The journey to seek symmetry in Quark-Gluon Plasma

Lijuan Ruan (BNL)

Discovery of Quark-Gluon Plasma

Chiral symmetry

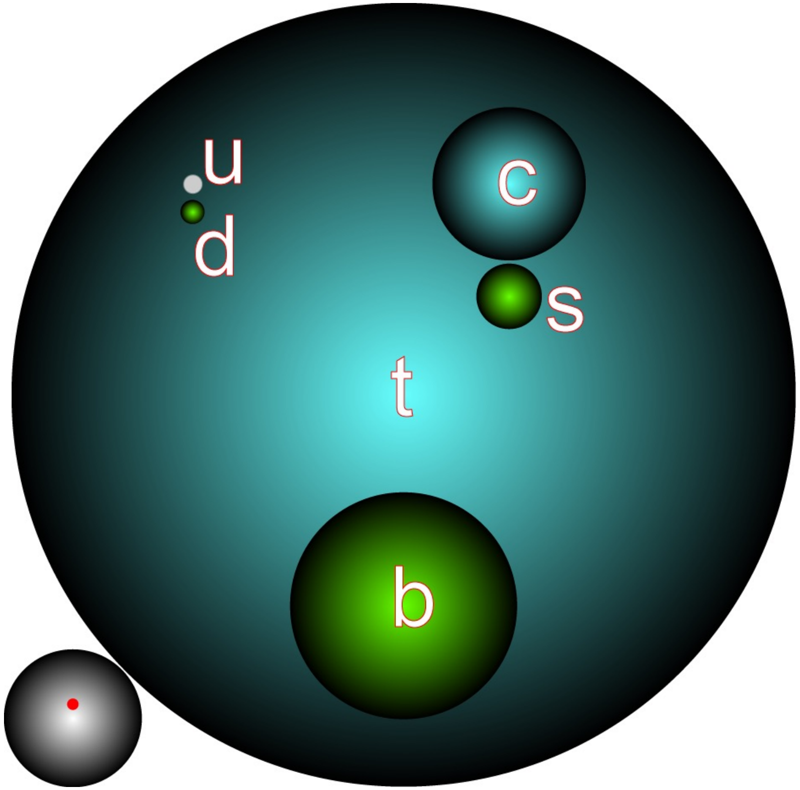
Our experimental approach and results

Summary

@BrookhavenLab

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.

Quantum Chromodynamics (QCD)

- Quarks are bound together to form protons and neutrons.

- Discovery of asymptotic freedom: attraction between quarks becomes weaker as quarks approach one another more closely; becomes stronger as they are separated

- QCD: correct theory of the strong nuclear force, one of the four fundamental forces in nature (Gross, Wilczek, Politzer, 2004 Nobel Prize).

Quark-Gluon Plasma

Wikipedia: Quark–gluon plasma is a state of matter in which the elementary particles that make up the hadrons of baryonic matter are freed of their strong attraction for one another under extremely high energy densities. These particles are the **quarks** and **gluons** that compose baryonic matter.

Quark-Gluon Plasma is believed to exist in the moments after the Big-Bang.

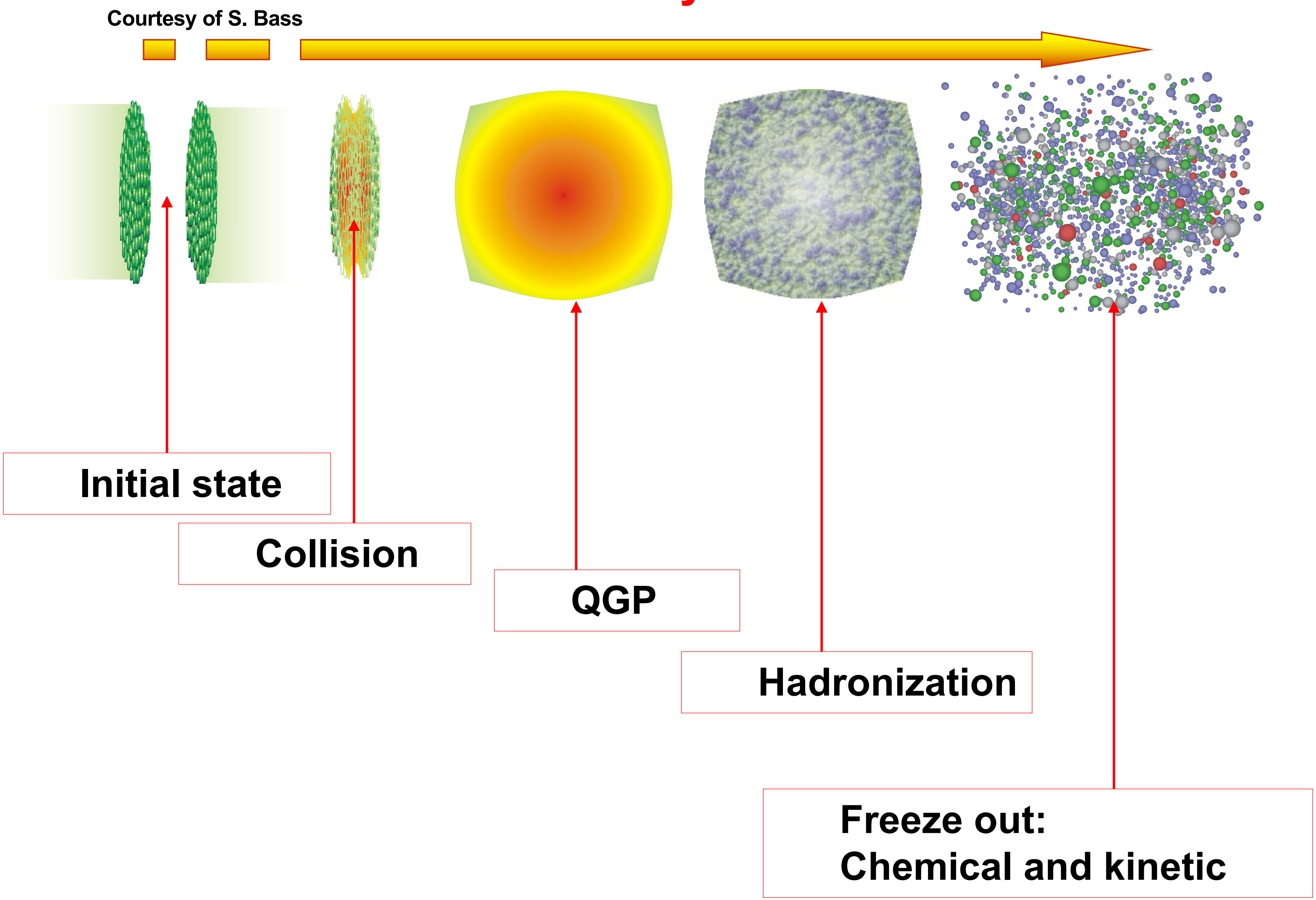
At BNL and CERN , physicists trying to create Quark-Gluon Plasma (QGP) using high energy heavy ion collisions.

Study the image of QGP, will help us to understand the early universe.

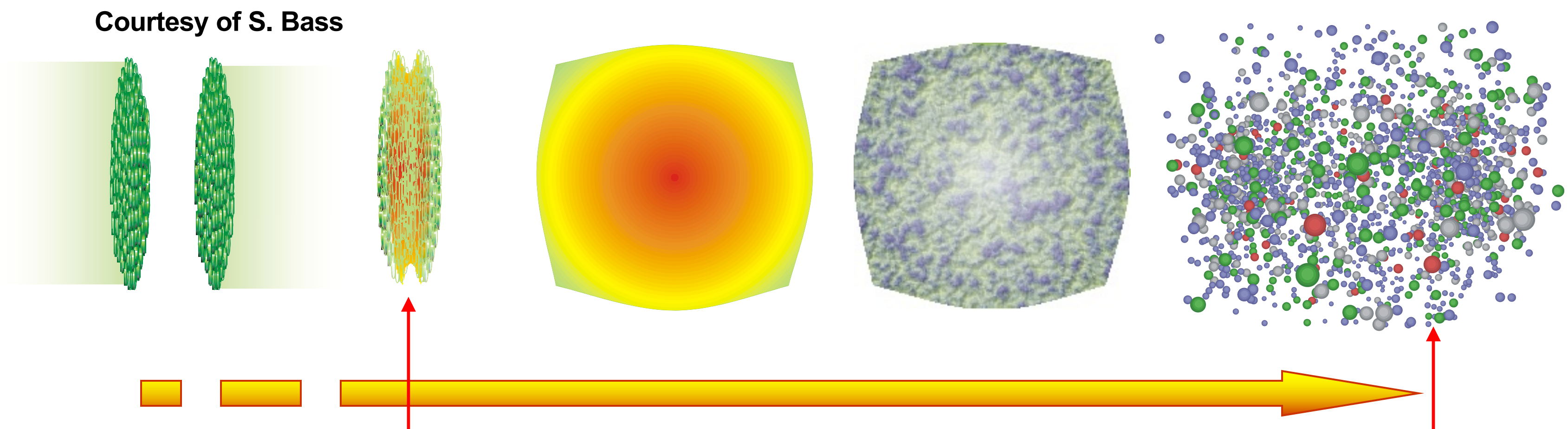
RHIC @ Brookhaven National Laboratory

23 years of RHIC operation

Relativistic heavy ion collision



Physics Goals at RHIC



Identify and study the properties of matter with partonic degrees of freedom.

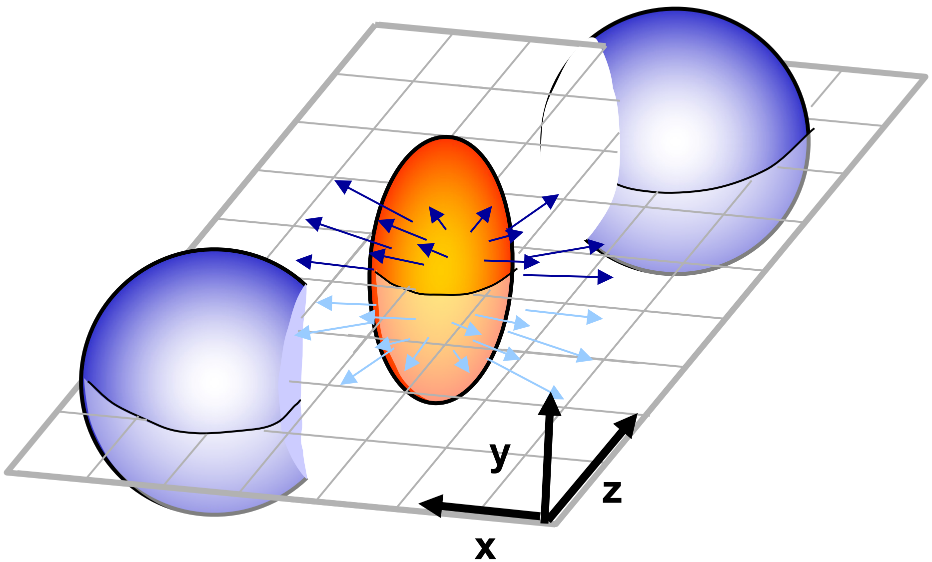
Penetrating probes

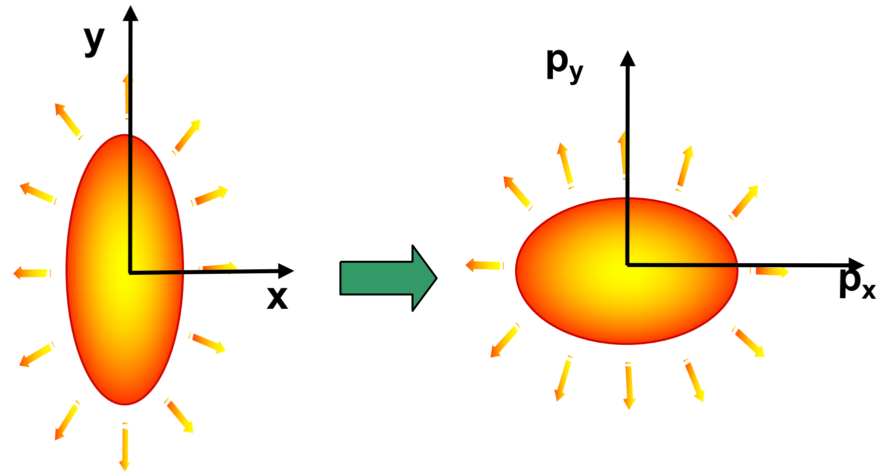
- **"jets" and heavy flavor**

Bulk probes

- **v_2 → partonic collectivity**
- **spectra at low p_T, particle ratios.**

Elliptic flow v_2





Non-central collisions: azimuthal anisotropy in coordinate-space
Interactions ➔ asymmetry in momentum-space
Sensitive to early time in the system's evolution

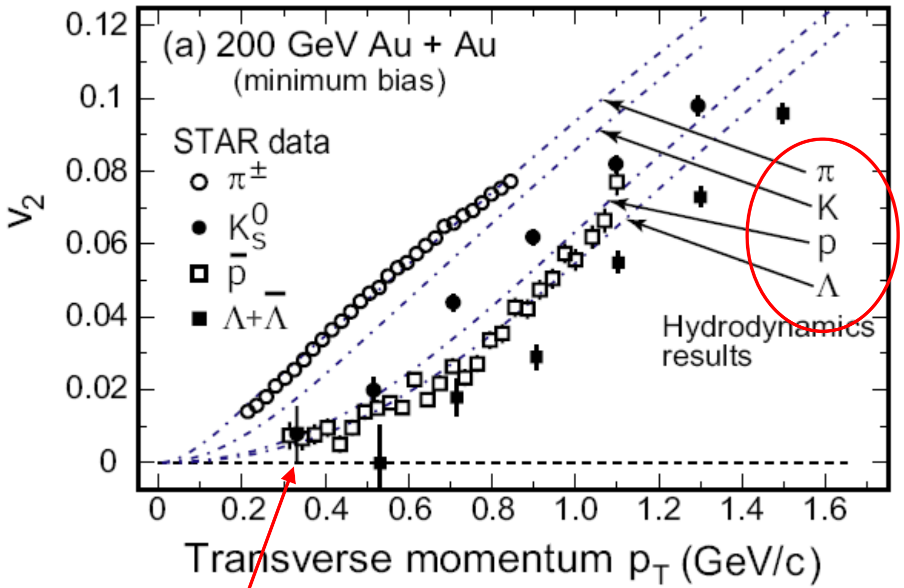
Measurement: Fourier expansion of the azimuthal p_T distribution

$$E\frac{d^3N}{d^3p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2 dy}\left[1 + 2v_1\cos(\varphi - \Psi_R) + 2v_2(2[\varphi - \Psi_R]) + \ldots\right]$$

$$v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

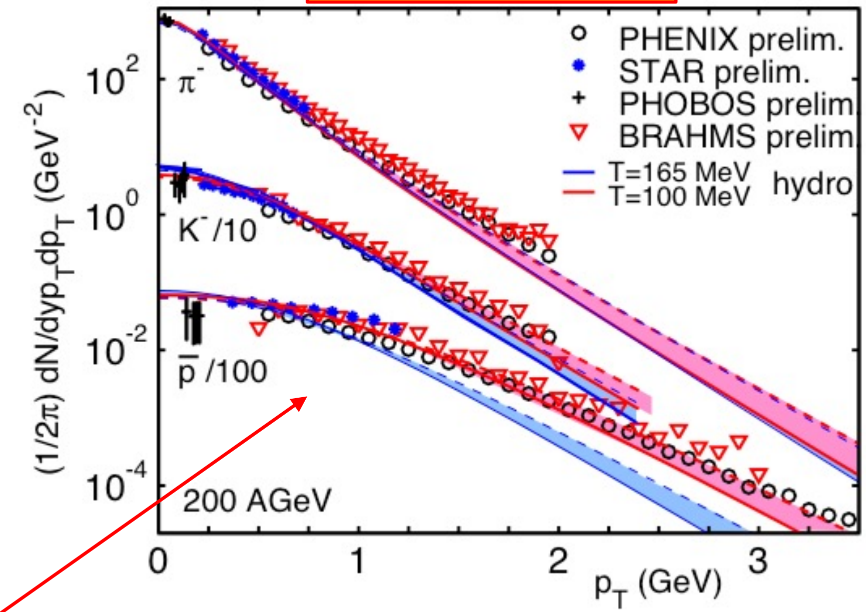
Low p_T: bulk property

Elliptic flow v_2



STAR: Nucl. Phys. A 757 (2005) 102

p_T distributions

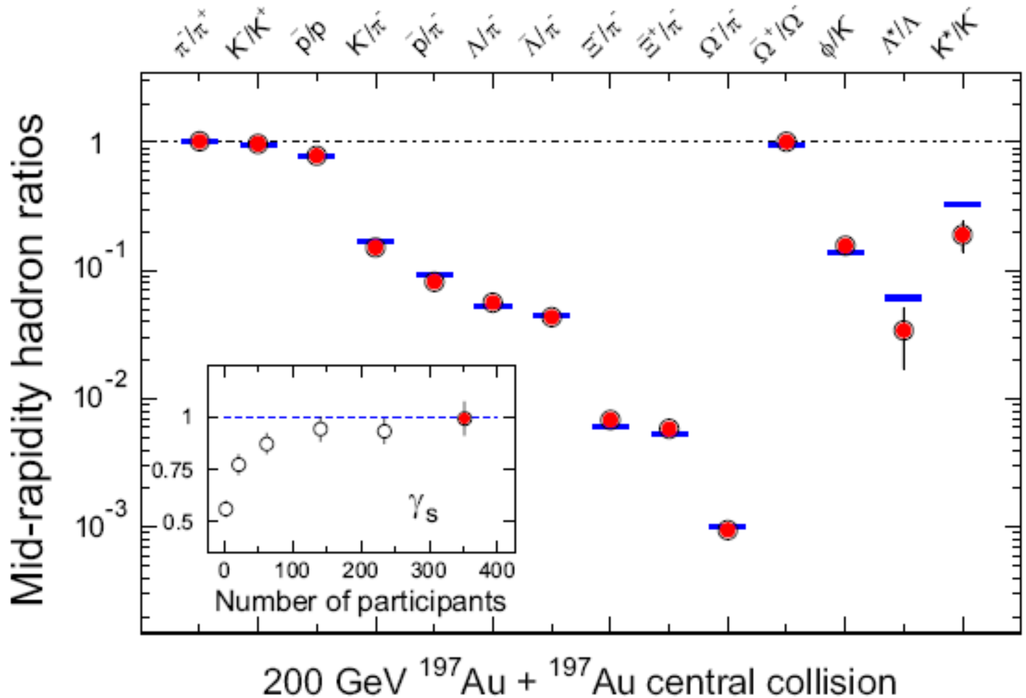


M. Calderon de la Barca Sanchez, ISMD2003

Hydrodynamical models can reproduce mass dependence of v_2 and spectra at p_T<2 GeV/c.

Low p_T: bulk property

Particle ratios: chemical freeze out



STAR: Nucl. Phys. A 757 (2005) 102

A few parameters in the model:
Chemical freeze out temperature T_{ch}

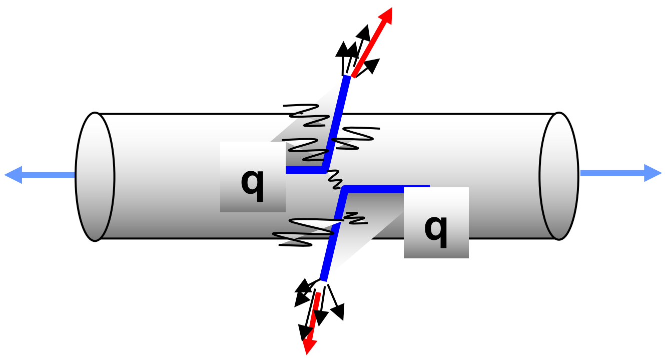
Baryon chemical potential μ_B (μ_B=0 if pbar/p=1)

Strangeness saturation factor: γ_s

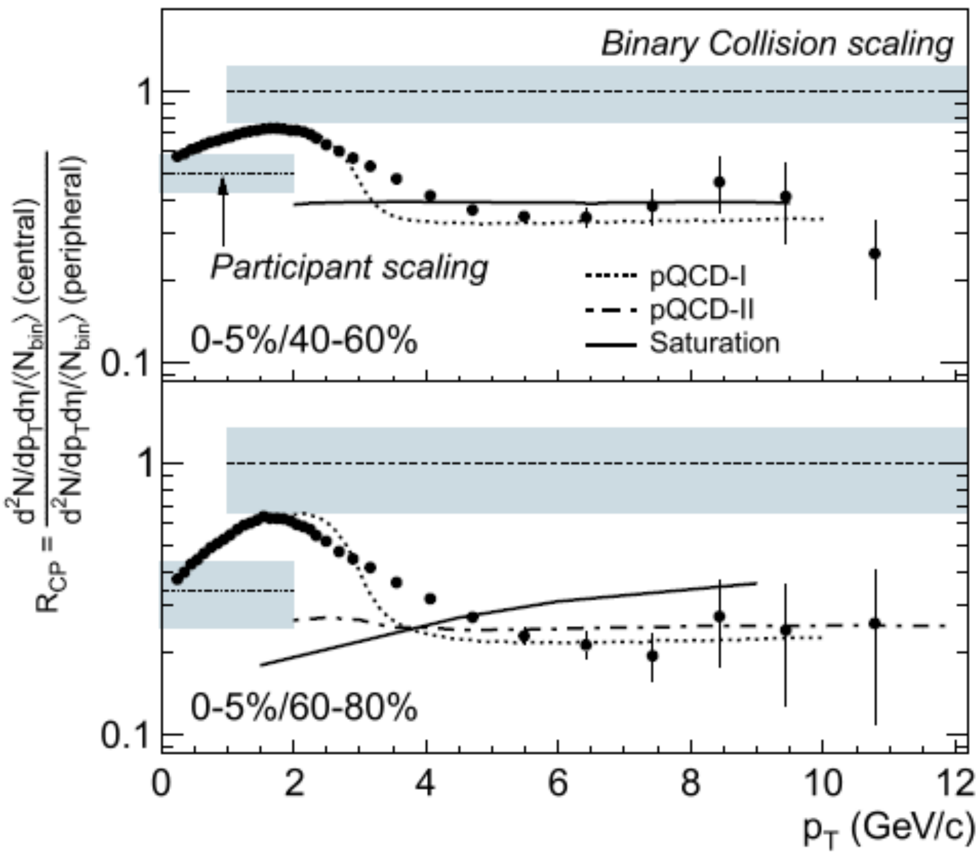
T_{ch}=163±4 MeV, μ_B=24±4 MeV
γ_s=0.99±0.07

γ_s approach 1 in central Au+Au collisions: thermalization within the framework of this model.

High p_T: penetrating probe



$$R_{cp} = \frac{(d^2N/(2\pi p_T dp_T dy)/N_{bin})\,|\,central}{(d^2N/(2\pi p_T dp_T dy)/N_{bin})\,|\,peripheral}$$

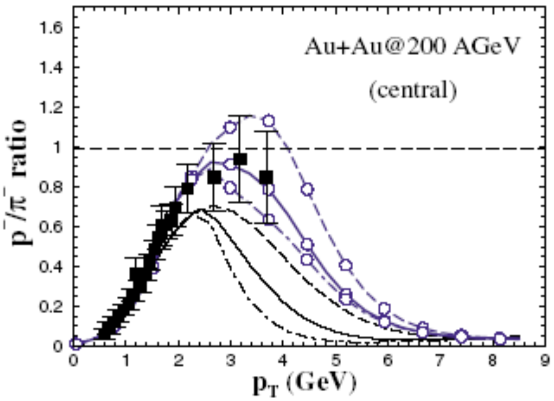


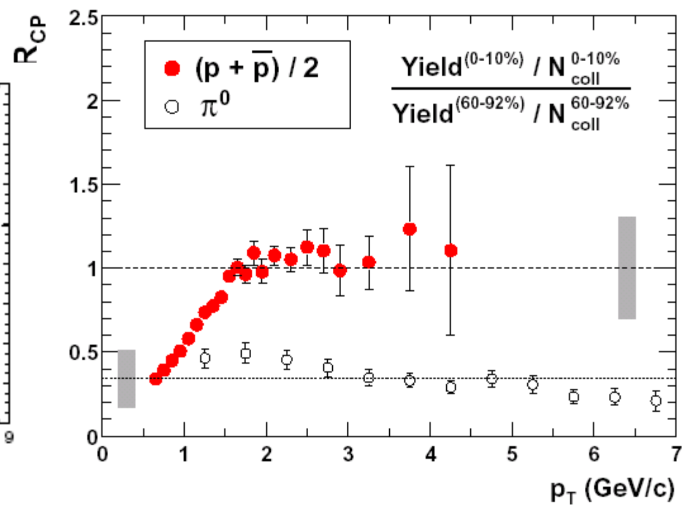
STAR: Nucl. Phys. A 757 (2005) 102

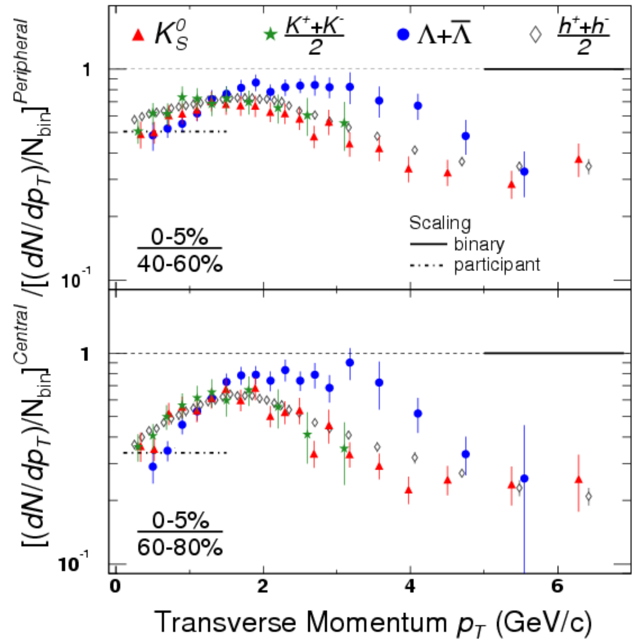
In central Au+Au collisions at RHIC: Fragmentation (q/g→hadrons) + energy loss at p_T > 6 GeV/c:

Significant suppression of inclusive charged hadron observed at p_T>6 GeV/c: dN_g/dy~1000. **M. Gyulassy et al., nucl-th/0302077.**

Intermediate p_T: baryon/meson pattern



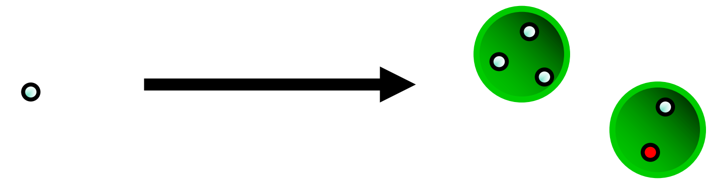




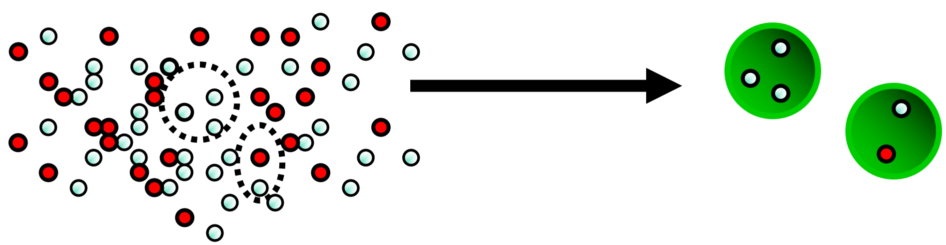
At p_T~2 GeV/c, pbar/π ratio ~1. →It can not be factorized jet fragmentation.

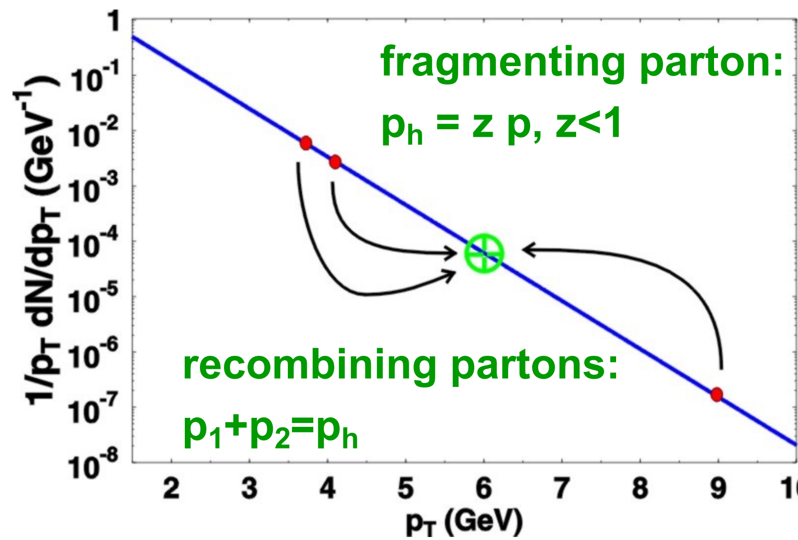
At 2<p_T<6 GeV/c, p, Λ increase faster than π, K_S, K from peripheral to central collisions. STAR: Phys. Rev. Lett. 92 (2004) 052302; PHENIX: Phys. Rev. Lett. 91 (2003) 172301; V. Greco, et al., Phys. Rev. Lett. 90, 202302 (2003).

Recombination/Coalescence at hadronization



Fragmentation works for p+p collisions for hadrons at p_T > 2 GeV/c

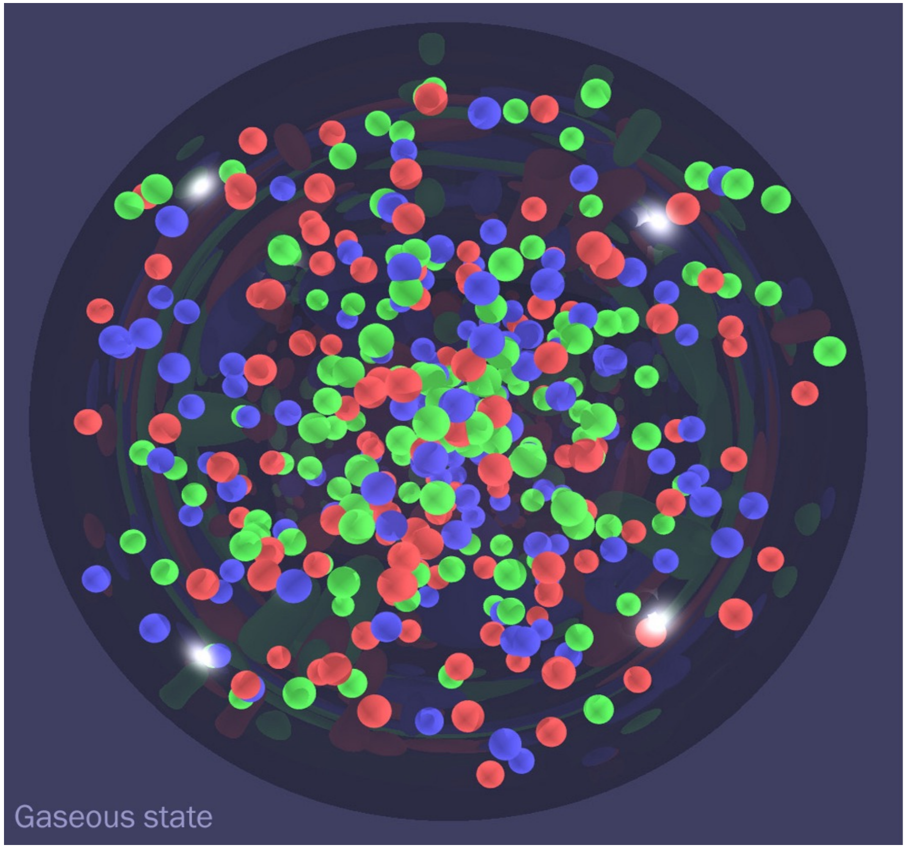


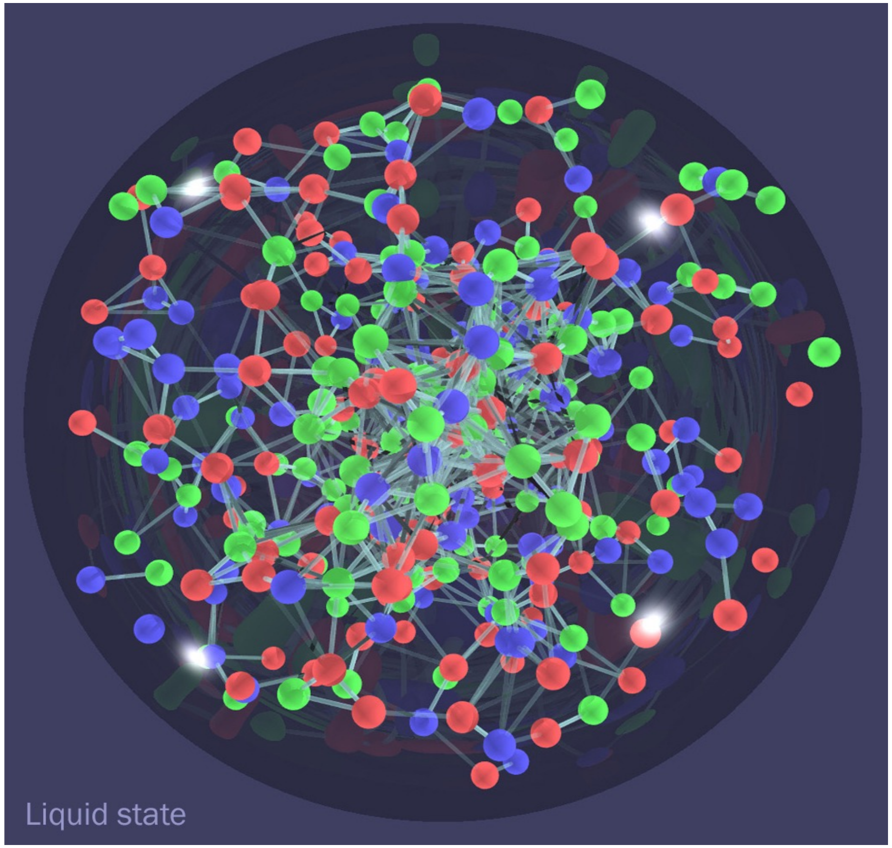


R.J. Fries, QM2004

If phase space is filled with partons, recombine/coalesce them into hadrons. At 2 < p_T < 6 GeV/c, baryon enhancement, v_2 number of constituent quark scaling.

Perfect Liquid discovery



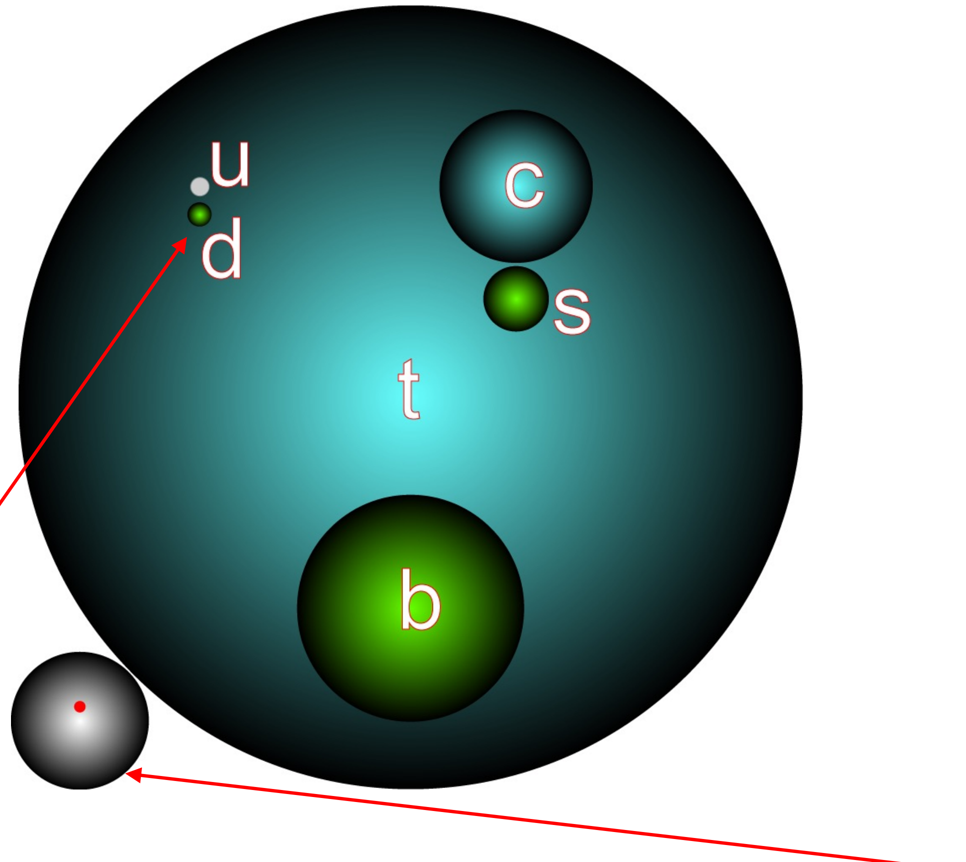


In 2005, BNL announced a discovery of perfect liquid at RHIC

https://www.bnl.gov/newsroom/news.php?a=110303

Elementary particles

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

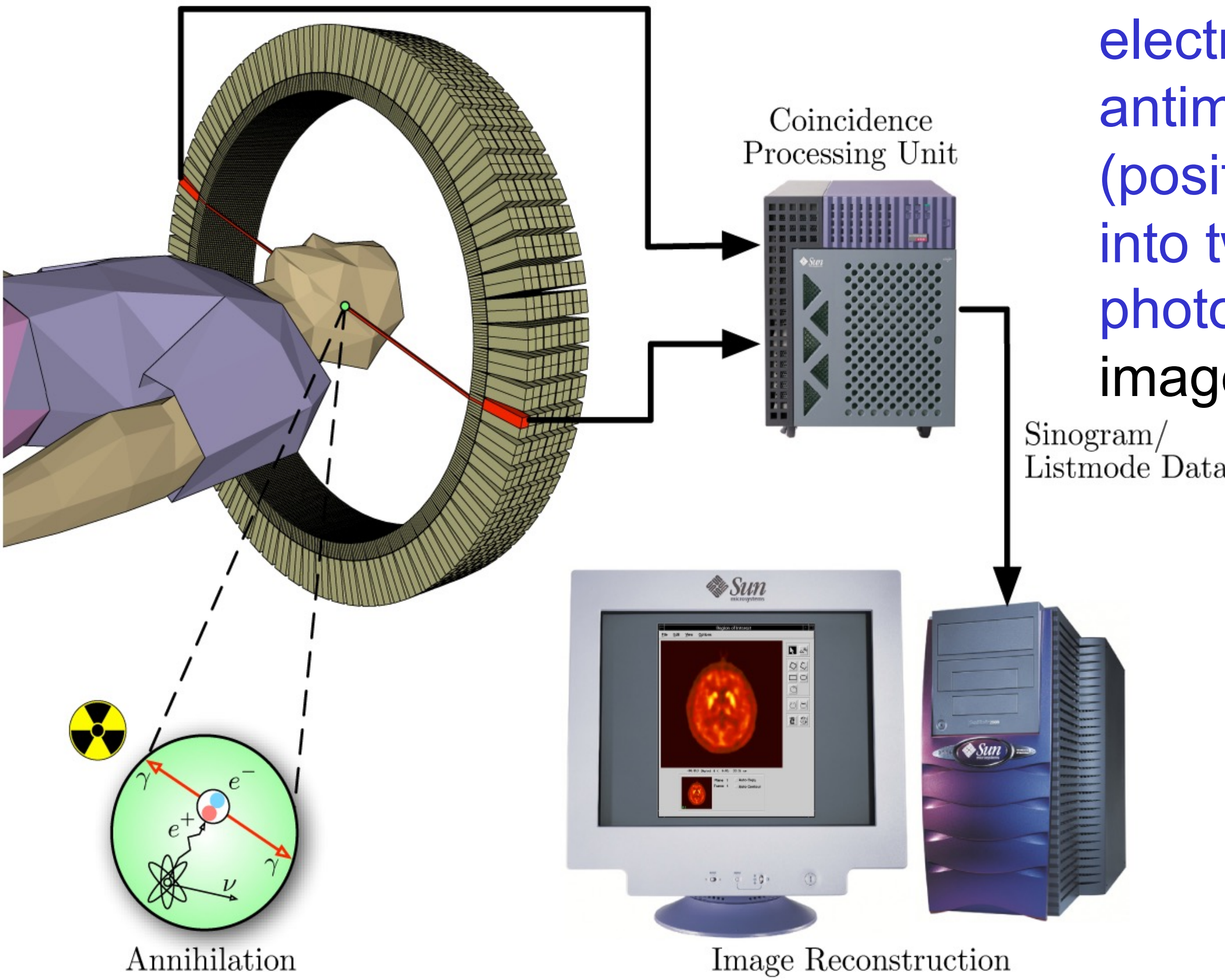


- u and d quarks are the lightest ones, proton is much heavier.

Elementary particles

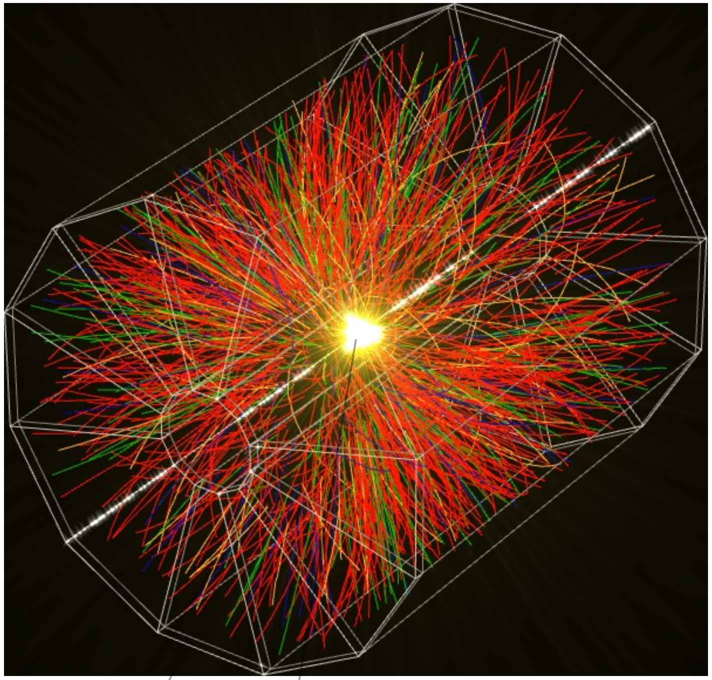
- Electrons interact with matter through the exchange of photons.
- Electrons and photons do not interact with matter strongly.
- Quarks interact with matter through the exchange of gluons. Strong interaction.
- Positron is antimatter electron.
- Anti-quark is antimatter quark.

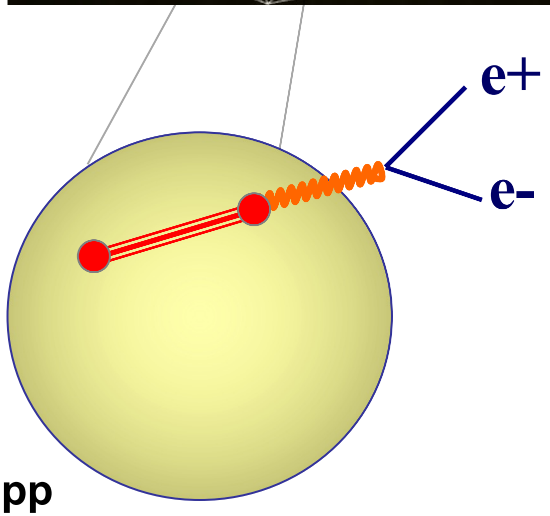
Traditional Positron-emission Tomography (PET)



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

Special PET scans
(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.

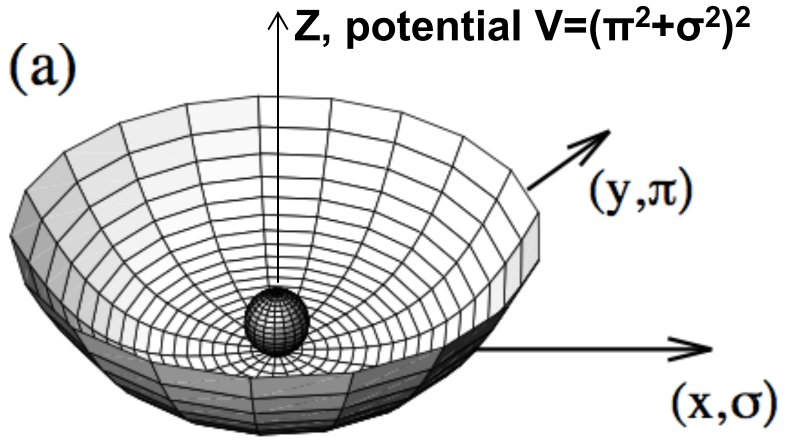
- Using electron-positron tomography, we would like to study the symmetry of the Quark-Gluon Plasma.

The Quark-Gluon Plasma

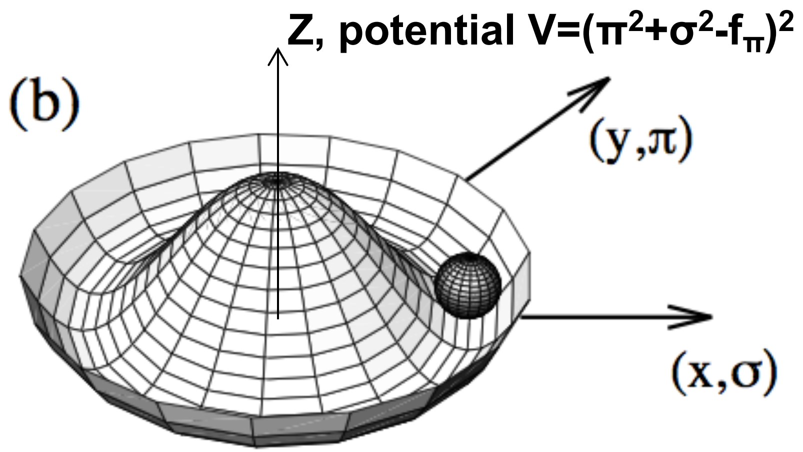
- In Quark-Gluon Plasma, there are u, d quarks and gluons.

- 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.

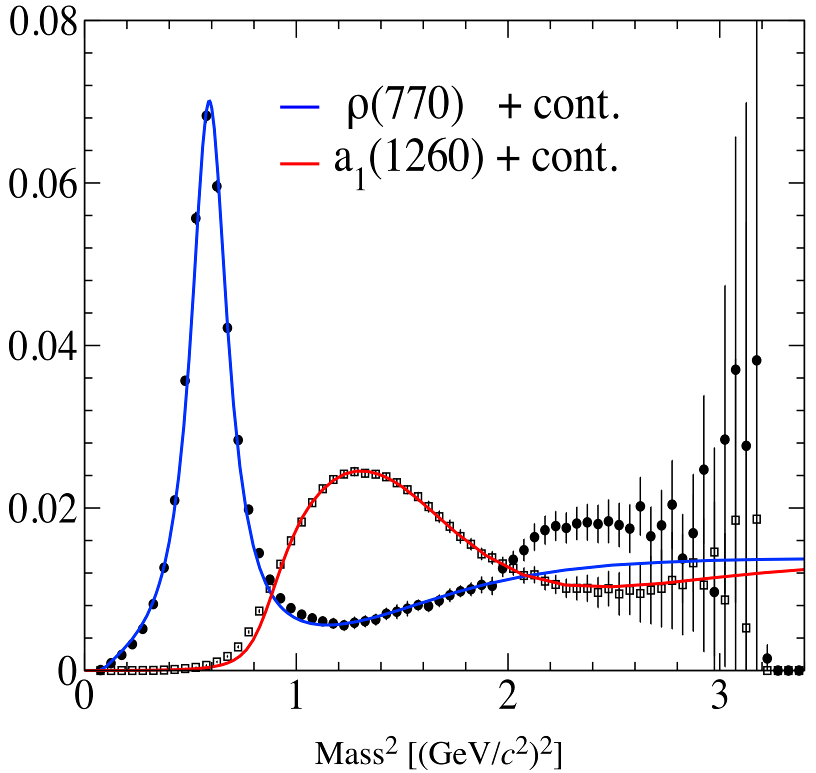
Is chiral symmetry restored in Quark-Gluon Plasma?

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?

ρ and a1 resonance (spectrum function) in vacuum

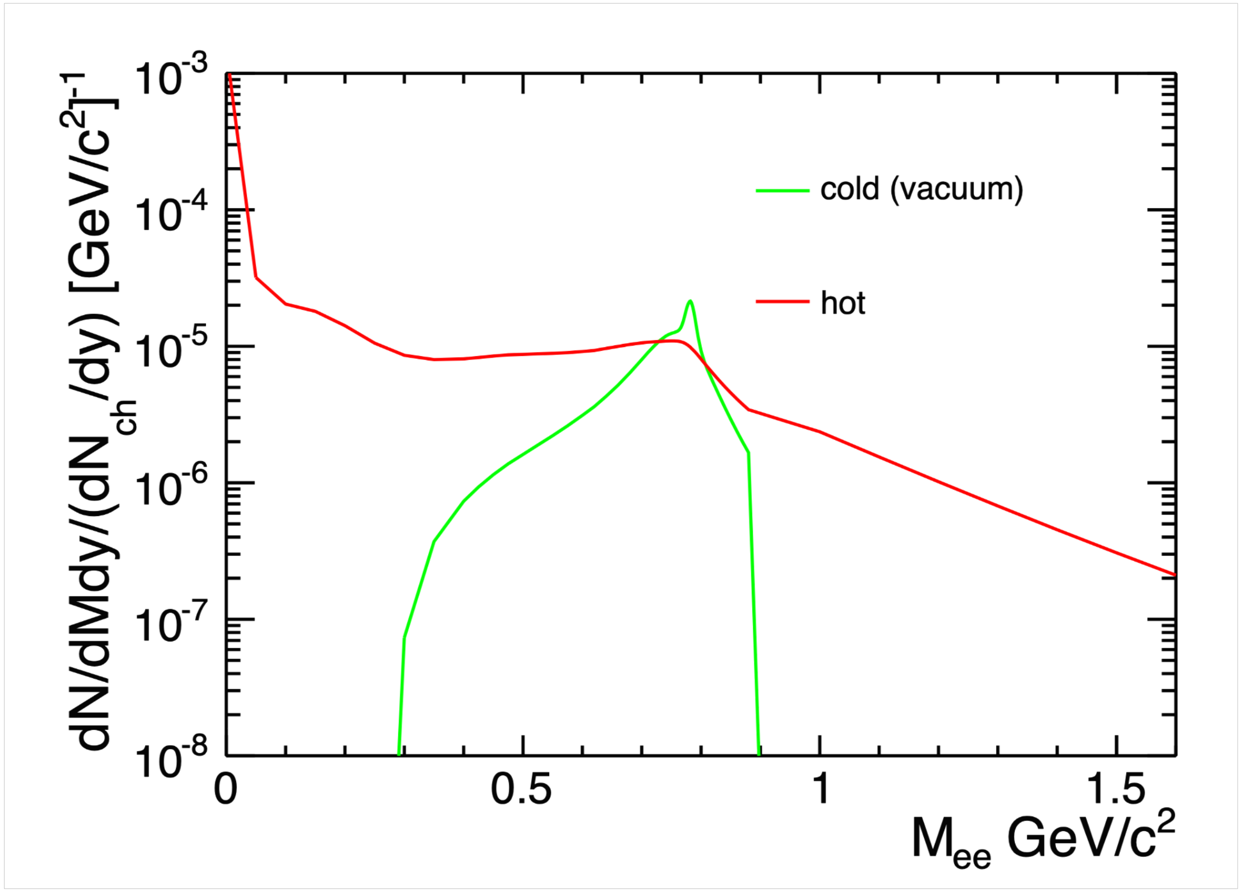


ALEPH: EPJC4 (1998) 409;
R. Rapp Pramana 60 (2003) 675.

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!

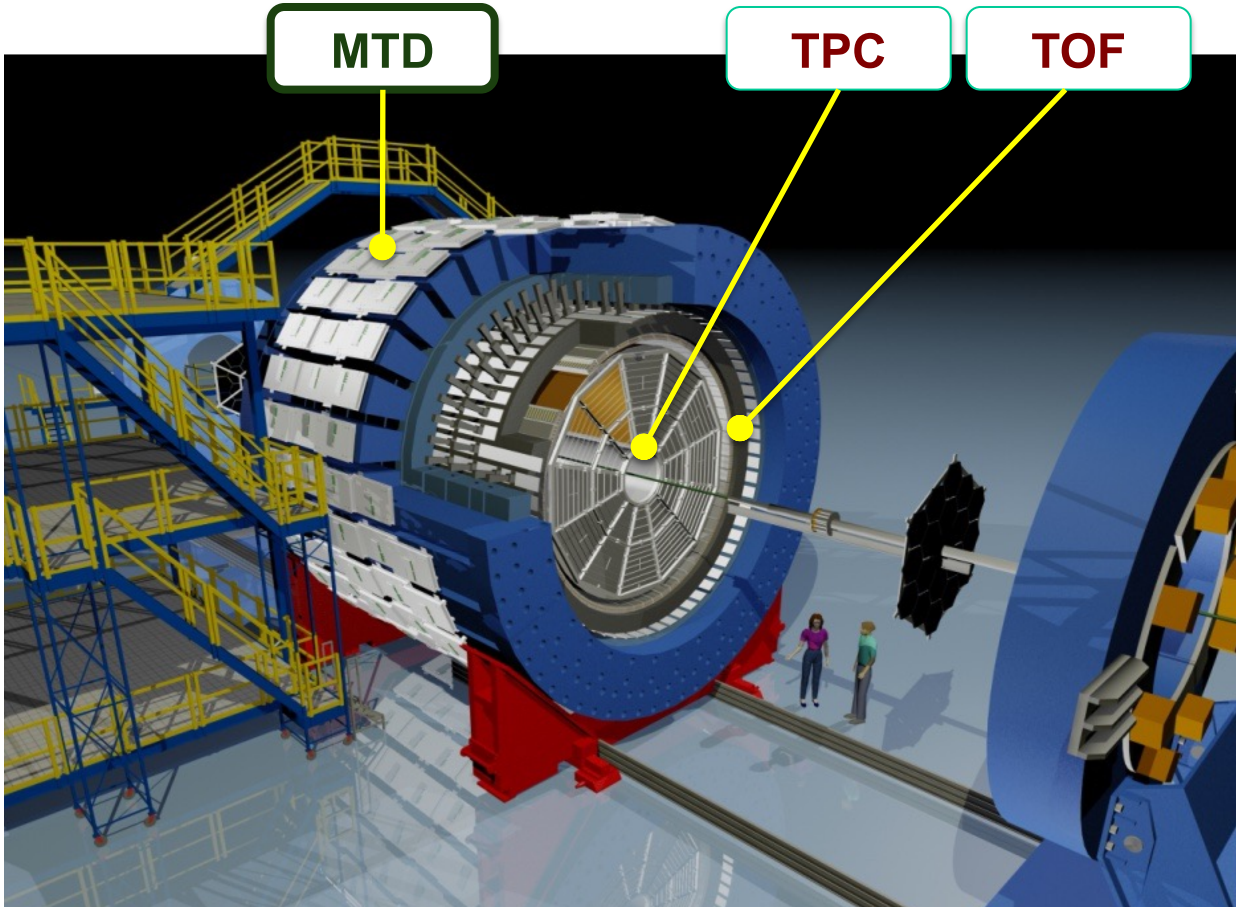
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

My physics interest

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

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

The STAR Detector

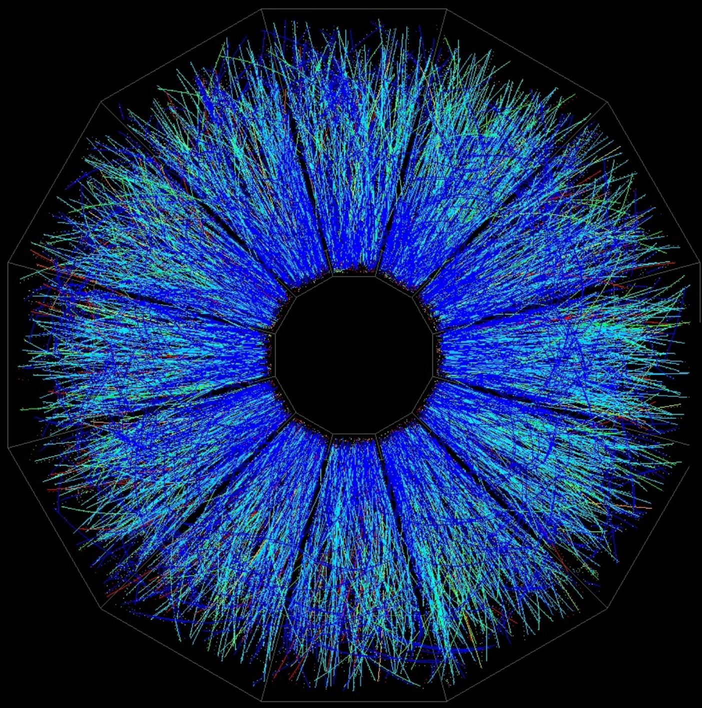


Solenoidal Tracker at RHIC (1200 tons)

Time Projection Chamber

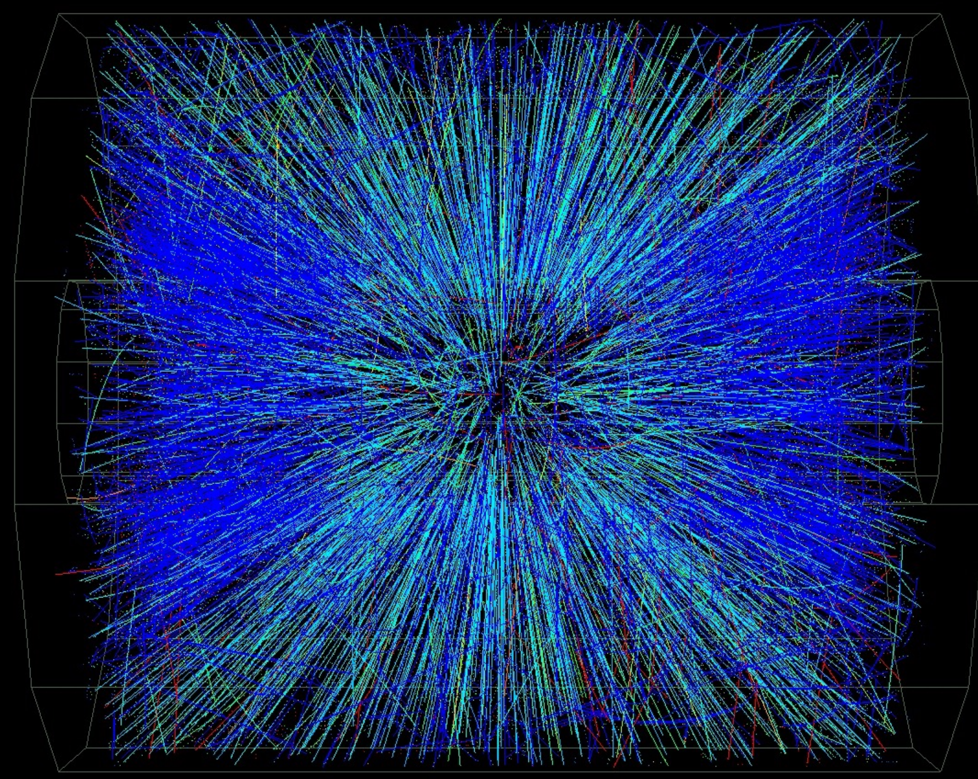
1. **Second largest device of its kind ever built**
2. **3D camera to take photos of the collisions**
3. **Measure ionization energy loss (dE/dx) and momentum**

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



Central Event

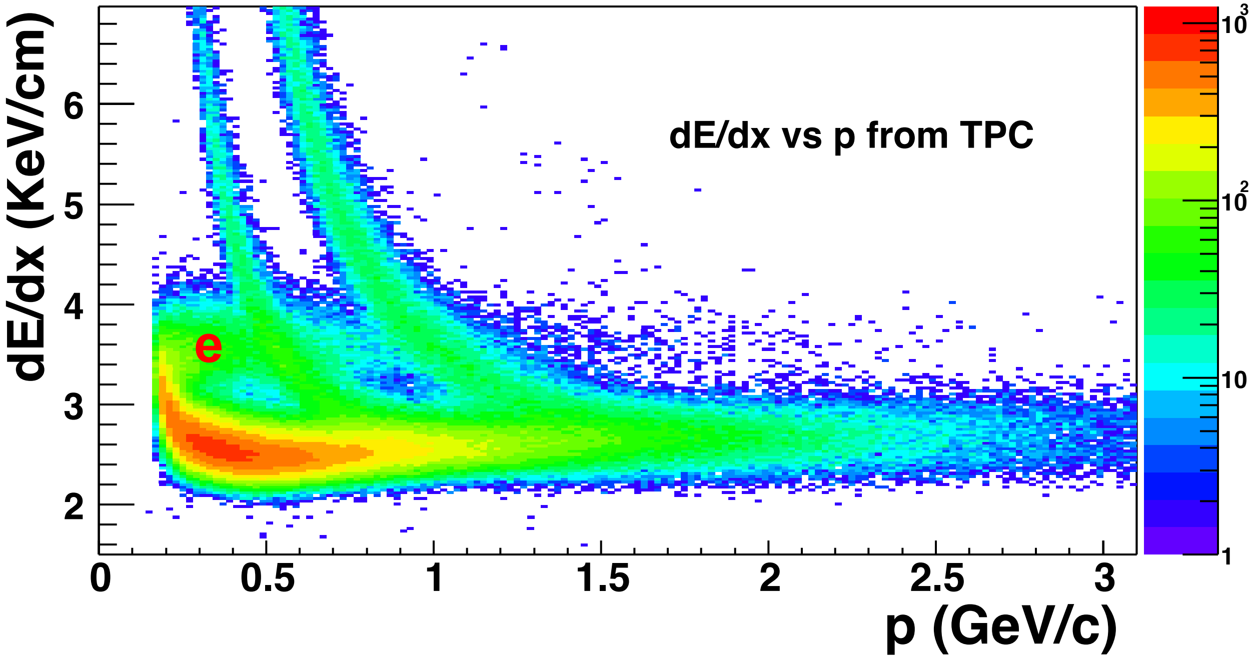
$E = m c^2$



STAR

(real-time Level 3)

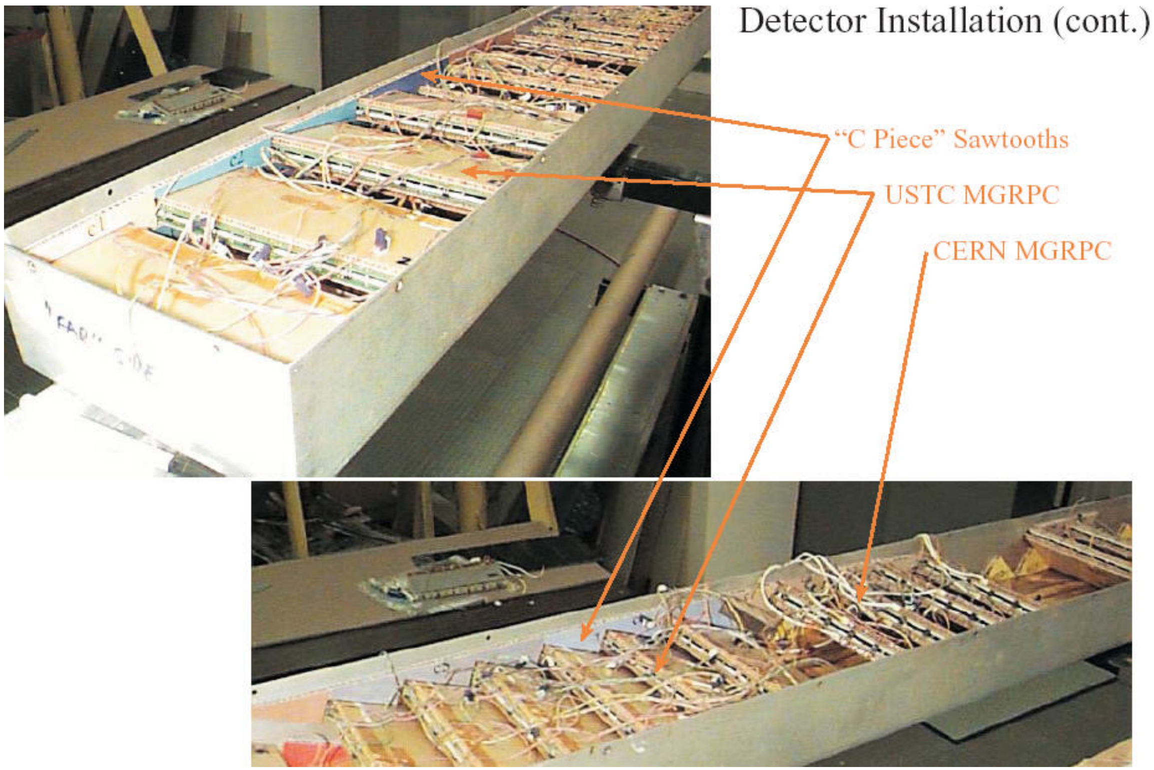
Particle identification

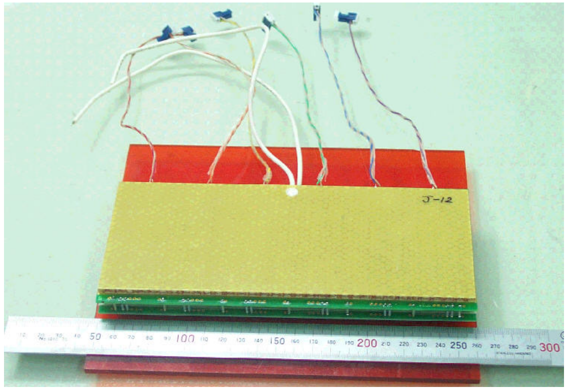


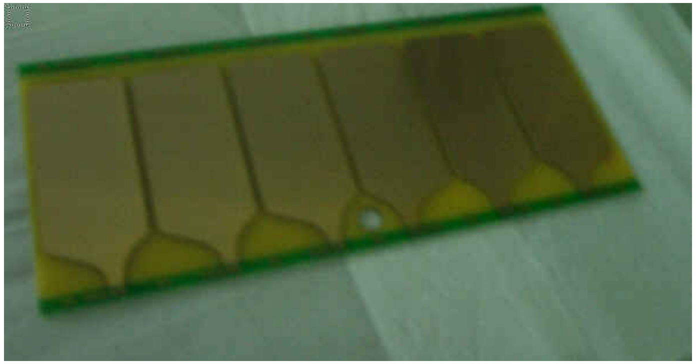
Electrons are difficult to find.

Need new experimental tool!

MRPC TOFr 2003





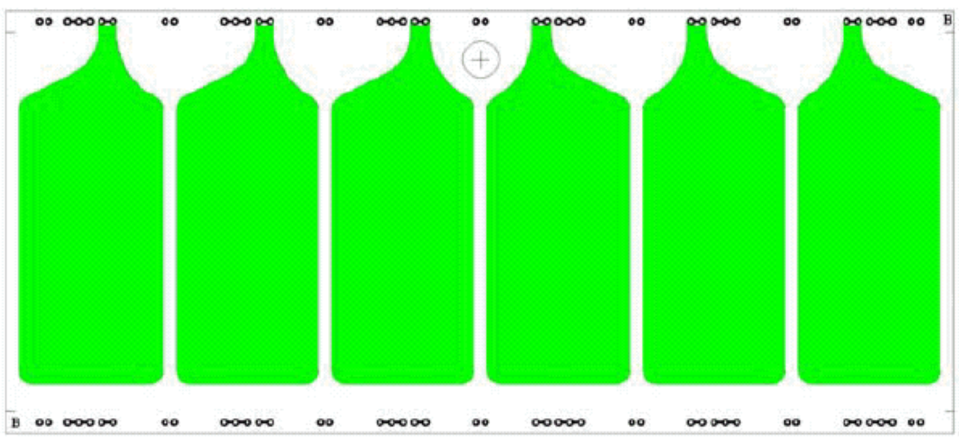


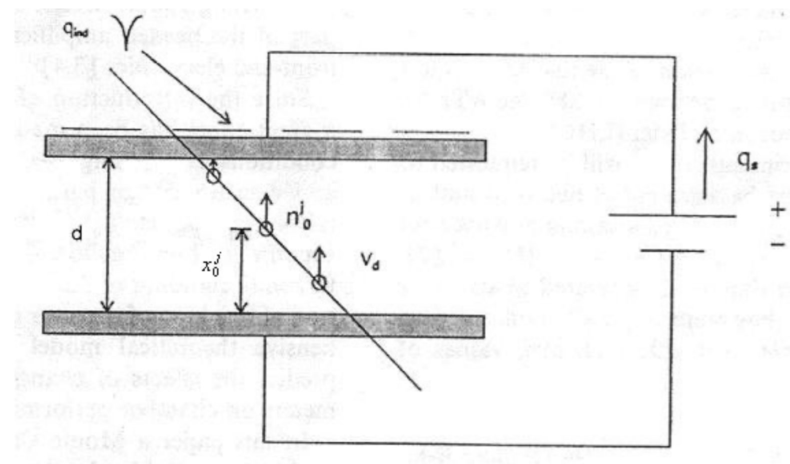
Multigap Resistive Plate Chamber (MRPC) Technology

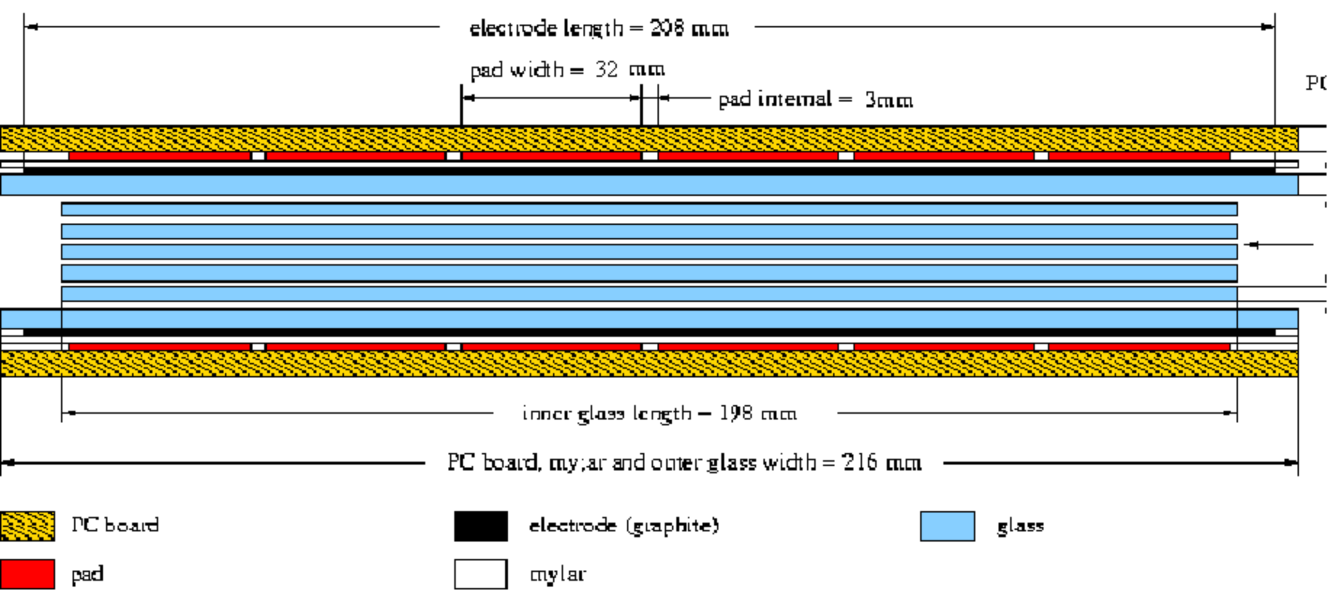
low cost, high timing resolution $<100 \times 10^{-12}$ second

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

Structure of MRPC Module



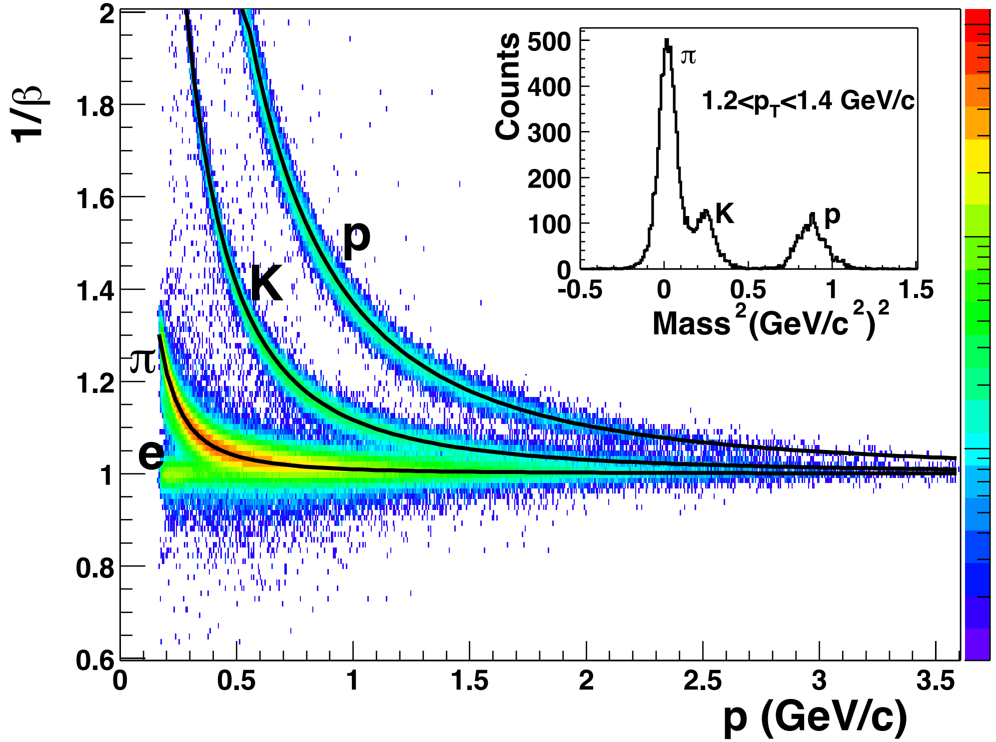




Read out pad size: 3.15cm×6.3cm, gap: 6×0.22mm

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

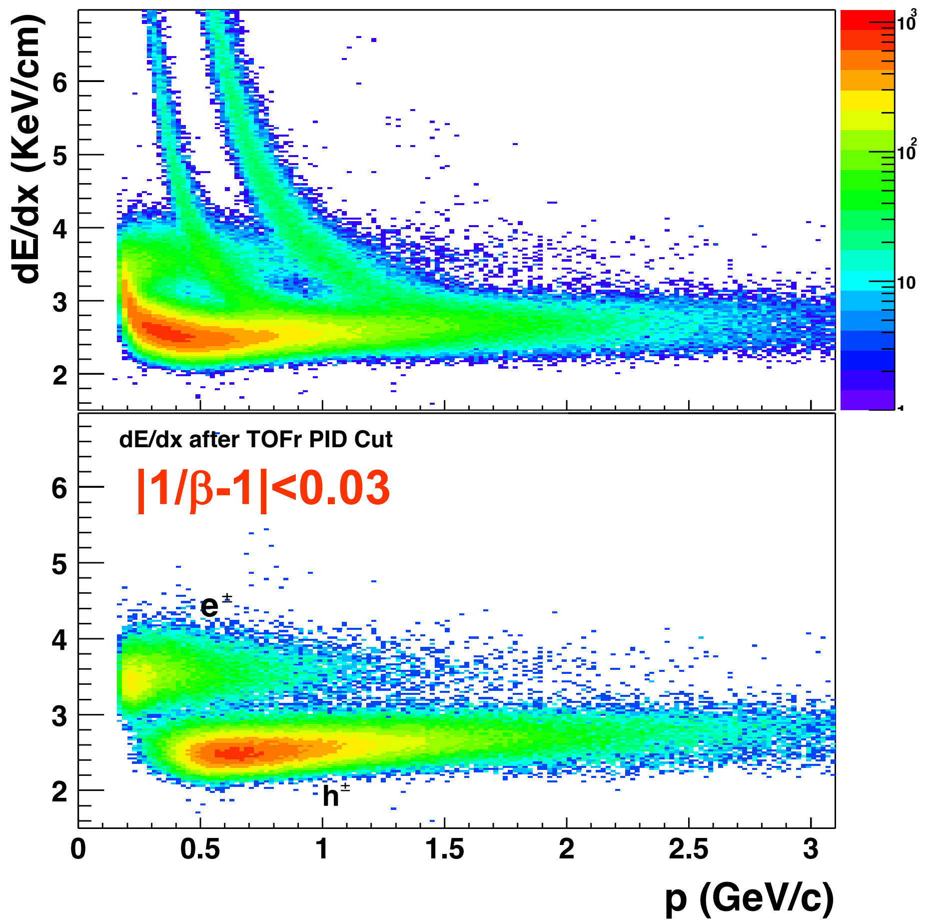


STAR Collaboration, PLB616(2005)8

Curve:

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

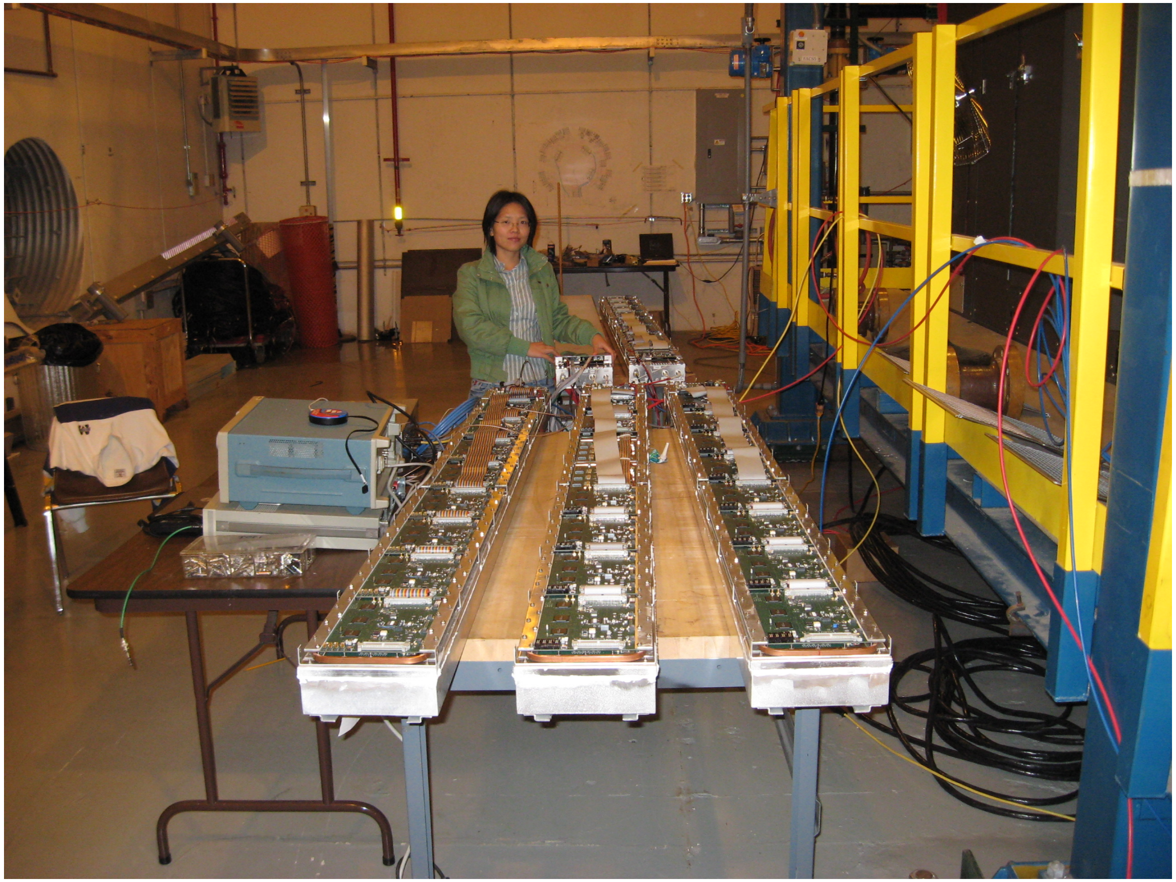
Electron identification



STAR Collaboration, PRL94(2005)062301

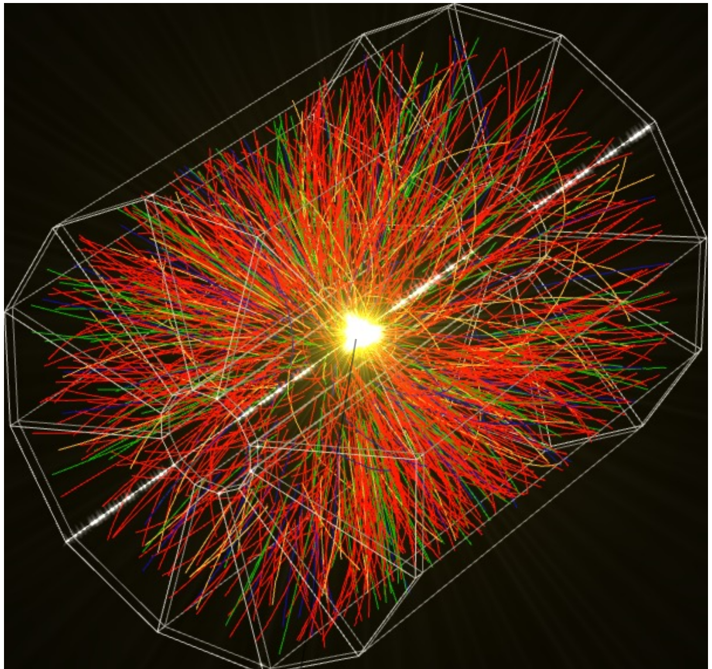
Clean electron samples!

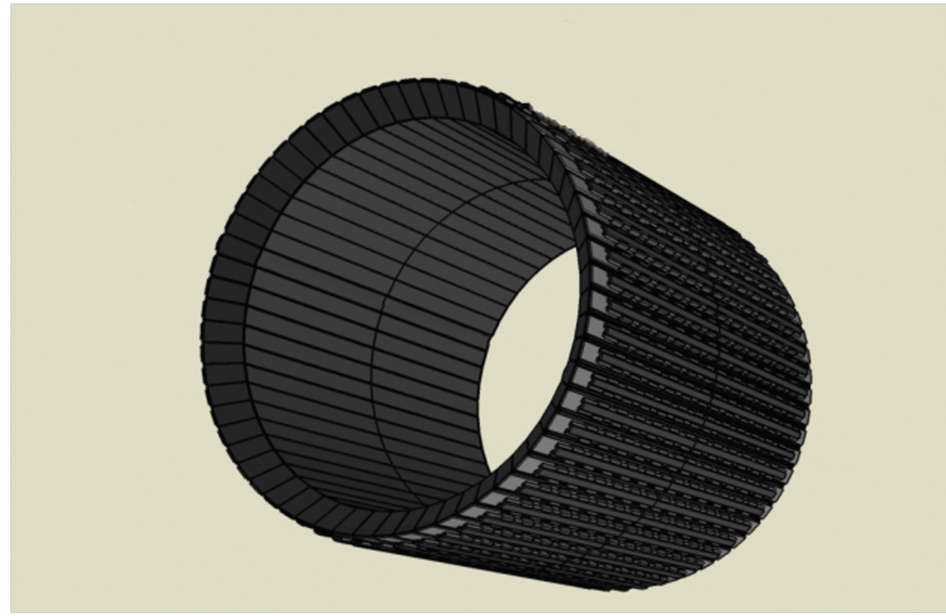
Time of Flight Detector upgrade

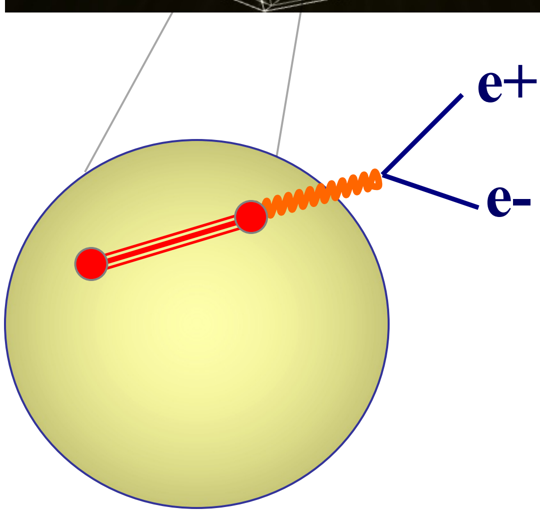


US-China Collaboration, 120 units in total:
2008: 4%; 2009: 72%; 2010: 100%

The special PET scan tools are now ready

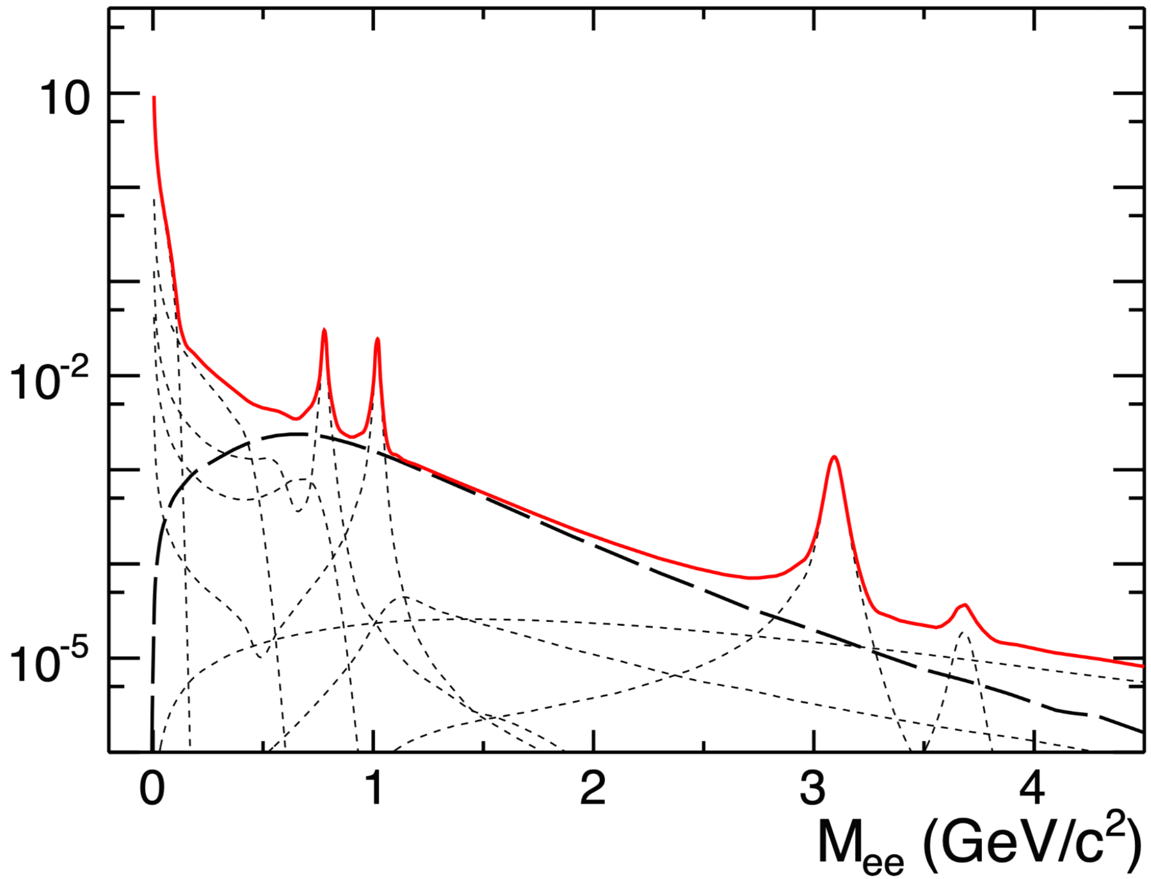






The Time of Flight Detector completes the experimental tool for electron-positron tomography.

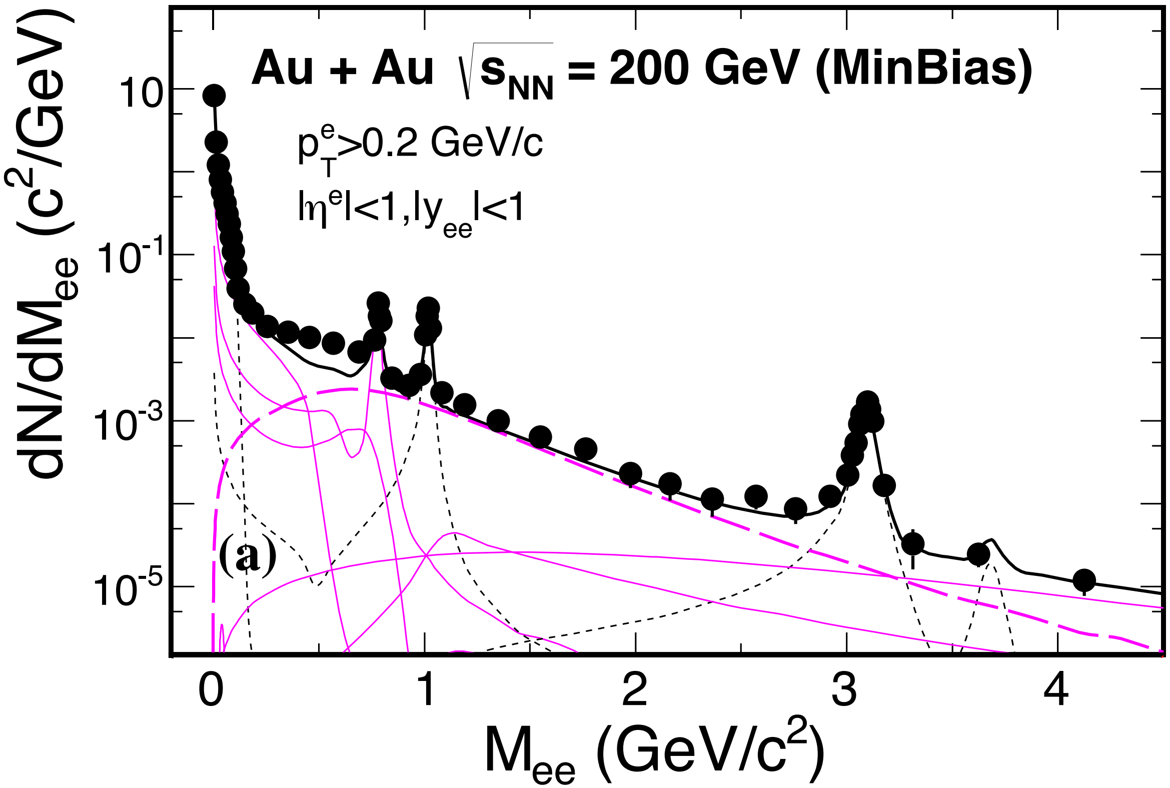
Electron-positron emission mass spectrum



In empty space (vacuum)

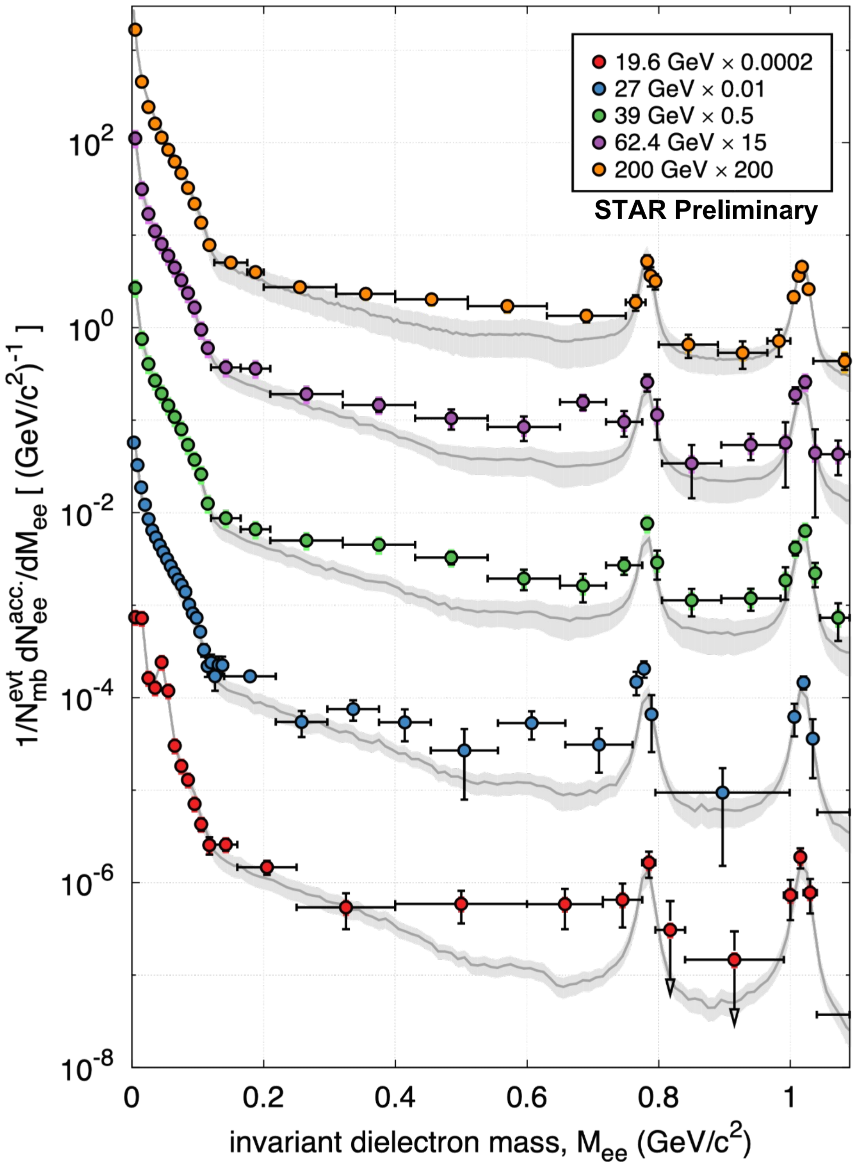
Electron positron emission mass spectrum in 200 GeV Au+Au

PRL113 (2014) 022301



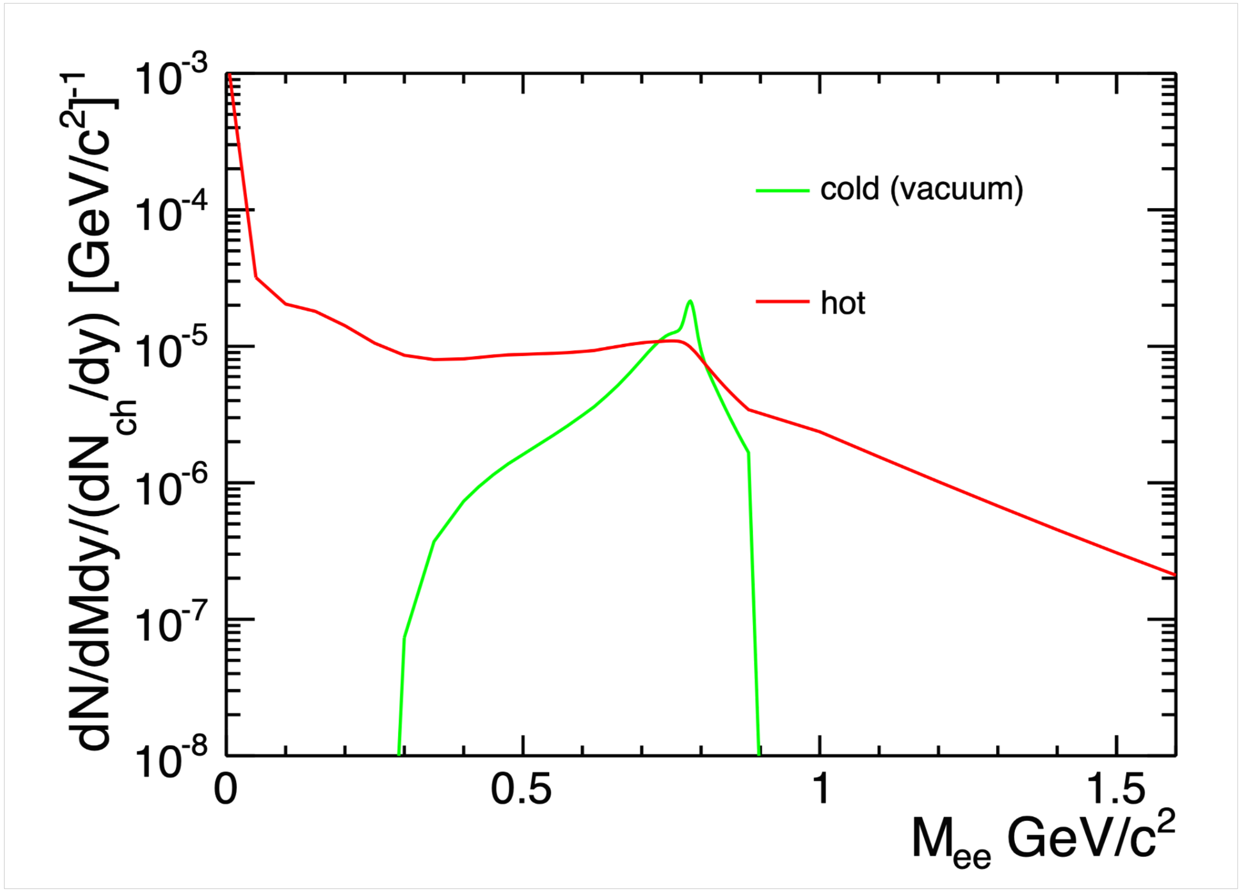
There are “hot” contributions!

Electron-positron emission at lower energies



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

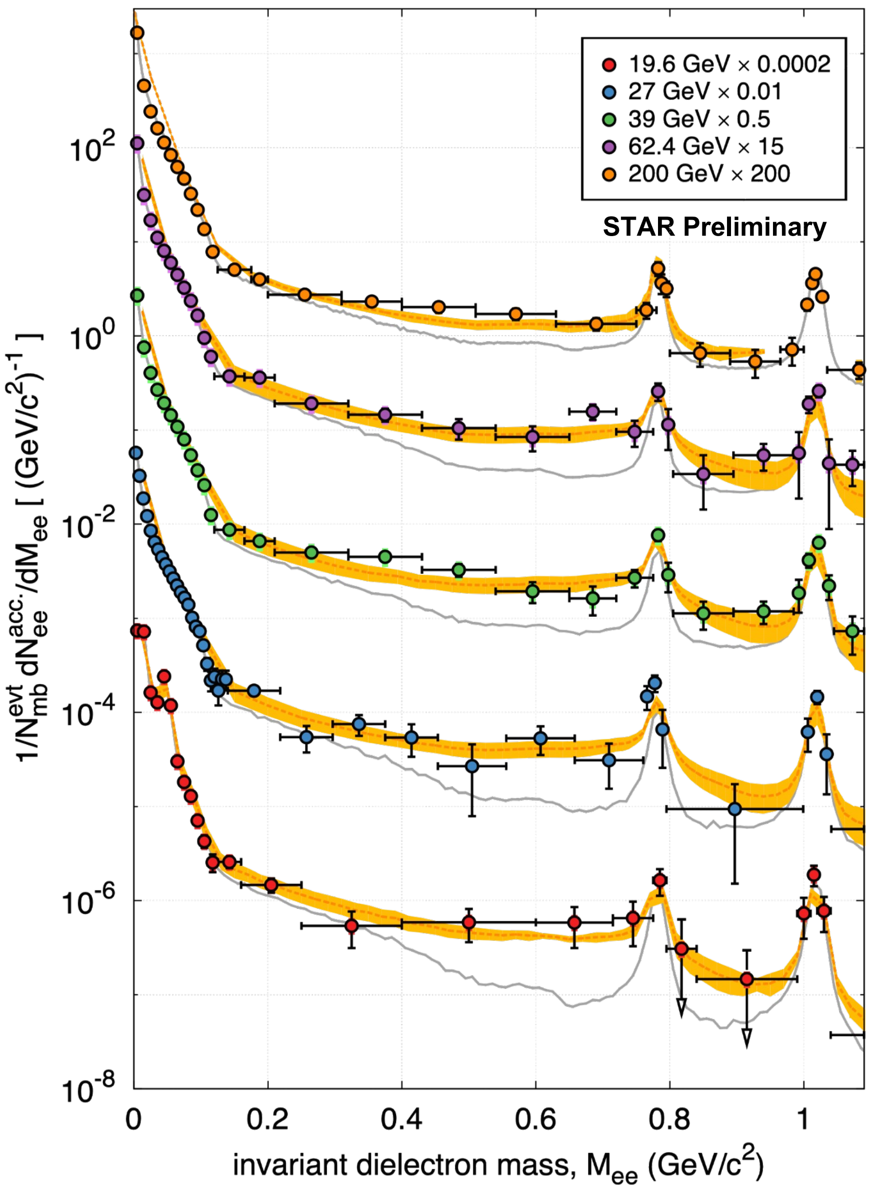
The "hot" mass distribution in 200 GeV Au+Au



The "hot" contribution is modified and broadened!

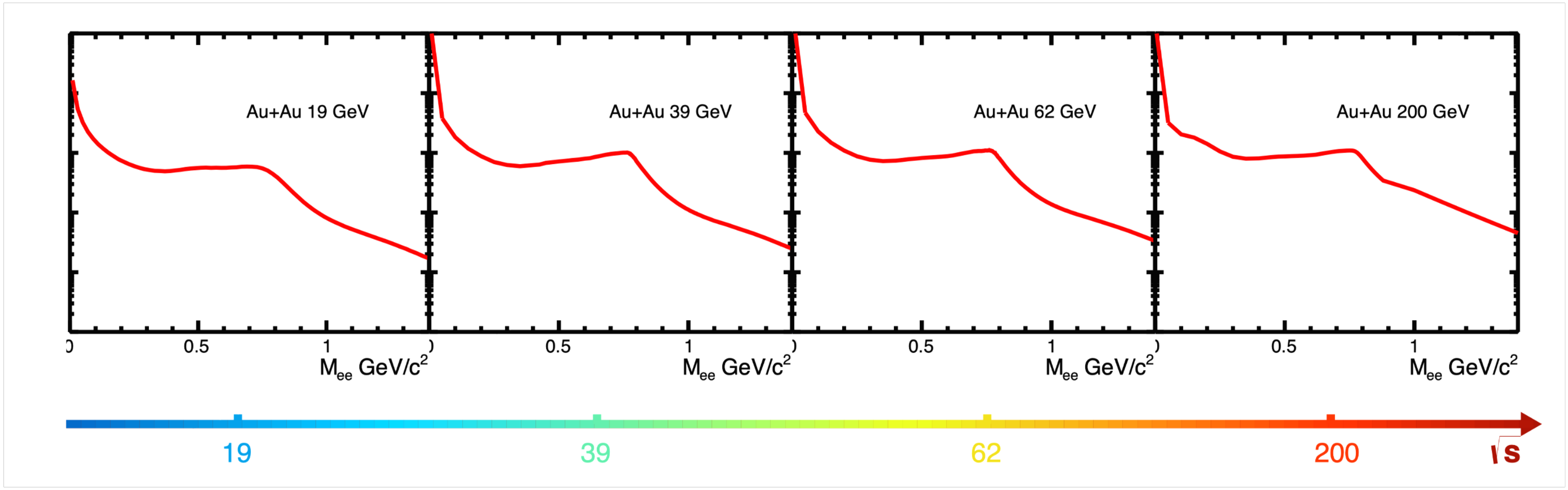
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

Electron-positron emission at lower energies



Observed “hot” distributions are broadened!

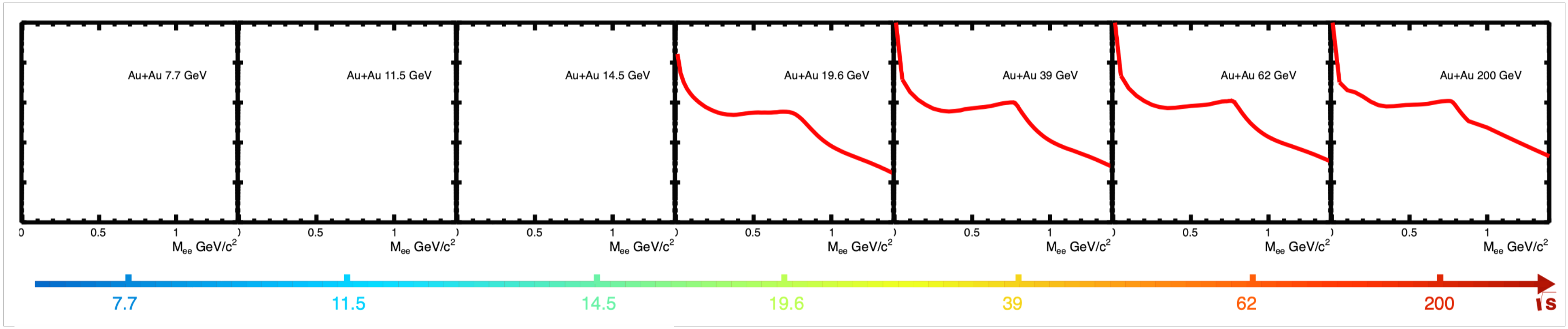
The “hot” contribution

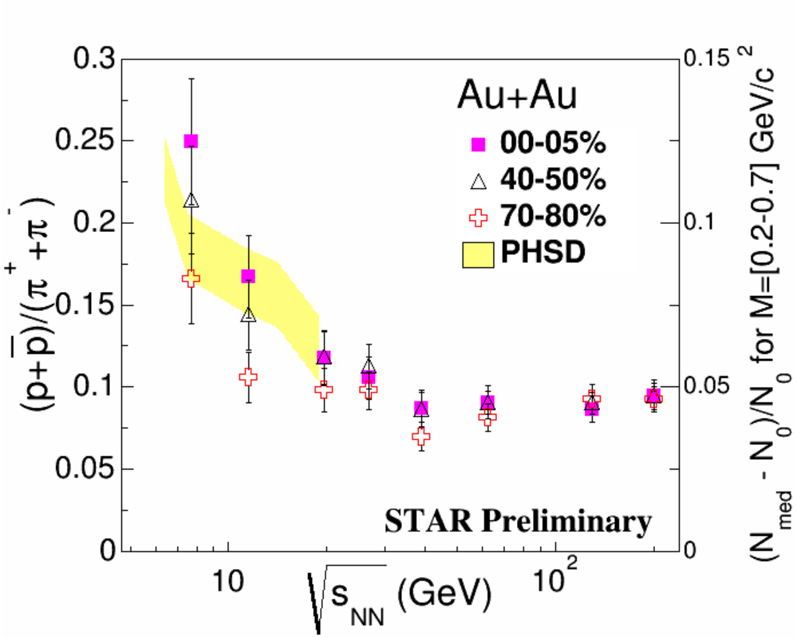


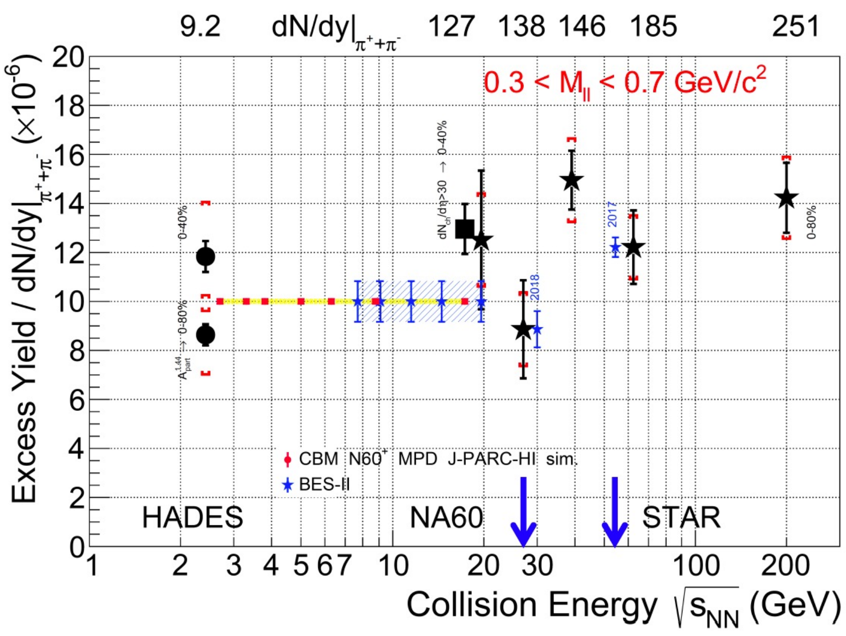
The electron-positron spectrum from hot, dense medium is consistent with a broadened ρ resonance in medium and the production yield normalized by dN_{ch}/dy is similar from 19.6 to 200 GeV.

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

Go to lower collisions energies
7.7 GeV to 19.6 GeV





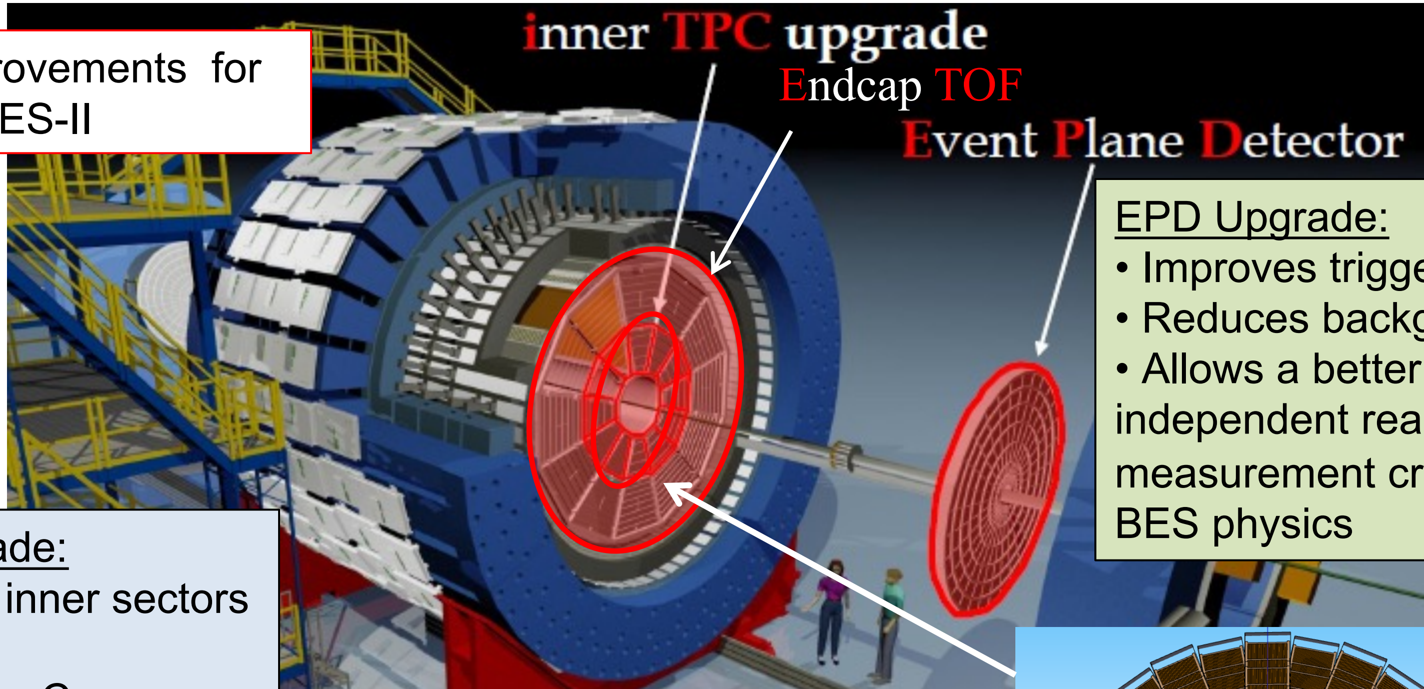


Broader and more "hot" contribution down to 7.7 GeV collision energy?

Beam Energy Scan II (BES-II) provides a unique opportunity to study chiral symmetry restoration!

STAR detector at BES-II

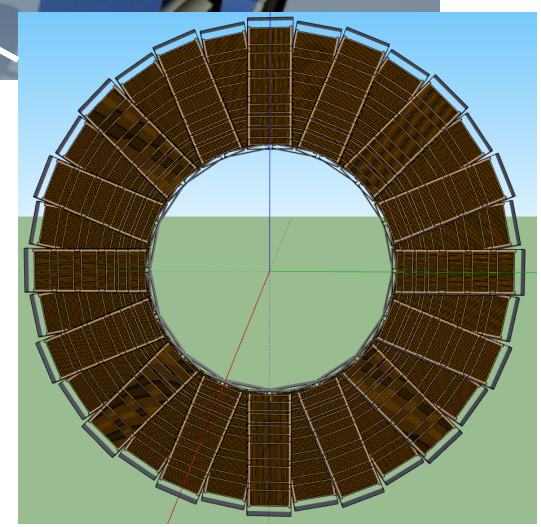
Major improvements for BES-II



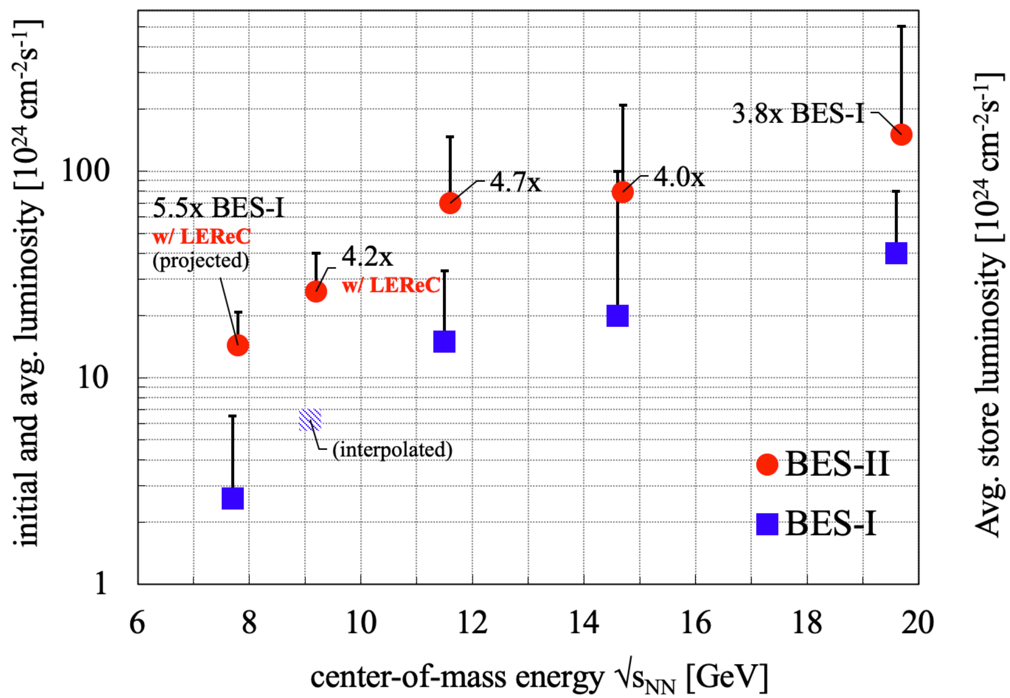
EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

iTPC Upgrade:
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1 to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR



Beam Energy Scan II in 2019-2021

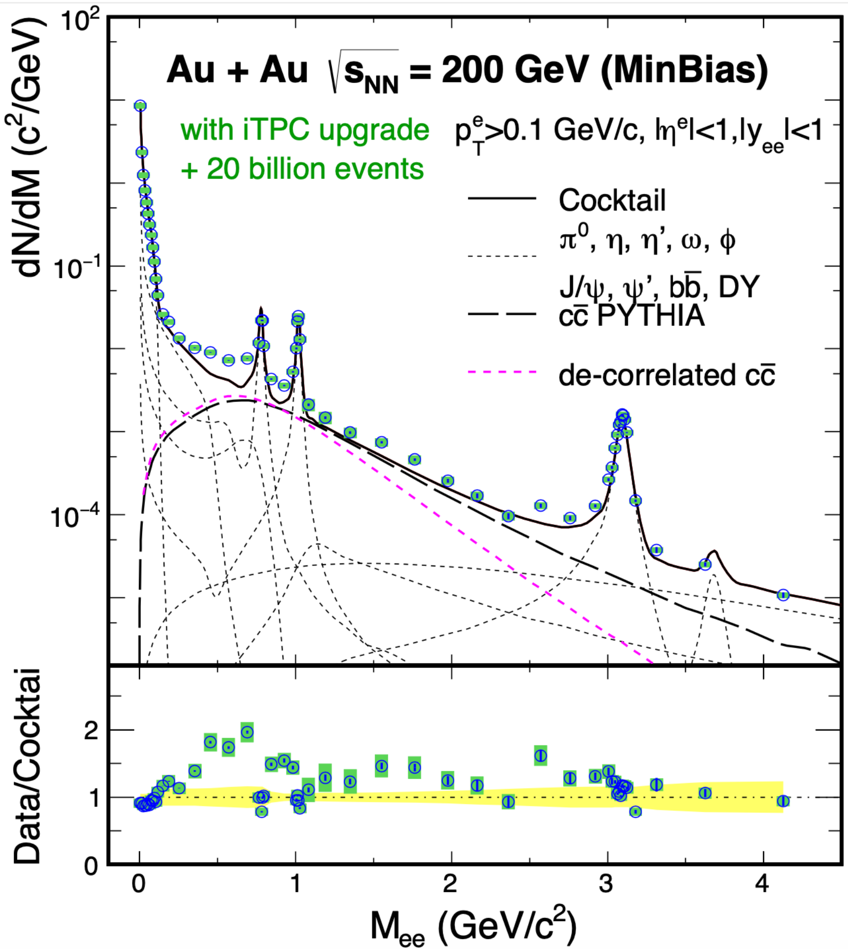


RHIC is unique to study chiral symmetry restoration:

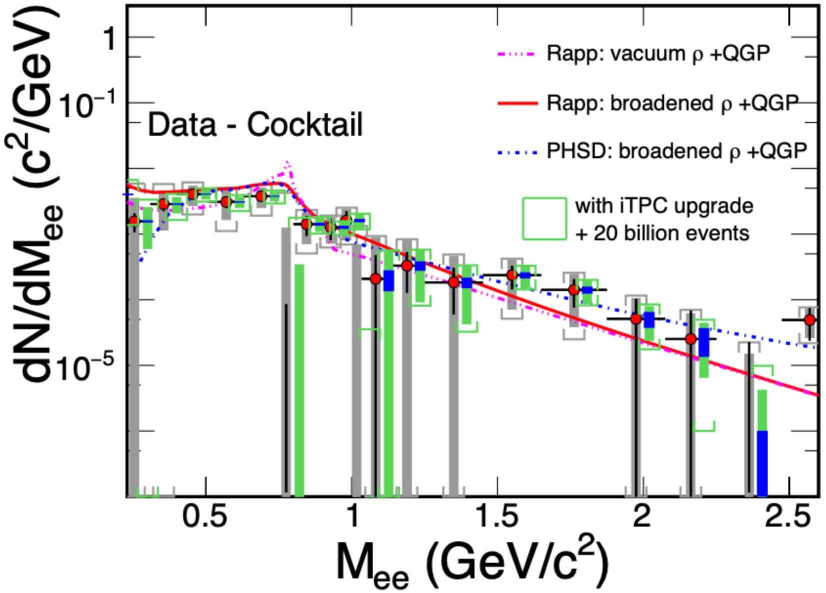
Beam energy scan II: collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV.

In 2021, collected the last collider data set at 7.7 GeV, completed the BES-II program.

Back to 200 GeV Au+Au in 2023-2025



low material, improved PID, extended η and p_T coverage by iTPC

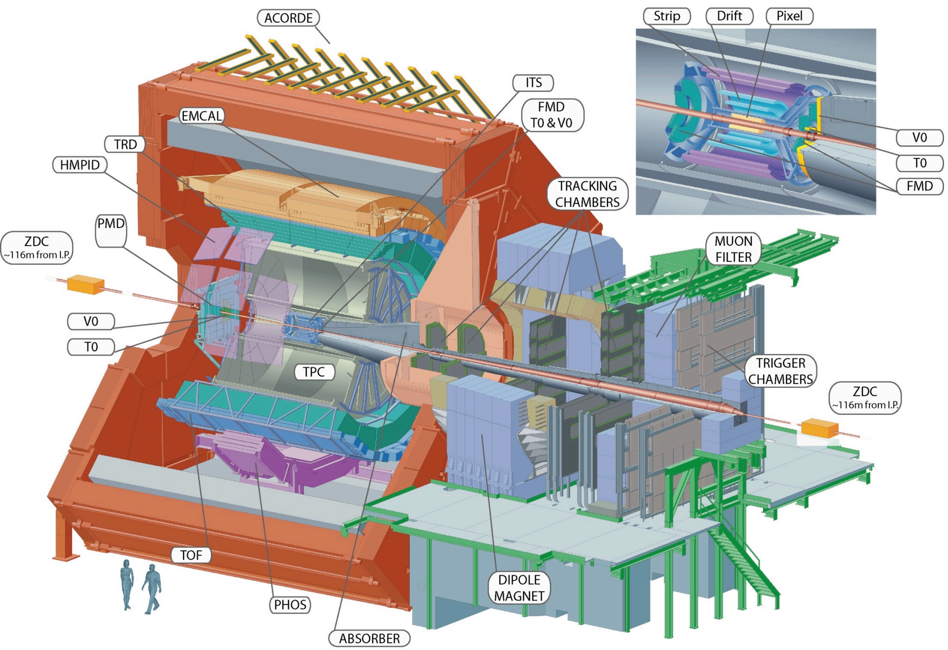


Low-mass dielectron measurement: **lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0**

Intermediate mass: **direct thermometer to measure temperature**

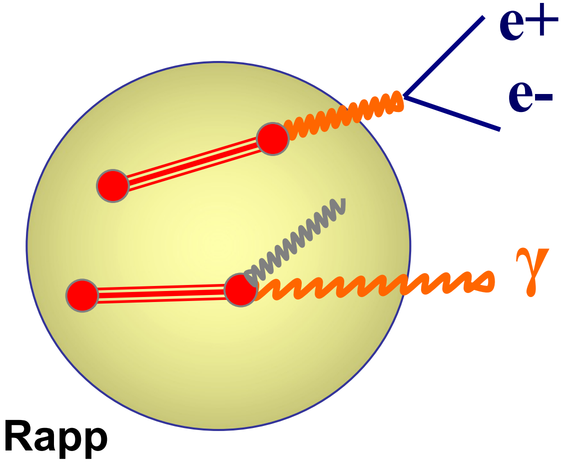
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

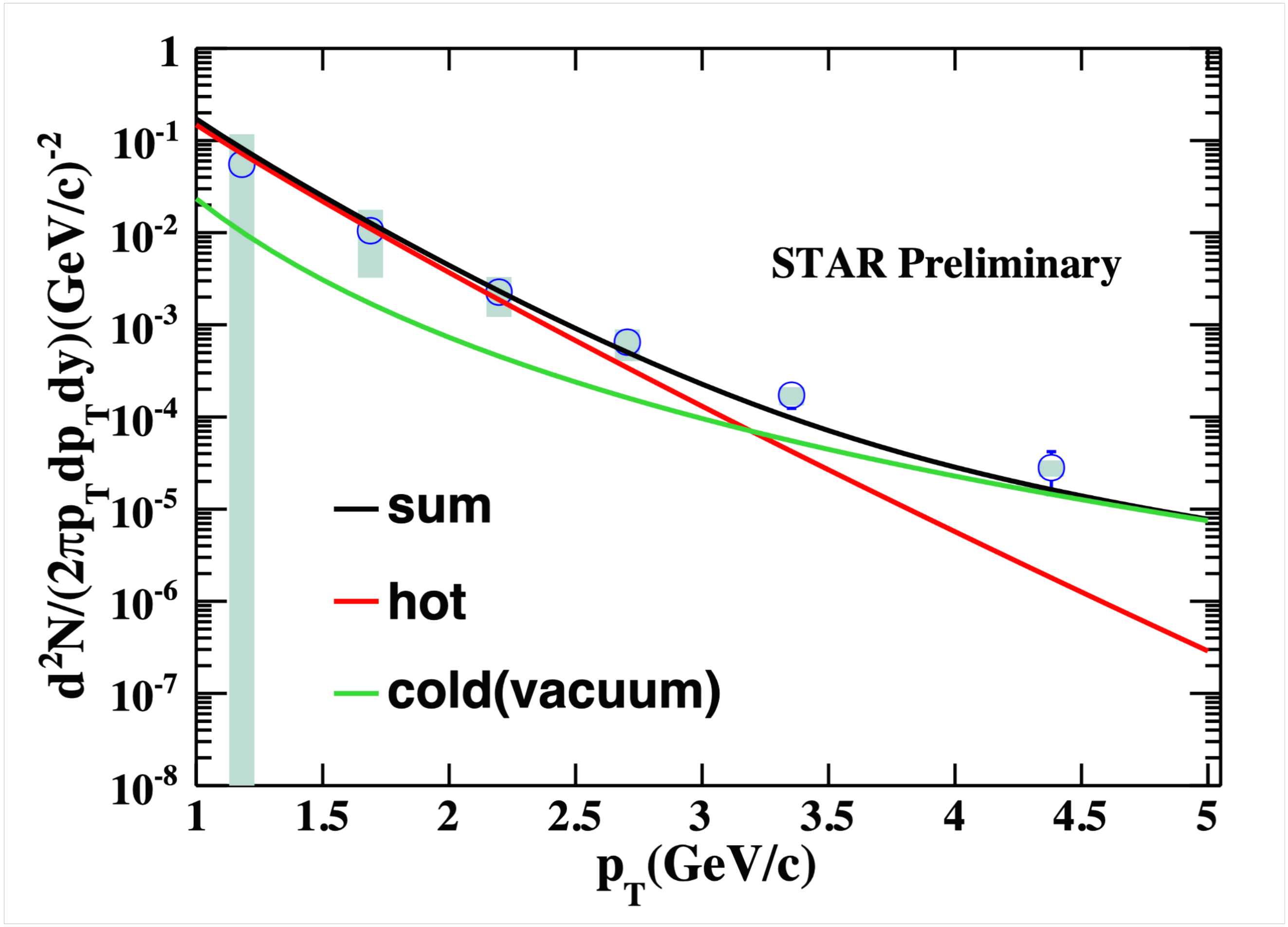
World-wide interest



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

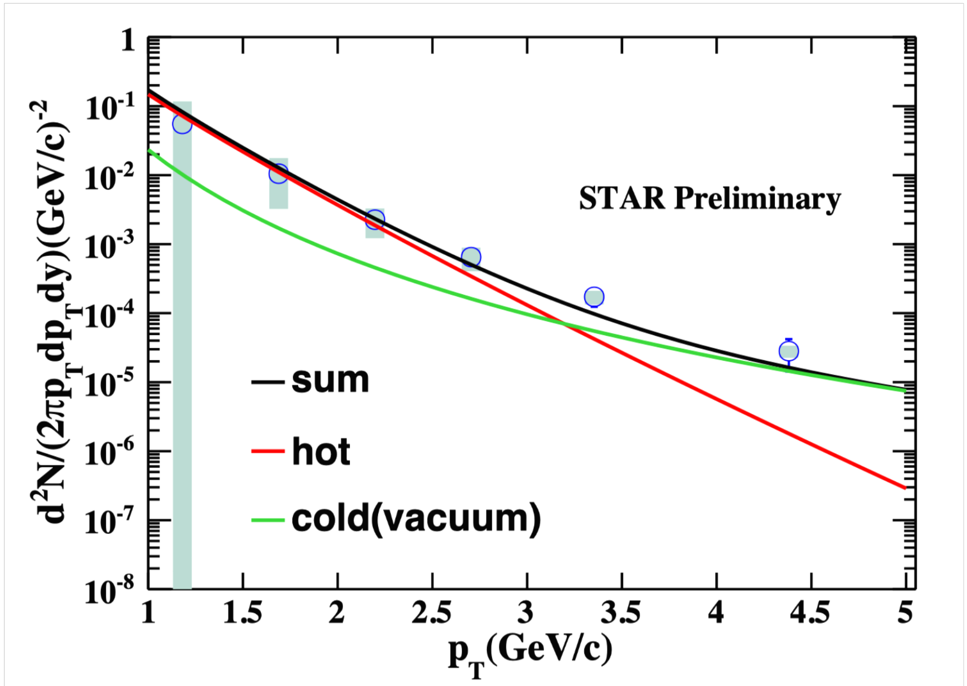
Photon emission

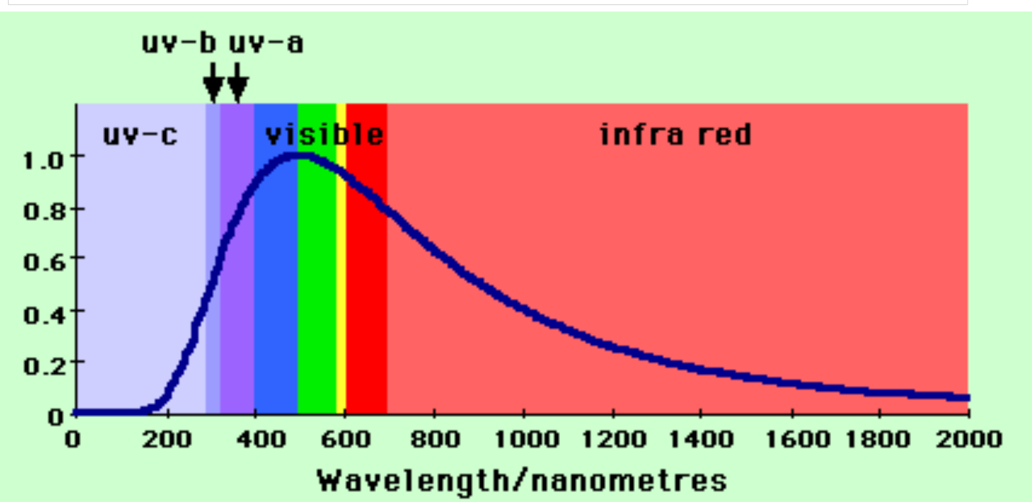




Hot contribution observed in the photon energy spectrum!

Photon emission



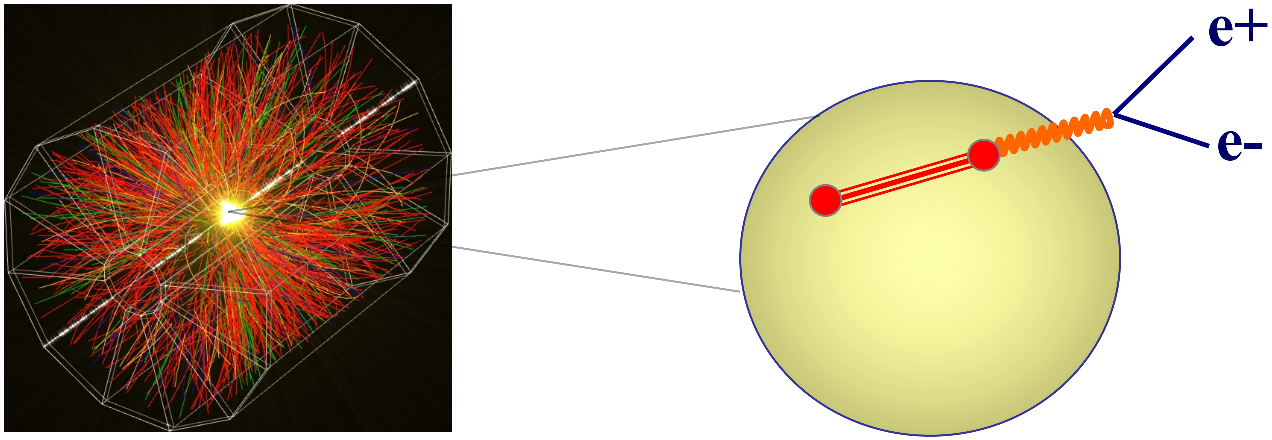


Quark-Gluon Plasma emission spectrum: photon energy a few 10^9 electron volts

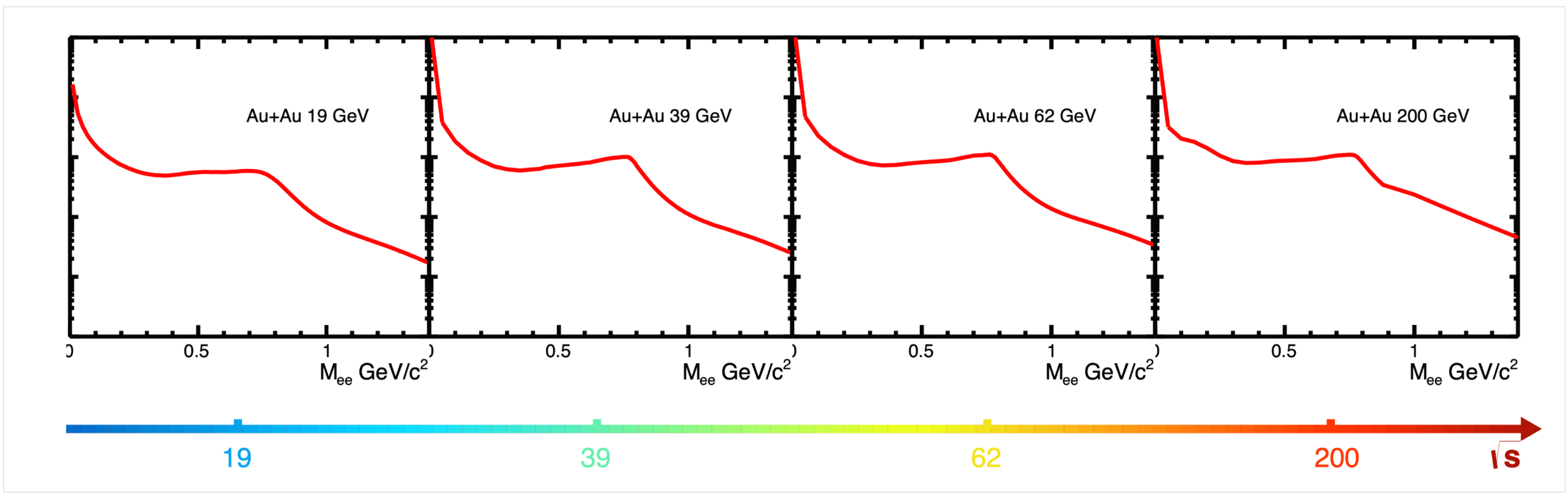
Sun emission spectrum: Photon energy a few electron volts.

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

Summary



Electron-positron tomography of Quark-Gluon Plasma:



Chiral symmetry restoration!

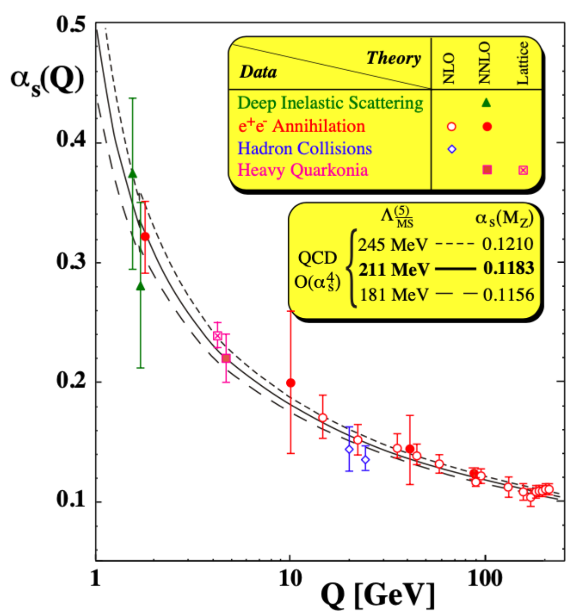
Backup

Quantum Chromodynamics (QCD)

- Quarks are bound together to form protons and neutrons.

- Discovery of asymptotic freedom: attraction between quarks becomes weaker as quarks approach one another more closely; becomes stronger as they are separated

- QCD: correct theory of the strong nuclear force, one of the four fundamental forces in nature (Gross, Wilczek, Politzer, 2004 Nobel Prize).



S. Bethke, arXiv: hep-ex/0211012