J-PARC Heavy Ion Experiment

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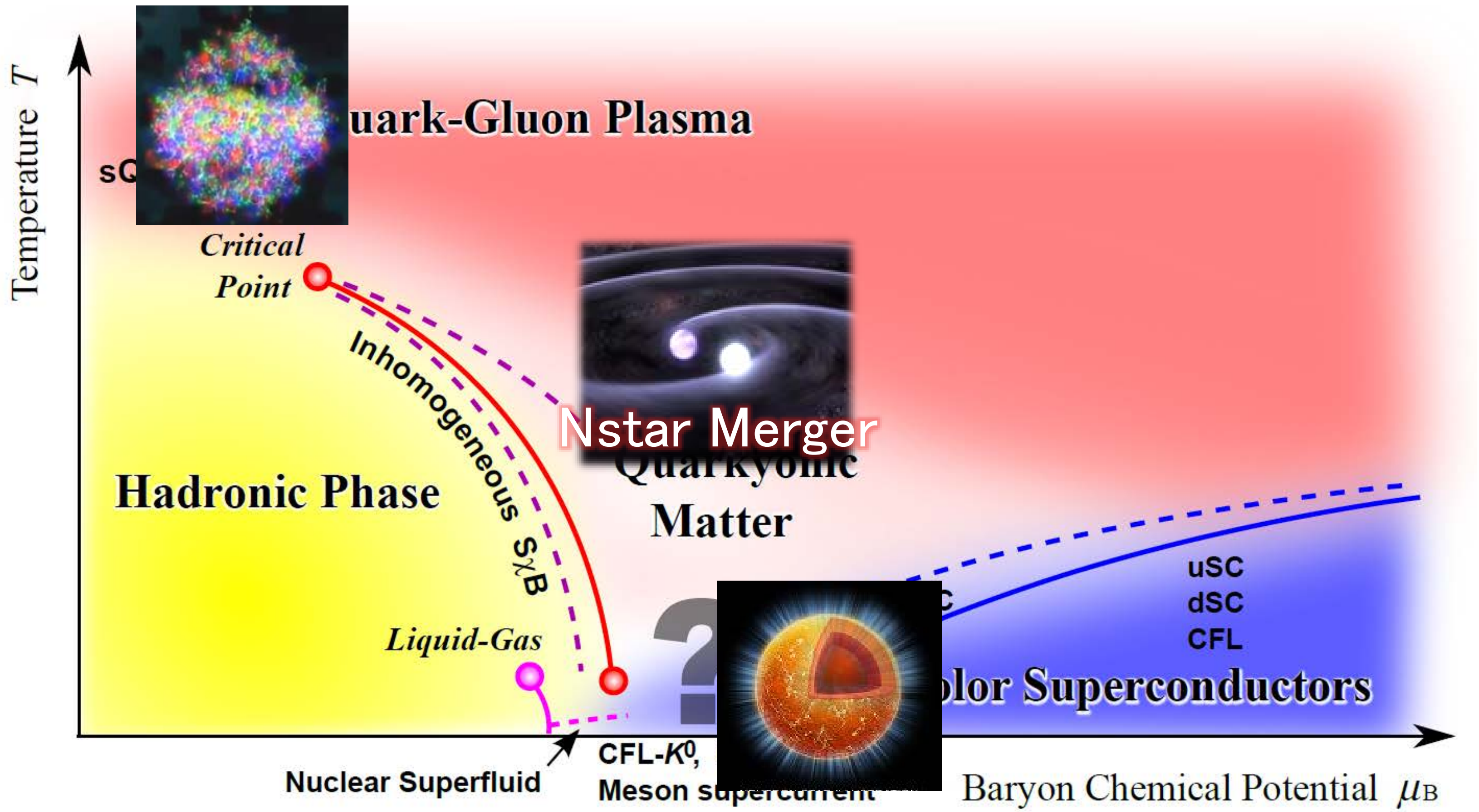
Nara Women's University & RIKEN BNL Research Center
For the J-PARC-HI collaboration

J-PARC-HI experiment :

Fixed target HI Experiment at J-PARC (√sNN=2-6GeV)

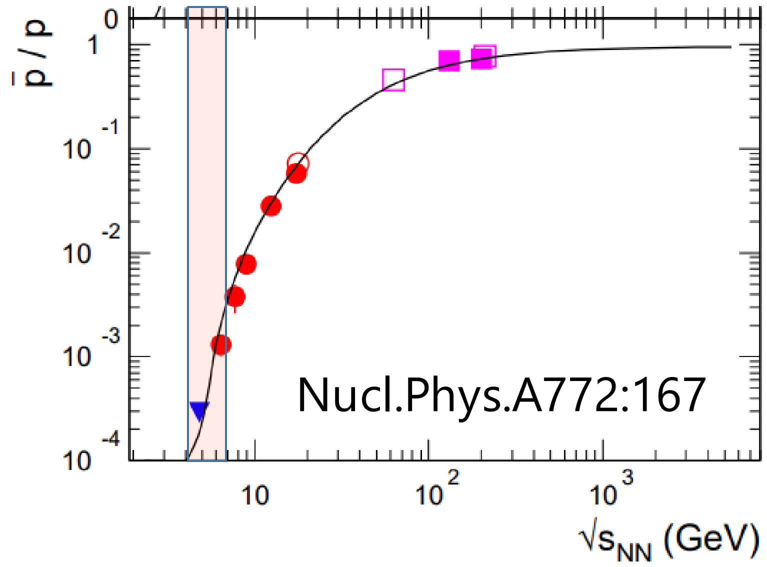
- QCD phase structure is not known at large μ_b
  - Search for 1st order phase transition and critical point
- EOS of the matter
  - Possibly similar with neutron star core and their merger
- Chiral symmetry restoration
- Strangeness factory

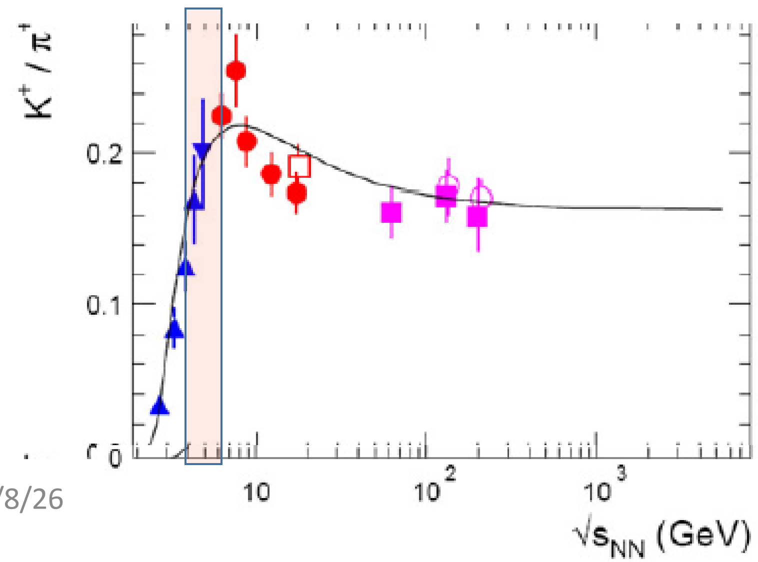


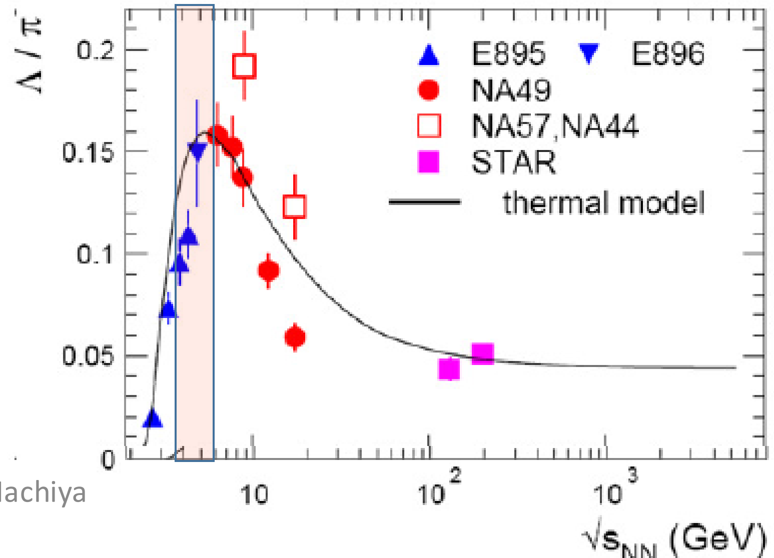
Experimental study at laboratory is necessary

Heavy Ion Collisions at J-PARC

- Collision energy : $\sqrt{s_{NN}}$=2-6GeV/c (~AGS)
- Large baryon stopping : high density matter
  - zero baryon density at higher energies (RHIC, LHC)
- Maximum strange production at J-PARC
  - Strange factory



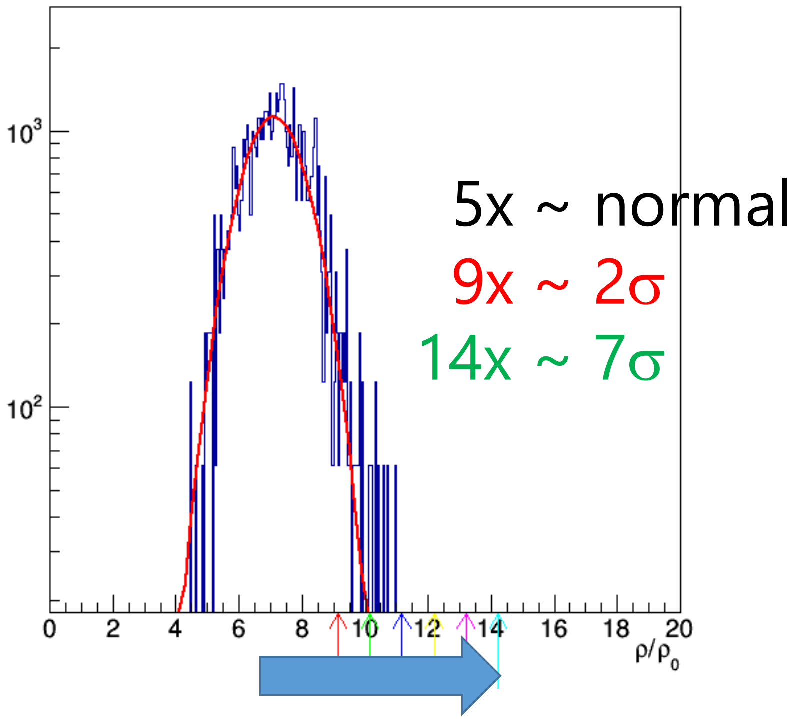




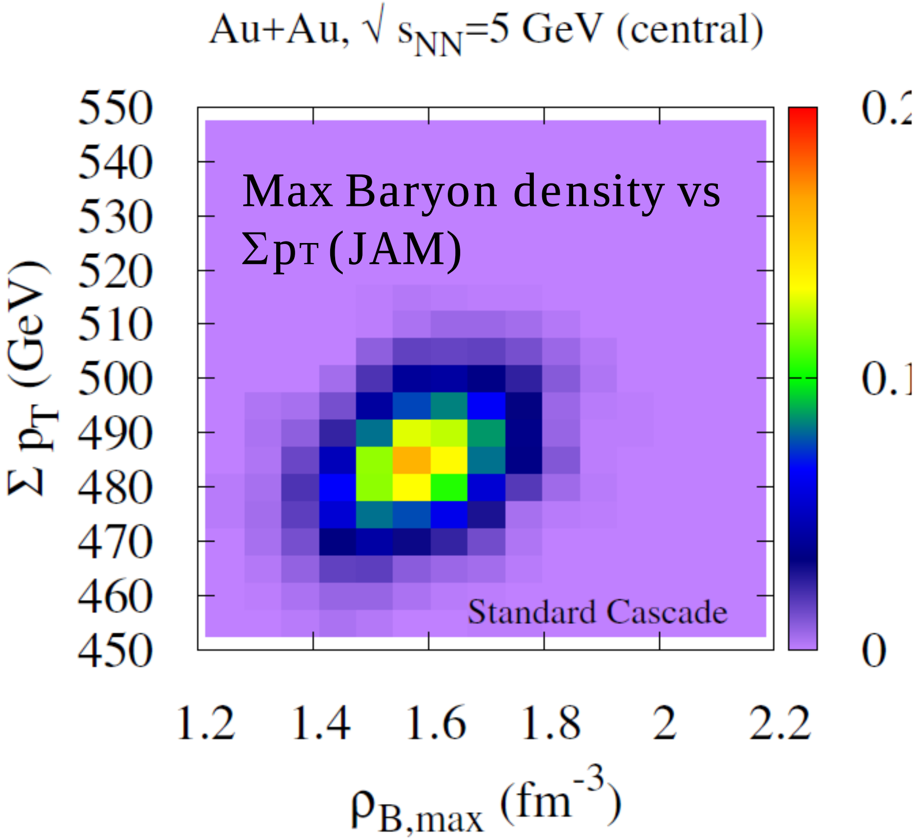
Higher baryon density by Event selection

- Baryon density can change event by event
  - Higher baryon density is achievable but rare

Baryon density distribution (JAM)

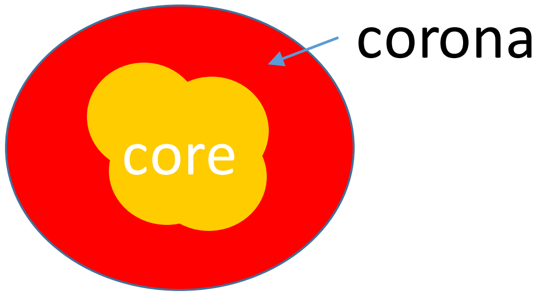


- Measure of baryon density
  - Sum p_T of charged particles
    - proportional to baryon density
  - Others?



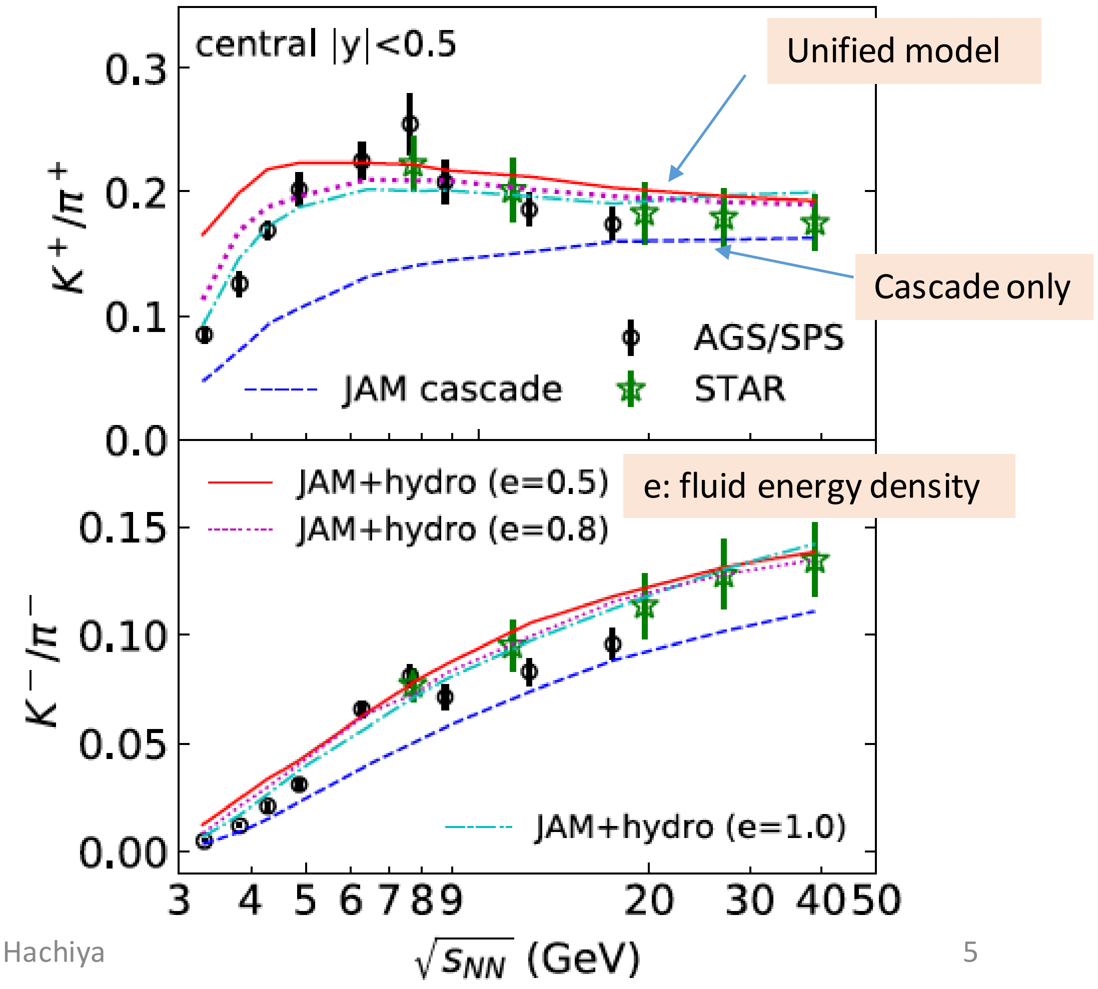
Higher statistics is needed to access "rare event"

System thermalized at J-PARC ?



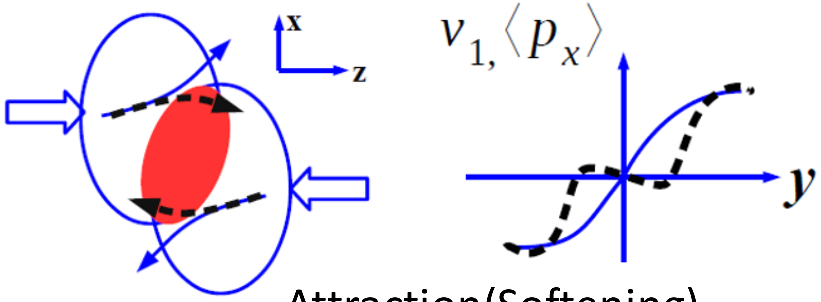
- A theory group in Japan develops a UNIFIED hydro - cascade model
  - Core-corona picture included
  - High density core : parton fluid
  - Low density corona : hadron (cascade)
- Data is described very well
  - Cascade only doesn't work
- This suggests that parton fluid in dense matter at J-PARC energy

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



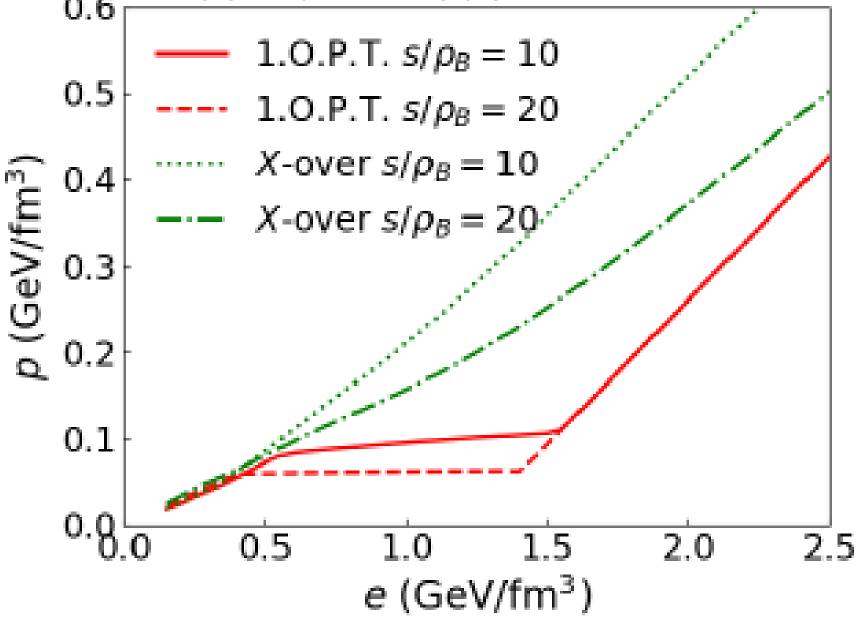
Collectivities constraining EOS

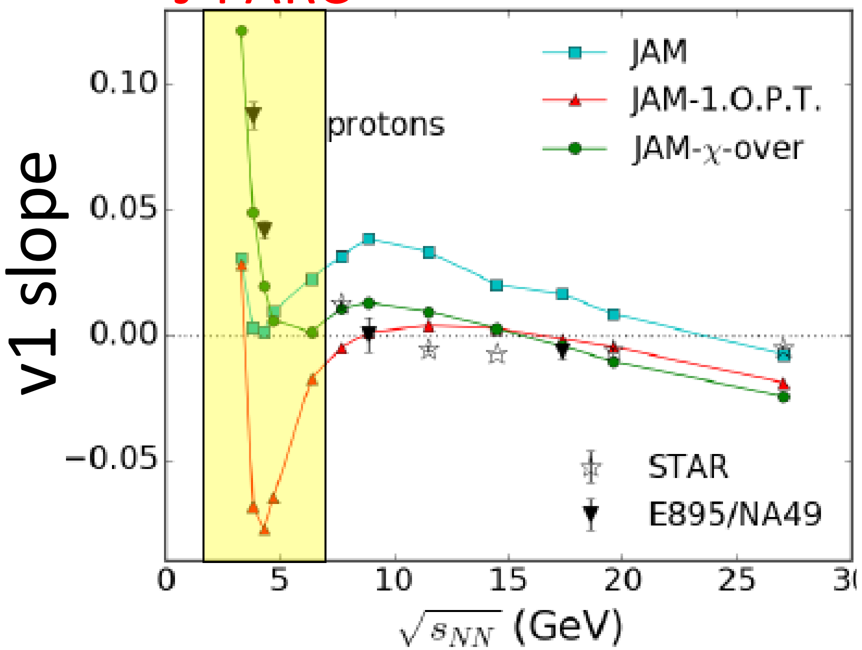
A. Ohnishi, Reimei HI, Aug 2016



Attraction(Softening)

- Sign of v1 slope (dv1/dy)
  - sensitive to phase transition
    - dv1/dy < 0 : Softening of EOS





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

Higher order flow : 3rd→4th→5th

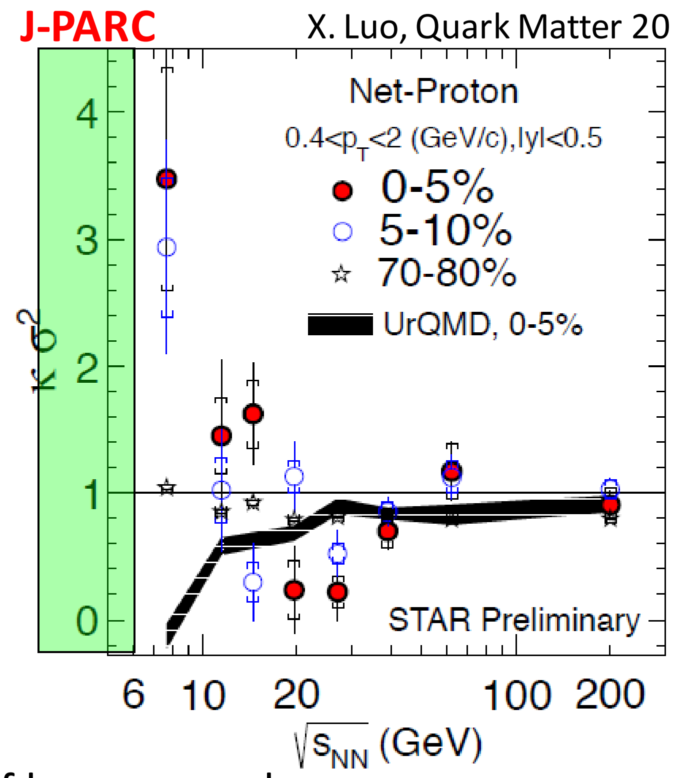
Property of dense matter (such as viscosity)

1-order higher flow→ need 10x more statistics

Event by Event Fluctuation

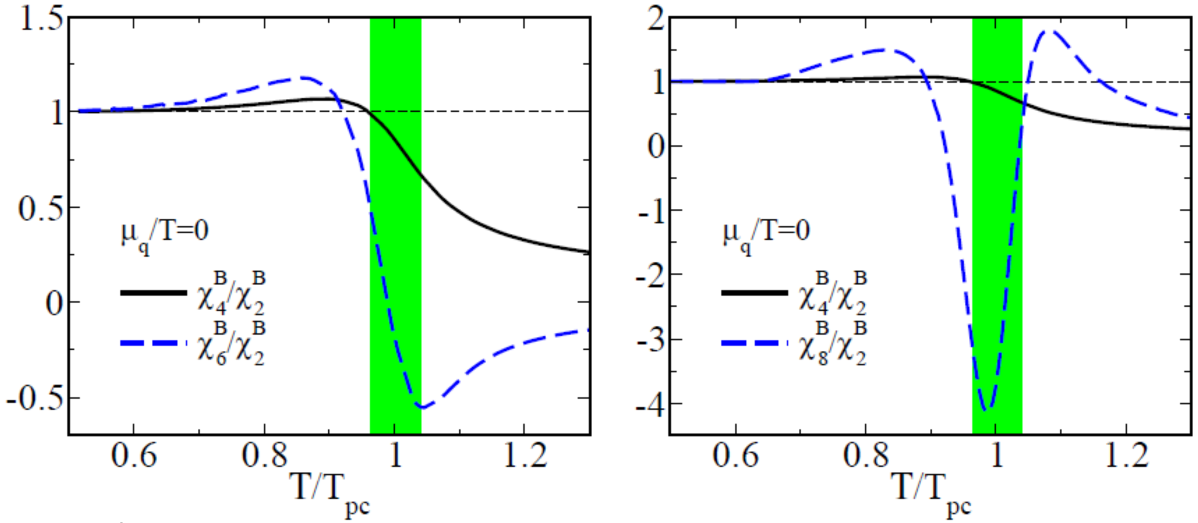
- E-by-E fluctuation of Conserved charge, Net baryon (proton)
  - Sensitive to critical point
    - Large fluctuation near critical point
  - RHIC-BES
    - Non-uniform at 7GeV but large uncertainty

X. Luo, Quark Matter 2015



- **Higher order fluctuation ($4^{th} \rightarrow 6^{th} \rightarrow 8^{th}$)**
  - Sensitive to chiral transition (even for crossover)
  - 2-order more statistics required with 1-order higher fluctuation

Cumulant ratio of baryon number

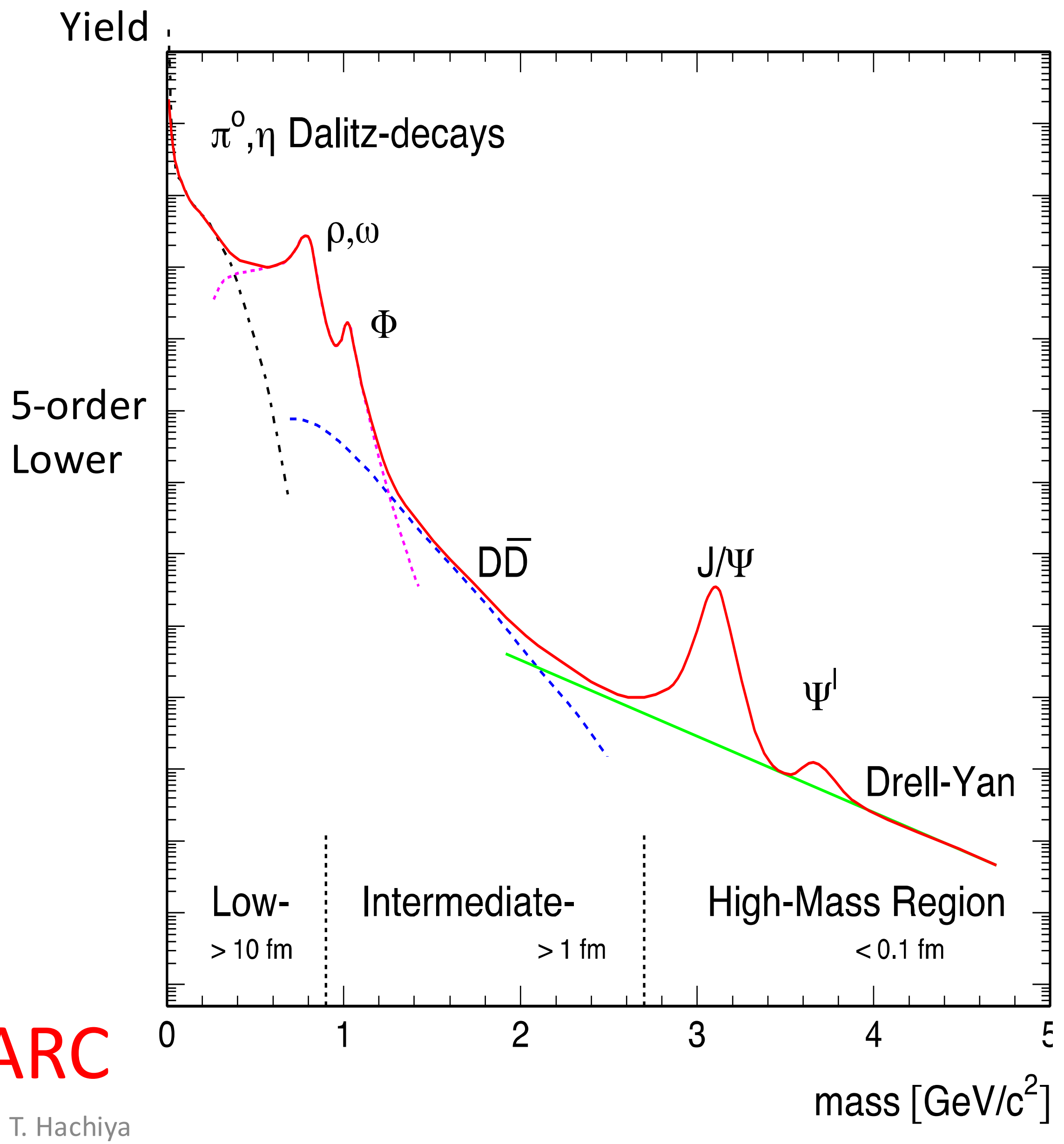


B. Friman et al., EPJ C 71 (2011) 1694

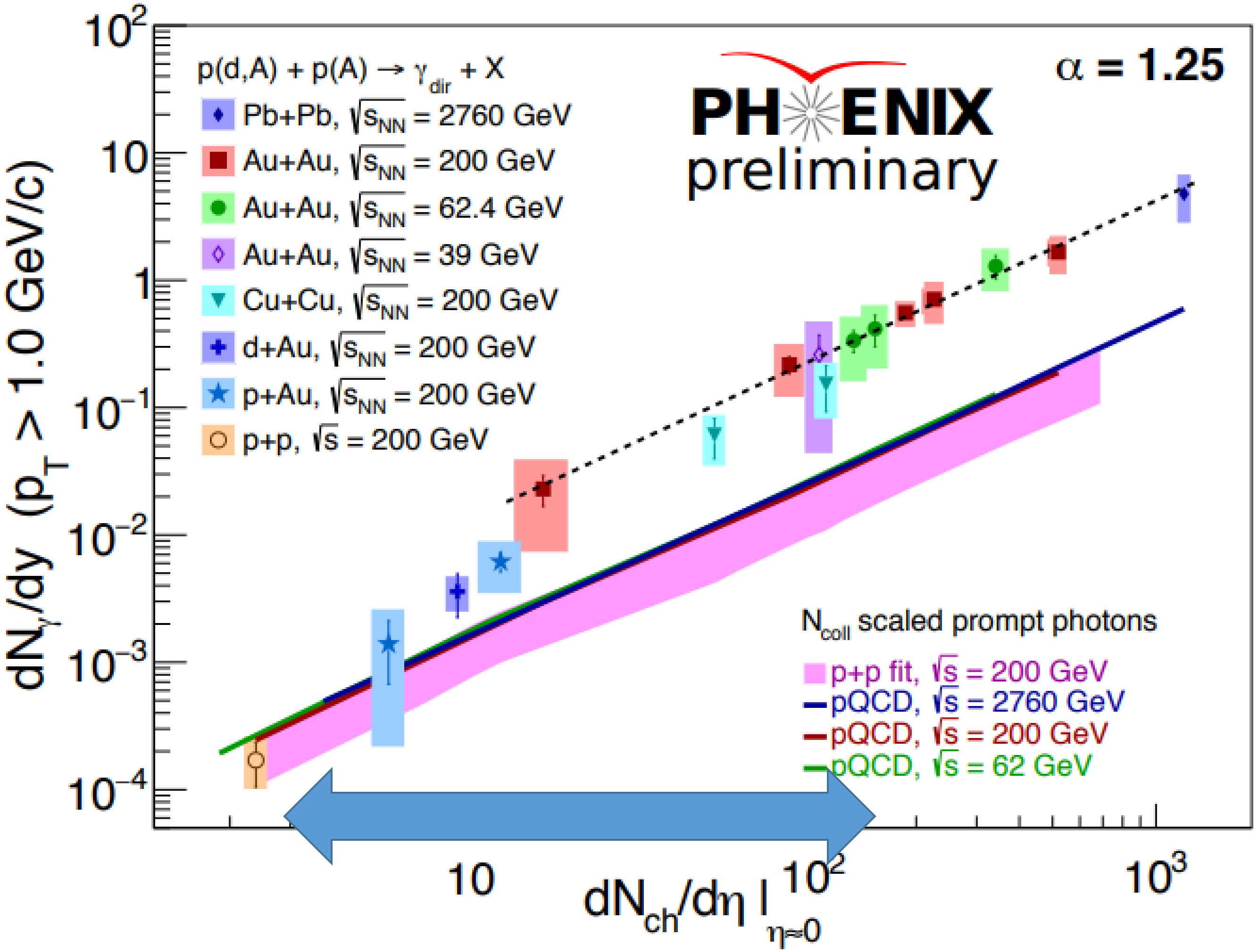
Di-Leptons

- No dilepton measurement at J-PARC energy
  - SPS/RHIC shows low mass enhancement
- Low mass : $\rho/\omega/\phi$ (~10^{-3})
  - Sensitive to chiral symmetry restoration by 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 (~10^{-8})
  - Thermal radiation without charm background
- High mass region : J/ψ (~10^{-7})

High-statistics enabled at J-PARC



Scaling of low p_T direct photon yield



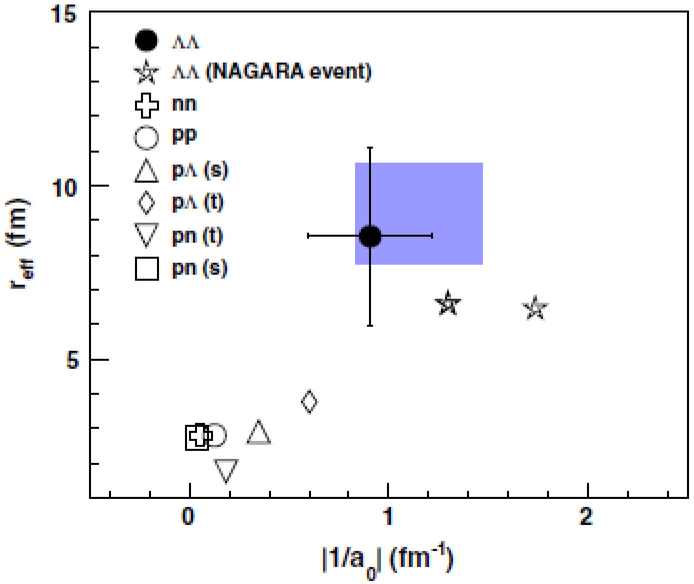
- Low pT direct photon as thermal radiation from dense matter
- 10x more direct photon from Ncoll scaled p+p
  - Pp – CuCu – AuAu – PbPb
  - 39 – 62 – 200 – 2760 GeV
  - No energy / system dependence
- Direct photon yield at small dN/dy is approaching to the scaling line
  - Seems a signal of transition to QGP

Thermal radiation at J-PARC-HI ?

Hyperon interactions

- Strange Factory at J-PARC-HI
- YN, YY interactions via 2p correlation
  - accessible S=-1 (Λ-N) to S=-6 (Ω-Ω)
  - Λ-Λ correlation by STAR
    - Need more statistics
  - Lattice predicts ΩΩ has bound state (1.6 MeV binding energy)
- Exotic states?
  - Strangelet, Di-baryon,
  - Λ(1405)…
  - Three body system (KPP)
  - more

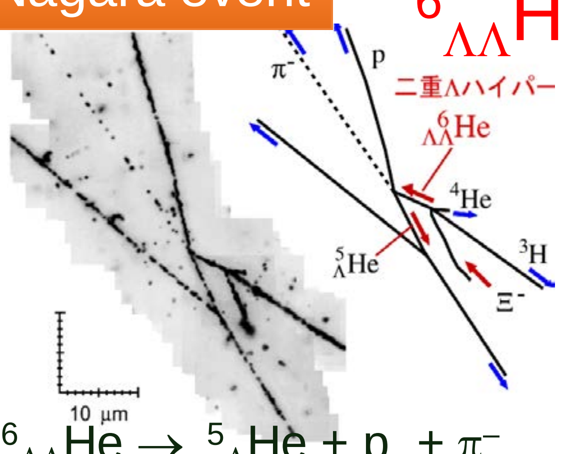
STAR, PRL114 (2015) 022301



PRL 87 (2001) 212502

Nagara event

$^{6}_{\Lambda\Lambda}He$

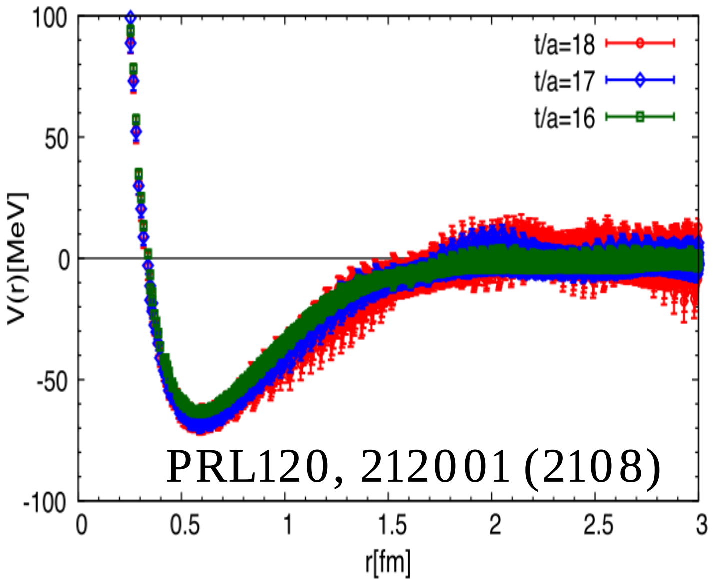


$^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$

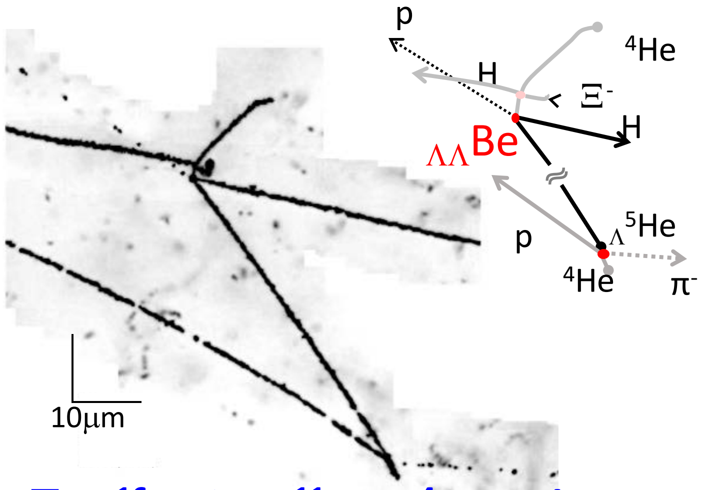
$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

Λ-Λ is weakly attractive

Ω-Ω potential



MINO event (J-PARC E07)



$\Xi^- + {}^{16}O \rightarrow {}^{11}_{\Lambda\Lambda}Be + {}^{4}He + d$

$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37$ MeV

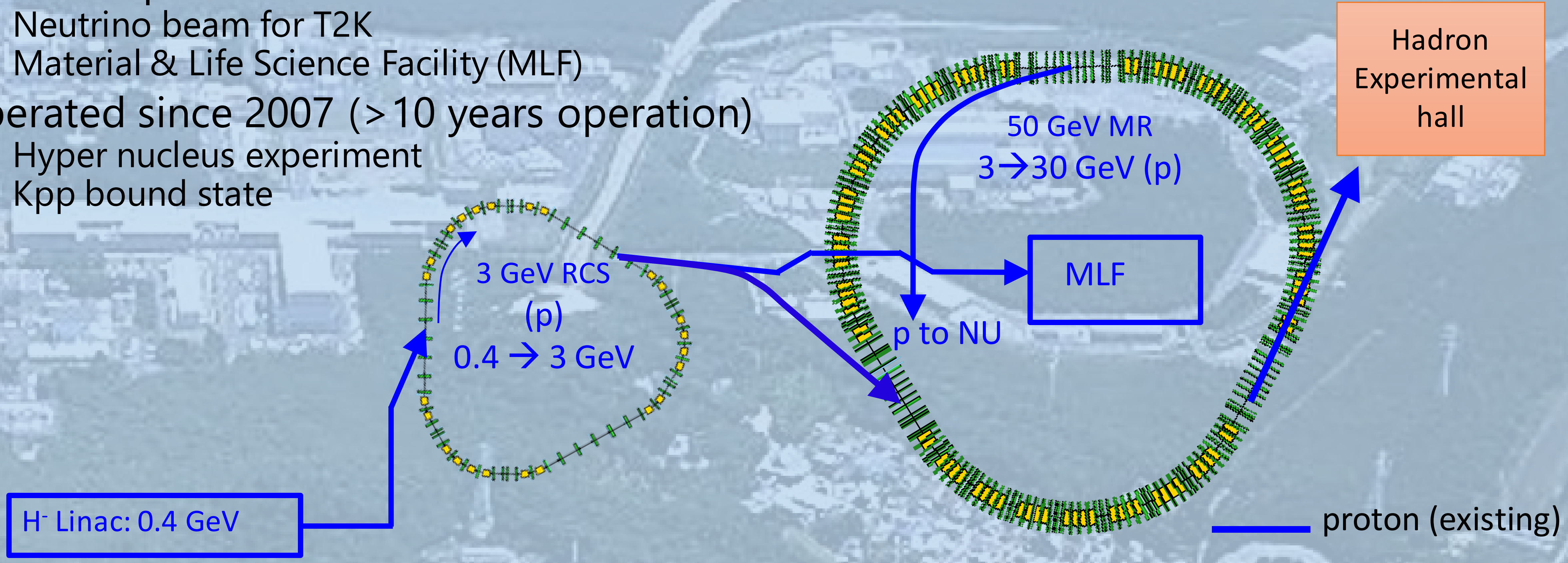
PTEP 2019 (2019) 021D02

Hyperon spectroscopy is of great interest

J-PARC accelerator complex

J-PARC accelerator complex

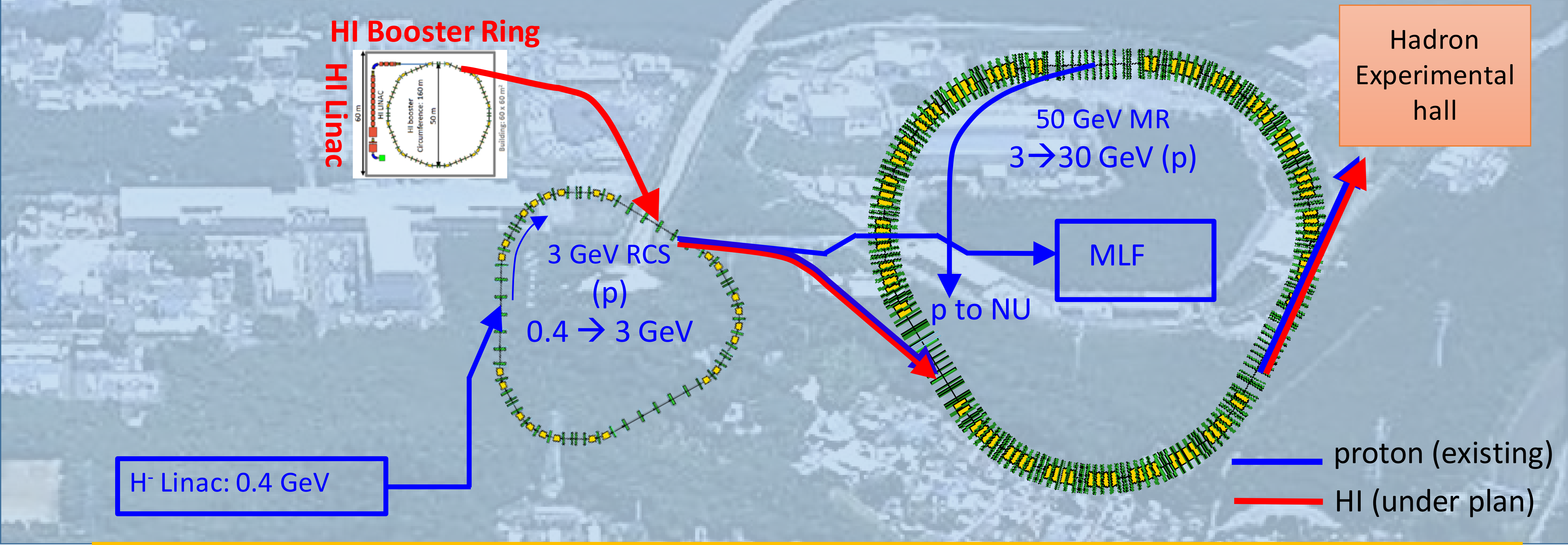
- World's Highest Intensity of proton with 30 GeV
  - ~10^{11} Hz, interaction rate ~ 10^{8}Hz
- Hadron experiments @ Hadron hall
  - Neutrino beam for T2K
  - Material & Life Science Facility (MLF)
- Operated since 2007 (>10 years operation)
  - Hyper nucleus experiment
  - Kpp bound state



J-PARC upgrade plan for Heavy Ion Collision

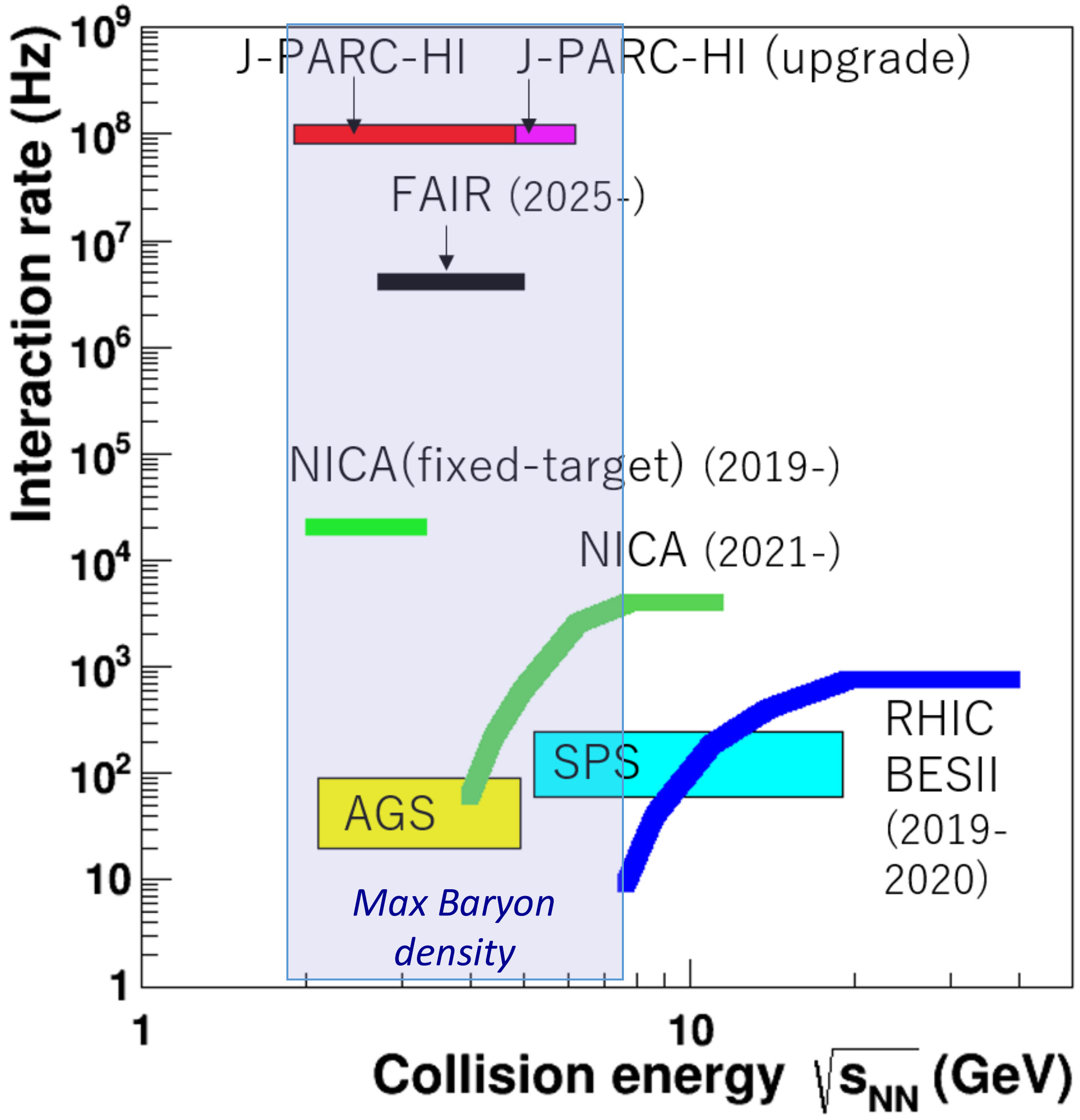
- World's Highest Intensity ~10^{11} Hz,
  - interaction rate ~ 10^{8}Hz

E_{lab}=1-19AGeV, $\sqrt{s_{NN}}$=1.9-6.2GeV (U)
Ion species: p, Si,…, Au, U



Only Linac and Booster Ring are required for Heavy Ion Collision

J-PARC-HI: Highest beam intensity



Highest beam rate × Fixed target

= World's highest interaction = 10^8Hz

→ 10^5 higher than AGS and SPS

1 year @ AGS ＝ 5 min. @ J-PARC-HI

This enables in one month experiment

ρ,ω,ϕ→ee: 10^{10} - 10^{12}

Hypernuclei: 10^4 – 10^{12}

Strangelets 1 - 10^2

Strategy for high-rate measurements

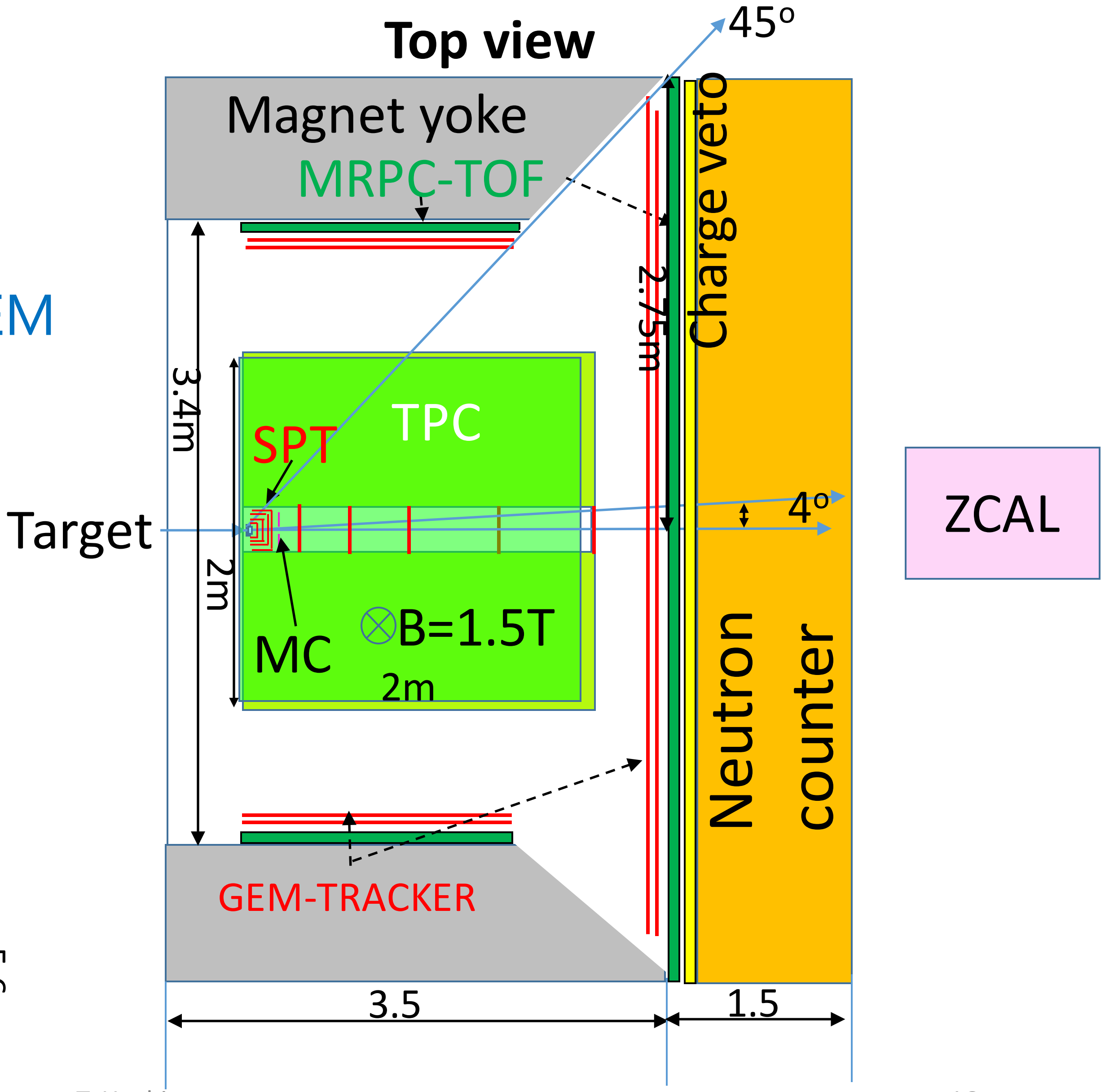
- High rate detectors
  - Silicon pixel trackers
- 10MHz DAQ system
  - Continuous readout + online data reduction
  - Online triggers (Centrality, dimuon, ….)
- Large acceptance (~4p)
  - E-by-E fluctuations, etc.

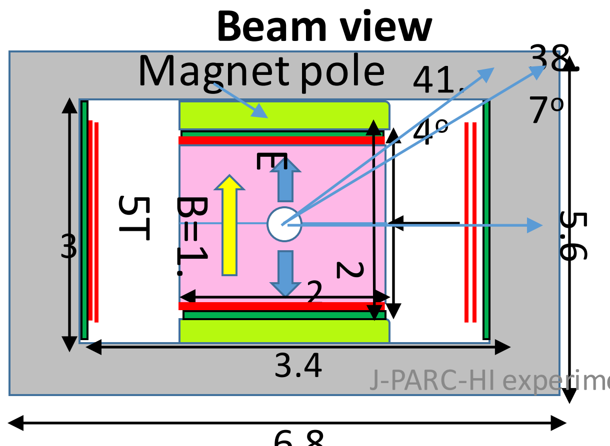
Staging approach with increasing beam intensity

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

1. Dipole Hadron Spectrometer

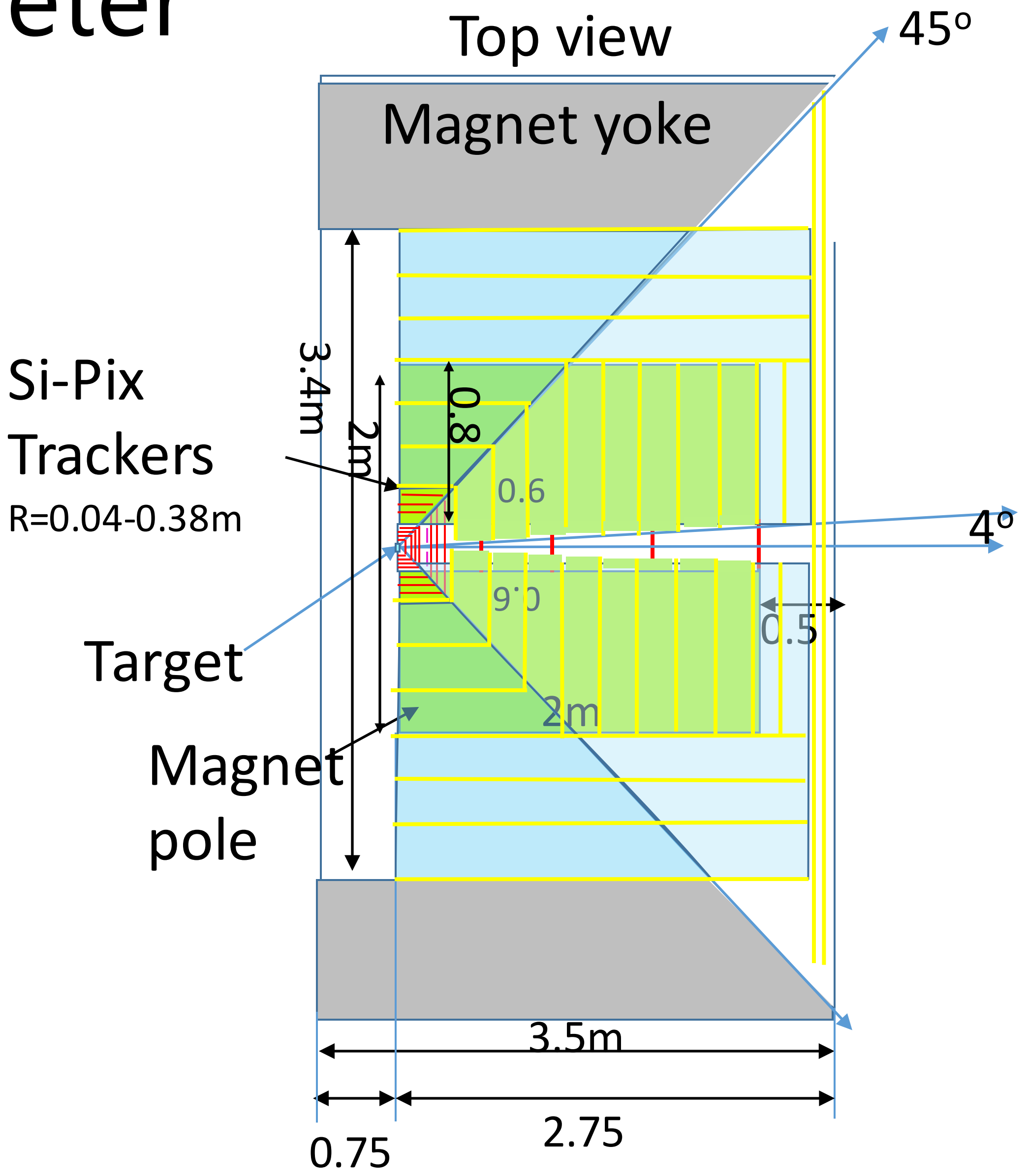
- Day-1 J-PARC-HI
- Charged particles (PID) + neutrons
- ~4π acceptance
  - Track : Si-Pix(θ < 4°), TPC (θ > 4°), GEM
  - PID : MRPC-TOF, Neutron counter
  - Centrality : Multiplicity Counter + Zero-degree CALorimeter
- Rate : <=10^6 Hz interaction
- Flow, E-by-E fluctuation

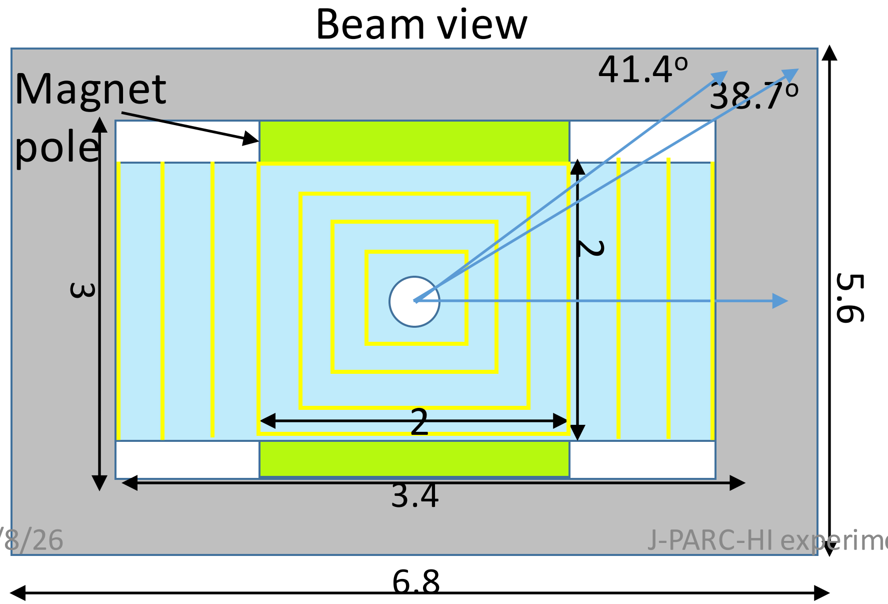




2. Dipole Dimuon Spectrometer

- Replace TPC by:
  - Pb absorbers ($4\lambda_I$)and GEM trackers
    - Dimuon Online Trigger
  - 7-layer forward and barrel Si-Pix Trackers
- Interaction Rate : 10^7 Hz
- Low mass vector meson, heavy flavor

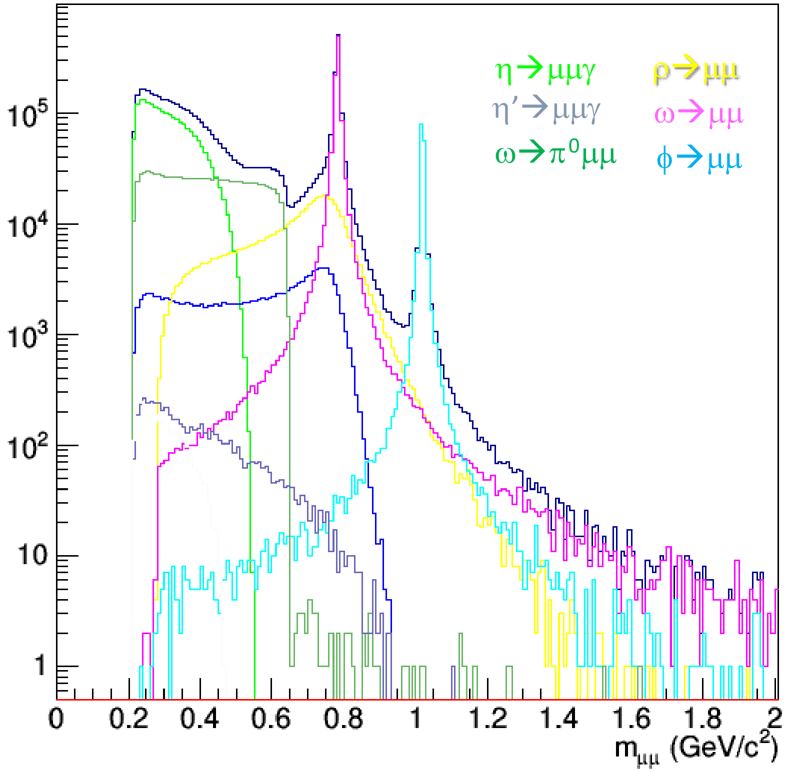




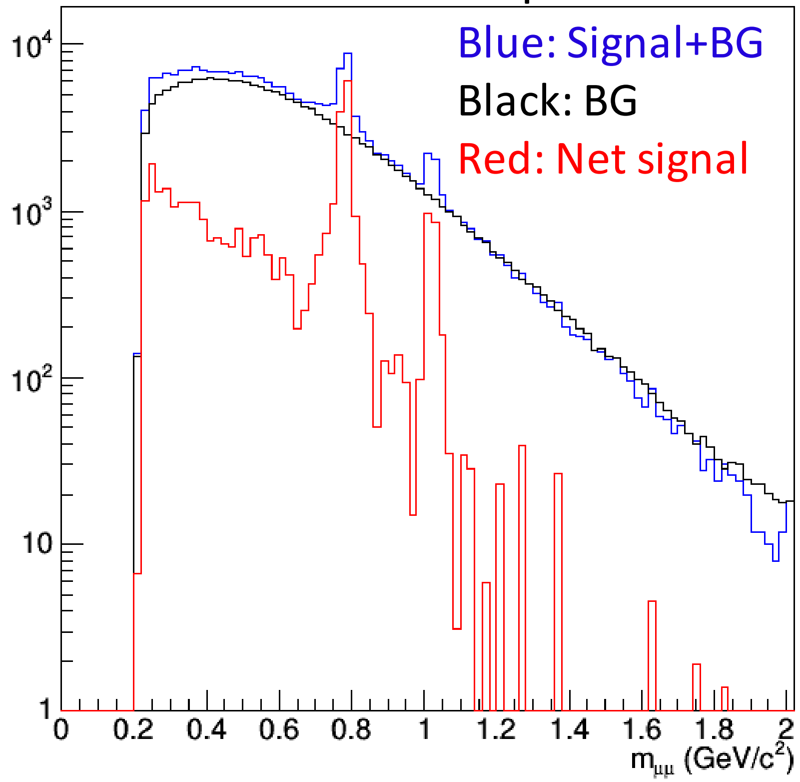
Expected dimuon spectrum

- $\mu^+\mu^-$ cocktail embedded into JAM events and processed using GEANT
  - U+U, $\sqrt{s_{NN}}$=4.5 GeV, Minimum bias JAM events
- Reconstruct tracks passing through 4 λ_I absorbers

Generated cocktail



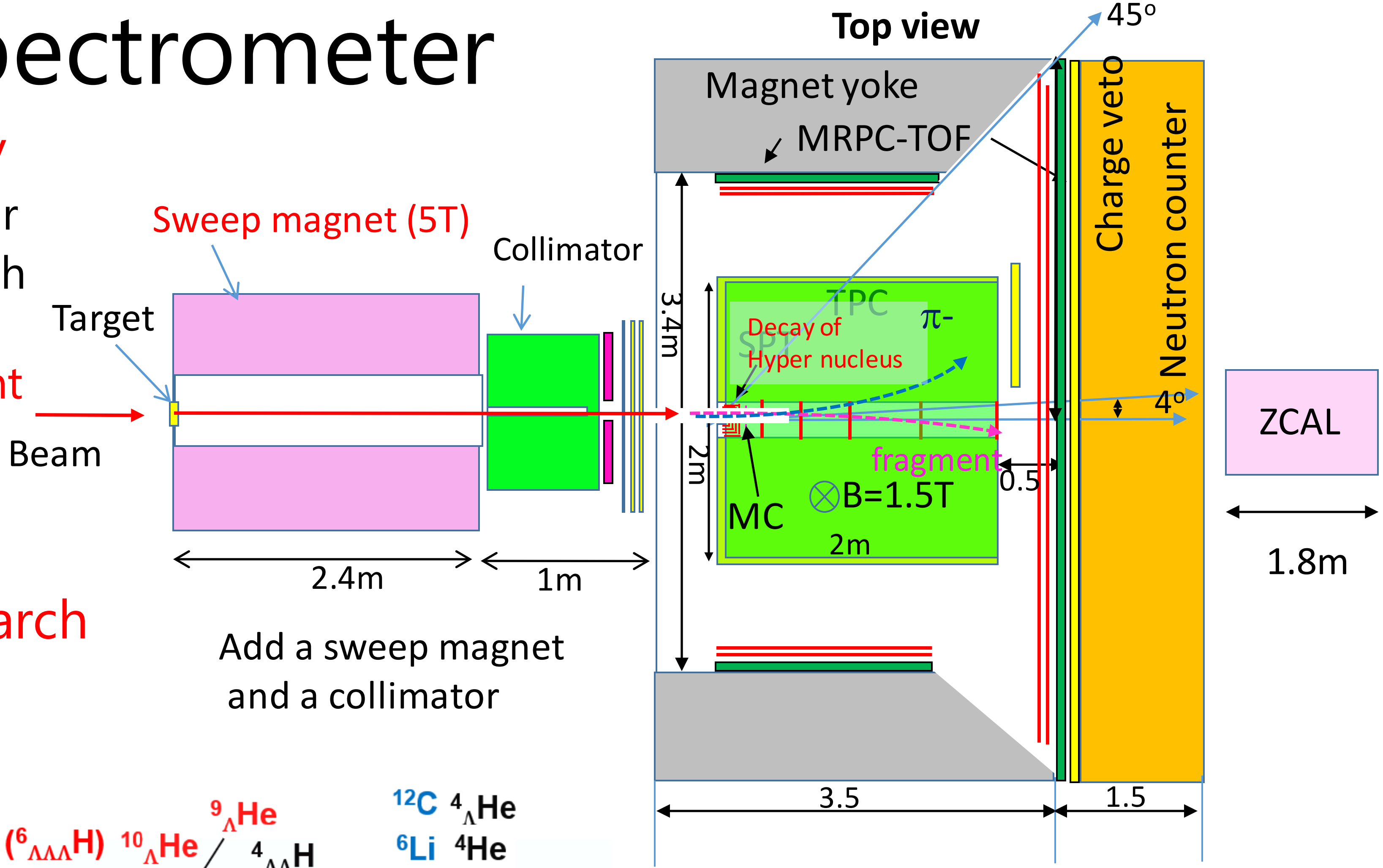
Reconstructed spectrum



Resolution is good to see ρ , ω , φ clearly

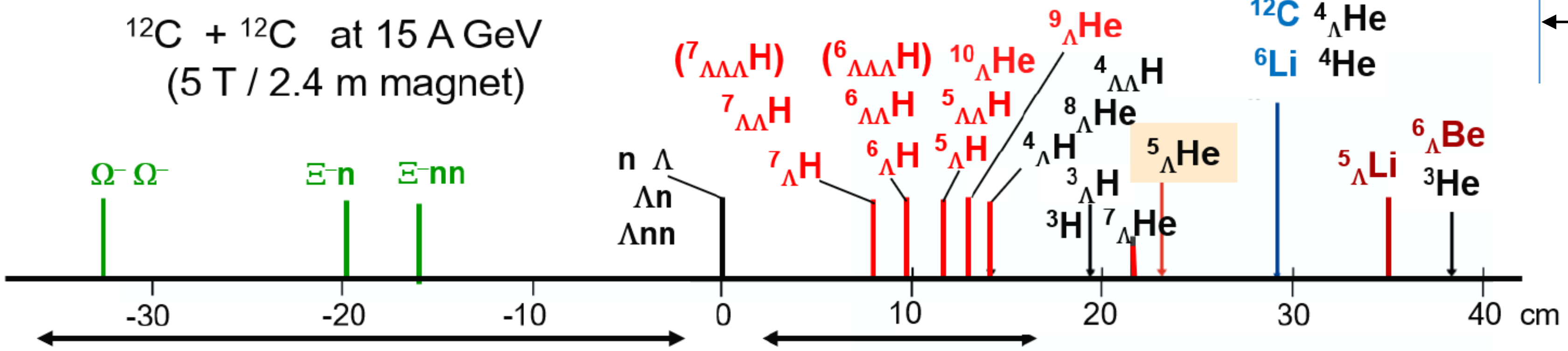
Hypernuclear Spectrometer

- Hypernuclei at beam rapidity
  - 1st Sweep magnet + Collimator
    → Only beam fragments reach the detector
  - Lifetime and Magnetic moment
- Interaction Rate : 10^8 Hz
- Strangelet and Di-baryon search



Add a sweep magnet and a collimator

Hyper-nuclei ID by reconstructed position

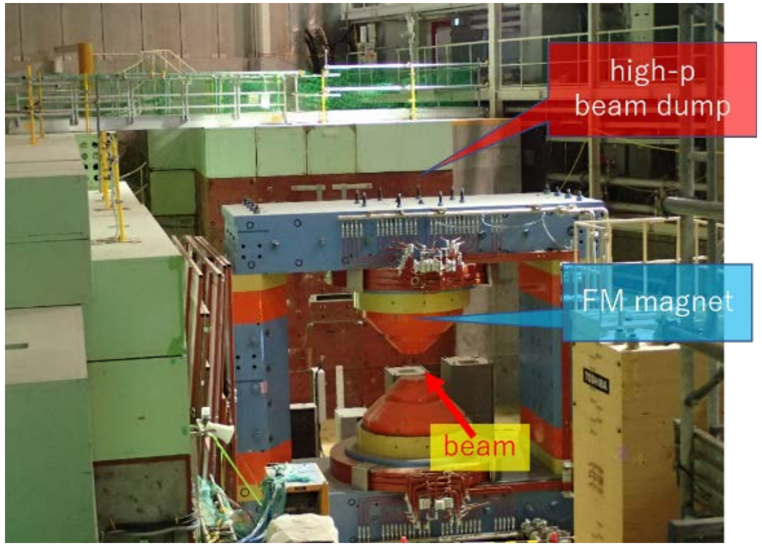


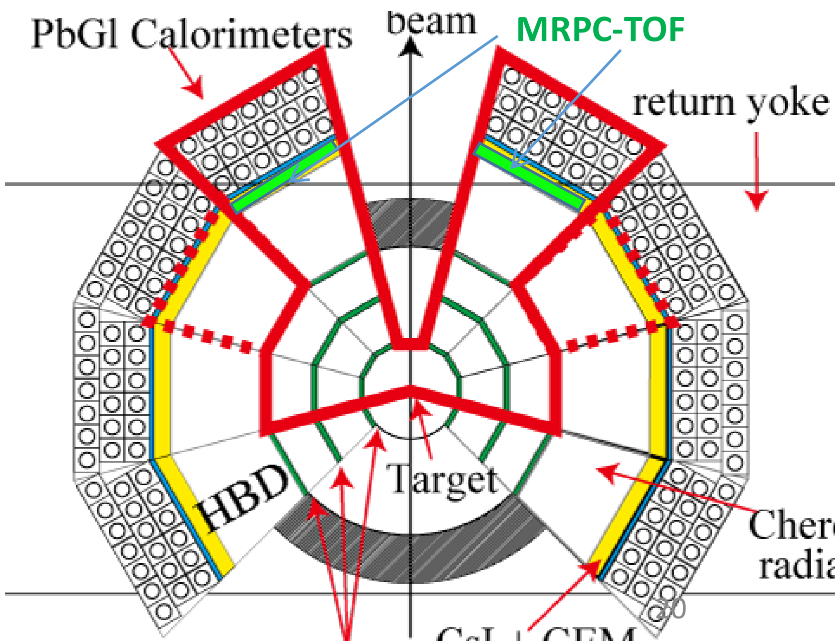
No contamination from non-strange nuclei

Project Status

- J-PARC-HI project will be approved as “Masterplan” of Science Council of Japan (starting from 2019)
- JAEA and J-PARC are positive
- Earliest possible start is 2026

- E16 experiment as a Phase-0 J-PARC-HI in p+A
  - ee pair spectrometer at J-PARC
    - Measure in-medium mass modification in p+A
  - Phase-0 for J-PARC-HI
    - Detector R&D with high intensity
      - MPRC-TOF, Continuous readout and online tracking
    - Hadron measurements for baseline of HIC
    - Will add ZCAL and Multiplicity Counter for event selection





Start taking data in 2020 spring

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
  - Flow, fluctuations, dileptons, photon, multi-strangeness systems
  - Large acceptance Dipole Spectrometers at J-PARC
- Linac and Booster only needed for heavy ion acceleration

Prospect

- Phase-0 p-A experiment (E16) will start 2020 Spring.
  - Baseline measurement and Detector R&D
- J-PARC HI will be approved on Masterplan of Science Council of Japan (2019)
  - Letter-Of-Intent submitted to J-PARC PAC (2016)
  - Design and R&D of Accelerator and Detectors going (2019-)

https://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/index.html

- Earliest possible start of the HI experiment (~2026)

103 members :

J-PARC-HI Collaboration

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment

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

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

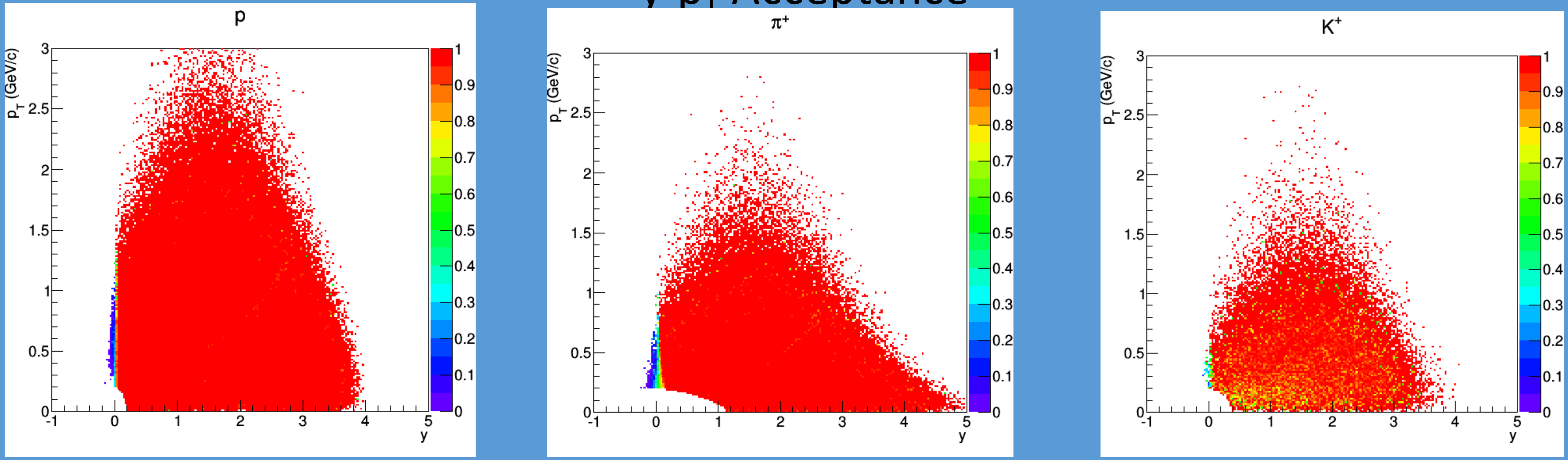
H. Harada, H. Hotchi, M. Kinsho, A. Kovalenko, J. Kamiya, H. Kuboki, Y. Kondo, Y. Liu, A. Miura, K. Moriya, T. Nakanoya, A. Okabe, M. Okamura, P. K. Saha, K. Shindo, Y. Shobuda, K. Suganuma, T. Takayanagi, F. Tamura, J. Tamura, N. Tani, Y. Watanabe, M. Yamamoto, M. Yoshii, M. Yoshimoto

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

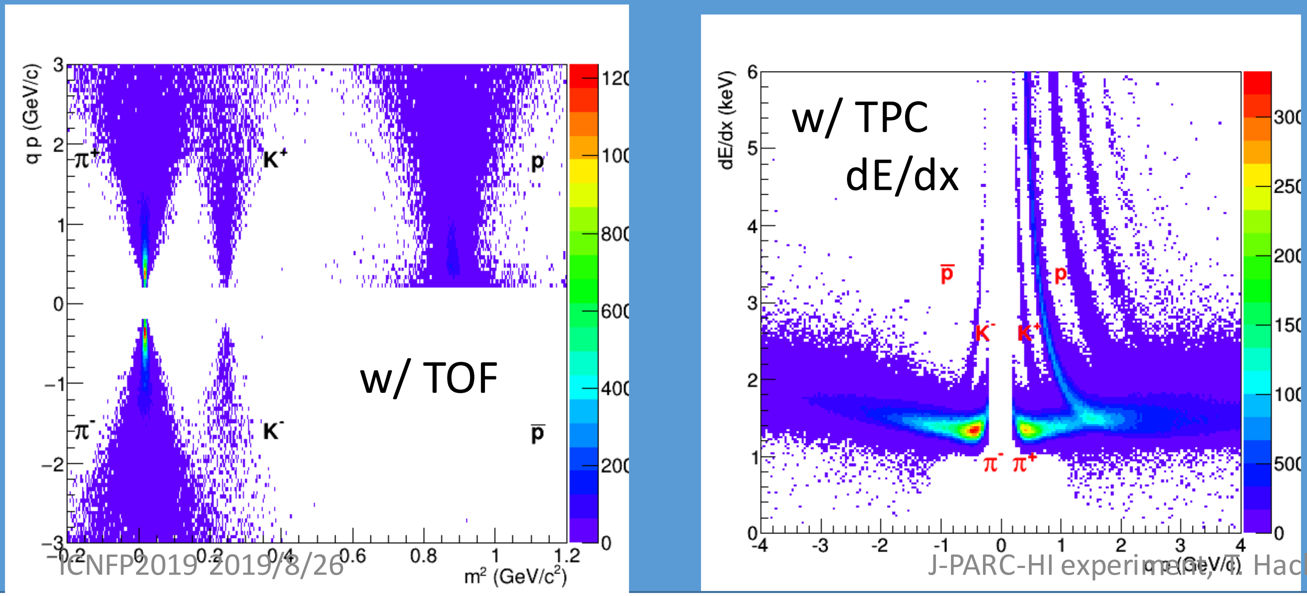
backup

Expected Performance- Dipole hadron spectrometer

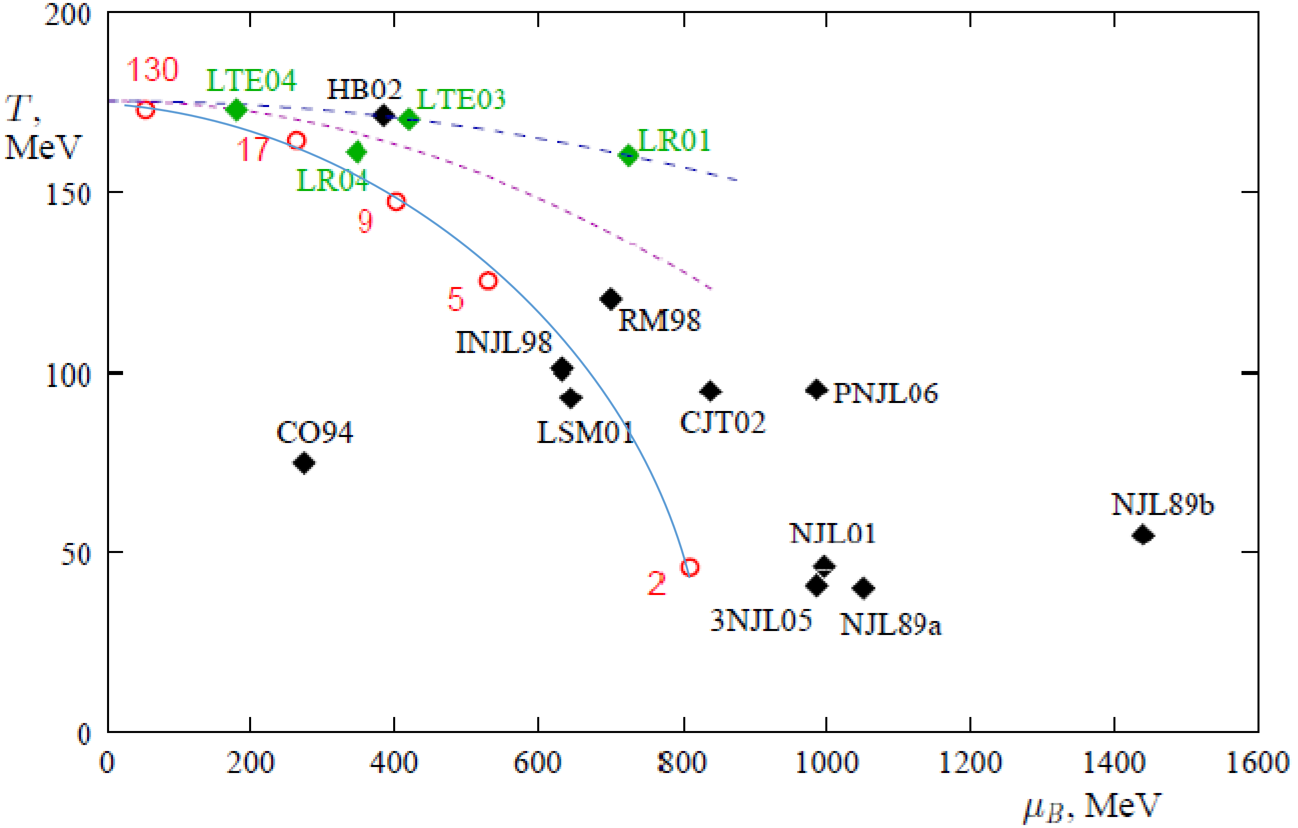
y-p_T Acceptance

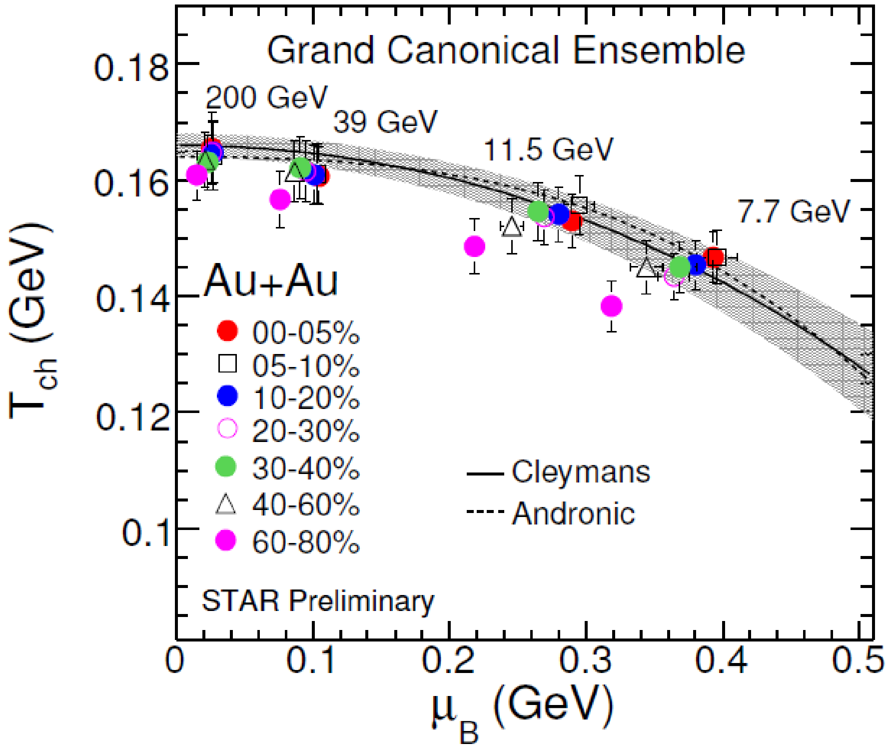


PID



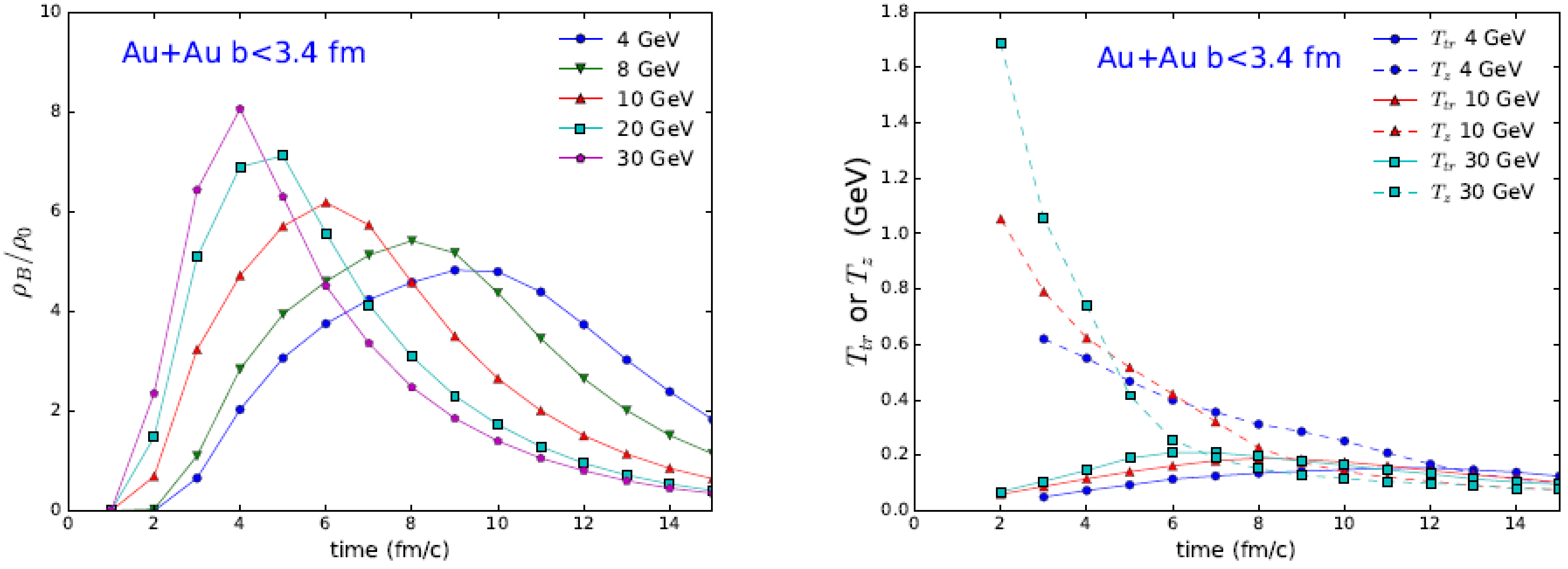
- Detector simulation using GEANT4
- U+U $\sqrt{s_{NN}}$=4.5 GeV, minimum bias JAM event



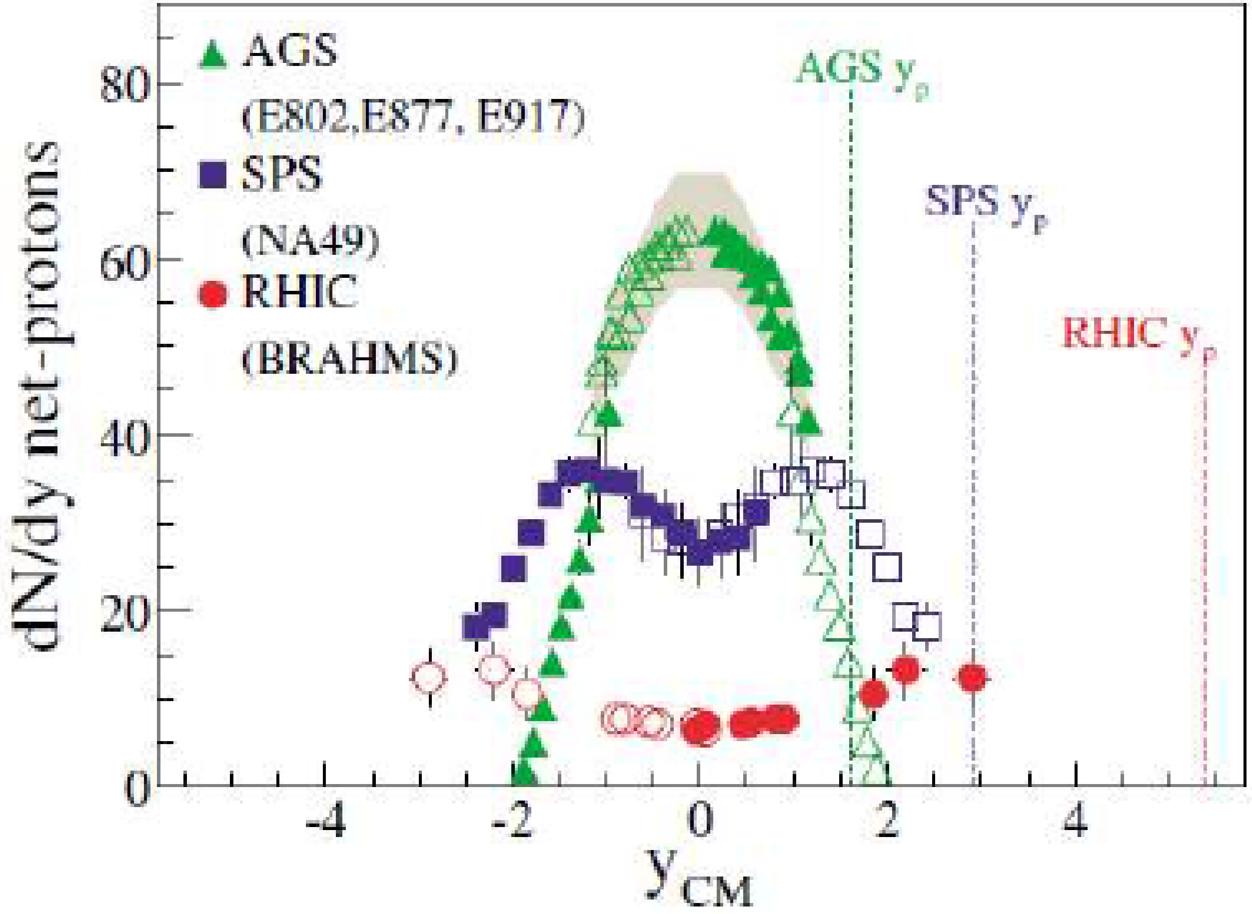


- Changing collision energy enable to scan QCD phase structure

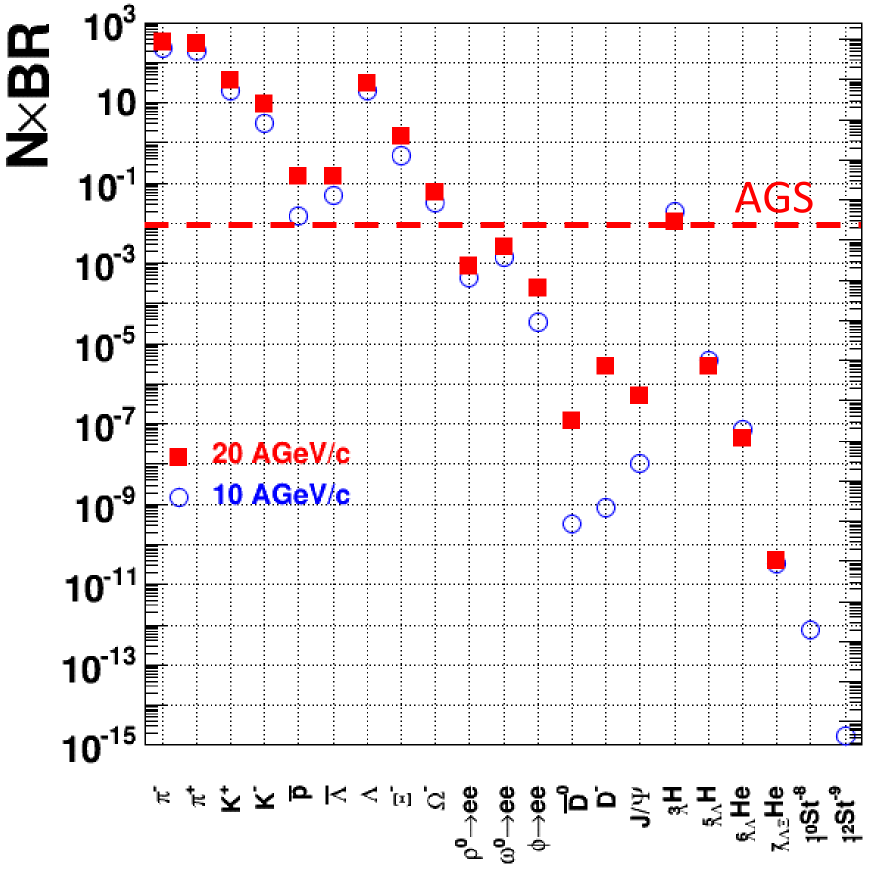
Baryon density vs time : JAM



- Equilibrium time : Ttr ~ Tz
  - 6 fm/c @ 30 GeV (8@10GeV) => ~5 time higher than nuclear density


AGS
(E802,E877, E917)
SPS
(NA49)
RHIC
(BRAHMS)
AGS y_p
SPS y_p
RHIC y_p
dN/dy net-protons
y_{CM}
0
20
40
60
80
-4
-2
0
2
4

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
- $\rho, \omega, \phi \rightarrow e^+e^-$: 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