Studies of extremely dense matter in heavy-ion collisions at J-PARC

Hiroyuki Sako (ASRC, JAEA / U. Tsukuba) for J-PARC-HI Collaboration

Outline

1. Overview of J-PARC-HI
2. Experimental design and simulations
3. Summary and Prospect

J-PARC Heavy-Ion Project (J-PARC-HI) - Studies of densest baryonic matter in the universe -

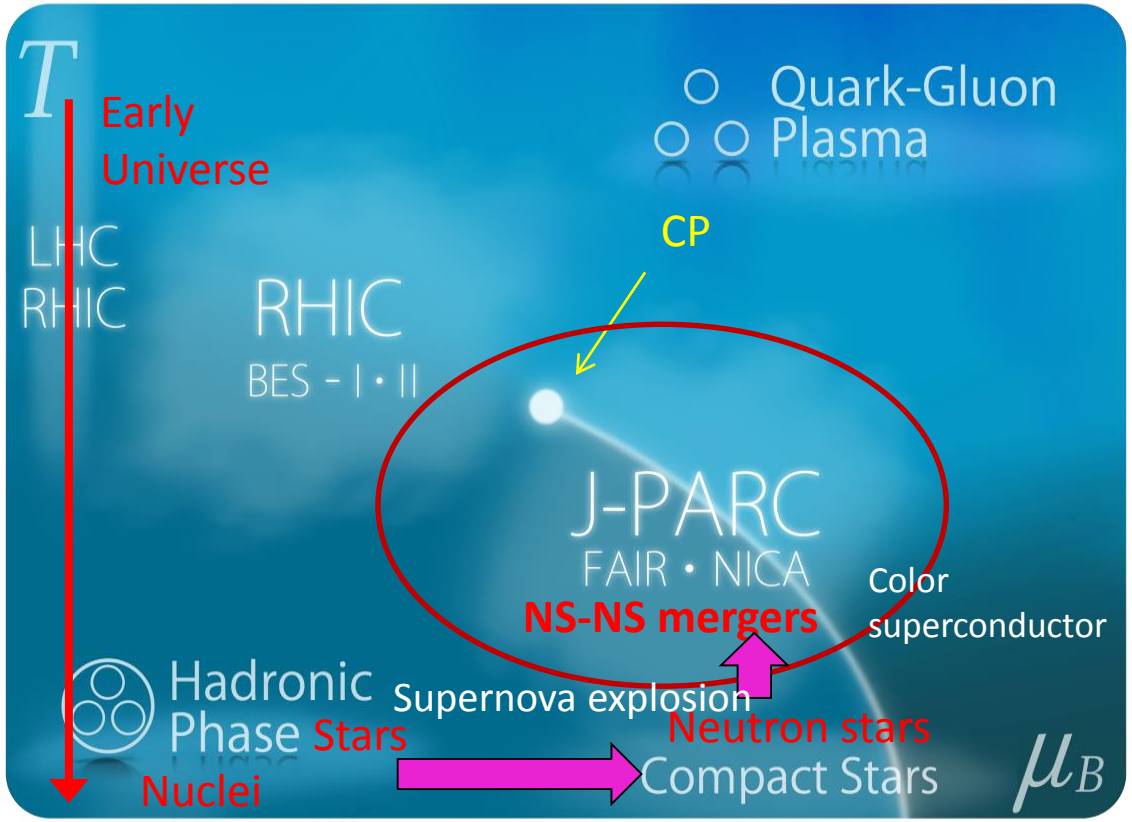
High-T, low density region
QGP produced (SPS/RHIC/LHC)
Phase transition is smooth cross-over

High density region
QCD phase structures (Phase transition, Critical Point) not discovered

Heavy-ion Collisions at J-PARC
Unique experimental tool to explore the high density region

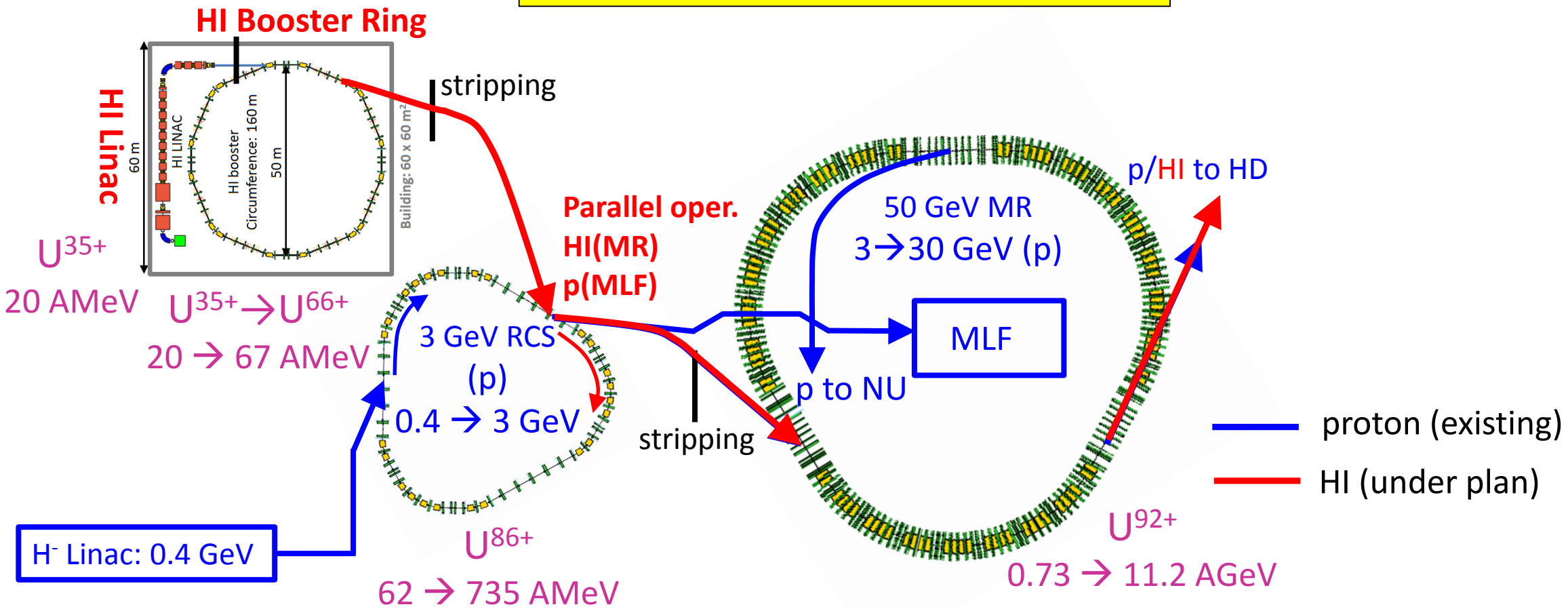
- QCD phase structure
- Properties of high-density matter (EOS etc)

QCD phase diagram



HI acceleration scheme

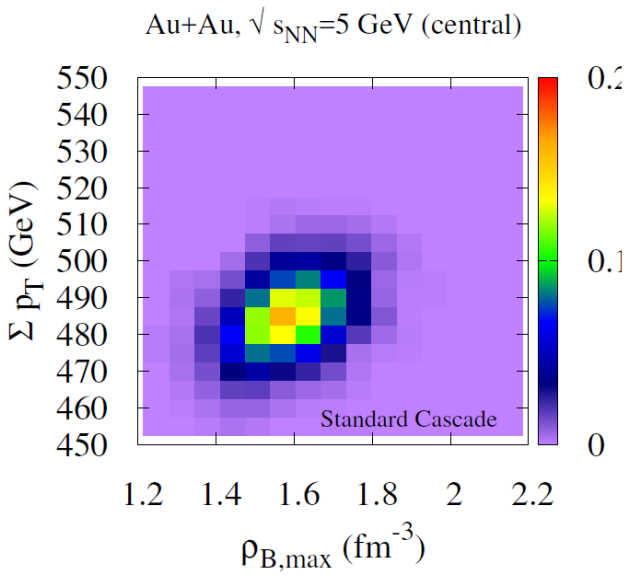
- ***World's highest intensity*** ~10^{11} Hz, Interaction rate ~ 10^{8} Hz
- E_{lab}=1-19AGeV, $\sqrt{s_{NN}}$=1.9-6.2GeV (U)
- Ion species: p, Si,…, Au, U



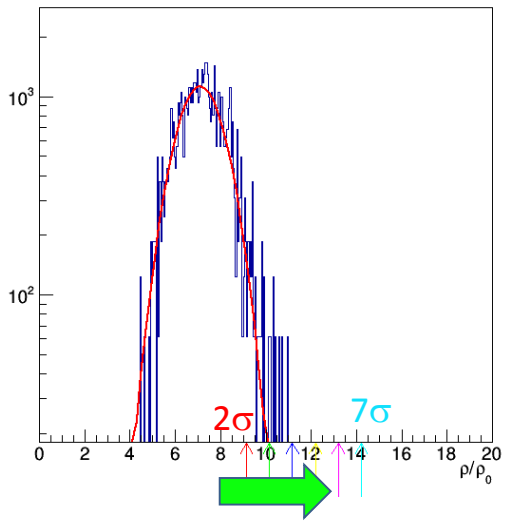
Event Selection and Observables

Selection of high density events
w/ correlated observables
(e.g. Sum p_T of charged particles)
Higher statistics→Higher baryon density events can be selected

Max Baryon density vs Sum of pt (JAM)



Max Baryon density distribution (JAM)



Higher statistics
→Higher density events

Observables

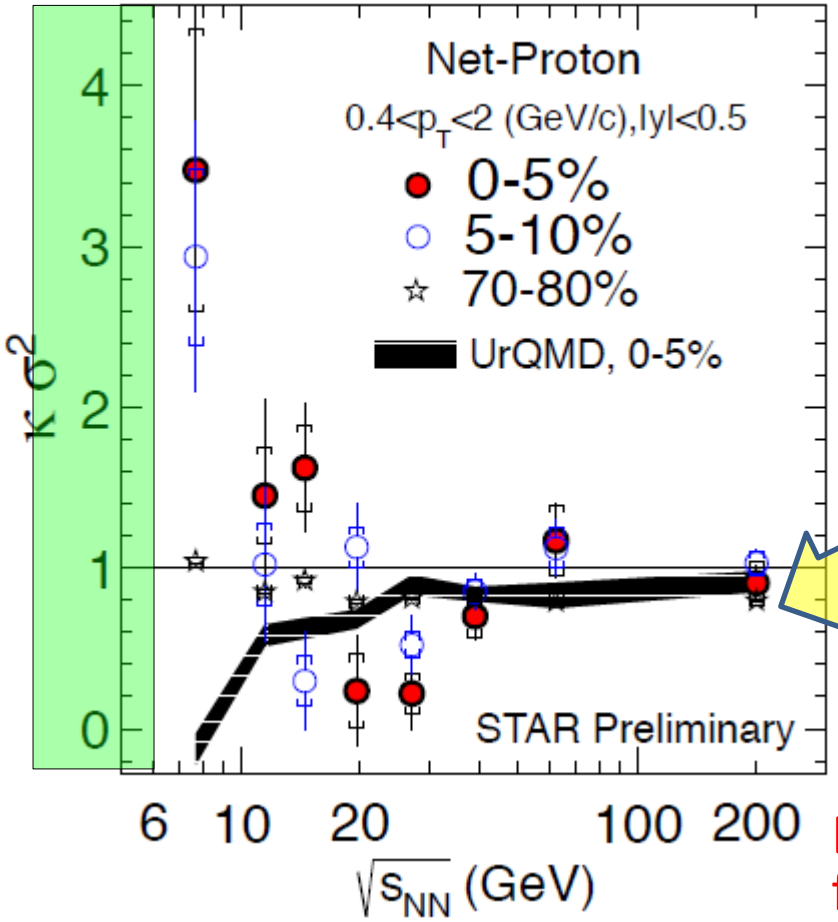
- Dileptons
- Hadrons
  - Event-by-event fluctuations
  - Collective flow
  - YN, YY interactions w/ two particle correlations
    - Important to construct EOS
- Multi-strangeness systems
  - Hypernuclei (|S|>=3), Strangelets

Event-by-event fluctuations

Event-by-event fluctuations of conserved charge:

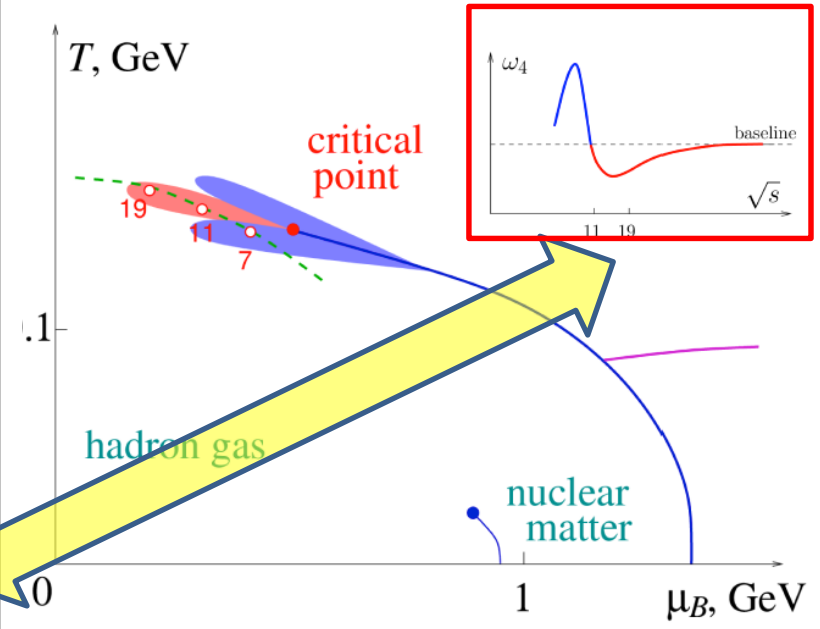
Probe to search for the critical point

J-PARC



X. Luo, Quark Matter 2015

Theory M.A. Stephanov, PRL107, 052301 (2011).



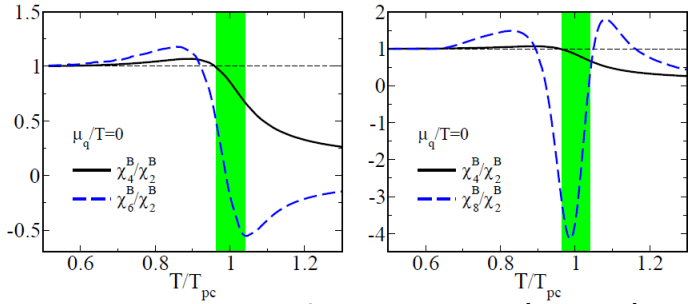
Enhancement of 4th-order fluctuations at low energies

Indications of the critical point?

4th→6th→8th 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

Dileptons

No dilepton measurement at J-PARC energy

- Extermely low mass region (<100MeV)
  - Soft mode associated with phase transition
- Low mass region

  $\rho/\omega/\phi$ ($\sim 10^{-3}$)

Study of chiral symmetry restoration

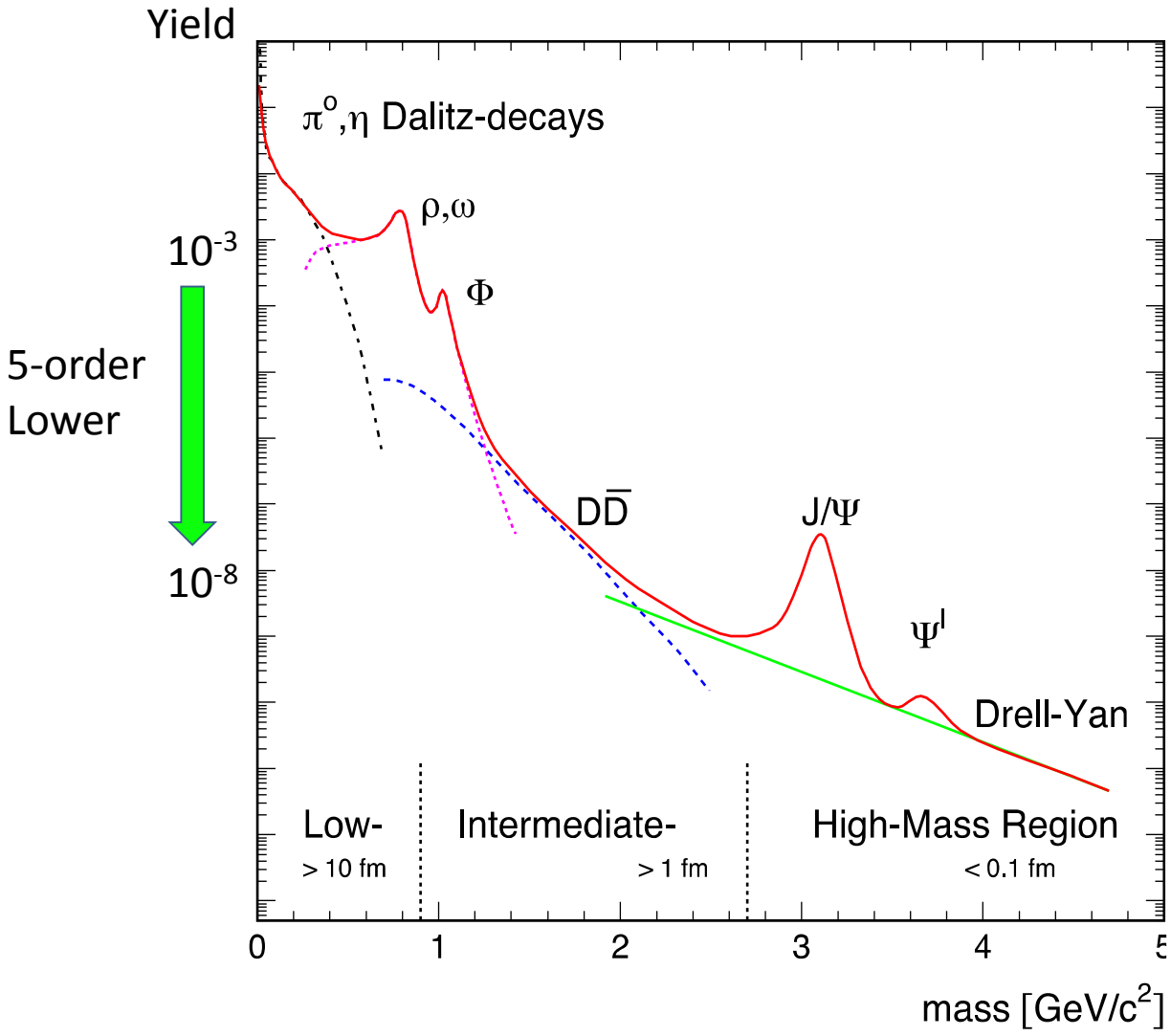
Spectra shape analysis with high statistics

→Direct comparison to theoretial models to estimate quark and gluon condensate

(Hayano and Hatsuda, RMP**82**, 2949)

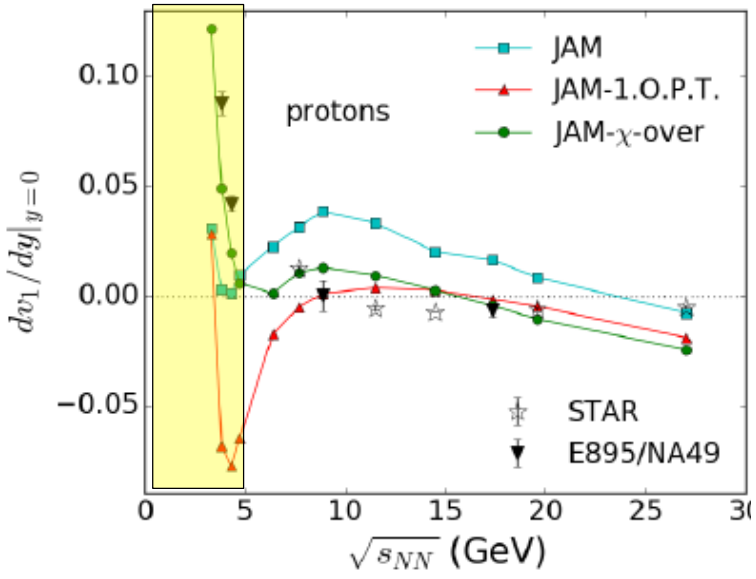
- Intermediate mass ($\sim 10^{-8}$)
  - Thermal radiation with low background
- High mass region
  - J/ψ ($\sim 10^{-7}$)

High-statistics measurements at J-PARC



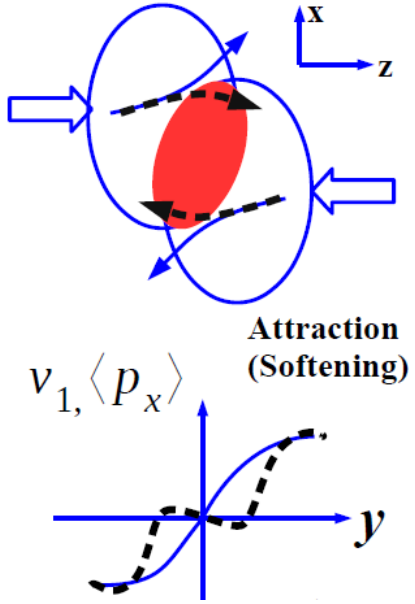
Constraining EOS with Flow

J-PARC

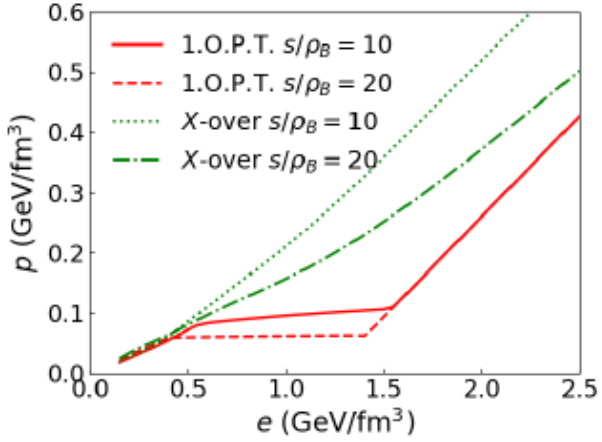


dv1/dy < 0 :softening of EOS (due to phase transition?)

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



EOS in JAM model



3rd→4th→5th order flow
Property of dense matter
(such as viscosity)
(1-order higher flow→1 order higher statistics)

A. Ohnishi, Reimei HI, Aug 2016

Y. Nara, et al, PLB769 (2017), EPJ A 54 (2018)

Y. Nara, KEK Theory group Workshop, Feb 2017

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.

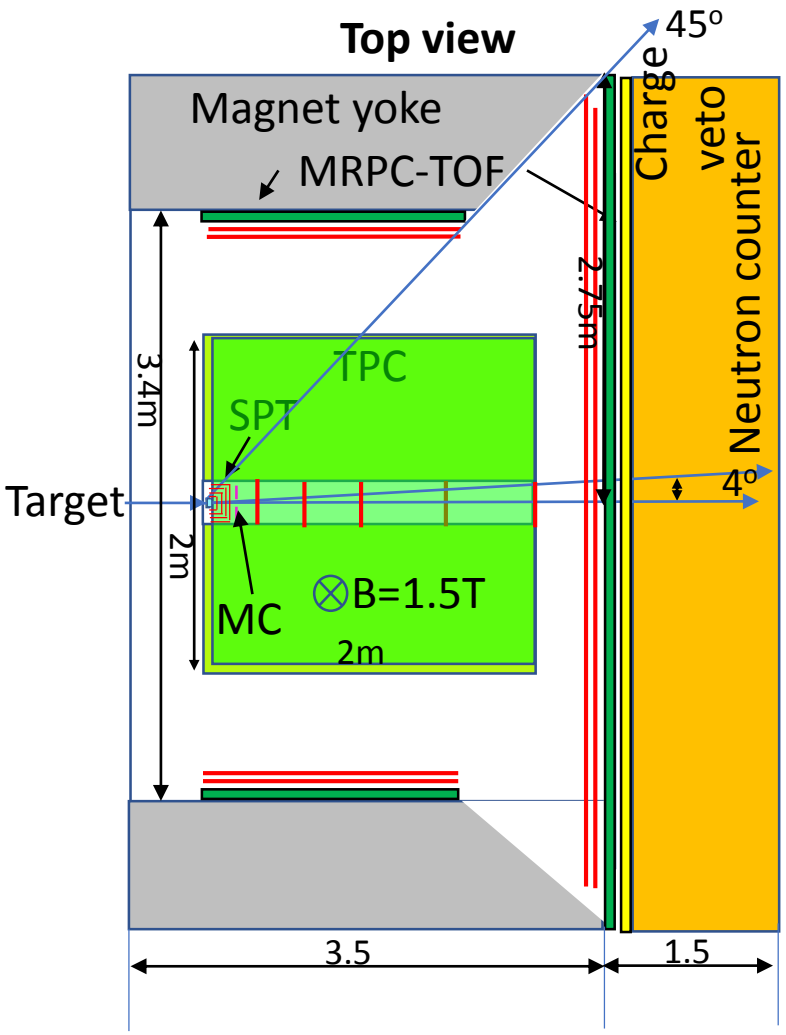
New design of Dipole magnet spectrometer

As beam intensity increases;

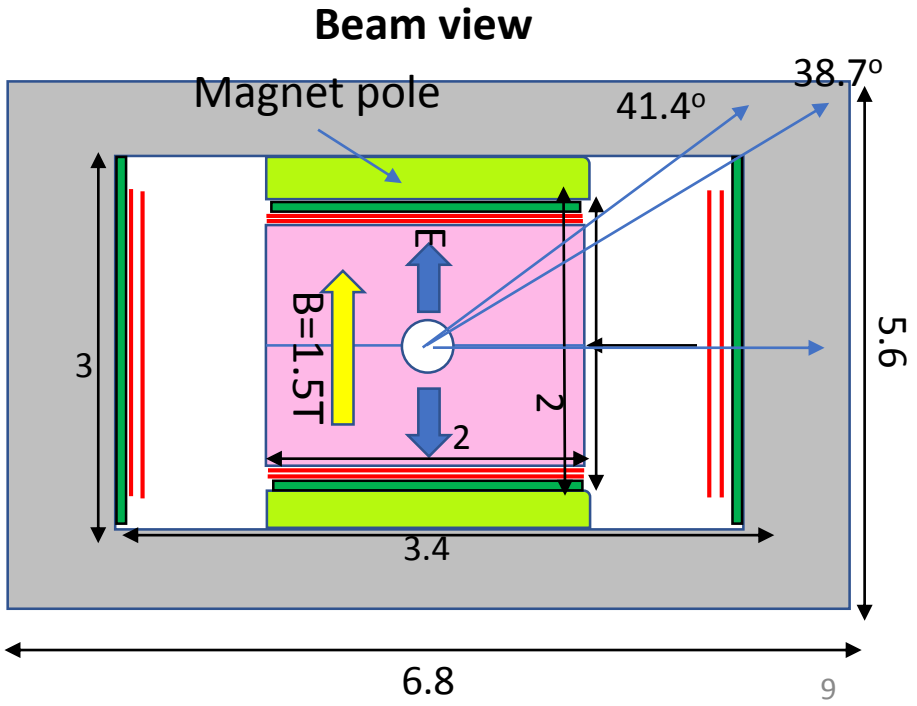
1. Dipole hadron spectrometer (10^6 Hz)
2. Dipole dimuon spectrometer (10^7 Hz)
3. Hypernuclear spectrometer (10^8 Hz)

Dipole hadron spectrometer

- Charged particles + neutrons
- ~4π acceptance
  - Silicon Pixel Tracker (SPT) ($\theta < 4^o$)
  - TPC ($\theta > 4^o$)
  - MRPC-TOF
  - neutron counter
- Rate : <=10^6 Hz interaction
- Centrality : Multiplicity counter + Zero-degree calorimeter



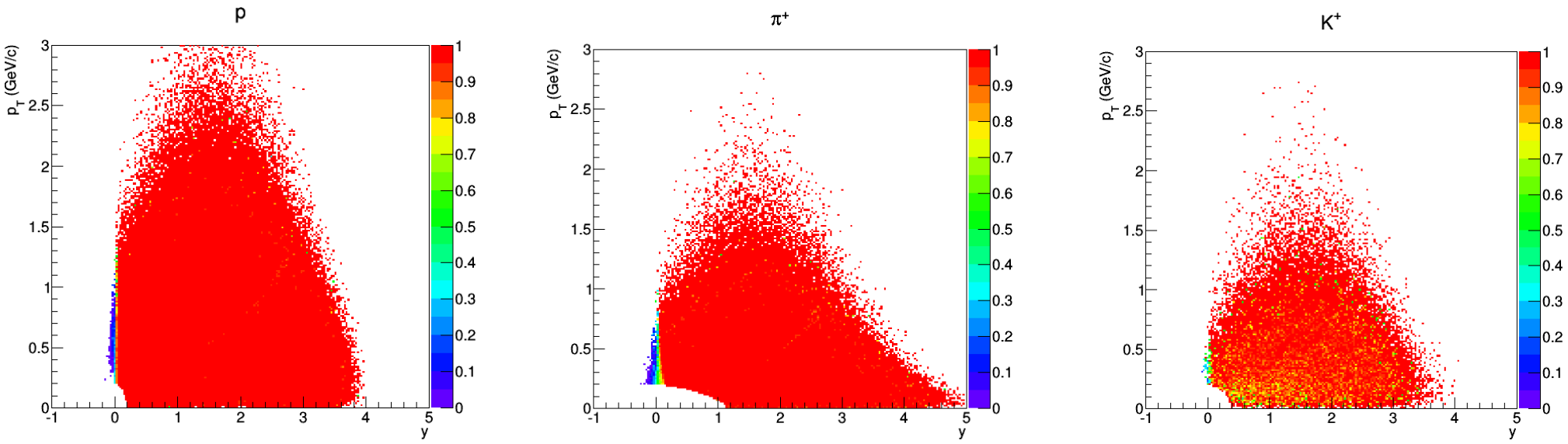
ZCAL



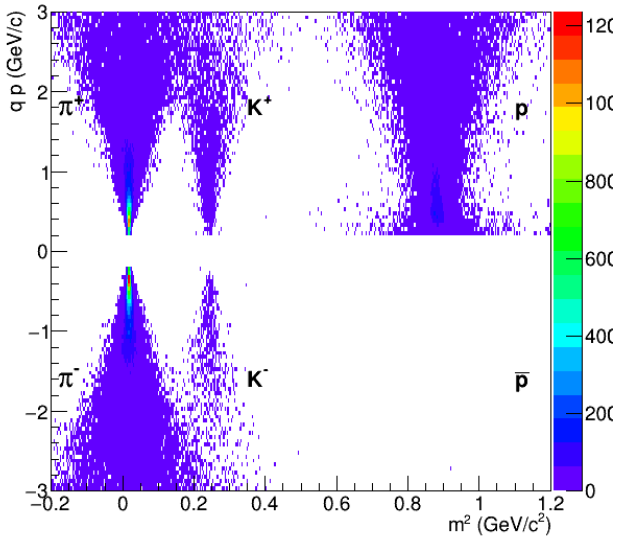
Spectrometer Performance (Preliminary)

J-PARC-HI simulation, U+U
$\sqrt{s_{NN}}$=4.5 GeV, minimum bias

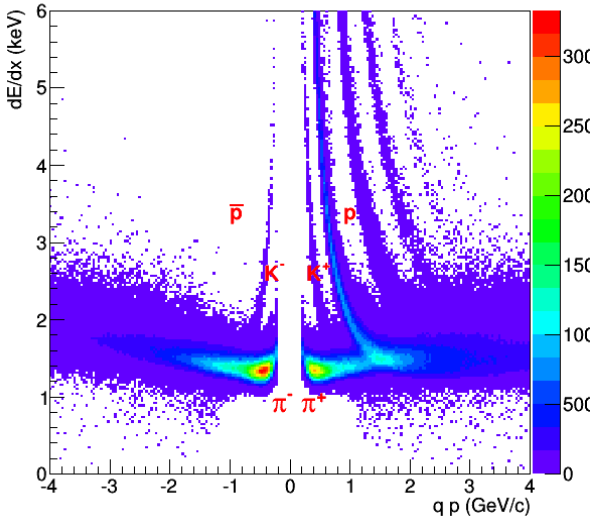
y-p_T Acceptance



PID with TOF

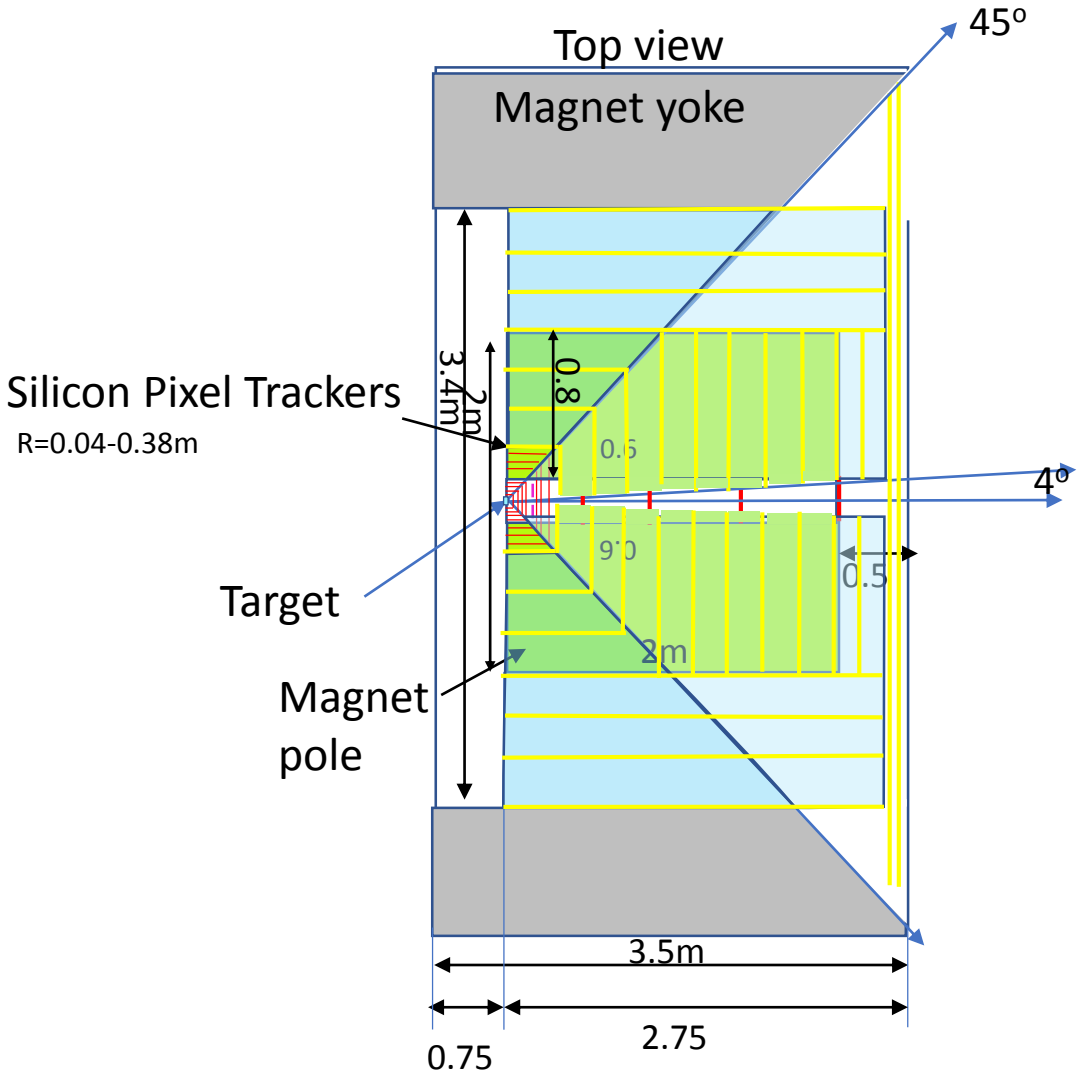


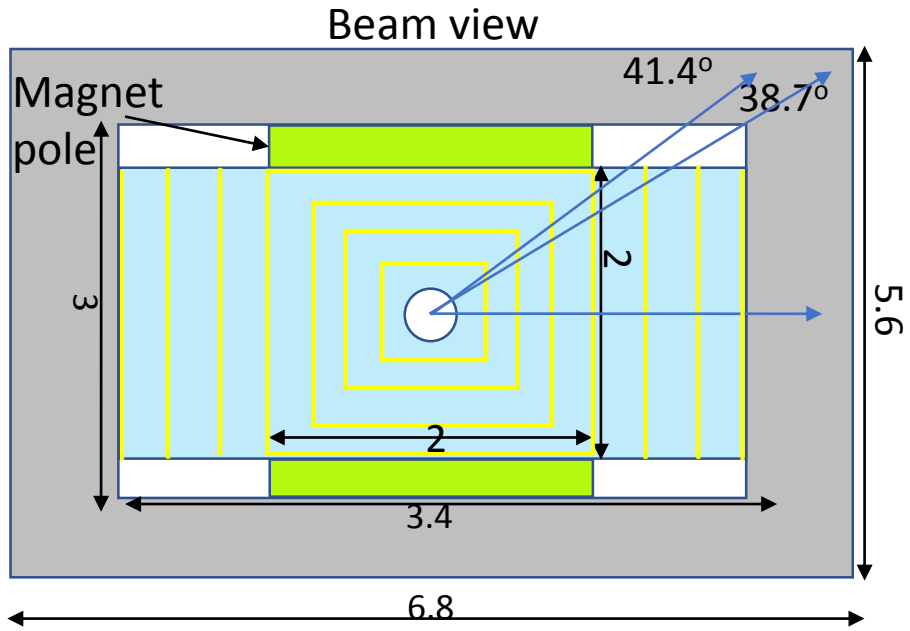
PID with TPC dE/dx



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





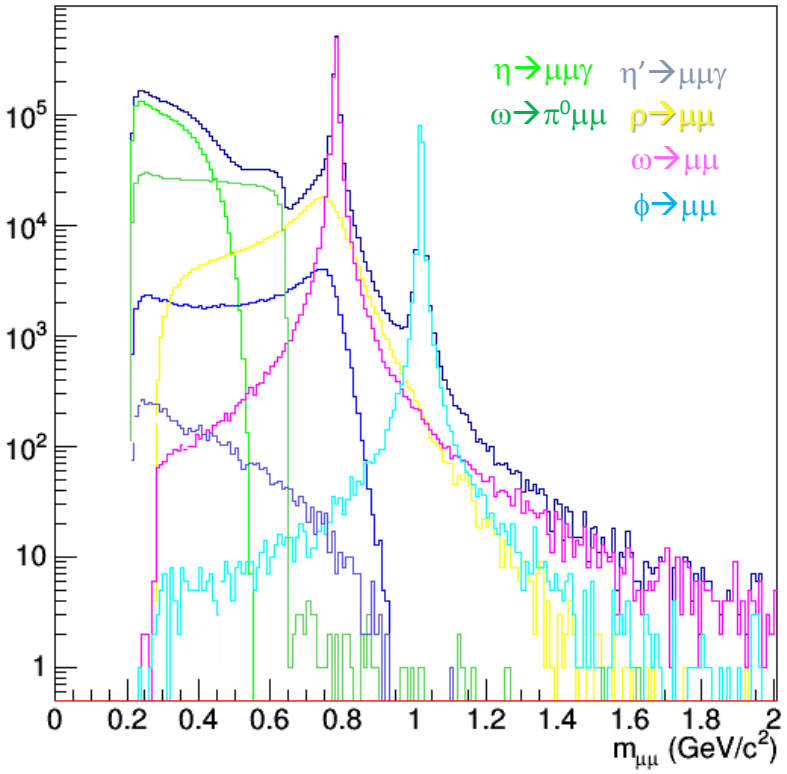
Expected dimuon spectrum (Preliminary)

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

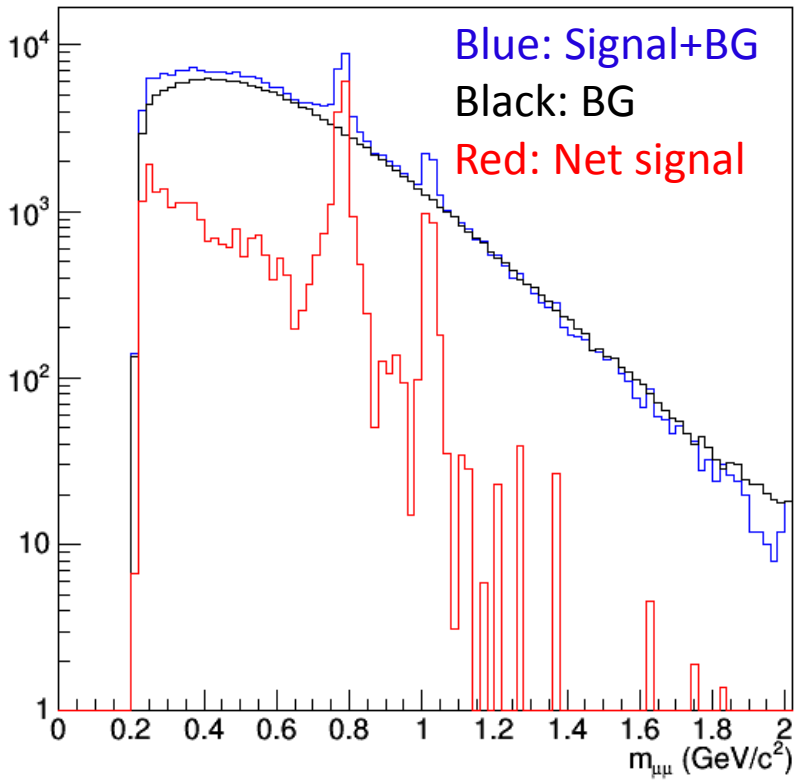
$\theta_{ee}>2^o$
$2^o<\theta<80^o$
$p_T>0.1$GeV/c

- $\mu+\mu-$ cocktail
  - $\eta, \rho, \omega, \eta', \phi \rightarrow \mu+\mu-$
  - BR of each $\mu+\mu-$ channel is enhanced by factor of 1000
- Generate JAM events as background
  - U+U, 10AGeV, Min-bias
- Mix $\mu+\mu-$ cocktail with JAM events and process through GEANT
  - Enabled weak decay
- Reconstruct tracks passing through muon absorbers with 4 λ_I

Generated cocktail



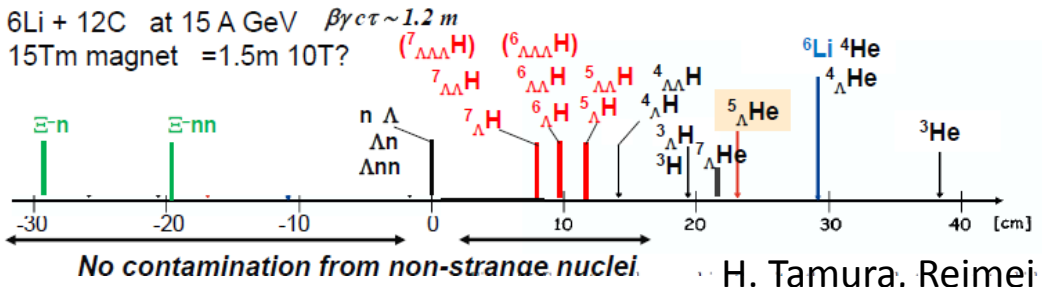
Reconstructed spectrum



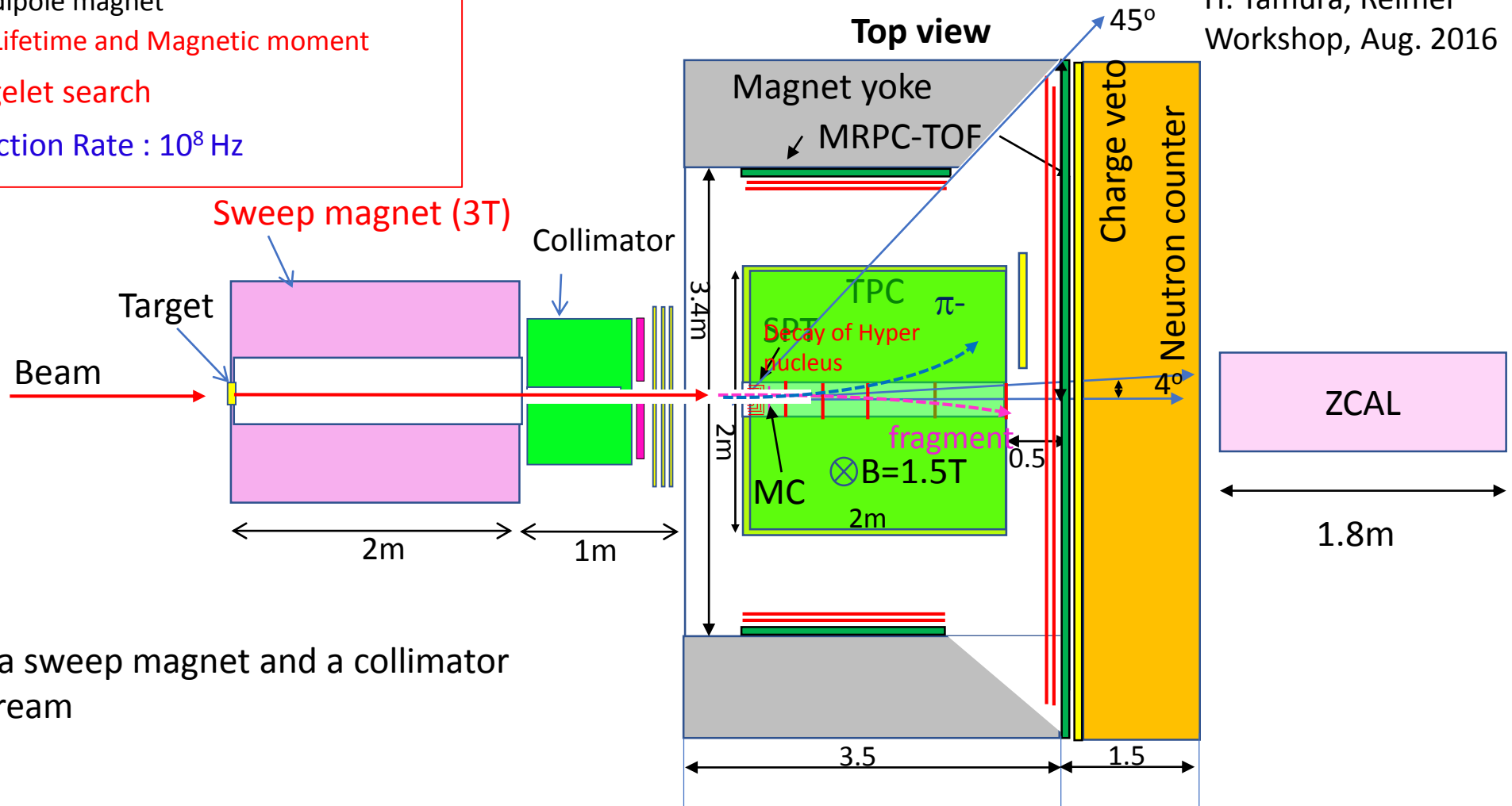
Hypernuclear Spectrometer

Add Sweeping magnet in upstream

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



H. Tamura, Reimei Workshop, Aug. 2016

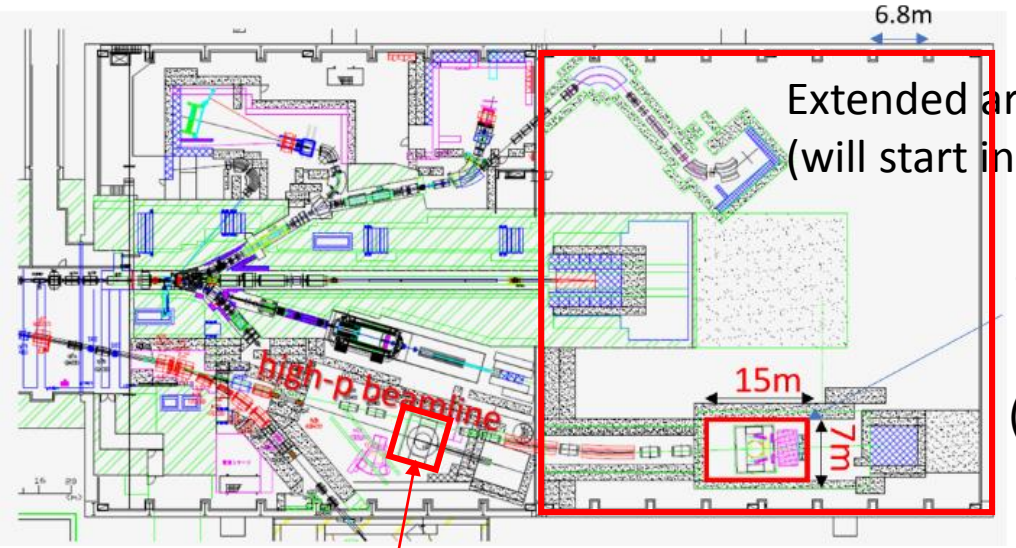


Add a sweep magnet and a collimator upstream

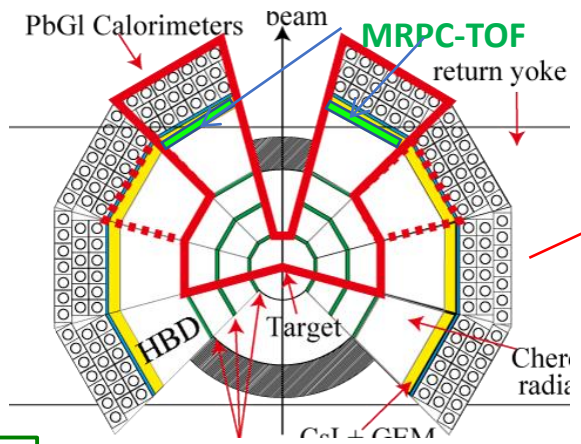
Status and plans towards J-PARC-HI

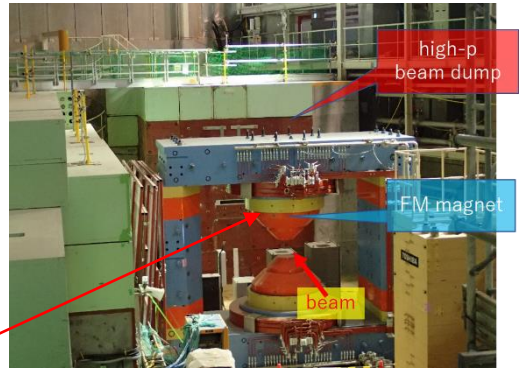
- J-PARC-HI spectrometer
  - Space kept in the high-p beamline
- R&D
  - MRPC-TOF (JAEA and Univ. Tsukuba)
    - 50ps resolution aimed with 60cmx60cm MRPC
  - Continuous readout and online tracking (ALICE)
- Plans
  - Test of MRPC-TOF and hadron measurements in p+A experiment (J-PARC E16), which will start in Jan. 2020.

Hadron Experimental Facility

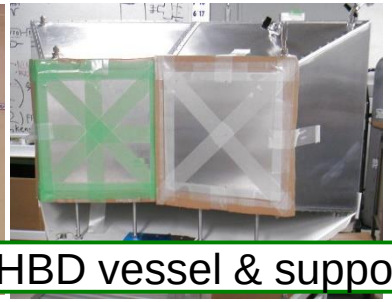


J-PARC E16
(Jan 2020 -)






LG frame


HBD vessel & suppor


GTR support

Summary and Prospect

- J-PARC-HI : Unique Lab to study QCD phase structures and EOS of dense matter
- World's highest rate HI beam of 10^{11} Hz is aimed
- Measurements of fluctuations, dileptons, and multi-strangeness systems
  - Large acceptance dipole spectrometers at the high-momentum beamline

Prospect

- Letter-Of-Intent submitted to J-PARC PAC (2016)
  (https://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-16.pdf)
- Design and R&D of Accelerator and Detectors
  → Proposal of the HI experiment to J-PARC PAC (2019-)
- Discussions on budget request is going on
- Earliest possible start of the experiment (~2025)

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