Workshop
"Prospects of precise spectroscopy of Λ hypernuclei with various beams“
(PPPY-Λ 2021)
Akiu, Sendai

TOHOKU UNIVERSITY

10th Dec. 2021

Precise spectroscopy of Lambda hypernuclei at HIHR, J-PARC

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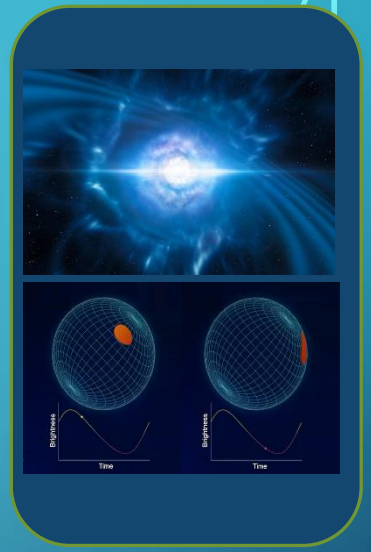
CURRENT PROBLEMS ON Λ HYPERNUCLEI



Recent astronomical observations

Hypertriton Puzzle

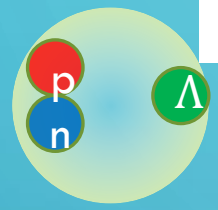
MAMI

Shallow bound
Short lifetime

J-PARC

ELPH

JLab
E12-19-002

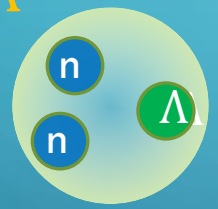


$^{3}_{\Lambda}n$ Puzzle

GSI

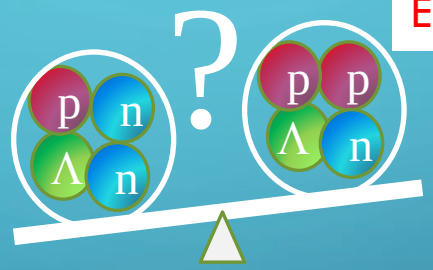
Bound?
Resonance?
Not Exist?

JLab
E12-17-003



CSB of Λ Hypernuclei

JLab
E12-15-008
E12-20-013



Hyperon Puzzle

Why massive NS exists?

$A=3$

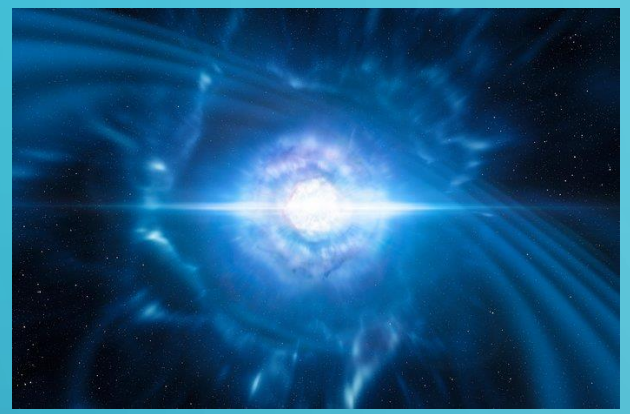
10^{-15} m

$A\sim10^{57}$

10^{4} m

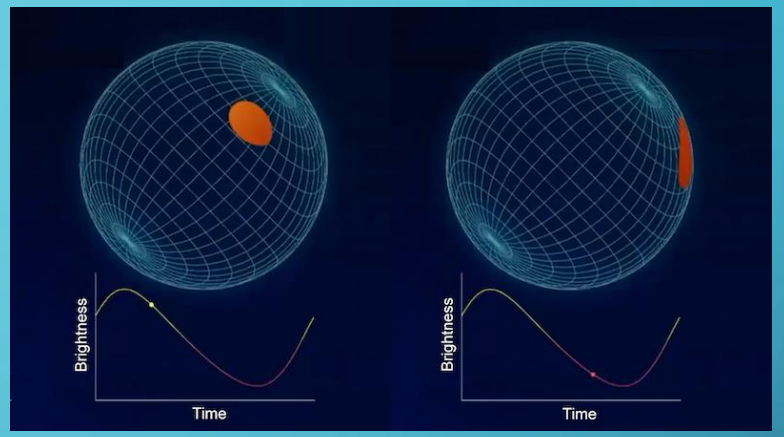
J-PARC HIHR

NEW ASTRONOMICAL OBSERVATIONS OF NS



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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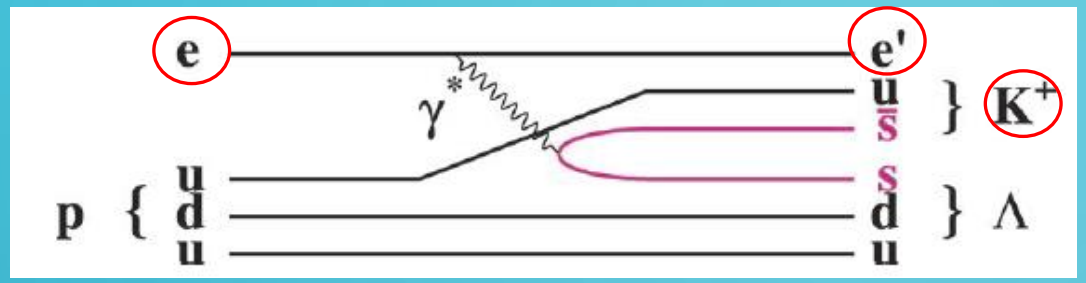
Electron beam vs. meson beams



(e,e'K^+)

Excellent mass resolution

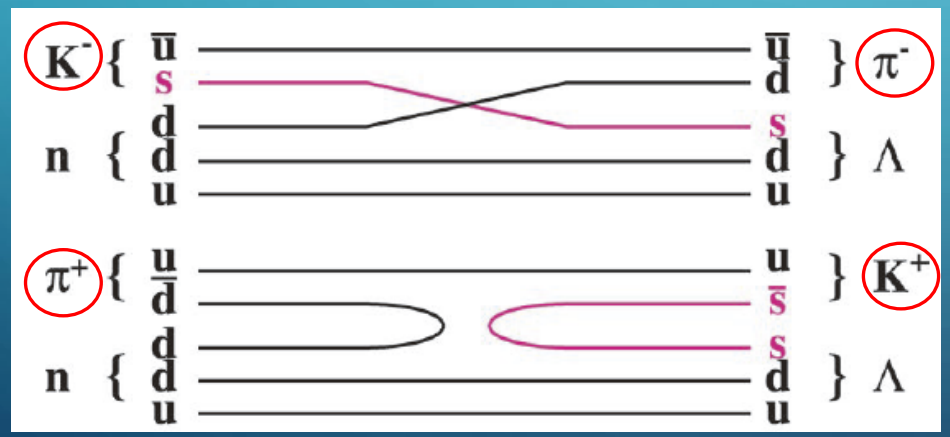
~ 0.5 MeV(FWHM)

Absolute energy calibration

p(e,e'K^+) Λ, Σ^0

Thin target (isotopically enriched)

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



(K^-, π^-)

1-2 MeV resolution

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

(π^+, K^+) → **HIHR**

Excellent mass resolution

< 0.4 MeV

Thin target (isotopically enriched)

HYPERON PUZZLE

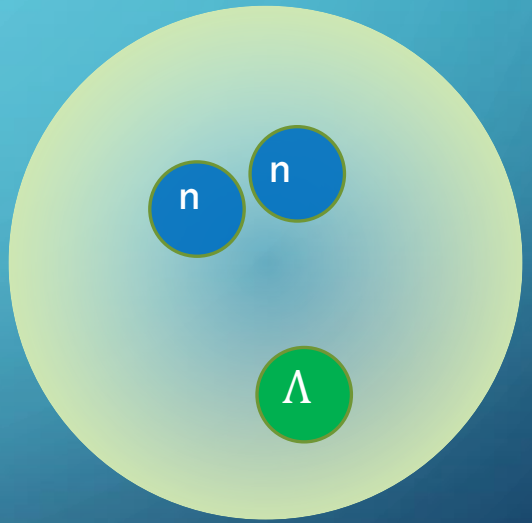
Two solar mass neutron stars

E12-15-008 ^{40,48}Ca targets

E12-19-002 Light targets

E12-18-013 ^{208}Pb targets

${}^{3}_{\Lambda}n$ Puzzle

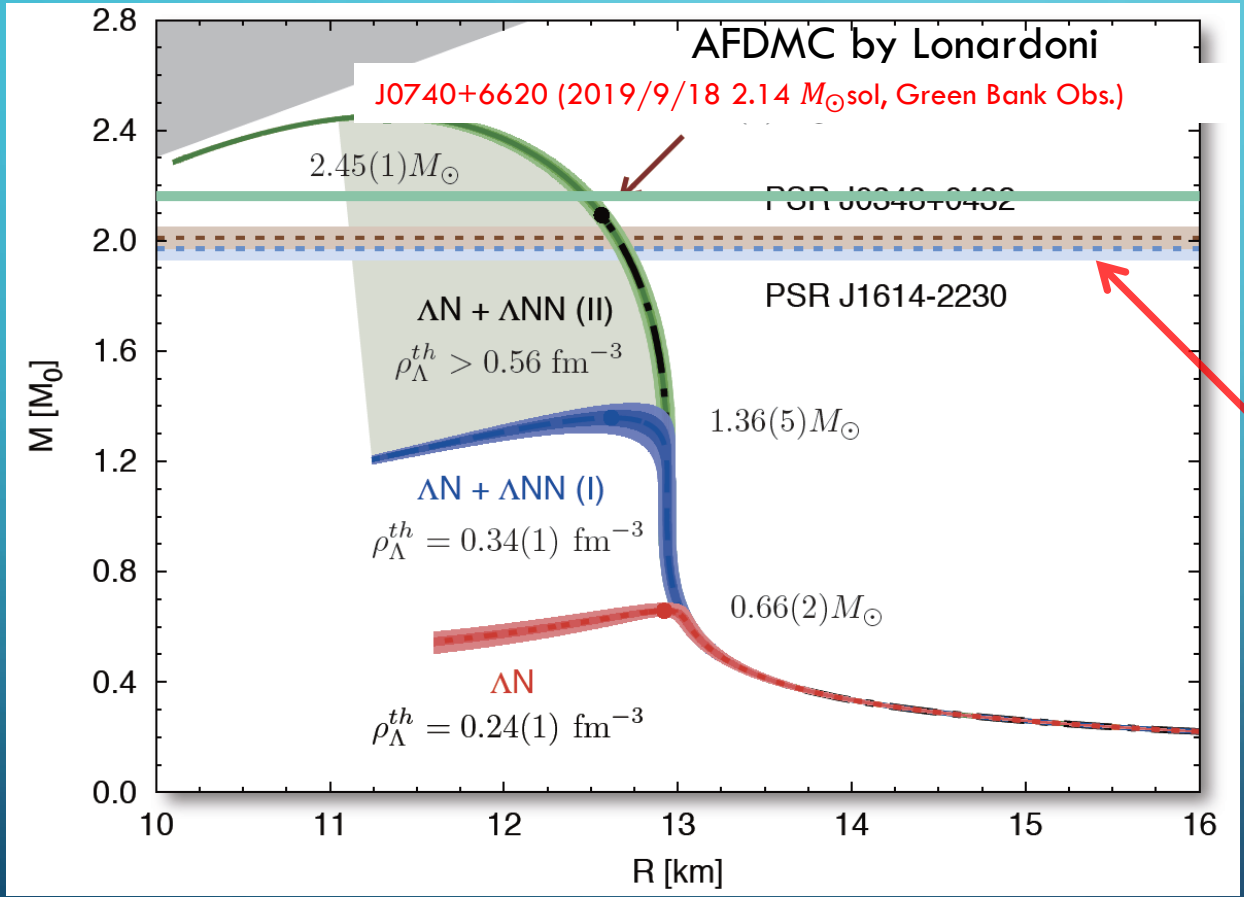


E12-17-003 ^{3}H target

HYPERON PUZZLE

Based on our knowledge on Baryonic Force:

Hyperon naturally appear at high density ($\rho=2\sim3\rho_0$)



Too Soft EOS

Contradict to observation

2 $M_\odot$ Neutron Stars

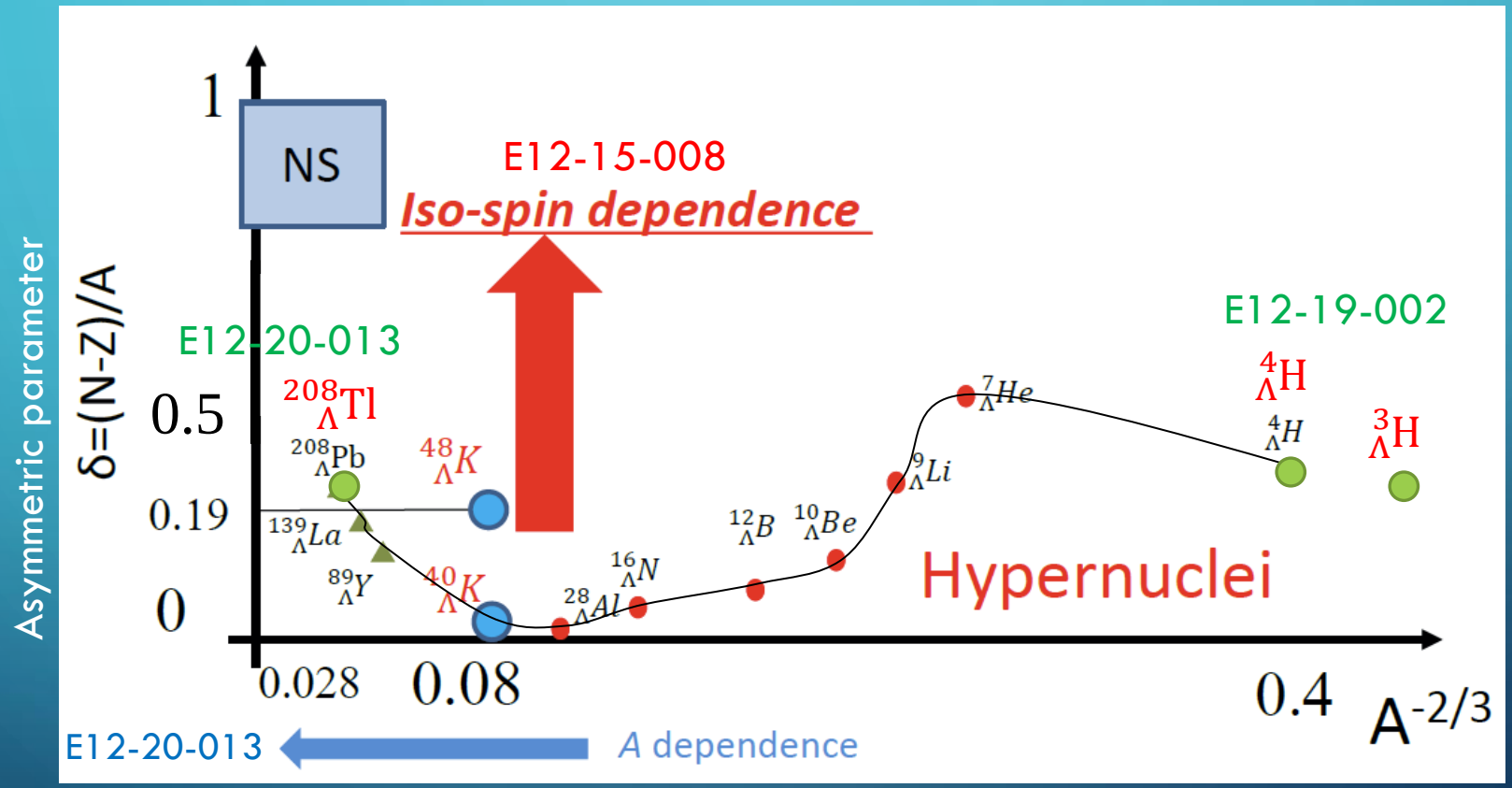
Additional Force to make EOS stiff

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

From Hypernuclei to NS

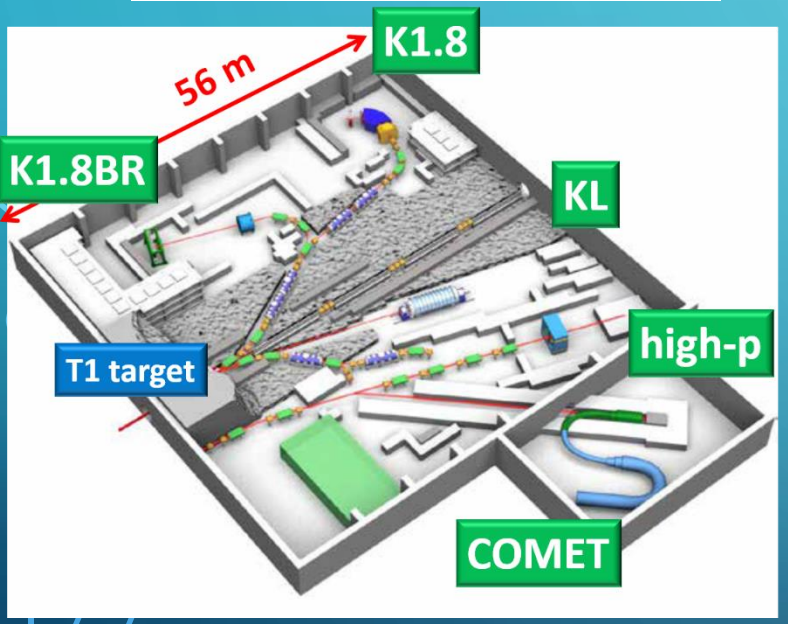


High resolution B_Λ measurements : JLab (e,e'K^+), MAMI (decay π)

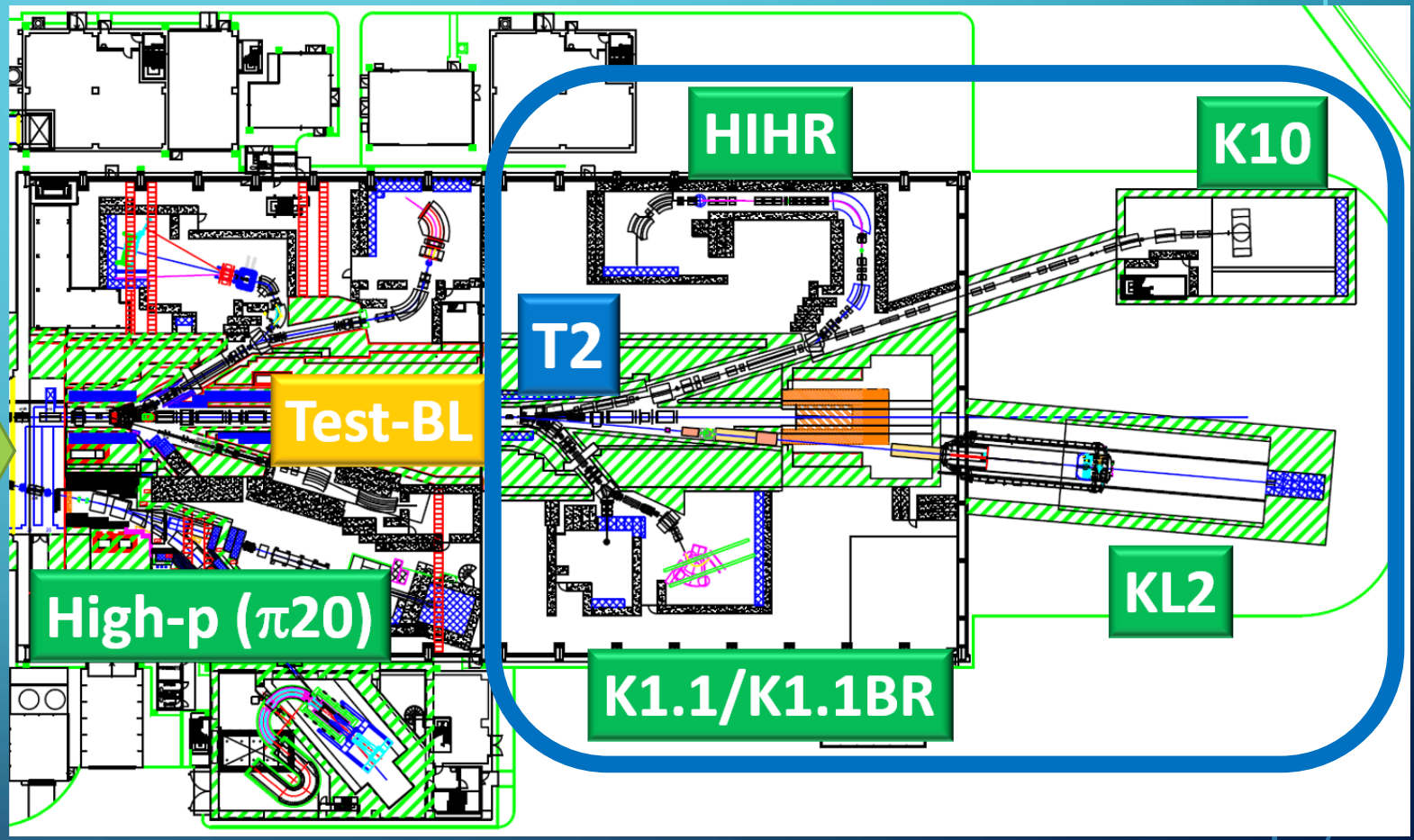
NEW key player : HIHR@J-PARC (π^+,K^+)

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

Present facility

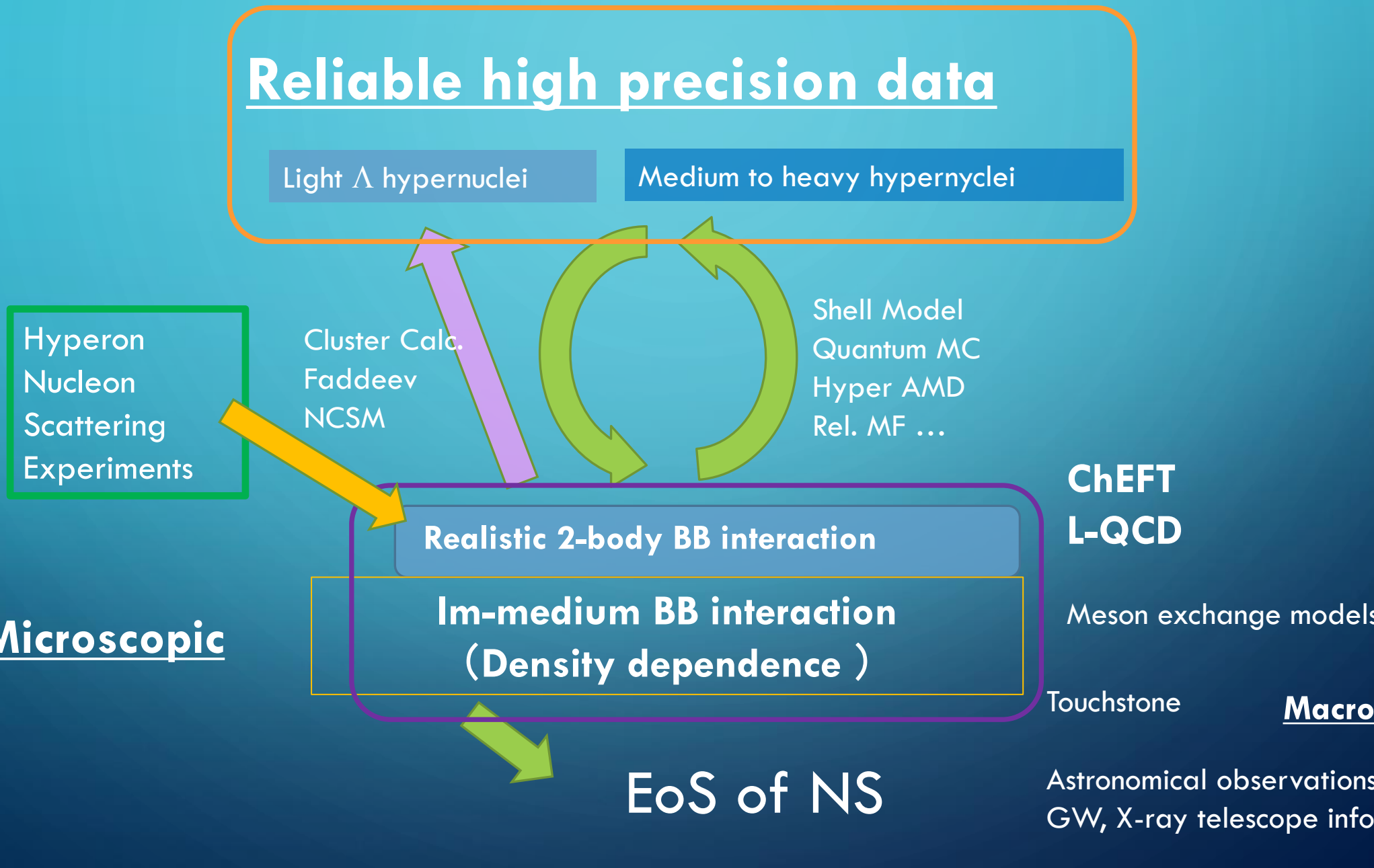


1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



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

Strategy to solve the hyperon puzzle



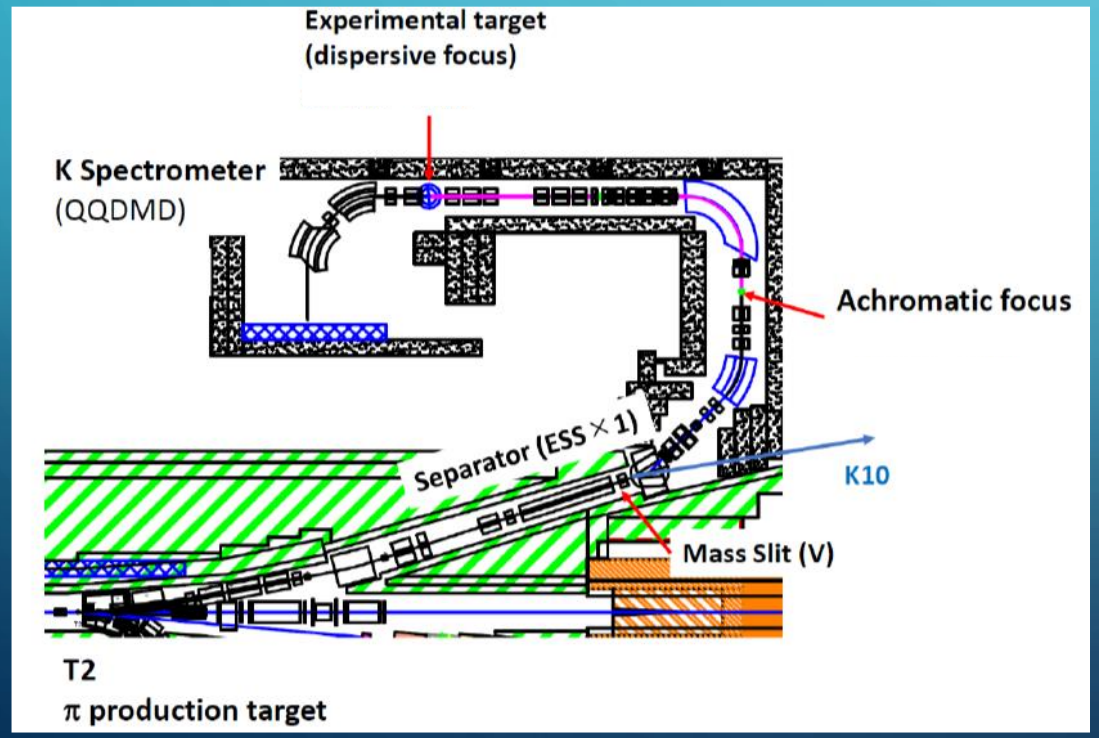
HIHR

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

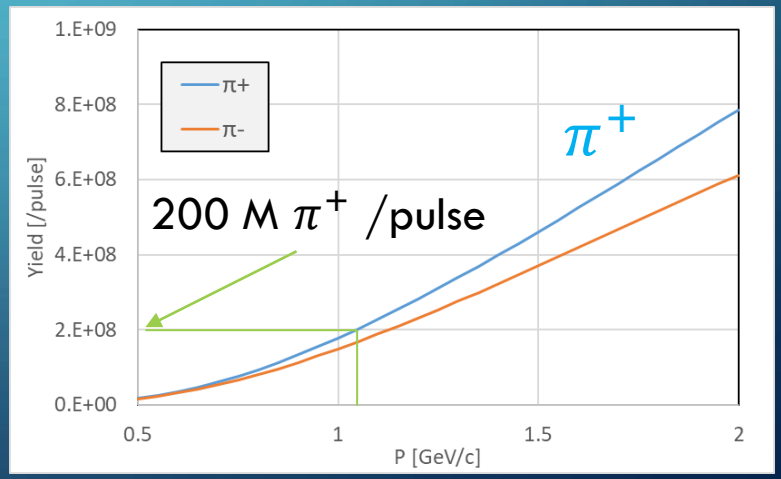
no beam tracking = **NO limit for π rate** from detectors

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

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



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

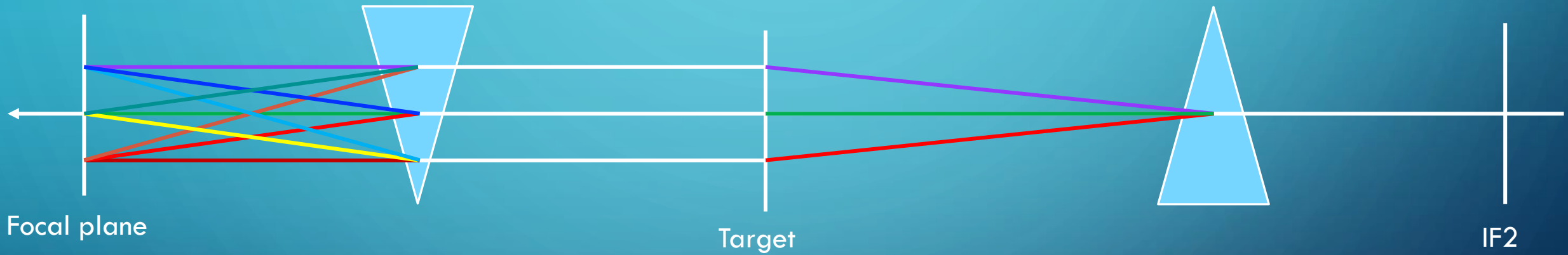


3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target (T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (From T. Takahashi)

Momentum dispersion match

Kaon spectrometer | Reaction part | Pion beamline

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



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

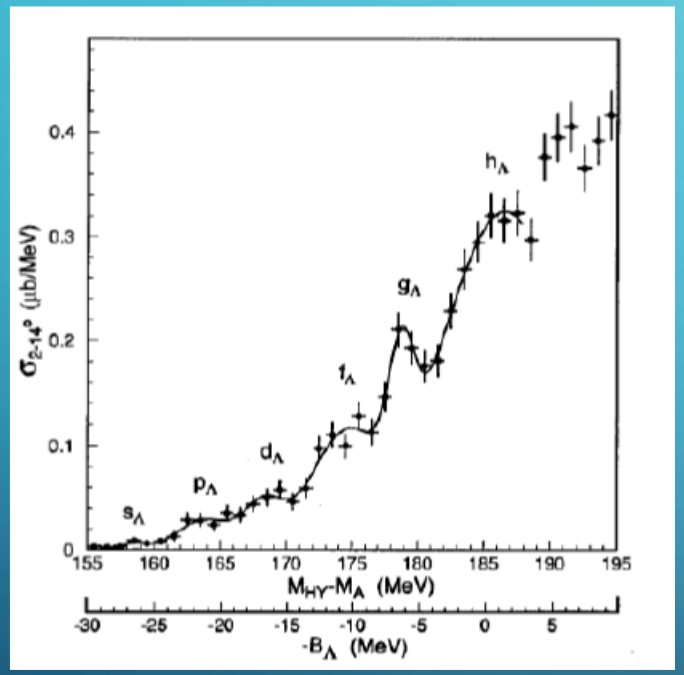
$+s_{16}DQ$ -------- a position shift by the excitation energy

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

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

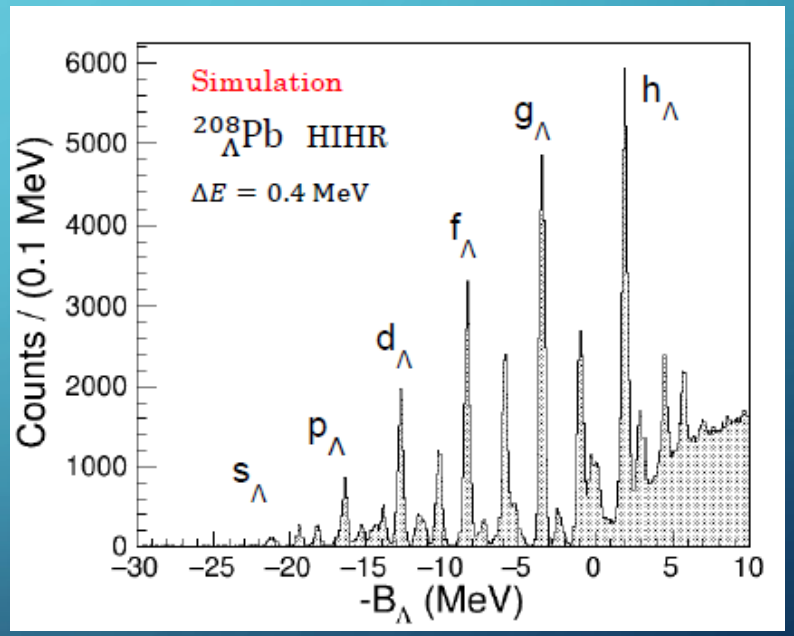
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)

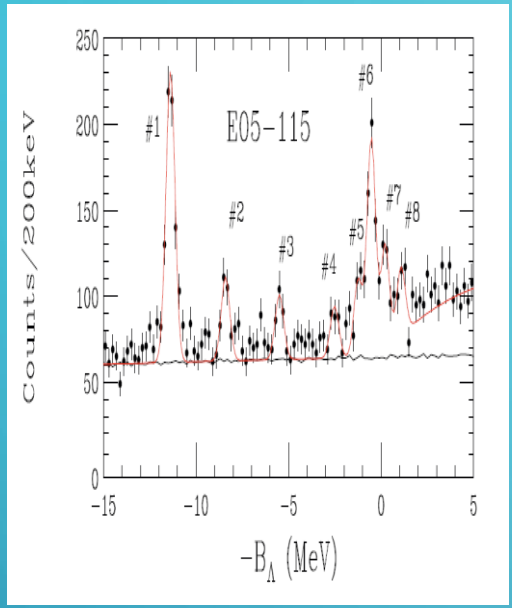
Expected at HIHR beamline



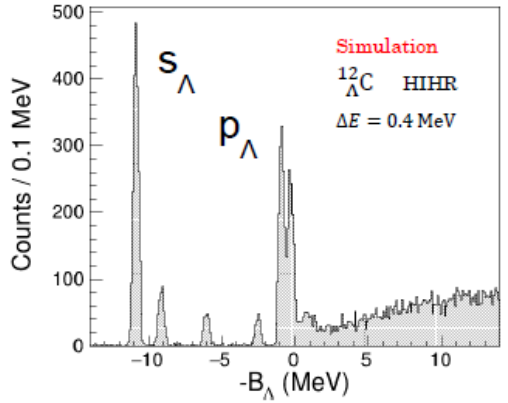
60 days × 200M π/spill @ HIHR

ΔE~0.4 MeV(FWHM)

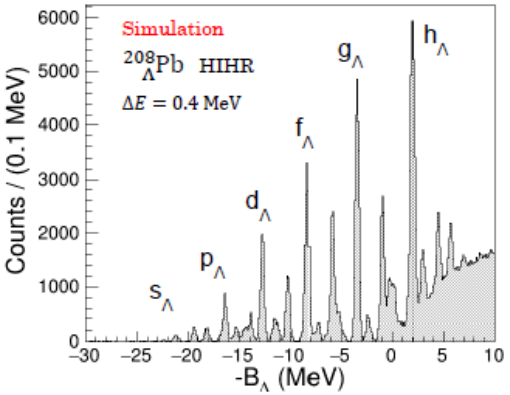
EXPECTED SPECTRA



$^{12}_{\Lambda}$B @ JLab E05 – 115

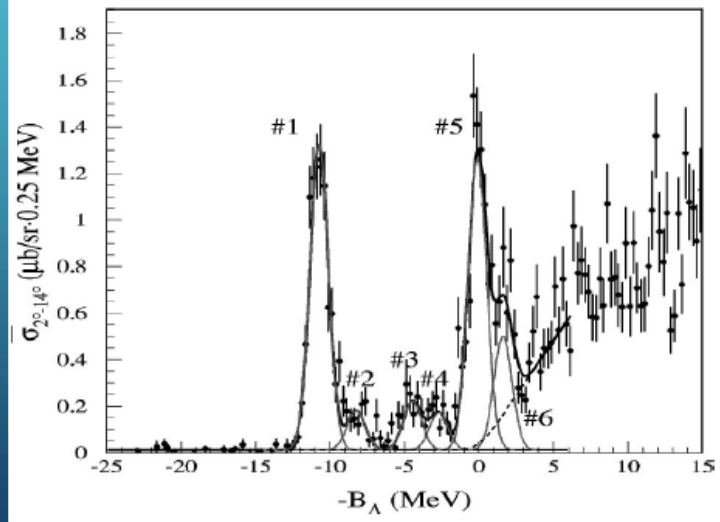


$^{12}_{\Lambda}$C @ HIHR Simulation

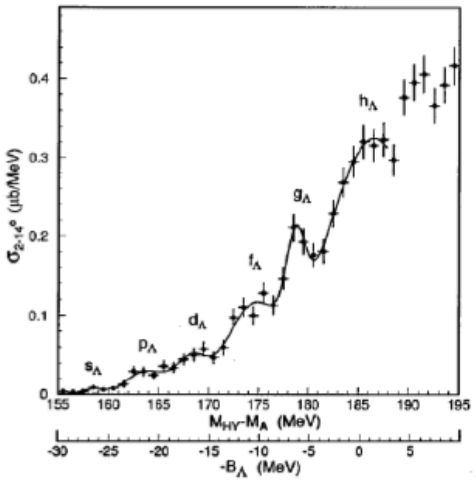


$^{208}_{\Lambda}$Pb @ HIHR Simulation

KEK-SKS
ΔE = 1.45 MeV



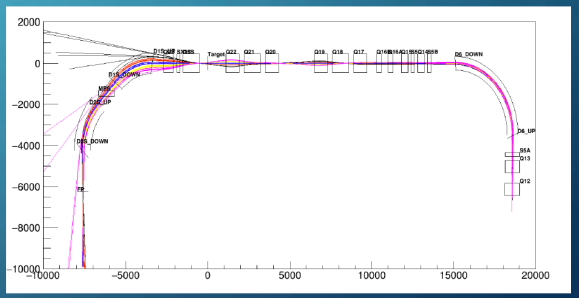
KEK-SKS
ΔE = 2.3 MeV

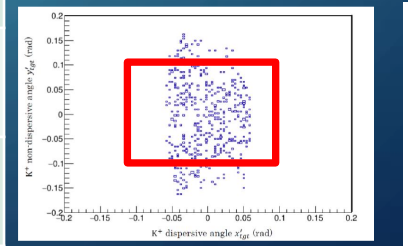


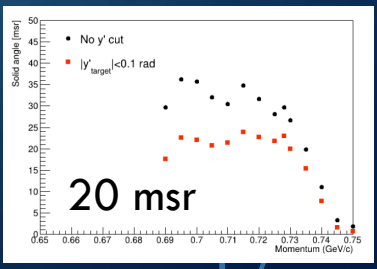
EXPECTED YIELD OF HYPERNULCLEI

	HIHR@J-PARC Ex. 1.1GeV/c π^+
Reaction	$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$
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

(σ~ 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)

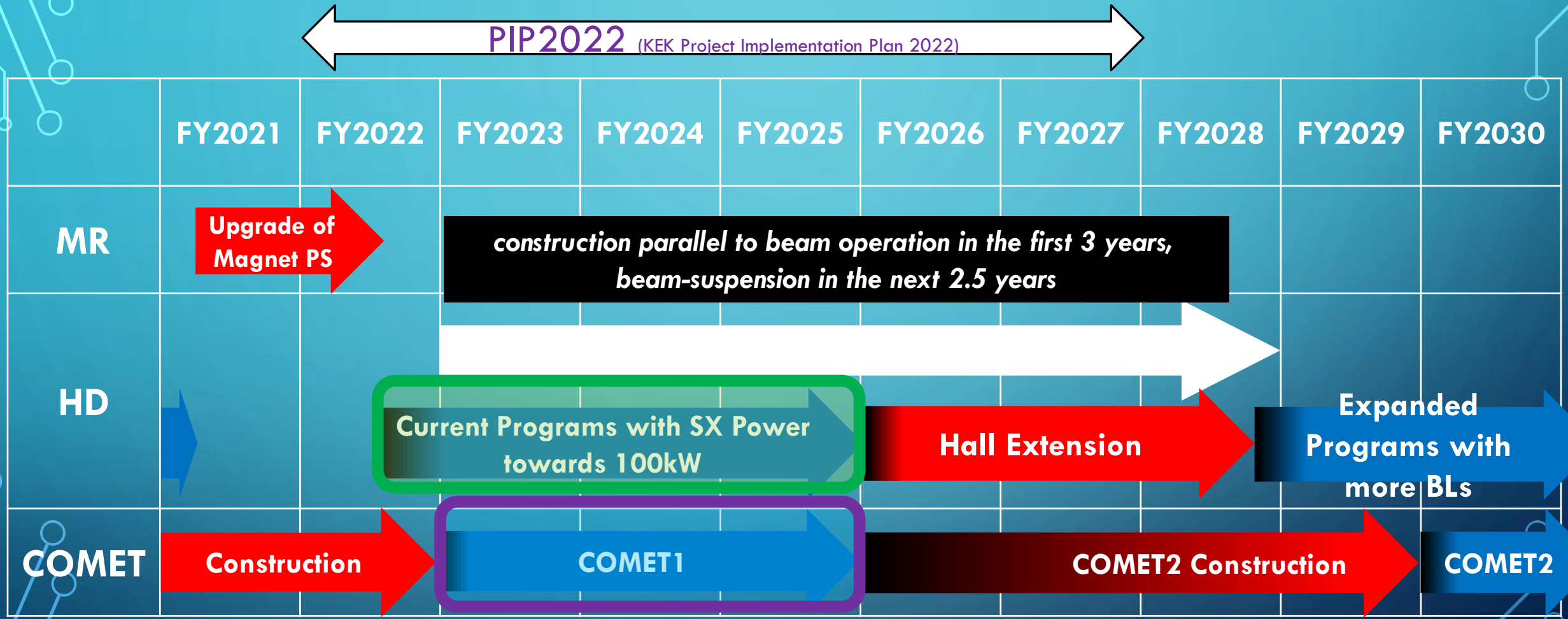
73 days for heavier targets

104 days for total

Selection of targets Not Finalized at all !

Suggestions for targets are more than welcome!

TIMELINE WITH THE CURRENT PROGRAMS



- We would like to start the project from FY2023
  - 4 years operation before beam suspension (except for COMET)
  - 3 years operation for COMET (Beamline completion in FY2022)

SUMMARY & PROSPECTS

- New HIHR beamline at J-PARC Hadron Hall Extension Project
- Spectroscopy of Λ hypernuclei with (π^+, K^+) reaction at HIHR (P84)

Precise Spectroscopy of Λ hypernuclei in all mass range

ΛNN 3-body force based on realistic 2-body interaction to be studied at New K1.1

Challenge to Hyperon Puzzle

Hypernuclear Factory

Standard B_Λ data for decades

We need theoretical supports!

ChEFT → LEC
Scat. EXP @ K1.1
Light HY

LQCD

Meson Exch. Pot.

→ Realistic YN interaction → Application to various HY systems → EOS → NS

Ab-initio calc.
Precise fewbody
Hyper AMD
BHF
Shell model
Mean field

→ Detailed Structuer of HY
Quantum Manybody systems