The J-PARC-HI Programme

E_{lab} (Au) = 1-12 AGeV → $\sqrt{s_{NN}}$ (Au) = 1.9-4.9 GeV

Takao Sakaguchi

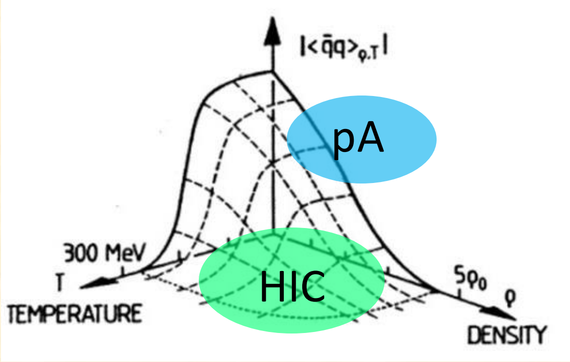
Advanced Science Research Center, Japan Atomic Energy Agency
(Brookhaven National Laboratory)

Outline
1. Charm of high baryon density
2. J-PARC-HI accelerator complex
3. Staged experimental plan
4. Summary and prospect

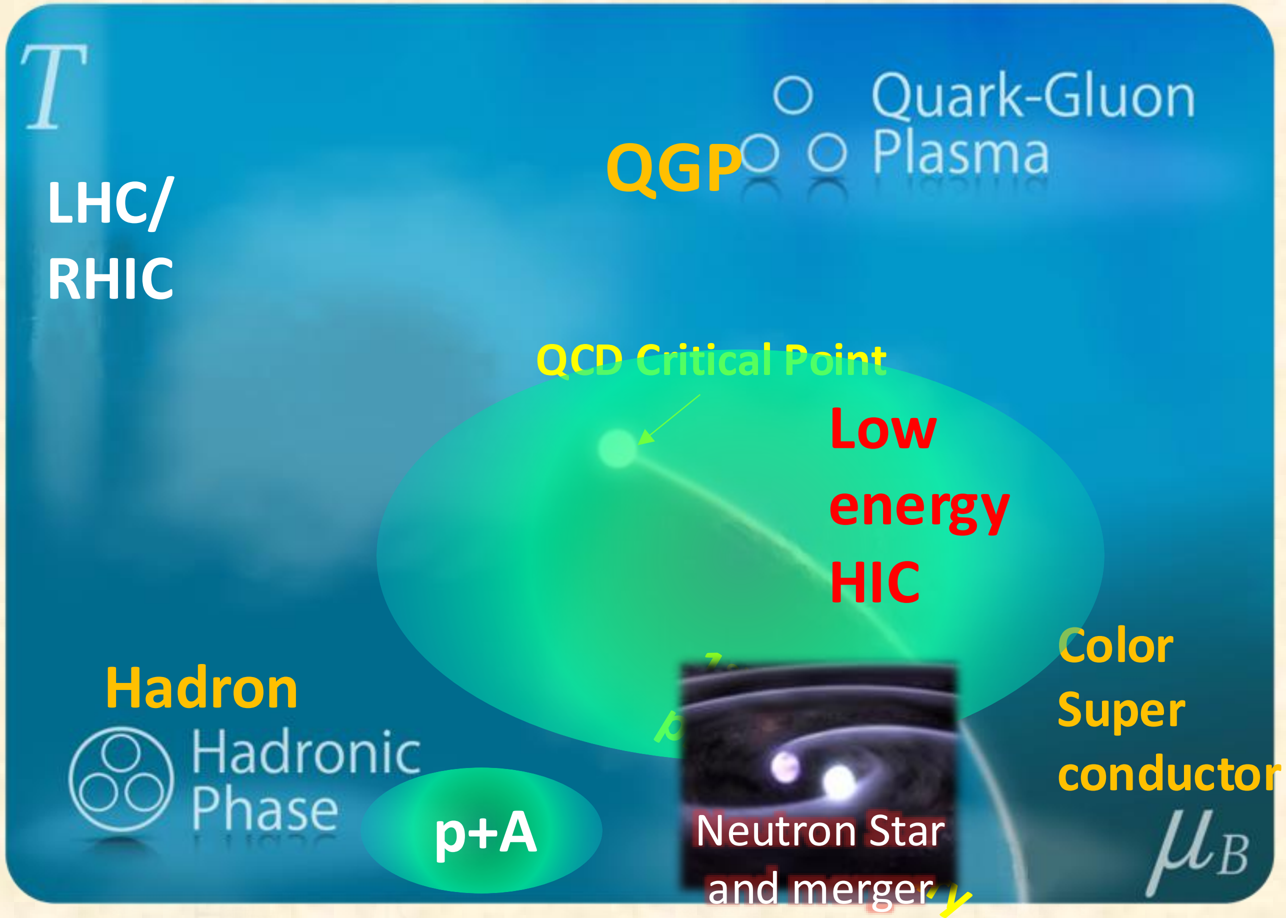
Charm of high baryon density regime

- 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



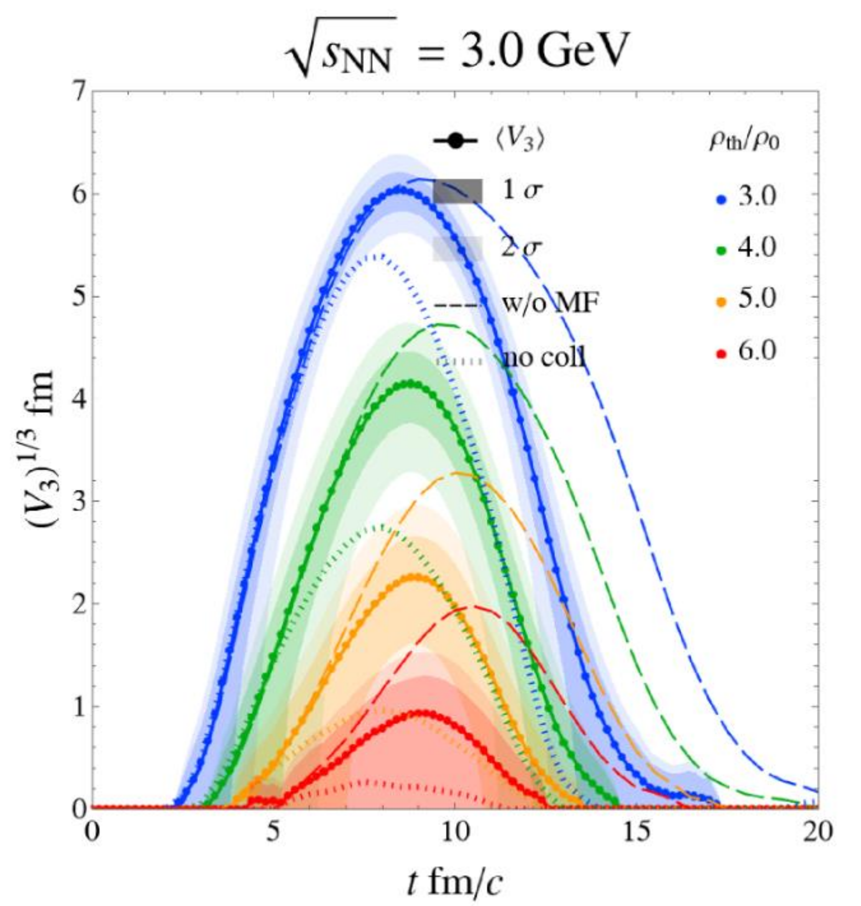
How high in density can we go? (JAM)

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

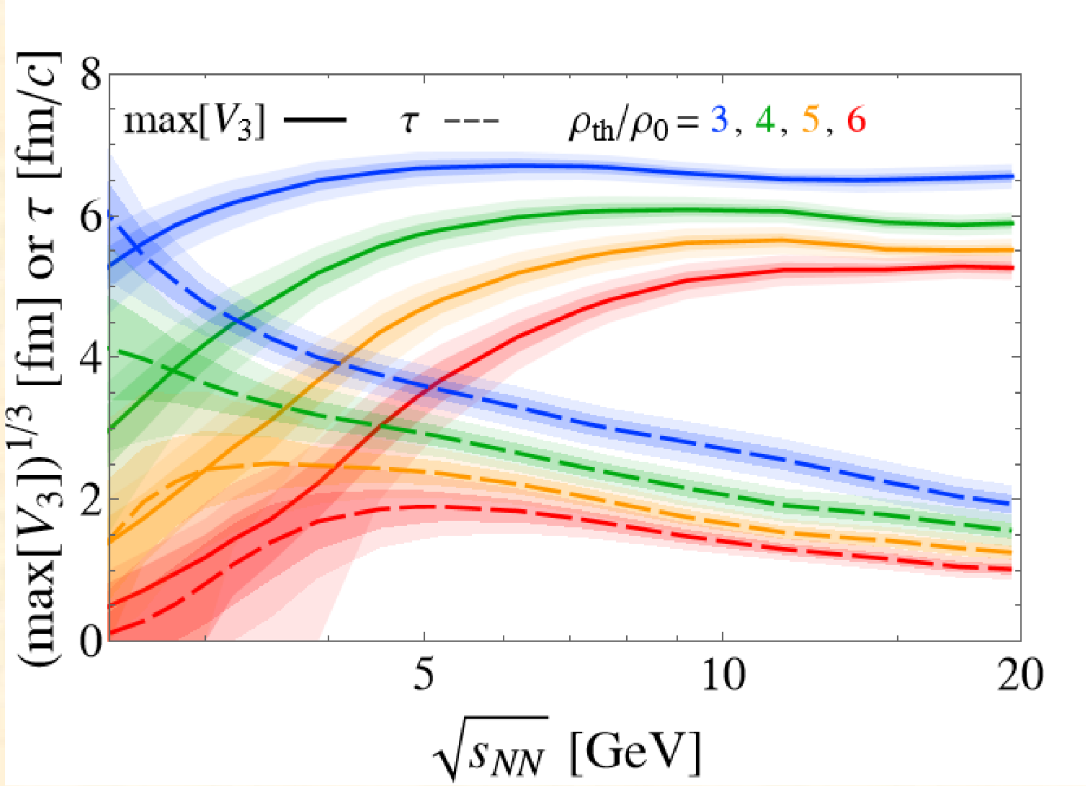
V_4 may be relevant for the dilepton production rate.

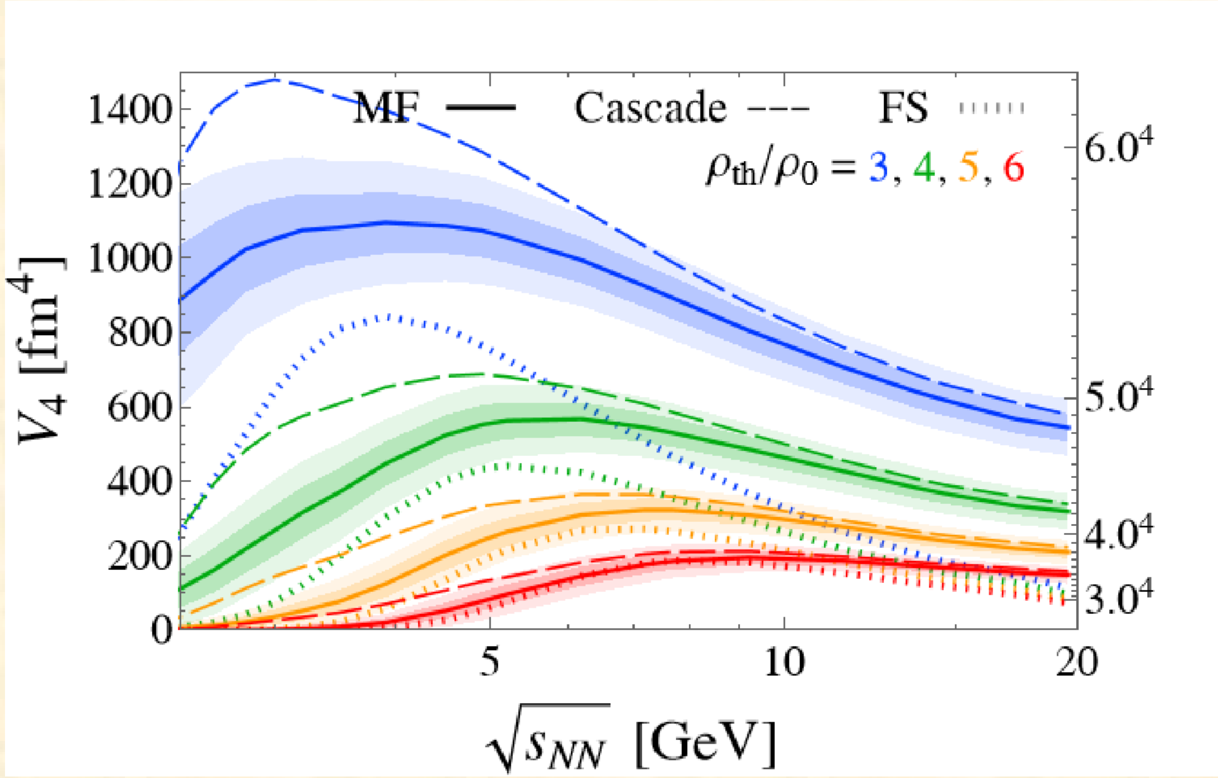
M. Kitazawa, Reimei Workshop, June 2024, H. Taya, A. Jinno, M. Kitazawa, Y. Nara, arXiv:2409.07685

ZIMÁNYI SCHOOL 2024

Where is the sweet-spot energy?

max V_3 , τ





□ $\sqrt{s_{NN}}=$ 2.6~5 GeV would be the best energy to create $\rho \geqq 3\rho_0$ with largest V_4.

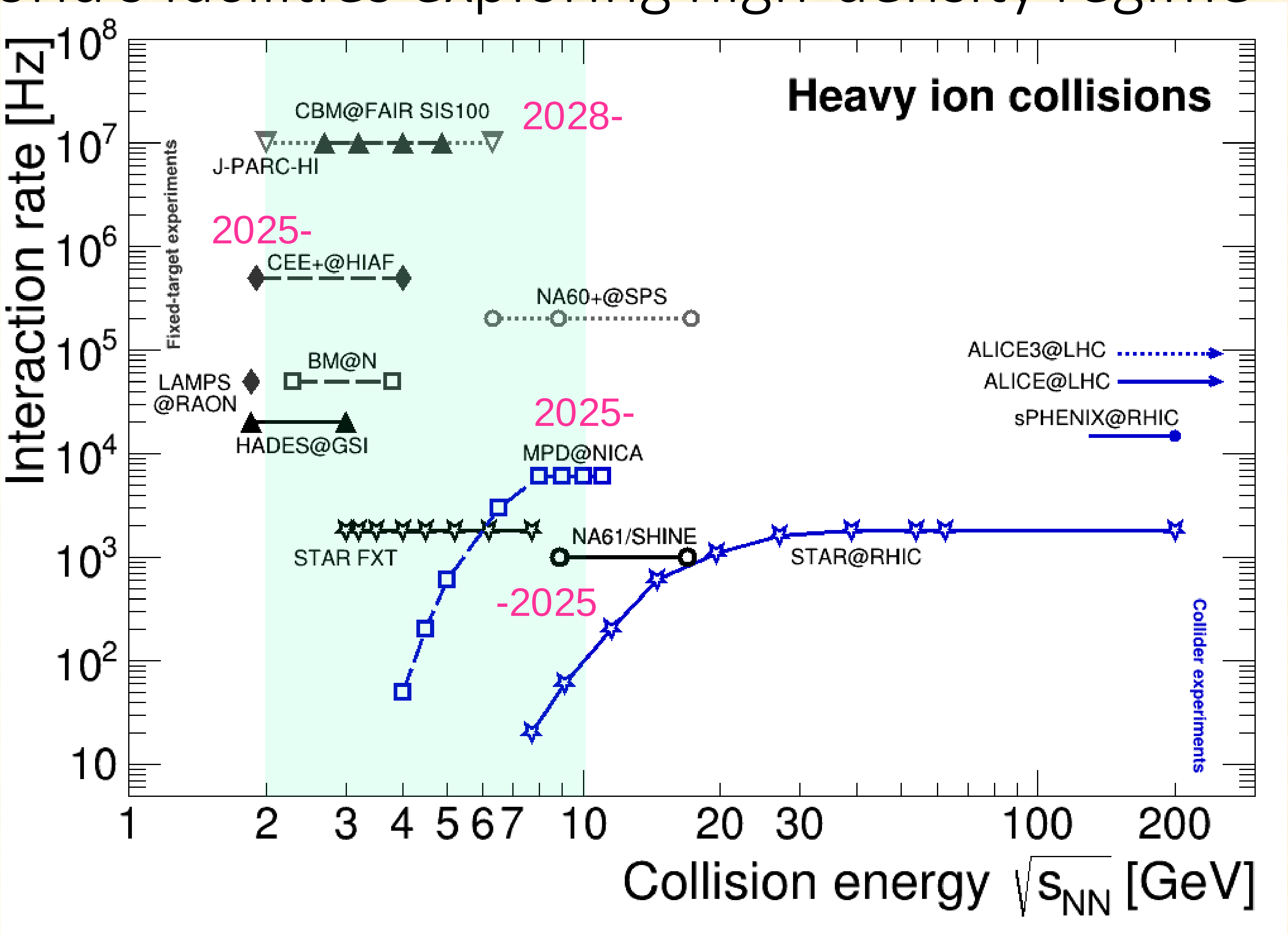
M. Kitazawa, Reimei Workshop, June 2024, H. Taya, A. Jinno, M. Kitazawa, Y. Nara, arXiv:2409.07685

Looks like it's AGS energy. Did we overlook in the past?

- Statistics
  - The high baryon density events are very rare.
  - AGS experiment didn't earn enough statistics to look for these events
- Event selection
  - Centrality is the main event classification variables.
  - We might have to invent new event selection variables to enrich the high baryon density events.
- Dilepton
  - Had the dilepton been measured at AGS, people may have discovered something strange, and have been motivated to run longer

There is no ifs in the history. We just should plan new experiments at AGS energy NOW

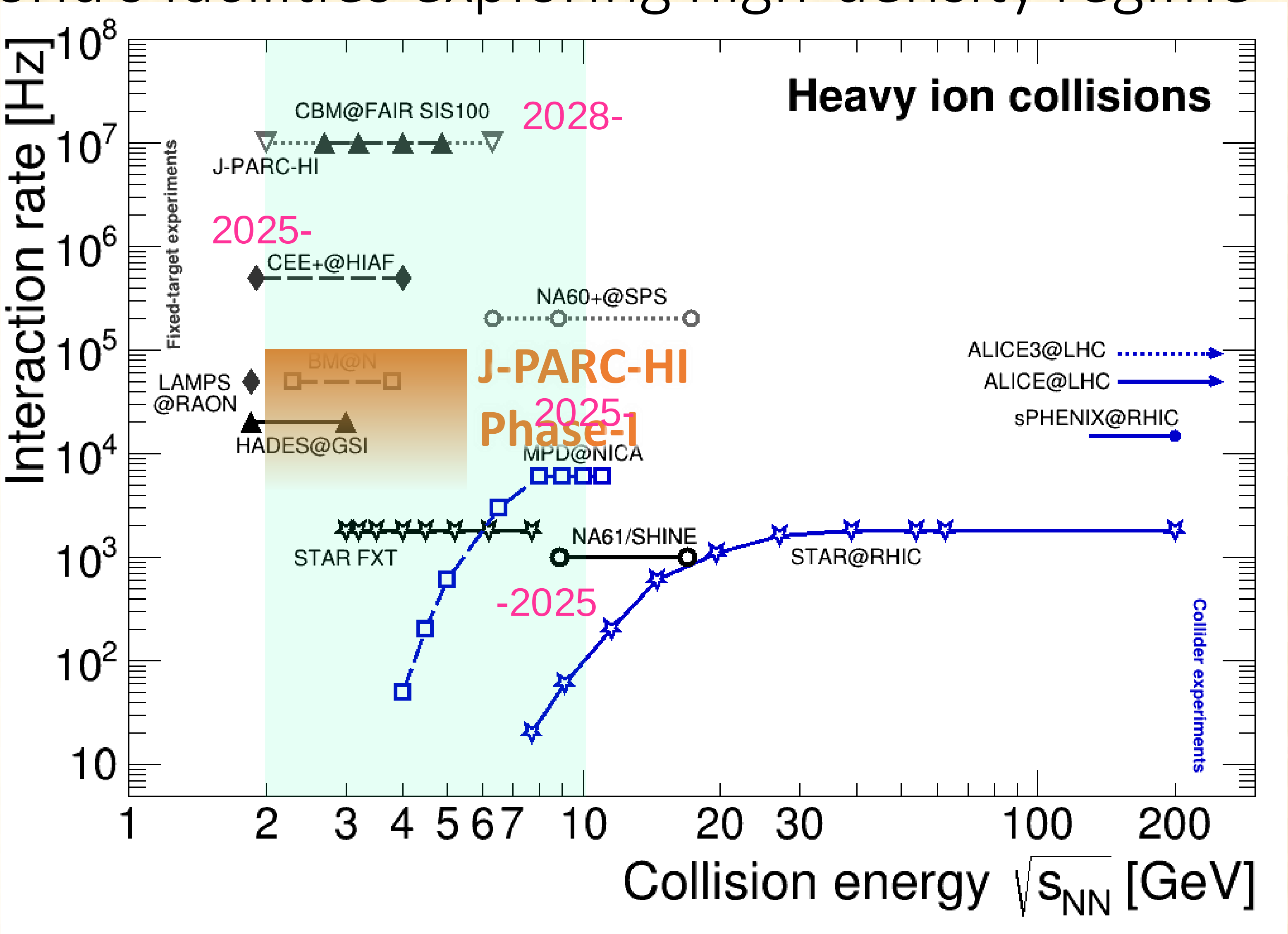
World’s facilities exploring high-density regime



- 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

World's facilities exploring high-density regime



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J-PARC:
E_{lab} (Au) = 1-12 AGeV →
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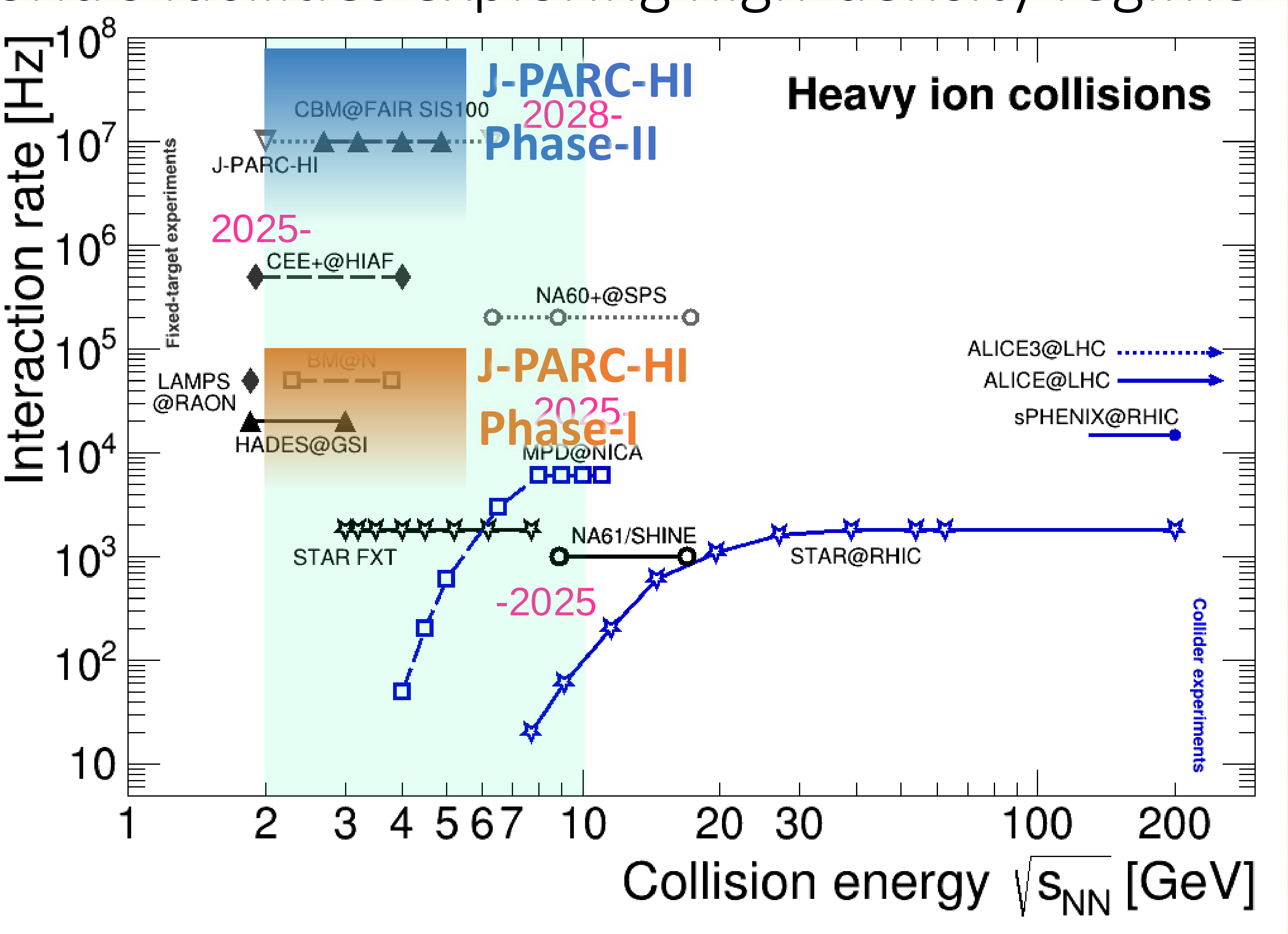

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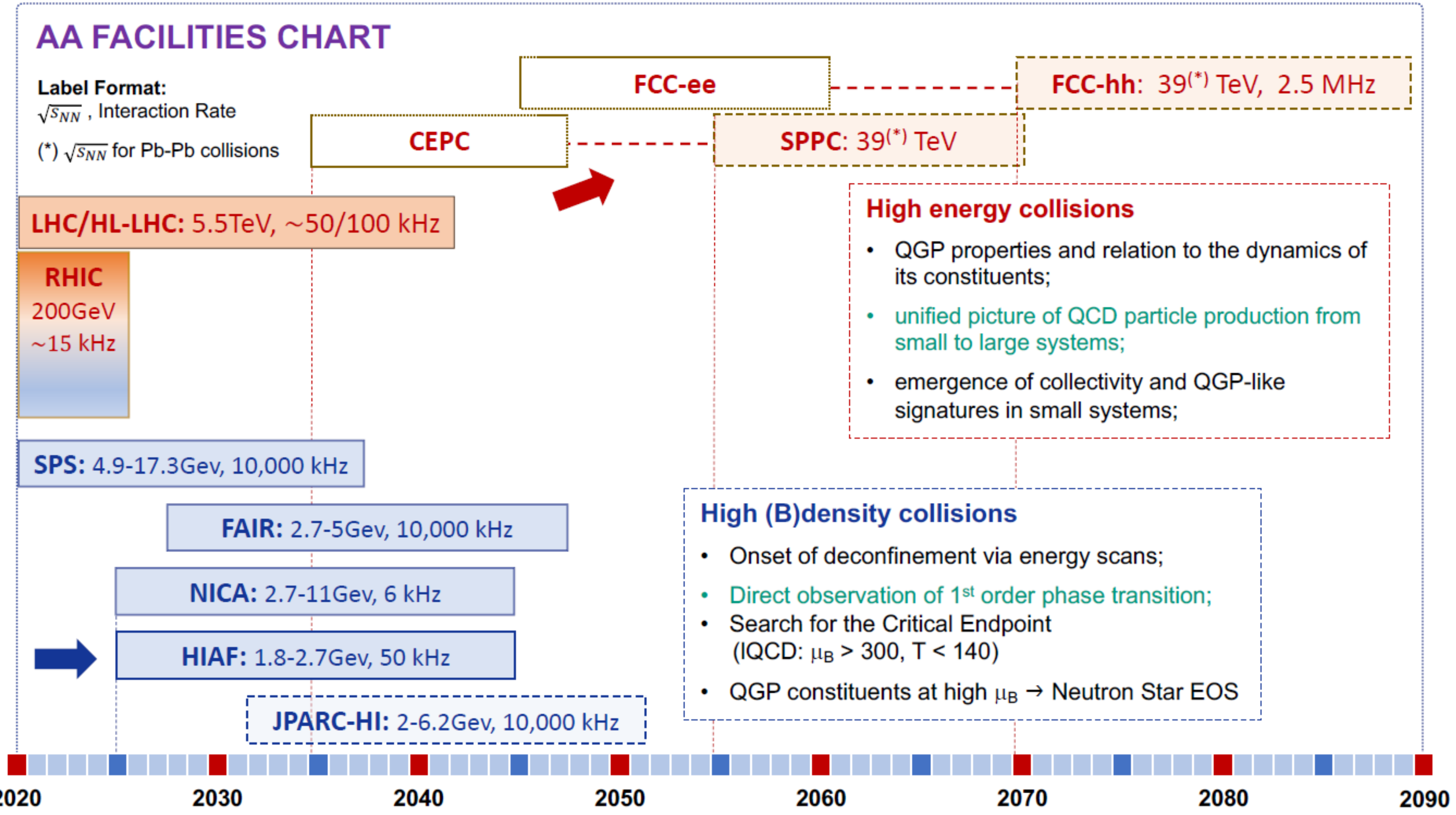
The evolution of AA Facilities



Luciano Musa (CERN) | QM2023 | 9 September 2023 2

J-PARC-HI Collaboration

135 members :

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment

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, M. Ichikawa, Y. Ichikawa, T. Ichisawa, K. Imai, M. Inaba, M. Kaneta, H. Kato, B. C. Kim, 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

Theory

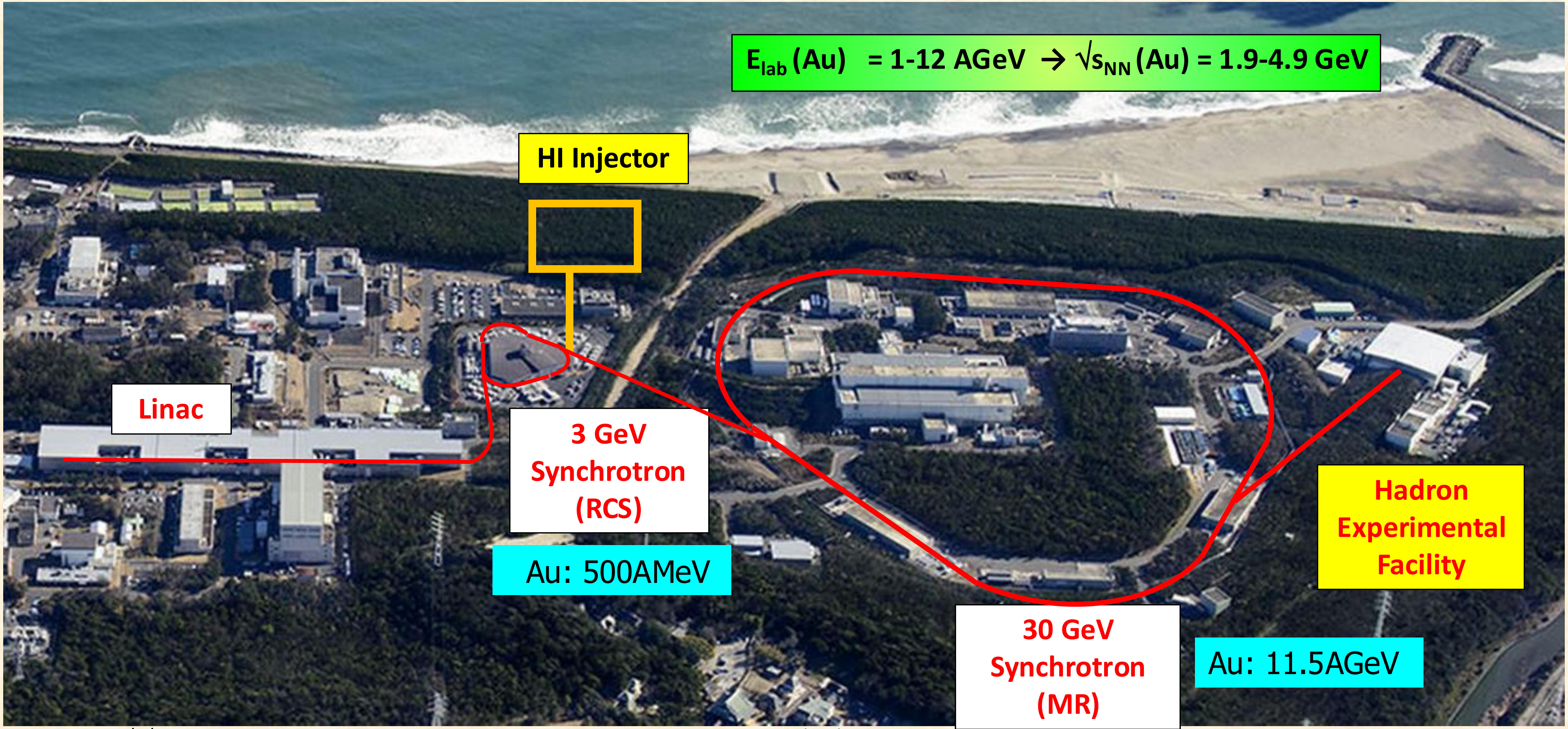
Y. Akamatsu, M. Asakawa, K. Fukushima, H. Fujii, T. Hatsuda, M. Harada, T. Hirano, K. Itakura, M. Kitazawa, T. Maruyama, K. Morita, K. Murase, A. Nakamura, Y. Nara, C. Nonaka, A. Ohnishi, M. Oka

Accelerator

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

ASRC/JAEA, J-PARC/JAEA, J-PARC/KEK, Tokyo Inst. Tech, Hiroshima U, Osaka U, U Tsukuba, Tsukuba U Tech, CNS, U Tokyo, Tohoku U, Nagasaki IAS, Kyoto U, RIKEN, Akita International U, Nagoya U, Sophia U, U Tokyo, YITP/Kyoto U, Nara Women's U, KEK, BNL, Mainz U, GSI, Central China Normal U, Korea U, Chonbuk National U, Pusan National U, JINR, U Belgrade, Wigner RCP, KRF, Stony Brook U, Bhaba Atomic Research Centre, Far Eastern Federal U, Grenoble U

HI acceleration scheme for J-PARC-HI



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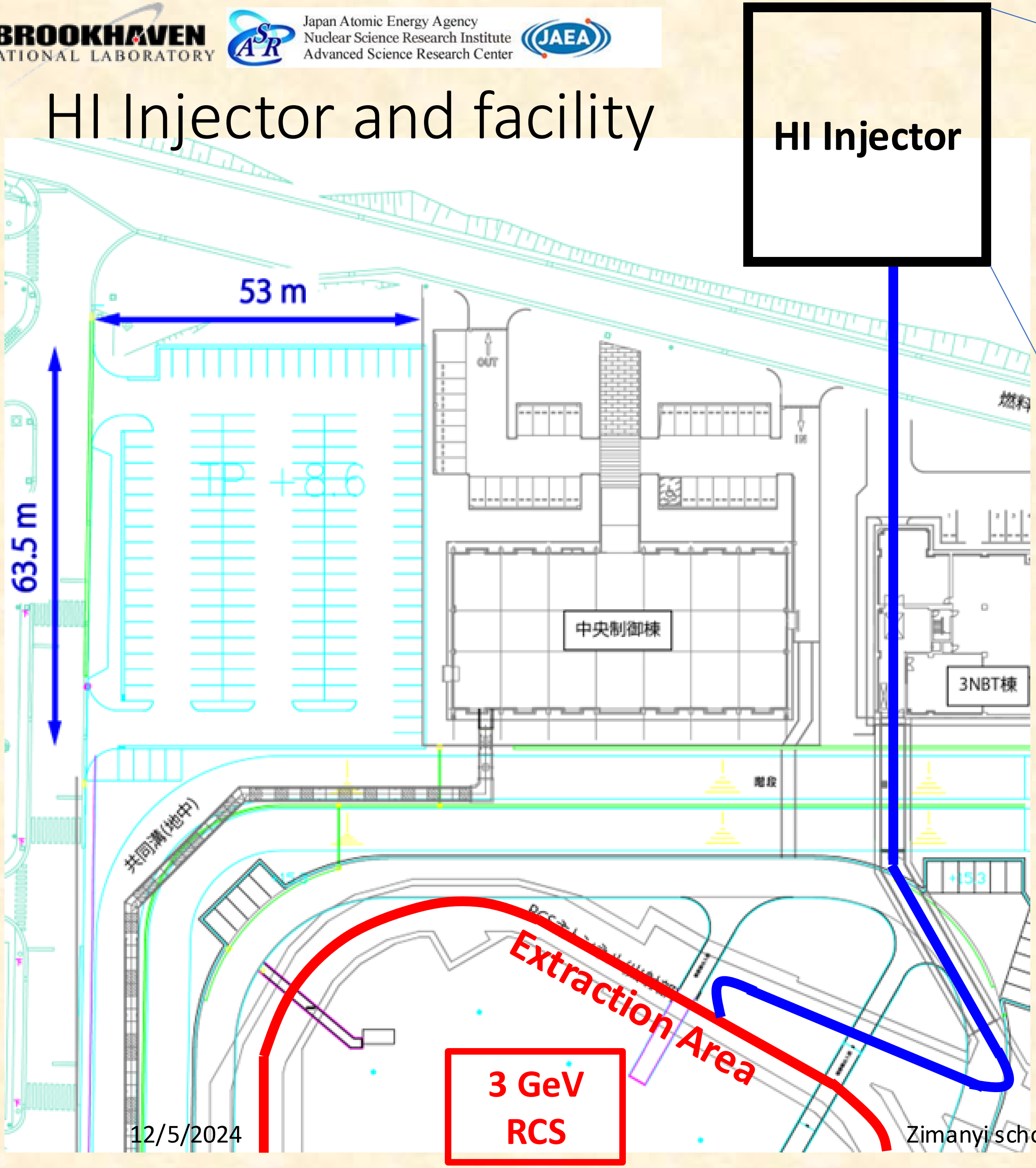
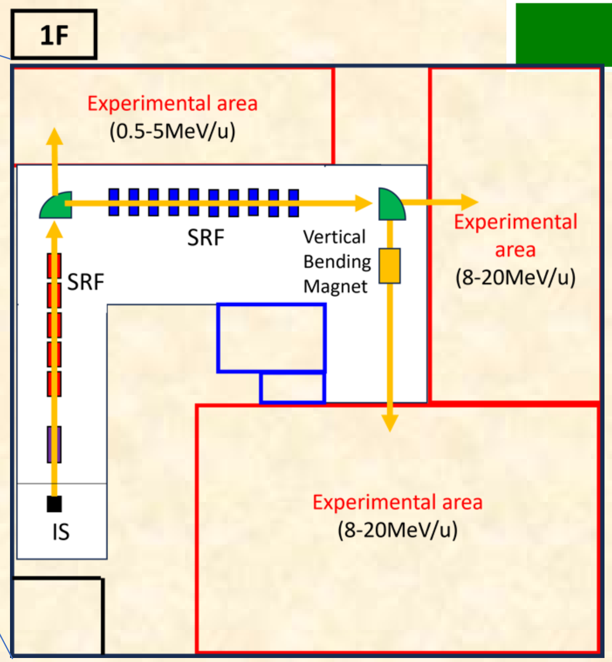
Japan Atomic Energy Agency Nuclear Science Research Institute Advanced Science Research Center JAEA

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

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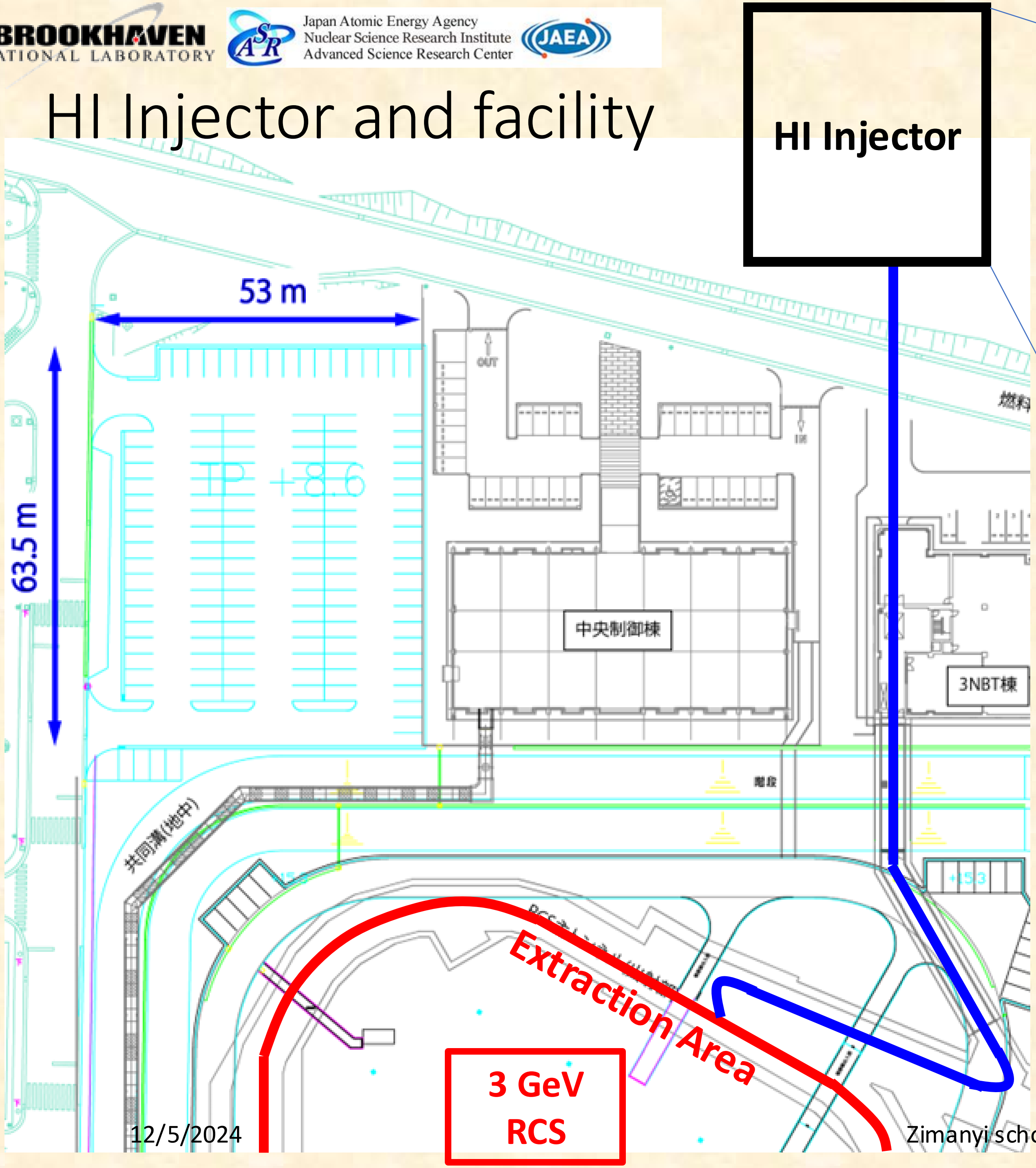

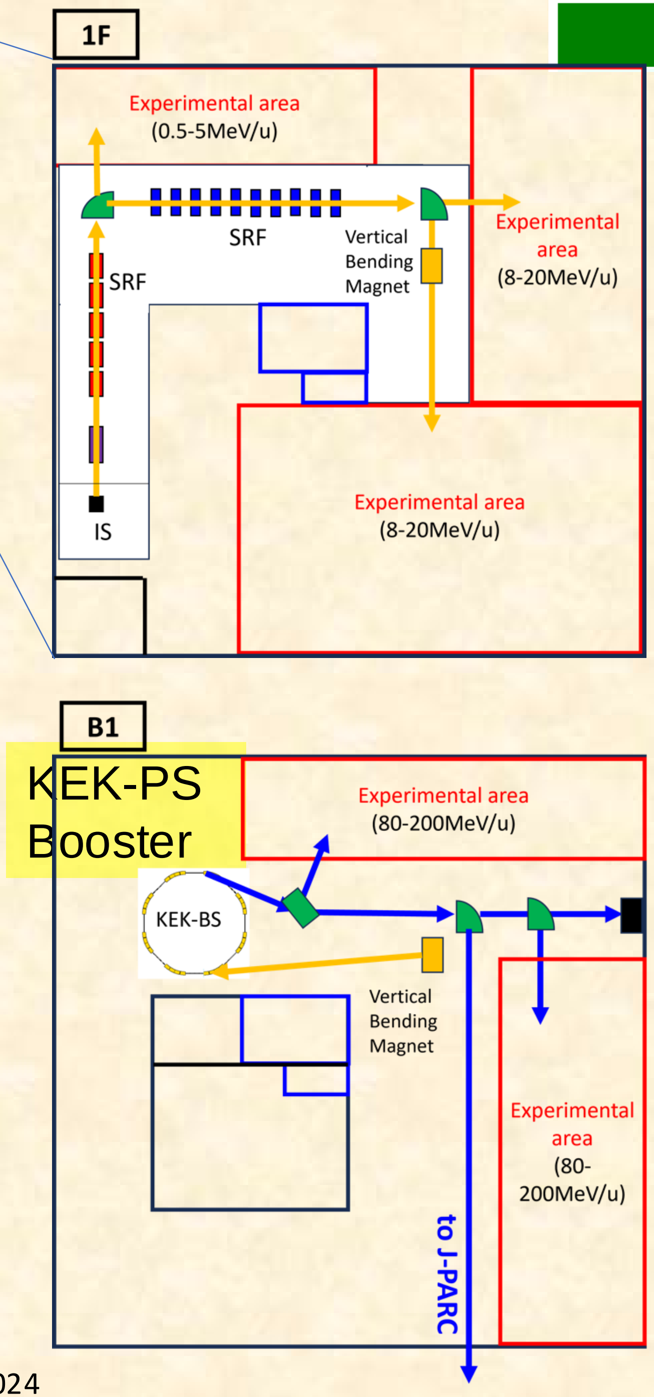

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Phase I
10^8 / spill

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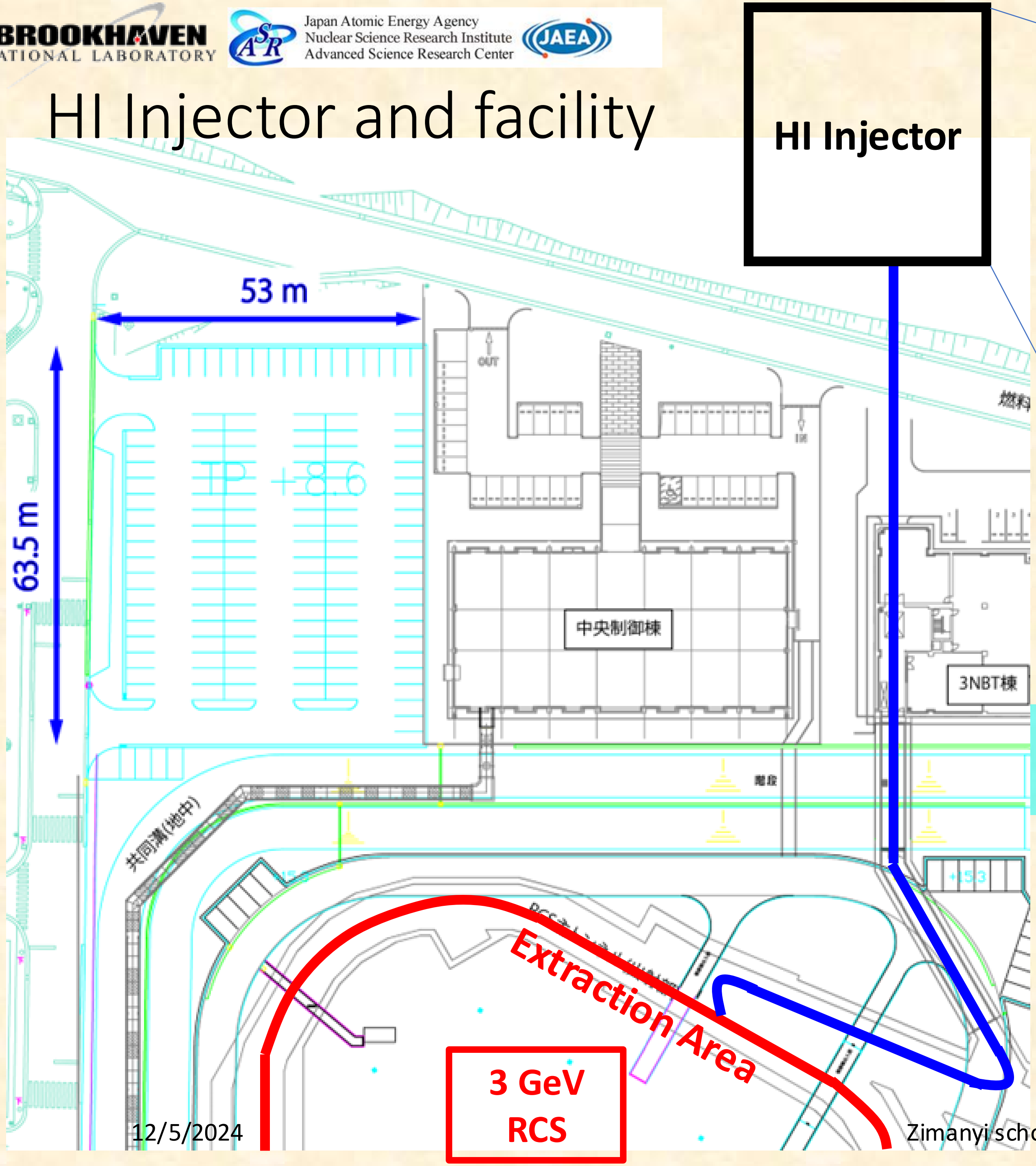
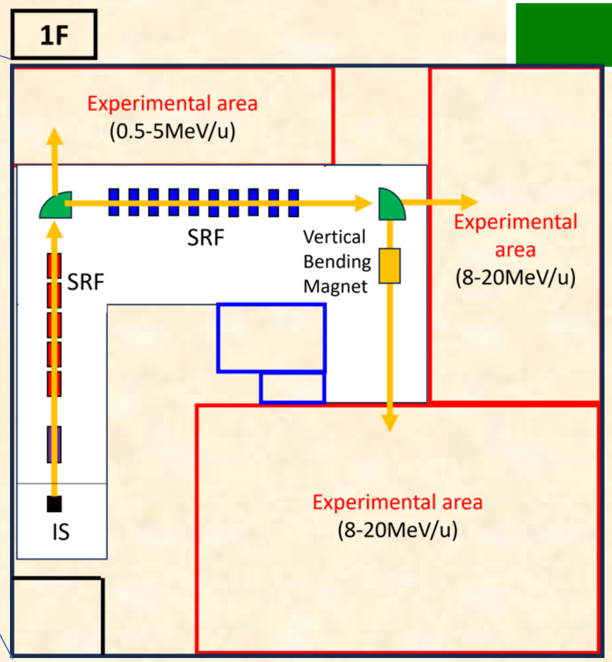
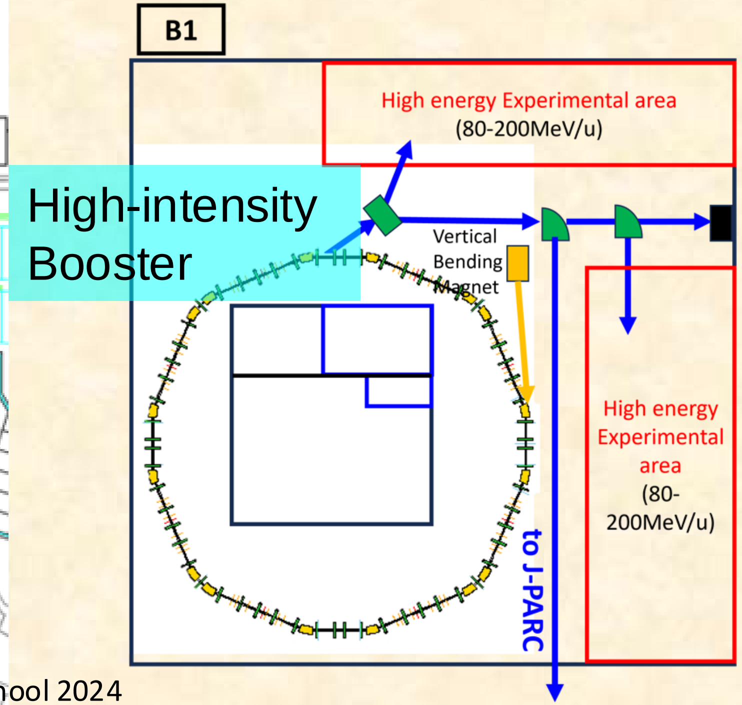
Japan Atomic Energy Agency
Nuclear Science Research Institute
Advanced Science Research Center

HI Injector and facility







Conceptual design
by H. Harada (J-PARC)

"Tokai HI Frontier Project" at JAEA

- Super-heavy nuclear physics
- Nuclear chemistry
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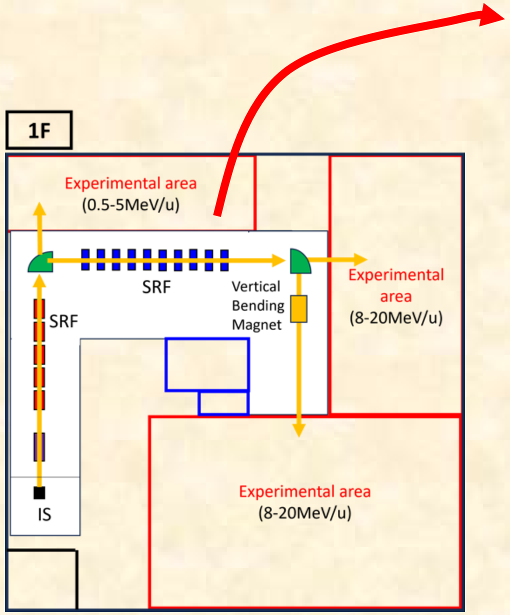
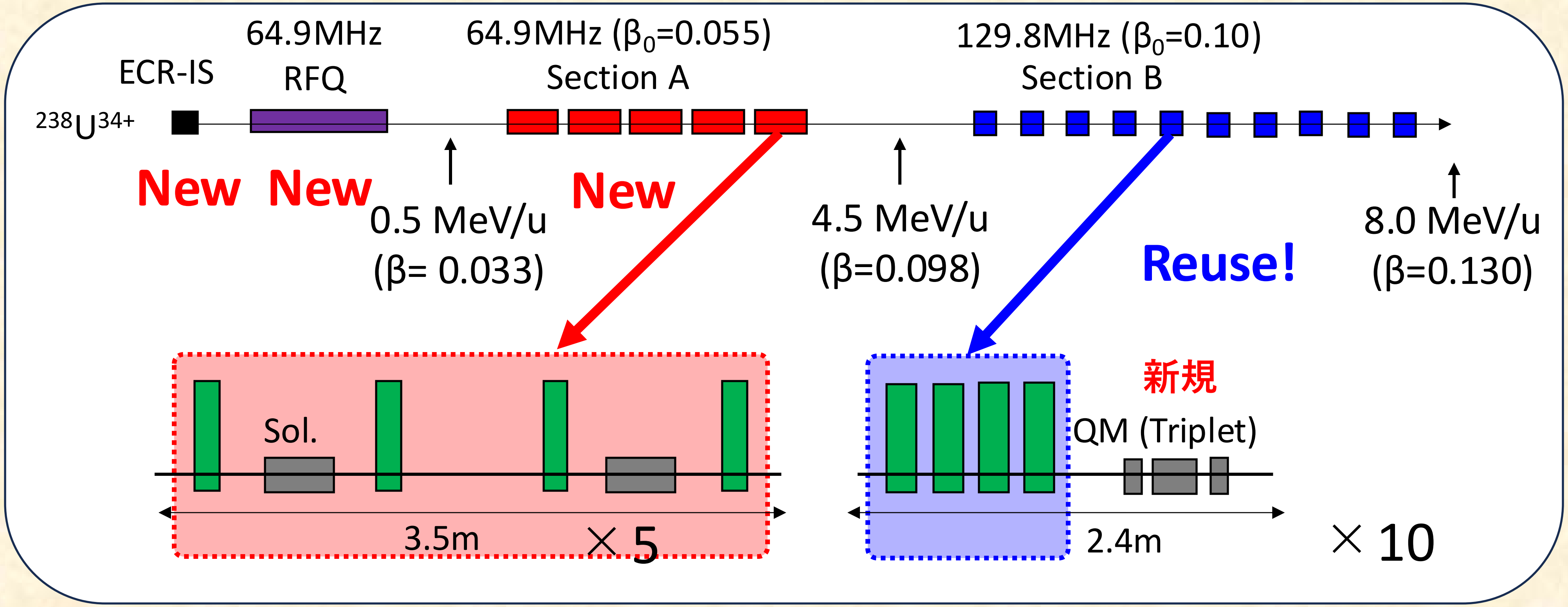
- J-PARC-HI Injector

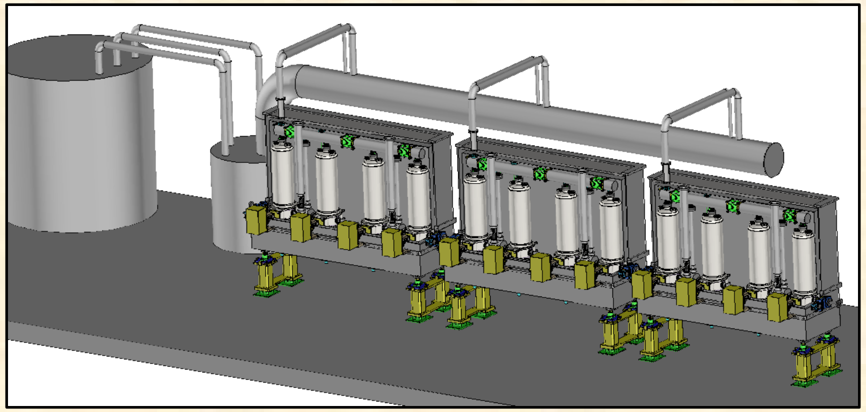
Phase II
10^{11}/ spill

New H-I Linac Construction using Old SC Cavity





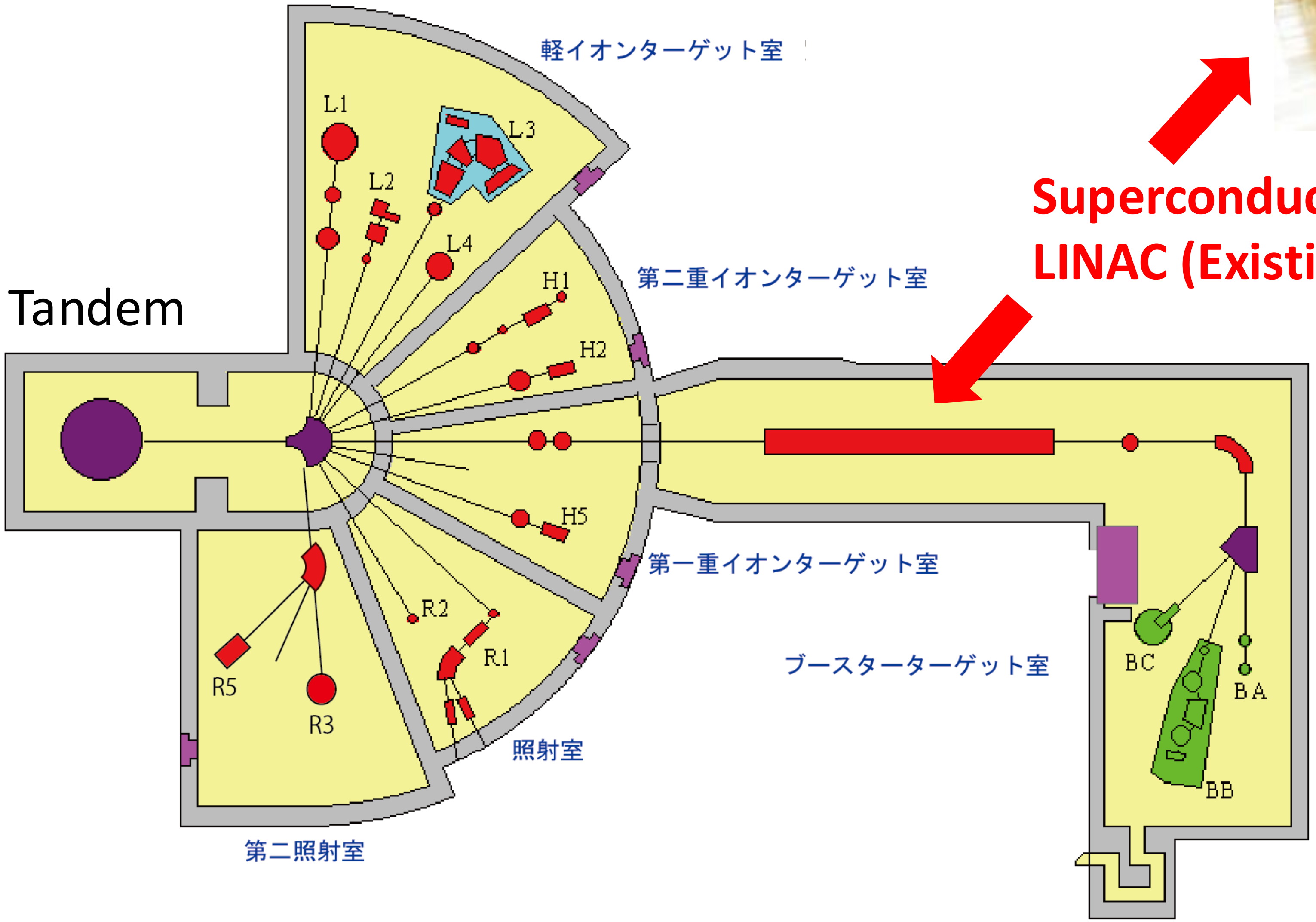
SC Cavity New System! Design Completed!

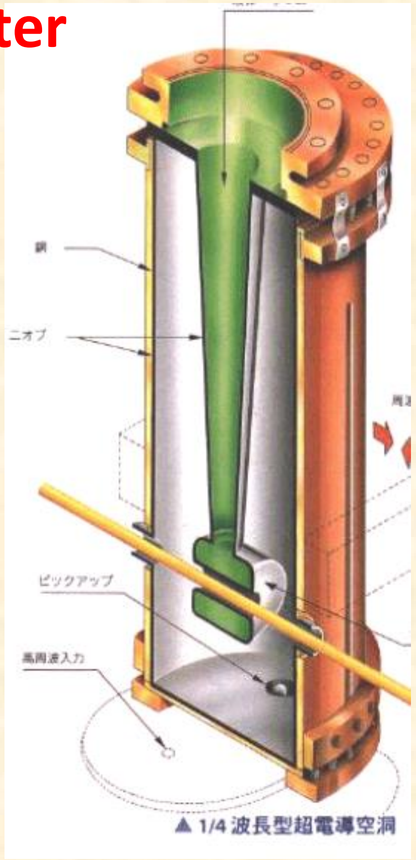


40 Existing SC Cavity

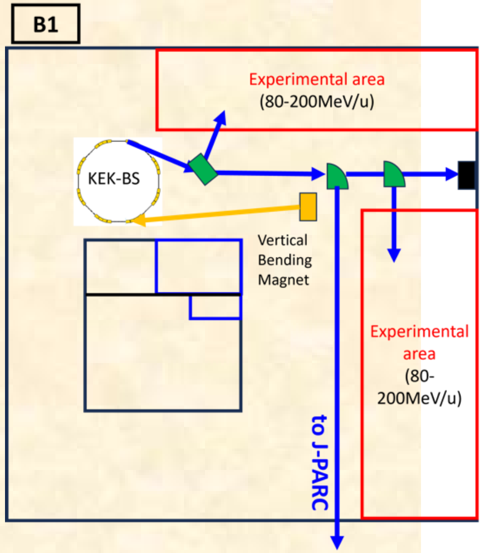
Superconducting Tandem Booster Linac

Superconducting Booster LINAC (Existing)





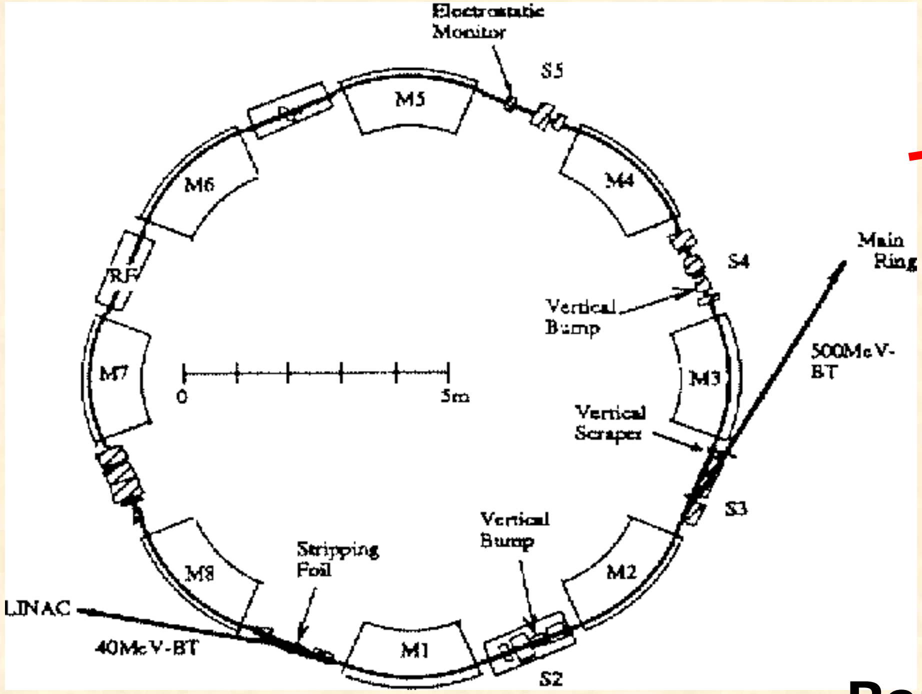
Demolishing old KEK-12GeV PS Accelerator Complex for…

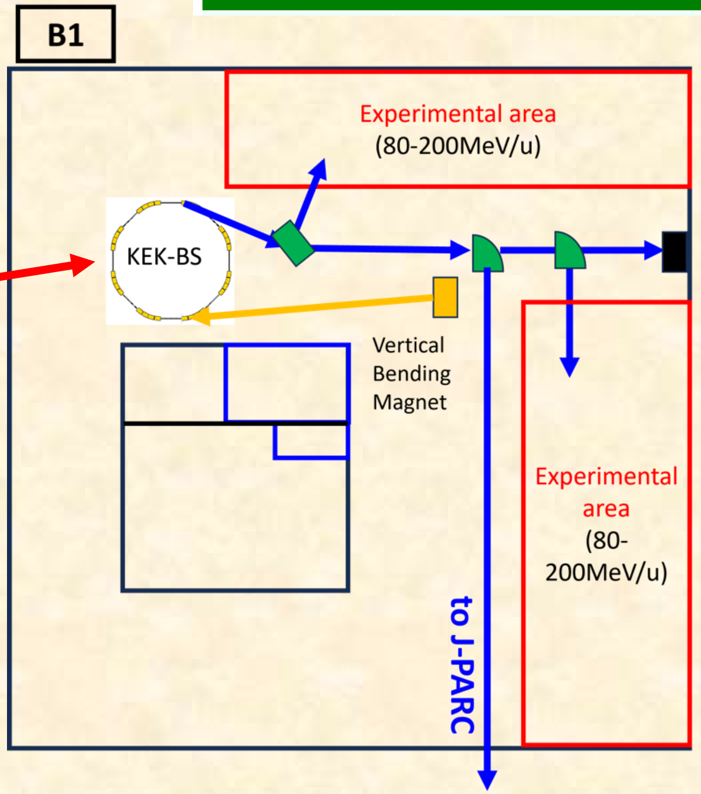


Already shut down

KEK 500MeV Booster

…KEK-PS Booster to be plugged into J-PARC-HI





- **Real Radius ~6m.**
- **Circumference 37.7m.**
- **Max. B 0.84T.**
- **Repetition Rate 10Hz.**
- **Betatron Frequency is $2.17_H/2.30_V$**
- **Max Energy (proton) 500MeV**

Particle production rates with ~10^{10} Hz beam

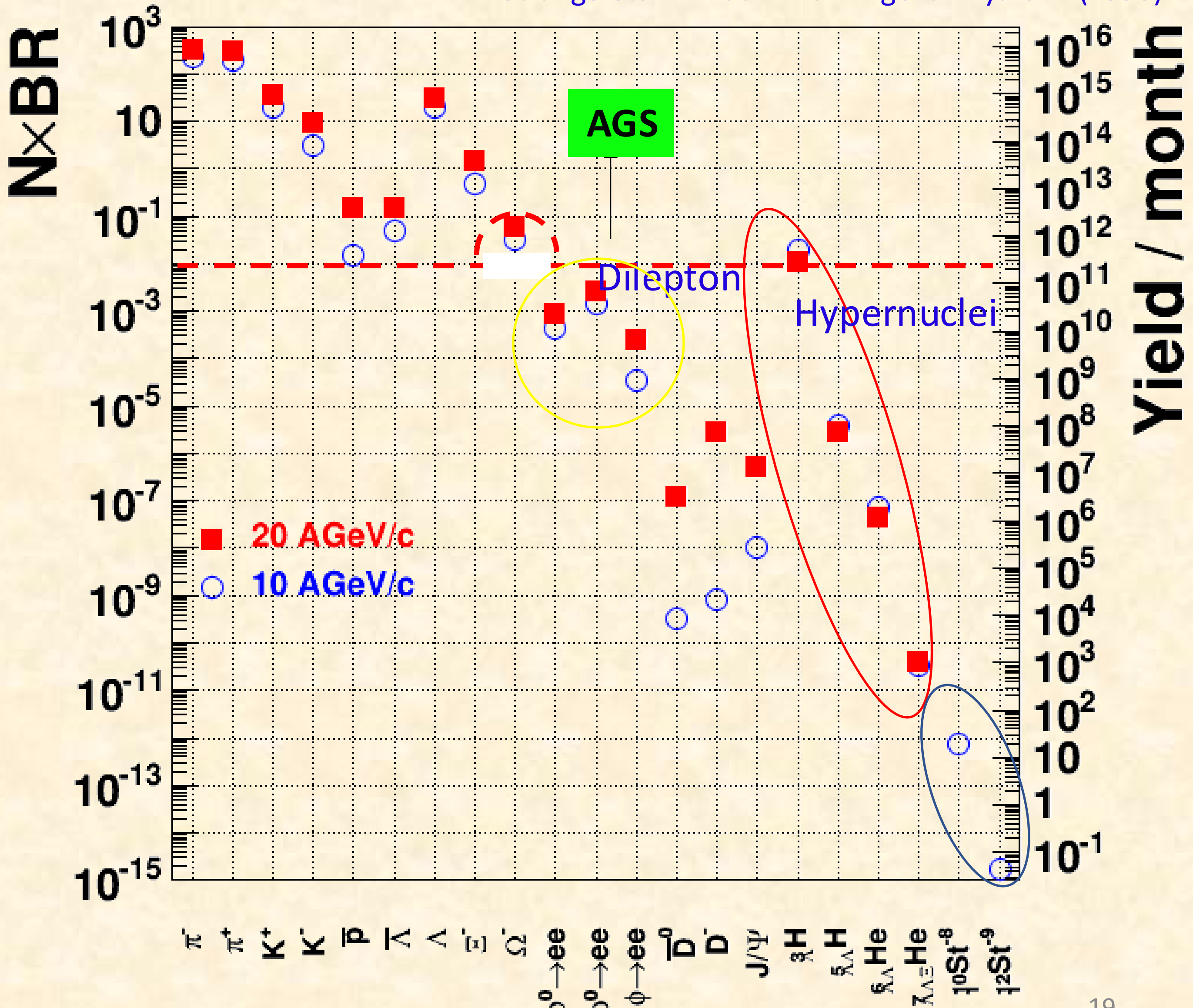
Spill time = 6 sec

Beam : ~10^{10} Hz
0.1 % target
→ Min-bias interaction rate 10^7Hz

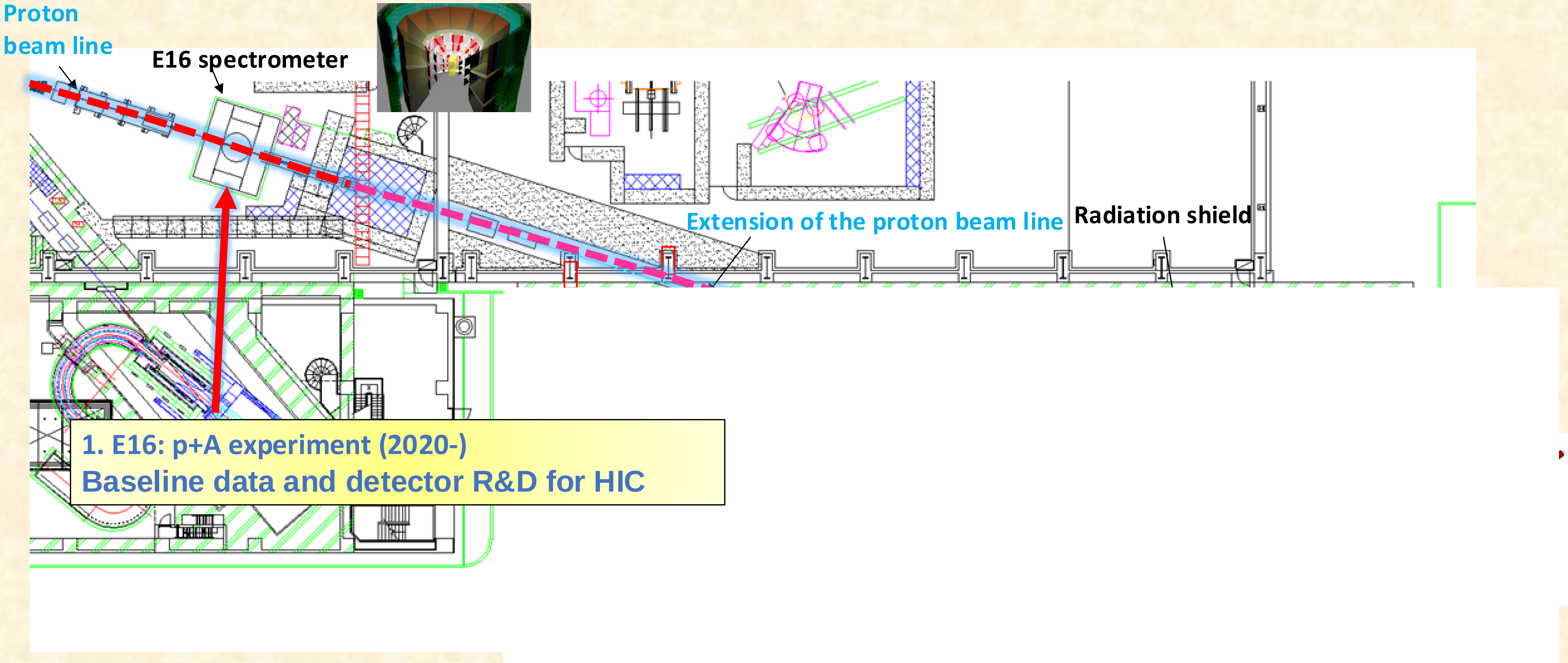
In 1 month experiment:
ρ,ω,φ→ee 10^9-10^{11}
Hypernuclei 10^3 -10^{11}
J/ψ 10^5

HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203

Strangelets: P. Braun-Munzinger J.Phys.G21 (1995)L17



J-PARC-HI Staging Strategy (Experiments)



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

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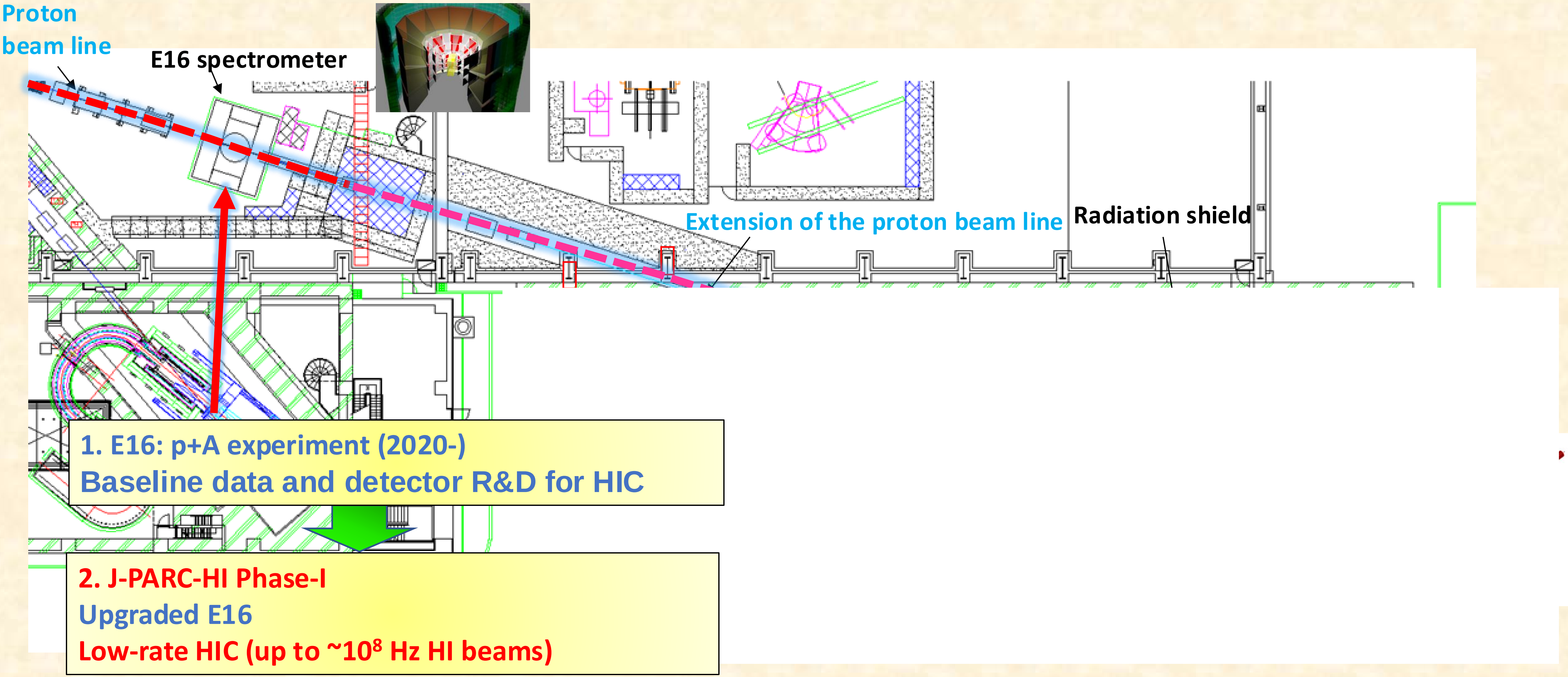
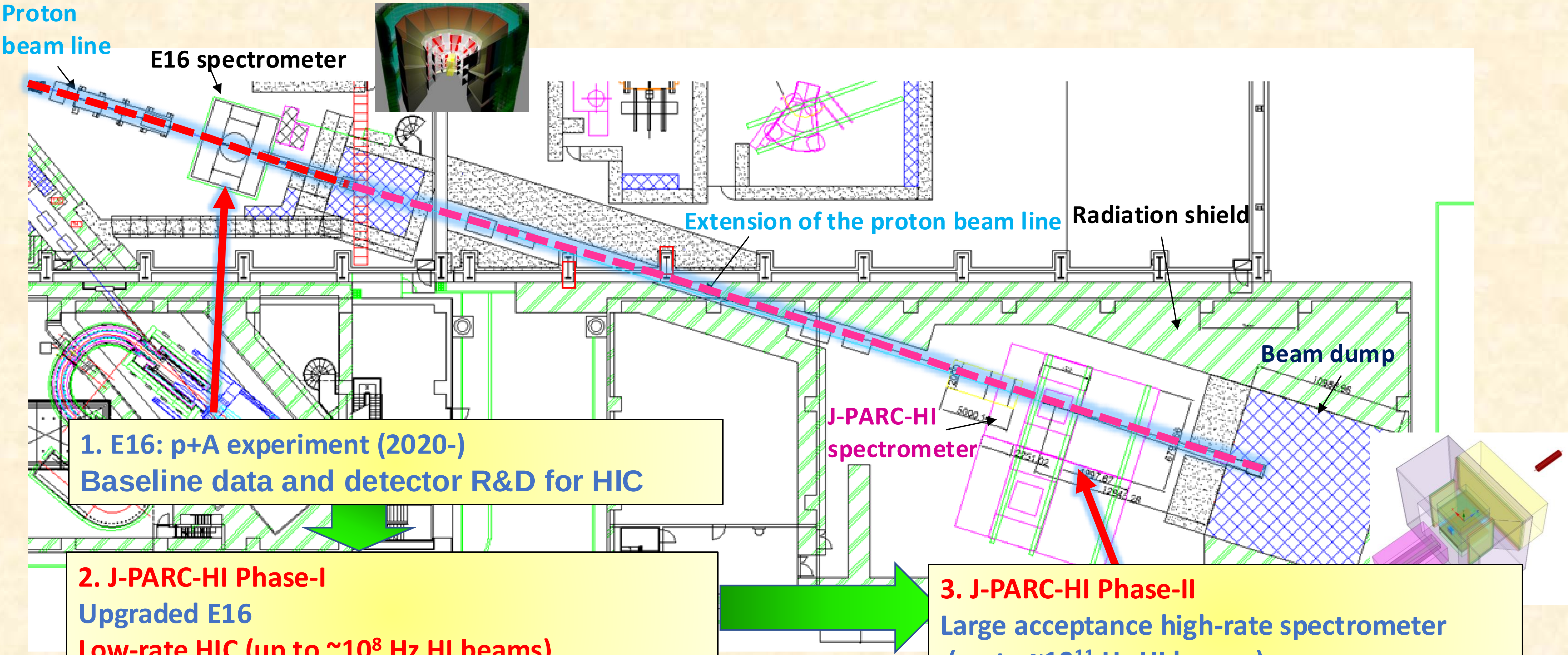


1. E16: p+A experiment (2020-)
Baseline data and detector R&D for HIC

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

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)

Initial focus: Dileptons

"Penetrating probe" w/o strong interaction
- Retain information of high-density matter
- Various physics can be studied in each mass range

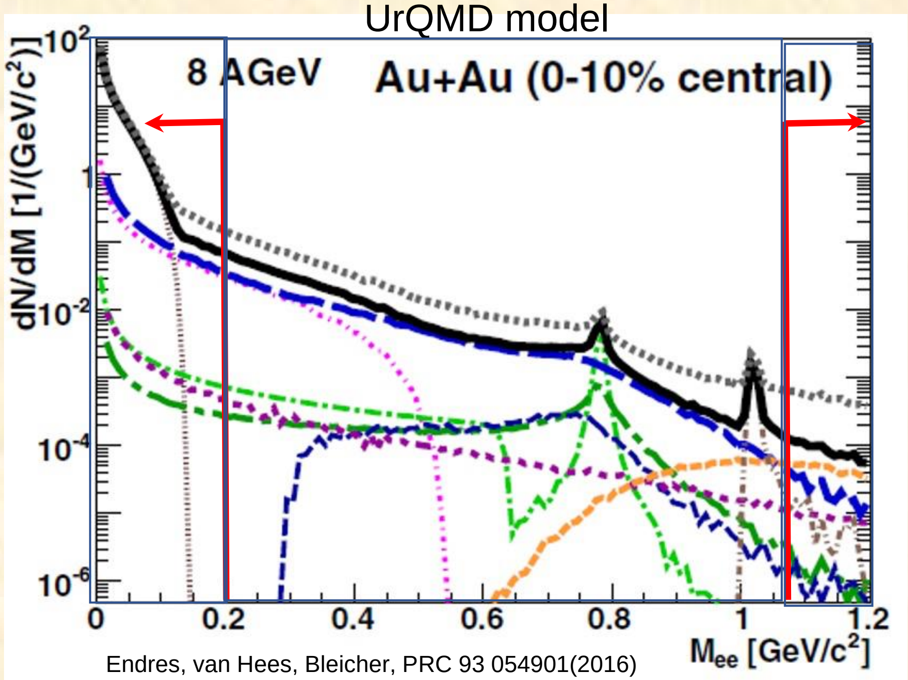
1. **π^0,η Dalitz decay region (m<0.2 GeV/c²)**
   Search for precursor of critical point or color superconductor

2. **ρ, ω, ϕ (LMR: 0.2-1.1 GeV/c²)**
   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

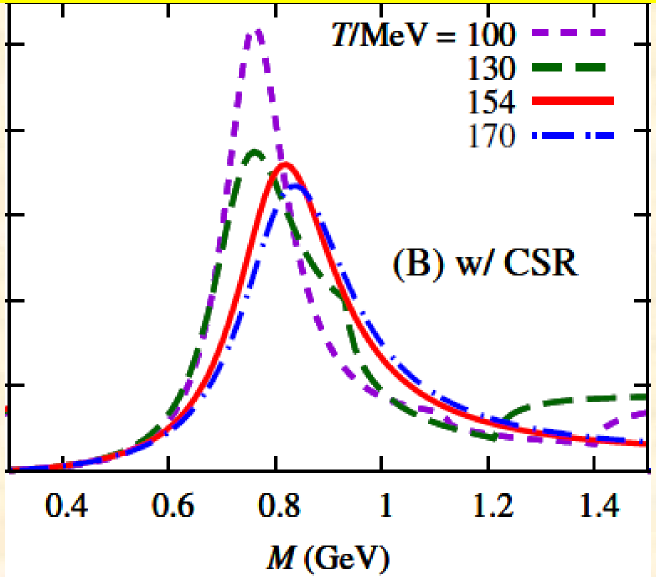
4. **Thermal photon (LMR: 0.2-1.1, IMR: 1.1-3 GeV/c²)**
   Search for phase transition with temperature measurement

UrQMD model



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

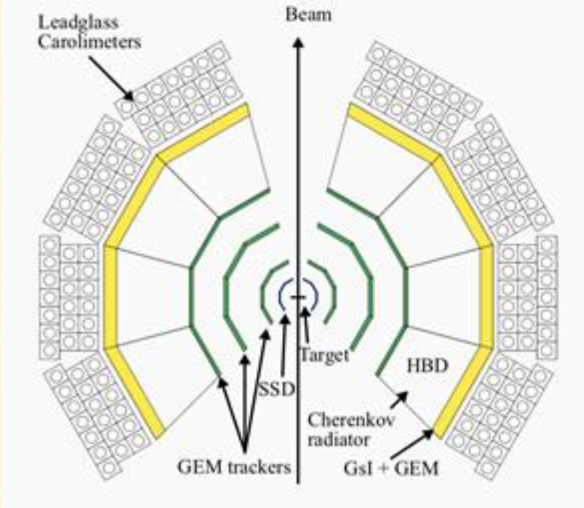
ρ–a_1 chiral mixing at high T and low density



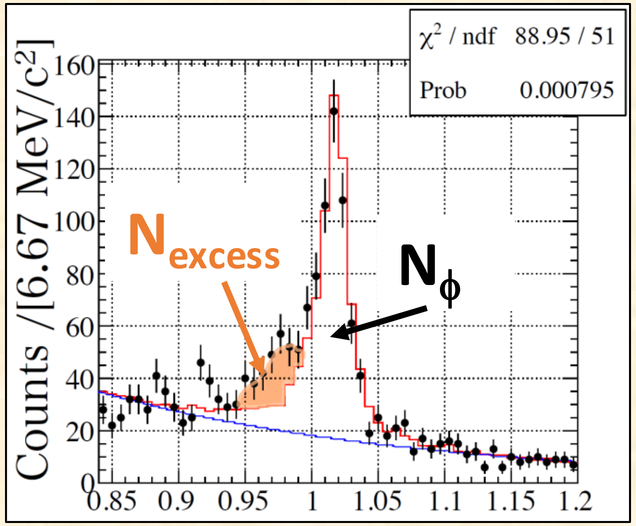
A. Sakai M. Harada, C. Nonaka, C. Sasaki, K. Shigaki, S. Yano, EPJ Web Conf. 296, 07008 (2024)

Current: J-PARC E16/E88 : ϕ -> e+e- and K+K- in p+A

E16: dielectron including ϕ→e+e-

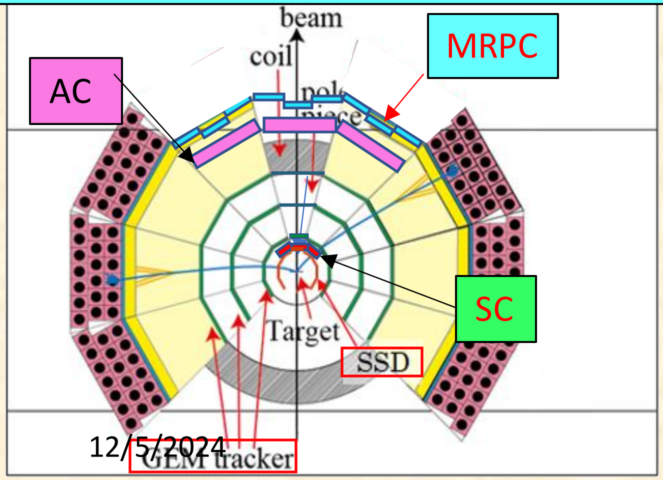


Expected spectrum (15k ϕ, p+Cu)

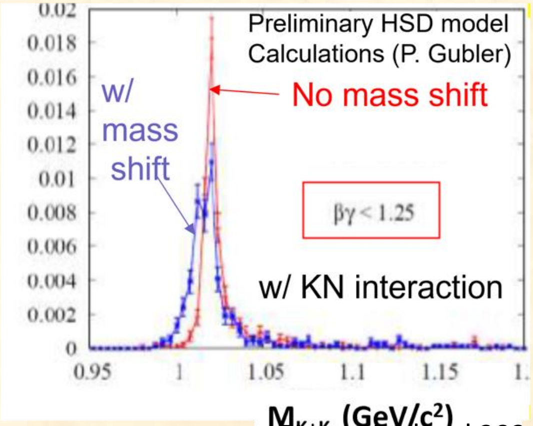


Previous experiment KEK-E325 ~ 3k ϕ→e+e-
JFY2020-2024 Commissioning completed
JFY2025- Physics Run 1
~15k ϕ→e+e- (6x E325)
JFY2027?- Physics Run 2
~69k ϕ→e+e- (23x E325)

E88: ϕ→K+K- (proposed in 2022)

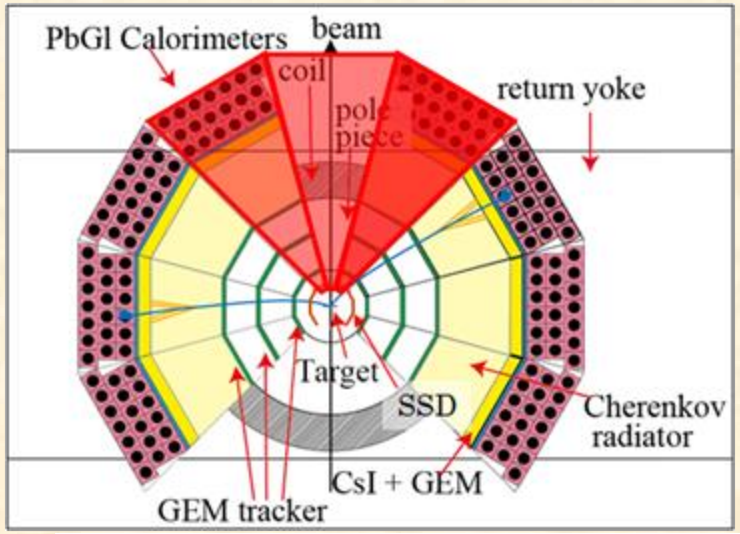


~1M ϕ→K+K-

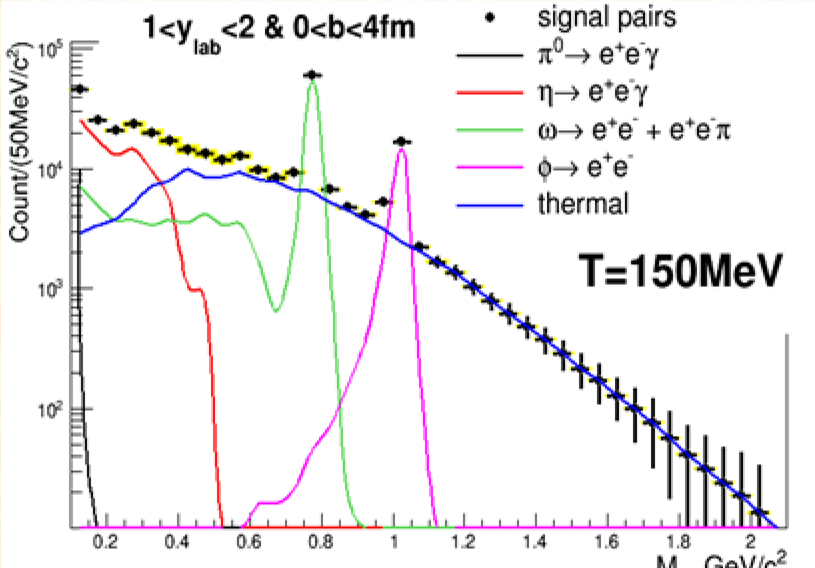


Thermal photon measurements through dielectrons

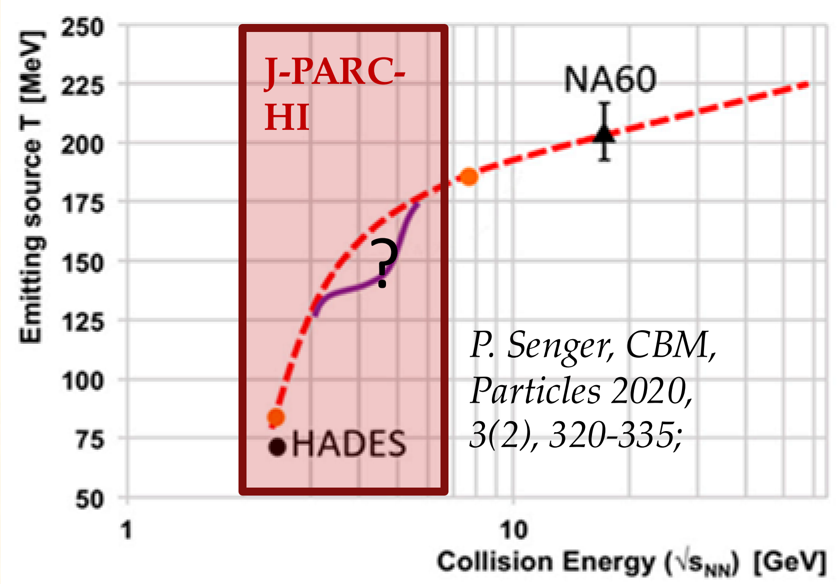
~Proposal submitted to PAC as Phase I HI physics (2022)~



► Upgrade of forward trackers and EM calorimeter of E16



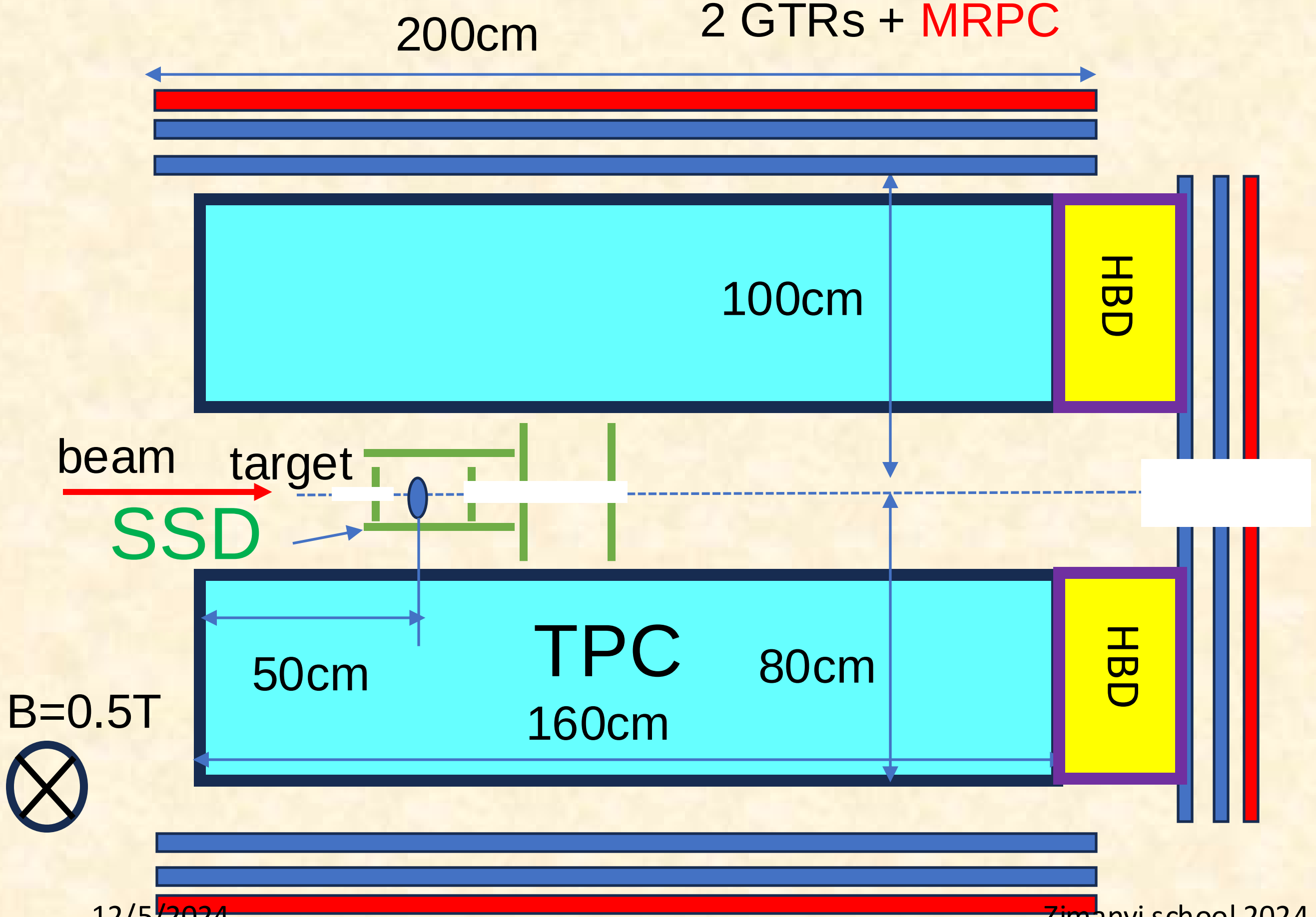
100-day
Beam time

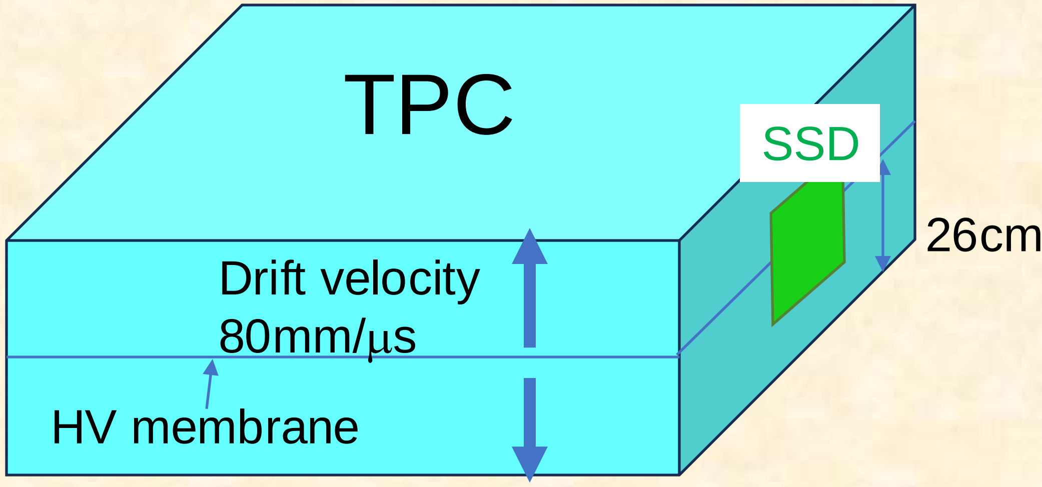


P. Senger, CBM, Particles 2020, 3(2), 320-335;

Next spectrometer design for “Phase 1.5”

- Studies in progress
- In Phase I and Phase II up to 1x10^8 Hz
- Large acceptance measurements of dielectrons and hadrons

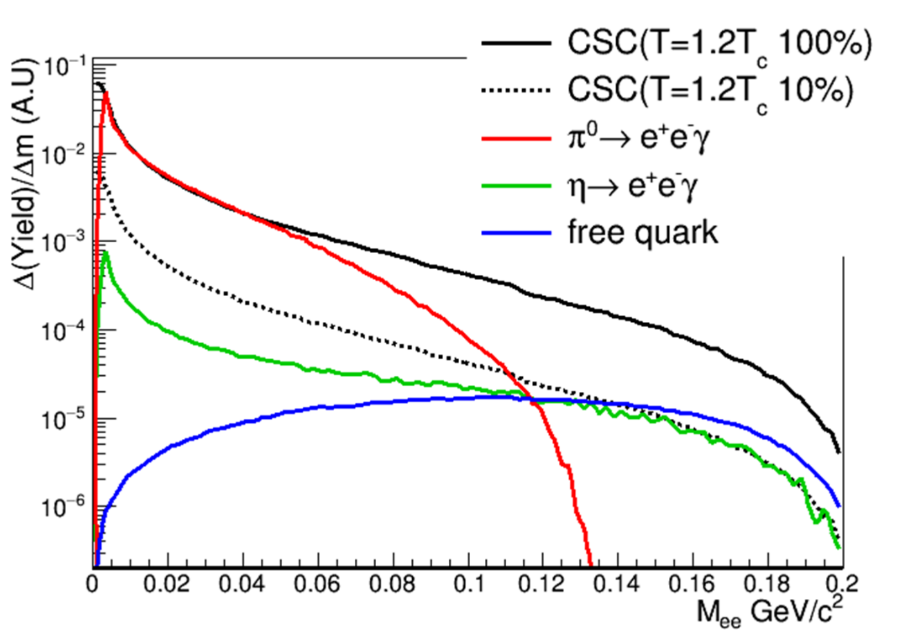




TOF : 2σ e-π separation p<=0.4 GeV/c

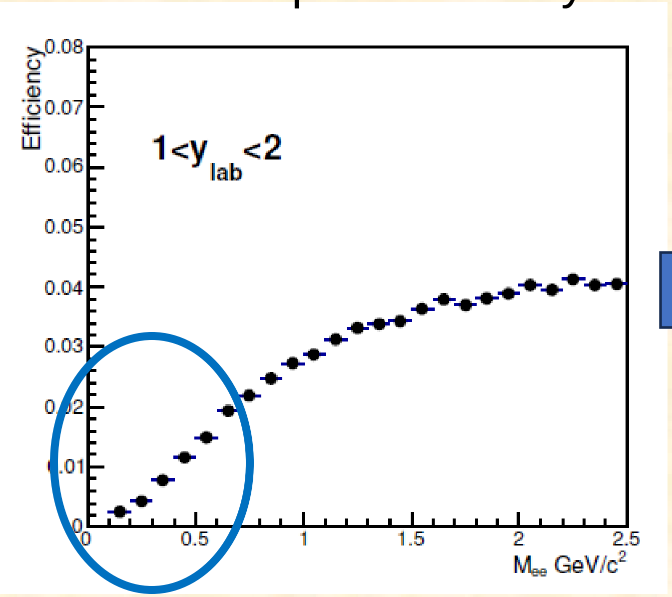
Low-mass di-electron measurement with Phase 1.5

e+e- invariant mass spectra
from CSC (color superconductor) precursor

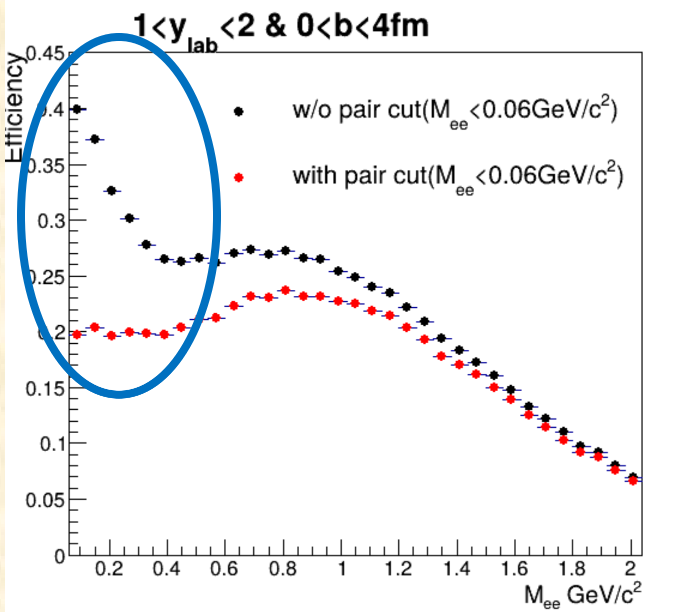


Based on theory calculation by T. Nishimura, M. Kitazawa, T. Kunihiro, PTEP 2022, 093D002

PHASE1 pair efficiency

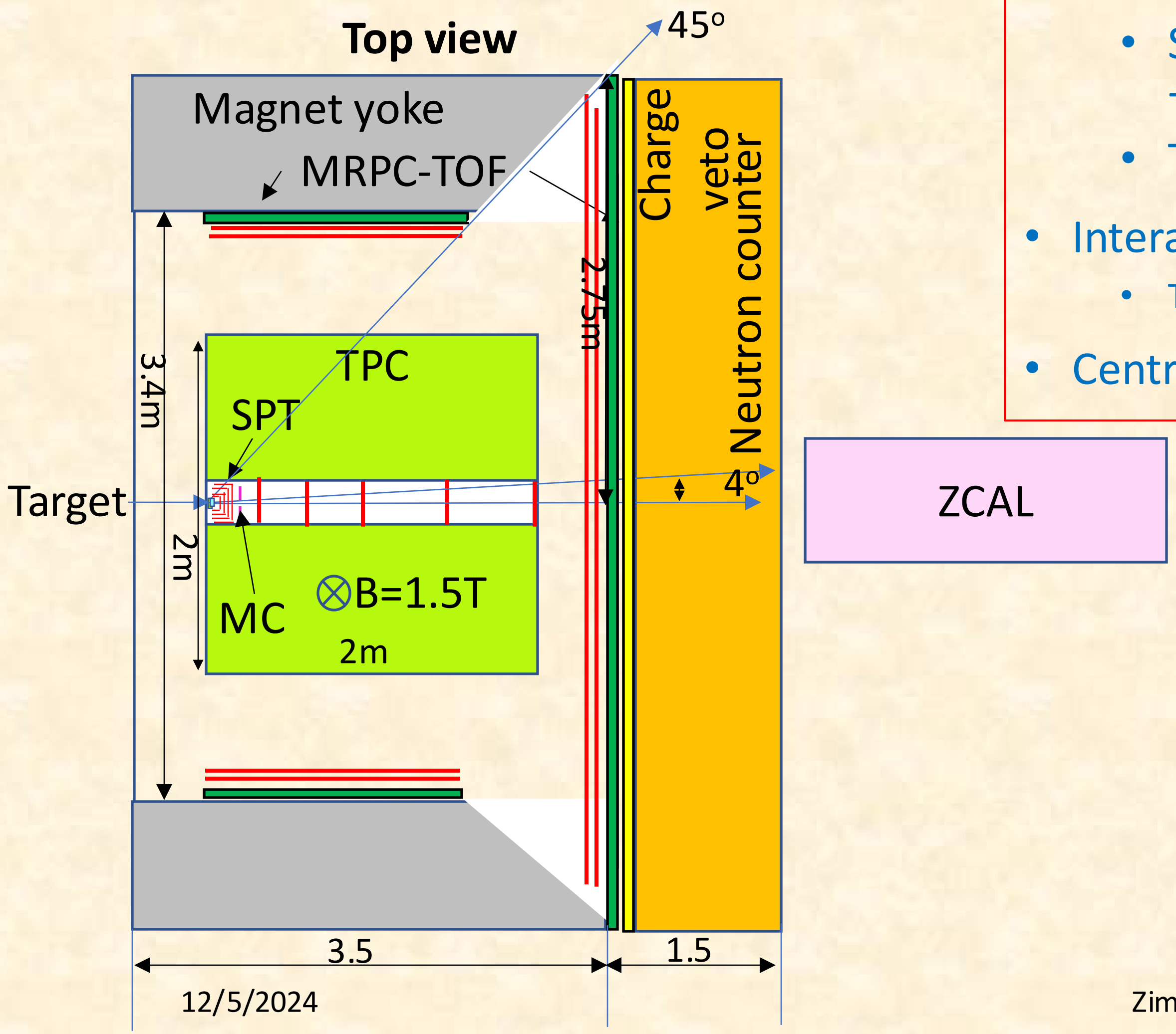


PHASE1.5 pair efficiency



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

Phase 2 Detector (Hadron, Dimuon, Hypernuclei)



- Identified charged particles
- ~4π acceptance
  - Silicon Pixel Tracker (SPT) ($\theta < 4^o$) (hadron) → GEM tracker +absorber (dimuon)
  - TPC ($\theta > 4^o$) , MRPC-TOF
- Interaction Rate : <=1 MHz
  - Triggerless DAQ system
- Centrality : Multiplicity counter + Zero-degree calorimeter

- Setup will be changed as going to hadron, dimuon, and hypernuclei measurement.
- Design is still conceptual and has a large degree of freedom to implement new idea.

Summary and prospect

- No High Energy Heavy-Ion Accelerator Facility in Asia Pacific region
  - J-PARC-HI will change the game plan of our field.
- J-PARC-HI project is making steady progress
  - Proposal of measuring thermal photons through dileptons have been submitted.

- HI injector and the facilities are being designed
  - Repurposing old but existing KEK-PS 500-MeV Booster ring and JAEA Tandem Booster linac, we save construction money and construction time of Heavy-Ion injector.
    - Conceptual design is planned to be wrapped up by the end of JFY2024.
  - Once the project was approved, the accelerator part will be completed in ~6 years.
- Staged plan for the experiment is settled.
  - Phase 1: Adding forward tracker and EM calorimeter to E16/E88 experiment
  - Phase 1.5: Repurpose of E16/E88 detector that still fits to the same area.
- Participation of international institutions is highly appreciated
  - And more proposals using J-PARC-HI beam/detector would help put forward the project.

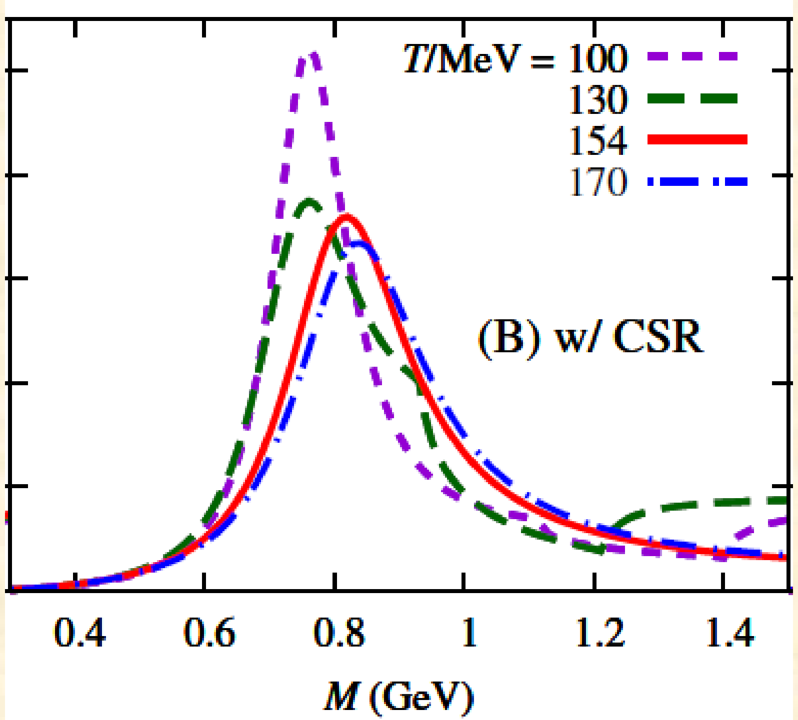
Backup

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

Chiral mixing → signal of axial vector in dilepton

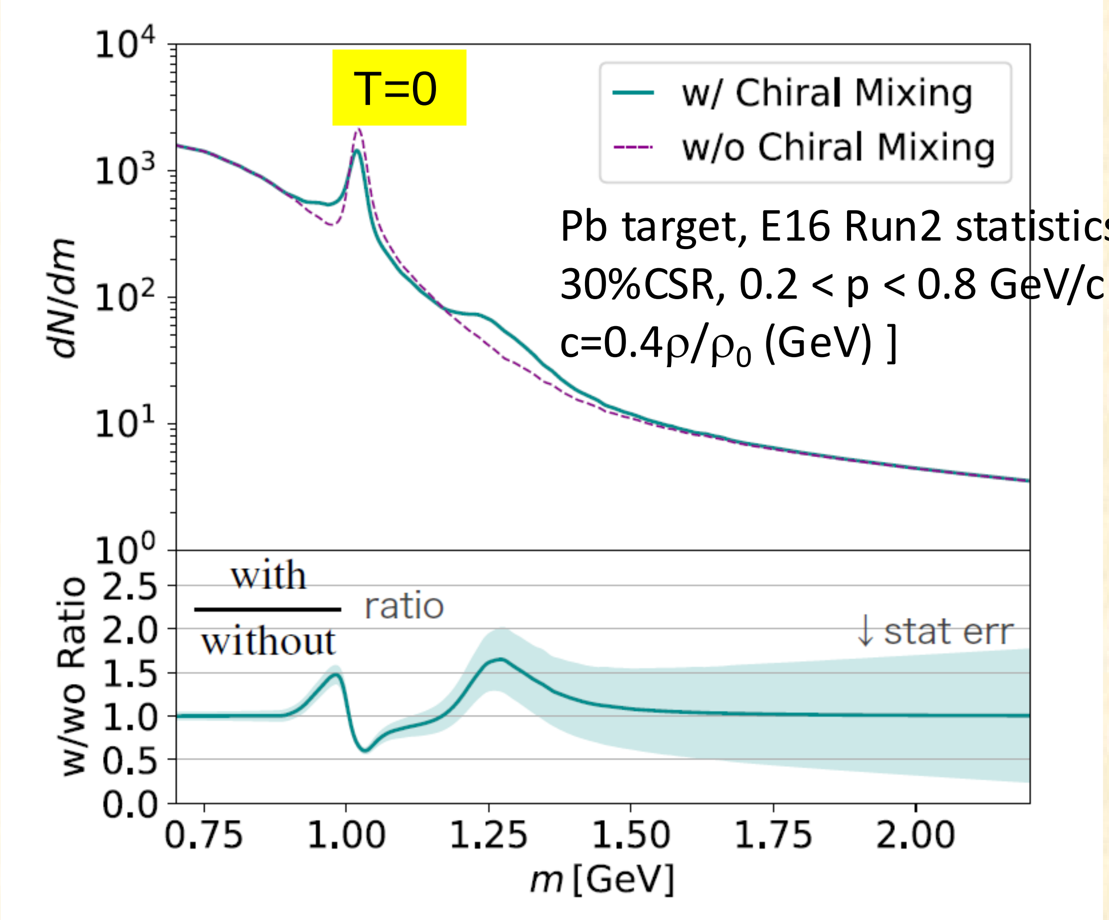
Chiral symmetry restoration → degeneration of vector and axial vector mesons → Change of dilepton spectrum

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 f-f_1 mixing



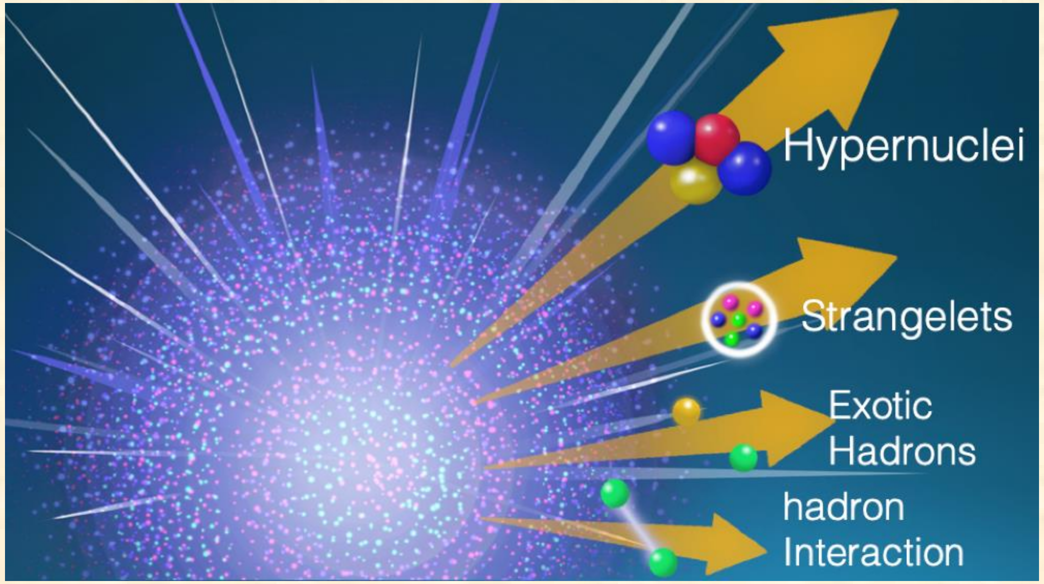
R. Ejima, P. Gubler, C. Sasaki, K. Shigaki, in preparation

Goals of J-PARC-HI (II)

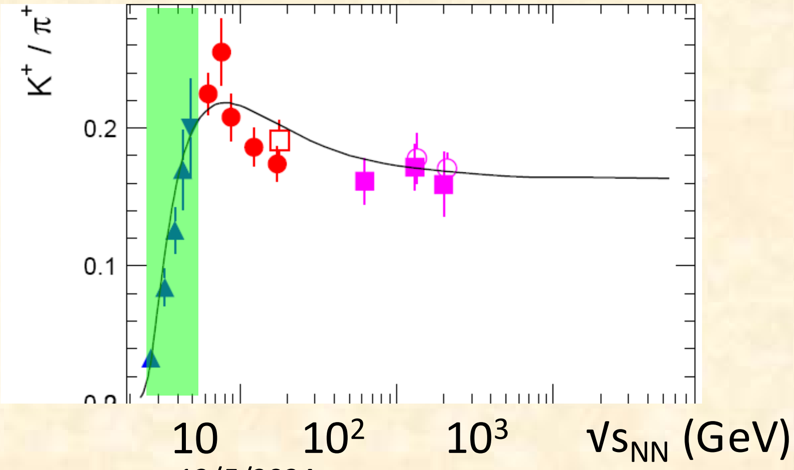
Search for multi-strangeness systems

- Efficient production of strangeness at J-PARC energy
- Search for Rare particles/nuclei
  - Hypernuclei, strangelets, dibaryons, etc.
- Particle interactions
  - Femtoscopy（two-particle momentum correlation）

  →EOS



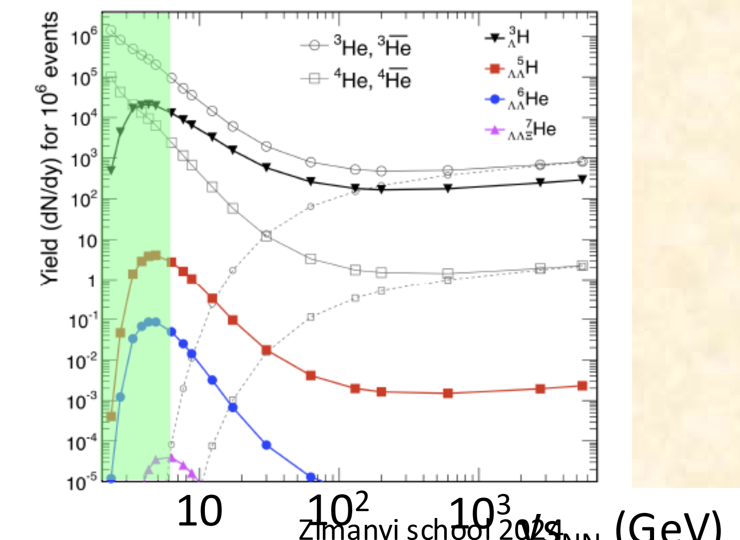
J-PARC-HI



A. Andronic, et al, Nucl. Phys. A 837 (2010) 65

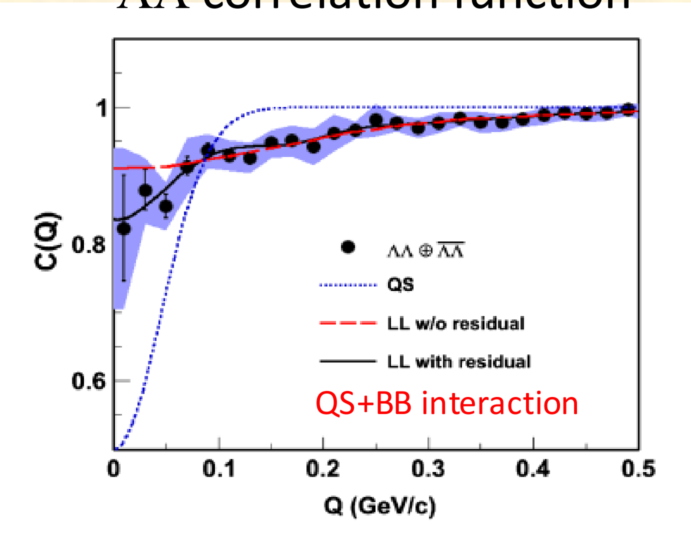
Hypernuclei

J-PARC-HI



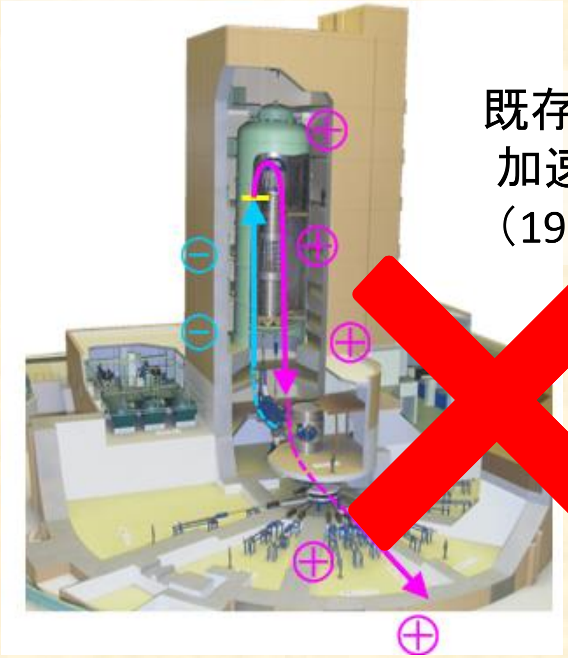
A. Andronic, PLB697 (2011) 203

ΛΛ correlation function



STAR, PRL114 (2015) 022301

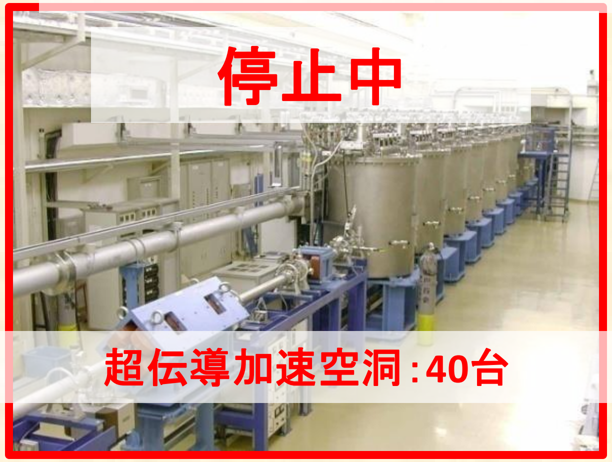
タンデム後継機～超伝導線形加速器～



既存タンデム
加速器施設
（1982年～）

2MeV/u
低強度

我が国で初めて超伝導加速
空洞による重イオン加速

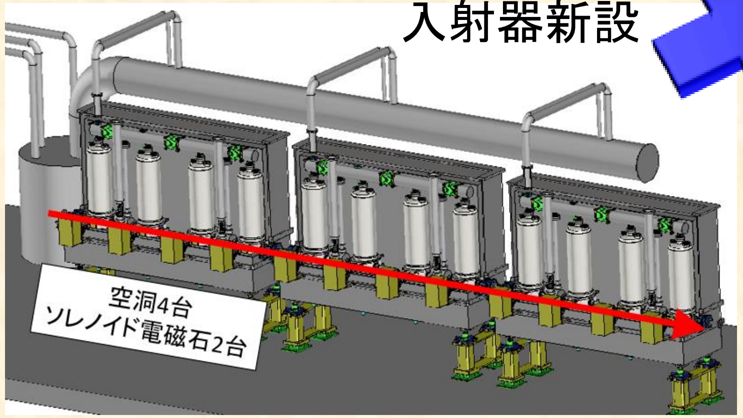


130MHz, 5MV/m, β=0.10

2MeV/u
低強度

エネルギー：4倍以上
ビーム強度：100倍以上

入射器新設



超伝導加速空洞
65MHz, 8MV/m, β=0.55

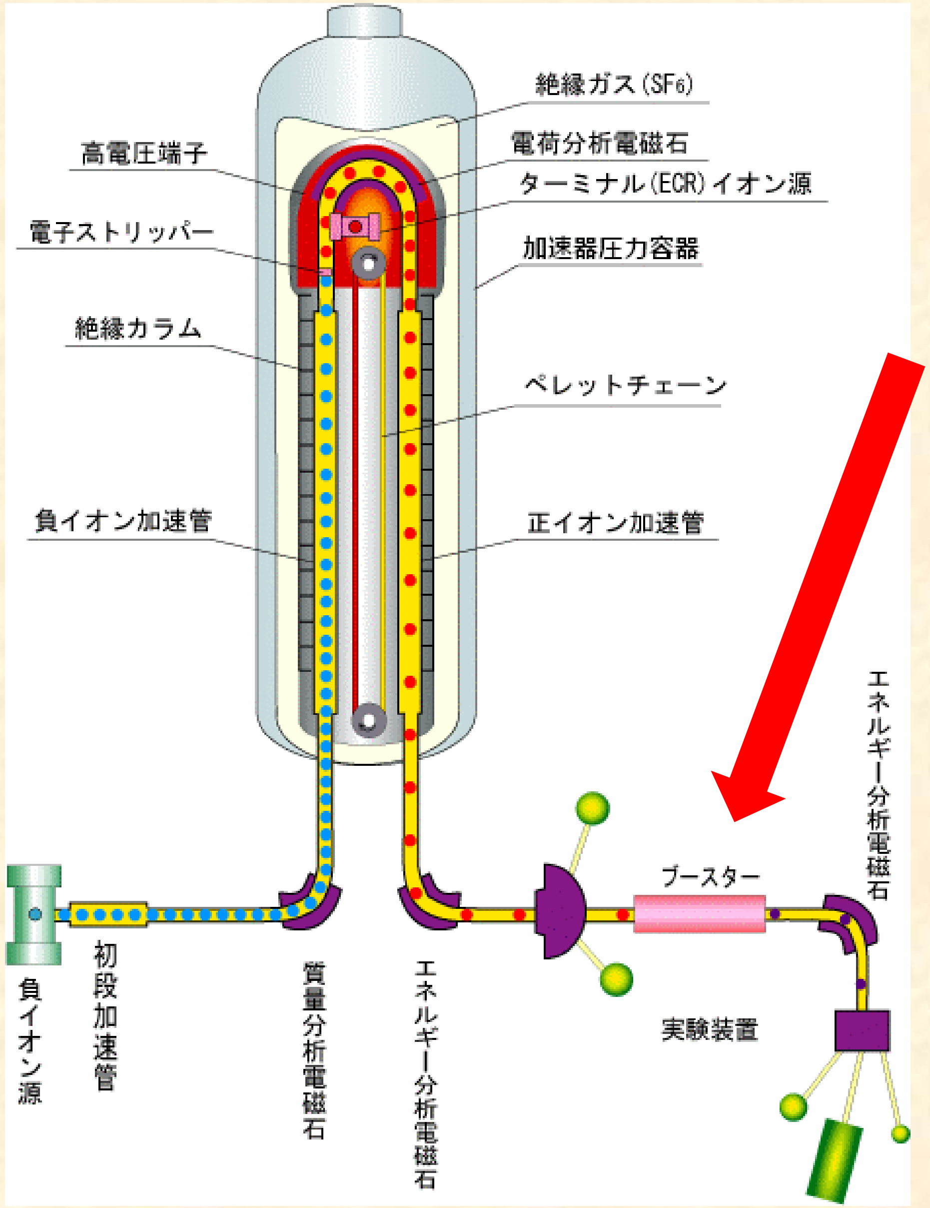
4.5MeV/u
大強度

再稼働

8.0MeV/u
大強度

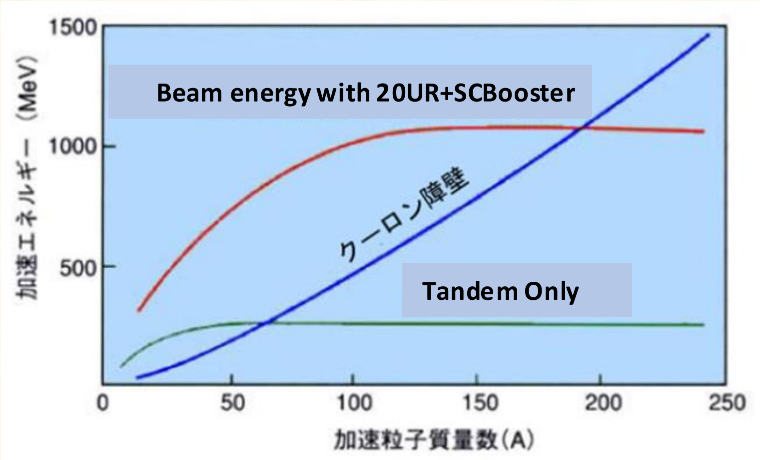
タンデム後継機
↓
重イオンフロンティア施設
（J-PARCへの入射器も兼用）

Existing SC Cavity at old 20UR Tandem VdG



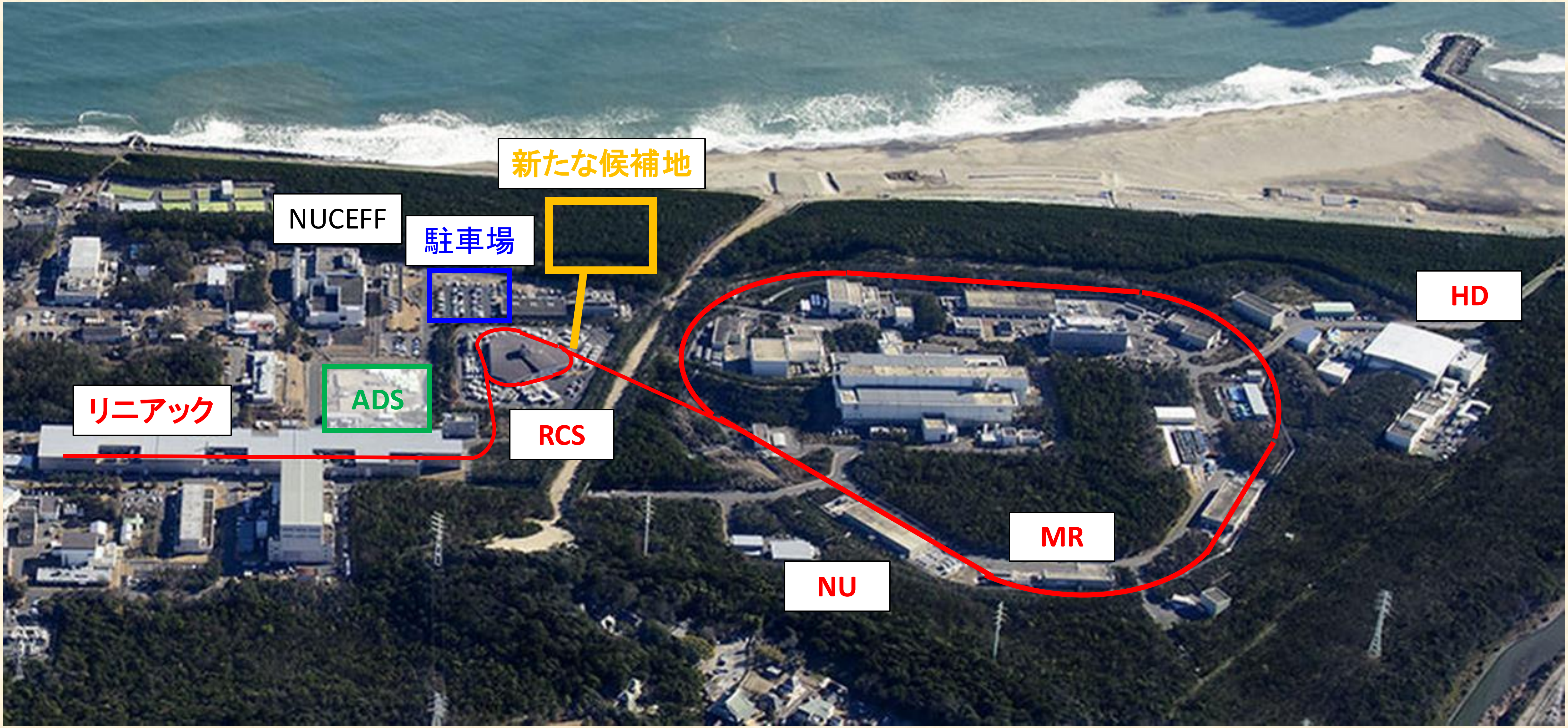
Superconducting Booster LINAC for 20UR Tandem VdG is existing!

Beam energy with 20UR+SCBooster



Typical Acceleration Energy
A ～100 region: 10 MeV/u
A ～50 region: 20 MeV/u

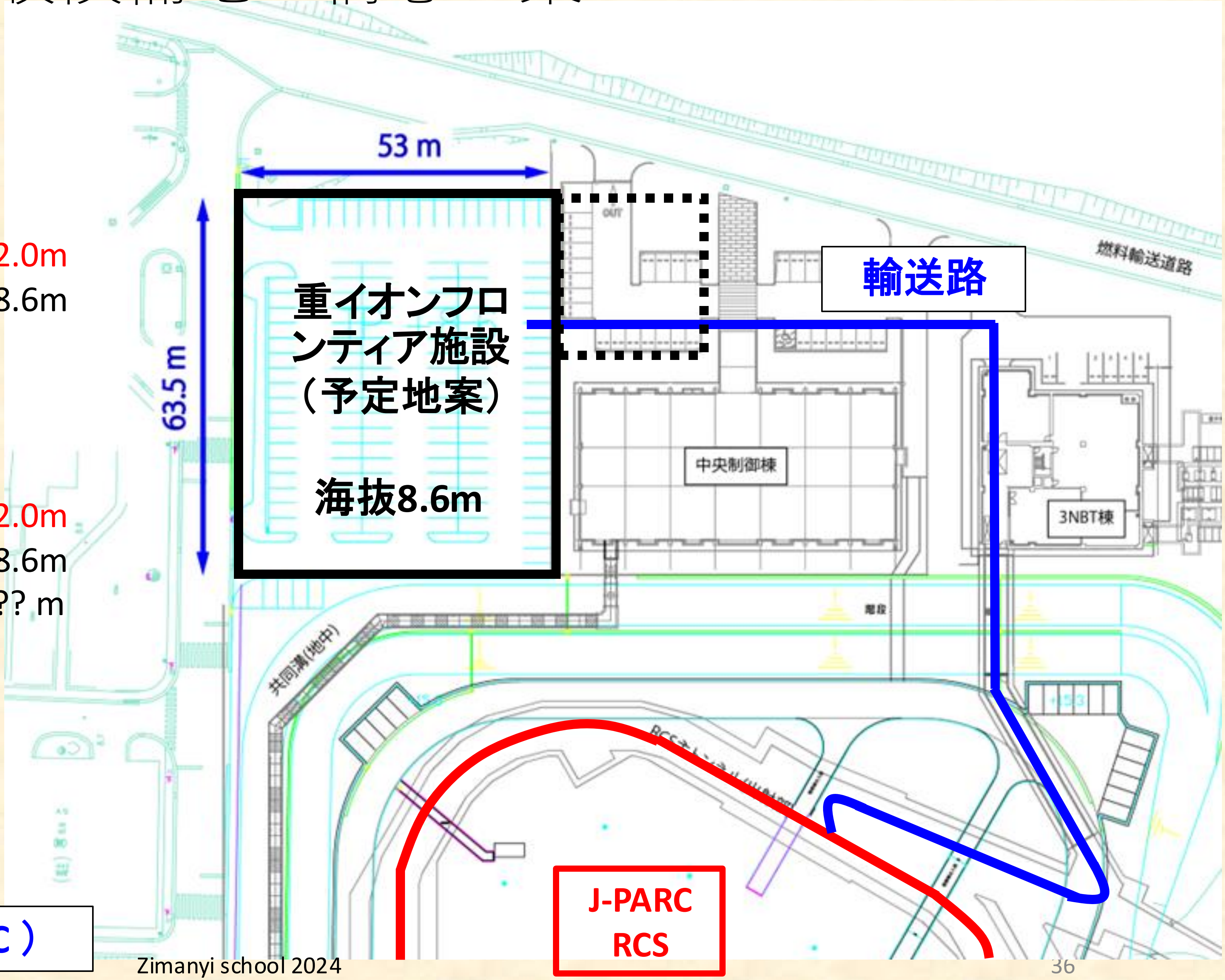
J-PARCの航空写真と新たな候補地



重イオンフロンティア施設候補地と構想の案

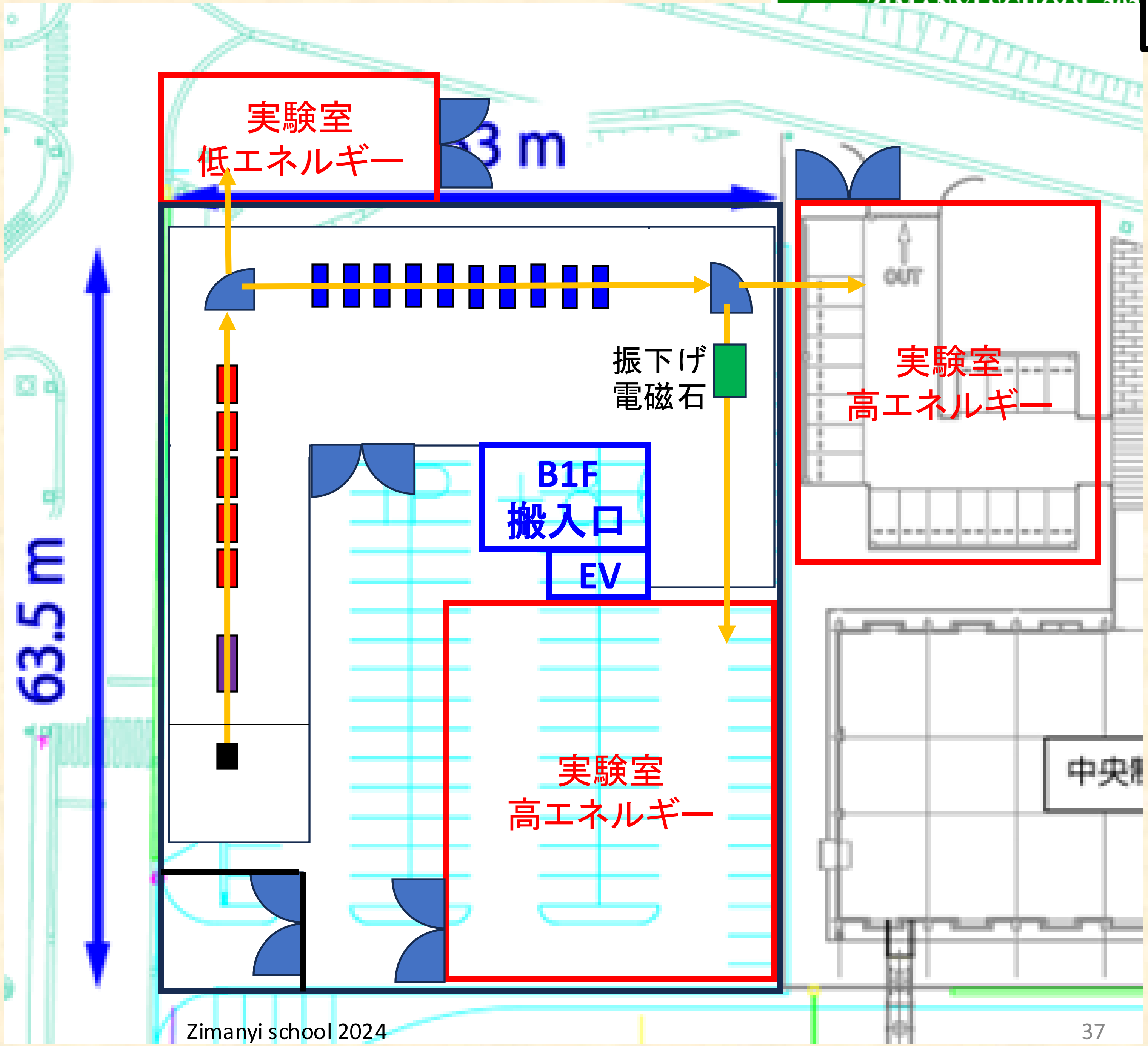
J-PARC RCSのトンネル床面（B2F） : 海抜2.0m
駐車場 : 海抜8.6m

重イオンフロンティア施設
リング＋輸送路＋α（B1F） : 海抜2.0m
リニアック＋実験施設（1F） : 海抜8.6m
制御室＋機械室＋電源室など（2F） : 海抜?? m

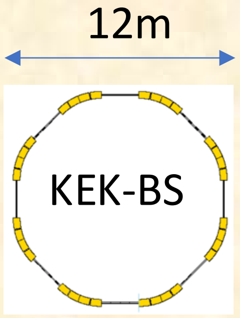


協力：竹田氏（J-PARC）

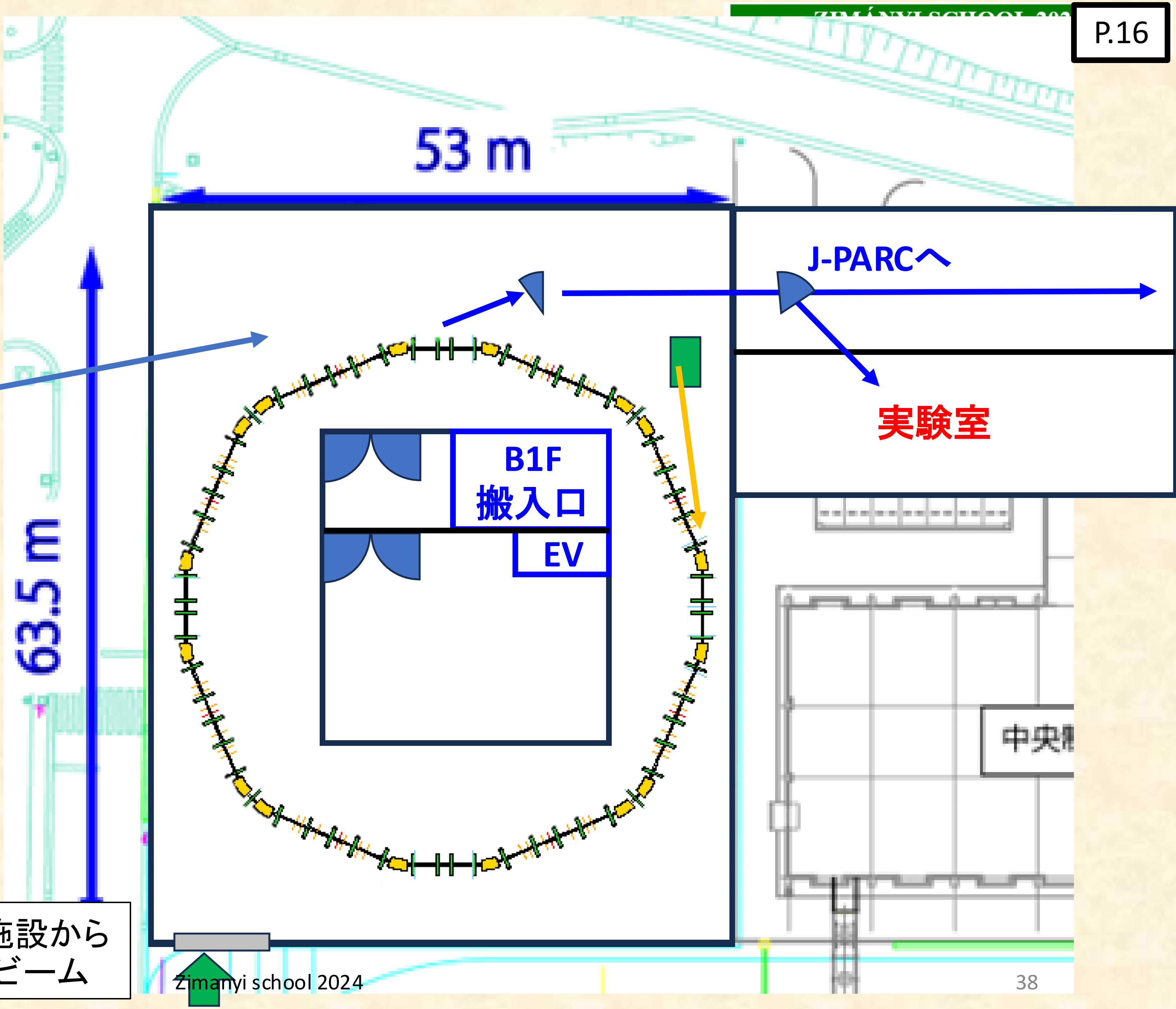
施設イメージ
地上1階(1F)



施設イメージ
地下1階(B1F)



計画の第1期



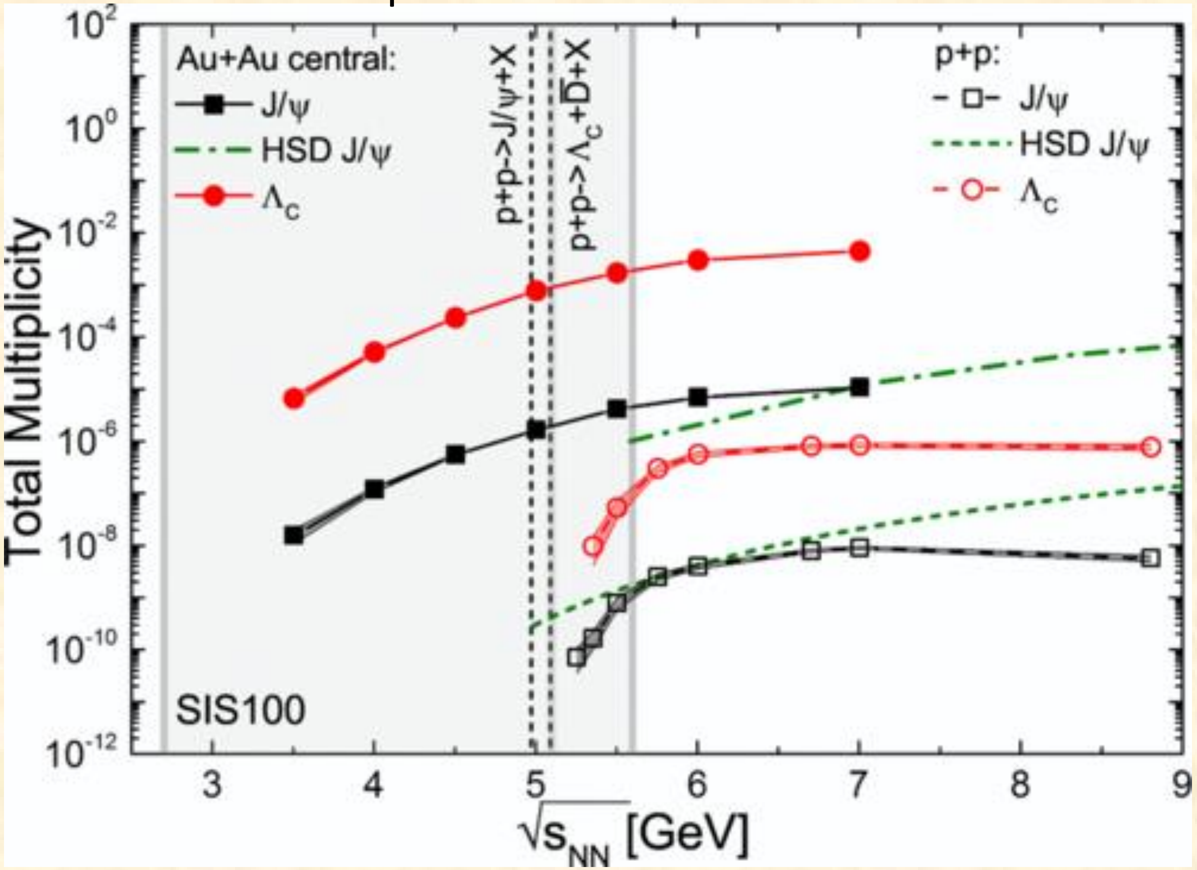
本案に関して建設部と工務技術部に意見を伺い、保安林の観点から別の候補地の提案をいただいた

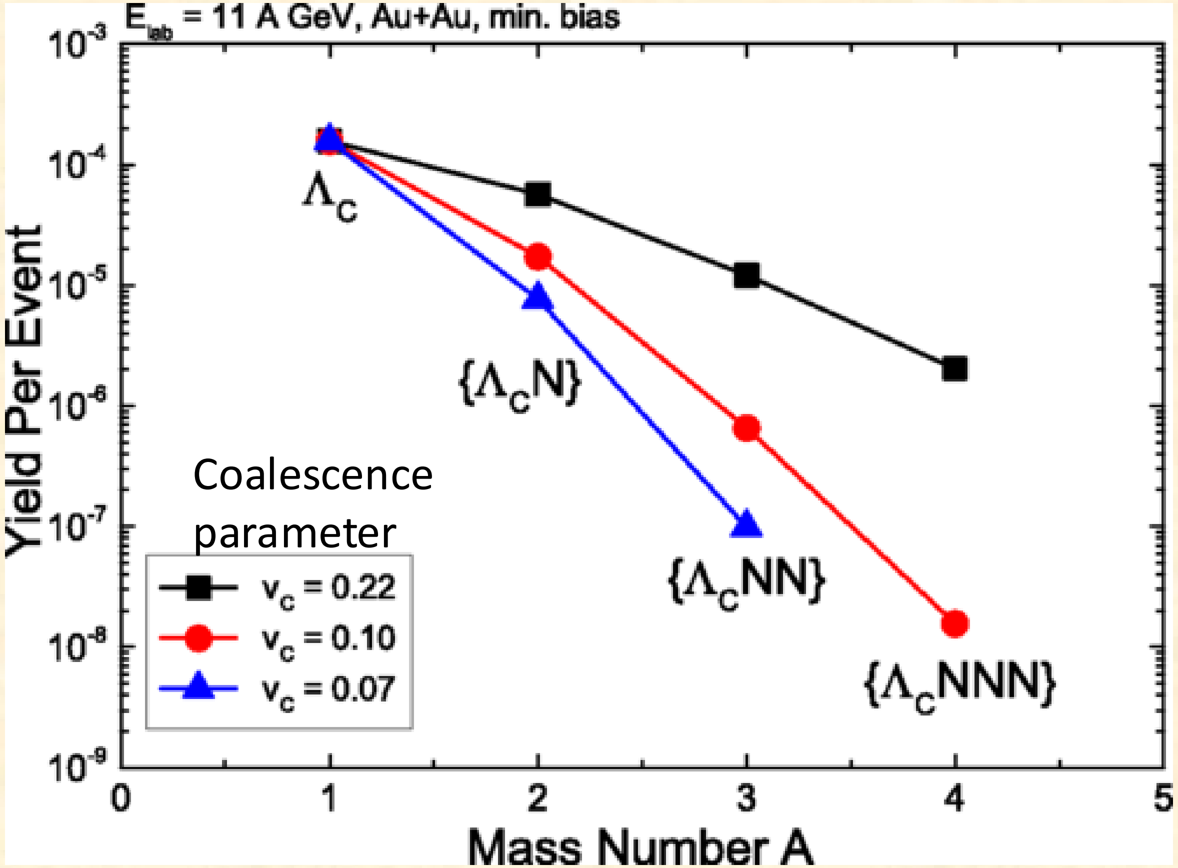
将来、核変換施設から
400MeV陽子ビーム

Charm hadrons at J-PARC-HI?

J. Steinheimer,[1] A. Botvina, M. Bleicher, PRC95 014911 (2017), UrQMD calculations

$\Lambda c+ \rightarrow pK-\pi+$





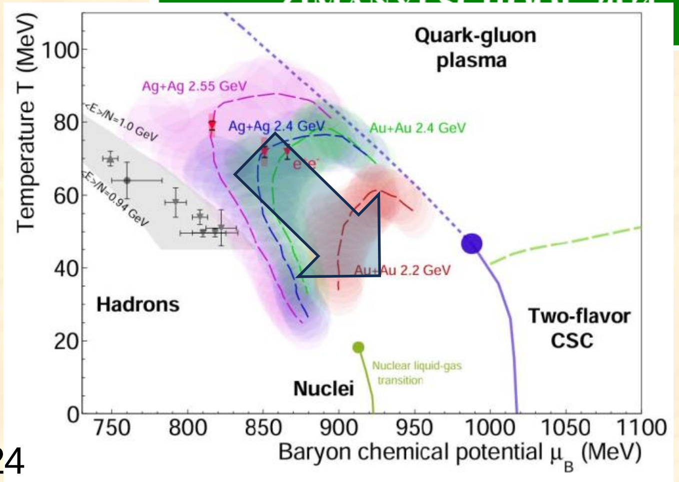
- Λc: Study of diquark contents in QGP?
- 1-2 order enhancement in A+A near threshold due to multi-step processes

HADES

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

- 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)

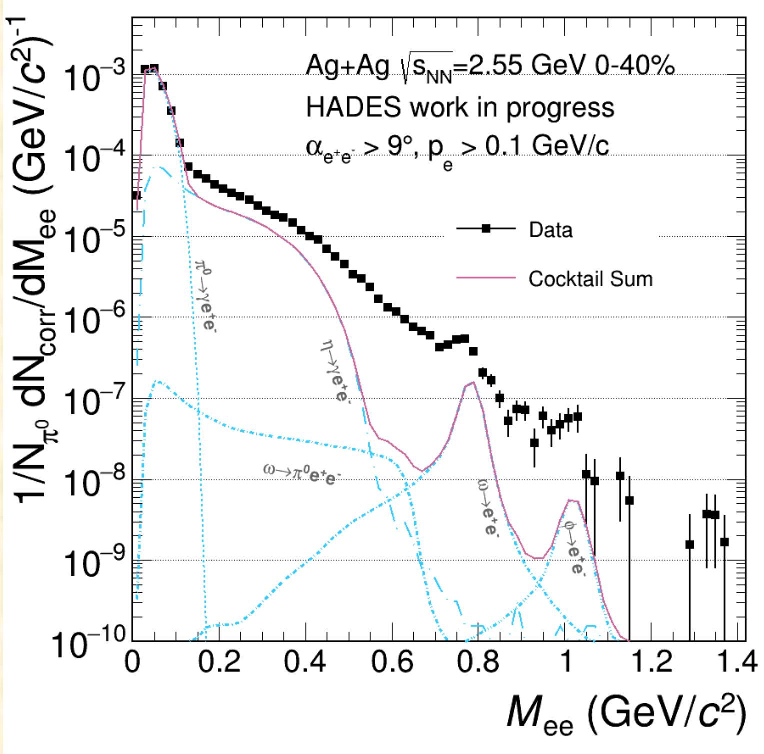
I. C. Udrea, HP2024

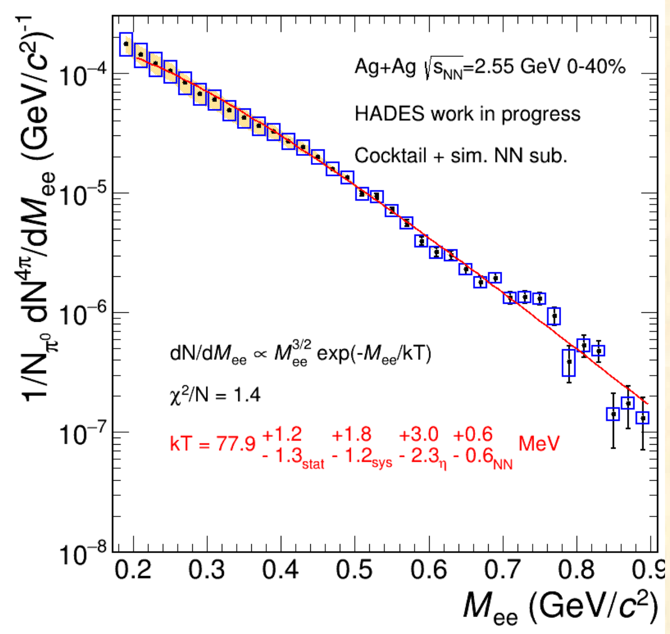


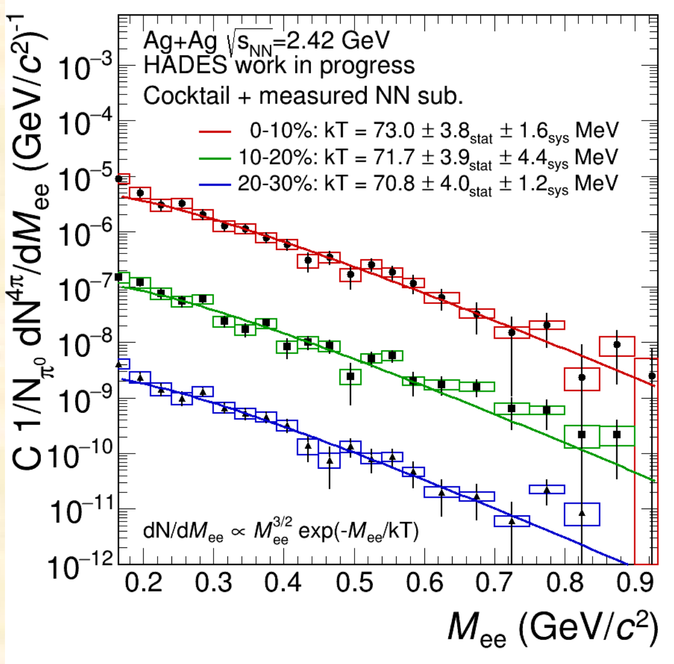
Excess radiation observed in Ag+Ag

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

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





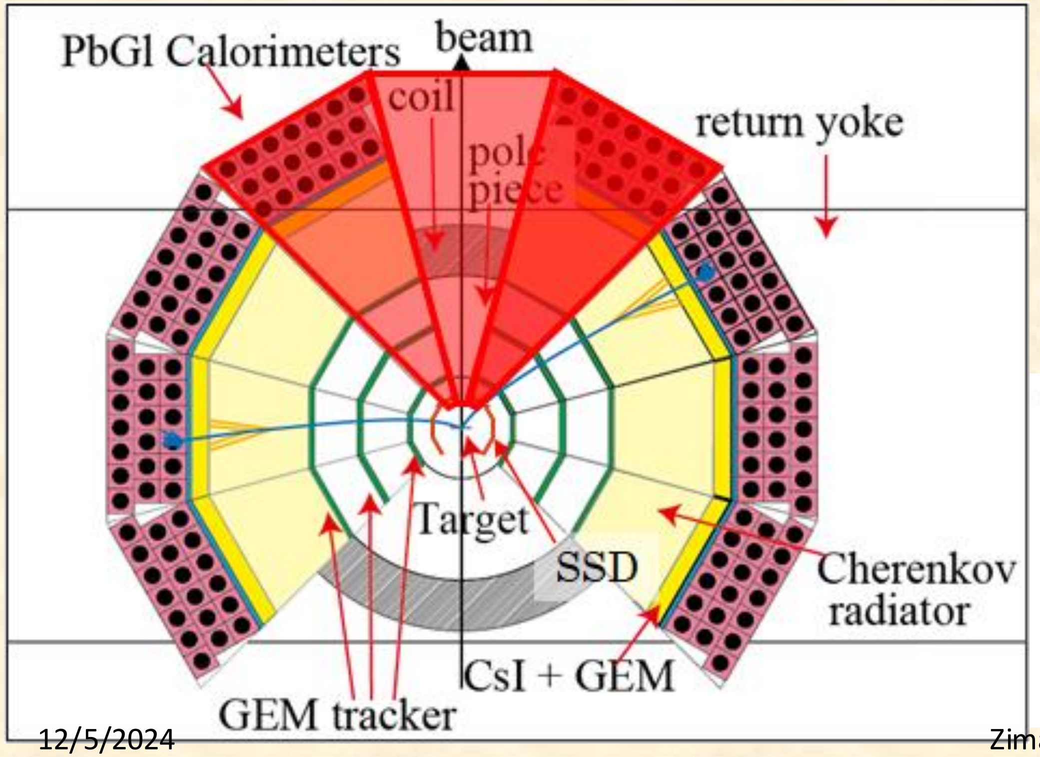


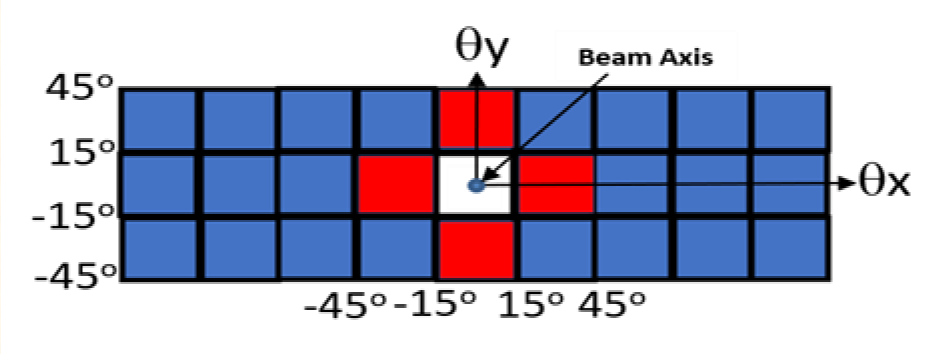
J-PARC E16 Collaboration

RIKEN S. Yokkaichi, H. En'yo, F. Sakuma
KEK K. Aoki, R. Honda, K. Ozawa, R. Muto, Y. Morino, W. Nakai, S. Sawada
U-Tokyo T.N. Murakami, J. Kakunaga
RCNP H. Noumi, K. Shirotori, T.N. Takahashi, S. Ashikaga
Kyoto-U M. Naruki, S. Nagafusa, S. Nakasuga, S. Ochiai
JASRI A. Kiyomichi
BNL T. Sakaguchi
JAEA M. Ichikawa, H. Sako, S. Sato
Tohoku-U S. Kajikawa
U-Tsukuba T. Chujo, S. Esumi, T. Nonaka
Hiroshima-U R. Ejima, K. Shigaki, R. Yamada, Y. L. Yamaguchi
NiAS H. Hamagaki
Academia Sinica W.-C. Chang, C.-H. Lin
GSI J. Heuser, A.R.Rodriguez, M.Teklishyn
Goethe-U/GSI A. Toia, D.R.Garces

First Proposal of J-PARC-HI at Phase I dielectron measurements at w/E16 upgrade

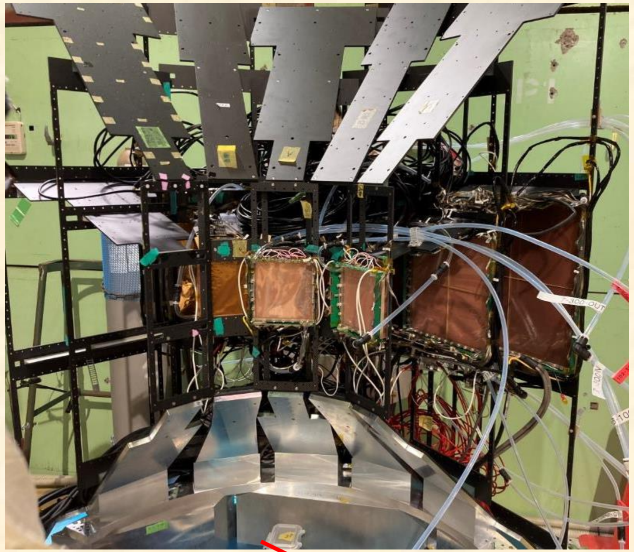
- ► **Forward modules will be upgraded for high multiplicity counting in HIC**
- ► **The most inner GEM Tracker must be upgraded and replaced with 4 SSDs**
- ► **Lead Glass Calorimeter are also upgraded to Lead Tungsten (PWO_4) Calorimeter**



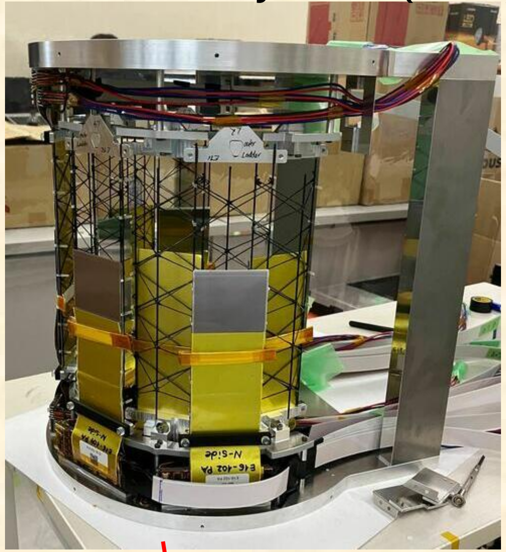


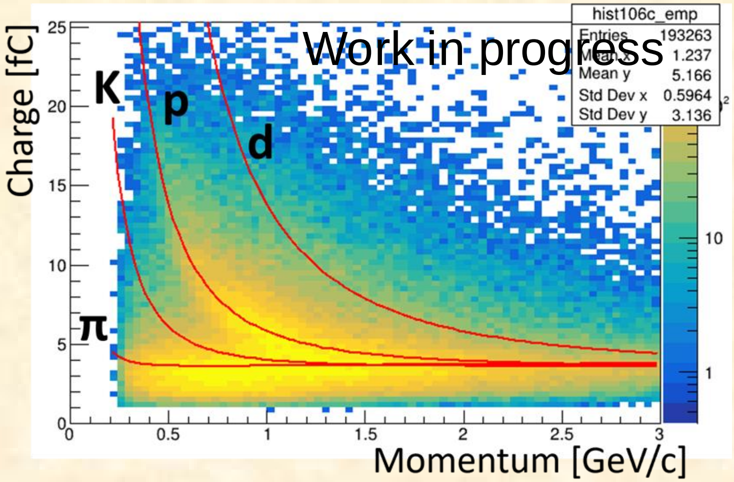
E16 detectors and performance

GEM Tracker (GTR)



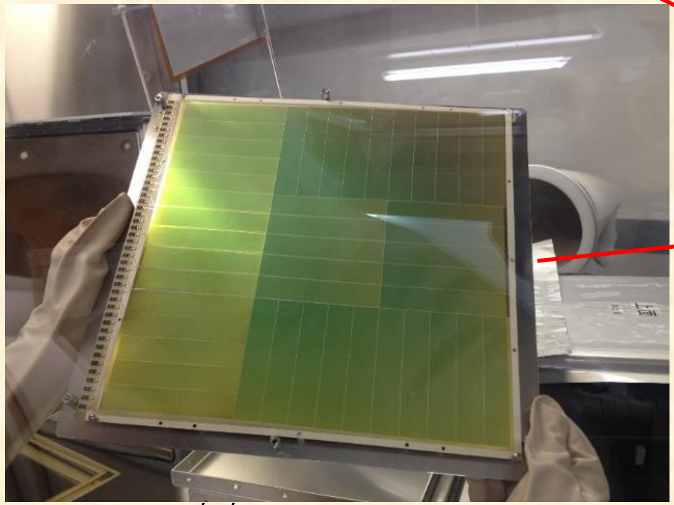
Silicon Tracker System (STS) from CBM

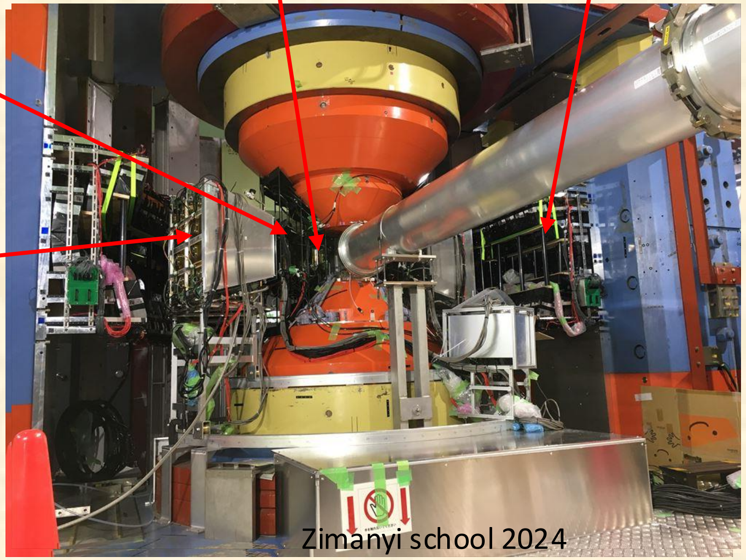


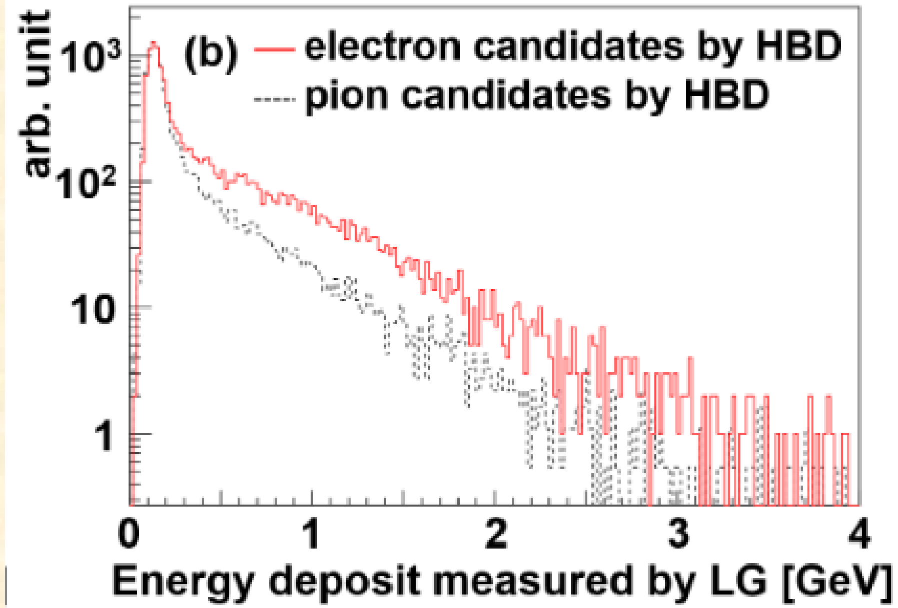


Lead Glass Calorimeter (LG)

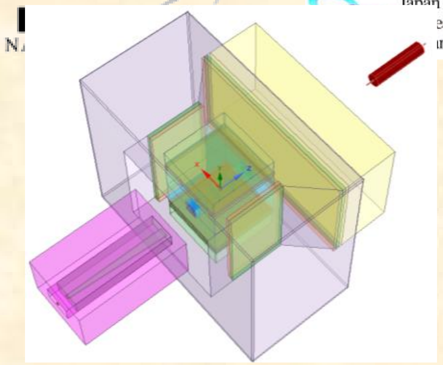
Hadron Blind Detector (HBD)



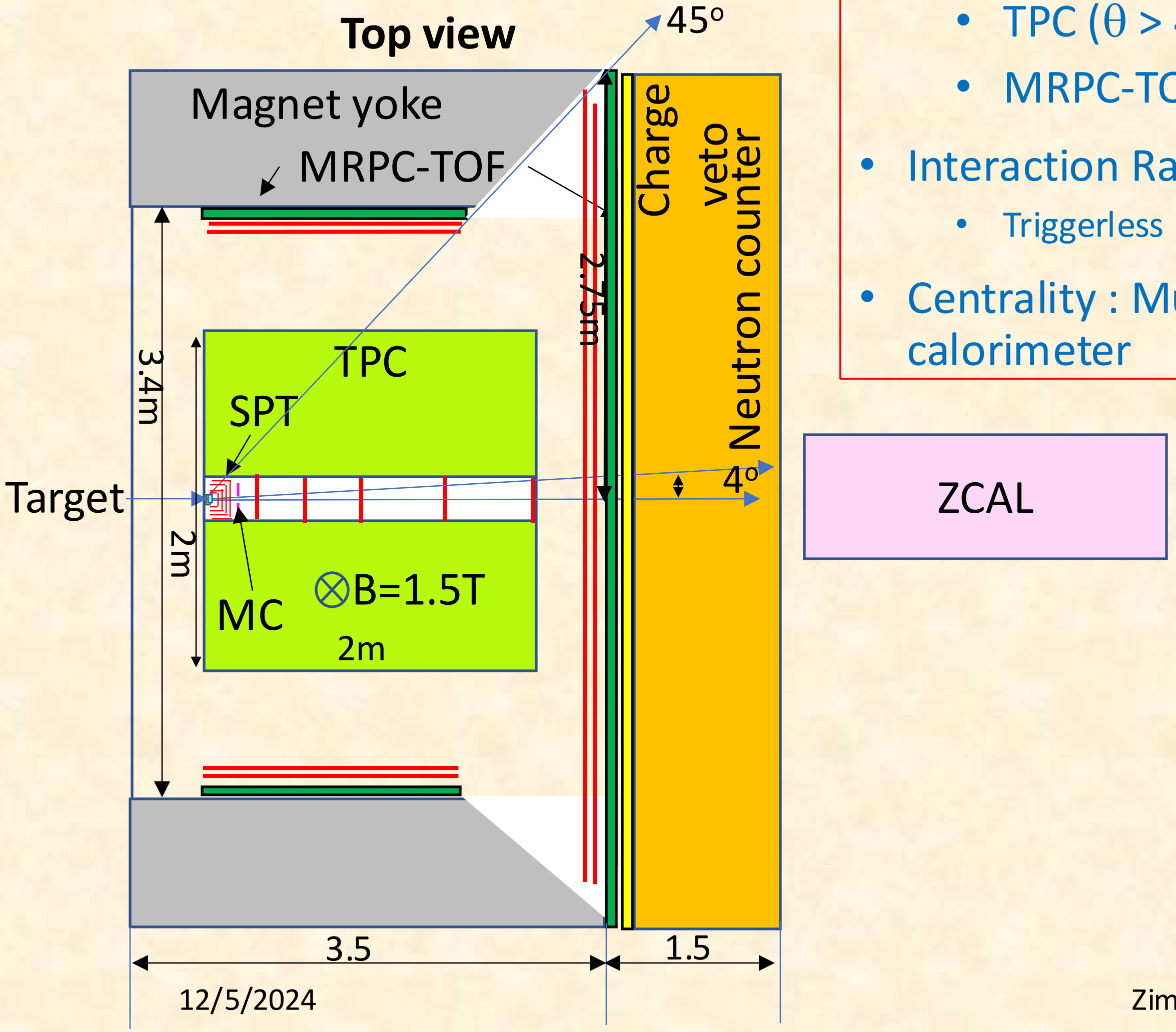


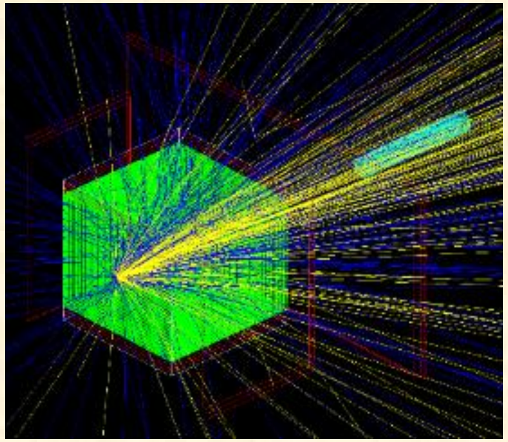


Phase II experiment (Hadron setup)

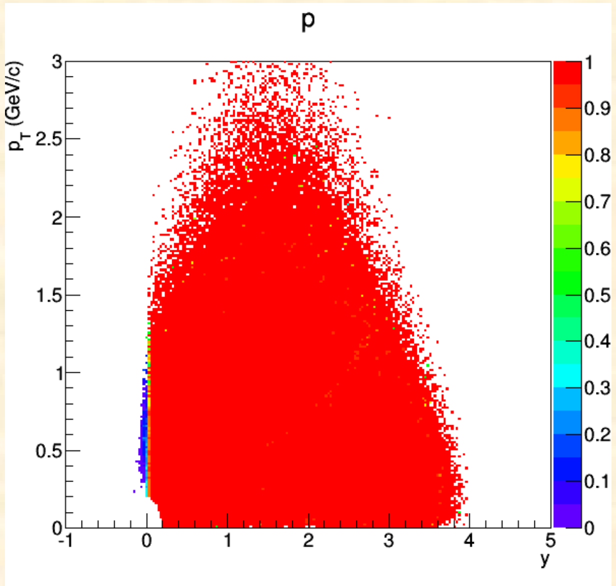


- Identified charged particles
- ~4π acceptance
  - Silicon Pixel Tracker (SPT) ($\theta < 4^o$)
  - TPC ($\theta > 4^o$)
  - MRPC-TOF
- Interaction Rate : <=1 MHz
  - Triggerless DAQ system
- Centrality : Multiplicity counter + Zero-degree calorimeter

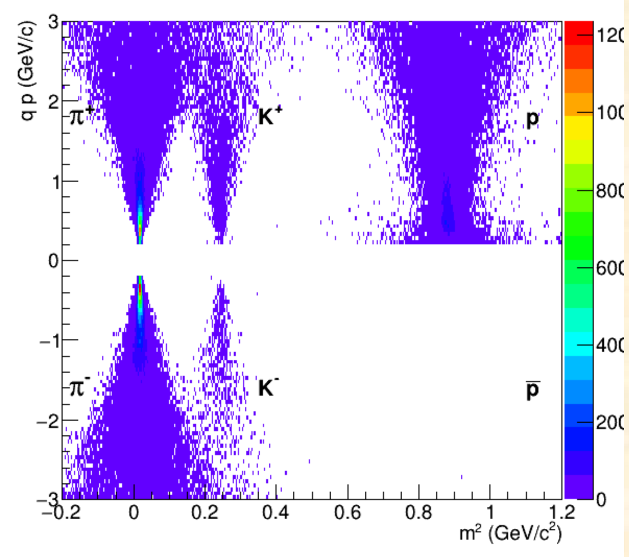




y-p_T Acceptance

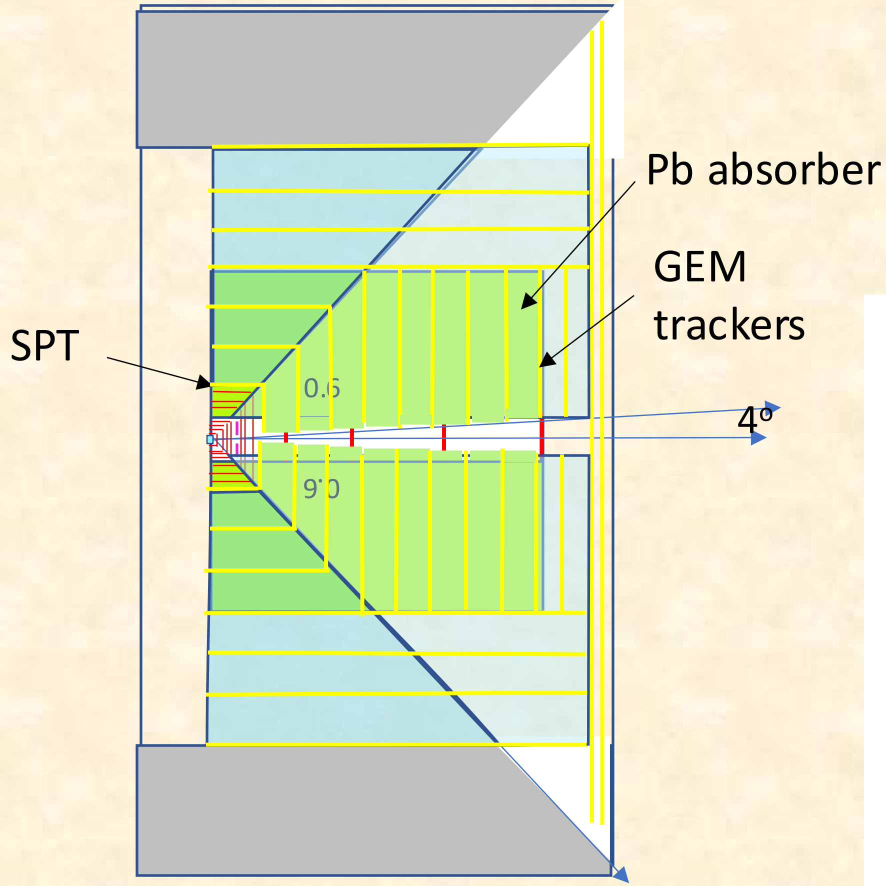


PID with TOF



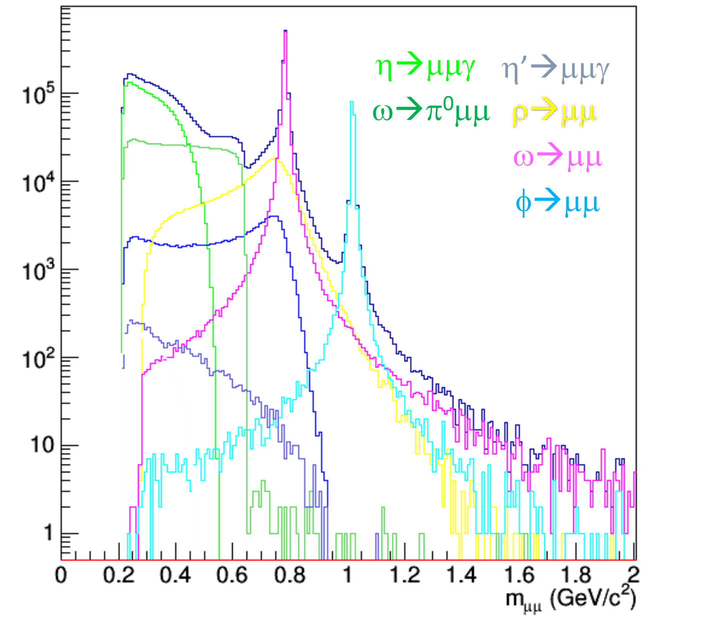
Phase II experiment (Dimuon Setup)

- Replace TPC by:
  - Pb absorbers and GEM trackers
    - Dimuon Online Trigger
  - 7-layer forward and barrel Silicon Pixel Trackers
- Interaction Rate : 10 MHz
- Dimuon trigger : event reduction of ~3/100 at 6 λ_I absorber

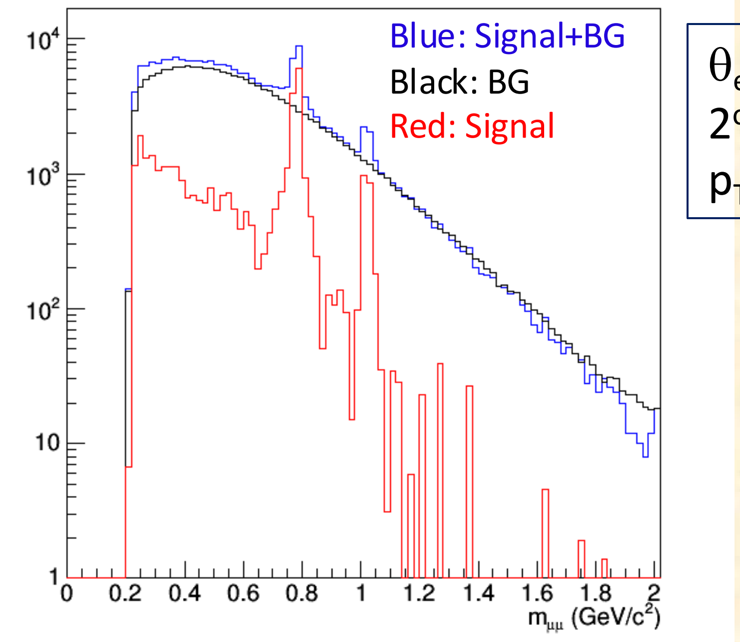


J-PARC-HI simulation, U+U $\sqrt{s_{NN}}$=4.5 GeV, Min-bias (54k)

Generated cocktail



Reconstructed spectrum



θ_{ee}>2°
2°<θ<80°
p_T>0.1GeV/c

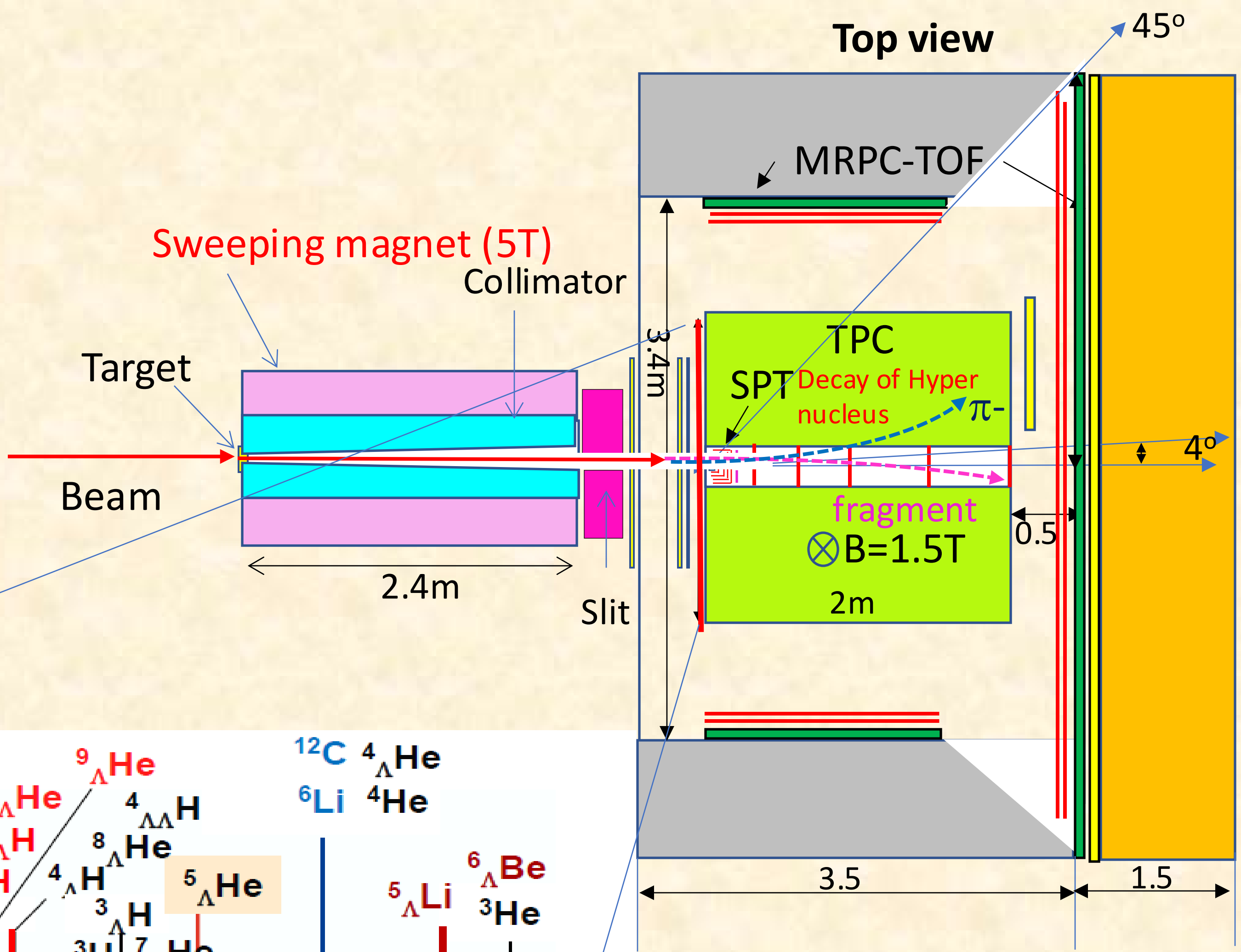
Phase II experiment (Hypernuclear Setup)

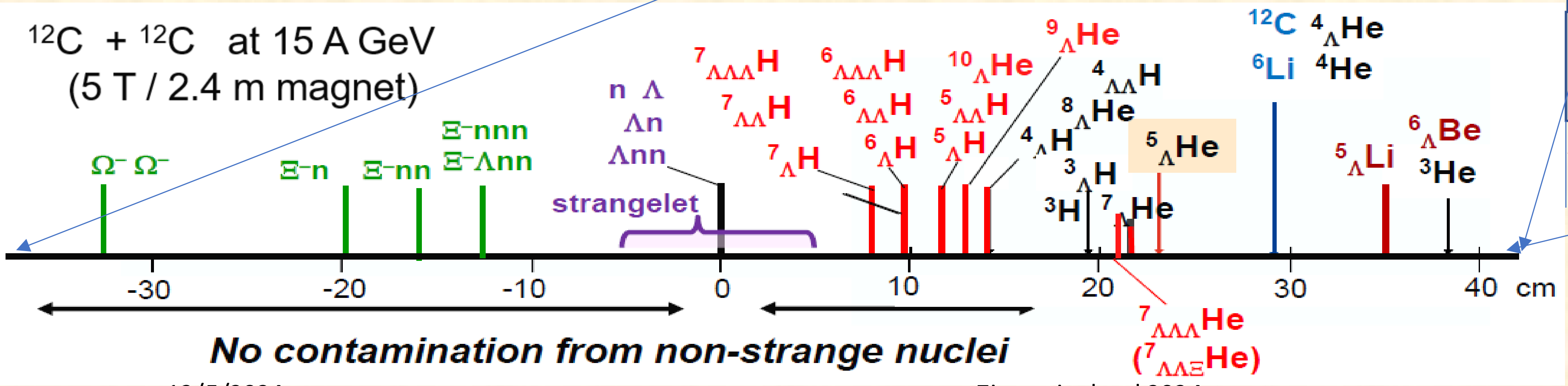
Closed geometry : Sweeping magnet and Collimator

Limit the acceptance to beam rapidity

Only beam and fragments can reach 2nd dipole magnet

- Lifetime and Magnetic moment of hypernuclei
- Search for new hypernuclei and strangelet
- Interaction Rate : ~100 MHz



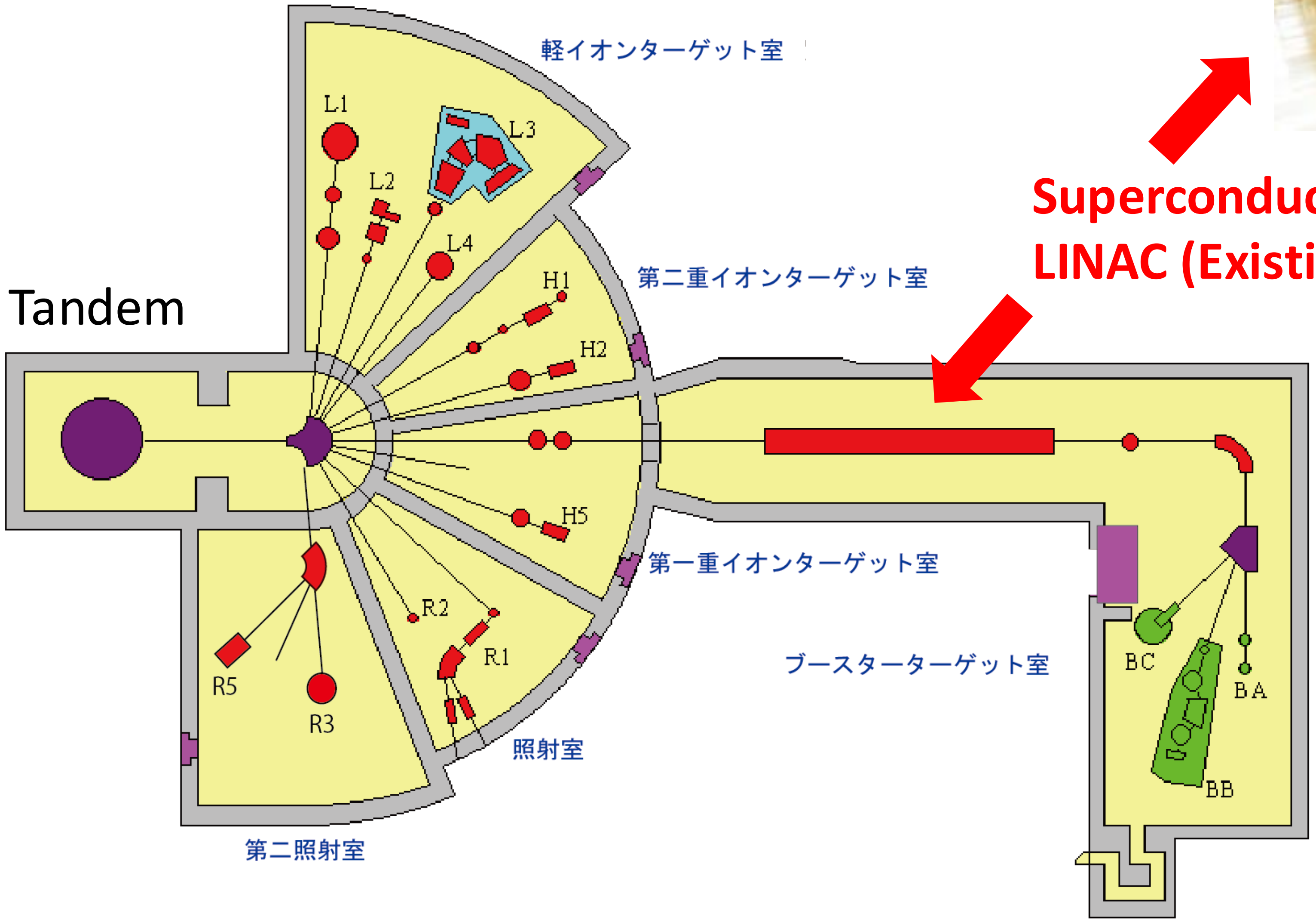


Horizontal Position ∝Z/A

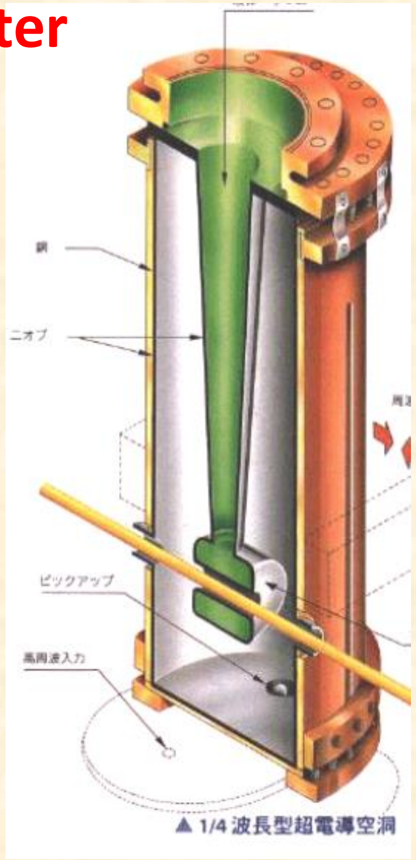
H. Tamura, J-PARC-HI Workshop (2018)

Superconducting Tandem Booster Linac

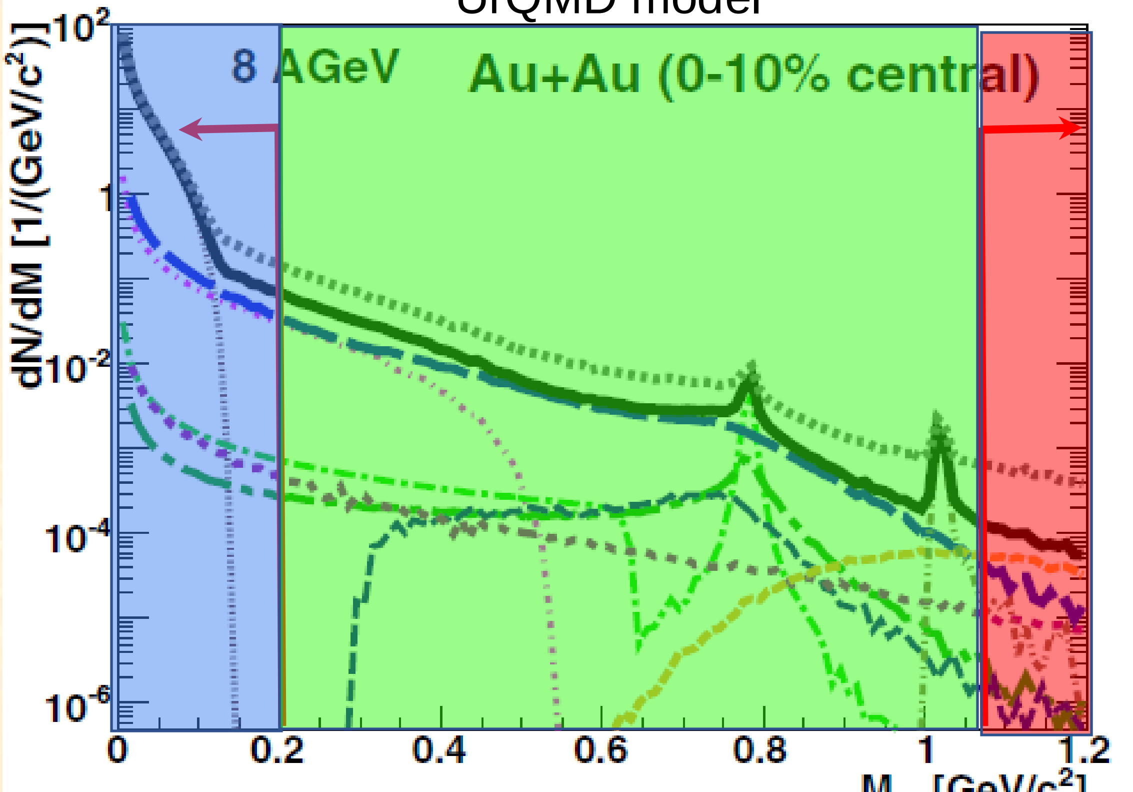
Tandem



Superconducting Booster LINAC (Existing)



UrQMD model



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