J-PARC HEAVY ION OVERVIEW

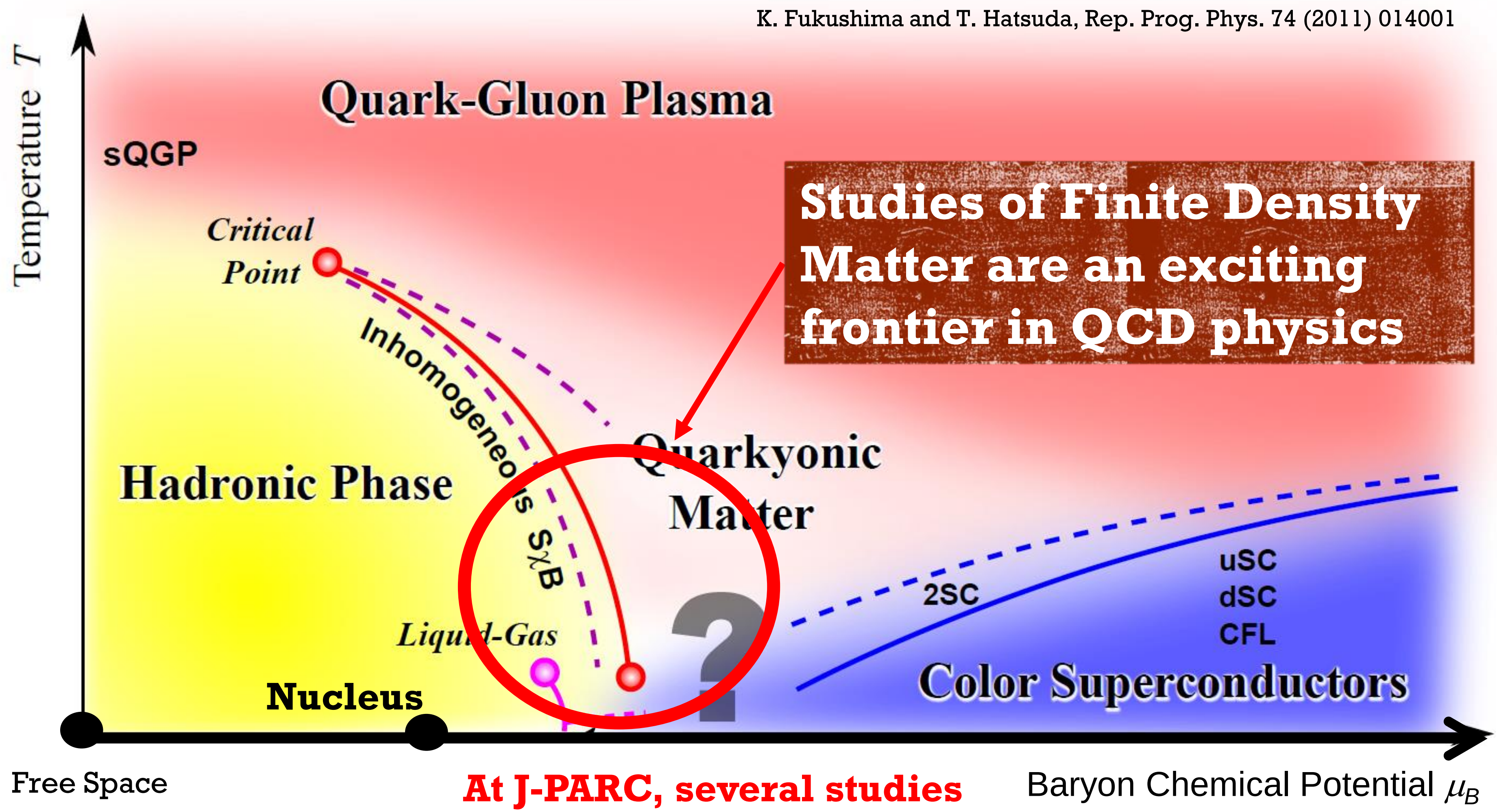
K. Ozawa (KEK, University of Tsukuba)

for the J-PARC HI collaboration

CONTENTS OF MY TALK

- Heavy Ion related activities at J-PARC
  - Vector mesons in nucleus
    - χ sym. restoration in finite density matter
  - Study of di-quark correlation in charmed baryons
- J-PARC Heavy Ion Program
  - Accelerator and detector plan
  - Staging approach

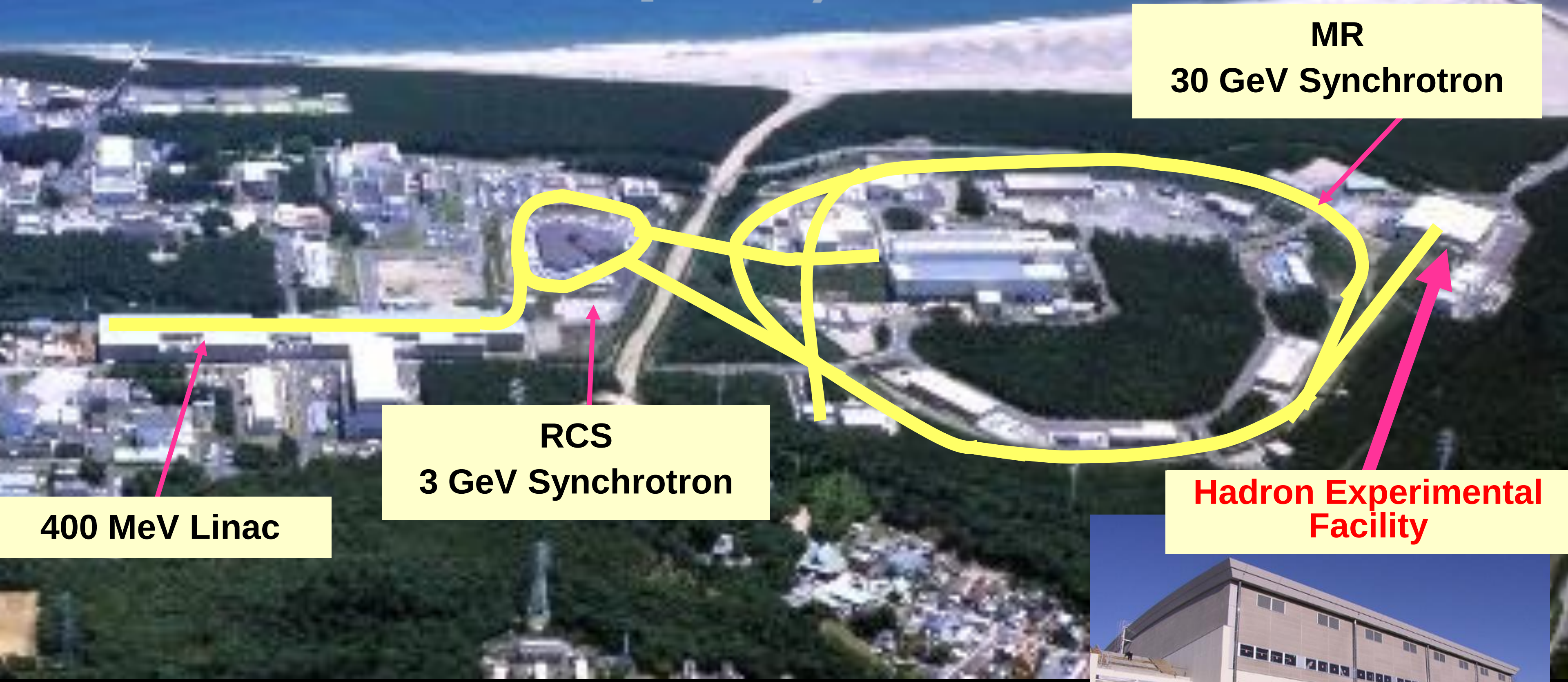
PHYSICS: FINITE DENSITY QCD MEDIUM



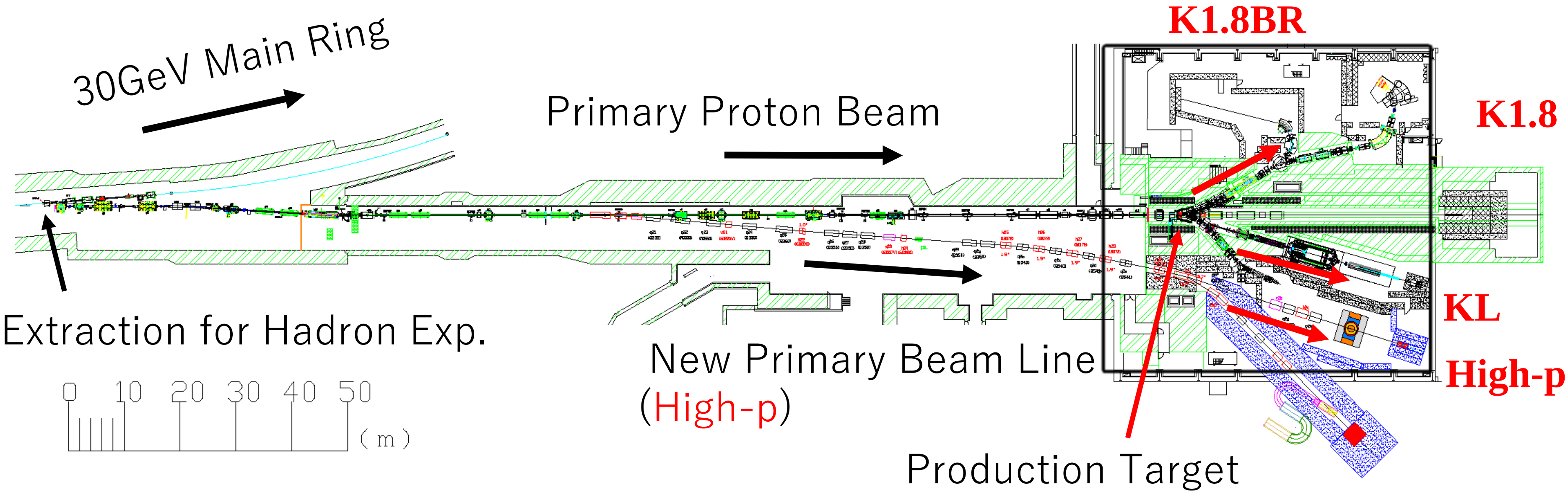
Studies of Finite Density Matter are an exciting frontier in QCD physics

At J-PARC, several studies related to finite-density medium are on-going!!

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

Name	Species	Energy	Intensity
High-p	primary	30GeV	~ 10^{10} Hz
	Unseparated	< 20GeV/c	~ 10^8 Hz

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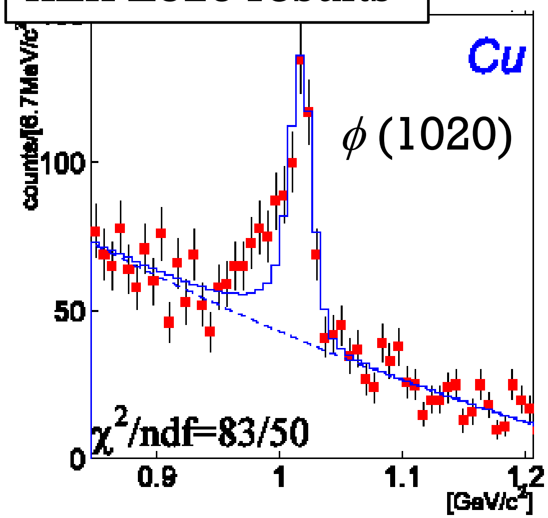
CURRENT J-PARC ACTIVITIES

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

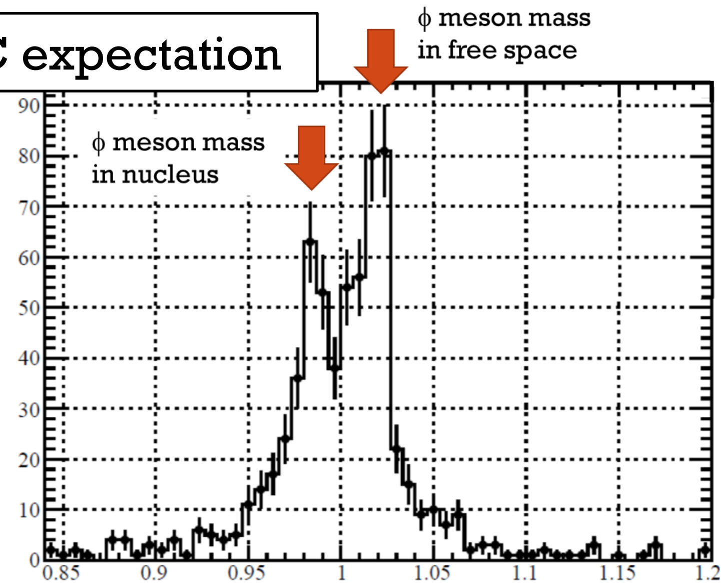
KEK E325 results



e^+e^- invariant mass

High Statistics
Better Resolution

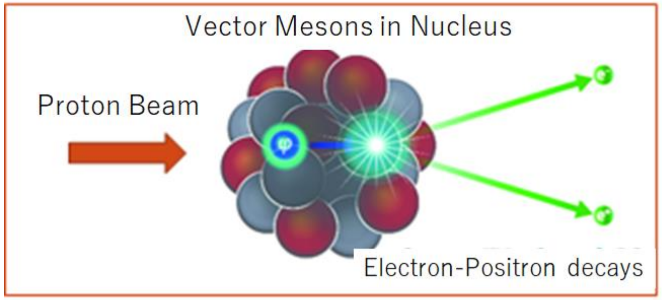
J-PARC expectation

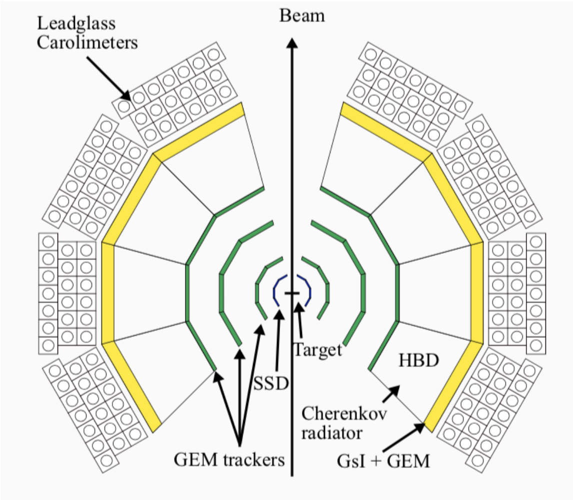


e^+e^- **invariant mass** [GeV/c^2]

J-PARC E16 Experiment

- Measurements of e^+e^- pair invariant mass spectra in nucleus
- 10 times larger statistics compared to the KEK experiment
  - 10^{10} protons per spill (10 times higher than KEK)
  - Counting rate: 5 kHz/mm^2 (maximum)
- Two times better resolution than KEK
  - Larger magnetic field
  - Better Position resolution (~100 μm)



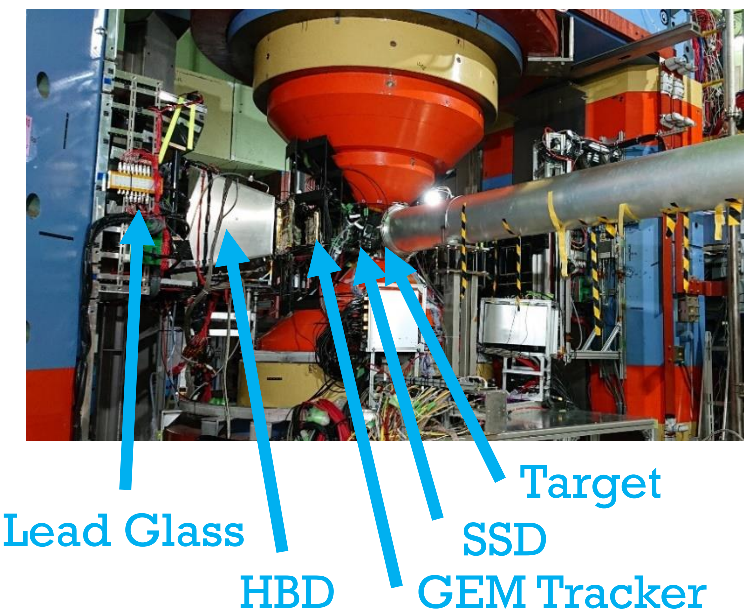


Cross section view of detectors at Beamline Plain

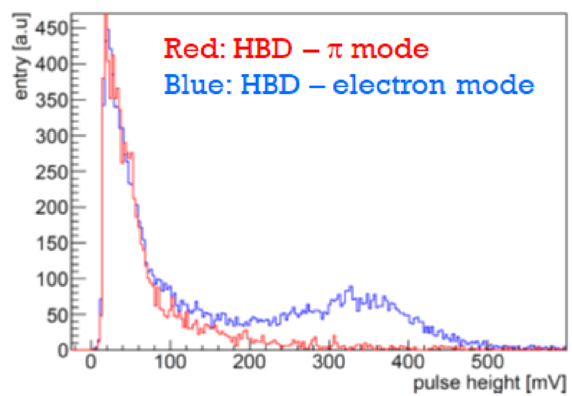
- Tracking Devices
  - Silicon Strip Detector (SSD)
  - 3 Layers of GEM Tracker (GemTR)
- Electron Identification Counters
  - Hadron Blind Detector (HBD)
  - Lead Glass Calorimeter (LG)

STATUS OF THE EXPERIMENT

- First beam: May 24, 2020.
- Commissioning runs: June 2020 and June 2021
  - All detectors, triggers, and DAQ worked well
  - Pilot Data were taken
- Data acquisition for Physics run: December 2022

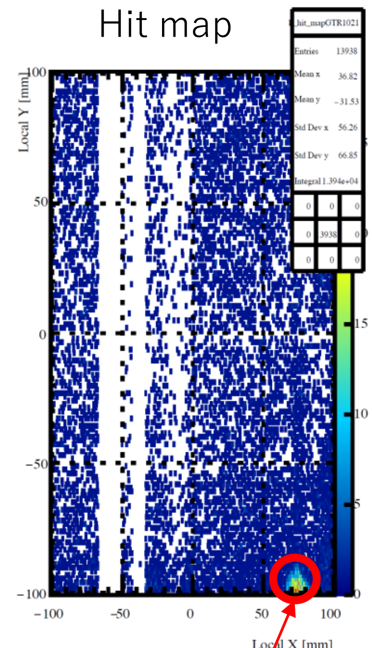


Electron Identification



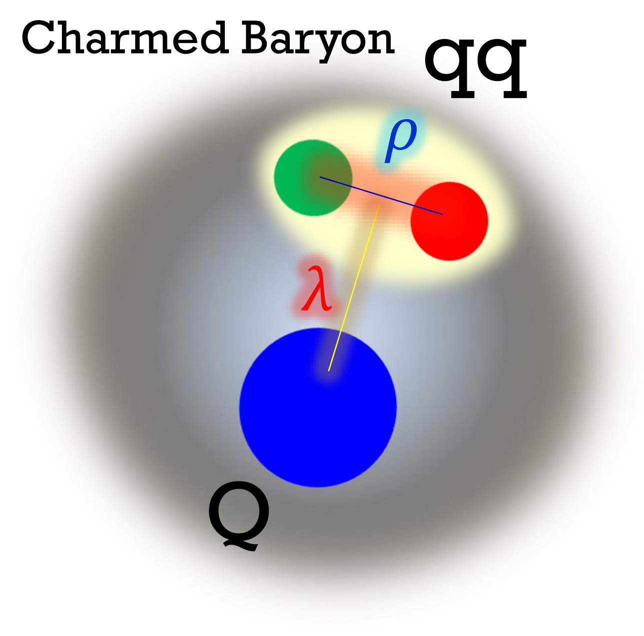
Pulse Hight Distribution of Lead Glass

GEM Tracker
Hit map



Corresponds to a trigger scinti

DI-QUARK CORRELATION AND CHARMED BARYON

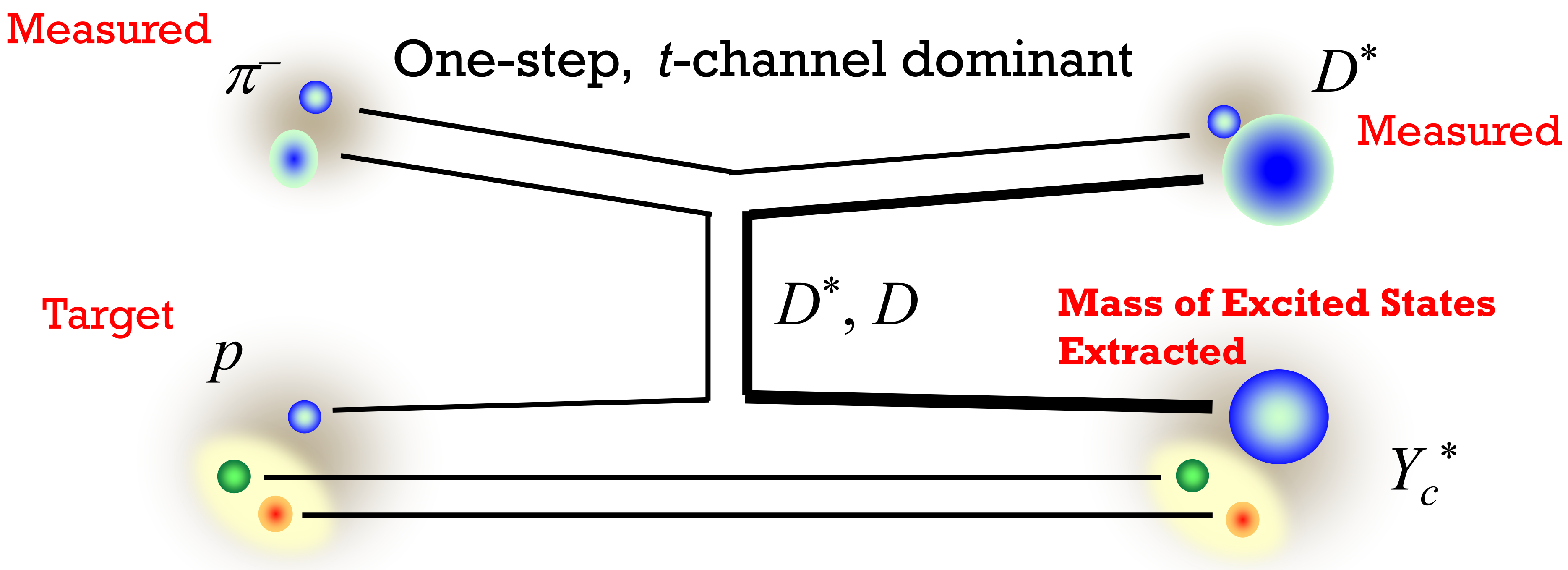


- Di-quark correlation can have an important role in a finite density matter
  - Quark-Quark condensates for color super conducting
- Charmed baryons have unique internal structures and are suitable to study quark-quark correlations
- Excitation states of charmed baryons can be identified as a di-quark motion (λ mode) or single charm quark motion (ρ mode)
- Measurements of excitation states of charmed baryons are important

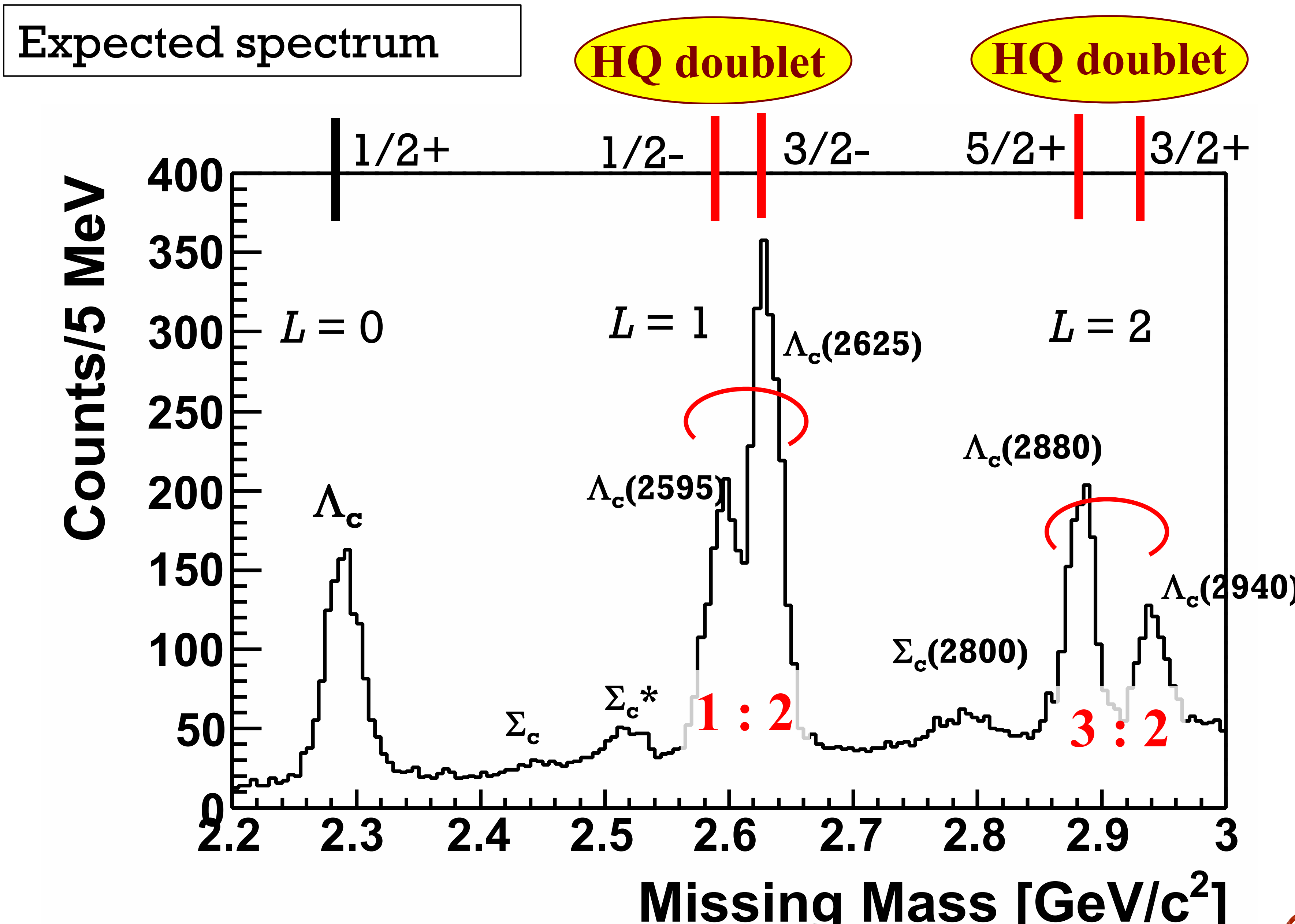
New experiment is proposed to measure the excitation states using a missing mass method. Physics importance of the experiment is already approved.

PROPOSED EXPERIMENT

S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori, PTEP 10, 103D01 (2014)



- ✓ Measurements of π^- beam and forward emitted D^*
  - ✓ Missing mass techniques to identify Charmed Baryon mass
  - ✓ Decay products are also detected to obtain further information

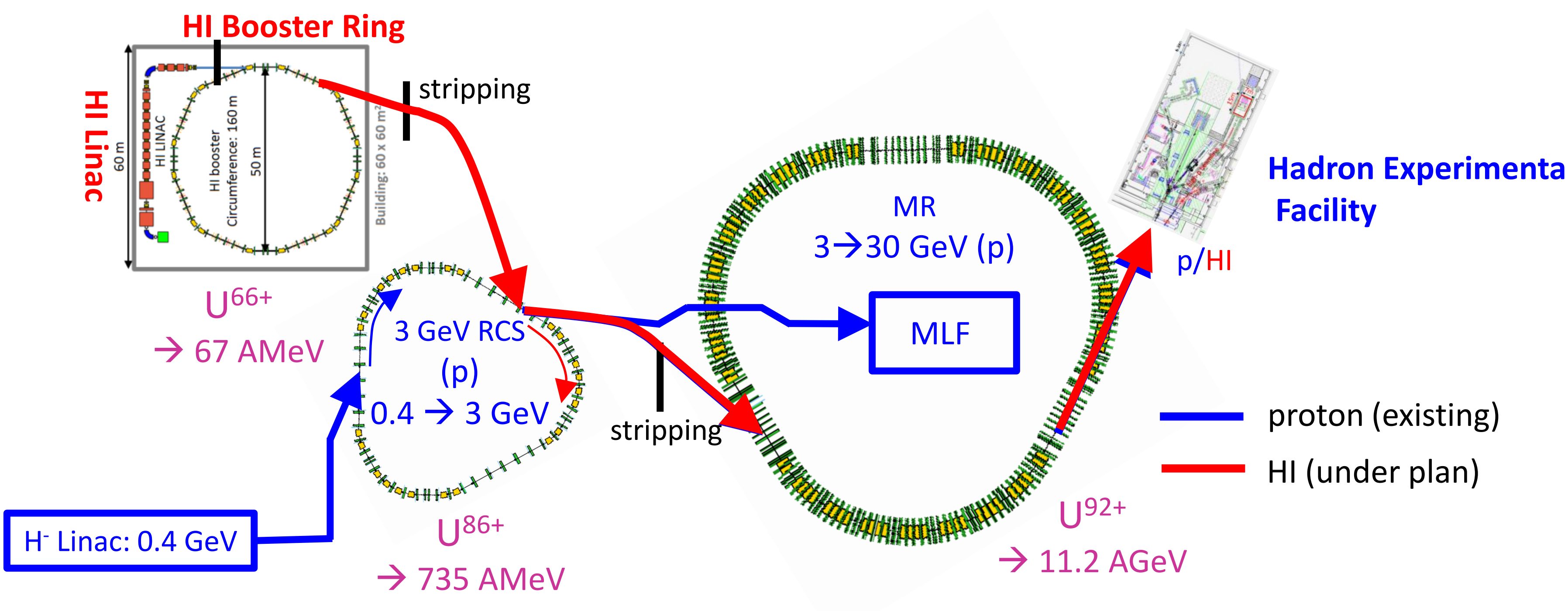

Expected spectrum
HQ doublet
HQ doublet
1/2+
1/2-
3/2-
5/2+
3/2+
L = 0
L = 1
L = 2
Λc
Σc
Σc*
Λc(2595)
Λc(2625)
1 : 2
Σc(2800)
Λc(2880)
Λc(2940)
3 : 2
Counts/5 MeV
Missing Mass [GeV/c²]
0
50
100
150
200
250
300
350
400
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3

13 HEAVY ION PROJECTS

HI ACCELERATION SCHEME AT J-PARC

Proton beam rate (slow extraction)
- 5.5×10^{13}/cycle (currently)
- 1.2×10^{14}/cycle (2022)

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

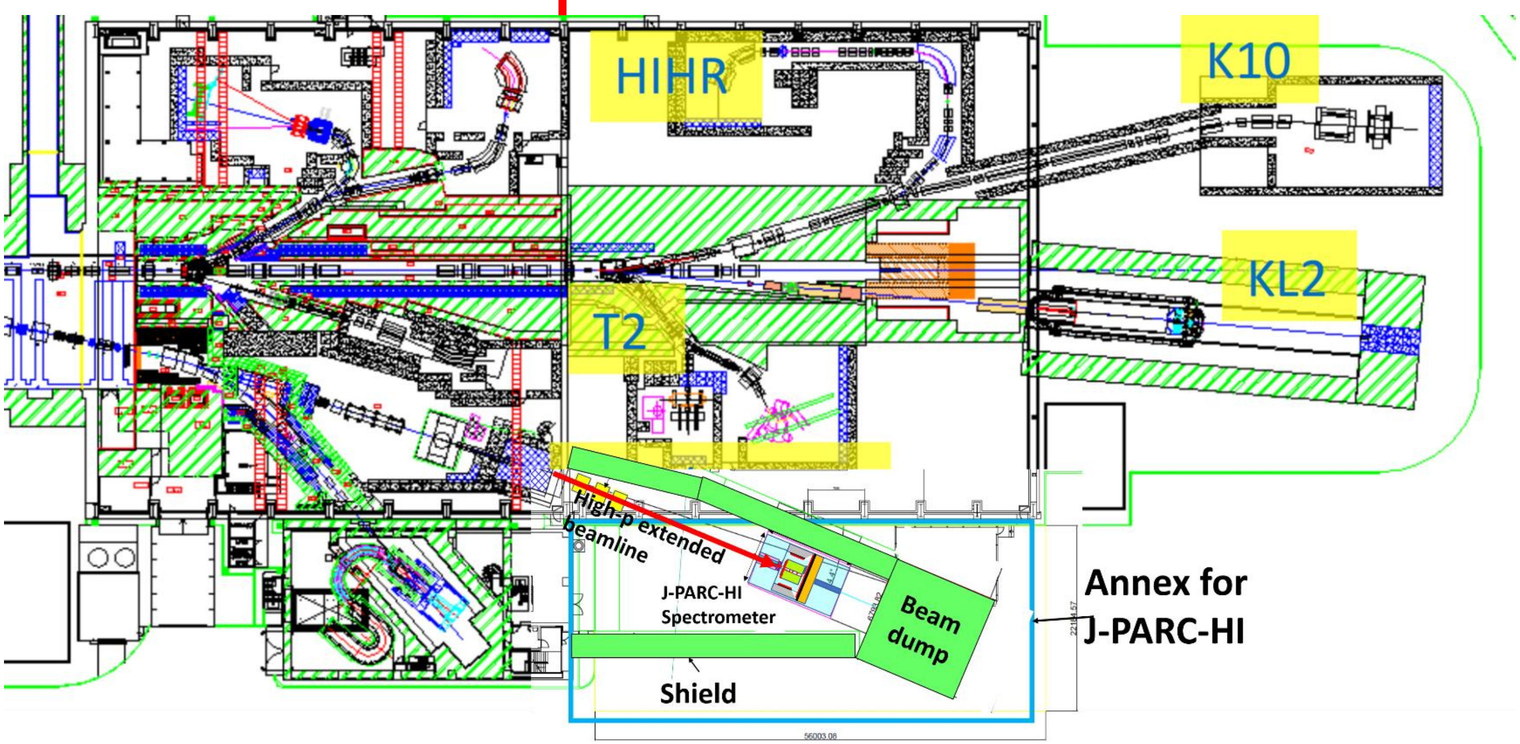


UPGRADES OF THE EXPERIMENTAL FACILITY

Current Experimental Hall

Upgrade Plan of the Experimental Hall

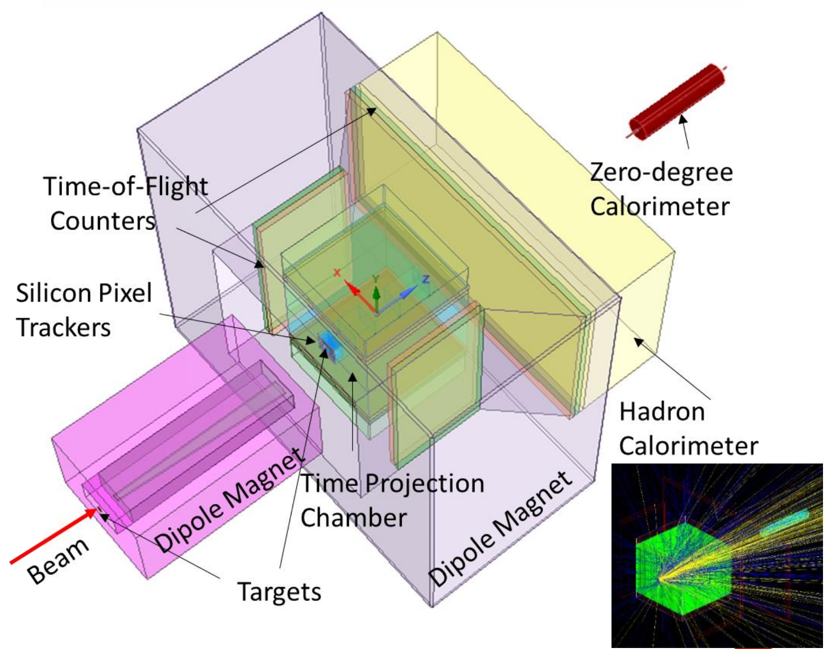
New Production target & New beamlines



SPECTROMETER

- High-intensity beam achievable by J-PARC
- Large acceptance and low p_T tracking detector concept with multi-dimentional event selectivity aiming at precision measurements of **fluctuations, dileptons, charmed hadrons, etc.**
  - Detector concepts are still under discussion and it should be a complement to FAIR-CBM from physics point of view

- Three configurations are planned
  - Hadron Spectrometer
    - Dipole + TPC
    - Large Acceptance for Correlations, Fluctuations
  - Di-muon Spectrometer
    - Dipole + GEM Tracker
    - Large Acceptance for rare probes
  - Hyper-nuclei Spectrometer
    - Closed configuration



EXPECTED DIMUON SPECTRUM

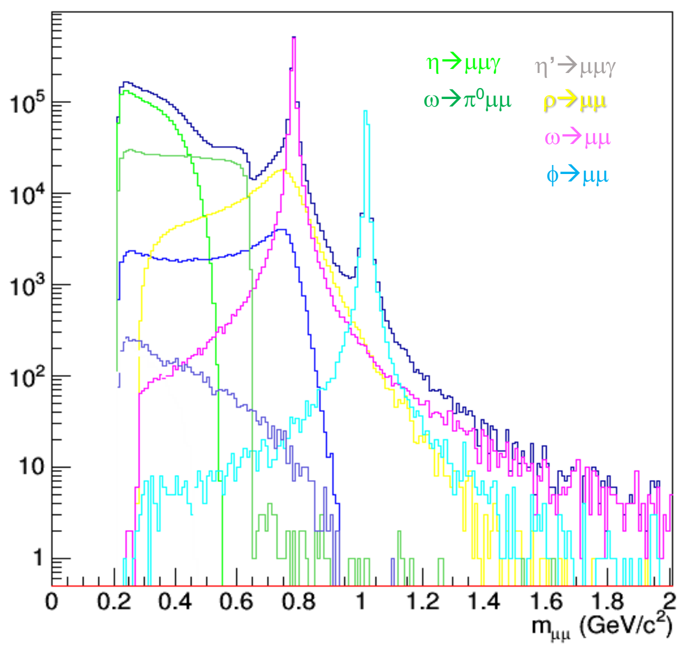
We have evaluated performance of our dimuon spectrometer

- 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 λ_I muon absorbers

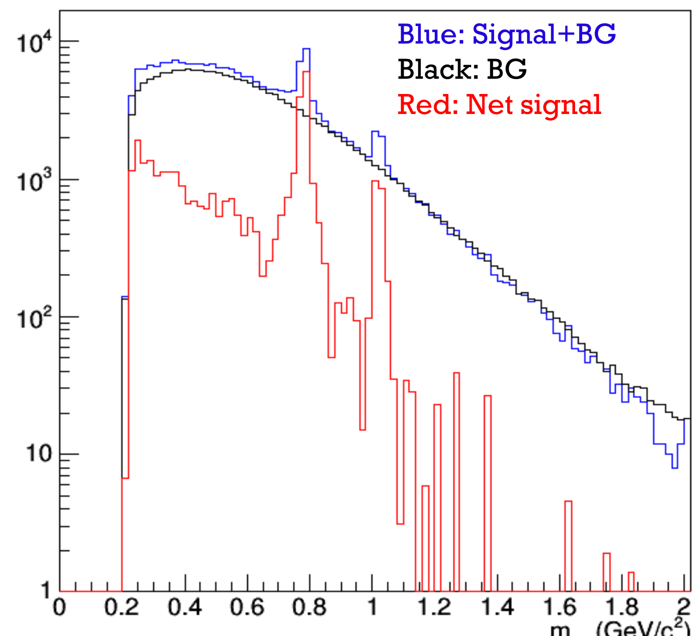
$\theta_{ee}>2°$, $2°<\theta<80°$, $p_T>0.1$GeV/c

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

Generated cocktail



Reconstructed spectrum



Enough Resolution even in low mass region

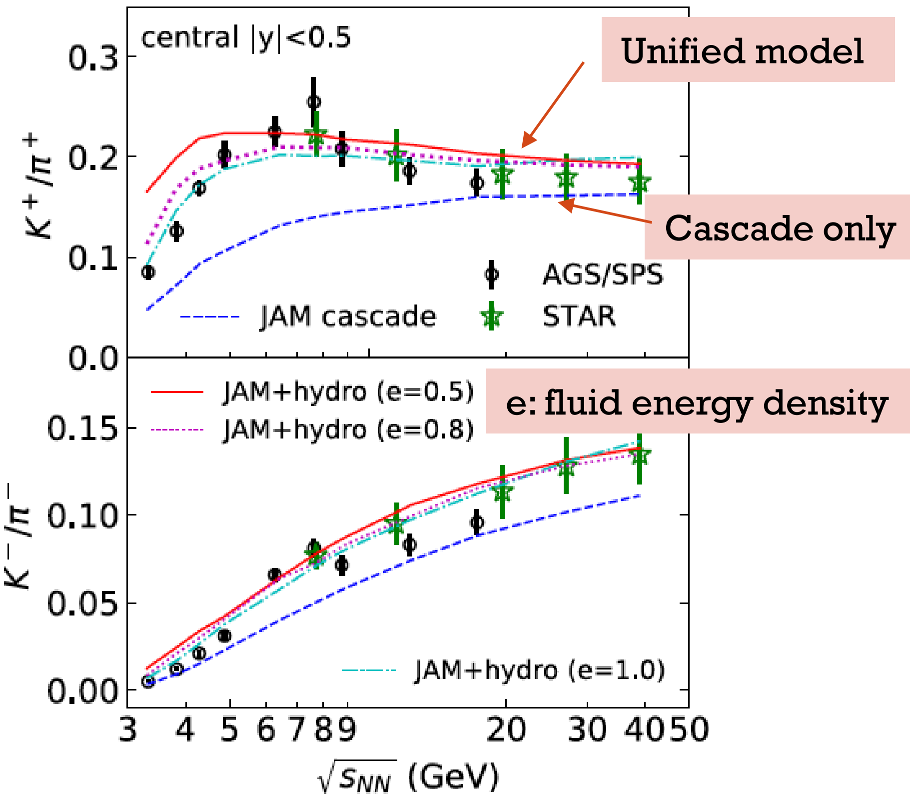
DEVELOPMENTS OF FURTHER OBSERVABLES

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

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

- 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

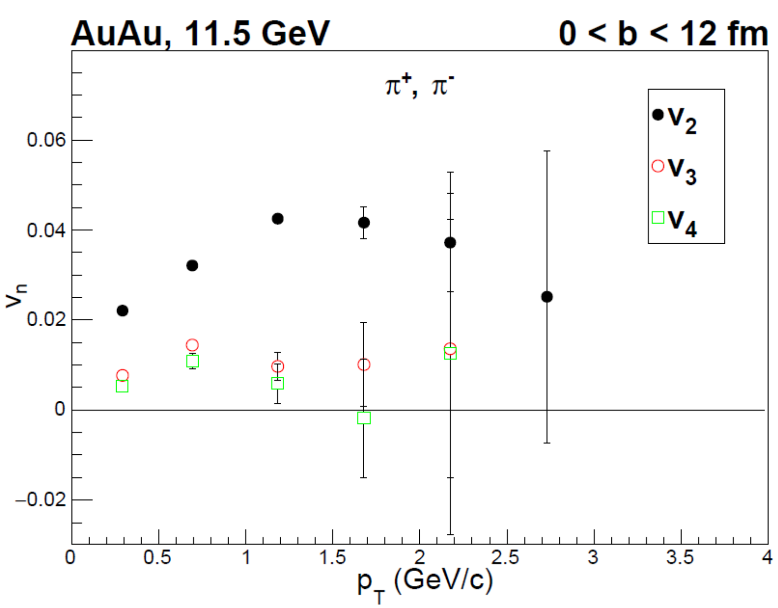
Akamatsu, et.al, PRC**98**, 024909 (2018)



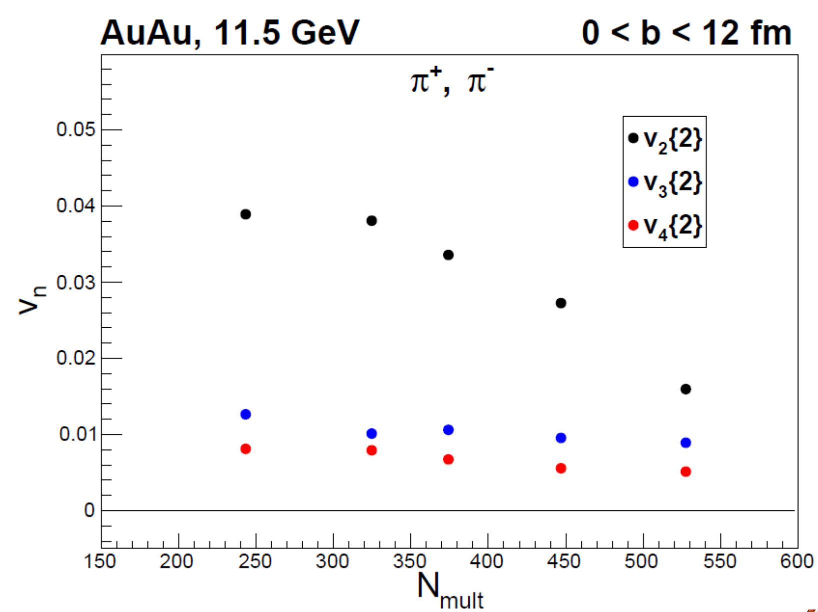
FLOW MEASUREMENTS

- 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)



STAGING APPROACH

- Required Upgrades for J-PARC Heavy Ion
  - Injector and Booster
  - Experimental area
  - Spectrometer

- It is hard to realize them in a reasonable time and we are discussing a staging approach
  - First, Minimum upgrades
  - Then, Full upgrades

MINIMUM UPGRADES (ACC. PART)

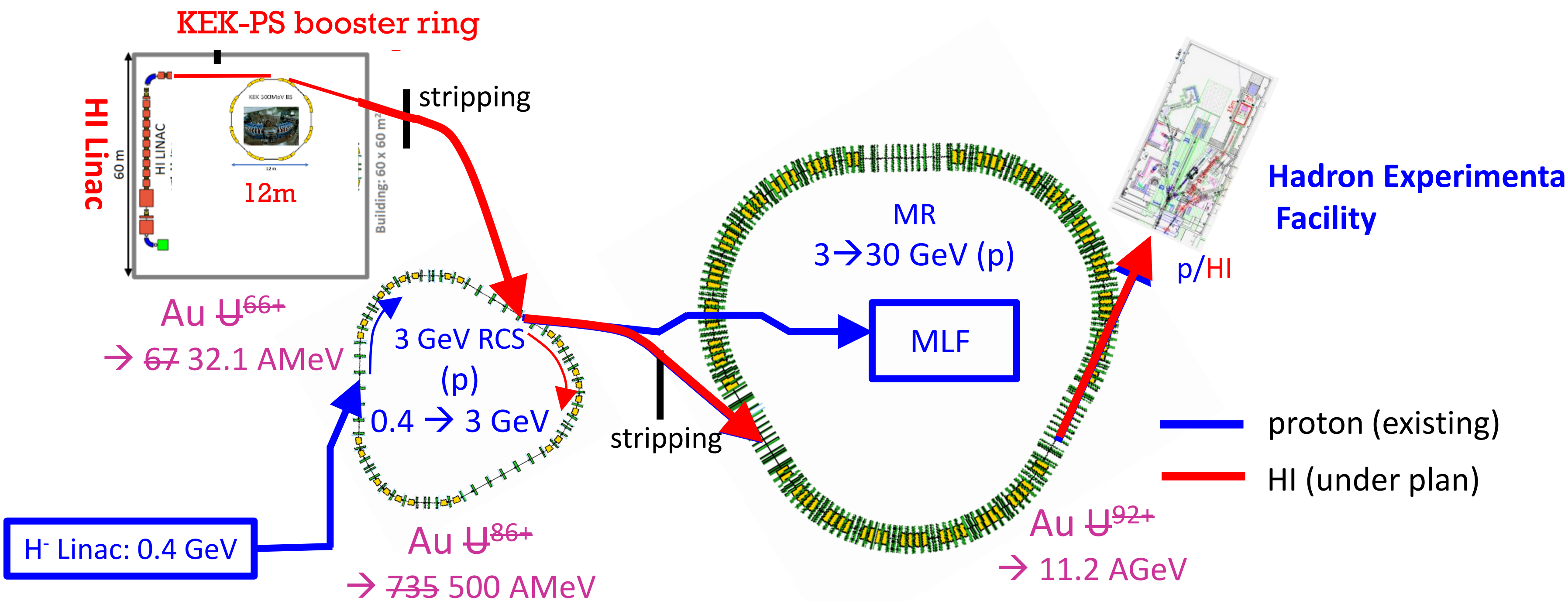
Heavy Ion LINAC

- 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)

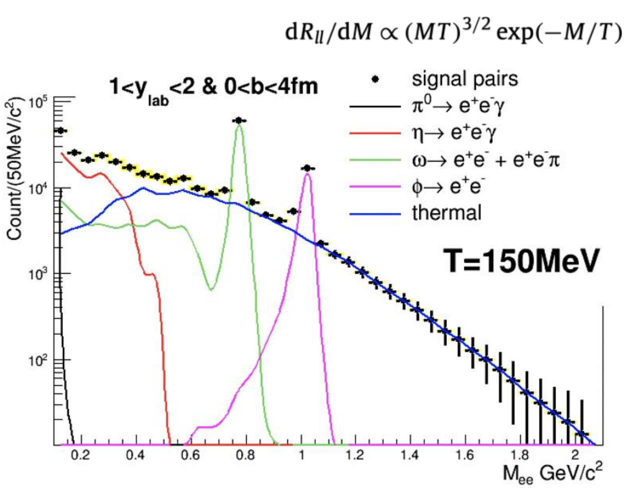
- HI beam rate ~$10^{\cancel{11}8}$ Hz
- E_{lab} (U) = 1-12 AGeV
- $\sqrt{s_{NN}}$ (U) = 1.9-4.9 GeV



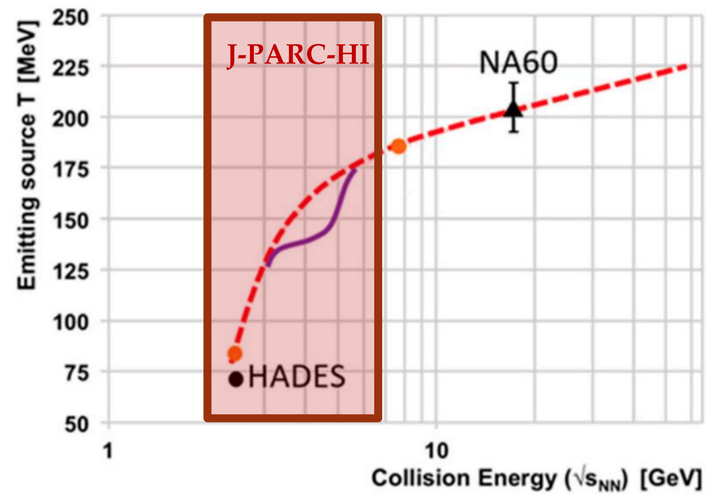
Intensity is limited by KEK-BS, which is a small ring and no flexible optics. Space charge effect is at a negligible level because the beam intensity is 10^{-3} lower than that of proton beam at present.

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

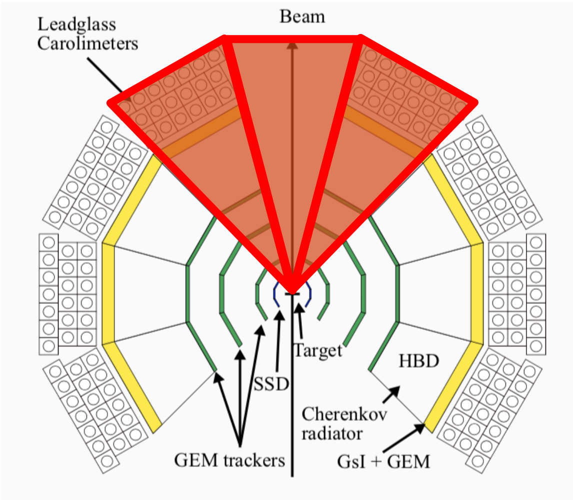


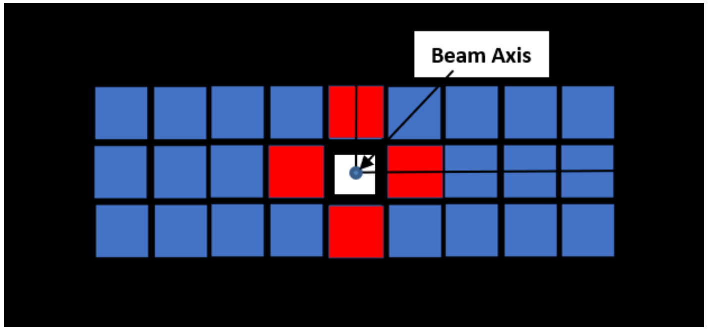
Energy Scan



REQUIRED UPGRADES OF THE SPECTROMETER

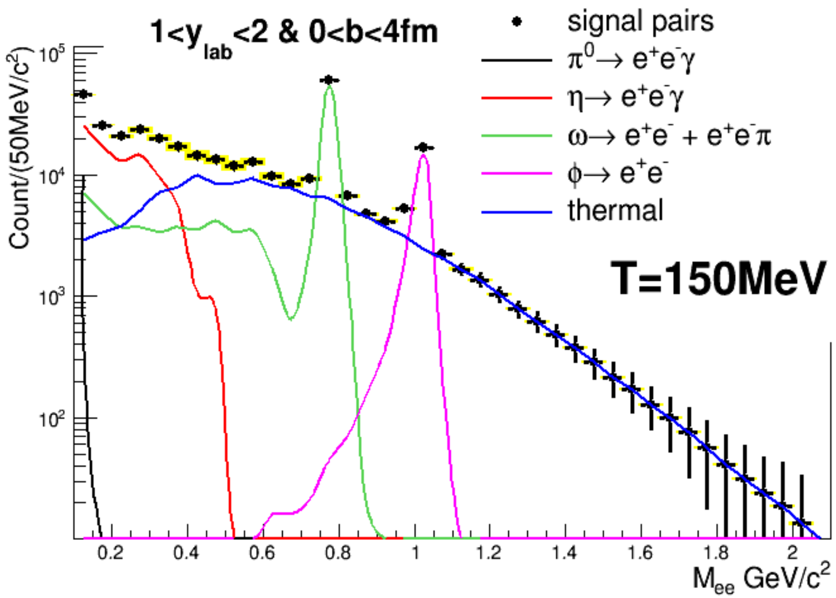
- The most forward modules should be upgraded to cope with a high hit-multiplicity environment
  - Hit occupancy should be reduced and finer segments are required
- Tracking device
  - The most inner GEM Trackers must be upgraded and replaced with SSDs
- Electron identification detectors
  - Lead glass 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

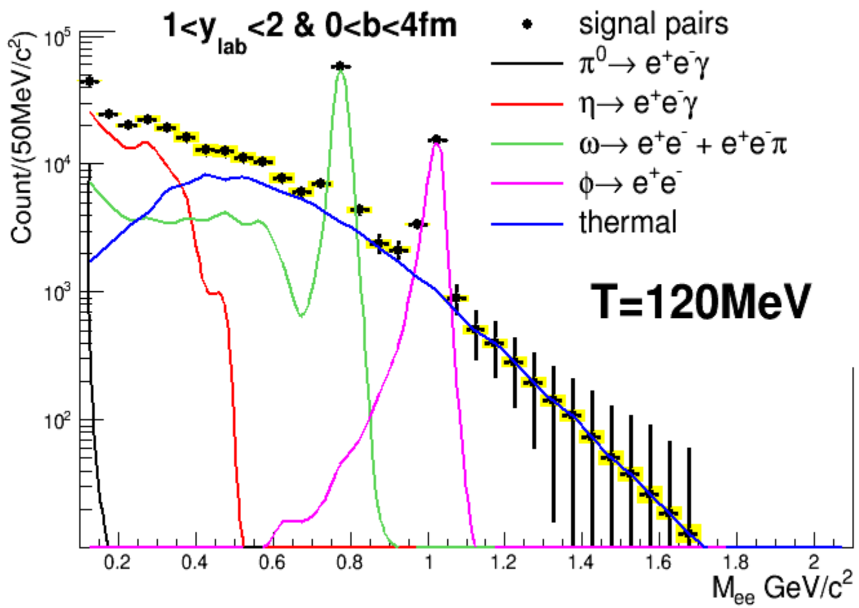




EXPECTED MASS DISTRIBUTIONS

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)

SUMMARY AND OUTLOOK

- Several studies related with finite density matter is on-going at J-PARC
  - Vector mesons in nucleus
  - Di-quark correlation in charmed baryons
- Future Heavy ion program at J-PARC is being prepared
  - We need Linac and Booster for heavy ion acceleration
  - 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.
- Outlook
  - Good News : The J-PARC heavy ion project is scheduled on the "J-PARC Calendar" !!
    - Bad News: Under the current budget situation, (even) the minimum upgrades will be completed in 2029 (at earliest)…
      - The main upgrade plan of J-PARC is an extension of the hadron hall facility
  - Detailed detector configurations for the final design will be determined in a year
    - Your comments are very welcome!

J-PARC-HI COLLABORATION

103 members :

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment

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

Theory

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

Accelerator

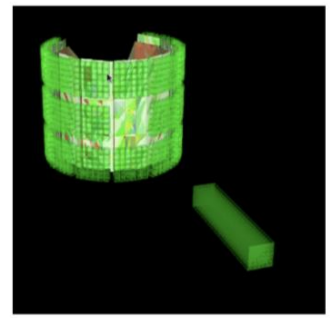
H. Harada, P. K. Saha, M. Kinsho, Y. Liu, J. Tamura, Y. Kondo, K. Moriya, T. Nakanoya, T. Takayanagi, K. Shindo, A. Miura, K. Suganuma, H. Kuboki, M. Yoshii, M. Okamura, A. Kovalenko, J. Kamiya, H. Hotchi, A. Okabe, F. Tamura, Y. Shobuda, N. Tani, Y. Watanabe, M. Yamamoto, M. Yoshimoto

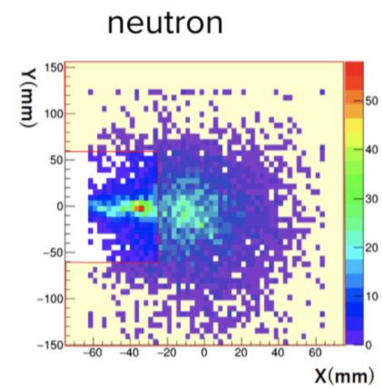
ASRC/JAEA, J-PARC/JAEA, J-PARC/KEK, Tokyo Inst. Tech, Hiroshima U, Osaka U, U Tsukuba, Tsukuba U Tech, CNS, U Tokyo, Tohoku U, Nagasaki IAS, Kyoto U, RIKEN, Akita International U, Nagoya U, Sophia U, U Tokyo, YITP/Kyoto U, Nara Women's U, KEK, BNL, Mainz U, GSI, Central China Normal U, Korea U, Chonbuk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

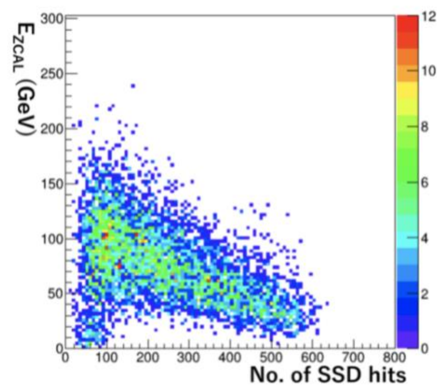
Back up

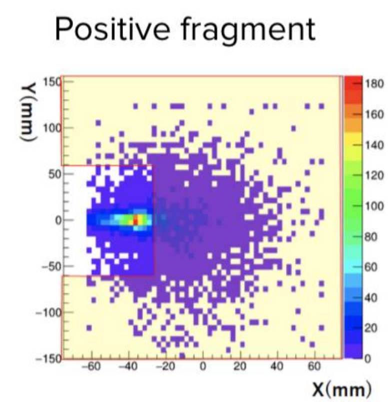
E16 UPGRADE: ZERO DEGREE CALORIMETER

- 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



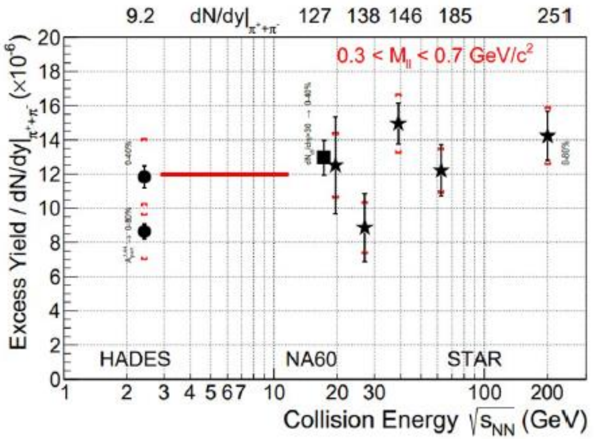






FEASIBILITY STUDIES : INPUTS

- Thermal dielectrons



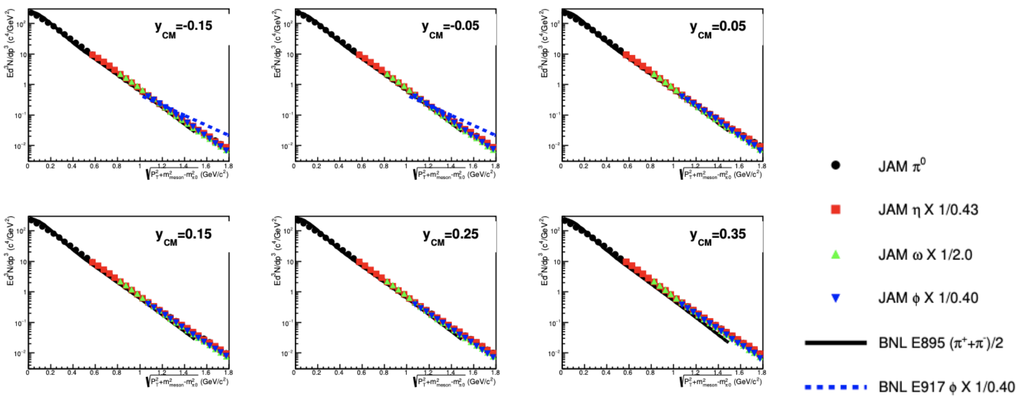
- dN_{ee}/dy ($0.3<M_{ee}<0.7$ GeV/c^2) = 1.2×10^{-5} x $dN_{\pi+-}/dy$ (105)
- $dN_{ee}/dM \propto (MT)^{3/2} \exp(-M/T)$
- $dN_{ee}/dPt \propto \exp(-Pt/T)$

Two cases studied

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

- Dielectrons from hadronic decays

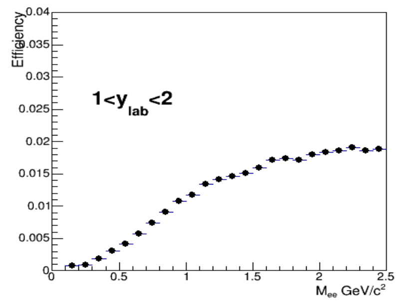
JAM event generator for Au+Au at 10 A GeV/c

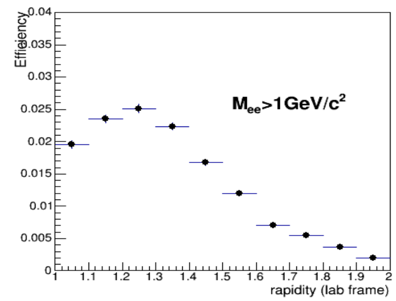


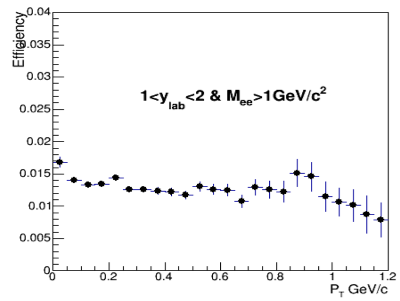
- Dielectron pairs are transported into GEANT4 simulation
- Full E16 acceptance & E16 achieved eID capability considered
- Tracking inefficiency due to high multiplicity effects taken into account

EFFICIENCIES AND RAW MASS DITRIBUTIONS

- Pair Efficiencies
  - Multiplicity effects not included

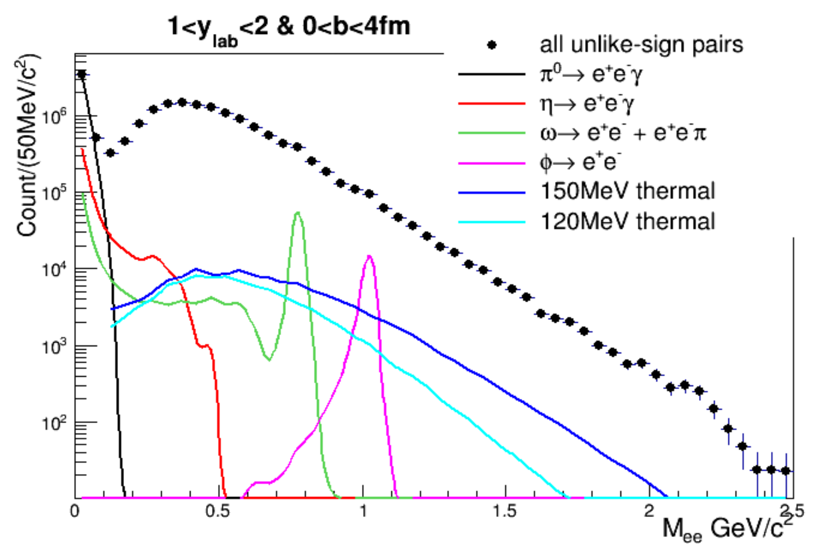






- Raw Mass Distributions
  - Thermal photons
  - known resonance decay $\pi^0 \rightarrow ee\gamma$, $\eta \rightarrow ee\gamma$, etc..
  - γ conversion in the target
  - miss ID π^{+-}
  - Combinatorial pairs

1×10^8/spill 10 AGeV Au beam x 100 days run
0.035 mm Au target(∼0.1% int. length)



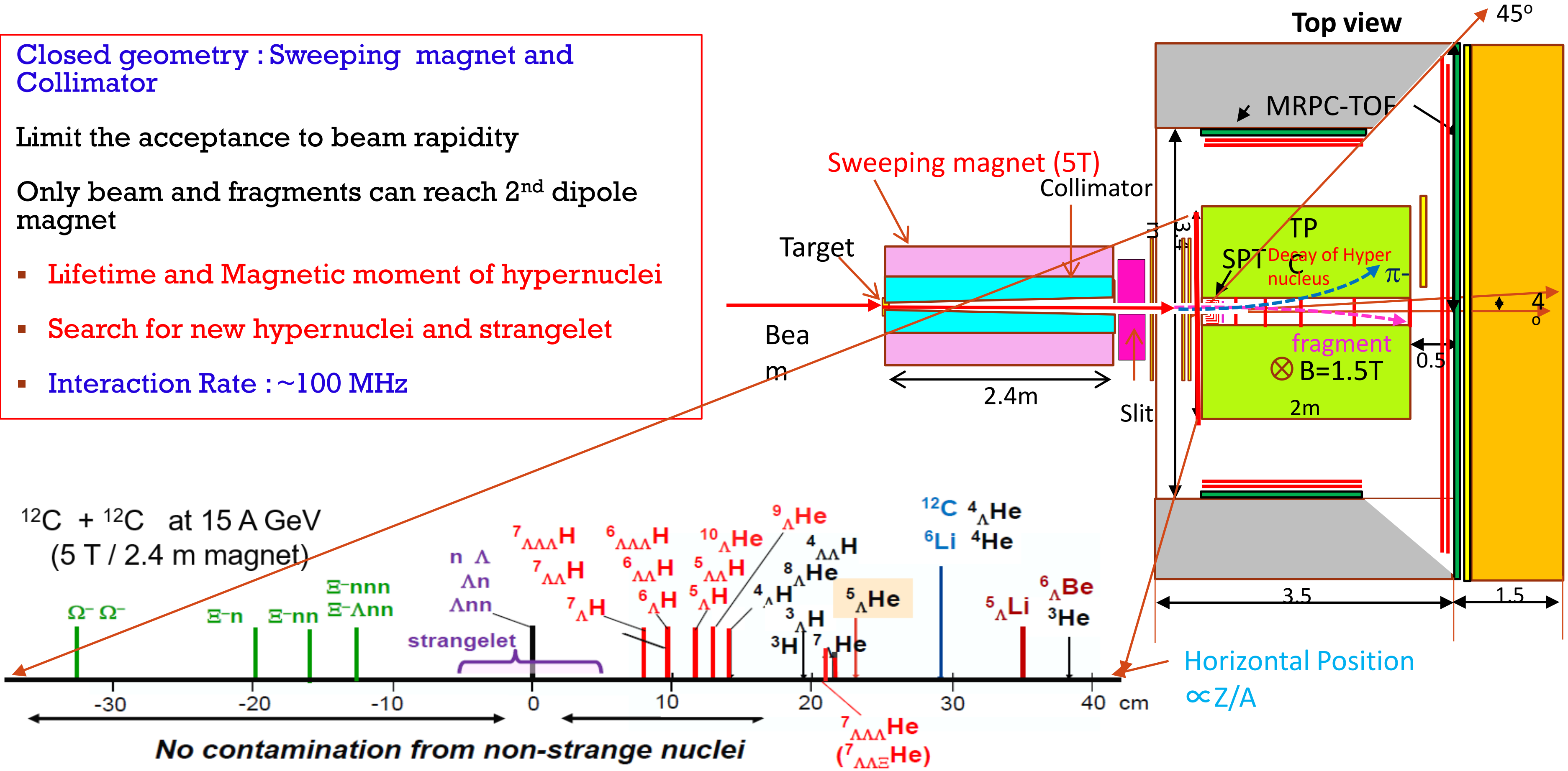
HYPERNUCLEAR SETUP

Closed geometry : Sweeping magnet and Collimator

Limit the acceptance to beam rapidity

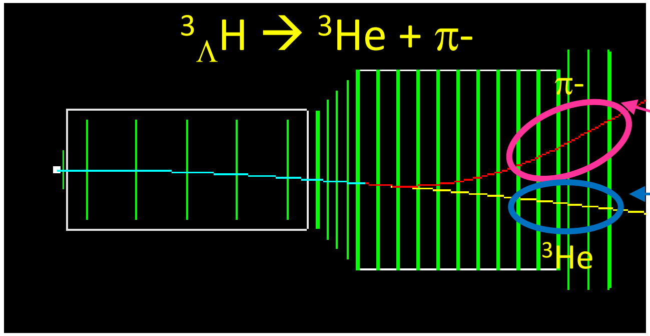
Only beam and fragments can reach 2nd dipole magnet

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



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

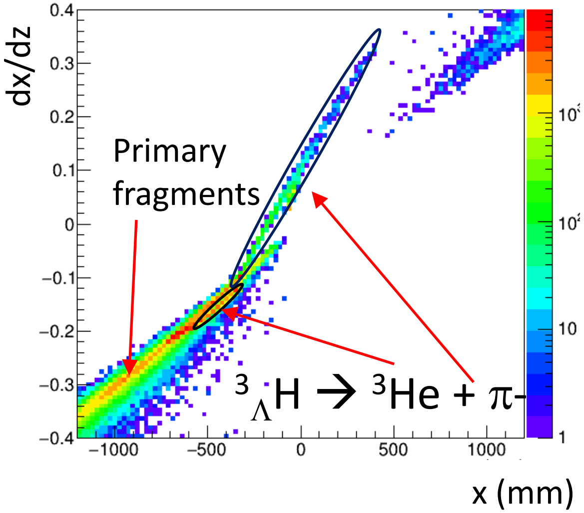
SIMULATION OF HYPERNUCLEAR MEASUREMENT



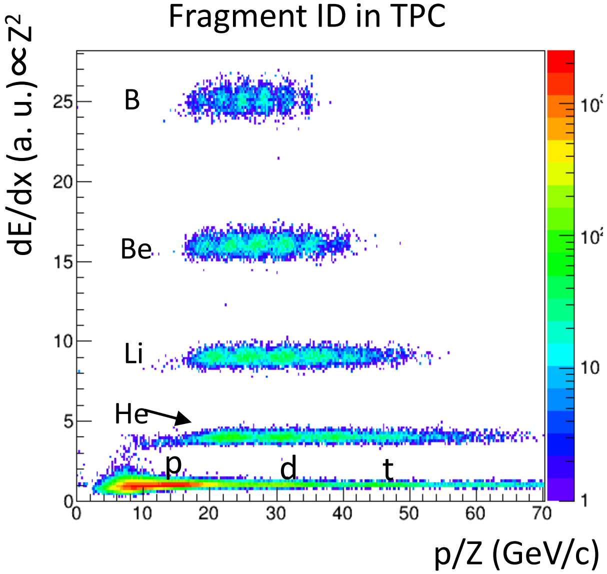
$^{3}_{\Lambda}$H embedded in JAM C+C events

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

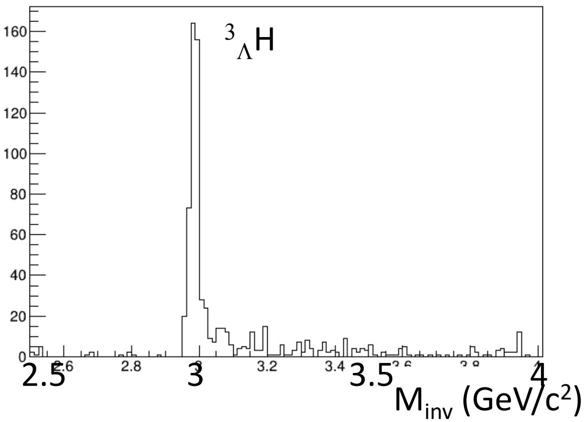
Horizontal position vs angle



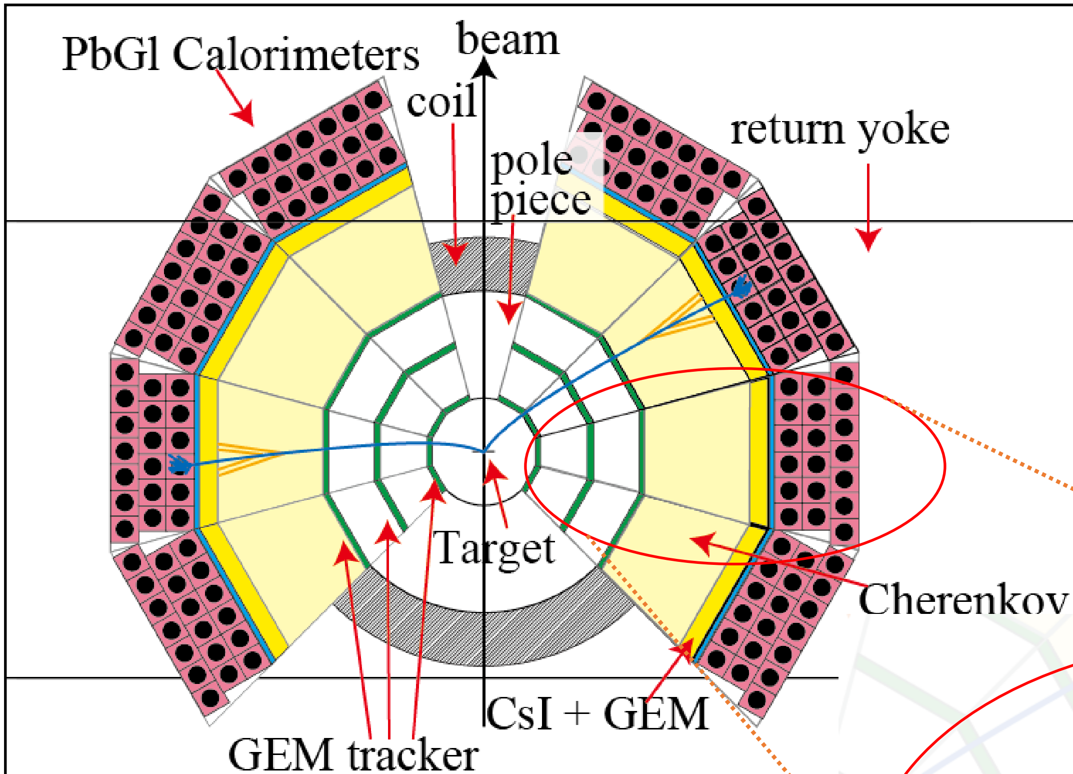
Fragment ID in TPC

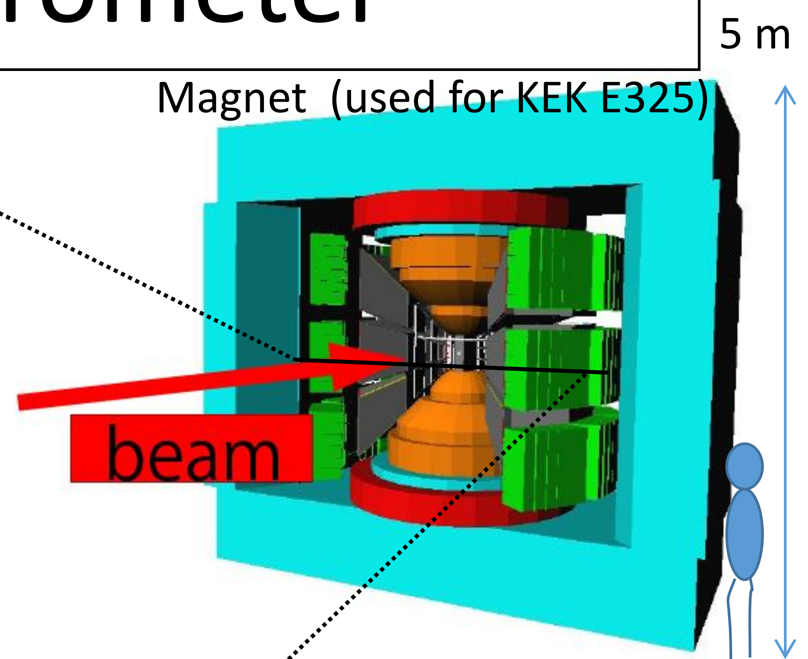


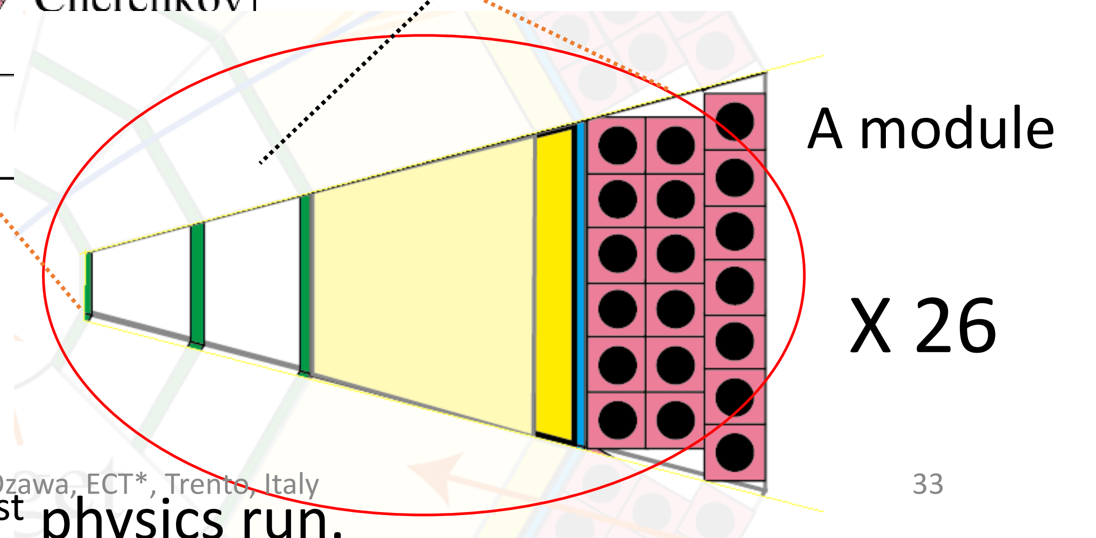
Reconstructed π- ^{3}He invariant mass



The J-PARC E16 spectrometer







SSD : Tracking

GTR : Tracking

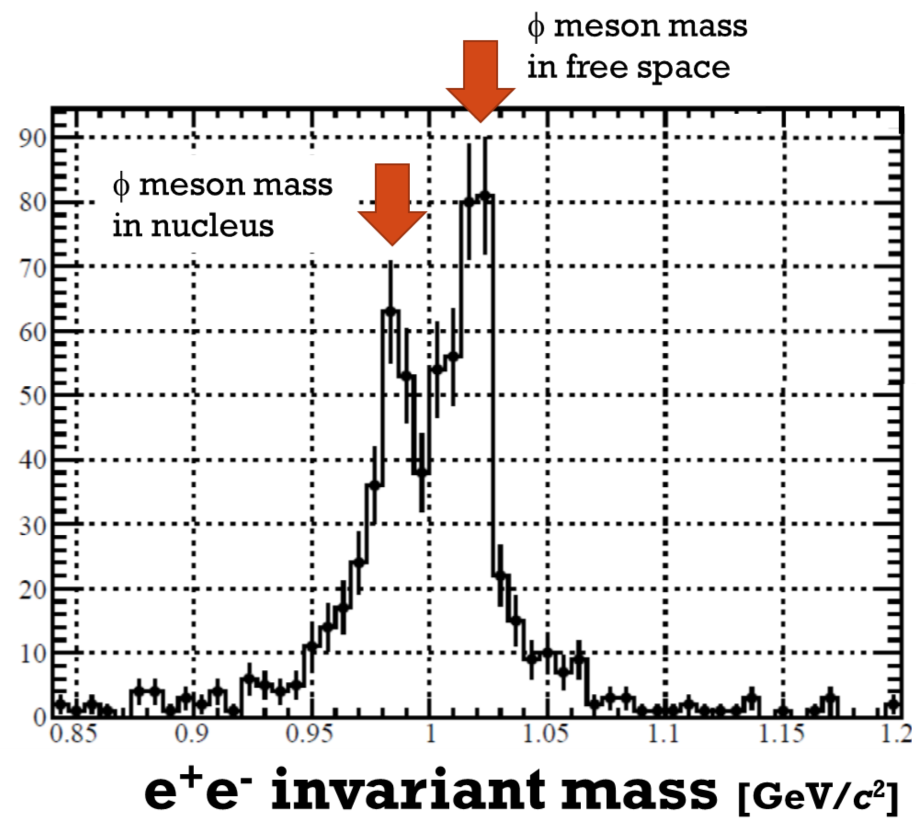
HBD : eID (Cherenkov)

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

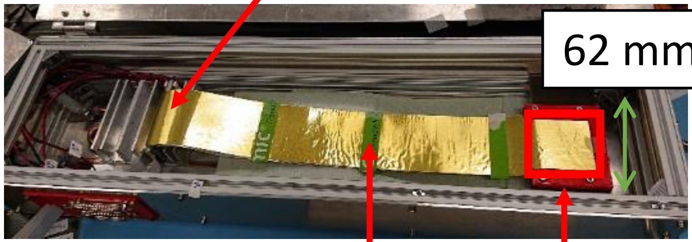


Expected Mass spectrum

Silicon Strip Detector

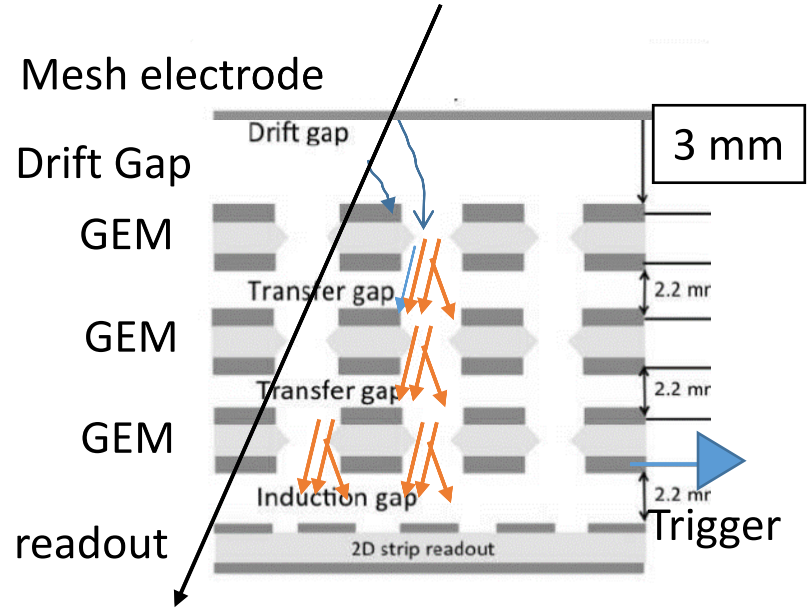
- Run0
  - Existing 6 SSDs used for another J-PARC experiment.
    - ATLAS sensor
    - Sensitive area: 61 mm x 62mm
    - Strip pitch 80 um. (1D)
    - Timing Resolution 4ns
    - It has large unwanted frame.
    - The readout ASIC is APV-25

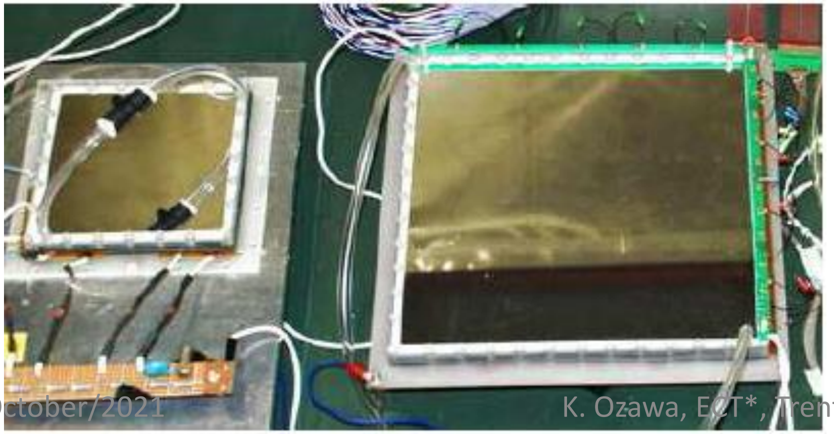
- Run1
  - Starting collaboration with FAIR-CBM
    - CBM developed sensor
    - Sensitive area: 60 mm x 60 mm
    - Strip pitch 50um (Double sides)
    - Almost no frame
    - The readout ASIC is a CBM special chip
      - Developed for the streaming DAQ, however it can be used for a triggered DAQ

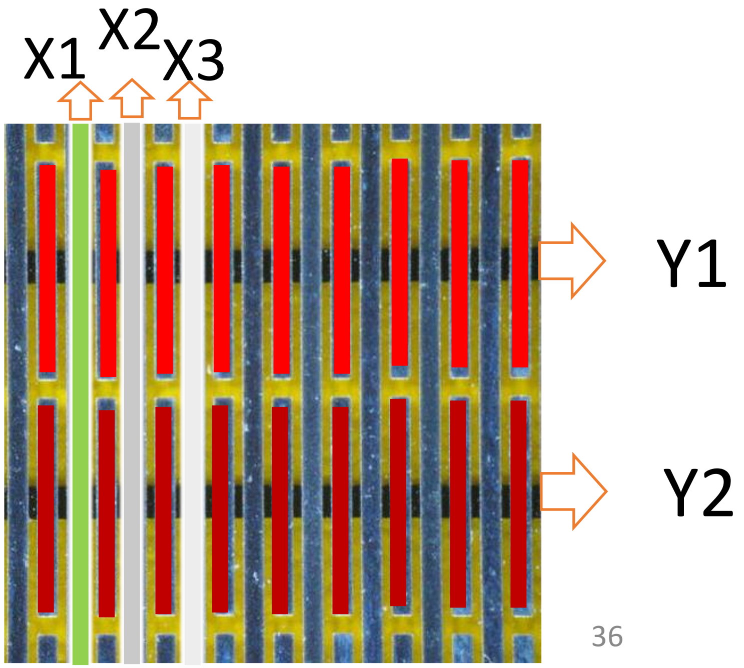


GTR (GEM Tracker)

- Ionization electrons in the drift gap are collected and amplified by GEMs.
- Charge collected on to 2D strip readout.
    - X: 350um pitch
        - Sensitive to bending direction.
        - 100 um resolution required.
    - Y: 1400um pitch
- Assembly works are on-going.

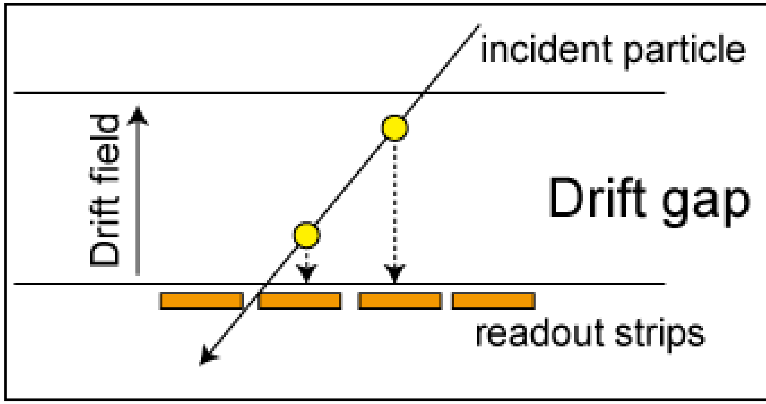






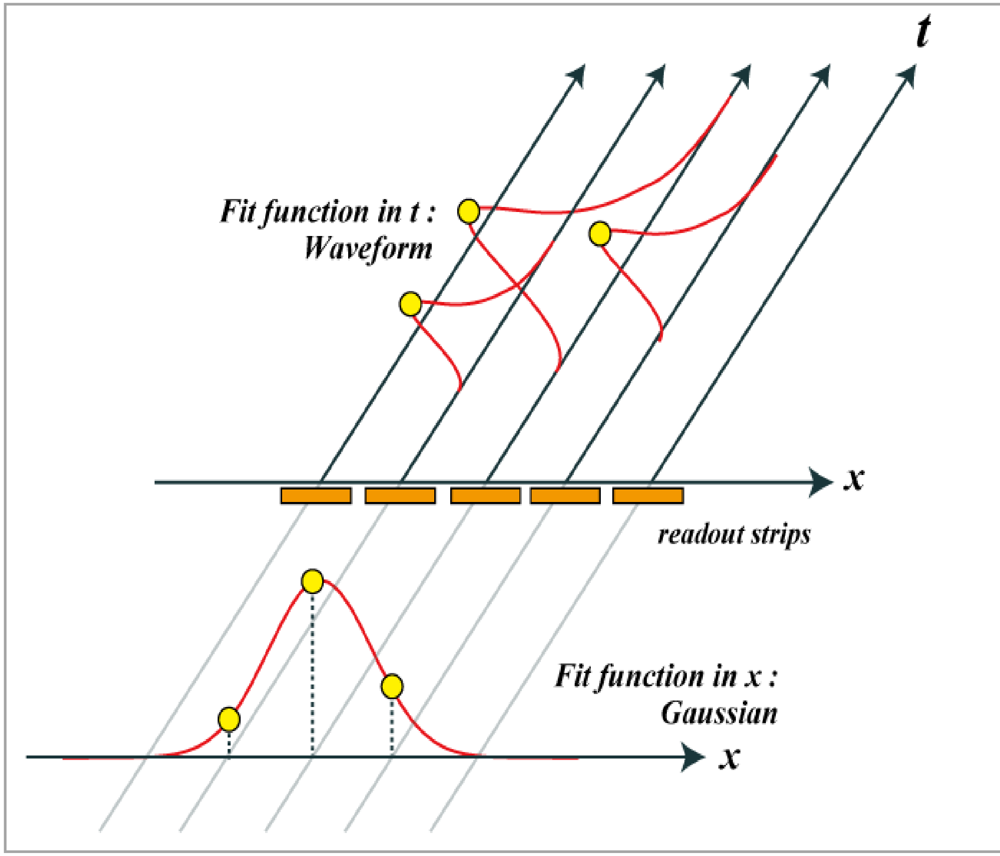
GTR Performance

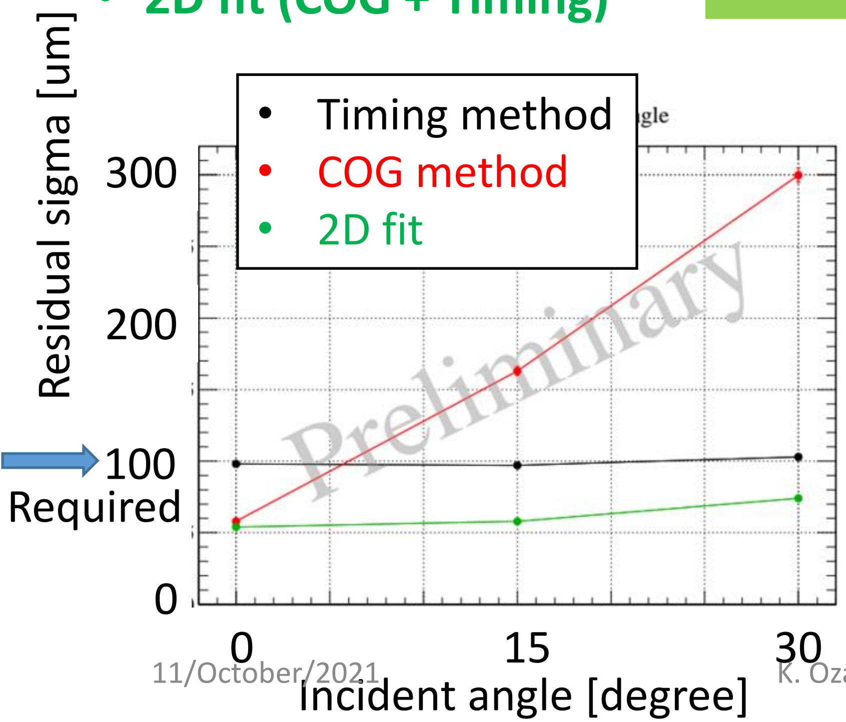
- Center Of Gravity (COG) Method
  - Ordinal analysis method
  - ~ 60 μm @ 0 degree of incident angle
  - Worse results for inclined tracks



- Timing method
  - Distance in drift field dir. Can be obtained using flight time like mini-TPC
  - ~ 100 μm for all tracks

- **2D fit (COG + Timing)**

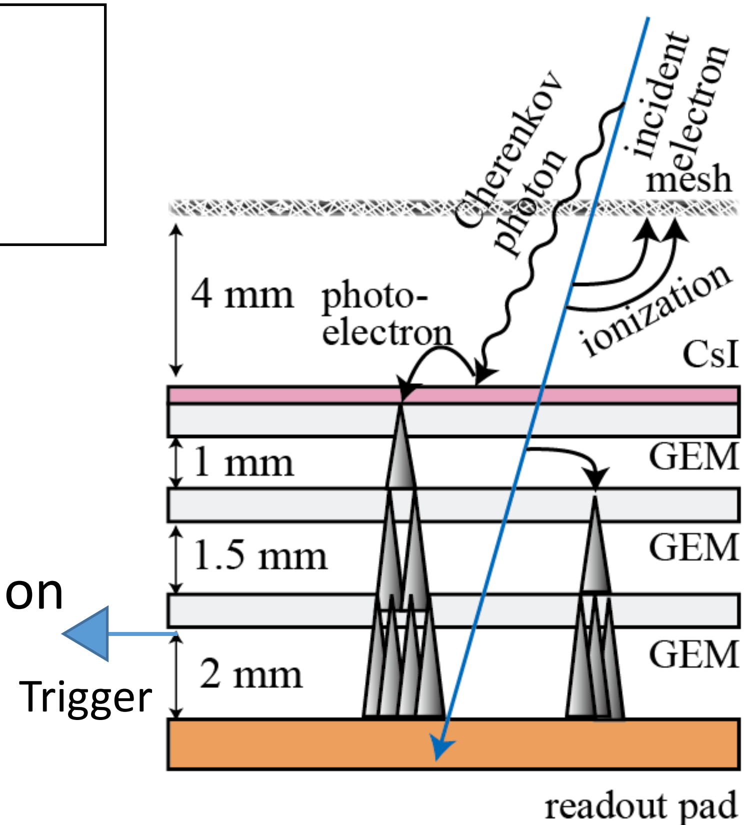


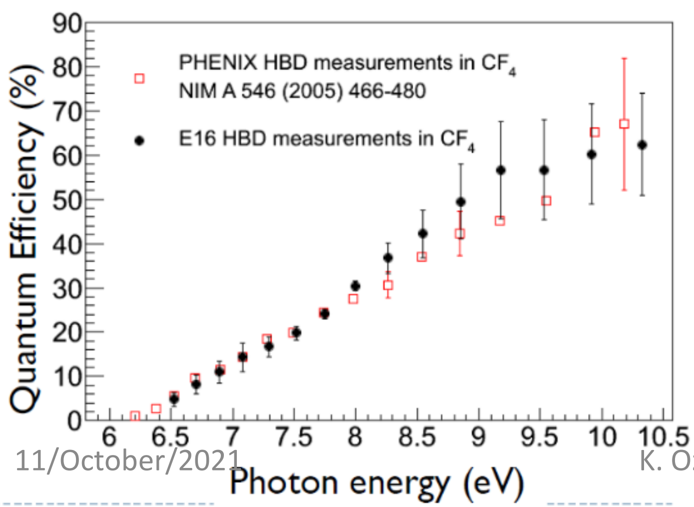


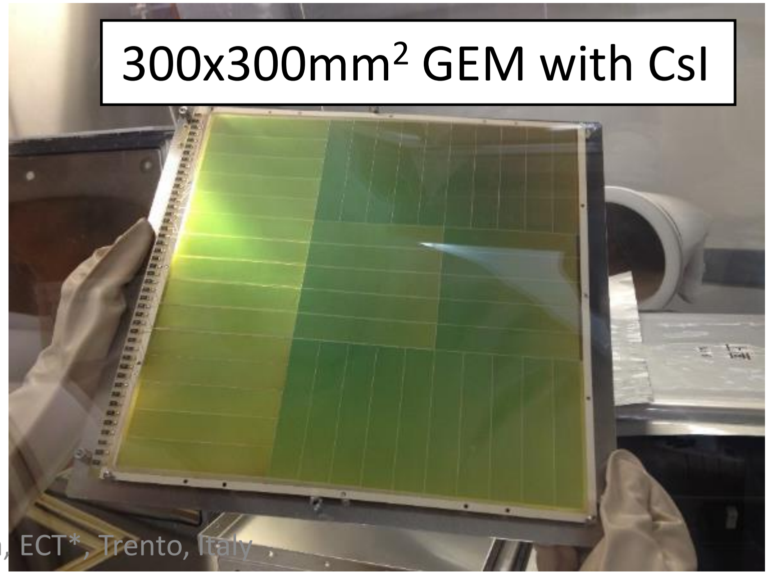
HBD
(Hadron Blind Detector)

- Based on PHENIX HBD.
- CF4 serves as radiator and amplification gas
  - Radiator 50 cm. / p.e. ~ 11

- Gas Electron Multiplier (**GEM**) for amplification
- **CsI** is evaporated on top GEM
  - Photocathode (> ~6eV)



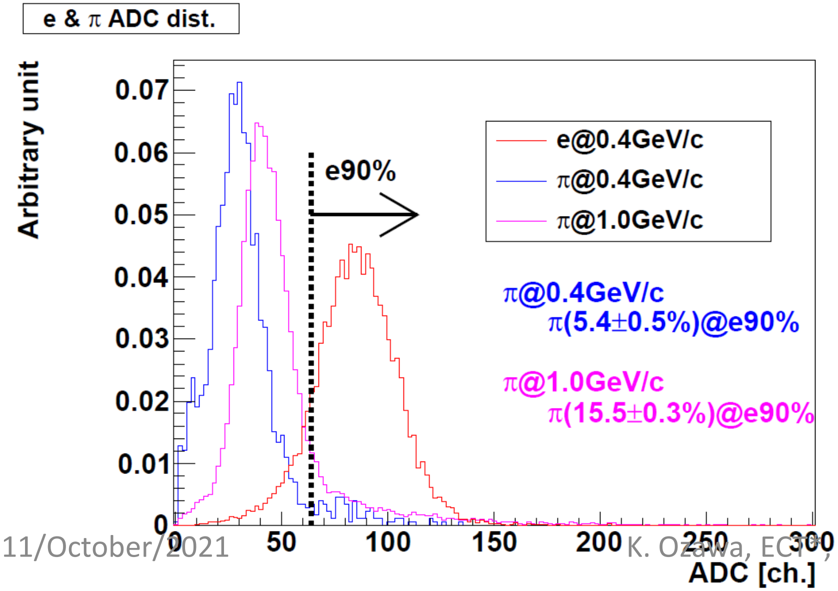


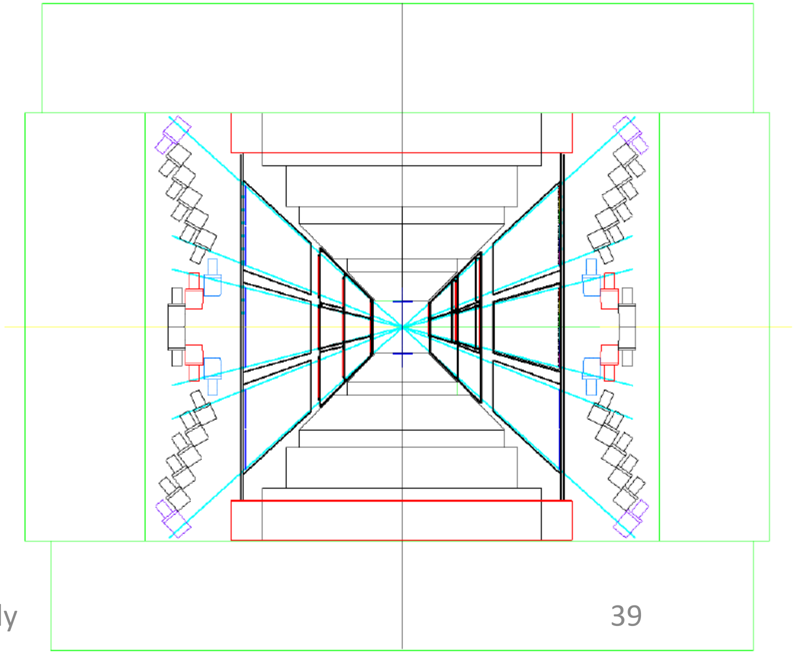


LG (Lead Glass Calorimeter)

- Reuse from TOPAZ
  - ~300 at the 1st stage.
  - ~1000 in total
  - We have all we need.
- Expected Rejection Power
  - ~25 offline (energy dep. th.)
  - ~10 online (fixed th.)

We've got all we need.





Beam Energy Consideration

- Currently, main ring of J-PARC has a beam energy of 30GeV for a proton acceleration.
  - It is the same as SIS100/FAIR.
    - For HI, 11AGeV, $\sqrt{s_{NN}} = 4.9\text{GeV}$
  - Original designed energy of the ring is 50GeV for proton
    - For HI, 19AGeV, $\sqrt{s_{NN}} = 6.2\text{GeV}$

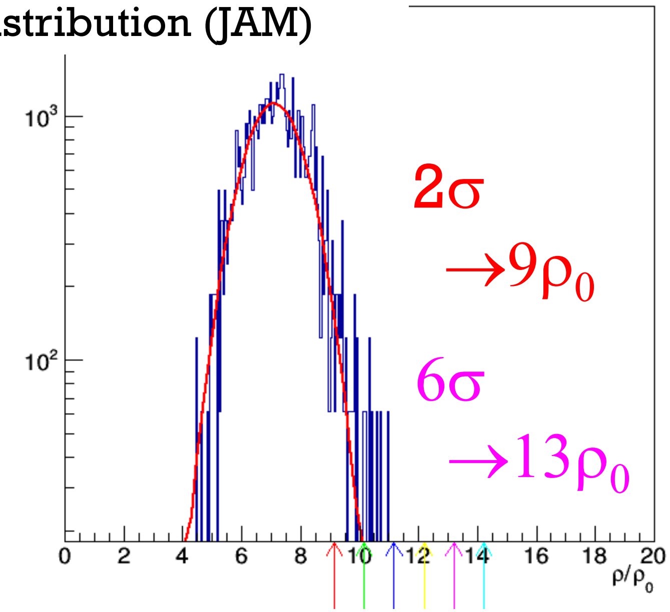
- Original designed energy should be recovered
  - Highest density expected at $\sqrt{s_{NN}} = 8\text{GeV}$
    - Randrup, PRC74(2006)047901
  - Significant increasing of charm production cross section
  - Seamless connection to SPS/RHIC BES
- New power supply is required

HIGH BARYON DENSITY MATTER AT J-PARC

Energy range: $\sqrt{S_{NN}}$ = 2~5 GeV, Maximum interaction rate: 10^8 Hz
With a collaboration with theorists, we are evaluating achievable baryon density

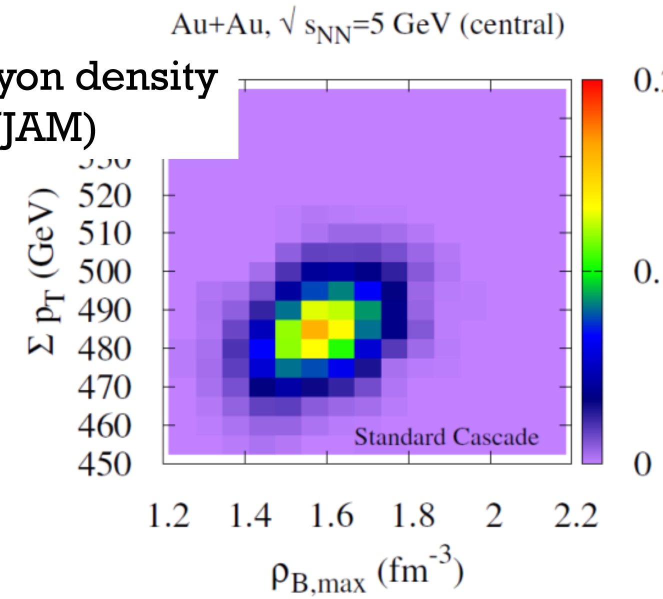
If we can select "rare event", higher baryon density can be studied

Max Baryon density distribution (JAM)



Selection of higher baryon density matter
We are looking for suitable valuables
e.g. p_T sum of charged particles

Max Baryon density vs $\Sigma\, p_T$ (JAM)

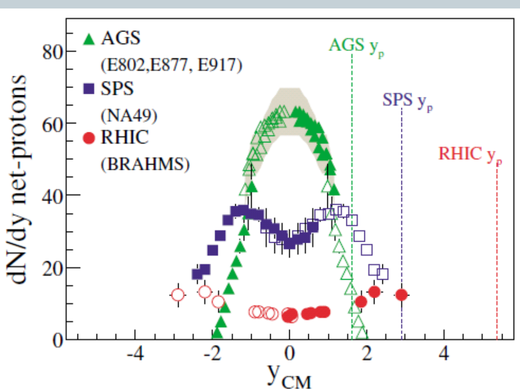


Statistics-starved "rare event" selection feasible at J-PARC-HI

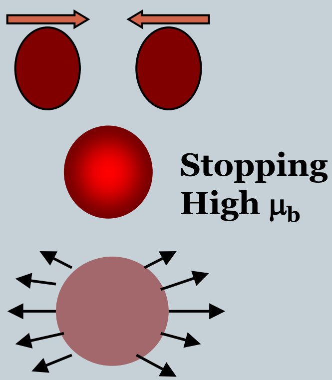
What's expected at J-PARC energy?

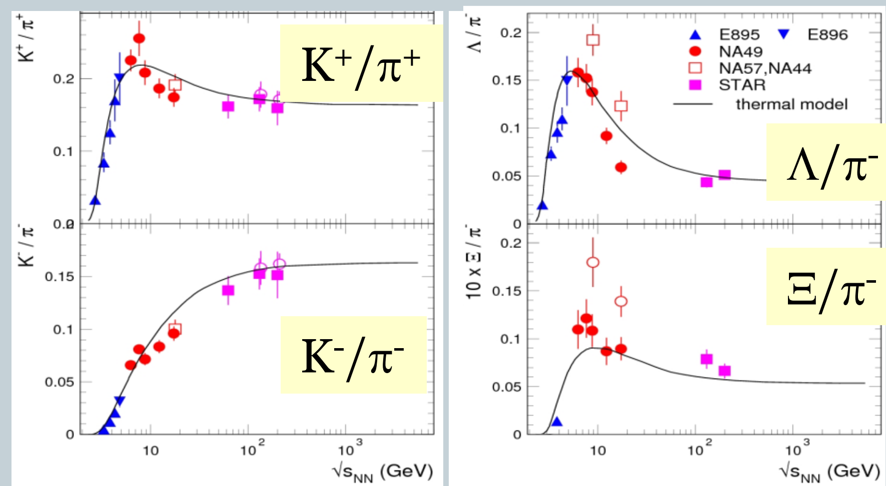
- Baryon is highly stopping at mid-y, at AGS (=J-PARC) energy
  - → **High density matter.** Nucleons pass through each other at SPS and above
- (K^+, Λ, Ξ,)/π ratio have maximum at $\sqrt{s_{NN}}$~5GeV
  - → **Strangeness fraction is largest at J-PARC energy.** (π is a proxy of multiplicity)

Au+Au: ~6ρ_0 , U+U: ~8.6ρ_0



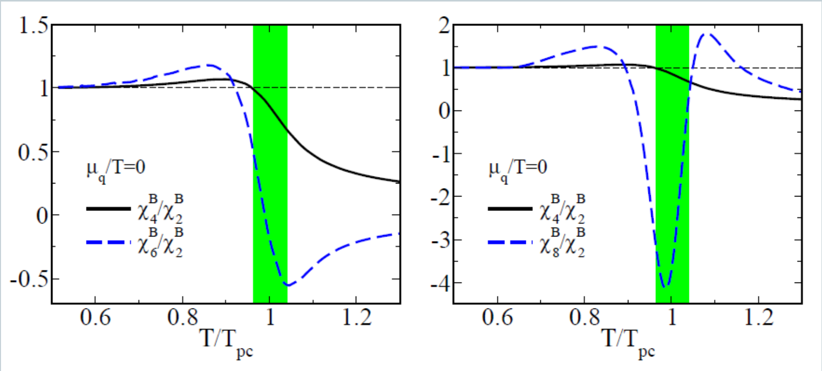
NPA772(2006)167



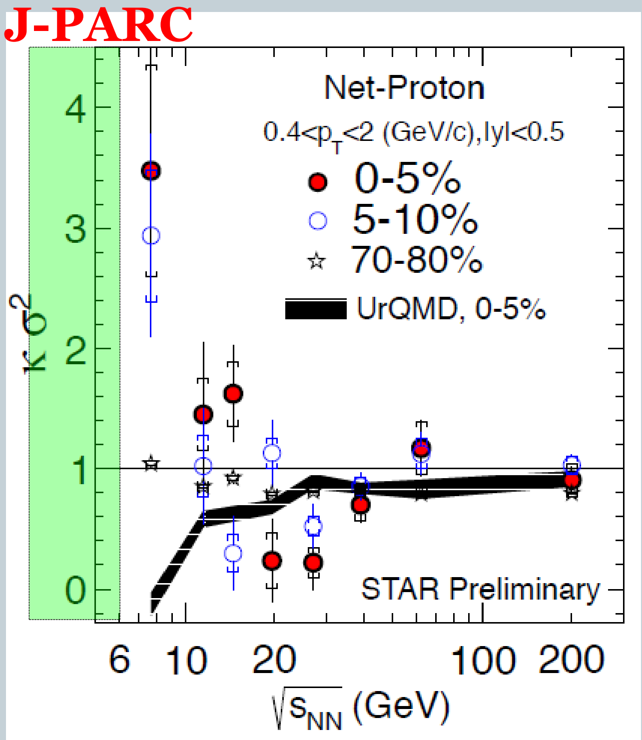


Observables: Event-by-event fluctuation

- Event-by-event fluctuations of conserved charge:
  - Observable to shoot the critical point
- 4^{th}, 6^{th}, 8^{th} baryon number fluctuations
  - Sensitive to chiral transition (even for crossover)
  - 2-order more statistics required with 1-order higher fluct.



B. Friman et al., EPJ C 71 (2011) 1694



X. Luo, Quark Matter 2015

Observables: Flow (constraining EOS)

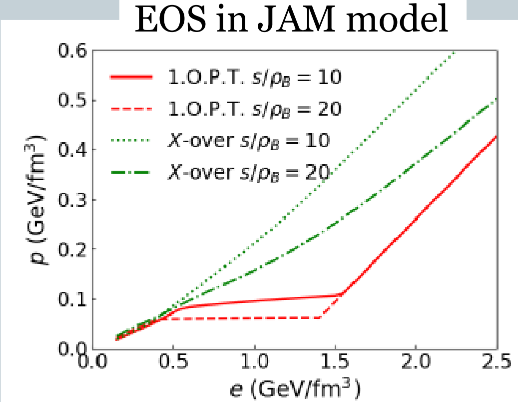
- Sign of v_1 slope changes around phase transition
- Measurement of dv_1/dy is a key to understand EOS
- Higher order flow (**3**[rd], **4**[th], **5**[th]) is of great interest
  - 1-order higher flow→1 order higher statistics

dv1/dy < 0 :softening of EOS (due to phase transition?)

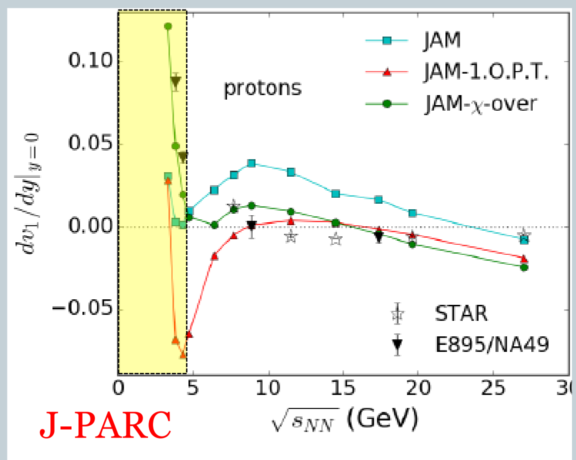
Assuming phase transition (crossover), JAM becomes closer to data.

A. Ohnishi, Reimei HI, Aug 2016

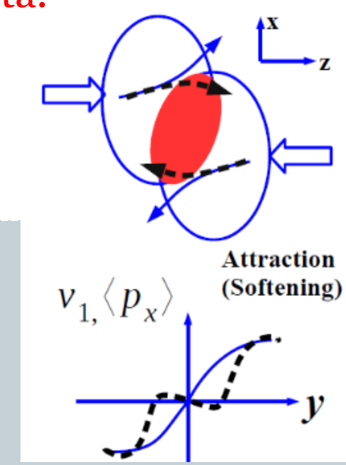
EOS in JAM model



Y. Nara, et al, PLB769 (2017), EPJA54 (2018)

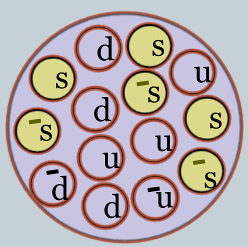


Y. Nara, KEK Theory group Workshop, Feb 2017

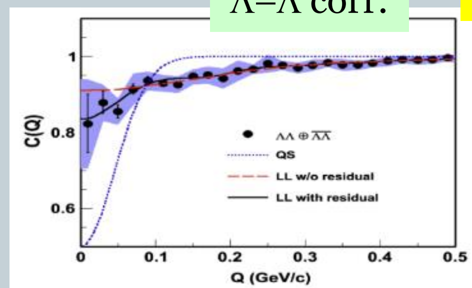


More observables…

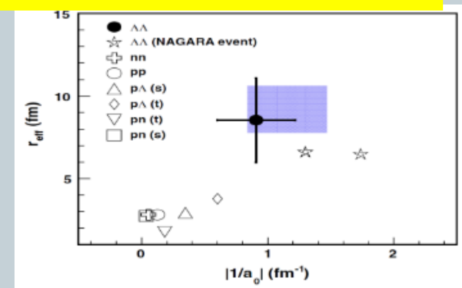
- Λ–Λ correlation
  - Baryon-baryon interaction measurement in high density matter?
- Ω–Ω bound states?
  - A recent Lattice result suggests a weak bound-states (B.E.=1.6MeV) of two Ω's
- More exotics?
  - Λ(1405), Dibaryon (H-dibaryon,…)
  - Kaonic nucleus (K-pp,…), Strangelet..
  - 6, 8, 10 quark states?
- …..



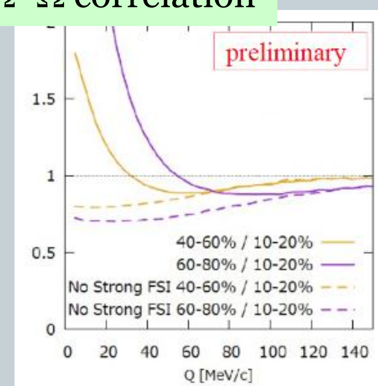
Λ–Λ corr.



STAR, PRL114, 022301 (2015)

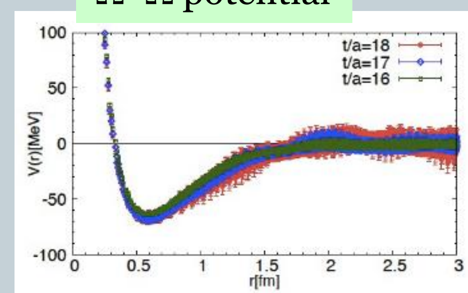


Ω–Ω correlation



K. Morita, et.al.

Ω–Ω potential



Gongyo et al.,
PRL120, 212001 (2108)