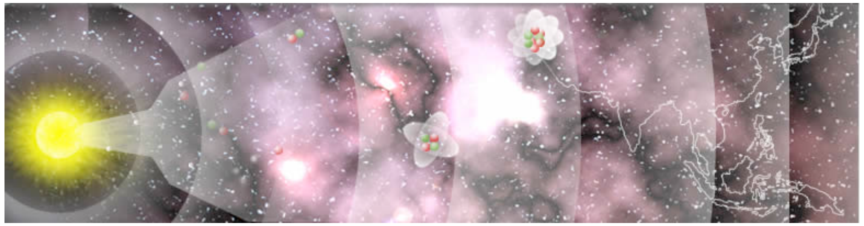
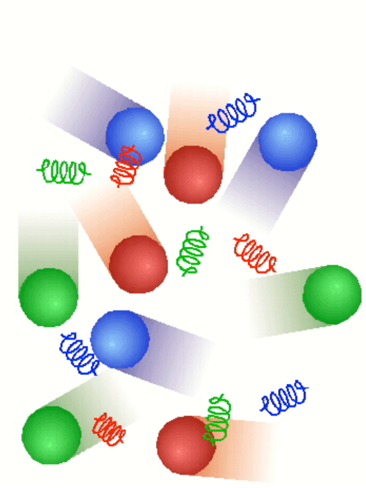


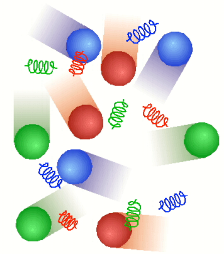
Heavy Ion Acceleration Plan at J-PARC



Quark Gluon Plasma with heavy ion collisions

Yasuo MIAKE, Univ. of Tsukuba
For the J-PARC-HI Collaboration

J-PARC-HI Collaboration



103 members :

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment

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Theory

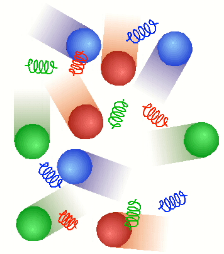
Y. Akamatsu, M. Asakawa, K. Fukushima, H. Fujii, T. Hatsuda, M. Harada, T. Hirano, K. Itakura, M. Kitazawa, T. Maruyama, K. Morita, K. Murase, A. Nakamura, Y. Nara, C. Nonaka, A. Ohnishi, M. Oka

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

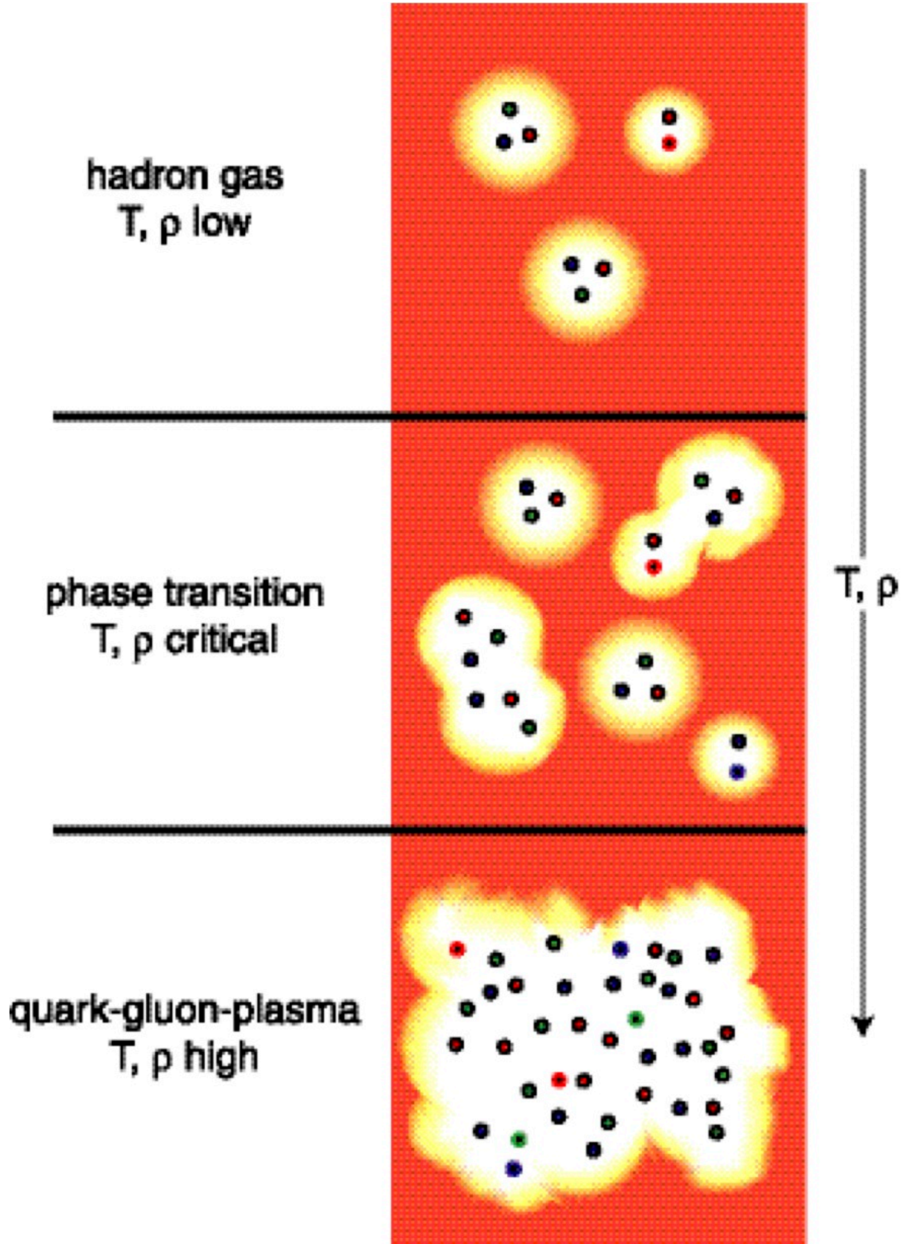
Outline



- ✓ 1) Introduction
  - What is Quark Gluon Plasma?
    - ➡ 1st order phase transition
- ✓ 2) What we learned at RHIC & LHC
  - Properties of Bulk matter
  - Beam Energy Scan at RHIC
- ✓ 3) J-PARC Heavy Ion Program
  - Experiment configurations
  - selected topics

- ✓ Summary and prospects

What is Quark Gluon Plasma?

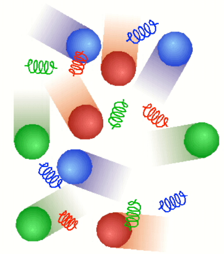


- ✓Hadrons made of quarks and gluons have a size of ~1 fm.
  - Described by QCD
- ✓When heated or compressed, they overlap each other
  - ➡Quarks and gluons move around in relatively large volume.

! Quark Gluon Plasma !

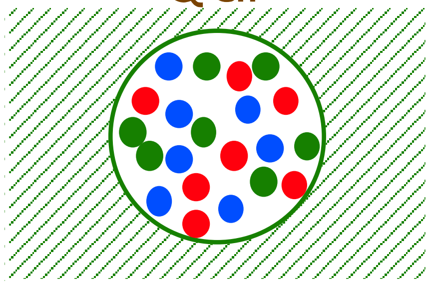
- ✓Phase Transition between QGP and hadrons

Toy Model (Ideal Gas) for QGP phase transition



Ideal Gas Model

QGP

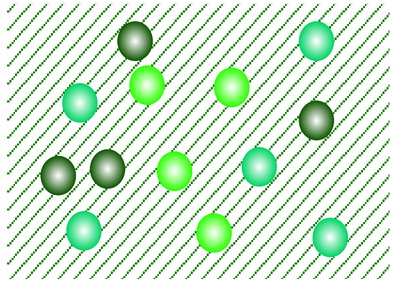


$$\varepsilon_{QGP} = f_{gluon} \cdot \varepsilon_{boson} + f_{quark} \cdot \varepsilon_{fermi}$$

$$\therefore \varepsilon_{QGP} = \frac{37\pi^2}{30} T^4 + B$$

$$\begin{cases} \varepsilon_{QGP} = \dfrac{37\pi^2}{30} T^4 + B \\ p_{QGP} = \dfrac{37\pi^2}{90} T^4 - B \end{cases}$$

Pion Gas



$$\varepsilon_{\pi} = f_{\pi} \cdot \varepsilon_{boson}$$

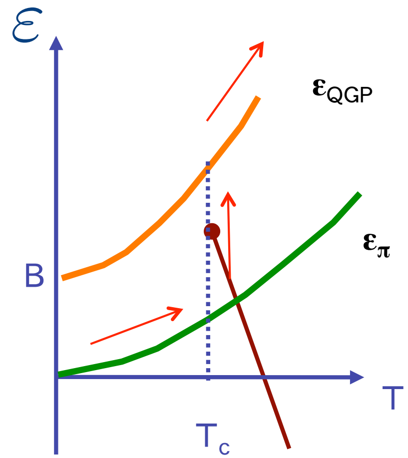
$$\therefore \varepsilon_{\pi} = \frac{\pi^2}{10} T^4$$

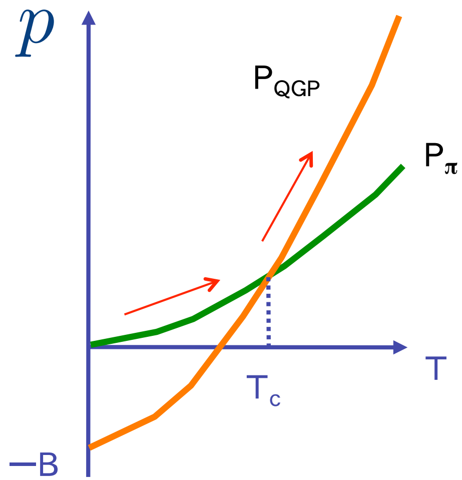
$$\begin{cases} \varepsilon_{\pi} = \dfrac{\pi^2}{10} T^4 \\ p_{\pi} = \dfrac{\pi^2}{30} T^4 \end{cases}$$

Stefan-Boltzman's $\varepsilon = \sigma T^4$

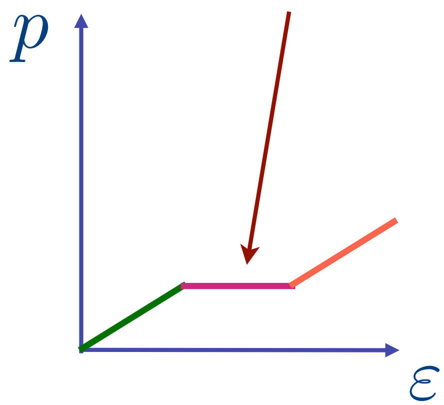
f ; degree of freedom

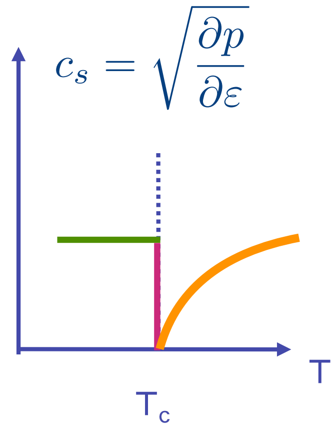
B ; bag constant





Latent heat
→1st order

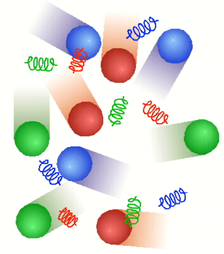




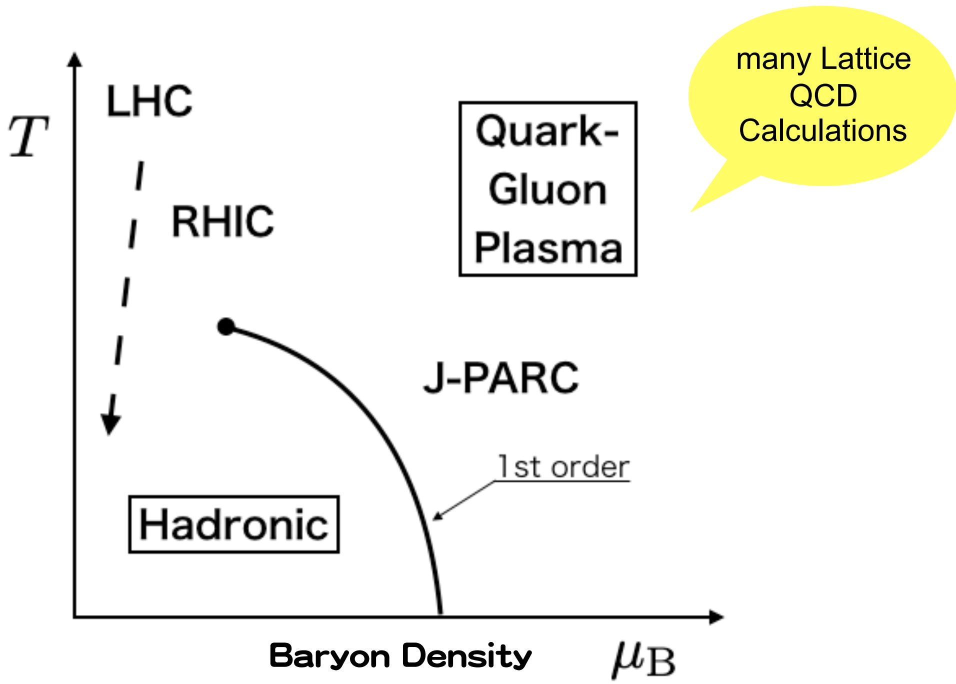
→ Smaller Hydrodynamical Expansion at Tc

Softening

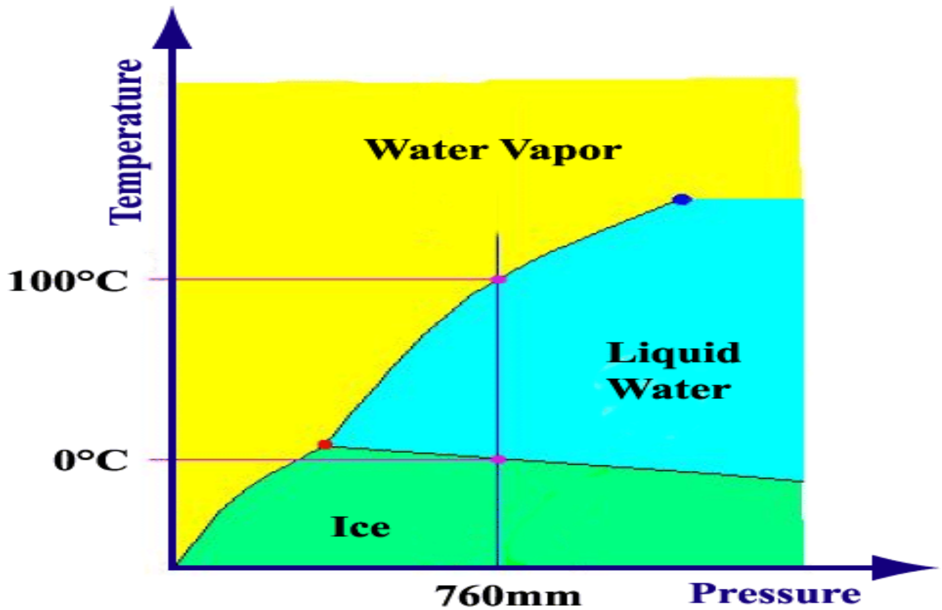
Phase Diagram of QCD matter



Phase Diagram of QCD matter

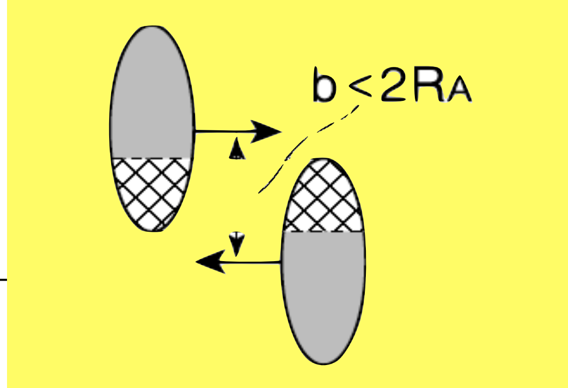


Phase Diagram of water



- ✓ Recent Lattice calc. predicts 1st order at high baryon density (μ_B)
  - On the other hand, at low baryon density, $\mu_B \sim 0$, region of RHIC & LHC, crossover. Critical Point expected.
- ✓ Just like the water, rich physics expected in phase diagram of QCD!
  - To study the region of high μ_B) , we need J-PARC-HI

Features of Heavy Ion Collisions



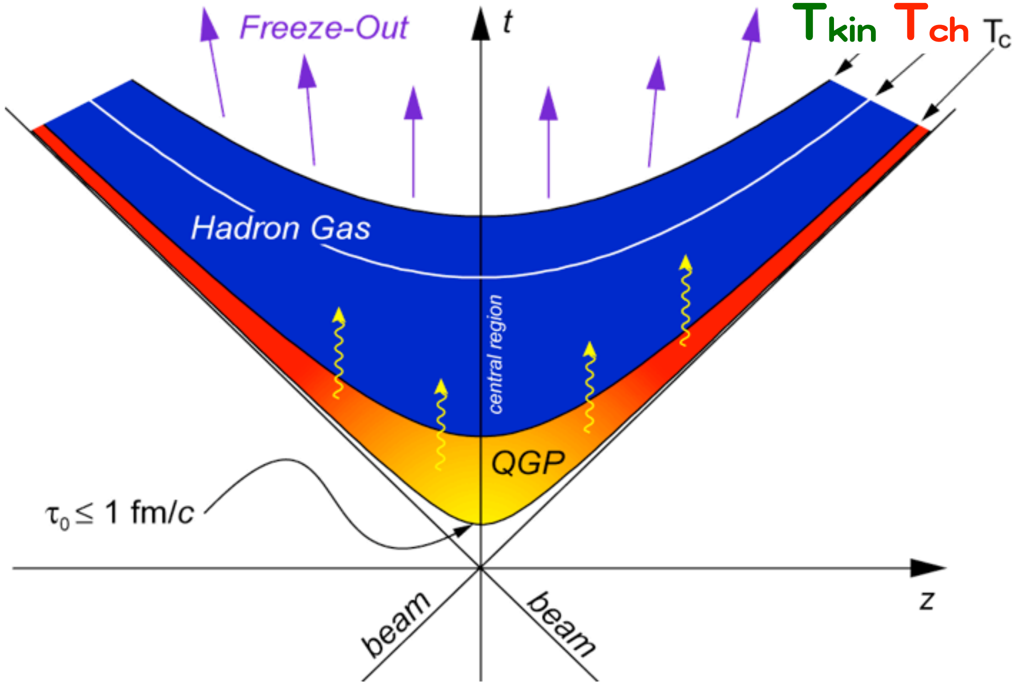
$$\epsilon_{\rm QGP} \sim 2\ [{\rm GeV/fm^3}]$$

$$< n_{q,\bar{q}} > \sim \frac{\epsilon_{\rm QGP}}{< m_T >} \sim \frac{2{\rm GeV}}{1{\rm GeV}} \sim 5$$

$$\lambda_q = \frac{1}{n\sigma_{qq}} \sim \frac{1}{5 \times 0.4} = 0.2\ [{\rm fm}]$$

$$\lambda_q \ll R_{\rm system}$$

$$\because \sigma_{qq} \sim \frac{\sigma_{NN}}{n_{\rm q}} \sim \frac{4[{\rm fm^2}]}{3} \sim 1$$



✓At QGP phase, $\lambda_q \ll R_{system}$, hydrodynamical behavior

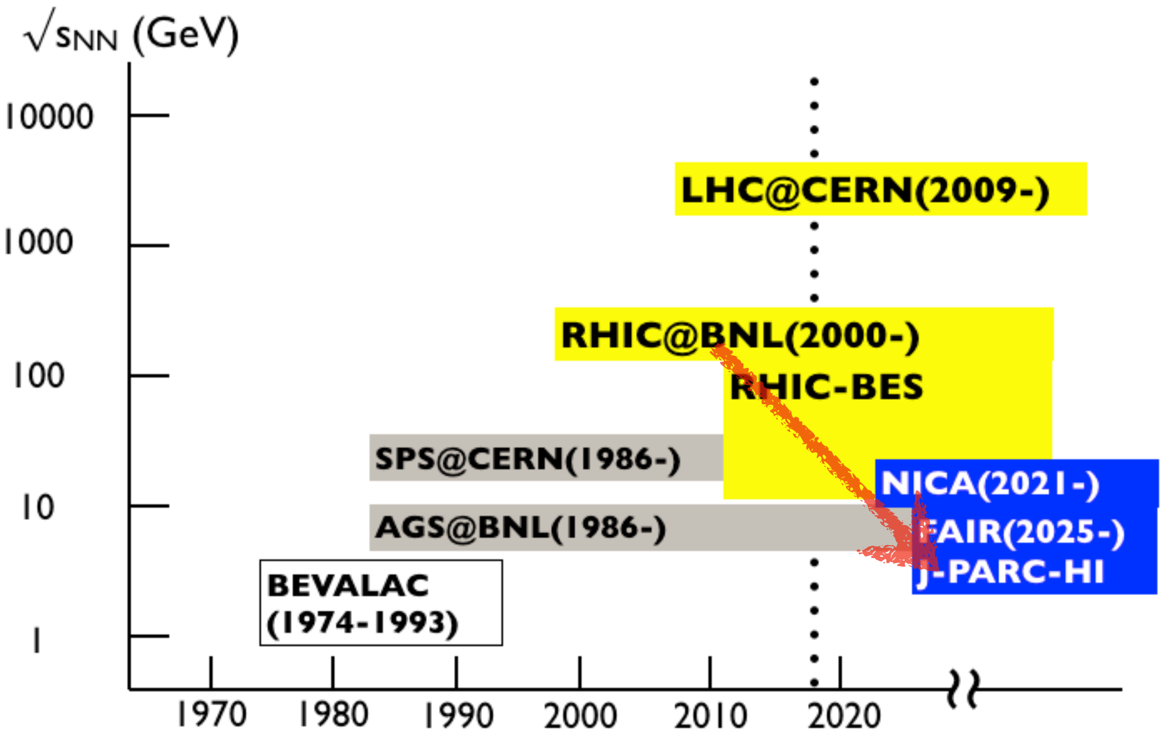
✓Space-Time evolution of collisions (Adiabatic expansion)

QGP → Hot & dense hadron gas

→ Chemical Freezeout (T_{ch}) ; no more particle production

→ Kinematical Fr. (T_{kin}); momentum of particles fixed

History of Heavy Ion Accelerations



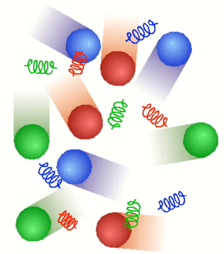
✓Until RHIC & LHC, beam energy simply going up.

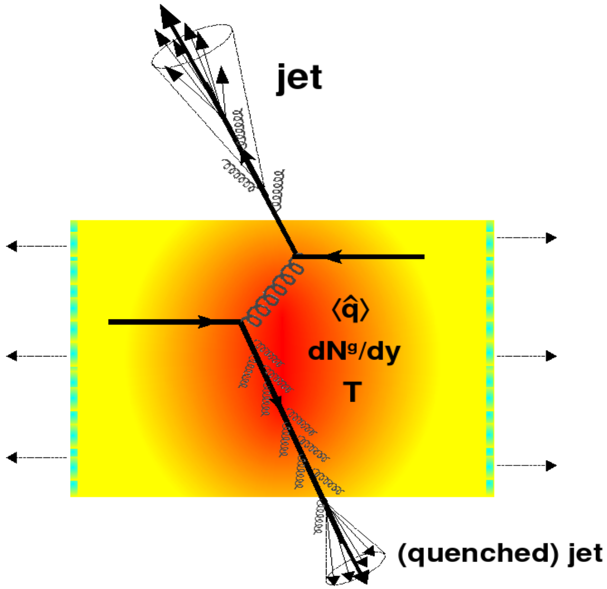
✓Now lower energy HI machine is proposed in Germany, Russia, China and Japan.

	Machine	Beam+Target	Ecm [GeV]
1987 -	BNL・AGS	Si+Au, Au+Au('92)	5A, 4A
1987	CERN・SPS	S+Pb, Pb+Pb('94)	20A, 17A
2000 -	BNL・ RHIC	Au + Au	130A - 200A
2011 -	CERN・LHC	Pb+Pb	2900-6300A
2025	FAIR	p, C, Ca ,,, Au	2 - 5 A
2023?? 2026?	NICA、HIAF、 J-PARC	p,,,U?	4 - 11A、( )、 2-6.2A

→ for the study of the phase transition, where and how

Quark Gluon Plasma @ RHIC

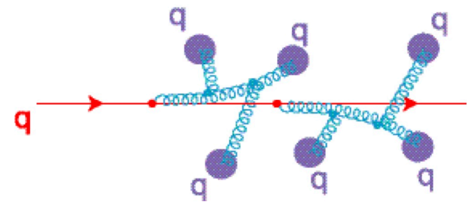




✓Key signatures of QGP

- 1) Characteristic Energy Loss of partons in QGP (“Jet Quench”)

  ➡Radiative loss of partons Characteristic in QCD

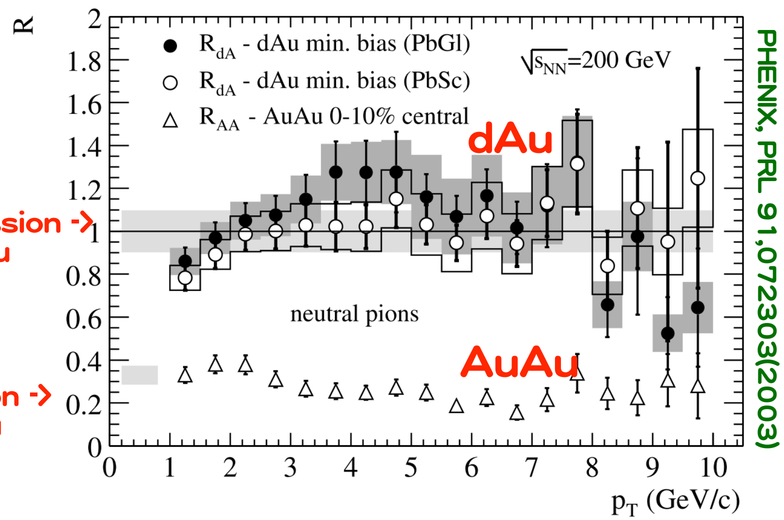


- 2) Hydrodynamical flow of partons

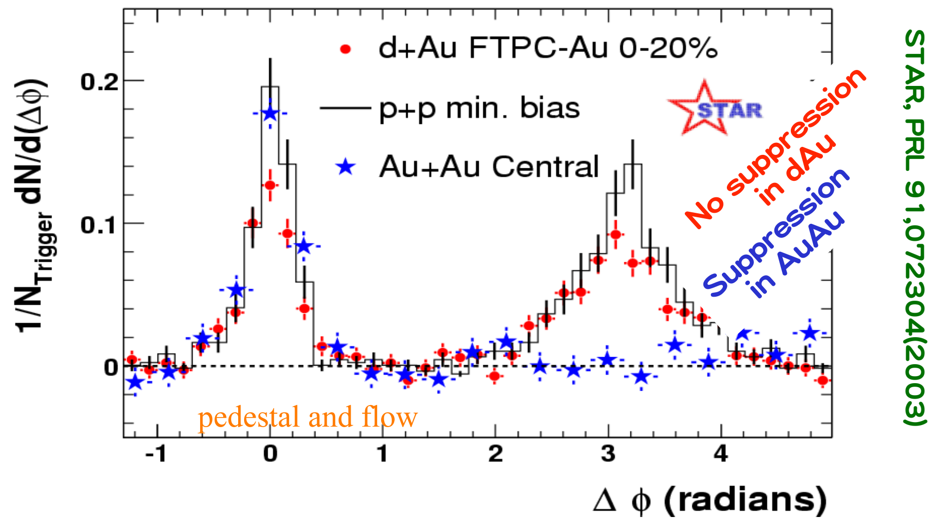
Suppression of high pt hadrons

No suppression -> in dAu

Suppression -> in AuAu



Disappearance of jets



Study of Hydrodynamical flow

2nd Fourier Harmonics

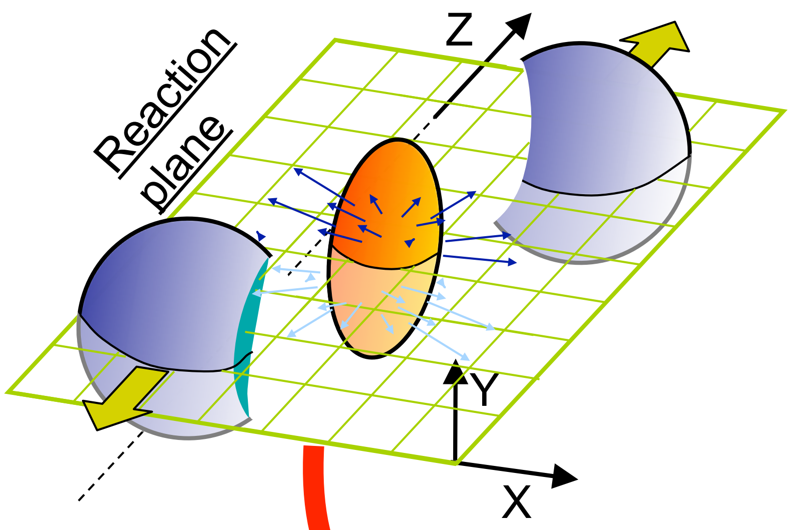
Eccentricity in Coordinate Space

$$\varepsilon_{ecc} = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle$$

Eccentricity in Momentum Space

$$v_2 = \langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \rangle$$

Initial State

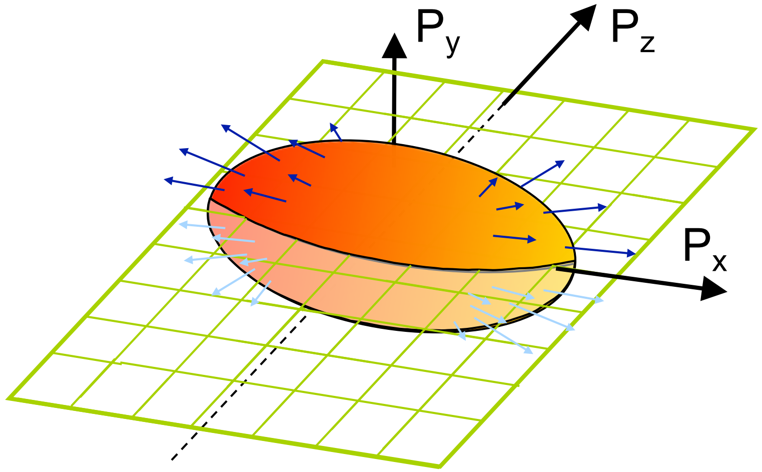


Experiment

Comparison

Theory

Final State

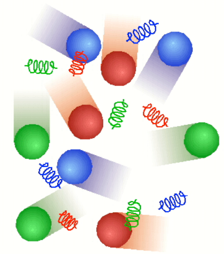


Hydrodynamical expansion
(driven by density gradient)

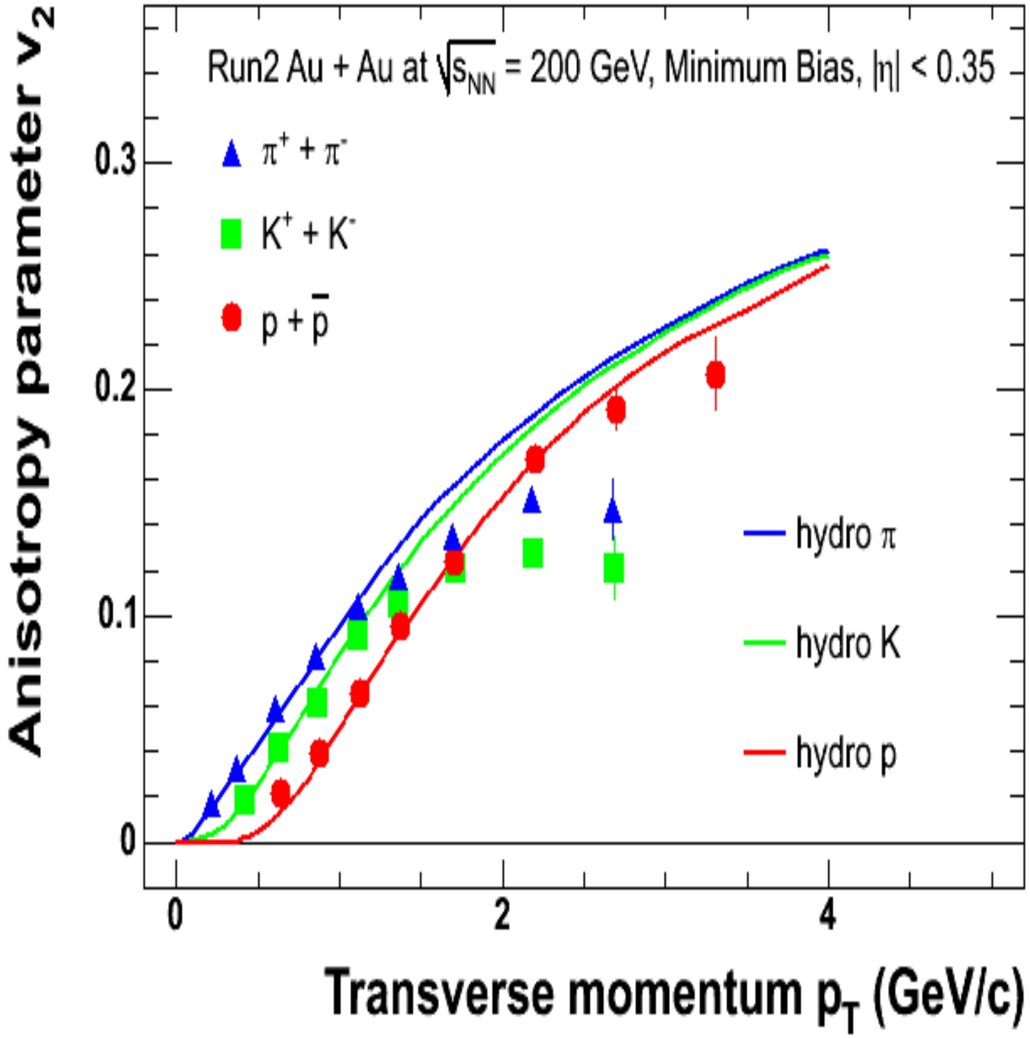
Viscosity, EOS

- **Experimentally, both initial & Final state can be determined.**
- **And comparison of exp. and theory gives property of QGP**

v_2, 2nd Fourier Harmonics



PHENIX : P.R.L. 91, 182301 (2003)



✓ v_2, 2nd Fourier harmonics in azimuthal distr. shows characteristic behavior !

➡ Mass Ordering of v_2 at low pt region, collective flow

- 1) Good agreement with hydrodynamics, in which

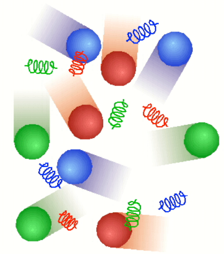
  early thermalization ~0.6 fm/c
  perfect fluid (small viscosity)

- 2) Departure at high pt region (> 1.5 GeV/c);

  ➡Quark Coalescence

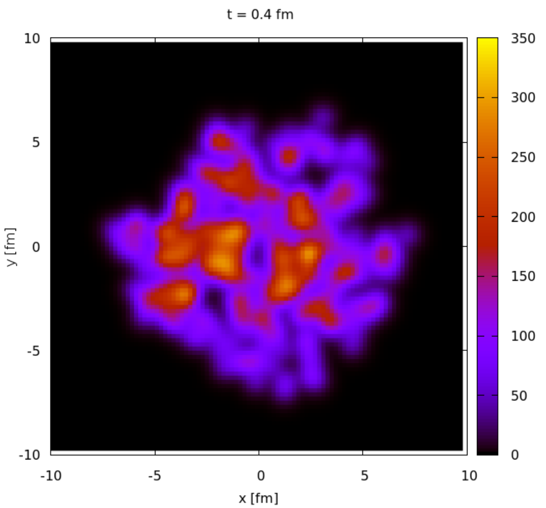
  ➡Quark Number Scaling Seen

Viscosity (η) from Higher harmonics

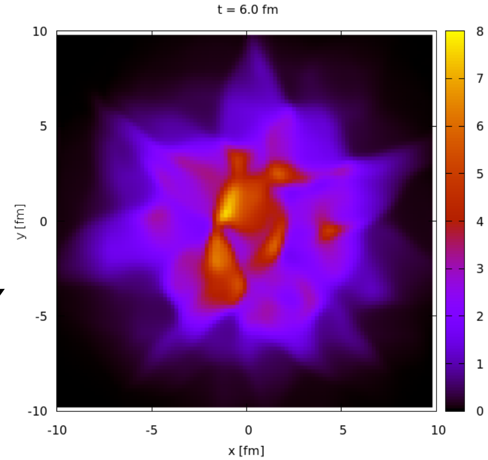


Event by event fluctuations of nucleon give higher order harmonics in hydrodynamics and found to be sensitive to viscosity of the fluid

Schenke and Jeon, Phys.Rev.Lett.106:042301

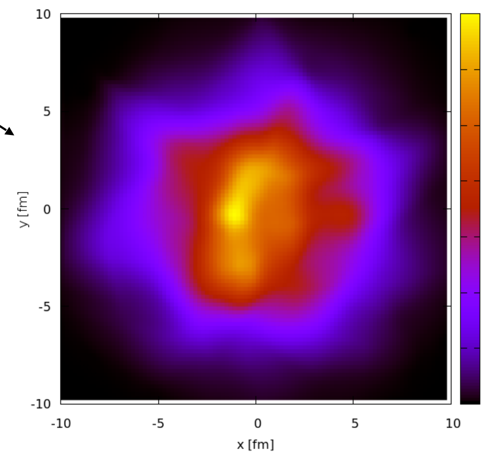


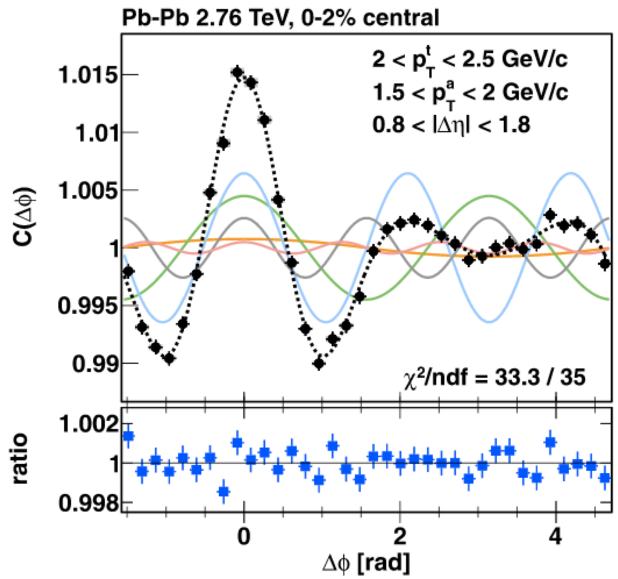
$\eta/s = 0$



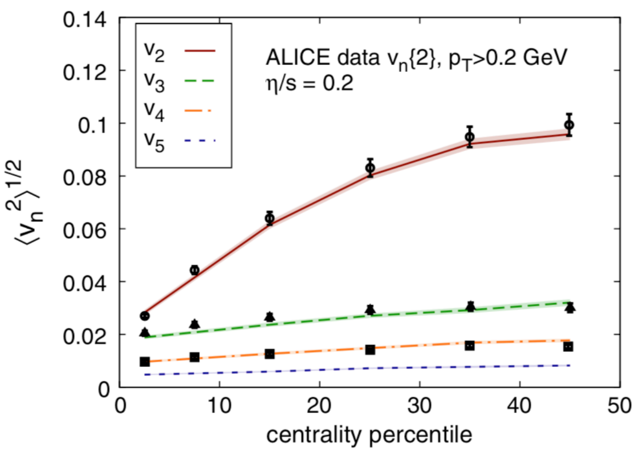
Time evolution

$\eta/s = 0.16$





ALICE, PLB, 708, (2012)

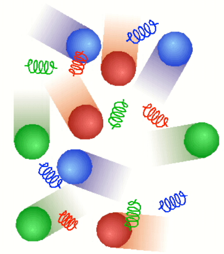


ALICE, PRL 110,012302(2013)

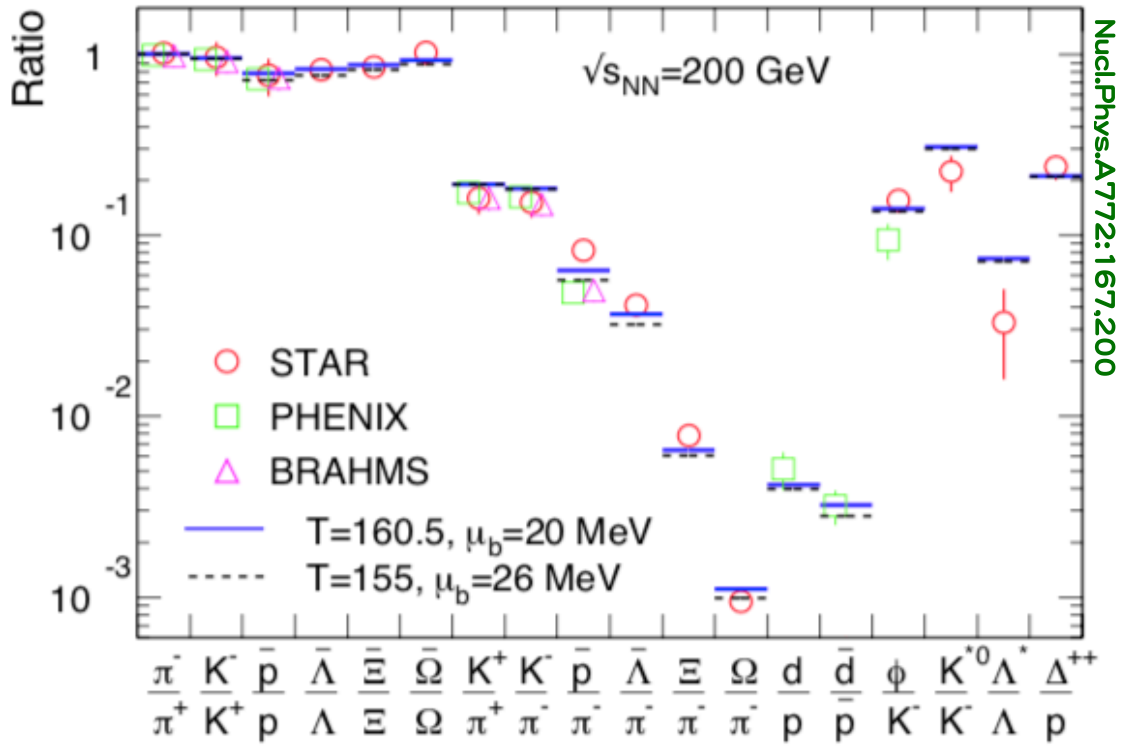
$\eta/s \sim 0.20$ at LHC,
$\eta/s \sim 0.12$ at RHIC

✓ **Very low viscosity !**

Study of Bulk property : hadron production at Chemical Fr.



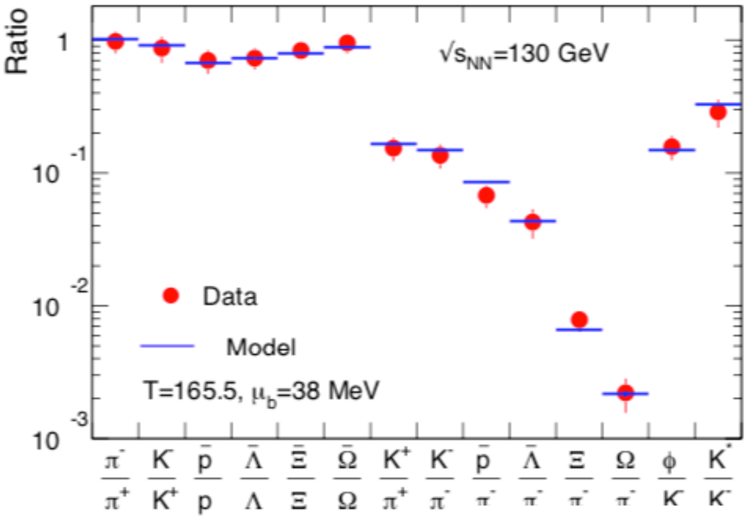
$$n_i = \frac{g_i}{2\pi^2}\int_0^{\infty}\frac{p^2\,dp}{e^{(E_i-\mu_i)/T}\pm 1}$$



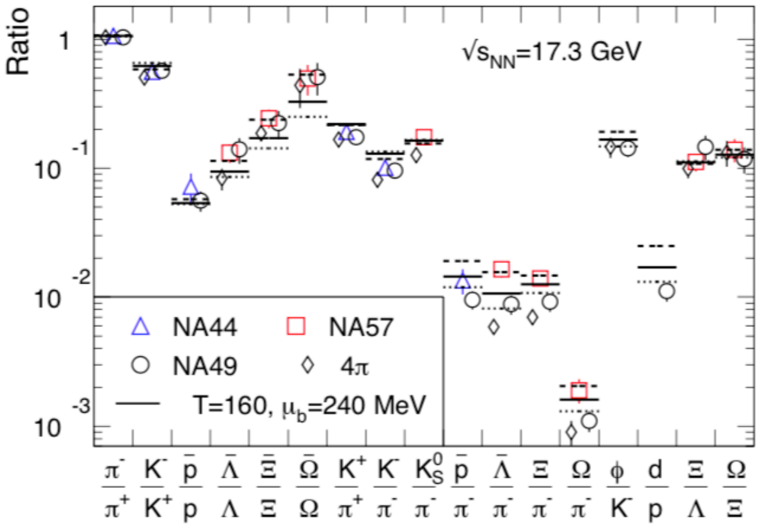
✓Chemical Eq. model with T and μ_B fits the ratios of particle yields very well

- Tc ; chemical freezeout temp., lower than T_{cr} ~170MeV, consistent with space-time evolution of QGP

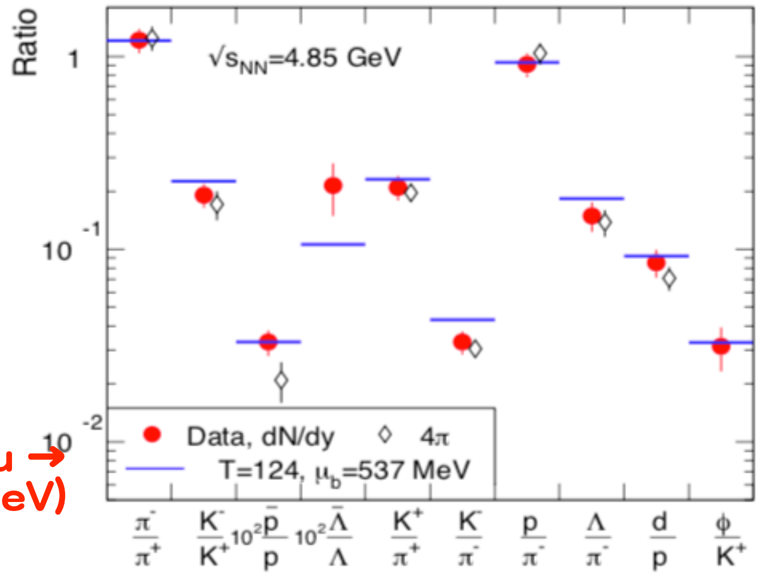
RHIC-SPS-AGS



← RHIC 130GeV Au+Au
(T = 165.5MeV, μ_B~38 MeV)

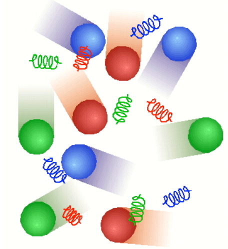


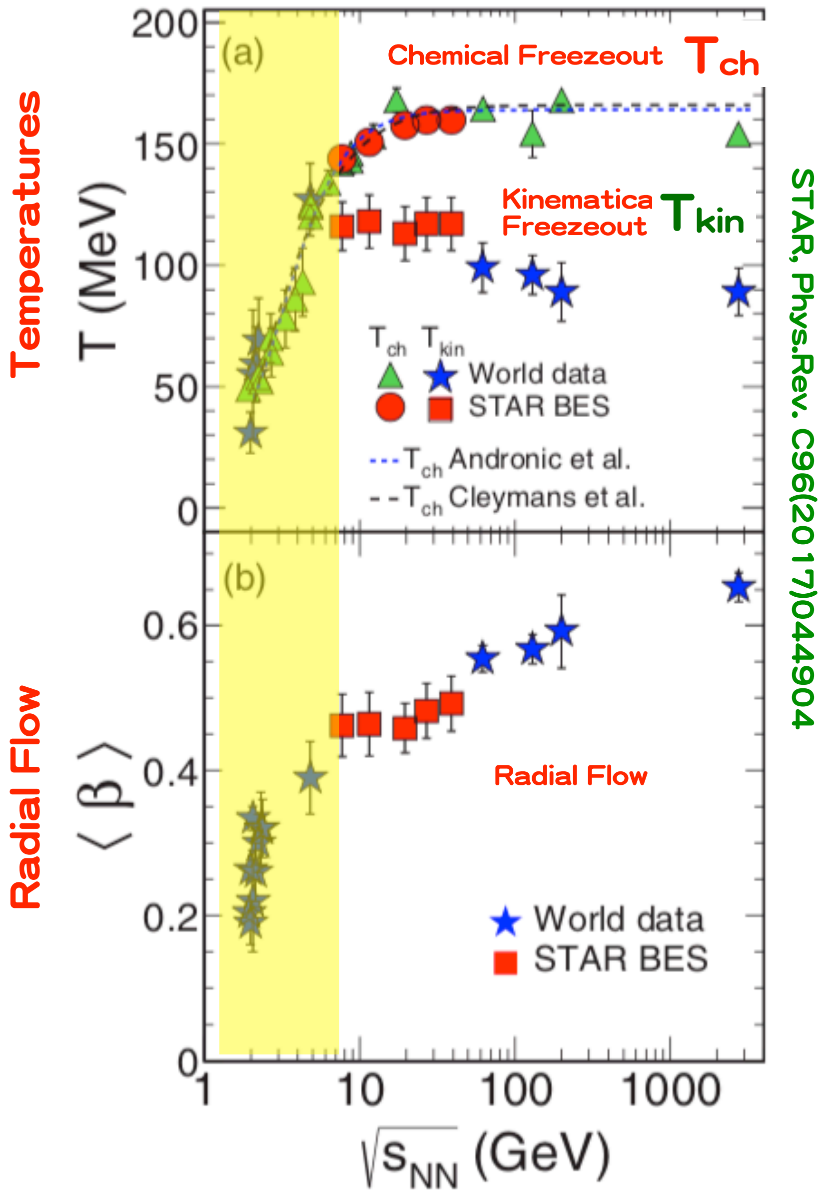
← SPS 17GeV Pb+Pb
(T = 160MeV, μ_B~240 MeV)

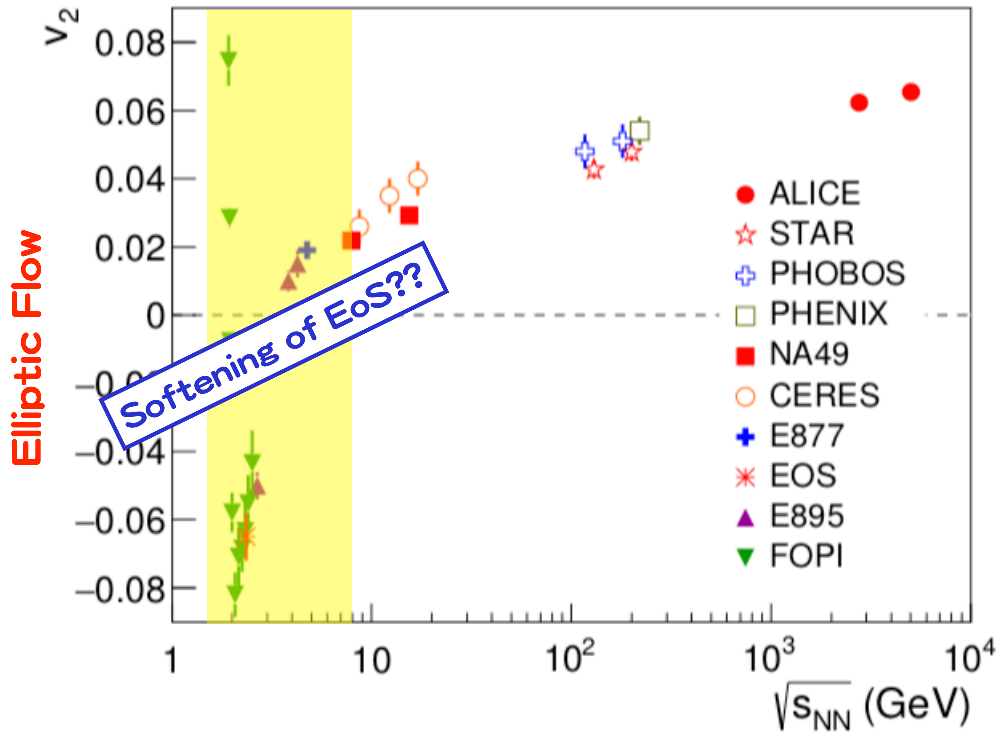


AGS 4.8GeV Au+Au →
(T = 124MeV, μ_B~537 MeV)

Summary plots of bulk property : Where is the phase transition?





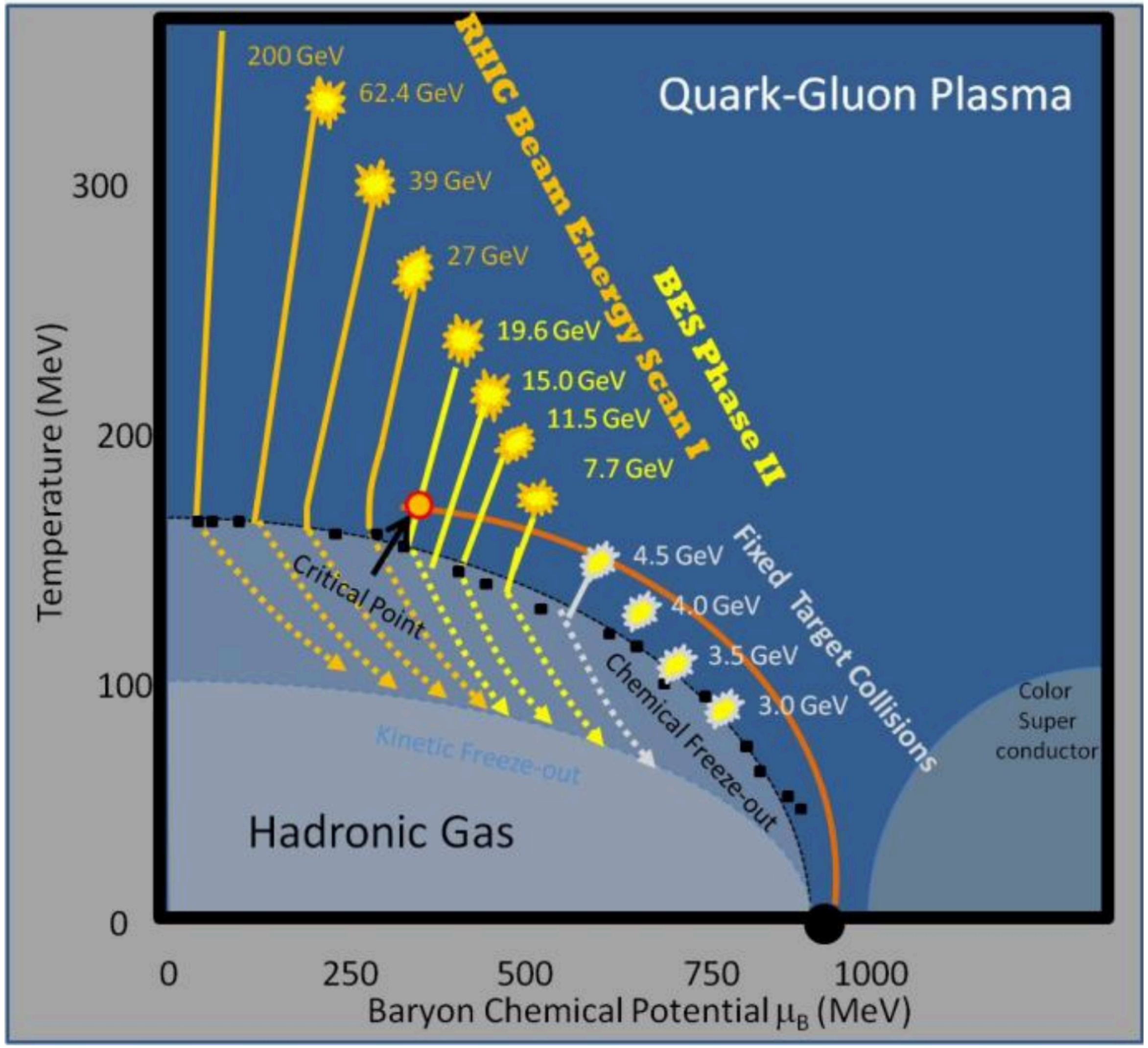


✓Temperature & hydrodynamical flow stay constant? till $\sqrt{S_{NN}}$~ 10 GeV

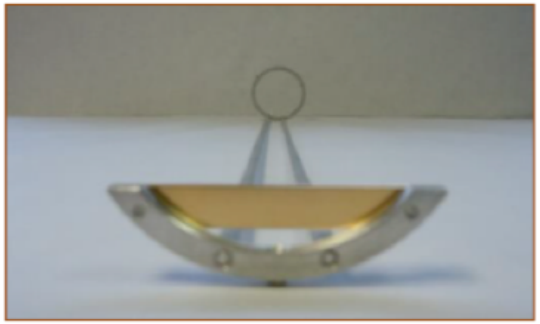
✓Then, things drastically changes in $\sqrt{S_{NN}}$=2~10 GeV, could be the phase tr.

Rigorous measurement at RHIC
Beam Energy Scan Program

Beam Energy Scan at RHIC

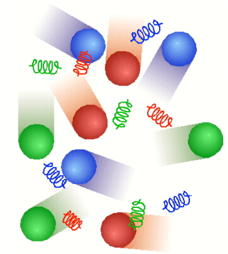


Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)
9.8	19.6	205
7.3	14.5	260
5.75	11.5	315
4.55	9.1	370
3.85	7.7	420
31.2	7.7 (FXT)	420
19.5	6.2 (FXT)	487
13.5	5.2 (FXT)	541
9.8	4.5 (FXT)	589
7.3	3.9 (FXT)	633
5.75	3.5 (FXT)	666
4.55	3.2 (FXT)	699
3.85	3.0 (FXT)	721

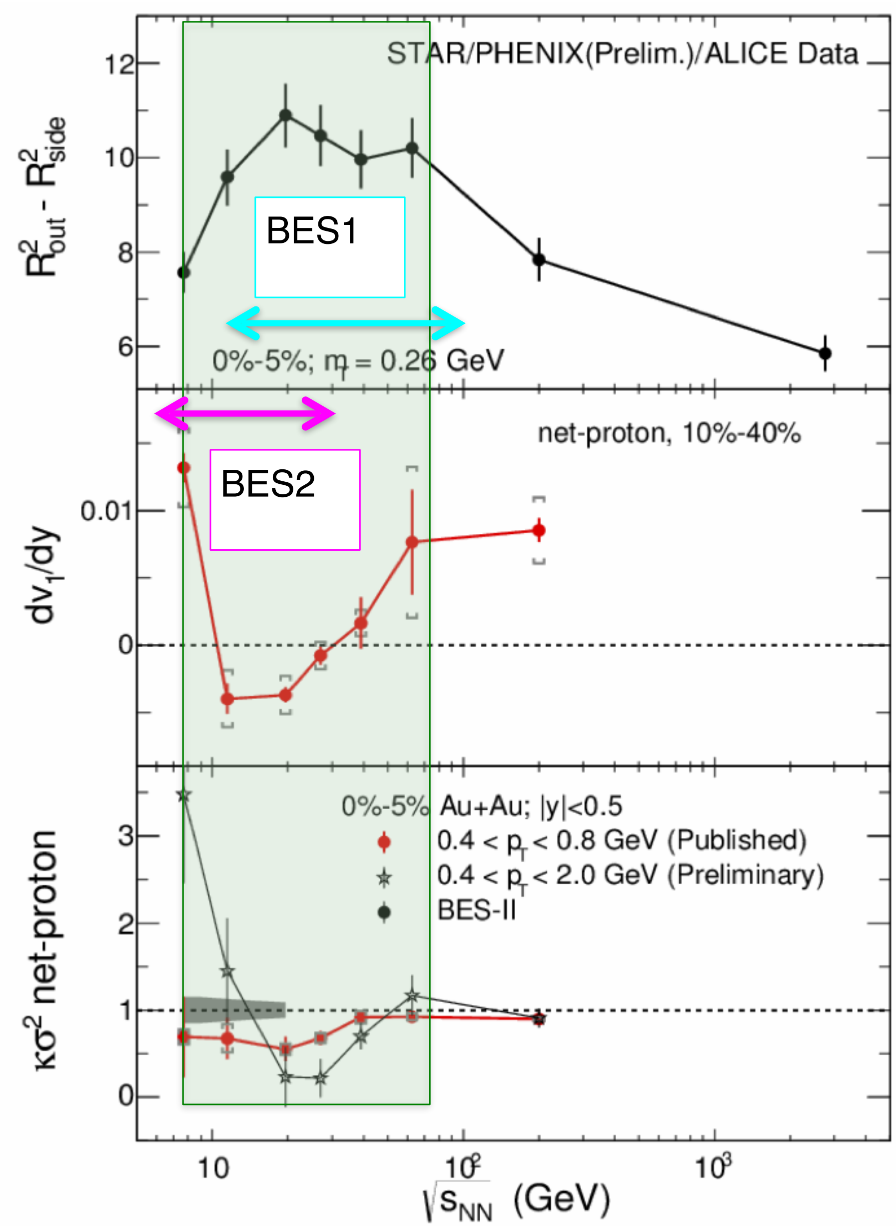


Thin Au foil in the beam pipe

Results by now

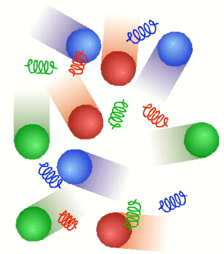


- ✓Rigorous measurement going on at RHIC Beam Energy Scan Program
- ✓No conclusion yet!



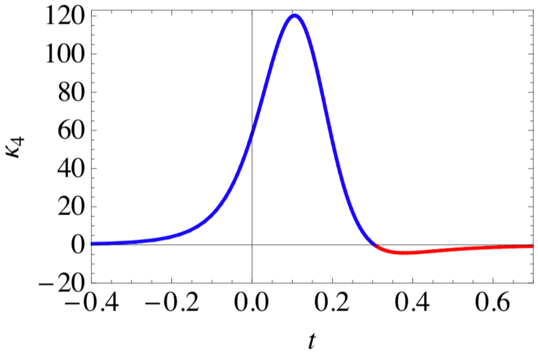
Z. Xu, ICPAQGP2015

Key signature for Critical Point Search

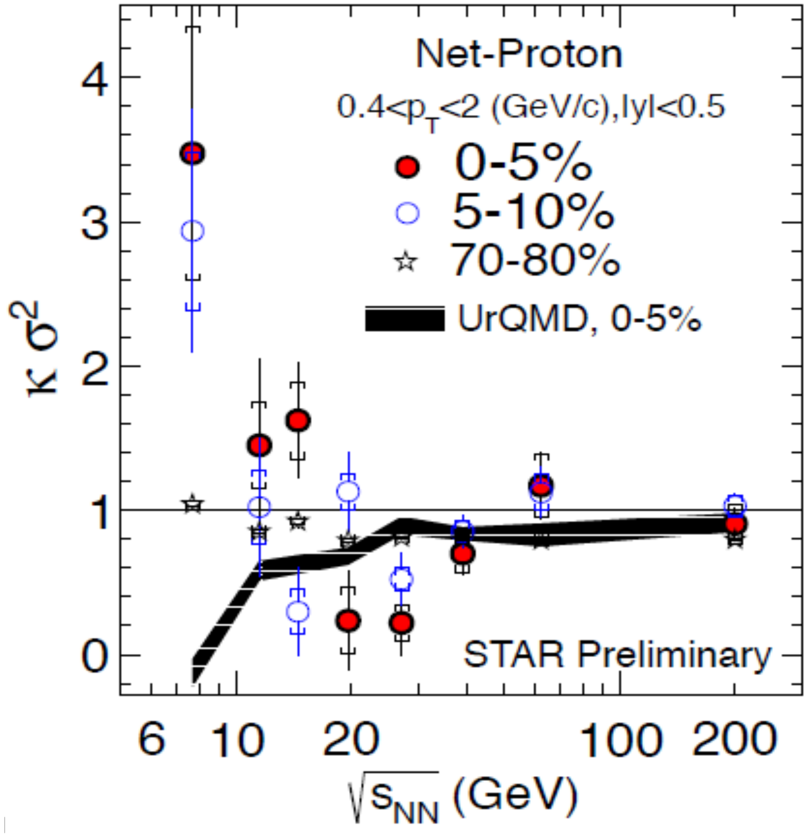


M.A.Stephanov, PRL107,052301(2011)

Probe of critical point



4th order flux. of net-protons



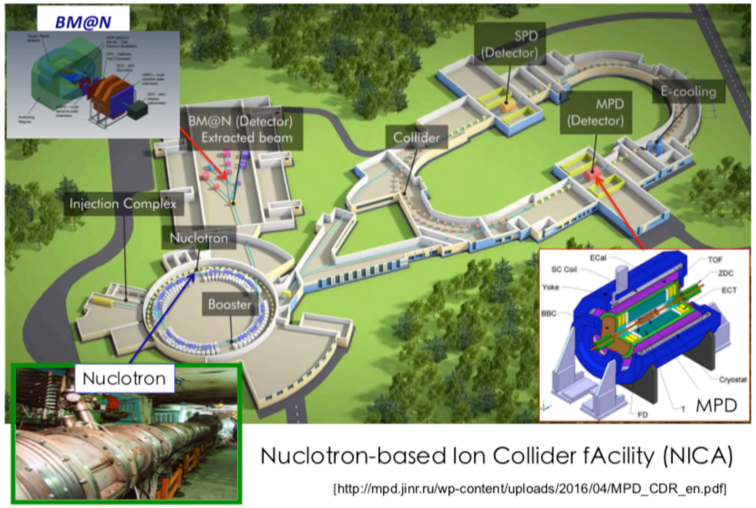
- ✓ Fluctuation in the number of particles as a signature
  - At around the critical point, correlation length extended and the fluctuation modified
- ✓ 4th order fluctuations seems to have structure
- ✓ Higher order, higher sensitivity. But requires much higher statistics !

➡ 6th order, T.Nonaka, S.Esumi et.al., PRC95,064912(2017)

RHIC BES is not enough !
Accelerator Plans in the World

Slides from Nu Xu @Tsukuba, March, 2018

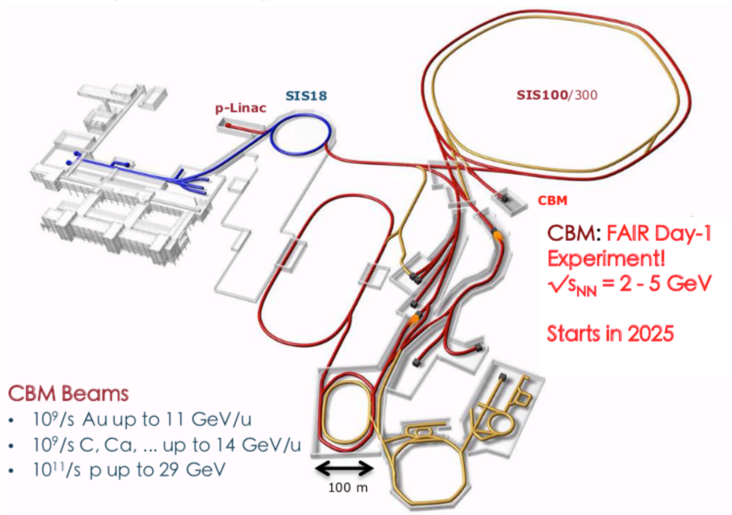
Experiments at NICA $\sqrt{s_{NN}}$ = 4 -11 GeV



Nuclotron-based Ion Collider fAcility (NICA)

[http://mpd.jinr.ru/wp-content/uploads/2016/04/MPD_CDR_en.pdf]

Facility for Antiproton & Ion Research: FAIR

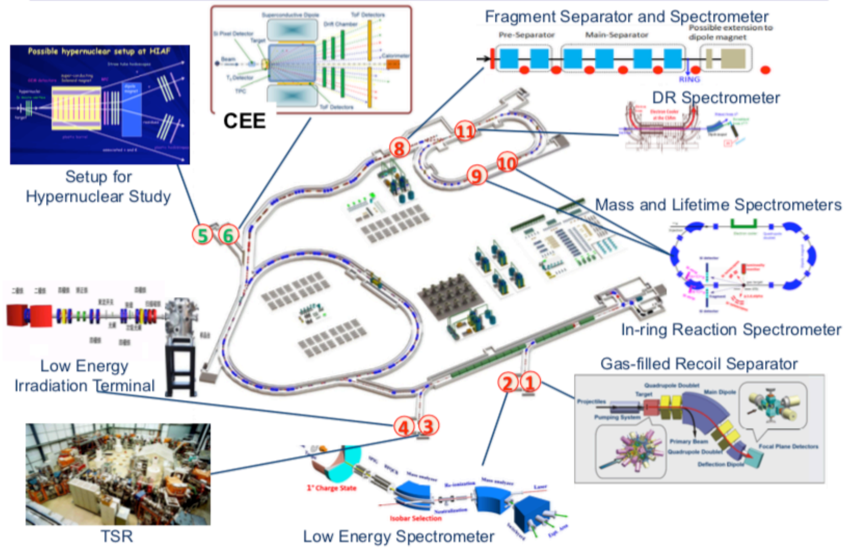


CBM: FAIR Day-1 Experiment!
$\sqrt{s_{NN}}$ = 2 - 5 GeV

Starts in 2025

CBM Beams
- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

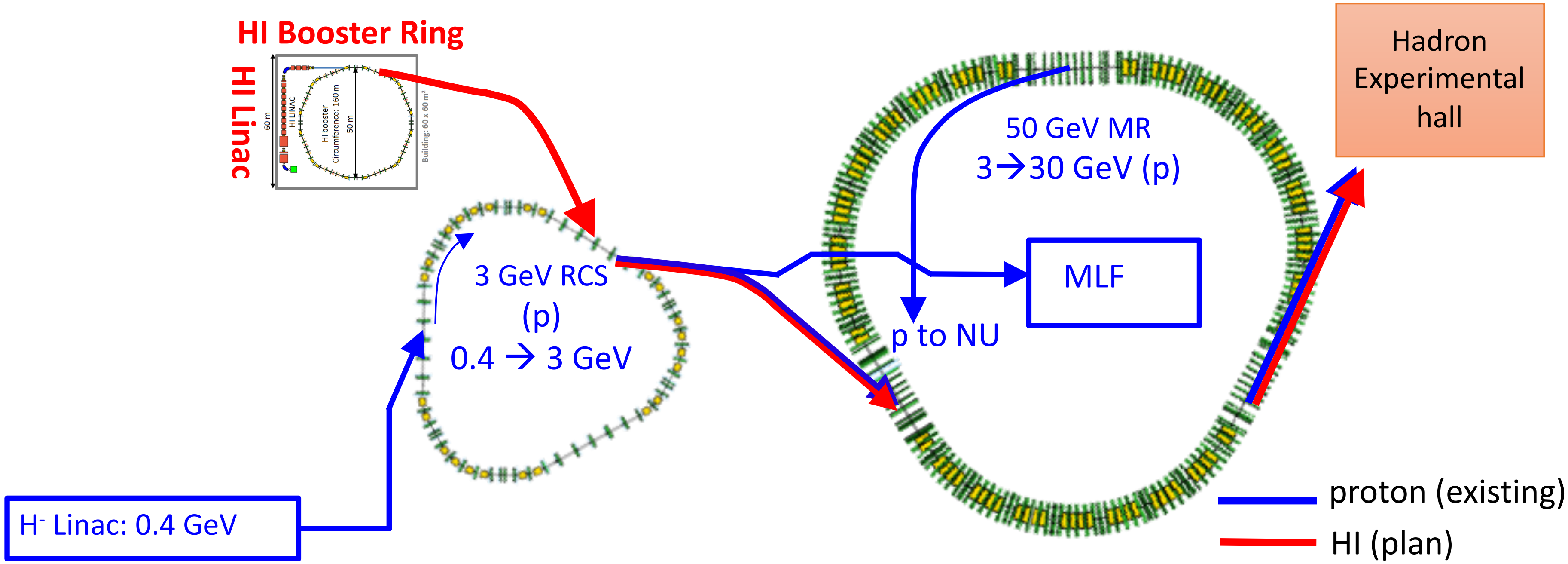
High Intensity Accelerator Facility (2023)



$\sqrt{s_{NN}} = 1 \sim 3$ GeV (2023?)

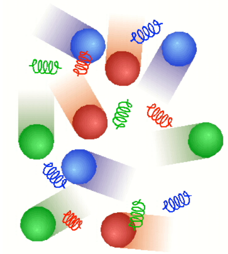
Heavy Ion Acceleration at J-PARC

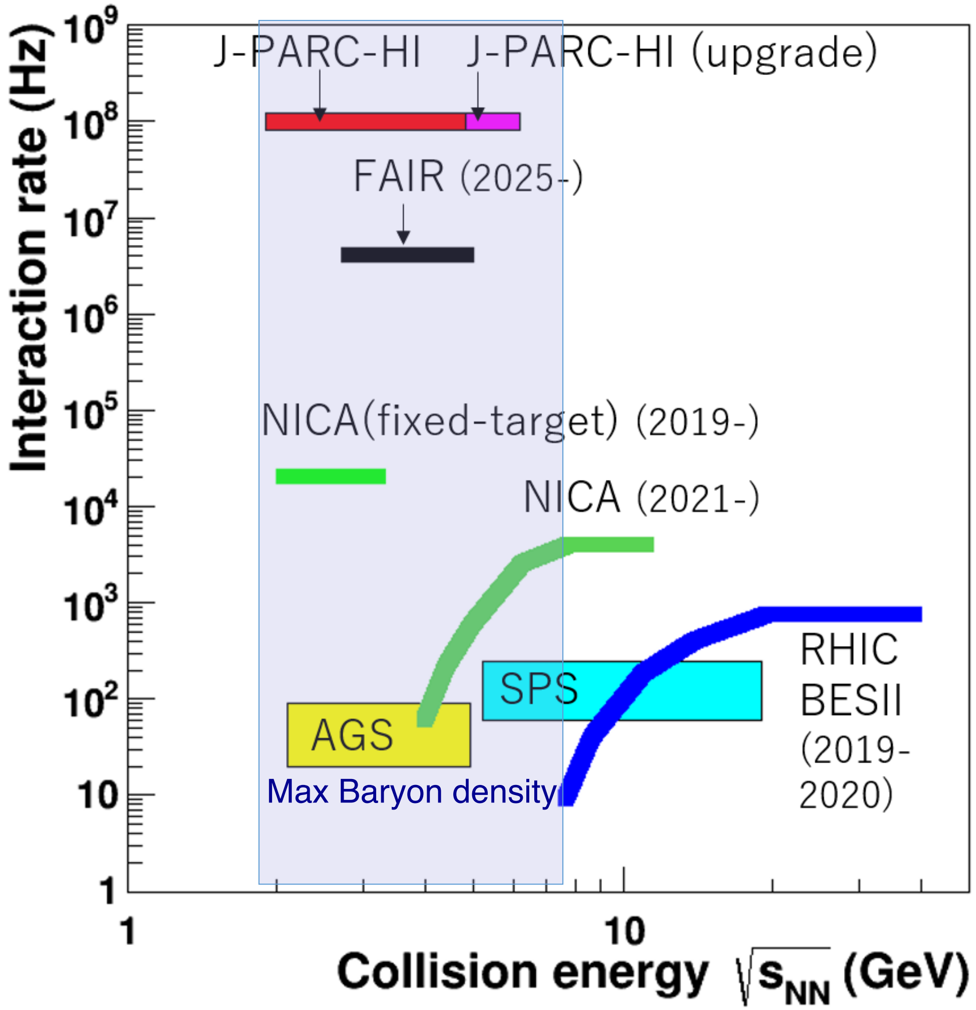
E_{lab}=1-19AGeV, $\sqrt{s_{NN}}$=1.9-6.2GeV (U)
Ion species: p, Si,…, Au, U



✓Only the HI linac and the booster is needed !

Most important feature : High Beam Intensity





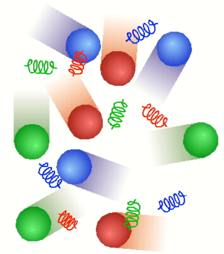
✓ 10^8Hz interaction rate can be achieved

➡1 year @ AGS = 5min @ J-PARC-HI

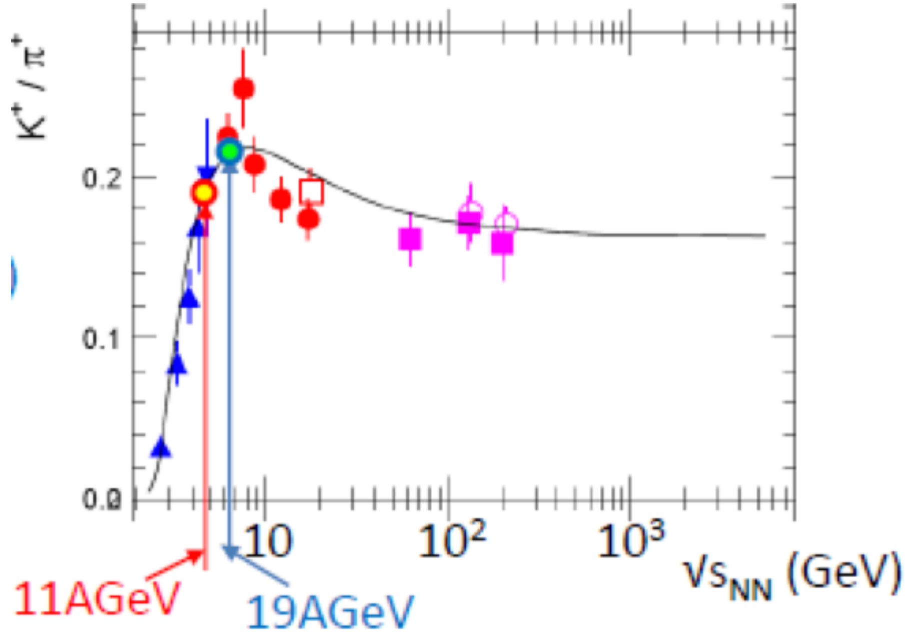
✓Besides the QCD phase diagram, as a a tool, many reasons to go for it !

- 1) Strangeness enhanc.
- 2) Baryon density

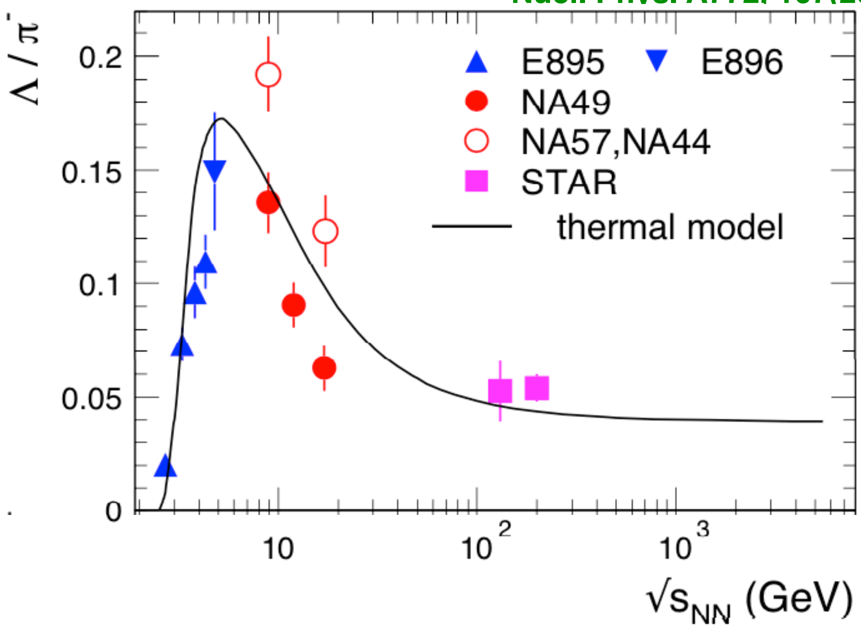
1) Strangeness Enhancement



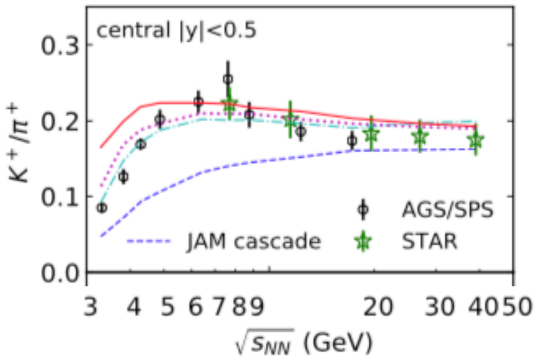
✓Most effective strangeness production



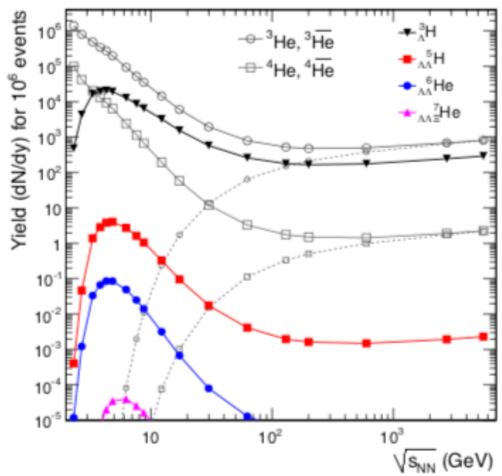
Nucl. Phys. A772, 167(2006)



Phys.Rev. C98 (2018) no.2, 024909

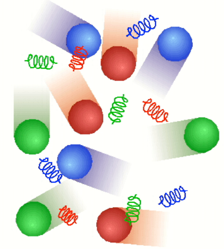


Theorist claims that characteristic bump cannot explain with hadronic cascade alone, it may suggest the existence of partonic fluid.



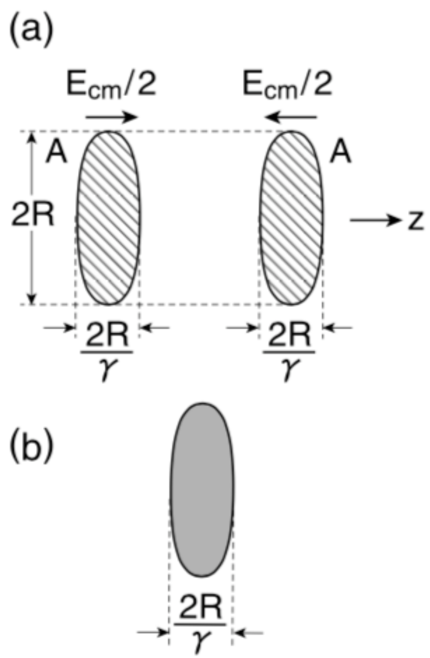
Phys.Lett. B697 (2011) 203-207

2) Highest Baryon Density



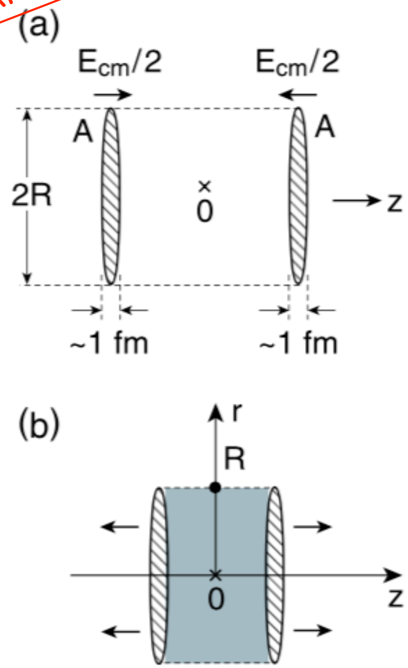
AGS, JPARC-HI

Landau

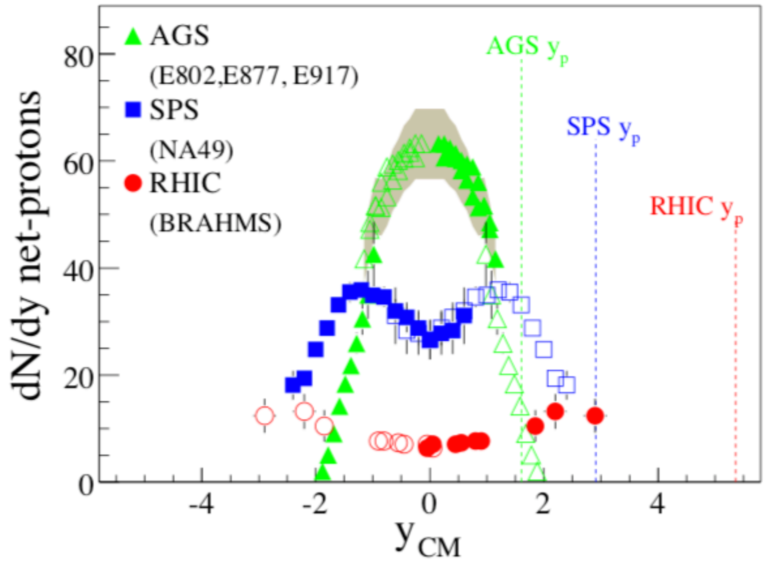


RHIC, LHC

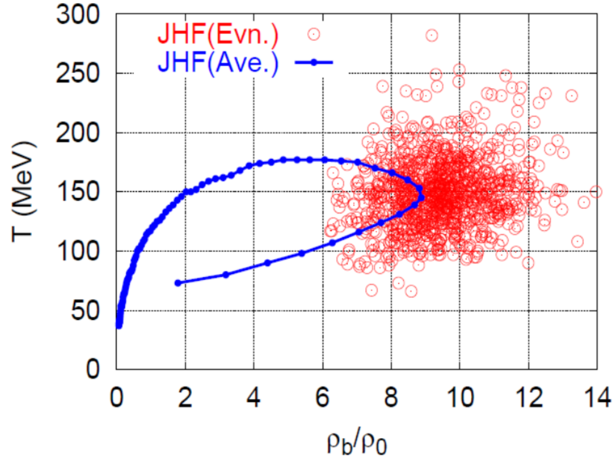
Bjorken



PRL, 93(2004)102301

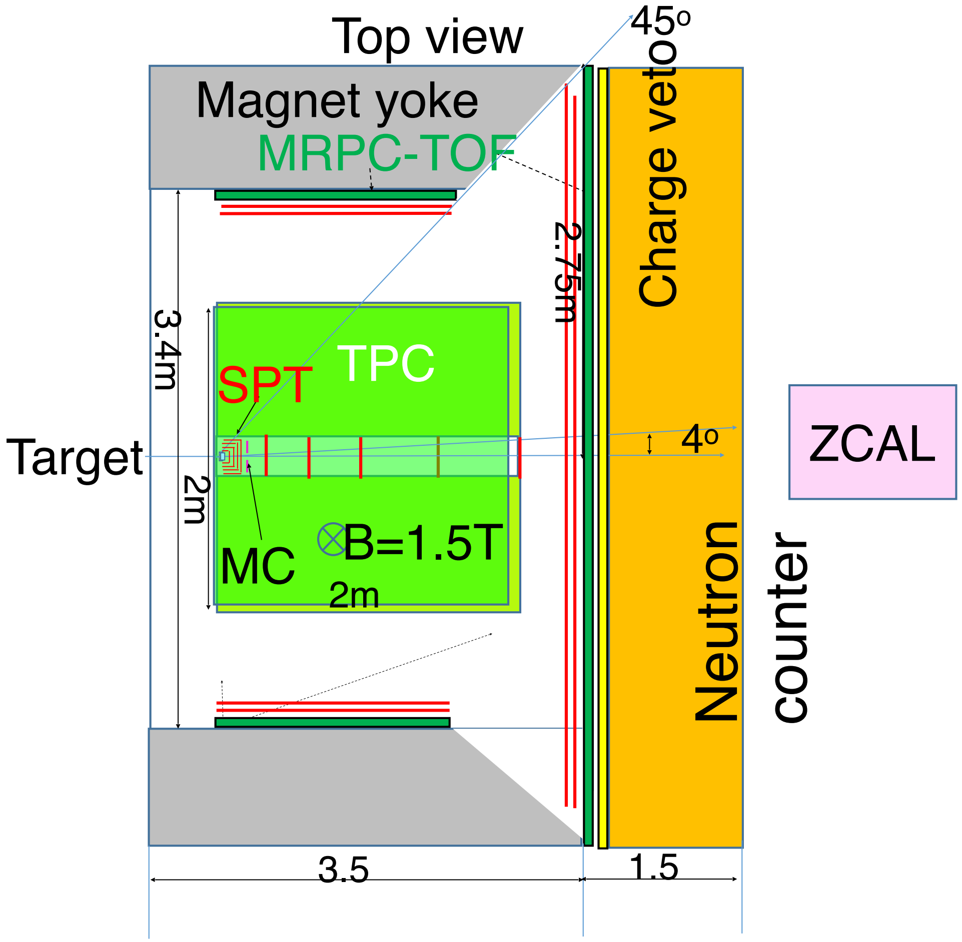


- ✓ Unlike Bjorken picture at RHIC and LHC, collisions at J-PARC-HI follows Landau picture, where incident nucleus stops at Center of Mass
  - Baryon Density as high as ~10 ρ_0 can be achieved by selecting rare events
- ✓ Equation of State at high baryon density
  - Physics of neutron star, neutron merger

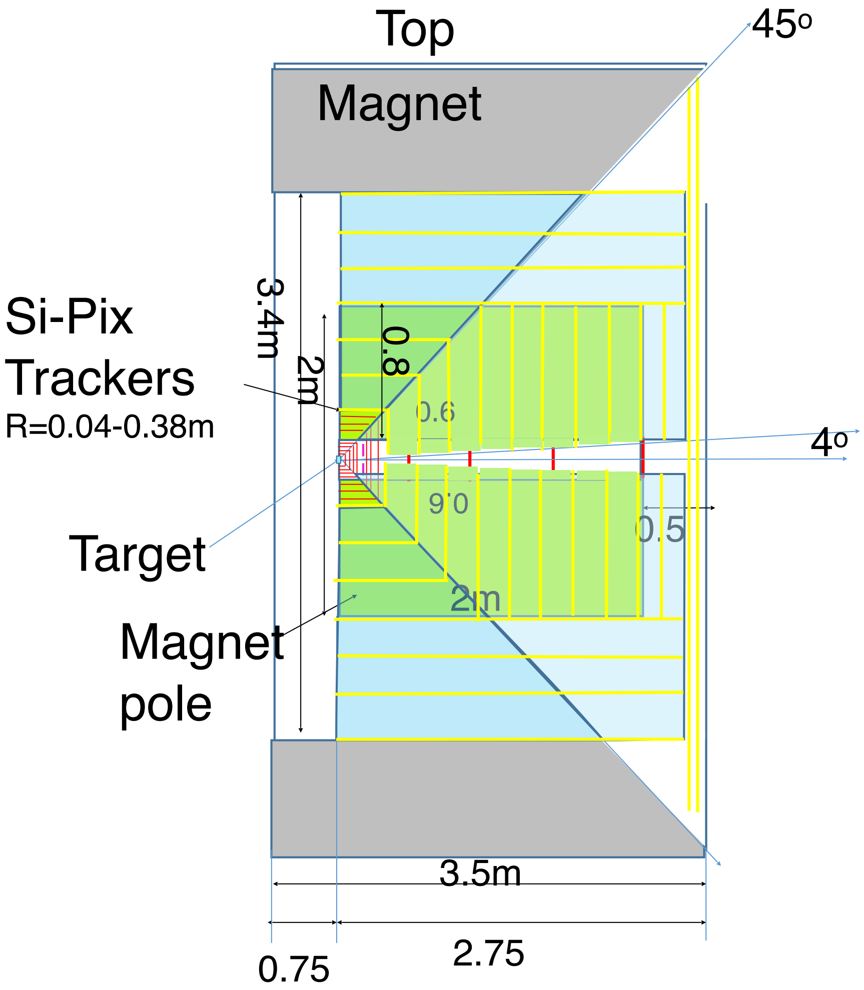


Configuration 1; Dipole Hadron Spectrometer

- ✓Interaction Rate : <10^6 Hz
- ✓Charged particles (PID) + neutrons
- ✓~4π acceptance
  - Track : Si-Pix(θ < 4o), TPC (θ > 4o), GEM
  - PID : MRPC-TOF, Neutron counter
  - Centrality : Multiplicity Counter + Zero-degree CALorimeter
- ✓**Flow, E-by-E fluctuation**

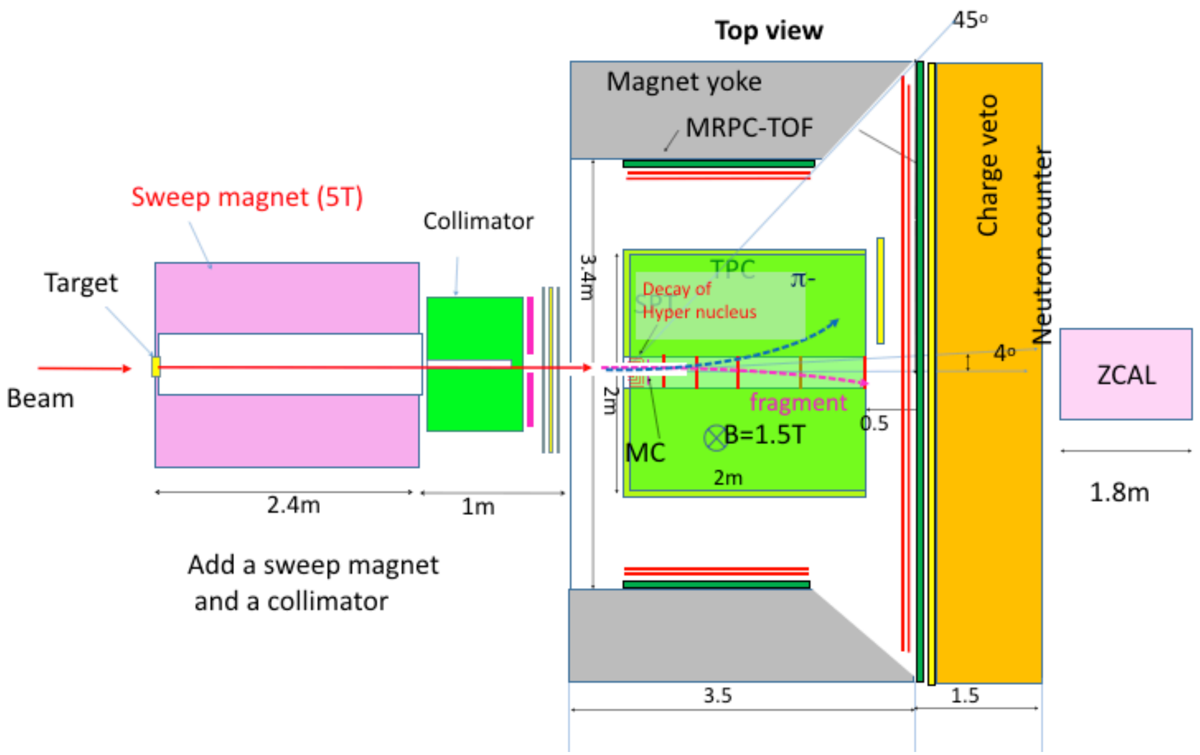


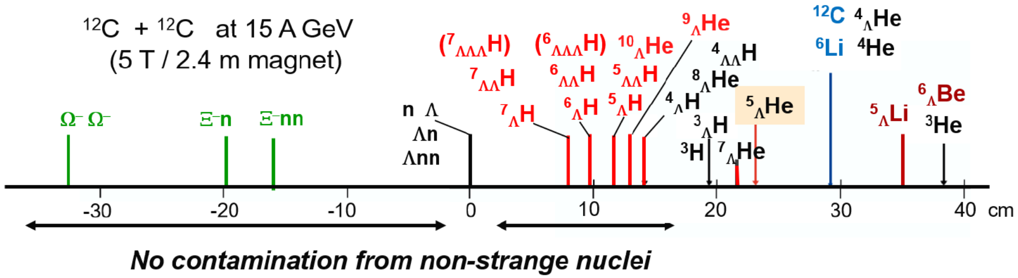
Configuration 2 ; Dipole Dimuon Spectrometer



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

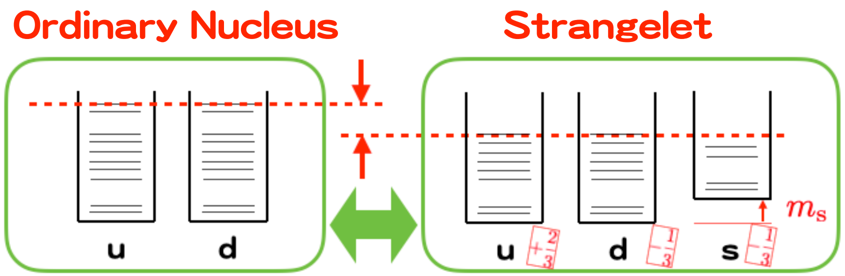
Configuration 3; Hypernuclear Spectrometer

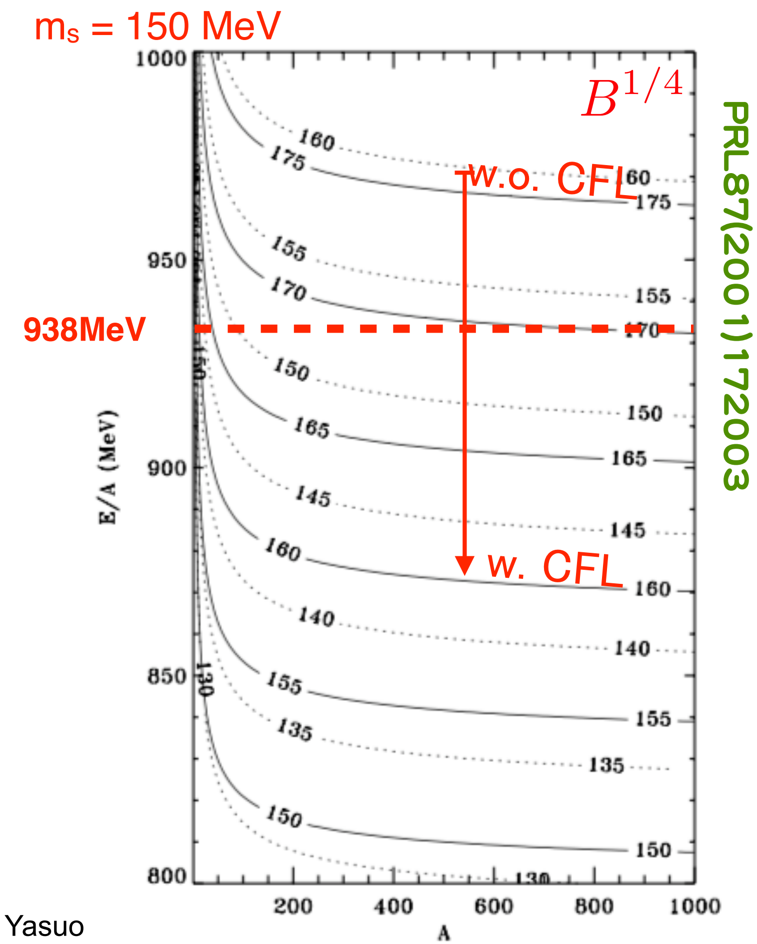


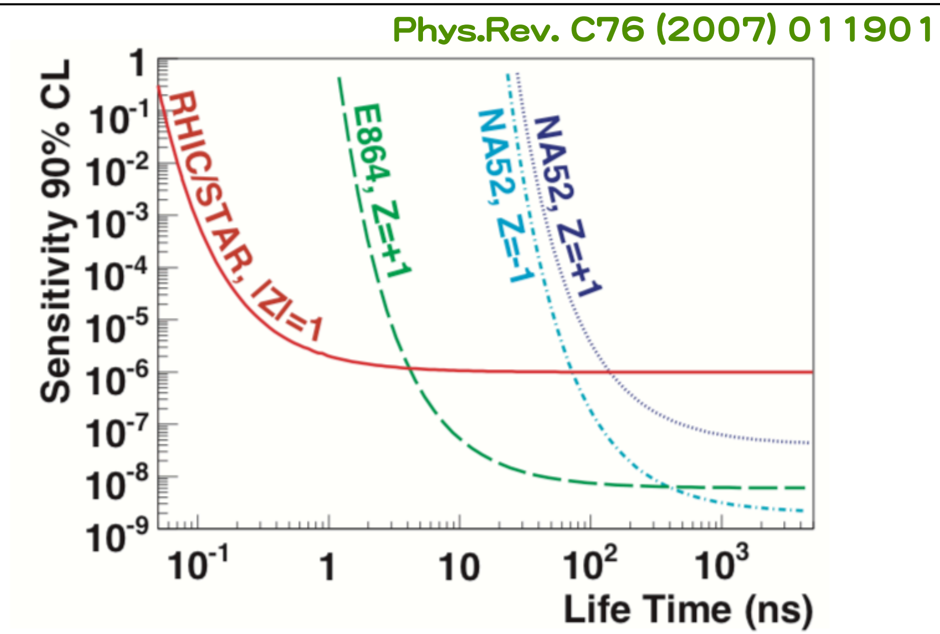


- ✓Interaction Rate : 10^8 Hz
- ✓Sweeping magnet + Collimator
  - Hypernuclei at beam rapidity
  - Collimator Selection by Charge/Mass
- ✓Hypernuclei, Strangelet and Di-baryon

Strangelet Search







√Strangelet search in heavy ion collisions

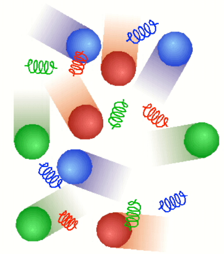
- AGS E864、central、Au+Pb 11.6 A GeV/c
- SPS NA52、central、Pb+Pb 158 A GeV/c
- RHIC STAR、Proj. region、$\sqrt{s_{NN}}$ = 200GeV

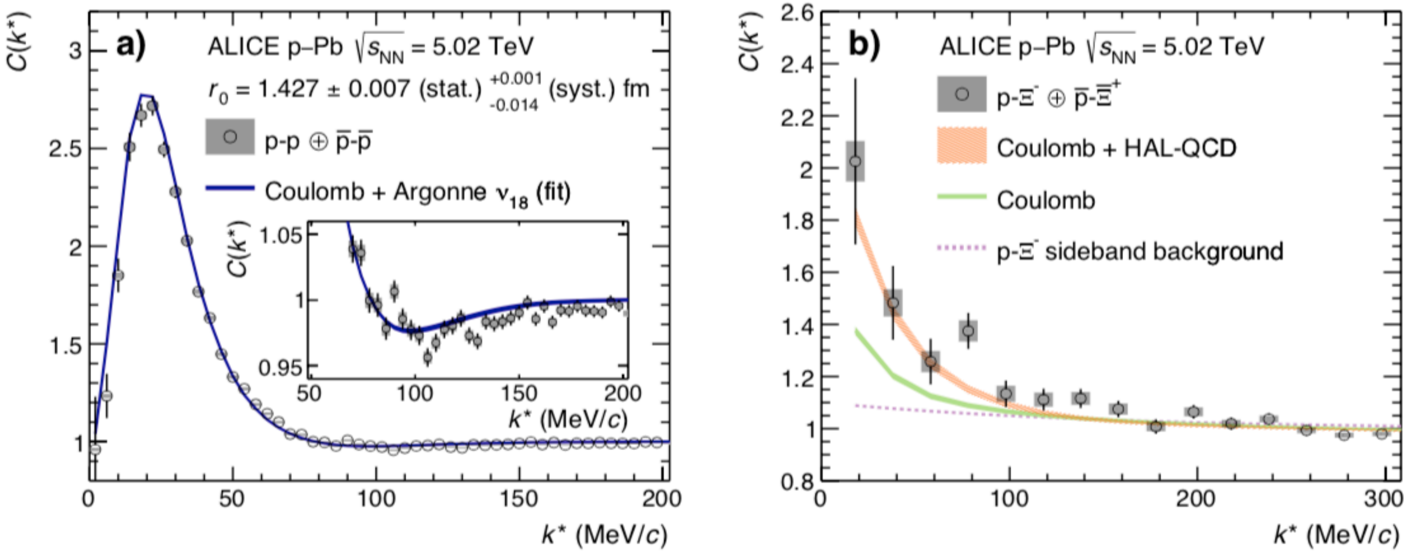
√Indeed, best place for Strangelet search

- High baryon density -> Larger coalescence
- Lower temp. & smaller flow -> Easier to cool
- Higher K/pi -> Higher s density, larger distillation effects
- At J-PARC-HI, 10^{-9} ~ 10^{-10} is easy level

➡Strong Sweeping Magnet + Hadronic Calorimeter

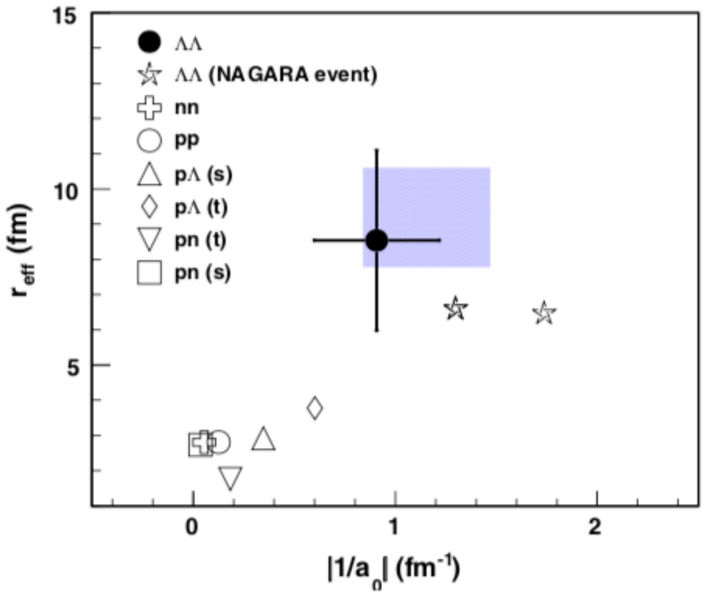
Study of Hyperon Interaction





arXiv:1904.12198(ALICE)

PRL114.022301 (STAR)



✓ Attractive interaction between p-Ξ⁻ (ALICE)

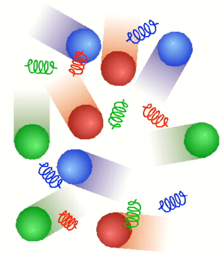
- Two part. corr. in p-Pb

✓ ΛΛ interaction in Au-Au (STAR)

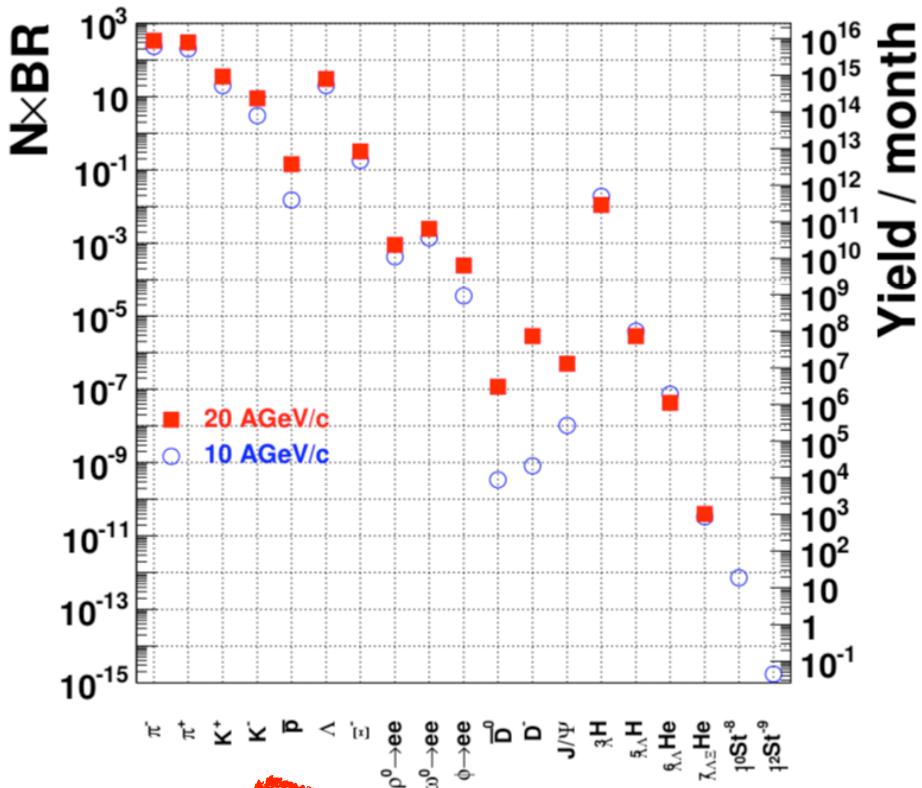
- Residual int. + source distr.

✓ J-PARC-HI provides great tools

Summary and Prospect



- √ J-PARC-HI provides unique opportunity to study QCD phase structure and EoS of dense matter
  - Sweat spot of beam energy $\sqrt{s_{NN}}$ = 2-6 G
  - High beam rate as high as 10^{11} Hz
- √ Only Linac and Booster needed
- √ Many reasons are,
  - Sweat spot
    - ➡Phase structure of QCD matter
  - Highest Baryon density
    - ➡EoS of neutron star
  - Highest Strangeness Production Ratio
    - ➡Hyperon interactions, Hyper Nuclei, Strangelet



- √ Letter of intent submitted to J-PARC PAC in 2016
- √ Phase-0 pA experiment (E16) will start in 2020
- √ J-PARC-HI on Master Plan of Science Council of Japan in 2020

Many other topics at J-PARC-HI !