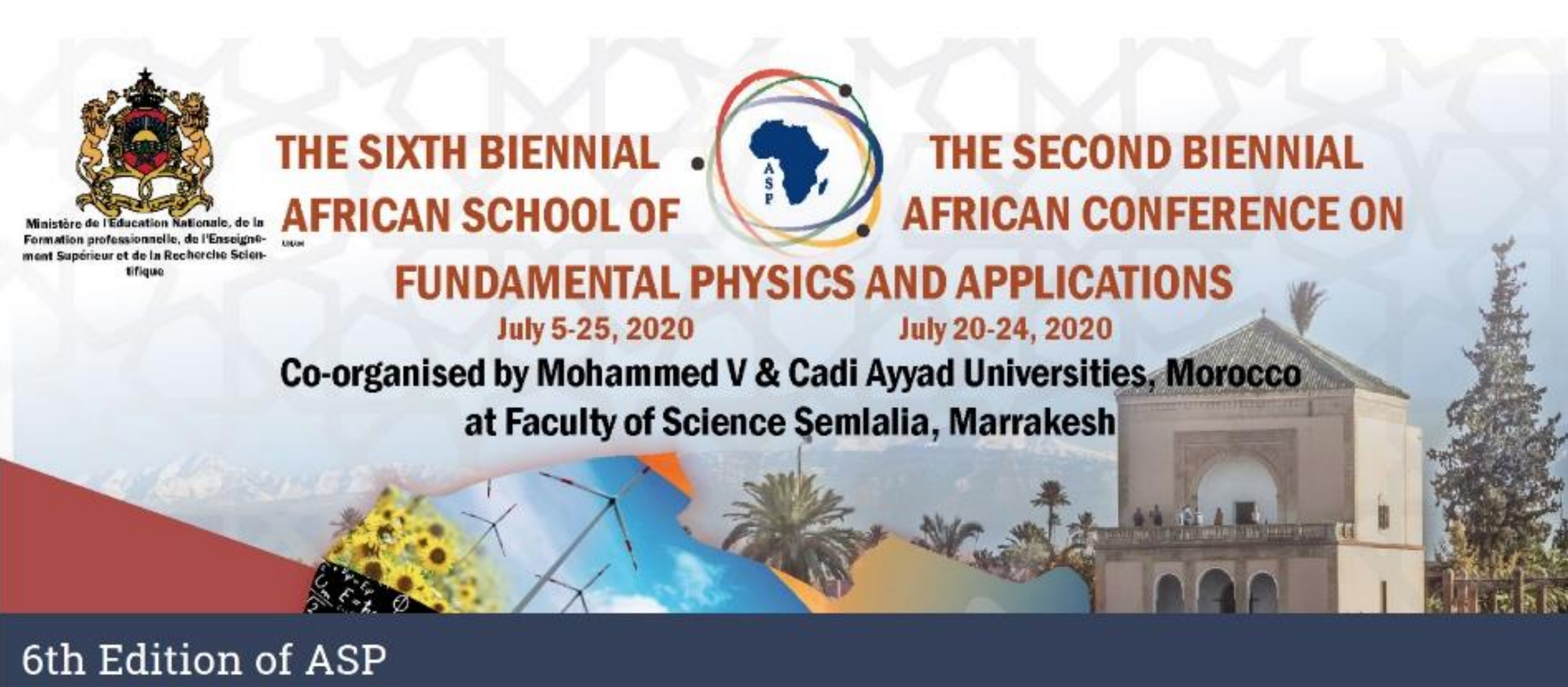

African School of

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

Relativistic Heavy Ion Physics

Lecture 2:

QGP Discovery at RHIC (Signatures)
Future Projects and Opportunities

Rachid Nouicer
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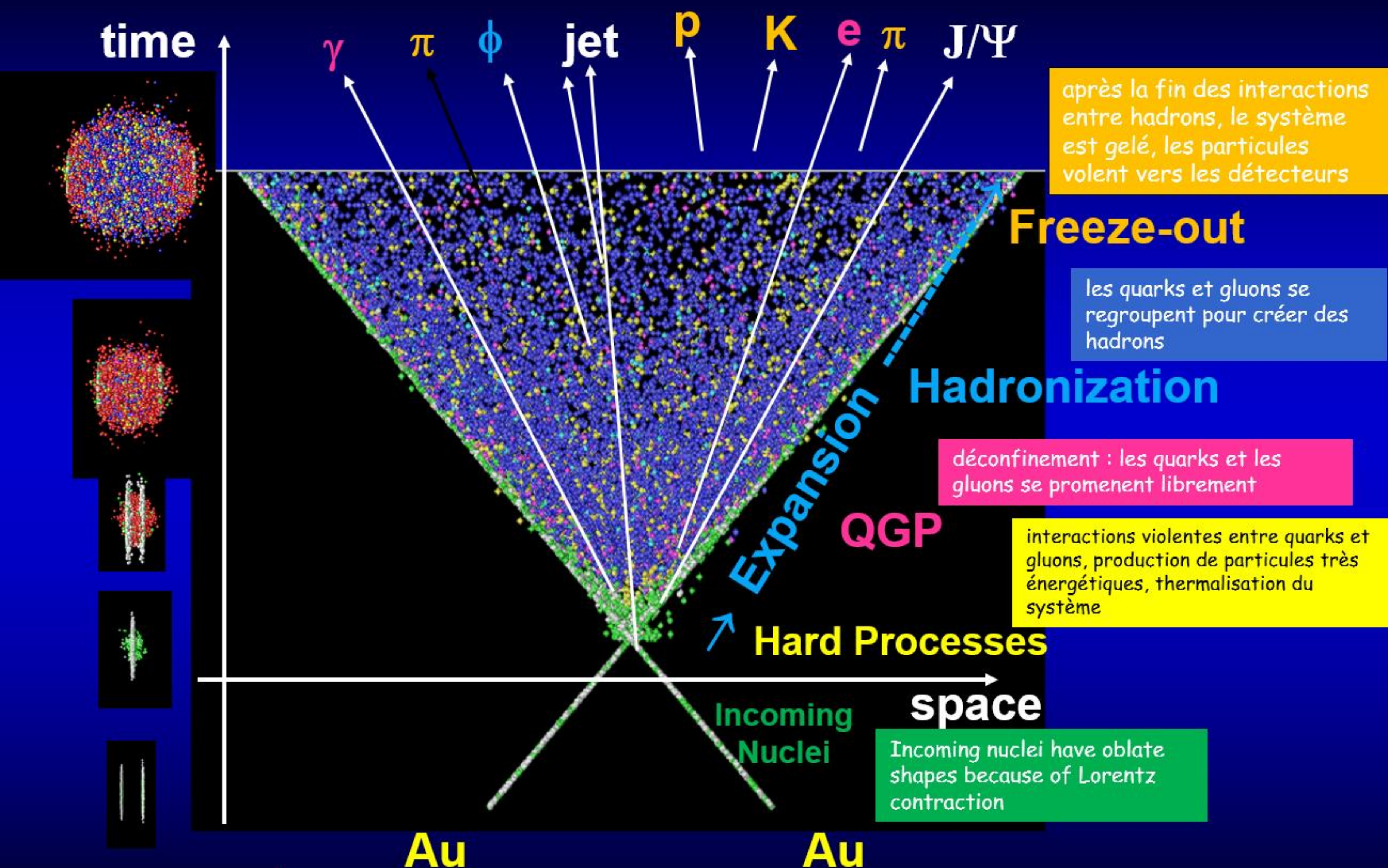
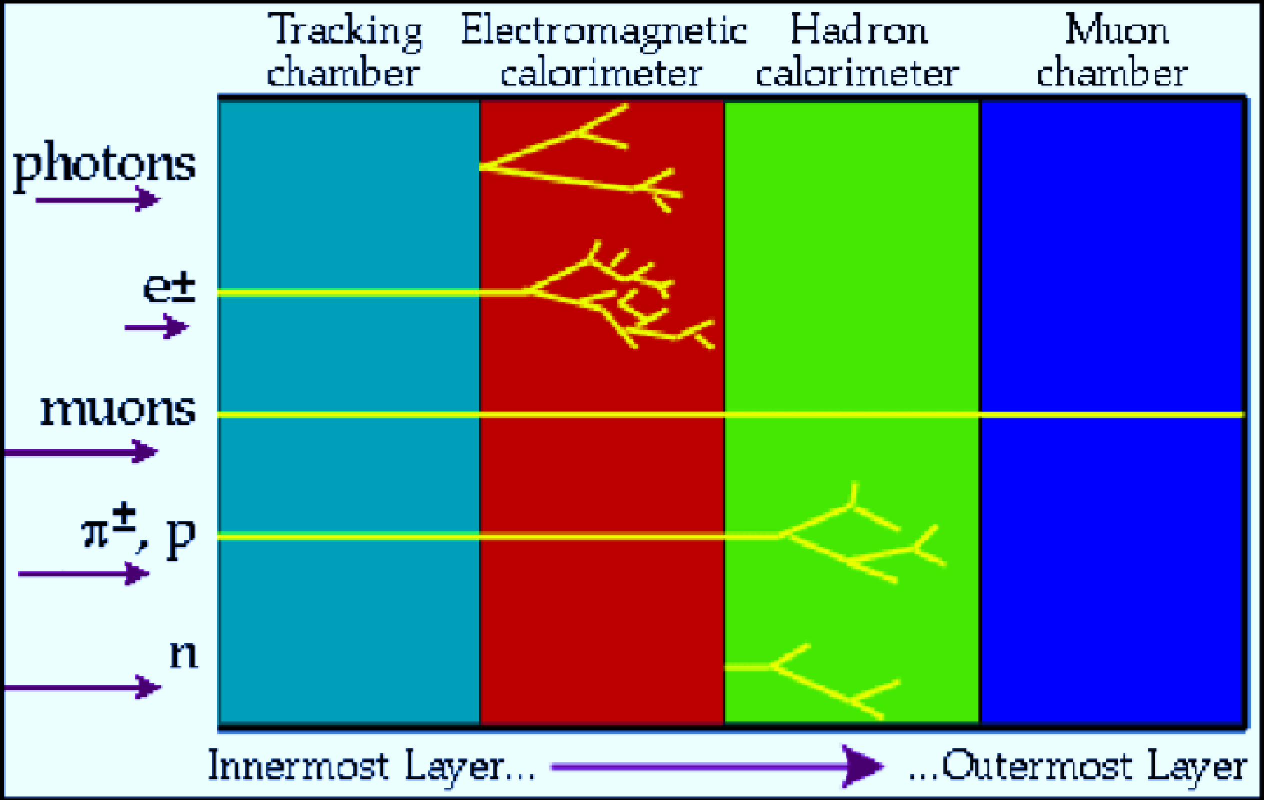
Students Requests (by e-mail) From Lecture Part 1



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

Students Requests (by e-mail) From Lecture Part 1

basic detector concepts



left part:
- vertices
- tracks
- momenta (magnetic field!)

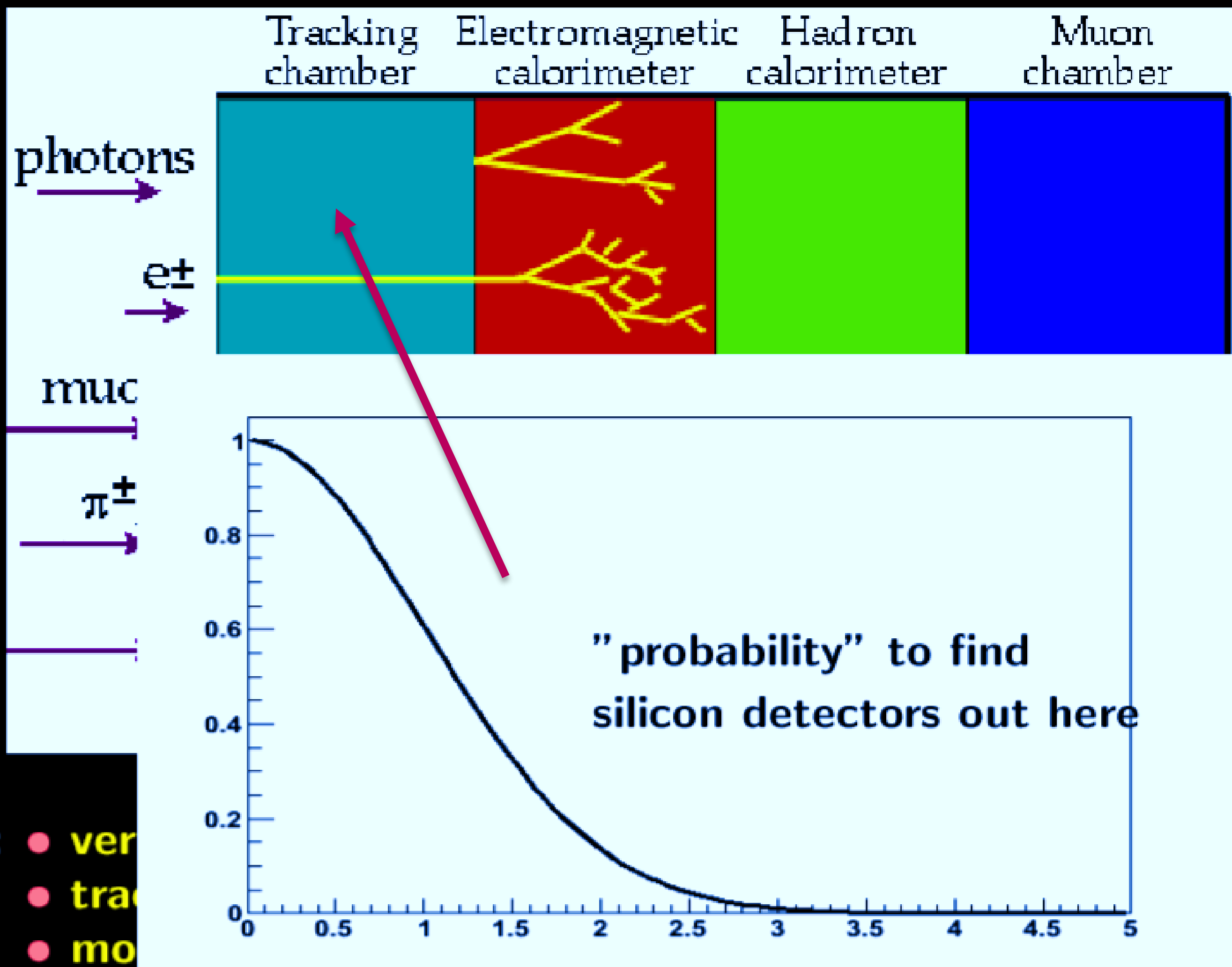
try to leave particles undisturbed

right part:
- energy measurement
- particle identification

use massive material

Students Requests (by e-mail) From Lecture Part 1

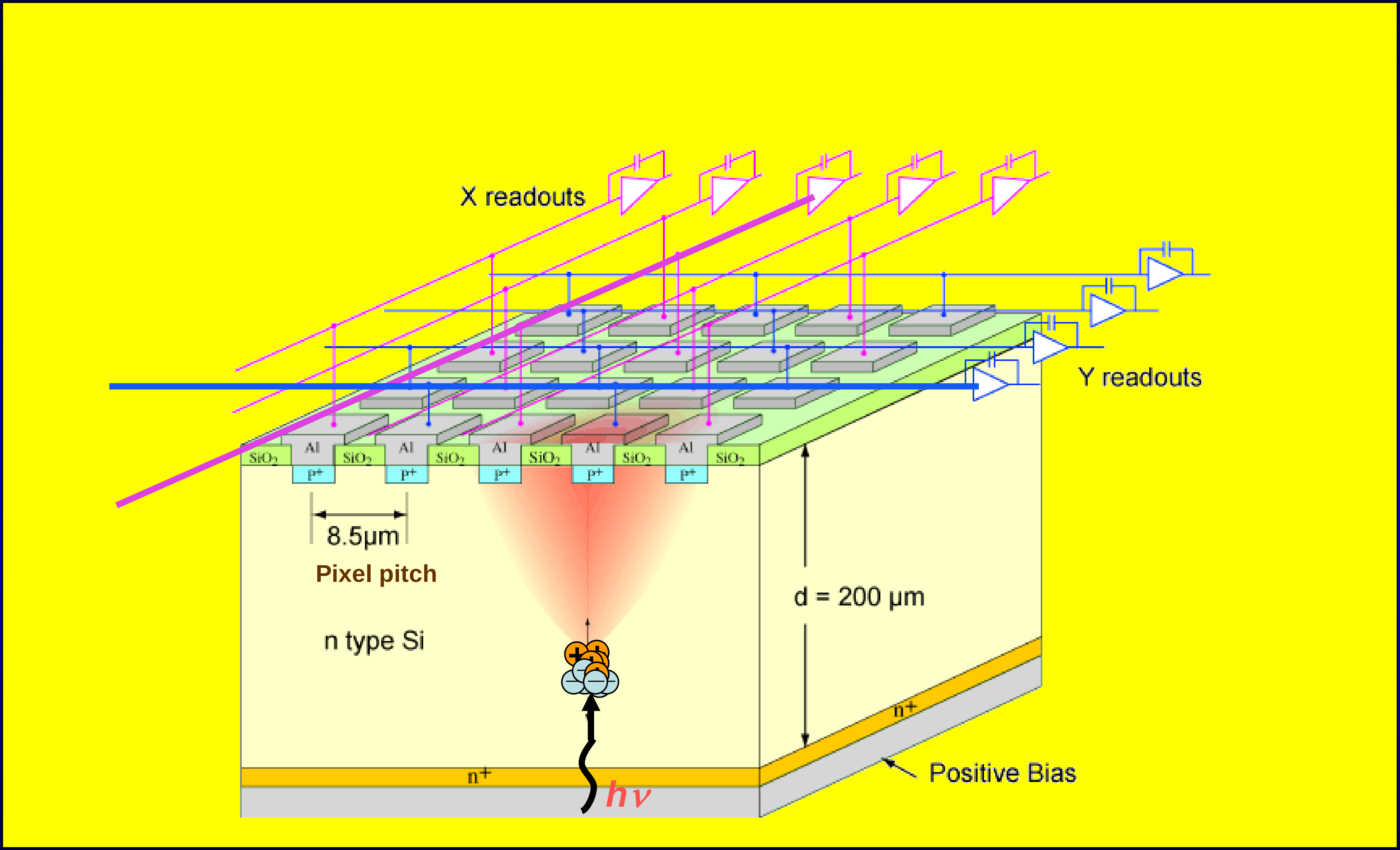
basic detector concepts



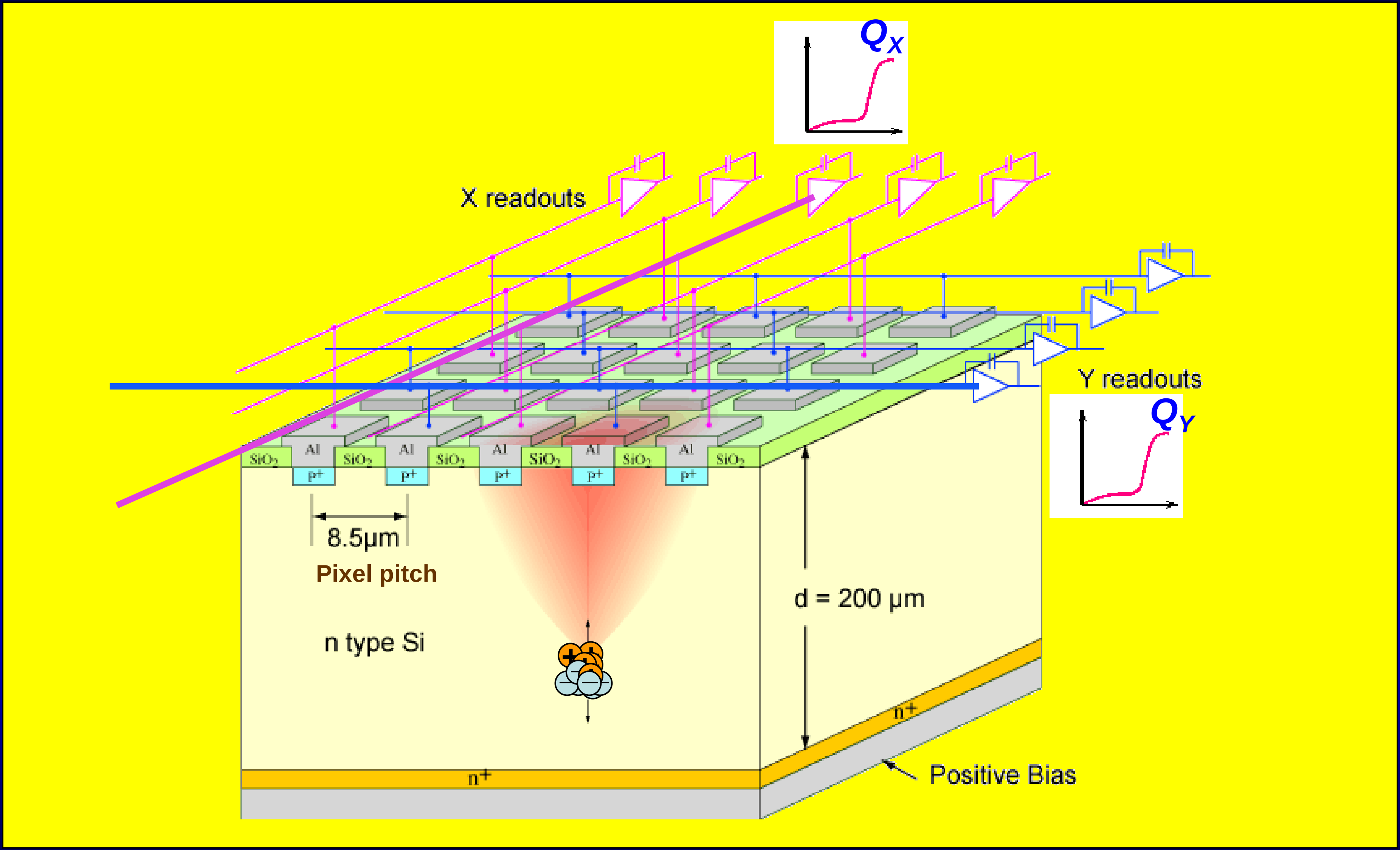
left part: • ver … easurement
• tra… dentification
• mo… e material

try to leave particles undisturbed

Silicon Detector: P-N Junction



Silicon Detector: P-N Junction



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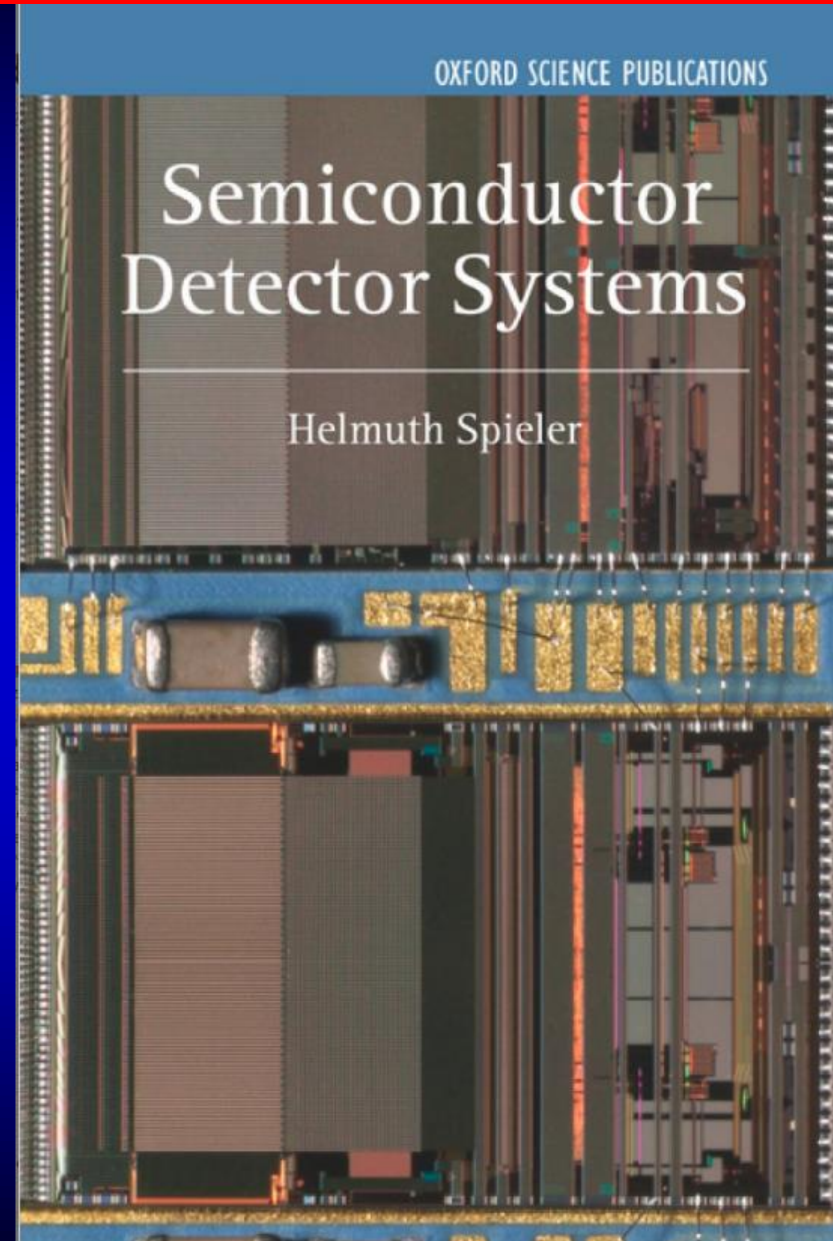

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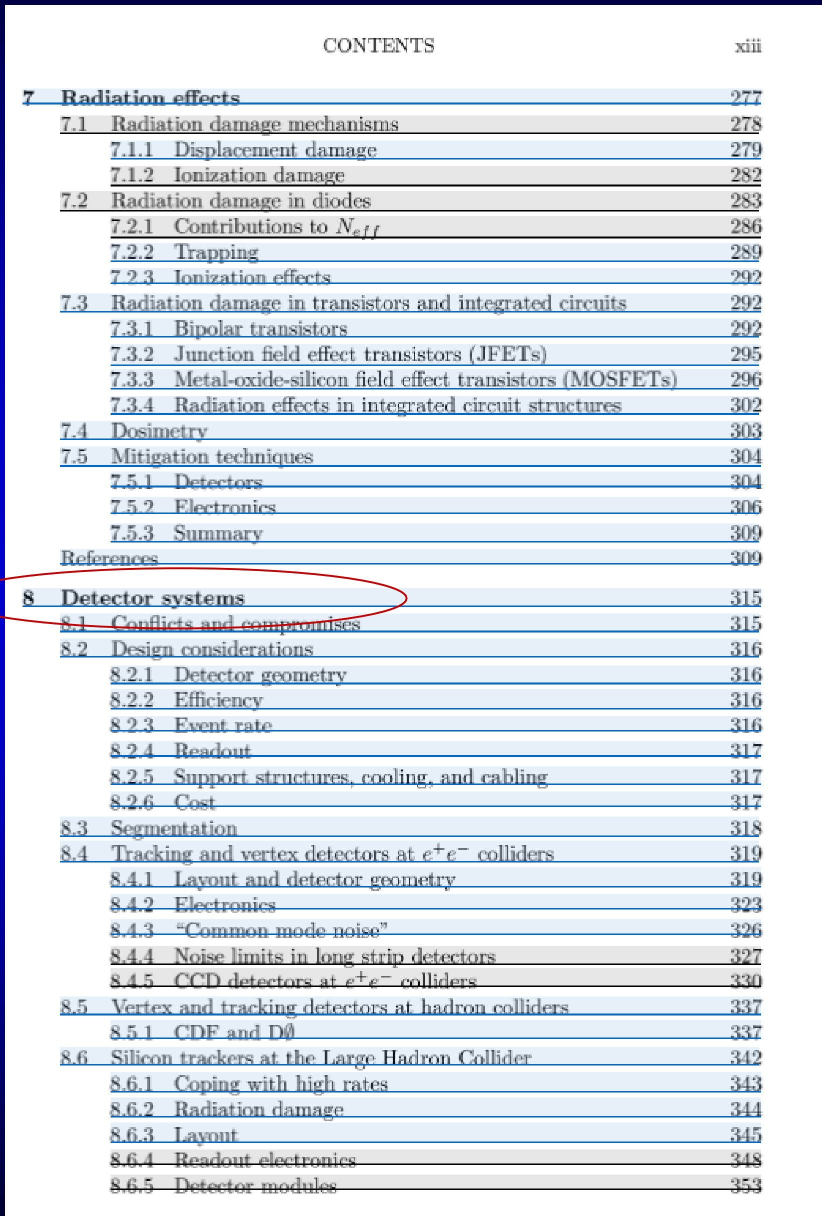
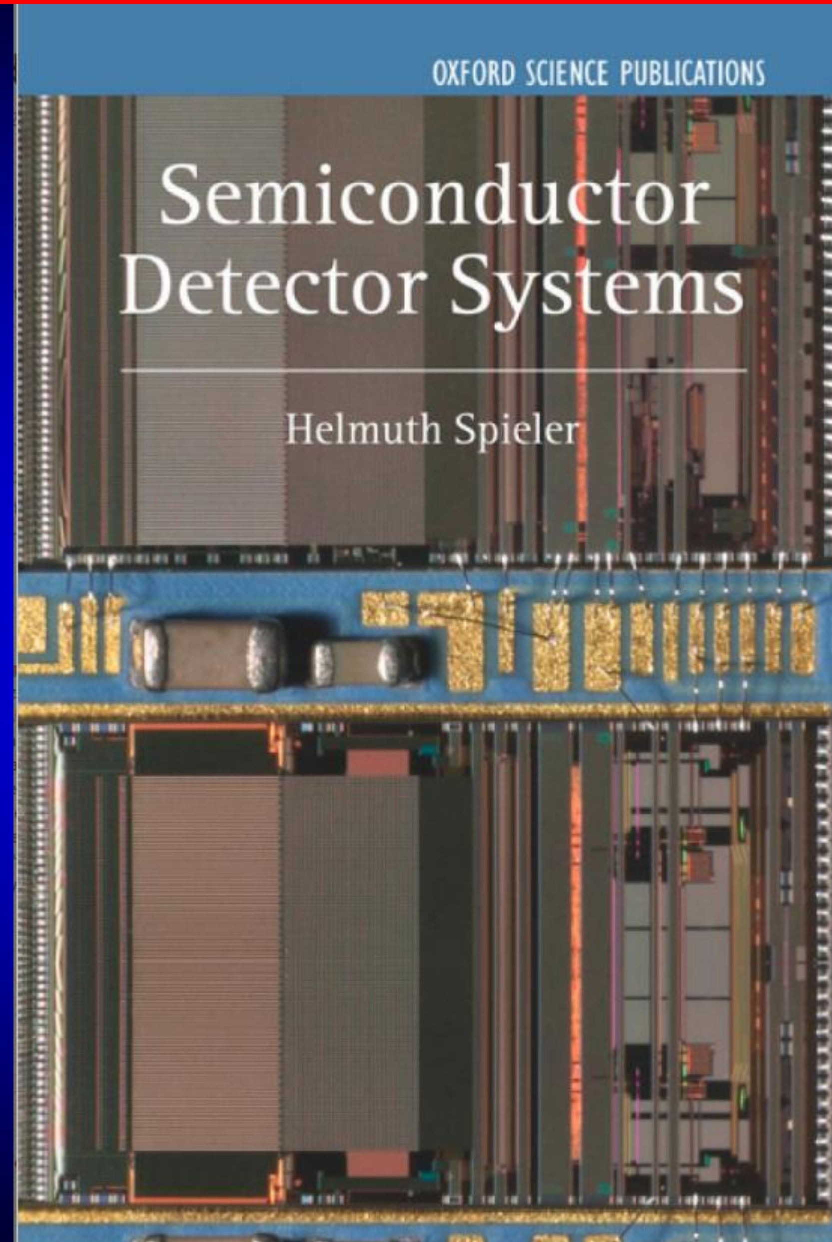
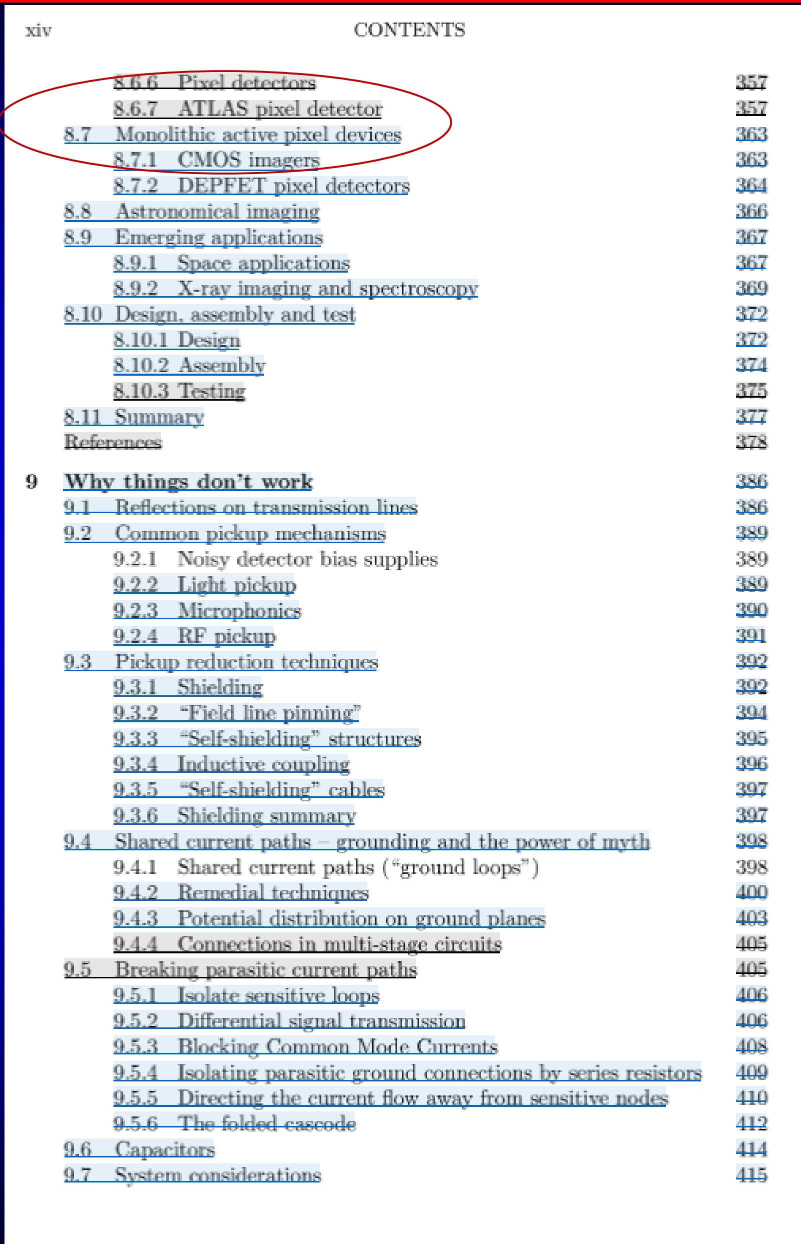
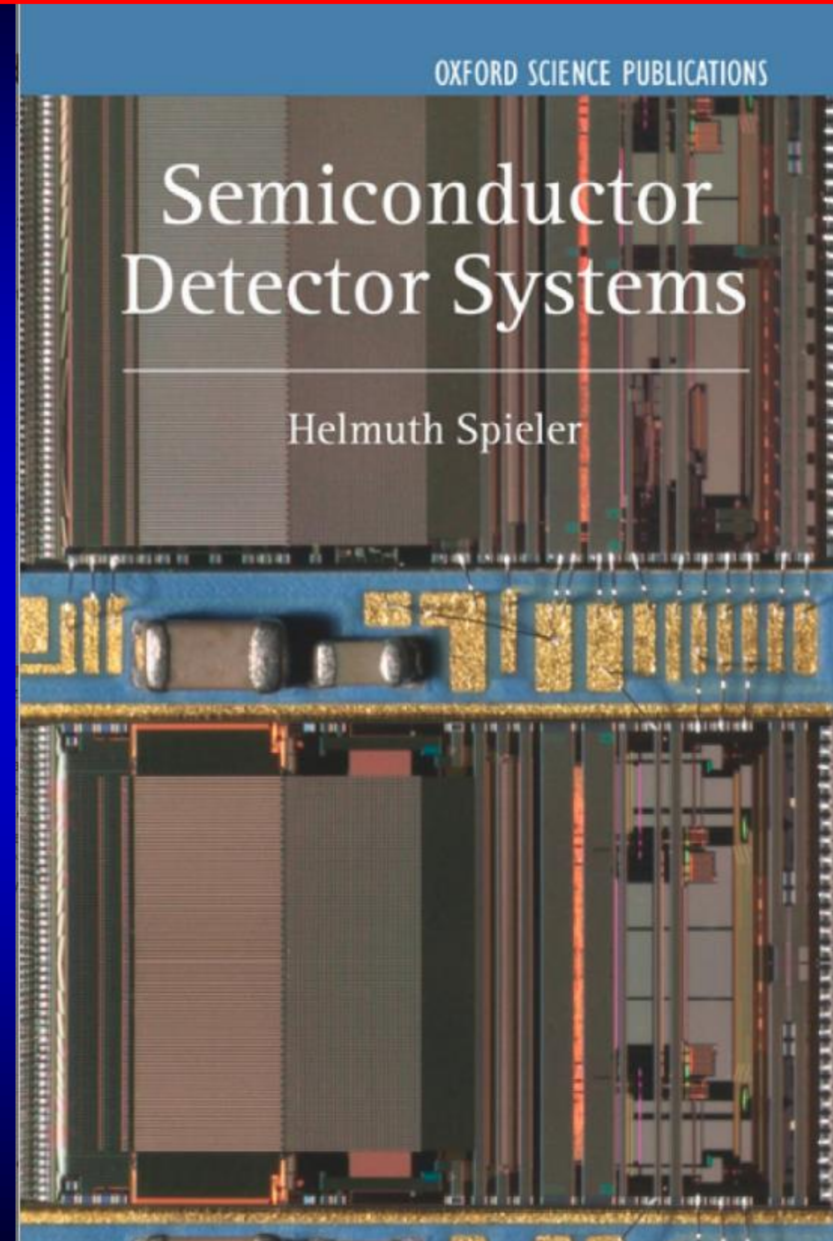




Students Requests (by e-mail) From Lecture Part 1


xiv CONTENTS



Outline

- Introduction
  - Kinematic variables

- Predicted but Totally Unexpected: Quark-Gluon Plasma Behaves as Perfect Liquid
  - Jet Quenching: created matter is very dense and opaque
  - High p_T Azimuthal Correlations
  - Elliptic flow: QGP behaves as perfect liquid

- Surprise: QGP-like Behavior in Small Colliding Systems
  - Non-zero p,d, ^{3}He + A $v_n(p_T)$ moments comparable to the A+A ones

- Quarkonia as Probe for Hot and Cold Nuclear Matter (**Required Another Lecture**)
  - J/ψ and Υ measurements: centrality, system size and energy Dependence

- From RHIC to EIC Future Project, and Opportunities

Rapidity

($c = 1$, z coordinate along collision axis)

Four-momentum:

$$p^{\mu} = (p^0, p^1, p^2, p^3) = (E, \vec{p}) = (E, \vec{p}_T, p_z = p_{//})$$

Addition of velocities along z:

$$v = v_1 + v_2 \quad \text{(Galileo)} \qquad \beta = \frac{\beta_1 + \beta_2}{1 + \beta_1 \beta_2} \quad \text{(relativistic)}$$

$$\tanh(y_1 + y_2) = \frac{\tanh y_1 + \tanh y_2}{1 + \tanh y_1 \tanh y_2}$$

$$y = \tanh^{-1} \beta = \frac{1}{2} \ln\left(\frac{1+\beta}{1-\beta}\right) \quad \text{“rapidity”}$$

Rapidity

$$y = \tanh^{-1}\beta = \frac{1}{2}\ln\left(\frac{1+\beta}{1-\beta}\right)$$

in the non-relativistic limit: $y = \beta$

under a Lorentz transformation to a frame moving with velocity β along z : $y \rightarrow y' = y - y_\beta$ (rapidities "add-up")

rapidity distributions are boost-invariant (along z): $\frac{dN}{dy'} = \frac{dN}{dy}$

it can be easily shown that:

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$$

For RHIC Au+Au at Eenergy = 200 GeV/n → y_{beam} = 5.37

Transverse Variables

Transverse momentum:

$$\vec{p}_T = (p_x, p_y) \qquad p_T = \sqrt{p_x^2 + p_y^2}$$

Transverse mass:

$$m_T = \sqrt{m^2 + p_T^2} \qquad E = \sqrt{m^2 + p^2} = \sqrt{m_T^2 + p_z^2}$$

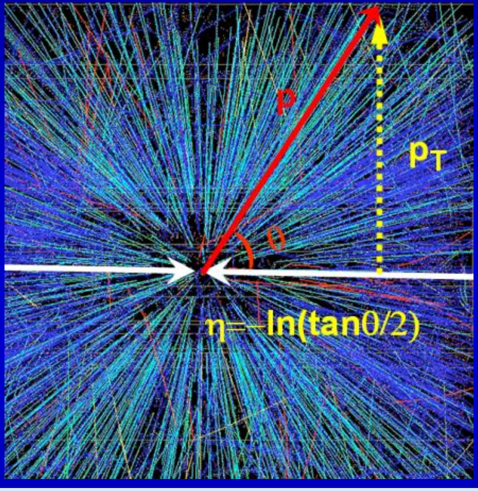
$$p_z = m_T \sinh(y) \qquad E = m_T \cosh(y)$$

Transverse energy:

$$E_T = \sum_i E_i \sin\theta_i \qquad \theta_i = \text{angle w.r.t. beam direction}$$

Pseudorapidity

- Sometimes the energy and momentum of a particle are not known, only its angle of emission θ with respect to the beam axis (z) is measured
- For high energy particles, it is possible to approximate the rapidity by the pseudorapidity:



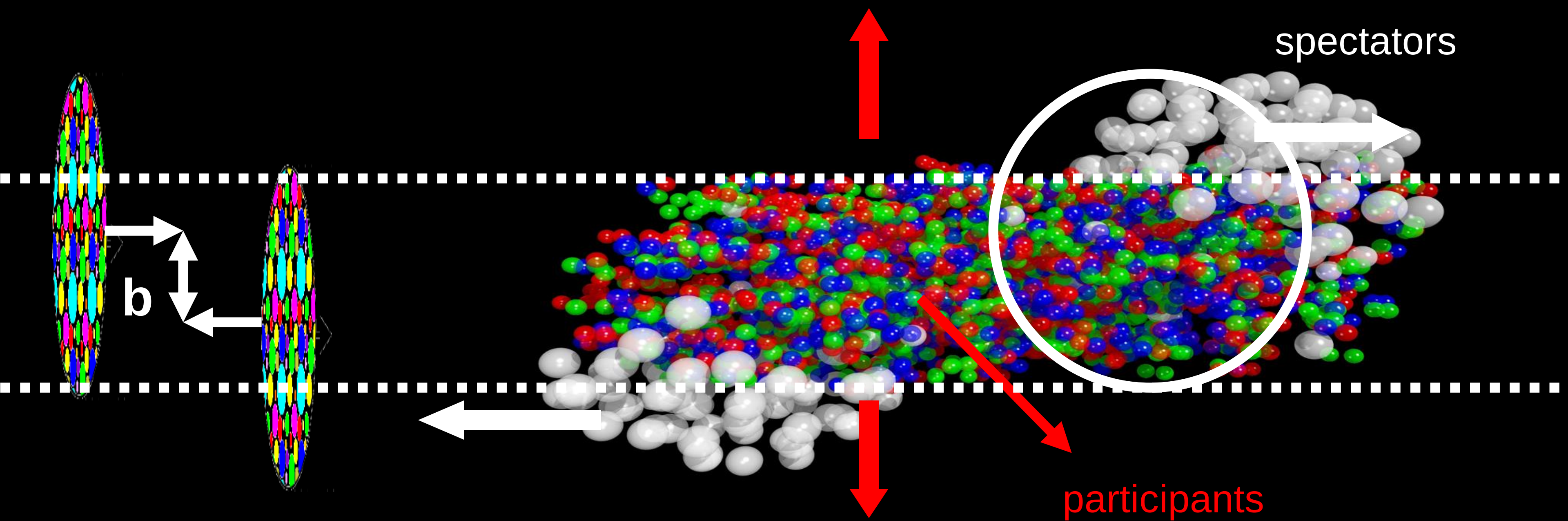
$$\eta = -\log \tan(\theta/2) = \frac{1}{2}\log\left(\frac{p+p_z}{p-p_z}\right)$$

in the ultra-relativistic limit:
$E \sim p$ and $\eta \sim y$

$$p_z = p_T \sinh(\eta) \qquad p = p_T \cosh(\eta)$$

Collision Centrality

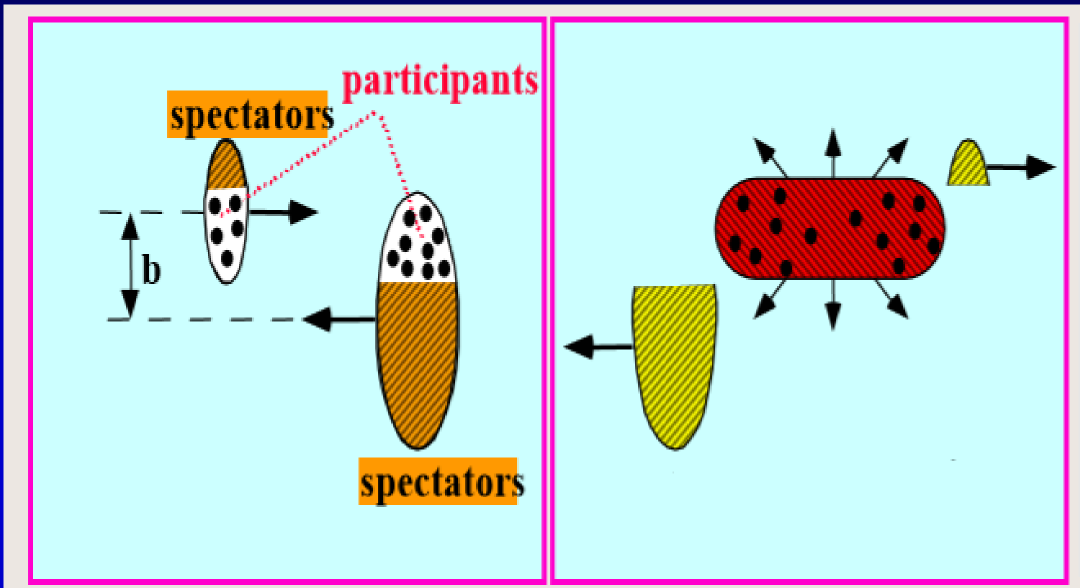
- Very simple illustration for N_{part} and N_{binary}

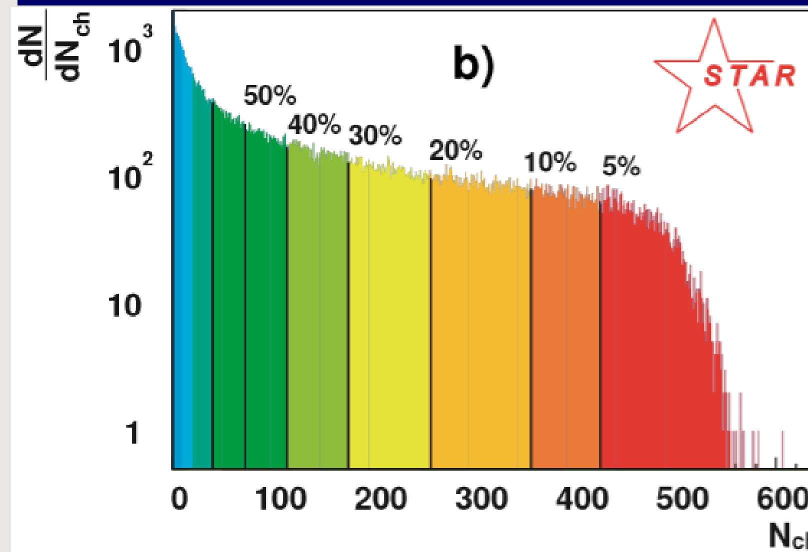


- Centrality characterized by:
  - N_{part}: number of nucleons which suffered at least one inelastic nucleon-nucleon collision
  - N_{binary}: number of inelastic nucleon-nucleon collisions

Collision Centrality

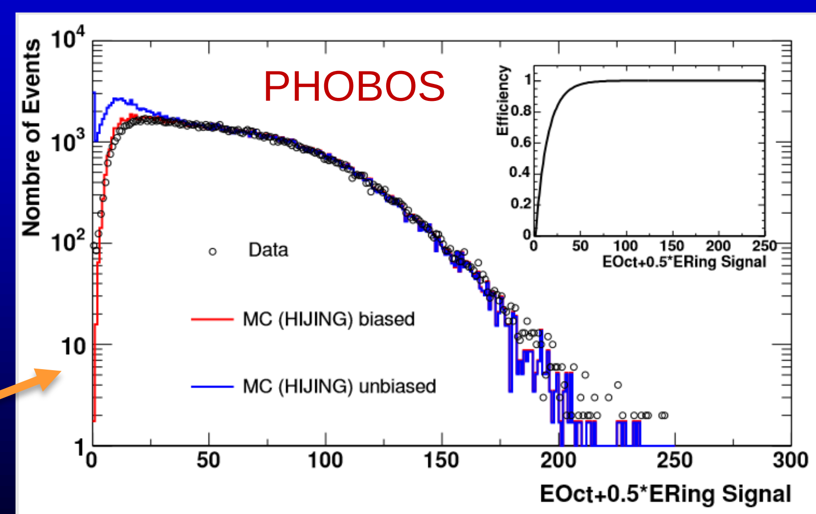
- How far do the centers of the two colliding nuclei pass each other?





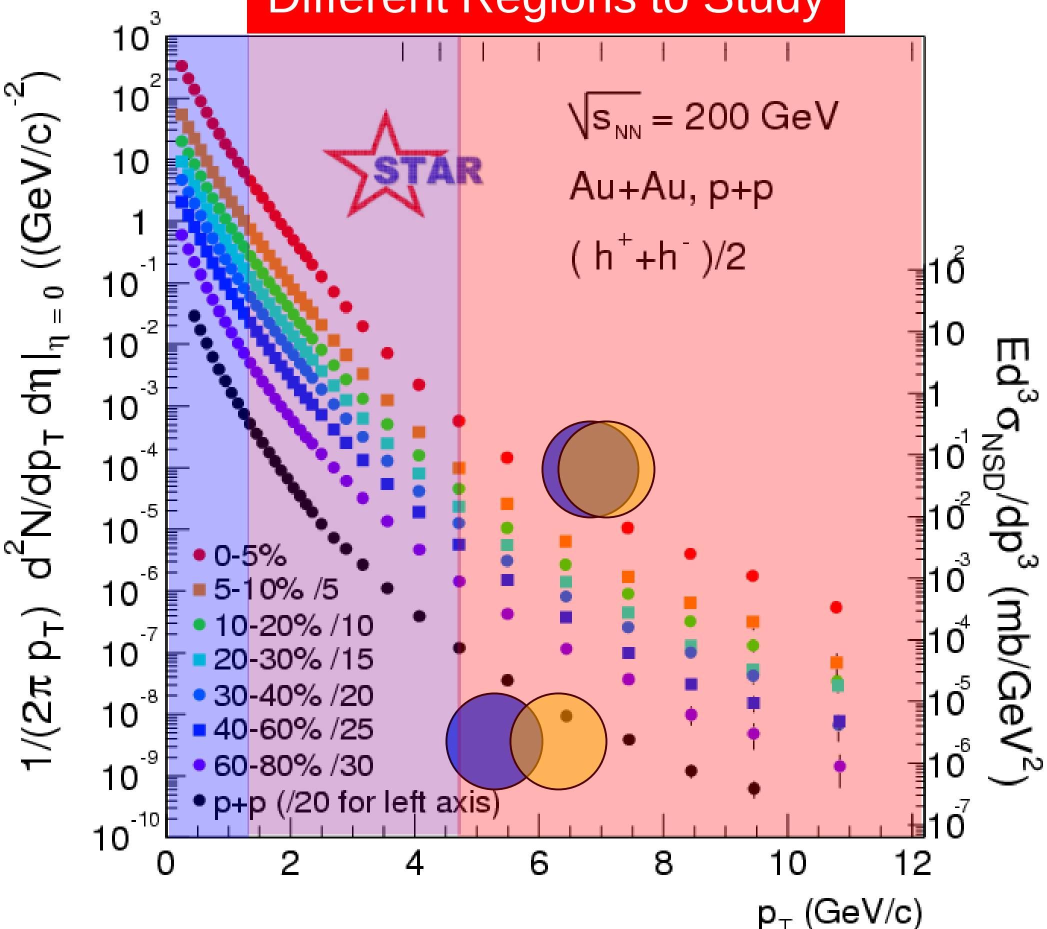
- Usually expressed in terms of:
  - – b (impact parameter)
  - – Number of participants $N_{part}(b)$

Using models like HIJING model for Au+Au



Hadron p_T Spectra in Au+Au

Different Regions to Study



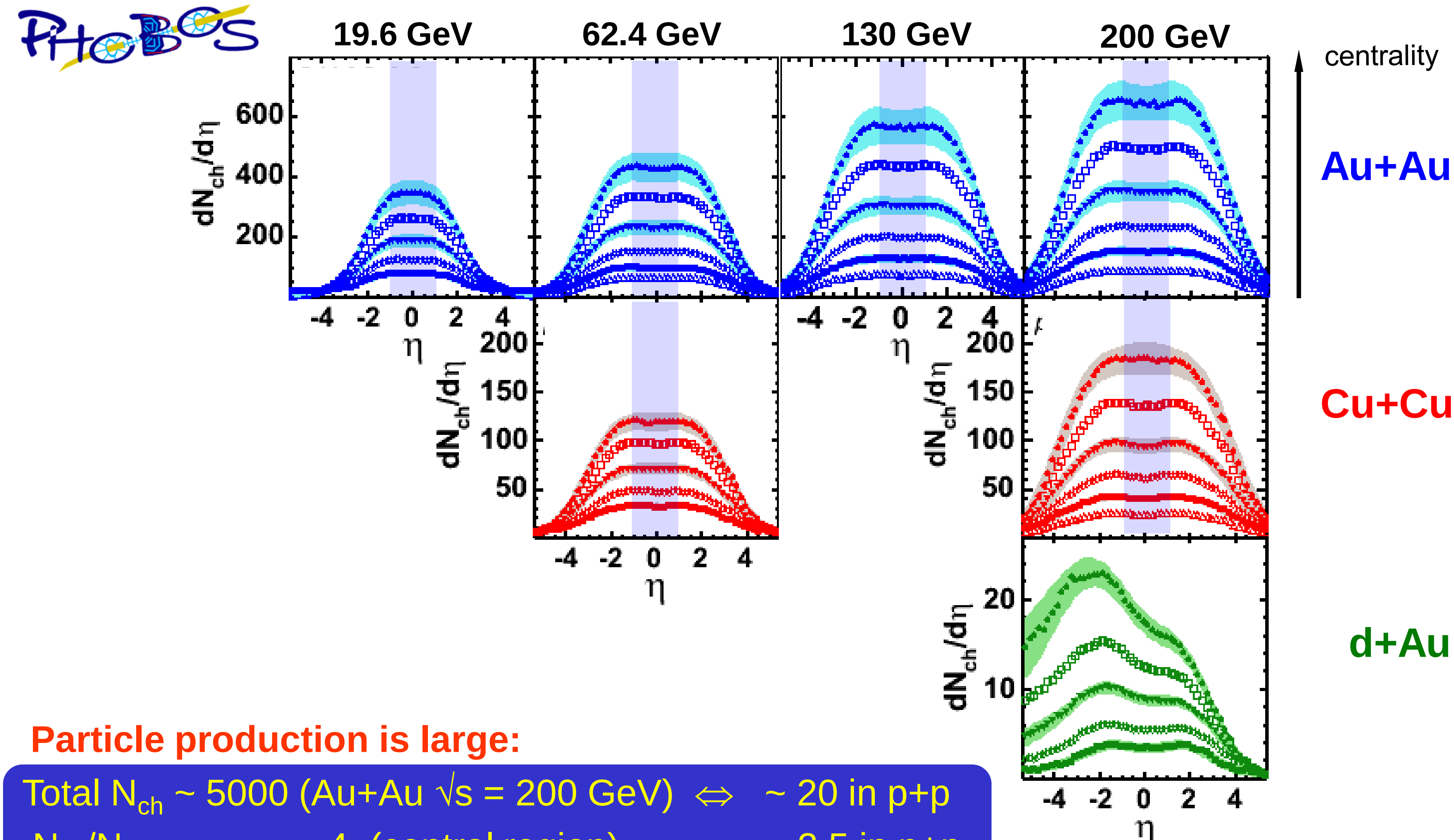
Low p_T: Measure Bulk/Global Properties (99% of particles)

High p_T: Small cross section, short wavelength

"Intermediate" p_T: soft/hard interplay, surprises?

Global Properties: Particle Density Distributions

We define the mid-rapidity region: $|\eta| < 1$

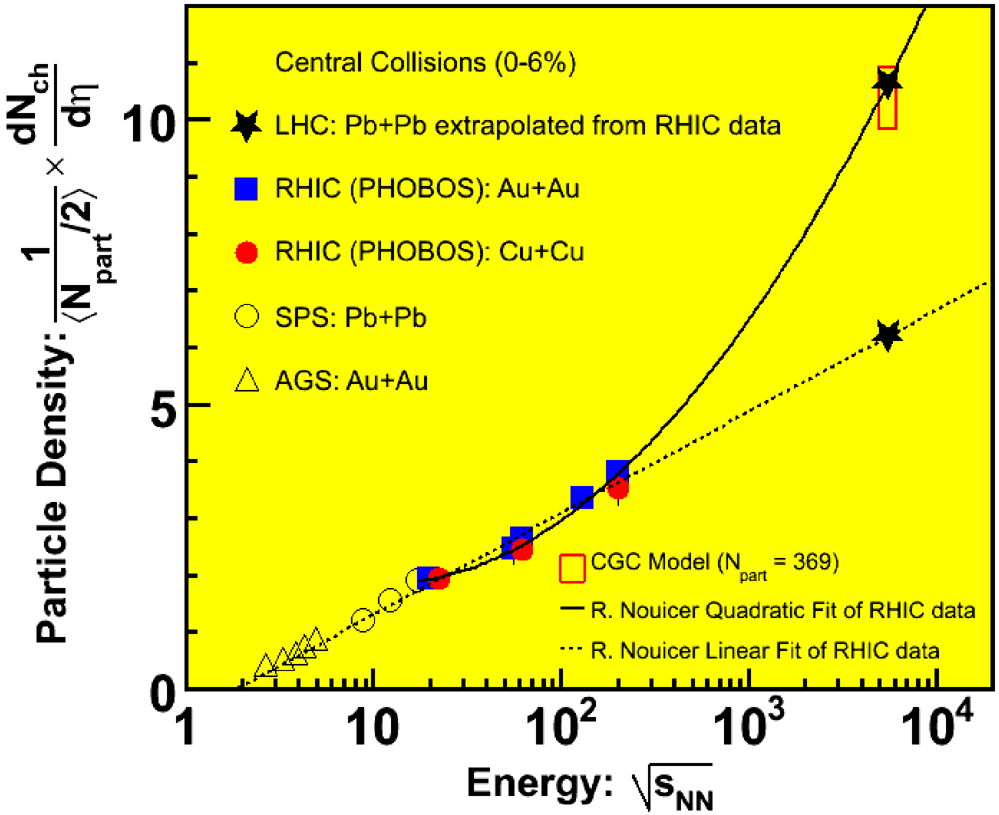


Particle production is large:

Total N_{ch} ~ 5000 (Au+Au $\sqrt{s}$ = 200 GeV) ⇔ ~ 20 in p+p

$N_{ch}/N_{participant\text{-}pair}$ ~ 4 (central region) ⇔ ~ 2.5 in p+p

Global Properties: Bjorken Energy Density



- Relativistic hydrodynamics in Bjorken model (boost invariance $\Rightarrow \eta \sim 0$) :

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau} \langle p_T \rangle \frac{3}{2} \frac{dN_{ch}}{d\eta} \qquad (R \sim A^{1/3}, \tau = 1 \text{ fm/c})$$

Under these simplifying assumptions, $\varepsilon \sim 5$ GeV/fm^3

$\Rightarrow$ well above critical energy density ~1 GeV/fm^3 from LQCD

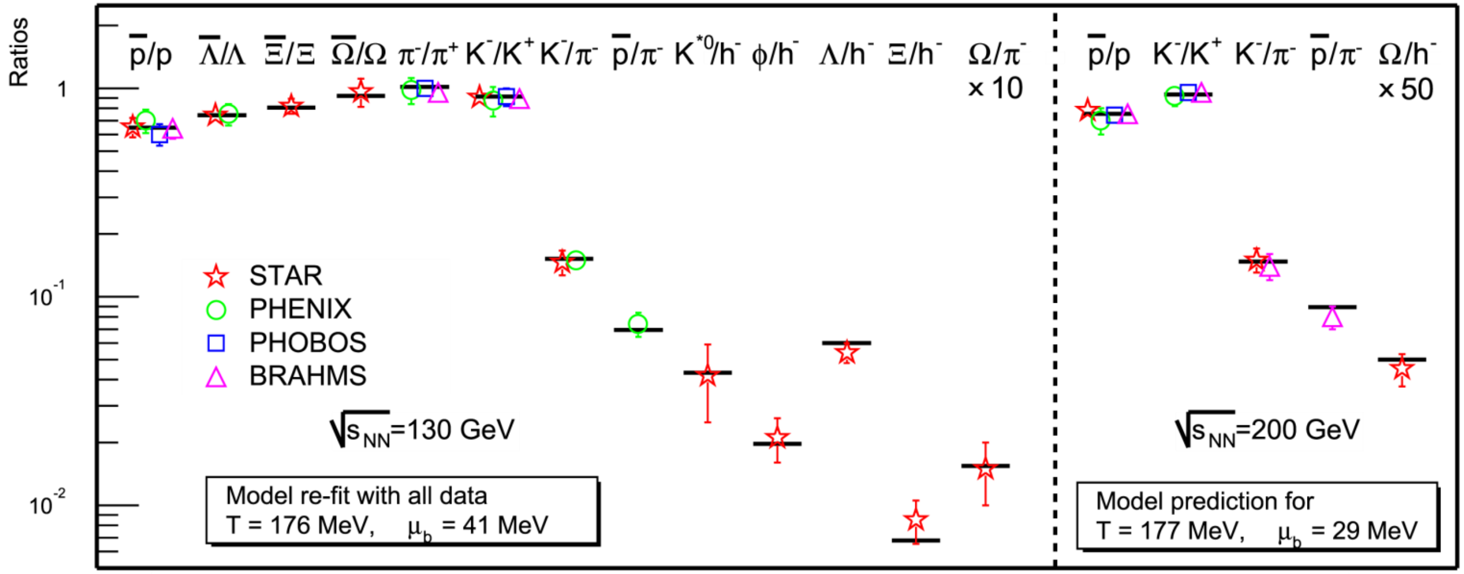
Global Properties: Particle Yields

Grand-canonical ensemble of particles in local equilibrium

- Assume all distributions described by one temperature T and one (baryon) chemical potential μ : $dn \sim e^{-(E-\mu)/T} d^3p$

- One ratio (e.g., $\bar{p}$ / p) determines μ / T : $\frac{\bar{p}}{p} = \frac{e^{-(E+\mu)/T}}{e^{-(E-\mu)/T}} = e^{-2\mu/T}$
- A second ratio (e.g., K / p) provides T ➔ μ

Then predict all other hadronic yields and ratios:



Braun-Munzinger et al., PLB 518 (2001) 41 D. Magestro (updated July 22, 2002)

Hadrons yields:
⇒ chemical equilibration across u, d and s quark sectors

What's next?

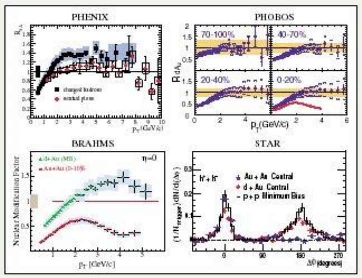
- We measured thousands of particles… What do we want to see?
  – Macroscopic behavior
- QGP is thermodynamic in nature
  – Gas or Fluid?
- Look for collective flow…

RHIC Discoveries in the Press

Physical Review Letters

Articles published week ending 15 August 2003

Volume 91, Number 7



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APS Published by The American Physical Society

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

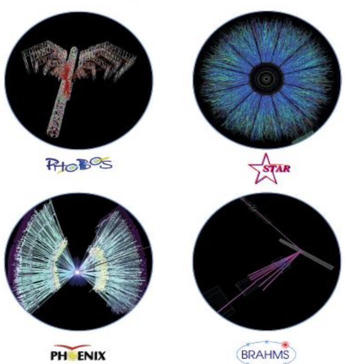
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005



Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

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Science News ... from universities, journals

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

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 o Laboratory)

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The Royal Society   Frontiers in Astronomy: one day symposium
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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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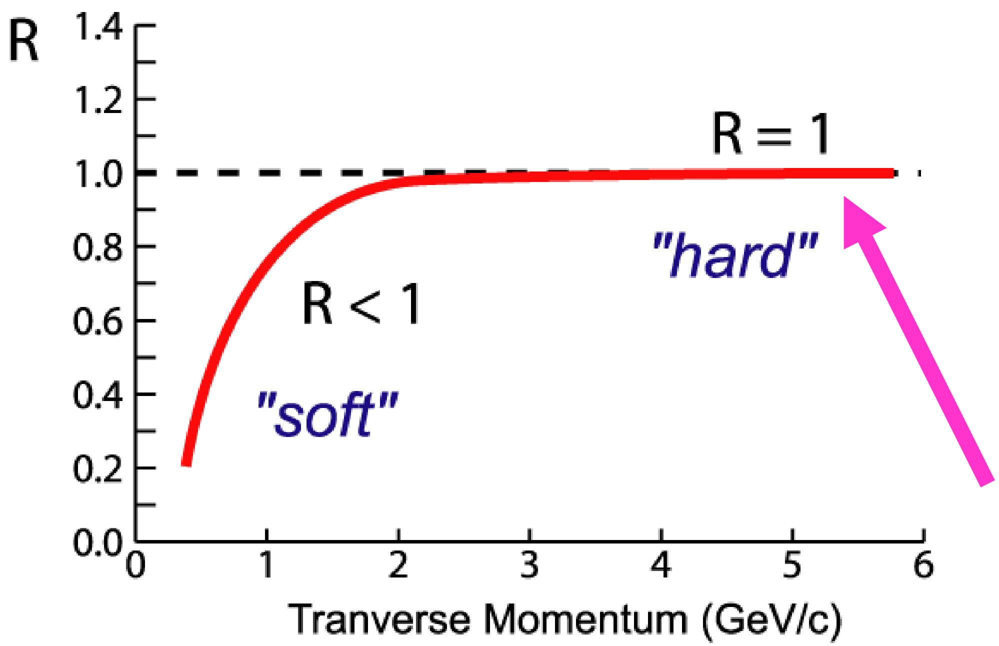
Jet Suppression - Nuclear Modification Factor

We define a nuclear modification factor, R_{AA}, in terms of the ratio of the p_t spectra in nucleus-nucleus collisions divided by the p_t spectra in p+p collisions

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$ ⟺ (Nuclear Geometry)



If no "effects":

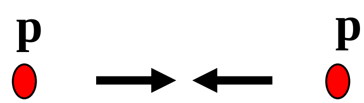
- R < 1 in regime of soft physics
- R = 1 at high-p_T where hard scattering dominates

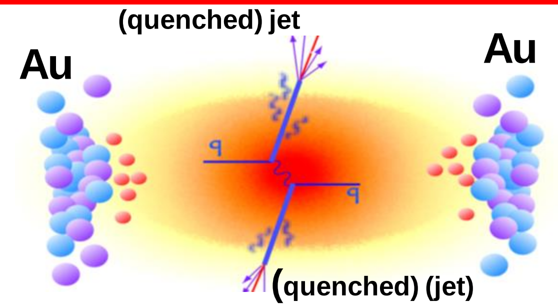
Suppression ?

- Is R < 1 at high-p_T ?

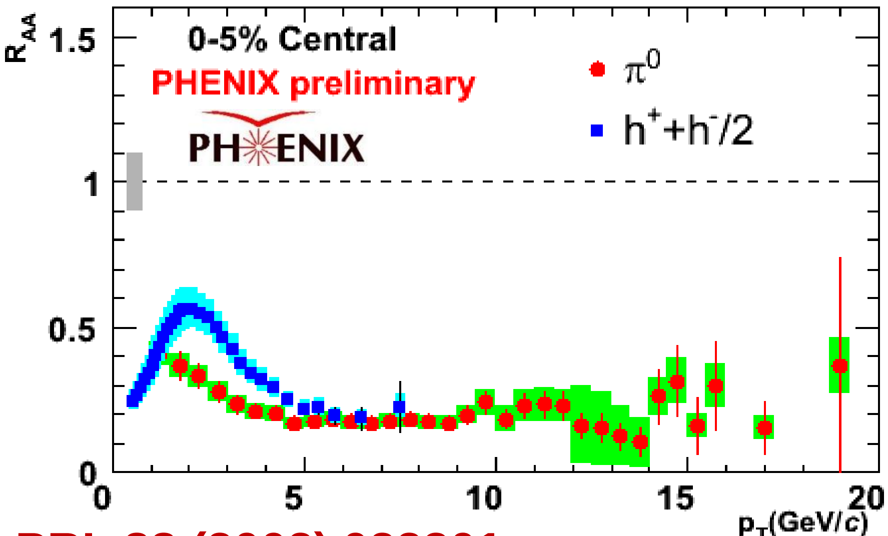
RHIC: Jet Quenching "Major Discovery"

$$R_{AA}(p_T, y, b) = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}(b)\rangle\, d^2\sigma^{NN}/dp_T d\eta}$$

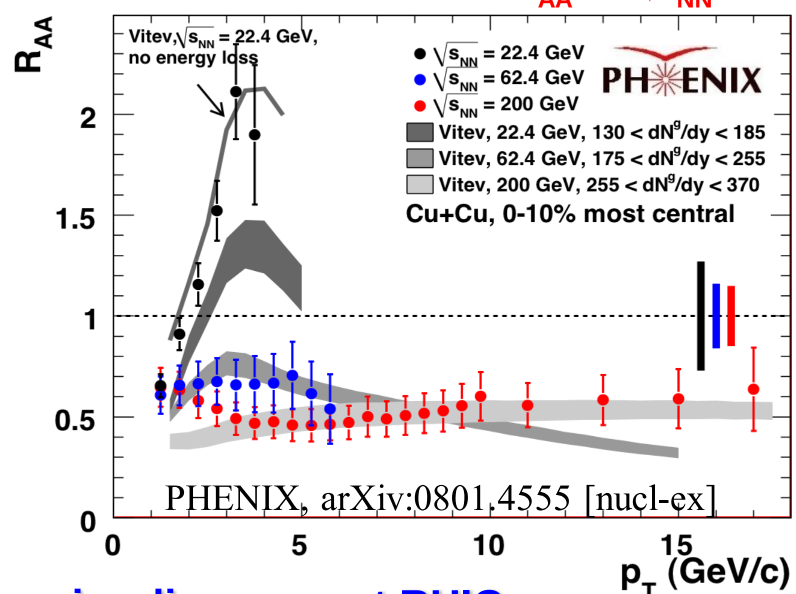




Au Au $\sqrt{s_{NN}}$=200 GeV-QM 2005



CuCu central 10% $\pi^0 R_{AA}$ vs $\sqrt{s_{NN}}$



PRL 88 (2002) 022301

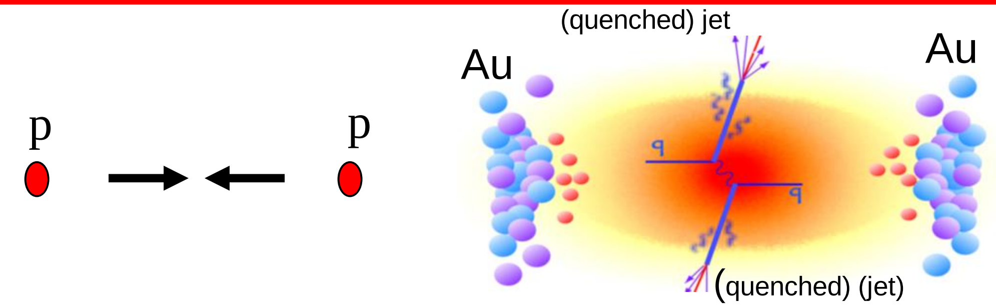
✓ **Suppression of π^0 is the major discovery at RHIC.**
Energy loss in medium?

→ **Suppression is unique at RHIC-different from low $\sqrt{s_{NN}}$ (22.4 < $\sqrt{s_{NN}}$ < 62.4GeV)**

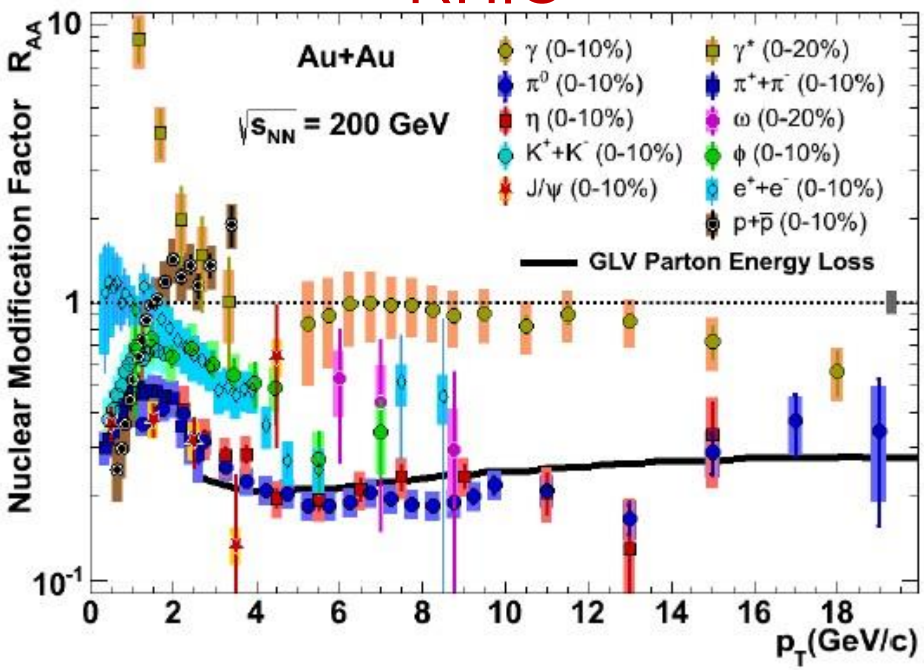
π^0 suppressed by a factor of 5 compared to point-like scaling for 3< p_T< 20 GeV/c!
Non-identified $h^\pm$ and π^0 are different for p_T < 6 GeV/c ⇒ particle ID is important.

RHIC: Jet Quenching "Major Discovery"

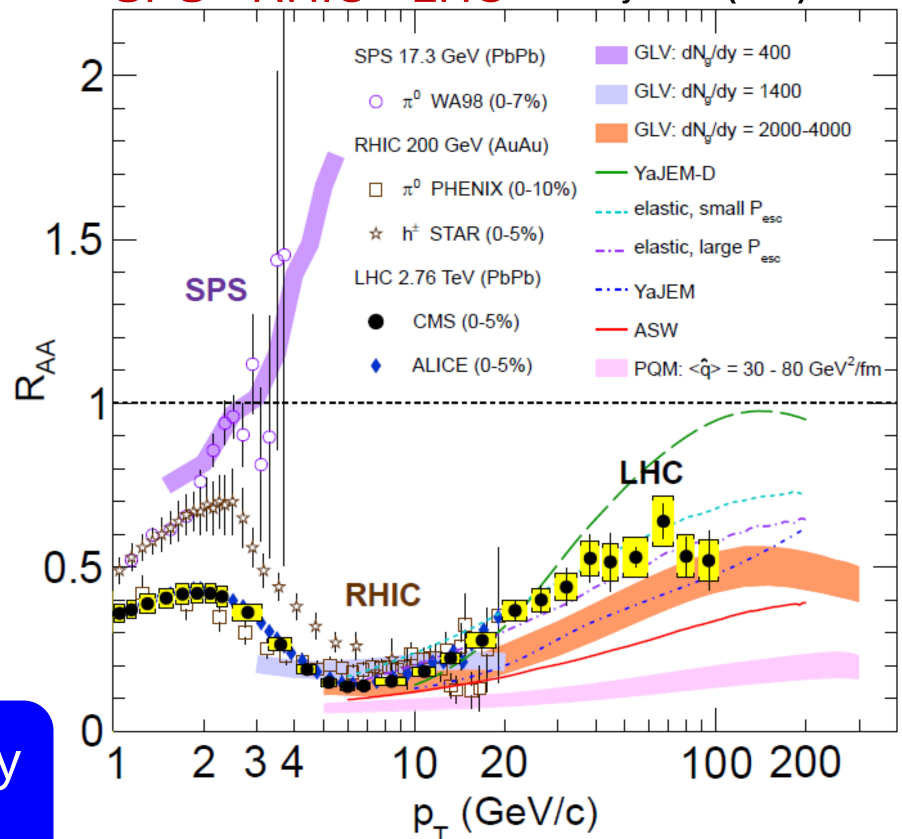
$$R_{AA}(p_T, y, b) = \frac{d^2N^{AA}/dp_T d\eta}{\langle T_{AA}(b)\rangle\, d^2\sigma^{pp}/dp_T d\eta}$$



RHIC



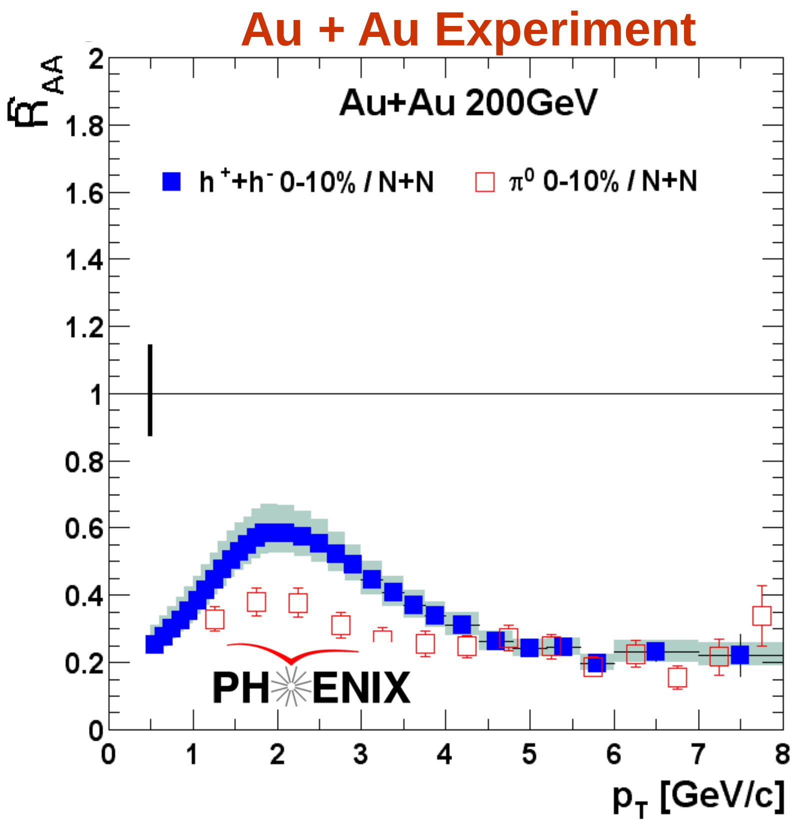
SPS - RHIC - LHC Eur. Phys. J. C (2012) 72:1945

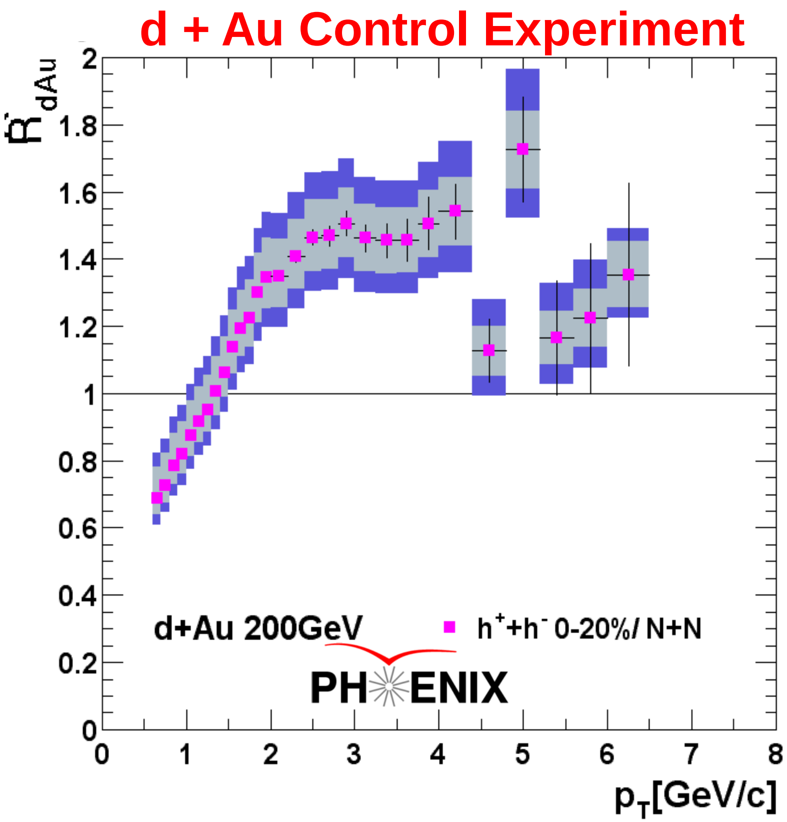


Suppression of π^0 is the major discovery at RHIC as well at LHC

Suppression of Leading Hadrons

The data from p+p, Au+Au and d+Au collisions establish that *a new effect* (a new state of matter?) is produced in central Au-Au collisions



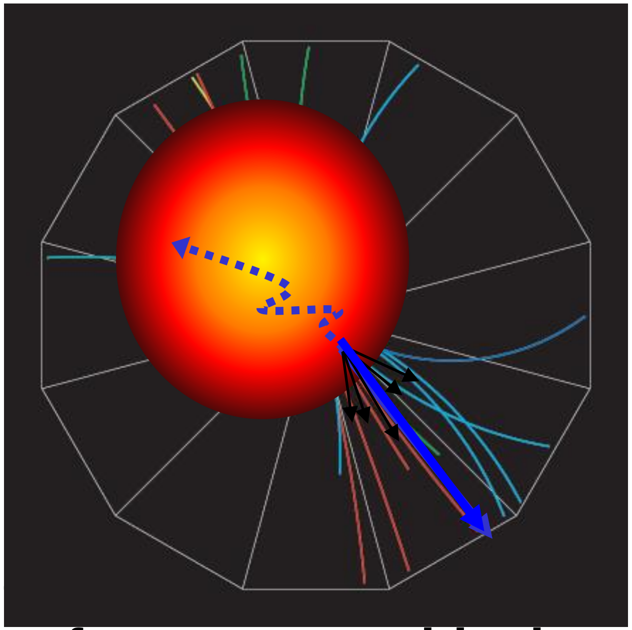


Suppression in central Au+Au due to final-state effects

High p_T Azimuthal Correlations (2-particle Azimuthal Distributions)

STAR event display of pp event

In central Au+Au collisions:



Near-si

• **partons fragment outside the medium**

"Trigger" $\phi = 0$

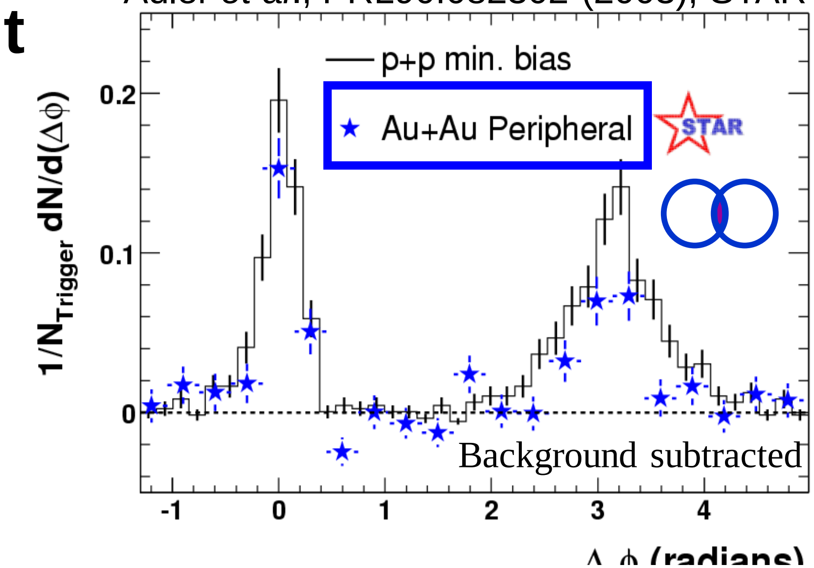
Away side:

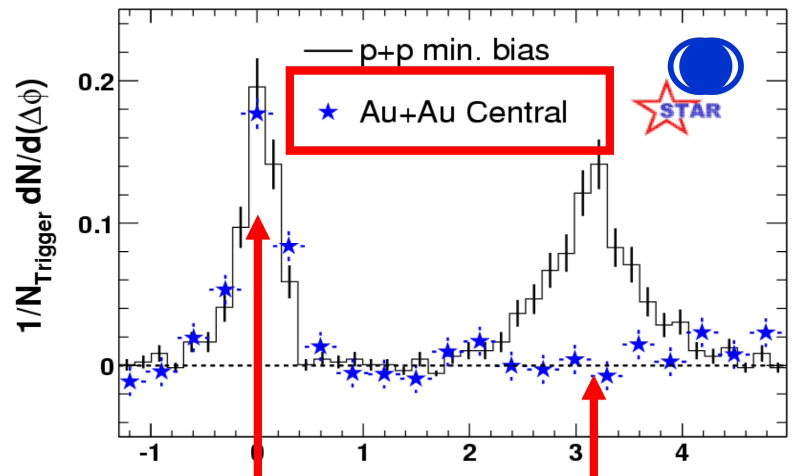
• **partons are absorbed by the medium**

Clear correlation of particles in azimuth

"Surface" or "Skin" emission

Adler *et al.*, PRL90:082302 (2003), STAR



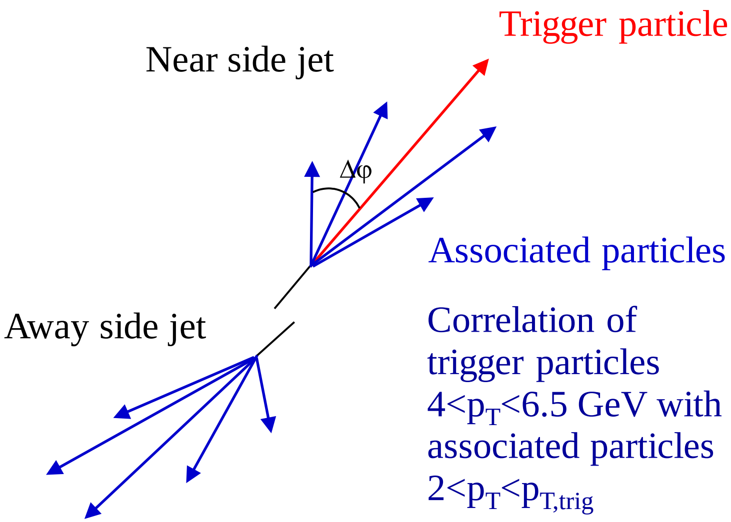


"Near side" jet identical!

"Away side" gone!

Again, can we get more information?

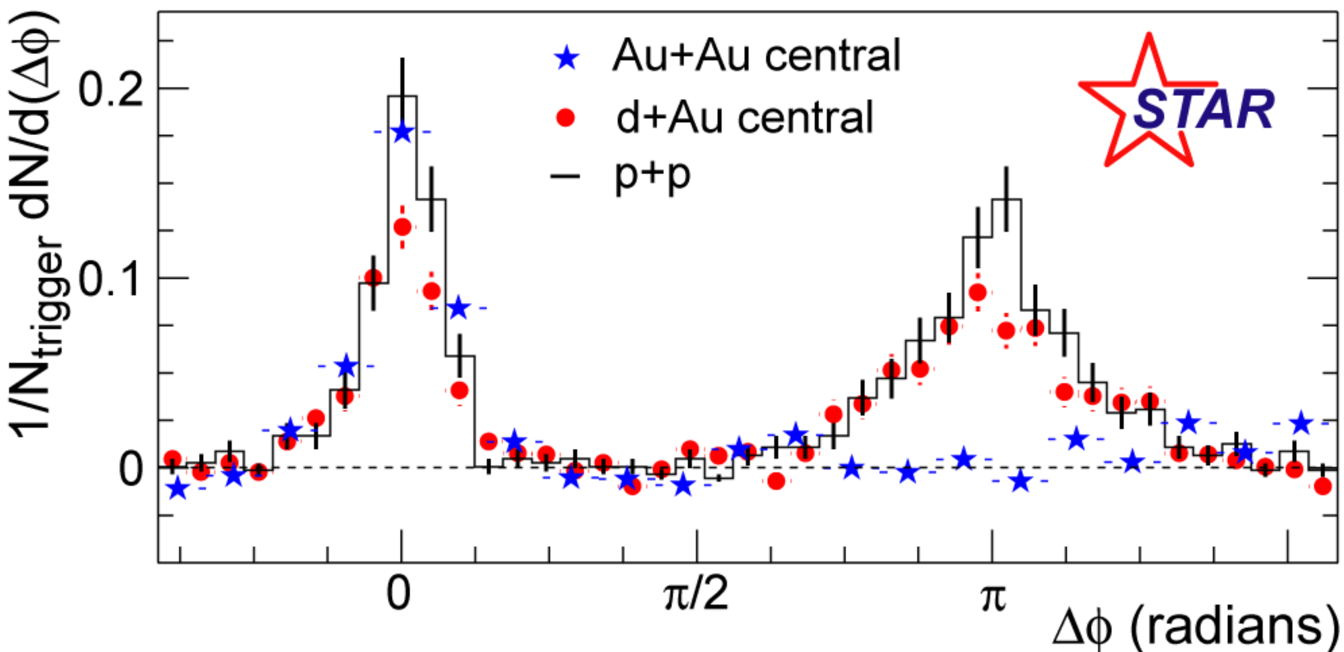
d+Au versus Au+Au collisions



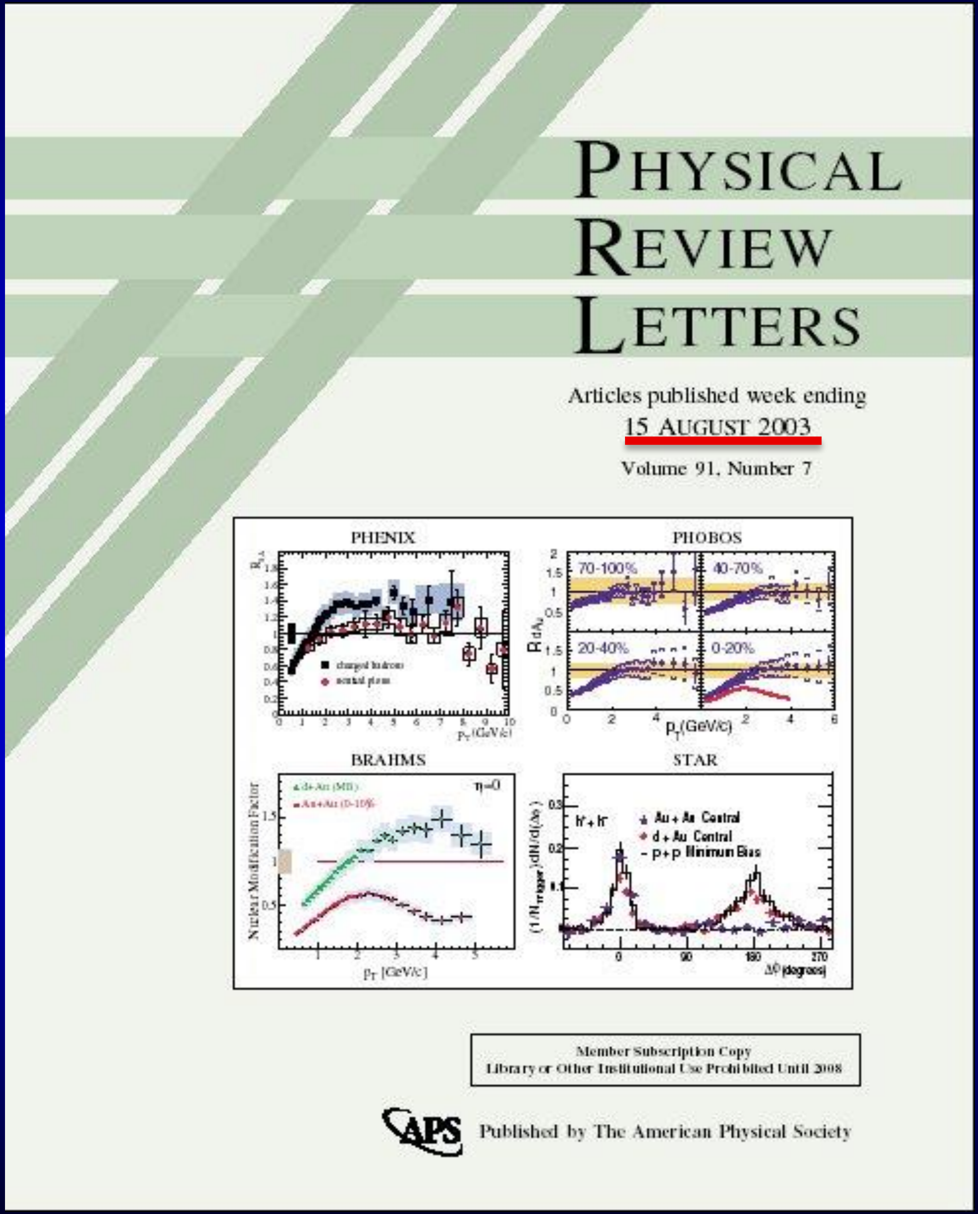
Correlation of trigger particles $4<p_T<6.5$ GeV with associated particles $2<p_T<p_{T,trig}$

Near side $\Delta\phi \approx 0$: p+p, d+Au, Au+Au similar

Back-to-back $\Delta\phi \approx \pi$:
Au+Au suppressed relative to p+p **and** d+Au



Au+Au @ 200 GeV (central): Suppression



Discovery of

high p_T suppression

(one of most significant

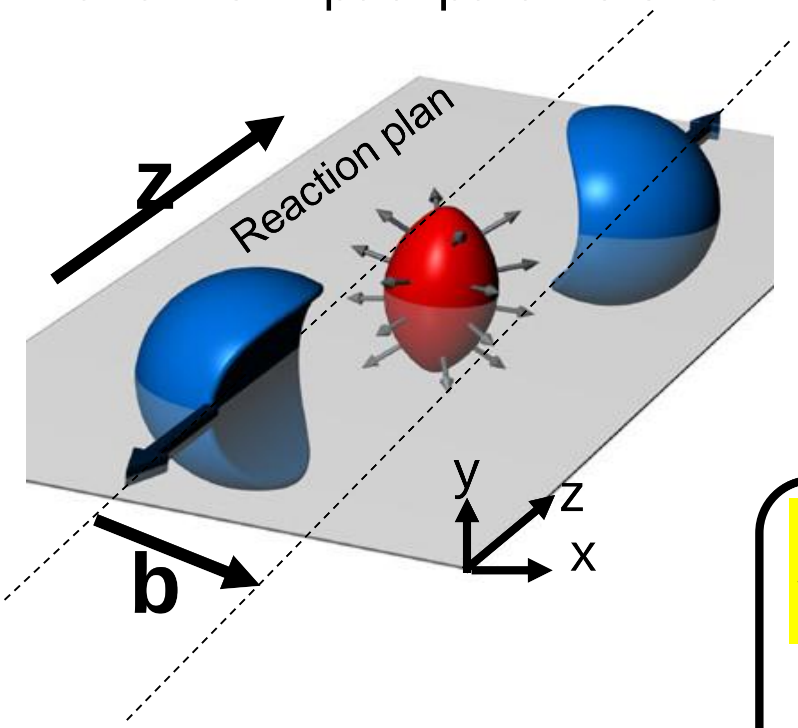
results @ RHIC so far)

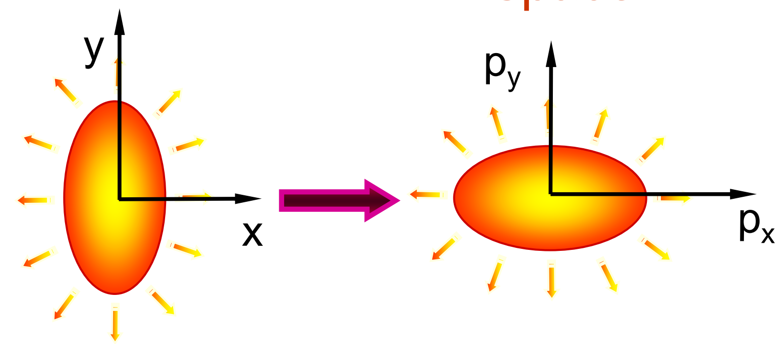
Suppression in central Au+Au due to final-state effects

Elliptic Flow a Unique Probe!

The reaction plane

- Spanned by the beam direction and the impact parameter **b**





Fourier transformation of the produced particles azimuthal distribution

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi-\Psi_r\right)\right)\right)$$

$$v_2 = \langle \cos 2(\varphi-\Psi_r)\rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

The almond shape of the created quark gluon plasma in non-central collisions leads to an azimuthal dependence of the observables sensitive to the medium properties

Why is elliptic flow interesting?

Flow correlations provide an important probe

- *Provides reliable estimates of pressure & pressure gradients*
- *Can address questions related to thermalization*
- *Gives insights on the transverse and longitudinal dynamics of the medium*
- *Provides access to the properties of the medium - EOS, viscosity, etc*

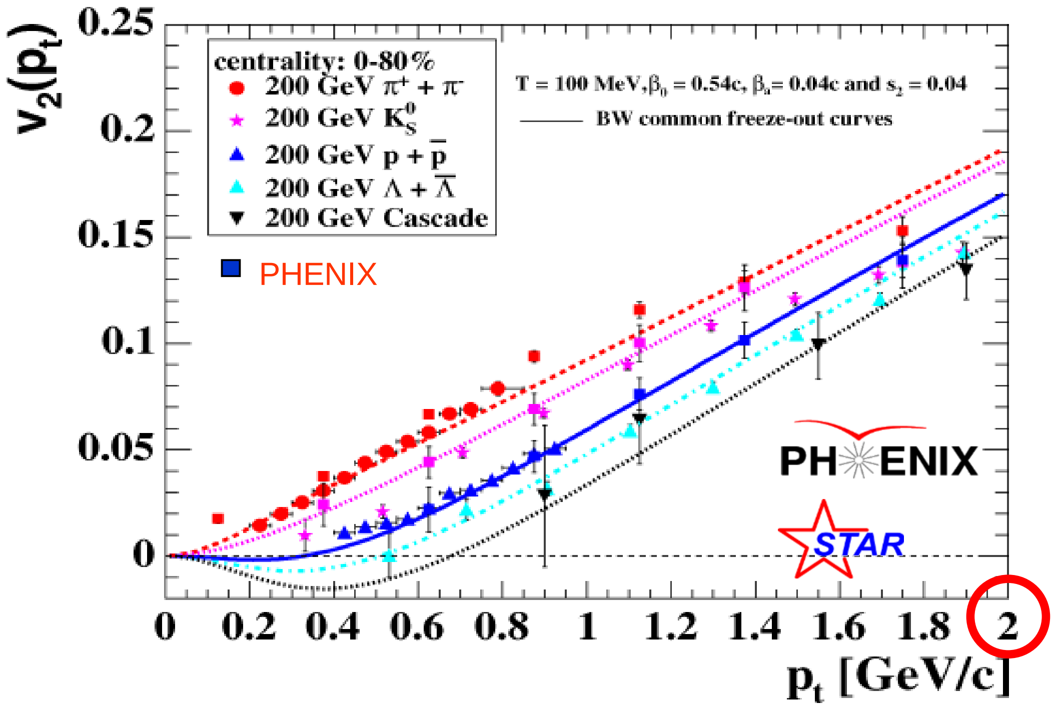
Elliptic flow => sensitivity to *early* system

“Elliptic flow”

- evidence of *collective* motion
- self-quenching

⇒ sensitive to *early* pressure

- evidence for
  - early thermalization
  - QGP in early stage
- Fluid cells expand with collective velocity v, different mass particles get different Δp



Elliptic flow at RHIC:

Magnitude, mass and p_T-dependence are in good agreement with ideal hydrodynamic flow, for the first time in HIC

Ideal hydrodynamics: (QGP equation-of-state)

viscosity/entropy~0.1

⇒ **near-perfect fluid!**

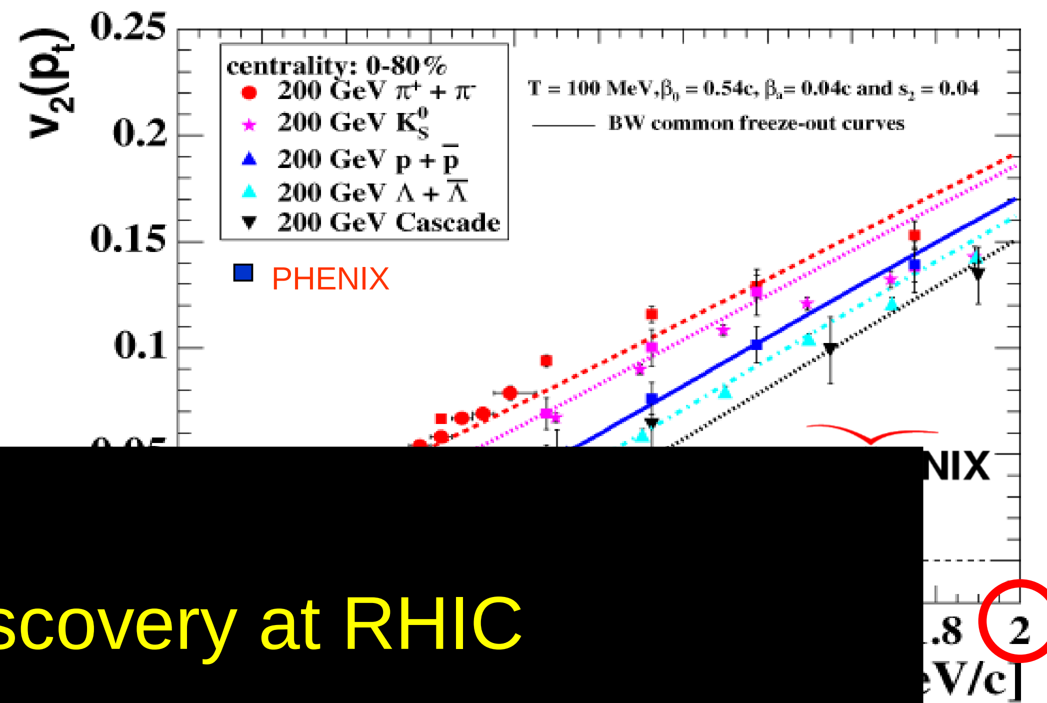
Elliptic flow => sensitivity to *early* system

"Elliptic flow"

- evidence of *collective* motion
- self-quenching

⇒ sensitive to *early* pressure

- ev
  -
  -
- Fl
  velocity v, different mass particles get different Δp



Major Discovery at RHIC

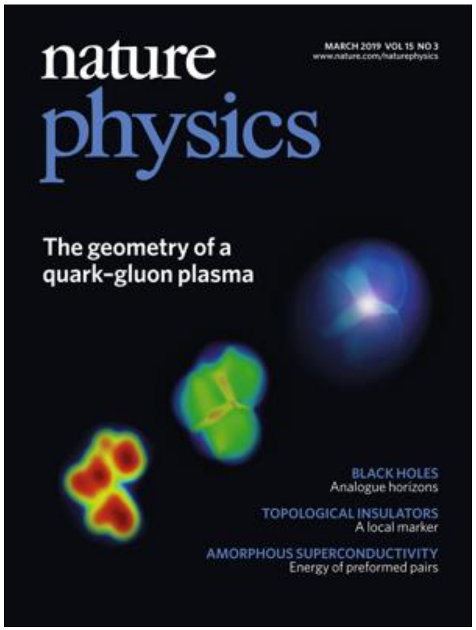
magnitude, mass and p_T-dependence are in good agreement with ideal hydrodynamic flow, for the first time in HIC

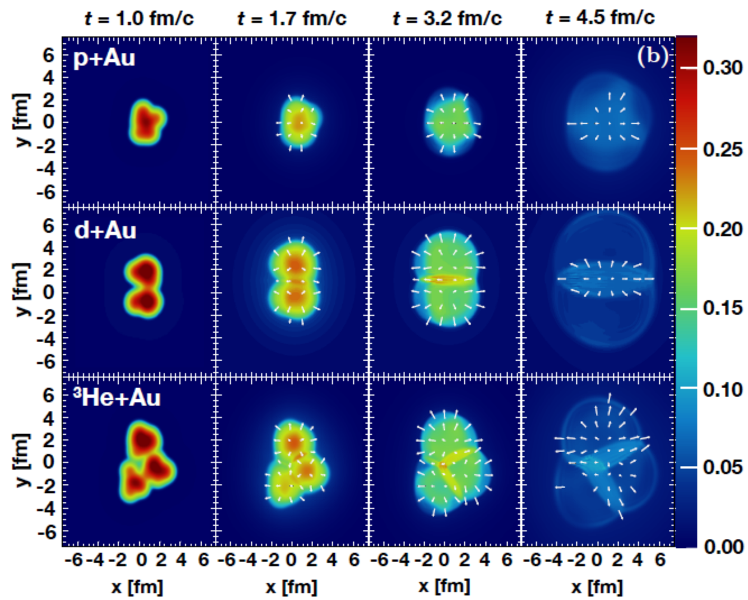
Ideal hydrodynamics: (QGP equation-of-state)
viscosity/entropy~0.1
⇒ **near-perfect fluid!**

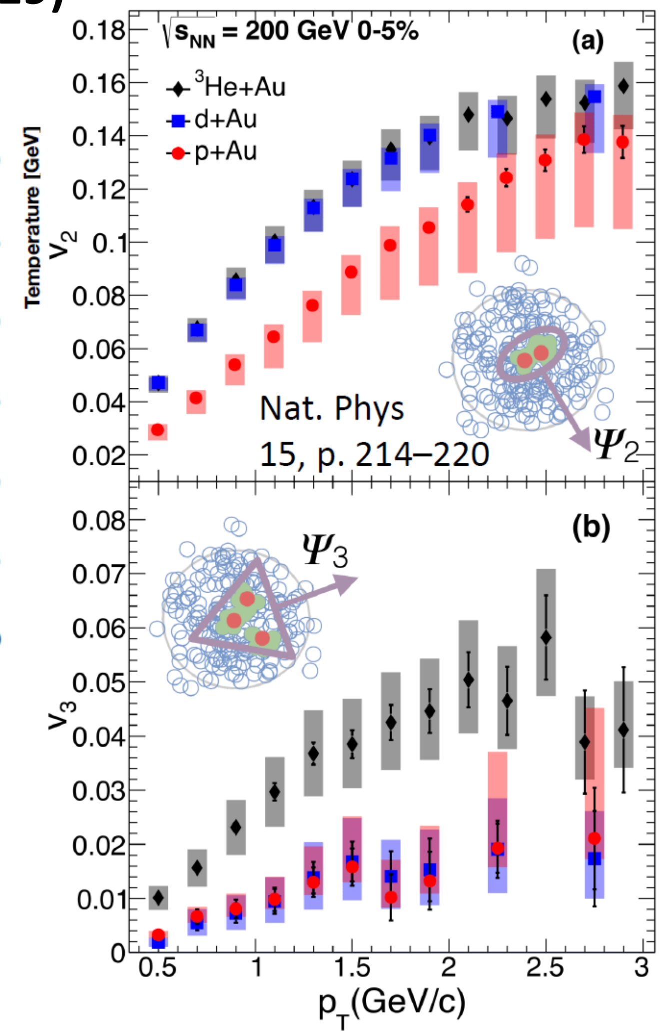
Results in Small Systems: Flow

Evidence of QGP Droplets in Small Systems

Nature Physics **15, pages 214–220 (2019)**







Lower v_2 in p+Au

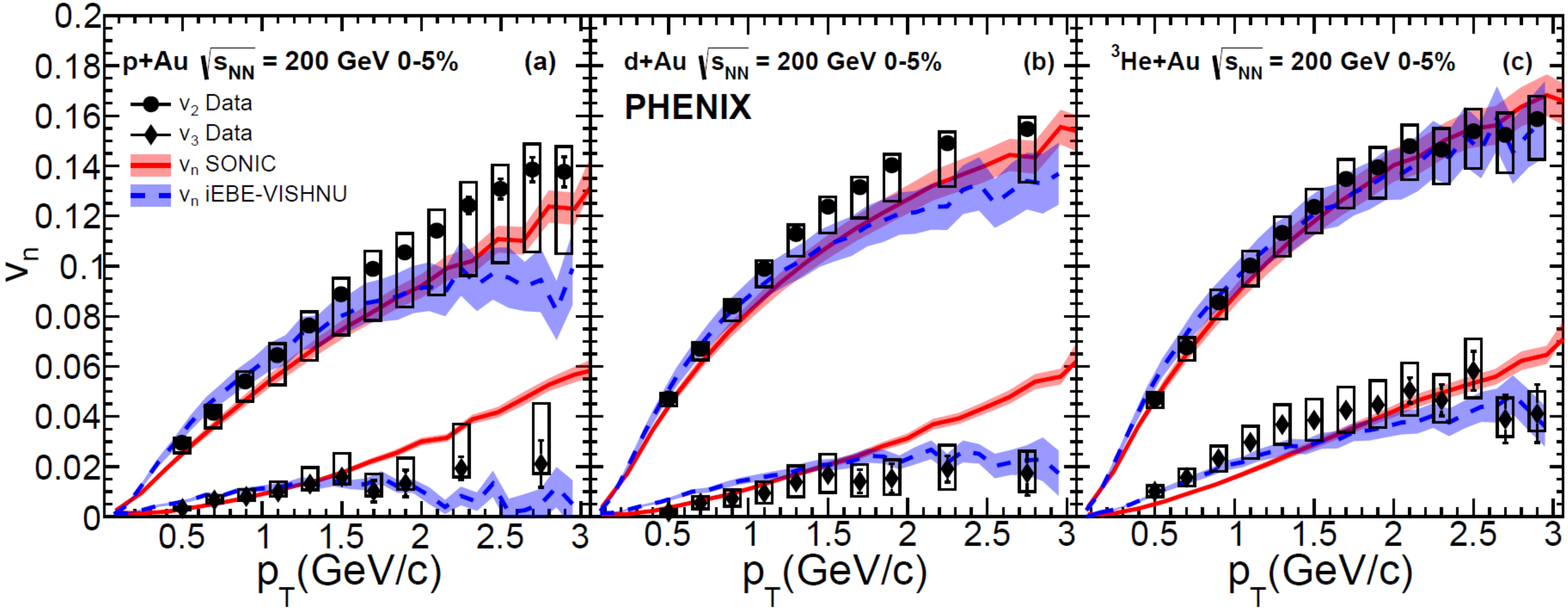
Higher v_3 in ^{3}He+Au

Importance of initial state geometry

Evidence of QGP Droplets in Small Systems

Nature Physics **15, pages214–220 (2019)**

Central Collisions: 0-5%



Excellent agreement between data and hydrodynamic predictions

Only hydrodynamic models reproduce the data

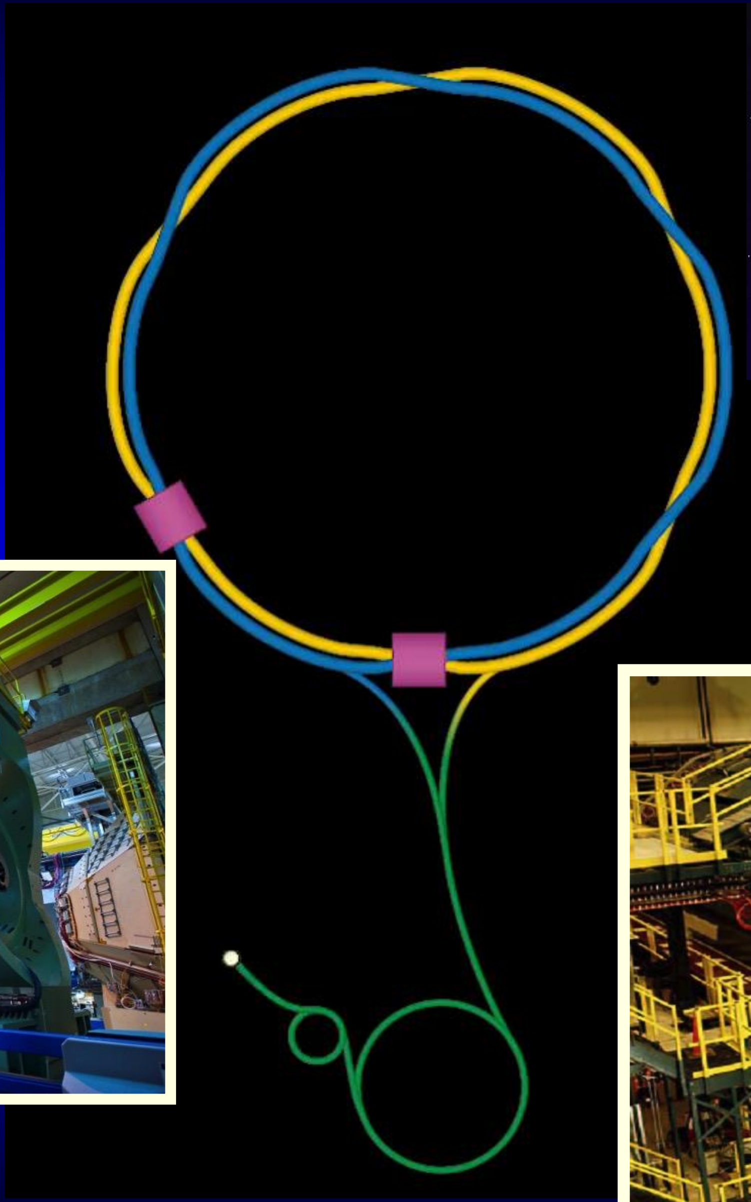
Models indicate the temperatures achieved in small systems sufficient for QGP formation: **QGP Droplets!**

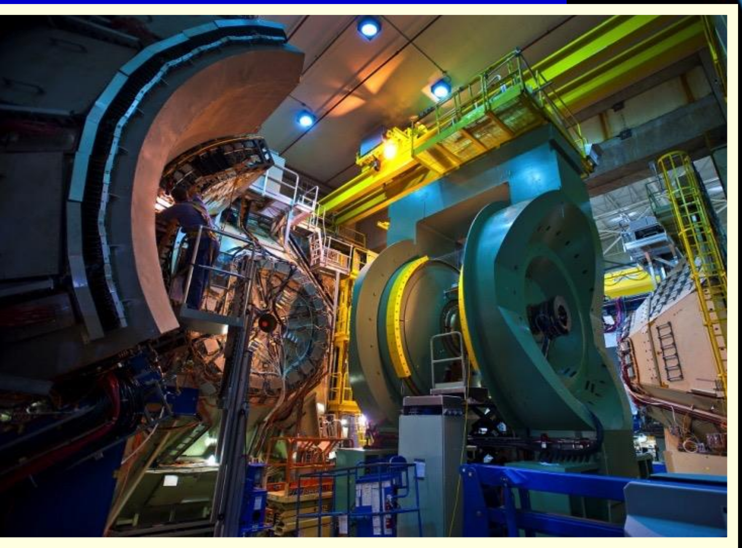
From RHIC to EIC Future Project, and Opportunities

RHIC-I

PHENIX

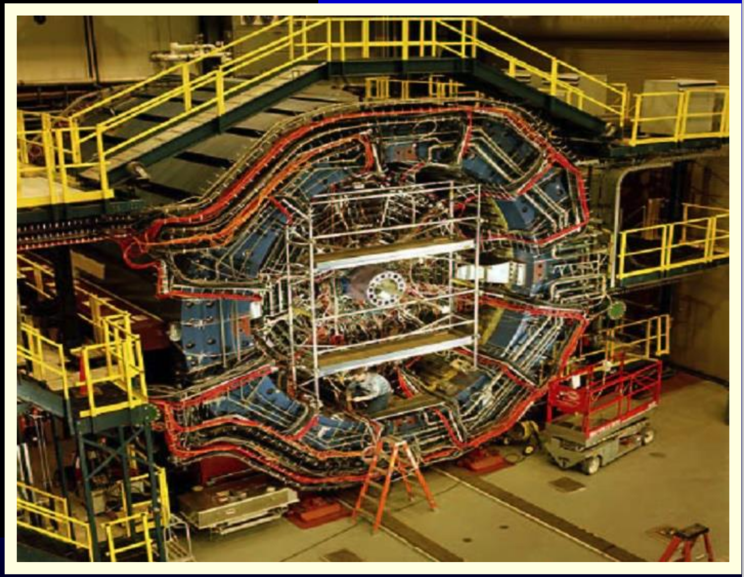
2000-2016





STAR

2000-
to present

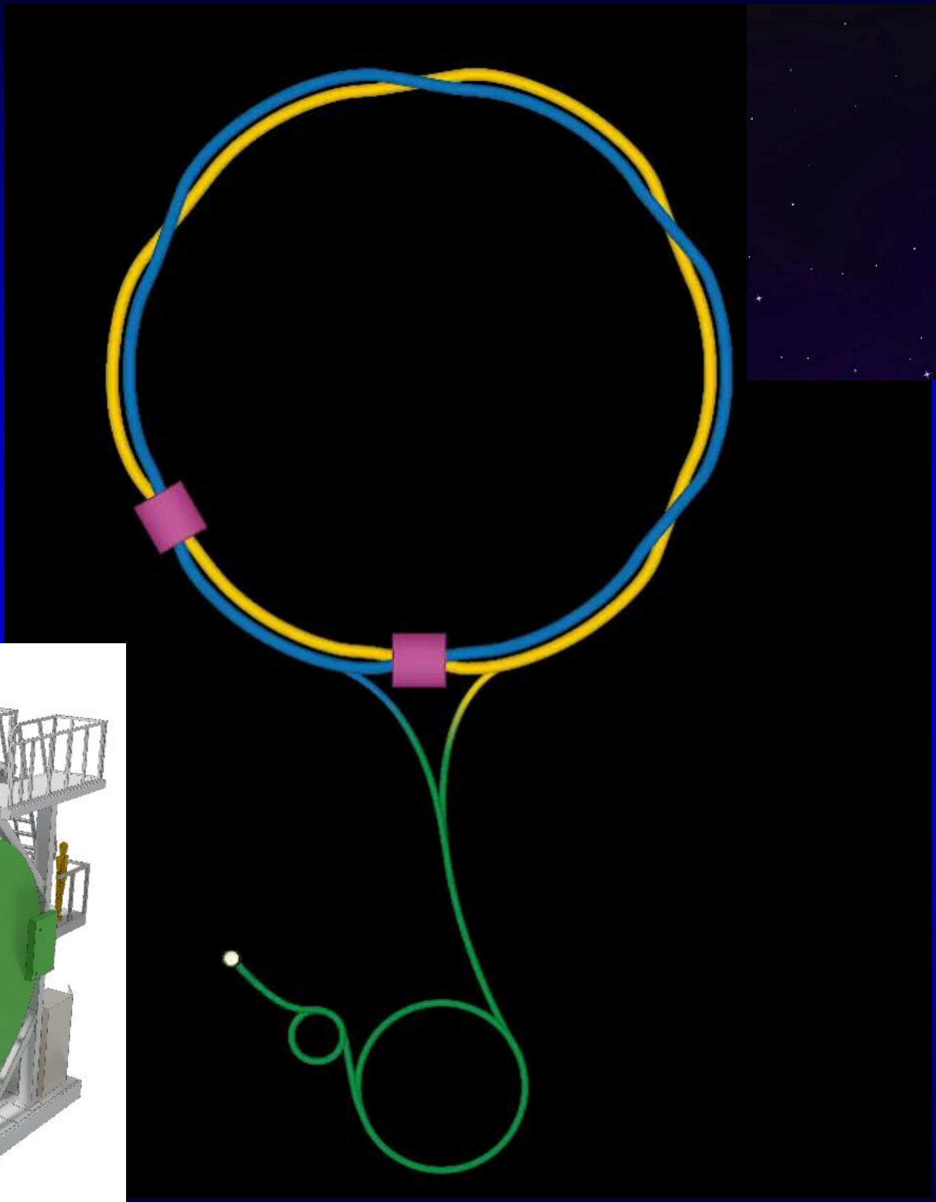


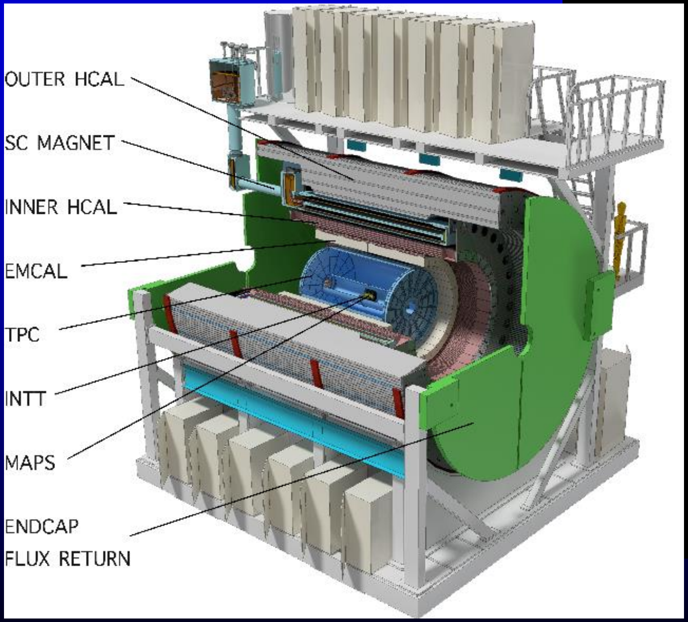
New Detector at RHIC-II

sPHENIX

2016-2023
construction

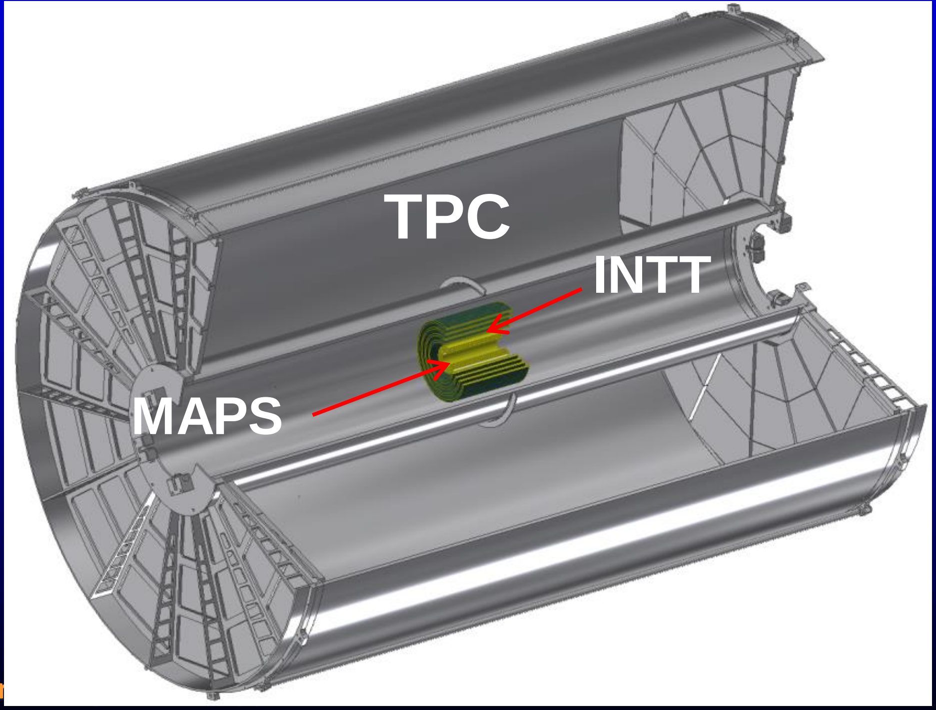
2023 – 2029
(when EIC start)





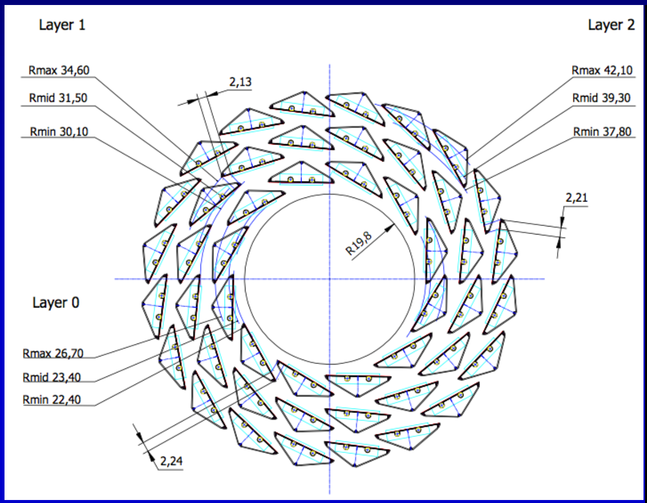
sPHENIX: Importance of Tracking

Physics Goal	Detector Requirement
Fragmentation Functions	Excellent Momentum Resolution: dp/p ~ 0.2%p to > 40 GeV/c
Jet Substructure	Excellent track pattern recognition
Distinguish Upsilon States	Mass resolution: $\sigma_M < 100$ MeV/c^2
HF jet tagging	Precise DCA resolution $\sigma_{DCA} < 100$ µm
High Statistics Au+Au 200 GeV	Handle multiplicity and full RHIC luminosity



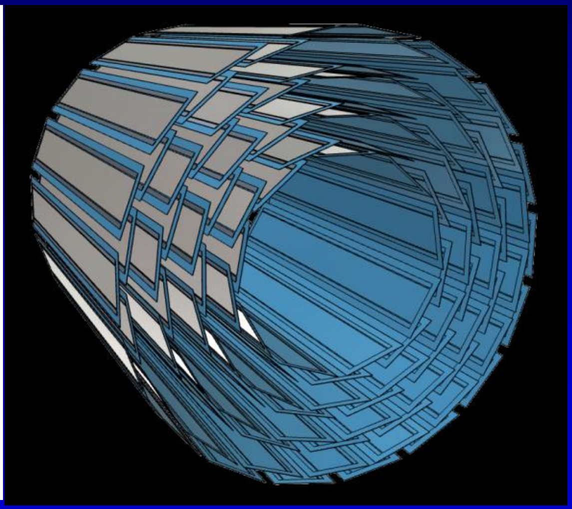
sPHENIX: Tracking Subsystems

MAPS



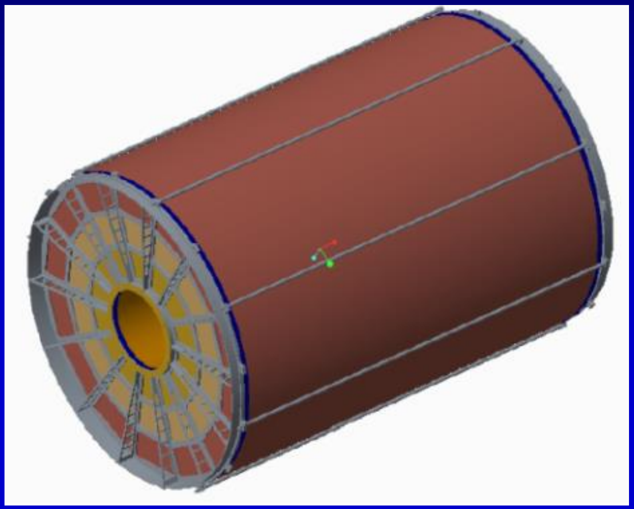
- 3 layers Si sensors
- Based on ALICE ITS upgrade
- $DCA_{xy} < 70$ μm
- $|z_{vtx}| < 10$ cm

INTT



- 4 layers Si strips
- Use PHENIX-FVTX electronics
- Pattern recognition, DCA, connect tracking systems, reject pile-up
- Trigger

TPC



- Radius 20–78 cm
- ~ 250 μm effective hit resolution
- Continuous (non-gated) readout
- Pattern recognition, momentum resolution, p_T 0.2-40 GeV/c

Electron-Ion Collider (EIC) News

RHIC collider at BNL has a bright future→ Electron-Ion Collider (EIC)

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Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

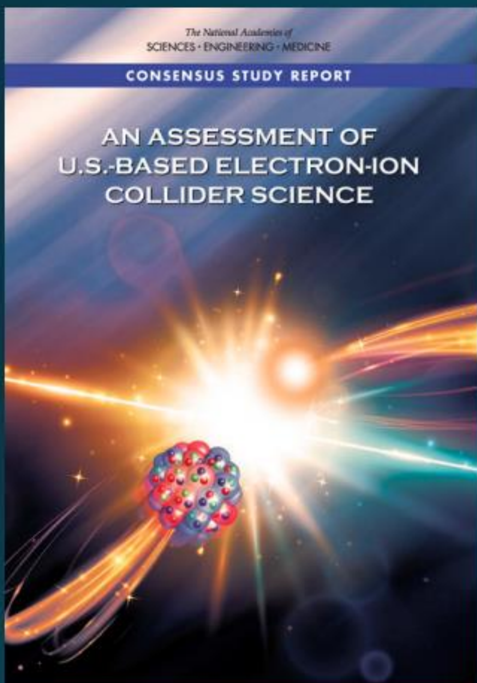
Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

Glimpse on EIC Physics

EIC Science Assessment by NAS



Finding 1:

An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

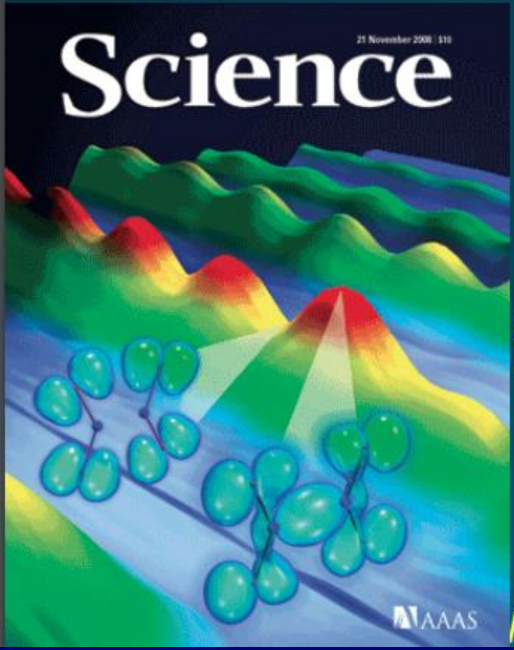
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Glimpse on EIC Physics

How does QCD generate the nucleon mass?

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" ***The 2015 Long Range Plan for Nuclear Science***

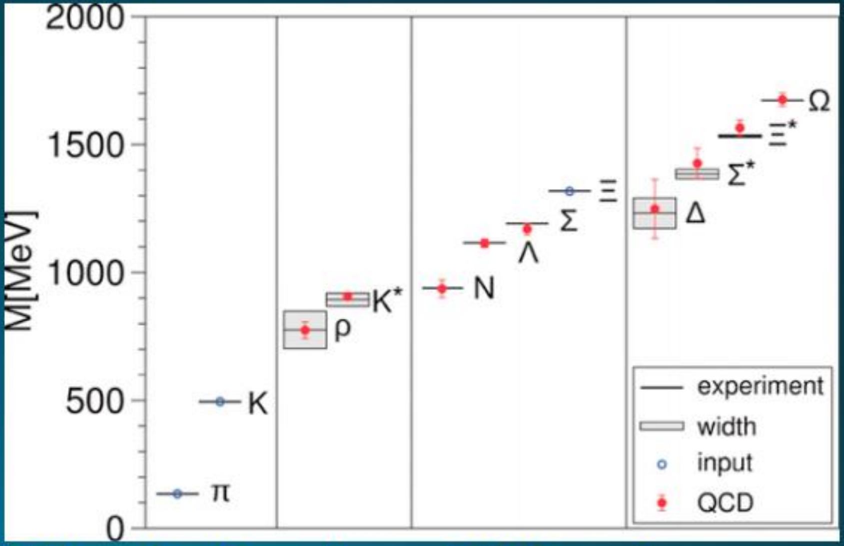
❑ Hadron mass from Lattice QCD calculation:



Ab Initio Determination of Light Hadron Masses
S. Dürr, Z. Fodor, C. Hoelbling, R. Hoffmann, S.D. Katz, S. Krieg, T. Kuth, L. Lellouch, T. Lippert, K.K. Szabo and G. Vulvert

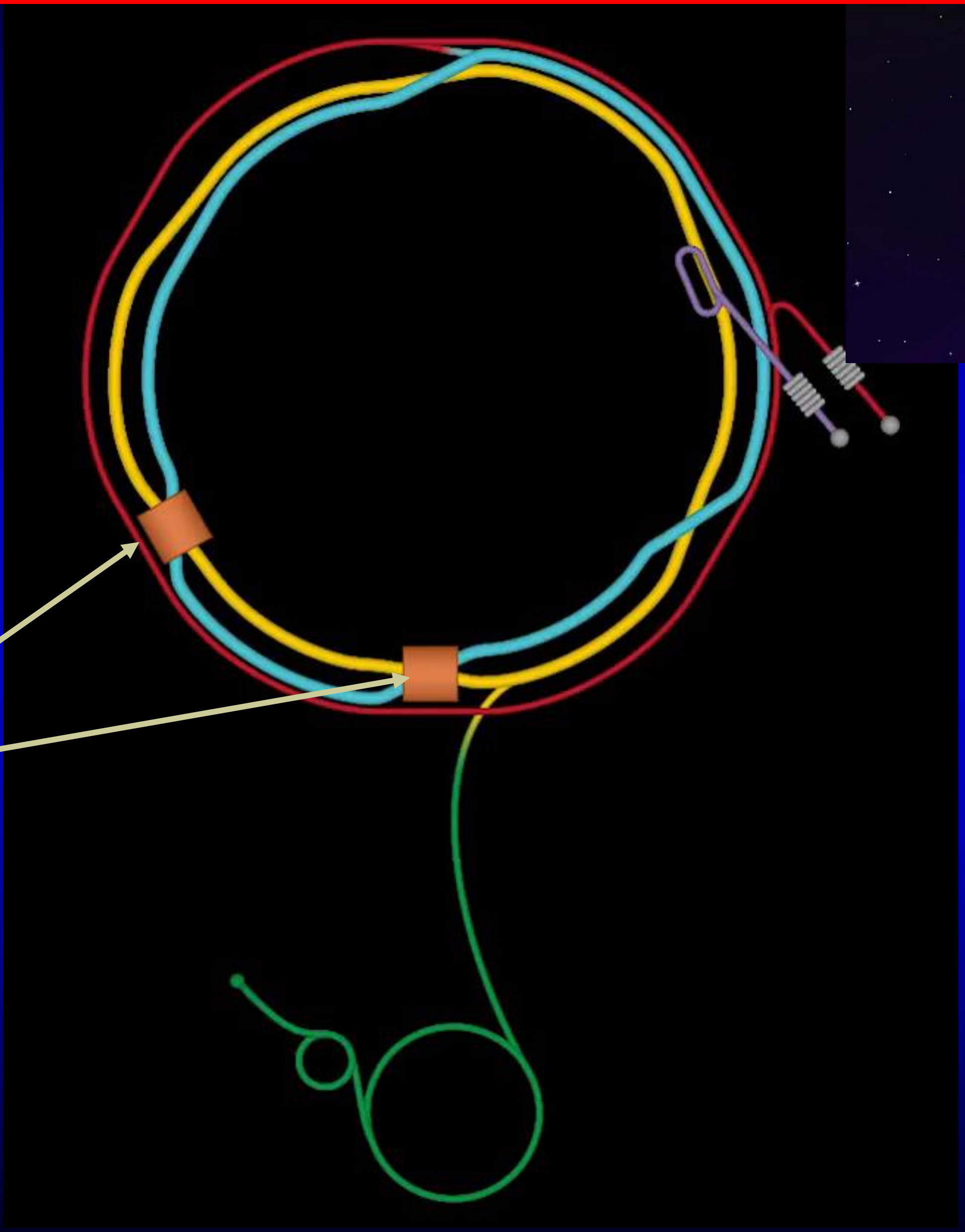
2008
Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233

568 citations



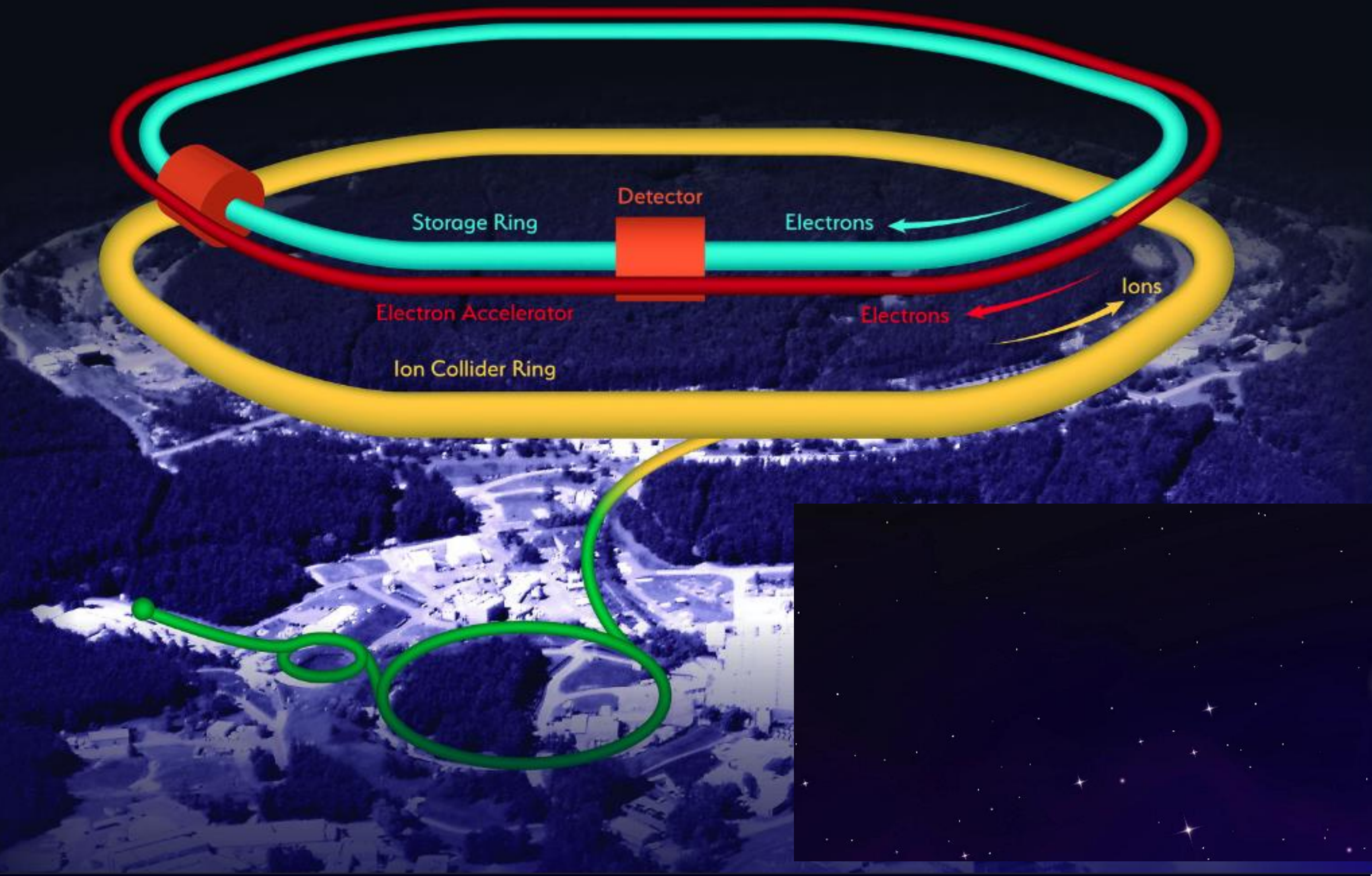
How does QCD generate this? The role of quarks and of gluons?

Electron-Ion Collider (EIC) News



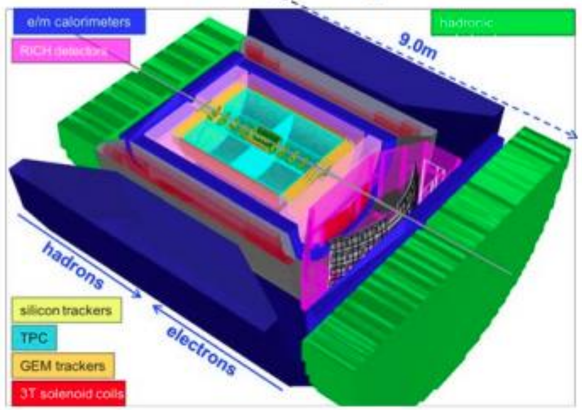
Two experiments

EIC Concept

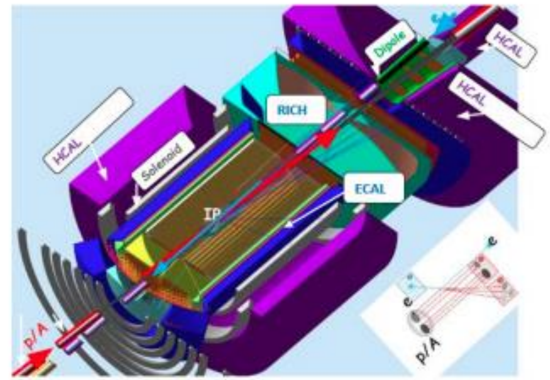

Detector
Storage Ring
Electrons
Ions
Electron Accelerator
Electrons
Ion Collider Ring

Current EIC General Purpose Detector Concepts

Brookhaven concept: BEAST

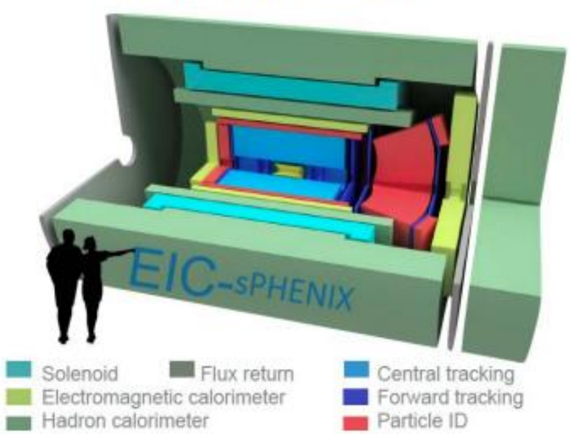


Jefferson lab concept: JLEIC

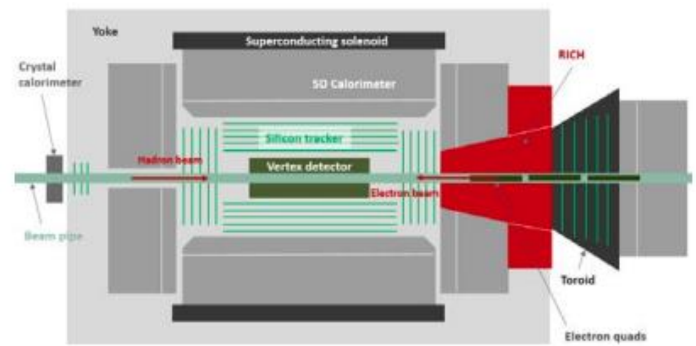


Courtesy of Abhay Deshpande

sPHENIX → EIC



Argonne concept: TOPSiDE



Critical Decision Process DOE

Courtesy of Abhay Deshpande

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS					
Project Planning Phase		Project Execution Phase			Mission
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations
CD-0 Approve Mission Need	CD-1 Approve Preliminary Baseline Range	CD-2 Approve Performance Baseline	CD-3 Approve Start of Construction	CD-4 Approve Start of Operations or Project Closeout	

Expected Soon (2019) → CD-0

Technical feasibility (~2029) → CD-4

CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

January 11th, 2019 PED: Project Engineering & Design The US Electron Ion Collider Project: Abhay Deshpande 15

Thank You

End of Lecture 2