Muon Telescope Detector and Quarkonia

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Lecture for NuSTEAM Program

About myself

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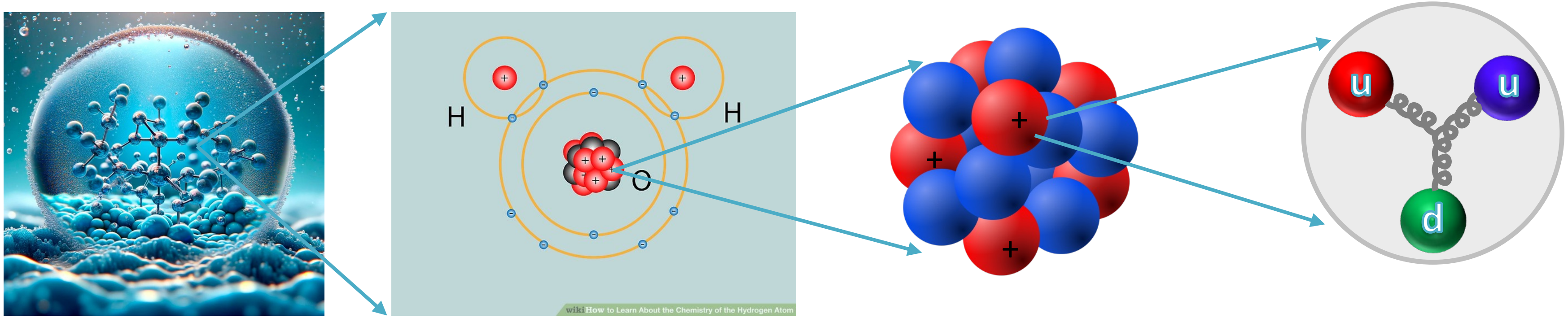
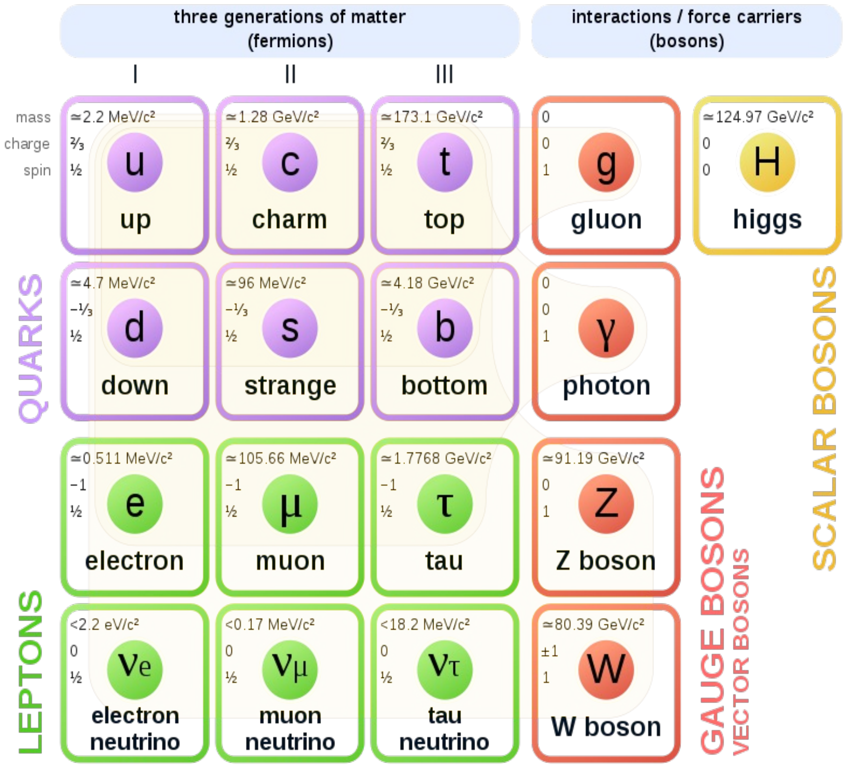
Building blocks of the universe

Molecule | Atom | Nucleus | Quarks & Gluons



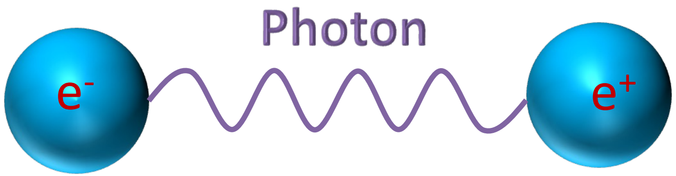
Images:
https://scitechdaily.com/rethinking-h2o-water-molecule-discovery-contradicts-textbook-models/
https://www.wikihow.life/Learn-About-the-Chemistry-of-the-Hydrogen-Atom
https://en.wikipedia.org/wiki/Nucleon

Standard Model of Elementary Particles

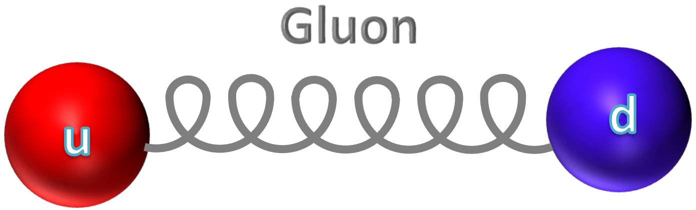


Strong force

- Electromagnetic force
  - ✓ Electric charge: positive and negative

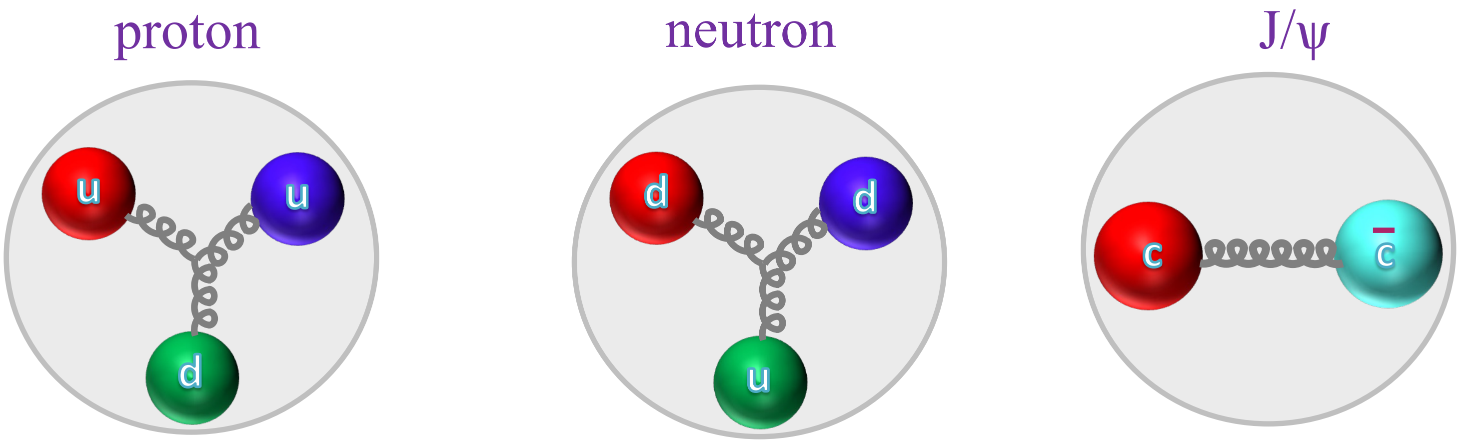


- **Strong force**
  - ✓**Color charge**: Red, Blue, Green

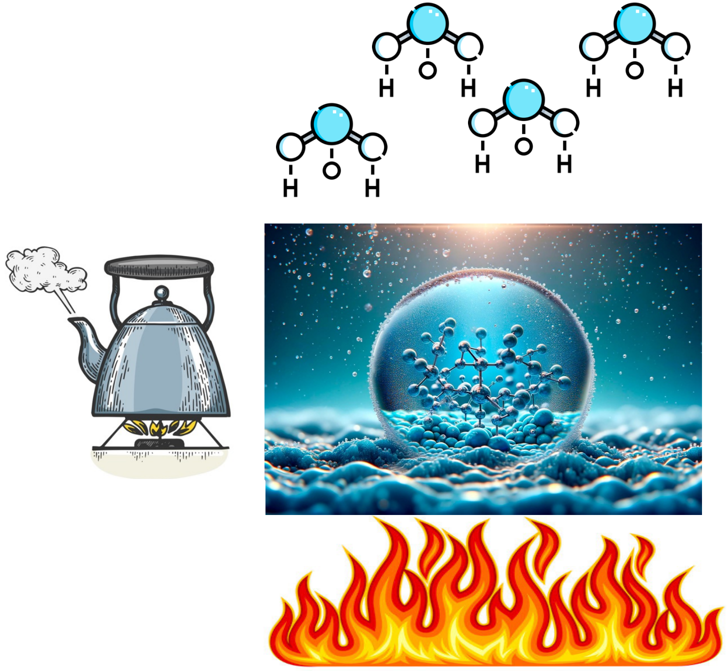


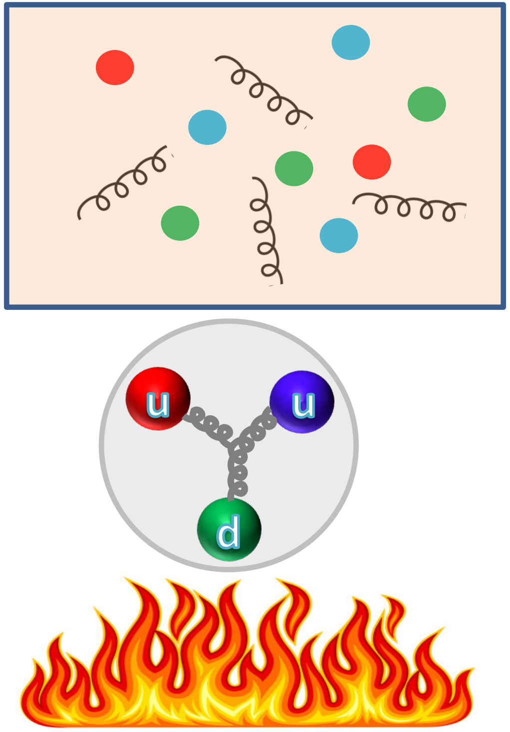
Color confinement

➢ **Confinement:** quarks (“colored” objects) always constrained within color-less composite particles, and they have never been individually observed experimentally



Can we deconfine matter?

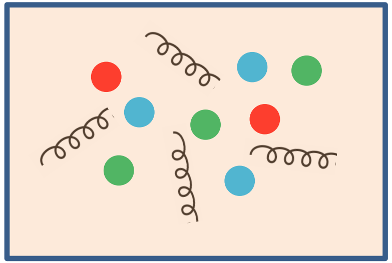




Yes, we can and it has happened before

Time

0 | 10^{-6} s | 9 billion years | 13.8 billion years



Quark-Gluon Plasma (QGP)

- A novel state of matter, made of deconfined quarks and gluons which are ordinarily confined in the world as we know

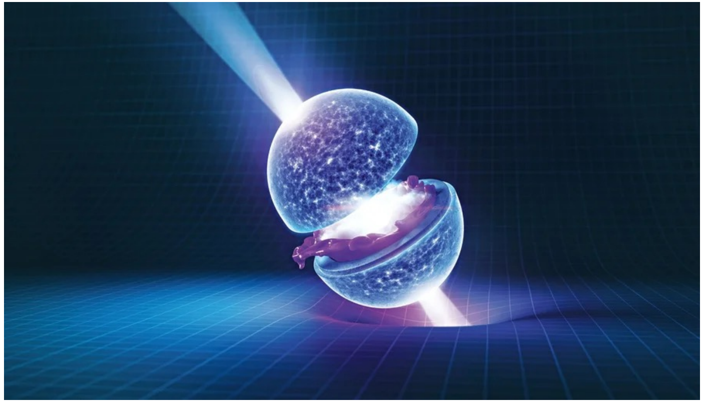
https://today.uic.edu/collider-reveals-sharp-change-from-quark-soup-to-atoms

Why study QGP?

- Understand properties of matter under extreme conditions, such as high temperature or high density

Early Universe

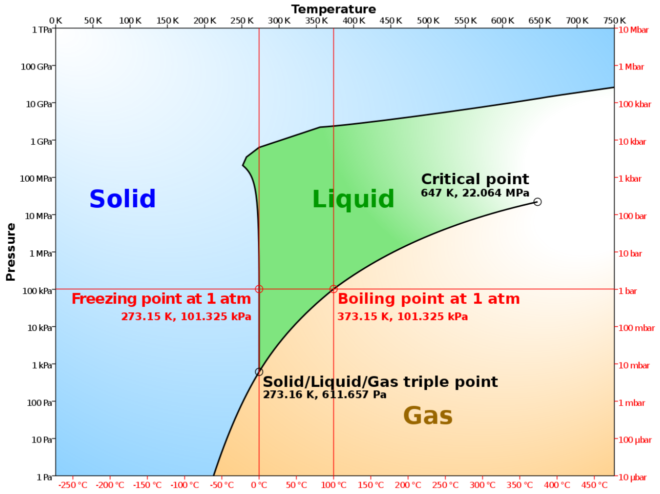
Neutron star



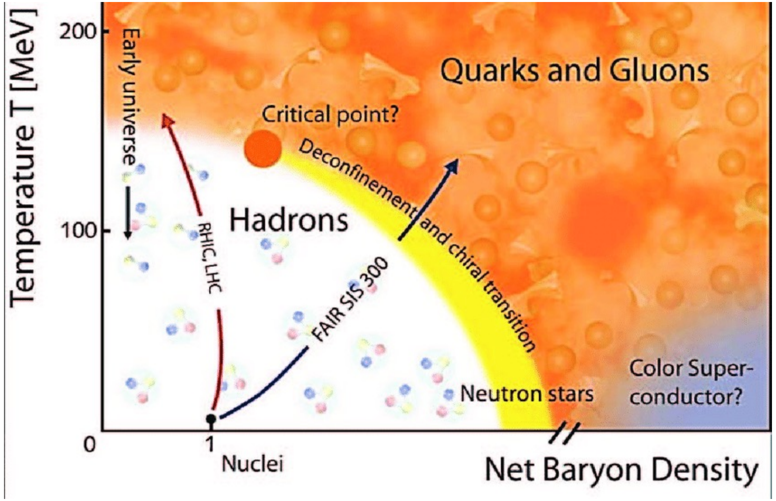
https://www.newscientist.com/article/mg22429991-000-how-to-think-about-the-big-bang
https://www.scientificamerican.com/article/neutron-stars-natures-weirdest-form-of-matter

How to create the QGP?

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



Water

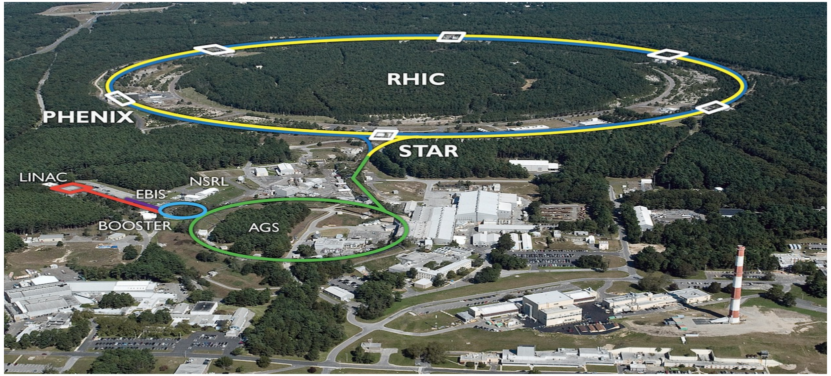


QCD matter

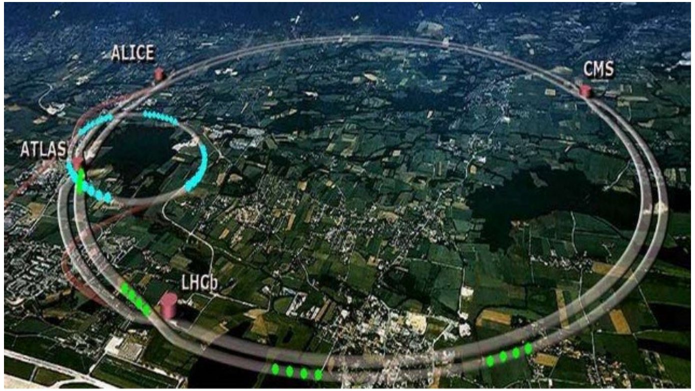
How to realize it in a lab?

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

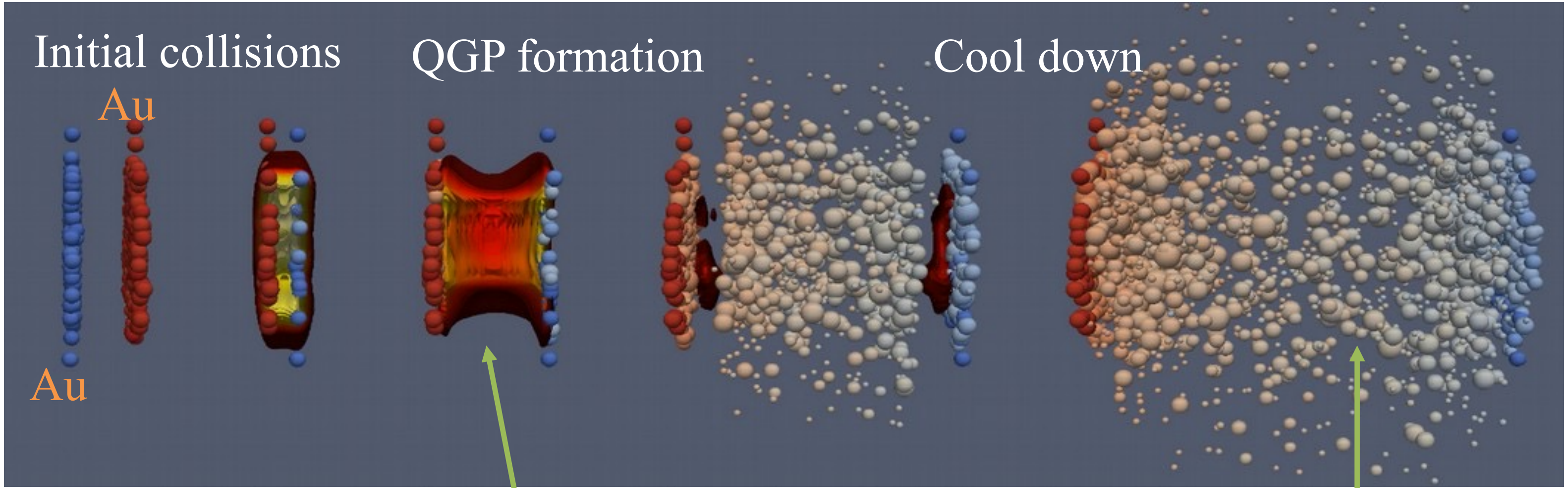
RHIC: Au+Au



LHC: Pb+Pb



Au+Au collisions: “Little Bang”



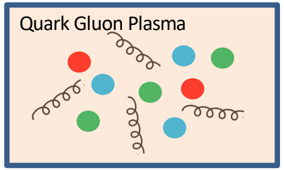
MADAI collaboration, Hannah Petersen and Jonah Bernhard

What we want

What we get

How does QGP “look” like?

	QGP	Human	Sun
Size	10^{-14} m	1.8 m	1.4×10^{9} m
Lifetime	10^{-22} s	100 year	10^{10} year
Temperature	$>2\times10^{12}$ °C	36 °C	10^{7} °C




How to study QGP?

1. Its own collective behavior

→ How easily it flows?

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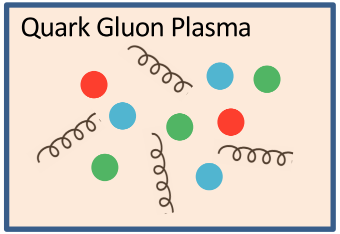
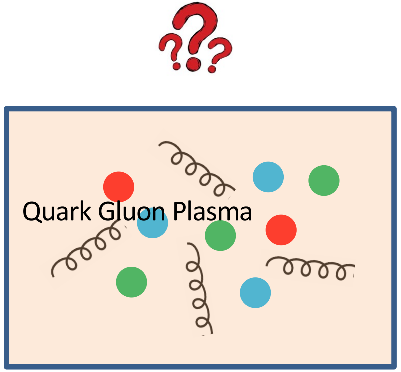


2. “External” probes

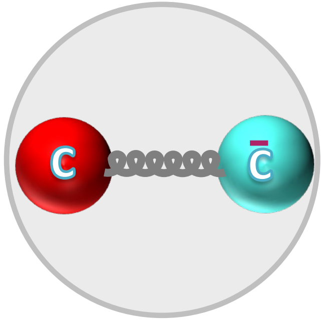
→ Will they stay or dissolve?



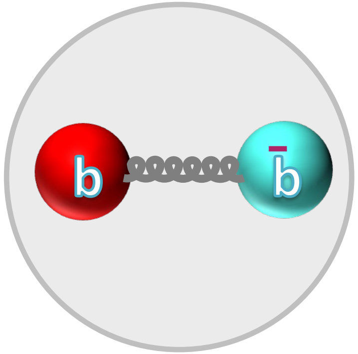
What is a quarkonium?

- A quarkonium is a meson made up of a pair of heavy quark and its anti-quark.

J/ψ



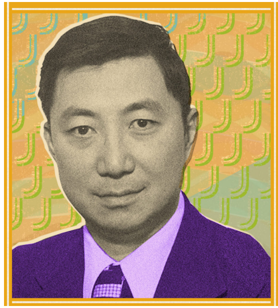
Υ



“November Revolution” at BNL

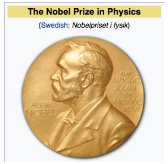
- Discovery of J/ψ in 1974: evidence for quark model

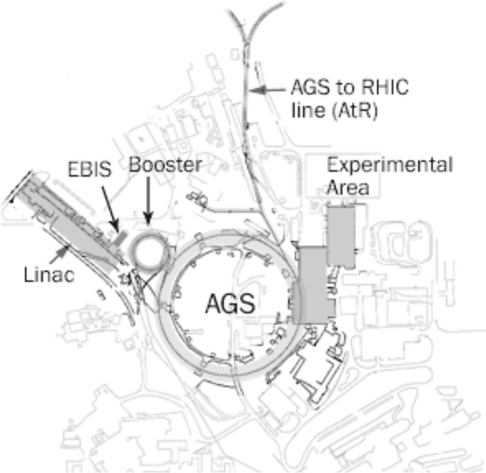
Sam Ting



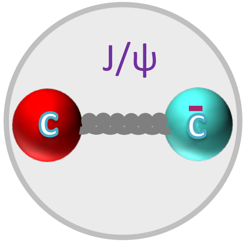
Burton Richter

1976





Alternating Gradient Synchrotron



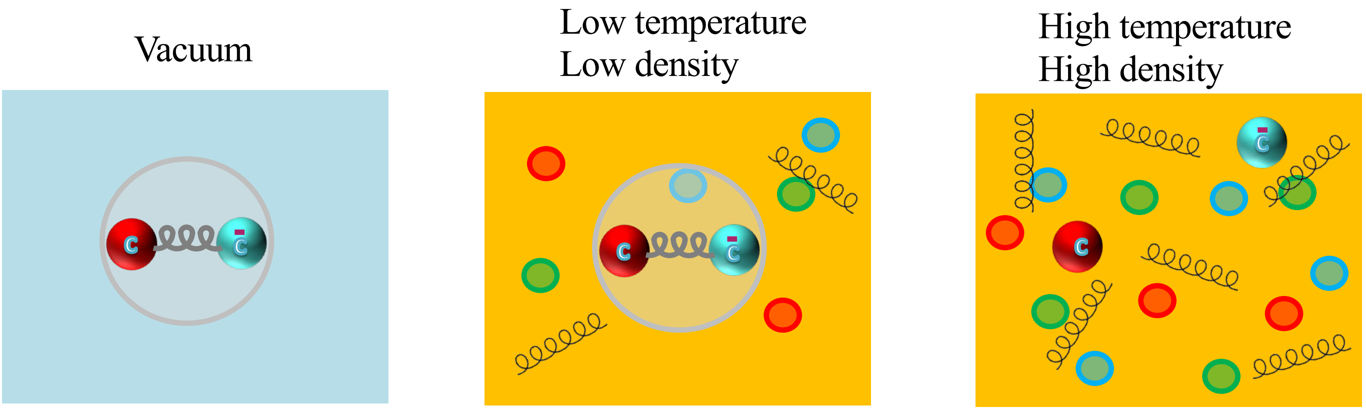
$J/\psi \to e^+ + e^-$

$J/\psi \to \mu^+ + \mu^-$

https://www.symmetrymagazine.org/article/november-2014/the-november-revolution

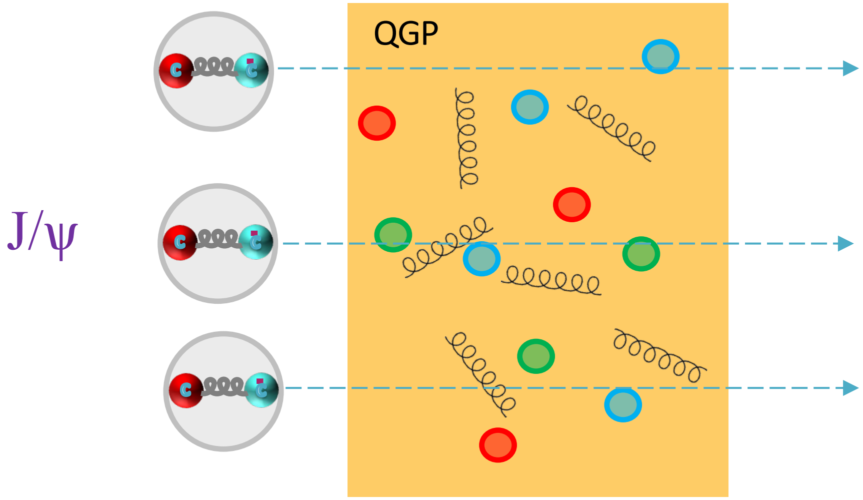
“Drop” J/ψ into QGP

- Produced in Au+Au collisions before QGP is formed
- Can dissolve or “melt” in the QGP → Evidence for QGP formation



A counting experiment

- Experimentally, one expects a reduced production yield



How many J/ψ's survive?

Nuclear Modification Factor (R_{AA})

- Quantify the level of J/ψ suppression in Au+Au collisions

$$R_{AA} = \frac{\text{J/}\psi\text{ yield after going through QGP}}{\text{J/}\psi\text{ yield before going through QGP}} = \frac{\text{J/}\psi\text{ yield in gold+gold collisions}}{\text{J/}\psi\text{ yield in proton+proton collisions (scaled)}}$$

- $R_{AA} < 1$: suppression
- $R_{AA} > 1$: enhancement

How to detect a J/ψ?

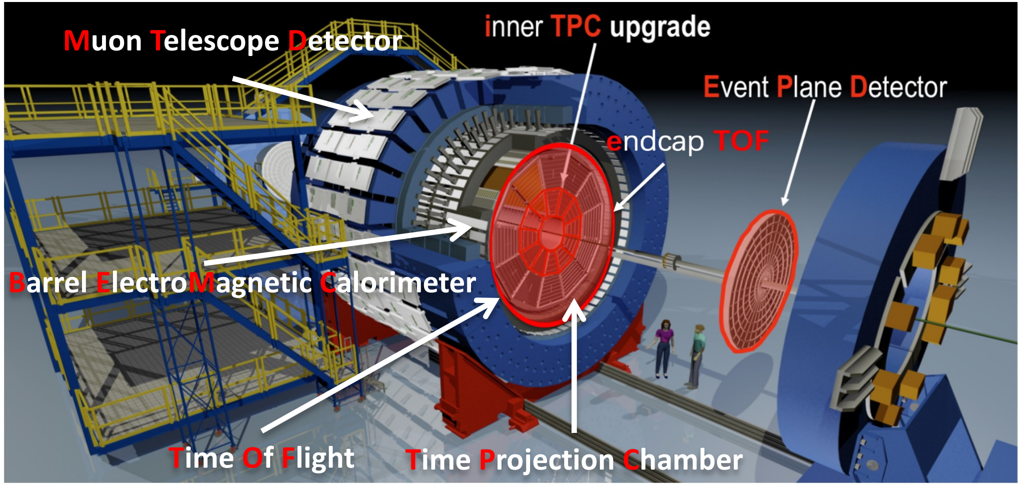
- Mass = 3.0969 GeV/c^2 = $5.52*10^{-27}$ kg
- Mean lifetime = $7.2*10^{-12}$ s

- Decay into electron and muon pairs, which can be measured in detectors and used to reconstruct the J/ψ
- Both channels have been used to measure J/ψ, and we will focus on the muon channel in this lecture

$$J/\psi \rightarrow \mu^{+} + \mu^{-}$$

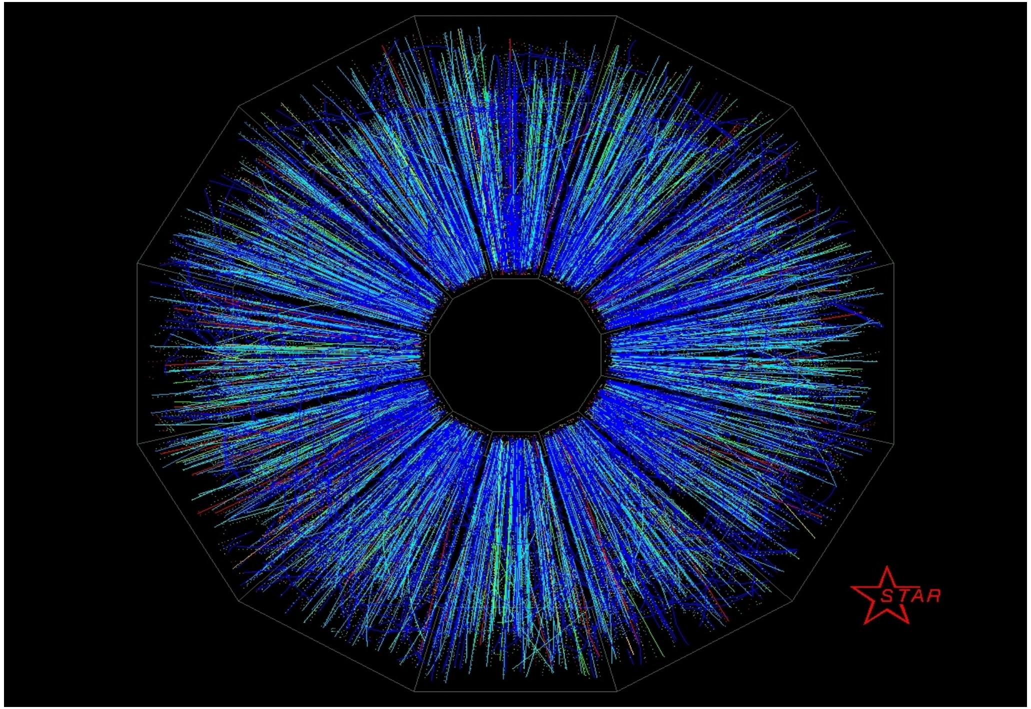
STAR @ RHIC

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

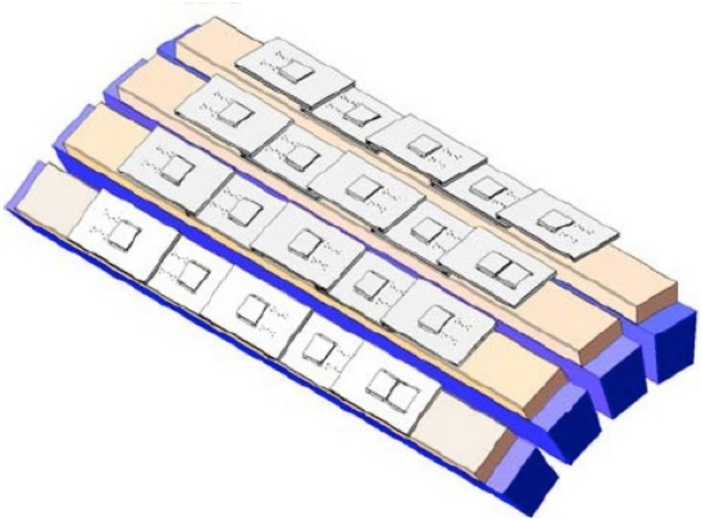


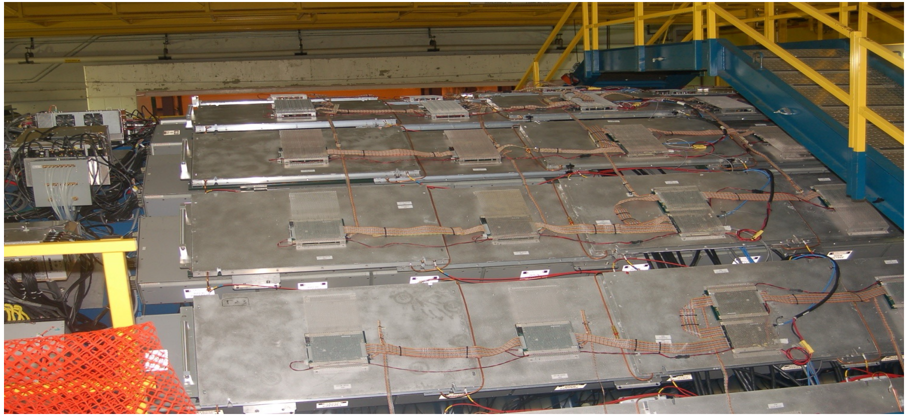
- Sub-detectors
  - **T**ime **P**rojection **C**hamber
  - Time-**O**f-**F**light detector
  - **B**arrel **E**lectro**M**agnetic **C**alorimeter
  - **M**uon **T**elescope **D**etector
  - …

A real collision recorded by STAR



Muon Telescope Detector





Muon Telescope Detector

- MTD consists of 122 trays
- Each tray is made of a MRPC, electronics and supporting structure

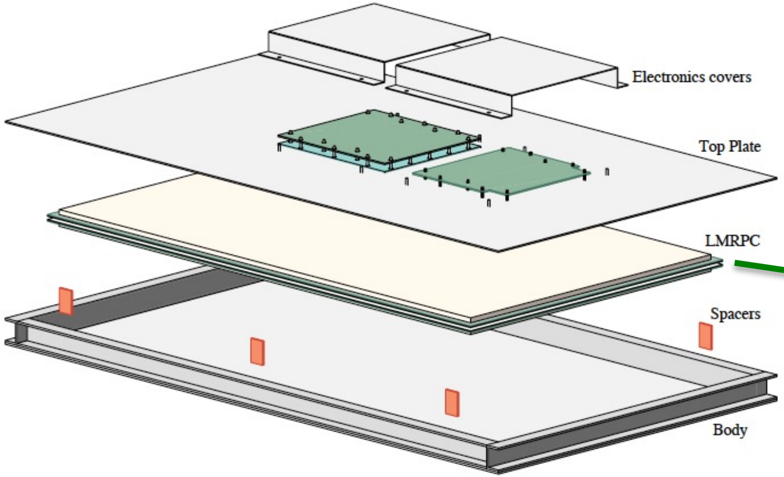
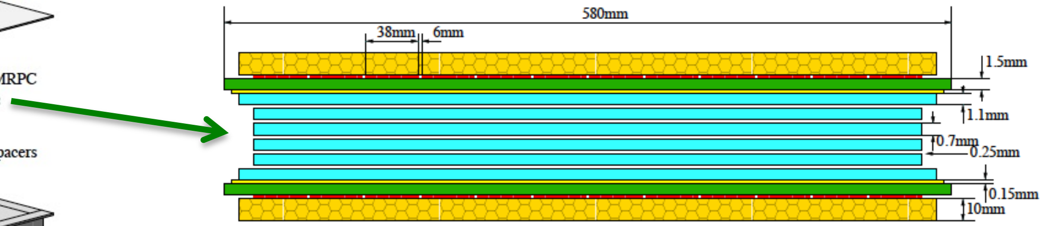
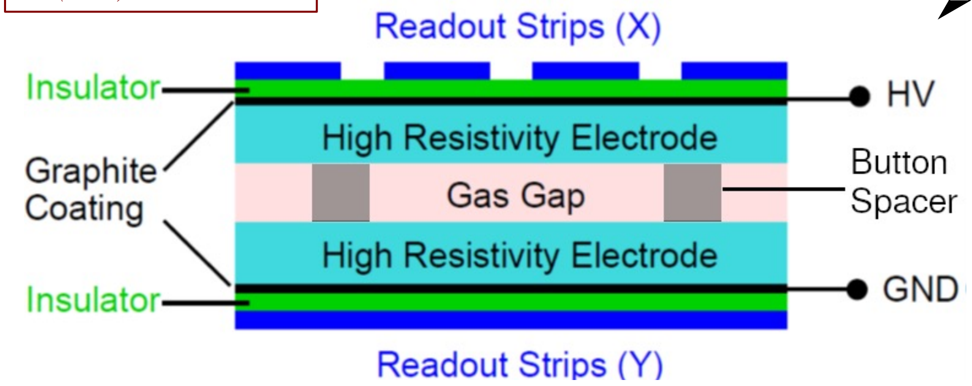


Figure 33. An exploded view of an MTD tray.



Resistive Plate Chambers (RPC)

S. Mondal, et al JINST 14 (2019) 04009



- Working principle:
  - a traversing particle ionizes the gas atoms
  - knocked-out electrons drift in the external electric field and ionize more atoms
  - moving electrons induce signals on readout strips

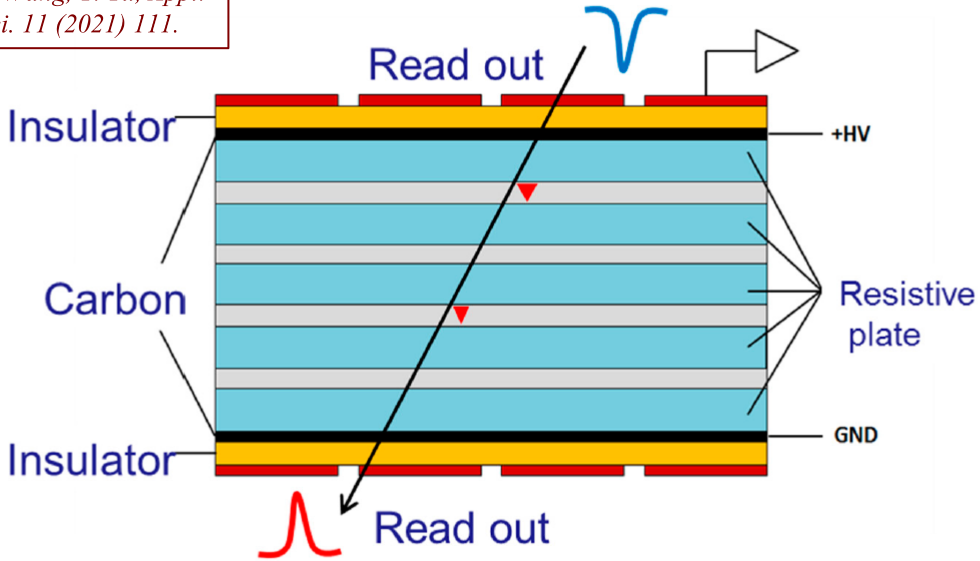
✧ To improve timing resolution, one can decrease gap width, which however leads to lower efficiency

→ More gaps

W. Riegler, et al, NIM A 500 (2003) 144

Multigap Resistive Plate Chambers (MRPC)

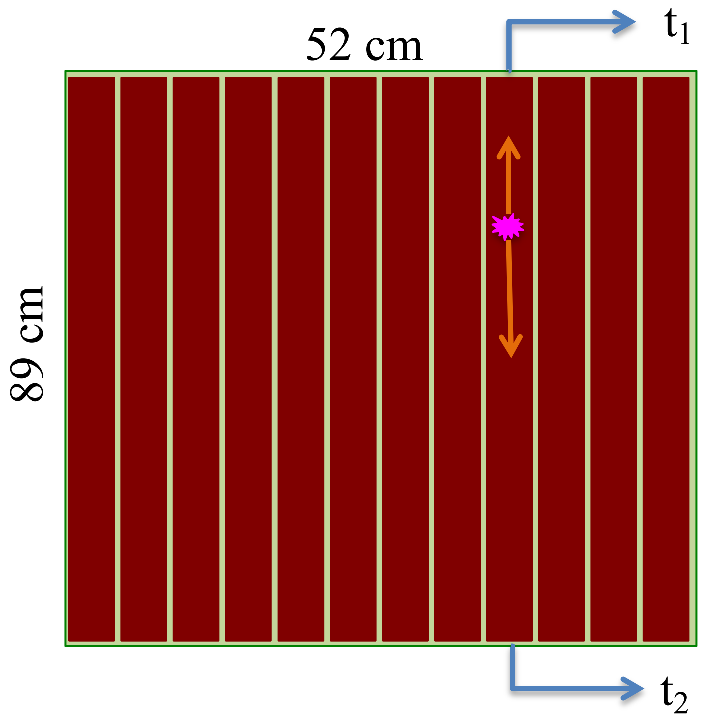
Y. Wang, Y. Yu, Appl. Sci. 11 (2021) 111.



- Ionization can happen in multiple gaps, and readout strips pick up signals from all gaps
- Improve timing resolution and efficiency
- Resistive plates prevent cross-talk between gaps

High rate, easy construction, large area, cost effective

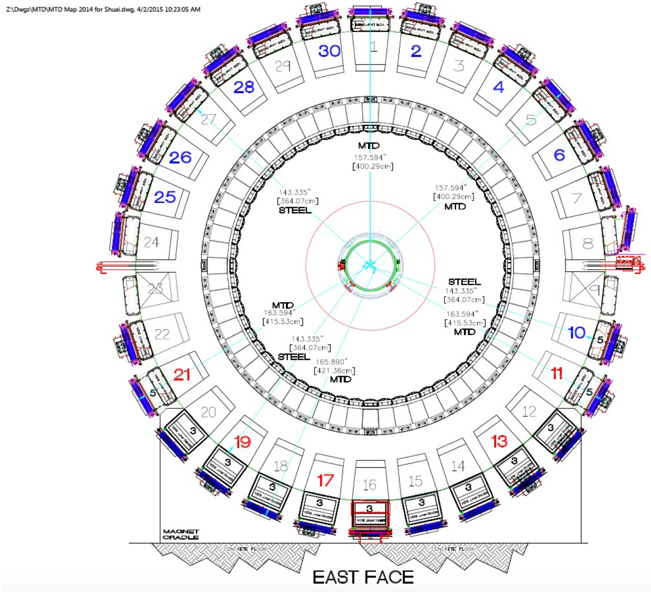
Double-ended readout strips

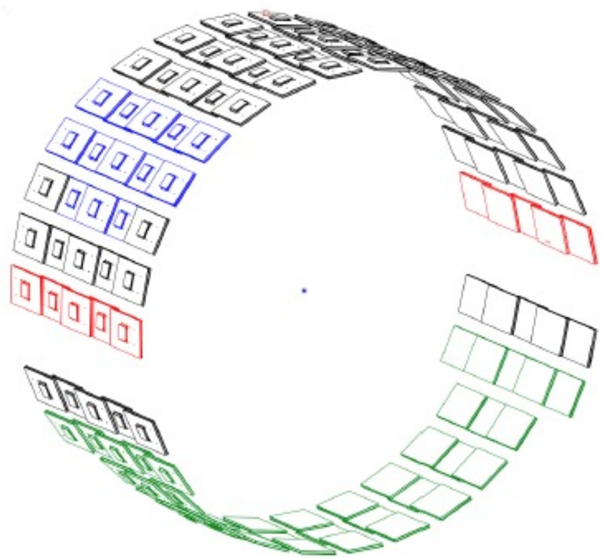


- Each tray has 12 strips
- Each strip is 38 mm wide, with a 6 mm gap in between, and 89 cm long
- Double-ended readout to measure hit time and position

HW: given that the time signals for a particle hitting a strip of length L are t_1 and t_2, and the signal travel velocity in the strip is v, what is the time and position of the hit?

MTD geometry



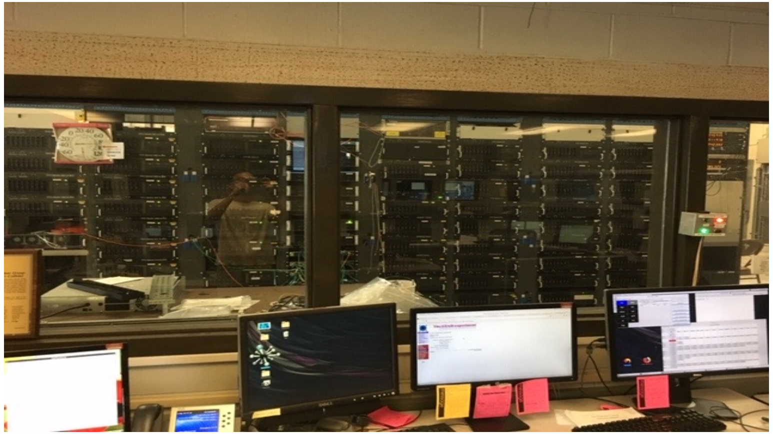


- Located outside of the STAR magnet (~5 interaction lengths), acting as an absorber
- 122 trays on 28 backlegs; 1439 readout strips

HW: what is the interaction length? Why is important for MTD?

Go from electronic signal to data

- **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: ~5 kHz for Au+Au @ 200 GeV, > 1 PB/week



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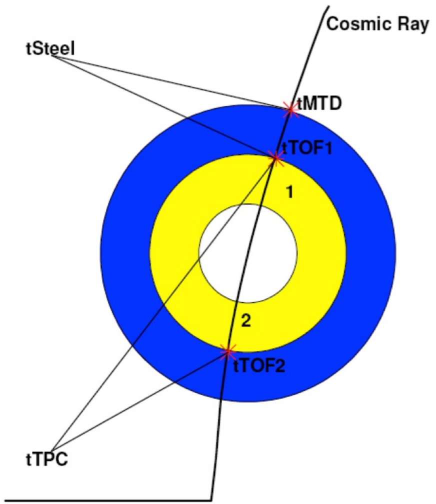
- **Calibration**
  - Convert electronics signal to physical quantities
  - Detector alignment
  - T0 calibration



Go from electronic signal to data

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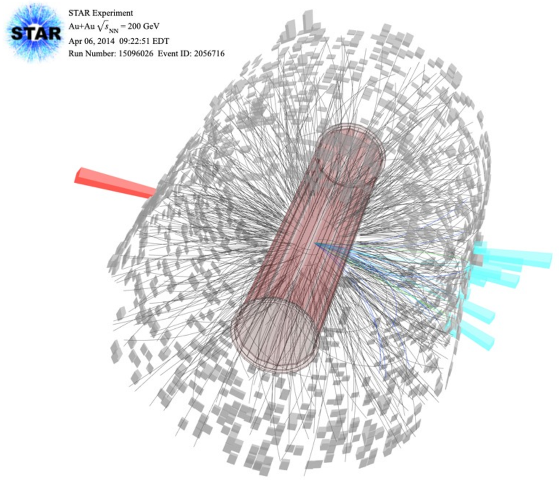
- **Calibration**
  - Convert electronics signal to physical quantities
  - Detector alignment
  - T0 calibration
- **Data production**
  - Vertex: position where the collision happens
  - Tracks: momentum, position, charge …
  - Hits: energy, position, timing …

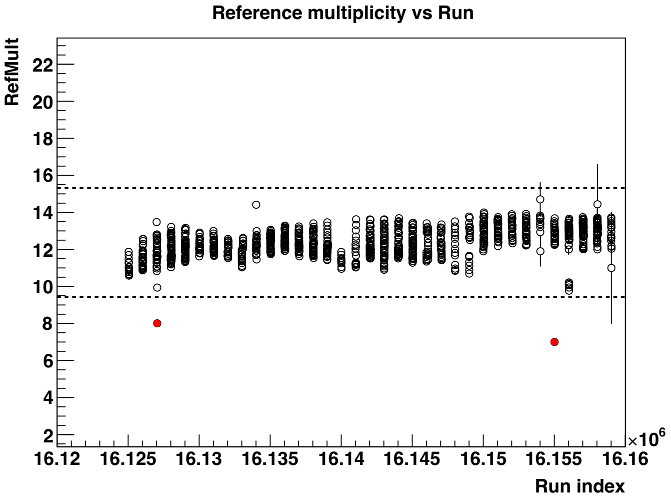


Data analysis

- Quality assurance
- Signal extraction
- Detector effect correction
- Physics results

Quality assurance

- To make sure the detector performance is stable across all the runs
  - A run is a period of time (30-45 min) during data taking



➢ Typical procedure
1) Plot quantity of interest against run indices
   - Left: number of reconstructed charged particles
2) Project the figure to y-axis and obtain the distribution of the quantity. Fit the distribution with a Gaussian distribution, and define exclusion zone, e.g. 4σ
3) Check records to find out the cause of the abnormal behavior.
   - If understood, these runs could be used in principle
4) Runs in exclusion zone are labeled "bad", and removed for further analysis

HW: what is fraction of runs excluded with 4σ cut due to statistical fluctuations?

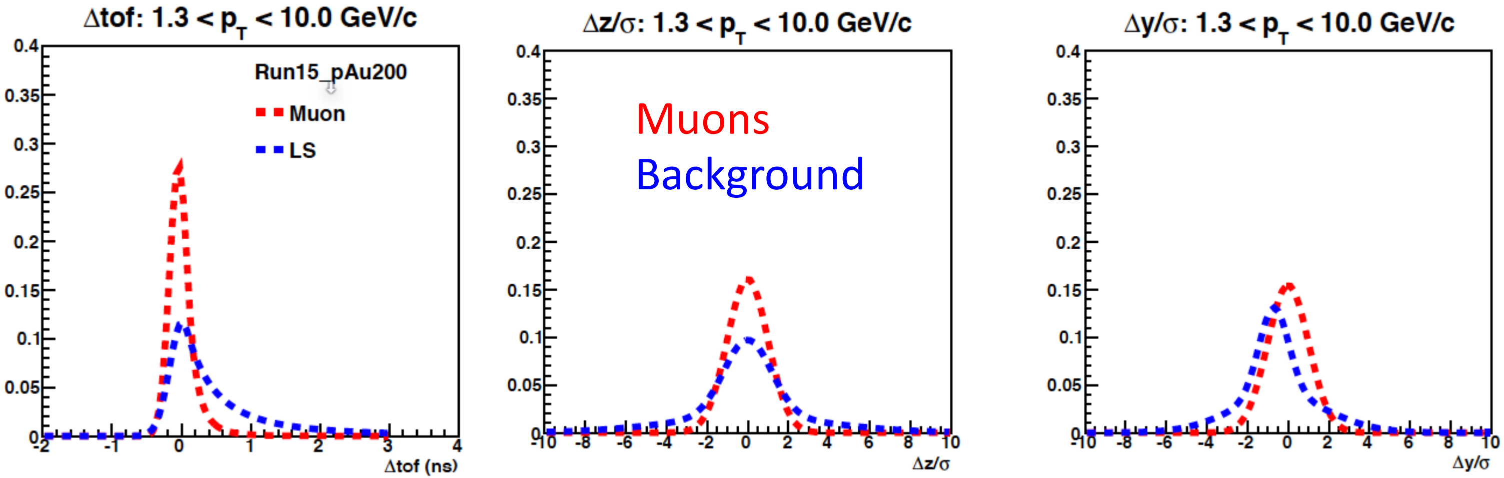
Signal extraction

- Process of interest: $J/\psi \rightarrow \mu^{+}+\mu^{-}$
- Signal reconstruction
  - Identify muons
  - Calculate invariant mass, i.e. rest mass (3.0969 GeV/c^2 for J/ψ), of the dimuon pairs. It is conserved during particle decay.
  - Fit the invariant mass distribution to obtain J/ψ counts

HW: how to calculate the invariant mass from decay muons' momenta?

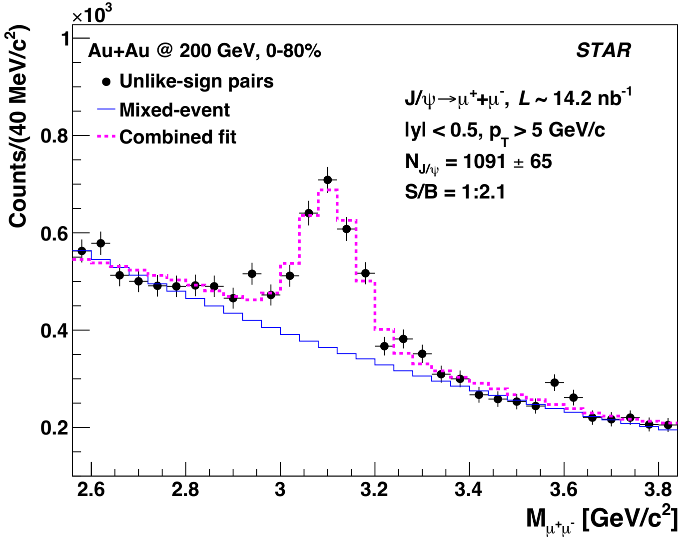
Muon identification

- PID: cut on measured quantities related to particle characteristics, e.g. mass, interaction with material, etc.
- Remaining contamination in the selected sample



Signal extraction

STAR, PLB 797 (2019) 134917



- Black circles: invariant mass of $\mu^+\mu^-$ pairs (unlike-sign, UL)
- Background
  - Random combination of $\mu^+\mu^-$ pairs: combine candidate μ^+ and μ^- from different collisions (ME, blue histogram)
  - Other physical sources of residual background
- Fit UL-ME distribution with a Gaussian (J/ψ) plus polynomial (res. bkg.) function
- J/ψ counts: integral of the Gaussian function

Corrections for detector effects

- Detector effects
  - Acceptance: a detector covers limited phase space
  - Efficiency: probability to measure a given particle in the acceptance
  - Resolution: the accuracy of the measured quantities, such as a particle's momentum or energy

- All these need to be corrected for, in order to obtain physics results, which should not depend on the specific experiment measuring it.

Corrections for detector effects

- How to estimate detector effects?

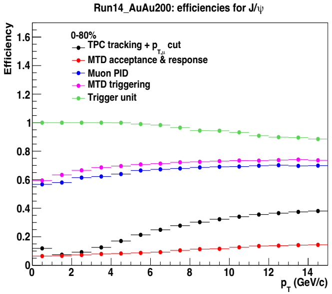
1. Simulate physics process with Monte Carlo generators, e.g. PYTHIA

2. Pass simulated signal through detector simulations, e.g. GEANT, and embed it into real data

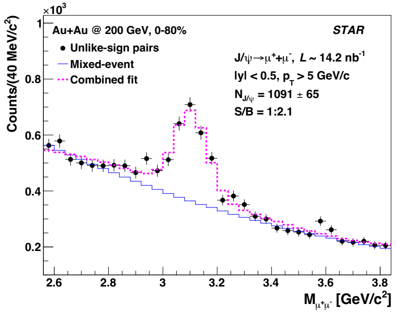
3. Reconstruct embedded events the same way as real data

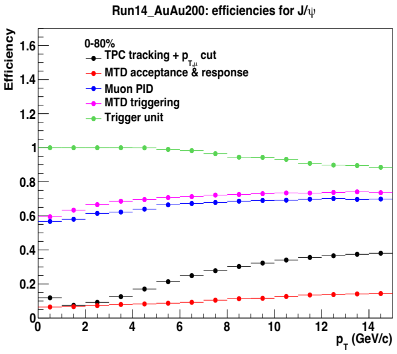
4. Evaluate detector effects:

$$\varepsilon = \frac{\text{output}}{\text{input}}$$

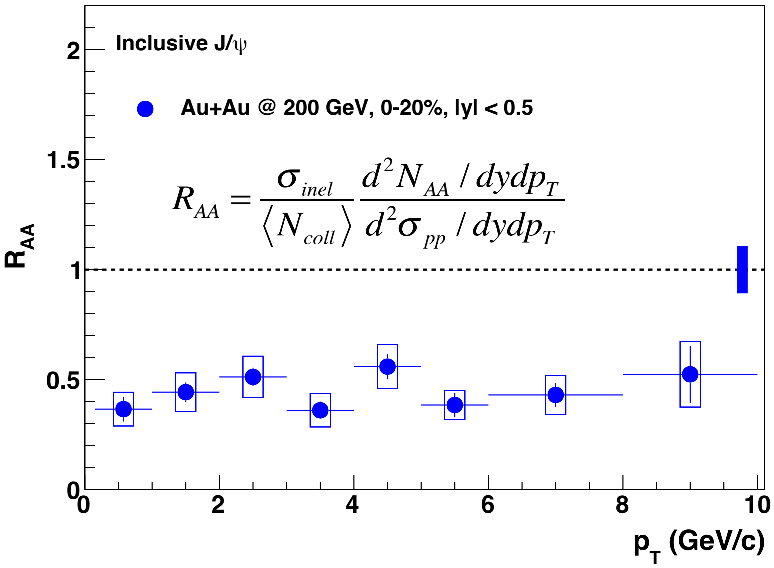


Physics results





STAR, PLB 797 (2019) 134917



suppression -> "melting" → QGP formation

Summary

- One of the main goals of heavy-ion physics is **to study the properties of the QGP** created in these collisions.
  - QGP: consisting of deconfined quarks and gluons
- Use J/ψ as a probe to study the QGP → dissociation/suppression expected
- Measure J/ψ → $\mu^{+}+\mu^{-}$ process with the Muon Telescope Detector
  - MTD is based on MRPC technology
- ***Suppression of J/ψ yields is observed in Au+Au collisions → evidence for QGP formation***

Homework

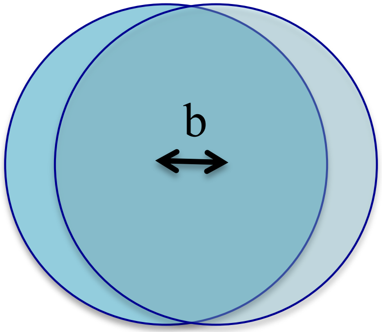
1) Given that the time signals for a particle hitting a strip of length L are t_1 and t_2, and the signal travel velocity in the strip is v, what is the time and position of the hit?
2) What is the interaction length? Why is it important for MTD analysis?
3) What is fraction of runs excluded with 4σ cut due to statistical fluctuations?
4) How to calculate the invariant mass from decay muons' momenta?

Backup

What is Centrality?

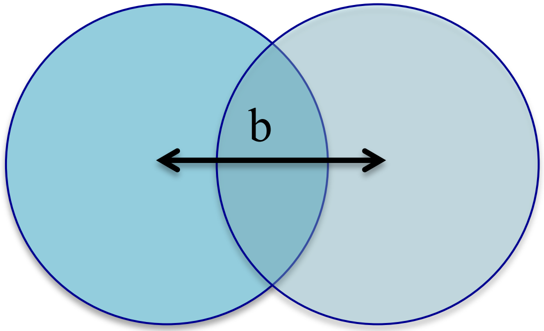
- Used to quantify the collision geometry/impact parameter

central



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

peripheral



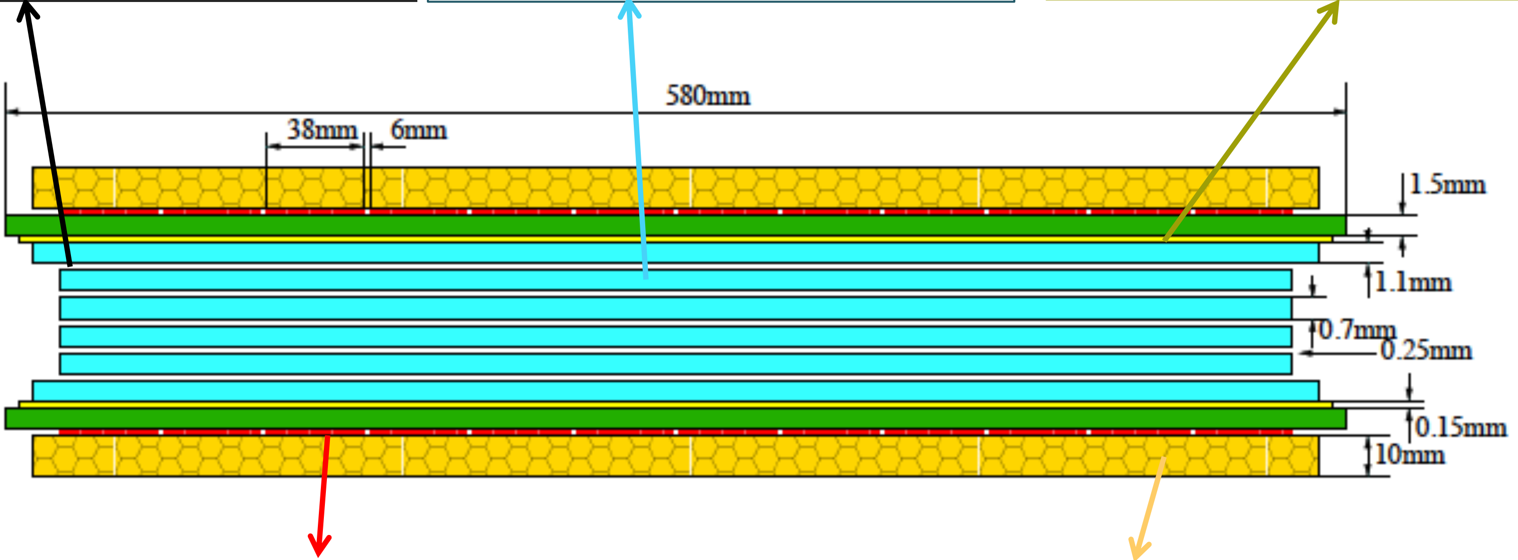
- Large impact parameter
- Small N_{coll}
- Smaller/no medium

MRPC in MTD

5 gas gaps ~ 0.25 mm, realized with fishing line

glasses used as resistive plates

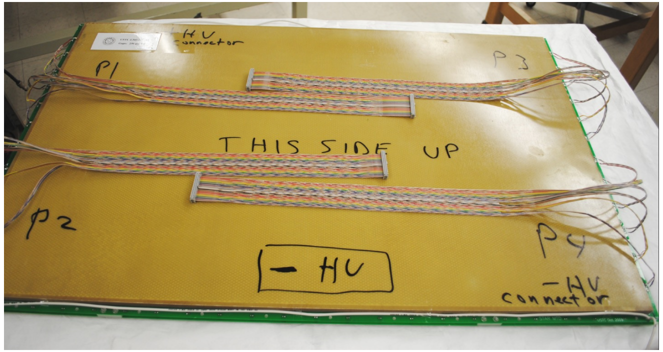
Electrodes formed with paint

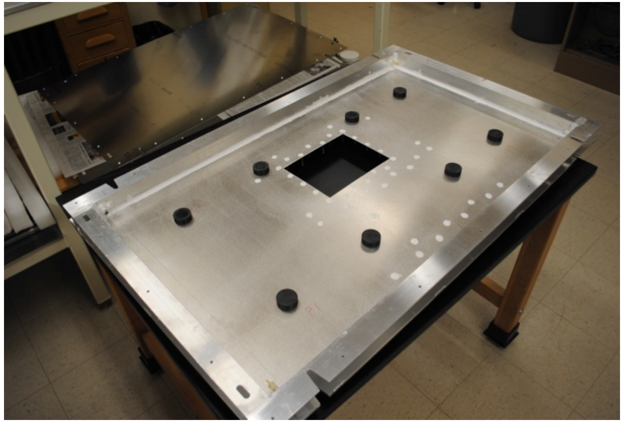


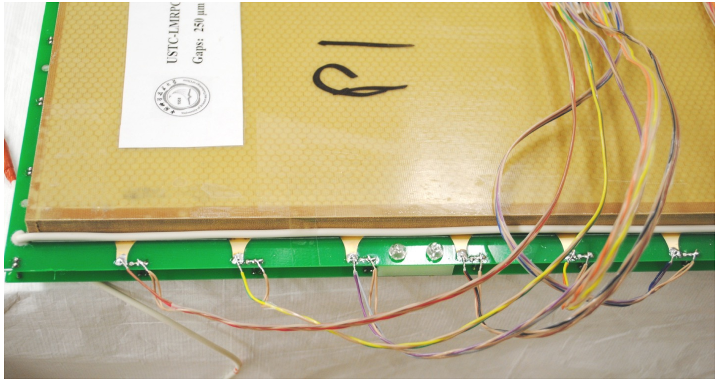
Readout strips on PCB

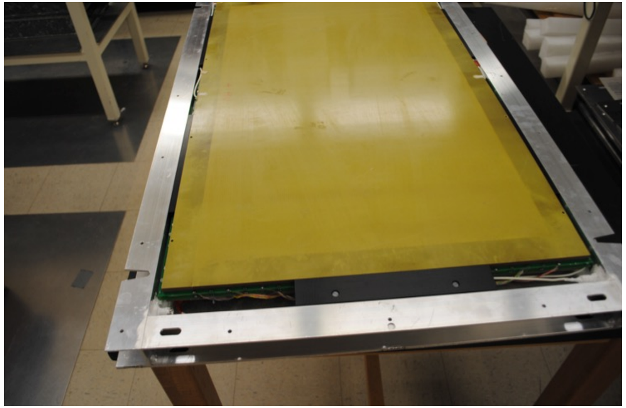
Honeycomb as protection

Tray assembly









MTD operation

- Gas mixture: 95% Freon + 4.5% Isobutane + 0.5% SF_6
  - Isobutane and SF_6 are used to control ionization process
- High voltage: +6300V, -6300V
- 24/7 on-call experts

Event trigger

- A trigger is used to select (rare) events of interest during online data-taking
  - Increase signal counts for limited data-taking bandwidth
  - Save disk space
  - Facilitate offline analysis

- For example, a $J/\psi \rightarrow \mu^{+}+\mu^{-}$ is produced in every ~10k Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
  - 1 measured J/ψ in every 3M events

MTD dimuon trigger

- Process: $J/\psi \rightarrow \mu^{+}+\mu^{-}$
- Trigger condition: two signals in the MTD based on timing
- Rejection power: 1 to 30
  - Still dominated by background
- Triggered events are saved in dedicated files for later processing