7th June 2023

Genova, Italy

THE UNIVERSITY OF TOKYO

Satoshi N. Nakamura

The University of Tokyo

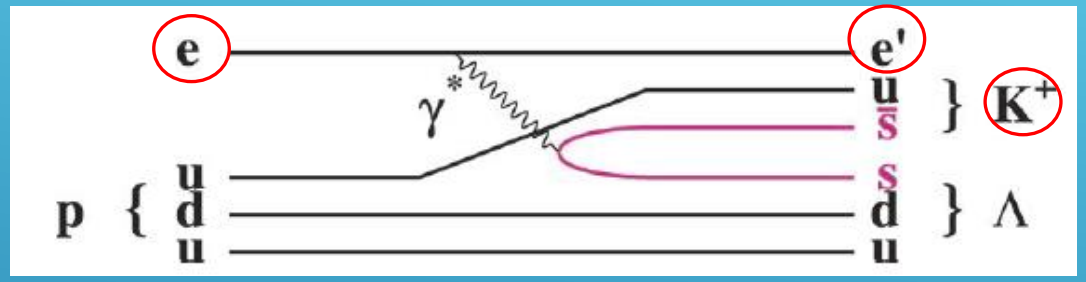
Reaction spectroscopy of Lambda hypernuclei at JLab and J-PARC

Jefferson Lab
EXPLORING THE NATURE OF MATTER

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

Lambda production with electron and meson beams

(e,e'K^+) @ JLab



Excellent mass resolution

~ 0.5 MeV(FWHM)

Absolute energy calibration

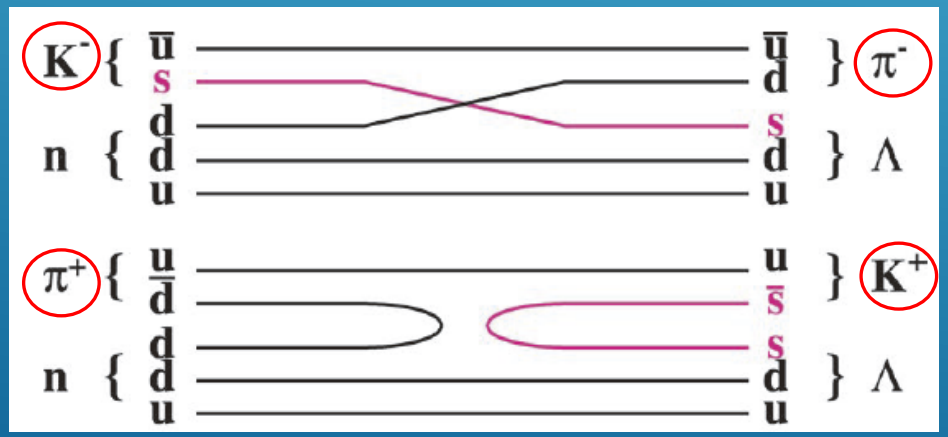
p(e,e'K^+) Λ, Σ^0

High Intensity

100 μA = 6×10^{14} /s

Thin target (isotopically enriched)

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



(K^-, π^-)

(π^+, K^+)

Intensity limitation < a few × 10^6 /s

1-2 MeV resolution

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

Lambda production with electron and meson beams

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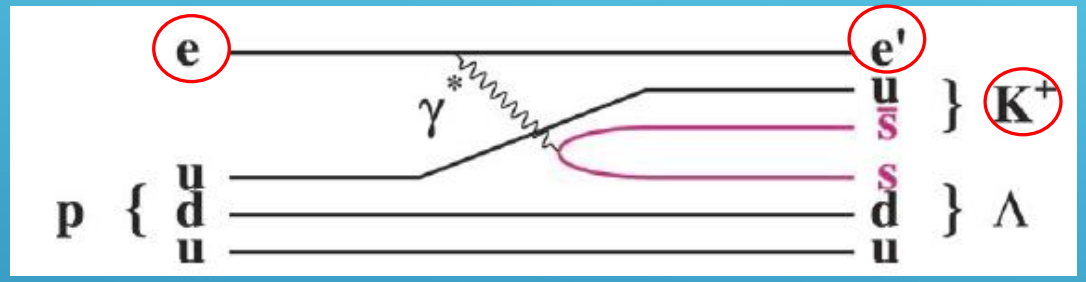

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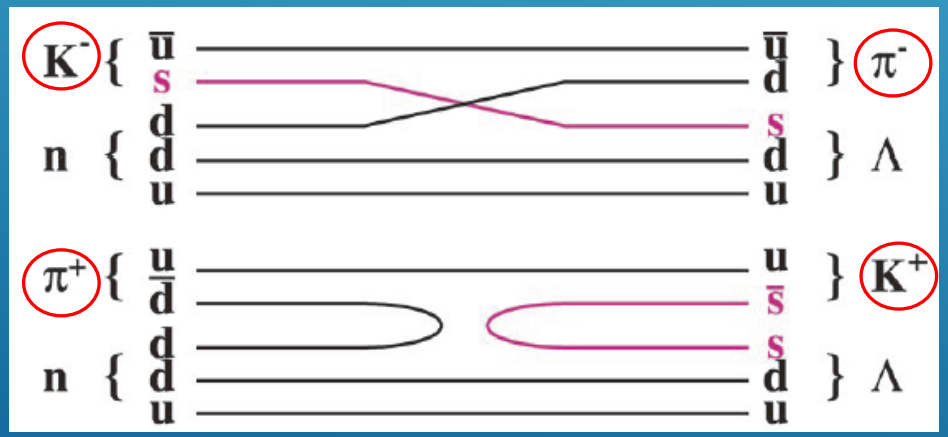


(K$^-$, π^-)

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

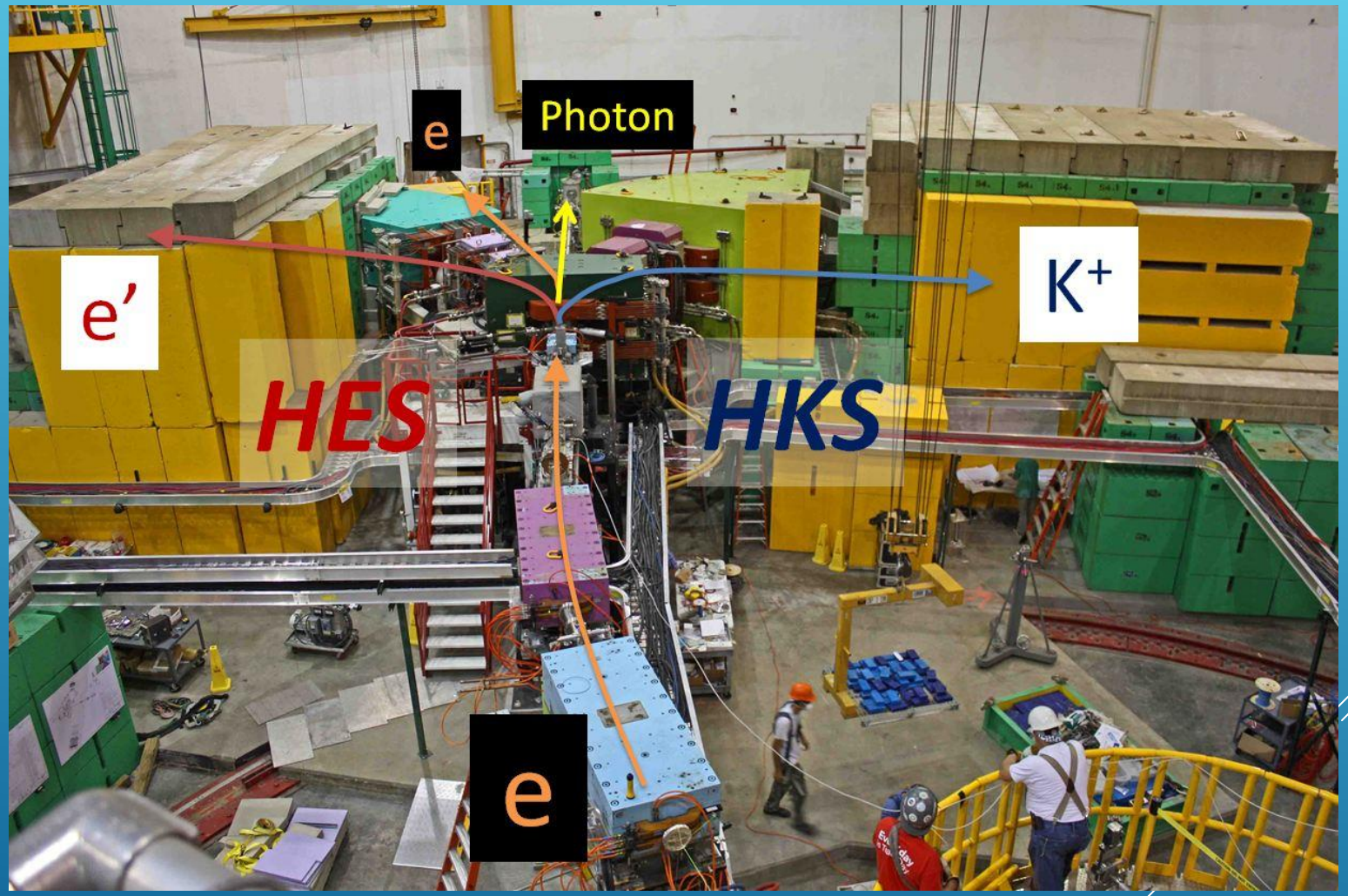
< 0.4 MeV

Thin target (isotopically enriched)

No limitation for beam intensity

(e,e'K^+) reaction spectroscopy

Jefferson Lab
EXPLORING THE NATURE OF MATTER



HKS + HES + SPL @JLab Hall-C (2009)

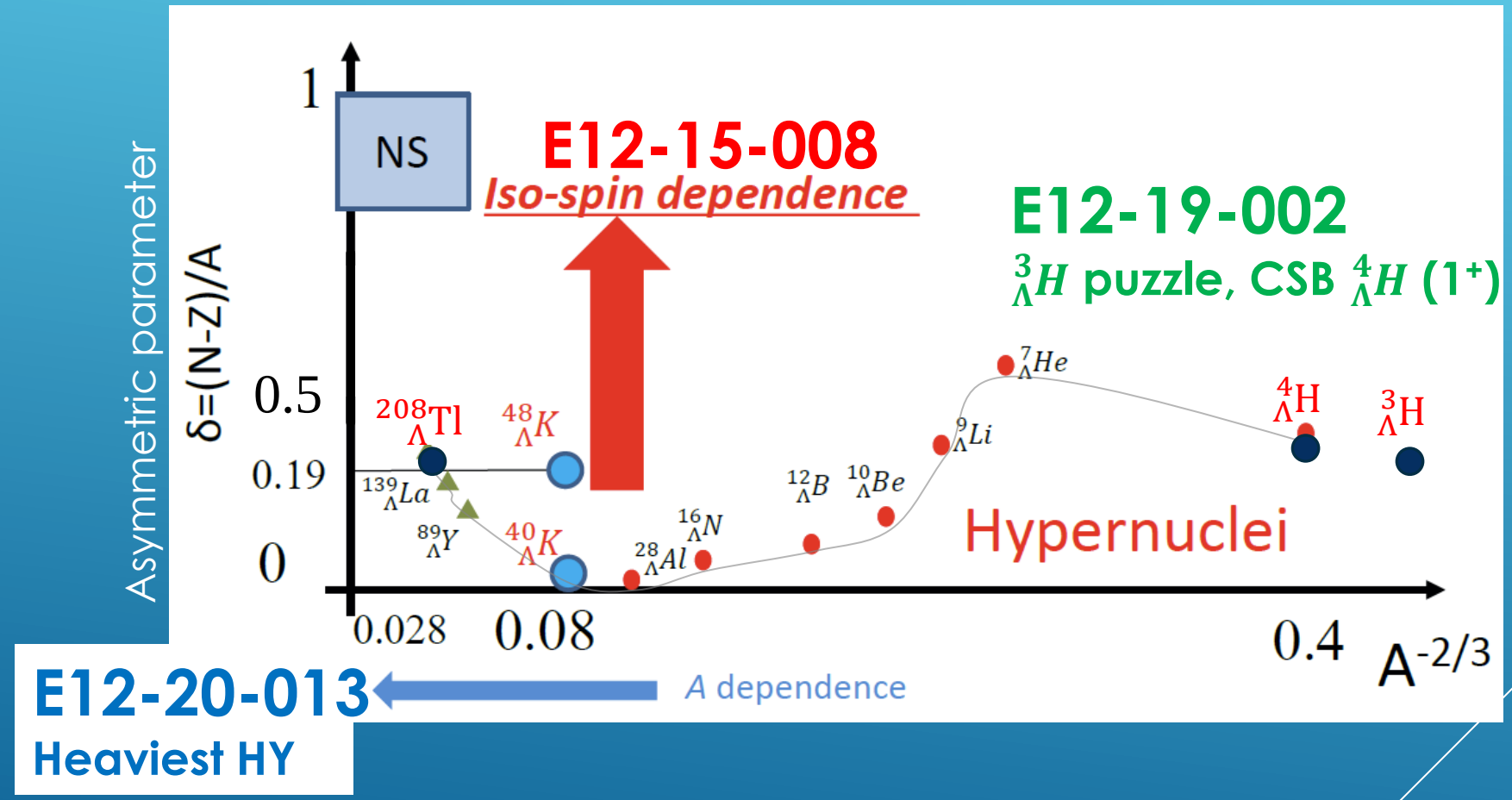
Approved JLab Hypernuclear Experiments

E12-15-008 $^{40,48}\mathrm{Ca}\,(e,e'K^{+})\,^{40,48}_{\Lambda}\mathrm{K}$ (on the jeopardy list To be re-approved)

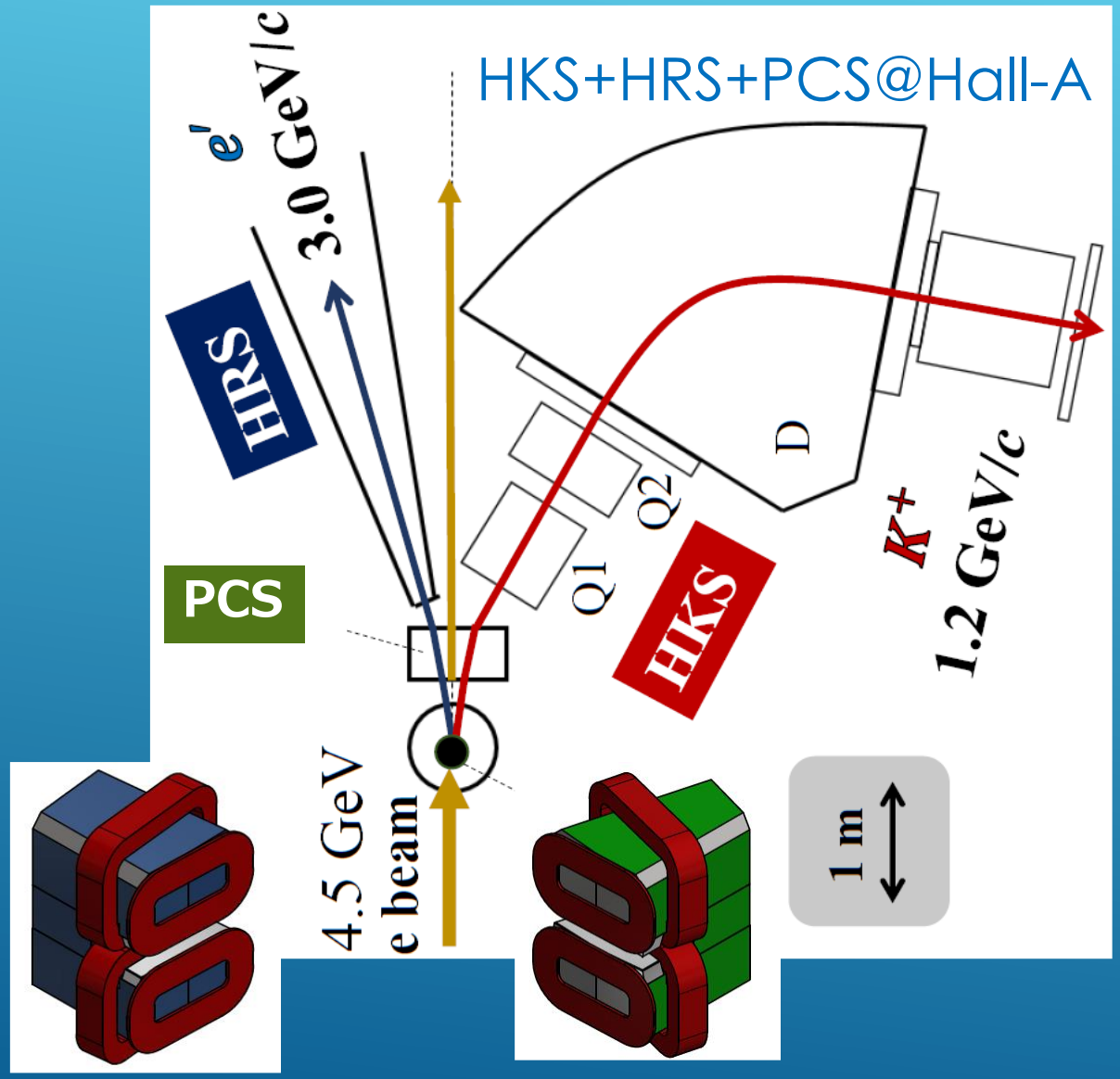
E12-19-002 Cryo. Gas $^{3,4}\mathrm{He}$ (e,e'K) $^{3,4}_{\Lambda}\mathrm{H}$

E12-18-013 $^{208}\mathrm{Pb}$ (e,e'K) $^{208}_{\Lambda}\mathrm{T}l$

From Hypernuclei to Neutron Stars



E12-15-008 ($^{40,48}_{\Lambda}$K), E12-20-013 ($^{208}_{\Lambda}$Tl), E12-19-002 ($^{3,4}_{\Lambda}$H)



Originally proposed setup (PAC44, 2016)

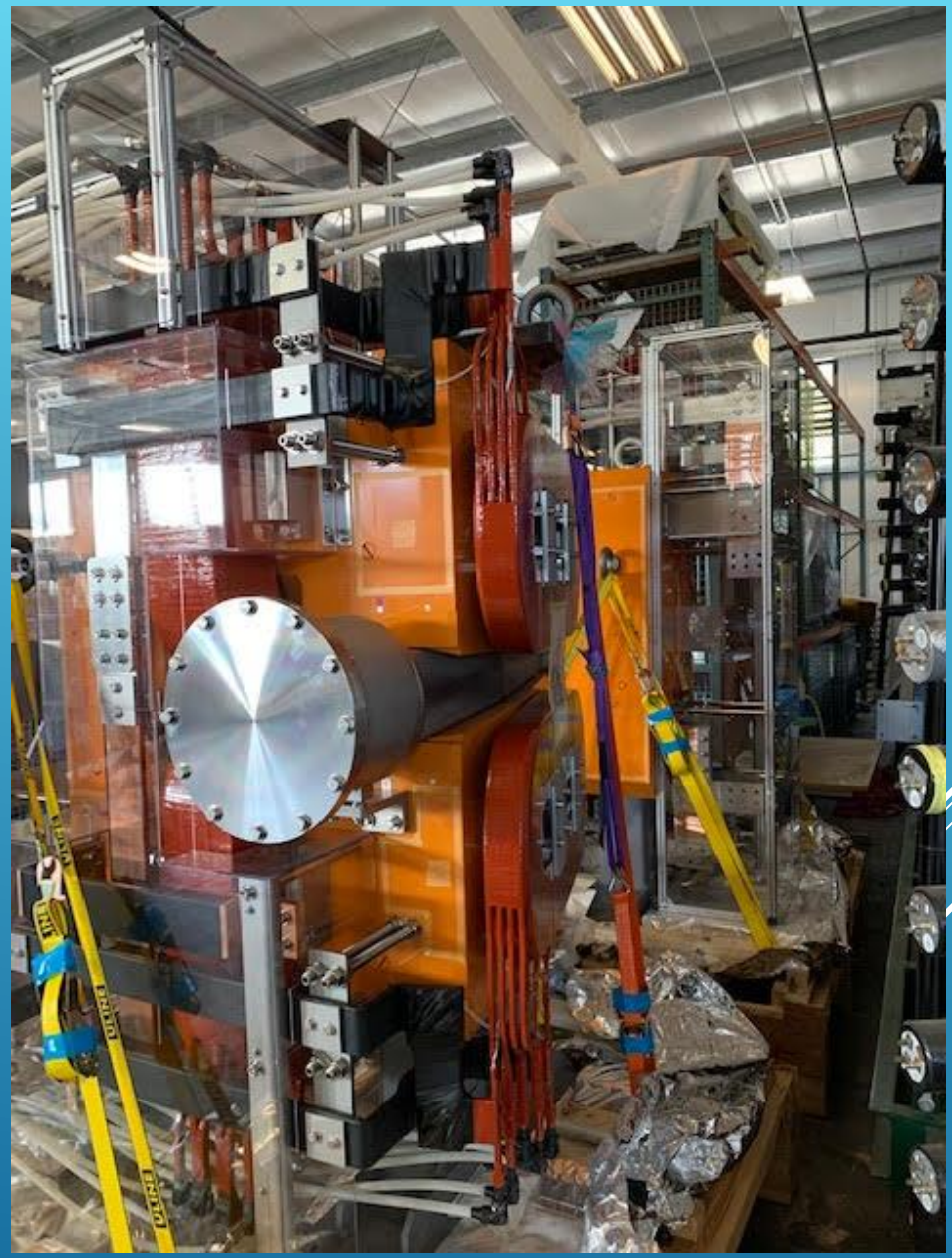
Increase beam energy

Introduction PCS magnets

Vertical bending Spectrometer HRS

Excellent S/N ratio
Suitable for high-Z targets
Z-vertex info. for gas targets

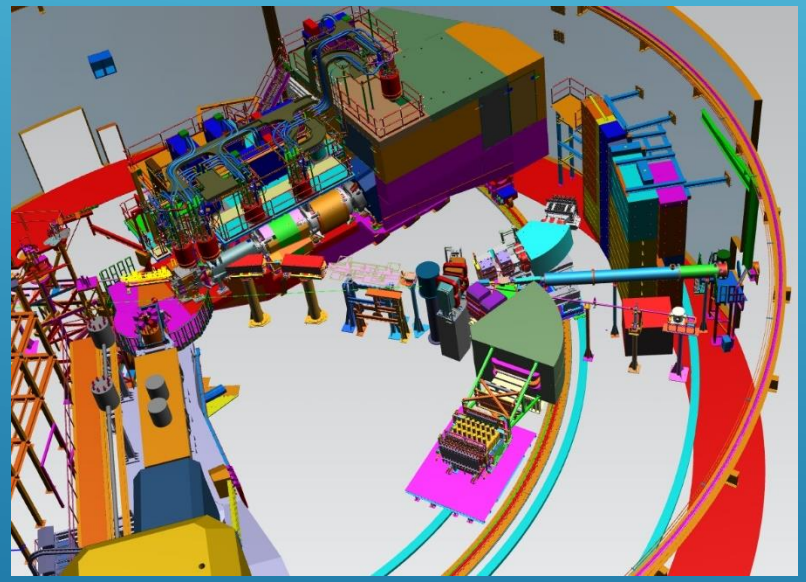
Newly constructed PCS magnets (TOKIN, 2020.3)



Finally delivered to JLab (2022.2 @ JLab)

RE-OPTIMIZATION FOR HALL-C

Reconsider Hall-C option due to beam availability in Hall-A



HKS+HES(H)+PCS@Hall-C

	Original	Updated
Experimental Hall	Hall-A	Hall-C
Beam Energy [/(GeV)]	4.532	2.240
Electron spectrometer	HRS	HES
Bending direction	Vertical	Horizontal
Central momentum [/(GeV/c)]	3.03	0.74
Kaon spectrometer	HKS	HKS
Bending direction	Horizontal	Horizontal
Central momentum [/(GeV/c)]	1.20	1.20

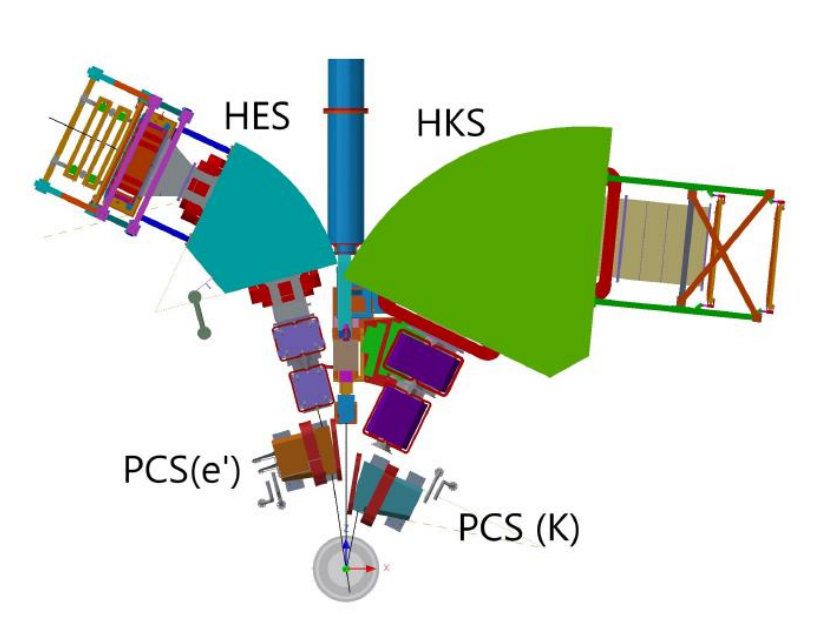
Better S/N

Better Res.

Larger SA (PCS+HRS)

Thicker Targets

Current plan of JLab hypernuclear experiments



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}

First campaign : concentrate on solid targets

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

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

LoI1 ^{27} **Al (e,e'K)** $^{27}_{\Lambda}\mathrm{Mg}$ **: triaxial deform.** ^{26}**Mg**

LoI2 ^{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**

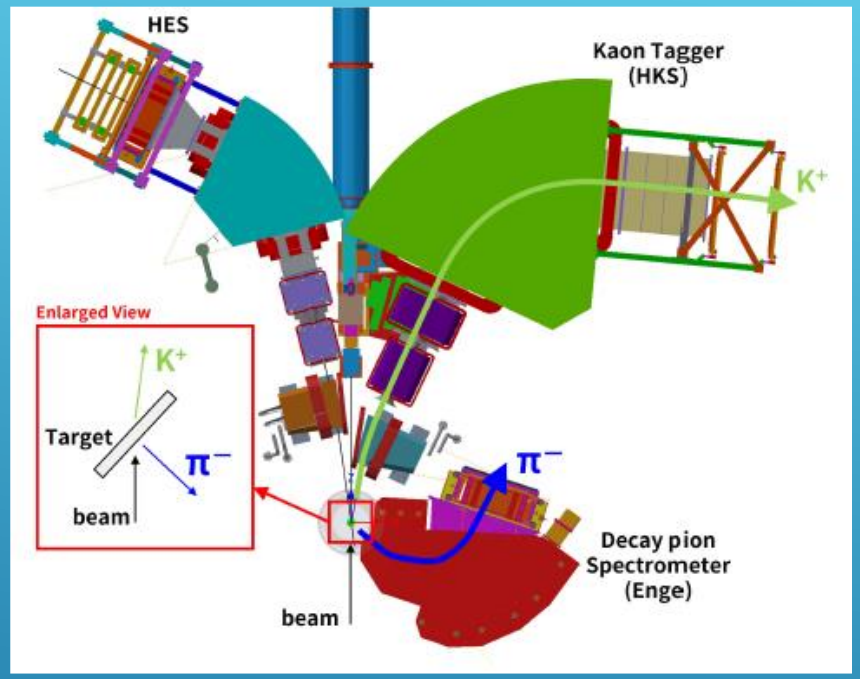
LoI3 Decay π Spectroscopy with ENGE

Future programs : cryogenic gas targets

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

E12-17-003ext Cryo. Gas ^{3}H (e,e'K) [nnΛ]

Current plan of JLab hypernuclear experiments



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

LoI1 ^{27}Al (e,e'K) $^{27}_{\Lambda}$Mg : triaxial deform. ^{26}Mg

LoI2 ^{6}Li (e,e'K) $^{6}_{\Lambda}$He, ^{9}Be (e,e'K) $^{9}_{\Lambda}$Li, ^{11}B(e,e'K)$^{11}_{\Lambda}$Be CSB

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Future programs : cryogenic gas targets

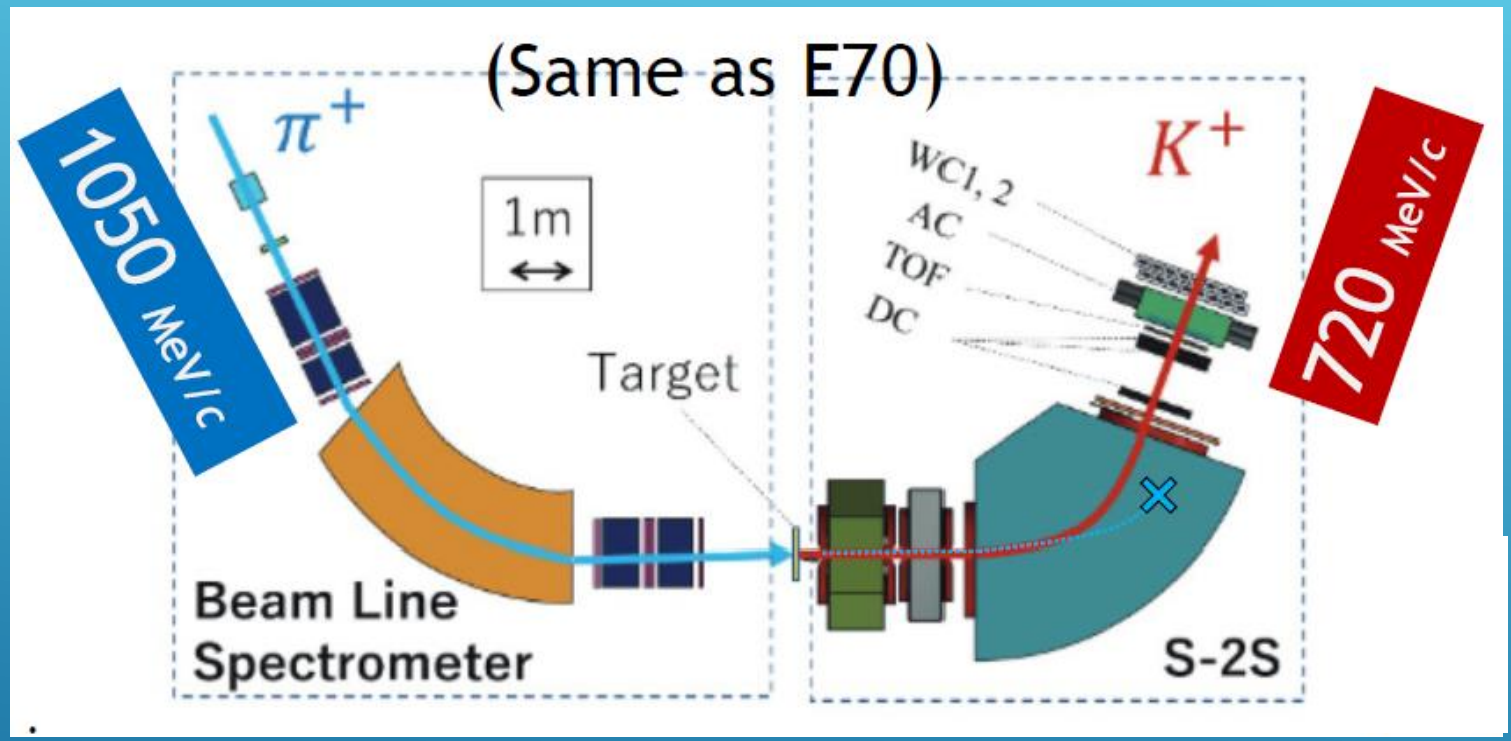
E12-19-002 Cryo. Gas ^{3,4}He (e,e'K) $^{3,4}_{\Lambda}$H

E12-17-003ext Cryo. Gas ^{3}H (e,e'K) [nnΛ]

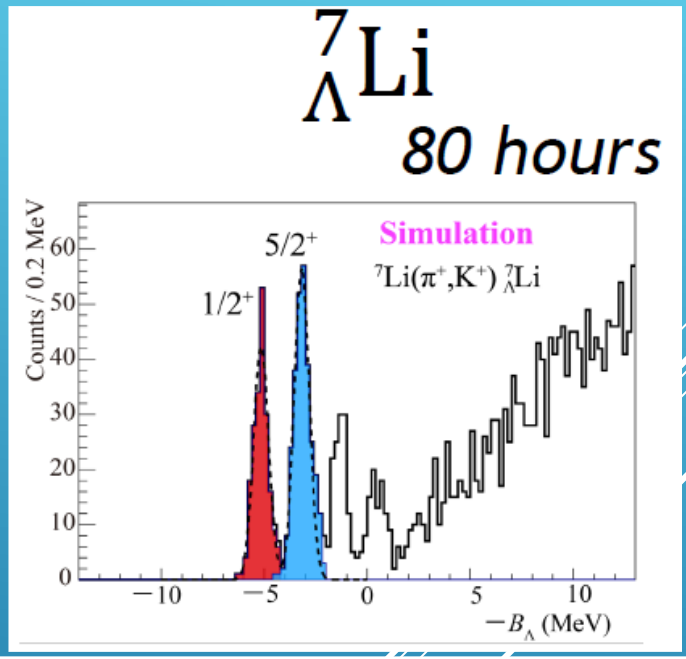
S. Nagao's talk (8th June) DπS at MAMI

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

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

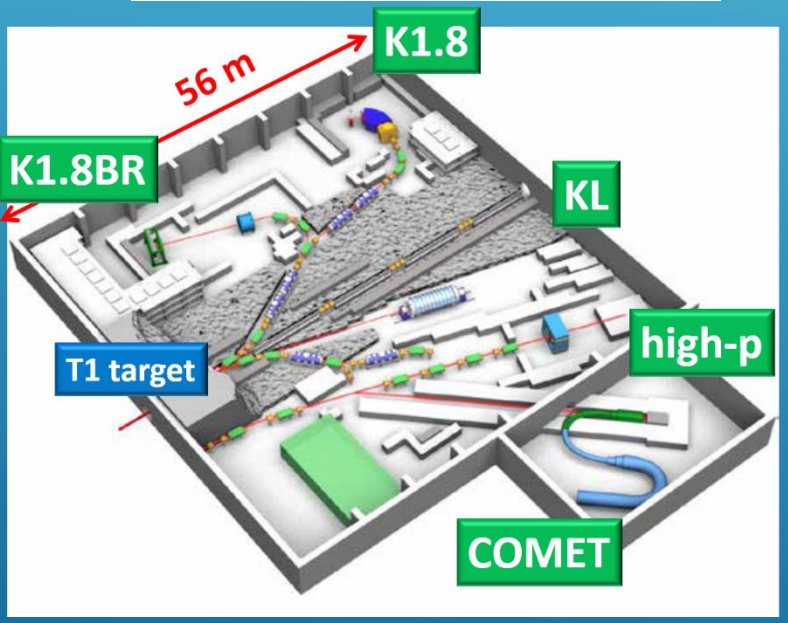
$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$ Precise measurement of B_Λ

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

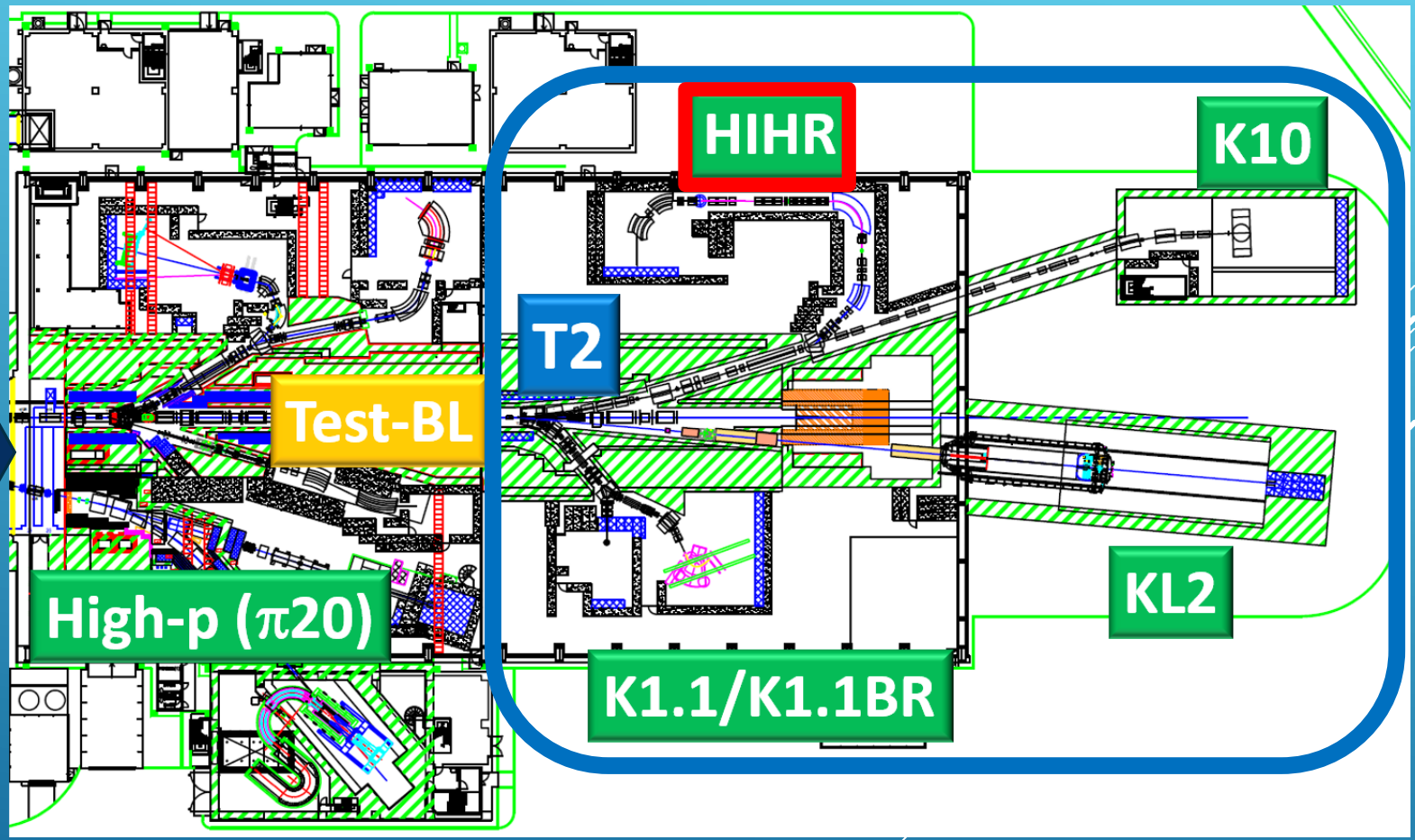
HADRON EXPERIMENTAL FACILITY EXTENSION (HEF-EX) PROJECT @J-PARC

F.Sakuma (8th June) @ New Facility Session

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)

International competition for High-resolution (π^+,K^+) spectroscopy at HIHR

HIHR, JLab and MAMI are possible competitors. But simultaneously complementary!

	HIHR	JLab	Mainz
Reaction	n$(\pi^+, K^+)\Lambda$	p(e,e'K$^+$)Λ	Decay π
Achievable Precision (keV)	◎ <100	◎ <100	◎ <100
Applicable hypernuclei	◎ All Z	○ Light – Medium Heavy (Larger Z, higher BG)	× Only Ground states of light hypernuclei
Flexibility of beamtime	◎ Standing Beamline with dedicated spectrometer Hypernuclear Factory	× Large-scale Installation (several months)	○ Kaon Spectrometer Installation (a few weeks)
Absolute Energy Calibration	△ $^{12}_{\Lambda}$C , $^{7}_{\Lambda}$Li $p(\pi^-, K^+)\Sigma^-$ Decay π	◎ $p(e, e'K^+)\Lambda, \Sigma^0$	◎ Elastic e scattering Abs Ee measure

HIHR

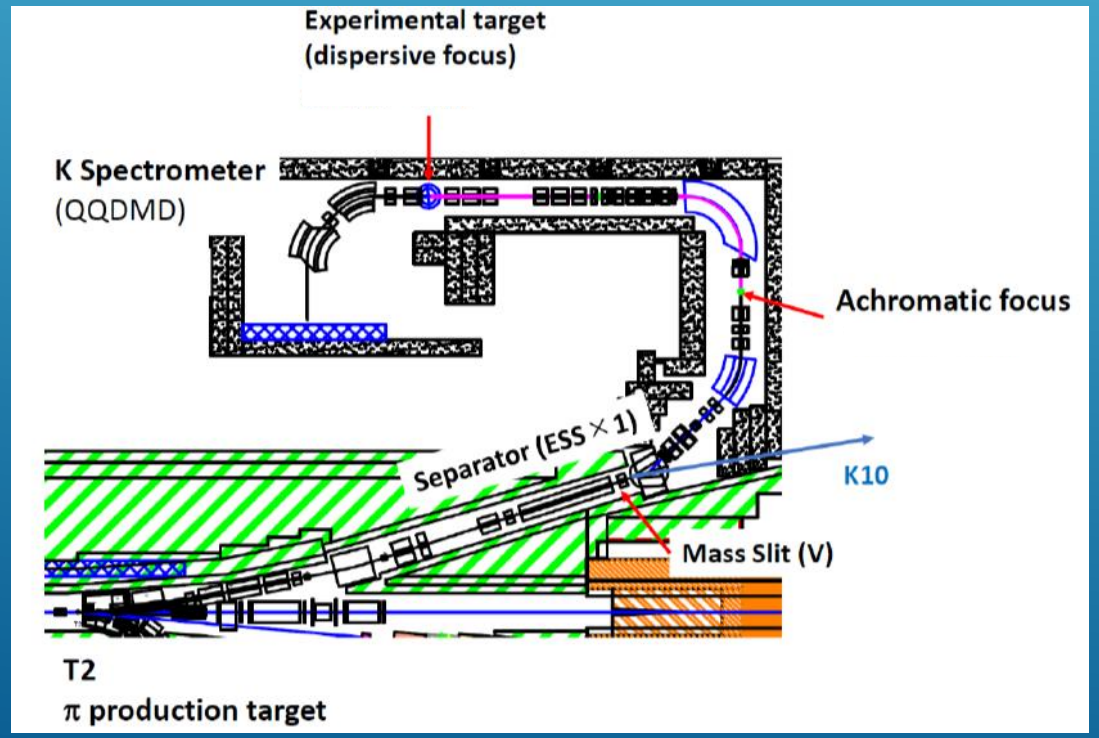
High-Intensity High-Resolution Beamline for High Precision (π, K) Spectroscopy

Exist beamlines:
~10^6 pions/pulse, Δp/p ~ 1/1000

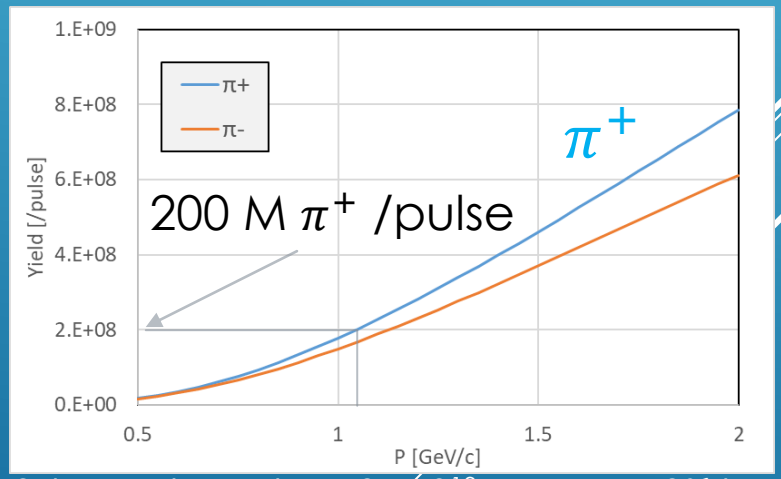
200 x 10^6 pions/pulse, Δp/p ~ 1/10000

- Momentum dispersion matching

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



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

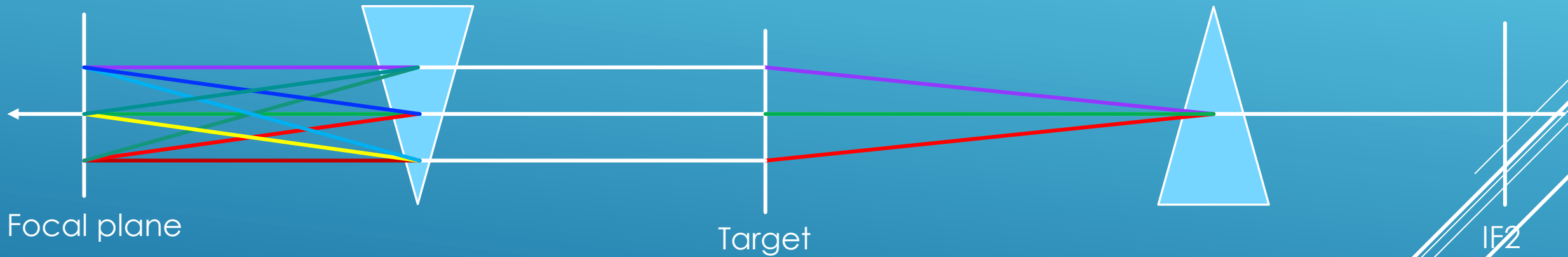


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss
target (T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

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

$+(s_{11} + s_{16}K)\theta$ -------- kinematical correction → 0

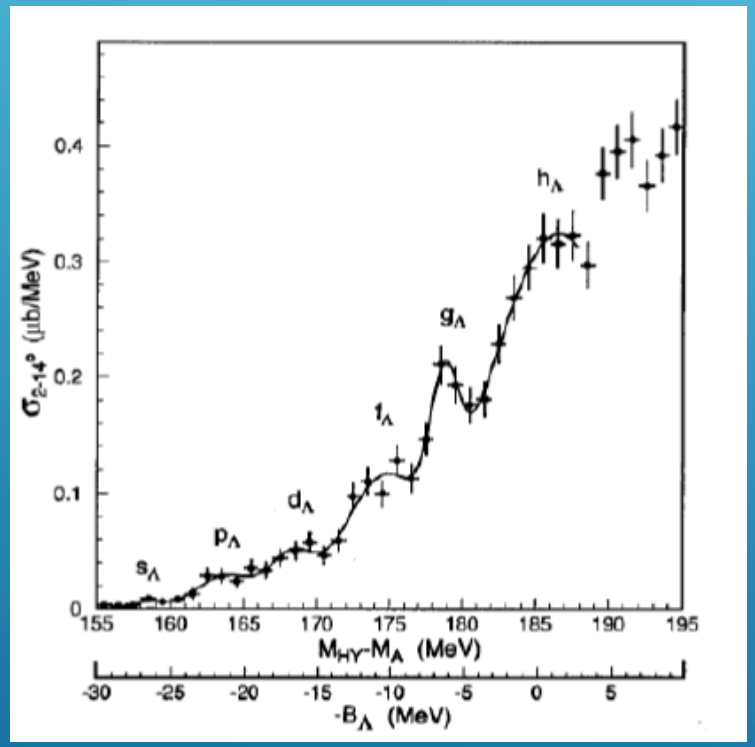
$+s_{16}DQ$ -------- a position shift by the excitation energy

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

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

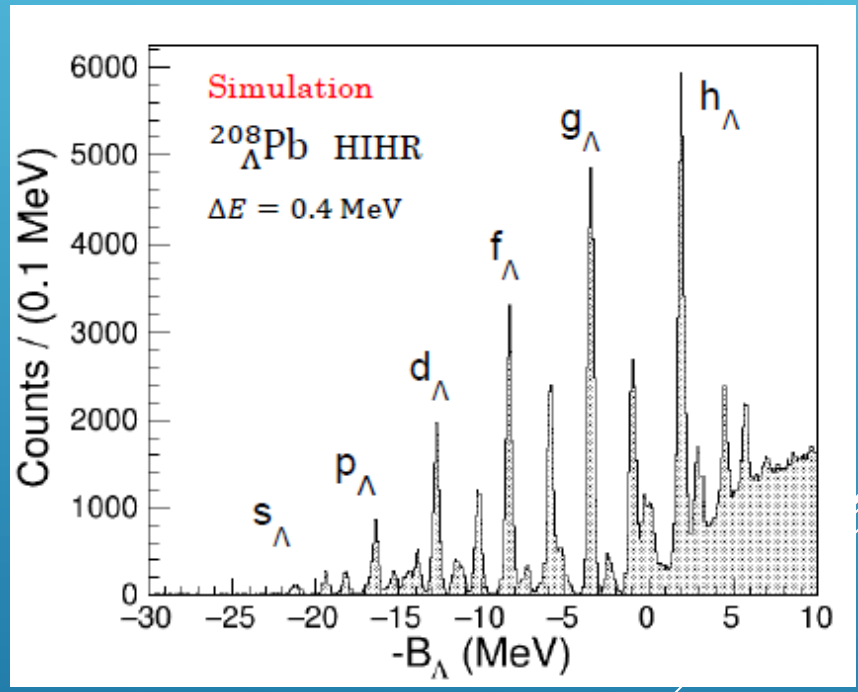
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)

Expected at HIHR beamline

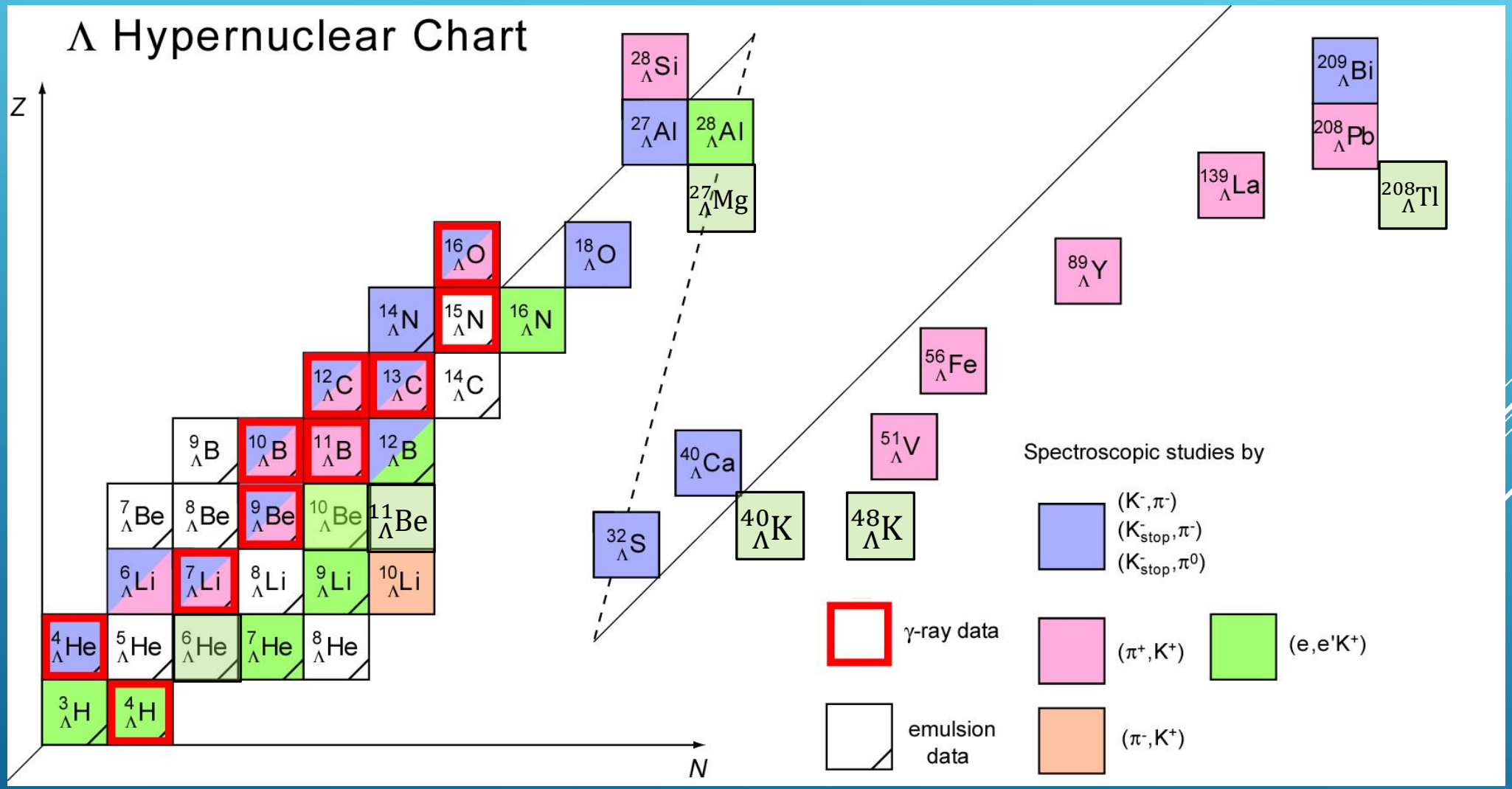


60 days × 200M π/spill @ HIHR

ΔE~**0.4 MeV(FWHM)**

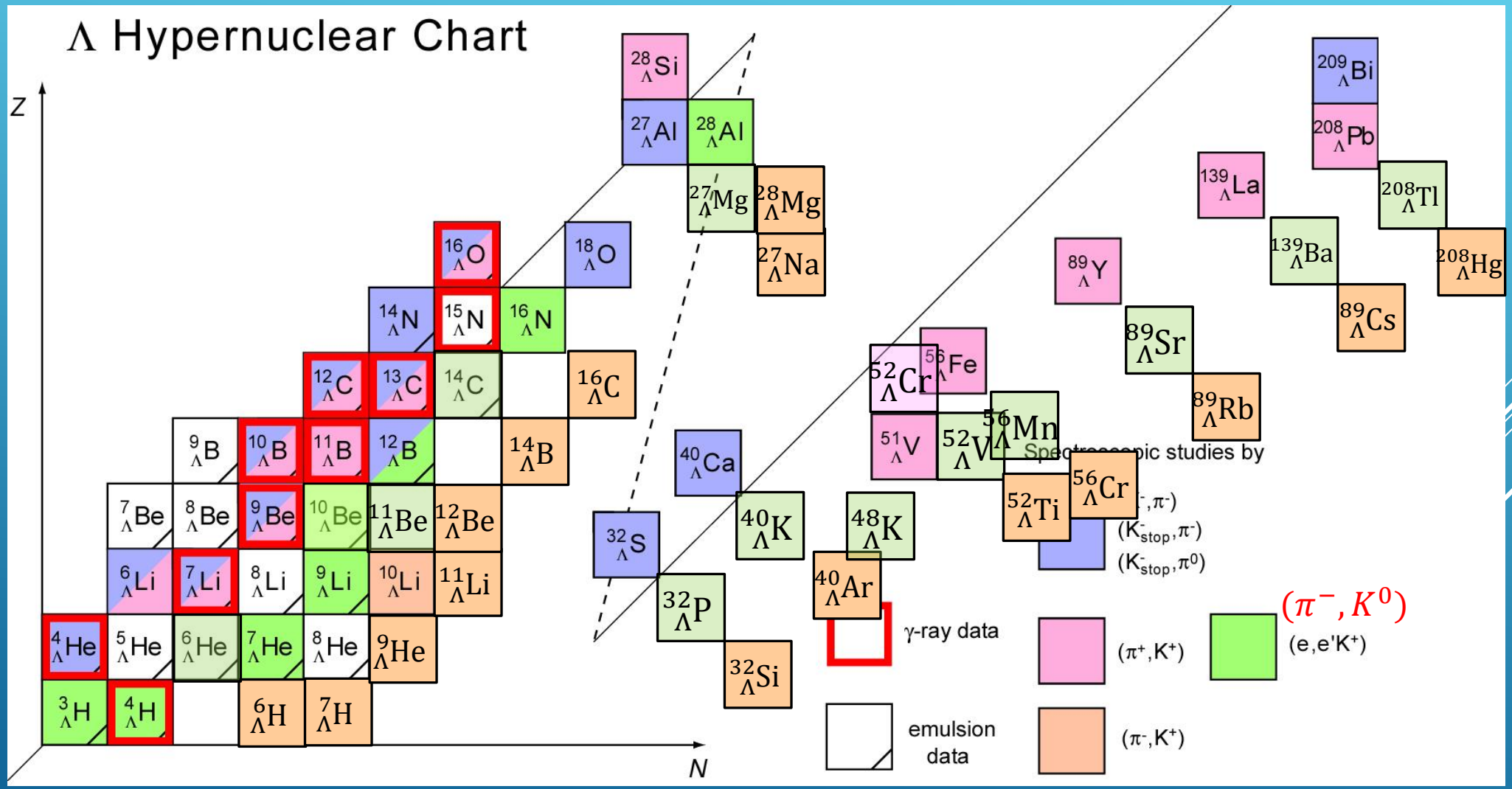
Various options for HIHR

SπK	${}^{A}Z(\pi^+, K^+){}^{A}_{\Lambda}Z$	**Super high resolution** πK **Standard HIHR**
DCX	${}^{A}Z(\pi^-, K^+){}^{A}_{\Lambda}(Z-2)$	Change beam polarity
πK^0	${}^{A}Z(\pi^-, K^0){}^{A}_{\Lambda}(Z-1)$ $\rightarrow \pi^- + \pi^+$	Additional π spectrometer intermediate detector
Decayπ	${}^{A}_{\Lambda}Z \rightarrow {}^{A}(Z+1) + \pi^-$	Additional π spectrometer



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.

SUMMARY

- ***Hypernuclear physics is now more important than previous.***
- At JLab,$(e, e'K^+)$: ${}^{40,48}_{\Lambda}\mathrm{K}$, ${}^{208}_{\Lambda}Tl$, ${}^{6}_{\Lambda}\mathrm{He}$, ${}^{9}_{\Lambda}\mathrm{Li}$, ${}^{11}_{\Lambda}\mathrm{Be}$, ${}^{27}_{\Lambda}\mathrm{Mg}$, Decay π in Hall-C
- At J-PARC $(\pi^+, K^+)$with S-2S: ${}^{7}_{\Lambda}\mathrm{Li}$, ${}^{10}_{\Lambda}\mathrm{B}$, ${}^{12}_{\Lambda}\mathrm{C}$

- 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

  Challenge to Hyperon Puzzle

  Hypernuclear Factory
- Various options at HIHR, (π^-, K^+), (π^-, K^0), Decay π as well as (π^+, K^+)