Electron-positron tomography at STAR: seeking symmetry in the Quark-Gluon Plasma

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Outline:

- What is electron-positron tomography?
- Why study Quark-Gluon Plasma?
- What is symmetry?
- Our experimental approach and results
- Summary

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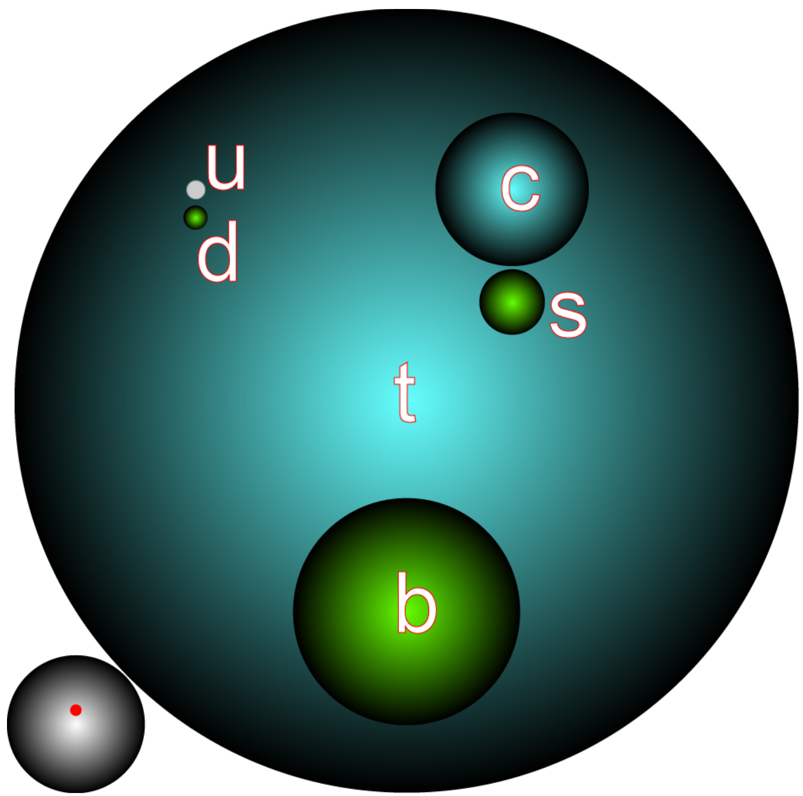
a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Elementary particles

- Electron and quarks are elementary particles
- There are 6 flavors of quarks with different masses.



- u and d quarks are the lightest ones.

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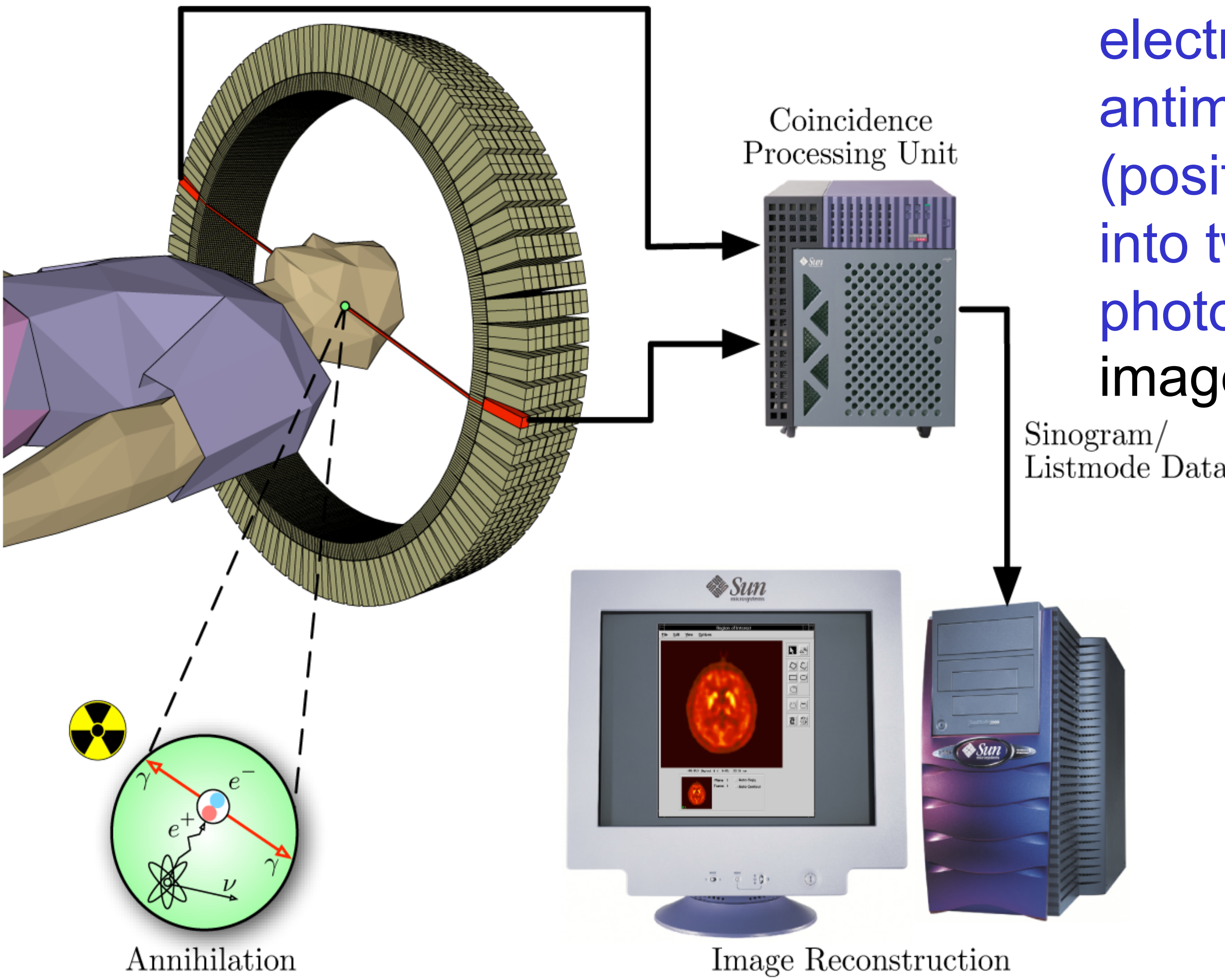
Elementary particles

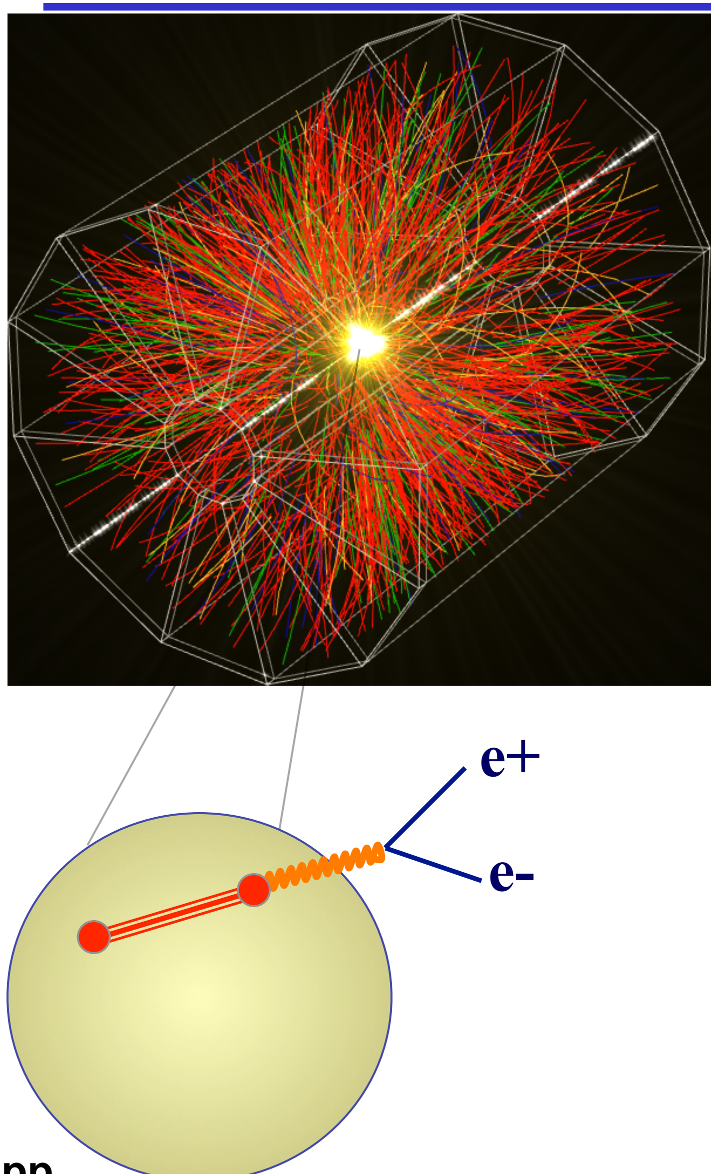
- Electrons interact with matter through the exchange of photons.
- Electrons and photons do not interact with matter strongly.
- Quarks interact with matter through the exchange of gluons. Strong interaction.
- Positron is antimatter electron.
- Anti-quark is antimatter quark.

Traditional Positron-emission Tomography (PET)



PET scan uses electron and antimatter electron (positron) annihilation into two back-to-back photons to create an image.

Electron-positron Tomography



Rapp

- In our method, we detect electron and positron pairs from quark-antiquark annihilation.
- Electron-positron pairs are penetrating probes and can provide information deep into the system and early time.
- Using electron-positron tomography, we would like to study the symmetry of the Quark-Gluon Plasma.

Why study Quark-Gluon Plasma

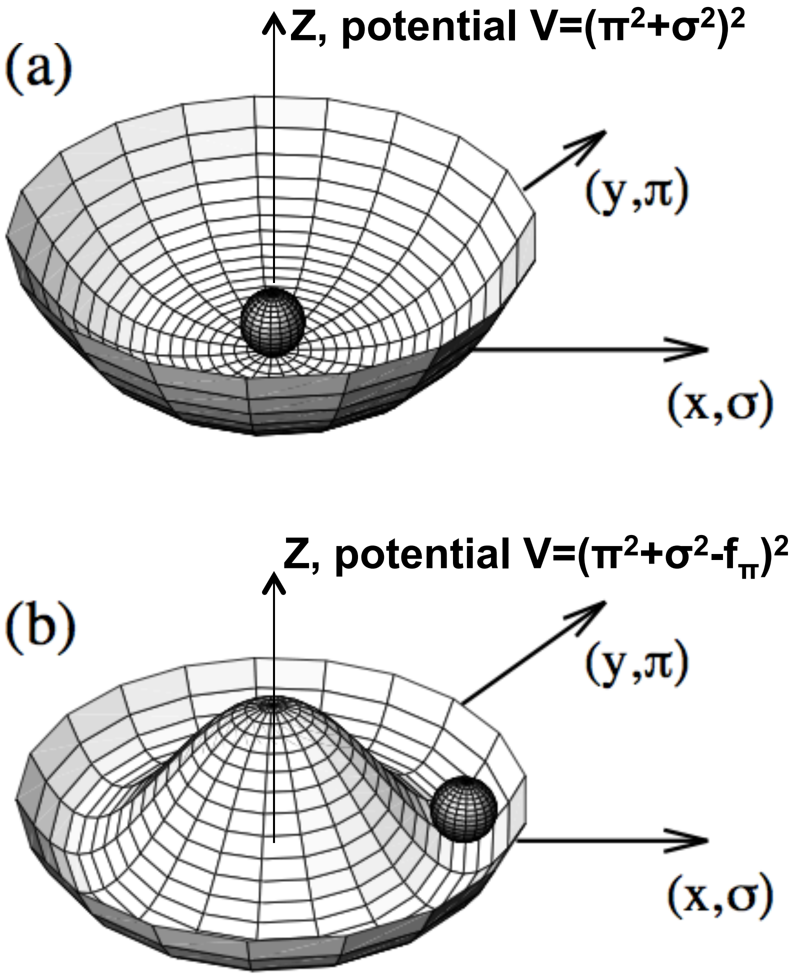
- Quark-Gluon Plasma is believed to exist in the moments after the Big-Bang.
- At Brookhaven National Lab, physicists trying to create Quark-Gluon Plasma (QGP) using high energy heavy ion collisions.
- Study the image of QGP, will help us to understand the early universe.

The Quark-Gluon Plasma

- In Quark-Gluon Plasma, there are u, d quarks and gluons.

- Motion of the system has chiral symmetry.

Chiral symmetry and symmetry breaking



- Early universe, hot, chiral symmetry
- The world we live in now, cold, spontaneous chiral symmetry breaking

motion of the system: potential + ball (ground state)

Spontaneous chiral symmetry breaking

Microscopic picture:

- quark condensate: left-handed quark and right-handed antiquark attract each other through the exchange of gluons. Generate 99% of visible mass in the universe.

- electron condensate: electrons attract each other through the vibration of the crystal at low temperature. Generate superconductivity in the metal.

Is chiral symmetry restored in Quark-Gluon Plasma?

Early universe	Chiral symmetry	Quark Gluon Plasma
The world we live	Spontaneous chiral symmetry breaking	particles we observe

In the Quark-Gluon Plasma, as hot as early universe, is chiral symmetry restored?

Do we have experimental observable?

Is chiral symmetry restored in Quark-Gluon Plasma?

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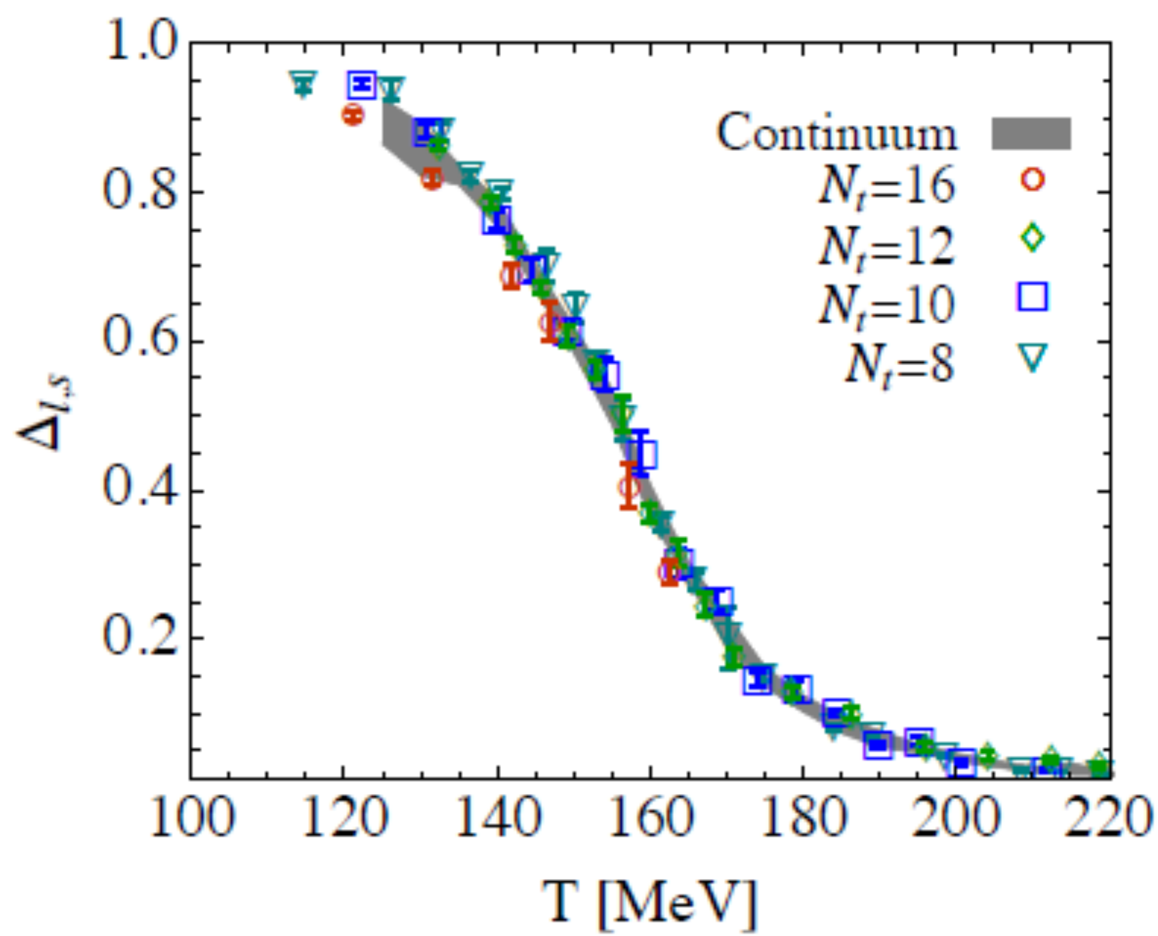
Lattice QCD tells us:

T_c= 155 MeV

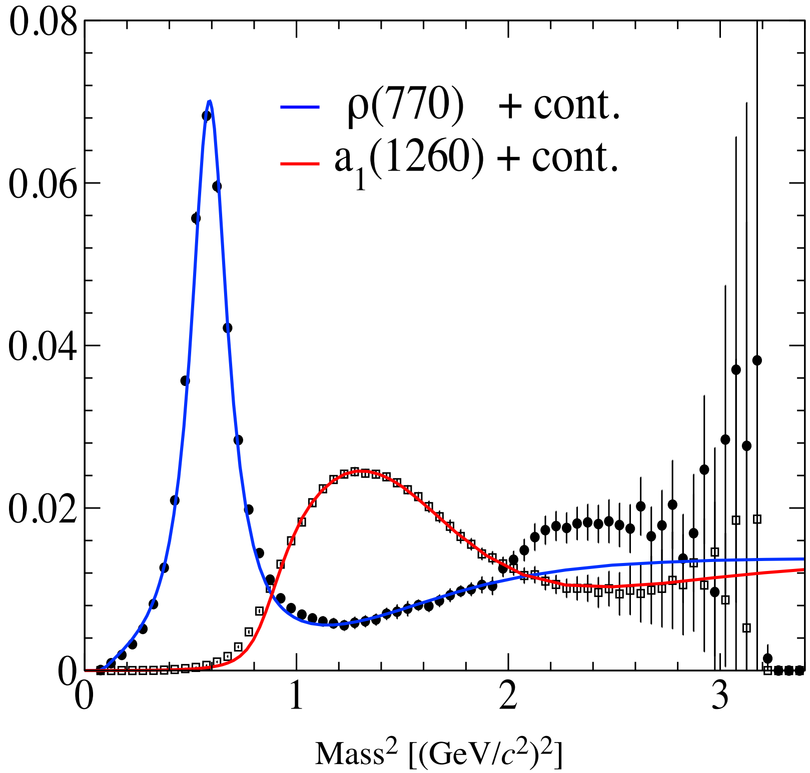


What is the temperature of the QGP?

T_{QGP}>T_c

$\Delta_{l,s}$: subtracted chiral condensate
Z. Fodor, Lattice 2010

ρ and a1 resonance (spectrum function) in vacuum

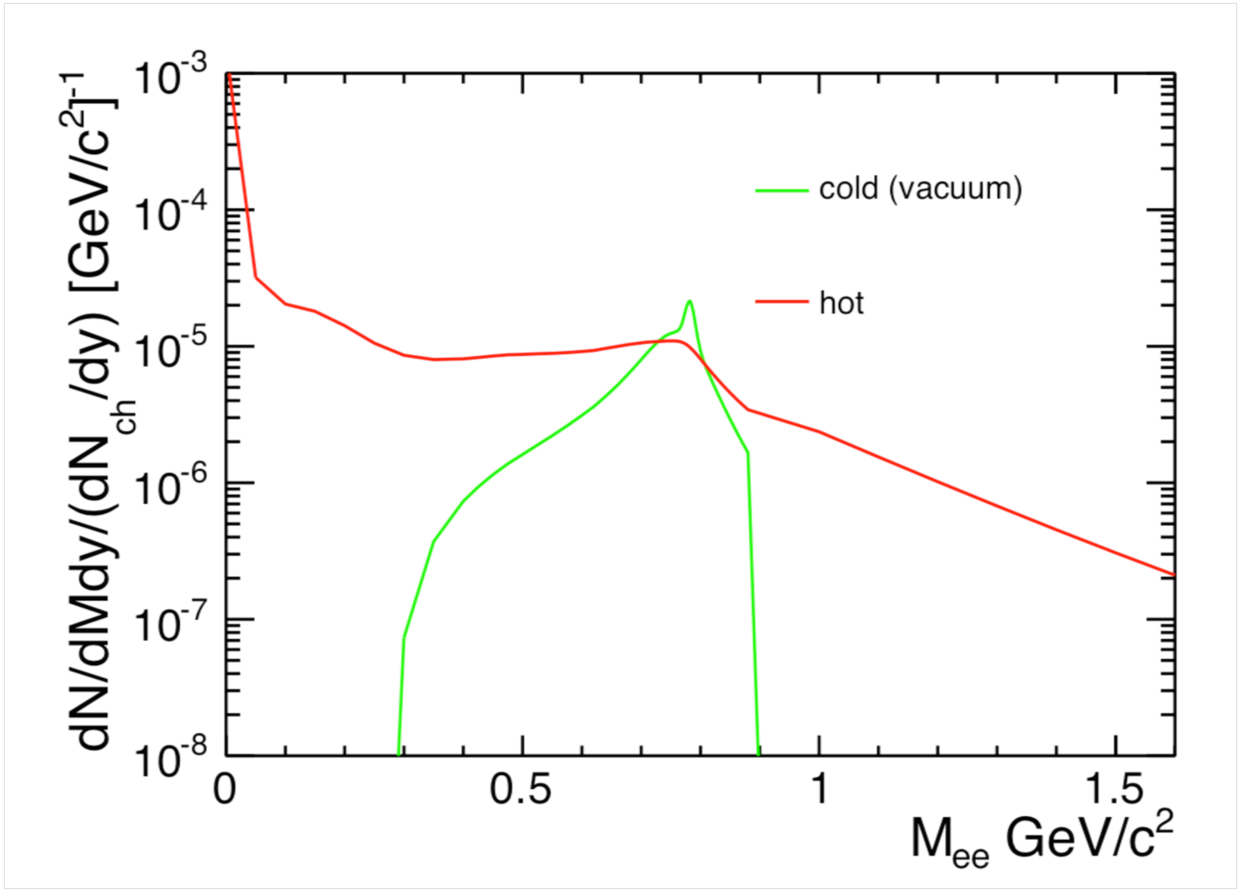


ALEPH: EPJC4 (1998) 409;
R. Rapp Pramana 60 (2003) 675.

Spontaneous chiral symmetry breaking: mass distributions are different

Chiral symmetry restoration: mass difference disappears

The ρ resonance mass spectrum function



Observable for chiral symmetry restoration:

a broadened ρ spectra function and ultimately the peak structure disappears!

Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

My physics interest

Study the image of the Quark Gluon Plasma and chiral symmetry restoration using electron-positron tomography.

Experimentally identify the signature and quantify the effect of chiral symmetry restoration in the Quark-gluon Plasma, as hot as early universe.

RHIC @ Brookhaven National Laboratory

A heavy-ion collision event

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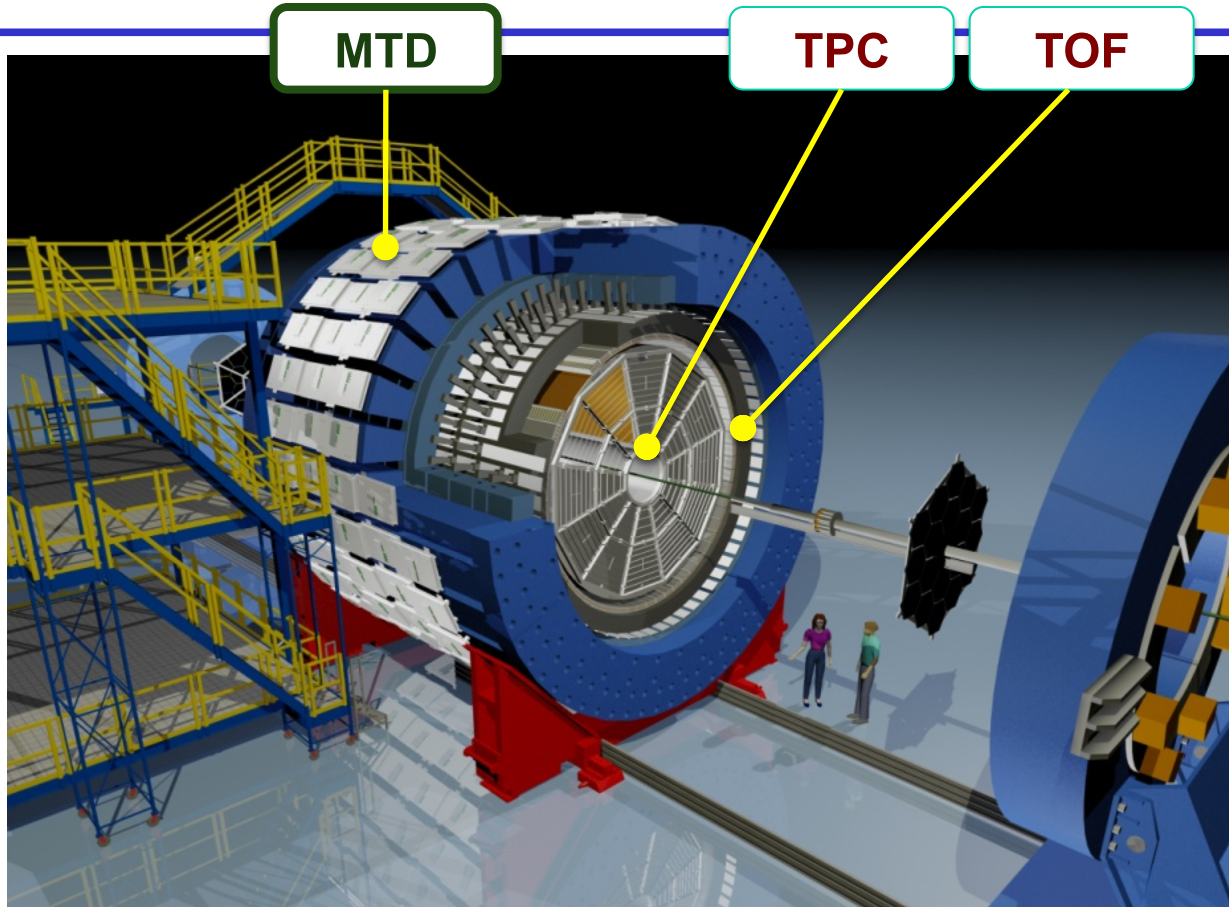
The STAR Detector

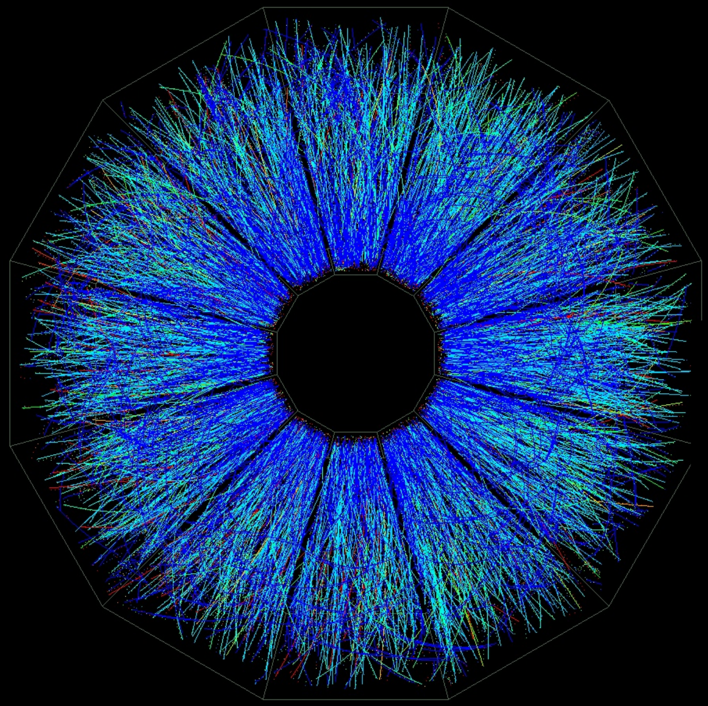


Solenoidal Tracker at RHIC (1200 tons)

Time Projection Chamber

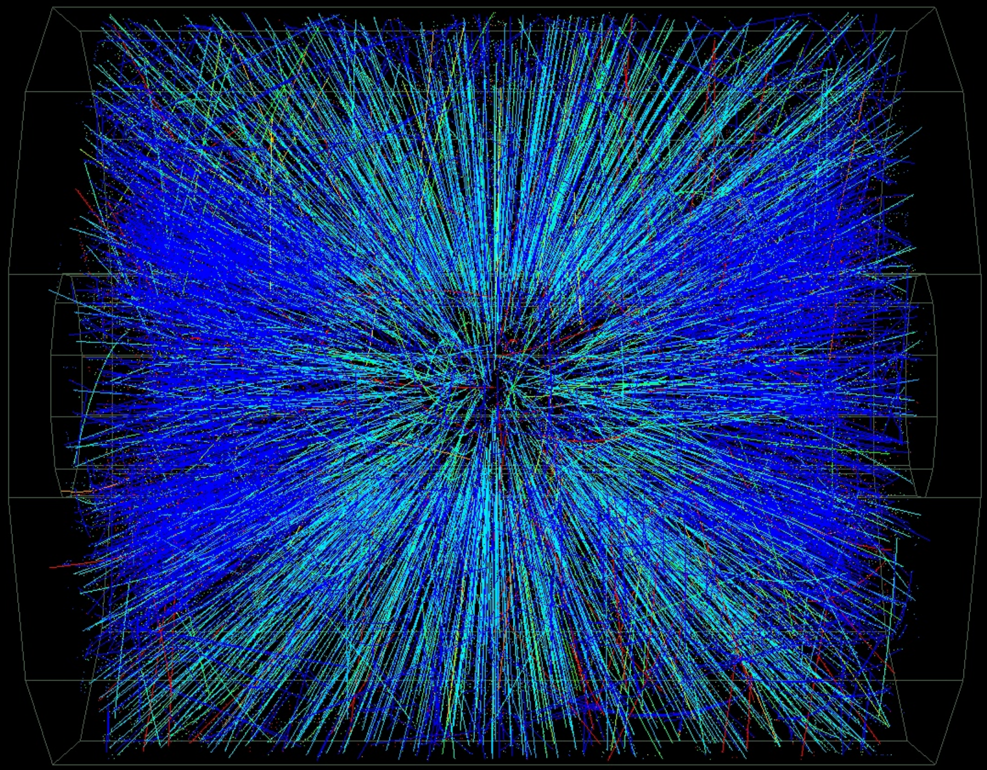
1. **Second largest device of its kind ever built**
2. **3D camera to take photos of the collisions**
3. **Measure ionization energy loss (dE/dx) and momentum**

$^{197}Au + ^{197}Au$ Collisions at RHIC



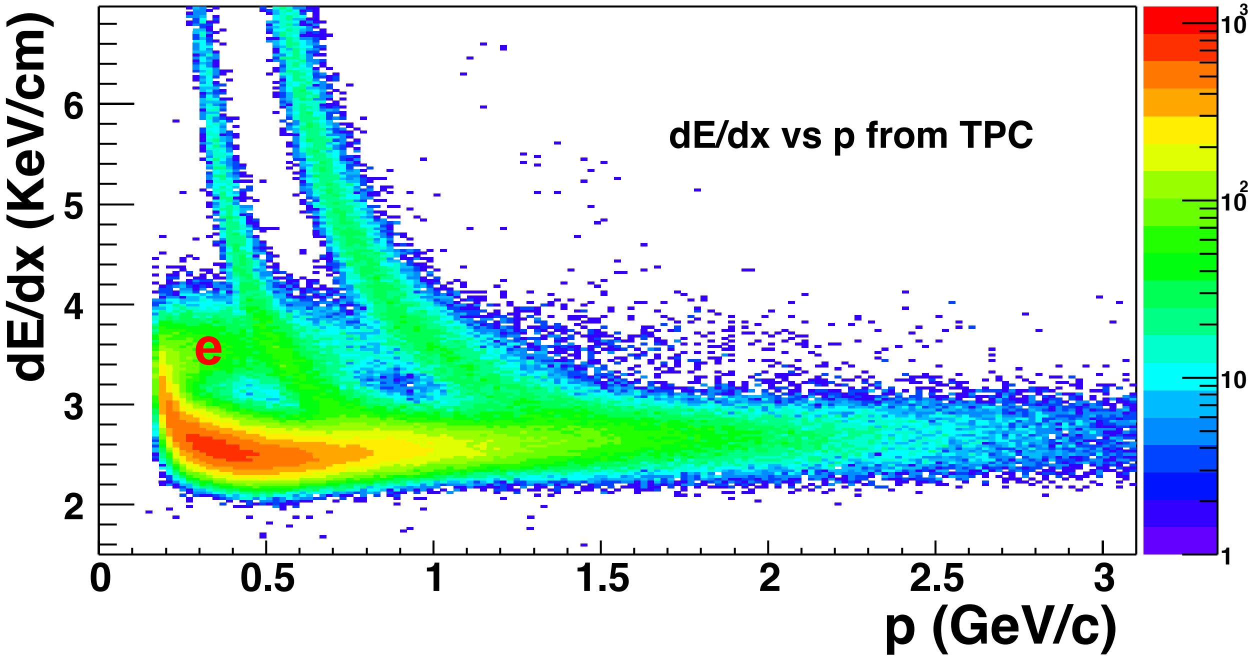
Central Event

$E = m c^2$



STAR (real-time Level 3)

Particle identification



Electrons are difficult to find.

Need new experimental tool!

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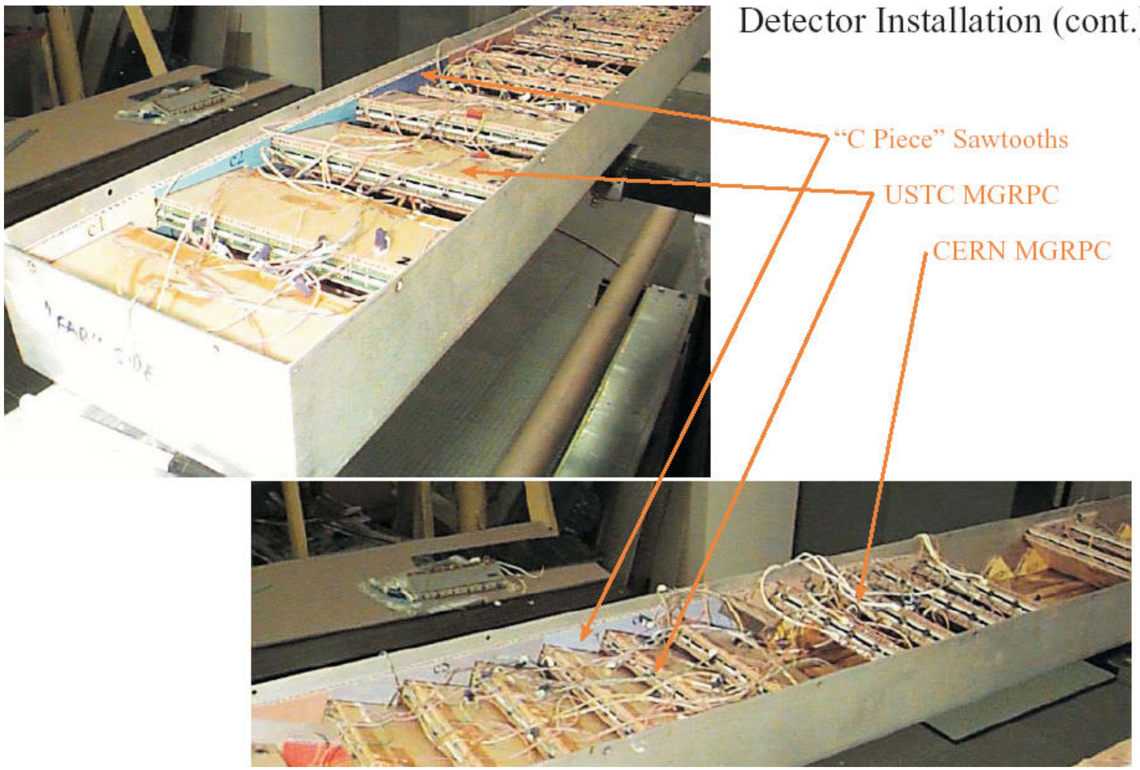
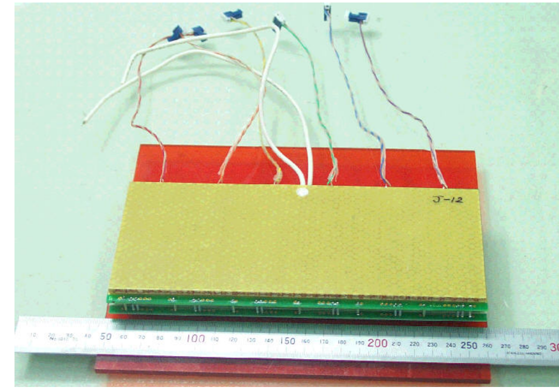
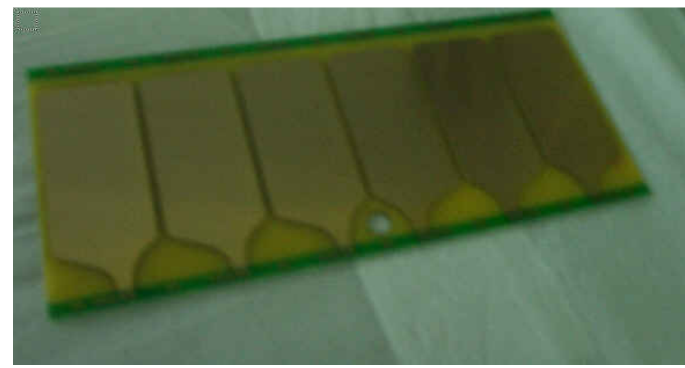
MRPC TOFr 2003





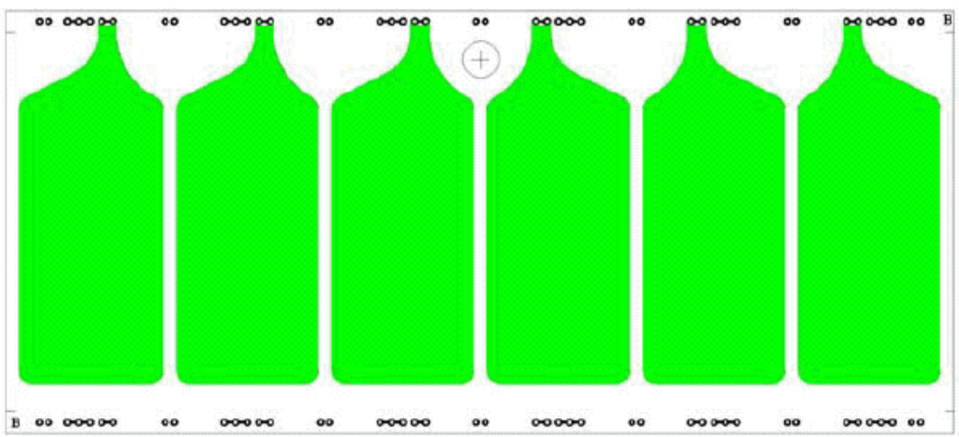


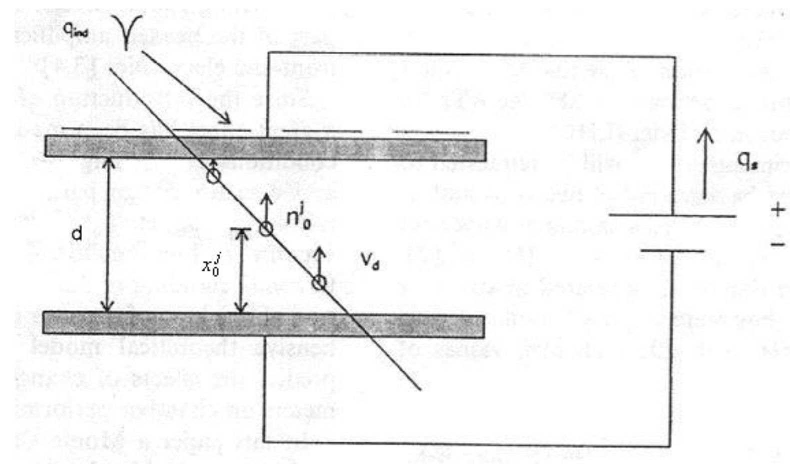
Multigap Resistive Plate Chamber (MRPC) Technology

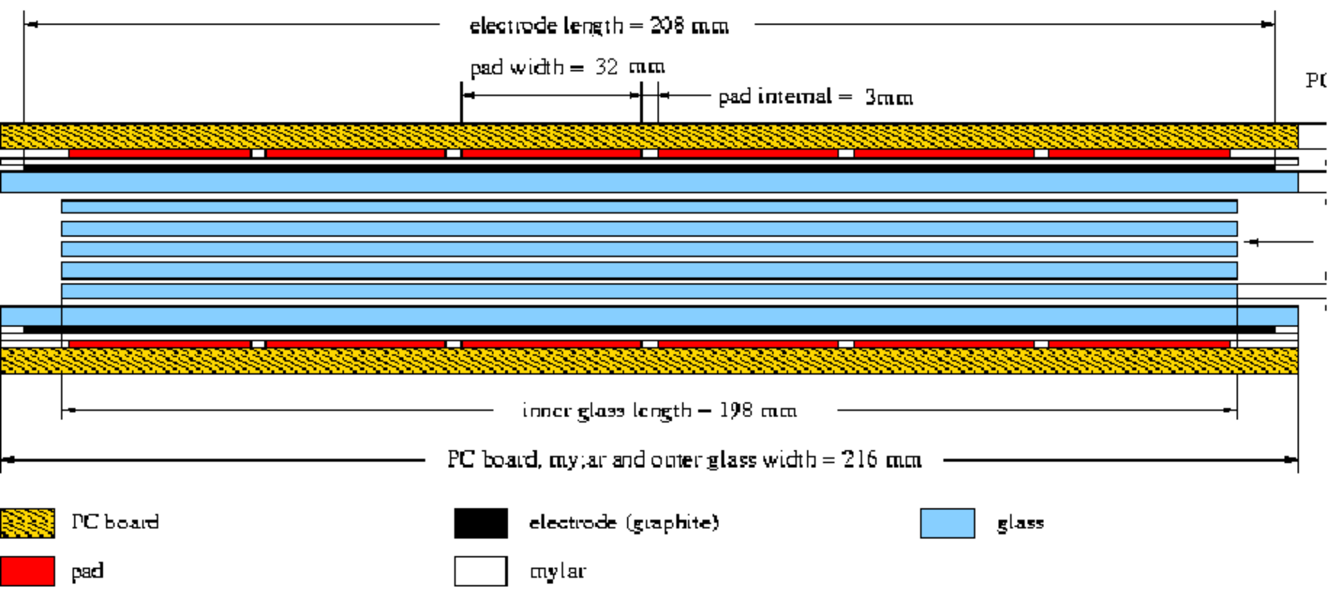
low cost, high timing resolution $<100\times10^{-12}$ second

A prototype tray (TOFr) was installed in 2002-2003

Structure of MRPC Module



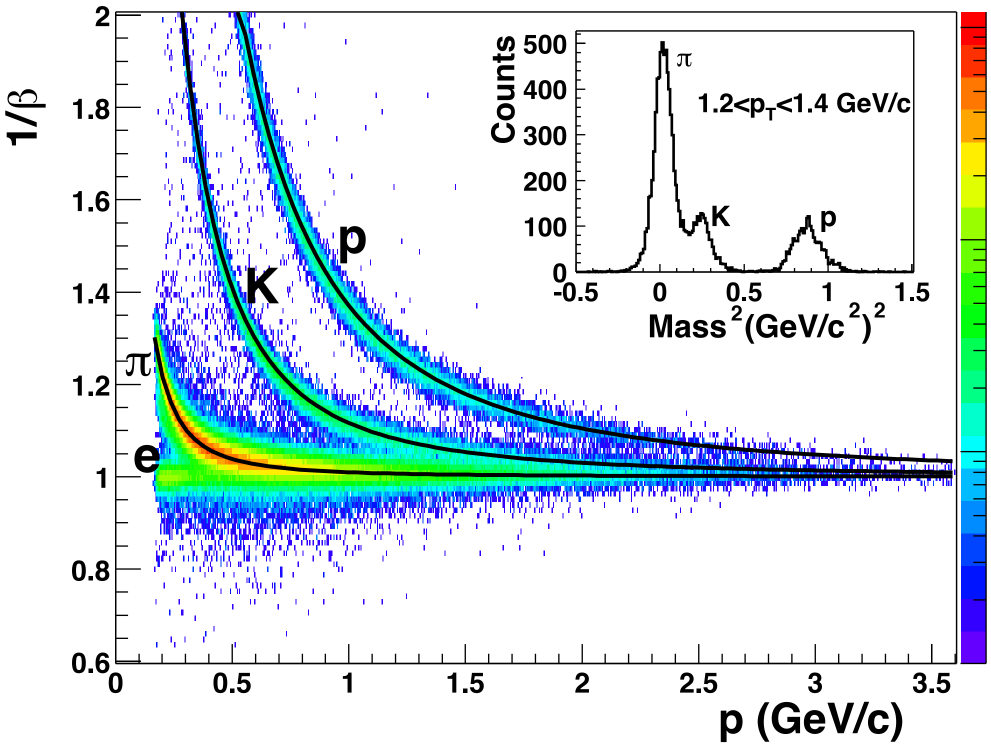




Read out pad size：3.15cm×6.3cm, gap：6×0.22mm

M. Abbrescia et al., Nucl. Instr. and Meth. A 398 (1997) 173-179
M. Abbrescia et al., Nucl. Instr. and Meth. A 431 (1999) 413-427

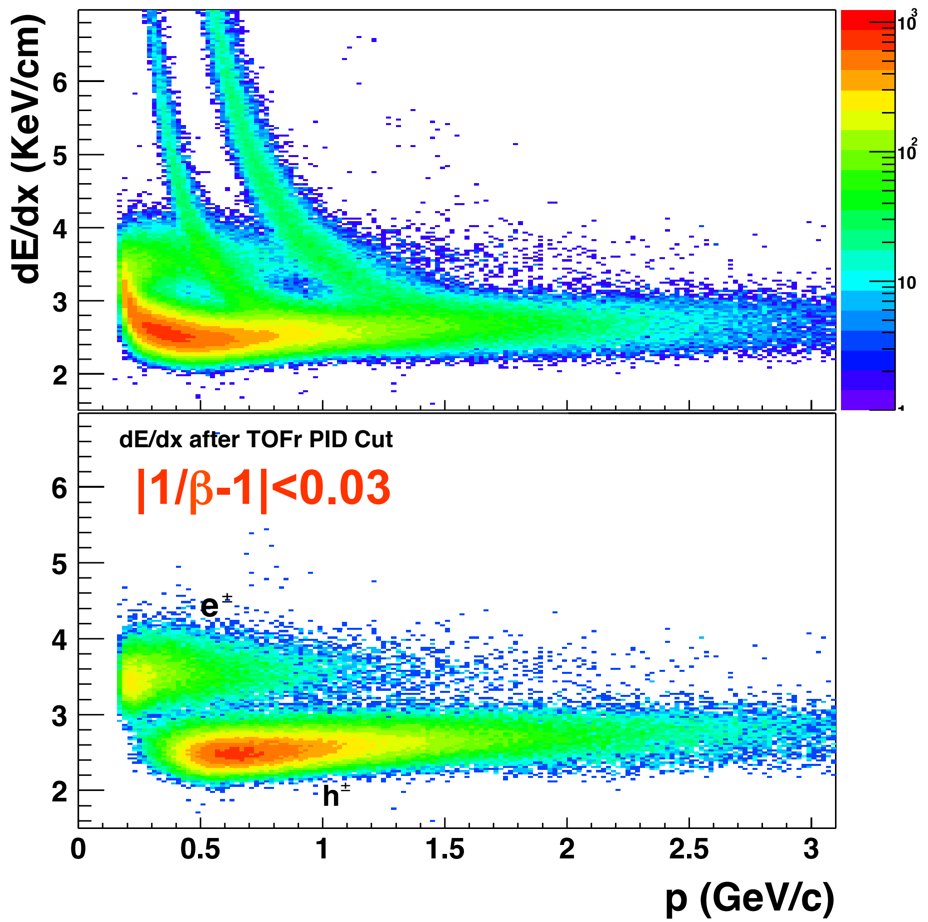
Particle identification from TOFr



STAR Collaboration, PLB616(2005)8

Curve: $$\frac{1}{\beta} = \sqrt{\frac{m^2}{p^2} + 1}$$

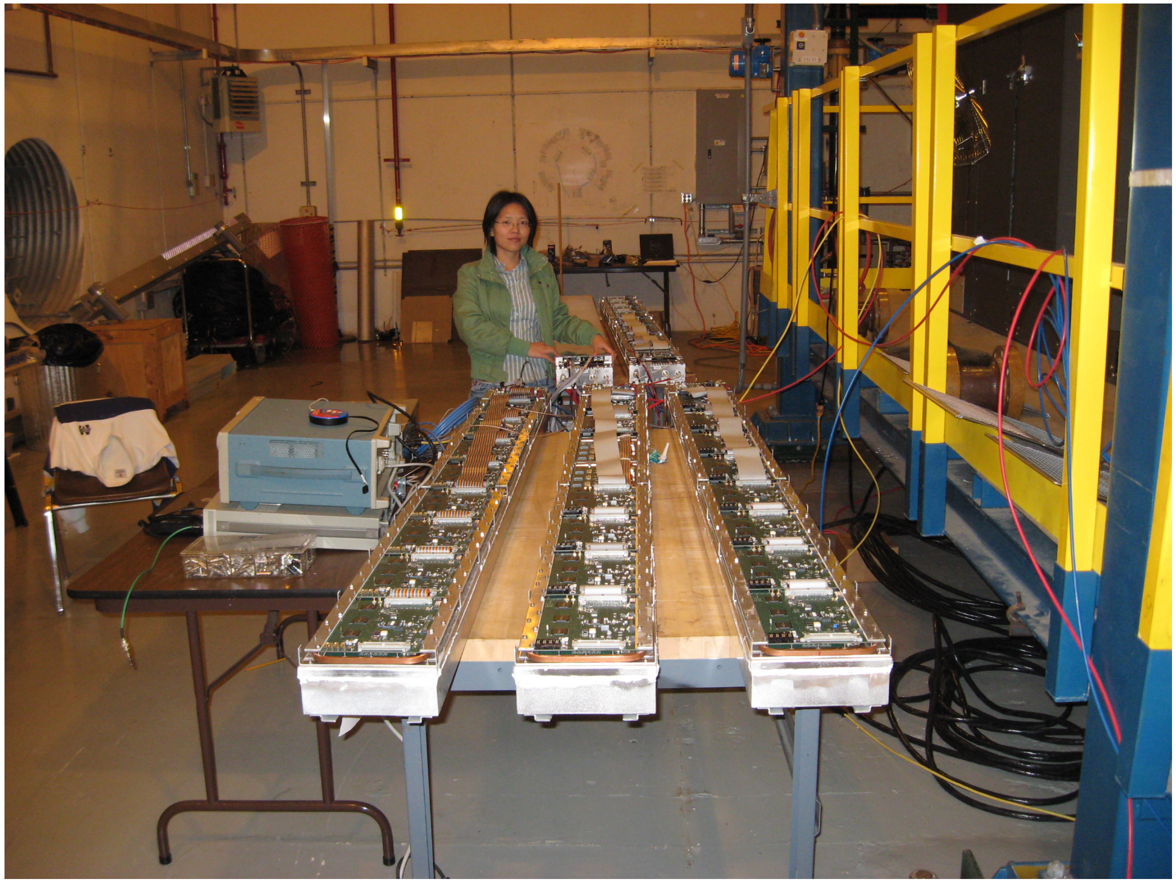
Electron identification



Clean electron samples!

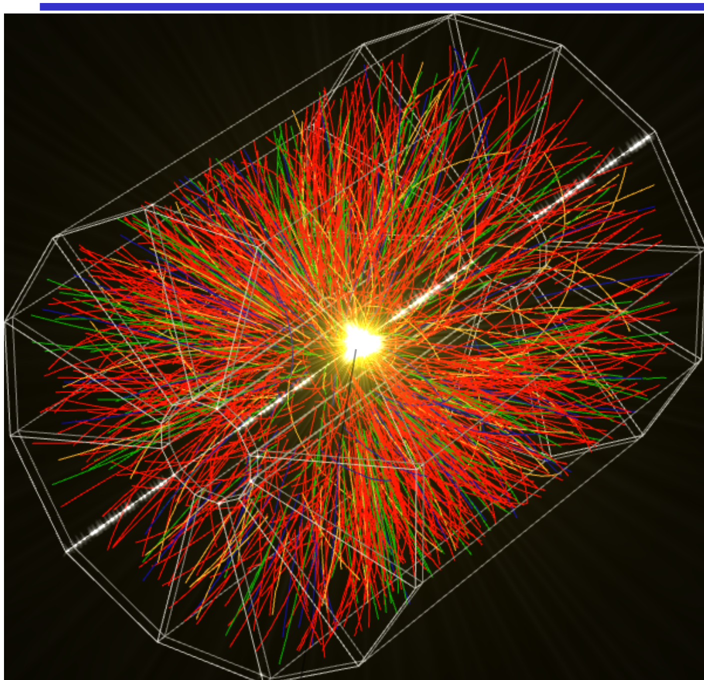
STAR Collaboration, PRL94(2005)062301

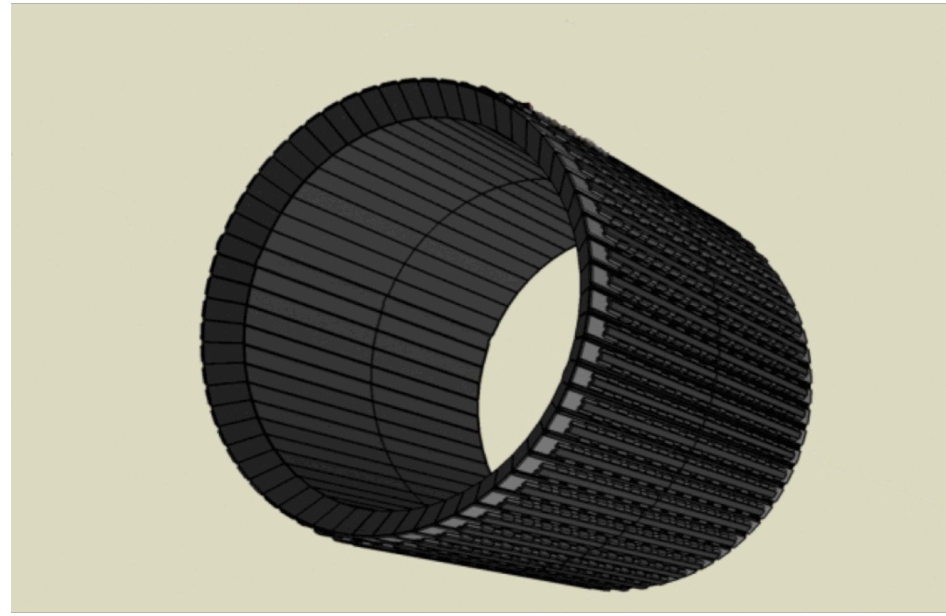
Time of Flight Detector upgrade

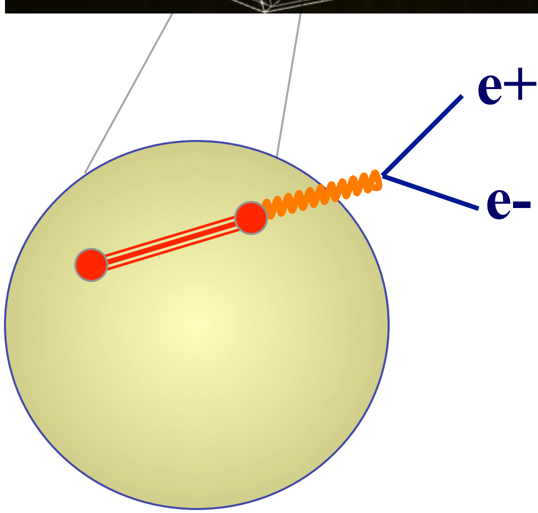


US-China Collaboration, 120 units in total:
2008: 4%; 2009: 72%; 2010: 100%

The electron-positron tomography tools

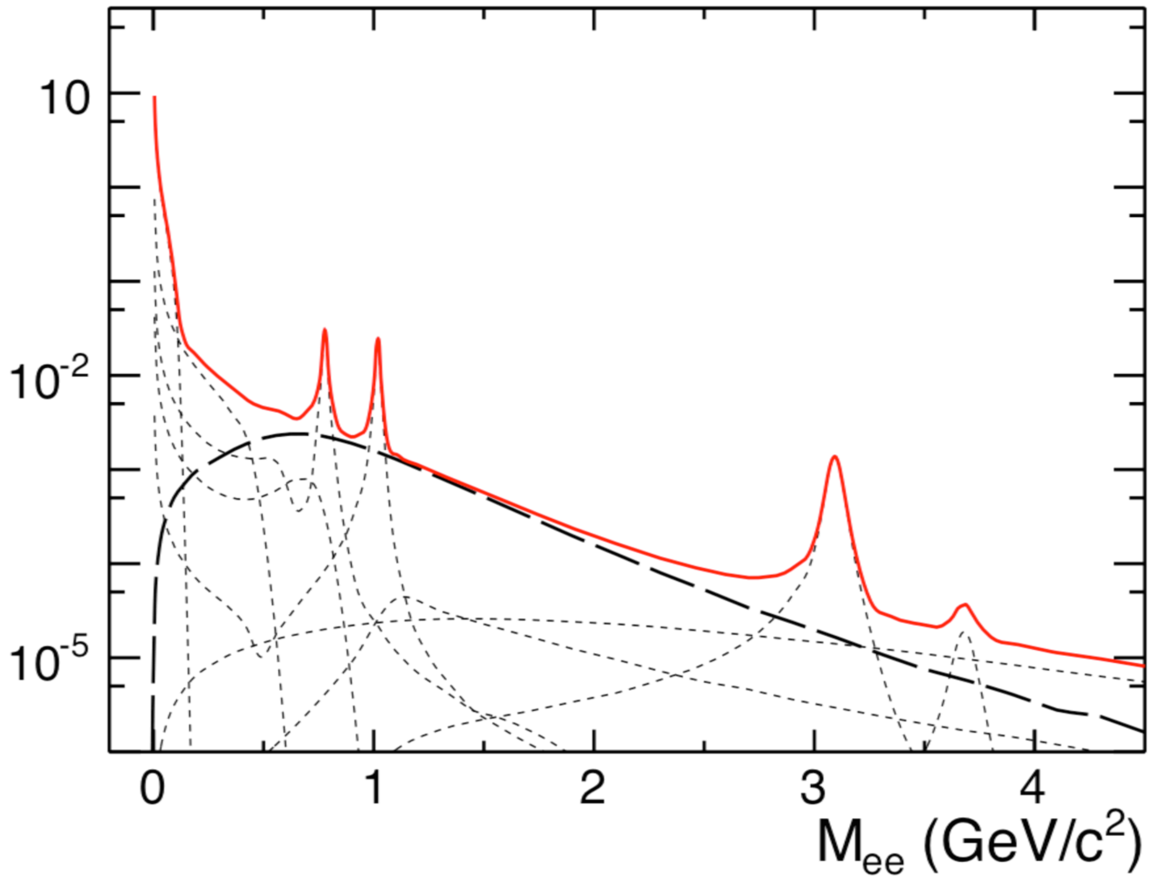






The Time of Flight Detector completes the experimental tool for electron-positron tomography: clean electron identification and large acceptance.

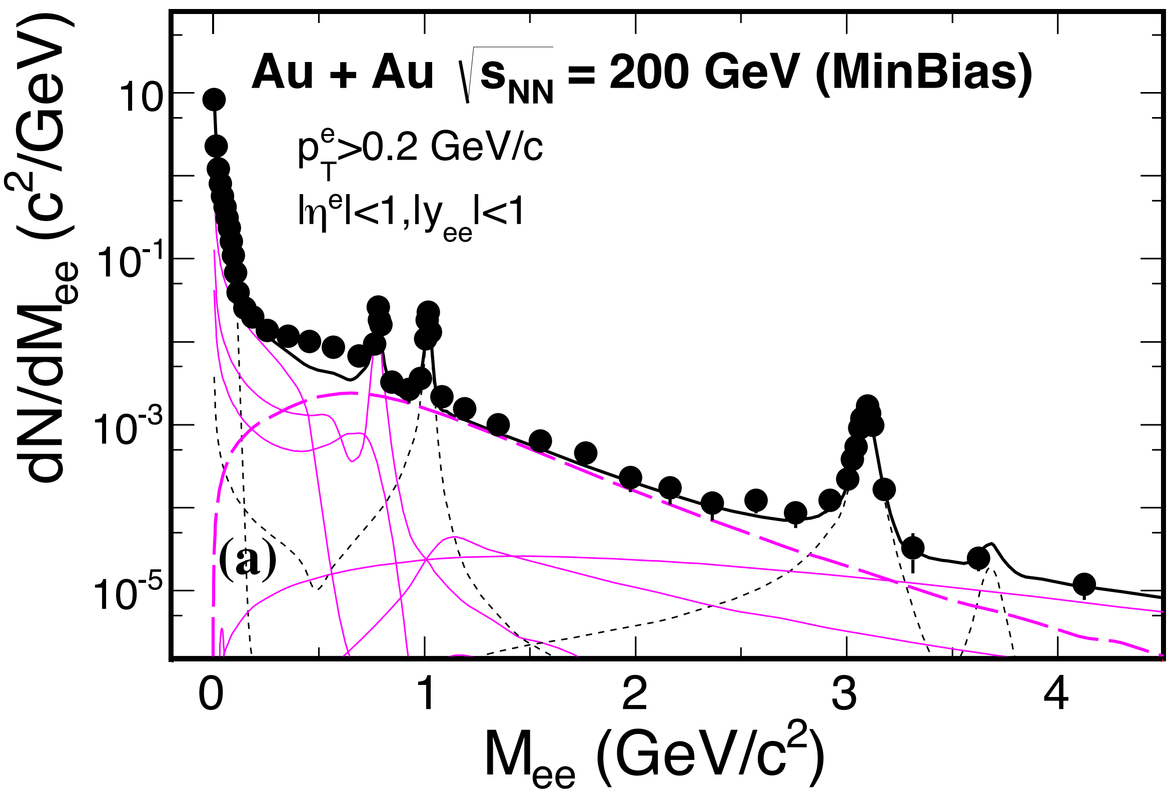
Electron-positron emission mass spectrum



In empty space (vacuum)

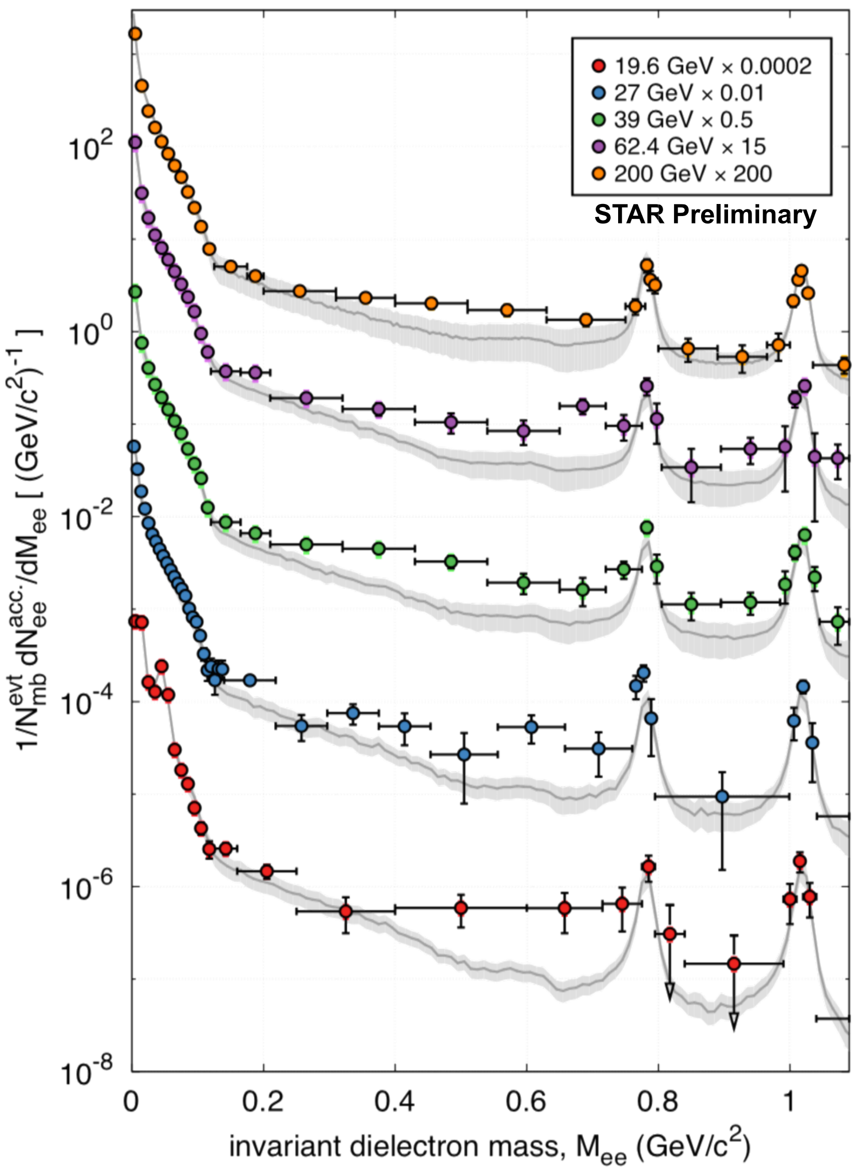
Electron positron emission mass spectrum in 200 GeV Au+Au

PRL113 (2014) 022301



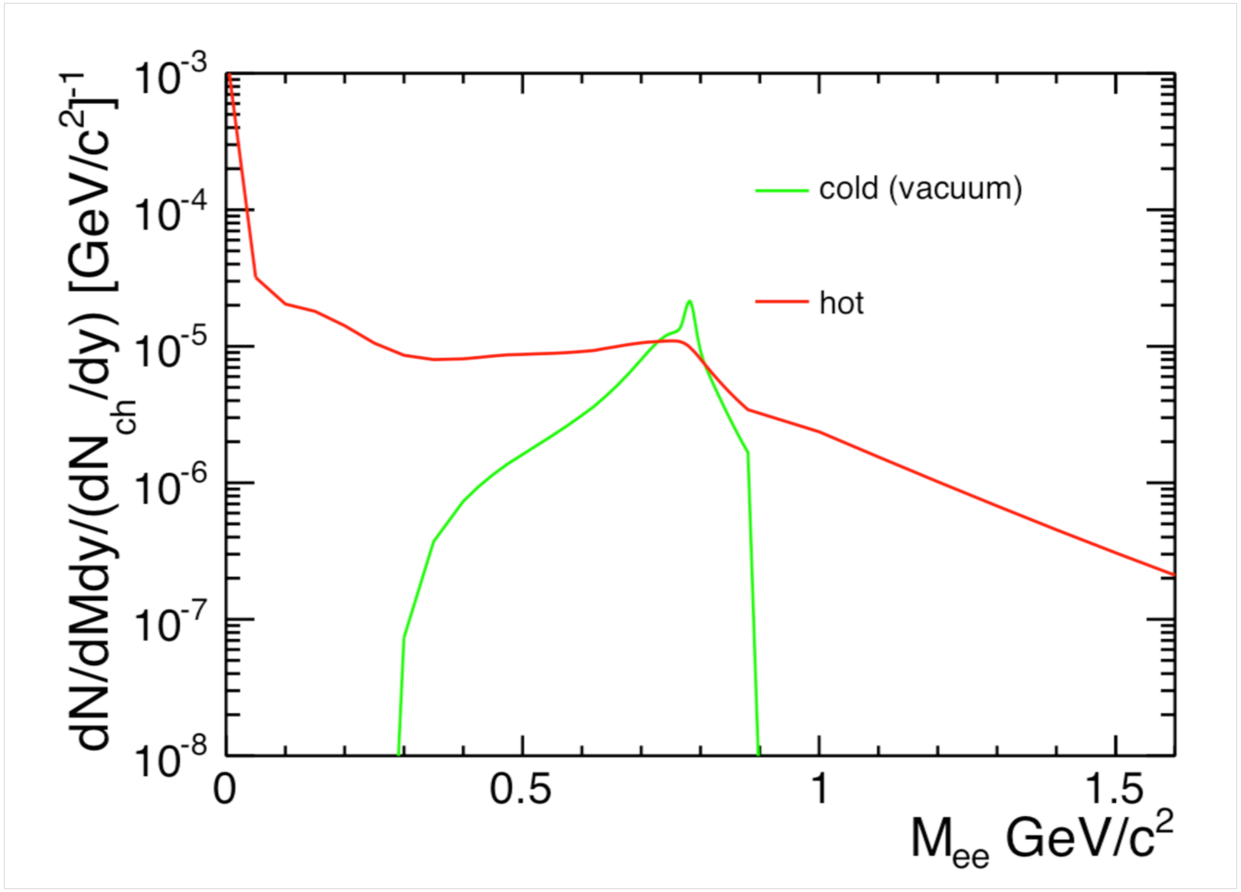
There are "hot" contributions!

Electron-positron emission at lower energies



"Hot" contributions observed in 19.6, 39, 62.4, and 200 GeV Au+Au collisions!

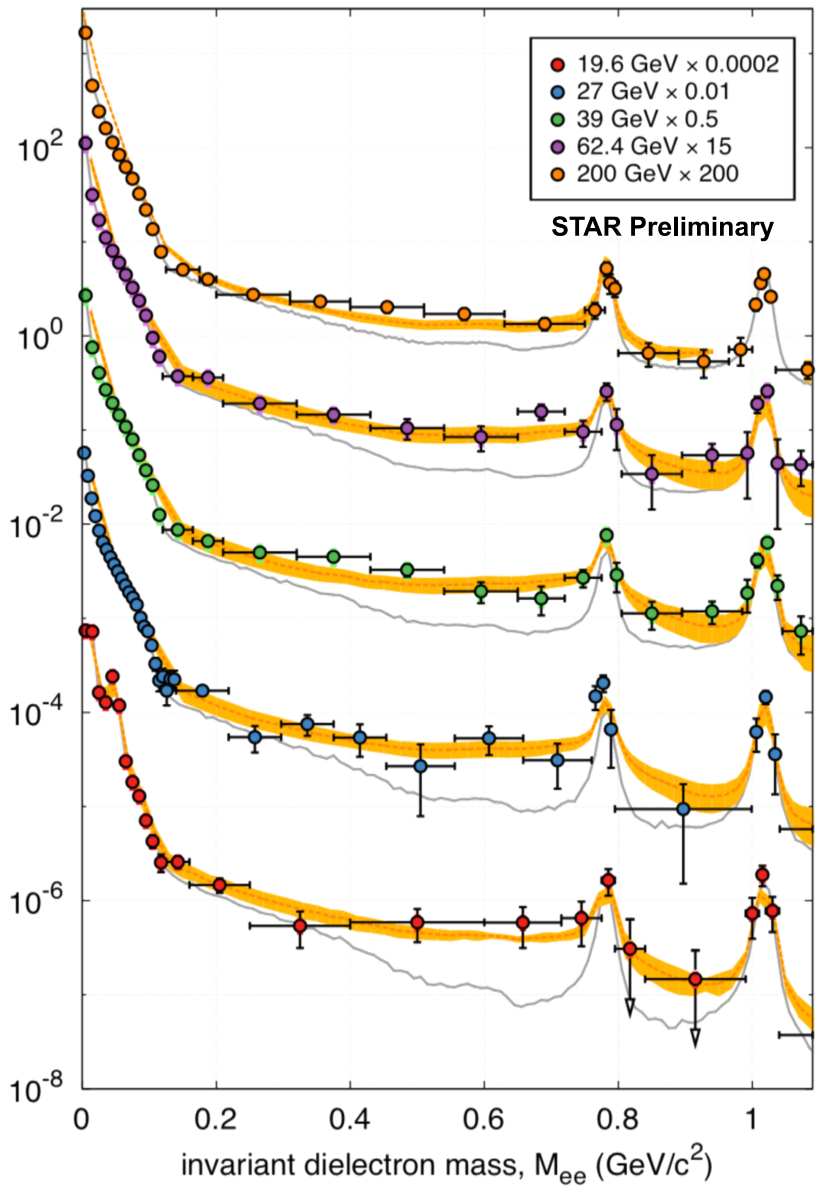
The "hot" mass distribution in 200 GeV Au+Au



The "hot" contribution is modified and broadened!

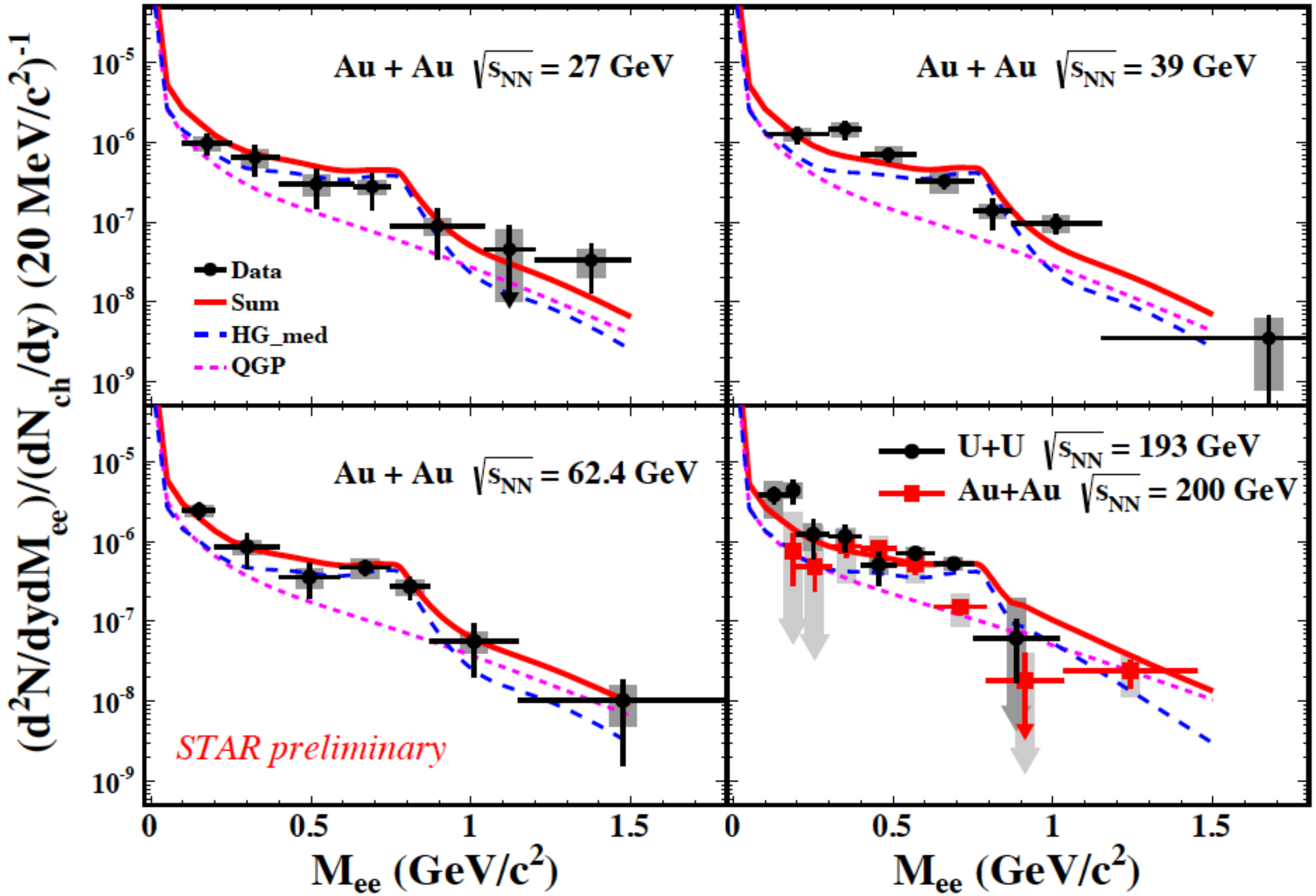
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

Electron-positron emission at lower energies



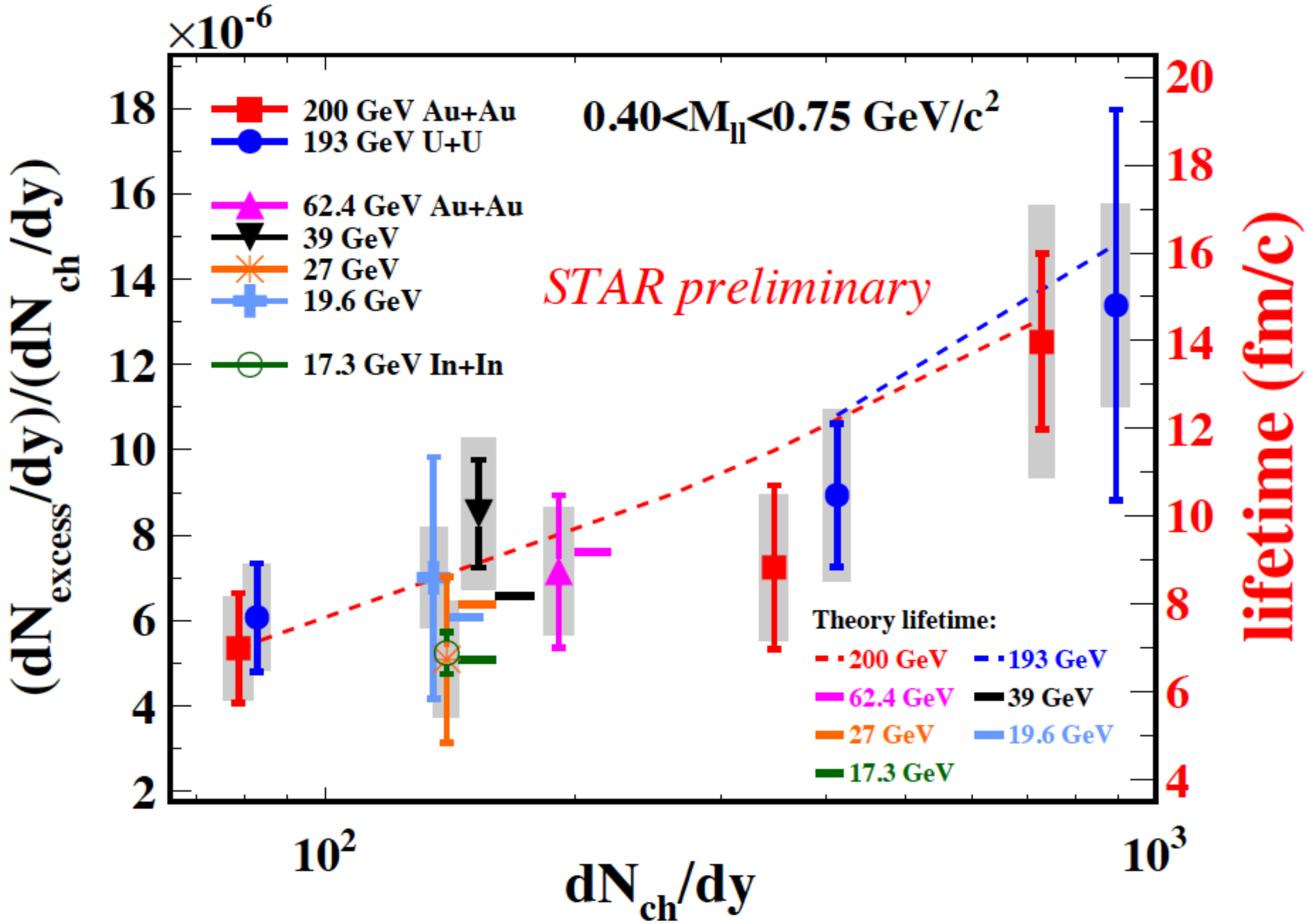
Observed "hot" distributions are broadened!

The ρ resonance spectrum function: broadened



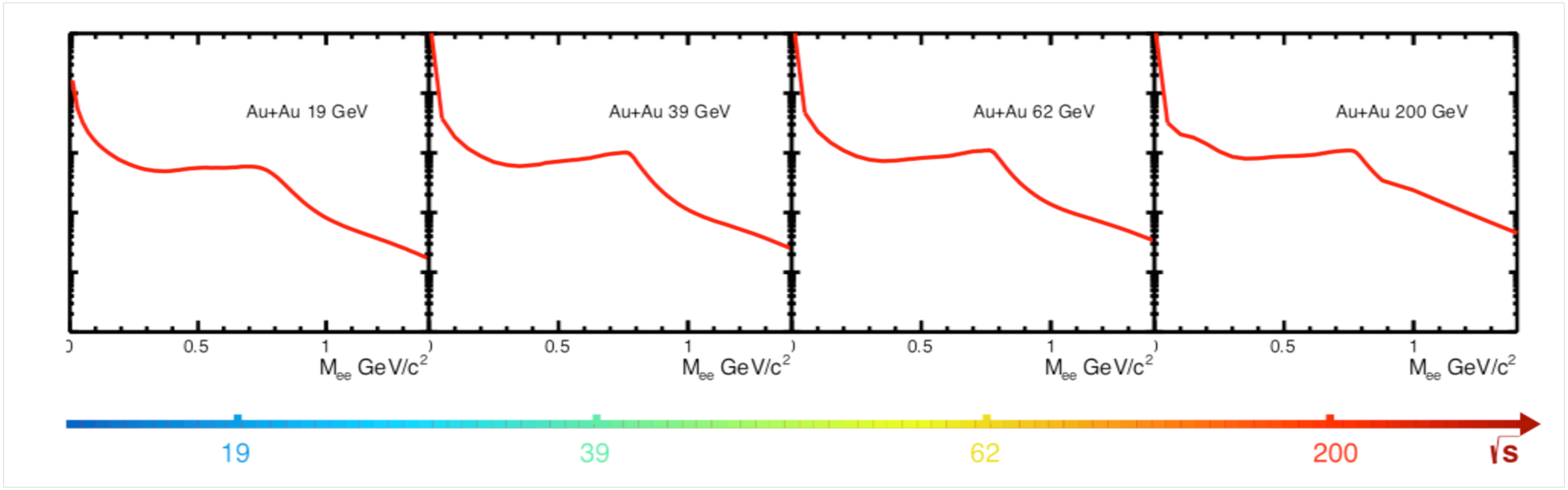
A broadened ρ spectrum function consistently describes the low mass electron-positron excess for all the energies 19.6-200 GeV.

The low mass measurements: lifetime indicator



Low-mass electron-positron production, normalized by dN_{ch}/dy, is proportional to the life time of the medium from 17.3 to 200 GeV.

The contribution from hot, dense medium



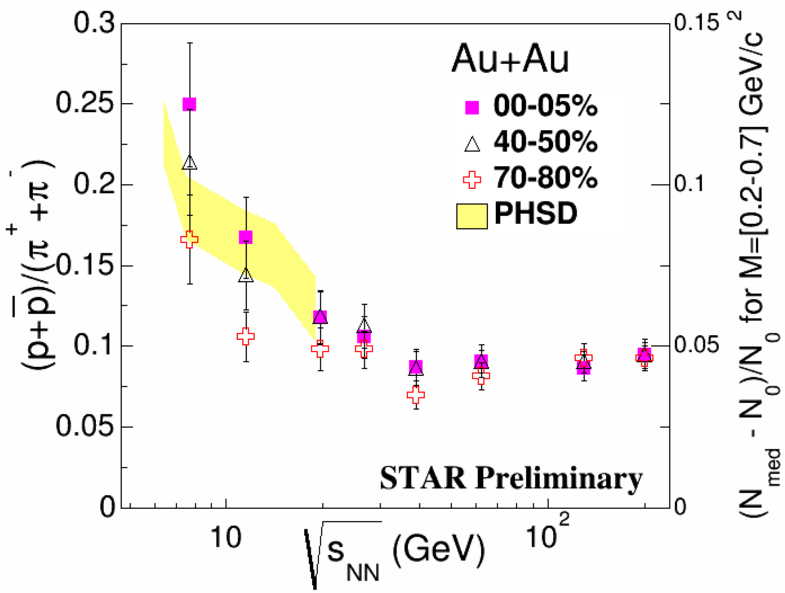
The electron-positron spectrum from hot, dense medium is consistent with a broadened ρ resonance in medium.

The production yield normalized by dN_{ch}/dy is proportional to lifetime of the medium from 17.3 to 200 GeV. Why?

The contribution from hot, dense medium from 17.3 to 200 GeV

Low-mass electron-positron emission depends on T, total baryon density, and lifetime

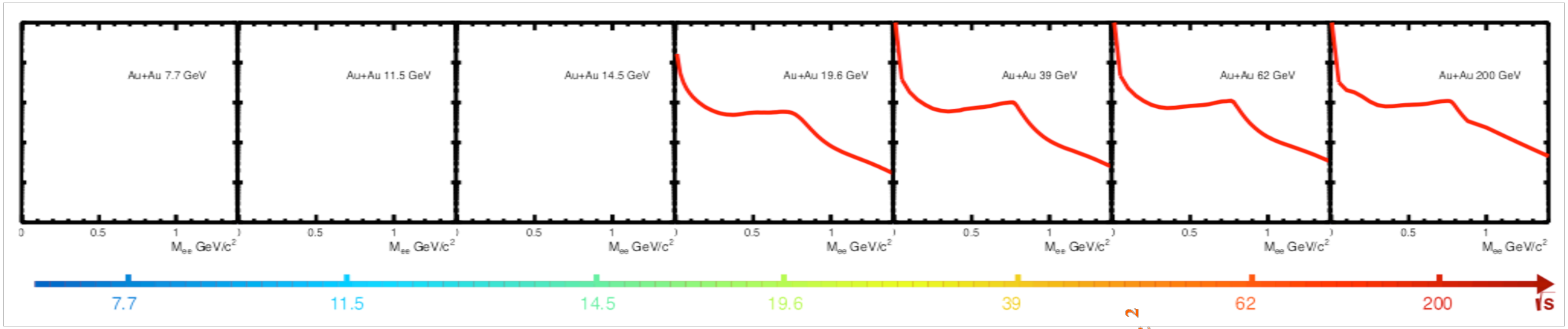
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.

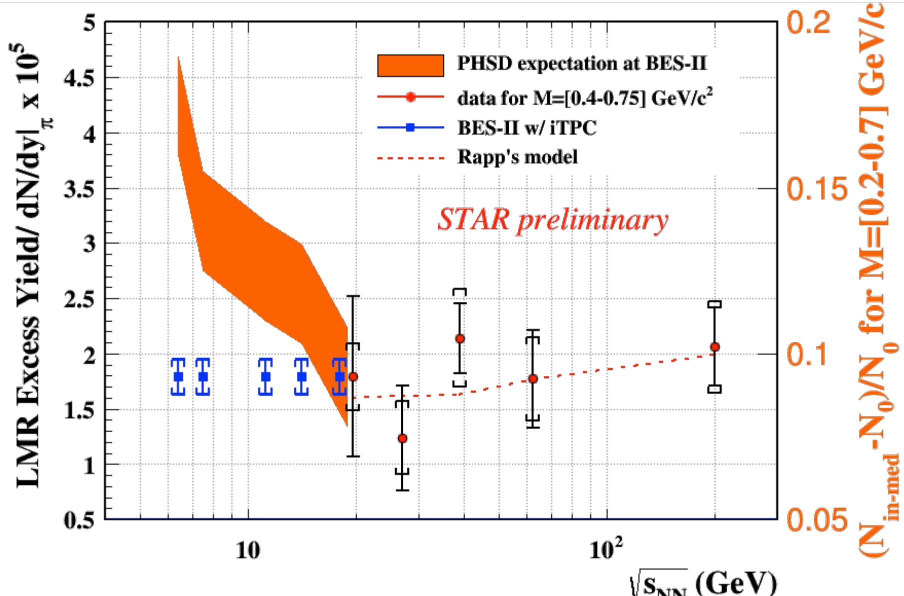


Normalized low-mass electron-positron production, is proportional to the life time of the medium from 17.3 to 200 GeV, given that the total baryon density is nearly a constant and that the emission rate is dominant in the Tc region.

Probe total baryon density effect

7.7 GeV to 19.6 GeV (RHIC beam energy scan II)

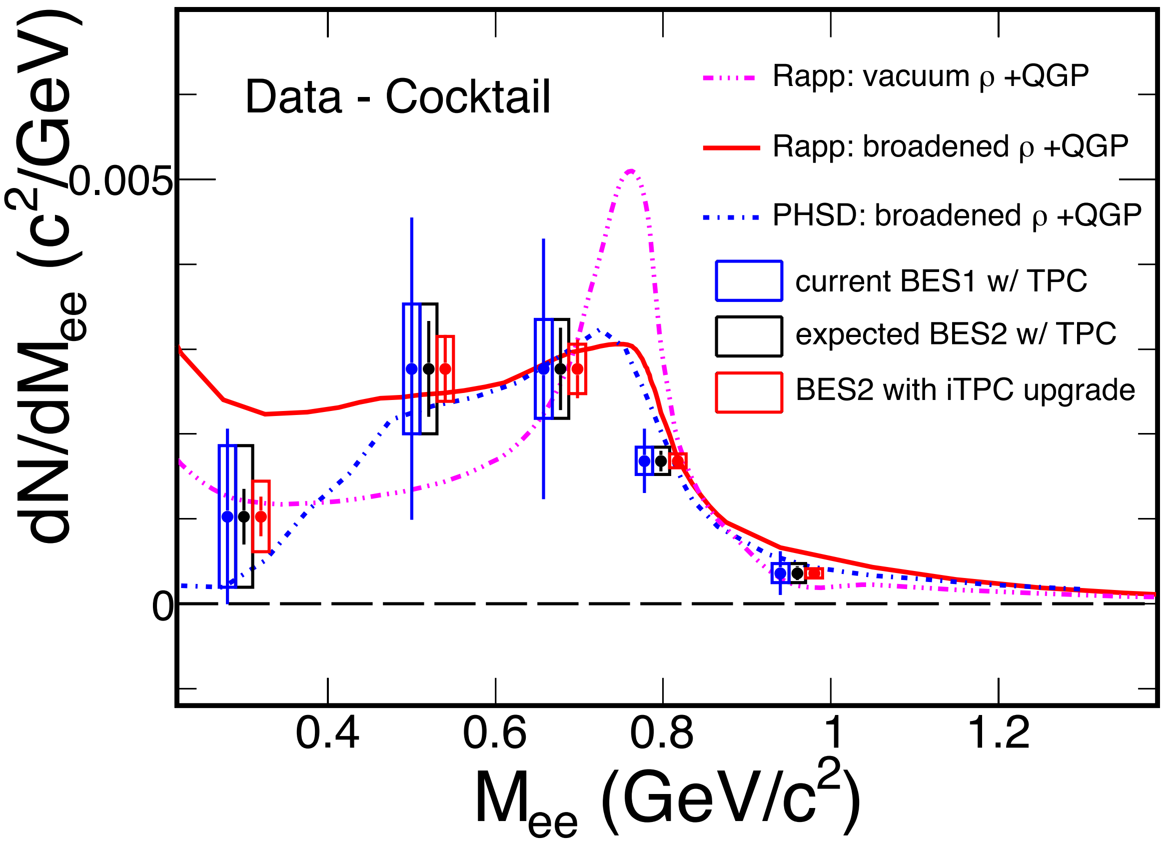




Broader and more electron-positron excess **down to 7.7 GeV collision energy?**

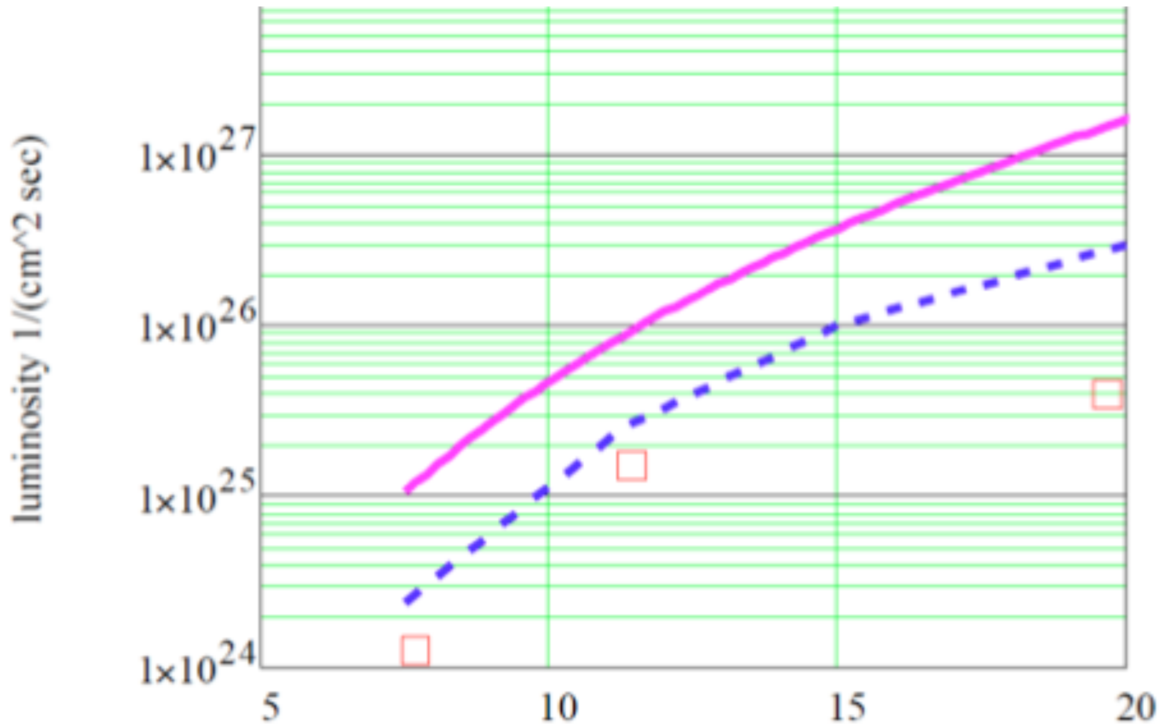
Beam Energy Scan II provides a unique opportunity to quantify the total baryon density effect on the ρ broadening!

Distinguish the mechanisms of ρ broadening



Knowing the mechanism that causes in-medium ρ broadening and its temperature and baryon-density dependence is fundamental to our understanding and assessment of chiral symmetry restoration in hot QCD matter !

Beam Energy Scan II in 2019-2020

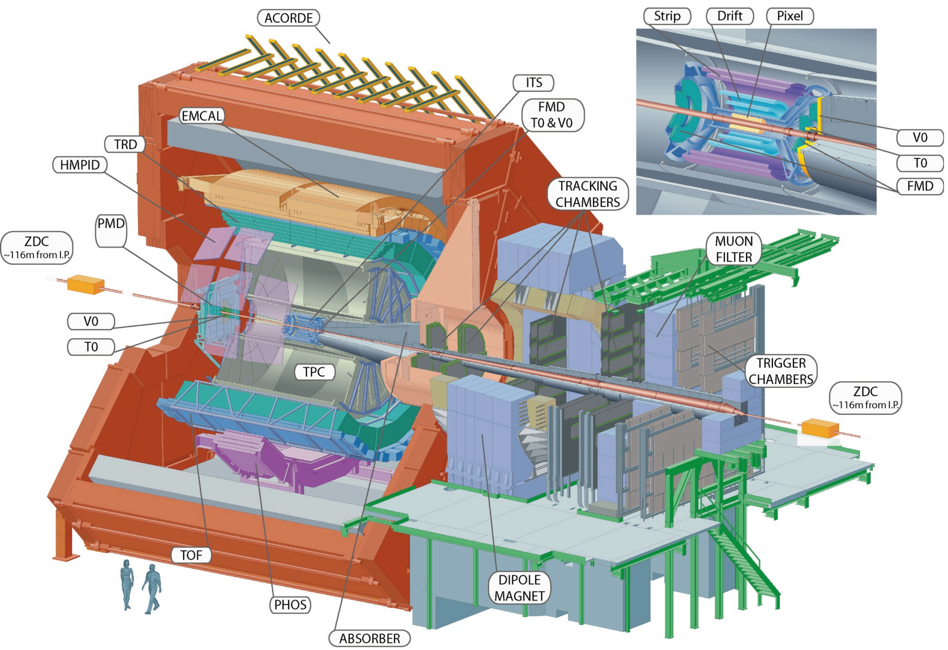


RHIC is unique to study chiral symmetry restoration:

Beam energy scan II: collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV.

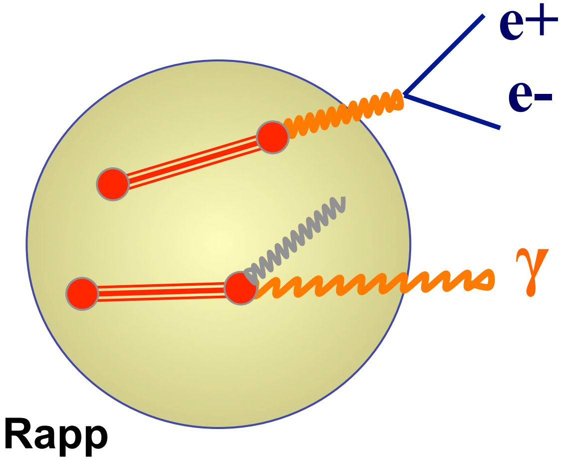
Electron cooling from CAD will increase collision rate from 3-10.

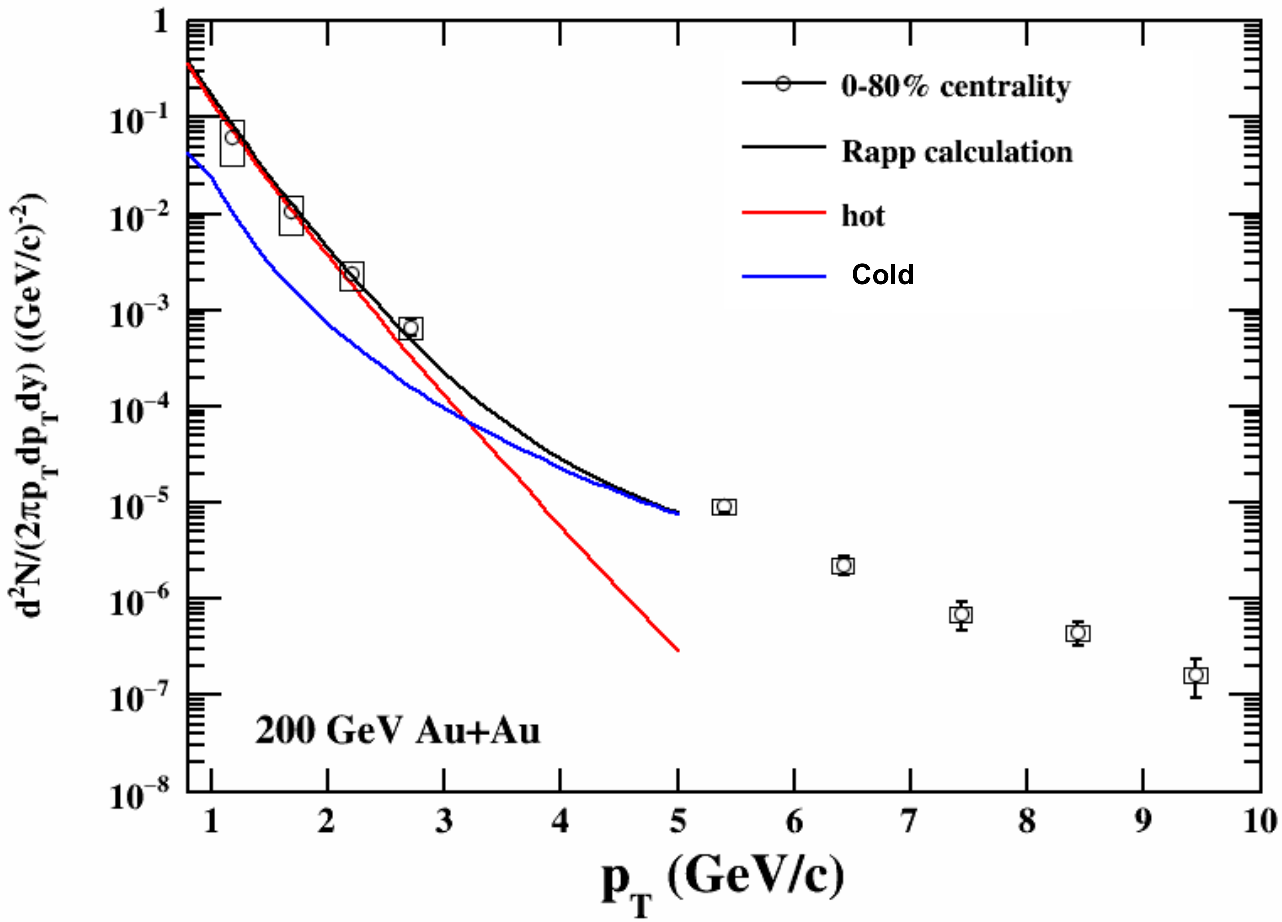
World-wide interest



- World interest: SPS, PHENIX, LHC, FAIR, KEK

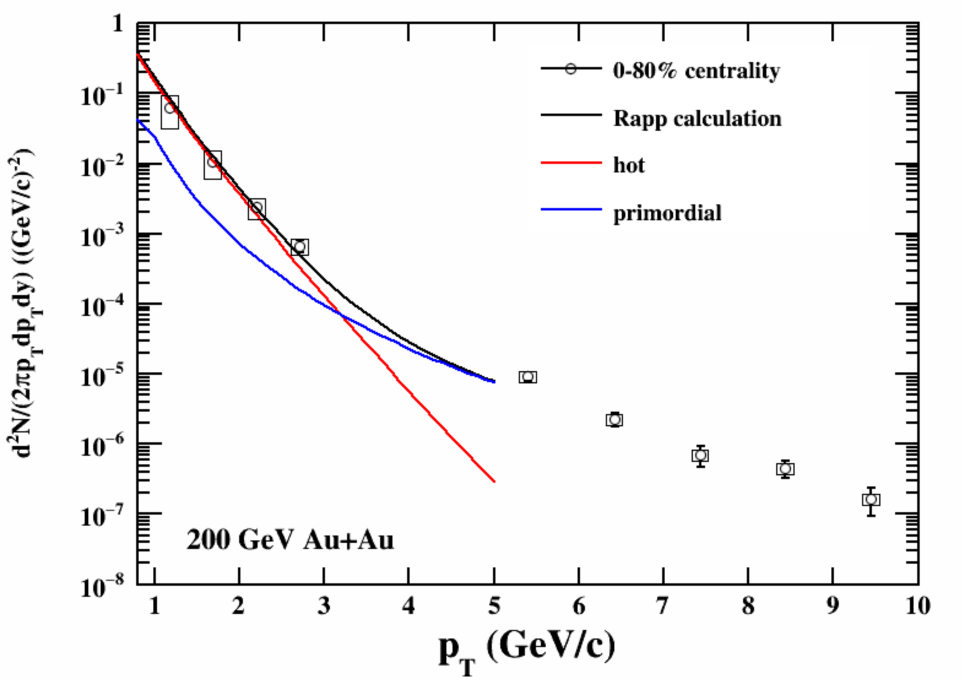
Photon emission

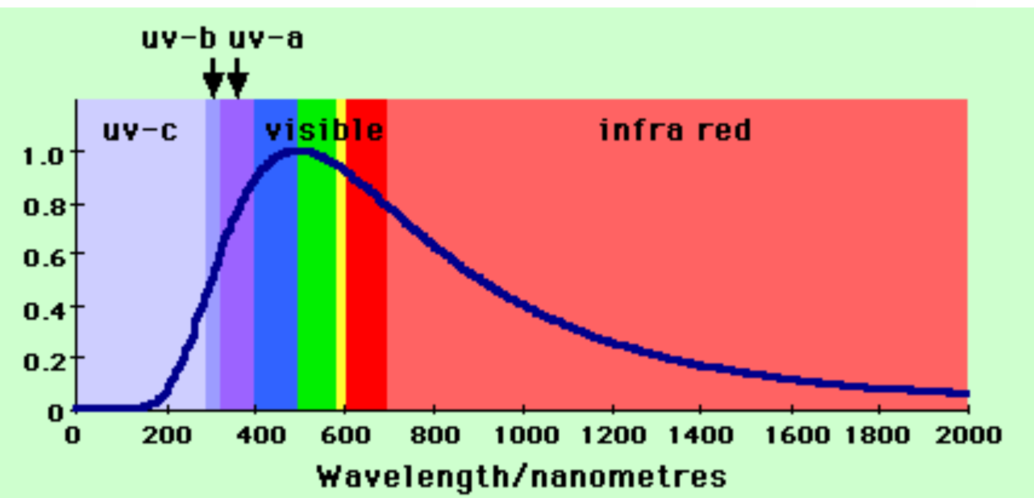




Hot contribution observed in the photon energy spectrum!

Photon emission



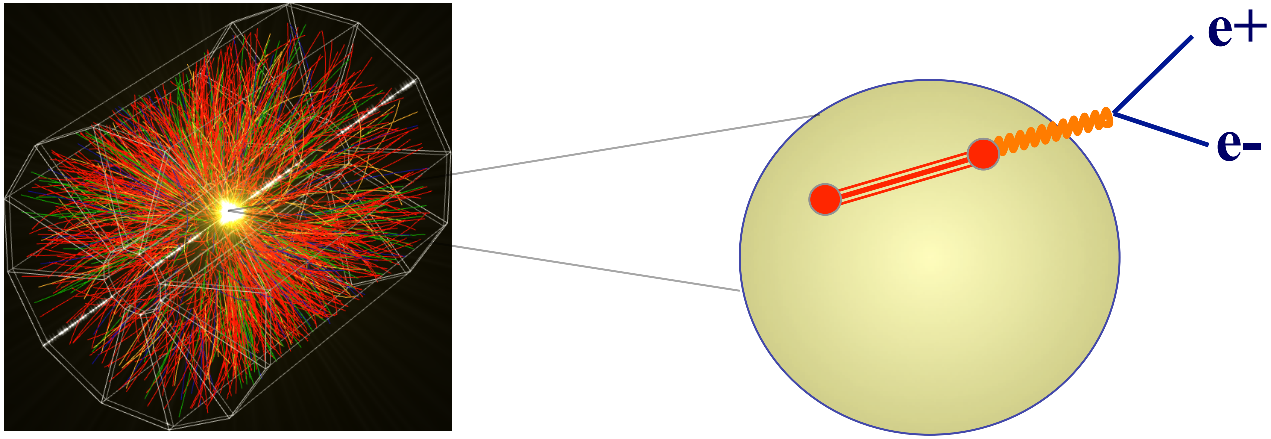


Quark-Gluon Plasma emission spectrum: photon energy a few 10^9 electron volts

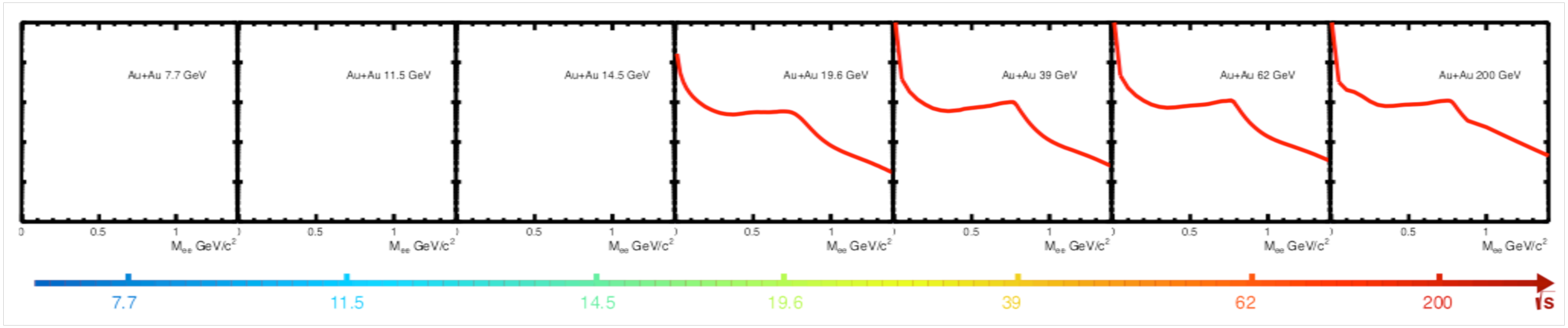
Sun emission spectrum: Photon energy a few electron volts.

Hottest matter in the universe: a few trillion degree Celsius!

Summary



Electron-positron tomography of Quark-Gluon Plasma:



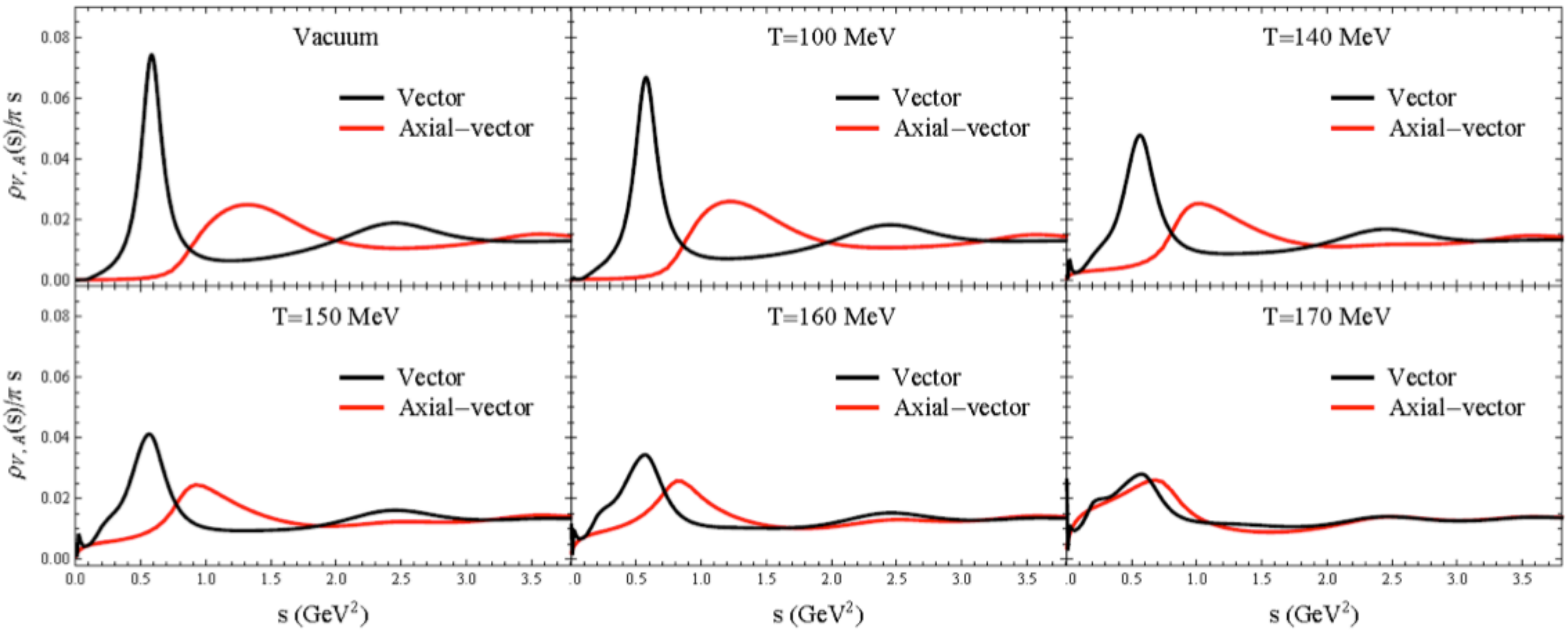
Structureless mass distribution would form the last piece of evidence of chiral symmetry restoration!

The future electron-positron program

To link electron-positron measurements to chiral symmetry restoration need more precise measurement at $\mu_B = 0$:

- **Lattice QCD calculation is reliable at $\mu_B = 0$.**

- **Theoretical approach: derive the a1(1260) spectral function by using the broadened rho spectral function, QCD and Weinberg sum rules, and inputs from Lattice QCD; to see the degeneracy of the rho and a1 spectral functions (Hohler and Rapp 2014).**



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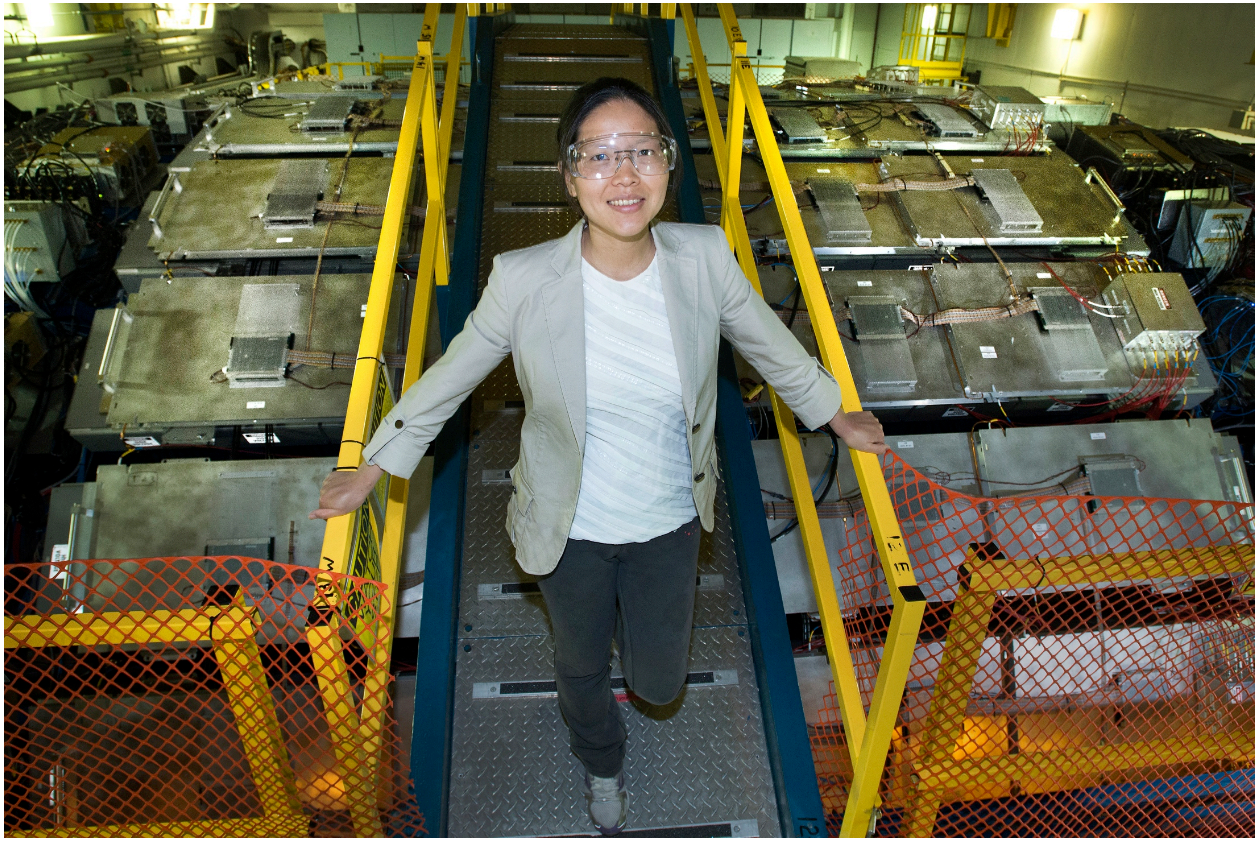
Muon Telescope Detector at STAR



- Based on MRPC technology.
- Use muon and anti-matter muon pairs to study the melting of heavy particles.

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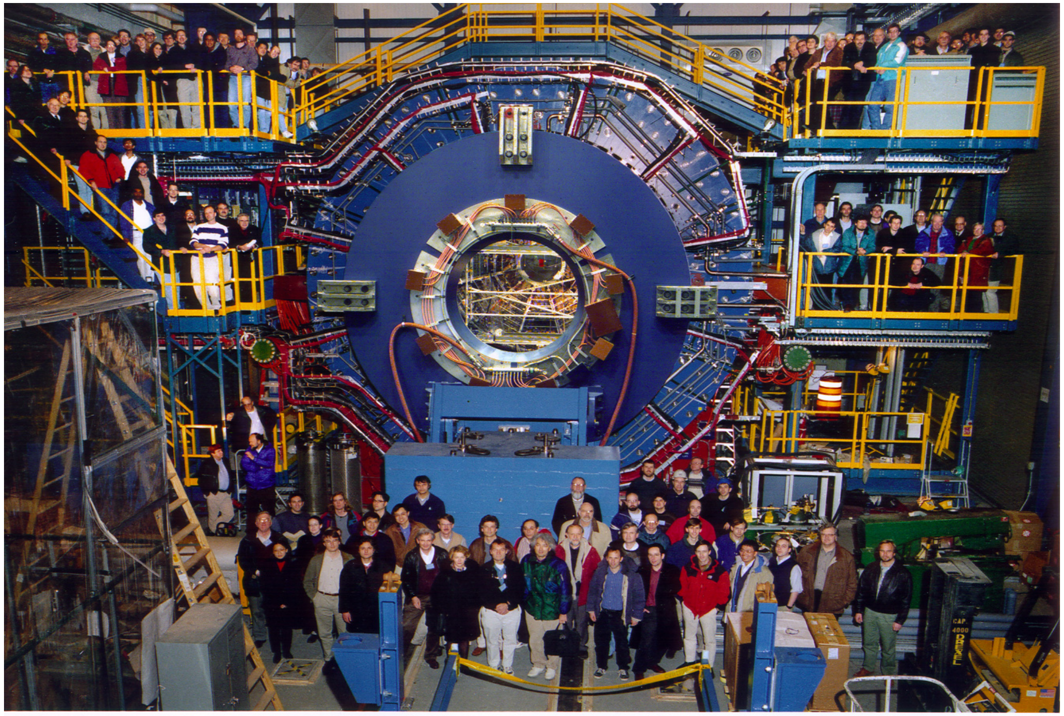
Acknowledgement



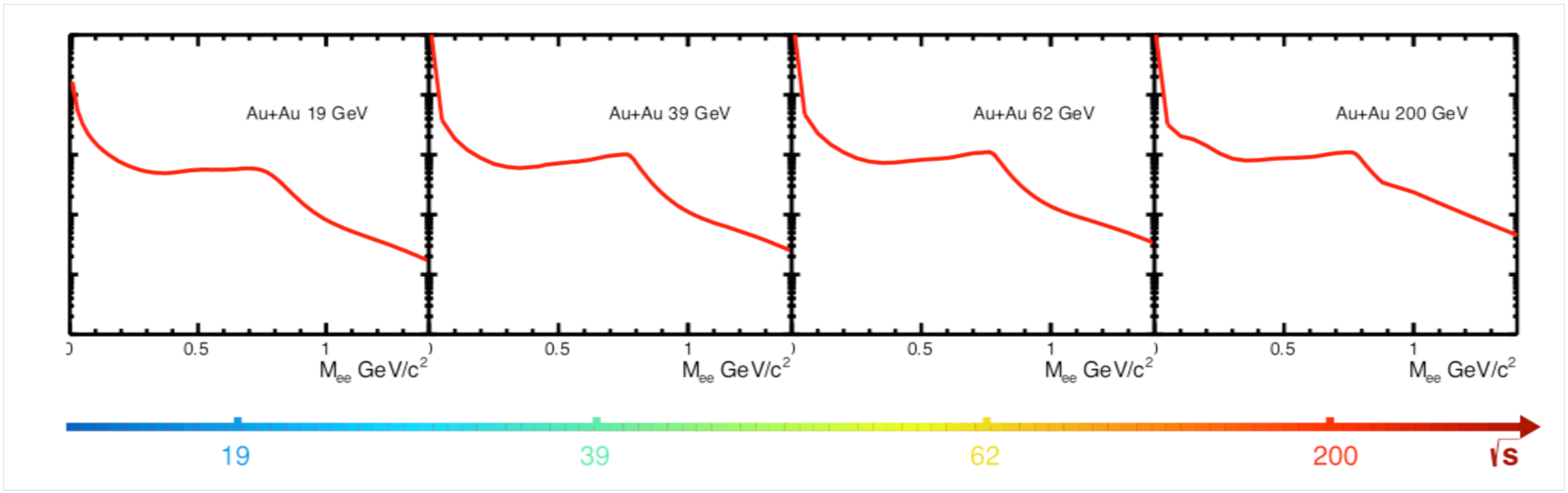
Thank STAR Collaborators: **626 Collaborators, 59 institutes and 12 countries.**

Thank my students and post-docs: **Xiangli Cui, Bingchu Huang, Xinjie Huang, Rongrong Ma, Zebo Tang, Takahito Todoroki, Yichun Xu, Chi Yang, Qian Yang, Shuai Yang, Yi Yang, and Wangmei Zha**

Thank DOE Office of Science for supporting me with Early Career Award.

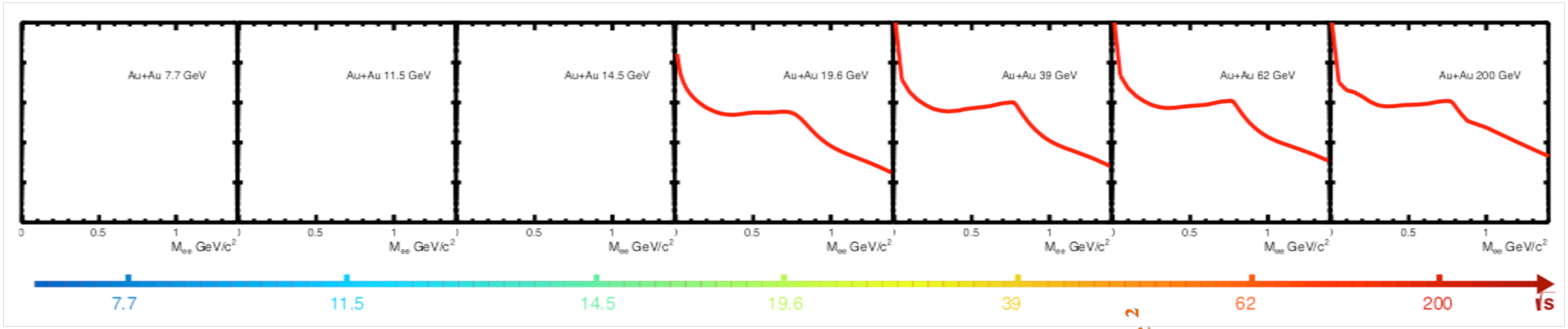
Backup

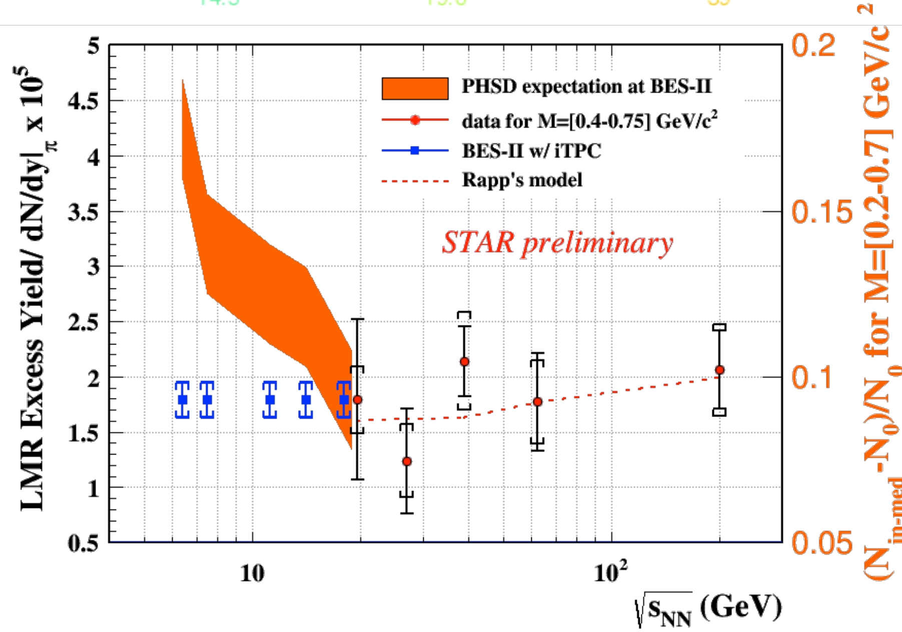
The "hot" contribution



"Hot" contributions from 19.6 to 200 GeV Au+Au collisions are similar !

Go to lower collisions energies
7.7 GeV to 19.6 GeV





Broader and more "hot" contribution down to 7.7 GeV collision energy?

Last piece of evidence for chiral symmetry restoration!