PROCEEDINGS OF SCIENCE

Prospect of Heavy-ion Collision Experiments at J-PARC

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In order to explore phase structures in high-baryon density regime of the QCD phase diagram and study dense quark/hadronic matter which may exist in the core of neutron stars, we proposed a heavy-ion program at J-PARC (J-PARC-HI). In heavy-ion collisions at J-PARC (1-19 AGeV/c), the maximum baryon density reaches 5-10 times the normal nuclear density. We designed heavy-ion acceleration scheme at J-PARC. A heavy-ion beam will be produced in a new heavy-ion injector (a linac and a booster ring) and accelerated in the existing 3-GeV and 50-GeV synchrotrons (Rapid-Cycling Synchrotron and Main Ring).
One of the world's highest intensity proton accelerator complex J-PARC, is expected to produce the world's highest heavy-ion beams (up to U) of 10^{11} Hz, which provides extremely high rate heavy-ion collisions to measure rare observables in high statistics. We aim at measuring dileptons (di-electrons and di-muons), photons, higher-order fluctuations of conserved charges, (higher-order) collective flow to explore phase structures, and multi-strangeness hadrons and nuclei, and two-particle correlations for physics related to neutron stars. We designed a multi-purpose large acceptance Toroidal magnet spectrometer for lepton, photon, and hadron measurements. We also designed a spectrometer which measures hadrons and nuclei only around beam rapidity region to search for various hypernuclei and strangelets. The latter spectrometer could accept the full beam intensity of J-PARC. In this talk, physics goals, experimental design of the spectrometers, and expected physics results will be discussed.

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[1] Speaker

1. Introduction

At high-energy heavy-ion collisions at SPS, RHIC, and LHC at a high temperature and low baryon density regime of the QCD phase diagram shown in Fig. 1, quark-gluon plasma has been discovered [1-4], and its properties have been studied. It is known from Lattice QCD calculations that the phase transition in this regime is smooth crossover. On the other hand, a high-density regime, phase structures such as the first-order phase boundary, and its critical end point, and color superconducting phases are theoretically predicted. However, experimental evidence for these phase structures has not been discovered.

In heavy-ion collisions at J-PARC, dense baryonic matter will be created whose density is around 7 times as high as the normal nuclear density according to calculations by JAM model [5]. This density is close to the density of matter in the core of neutron stars, or neutron star mergers.

The goals of J-PARC Heavy-Ion Program (J-PARC-HI) are 1) to explore QCD phase structures in a high-density regime, and 2) to study properties of dense matter related to neutron stars.

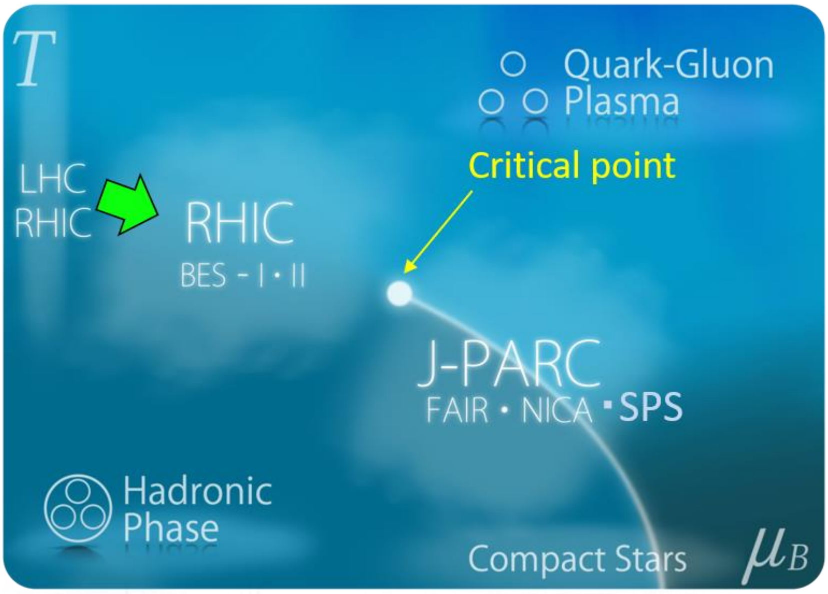

Figure 1: QCD phase diagram.

2. Heavy-ion acceleration

In this section. we show present status of J-PARC accelerators, and an acceleration scheme of heavy-ion beams.

2.1 J-PARC proton beam status

J-PARC is one of the world’s highest intensity proton acclerator complex. It consists of a 400 MeV H^- linac, 3-GeV Rapid-Cycling Synchrotorn (RCS), and 50-GeV Main Ring Synchrotoron (MR) which is currently operated at 30 GeV. From MR, proton beams are slowly extracted to Hadron Experimental Hall, where hadron and nuclear experiments using pion, Kaon, and proton beams are being carried out, and future heavy-ion experiments are expected to be performed.

In July 2017, the beam power of slowly extracted proton beams reached 37 kW, which corresponds to the number of protons per pulse of 4.3×10^{13}. In 2019, they will increase to the designed values of 100 kW, and 1.2×10^{14}, respectively.

2.2 Heavy-ion beams

We aim at producing the world's highest rate heavy-ion beams of 10^{11} Hz, at the beam energy from 1 to 19 AGeV/c corresponding to $\sqrt{s_{NN}}$=1.9-6.2 GeV, with the ion species from p to U. The interaction rate of J-PARC-HI will be 10^8 Hz, assuming a target with 0.1 % interaction length where no detector or data acquisition limit is considered.

2.3 Heavy-ion acceleration scheme

We designed an acceleration scheme of heavy-ion beams at J-PARC as shown in Fig. 2. Heavy-ion beams will be produced in a new heavy-ion injector consisting of a linac and a booster ring, and accelerated with the existing two synchrotrons, RCS and MR. For a U ion, it is produced as U^{35+} in the ion source and accelerated to 67 AMeV in U^{66+} state in the booster ring, then it is accelerated to 735 AMeV as U^{86+} in RCS, and finally accelerated to 11.2 AGeV in MR as full stripped U^{92+} state, where we assume acceleration in MR to the energy corresponding to 30 GeV protons.

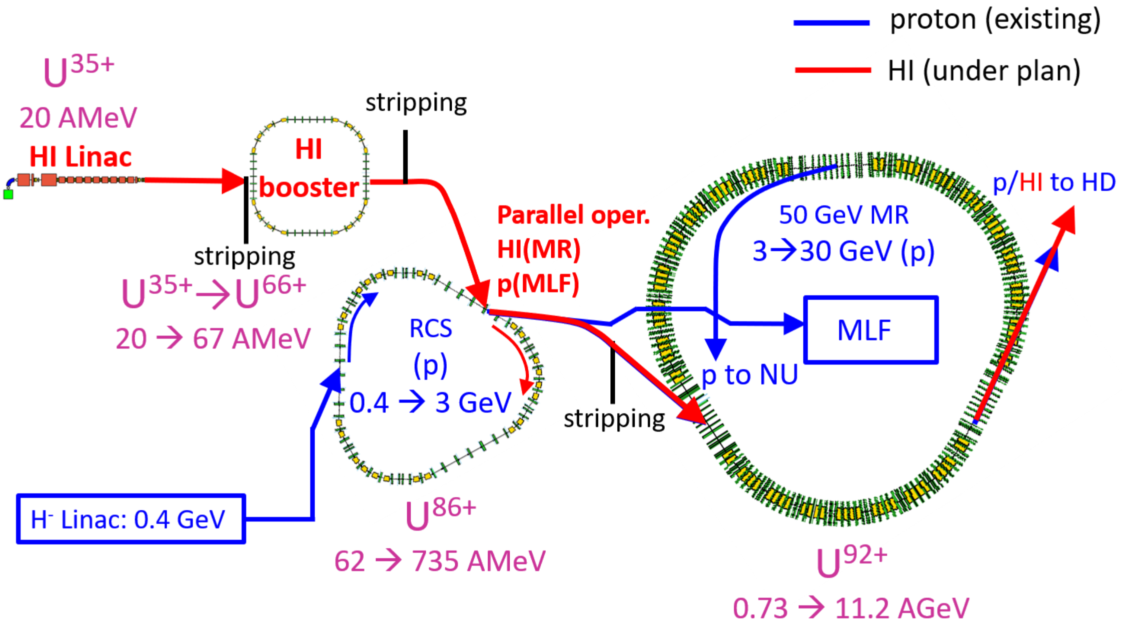

Figure 2: A schematic view of J-PARC accelerator complex for heavy-ion acceleration.

3. Heavy-ion experiments

At In this section. we show plans of heavy-ion experiments at J-PARC.

3.1 Expected statistics

Figure 3 shows expected particle yields for J-PARC-HI. At heavy-ion experiments at AGS at 12 AGeV/c Au beams which was performed 1990's, the measured particles were limited as shown in the figure due to lower beam intensity and rate limitation of detectors and data acquisition systems. Neither dilepton nor charmed meson was measured, and only hypertriton was measured for hypernuclei.

Assuming the interaction rate of 10^7Hz and an experiment for one month, 10^9-10^{11} of dilepton decays of ρ, ω, ϕ, and 10^3-10^{11} of hypernuclei are expected.

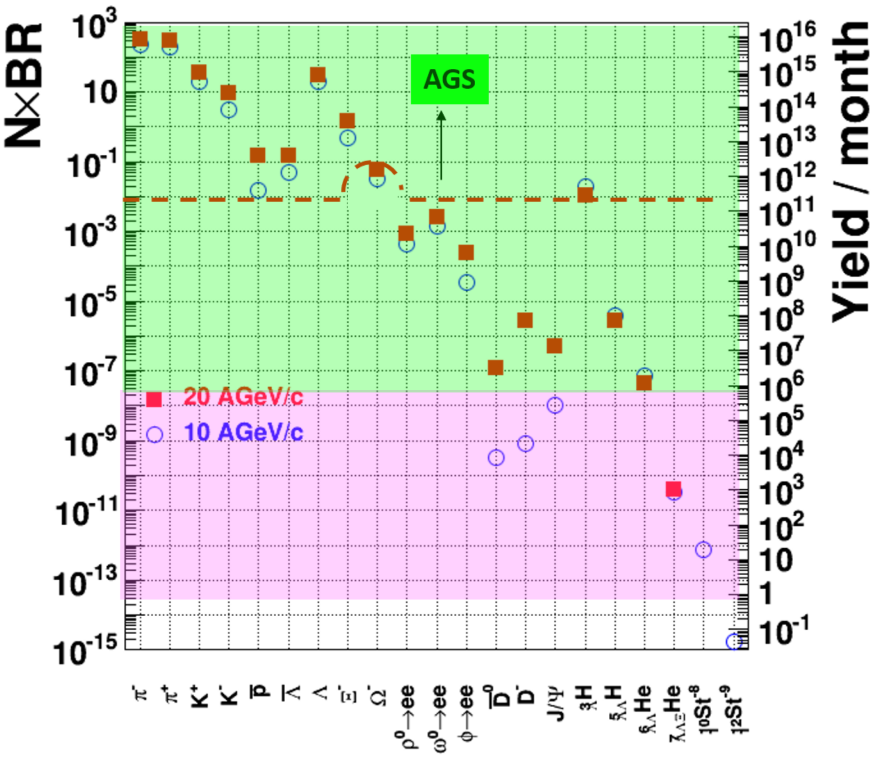

Figure 3: Particle multiplicity (left vertical axis) and particle yield per month (right vertical axis) for J-PARC-HI.

3.2 Exploring hadron/nuclear physics at high density at J-PARC

As shown in Fig. 4, currently we are studying hadrons and nuclei physics at J-PARC using π, K secondary beams and the primary proton beam. We study exotics hadrons such as Θ^+ pentaquark and H-dibaryon, single and double-Λ hypernuclei, the smallest hypernucleus of K^-pp, and a change of vector meson mass in nucleus.

These studies are limited for hadrons at the normal nuclear density or less. Using heavy-ion collisions at J-PARC-HI, we are going to extend these studies at high baryon density comarable to the neutron star core. With heavy-ion collisions, we could distinguish the structure of exotic hadrons using production yield, we could discover hypernuclei with the number of strange quarks of 3 or more, and we can search for strangelet (small strange quark matter).

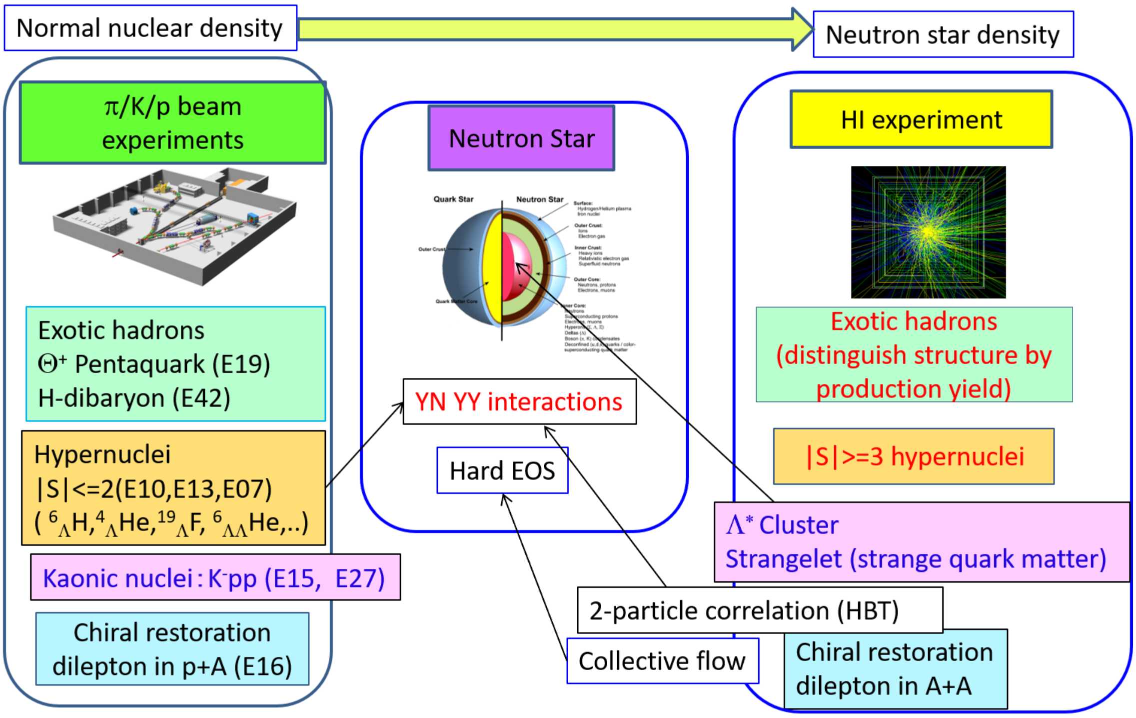

Figure 4: Schematic picture showing relation between hadron/nuclear experiments (left side) and heavy-ion experiments (right side) at J-PARC.

3.3 Physics and observables at J-PARC-HI

The observables to be mesured in J-PARC-HI are summarized as follows;

1. Dileptons
2. Hadrons with high statistics
    - Event-by-event fluctuations of conserved charge
    - Collective flow
3. Photons
4. Charmed mesons

Dileptons are so called “penetrating probes”, from which some information of dense matter could be extacted. In particular, changes of vector mesons (ρ, ω, ϕ) may be related to the chiral symmetry restoration. At J-PARC, we are going to measure both di-electrons and di-muons systematically in high statistics. At J-PARC energy region, no dilepton mesurement has been performed. With very high statistics data, we can do detailed analysis. For example, by comapring the measured moment of dilepton pair with prediction from theoretical models such as QCD sum rules, important physical value such as quark condensate could be extracted [6].

Hadrons can be measured in extremely high statistics. Event-by-event fluctuations of conserved charges such as electric charge, baryon number, in particular, high-order fluctuations of them can be sensitve to the critical point, according to Lattice QCD calculations. STAR experiment measured the ratio of 4th-order cumulant to 2nd-order culumant of net-proton number in $\sqrt{s_{NN}}$=7.7-200 GeV [7]. They observed non-monotonic dependece in most central events. The tendency is similar to a model assuming the existence of the critical point [8]. The model predicts a peak at the energy corresponding to the critical point. It is important to measure the net proton fluctuations at lower energies at J-PARC-HI to search for the peak. The collective flow could signal softning of the equation of state due to the first order phase transition [9].

From photon mesurements, thermal radiations from QGP can be searched for. Charmed mesons (D mesons and J/ψ) may be sensitive to the initial dense matter in which they are produced. We look for an observable which can be used to select events with extremely high baryon densities, in addition to conventional centrality triggers, utilizing very high statistics in J-PARC-HI. We found the sum of p_T of all charged particles is strongly correlated with the maximum baryon density reached in the collision in JAM model [10] as shown in Fig. 5. We could implement this as an online or offline trigger.

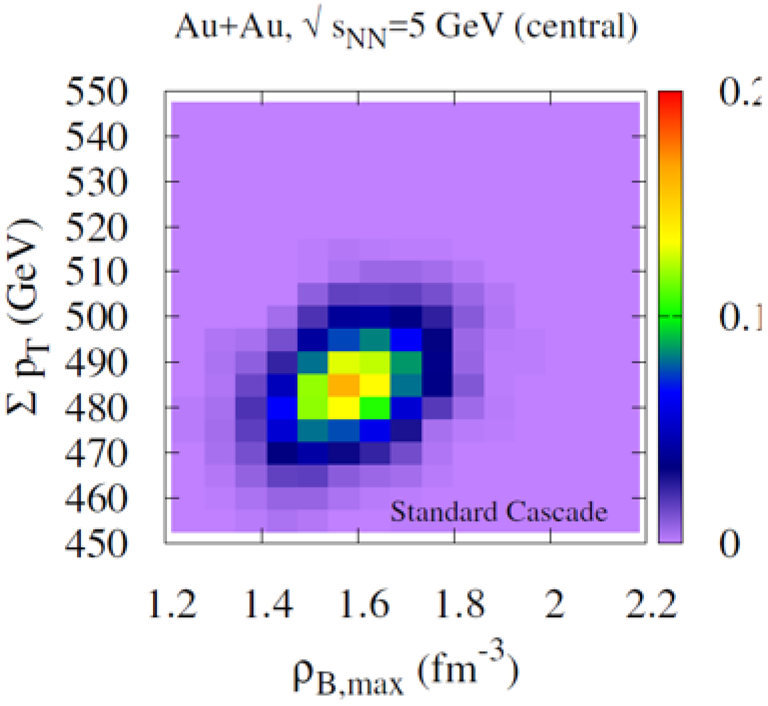

Figure 5: The sum of p_T of all charged particles in each event as a function of the maximum baryon density in the event calculated with JAM model.

3.4 J-PARC Heavy-Ion Toroidal Spectrometer (JHITS)

We designed a large acceptance spectrometer for dilepton, photon, and hadron measurements as shown in Fig. 6. The spectrometer requires the followings;

1. High rate capability

   We require fast response detectors such as Silicon Vertex Detectors and GEM trackers. We also require an extremely fast data-acquisition system of 10-100MHz, which can be implemented with triggerless continuous readout electronics and online data reduction which is adopted in ALICE and CBM experiments.

2. Large acceptance close to 4π solid angle

It is required for acceptance at low beam energies, and to have high multiplicity for event-by-event fluctuation measurements

3. Magnetic field free region around the target

   It is required to reject external conversion efficiently.

To fulfill these requirements, we adopt a spectrometer based on toroidal coils shown in Fig. 6. The twelve-fold thin toroidal coils form the magnetic field in the azimuthal direction. Centrality is determined with a multiplicity counter (MC), and a zero-degree calorimeter (ZCAL). Around the target, there are 4 layers of Silicon Vertex Detectors (SVD). A half-spherical shape Ring-Imaging Cherenkov Counter (RICH) will identify electrons, and MRPC-TOF (Multi Resistive Plate Chamber – Time of Flight) will identify charged particles such as protons, pions, and Kaons. Electro-Magnetic Calorimeter (EMCAL) measured photons, Neutron detector measures neutrons, and Muon trackers with iron absorbers measure muons. Many layers of GEM trackers will reconstruct charged particle tracks.

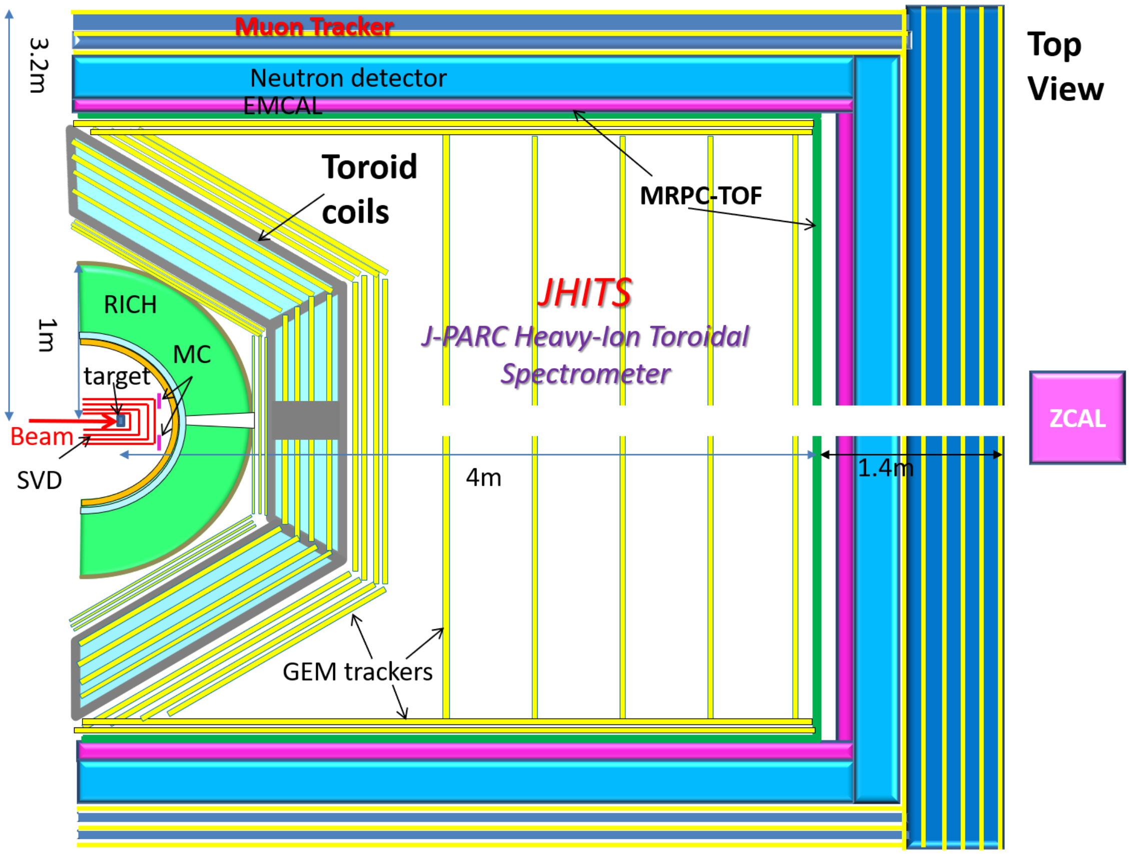

Figure 6: A top view of JHITS (J-PARC Heavy-Ion Toroidal Spectrometer).

Figure 7 demonstrates dilepton measurement performance of the spectrometer. We generated dilepton signals from JAM model, and embed them into JAM events including all particles produced in 10 AGeV/c U+U collisions. The produced particles are processed as detector hits with GEANT4 simulation. We then reconstract particle tracks and identify electrons and muons using RICH and muon trackers. The resulting reconstructed invariant mass spectra of dielectrons and dimuons show clear ω and ϕ peaks.

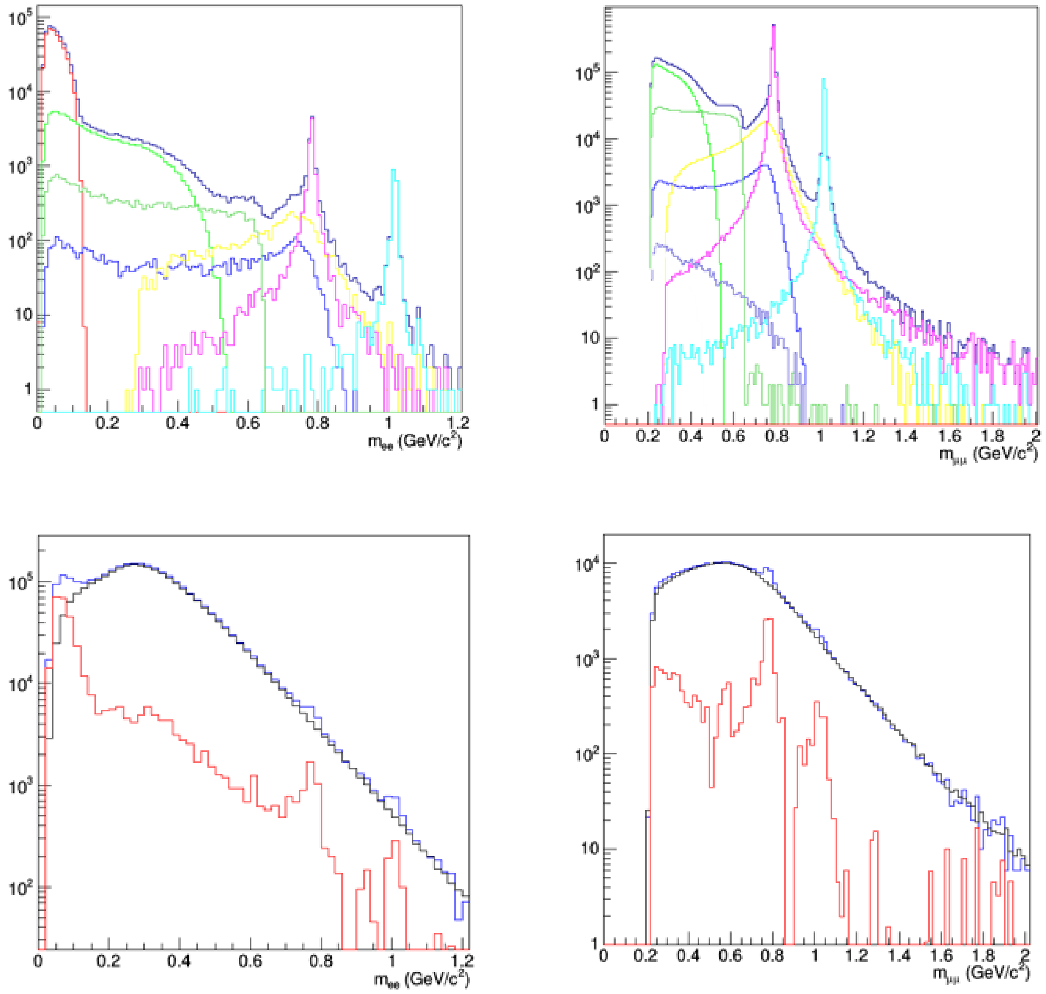

Figure 7: Generated (top) and reconstructed (bottom) dilepton spectra. Left figures are for dielectron spectra, and right figures are for dimuon spectra.

3.5 J-PARC Heavy-Ion Hypernuclear Spectrometer (JHIPER)

We design also a spectrometer dedicated for hypernuclei measurements at the beam rapidity as shown in Fig. 8. It can measure the life time of hypernuclei precisely, and their magnetic moments with precessing angles. Discovery of new hypernuclei with s=-1,-2,-3,... is expected. Also strangelet will be searched for as a hadron with a small charge to mass ratio.

The spectrometer consists of two dipole magnets. The upstream magnet sweeps out light charged hadrons and stops them at the collimator, but passes the beam and near-neutral fragments. The downstream magnet contains a Time Projection Chamber, where weak decays of hypernuclei are reconstructed. The lower plot of Fig. 8 shows horizontal distribution of various hypernuclei just after the collimator assuming the upstream magnet of 15 Tm [11]. Various hypernuclei are expected to be produced. In particular, negative charged hypernuclei, Ξ^-n and Ξ^-nn are interesting, which are expected to be bound.

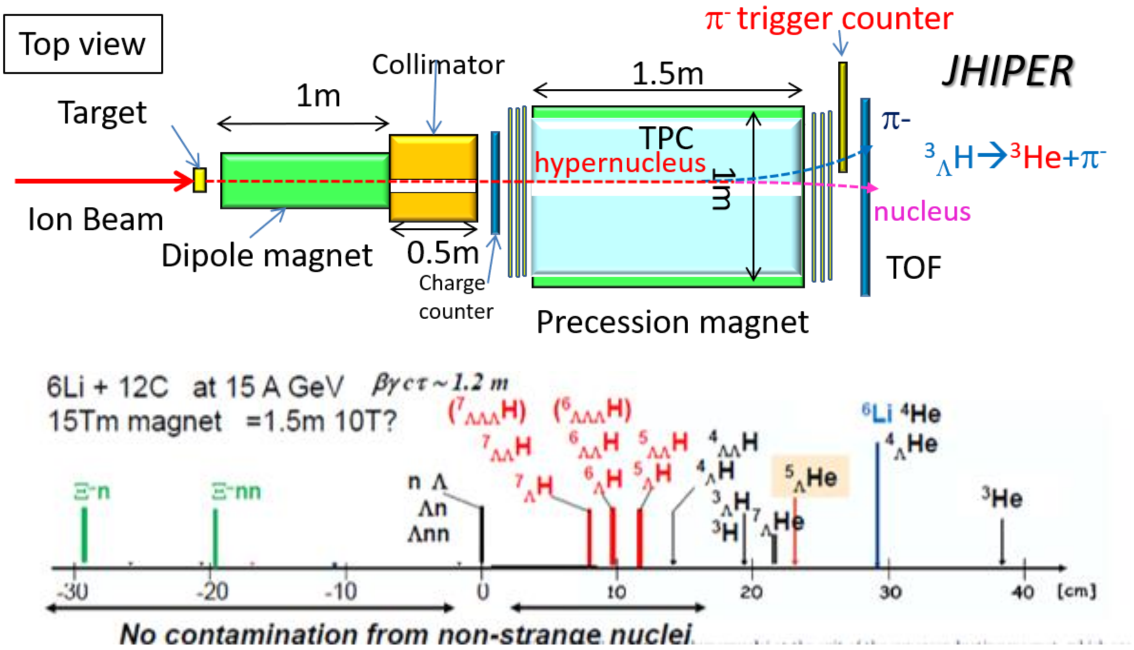

Figure 8 : Top: Top view of JHIPER (J-PARC Heavy-Ion Hypernuclear Spectrometer), Bottom: Horizontal separation of hypernuclei at the charged counter position.

4. Conclusions

A In summary, J-PARC-HI is a unique laboratory to study QCD phase structures, and properties of dense matter related to neutron stars. We expected to achieve the world's highest rate heavy-ion beams of 10^{11} Hz by building a new heavy-ion injector, and utilizing existing 3 GeV and 50 GeV synchrotrons. We are going to measure various observables, such as dileptons event-by-event fluctuations, and multi-strangeness systems, using a large acceptance toroidal magnet spectrometer, and a beam rapidity hypernuclear spectrometer. We submitted Letter-Of-Intent of J-PARC-HI to J-PARC Program Advisory Committee in 2016 [12]. We are working on R&D of detectors such as MRPC-TOF and triggerless data acquisition system with ALICE experiment. We expect the earliest possible start of the experiment to be in 2025.

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