11th December 2024

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THE UNIVERSITY OF TOKYO

QNSI
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Future Hypernuclear studies at J-PARC and JLab

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

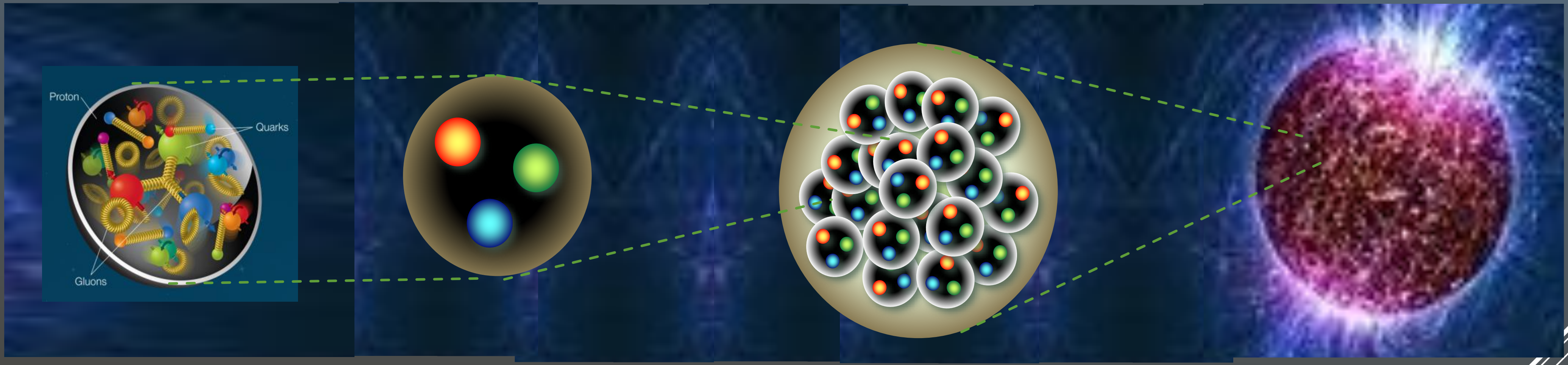
Jefferson Lab
EXPLORING THE NATURE OF MATTER

Quantum many-body systems which strong force governs

Nucleon

(Hyper)Nucleus

Neutron Star



Gluons and Sea Quarks

Hadron from Valence Quarks

Nucleus from Hadrons

Materials from Nuclei
incl. **Neutron Stars**

HYPERON Puzzle

Mystery of heavy Neutron Stars.

Based on our knowledge of baryonic force,
Hyperon naturally appear at high density $(\rho \sim 2{,}3\rho_0)$

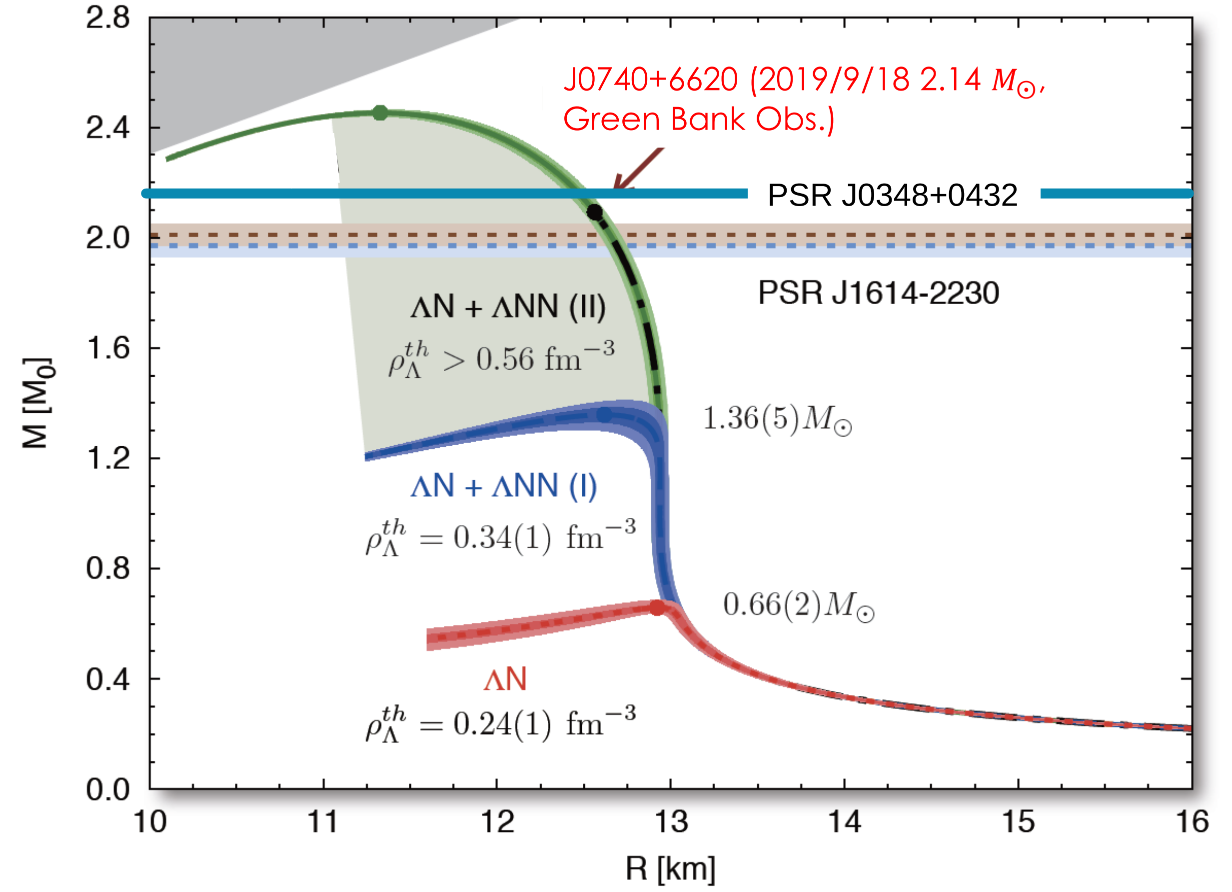
Too soft EOS. **NS cannot support mass of 2 $M_\odot$**

Contradict to astronomical observations.

Need **additional repulsive force**
(ΛNN 3-body repulsive force)
Make stiffer EOS

Neutron star : **Large $(N-Z)/A \geq$ 0.9 and Large A**

Iso-spin dependence A dependence

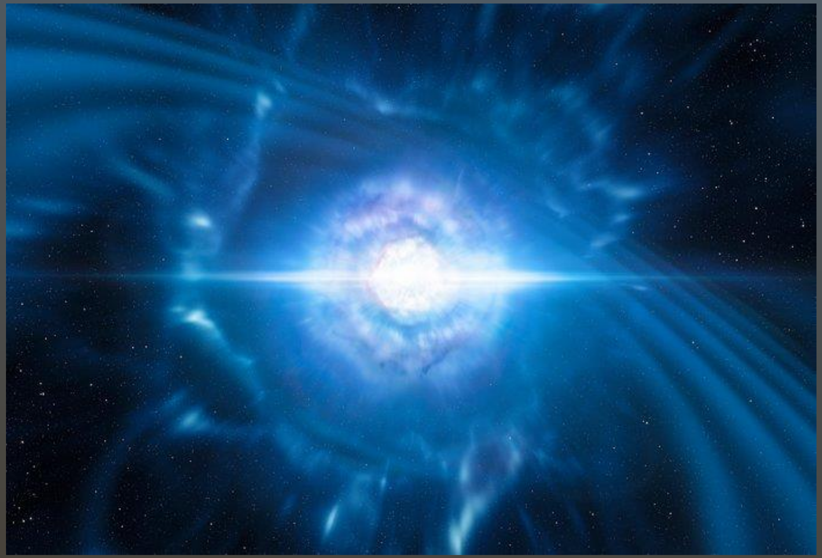


2 solar mass NS

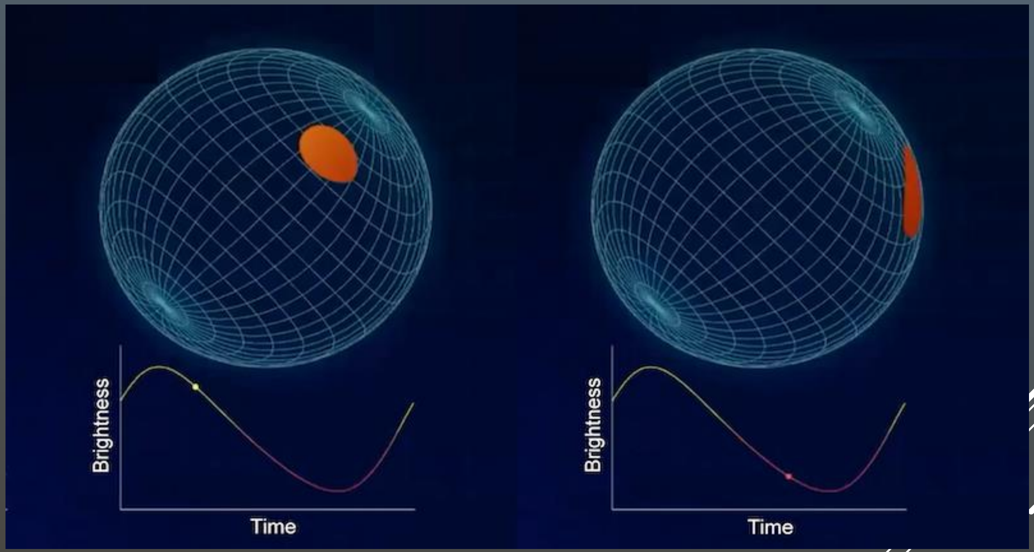
New astronomical observations

New Gravitational Waves from NS mergers and NICER (Neutron star Interior Compsition ExploreR)

CC4.0 ESO/L. Calçada/M. Kornmesser



Gravitation Wave from neutron star mergers
LIGO/Virgo PRL **119**, 161101 (2017)

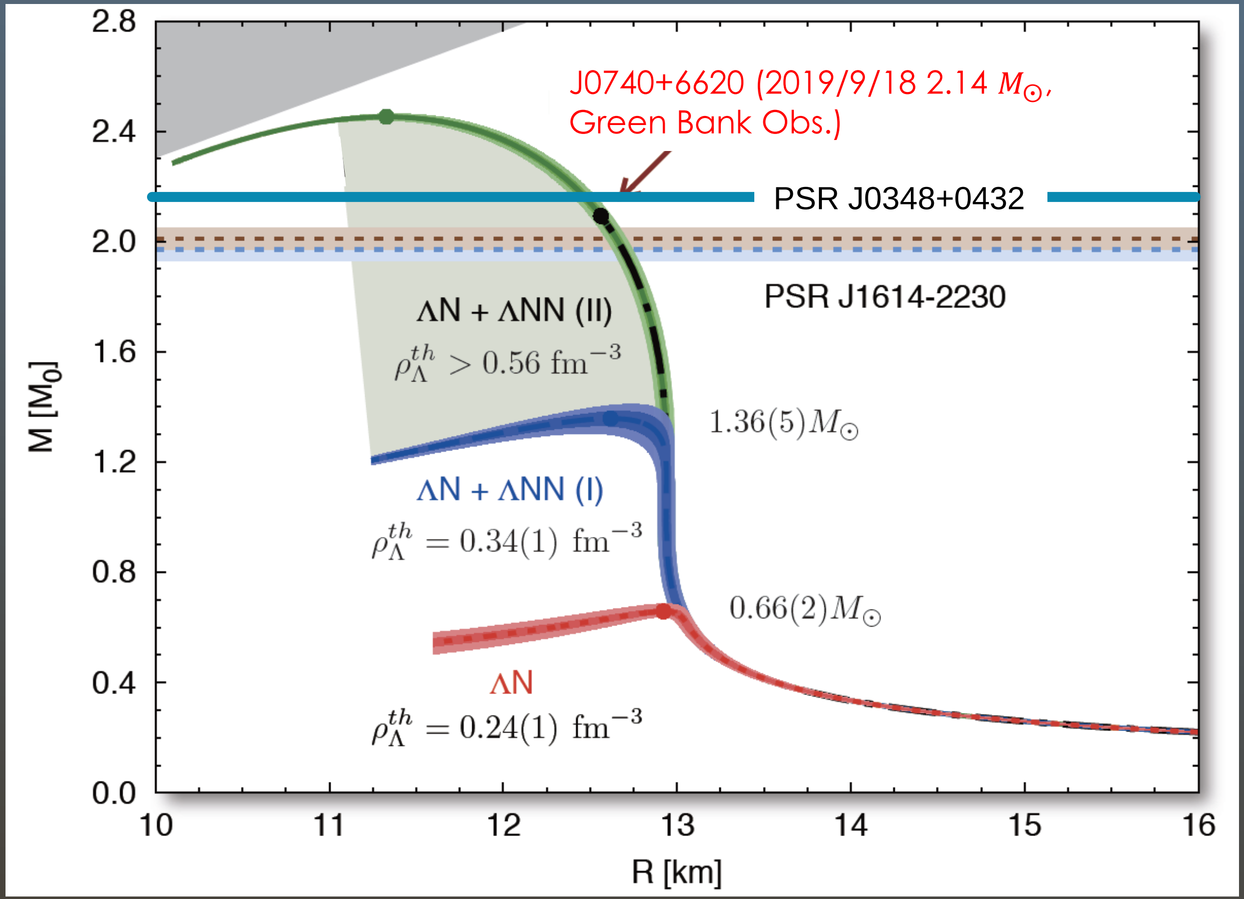


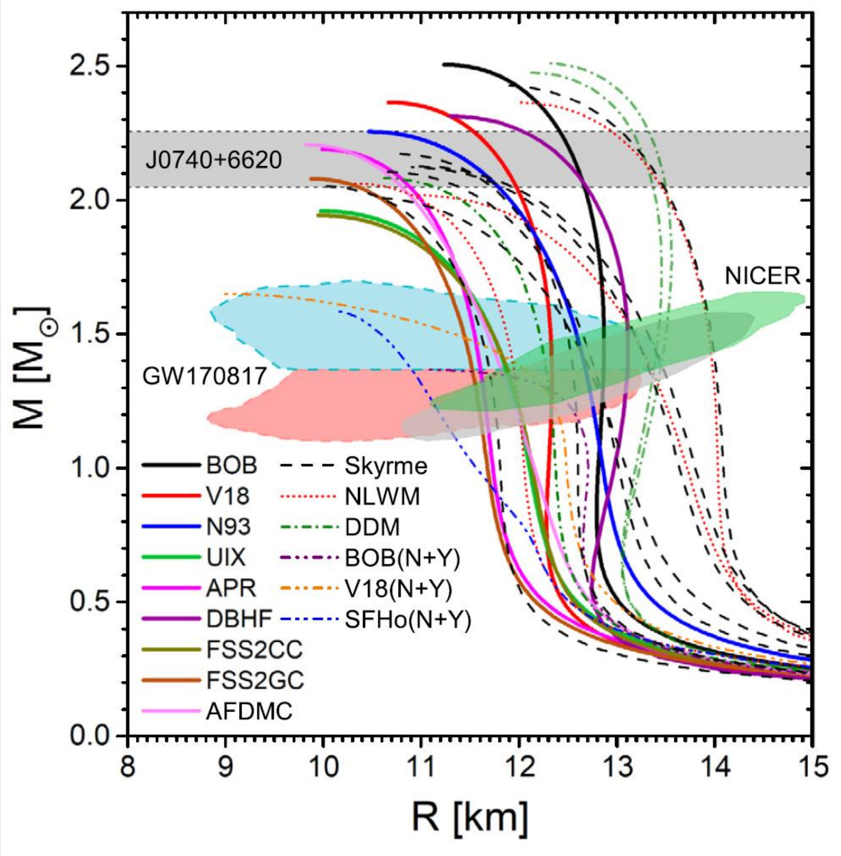
Goddard Space Flight Center

NICER : NS x-ray hot spot measurement
Physics 14, 64 (Apr. 29, 2021)

Macropscopic features of NS : Tidal deformability, Radius and Mass

NEW CONSTRAINS FROM ASTRONOMICAL OBSERVATIONS





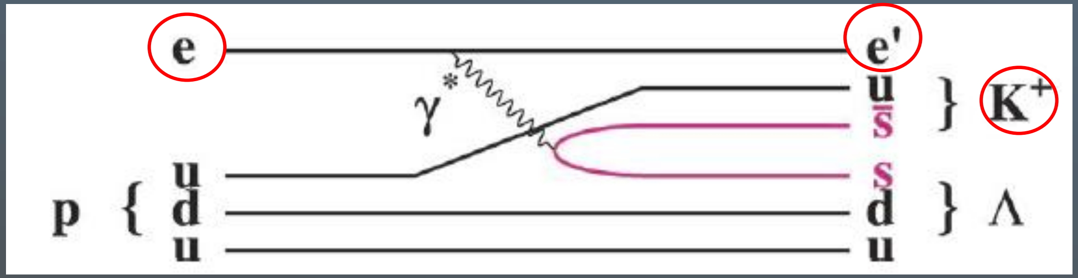
C.F.Burgio et al. Prog. Part. Nucl. Phys 120 (2021) 103879.

Macroscopic understanding of NS made great progresses.
But we would like to know why NS is so heavy and large.

Microscopic study (nuclear physics exp) becomes more important than ever!

Lambda production with electron and meson beams

(e,e'K$^+$) @ JLab

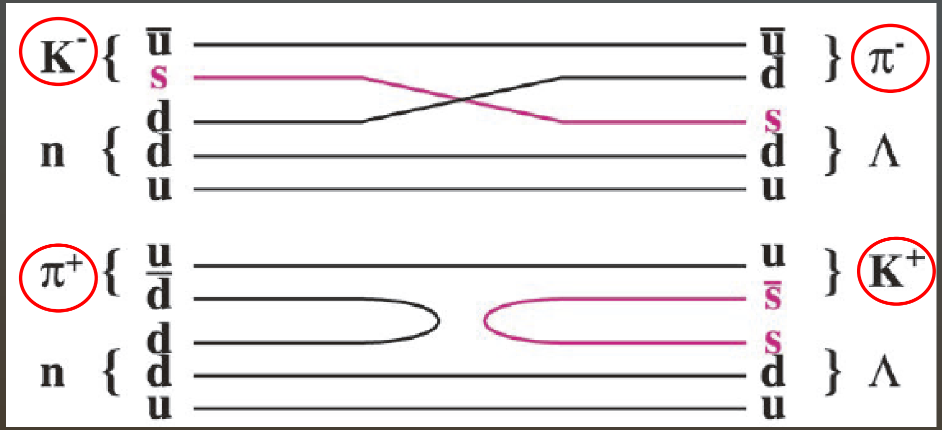


Excellent mass resolution
~ 0.5 MeV(FWHM)

Absolute energy calibration
p(e,e'K$^+$) Λ, Σ^0

High Intensity
100 μA = 6×10^{14} /s

Thin target (isotopically enriched)
eg. ^{40,48}Ca, ^{3}H



(K$^-$, π^-)

Intensity limitation < a few $\times 10^6$ /s

1-2 MeV resolution
Normalized to $^{12}_{\Lambda}$C mass

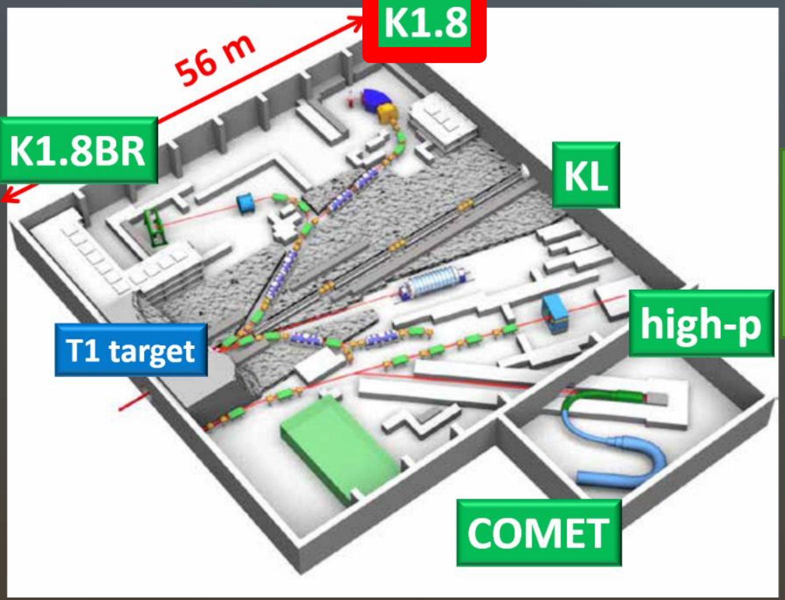
(π^+, K$^+$)

HIHR@J-PARC HEF Ex

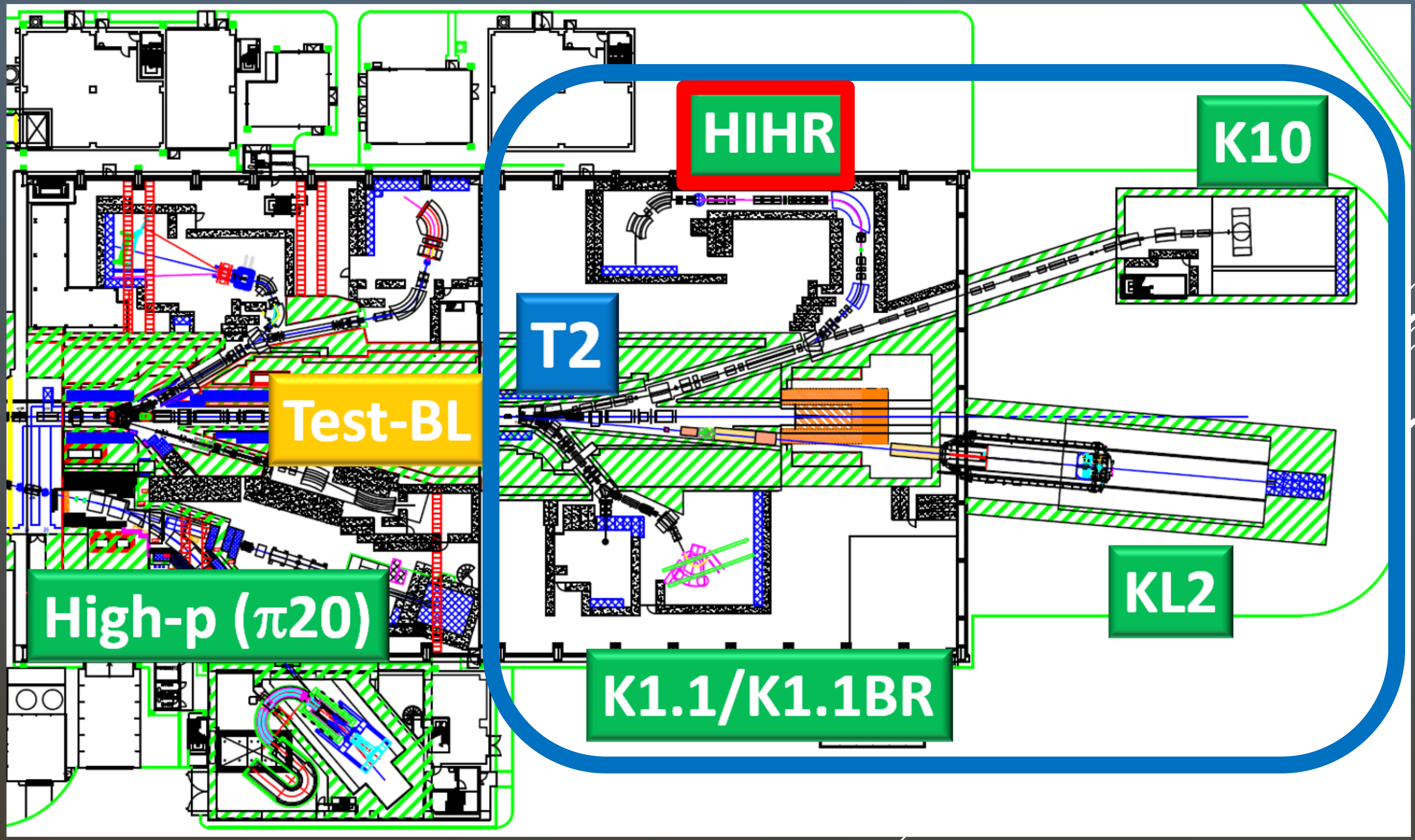
Excellent mass resolution
< 0.4 MeV
Thin target (isotopically enriched)
No limitation for beam intensity

Hadron Experimental Facility EXtension (HEF-EX) Project @J-PARC

Present facility



1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



1 new production target (T2) +
4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +
2 modified beamlines (High-p (π20), Test-BL)

HIHR

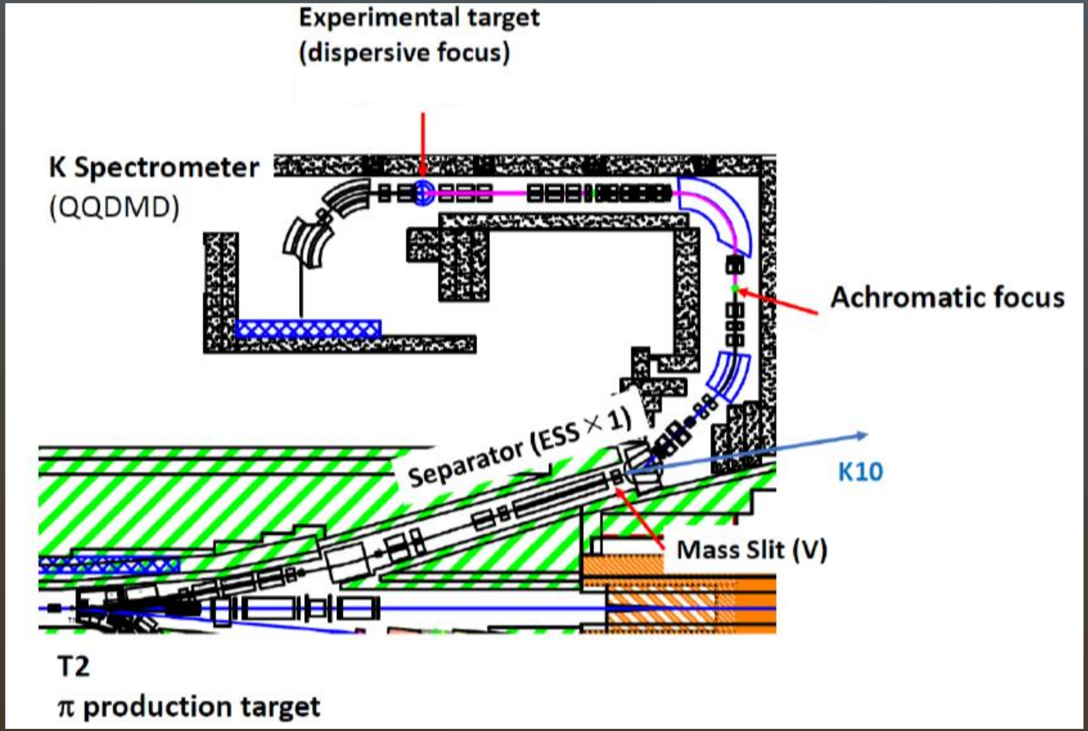
High-Intensity High-Resolution Beamline for High Precision (π, K) Spectroscopy

Exist beamlines:
~10^6 pions/pulse, $\Delta p/p$ ~ 1/1000

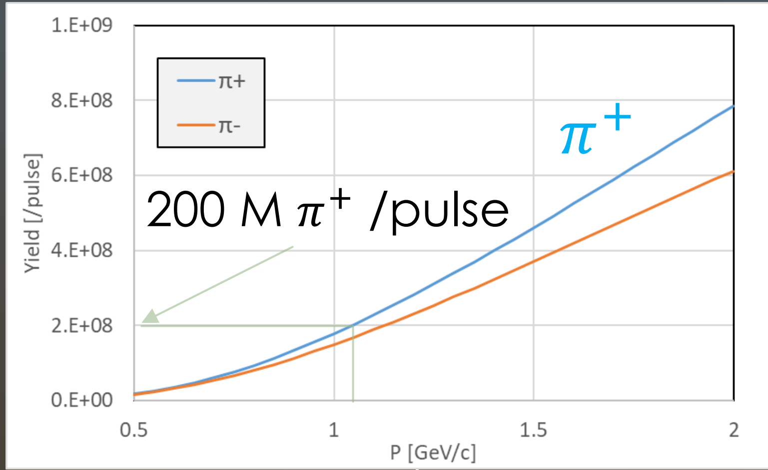
200 x 10^6 pions/pulse, $\Delta p/p$ ~ 1/10000

- Momentum dispersion matching

no beam tracking = **NO limit for π rate** from detectors



HR beamline (P_{max} = 2 GeV/c)
+ High Res. Kaon sectrometer

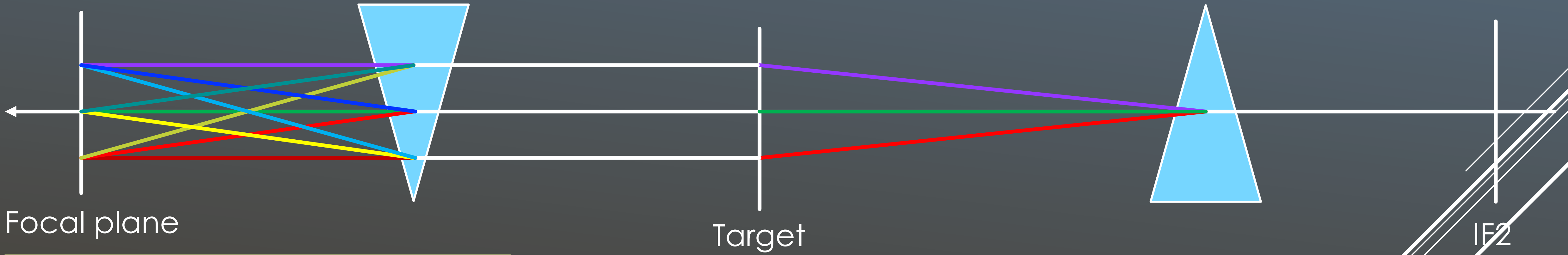


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target (T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

MOMENTUM DISPERSION MATCH

Scattered spectrometer — Reaction — Beam line

$$\begin{pmatrix} x_f \\ \theta_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} T & 0 & 0 \\ 0 & \theta/\theta_1 + 1 & 0 \\ 0 & 0 & (K\theta + DQ)/\theta_0 + C \end{pmatrix} \begin{pmatrix} b_{11} & b_{12} & b_{16} \\ b_{21} & b_{22} & b_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ \theta_0 \\ \delta_0 \end{pmatrix}$$



Momentum matching condition

$x_f = (s_{11}b_{11}T + s_{12}b_{26})x_0$ -------- total magnification → minimize

$+(s_{11}b_{12}T + s_{12}b_{22})\theta_0$ -------- point-to-point focus → 0

$+(s_{11}b_{16}T + s_{12}b_{26} + s_{16}C)\delta_0$ --- momentum matching → 0

$+(s_{1s} + s_{16}K)\theta$ -------- kinematical correction → 0

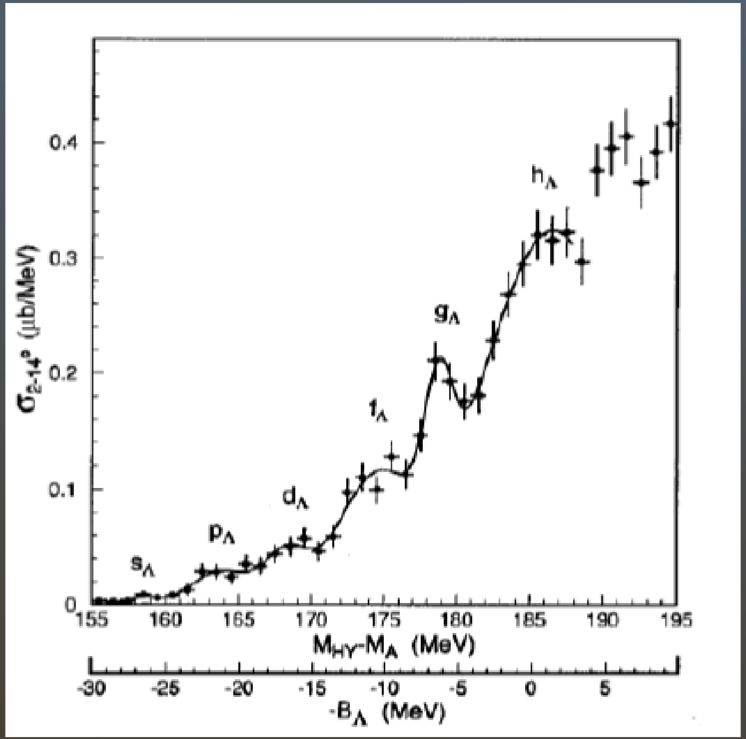
$+s_{16}DQ$ -------- a position shift by the excitation energy

$$\begin{aligned} \theta_1 &= b_{21}x_0 + b_{22}\theta_0 + b_{26}\delta_0, \\ K &= (\partial p_{scat}/\partial\theta)(1/p_{scat}), \\ C &= (\partial p_{scat}/\partial p_{beam})(p_{beam}/p_{scat}), \\ D &= (\partial p_{scat}/\partial Q)(1/p_{scat}). \end{aligned}$$

Super high resolution (π^+,K^+) spectroscopy

^{12}C, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{28}Si, ^{40}Ca, ^{51}V, ^{89}Y, ^{139}La, ^{208}Pb

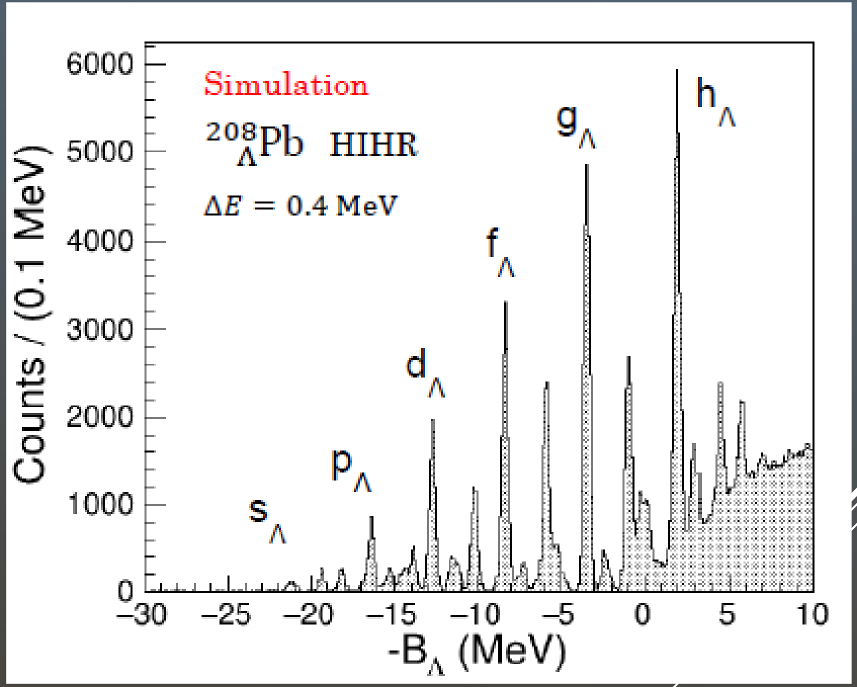
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

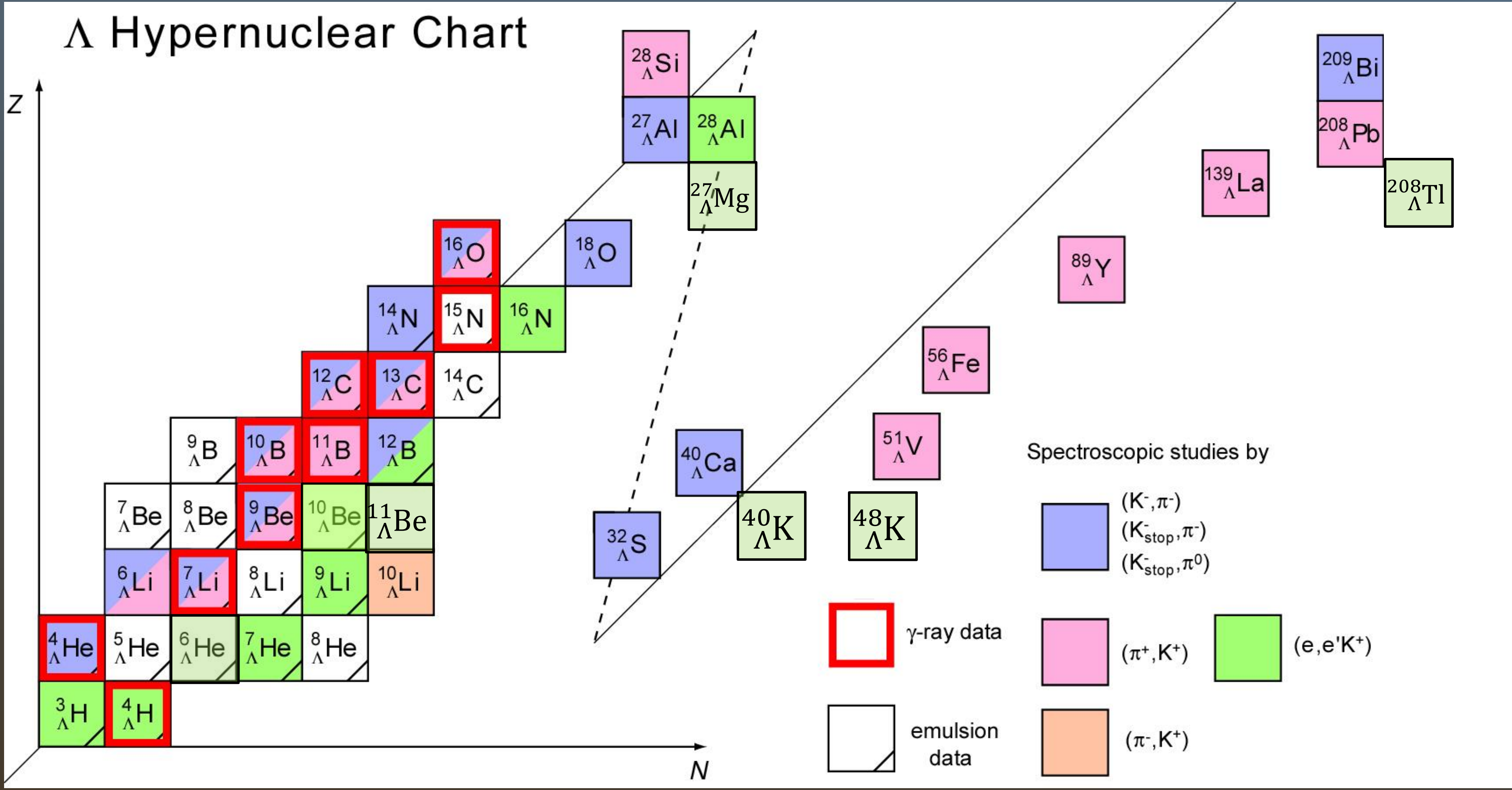
ΔE~2.3 MeV(FWHM)

Expected at HIHR beamline



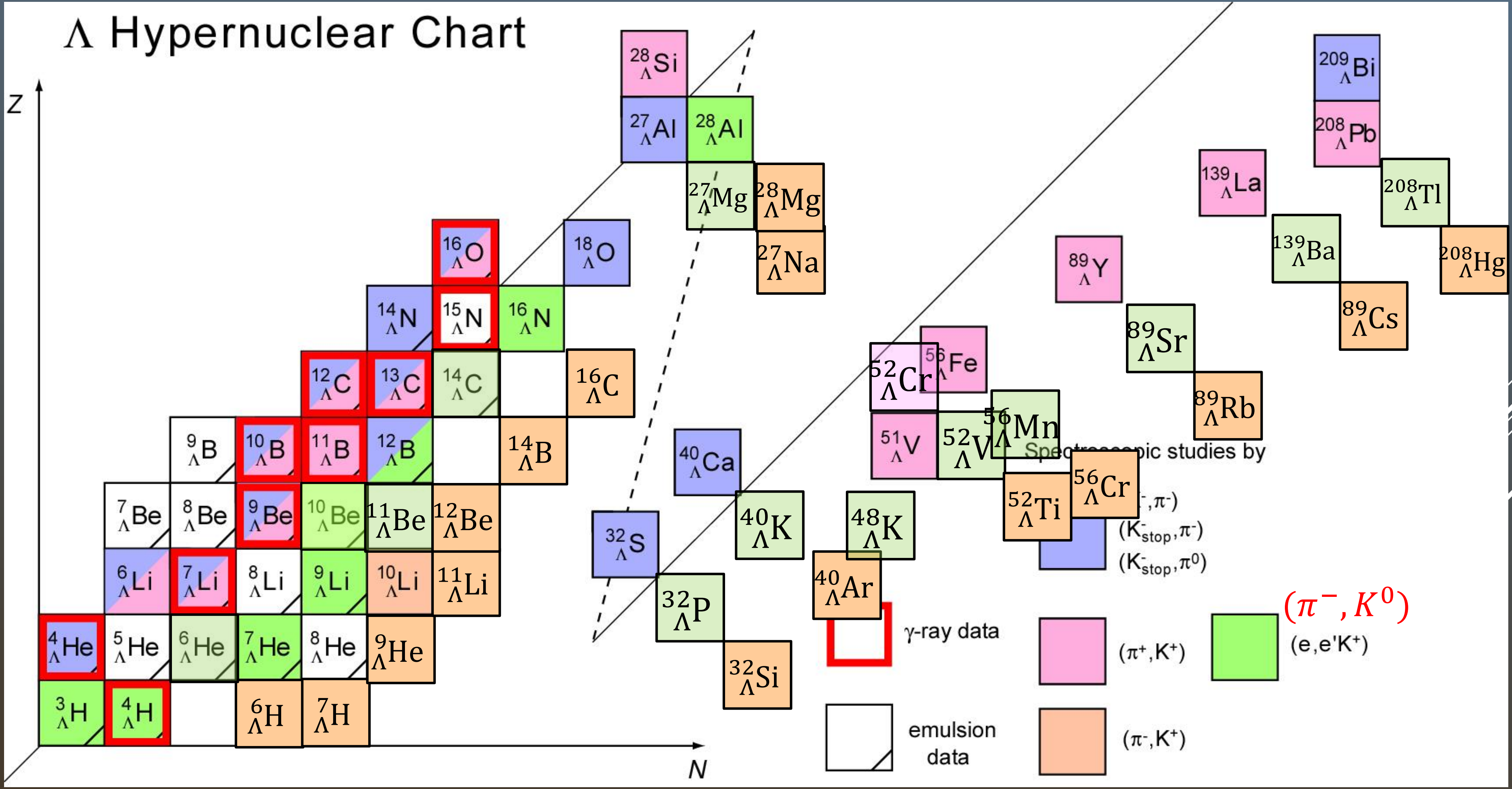
60 days × 200M π/spill @ HIHR

ΔE~**0.4 MeV(FWHM)**



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Hypernuclear Factory at HIHR

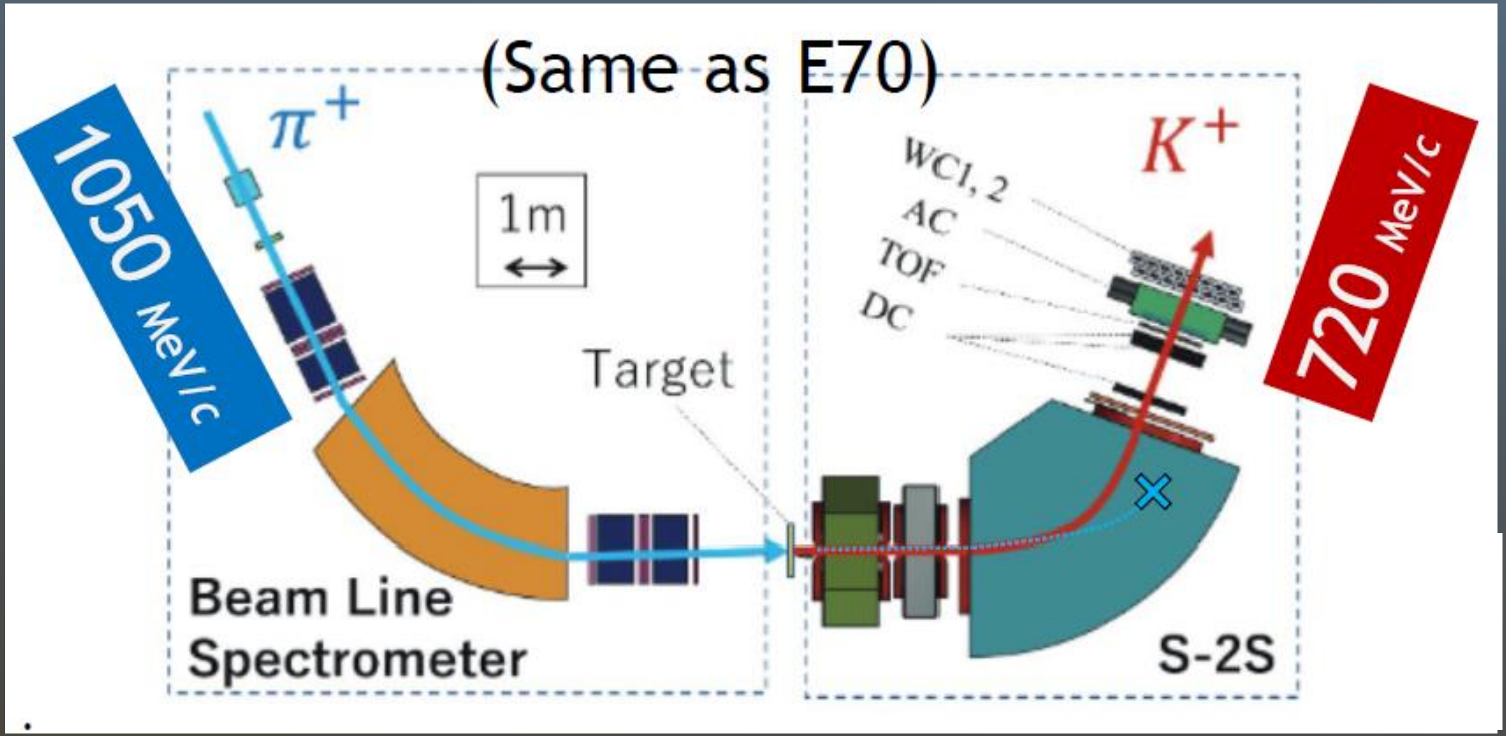


Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

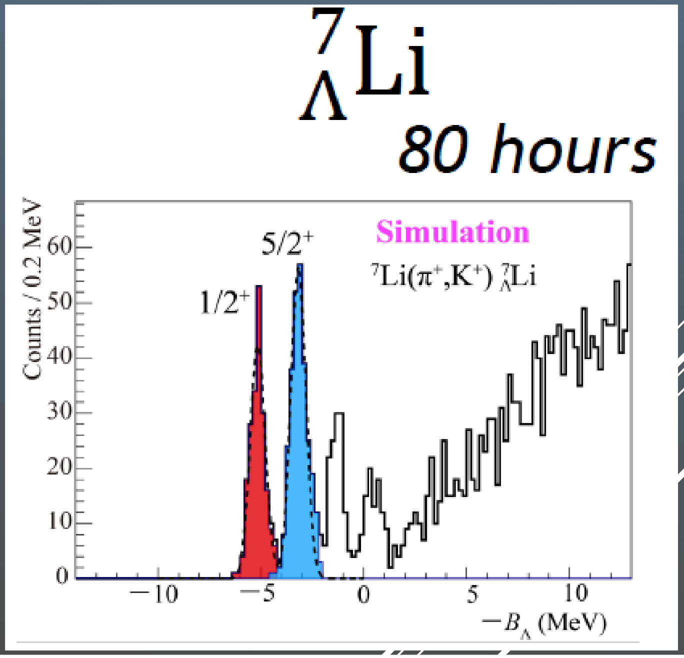
Pre HIHR Project at J-PARC

J-PARC E94 (π^+, K^+) Spectroscopy of Λ hypernuclei with S-2S

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex



T.Gogami J-PARC PAC presentation



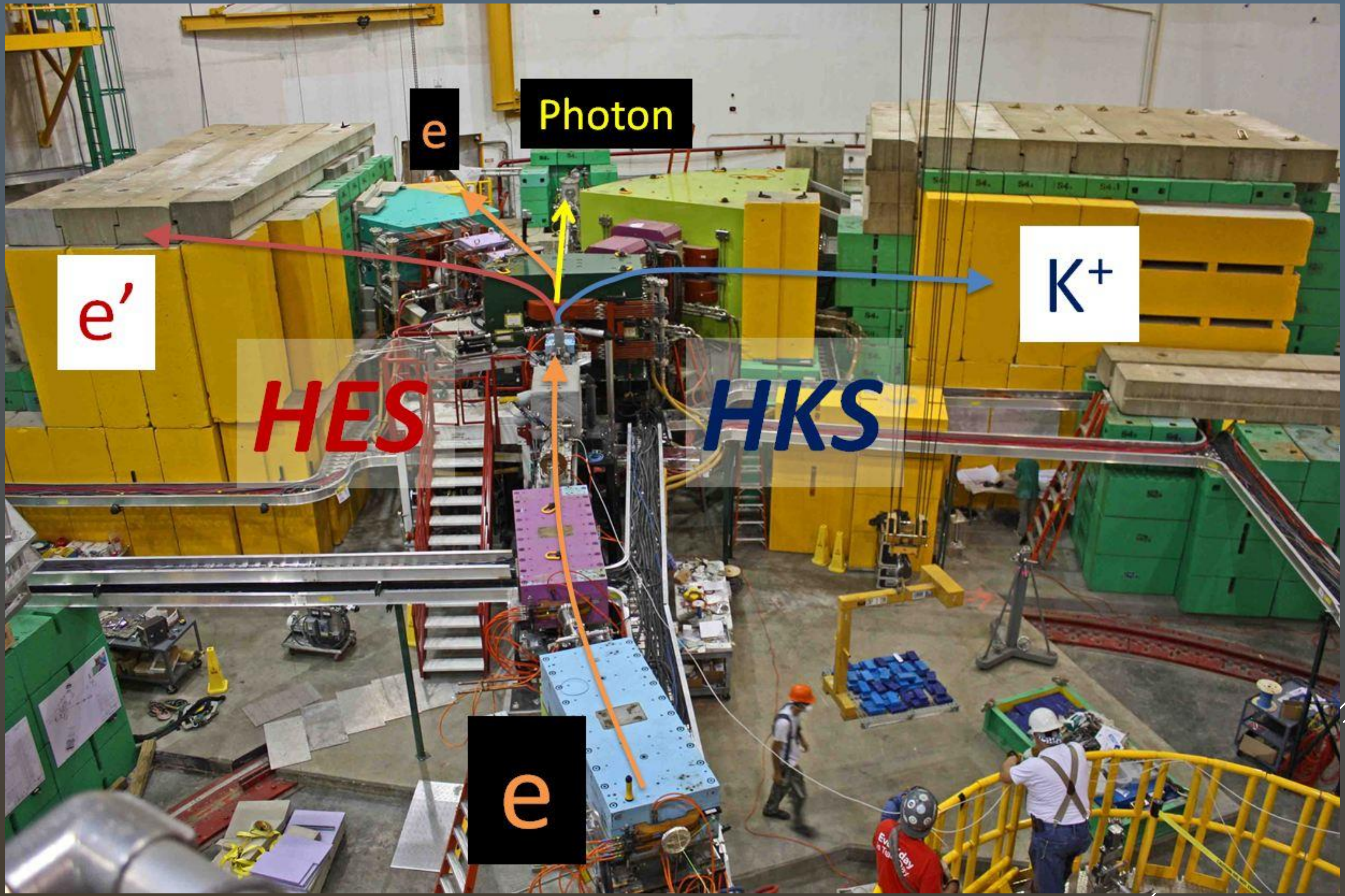
$^{7}\mathrm{Li}(\pi^+,K^+)^{7}_{\Lambda}\mathrm{Li}$ New energy calibration reference

$^{10}\mathrm{B}(\pi^+,K^+)^{10}_{\Lambda}\mathrm{B}$ Charge Symmetry Breaking

$^{12}\mathrm{C}(\pi^+,K^+)^{12}_{\Lambda}\mathrm{C}$ Precise measurement of B_Λ

Hypernucleus	$^{7}_{\Lambda}$Li (g.s.)	$^{10}_{\Lambda}$B (g.s.)	$^{12}_{\Lambda}$C (g.s.)
Differential Cross Section $\frac{d\sigma}{d\Omega}$ [/(μb/sr)]	1.2	1.2	5
Target (thickness)	^{7}Li (1 g/cm^2)	^{10}B (1 g/cm^2)	^{12}C (1 g/cm^2)
The Number of Target Nuclei N_{target} (/cm^{-2})	8.60×10^{22}	6.02×10^{22}	5.02×10^{22}
Solid Angle Acceptance $\Delta\Omega$ (/msr)	55		
Total Efficiency ϵ	0.1 [K^+ survival ratio (= 0.2) and others (= 0.5)]		
Beam Intensity	5M pions / spill (4.2 sec)		
Beam time (/hours)	80	112	36
Yield	194	190	212

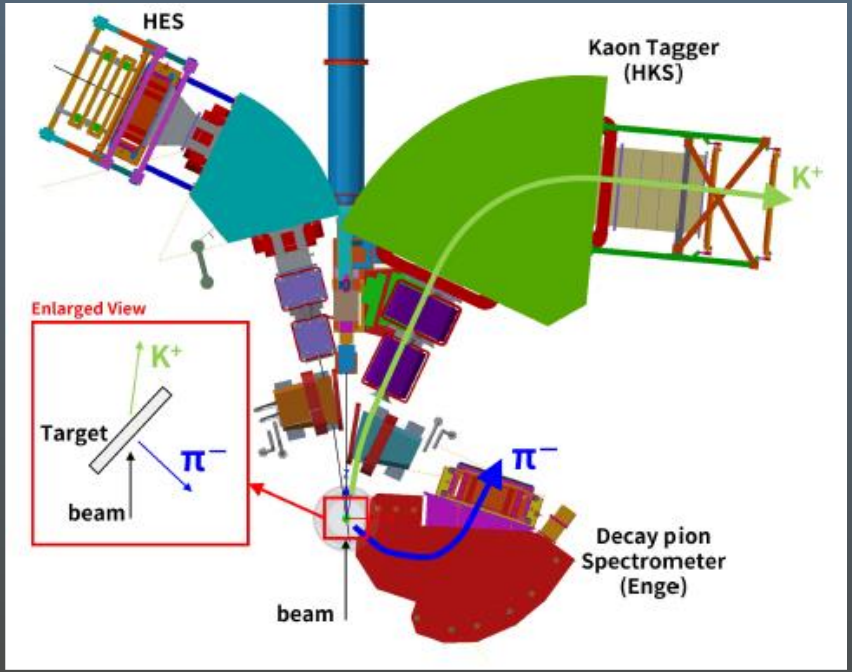
(e,e'K$^+$) reaction spectroscopy



Jefferson Lab
EXPLORING THE NATURE OF MATTER

HKS＋HES＋SPL @JLab Hall-C (2009)

Approved JLab Hypernuclear Experiments (PAC52, July 2024)



Beam	Energy E_e [/(GeV)]	2.240
	Energy stability $\Delta E_e/E_e$	3×10^{-5}
PCS + HES	Central momentum P_e [/(GeV/c)]	0.744
	Central angle $\theta_{e,e'}$ [/(deg)]	8
	Solid angle $\Delta\Omega_{e'}$ [/(msr)]	3.4
	Momentum resolution $\Delta P_{e'}/P_{e'}$	4.4×10^{-4}
PCS + HKS	Central momentum P_K [/(GeV/c)]	1.200
	Central angle θ_K [/(deg)]	15
	Solid angle $\Delta\Omega_K$ [/(msr)]	8.3
	Momentum resolution $\Delta P_K/P_K$	2.9×10^{-4}

E_{γ^*} = 1.5 GeV

First campaign : concentrate on solid targets

E12-15-008/E12-24-013 $^{40,48}\mathrm{Ca}\,(e,e'K^+)\,^{40,48}_{\Lambda}\mathrm{K}$

E12-18-013/E12-24-003 $^{208}\mathrm{Pb}$ (e,e'K) $^{208}_{\Lambda}\mathrm{Tl}$

E12-24-011 ^{27}Al (e,e'K) $^{27}_{\Lambda}\mathrm{Mg}$: triaxial deform of $^{26}\mathrm{Mg}$ nucleus

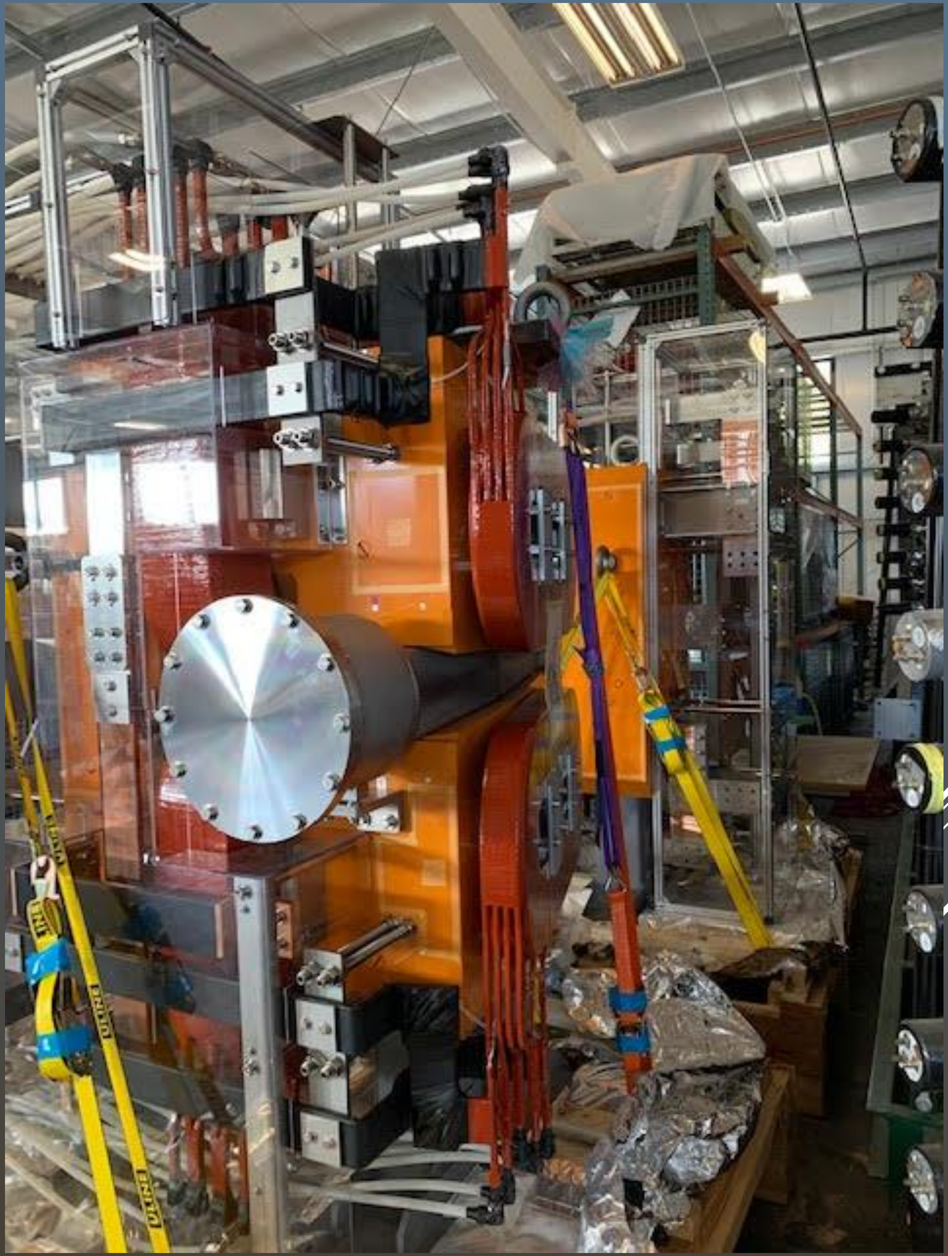
E12-24-004 ^{6}Li (e,e'K) $^{6}_{\Lambda}\mathrm{He}$, ^{9}Be (e,e'K) $^{9}_{\Lambda}\mathrm{Li}$, ^{11}B(e,e'K)$^{11}_{\Lambda}\mathrm{Be}$ CSB

E12-15-008A/ E12-18-013A Decay π Spectroscopy with ENGE

Future programs : cryogenic gas targets

E12-19-002 Cryo. Gas ^{3,4}He (e,e'K) $^{3,4}_{\Lambda}\mathrm{H}$

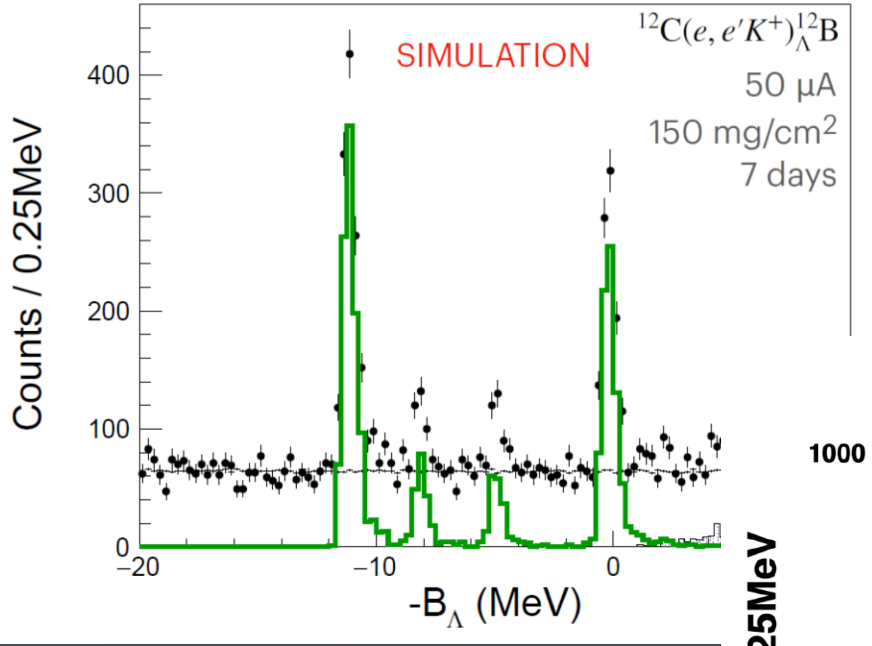
Newly constructed PCS magnets (TOKIN, 2020.3)

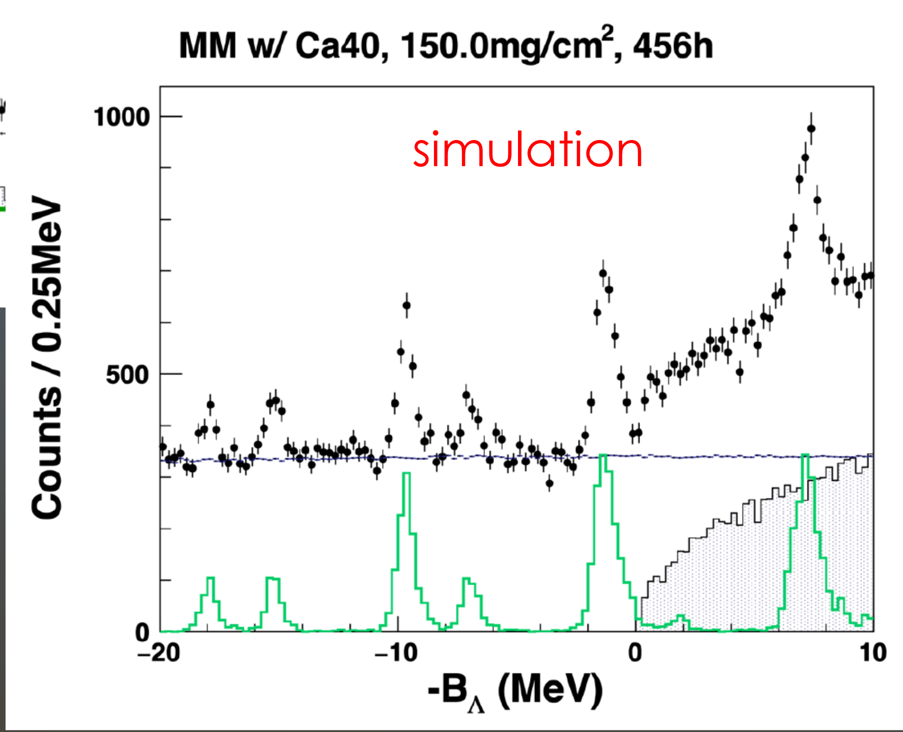


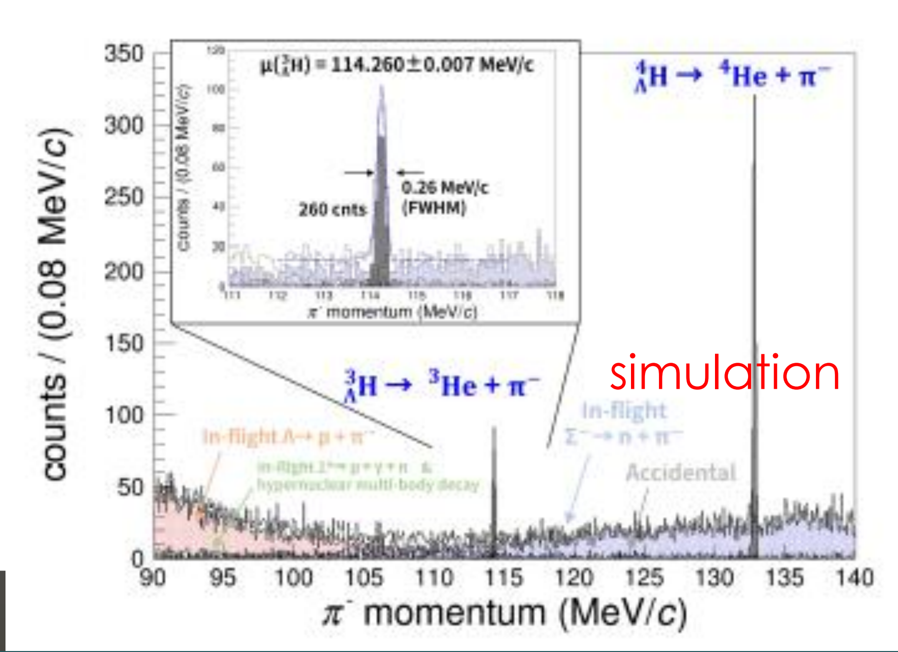
Finally delivered to JLab (2022.2 @ JLab)

Expected missing mass spectra for ${}^{12}_{\Lambda}\mathrm{B}$, ${}^{40}_{\Lambda}\mathrm{K}$

Expected resolution 0.6 MeV (FWHM)







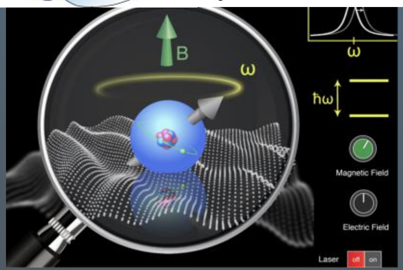
Expected π- momentum spectrum DπS

QNSI
Quark Nuclear Science Institute, UTokyo

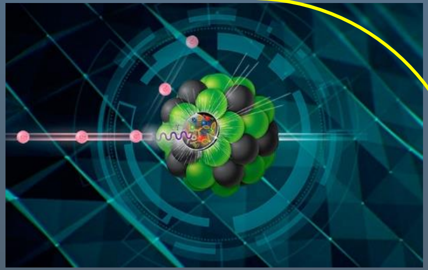
Quark Nuclear Science Institute (QNSI), UTokyo

Newly established on July 1st, 2024

Unraveling the mysteries
from quarks to nucleons and hadrons,
atomic nuclei as quantum many-body systems,
and neutron stars
based on quantum chromodynamics!



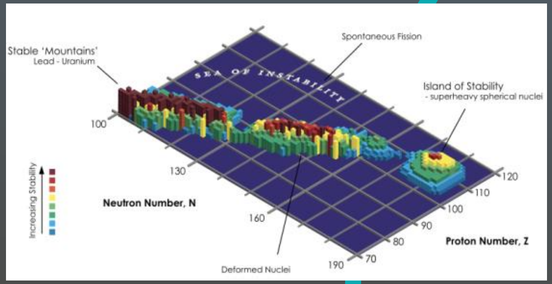
Fundamental Symmetry

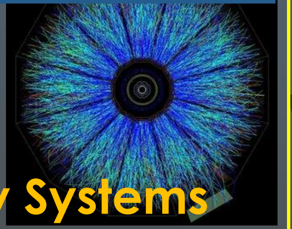


EIC

High-energy Heavy Ion

High-energy QCD





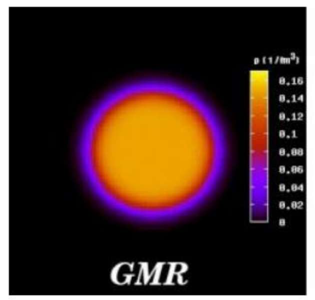
QCD
Quantum Many-body Systems

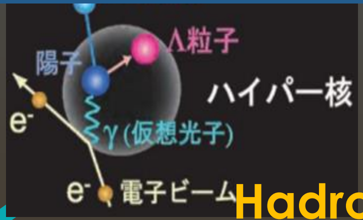
Large-scale computing,
AI Research

Nuclear Many-body Systems

Quark Many-body Systems

Nuclear Structure
Nuclear Reaction
Astro-physics





Hadron Spectroscopy
Hypernuclei

Fostering future academic leaders
at cutting-edge research facilities

Collaboration with External organizations

RIKEN
大強度陽子加速器施設 J-PARC Japan Proton Accelerator Research Complex
Brookhaven National Laboratory
Jefferson Lab
CERN
MAMI MAINZER MIKROTRON

Collaboration with Internal organizations

トランススケール量子科学 国際連携研究機構 Trans-Scale Quantum Science Institute
東京大学 素粒子物理国際研究センター International Center for Elementary Particle Physics The University of Tokyo
東京大学 放射線科学連携研究機構
東京大学大学院 工学系研究科 SCHOOL OF ENGINEERING THE UNIVERSITY OF TOKYO
KAVLI IPMU
東京大学 大学院 新領域創成科学研究科

SUMMARY

- ***Spectroscopy of hypernuclei is now more important than previous. Key to solve the hyperon puzzle.***
- New HIHR beamline at J-PARC Hadron Hall Extension Project
- Spectroscopy of Λ hypernuclei with (π^+, K^+) reaction at HIHR

  Precise Spectroscopy of Λ hypernuclei in all mass range

  Hypernuclear Factory
- At J-PARC $(\pi^+, K^+)$with S-2S: ${}^{7}_{\Lambda}$Li, ${}^{10}_{\Lambda}$B, ${}^{12}_{\Lambda}$C is going to start
- At JLab,$(e, e'K^+)$: ${}^{40,48}_{\Lambda}$K, ${}^{208}_{\Lambda}$Tl, ${}^{6}_{\Lambda}$He, ${}^{9}_{\Lambda}$Li, ${}^{11}_{\Lambda}$Be, ${}^{27}_{\Lambda}$Mg, Decay π in Hall-C

  Complimentary studies of Λ hypernuclear study at JLab and J-PARC