Prospect of Heavy-ion Collision Experiments at J-PARC

H. Sako (*JAEA & Univ. of Tsukuba*)
for J-PARC-HI Collaboration

Critical Point and Onset of Deconfinement 2017
Stony Brook, Aug. 11, 2017

Outline

1. Introduction
2. HI acceleration
3. Physics goals
4. Experimental design
5. Summary and prospect

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

J-PARC-HI Project
- Lab of dense baryonic matter -

QGP produced at RHIC/LHC at high T and low ρ

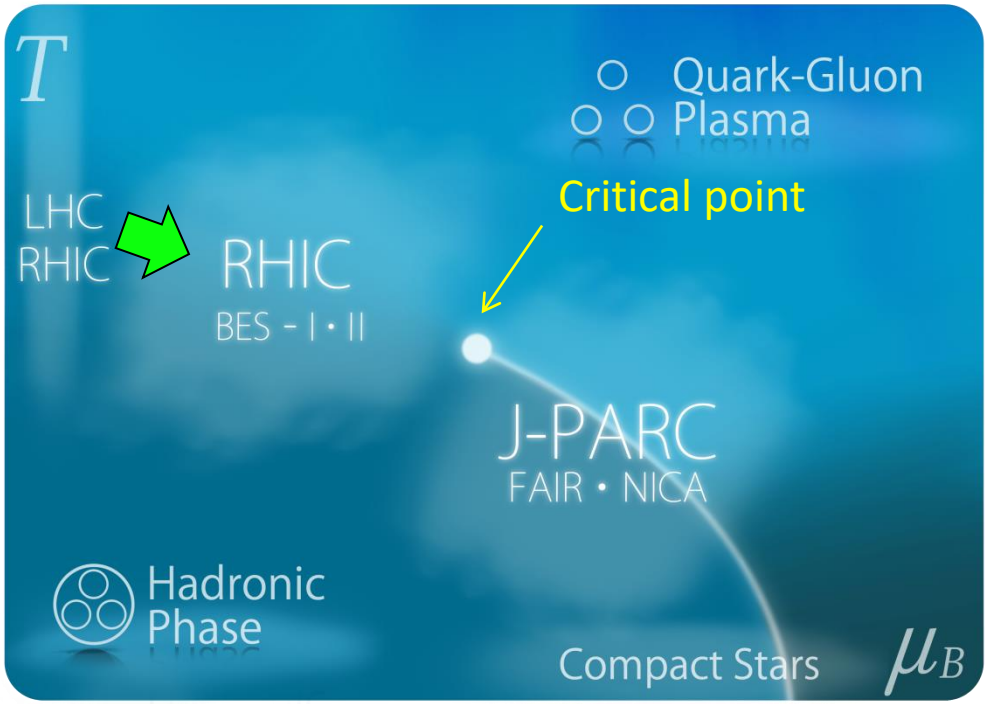
⇔ In high density regime, QCD phase structures (critical point, phase boundary) has not been discovered

In HIC at J-PARC, dense baryonic matter will be created

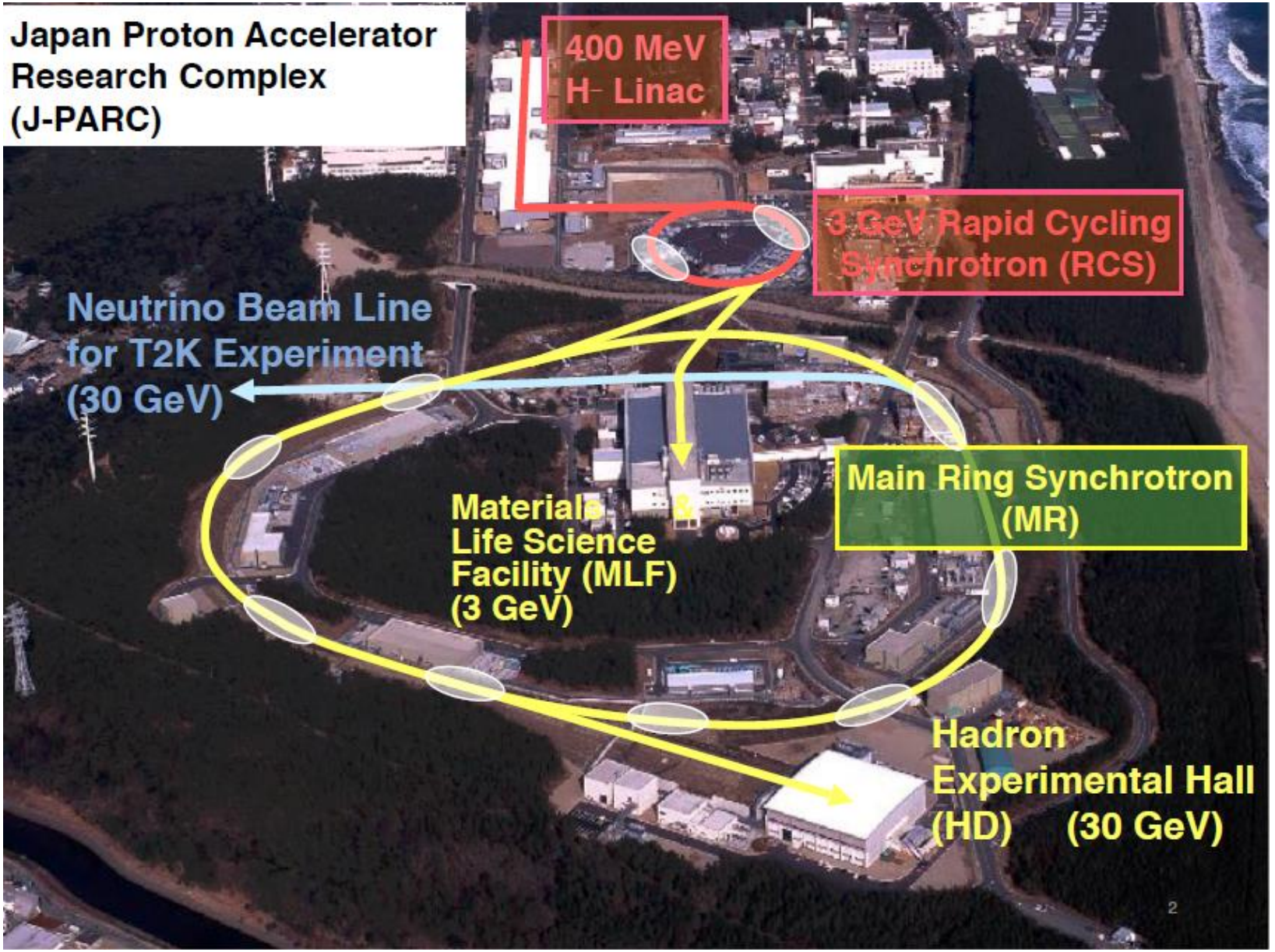
~$8\rho_0$* ~ neutron star core

Goals of J-PARC-HI

- Exploring QCD phase structures
- Studying hadron/nuclear properties related to neutron stars

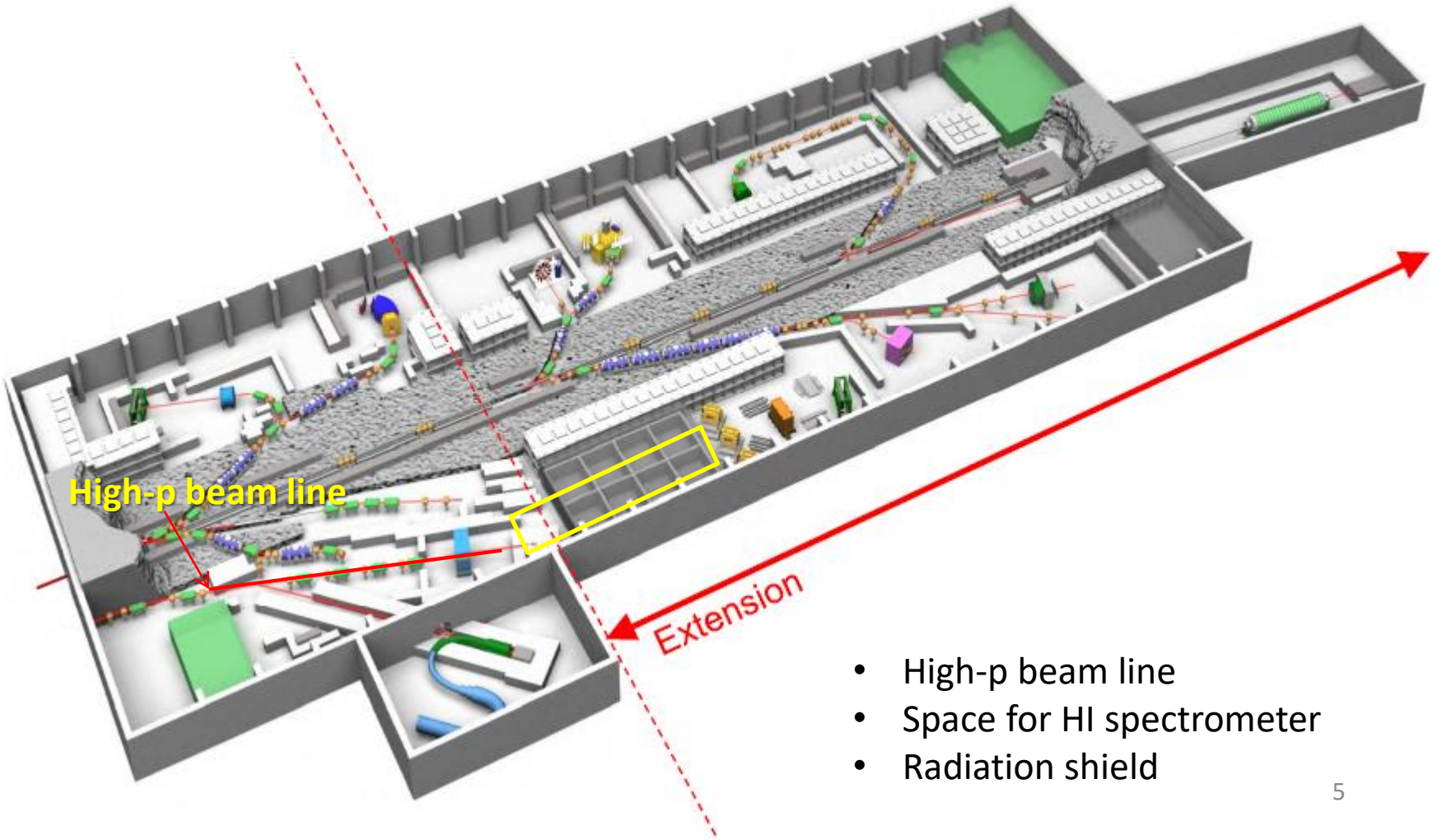


*JAM model
Y. Nara, et al, Phys. Rev. C61,024901(1999)



F. Naito, J-PARC PAC, July 2017

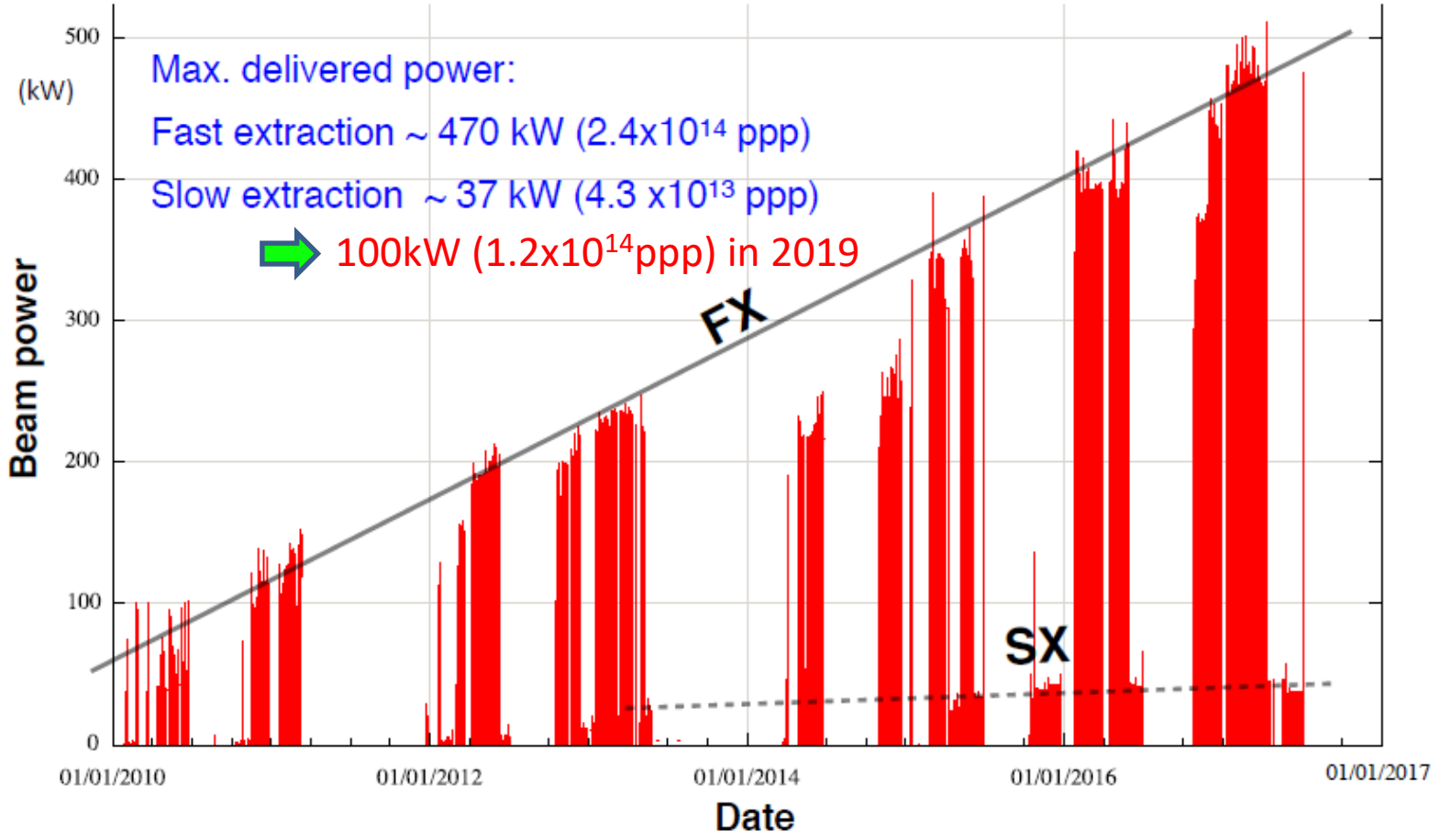
Possible HI spectrometer location



- High-p beam line
- Space for HI spectrometer
- Radiation shield

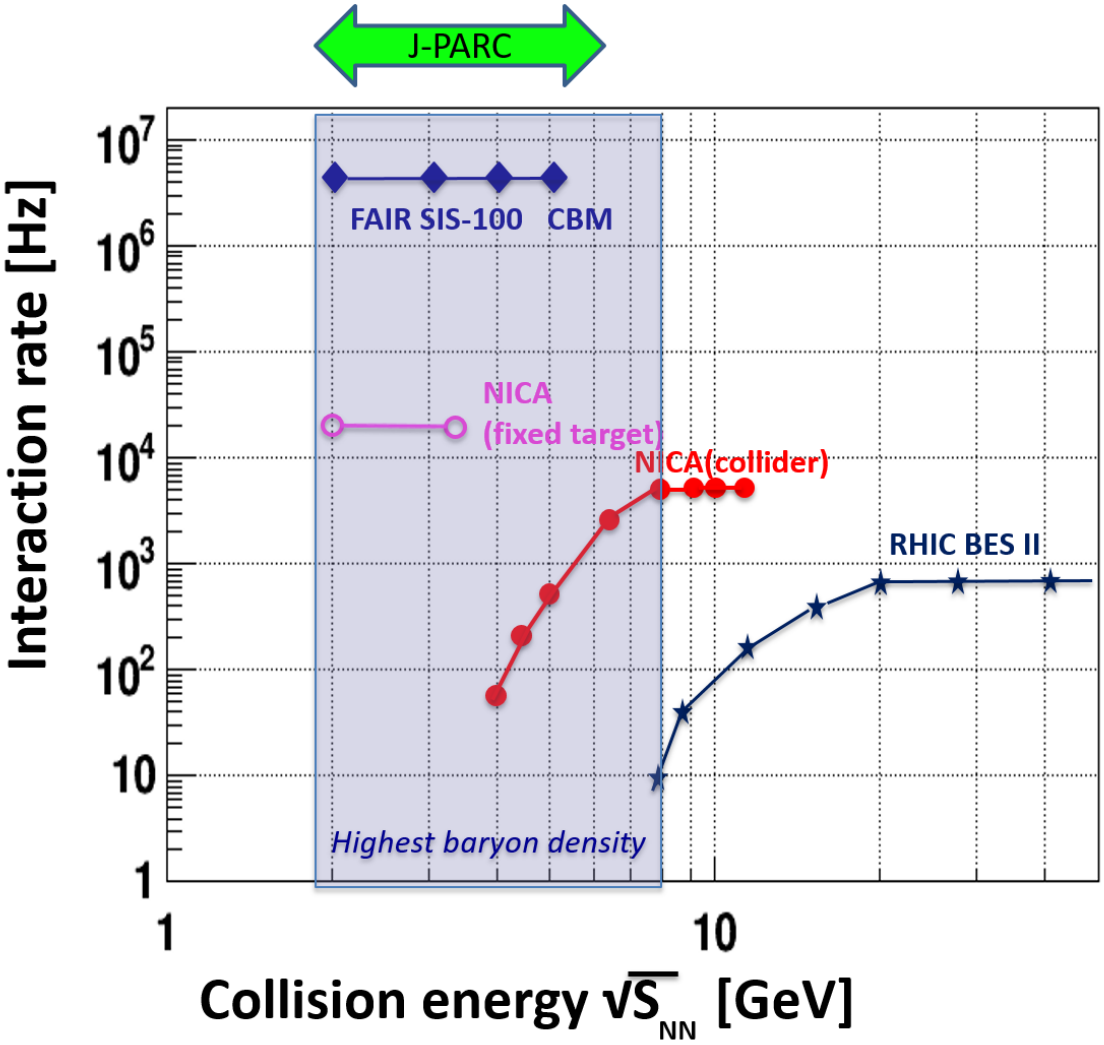
MR: Beam power history

- In the operation from Jan to April 2017, the beam power was mostly about 470 **kW with 2.4×10^{14} protons per pulse**.
- The beam power of SX mode was limited to **~37 kW** in June 2017 because of ESS trouble.

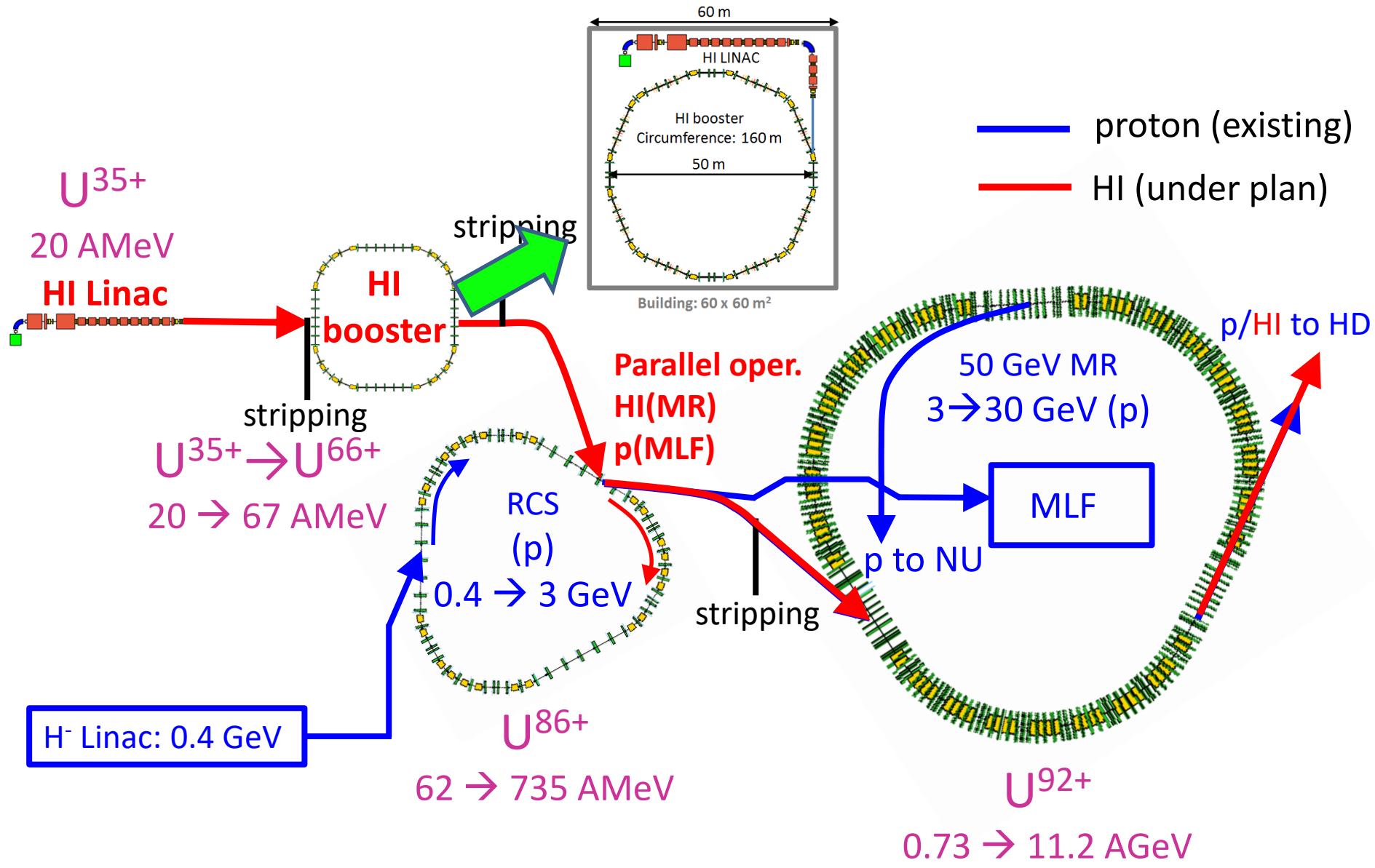


J-PARC-HI beam

- ***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



HI accelerator scheme



Particle production rates

Beam : 10^{10} Hz

0.1 % target

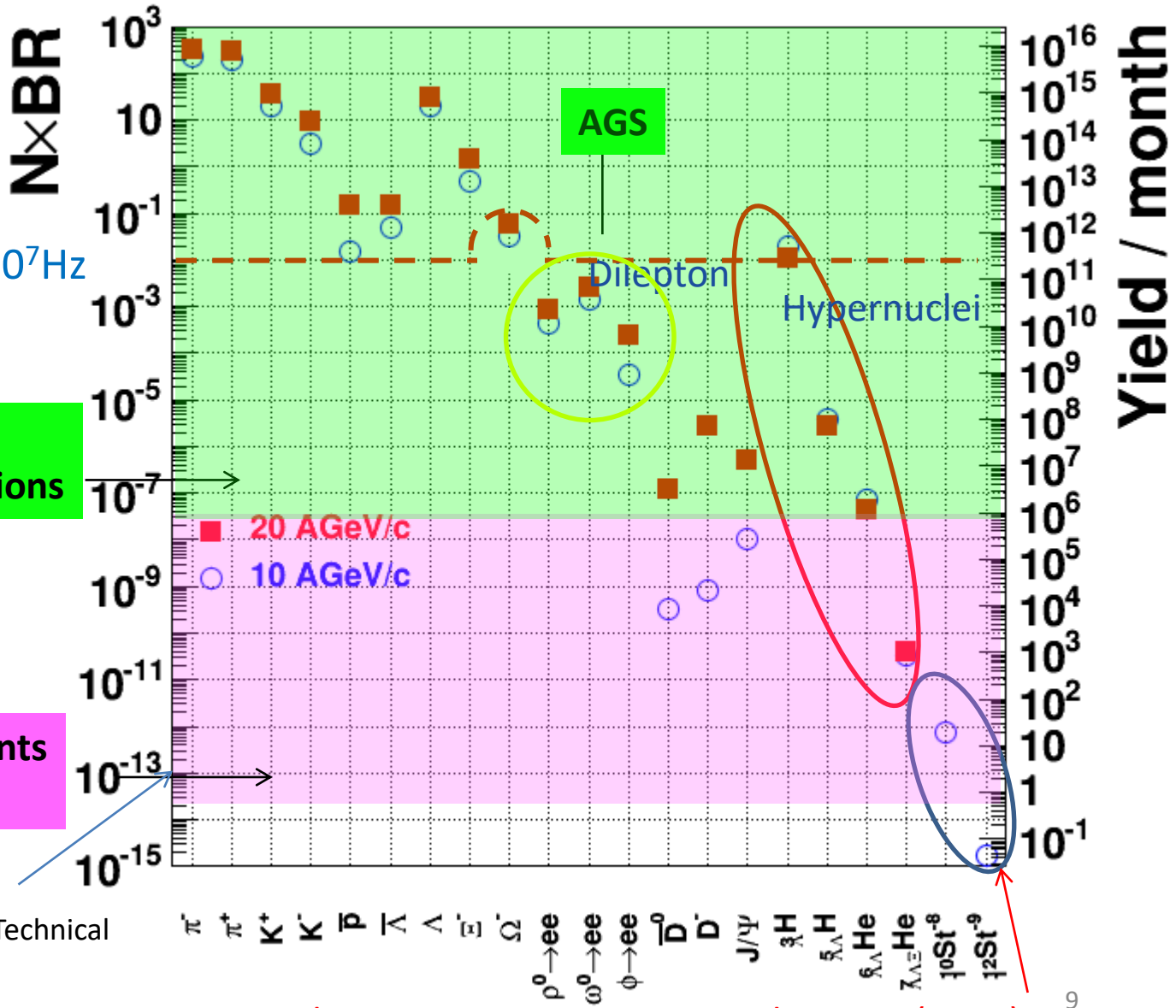
→ Min-bias event rate 10^7Hz

In 1 month experiment:

ρ,ω,ϕ→ee 1

Hypernuclei

Y, pt spectra
Event selections



Measurements and Search

10^{-13} sensitivity at J-PARC

HSD calculations in FAIR Baseline Technical Report (Mar 2006)

A. Andronic, PLB697 (2011) 203

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

Observables for QCD phase structures

- Dileptons
  - Penetrating probes of dense matter
  - Modification of $\rho/\omega/\phi$ linked to chiral symmetry restoration
- Hadron measurements (high statistics)
  - Event-by-event fluctuations
  - Collective flow (search for 1st order transition)
- Photons (real and virtual)
  - Thermal radiations from QGP
- Charm
  - J/ψ, D,…
    - Sensitive to initial dense matter

Extension of Hadron nuclear physics to high density at J-PARC with HIC

Normal nuclear density → Neutron star density

π/K/p beam experiments

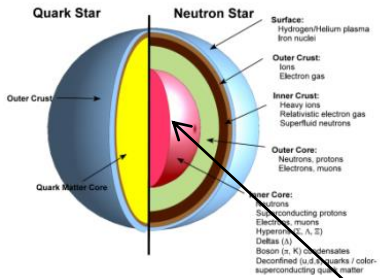
Exotic hadrons
Θ⁺ Pentaquark (E19)
H-dibaryon (E42)

Hypernuclei
|S|<=2(E10,E13,E07)
(${}^{6}_{\Lambda}$H,${}^{4}_{\Lambda}$He,${}^{19}_{\Lambda}$F, ${}^{6}_{\Lambda\Lambda}$He,..)

Kaonic nuclei : K⁻pp (E15, E27)

Chiral restoration dilepton in p+A (E16)

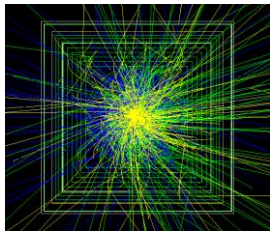
Neutron Star



YN YY interactions

Hard EOS

HI experiment



Exotic hadrons
(distinguish structure by production yield)

|S|>=3 hypernuclei

Λ* Cluster
Strangelet (strange quark matter)

2-particle correlation (HBT)

Collective flow

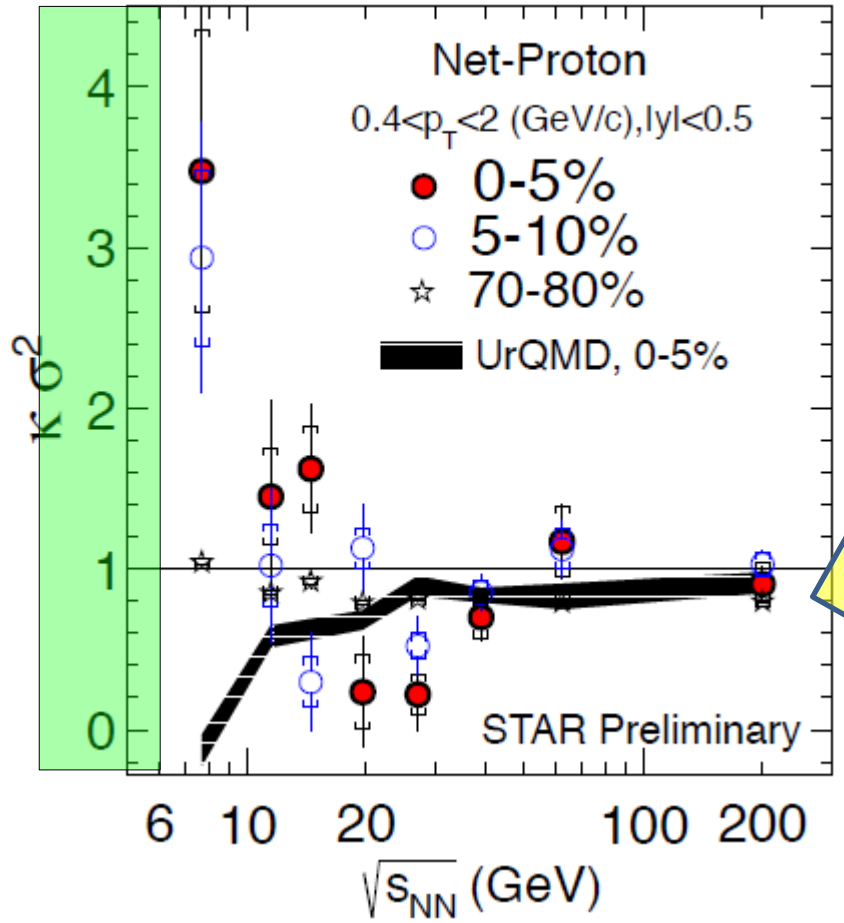
Chiral restoration dilepton in A+A

Event-by-event fluctuations

Event-by-event fluctuations of conserved charge:

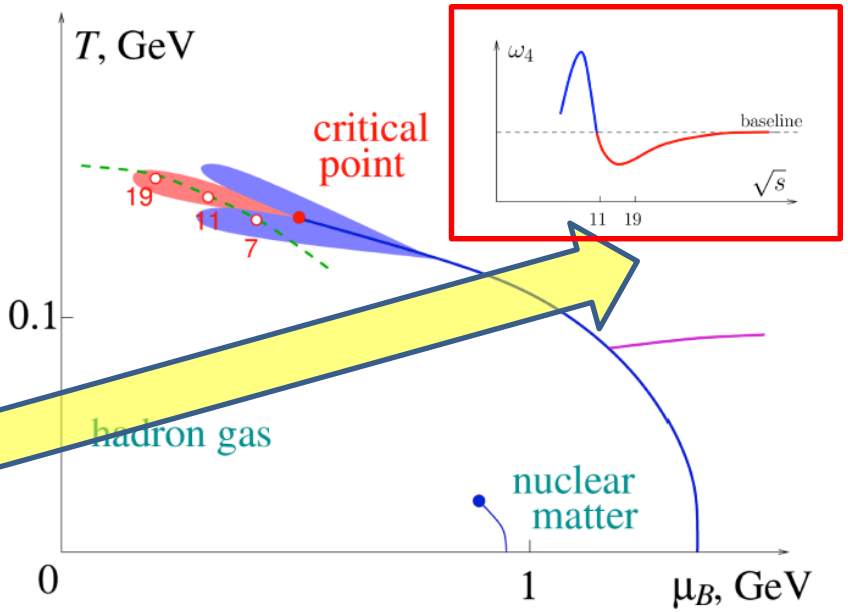
Probe to search for the critical point

J-PARC



Theory

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



Enhancement of 4th-order fluctuations at low energies

Indications of the critical point?

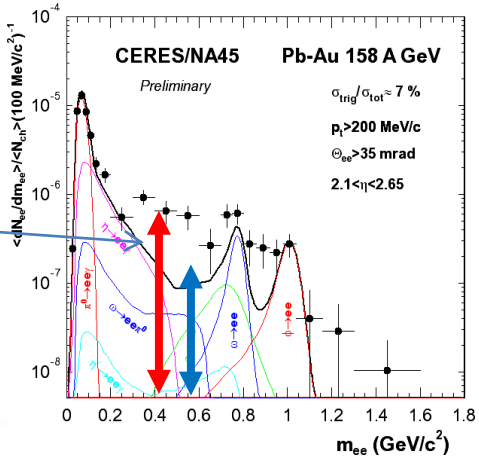
→ J-PARC-HI may answer that.

X. Luo, Quark Matter 2015

Low-mass dileptons

No dilepton measurement at J-PARC energy

Low mass enhancement factor
= Measured e+e- (ρ region)
p+p superposition (Cocktail)

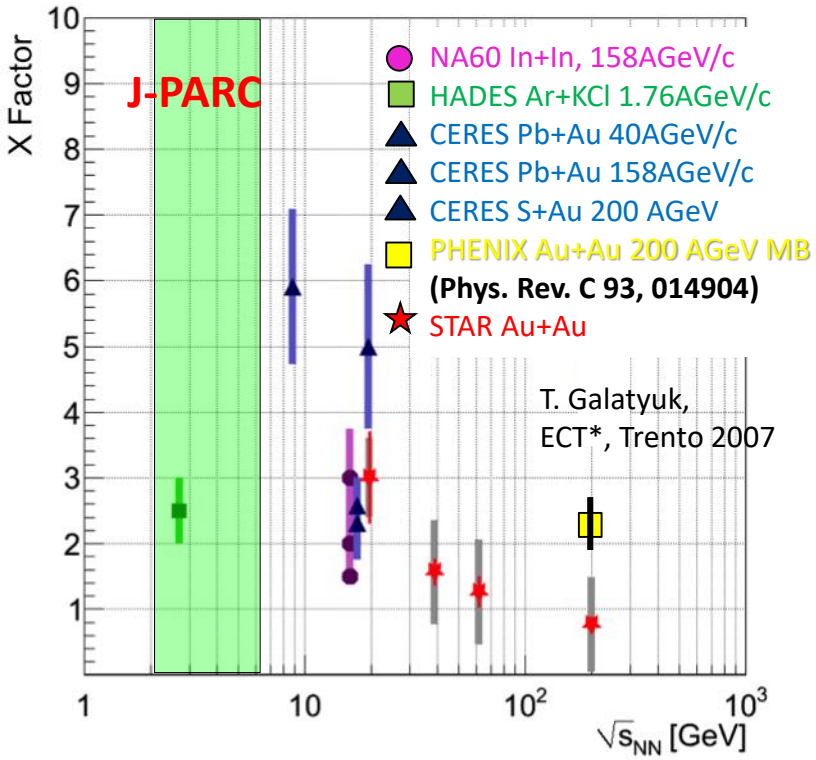


- Dielectron
  - γ conversion at low mass (background)
- Dimuon
  - π,K → μ decay (background)
  - Higher rate beam can be used

- High statistics at J-PARC
  - Higher by 3-orders compared to CERES
  - Moment analysis (never done)

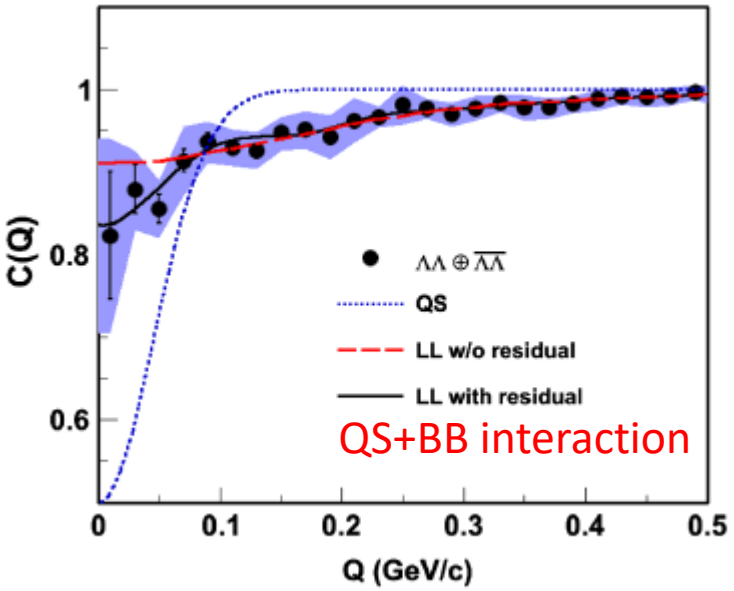
$$\int dm_{ee} N(m_{ee}) {m_{ee}}^{n} \; (n = 1,2,\dots)$$

→Direct comparison to theoretial models (e.g. QCD sum rules, related to quark and gluon condensate)
Hayano and Hatsuda, RMP**82**, 2949

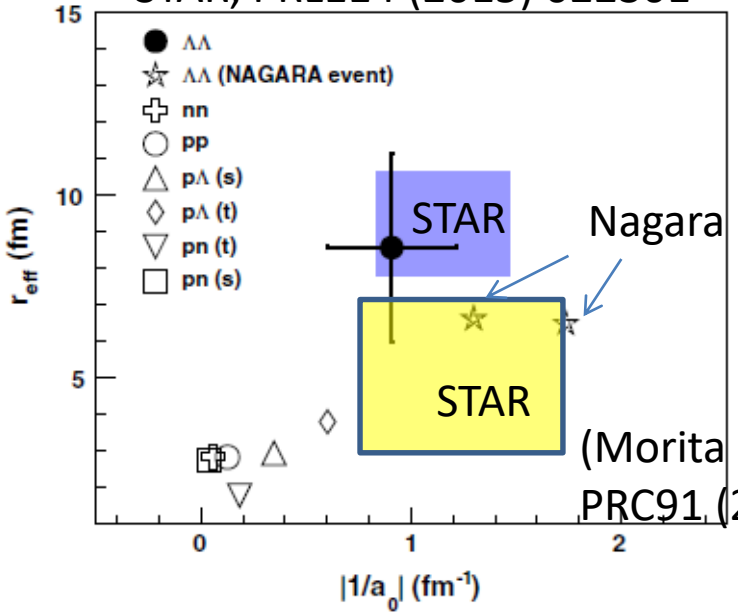


Hyperon correlation in HI collisions (STAR)

ΛΛ correlation function



STAR, PRL114 (2015) 022301

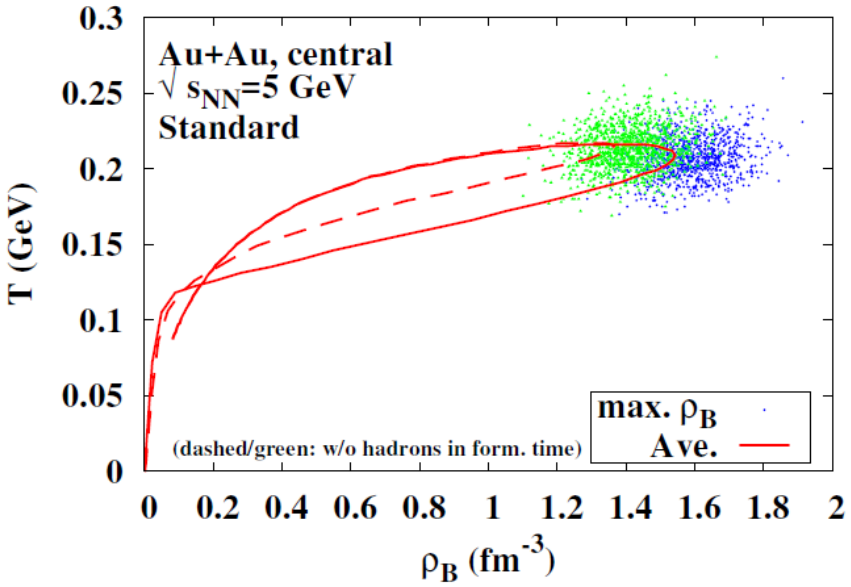


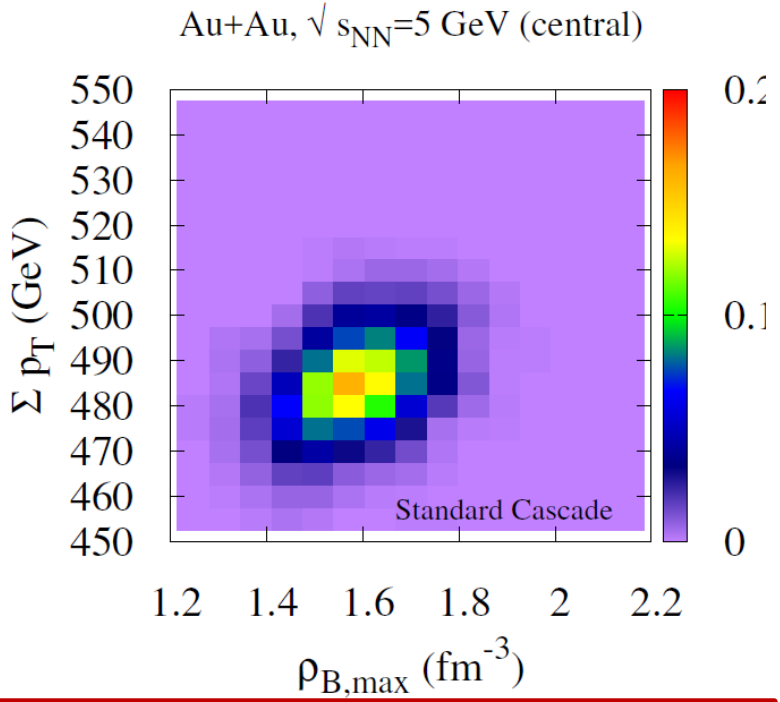
(Morita et al PRC91 (2015) 024916)

- Study of ΛΛ interactions from two-particle momentum correlation
- Other YN, YY, YYN correlation measurements possible
  - Ξ^- and Ω multiplicity = 0.6/0.03 at 10 AGeV
  - Ωp : K. Morita et al, Phys. Rev. C94 (2016) 031901

New event selection for higher baryon density (preliminary)

- $\sum p_T$ of hadrons correlates with baryon density
  - Cascade model calculation (JAM)
  - *A. Ohnishi, Y. Nara, M. Kitazawa, T. Sakaguchi, H. Sako, private comm.*
- Possibility of implementing an experimental trigger





Statistics-starved "rare event" selection feasible with high luminosity beam at J-PARC-HI

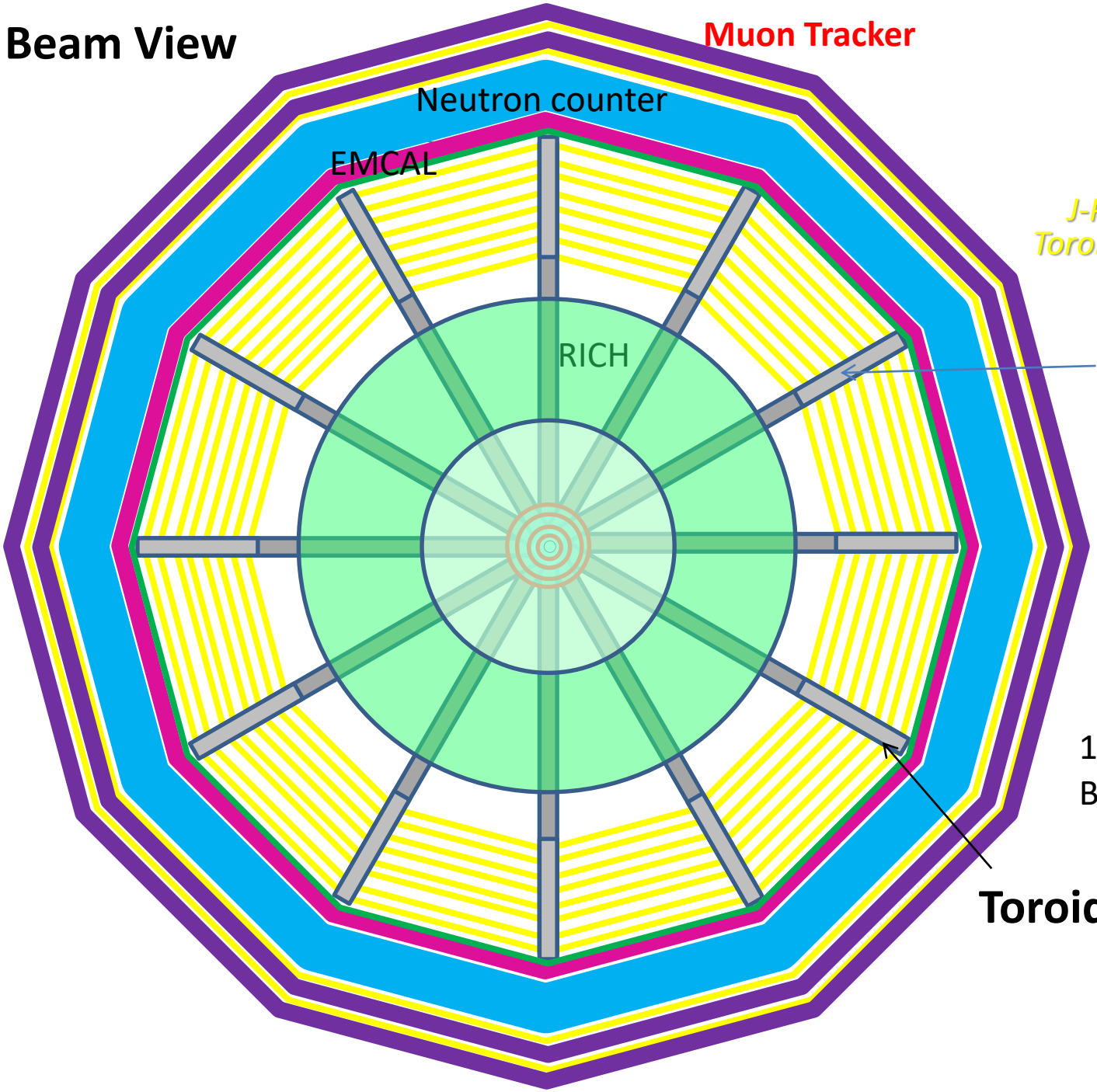
Experimental challenges

- High rate capability
  - Fast detectors
    - Silicon Vertex Detectors, GEM trackers, …
  - Extremely fast DAQ of 10-100MHz

    → Triggerless continuous readout + online data reduction
- Large acceptance (~4π)
  - Coverage for low beam energies
  - Maximum multiplicity for e-b-e fluctuations

⇨ Toroidal magnet spectrometer

Beam View



JHITS

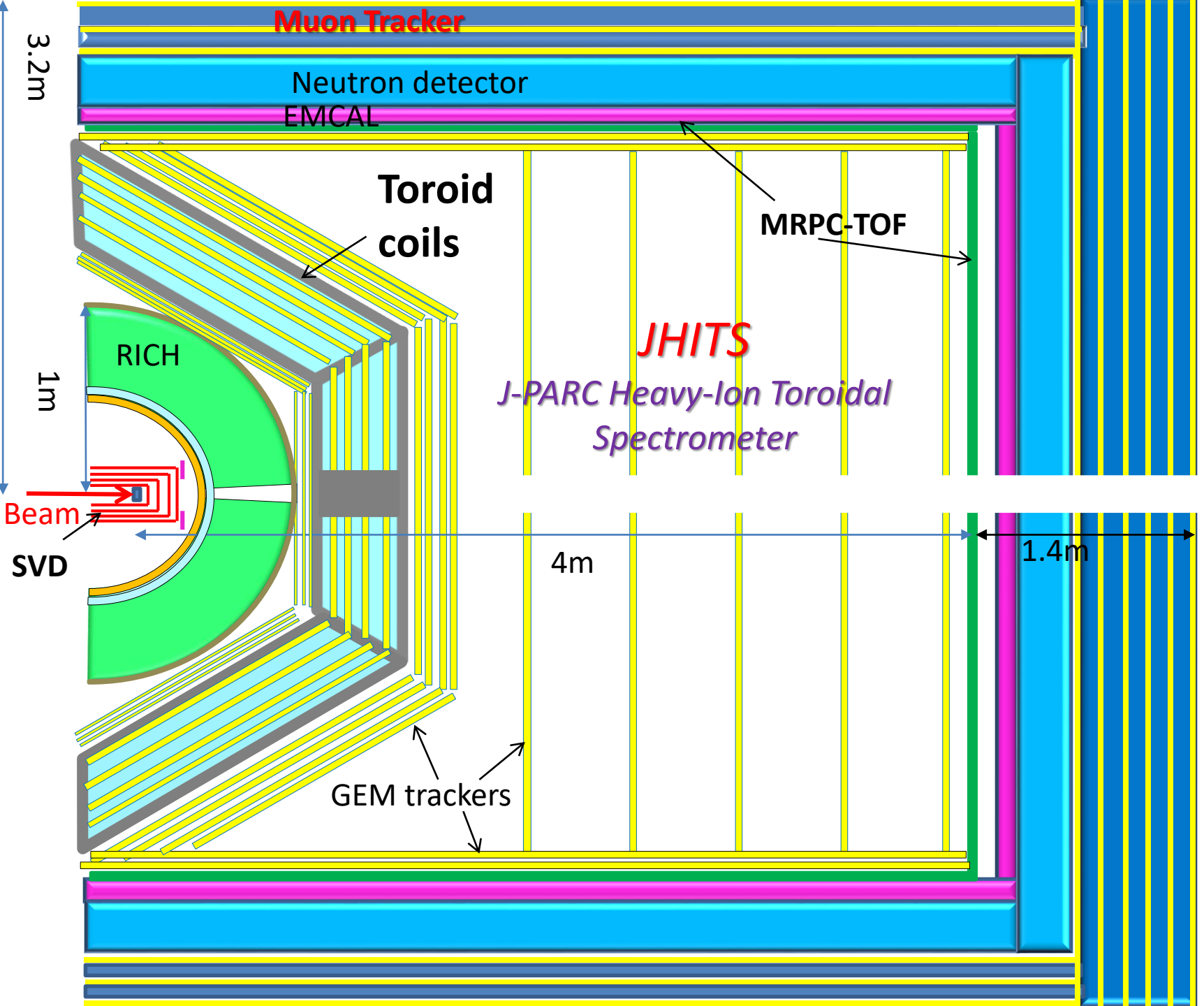
J-PARC Heavy Ion Toroidal Spectrometer

Coils = insensitive area

12-fold coils

Bϕ variations ~+-20%

Toroid coils


Muon Tracker
3.2m
Neutron detector
EMCAL
Toroid
coils
MRPC-TOF
RICH
1m
JHITS
J-PARC Heavy-Ion Toroidal
Spectrometer
Beam
SVD
4m
1.4m
GEM trackers
Top
View
ZCAL

Simulated dilepton spectra

Generated

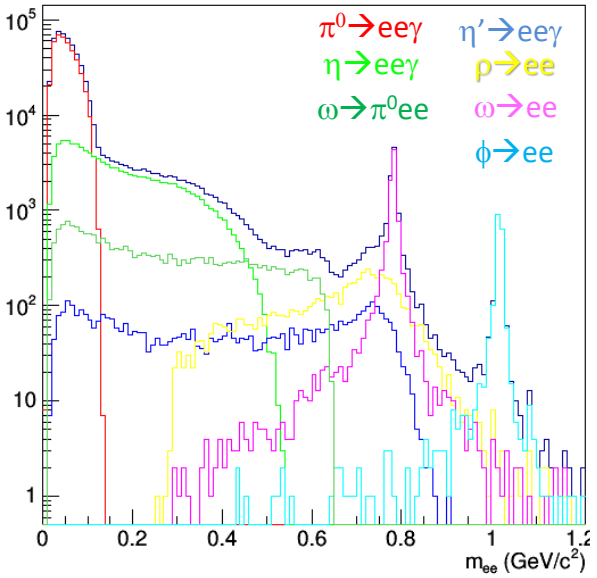
Reconstructed

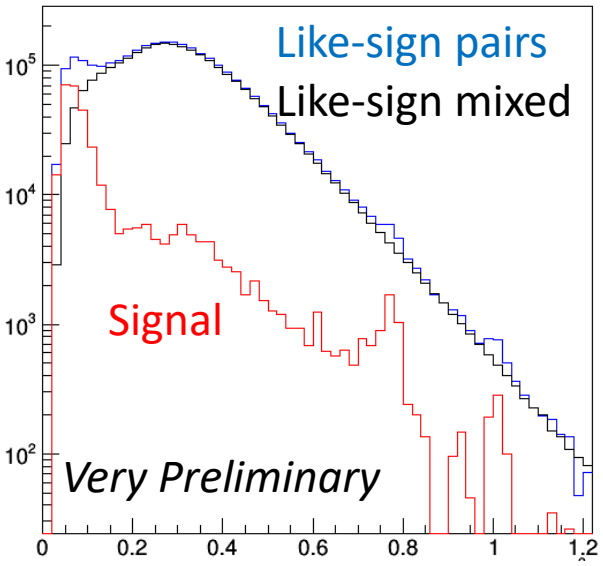
Dielectrons

$\theta_{ee}>5^o$
$2^o<\theta<80^o$
$p_T>0.1$ GeV/c

e^+e^- cocktail (8.6 M events)

No γ external conversion



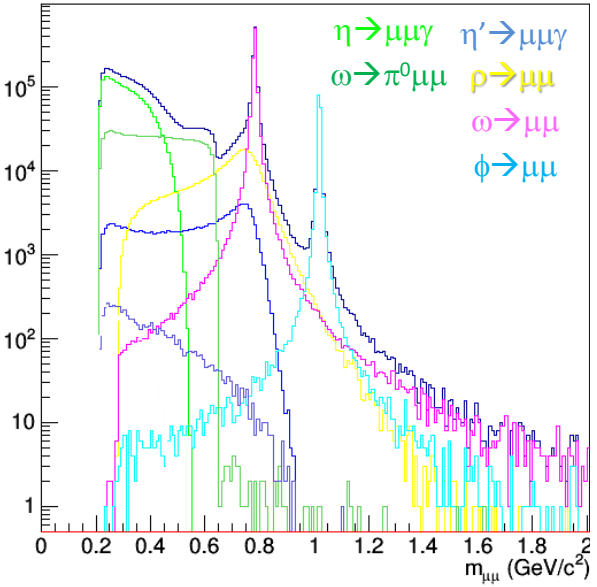


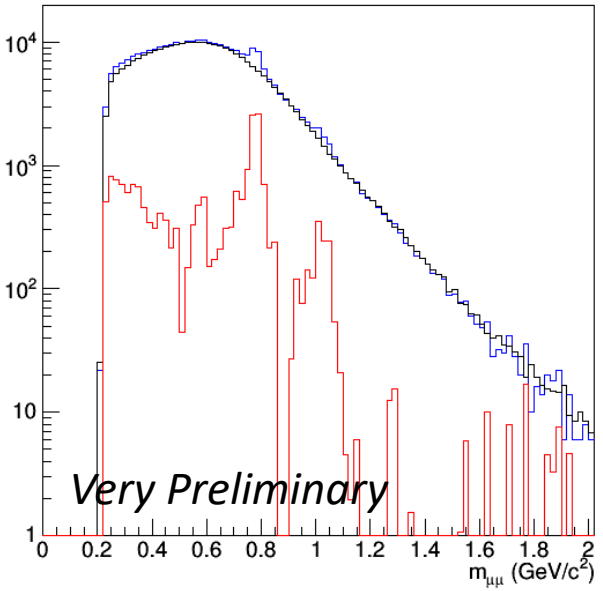
Dimuons

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

$\mu^+\mu^-$ cocktail (0.6 M events)

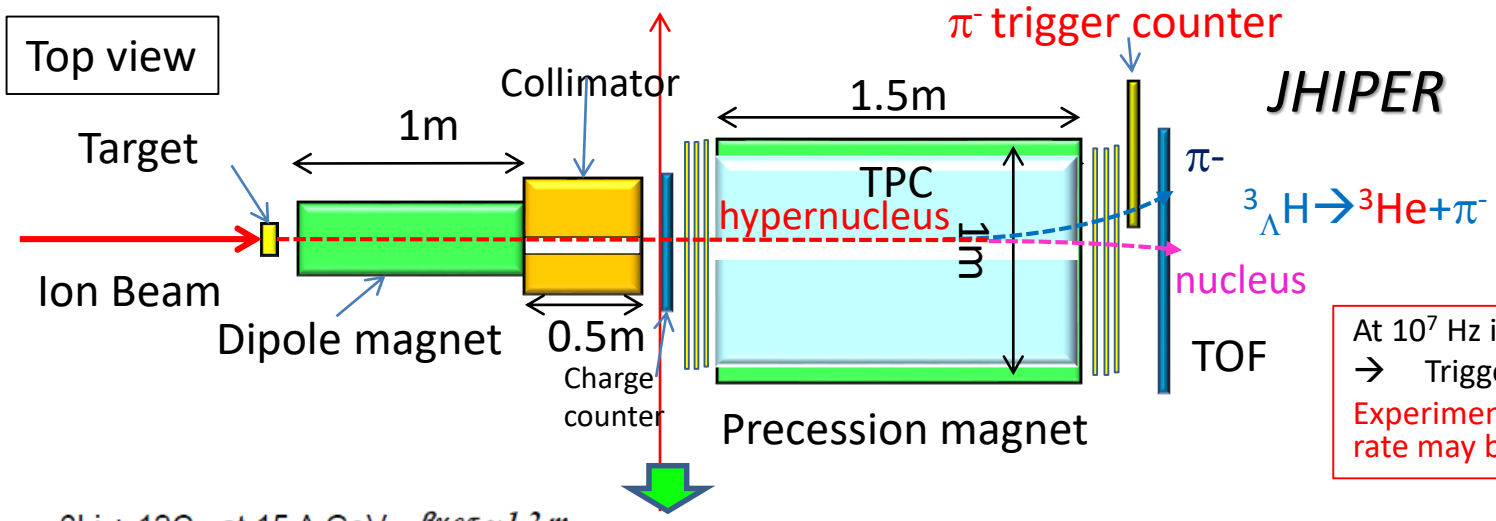
With K,π weak decay background



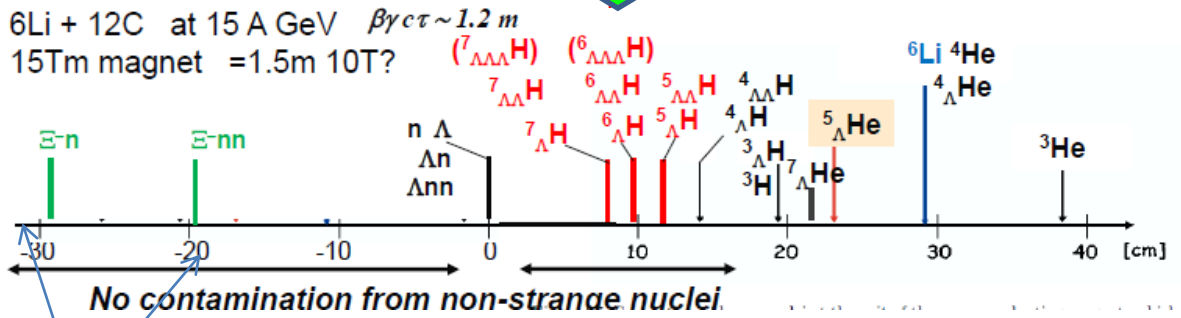


Hypernuclear spectrometer (JHIPER)

- Hypernuclear measurement at y_{beam}
  - Lifetime
  - Magnetic moment
  - S=-1,-2,-3,…
  - Strangelet



At 10^7 Hz interaction rate
→ Trigger rate : 4.0×10^3 Hz
Experiment with full beam rate may be feasible!



If found, discovery of negative nuclei

H. Tamura, Reimei Workshop, 10 Aug 2016, Tokai, Japan

R&D status

- Fast Data Acquisition System
  - Participation in ALICE-Online-Offline Computing (O^2) (RIKEN, Nagasaki IAS, CNS U. Tokyo, U. Tsukuba)
  - Continuous fast data readout, online data compression, online tracking
- Detectors
  - MRPC-TOF (JAEA, U. Tsukuba, KEK)
    - 60ps time resolution, test with hadron measurements in p+A at J-PARC E16
- Theory : Development of dynamical model at J-PARC energy
  - M. Kitazawa, T. Hirano, A. Ohnishi, Y. Nara, C. Nonaka, Akamatsu, K. Morita, …

Summary and Prospect

- J-PARC-HI : Unique Lab to study QCD phase structures and neutron stars
- World's highest rate HI beam of 10^{11} Hz achieved by building a new HI injector
- Measurements of event-by-event fluctuations, dileptons, multi-strangeness systems
  - Large acceptance toroidal spectrometer
  - Hypernuclear spectrometer

Plans

- Letter-Of-Intent of J-PARC-HI 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 (2018-)
- Aiming at Proposal in Master Plan of Science Council of Japan (Mar 2019)
- Earliest possible start of the experiment (~2025)