Electromagnetic radiation in hadronic interactions: from pp to AA collisions

Lijuan Ruan
(*Brookhaven National Laboratory*)

Outline:

- **Introduction**
- **Recent results on dileptons (dielectrons)**
- **Recent results on thermal photons**
- **Future measurements**
- **Summary**

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a passion for discovery

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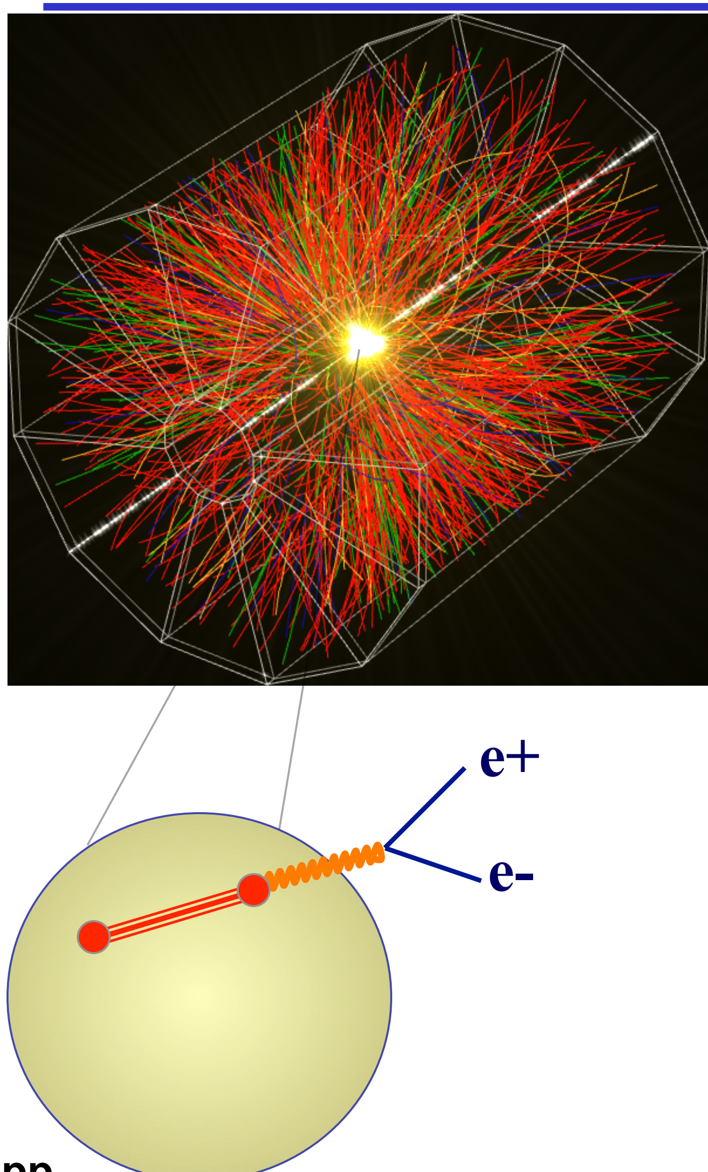
EM probe: electron-positron tomography



Rapp

- 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.

Spontaneous chiral symmetry breaking

Generate 99% of visible mass in the universe.

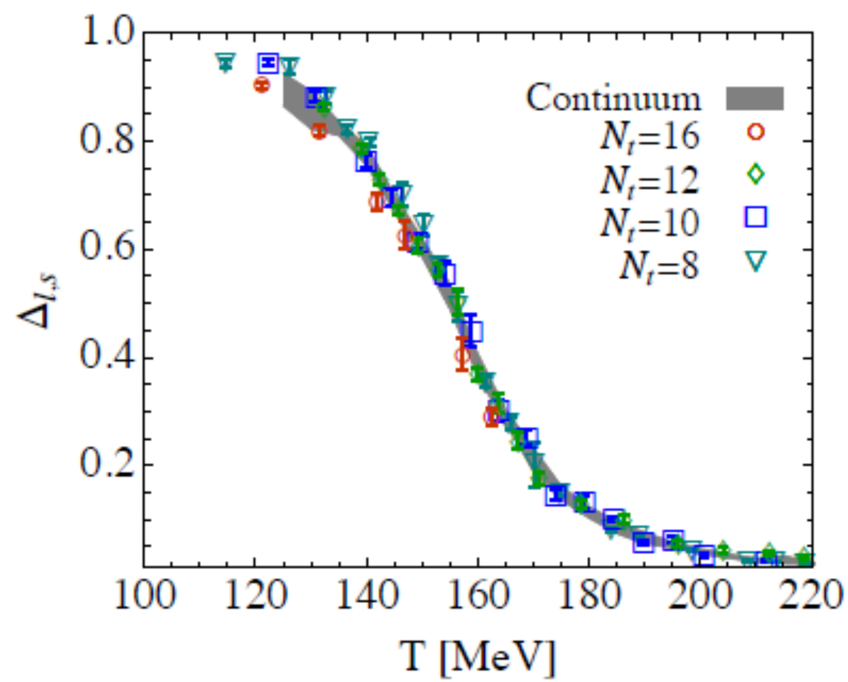
Microscopic picture:

- 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?

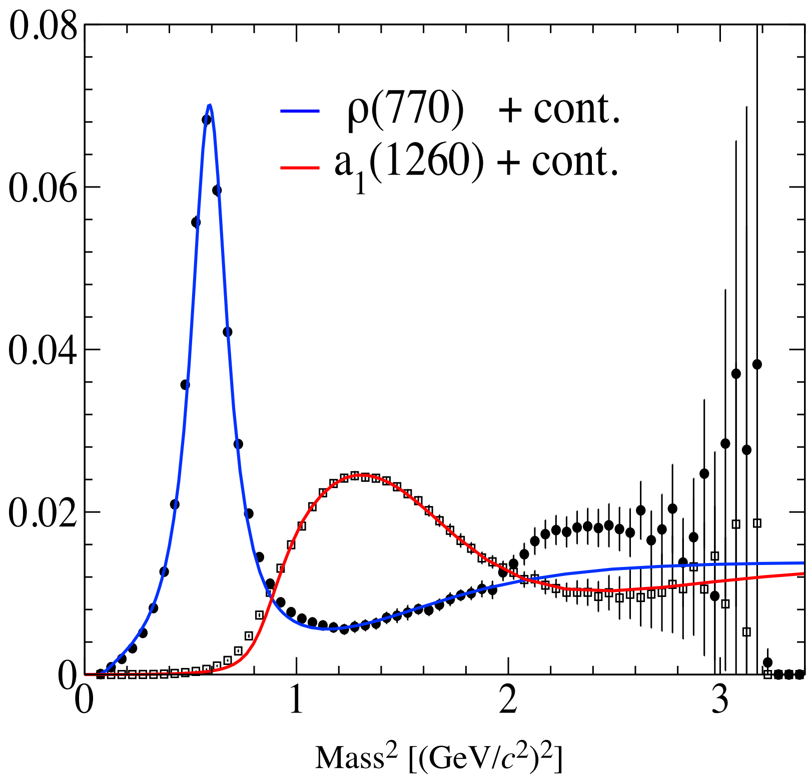
T_c= 155 MeV

Do we have experimental observable?



$\Delta_{l,s}$: subtracted chiral condensate
Z. Fodor, Lattice 2010

ρ and a1 resonance (spectrum function) in vacuum

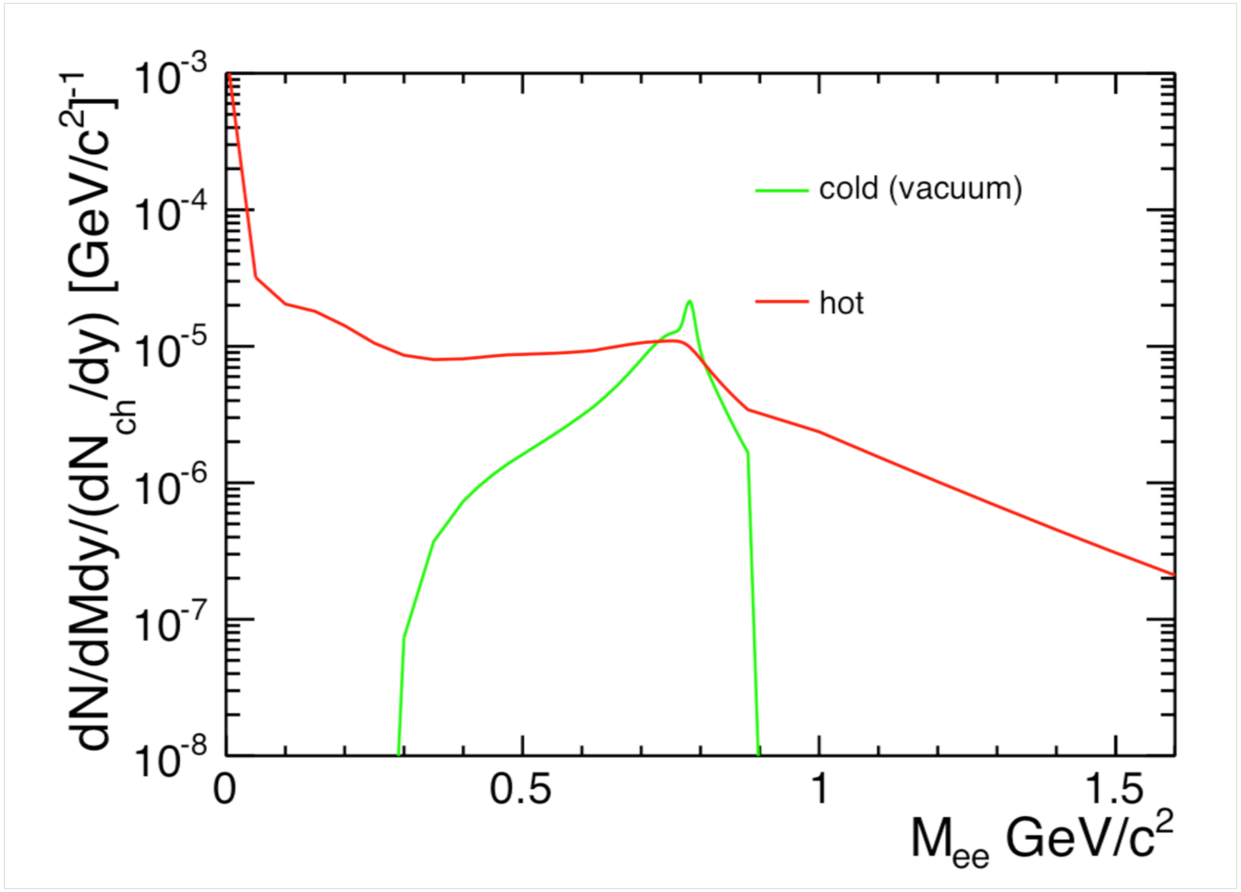


ALEPH: EPJC4 (1998) 409;
R. Rapp Pramana 60 (2003) 675.

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

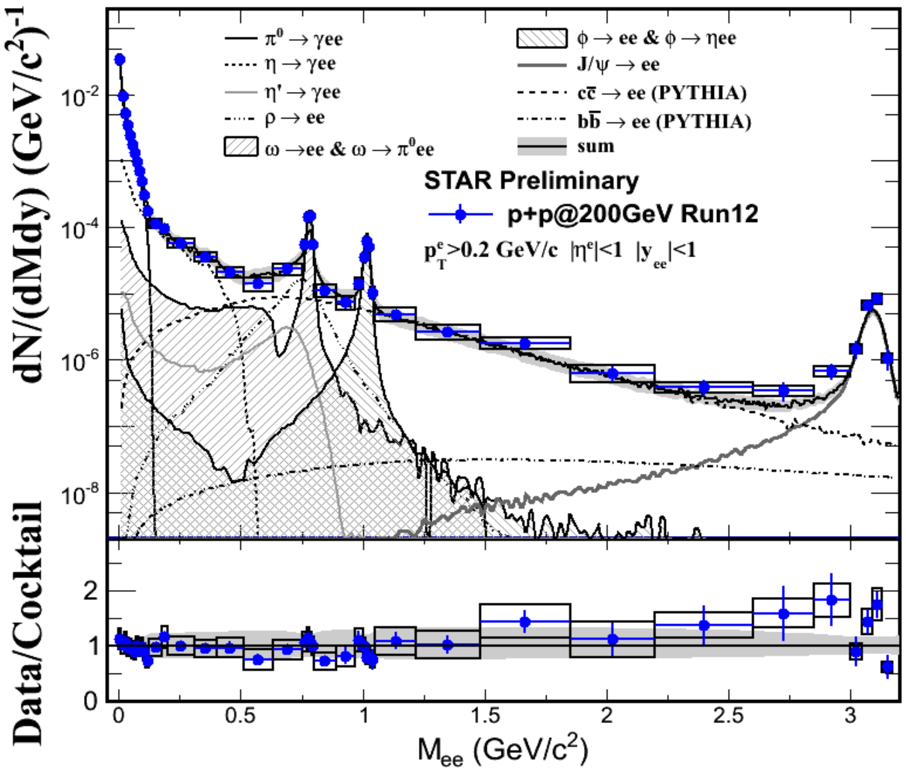
Model: Rapp & Wambach, priv. communication
Adv. Nucl.Phys. 25, 1 (2000); Phys. Rept. 363, 85 (2002)

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

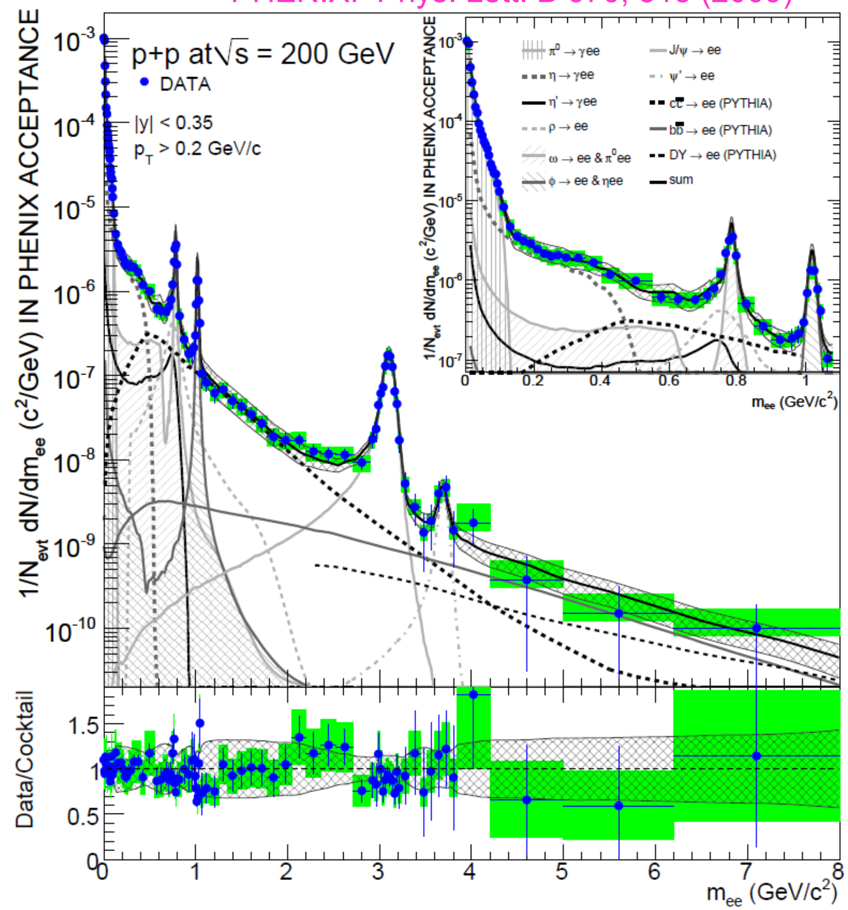
Energy and centrality dependence → Constrain T_0, t_0, lifetime, and density profile …

Dielectron mass spectrum in 200 GeV p+p collisions



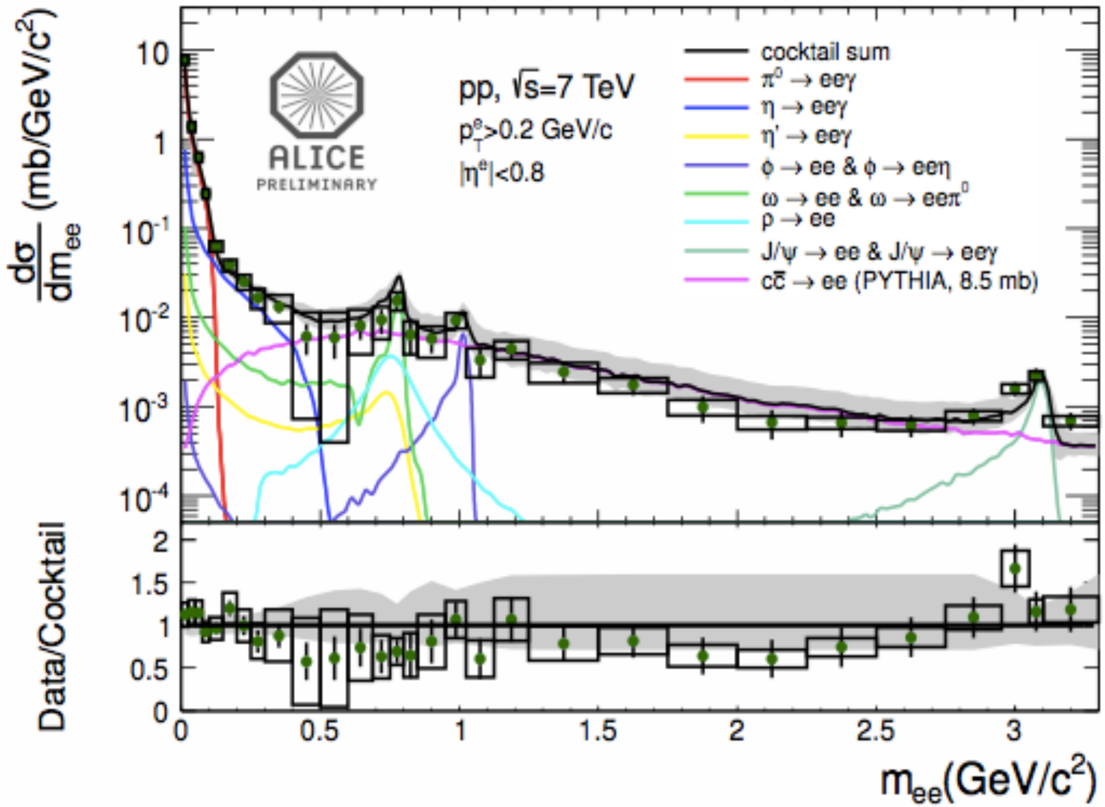
STAR: QM2014

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



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

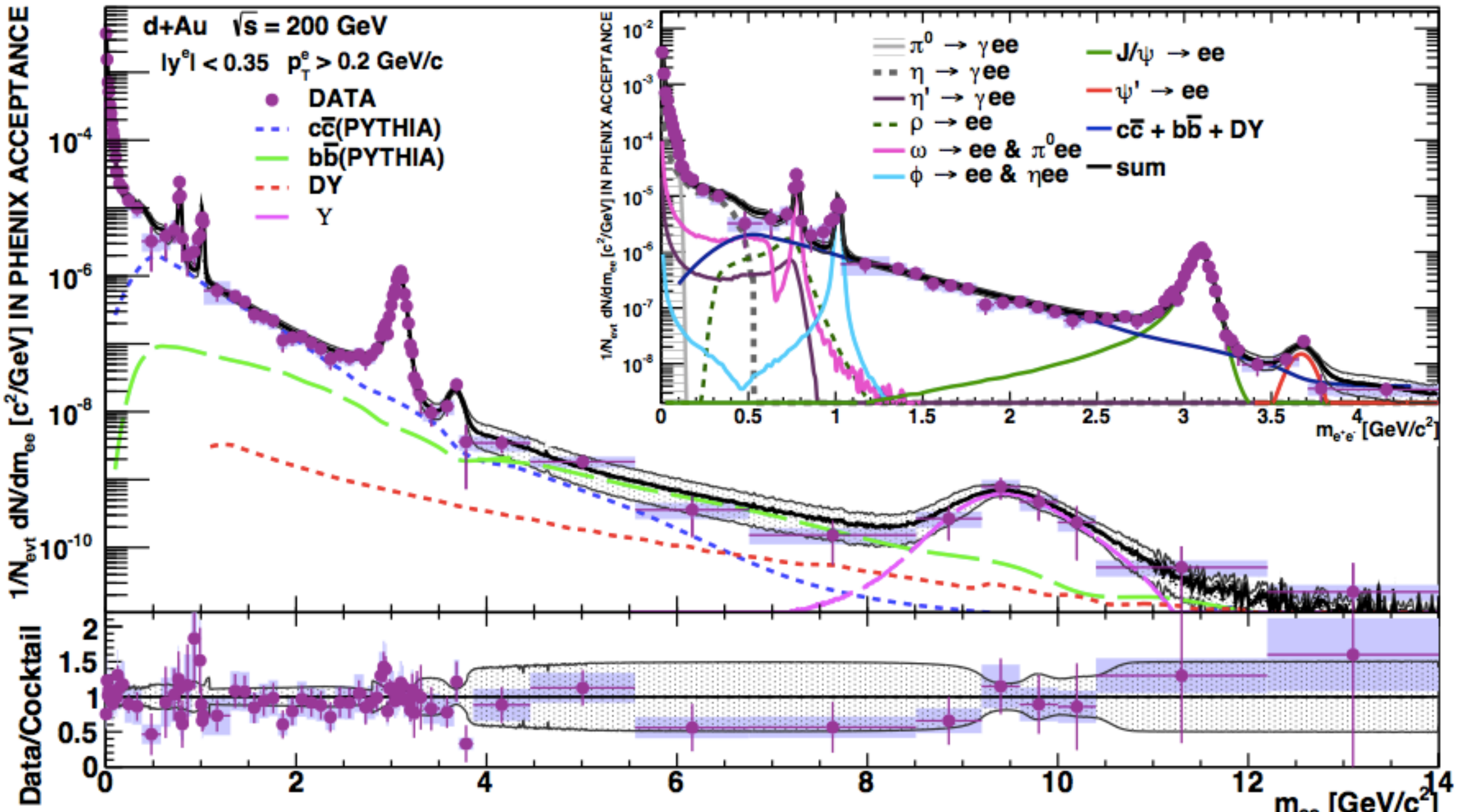
Dielectron measurements in p+p collisions



Charm correlation contribution **increases from RHIC to LHC** **at 0.4<M_{ee}<0.5 GeV/c^2.**

No medium radiation observed in p+p collisions!

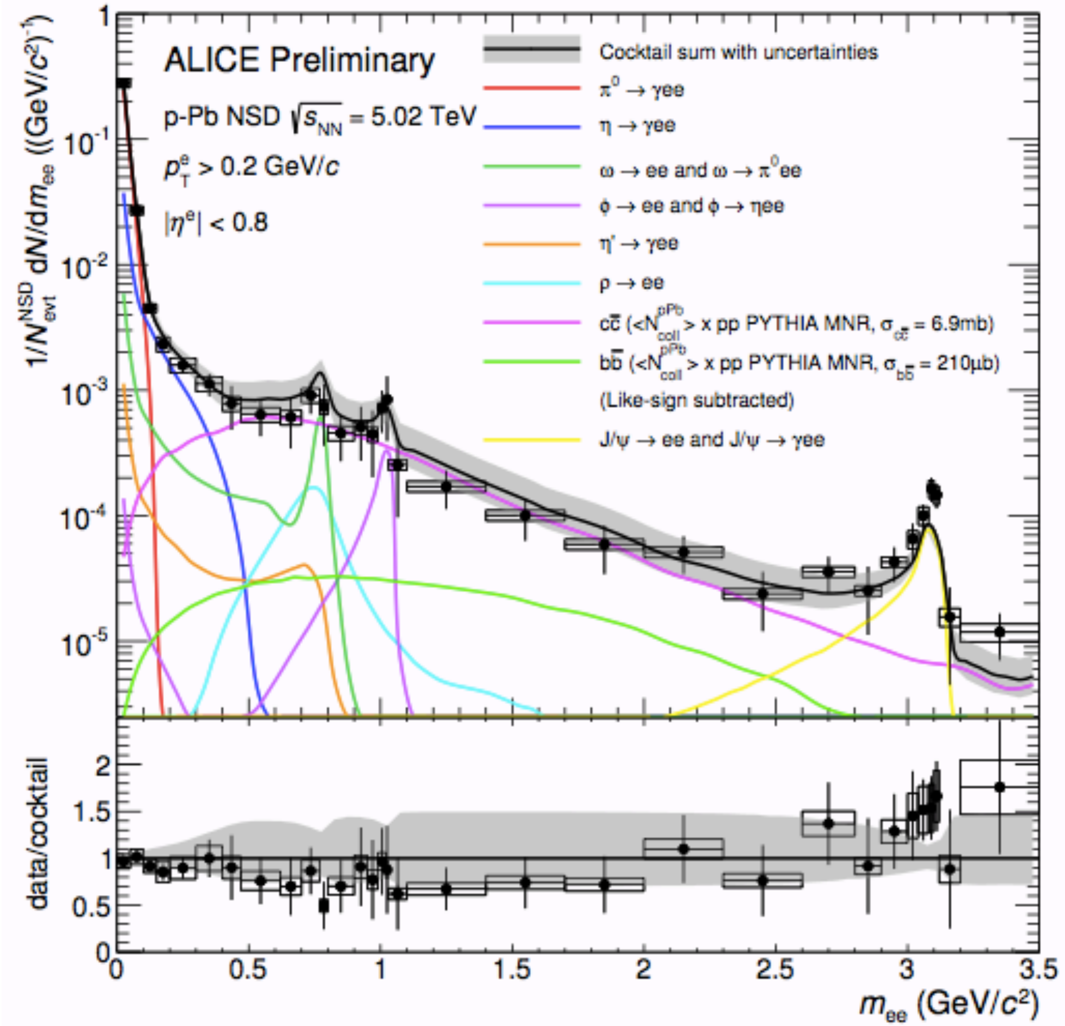
Dielectron measurements in d+Au collisions



PHENIX: PRC91(2015)014907

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

Dielectron measurements in p+Pb collisions



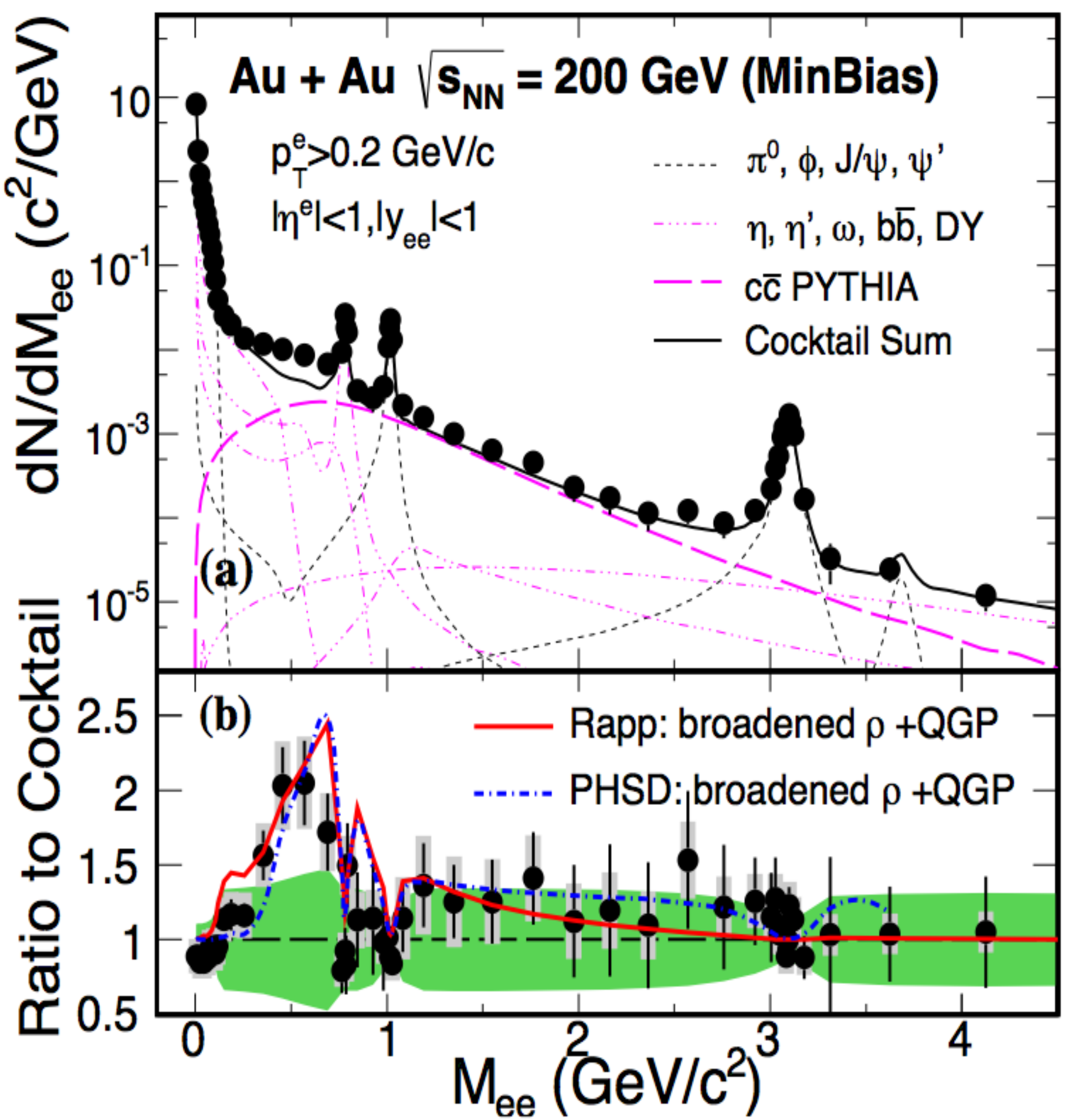
ALICE: M. Kohler

Hadronic cocktail is consistent with data in p+Pb collisions.

There is no medium radiation observed in p(d)+A 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.

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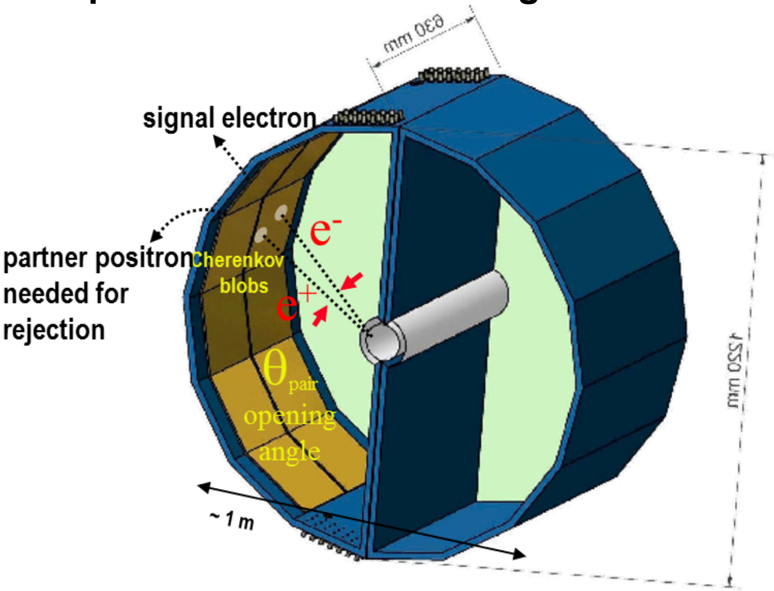
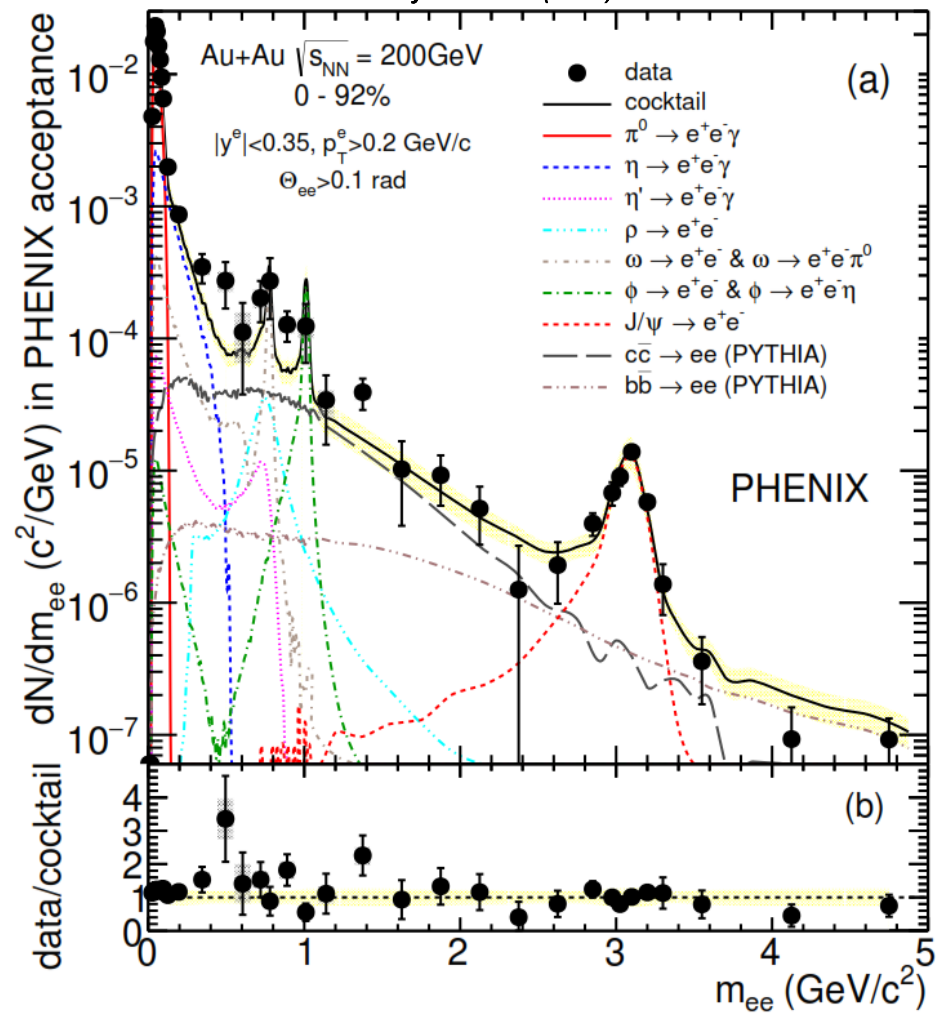
PHENIX HBD Upgrade

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



PHENIX Phys. Rev. C (2016)



- 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 GeV Au+Au

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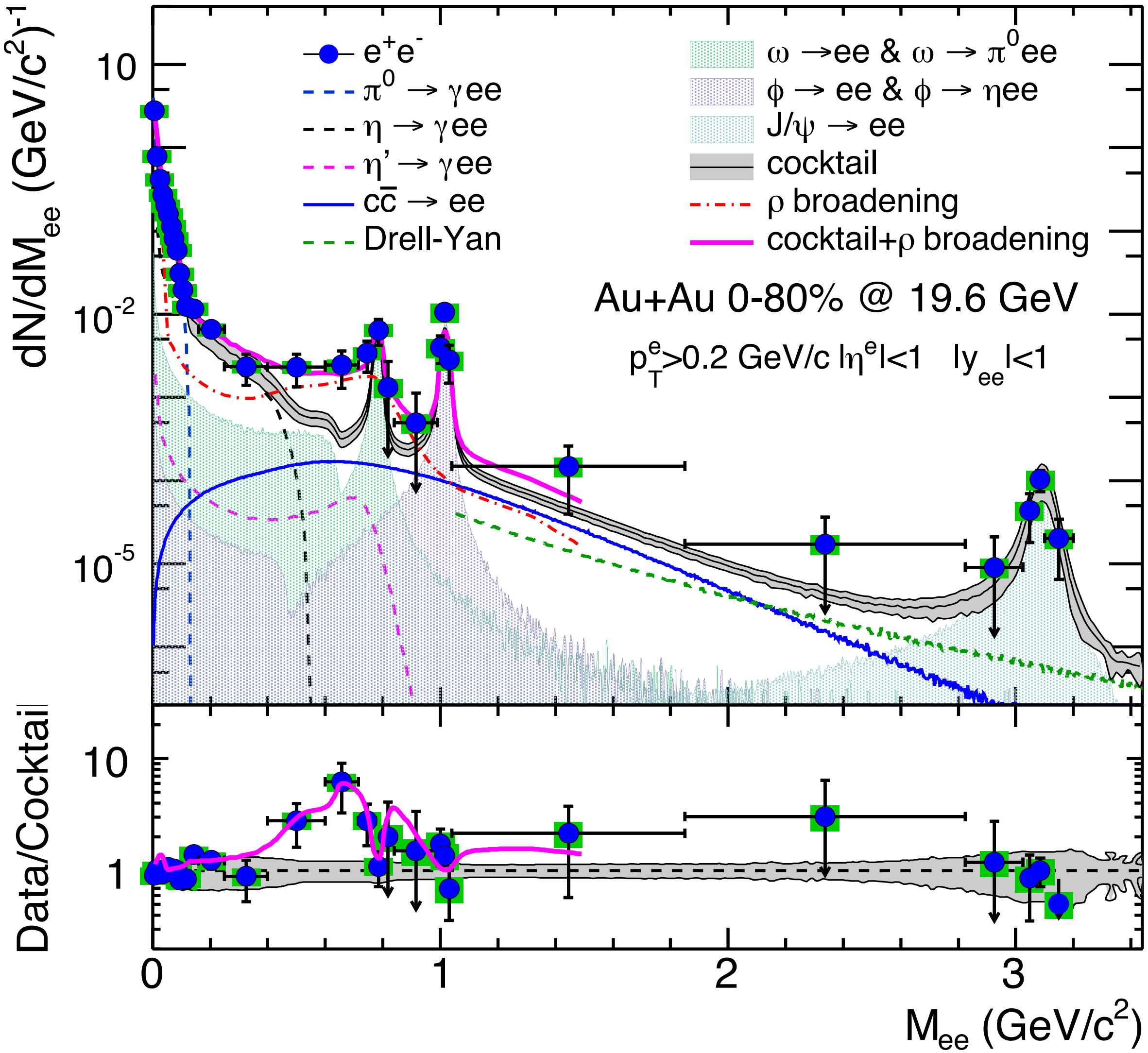
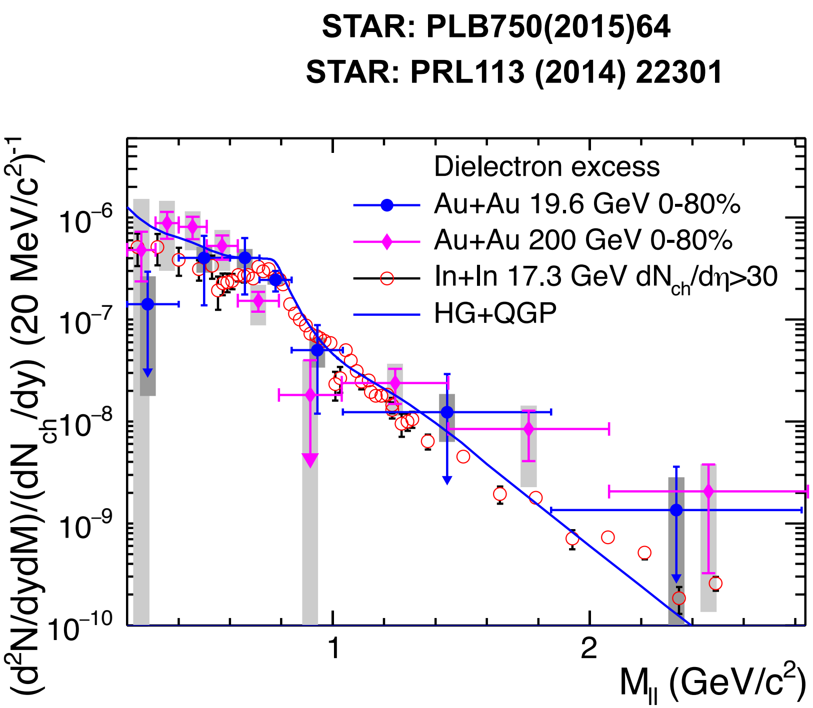
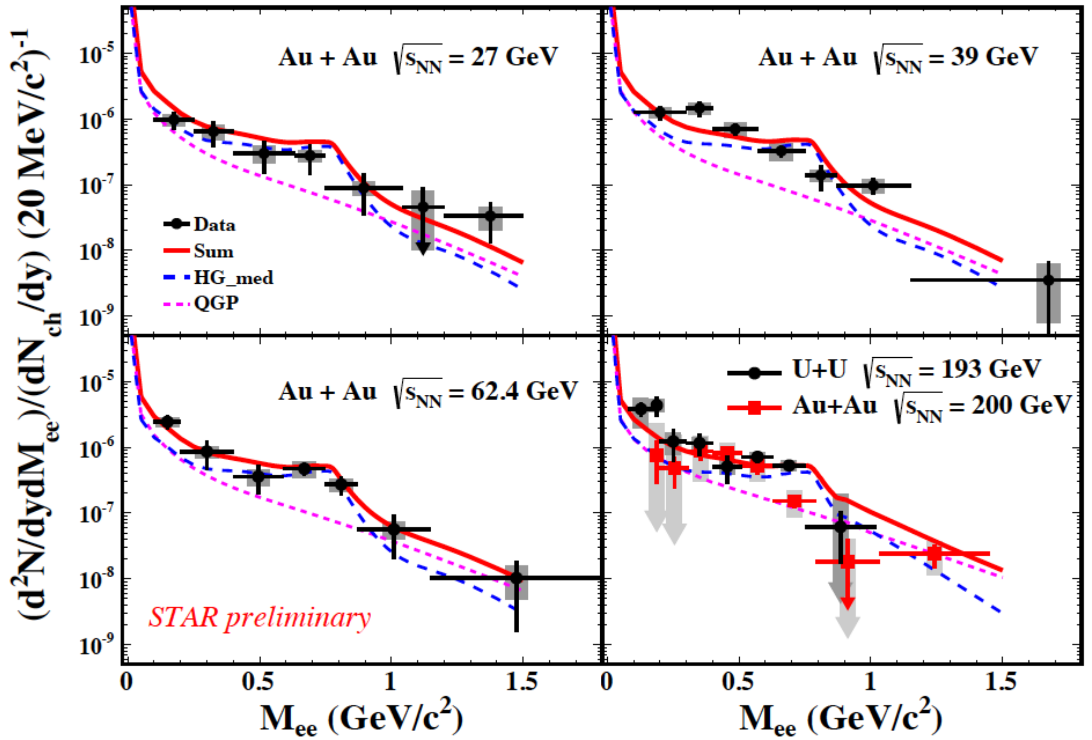
STAR: PLB750(2015)64



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

The dielectron excess spectrum

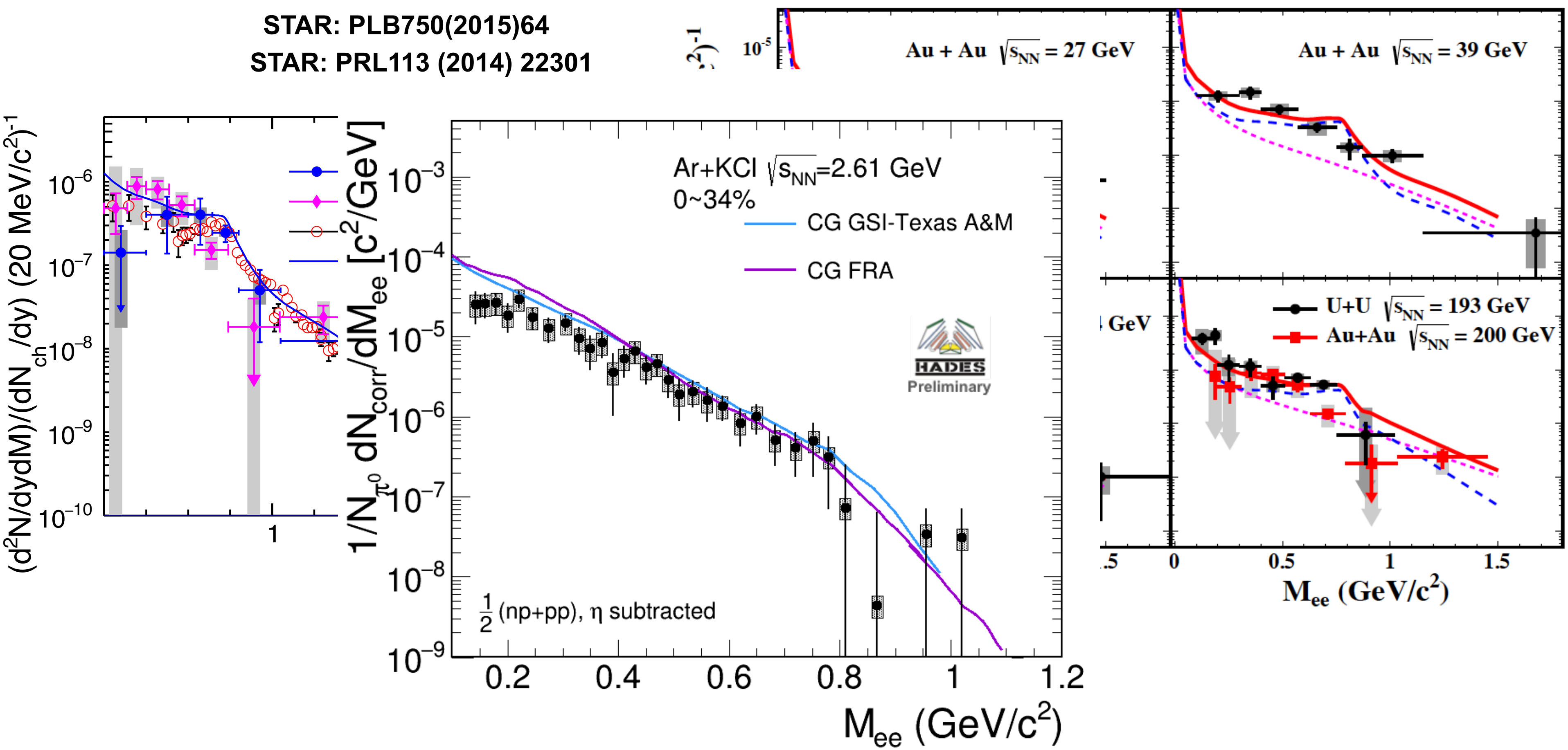




A broadened ρ spectral function consistently describes the low mass dielectron excess for all the energies 19.6-200 GeV and 2.61 GeV.

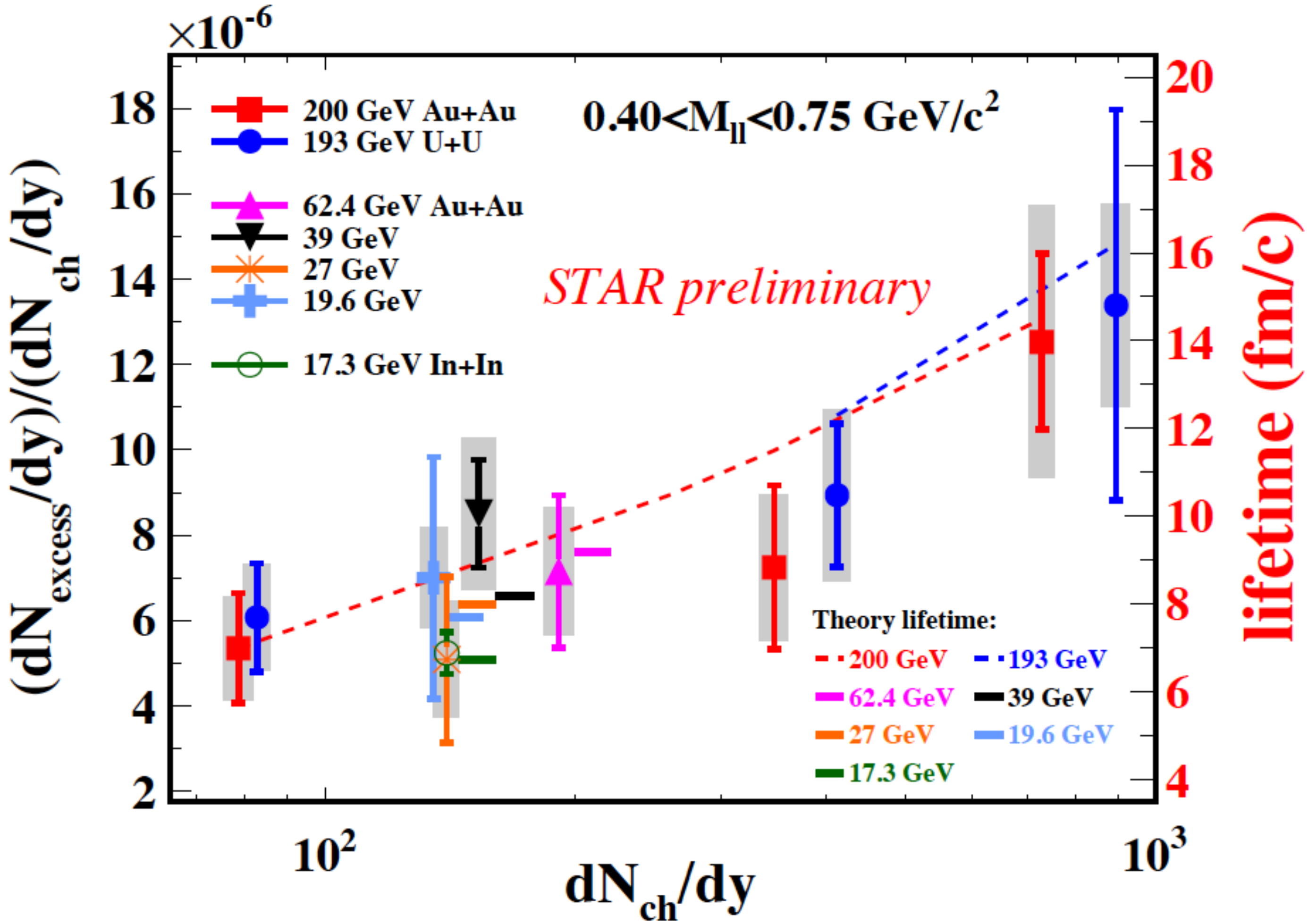
The dielectron excess spectrum

STAR: PLB750(2015)64
STAR: PRL113 (2014) 22301



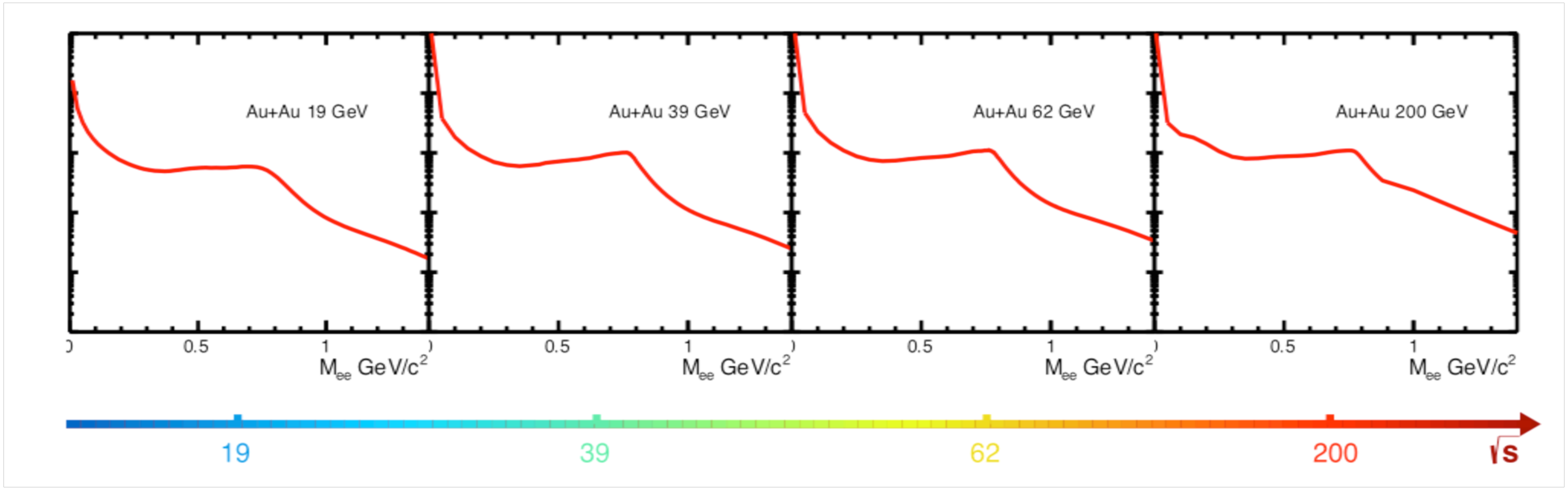
A broadened ρ spectral function consistently describes the low mass dielectron excess for all the energies 19.6-200 GeV and 2.61 GeV.

The low mass measurements: lifetime indicator



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

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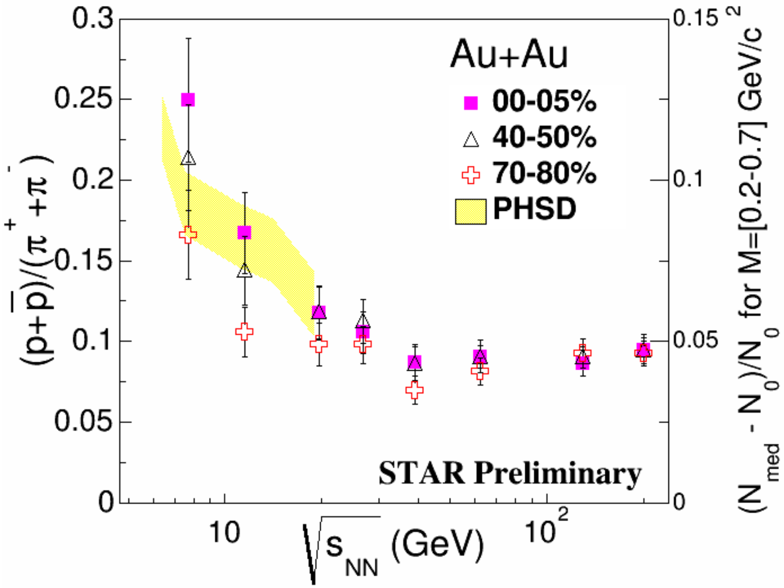
Low-mass electron-positron emission depends on T, total baryon density, and lifetime

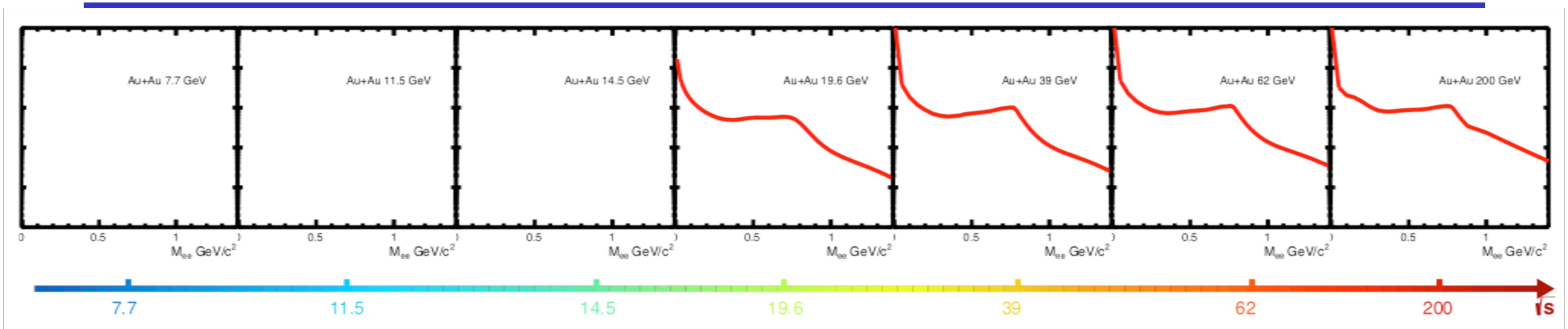
Coupling to the baryons plays an essential role to the modification of ρ spectral function in the hot, dense medium.

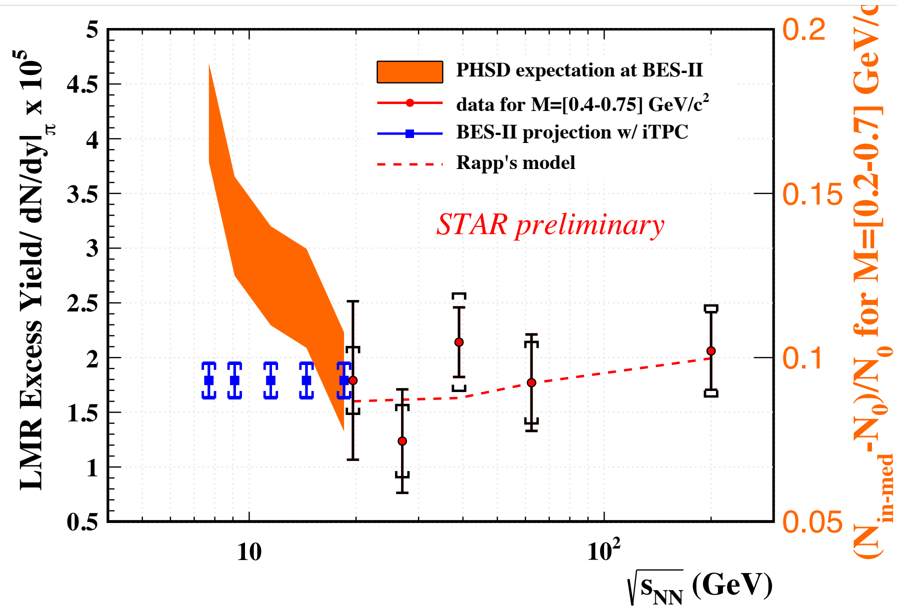


Normalized low-mass electron-positron production, is proportional to the life time of the medium from 17.3 to 200 GeV, given that the total baryon density is nearly a constant and that the emission rate is dominant in the Tc region.

Probe total baryon density effect

7.7 GeV to 19.6 GeV (RHIC beam energy scan II)

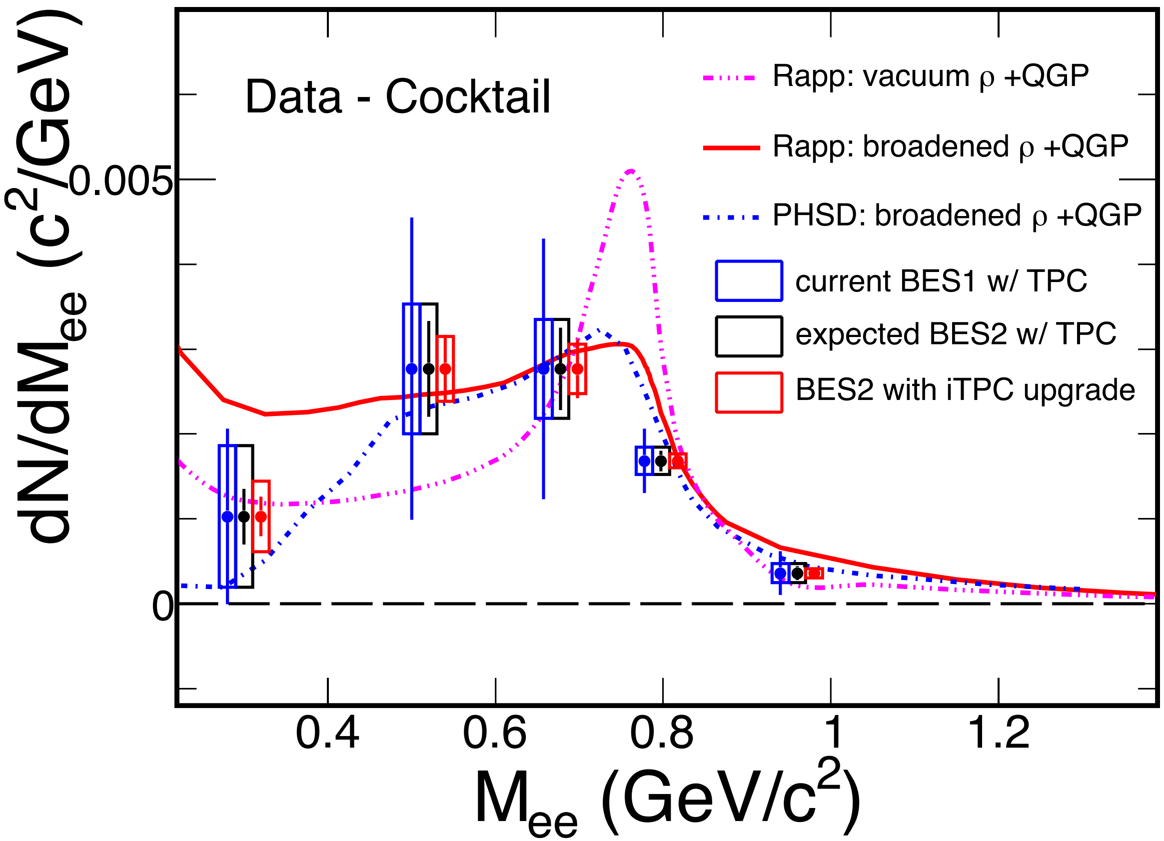




Broader and more electron-positron excess down to 7.7 GeV collision energy?

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

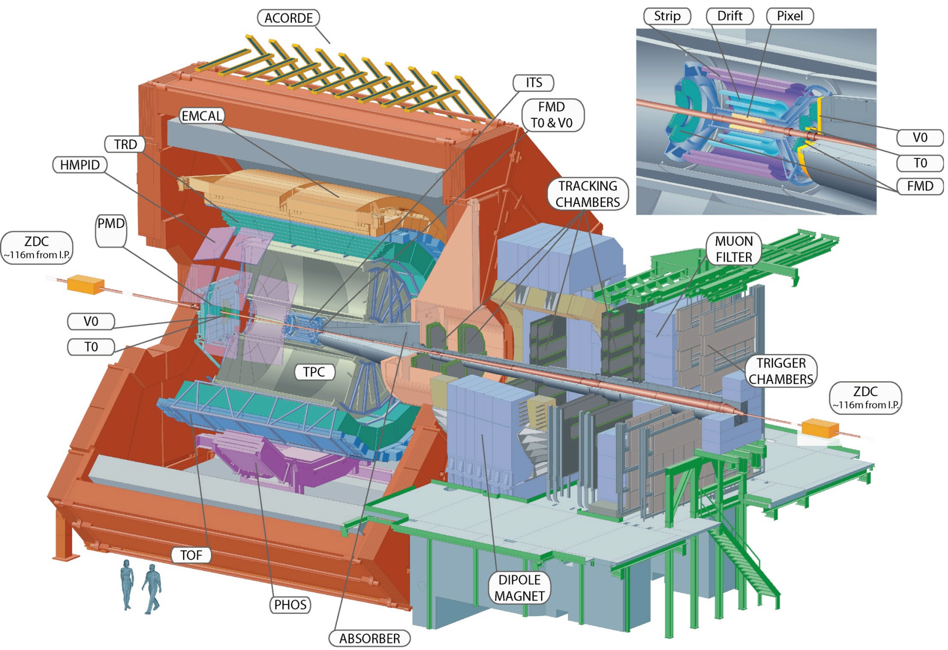
Distinguish the mechanisms of rho broadening



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

World-wide interest



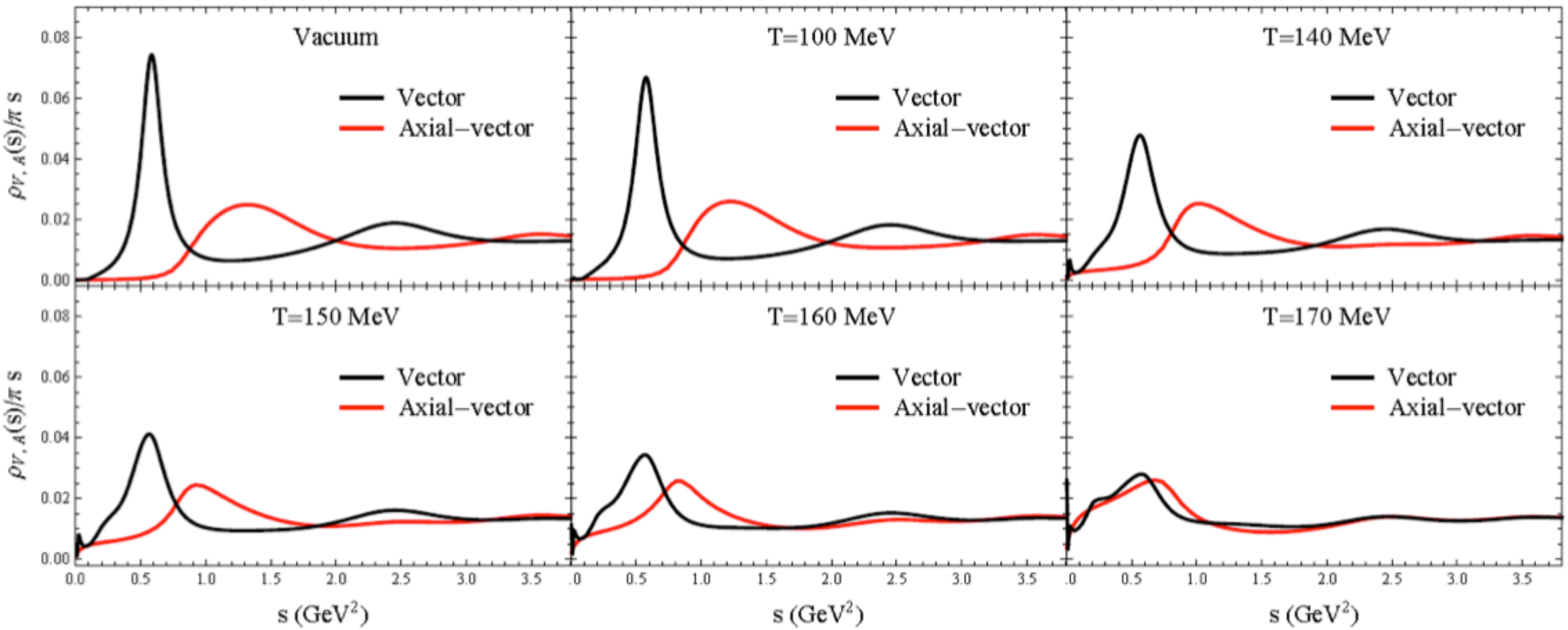
- World interest: SPS, PHENIX, LHC, HADES,FAIR, NICA, KEK

The future electron-positron program

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).



The future electron-positron program

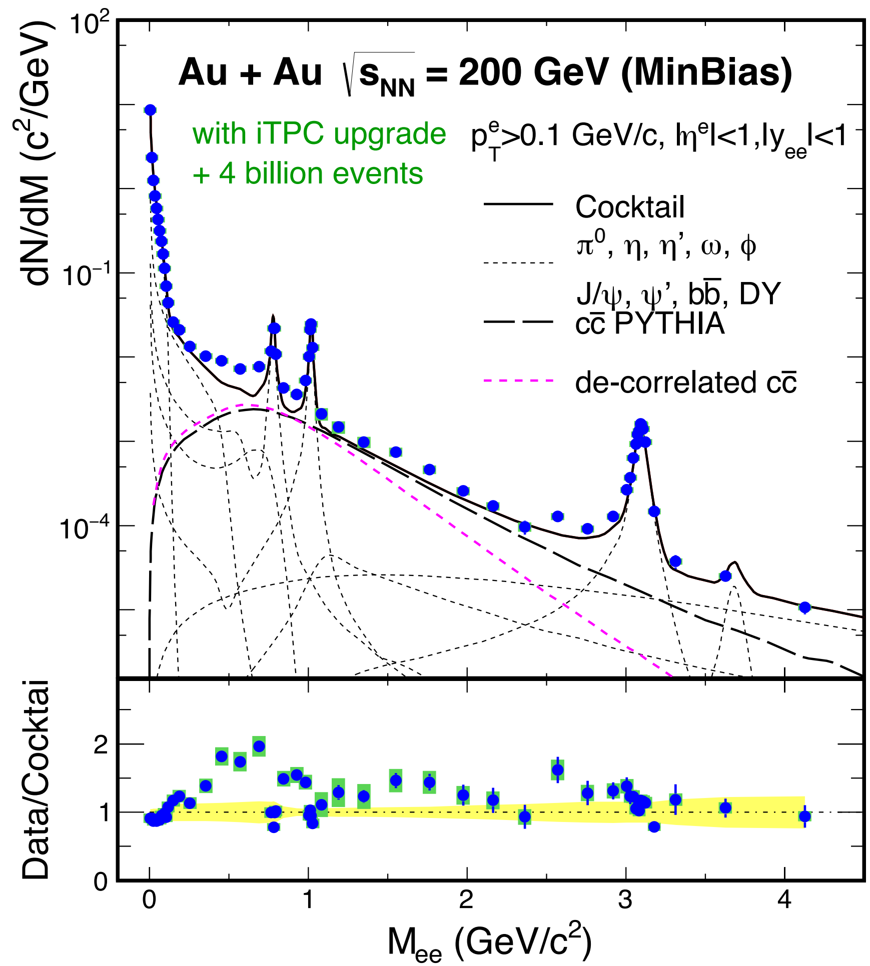
Beyond 2020+

Mid-rapidity: e^+e^- measurement at $\mu_B \sim 0$

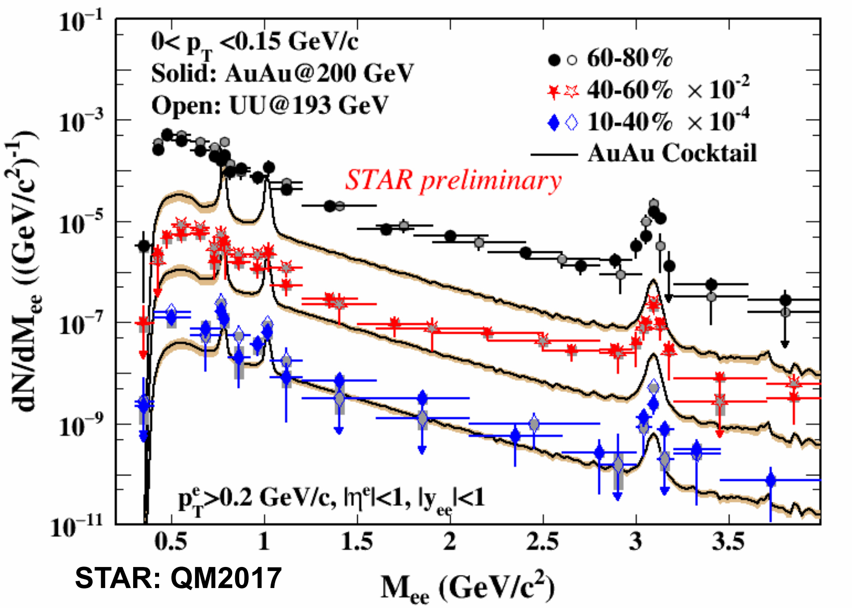
Connection to chiral symmetry restoration

Thermal radiation from QGP: The slope in the intermediate mass region represents the true average temperature T of the medium.

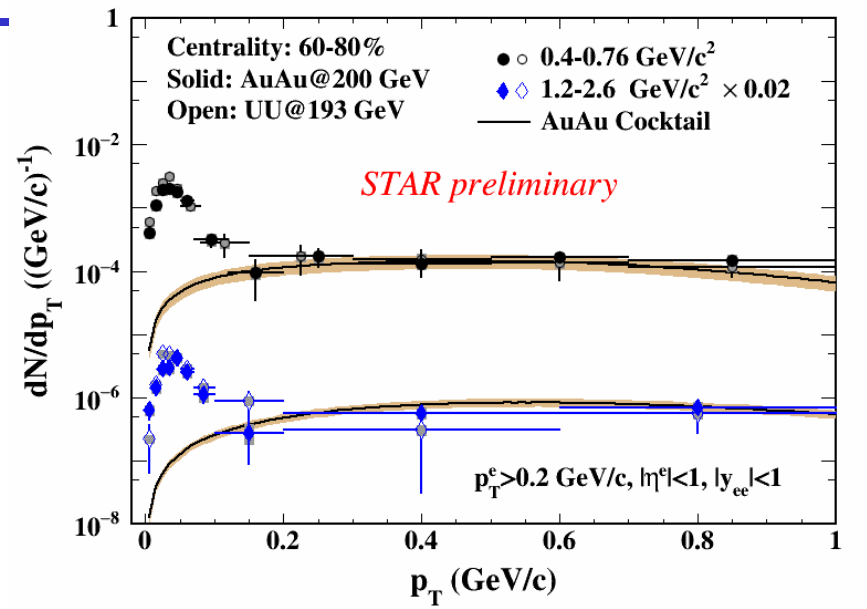
Low-mass electron-positron emission depends on T, total baryon density, and life time, and enables systematic life-time measurements.

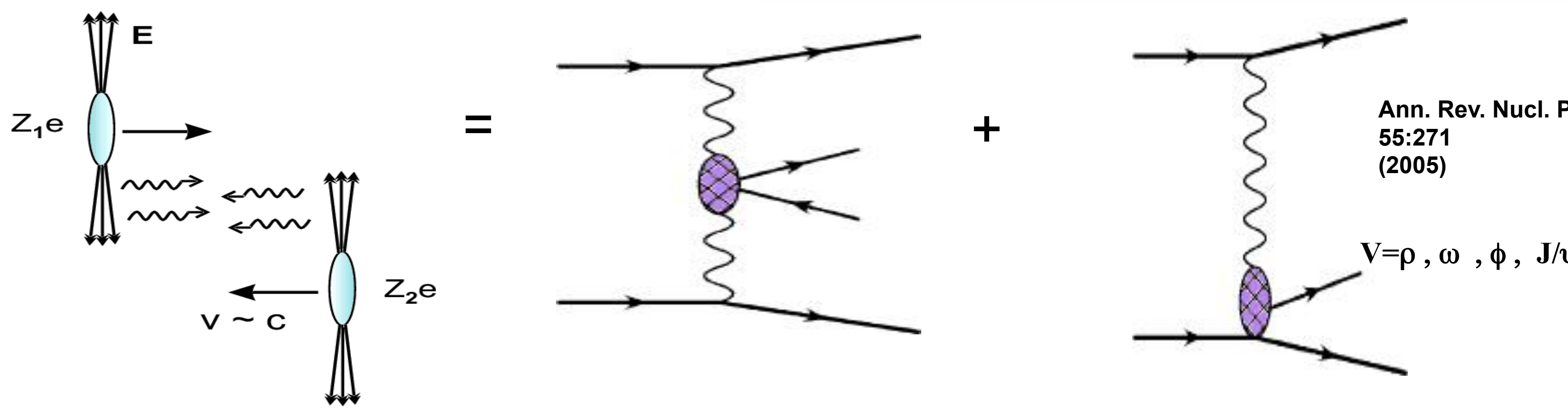


Very low p_T electron-positron



STAR: QM2017





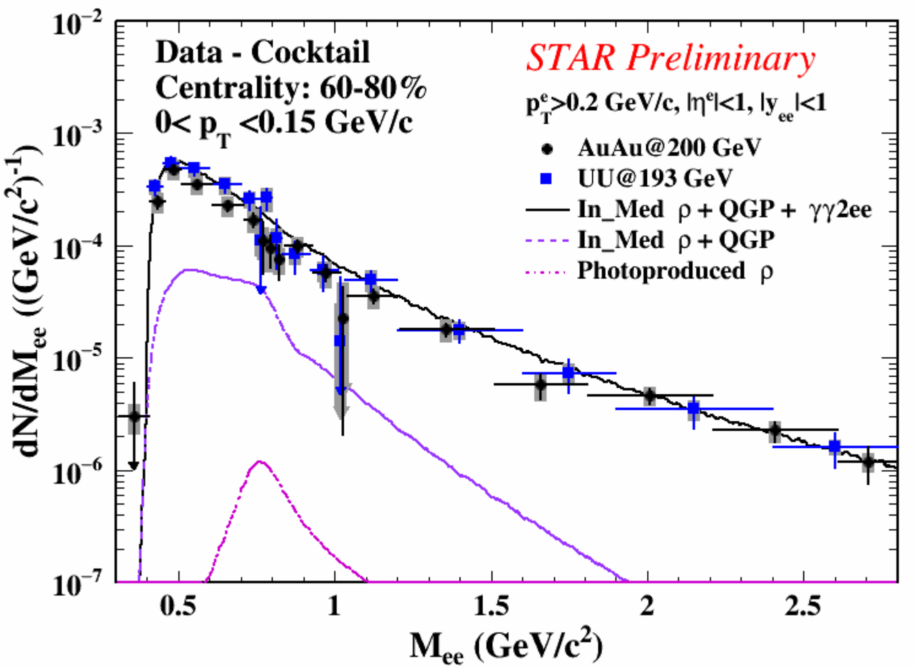
Ann. Rev. Nucl. Part. Sci. 55:271 (2005)

Two-photon

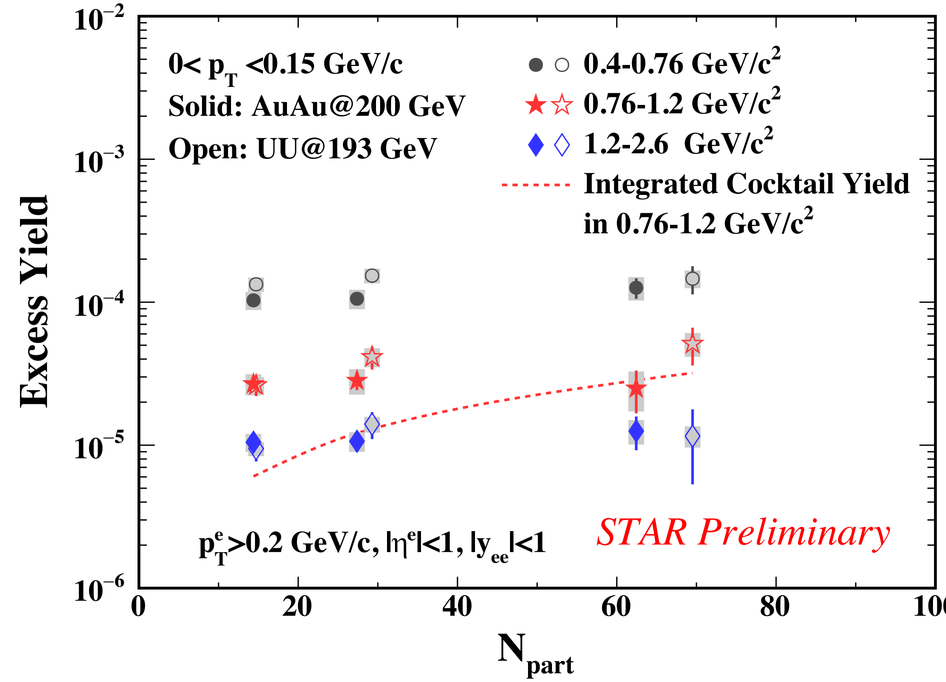
photonuclear

Coherent photonuclear and two-photon processes?

Very low p_T electron-positron



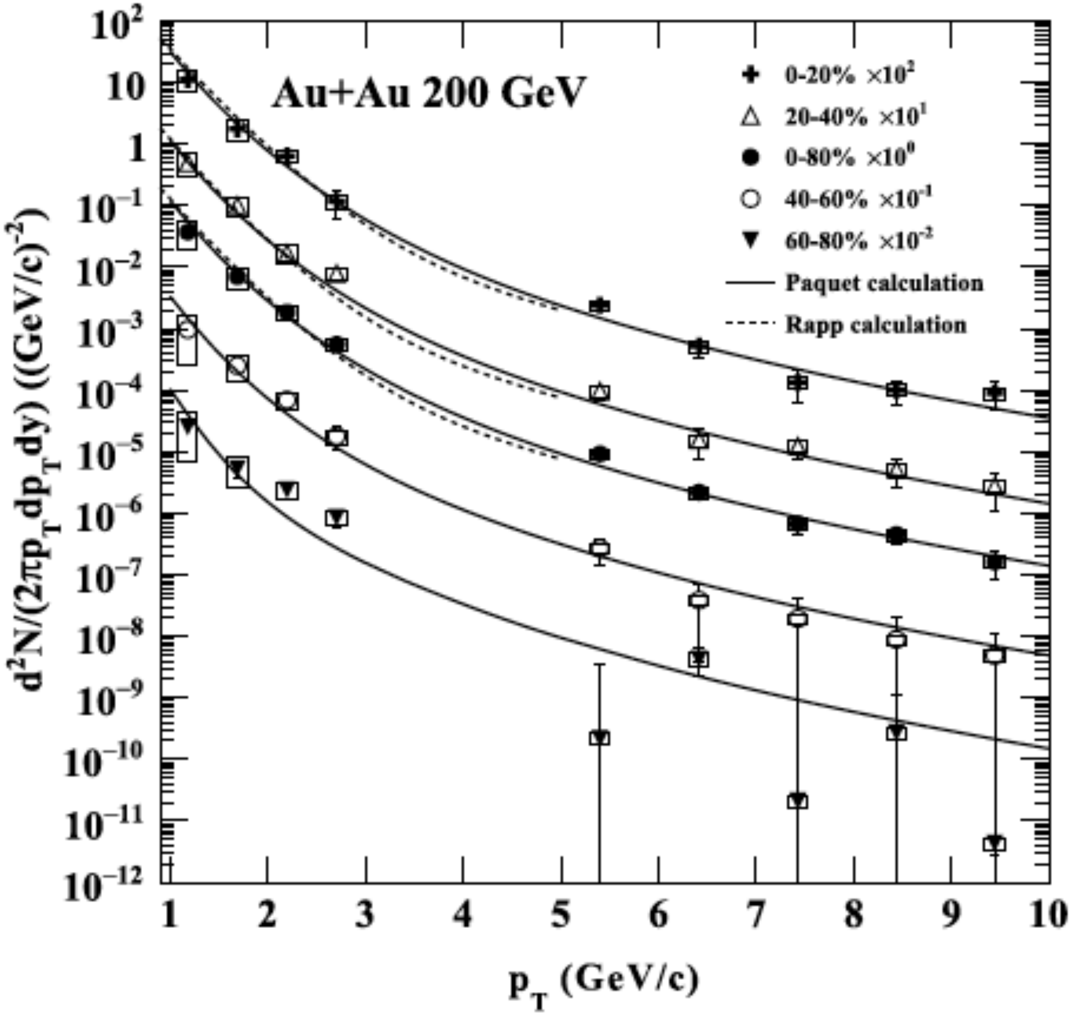
STAR: PANIC2017



The centrality dependence of excess yield: insignificant compared to those for hadronic processes

Call for a coherent theoretical calculation taking into account the photoproduction, cold and hot QCD medium effects, and their space-time evolutions!

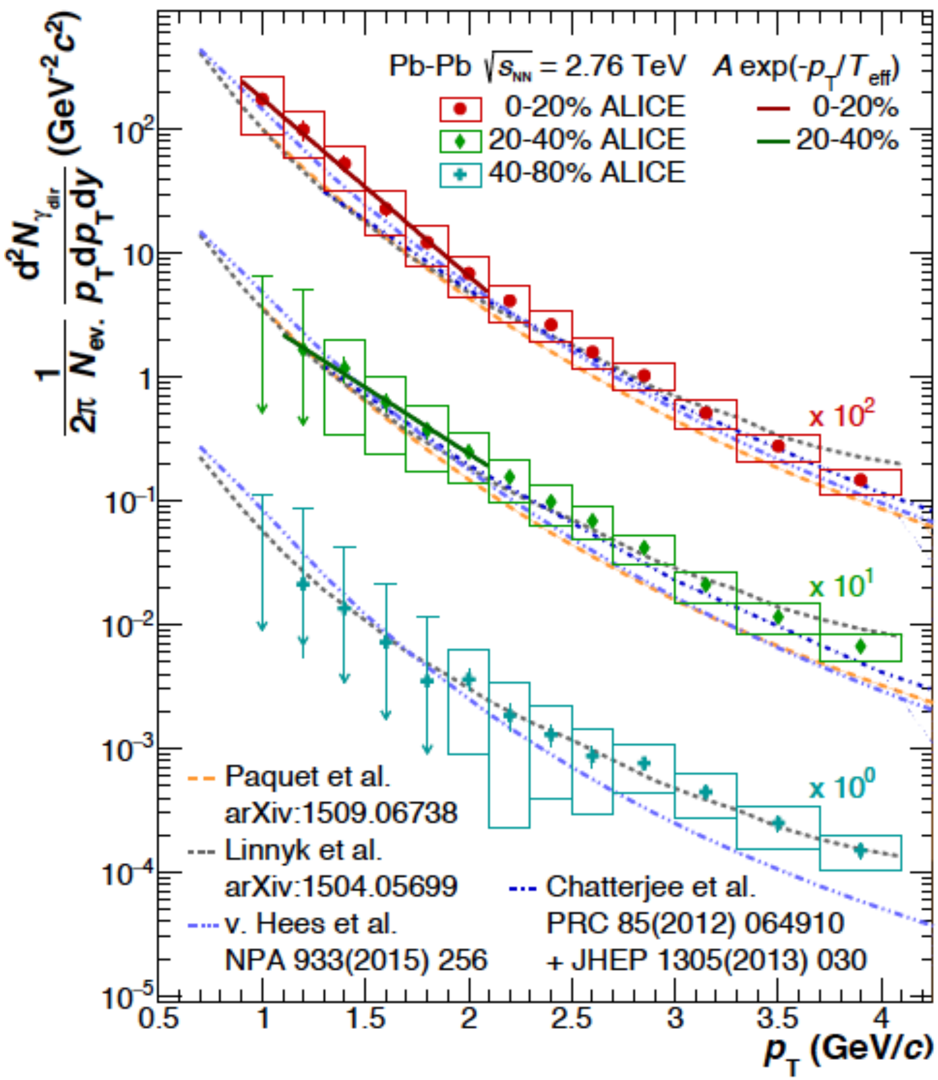
Direct virtual photon in Au+Au



STAR: PLB770(2017)451

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

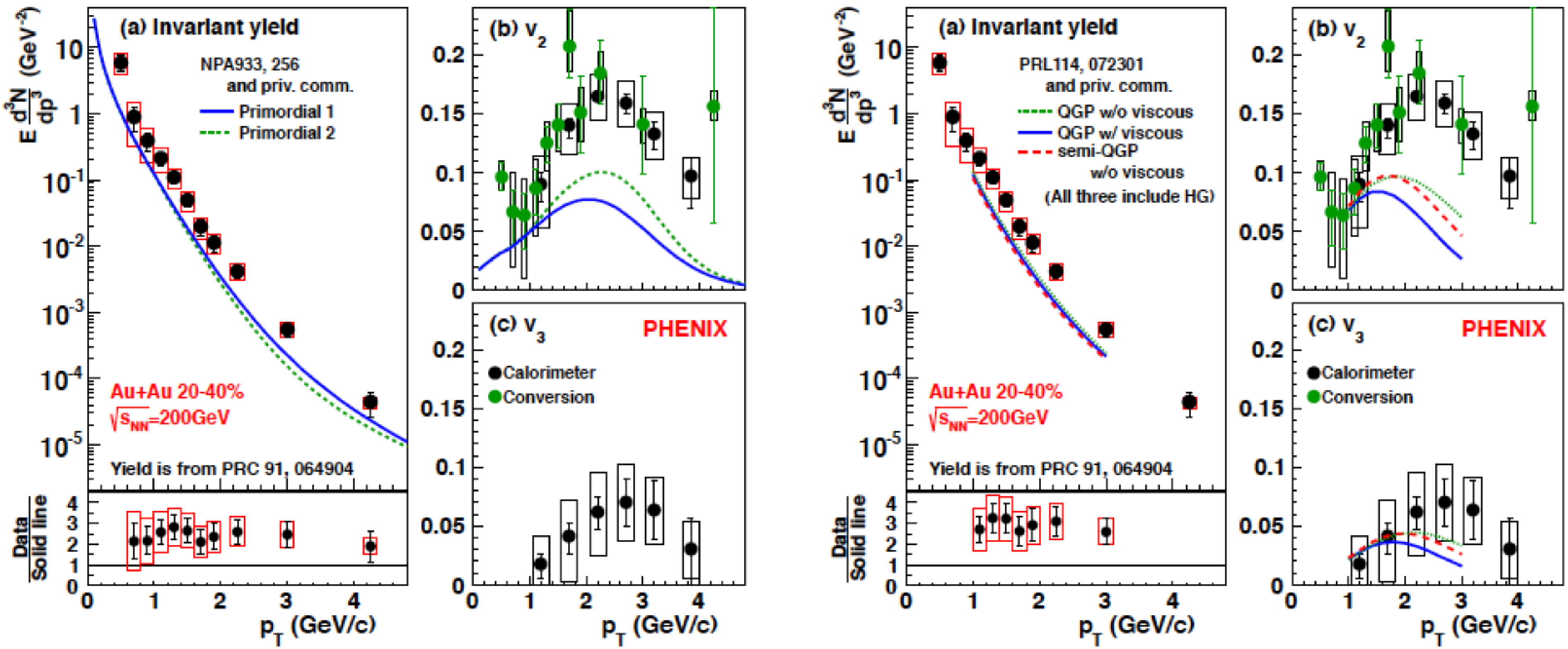
Direct photon in Pb+Pb



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

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

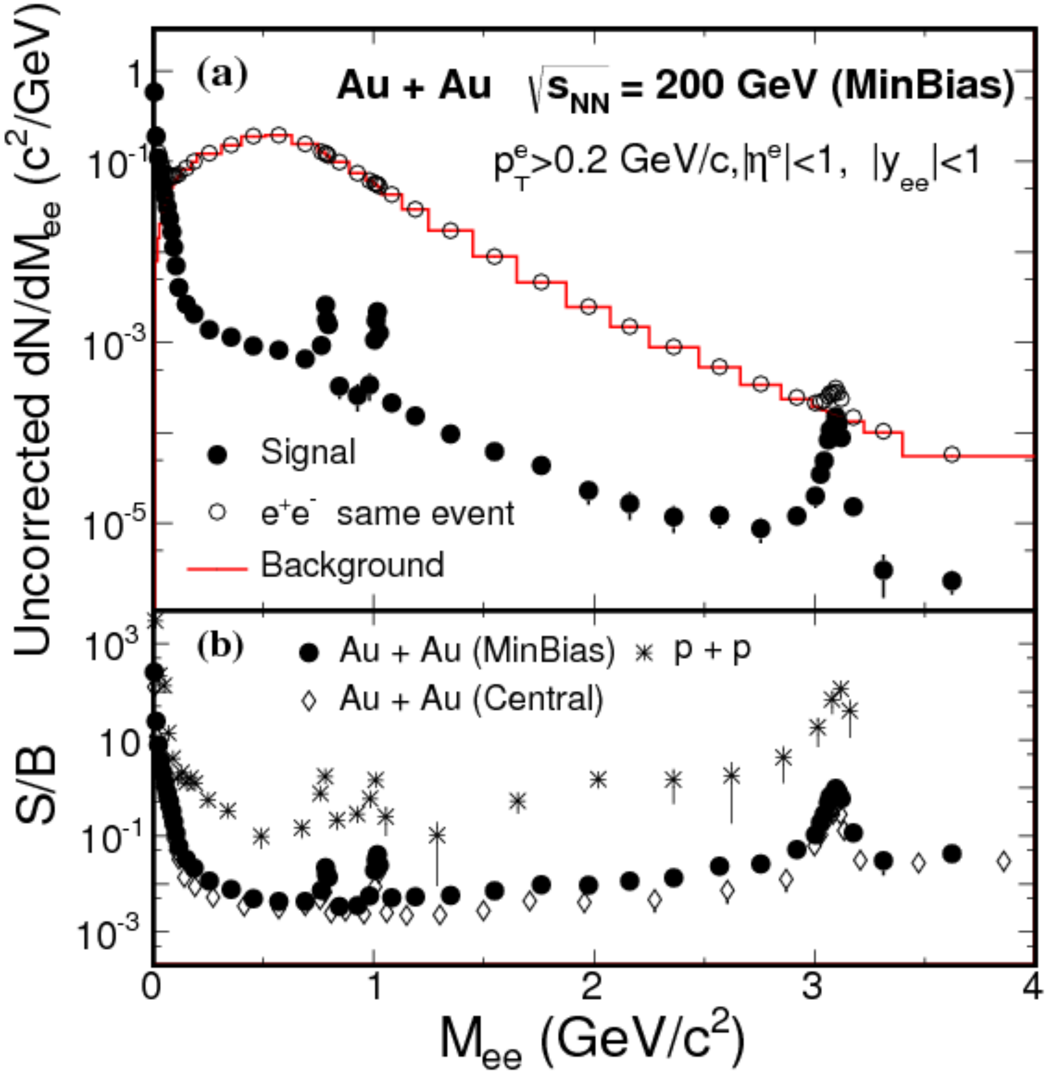
Beam Energy Scan II (7.7-19.6 GeV) will provide a unique opportunity to quantify the effect of Chiral Symmetry Restoration via total baryon density effect on the ρ broadening.

Enable unique measurements of the temperature and lifetime of hot, dense medium

Beyond 2020+, precise measurements at μ_B~0 are necessary for the community to establish connection between dilepton observables and chiral symmetry restoration.

Backup

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

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

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

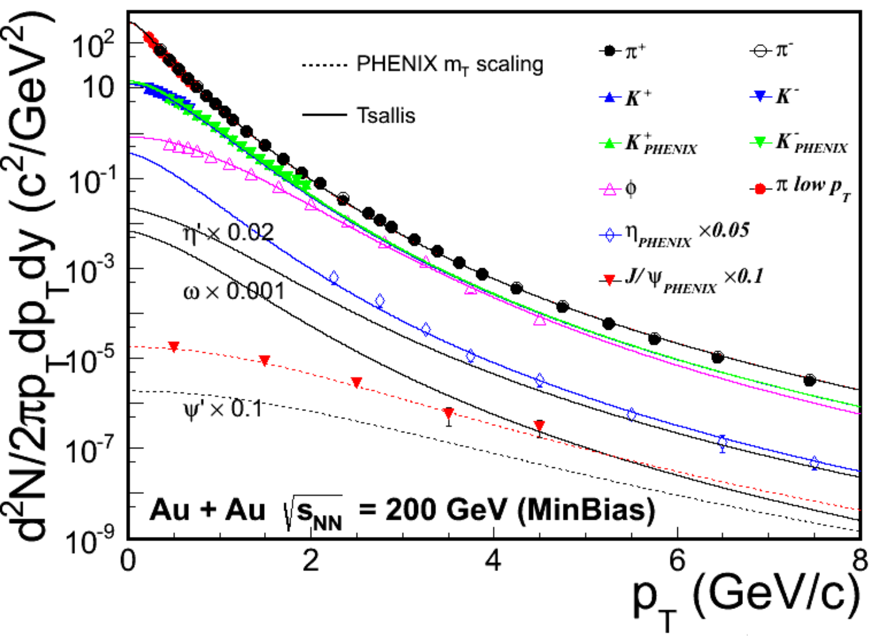
Drell-Yan contribution

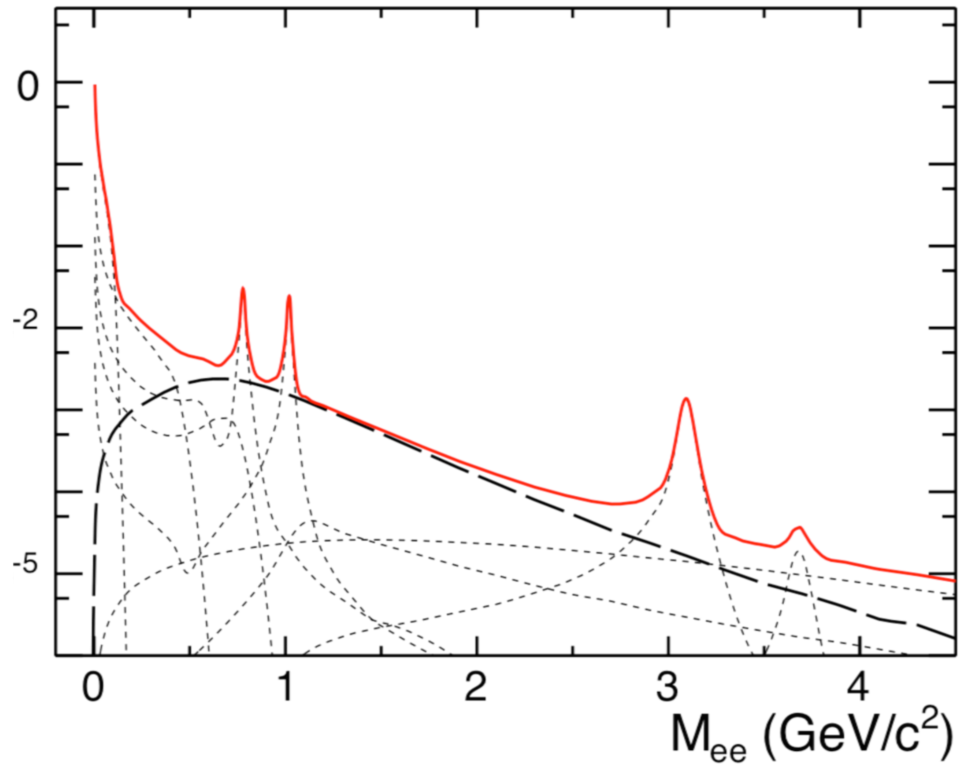
In Au+Au collisions, we search for

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



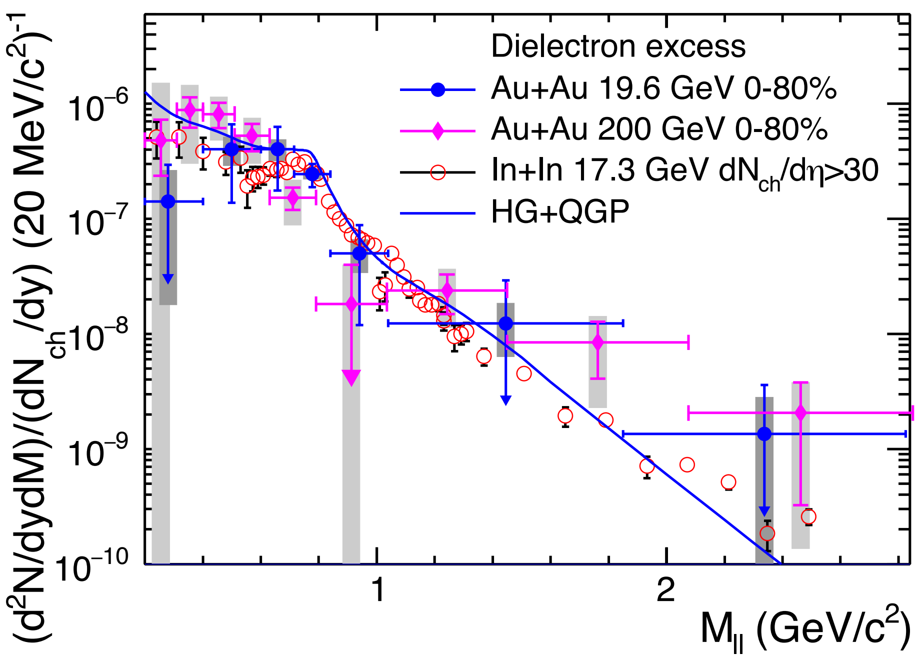


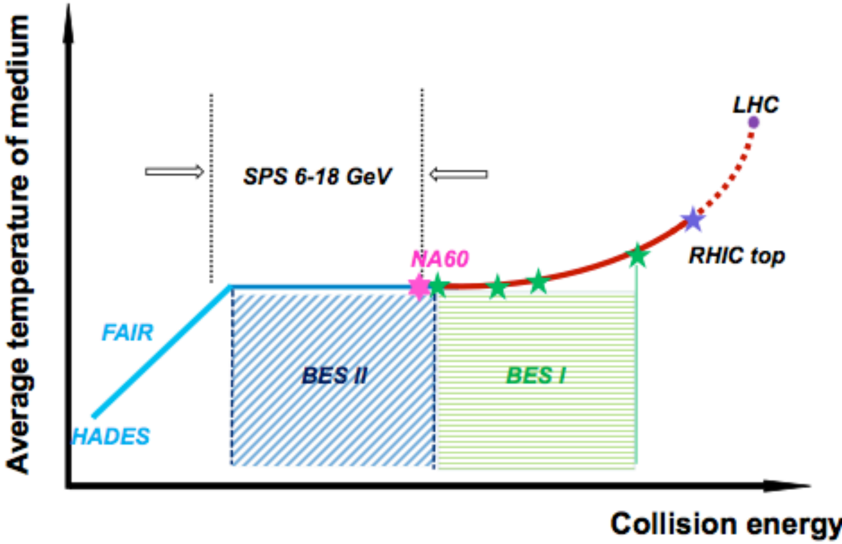
PHENIX Collaboration, Phys. Rev. C 81, 034911 (2010)
STAR Collaboration, Phys. Rev. Lett. 92, 112301 (2004)
STAR Collaboration, Phys. Lett. B 612, 181 (2005).
STAR Collaboration, Phys. Rev. Lett. 97, 152301 (2006)
Z. Tang et al. Phys. Rev. C 79, 051901 (2009)

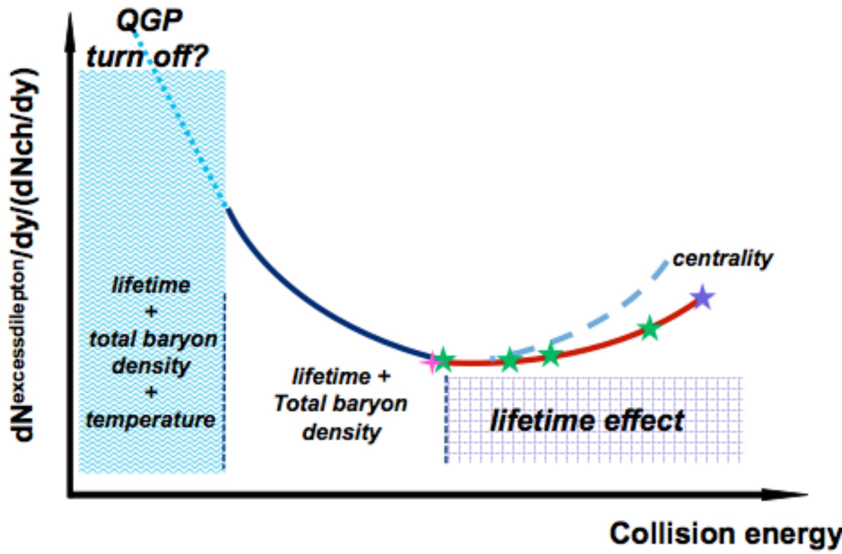
Electron-positron mass spectrum from known hadronic sources without hot, dense medium contribution.

The future electron-positron program

- **The slope in the intermediate mass region represents the true average temperature T of the medium.**

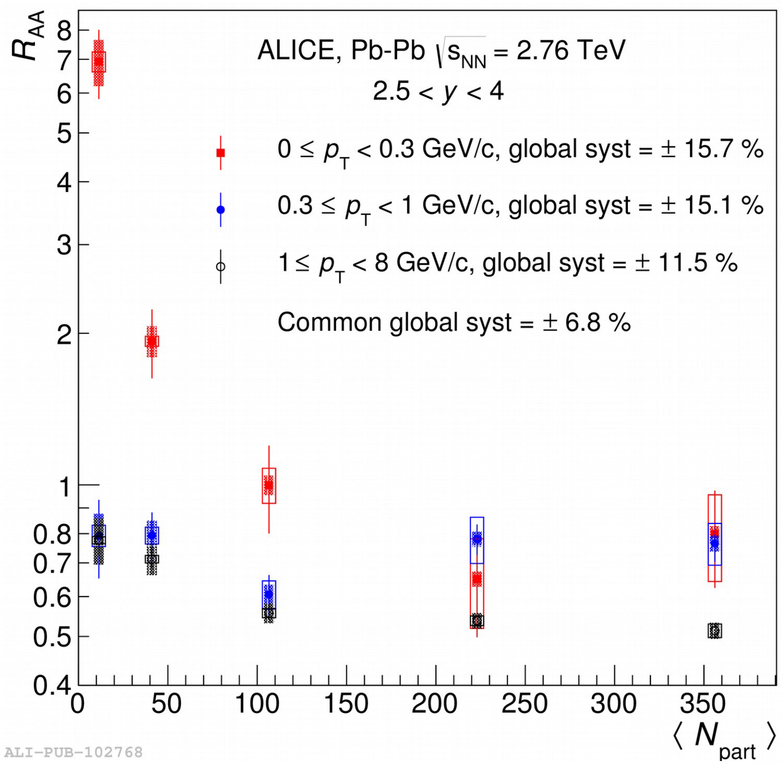


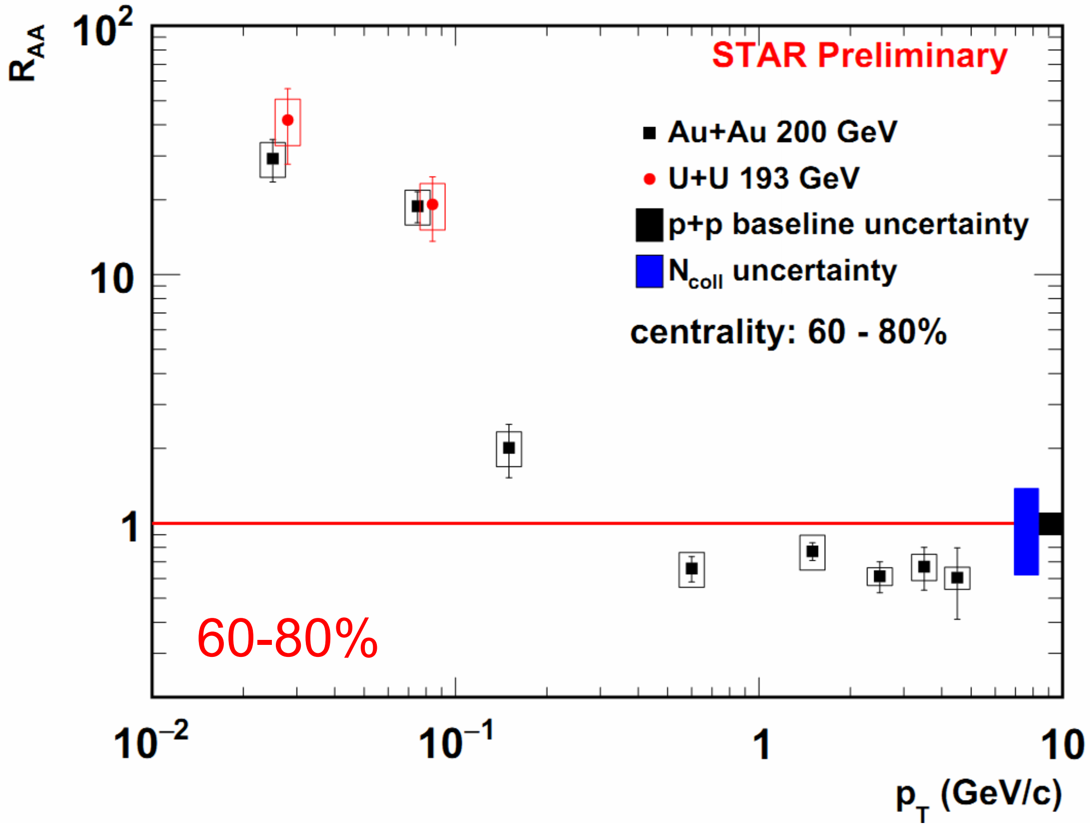




- **Low-mass electron-positron emission depends on T, total baryon density, and life time, and enables systematic life-time measurements.**

Very low pt J/ψ: largely enhanced!

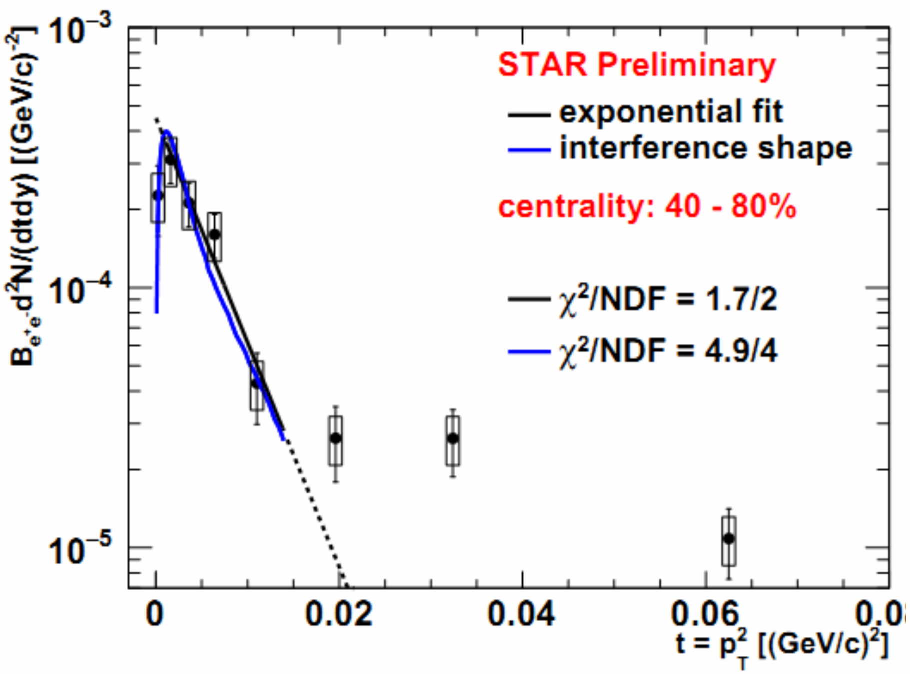


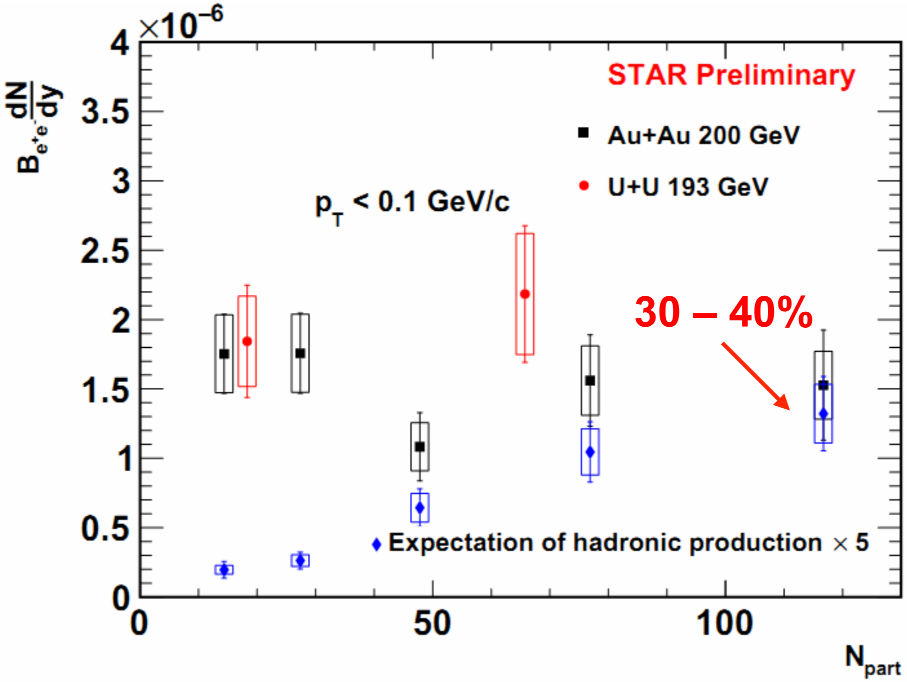


Large enhancement of J/ψ yield observed in peripheral A+A collisions!

Prominent centrality and p_T dependence.

J/ψ yield :$t=p_T^2$ and centrality dependence





Slope parameter consistent with the size of the Au nucleus. Interference structure observed. Coherent photon-nucleus interactions?

No significant centrality dependence of the excess yield! Interplay between photon flux cancellation in the overlapped area and the distance of the spectators of the two nuclei?

Simulations ongoing and need theoretical inputs!