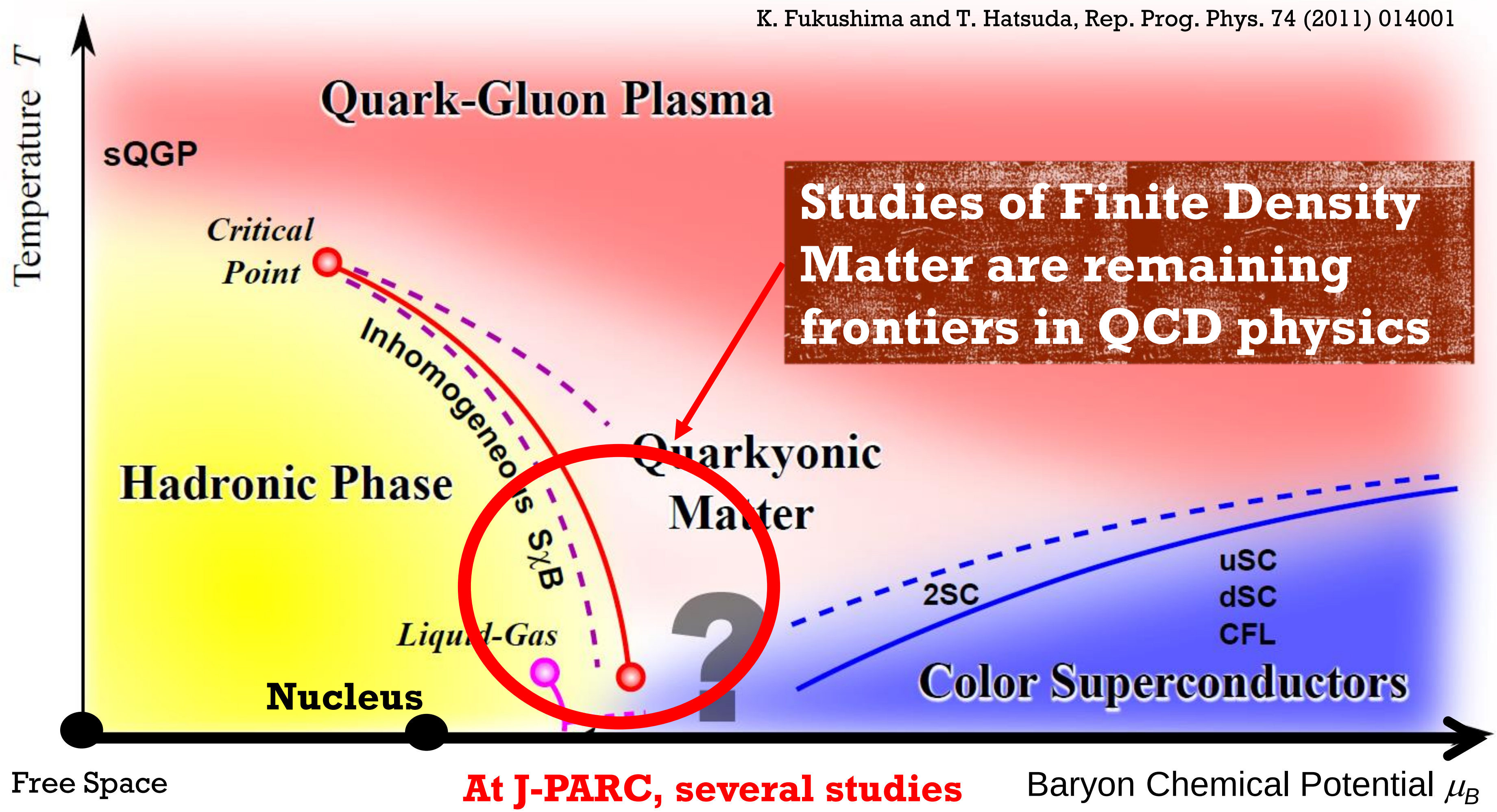
J-PARC AND HEAVY ION PROGRAM

K. Ozawa (KEK, University of Tsukuba)
for the J-PARC HI collaboration

PHYSICS: FINITE DENSITY QCD MEDIUM



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

J-PARC Activities

- Elementary interactions with strangeness
  - Hyperon – Nucleon interactions
    - Hyper-nuclei
    - Direct scattering measurements
  - Kaonic nuclear bound states
- Vector mesons in nucleus
  - χ sym. restoration in finite density matter
- Explore high baryon density medium in Heavy Ion collisions

HYPERNUCLEI BOUND STATES

Nucleus is a stable object and can have a bound state with hyperons

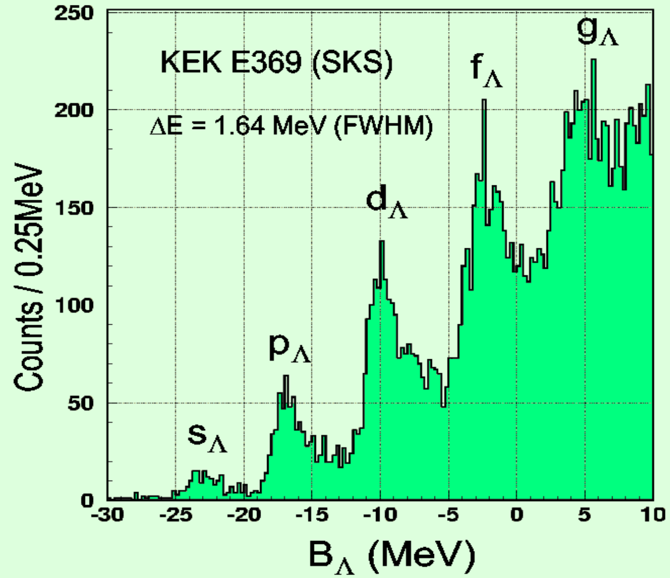
If a bound state is observed, we can measure a binding energy

The binding energy can be interpreted to the strength of interaction between nucleon and hyperon.

Measured bound states spectrum by Prof. Nagae

PRC 64 (2001) 044302

$^{89}Y\ (\pi^+, K^+)\ ^{89}{}_{\Lambda}Y$



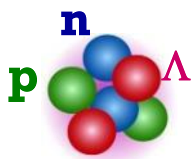
-> U_Λ = - 30 MeV

(c.f. U_N = -50 MeV)

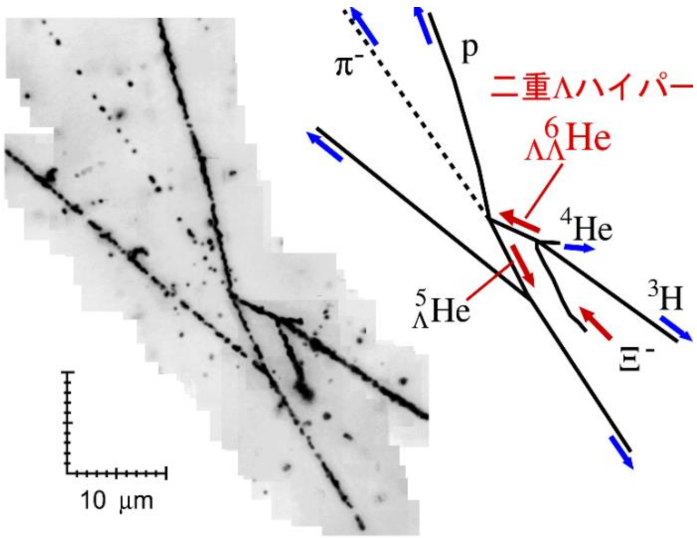
This method is a powerful tool to study hyperon interactions and we extend this study to S=-2 system

PIONEERING RESULTS FOR S=-2 SYSTEM

Nagara event



H. Takahashi et al., PRL 87 (2001) 212502

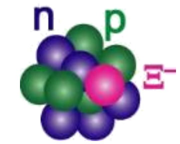


$^{6}{}_{\Lambda\Lambda}\mathrm{He} \rightarrow {}^{5}{}_{\Lambda}\mathrm{He} + p + \pi^{-}$

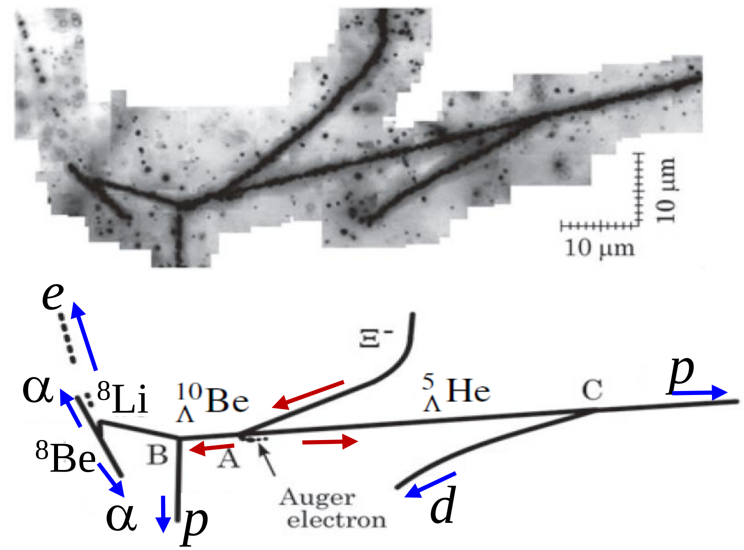
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

Λ-Λ is weakly attractive

Kiso event



K. Nakazawa et al. PTEP 2015, 033D02



$\Xi^{-} + {}^{14}\mathrm{N} \rightarrow {}_{\Xi}{}^{15}\mathrm{C} \rightarrow {}_{\Lambda}{}^{10}\mathrm{Be} + {}_{\Lambda}{}^{5}\mathrm{He}$

$B_{\Xi^-} = 4.38 \pm 0.25$ MeV,
$\sim 1.11 \pm 0.25$ MeV

Ξ-N is attractive !

$\Sigma^{\pm}$ – PROTON SCATTERING

Physics Motivation:

J-PARC E40: Prof. K. Miwa (Tohoku univ.)

Systematic study of the Σp interaction

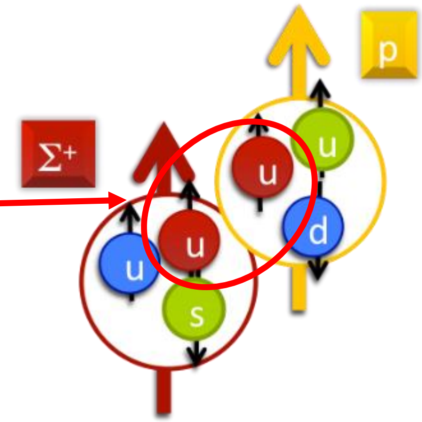
Σp interactions are repulsive and Σ hyper-nuclei formation is difficult

Pauli blocking effect between quarks

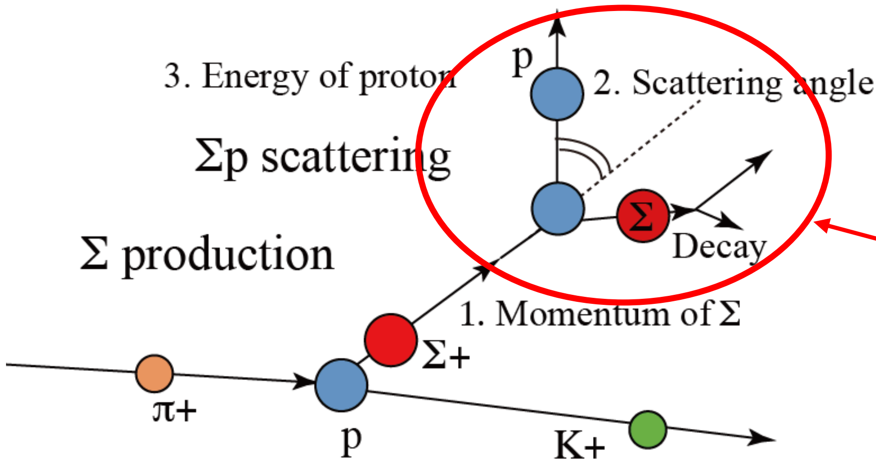
Origin of repulsive force in Σ^{+}p interaction

Suggested by HAL QCD Lattice calc.

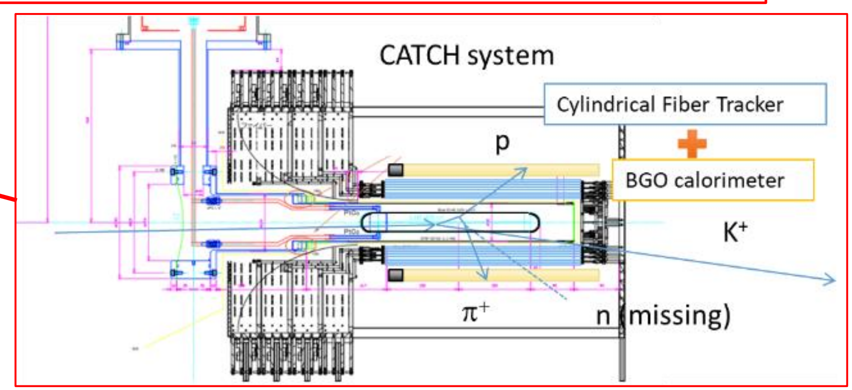
(H. Nemura et al. Few-Body Syst (2013) 54:1223-1226)



Two successive two-body reactions



Detection of Σp scattering event by CATCH detector



Half of data is already collected in 2019!

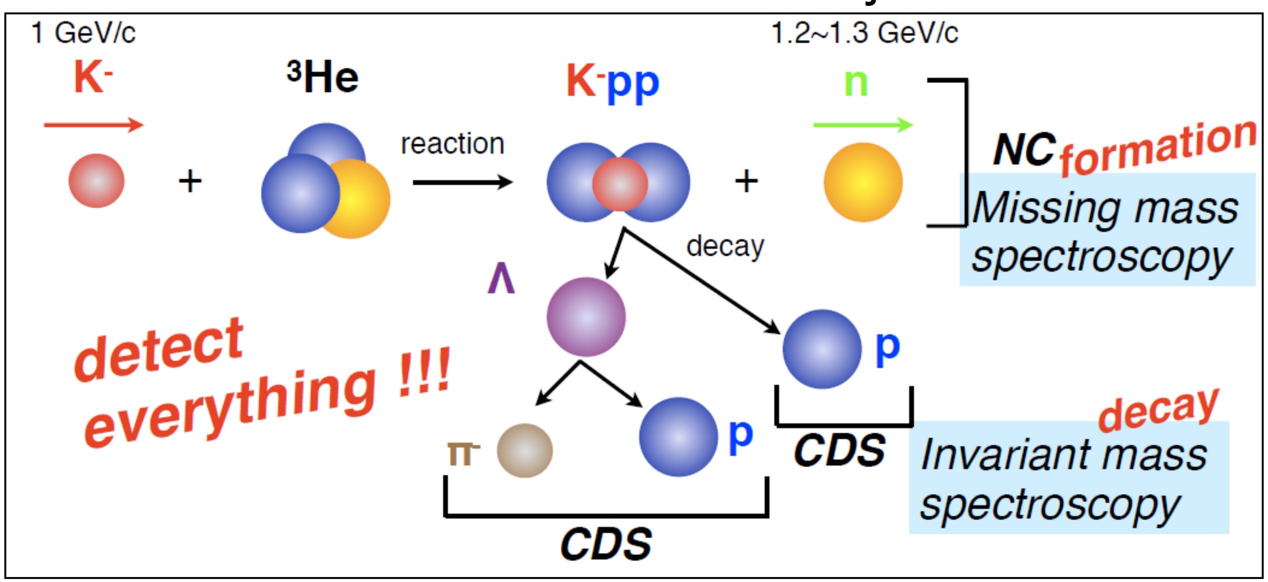
K-NN BOUND SYSTEM

To study a finite density system, understanding of three-body system is important.
Especially, K^{-}NN system is interesting

- Attractive K^{-}N interaction in I=0 is suggested by properties of $\Lambda(1405)$
- A bound state of K^{-}pp system is predicted by several theoretical calculations
  - Various predicted values of binding energy and width
  - Existing experimental data is not agree with theoretical predictions

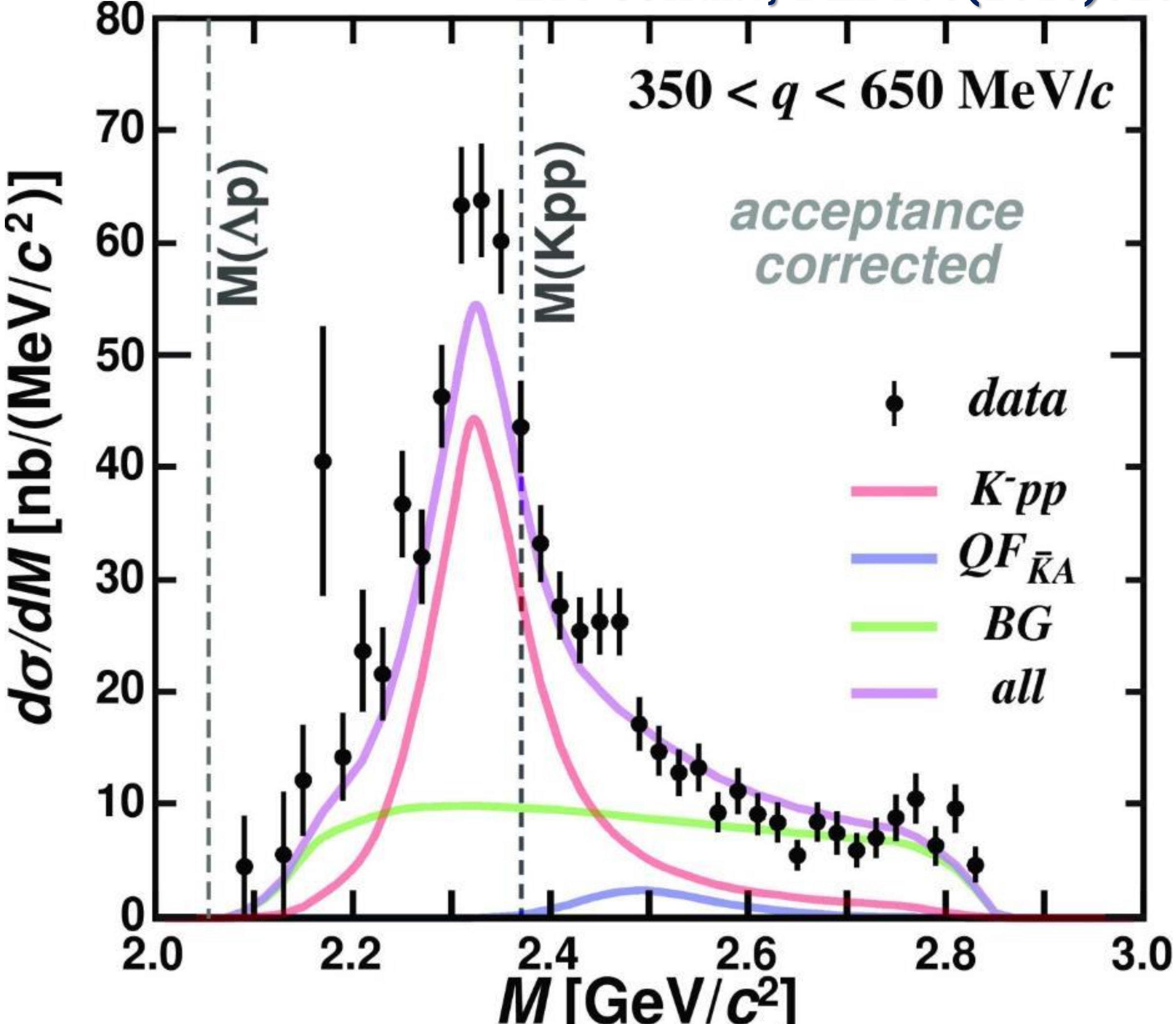
A new experiment is executed using a new technique!

J-PARC E15: Prof. Iwasaki (RIKEN)



CLEAR K-PP BOUND STATE IS OBSERVED

E15 collab., PLB789(2019)620.



Invariant mass distribution of Λp

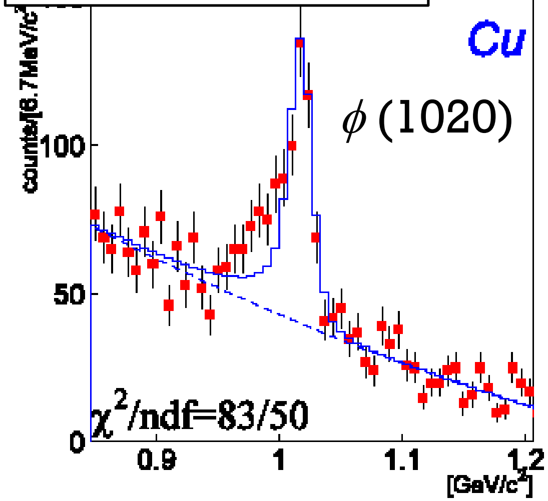
Quasi-Free and Background contributions are evaluated using missing mass information

- **Binding energy: ~50 MeV**
- **Width: ~100 MeV**

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

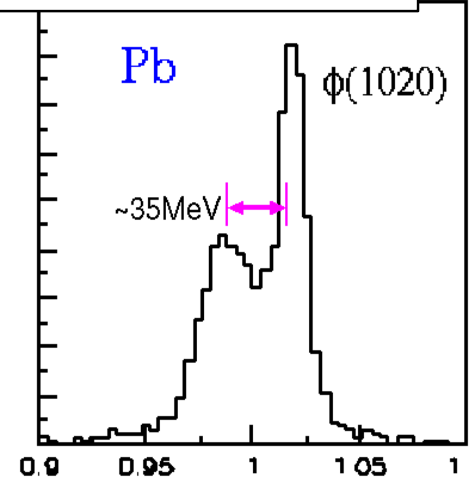
KEK E325 results



e^+e^- invariant mass

High Statistics
Better Resolution

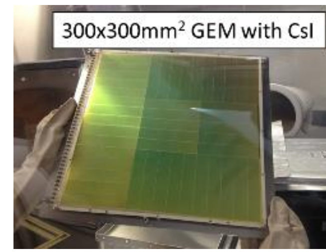
J-PARC expectation



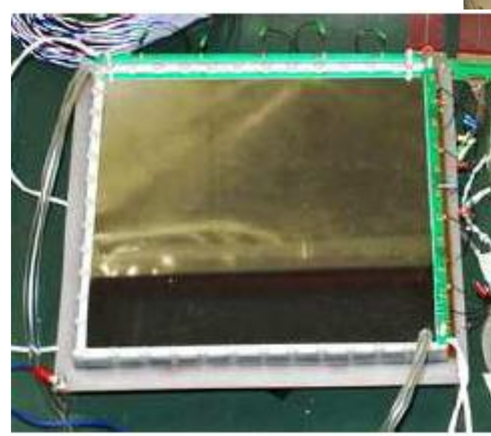
e^+e^- invariant mass

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)



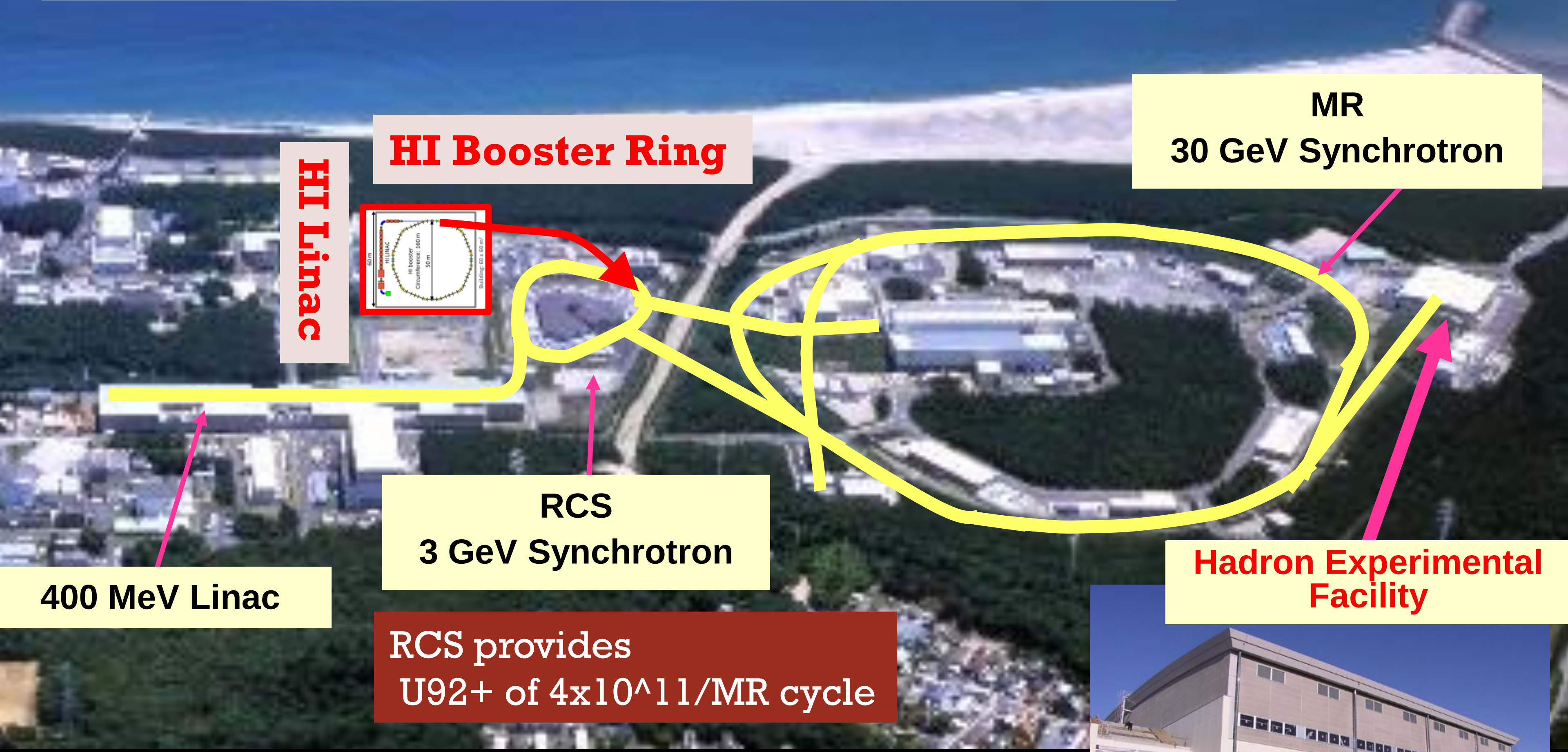
Electron ID



GEM Tracker

We will start data acquisition in 2020 spring

J-PARC Heavy Ion Program



Only Linac and Booster ring are required for Heavy Ion!

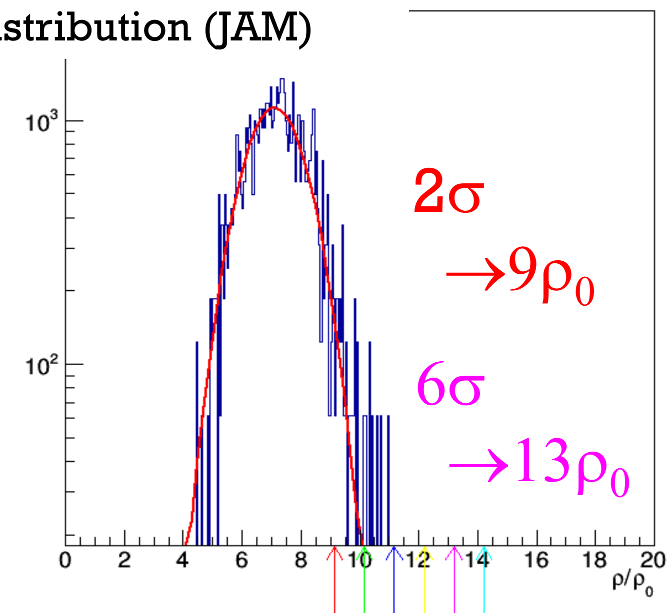
Designed by H. Harada and P.K. Saha

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)

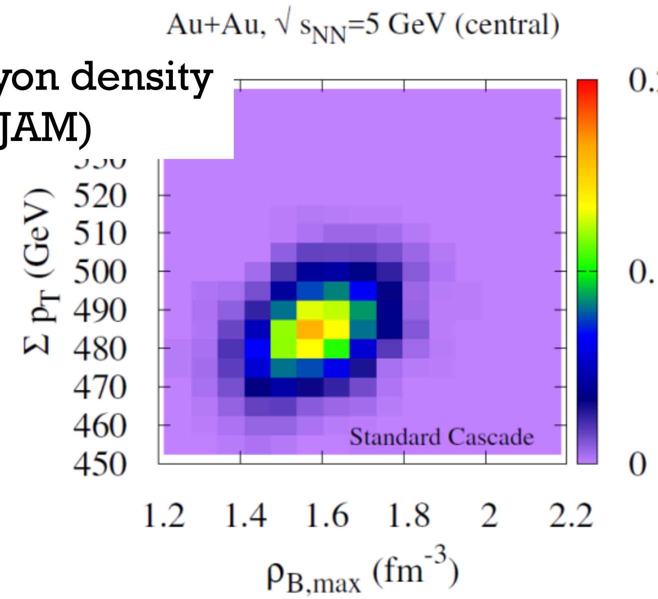


Selection of higher baryon density matter

We are looking for suitable valuables

e.g. p_T sum of charged particles

Max Baryon density vs Σp_T (JAM)



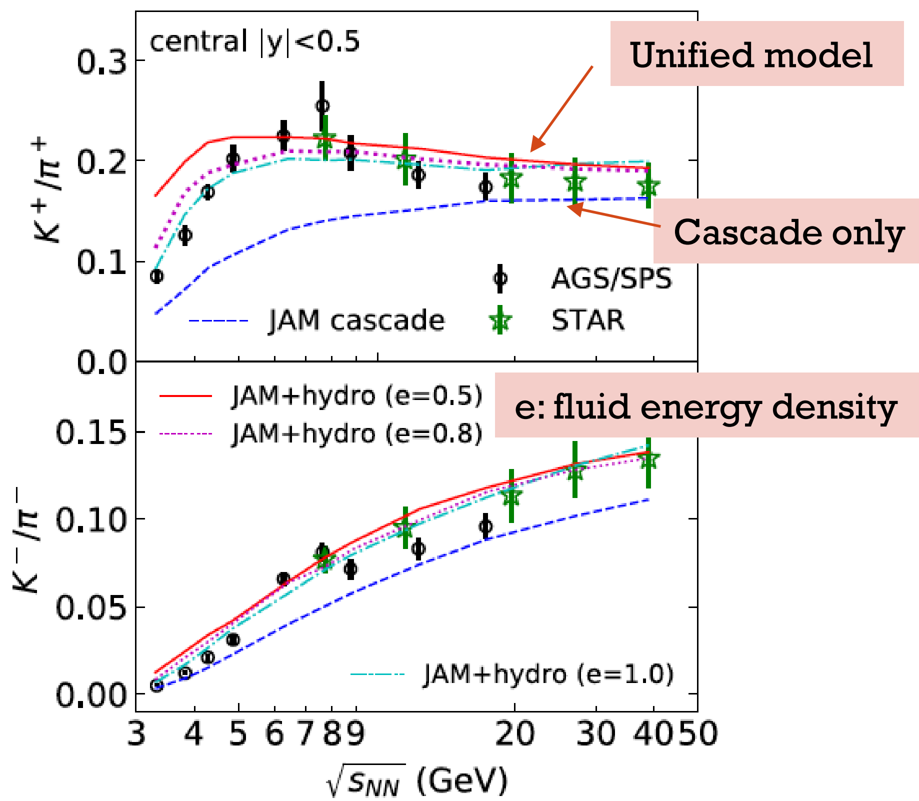
Statistics-starved "rare event" selection feasible at J-PARC-HI

"FLUID" EXISTS AT THE J-PARC ENERGY?!

An issue in this energy region is that theoretical calculations for thermalized phase is not enough

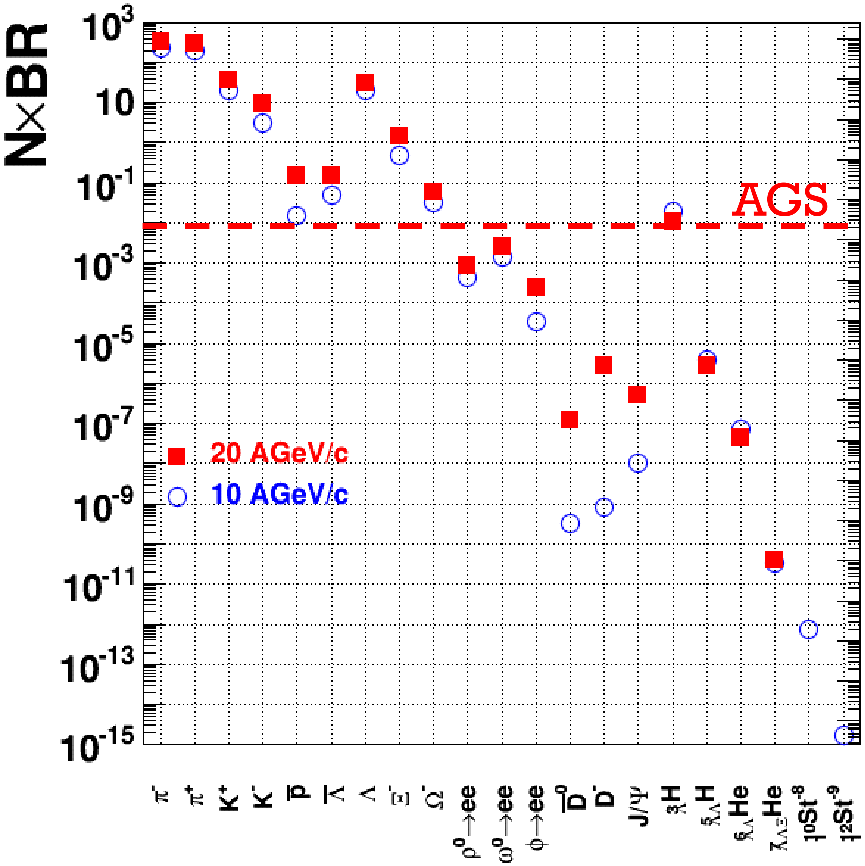
Recently, a Japanese group develops an "unified" hydro-cascade model

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 very well, while cascade only doesn't
  - It seems we can expect parton fluid phase even at the J-PARC energy

OUR STAGING APPROACH & GOALS



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

First step
- Interaction rate: 10^5 Hz
- E16 di-electron spectrometer
- $\rho, \omega, \phi \to e^+e^-$: 10^4 events

Second step
- Interaction rate: 10^6 Hz
- Dipole hadron spectrometer
- Flow, event-by-event fluctuation

Third step
- Interaction rate: 10^7 Hz
- Dipole muon spectrometer
- Precise low mass vector meson
- Heavy Flavor

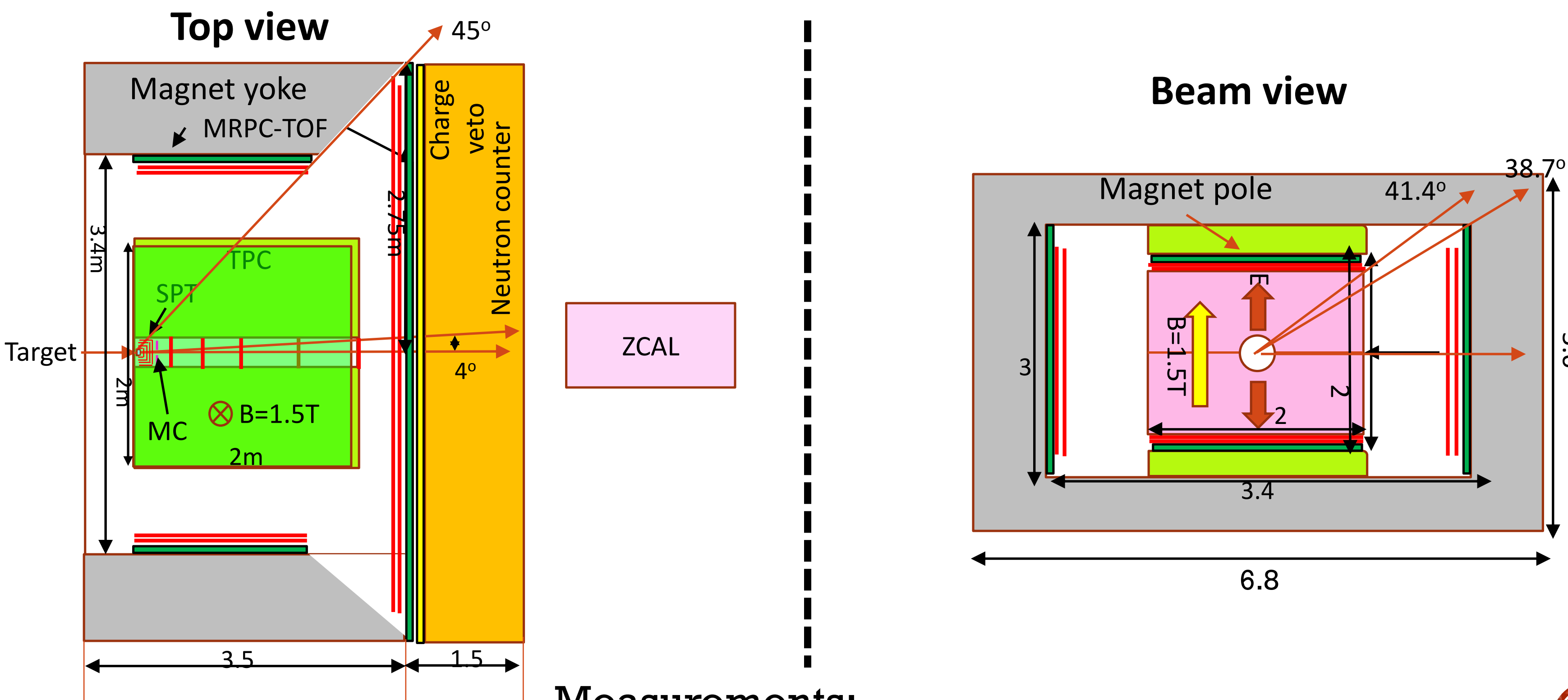
Final step
- Interaction rate: 10^8 Hz
- Rare events: Highest Density matter
- Hyper nuclear physics
- Strangelet search

DIPOLE HADRON SPECTROMETER

Charged particles + neutrons , ~4π acceptance
- Silicon Pixel Tracker (SPT) (θ < 4o), TPC (θ > 4o)
- MRPC-TOF, neutron counter

Rate : <=10^6 Hz interaction

Centrality : Multiplicity counter + zero-degree calorimeter



Measurements:
Higher order Flow, event-by-event fluctuation

DIMUON SPECTROMETER

Replace TPC by:

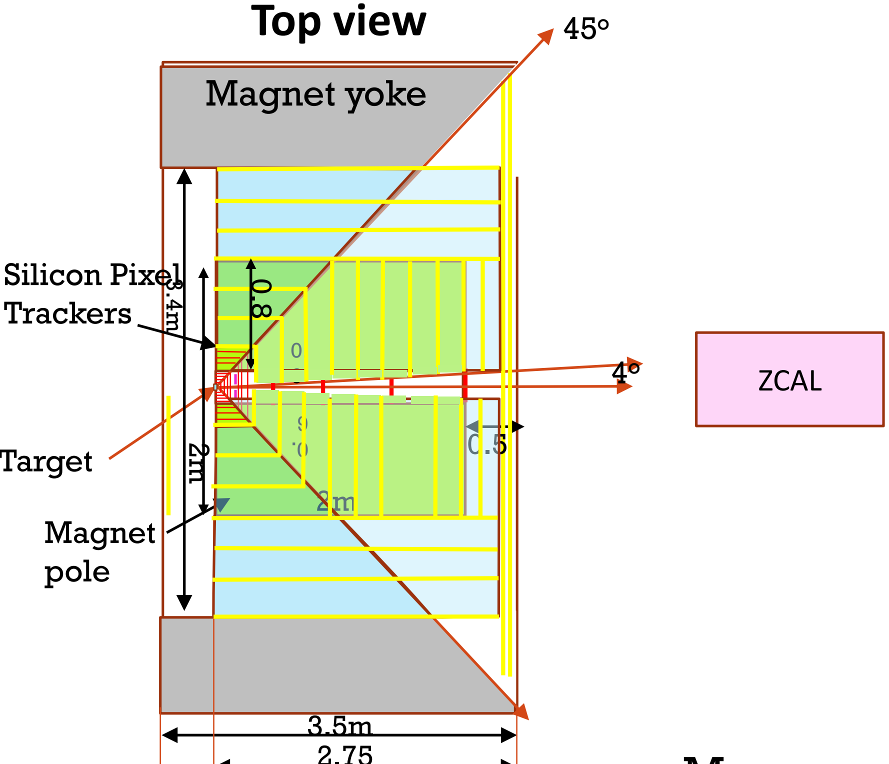
Pb absorbers and GEM trackers

Dimuon Online Trigger

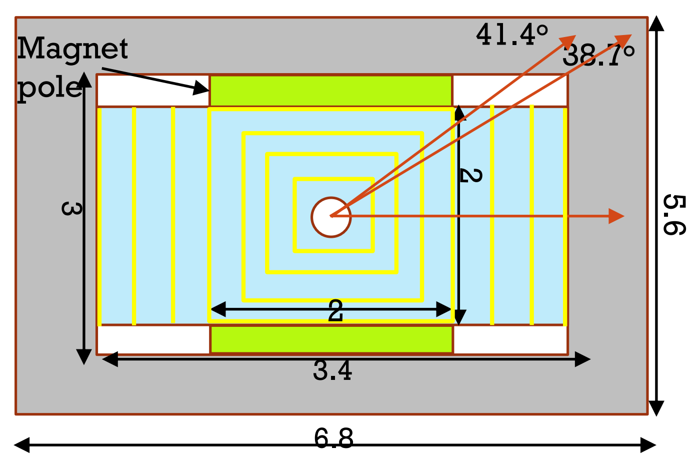
7-layer forward and barrel Silicon Pixel Trackers

Interaction Rate : 10^7 Hz

Top view



Beam view



Measurements:

Low mass dilepton, Heavy flavor

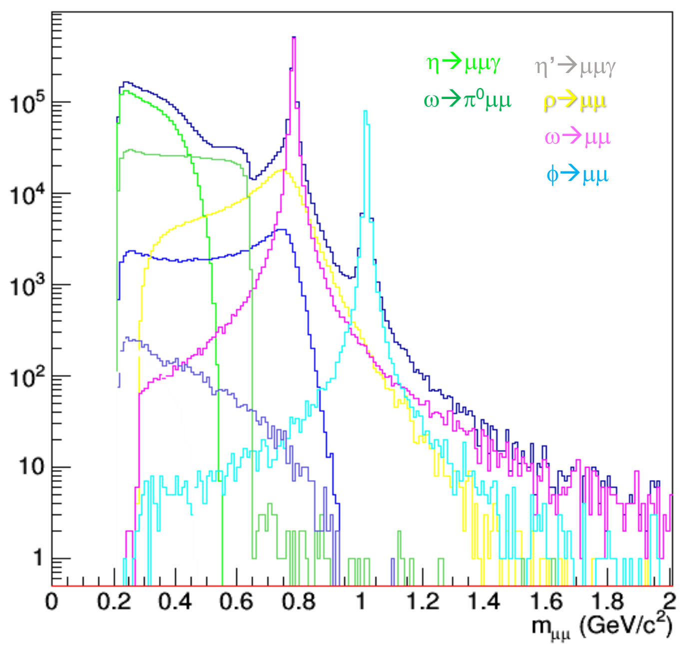
EXPECTED DIMUON SPECTRUM

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, Minbias JAM events
- Reconstruct tracks passing through 4 λ_I muon absorbers

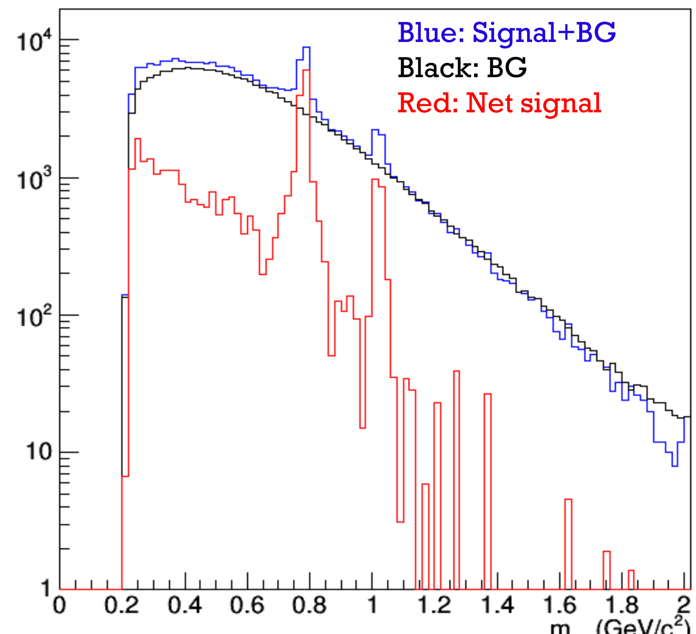
θ_{ee}>2°, 2°<θ<80°, p_T>0.1GeV/c

Generated cocktail



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

Reconstructed spectrum

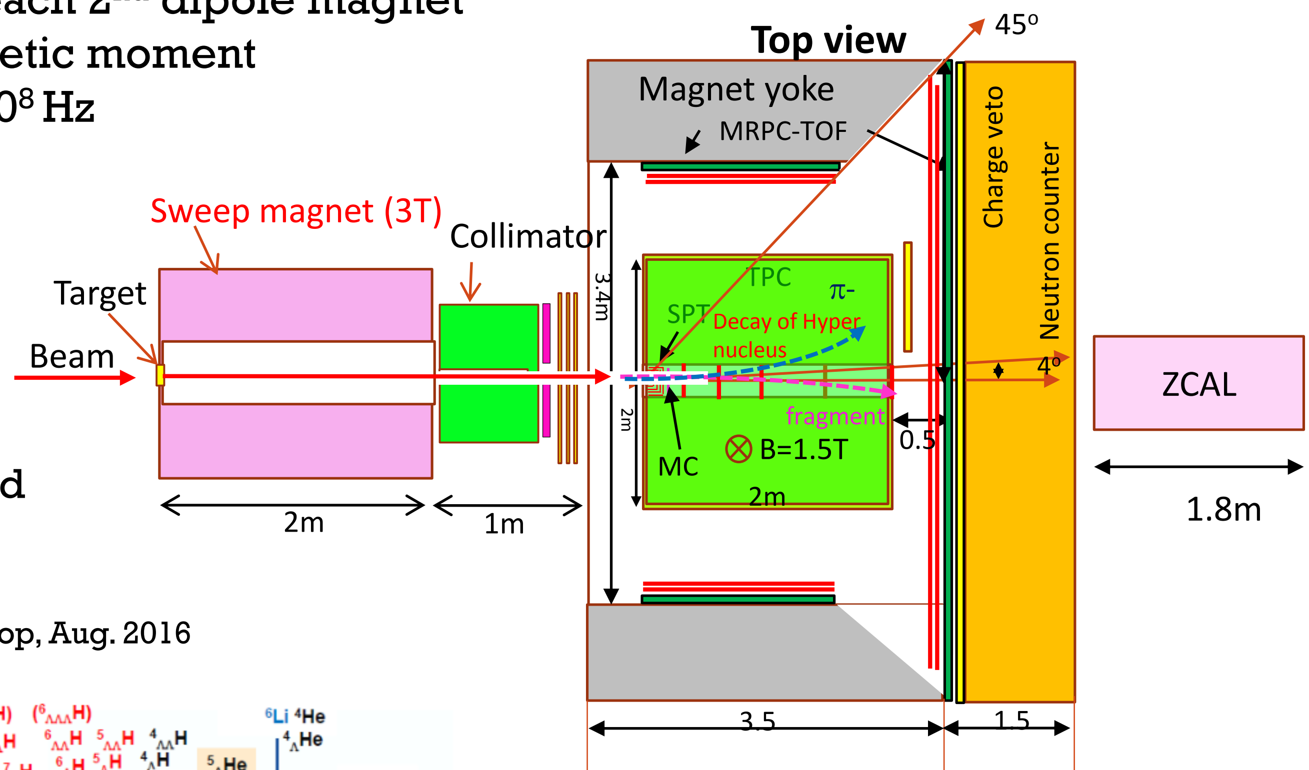


Enough Resolution even in low mass region

HYPERNUCLEAR SPECTROMETER

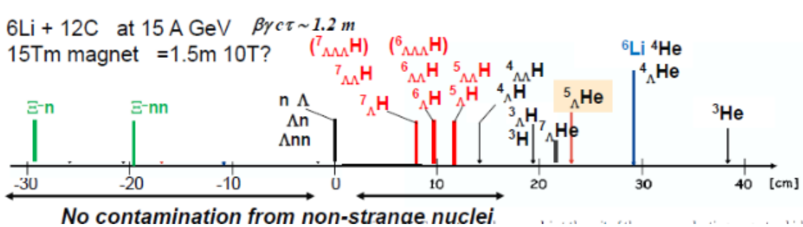
- Hypernuclei at beam rapidity
  - 1st dipole magnet + collimator → Only beam fragments reach 2nd dipole magnet
  - Lifetime and Magnetic moment
  - Interaction Rate : 10^8 Hz

- Strangelet search



Add a sweep magnet and a collimator upstream

H. Tamura, Reimei Workshop, Aug. 2016



SUMMARY

- Several studies related with finite density matter is on-going at J-PARC
  - Hypernuclei
  - Hyperon-Nucleon scattering
  - Kaon bound states
  - Vector mesons in nucleus
- We can have much results in a few years

- Future Heavy ion program at J-PARC is being prepared
  - We need Linac and Booster for heavy ion acceleration
  - First, we can start with di-electron spectrometer, which is being built for a pA experiment
  - Then, further study of high baryon density matter will be done using upgrade detectors

J-PARC-HI COLLABORATION

94 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

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

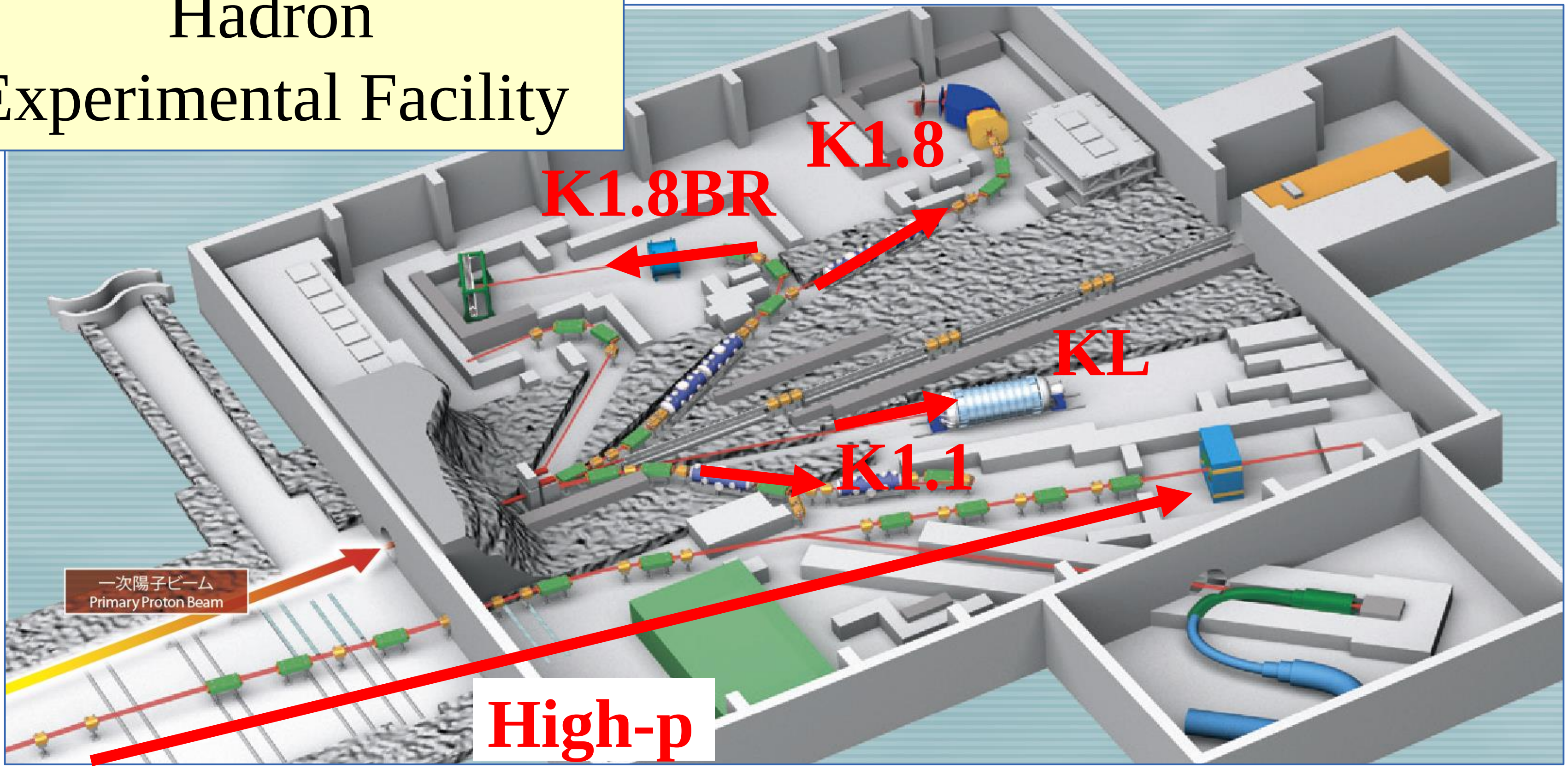
Accelerator

H. Harada, P. K. Saha, M. Kinsho, Y. Liu, J. Tamura, 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

Back up

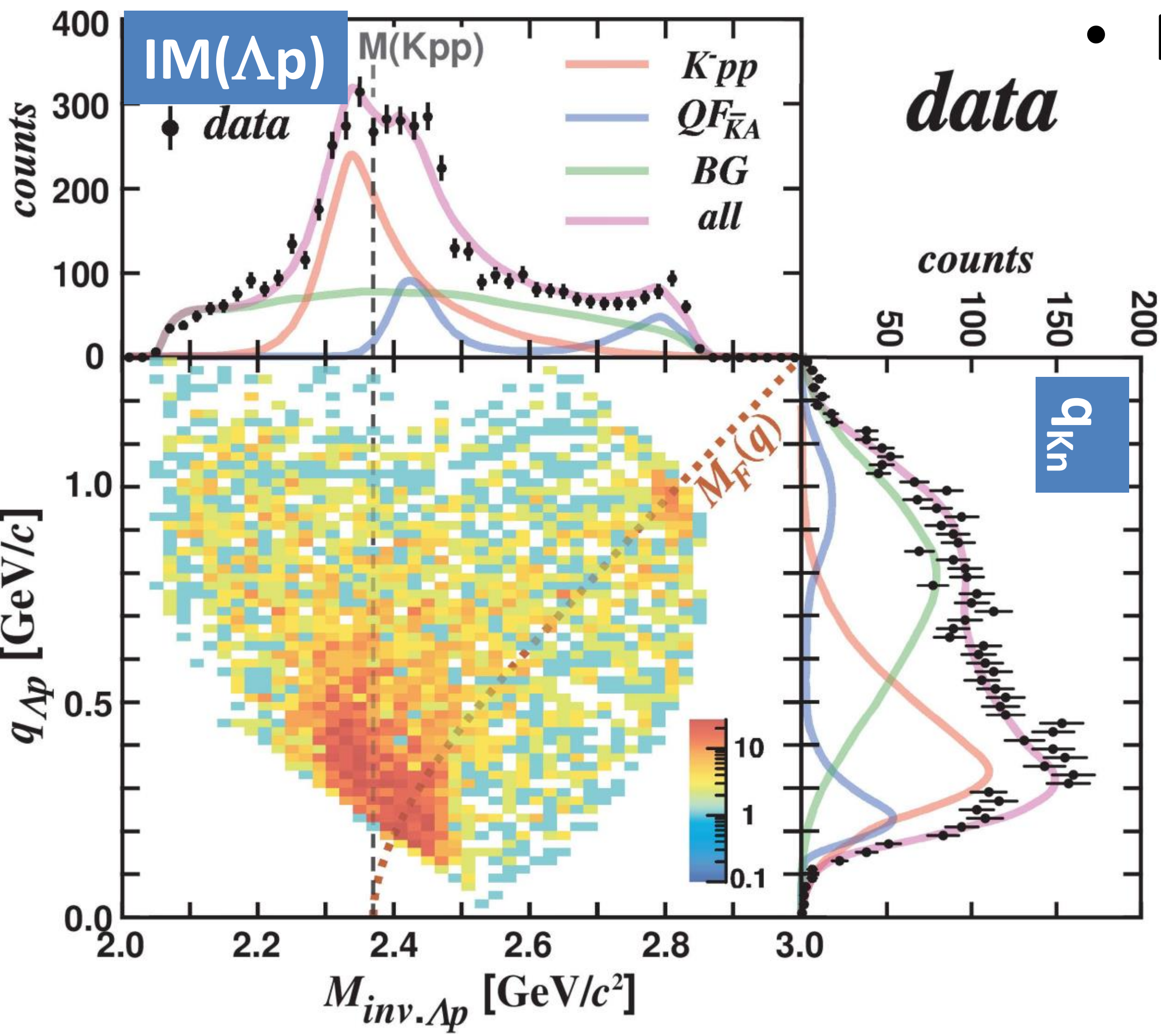
Hadron Experimental Facility



	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^+
	K1.1	$\pi^{\pm}$, $K^{\pm}$	< 1.1 GeV/c	~ 10^4 Hz for K^+
New Beamline	High-p	proton	30GeV	~ 10^{10} Hz
		Unseparated	< 20GeV/c	~ 10^8 Hz

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.



- Fit with 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**
    - BW*(Gauss form-factor)

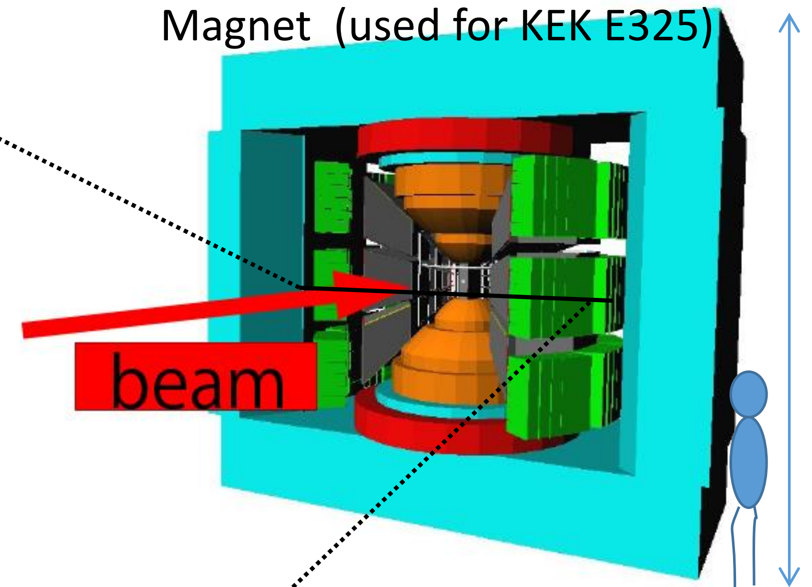
$$f_{\{Kpp\}}(M,q) = \frac{A_{Kpp}\,(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2}\, e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

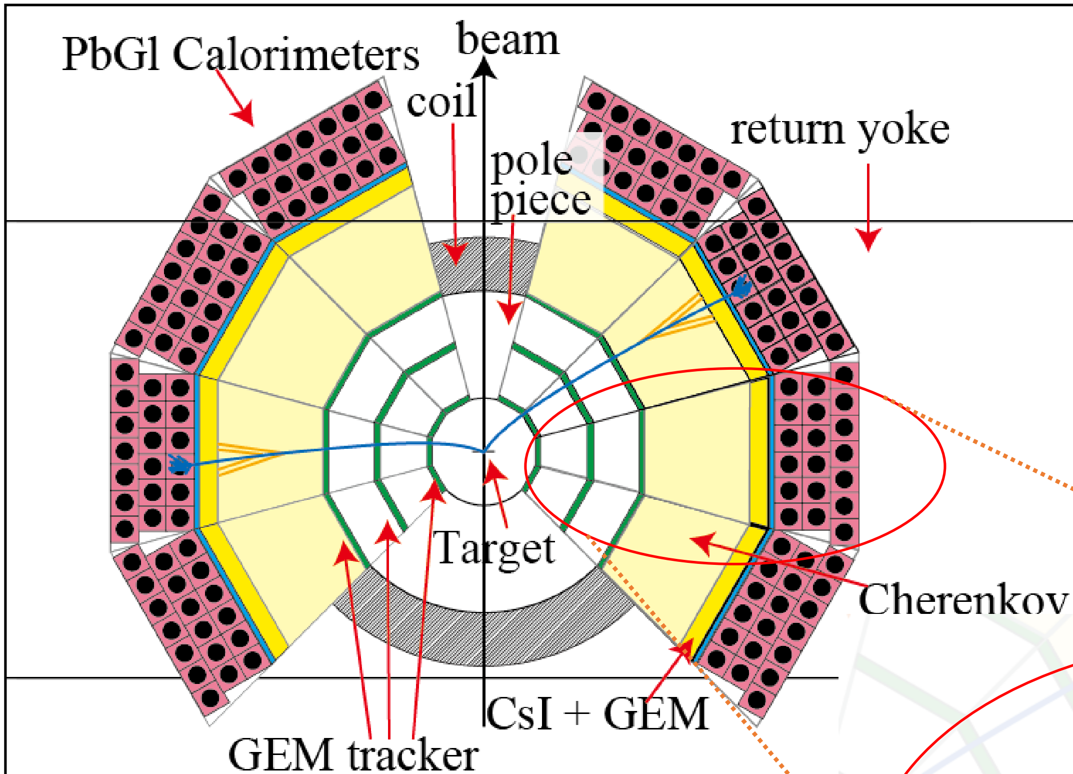
  - **Quasi-elastic K^- abs.**
    - **centroid depends on q_{Kn}**
    - Followed by Λp conversion

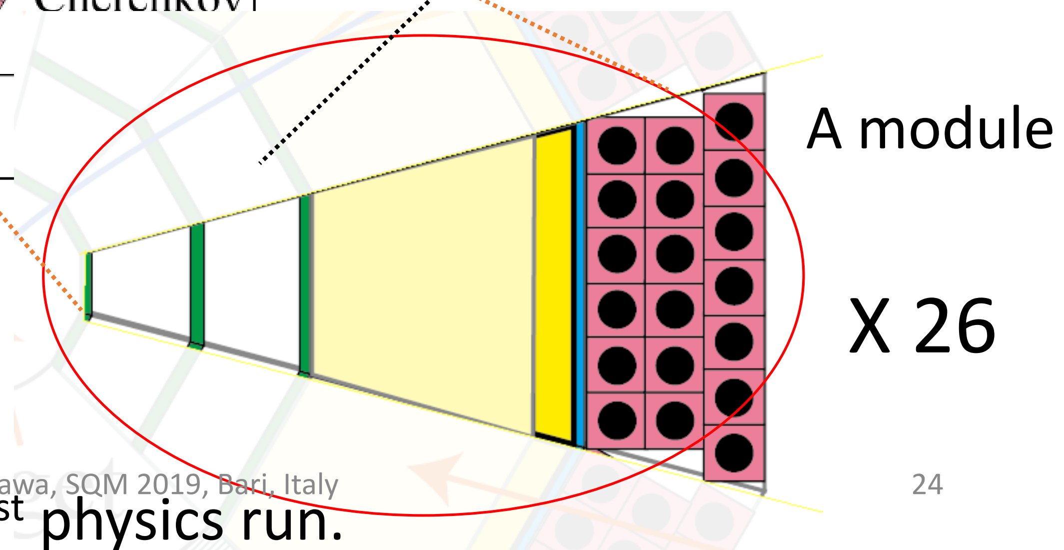
$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

  - **Background**
    - Broad distribution

The J-PARC E16 spectrometer







SSD : Tracking

GTR : Tracking

HBD : eID (Cherenkov)

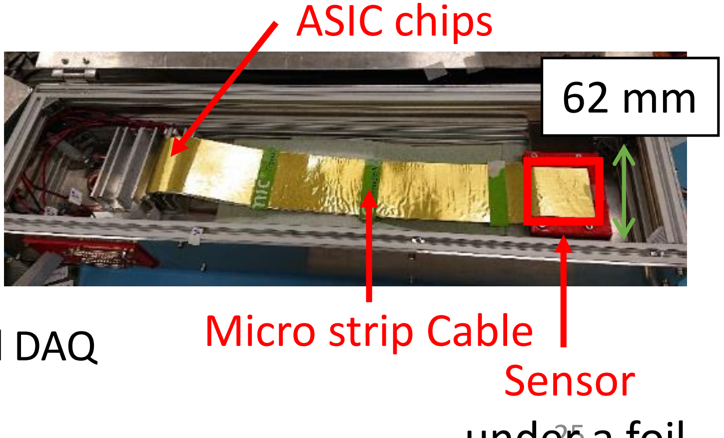
LG : eID (Calorimeter)

26 modules in total. 8 for the 1st physics run.

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

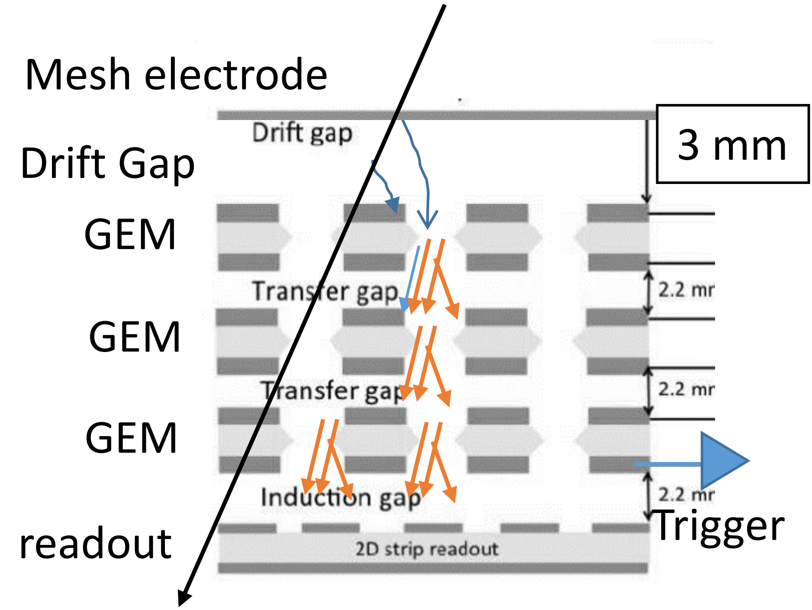


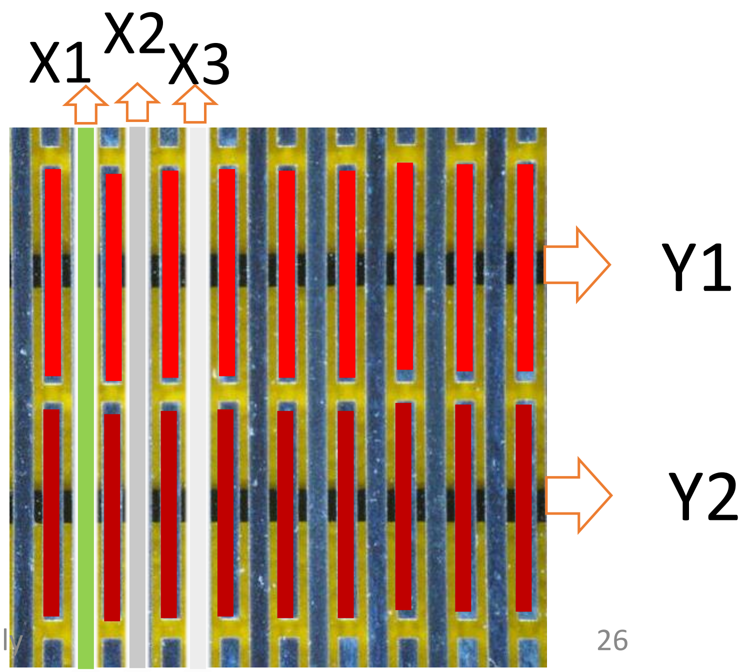
GTR (GEM Tracker)

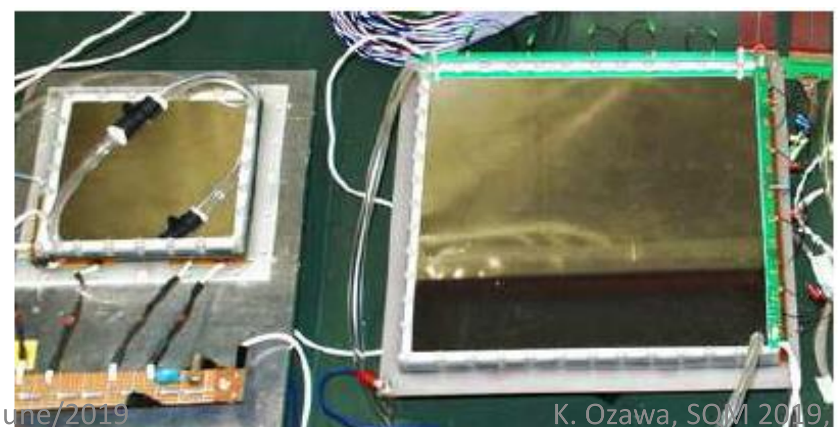
- Ionization electrons in the drift gap are collected and amplified by GEMs.

- 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.

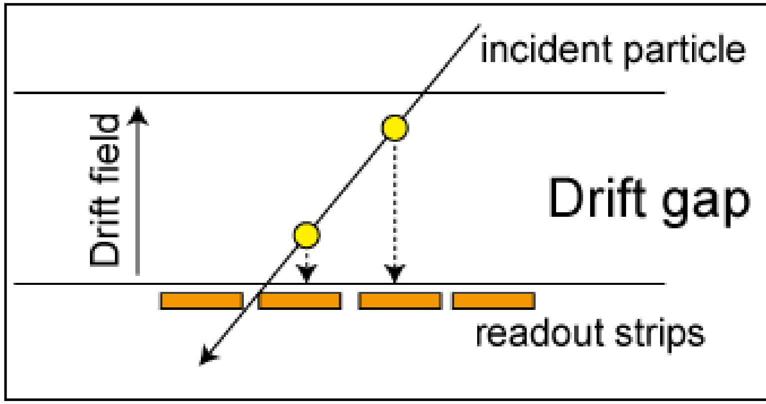






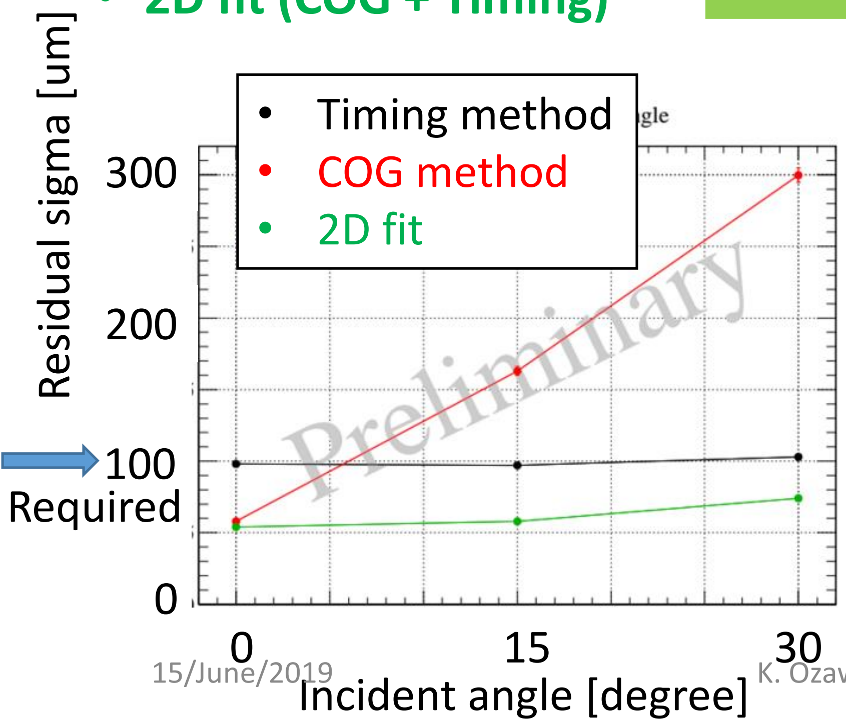
GTR Performance

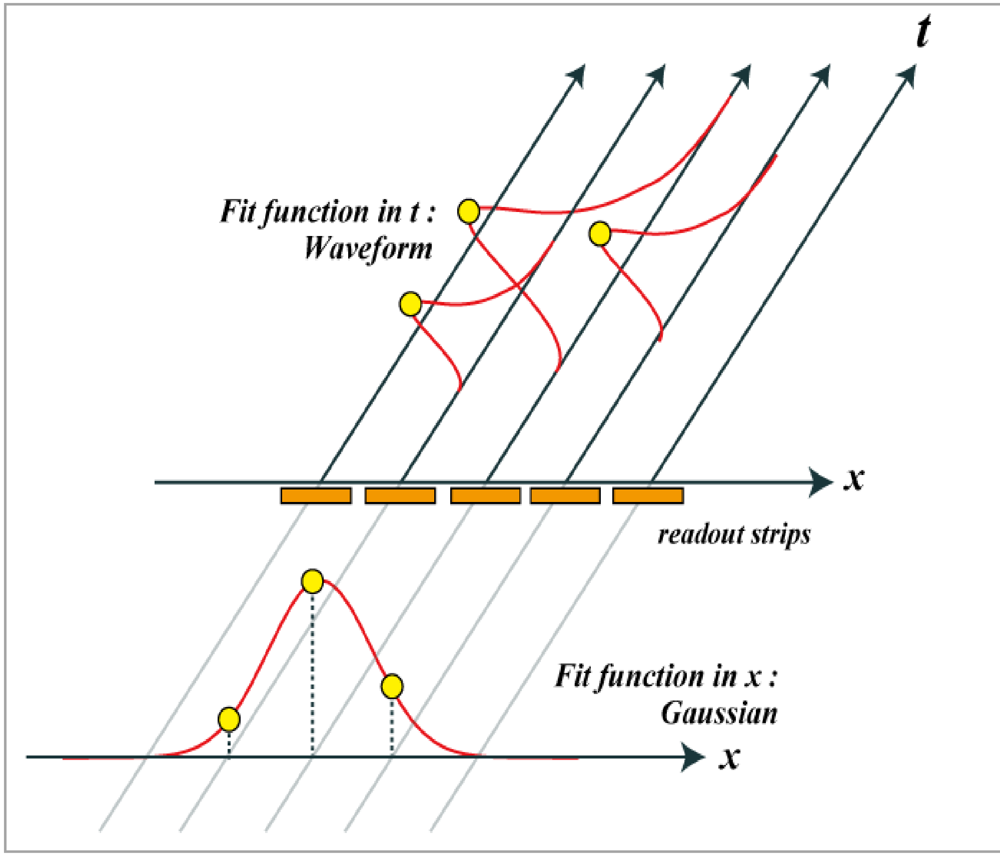
- Center Of Gravity (COG) Method
  - Ordinal analysis method
  - ~ 60 μm @ 0 degree of incident angle
  - Worse results for inclined tracks



- 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)**

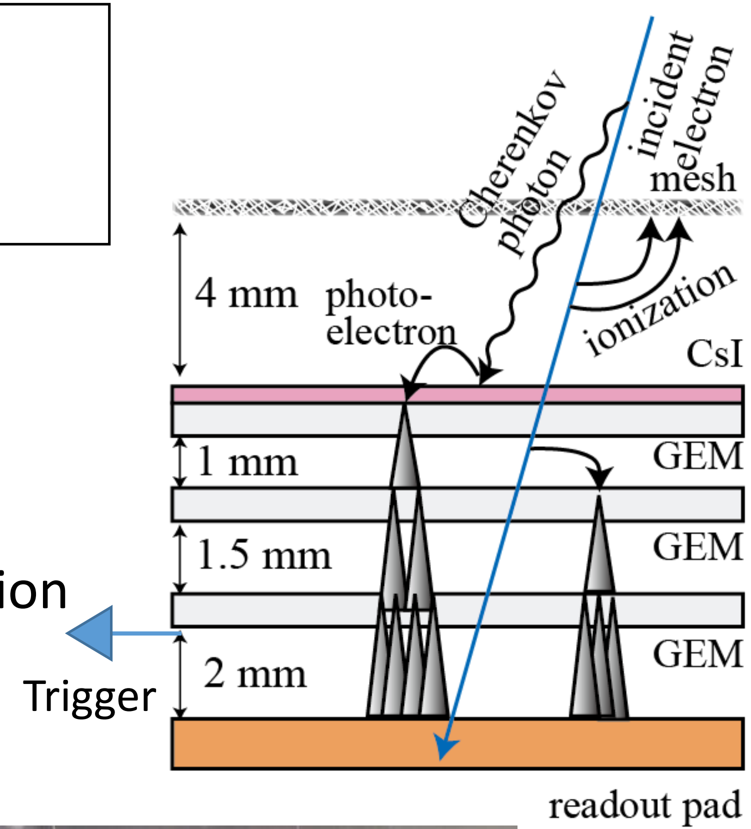


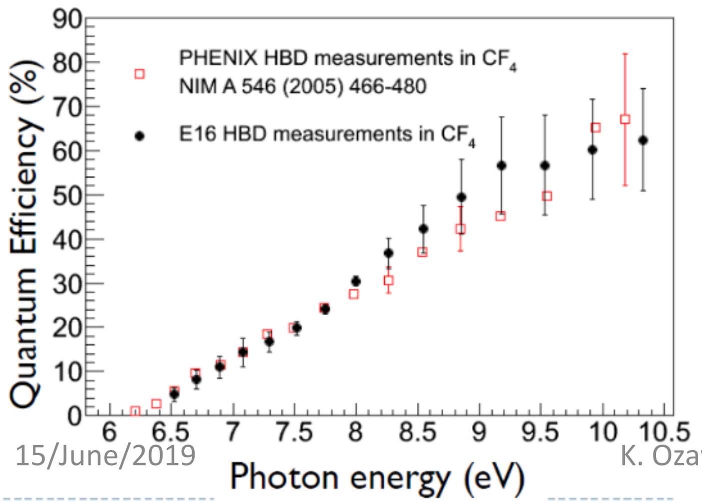


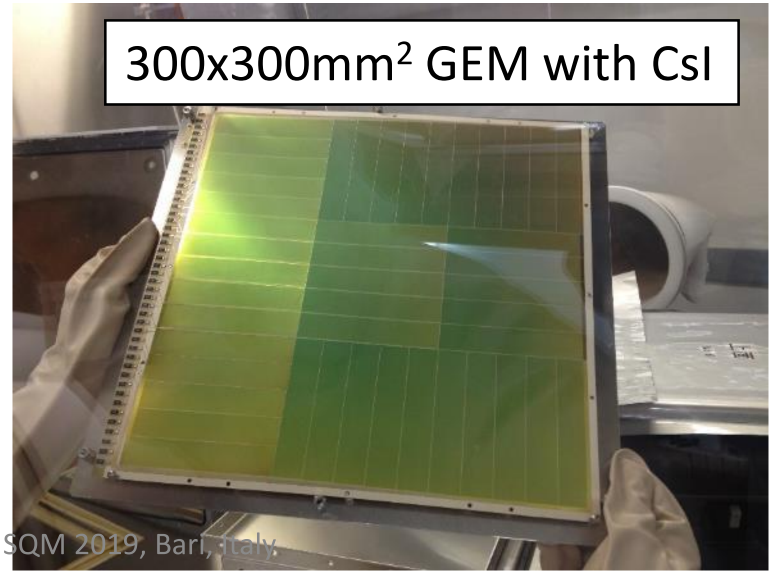
HBD (Hadron Blind Detector)

- 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)



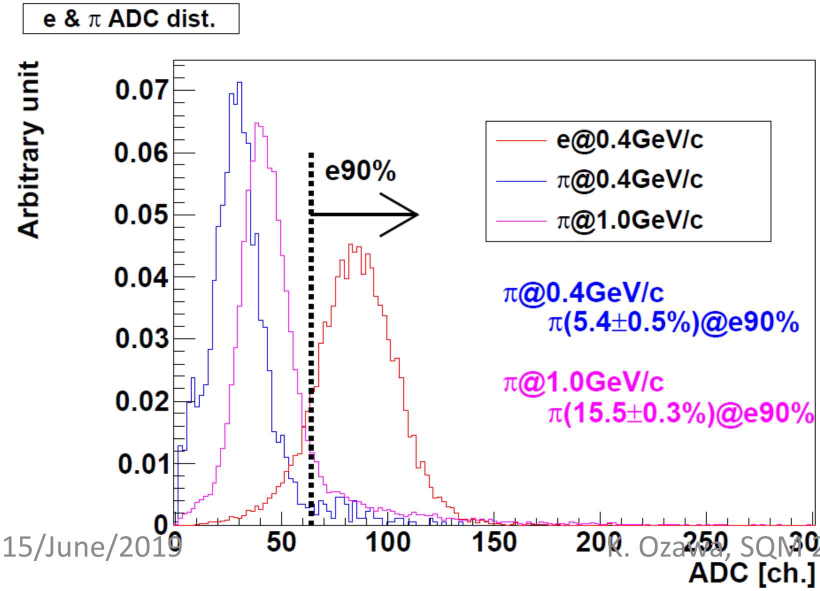


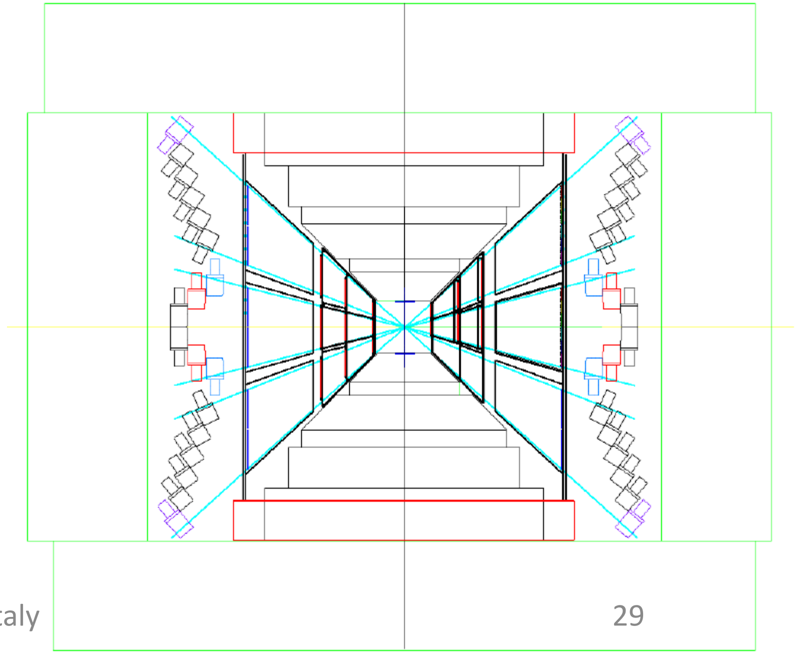


LG (Lead Glass Calorimeter)

- 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.



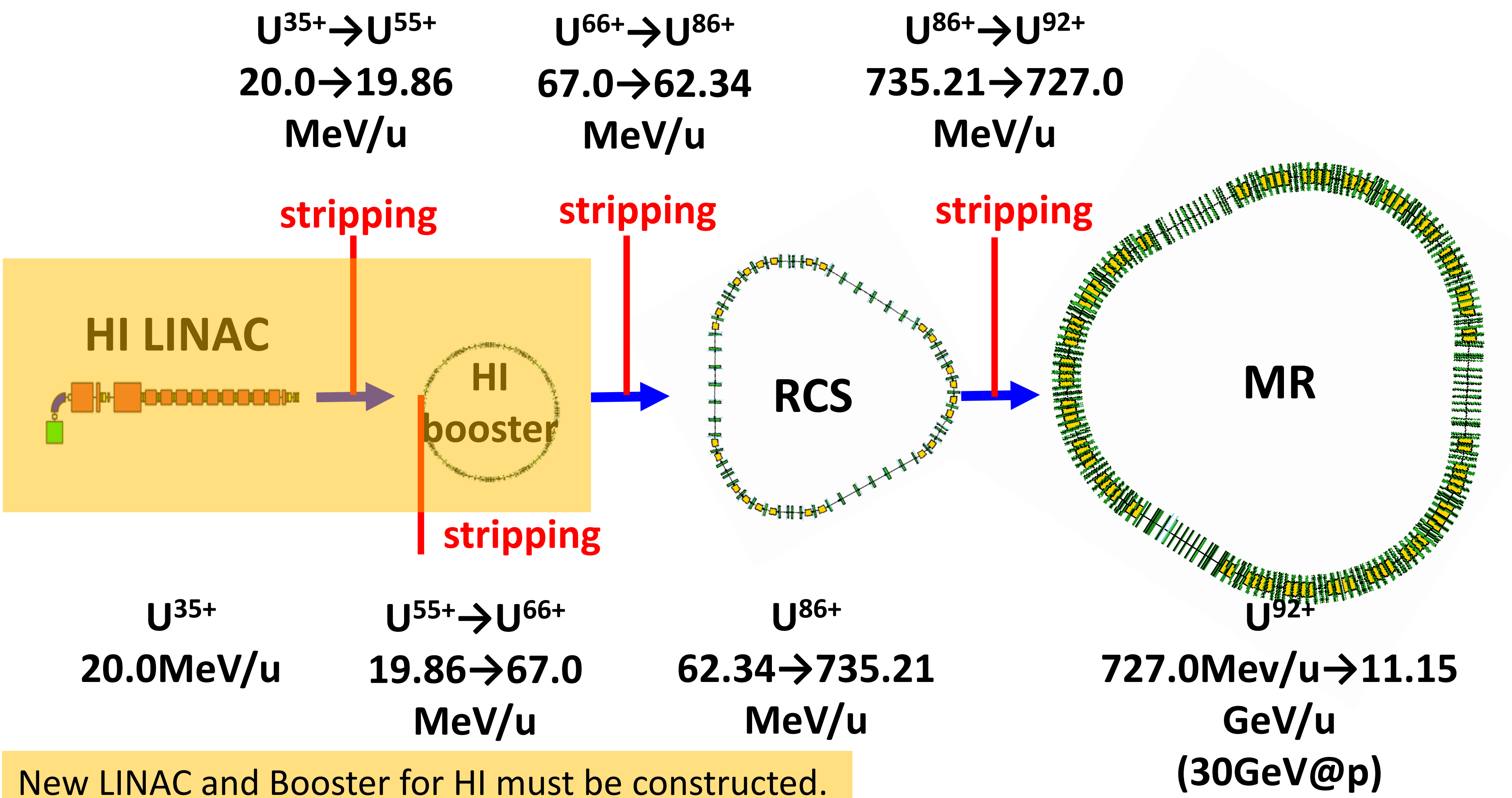


Beam Energy Consideration

- 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, $\sqrt{s_{NN}} = 4.9\mathrm{GeV}$
  - Original designed energy of the ring is 50GeV for proton
    - For HI, 19AGeV, $\sqrt{s_{NN}} = 6.2\mathrm{GeV}$
- Original designed energy should be recovered
  - Highest density expected at $\sqrt{s_{NN}} = 8\mathrm{GeV}$
    - Randrup, PRC74(2006)047901
  - Significant increasing of charm production cross section
  - Seamless connection to SPS/RHIC BES
- New power supply is required

J-PARC HI Project

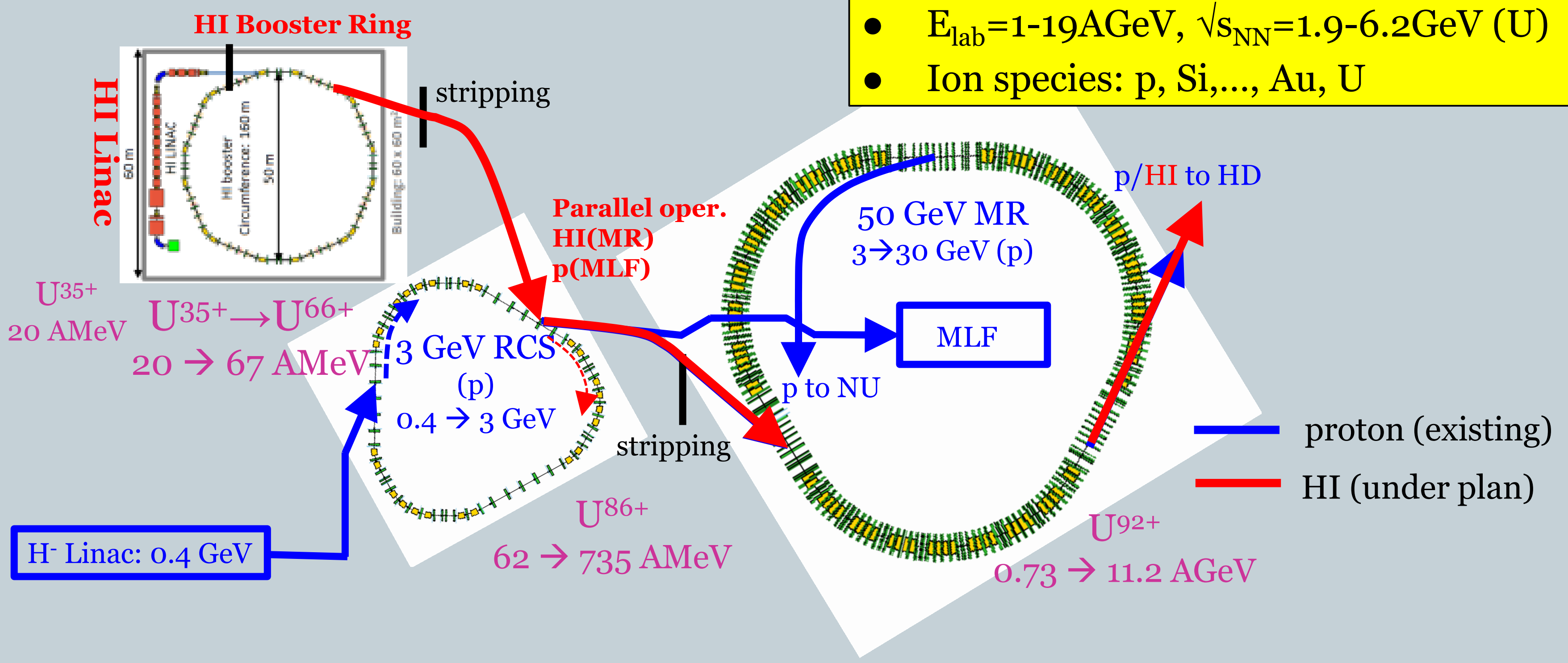
Acceleration Scheme for Uranium case(Proposed by H. Harada, J-PARC)



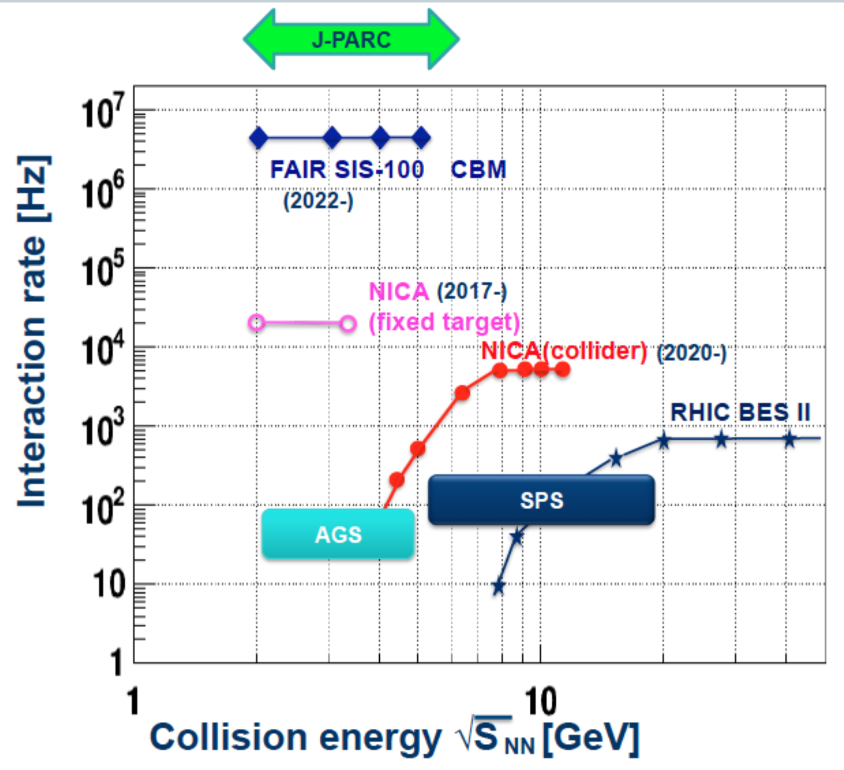
New LINAC and Booster for HI must be constructed.

HI acceleration scheme in nutshell

- ***World's highest intensity*** ~10^{11} Hz, Interaction rate ~ 10^8 Hz
- E_{lab}=1-19AGeV, $\sqrt{s_{NN}}$=1.9-6.2GeV (U)
- Ion species: p, Si,…, Au, U



Available beam and rate



Statistics
1 year at AGS = 5 min at J-PARC-HI

Assumed beam rate: 10^{11} Hz

0.1% λ_I target →Event rate: 100MHz

In one month experiment:

$\rho,\omega,\phi \rightarrow ee$: 10^{10} - 10^{12}
Hypernuclei: 10^4 - 10^{12}
Strangelets: 1 - 10^2

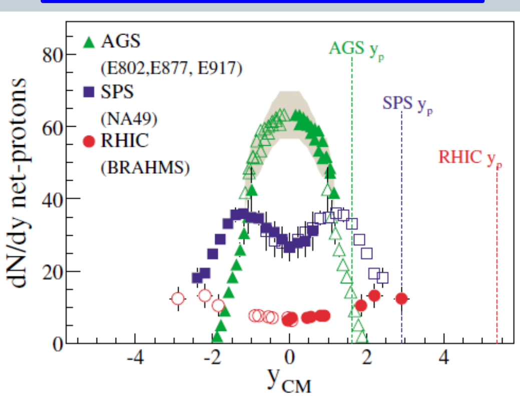
Ref: HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203

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

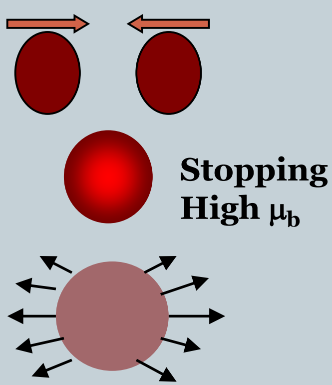
What's expected at J-PARC energy?

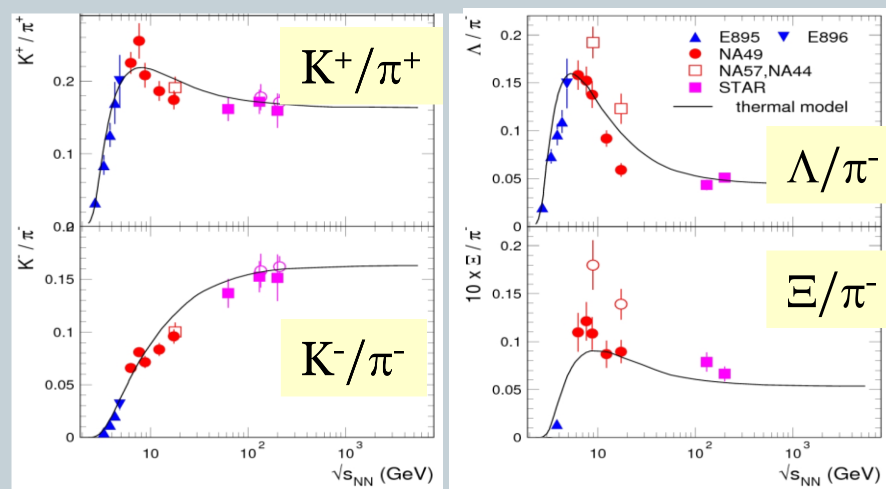
- Baryon is highly stopping at mid-y, at AGS (=J-PARC) energy
  - → **High density matter.** Nucleons pass through each other at SPS and above
- (K^+, Λ, Ξ,)/π ratio have maximum at $\sqrt{s_{NN}}$~5GeV
  - → **Strangeness fraction is largest at J-PARC energy.** (π is a proxy of multiplicity)

Au+Au: ~6ρ_0 , U+U: ~8.6ρ_0



NPA772(2006)167





Observables: Dileptons

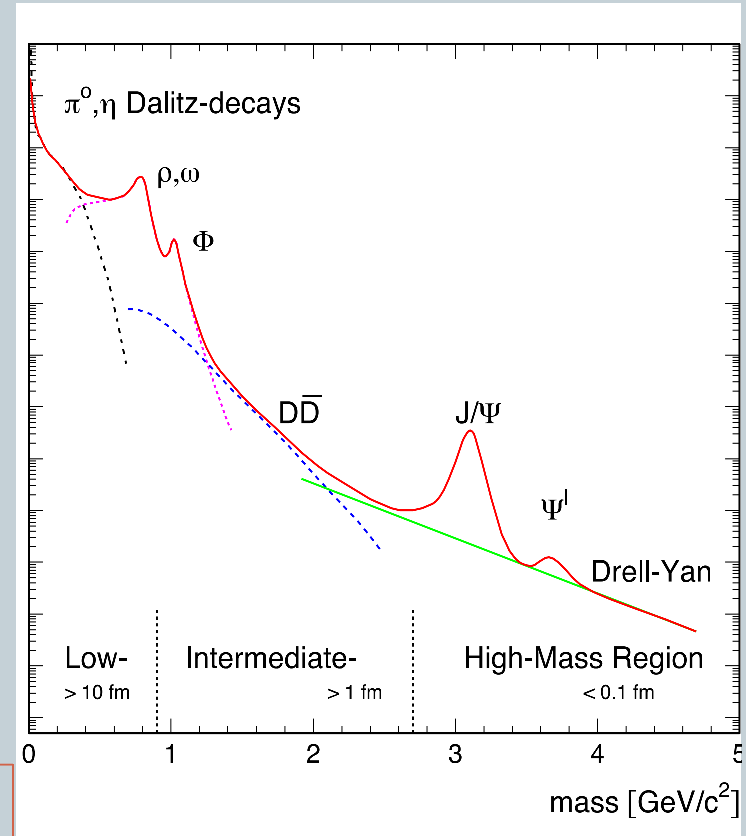
No dilepton measurement at $\sqrt{s_{NN}}$~5GeV

- Very low mass region (<100MeV)
  - Soft mode associated with phase transition
- Low mass region: ρ/ω/ϕ (~10^{-3})
  - Chiral symmetry restoration study by spectra shape analysis with high statistics

$$\int dm_{ee} N(m_{ee}) {m_{ee}}^n \; (n = 1,2, \ldots)$$

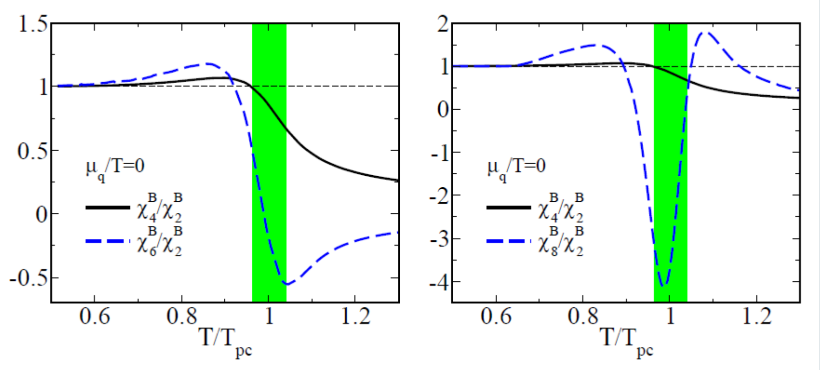
  - →Comparison to models with q/g condensation (Hayano and Hatsuda, RMP**82**, 2949)
- Intermediate mass
  - Thermal radiation. c-cbar free at J-PARC energy
- High mass region: J/ψ?

Fully exploiting high luminosity at J-PARC

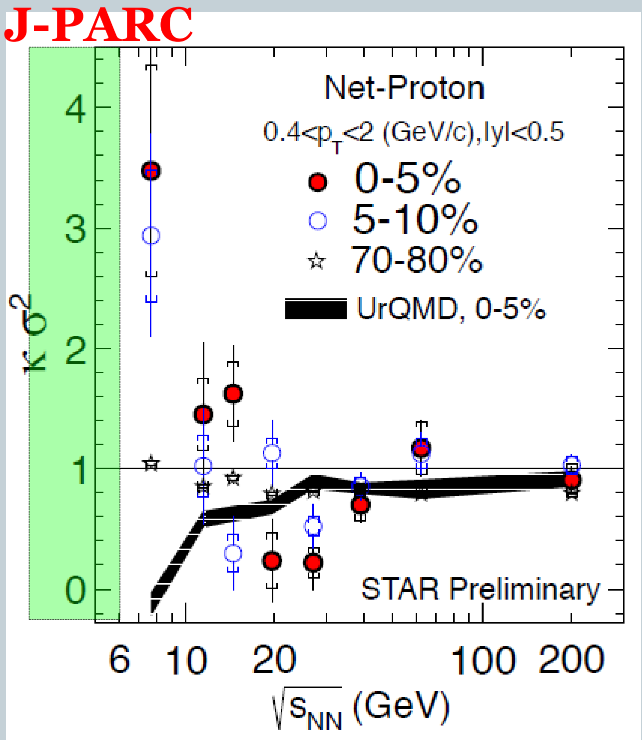


Observables: Event-by-event fluctuation

- 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

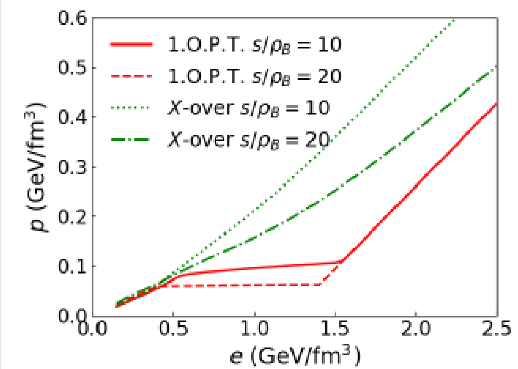
Observables: Flow (constraining EOS)

- 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

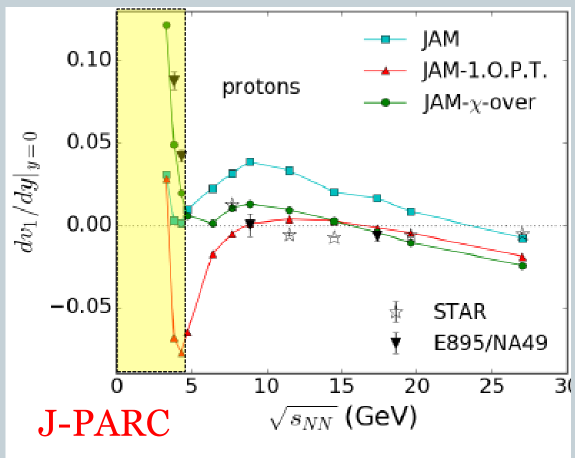
dv1/dy < 0 :softening of EOS (due to phase transition?)

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

EOS in JAM model

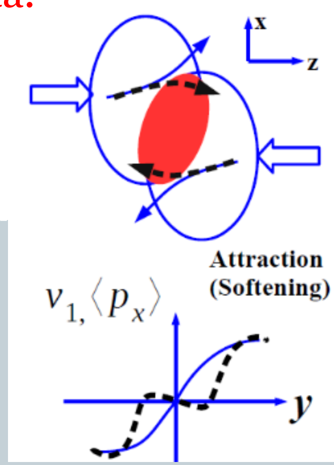


Y. Nara, et al, PLB769 (2017), EPJA54 (2018)



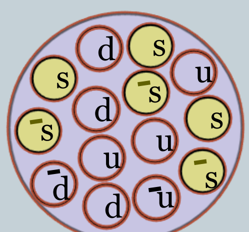
A. Ohnishi, Reimei HI, Aug 2016

Y. Nara, KEK Theory group Workshop, Feb 2017

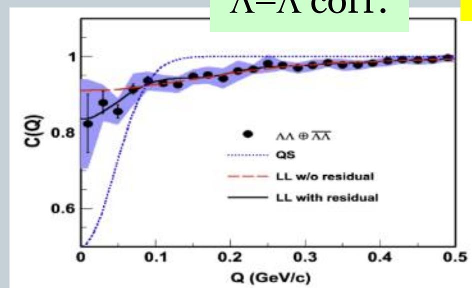


More observables…

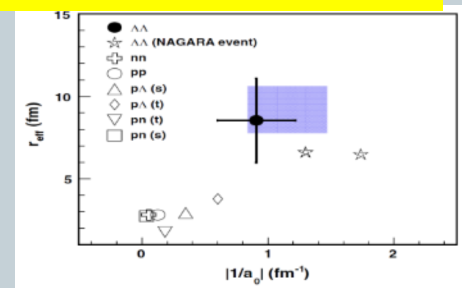
- Λ–Λ correlation
  - Baryon-baryon interaction measurement in high density matter?
- Ω–Ω bound states?
  - A recent Lattice result suggests a weak bound-states (B.E.=1.6MeV) of two Ω's
- More exotics?
  - Λ(1405), Dibaryon (H-dibaryon,…)
  - Kaonic nucleus (K-pp,…), Strangelet..
  - 6, 8, 10 quark states?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



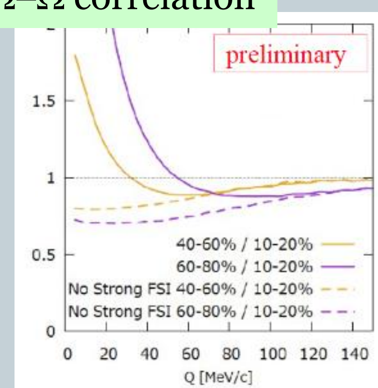
Λ–Λ corr.



STAR, PRL114, 022301 (2015)

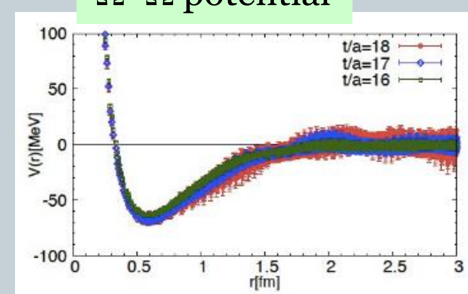


Ω–Ω correlation



K. Morita, et.al.

Ω–Ω potential



Gongyo et al.,
PRL120, 212001 (2108)

Strategy for high-rate measurements

- 10MHz DAQ system
  - Continuous readout + online data reduction
  - Online triggers (Centrality, dimuon, ….)
- High rate detectors
  - Silicon pixel trackers
- Large acceptance (~4π)
  - E-b-e fluctuations, etc.

New design of Dipole magnet spectrometer

As beam intensity increases;

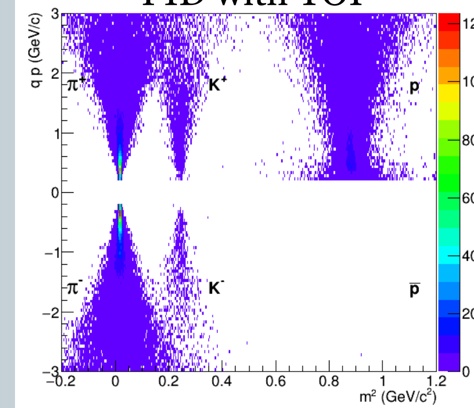
1. Dipole hadron spectrometer (10^6 Hz)
2. Dipole dimuon spectrometer (10^7 Hz)
3. Hypernuclear spectrometer (10^8 Hz)

Basic spectrometer Performance

40

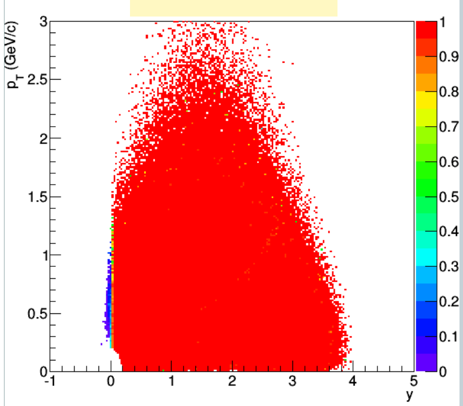
- Detector simulation using GEANT
- U+U $\sqrt{s_{NN}}$=4.5 GeV, MinBias JAM events

PID with TOF

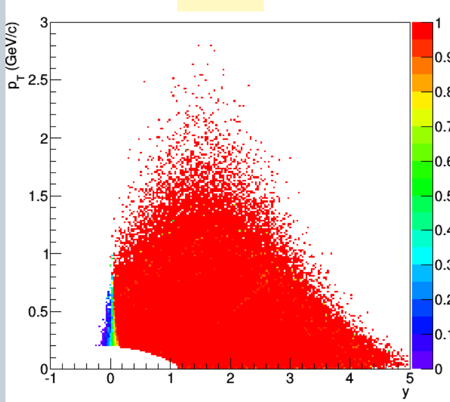


y-p_T Acceptance

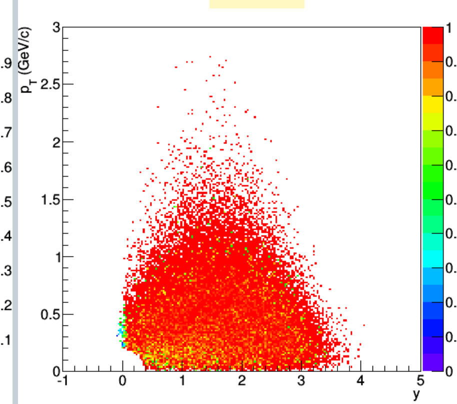
Protons



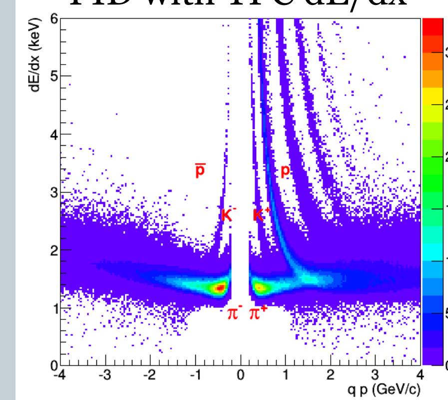
π^+



K^+



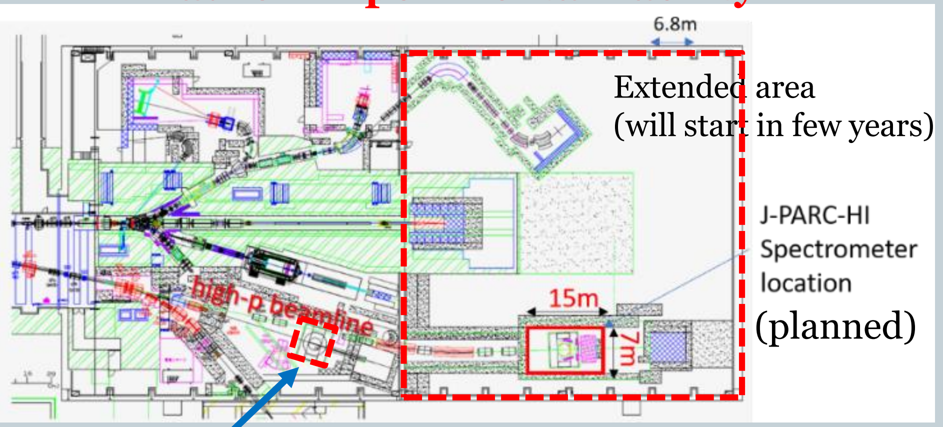
PID with TPC dE/dx

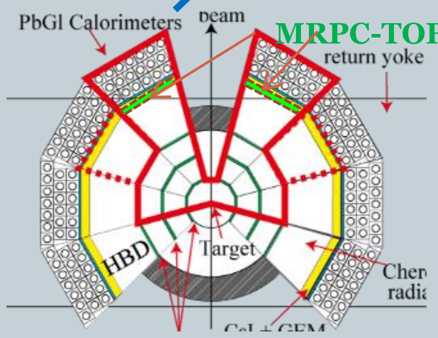


Status and plan

- Accelerator side
  - JAEA and J-PARC are positive for building an ion source, a linac and a booster (~$140M)
  - We are documenting a project proposal for the Masterplan of Science Council of Japan (5 year-plan starting 2019)
- Facility side
  - Identified location for detectors on the high-momentum beamline
- R&D and Phase-0 experiment
  - Continuous readout and online tracking
  - MRPC-TOF (σ=50ps) test and hadron measurements in p+A in Jan. 2020.
    - At J-PARC E16 exp.

Hadron Experimental Facility





J-PARC E16