U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

Searching for and understanding the quark-gluon plasma in heavy-ion collisions

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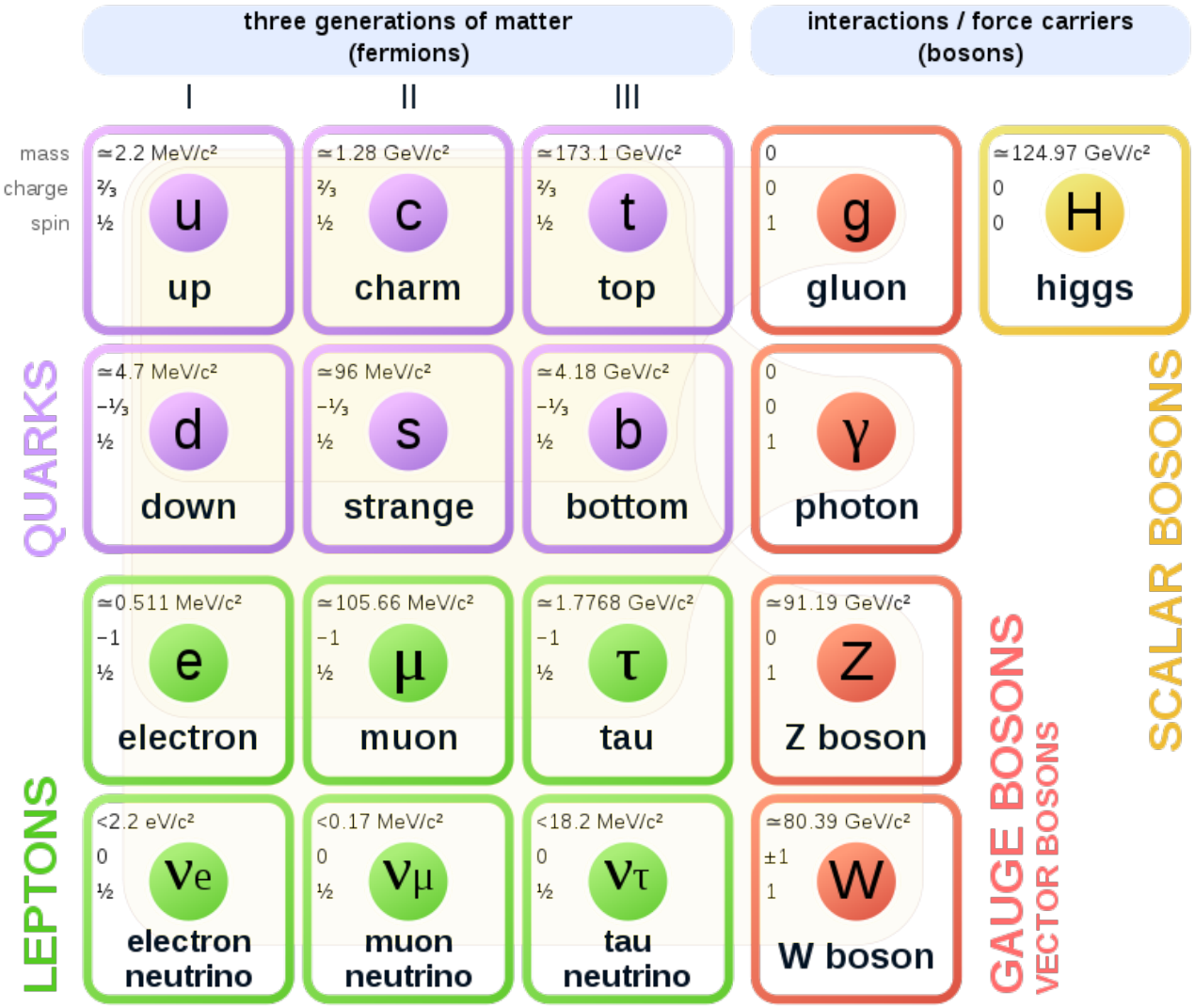
07/23/2019

Summer Student Lecture

Outline

- What is the Quark-Gluon Plasma (QGP)?
- Why is the QGP interesting?
- How to create the QGP in a lab?
- How to study the QGP in a lab?
  - How do we access the QGP?
  - What have we learnt about the QGP?
- What is the future of heavy-ion experiments?

Standard Model of Elementary Particles



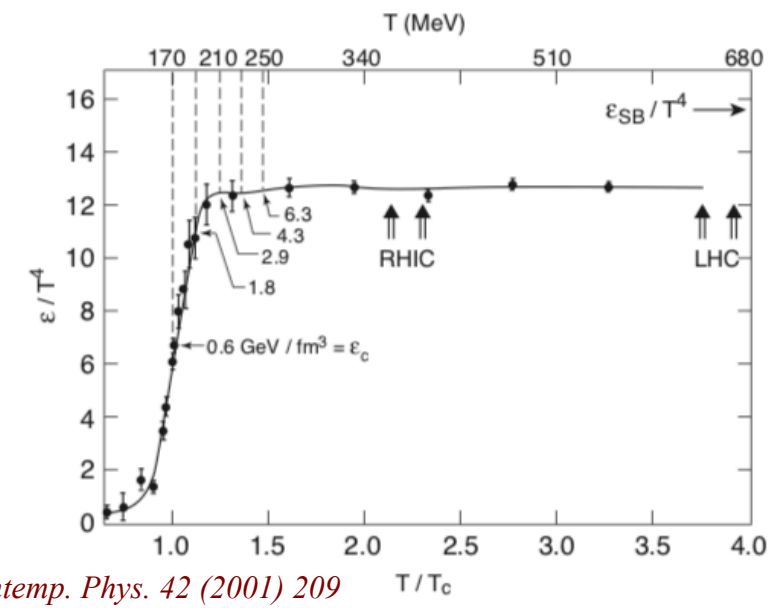
- Color-confinement: all visible matter are color neutral

What is the QGP?

- **Quark-gluon plasma**: a state of matter in the QCD, consisting of asymptotically *free moving quarks and gluons* which are ordinarily confined within nucleons by color confinement. This state is believed to exist at extremely high temperature and/or density

- Lattice-QCD predicts a phase transition from confined hadrons to the QGP
  - $\varepsilon_c \sim 1$ GeV/fm^3; $T_c \sim 165$ MeV

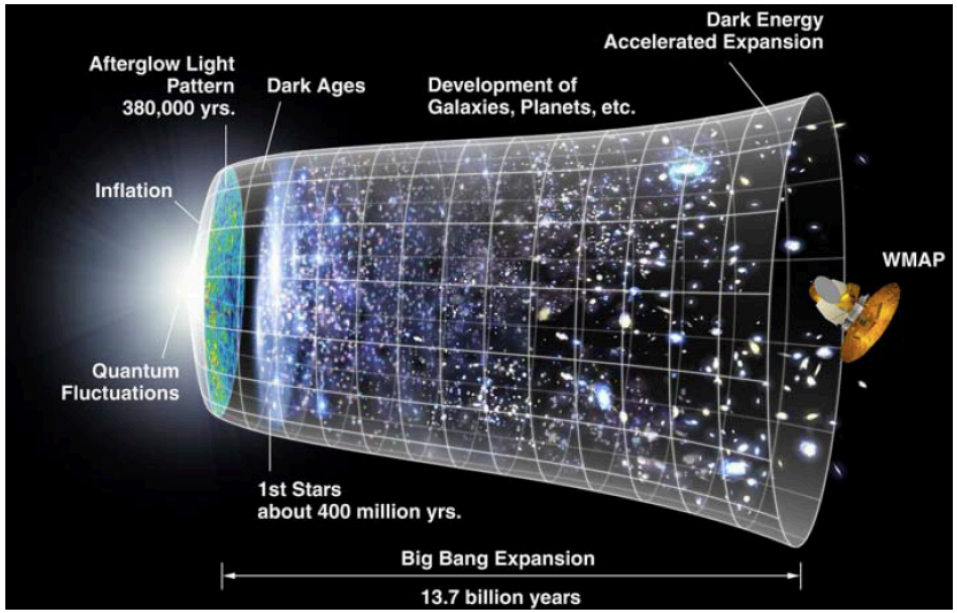
Core of sun: 1.5e7 K
$T_C \sim 2e12$ K

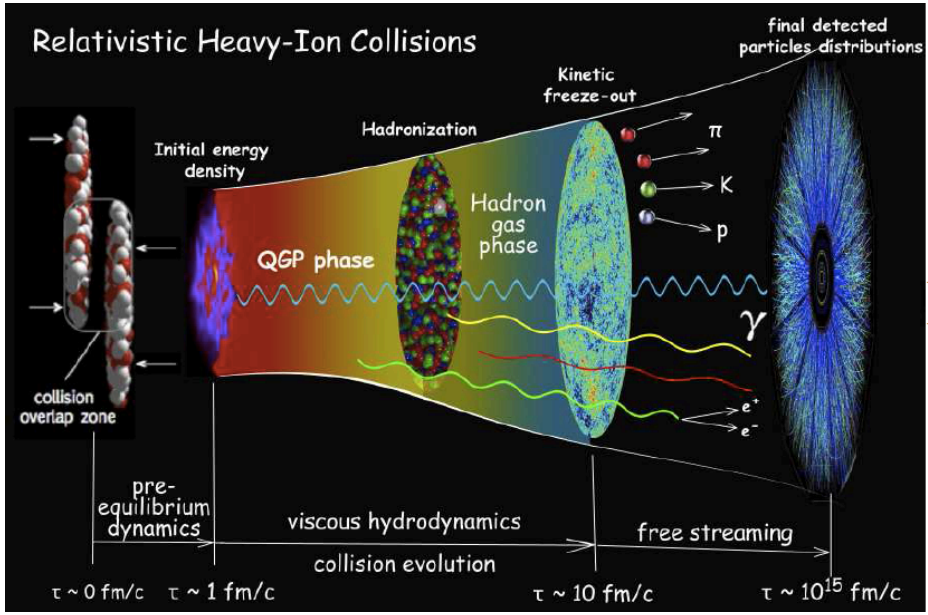


S. Hands, Contemp. Phys. 42 (2001) 209

Why is QGP interesting?

- **Big Bang vs. Little Bangs: t ~ 10^{-6}s**



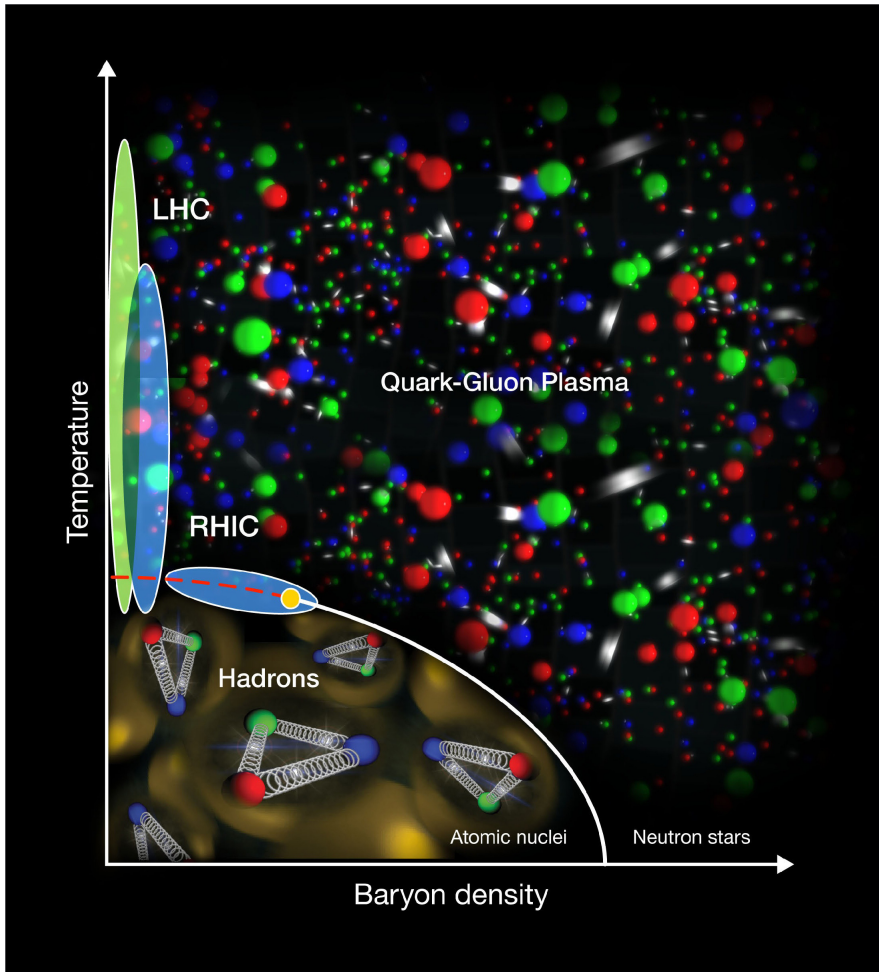


- Similarities:
  - Hubble-like expansion
  - Hierarchy of decoupling processes
  - Imprint initial fluctuations
- Differences:
  - Pressure ingredient vs. gravity
  - Time and dimension scales
  - …

U. Heinz, Journal of Physics: Conference Series 455 (2013) 012044

Why is QGP interesting?

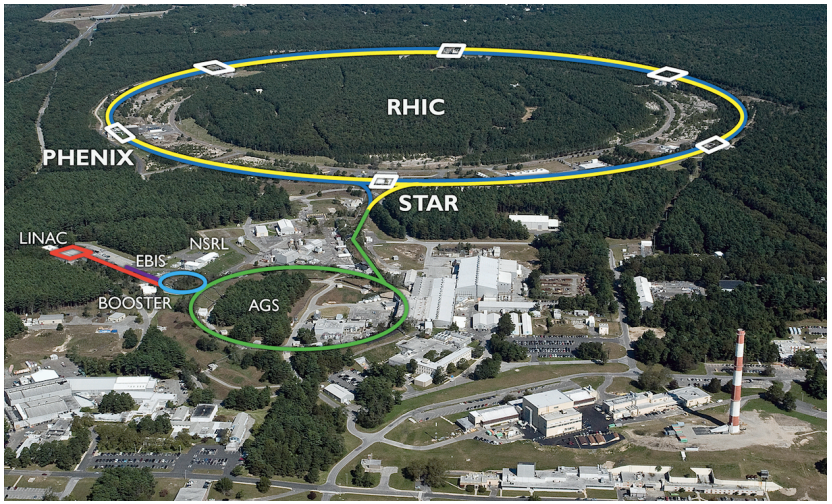
- **A rich QCD lab**
  - How does the system reach the status of the QGP?
  - Why does the QGP behave as it is? What QCD properties do they relate to?
  - What does the QCD phase diagram look like? What QCD dynamics drives it?
  - What role does color confinement play in hadronization? And how?
  - …



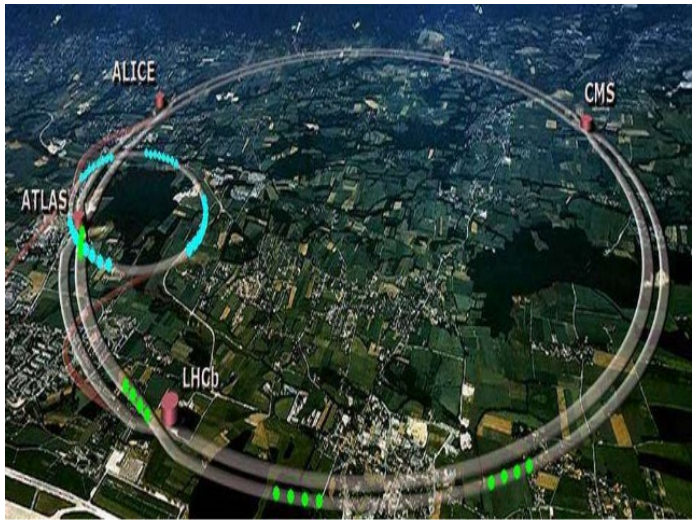
How to create the QGP in a lab?

- **Heavy-ion collisions**
  - T.D. Lee, 1974: We should investigate phenomena by distributing high energy or high nucleon density over a relatively large volume

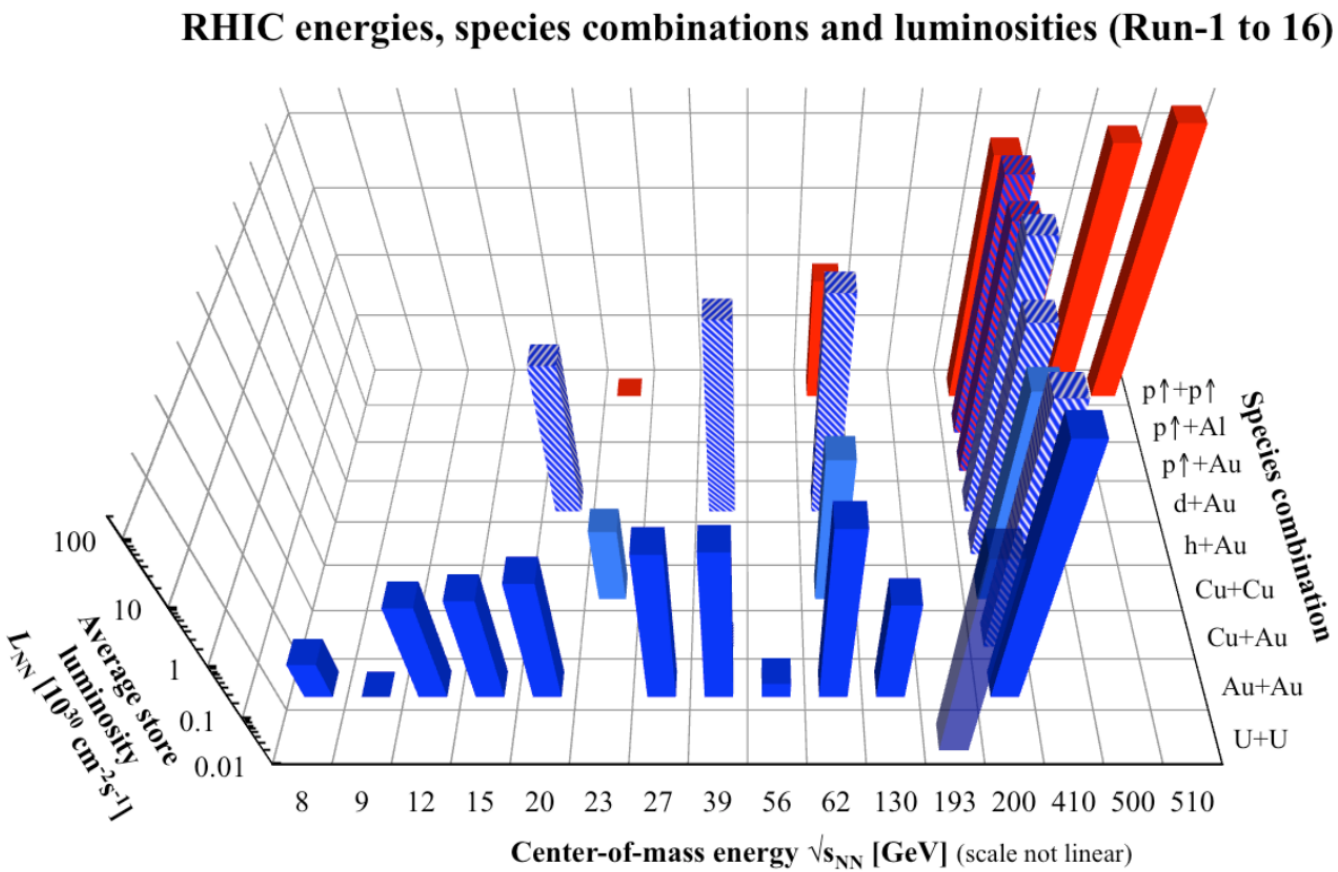
RHIC: Au+Au



LHC: Pb+Pb



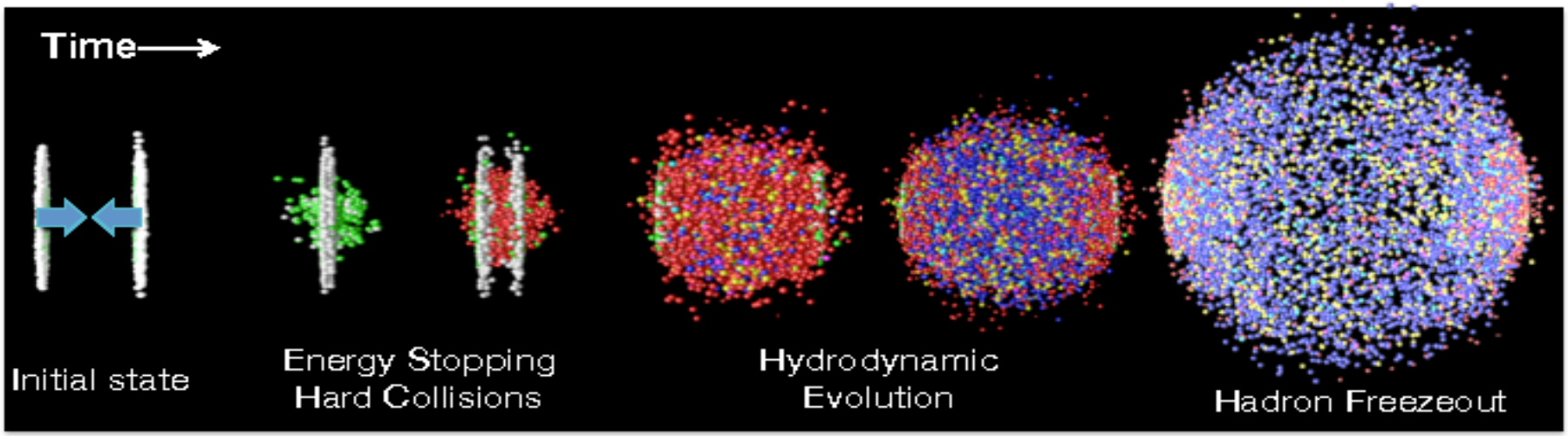
RHIC – a versatile machine



- RHIC: two rings → flexible
- LHC: one ring → great constraint on beam energy

How to study the QGP in a lab?

Heavy-ion collisions



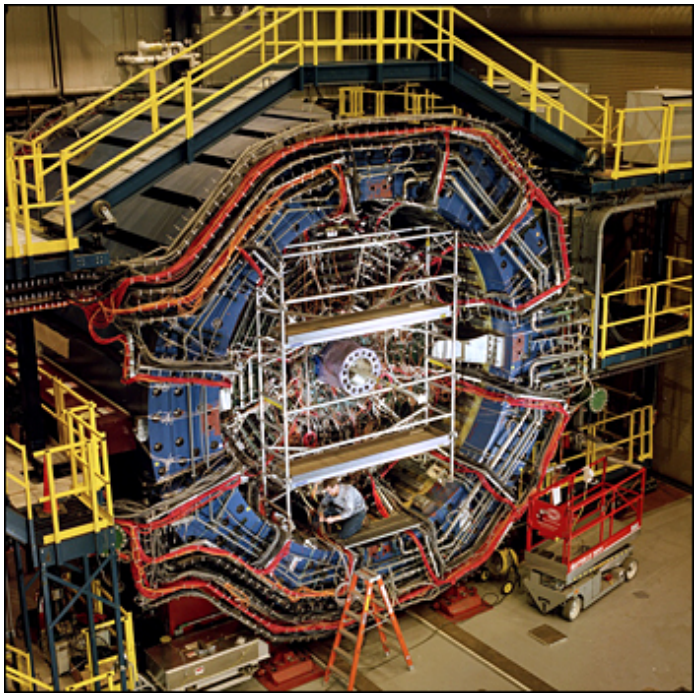
- How to measure final-state particles? → Detectors
- How to probe the QGP? → Internal probes
  - External probes are not possible due to its very short life time (~10^{-23} s)

General requirements for detectors

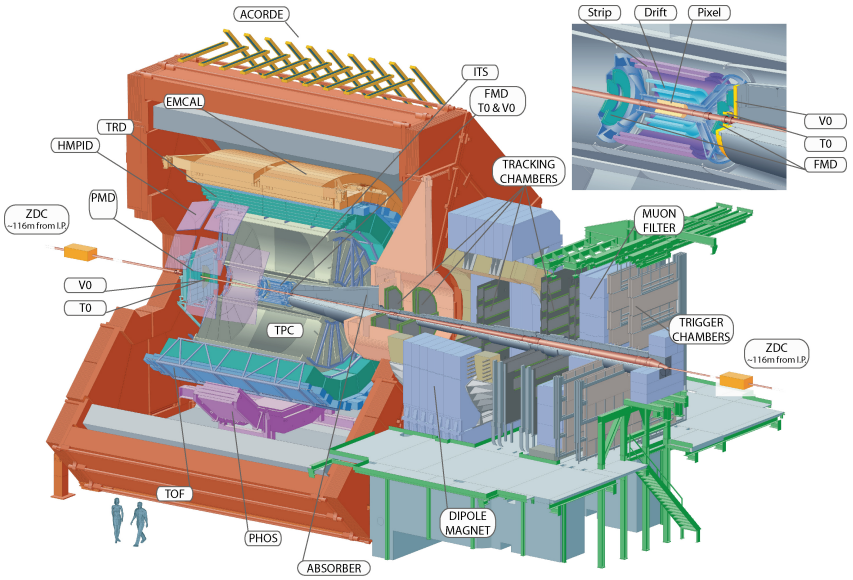
- Large acceptance
  - cover large phase space
- High efficiency
  - measure as many particles, charged and neutral, as one can within acceptance
- High resolution
  - measure the particles' momentum or energy as precise as one can
- *Particle identification capability*
  - identify the species of the measured particles, e.g. pions, kaons, protons, etc

Heavy-ion experiments

STAR @ RHIC



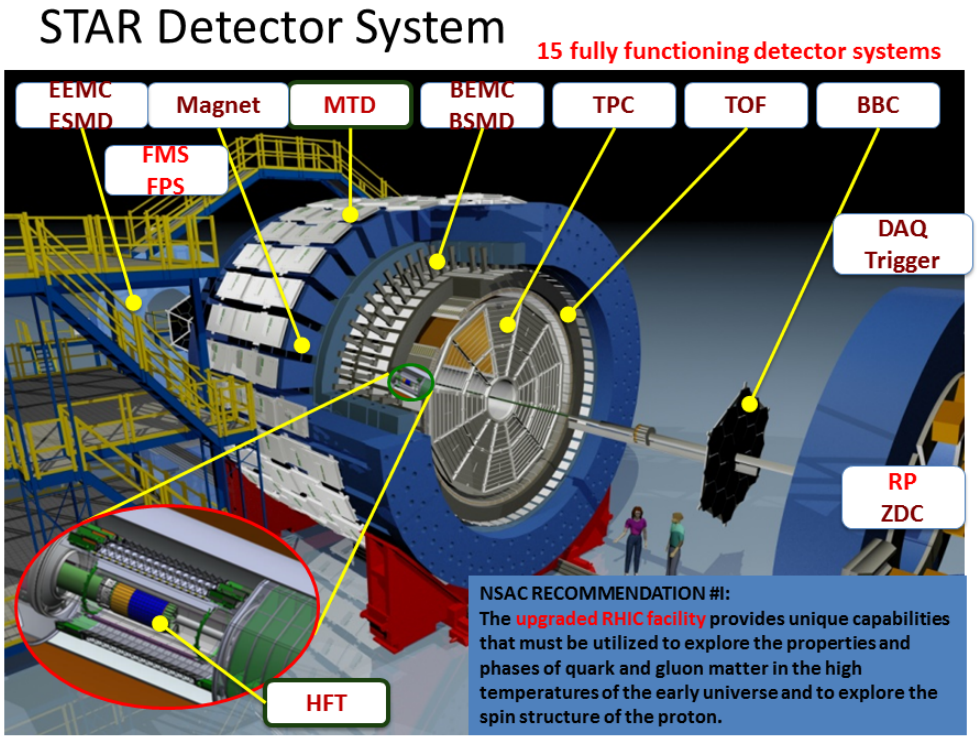
ALICE @ LHC



- RHIC: PHENIX shut down in 2016
- LHC: CMS, ATLAS and LHCb also take heavy-ion data

STAR @ RHIC

- Heavy-ion collisions happen at the center of STAR
- Cylindrical shape; magnet sits at radius ~ 3 m

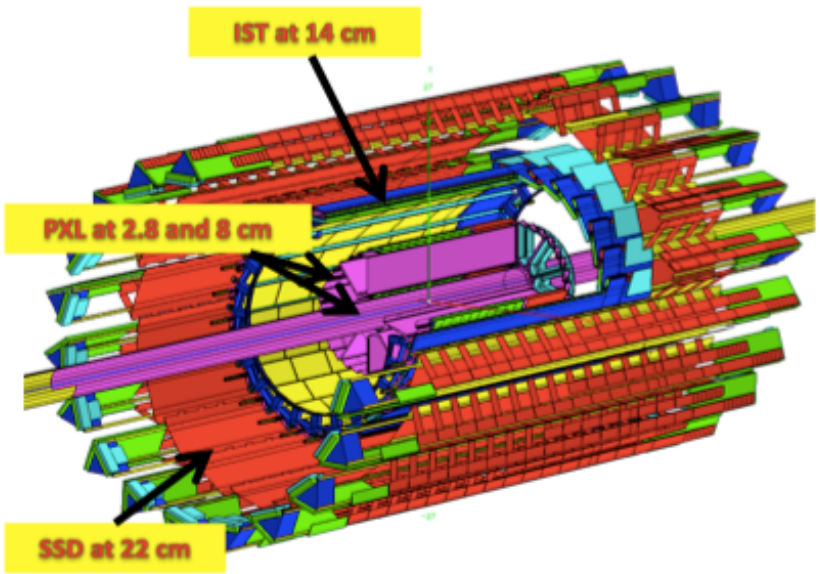


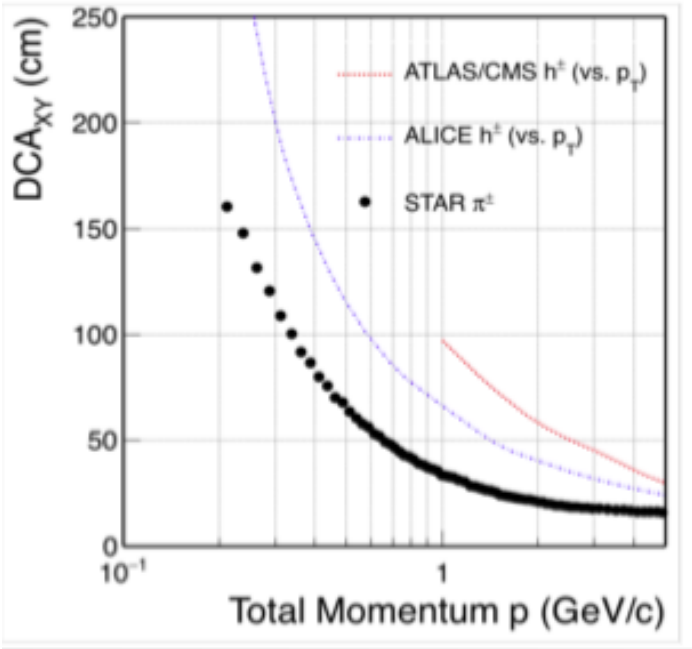
X10³ increases in DAQ rate since 2000, most precise Silicon Detector (HFT)

- Sub-detectors
  - **H**eavy **F**lavor **T**racker
  - **T**ime **P**rojection **C**hamber
  - **T**ime-**O**f-**F**light detector
  - **B**arrel **E**lectro**M**agnetic **C**alorimeter
  - **M**uon **T**elescope **D**etector

Heavy Flavor Tracker (2014-16)

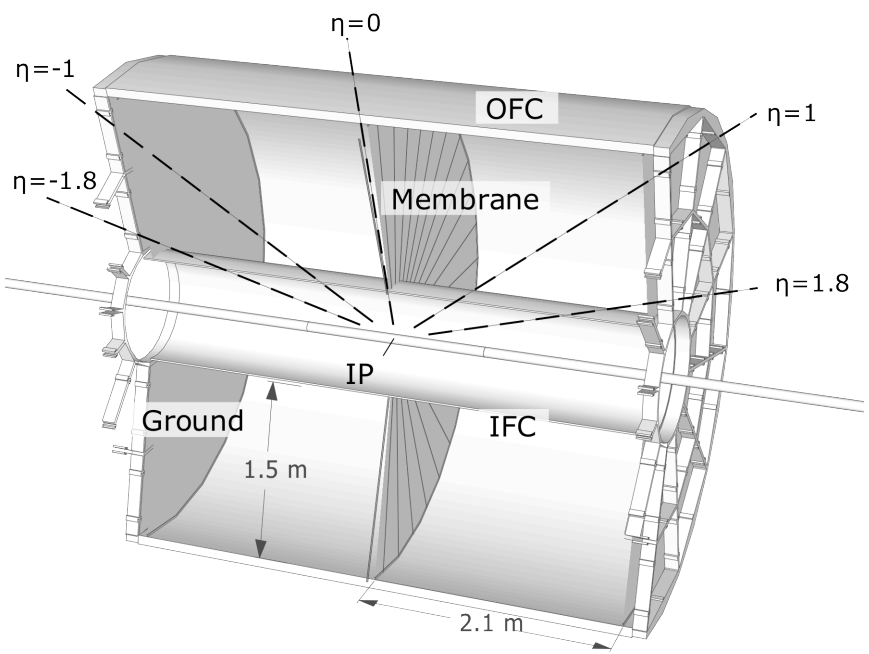
- **Silicon detector** sitting close to the interaction region
- Composed of four layers
- Very high precision for measuring space points
  - *Secondary decays*
- Very costly: ~ 20M project

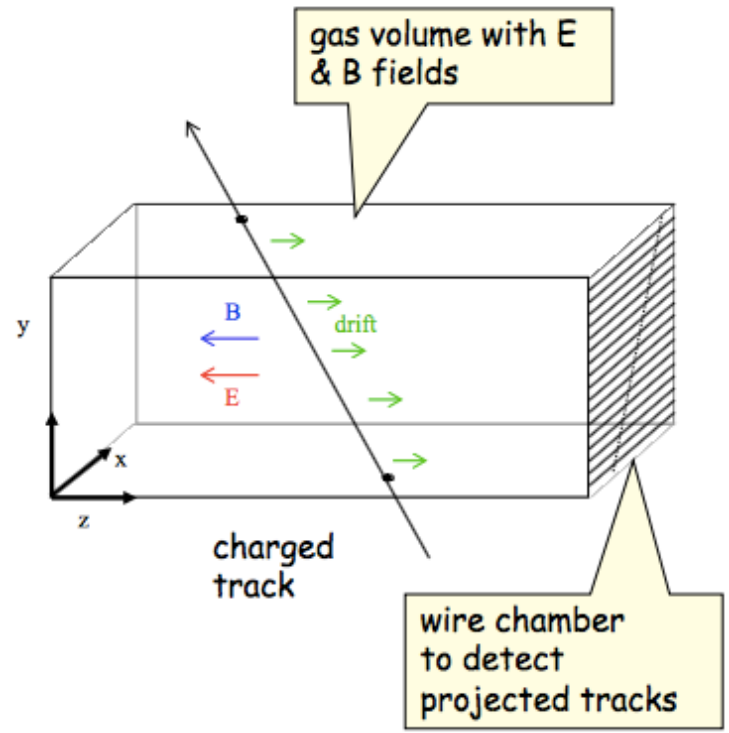




Time Projection Chamber

- **Gaseous detector** taking 3D photos of passing charged particles





- Trajectory → momentum & charge $p_T = mv_T = qBr$

Time Projection Chamber

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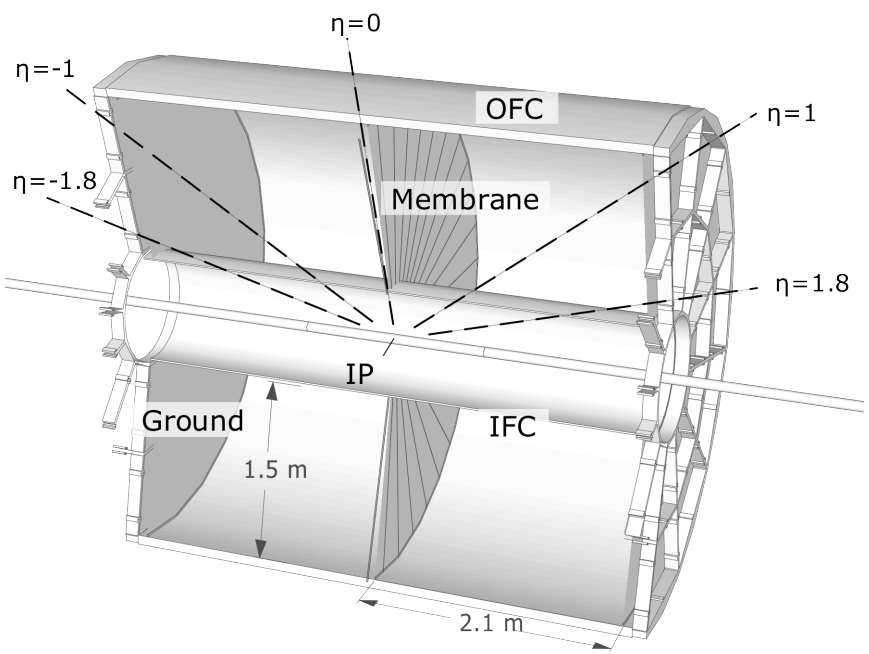
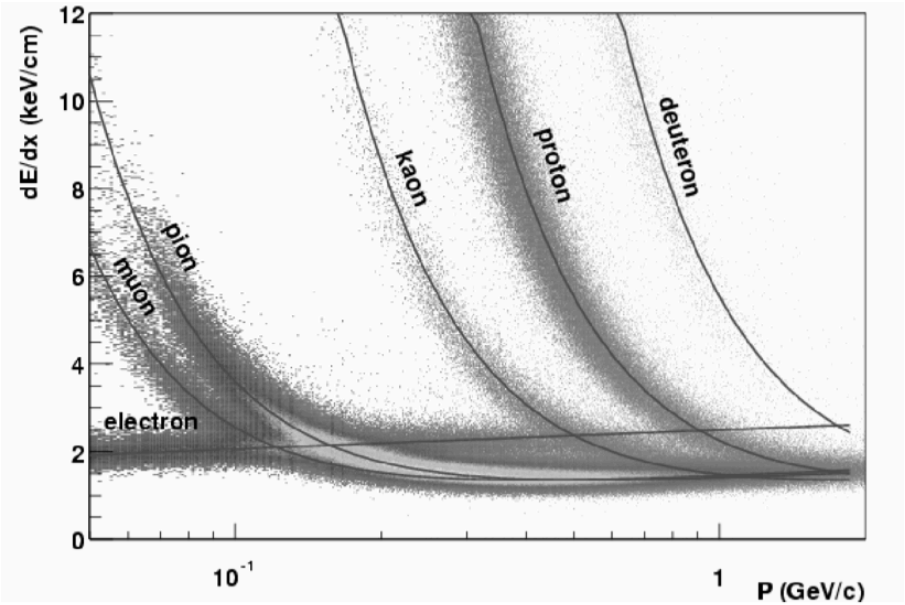
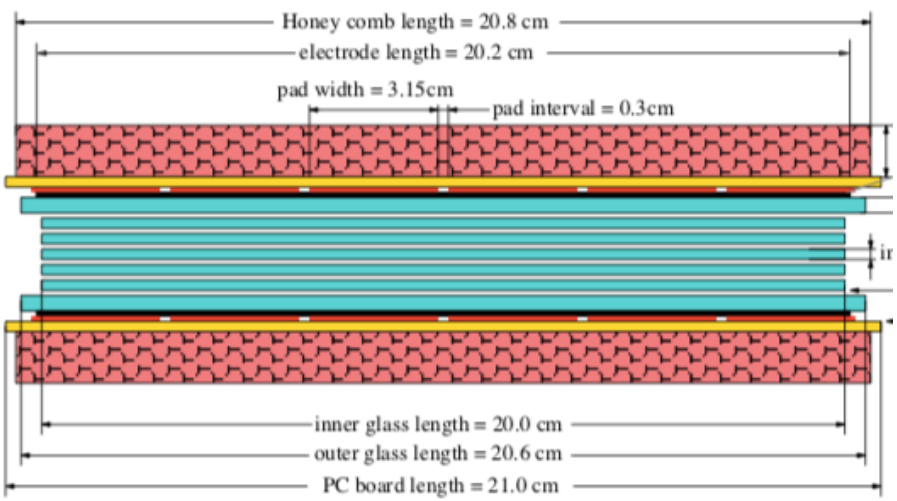


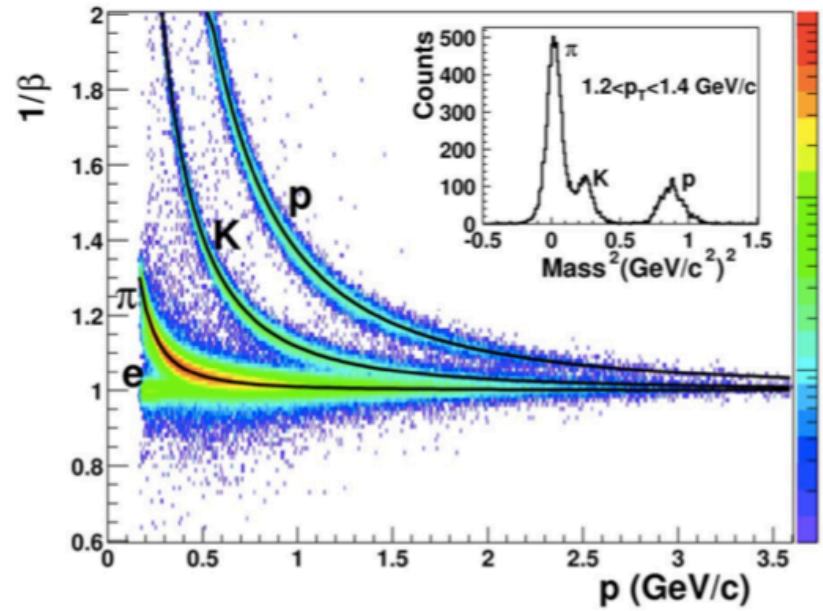


- Energy loss → particle species
- *Limited at higher momenta*

Time-Of-Flight detector

- **MRPC** (Multi-gap Resistive Plate Chamber) with good timing resolution ~ 95 ps
  - High efficiency, low cost

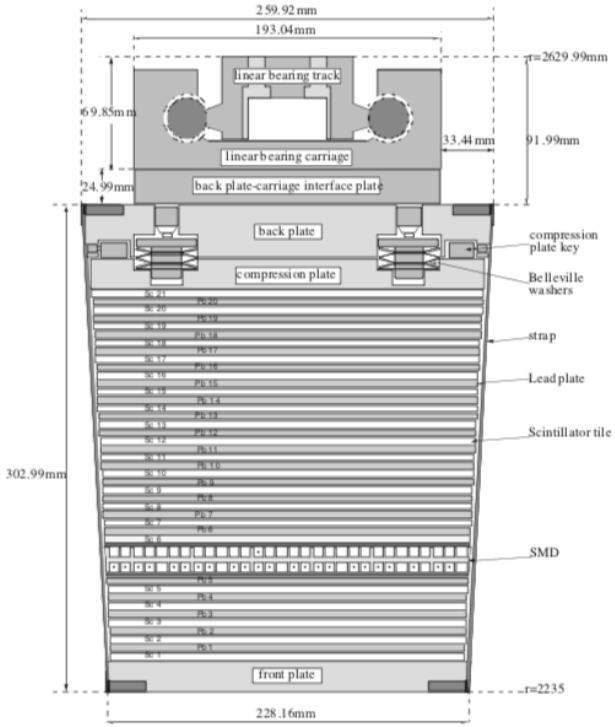


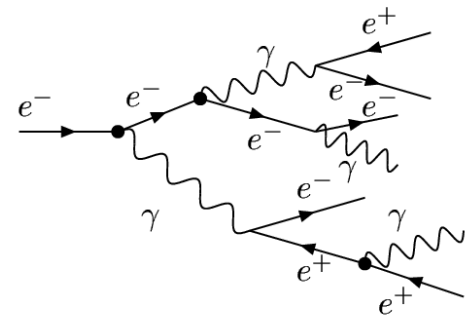


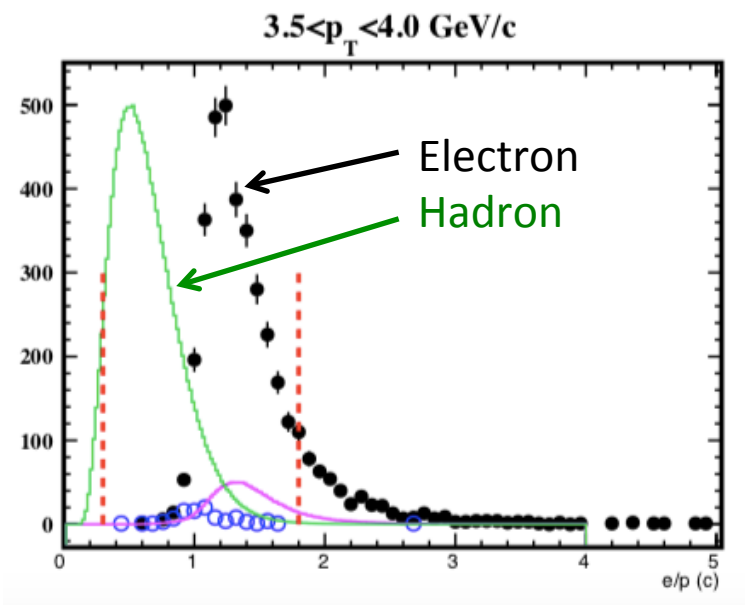
- Mass difference at given momentum → Velocity → particle species
- Extend PID capability
  - π/K separation up to 1.6 GeV/c
  - (π+K)/p separation up to 3 GeV/c

Barrel ElectroMagnetic Calorimeter

- **Pb-scintillator sampling** calorimeter: measure the energy loss of electrons and photons
- ***Trigger*** on and identify electrons

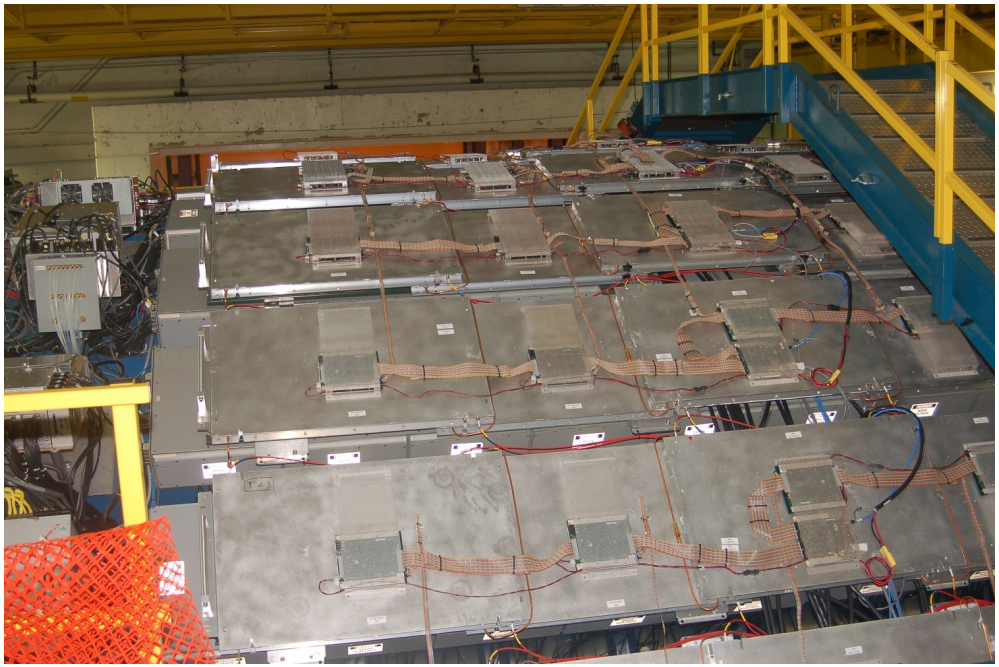


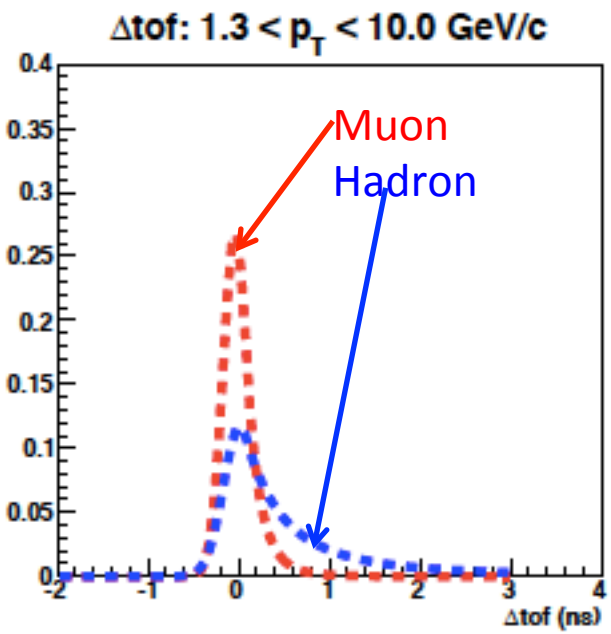




Muon Telescope Detector

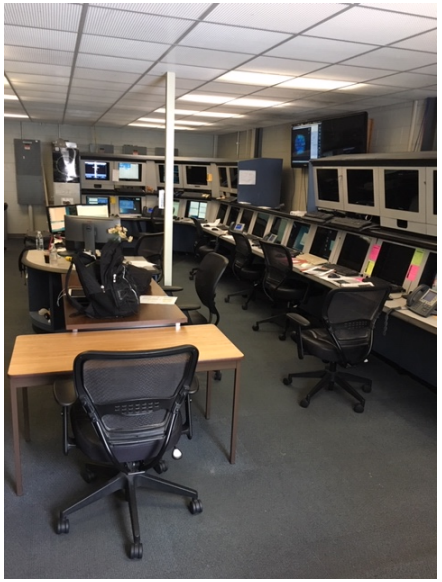
- **MPRC** with double readout: timing (~100ps) and position information (~1-2 cm)
- Reside outside of the magnet, which is used as an absorber to hadrons
- Trigger on and identify muons





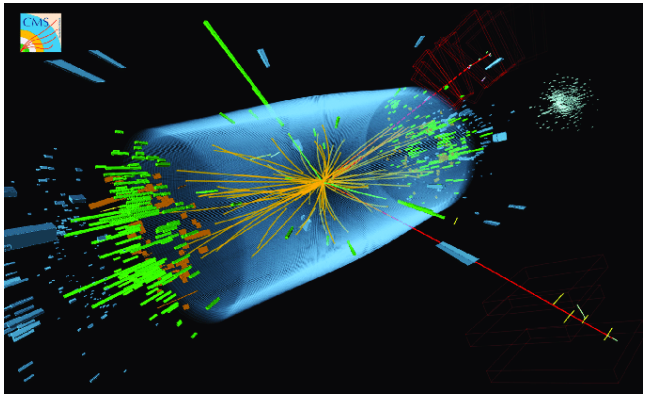
Go from electronic signal to physics

- **Data-taking**
  - Usually in the first half of a year
  - 24/7 4-person shift to take data and monitor the status of detectors
  - Rates: ~2 kHz for Au+Au @ 200 GeV, 500 TB/week

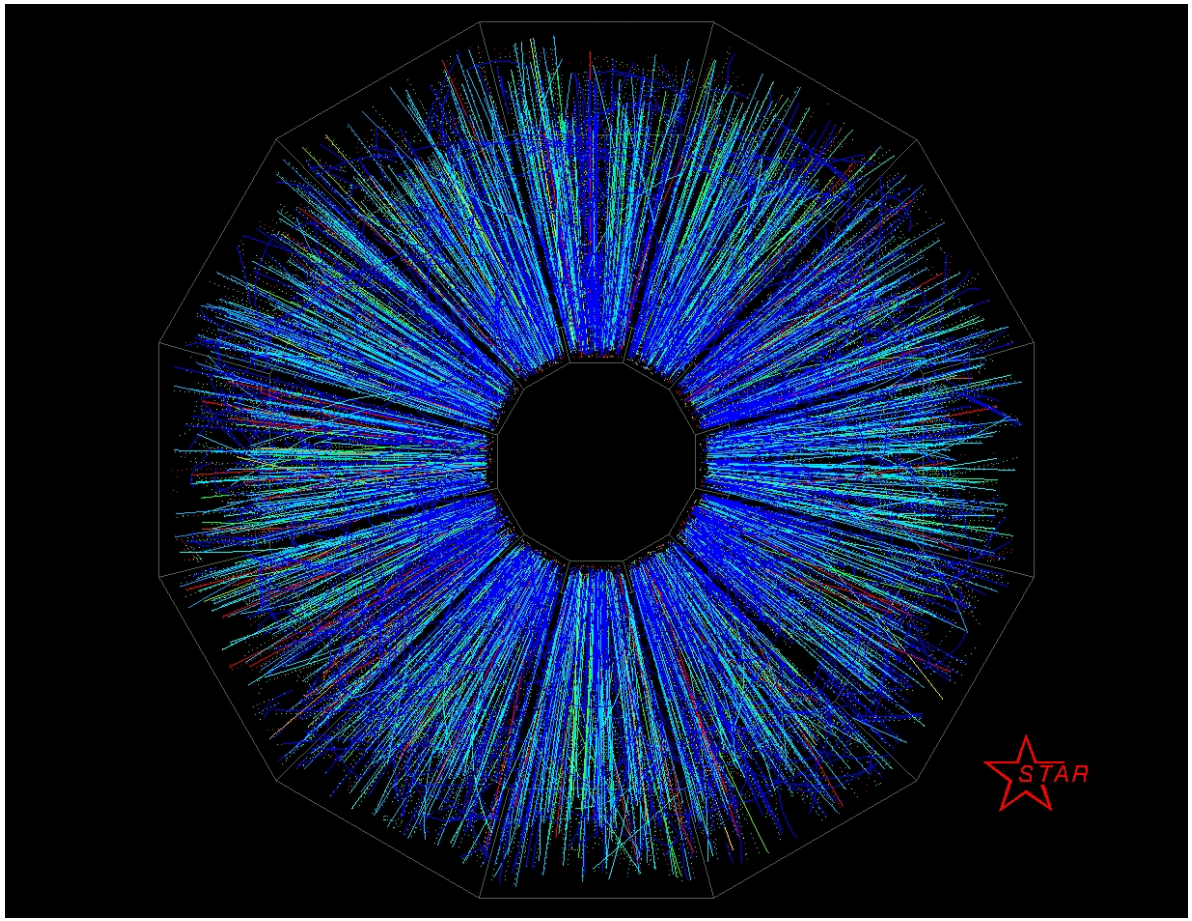


Go from electronic signal to physics

- **Data-taking**
  - Usually in the first half of a year
  - 24/7 4-person shift to take data and monitor the status of detectors
  - Rates: ~2 kHz for Au+Au @ 200 GeV, 500 TB/week
- **Calibration**
  - Convert electronics signal to physical quantities (ADC → E)
  - Detector alignment
  - T0 calibration
- **Data production**
  - Vertex: position where the collision happens
  - Tracks: momentum, position, charge …
  - Hits: energy, position, timing …



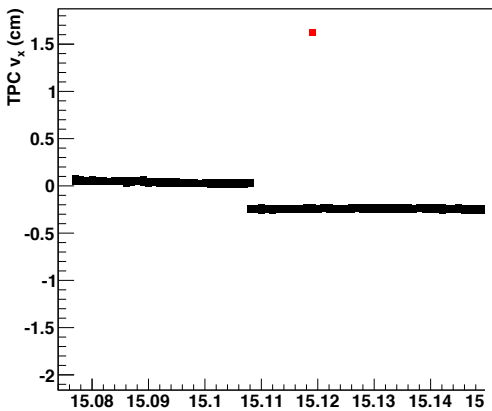
A real event taken by STAR



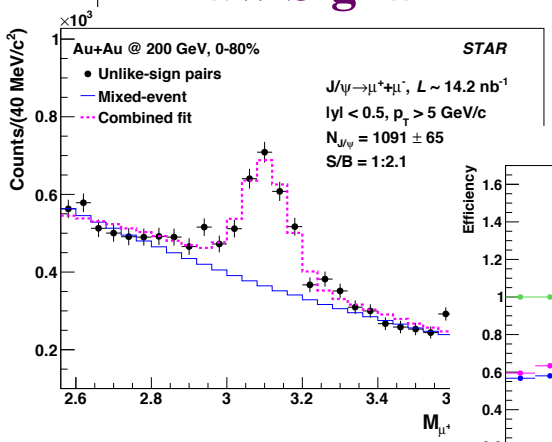
Go from electronic signal to physics

- **Data analysis**

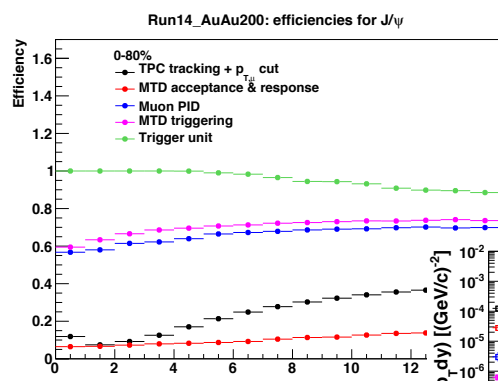
Quality Assurance



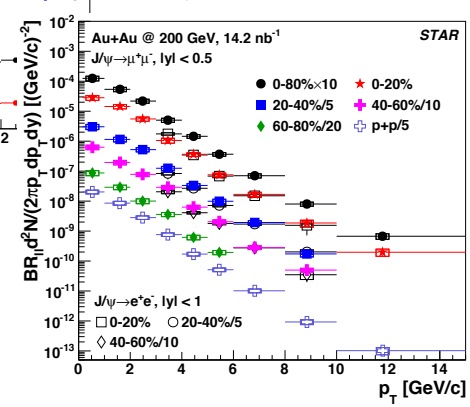
Raw Signal



Correction

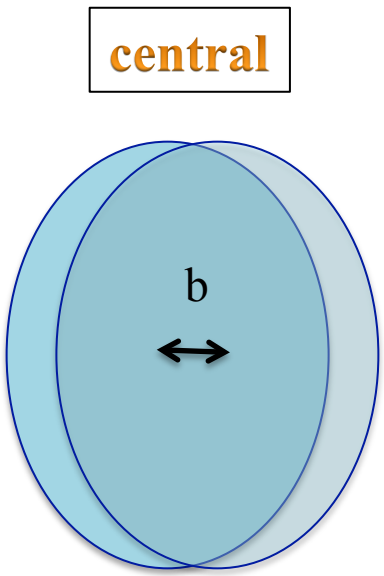


Physics Results

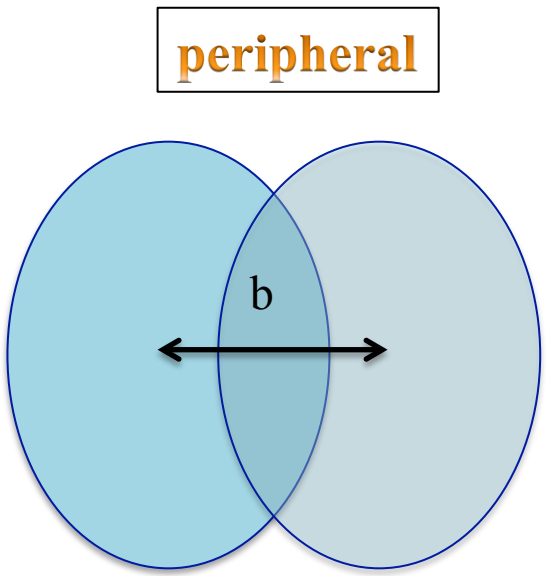


What is Centrality?

- Used to quantify the collision geometry/impact parameter



- Small impact parameter
- Large N_{coll}
- Larger/hotter medium

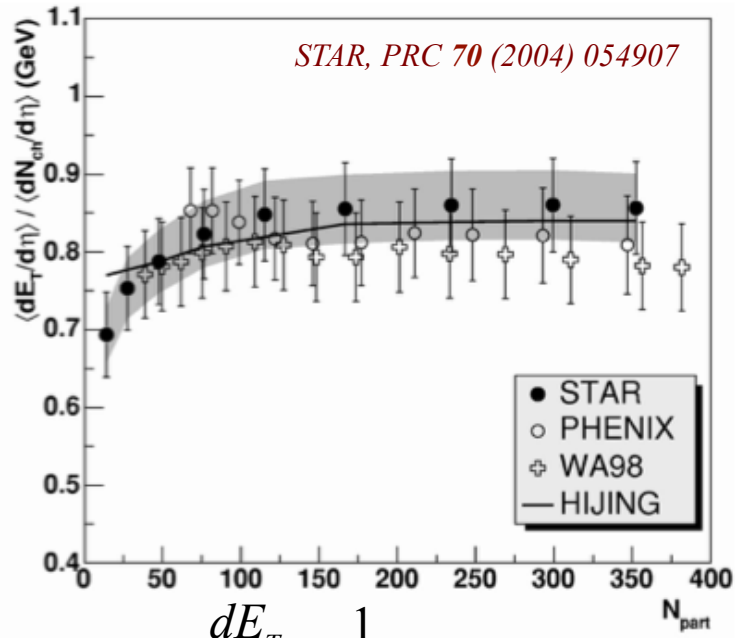


- Large impact parameter
- Small N_{coll}
- Smaller/no medium

Initial energy & temperature

- Recall: $\varepsilon_c \sim 1$ GeV/fm^3; $T_c \sim 165$ MeV

Energy/particle vs. centrality

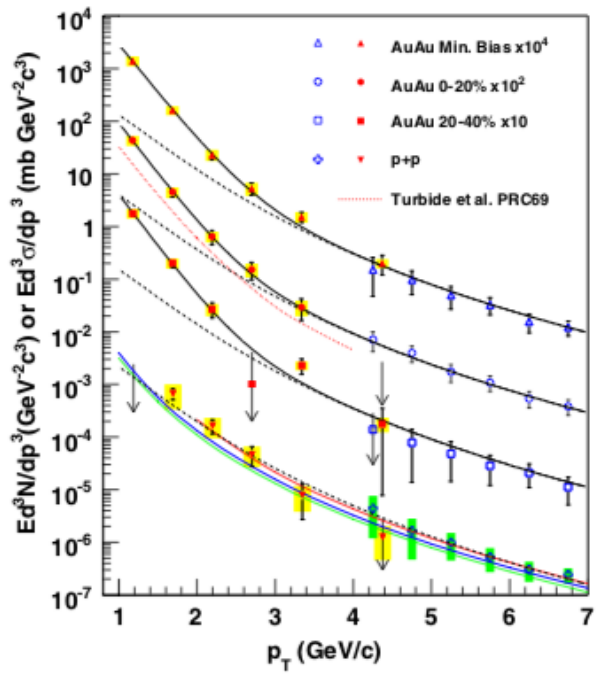


$$e_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$

$$\tau_0 \sim 1 \text{ fm}/c,\ R \approx 1.2 A^{1/3} \text{ fm}$$

$$e_{Bj} = 4.9 \pm 0.3 \text{ GeV/fm}^3$$

Thermal photon spectrum

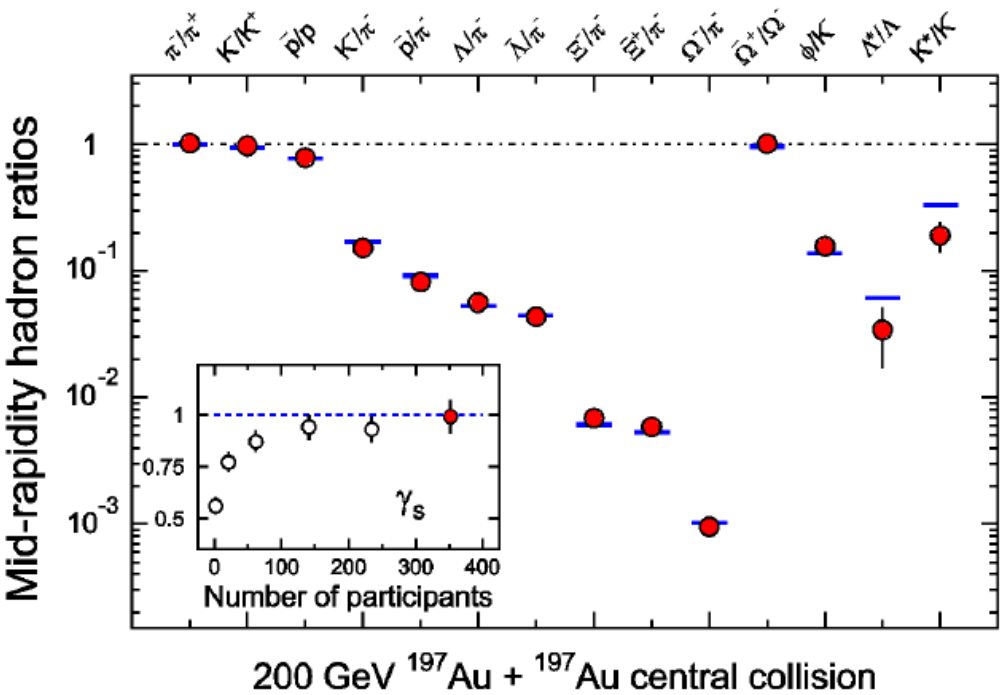


- Inverse slope T ~ 221 MeV for 0-20% centrality
- $T_{init} = 1.5\text{-}3 \times T$

PHENIX: PRL 104 (2010) 132301

Chemical freeze-out

- Particle yields freeze

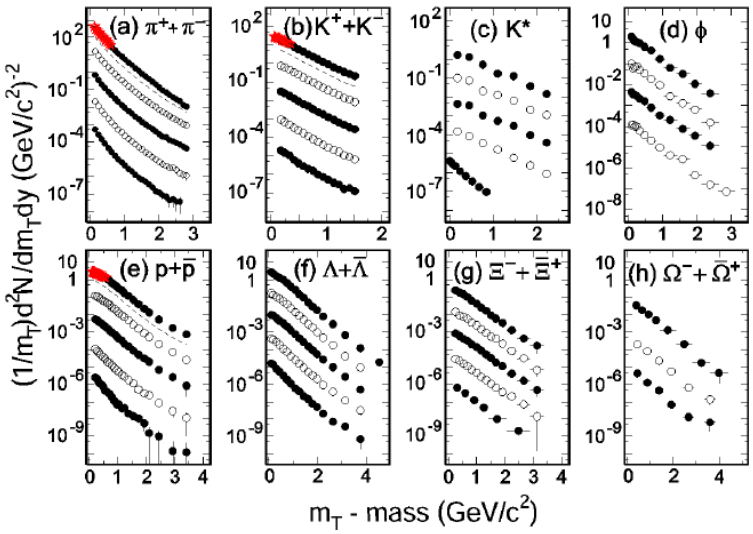


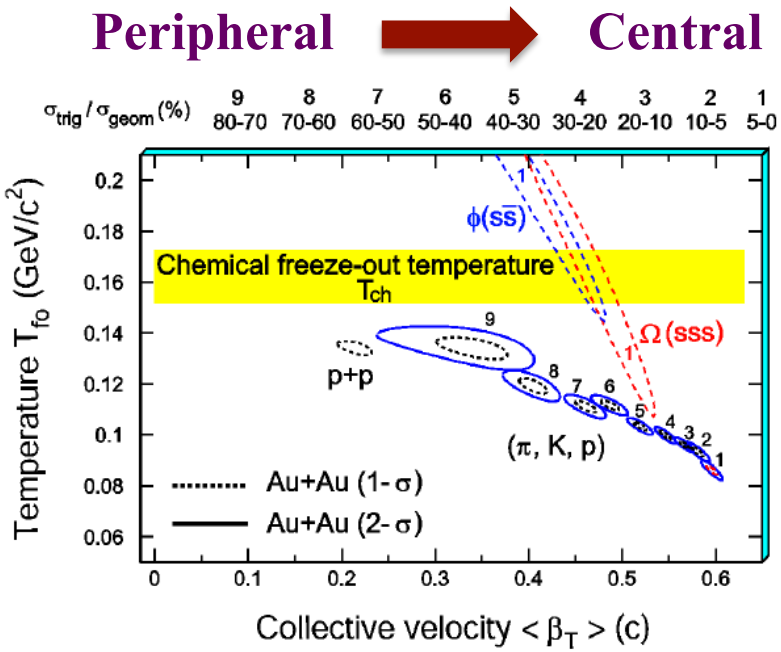
- Particle ratios described very well by statistical model assuming thermal and chemical equilibrium
- $T_{ch} = 163 \pm 5$ MeV

STAR, NPA 757 (2005) 102

Kinetic freeze-out

- Particle kinematics freeze

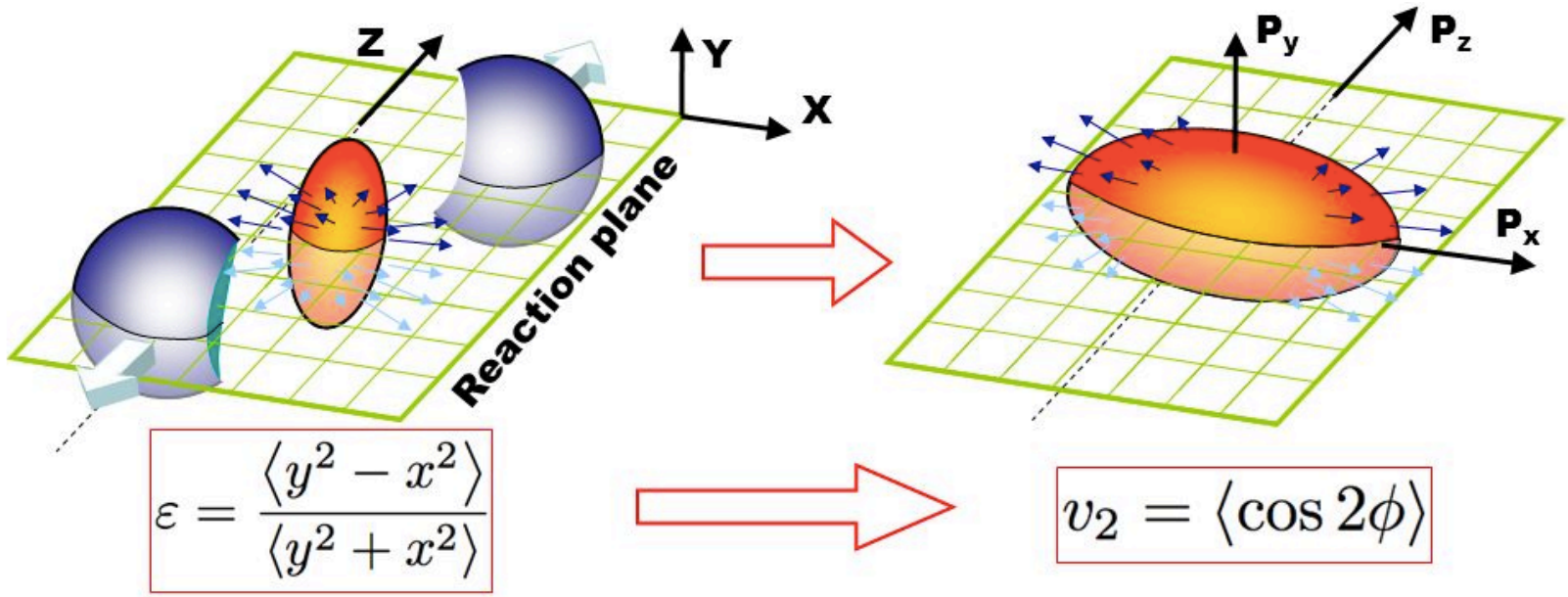




- Fit m_T-m_0 distributions of various particle species
  - $m_T^2 = m_0^2 + p_T^2$
- Peripheral → central collisions: the system expands faster and becomes cooler when reaching kinetic freeze-out

STAR, NPA 757 (2005) 102

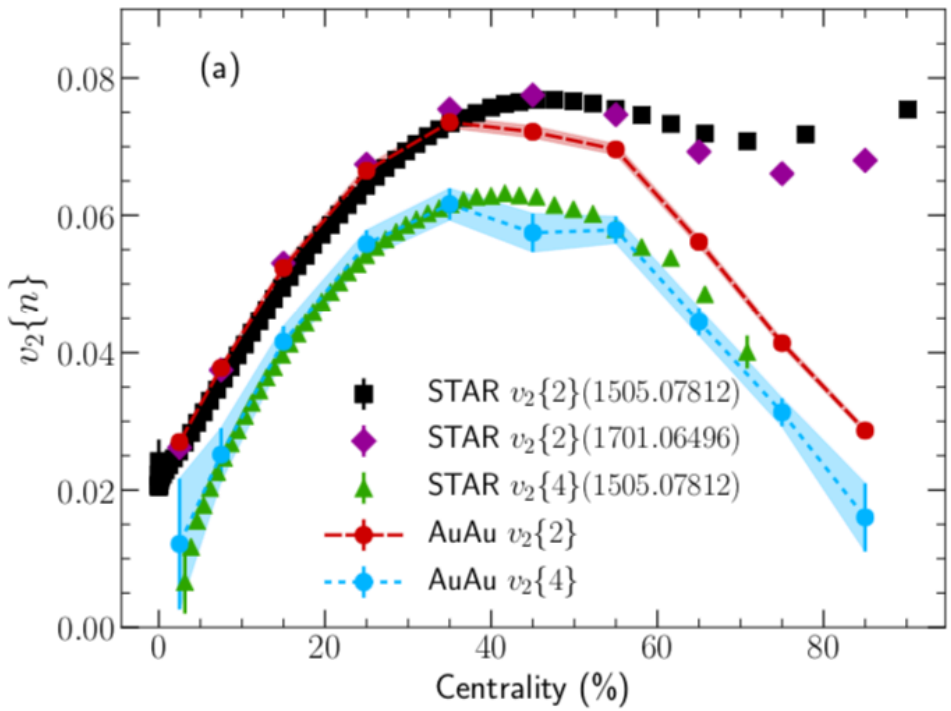
Elliptic Flow (v_2)



- Initial spatial anisotropy → final momentum anisotropy
  - Different pressure gradients in-plane and out-of-plane
  - Depends on overlapping geometry, equation of state, etc

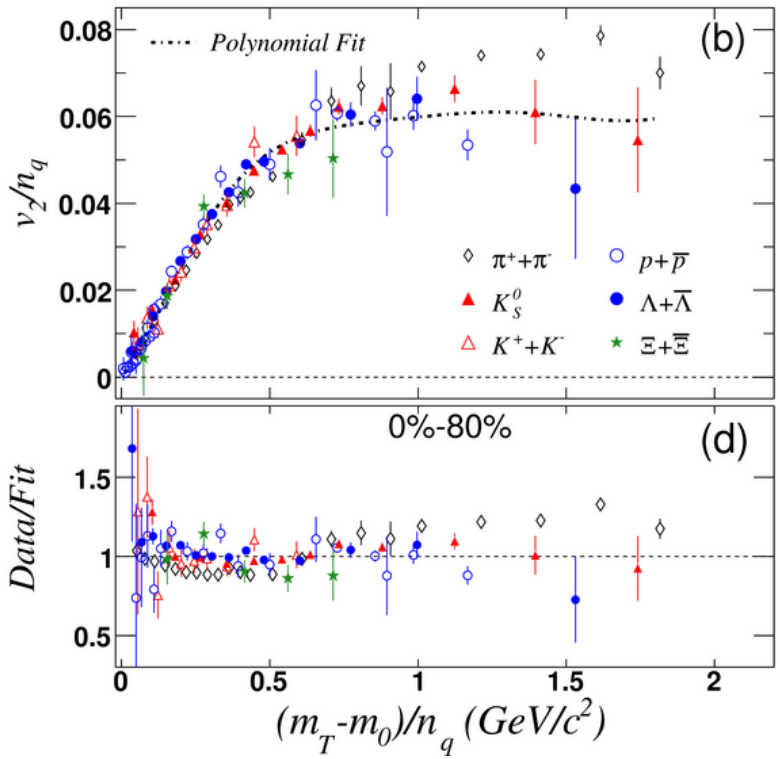
A "perfect" fluid

B. Schenke, et. al, PRC 99 (2019) 044908



- Large elliptic flow successfully described by hydrodynamic calculation
  - $\eta/s \sim 0.12$ → a "perfect" fluid (quantum limit = $1/4\pi$)
- Strong interactions between partons to achieve equilibrium and the system expands hydrodynamically

The famous NCQ scaling



- Mesons (qq) and baryons (qqq) collapse into one common curve when plotting v_2/n_q vs. $(m_T - m_0)/n_q$
- Indicating that flow builds up at the partonic stage of the system

STAR, PRC 75 (2007) 054906

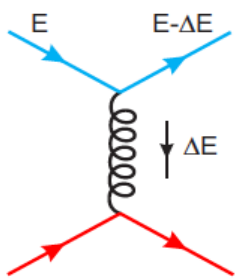
Hard probes

- Another way to study the properties of the QGP is to use the internally produced hard probes.
- Hard probe: large mass or large energy
  - Can be well calculated using pQCD
  - Produced at the beginning of the collisions
  - Experience the entire evolution of the QGP
- Two types
  - Large energy partons with color charges
  - Heavy quarkonium

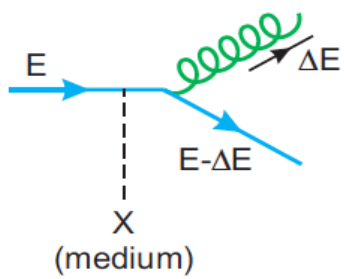
Jet quenching

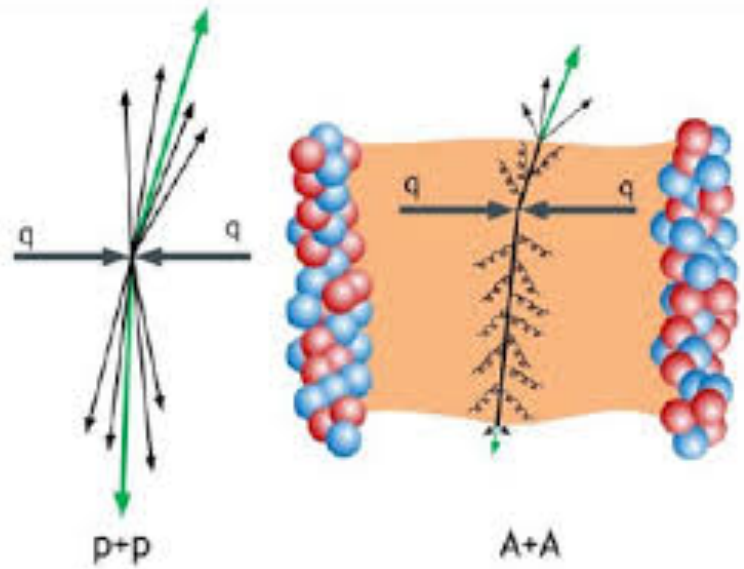
- Large energy/mass partons traverse the medium; hard to be thermalized
- QGP is believed to be "opaque" to them; expect energy loss due to strong interactions

Collisional



Radiative





Nuclear Modification Factor (R_{AA})

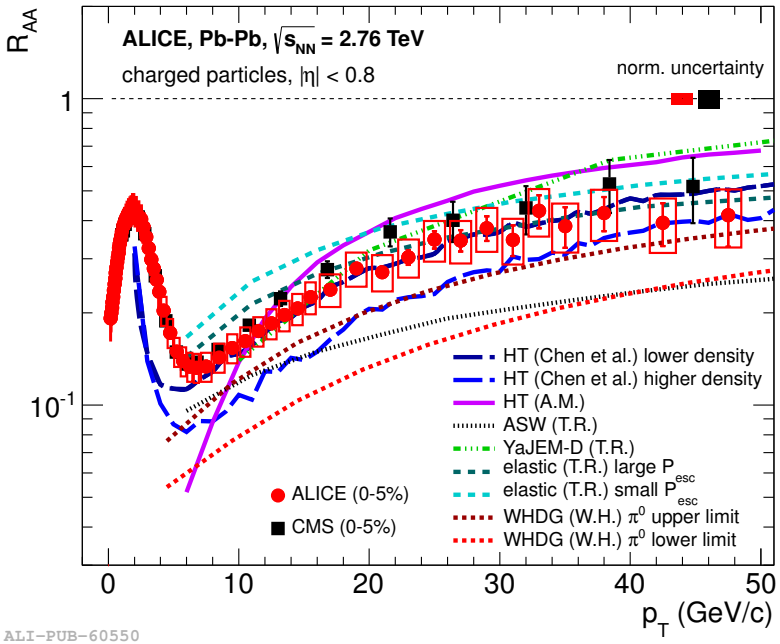
$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dydp_T}{d^2 \sigma_{pp} / dydp_T}$$

- $R_{AA} < 1$: suppression
- $R_{AA} = 1$: no (net) medium effects
- $R_{AA} > 1$: enhancement

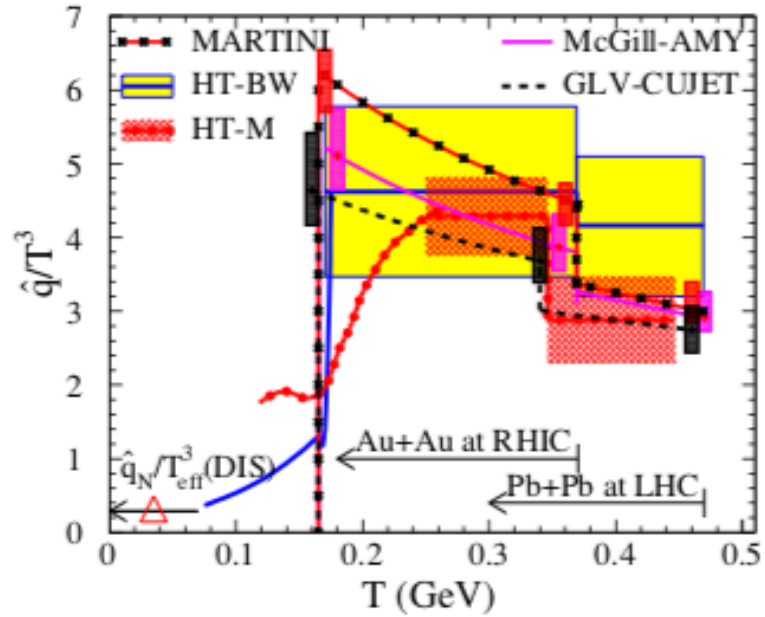
- Used to quantify the energy loss effect

Charged hadron R_{AA}

ALICE, PLB 720 (2013) 52

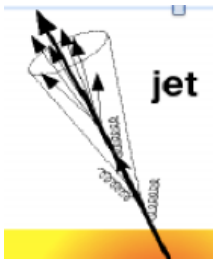


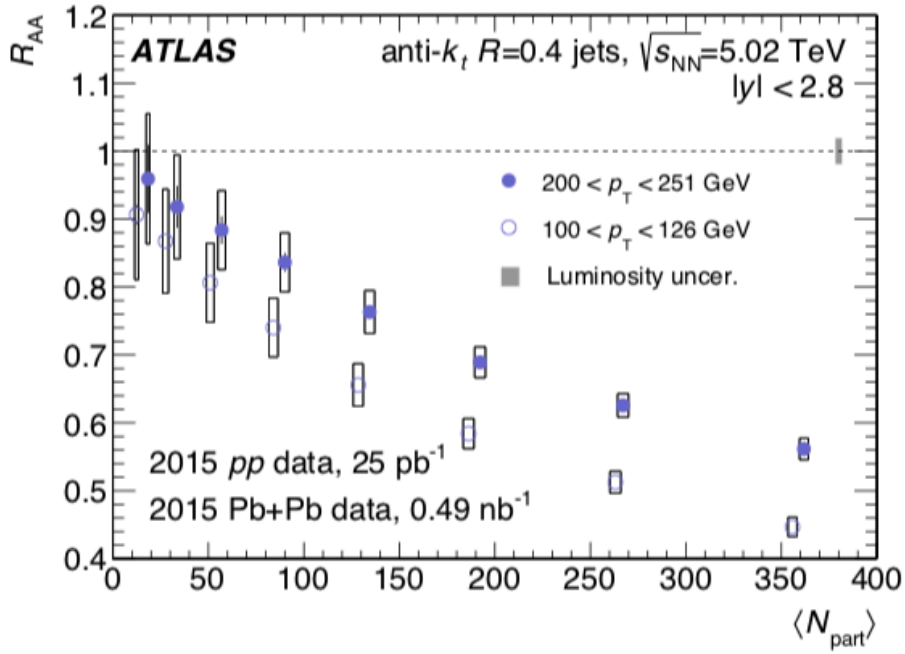
The JET Collaboration: PRC 90 (2014) 014909



- Up to a factor of 7-8 suppression around $6 < p_T < 8$ GeV/c → strong interaction and energy loss of hard probes in the medium
- Comparison to theoretical calculations extracts the fundamental properties of the QGP: qhat

The “real” jet quenching



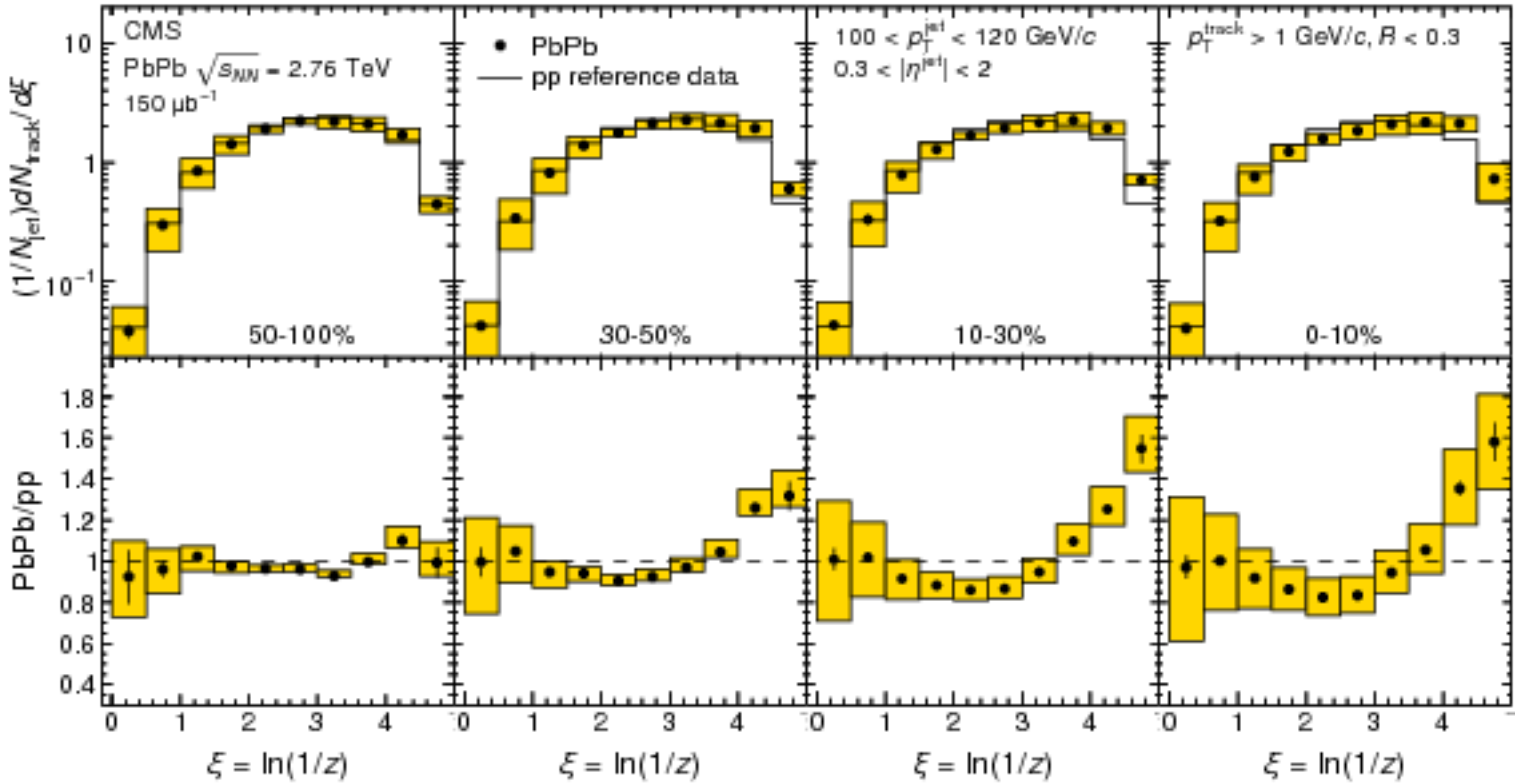


ATLAS, PLB 790 (2019) 108

- Fully reconstructed jets are also quenched by about a factor of 2 in central collisions
- Confirms strong interaction between partons and medium

Do jets look different?

CMS, PRC 90 (2014) 024908



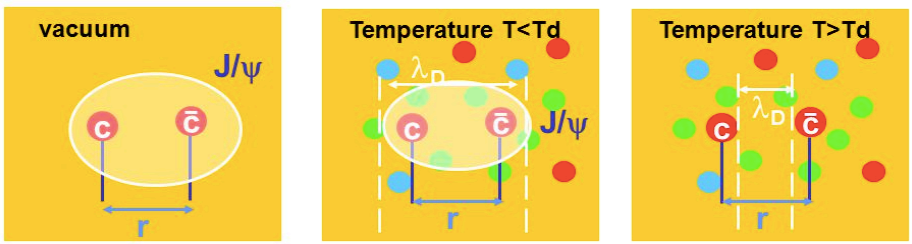
- Enhancement of low-z constituents
- Depletion of intermediate-z constituents

$$z = \frac{p_{track}\cos(\theta)}{p_{jet}}$$

Another probe: Quarkonium ($Q\bar{Q}$)

- J/ψ: charm anti-charm pair
- Υ: bottom anti-bottom pair
- **Proposed signature of deconfinement**: quark-antiquark potential color-screened by surrounding partons → *dissociation*
  - **J/ψ suppression was proposed as a direct proof of QGP formation**

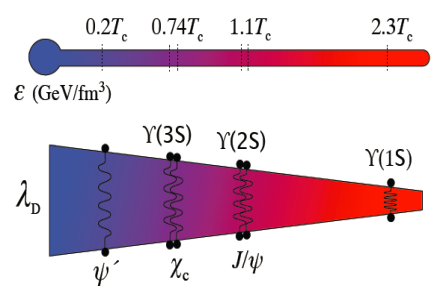
T. Matsui and H. Satz, PLB 178 (1986) 416



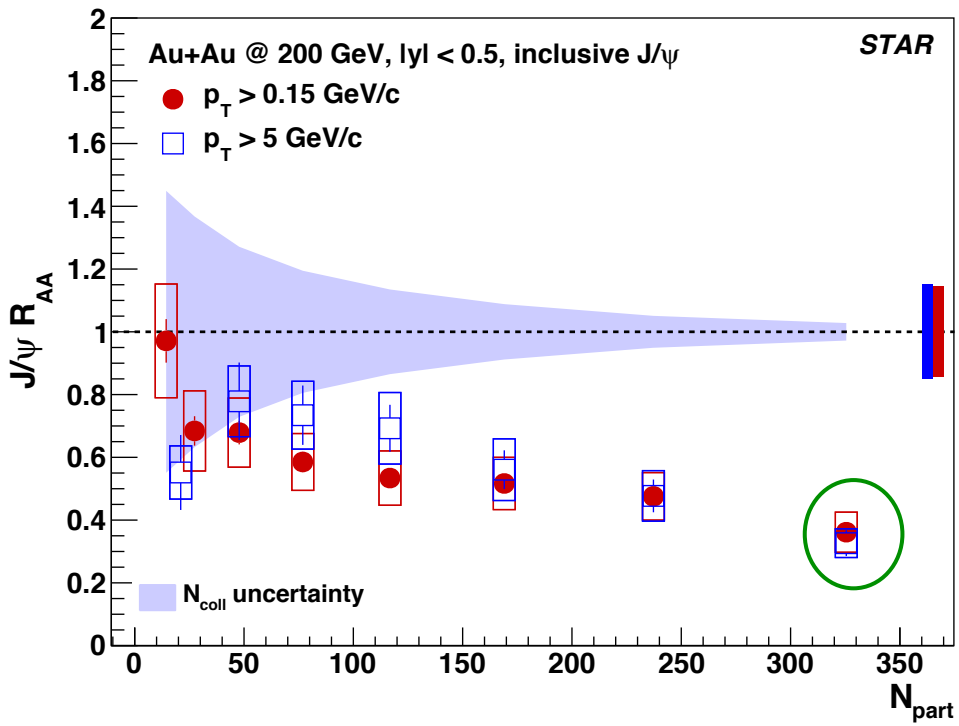
$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

- **"Thermometer"**: different states dissociate at different temperatures → *sequential suppression*

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
E_b (MeV)	~ 1100	~ 500	~ 200



Signature of deconfinement

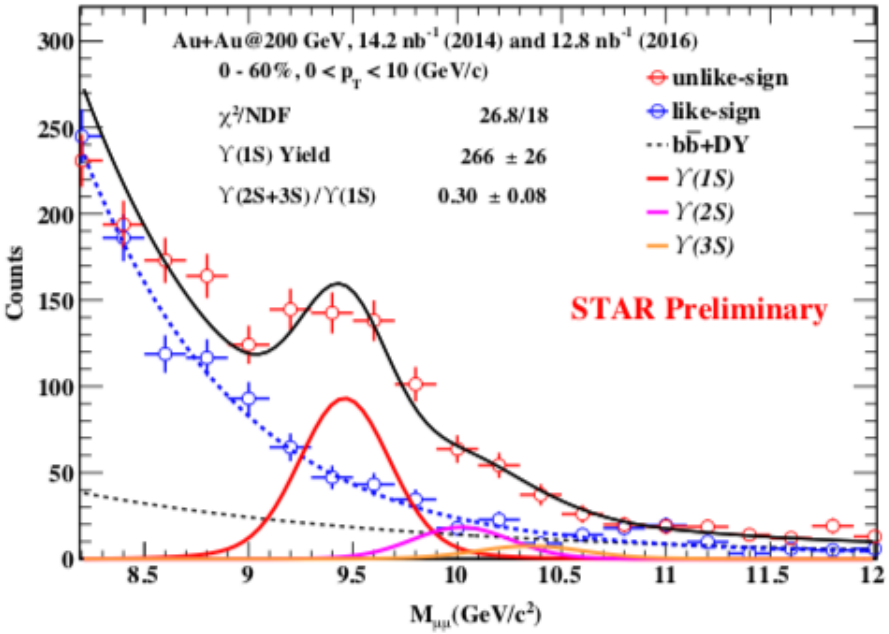


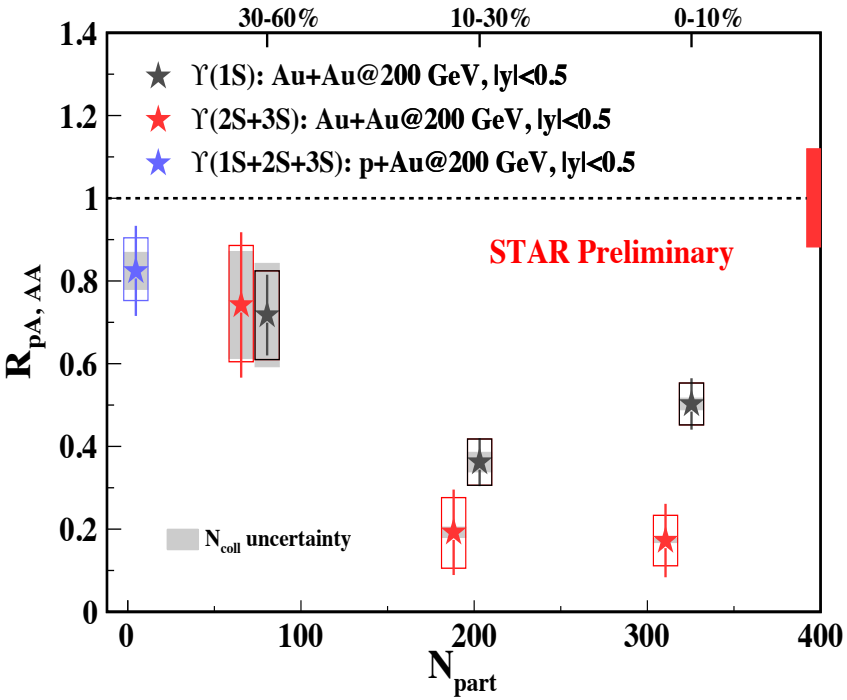
- Strong suppression of high-p_T J/ψ in central collisions

Dissociation In Effect

Sequential suppression of ϒ family

- Very challenging measurements at RHIC due to small production rates
  - ~350 ϒ from about 4.5B triggered events



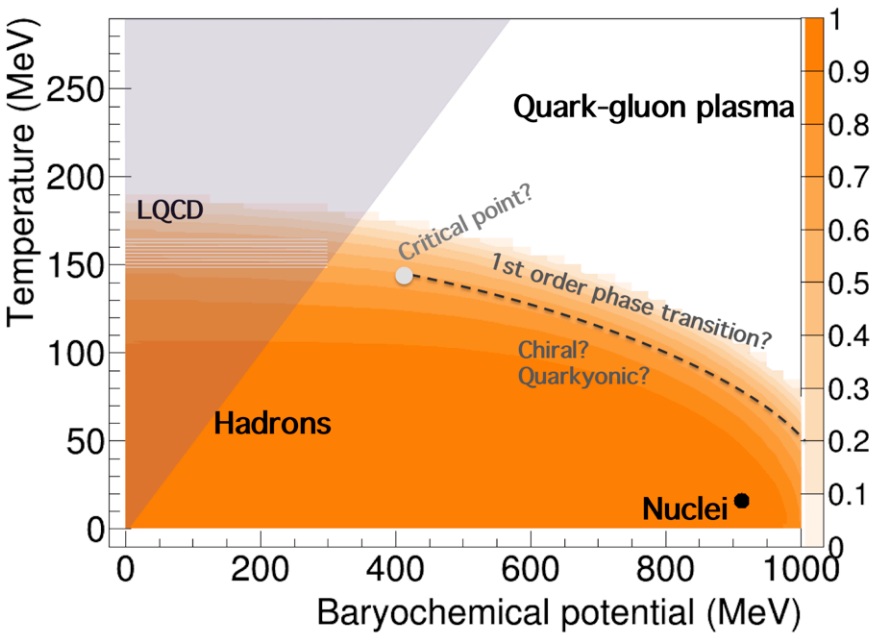


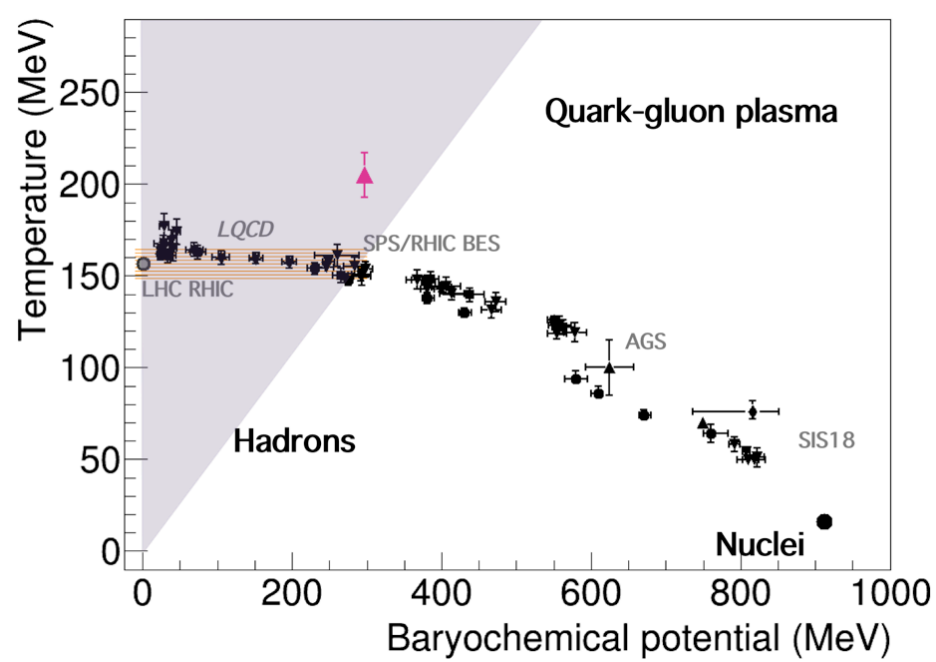
- $R_{AA}^{peri} > R_{AA}^{cent}$: increasing hot medium effects
- RHIC: $R_{AA}^{\Upsilon(2S+3S)} < R_{AA}^{\Upsilon(1S)}$ in 0-10% central

→ sequential suppression

Future of heavy-ion experiments

- **Explore QCD phase diagram and QGP properties** with **detector upgrades, significantly more recorded events and new facilities**





Courtesy of T. Galatyuk, QM2018

Future of HI experiments: low √s

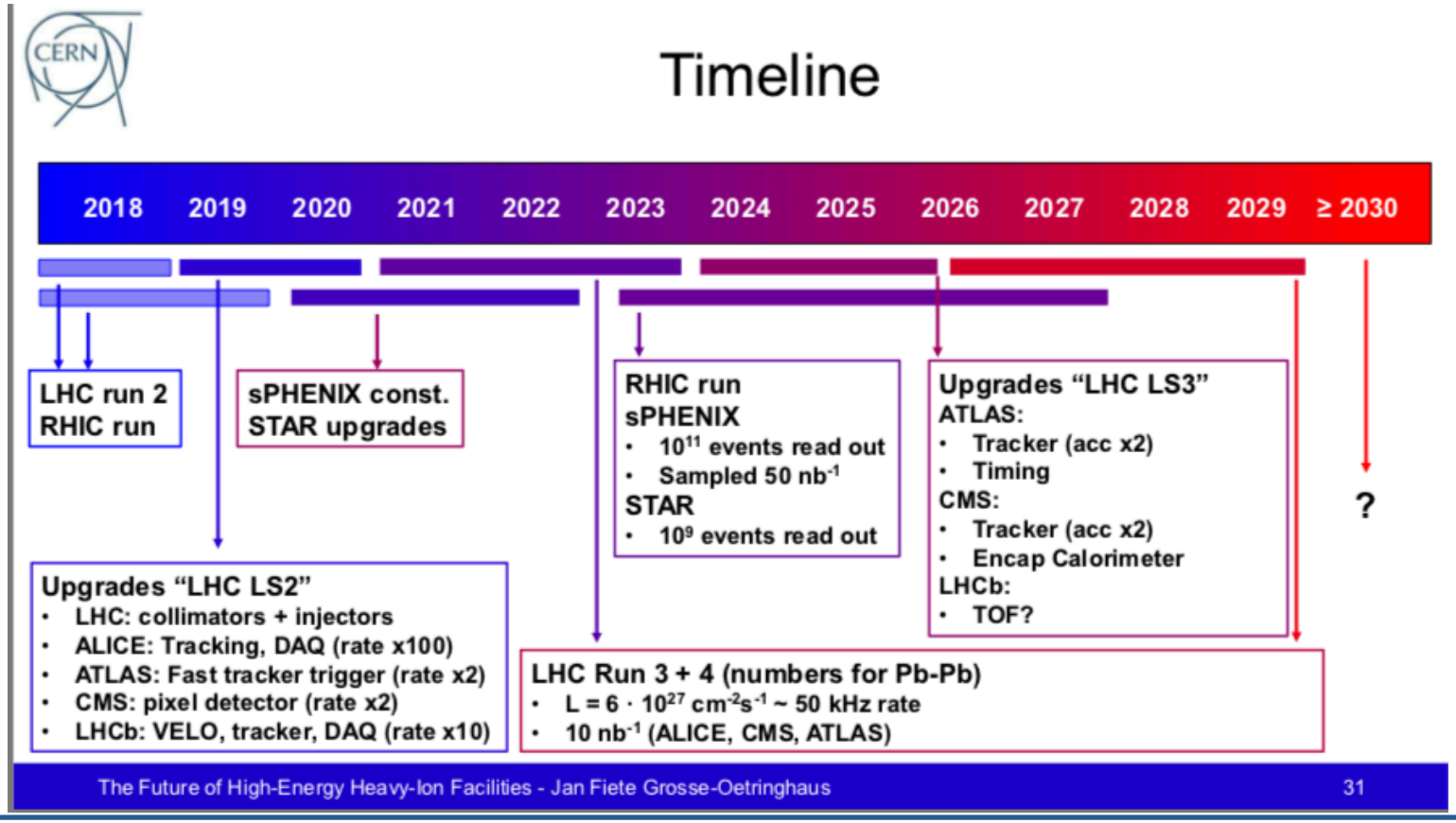
- **Explore QCD phase diagram** and QGP properties with detector upgrades, significantly more recorded events and new facilities

Facility	SIS18	HIAF	Nuclotron	J-PARC-HI	SIS100	NICA	RHIC	SPS	SPS
Experiment	HADES / miniCBM	CEE	BM@N	DHS, D2S	CBM / HADES	MPD	STAR	NA61	NA60+
Start	2012, 2018	2023	2019 (Au)	>2025(?)	2025	2021	2010,2019	2009, 2022	>2025(?)
$\sqrt{s_{NN}}$, GeV	2.4 – 2.6	1.8 – 2.7	2 – 3.5	2 – 6.2	2.7 – 5	2.7 - 11	3 – 19.6	4.9 – 17.3	4.9 – 17.3
μ_B, MeV	880 – 670	880 – 750	850 – 670	850 – 490	780 – 400	750 – 330	720 – 210	560 – 230	560 – 230

Courtesy of T. Galatyuk, QM2018

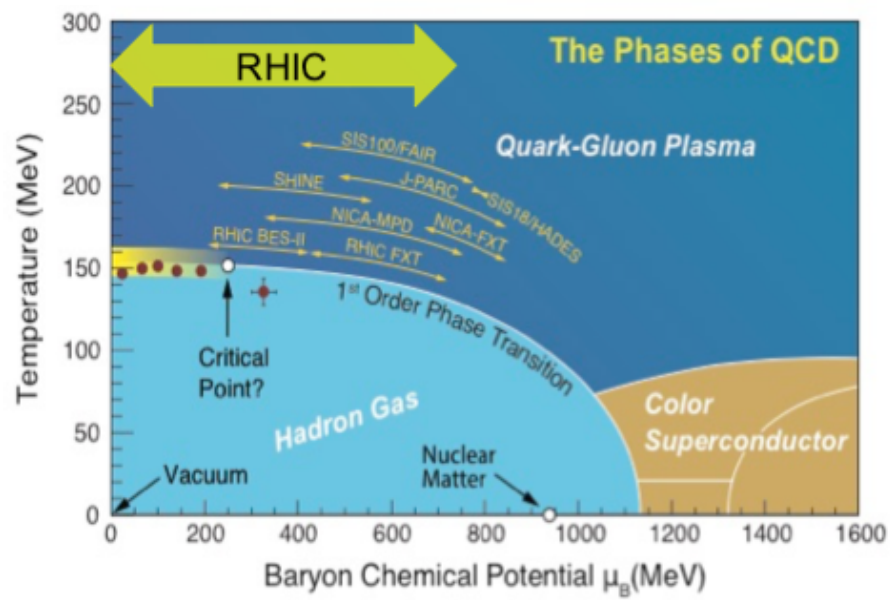
Future of HI experiments: high √s

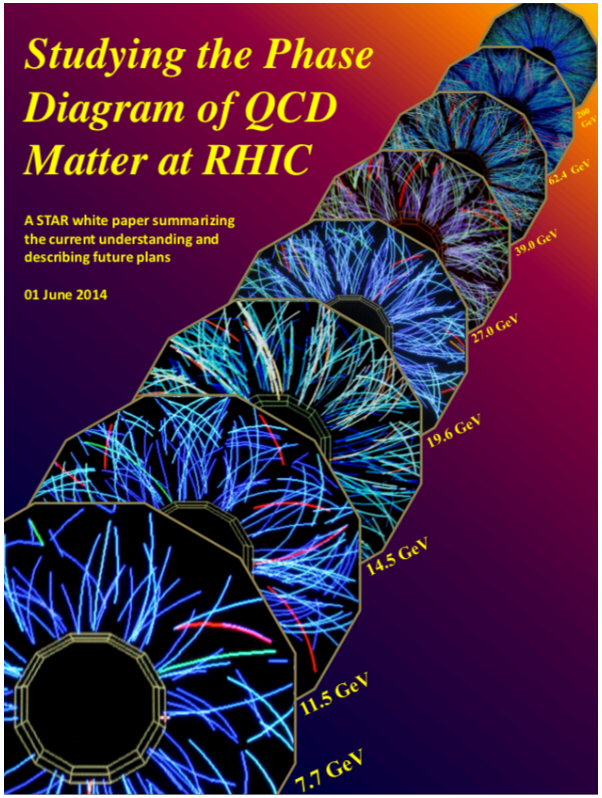
- Explore QCD phase diagram and **QGP properties** with detector upgrades, significantly more recorded events and new facilities



Future is happening now

- STAR BES-II program is under the way





https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Summary

- What is the Quark-Gluon Plasma (QGP)?
  - ✓ A state of matter with deconconfined partons
- Why is the QGP interesting?
  - ✓ Existed at early Universe; QCD dynamics
- How to create the QGP in a lab?
  - ✓ Heavy-ion collisions
- How to study the QGP in a lab?
  - – How do we access the QGP? → Detectors; internal probes
  - – What have we learnt about the QGP?
  - → "Perfect" fluid; quench jets; dissociate quarkonium …
- What is the future of heavy-ion experiments?
  - ✓ Exciting 10 years of physics program ahead and more …
  - ✓ Electron-Ion collider