Future Facilities: J-PARC-HI

Hiroyuki Sako for J-PARC-HI/E16 Collaboration
Japan Atomic Energy Agency
HP2024, 2024/9/25

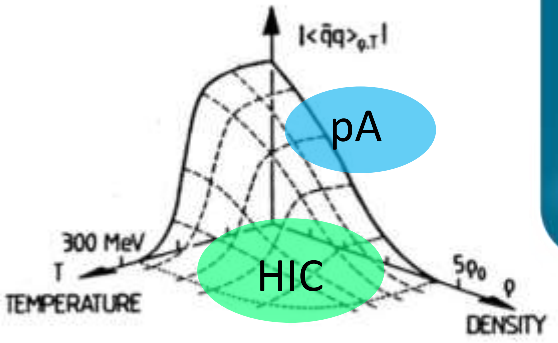
Outline

1. Goals of low and medium energy HIC
2. Status and plans for world facilities
3. J-PARC p+A experiment and J-PARC-HI
4. Summary

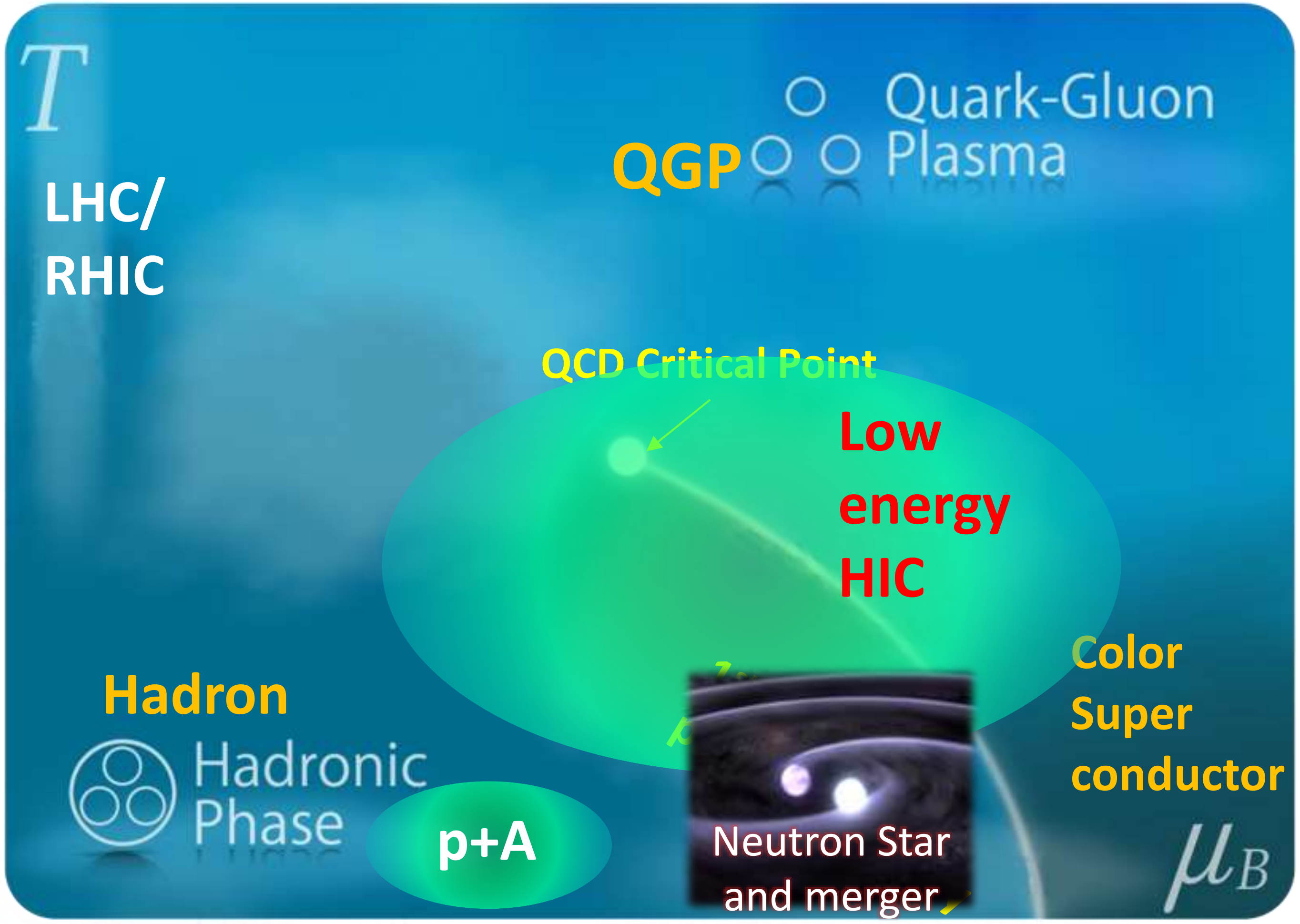
Physics of High baryon density regime

– QCD Phase structures
  - 1st order phase boundary, QCD critical point, color superconductor
– Restoration of chiral symmetry
  - In-medium modification of vector mesons
– Properties of high-density matter
  - Baryon density, EOS, and hydrodynamical properties (viscosity) etc.

  → Neutron stars and mergers



QCD Phase diagram



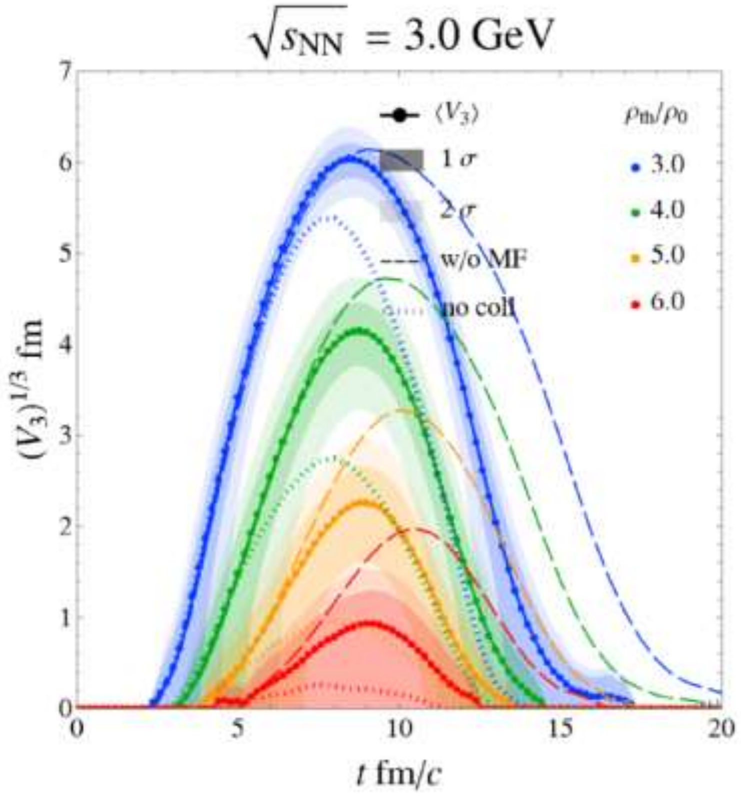
High-density volume in transport model (JAM)

Four Volume

$$V_4(\rho_{\rm th}) = \int_{-\infty}^{\infty} dt \int_{\rho(x)>\rho_{\rm th}} d^3\boldsymbol{x}$$

Lifetime

$$\tau(\rho_{\rm th}) = \frac{V_4(\rho_{\rm th})}{\max V_3(\rho_{\rm th}, t)}$$



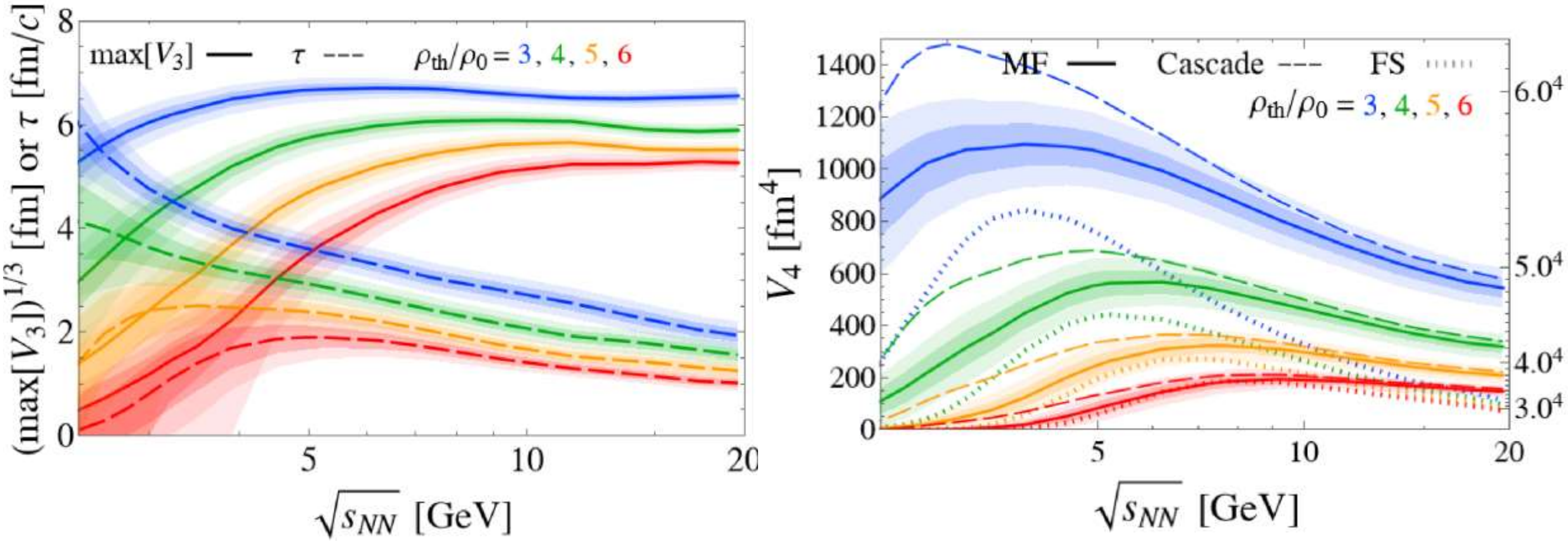
Note

V_4 may be relevant for the dilepton production rate.

M. Kitazawa, Reimei Workshop, Jeju, Korea, June 2024, H. Taya, A. Jinno, M. Kitazawa, Y. Nara, arXiv:2409.07685

Collision Energy Dependence

max V_3 , τ



- $\sqrt{s_{NN}} = 2.6\sim5$ GeV would be the best energy to create $\rho \geqq 3\rho_0$ with largest V_4.

M. Kitazawa, Reimei Workshop, Jeju, Korea, June 2024, H. Taya, A. Jinno, M. Kitazawa, Y. Nara, arXiv:2409.07685

Dilepton production

"Penetrating probe" w/o strong interaction

- Retain information of high-density matter
- Various physics can be studied in each mass range

1. **π^0,η Dalitz decay region (m<0.2 GeV/c^2)**
   Search for precursor of critical point or color superconductor

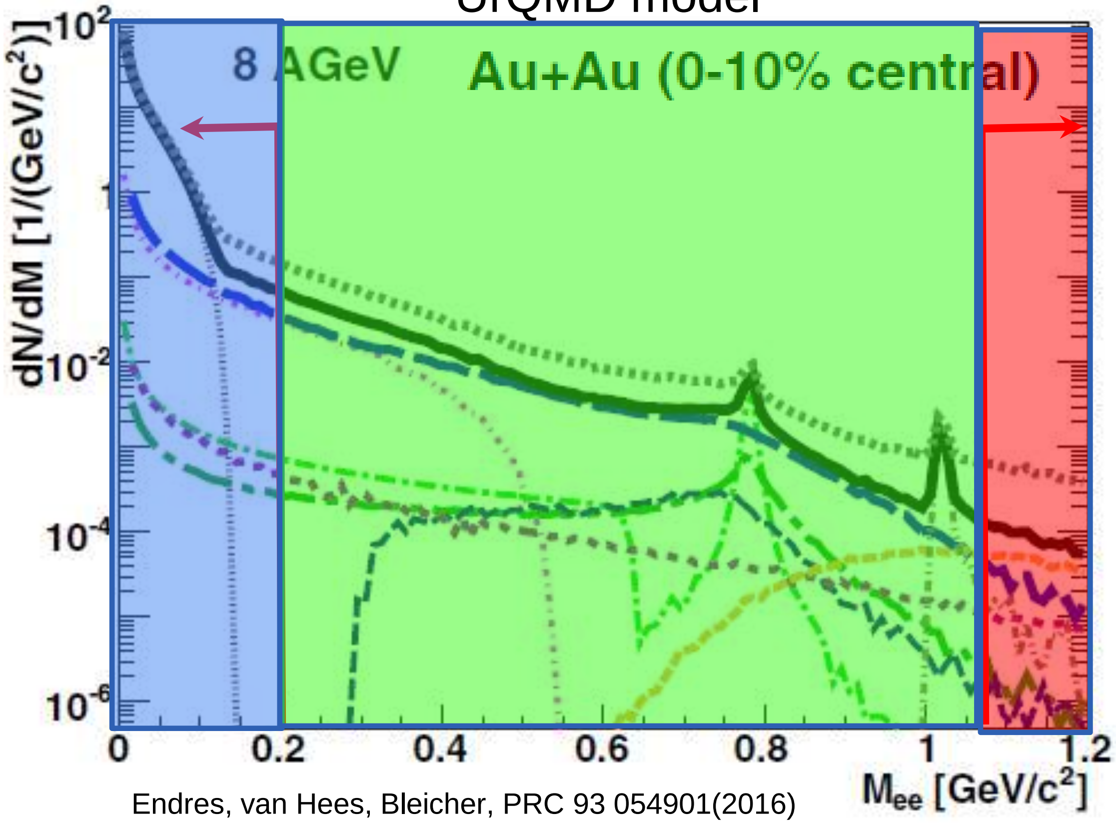
2. **ρ, ω, ϕ (LMR: 0.2-1.1 GeV/c^2)**
   In-medium modification due to chiral symmetry restoration

3. **ϕ and higher mass (IMR: 1.0-1.5 GeV/c)**
   Spectral change due to chiral mixing of ρ-a_1 and ϕ-f_1

4. **Thermal photon (LMR: 0.2-1.1, IMR: 1.1-3 GeV/c^2)**
   Search for phase transition with temperature measurement

5. **Charmonium production/suppression (HMR: m>3 GeV/c^2)**

UrQMD model



Endres, van Hees, Bleicher, PRC 93 054901(2016)

Low-mass di-electrons

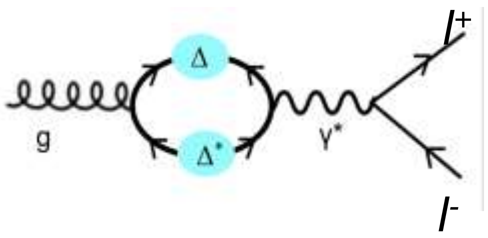
Probe for precursor of color superconductor (CSC) and the QCD critical point (CP)

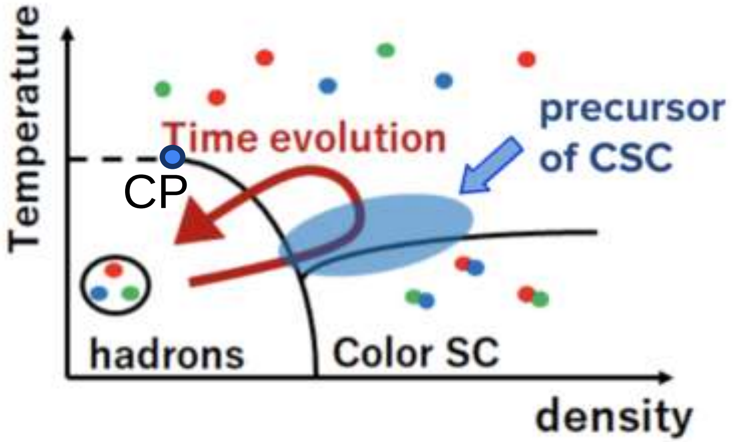
Dielectron enhancement at low M_{ee}

Near T_c or CP due to diquark or quark-antiquark fluctuations

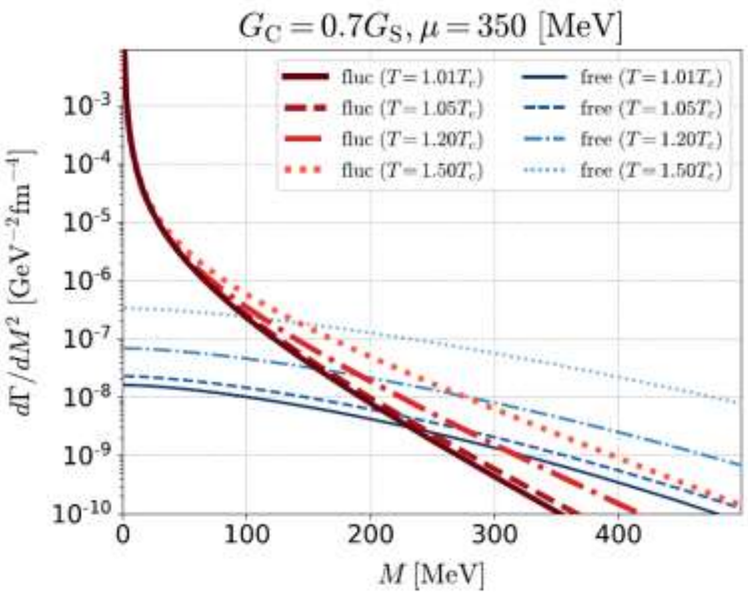
Detectors suitable for these searches should be designed

Rapp+ , 2002, Hatsuda+, 2005



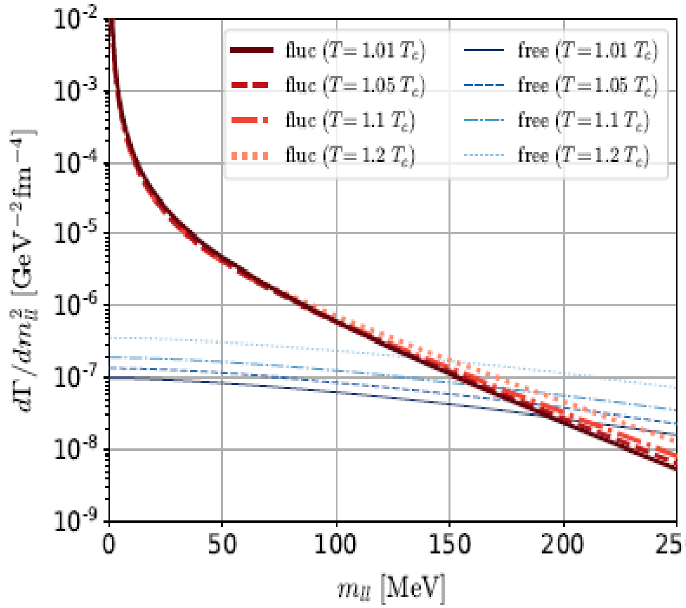


Precursor of CSC



T. Nishimura, M. Kitazawa, T. Kunihiro, PTEP 2022 093D02

Soft mode near CP



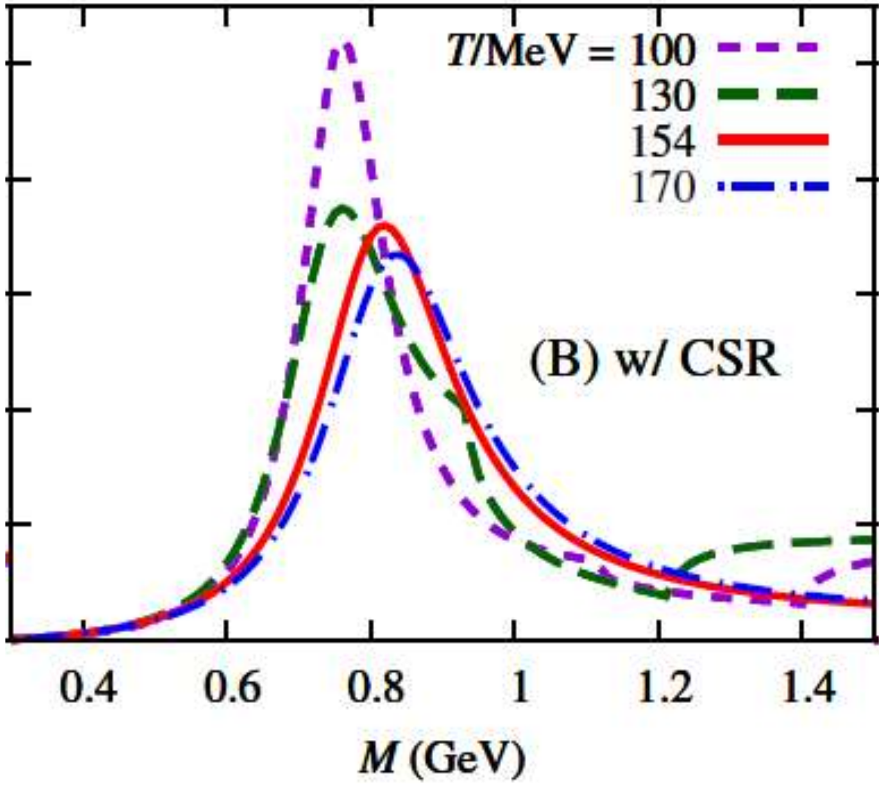
T. Nishimura, M. Kitazawa, T. Kunihiro, arXiv 2302.03191

ρ–a_1 and ϕ-f_1 chiral mixing in dilepton spectra

Chiral mixing → signal of axial vector in dilepton

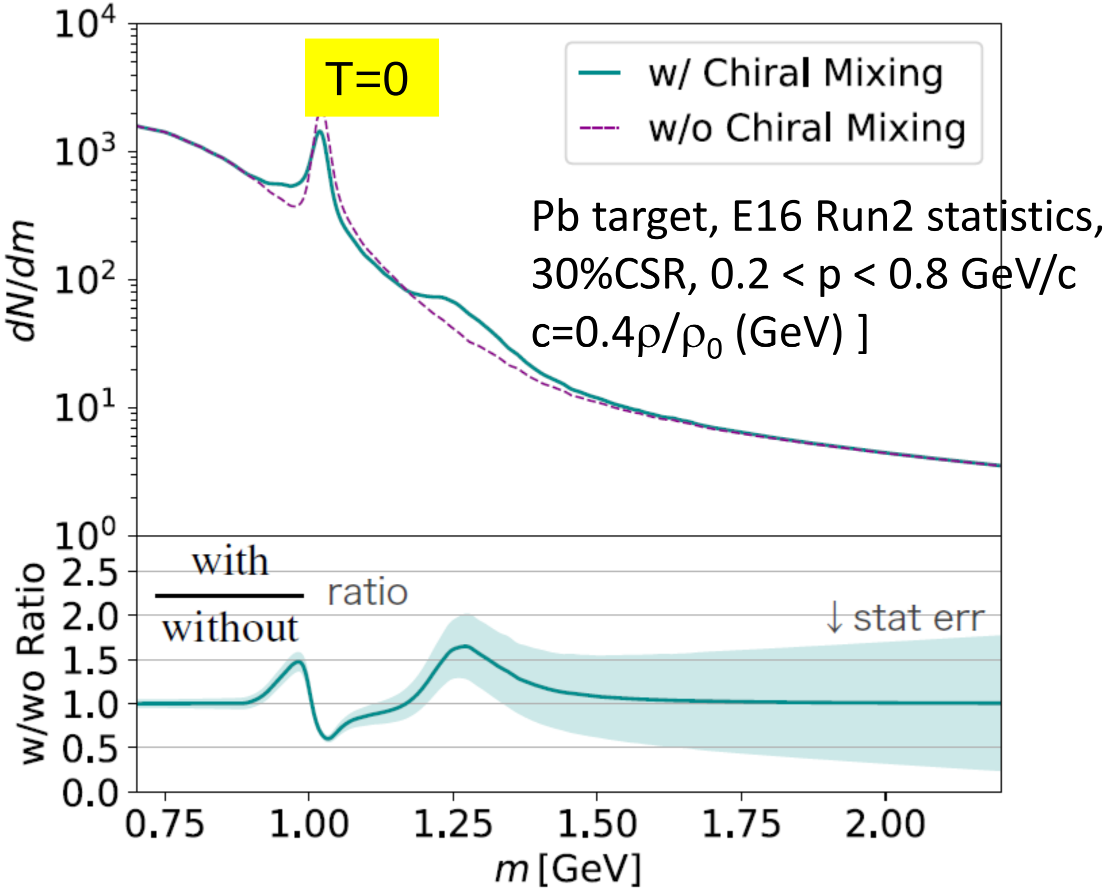
Chiral symmetry restoration → degeneration of vector and axial vector mesons → Change of dilepton spectrum

ρ–a_1 chiral mixing at high T and low density



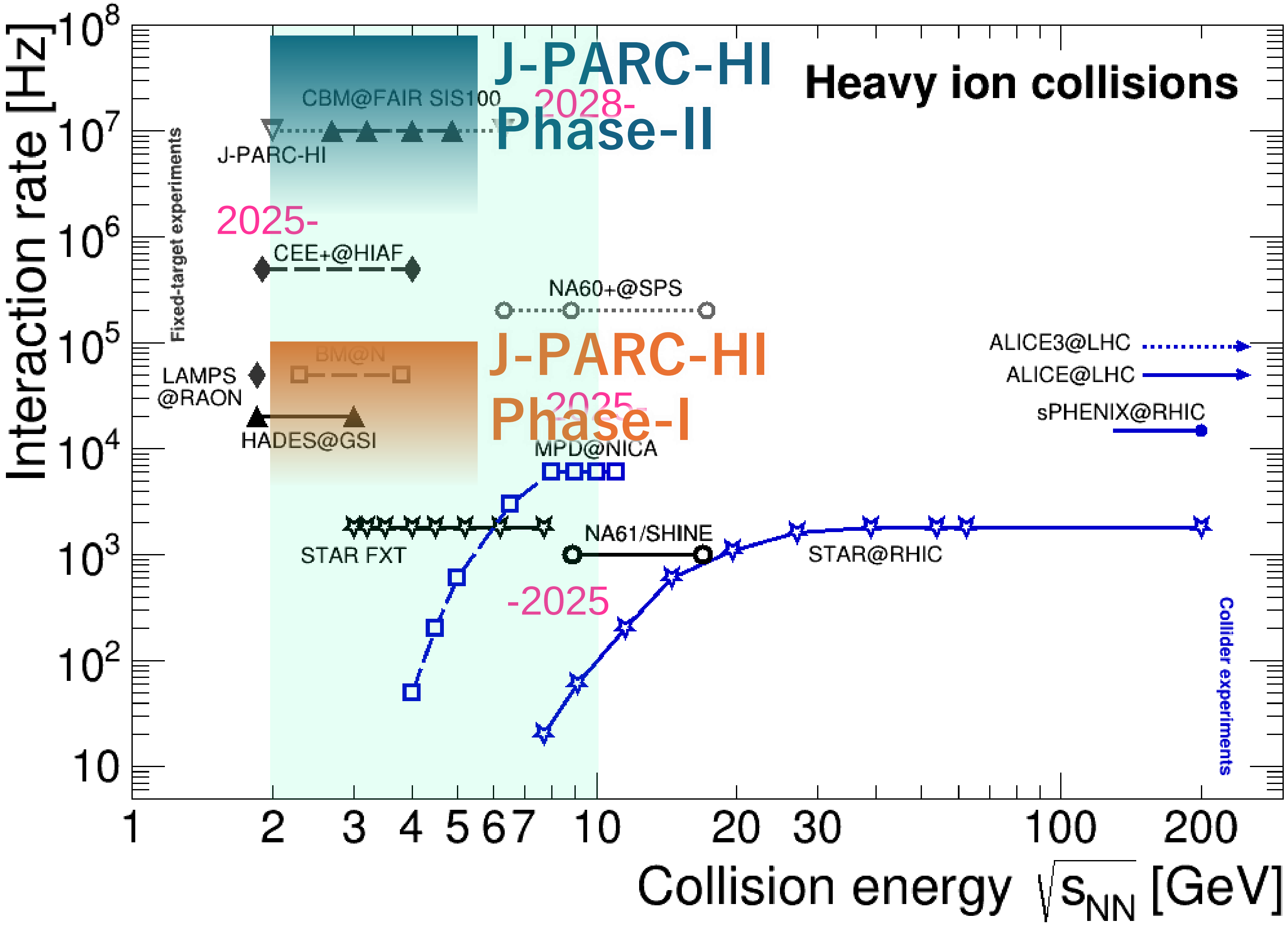
A. Sakai M. Harada, C. Nonaka, C. Sasaki, K. Shigaki, S. Yano, EPJ Web Conf. 296, 07008 (2024)

Dilepton invariant mass distribution expected at J-PARC E16 in p+A with ϕ-f_1 mixing



R. Ejima, P. Gubler, C. Sasaki, K. Shigaki, in preparation

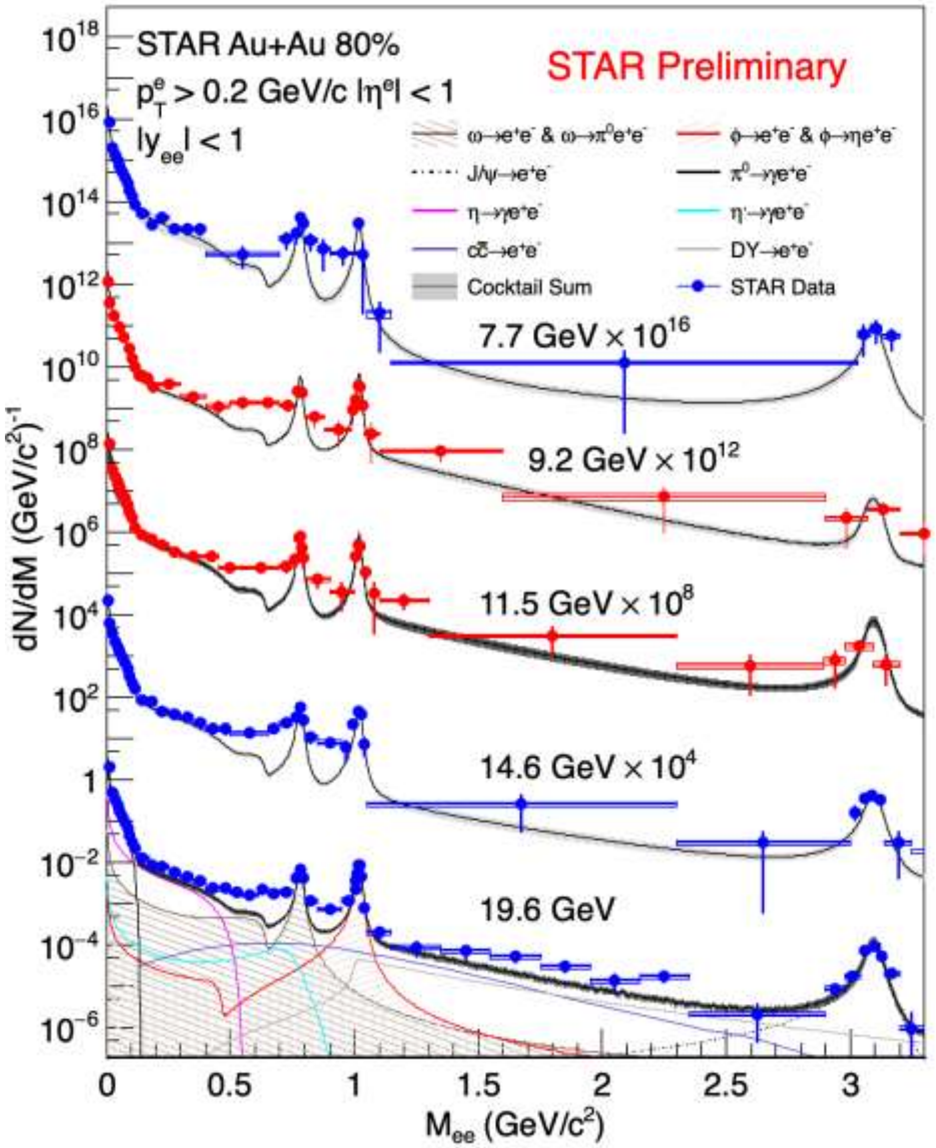
World's facilities exploring high-density regime



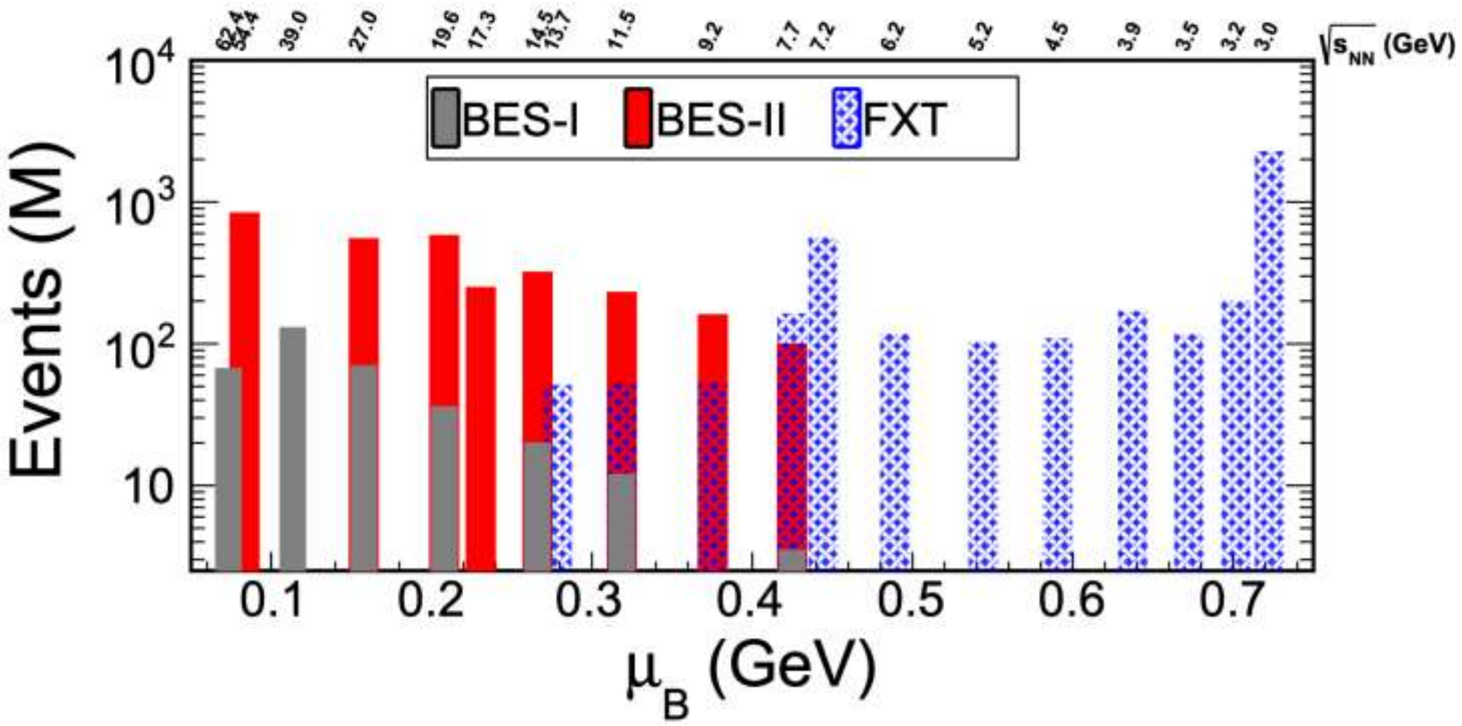
- Energy ranges: $\sqrt{s_{NN}}$=2-10GeV to explore high-density regime
- High-luminosity measurements are very important for dileptons

T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, updated in Feb. 2024

Dielectron spectra in STAR BES-II

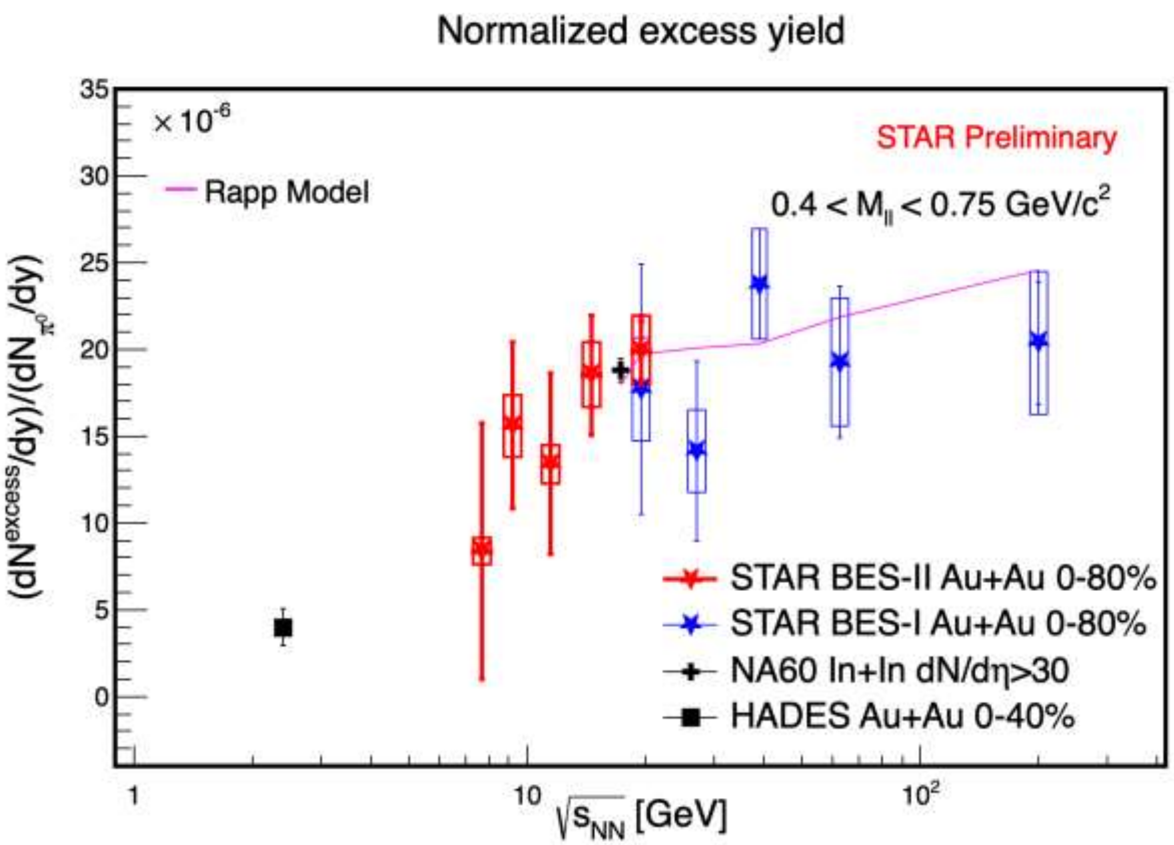


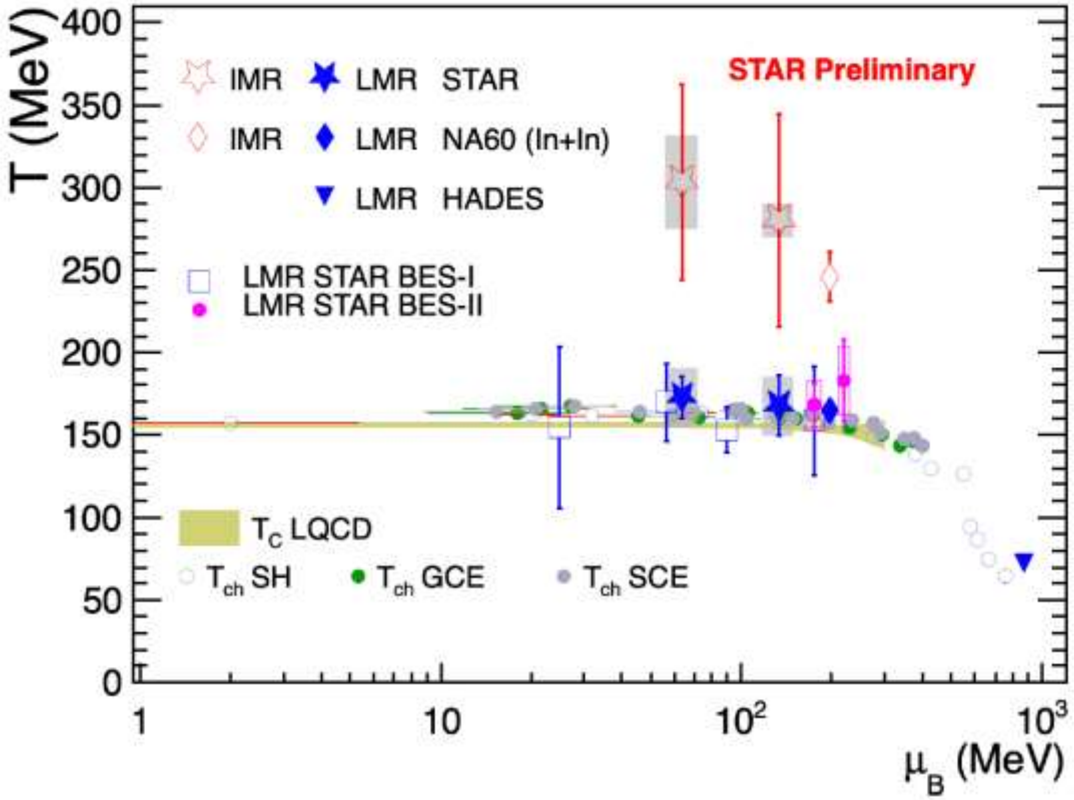
- New BES-II data at $\sqrt{s_{NN}}$=7.7-19.6 GeV
- 10x more statistics than BES-I
- Excess observed in LMR



Chenliang Jin, HP 2024, Sep 24

Thermal dielectron in STAR BES-I/II

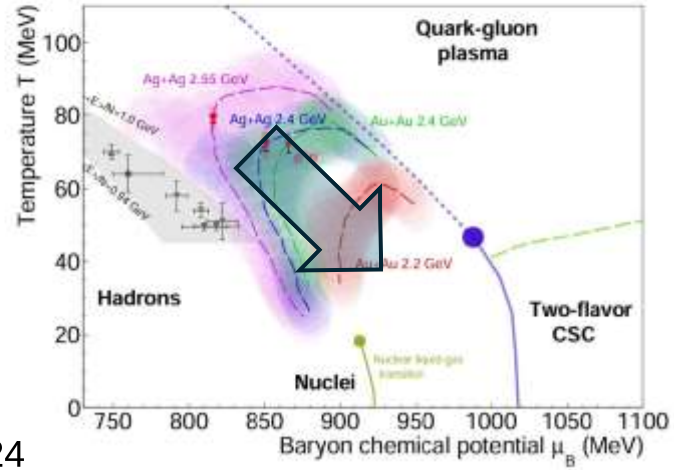




- Decreasing excess trend toward low $\sqrt{s_{NN}}$
- T ~ pseudo critical temperature at $\sqrt{s_{NN}}$ =14.6 and 19.6 GeV

HADES

Dilepton excess radiation from $\mathrm{Ag}+\mathrm{Ag}\ (\sqrt{s_{NN}}=2.5\ \mathrm{GeV})$



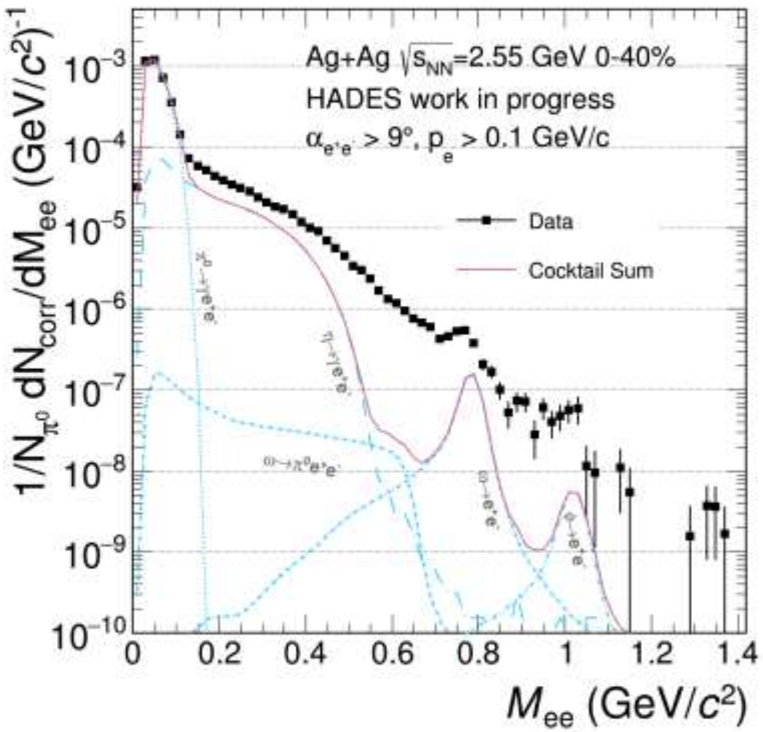
- Lower beam energies toward higher density region
- 2024:Au+Au $\sqrt{s_{NN}}$=2.23,2.14GeV
- 2025:Au+Au $\sqrt{s_{NN}}$=2.23, low B-field (for lower Mee)

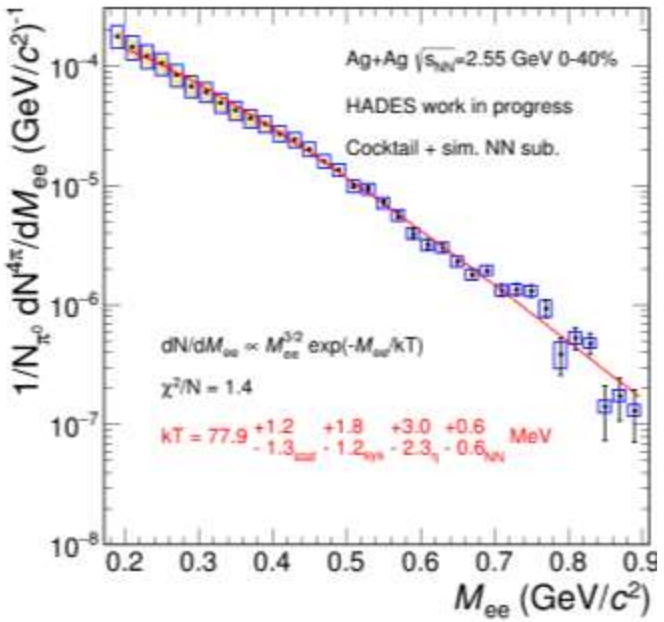
I. C. Udrea, HP2024

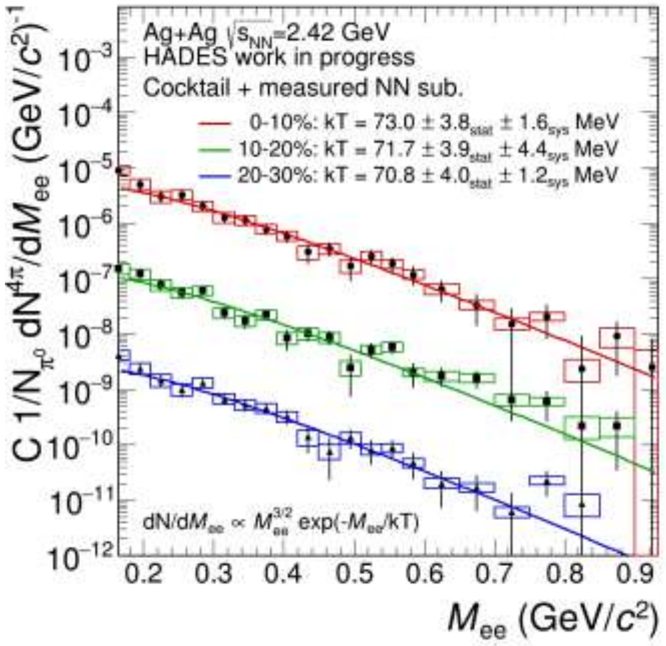
Excess radiation observed in Ag+Ag

Ag+Ag at $\sqrt{s_{NN}}=2.55$ GeV

Ag+Ag at $\sqrt{s_{NN}}=2.42$ GeV







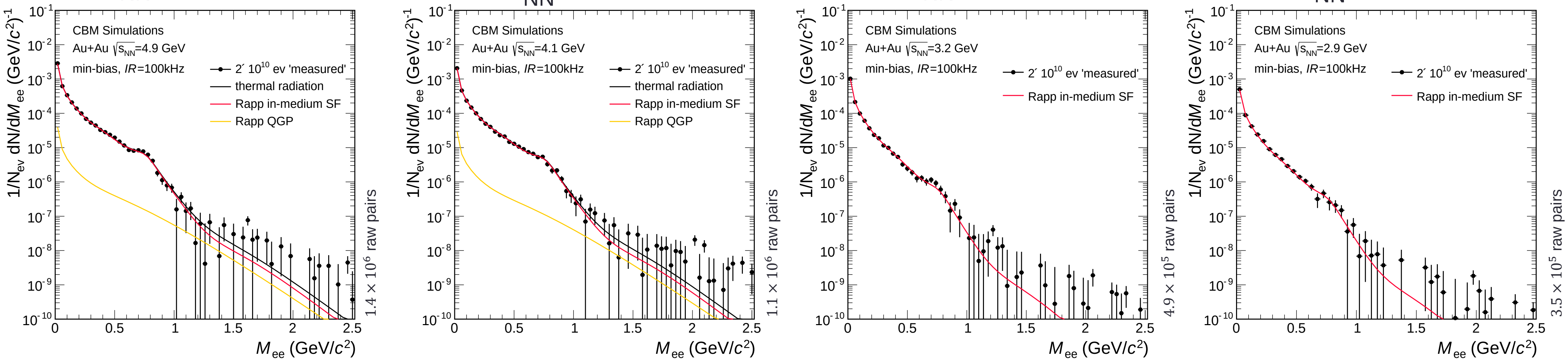
CBM expected dielectron spectra in the first year

Dielectron performance (1 year, 5 days / energy)

Isolated dielectron thermal radiation yield, corrected for acceptance x efficiency:

- Dominated by ρ contribution at low mass ($M_{\ell\ell}$ <1GeV/c^2); can be reconstructed with precision of 1.5 – 4.5%
  - allows fireball lifetime measurement
  - transport properties – electrical conductivity? $\sigma_{el}(T) = -e^2 \lim_{q_0 \to 0} \frac{\delta}{\delta q_0} Im\Pi_{em}(q_0, q = 0; T)$
- Intermediate mass range ($M_{\ell\ell}$>1GeV/c^2) accessible, statistics will not (yet) be sufficient to extract physics

$\sqrt{s_{NN}}$=4.9 GeV $\sqrt{s_{NN}}$=4.1 GeV $\sqrt{s_{NN}}$=3.2 GeV $\sqrt{s_{NN}}$=2.9 GeV

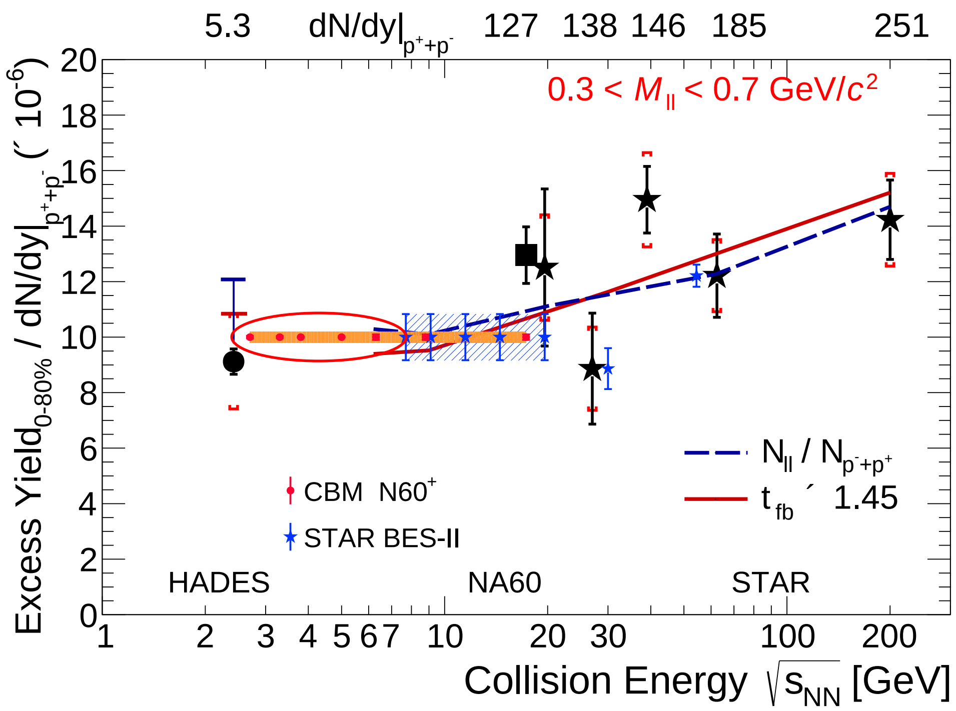


T vs. baryon density effects
from partonic to hadronic fireballs

CBM expected excess yield and temperature

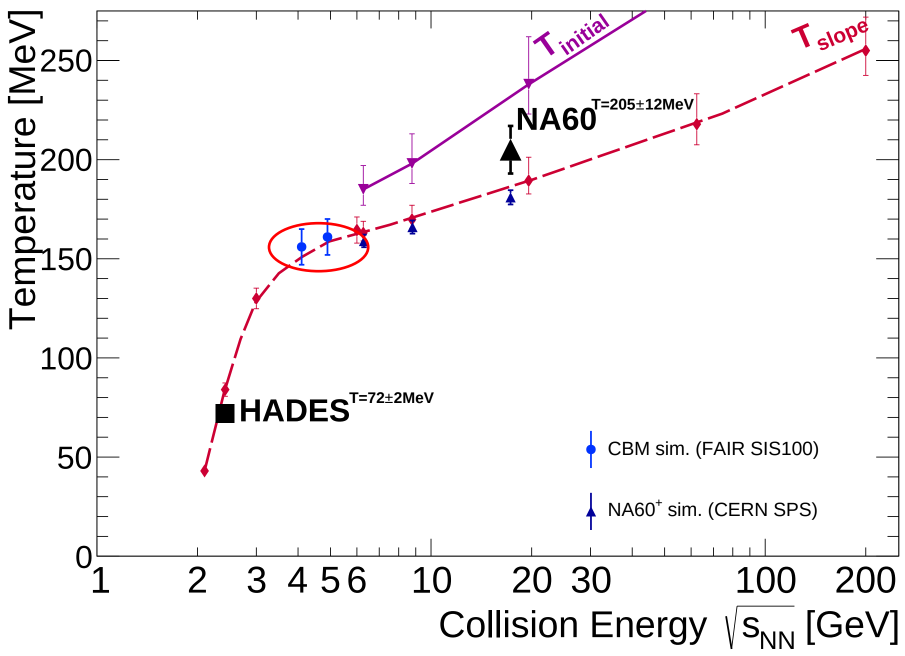
Dielectron performance (1 year, 5 days / energy)

Excess yield in LMR tracks fireball lifetime



T. Galatyuk, JPS Conf.Proc. 32 (2020) 010079

Invariant mass slope measures radiating source temperature

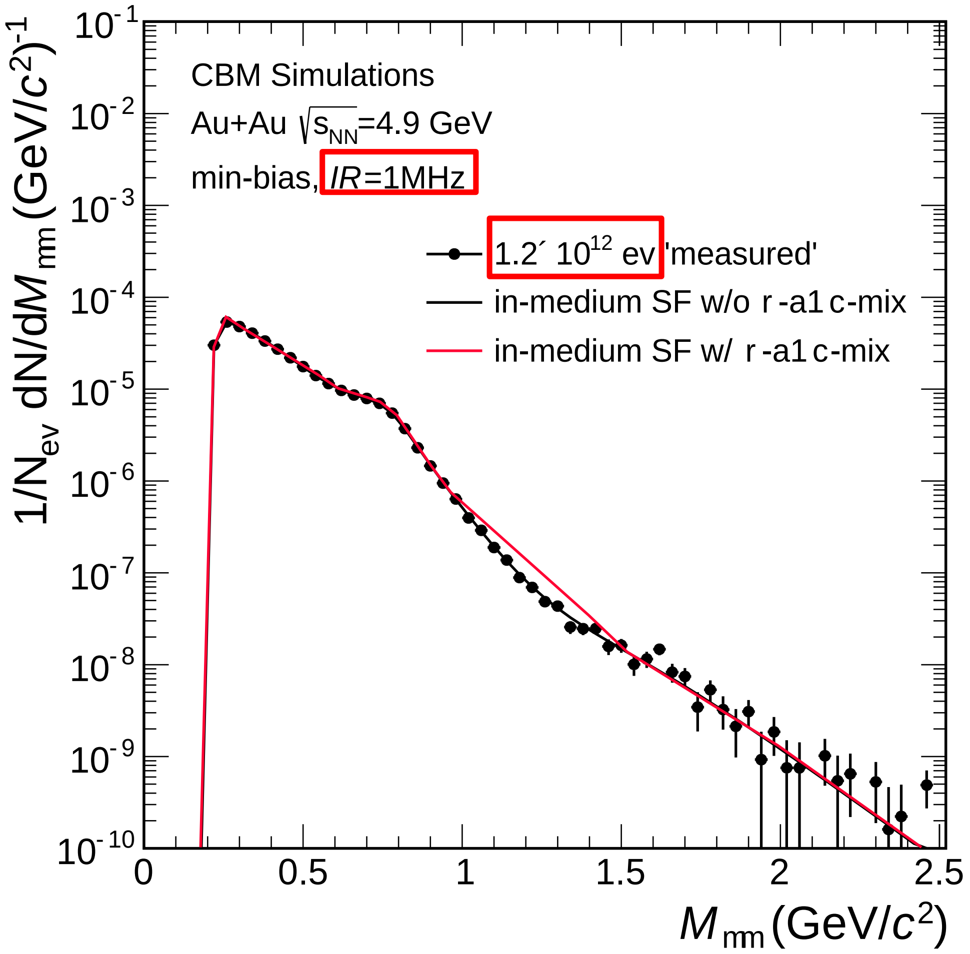


Rapp and v. Hess, PLB 753 (2016) 586
T. Galatyuk *et al.*, EPJA 52 (2016) 131
https://github.com/tgalatyuk/QCD_caloric_curve

CBM expected dimuon spectra

Study of the effect of $\rho - a_1$ chiral mixing

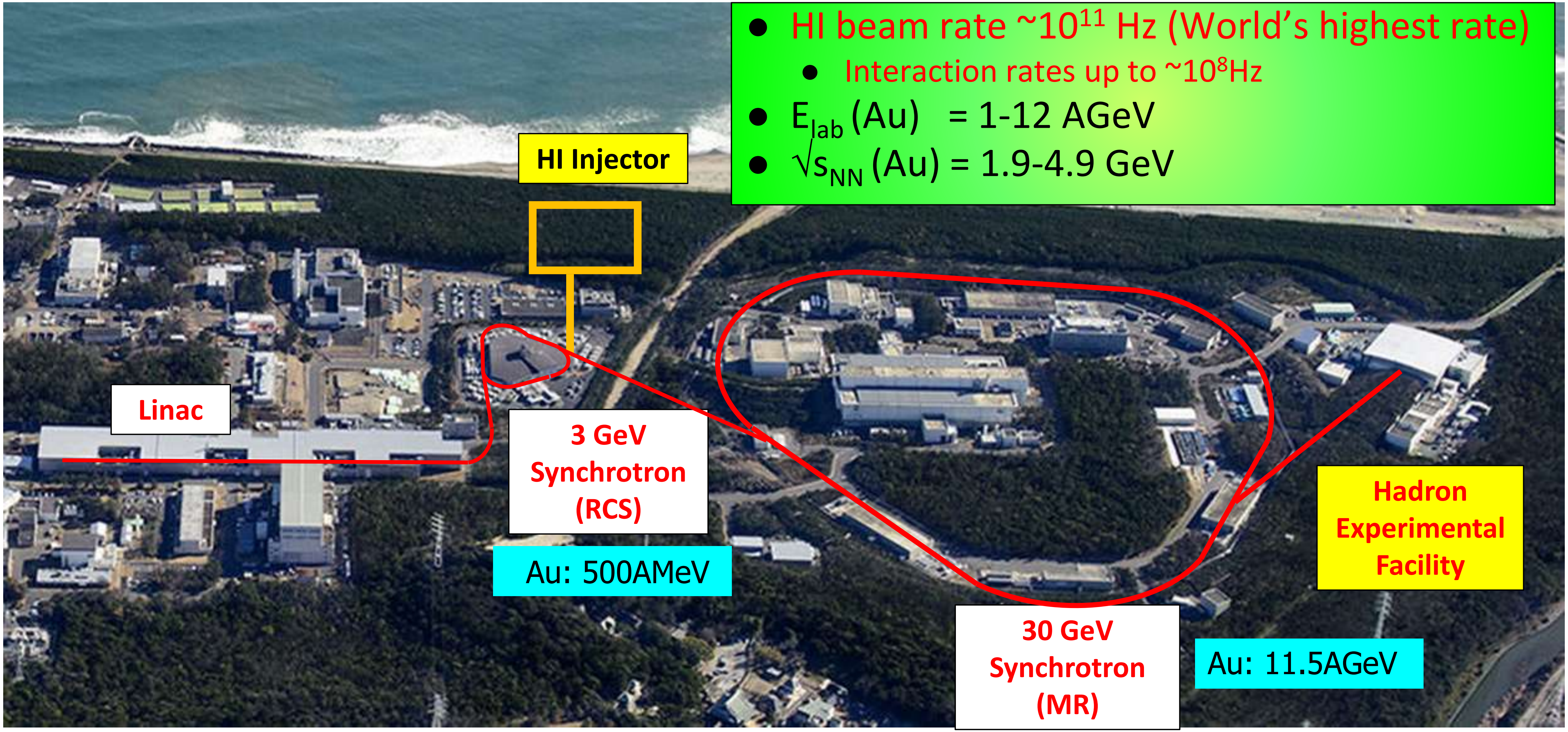
CBM energies: negligible correlated charm contribution, decrease of QGP, Drell-Yan contribution pp, pA



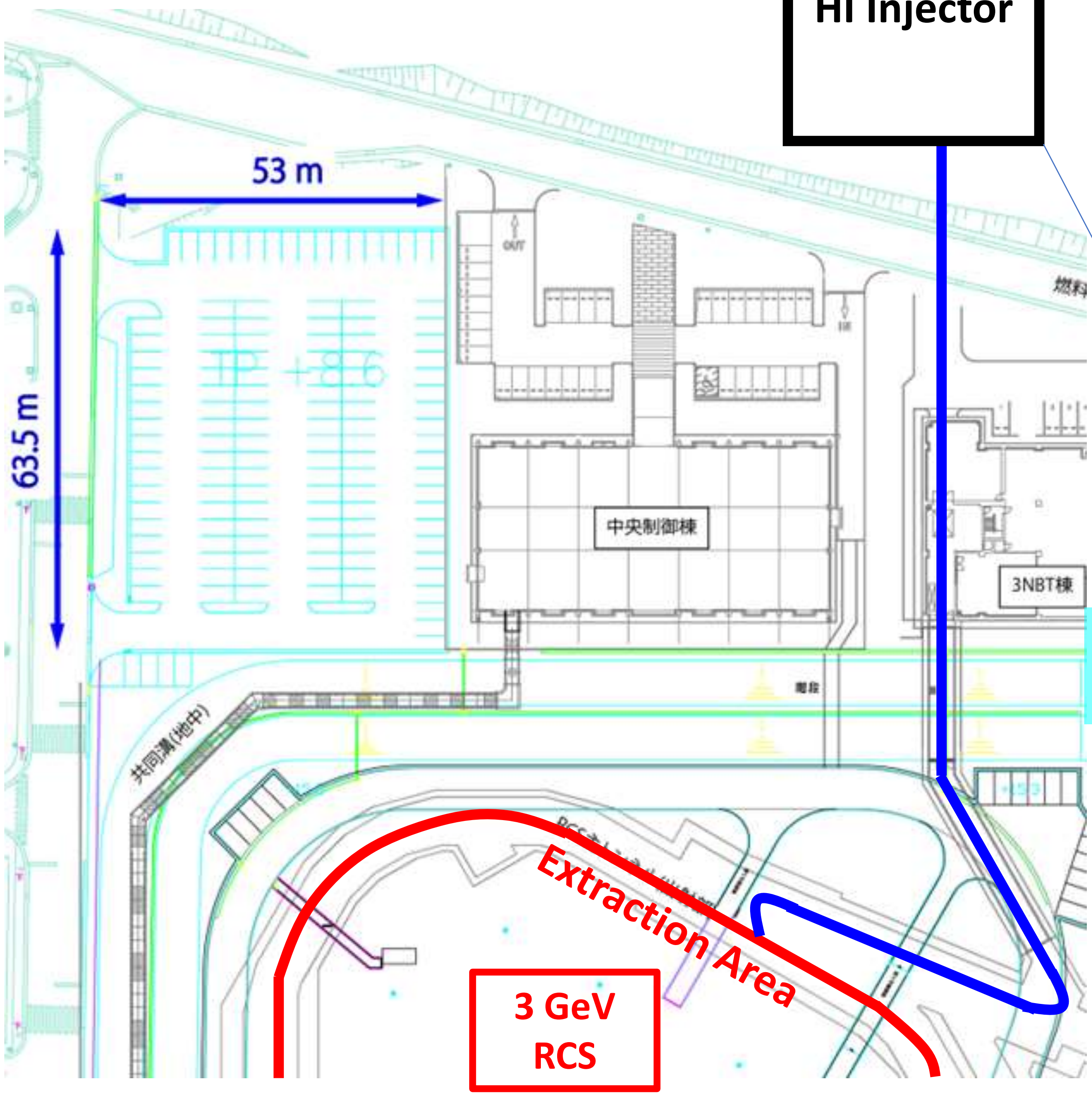
Model calculation based on R. Rap and H. van Hees Phys. Lett. B 753 (2016) 586

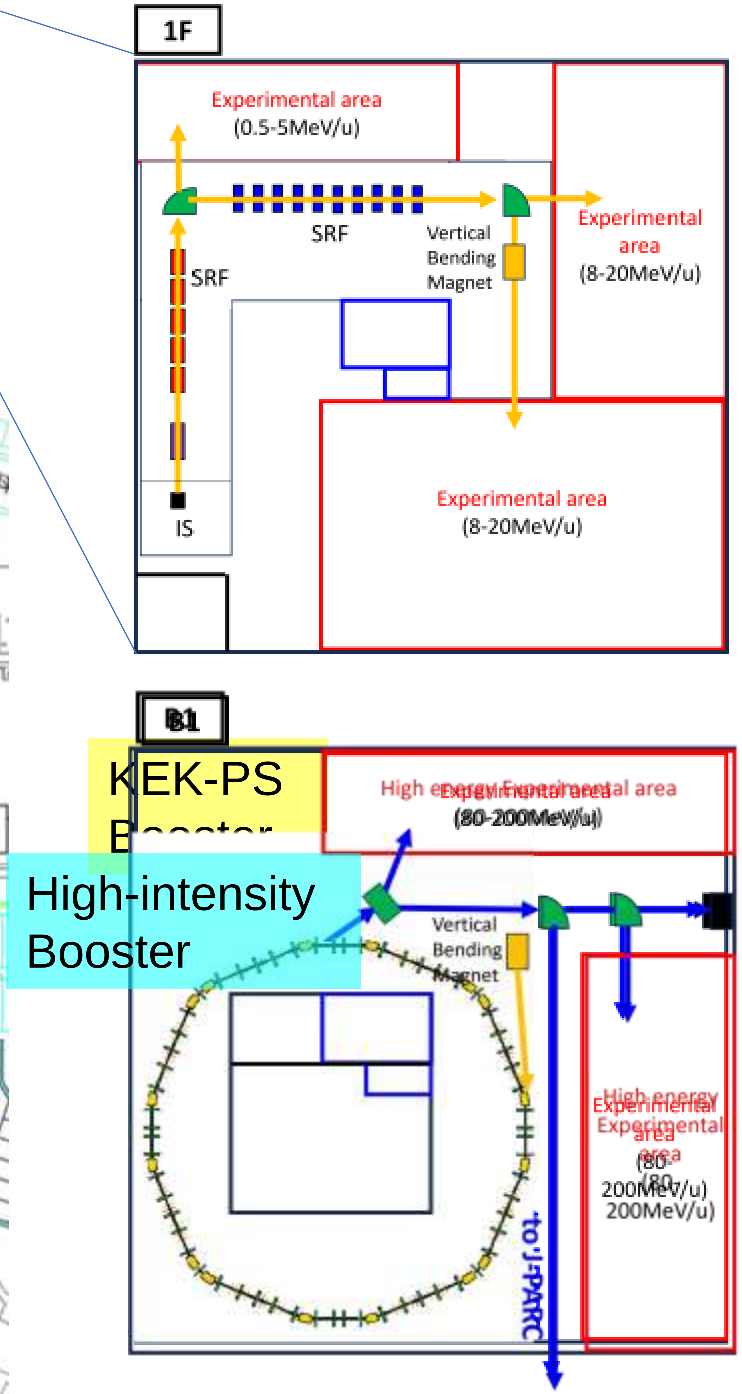
HI acceleration scheme for J-PARC-HI

- HI beam rate ~10^{11} Hz (World's highest rate)
  - Interaction rates up to ~10^{8}Hz
- E_{lab} (Au) = 1-12 AGeV
- $\sqrt{s_{NN}}$ (Au) = 1.9-4.9 GeV



HI Injector and facility





Conceptual design
by H. Harada (J-PARC)

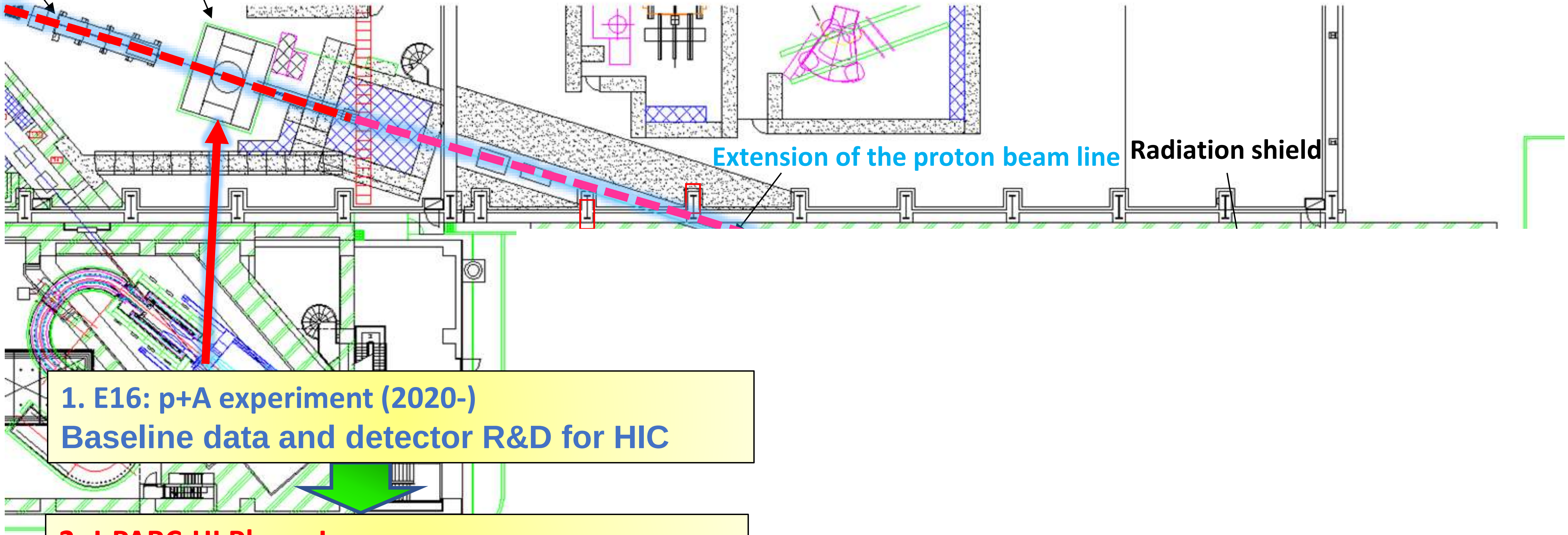
"Tokai HI Frontier Project" at JAEA

- Super-heavy nuclear physics
- Nuclear chemistry
- Reactor fuels and materials
- J-PARC-HI Injector

Phase I
10^8 / spill

Phase II
10^{11}/ spill

J-PARC-HI Staging Strategy (Experiments)



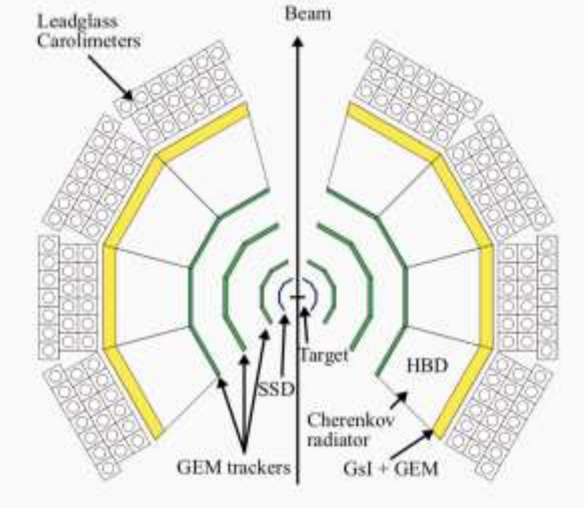
1. E16: p+A experiment (2020-)
Baseline data and detector R&D for HIC

2. J-PARC-HI Phase-I
Upgraded E16
Low-rate HIC (up to ~10^8 Hz HI beams)

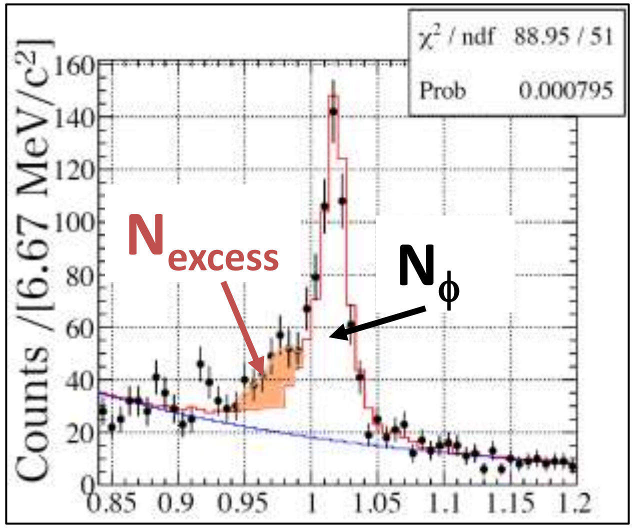
3. J-PARC-HI Phase-II
Large acceptance high-rate spectrometer
(up to ~10^{11} Hz HI beams)

ϕ mass modification in nuclei
J-PARC E16/E88 : e+e- and K+K- measurements in p+A

E16: dielectron including ϕ→e+e-



Expected spectrum (15k ϕ, p+Cu)



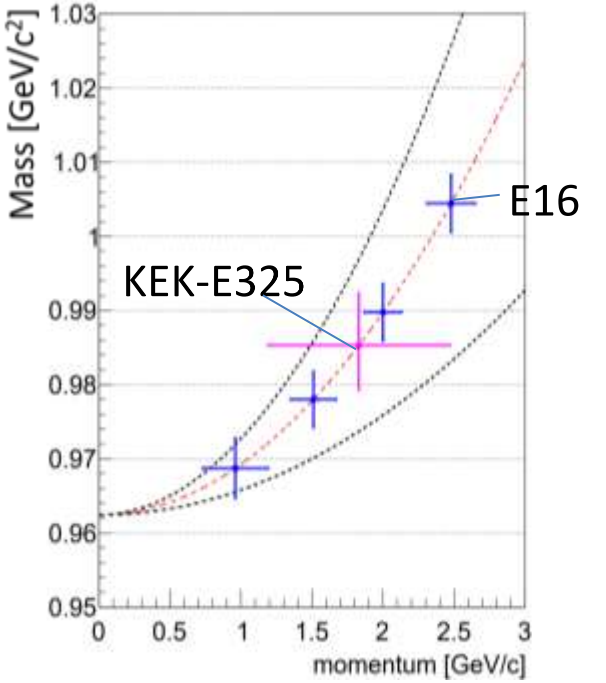
Previous experiment KEK-E325 ~ 3k ϕ→e+e-

JFY2020-2024 Commissioning completed

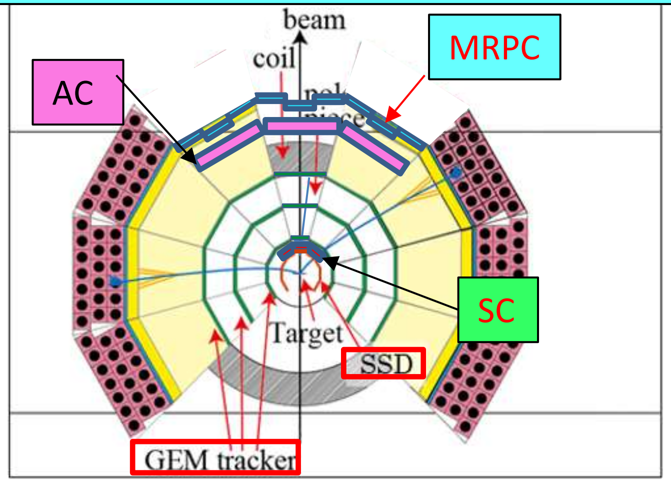
JFY2025- Physics Run 1
~15k ϕ→e+e- (6x E325)

JFY2027?- Physics Run 2
~69k ϕ→e+e- (23x E325)

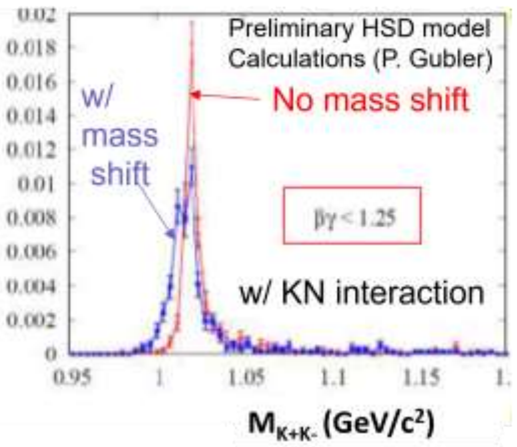
Mass vs p (30k ϕ, p+Cu)



E88: ϕ→K+K- (proposed in 2022)



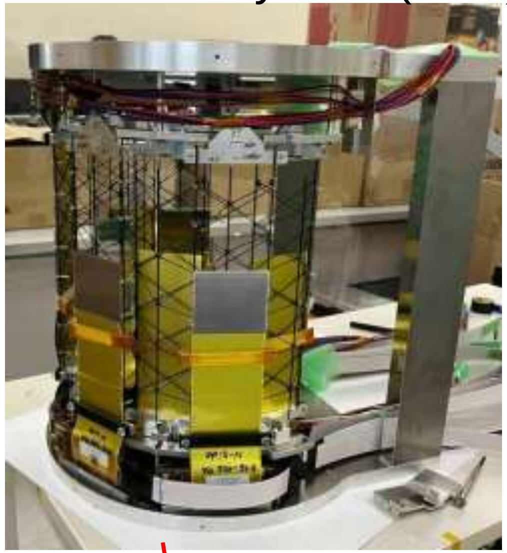
~1M ϕ→K+K-

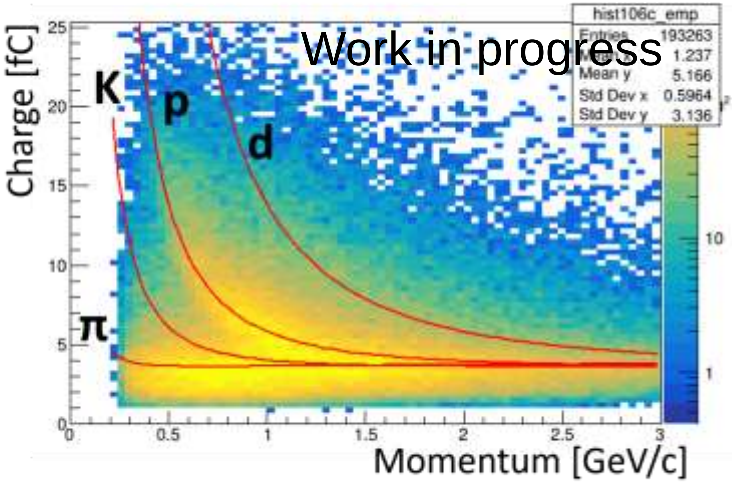


E16 detectors and performance

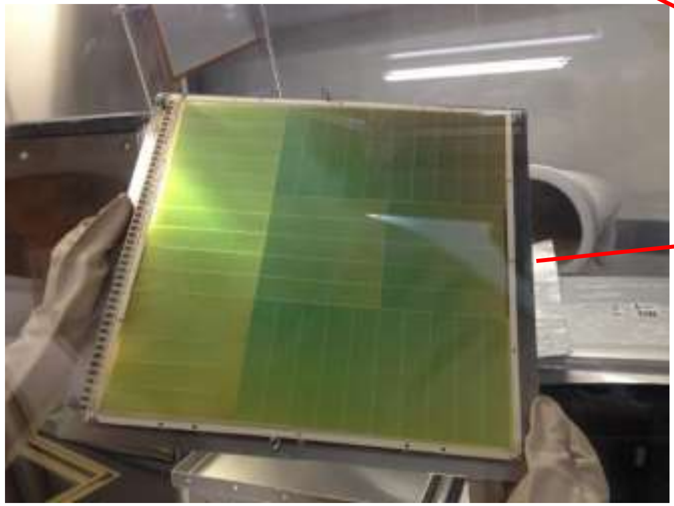
GEM Tracker (GTR)

Silicon Tracker System (STS) from CBM

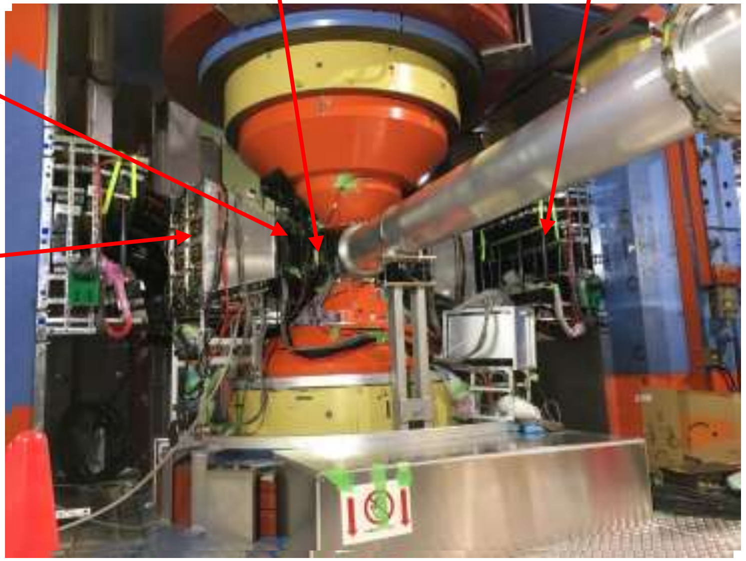


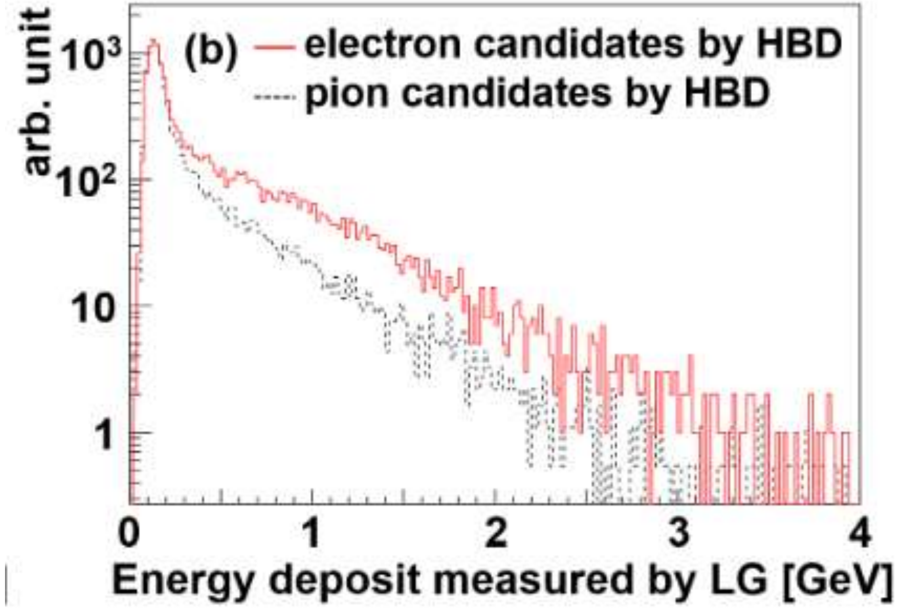


Hadron Blind Detector (HBD)

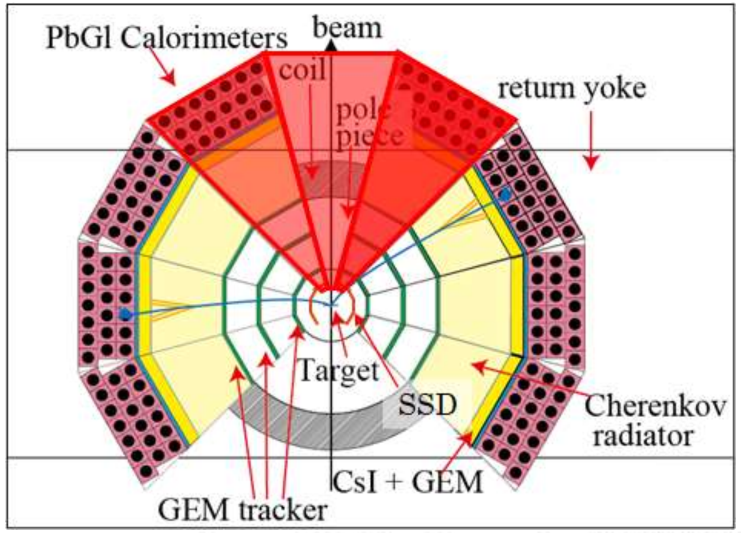


Lead Glass Calorimeter (LG)

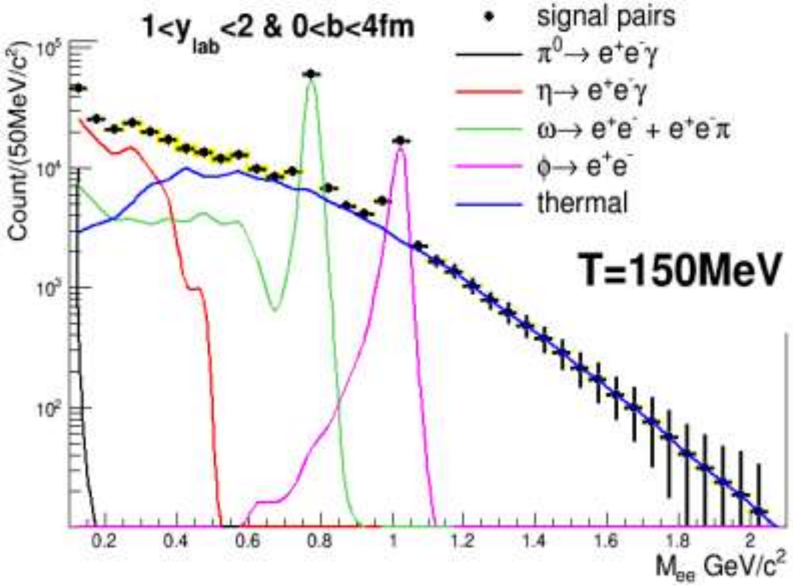




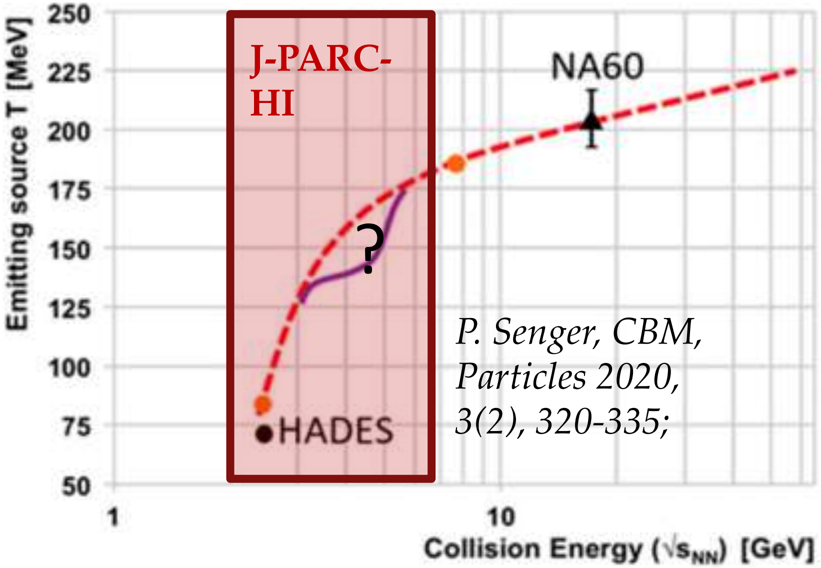
Proposal for Phase I (2022)
Thermal photon measurements w/ dielectrons



► Upgrade of forward trackers and EM calorimeter of E16



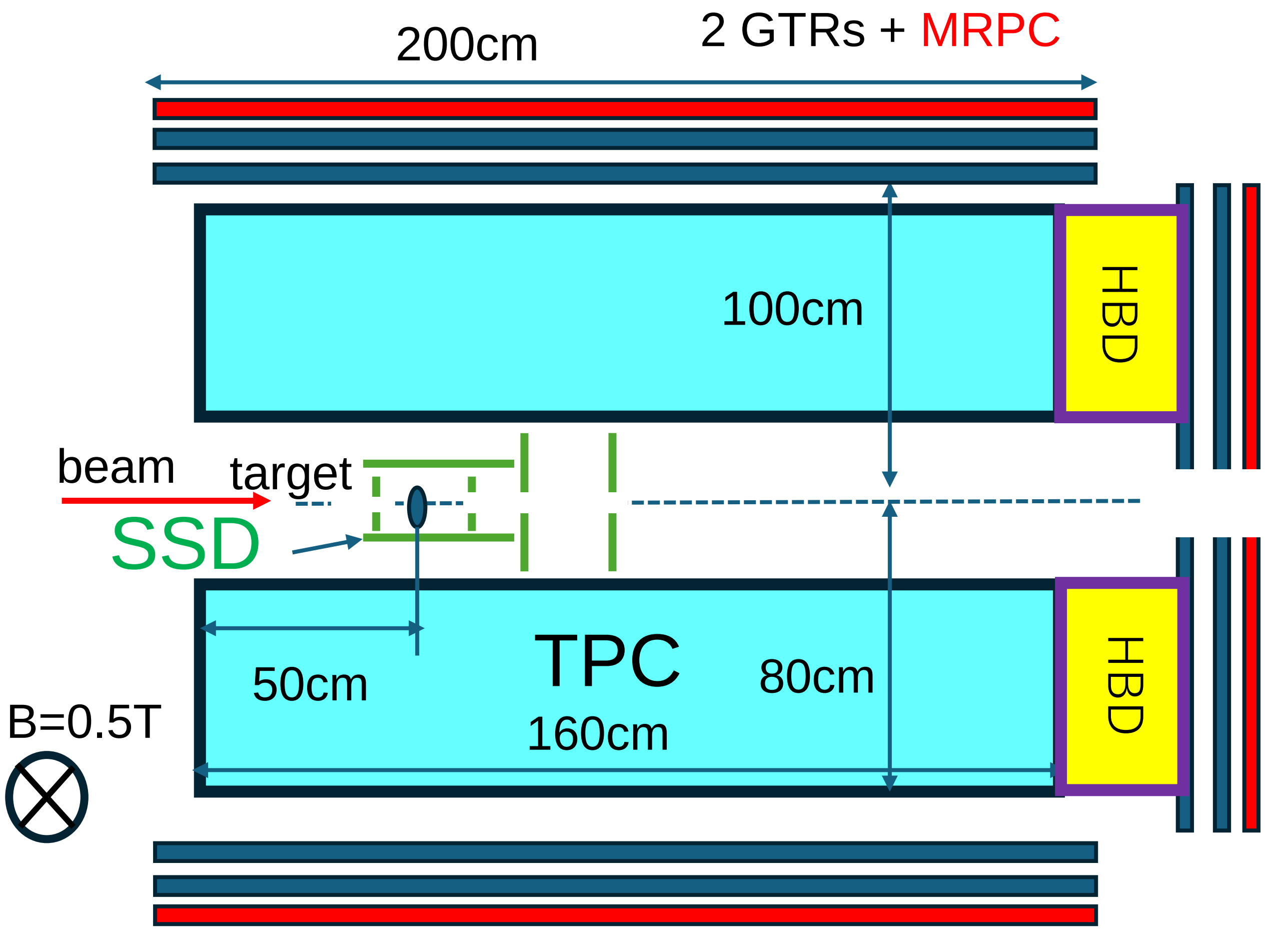
100-day
Beam time

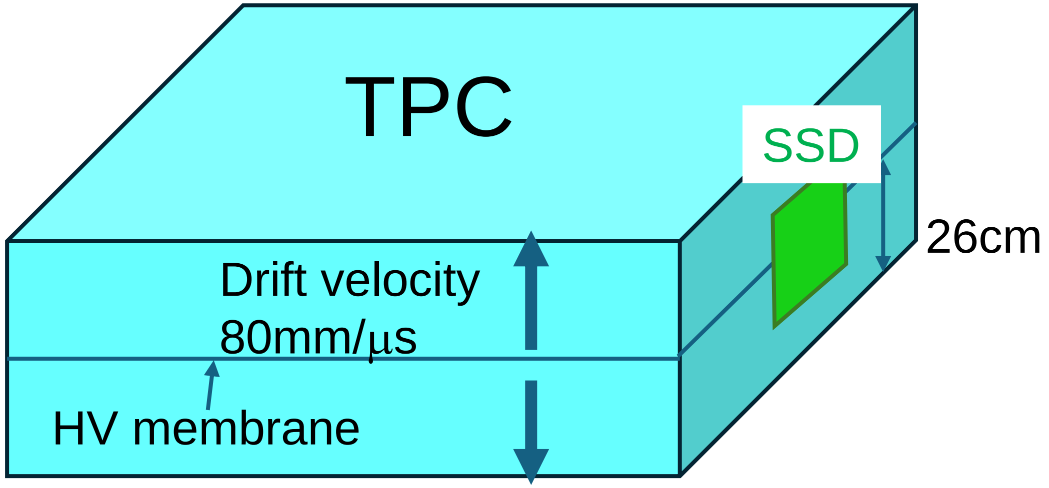


P. Senger, CBM, Particles 2020, 3(2), 320-335;

New spectrometer design for “Phase 1.5”

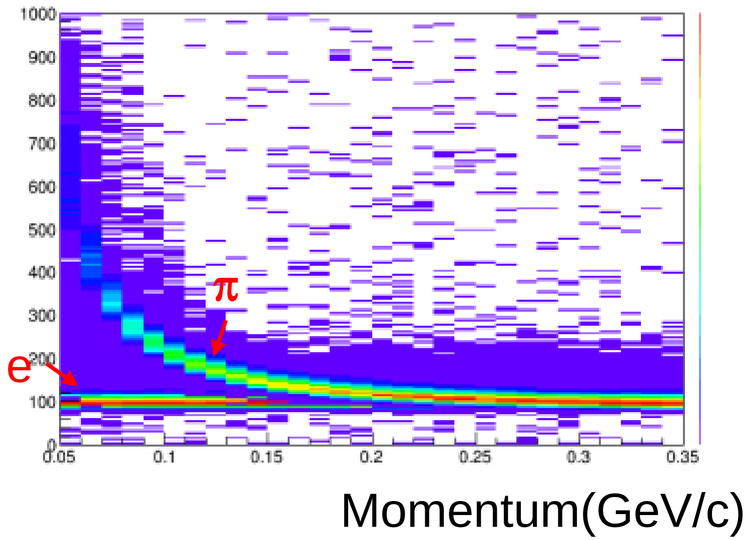
- Studies in progress
- In Phase I and Phase II up to 1×10^8 Hz
- Large acceptance measurements of dielectrons and hadrons





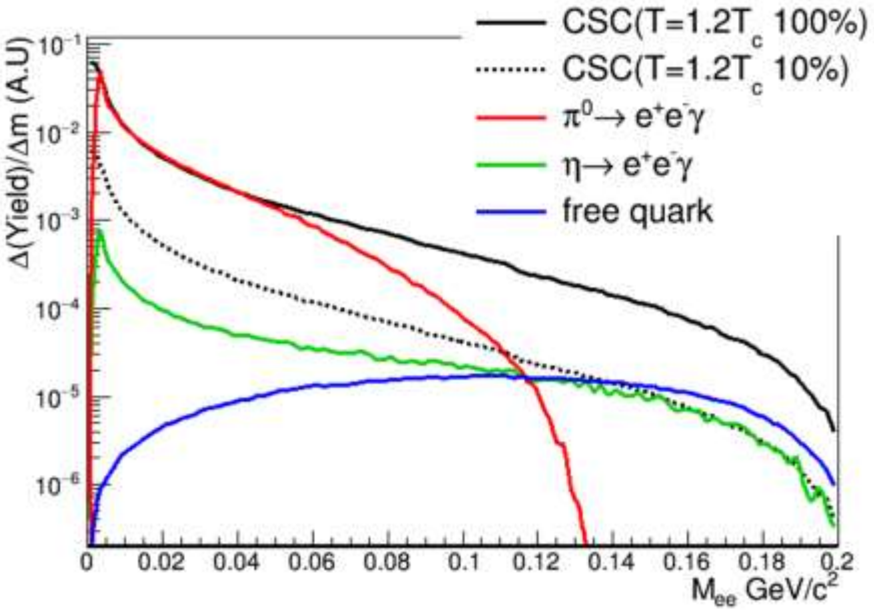
TOF : 2σ e-π separation p<=0.4 GeV/c

dE/dx of SSDs



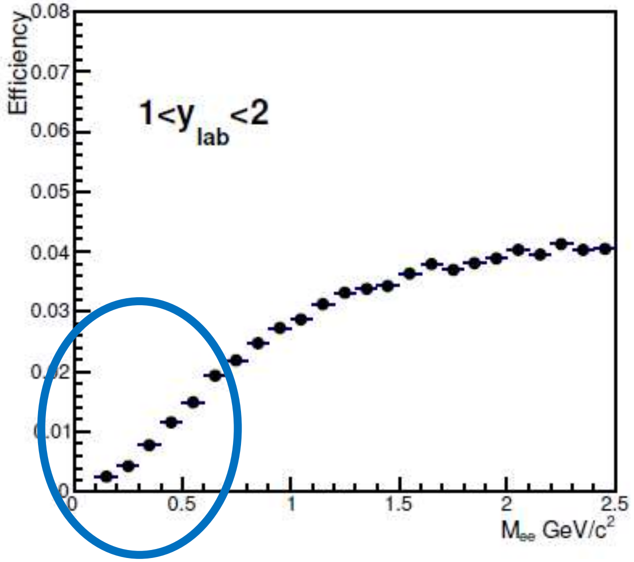
Low-mass di-electron measurement

e+e- invariant mass spectra
from CSC precursor

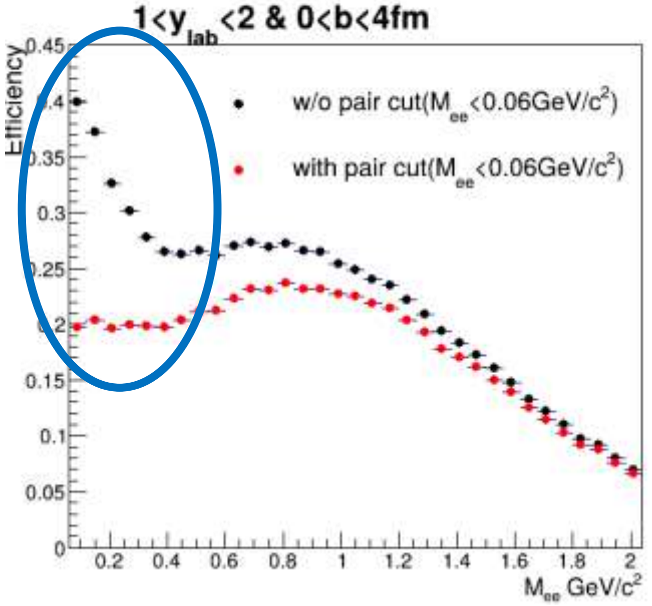


Based on theory calculation by T. Nishimura, M. Kitazawa, T. Kunihiro, PTEP 2022, 093D002

PHASE1 pair efficiency



PHASE1.5 pair efficiency



- Improvement of pair efficiency
  - Factor of 10～100 at LMR
  - Factor of ～5 at IMR

Summary and Outlook

- A variety of physics can be studied using EM probes in high-density regime of QCD phase diagram.
- World's facilities (STAR BES II, HADES, NICA, CBM, J-PARC-HI, HIAF) plan to measure dileptons to study;
  - Thermal dileptons in LMR and IMR
  - Search for precursor of CP and CSC at low mass
  - Chiral mixing at IMR
- J-PARC-HI
  - Design of HI injector and the building is in progress. Conceptual design report in the end of JFY2024.
  - New design for a large acceptance spectrometer is underway.

Exciting new results are expected from existing and new facilities.

Related presentations at HP2024

- I. C. Udrea, Low-mass, low-momentum virtual photon measurements with HADES at SIS18 (Poster 9/24)
- Y. Wang, Reconstruction of photons and neutral mesons in heavy-ion collisions with MPD (Poster 9/24)

Special thanks to:

T. Galatyuk (TU Darmstadt), N. Xu (LBL), C. Sasaki (U Wroclaw, Hiroshima U), and M. Kitazawa (Kyoto U)