物理学セミナー

J-PARCにおけるハドロン・原子核研究と超高密度バリオン物質研究への展望

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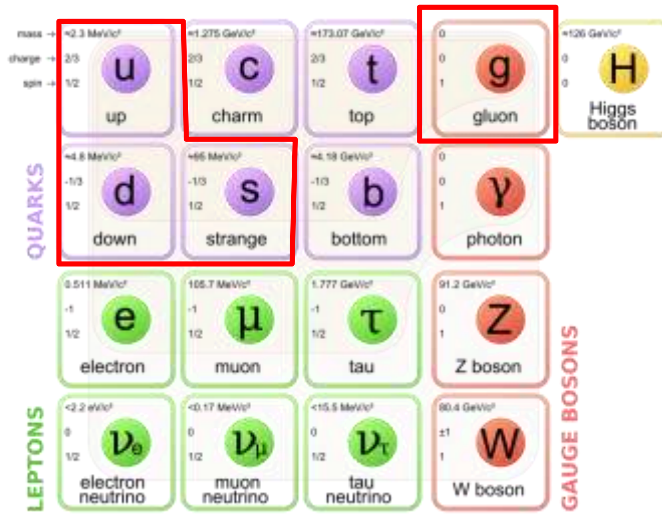
日本原子力研究開発機構　先端研)

２０１７年１２月６日

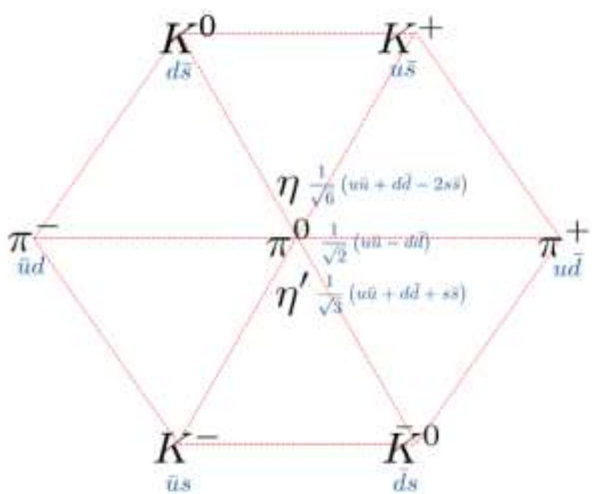
Outline

1. J-PARCの紹介
2. J-PARCにおけるハドロン・原子核実験
3. J-PARCにおける重イオン将来計画
4. まとめ

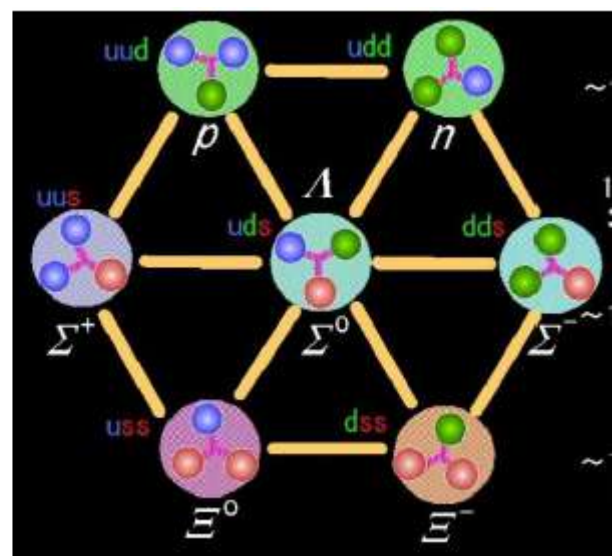
素粒子とハドロン



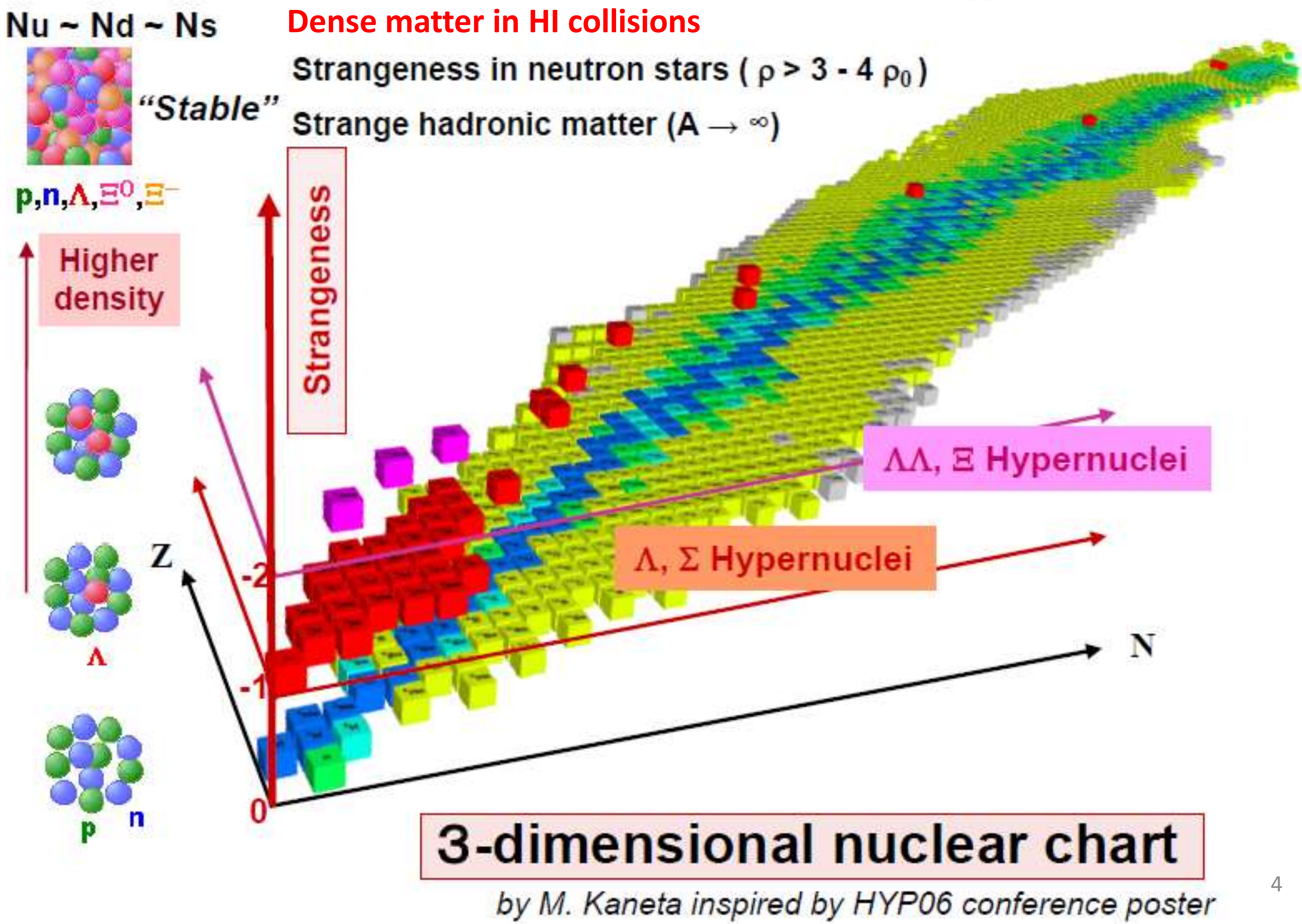
メソン

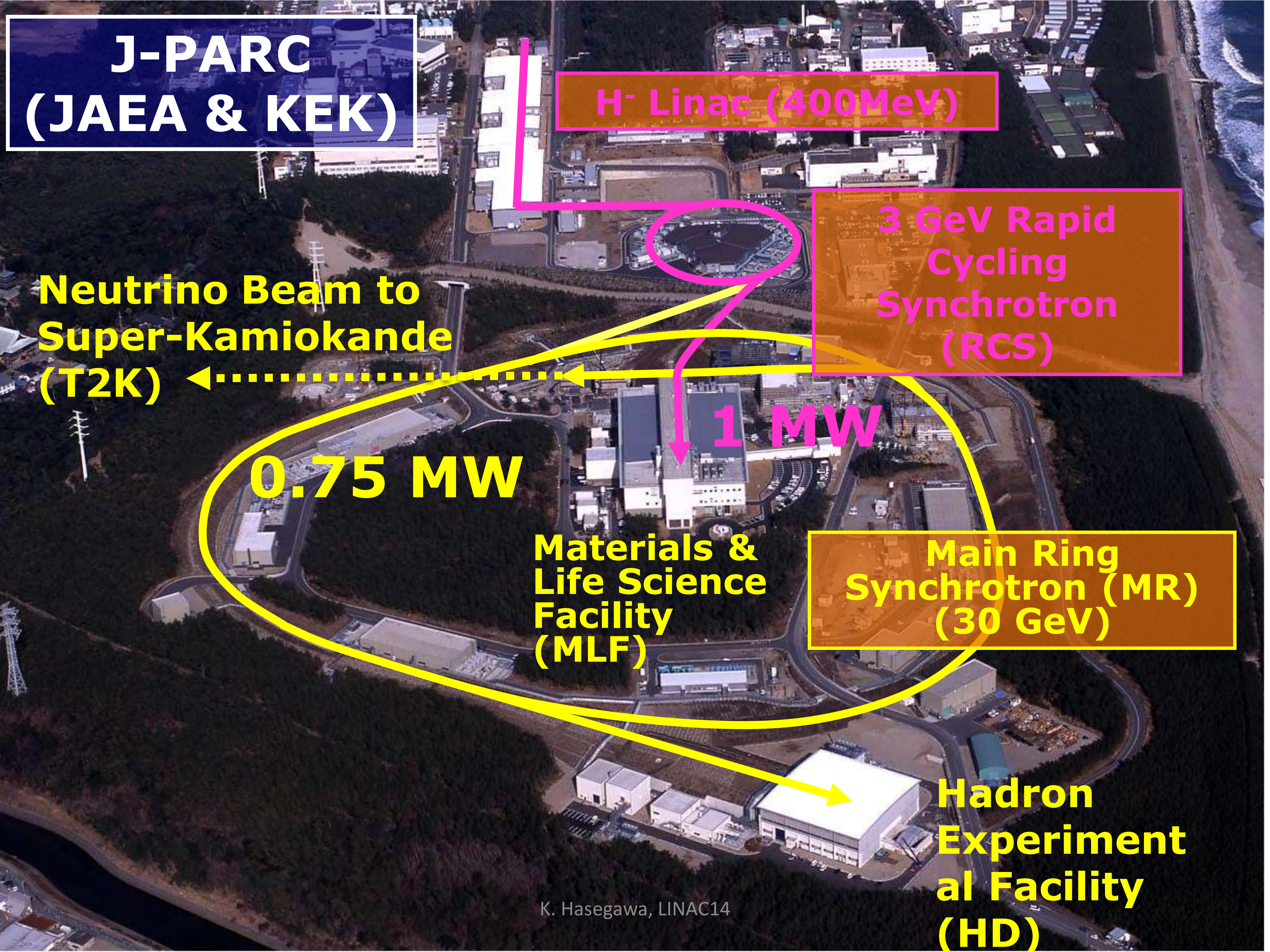


バリオン



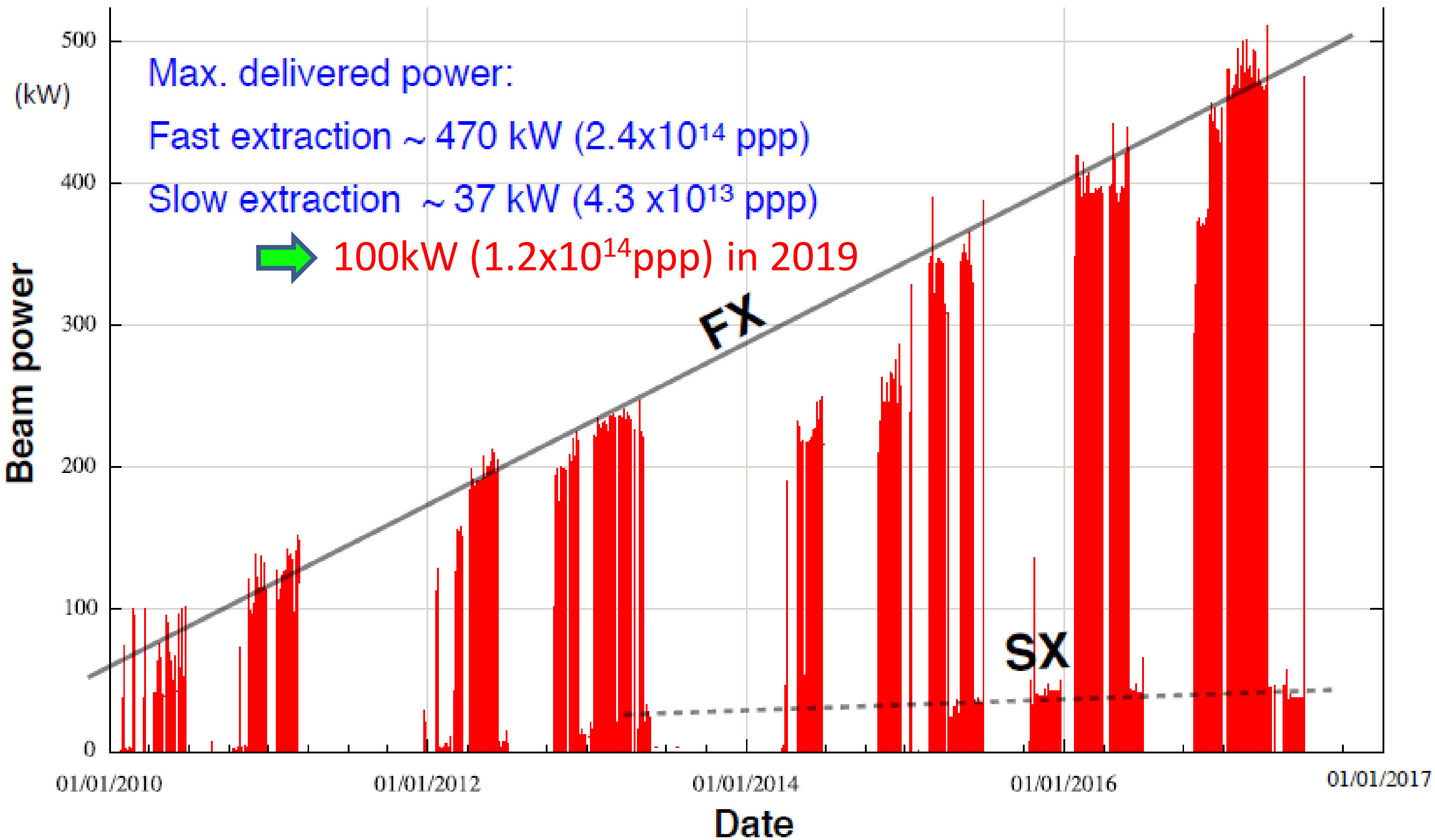
J-PARCにおけるハドロン・原子核物理の目標




J-PARC
(JAEA & KEK)
H- Linac (400MeV)
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino Beam to Super-Kamiokande (T2K)
1 MW
0.75 MW
Materials & Life Science Facility (MLF)
Main Ring Synchrotron (MR) (30 GeV)
Hadron Experimental Facility (HD)

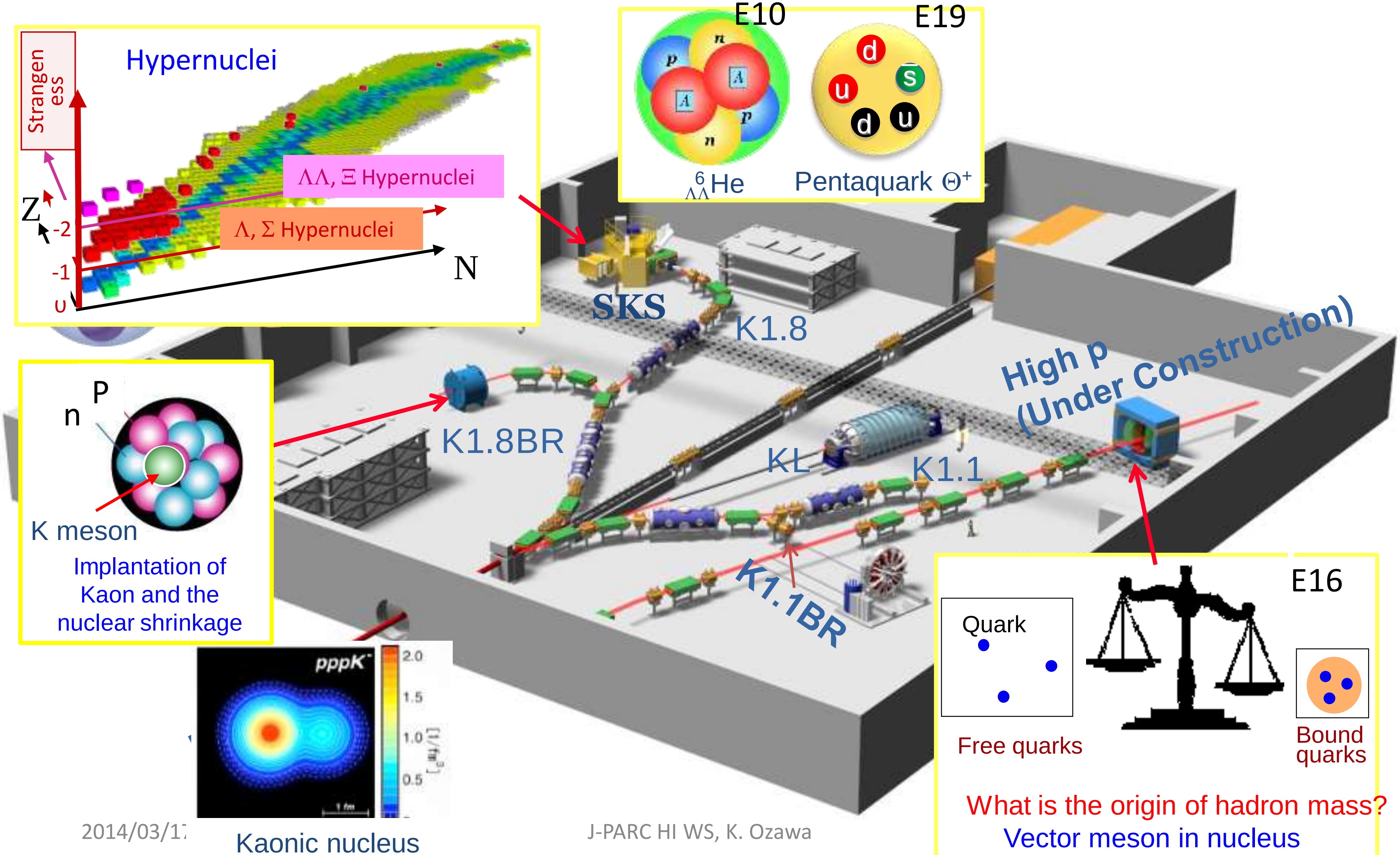
J-PARC MR: Beam power history

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

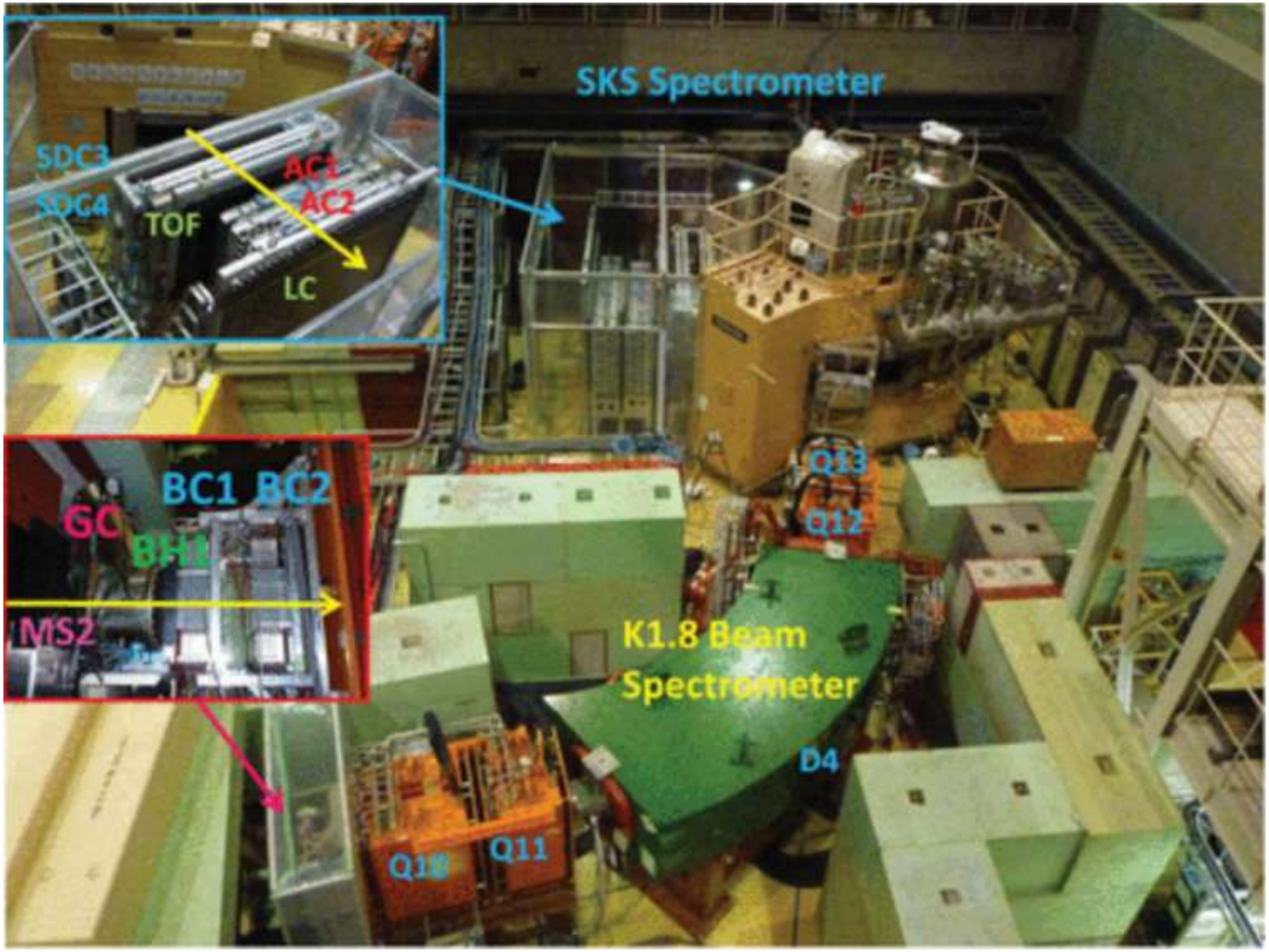


F. Naito, J-PARC PAC, July 2017

J-PARCハドロン実験施設



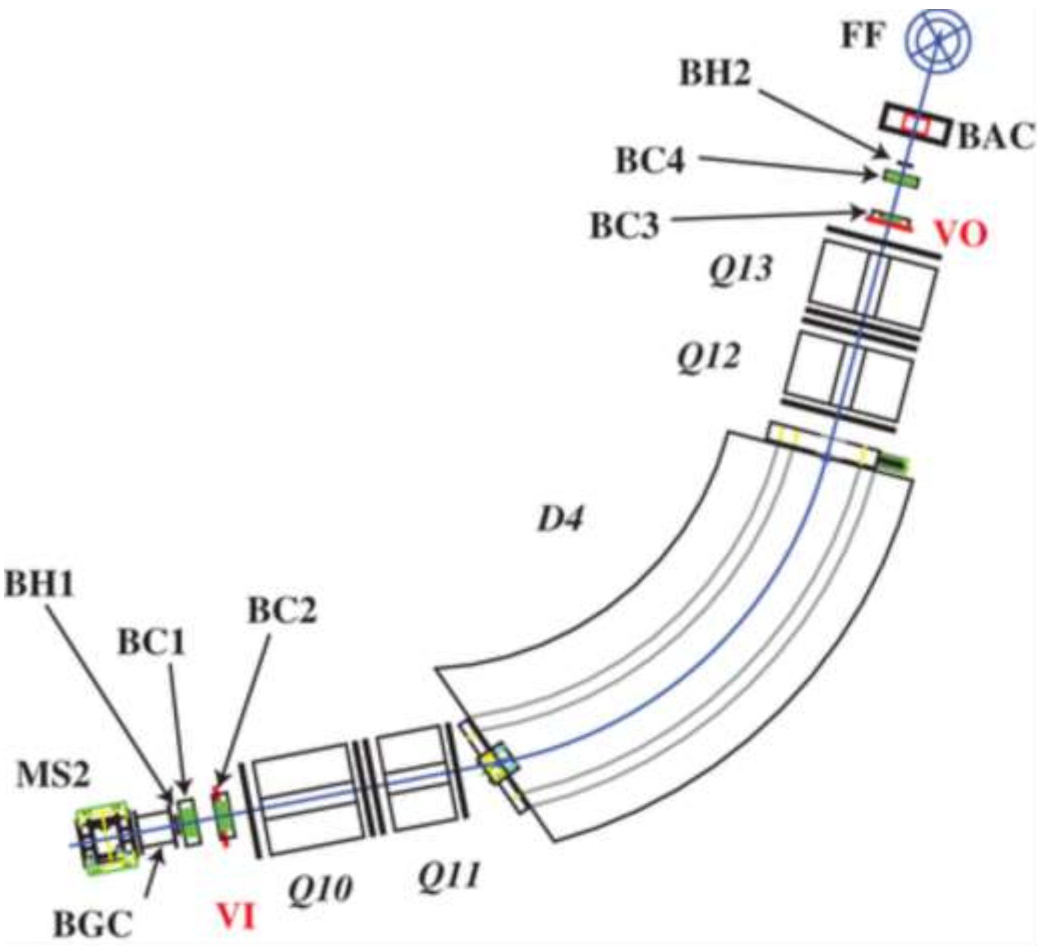
K1.8 Beamline



H. Takahashi, et al, Prog Theor Exp Phys. 2012;2012(1). doi:10.1093/ptep/pts023

K1.8 beamline spectrometer

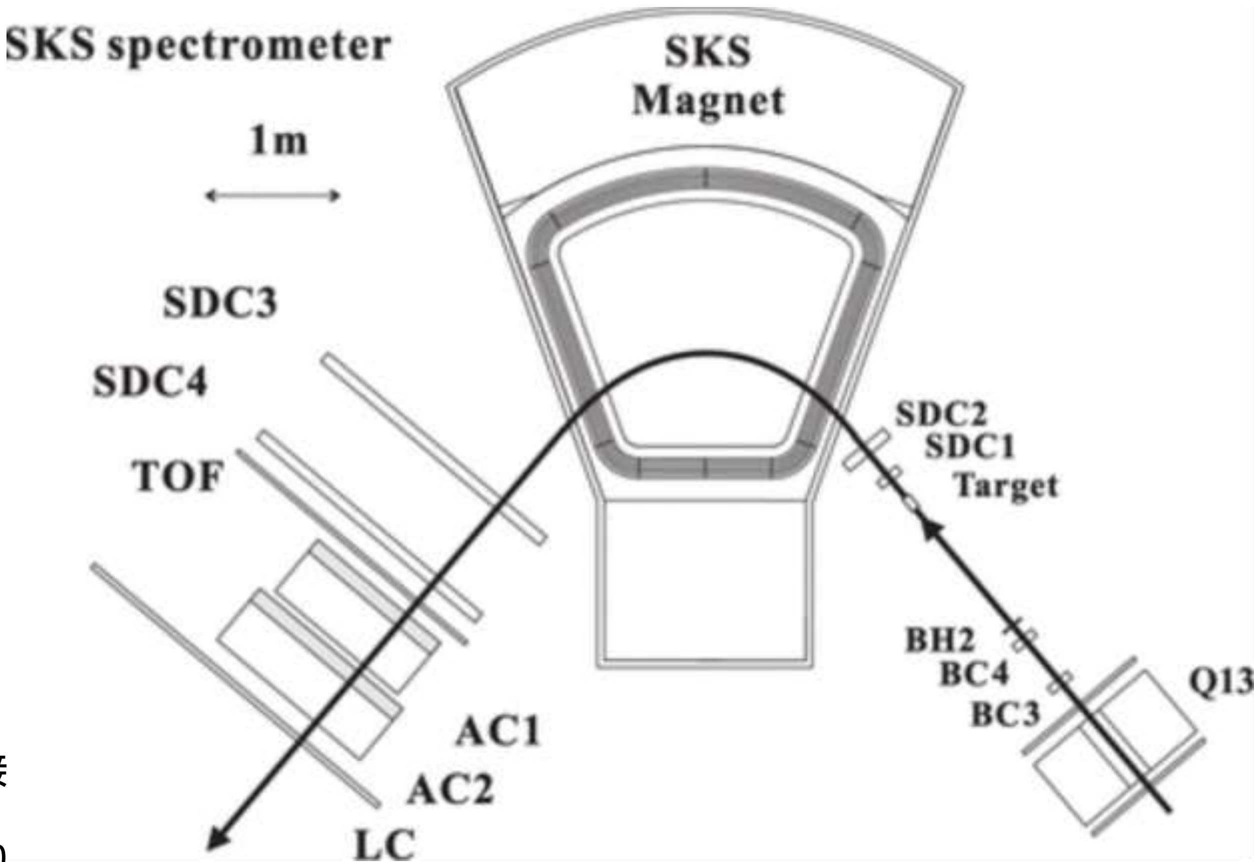
- BH1, BH2
  - Scintillation counter
  - π/K/p separation with TOF
- BAC
  - Beam Aerogel Cherenkov counter
- BC1-BC4
  - Beam tracking wire chambers



H. Takahashi, et al, Prog Theor Exp Phys. 2012;2012(1). doi:10.1093/ptep/pts023

SKS Spectrometer

- SKS: Superconducting dipole magnet (2.5 T)
- SDC1-4 : drift chambers
- AC1-2: Aerogel Cherenkov counters (π)
- LC : Lucite Cherenkov counter (π, K)
- TOF : Time-of-Flight counter (plastic scintillator)



Missing mass法

- 反応 : A+B->C+D m_d=sqrt((E_a+E_b-E_c)^2-(p_a+p_b-p_c)^2)
- 直接測定できないdの質量を間接的に測定する方法
- A:ビーム (π, K)、B : 固定標的(p_b=0, E_b=m_b), C: leading 生成粒子(π, K)
- 例えば　K- + p → K+ + X

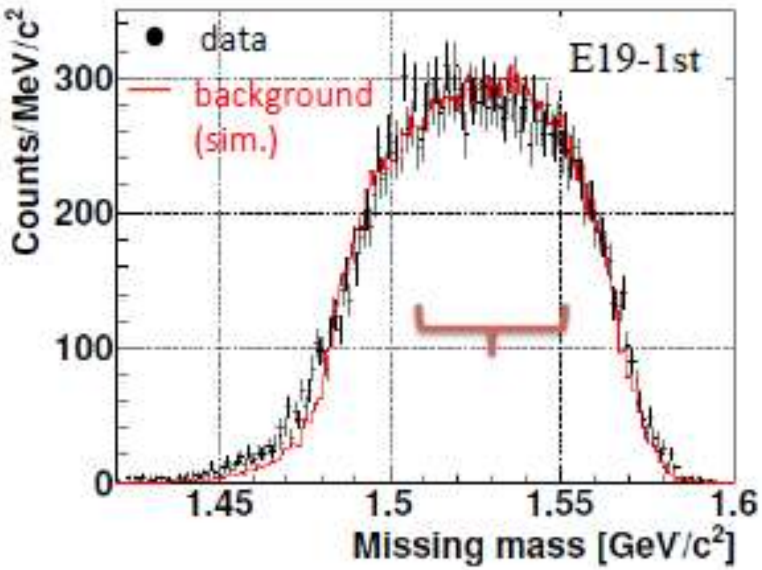
H. Takahashi, et al, Prog Theor Exp Phys. 2012;2012(1). doi:10.1093/ptep/pts023

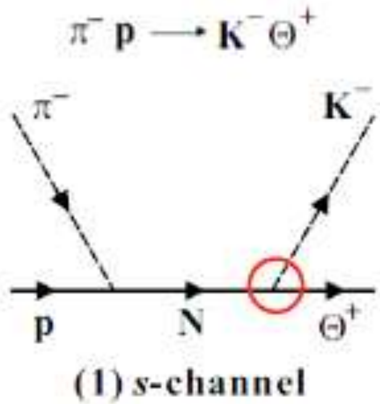
E19

Search for pentaquark $\Theta^+(uudd\bar{s})$

Shirotori et al., PRL 109, 132002 (2012).

$\pi^- + p \rightarrow K^- + X$ @ 1.92 GeV/c





- **No prominent peak structure**
- **Upper limit:** $< 0.26\ \mu b/sr$ @ 1.51–1.55 GeV/c²

✓ s-channel dominance

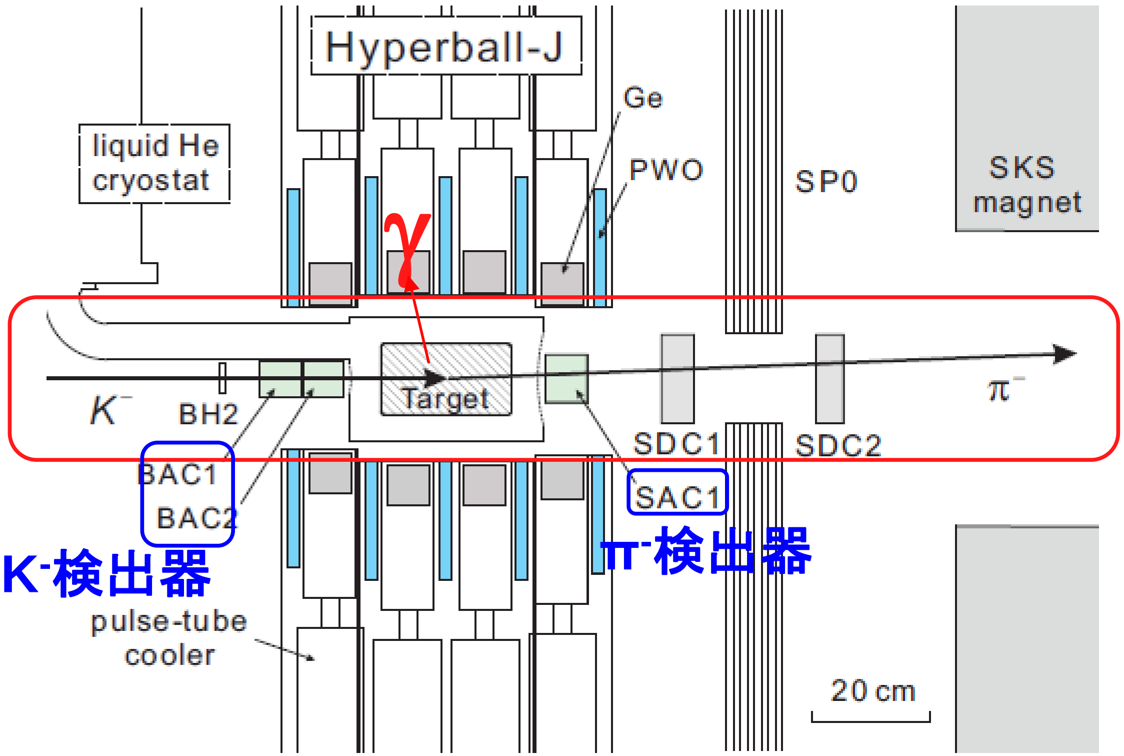
✓ $\Gamma_\Theta \propto g^2_{KN\Theta} \propto \sigma_{tot}$

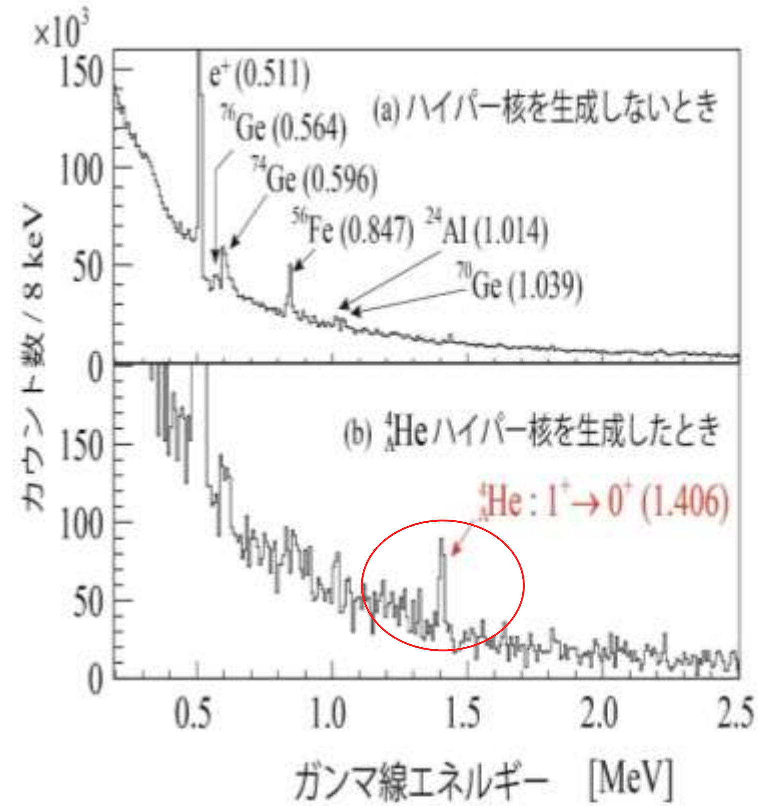
➔ Upper limit of decay width

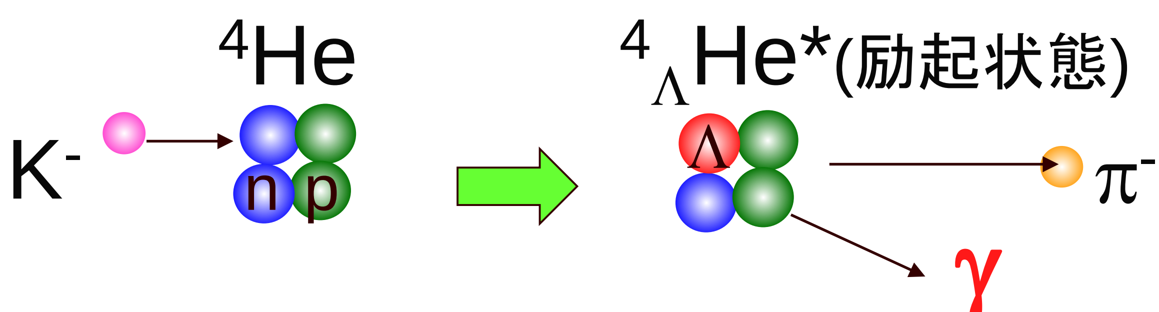
- 0.72 MeV for ½+
- 3.1 MeV for ½-

9

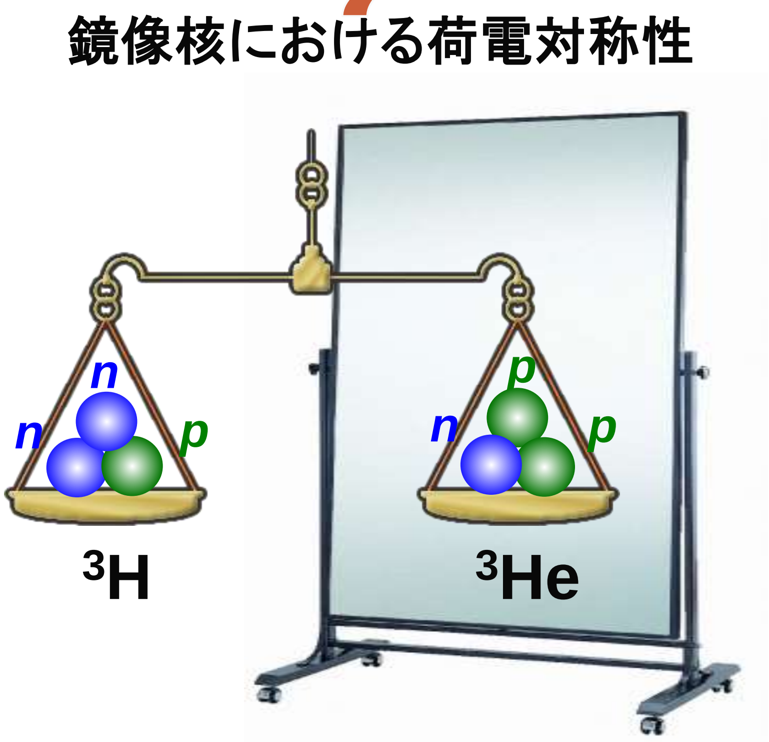
J-PARC E13実験 (2015年4月)





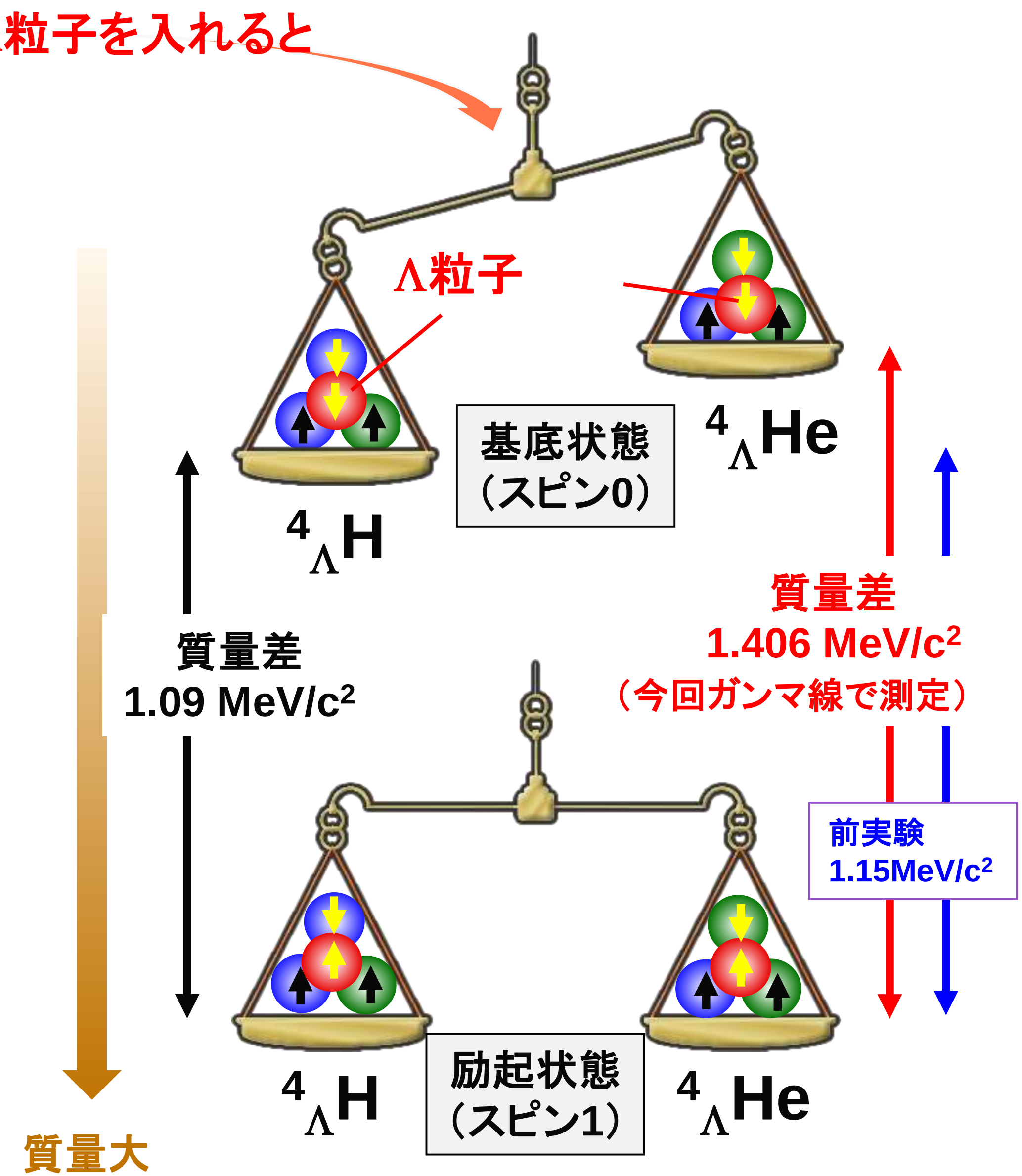


荷電対称性の破れの発見



p：陽子

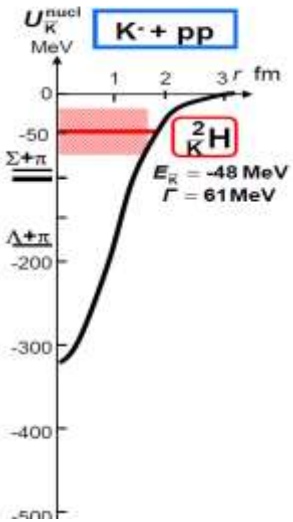
n：中性子



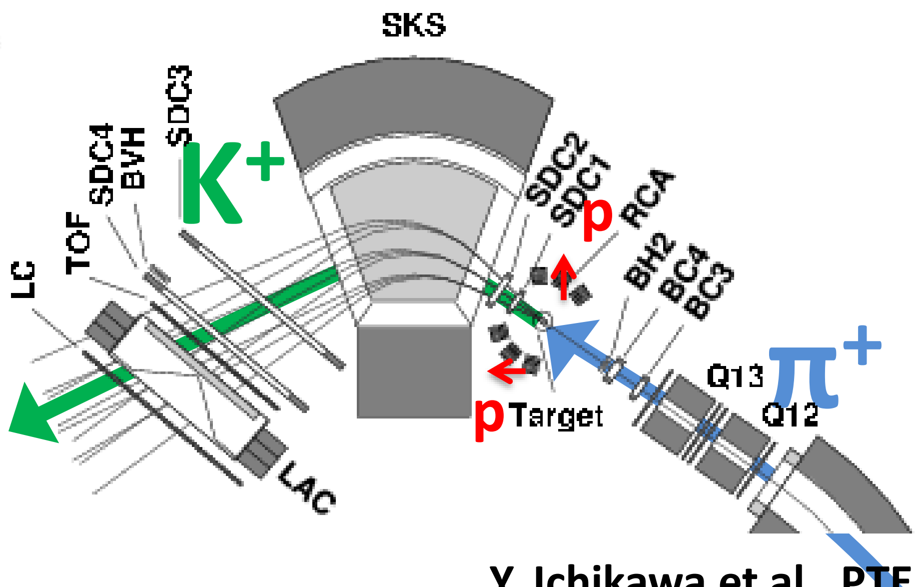
Λ-n間とΛ-p間の相互作用はスピン
状態によって大きく異なる

E27

Search for a $K^{-}pp$ bound state

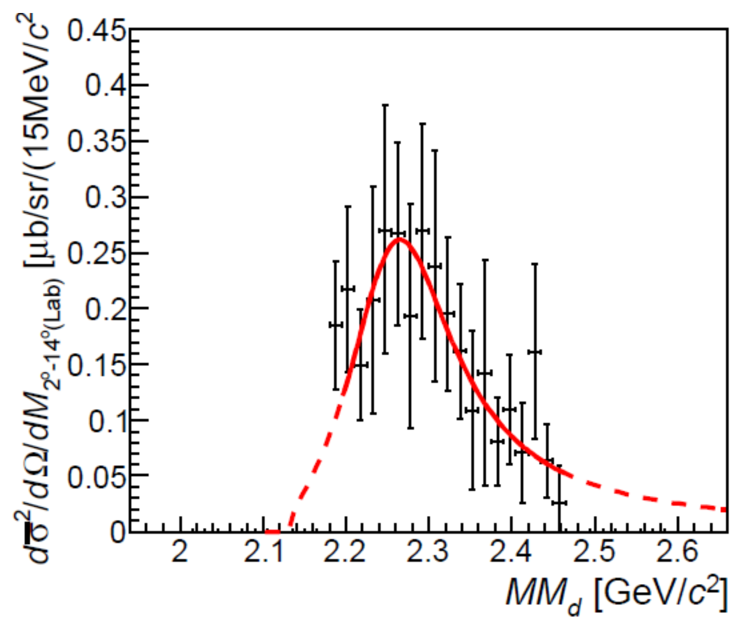


- **attractive $K^{bar}N$ interaction**
- **Kbar – nuclei bound states?**



$\pi^{+}d \rightarrow K^{+}X$

$X=K^{-}pp \longrightarrow \Lambda p$, $\Sigma^{0}p$, $Y\pi p$

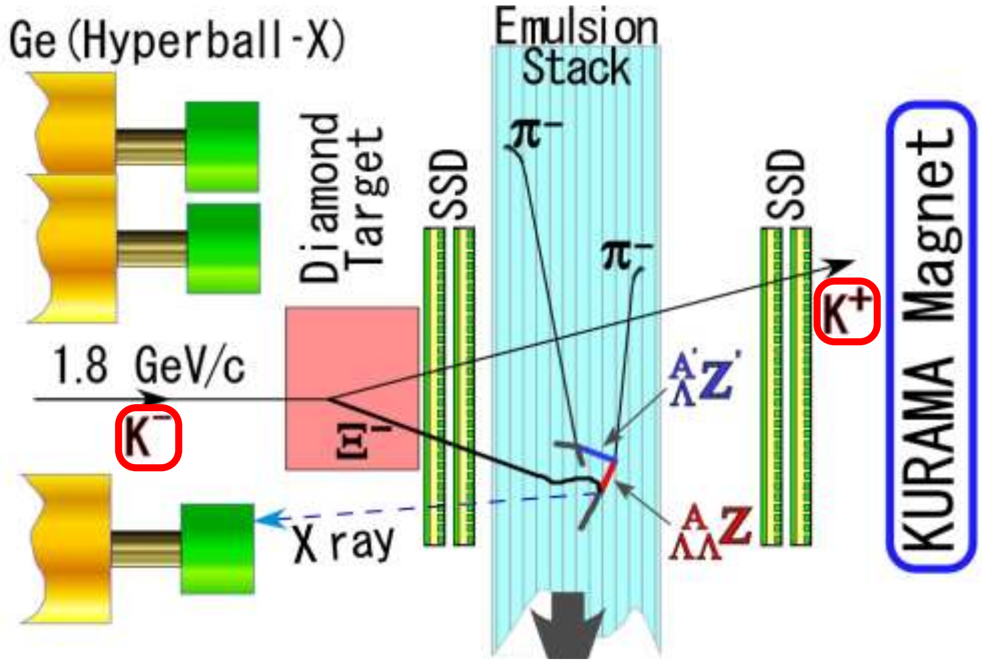


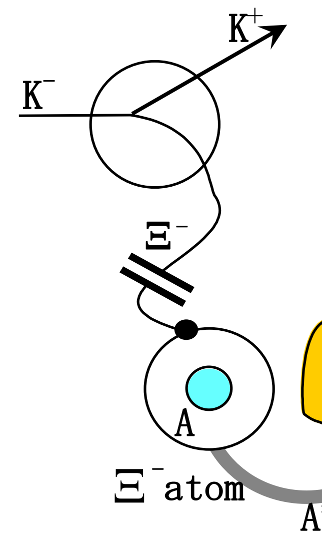
M=2275+-18 MeV

Binding energy = 95+-18 MeV

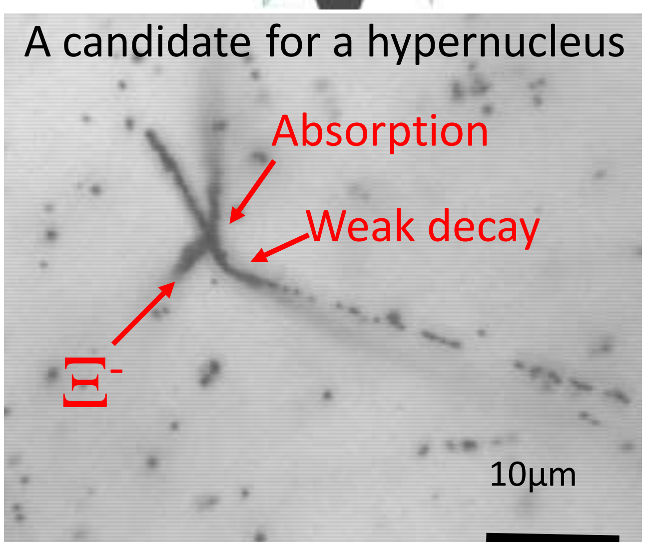
Y. Ichikawa et al., PTEP (2015) 021D01.

E07
Double Hypernuclei with Emulsion





$\Xi^- p \Rightarrow \Lambda\Lambda + 28$ MeV



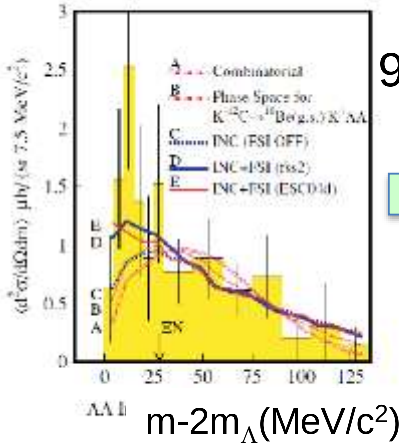
Aiming at measurement of 100 double hypernuclei

Experiment done in Apr-Jul 2017
Emulsion analysis is underway

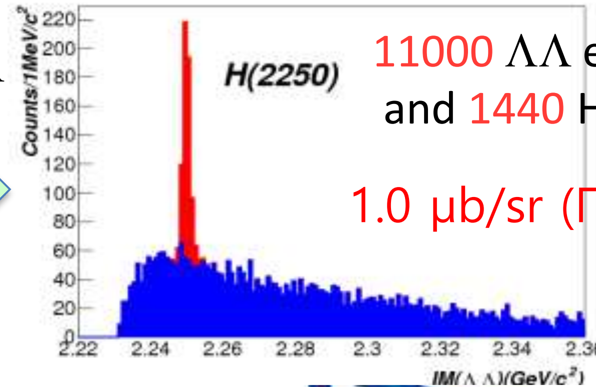
E42

Search for H-dibaryon (*uuddss*) in $^{12}C(K^-,K^+)X$

KEK-E522



90 ΛΛ

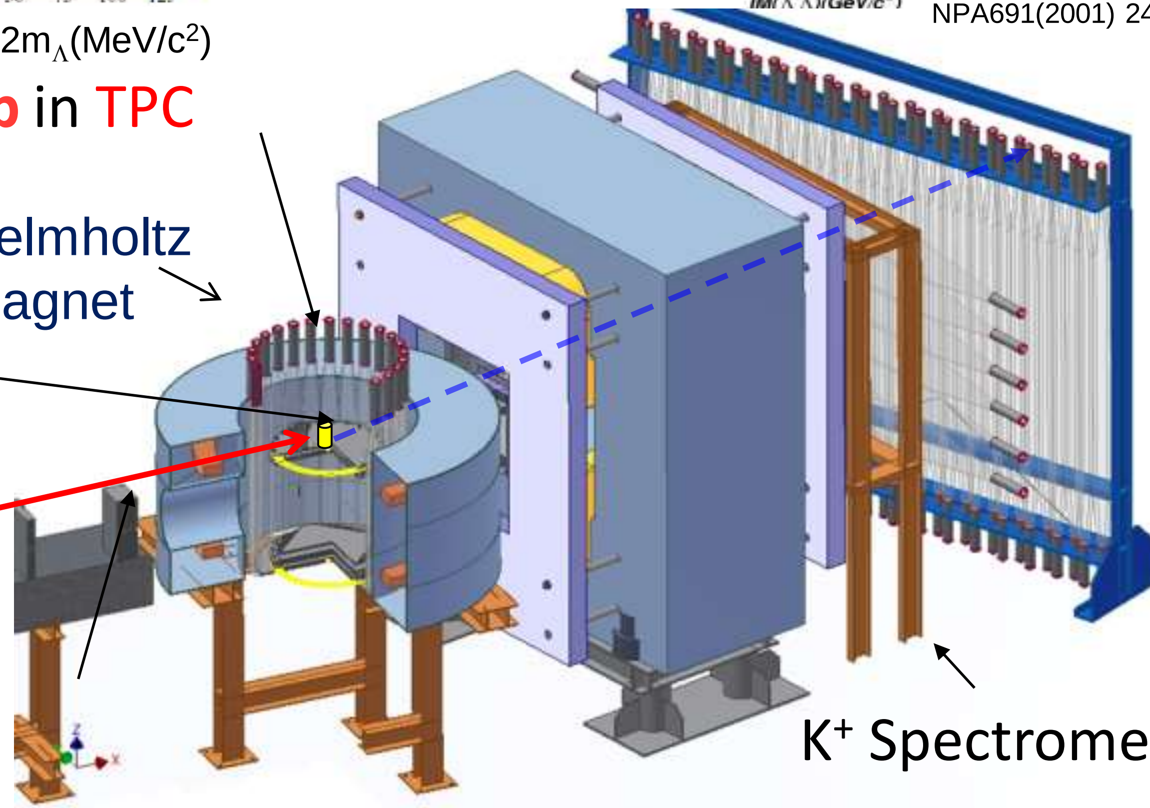


11000 ΛΛ events
and 1440 H-dibaryons

1.0 μb/sr (Γ_H=0)

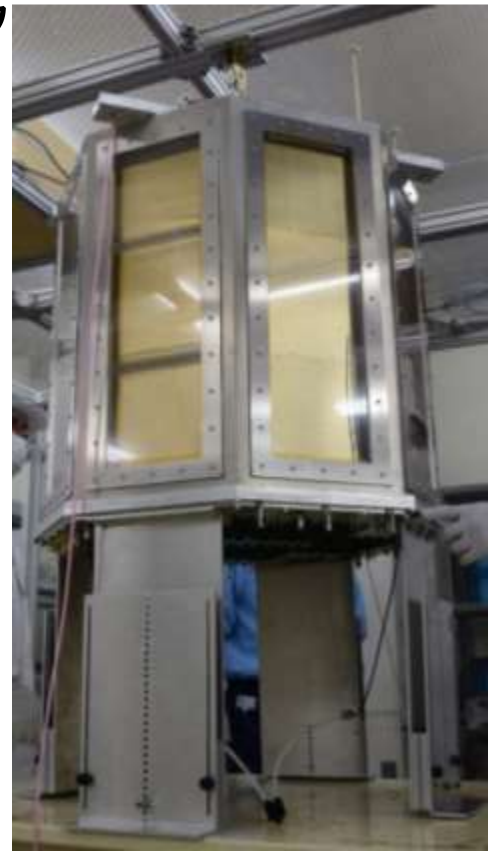
Y. Nara et al, NPA 614 (1997) 433
A. Ohnishi et al, NPA670 (2000) 297c;
Few-body Syst. Suppl. 12 (2000) 367;
NPA684(2001),595
NPA691(2001) 242c.

H→2Λ→π⁻π⁻pp in TPC

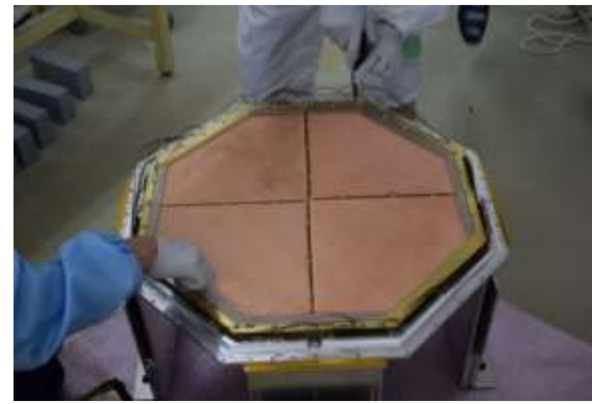


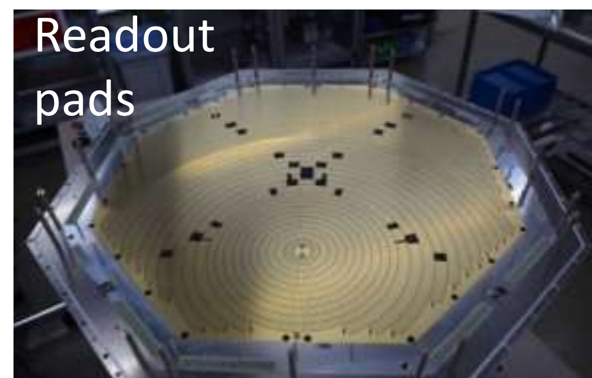
HypTPC

- 10^6Hzビームを直接drift volumeに照射
  - GEM、Gating Gridによる陽イオンバックフローの抑制
- 標的をdrift volume内に設置→大立体角

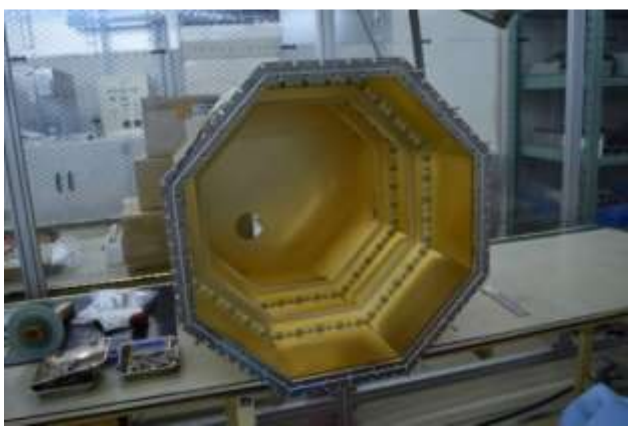


GEM

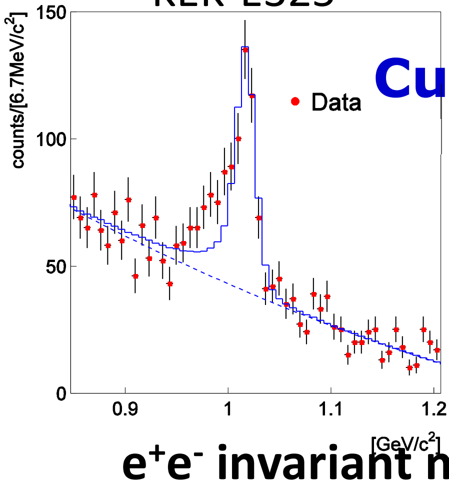


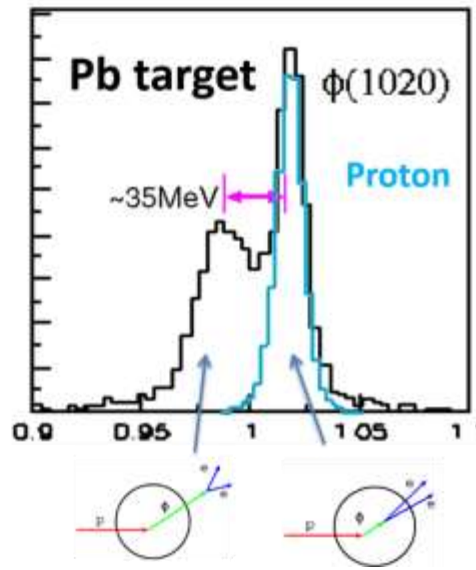


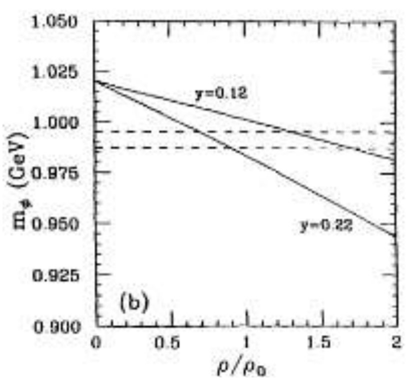
Field cage



E16 : p+A衝突における電子対生成 原子核中のφ中間子の変化





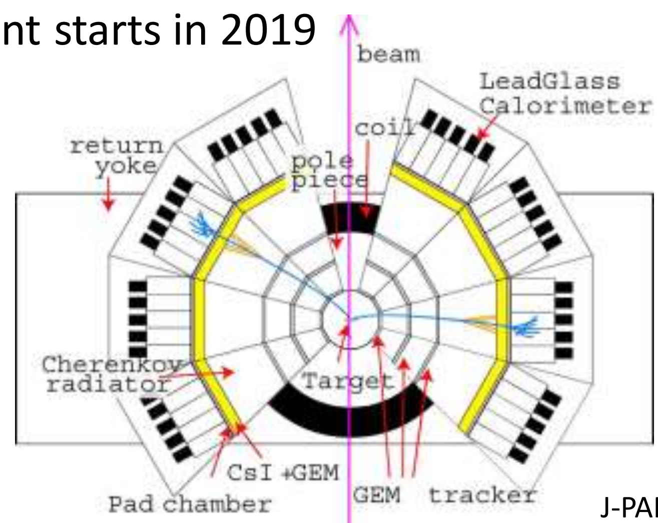


$$M_V^*/M_V = 1 - C_V \cdot (\rho/\rho_0)$$

$$C_V = 0.30\langle s\bar{s}\rangle/(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$$

T. Hatsuda, QM97

Experiment starts in 2019



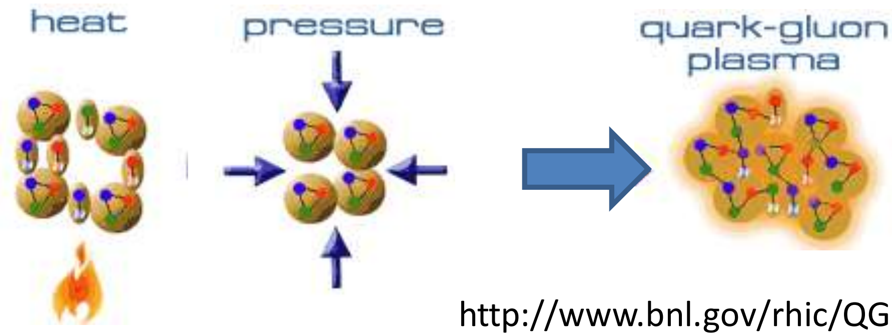
休憩

前半終了

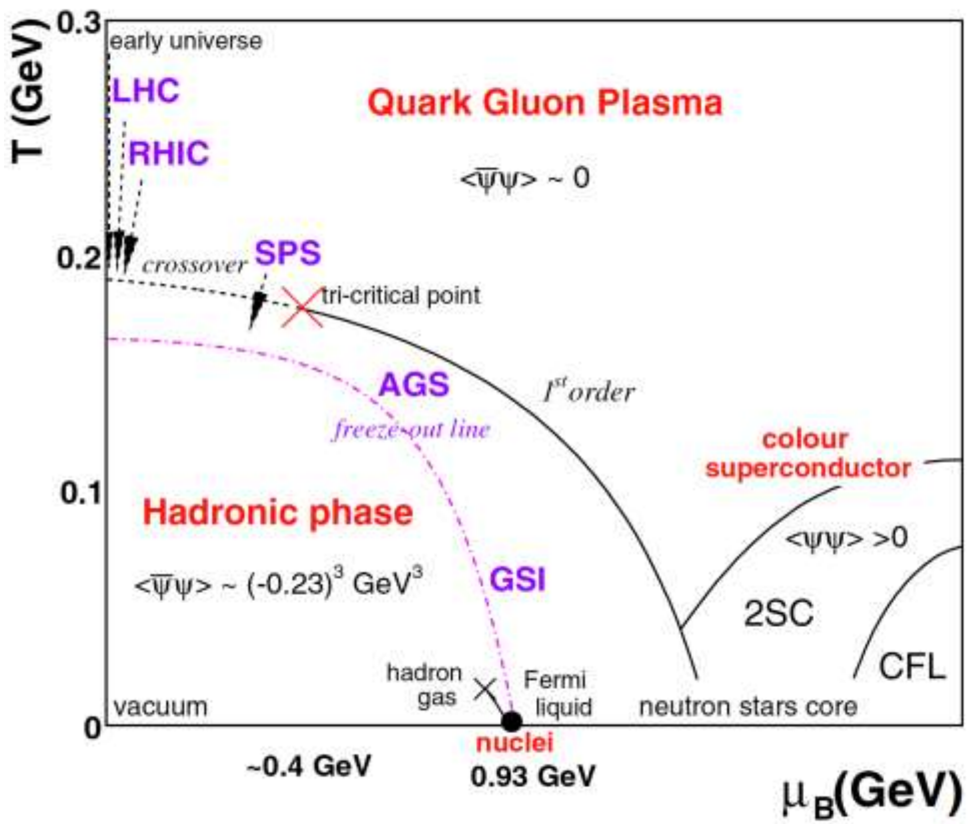
高エネルギー重イオン衝突の基礎

- QCD 相図
- 時空発展

QGP and QCD Phase Diagram

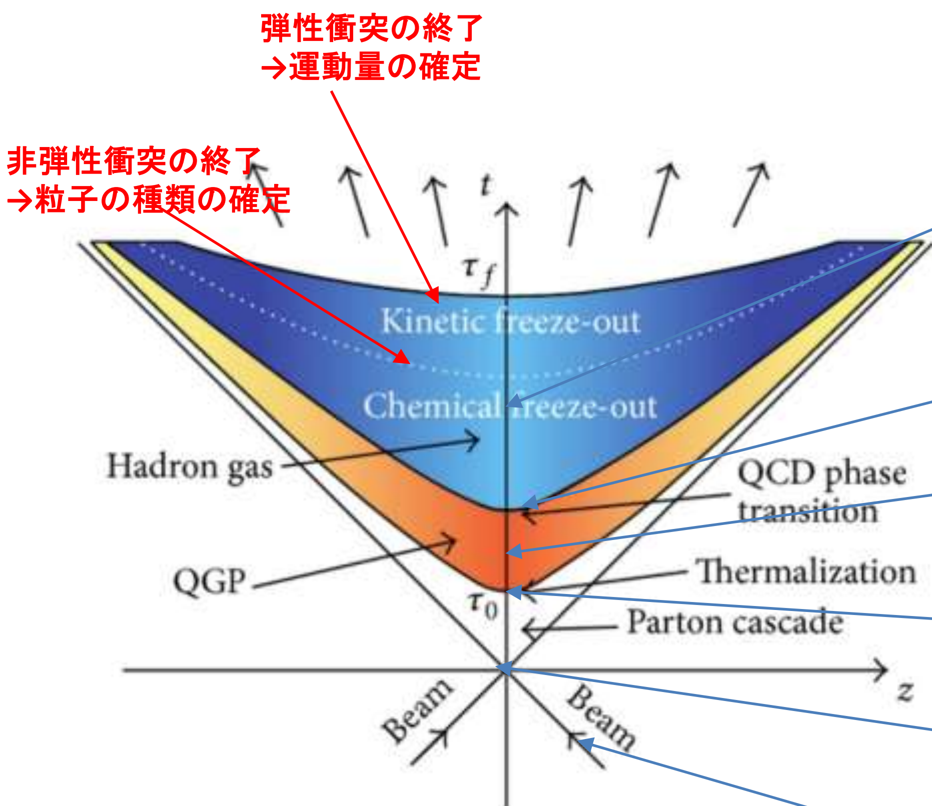


http://www.bnl.gov/rhic/QGP.htm

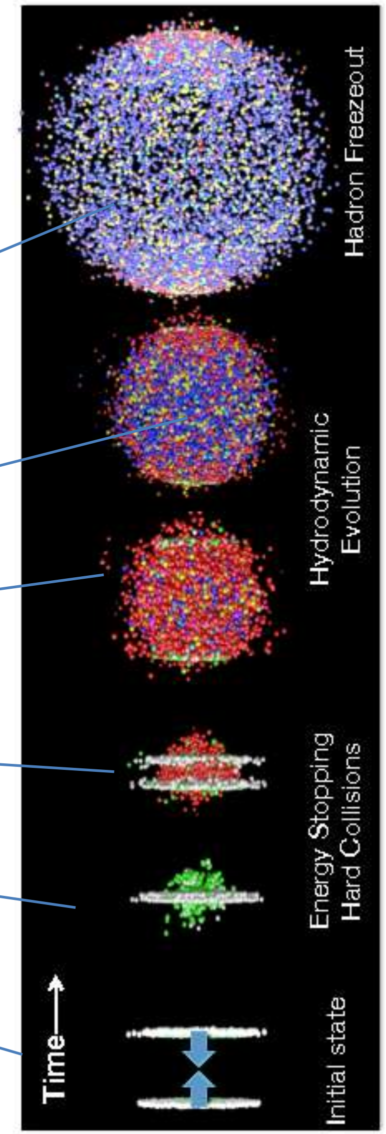


R. Pasechnik, Universe 3 (2017) no.1, 7

Time evolution of a heavy-ion collision



H. Wang, arXiv:1304.2073 [nucl-ex]



T. Nayak, Pramana 79 (2012) 719-735

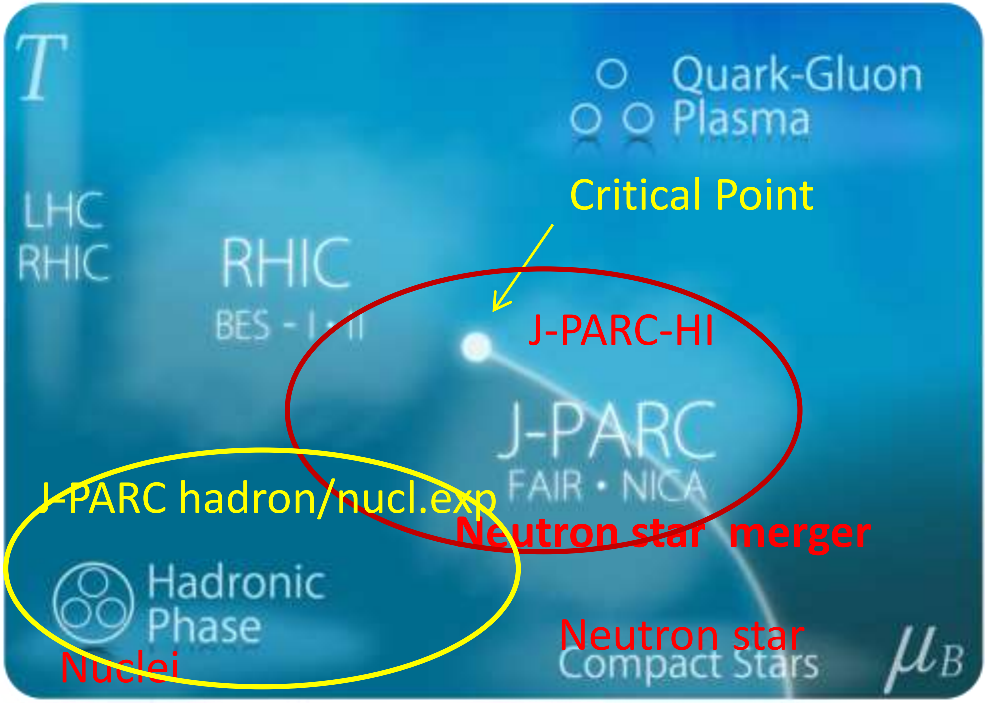

200 GeV Gold + Gold
RHIC at BNL

J-PARC重イオン計画(J-PARC-HI)

SPS/RHIC/LHCにおけるQGPの発見（高温、低バリオン密度）
相転移はクロスオーバー（格子QCD計算による）

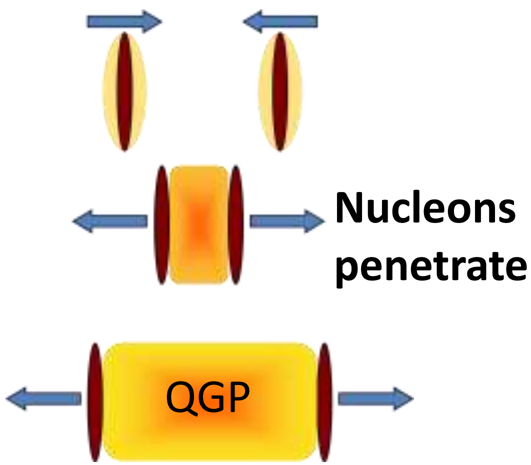
高密度領域における QCD 相構造は未発見(一次相転移、臨界点)

J-PARC-HI は最高密度物質を生成($\rho_B \sim 7\rho_0$)
J-PARC-HIの目標
- QCD相構造の解明
- 超高密度物質の性質の解明
  - 状態方程式（EOS）等

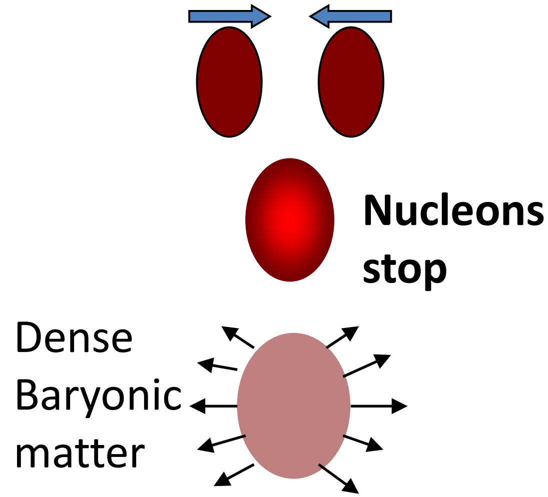


Highest baryon density in HIC at J-PARC-HI

RHIC/LHC($\sqrt{s_{NN}}$>=200GeV)



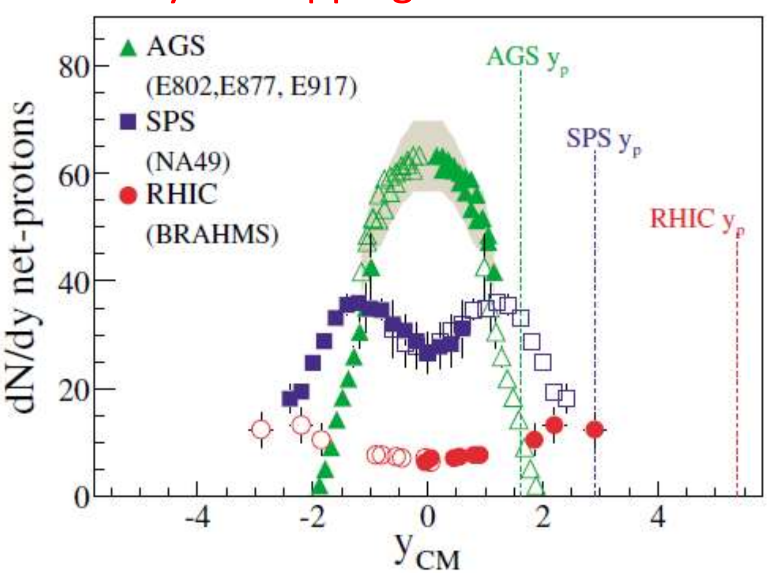
J-PARC/AGS($\sqrt{s_{NN}}$=4~6GeV)

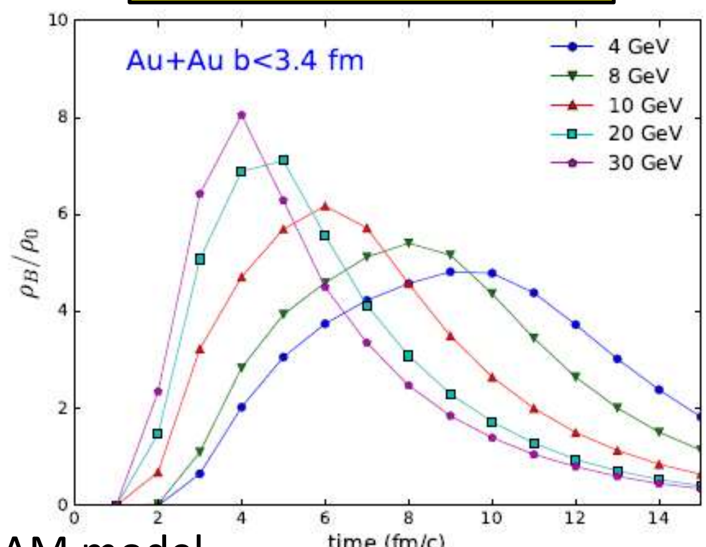


K. Itakura

ρ_{max} ~ $7\rho_0$ at 20 AGeV

Baryon stopping observed at AGS

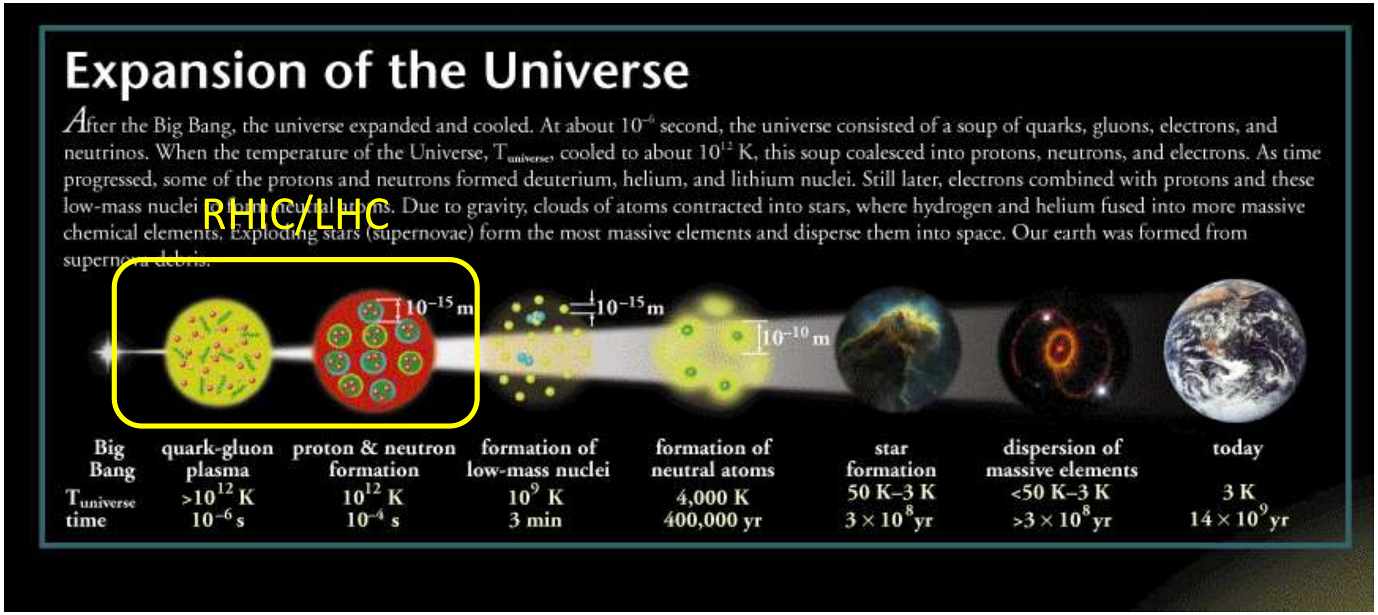


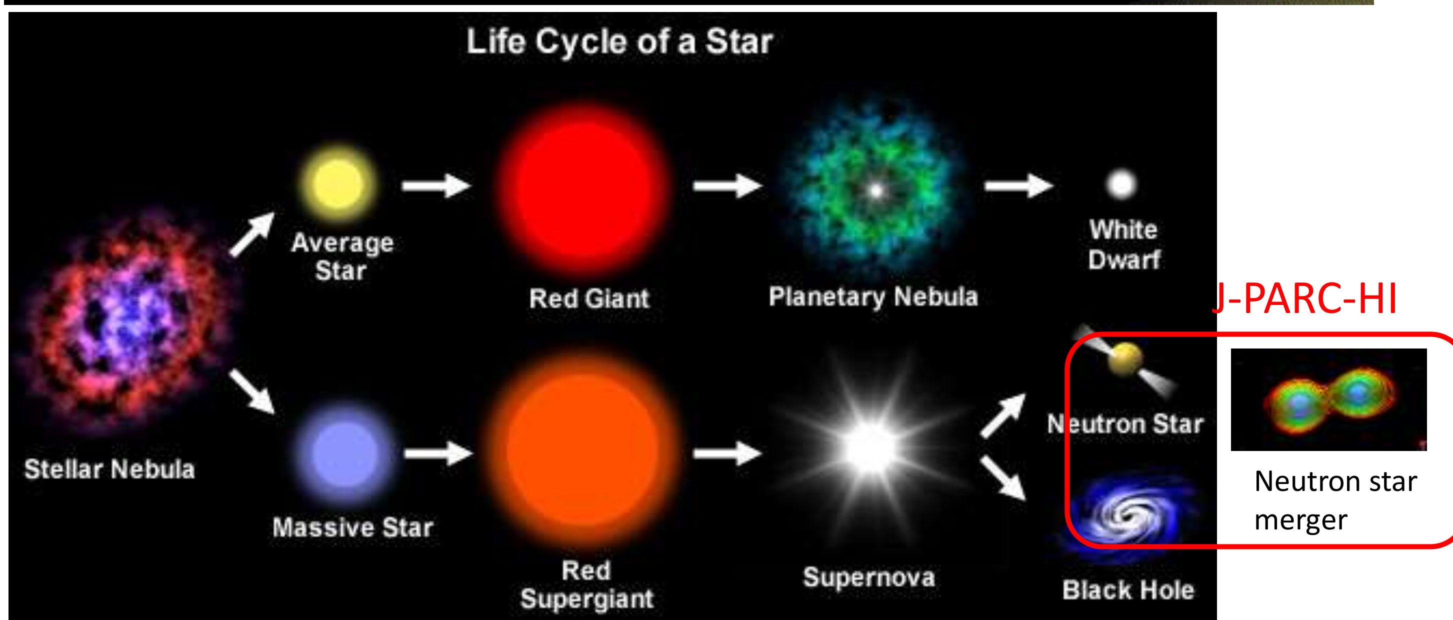


JAM model

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

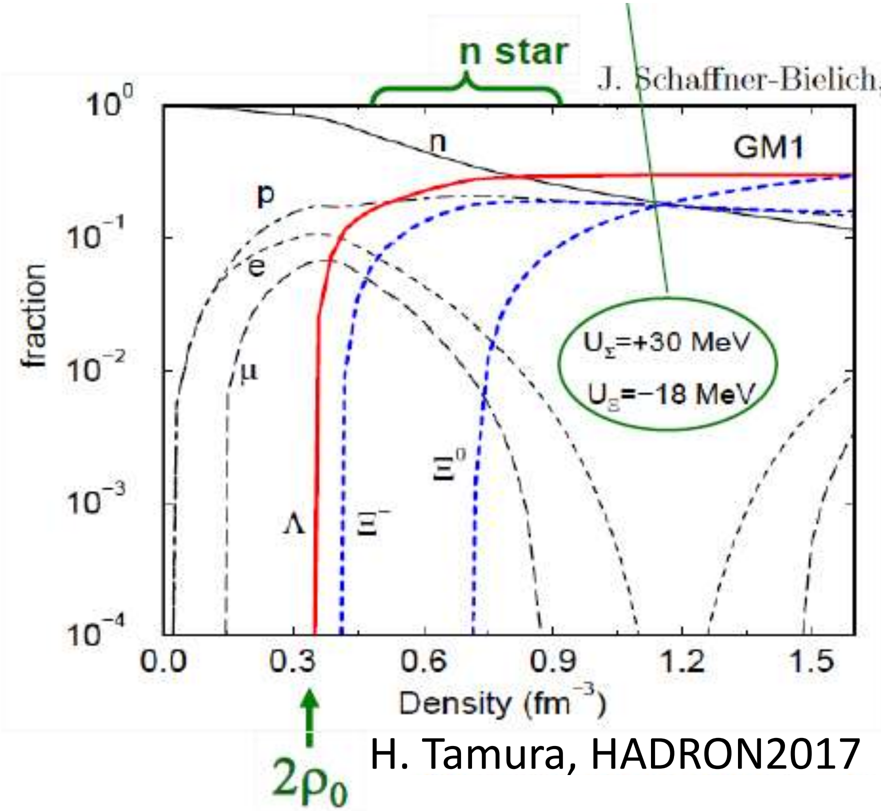
Evolution of the Universe



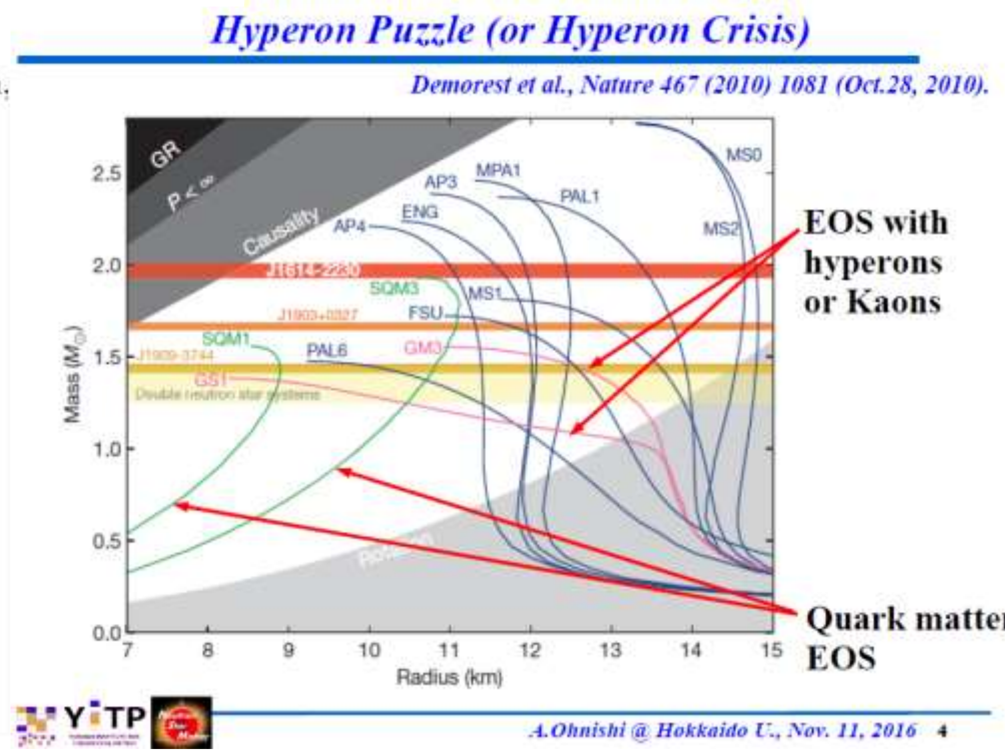


ハイペロンクライシス

太陽質量の2倍の超重中性子星の発見



H. Tamura, HADRON2017



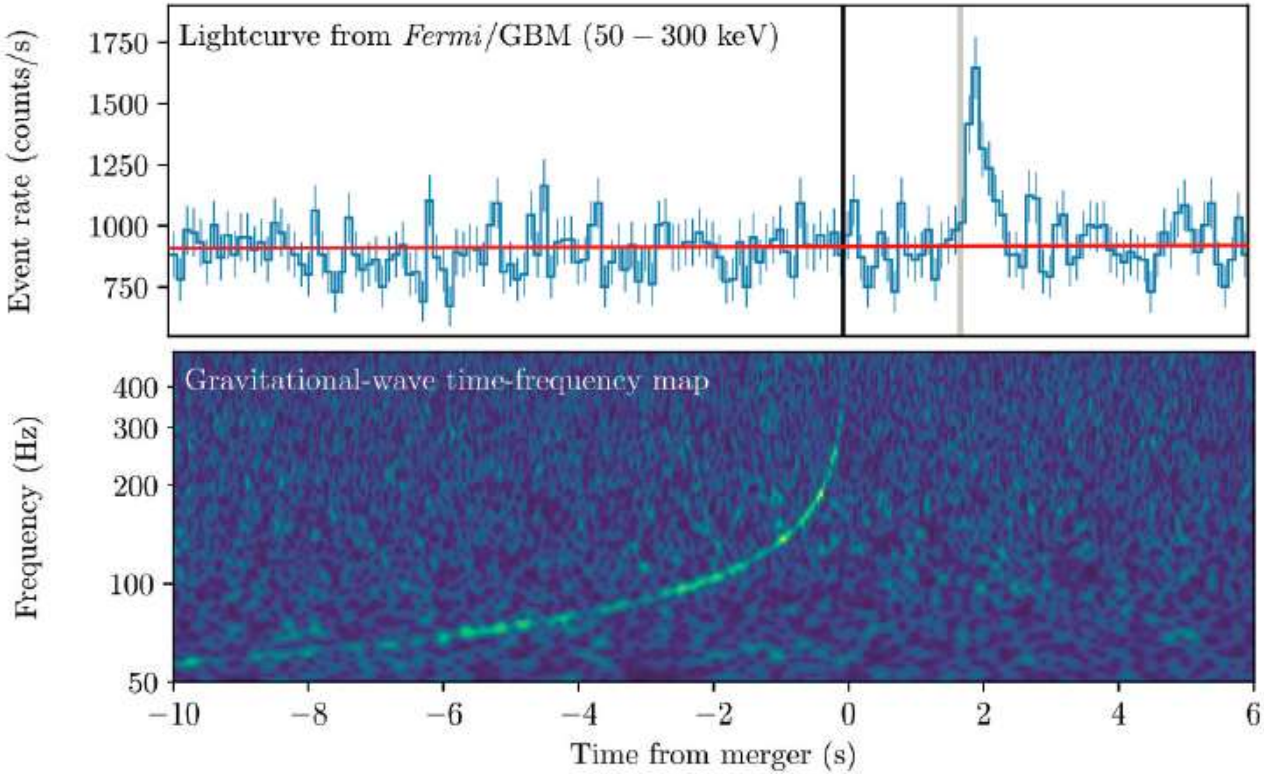
n,pのパウリ排他律により、
高密度になるとより重いΛ
の方が生成しやすくなる

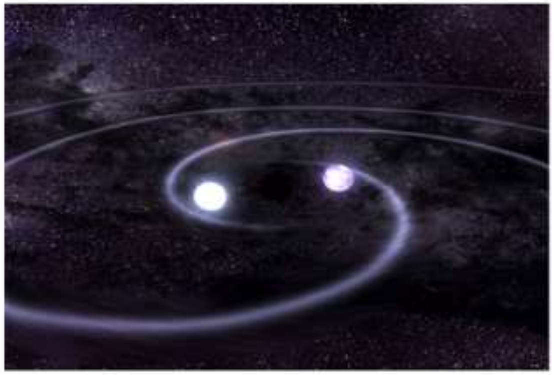
Proposed solutions

- YYY, YYN, YNN 3体力
- Hadron-Quark物質相転移

Gravitational waves from neutron star mergers

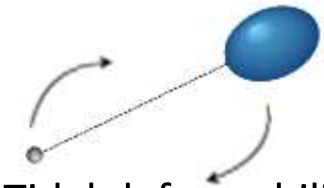
On 17 Aug. 2017: Gravitational wave signal with associated electromagnetic counterpart across spectrum



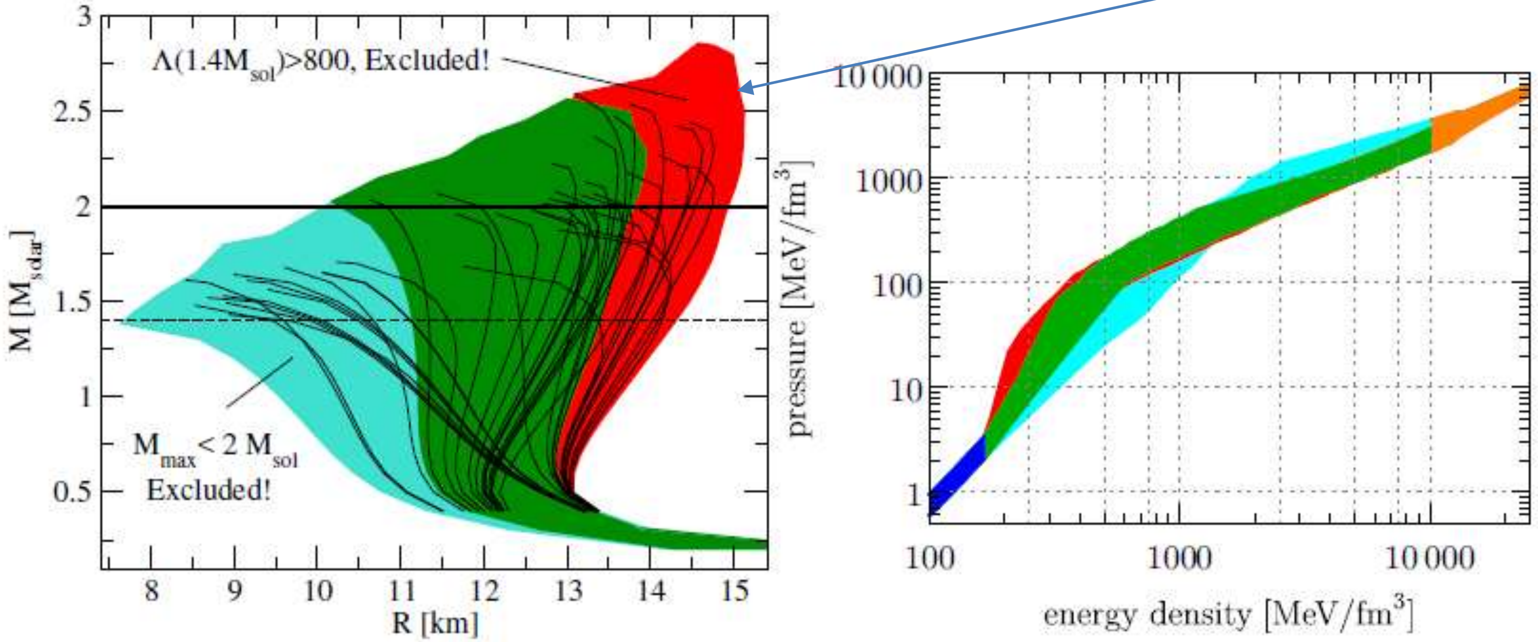


Gravitational waves: PRL. 119, 161101 (2017), γ-ray: APJ. 848 (2017) L13
Aslo: X-ray, UV, Optical, IR, Radio APJL, 848 (2017) L12

Talk in ALICE Week, Nov. 2017, Aleksi Kurkela



Constraining QCD using neutron star properties



- Requiring $\Lambda(1.4M_\odot) < 800$ implies that the matter is soft enough
- Upper limit for radius: $R(1.4M_\odot) < 13.4\text{km}$
- Uncertainty in $e(p)$ at worst $\pm 60\%$

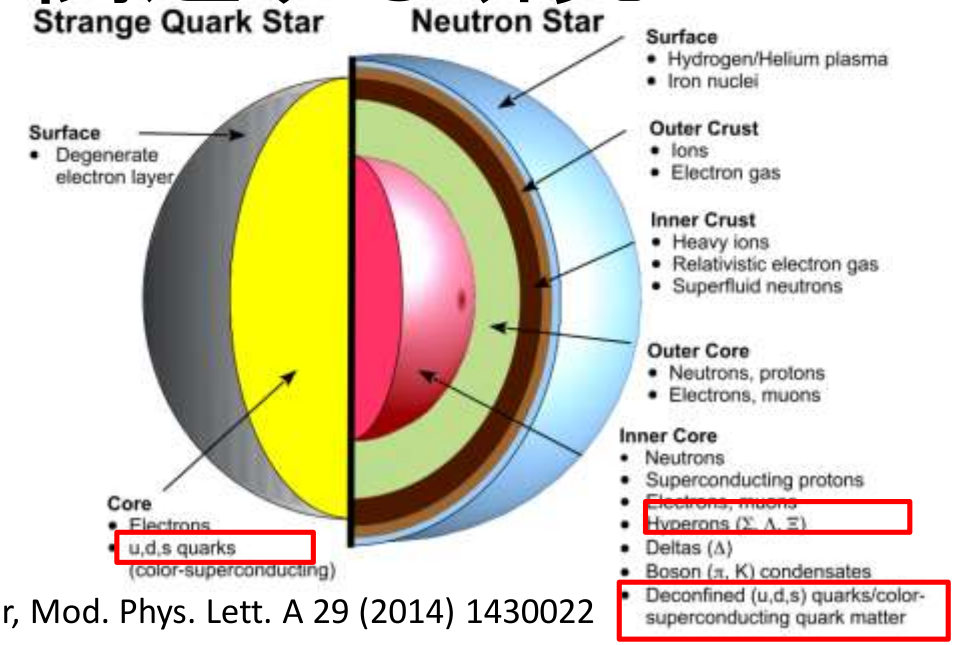
Talk in ALICE Week, Nov. 2017, Aleksi Kurkela

重イオン衝突を用いた中性子星に関連する研究

EOS
Collective flow (→ initial pressure)

YN, YY, YYN interactions
Two/three-particle momentum correlations

Strange quark matter
Search for strangelets
(E. Witten, PRD30 (1984) 272)



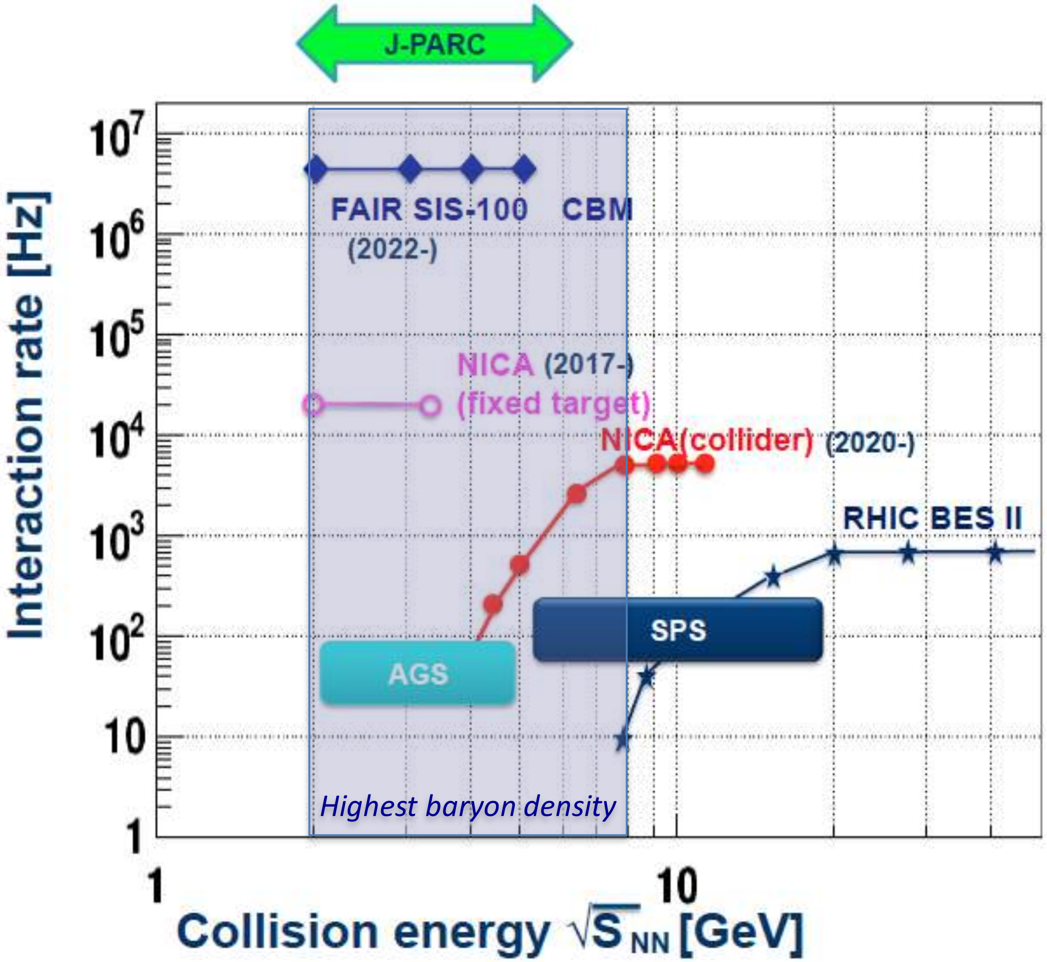
F. Weber, Mod. Phys. Lett. A 29 (2014) 1430022

	NS	NS-NS merger	HIC
T (MeV)	<10	40-70*	~120 (@ chem. freezeout)
B (G)	10^{10}-10^{13} **	~10^{13}***	~10^{16} **
Z, N	Z~0	Z~0	Z~N
lifetime	~10^9 y	~1 s	~10 fm/c ~ 10^{-23}s

*R. Oechslin et al, Astron. Astrophys. 467 (2007) 395, **K. Tuchin, Adv. High Energy Phys. 2013:490495
***T. Kawamura et al, PRD94 064012 (2016)

J-PARCにおける重イオンビーム

- ***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



Statistics
1 year at AGS = 5 min at J-PARC-HI

Beam rate: 10^{11} Hz

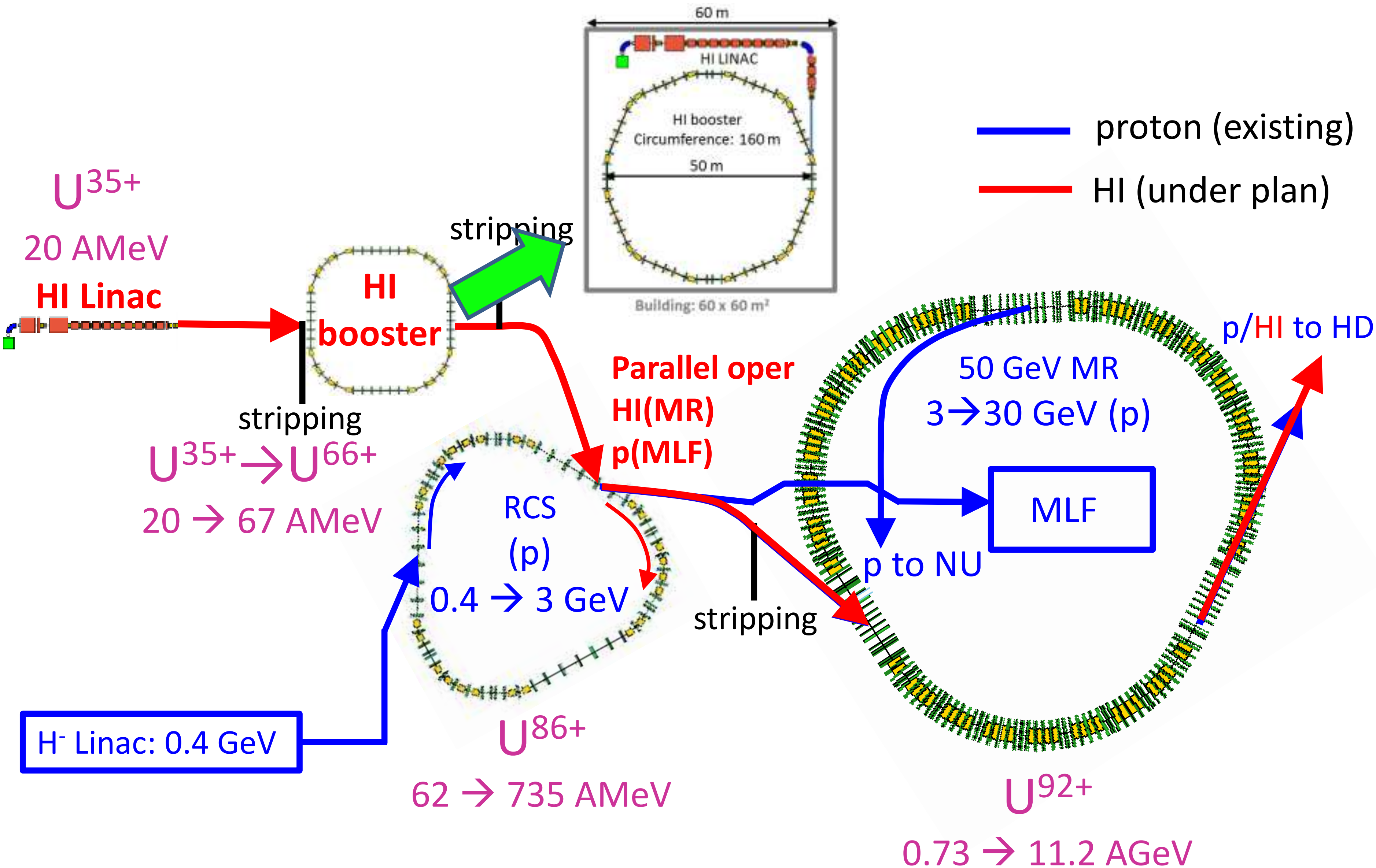
0.1% λ_I target
→ Interaction rate: 10^8Hz

In one month experiment:
ρ,ω,ϕ→ee: 10^{10} - 10^{12}
Hypernuclei: 10^4 – 10^{12}
J/Ψ, D : 10^7-10^9
Strangelets: 1 - 10^2

Ref: HSD calculations in FAIR Baseline Technical Report (Mar 2006)
A. Andronic, PLB697 (2011) 203

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

重イオンビーム加速



60 m
HI LINAC
HI booster
Circumference: 160 m
50 m
Building: 60 x 60 m²
proton (existing)
HI (under plan)
U^{35+}
20 AMeV
HI Linac
HI
booster
stripping
stripping
$U^{35+} \rightarrow U^{66+}$
20 → 67 AMeV
RCS
(p)
0.4 → 3 GeV
U^{86+}
62 → 735 AMeV
H^- Linac: 0.4 GeV
Parallel oper
HI(MR)
p(MLF)
stripping
50 GeV MR
3→30 GeV (p)
MLF
p to NU
p/HI to HD
U^{92+}
0.73 → 11.2 AGeV

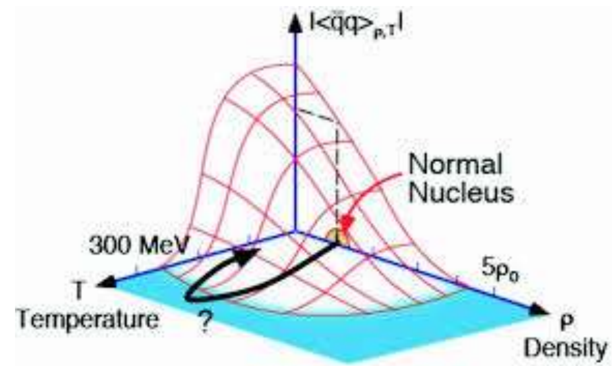
J-PARC-HIにおけるQCD相構造・中性子星EOSに関連する観測量

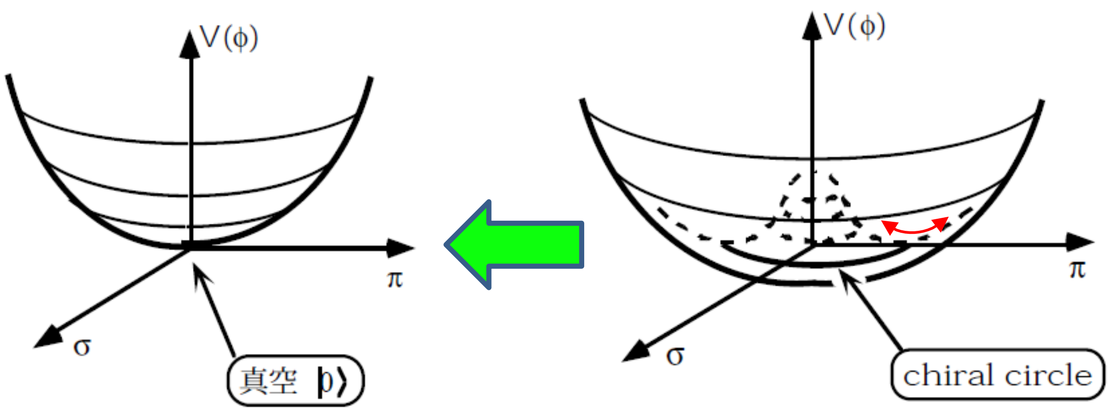
- レプトン対
  - Modification of $\rho/\omega/\phi$ linked to QCD vacuum properties
- ハドロン（高統計）
  - Event-by-event fluctuations
  - Collective flow (search for 1^{st} order transition)
  - 2 particle correlations of hyperons and nucleons
- 光子
  - Thermal radiations from QGP
- チャームハドロン
  - J/ψ, D,…
    - Sensitive to initial dense matter

自発的対称性の破れとクォーク凝縮

- 低温、低密度真空中では、南部理論により、カイラル対称性*が自発的に破れている
  - 軽い質量の南部-Goldstoneボゾン（π中間子）
  - 有限のクォーク凝縮$\langle q\bar{q}\rangle$
- 高温、高密度になると対称性の回復が起こる
  - $\langle q\bar{q}\rangle$=0

*カイラル対称性：クォークのフレーバーを右巻きスピン成分と左巻きスピン成分で独立に変換する対称性

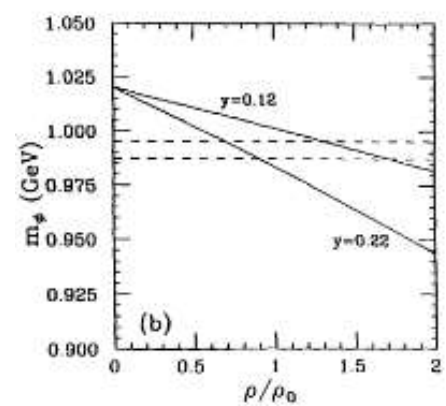




高温/高密度
$\langle q\bar{q}\rangle = 0$

低温・低密度
$\langle q\bar{q}\rangle \neq 0$

保坂淳、原子核三者若手夏の学校2002



φ質量の密度による変化

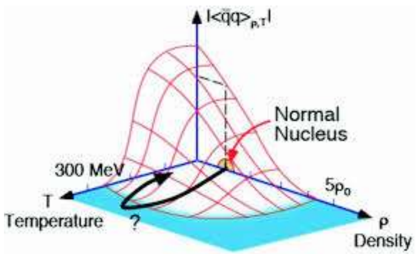
$$M_V^*/M_V = 1 - C_V \cdot (\rho/\rho_0)$$

$$C_V = 0.30\langle s\bar{s}\rangle/(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$$

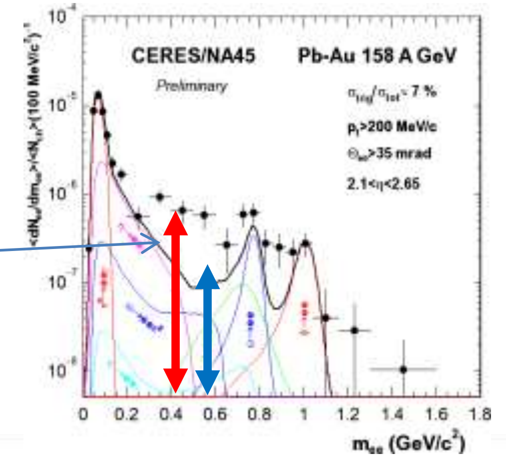
T. Hatsuda, QM97

Low-mass di-leptons

Modification of vector mesons (ρ, ω, ϕ) in high density matter
→Change of QCD vacuum property (quark condensate)



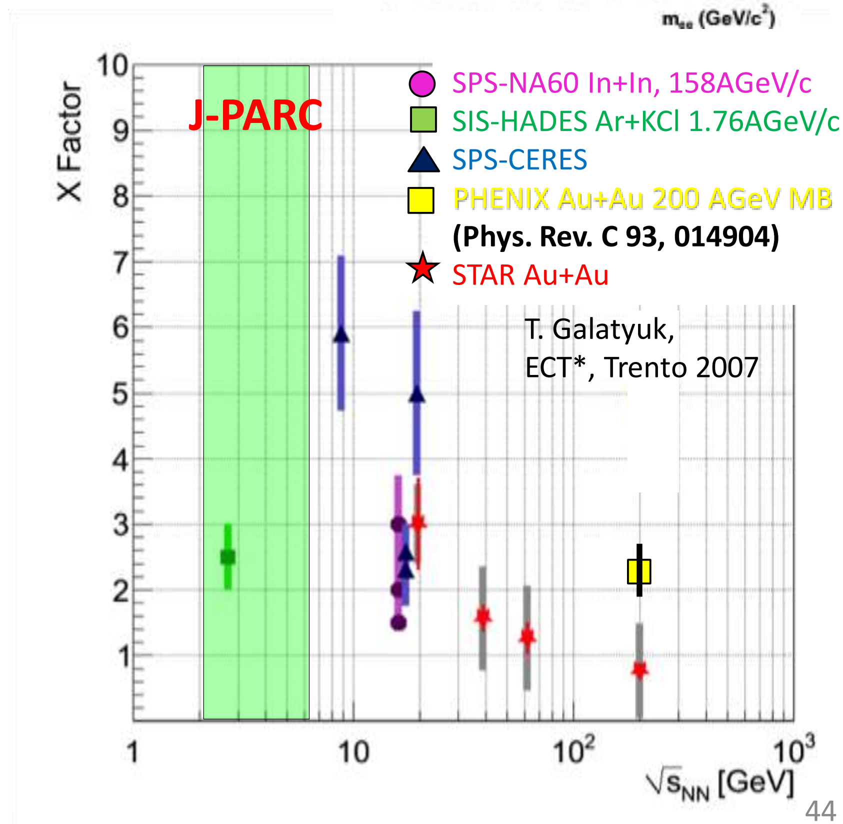
Low mass enhancement factor
= Measured dilepton (ρ region) / Baseline in p+p collision



- Dielectron and Dimuon measurements
  - Good systematic studies
- Highest ever statistics at J-PARC
  - Moment analysis

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

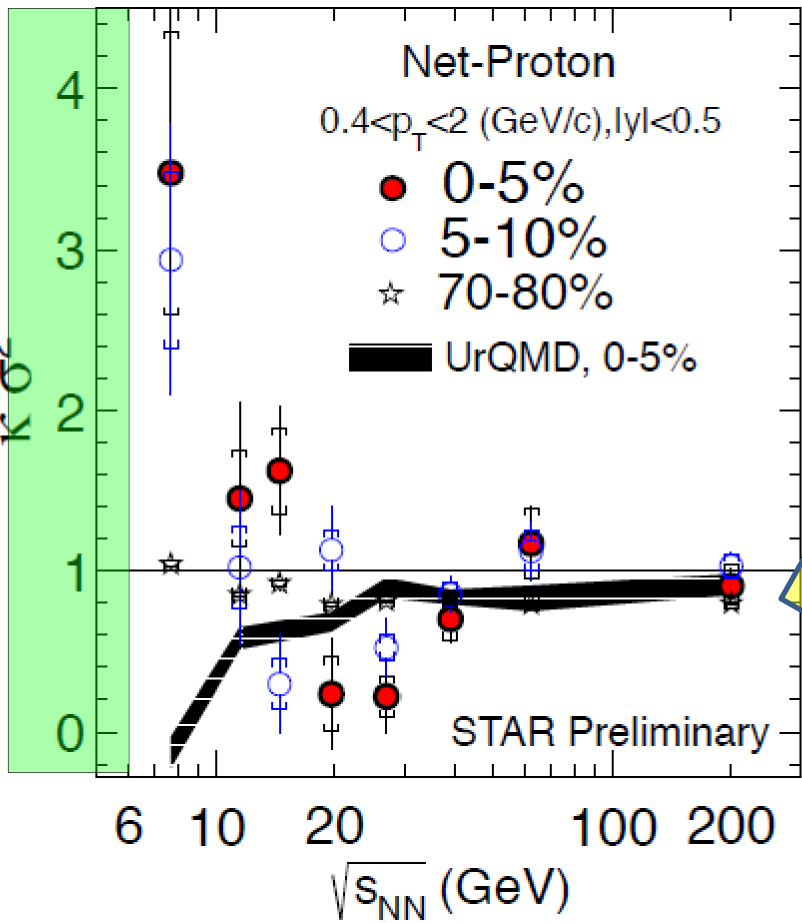
→Direct extraction of QCD vaccuum property
(quark and gluon condensate)
Hayano and Hatsuda, RMP**82**, 2949



Event-by-event fluctuations

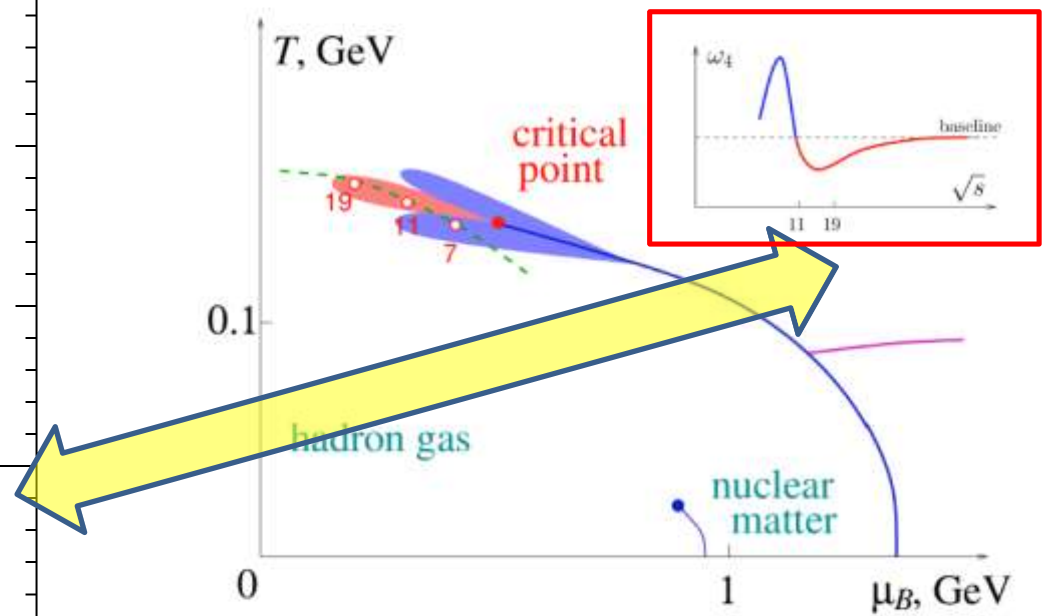
Event-by-event fluctuations of conserved charge:

Probe to search for the critical point



Theory

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



Enhancement of 4th-order fluctuations at low energies

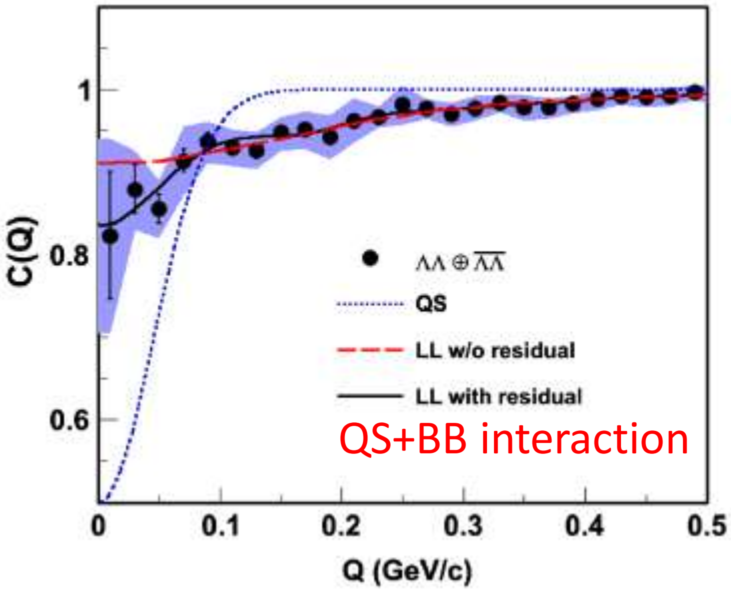
Indications of the critical point?

→ J-PARC-HI may answer that.

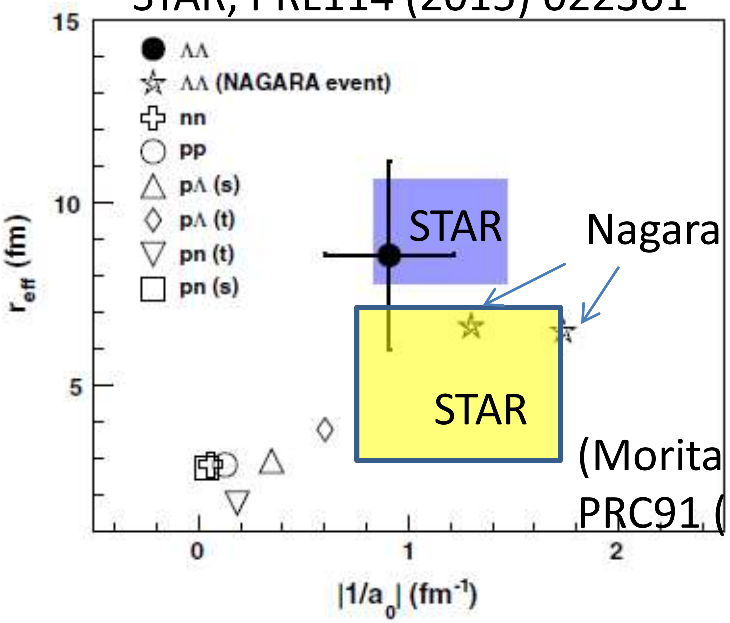
X. Luo, Quark Matter 2015

Hyperon correlation in HI collisions

$\Lambda\Lambda$ correlation function



STAR, PRL114 (2015) 022301

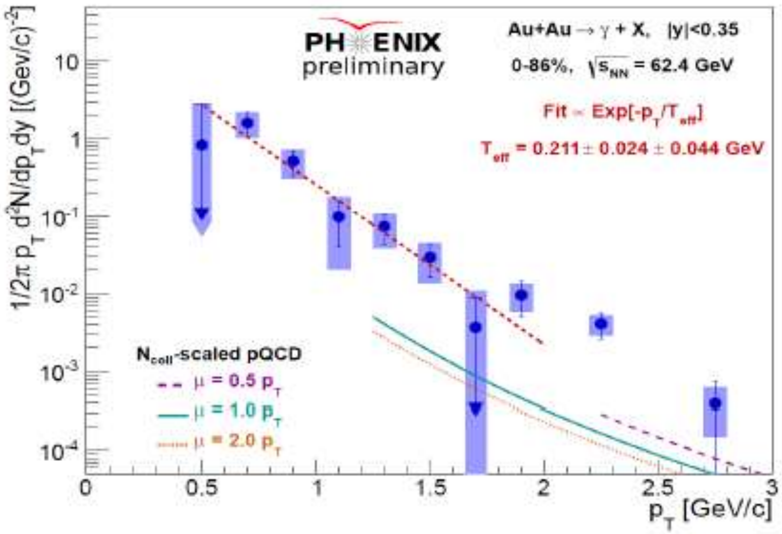


(Morita et al PRC91 (2015) 024916)

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

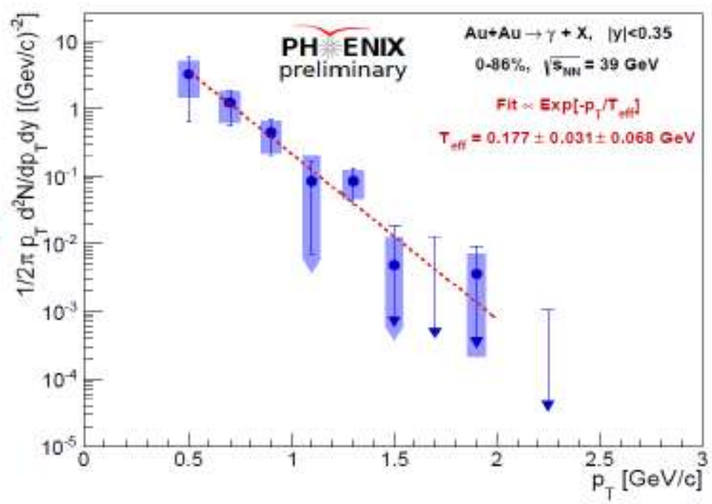
Direct photon production at RHIC

3.



← The invariant yield of direct photons in min bias 0-86% at 62.4 GeV collision energy

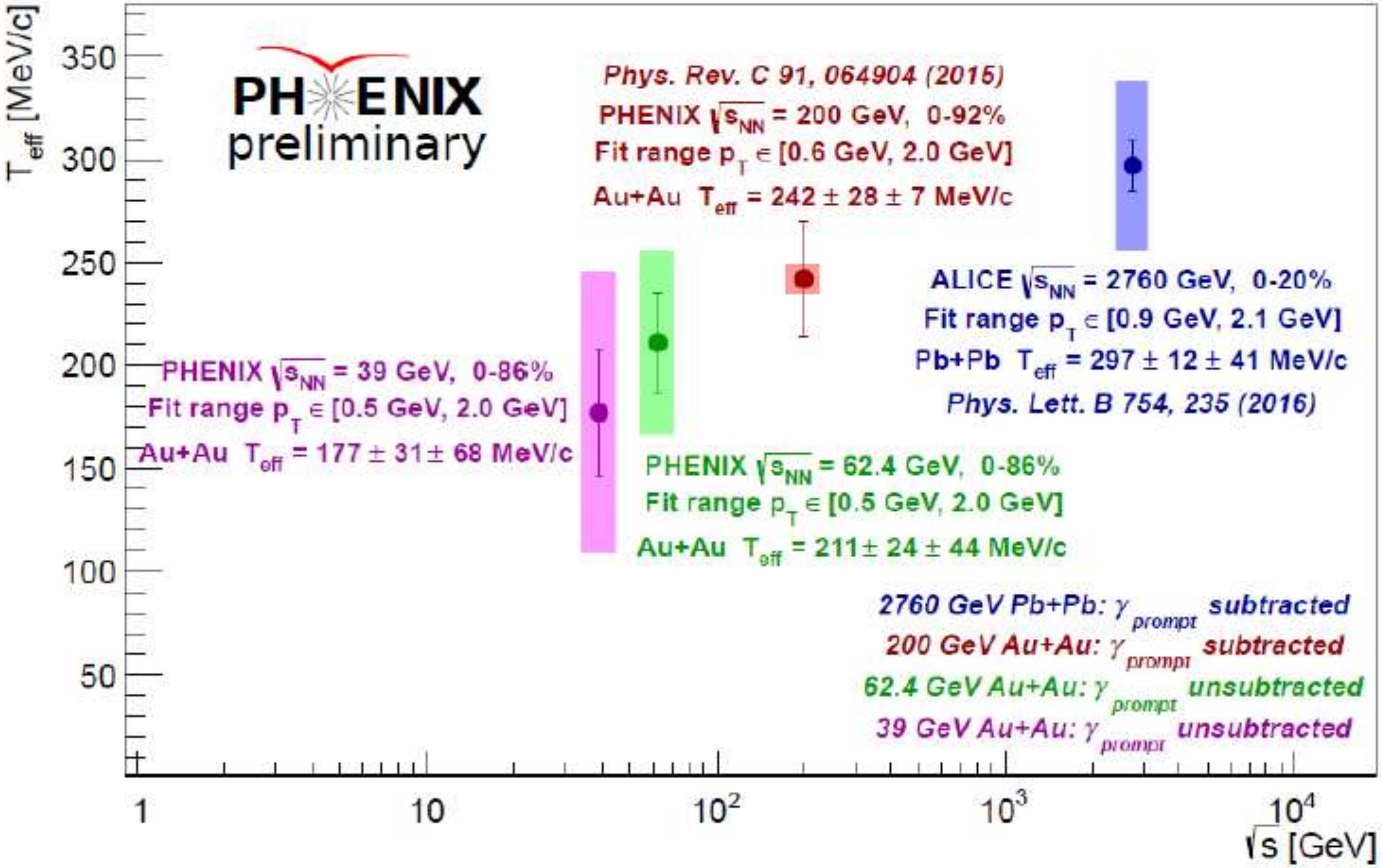
The invariant yield of direct photons in min bias 0-86% at 39 GeV collision energy →



14 V. Khachatryan CPOD 17

3.

T_{eff} vs. collision energy



The extracted T_{eff} at four collision energies: 2760 GeV, 200 GeV, 62.4 GeV and 39 GeV

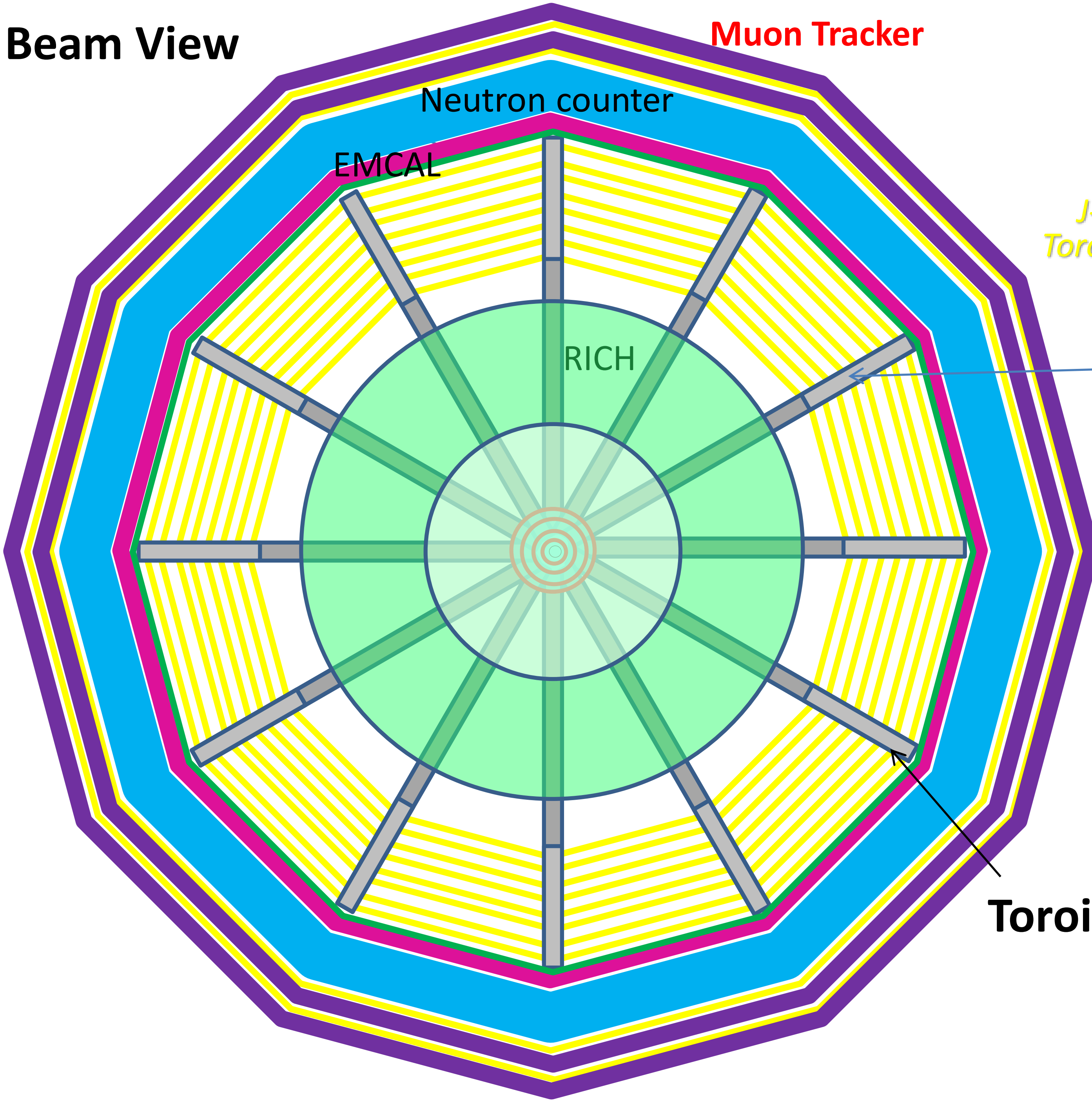
Experimental challenges

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

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

⇨ Toroidal magnet spectrometer

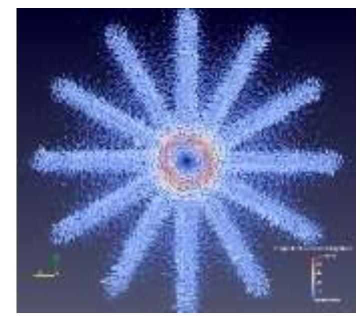
Beam View



JHITS

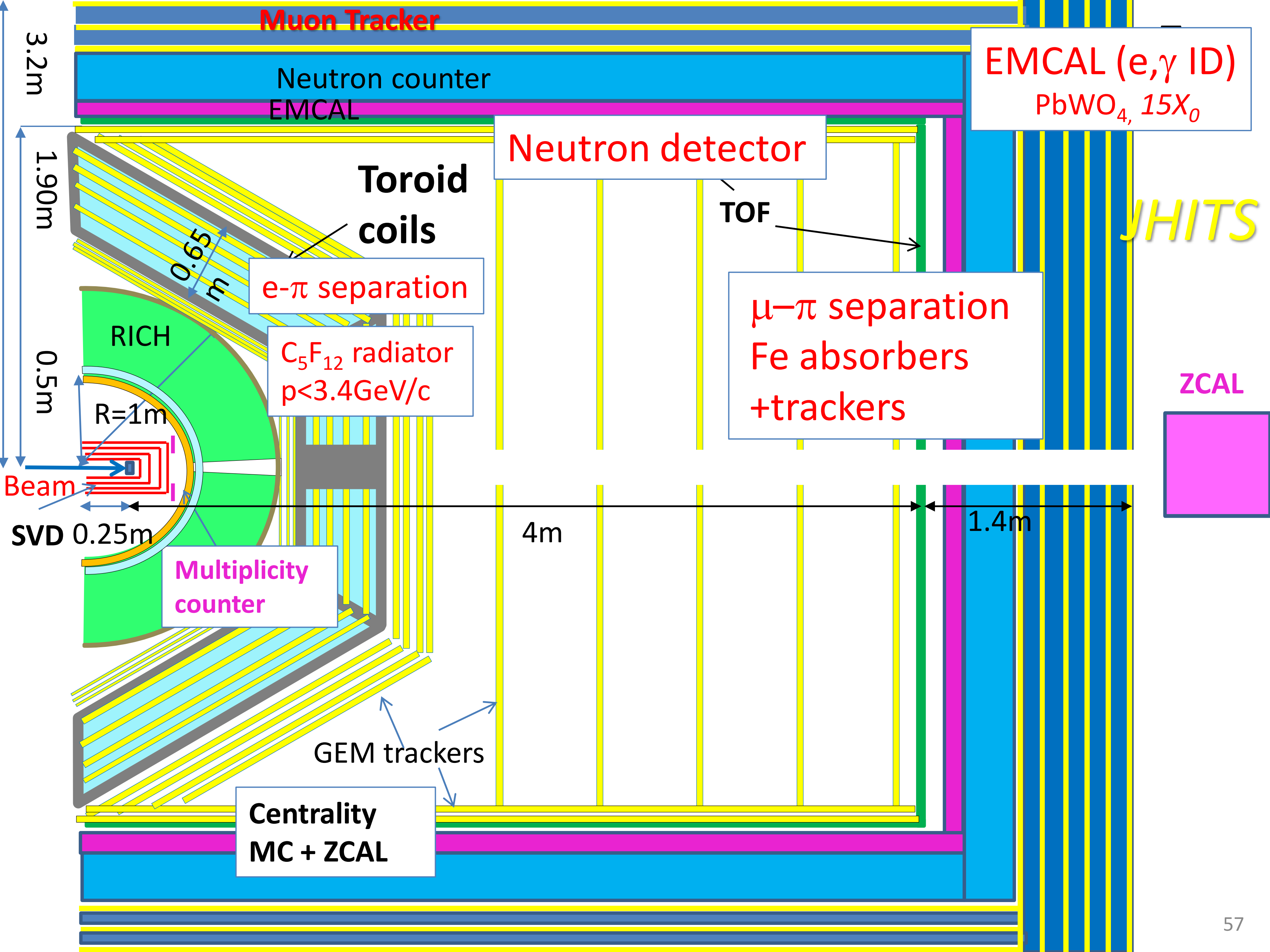
J-PARC Heavy Ion Toroidal Spectrometer

Coils = insensitive area

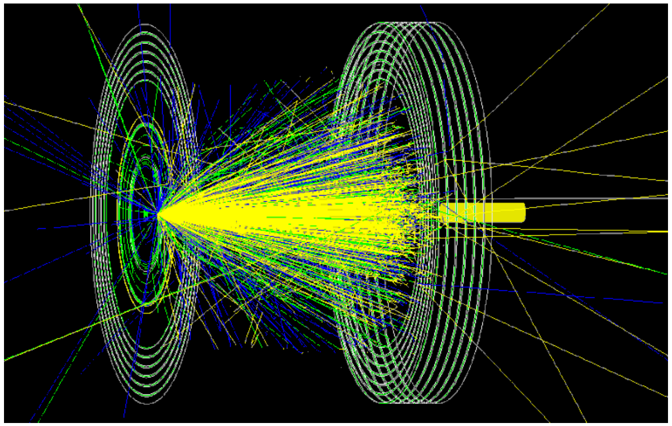


12-fold coils
Bϕ variations ~+-20%

Toroid coils


Muon Tracker
3.2m
Neutron counter
EMCAL
EMCAL (e,γ ID)
PbWO4, 15X0
Neutron detector
Toroid
coils
TOF
1.90m
0.65 m
e-π separation
JHITS
RICH
C5F12 radiator
p<3.4GeV/c
μ−π separation
Fe absorbers
+trackers
0.5m
ZCAL
R=1m
Beam
SVD 0.25m
4m
1.4m
Multiplicity
counter
GEM trackers
Centrality
MC + ZCAL

Spectrometer performance



H. Sako, B.C. Kim

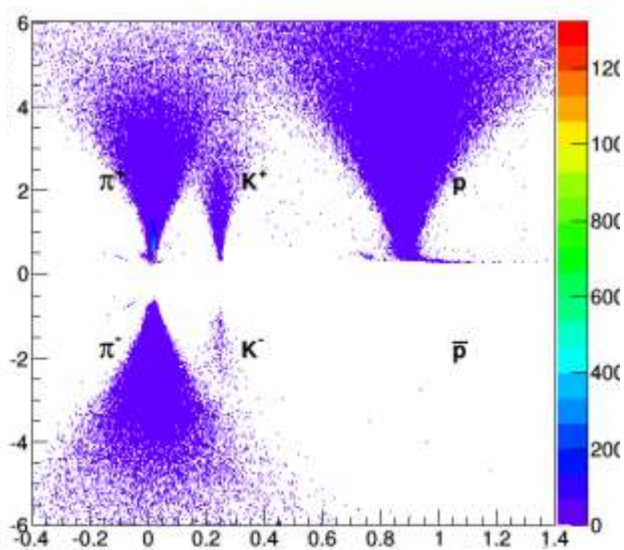
U+U at 10AGeV/c with JAM + GEANT4

- Assumption for simplicity
  - Half-spherical toroidal shape
  - Uniform B_ϕ field
  - No dead area due to coils
- Acceptance >= 78 %
- π/K separation 2.5GeV/c (2.5σ)

Assuming TOF resolution of 50 ps

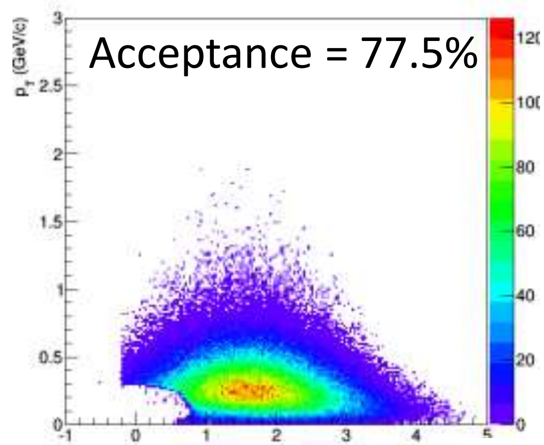
Forward trackers

p/Z (GeV/c)



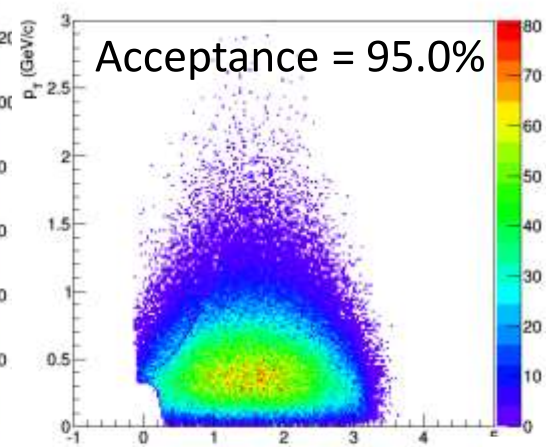
m² (GeV/c²)

π^+



y

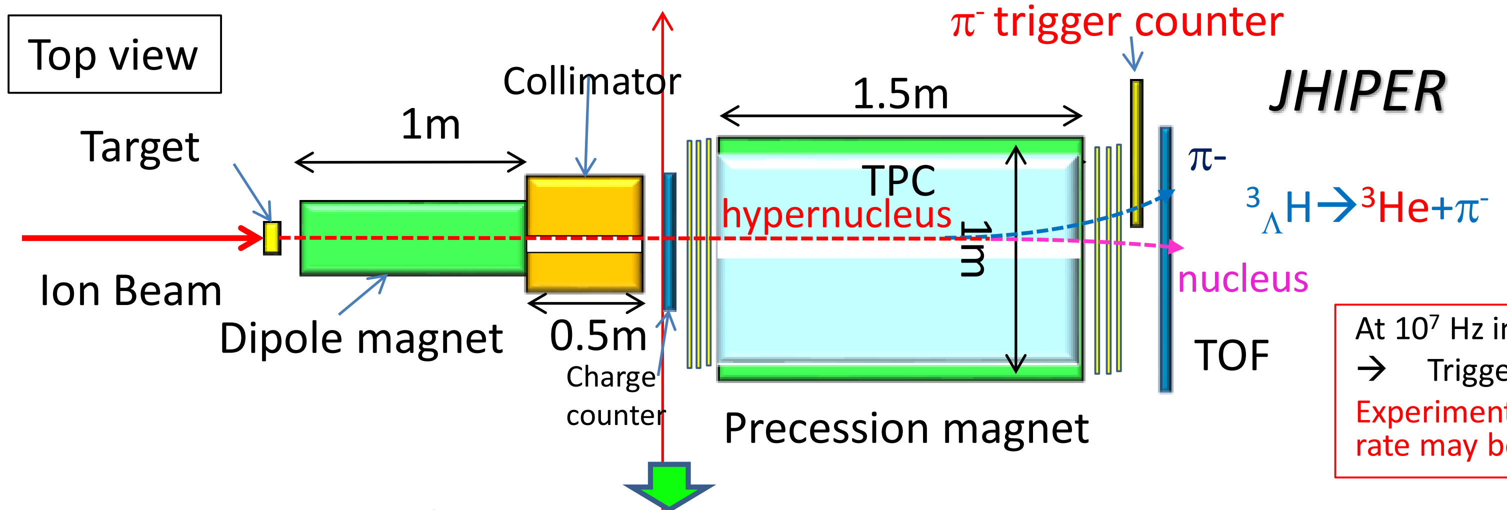
p



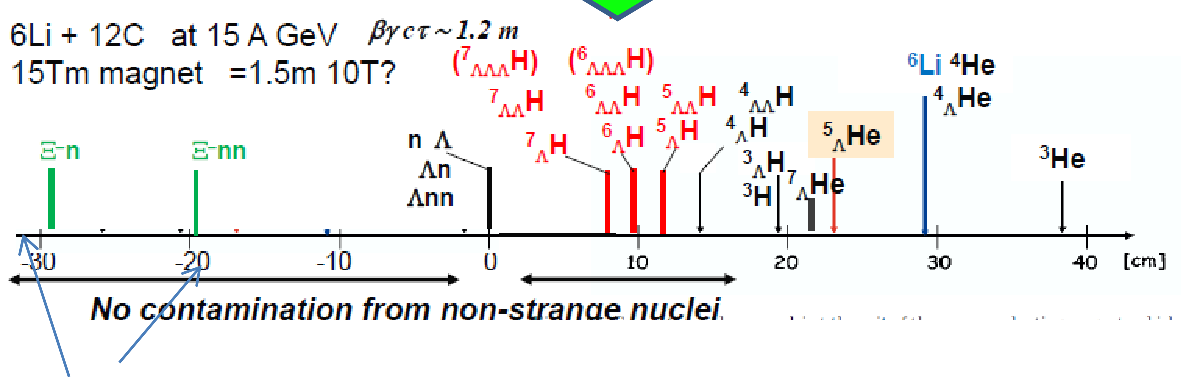
y

Hypernuclear spectrometer (JHIPER)

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



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



If found, discovery of negative nuclei

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

まとめ

π/K/pビームによるJ-PARCのハドロン実験

- ハイパー核、エキゾティックハドロン、K中間子原子核、原子核中のベクトル中間子の研究等

J-PARC重イオン将来計画

- 超高バリオン密度物質の生成による、QCD相構造と中性子星に関連する超高密度物質の研究
- 世界最高レートの重イオンビーム（10^{11} Hz）による超高統計物理
  - 1990年代に行われたAGSでは測定できなかった重要観測量の測定
  - Event-by-event fluctuations, dileptons, multi-strangeness systems
- 2025年開始を目指す

J-PARC-HI Collaboration

94 members :

Experimental and Theoretical Nuclear Physicists and Accelerator Scientists

Experiment

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

Theory

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

Accelerator

H. Harada, P. K. Saha, M. Kinsho, Y. Liu, J. Tamura, M. Yoshii, M. Okamura, A. Kovalenko, J. Kamiya, H. Hotchi, A. Okabe, F. Tamura, Y. Shobuda, N. Tani, Y. Watanabe, M. Yamamoto, M. Yoshimoto

ASRC/JAEA, J-PARC/JAEA, J-PARC/KEK, Tokyo Inst. Tech, Hiroshima U, Osaka U, U Tsukuba, Tsukuba U Tech, CNS, U Tokyo, Tohoku U, Nagasaki IAS, Kyoto U, RIKEN, Akita International U, Nagoya U, Sophia U, U Tokyo, YITP/Kyoto U, Nara Women's U, KEK, BNL, Mainz U, GSI, Central China Normal U, Korea U, Chonbuk National U, Pusan National U, JINR, U Belgrade, Wigner RCP, KRF, Stony Brook U, Bhaba Atomic Research Centre, Far Eastern Federal U