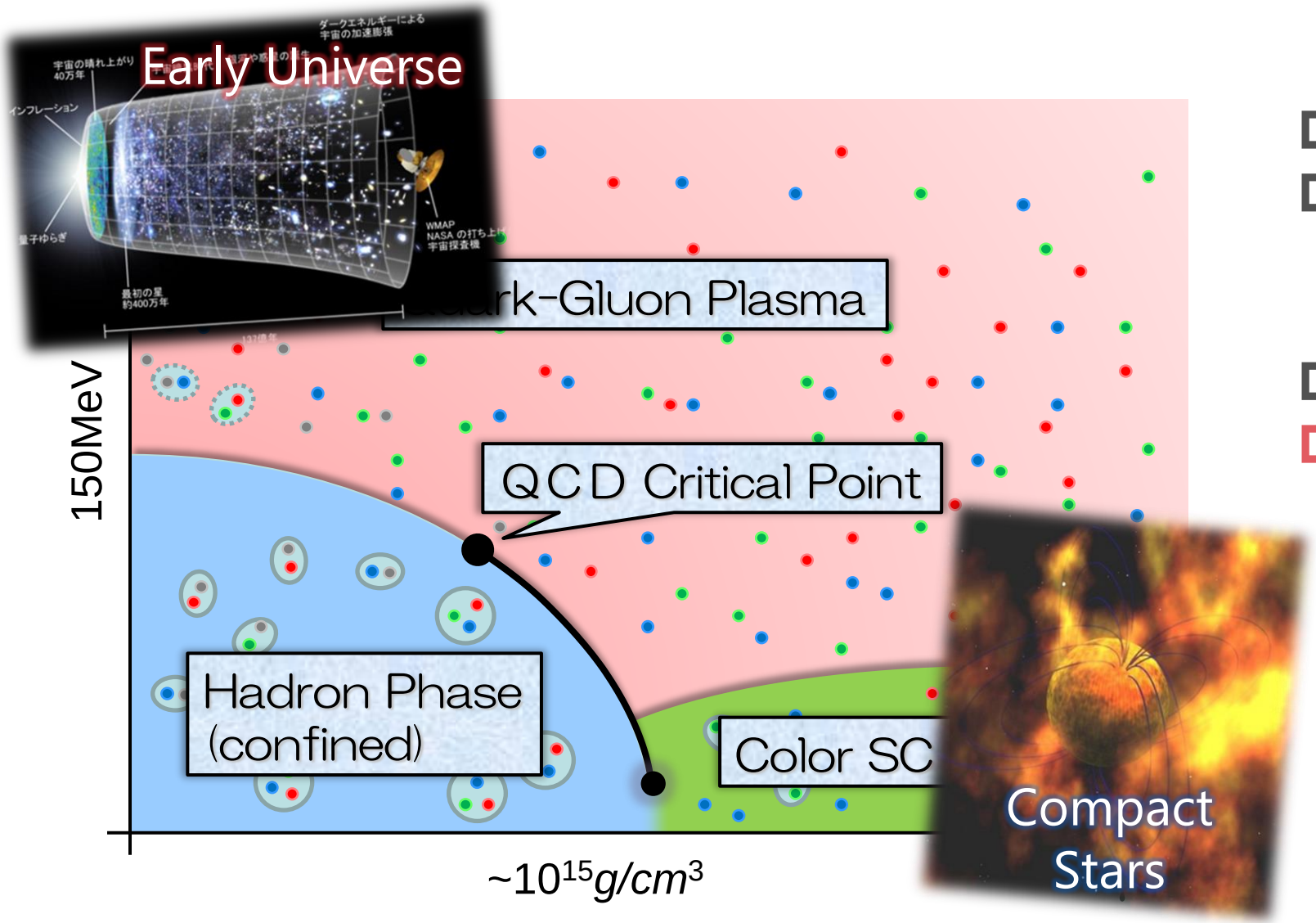
2024年度第2回宇宙史研究センター構成員会議・成果報告会、2024/12/16、筑波大学

重イオン衝突実験を用いた高密度核物質探索

北沢正清
(京大基研)

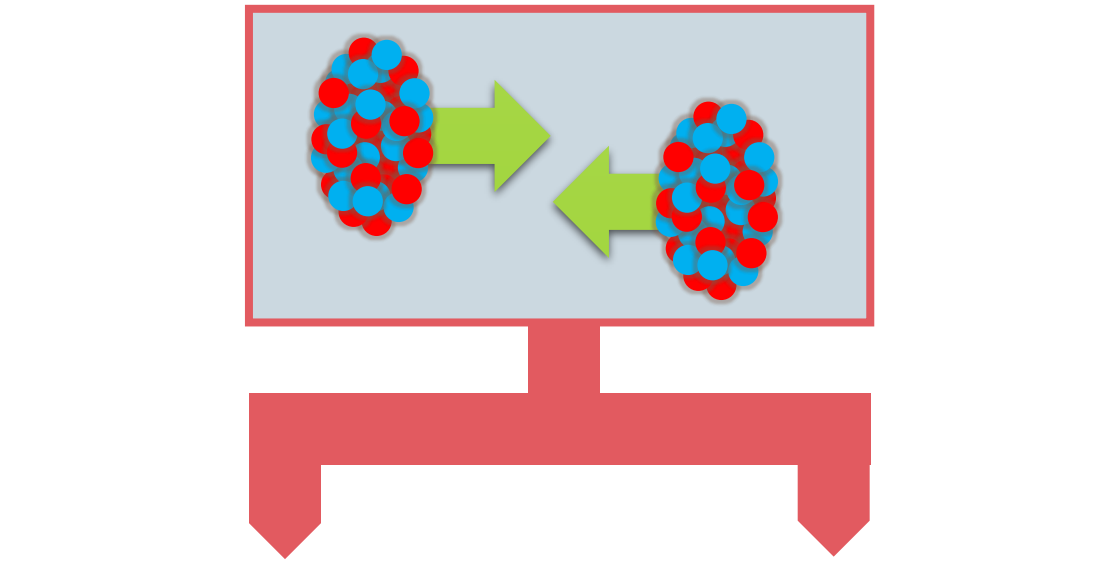
QCD Phase Diagram



- Crossover at zero density
- Possible first-order transition and QCD critical point in dense region
- Multiple QCD-CP? MK+ ('02)
- Color superconducting phases in dense and cold quark matter

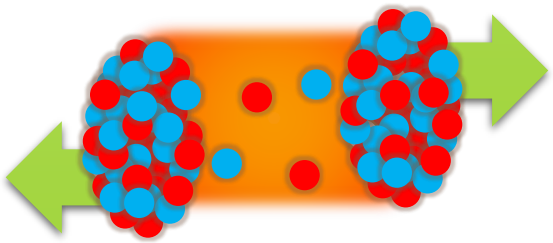
Beam-Energy Scan in HIC

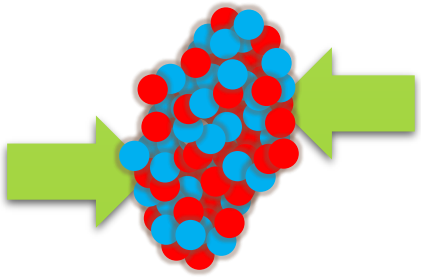
STAR, 2012



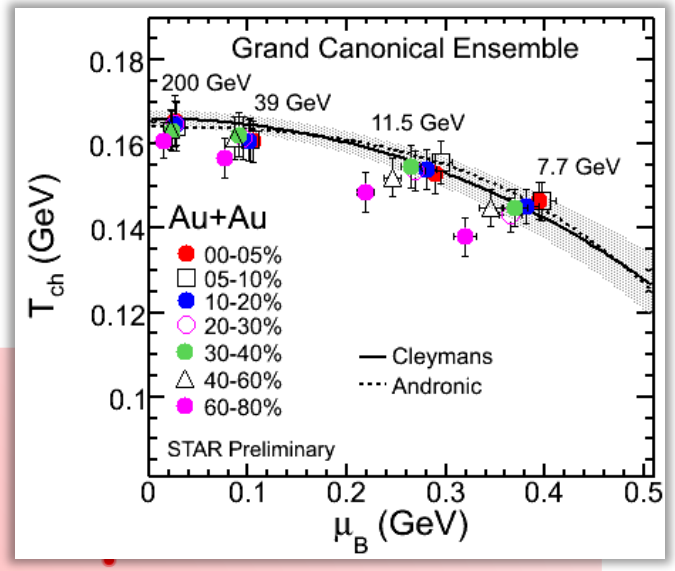
High E

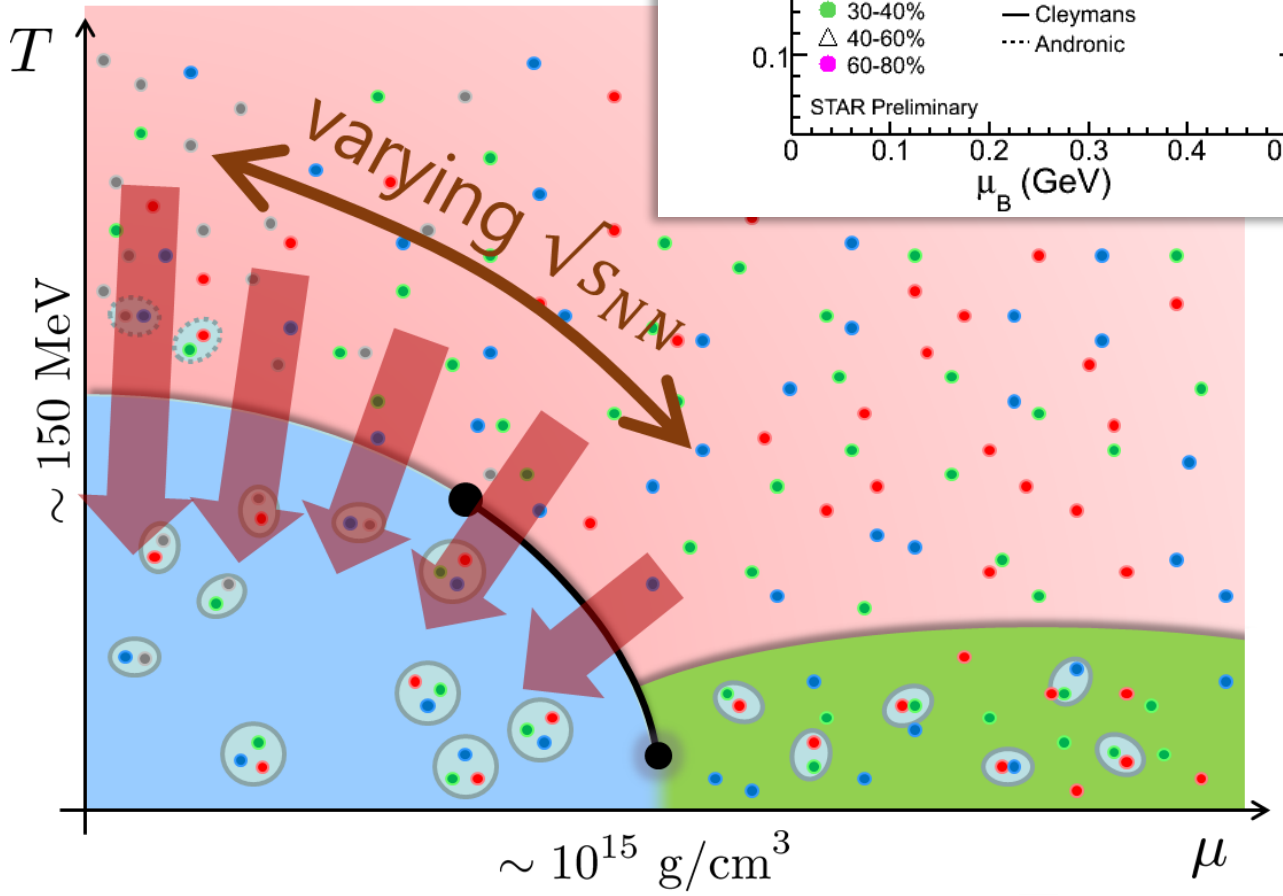
Low E



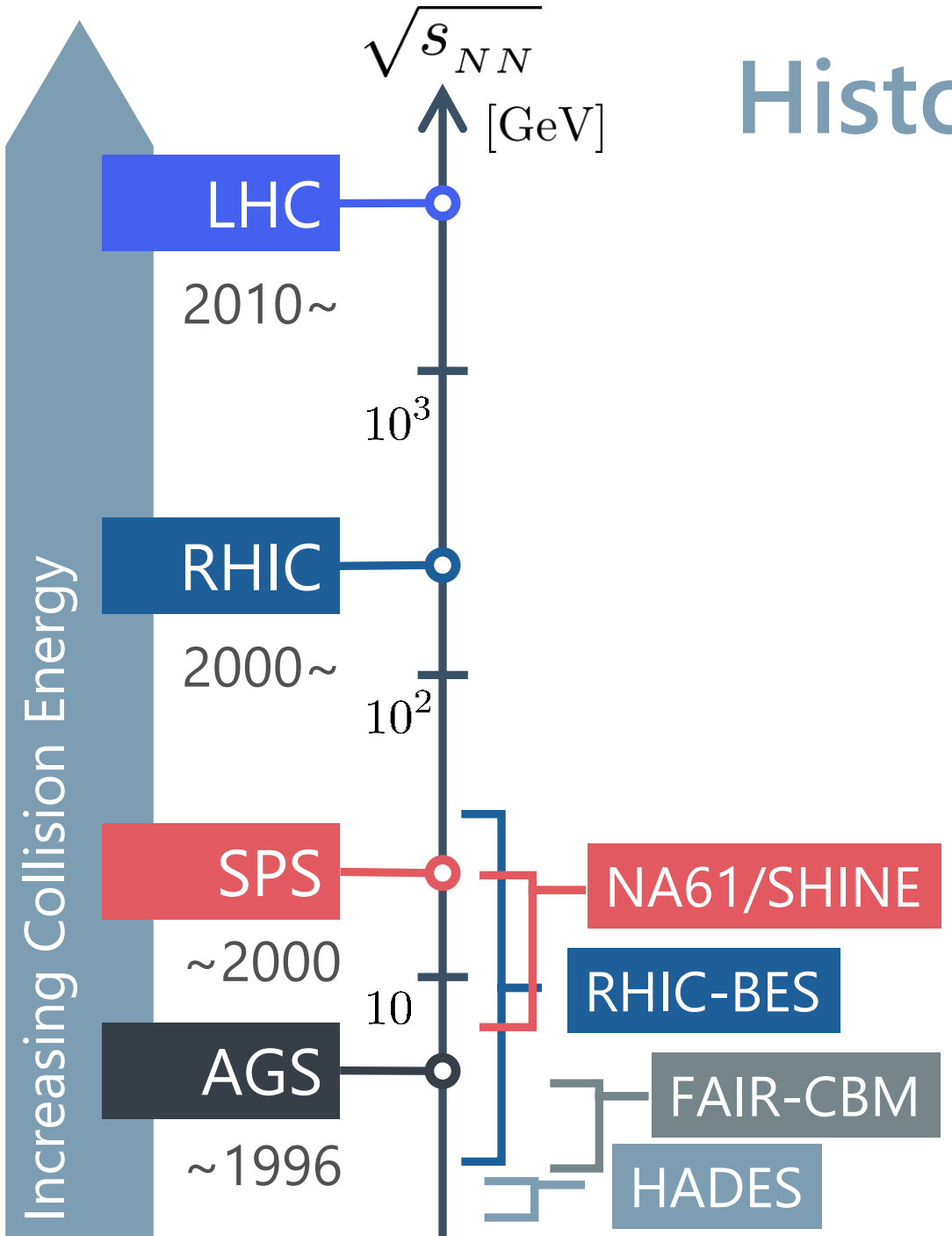


Baryon stopping

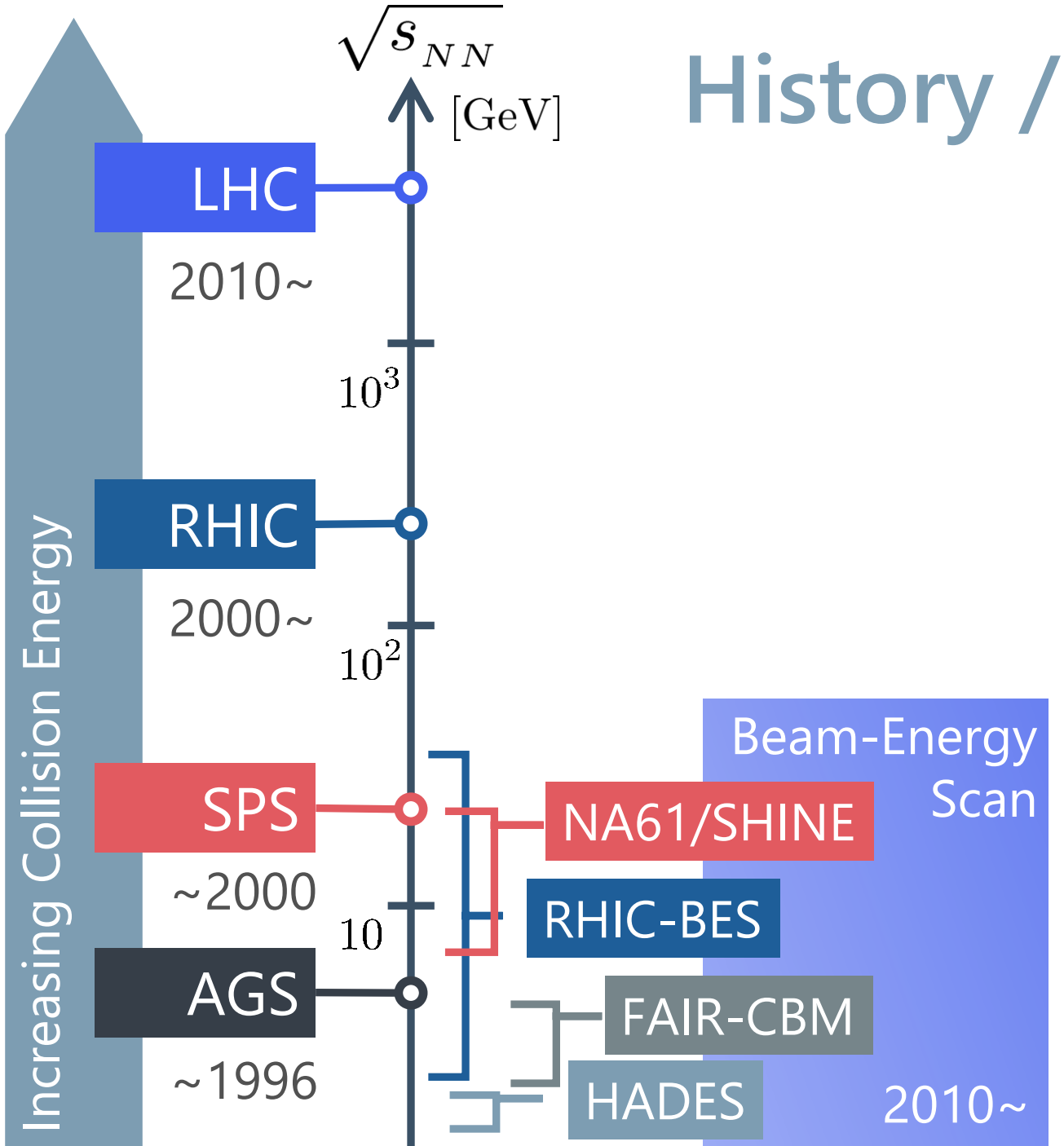


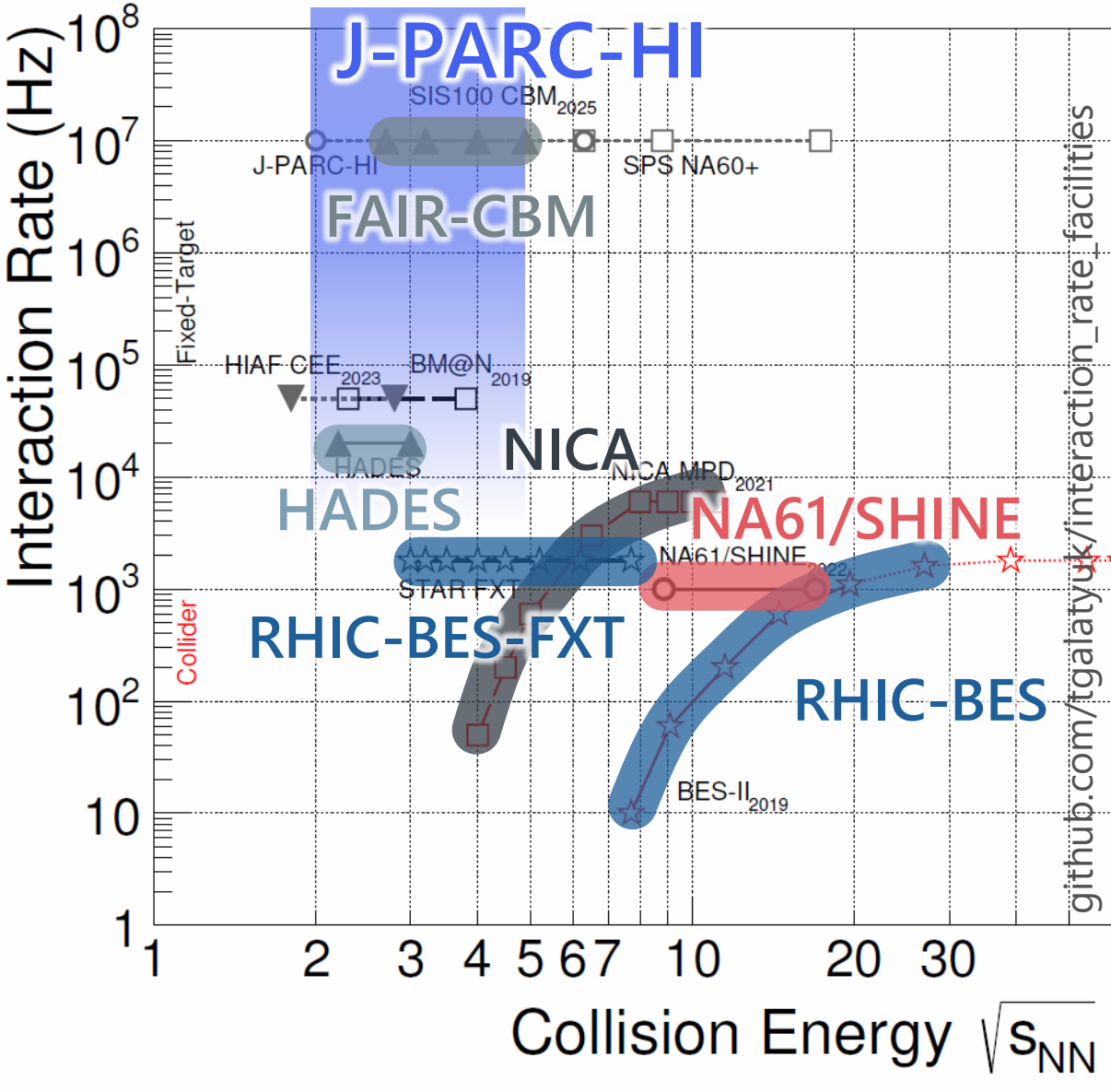


History / Current Status of HIC



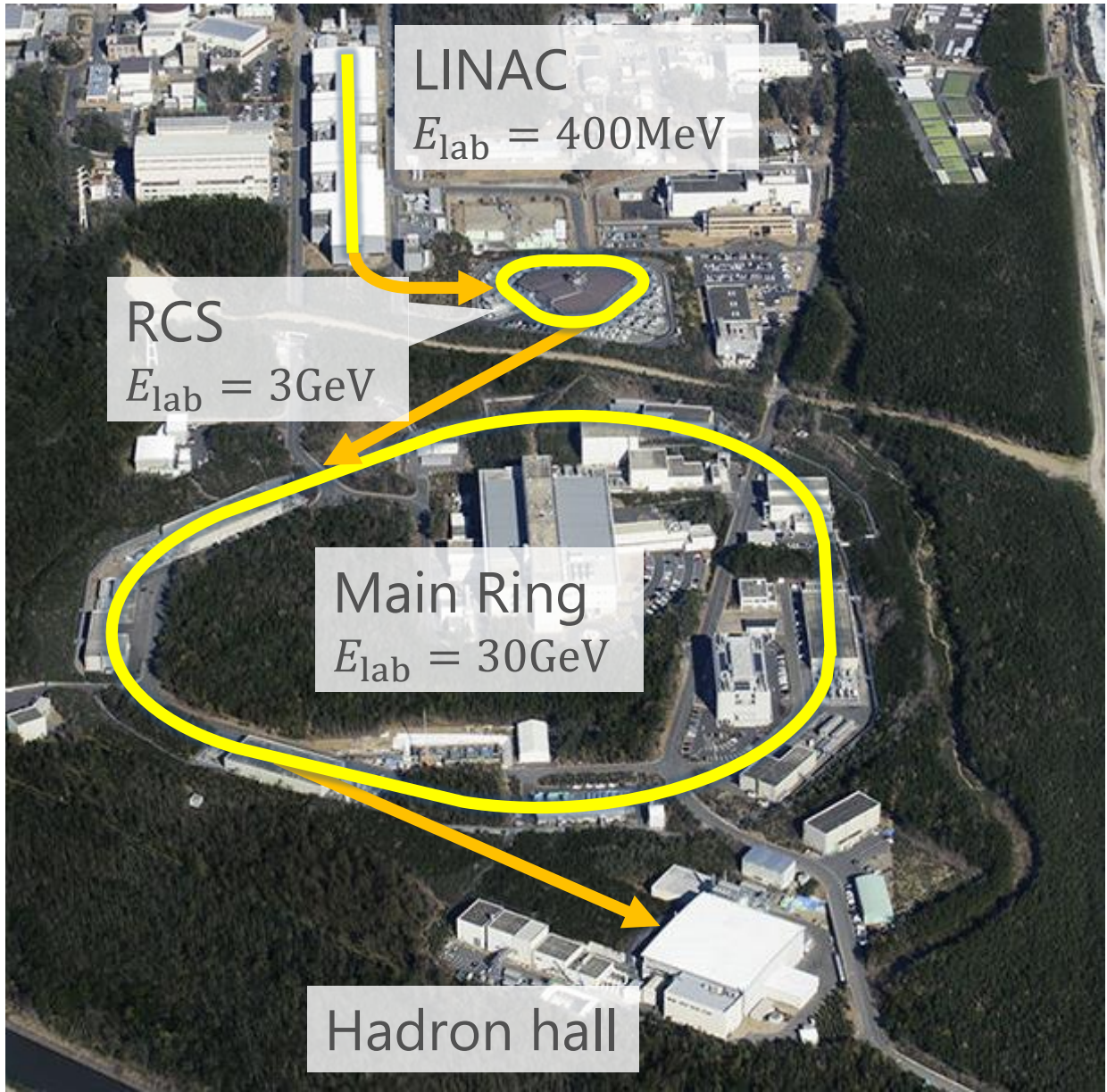
History / Current Status of HIC





J-PARC-HI = J-PARC Heavy-Ion Project

- **New HI injector** + existing accelerators (**RCS, MR**)
- Heavy-ion beams with **world highest luminosity**
- Realize various new experiments at J-PARC



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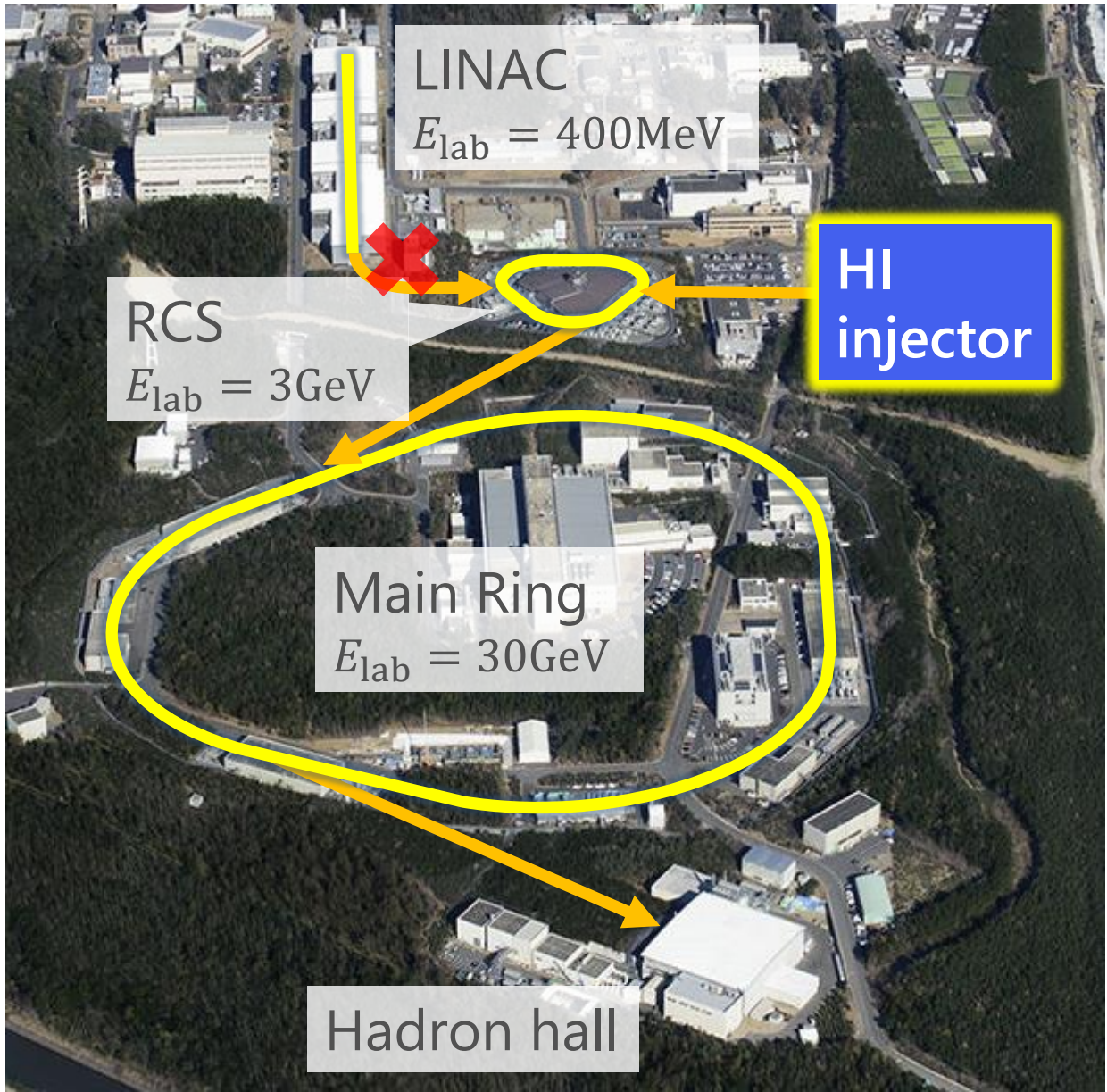
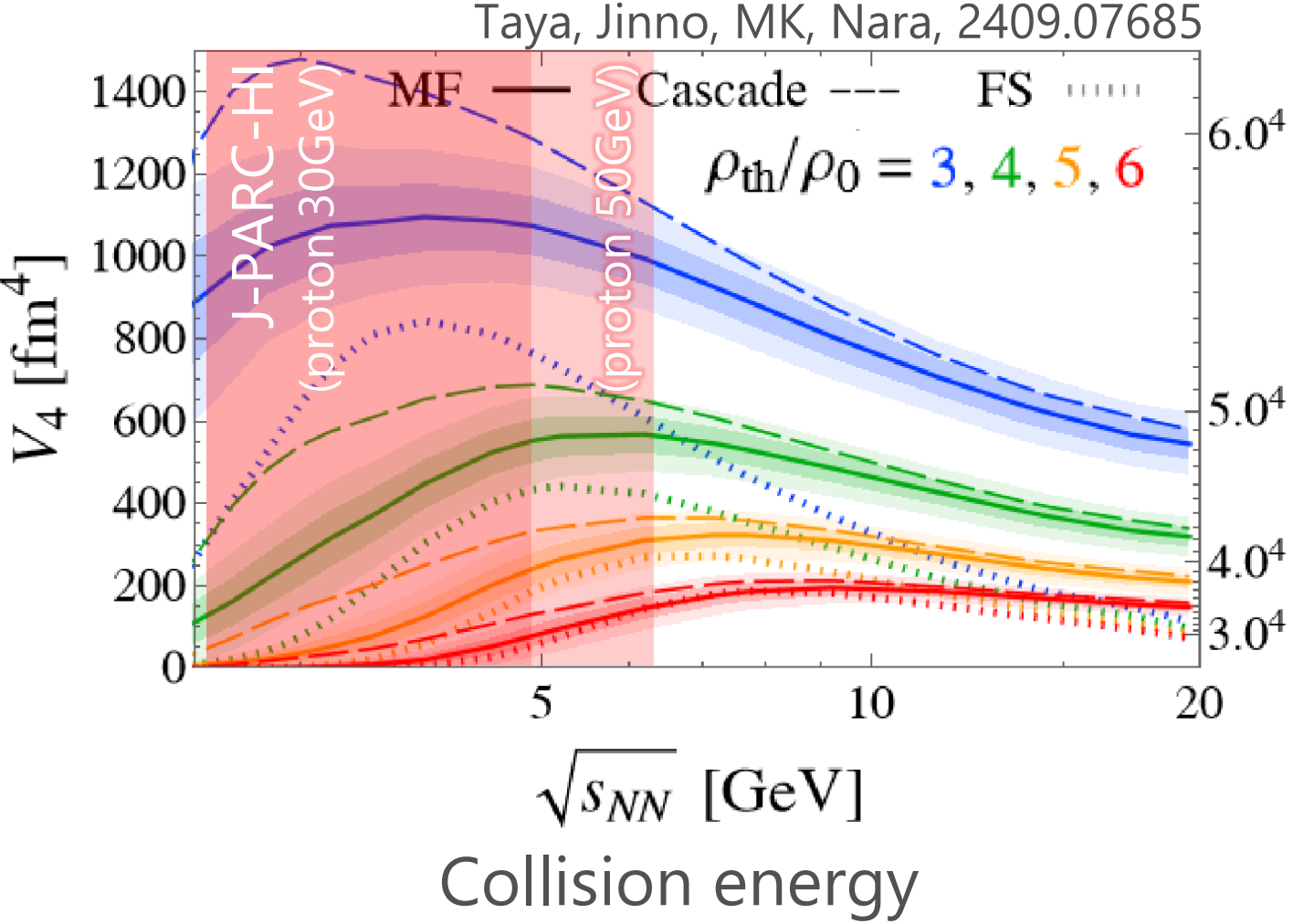


How High Density? Where is optimal $\sqrt{s_{NN}}$?

Four-volume of high-density region

Taya, Jinno, MK, Nara, 2409.07685



Collision energy

Medium with $\rho > 3\rho_0$ can be formed for $V_4 \simeq (6\ \mathrm{fm})^4$ at J-PARC-HI energy

The density is comparable with the cores of neutron stars

J-PARC-HI = experiments to create **the highest baryon-density matter in the Universe**

Quark-G
Plasma

J-PARC
FAIR • NICA

Compact Stars

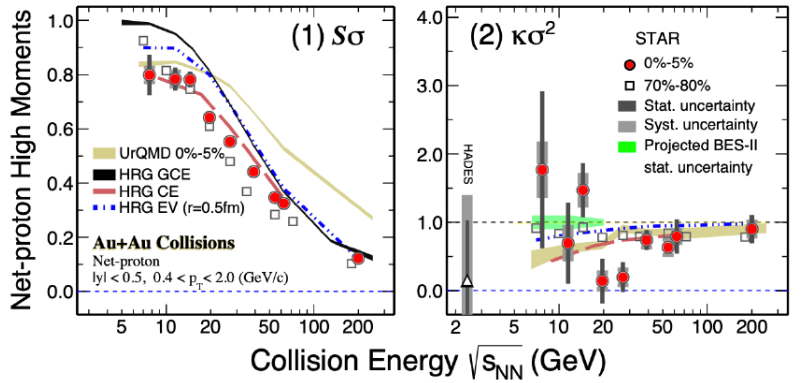
Exploring Dense Medium

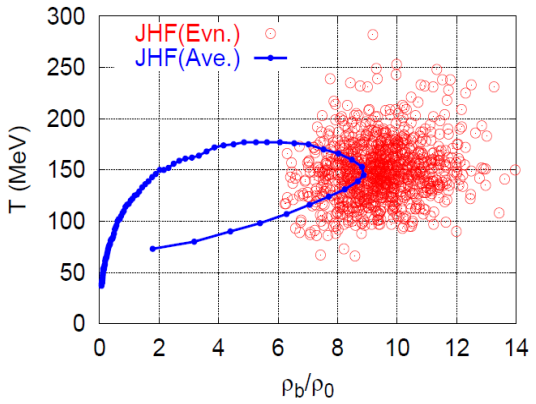
Equation of state

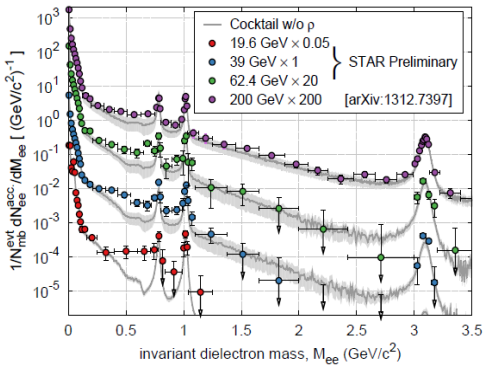
QCD critical point /
1st order transition /
Color superconductivity

Dilepton production rate

Event selection /
Higher correlations



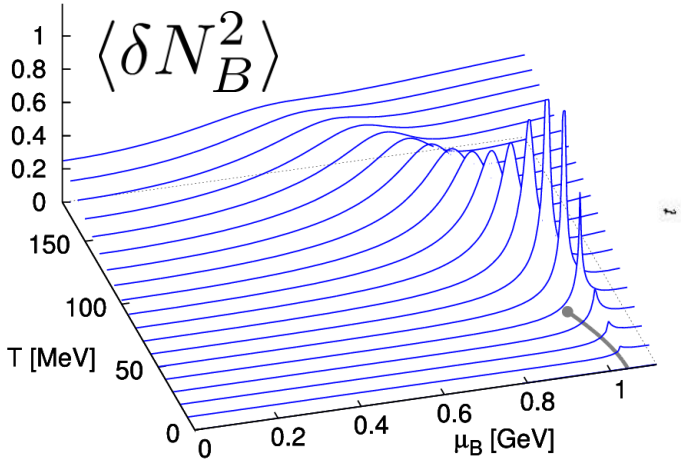




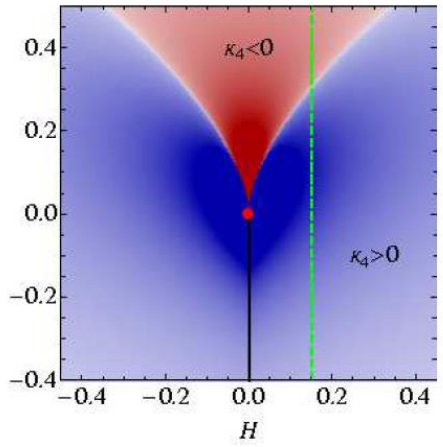
Event-by-event Fluctuations

Theoretical Predictions
on conserved charge fluctuations

— Higher-order cumulants
— Signal of QCD CP



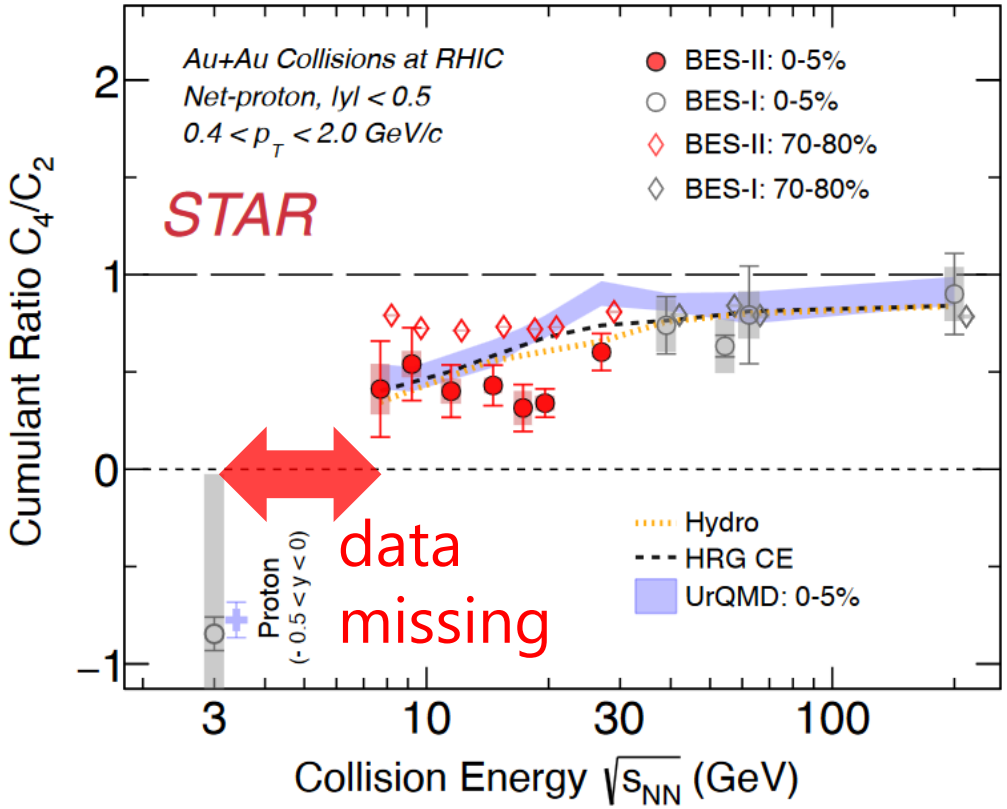
Asakawa, Ejiri, MK (2009)



Stephanov (2011)

Experimental Result

STAR (2024)



A Coin Game

① Bet 25 Euro
② You get head coins of

A. 50 x 1 Euro

B. 25 x 2 Euro

Same expectation value.

A Coin Game

① Bet 25 Euro
② You get head coins of

A. 50 x 1 Euro

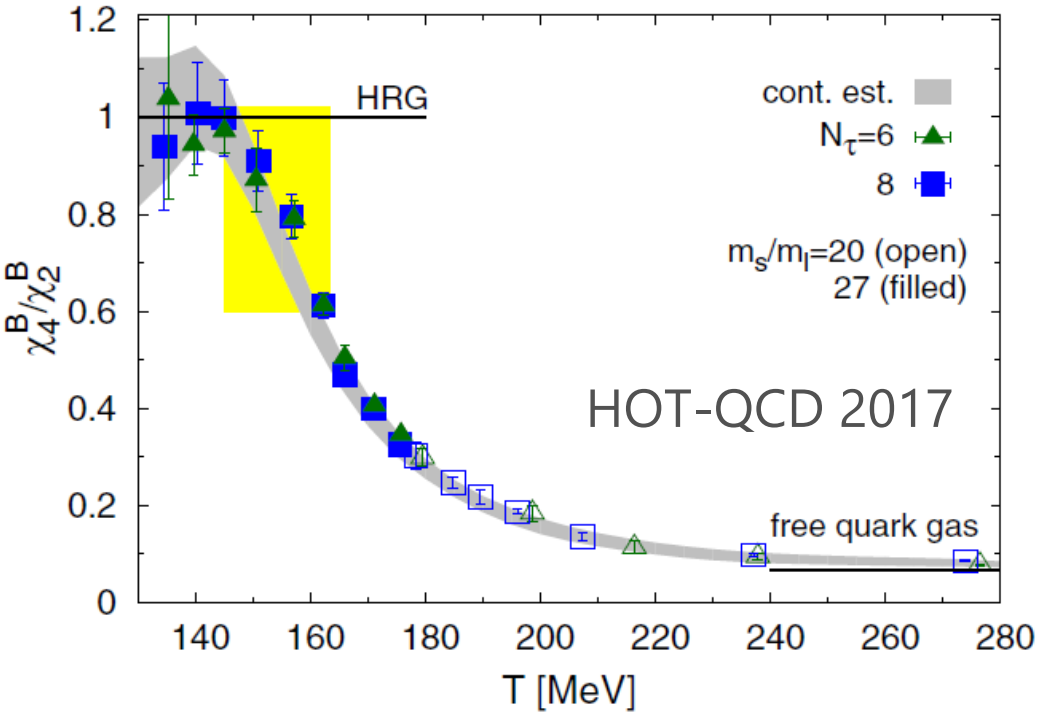
B. 25 x 2 Euro

C. 1 x 50 Euro

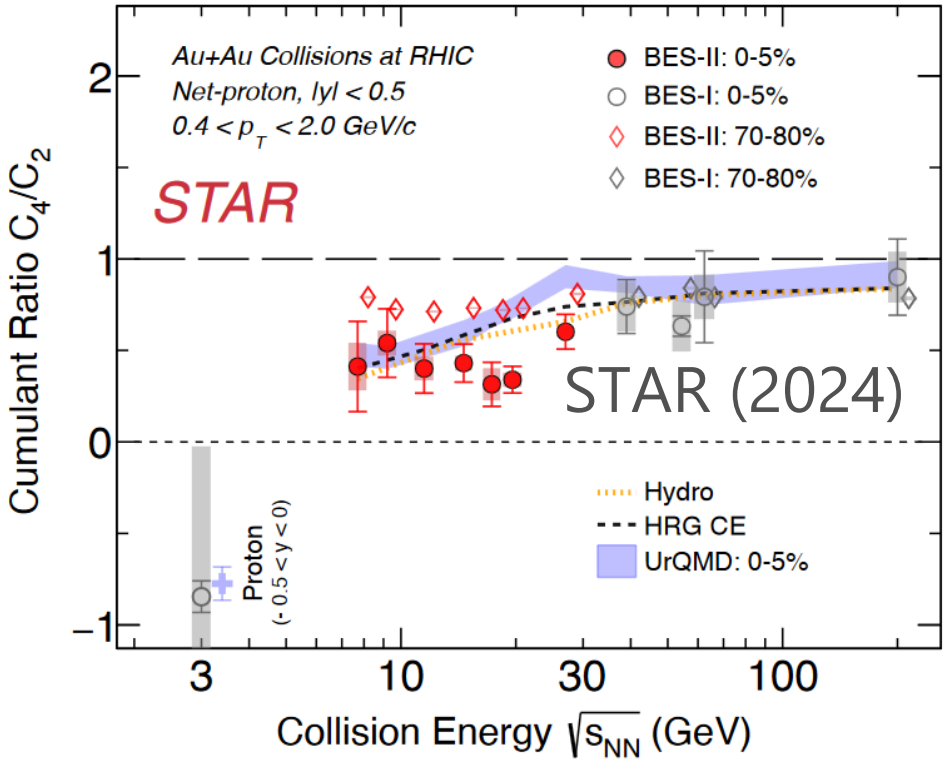
Same expectation value.

Lattice & Exp. Cooperate

Lattice Data



Experimental Result



Lattice-QCD Numerical Simulations:
equations of state, fluctuation, viscosity, …

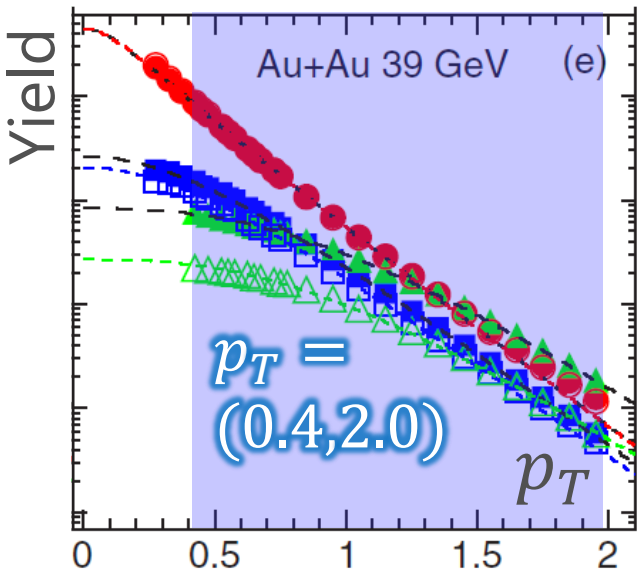
Baryon/Charge Cumulant Ratio

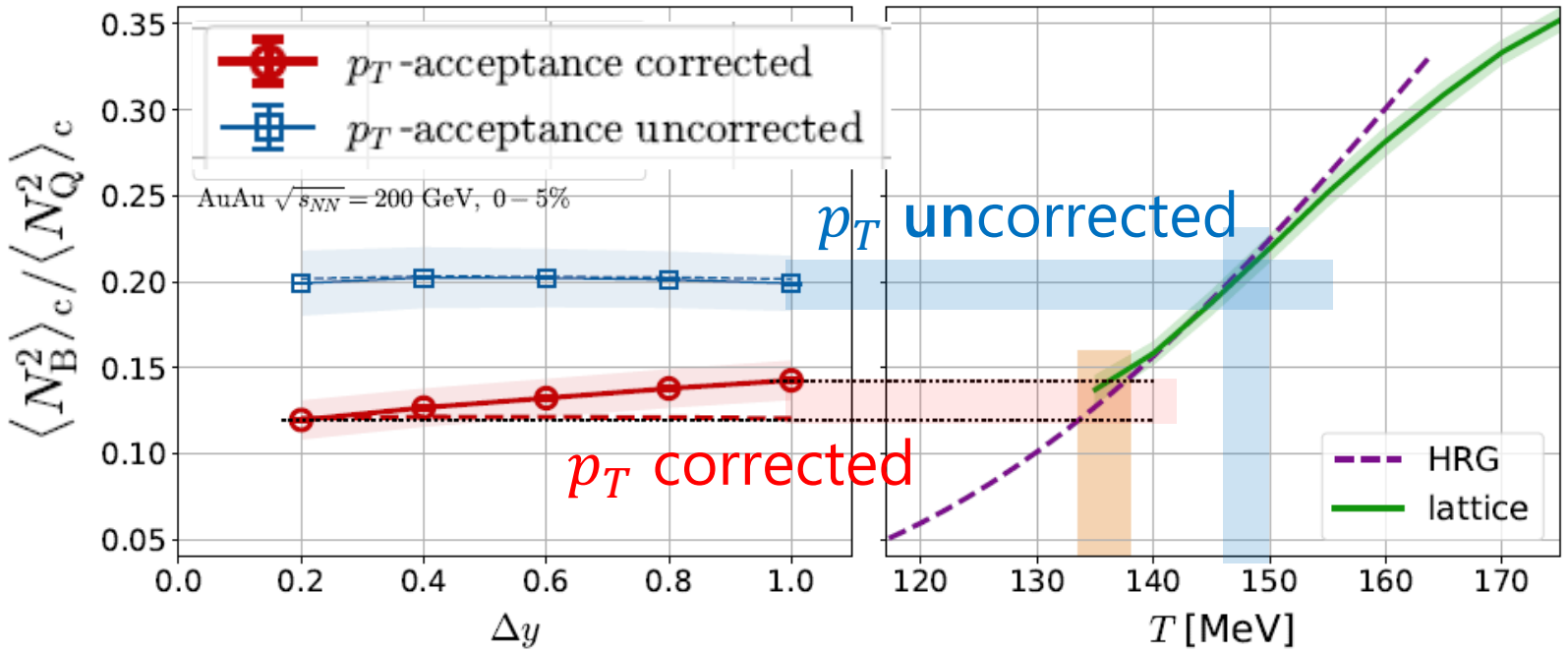
$$\langle N_{\mathrm{B}}^2\rangle_c/\langle N_{\mathrm{Q}}^2\rangle_c \simeq \chi_2^{\mathrm{B}}/\chi_2^{\mathrm{Q}}$$

MK, Esumi, Nonaka, Nucl. Phys. A, 2023

STAR, 200GeV ⟷ Lattice QCD + HRG

p_T-acceptance correction





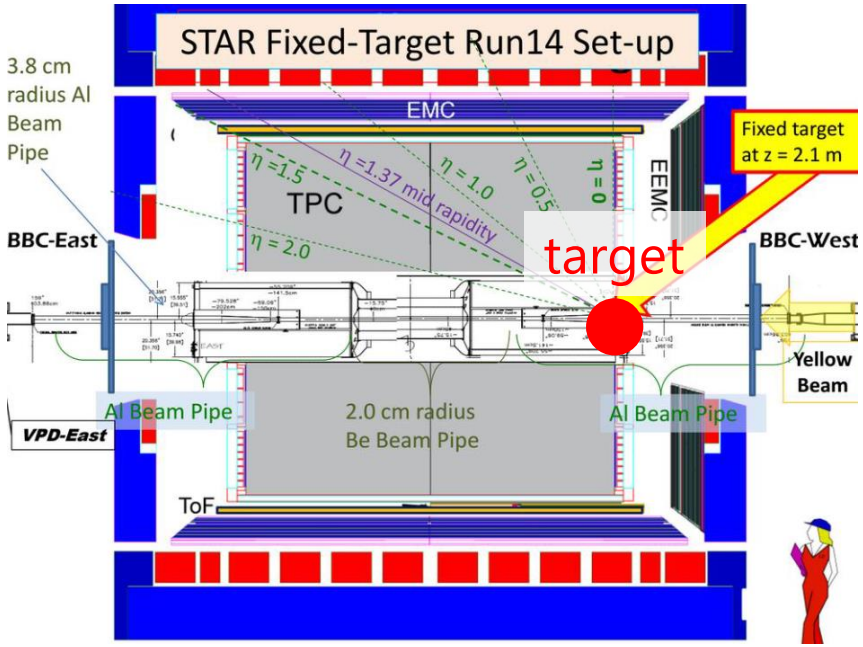
- Electric charge: 49%
- Protons: 82%

- Finite acceptance modifies the ratio strongly.
- Wider acceptance/efficiency is desirable.

Acceptance of Detectors

STAR Fixed Target

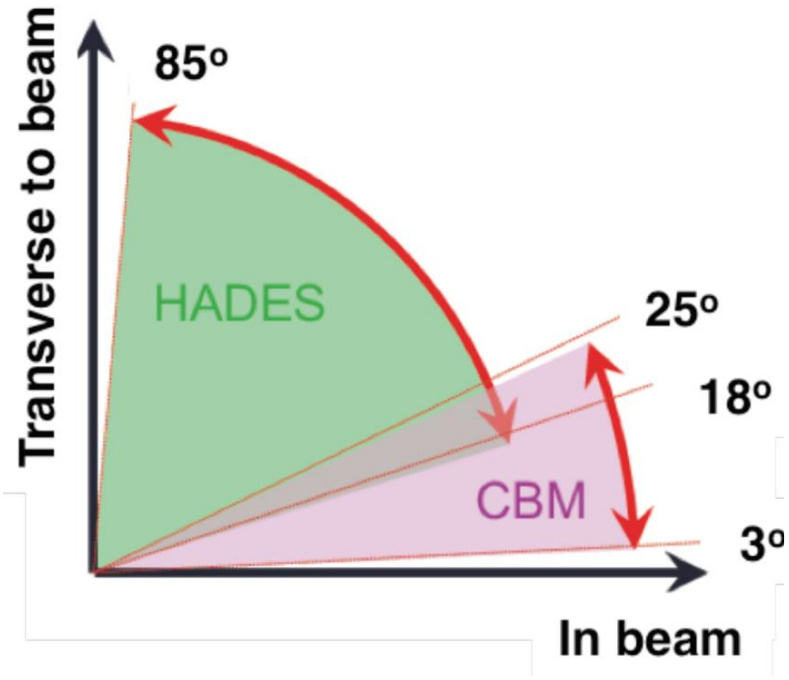
$3 < \sqrt{s_{NN}} < 7.7$ GeV

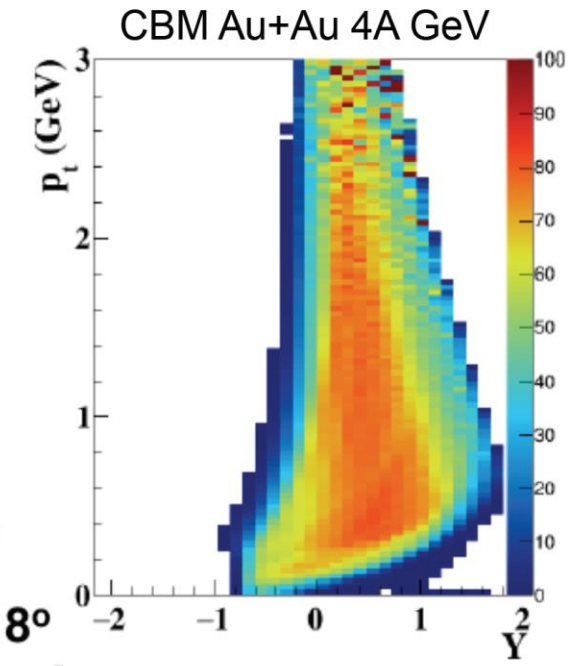


from slide of D. Sebra

FAIR (GSI)

$2 < \sqrt{s_{NN}} < 5$ GeV

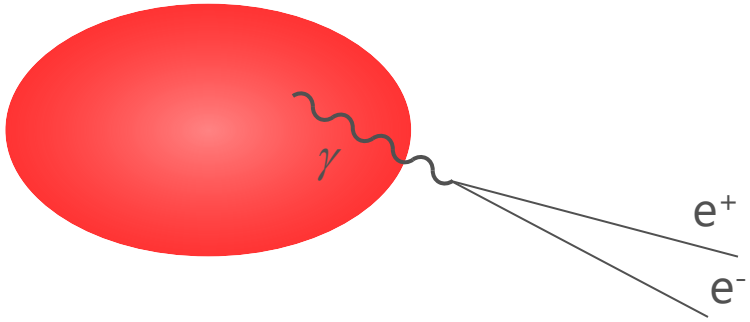




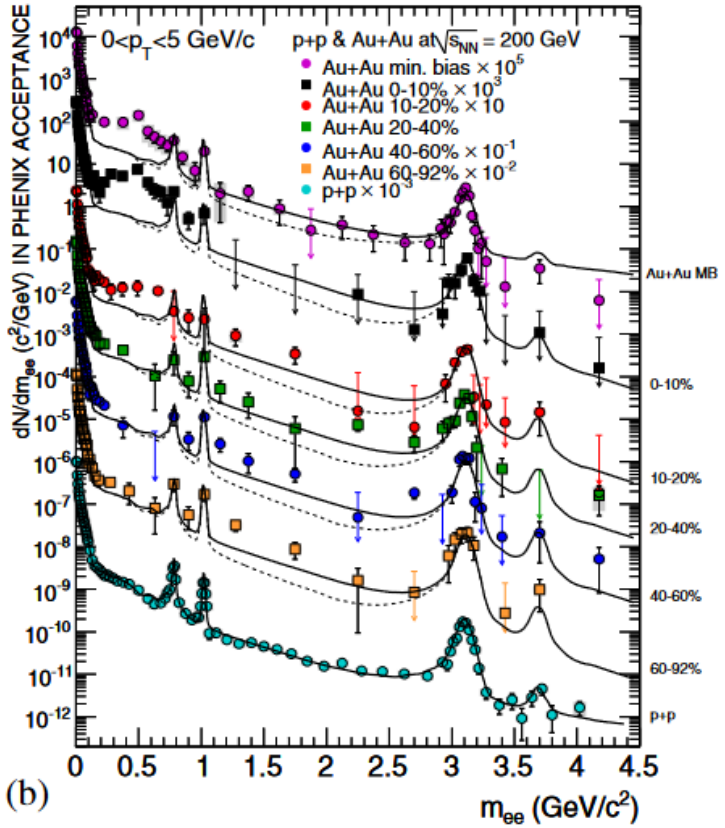
Each detector has individual acceptance and efficiency.

Checking detector-response correction is important.

Dilepton Production Rate



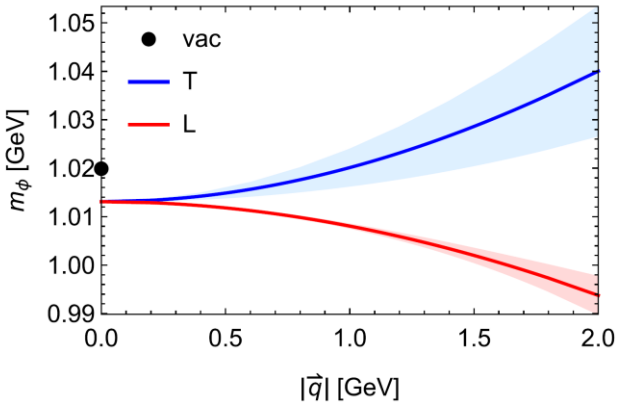
—Generated by the decay of virtual photons
—Carry information of primordial medium



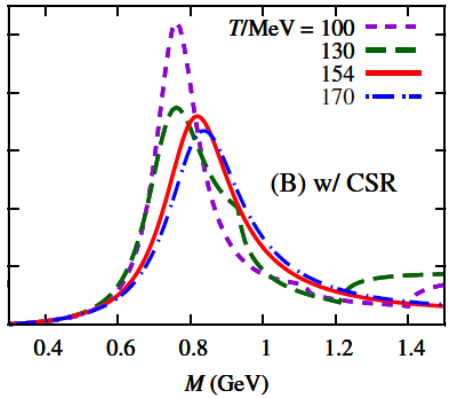
PHENIX, '10

Physics accessible with DPR

— Medium temperature
— Dispersion relations
— Chiral mixing by chiral restoration
— Signal of phase transitions

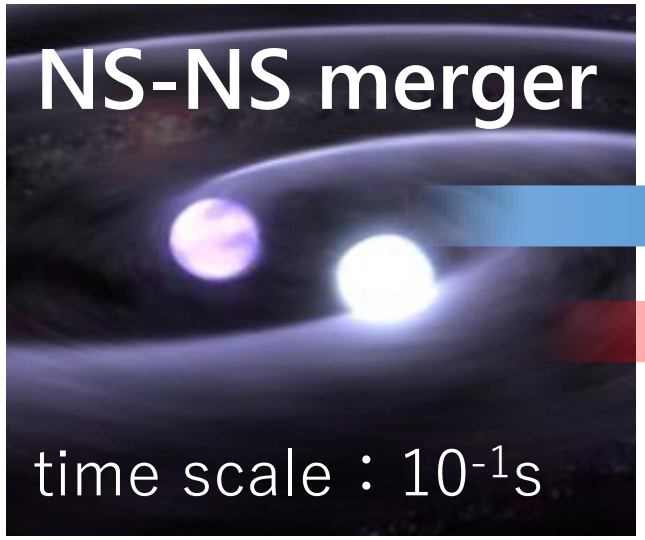


Kim, Gubler, 2020



Sakai+, 2024

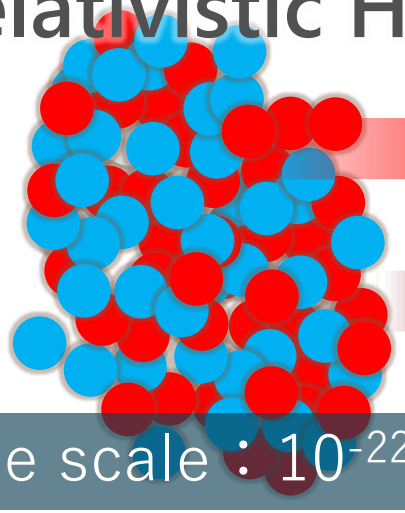
“Multi-Messenger” Observation



gravitational waves

electromagnetic waves

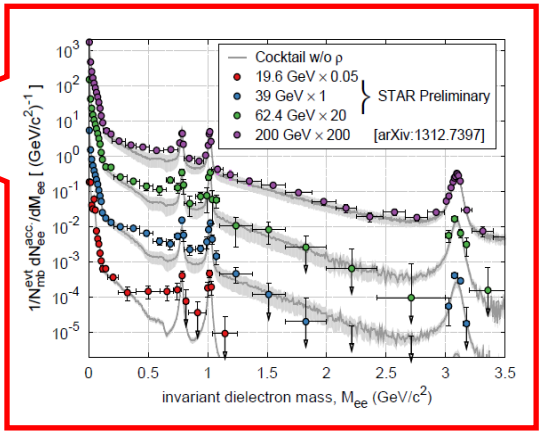
Relativistic HIC



time scale : 10^{-22}s

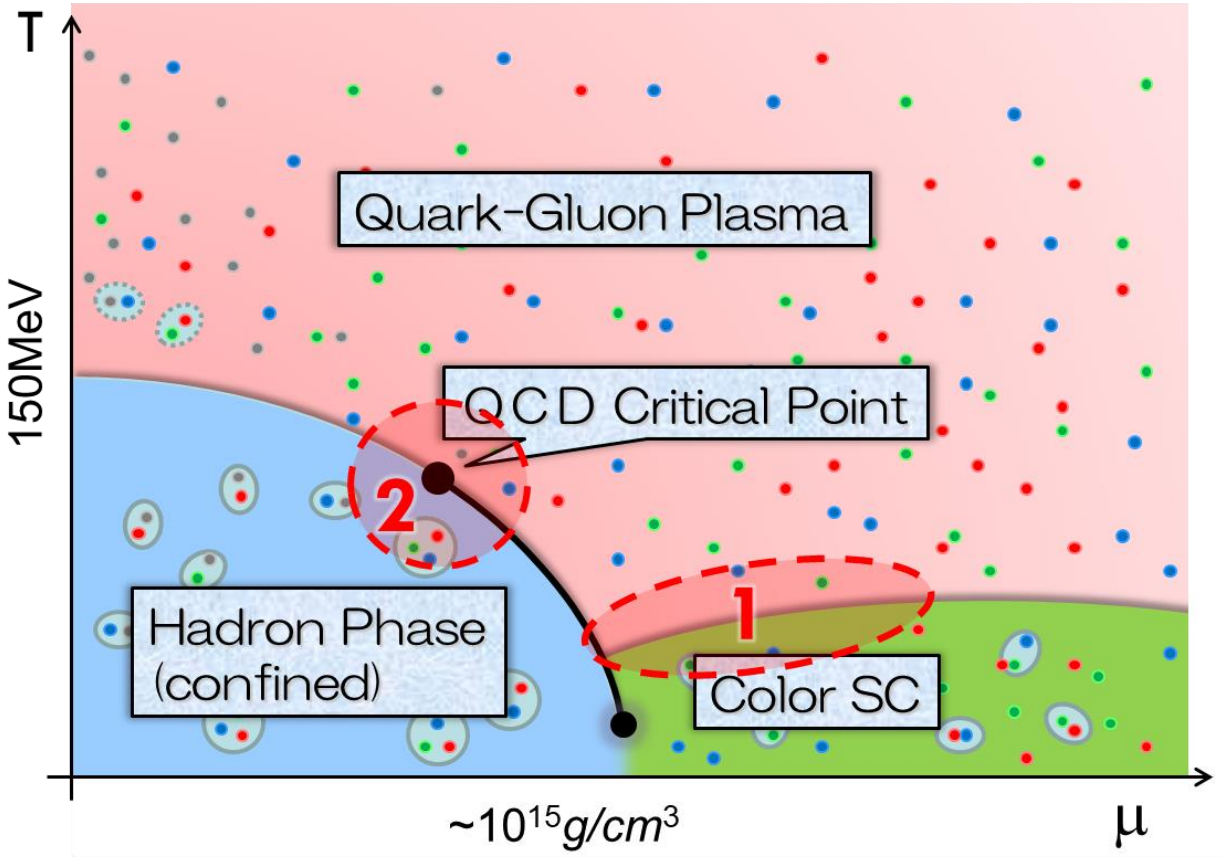
leptons,
photons

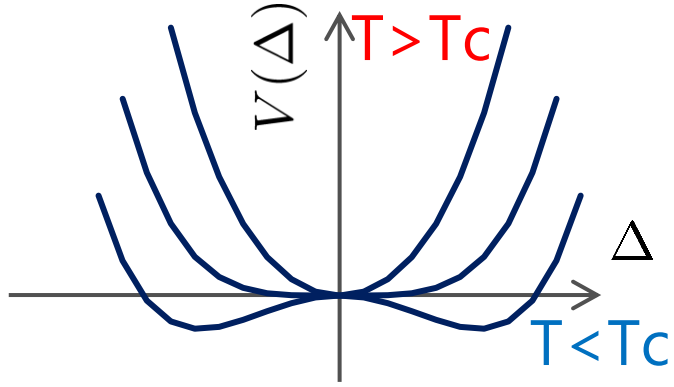
hadronic observables



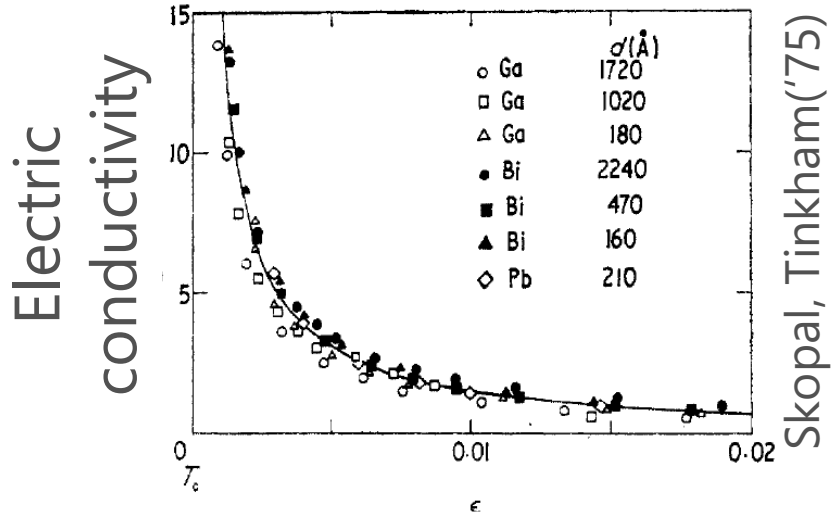
Dileptons and Phase Transitions

2nd-order phase transition → Formation of the soft modes





Anomalous phenomena



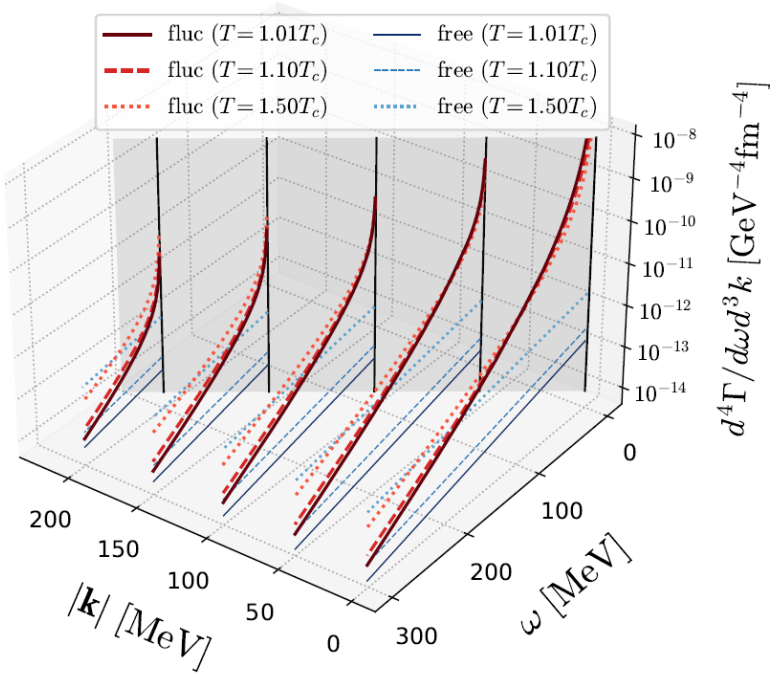
$$\varepsilon = \frac{T - T_c}{T_c}$$

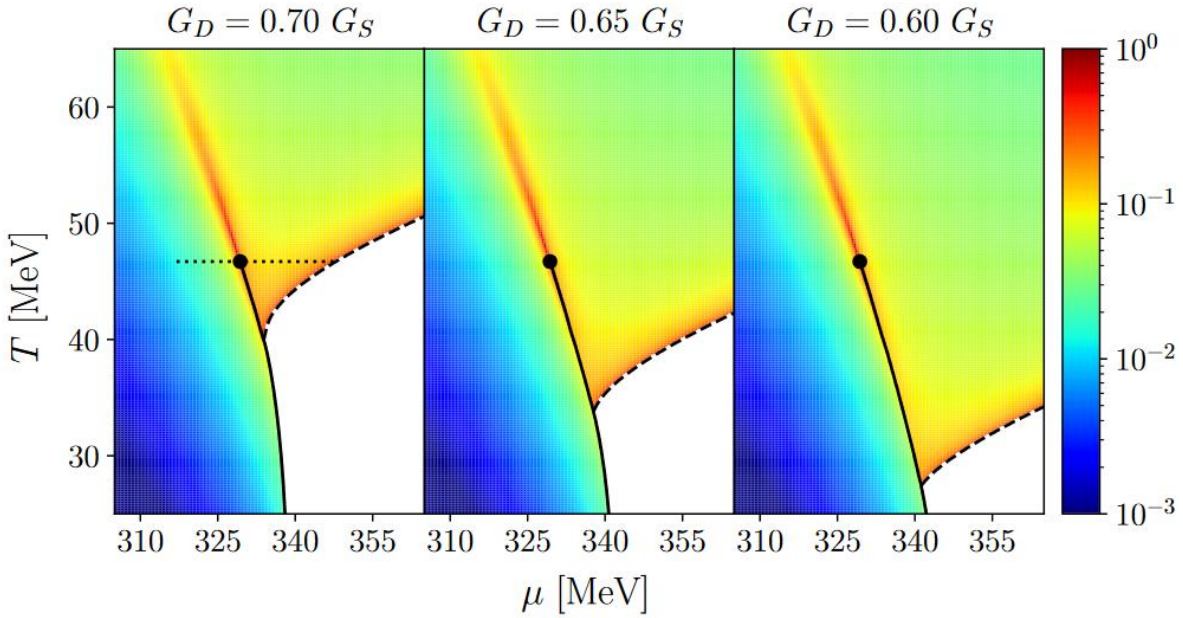
Dilepton at Ultra-Low-Mass Region

Signal for QCD-CP & Color SC

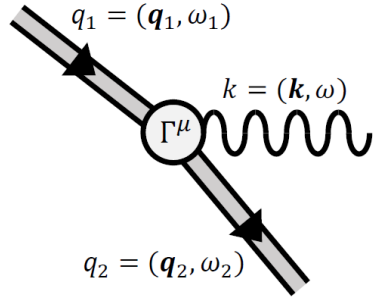
Nishimura, MK, Kunihiro, ‘22; ‘23; ‘24

Anomalous dilepton production due to **soft modes** at phase transitions

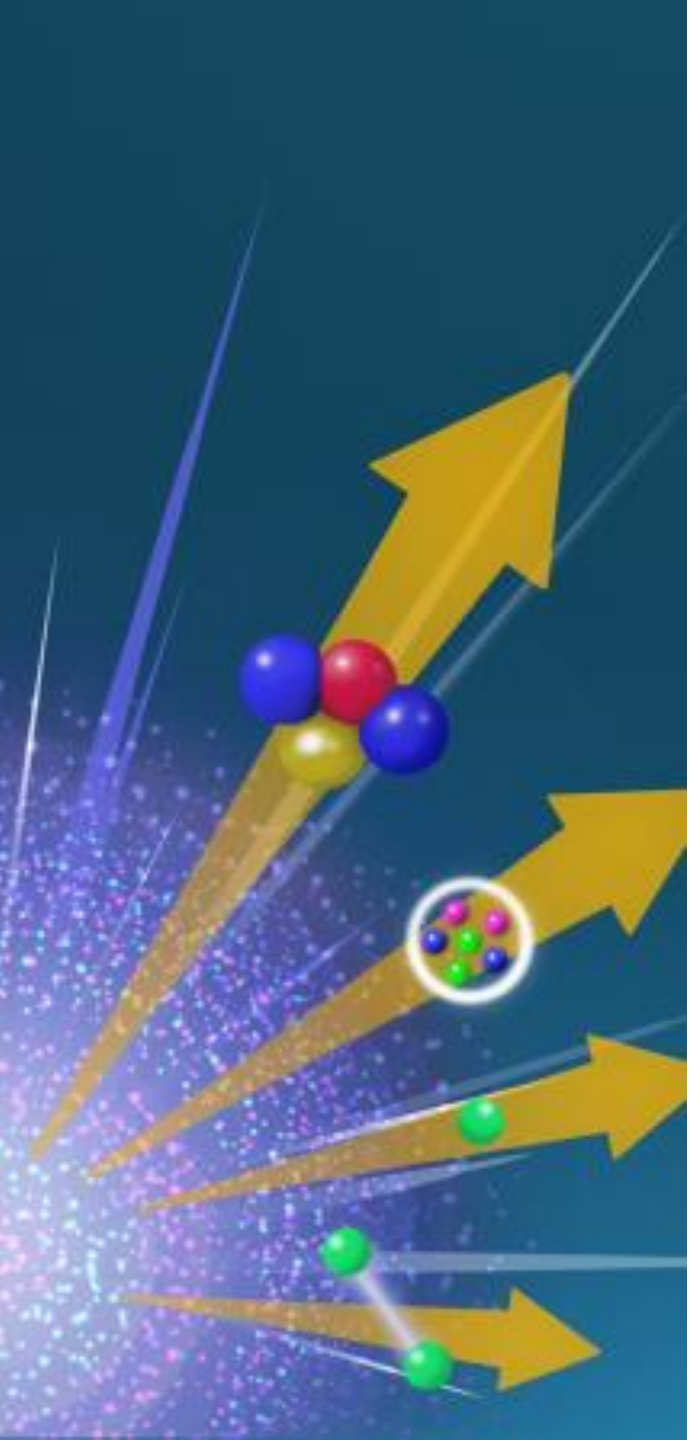




production process:

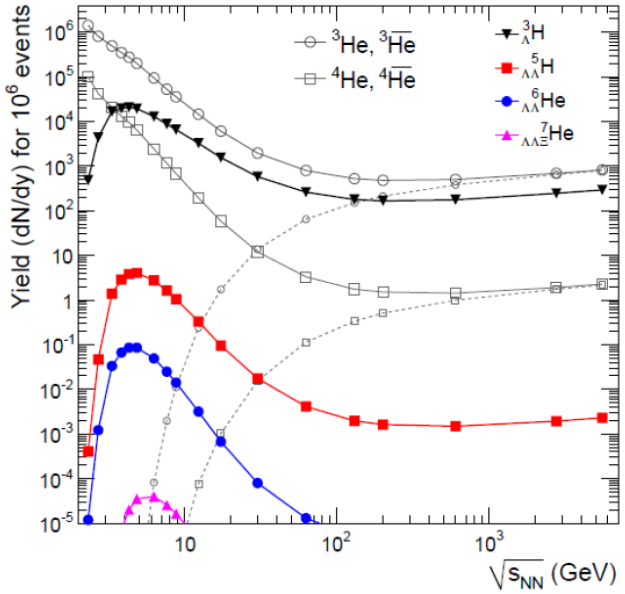


Two “hot spots” on the T-μ plane?



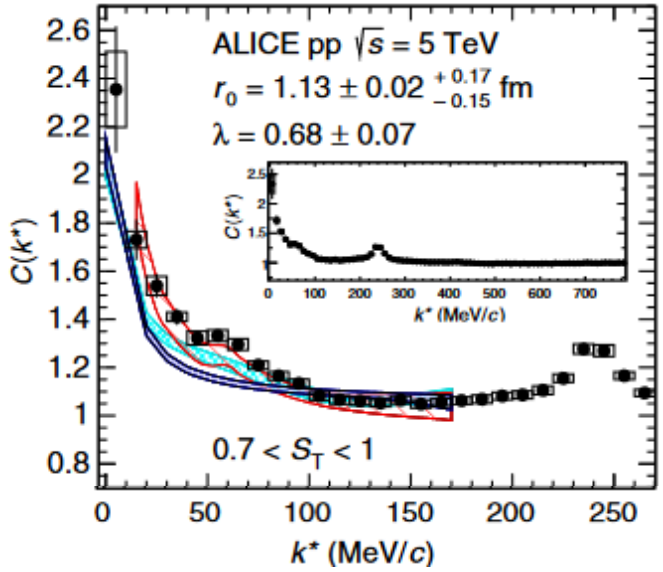
Hadron/Hypernuclear Physics

Hypernuclei

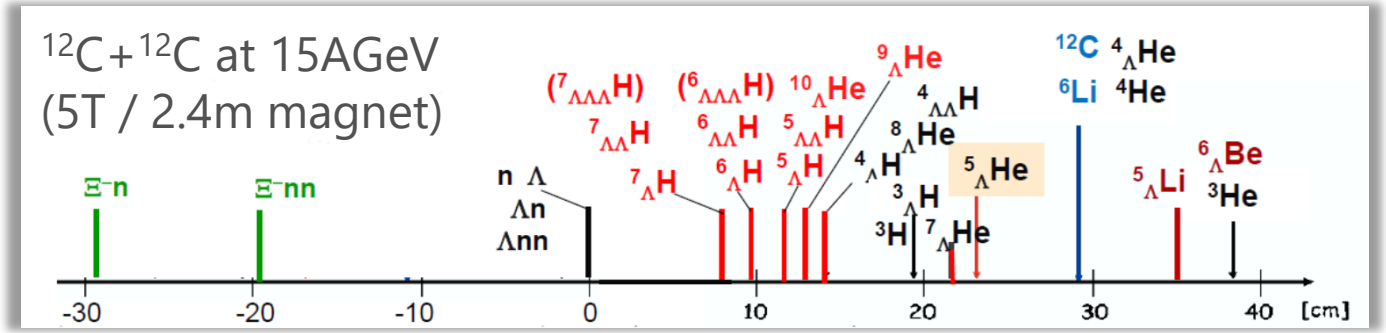


Correlation functions

→hadron interaction

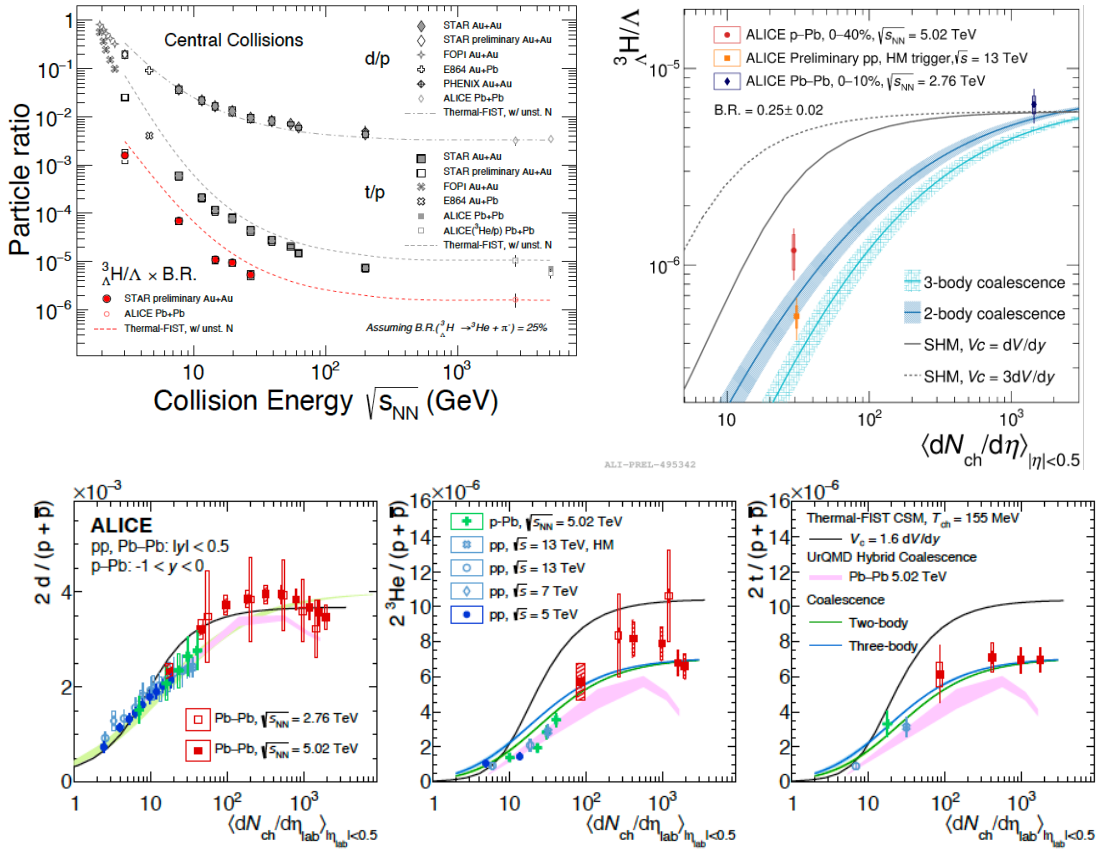


ALICE,2020



Light-/hyper-Nuclear Production

Measurement of light/hyper-nuclei

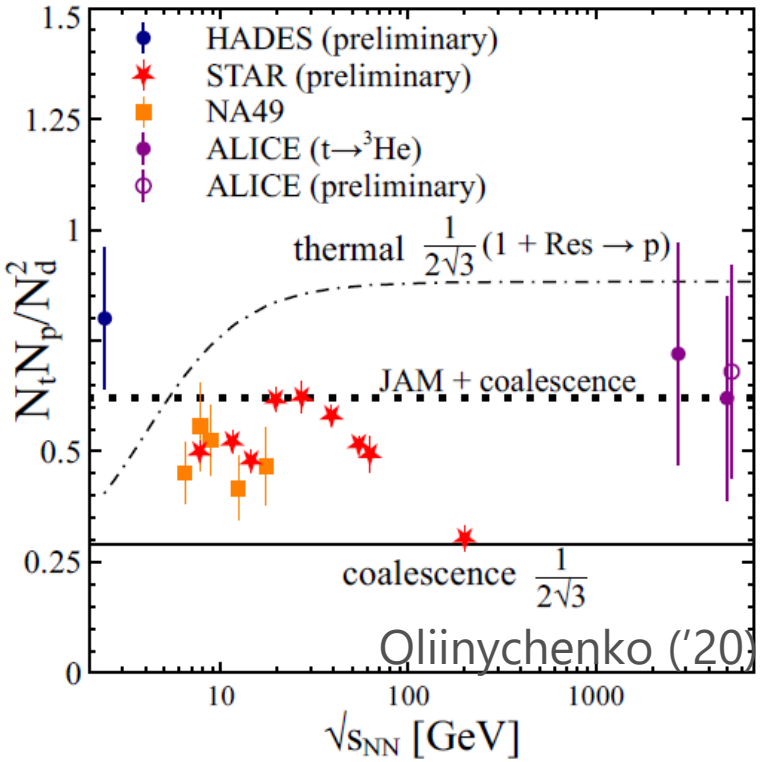


from QM2023

Precise data will lead us to a better understanding of production mechanism

Light-nuclei production

as a signal of QCD critical point

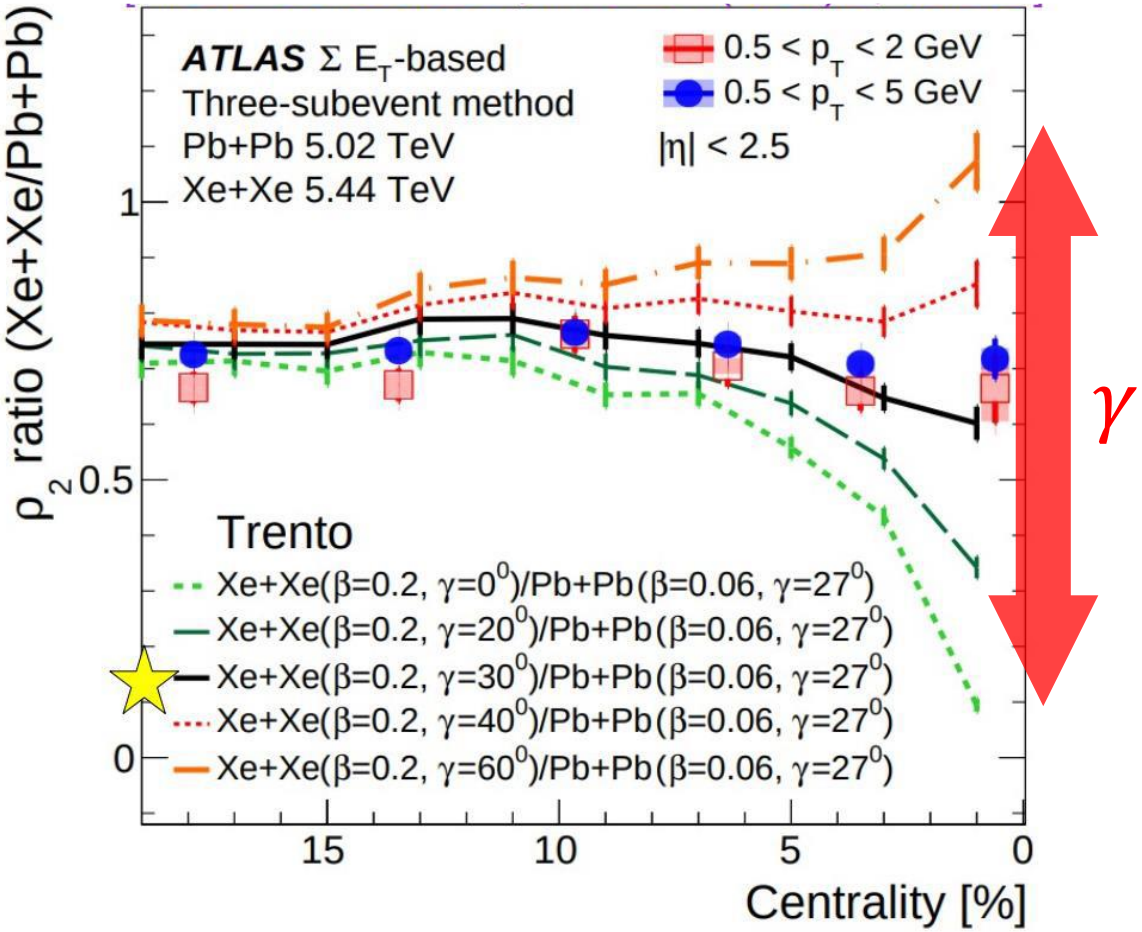


baryon fluctuations

→ enhancement of light nuclei?

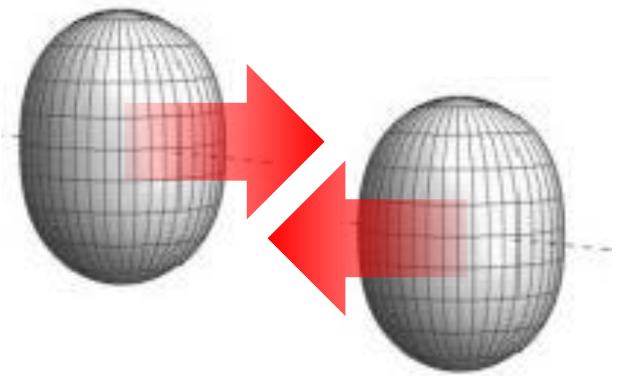
Sun+ ('18)

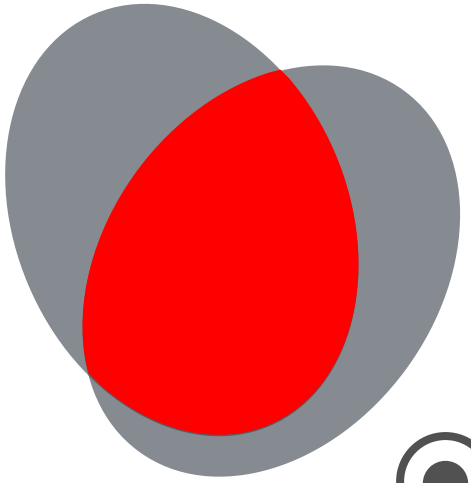
Shape of Nuclei



ATLAS, PRC107 ('23)

Deformation parameter β, γ can be estimated from HIC using flow correlations.





Beam axis

J-PARC-HI

Future Plan

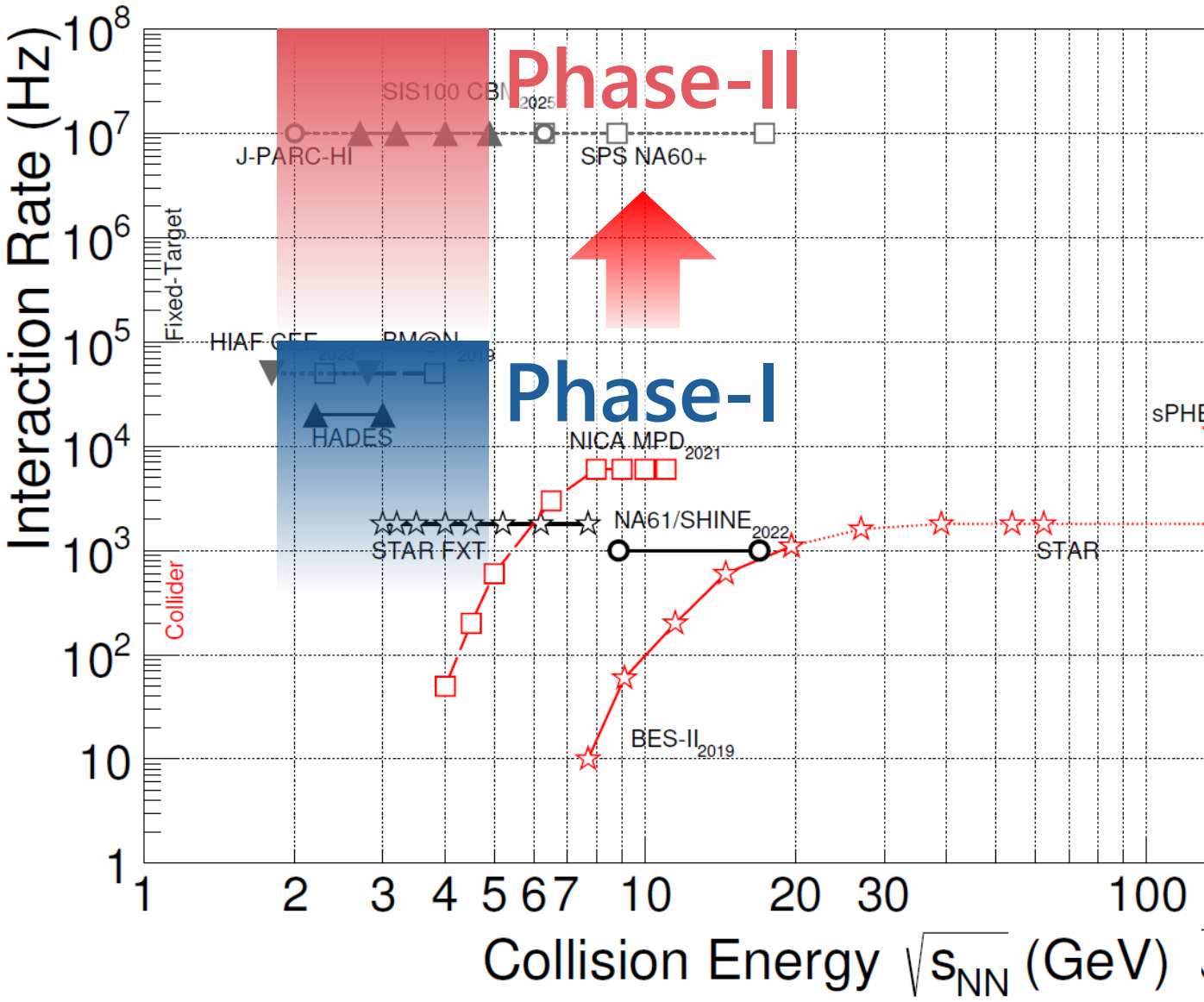
J-PARC-HI Staging Plan

Phase-I

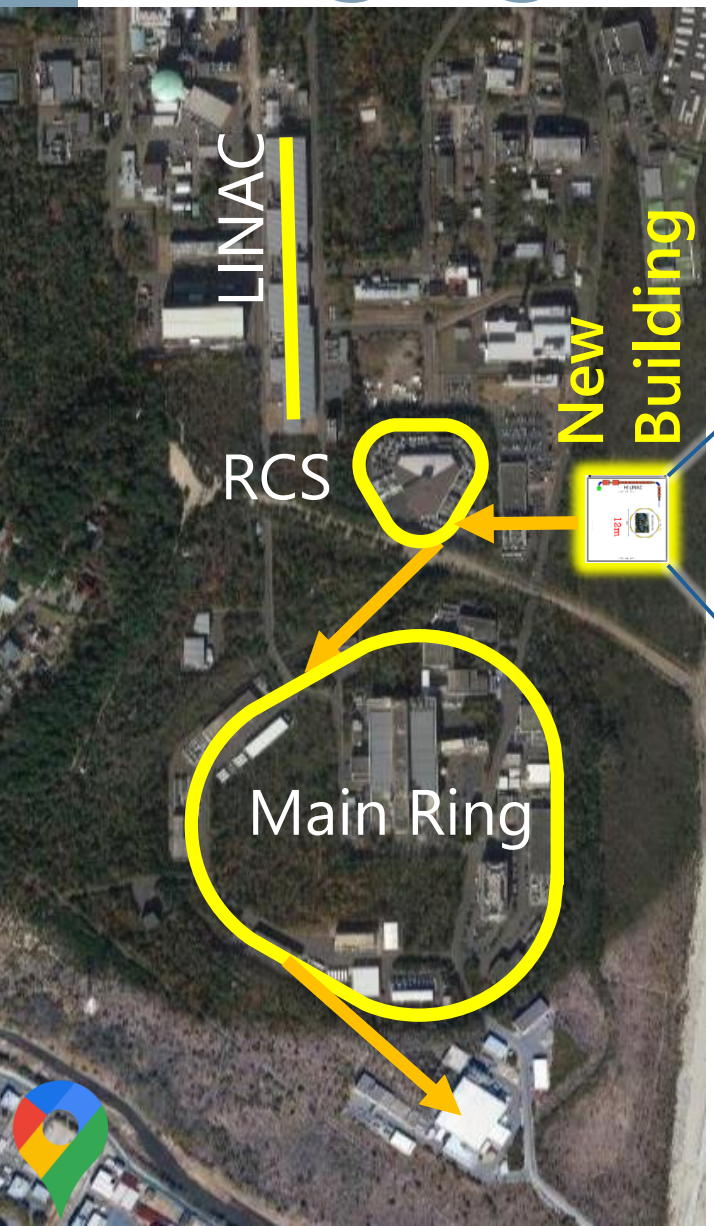
—KEK-BS booster
—E16+α spectrometer

Phase-II

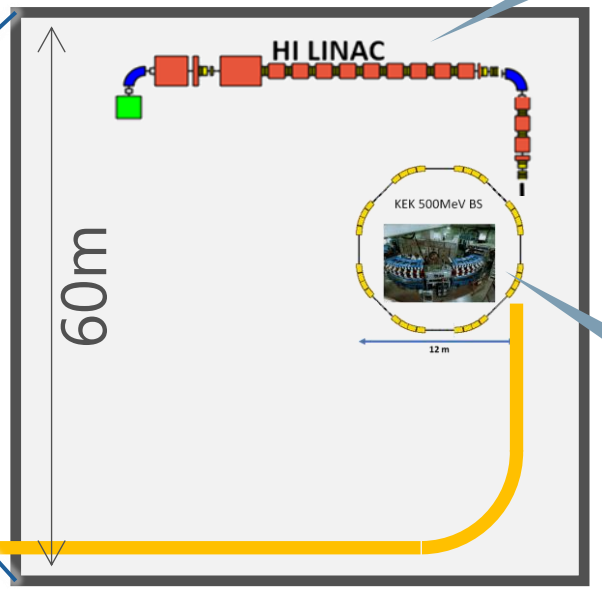
—NEW HI booster
—NEW spectrometer



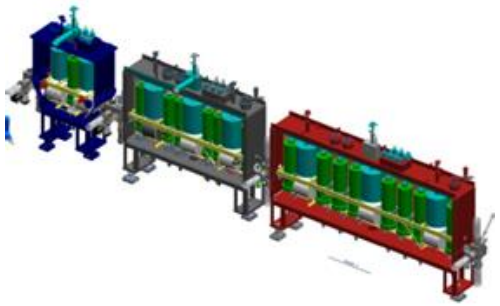
Staging of HI Booster



Phase-I



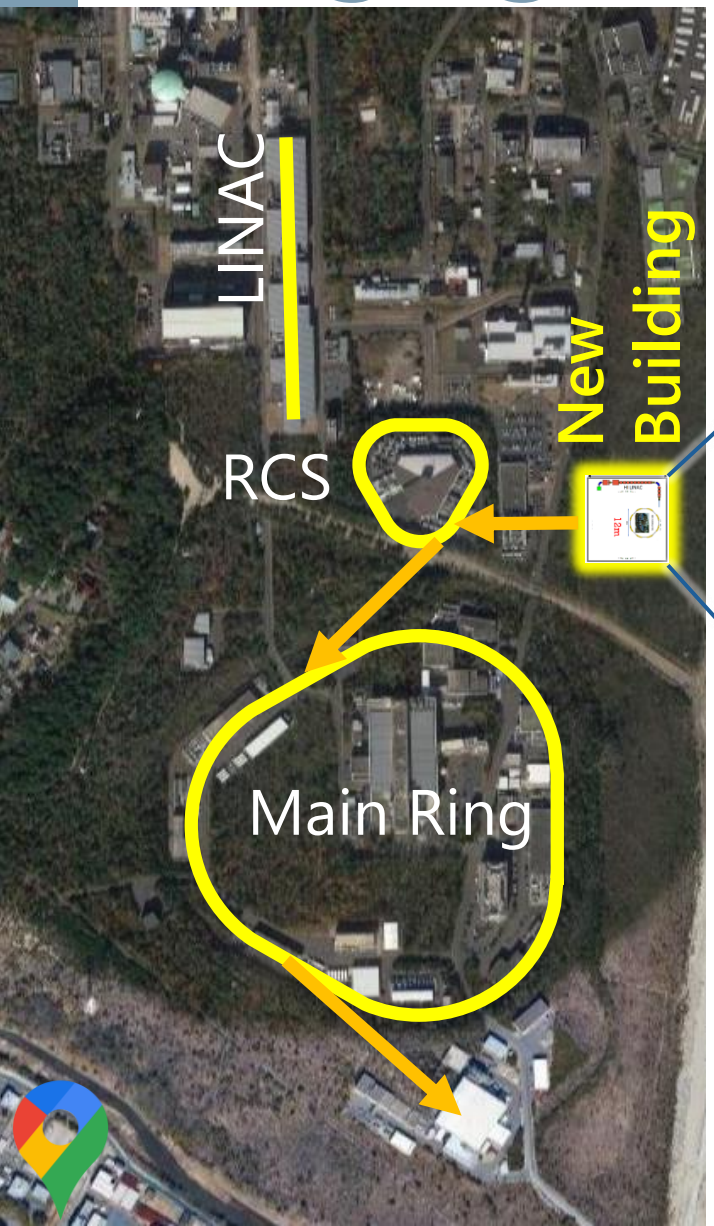
HI LINAC



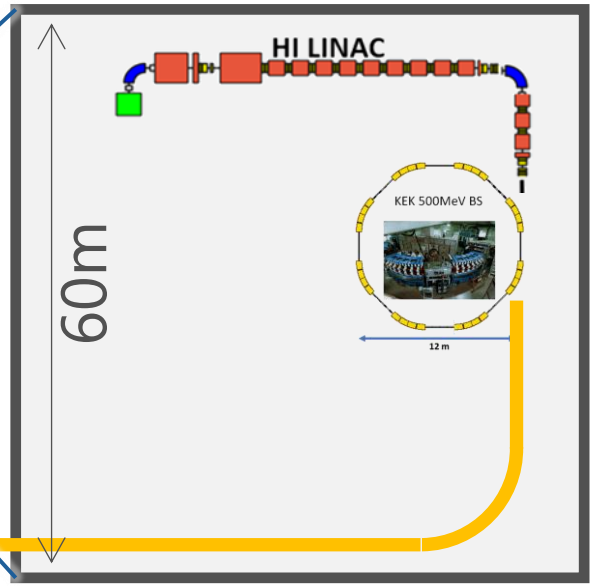
KEK 500MeV BS

$$\sim 10^5 \mathrm{Hz}$$

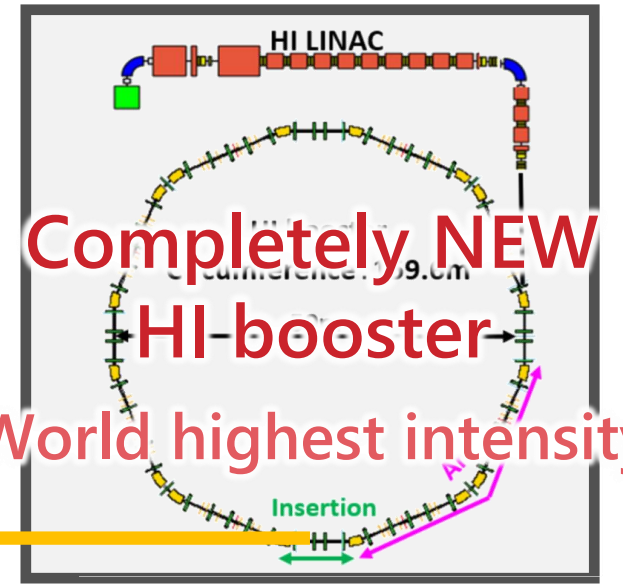
Staging of HI Booster



Phase-I



Phase-II



Interaction rate

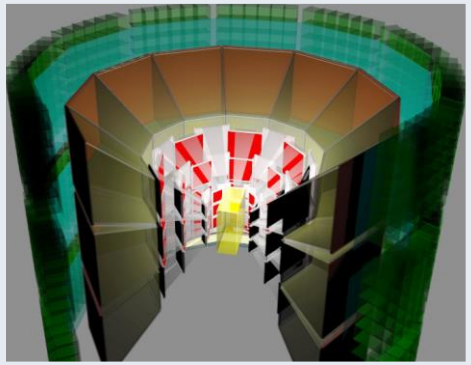
$\sim 10^5 \mathrm{Hz}$

$\sim 10^8 \mathrm{Hz}$

Detector Phase-I

E16 Spectrometer

— $\phi \to e^+e^-, \phi \to K^+K^-$
— In-medium mass modification
— Commissioning 2020-2024

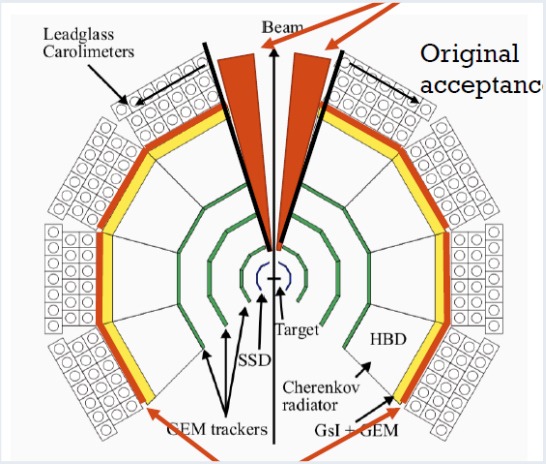


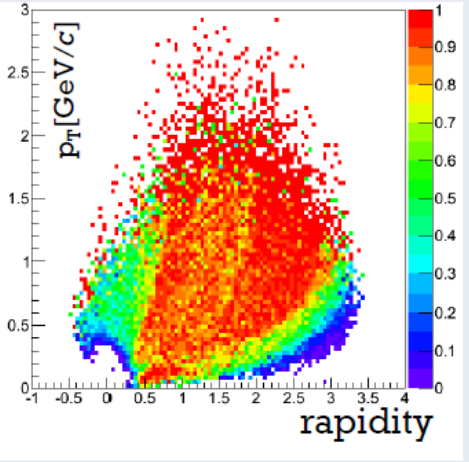
UPGRADE

E16+α

Upgrade forward region for high-multiplicity counting

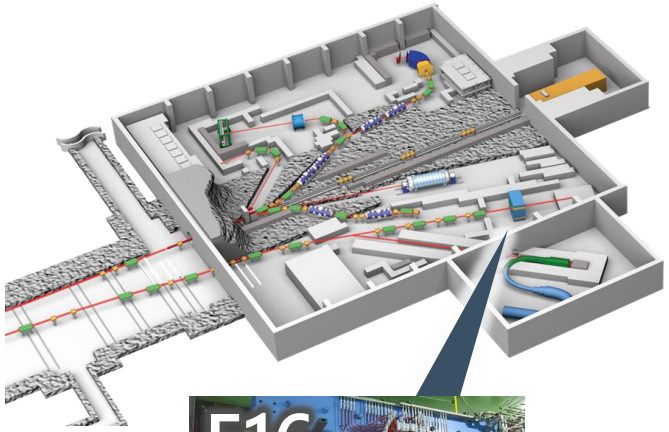
› Hadron/lepton measurement at wide acceptance



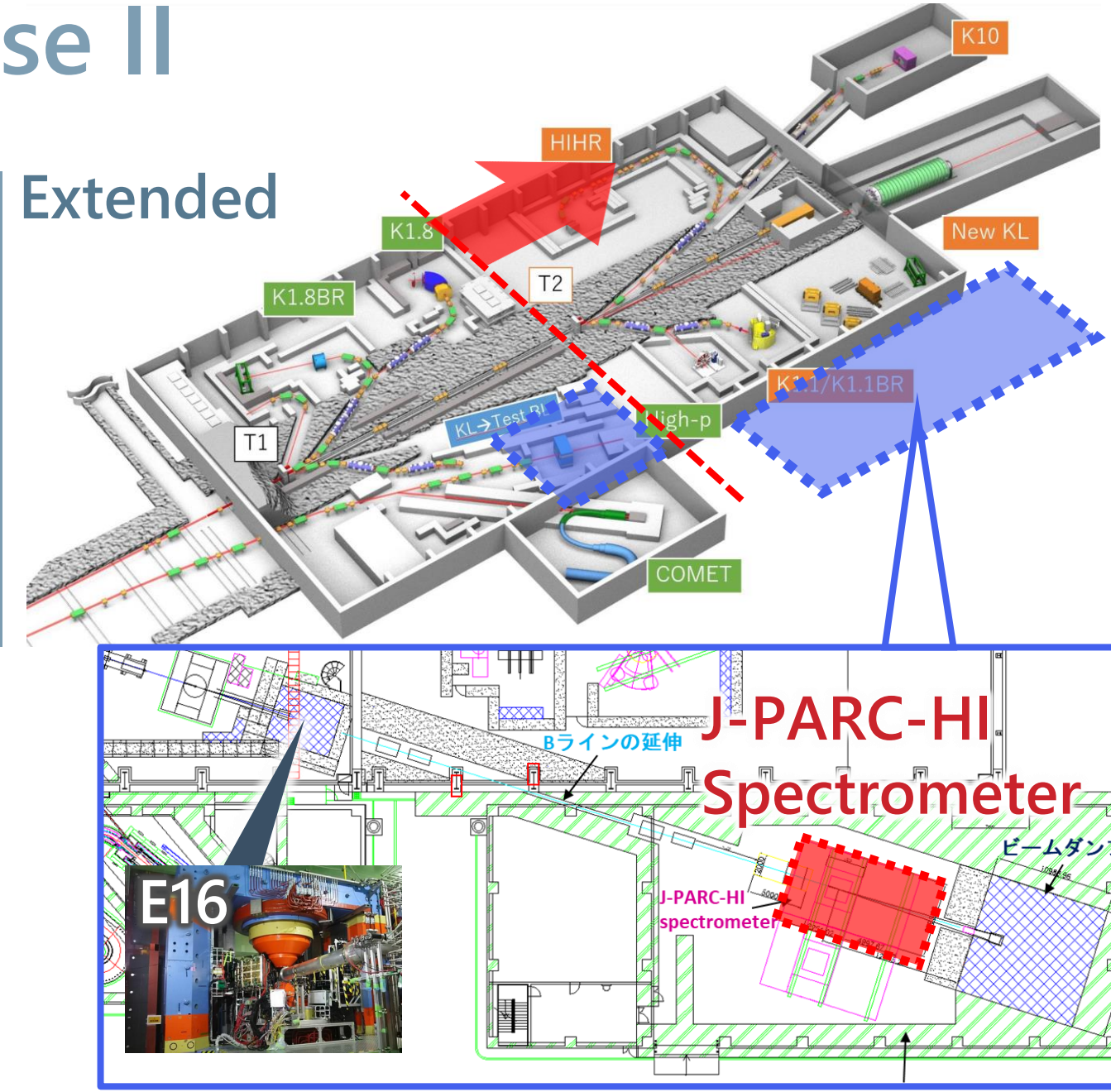


Detectors for Phase II

Present



Extended



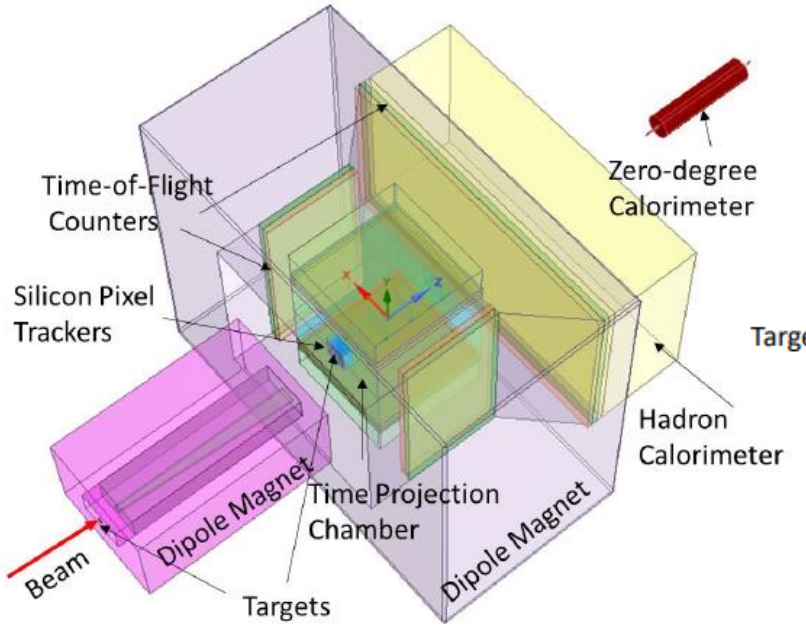
— J-PARC-HI spectrometer will be installed in an annex
— E16 will also be replaced

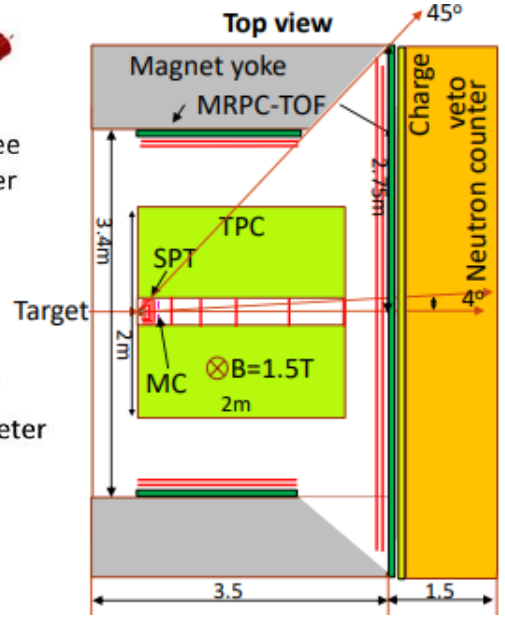
Hadron Spectrometer

Phase-II

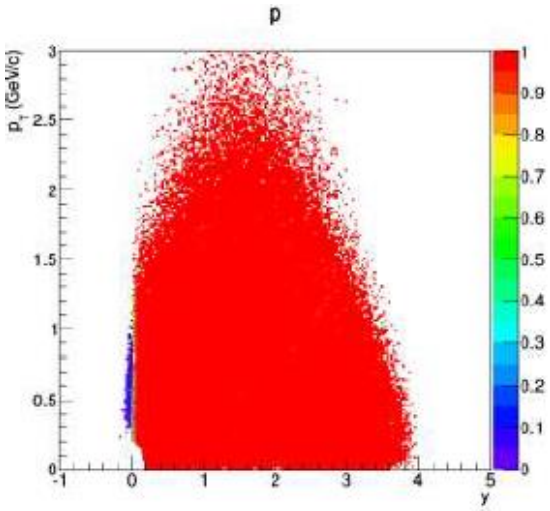
- 4π acceptance, high-intensity beam
  - Precise measurement of fluctuations, dileptons
- Detailed design are under discussion

Hadron calorimeter

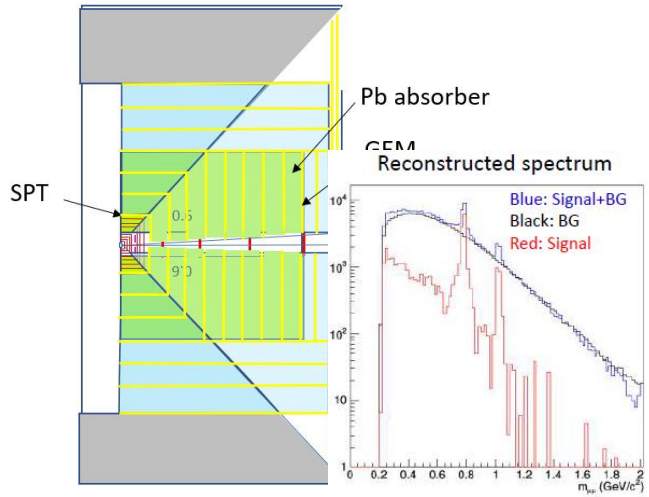




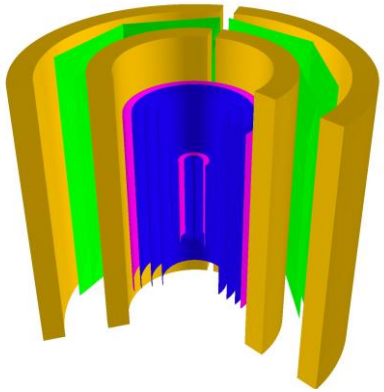
acceptance



Dimuon Setup



ALICE3-like dipole



Summary

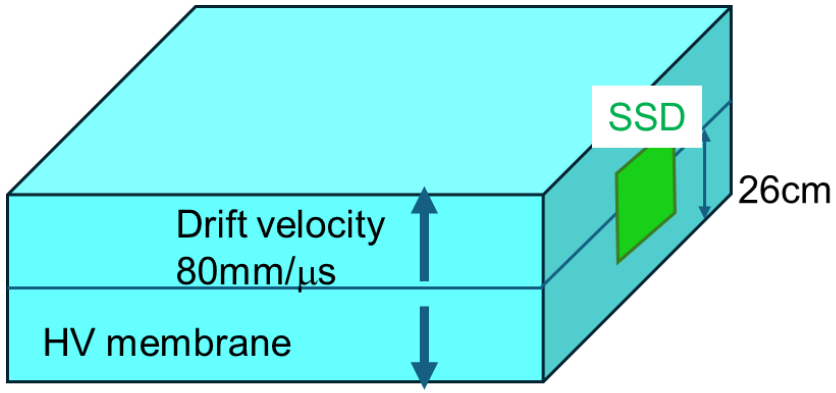
- Relativistic HIC can investigate extremely hot/dense medium.
- Density/temperature dependence of the produced medium can be studied by the beam-energy scan.
  - Investigation of QCD phase diagram: QCD-CP, color-SC, etc.
- Various observables
  - fluctuations, dilepton production rate, light/hyper-nuclear production, …
- Other applications: hadron interaction, nuclear shape, …

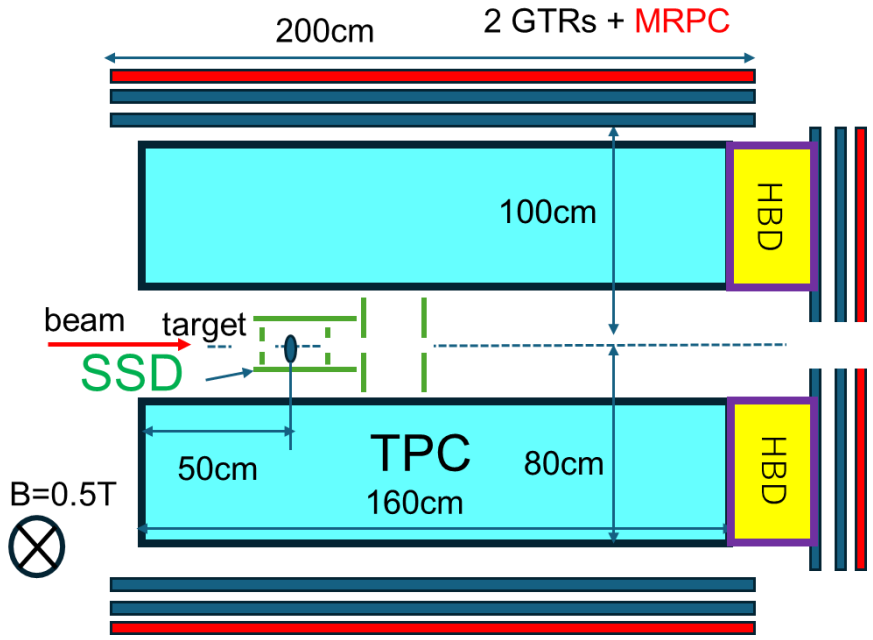
- **J-PARC-HI** will pursue this realm further.
  - world's highest interaction rate
  - best collision energy to study

Dilelectron Measurements

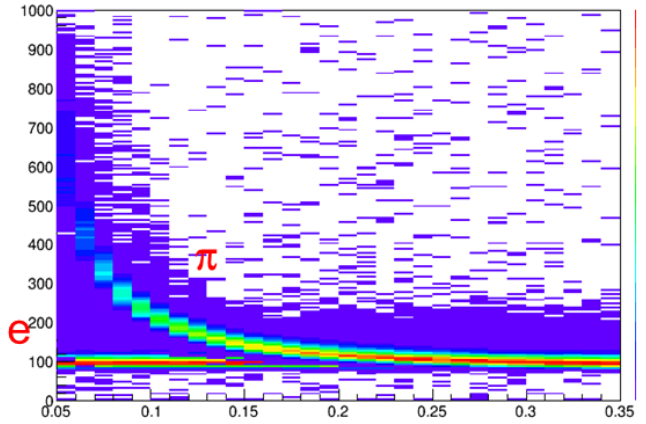
Phase-II

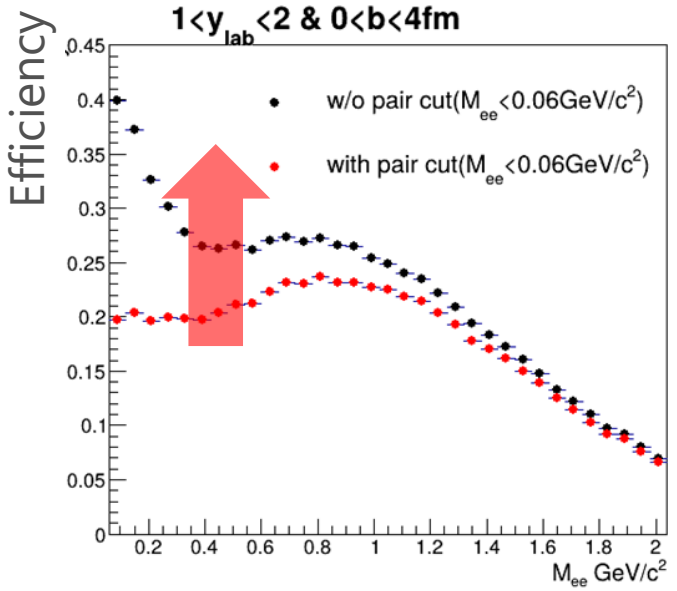
— Large acceptance measurement of dielectrons and hadrons





dE/dx of SSDs





Precise measurement of low-mass dielectrons

› search for QCD-CP & CSC phase transition

Hypernuclear Spectrometer

Phase-II

- Closed geometry : Sweeping magnet and Collimator
- Interaction Rate : ~100 MHz
- Lifetime and Magnetic moment Search for new hypernuclei and strangelet