Dilepton measurements at STAR

Lijuan Ruan (BNL)

Introduction: why dileptons?

Existing measurements at STAR

Future measurements at STAR

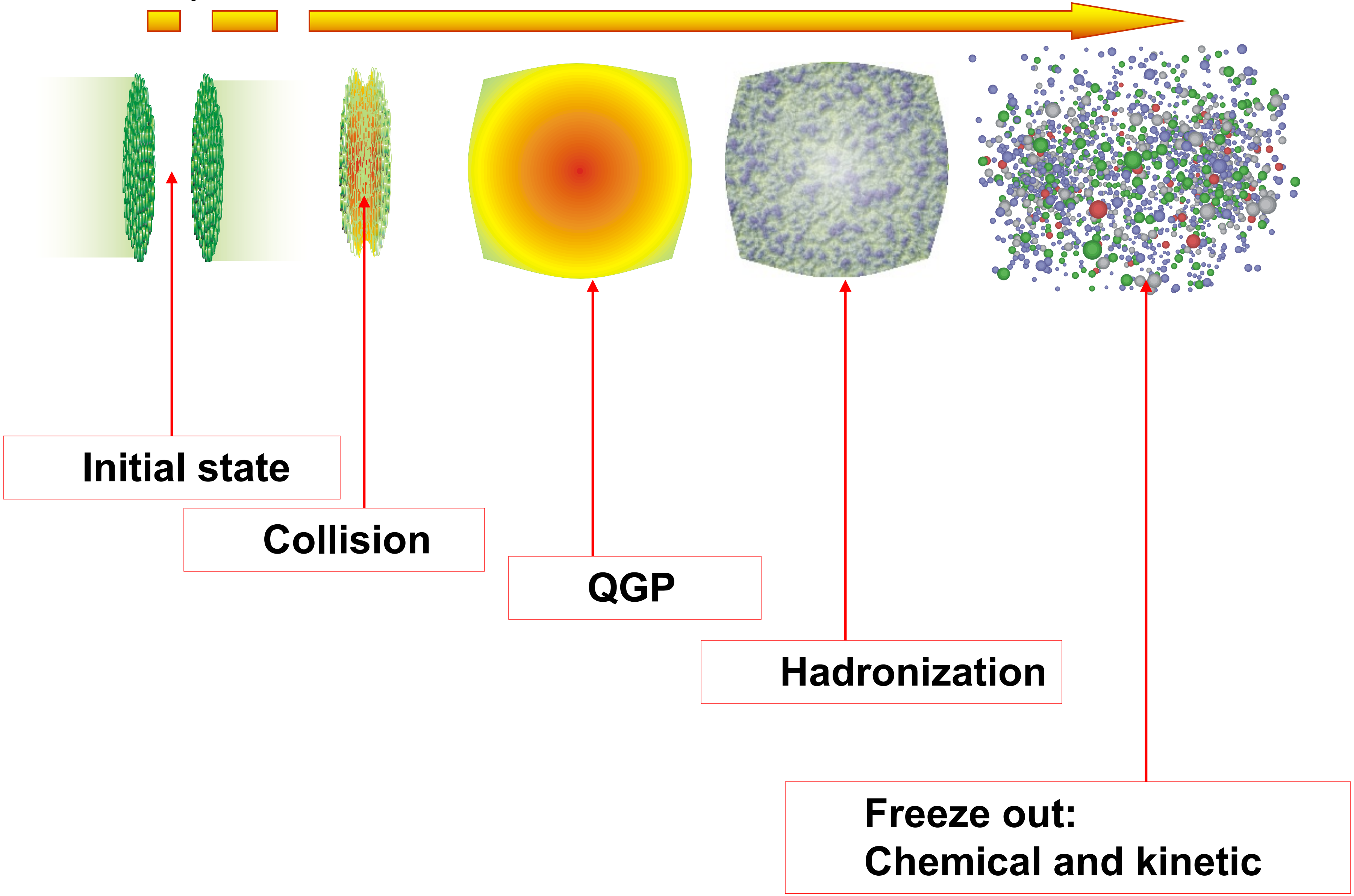
Summary

Reimei Workshop “Hadrons in dense matter at J-PARC
Feb 21-23, 2022 online/KEK Tokai Campus

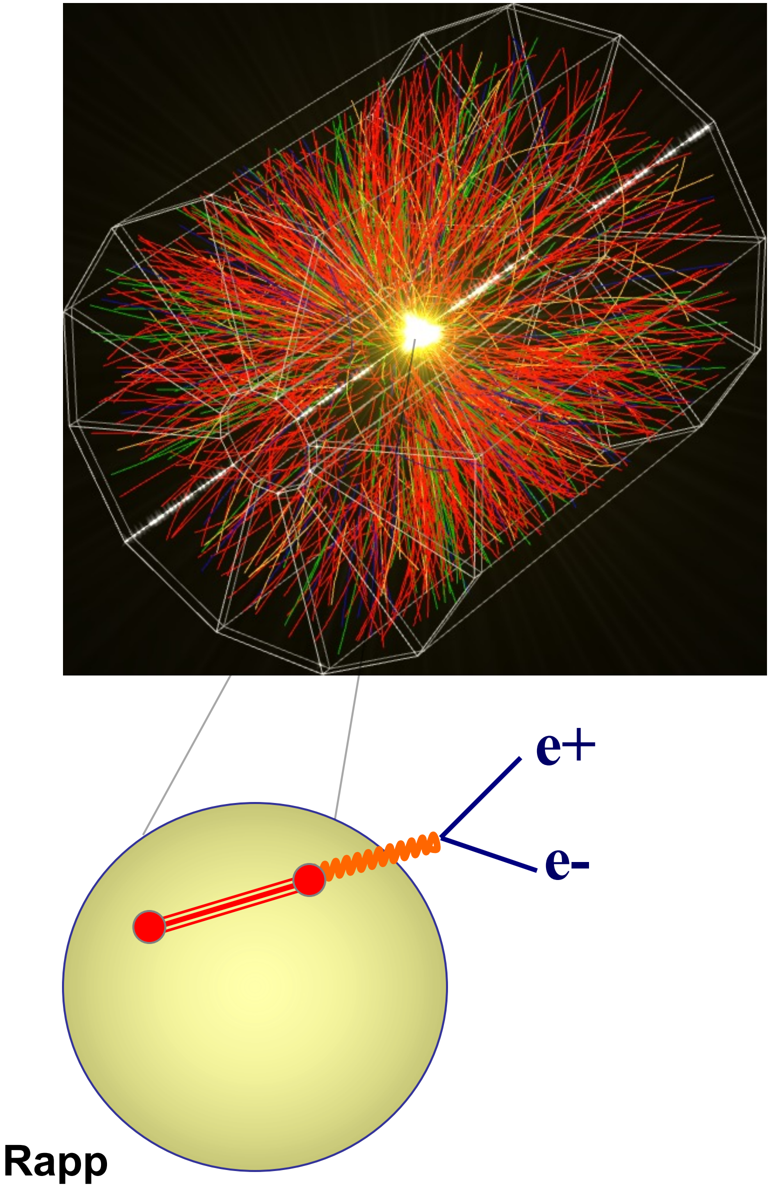
@BrookhavenLab

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:

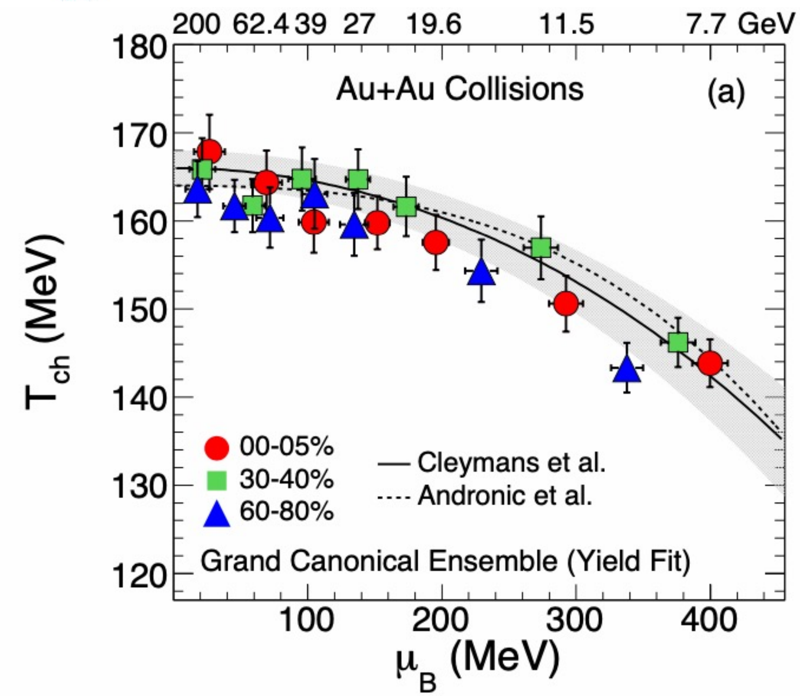
- quark condensate: left-handed quark and right-handed antiquark attract each other through the exchange of gluons.

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

T_c (μ_B=0) = 156.5 ±1.5 MeV HotQCD, PLB 795 (2019)15

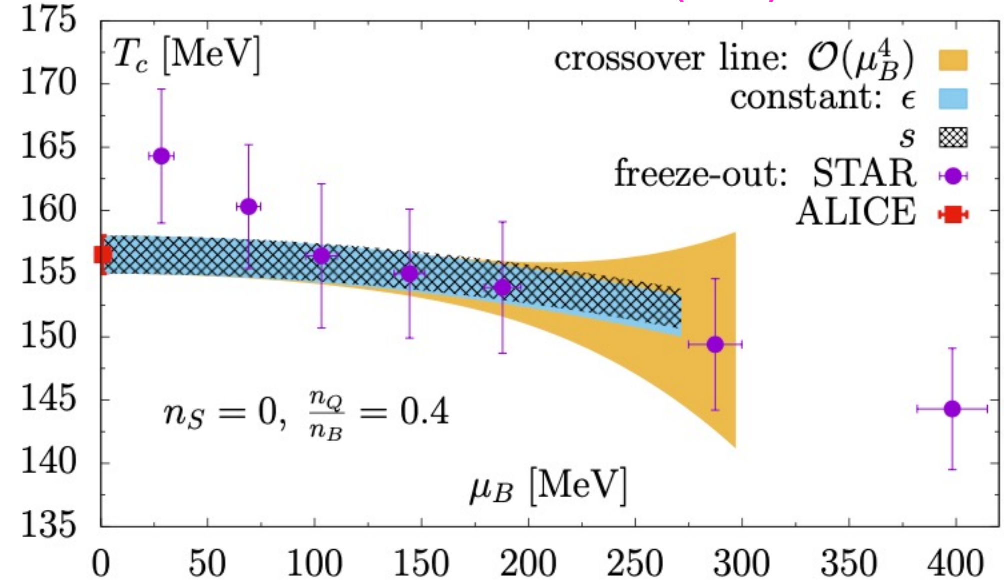
What do we know about the temperature experimentally?

Freeze out temperatures



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

HotQCD, PLB 795 (2019)15

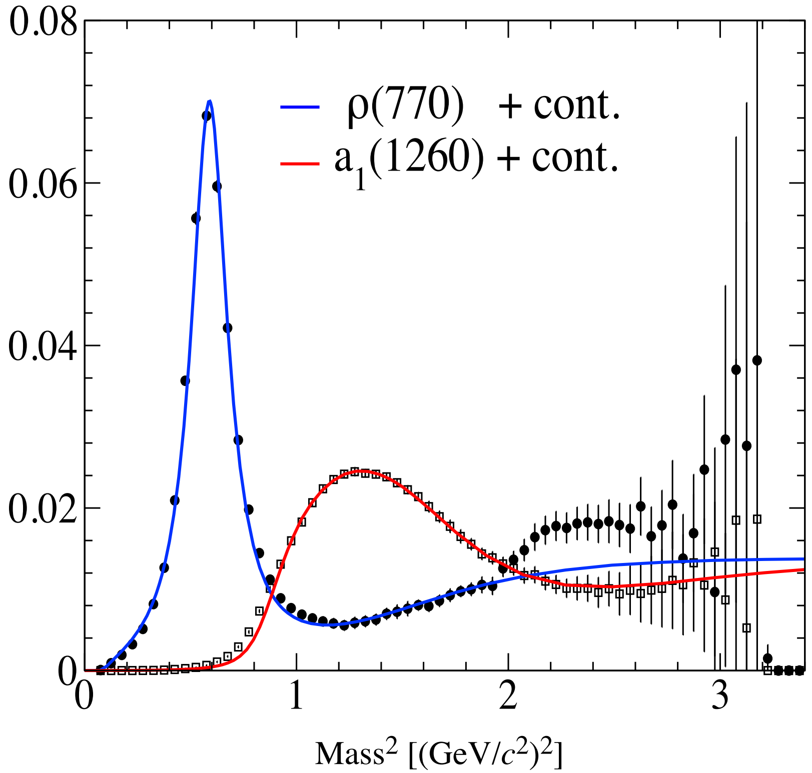


At 200 GeV, T_{ch}~T_C

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

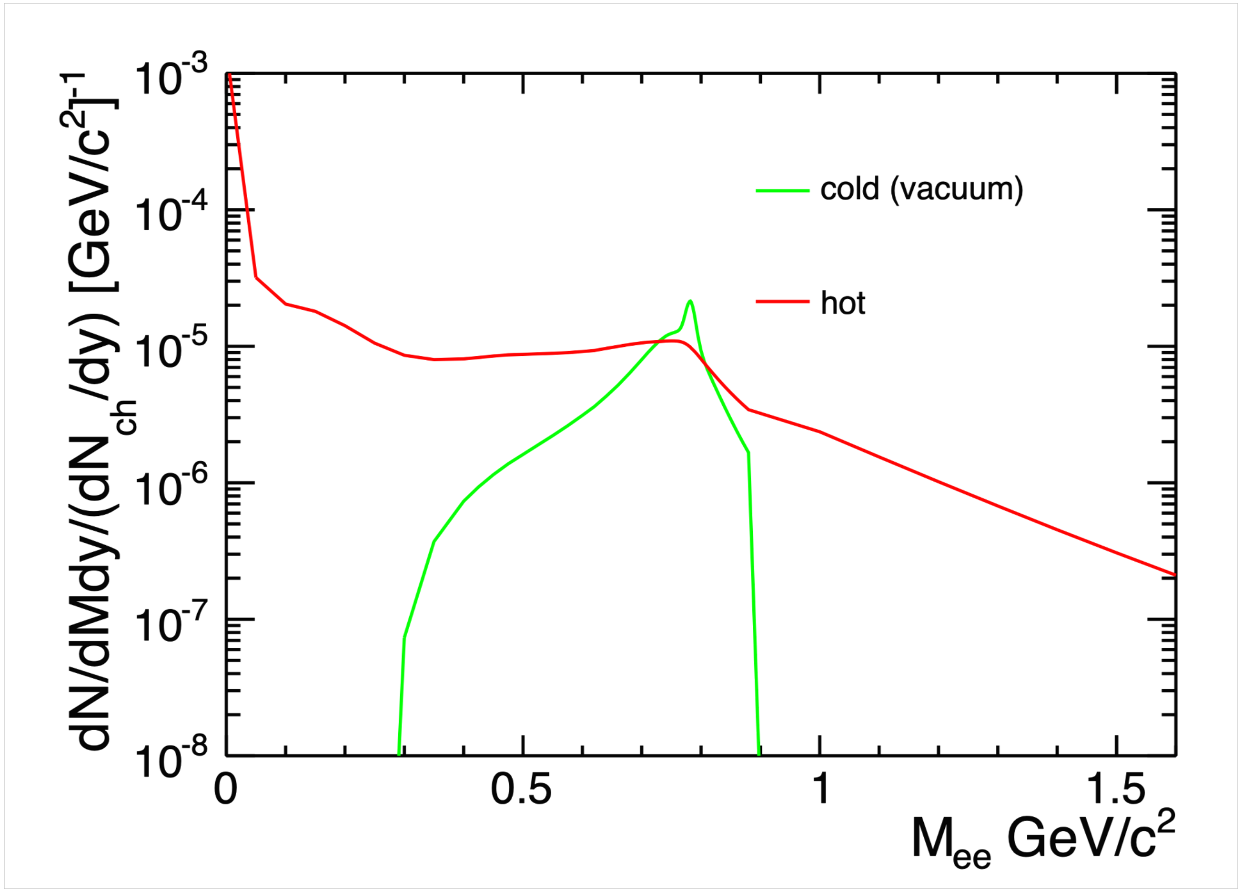


ALEPH: EPJC4 (1998) 409;
R. Rapp Pramana 60 (2003) 675.

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

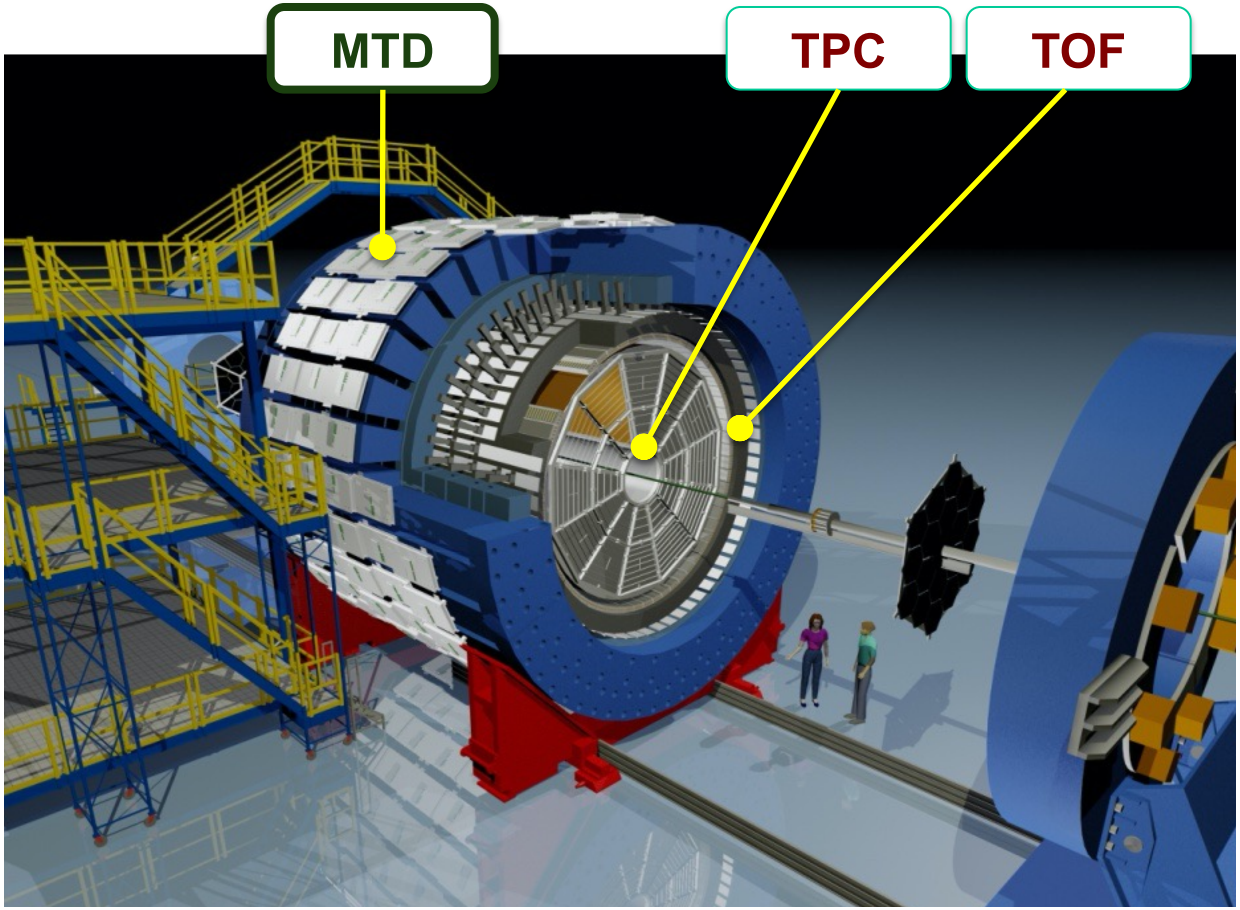
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

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)	vector meson in-medium modifications, link to Chiral Symmetry Restoration
Intermediate mass dileptons (1.1<M_{ll}<3.0 GeV/c^2) (Spectrum and v_n versus M_{ll}, p_T)	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

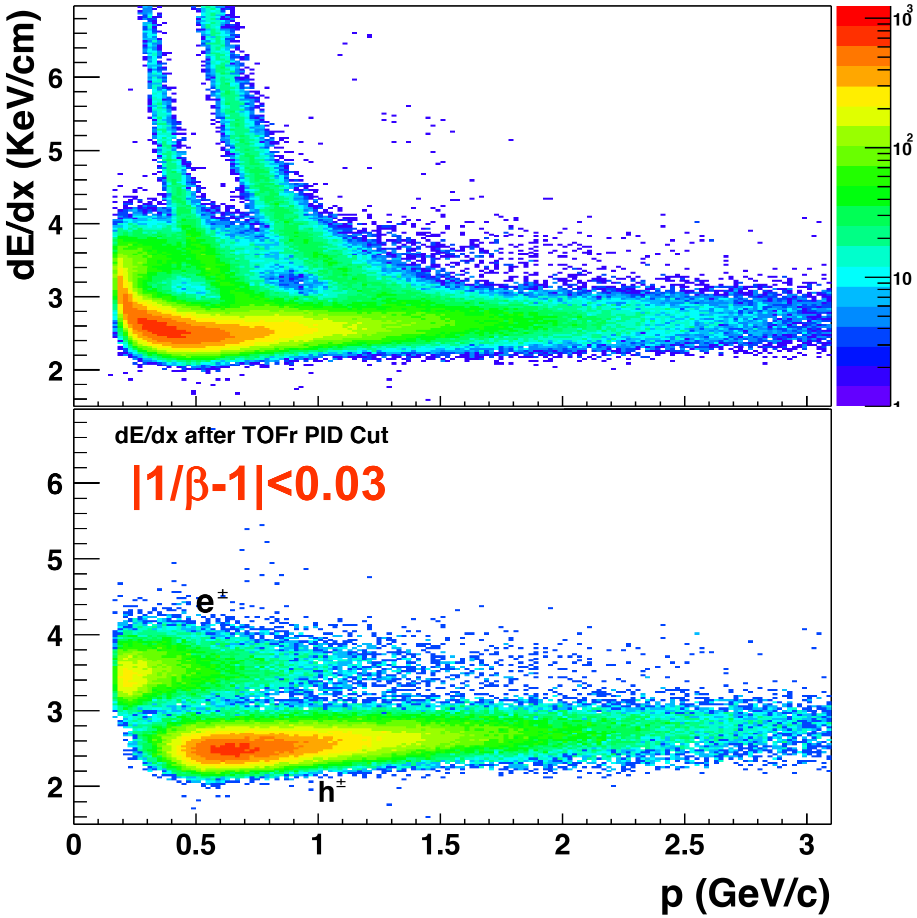


Time Projection Chamber (TPC):
measure ionization energy loss and Momentum

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

has precise timing measurement, <100 ps timing resolution

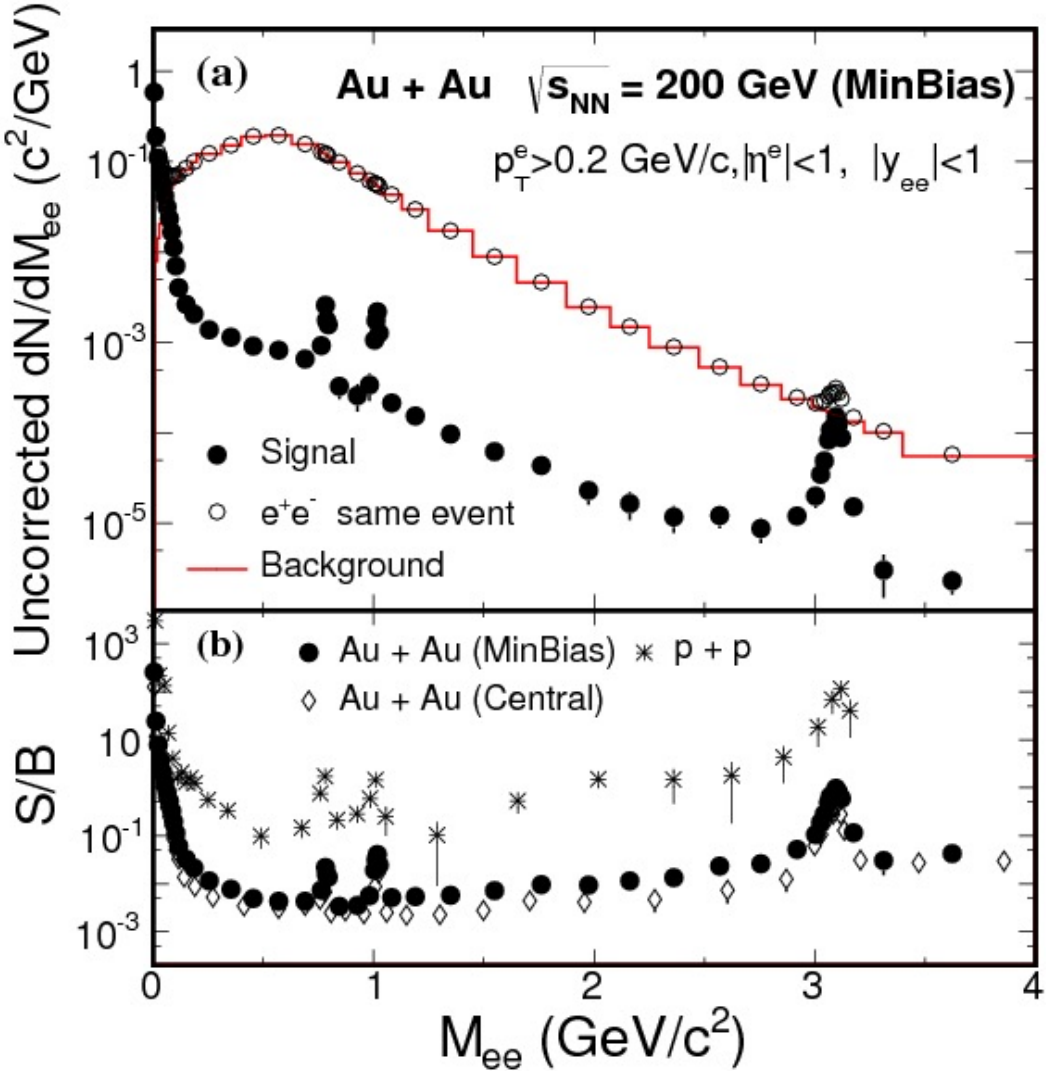
Electron identification



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, η' → γe^+e^-

Vector meson decays: ρ^0, ω, ϕ → e^+e^-, ω → $\pi^0 e^+e^-$, ϕ → ηe^+e^-

Heavy flavor decays: J/ψ → e^+e^-, ccbar → e^+e^- X, bbbar → e^+e^- X

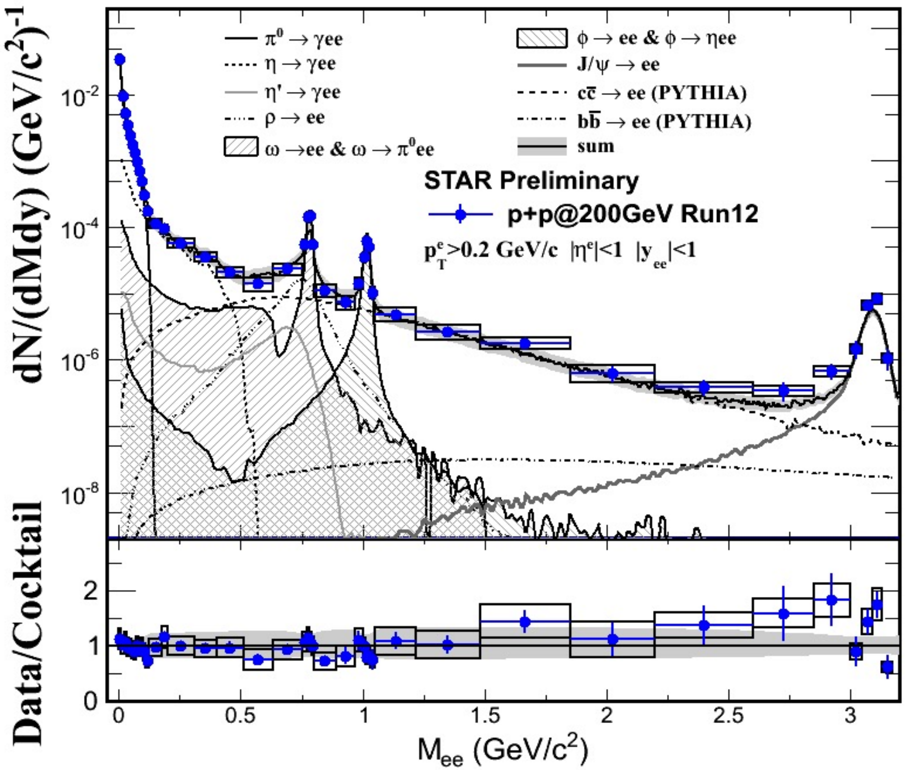
Drell-Yan contribution

In Au+Au collisions, we search for

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

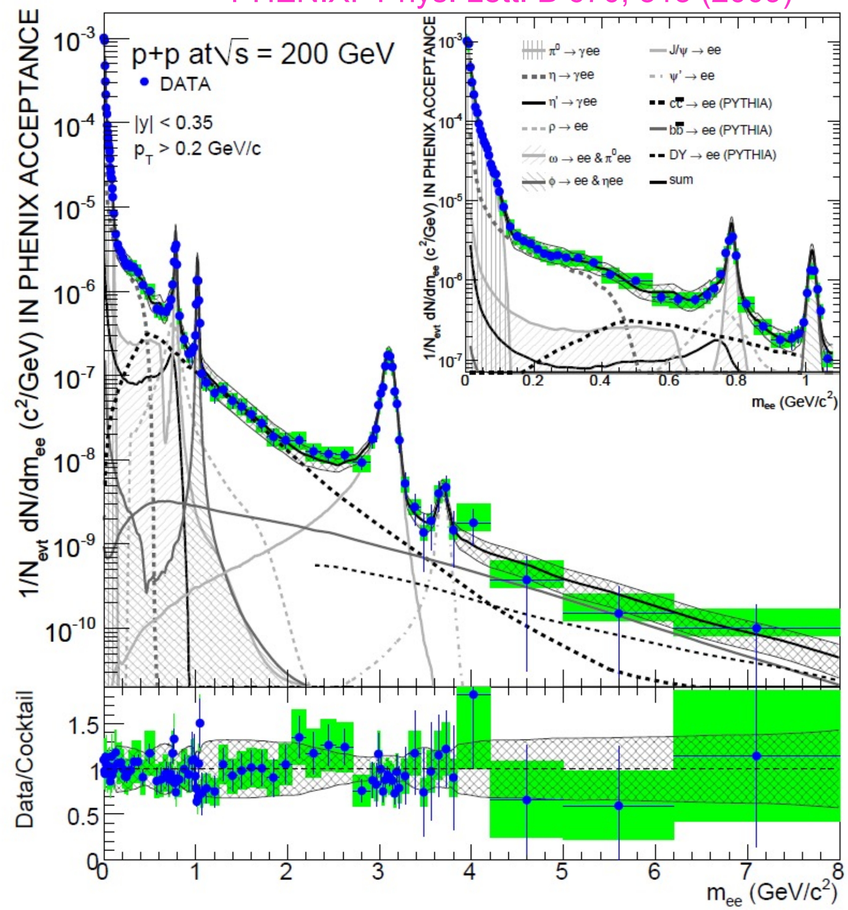
Vector meson in-medium modifications at $M_{ee}<1.1$ GeV/c^2 (low mass range)

Dielectron mass spectrum in 200 GeV p+p collisions



STAR: QM2014

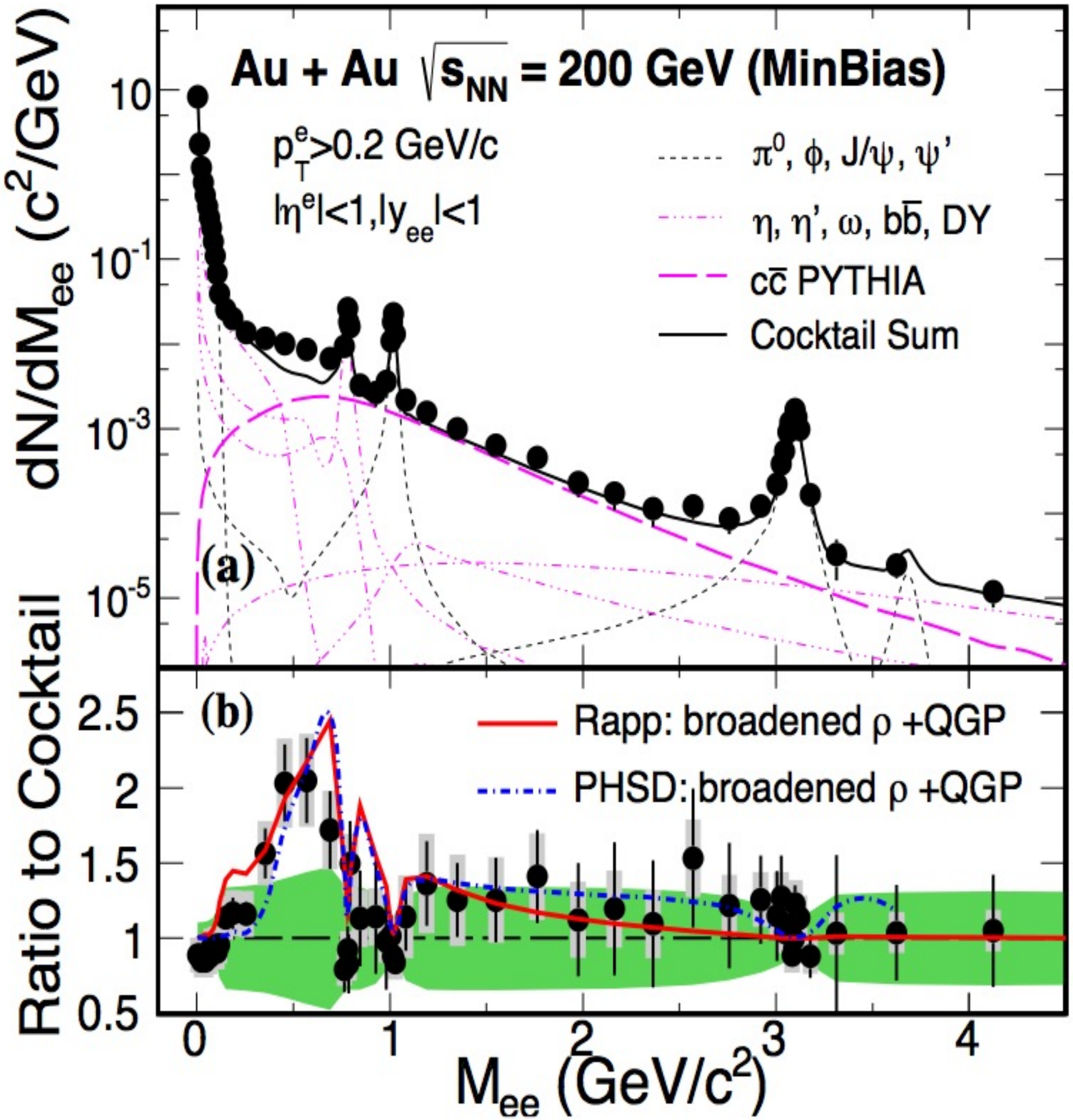
PHENIX: Phys. Lett. B 670, 313 (2009)



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

dielectron mass spectrum in 200 GeV Au+Au

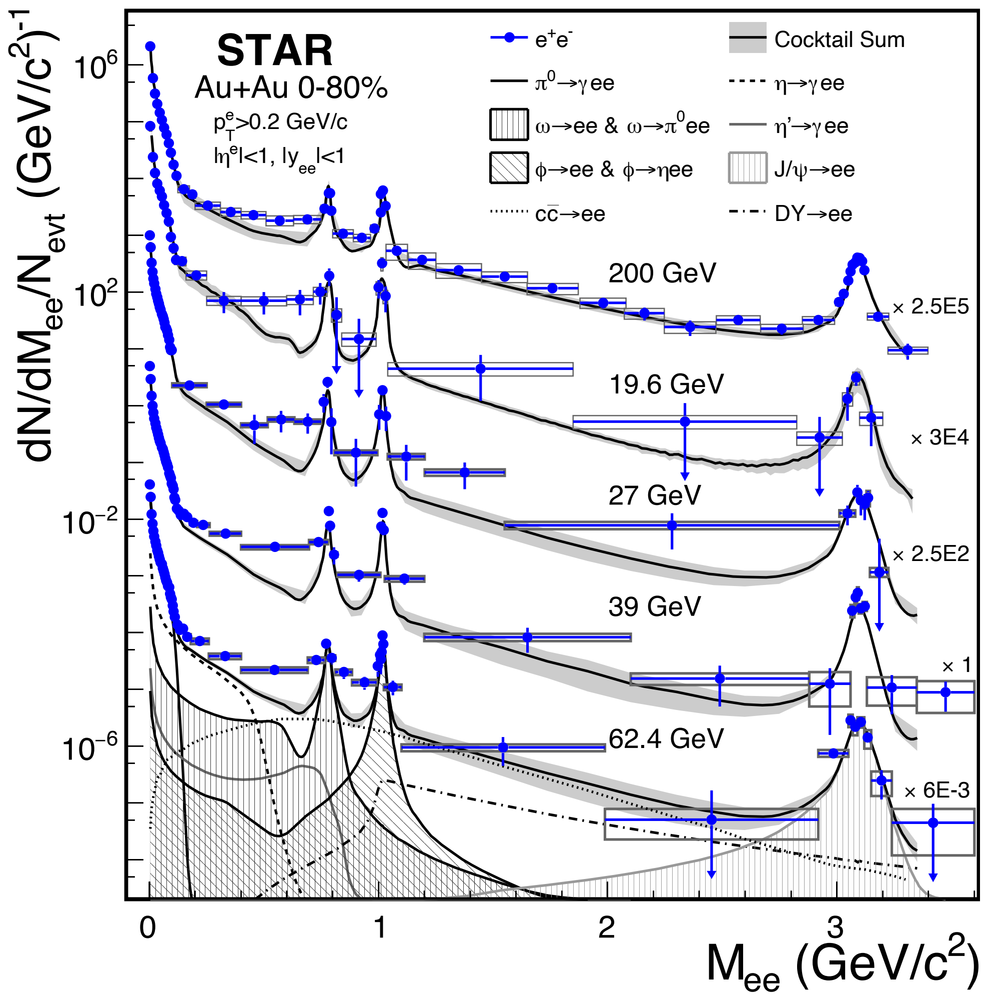
STAR: Phys. Rev. Lett. 113 (2014) 22301



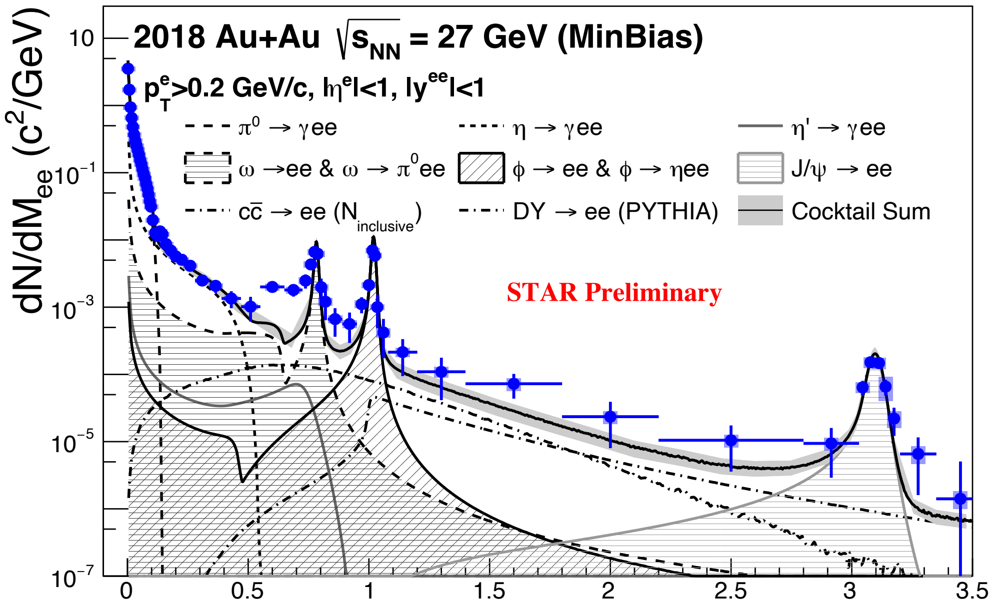
Significant excess is observed for $0.3<M_{ee}<0.8$ GeV/c^2, representing **the hot, dense medium contribution.**

dielectron mass spectrum in 19.6-62.4 GeV Au+Au

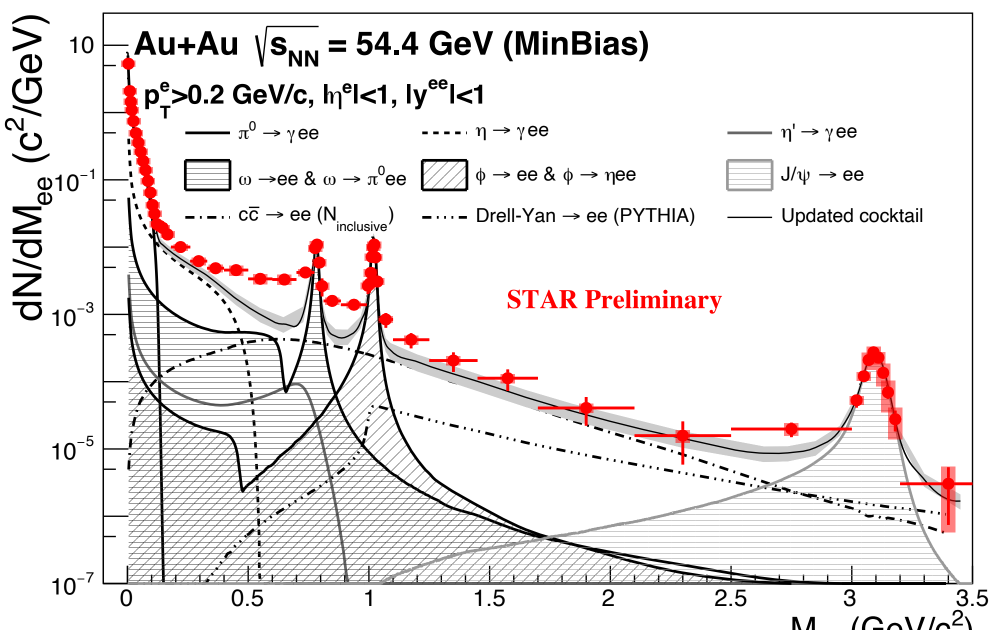
STAR: arXiv: 1810.10159, PLB750(2015)64



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

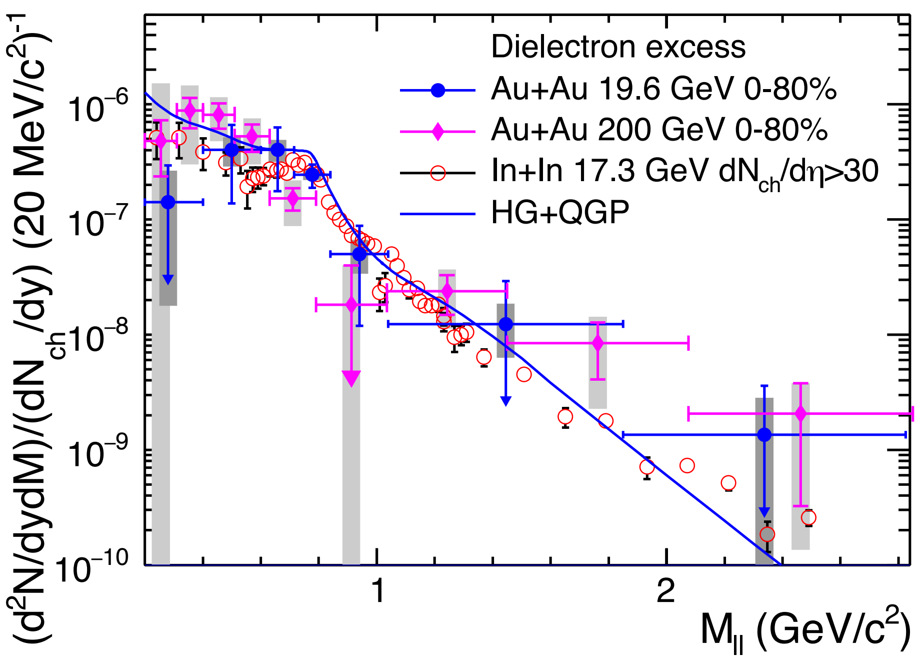


A possible hint of QGP thermal radiation in the intermediate mass region

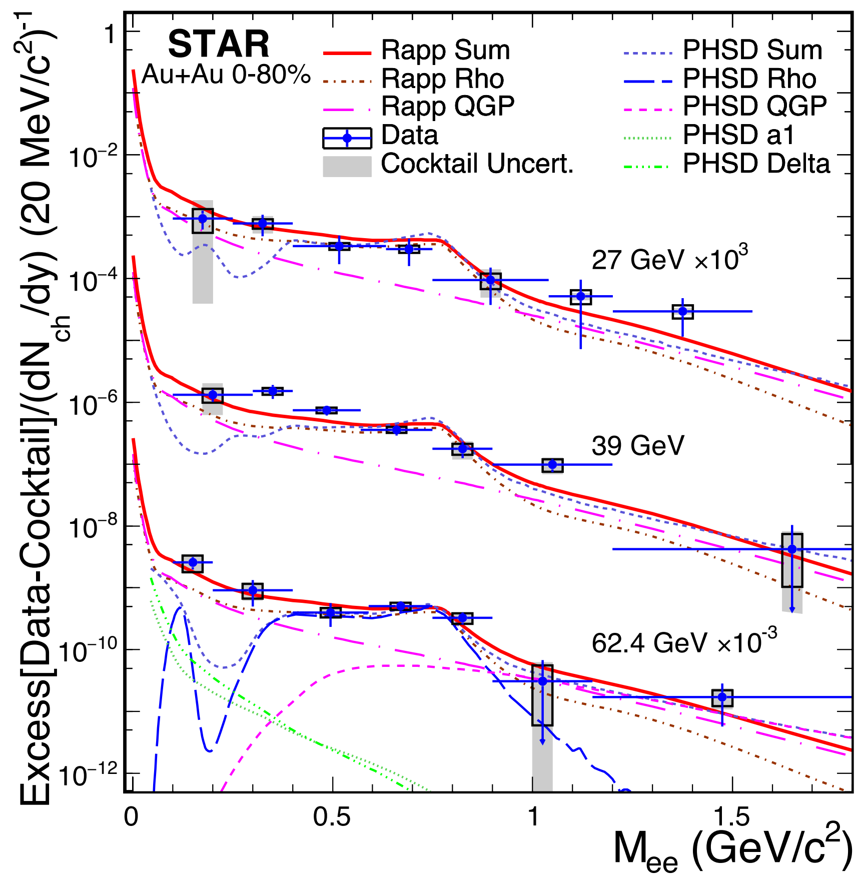
STAR: HP2020

The dielectron excess spectrum

STAR: PLB750(2015)64



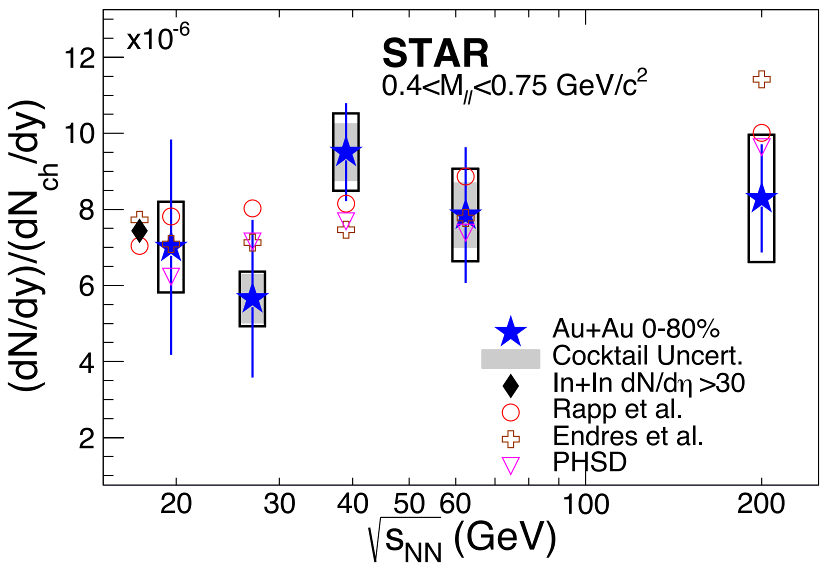
STAR: arXiv: 1810.10159

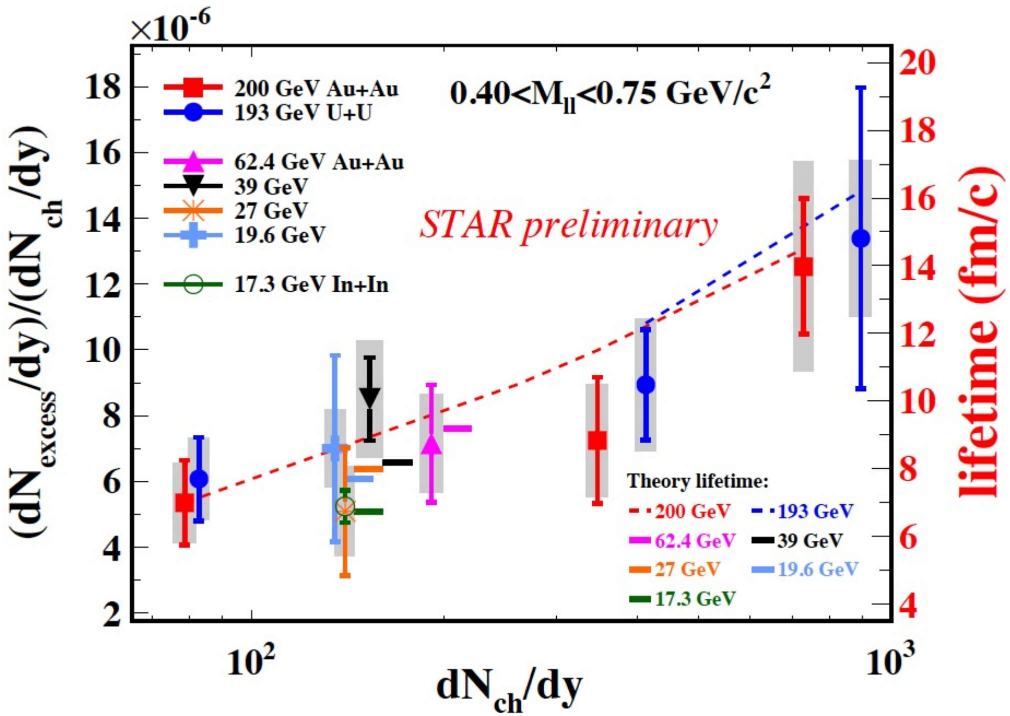


A broadened ρ spectral function consistently describes the low mass dielectron excess for all the energies 19.6-200 GeV.

The low mass measurements: lifetime indicator

STAR: arXiv: 1810.10159

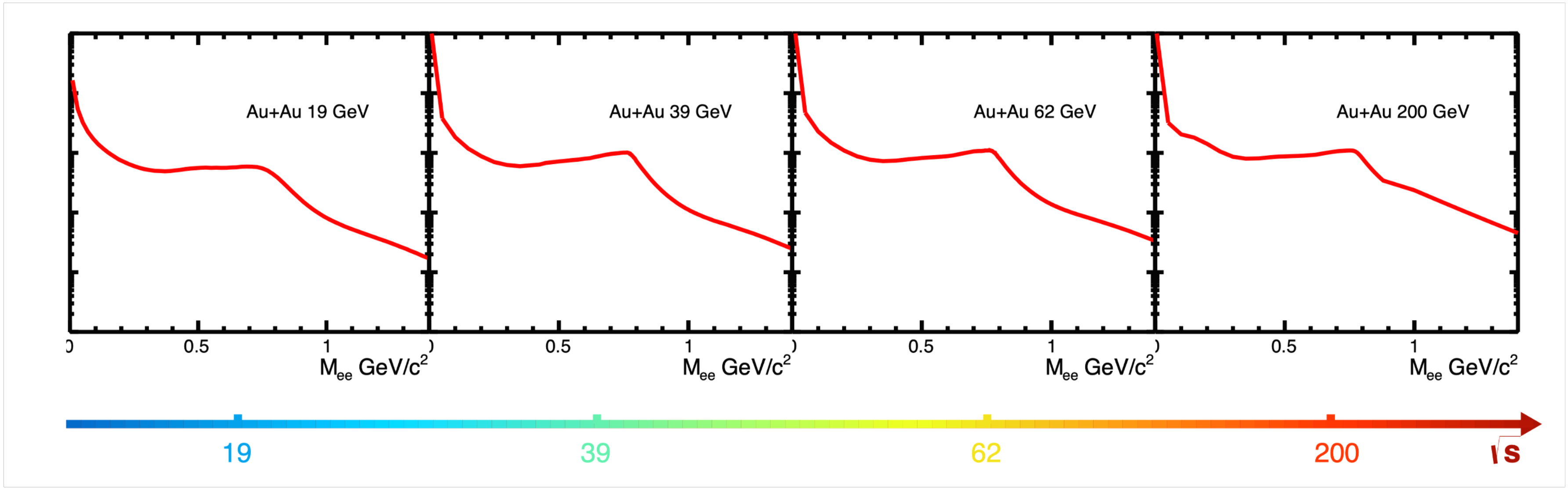




STAR: QM2015

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



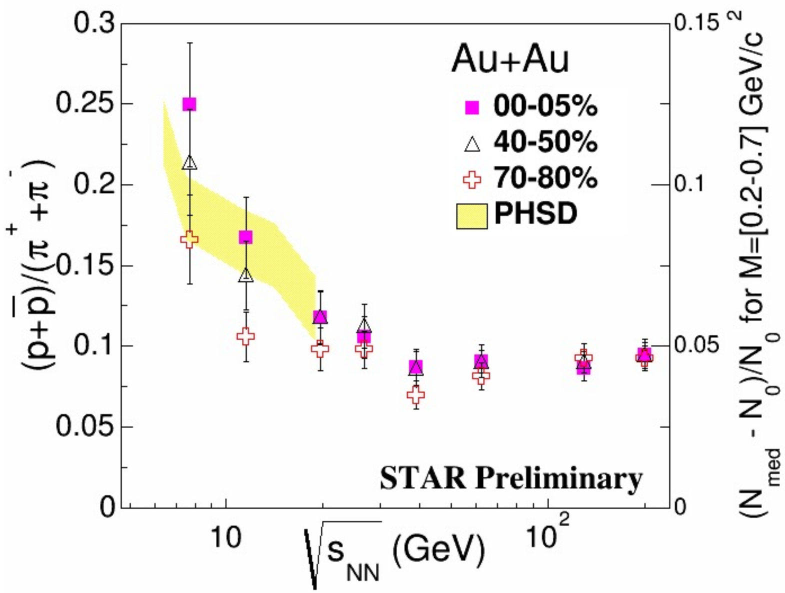
The electron-positron spectrum from hot, dense medium is consistent with a broadened ρ resonance in medium.

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

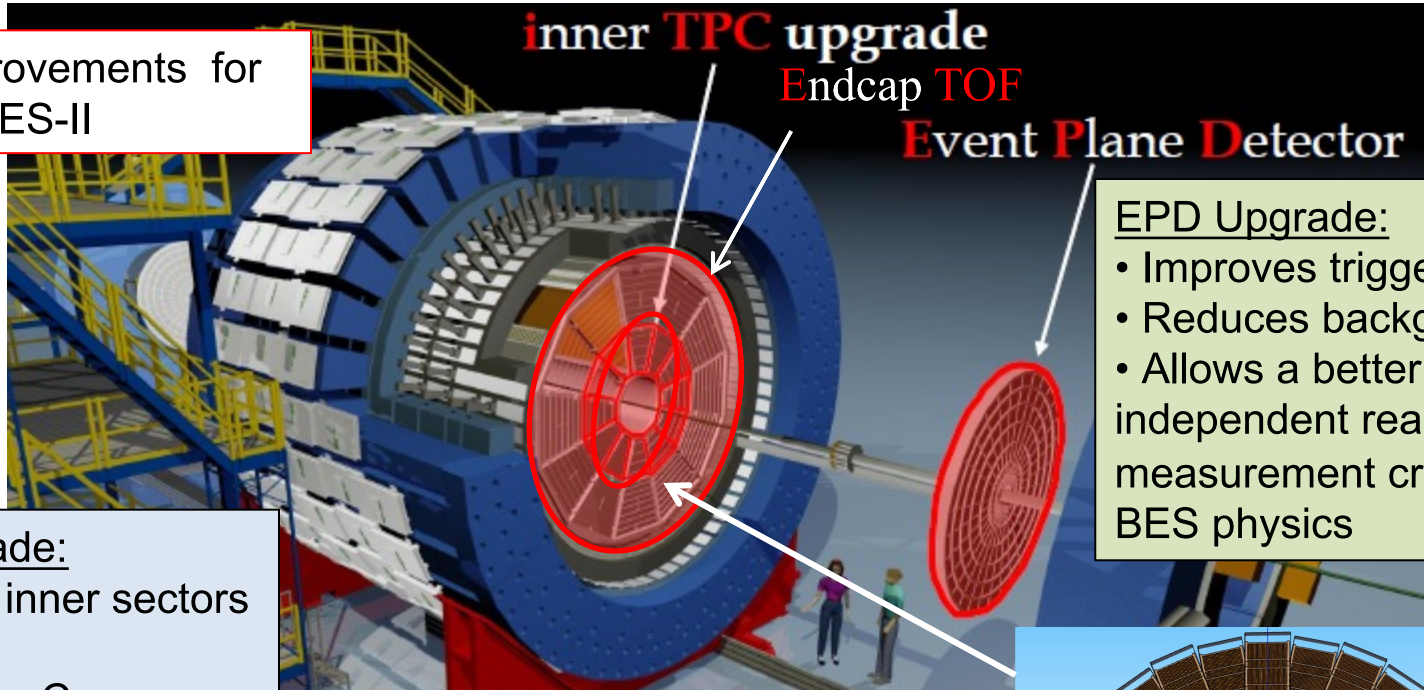
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.



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

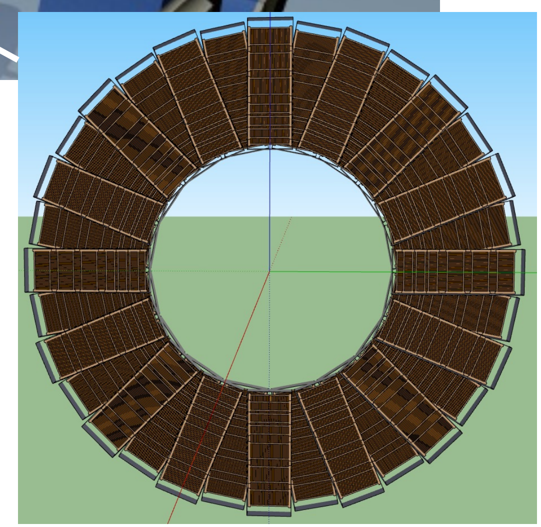
Major improvements for BES-II



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**

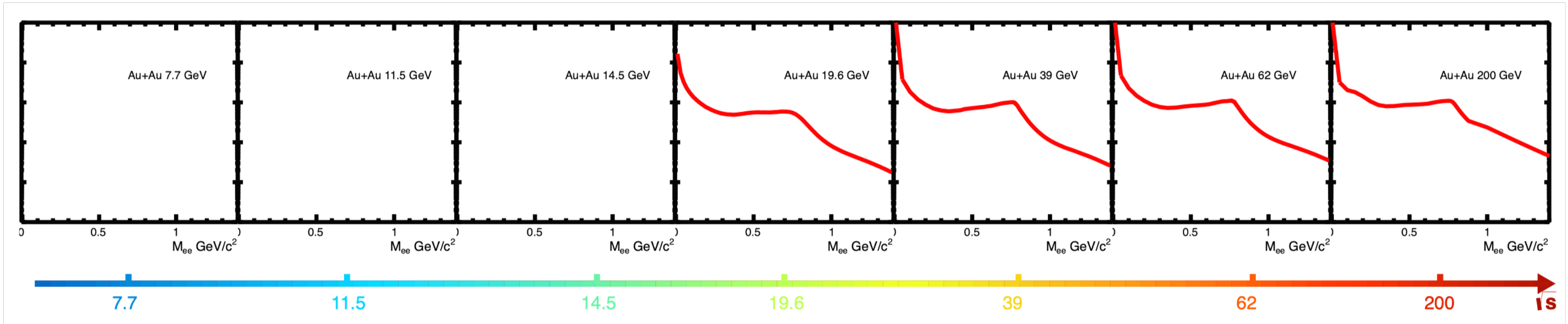
A factor of 2 reduction in the systematic uncertainties for dielectron excess yield

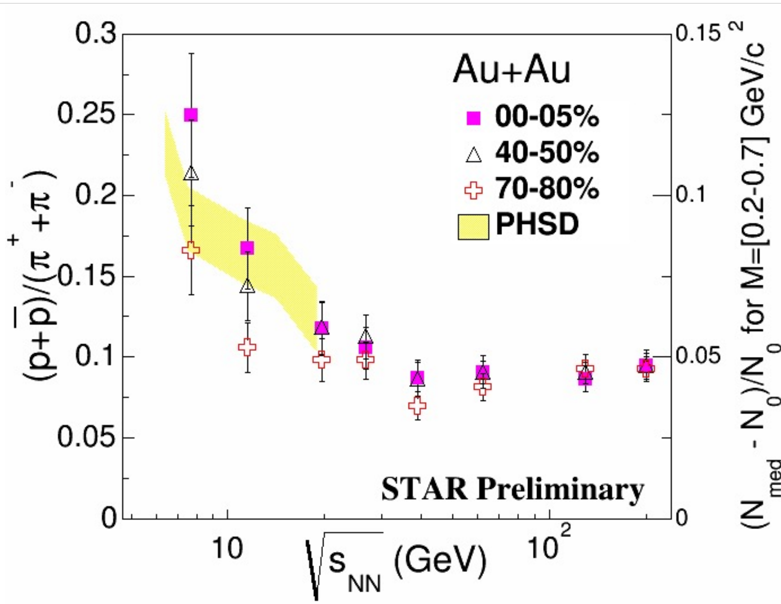
Improves the acceptance for dielectron measurement by more than a factor of 2 in the low mass region, lowers the statistical uncertainties.

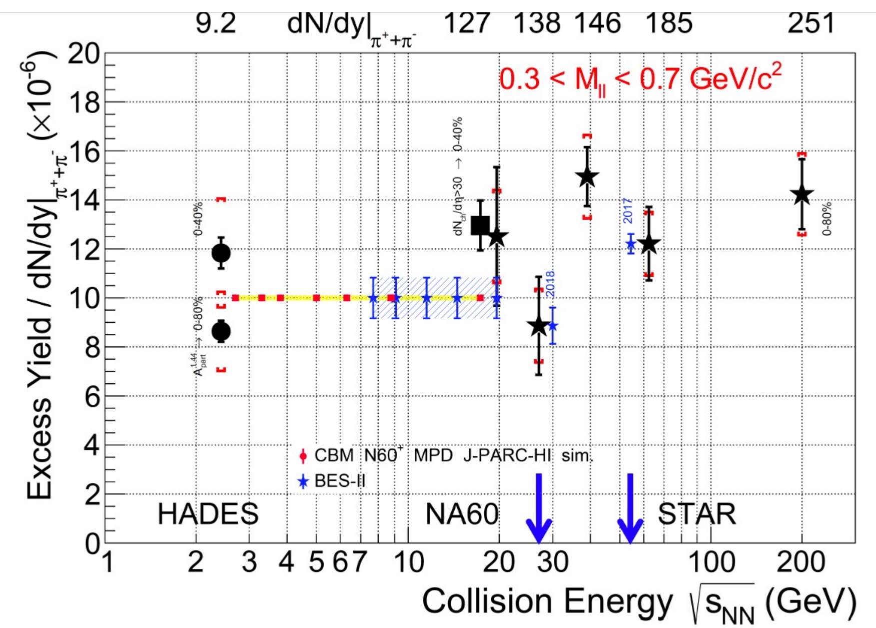
BES-II data taking: completed in Run-21

$\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV/nucleon)	Collider or Fixed Target	$y_{center\ of\ mass}$	μ_B (MeV)	Run Time (days)	No. Events Collected (Request)	Date Collected
200	100	C	0	25	2.0	138 M (140 M)	Run-19
27	13.5	C	0	156	24	555 M (700 M)	Run-18
19.6	9.8	C	0	206	36	582 M (400 M)	Run-19
17.3	8.65	C	0	230	14	256 M (250 M)	Run-21
14.6	7.3	C	0	262	60	324 M (310 M)	Run-19
13.7	100	FXT	2.69	276	0.5	52 M (50 M)	Run-21
11.5	5.75	C	0	316	54	235 M (230 M)	Run-20
11.5	70	FXT	2.51	316	0.5	50 M (50 M)	Run-21
9.2	4.59	C	0	372	102	162 M (160 M)	Run-20+20b
9.2	44.5	FXT	2.28	372	0.5	50 M (50 M)	Run-21
7.7	3.85	C	0	420	90	100 M (100 M)	Run-21
7.7	31.2	FXT	2.10	420	0.5+1.0+ scattered	50 M + 112 M + 100 M (100 M)	Run-19+20+21
7.2	26.5	FXT	2.02	443	2+Parasitic with CEC	155 M + 317 M	Run-18+20
6.2	19.5	FXT	1.87	487	1.4	118 M (100 M)	Run-20
5.2	13.5	FXT	1.68	541	1.0	103 M (100 M)	Run-20
4.5	9.8	FXT	1.52	589	0.9	108 M (100 M)	Run-20
3.9	7.3	FXT	1.37	633	1.1	117 M (100 M)	Run-20
3.5	5.75	FXT	1.25	666	0.9	116 M (100 M)	Run-20
3.2	4.59	FXT	1.13	699	2.0	200 M (200 M)	Run-19
3.0	3.85	FXT	1.05	721	4.6	259 M -> 2B(100 M -> 2B)	Run-18+21

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



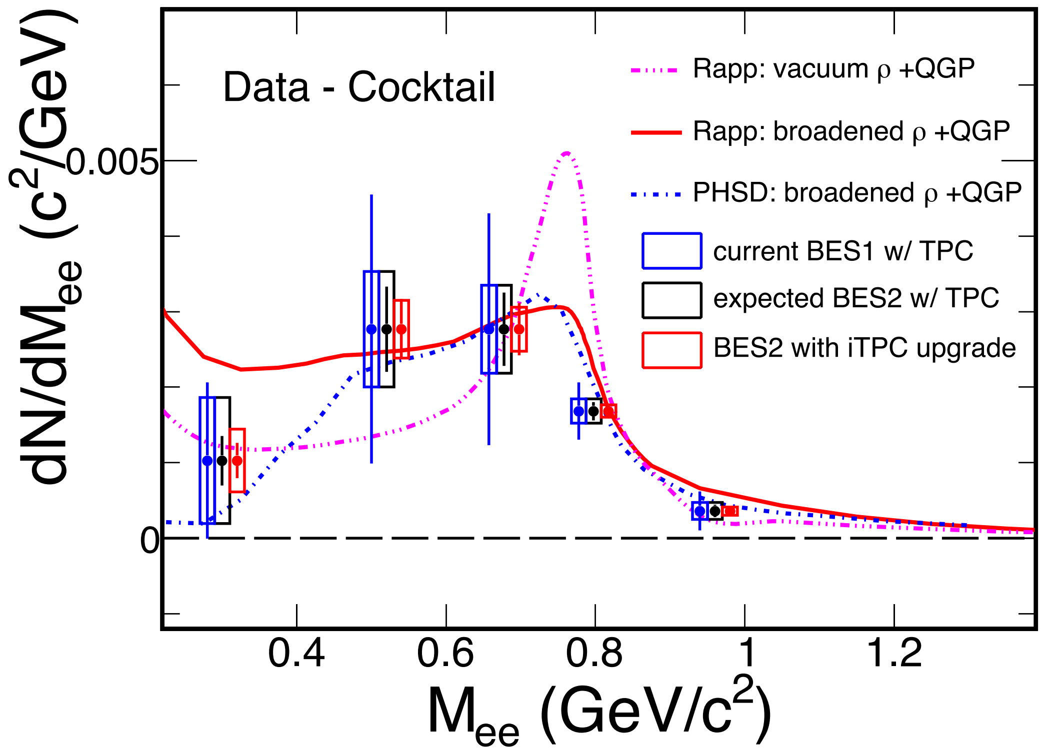




Broader and more electron-positron excess down to 7.7 GeV collision energy?

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

Distinguish the mechanisms of rho broadening



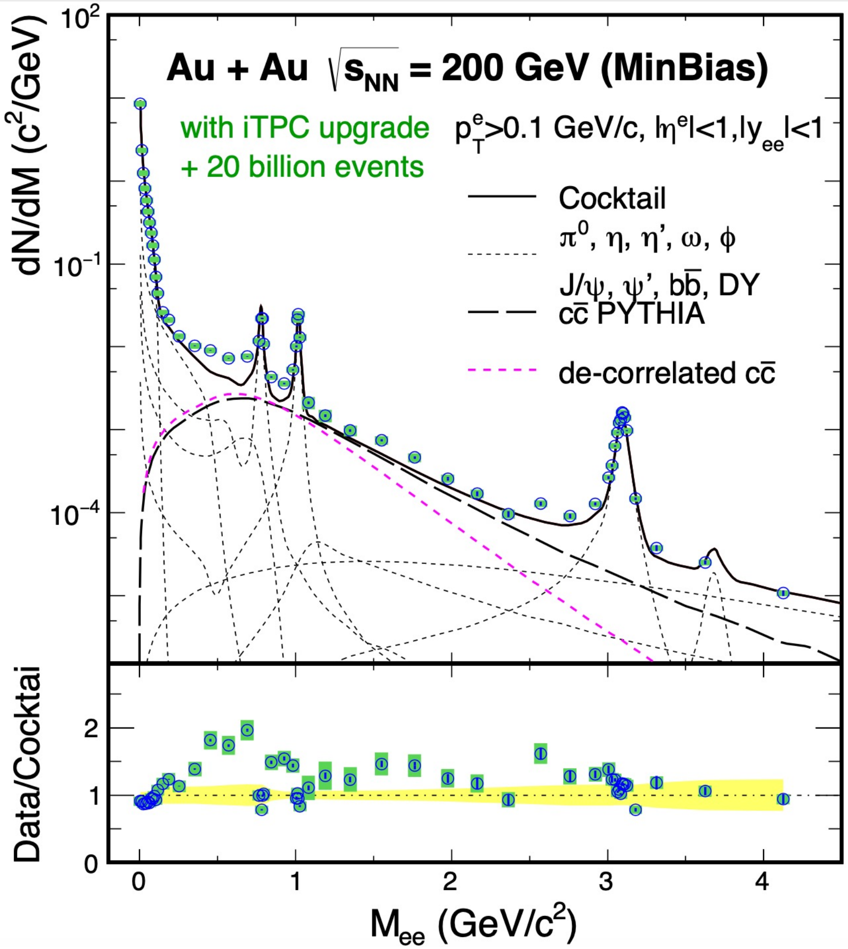
Knowing the mechanism that causes in-medium rho broadening and its temperature and baryon-density dependence is fundamental to our understanding and assessment of chiral symmetry restoration in hot QCD matter !

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

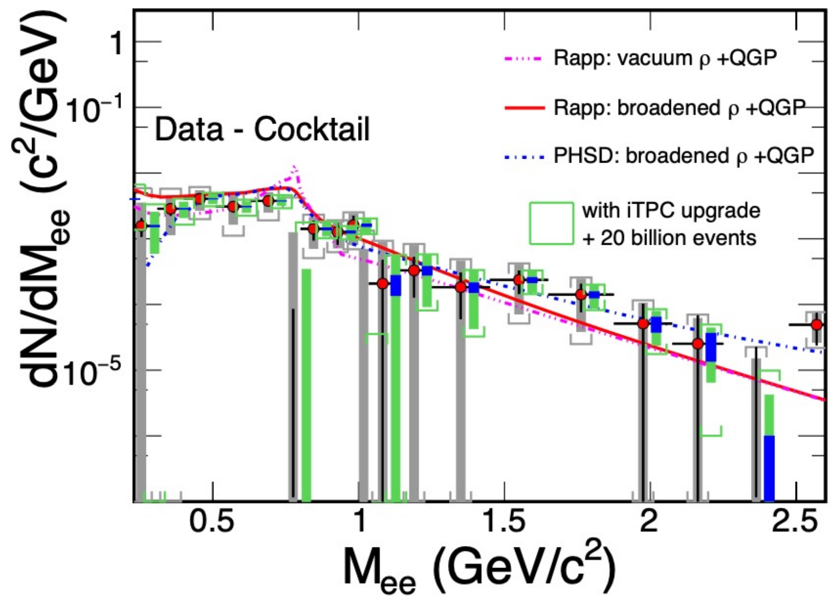
Rapp: macroscopic effective many-body theory model

PSHD: microscopic transport dynamic model

Back to 200 GeV Au+Au in 2023-2025



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



STAR BUR21

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~ 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 Γ ~ 400 MeV, Γ (T_C) ~ 600 MeV]

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

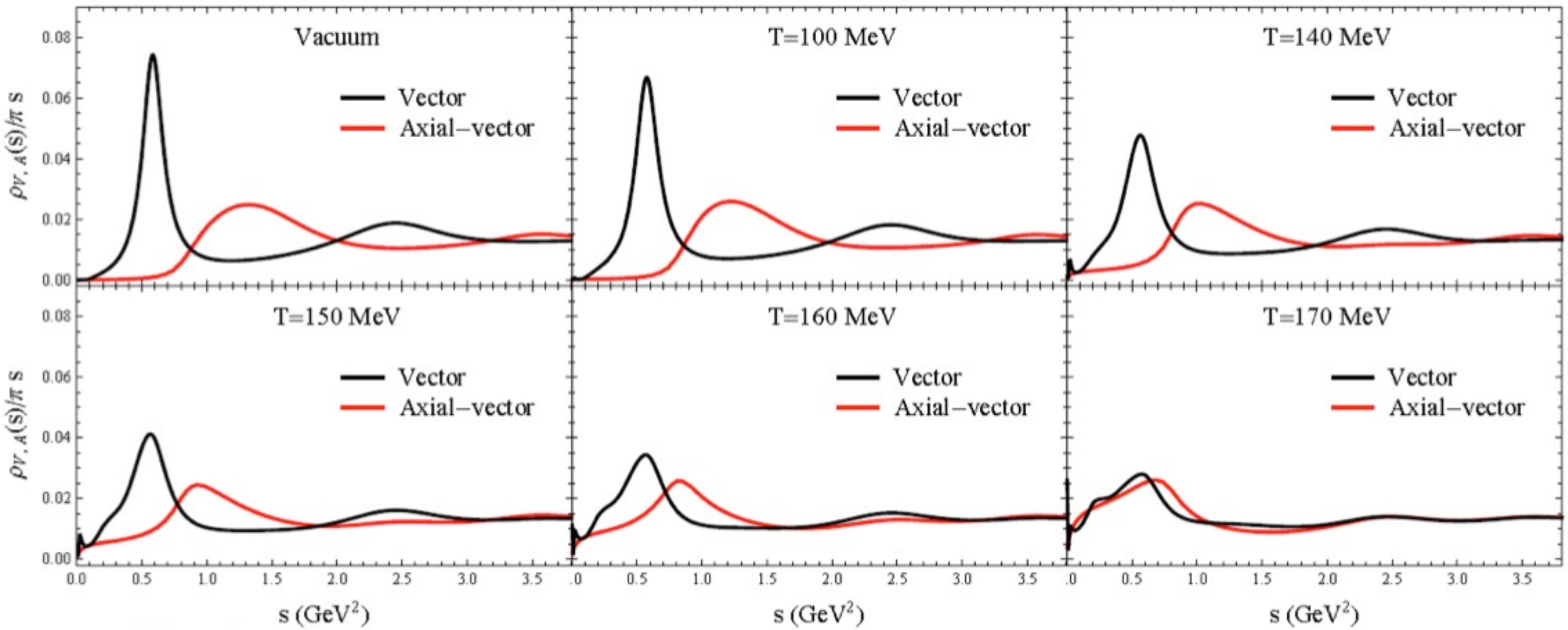
Is it an evidence?

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

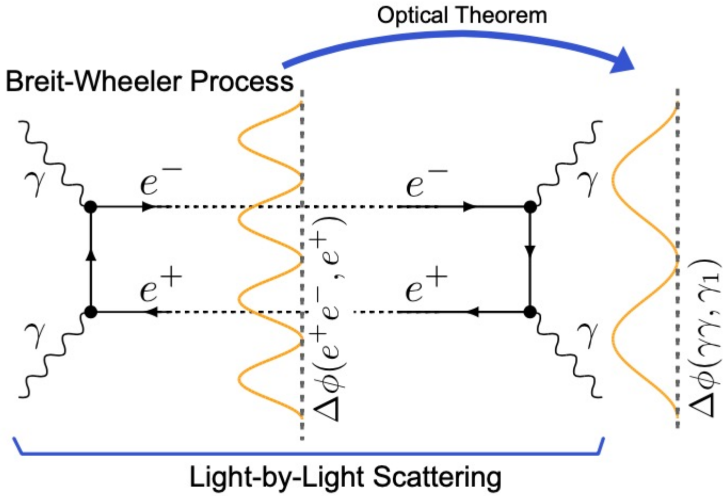
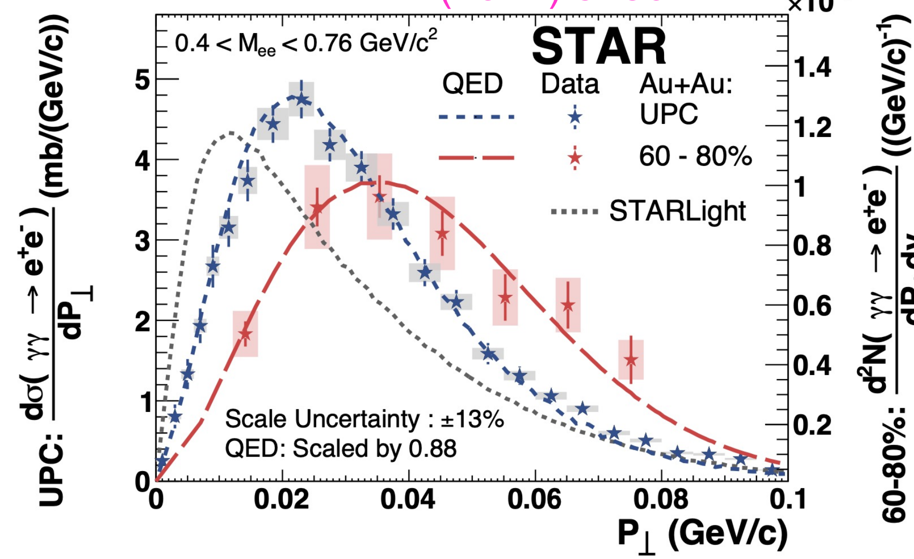
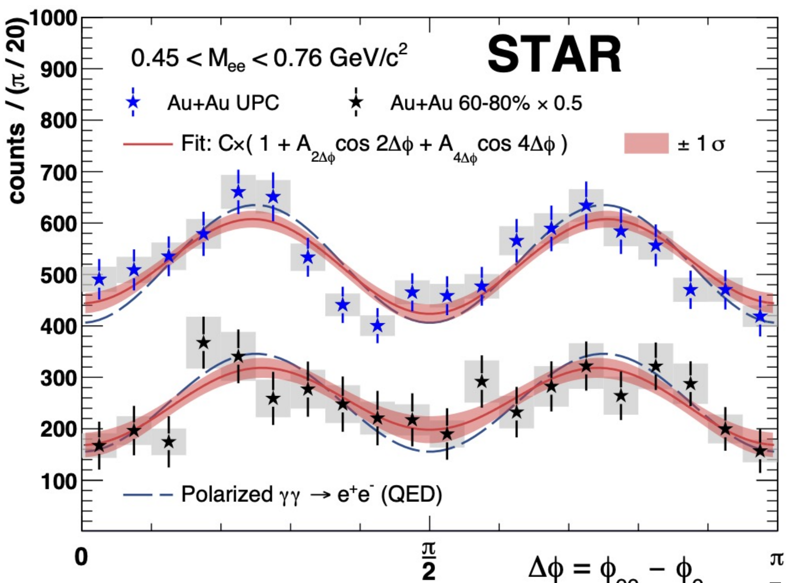


FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.

PRL127 (2021) 52302





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

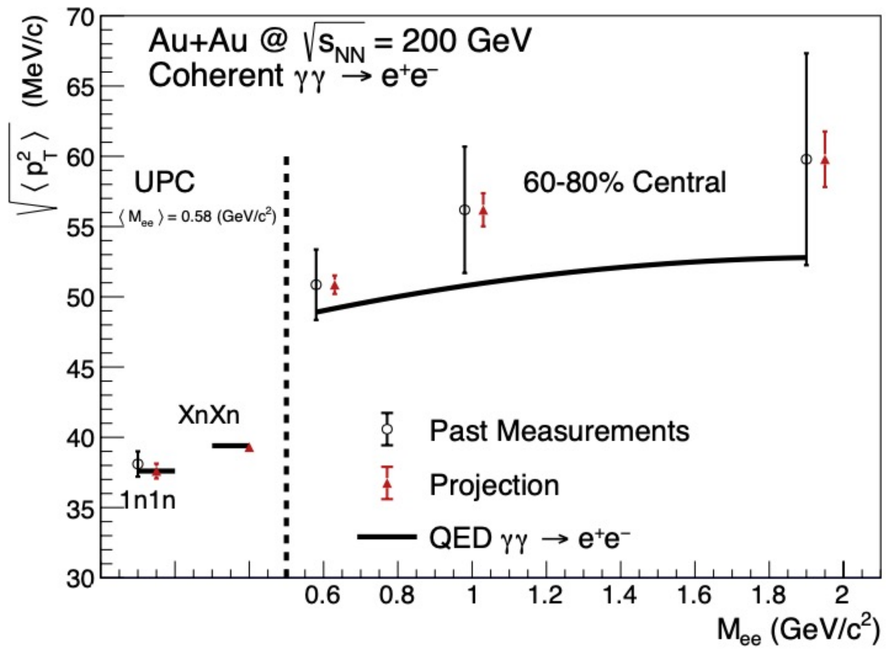
Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in Ultra-peripheral collisions

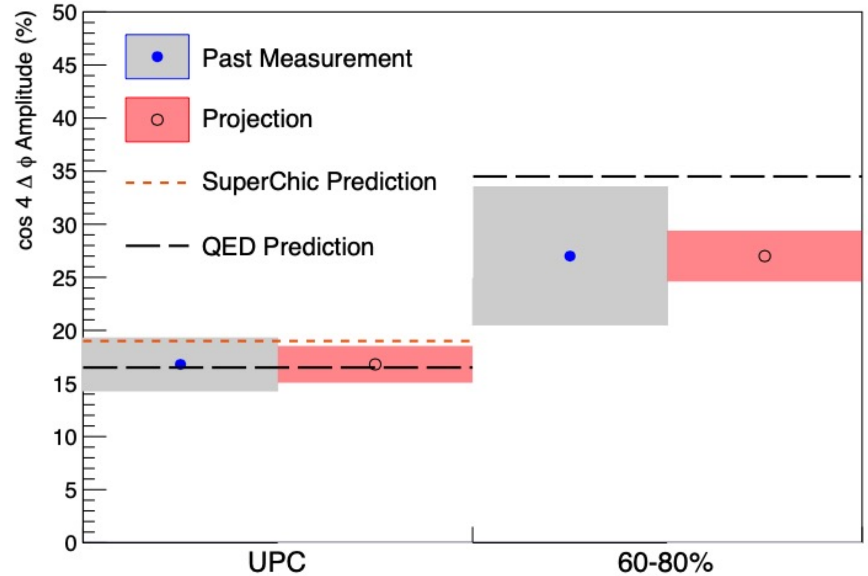
Collisions of Light Produce Matter/Antimatter from Pure Energy:
https://www.bnl.gov/newsroom/news.php?a=119023

Photon Wigner function and magnetic effects in QGP

STAR BUR21



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.

Summary

We observed:

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

In 2019-2021:

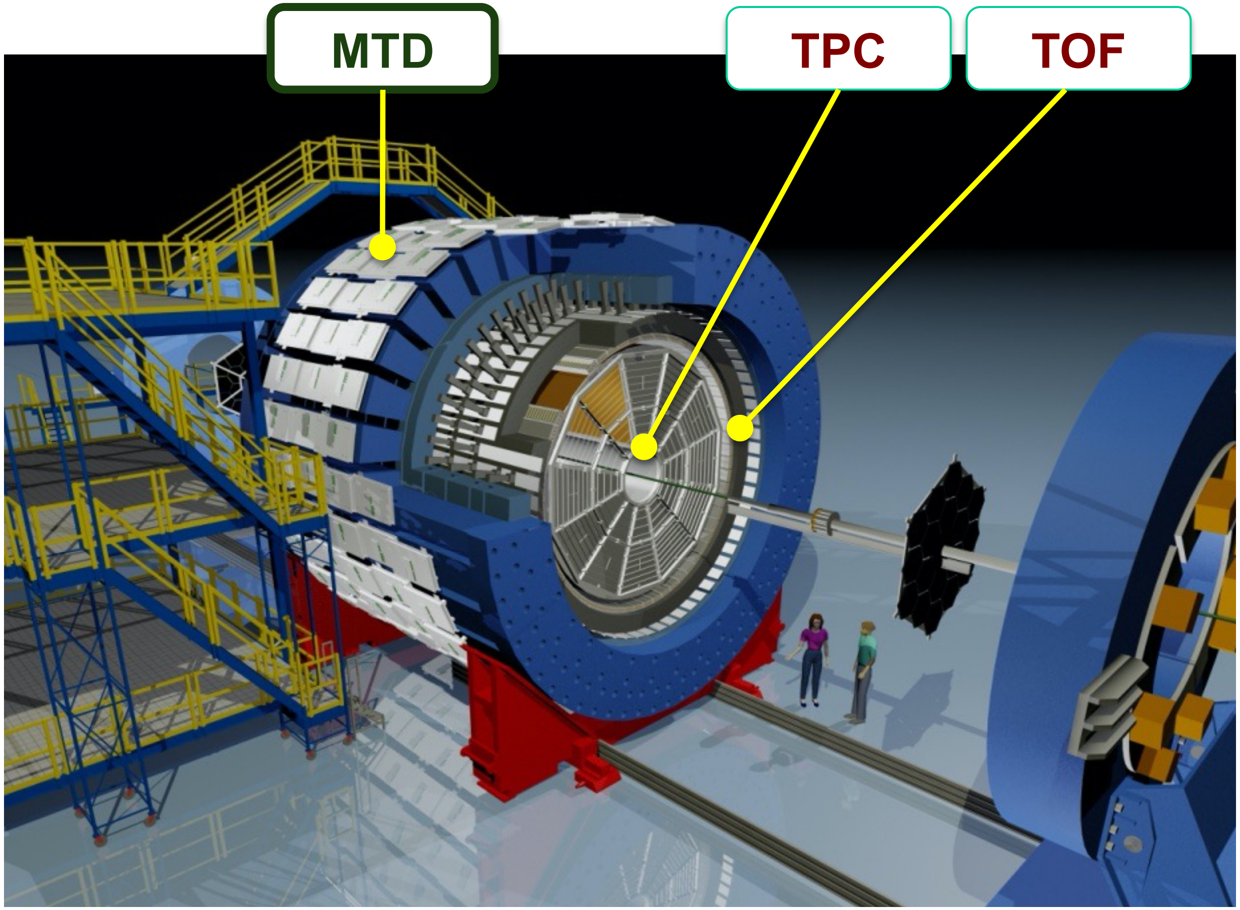
- **Beam Energy Scan II (7.7-19.6 GeV) will provide a unique opportunity to quantify the effect of Chiral Symmetry Restoration via total baryon density effect on the ρ broadening.**

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



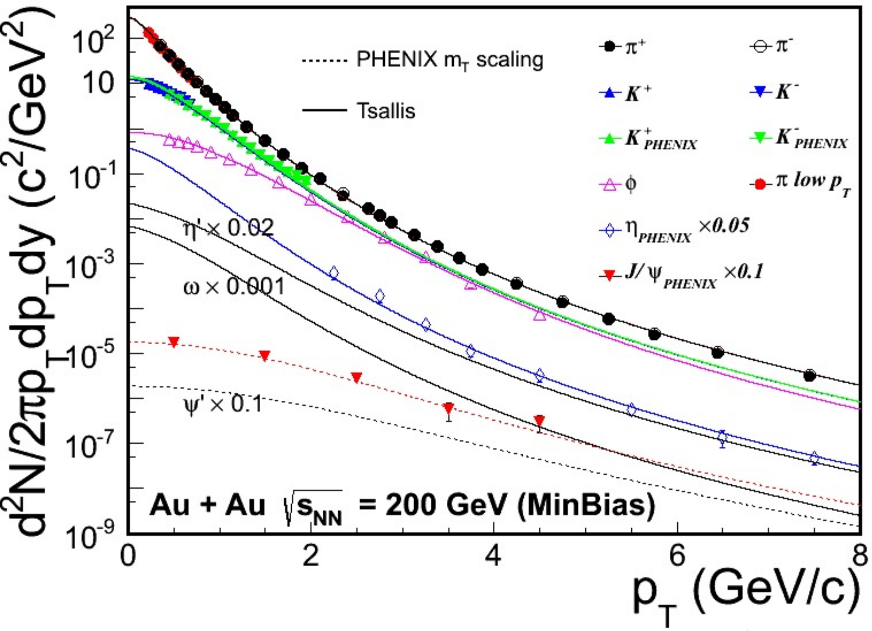
Time of Flight Detector (TOF) & Muon Telescope Detector (MTD):
Multi-gap Resistive Plate Chamber (MRPC), gas detector, avalanche mode

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

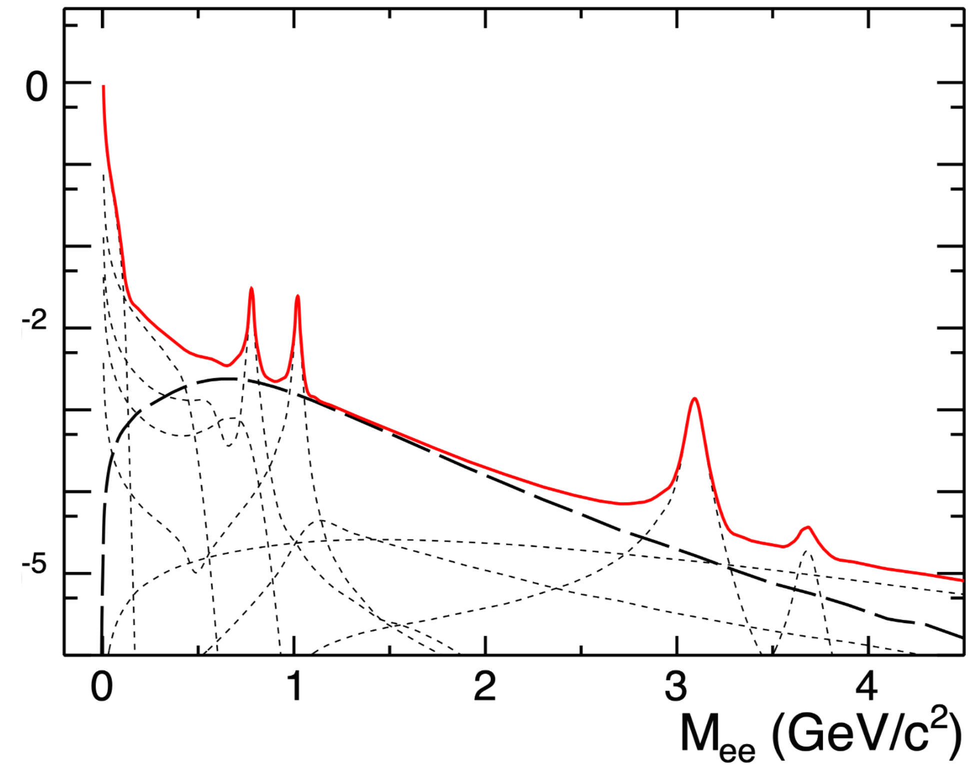
MTD: provide trigger capabilities in heavy ion collisions and muon identification with precise timing and position information

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

Electron-positron emission mass spectrum

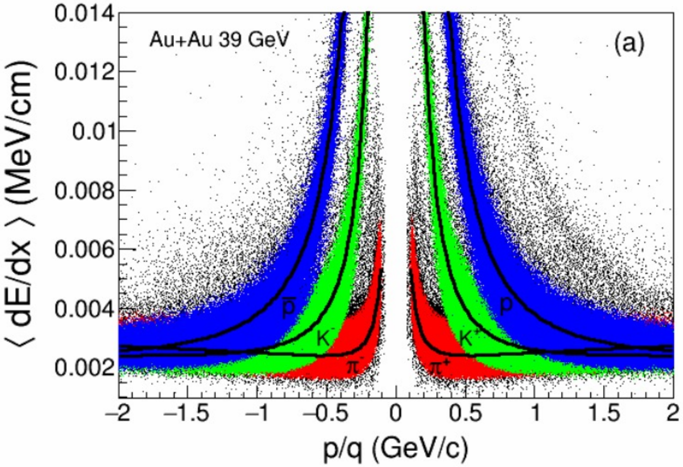


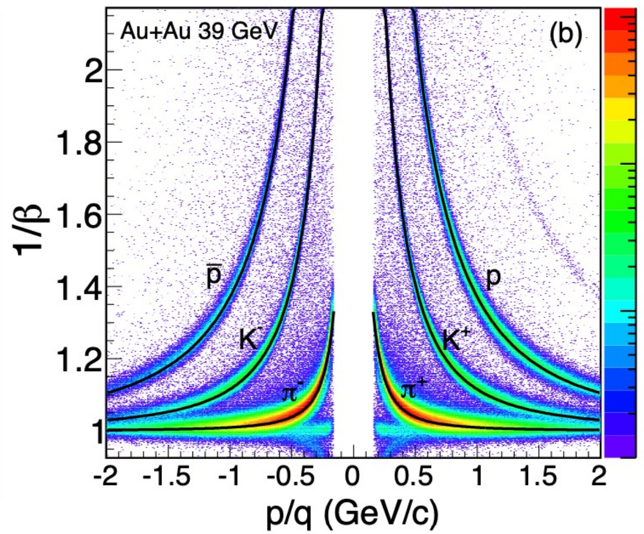
PHENIX Collaboration, Phys. Rev. C 81, 034911 (2010)
STAR Collaboration, Phys. Rev. Lett. 92, 112301 (2004)
STAR Collaboration, Phys. Lett. B 612, 181 (2005).
STAR Collaboration, Phys. Rev. Lett. 97, 152301 (2006)
Z. Tang et al. Phys. Rev. C 79, 051901 (2009)

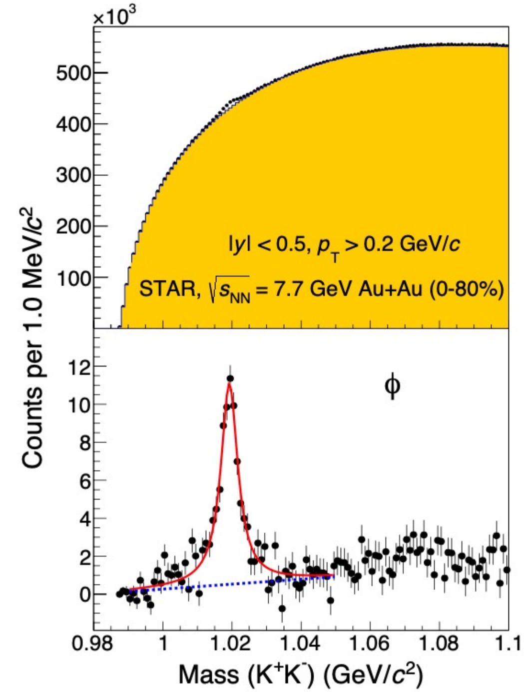


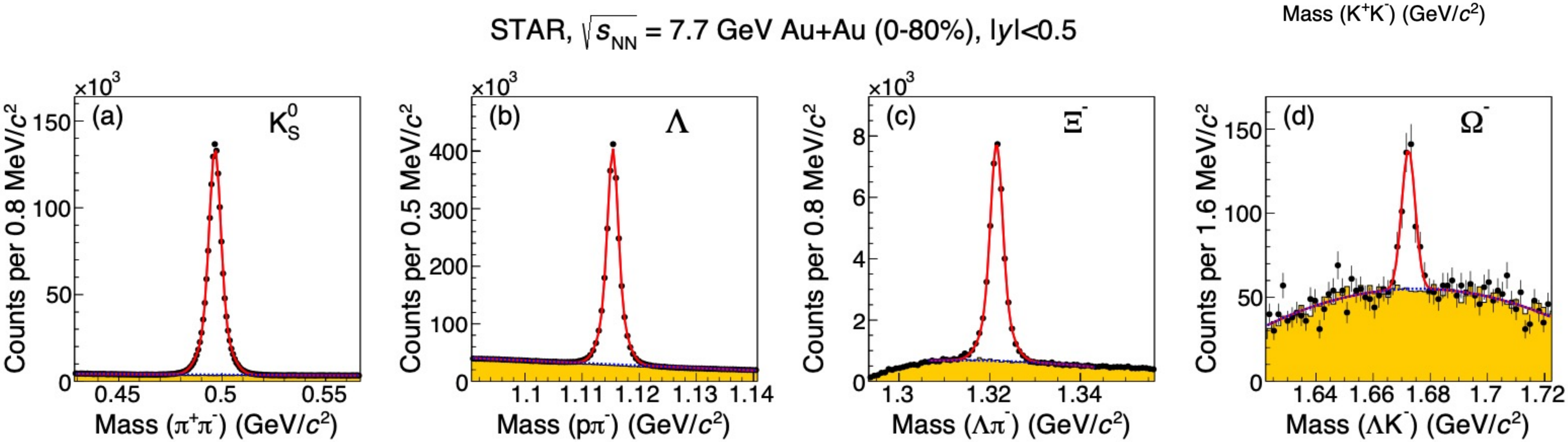
Electron-positron mass spectrum from known hadronic sources without hot, dense medium contribution.

Particle identification at STAR

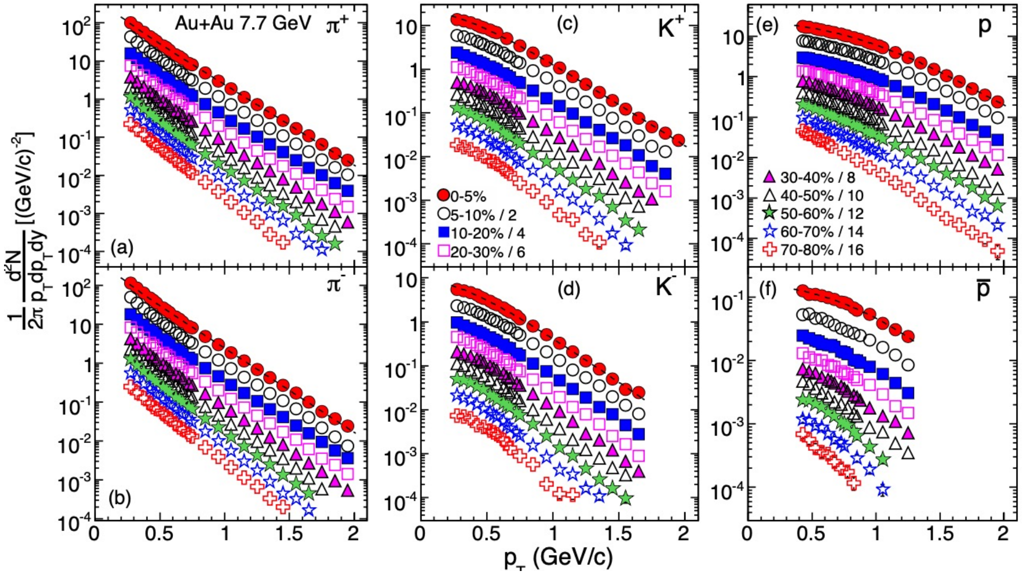


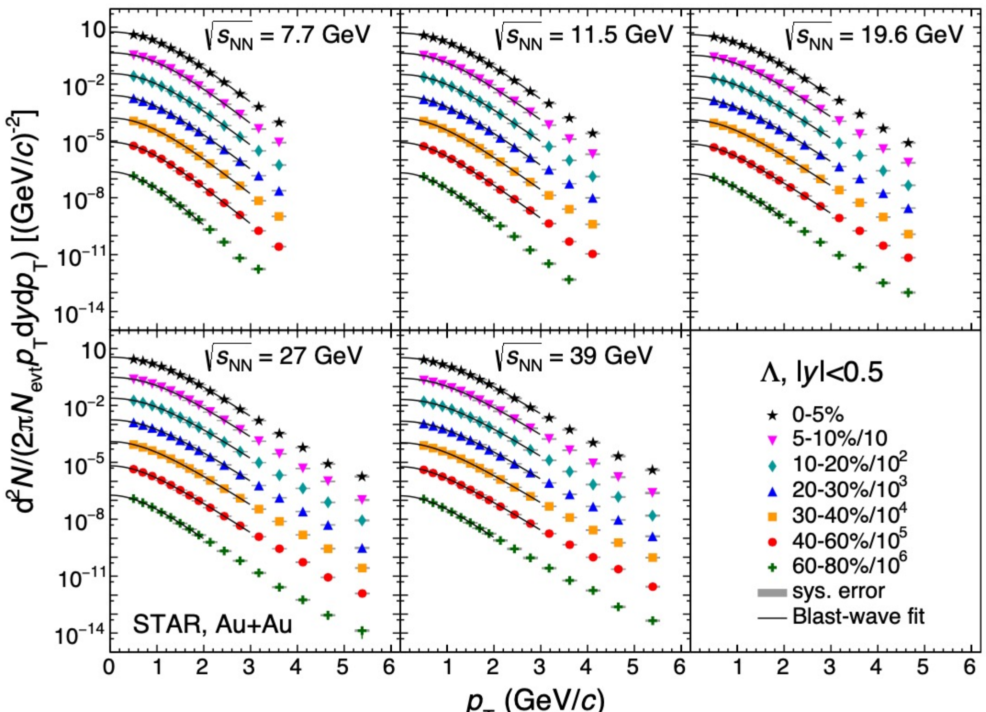






Identified particle spectra





Pion, kaon, proton spectra

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

Strange hadron spectra

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

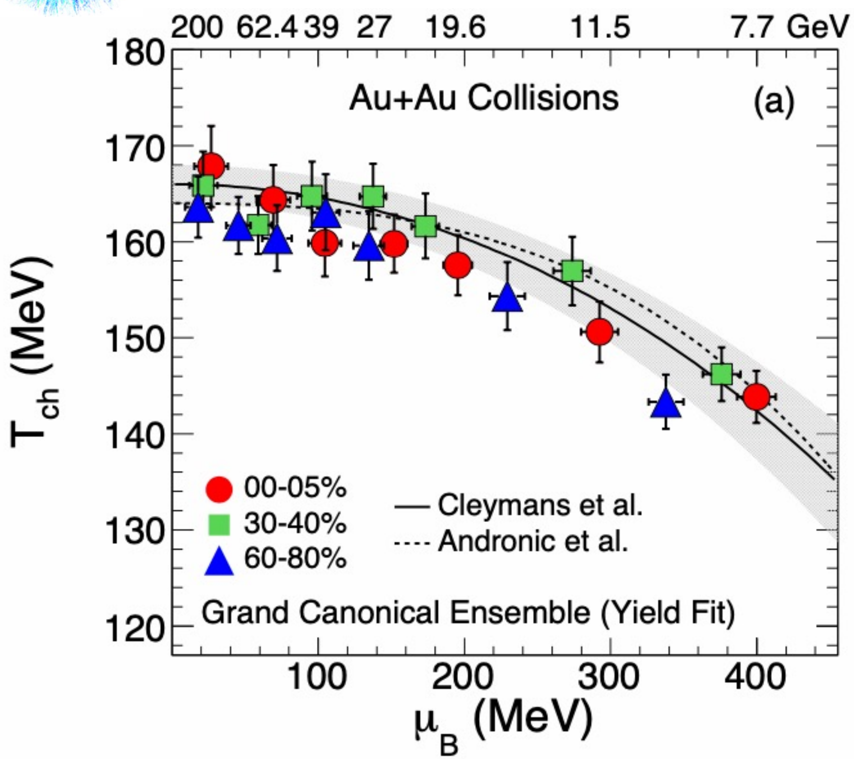
Particle yields

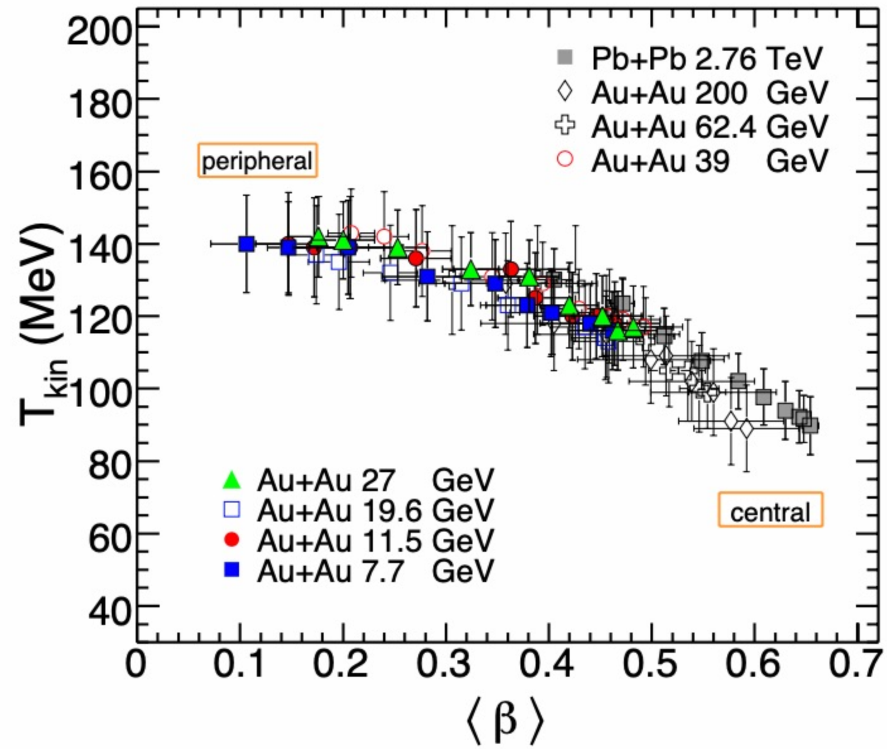
$\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, Λ, $\bar{\Lambda}$, Ξ, and $\overline{\Xi}$.

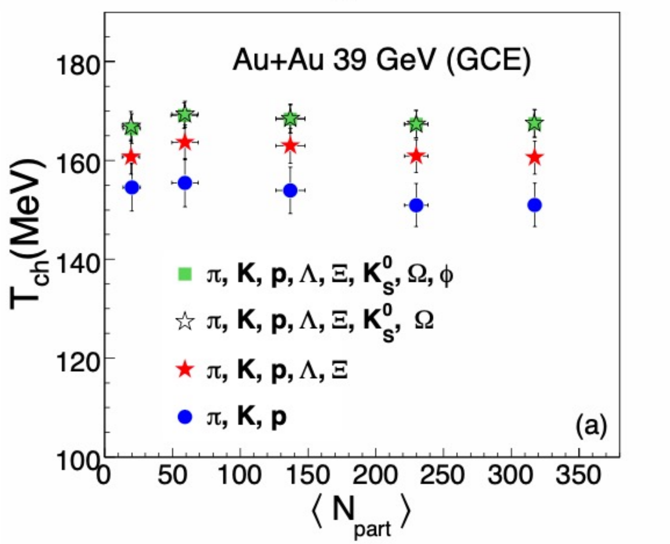
Particle ratios

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





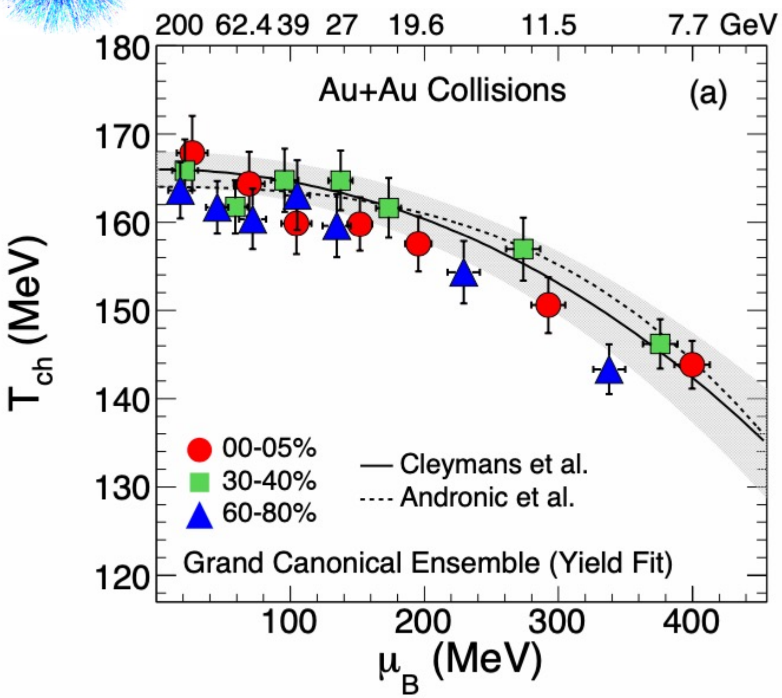


At 200 GeV, T_{ch}~ T_C

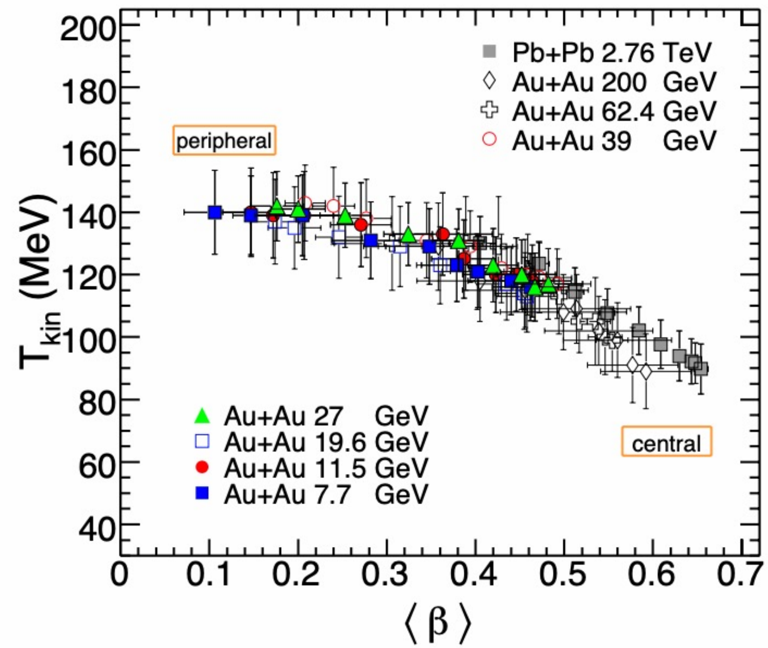
The initial temperature T_0 must be higher than T_C ?

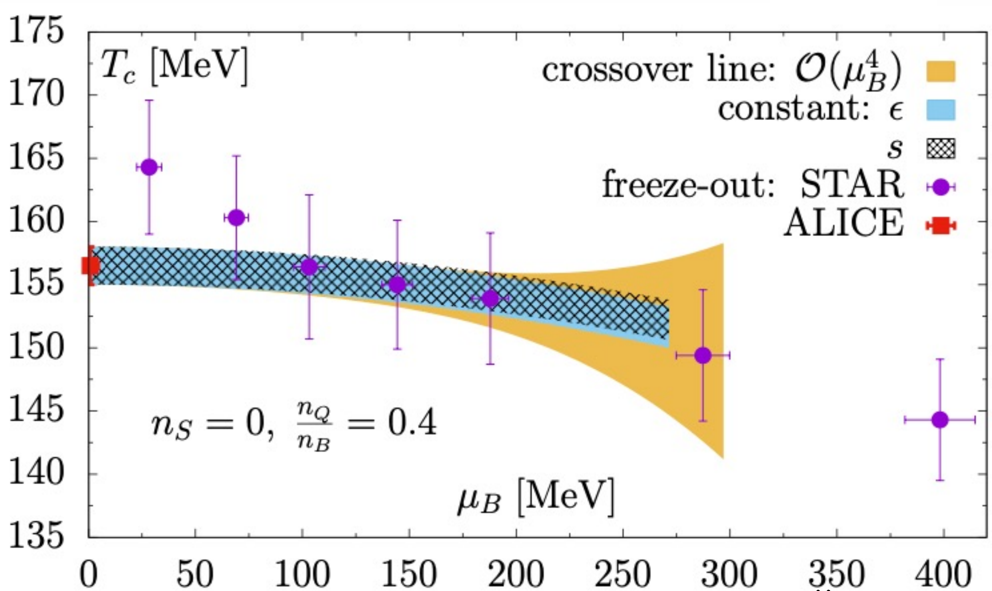
Chiral symmetry should be restored at μ_B~0

Freeze out temperatures



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





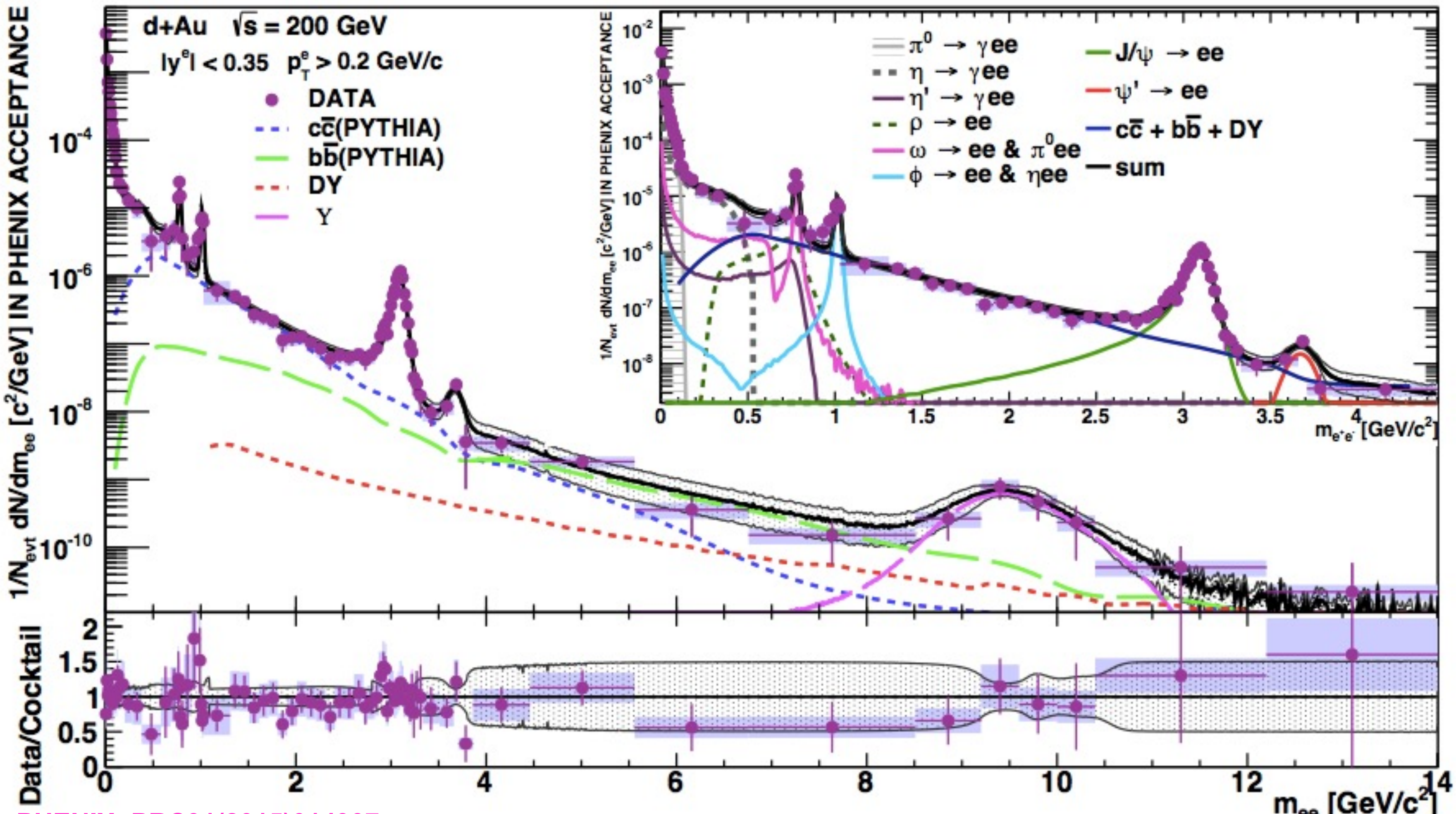
HotQCD, PLB 795 (2019)15

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

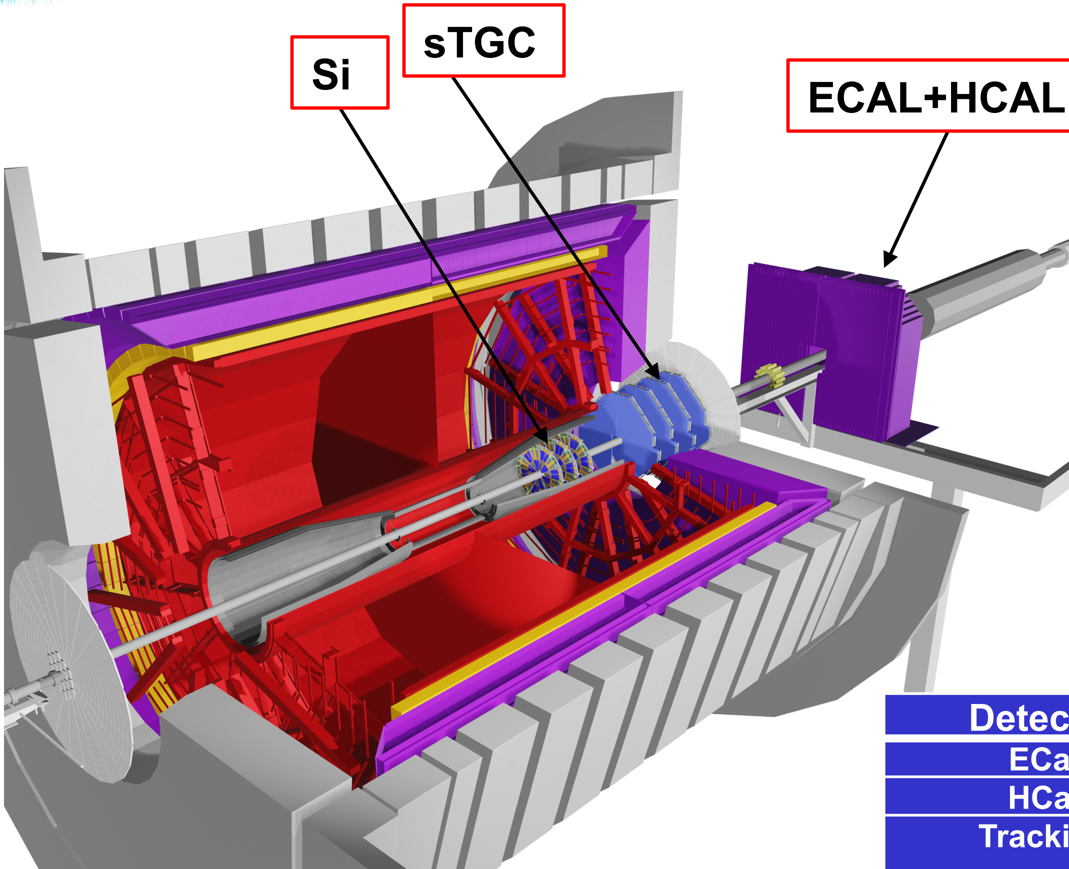
Dielectron measurements in d+Au collisions



PHENIX: PRC91(2015)014907

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

STAR forward upgrades



At $2.5<\eta<4$

- Jets
- PID (π^0, γ, e, Λ)
- 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 commissioned in Run-21

Installation of entire Si and sTGC completed by October 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 BUR21

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	|vz|<70cm	|vz|<30cm	
2014 2016	2	27	19	16	TPC+TOF+HFT+MTD
2023 2025	20	63	56	38	iTPC+EPD+eTOF+TOF +MTD Forward upgrades

A factor of 10 more minimum bias data compare to Run-14 + Run-16
A factor of 2.3 more luminosity for high-p_T trigger