Dileptons/photons from RHIC BES

Lijuan Ruan (BNL)

Introduction: why dileptons/photons?

Existing measurements at RHIC

Future measurements at RHIC

Summary

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

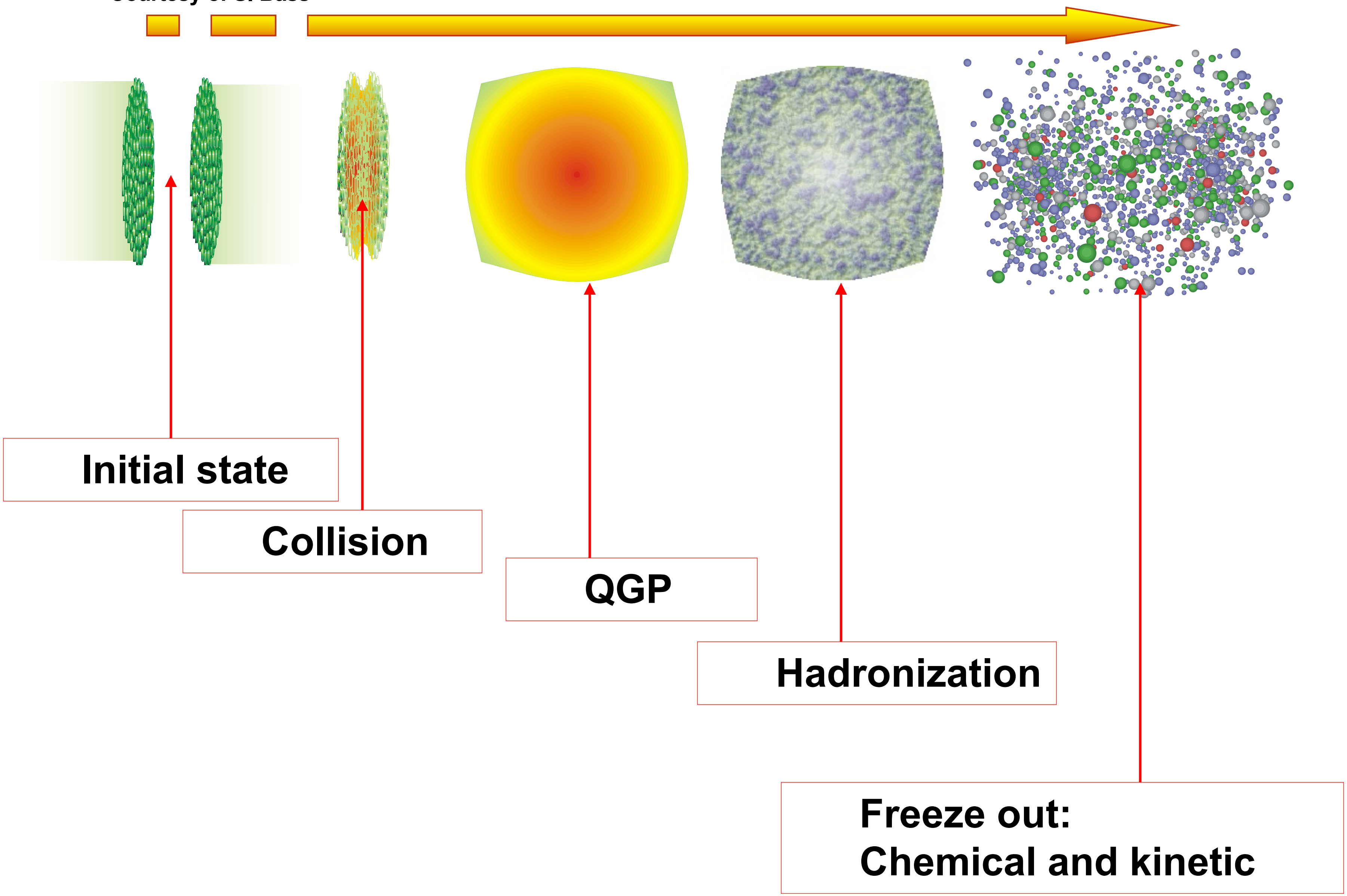
BROOKHAVEN SCIENCE ASSOCIATES

Online seminar for the workshop of
RHIC BES Physics – theory and experiment

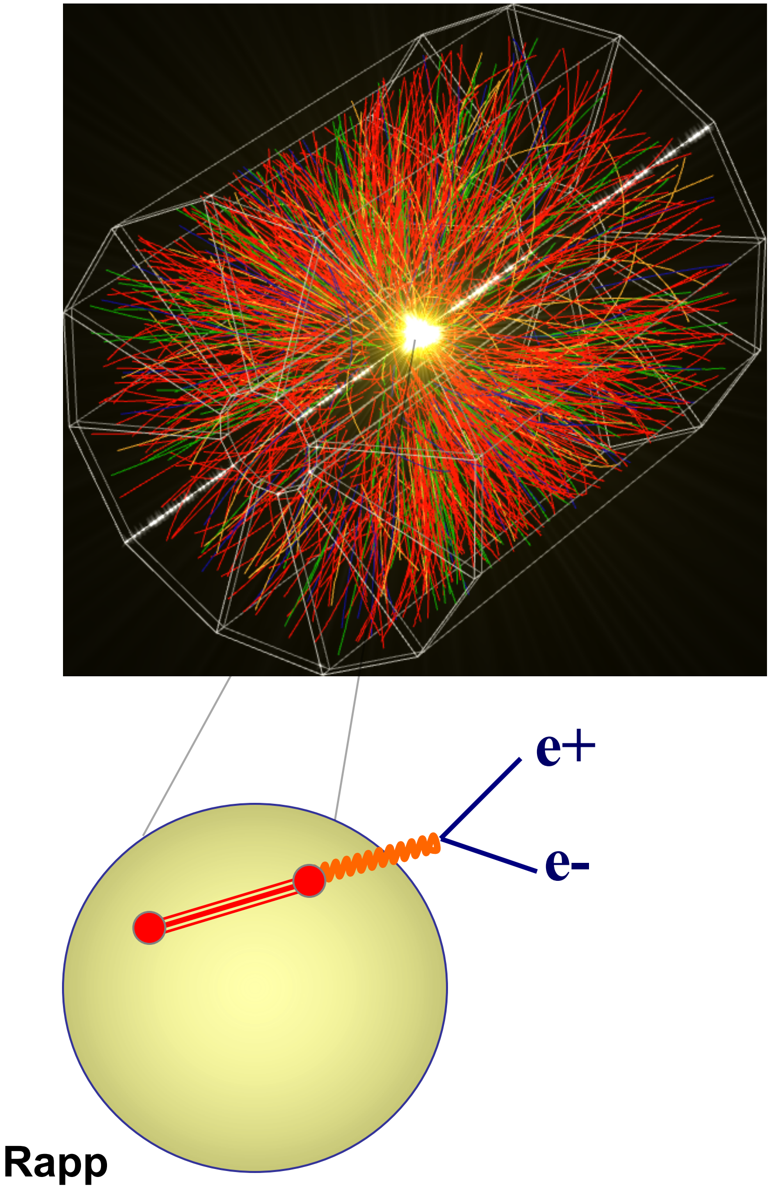
RHIC @ Brookhaven National Laboratory

Relativistic heavy ion collision

Courtesy of S. Bass



Electron-positron (dilepton) tomography



- 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

Generate 99% of visible mass in the universe.

Microscopic picture:

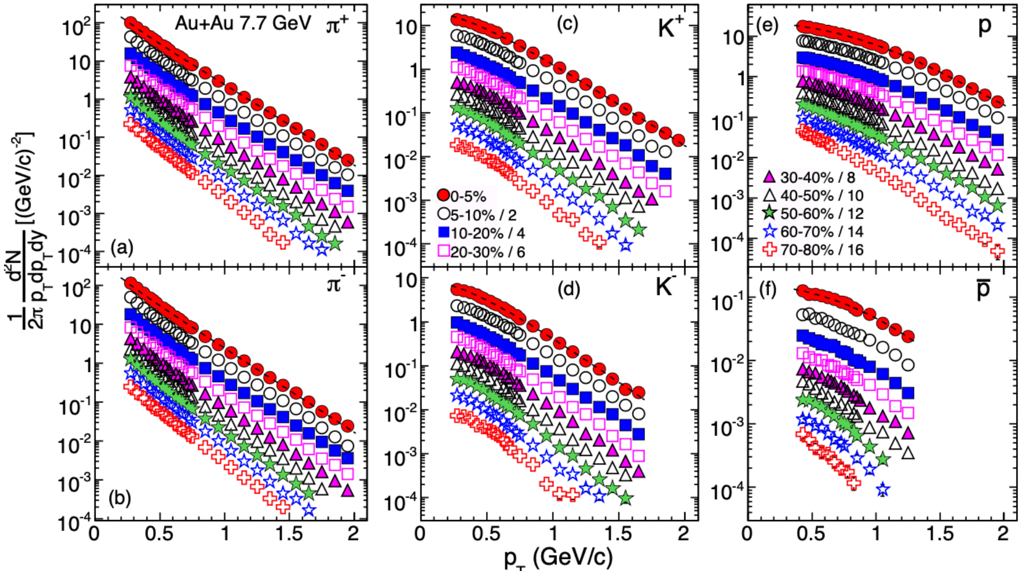
- quark condensate: left-handed quark and right-handed antiquark attract each other through the exchange of gluons.

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

T_c (μ_B=0) = 156.5 $\pm$1.5 MeV **HotQCD, PLB 795 (2019)15**

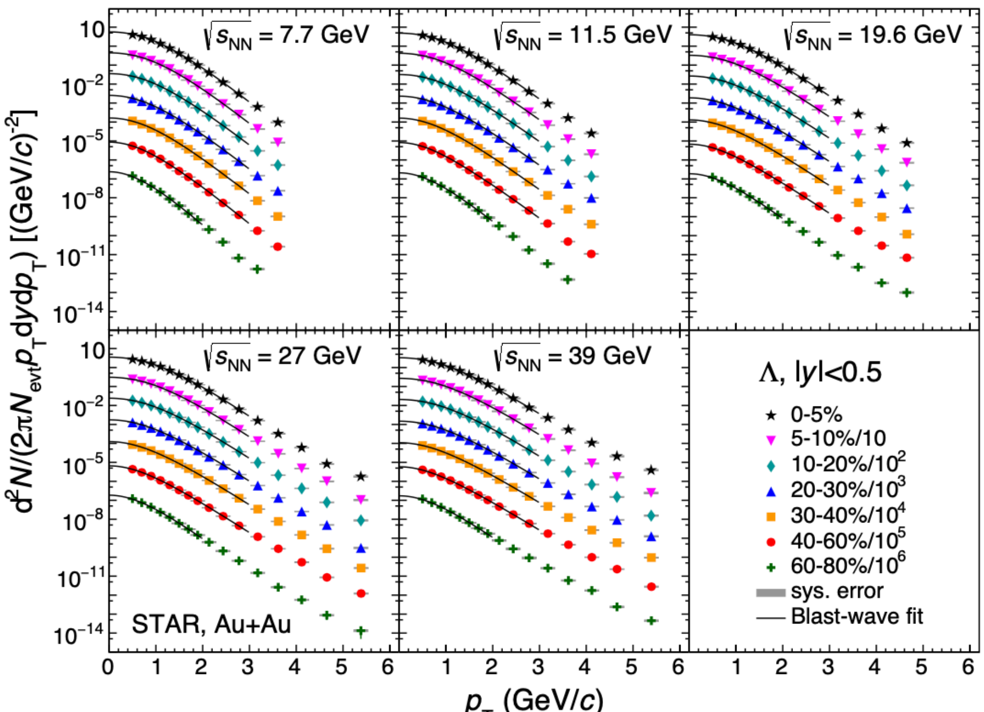
What do we know about the temperature experimentally?

Identified particle spectra



Pion, kaon, proton spectra

Phys. Rev. C **96** (2017) 44904



Strange hadron spectra

Phys. Rev. C **102** (2020) 34909

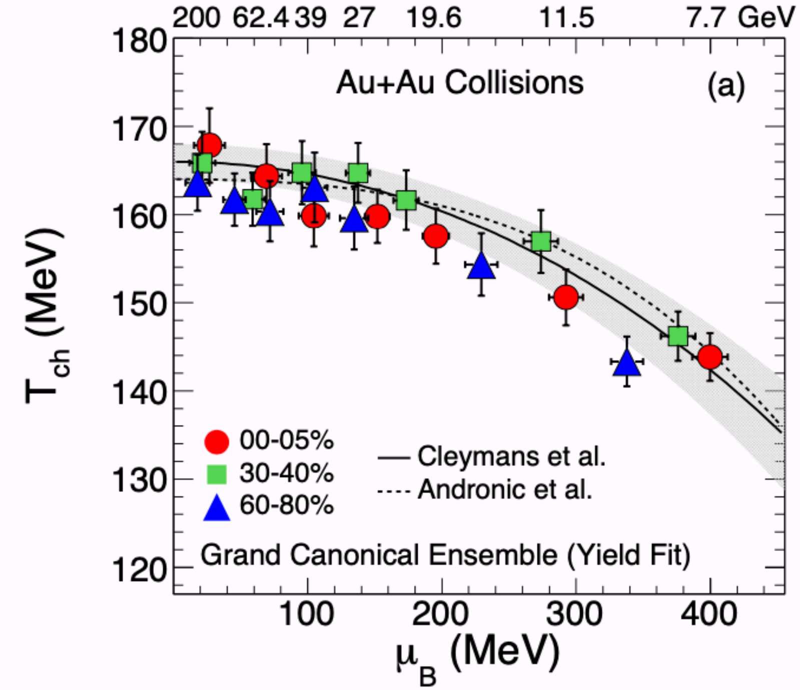
Particle yields

$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, and $\overline{\Xi}$.

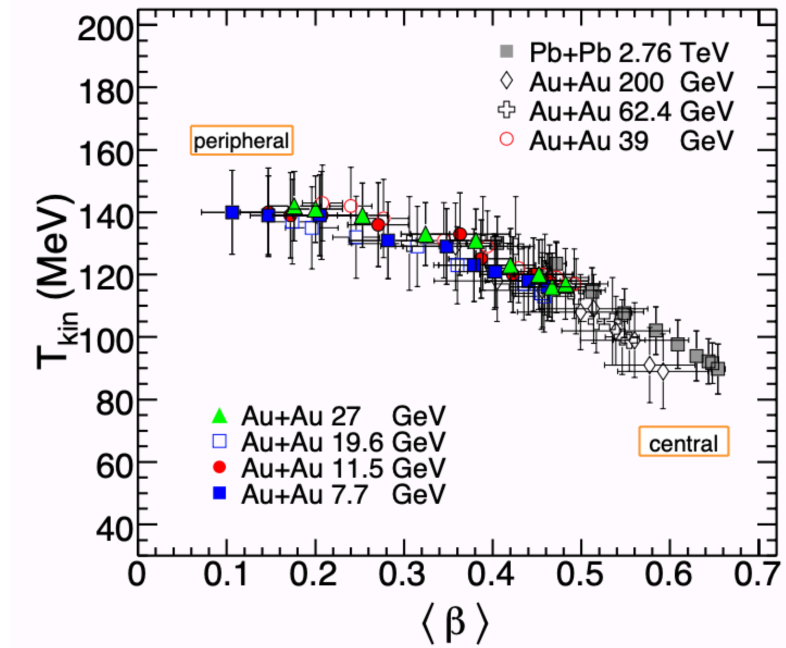
Particle ratios

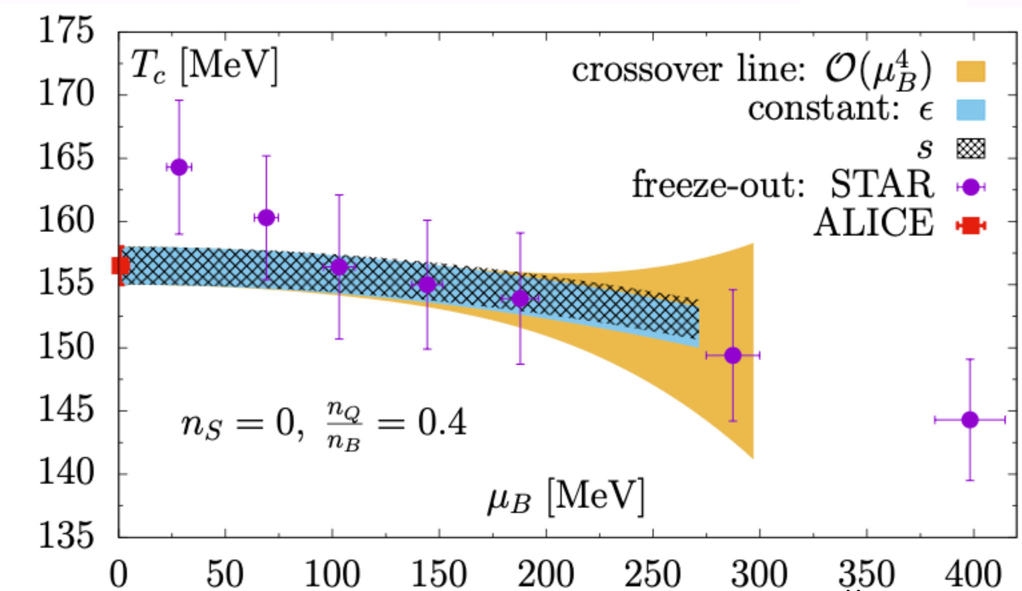
π^-/π^+, K^-/K^+, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, $\overline{\Xi}/\Xi$, K^-/π^-, $\bar{p}/\pi^-$, Λ/π^-, and $\overline{\Xi}/\pi^-$.

Freeze out temperatures



Phys. Rev. C **96** (2017) 44904





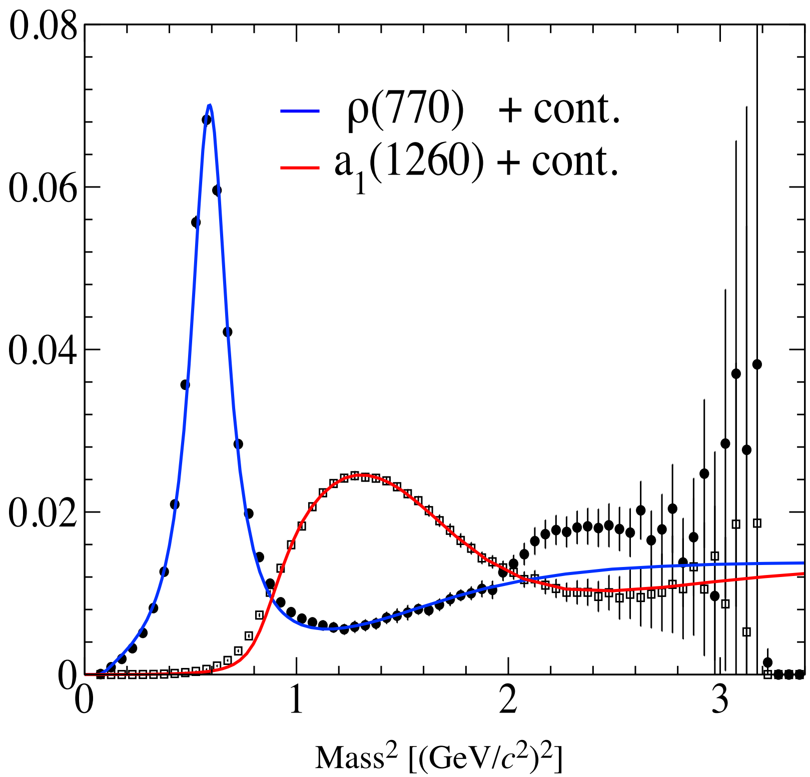
HotQCD, PLB 795 (2019)15

At 200 GeV, T_{ch}~T_C

The initial temperature T_0 must be higher than T_C ?

If so, chiral symmetry should be restored at μ_B~0

ρ and a1 resonance (spectrum function) in vacuum

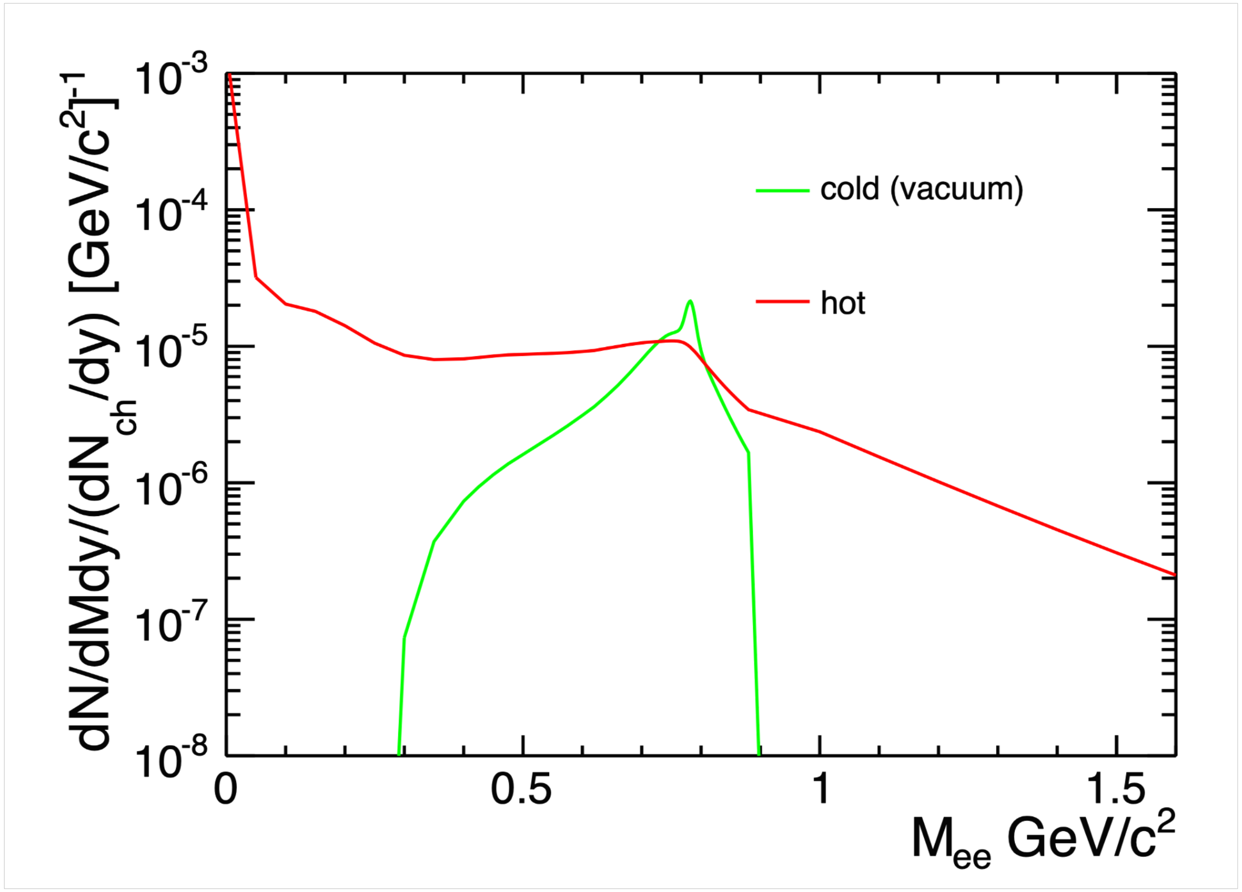


ALEPH: EPJC4 (1998) 409;
R. Rapp Pramana 60 (2003) 675.

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 modified (broadened) ρ spectral function

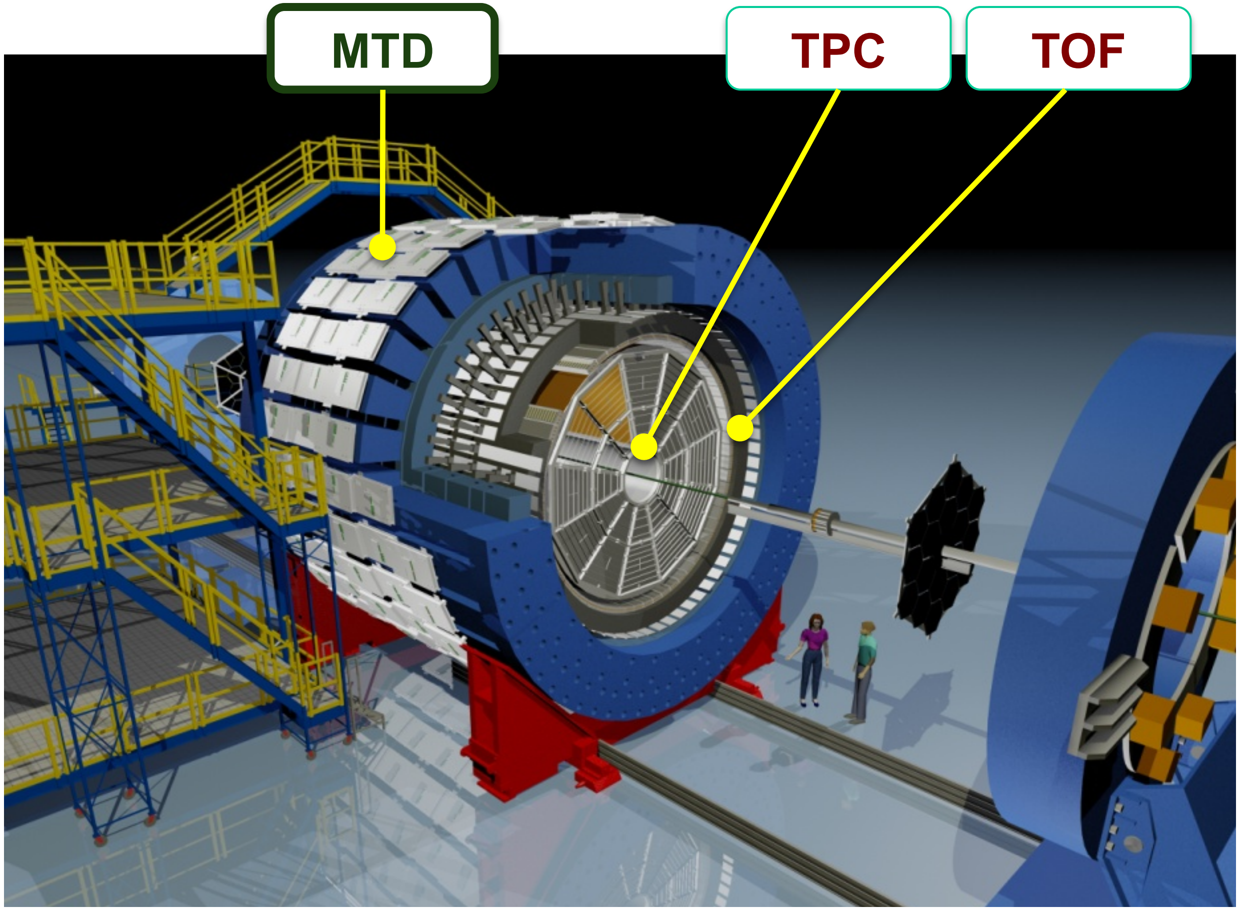
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

Penetrating probe of the hot, dense medium

Low mass dileptons (M_{ll}<1.1 GeV/c^2) (Spectrum and v_n versus M_{ll}, p_T) Intermediate mass dileptons (1.1<M_{ll}<3.0 GeV/c^2) (Spectrum and v_n versus M_{ll}, p_T)	vector meson in-medium modifications, link to Chiral Symmetry Restoration QGP thermal radiation, charm correlation modification.
Thermal photons (p_T<4 GeV/c) (p_T spectrum and v_n)	QGP thermal radiation, hadron gas thermal radiation

Energy and centrality dependence → Constrain T_0, t_0, lifetime, and density profile …

The STAR (Solenoidal Tracker at RHIC) Detector

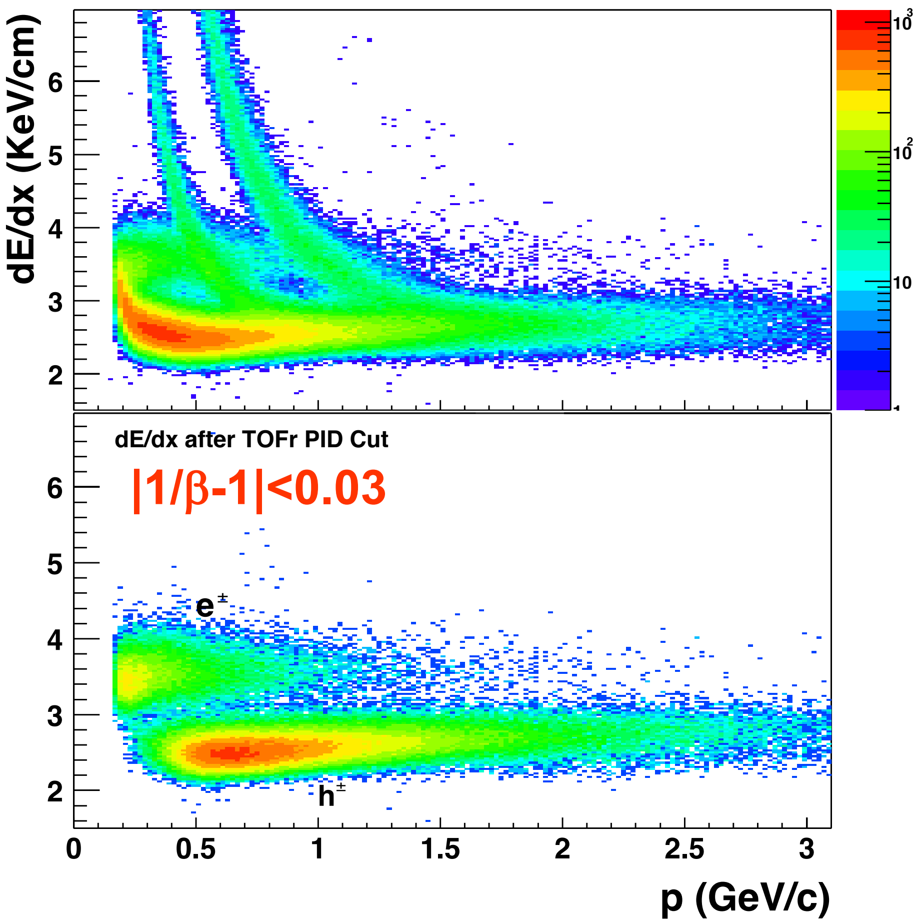


Time Projection Chamber (TPC):
measure ionization energy loss and Momentum

Time of Flight Detector (TOF) :
Multi-gap Resistive Plate Chamber, gas detector, avalanche mode

has precise timing measurement, <100 ps timing resolution

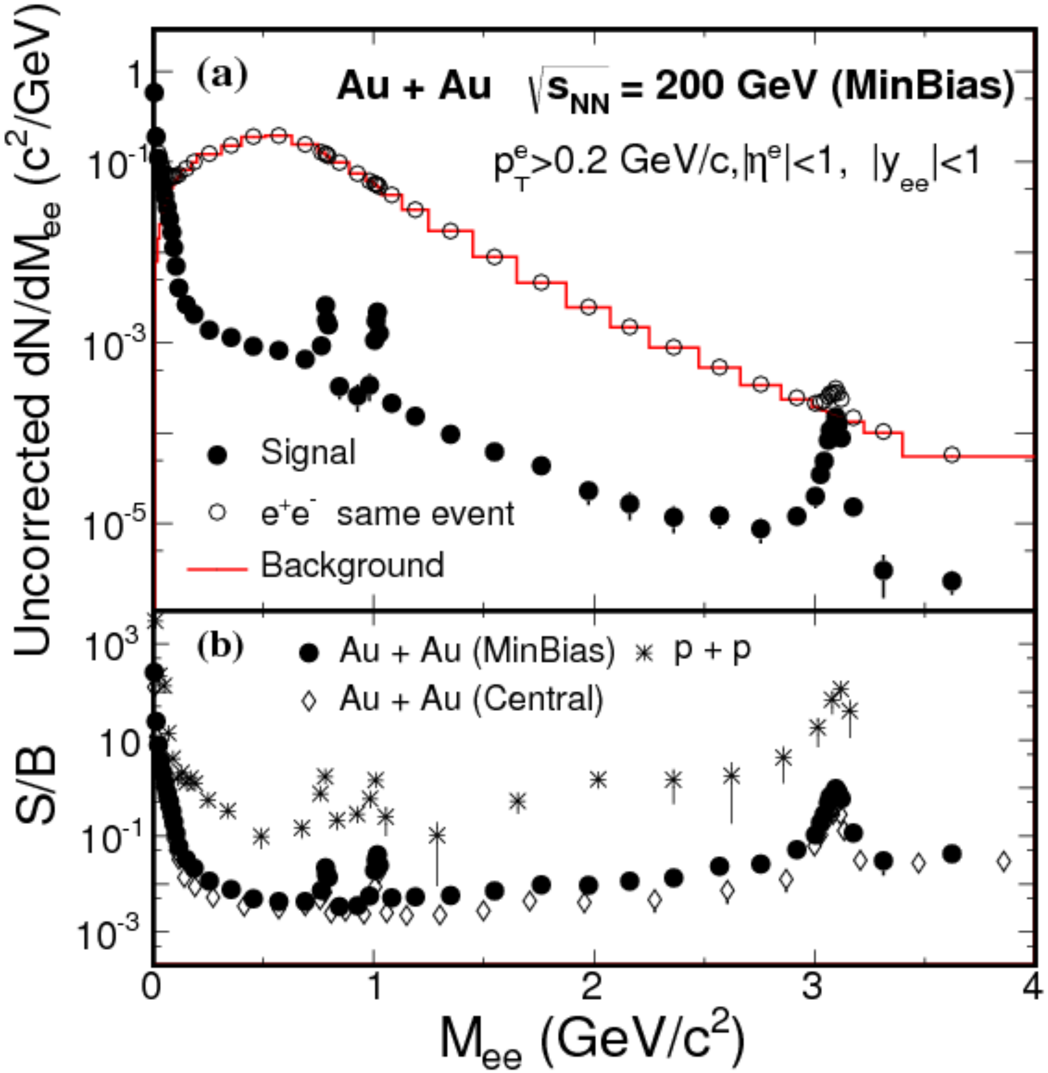
Electron identification



STAR Collaboration, PRL94(2005)062301

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

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, $\eta' \rightarrow \gamma e^+e^-$

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

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

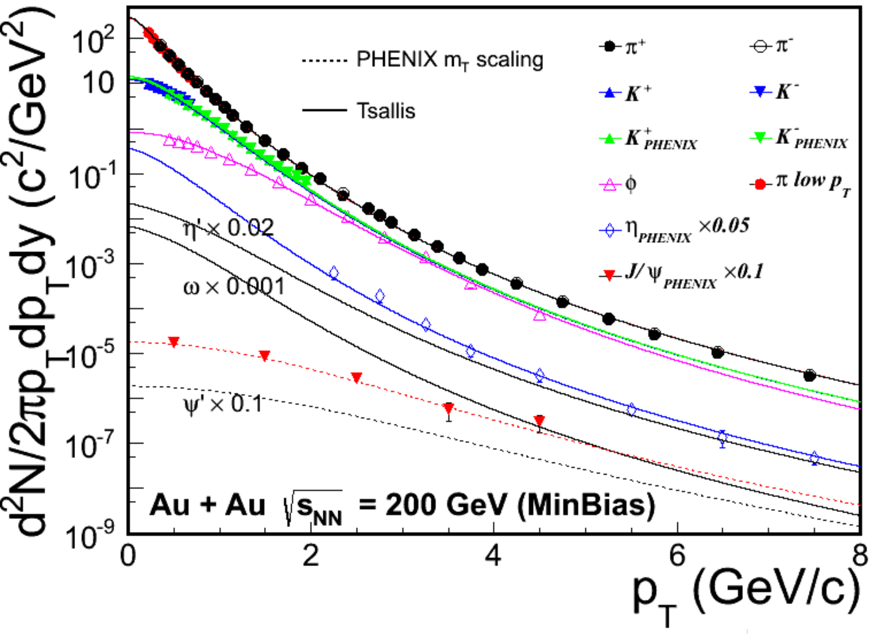
Drell-Yan contribution

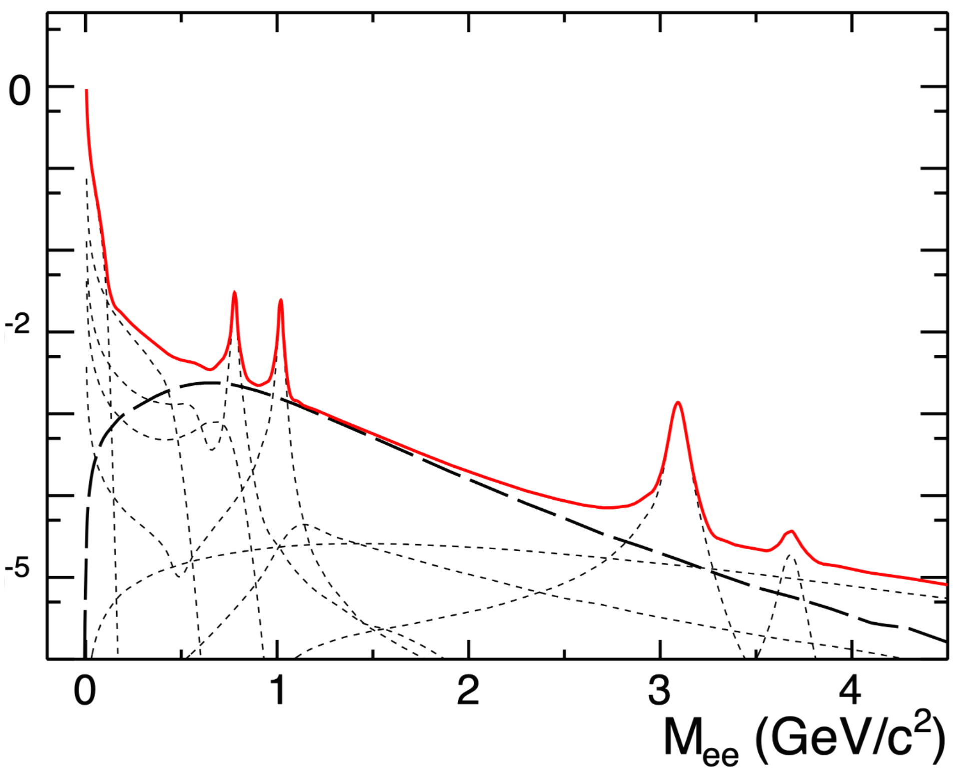
In Au+Au collisions, we search for

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

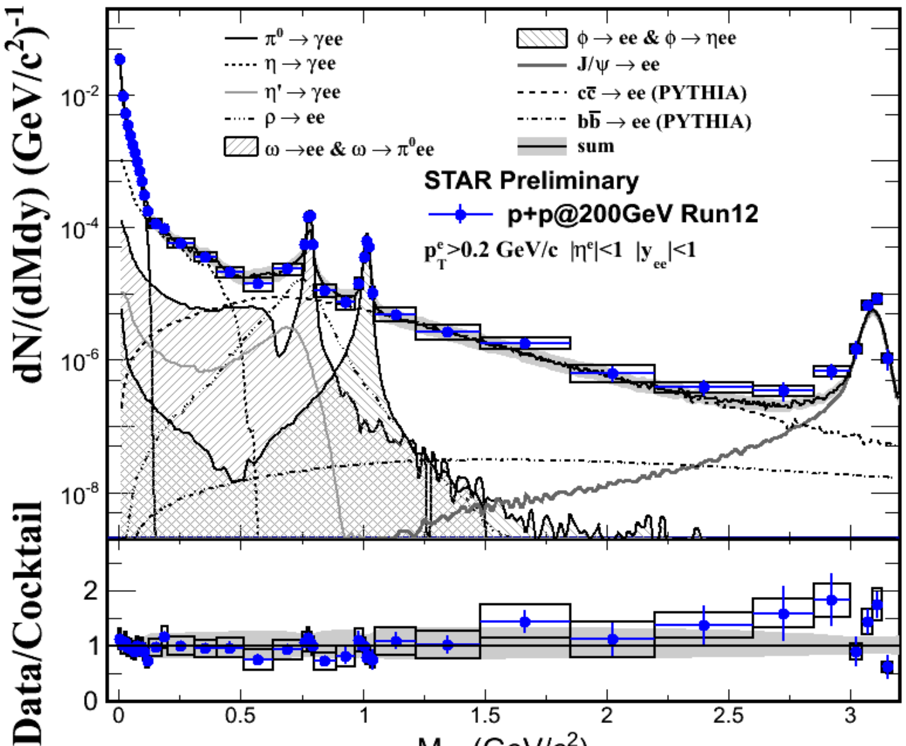




PHENIX Collaboration, Phys. Rev. C 81, 034911 (2010)
STAR Collaboration, Phys. Rev. Lett. 92, 112301 (2004)
STAR Collaboration, Phys. Lett. B 612, 181 (2005).
STAR Collaboration, Phys. Rev. Lett. 97, 152301 (2006)
Z. Tang et al. Phys. Rev. C 79, 051901 (2009)

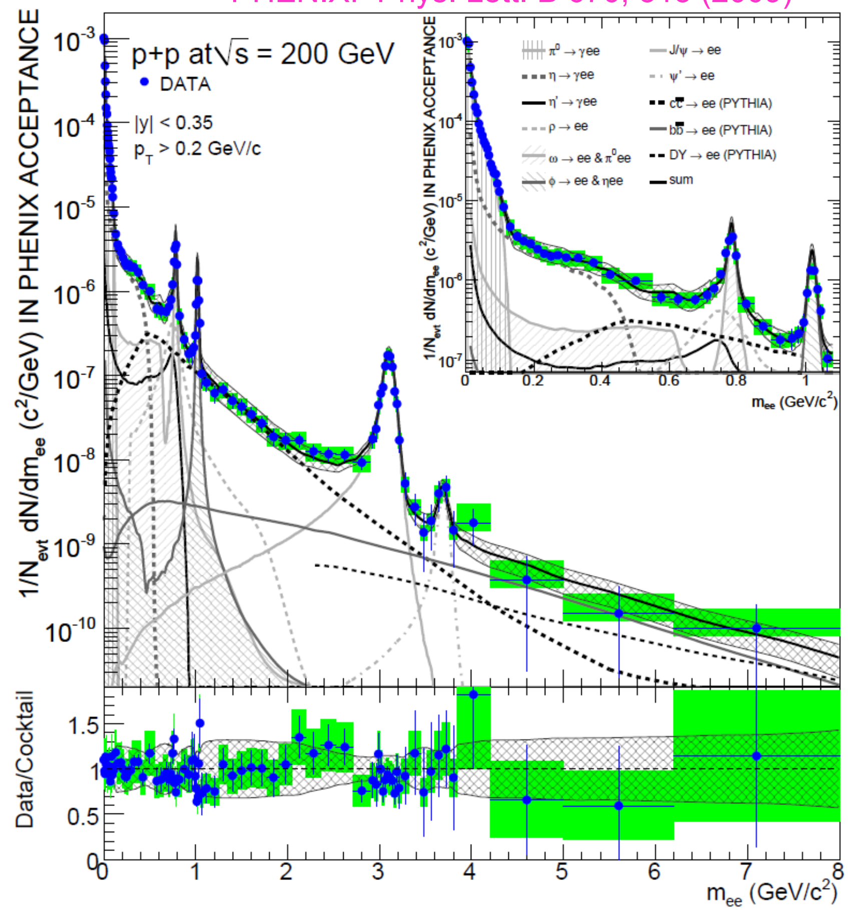
Electron-positron mass spectrum from known hadronic sources without hot, dense medium contribution.

Dielectron mass spectrum in 200 GeV p+p collisions



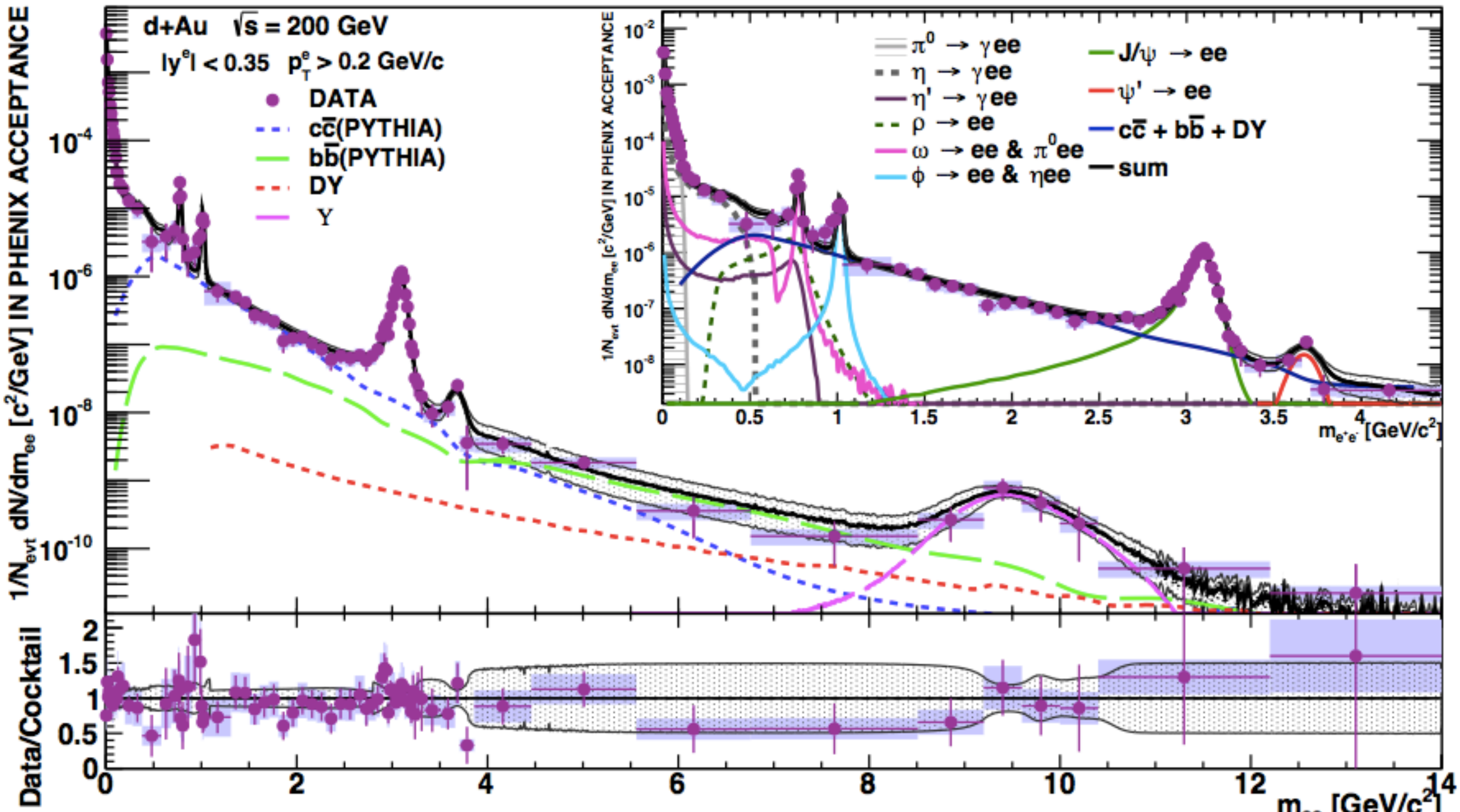
STAR: QM2014

PHENIX: Phys. Lett. B 670, 313 (2009)



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

Dielectron measurements in d+Au collisions

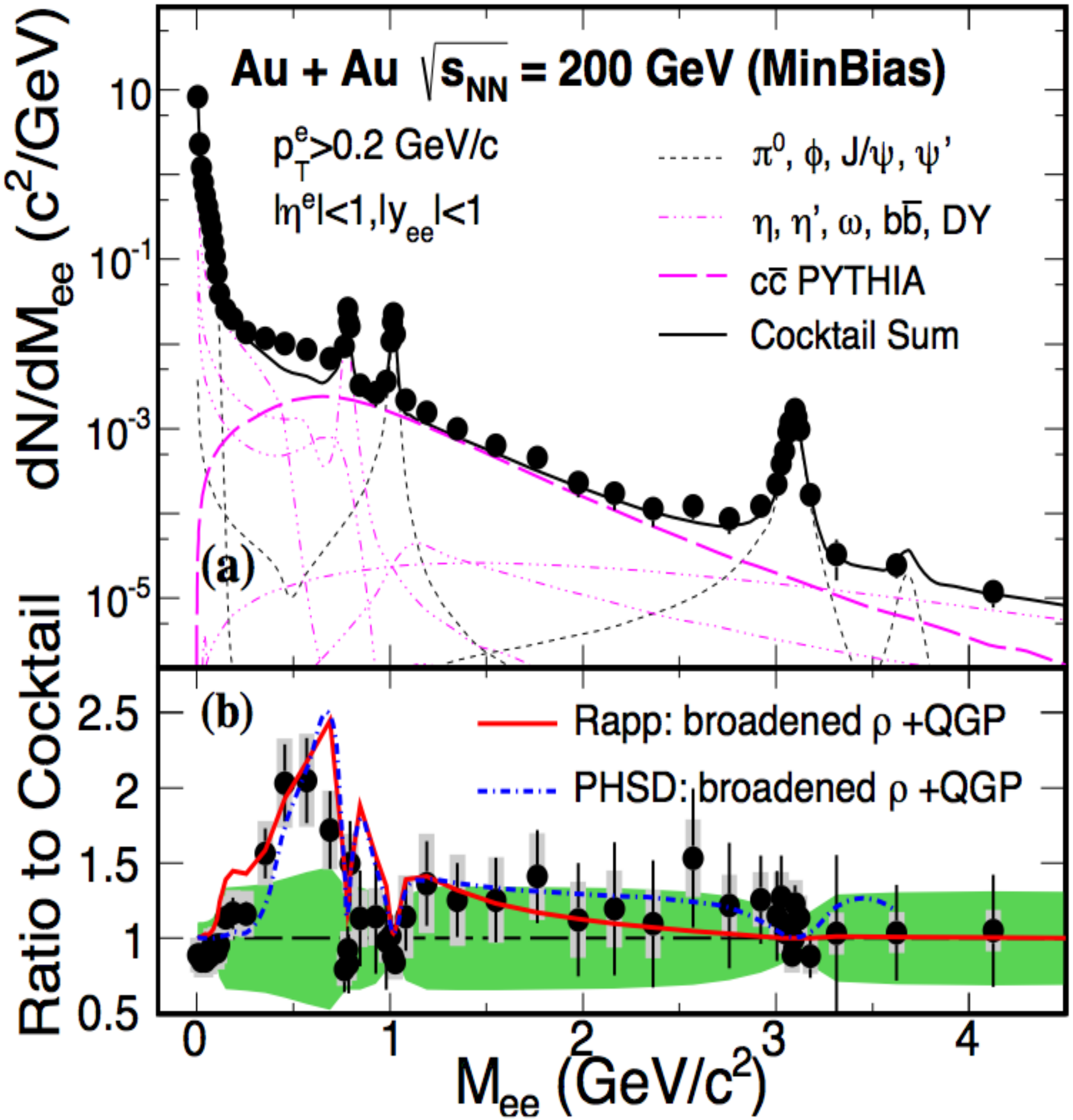


PHENIX: PRC91(2015)014907

Hadronic cocktail is consistent with data in d+Au collisions.

dielectron mass spectrum in 200 GeV Au+Au

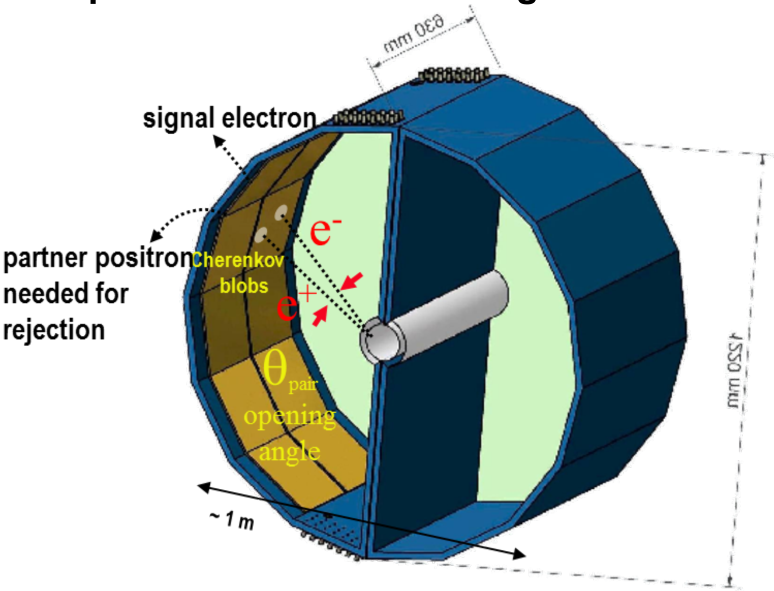
STAR: Phys. Rev. Lett. 113 (2014) 22301

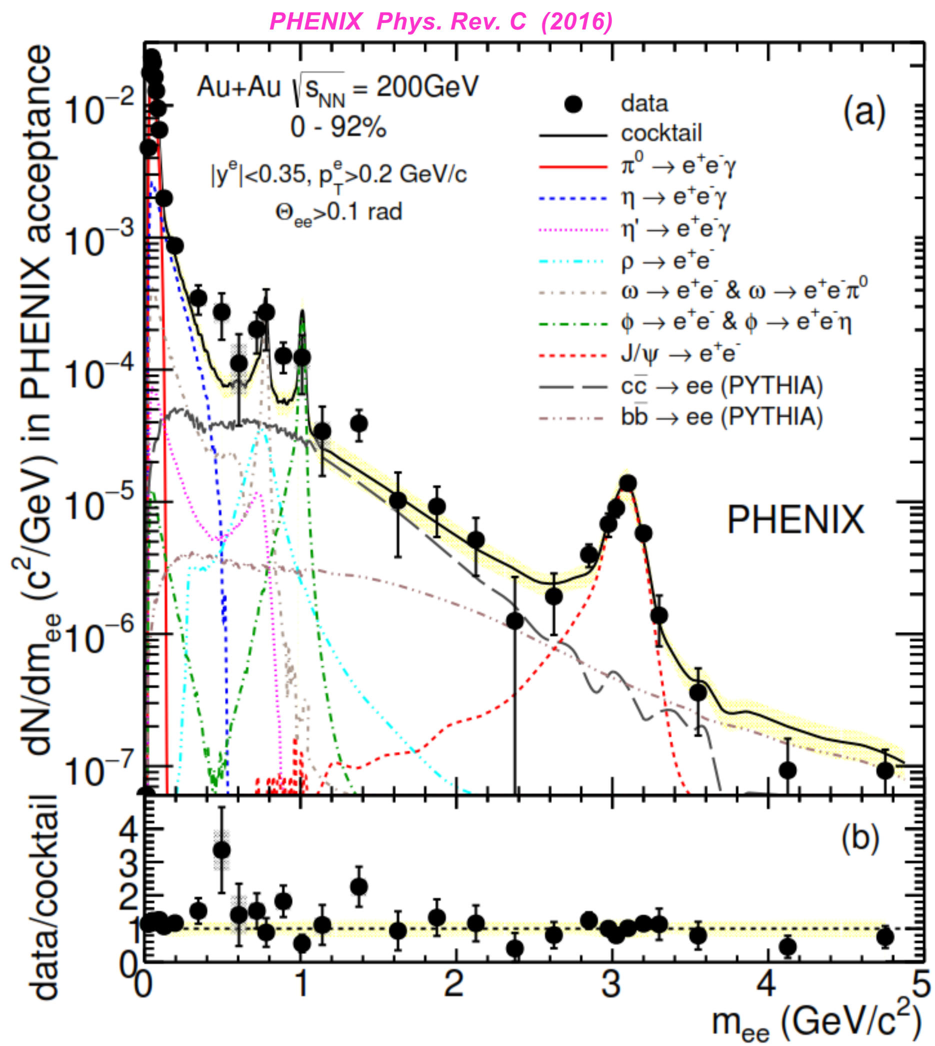


Significant excess is observed for $0.3<M_{ee}<0.8$ GeV/c^2, representing the hot, dense medium contribution.

PHENIX HBD Upgrade

Window less CF4 Cherenkov detector
GEM/CSI photo cathode readout
Operated in B-field free region

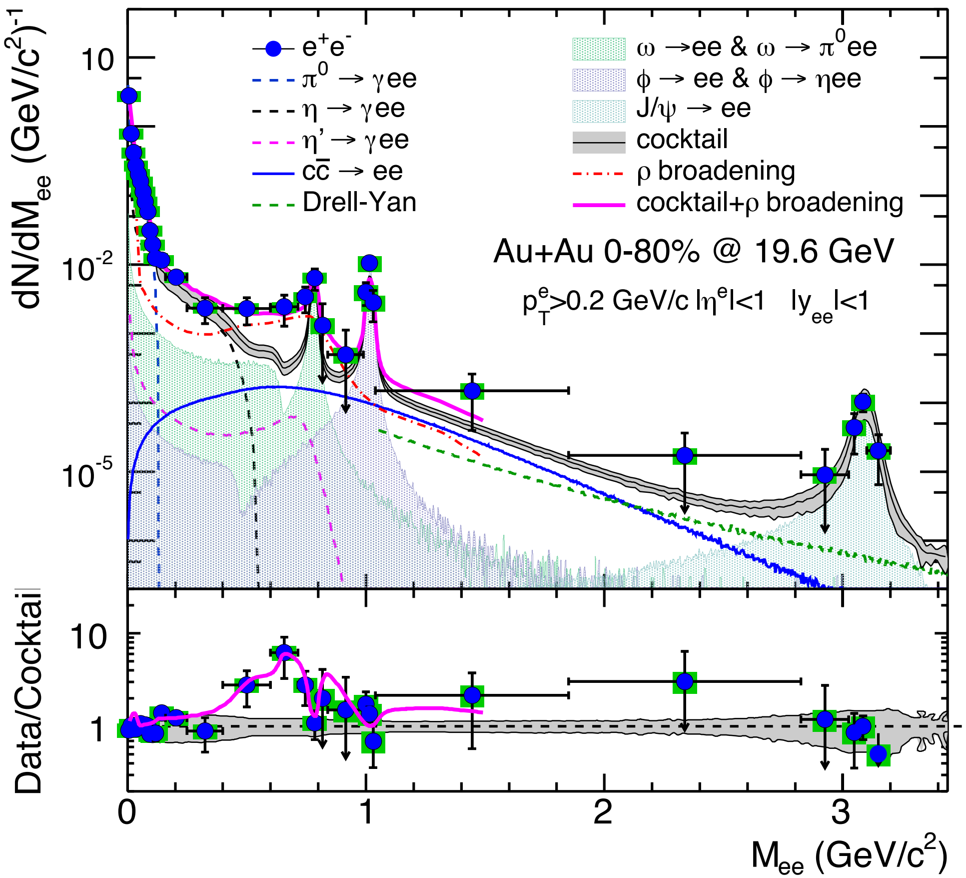




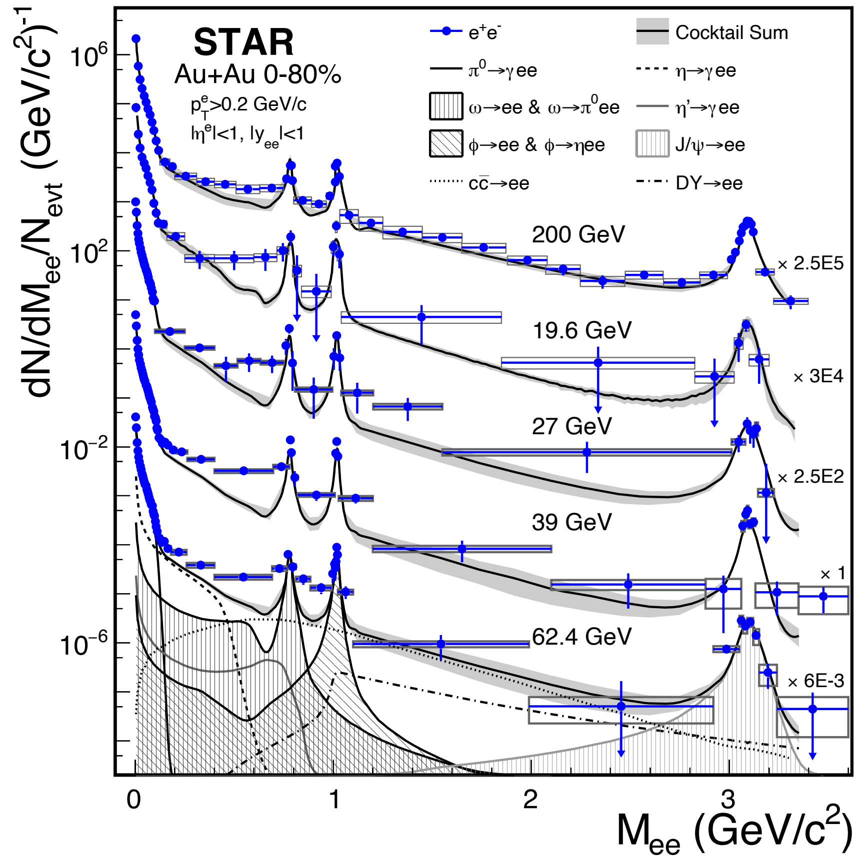
- HBD provides active background rejection scheme
  - Veto on double tracks
  - Conversion rejection ~ 90%
  - Dalitz rejection ~ 80%
  - Improve S/B factor 5
  - However statistics limited

dielectron mass spectrum in 19.6-62.4 GeV Au+Au

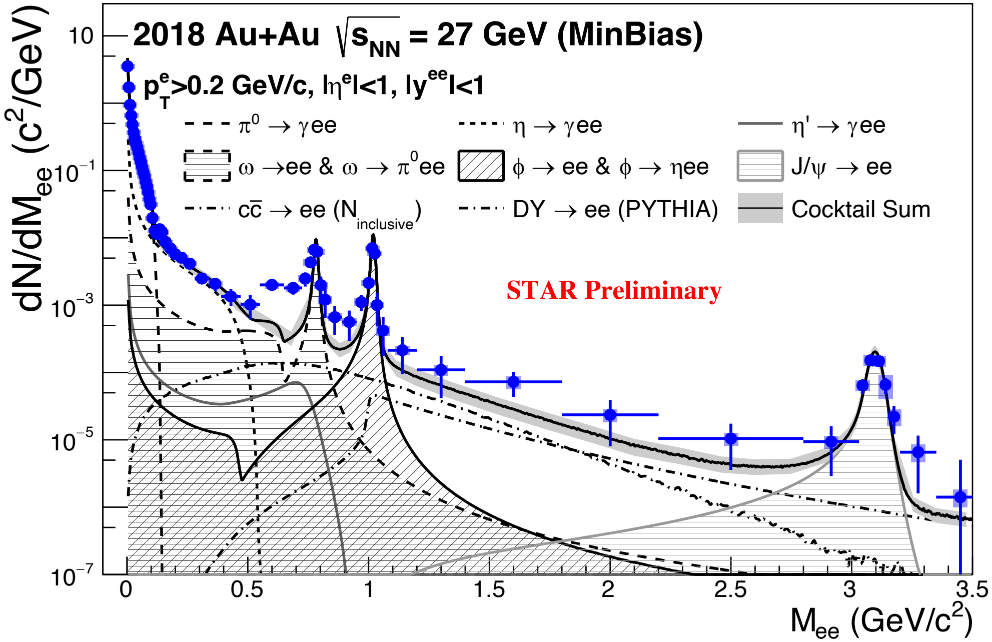
STAR: PLB750(2015)64



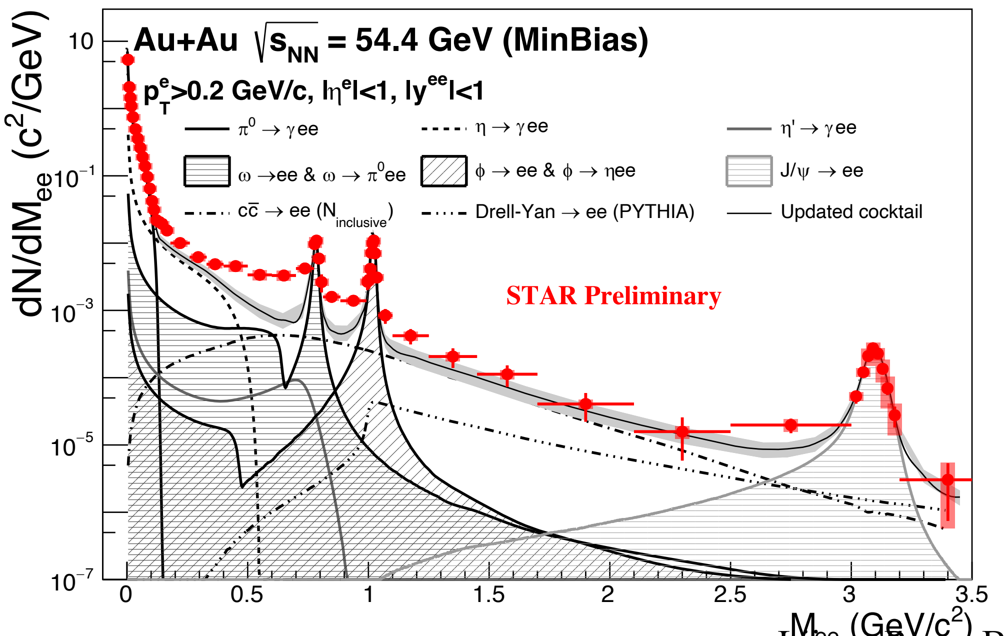
STAR: arXiv: 1810.10159



Dileptons at 54.4 and 27 GeV



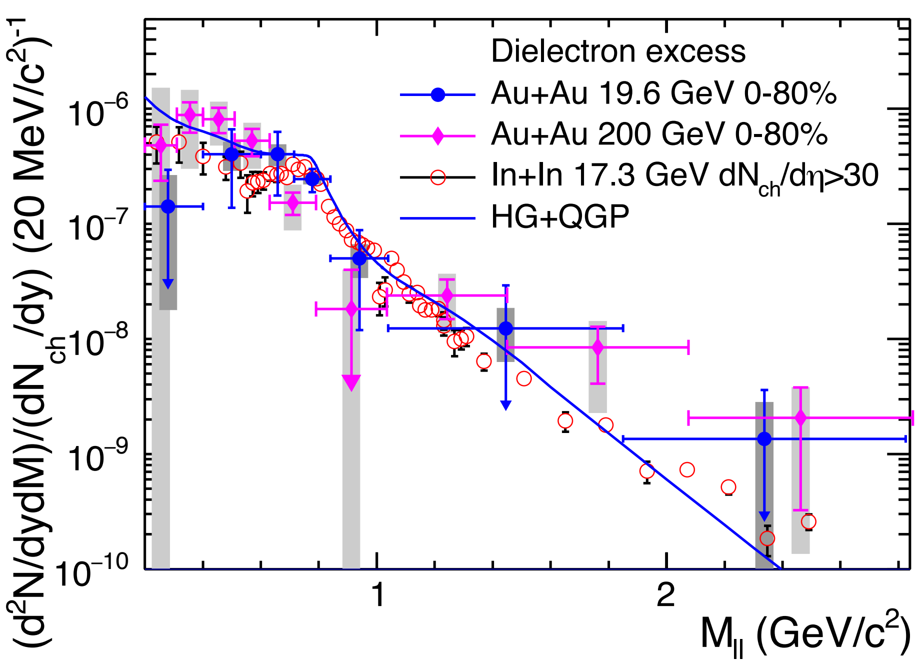
Year	Energy	Used events
2018	27 GeV	500M
2017	54.4 GeV	875M
2011	27 GeV	68M
2010	39 GeV	132M
2010	62.4 GeV	62M

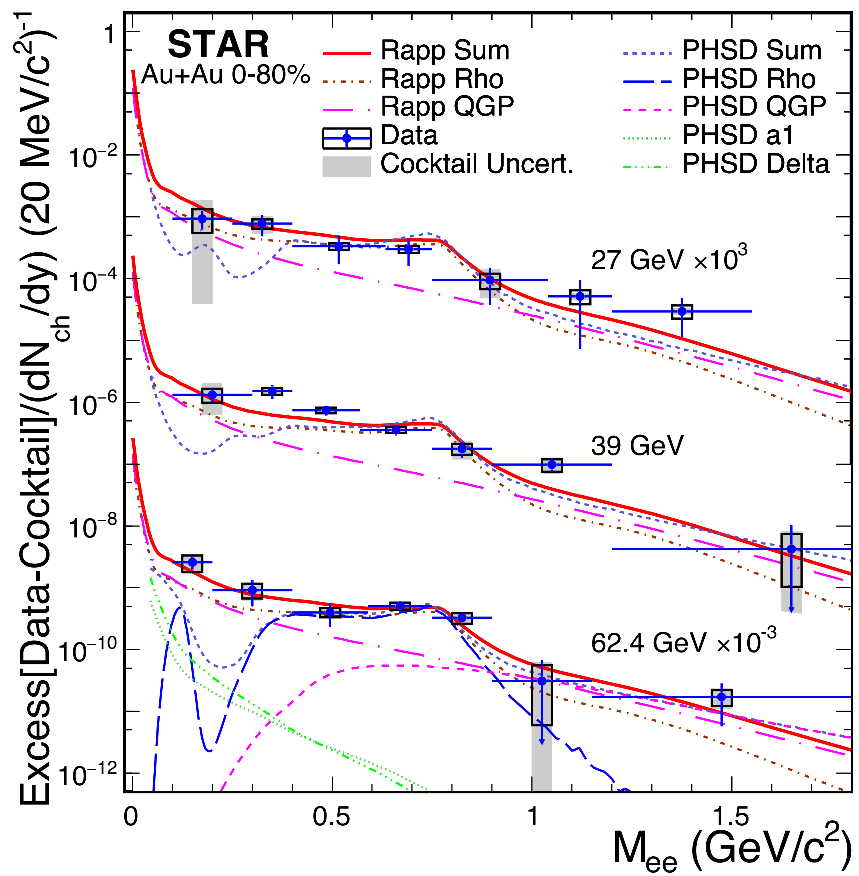


A possible hint of QGP thermal radiation in the intermediate mass region

STAR: HP2020

The dielectron excess spectrum

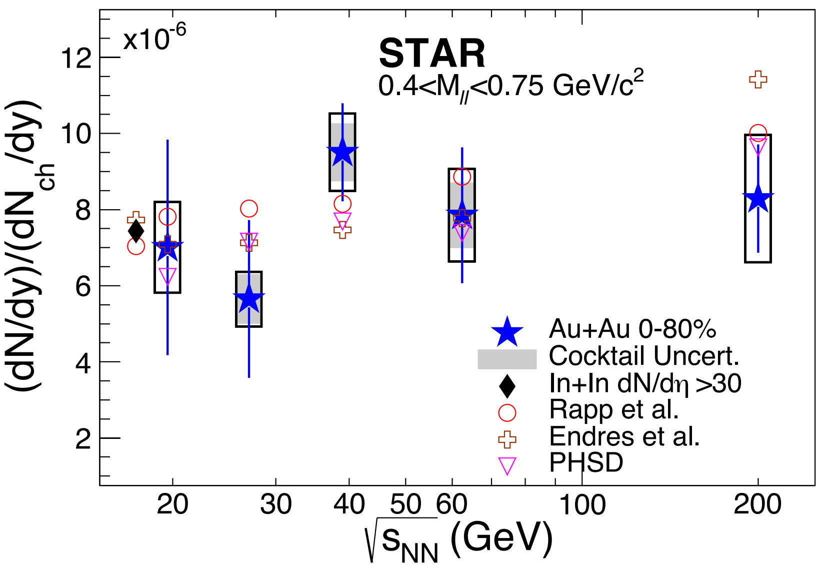


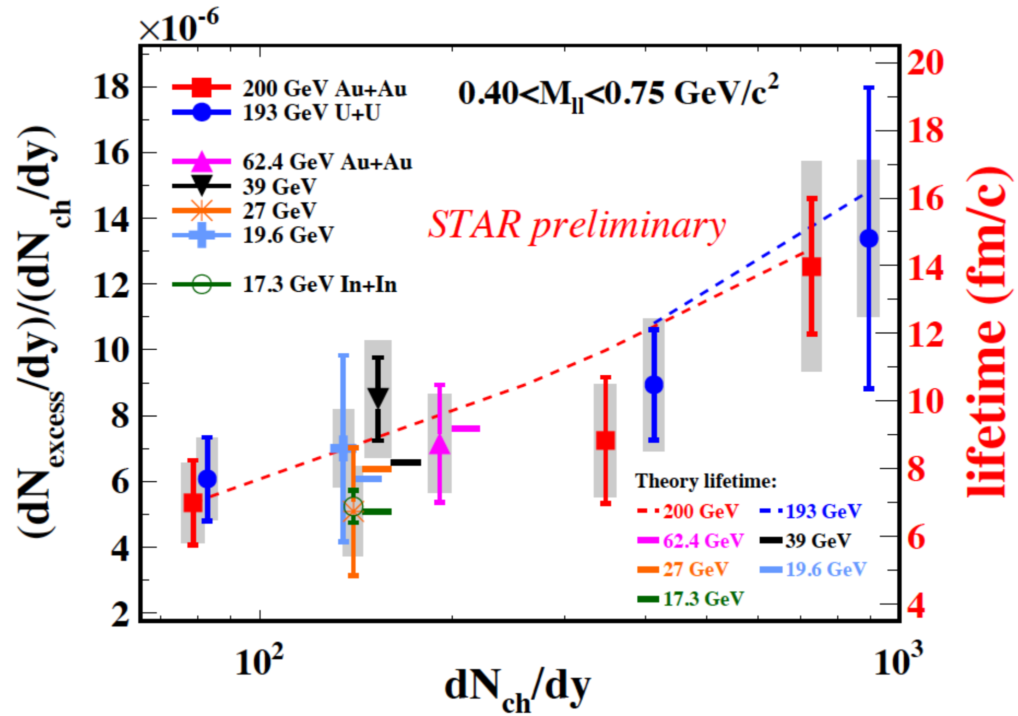


A broadened ρ spectral function consistently describes the low mass dielectron excess for all the energies 19.6-200 GeV.

The low mass measurements: lifetime indicator

STAR: arXiv: 1810.10159

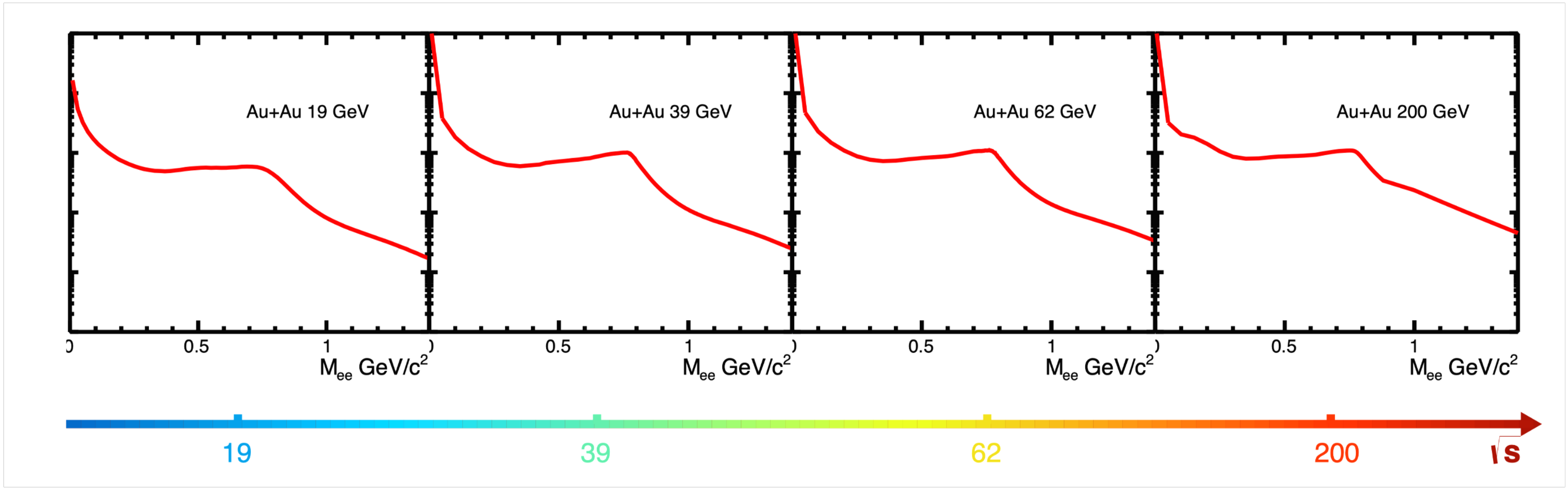




STAR: QM2015

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



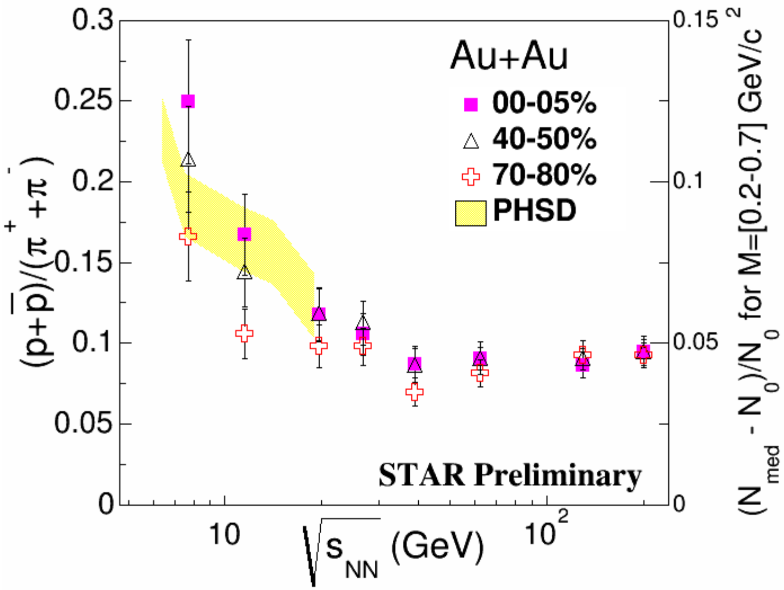
The electron-positron spectrum from hot, dense medium is consistent with a broadened ρ resonance in medium.

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

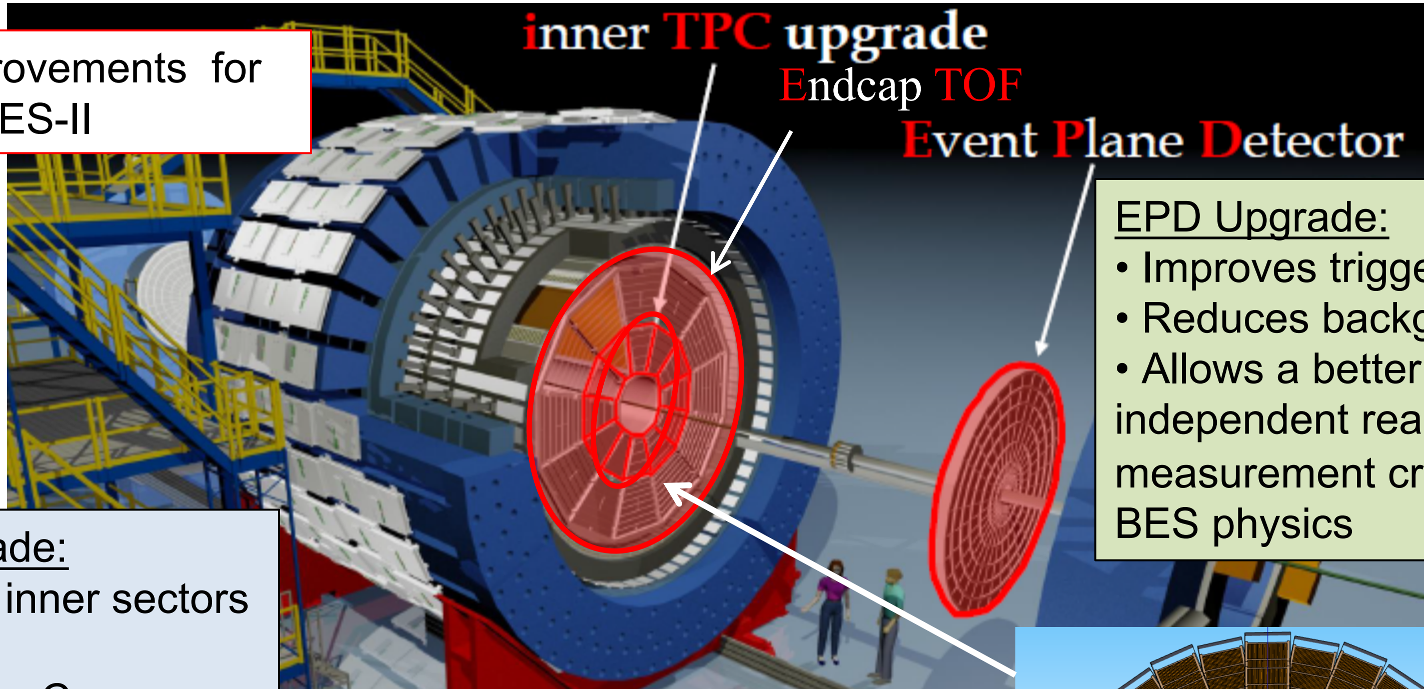
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.



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.

STAR detector at BES-II

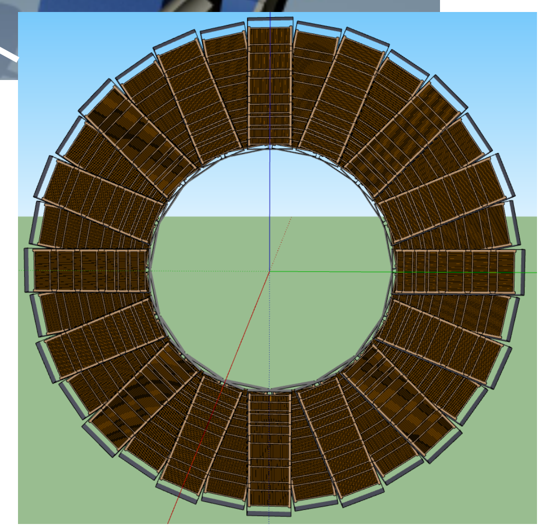
Major improvements for BES-II



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



What iTPC upgrade brings to dielectron measurements

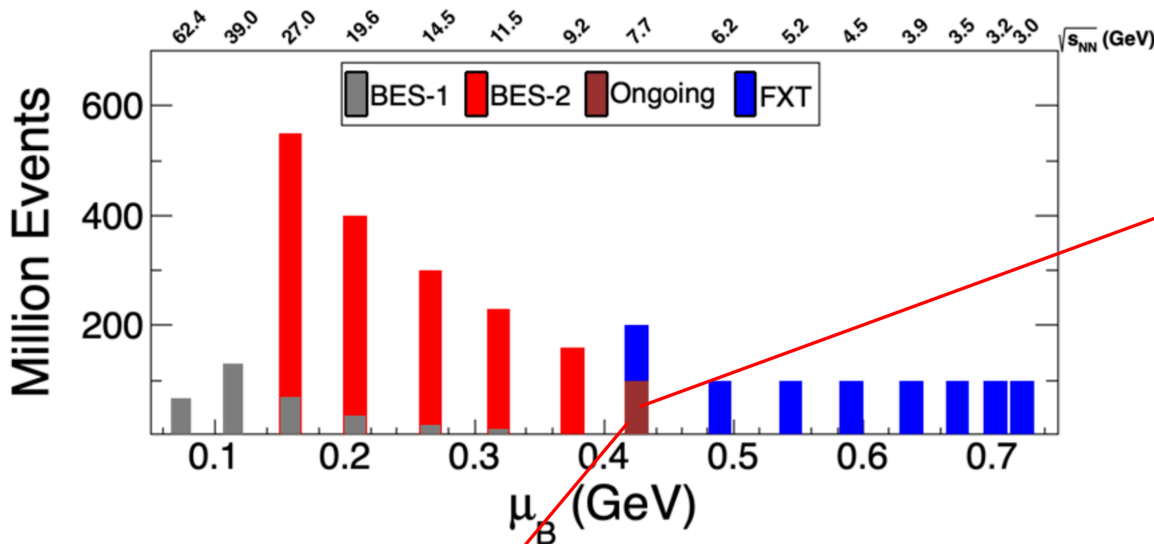
Reduce the systematic uncertainties due to

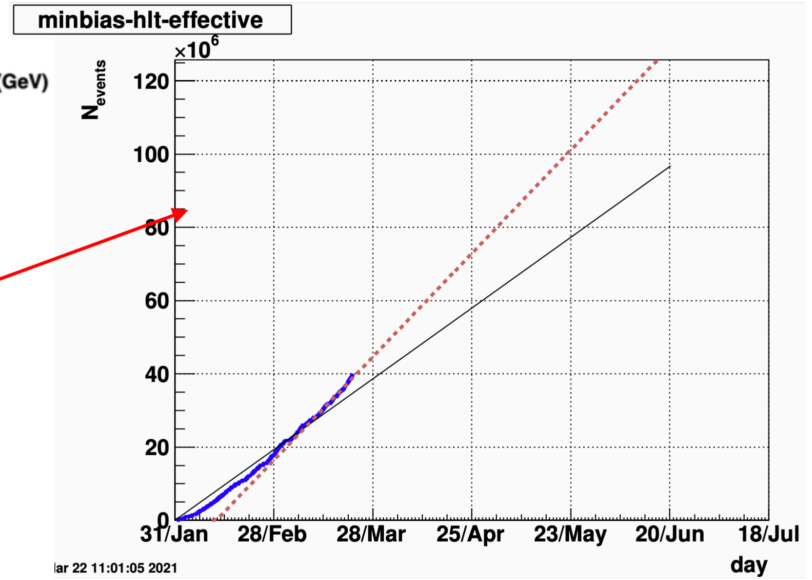
- hadron contamination
- efficiency corrections
- acceptance differences between unlike-sign and like-sign pairs
- cocktail subtraction

A factor of 2 reduction in the systematic uncertainties for dielectron excess yield

Improves the acceptance for dielectron measurement by more than a factor of 2 in the low mass region, lowers the statistical uncertainties.

BES-II data taking

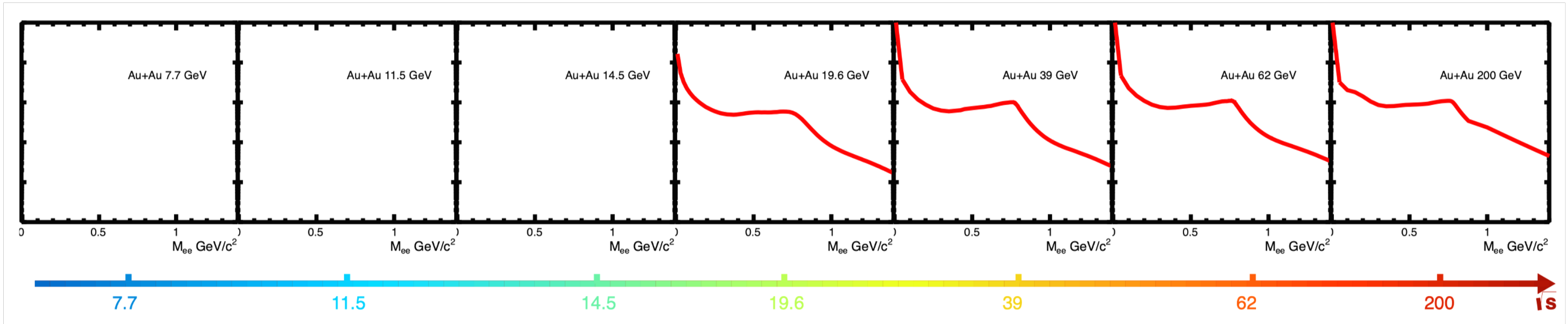


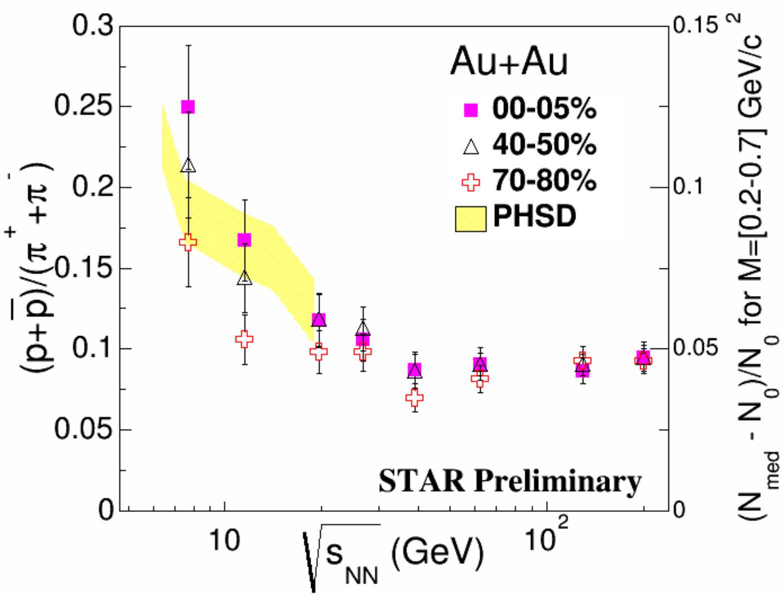


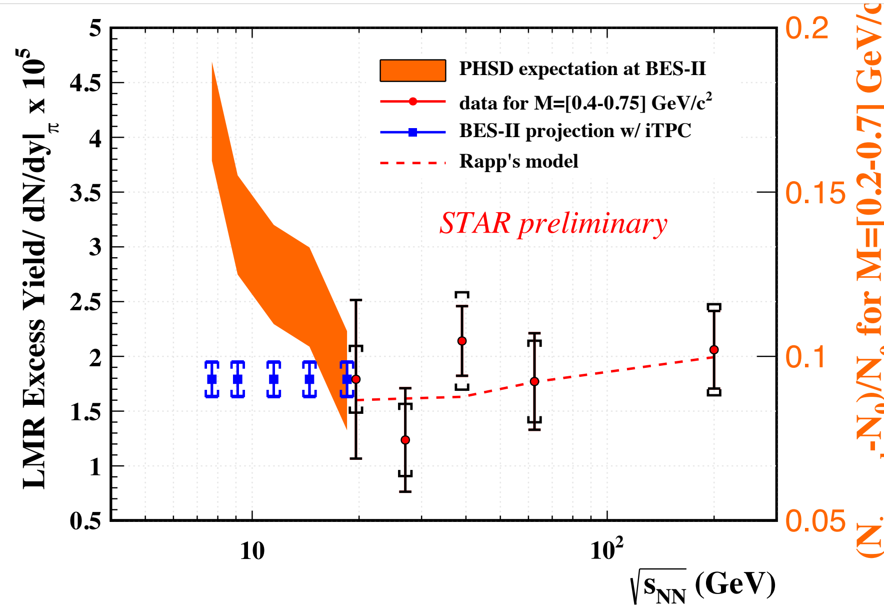
STAR BUR20 for Run-21

Single-Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority
3.85	7.7	11-20 weeks	Au+Au	100 M	1
3.85	3 (FXT)	3 days	Au+Au	300 M	2
44.5	9.2 (FXT)	0.5 days	Au+Au	50 M	2
70	11.5 (FXT)	0.5 days	Au+Au	50 M	2
100	13.7 (FXT)	0.5 days	Au+Au	50 M	2
100	200	1 week	O+O	400 M 200 M (central)	3
8.35	17.1	2.5 weeks	Au+Au	250 M	3
3.85	3 (FXT)	3 weeks	Au+Au	2 B	3

Probe total baryon density effect
7.7 GeV to 19.6 GeV (2019-2021)





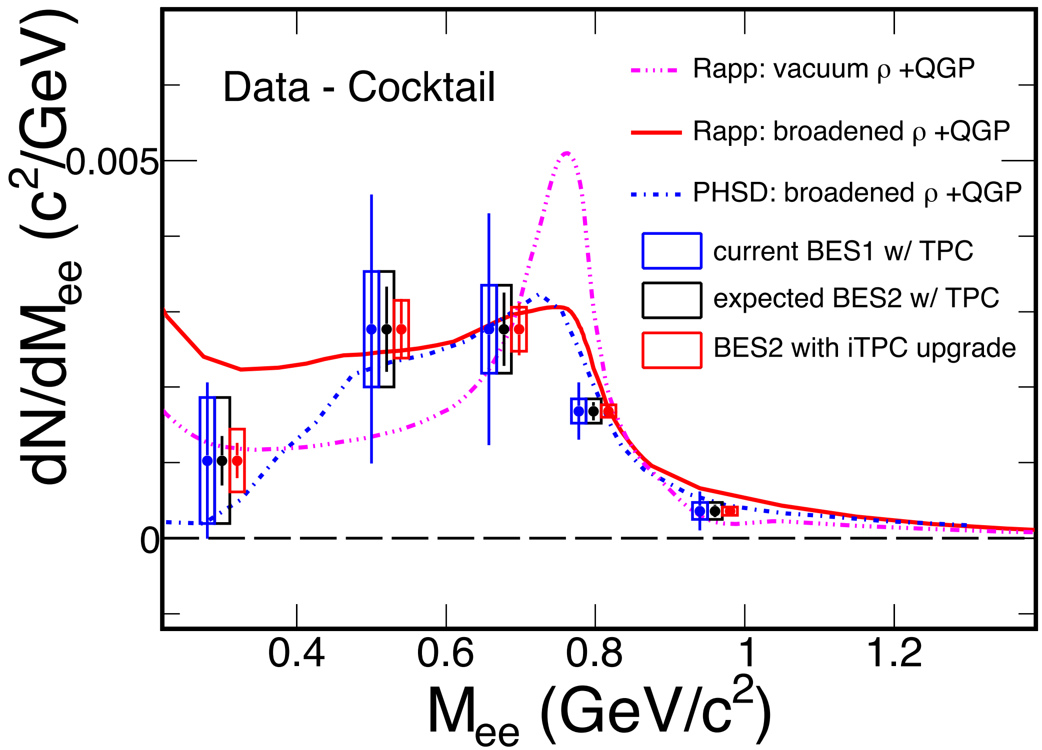


Broader and more electron-positron excess down to 7.7 GeV collision energy?

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

Lijuan Ruan, BNL

Distinguish the mechanisms of rho broadening



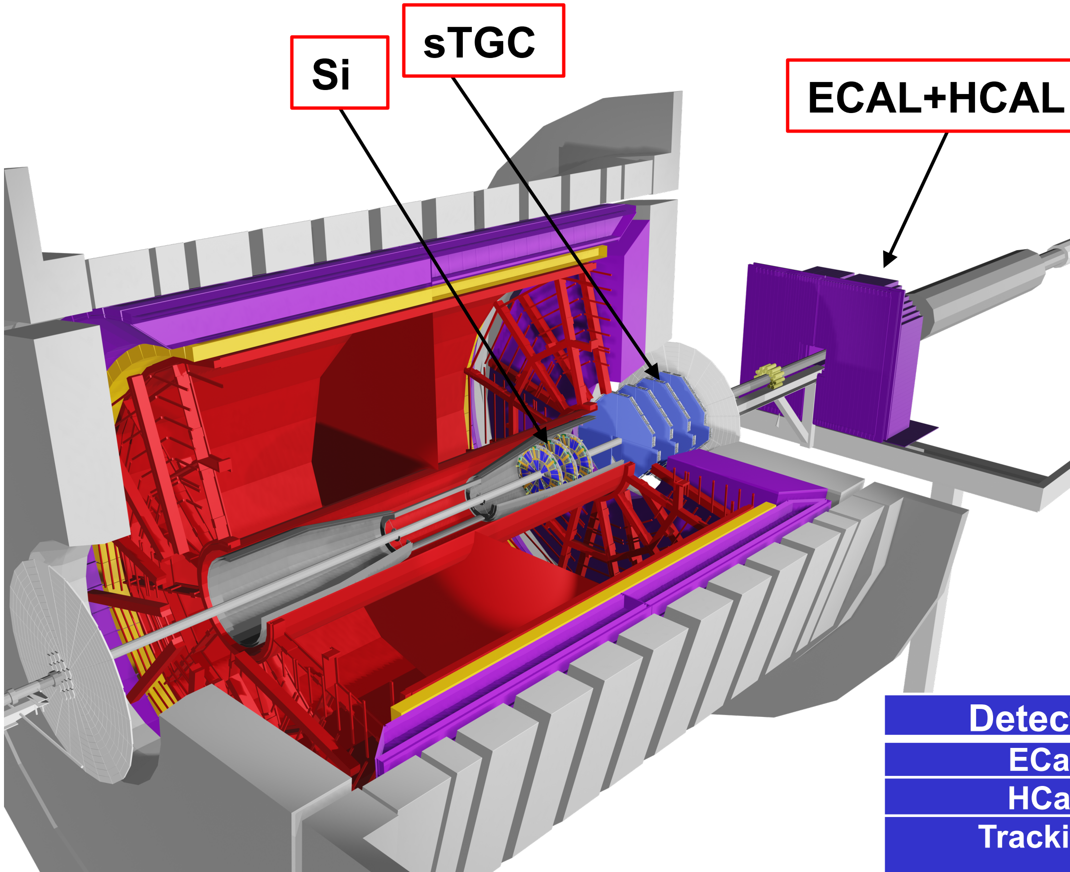
Knowing the mechanism that causes in-medium rho broadening and its temperature and baryon-density dependence is fundamental to our understanding and assessment of chiral symmetry restoration in hot QCD matter !

Other effects: production rate, non-equilibrium dynamics, space-time evolution

Rapp: macroscopic effective many-body theory model

PSHD: microscopic transport dynamic model

STAR forward upgrades



At $2.5<\eta<4$

- Jets
- PID (π^0, $\boldsymbol{\gamma}$, e, $\boldsymbol{\Lambda}$)
- charged particle momentum resolution 20-30% at $0.2<p_T<2$ GeV/c
- event-plane reconstruction and trigger capability

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

Installation of entire system (HCAL + ECAL + electronics) completed;
System being commissioned in Run-21

Installation of entire Si and sTGC completed by mid-September 2021

STAR detector and Au+Au data sets

Low material, PID capability over extended η and p_T, improved trigger capability
forward π^0, γ, e, Λ, charged hadron, jets

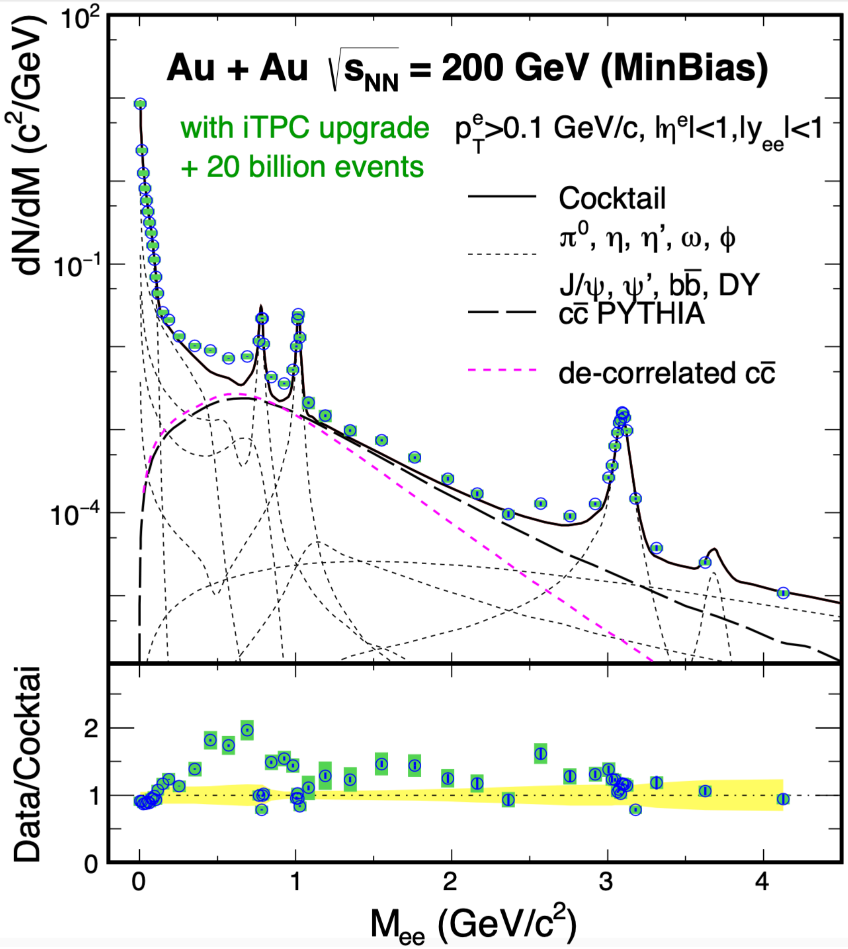
STAR BUR20

24 weeks data taking for Run-23 and 25 each

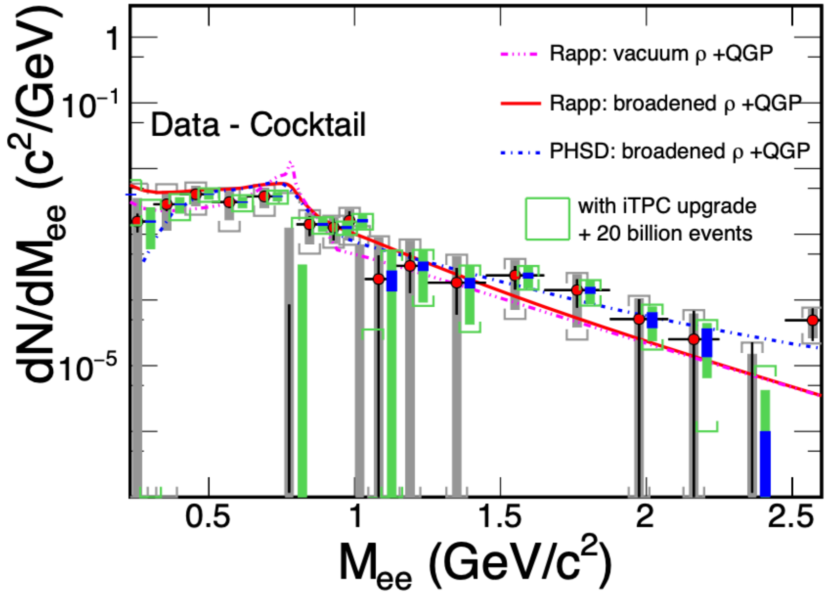
year	minimum bias [$\times 10^9$ events]	high-p_T int. luminosity [nb^{-1}] all vz	$\lvert vz \rvert < 70$cm	$\lvert vz \rvert < 30$cm	
2014 2016	2	26.5	19.1	15.7	**TPC+TOF+HFT+MTD**
2023	10	43	38	32	**iTPC+EPD+eTOF+TOF +MTD Forward upgrades**
2025	10	58	52	43	

A factor of 10 more minimum bias data compare to Run-14 + Run-16
A factor of 4 more luminosity for high-p_T trigger

Back to 200 GeV Au+Au in 2023-2025



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



STAR BUR20

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)

Link to chiral symmetry restoration

- $T_C \sim T_{ch}$ (T_{ch} will be improved with iTPC upgrades from BESII and beyond)
- $T_0 > T_{ch}$ (a reasonable guess)
- Low-mass dielectron emission dominates at T_c region (based on theory calculations)
- Rho meson significantly broadened: [average width $\Gamma \sim 400$ MeV, Γ (T_C) ~ 600 MeV]

The rho-meson in-medium broadening is a manifestation of chiral symmetry restoration!

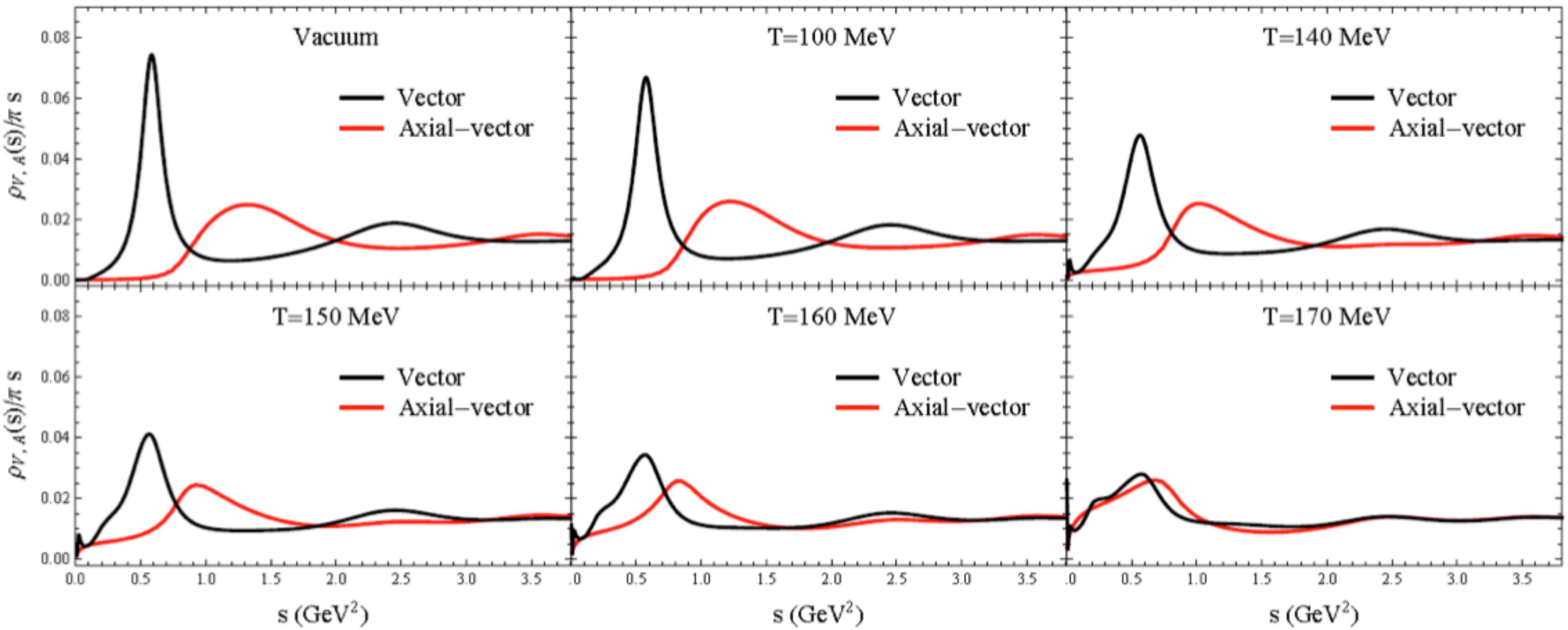
Is it an evidence?

Link to chiral symmetry restoration

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

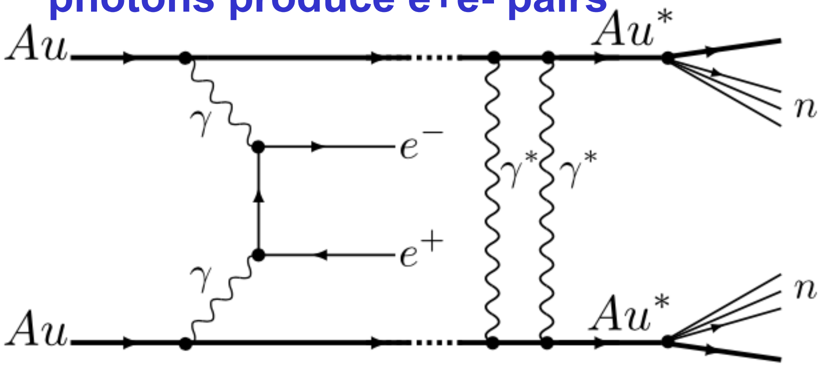
- **Lattice QCD calculation is reliable at $\mu_B = 0$.**

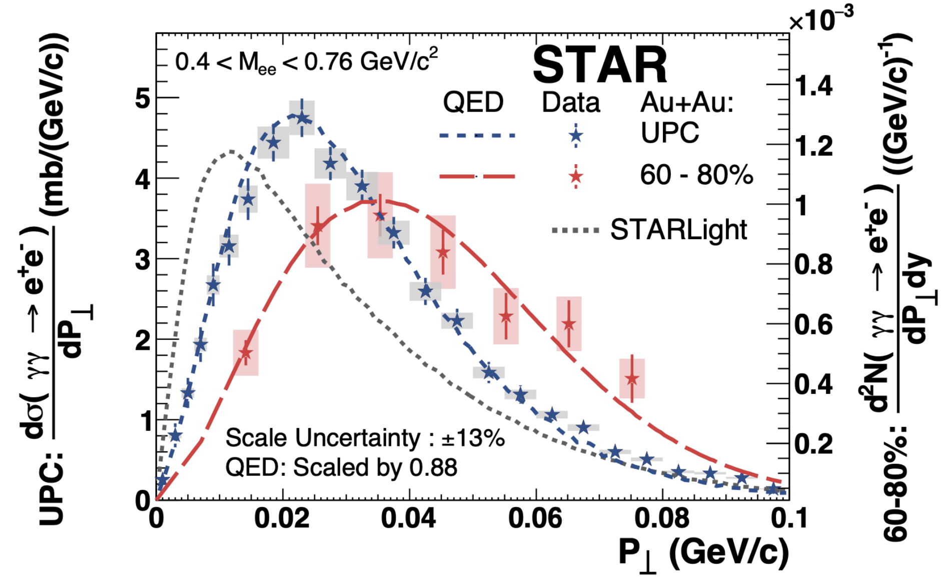
- **Theoretical approach: derive the a1(1260) spectral function by using the broadened rho spectral function, QCD and Weinberg sum rules, and inputs from Lattice QCD; to see the degeneracy of the rho and a1 spectral functions (Hohler and Rapp 2014).**

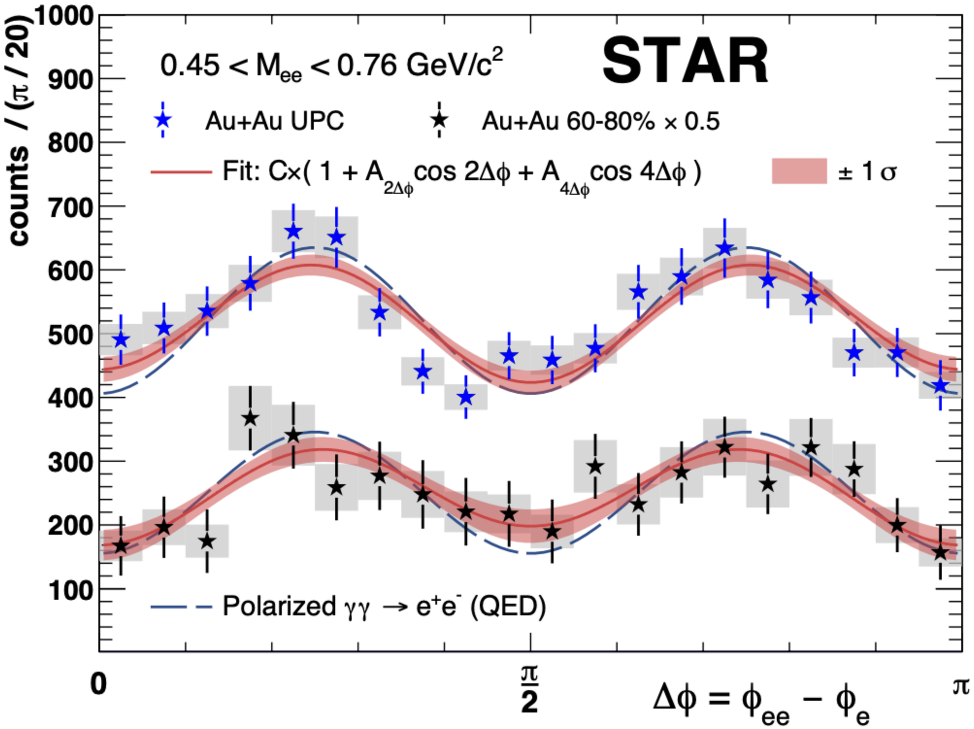


Discoveries of Breit-Wheeler process and vacuum birefringence

linearly polarized quasi-real photons produce e+e- pairs







Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

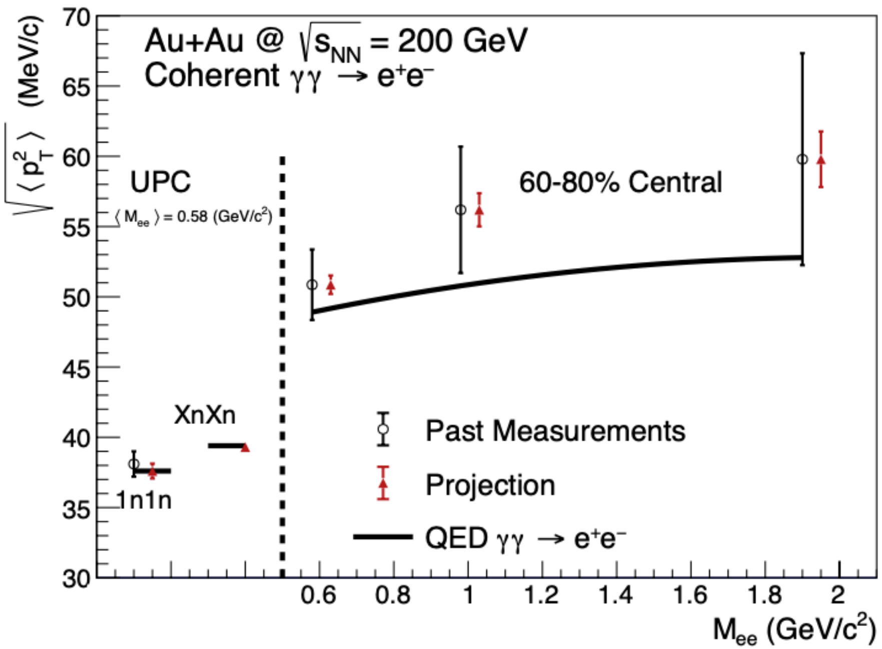
Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in UPC

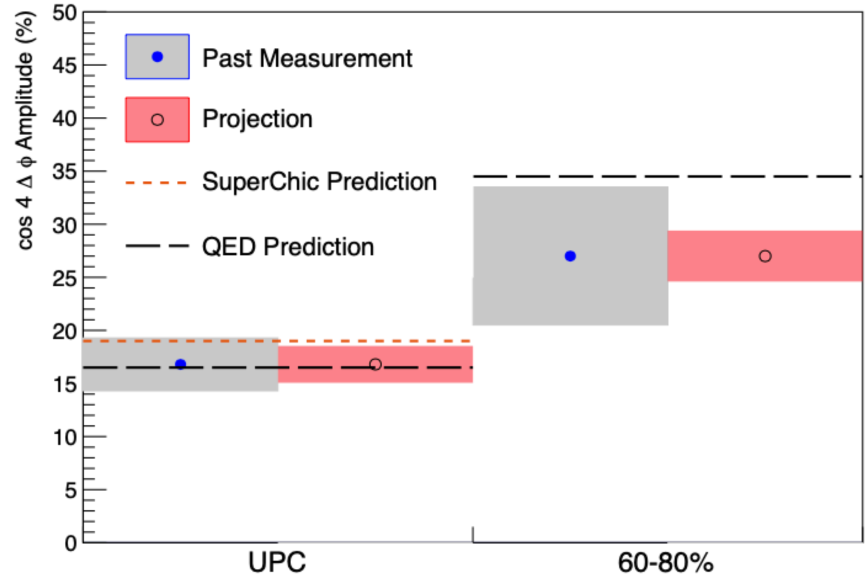
arXiv: 1910.12400, submitted to PRL

Photon Wigner function and magnetic effects in QGP

STAR BUR20



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



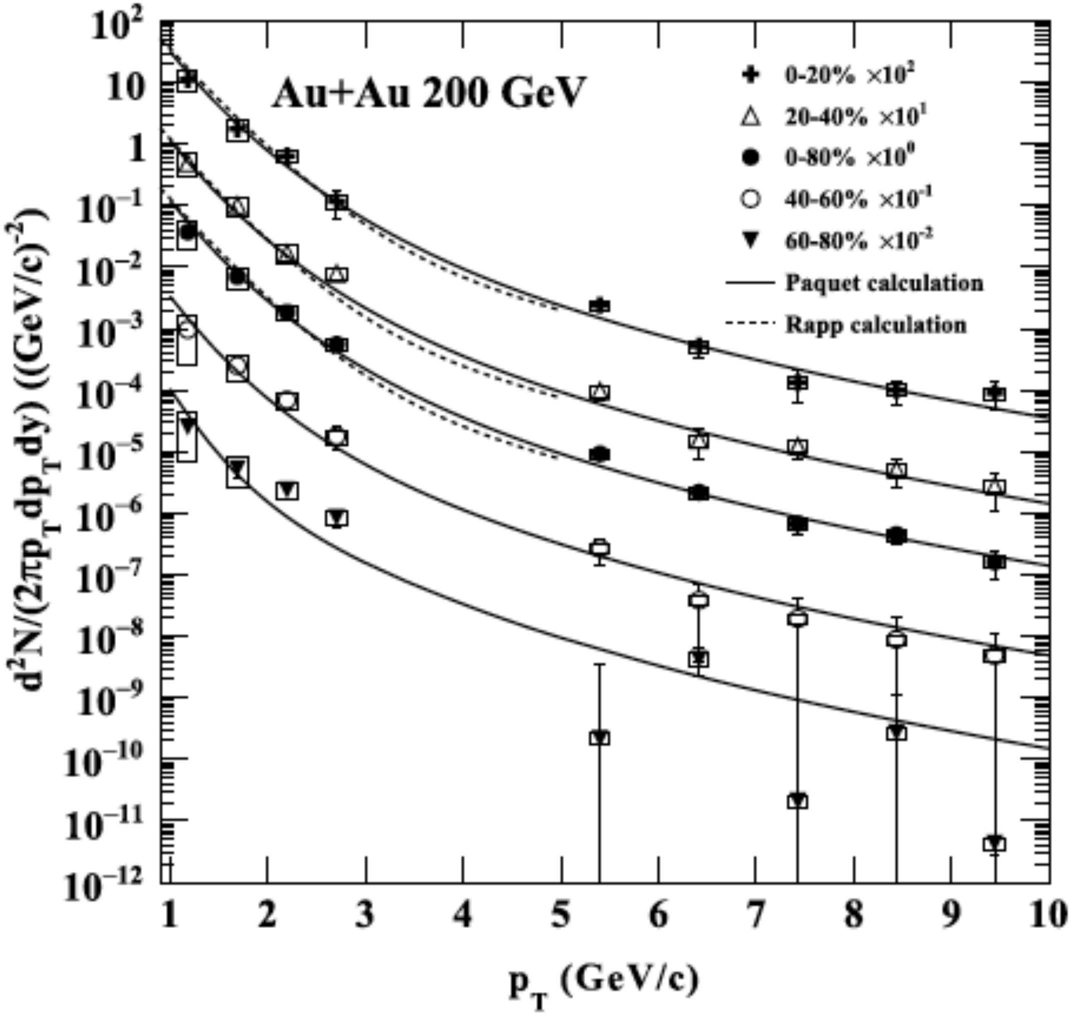
p_T broadening and azimuthal correlations of e^+e^- pairs sensitive to electro-magnetic (EM) field;
Impact parameter dependence of transverse momentum distribution of EM production is the key component to describe data.

Is there a sensitivity to final magnetic field in QGP?

Precise measurement of p_T broadening and angular correlation will tell at >3σ for each observable.

Fundamentally important and unique input to CME phenomenon.

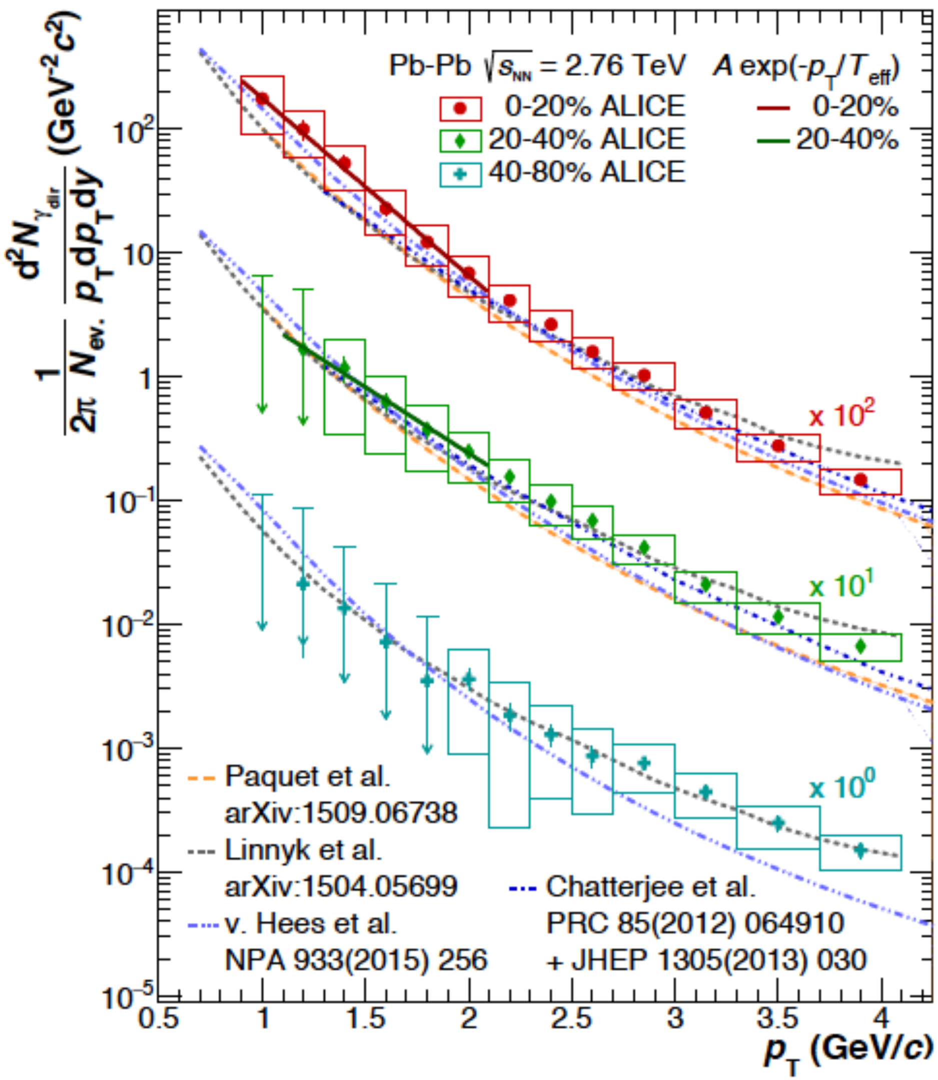
Direct virtual photon in Au+Au



STAR: PLB770(2017)451

Models describing the low-mass e^+e^- pairs agree with STAR photon data.

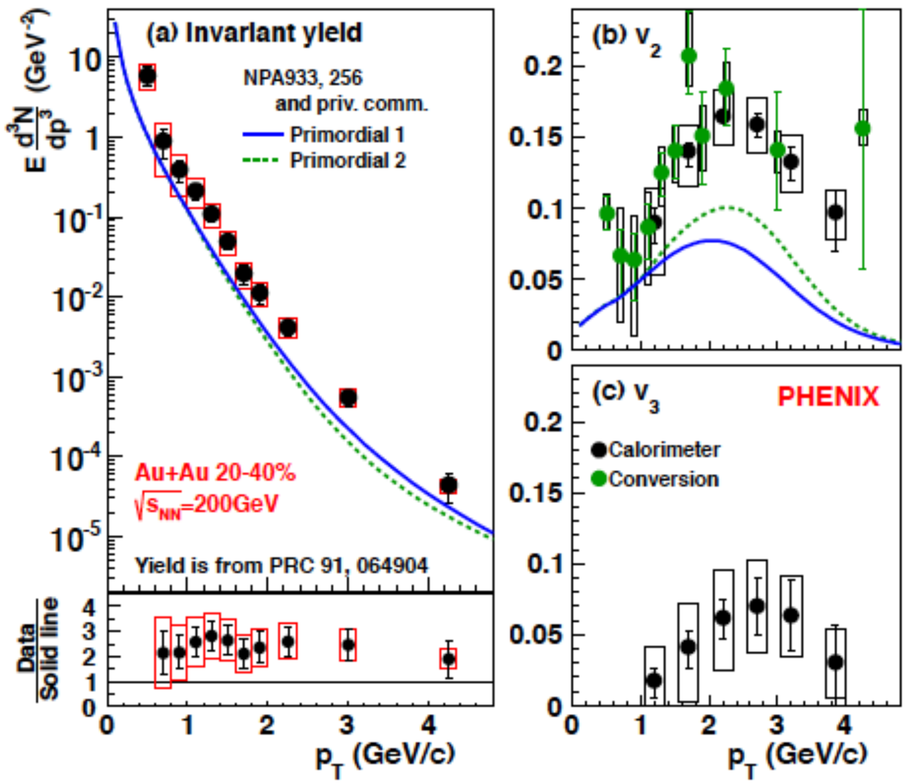
Direct photon in Pb+Pb

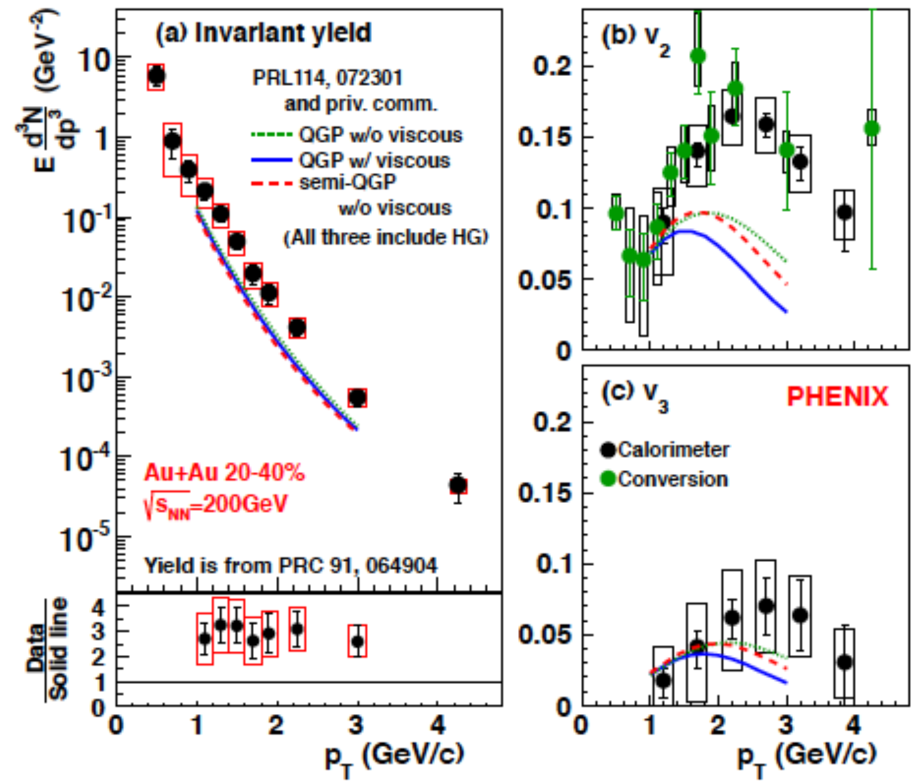


Calculations from the same models agree with ALICE photon data.

ALICE: PLB754(2016)235

Direct photon yields and v_n from PHENIX





- Results from PHENIX in 200 GeV Au+Au challenge model calculations.

  PHENIX: PRC94(2016)064901

- **Precise measurements from various experiments, different system sizes and collisions energies are crucial!**

Summary

We observed:

- **A broadened ρ spectrum function consistently describes the low mass electron-positron excess in A+A collisions**

In 2019-2021:

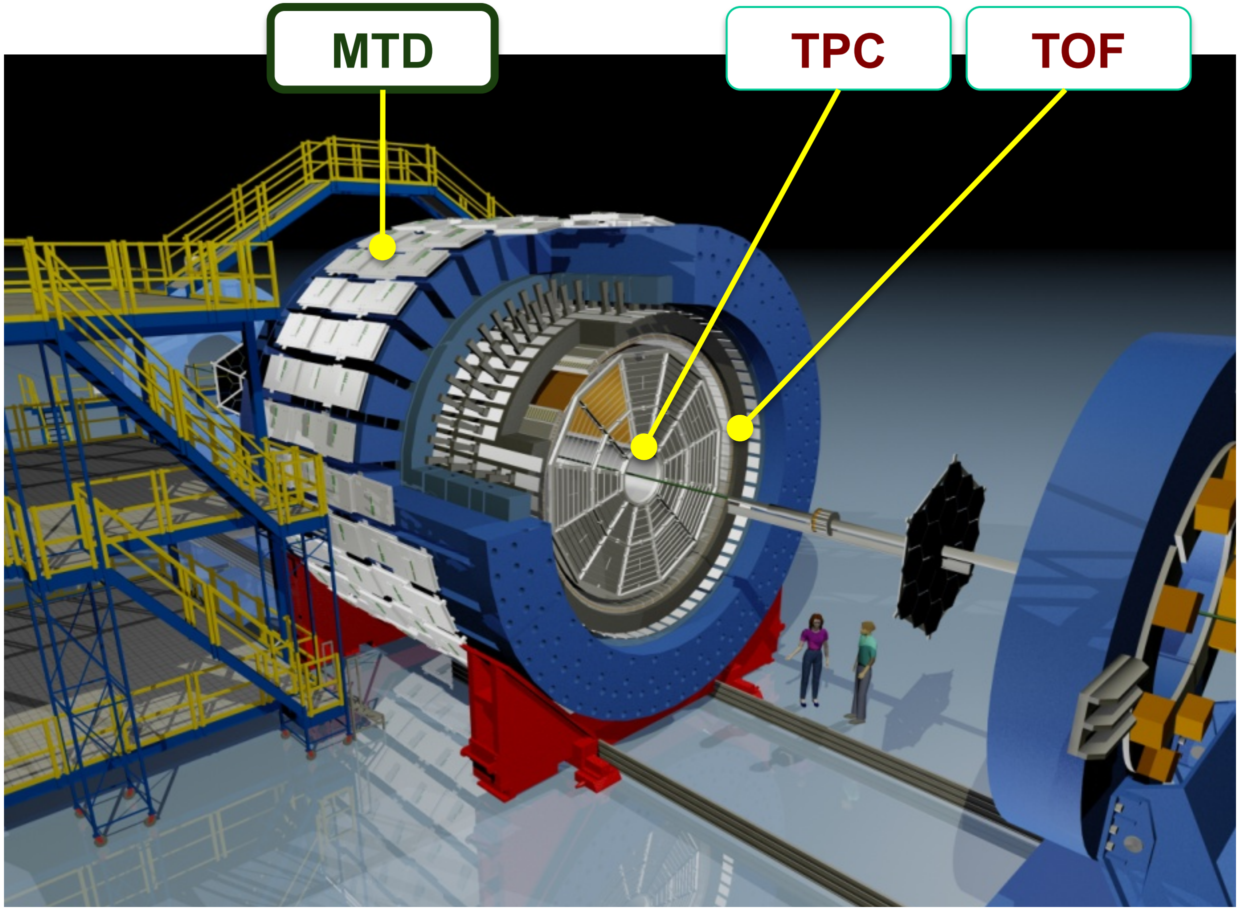
- **Beam Energy Scan II (7.7-19.6 GeV) will provide a unique opportunity to quantify the effect of Chiral Symmetry Restoration via total baryon density effect on the ρ broadening.**

In 2023+2025, indispensable mission with 200 GeV Au+Au data:

- **Measure the temperature and lifetime of hot, dense medium**
- **Provide input for the community to establish connection between dilepton observables and chiral symmetry restoration**
- **Gain a quantitative understanding of magnetic field evolution in heavy ion collisions.**
- **Solve photon puzzle**

Backup

The STAR (Solenoidal Tracker at RHIC) Detector



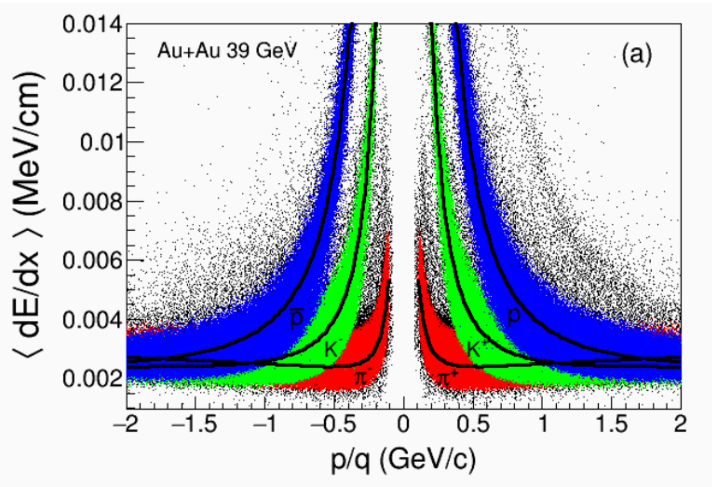
Time of Flight Detector (TOF) & Muon Telescope Detector (MTD):
Multi-gap Resistive Plate Chamber (MRPC), gas detector, avalanche mode

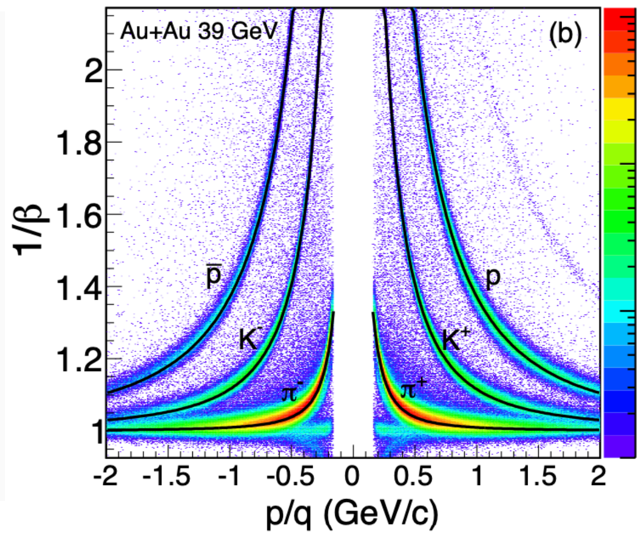
TOF: has **precise timing** measurement, <100 ps timing resolution

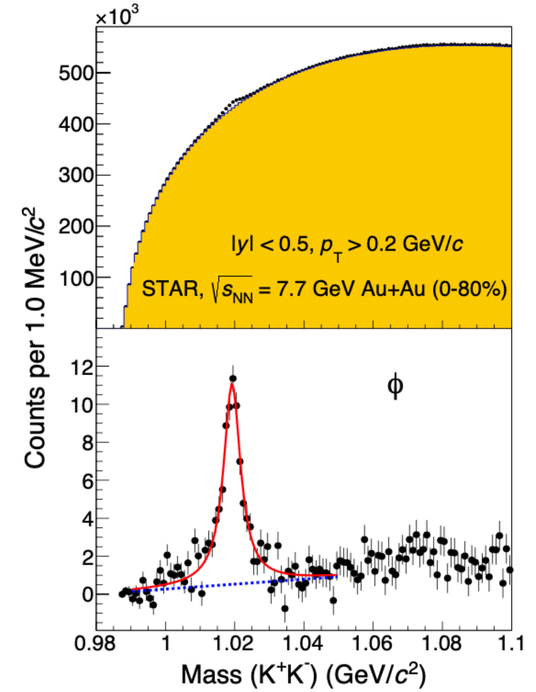
MTD: provide **trigger capabilities** in heavy ion collisions and **muon identification** with **precise timing and position** information

Time Projection Chamber (TPC): Measure ionization energy loss (dE/dx) and momentum

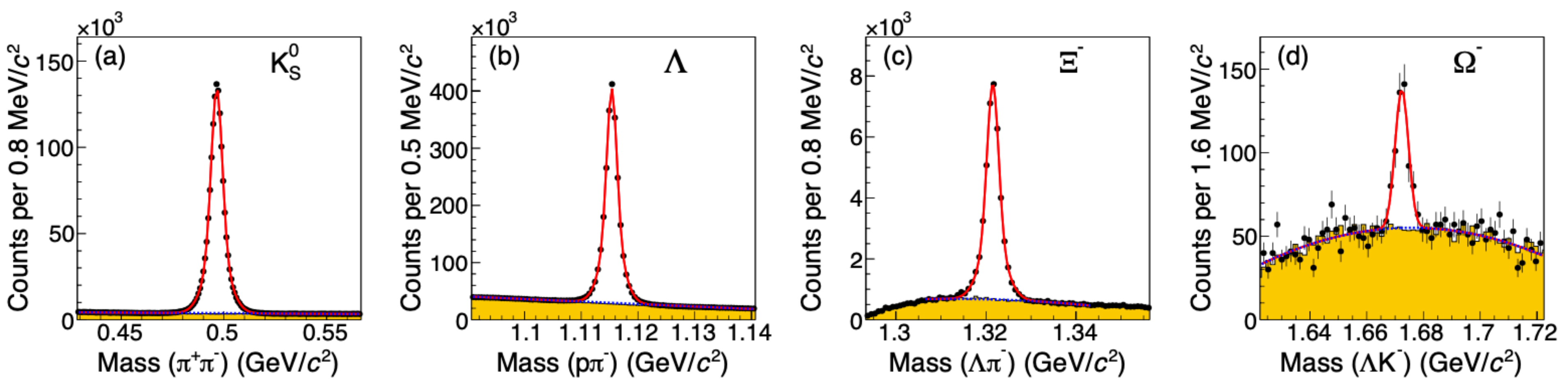
Particle identification at STAR



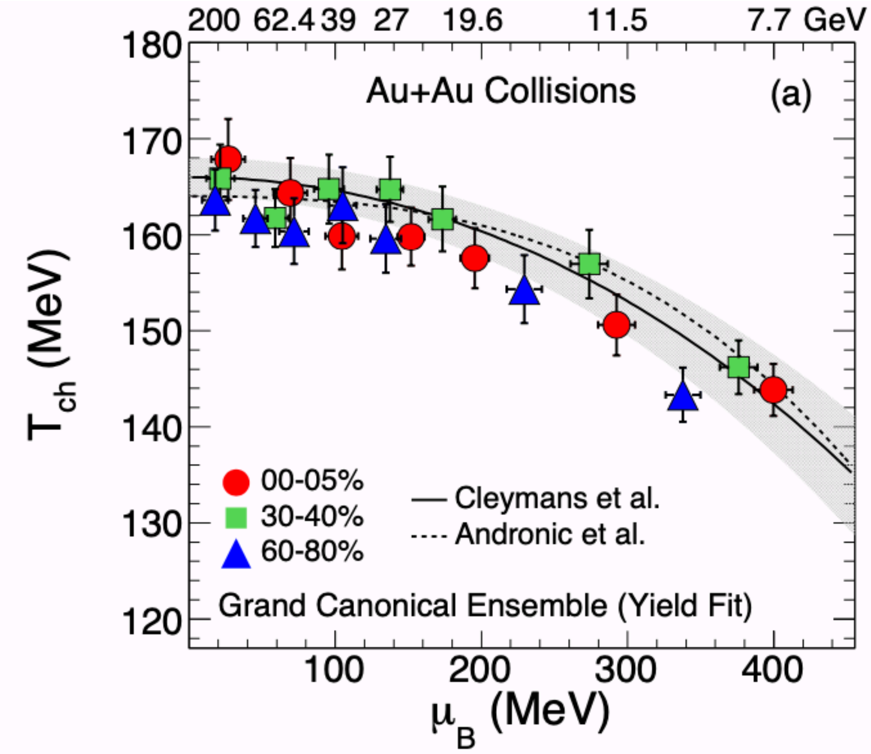


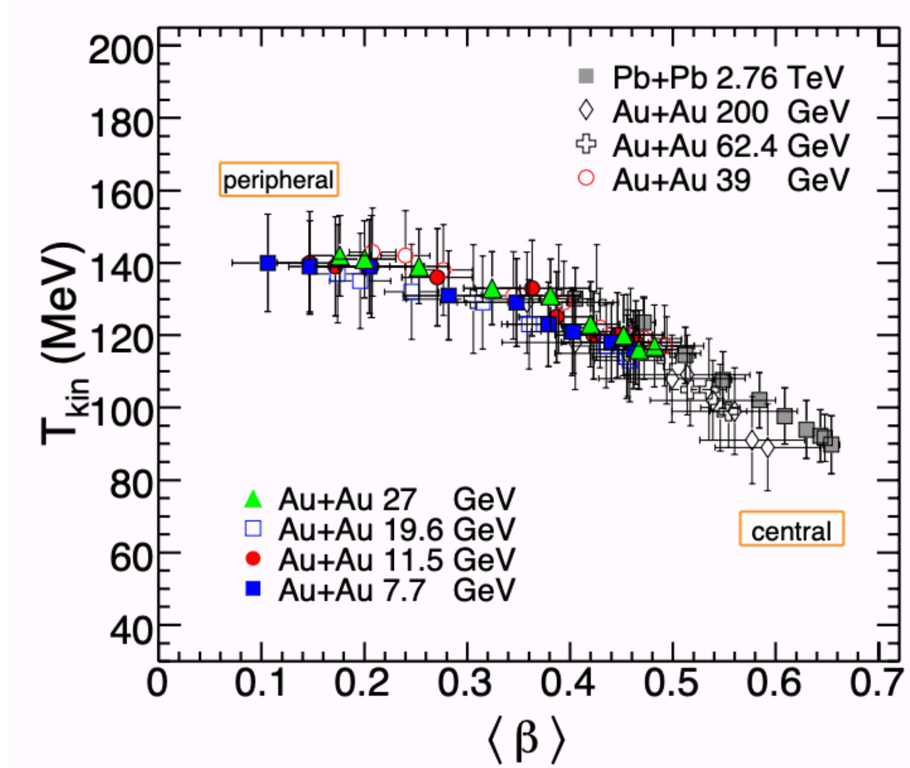


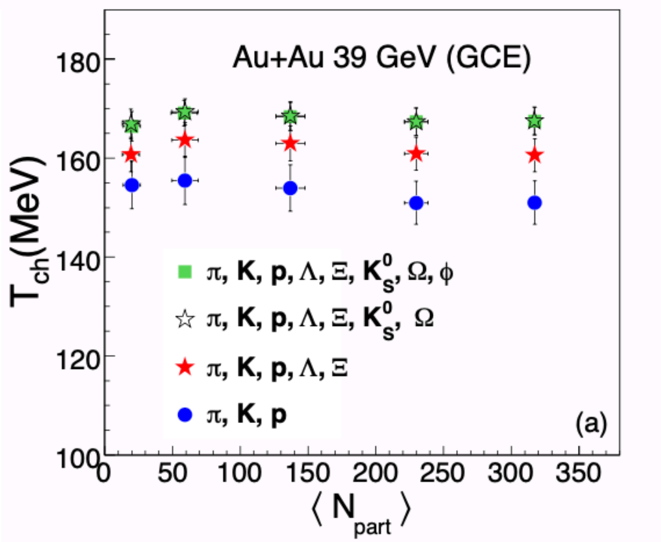
STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), |y|<0.5



Freeze out temperatures







At 200 GeV, T_{ch}~ T_C

The initial temperature T_0 must be higher than T_C ?

Chiral symmetry should be restored at μ_B~0