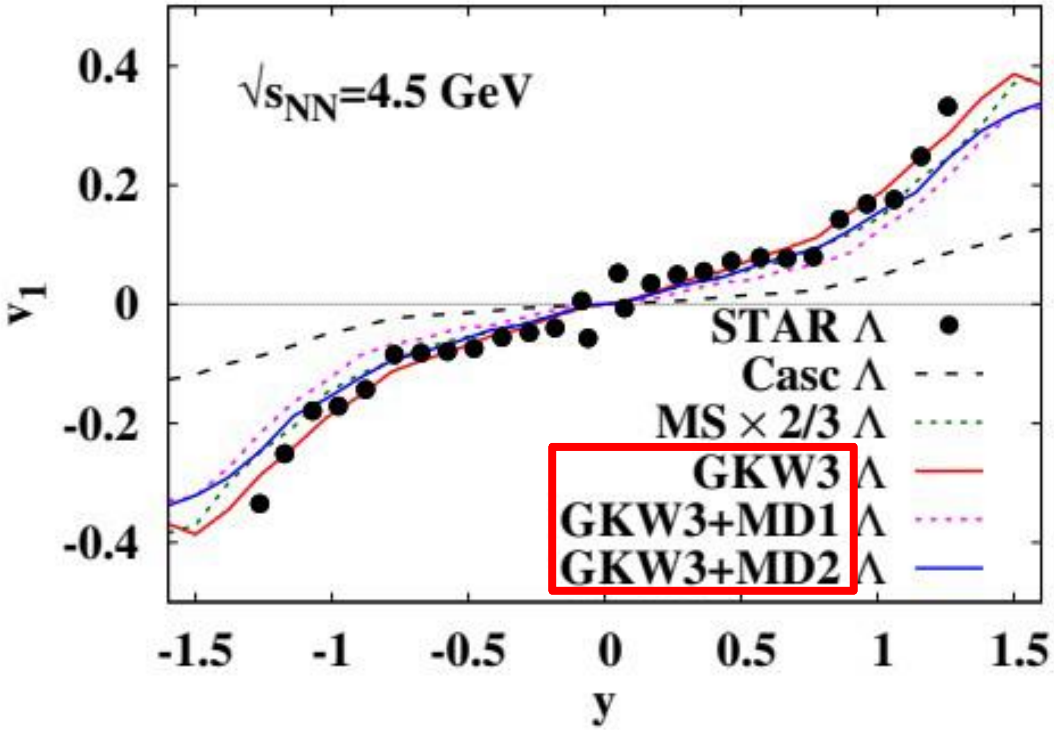
# J-PARC HEAVY ION PROJECT

K. Ozawa (KEK/J-PARC) for the J-PARC HI collaboration

# HEAVY ION COLLISIONS:
# A NEW TOOL FOR STRANGENESS PHYSICS

Data: STAR PRL 1708.0713; PLB 2108.00908
Calc.: Presentation by A. Ohnishi

- Study of Hyperon interactions
  - Flow
  - Two-particle correlations
- Study of strangeness composite system
  - Production of hypernuclei
  - Search for strangelet, dibaryons

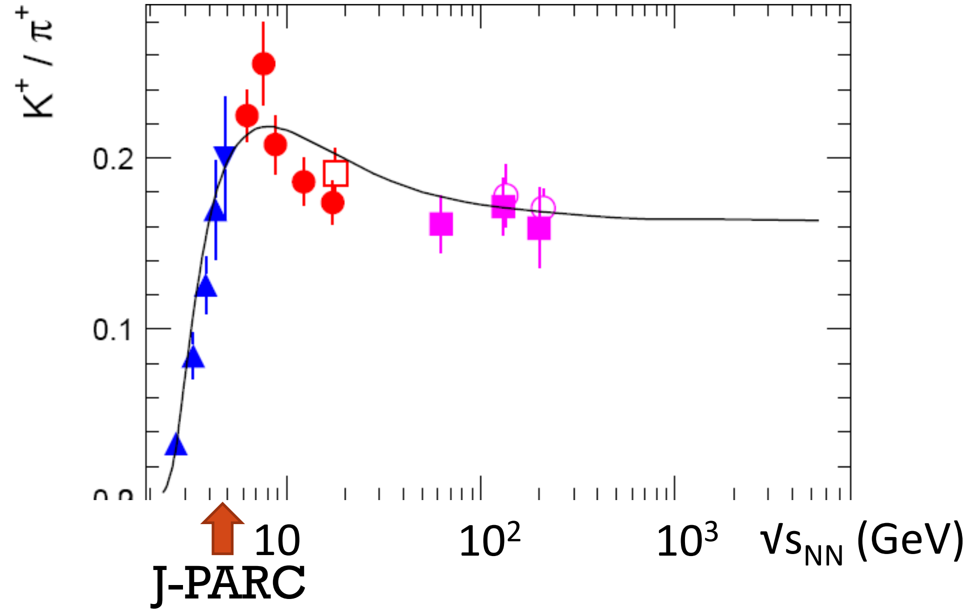



Directed Flow v.s. Rapidity (y)

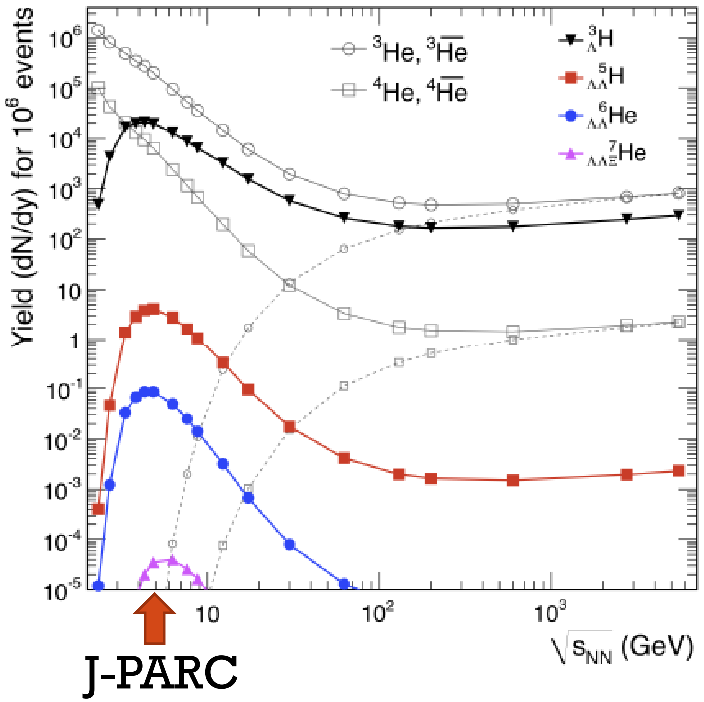
# AT J-PARC ENERGY, EFFICIENT PRODUCTION OF STRANGENESS

A. Andronic *et al.*, PLB697 (2011) 203

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




Measured $K^+/\pi^+$ ratio

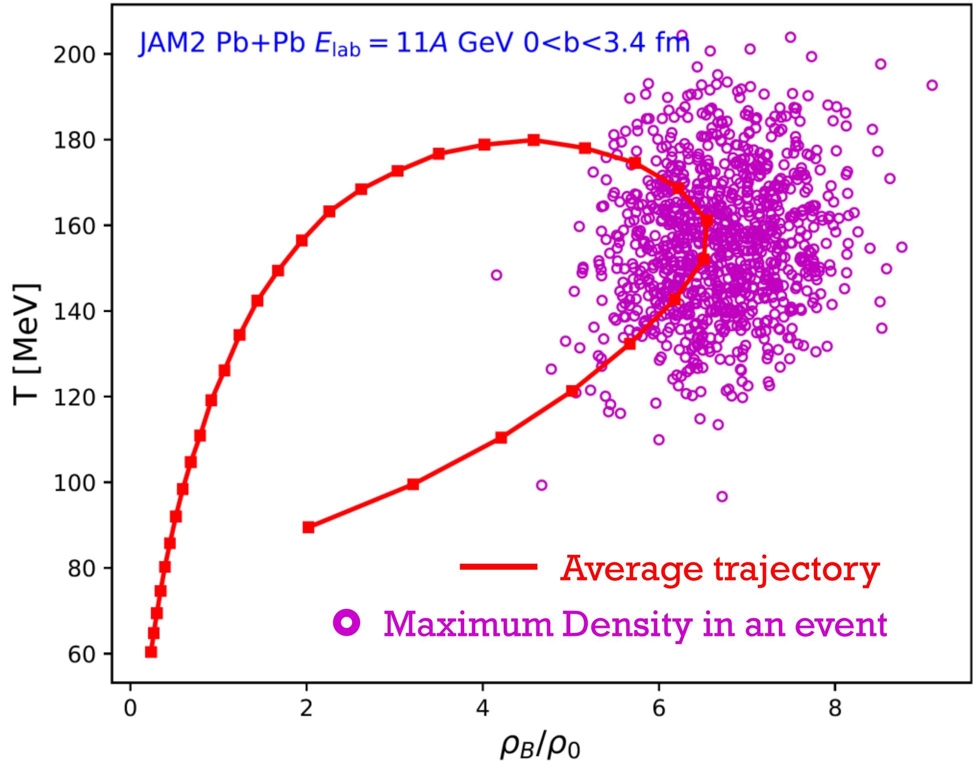



Expected Hypernuclei production

# DIRECT STUDY OF HIGH-DENSITY MATTER

- Search for QCD Phase structures
  - 1st order phase transition
  - Color superconductor
    - Di-quark correlations
- Properties of dense matter
  - Maximum density, EOS, transport properties (viscosity), etc.
  - Studies of neutron stars
- Chiral symmetry restoration
  - Medium modification of vector mesons

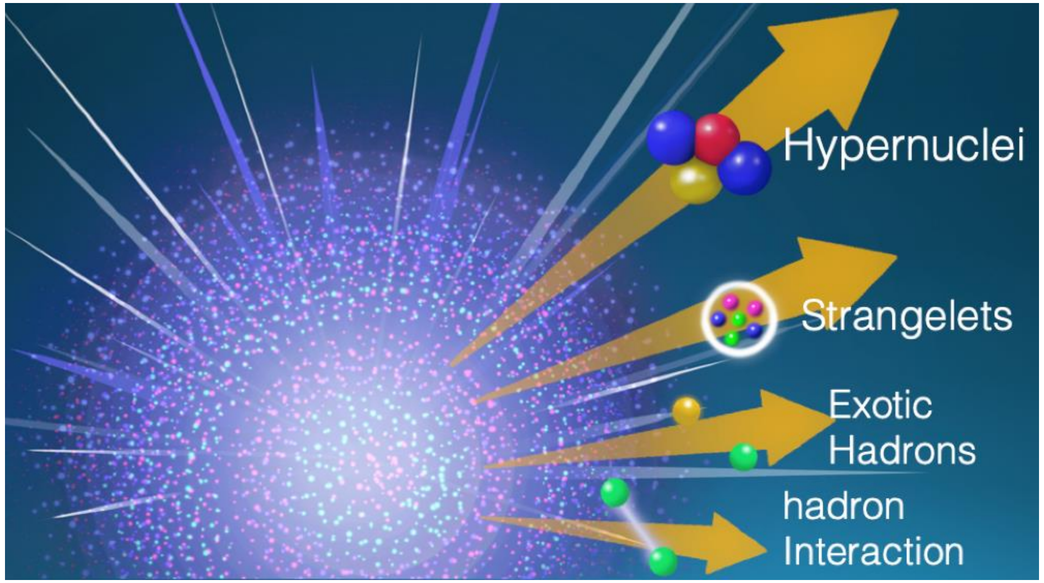
JAM2 Calculation by Y. Nara:
https://gitlab.com/transportmodel/jam2




Calculated Temperature and Density

# J-PARC HEAVY ION PROJECT

- Main Physics topics
  - Study of strangeness systems and hyperon interactions
  - QCD phase structure in high density region




- Heavy Ion Beam specifications
  - Beam Energy: $\sqrt{S_{NN}} \sim 2 - 5$ GeV
  - Species: Up to Uranium
  - Maximum Beam Intensity: $10^{11}$ Hz

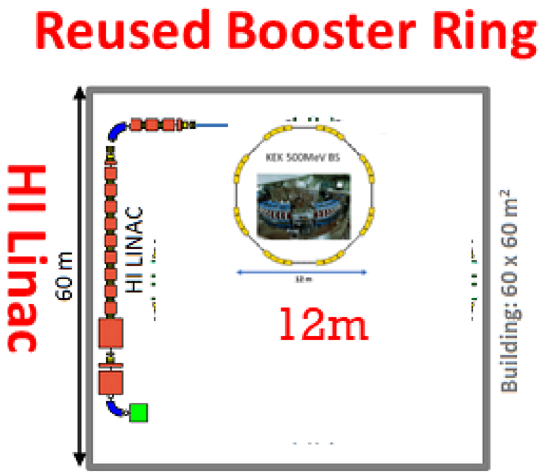
# FACILITIES TO BE UPGRADED FOR HEAVY ION

- New Heavy Ion Injector (LINAC and BOOSTER)
- New Experimental area and Spectrometers

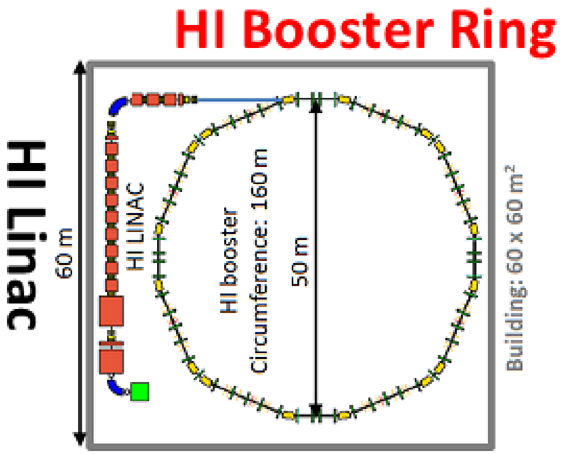
# STAGING PLAN

- On-going
  - pA collisions using existing beam line and spectrometer
    - Main Physics topic: Vector meson measurements in $e^+e^-$ decay modes
  - + Upgrades of the spectrometer for hadron measurements
  - Pilot data for Heavy Ion physics
- Phase I (2029~)
  - New LINAC and reuse of KEK-PS booster
  - Upgrades of the existing spectrometer
  - Beam Intensity: $10^8$ Hz for Au
- Phase II (2032~)
  - New Booster and New spectrometer
  - Final configuration

Phase 1

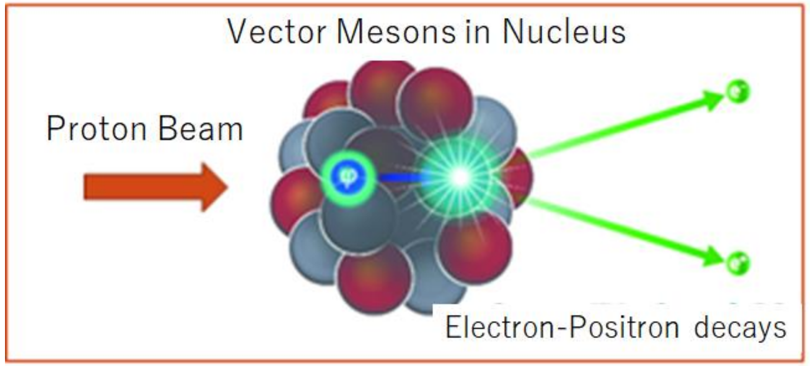



Phase 2



# ON-GOING EXPERIMENT

- Measurements of vector meson mass spectra in pA collisions (J-PARC E16)
  - Modifications of the spectra due to a partial chiral symmetry restoration in a nucleus
    - See P. Gubler's talk for detailed physics
  - It is also related with $\phi$N interactions
- A primary beamline is constructed. The beamline can be used as a heavy ion beam line
- A new spectrometer is constructed
  - Dedicated measurements for $e^+e^-$ decays of vector mesons in a target rapidity region




Reaction

Photo of experimental area

# STATUS OF THE EXPERIMENT

- First beam: May 24, 2020.
- Commissioning runs: June 2020 and June 2021
  - All detectors, triggers, and DAQ worked well
  - Detector performance in commissioning data

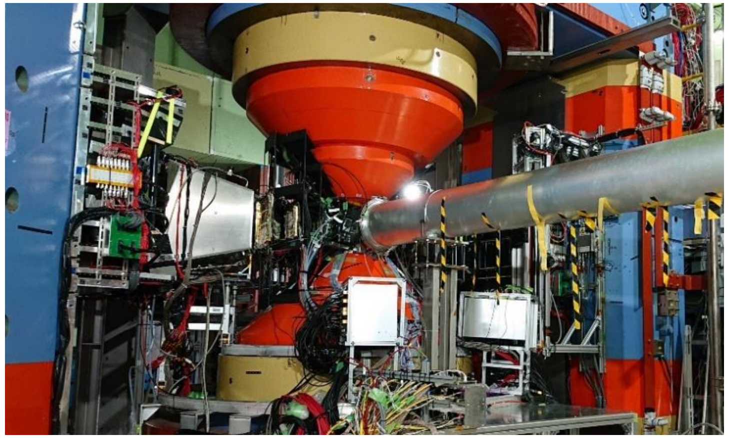
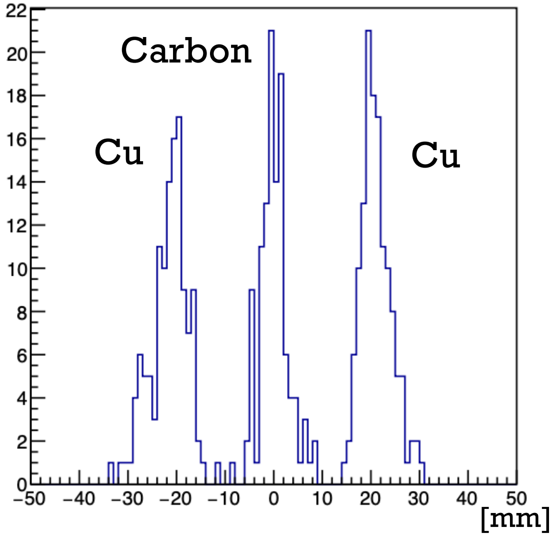


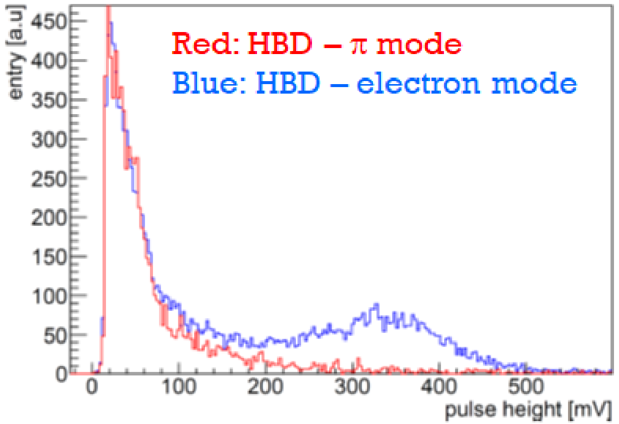
Photo of Spectrometer

Track reconstruction



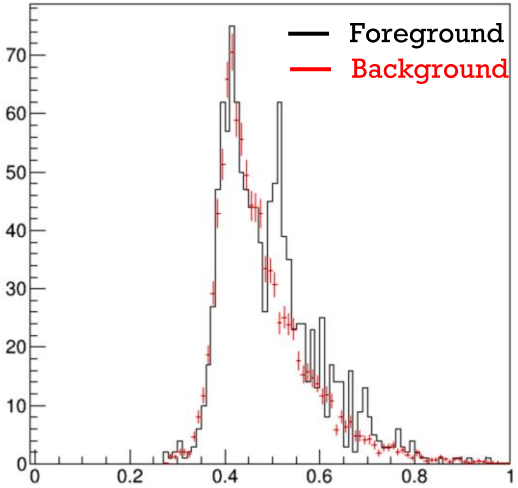

Reconstructed Target Profile

Electron Identification




Pulse Hight Distribution of Lead Glass

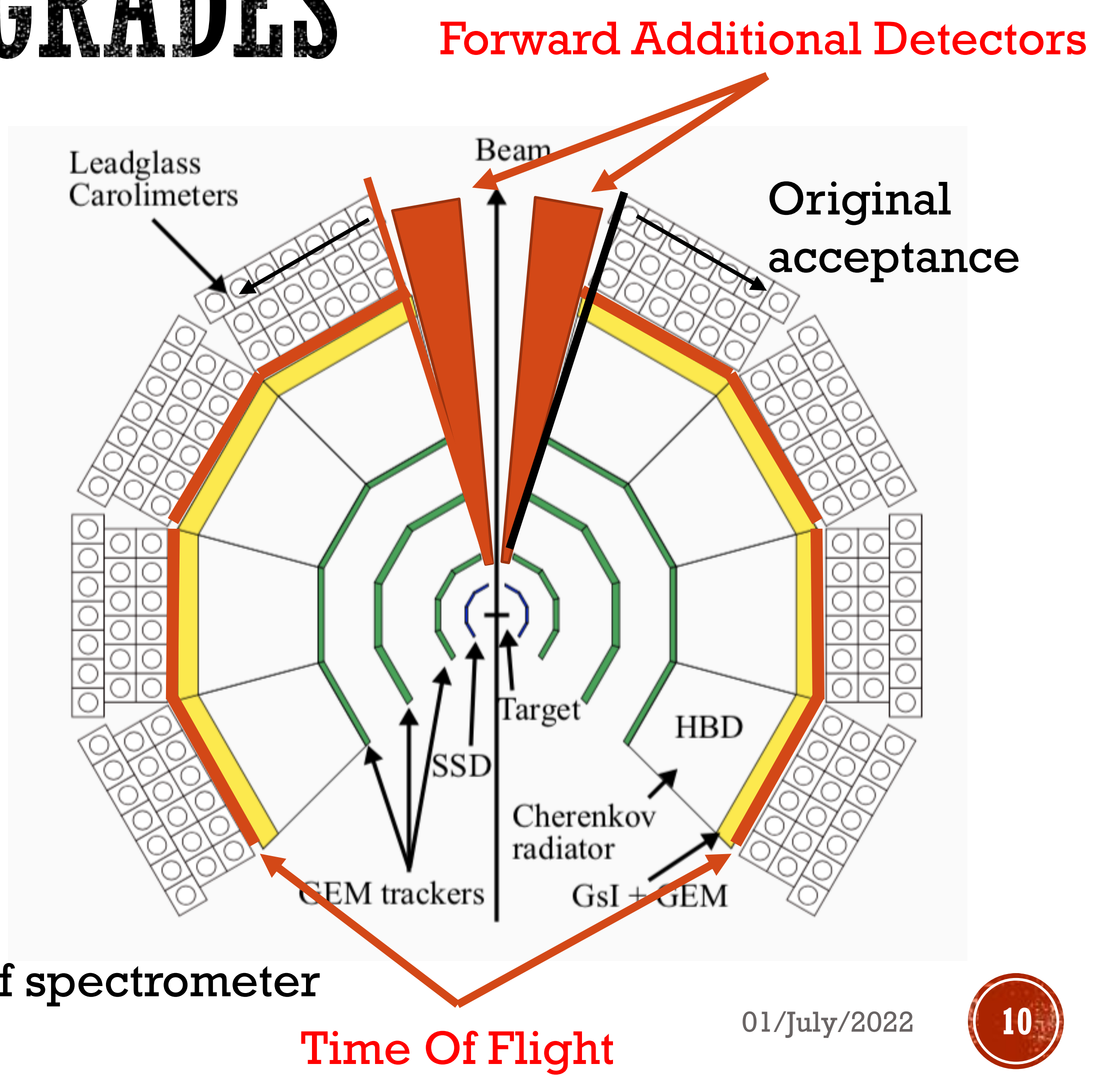
Momentum reconstruction




Invariant Mass of $\pi^+\pi^-$ [GeV/$c^2$]

# HEAVY ION: PHASE I EXPERIMENT AND SPECTROMETER UPGRADES

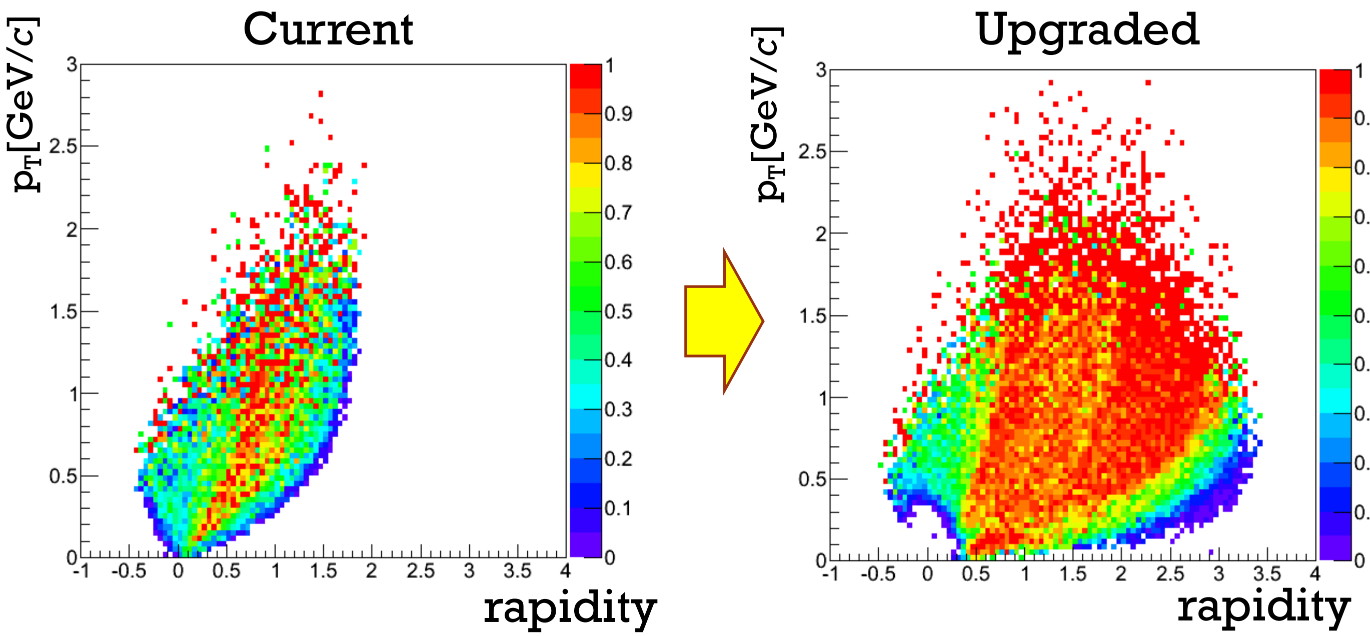
- Physics Goal of phase I experiment
  - Hadron interactions in dense medium
  - Search for a quark phase
    - Flow, Two particle correlations
    - Di-electron
- Heavy Ion beams
  - Species: Au
  - Intensity: $10^8$ Hz
- Detector Upgrades
  - Hadron measurements
    - It will be partially installed for pA experiment
  - Additional detectors in forward region




Schematic view of spectrometer

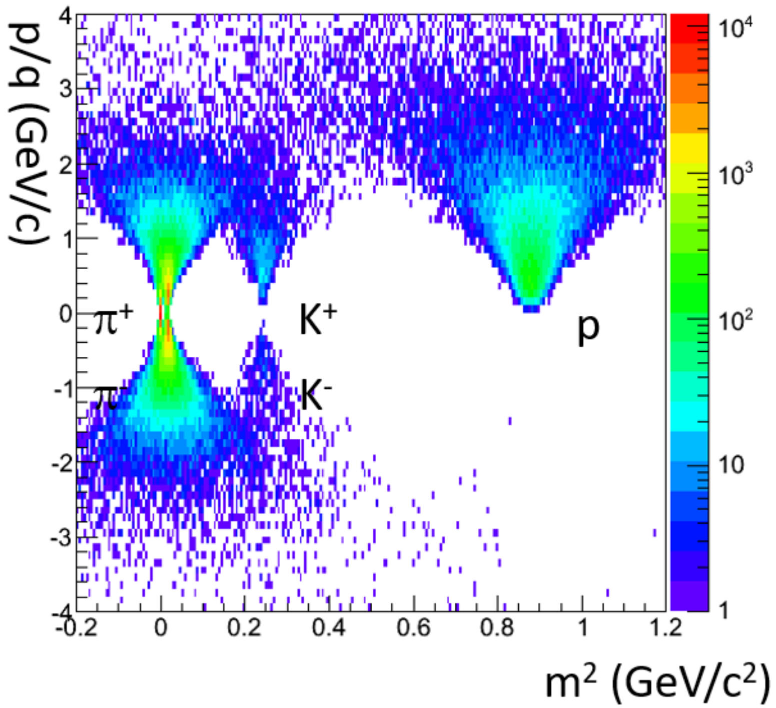
# HADRON MEASUREMENTS CAPABILITIES

- Enhance the rapidity region with forward detectors



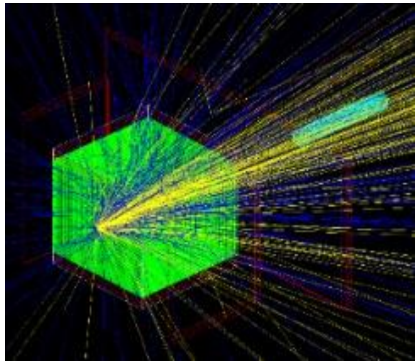

Proton acceptance in A+A

Enough particle ID capabilities

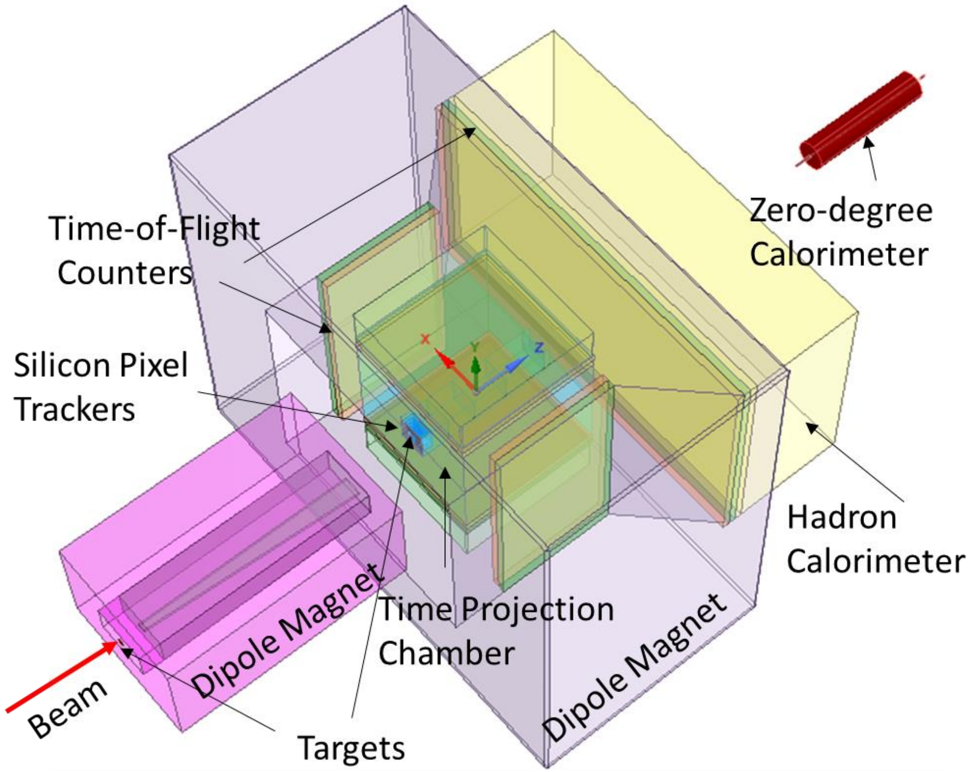



Momentum vs. Mass$^2$

# PHASE II: SPECTROMETER



- Experiment with High-intensity beam ($10^{11}$ Hz)
- Large acceptance and low $p_T$ tracking detector
  - higher flows, fluctuations, charmed hadrons
  - Detailed detector designs are still under discussion
- Current plan
  - Hadron Spectrometer
    - Dipole + TPC
    - Large Acceptance for Correlations, Fluctuations
  - Hyper-nuclei Spectrometer
    - Closed configuration
    - Hadron Spectrometer + Sweeping magnet

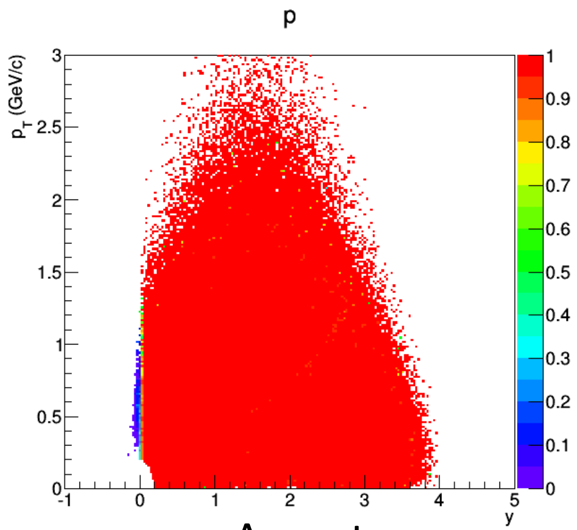



Schematic view of Hyper-nuclei spectrometer

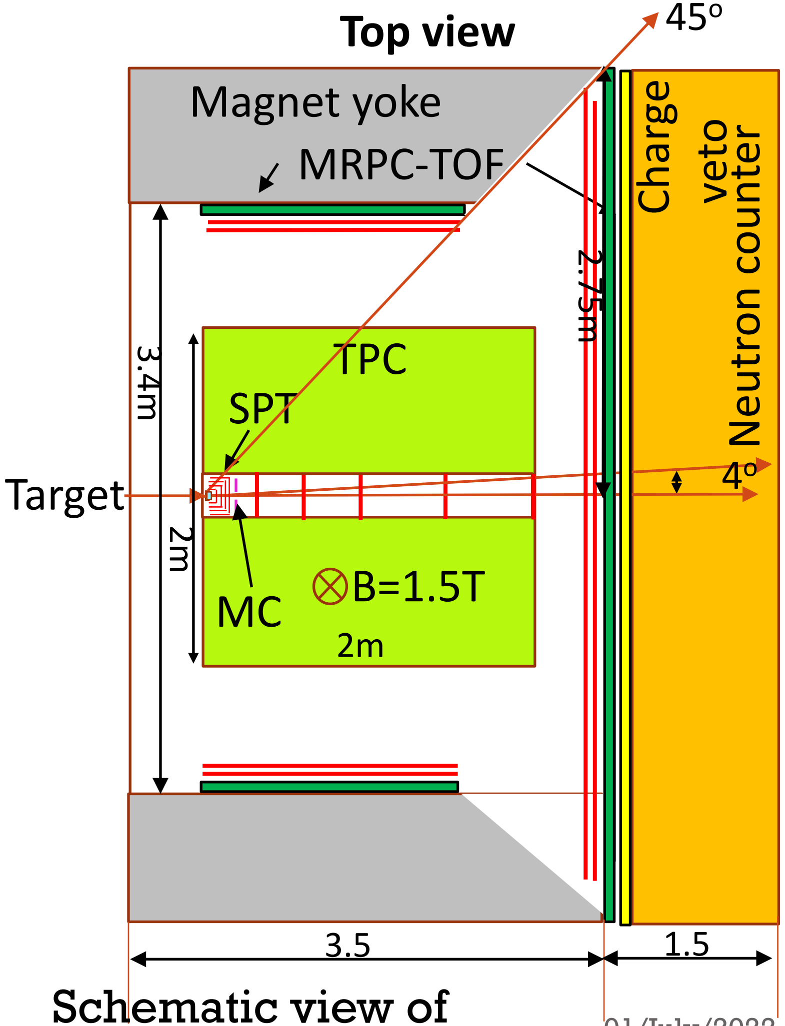
# PHASE II: HADRON MEASUREMENTS

- Identified charged particles for ~$4\pi$ acceptance
  - Silicon Pixel Tracker (SPT) ($\theta < 4^{\circ}$)
  - TPC ($\theta > 4^{\circ}$)
  - MRPC-TOF for particle identifications
- Trigger-less DAQ and high-rate counting

- Enhance the physics capabilities for rare events, fluctuations, higher order flows.



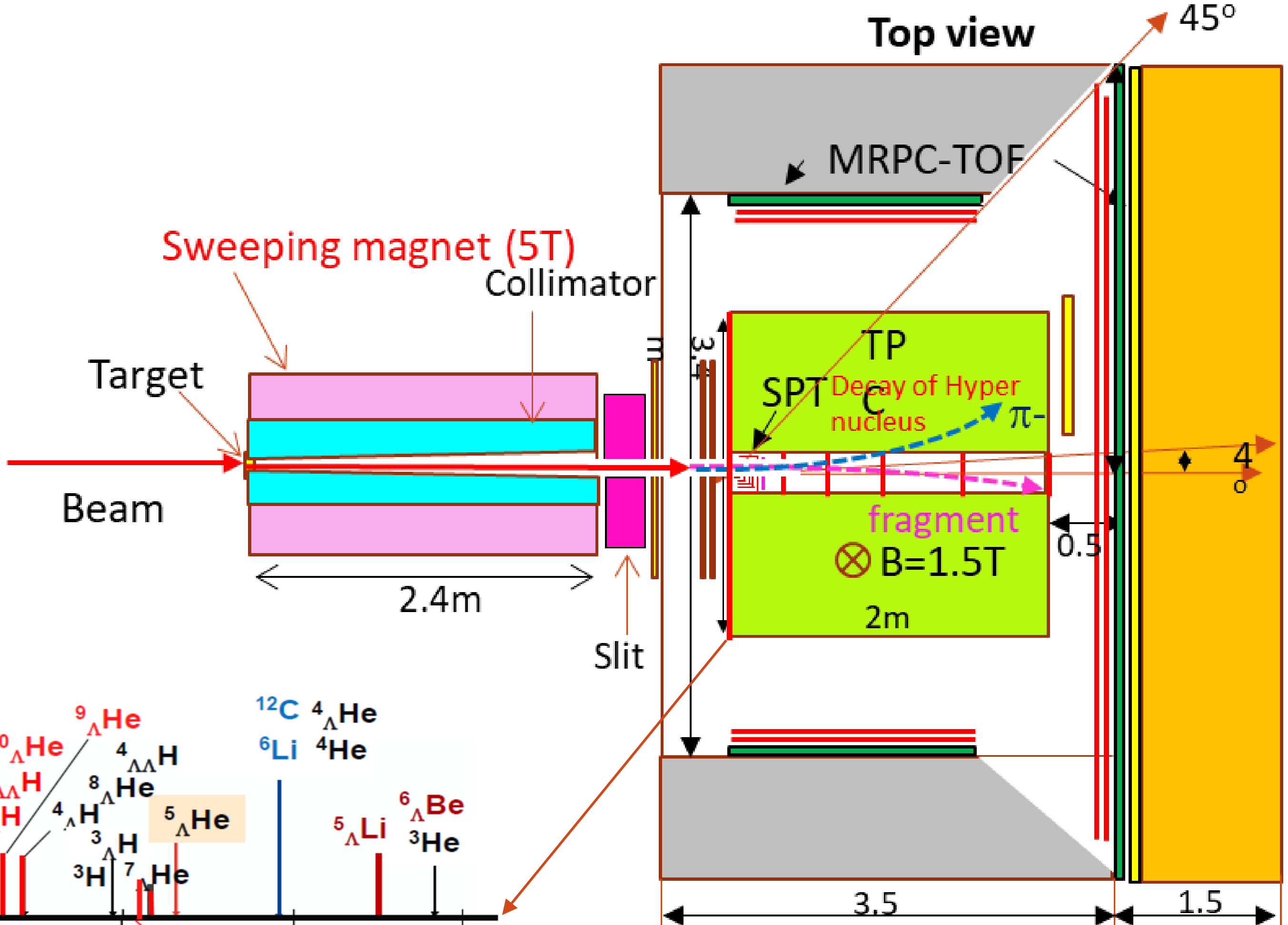
y-$p_T$ Acceptance



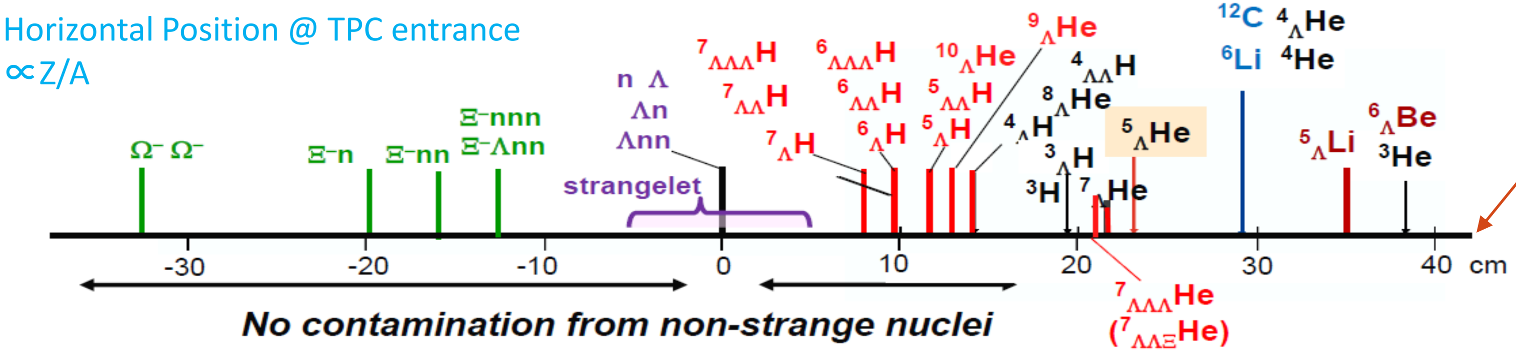
Schematic view of Hadron spectrometer

# HYPER-NUCLEI SPECTROMETER

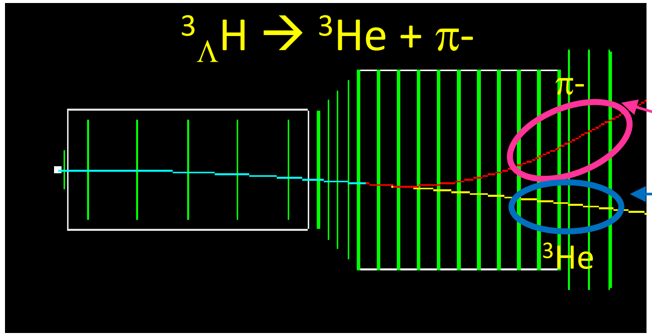
- Closed geometry : Sweeping magnet and Collimator
  - Limit the acceptance to beam rapidity
  - Only beam and fragments can reach 2nd dipole magnet
  - Interaction Rate : ~100 MHz
- Lifetime and Magnetic moment of hypernuclei
- Search for new hypernuclei and strangelet




Schematic view of Hyper-nuclei spectrometer



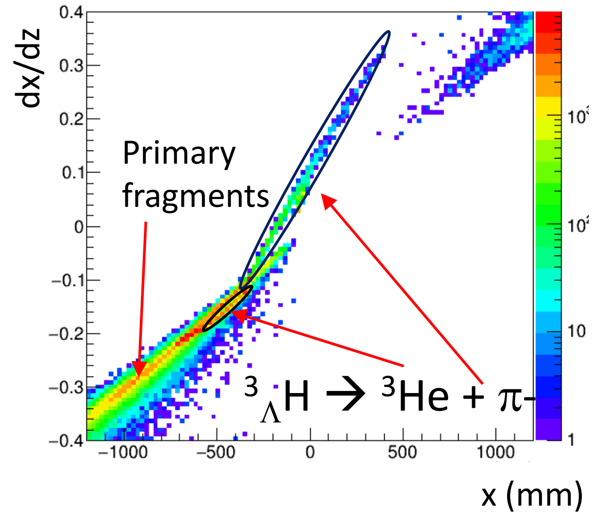
# AN EXAMPLE OF EXPECTED RESULT: $^{3}_{\Lambda}H$



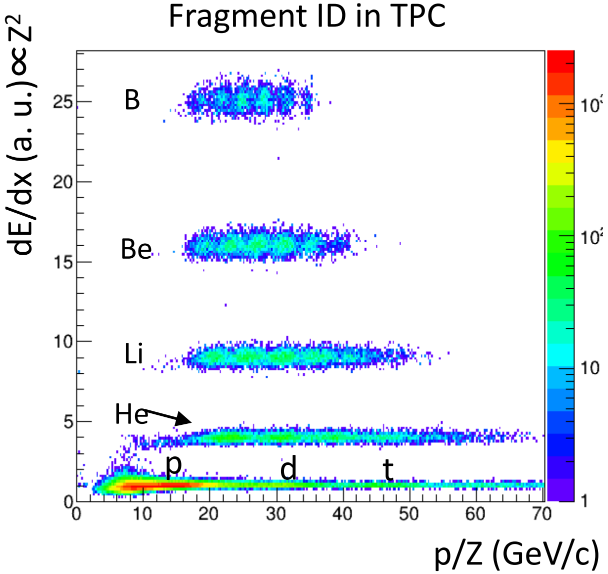

$^{3}_{\Lambda}$H embedded in JAM C+C events

1. Tag π- with the track angle and position
2. Identify fragment by Z and p/Z
3. Invariant mass of (π-, fragment) pair

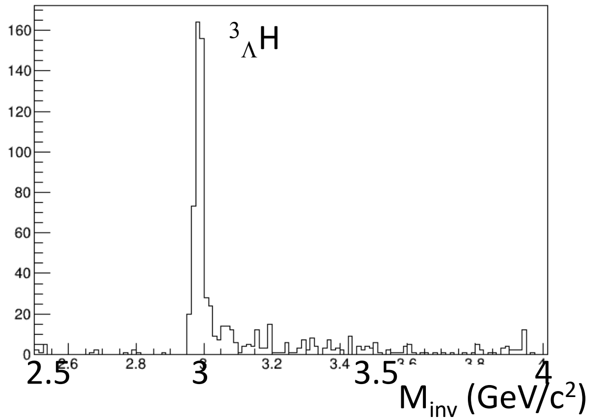
Horizontal position vs angle




Fragment ID in TPC




Reconstructed π- ³He invariant mass



# SUMMARY

- Future Heavy ion experiments at J-PARC are planned to study strangeness physics and high-density matter
- Significant Facility upgrades are required for Heavy Ion experiments
  - We need Linac and Booster for heavy ion acceleration
  - New Spectrometer and new experimental area
- Staging approach is under discussion. First, we can start with minimum upgrades based on existing accelerator equipment and di-electron spectrometer. Then, we are planning to have full upgrades.
- Detailed design of detector configurations for each stage will be finished in a year and a project proposal will be submitted to the J-PARC

**134 members :**

# *J-PARC-HI Collaboration*

**Experimental and Theoretical Nuclear Physicists and Accelerator Scientists**

**Experiment**

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**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

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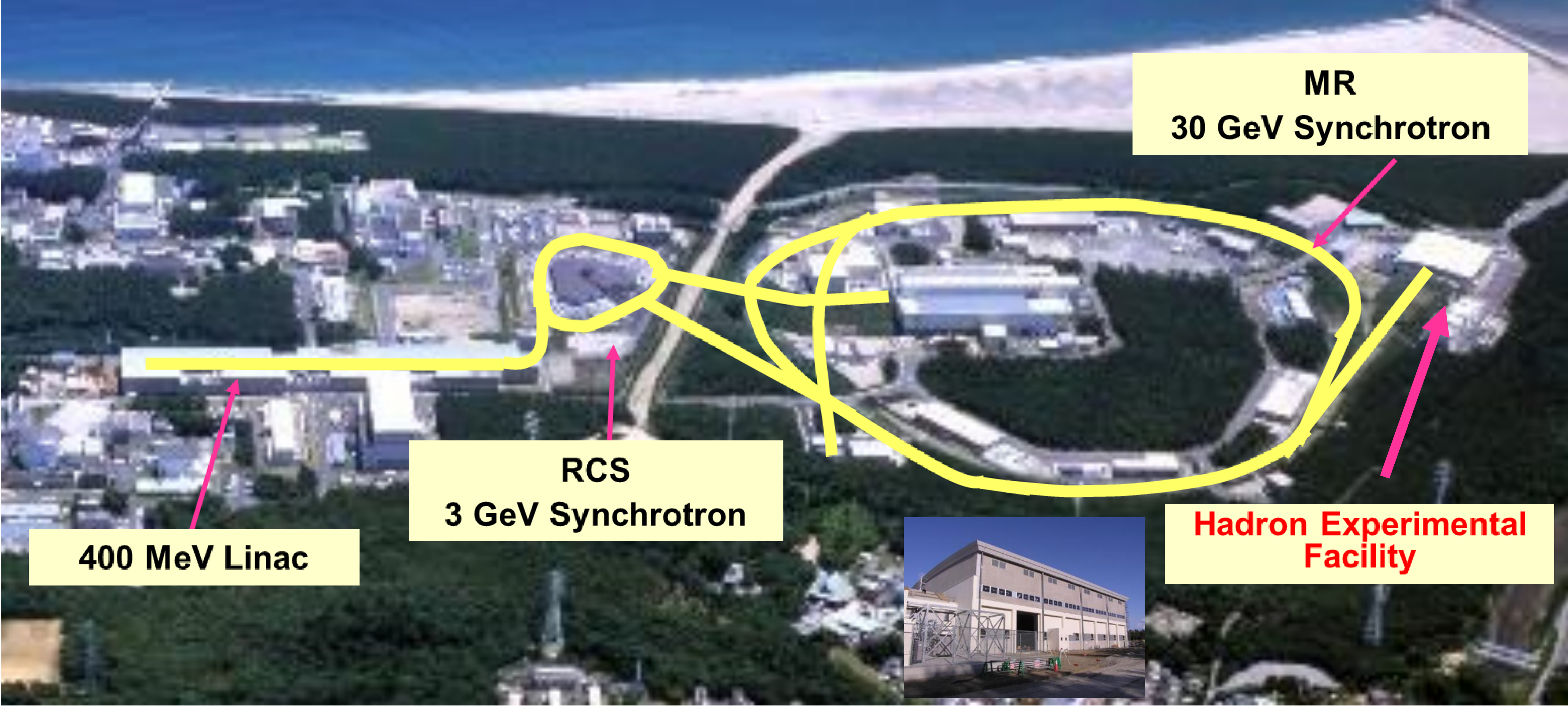
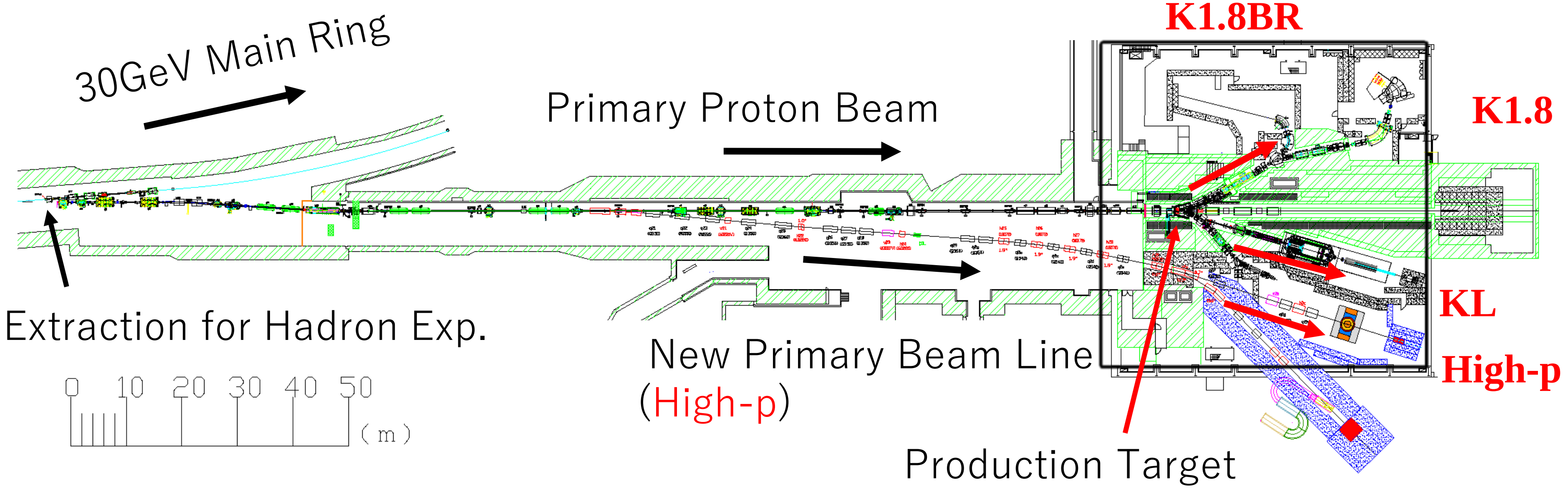
# BACK UP

# J-PARC (Japan Proton Accelerator Research Complex)



# HADRON EXPERIMENTAL FACILITY




| Name | Species | Energy | Intensity |
|---|---|---|---|
| K1.8 | $\pi^\pm$, $K^\pm$ | < 2.0 GeV/c | ~$10^5$ Hz for $K^+$ |
| K1.8BR | $\pi^\pm$, $K^\pm$ | < 1.0 GeV/c | ~ $10^4$ Hz for $K^+$ |
| KL | $K_L$ | 2.0 GeV/c (Ave.) | ~ $10^7$ Hz for $K^0$ |

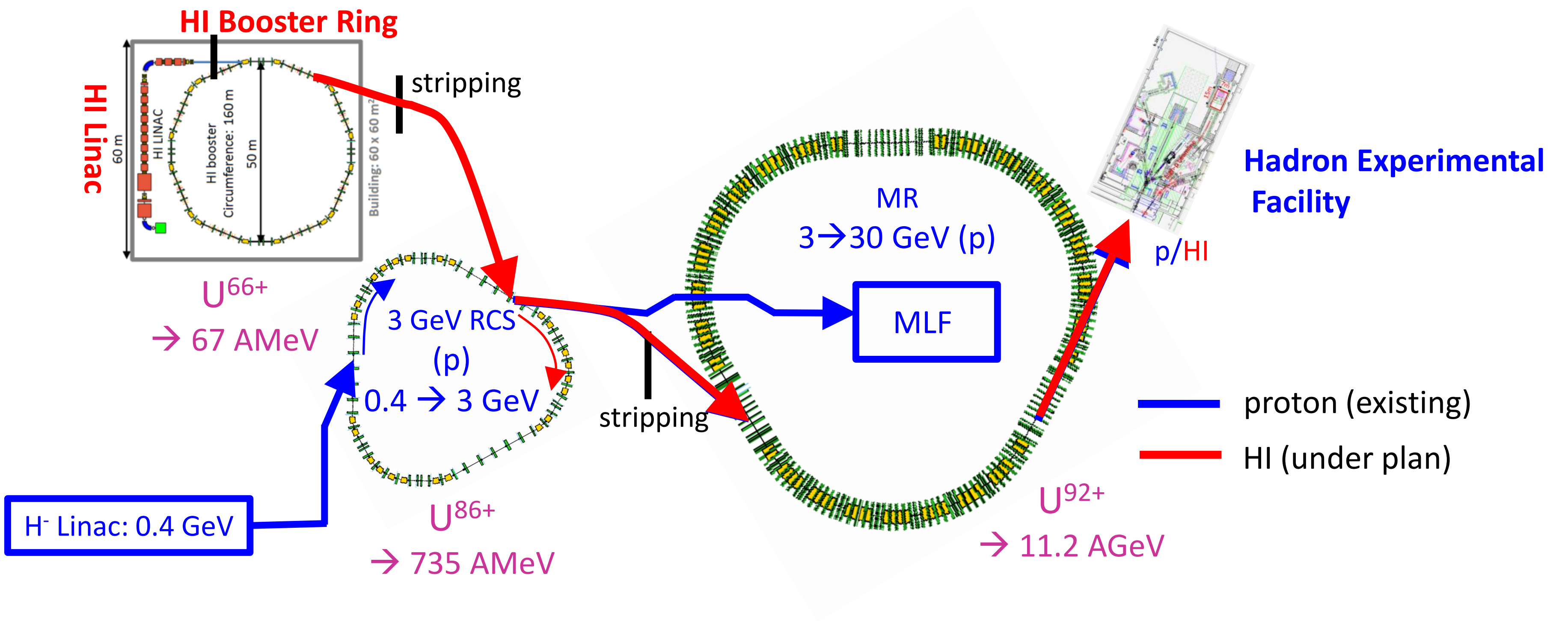
**New Beamline**

| | | | |
|---|---|---|---|
| High-p | primary | 30GeV | ~ $10^{10}$ Hz |
| | Unseparated | < 20GeV/c | ~ $10^8$ Hz |

# HI ACCELERATION SCHEME AT J-PARC

Proton beam rate (slow extraction)
- 5.5x10$^{13}$/cycle (currently)
- 1.2x10$^{14}$/cycle (2022)

- HI beam rate ~10$^{11}$ Hz
- $E_{lab}$ (U) = 1-12 AGeV
- $\sqrt{s_{NN}}$ (U) = 1.9-4.9 GeV

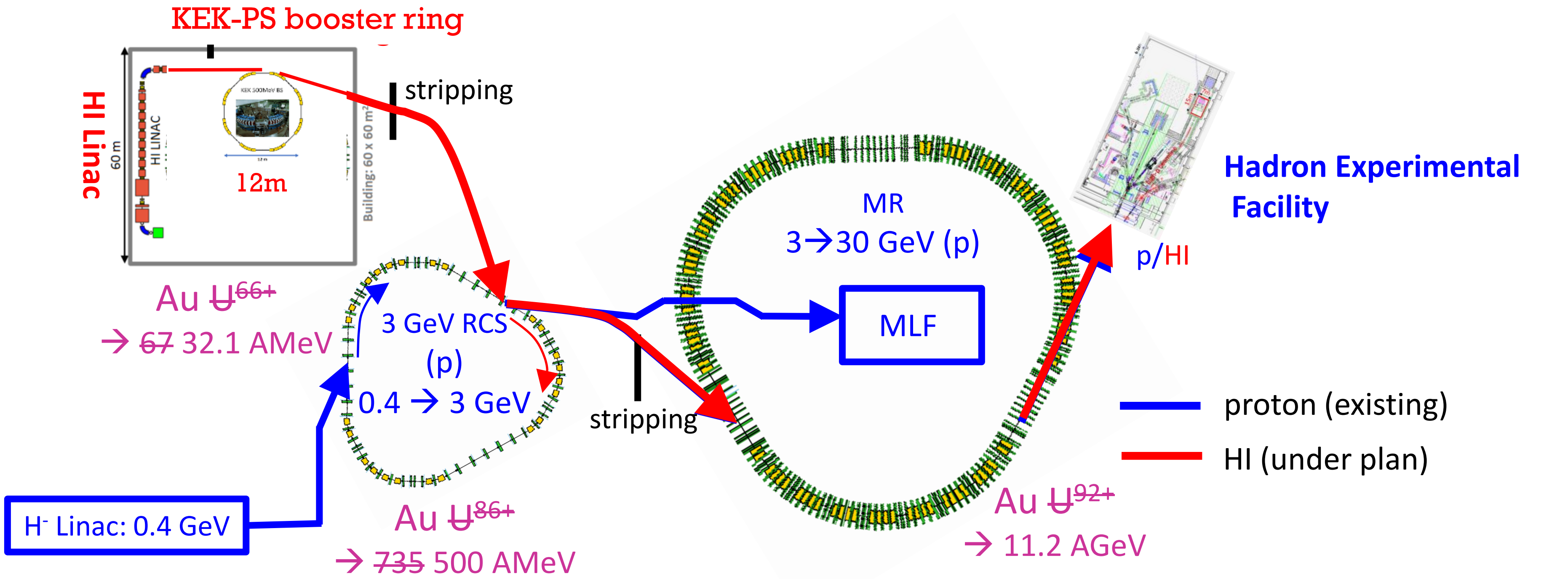


# MINIMUM UPGRADES (ACC. PART)

Heavy Ion LINAC
- Budget request as a low energy heavy ion project
- Reuse of cavities which is used at JAEA Tandem

Booster
- Reuse of KEK-PS Booster Ring (KEK-BS)

- HI beam rate ~$10^{\not{11}\,8}$ Hz
- $E_{lab}$ (U) = 1-12 AGeV
- $\sqrt{s_{NN}}$ (U) = 1.9-4.9 GeV



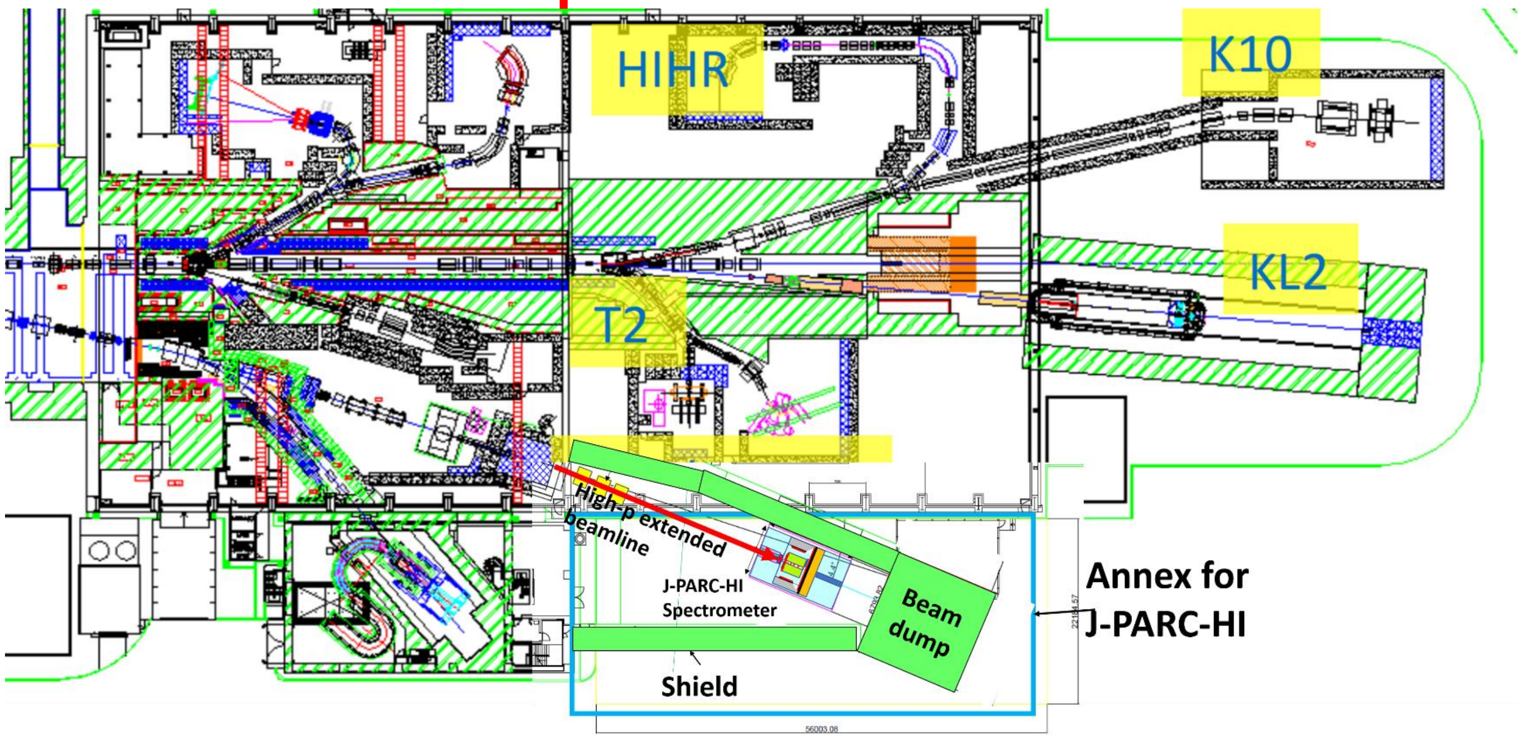

Intensity is limited by KEK-BS, which is a small ring and no flexible optics. Space charge effect is at a negligible level because the beam intensity is $10^{-3}$ lower than that of proton beam at present.

# UPGRADES OF THE EXPERIMENTAL FACILITY

Current Experimental Hall

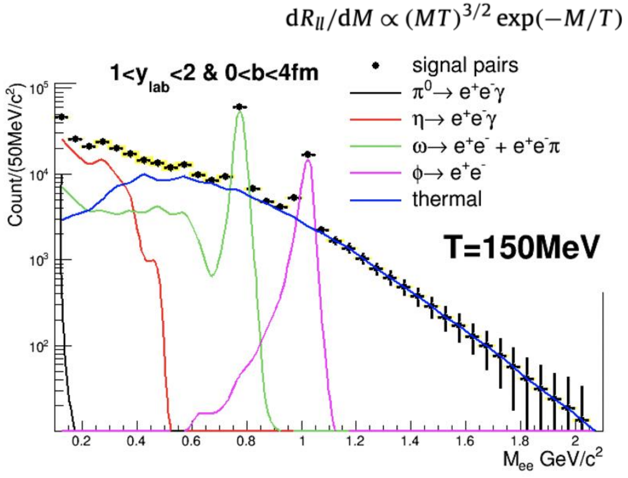
Upgrade Plan of the Experimental Hall

New Production target & New beamlines

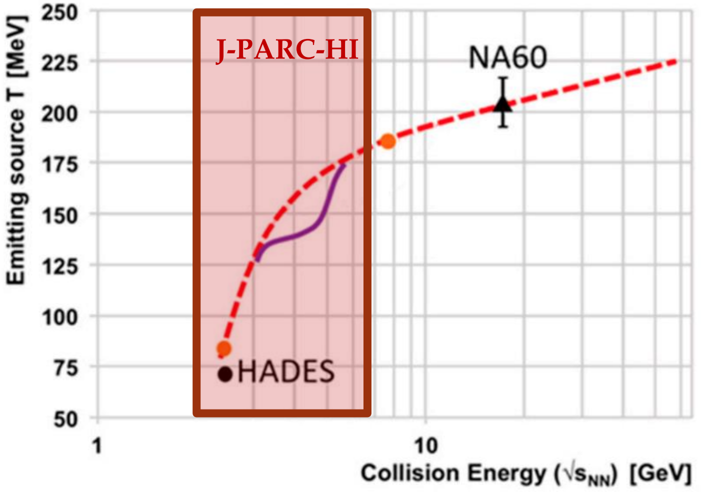


# EXPERIMENT W EXISTING E+E- SPECTROMETER

- Dielectron measurements in heavy-ion collisions at J-PARC with E16 upgrade
  - $10^8$ beam/spill, IR rate ~ 50 kHz with 0.035 mm Au target (~0.1% int. length)
- Experimental area will be used as it is
- First Proposal is submitted to J-PARC Program Advisory Committee in this July
  - Temperature and yield measurements of di-electrons above $M_{ee} > 1$ GeV
    - Search for a (onset of) partonic matter
    - "Caloric curve" to map out the phase diagram below $\sqrt{s_{NN}} < 10$ GeV

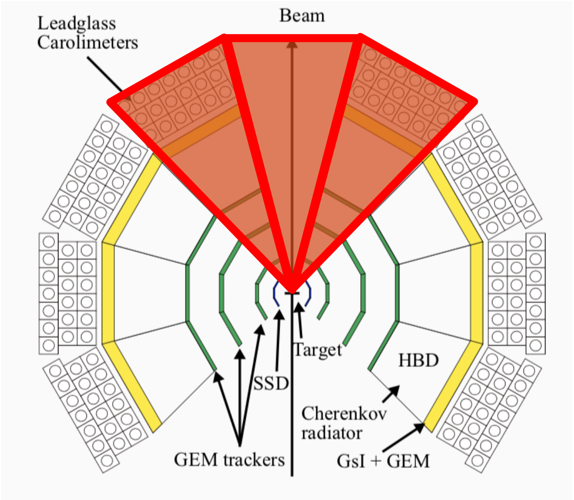


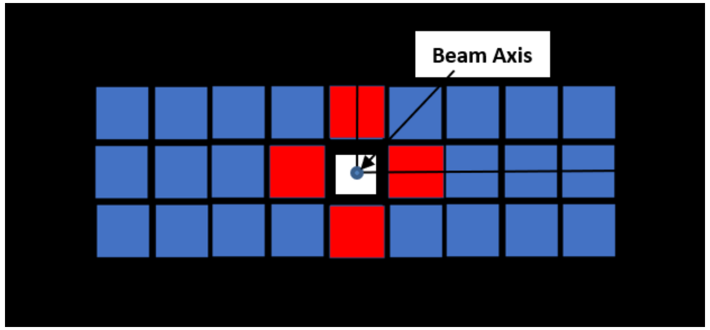

Energy Scan



# REQUIRED UPGRADES OF THE SPECTROMETER

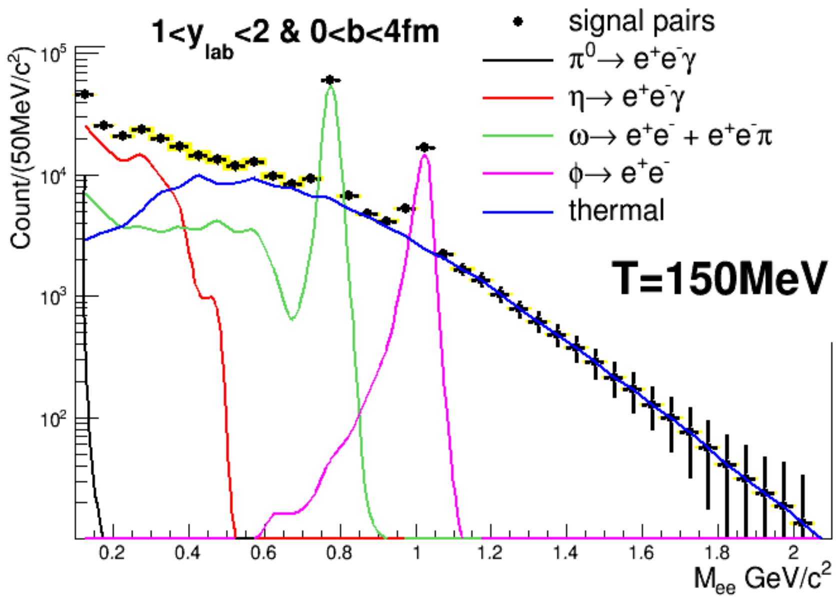
- The most forward modules should be upgraded to cope with a high hit-multiplicity environment
  - Hit occupancy should be reduced and finer segments are required
- Tracking device
  - The most inner GEM Trackers must be upgraded and replaced with SSDs
- Electron identification detectors
  - Lead glass calorimeter must be upgraded to finer segmented detectors
    - Lead Tangsten ($PWO_4$ is a candidate)
- Zero degree calorimeter
  - New detector for a centrality determination
- Readout and DAQ system
  - Current system assume 1 kHz event trigger
  - New system should be run at 50kHz interactions

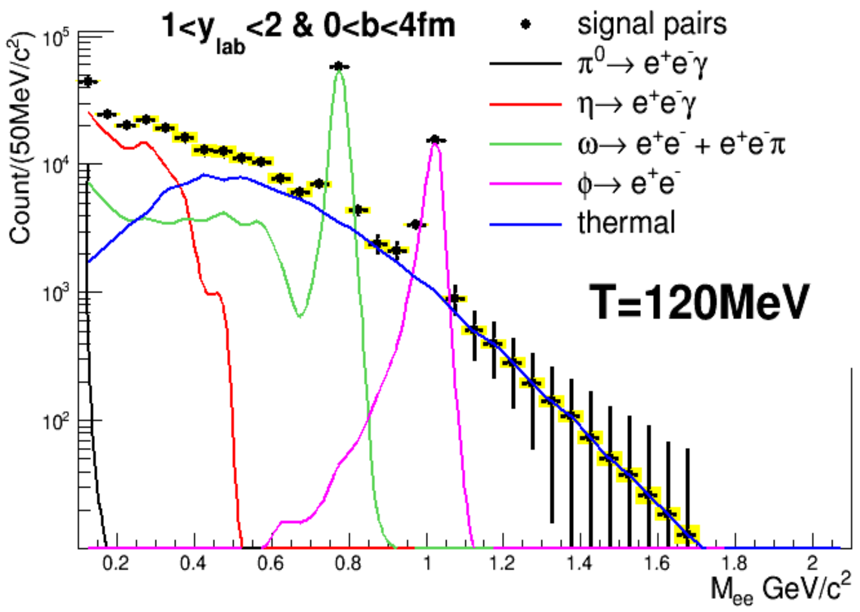


# EXPECTED MASS DISTRIBUTIONS

100 days run, 0.1% sys error assumed for combinatorial background subtraction (PHENIX, ALICE)




- ~ 6% accuracy of T can be expected from $M_{ee}$>1.1GeV/$c^2$ in the case of 150 MeV
- ~10% accuracy of T can be expected from $M_{ee}$>0.9GeV/$c^2$ in the case of 120 MeV
- ~20% accuracy of integrated excess yield (0.4<$M_{ee}$<0.7GeV/$c^2$)
  (sys error from the known resonances is dominated)

# EXPECTED DIMUON SPECTRUM

We have evaluated performance of our dimuon spectrometer

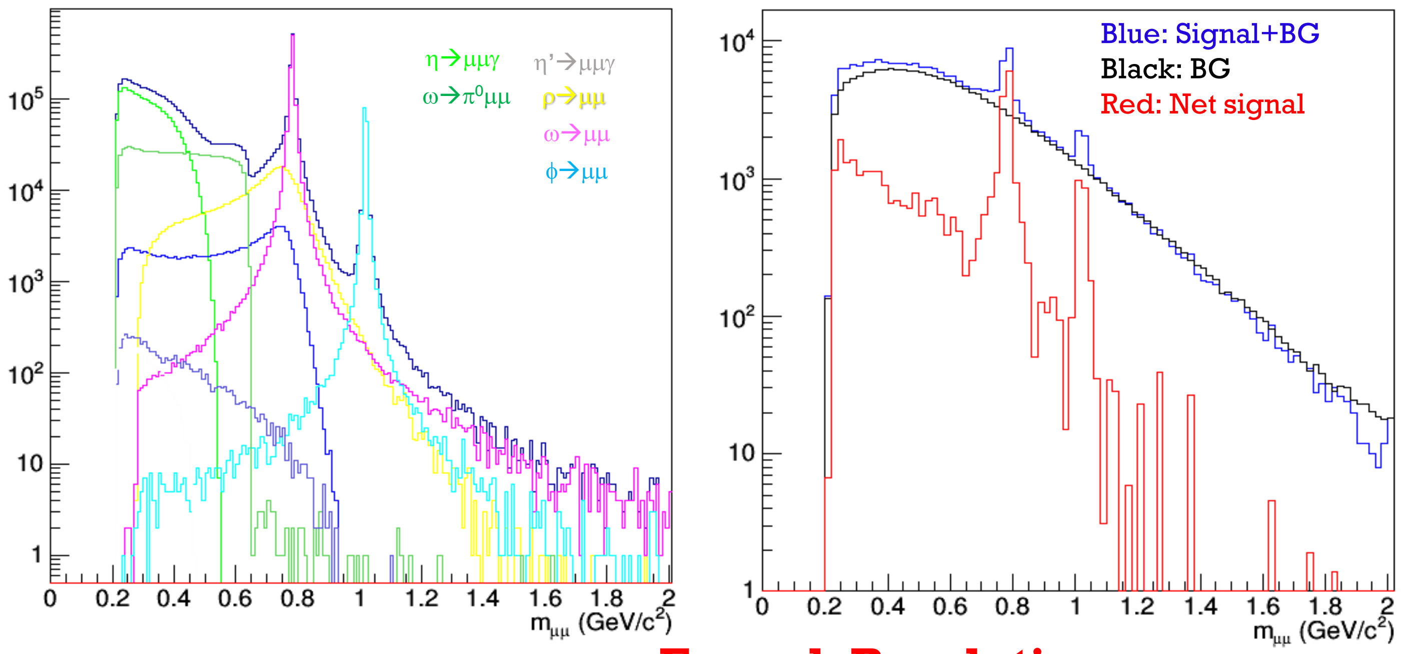
- Embed $\mu^+\mu^-$ into JAM events and process by GEANT
  - U+U, $\sqrt{s_{NN}}$=4.5 GeV, Min. bias JAM events
- Reconstruct tracks passing through 4 $\lambda_I$ muon absorbers

$\theta_{ee}$>2°, 2°<θ<80°, $p_T$>0.1GeV/c

Generated cocktail

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

Reconstructed spectrum



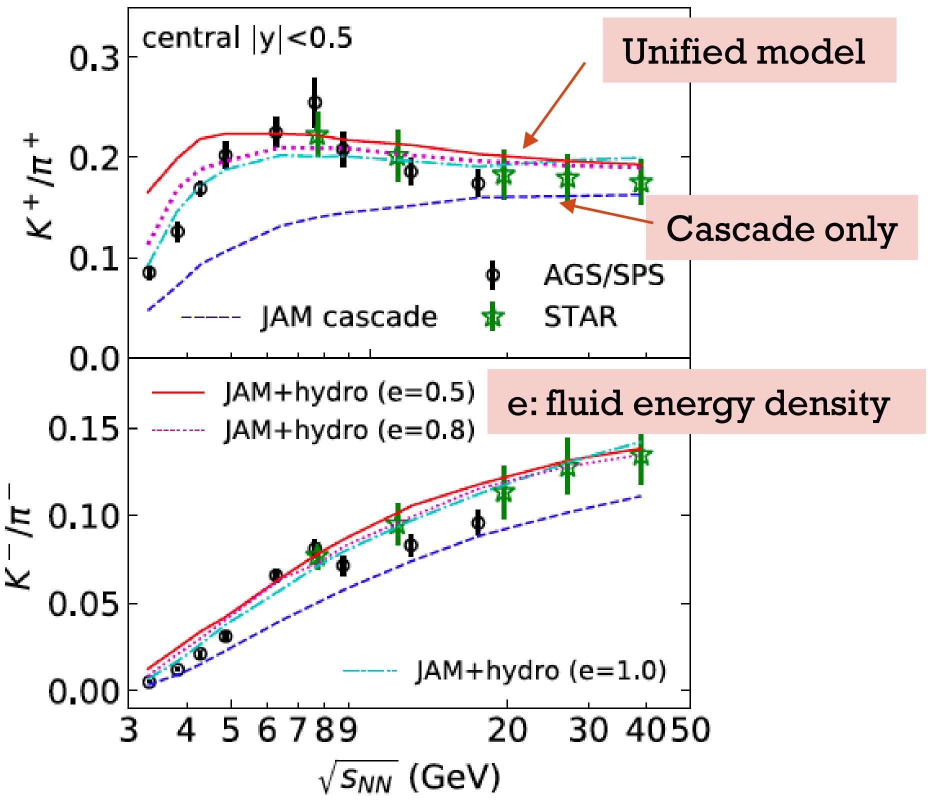

Enough Resolution even in low mass region

# DEVELOPMENTS OF FURTHER OBSERVABLES

Calculations for thermalized phase are being developed by a collaboration of theoretical groups

Example: A Japanese group develops an "unified" hydro-cascade model

Akamatsu, et.al, PRC**98**, 024909 (2018)

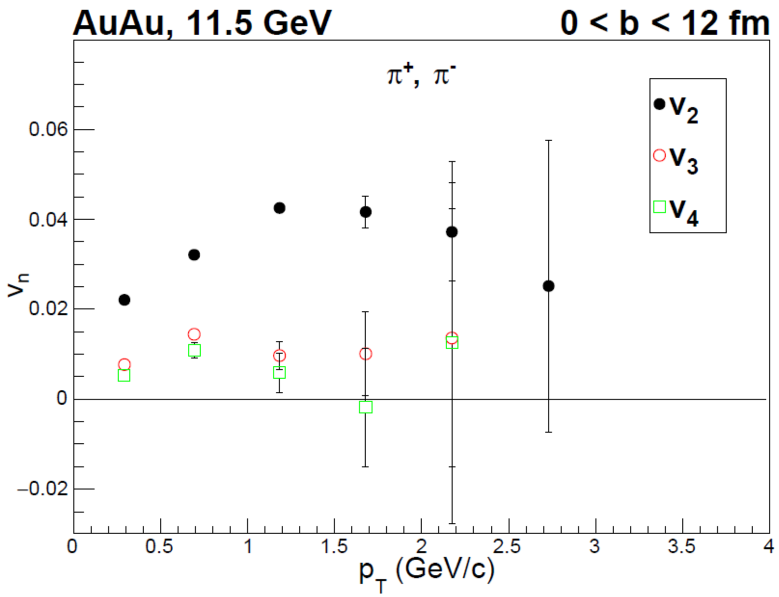



- Simultaneously evolve both fluid element and hadrons in time
  - High density hadrons → "parton fluid"
  - Cooled "parton fluid" → hadrons
- Unified model describes data well, while cascade only doesn't
  - It seems we can expect parton fluid phase even at the J-PARC energy

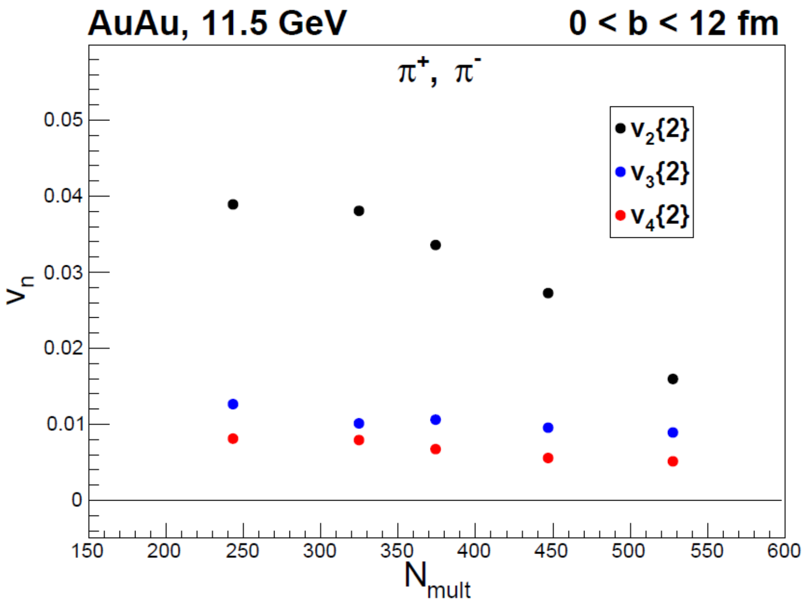
# FLOW MEASUREMENTS

- Using the developed model, significance of flow measurements are evaluated
  - Au+Au events of hydro + JAM cascade model (JAM-1.9043)
  - Higher-order flow can be measured for study of "fluid" properties of generated medium

Higher-order harmonics with 2-particles correlation (4.5 M events)

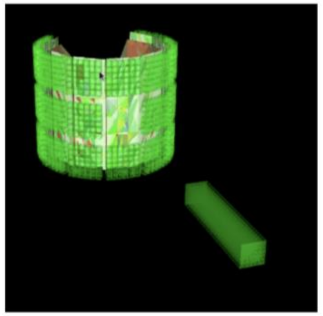


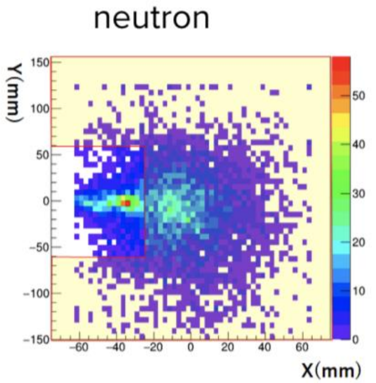

Higher-order harmonics with Cumulants (54M events)

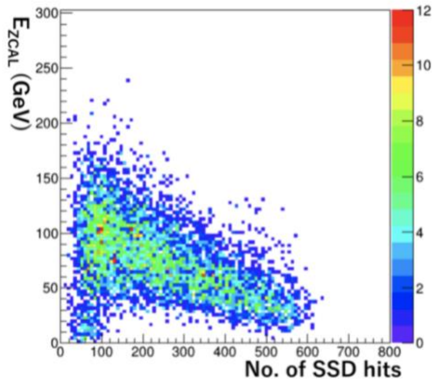


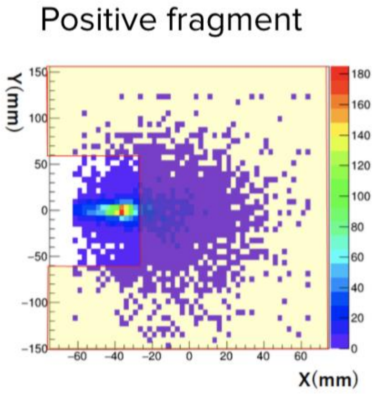
# E16 UPGRADE: ZERO DEGREE CALORIMETER

- Centrality is defined with the number of SSD hits and the energy deposit at zero-degree calorimeter (ZCAL)
- **ZCAL**
  - Located at 4.5m downstream from the target (just in front of the beam dump)
  - Dimension: 15cm(x)x30cm(y)x50cm(z)
  - $4.0\lambda_I/11.3X_0$Tungsten-MPPA fiber sampling calorimeter (based on RHIC ZDC)
  - Acceptance to avoid positive fragments and beam but detect neutrons



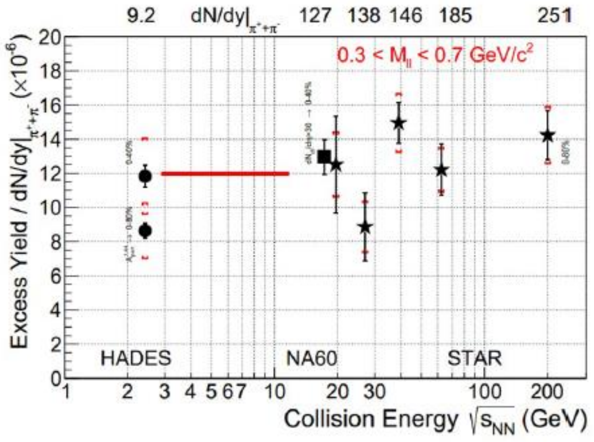


# FEASIBILITY STUDIES : INPUTS

- Thermal dielectrons



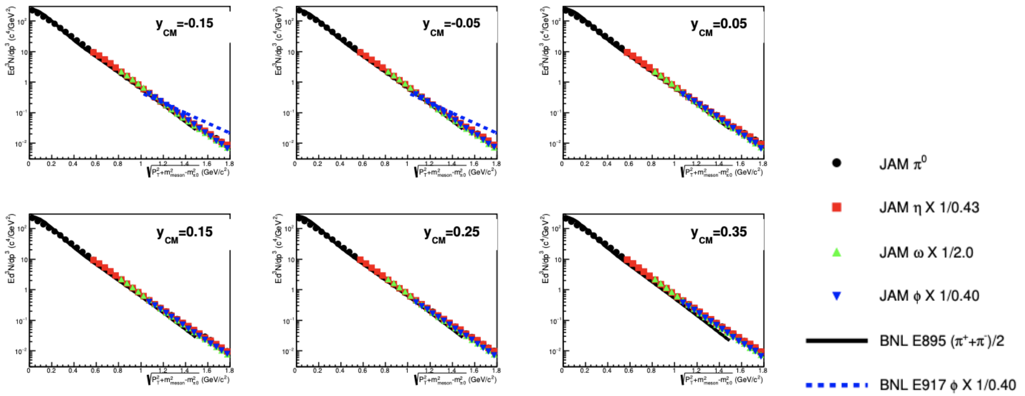

- $dN_{ee}/dy$ ($0.3<M_{ee}<0.7$ GeV/$c^2$) = $1.2\times10^{-5}$ x $dN_{\pi+-}/dy$ (105)
- $dN_{ee}/dM \propto (MT)^{3/2}\exp(-M/T)$
- $dN_{ee}/dPt \propto \exp(-Pt/T)$

Two cases studied

- T = 150MeV (cross-over transition)
- T = 120MeV (1st order phase transition)

Dielectrons from hadronic decays

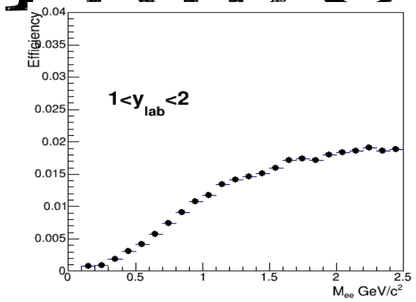
JAM event generator for Au+Au at 10 A GeV/c

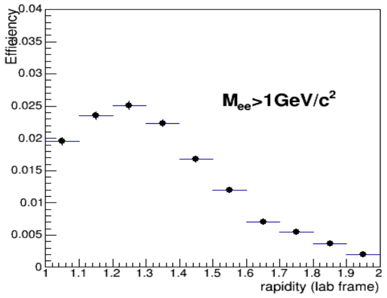


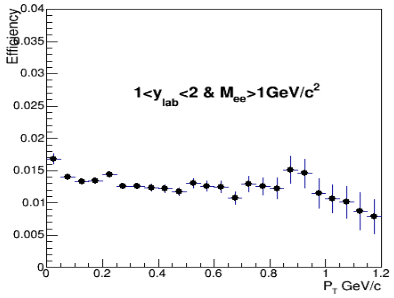

- Dielectron pairs are transported into GEANT4 simulation
- Full E16 acceptance & E16 achieved eID capability considered
- Tracking inefficiency due to high multiplicity effects taken into account

# EFFICIENCIES AND RAW MASS DITRIBUTIONS

- Pair Efficiencies
  - Multiplicity effects not included

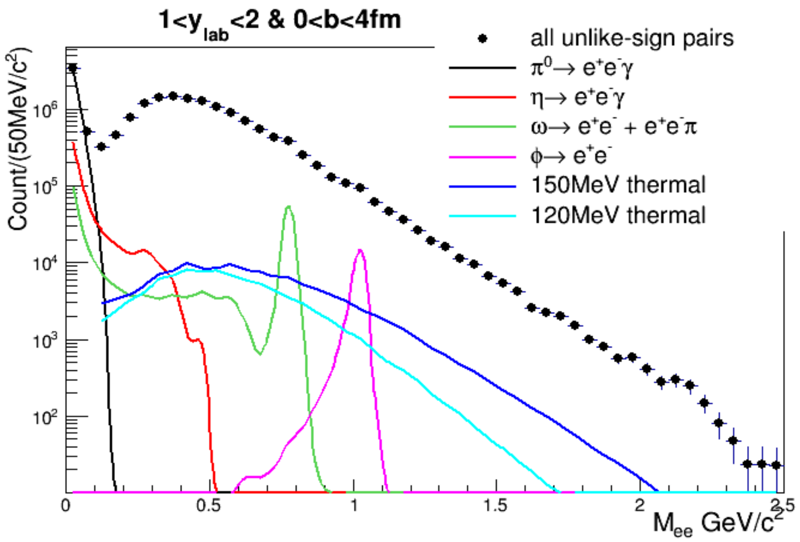


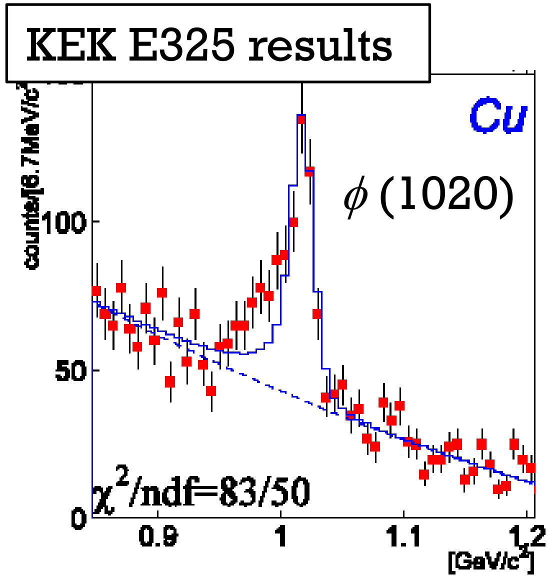

- Raw Mass Distributions
  - Thermal photons
  - known resonance decay $\pi^0\rightarrow ee\gamma$, $\eta\rightarrow ee\gamma$, etc..
  - $\gamma$ conversion in the target
  - miss ID $\pi^{+-}$
  - Combinatorial pairs

1x10⁸/spill 10 AGeV Au beam x 100 days run
0.035 mm Au target(∼0.1% int. length)



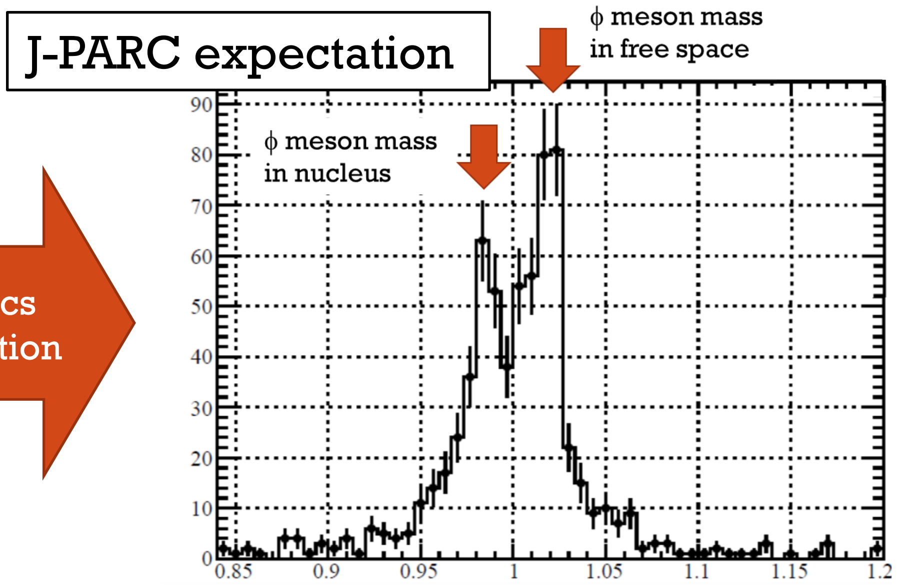
# VECTOR MESONS IN NUCLEUS

- Spectral changes of vector mesons in QCD medium provide crucial information on the non-trivial structure of QCD medium
  - Spontaneously broken chiral symmetry and its (partial) restoration in a finite density matter.
  - Upgrades of the KEK-PS E325 experiment



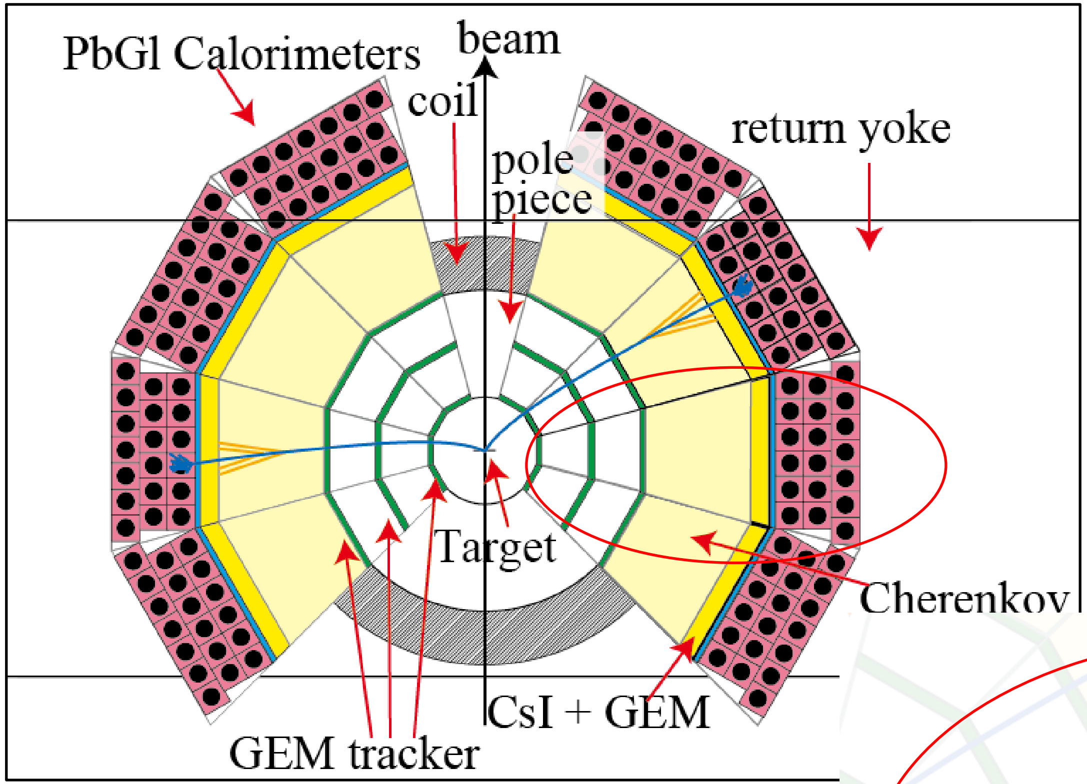

$e^+e^-$ invariant mass

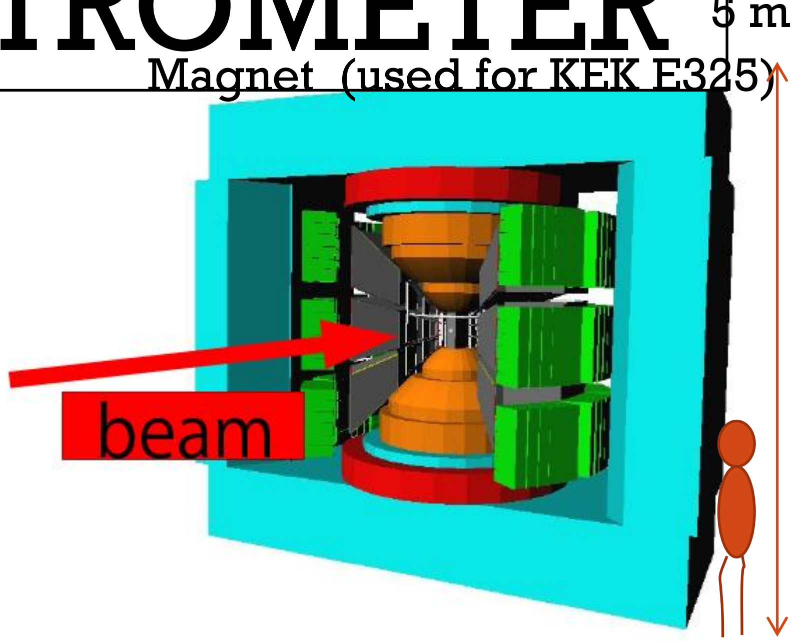
High Statistics
Better Resolution

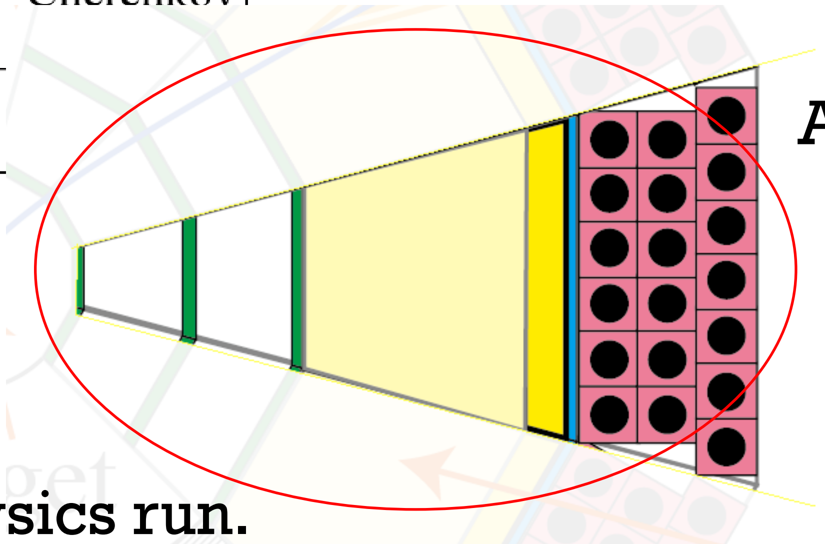



$e^+e^-$ invariant mass [GeV/$c^2$]

# THE J-PARC E16 SPECTROMETER



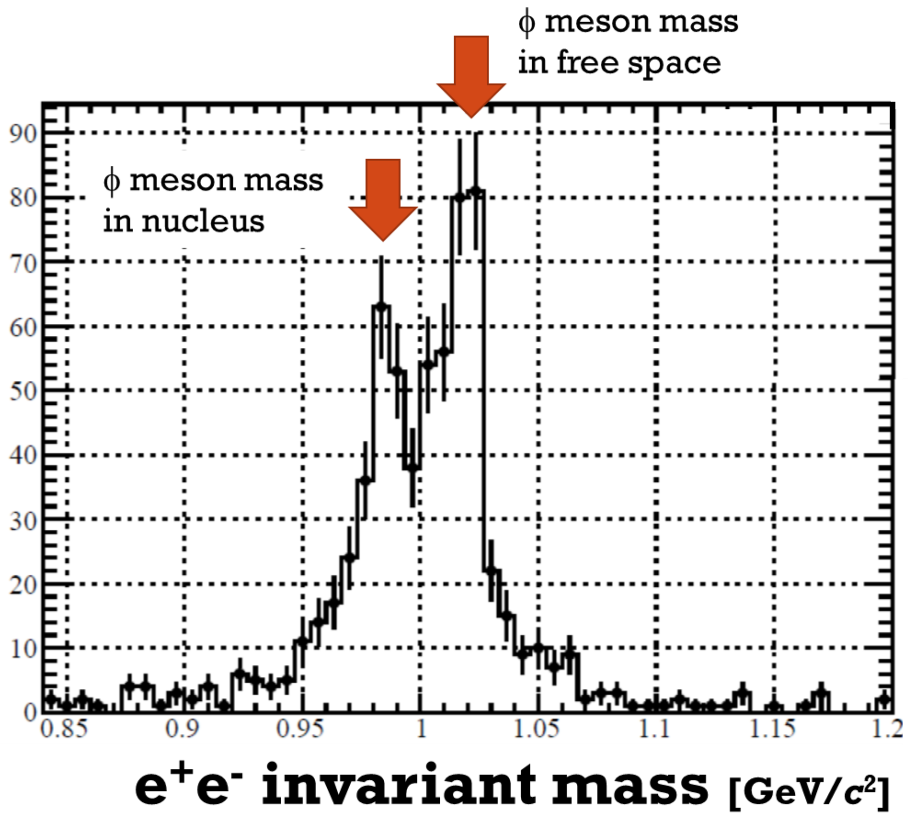




SSD : Tracking
GTR : Tracking
HBD : eID (Cherenkov)
LG : eID (Calorimeter)
26 modules in total. 8 for the 1st physics run.

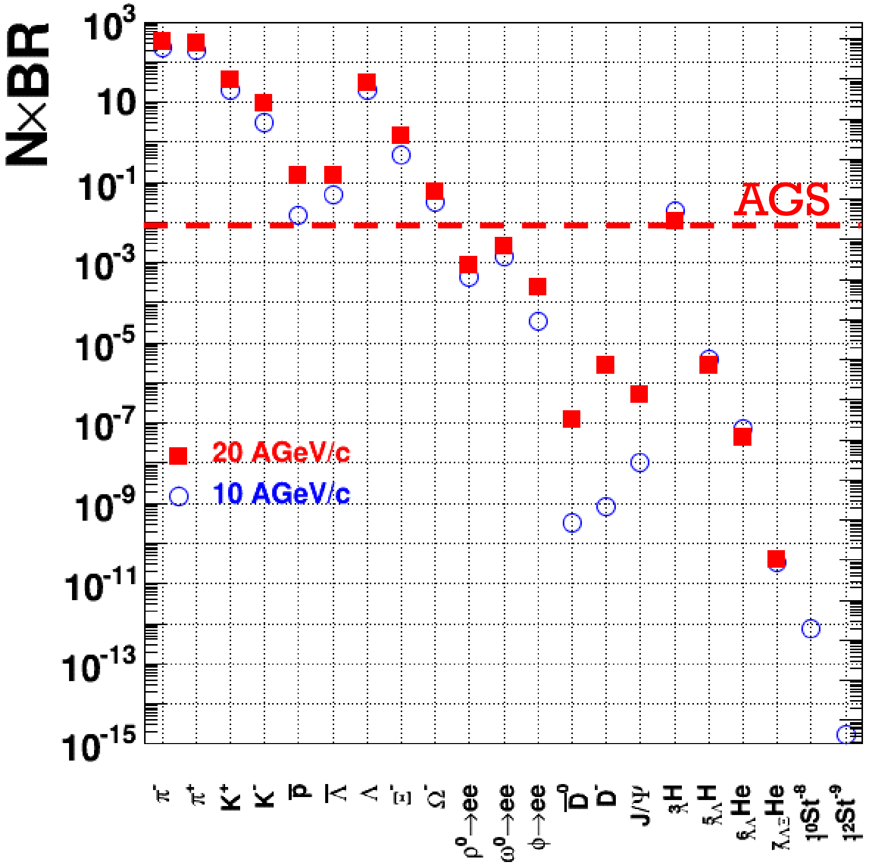
# EXPECTED RESULTS FOR THE FIRST EXP.

- Measurements of changes of hadron properties in a nucleus
  - Hadron mass can be changed in a finite density due to a partial restoration of chiral symmetry
- Same effects are expected in a high energy heavy ion collisions
- Much clear measurements can be done in a nucleus




Expected Mass spectrum

# PRODUCTION RATE




HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203
P. Braun-Munzinger J.Phys.G21 (1995)L17