

The 4th J-PARC Symposium, Mito, Japan, 2024/10/15

Physics of J-PARC Heavy-Ion Project

Masakiyo Kitazawa

(YITP, Kyoto)

for J-PARC-HI Collaboration

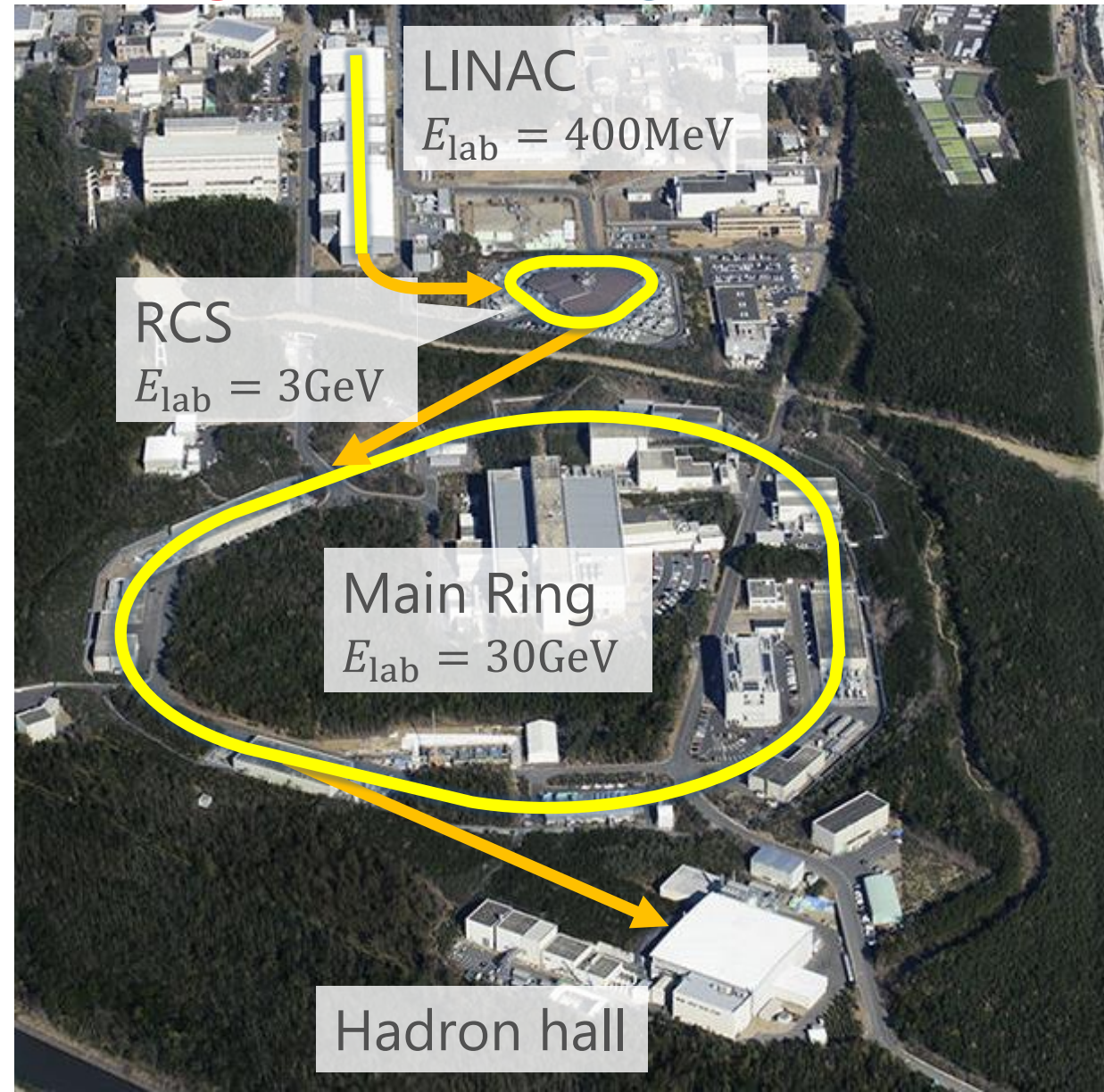
An aerial photograph of the J-PARC (Japan Proton Accelerator Research Complex) facility. The image shows a large industrial and research complex with numerous buildings, parking lots, and roads. The facility is situated along a coastline, with a large body of water to the right and a river or bay to the left. The surrounding area includes green fields and residential neighborhoods. Overlaid on the image is white text with a yellow highlight for the phrase 'heavy-ion beams'.

Imagine J-PARC 20 years from now!

New experiments with **heavy-ion beams** will enrich the future of J-PARC.

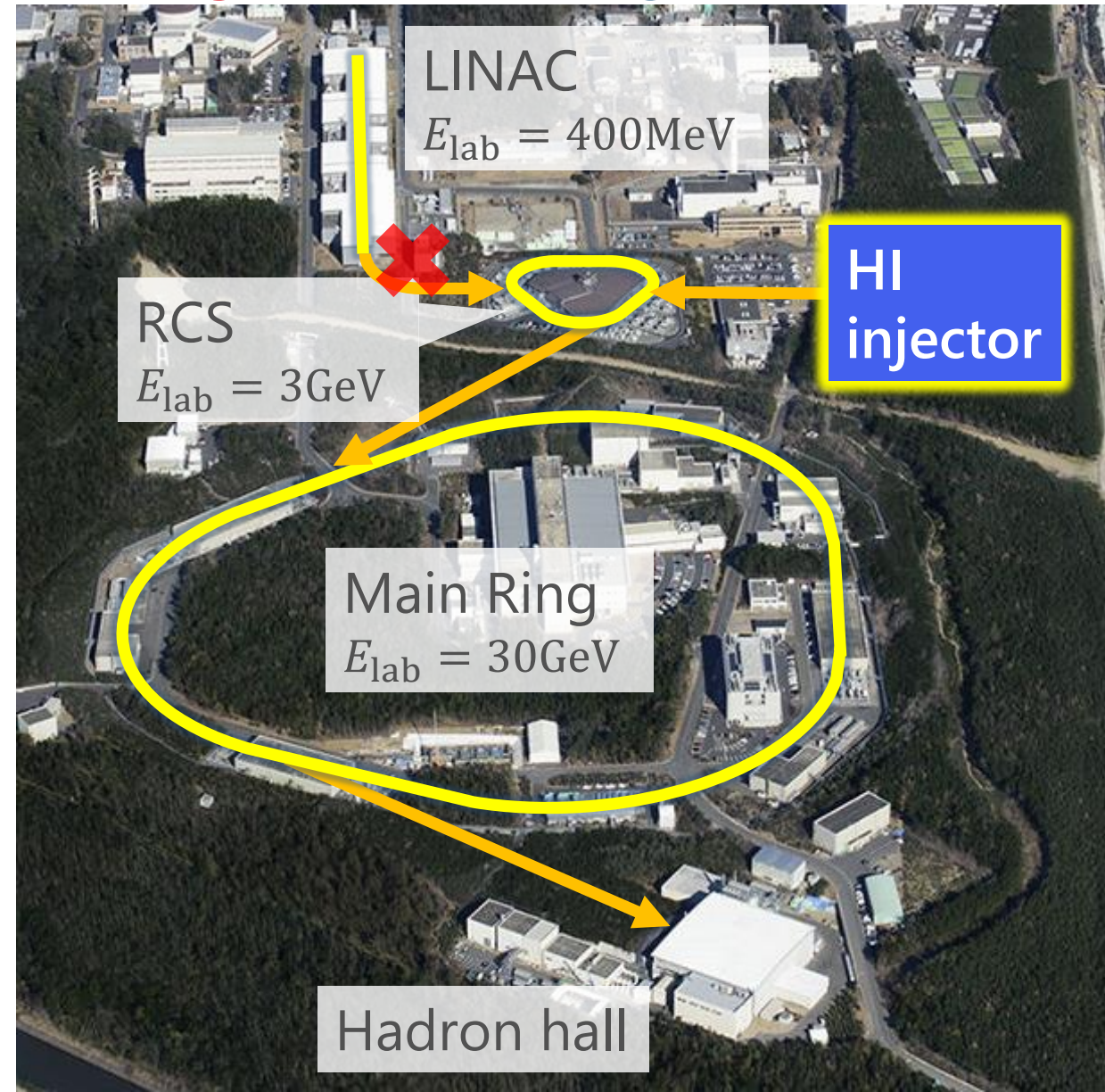
J-PARC-HI = J-PARC Heavy-Ion Project

- **New HI injector** + existing accelerators (**RCS, MR**)
- Heavy-ion beams with **world highest luminosity**
- Realize various new experiments at J-PARC



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Who am I??

Masakiyo Kitazawa

Yukawa Institute for **Theoretical** Physics, Kyoto U.

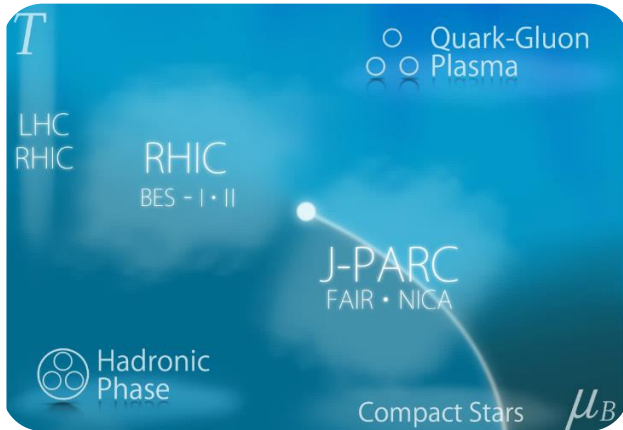
Working with J-PARC-HI since 2014

Research Interests:

- QCD in medium
- Relativistic heavy-ion collisions
- Lattice QCD Monte-Carlo simulations

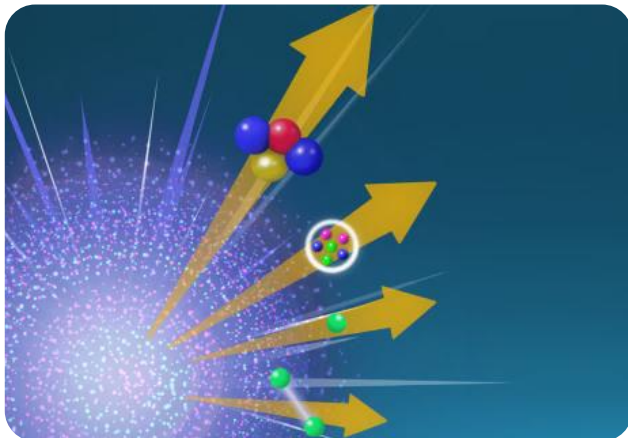


Relativistic HI Collisions at J-PARC: Physics Goals



Exploring extremely dense medium

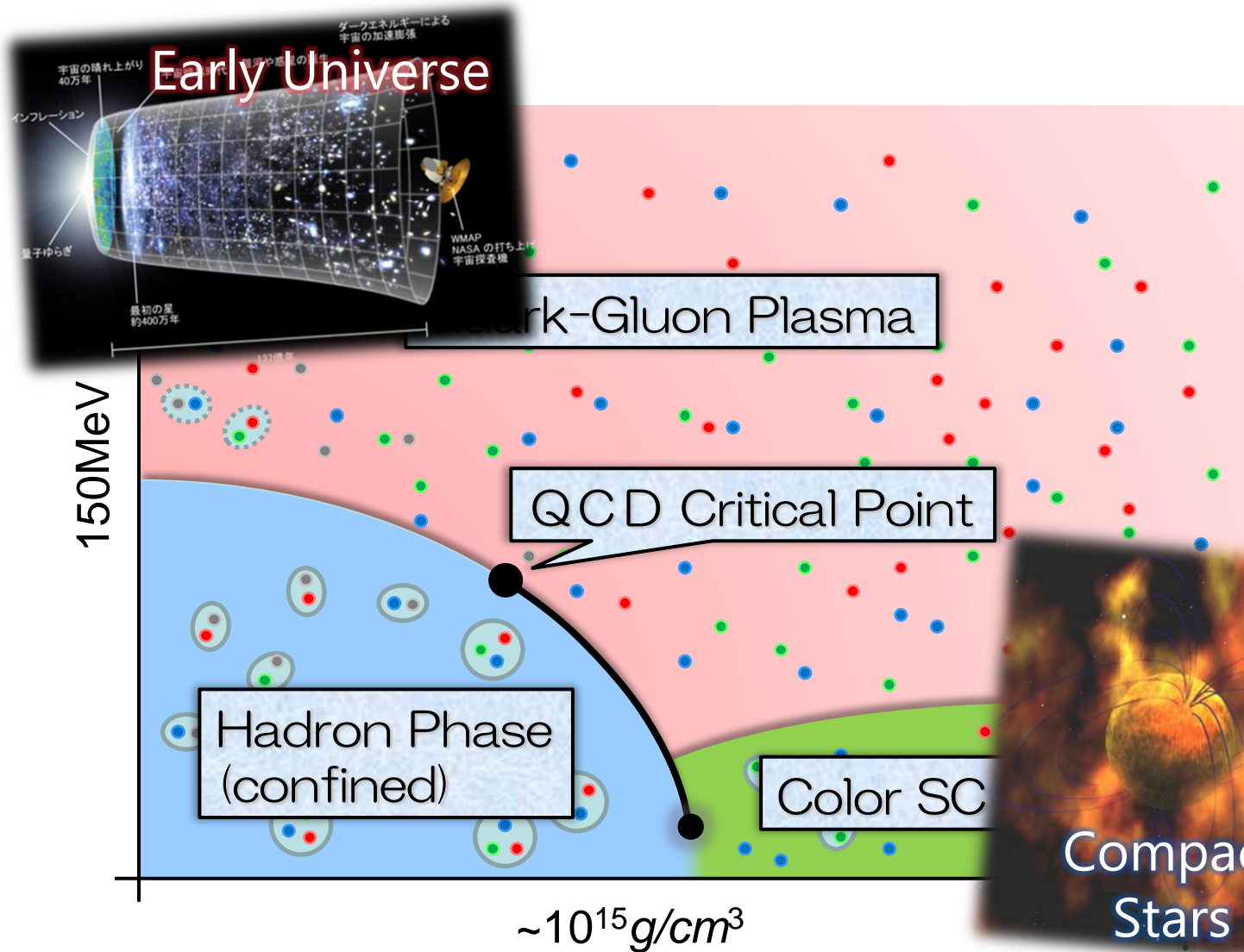
- QCD phase transitions
- Equation state for neutron stars



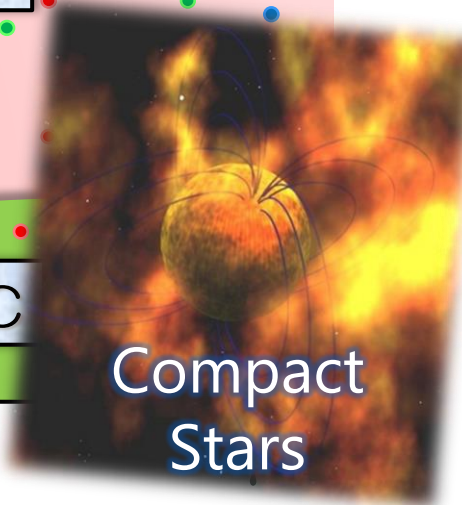
Hadron/hypernuclear physics

- Hadron interaction/structure
- Search for rare events
- Hypernuclear physics

QCD Phase Diagram

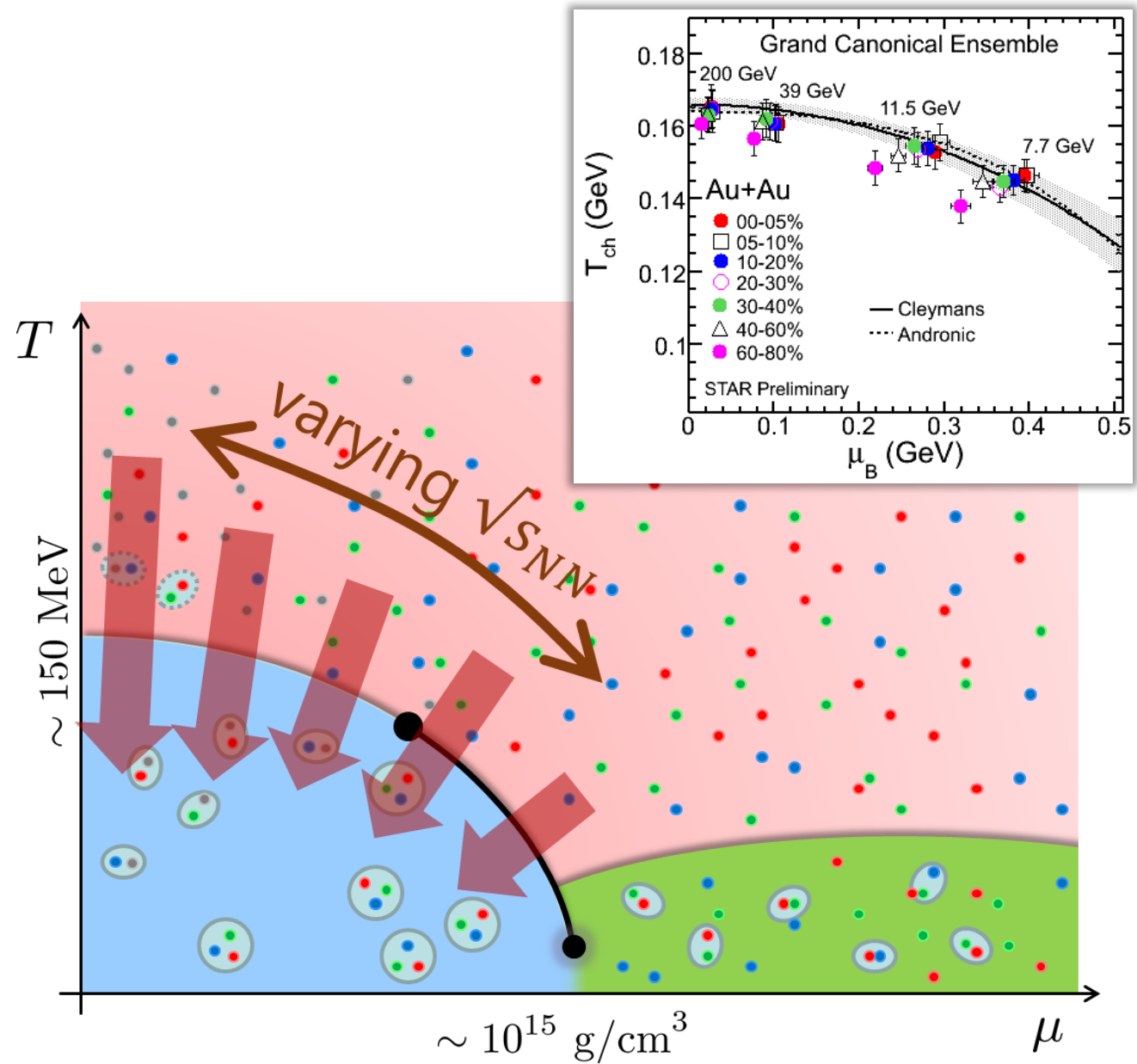
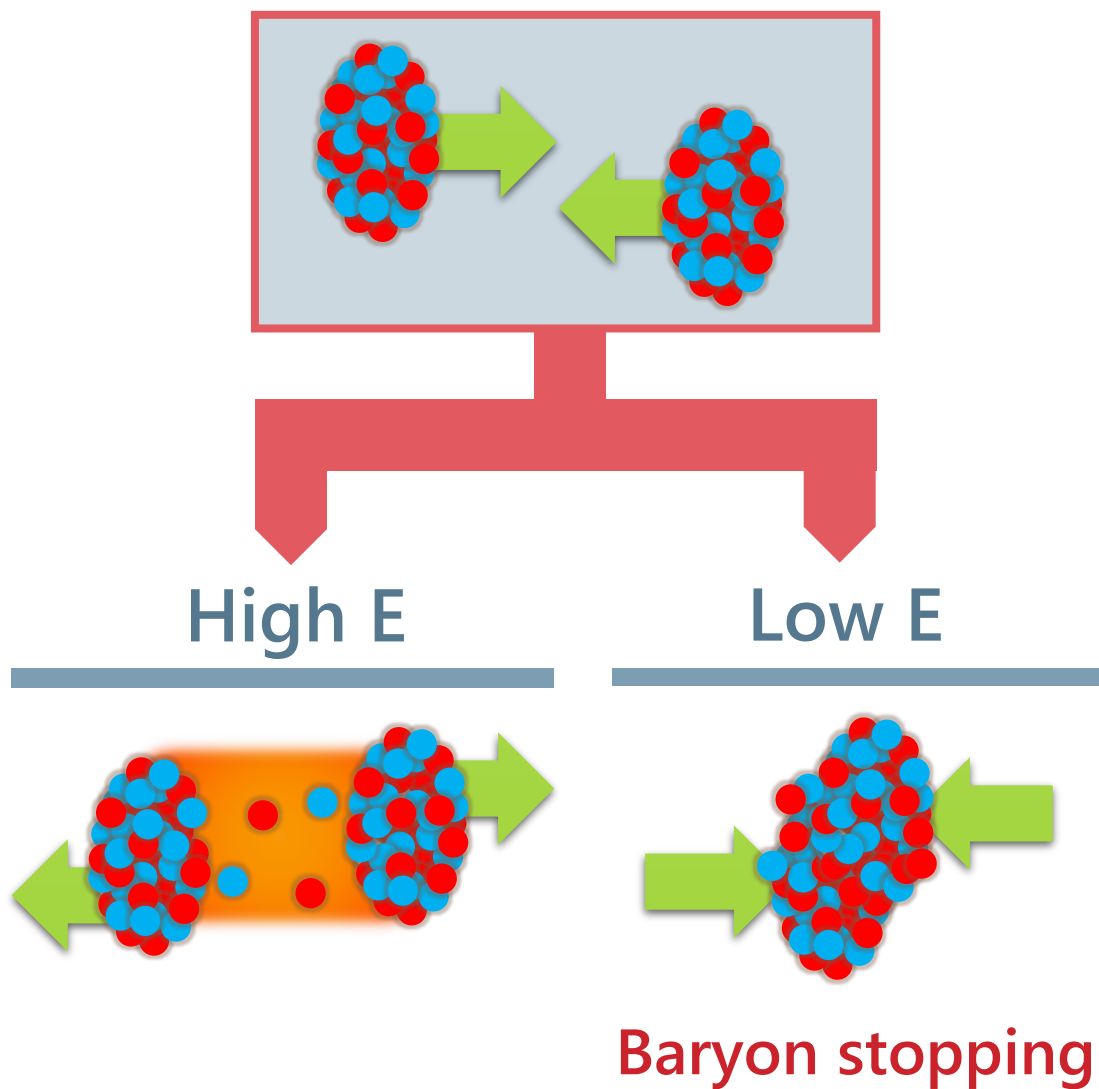


- ❑ Crossover at zero density
- ❑ Possible **first-order transition** and **QCD critical point** in dense region
- ❑ Multiple QCD-CP? **MK+** ('02)
- ❑ **Color superconducting phases** in dense and cold quark matter

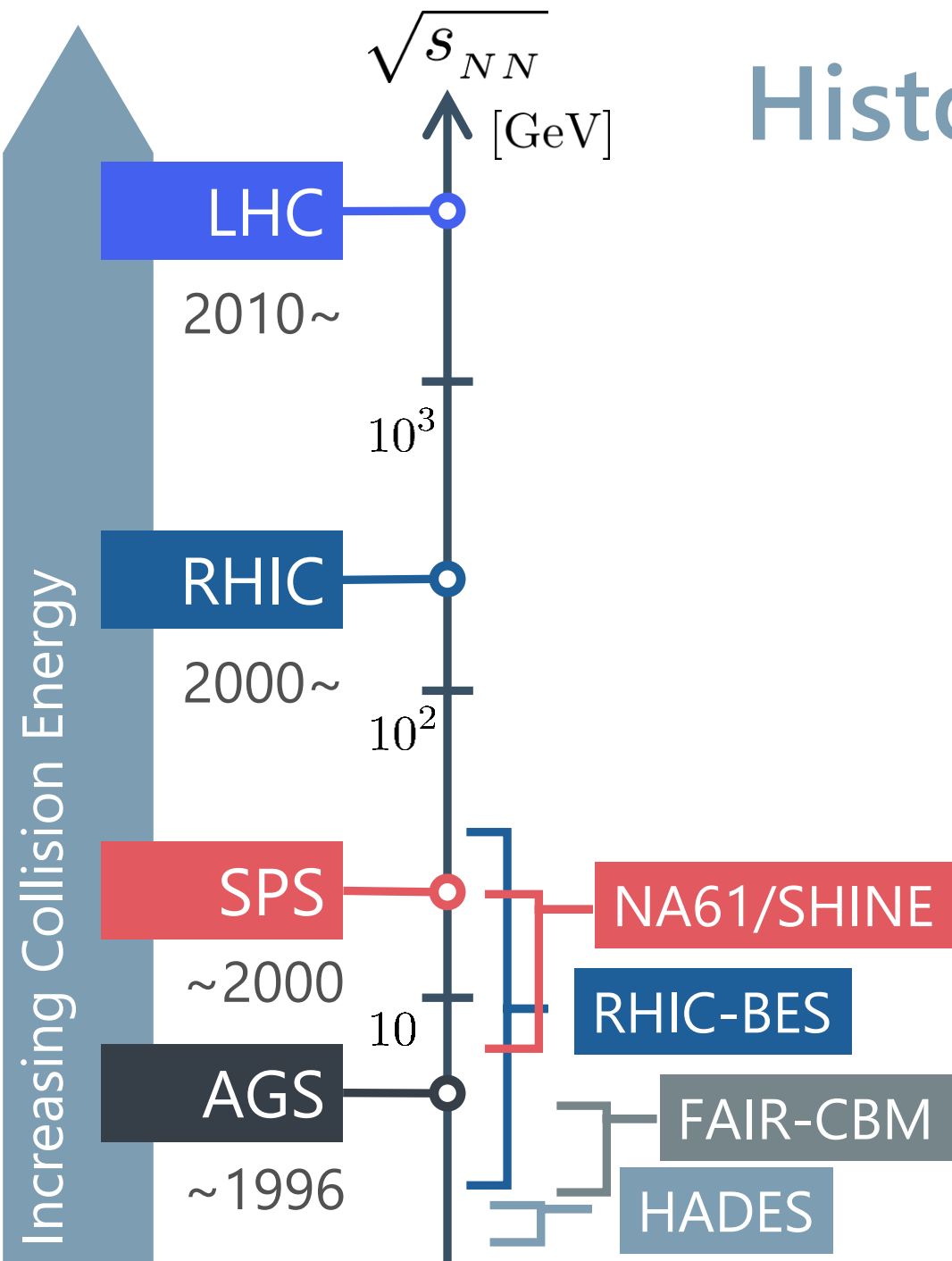


Beam-Energy Scan

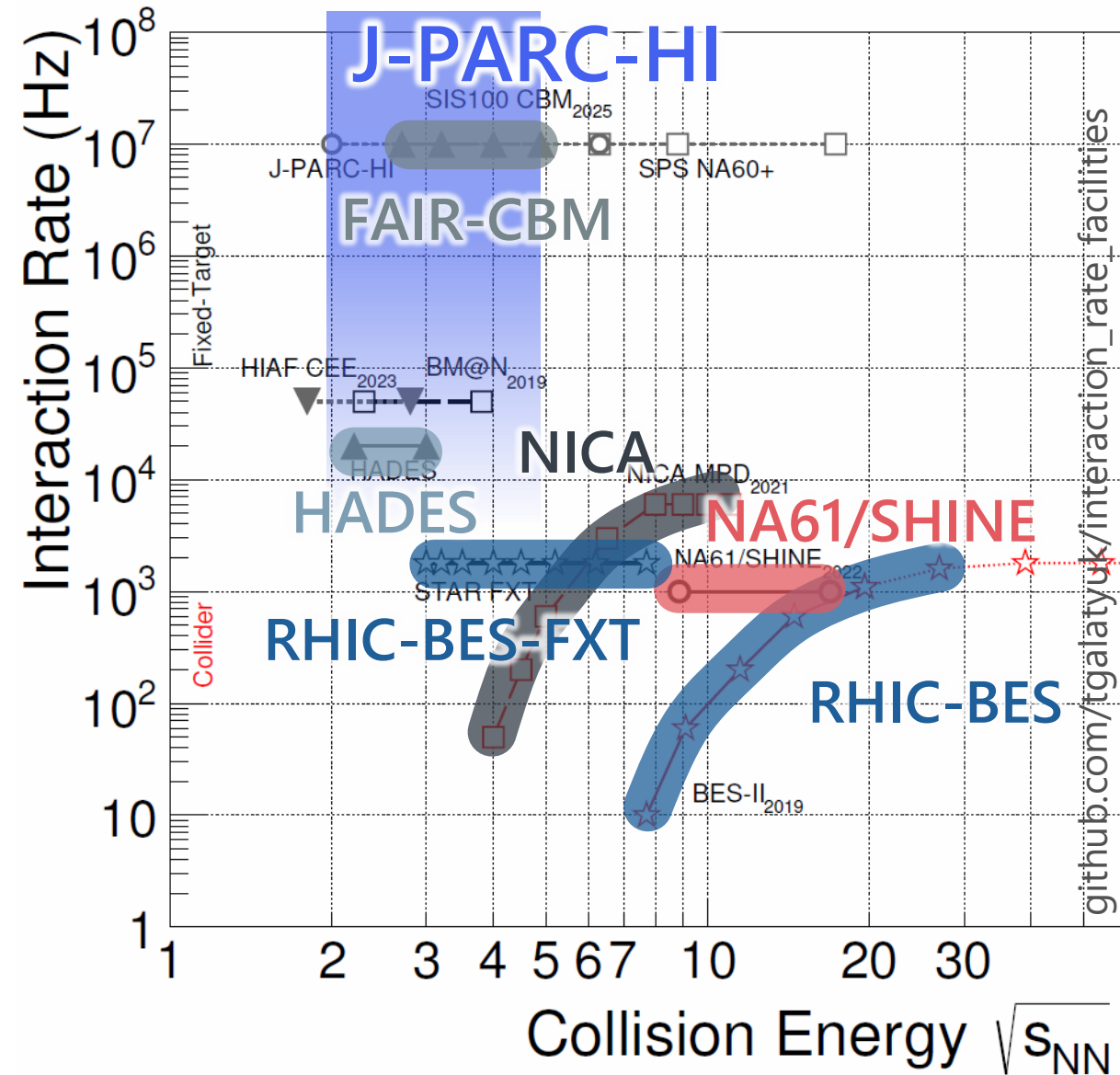
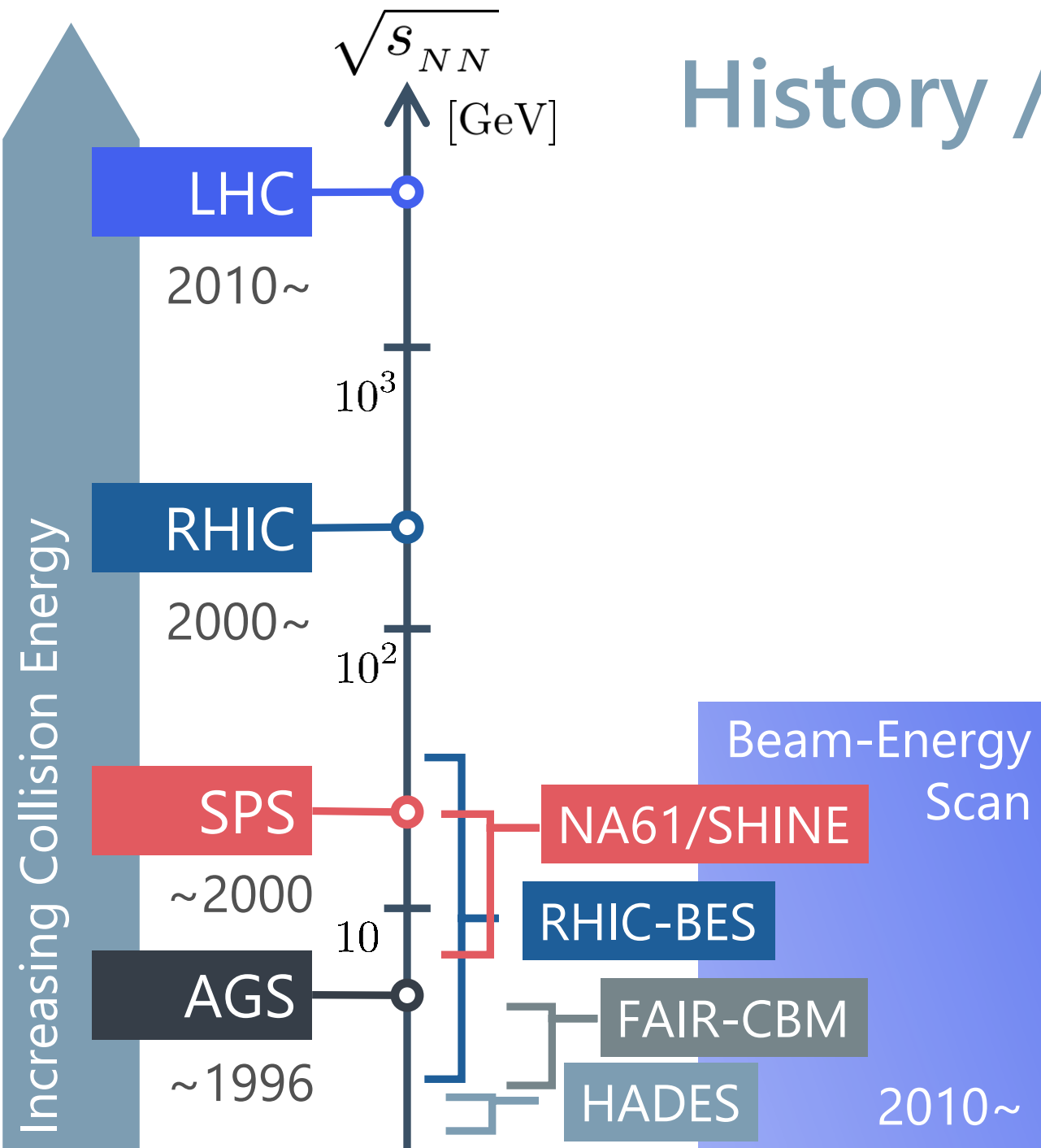
STAR, 2012



History / Current Status of HIC



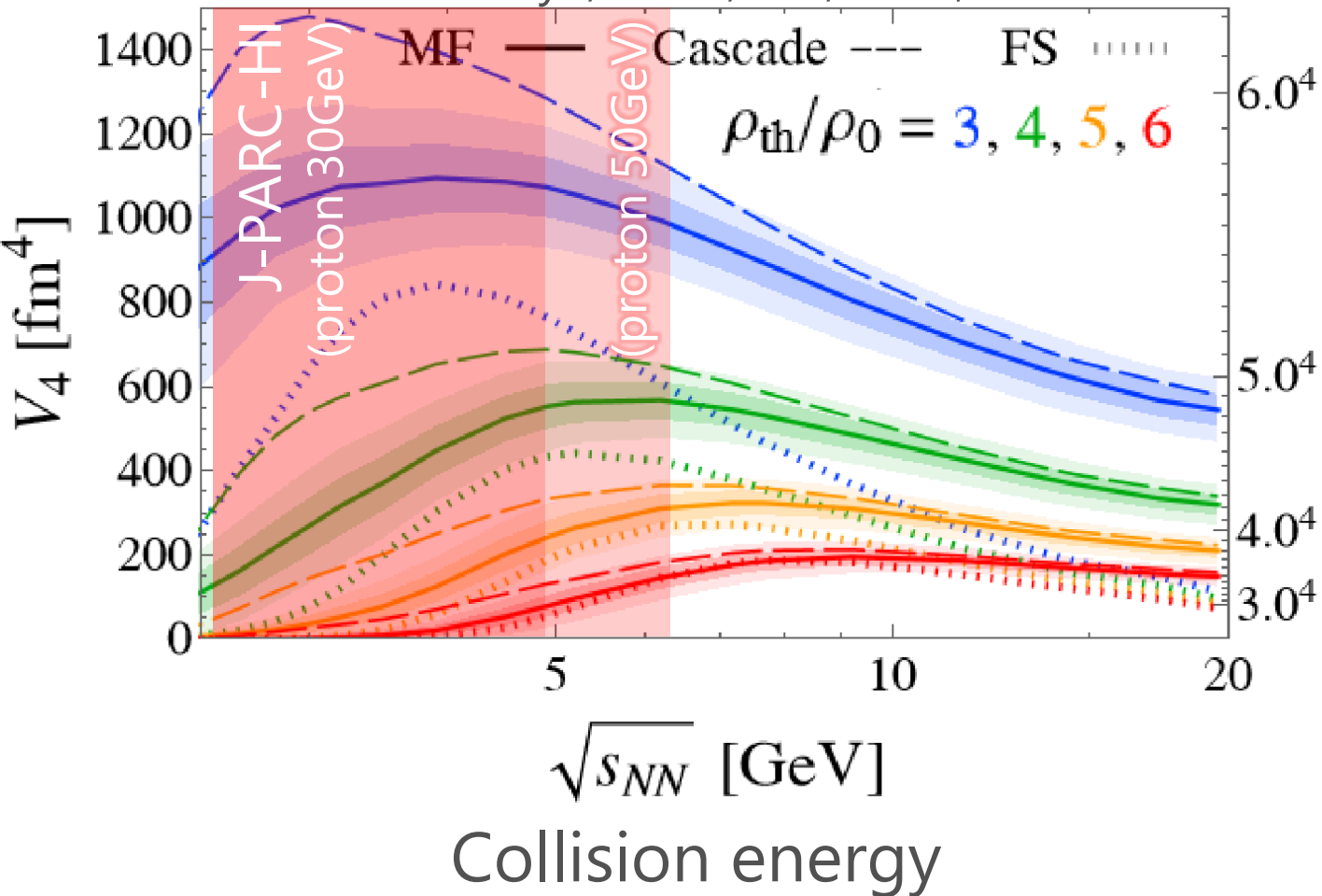
History / Current Status of HIC



How High Density? Where is optimal $\sqrt{s_{NN}}$?

Four-volume of high-density region

Taya, Jinno, MK, Nara, 2409.07685



Medium with $\rho > 3\rho_0$ can be formed for $V_4 \simeq (6 \text{ fm})^4$ at J-PARC-HI energy

The density is comparable with the cores of neutron stars



J-PARC-HI = experiments to create **the highest baryon-density matter in the Universe**

Quark-Gluon Plasma

Exploring Dense Medium



Equation of state



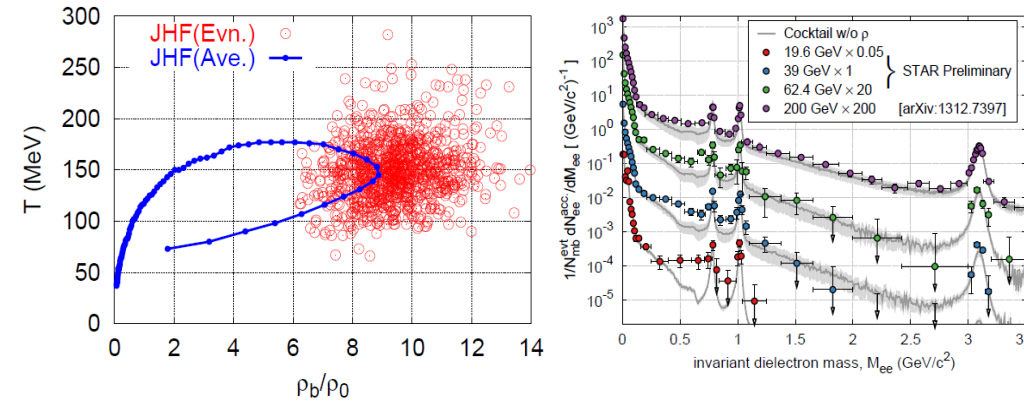
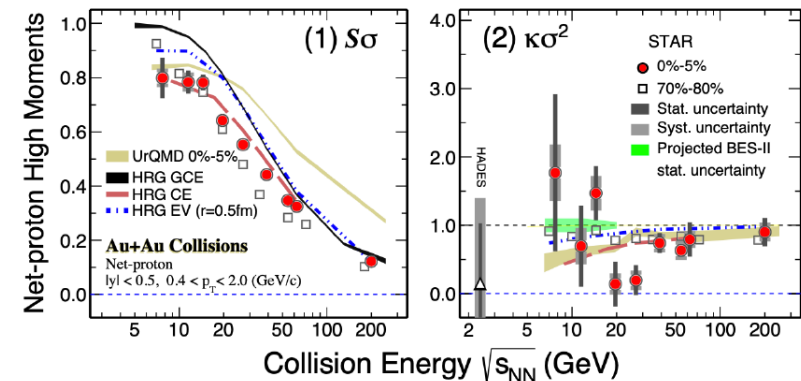
QCD critical point /
1st order transition /
Color superconductivity



Dilepton production rate



Event selection /
Higher correlations



J-PARC
FAIR • NICA

Compact Stars

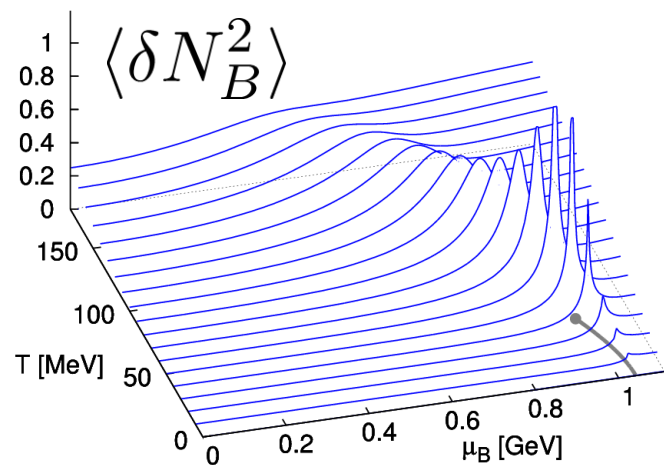
Event-by-event Fluctuations

Theoretical Predictions
on conserved charge fluctuations

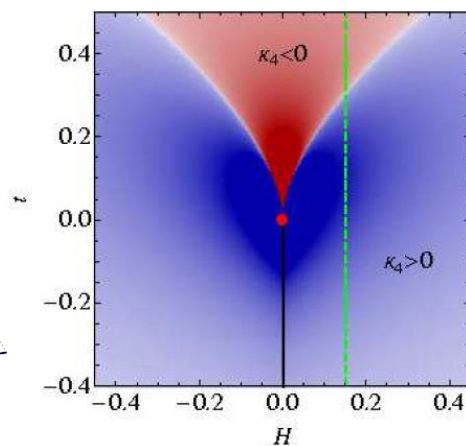


Experimental Result

- Higher-order cumulants
- Signal of QCD CP

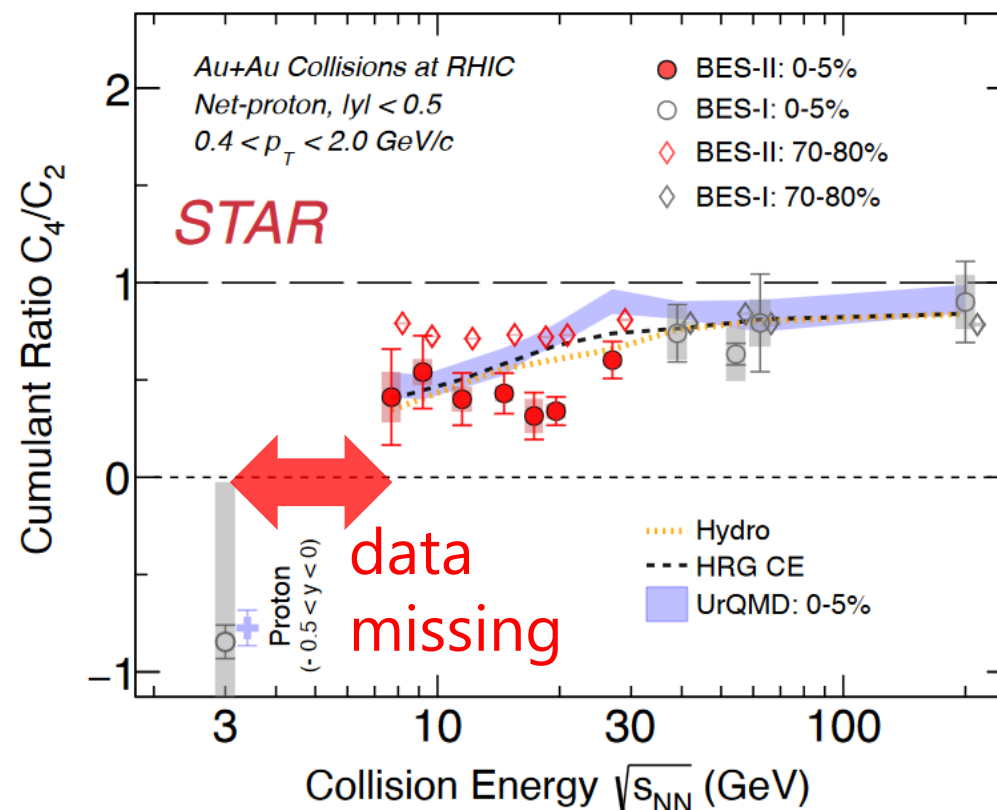


Asakawa, Ejiri, MK (2009)



Stephanov (2011)

STAR (2024)

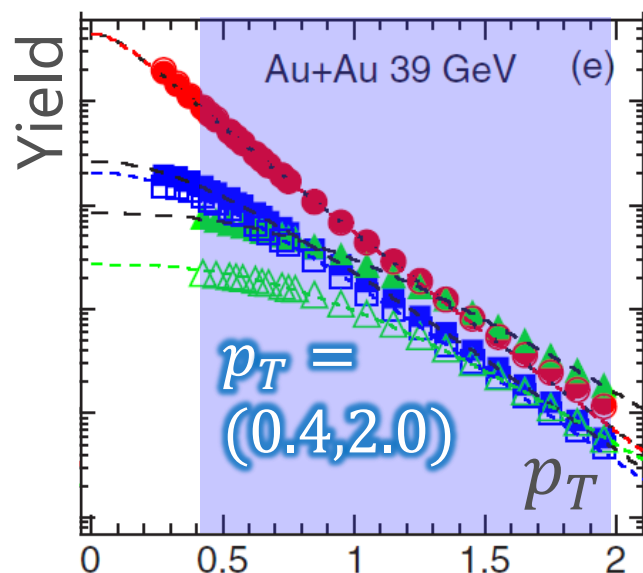


Baryon/Charge Cumulant Ratio

MK, Esumi, Nonaka, Nucl. Phys. A, 2023

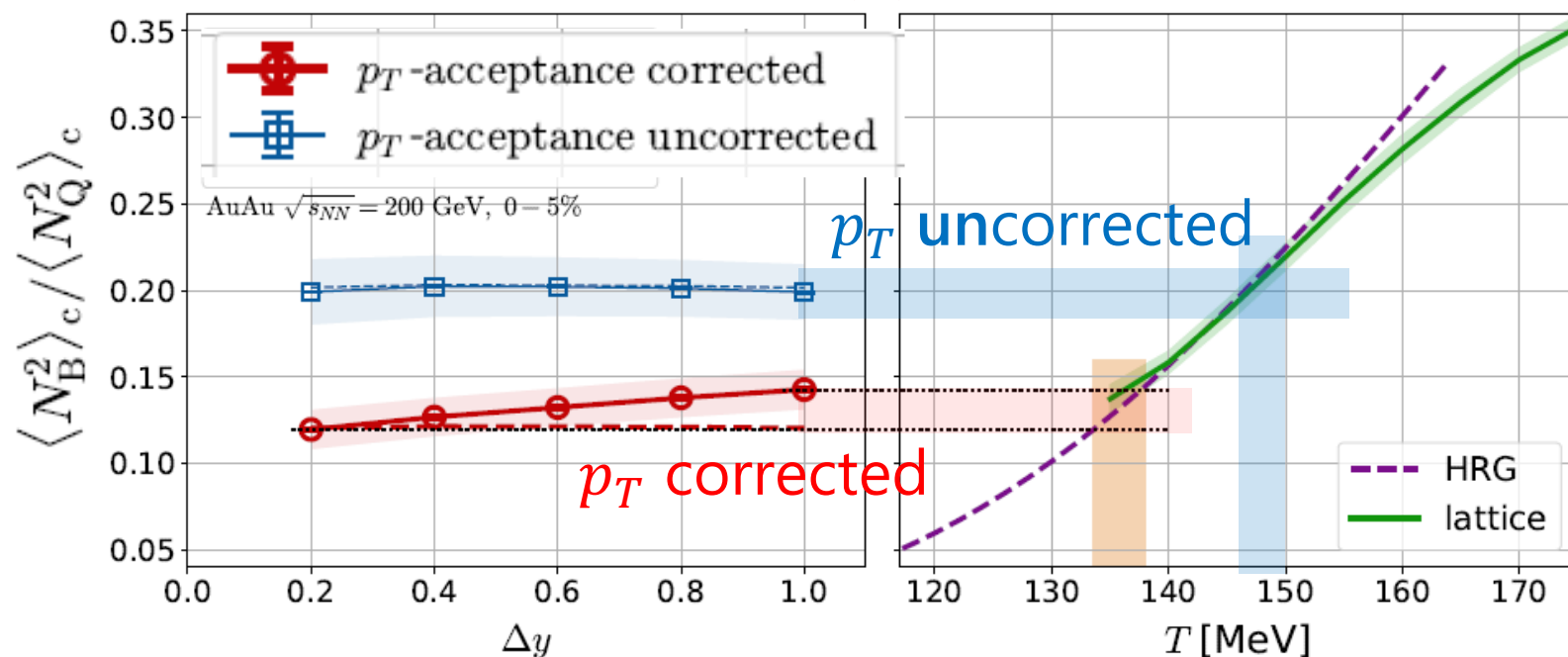
$$\langle N_B^2 \rangle_c / \langle N_Q^2 \rangle_c \simeq \chi_2^B / \chi_2^Q$$

p_T -acceptance correction



- Electric charge: **49%**
- Protons: **82%**

STAR, 200GeV \longleftrightarrow Lattice QCD + HRG

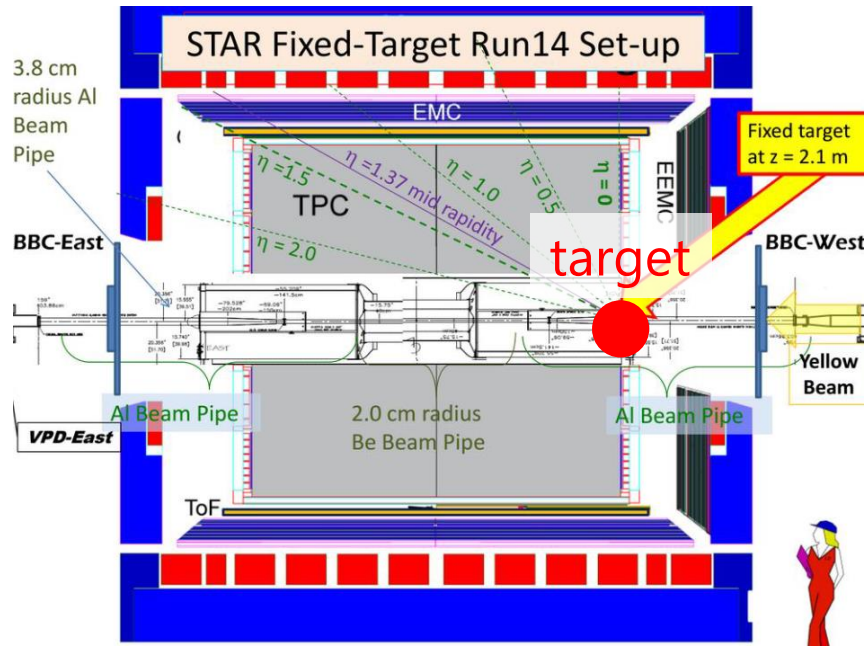


- **Finite acceptance modifies the ratio strongly.**
- Wider acceptance/efficiency is desirable.

Acceptance of Detectors

STAR Fixed Target

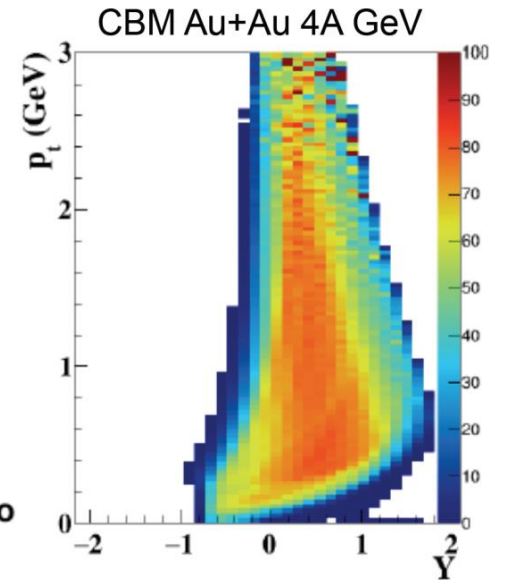
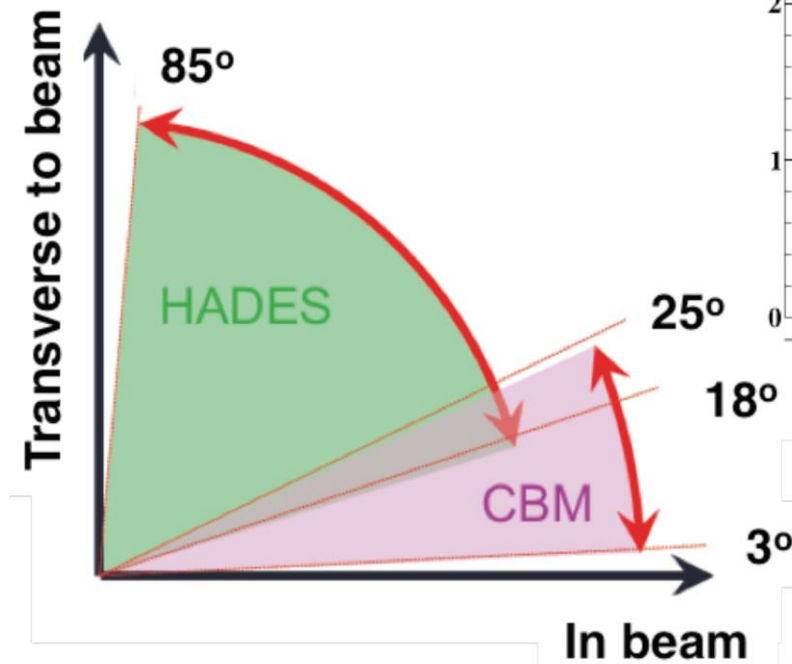
$$3 < \sqrt{s_{NN}} < 7.7 \text{ GeV}$$



from slide of D. Sebra

FAIR (GSI)

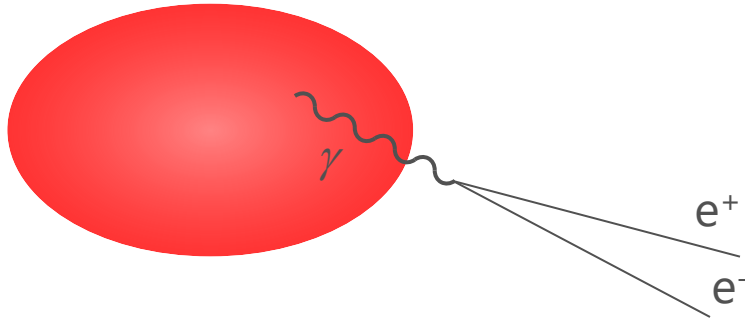
$$2 < \sqrt{s_{NN}} < 5 \text{ GeV}$$



Each detector has individual acceptance and efficiency.

➤ Checking detector-response correction is important.

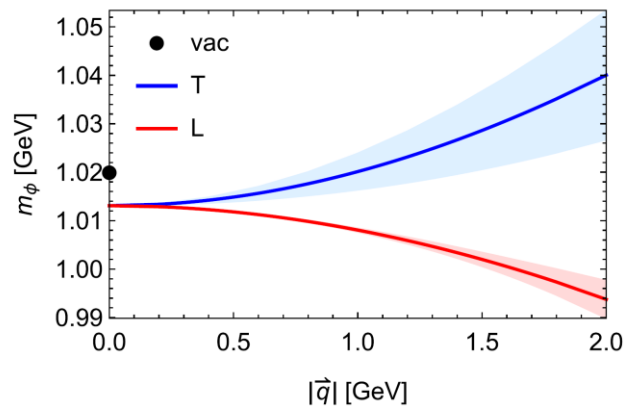
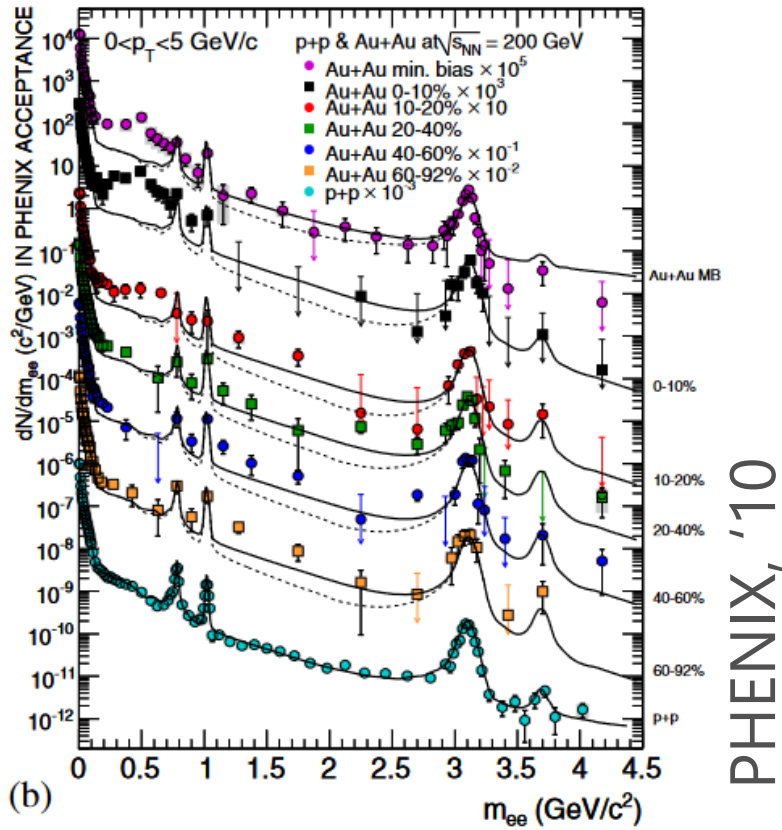
Dilepton Production Rate



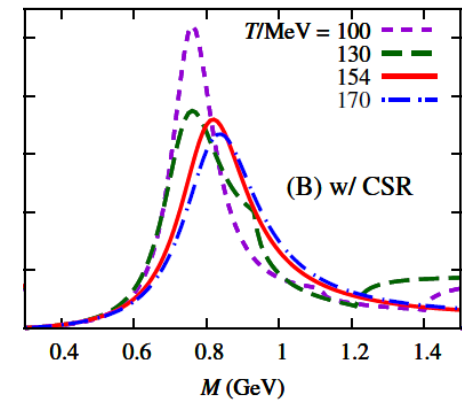
- Generated by the decay of virtual photons
- Carry information of primordial medium

Physics accessible with DPR

- Medium temperature
- Dispersion relations
- Chiral mixing by chiral restoration
- Signal of phase transitions



Kim, Gubler, 2020



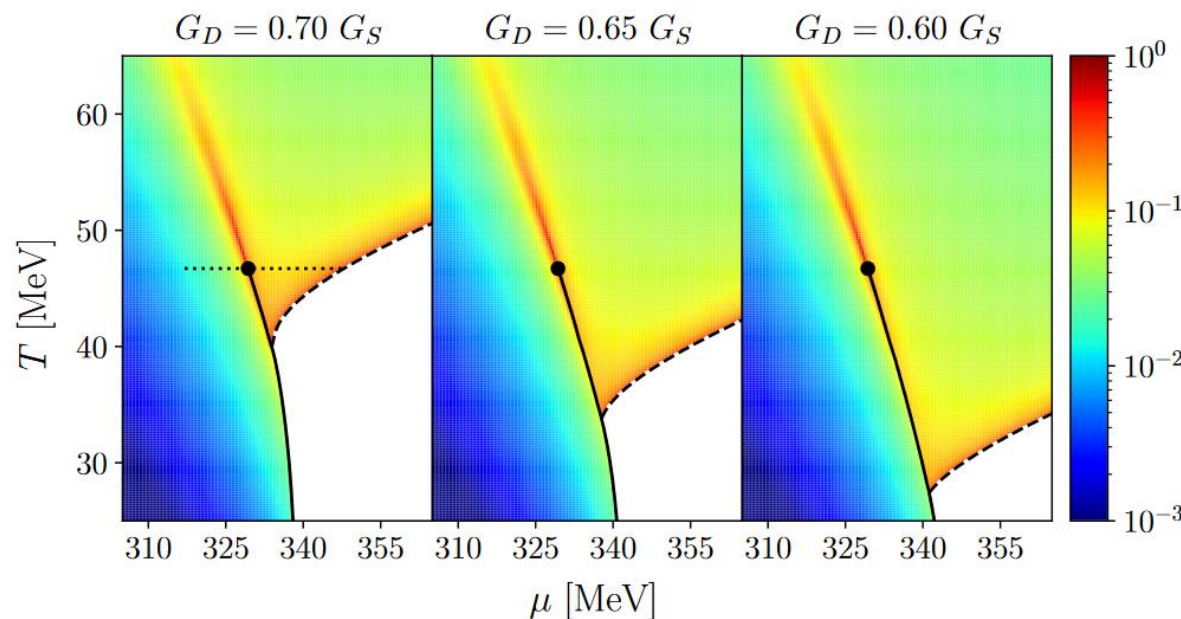
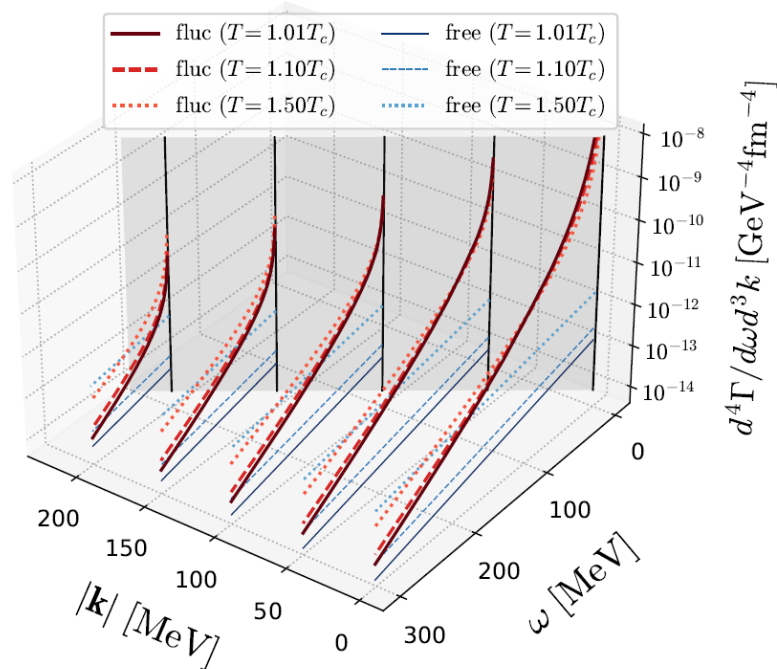
Sakai+, 2024

Dilepton at Ultra-Low-Mass Region

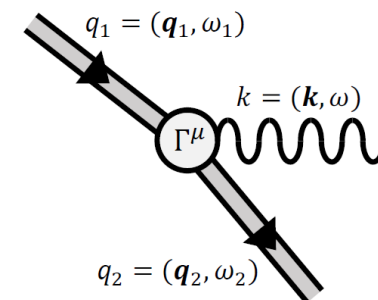
Signal for QCD-CP & Color SC

Nishimura, MK, Kunihiro, '22; '23; '24

Anomalous dilepton production due to soft modes at phase transitions



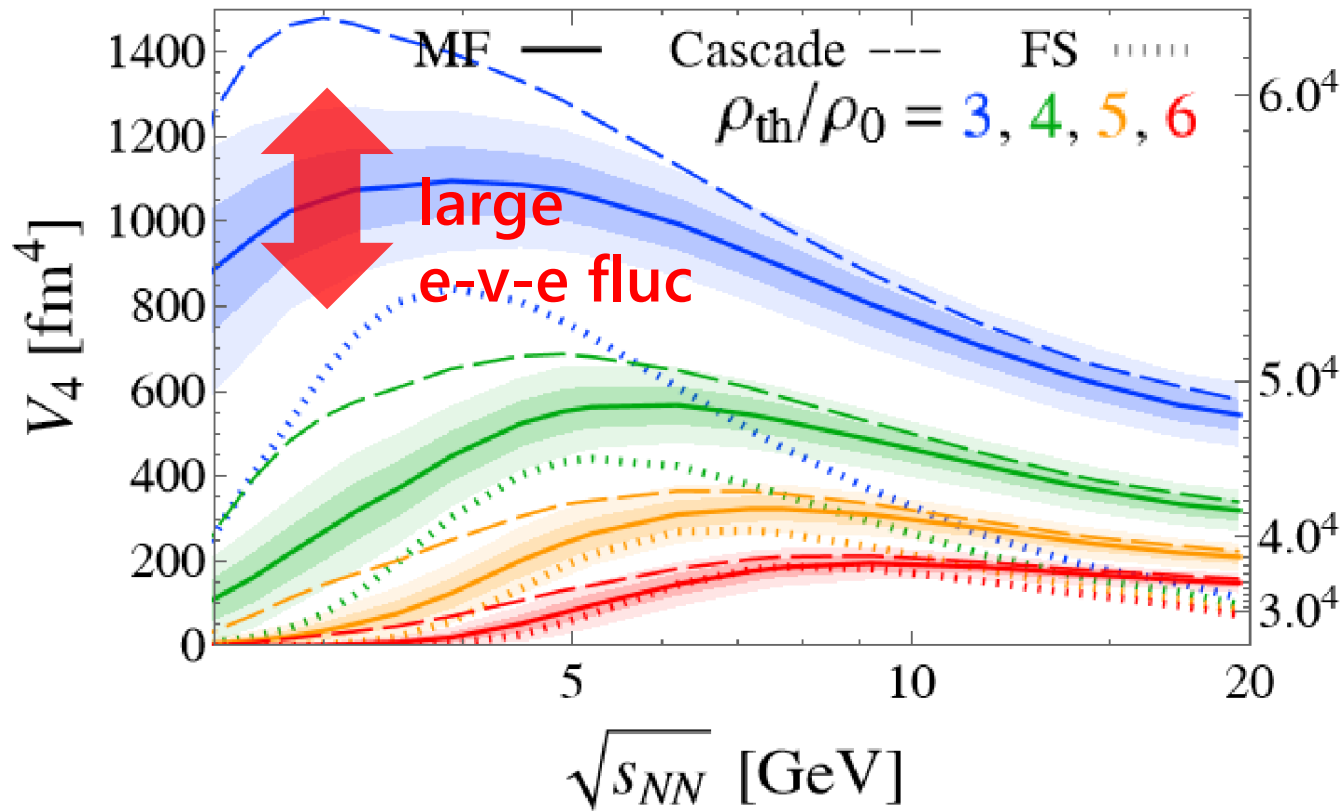
production process:



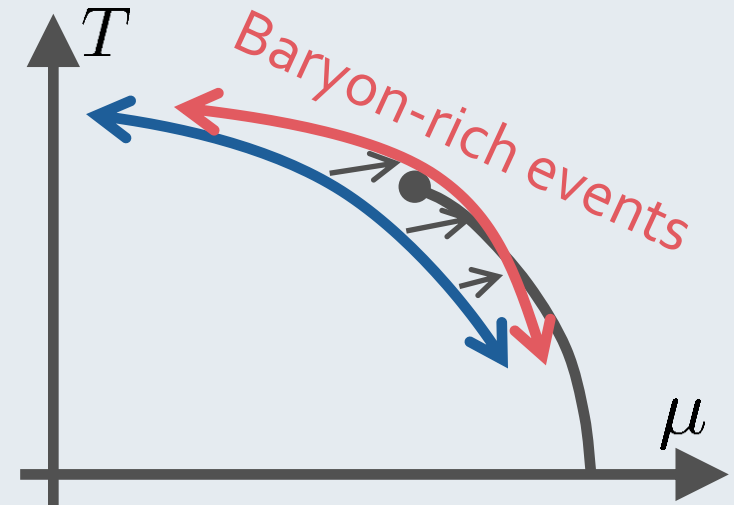
Two "hot spots" on the $T-\mu$ plane?

Event Selection

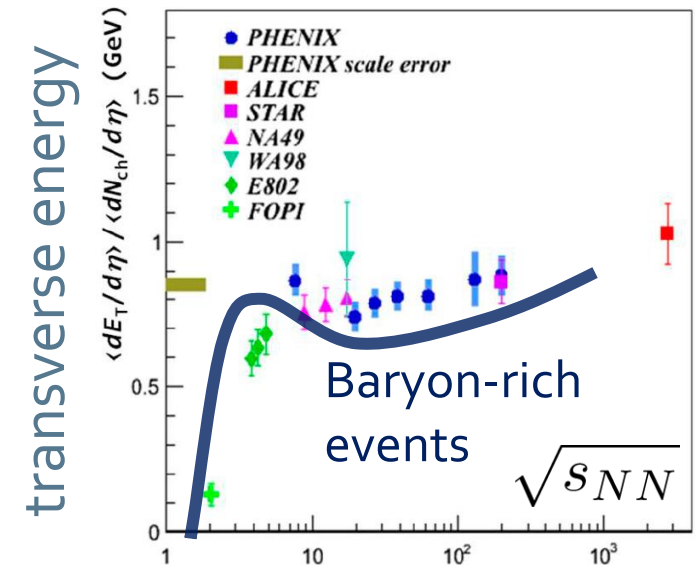
Taya, Jinno, MK, Nara, 2409.07685



Density Scan?



■ Event selections via highest baryon/energy density will allow us a detailed study of QCD phase diagram.



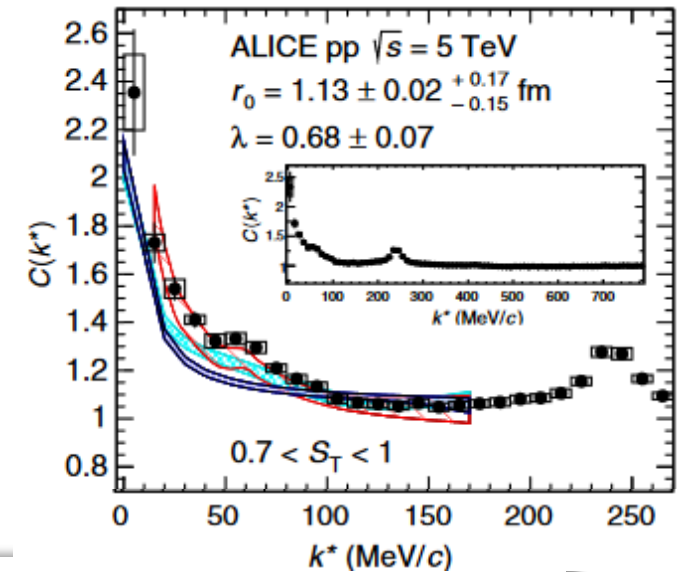
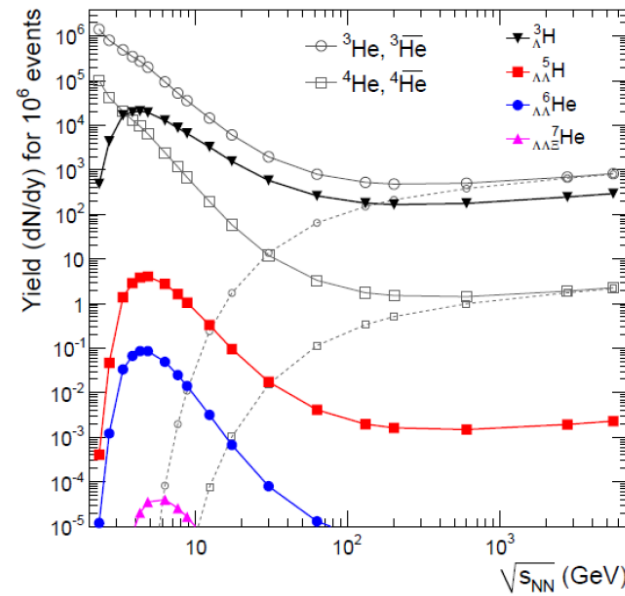
Hadron/Hypernuclear Physics

➔ Hyodo (today) Mantovani Sarti (16th)

Hypernuclei

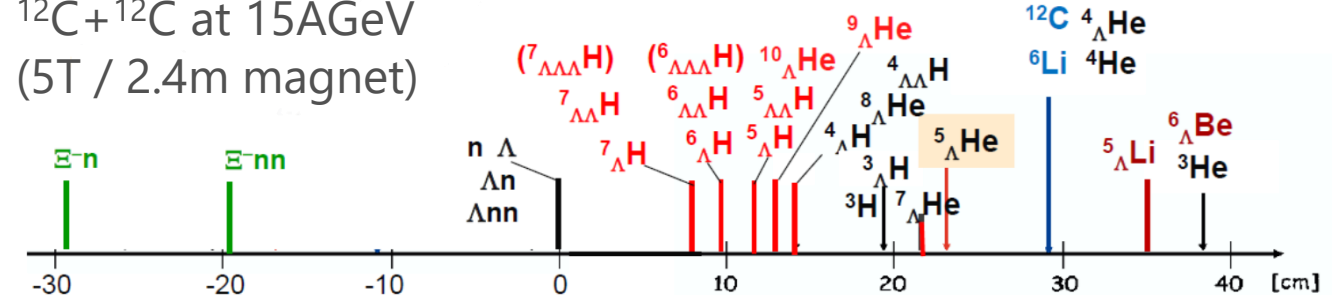
Correlation functions

➔ hadron interaction

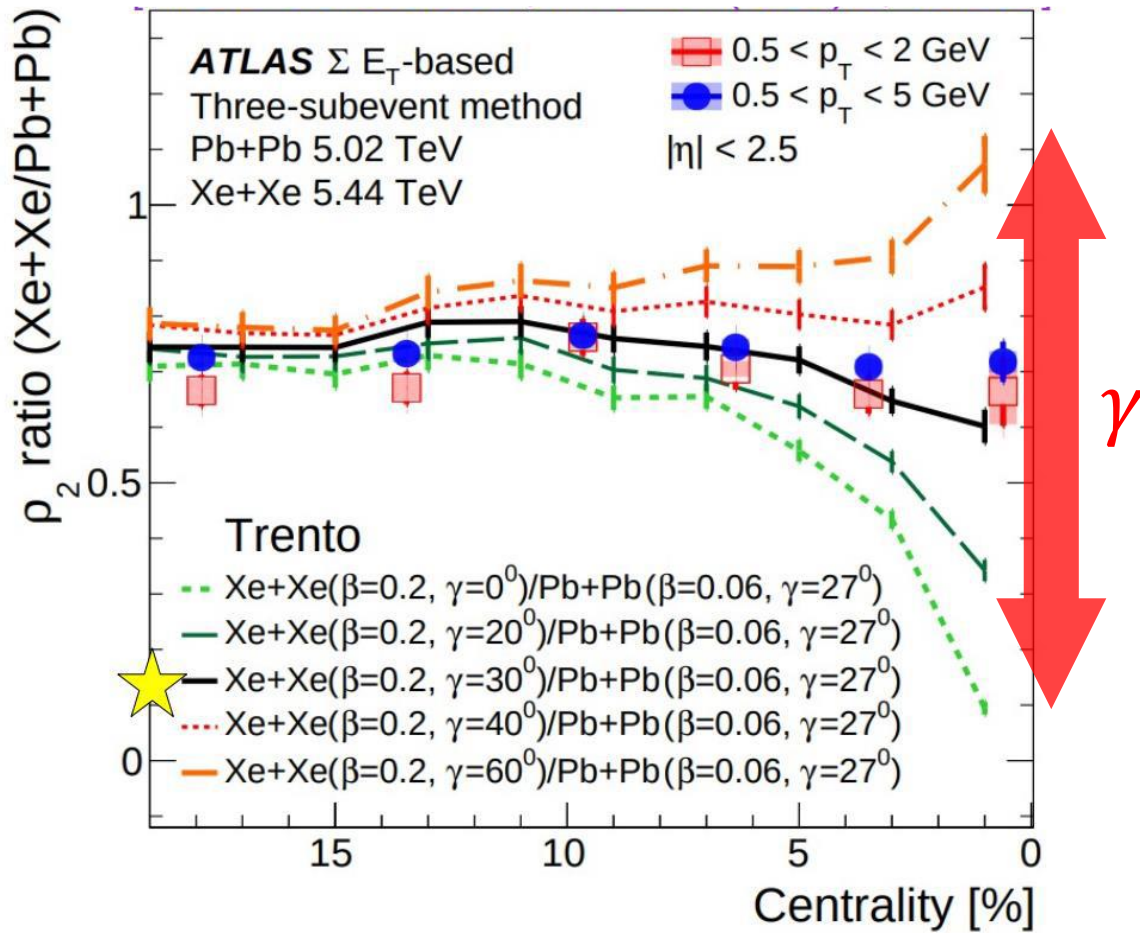


ALICE, 2020

${}^{12}\text{C} + {}^{12}\text{C}$ at 15 A GeV
 (5T / 2.4m magnet)

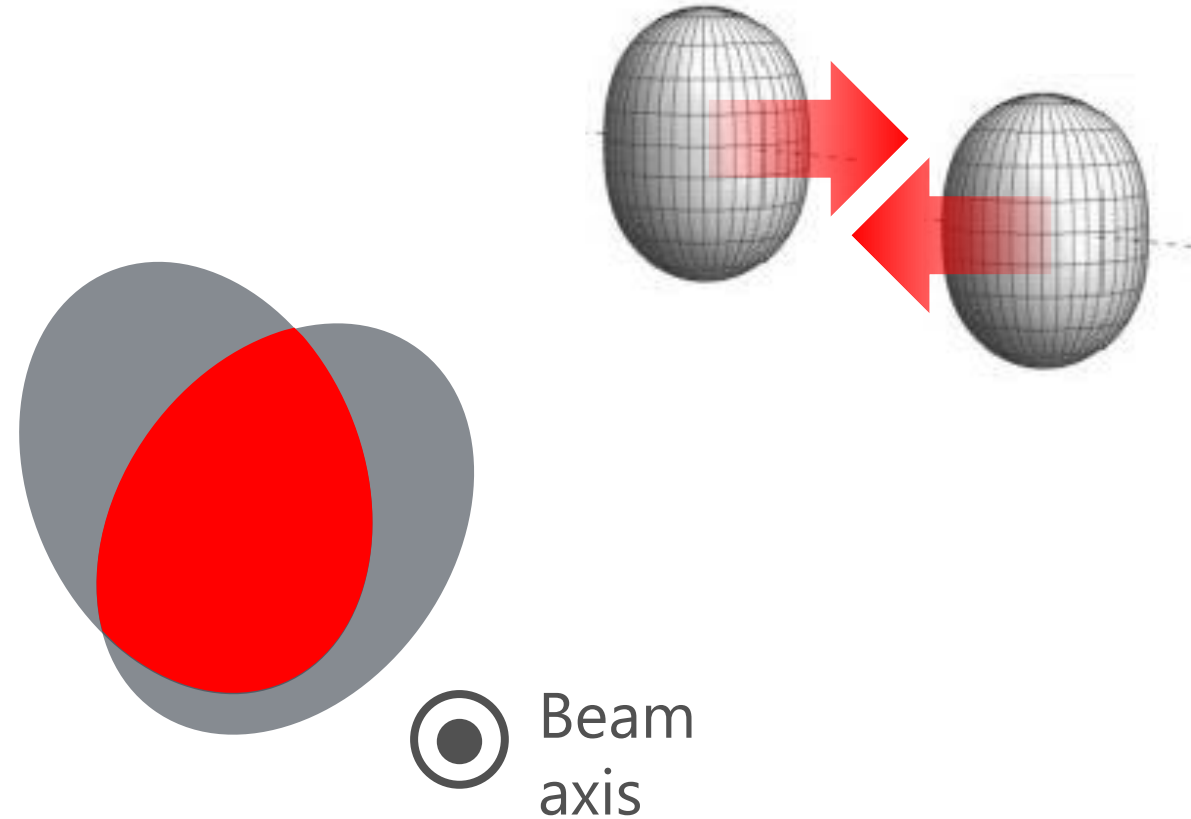


Shape of Nuclei



ATLAS, PRC107 ('23)

Deformation parameter β, γ can be estimated from HIC using flow correlations.



J-PARC-HI

Future Plan

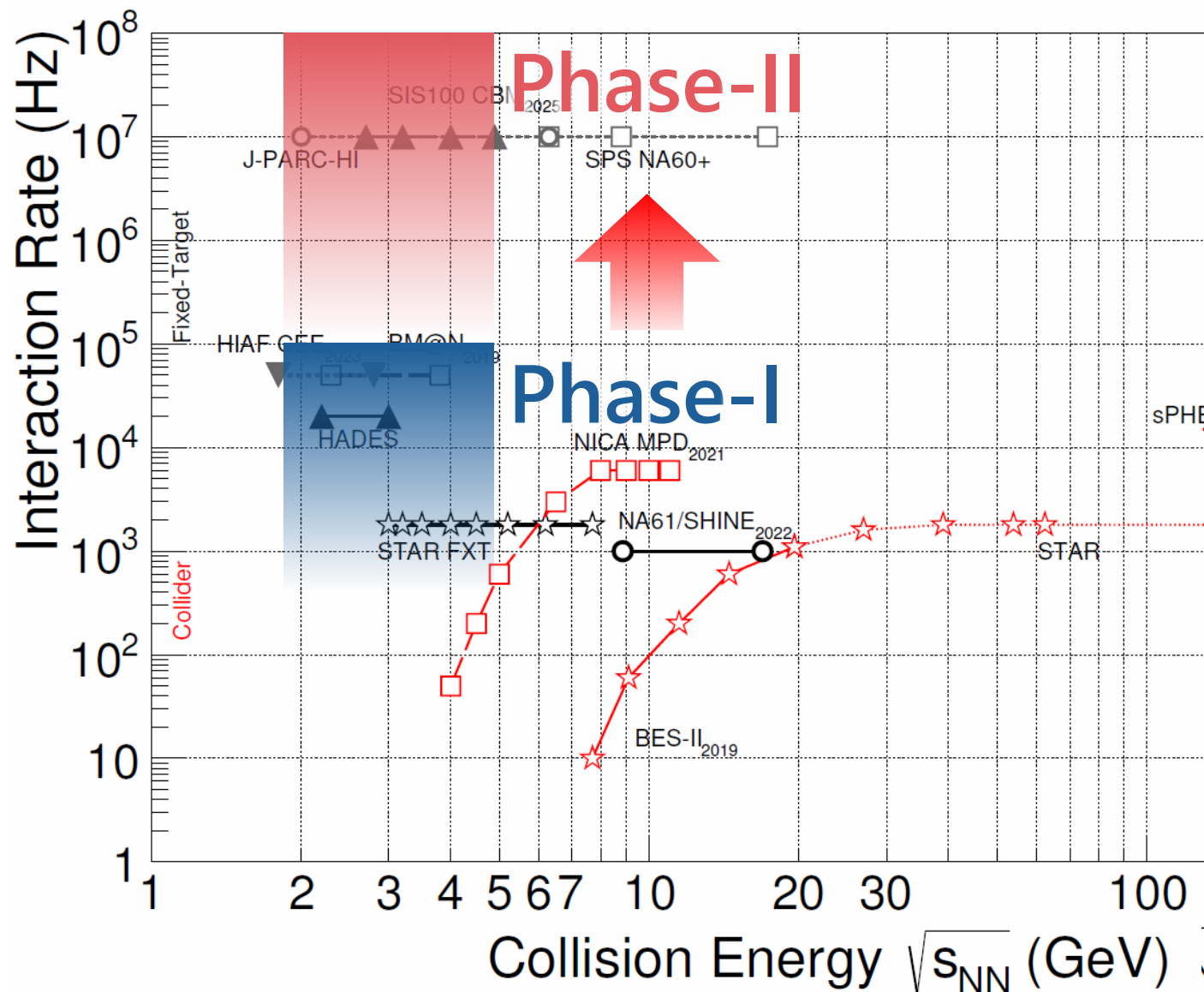
J-PARC-HI Staging Plan

Phase-I

- KEK-BS booster
- E16+ α spectrometer

Phase-II

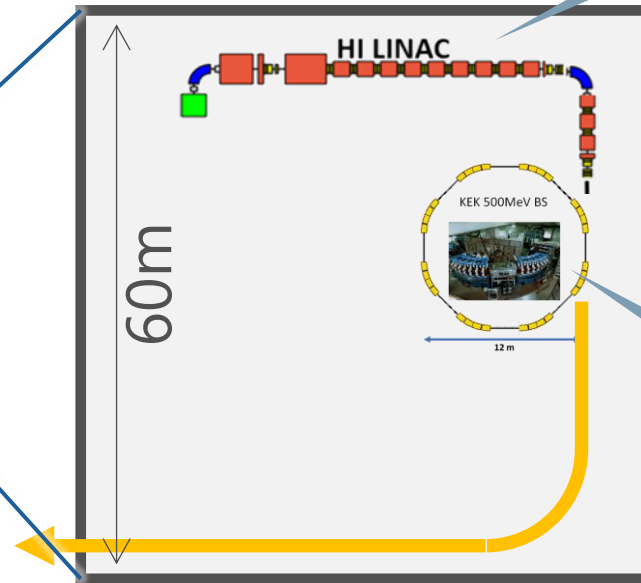
- **NEW** HI booster
- **NEW** spectrometer



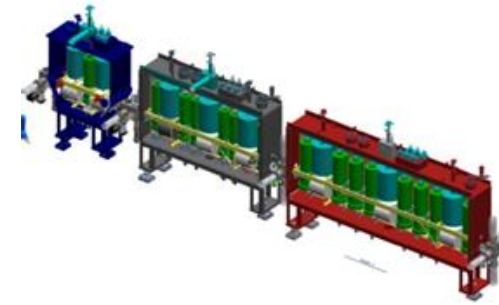
Staging of HI Booster



Phase-I



HI LINAC



KEK 500MeV BS

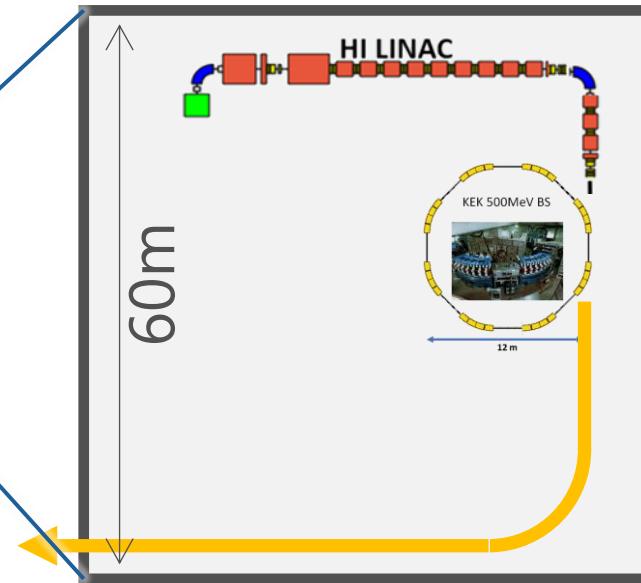


$\sim 10^5 \text{ Hz}$

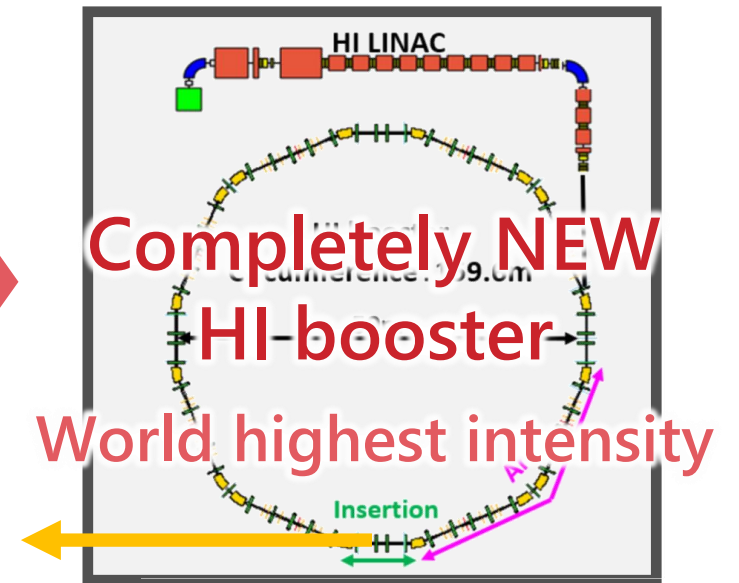
Staging of HI Booster



Phase-I



Phase-II



Interaction rate

$$\sim 10^5 \text{ Hz}$$

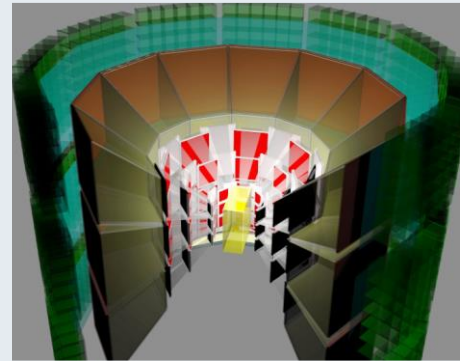
$$\sim 10^8 \text{ Hz}$$

Detector Phase-I

➤ Morino (15th), Ozawa (Poster)

E16 Spectrometer

- $\phi \rightarrow e^+e^-$, $\phi \rightarrow K^+K^-$
- In-medium mass modification
- Commissioning 2020-2024

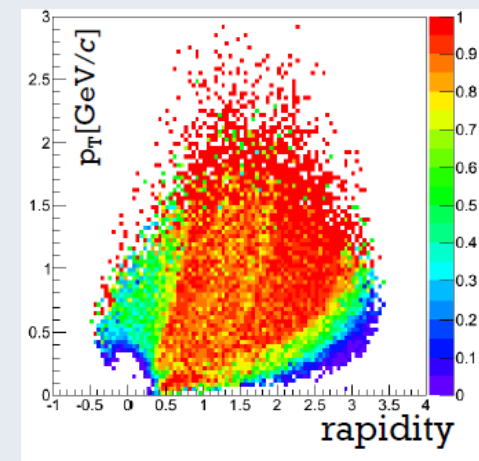
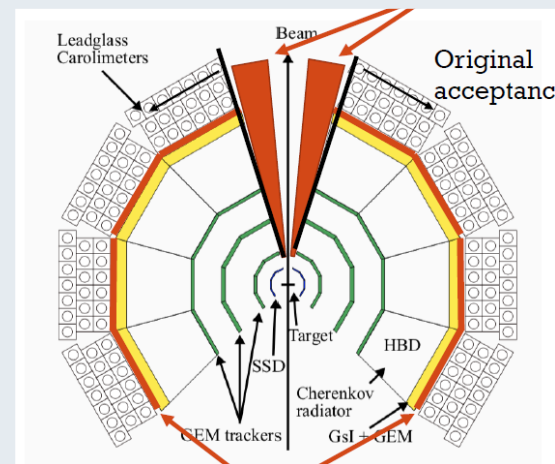


UPGRADE

E16+ α

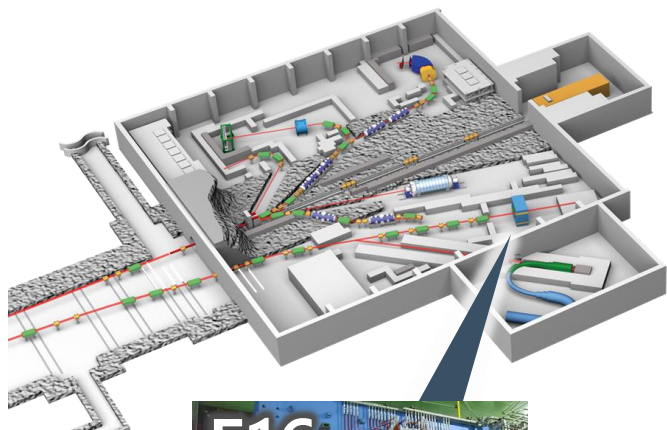
Upgrade forward region for high-multiplicity counting

➤ Hadron/lepton measurement at wide acceptance

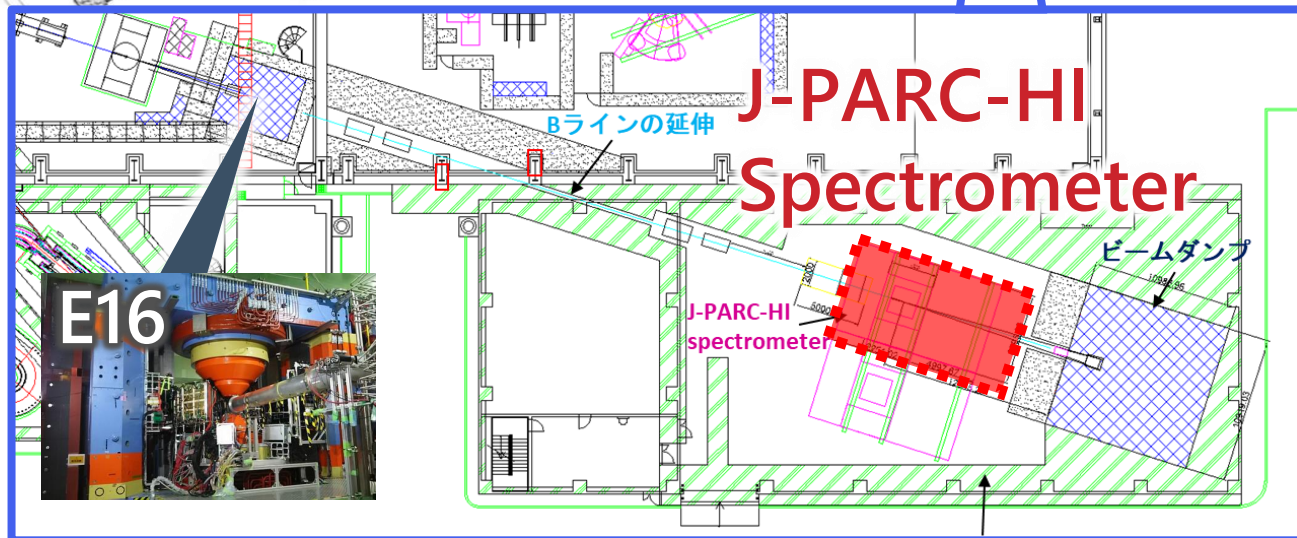
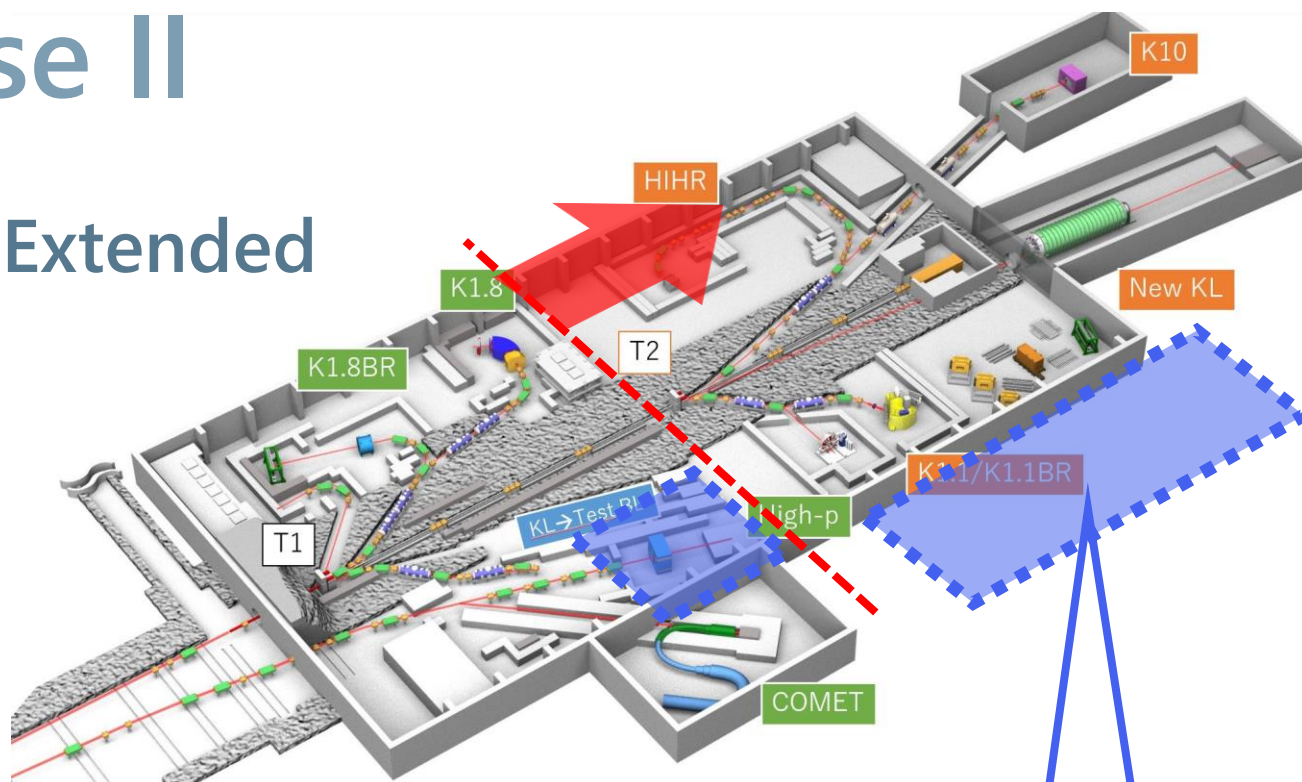


Detectors for Phase II

Present



Extended



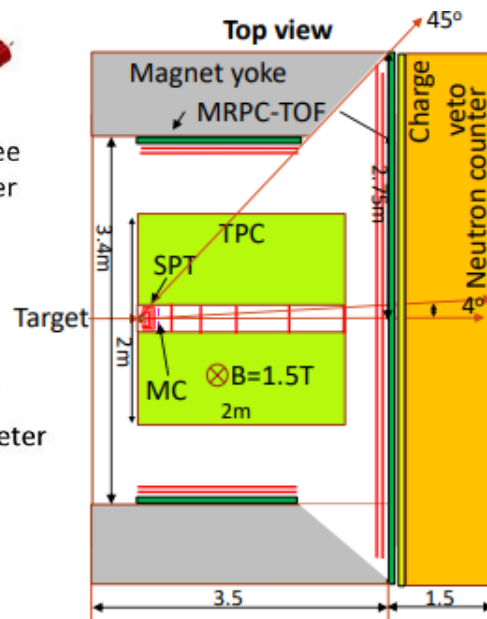
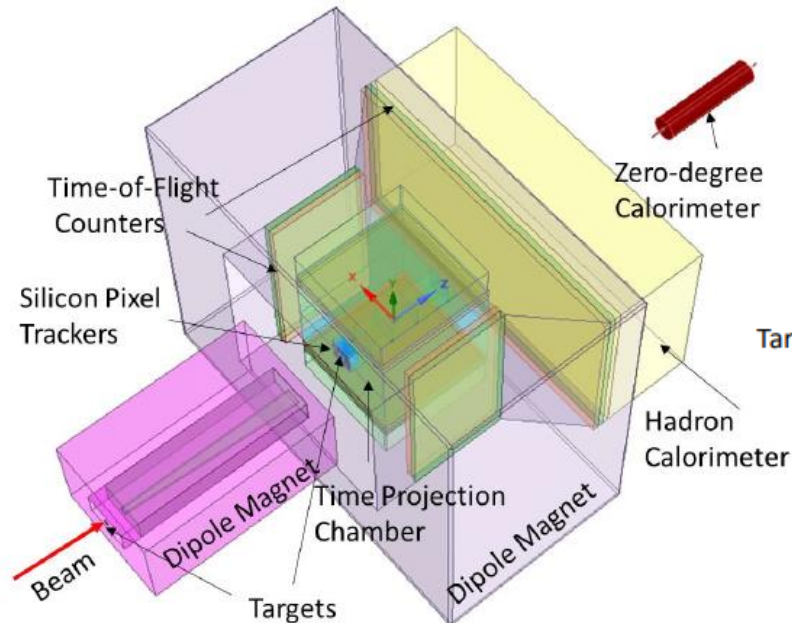
- J-PARC-HI spectrometer will be installed in an annex
- E16 will also be replaced

Hadron Spectrometer

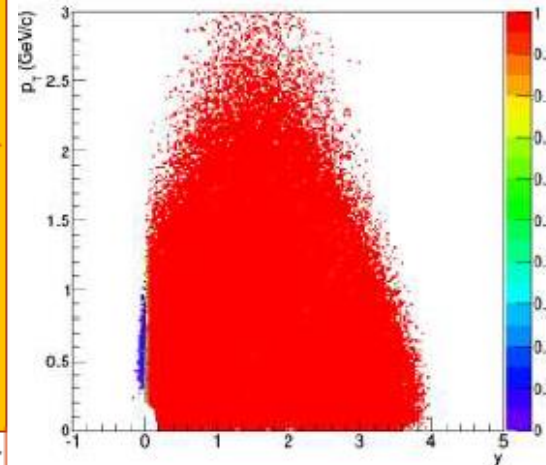
Phase-II

- 4π acceptance, high-intensity beam
 - Precise measurement of fluctuations, dileptons
- Detailed design are under discussion

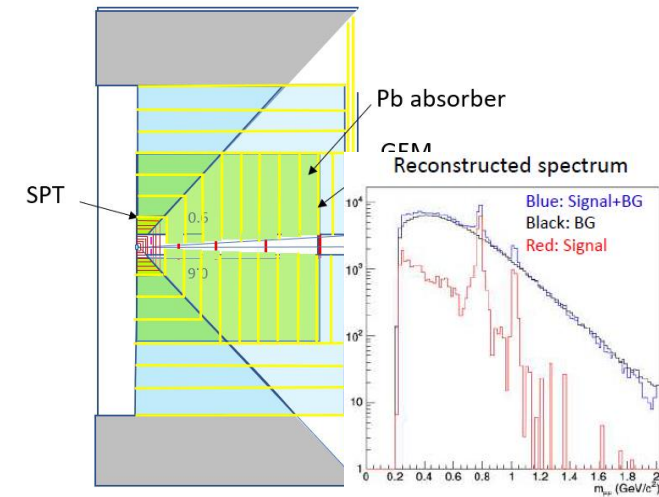
Hadron calorimeter



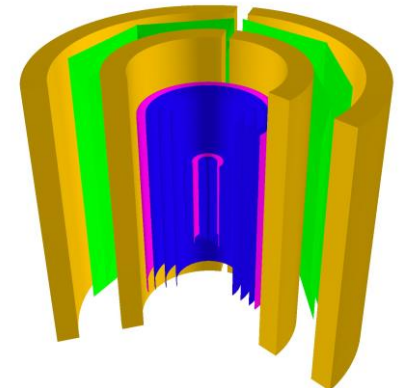
acceptance



Dimuon Setup



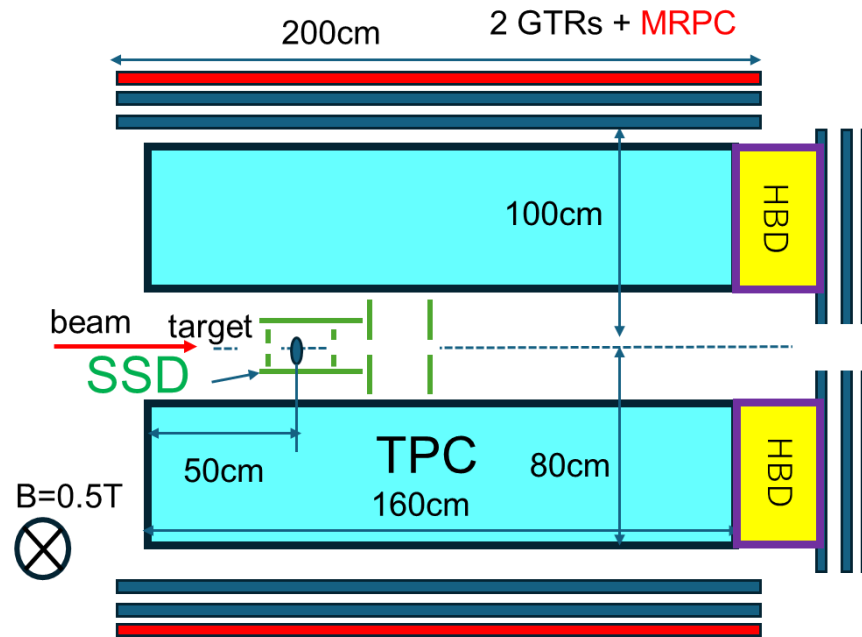
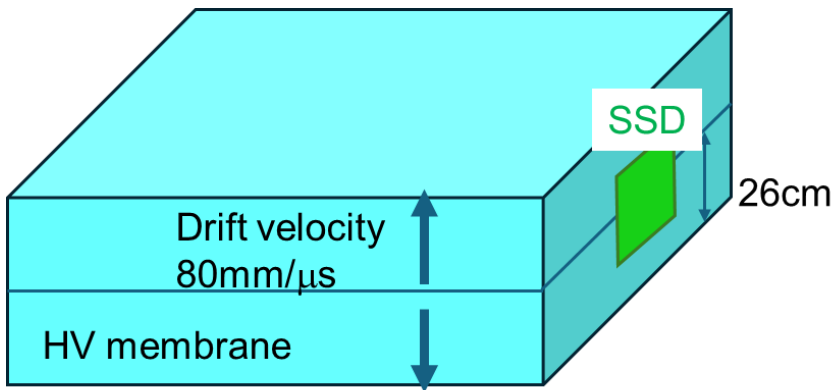
ALICE3-like dipole



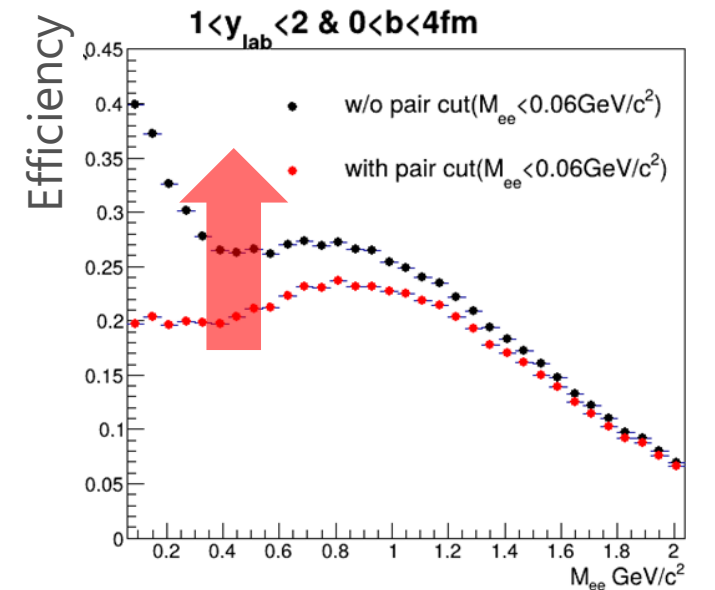
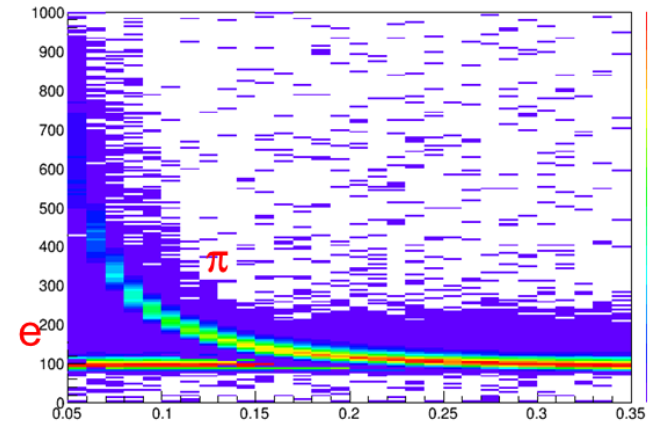
Dilelectron Measurements

Phase-II

— Large acceptance measurement of dielectrons and hadrons



dE/dx of SSDs

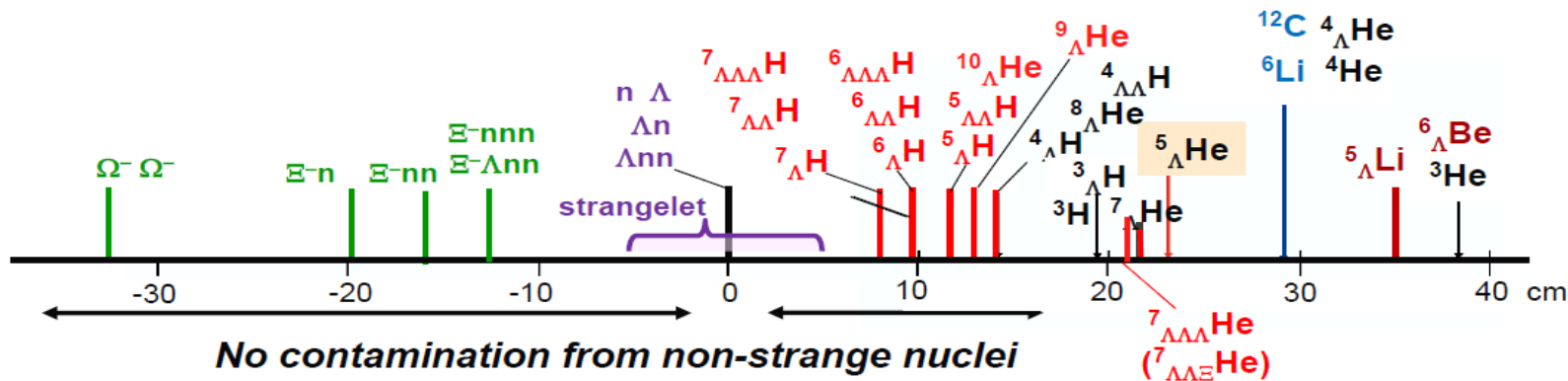
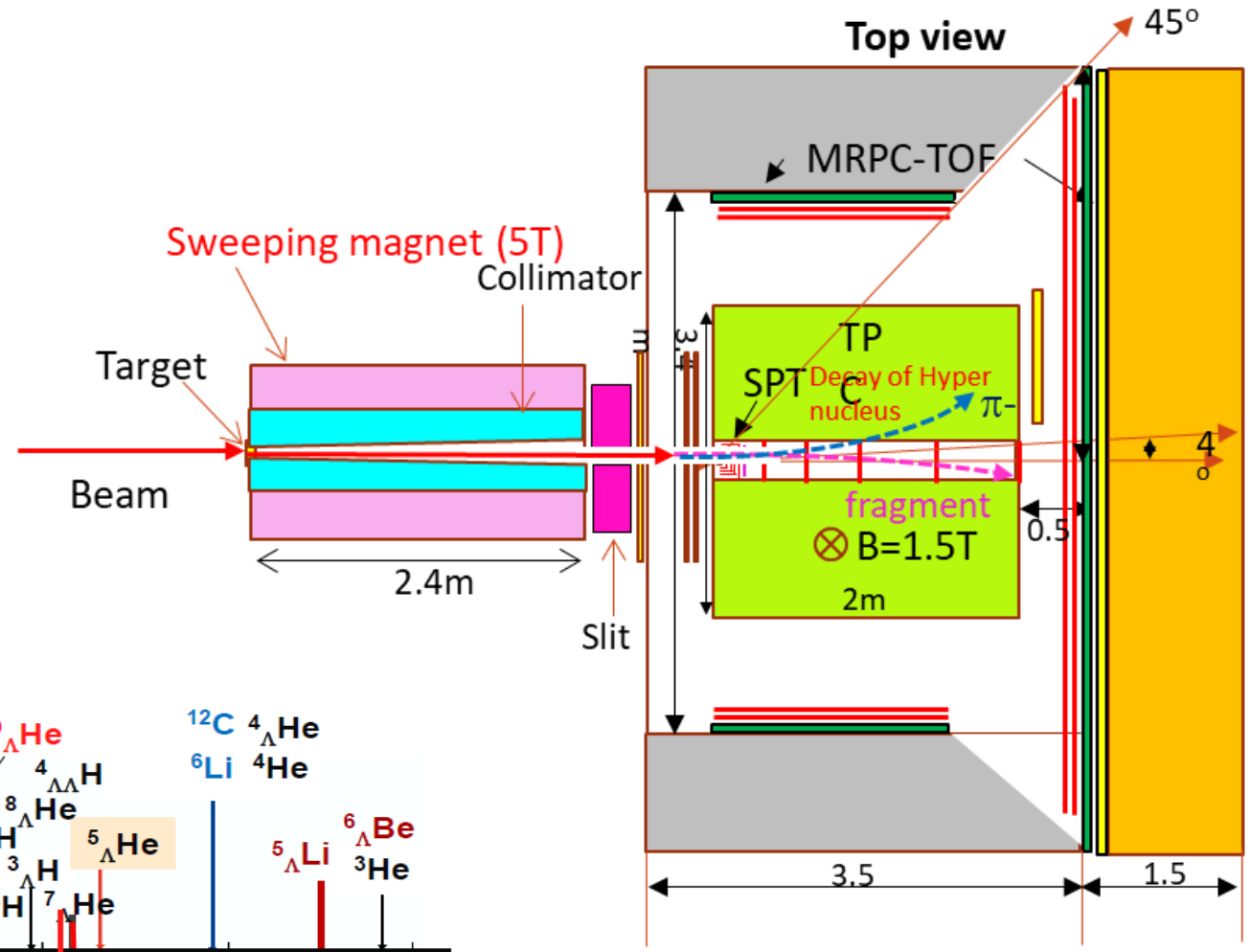


Precise measurement of low-mass dielectrons
➤ search for QCD-CP & CSC phase transition

Hypernuclear Spectrometer

Phase-II

- Closed geometry : Sweeping magnet and Collimator
- Interaction Rate : ~ 100 MHz
- Lifetime and Magnetic moment Search for new hypernuclei and strangelet



An aerial photograph of the J-PARC (Japan Proton Accelerator Research Complex) facility. The image shows a large industrial and research complex with numerous buildings, parking lots, and roads. The facility is situated along a coastline, with a large body of water to the right and a river or bay to the left. The surrounding area includes residential neighborhoods and green fields. Overlaid on the image is white text with a yellow highlight for the phrase 'heavy-ion beams'.

Imagine J-PARC 20 years from now!

New experiments with **heavy-ion beams** will enrich the future of J-PARC.

Summary

J-PARC-HI will

- realize high-precision HI experiments to explore
 - extremely dense QCD
 - hadron/hypernuclear physics, etc.
- be realized through the staging plan:
 - Phase-I: Experiment utilizing existing equipment
 - Phase-II: Full-spec experiment with world highest rate

Still many things to do



- We need continuous support from community.
- New challengers are welcome!

J-PARC-HI Collaboration

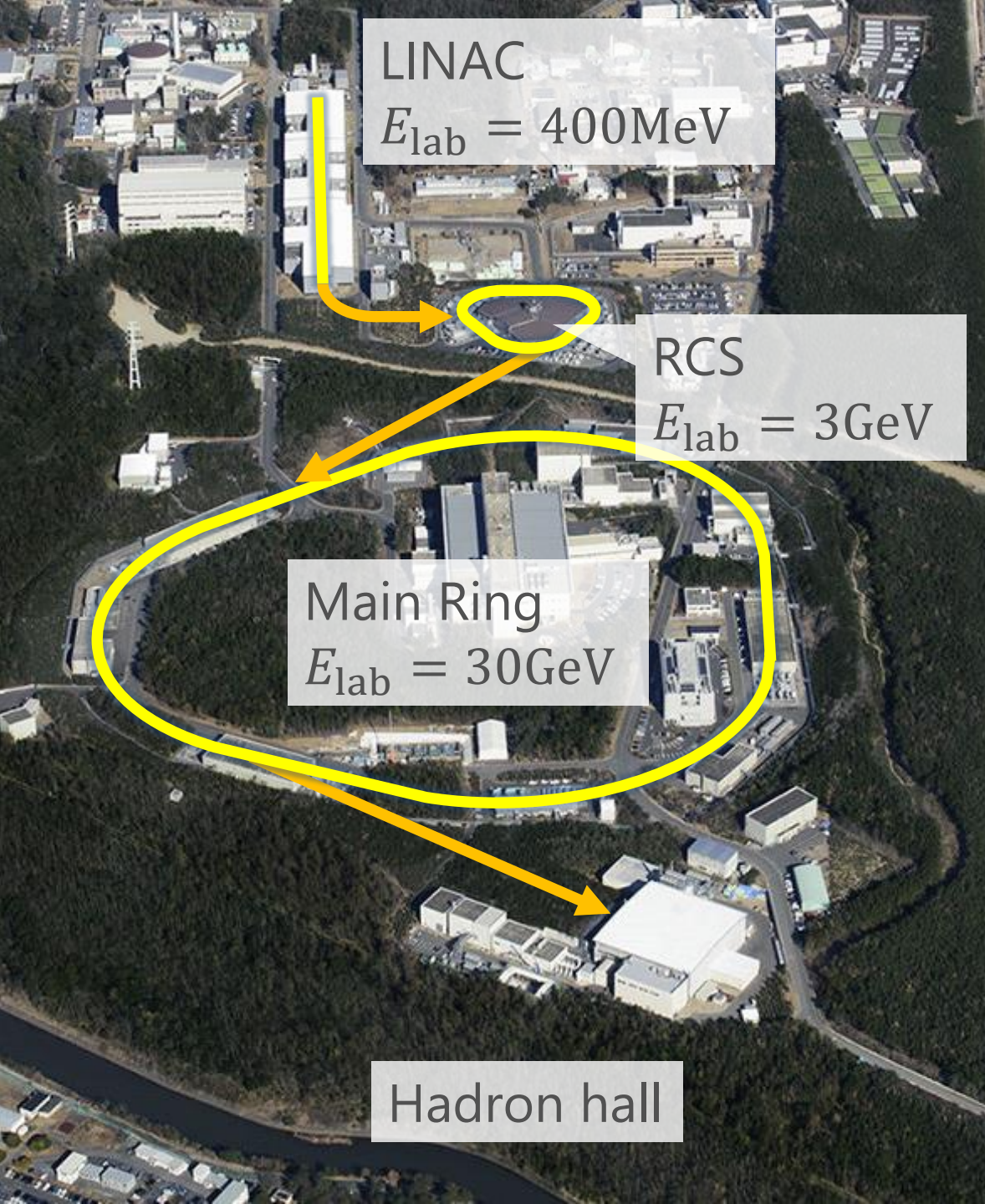


and **138** members in total

Exp.: J. K. Ahn , K. Aoki, S. Ashikaga, O. Busch, M. Chiu, T. Chujo , P. Cirkovic , T. Csorgo , D. Devetak , G. David, M. Djordjevic, S. Esumi , P. Garg, R. Guernane , T. Gunji , T. Hachiya , H. Hamagaki , S. Hasegawa, B. S. Hong, S. H. Hwang, Y. Ichikawa, T. Ichisawa , K. Imai, M. Inaba, M. Kaneta , H. Kato, B. C. E. J. Kim, X. Luo, Y. Miake , J. Milosevic, D. Mishra, Y. Morino, L. Nadjdjerdj , S. Nagamiya , T. Nakamura, M. Naruki , K. Nishio , T. Nonaka, M. Ogino, K. Oyama , K. Ozawa, T. R. Saito, A. Sakaguchi , T. Sakaguchi , S. Sakai, H. Sako, K. Sato, S. Sato, S. Sawada, K. Shigaki , S. Shimansky , M. Shimomura, M. Stojanovic , H. Sugimura, Y. Takeuchi, H. Tamura, K. H. Tanaka, Y. Tanaka, K. Tanida, N. Xu, S. Yokkaichi, I. K. Yoo

Theor.: Y. Akamatsu, M. Asakawa, K. Fukushima, H. Fujii , T. Hatsuda , M. Harada, T. Hirano, K. Itakura M. Kitazawa , T. Maruyama , K. Morita, K. Murase A. Nakamura, Y. Nara, C. Nonaka, A. Ohnishi, M. Oka

Acc.: E. Chishiro , H. Harada, Y. Hashimoto, N. Hayashi, K. Hirano, H. Hotchi , K. Ishii, T. Ito, M. Kinsho , R. Kitamura, A. Kovalenko, J. Kamiya , N. Kikuzawa , T. Kimura, Y. Kondo, H. Kuboki , Y. Kurimoto, Y. Liu S. Meigo , A. Miura, T. Miyao , T. Morishita , Y. Morita, K. Moriya, R. Muto, T. Nakanoya , K. Niki, H. Oguri , C. Ohmori , A. Okabe, M. Okamura, P. K. Saha , K. Sato, Y. Sato, T. Shibata, T. Shimokawa , K. Shindo , S. Shinozaki, M. Shirakata , Y. Shobuda , K. Suganuma , Y. Sugiyama, H. Takahashi, T. Takayanagi , F. Tamura, J. Tamura, N. Tani , M. Tomisawa , T. Toyama, Y. Watanabe, K. Yamamoto, M. Yamamoto, M. Yoshii, M. Yoshimoto



LINAC
 $E_{\text{lab}} = 400\text{MeV}$

RCS
 $E_{\text{lab}} = 3\text{GeV}$

Main Ring
 $E_{\text{lab}} = 30\text{GeV}$

Hadron hall

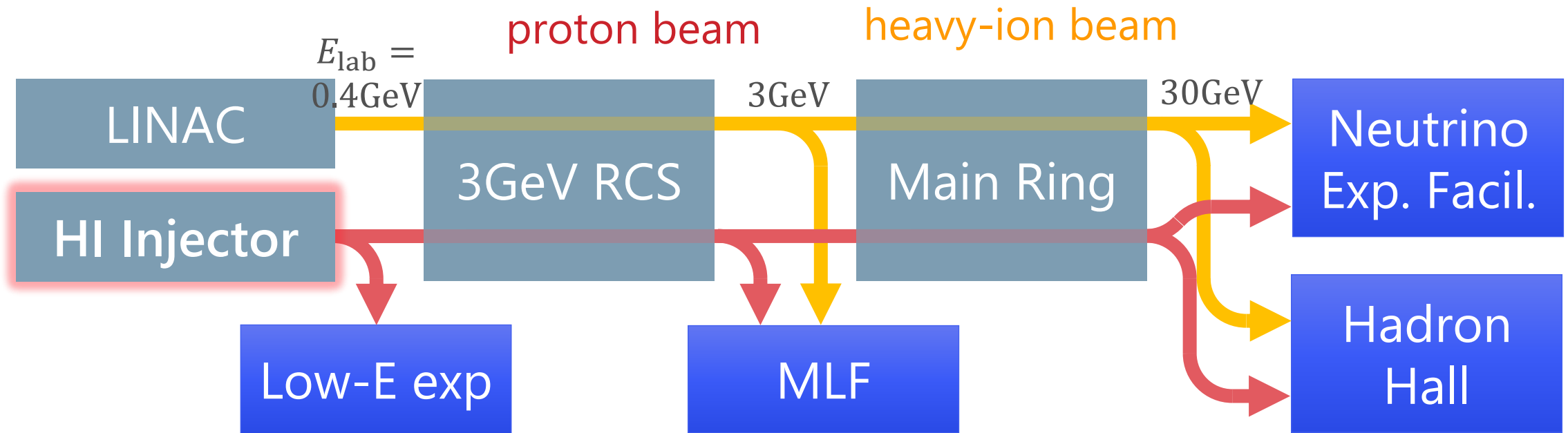
Accelerators

- LINAC
- RCS
- Main Ring(MR)
- High intensity $I = 1\text{MW}$

Purposes

- Hadron/Nuclear physics
- Neutrino physics
- Material/Life science

J-PARC-HI = J-PARC Heavy-Ion Project



- **New HI injector + existing synchrotrons (RCS, MR)**
- Supply heavy-ion beams with **world highest luminosity**
- Realize various new experiments at J-PARC