6th October 2022

Workshop of Electro- and Photoproduction of Hypernuclei and Related Topics 2022

High precision spectroscopy of Lambda hypernuclei at the HIHR beamline of the J-PARC Hadron Hall Extension Project

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Strategy to solve the hyperon puzzle

Reliable high precision data

Light Λ hypernuclei

Medium to heavy hypernyclei

Hyperon
Nucleon
Scattering
Experiments

Cluster Calc.
Faddeev
NCSM

Shell Model
Quantum MC
Hyper AMD
Rel. MF …

ChEFT
L-QCD
Meson exchange models

Realistic 2-body BB interaction

In-medium BB interaction
(Density dependence, 3BF)

Femtoscopy

Microscopic

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

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

Touchstone

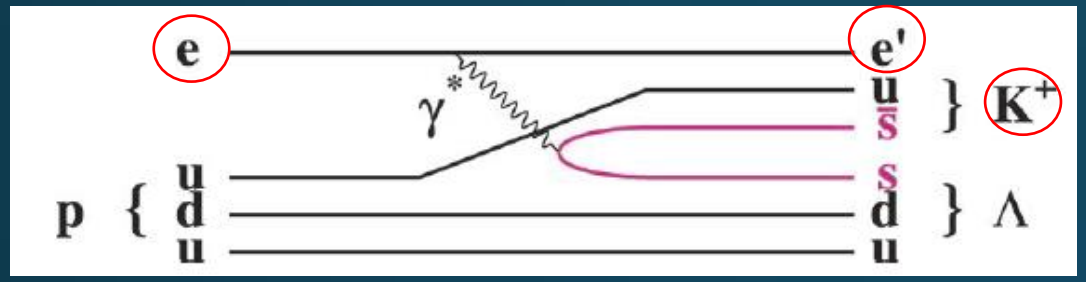
Macroscopic

EoS of NS

Astronomical observations
GW, X-ray telescope info.

Electron beam vs. meson beams

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



Excellent mass resolution

~ 0.5 MeV(FWHM)

Absolute energy calibration

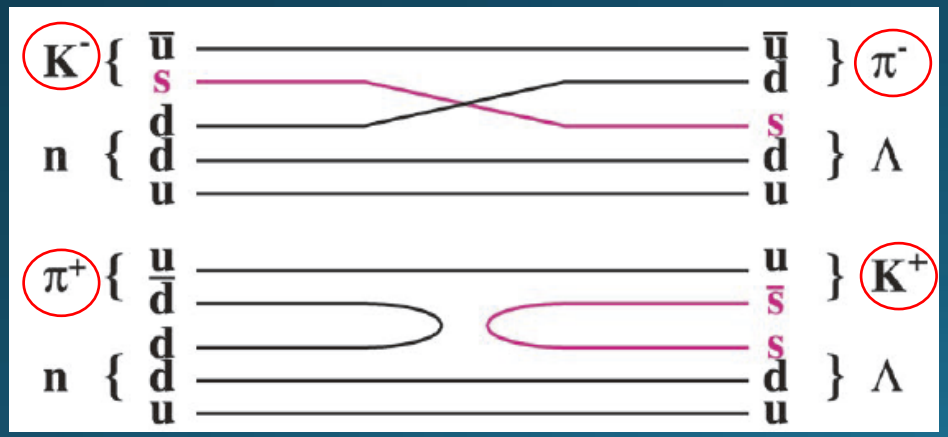
p(e,e'K$^+$) Λ, Σ^0

High Intensity

100 μA = 6×10^{14} /s

Thin target (isotopically enriched)

eg. ^{40,48}Ca, ^{3}H



(K$^-$, π^-)

Intensity limitation

< a few × 10^6 /s

1-2 MeV resolution

Normalized to $^{12}_{\Lambda}$C mass

(π$^+$, K$^+$) → **HIHR@J-PARC HD. Ex**

Excellent mass resolution

< 0.4 MeV

Thin target (isotopically enriched)

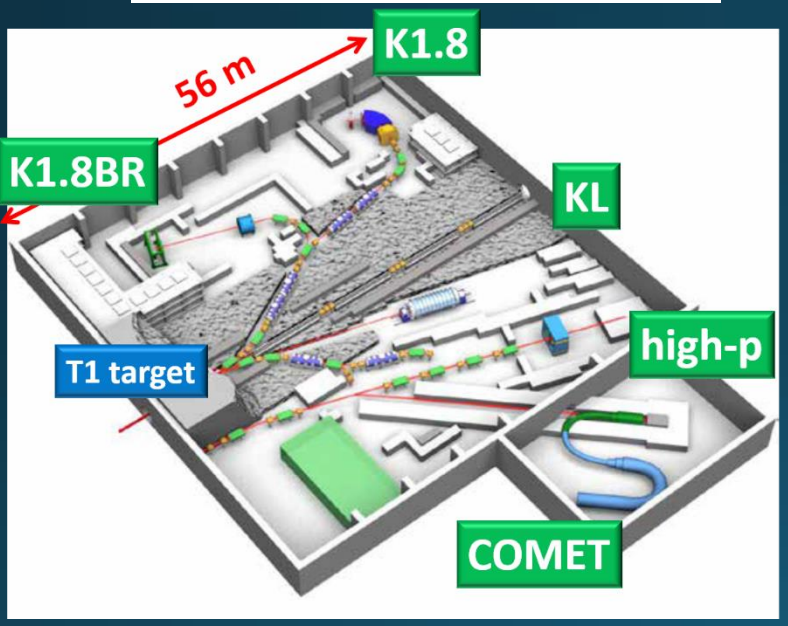
No limitation for beam intensity

High Intensity High Resolution beamline

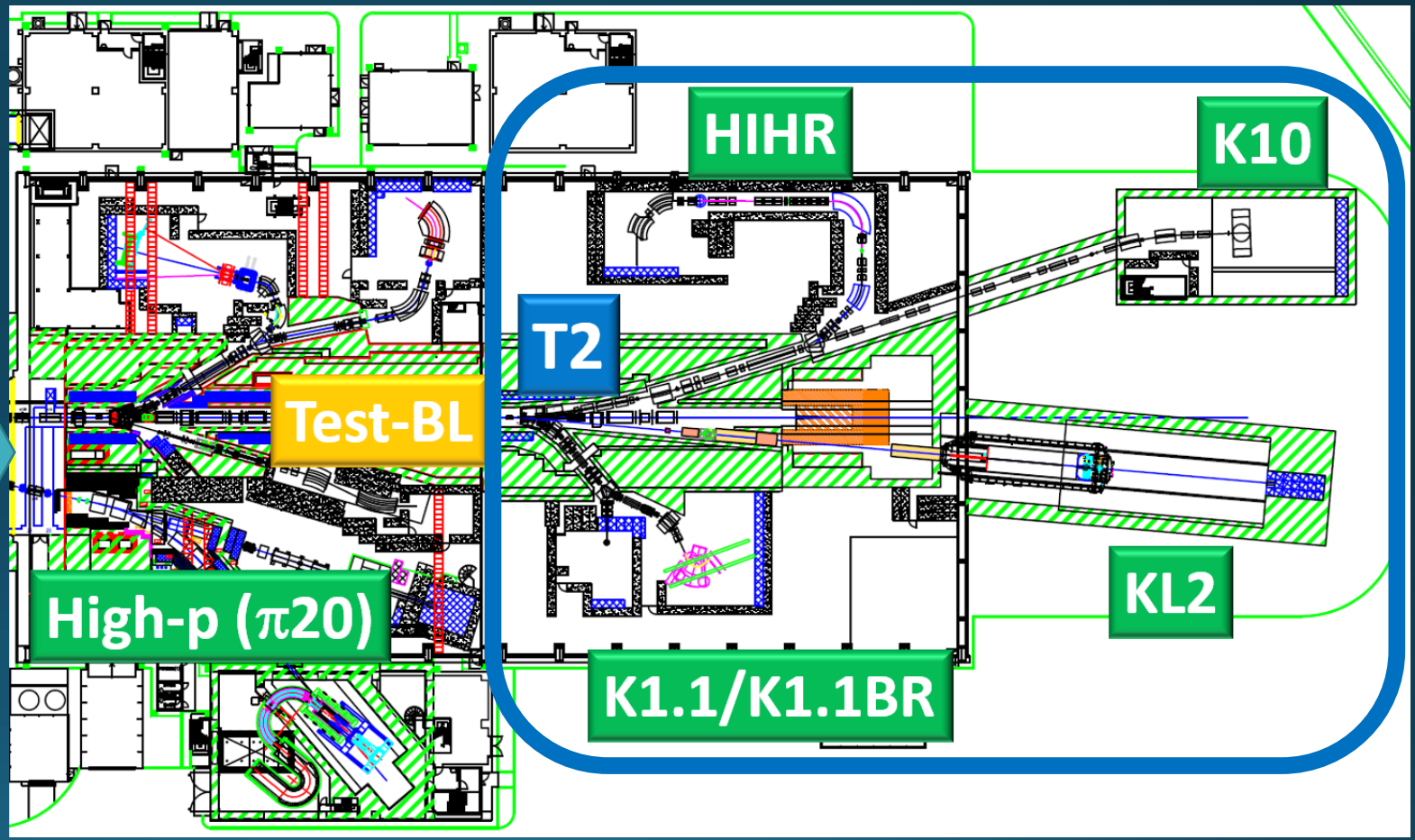
Hadron Experimental Facility EXtension (HEF-Ex) Project @J-PARC

150 Oku-Yen Project
(2.5 billion CZK)

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)

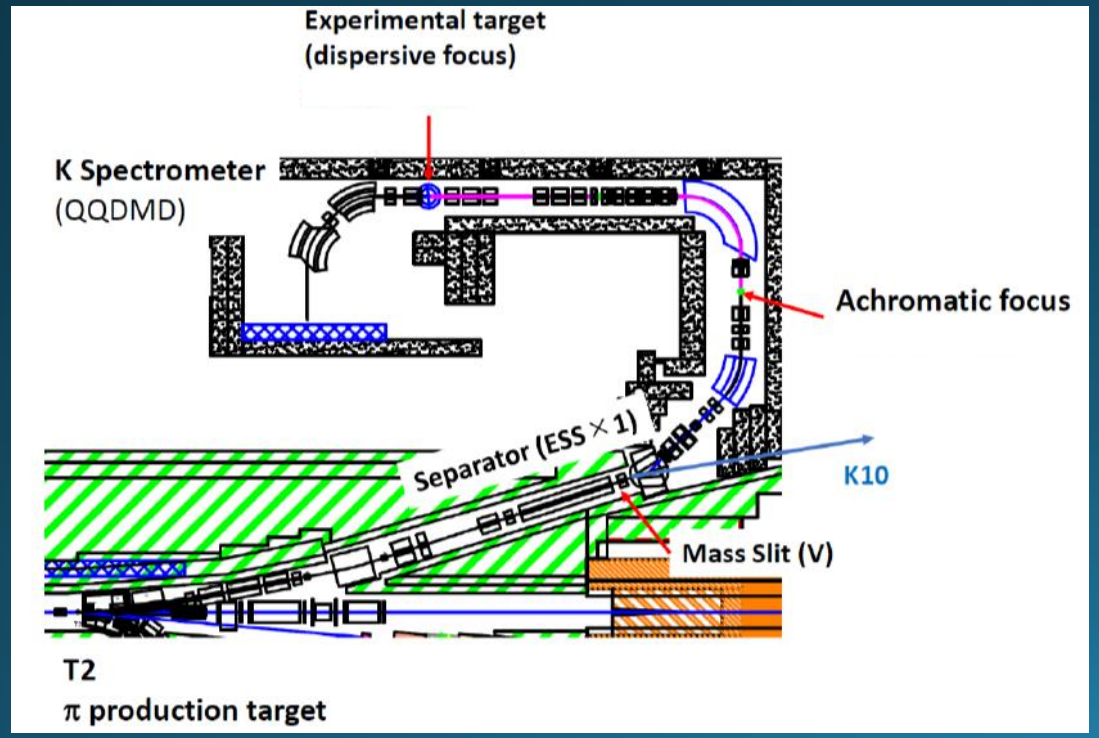
HIHR

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

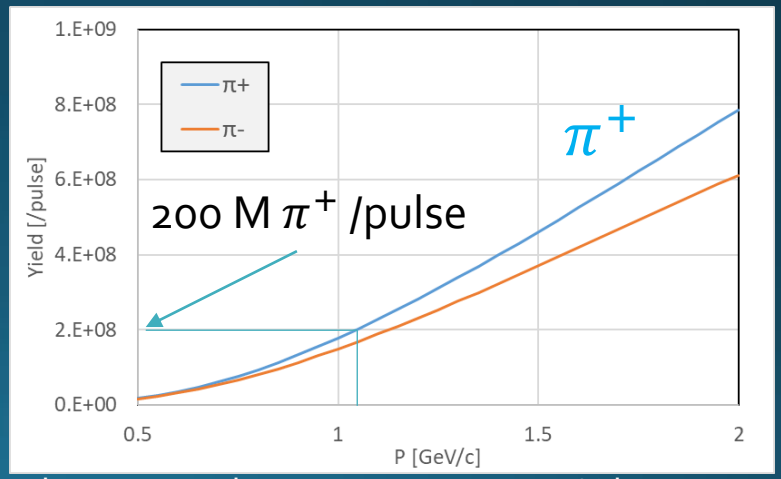
- High-Intensity High-Resolution Beamline for High Precision (π, K^+) Spectroscopy
  - Momentum dispersion matching

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

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



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

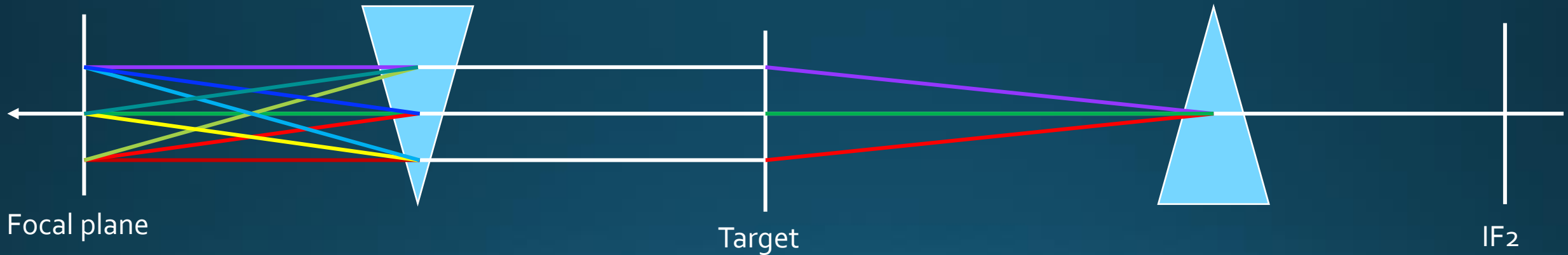


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target
(T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

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 → o

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

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

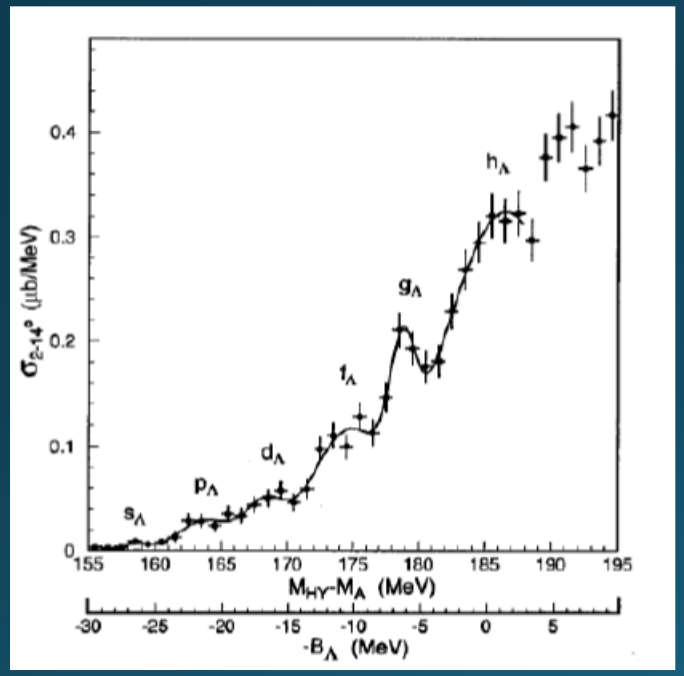
$+s_{16}DQ$ -------- a position shift by the excitation energy

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

High precision (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

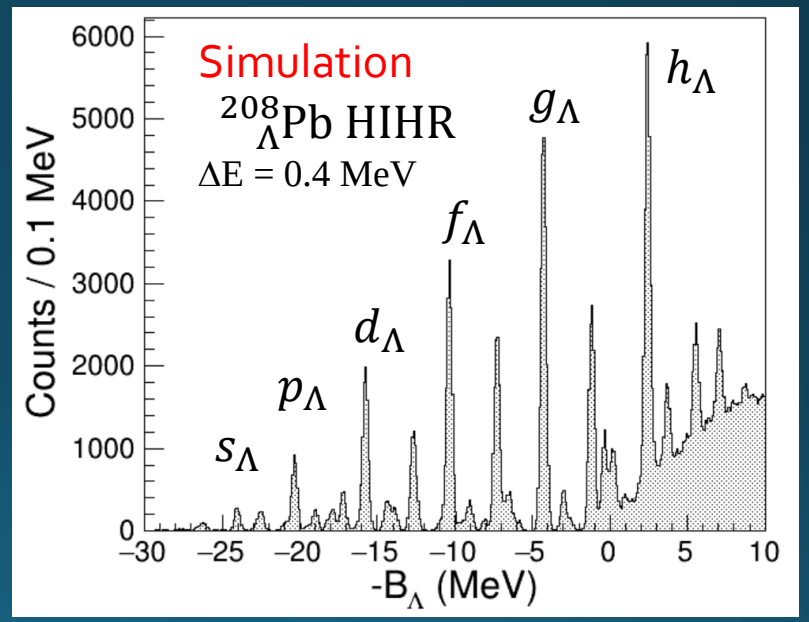
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)

Expected at HIHR beamline

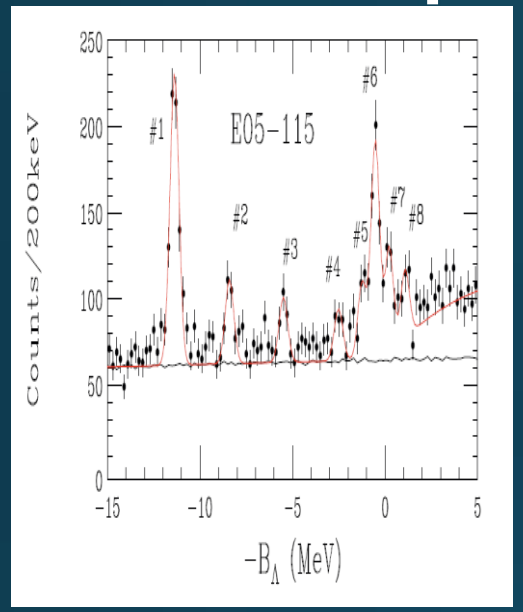


60 days × 200M π/spill @ HIHR

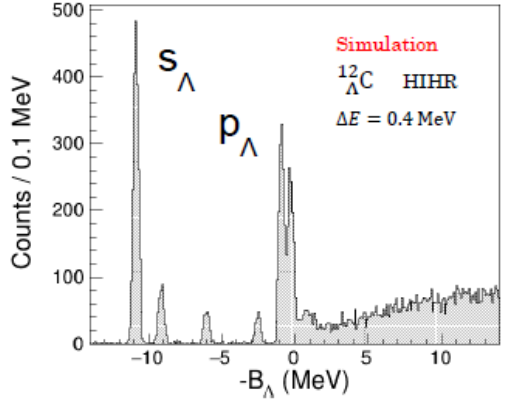
ΔE~0.4 MeV(FWHM)

Based on Motoba-san's old paper.

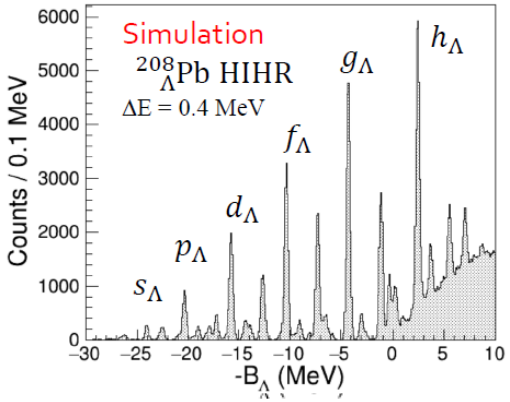
Expected spectra



$^{12}_{\Lambda}$B @ JLab E05 − 115

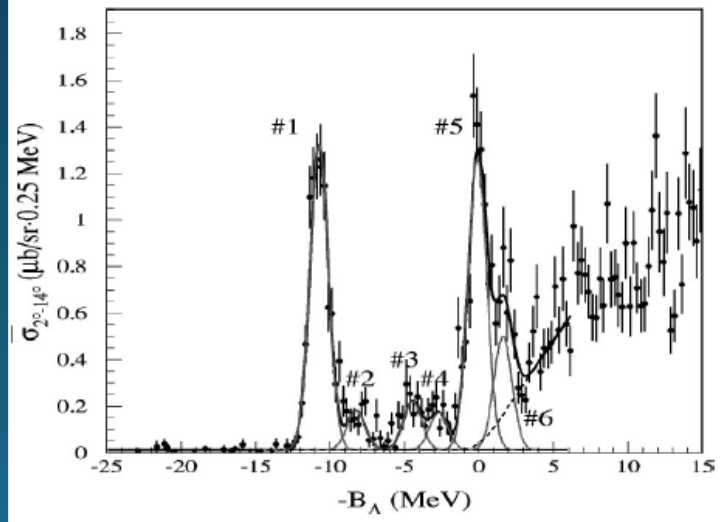


$^{12}_{\Lambda}$C @ HIHR Simulation

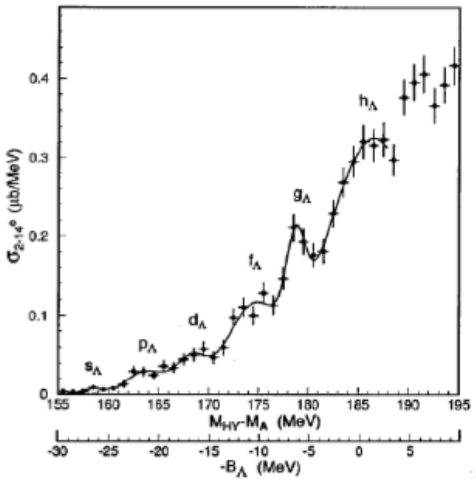


$^{208}_{\Lambda}$Pb @ HIHR Simulation

KEK-SKS
ΔE = 1.45 MeV



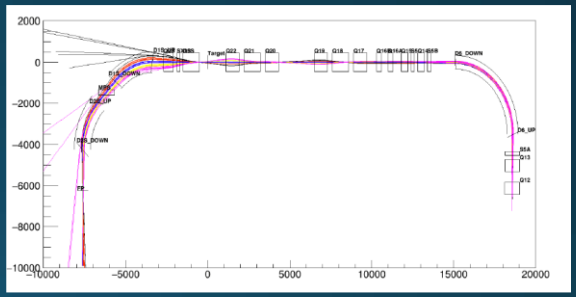
KEK-SKS
ΔE = 2.3 MeV

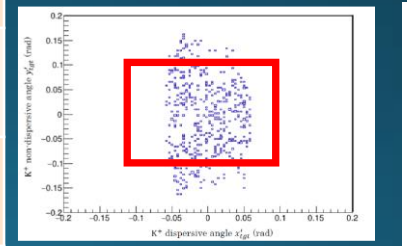


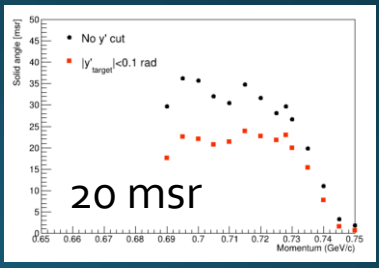
Expected Yield of Hypernulclei

	HIHR@J-PARC Ex. 1.1GeV/c π^+
Reaction	$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$
Beam on target (/ sec)	3.85×10^7 π^+ (200 M/spill, 50kW)
Target Thick (mg/cm^2)	400 (1.8 g/cm^3 x 0.22 cm)
Solid Angle for K^+ (msr)	>20
Kaon Survival Ratio	0.12 (11.4 m for QSQDMD)
Cross section (μb/sr)	8.1
Expected Yield (/h)	53.1

GEANT4 simulation







Proposal of 1st Campaign, J-PARC P84

Table 6-I : Summary of requesting beamtime for 50 kW proton beam power. Differential cross sections at $\theta_K \sim 0$ were estimated by using data of prior (π^+, K^+) experiments [PIL91, HAS94, HAS96, HOT01, HAS06].

	Assumed g.s. Cross Section (μb/sr)	Target thickness (mg/cm^2)	Expected Yield(/h)	Requested number of events for g.s.	Beam Time (h)
$^{12}_{\Lambda}$C	8.1	100	13.3	1000	79
$^{12}_{\Lambda}$C	8.1	200	26.6	2000	79
$^{12}_{\Lambda}$C	8.1	400	53.1	2000	39
$^{6}_{\Lambda}$Li	1.9	200	12.7	100	8
$^{7}_{\Lambda}$Li	1.9	200	10.9	100	10
$^{9}_{\Lambda}$Be	0.2	200	1.1	100	98
$^{10}_{\Lambda}$B	0.9	200	3.5	100	30
$^{11}_{\Lambda}$B	0.9	200	3.2	100	33
$^{28}_{\Lambda}$Si	0.5	400	1.4	100	75
$^{40}_{\Lambda}$Ca	0.5	400	0.94	100	112
$^{51}_{\Lambda}$V	1.2	400	1.8	100	59
$^{89}_{\Lambda}$Y	0.6	400	0.53	100	199
Sub total (light-mid heavy)					724 (30 days)

30 days for lighter targets

GOAL : Peak determination precision 40 keV

($\sigma \sim$ 17 keV)

$^{139}_{\Lambda}$La	0.3	200	0.085	20	236
$^{139}_{\Lambda}$La	0.3	400	0.17	80	471
$^{208}_{\Lambda}$Pb	0.3	200	0.057	20	352
$^{208}_{\Lambda}$Pb	0.3	400	0.11	80	705
Sub total (heavy)					1764 (73 days)
Grand Total					2488 (104 days)

73 days for heavier targets

104 days for total

KEK Project Implementation Plan (PIP) 2022, June 24

HEF-ex project was selected as No.1 (out of 4) project to make new budget requests in the next KEK mid-term period (2022-2028).

J-PARC International Advisory Committee 2022

IAC Report
http://j-parc.jp/c/uploads/2022/JPARC-IAC2022-report.pdf#zoom=100

SUMMARY OF THE RECOMMENDATIONS BY SECTIONS IN THE REPORT

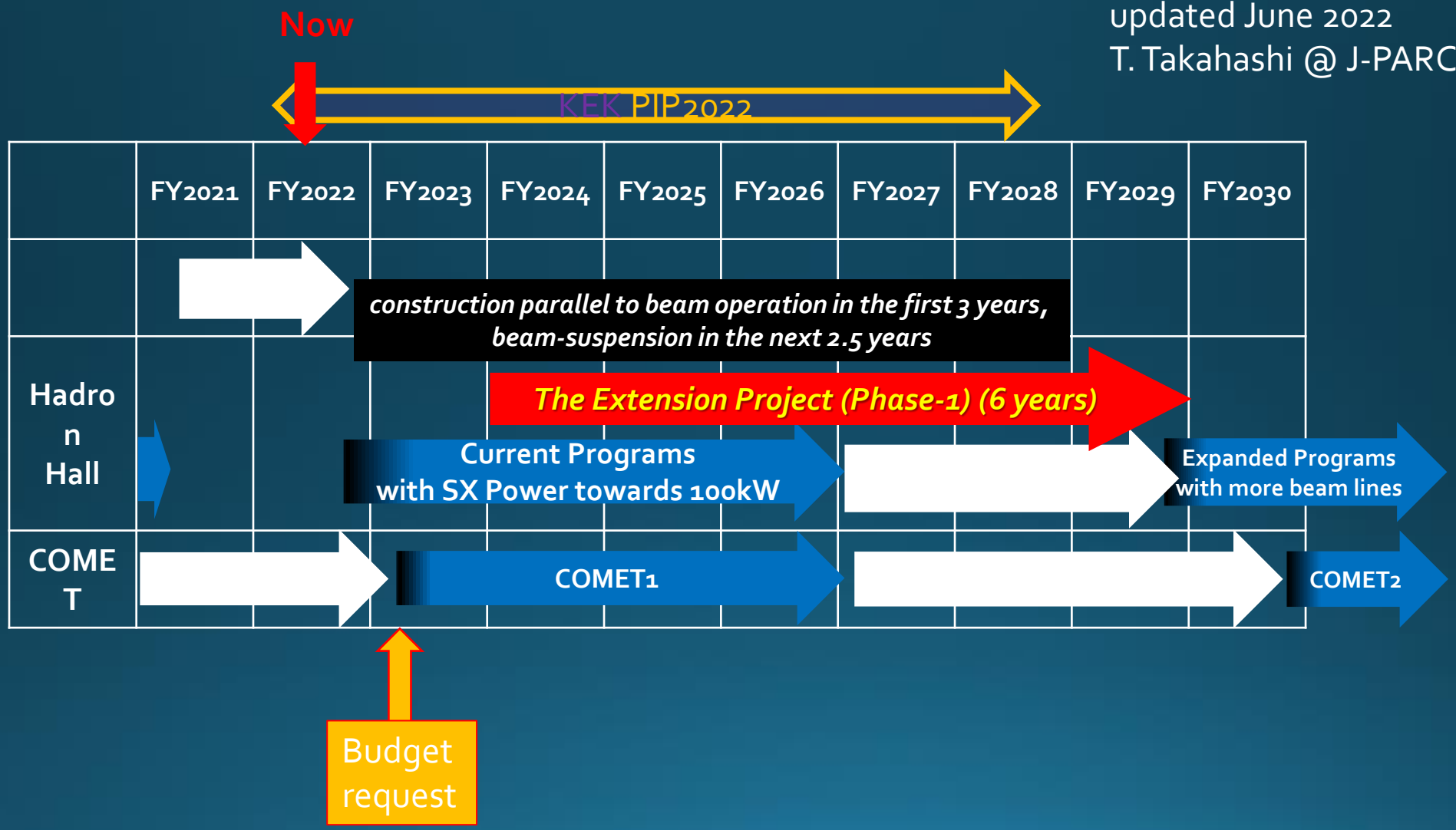
Particle and Nuclear Physics

- The IAC recommends construction of the hadron hall extension as soon as possible. This will enrich the scientific program considerably by addressing timely questions in nuclear and particle physics.
- J-PARC should dedicate additional efforts to increase and optimize use of beam time for the current and planned experiments.

- The hadron hall extension will not only provide more space for the planned instrumentation, like the high-resolution spectrometer, but at the same time enable a more efficient operation of the experimental program in terms of efficiency of data taking, as well as mounting and dismounting of instrumentation. The recent workshops on the hadron hall extension were successful and demonstrate strong support from the community for the hadron hall extension and its science program.

Timeline of the Project

updated June 2022
T. Takahashi @ J-PARC PAC 202208



Summary

Recent progresses of astrophysical observations of NS

→ Microscopic understanding becomes more important

High precision spectroscopy of hypernuclei

Challenge to Hyperon Puzzle

(e,e'K) at JLab

New programs:
Hypertriton puzzle and CSB study (${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$),
Triaxial deformation (${}^{27}_{\Lambda}\mathrm{Mg}$)
Isospin dependence (${}^{40}_{\Lambda}\mathrm{K}$, ${}^{48}_{\Lambda}\mathrm{K}$),
Heaviest hypernuclei (${}^{208}_{\Lambda}\mathrm{Tl}$)

HIHR at J-PARC HD-Ex.

Spectroscopy of Λ hypernuclei with (π^+, K^+) reaction at HIHR (P84)
Precise Spectroscopy of Λ hypernuclei in all mass range

Realize Hypernuclear Factory!