Electron-Positron Tomography of Hot, Dense Medium Created in Heavy Ion Collisions

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Outline:

- Electron-Positron Tomography
- Chiral symmetry
- Our experimental approach and results
- Summary

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a passion for discovery

Office of Science
U.S. DEPARTMENT OF ENERGY

Traditional Positron-emission Tomography (PET)

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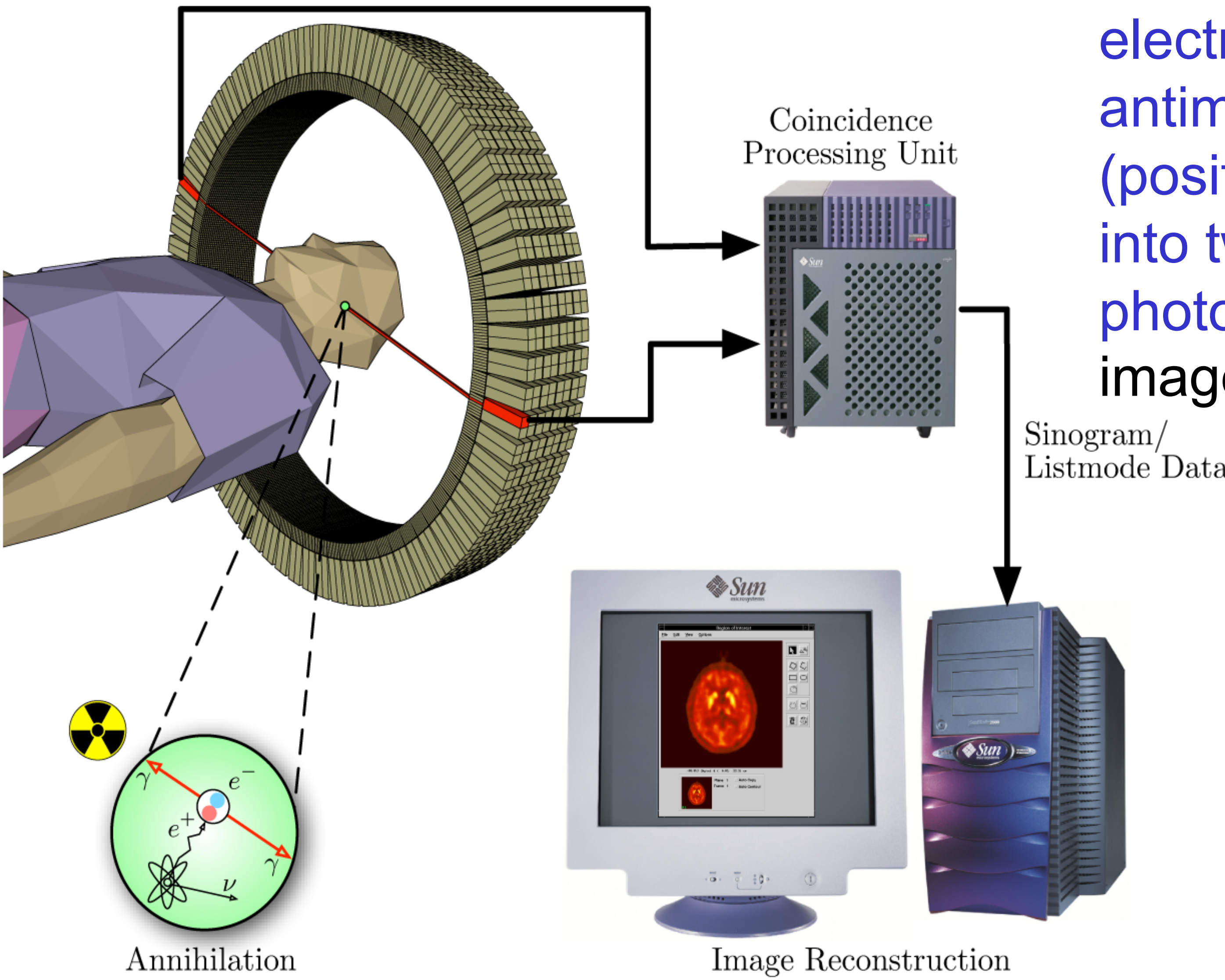
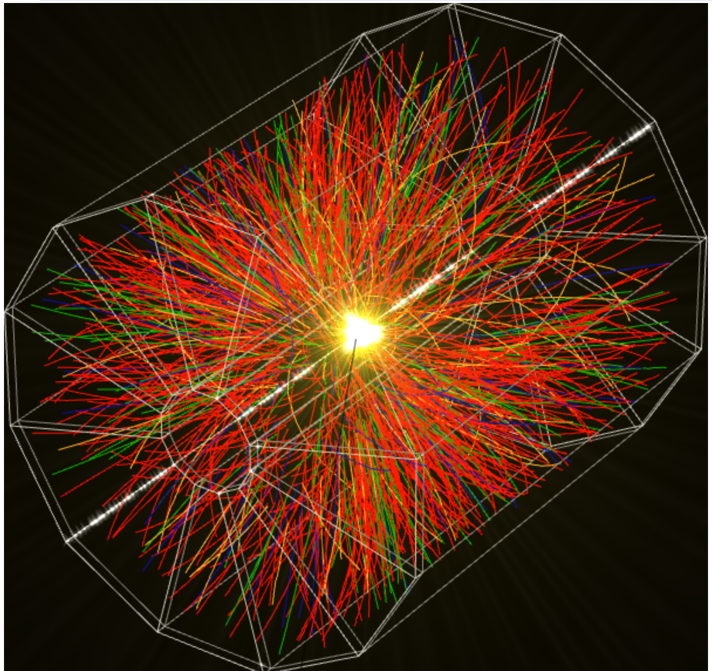
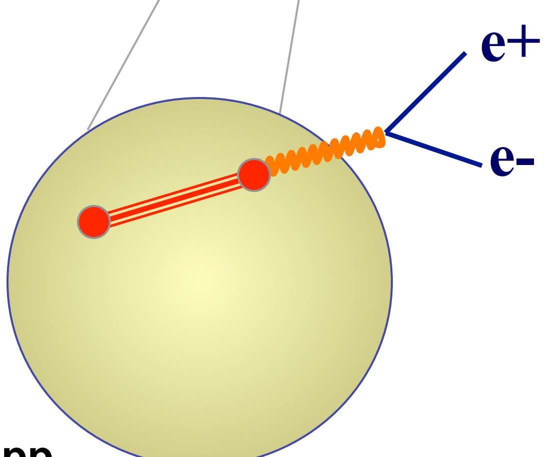


PET scan uses electron and antimatter electron (positron) annihilation into two back-to-back photons to create an image.

Electron-positron Tomography





- 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.

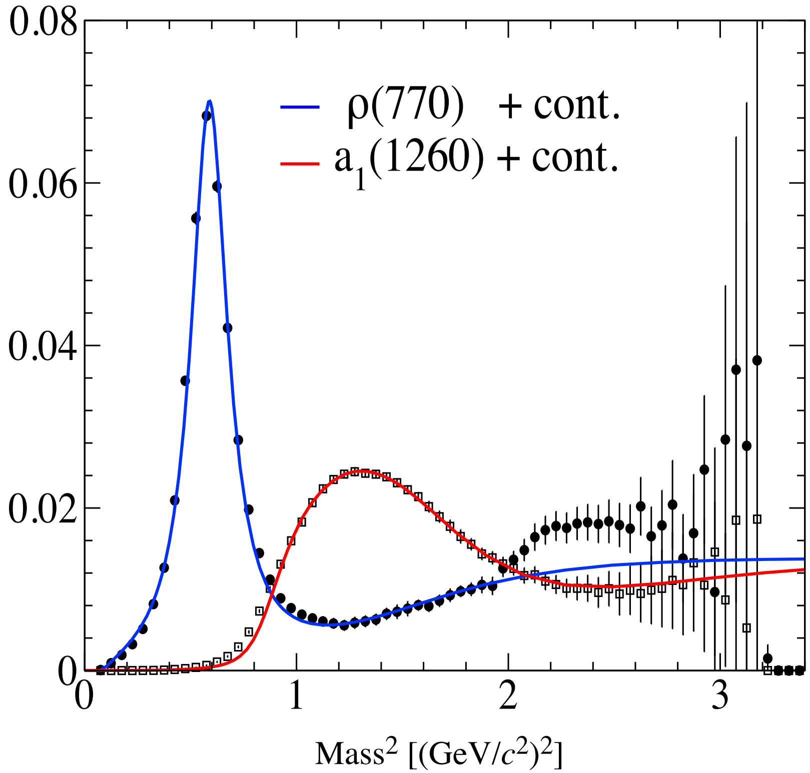
Spontaneous chiral symmetry breaking

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.

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

Is chiral symmetry restored in Quark-Gluon Plasma?

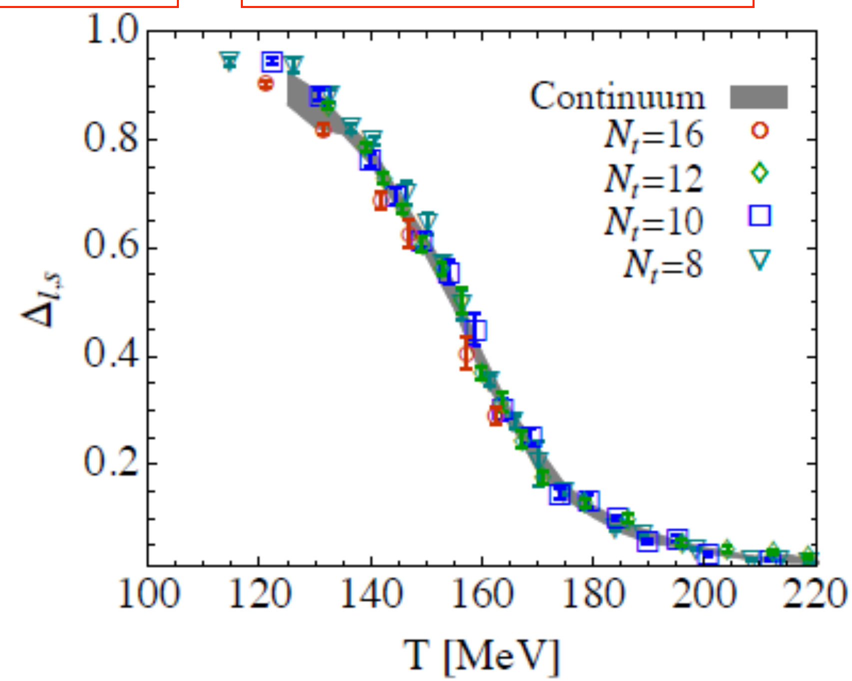
Early universe ⟺ Chiral symmetry ⟺ Quark Gluon Plasma

The world we live ⟺ Spontaneous chiral symmetry breaking ⟺ Particles we observe

In the Quark-Gluon Plasma, which is hot and dense, is chiral symmetry restored?

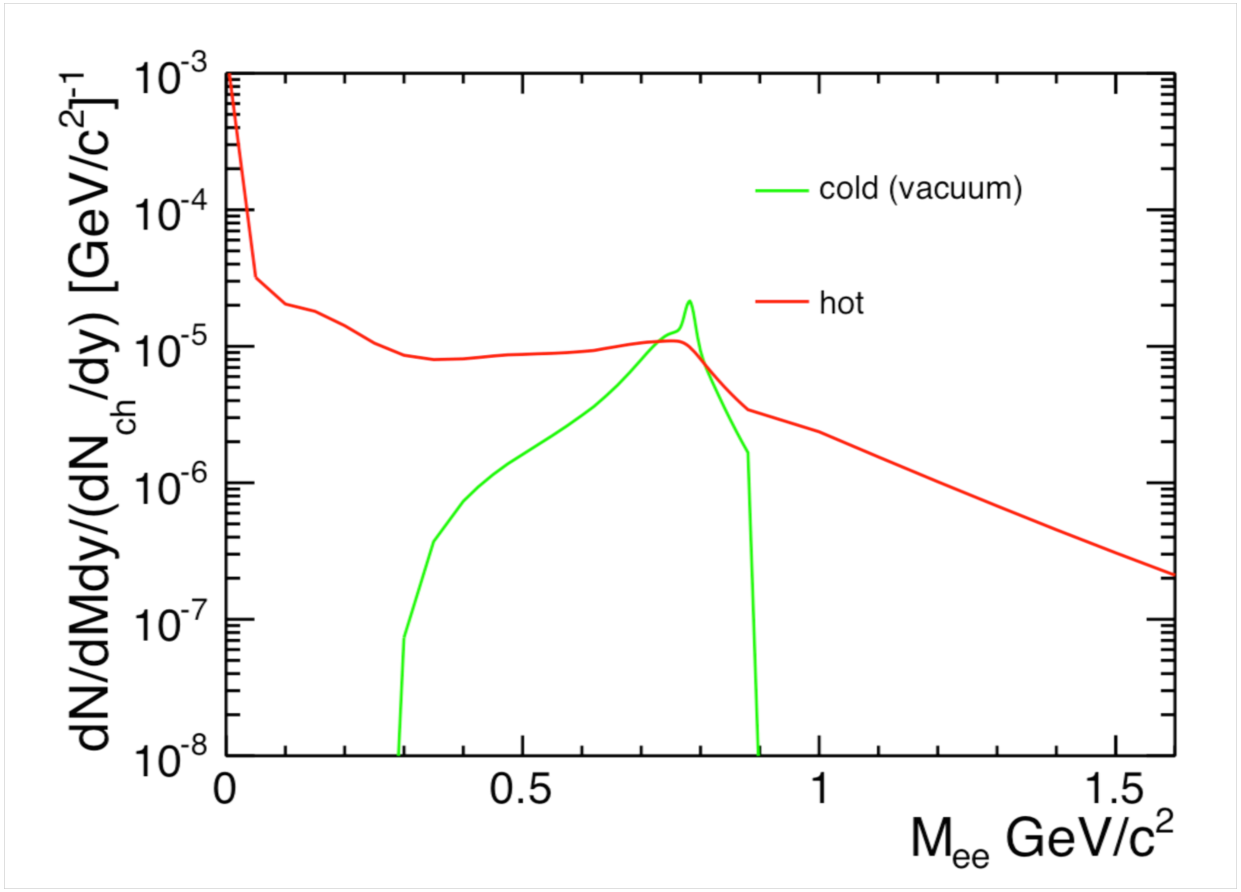
T_c= 155 MeV

Do we have experimental observable?



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

The ρ resonance mass spectrum function



Observable for chiral symmetry restoration:

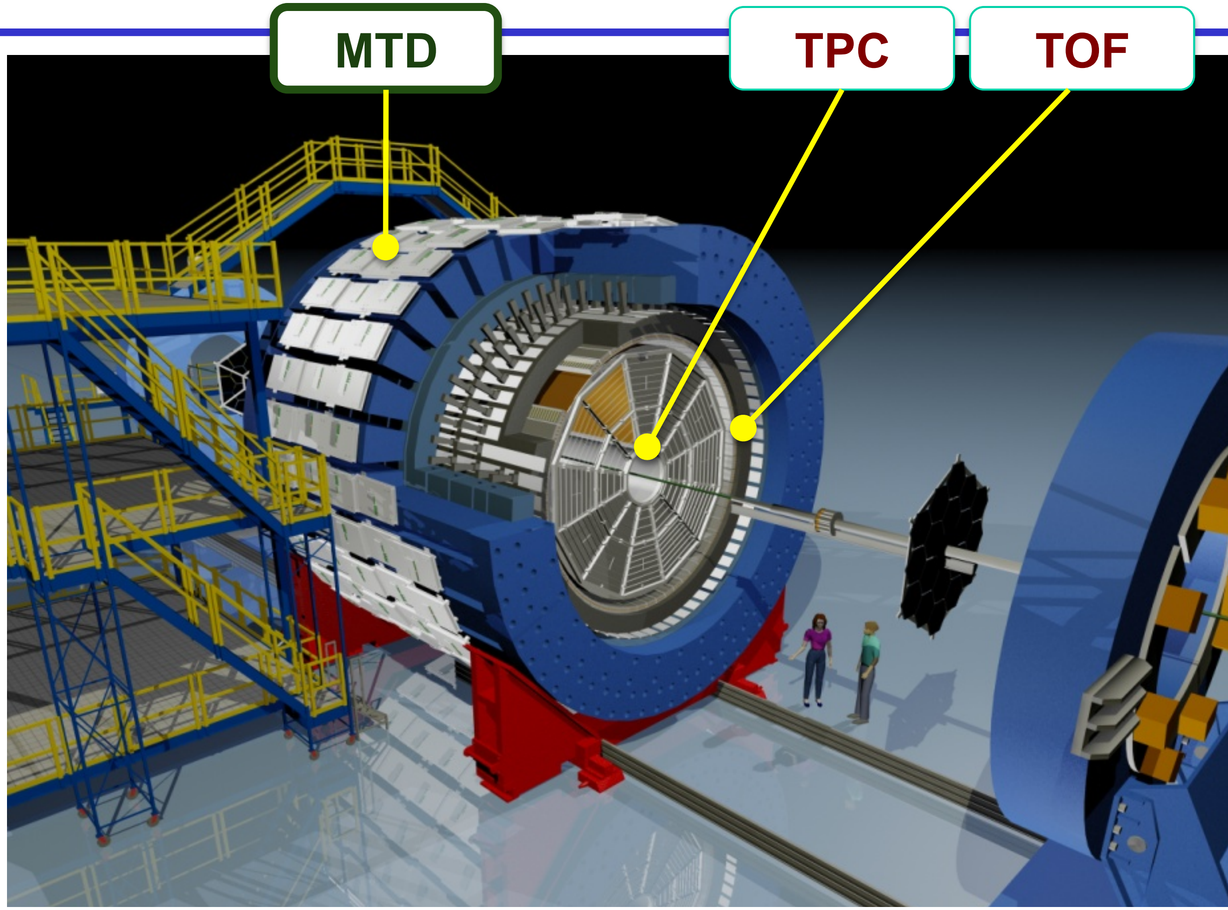
a broadened ρ spectral function and ultimately the peak structure disappears!

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

RHIC @ Brookhaven National Laboratory

A heavy-ion collision event

The STAR Detector



Solenoidal Tracker at RHIC (1200 tons)

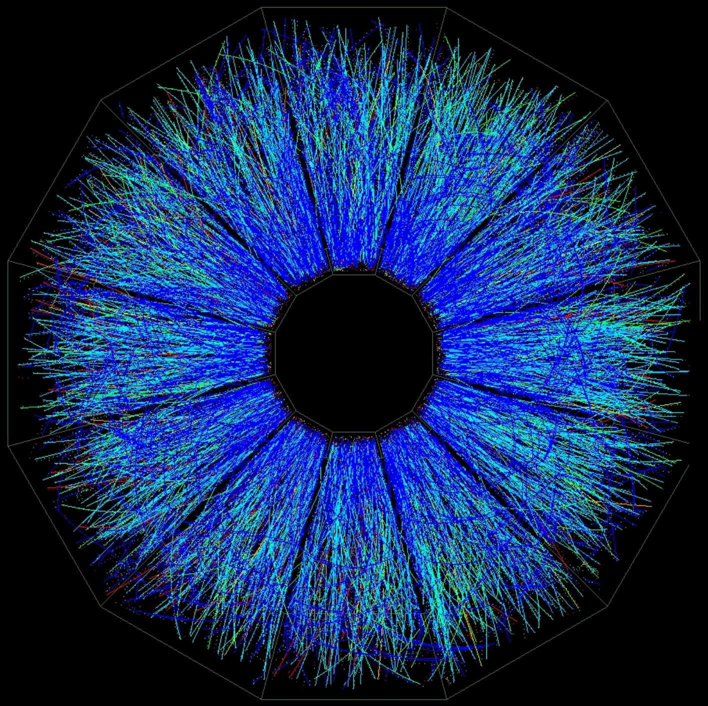
Time Projection Chamber

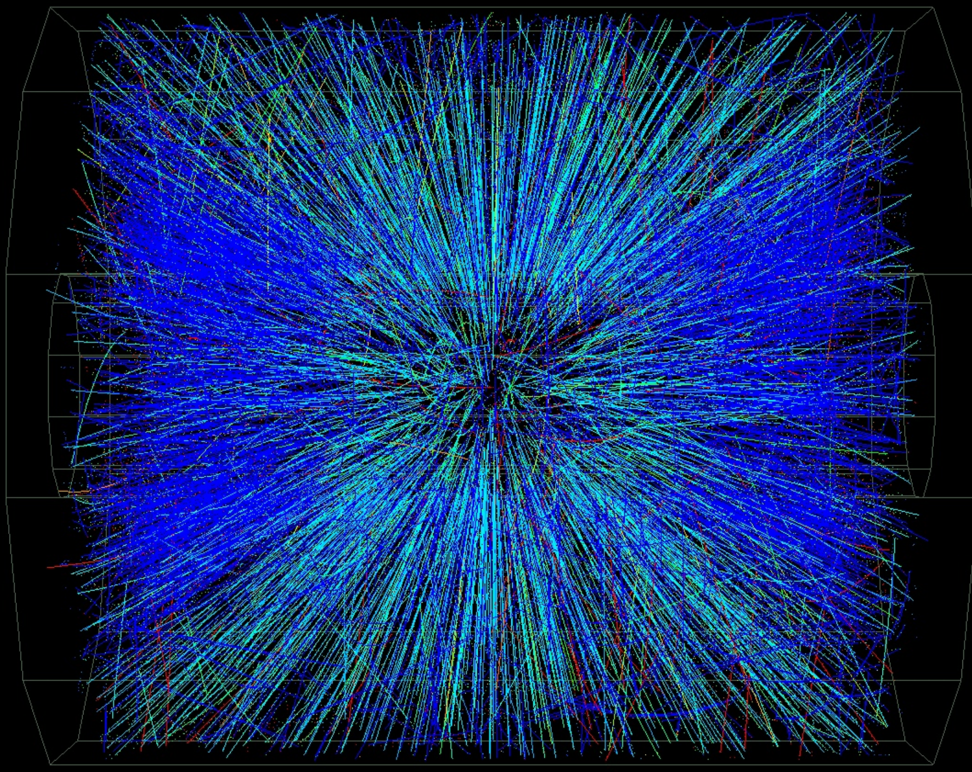
1. **Second largest device of its kind ever built**

2. **Measure ionization energy loss (dE/dx) and momentum**

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

Central Event

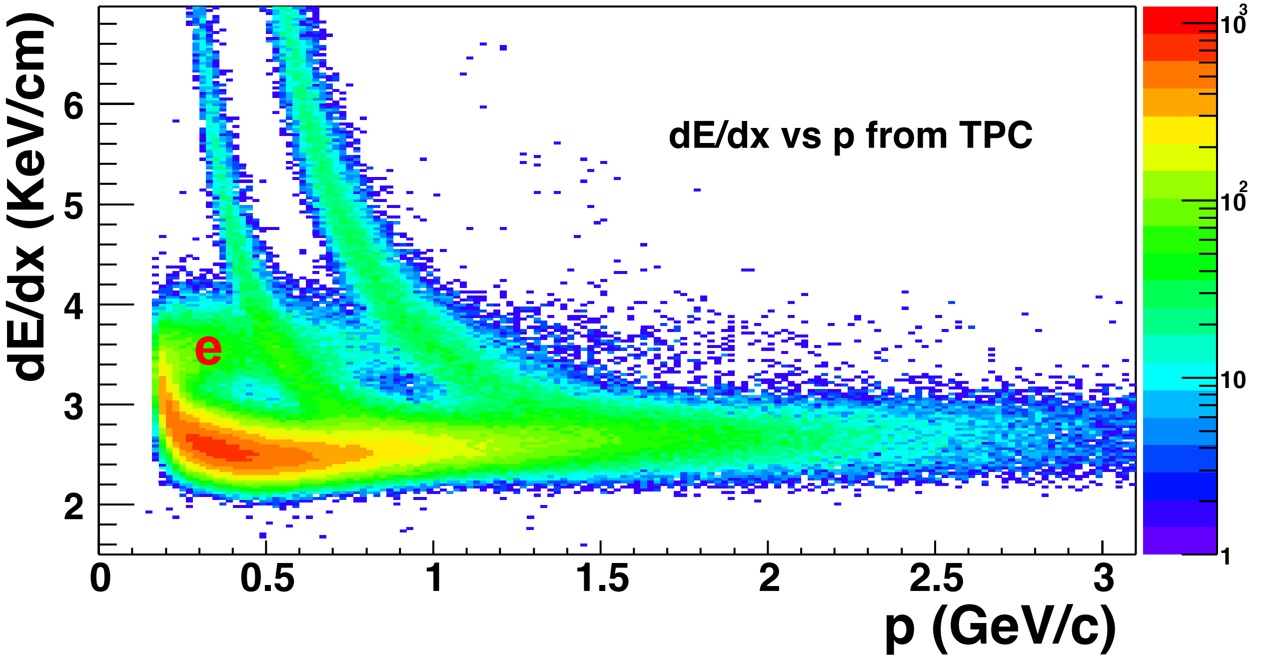




STAR

(real-time Level 3)

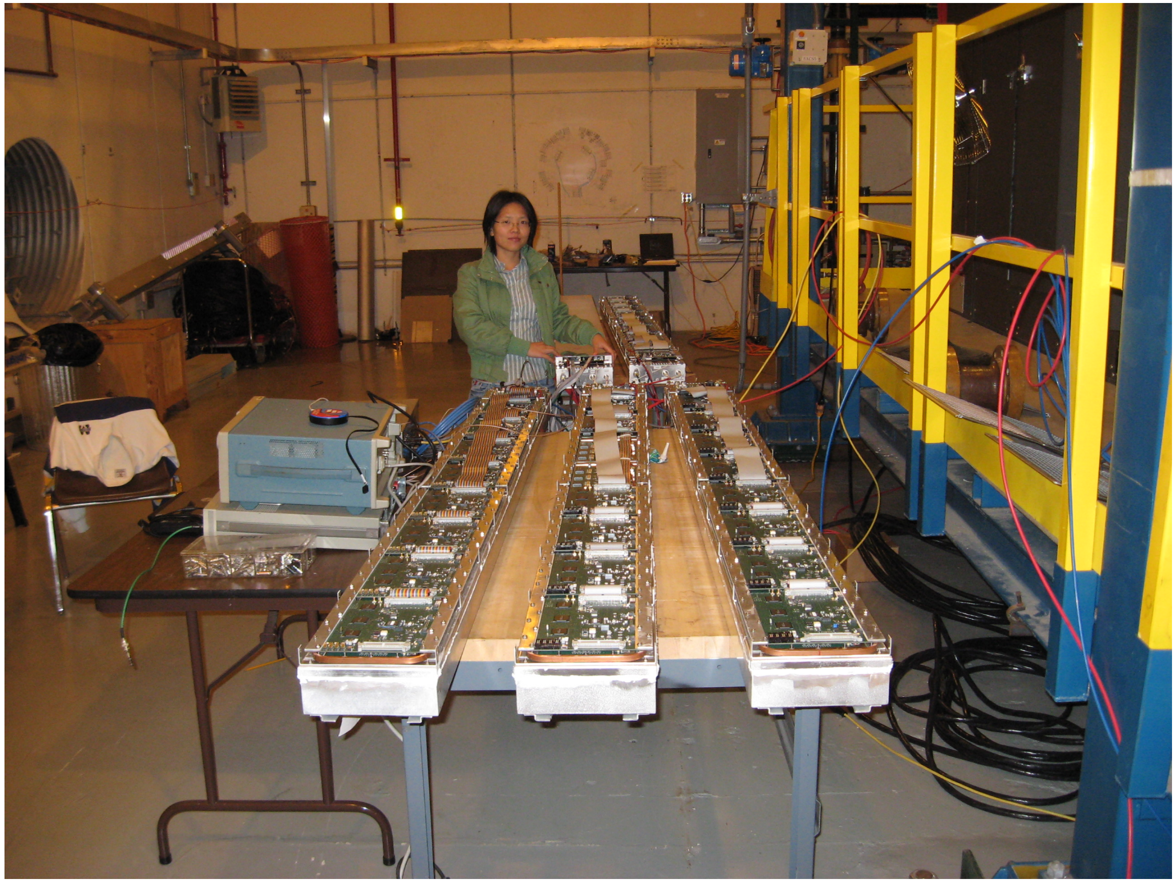
Particle identification



Electrons are highly contaminated by other particles.

Need new experimental tool to clearly identify electrons!

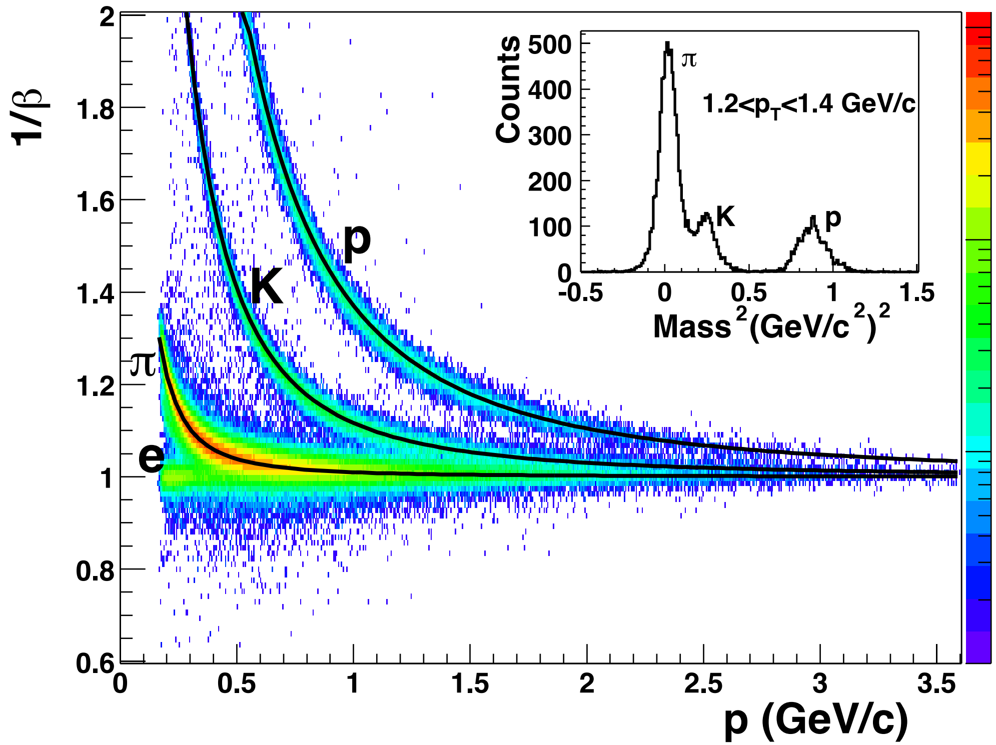
Time of Flight Detector upgrade



US-China Collaboration, Multigap Resistive Plate Chamber (MRPC) Technology, low cost, high timing resolution $<100\times10^{-12}$ second

120 units in total: 2008: 4%; 2009: 72%; 2010: 100%

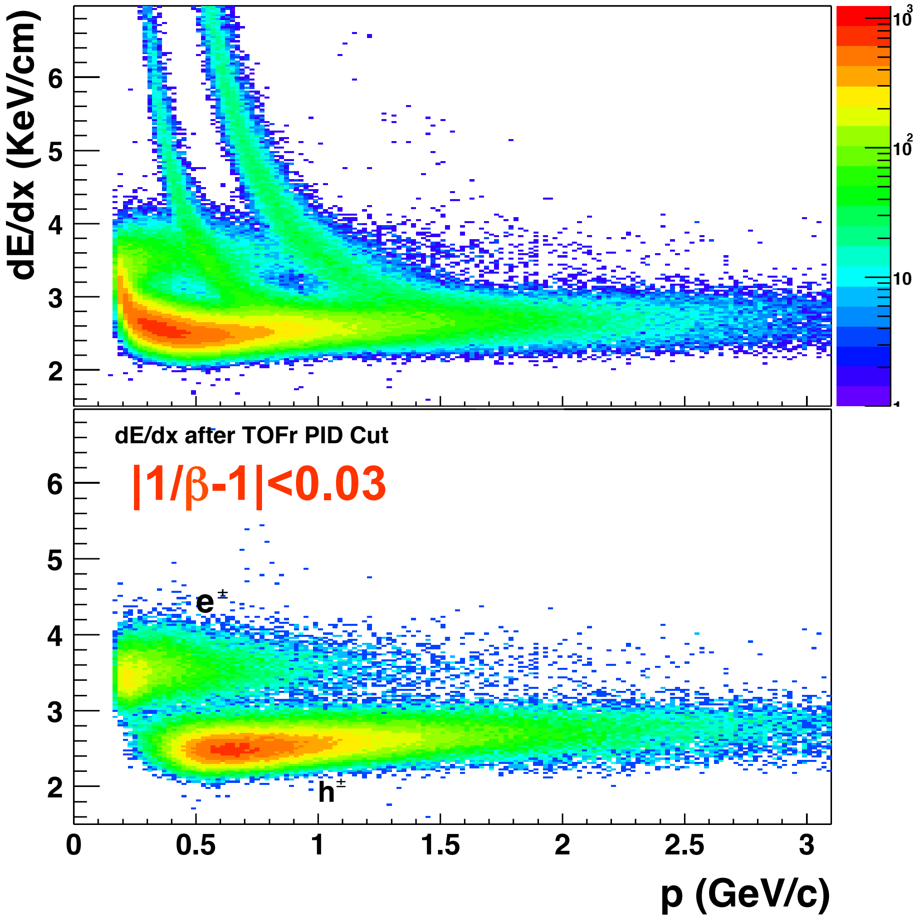
Particle identification from TOF



STAR Collaboration, PLB616(2005)8

Hadron identification: proton up to 3 GeV/c, kaon and pion up to 1.6 GeV/c

Electron identification



STAR Collaboration, PRL94(2005)062301

Combining information from the TPC and TOF, we obtain clean electron samples at p_T<3 GeV/c.

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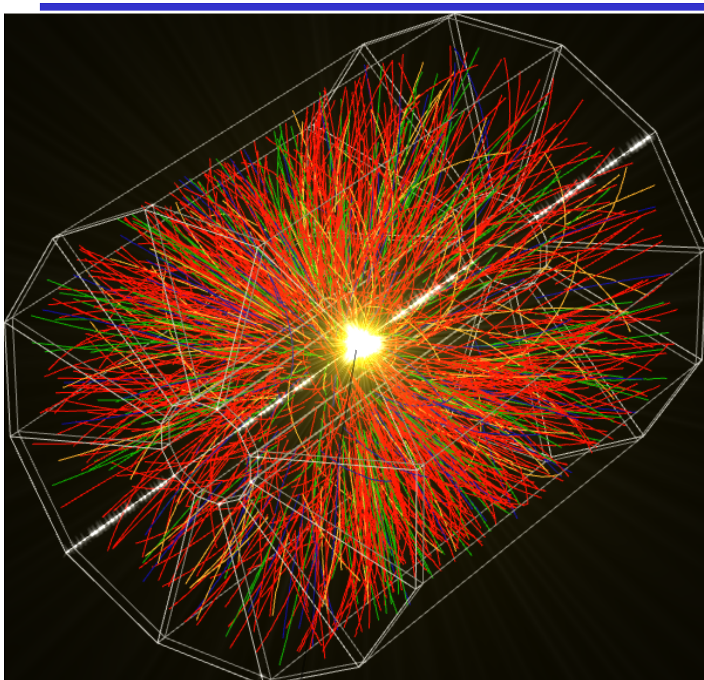
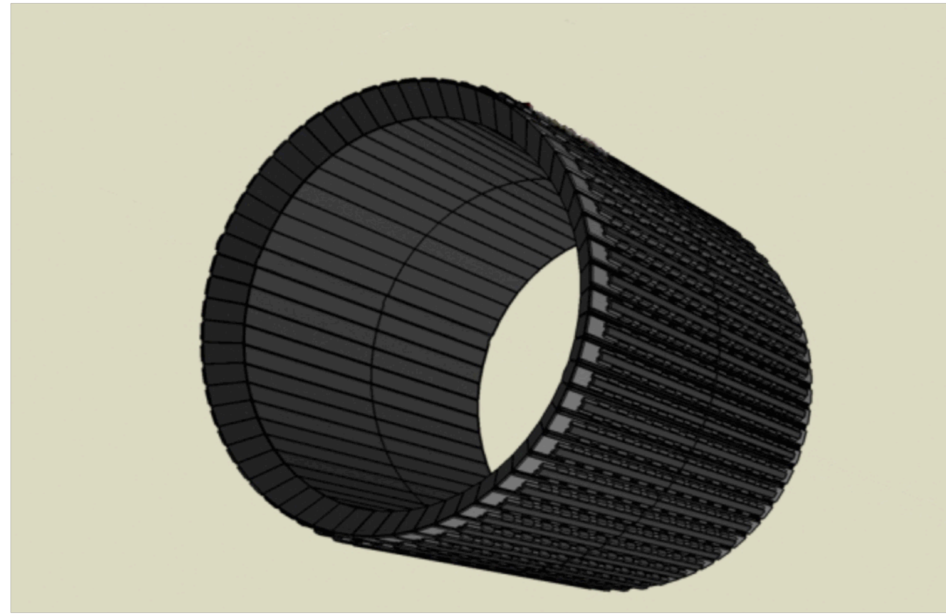
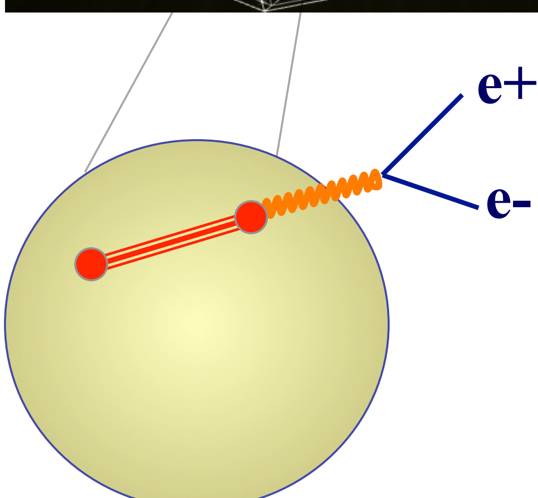
The electron-positron tomography tools

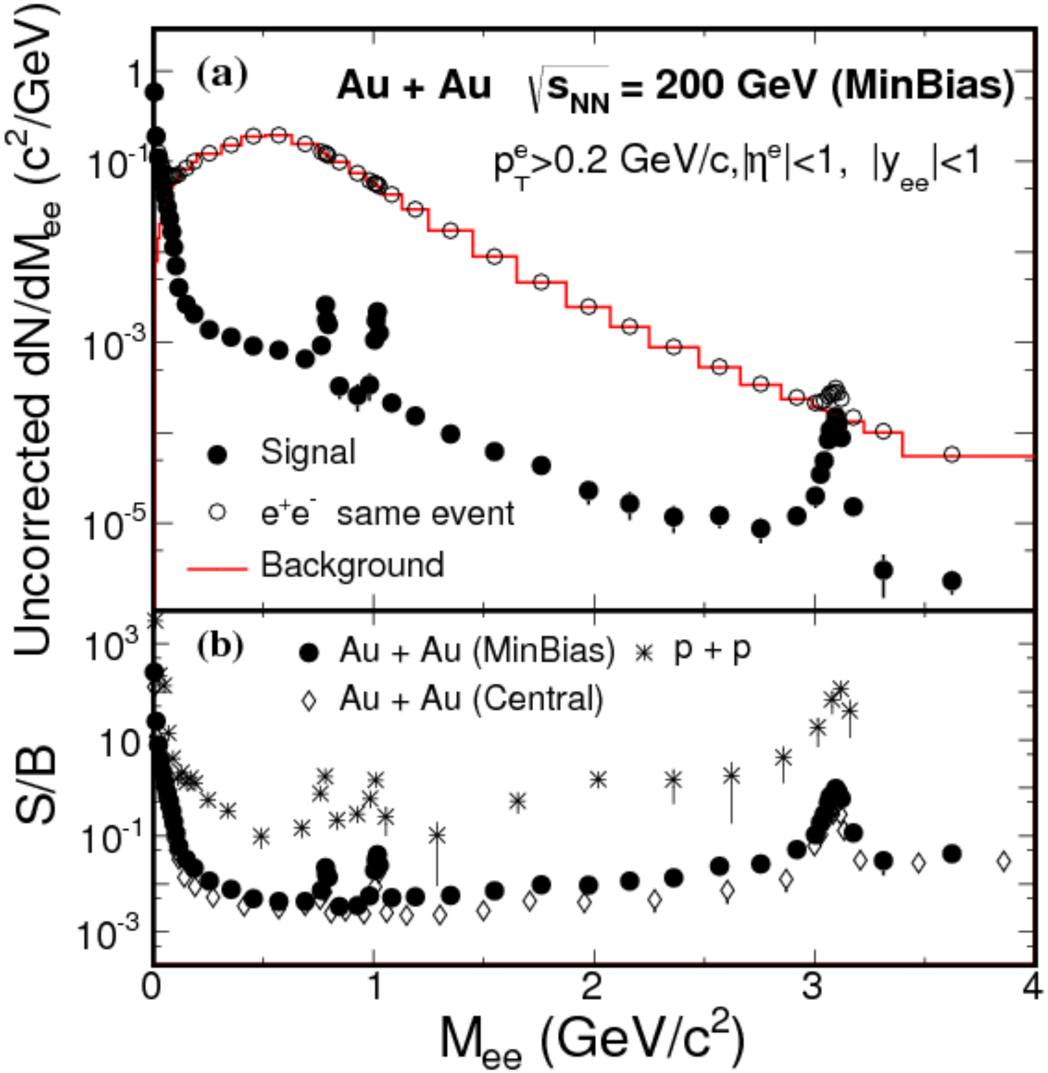






The Time of Flight Detector completes the experimental tool for electron-positron tomography: clean electron identification and large acceptance.

Electron-positron invariant mass distribution



At M_{ee}=0.5 GeV/c^2,
S/B =1/10 in proton+proton,
=1/250 in head-on Au+Au

A good measurement requires **low material budget** to control background and **high statistics** Data sample

Mee < 1 GeV/c^2 Like sign background
Mee >= 1 GeV/c^2 Mixed event background

Electron-positron signal

Electron-positron signal:

e+e- pairs from light flavor meson and heavy flavor decays (charmonia and open charm correlation):

Pseudoscalar meson Dalitz decay: π^0, η, η' $\rightarrow \gamma e^+e^-$

Vector meson decays: ρ^0, ω, ϕ $\rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\phi \rightarrow \eta e^+e^-$

Heavy flavor decays: $J/\psi \rightarrow e^+e^-$, ccbar$\rightarrow$ e^+e^- X, bbbar$\rightarrow$ e^+e^- X

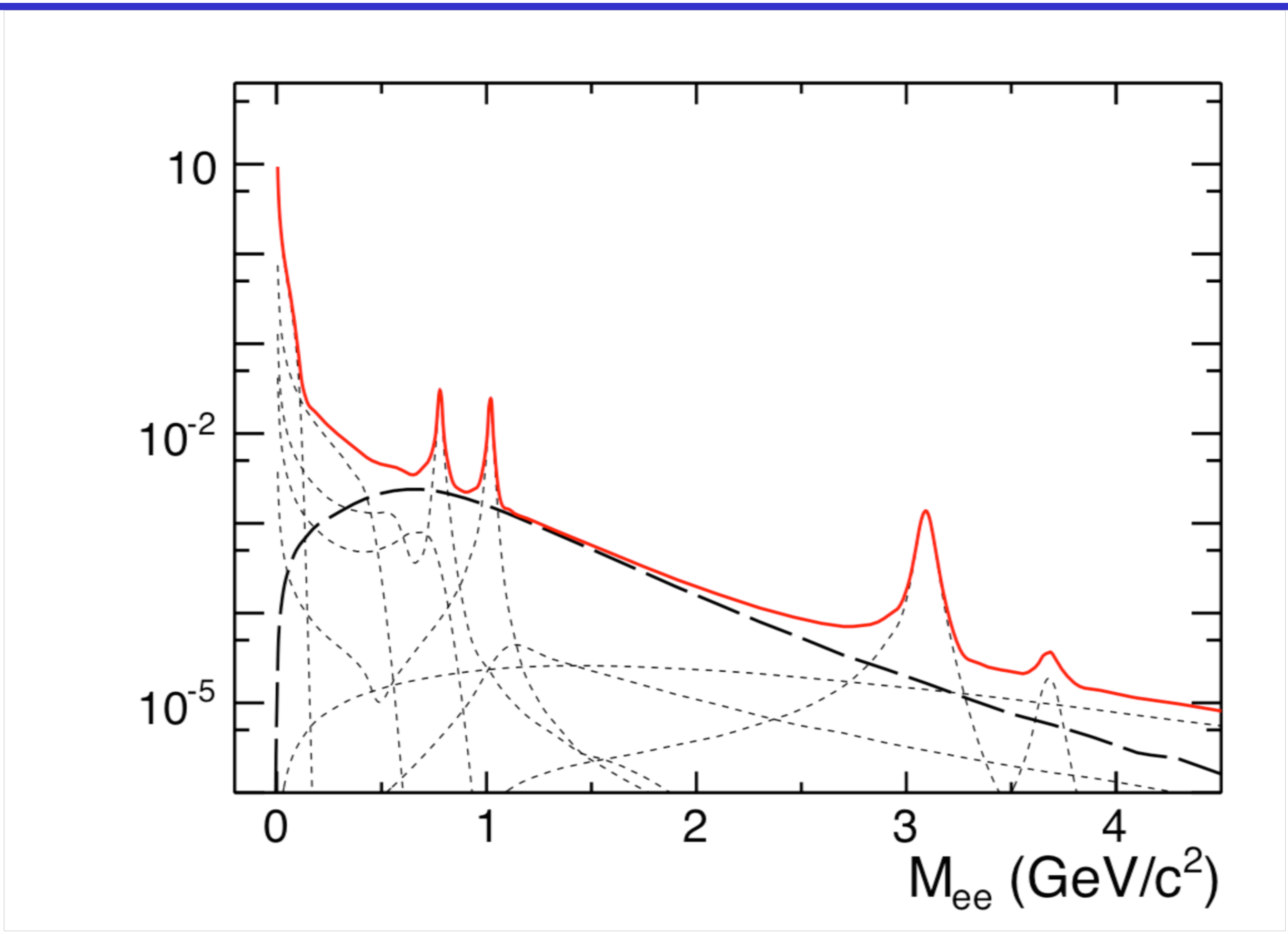
Drell-Yan contribution

In Au+Au collisions, we search for

QGP thermal radiation at $1.1<M_{ee}<3.0$ GeV/c^2 (intermediate mass range)

Vector meson in-medium modifications at $M_{ee}<1.1$ GeV/c^2 (low mass range)

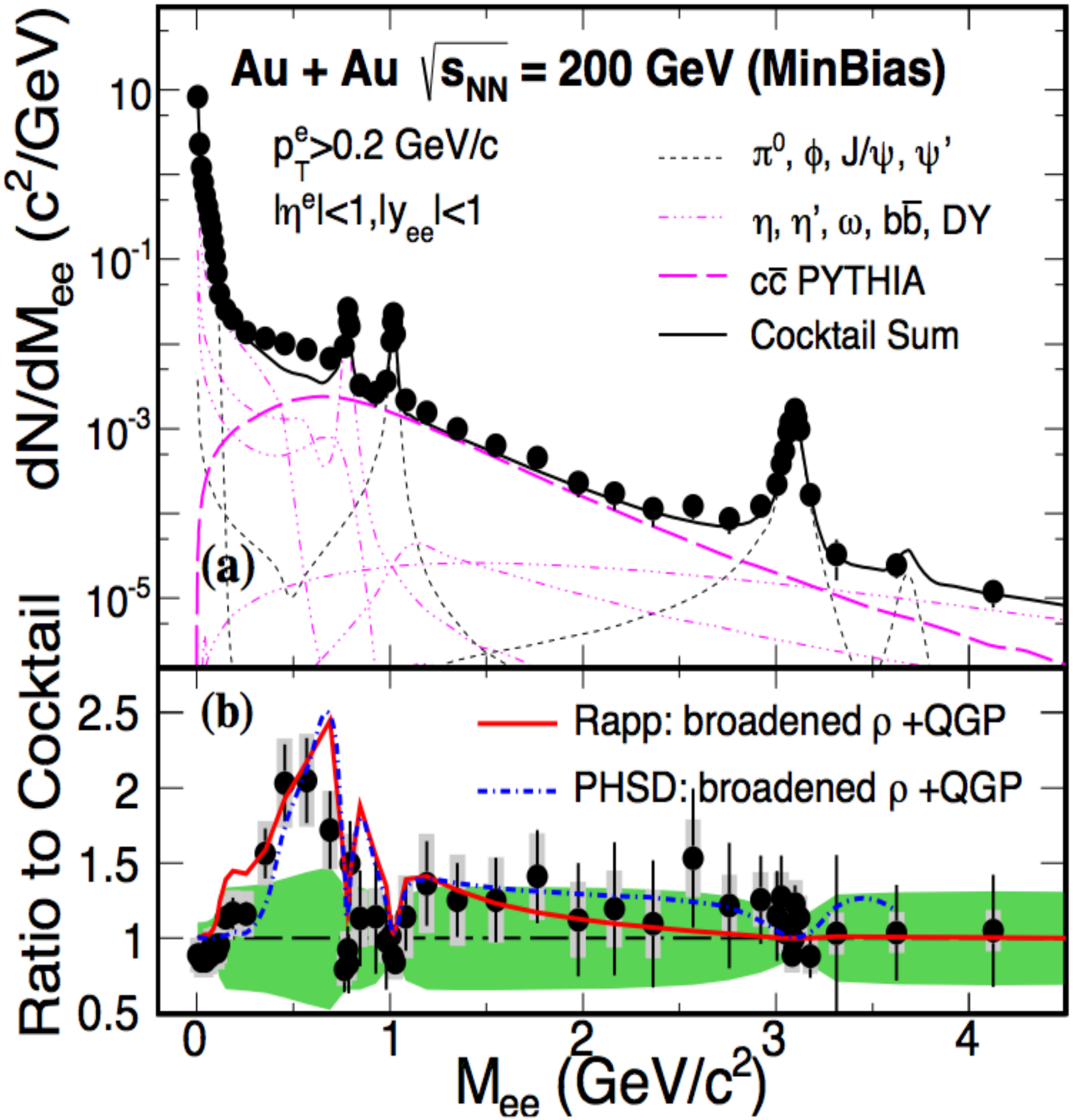
Electron-positron emission mass spectrum



Electron-positron mass spectrum from known hadronic sources without hot, dense medium contribution.

Electron positron emission mass spectrum in 200 GeV Au+Au

Phys. Rev. Lett. 113 (2014) 22301



Significant excess is observed for $0.3<M_{ee}<0.8$ GeV/c^2, representing the hot, dense medium contribution.

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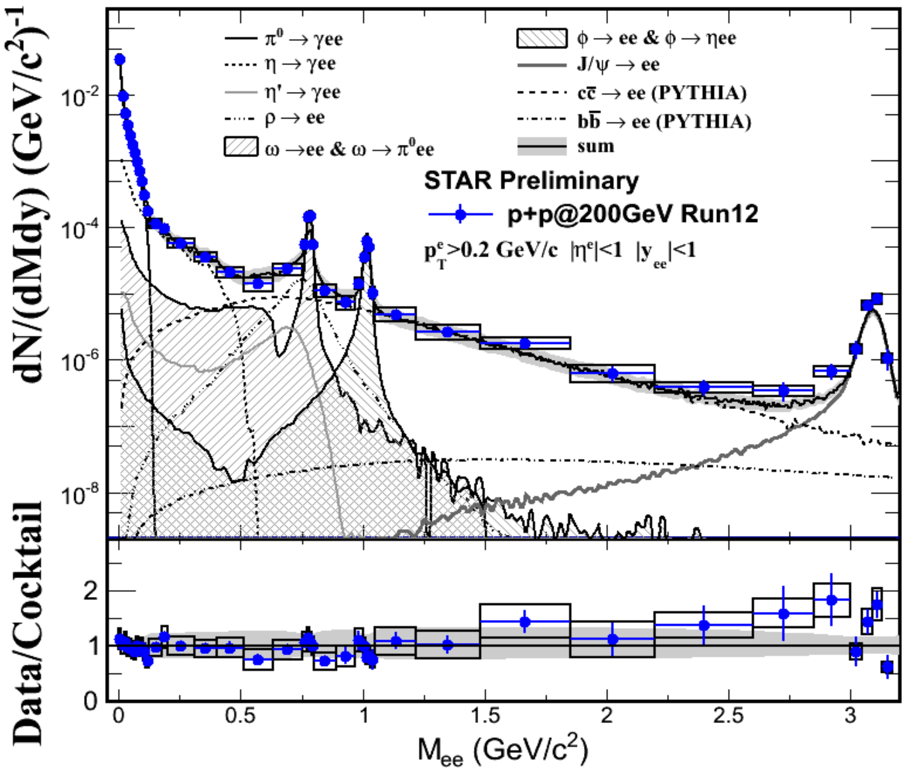
Electron positron emission mass spectrum in 200 GeV proton+proton collisions



STAR: QM2014

The cocktail simulation with expected hadronic contributions, is consistent with data in proton+proton collisions.

No hot, dense medium, no excess!

Electron positron emission mass spectrum in 19.6 GeV Au+Au

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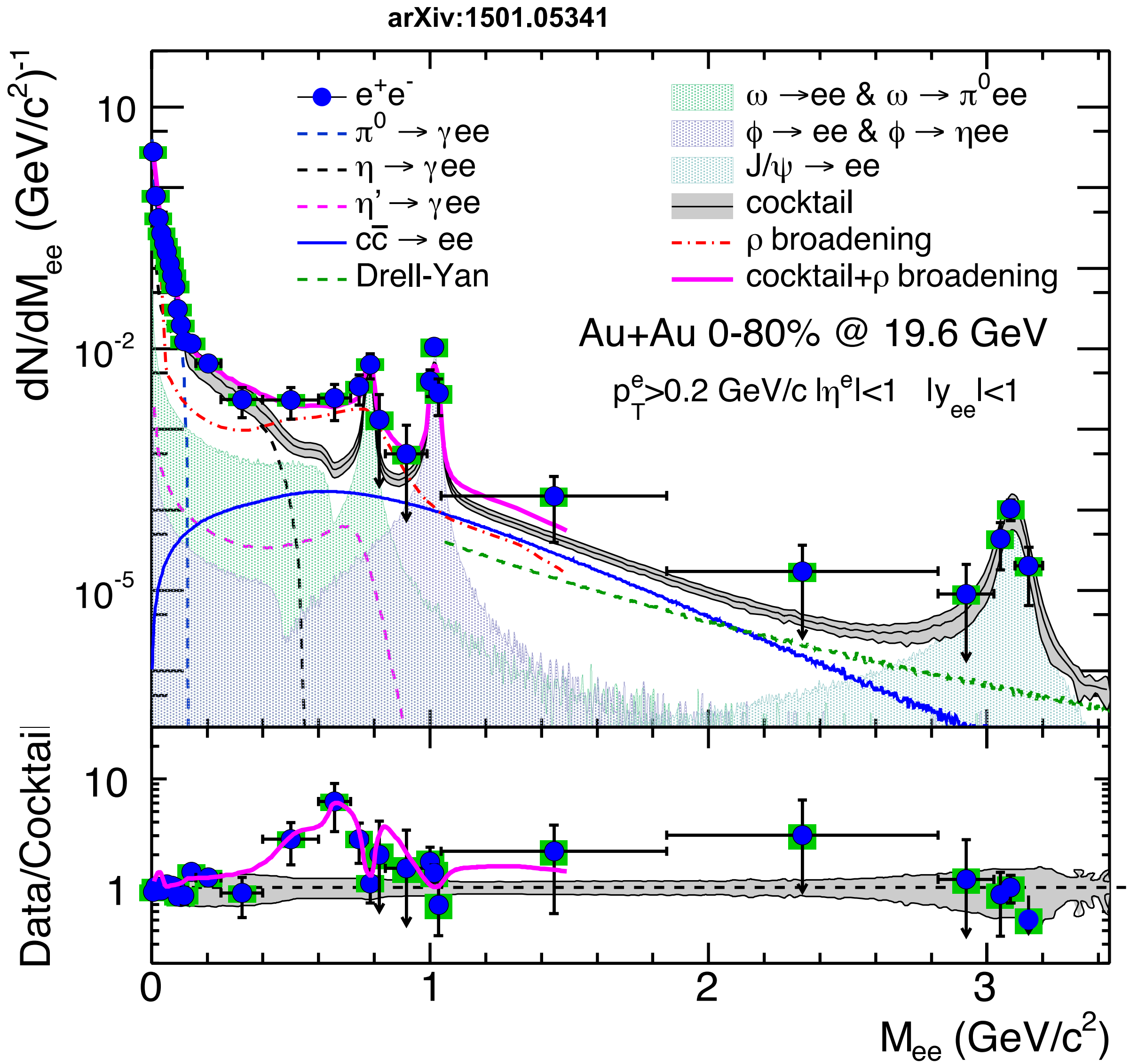
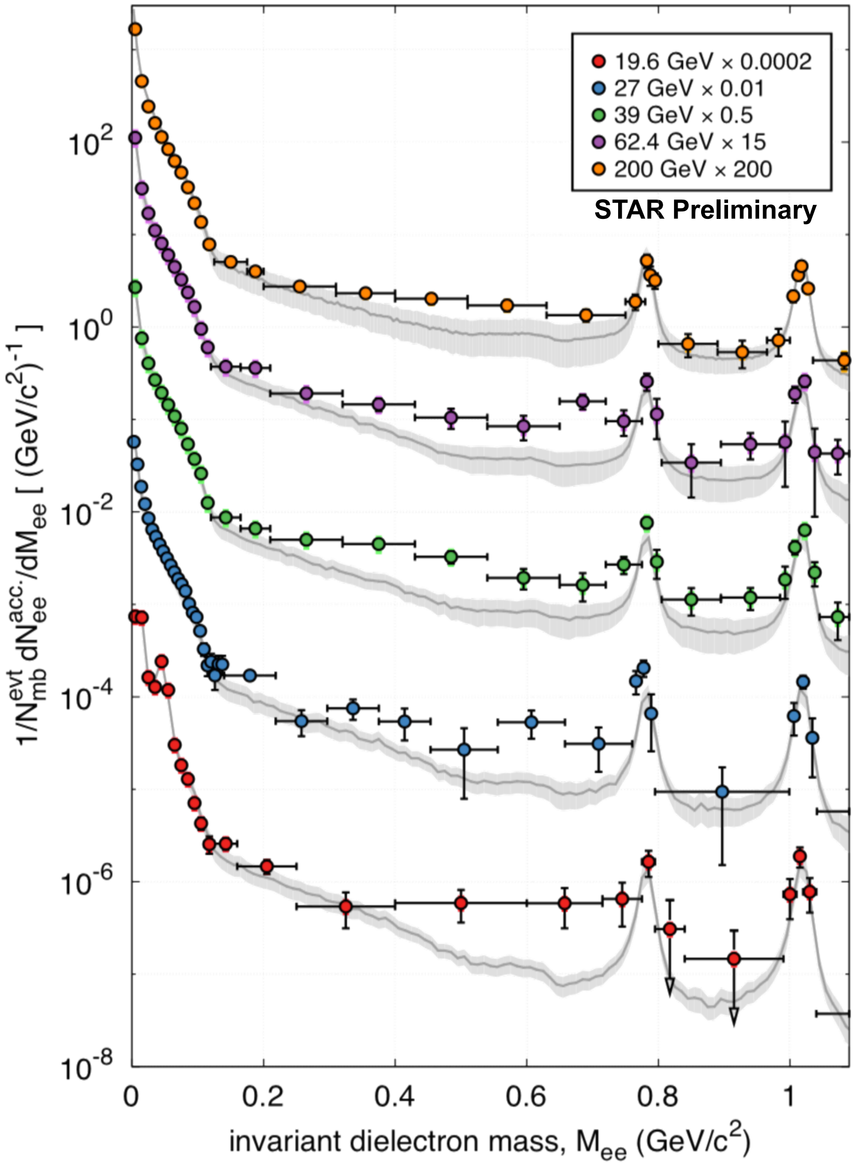


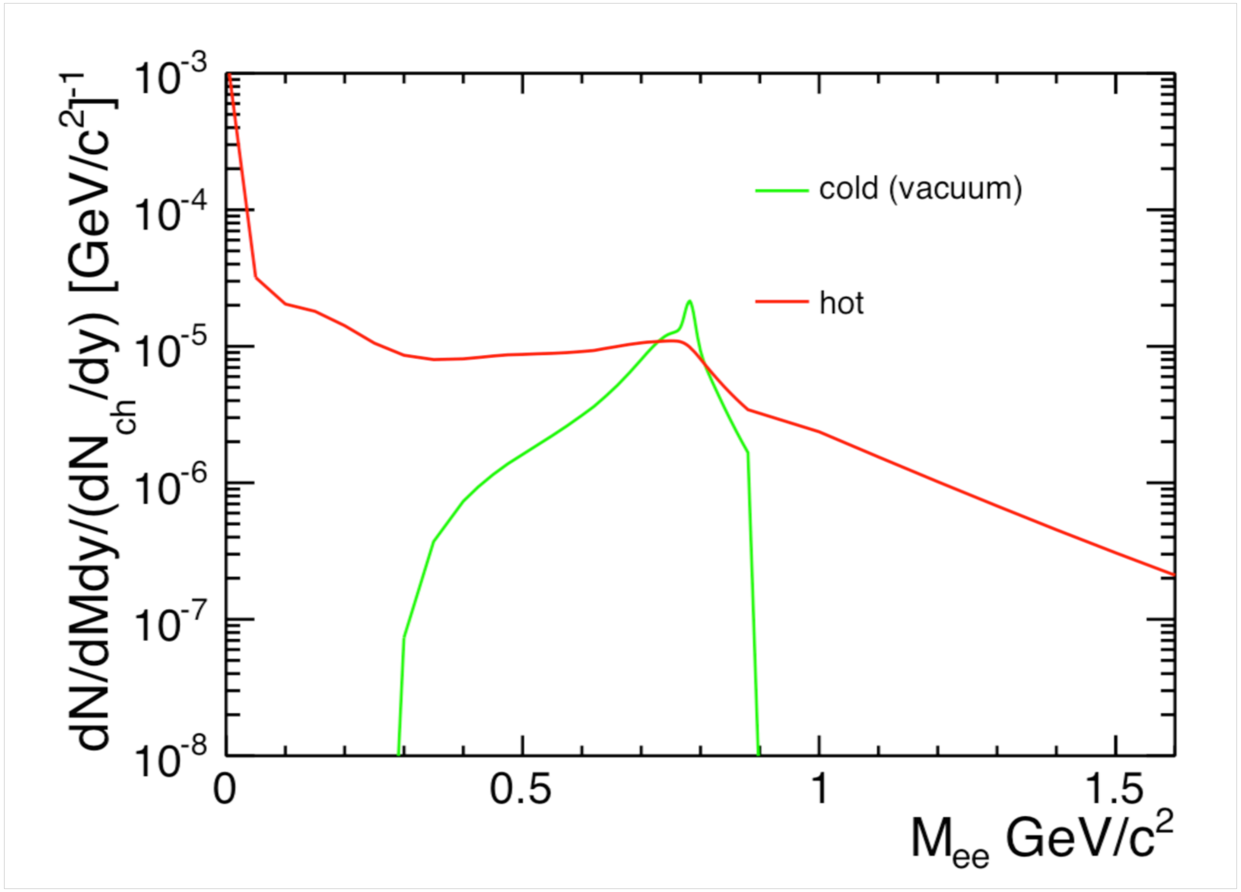
Significant excess is observed in $0.3<M_{ee}<0.8$ GeV/c^2, representing the hot, dense medium contribution.

Electron-positron emission at lower energies



Low-mass excess is observed for 19.6, 27, 39, 62.4, and 200 GeV Au+Au collisions!

The mass distribution from hot, dense medium in 200 GeV Au+Au

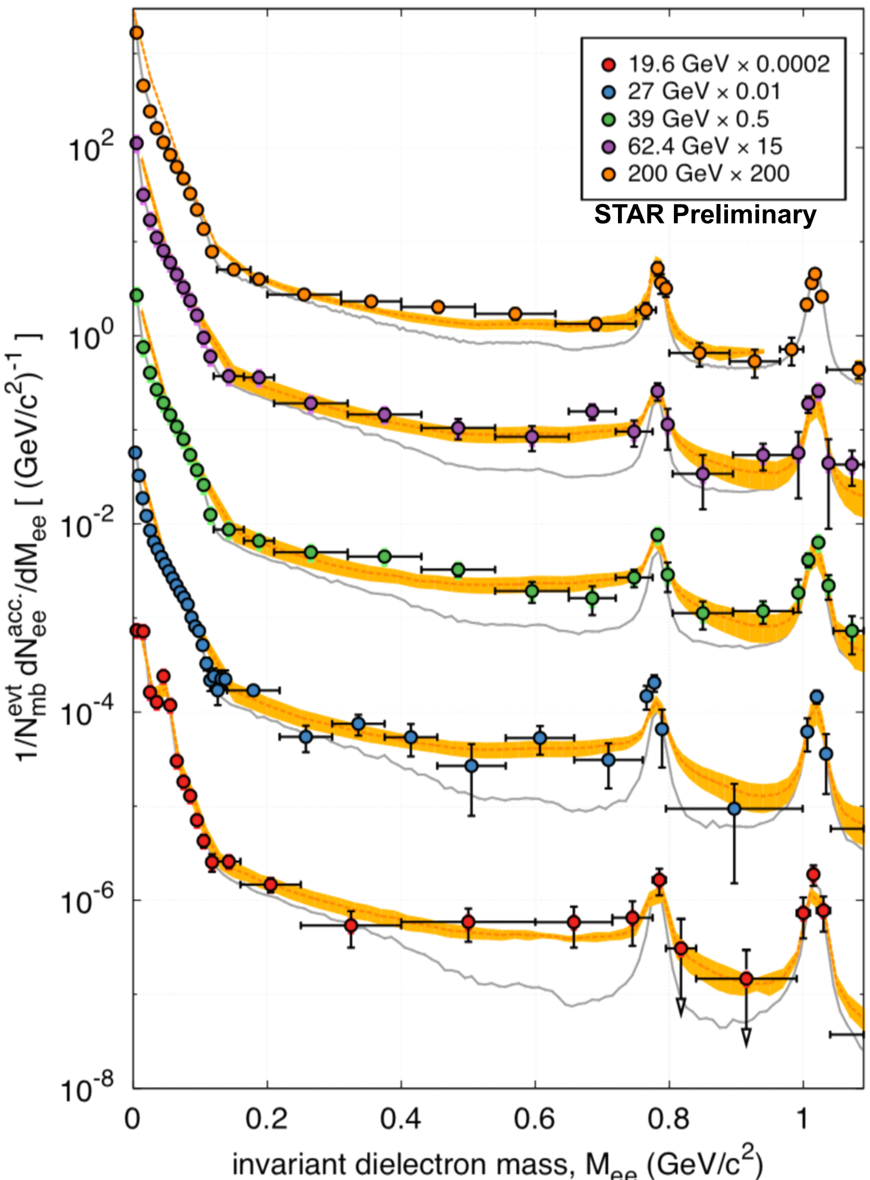


Red: a broadened ρ spectrum function

Green: vacuum-like spectrum function

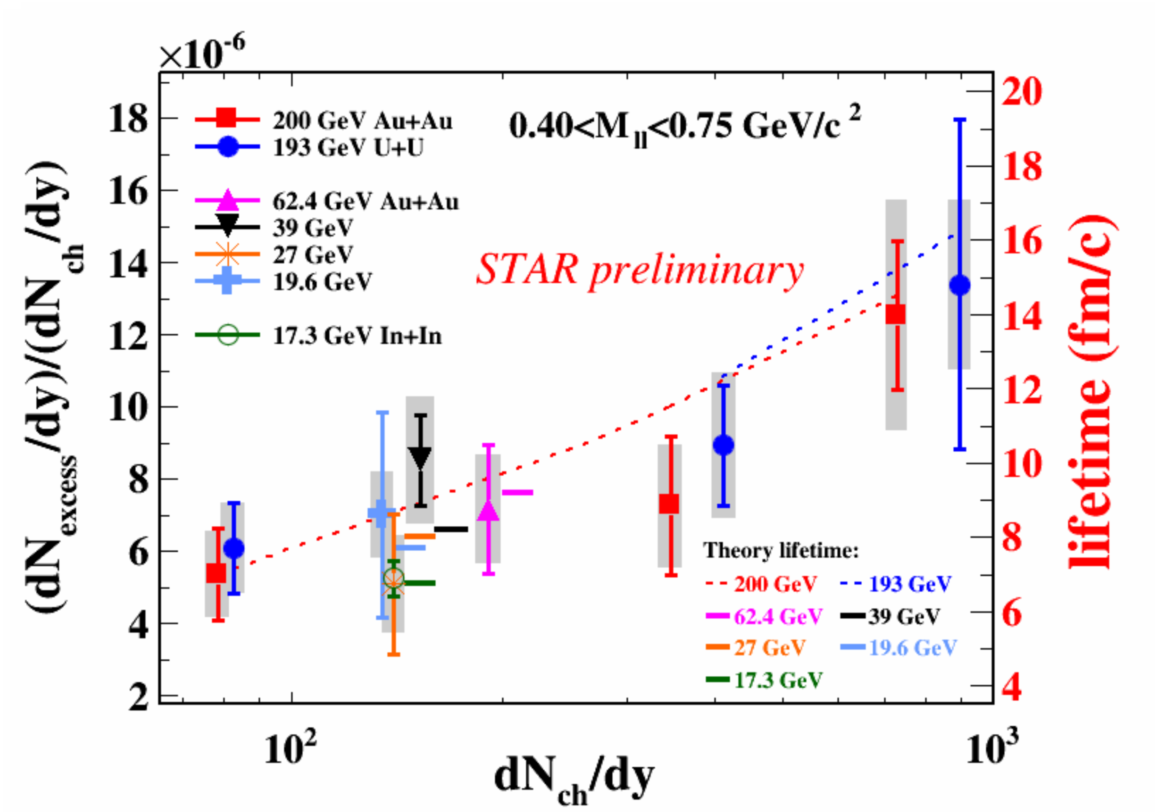
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

Electron-positron emission at lower energies



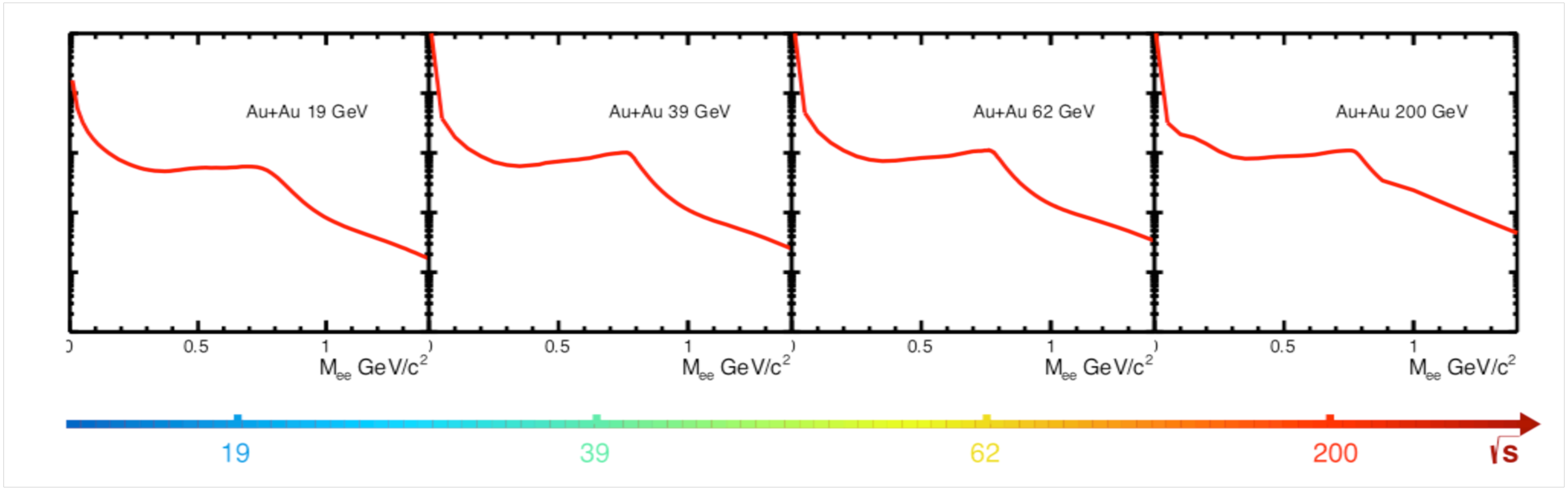
A broadened ρ spectrum function consistently describes the low mass electron-positron excess for all the energies 19.6-200 GeV.

Electron-positron emission versus lifetime



- 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

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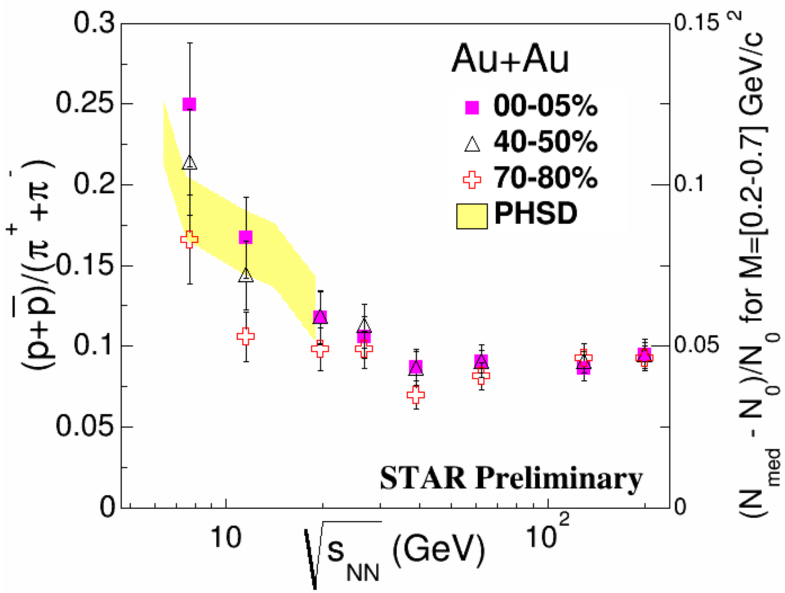
Low-mass electron-positron emission depends on T, total baryon density, and lifetime

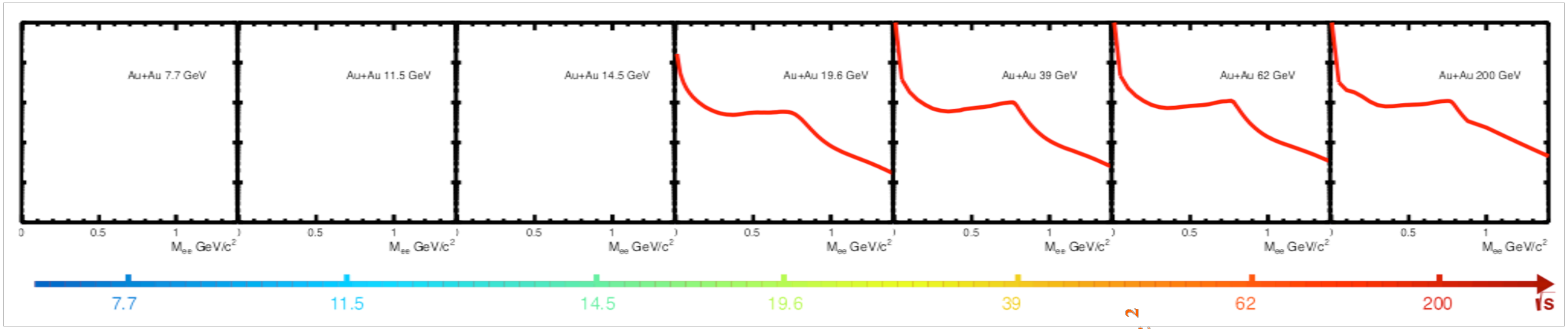
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.

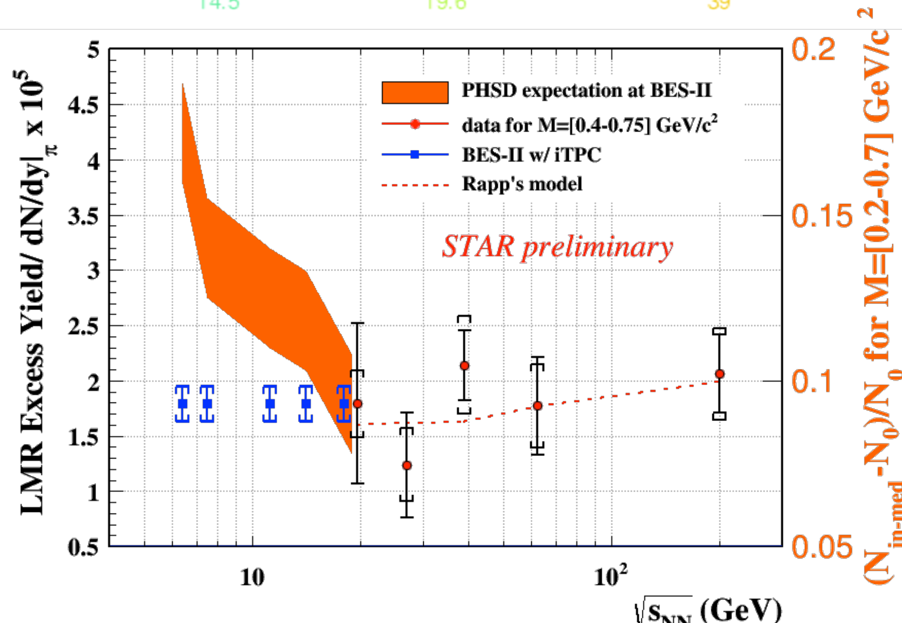


Normalized low-mass electron-positron production, is proportional to the life time of the medium from 17.3 to 200 GeV, given that the total baryon density is nearly a constant and that the emission rate is dominant in the Tc region.

Probe total baryon density effect

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

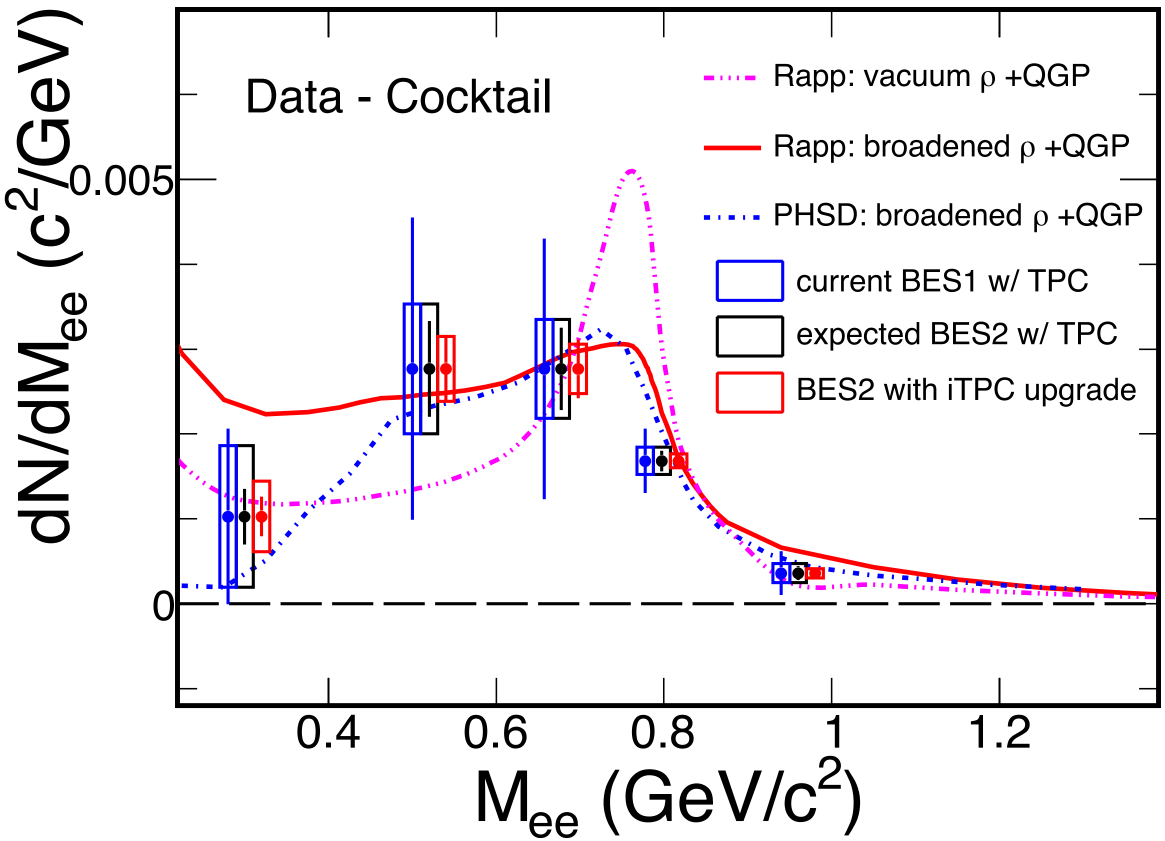




Broader and more electron-positron excess down to 7.7 GeV collision energy?

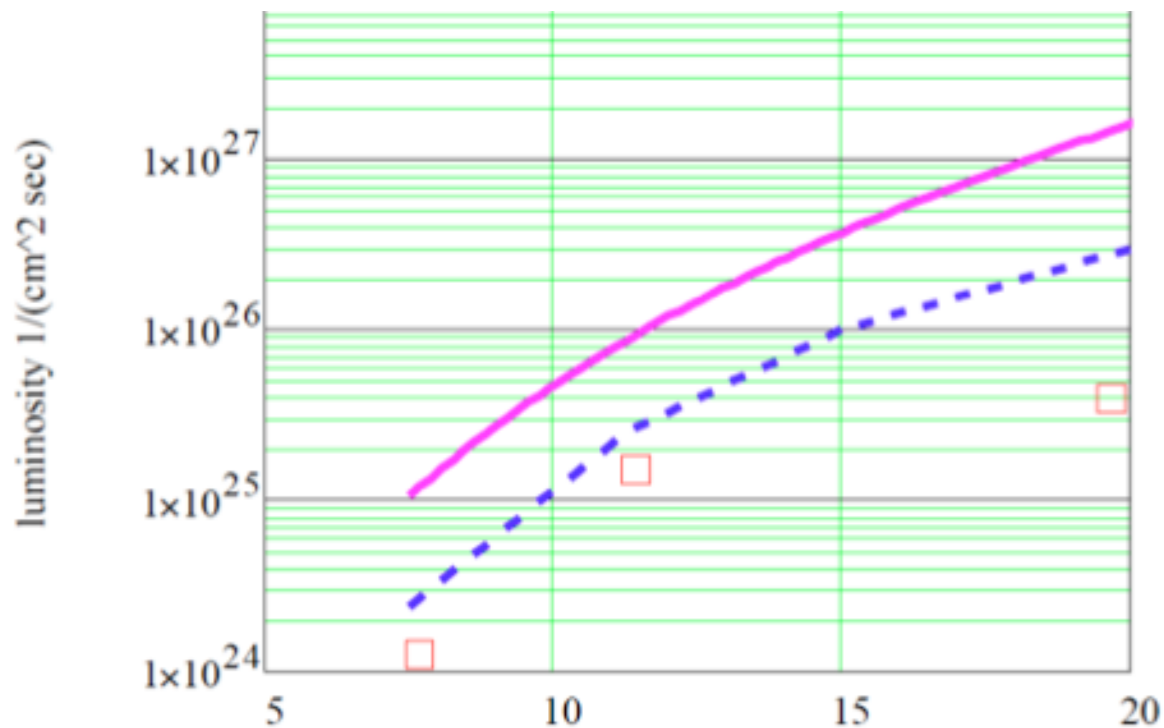
Beam Energy Scan II provides a unique opportunity to quantify the total baryon density effect on the ρ broadening!

Distinguish the mechanisms of rho broadening



Knowing the mechanism that causes in-medium rho 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

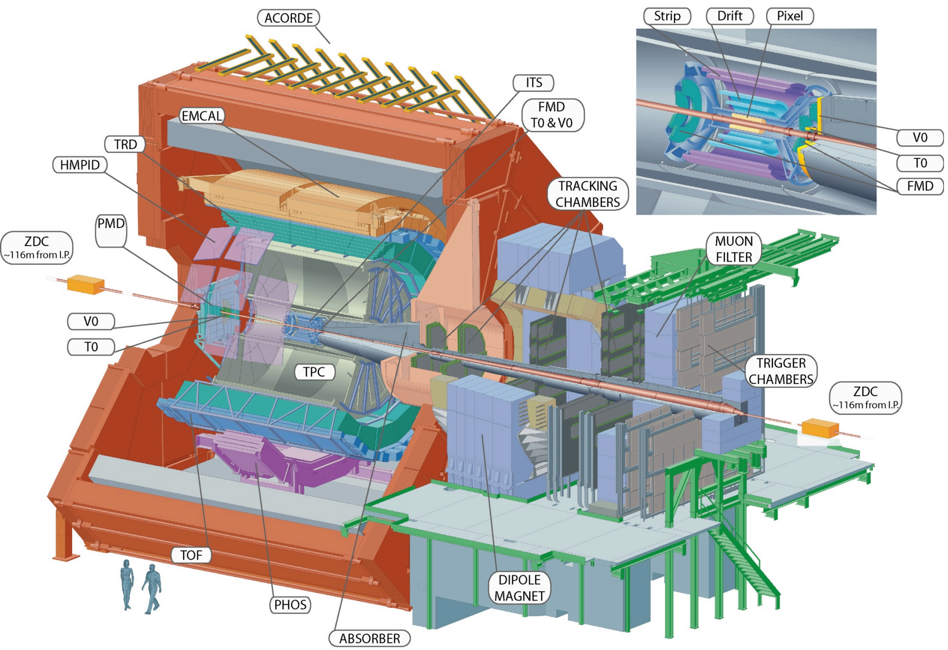


RHIC is unique to study chiral symmetry restoration:

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



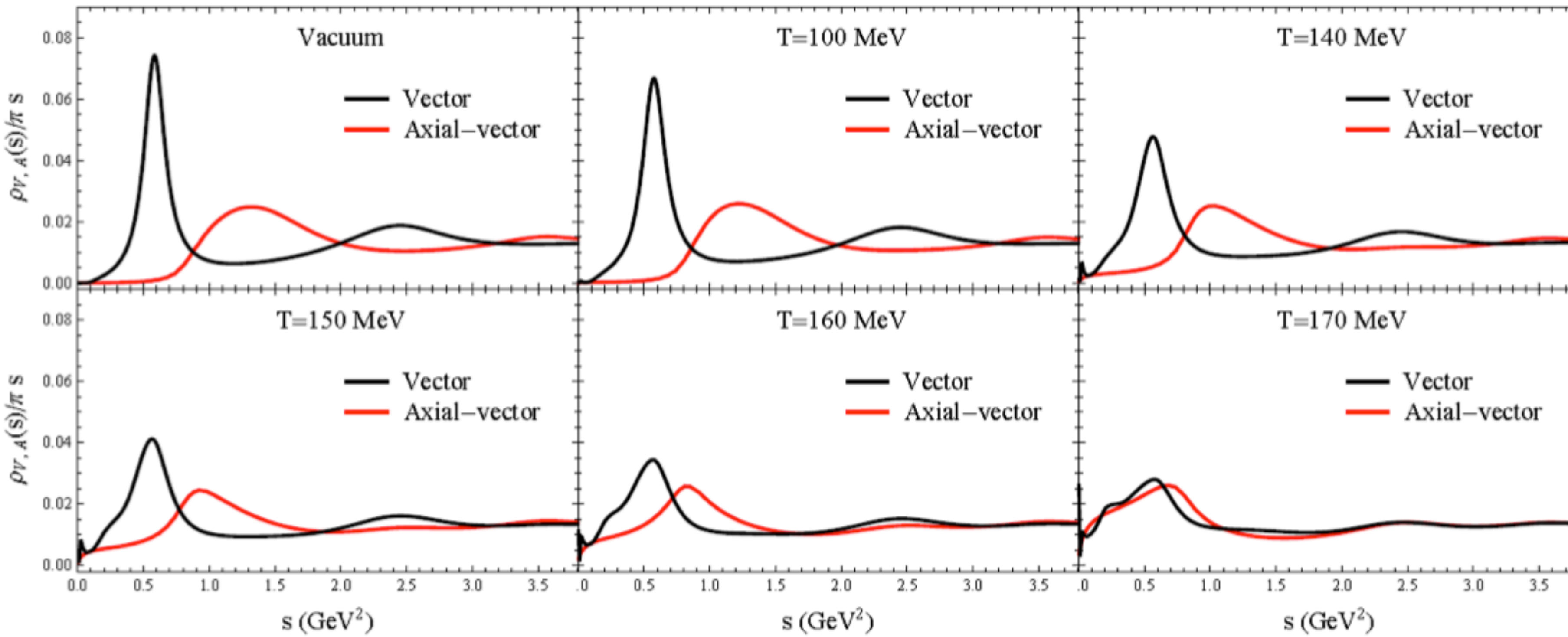
- World interest: SPS, PHENIX, LHC, FAIR, KEK

The future electron-positron program

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

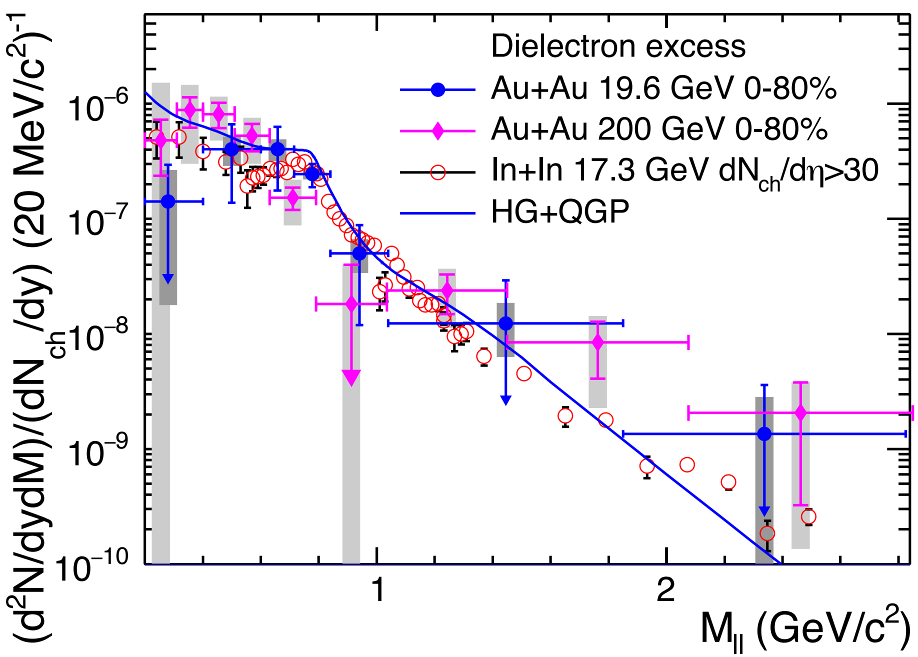
- **Lattice QCD calculation is reliable at $\mu_B = 0$.**

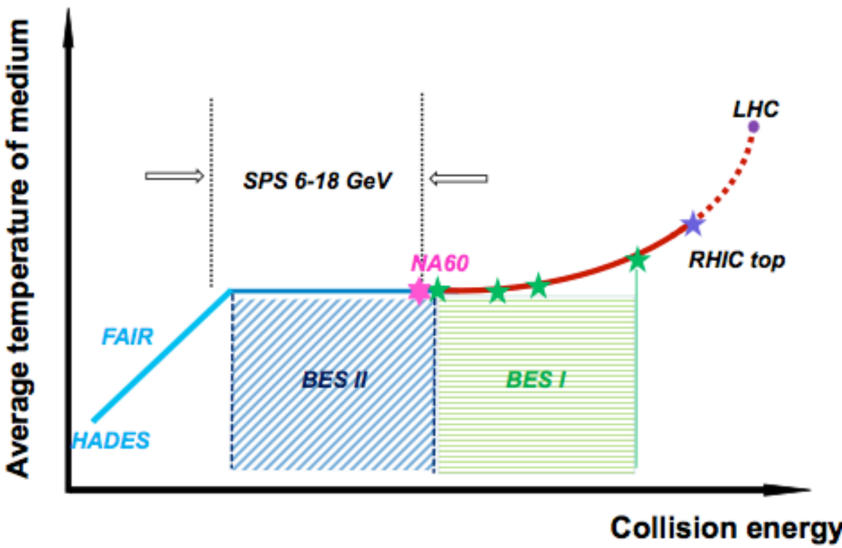
- **Theoretical approach: derive the a1(1260) spectral function by using the broadened rho spectral function, QCD and Weinberg sum rules, and inputs from Lattice QCD; to see the degeneracy of the rho and a1 spectral functions (Hohler and Rapp 2014).**

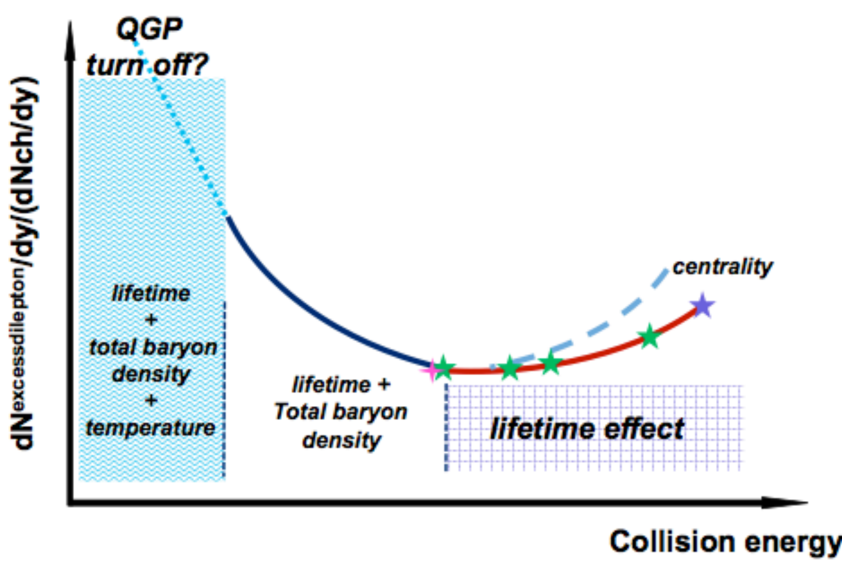


The future electron-positron program

- The slope in the intermediate mass region represents the true average temperature T of the medium.

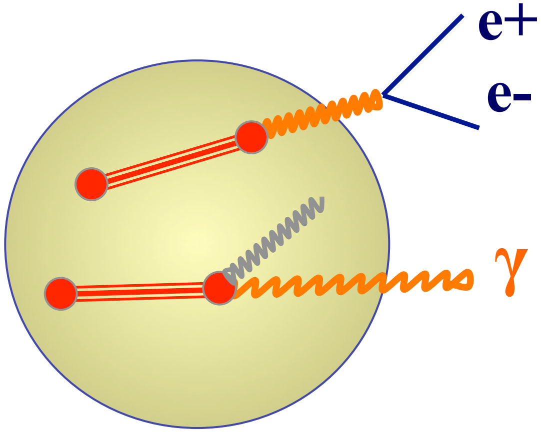


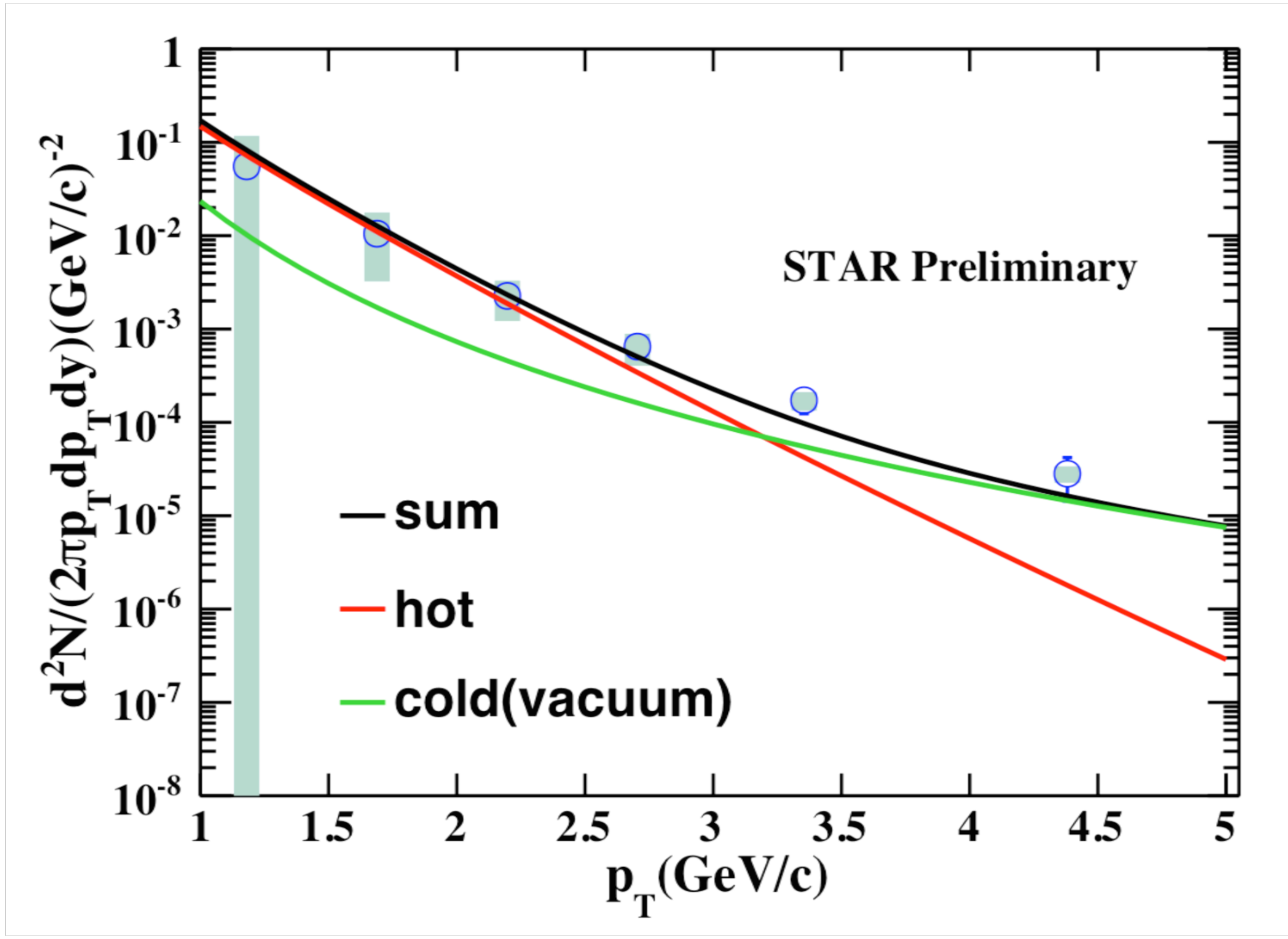




- Low-mass electron-positron emission depends on T, total baryon density, and life time, and enables systematic life-time measurements.

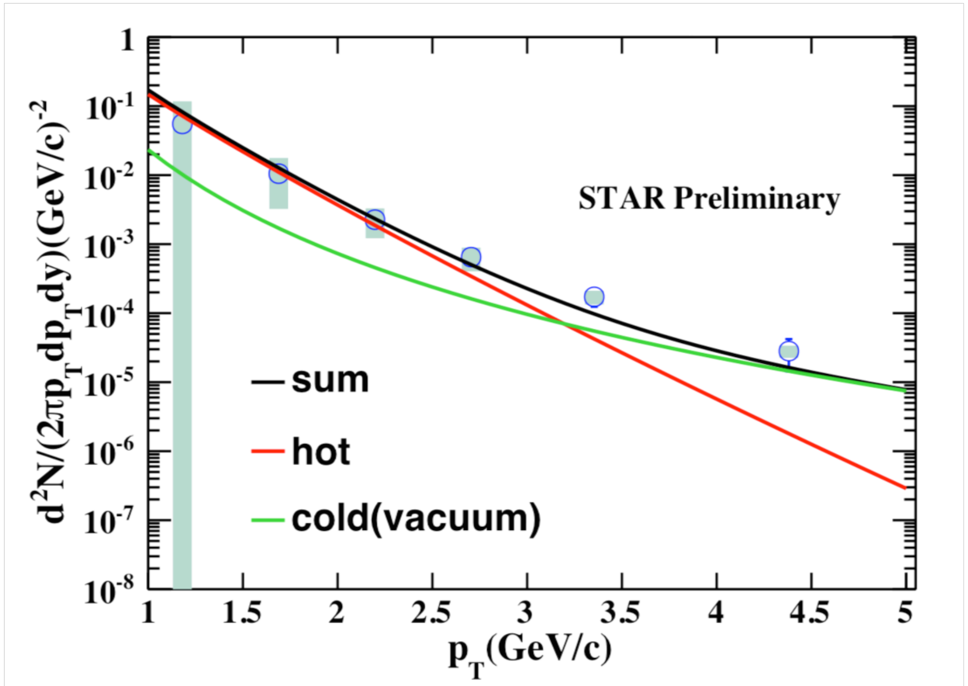
Photon emission

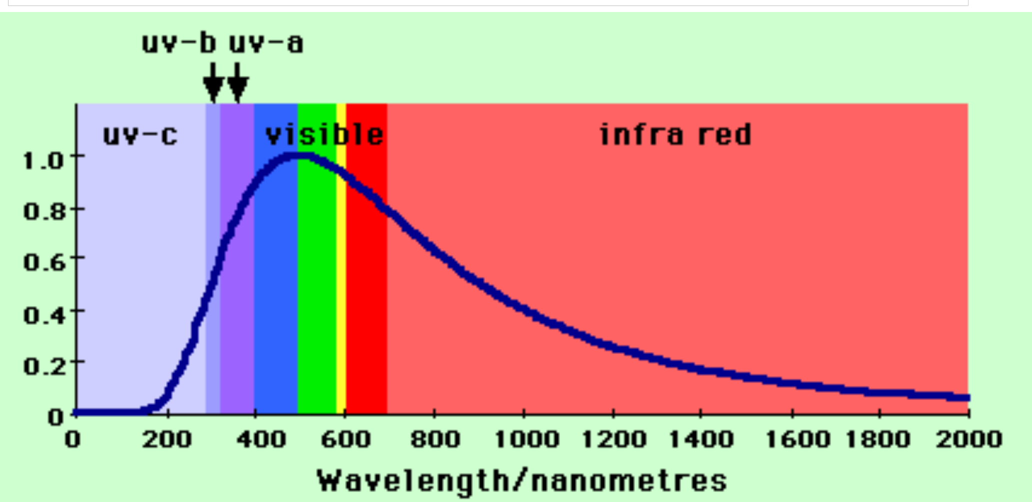




Hot contribution observed in the photon energy spectrum!

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 is enabled by the Time of Flight Detector at STAR.

A broadened ρ spectrum function consistently describes the low mass electron-positron excess in Au+Au collisions for all the energies 19.6, 27, 39, 62.4 and 200 GeV.

Beam Energy Scan II (7.7-19.6 GeV) will provide a unique opportunity to quantify the effect of Chiral Symmetry Restoration via total baryon density effect on the ρ broadening:

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

Enable unique measurements of the temperature and lifetime of hot, dense medium