

The journey to seek symmetry in Quark-Gluon Plasma



Lijuan Ruan (BNL)



Discovery of Quark-Gluon Plasma

Chiral symmetry

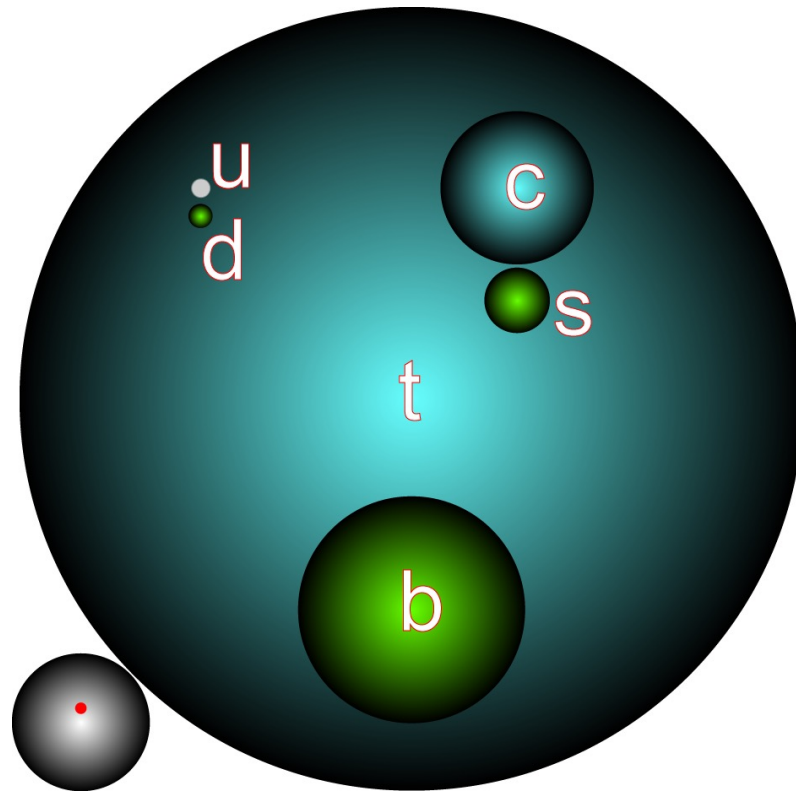
Our experimental approach and results

Summary



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**.

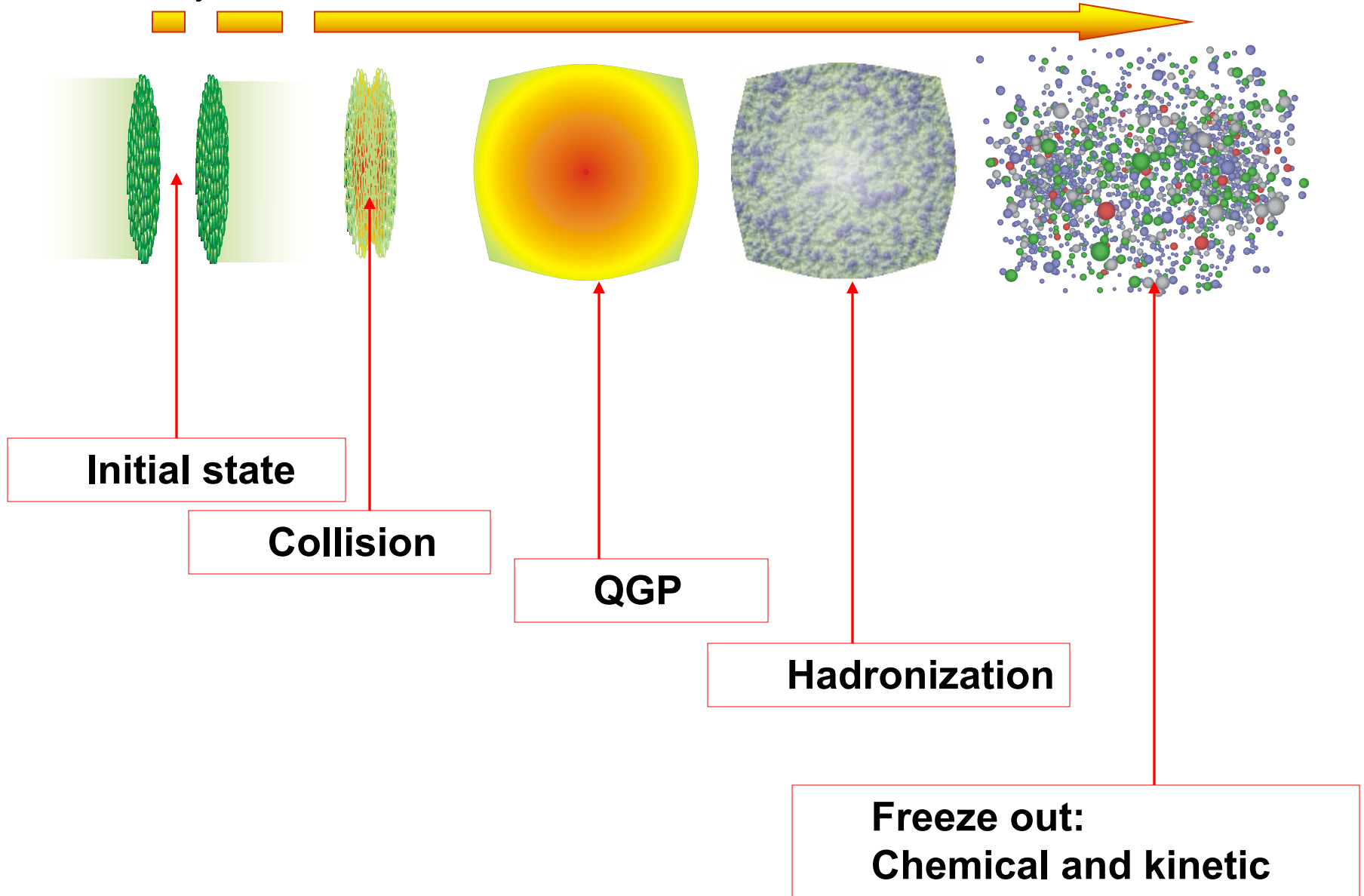
RHIC @ Brookhaven National Laboratory



22 years of RHIC operation

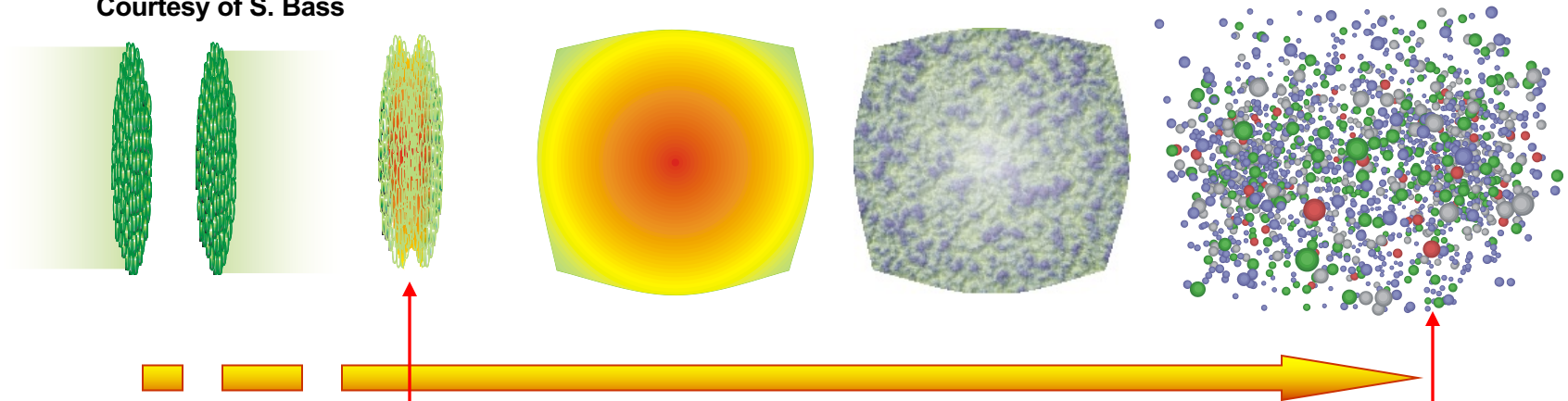
Relativistic heavy ion collision

Courtesy of S. Bass



Physics Goals at RHIC

Courtesy of S. Bass



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

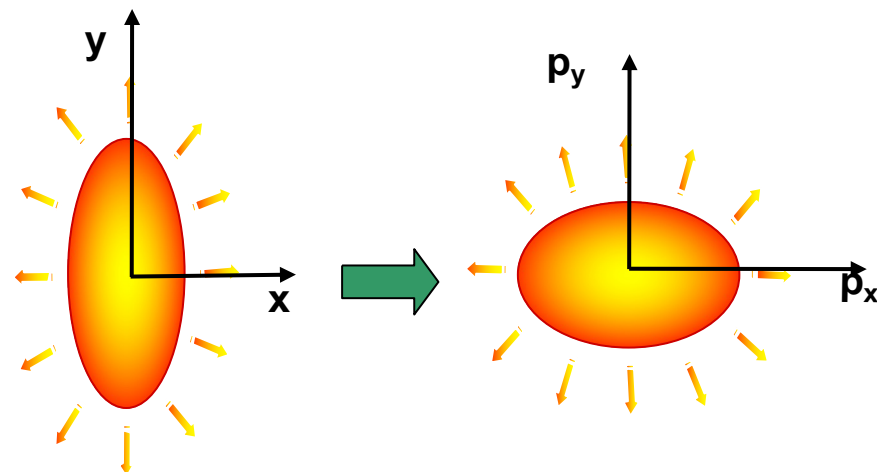
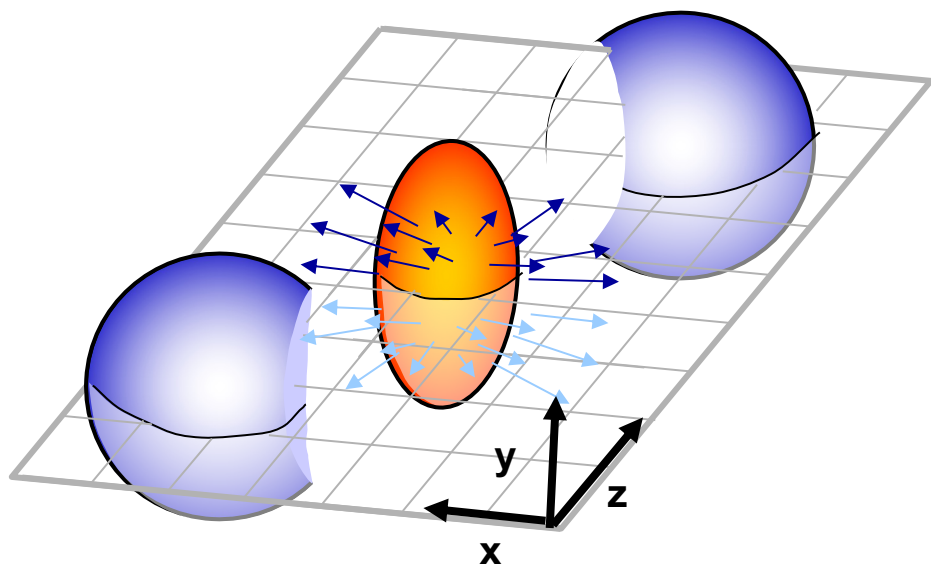
Penetrating probes

- “jets” and heavy flavor

Bulk probes

- $v_2 \rightarrow$ 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

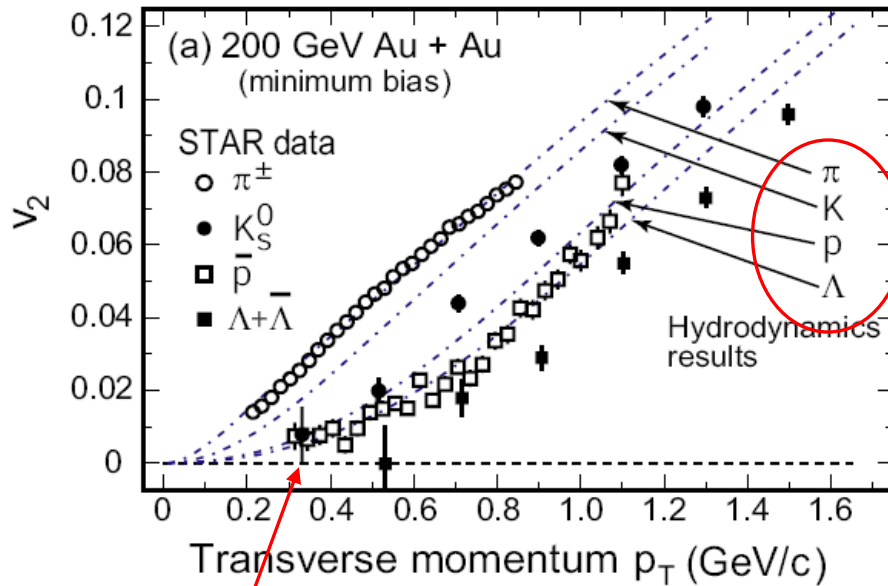
$$E \frac{d^3 N}{d^3 p} = \frac{1}{\pi} d^2 \frac{N}{dp_T^2 dy} [1 + 2v_1 \cos(\varphi - \Psi_R) + 2v_2 (2[\varphi - \Psi_R]) + \dots]$$



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

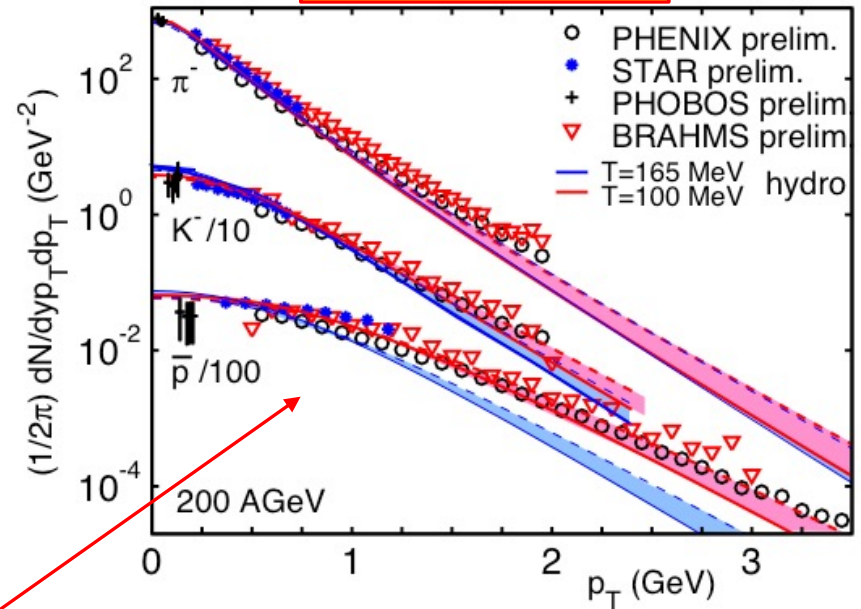
Low p_T : bulk property

Elliptic flow v_2



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

p_T distributions

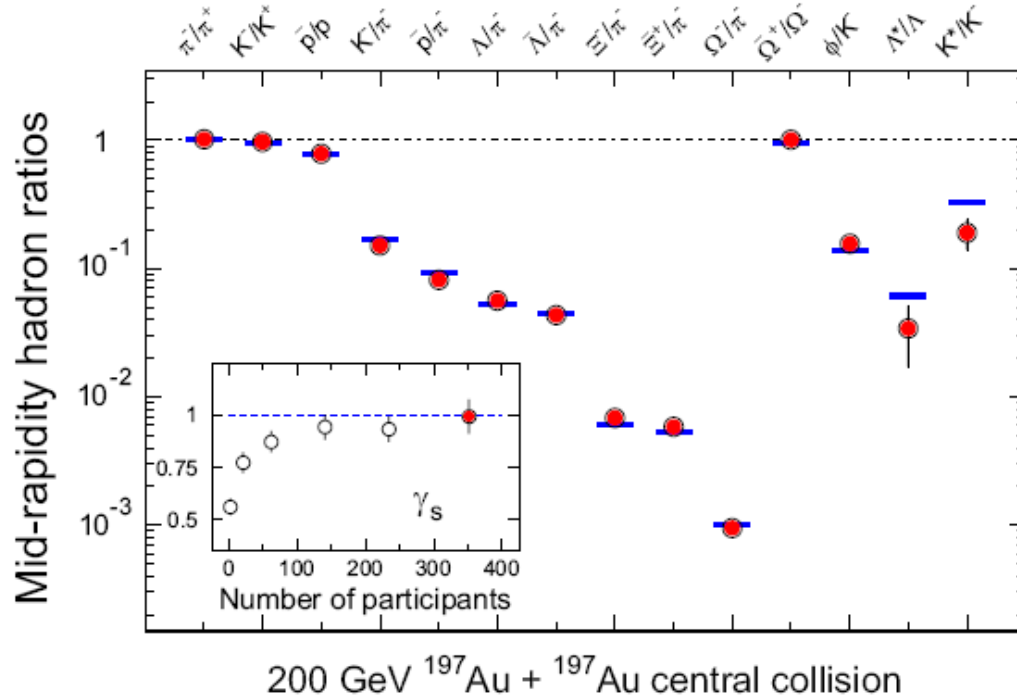


M. Calderon de la Barca Sanchez, ISMD2003

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 ($\mu_B=0$ if $p_{\text{bar}}/p=1$)

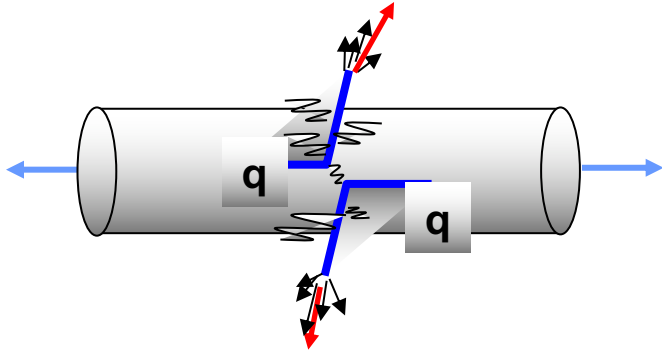
Strangeness saturation factor: γ_s

$$T_{\text{ch}} = 163 \pm 4 \text{ MeV}, \mu_B = 24 \pm 4 \text{ MeV}$$

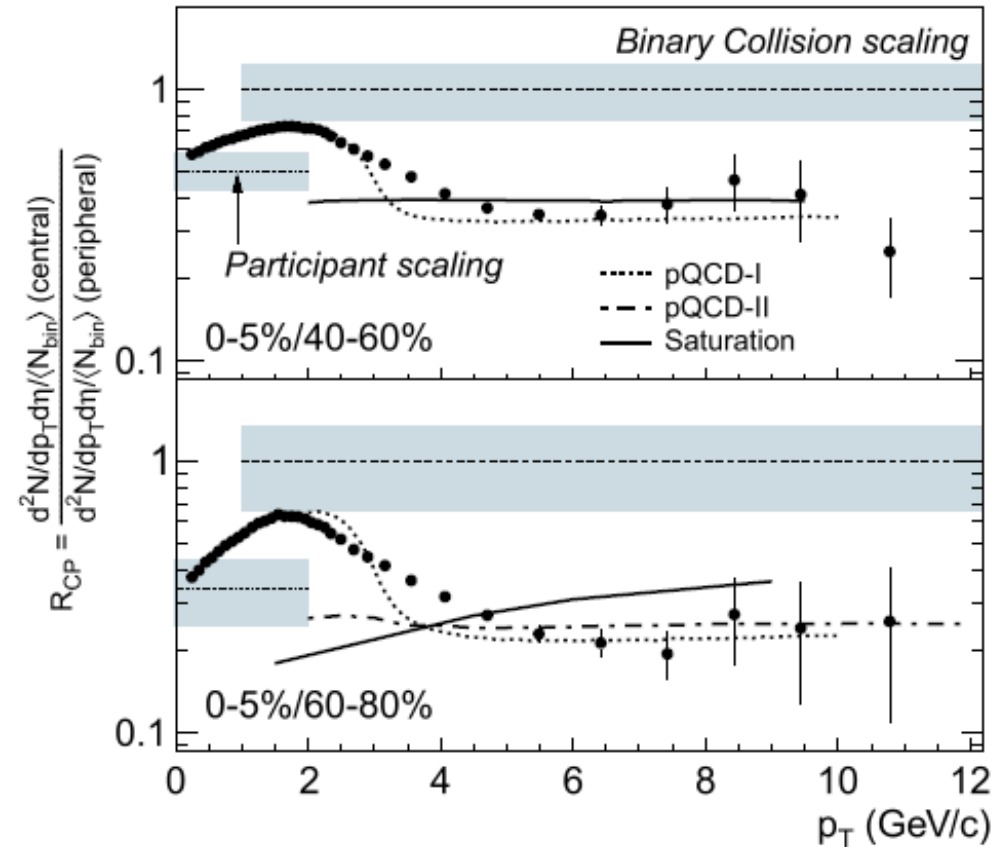
$$\gamma_s = 0.99 \pm 0.07$$

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

High p_T : penetrating probe



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

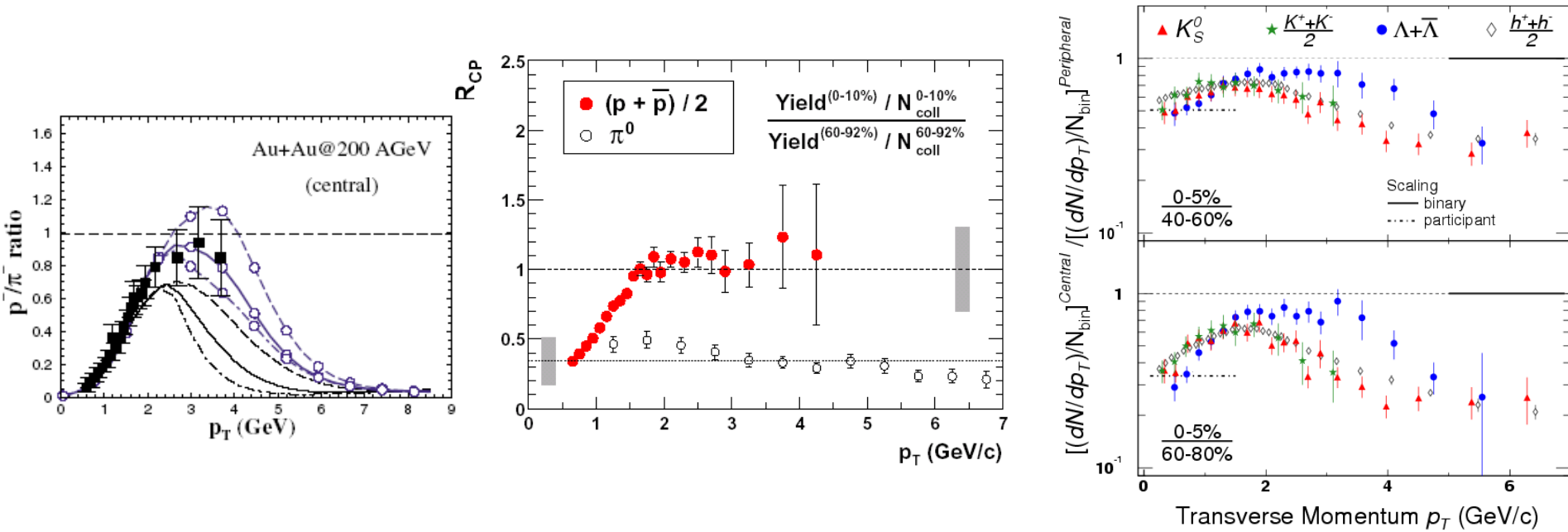


STAR: Nucl. Phys. A 757 (2005) 102

In central Au+Au collisions at RHIC: **Fragmentation ($q/g \rightarrow \text{hadrons}$) + energy loss** at $p_T > 6$ GeV/c:

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

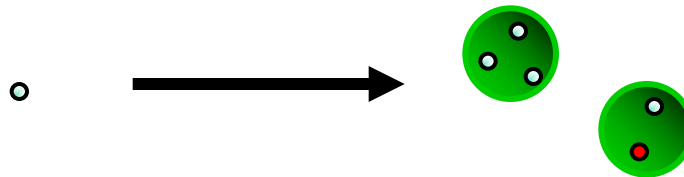
Intermediate p_T : baryon/meson pattern



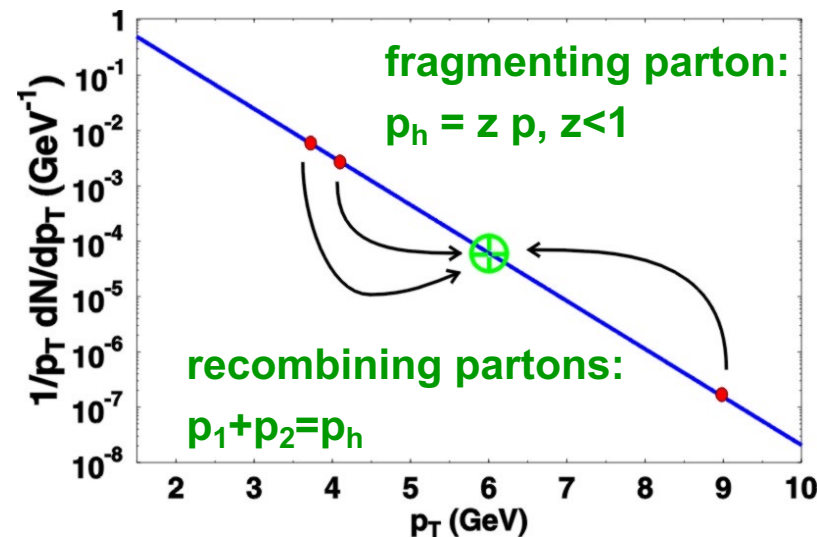
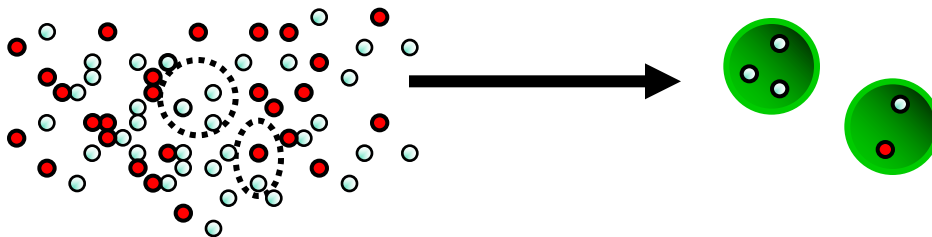
At $p_T \sim 2$ GeV/c, p/π ratio ~ 1 . $\rightarrow$ It can not be factorized jet fragmentation.

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



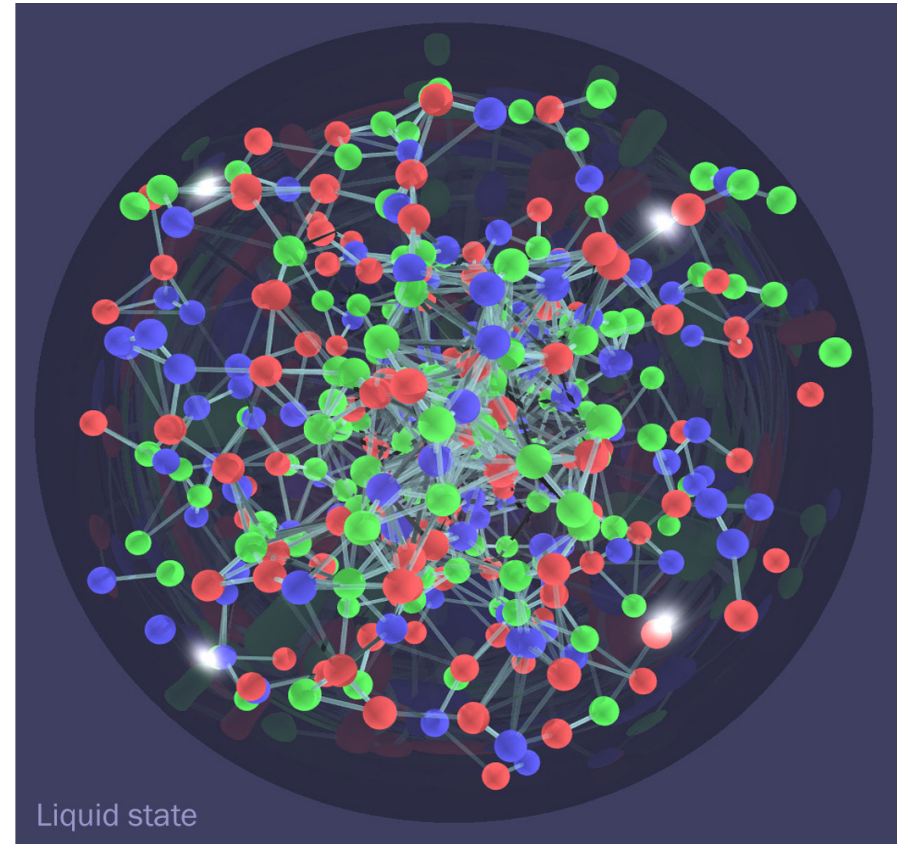
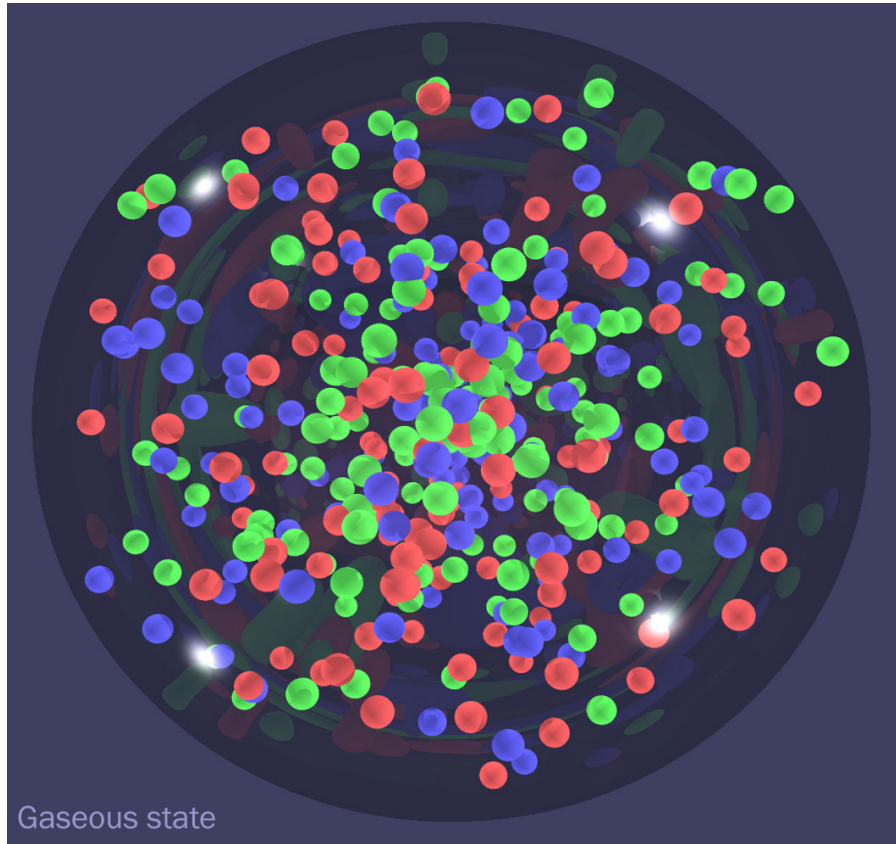
Fragmentation works for p+p collisions for hadrons at $p_T > 2$ GeV/c



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

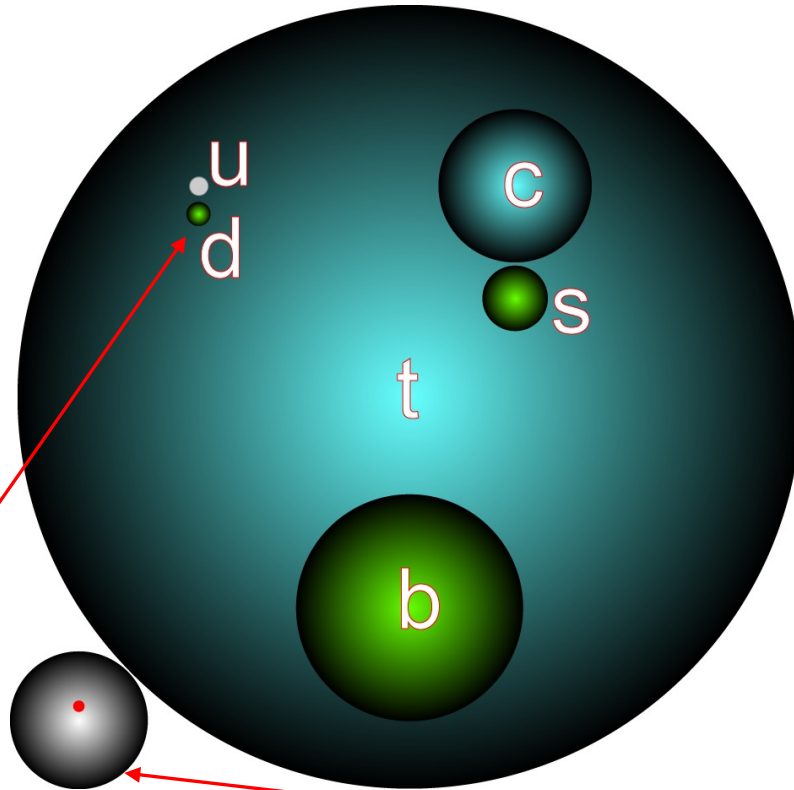


In 2005, BNL announced a discovery of perfect liquid at RHIC

<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.

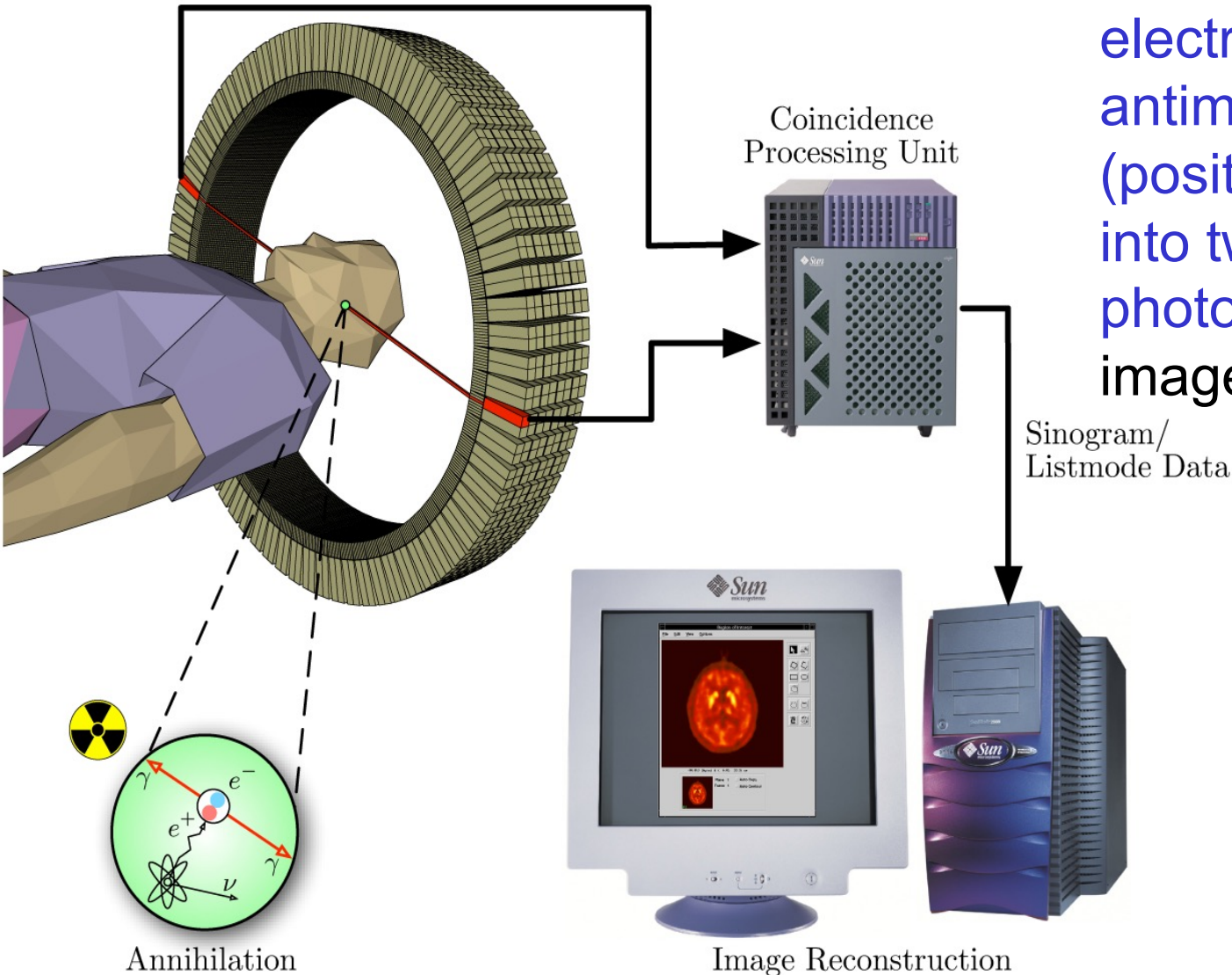
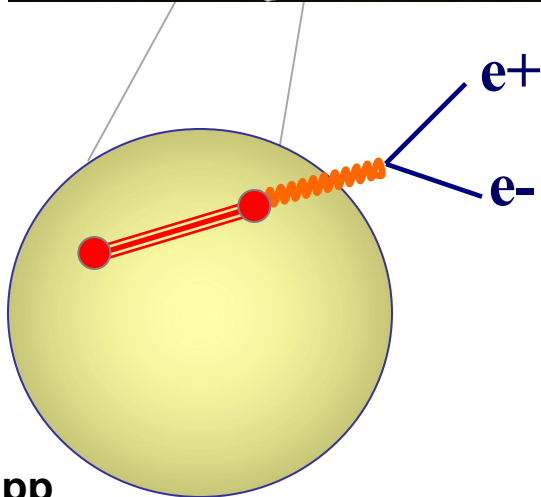
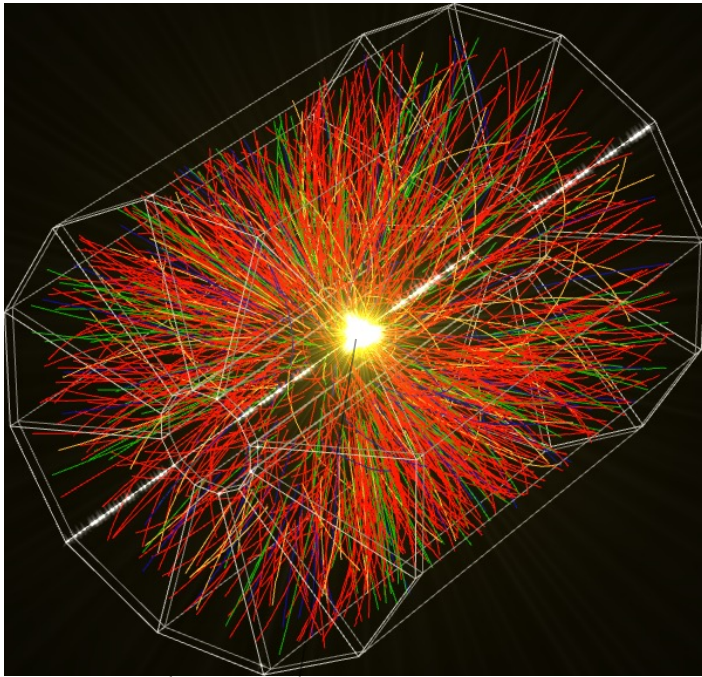


Image Reconstruction

Special PET scans (electron-positron tomography)

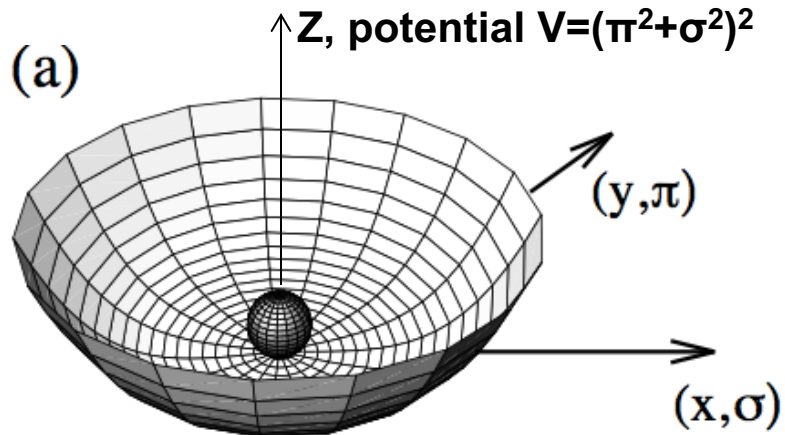


- In our method, we detect electron and positron pairs from quark-antiquark annihilation.
- Electron-positron pairs are penetrating probes and can provide information deep into the system and early time.
- Using electron-positron tomography, we would like to study the symmetry of the Quark-Gluon Plasma.

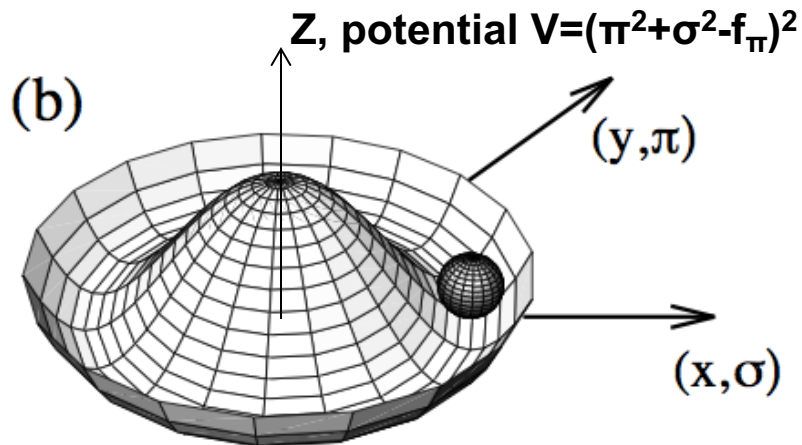
The Quark-Gluon Plasma

- 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

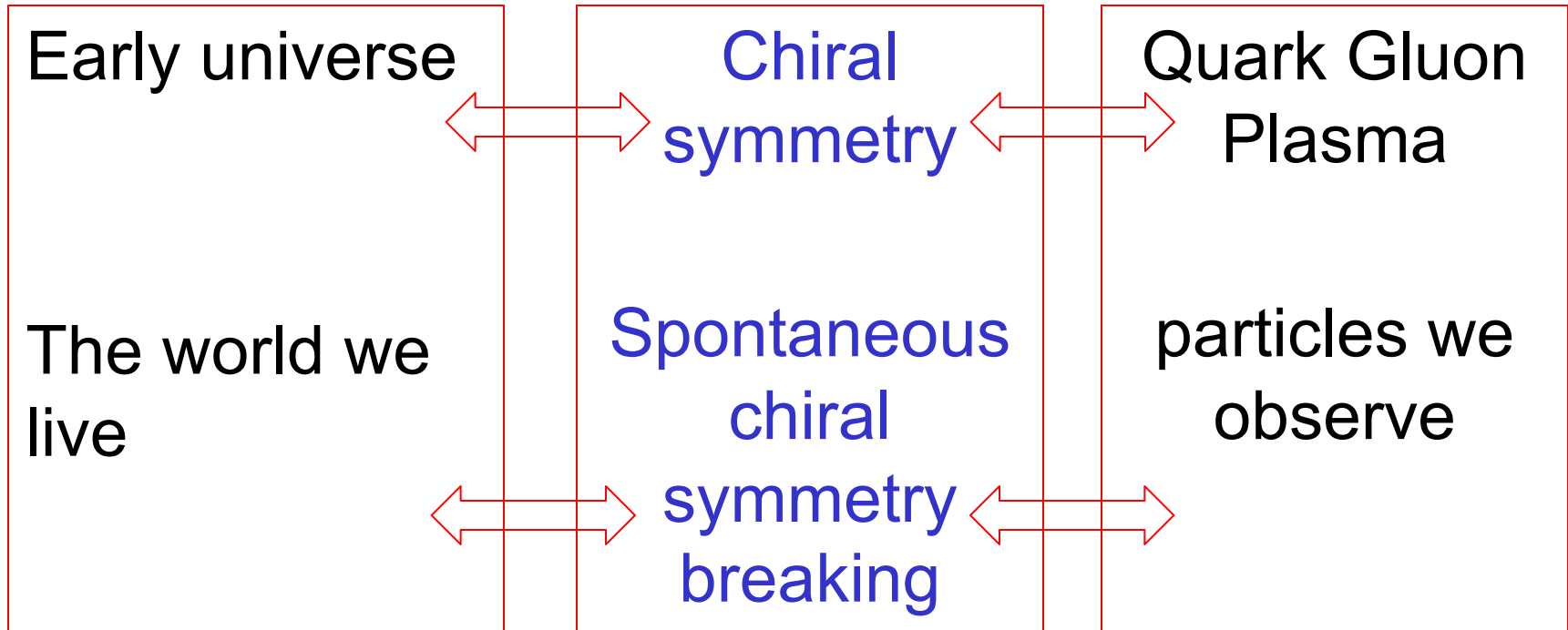
motion of the system: **potential + ball (ground state)**

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.

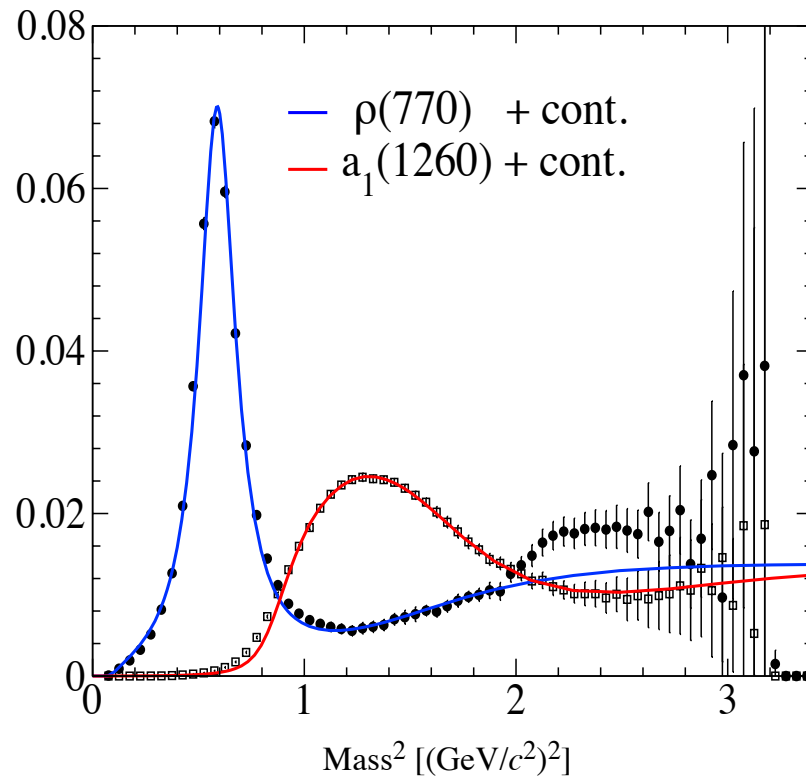
Is chiral symmetry restored in Quark-Gluon Plasma?



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

Do we have experimental observable?

ρ and a_1 resonance (spectrum function) in vacuum

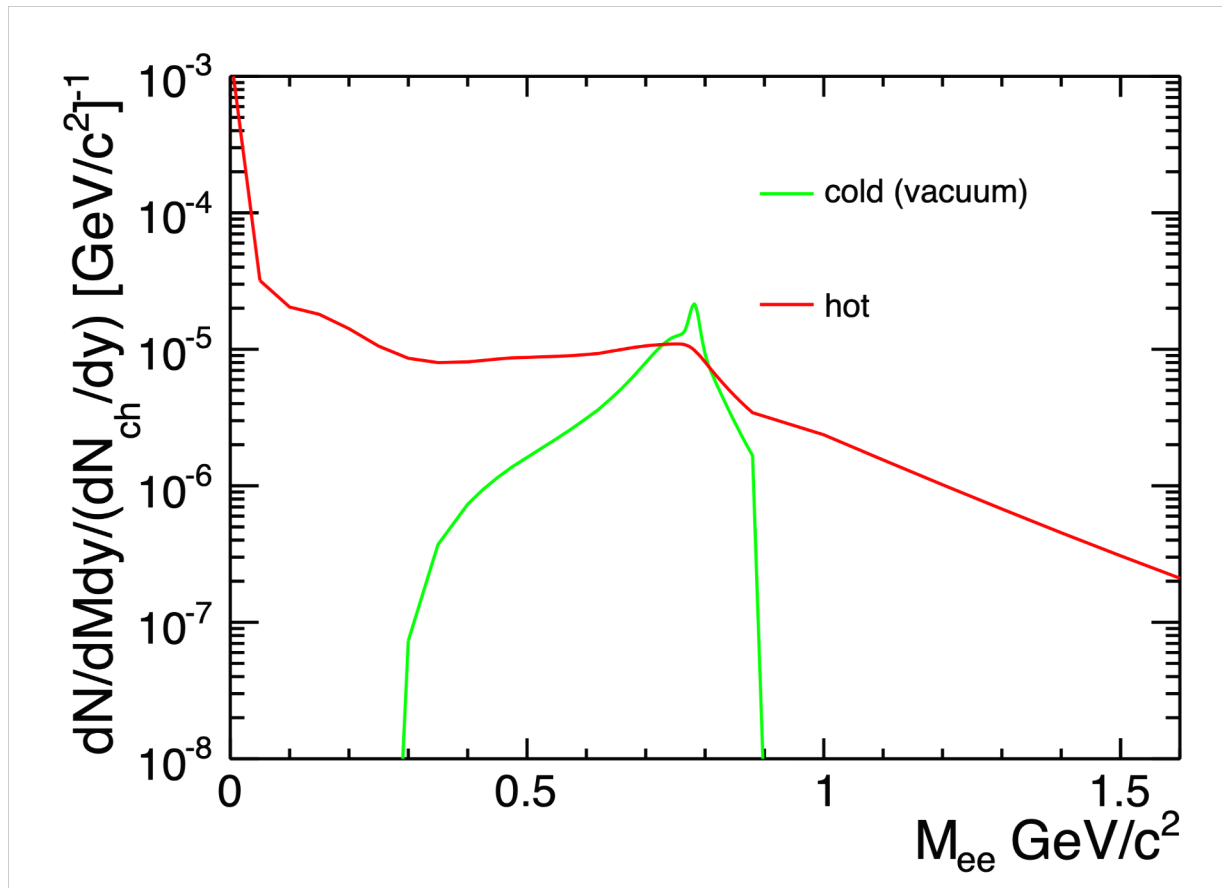


ALEPH: EPJC4 (1998) 409;
R. Rapp *Pramana* 60 (2003) 675.

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!

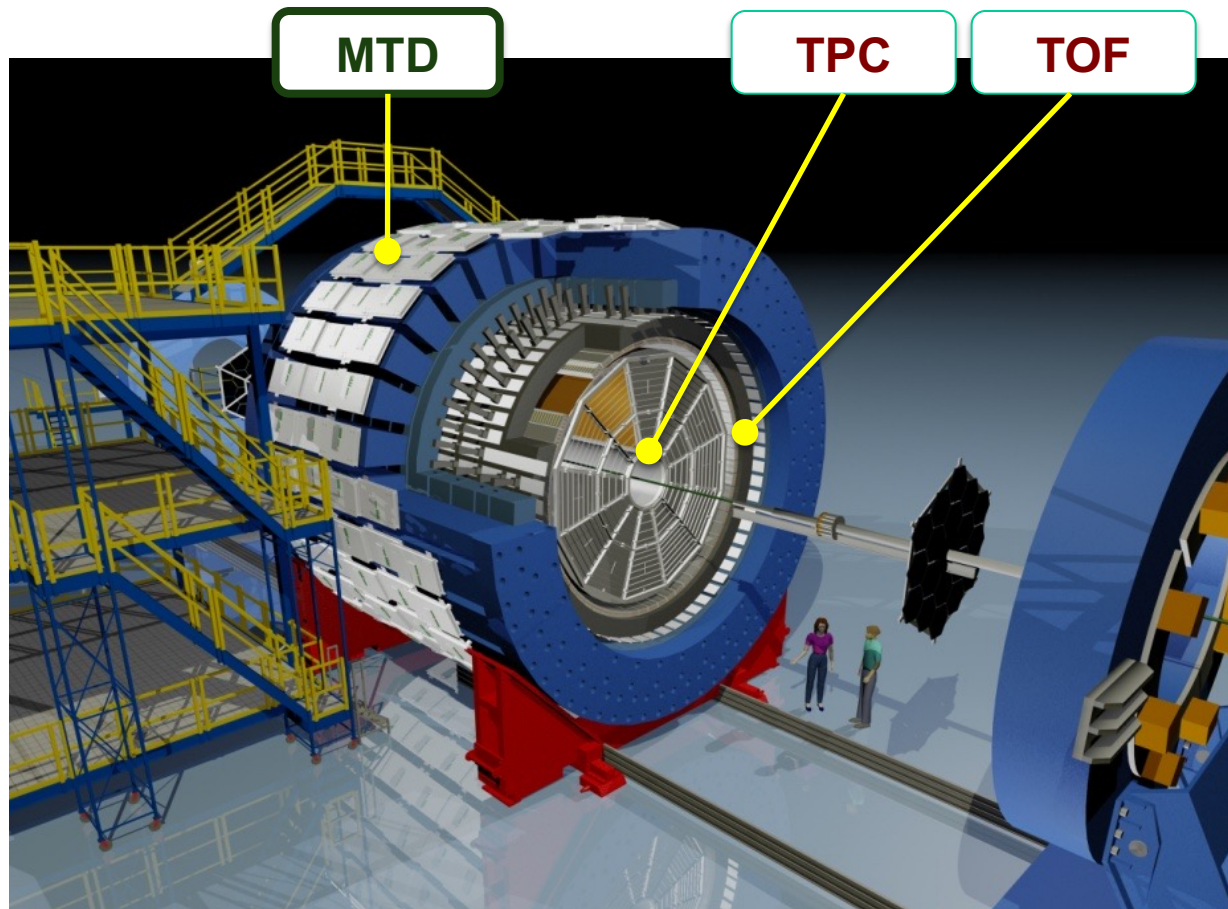
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

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

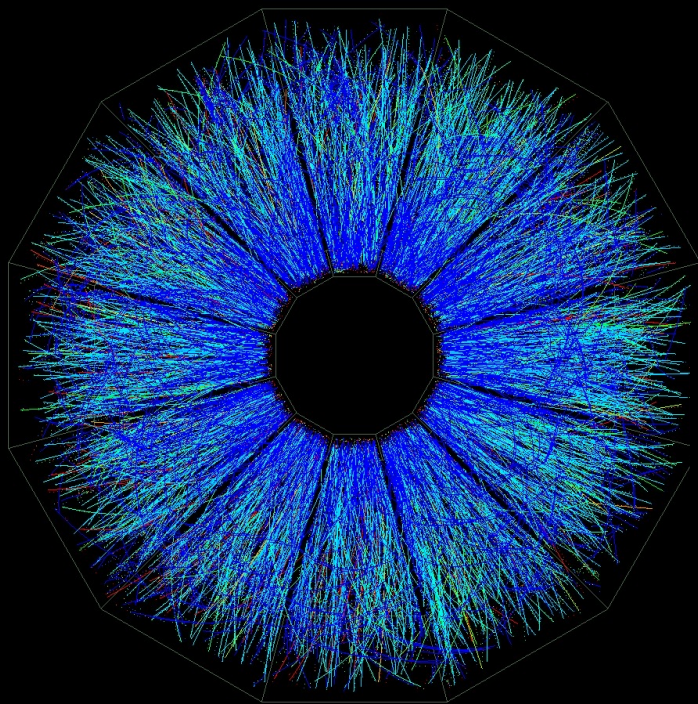


Solenoidal Tracker at RHIC (1200 tons)

Time Projection Chamber

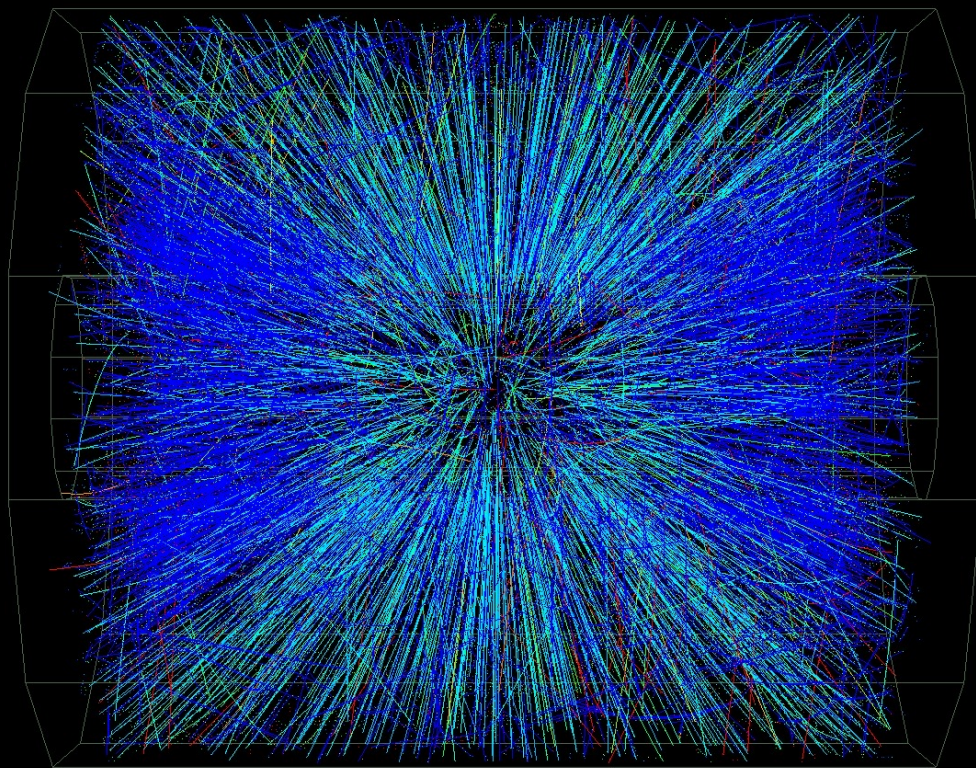
1. Second largest device of its kind ever built
2. 3D camera to take photos of the collisions
3. Measure ionization energy loss (dE/dx) and momentum

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



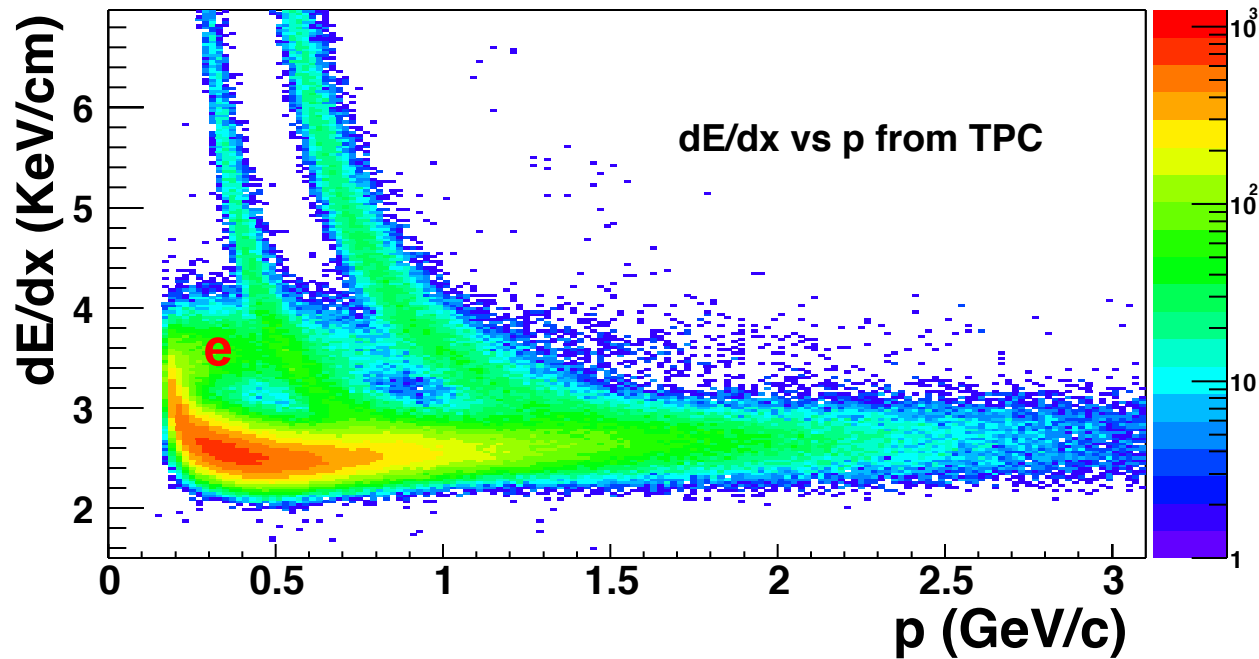
Central Event

$$E = m c^2$$



(real-time Level 3)

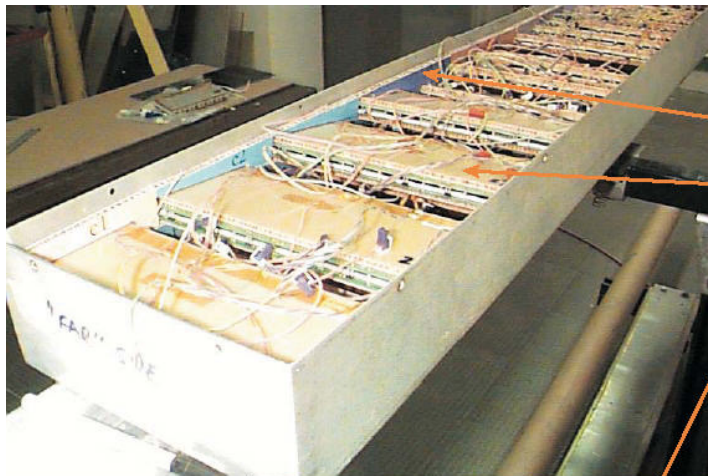
Particle identification



Electrons are difficult to find.

Need new experimental tool!

MRPC TOFr 2003

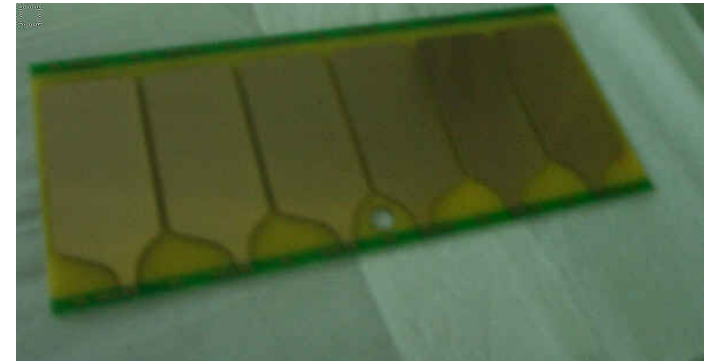
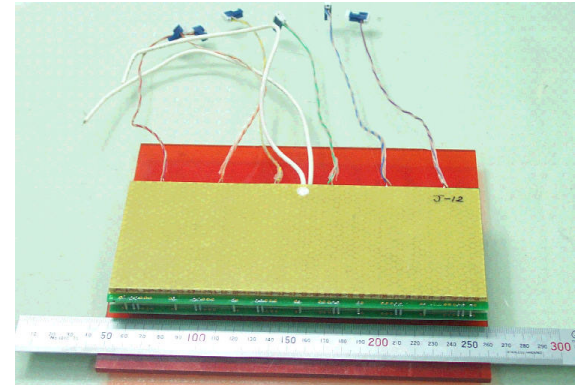
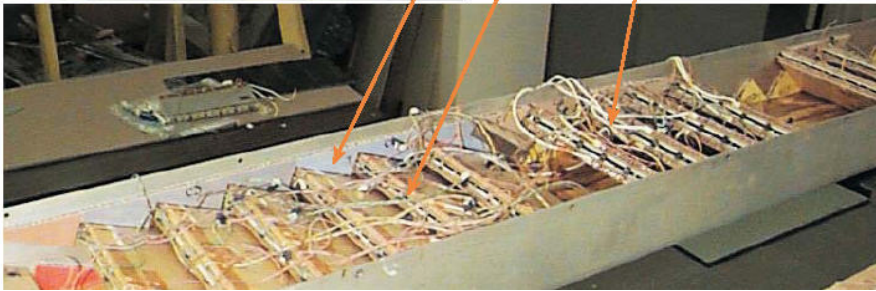


Detector Installation (cont.)

“C Piece” Sawtooths

USTC MGRPC

CERN MGRPC

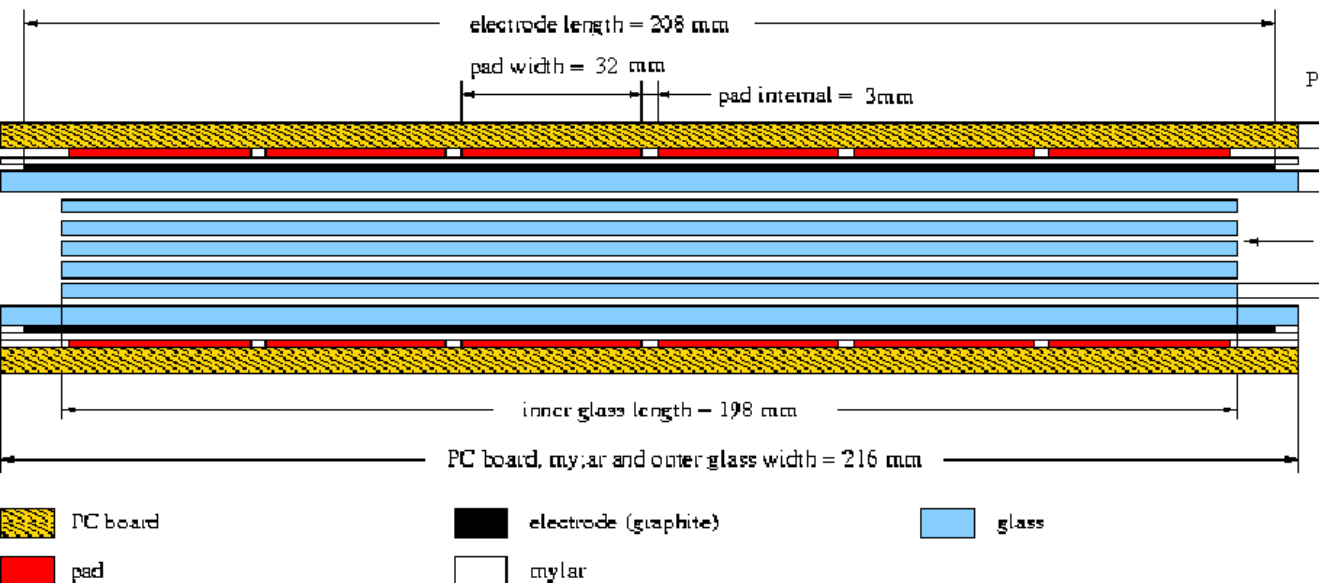
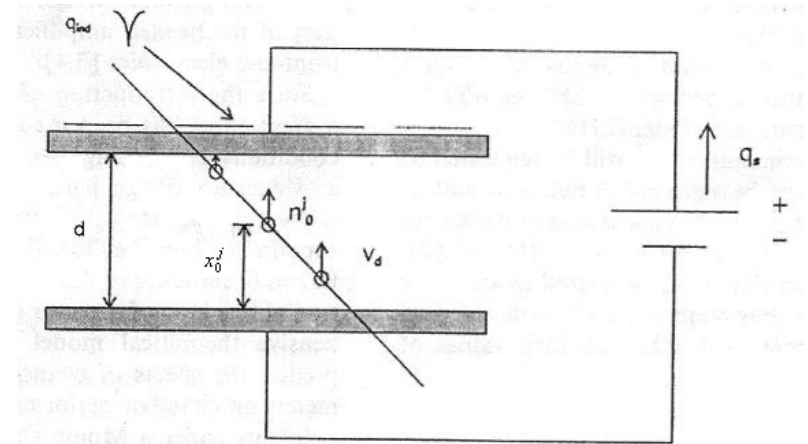
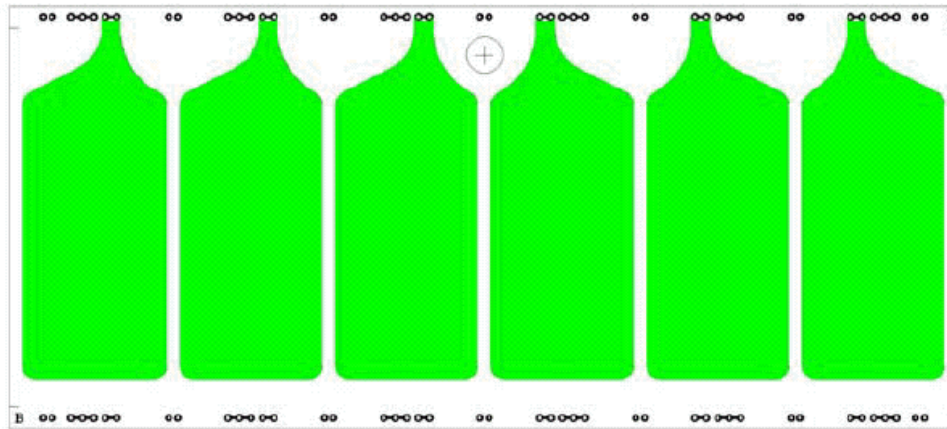


Multigap Resistive Plate Chamber (MRPC) Technology

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

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

Structure of MRPC Module

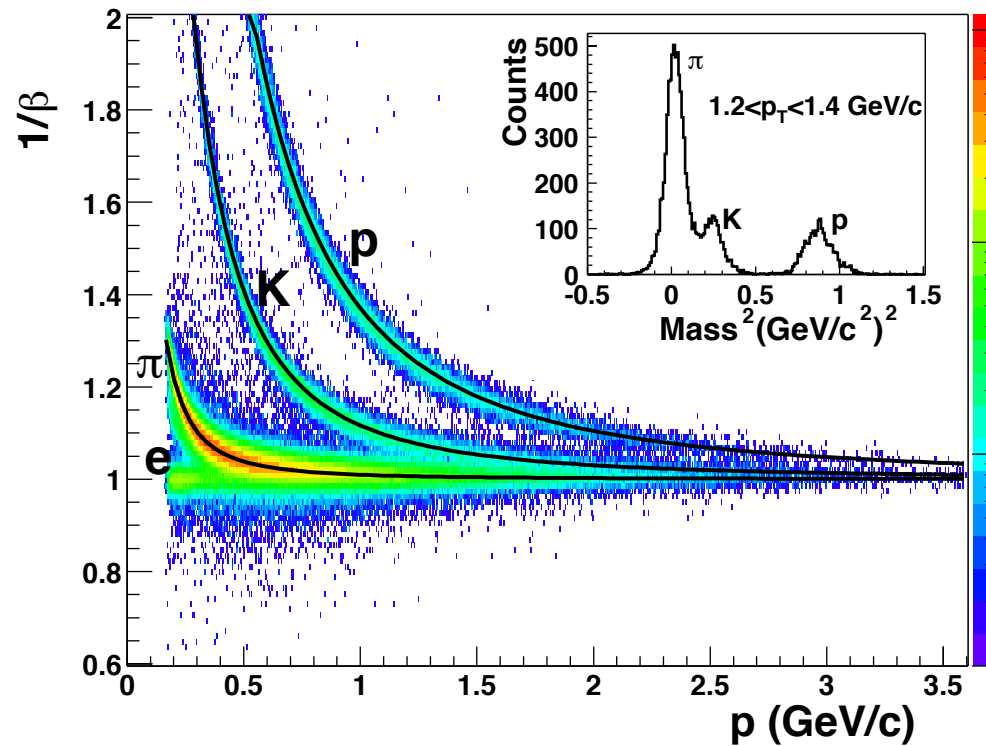


**Read out pad size:
3.15cm × 6.3cm,
gap: 6 × 0.22mm**

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

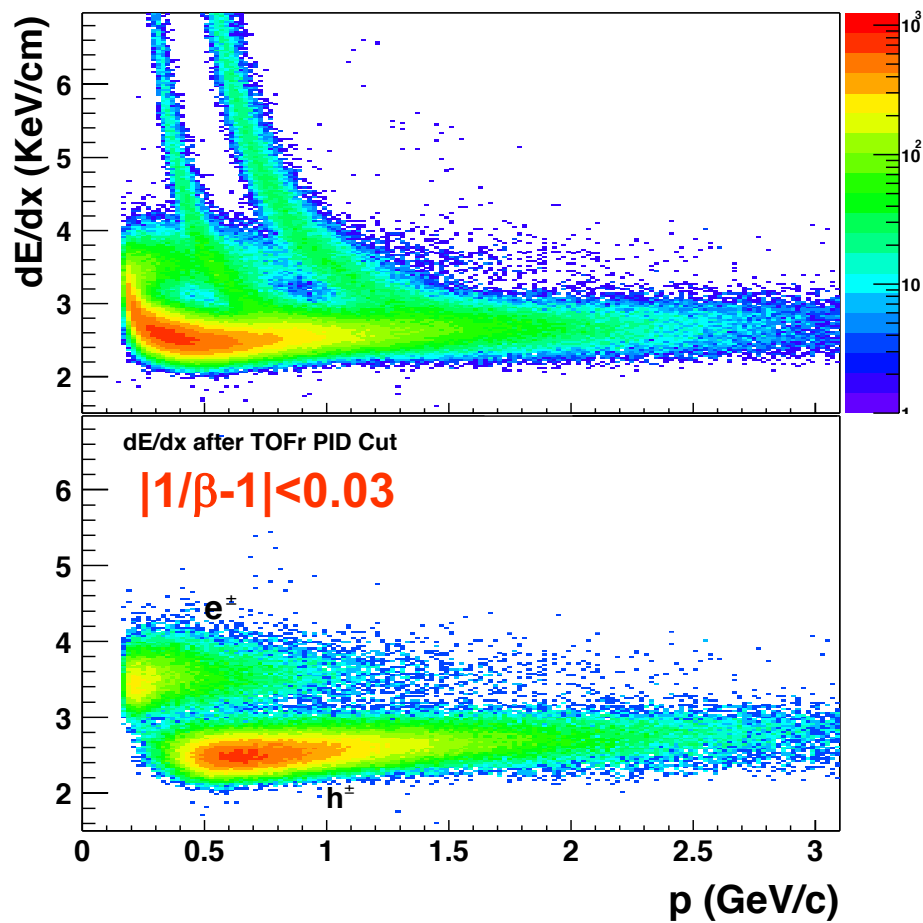
Particle identification from TOFr



STAR Collaboration, PLB616(2005)8

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

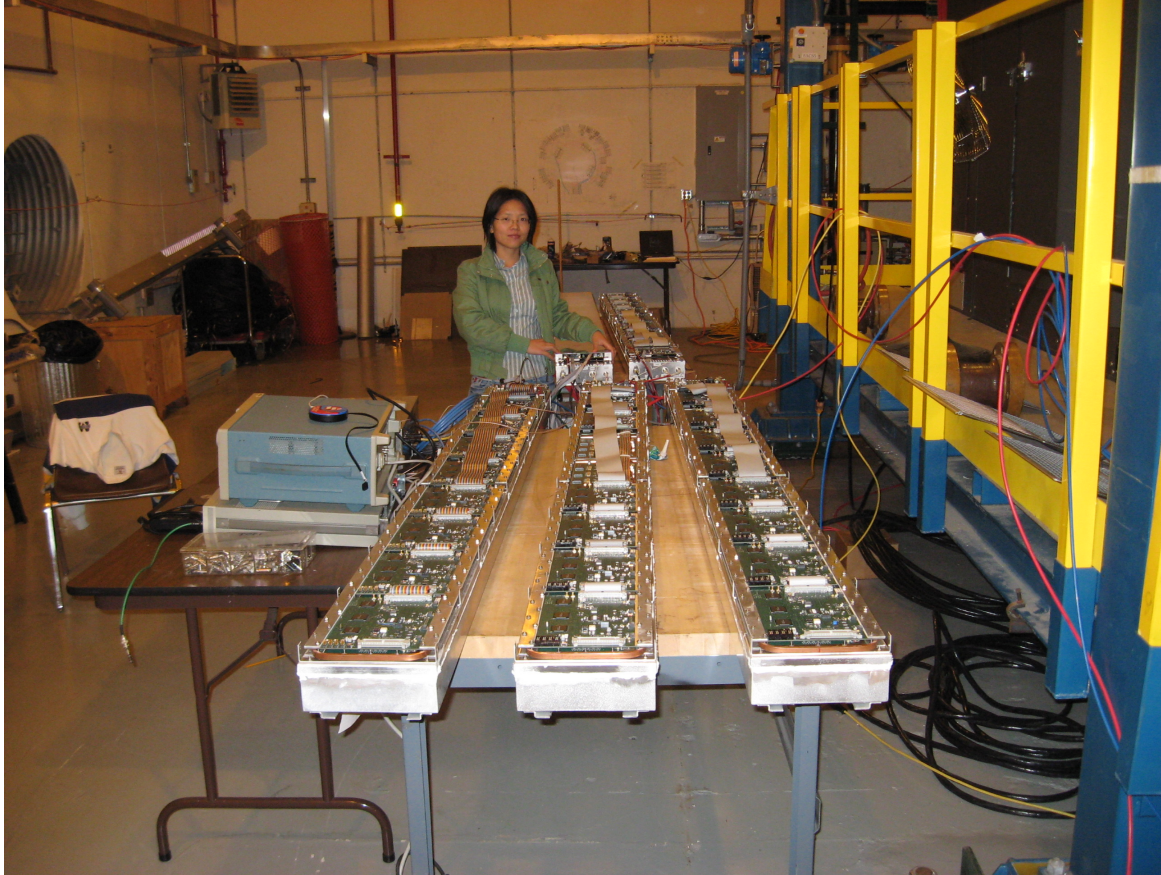
Electron identification



Clean electron samples!

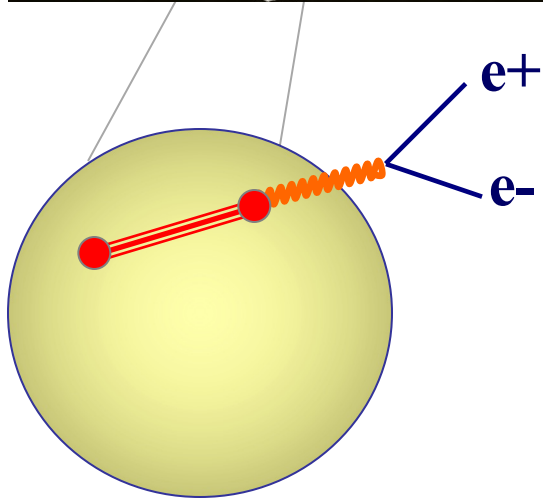
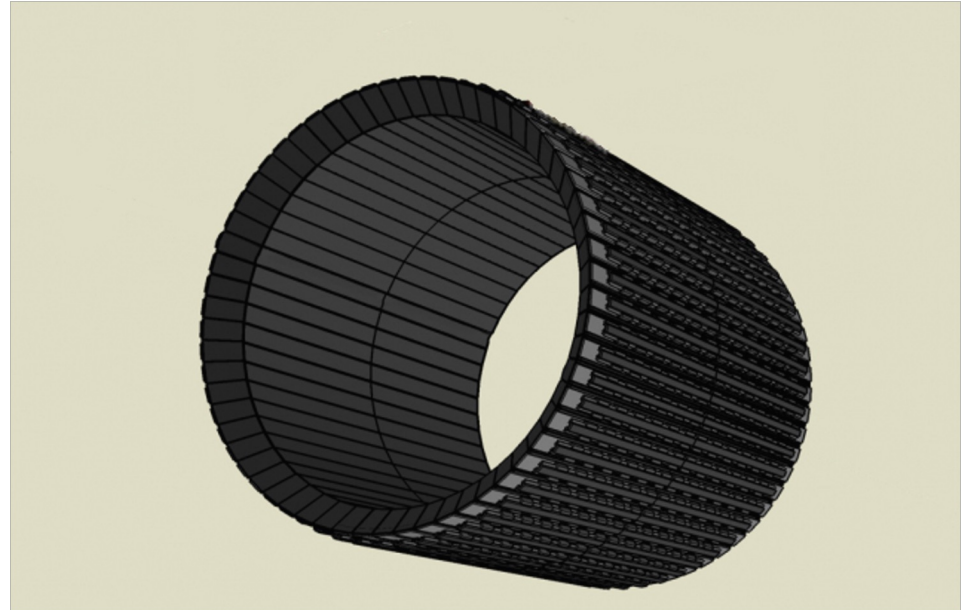
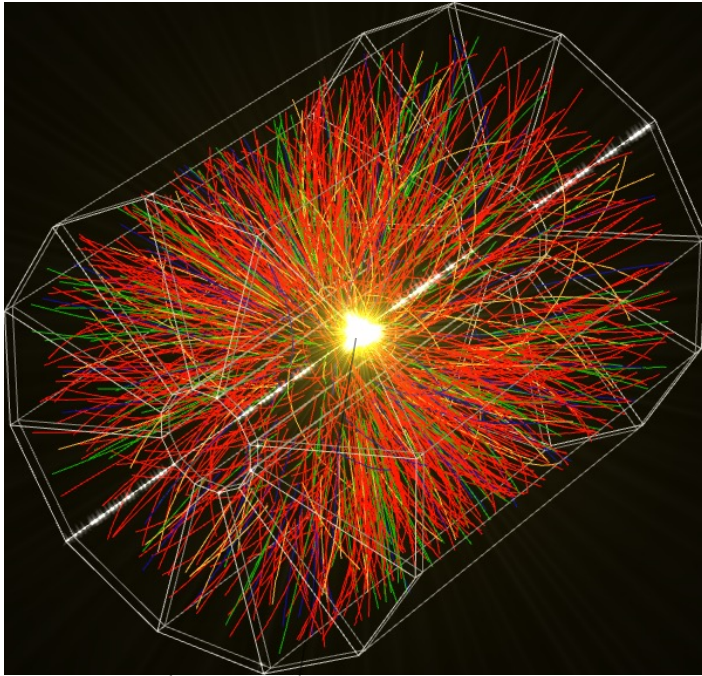
STAR Collaboration, PRL94(2005)062301

Time of Flight Detector upgrade



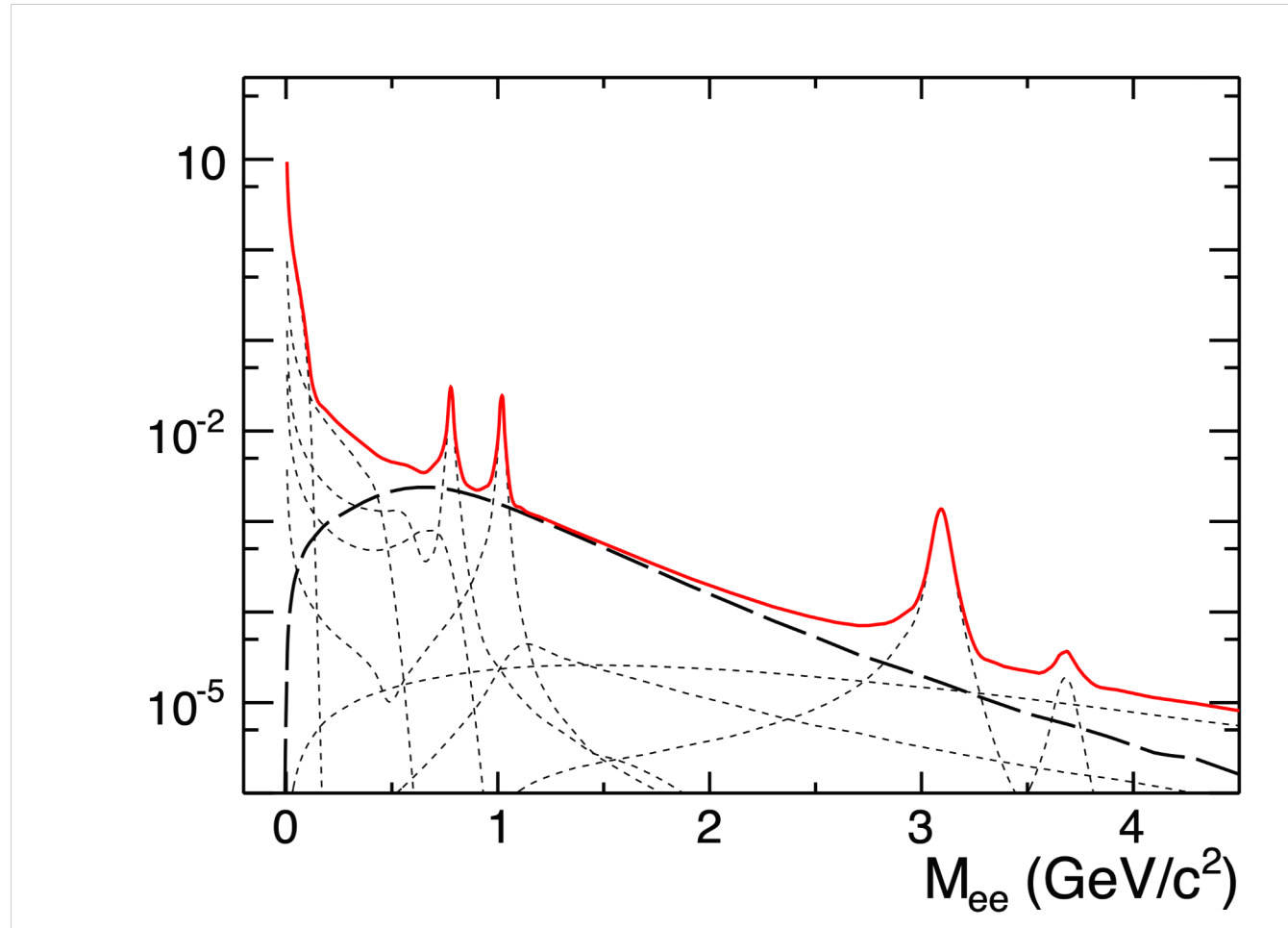
US-China Collaboration, 120 units in total:
2008: 4%; 2009: 72%; 2010: 100%

The special PET scan tools are now ready



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

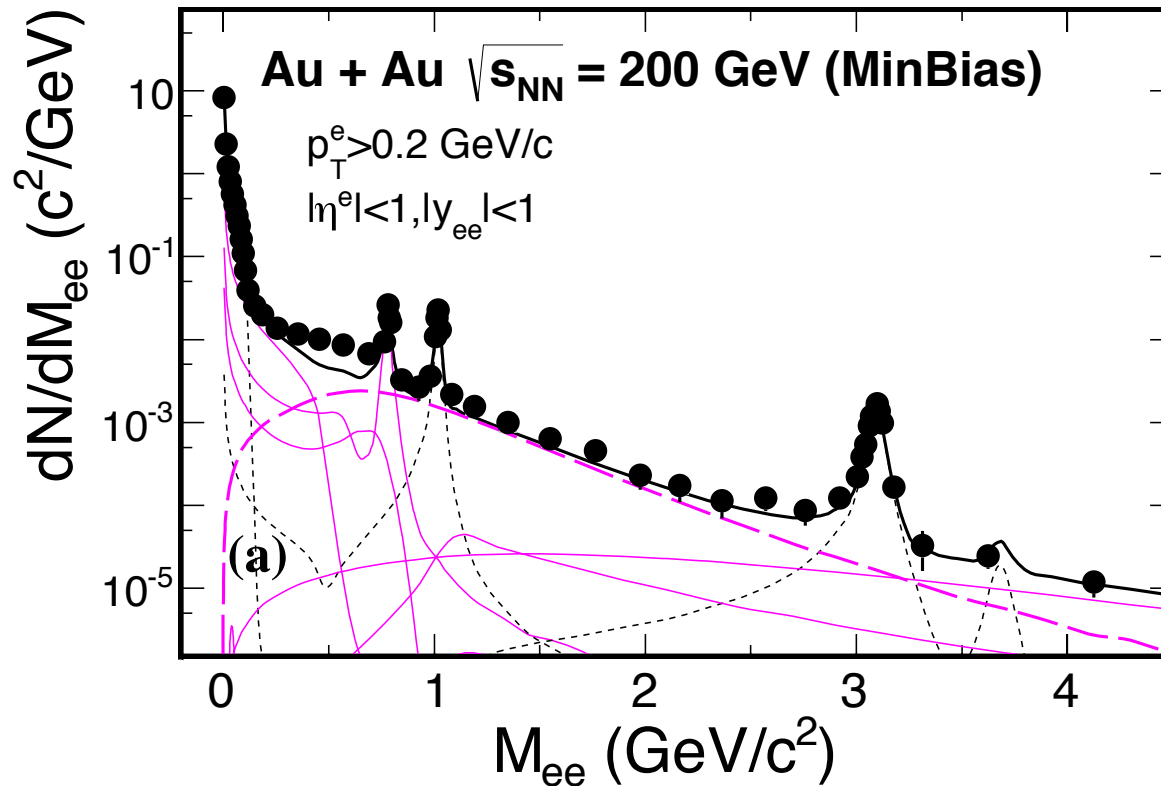
Electron-positron emission mass spectrum



In empty space (vacuum)

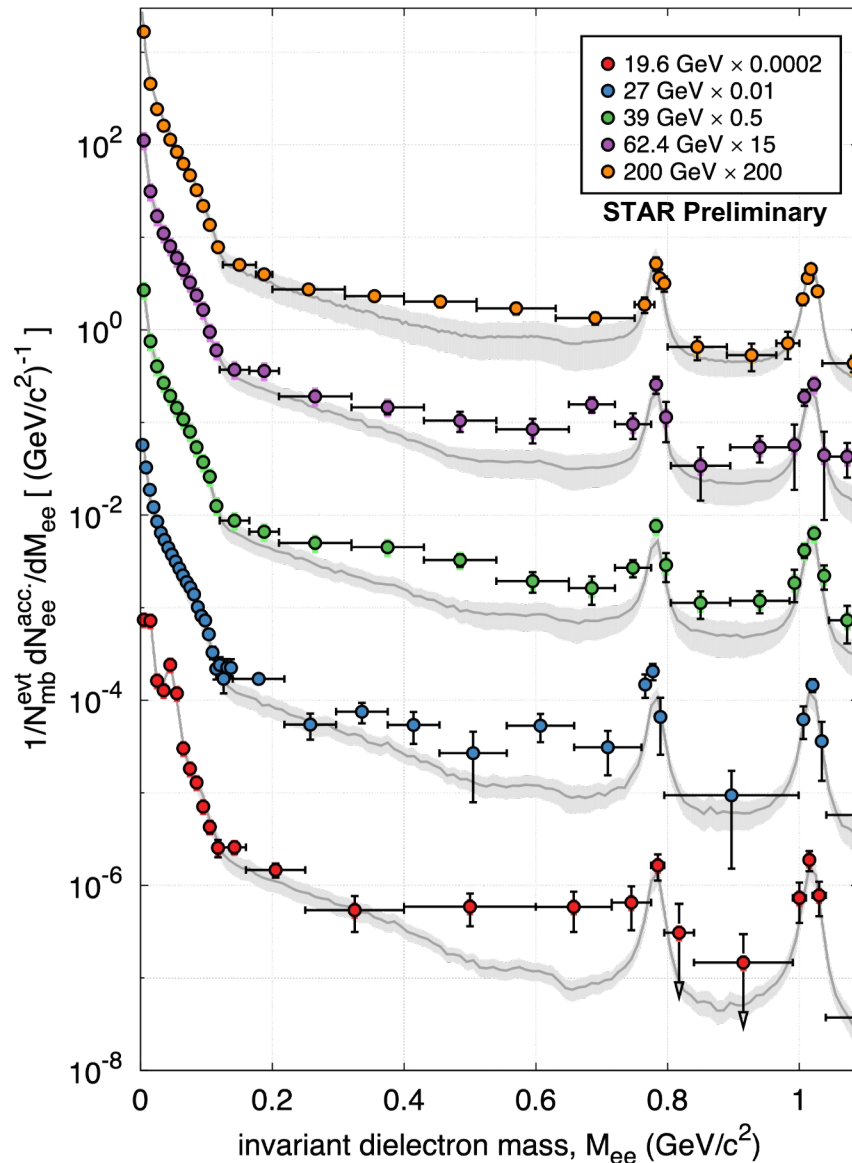
Electron positron emission mass spectrum in 200 GeV Au+Au

PRL113 (2014) 022301



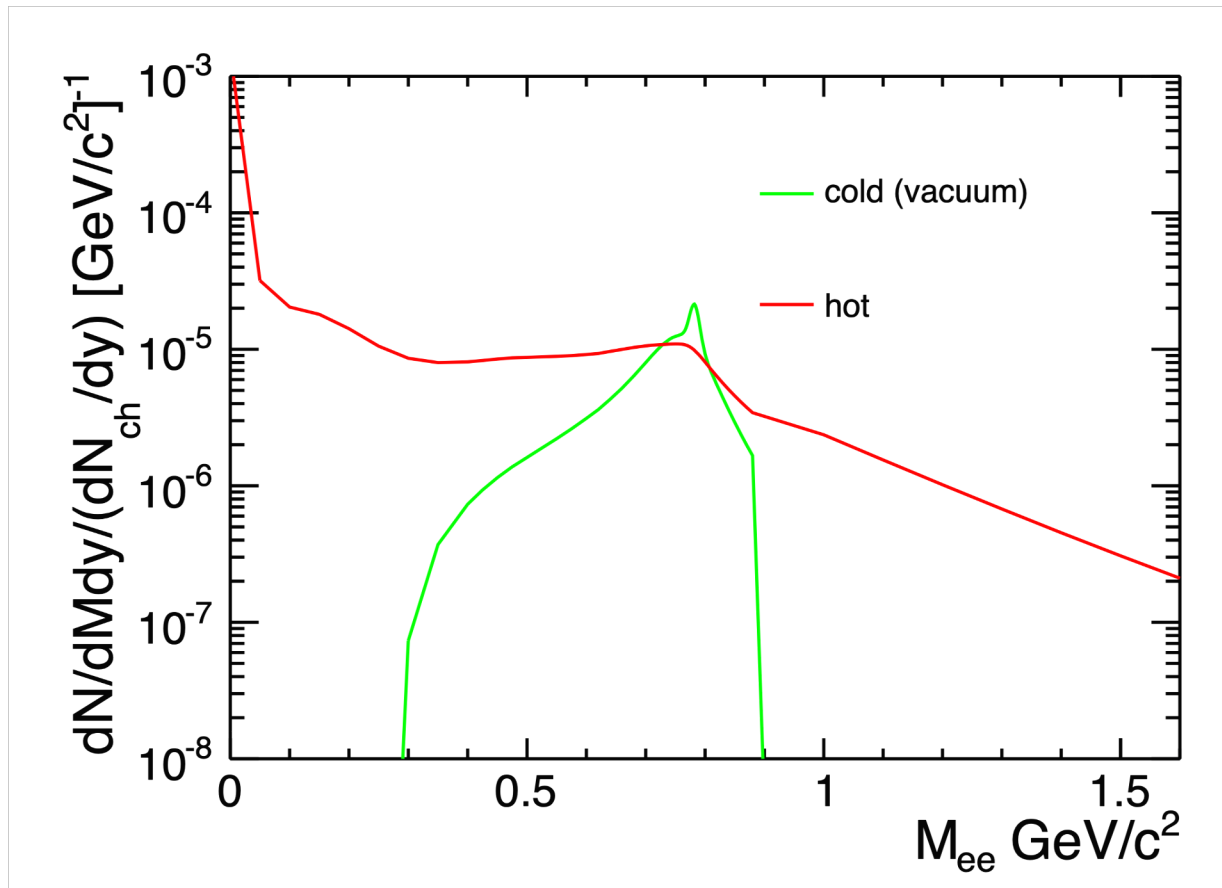
There are “hot” contributions!

Electron-positron emission at lower energies



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

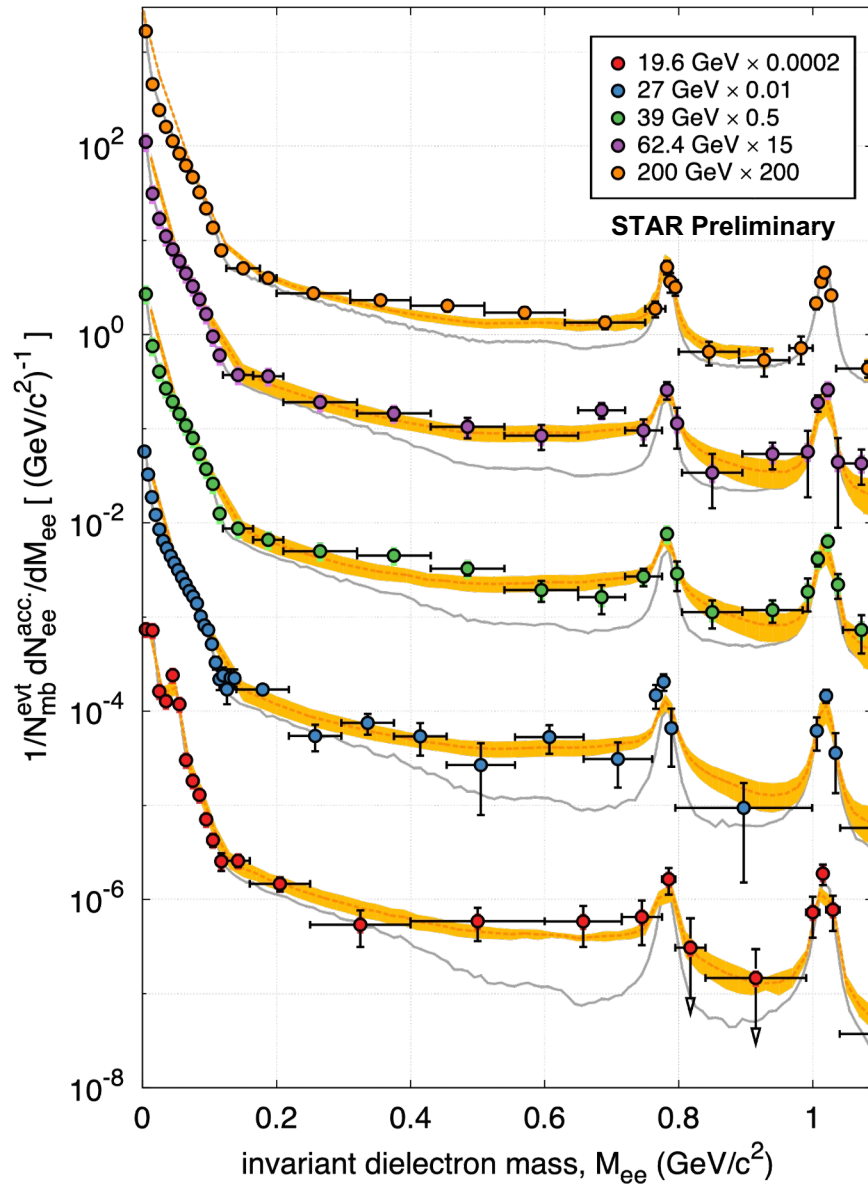
The “hot” mass distribution in 200 GeV Au+Au



The “hot” contribution is modified and broadened!

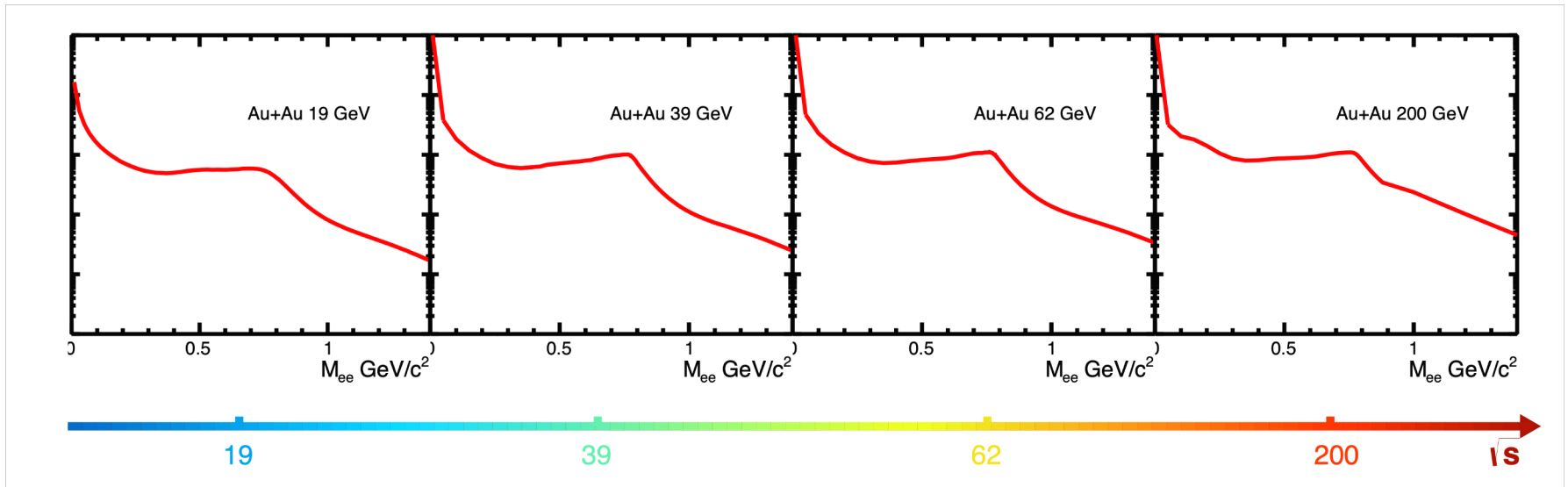
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

Electron-positron emission at lower energies



Observed “hot” distributions
are **broadened!**

The “hot” contribution

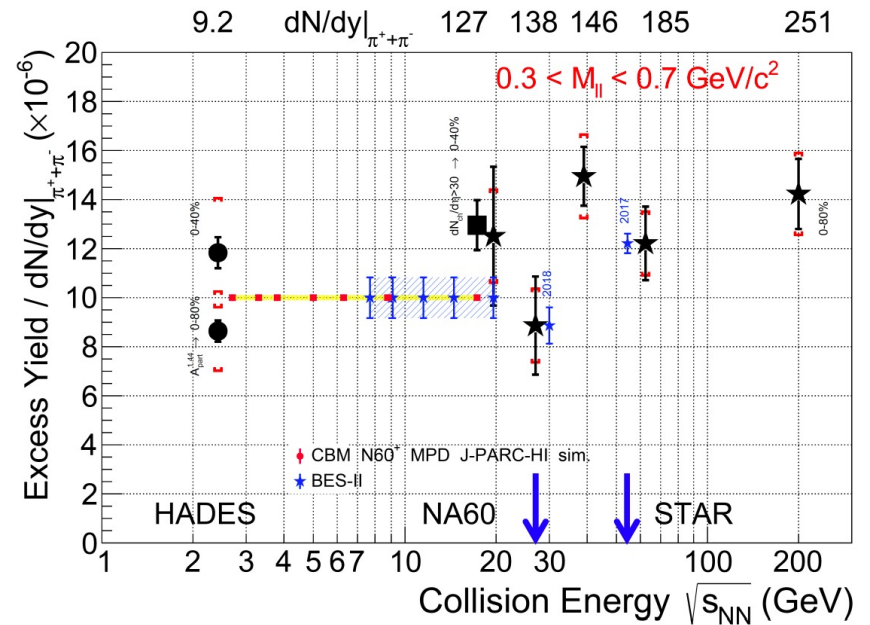
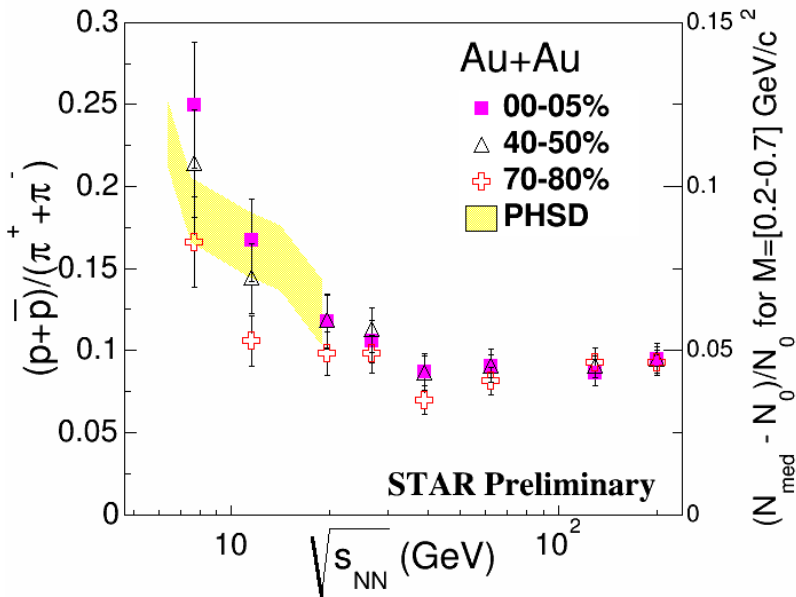
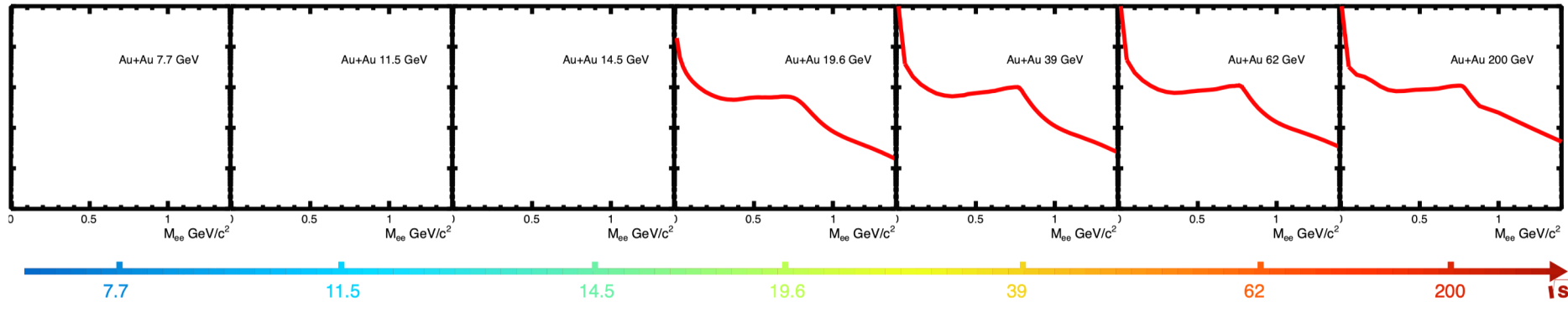


The electron-positron spectrum **from hot, dense medium** is consistent with a broadened ρ resonance in medium and the production yield normalized by dN_{ch}/dy is similar from 19.6 to 200 GeV.

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

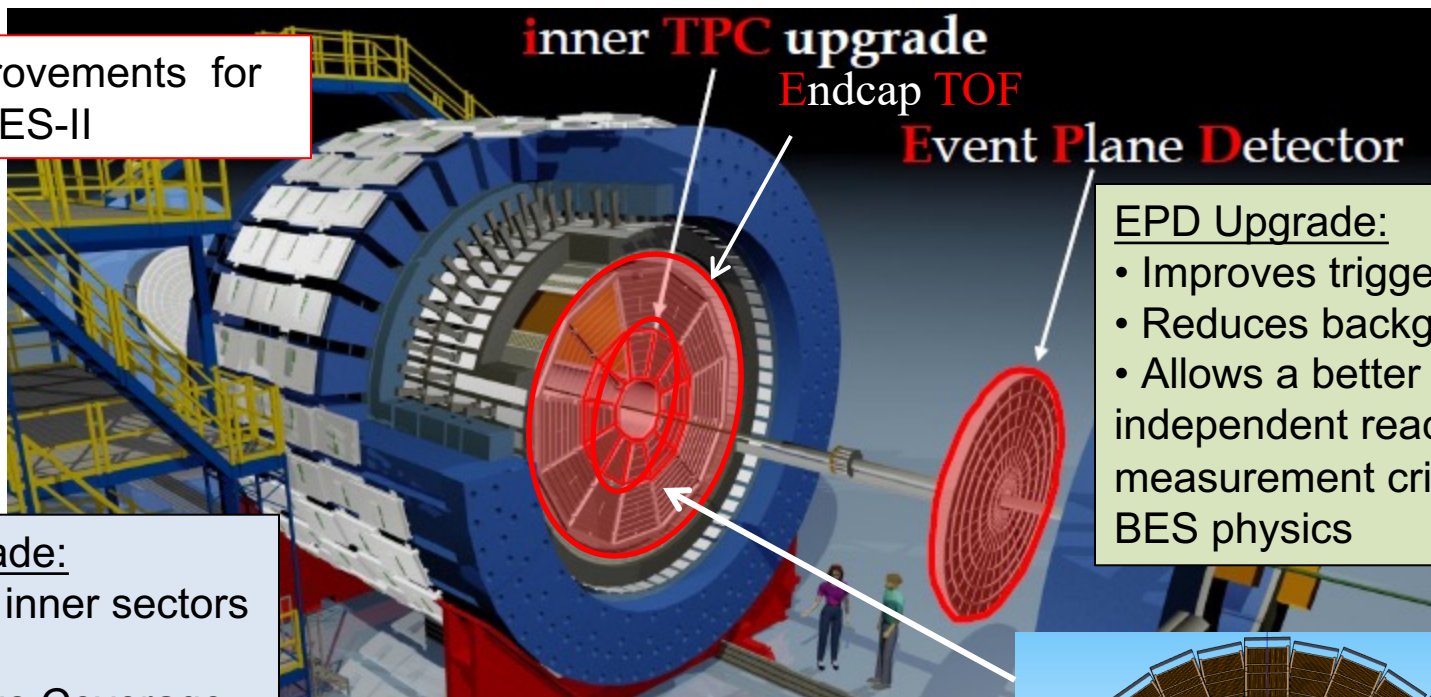


Broader and more “hot” contribution down to 7.7 GeV collision energy?

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



iTPC Upgrade:

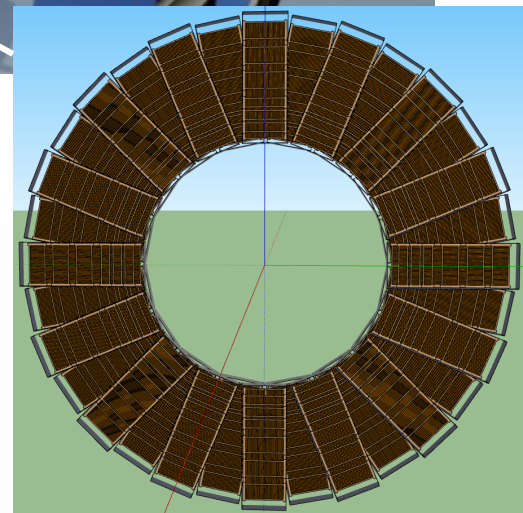
- Replaced inner sectors of the TPC
- Continuous Coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut from 125 MeV/c to 60 MeV/c

EndCap TOF Upgrade:

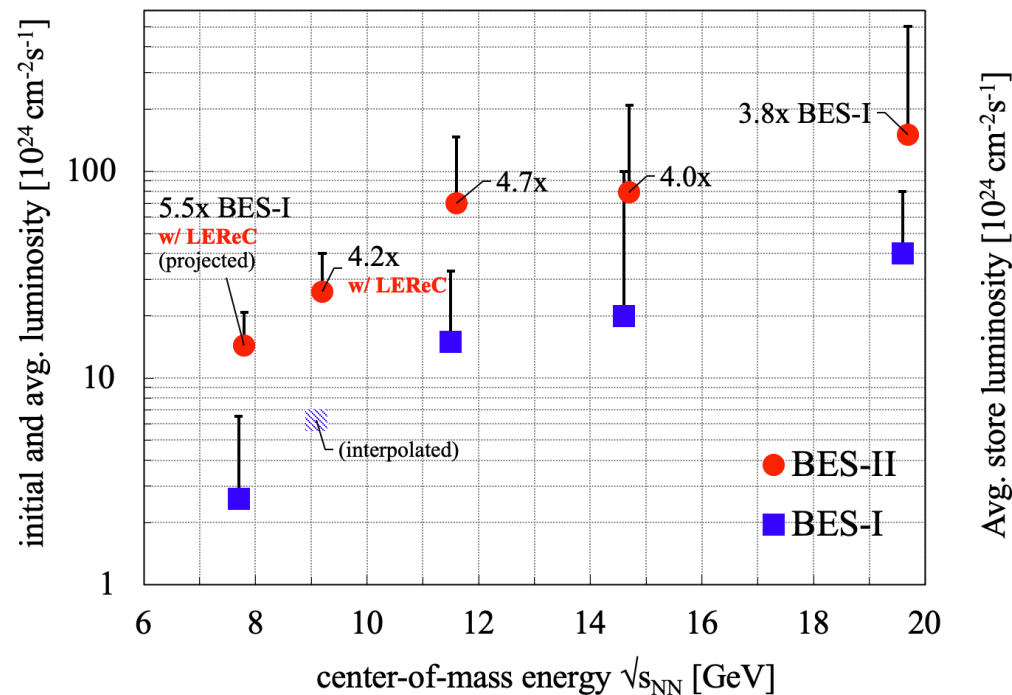
- Rapidity coverage is critical
- PID at $\eta = 1$ to 1.5
- Improves the fixed target program
- Provided by CBM-FAIR

EPD Upgrade:

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



Beam Energy Scan II in 2019-2021

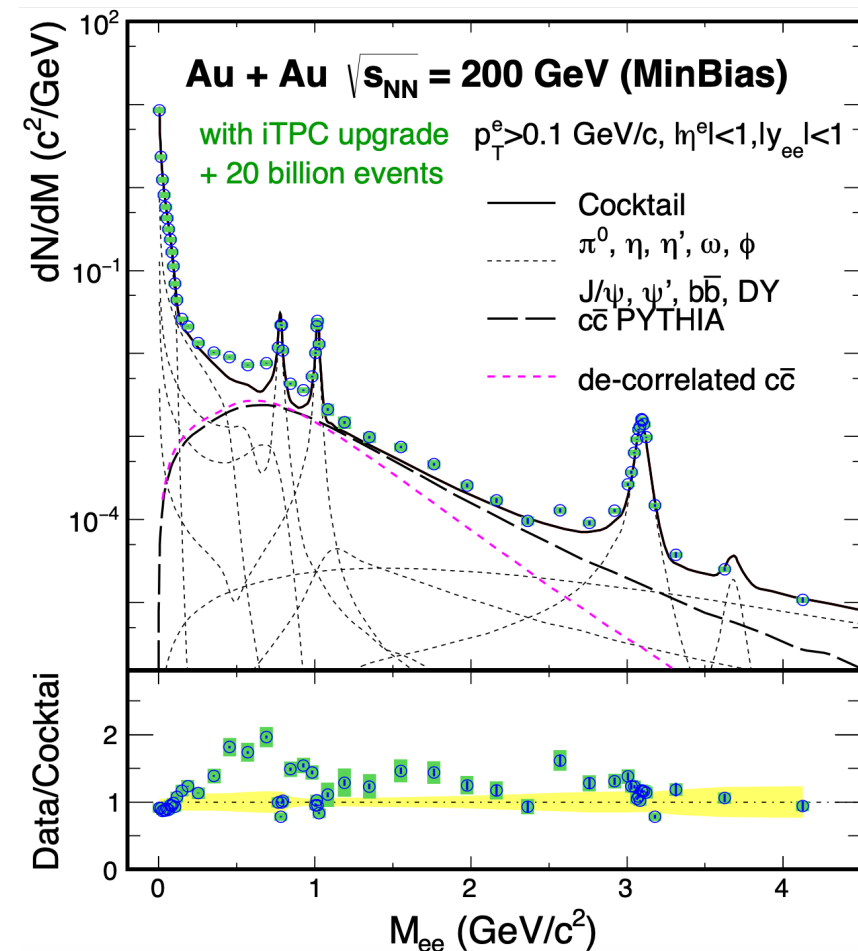


RHIC is unique to study chiral symmetry restoration:

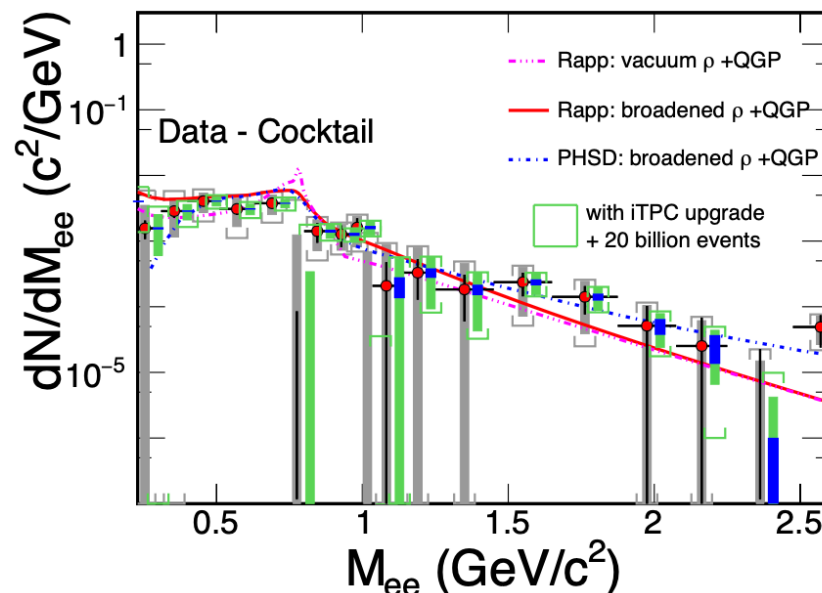
Beam energy scan II: collision energies 7.7, 9.1, 11.5, 14.5, 19.6 GeV.

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

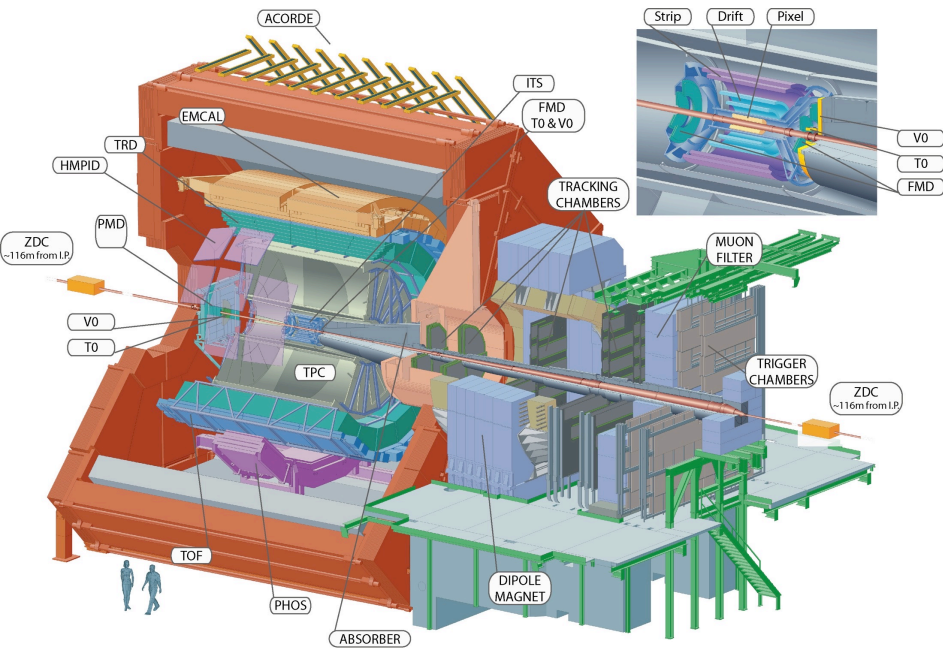


Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at $\mu_B=0$

Intermediate mass: direct thermometer to measure temperature

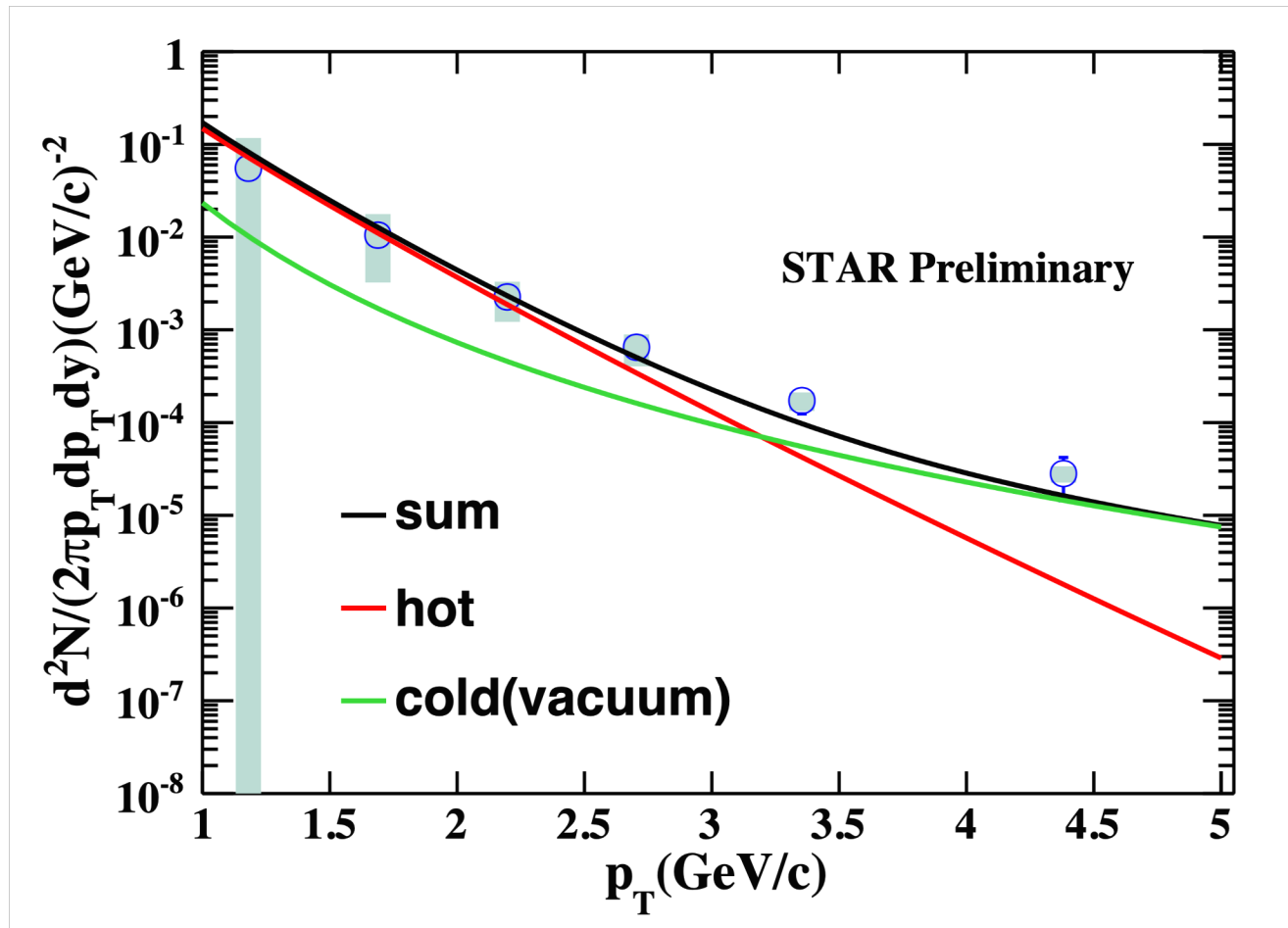
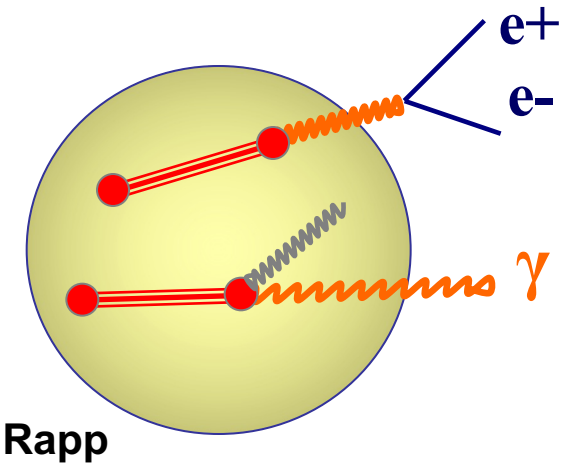
Enable dielectron v_2 and polarization, and solve direct photon puzzle (STAR vs PHENIX)

World-wide interest



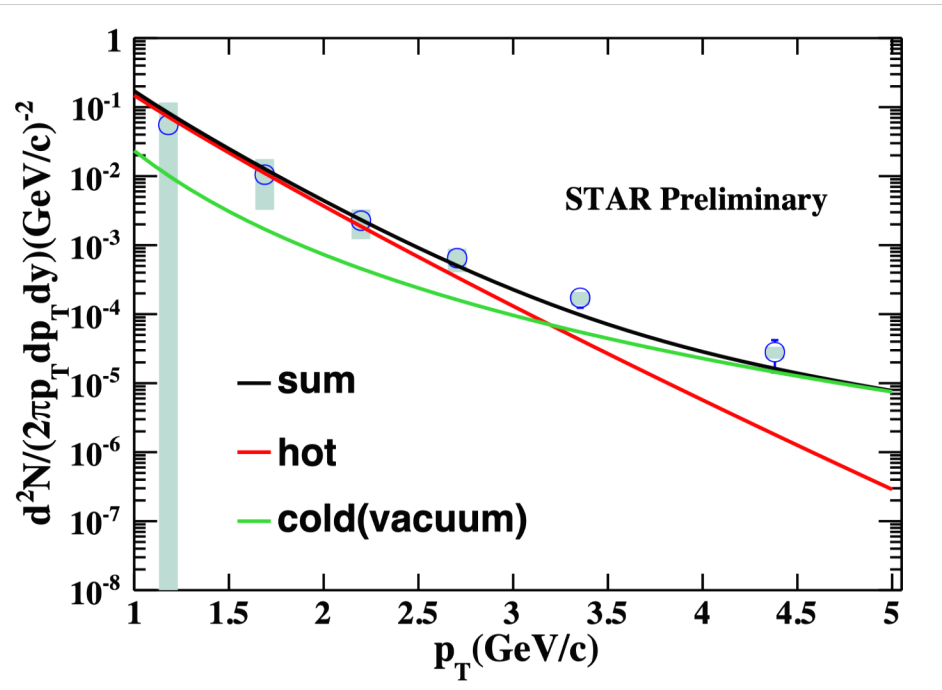
- World interest: SPS, PHENIX, LHC, FAIR, NICA, KEK

Photon emission



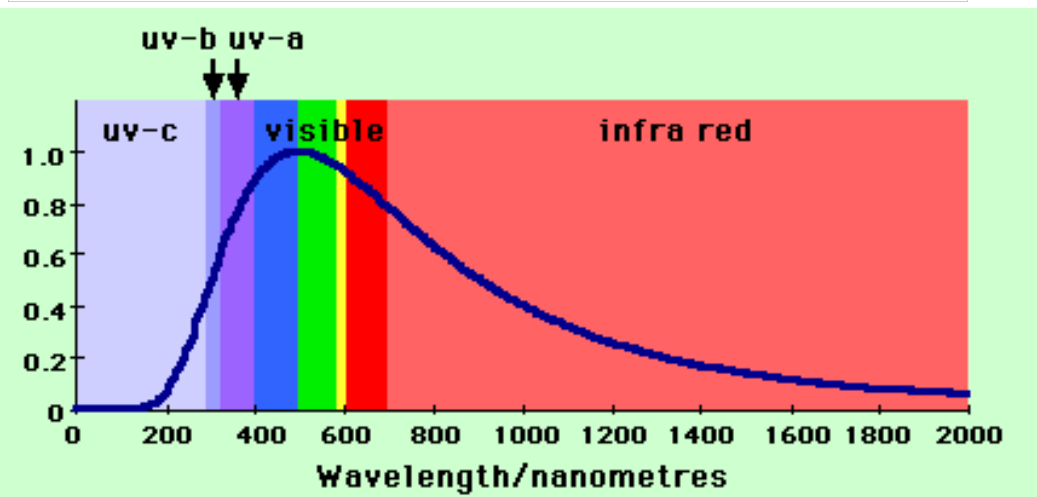
Hot contribution observed in the photon energy spectrum!

Photon emission



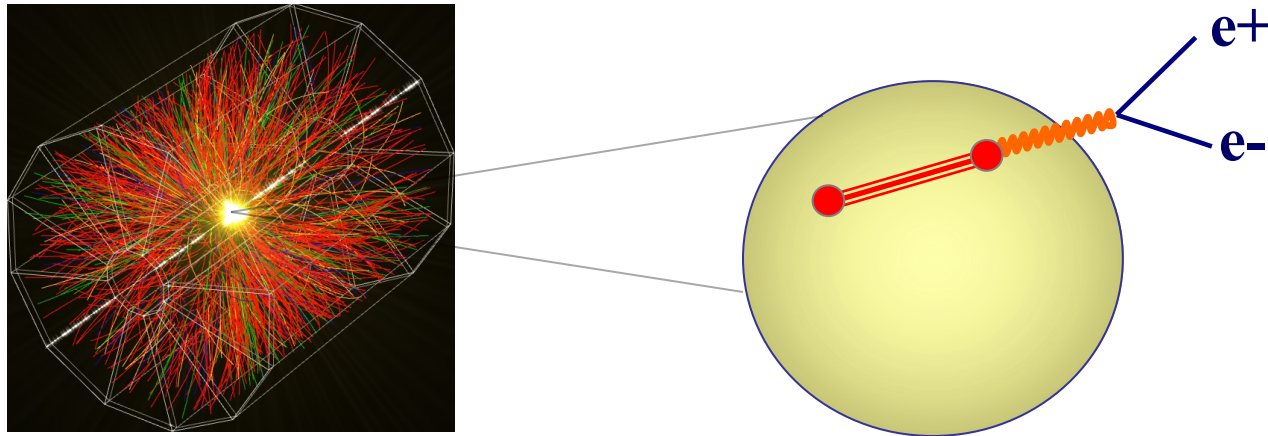
Quark-Gluon Plasma
emission spectrum:
photon energy a few 10^9
electron volts

Sun emission spectrum:
Photon energy a few
electron volts.

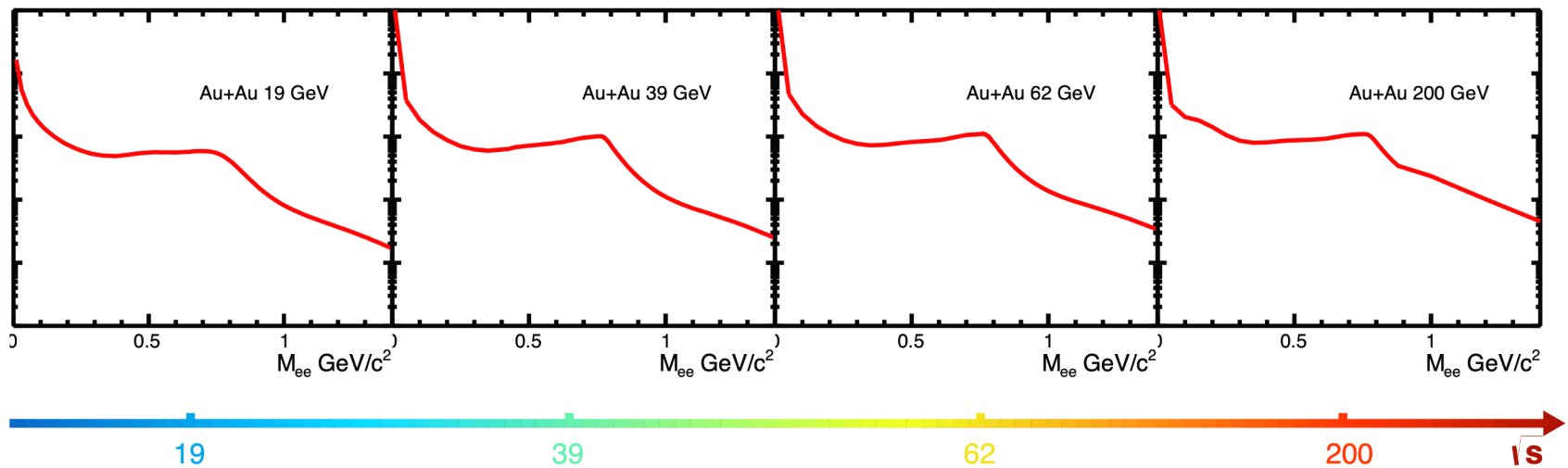


Hottest matter in the
universe: a few trillion
degree Celsius!

Summary



Electron-positron tomography of Quark-Gluon Plasma:

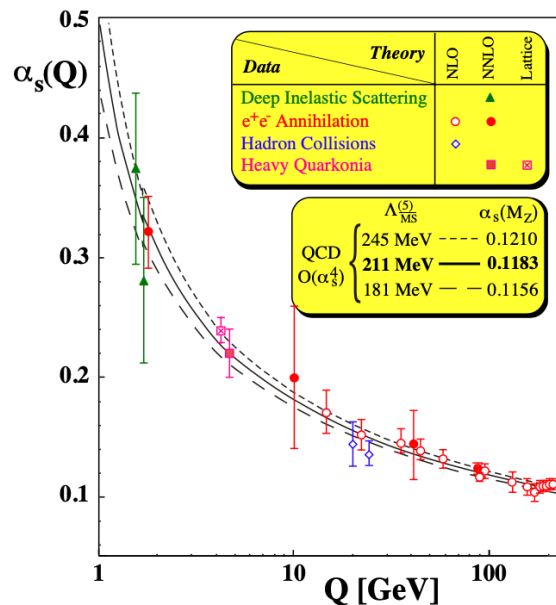


Chiral symmetry restoration!

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