Future prospects of spectroscopy of Lambda hypernuclei at JLab and J-PARC HIHR

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The University of Tokyo

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Jefferson Lab

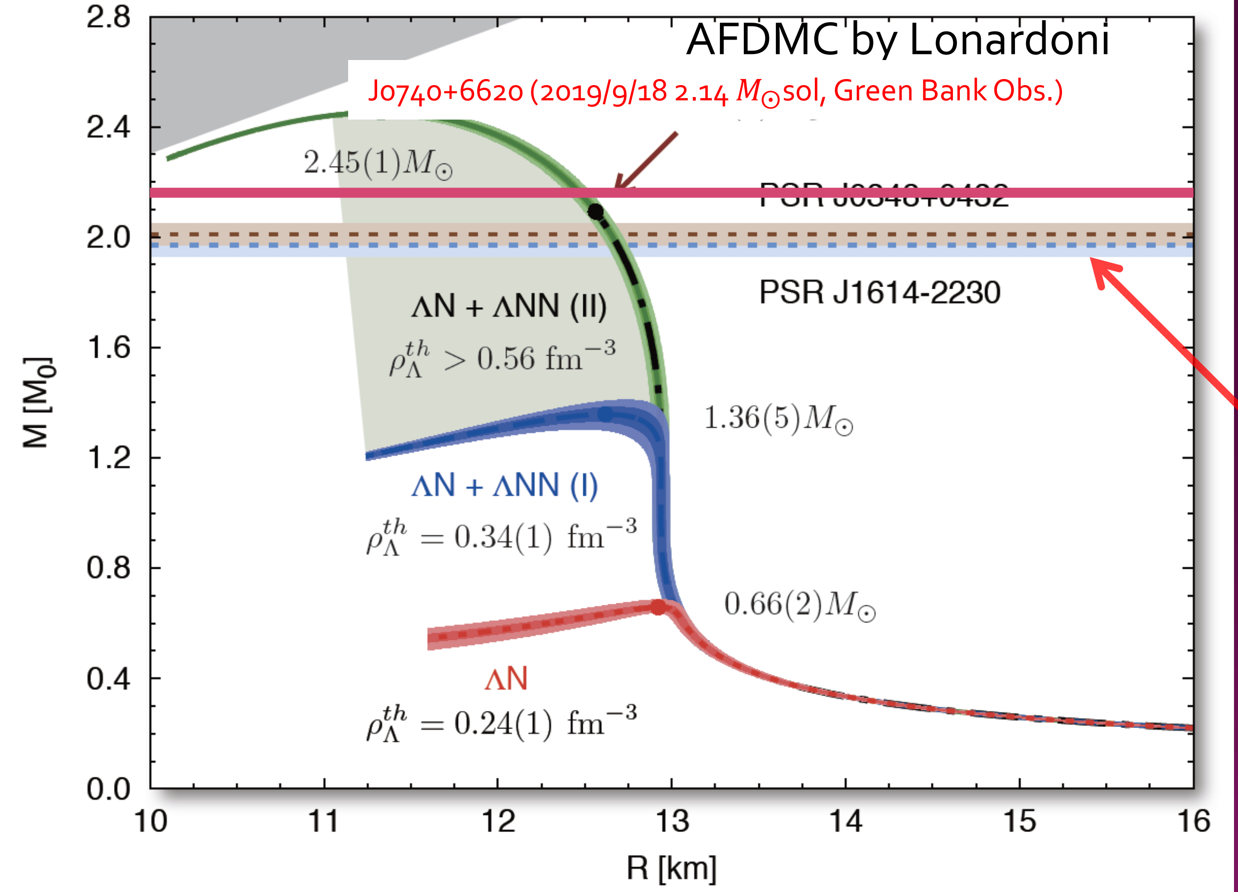
EXPLORING THE NATURE OF MATTER

J-PARC

Hyperon Puzzle

Based on our knowledge on Baryonic Force:

Hyperon naturally appear at high density (ρ=2~3ρ_0)



Too Soft EOS

Contradict to observation

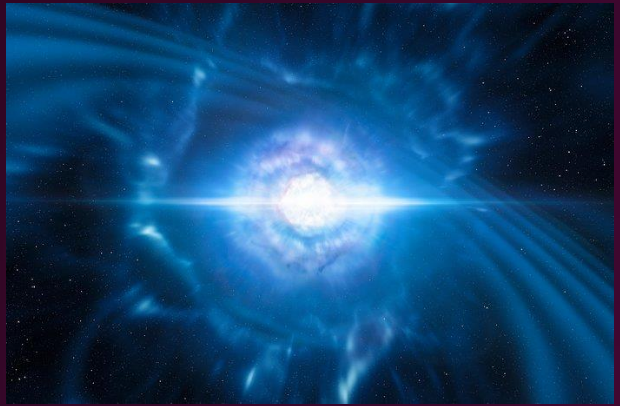
2 $M_{\odot}$ Neutron Stars

Additional Force
to make EOS stiff

AFDMC by Lonardoni et al. PRL114 (2015) 092301, updated (2016)

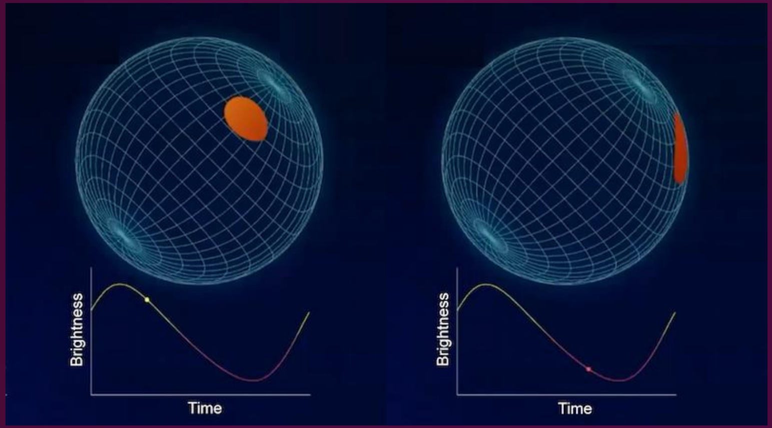
ESC08c + 3B/4B RF : G-Matrix Calc. by Yamamoto et al., PRC 90 (2014) 045805.
Variational Meth. + AV18+UIX by Togashi et al., PRC 93 (2016) 035808

New Astronomical Observations of Neutron Stars



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)

Great progresses
Macroscopic features of NS

⇩

Microscopic understanding
becomes more important!

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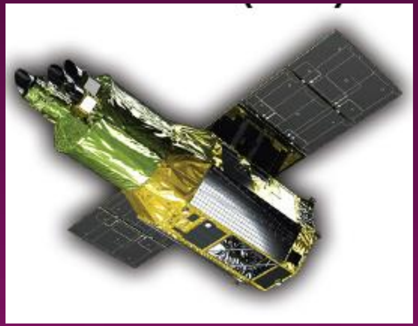
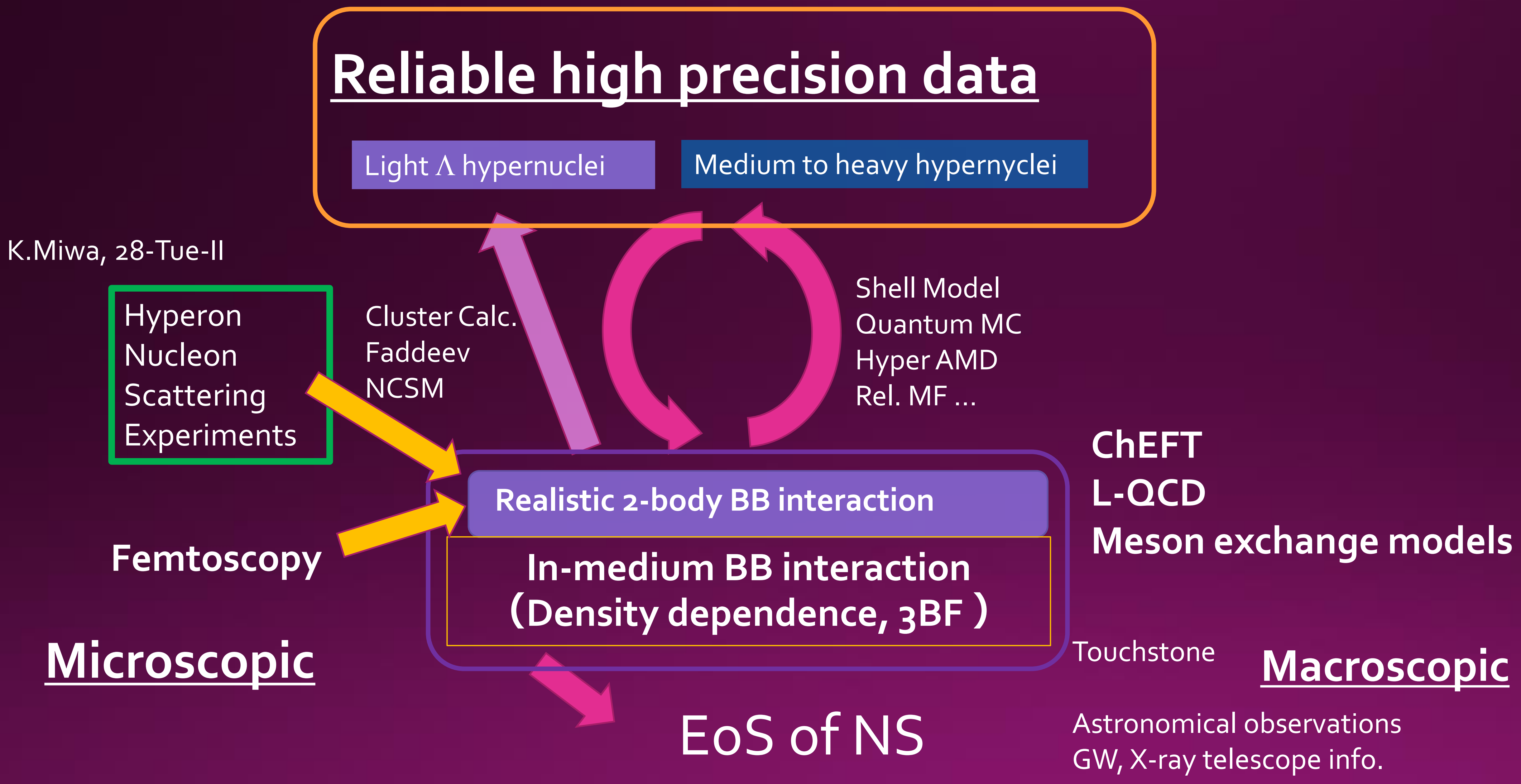


X-Ray Imaging and Spectroscopy Mission (XRISM) will launch in JFY 2022.

Strategy to solve the hyperon puzzle

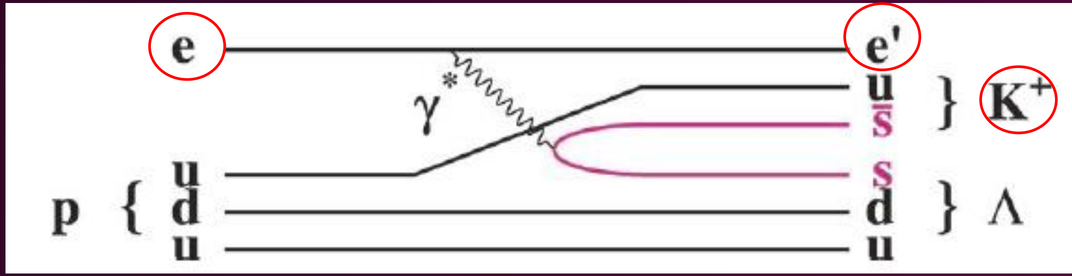


Electron beam vs. meson beams

(e,e'K⁺) @ JLab

Excellent mass resolution

~ 0.5 MeV(FWHM)



Absolute energy calibration

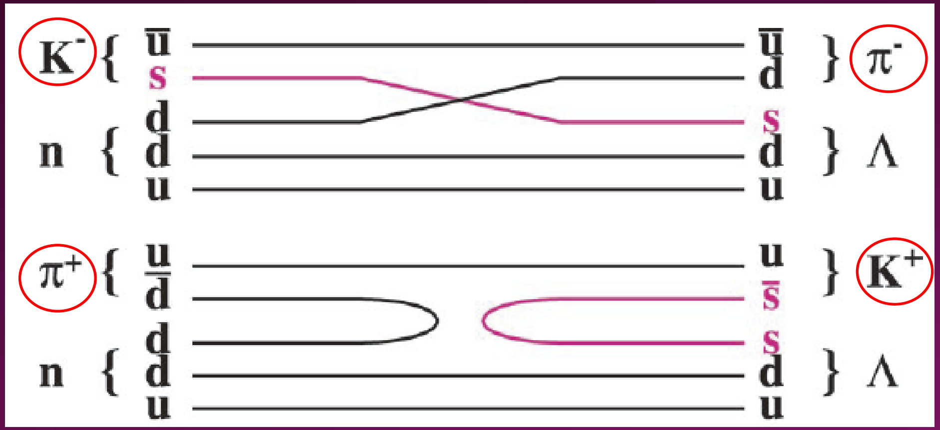
p(e,e'K⁺) Λ, Σ^0

High Intensity

100 μA = 6×10^{14} /s

Thin target (isotopically enriched)

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



(K⁻, π⁻)

Intensity limitation

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

1-2 MeV resolution

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

(π⁺, K⁺)

HIHR@J-PARC HD. Ex

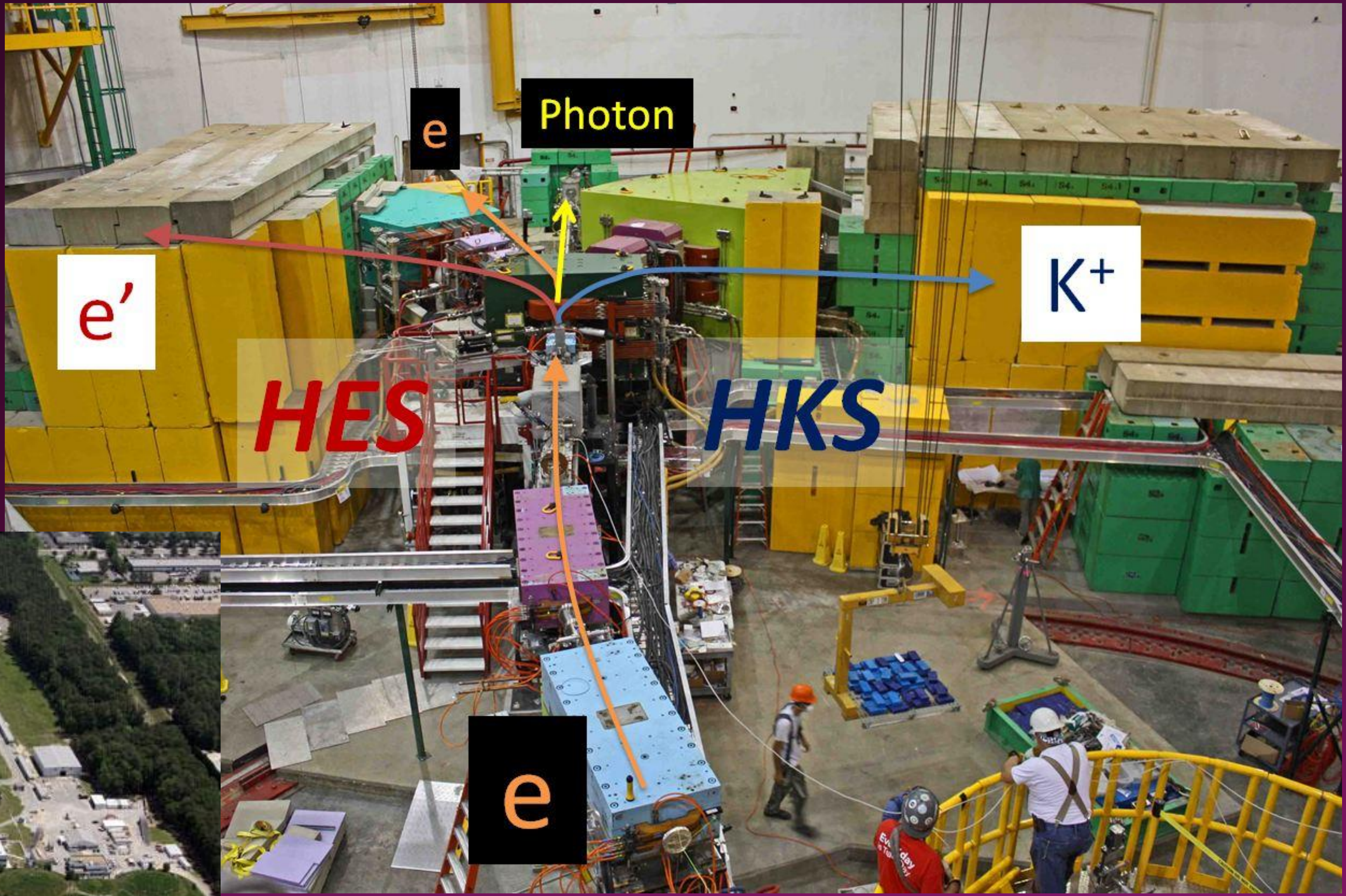
Excellent mass resolution

< 0.4 MeV

Thin target (isotopically enriched)

No limitation for beam intensity

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



Jefferson Lab
EXPLORING THE NATURE OF MATTER

Approved JLab Hypernuclear Experiments

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

T.Akiyama, 28 Tue-poster

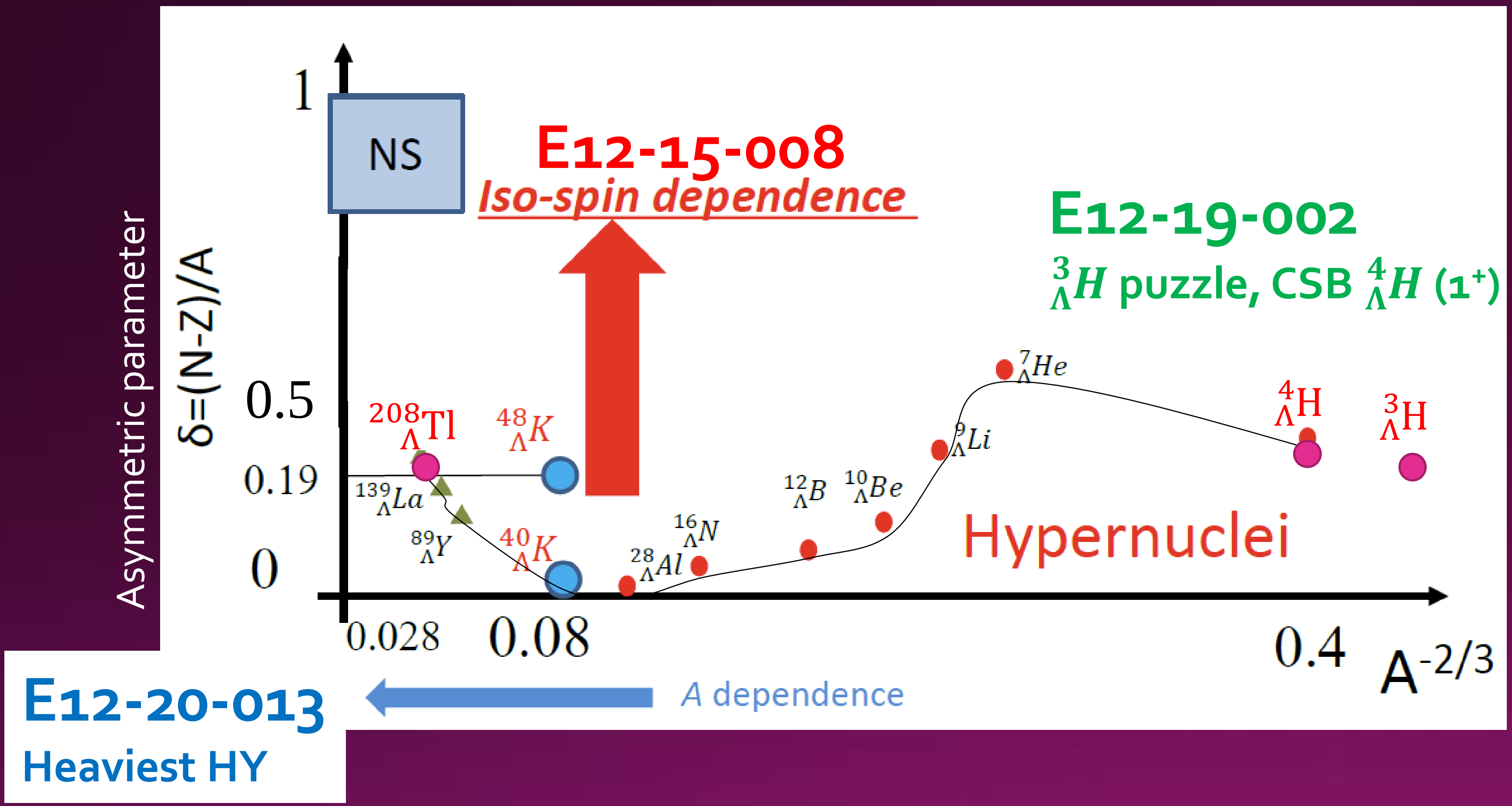
E12-19-002 Cryo. Gas $^{3,4}\text{He}\,(\text{e,e'K})\,^{3,4}_{\Lambda}\text{H}$

T.Gogami, 28 Tue-poster

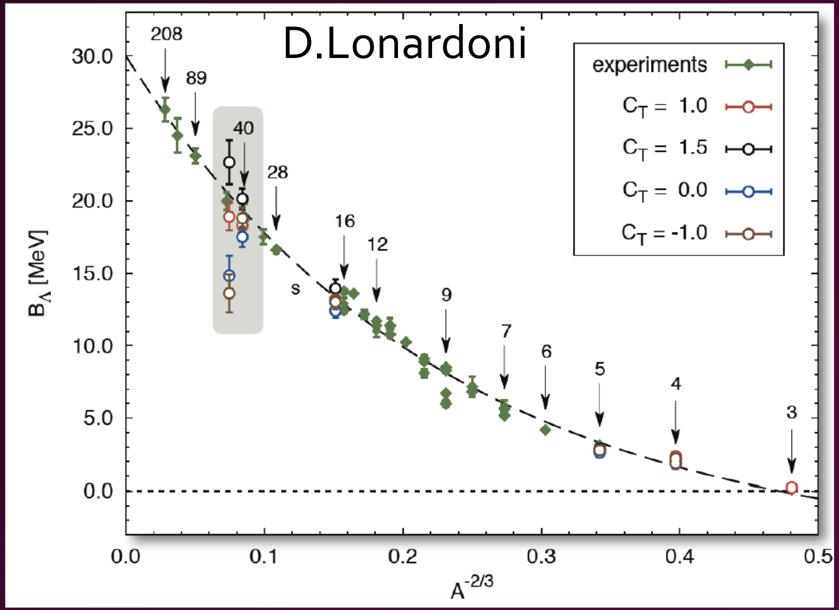
E12-18-013 $^{208}\text{Pb}\,(\text{e,e'K})\,^{208}_{\Lambda}\text{T}l$

F.Garibaldi, 30 Thu-IIb

From hypernuclei to NS

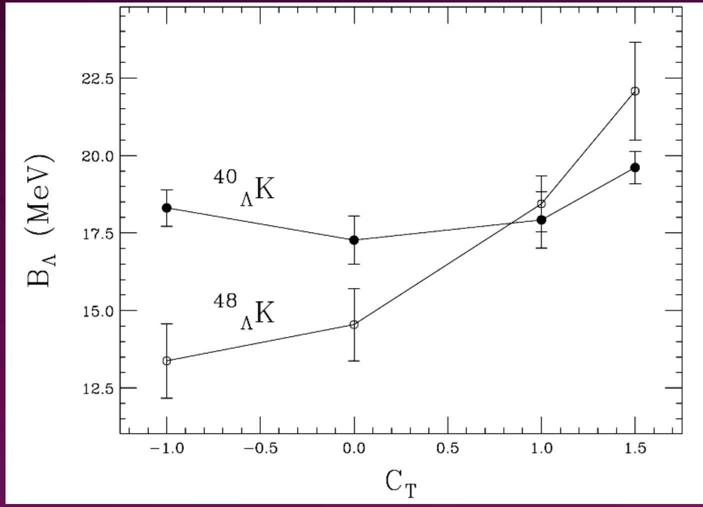


Phenomenological 3 BRF+AFDMC



C_T :Parameter to gauge
Λnn contribution
in ΛNN potential

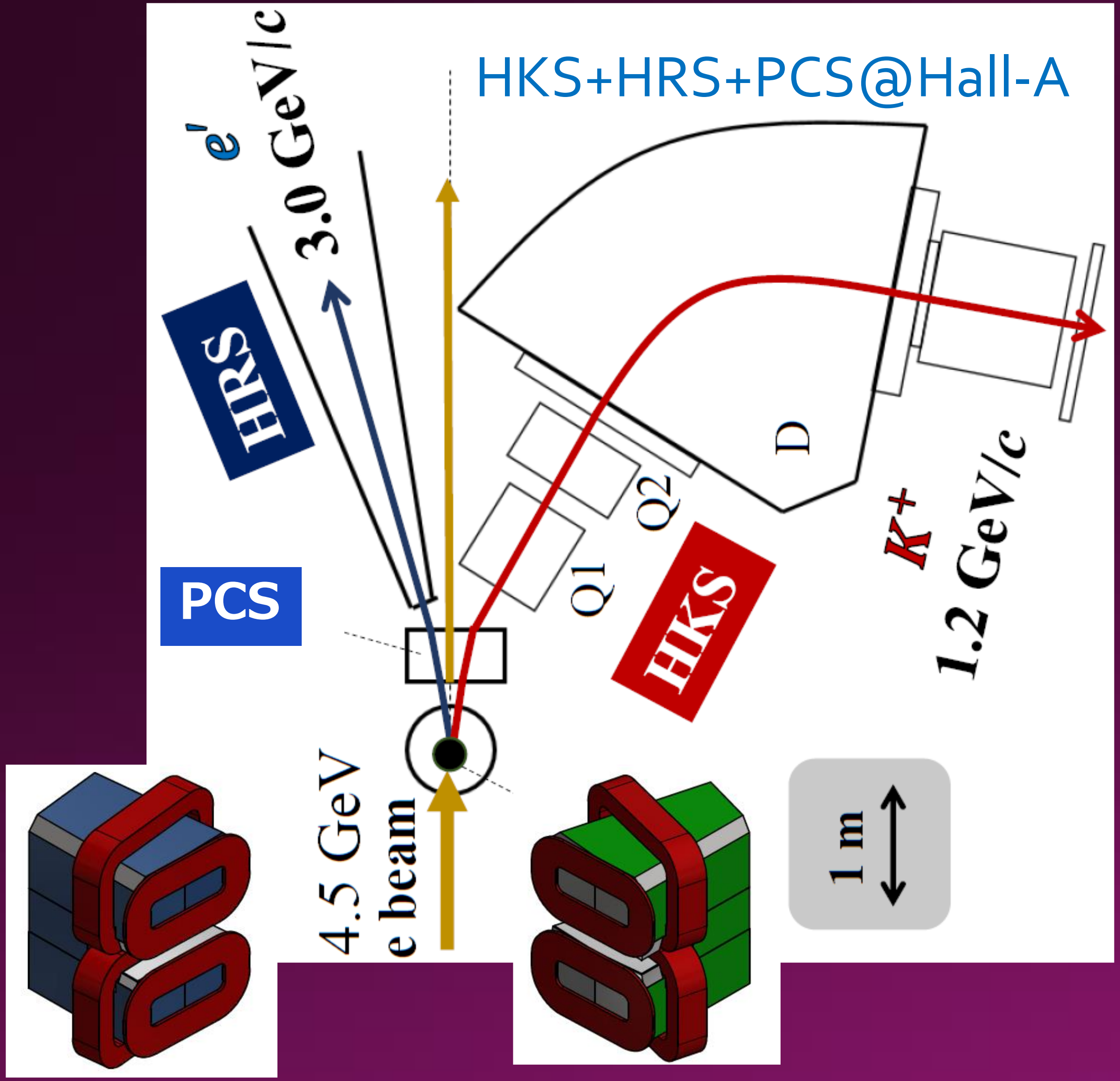
$$v^{T}_{\lambda ij}\,\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j = -3\,v^{T}_{\lambda ij}\,\mathcal{P}^{T_N=0}_{ij} + (1+C_T)\,v^{T}_{\lambda ij}\,\mathcal{P}^{T_N=1}_{ij}$$



^{40}Ca(e ,e′K$^+$)$^{40}{}_{\Lambda}$K and , ^{48}Ca(e, e′K$^+$)$^{48}{}_{\Lambda}$K

E12-15-008
accepted with GRADE A.

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

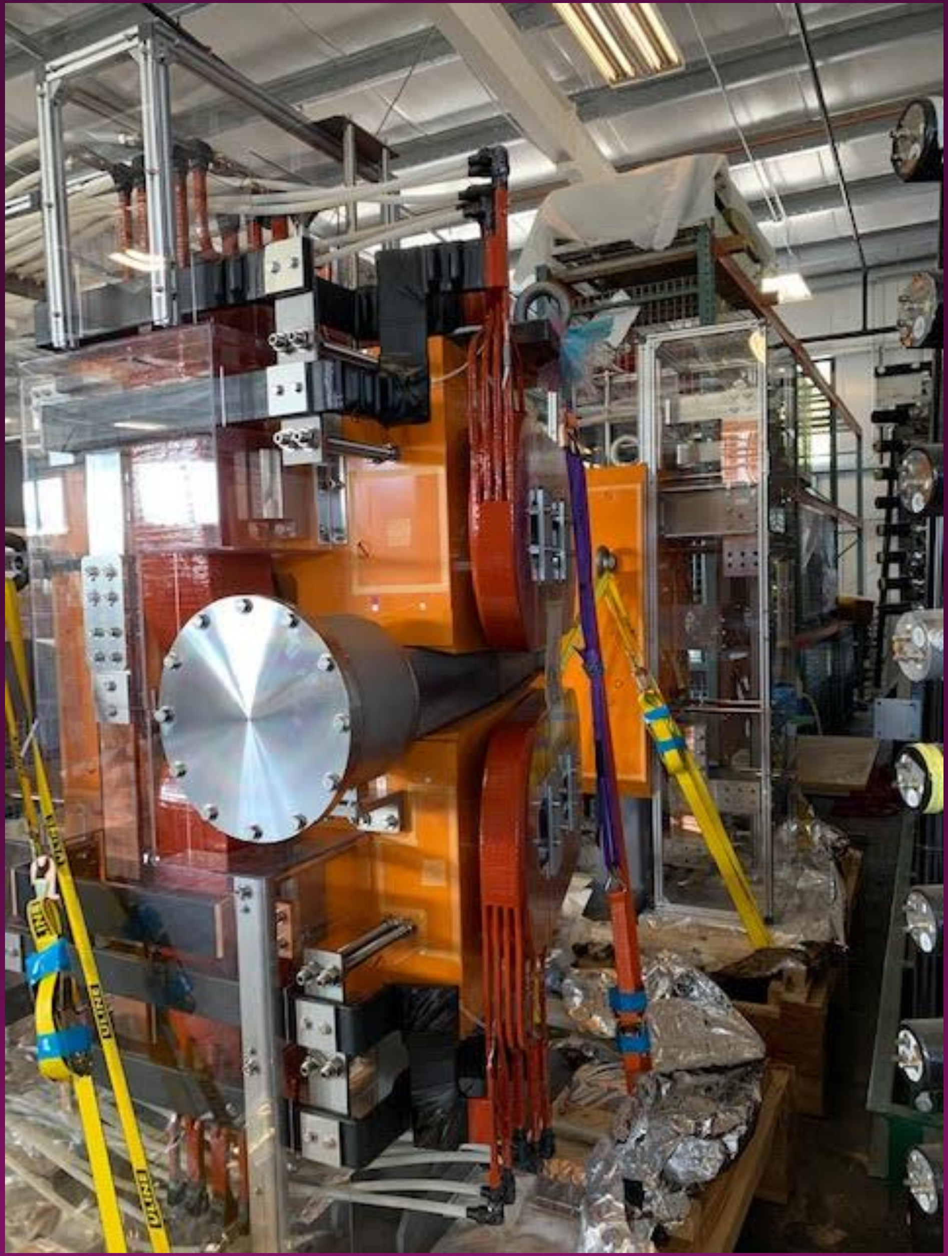


Increase beam energy

Introduction PCS magnets

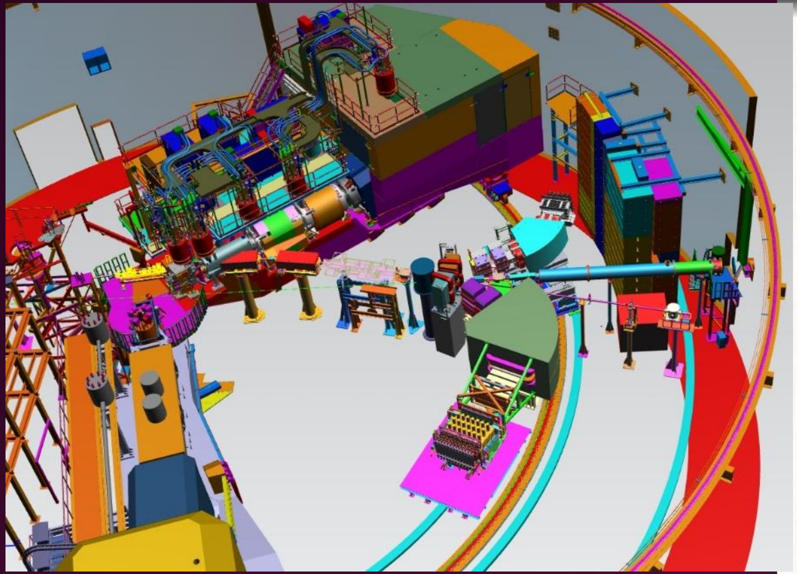
Vertical bending Spectrometer HRS

Newly constructed PCS magnets (TOKIN, 2020.3)



Finally delivered to JLab (2022.2 @ JLab)

Re-optimization for Hall-C

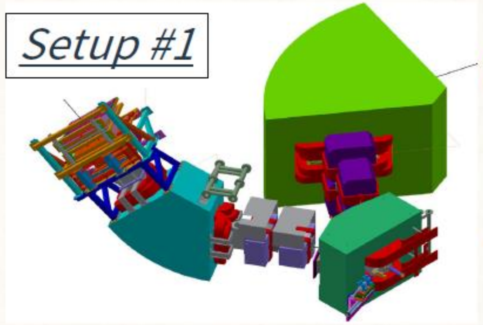


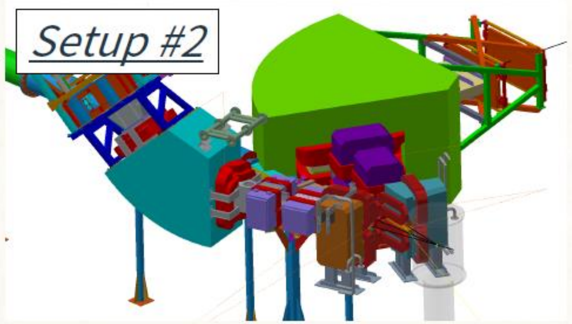
HKS+HES+PCS@Hall-C

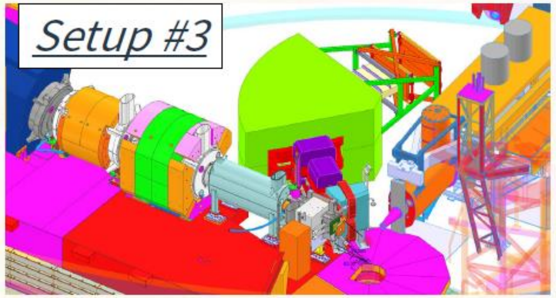
Setup Plans

The (e,e'K⁺) experiment requires two magnetic spectrometers.
Additional magnets getting the forward acceptance are necessary for higher hypernuclear yield.

	e'		K⁺		Yield	B.G.	Res. (MeV)	Z_t (cm)	Cost
	Fw. Magnet	Spec. Magnet	Fw. Magnet	Spec. Magnet					
#0	SPL	HES	SPL	HKS	H	H	0.5	×	L
#1	SPL	HES (V mode)	SPL	HKS	M	H	~ 0.5	2	H
#2	PCS(e')	HES (V mode)	PCS(K)	HKS	M	L	~ 0.5	2	H
#3		SHMS	PCS(K)	HKS	L	L	1	< 1	L







S.Nagao JLab hypernuclear collaboration meeting 2021/12/7

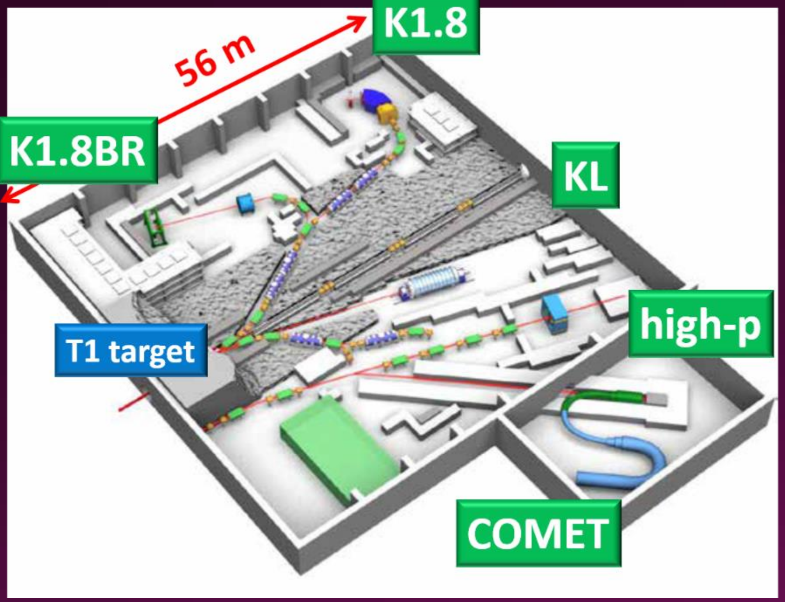
Aim to be ready for beam, 2024-2025

High Intensity High Resolution beamline

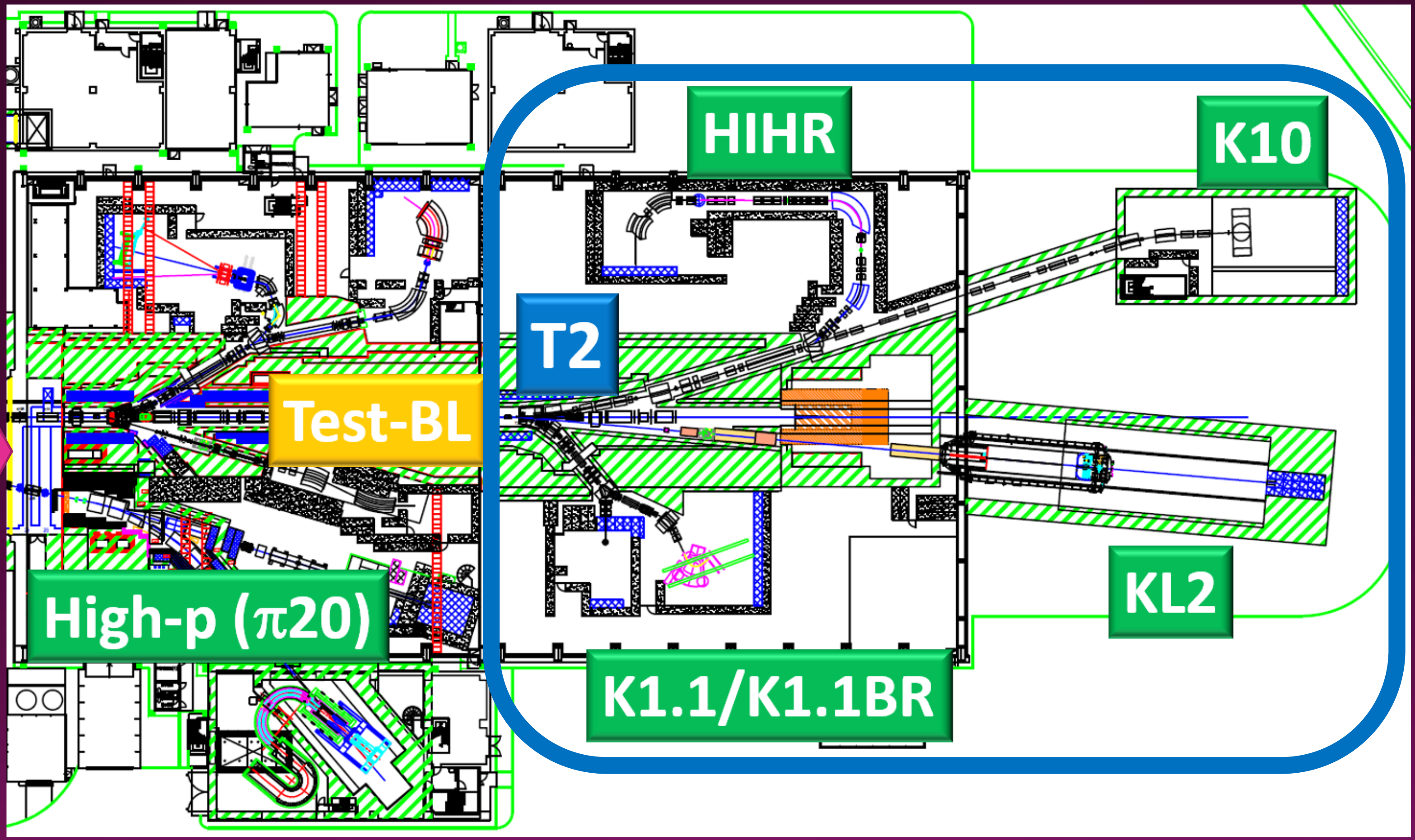
Hadron Experimental Facility Extension (HEF-Ex) Project @J-PARC

F.Sakuma Fri-II

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)

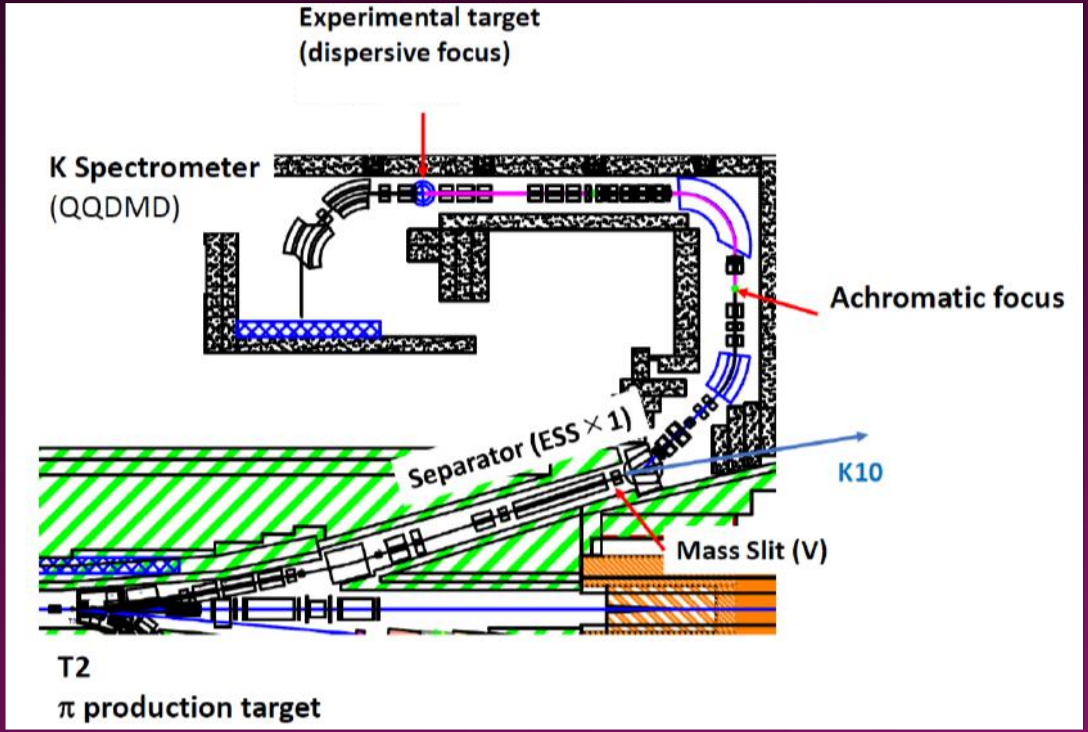
HIHR

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

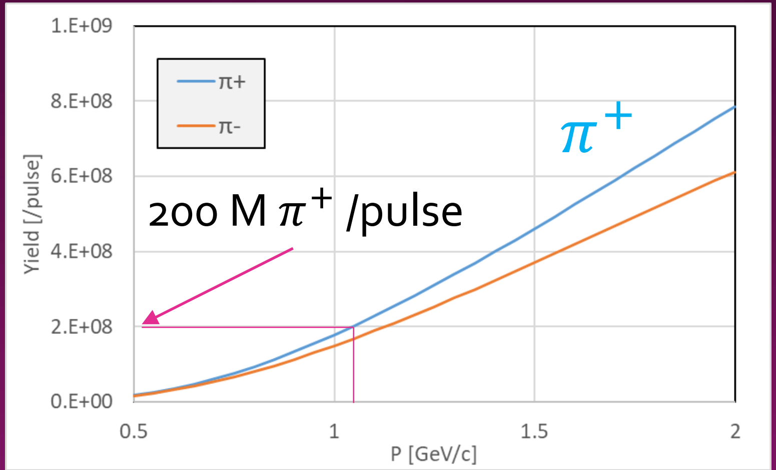
- High-Intensity High-Resolution Beamline for High Precision (π, K^+) Spectroscopy
  - Momentum dispersion matching

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

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



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

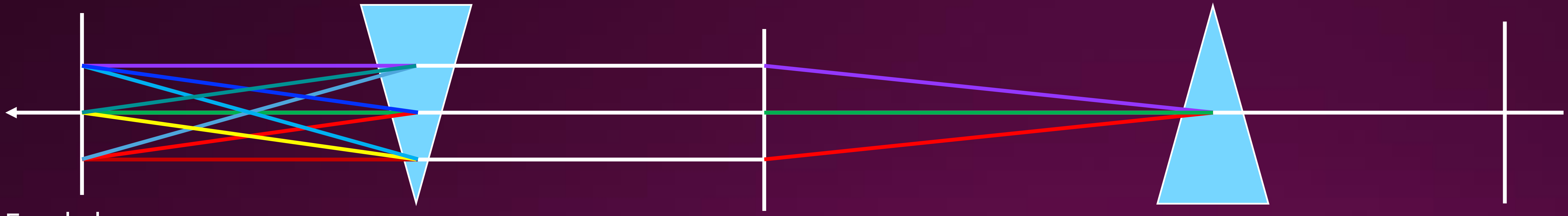


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target (T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

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

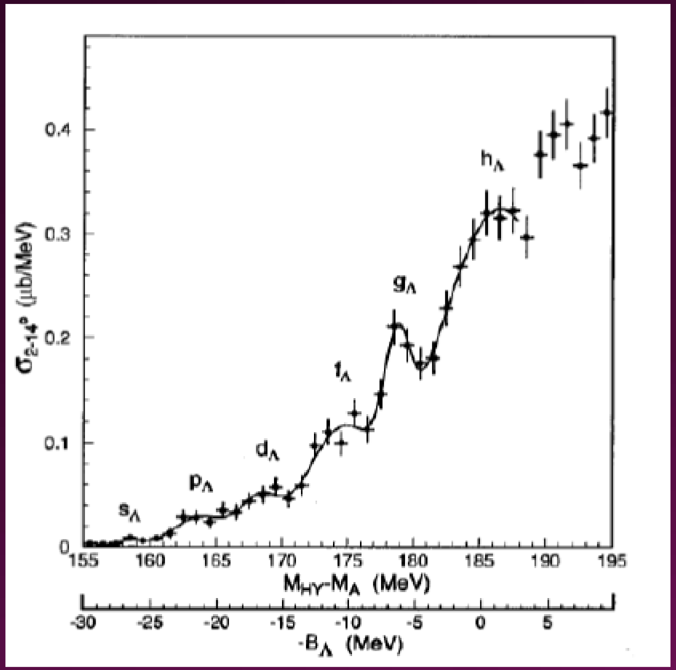
$+s_{16}DQ$ -------- a position shift by the excitation energy

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

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

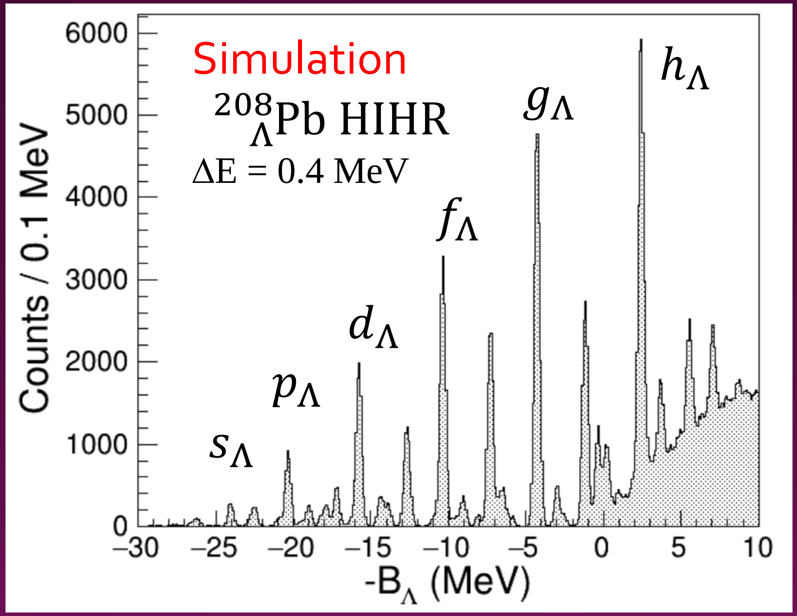
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)

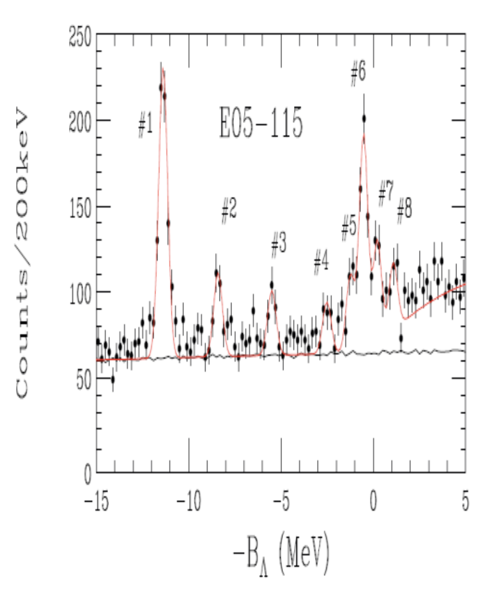
Expected at HIHR beamline



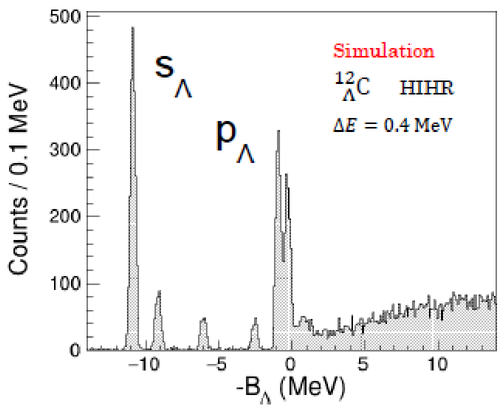
60 days × 200M π/spill @ HIHR

ΔE~0.4 MeV(FWHM)

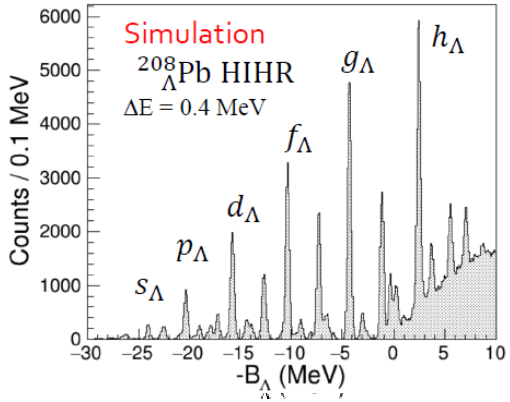
Expected spectra



$^{12}_{\Lambda}B$ @ JLab E05 − 115



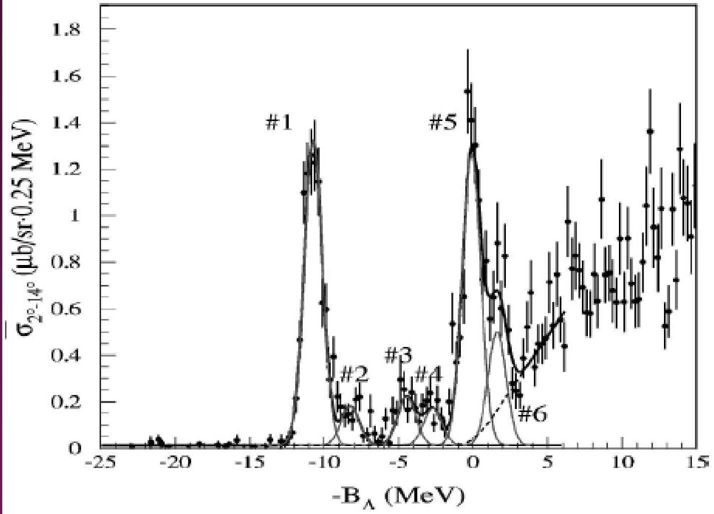
$^{12}_{\Lambda}C$ @ HIHR Simulation



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

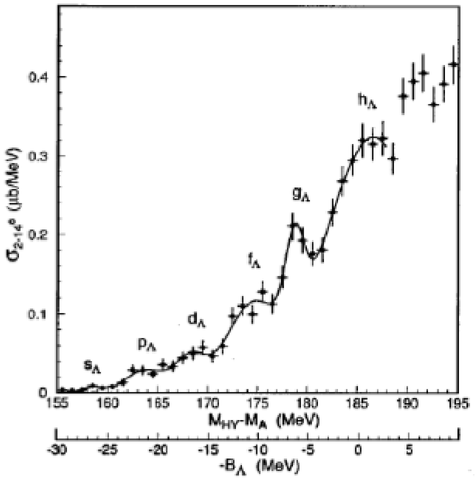
KEK-SKS

ΔE = 1.45 MeV



KEK-SKS

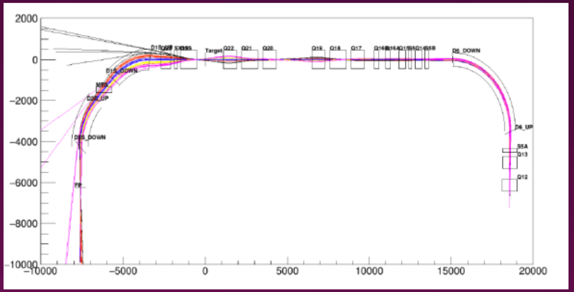
ΔE = 2.3 MeV

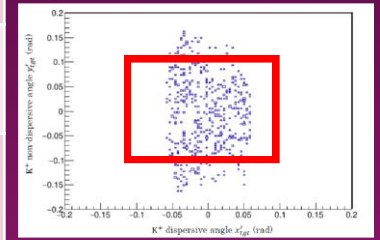


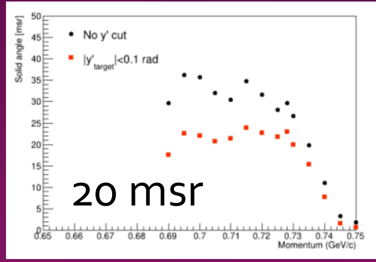
Expected Yield of Hypernulclei

	HIHR@J-PARC Ex. 1.1GeV/c π^+
Reaction	$^{12}C(\pi^+, K^+)^{12}_{\Lambda}C$
Beam on target (/ sec)	$3.85\times 10^7\ \pi^+$ (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

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 ($^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H),
Isospin dependence ($^{40}_{\Lambda}$K, $^{48}_{\Lambda}$K),
Heaviest hypernuclei ($^{208}_{\Lambda}$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!