Extracting temperature with di-leptons and quarkonia

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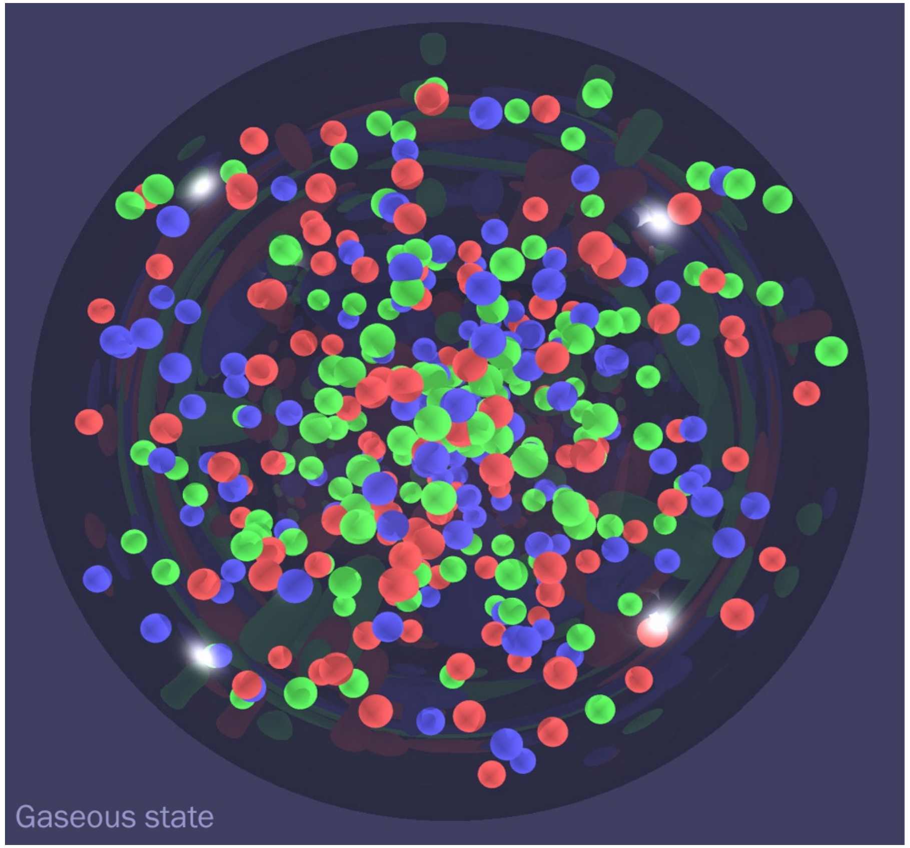
@BrookhavenLab

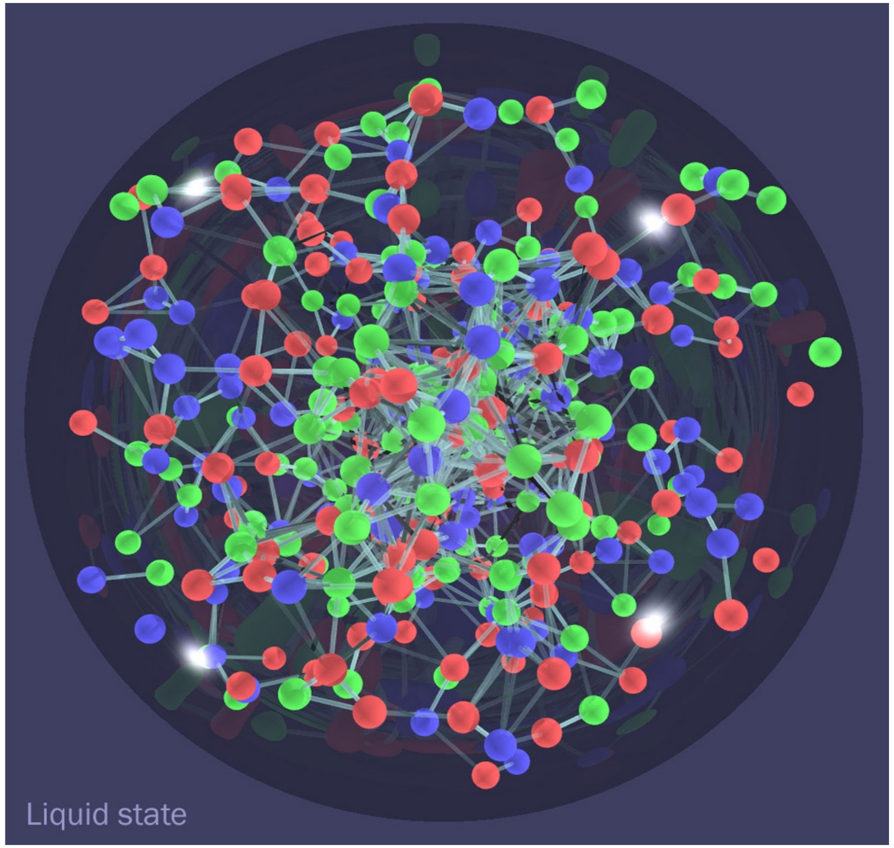
2024 ALICE-USA Open Day at Yale, New Haven, Connecticut

RHIC @ Brookhaven National Laboratory

24 years of RHIC operation

Perfect Liquid discovery



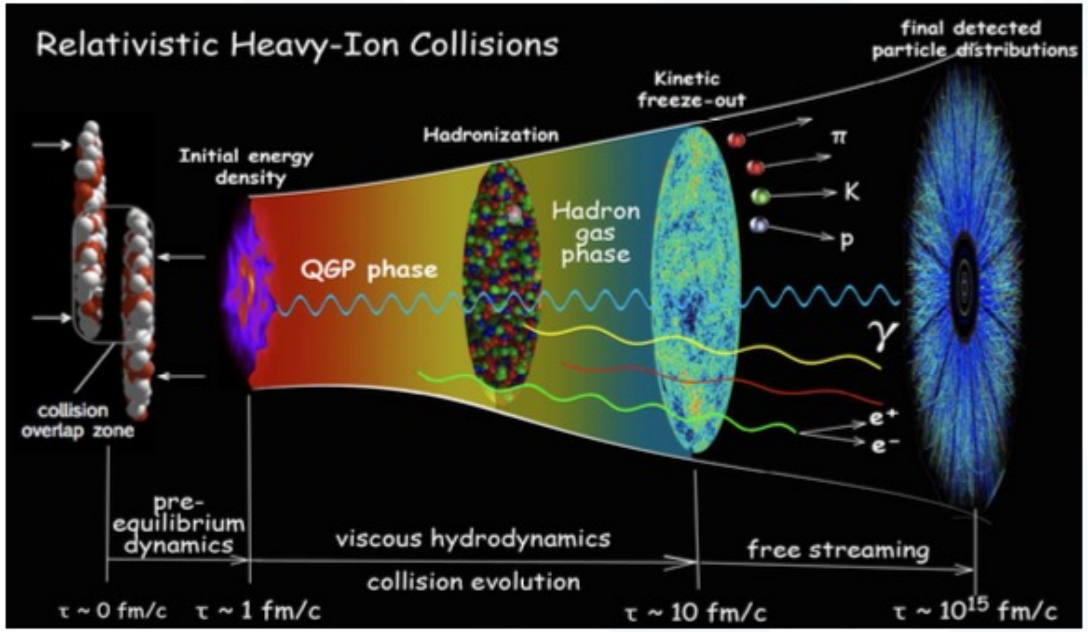


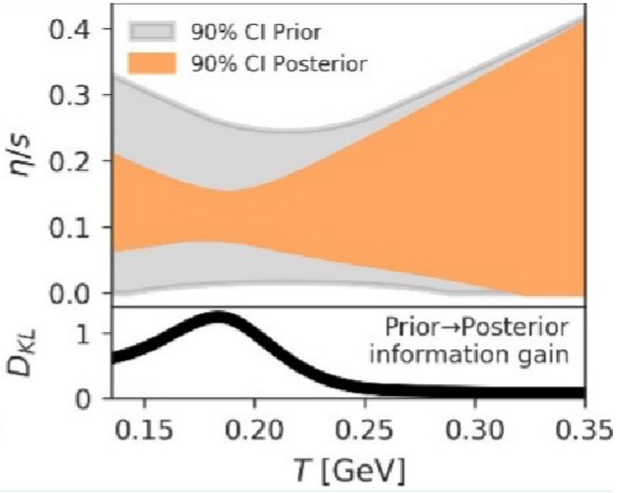
In 2005, BNL announced a discovery of perfect liquid at RHIC

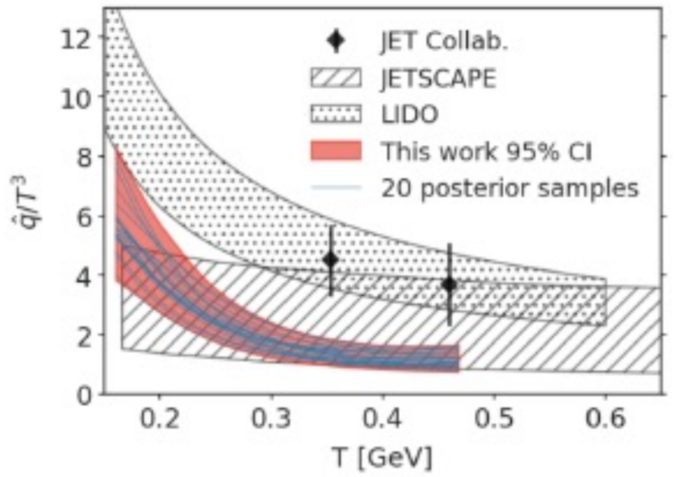
https://www.bnl.gov/newsroom/news.php?a=110303

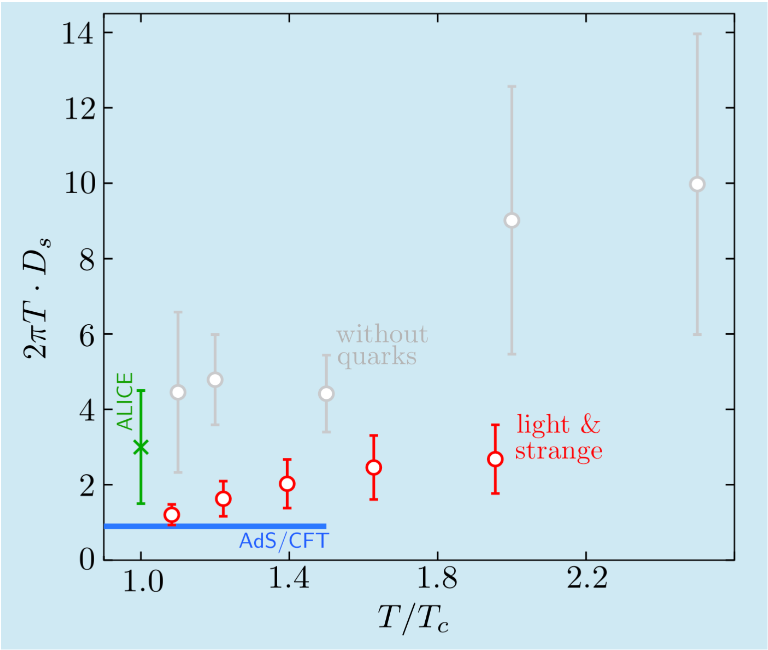
The properties of perfect liquid

The 2023 NSAC Long Range Plan for Nuclear Science









Essential questions to be addressed:

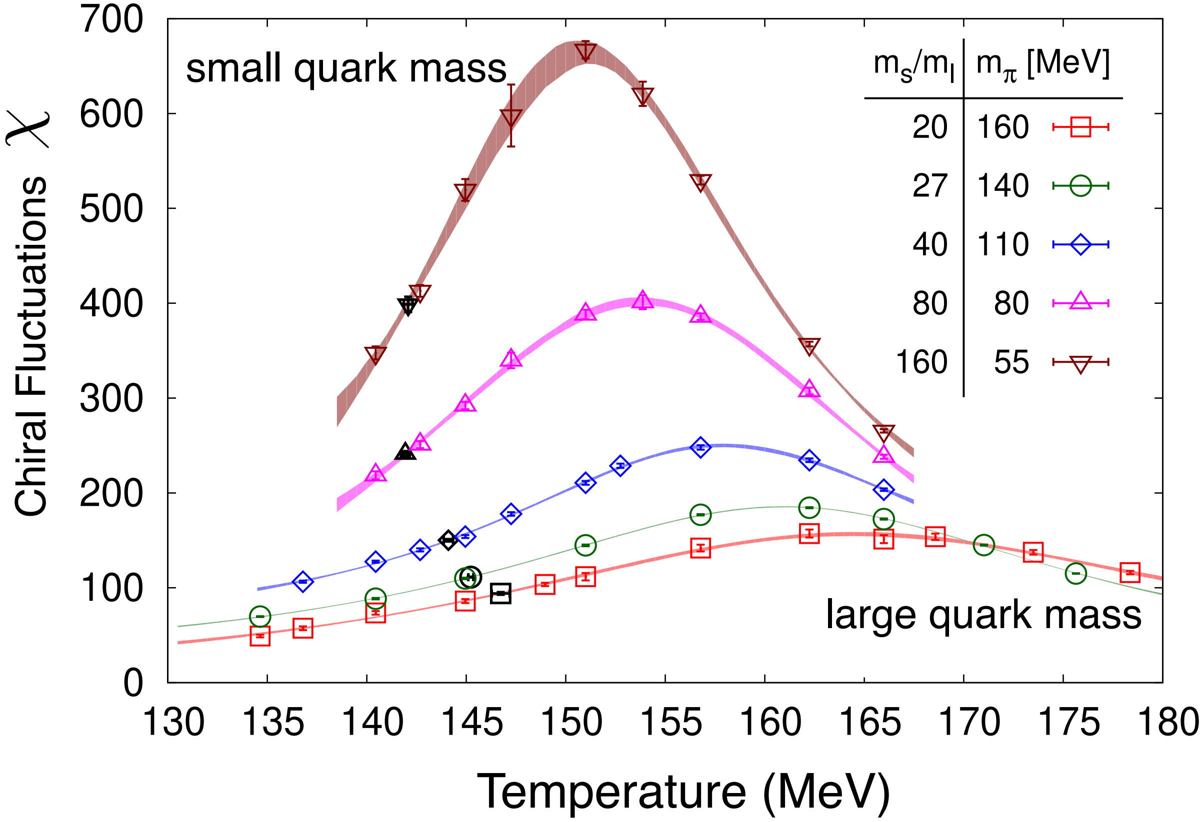
1. How do the fundamental interactions between quarks and gluons lead to the perfect fluid behavior of the quark-gluon plasma?
2. What are the limits on the fluid behavior of matter?
3. What are the properties of QCD matter?
4. What is the correct phase diagram of nuclear matter?

Chiral symmetry restoration in Lattice QCD

Lattice QCD: Chiral cross over transition temperature Tc($\mu_{B=0}$) = **158.0 ± 0.6 MeV**

Chiral symmetry restoration: chiral partners become degenerate, e.g. rho and a1.

Chiral condensate susceptibility vs. Temperature



Hot QCD Collaboration, PRL 123 (2019) 062002

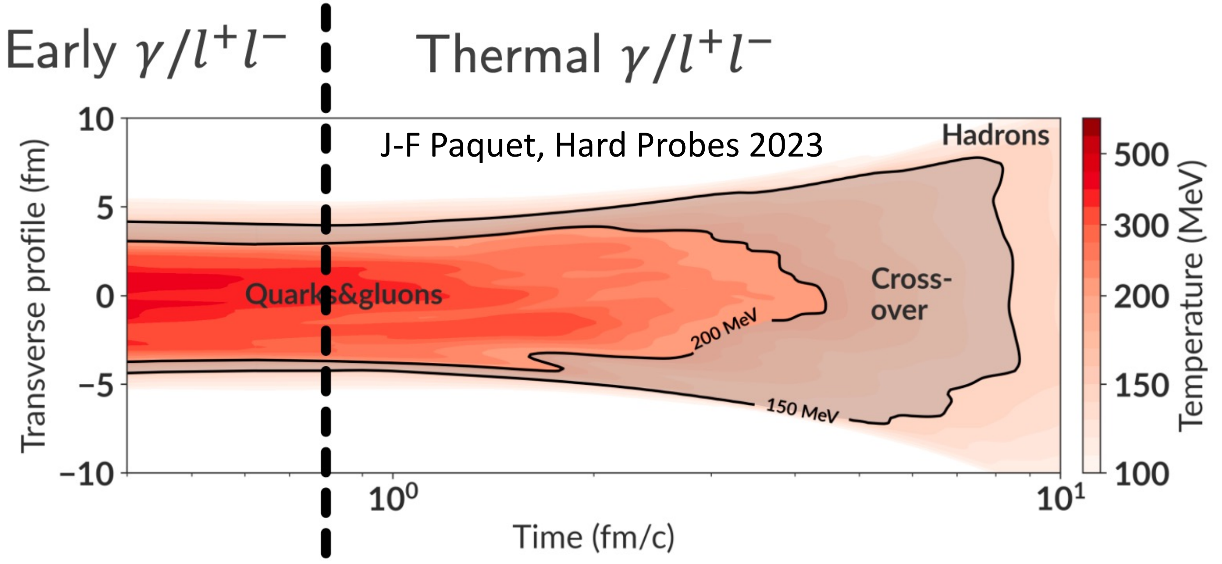
Hot QCD Collaboration, PLB 795 (2019) 15-21

Dileptons

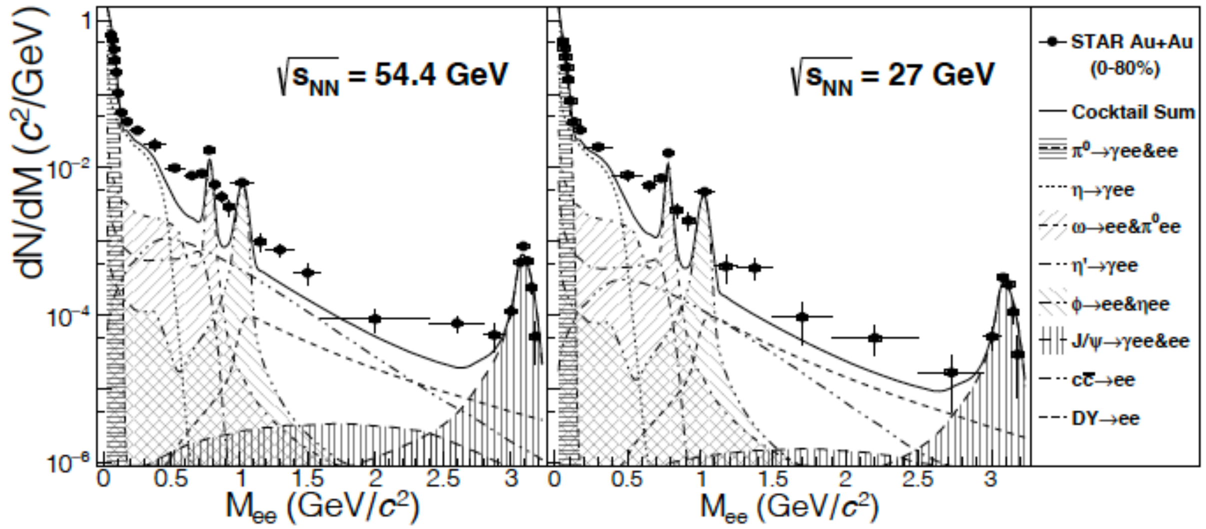
Utilizing penetrating probes, sensitive to the local properties of the emission source, we study

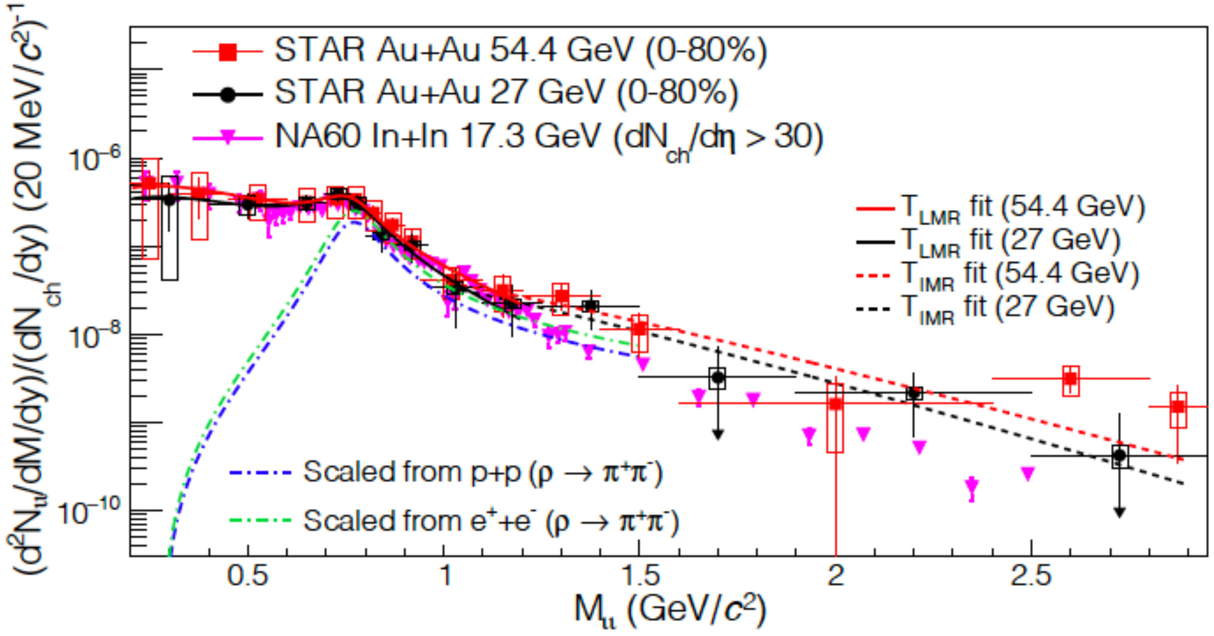
- The phase diagram of QCD
- The plasma temperature and its time evolution
- Medium properties such as shear and bulk viscosity
- Pre-equilibrium dynamics
- Chiral symmetry restoration

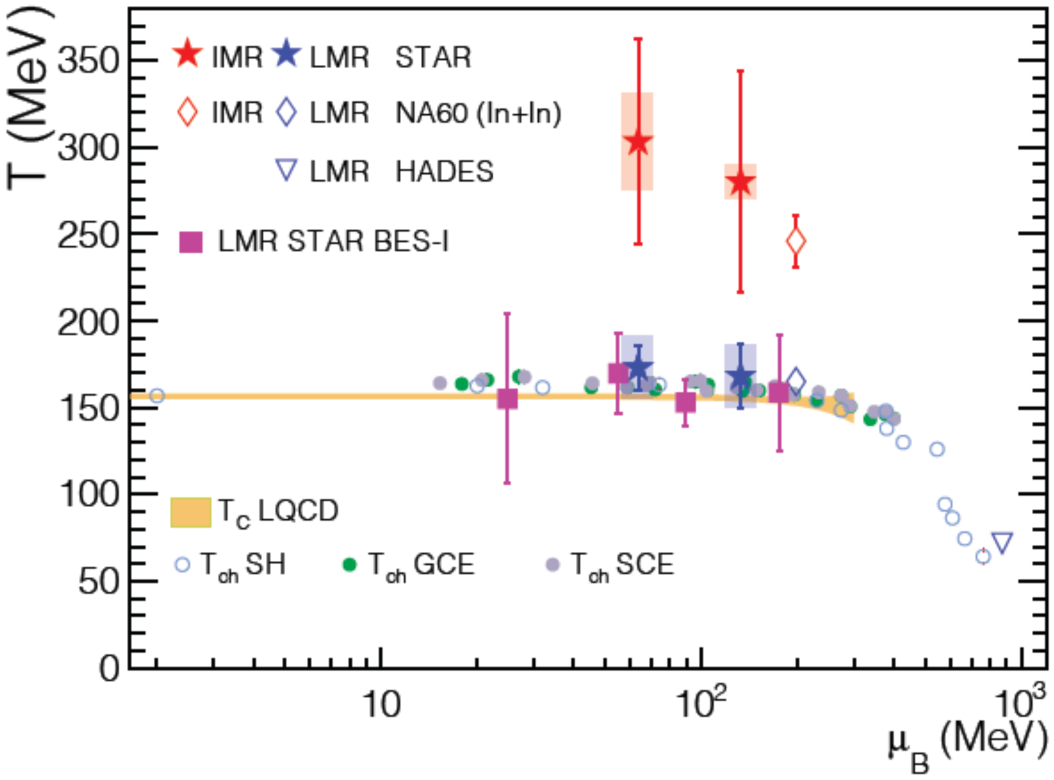
Experimentally very challenging due to enormous backgrounds



Dileptons in 27 and 54 GeV Au+Au collisions







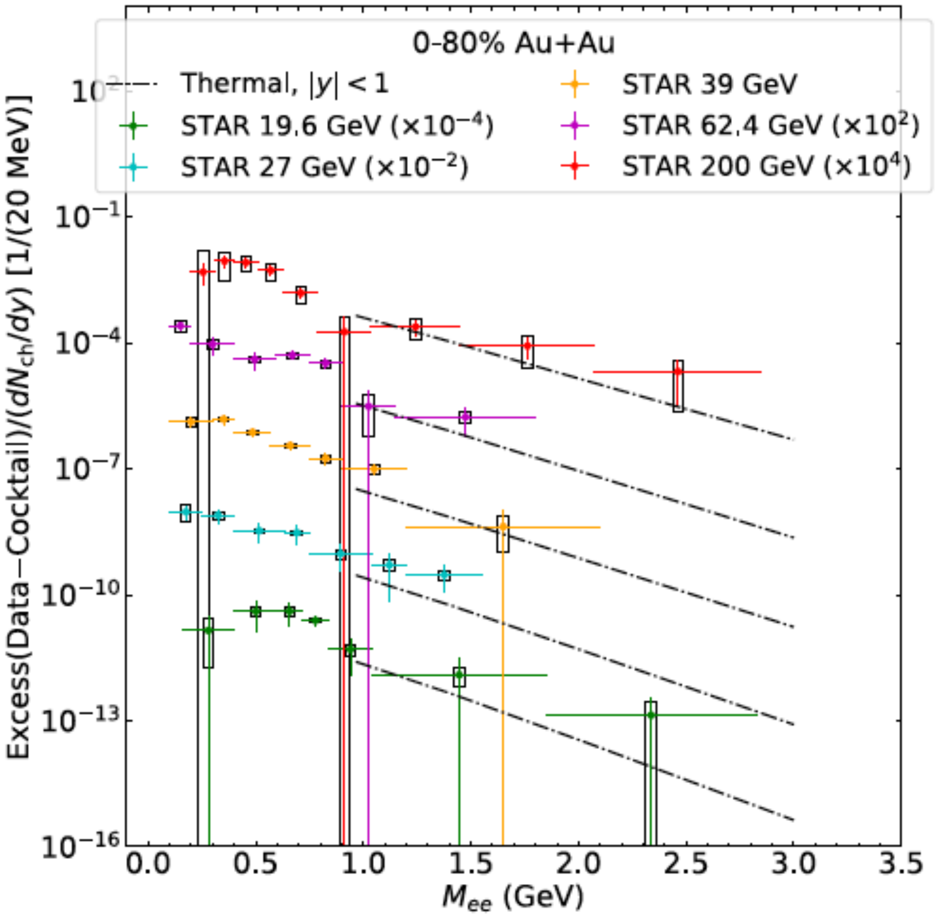
Low mass: emission temperature close to T_c , in-medium rho broadened, manifestation of chiral symmetry restoration

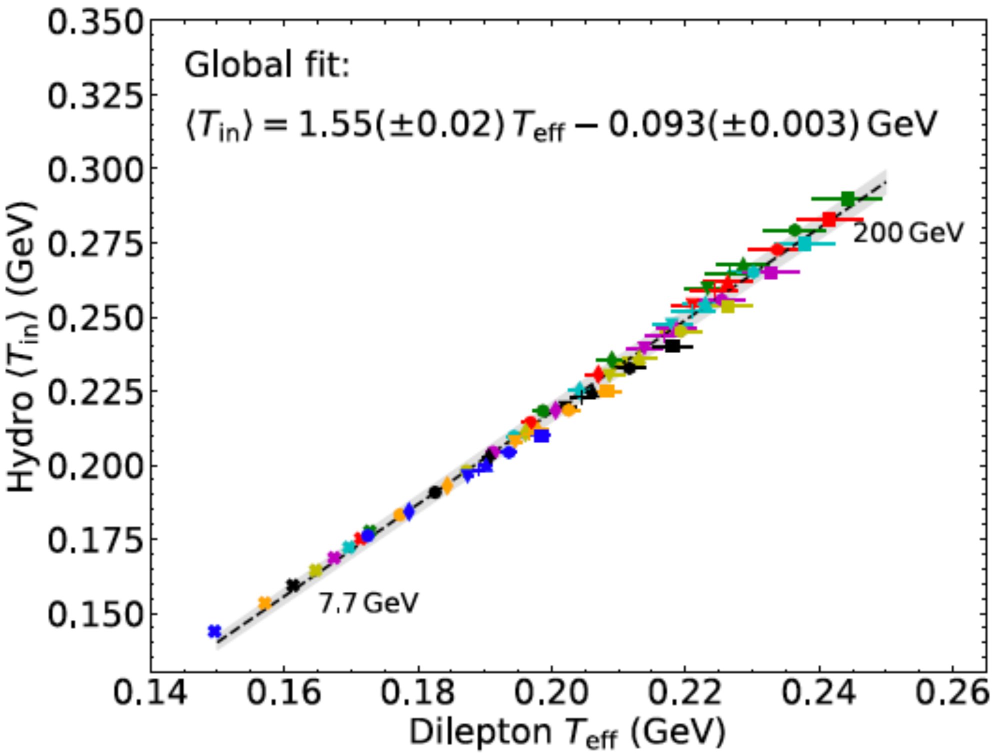
Intermediate mass: average emission temperature > T_c

arXiv: 2402.01998, submitted to Nature

Dileptons as thermometer

Lipei Du, CPOD 2024

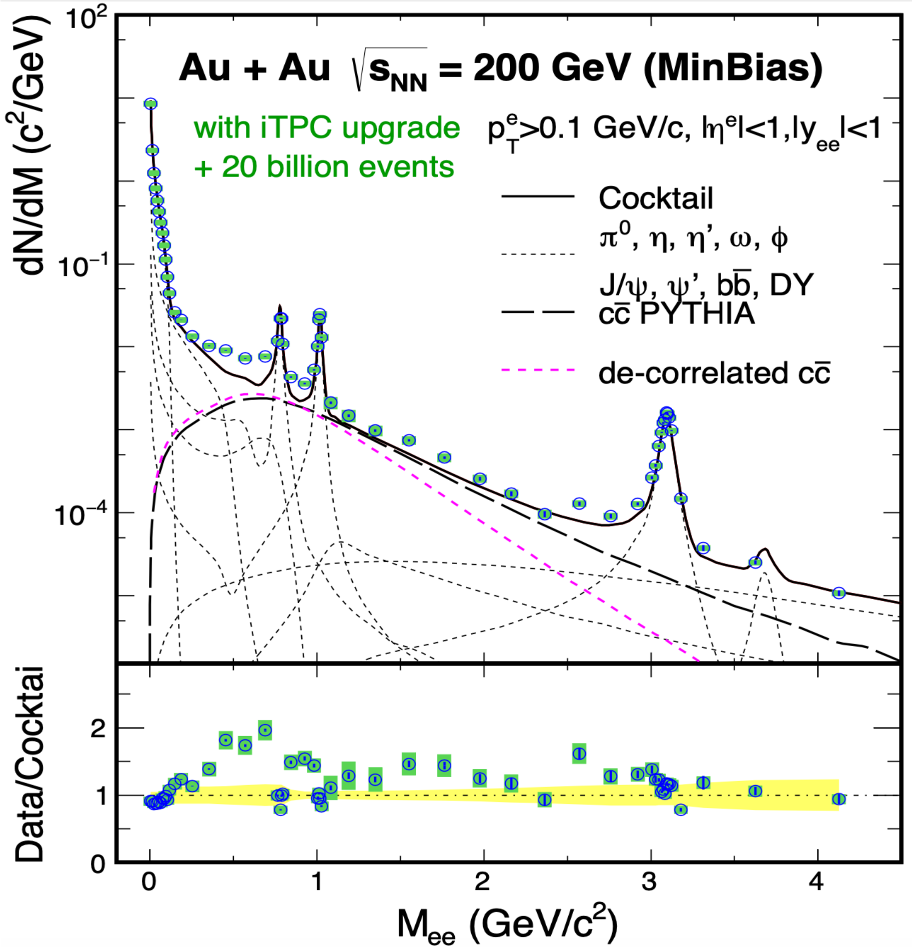




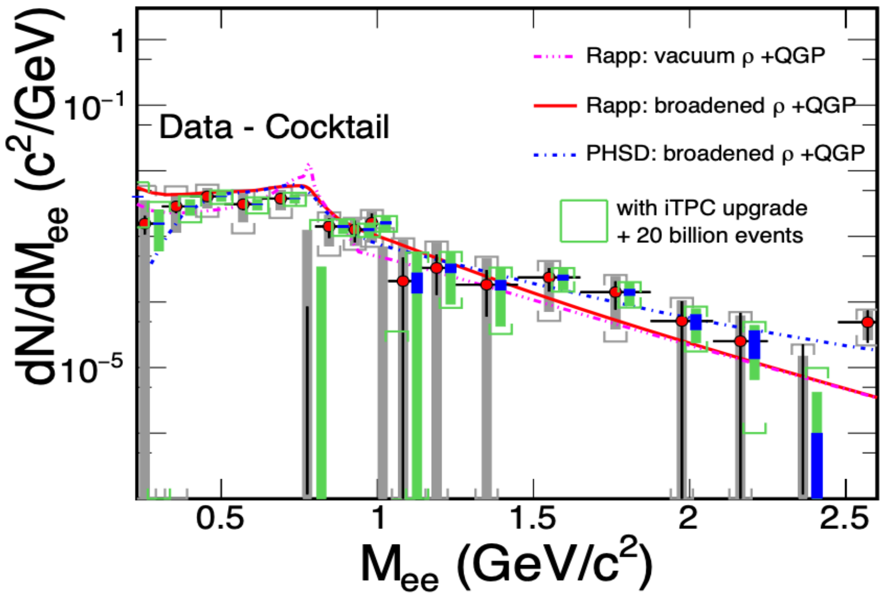
First estimate of NLO dilepton emission at nonzero μ_B with hydrodynamics: agree with data

Strong correlation between initial hydro temperature and average emission temperature derived from dileptons in the intermediate mass region

Towards the future: STAR



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

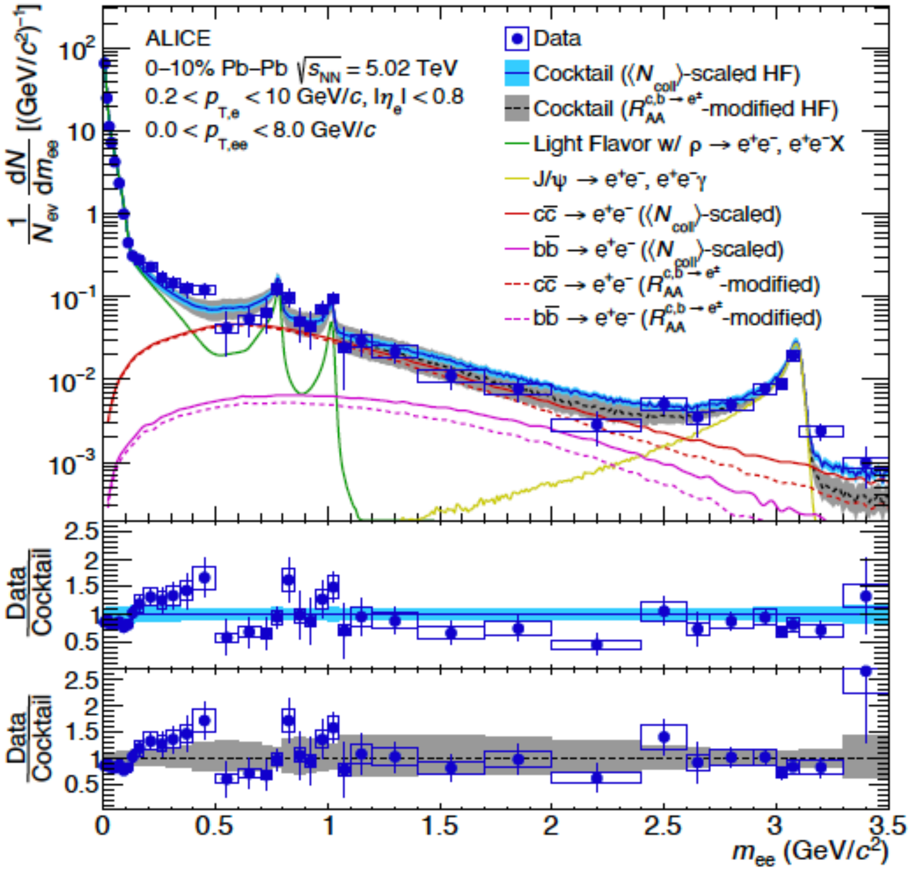


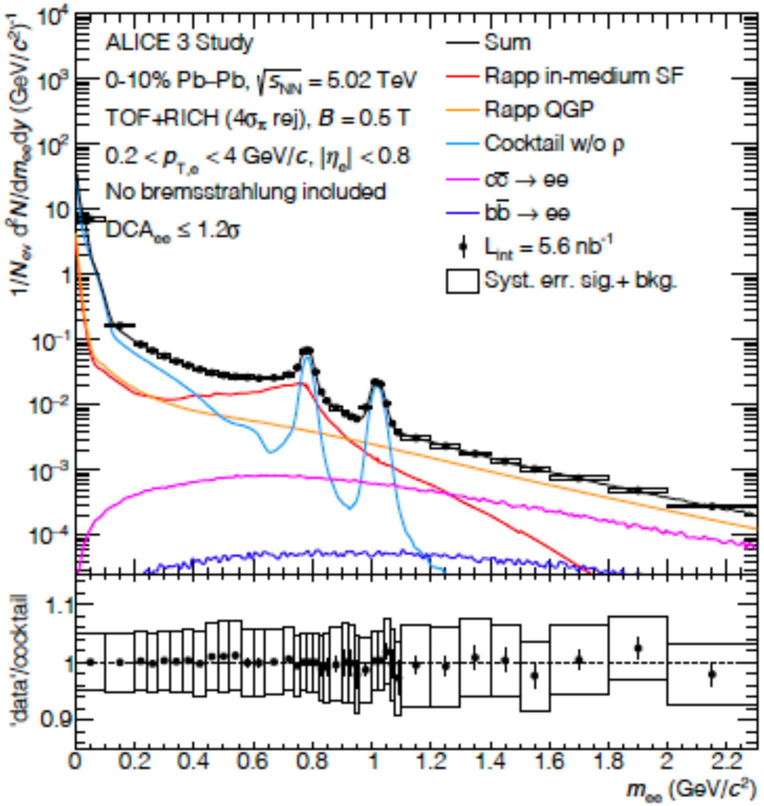
Low-mass dielectron measurement: lifetime indicator and provide a stringent constraint for theorists to establish chiral symmetry restoration at μ_B=0

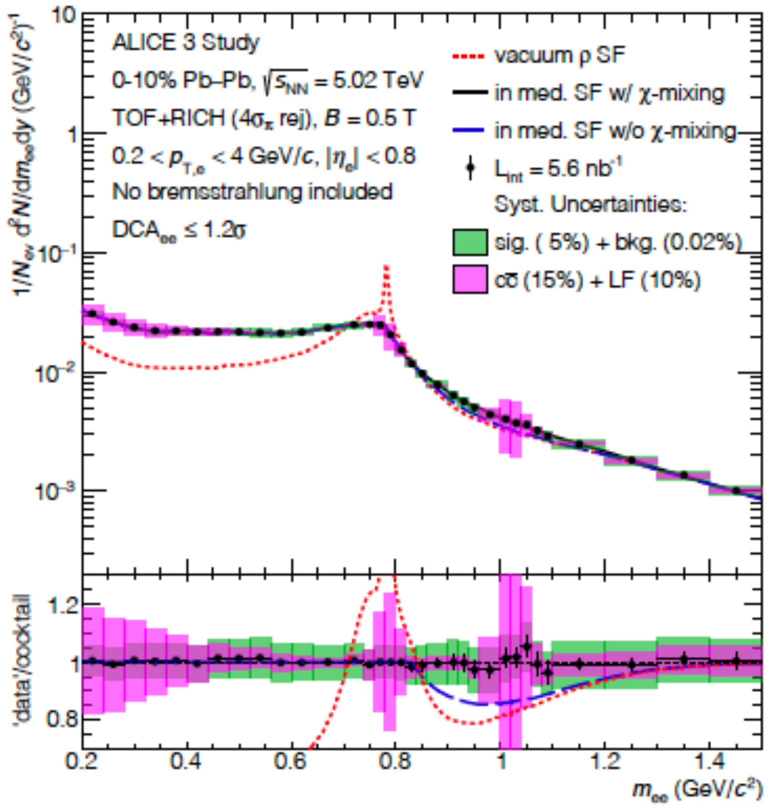
Intermediate mass: direct thermometer to measure temperature

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

Towards the future: ALICE3



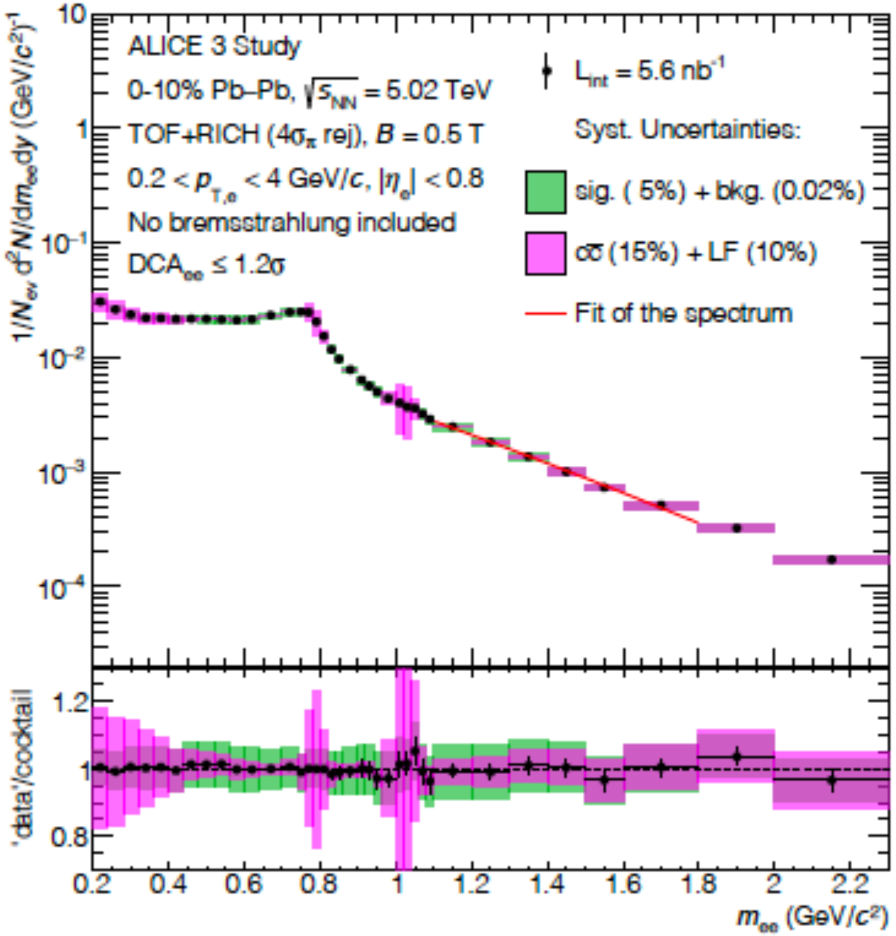


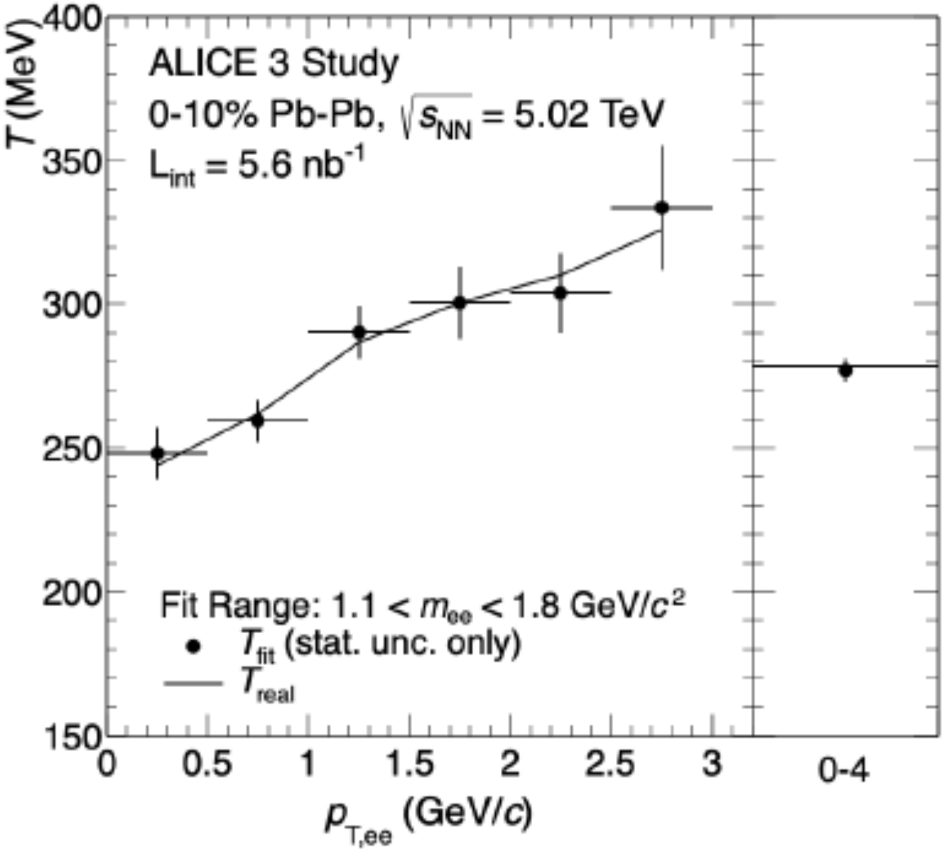


Existing measurements

ALICE3 projection: in medium rho-broadening and rho-a1 mixing to probe chiral symmetry restoration

Towards the future: ALICE3



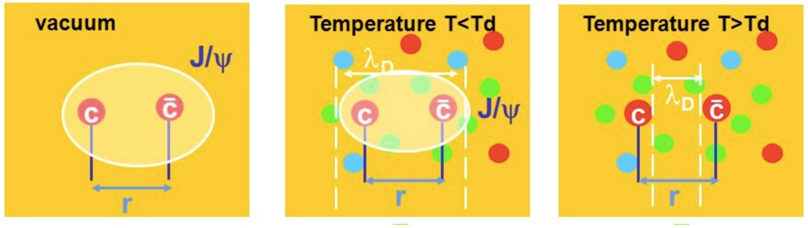


Precisely constrain temperature evolution

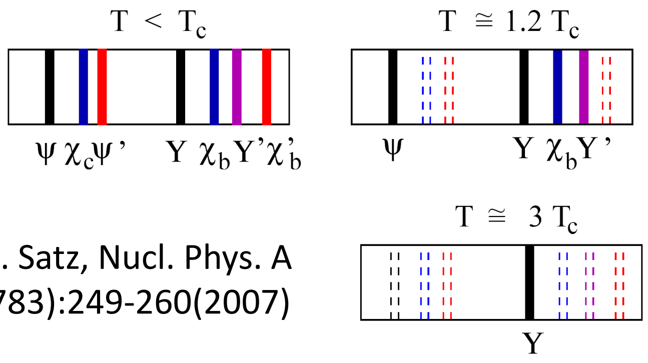
Other measurements: elliptic flow as a function of M_{ee} and p_T , polarization

Quarkonia as thermometer?

Color screening



$r_{q\bar{q}} \sim 1/E_{binding}$ vs. $\lambda_D \sim 1/T$



H. Satz, Nucl. Phys. A (783):249-260(2007)

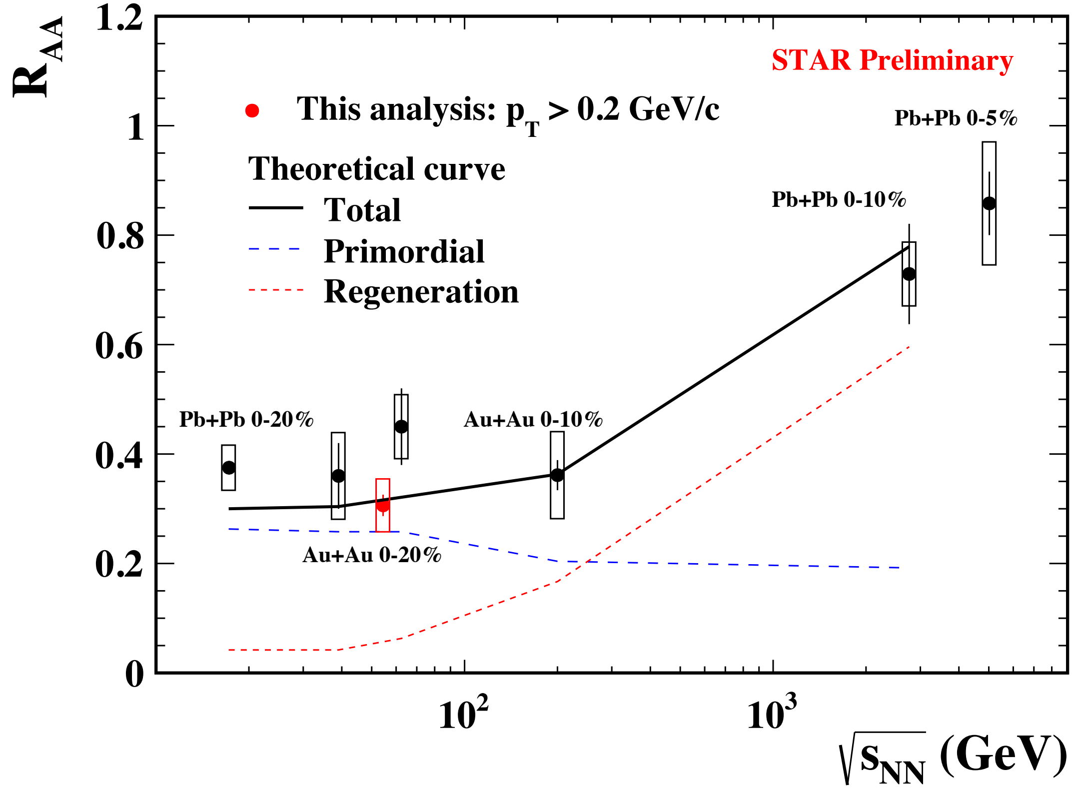
Dissociation: dynamic screening

Recombination

Cold nuclear matter effect

…

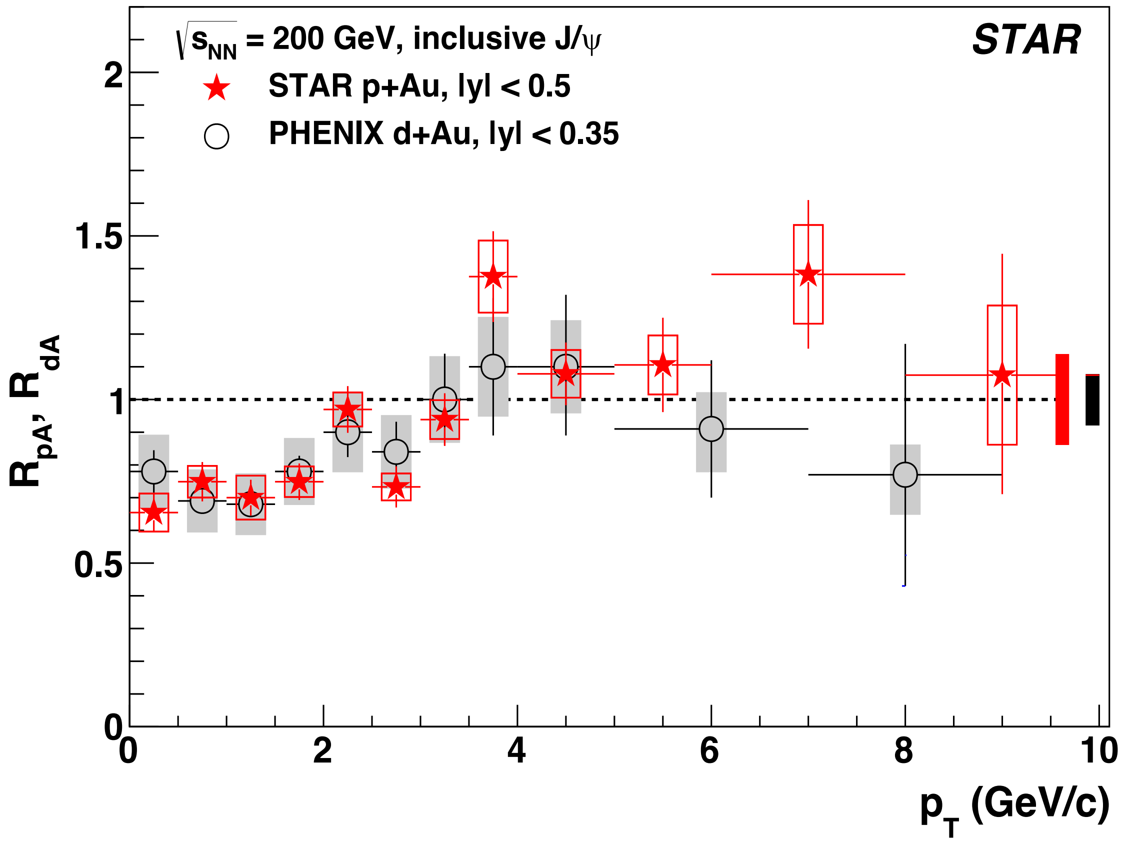
J/psi suppression from SPS to LHC



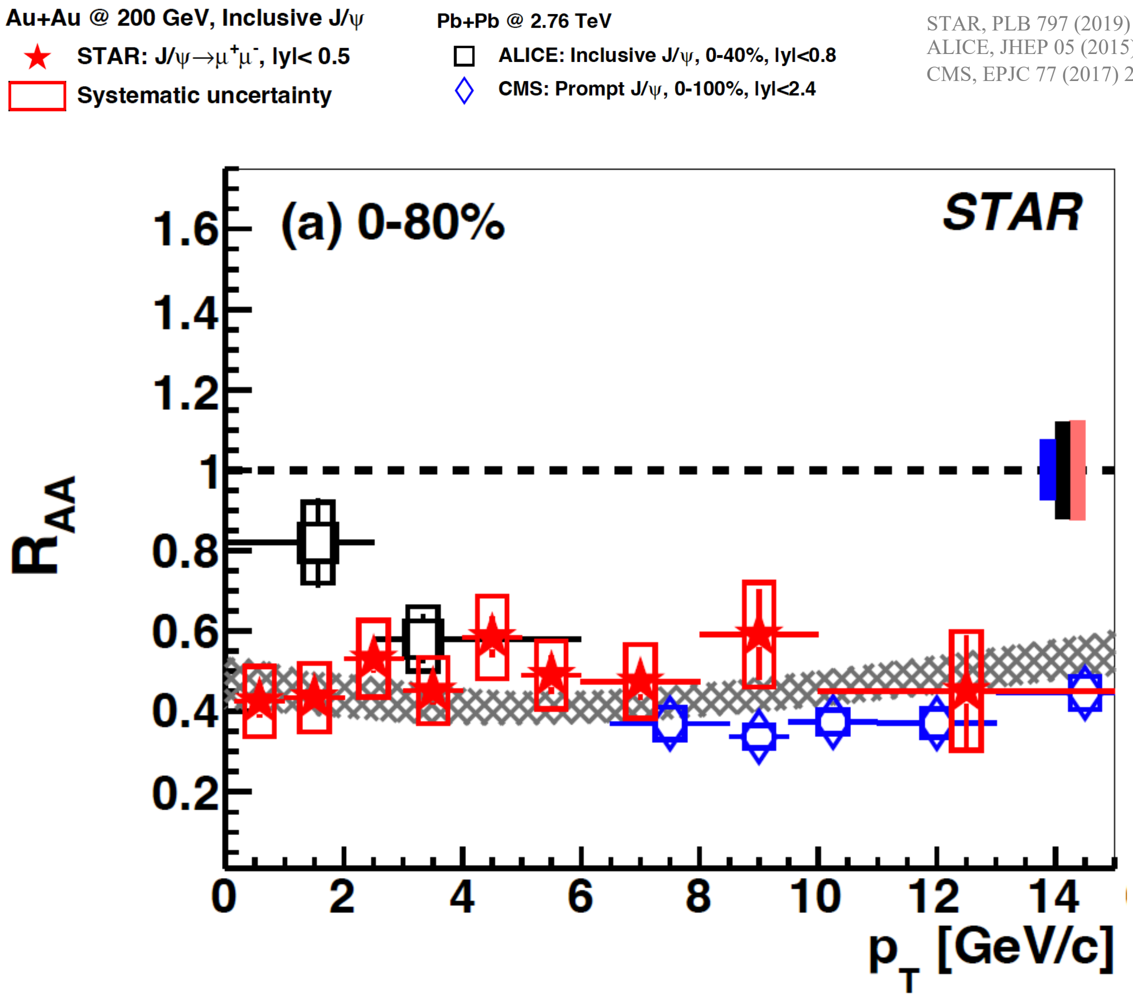
X. Zhao, R. Rapp, PRC 82 (2010) 064905
NA50, PLB 477 (2000) 28, STAR, PLB 771 (2017) 13, STAR, PLB 797 (2019) 134917
ALICE, PLB 734 (2014) 314, ALICE, NPA 1005 (2021) 121769

Interplay between CNM, color screening, dissociation, and recombination

J/psi suppression: p_T dependence



PHENIX, PRC 87 (2013) 034904; STAR, PLB 825 (2022) 136865

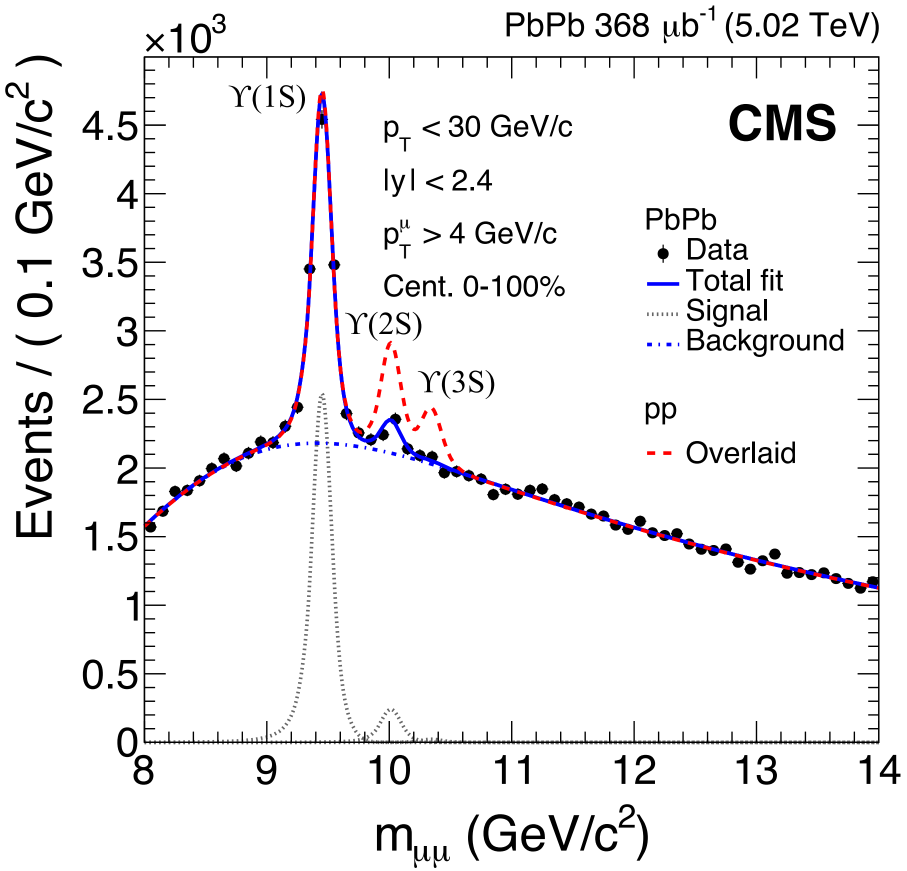


STAR, PLB 797 (2019) 134917
ALICE, JHEP 05 (2015) 051
CMS, EPJC 77 (2017) 252

High p_T suppression: evidence of color screening and dissociation

Sequential Upsilon suppression

CMS, PRL 120 (2018) 142301



ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

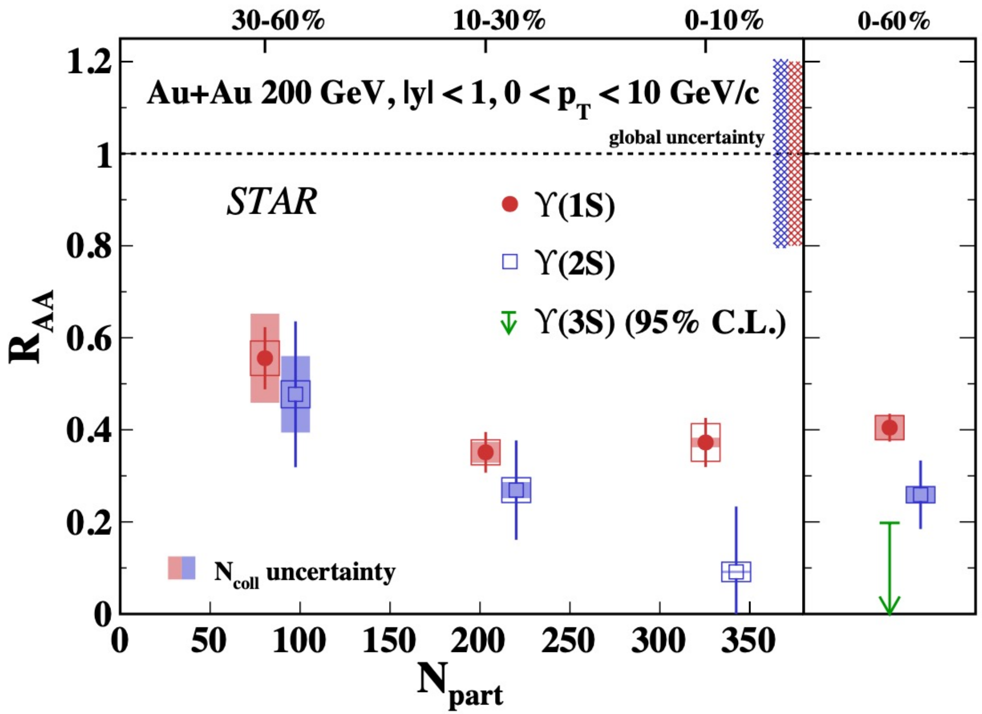
Much less contribution from b and bbar recombination

A better probe to study color screening feature of QGP.

Sequential ϒ suppression at LHC

Sequential Upsilon suppression

PRL 130 (2023) 112301



ϒ(1S), ϒ(2S), ϒ(3S) sizes: 0.28, 0.56, 0.78 fm

Negligible contribution from b and bbar recombination at RHIC

A better probe to study color screening feature of QGP.

ϒ(1S) R_{AA} = 0.40 ± 0.03 (stat.) ± 0.03 (sys.) ± 0.07 (norm.)

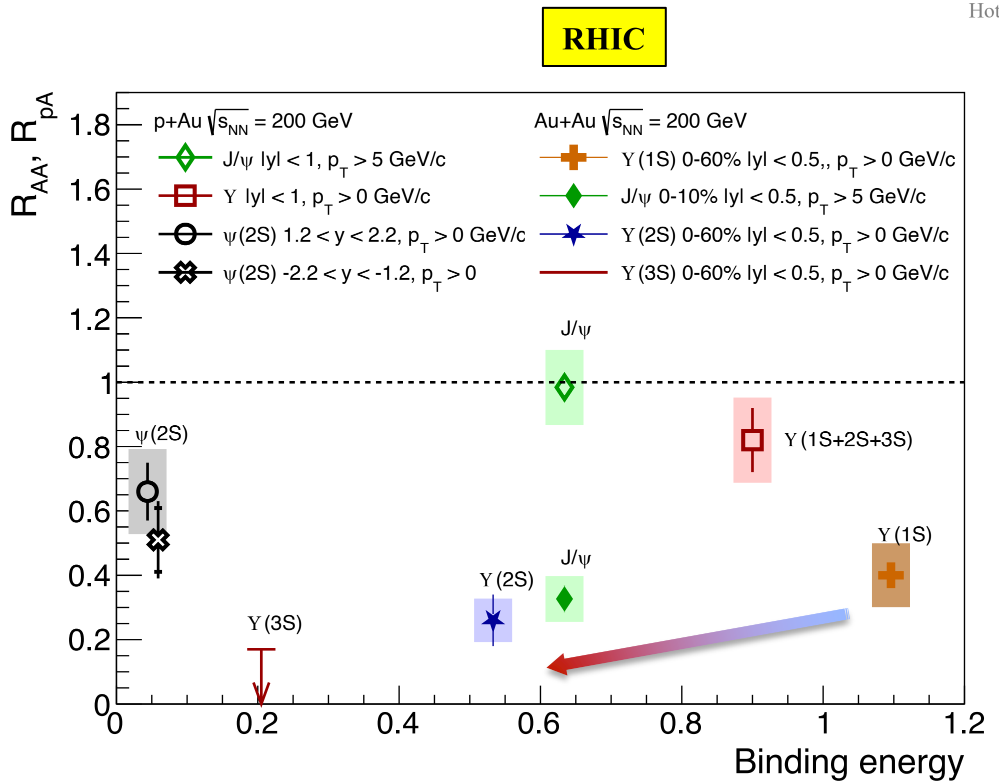
ϒ(2S) R_{AA} = 0.26 ± 0.07 (stat.) ± 0.02 (sys.) ± 0.04 (norm.)

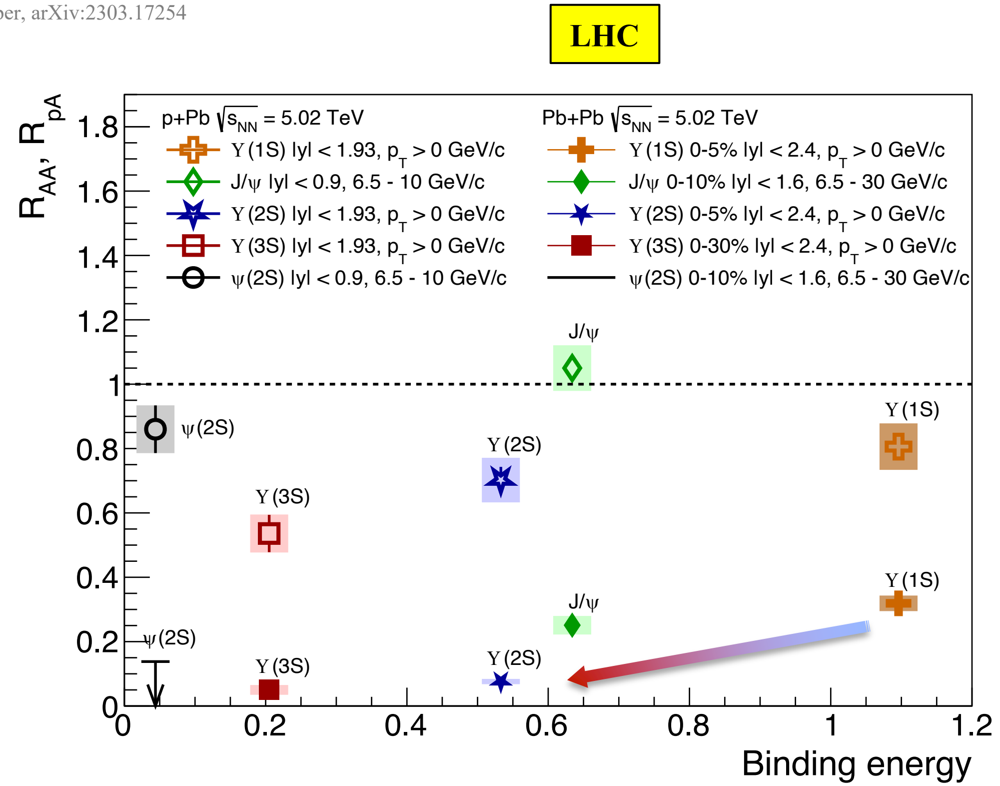
ϒ(3S) R_{AA} upper limit: 0.20 at a 95% confidence level

Sequential ϒ suppression at RHIC

Quarkonium suppression vs. binding energy

Hot QCD White Paper, arXiv:2303.17254



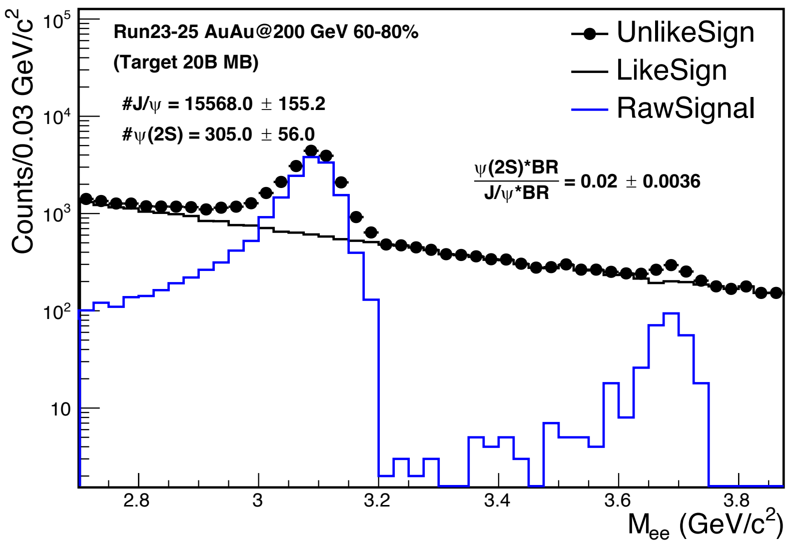


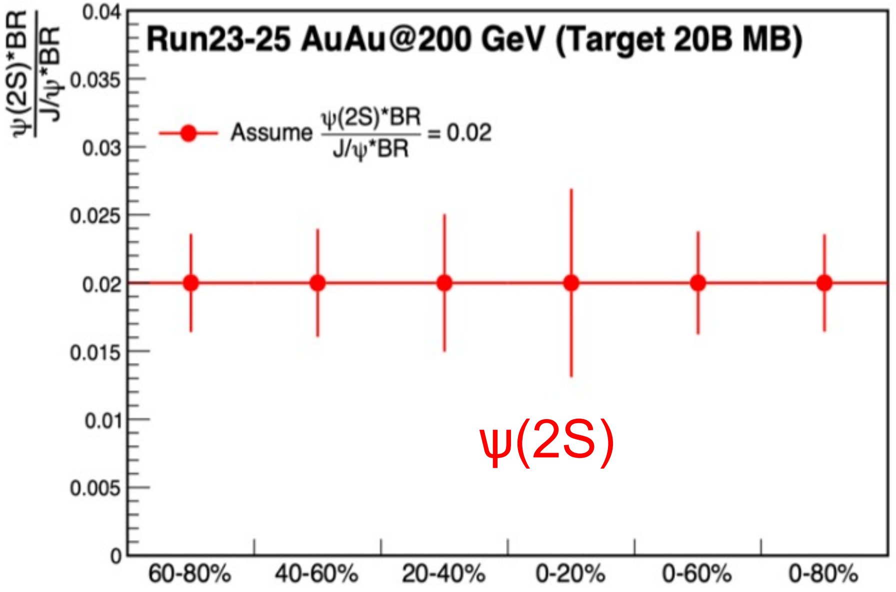
Sequential suppression pattern observed

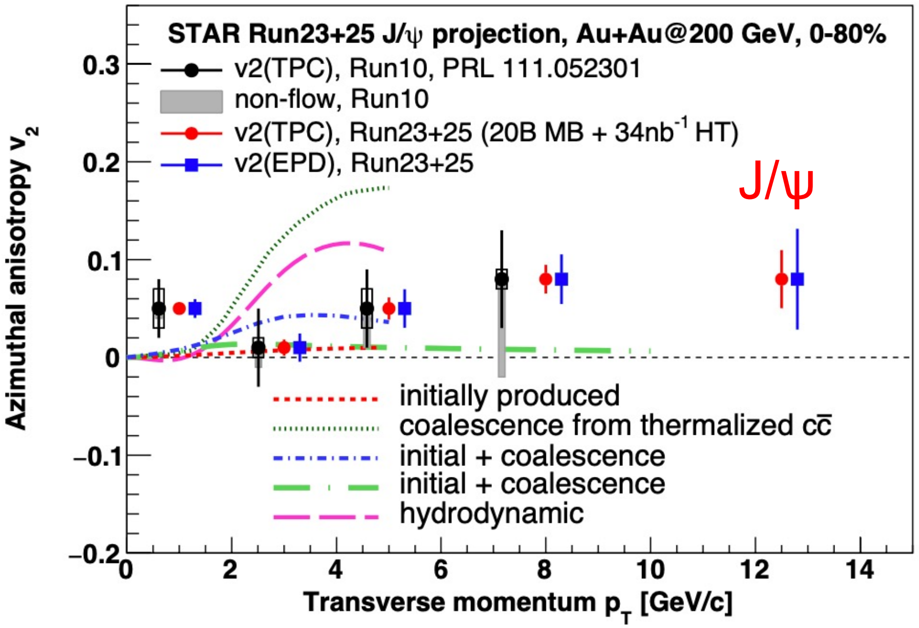
Caveats: corresponding p+Au measurements, precision

Towards the future

STAR Beam Use Request







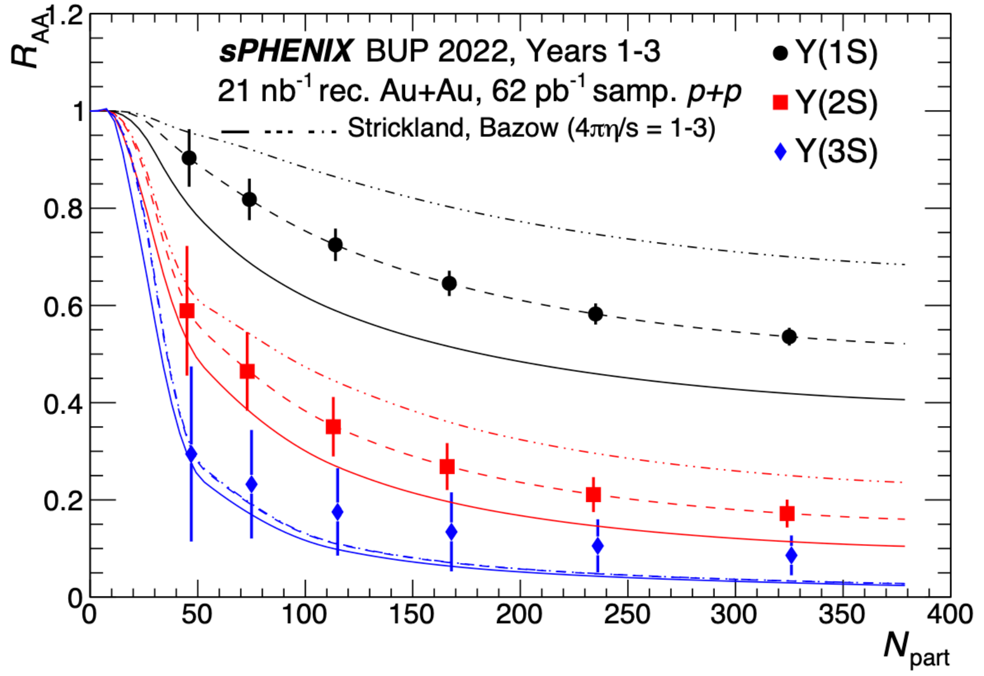
2023+2024+2025 data:

Enable first ψ(2S) measurement in Au+Au at RHIC

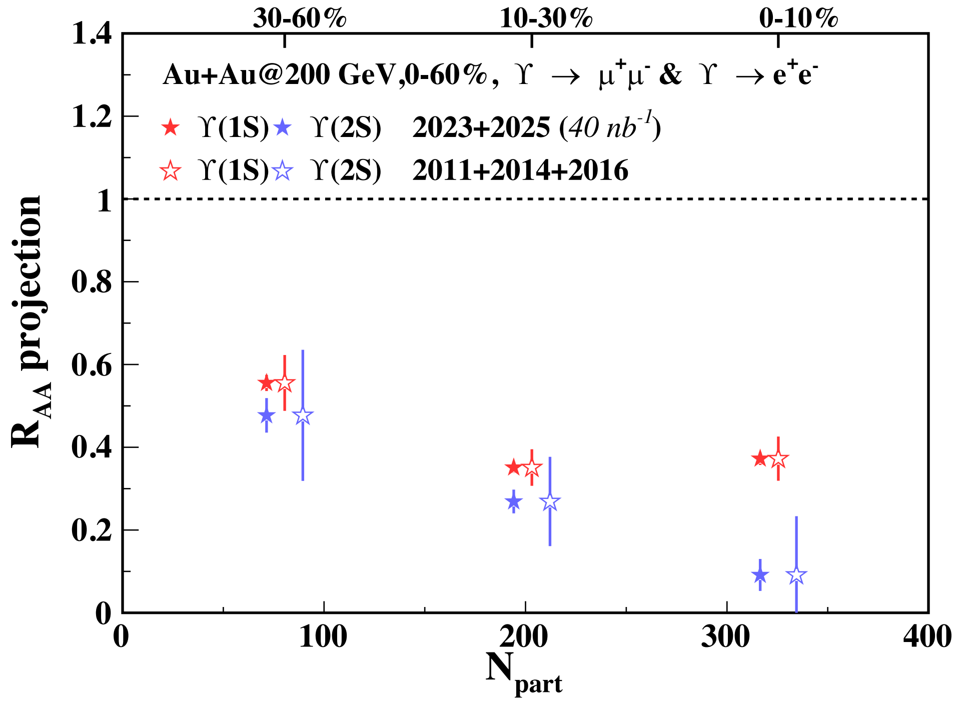
Improve J/ψ measurement significantly

Towards the future

sPHENIX Beam Use Proposal



STAR Beam Use Request



2023+2024+2025 data:

Enable first Upsilon(3S) R_{AA} measurement in Au+Au at RHIC

Improve Upsilon(1S) and Upsilon(2S) measurement significantly

What do we learn from quarkonia

Despite all the other effects, color screening and dissociation effects were observed, evidence of the in-medium strong force modification

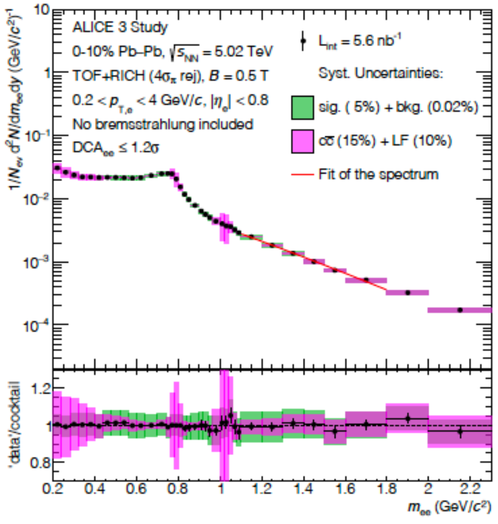
Not a direct thermometer, but can constrain medium temperature ($> 1.5\ T_c$)

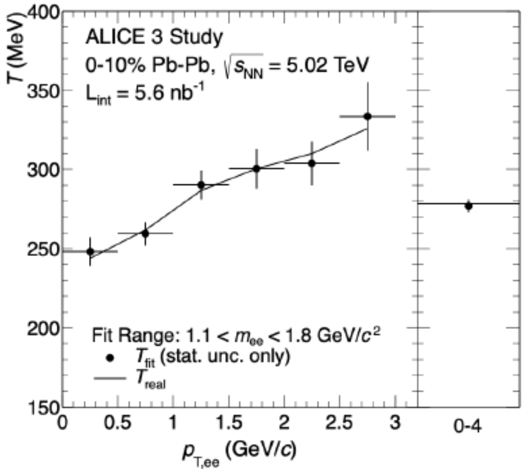
Important tool to understand deconfinement and hadronization

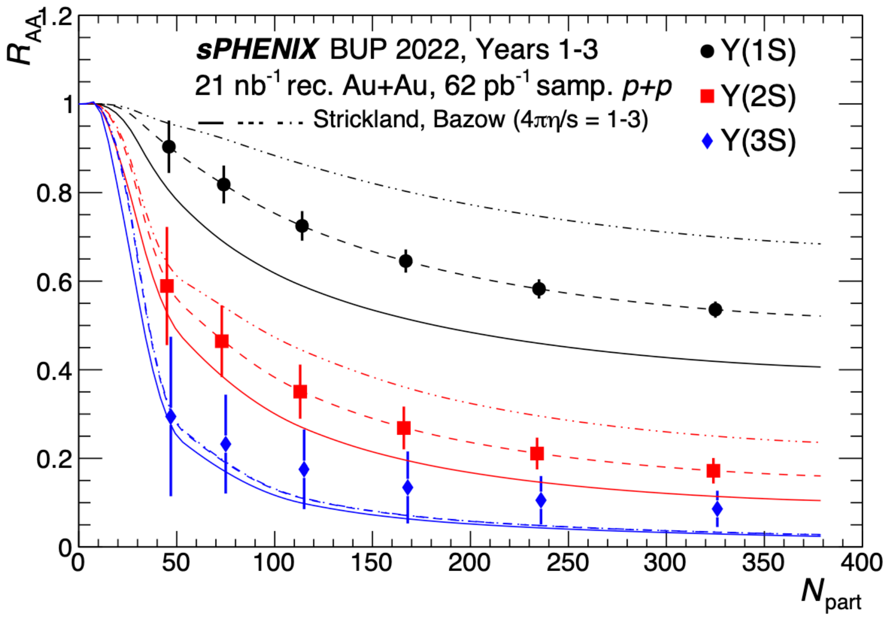
Call for a coherent picture to systematically understand quarkonium production in heavy ion collisions. Open quantum system? How about p+p, p+A?

HEFTY COLLABORATION

Summary





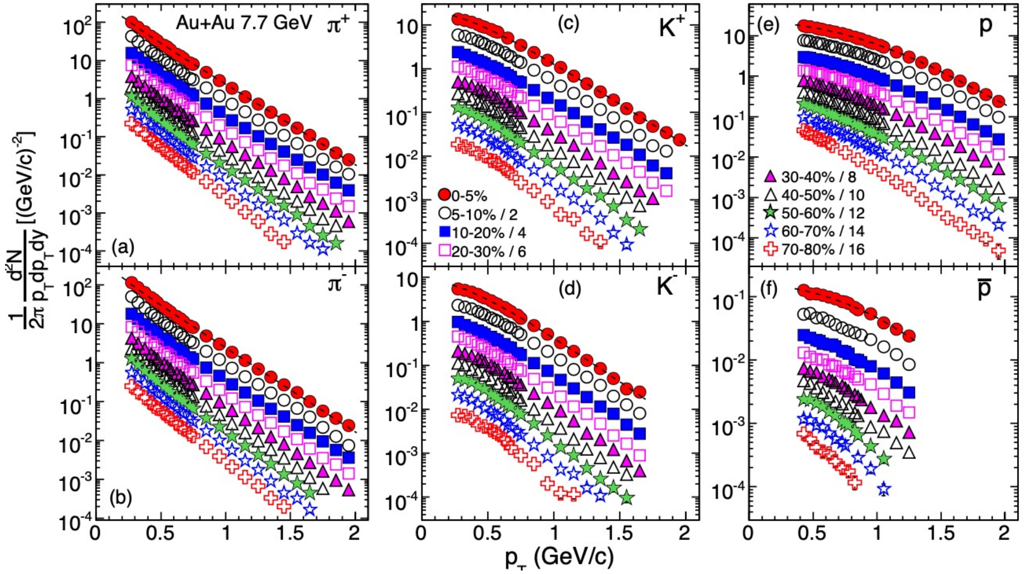


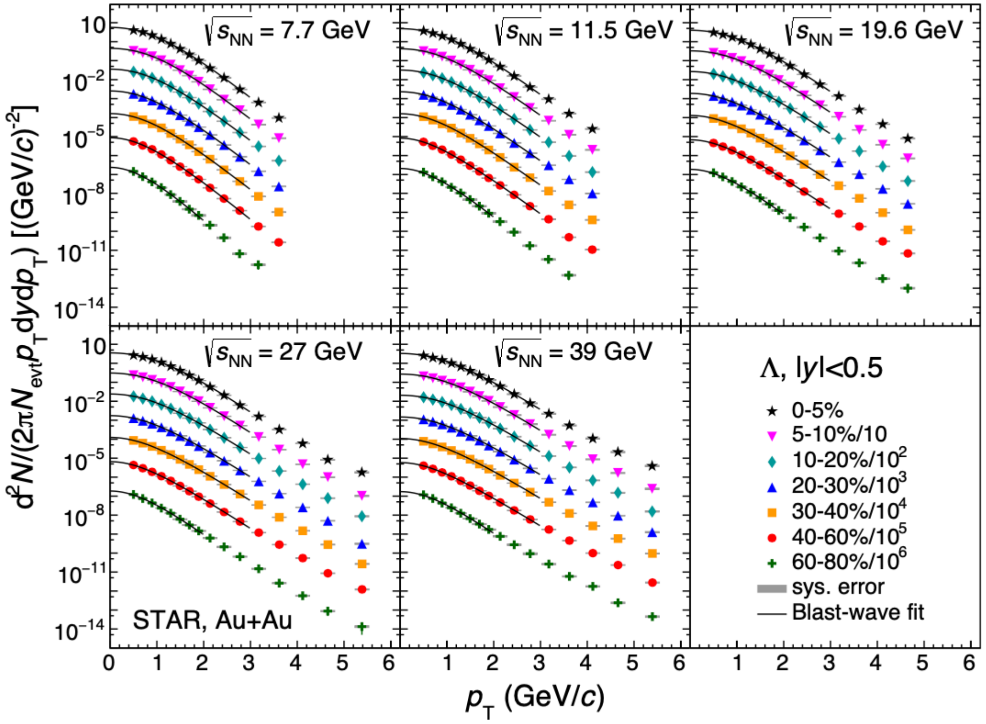
The newly built sPHENIX detector and upgraded STAR detector at RHIC, together with increased luminosity at the LHC and upgraded ALICE, ATLAS, CMS and LHCb detectors, will enable a multi-messenger era for hot QCD based on the combined constraining power of precise measurements using soft, hard, and electro-magnetic probes. --> Establish a coherent picture of heavy ion collisions and inform properties of quark-gluon matter with strong theory collaboration.

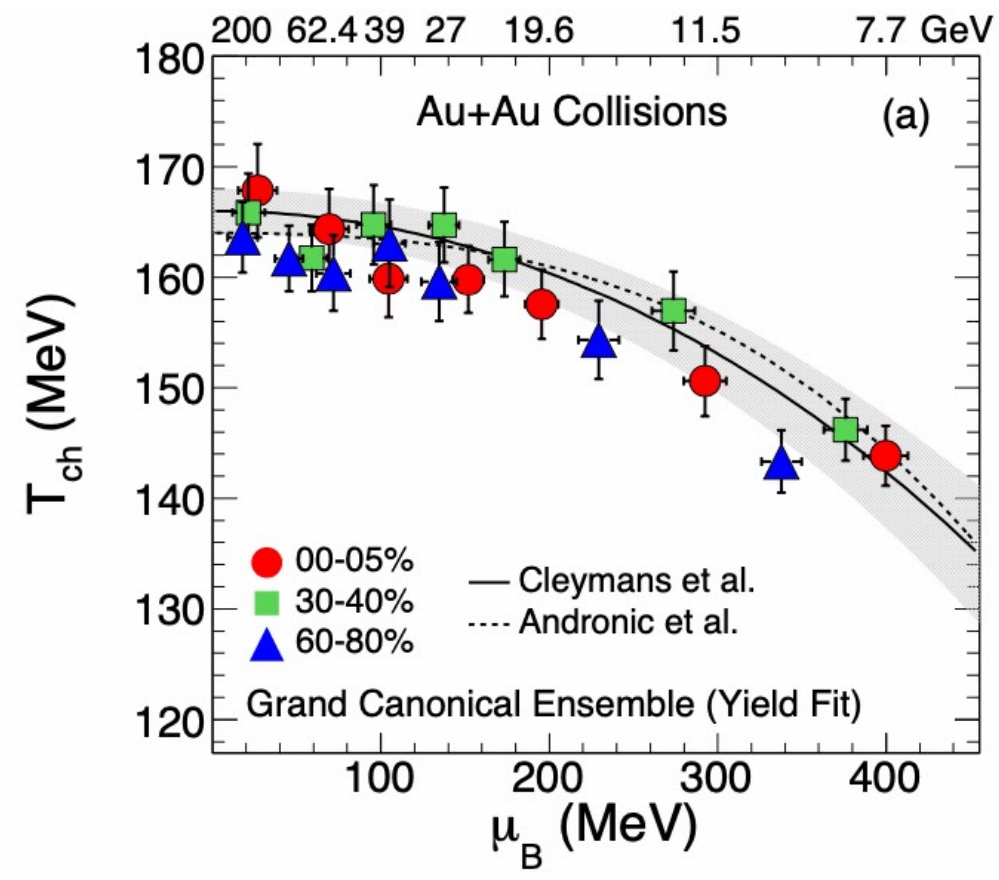
Backup

Chemical freeze out temperature

Phys. Rev. C 96 (2017) 44904







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

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