STAR

Dilepton measurements in heavy ion collisions

Lijuan Ruan (BNL)

Brookhaven National Laboratory

U.S. Department of Energy

Recent measurements

Plans for BES-II

Plans for 2023-2025

Summary

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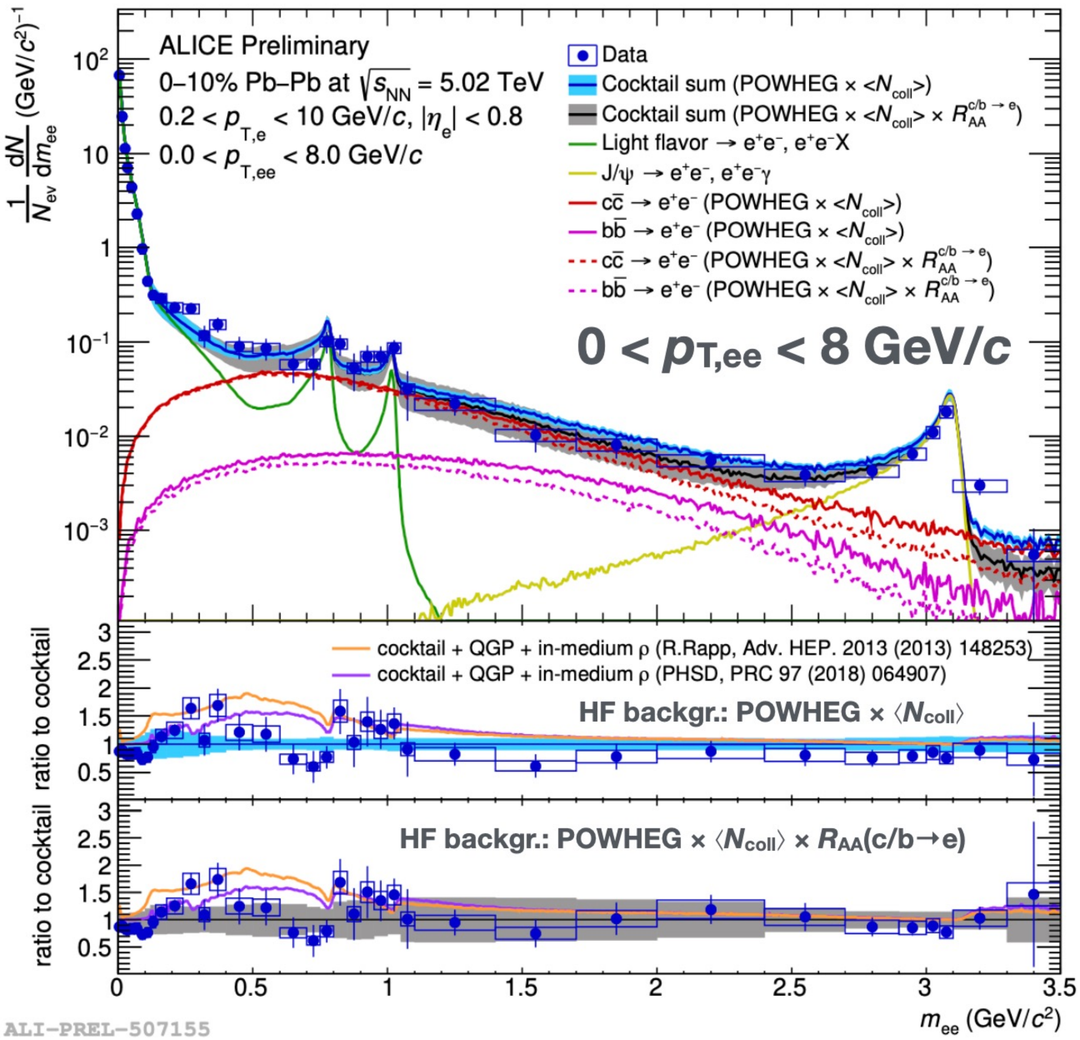
14th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2022) Aug 29-Sep 4, 2022

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 …

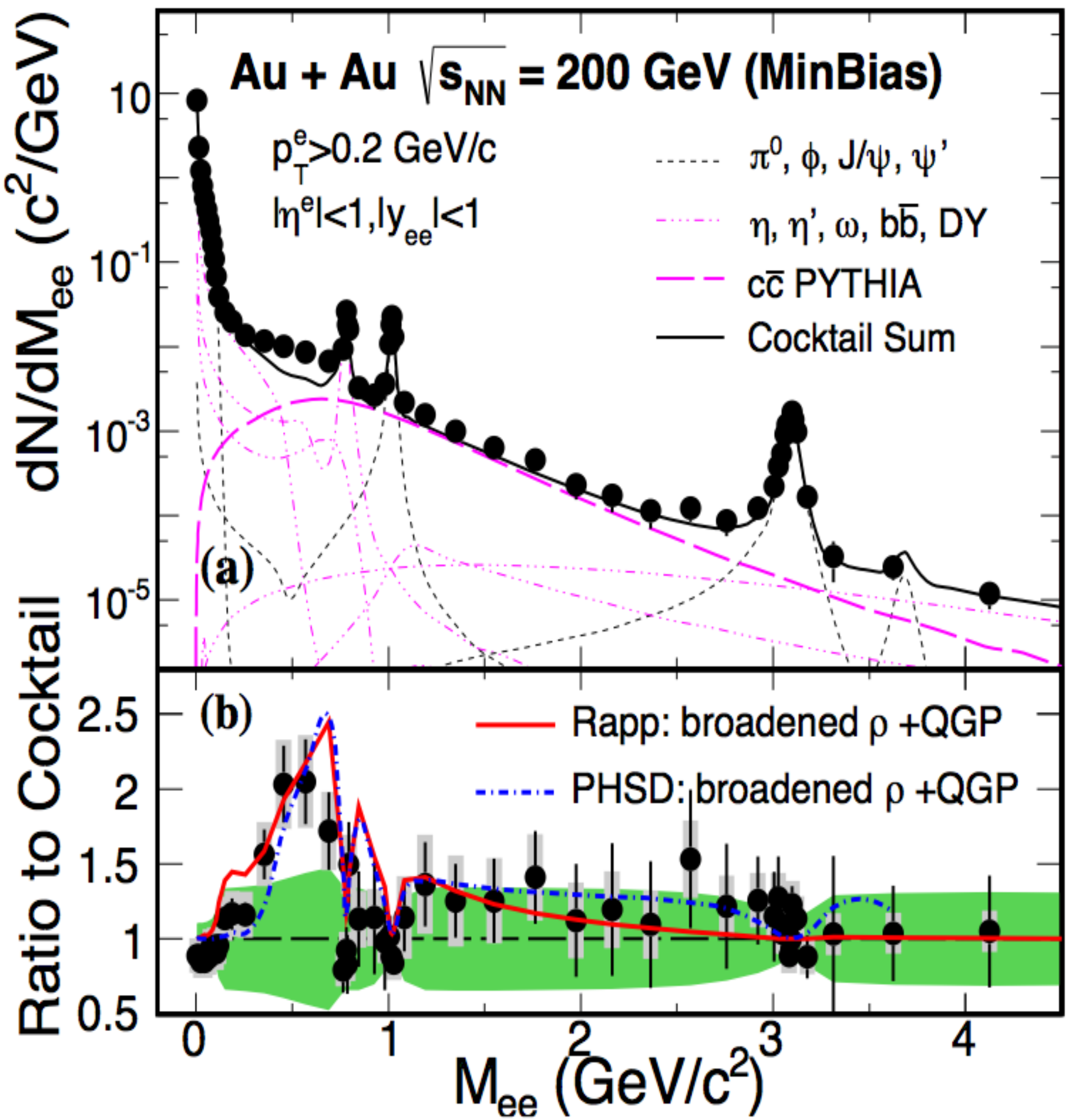
Dielectron mass spectrum in 5.02 TeV Pb+Pb



No significant excess within uncertainties

Dielectron mass spectrum in 200 GeV Au+Au

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

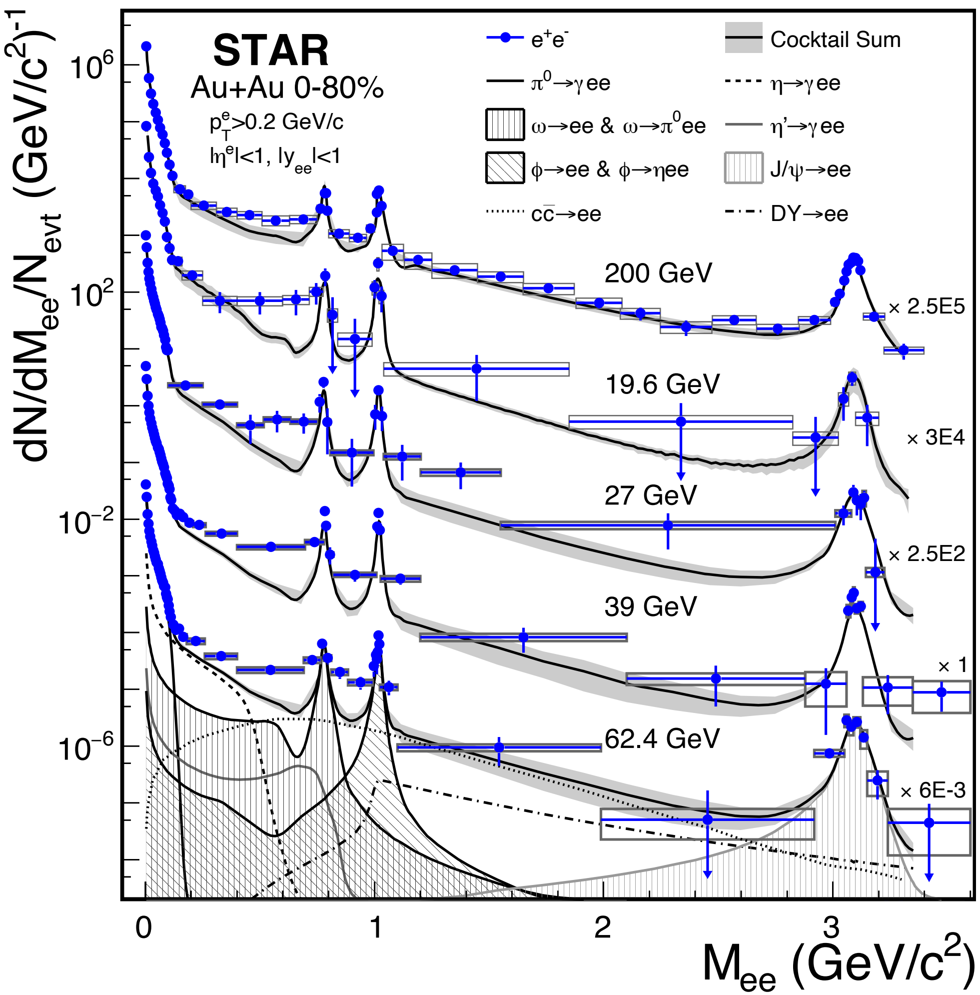


Significant excess

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

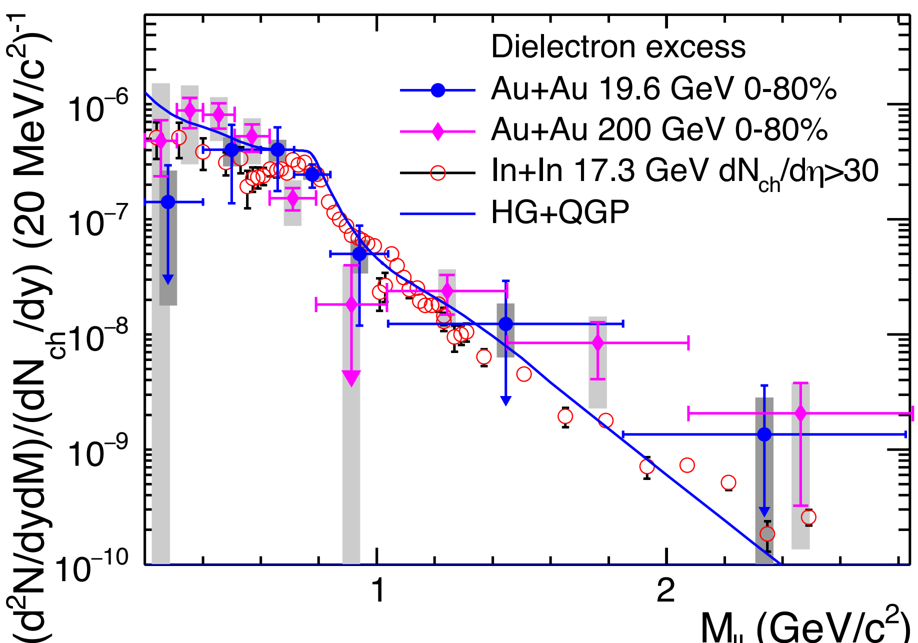
Dielectron mass spectrum in 19.6-62.4 GeV Au+Au

STAR: arXiv: 1810.10159, PLB750(2015)64

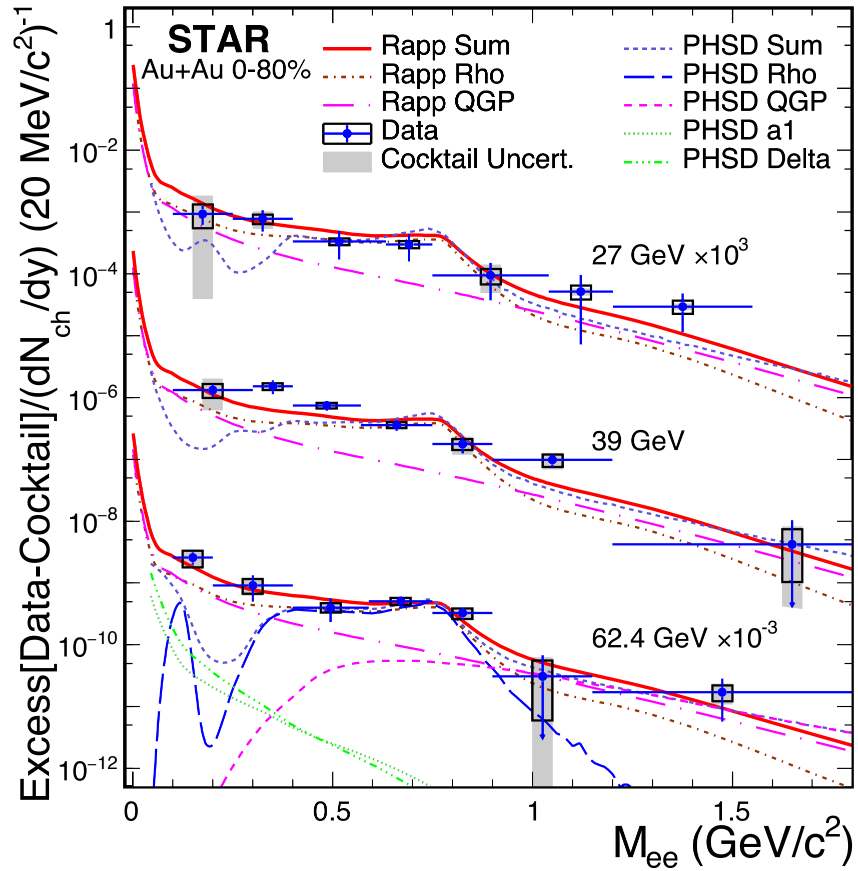


The dielectron excess spectrum

STAR: PLB750(2015)64



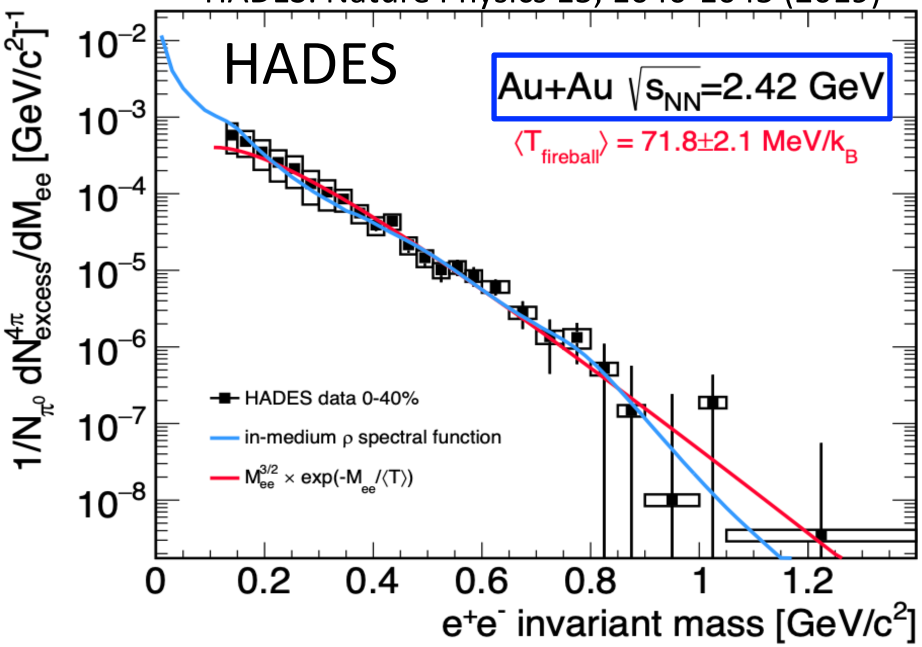
STAR: arXiv: 1810.10159

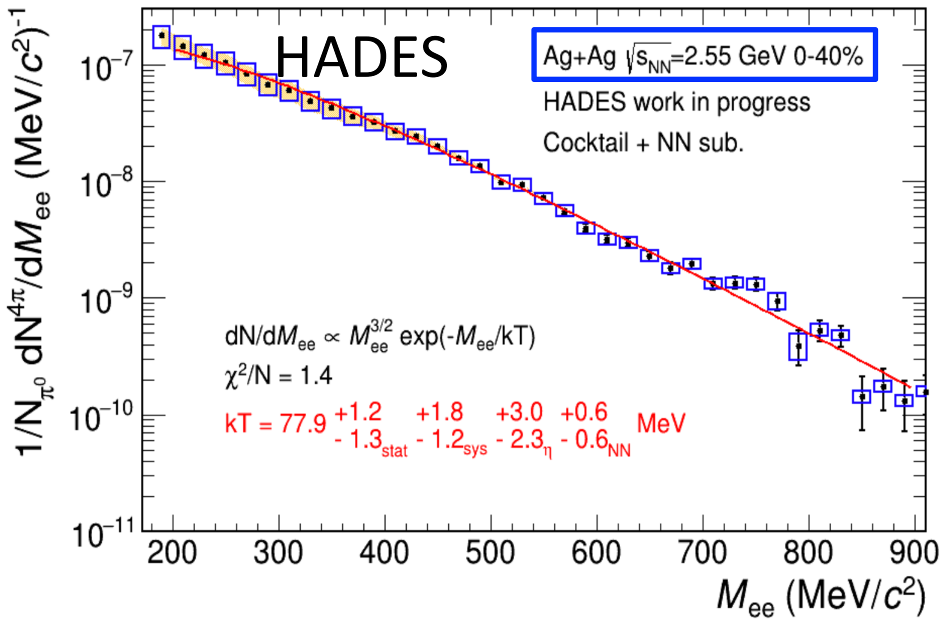


A broadened ρ spectral function consistently describes the low mass dielectron excess for all the energies 19.6-200 GeV.

The dielectron excess spectrum

HADES: Nature Physics 15, 1040-1045 (2019)

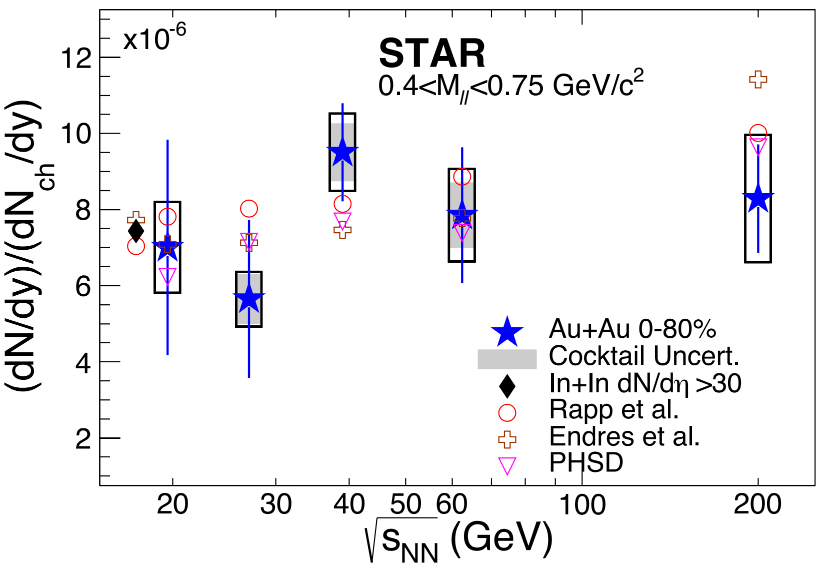


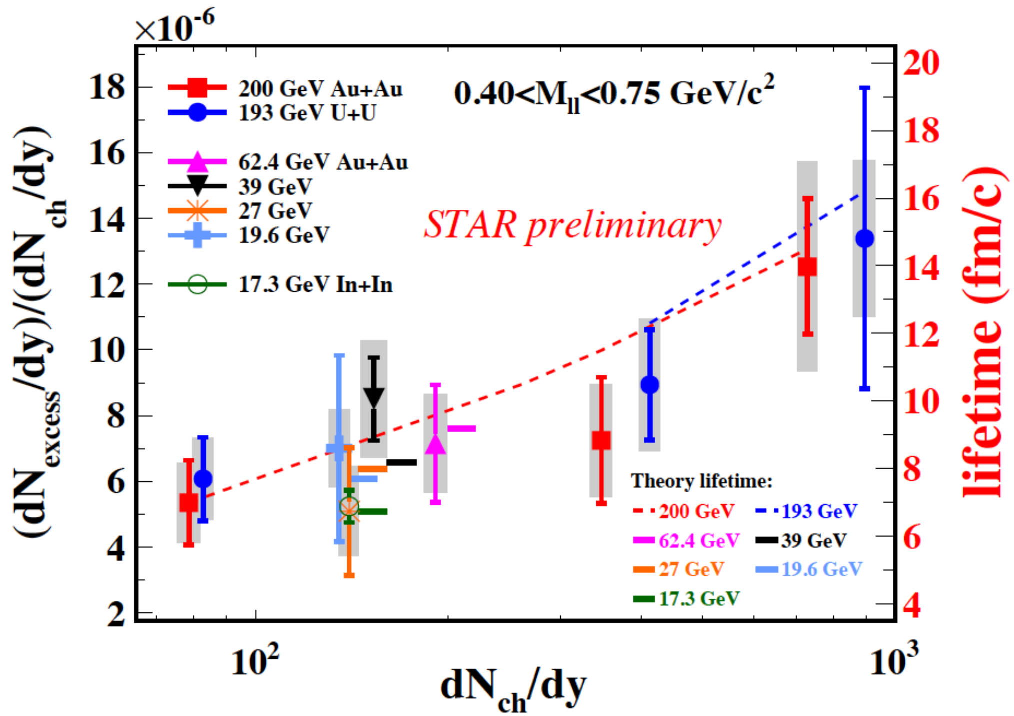


A broadened ρ spectral function consistently describes the low mass dielectron excess for lower energies.

The low mass measurements: lifetime indicator

STAR: arXiv: 1810.10159

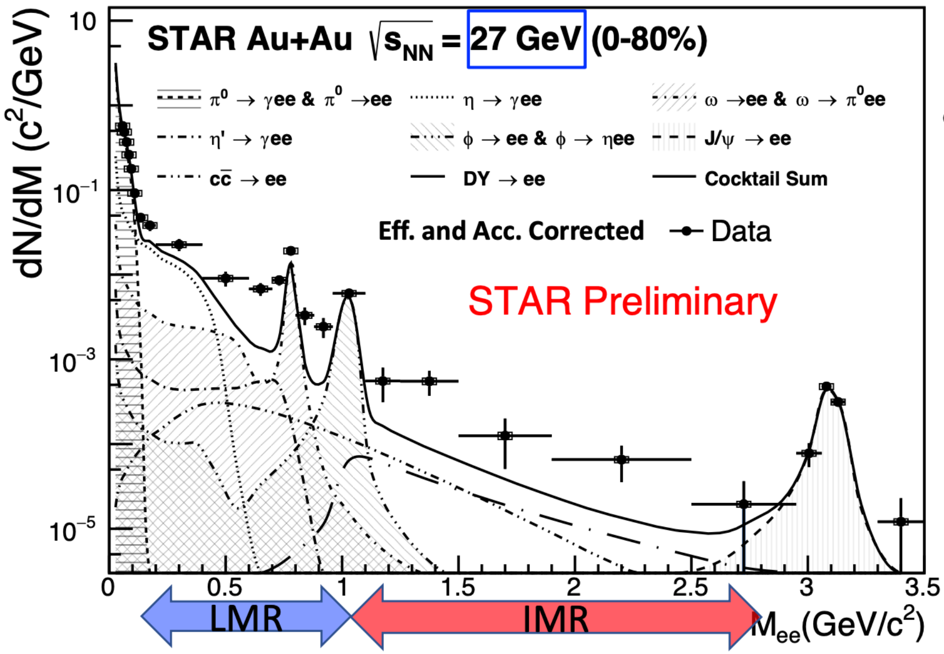


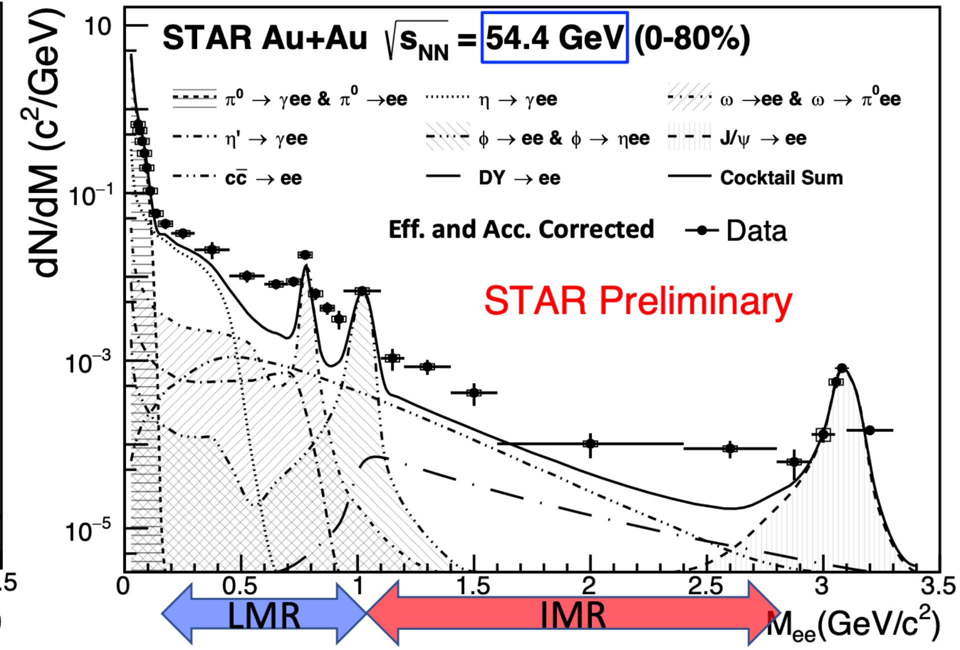


STAR: QM2015

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.

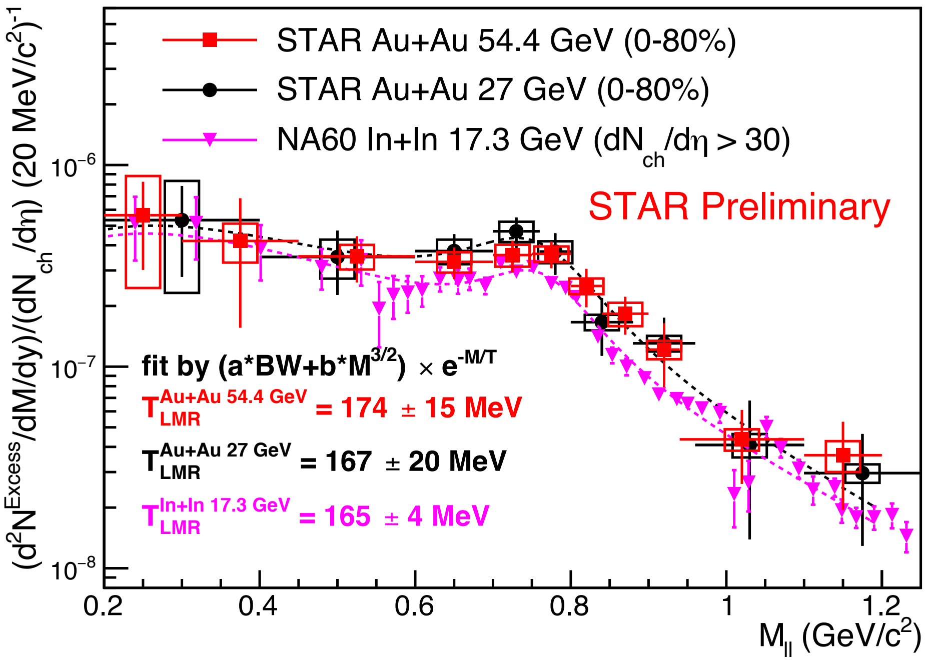
Dileptons at 54.4 and 27 GeV



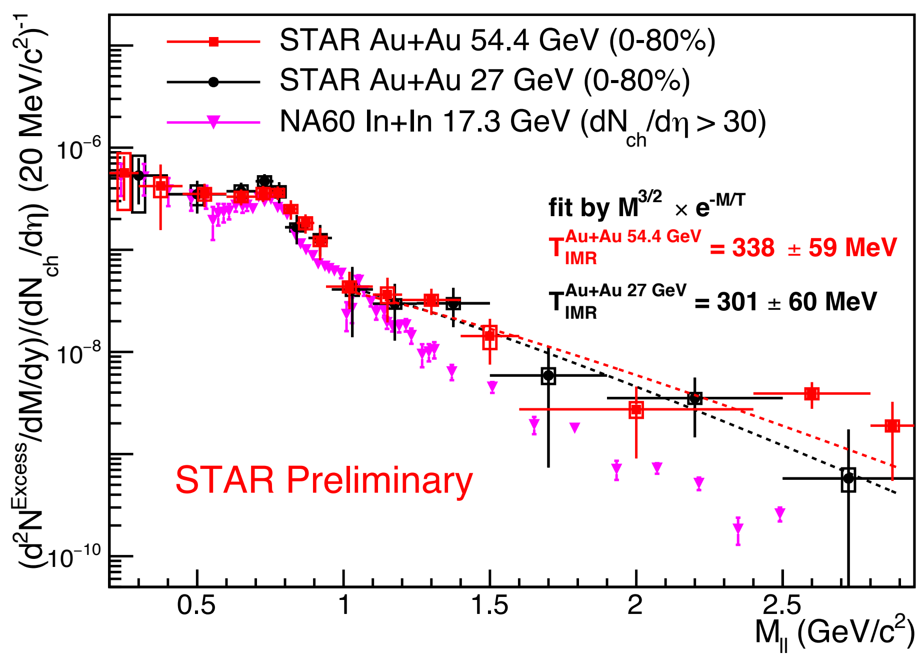


Year	Energy	Used events
2018	27 GeV	500M
2017	54.4 GeV	875M
2011	27 GeV	68M
2010	39 GeV	132M
2010	62.4 GeV	62M

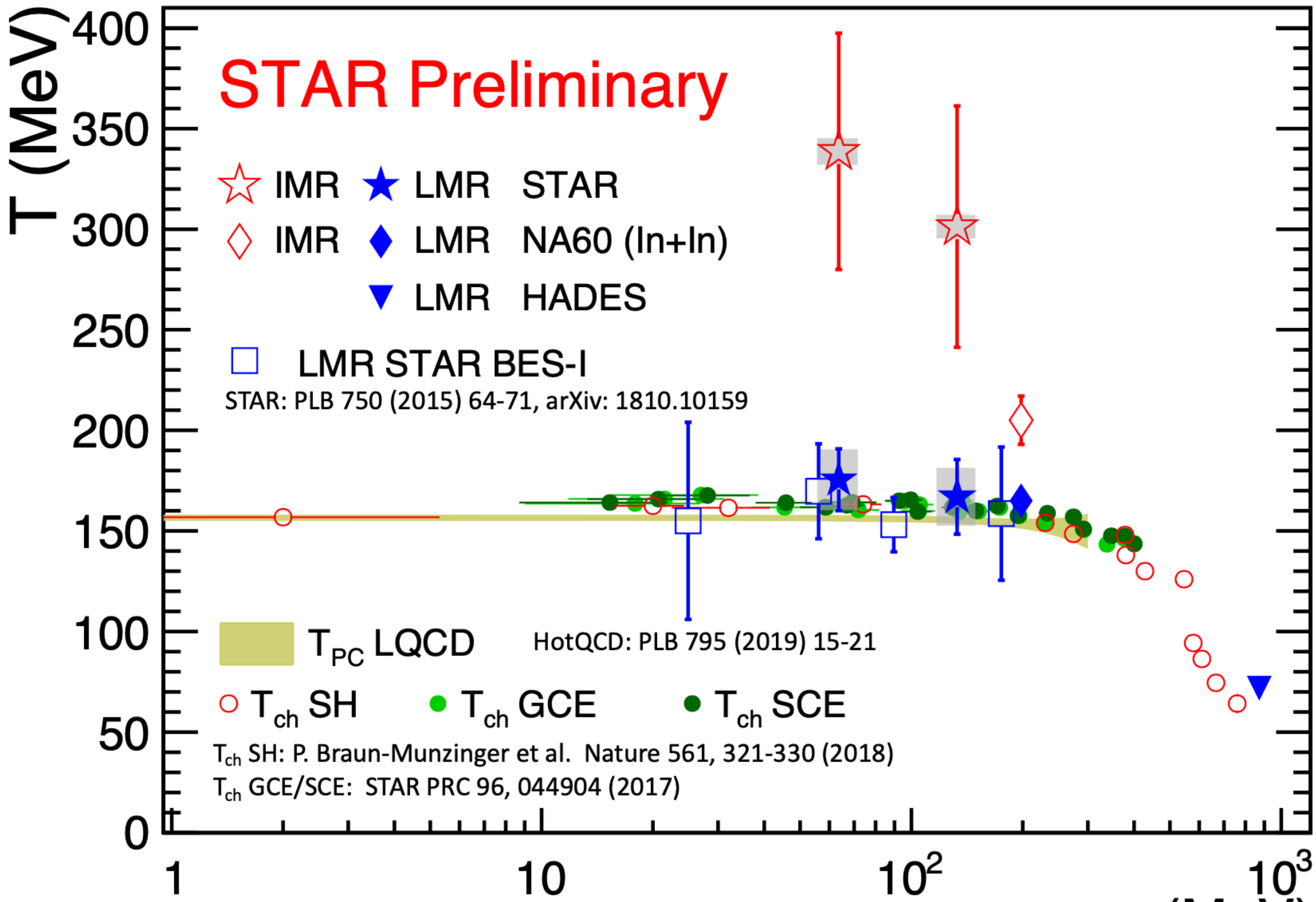
Thermal dileptons at 54.4 and 27 GeV



NA60: EPJC (2009) 59: 607–623



Temperature vs. μ_B



NA60: EPJC (2009) 59 607–623

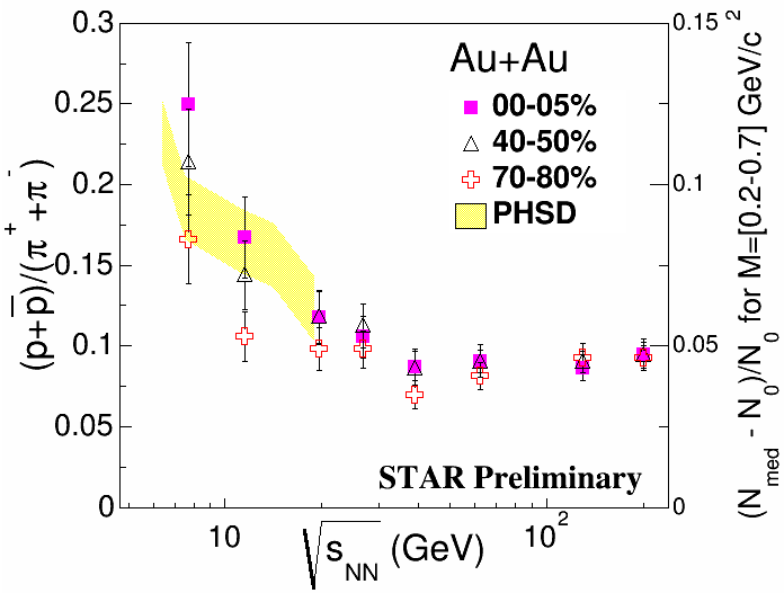
G. Tetyana: JPS Conf.Proc. 32 (2020) 010079

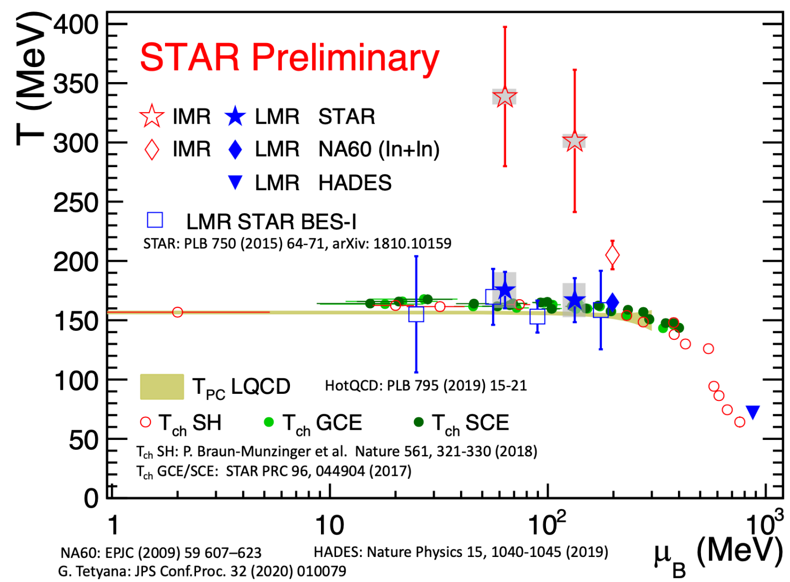
HADES: Nature Physics 15, 1040-1045 (2019)

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

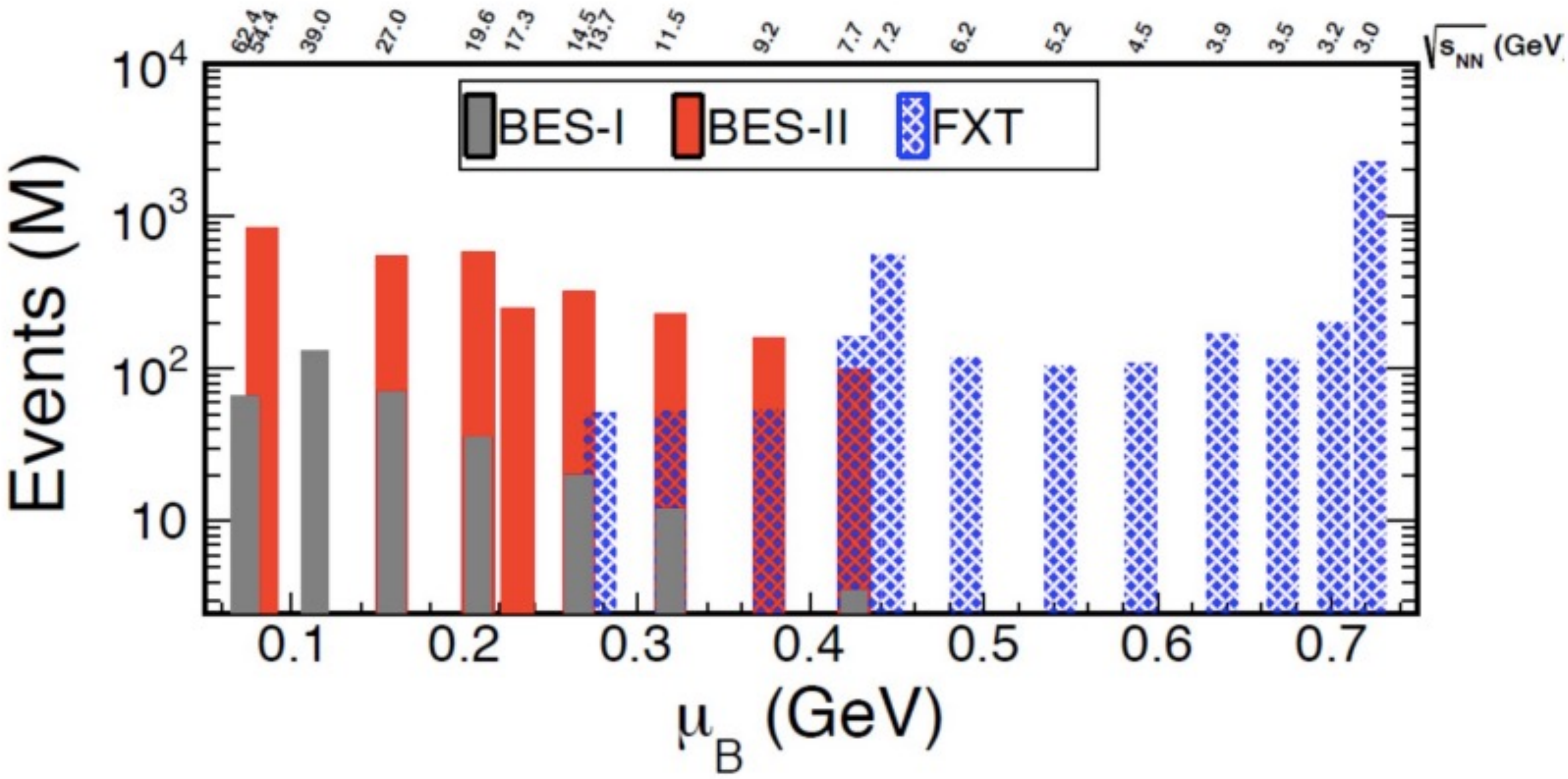
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.





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 T_C region.

BES-II data taking: completed in Run-21

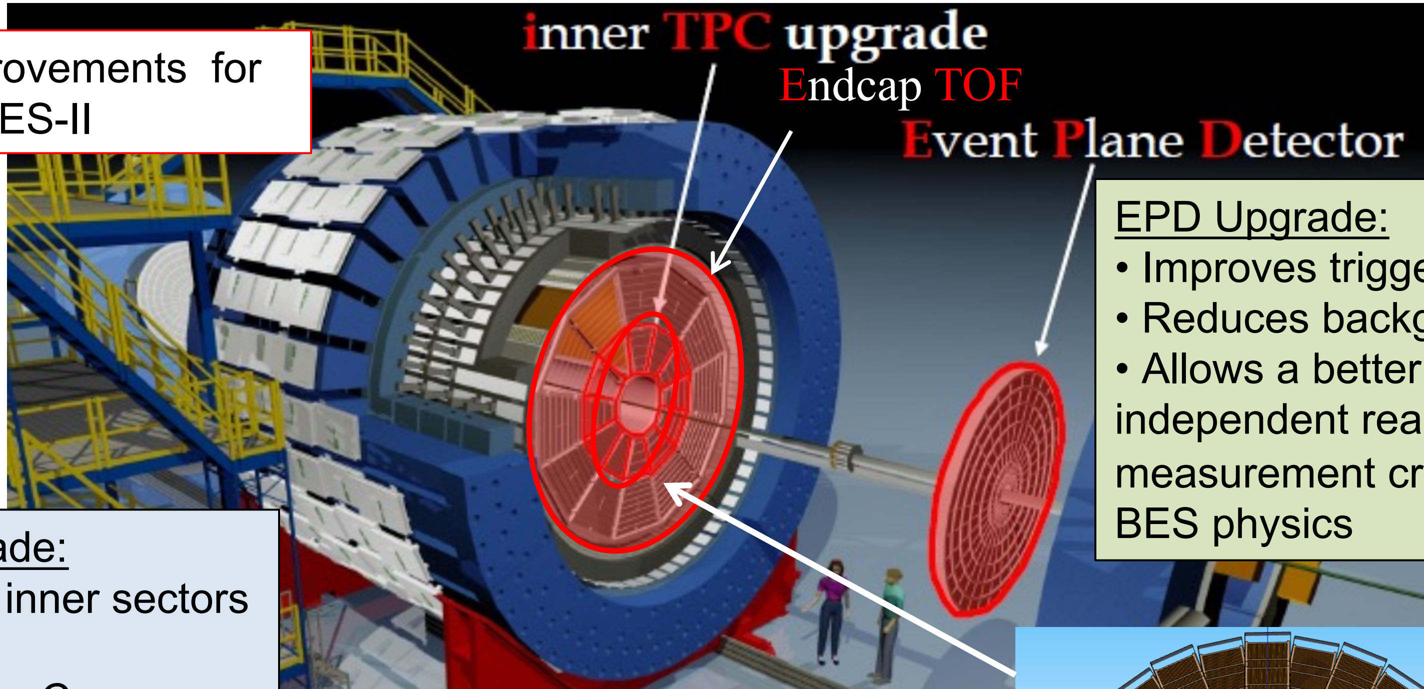


Collider mode: probe total baryon density effect

FXT mode: probe total baryon density and temperature effects

STAR detector at BES-II

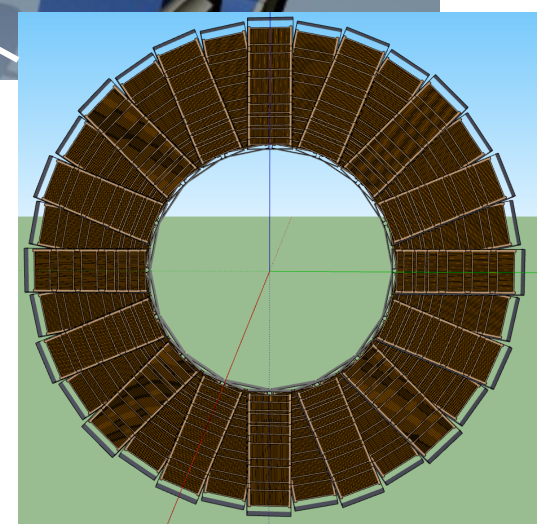
Major improvements for BES-II



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

<u>iTPC Upgrade:</u>
- 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

<u>EndCap TOF Upgrade:</u>
- 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

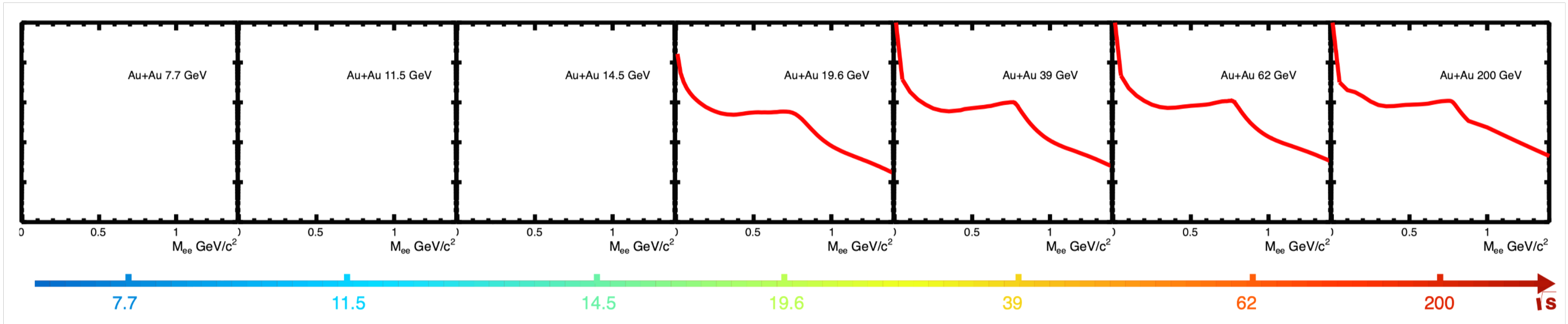
Reduce the systematic uncertainties due to

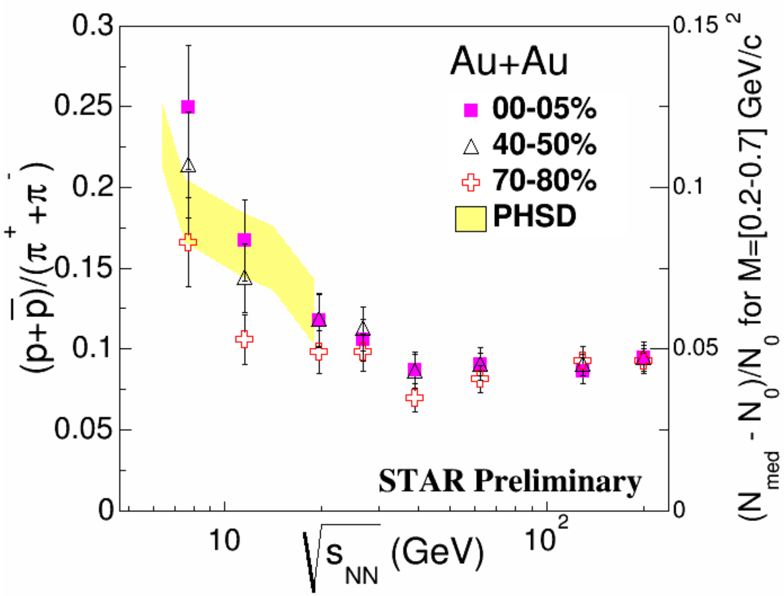
- **hadron contamination**
- **efficiency corrections**
- **acceptance differences between unlike-sign and like-sign pairs**
- **cocktail subtraction**

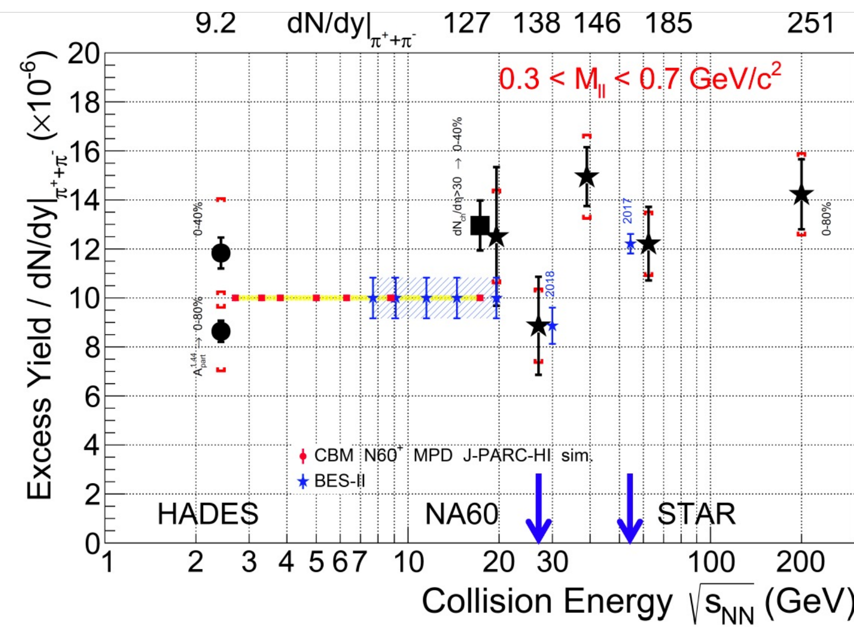
A factor of 2 reduction in the systematic uncertainties for dielectron excess yield

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

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



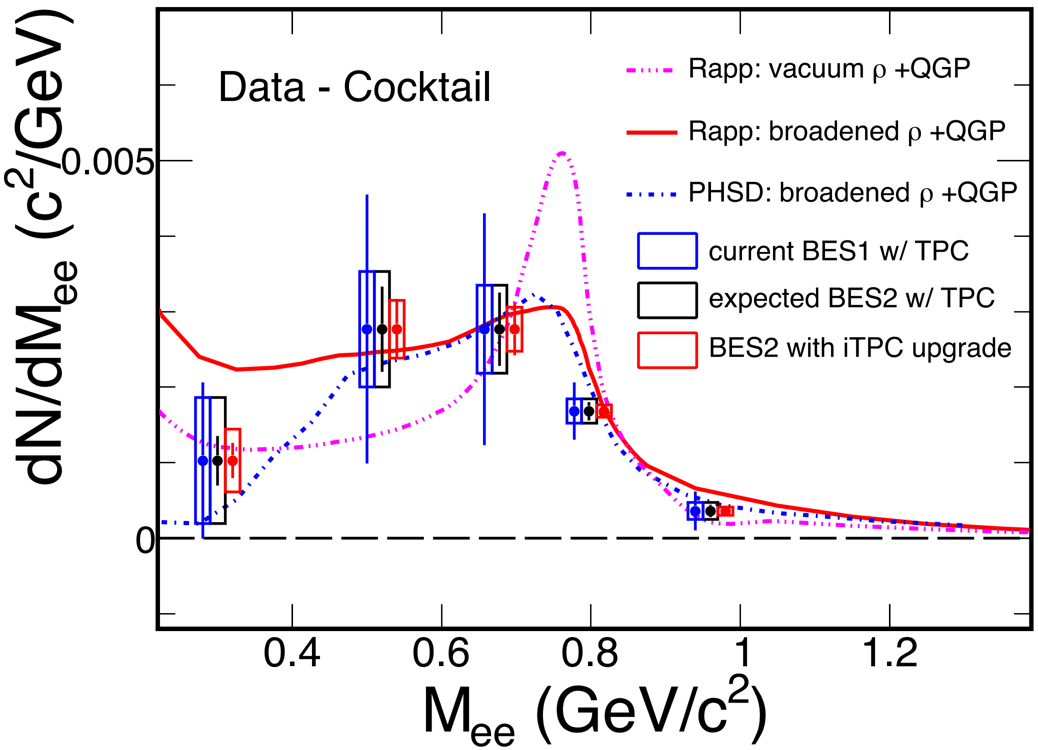


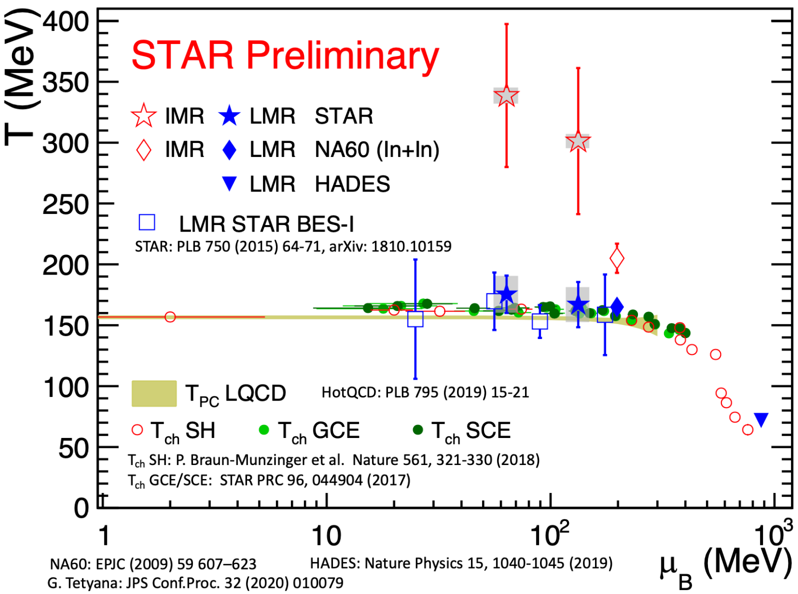


Broader and more electron-positron excess down to 7.7 GeV collision energy?

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

Link to chiral symmetry restoration

- T_C~ T_{ch} (T_{ch} will be improved with iTPC upgrades from BESII and beyond)
- $<T_{QGP}>$ larger than T_C , experimentally observed through intermediate-mass dilepton measurements
- In-medium ρ emission dominates at T_C region (based on theory calculations and measurements of low-mass dielectron)
- ρ 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!

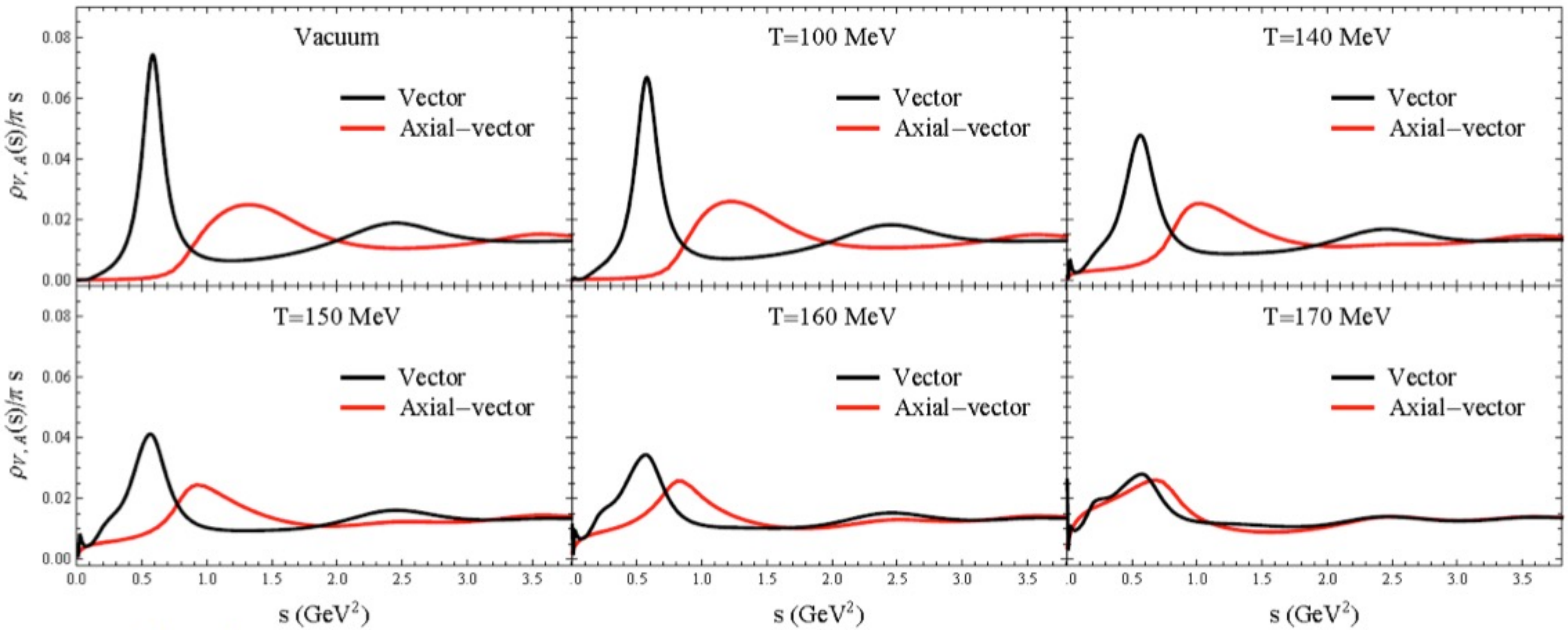
Is it an evidence?

Link to chiral symmetry restoration

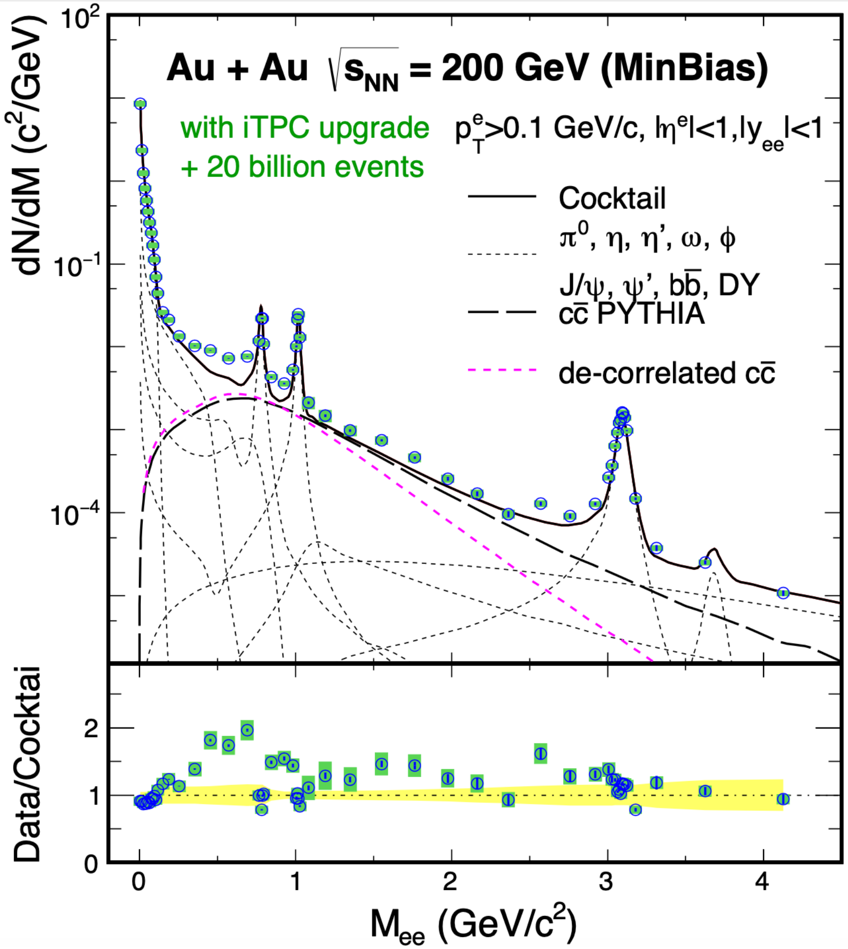
To link electron-positron measurements to chiral symmetry restoration need more precise measurement at $\mu_B = 0$:

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

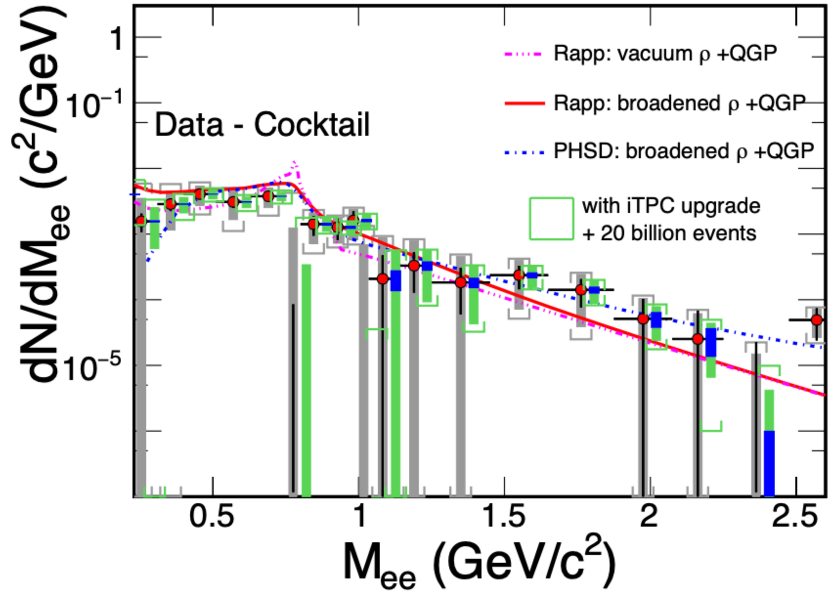
- Theoretical approach: derive the a1(1260) spectral function by using the broadened rho spectral function, QCD and Weinberg sum rules, and inputs from Lattice QCD; to see the degeneracy of the rho and a1 spectral functions (Hohler and Rapp 2014).



Back to 200 GeV Au+Au in 2023-2025



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



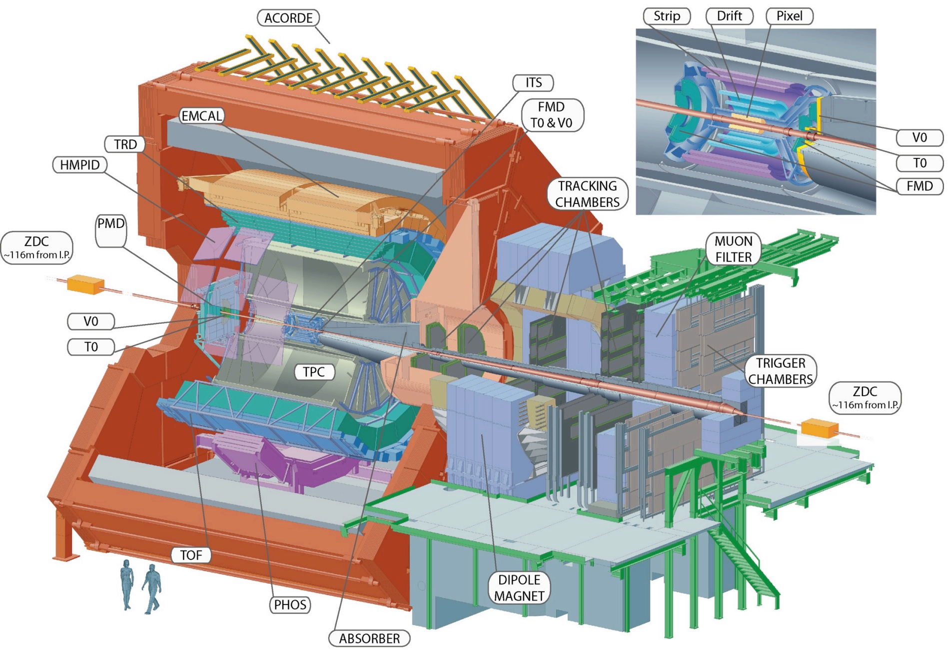
STAR BUR21

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)

World-wide interest



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

Discoveries of Breit-Wheeler process and vacuum birefringence

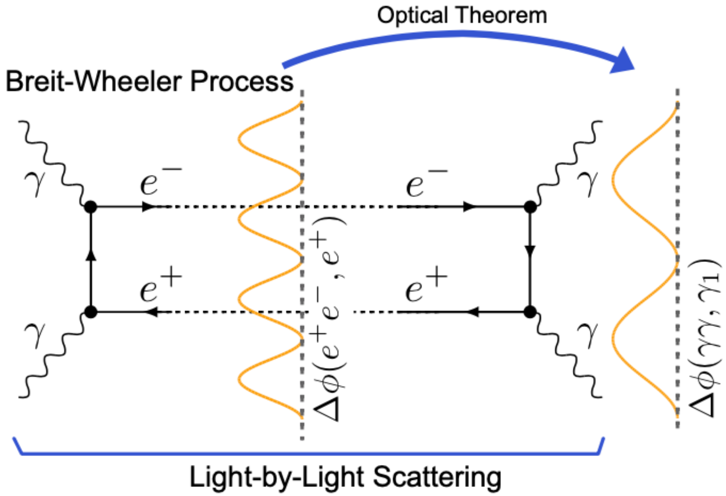
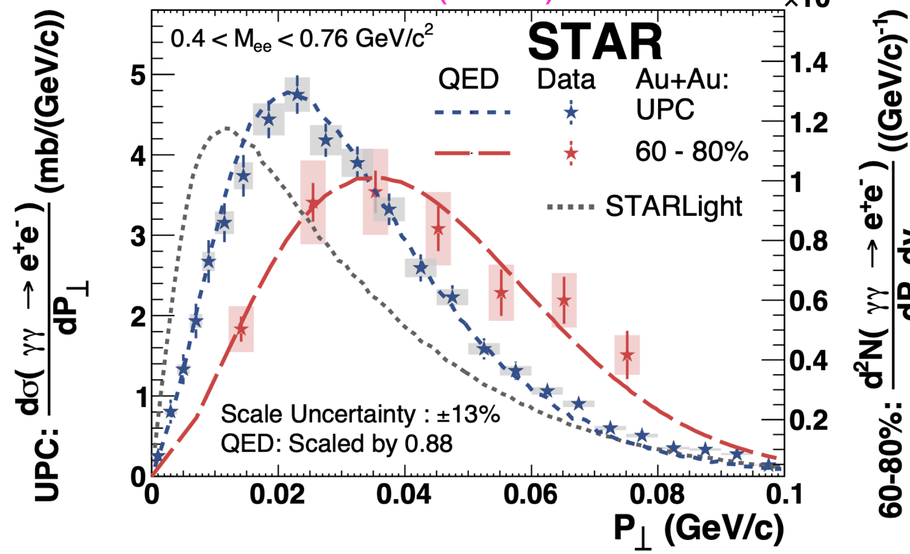
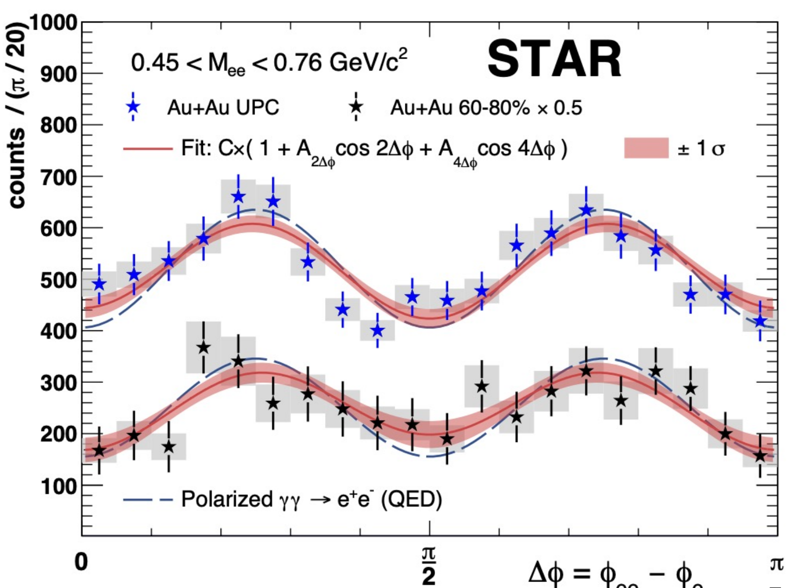


FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.

PRL127 (2021) 52302





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

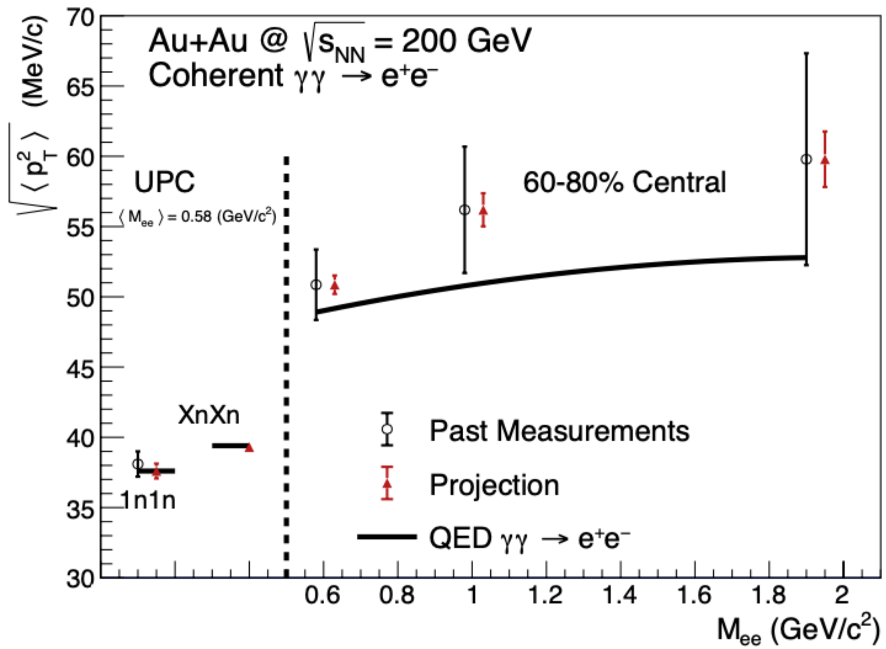
Dielectron p_T spectrum: broadened from large to small impact parameters

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

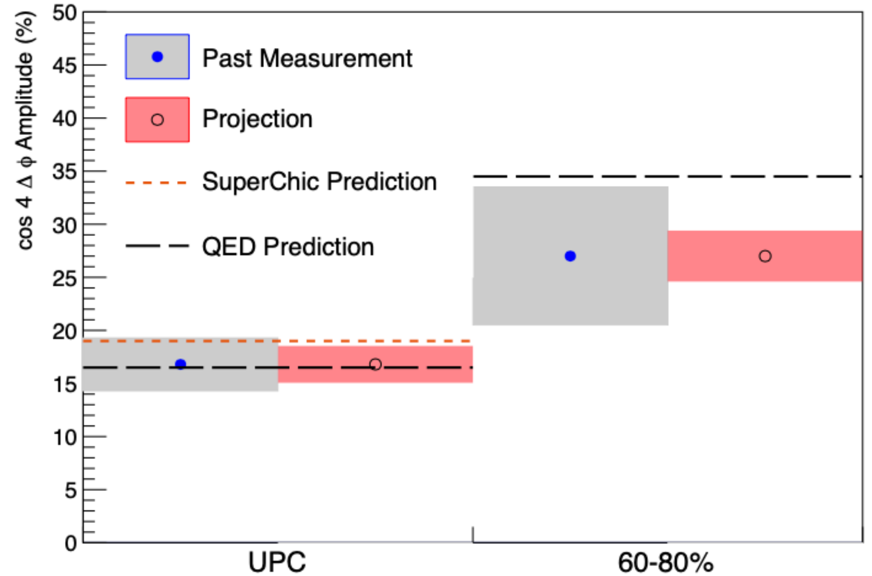
Collisions of Light Produce Matter/Antimatter from Pure Energy: https://www.bnl.gov/newsroom/news.php?a=119023

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 in A+A collisions:

- <T_{QGP}> greater than T_C
- In-medium ρ emission dominates at T_C
- In-medium ρ significantly broadened

In 2019-2021:

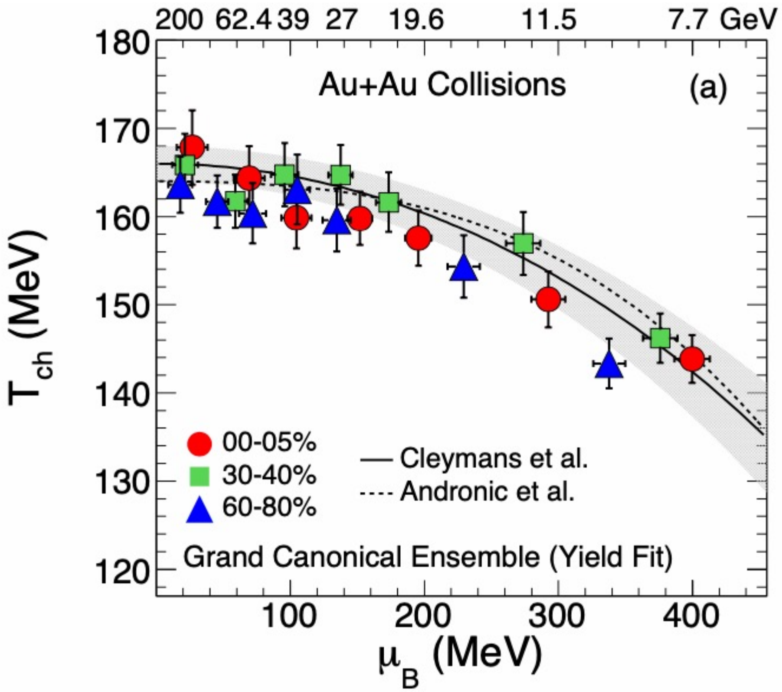
- Beam Energy Scan II (7.7-19.6 GeV) will provide a unique opportunity to quantify the effect of Chiral Symmetry Restoration via total baryon density effect on the ρ broadening.

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

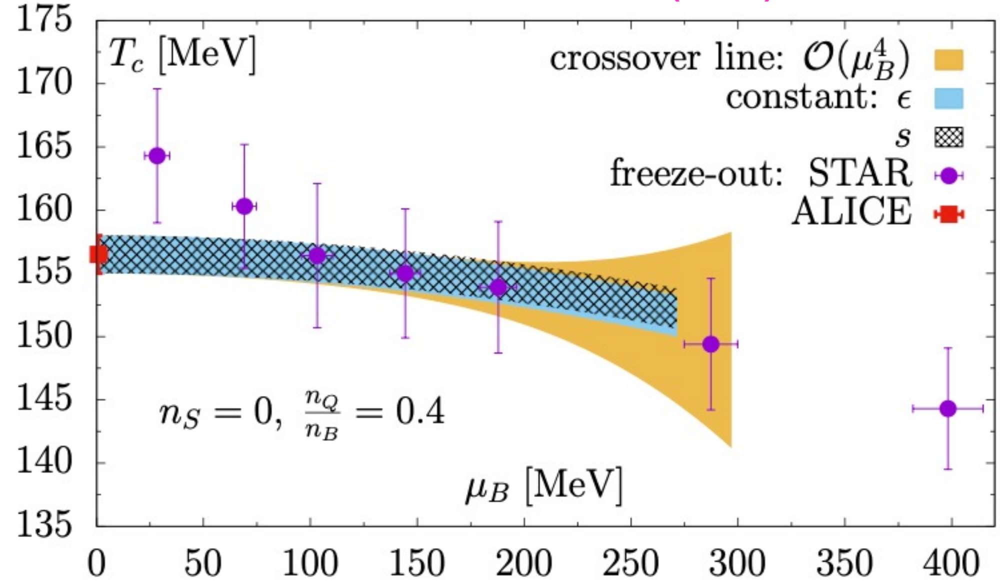
Backup

Freeze out temperatures



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

HotQCD, PLB 795 (2019)15

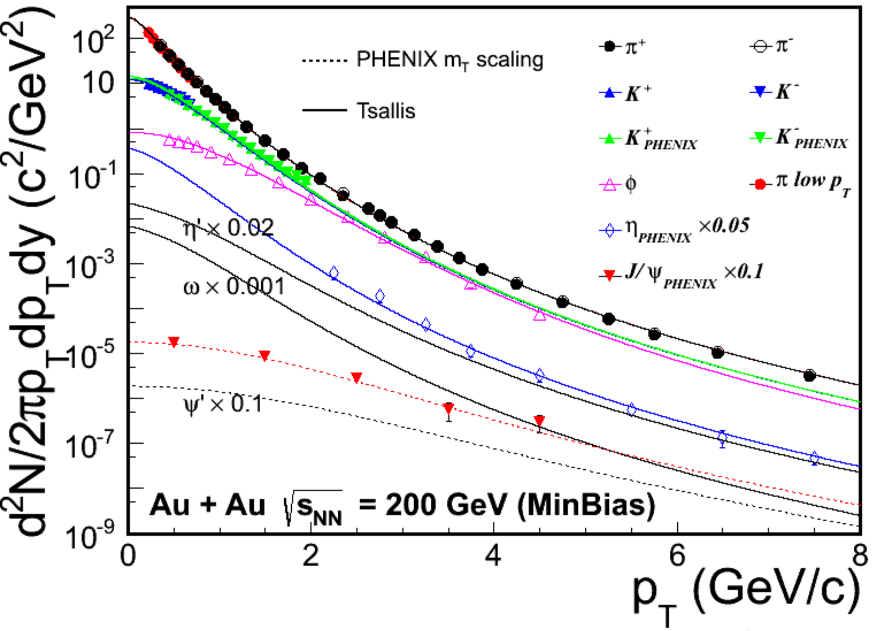


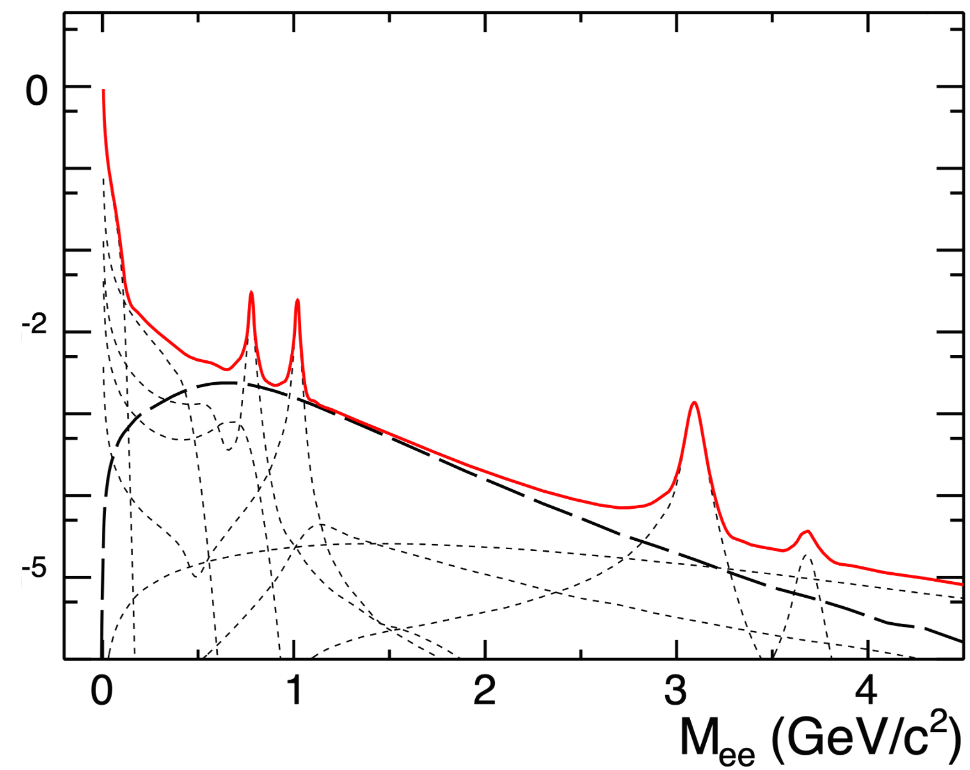
At 200 GeV, T_{ch}~T_C

The initial temperature T_0 must be higher than T_C ?

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

Electron-positron emission mass spectrum

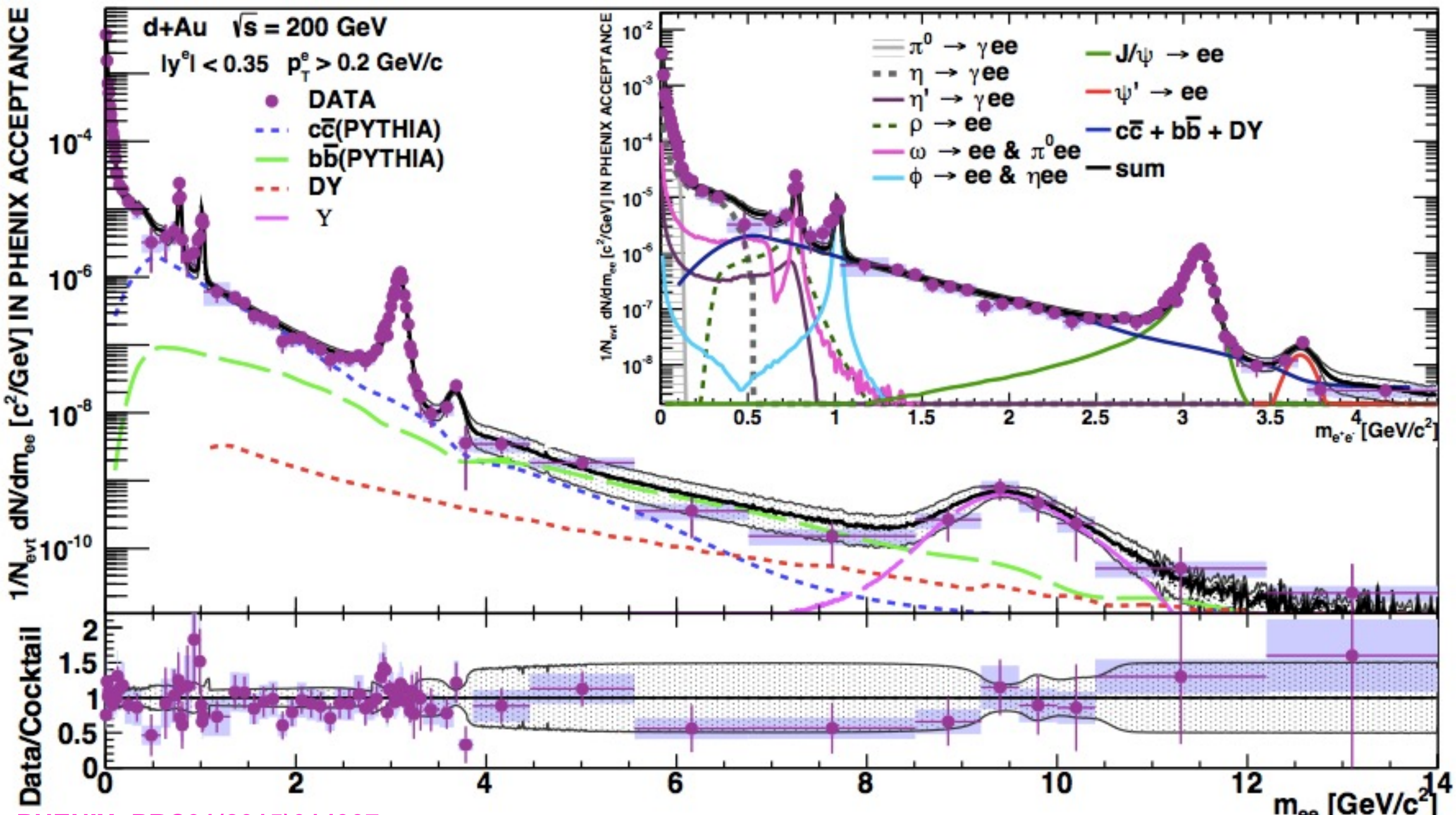




PHENIX Collaboration, Phys. Rev. C 81, 034911 (2010)
STAR Collaboration, Phys. Rev. Lett. 92, 112301 (2004)
STAR Collaboration, Phys. Lett. B 612, 181 (2005).
STAR Collaboration, Phys. Rev. Lett. 97, 152301 (2006)
Z. Tang et al. Phys. Rev. C 79, 051901 (2009)

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

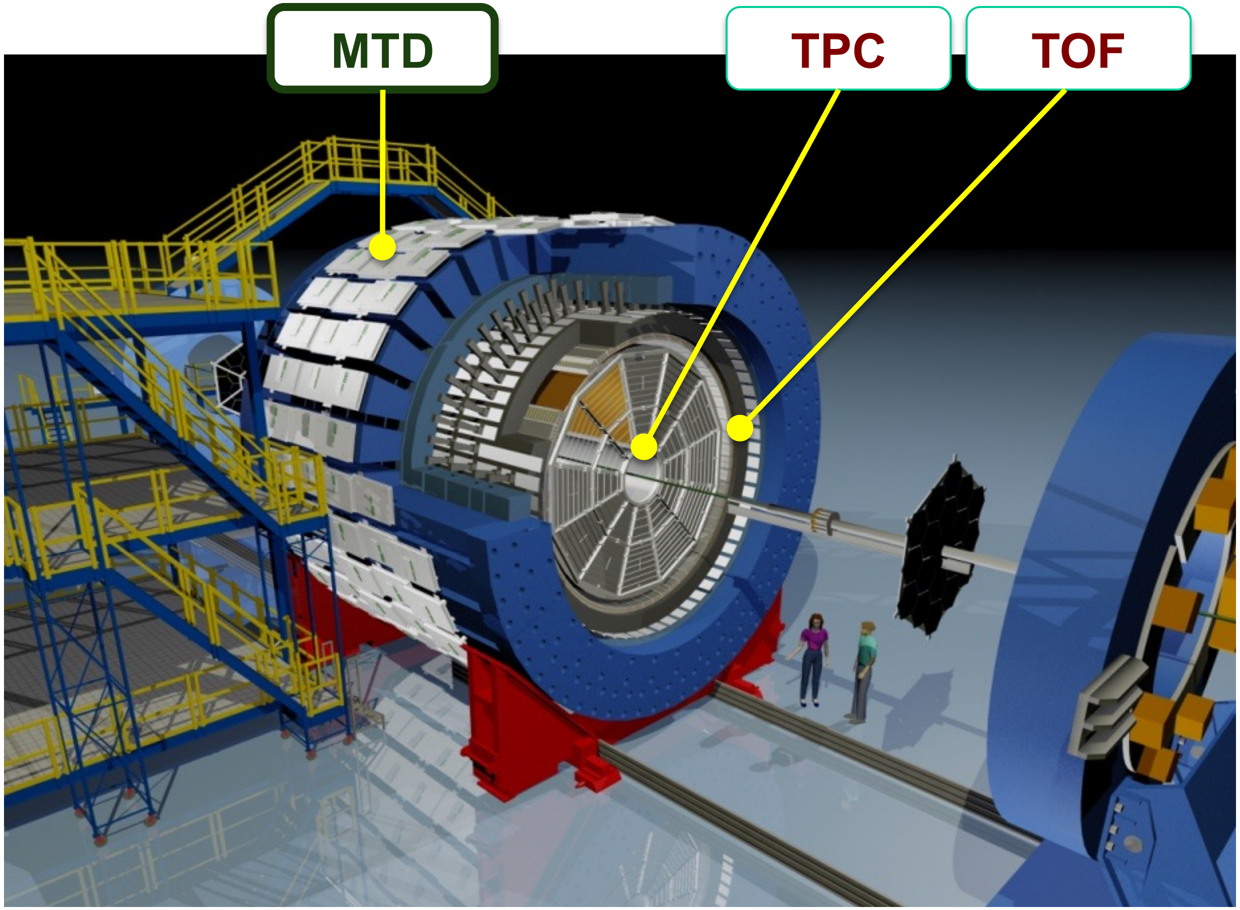
Dielectron measurements in d+Au collisions



PHENIX: PRC91(2015)014907

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

The STAR (Solenoidal Tracker at RHIC) Detector

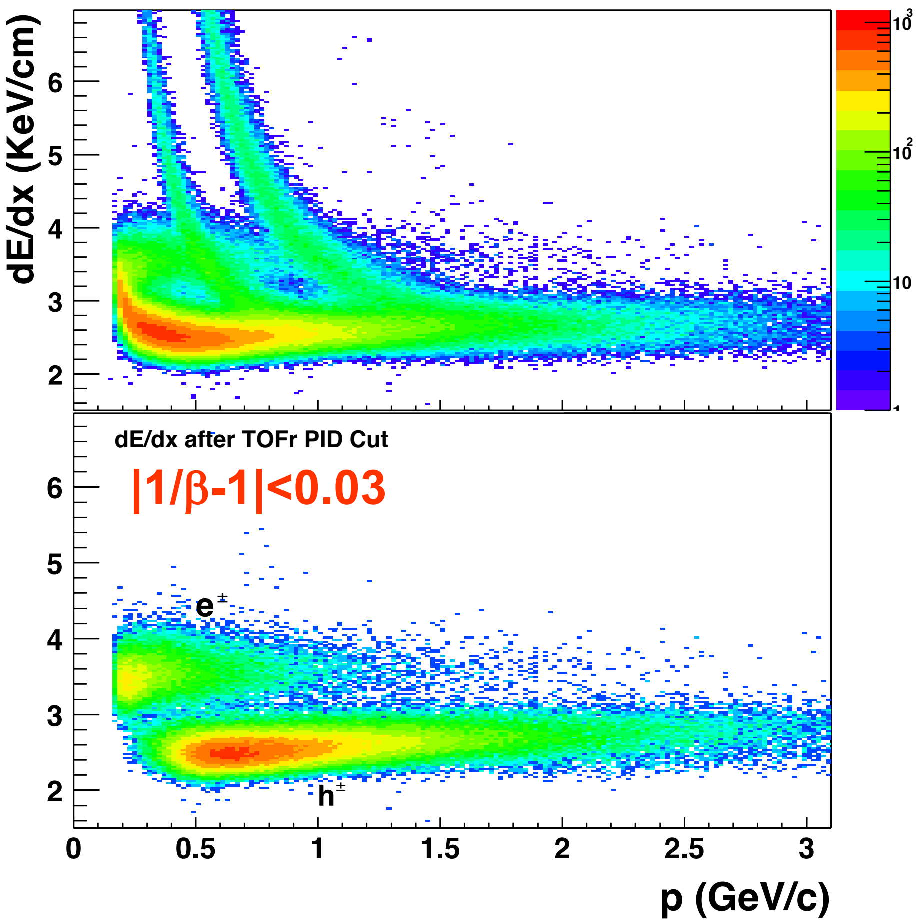


Time Projection Chamber (TPC):
measure ionization energy loss and Momentum

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

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

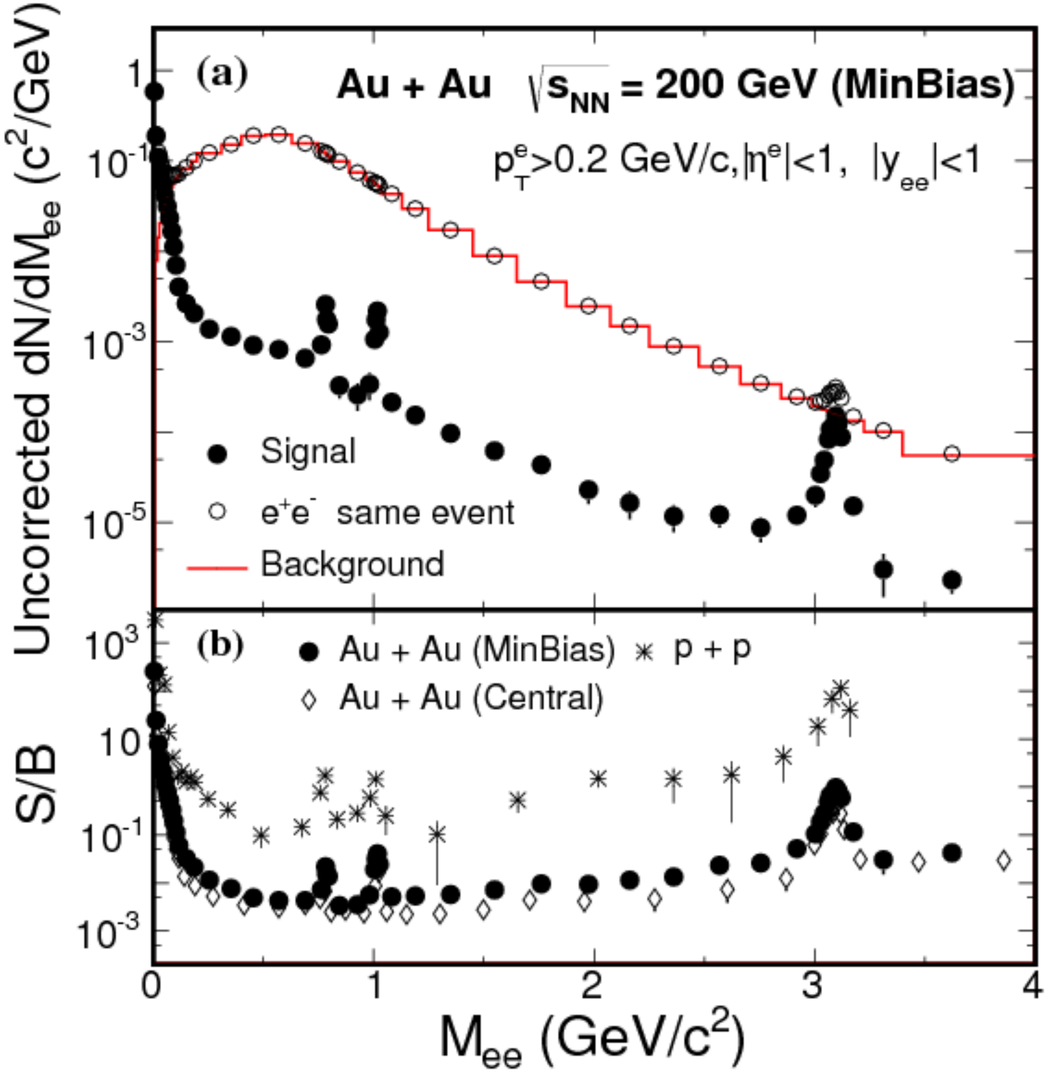
Electron identification



STAR Collaboration, PRL94(2005)062301

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

Dielectron 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

Dielectron 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

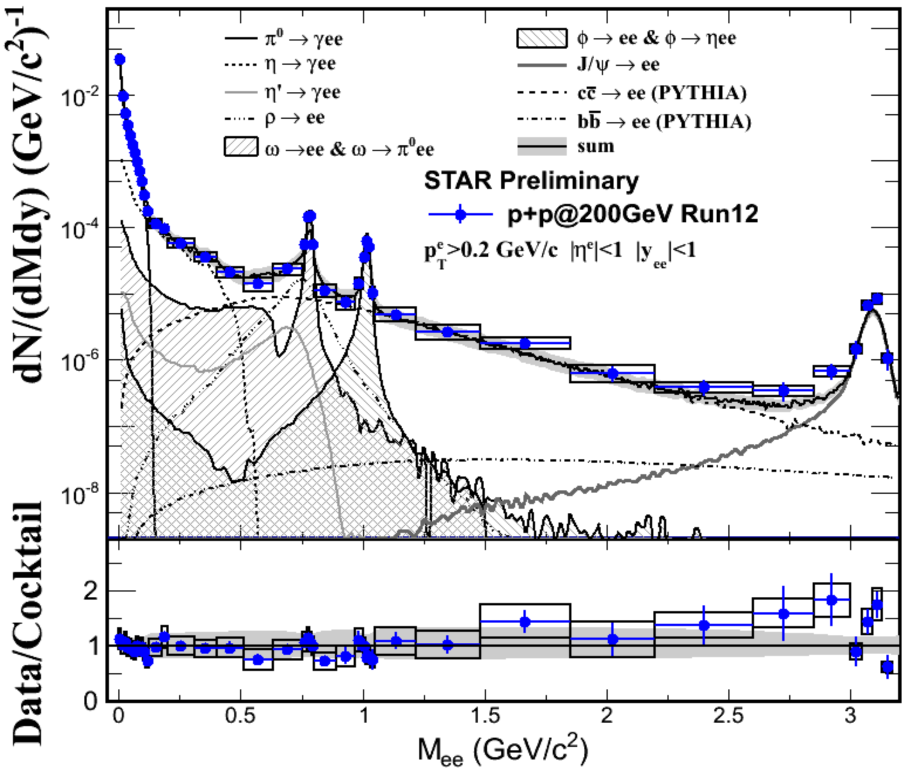
Drell-Yan contribution

In Au+Au collisions, we search for

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

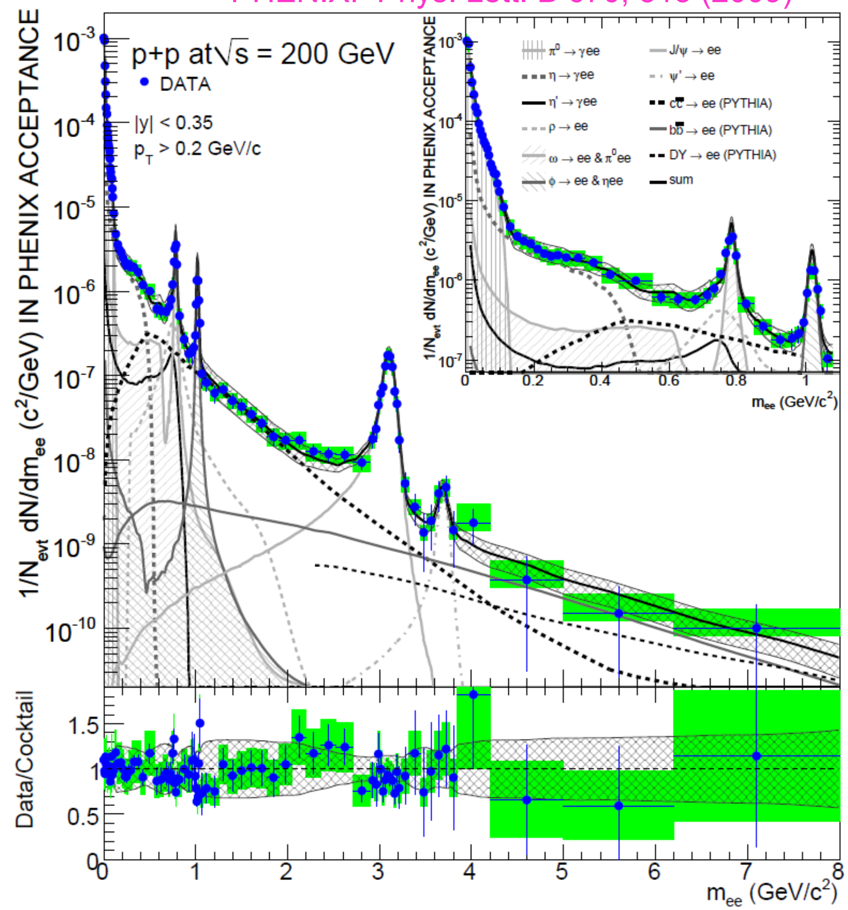
Vector meson in-medium modifications at $M_{ee}<1.1$ GeV/c^2 (low mass range)

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.