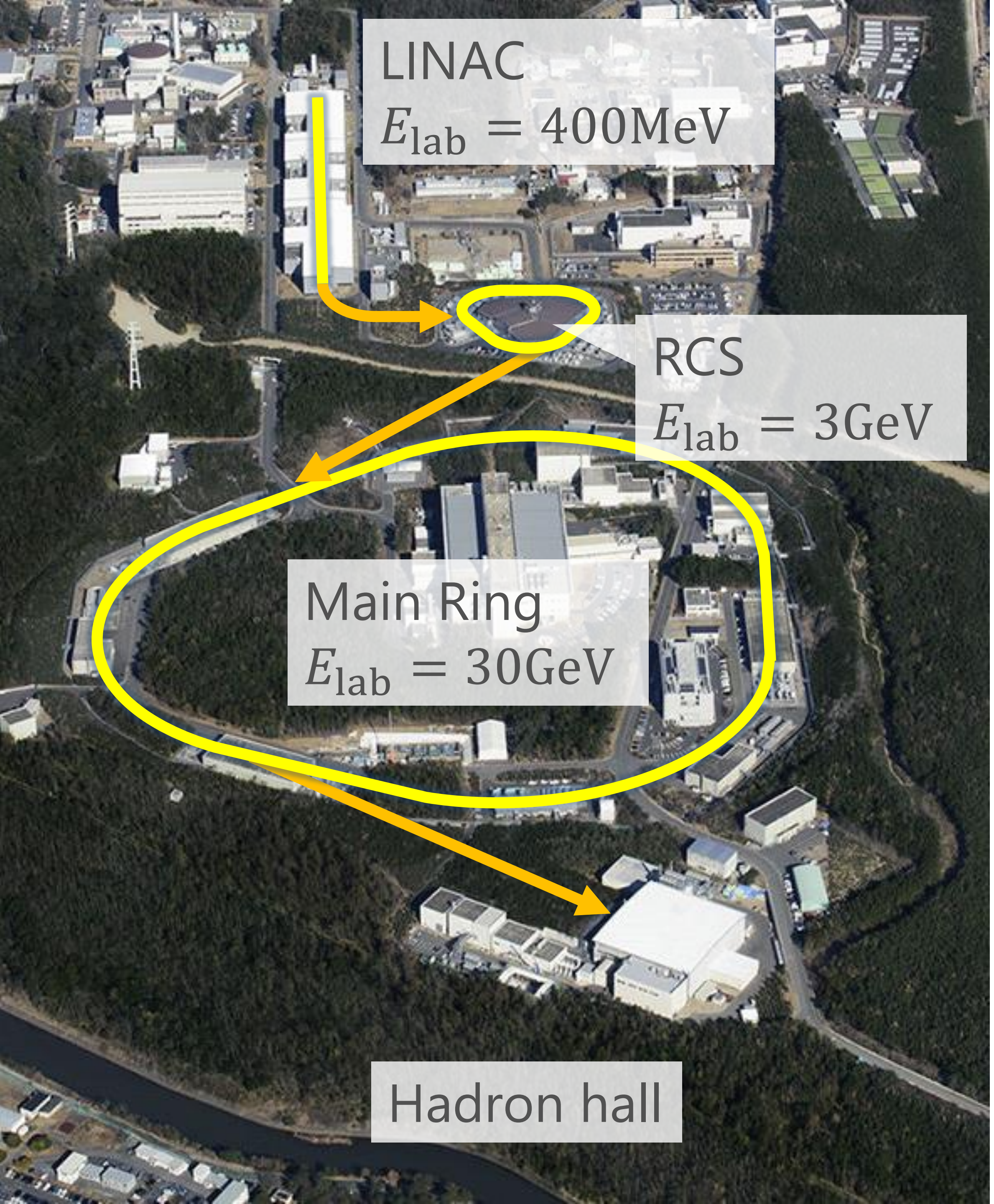
J-PARC-HI: Theory

Masakiyo Kitazawa

(YITP, Kyoto)

Workshop on nuclear physics with heavy ion reaction and related topics, 2023/9/30, Tohoku University

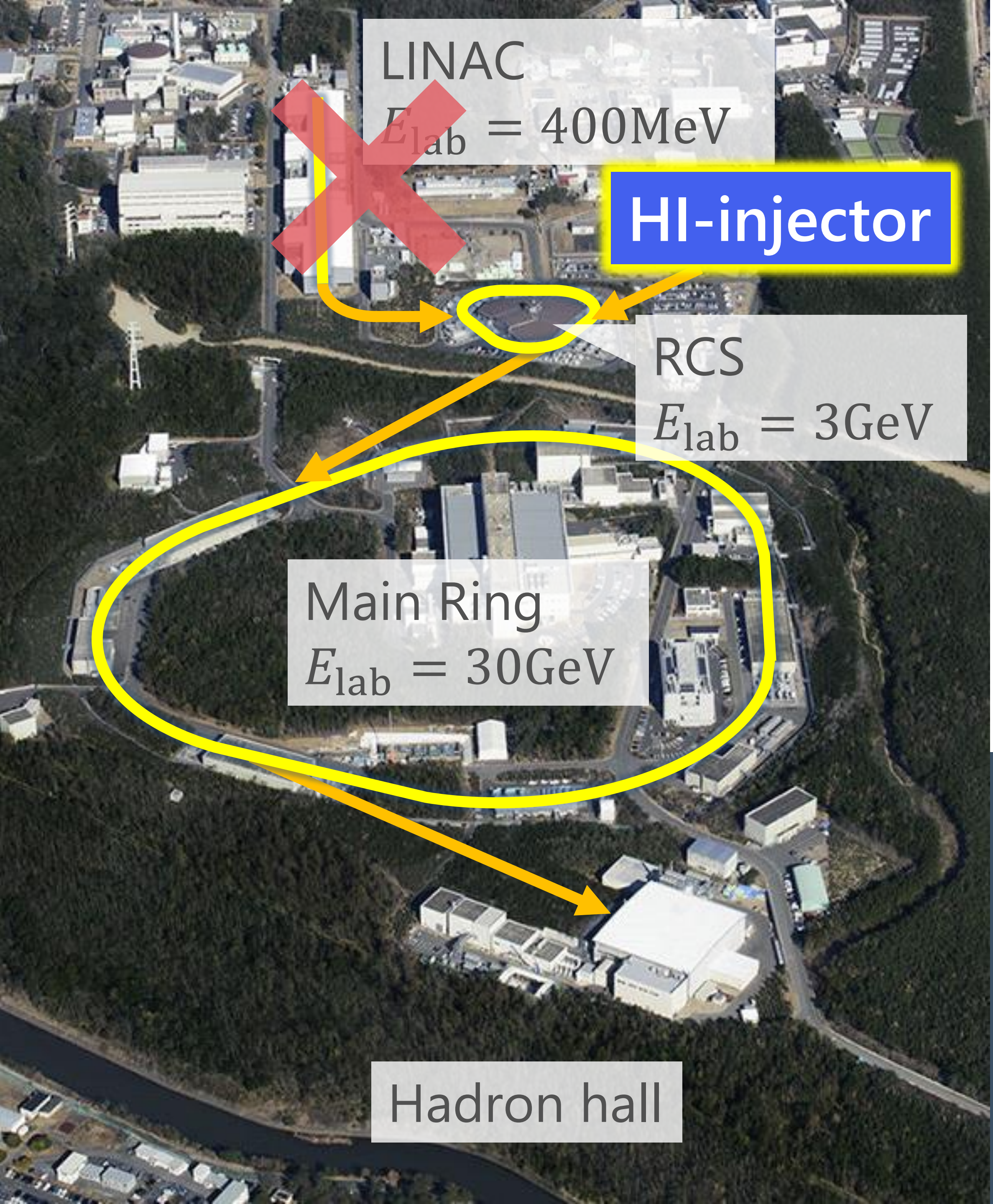


Accelerators

- LINAC
- RCS
- Main Ring
- High intensity $I = 1\mathrm{MW}$

Purposes

- Hadron/Nuclear physics
- Neutrino physics
- Material/Life science



Accelerators

- LINAC
- RCS
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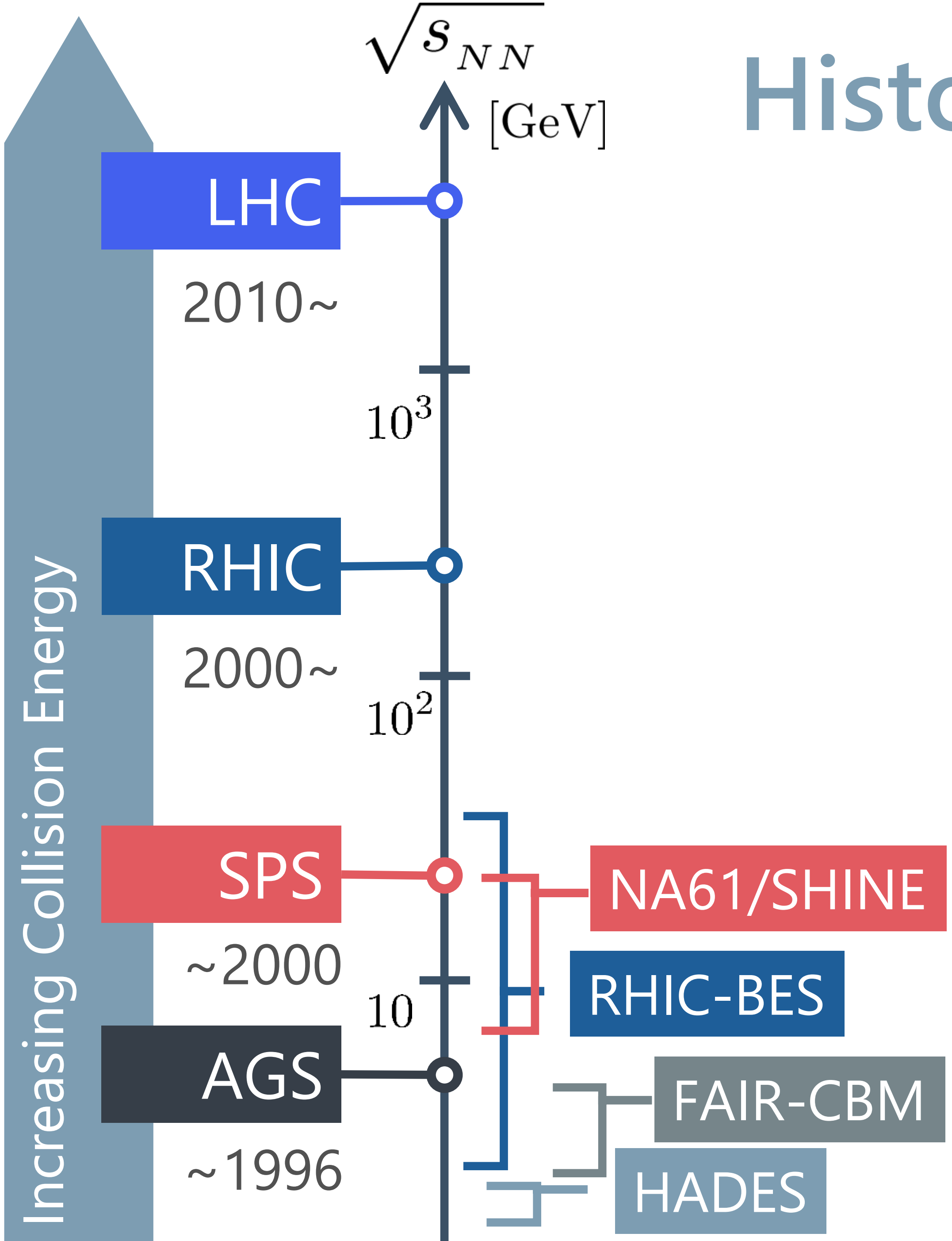
J-PARC-HI

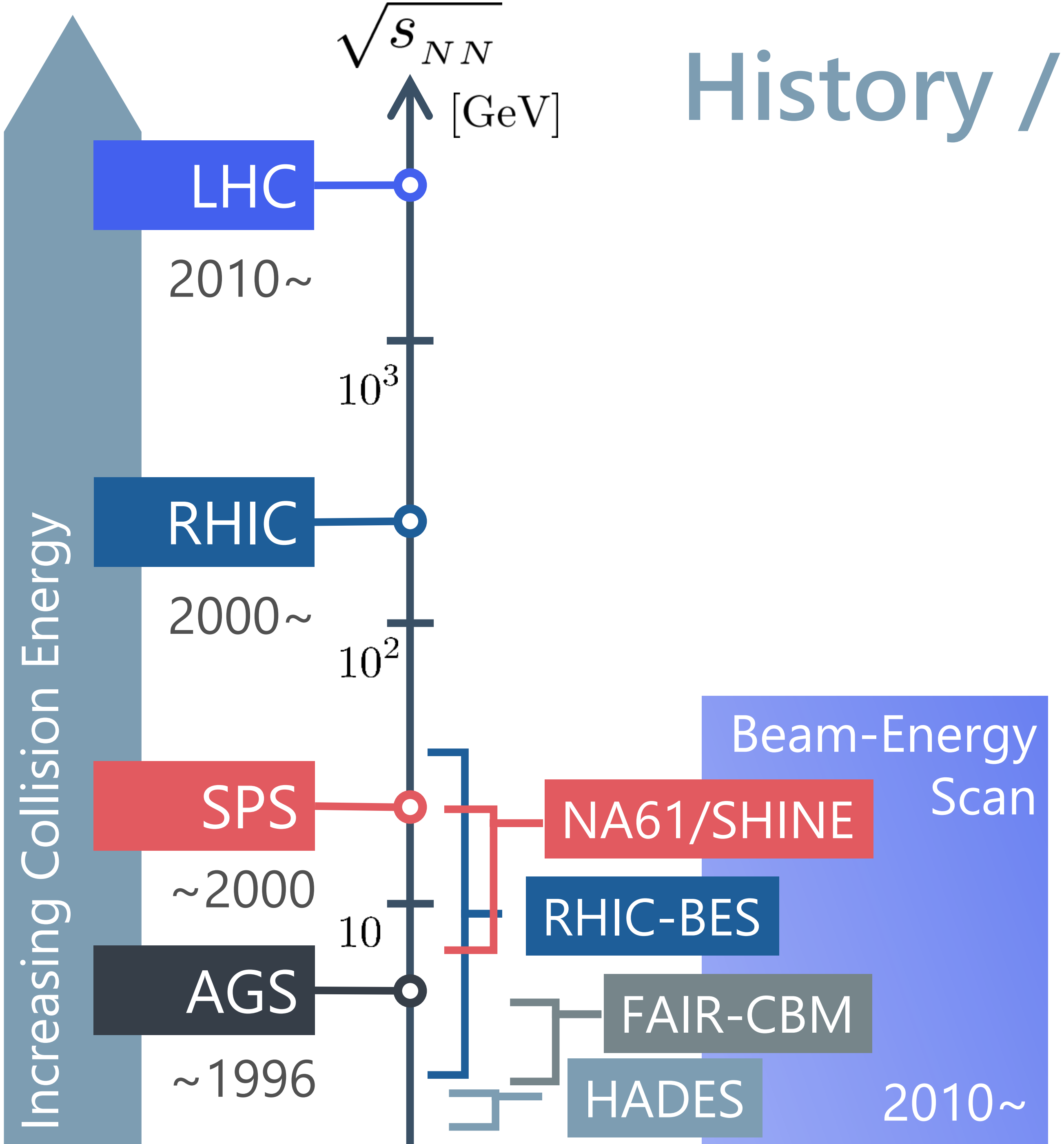
J-PARC Heavy Ion

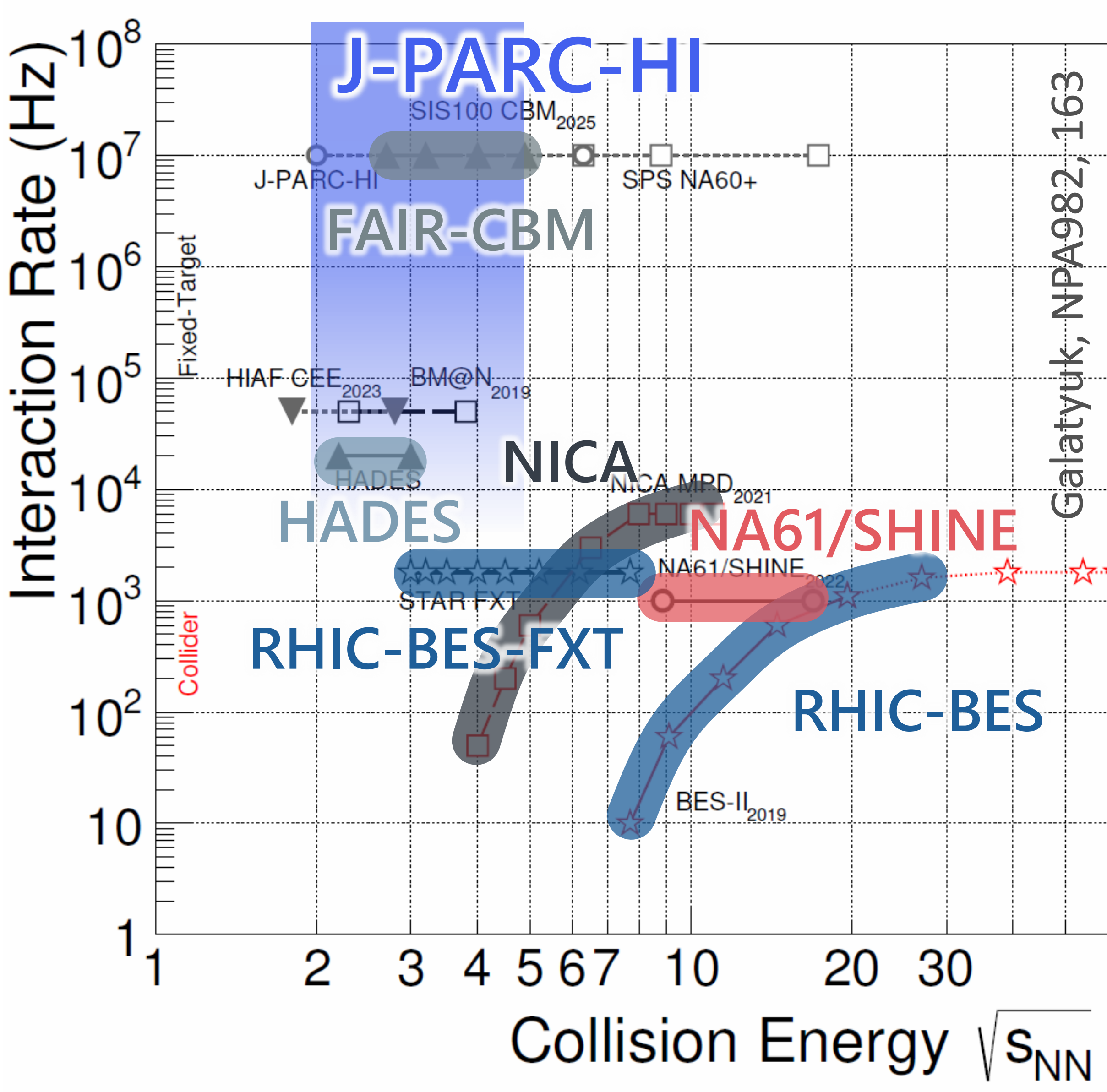
High intensity × Intermediate eneargy

History / Current Status of HIC



History / Current Status of HIC





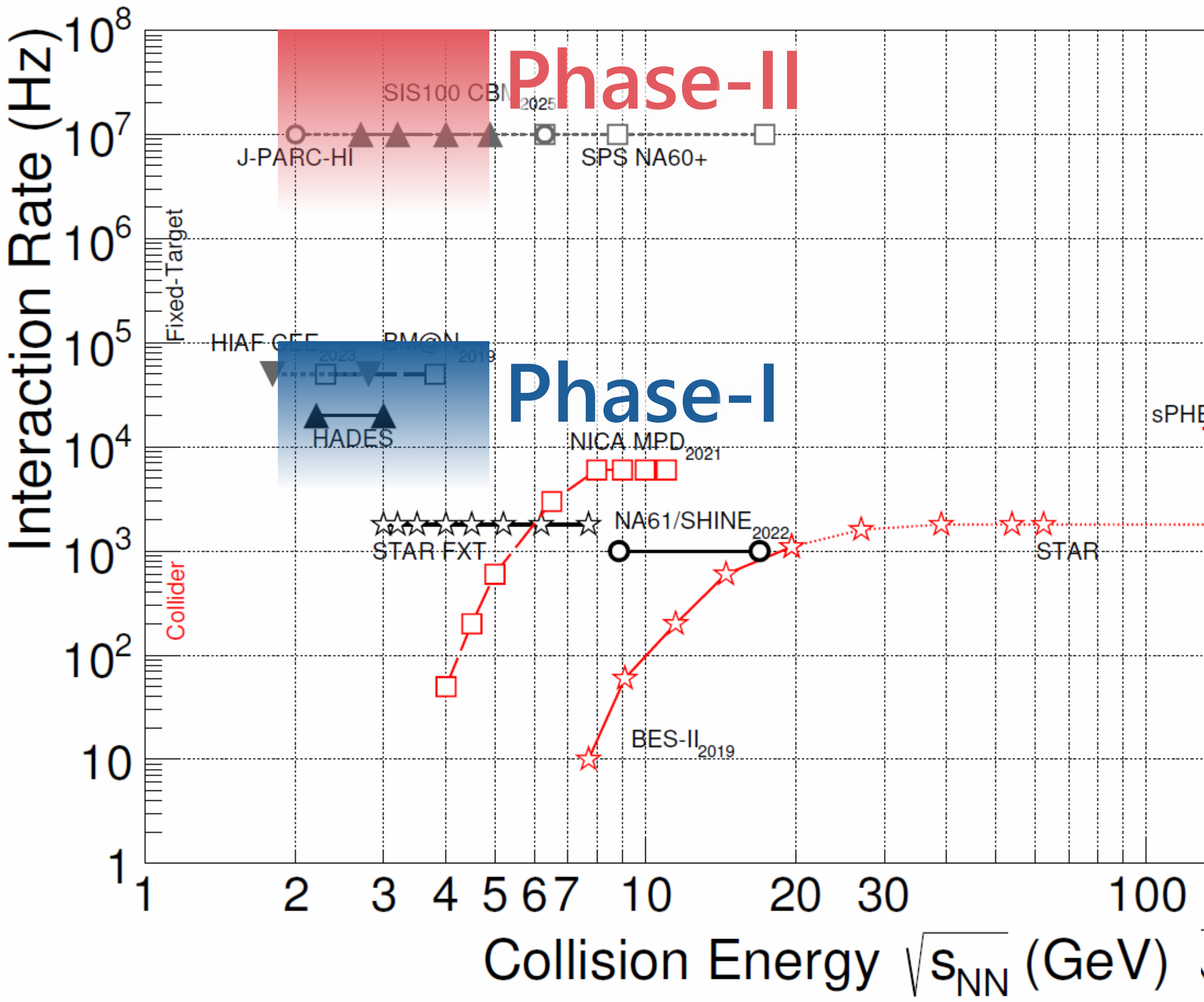
J-PARC-HI Staging Plan

Phase-I

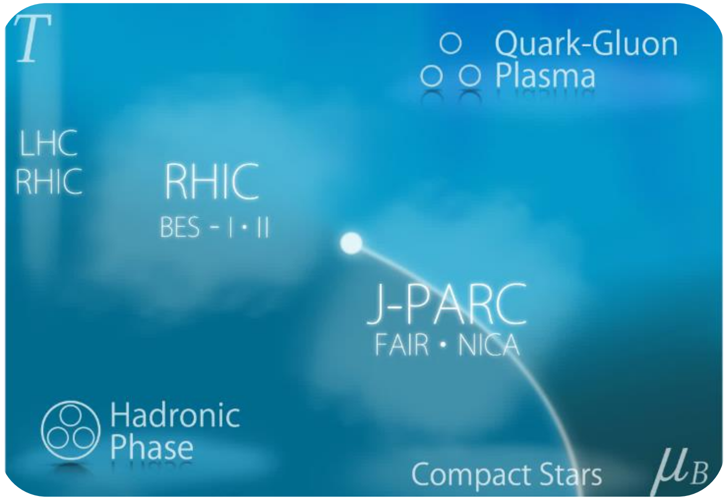
- KEK-BS booster
- E16+α spectrometer

Phase-II

- NEW HI booster
- NEW spectrometer

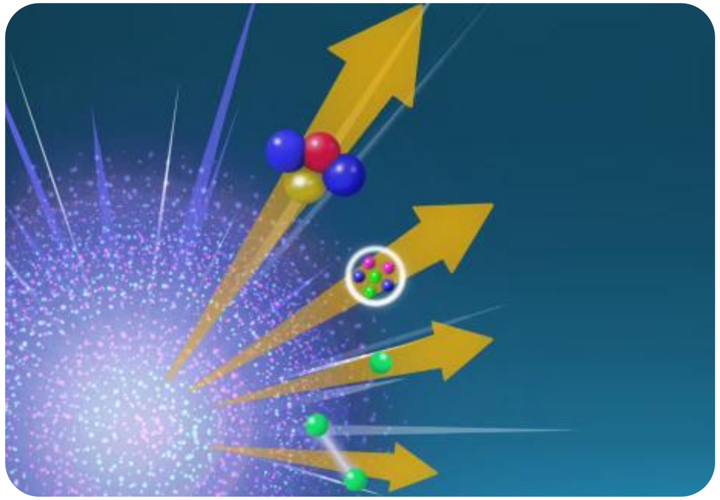


Physics Goals



Exploring

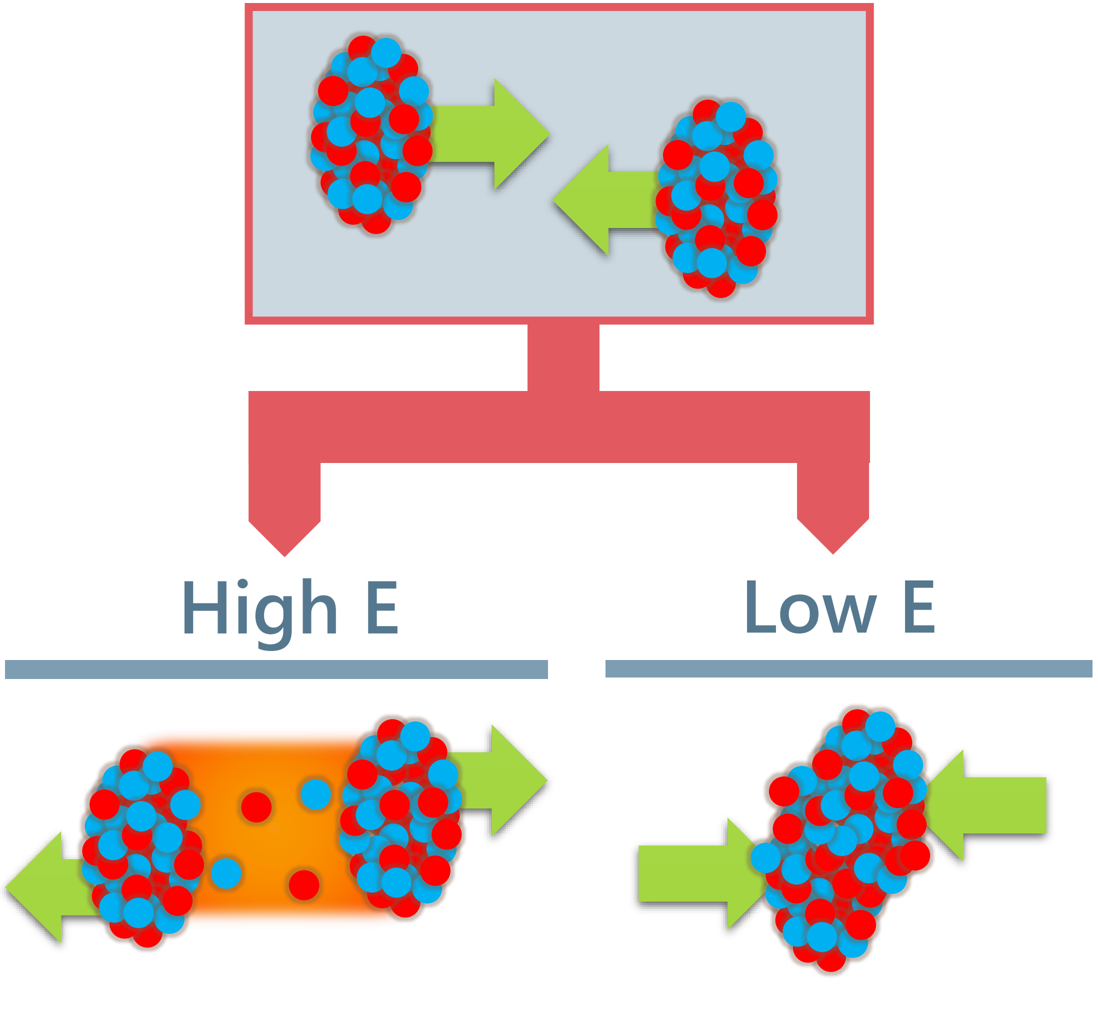
Extremely Dense Medium



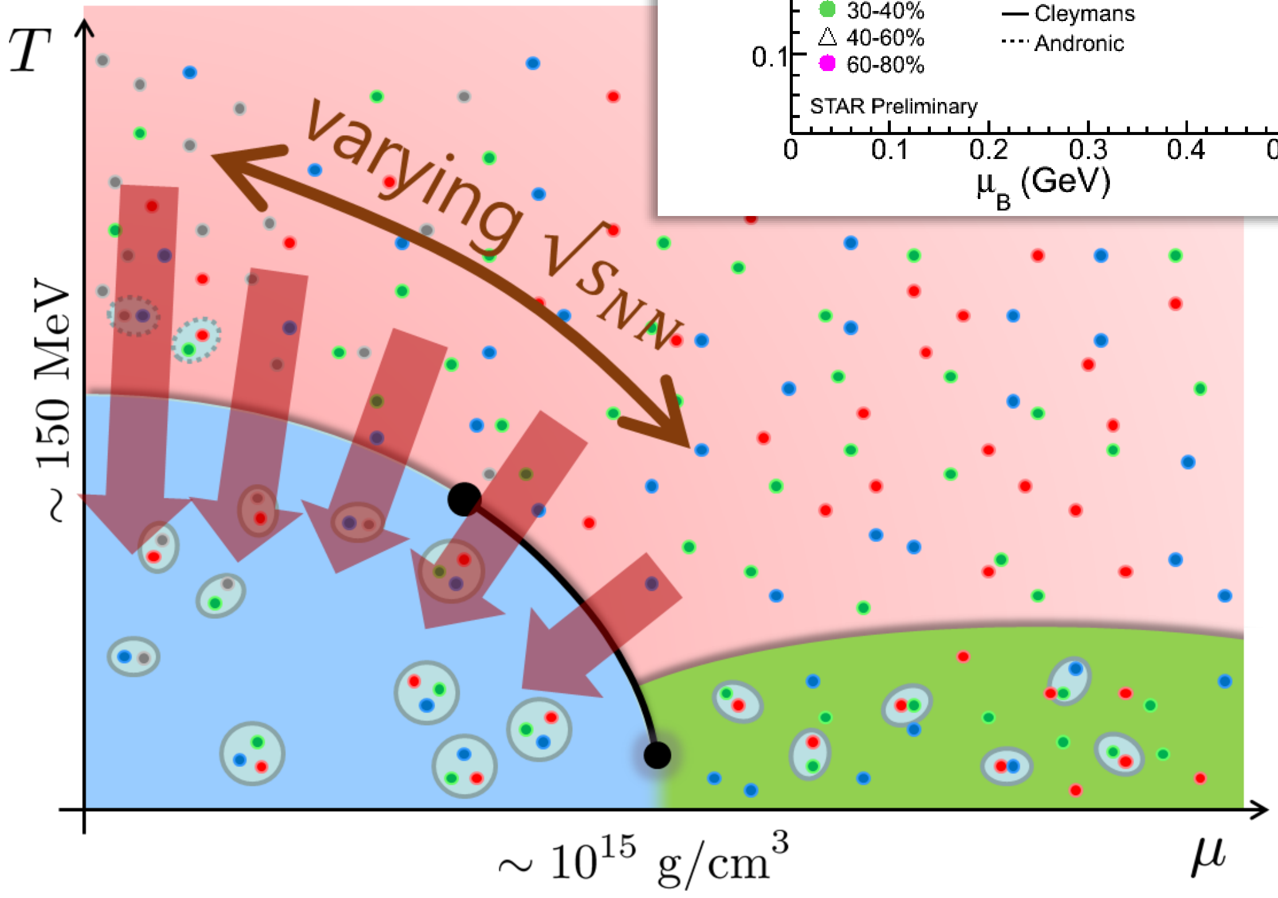
Search for

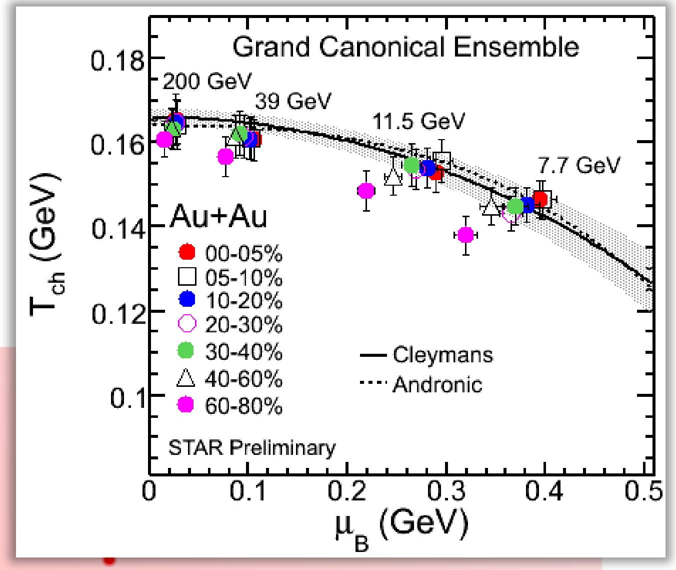
Rare Hadronic/Hypernuclear Events

Beam-Energy Scan

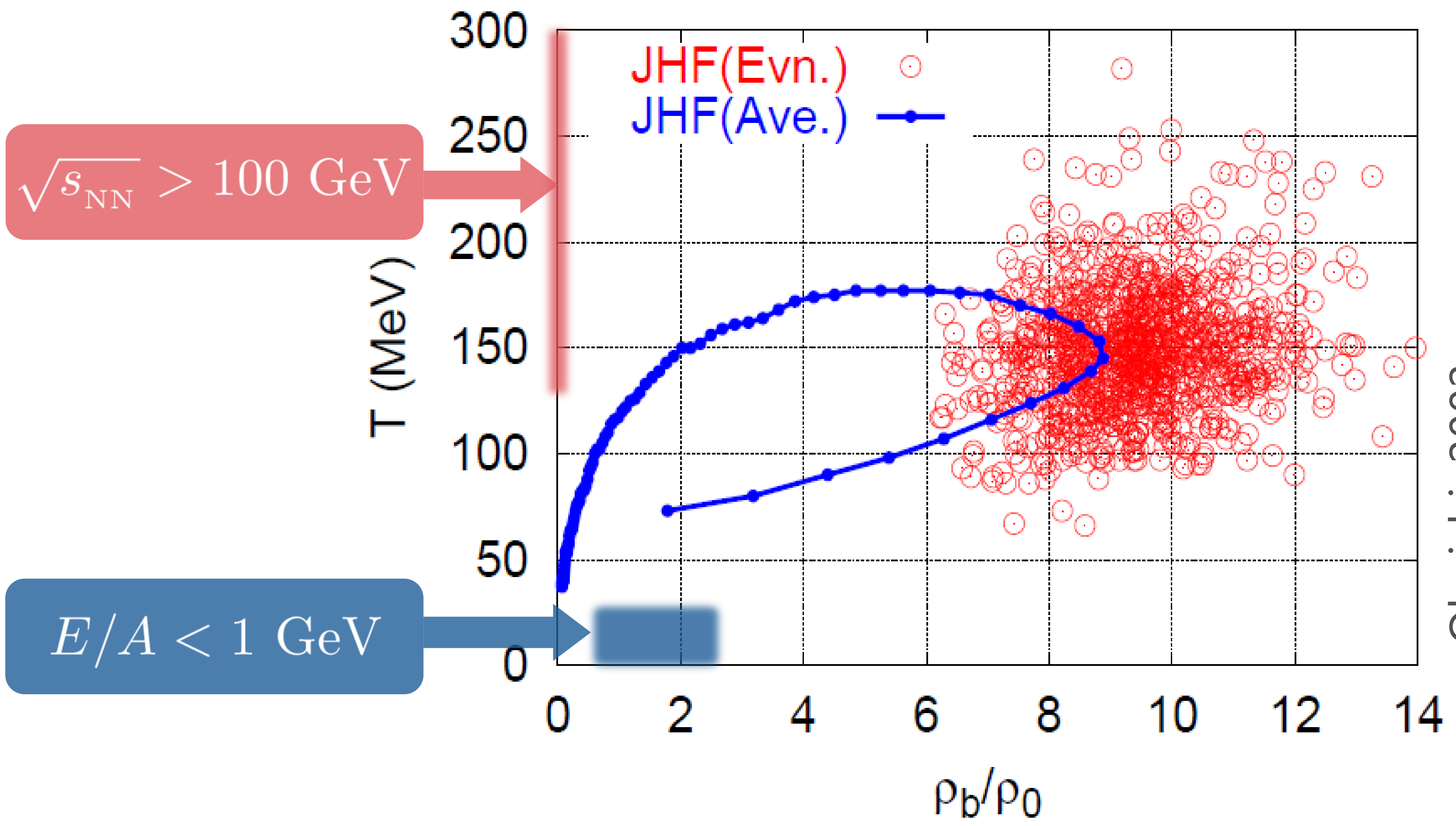


STAR, 2012





J-PARC-HI = Highest Baryon Density



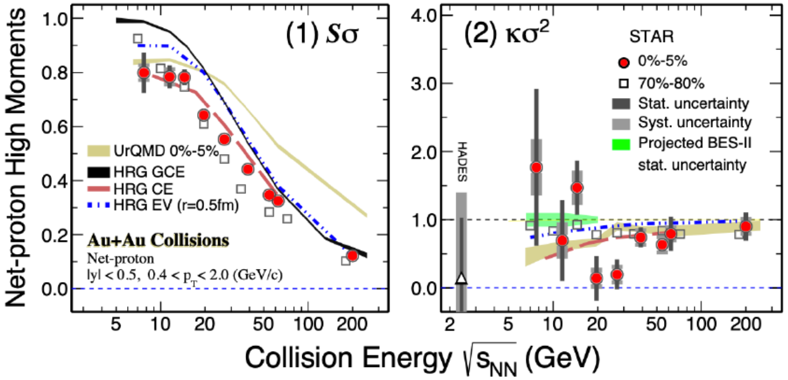
$E/A = 20\mathrm{GeV}$

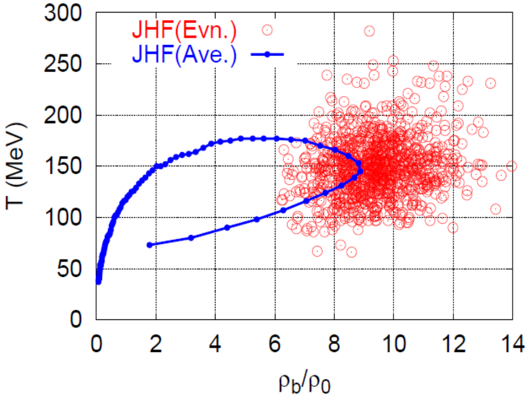
$\sqrt{s_{NN}} \simeq 6\mathrm{GeV}$

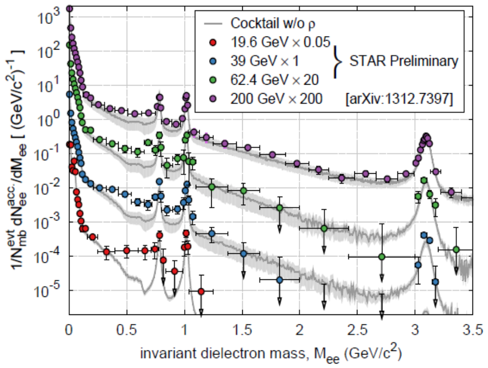
Ohnishi, 2002

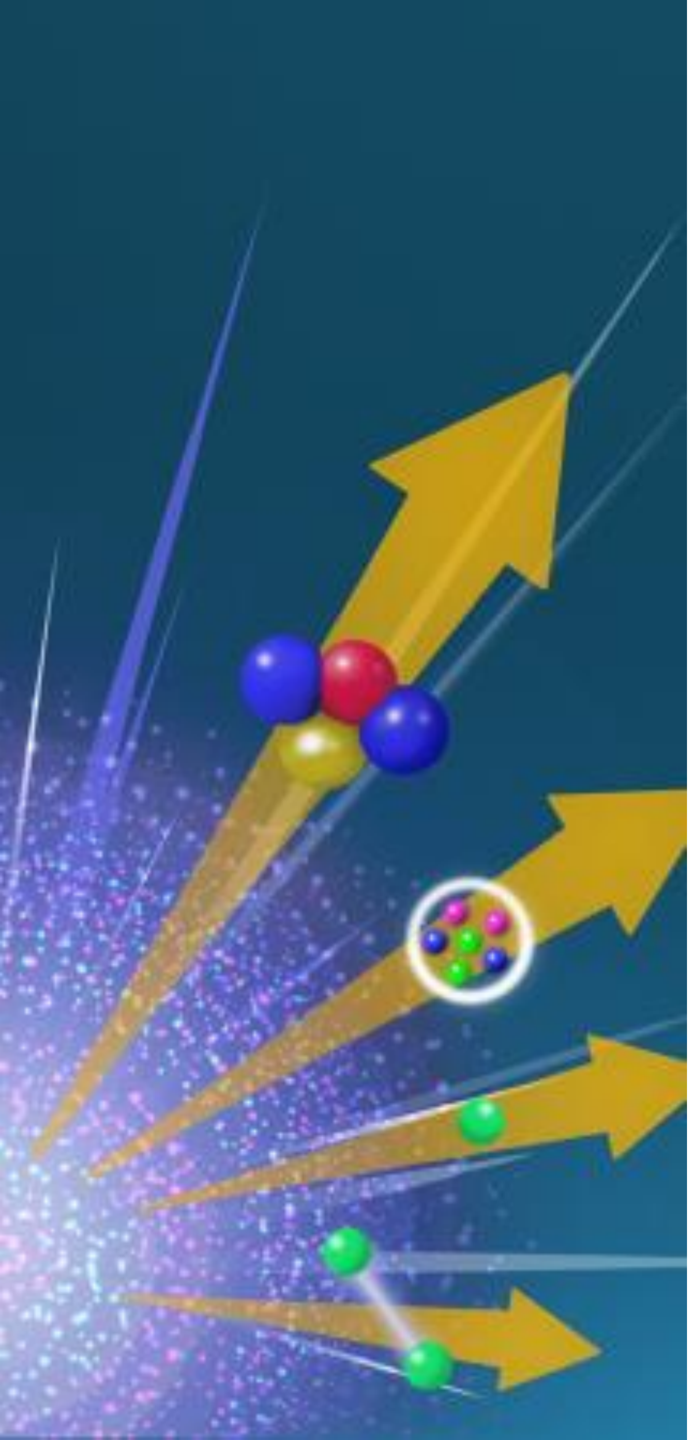
Exploring Dense Medium

- Equation of state
- QCD critical point / 1st order transition / Color superconductivity
- Dilepton production rate
- Event selection / Higher correlations



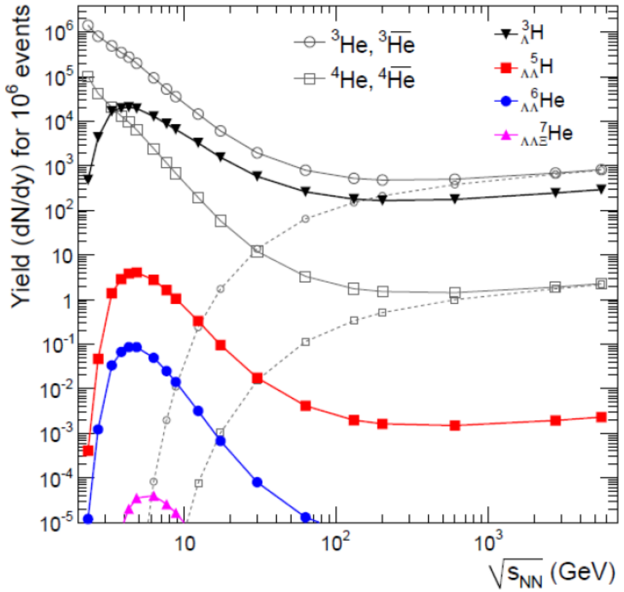






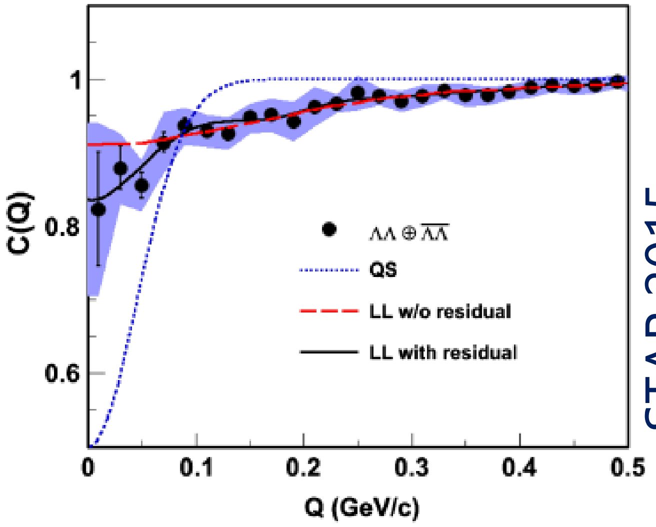
Hadron/Hypernuclear Physics

Hypernuclei

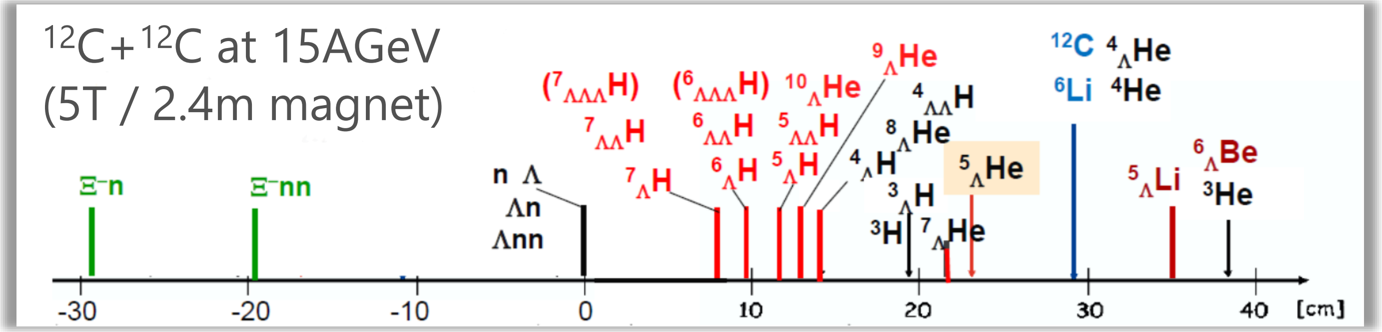


Correlation functions

→hadron interaction



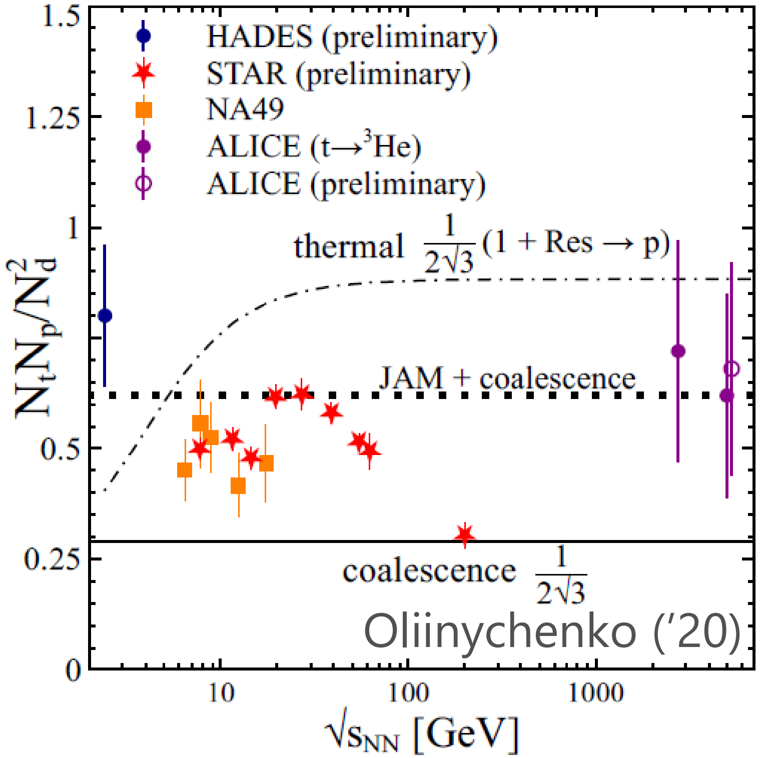
STAR,2015



Production Mechanism

Light-nuclei production

as a signal of QCD critical point



baryon fluctuations
→ enhancement of light nuclei?

Sun+ ('18)

Production Mechanism

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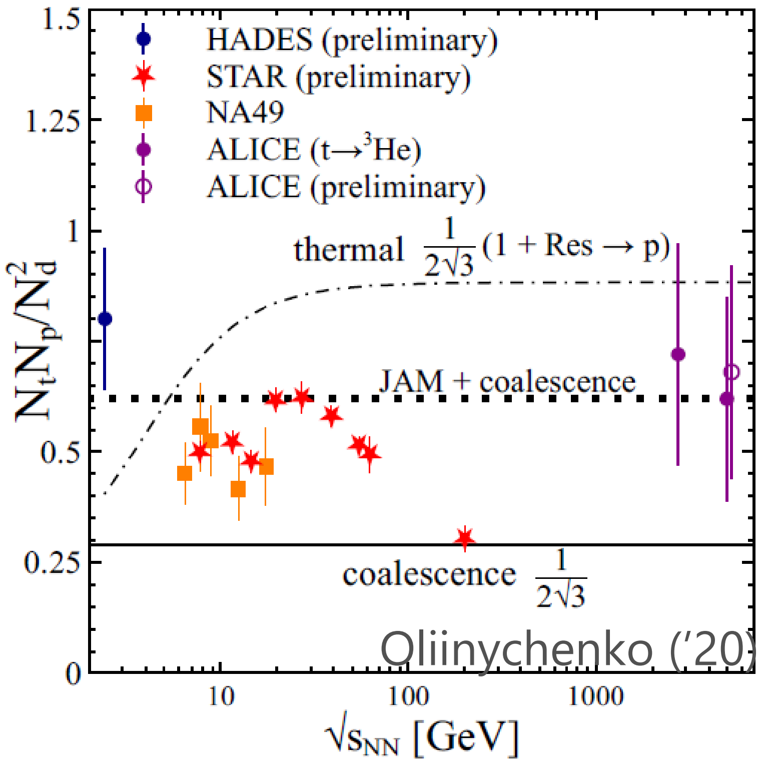


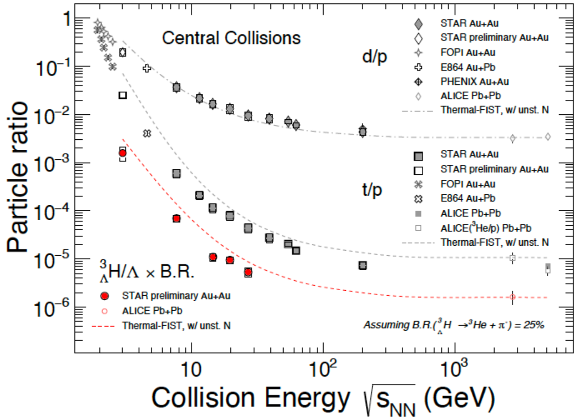
Oliinychenko ('20)

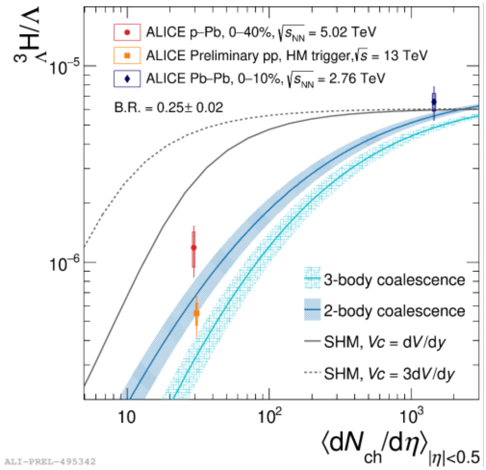
baryon fluctuations

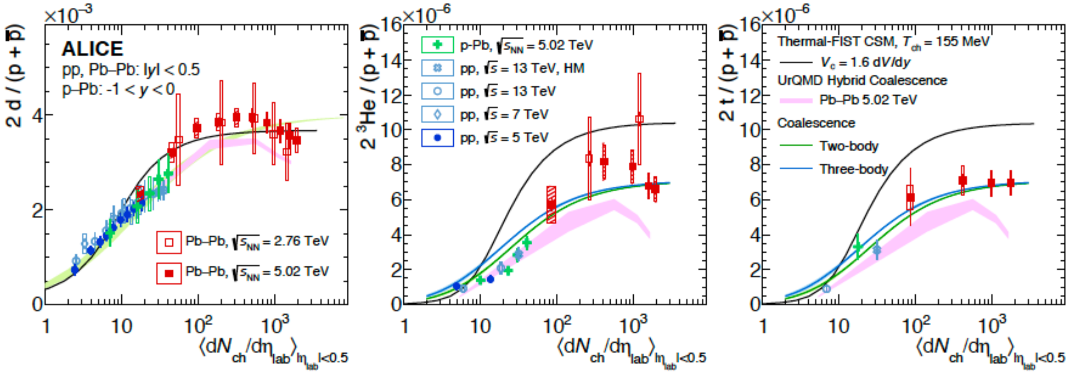
→ enhancement of light nuclei?

Sun+ ('18)

Measurement of light/hyper-nuclei







from QM2023

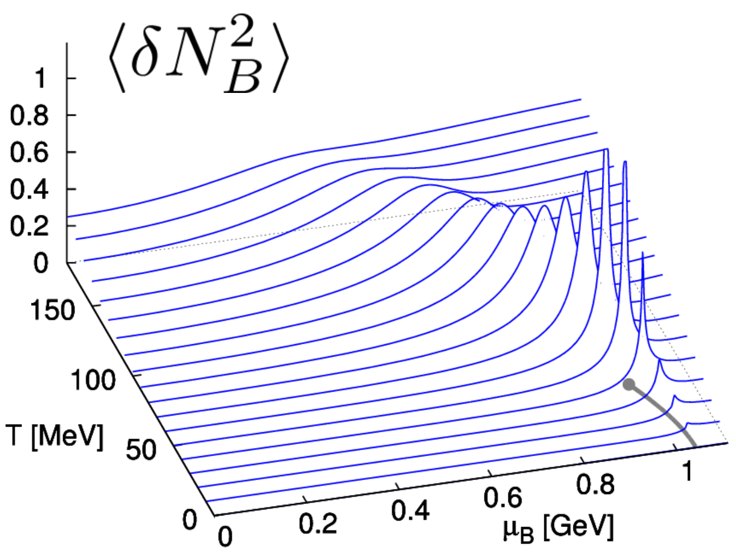
Precise data will lead us to a better understanding of production mechanism

Event-by-event Fluctuations of Conserved Charges

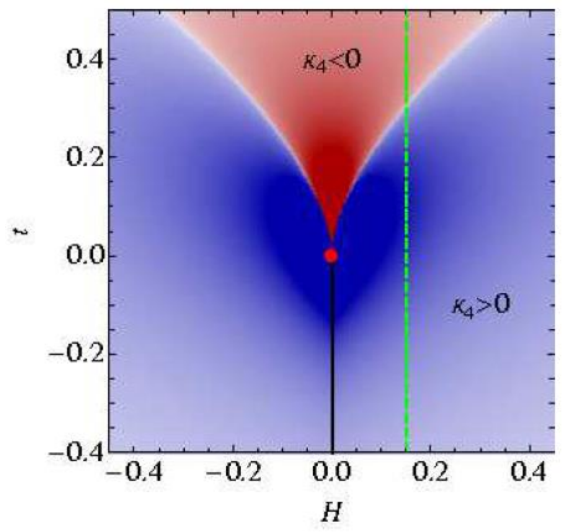
Fluctuations, Cumulants of Conserved Charges

$$\langle N^m \rangle_c = \chi_m V$$

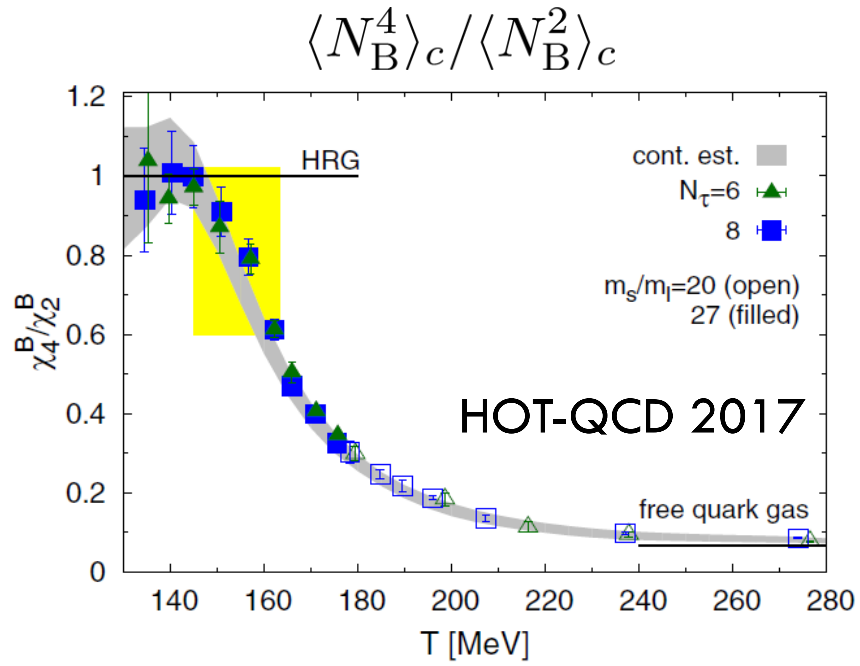
- ☐ Divergence and sign change at the QCD-CP. Stephanov,'09; Asakawa, Ejiri, MK,'09
- ☐ Volume dependence is canceled out in ratio. Ejiri, Karsch, Redlich,'05
- ☐ Direct comparison with lattice QCD simulations.
- ☐ Slower diffusion.



Asakawa, Ejiri, MK (2009)



Stephanov (2011)

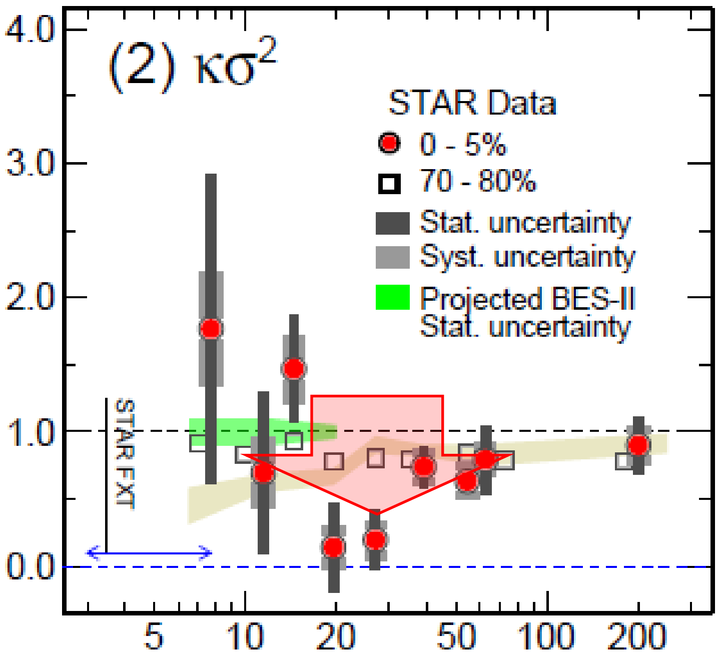


Experimental Results

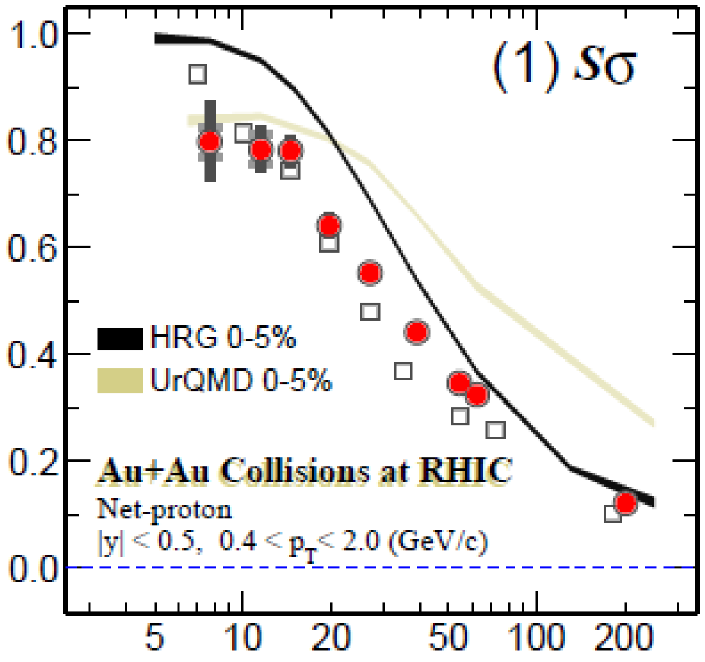
Net-proton number cumulants

STAR, 2020 (2001.02852)

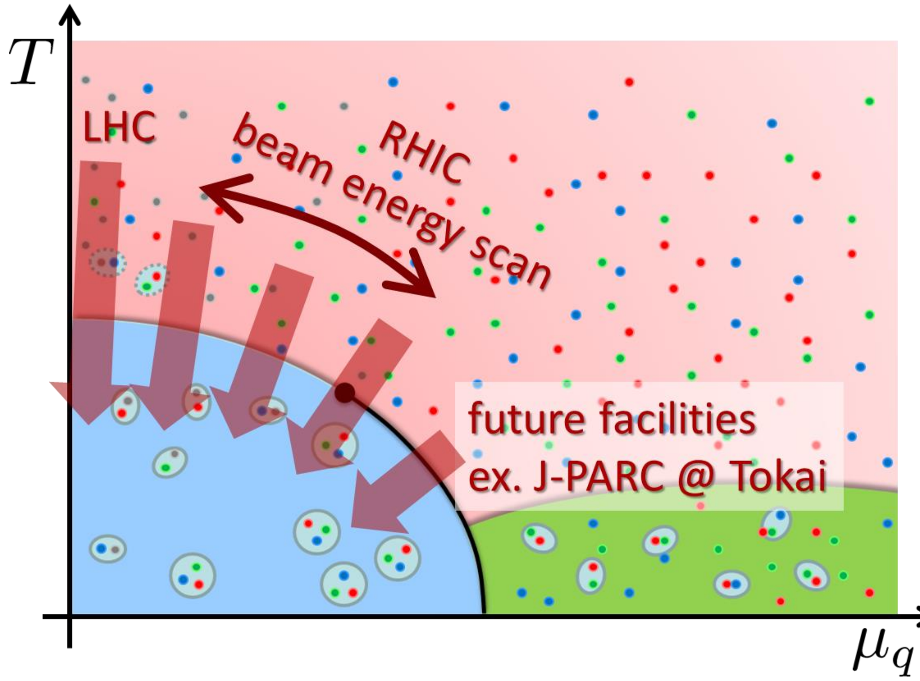
$\langle N_p^4 \rangle_c / \langle N_p^2 \rangle_c$



$\langle N_p^3 \rangle_c / \langle N_p^2 \rangle_c$



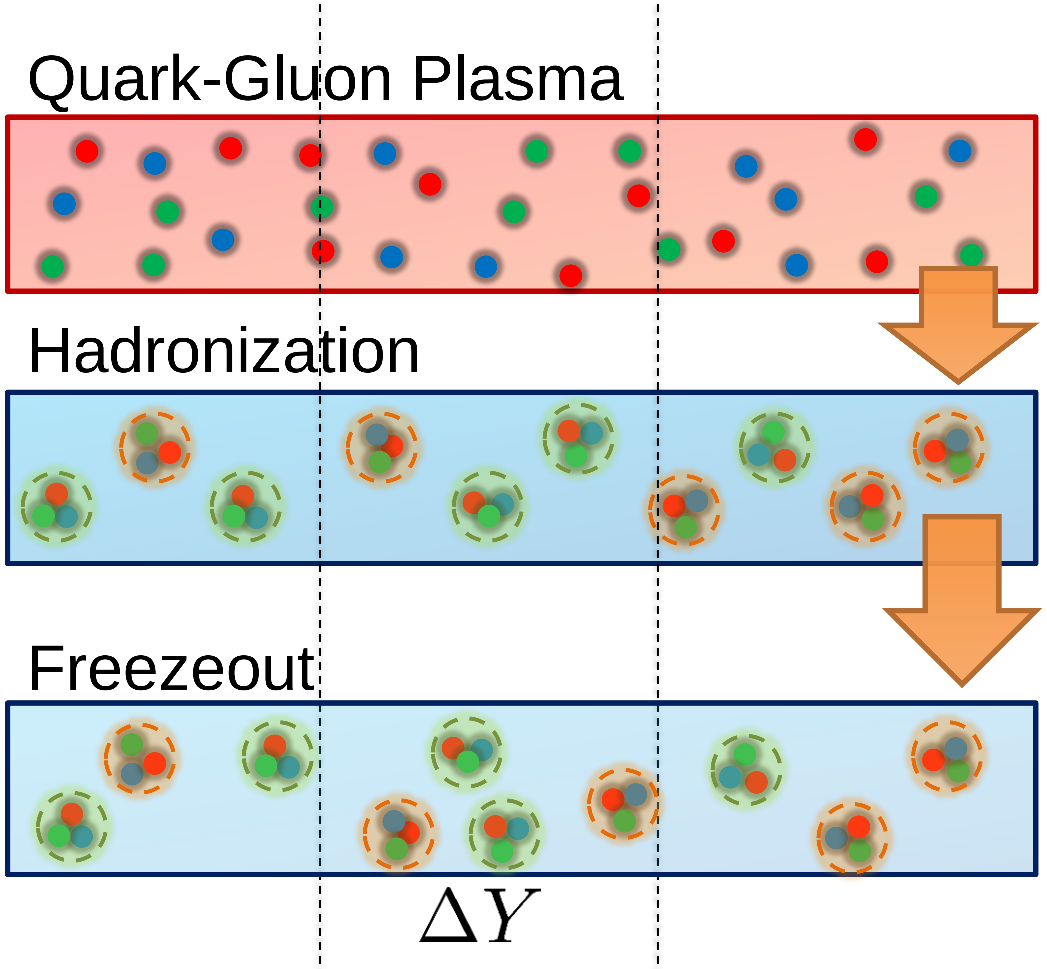
Non-Poisson and non-monotonic behaviors of the higher order cumulants.

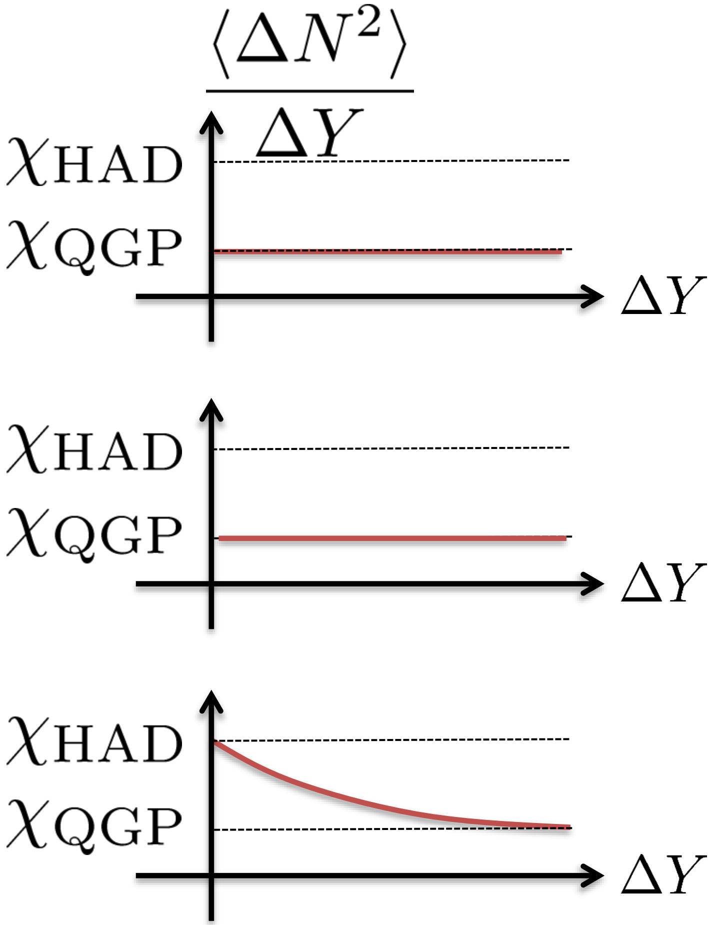


Questions

- ☐ When are these fluctuations generated?
- ☐ Is the use of proton # cumulants as a proxy of baryon's justified?

Evolution of Conserved-charge Fluctuations





Fluctuations of CC are modified by the diffusion.

Relaxation time becomes longer as ΔY →large.

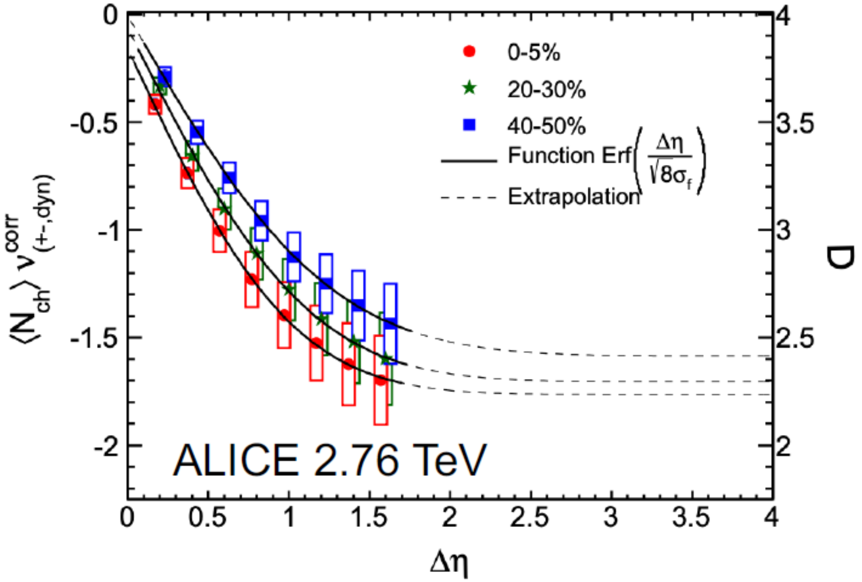
Experiments on $\langle N_Q^2 \rangle$

- ☐ No QGP signal @ RHIC ('02, '03)
- ☐ QGP signal? @ ALICE ('12)

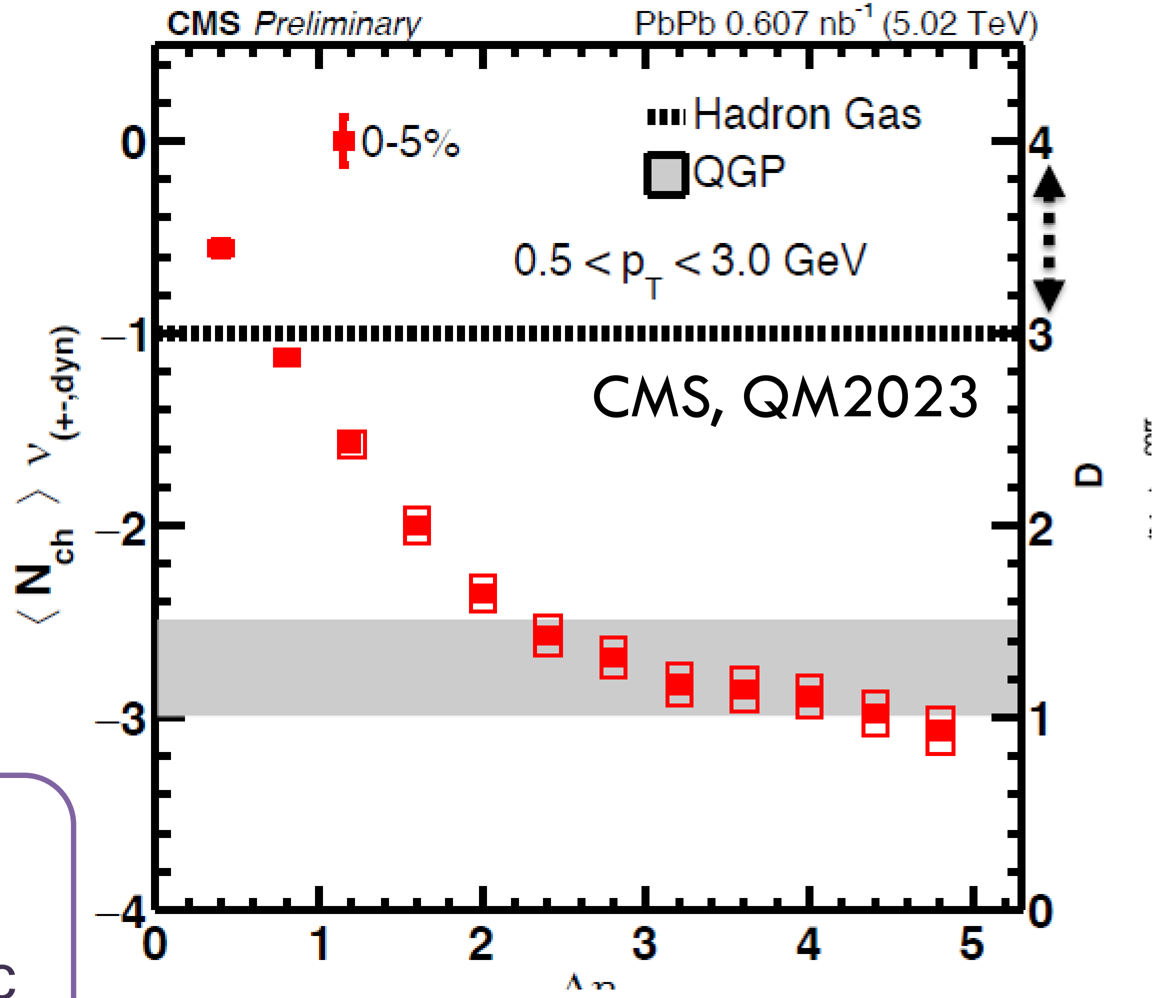
Asakawa, Heinz, Muller, 2000
Jeon, Koch, 2000; Shuryak, Stephanov, 2001

Electric-charge Fluctuations: Wider $\Delta\eta$

- D-measure



ALICE, PRL('12)

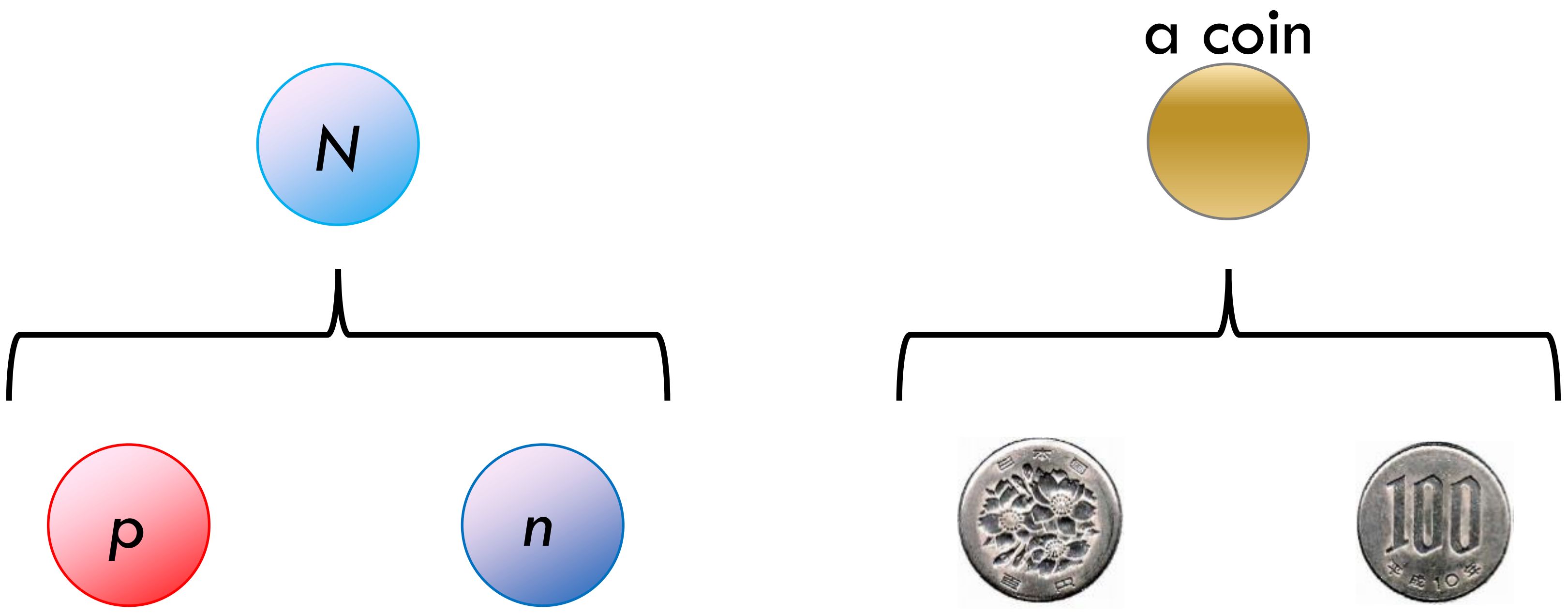


D-measure

$$D = 4\frac{\langle \delta N_Q^2\rangle}{\langle N_Q^+ + N_Q^-\rangle}$$

- D ~ 3-4 Hadronic
- D ~ 1-1.5 Quark

Nucleon's Isospin as Two Sides of a Coin

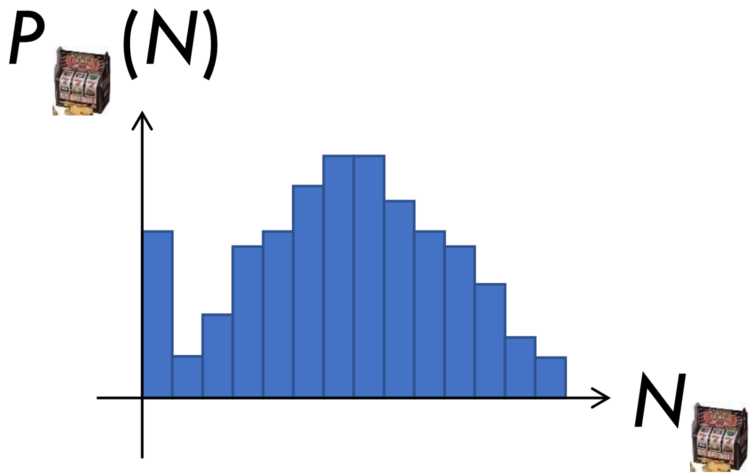


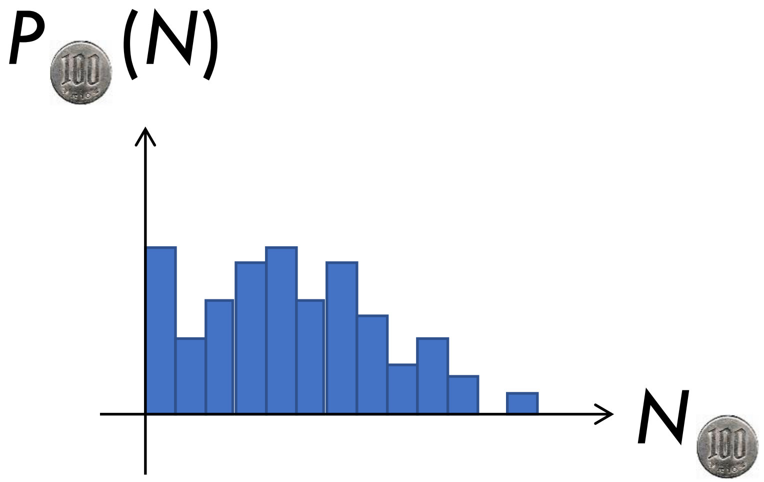
Nucleons have
two isospin states.

Coins have two sides.

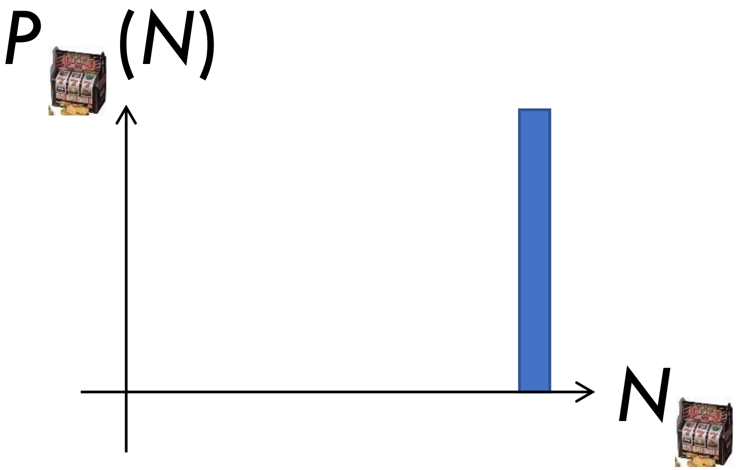
MK, Asakawa, 2012;2012

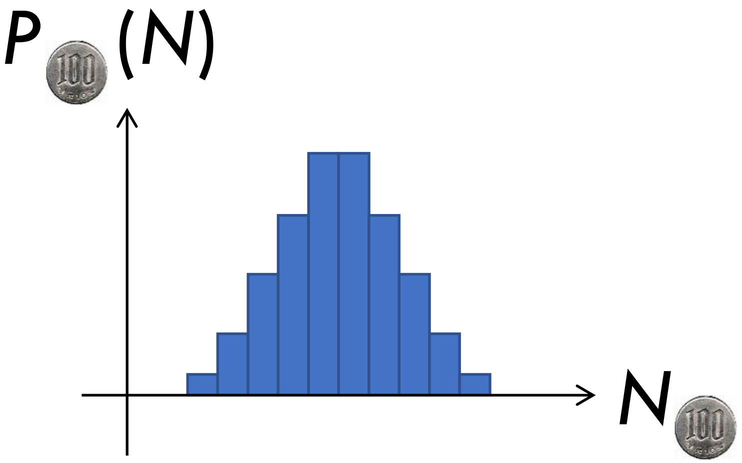
Slot Machine Analogy



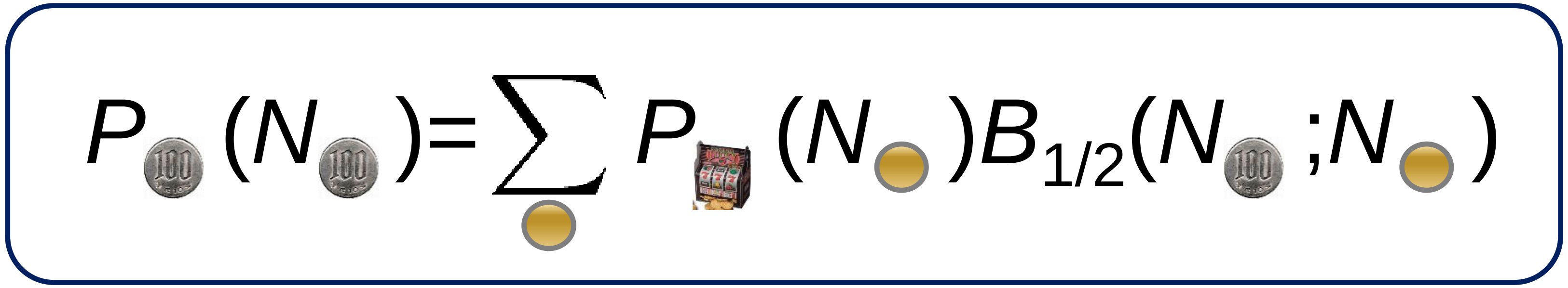


Fixed # of coins





Reconstruction of Total Coin



Example

$$
\begin{cases}
2\langle(\delta N_p^{(\mathrm{net})})^2\rangle = \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle + \frac{1}{2}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^2\rangle_{\mathrm{free}} \\
2\langle(\delta N_p^{(\mathrm{net})})^3\rangle = \frac{1}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle + \frac{3}{4}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^3\rangle_{\mathrm{free}} \\
2\langle(\delta N_p^{(\mathrm{net})})^4\rangle_c = \frac{1}{8}\langle(\delta N_{\mathrm{B}}^{(\mathrm{net})})^4\rangle_c + \cdots
\end{cases}
$$

genuine info. Poisson noise

Note: Higher order cumulants are more fragile.

MK, Asakawa, 2012;2012

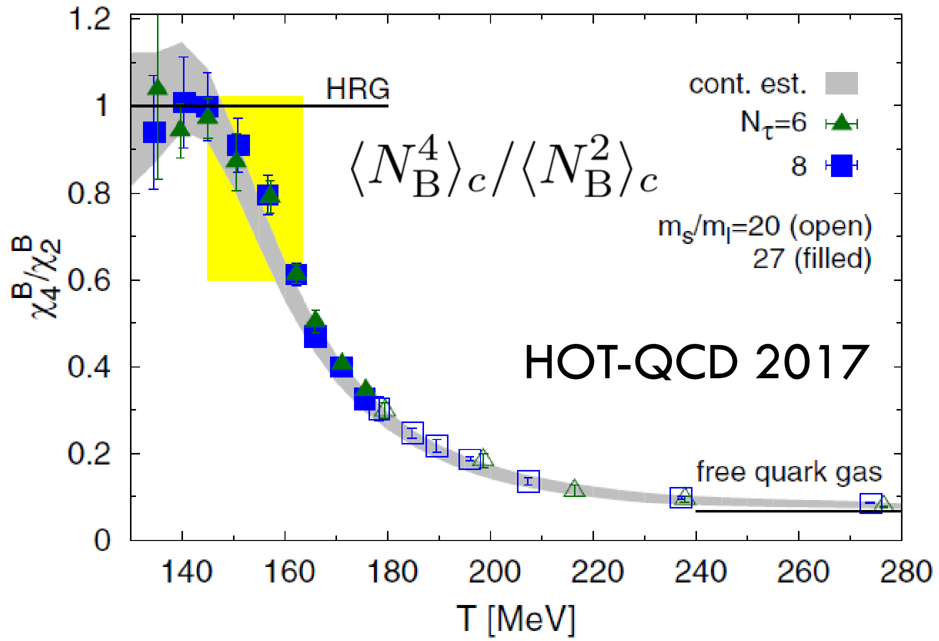
$\langle N_B^2\rangle_c/\langle N_Q^2\rangle_c$

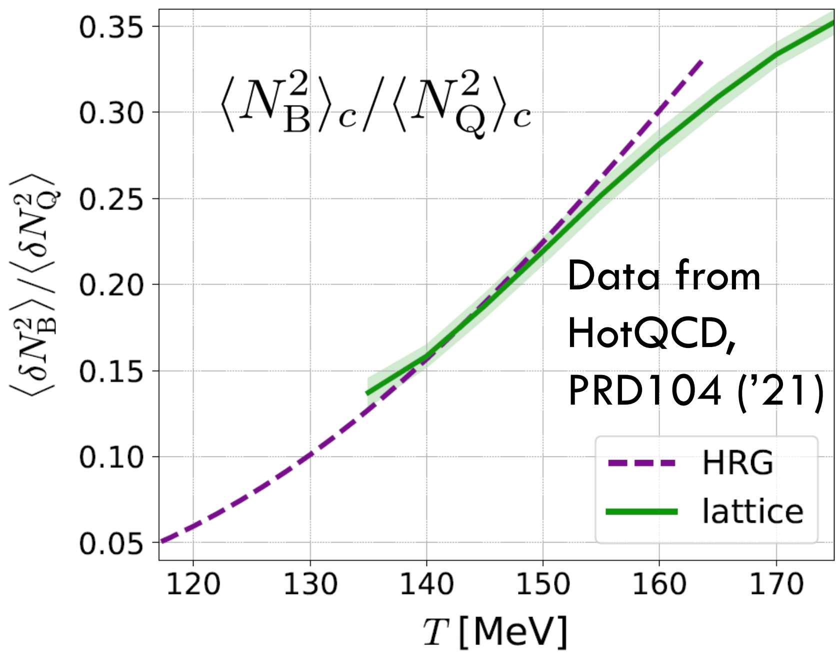
MK, Esumi, Nonaka, 2205.10030

$\langle N_{\rm B}^2\rangle_c/\langle N_{\rm Q}^2\rangle_c$

- Ratio of 2nd order: Suppress uncertainties from various experimental effects compared with higher orders.
- Almost linear T dependence around T_c^*.

- $\sqrt{s_{NN}} = 200\mathrm{GeV}$
- 0-5% centrality
- Δy dependence
- Construction of baryon number, p_T-acceptance correction





Experimental Data

$\langle N_p^2 \rangle_c$

STAR, PRC104,024902 (2021)

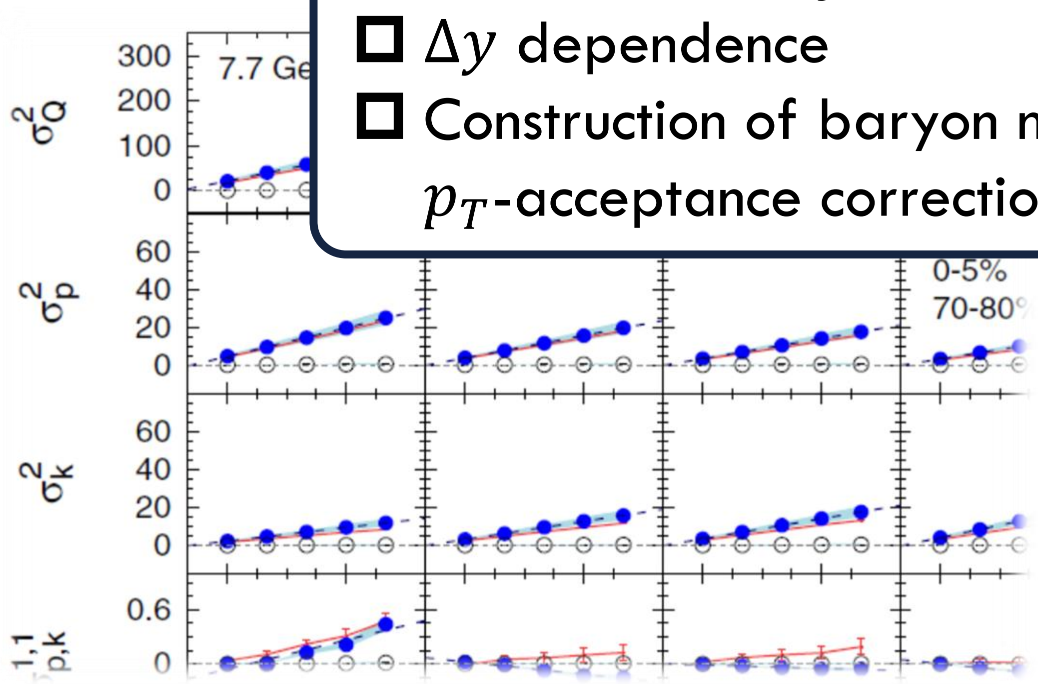
- proton cumulants up to 4th order
- **rapidity window** Δy
- $0.4 < p_T < 2.0$GeV/c

$\langle N_Q^2 \rangle_c$

STAR, PRC100,014902 (2019)

- 2nd mixed cumulants of p, ,pi, K, Q
- **pseudo-rapidity window** $\Delta \eta$
- $0.4 < p_T < 1.6$GeV/c
- Total charge: private comm. A. Chattergee

- ☐ $\sqrt{s_{NN}} = 200$GeV
- ☐ 0-5% centrality
- ☐ Δy dependence
- ☐ Construction of baryon number, p_T-acceptance correction



- ☐ proton → baryon cumulants MK, Asakawa,'12;'12
- ☐ Rapidity is better than pseudo-rapidity Ohnishi, MK, Asakawa, '16
- ☐ Wider acceptance is more desirable.

p_T-Acceptance Correction

p_T Acceptance

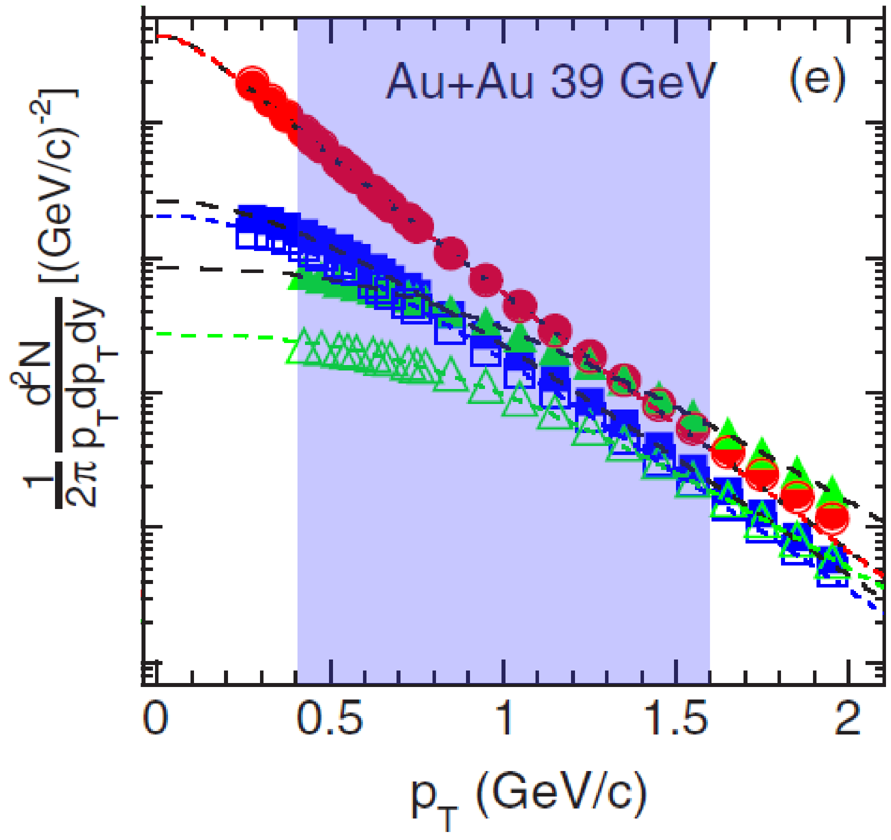
0.4<p_T<1.6 [GeV/c]
PRC100,014902('19)

0.4<p_T<2.0 [GeV/c]
PRC104,024902('21)

Particles in p_T space

- Electric charge: **49%**
- Protons: **82%**

blast wave model @ $\sqrt{s_{NN}}$=200 GeV



Modification by p_T-cut should be corrected.
This study: Binomial distribution model.

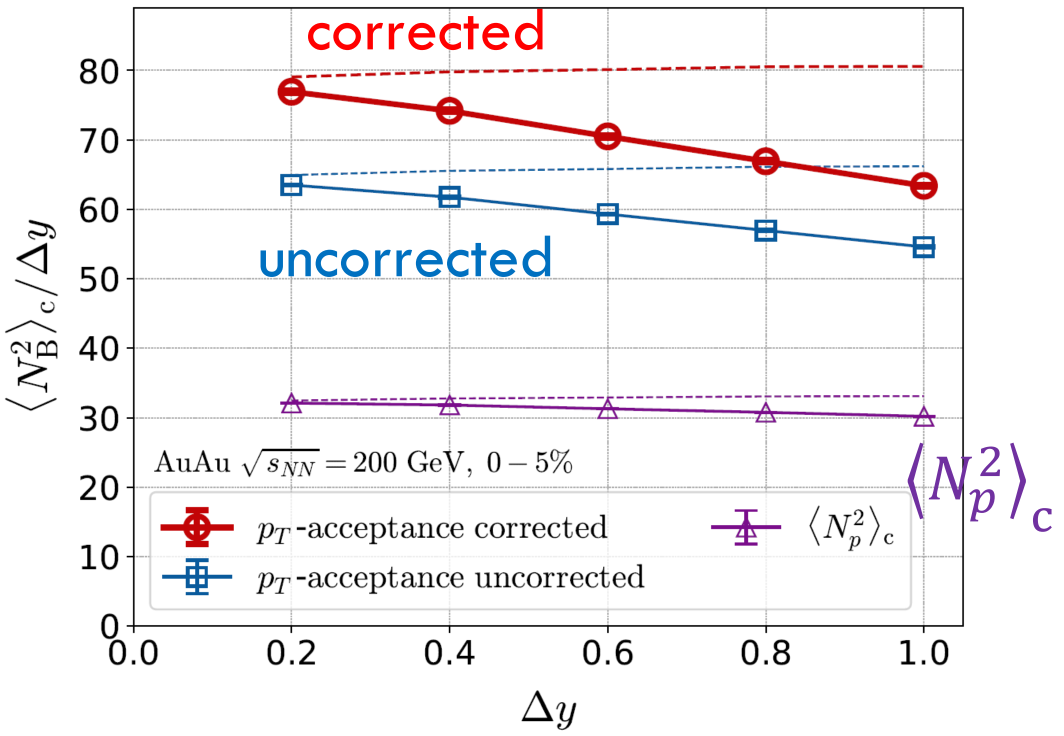
$$\langle N_{\rm net}^2\rangle_c^{\rm corrected} = \frac{1}{p^2}\Big(\langle n_{\rm net}^2\rangle_c - (1-p)\langle n_{\rm tot}\rangle_c\Big)$$

MK, Asakawa, '12, '12

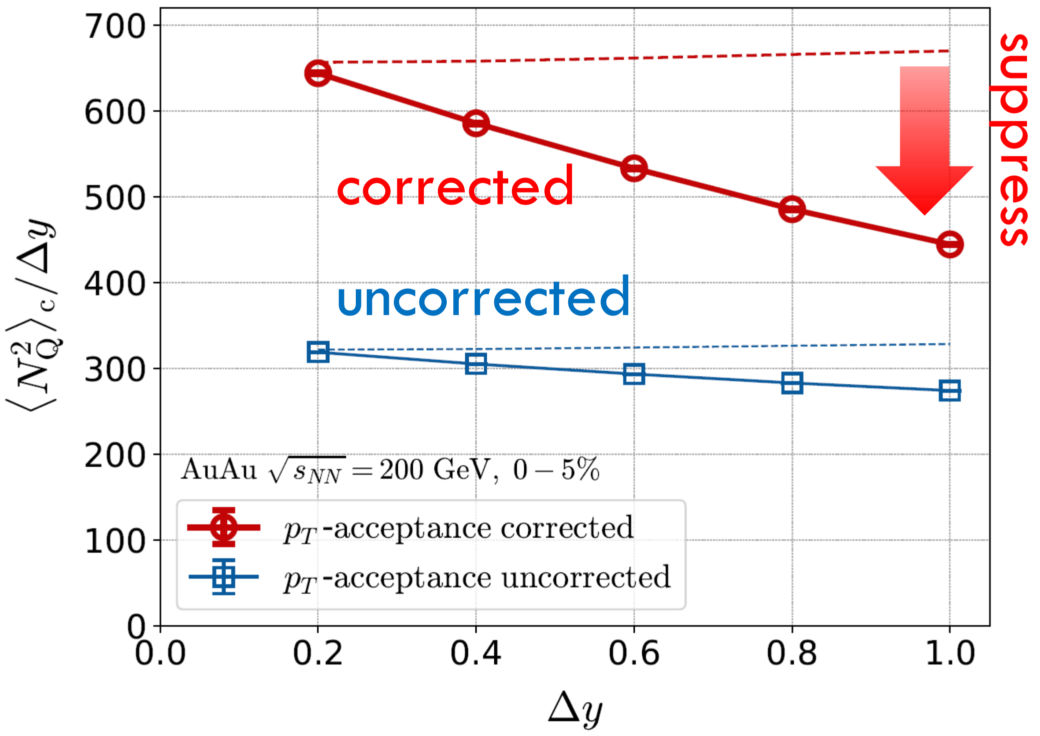
Cumulants: Proton→Baryon & Acceptance Correction

Data from STAR, '19, '21

$\langle N_B^2 \rangle_c / \Delta y$



$\langle N_Q^2 \rangle_c / \Delta y$



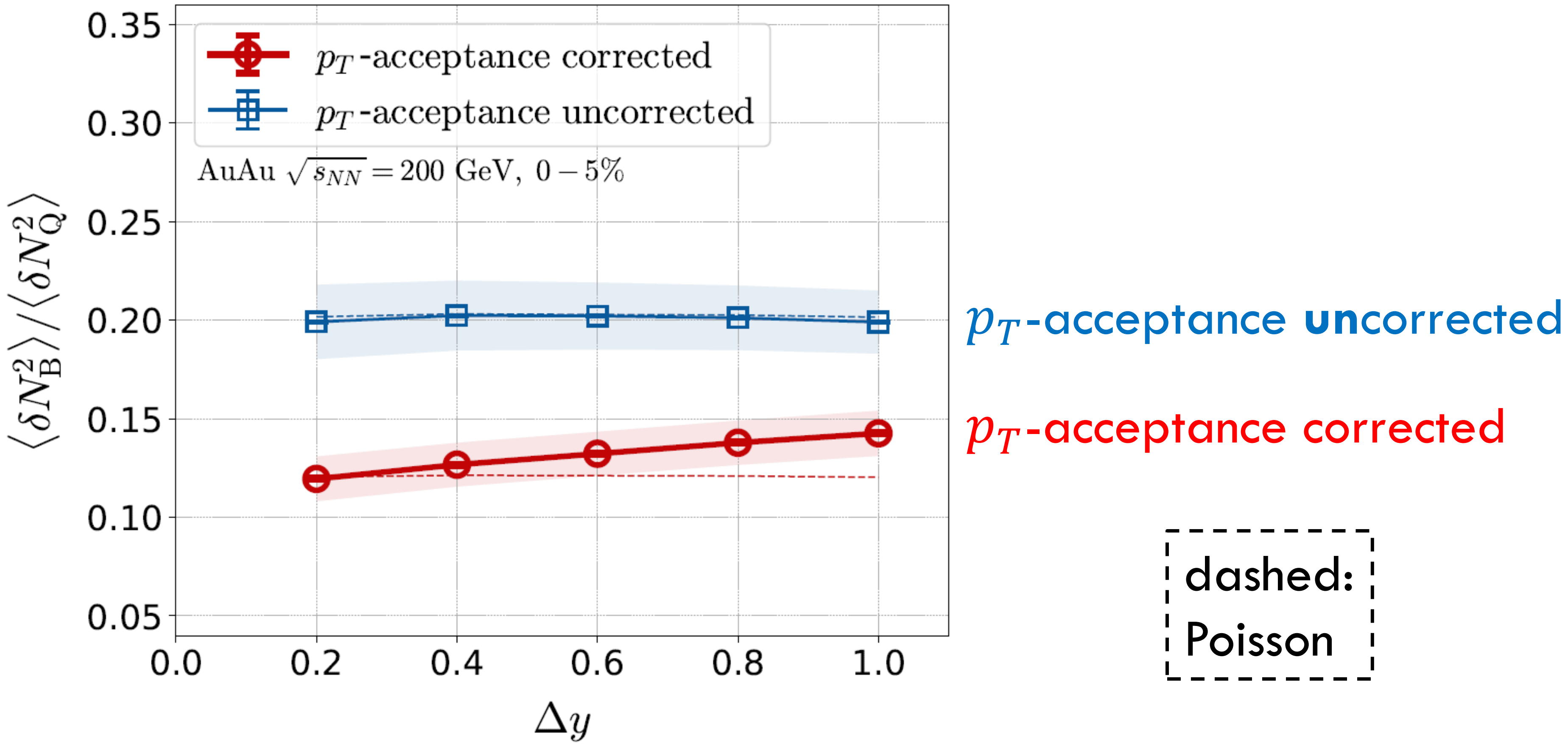
dashed:
$\langle N^{\rm tot} \rangle$
Poisson

- Deviation from Poissonian is clarified by the acceptance correction.

$$\langle N_{\rm net}^2 \rangle_c^{\rm corrected} = \frac{1}{p^2}\Big(\langle n_{\rm net}^2 \rangle_c - (1-p)\langle n_{\rm tot} \rangle_c \Big)$$

MK, Asakawa, '12, '12

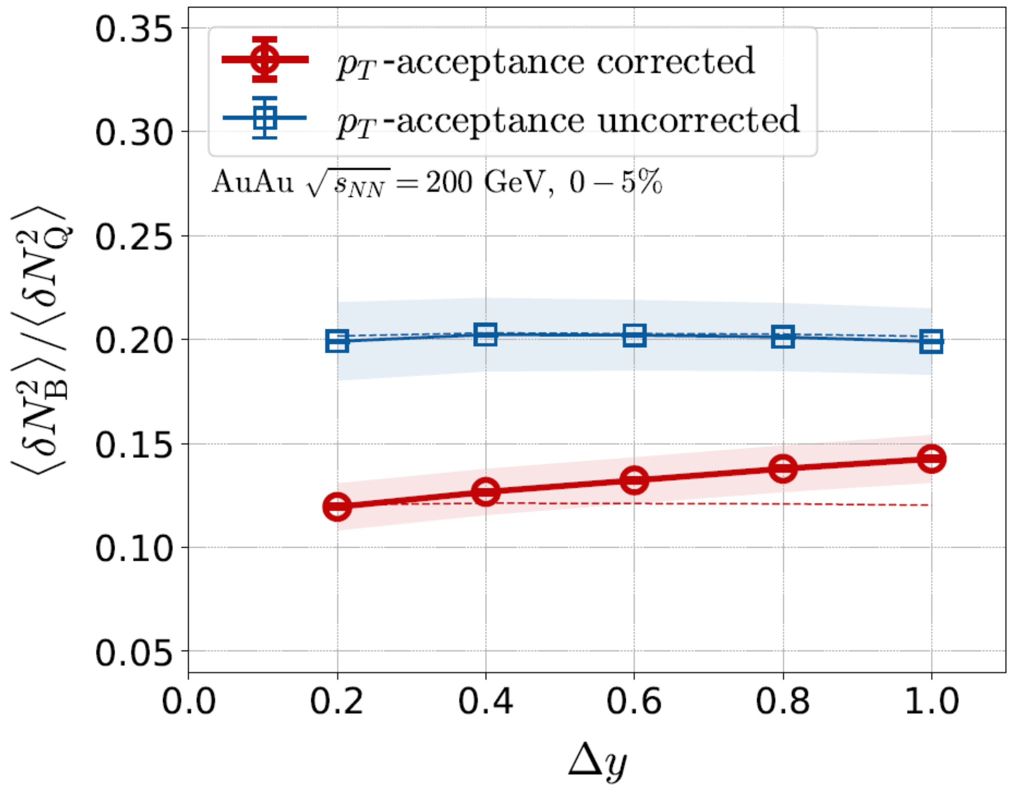
$\langle N_B^2 \rangle_c / \langle N_Q^2 \rangle_c$



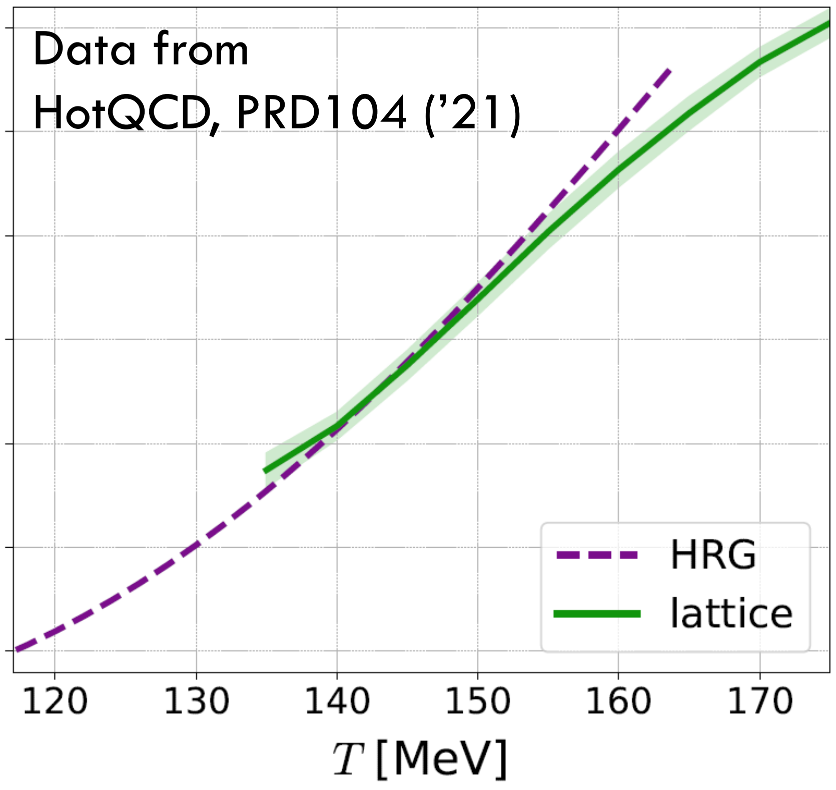
- $\langle N_B^2 \rangle_c / \langle N_Q^2 \rangle_c$ becomes smaller due to the p_T-acceptance correction.
- Clear Δy dependence ➡ non-thermal effects behind fluctuations

HIC vs HRG&LAT

From data @ STAR



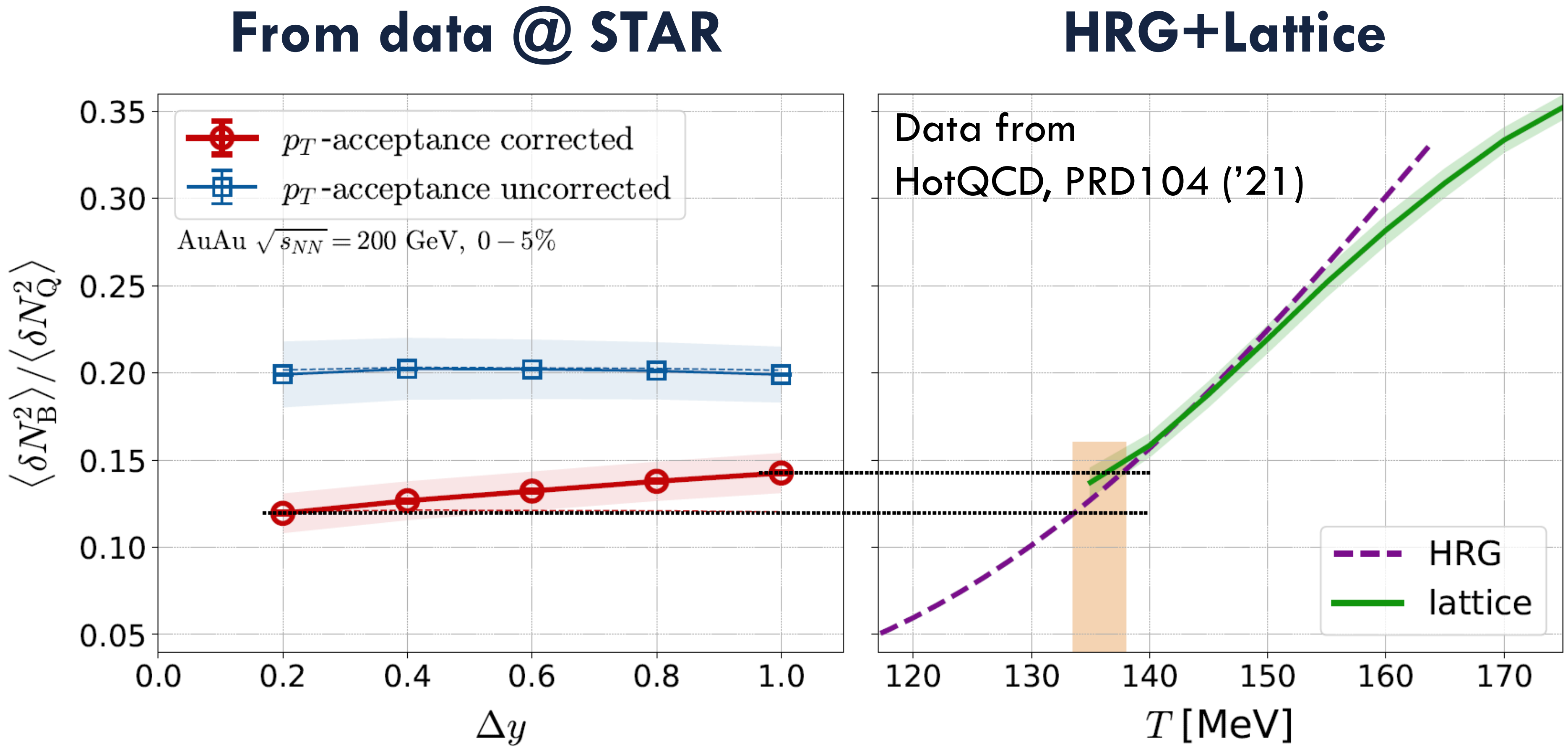
HRG+Lattice



- $T = 134 \sim 138$ MeV
- Significantly lower than $T_{\rm chem}$

HRG: QMHRG2020
Bollweg+, PRD104, 7 ('21)
Volume dep. corrected
plot by MK

HIC vs HRG&LAT



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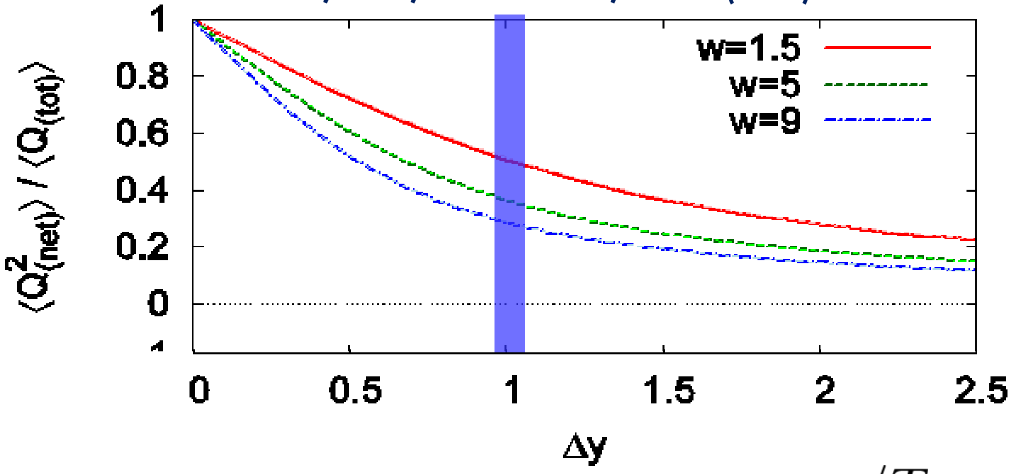
Volume dep. corrected
plot by MK

Effect of Diffusion and Rapidity Conversion

- Blurring due to diffusion & rapidity conversion ($Y \to y$)
  - Stronger modification in Q than B
- Resonance Decays
  - About 30% charged particles come from RD
  - Enhancement of charged particles

→ Increase $\langle N_Q^2 \rangle$; Reduce $\langle N_B^2 \rangle_c / \langle N_Q^2 \rangle_c$

Ohnishi, MK, Asakawa, PRC ('16)



$w = m/T$

These effects will be more important for higher order cumulants!

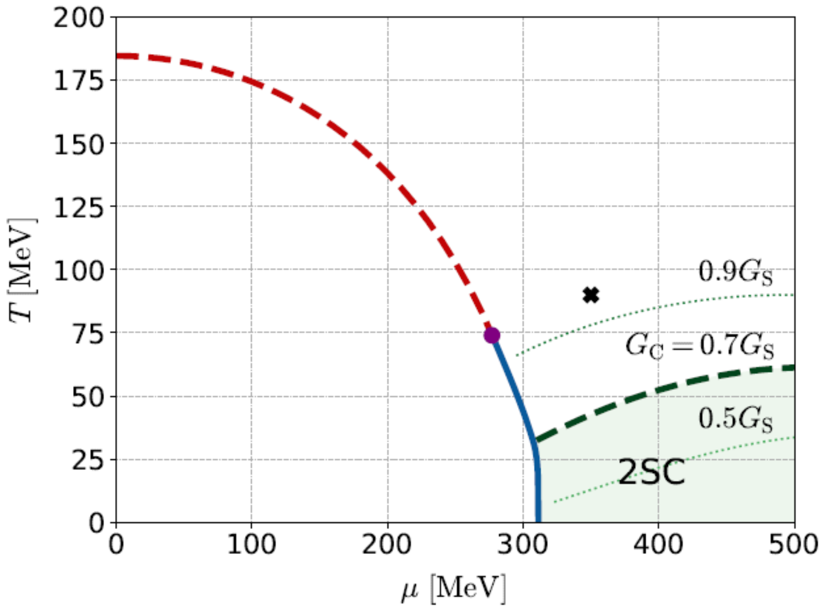
Dilepton Production
as experimental observables of
Color Superconductivity & QCD-CP

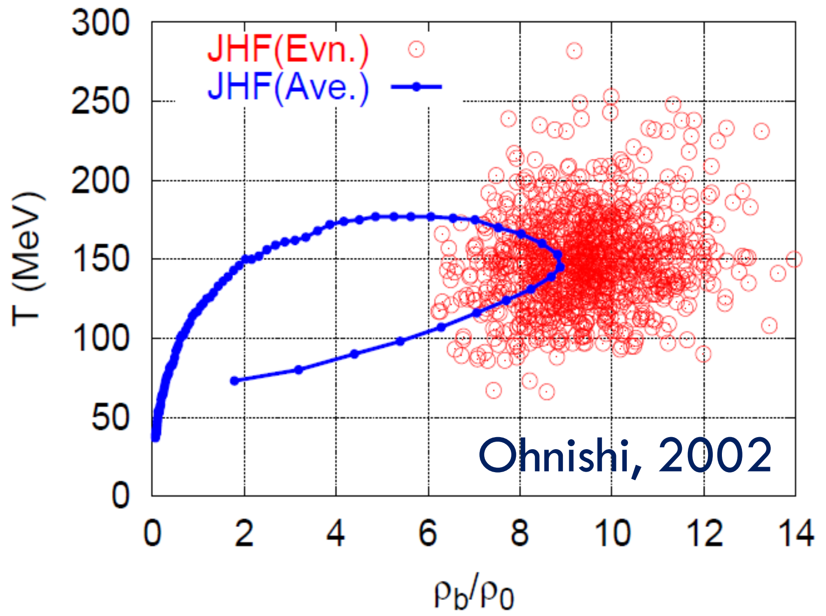
Nishimura, MK, Kunihiro, PTEP2022, 093D02
Nishimura, MK, Kunihiro, PTEP2023, 053D01

Observing CSC in HIC

- **Difficulties**
  - CSC would not be created if Tc is not high enough.
  - Even if created, its lifetime would be short.
  - Since CSC is created in the early stage, its signal would be blurred during the evolution in later stage.

- **Strategy** in the present study:
  - Use dilepton production as an observable
  - Focus on precursory phenomena of CSC



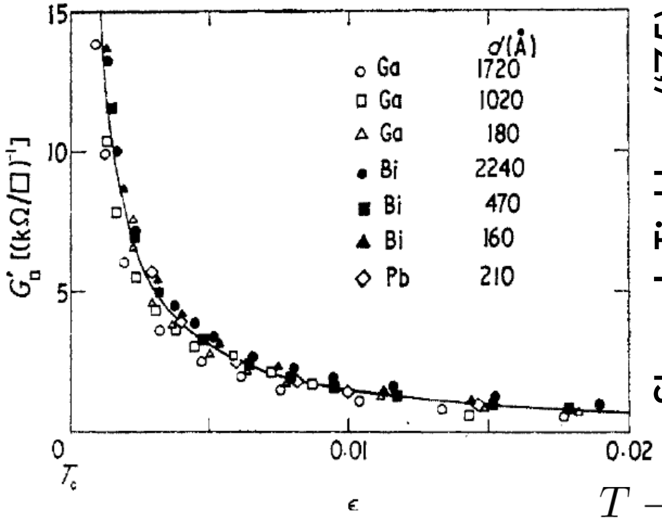


Precursor of CSC

- **Anomalous behavior of observables near but above Tc of SC**
  - electric conductivity
  - magnetic susceptibility
  - pseudogap

- Enhanced pair fluctuations is one of the origins of precursory phenomena.
- More significant phenomena in strongly-coupled systems.

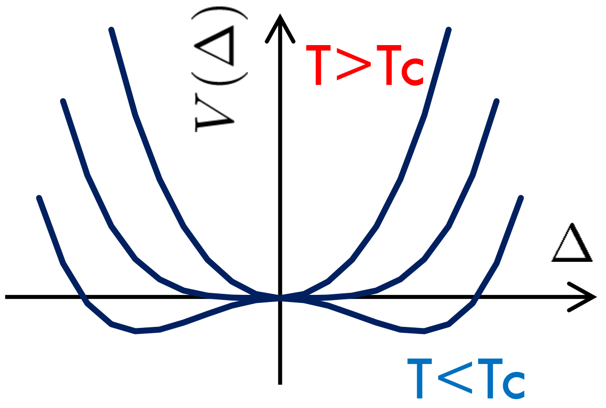
Electric conductivity



Skopal, Tinkham('75)

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

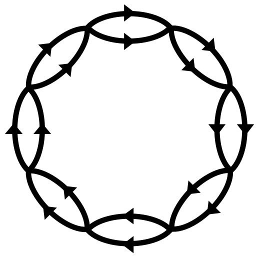
Landau's free energy



Precursor of Color Superconductivity

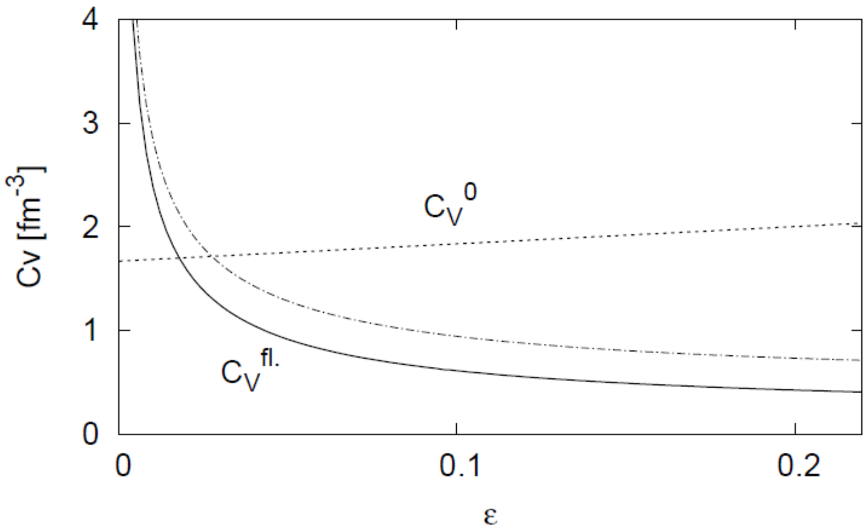
MK, Koide, Kunihiro, Nemoto, '03, '05

□Thermodynamic Potential

$\Omega =$ 

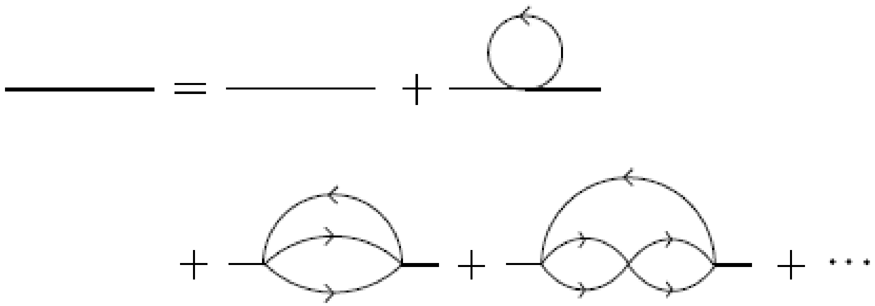
Specific heat

$$c = -T\frac{\partial^2\Omega}{\partial T^2}$$

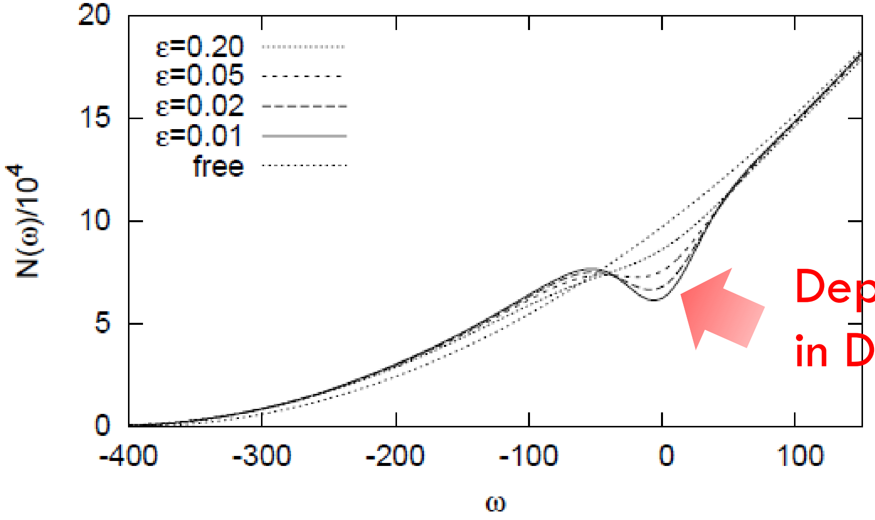


$$\varepsilon = \frac{T - T_c}{T_c}$$

□Pseudogap



density of states



Depression
in DoS above Tc

Model

NJL model (2-flavor)

$$\mathcal{L} = \bar{\psi} i \partial\!\!\!/ \psi + \mathcal{L}_S + \mathcal{L}_C$$

$$\mathcal{L}_S = G_S\left((\bar{\psi}\psi)^2 + (\bar{\psi} i\gamma_5 \tau \psi)^2\right)$$

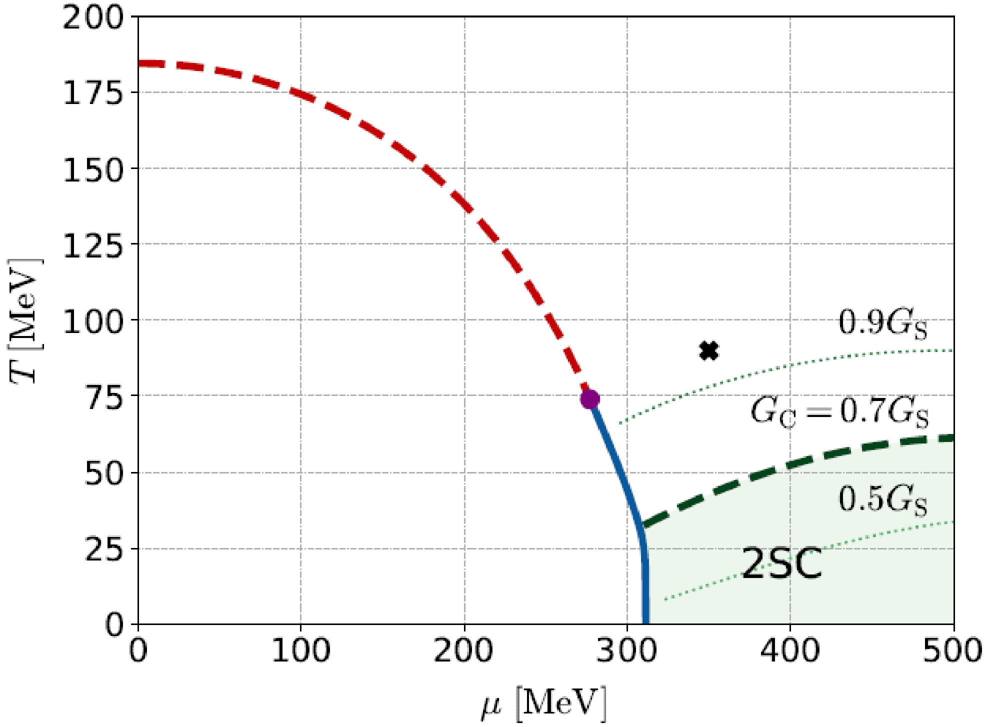
$$\mathcal{L}_C = G_C\left((\bar{\psi} i\gamma_5 \tau_A \lambda_A \psi^C)(\text{h.c.})\right)$$

diquark interaction

Parameters

$$G_S = 5.01\ \text{GeV}^{-2},\quad \Lambda = 650\text{MeV},\quad m_q = 0$$

Phase Diagram in MFA



- Order of phase transition
  - 2nd in the MFA
  - can be 1st due to gauge fluctuation

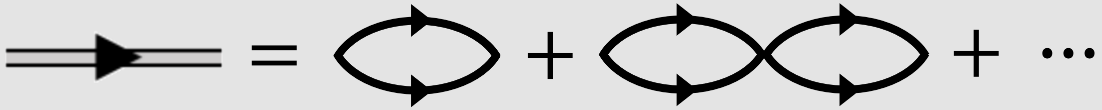
Matsuura+('04), Giannakis+('04)
Noronha+('06), Fejos, Yamamoto('19)

Di-quark Fluctuations

☐ Diquark Propagator

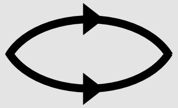
$$D^R(x) = \langle [\Delta^\dagger(x), \Delta(0)] \rangle \theta(t) =$$

☐ Random Phase Approximaion



$$= \frac{Q^R(\boldsymbol{k},\omega)}{1 + G_C Q^R(\boldsymbol{k},\omega)}$$

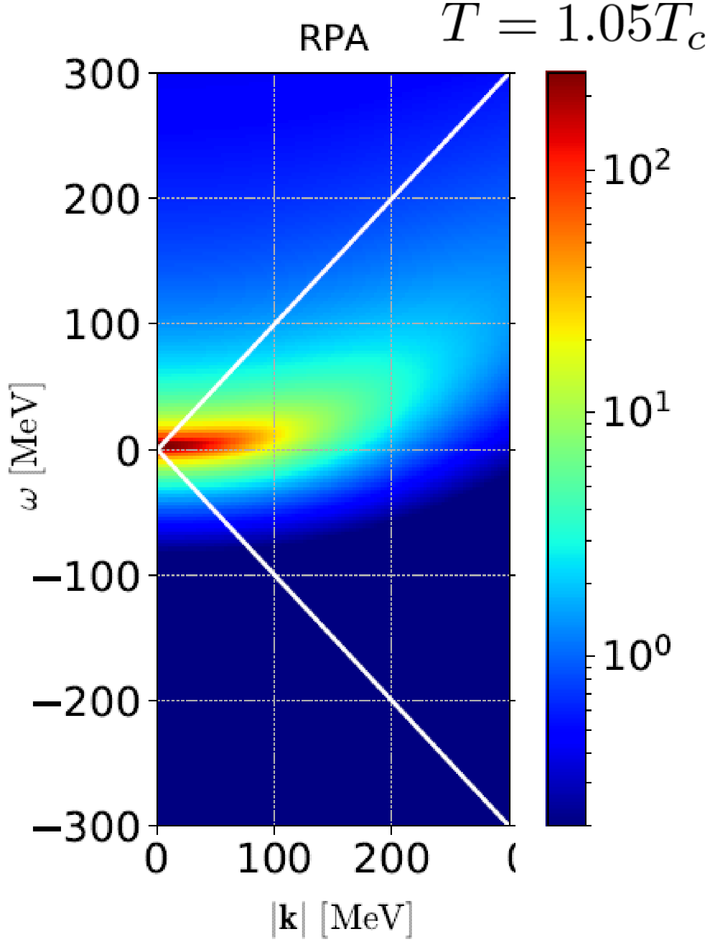
$$Q^R(\boldsymbol{k},\omega) =$$



- ☐ Diquark field becomes massless at T=Tc
- ☐ Soft mode of CSC transition
- ☐ Strength in the space-like region

Dynamical Structure Factor

$$S(\boldsymbol{k},\omega) = -\frac{1}{\pi}\frac{1}{1-e^{-\beta\omega}} \mathrm{Im D^R(k,\omega)}$$

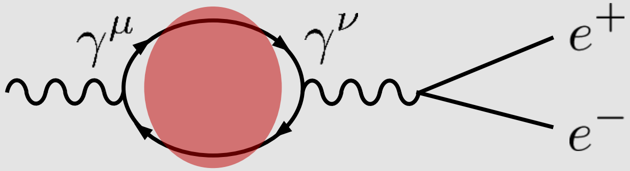


MK, Koide, Kunihiro, Nemoto, '01,'05

Photon Self-Energy: Precursor of CSC

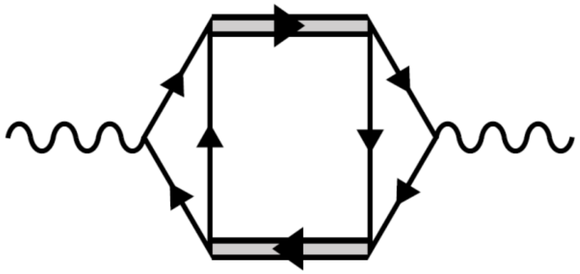
☐ Dilepton Production Rate

$$\frac{d^4\Gamma}{dk^4} = \frac{\alpha}{12\pi^4}\frac{1}{k^2}\frac{1}{e^{\beta\omega-1}}\mathrm{Im}\Pi^{R\mu}_{\mu}(k)$$

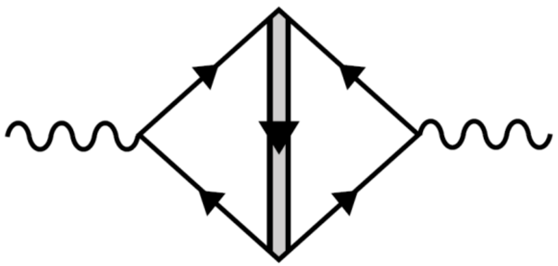


☐ Effect of Di-quarks on $\Pi^{\mu\nu}(k)$

Aslamasov-Larkin term

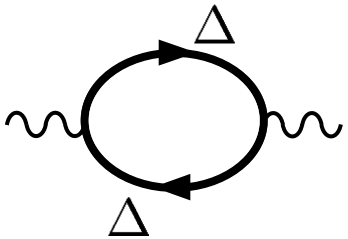


Maki-Thompson term

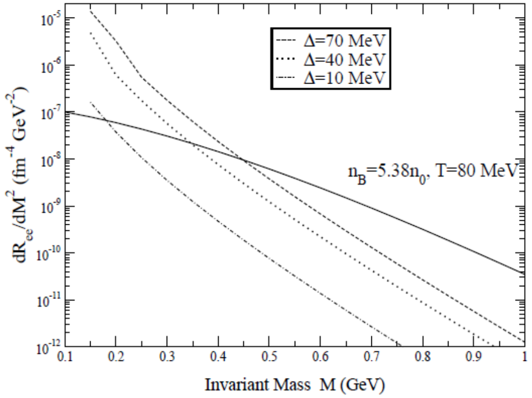


Well-known diagrams in metallic SC
for describing paraconductivity

☐ DPR from CFL phase

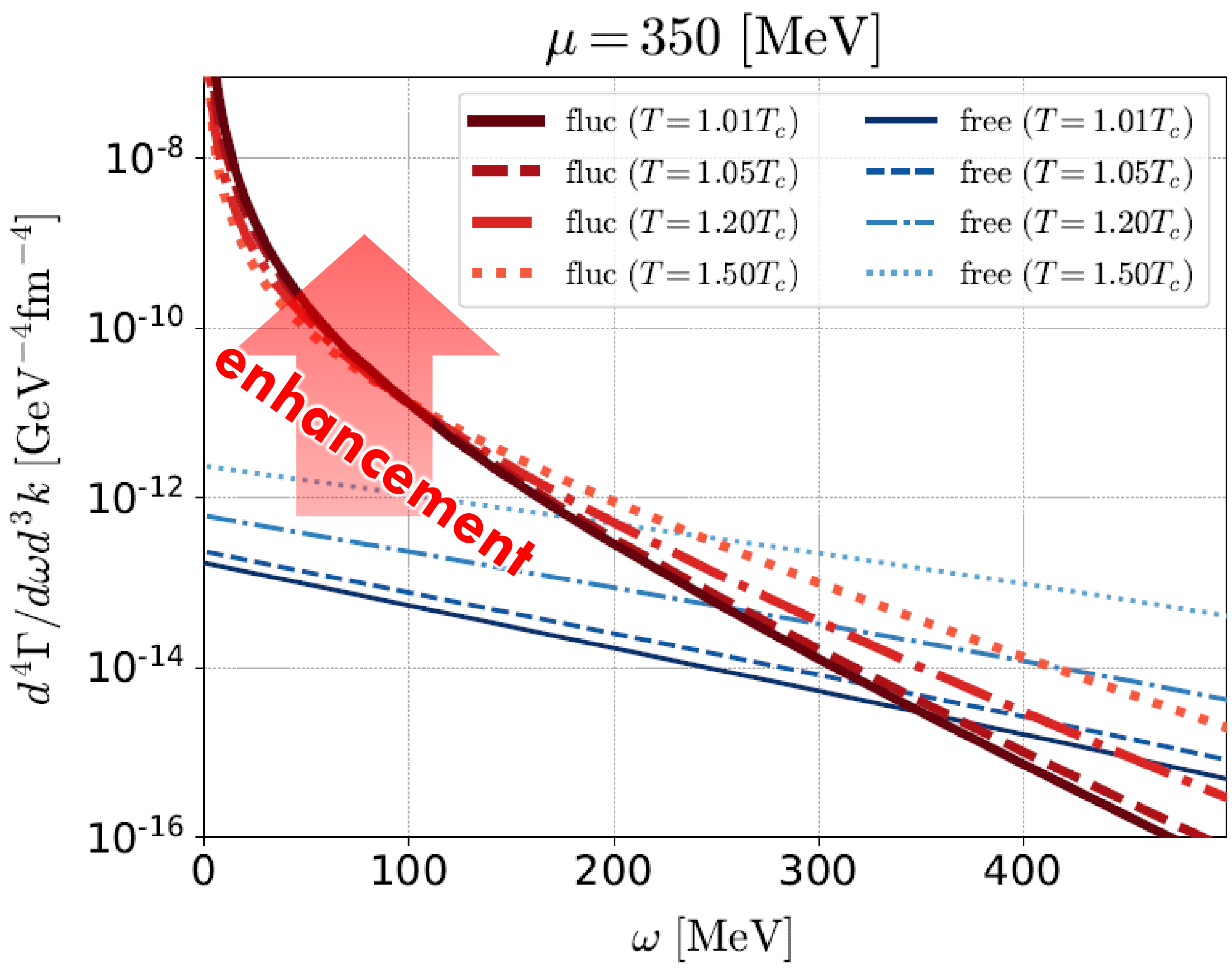


Jaikumar, Rapp, Zahed ('02)



Production Rate at $k = 0$

Nishimura, MK, Kunihiro ('22)



Red: fluctuation contribution

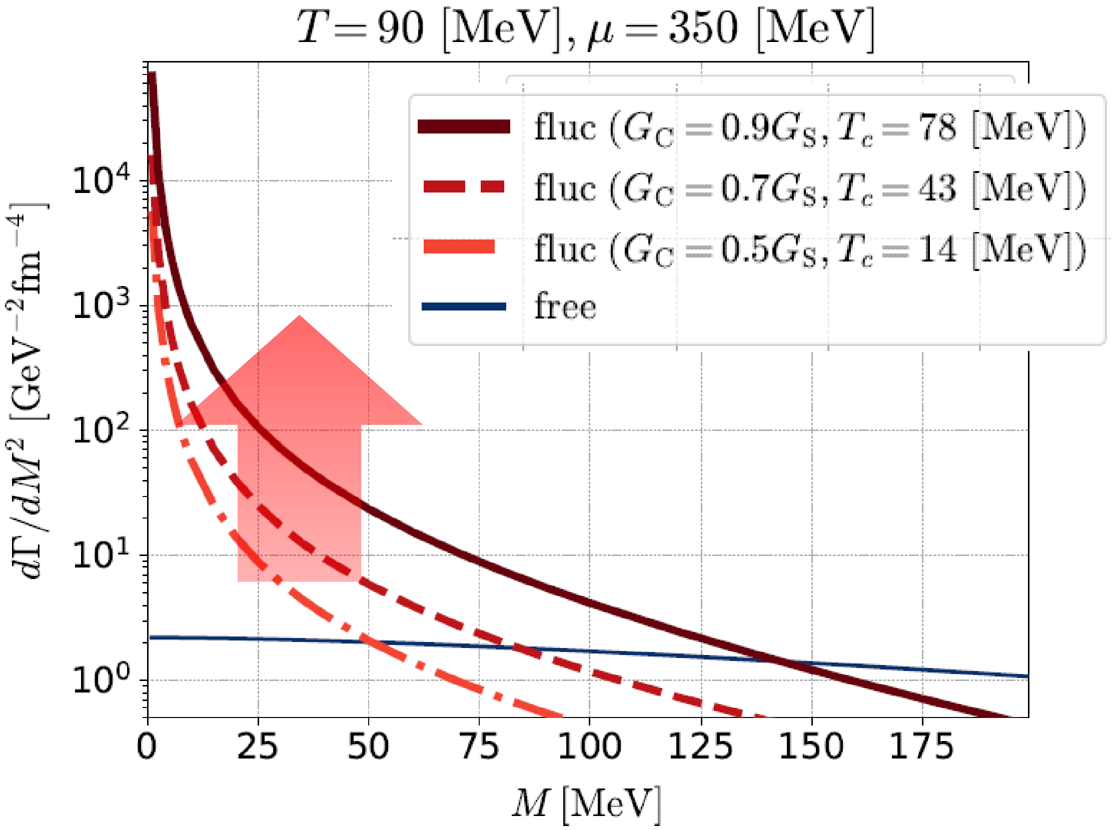
Blue: free quarks

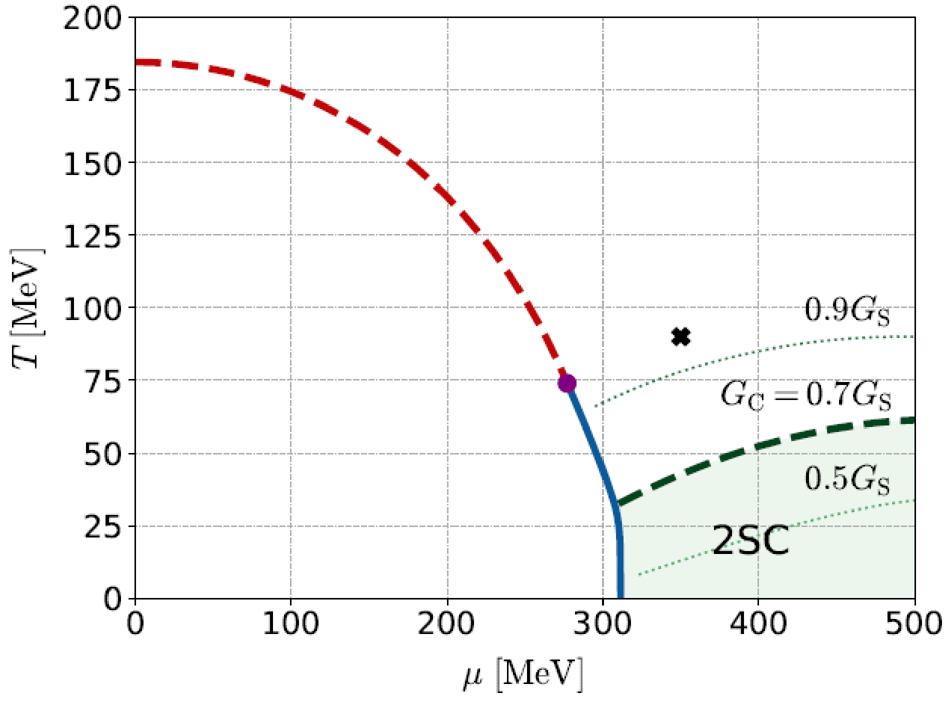
$G_C = 0.7G_s, T_c \simeq 45$ MeV

- Di-quark fluctuations give rise to large enhancement in the low energy region $\omega < 200$ MeV and $T < 1.5T_c$.
- Anomalous enhancement is not sensitive to T.

Invariant-Mass Spectrum

Nishimura, MK, Kunihiro ('22)





- Strong enhancement at low invariant mass.
- **Observable in the HIC?**

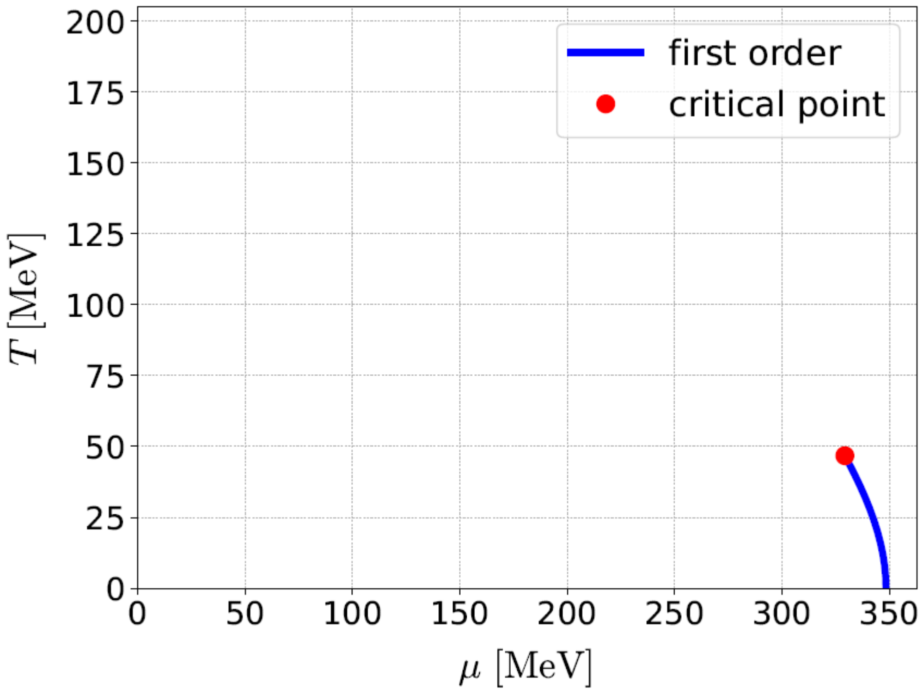
Dileptons from QCD Critical Point

NJL model (2-flavor)

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + G_S\left((\bar{\psi}\psi)^2 + (\bar{\psi}i\gamma_5\tau\psi)^2\right)$$

Parameters

$$G_S = 5.5\ \mathrm{GeV}^{-2},\ \Lambda = 631\mathrm{MeV},\ m_q = 5.5\ \mathrm{MeV}$$

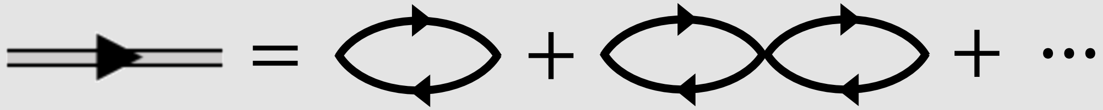


Soft Mode of QCD-CP

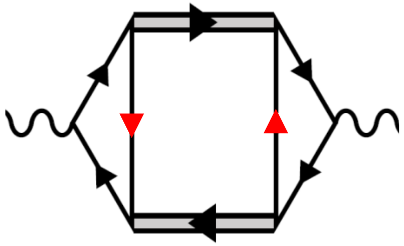
= fluctuation of scalar $(\bar{q}q)$ channel

$$D^R(x) = \langle[\bar{\psi}\psi(x), \bar{\psi}\psi(0)]\rangle\theta(t) =$$

- Random Phase Approximaion



Modification of dilepton production through

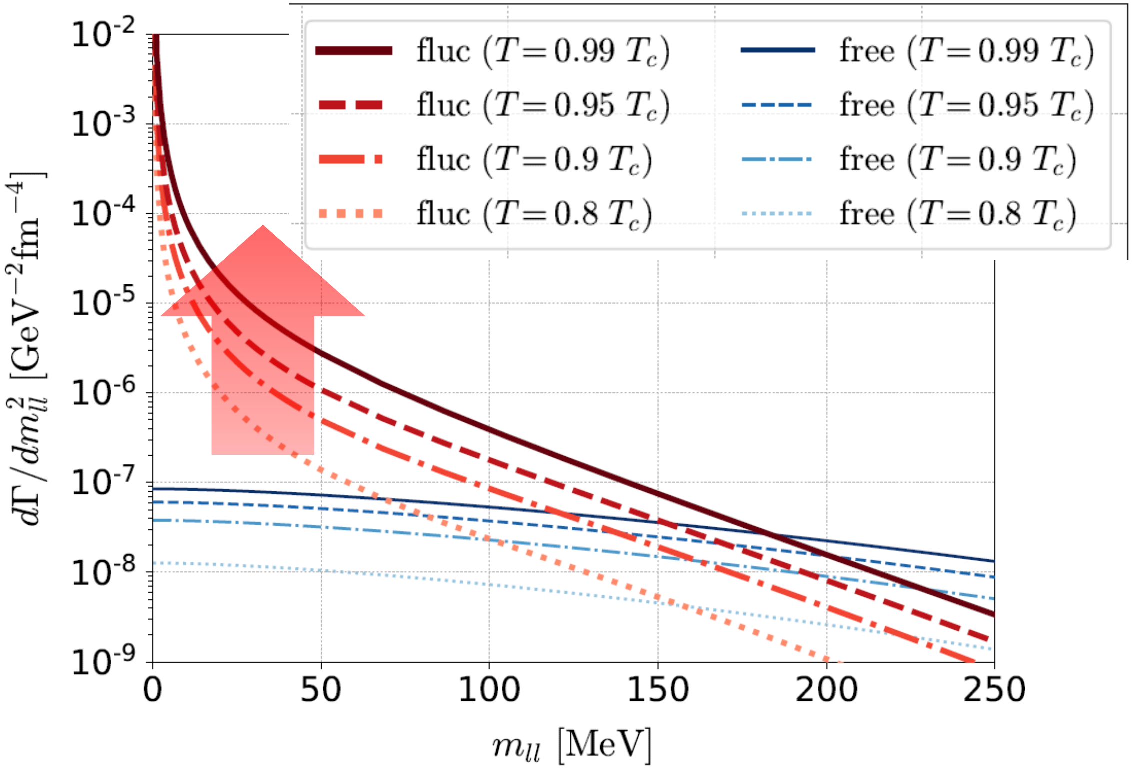


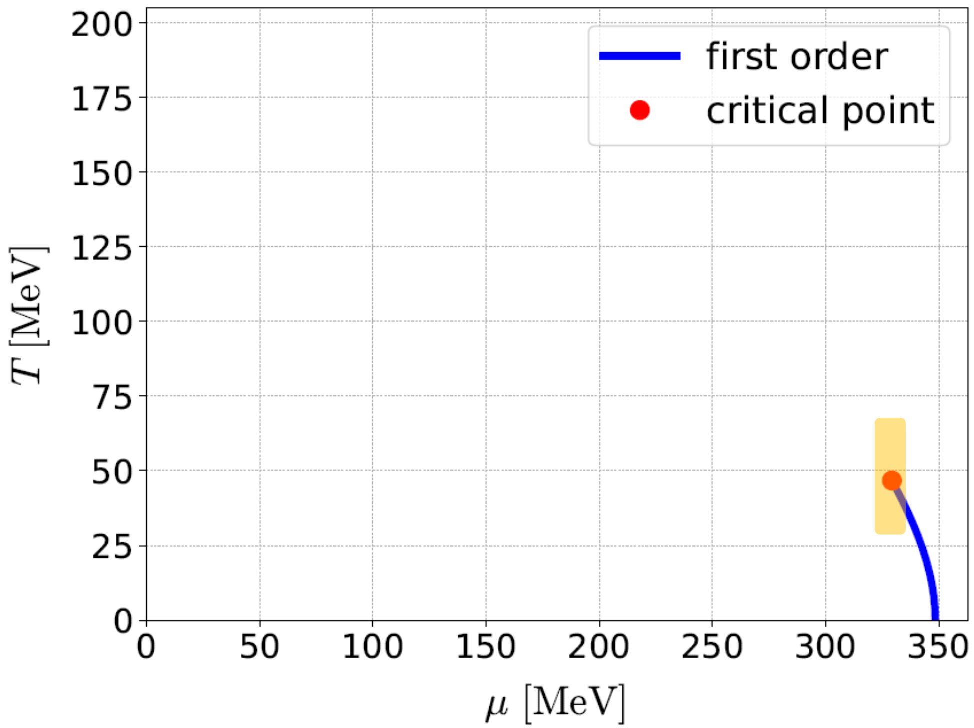
+ ··· MT, DoS

Dilepton production rate near QCD-CP

Nishimura, MK, Kunihiro ('23)

Invariant mass spectrum





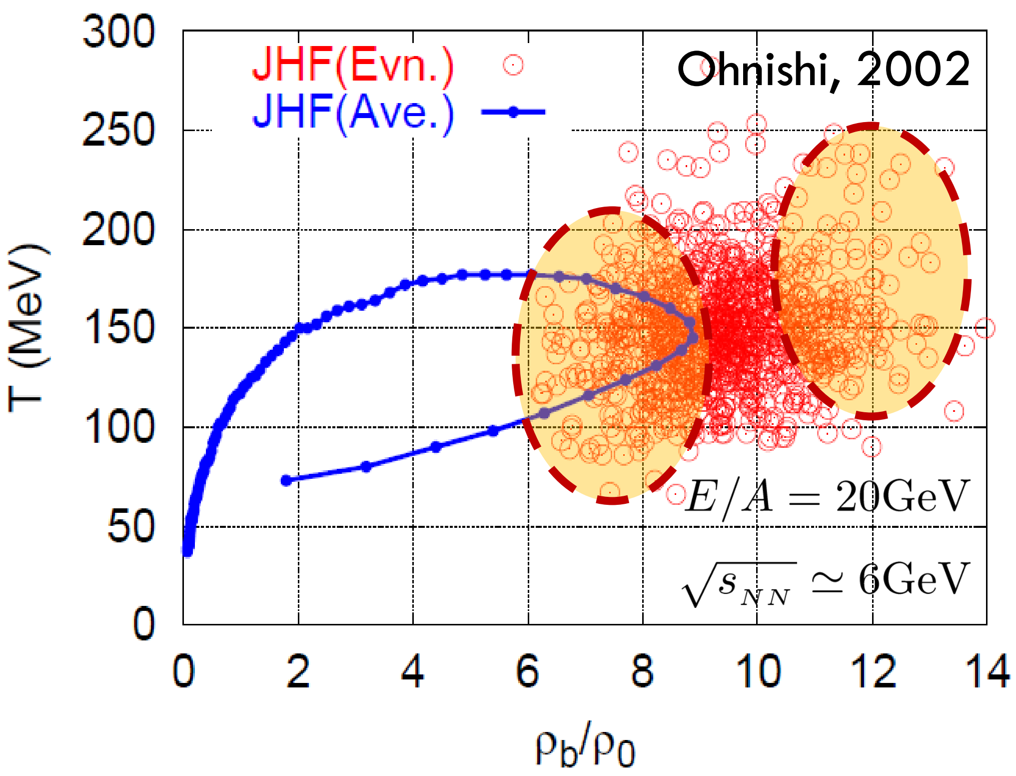
for fixed chem. pot.: $\mu = \mu_c$

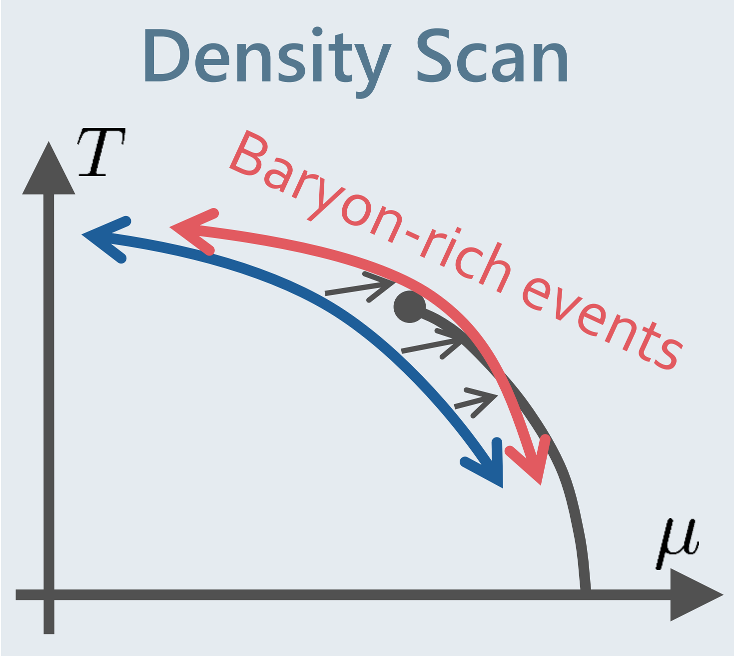
- ☐ Enhancement at low M_{ll} region near QCD-CP
- ☐ Distinguishment from diquark soft mode may be difficult.

Event Selection

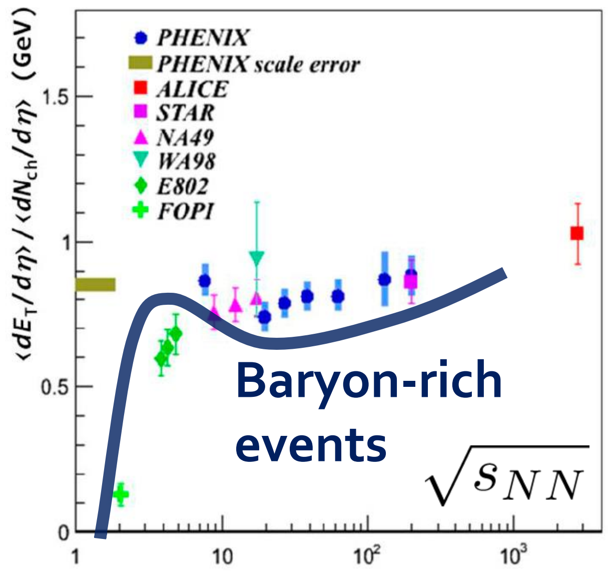
Sophisticated Event Selections

- ☐ Maximum baryon density has large event-by-event fluctuations

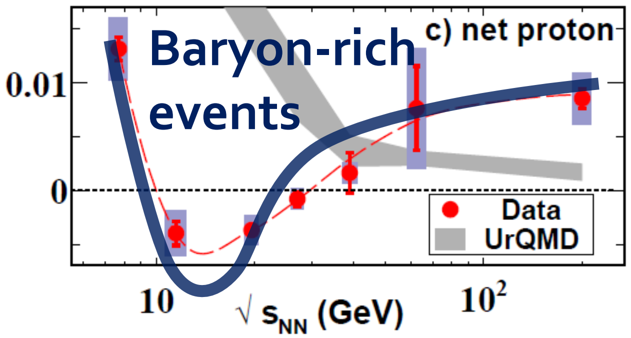




average transverse energy



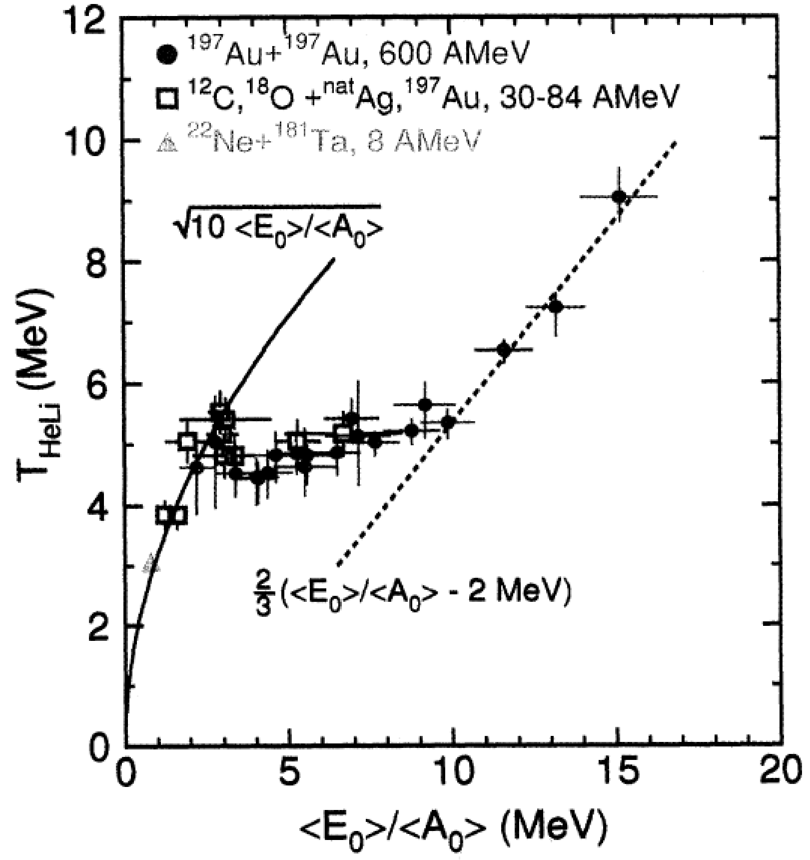
directed flow



- ☐ Event selection in terms of maximum baryon density (or, correlation analysis) should be a useful tool.

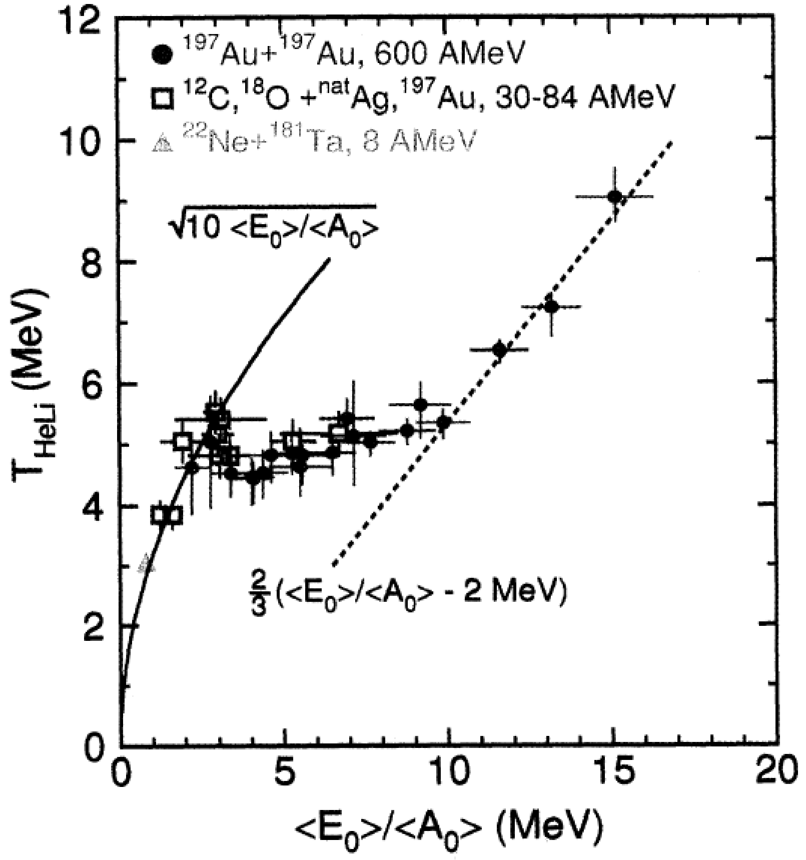
Nuclear Liquid-Gas Phase Transition

Pochodzalla+, PRL, 75, 1040 ('95)



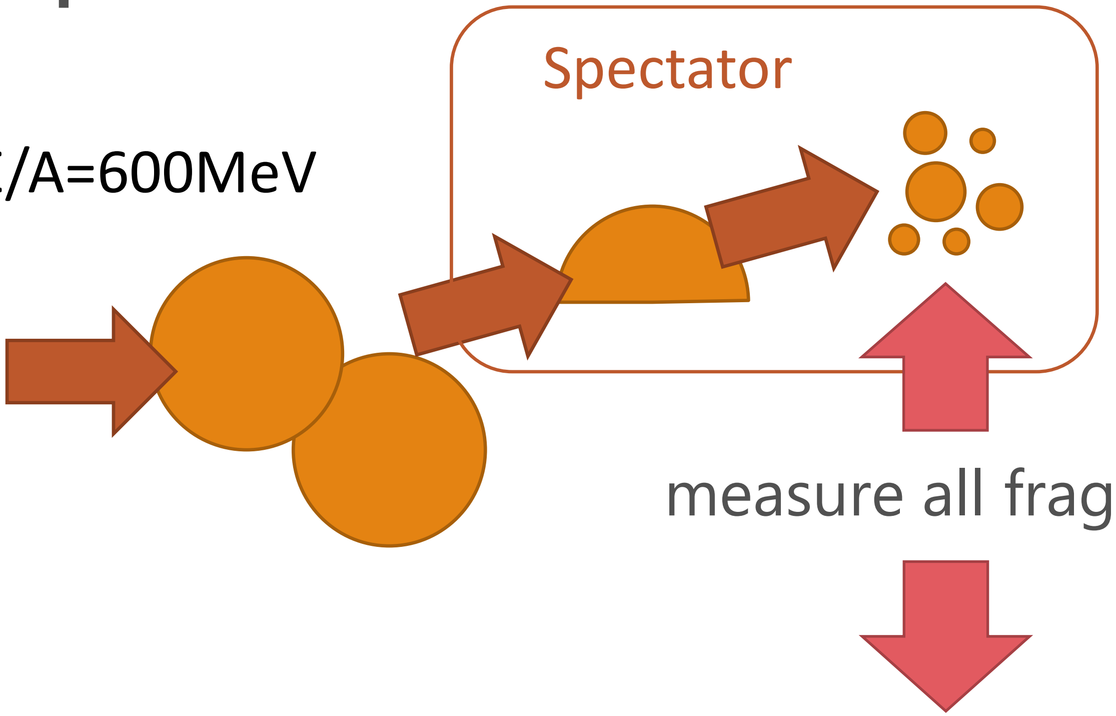
Nuclear Liquid-Gas Phase Transition

Pochodzalla+, PRL, 75, 1040 ('95)



Experiment:

E/A=600MeV



measure all fragments

energy of the spectator

- Similar analysis in relativistic HIC requires **event-by-event total energy of the fireball.**

Summary

- Beam-energy scan will reveal phase transitions in dense QCD.
- J-PARC-HI will play an invaluable role in the future development.

- Many interesting observables to reveal the QCD phase diagram:
    - Event-by-event fluctuations of conserved charges
    - Dilepton production at ultra-low-mass-region
    - Event selection via baryon/energy density
    - Light/hyper-nuclei production

J-PARC-HI Collaboration

and 138 members in total

Exp.: J. K. Ahn , K. Aoki, S. Ashikaga, O. Busch, M. Chiu, 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. Ichisawa , K. Imai, M. Inaba, M. Kaneta , H. Kato, B. C. E. J. Kim, X. Luo, Y. Miake , J. Milosevic, D. Mishra, Y. Morino, 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

Theor.: 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

Acc.: E. Chishiro , H. Harada, Y. Hashimoto, N. Hayashi, K. Hirano, H. Hotchi , K. Ishii, T. Ito, M. Kinsho , R. Kitamura, A. Kovalenko, J. Kamiya , N. Kikuzawa , T. Kimura, Y. Kondo, H. Kuboki , Y. Kurimoto, Y. Liu S. Meigo , A. Miura, T. Miyao , T. Morishita , Y. Morita, K. Moriya, R. Muto, T. Nakanoya , K. Niki, H. Oguri , C. Ohmori , A. Okabe, M. Okamura, P. K. Saha , K. Sato, Y. Sato, T. Shibata, T. Shimokawa , K. Shindo , S. Shinozaki, M. Shirakata , Y. Shobuda , K. Suganuma , Y. Sugiyama, H. Takahashi, T. Takayanagi , F. Tamura, J. Tamura, N. Tani , M. Tomisawa , T. Toyama, Y. Watanabe, K. Yamamoto, M. Yamamoto, M. Yoshii, M. Yoshimoto

J-PARC-HI

Future Plan

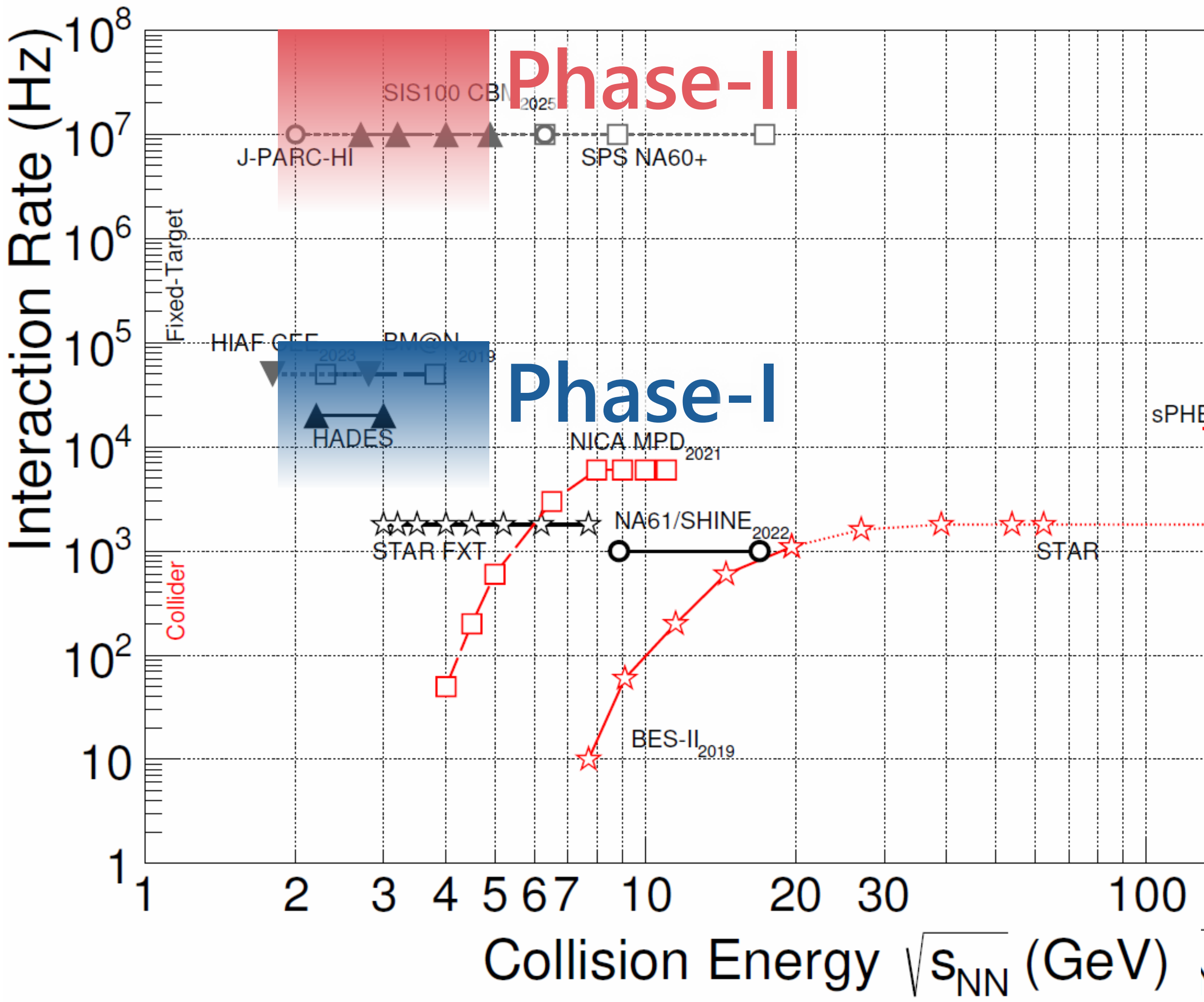
J-PARC-HI Staging Plan

Phase-I

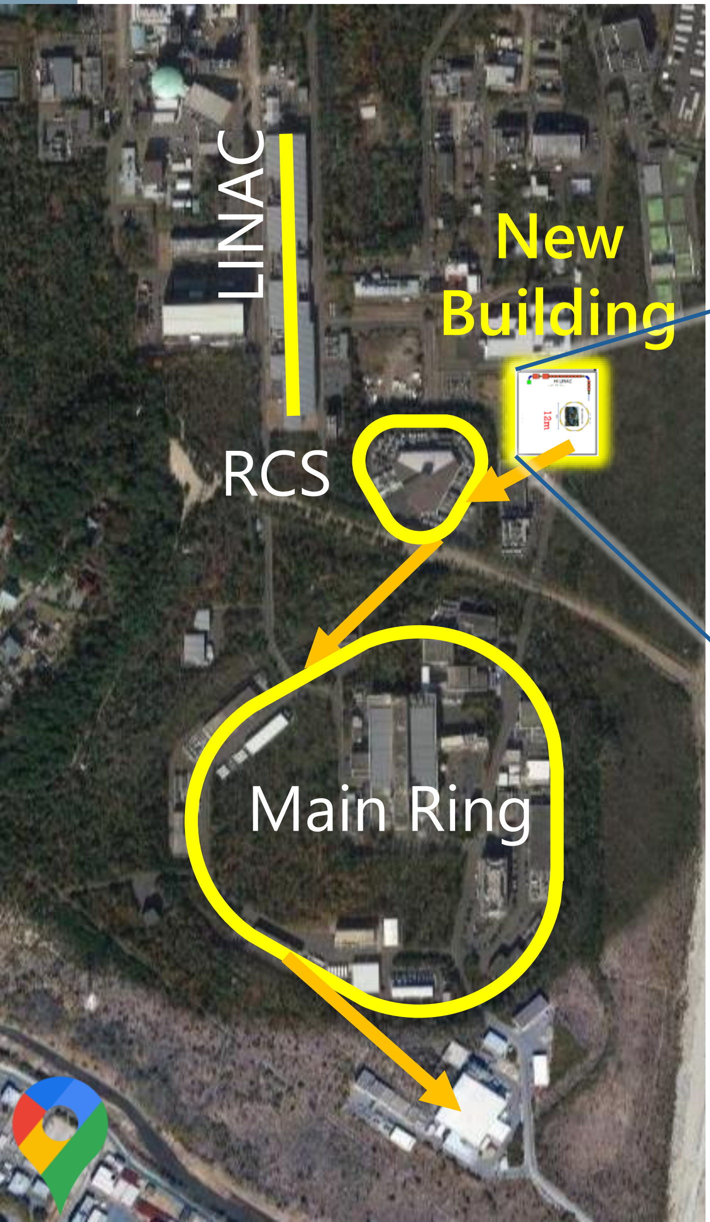
- KEK-BS booster
- E16+α spectrometer

Phase-II

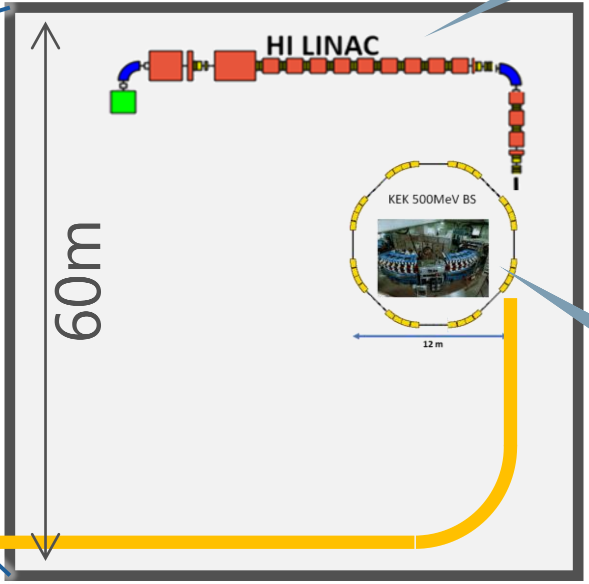
- **NEW** HI booster
- **NEW** spectrometer



Staging of HI Booster

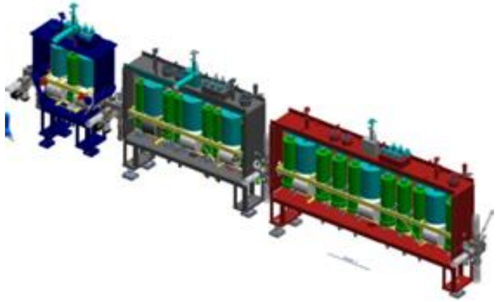


Phase-I



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

HI LINAC

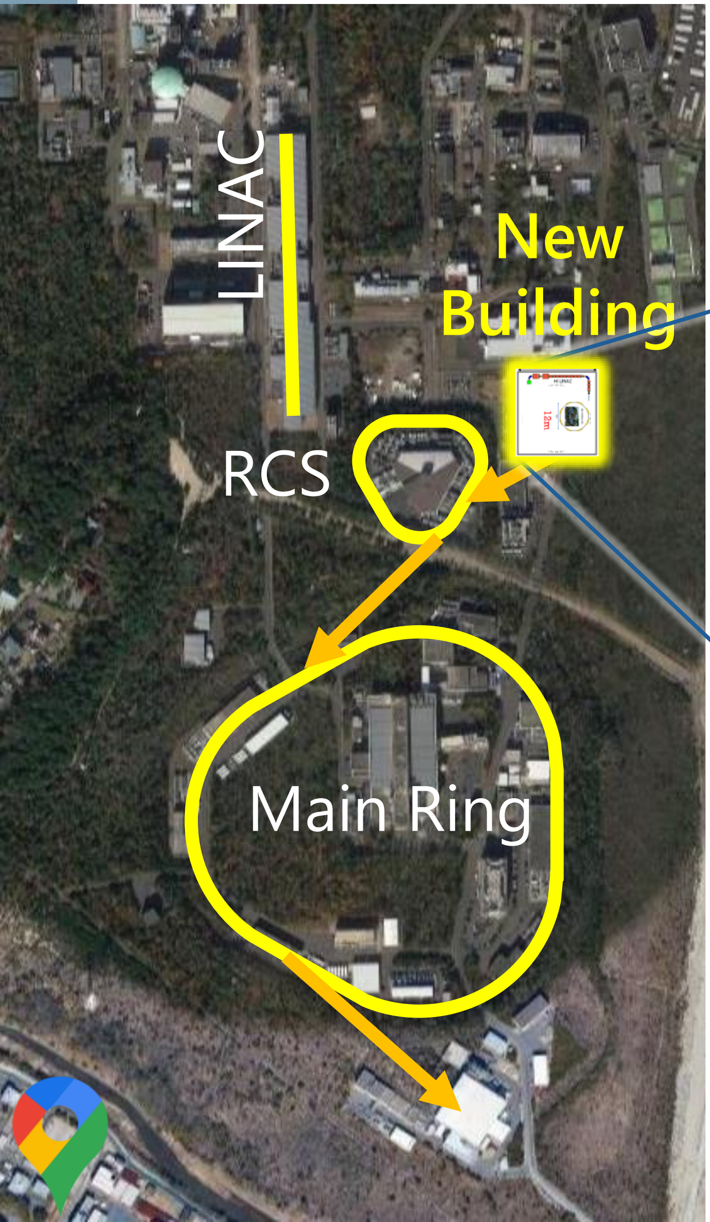


KEK 500MeV BS

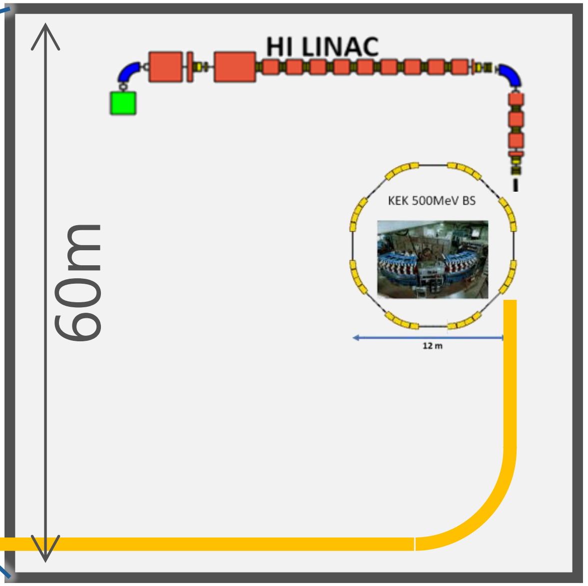
REUSE

kept in working condition

Staging of HI Booster



Phase-I



Phase-II

Interaction rate

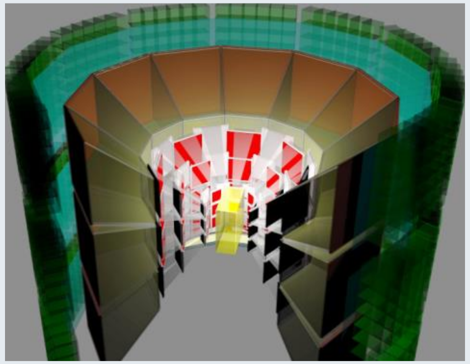
$\sim 10^5\text{Hz}$

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

Detector Phase-I

E16 Spectrometer

— $\phi \to e^+e^-, \phi \to K^+K^-$
— In-medium mass modification
— Pilot data taking in June

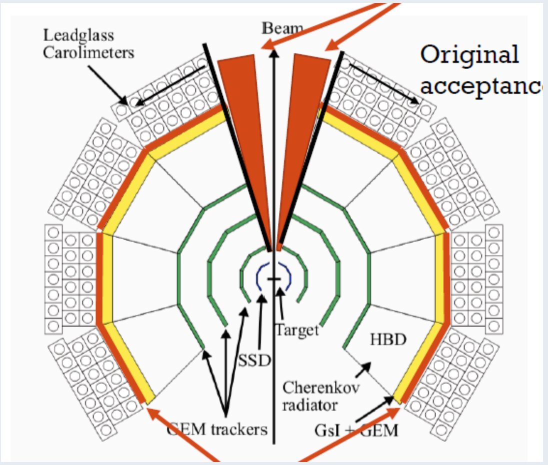


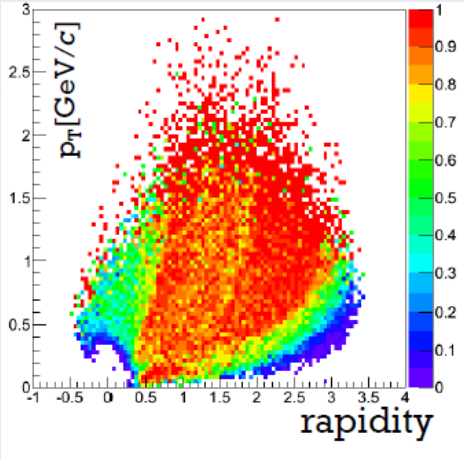
UPGRADE

E16+α

Upgrade forward region for high-multiplicity counting

Hadron/lepton measurement at wide acceptance

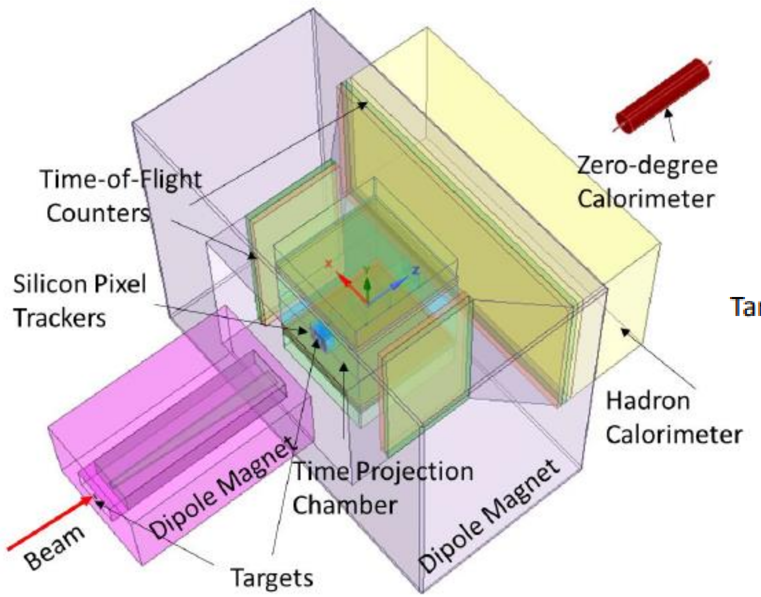


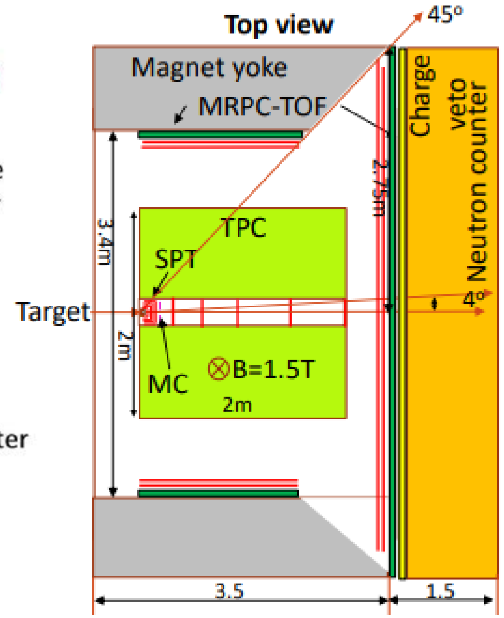


Detector **Phase-II**

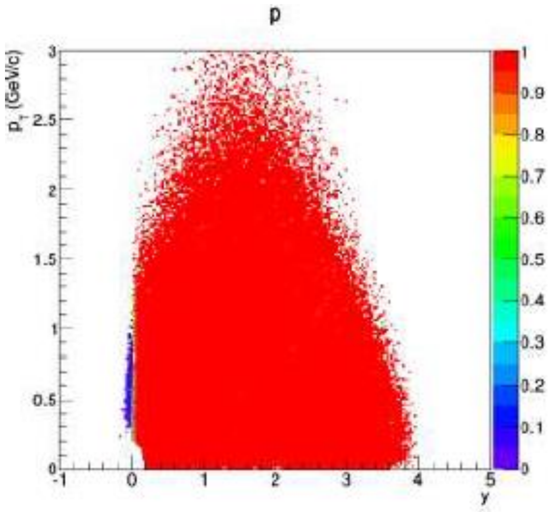
- 4π acceptance, high-intensity beam
  - Precise measurement of fluctuations, dileptons
- Detailed design are under discussion

Hadron calorimeter + hyper-nuclear measurement

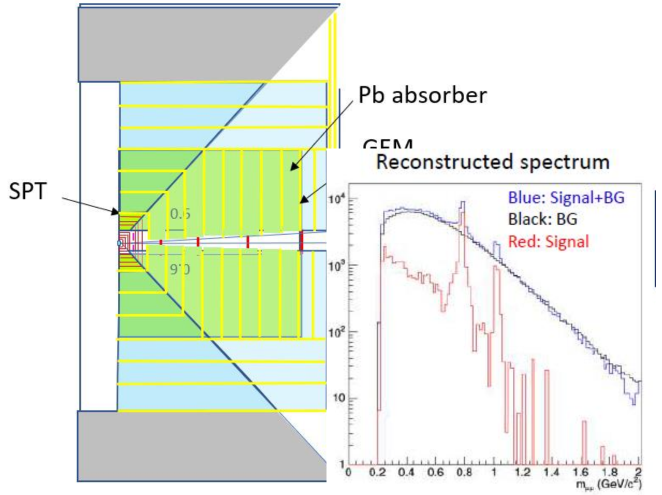




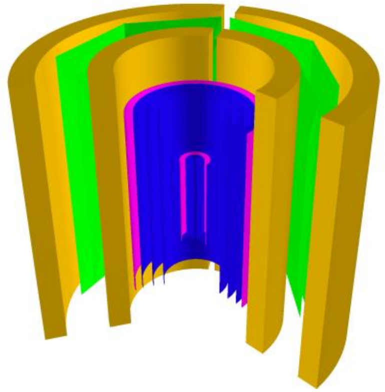
acceptance



Dimuon Setup

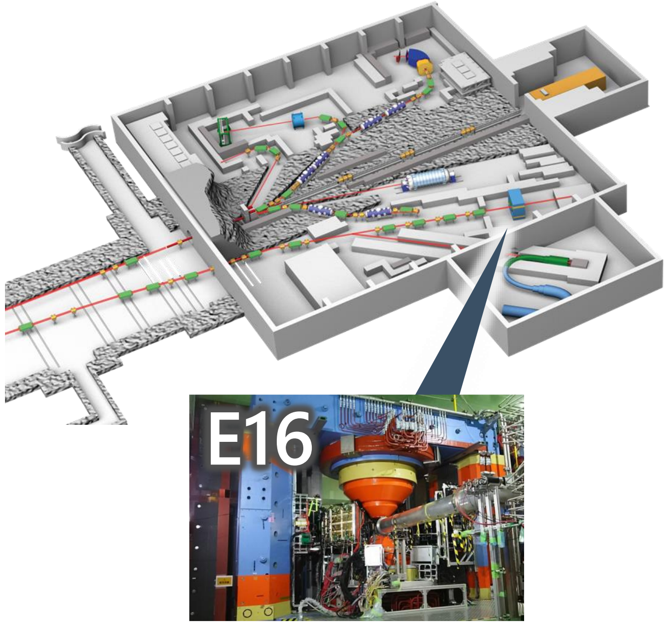


ALICE3-like dipole

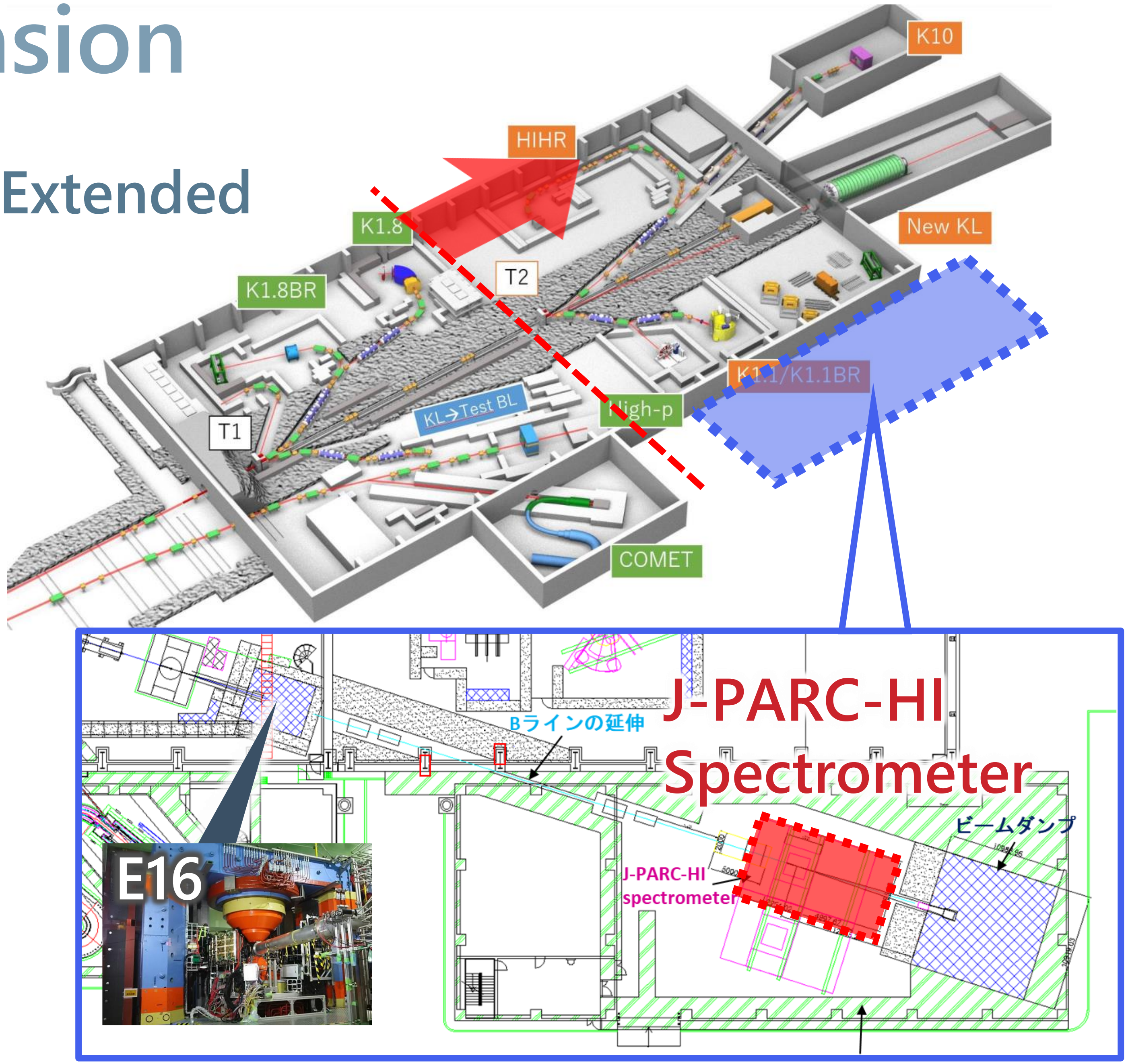


Hadron Hall Extension

Present



Extended



— Top priority at KEK-PIP2022
— J-PARC-HI spectrometer will be installed in an annex