HADRON 2021

Mexico city/zoom

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30th July 2021

Precise spectroscopy of Lambda hypernuclei with electron and meson beams

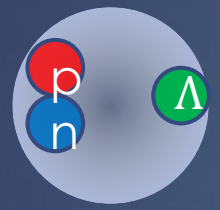
Jefferson Lab
EXPLORING THE NATURE OF MATTER

J-PARC

Current problems on Λ hypernuclei

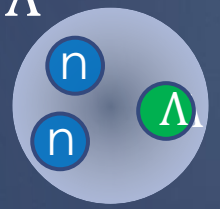
Hypertriton Puzzle

Shallow bound
Short lifetime

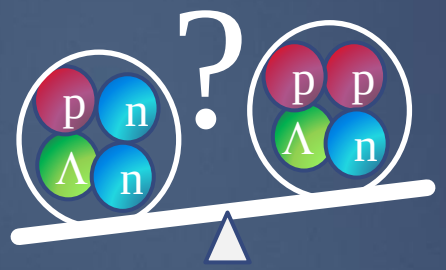


Bound?
Resonance?
Not Exist?

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



CSB of Λ Hypernuclei



Hyperon Puzzle

Why massive
NS exists?

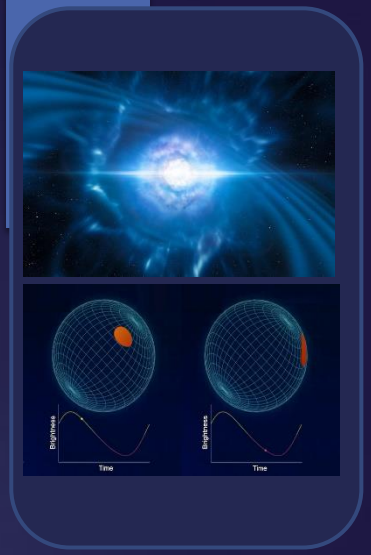
A=3

10^{-15} m

$A\sim10^{57}$

10^{4} m

Current problems on Λ hypernuclei



Recent astronomical observations

Hypertriton Puzzle

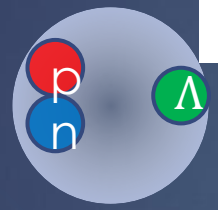
MAMI

JLab E12-19-002

Shallow bound
Short lifetime

J-PARC

ELPH

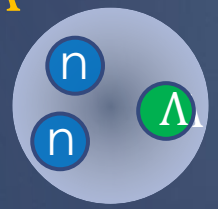


$^{3}_{\Lambda}n$ Puzzle

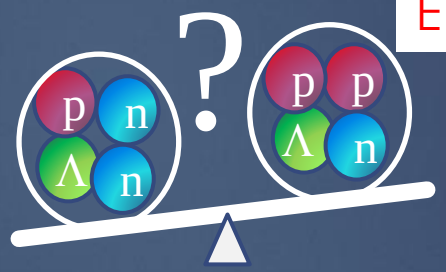
GSI

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

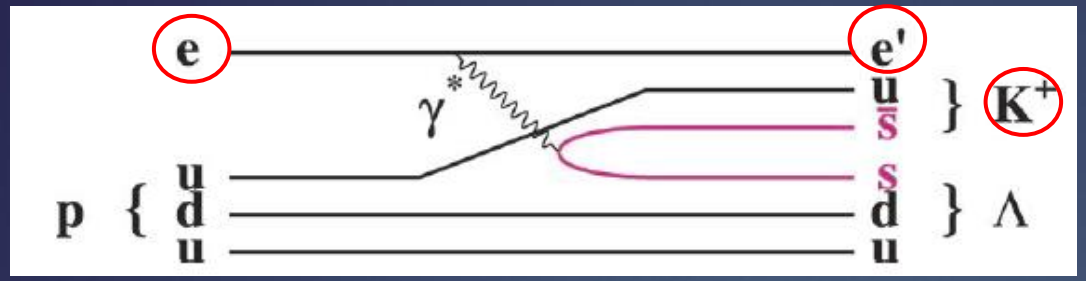
10^{-15} m

$A\sim10^{57}$

10^{4} m

J-PARC HIHR

Electron beam vs. meson beams



(e,e'K^+)

Excellent mass resolution

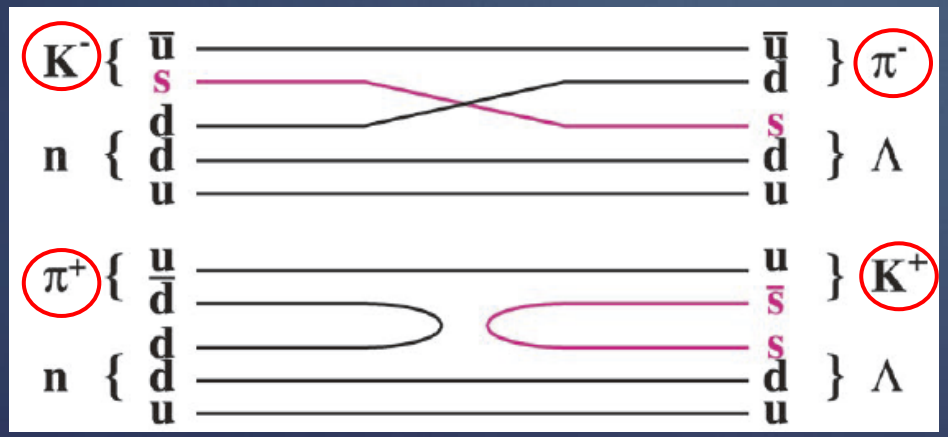
~ 0.5 MeV(FWHM)

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^+)

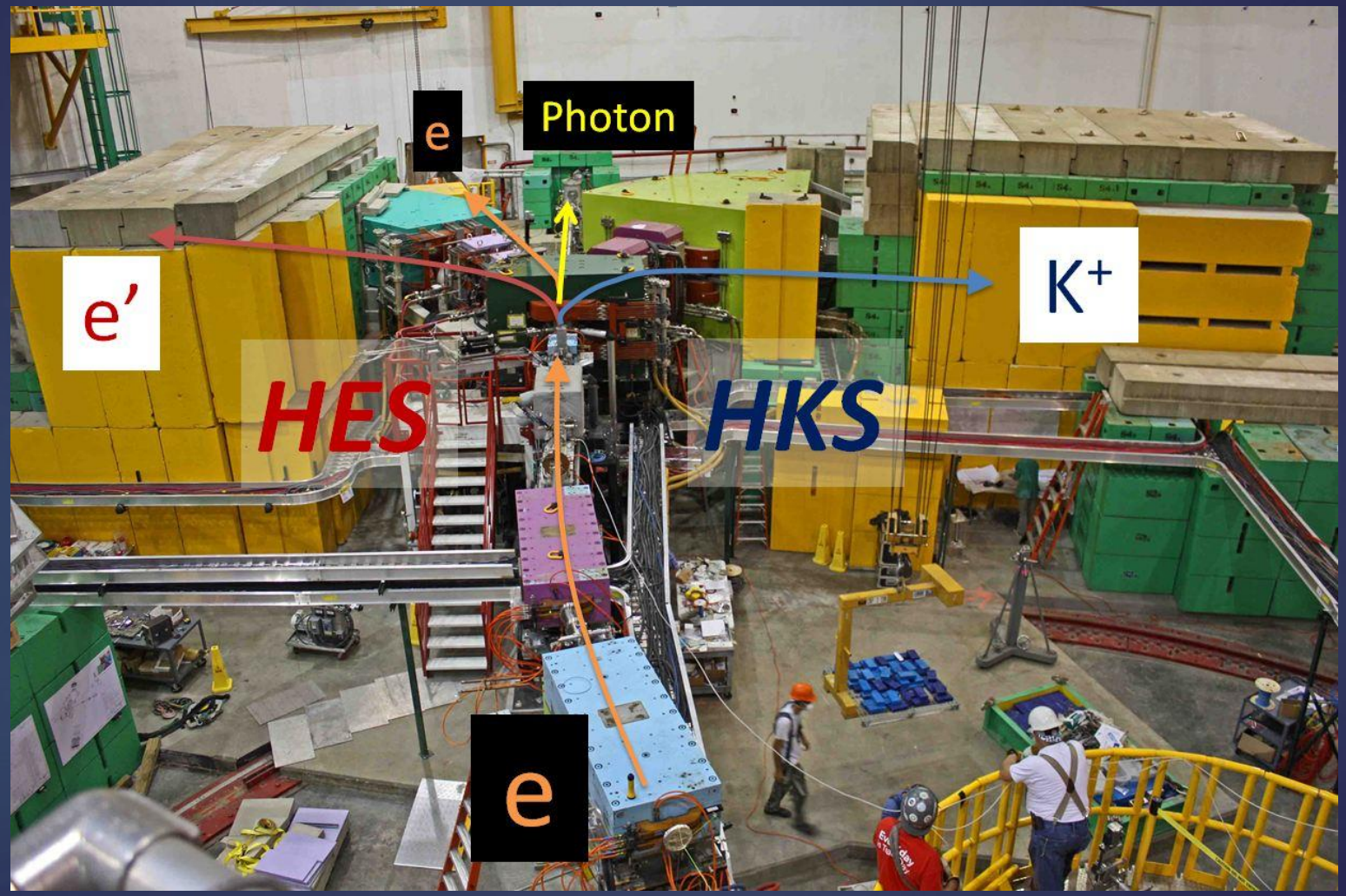
HIHR

Excellent mass resolution

< 0.4 MeV

Thin target (isotopically enriched)

(e,e'K^+) reaction spectroscopy



Hyperon Puzzle

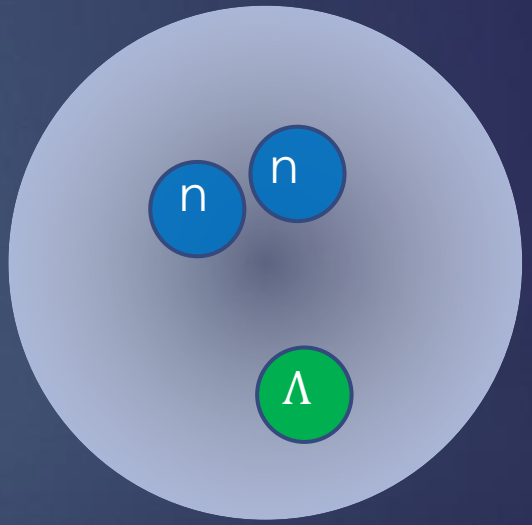
Two solar mass neutron stars

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

E12-19-002 Light targets

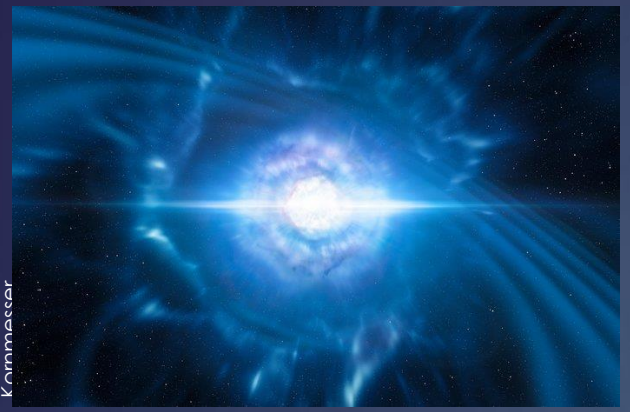
E12-18-013 ^{208}Pb targets

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



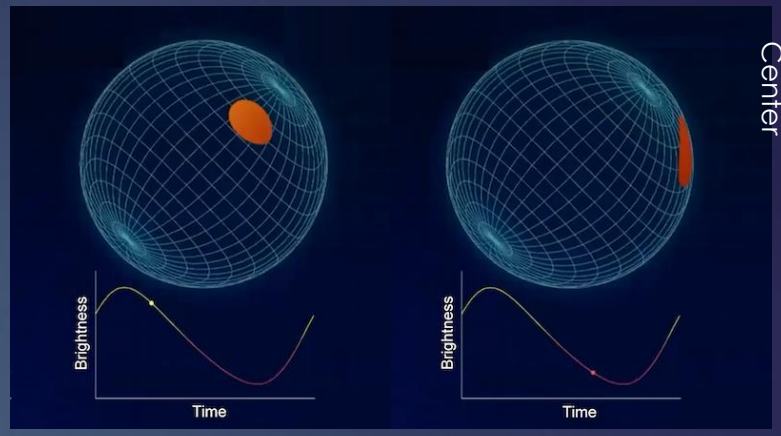
E12-17-003 ^{3}H target

New Astronomical Observations of NS



CC4.0 ESO/L. Calçada/M. Kornmesser

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

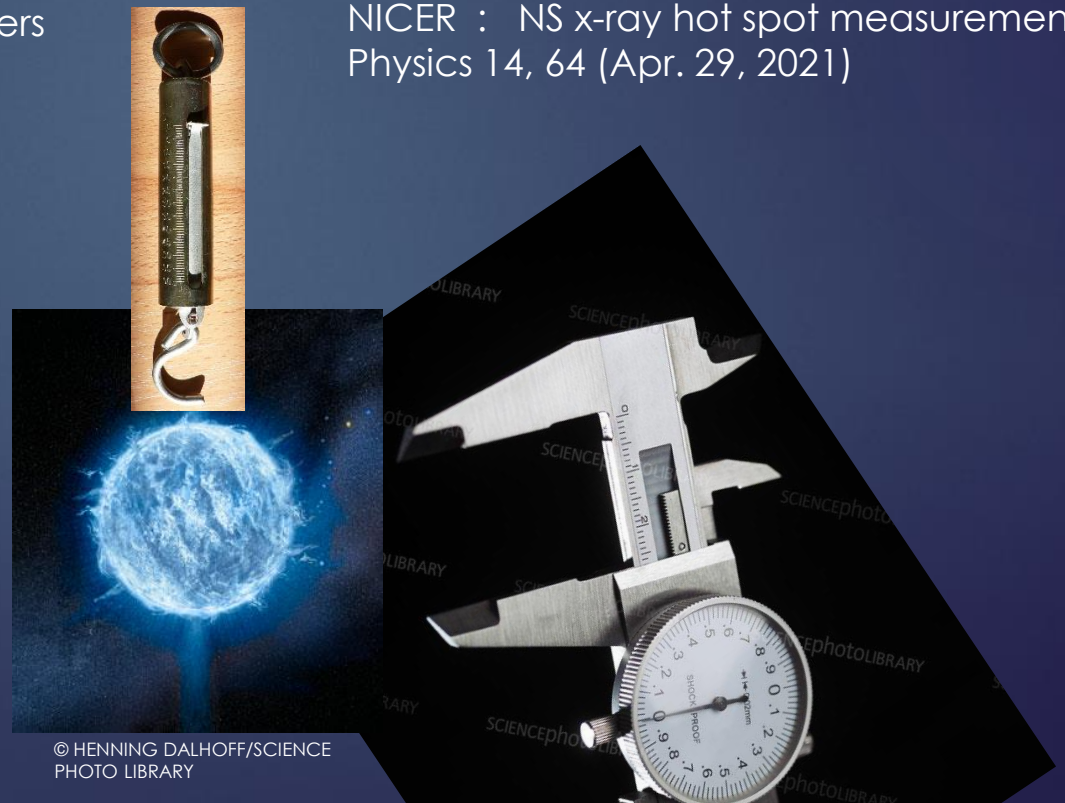


Goddard Space Flight Center

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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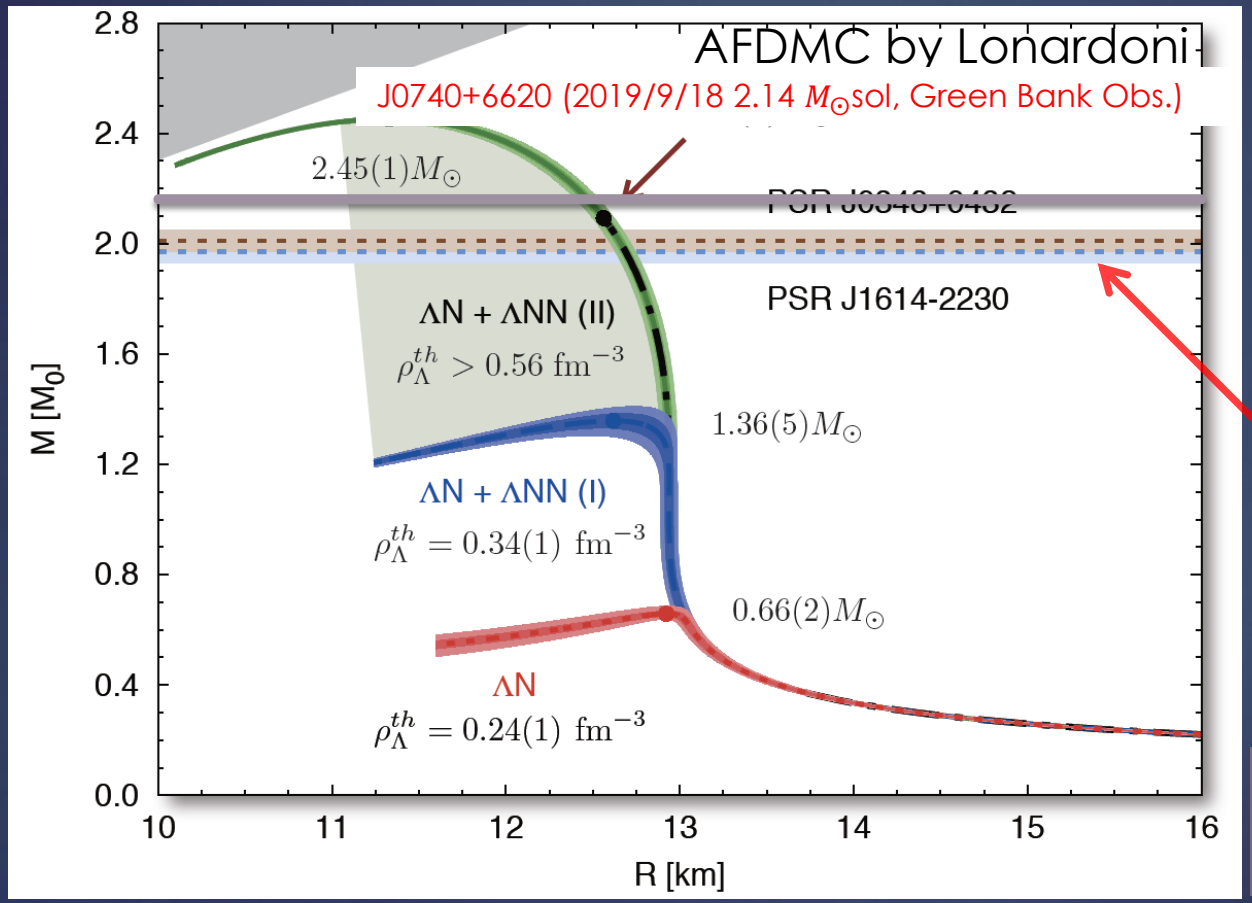
Hyperon Puzzle

Based on our knowledge on Baryonic Force:

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



Too Soft EOS

Contradict to observation

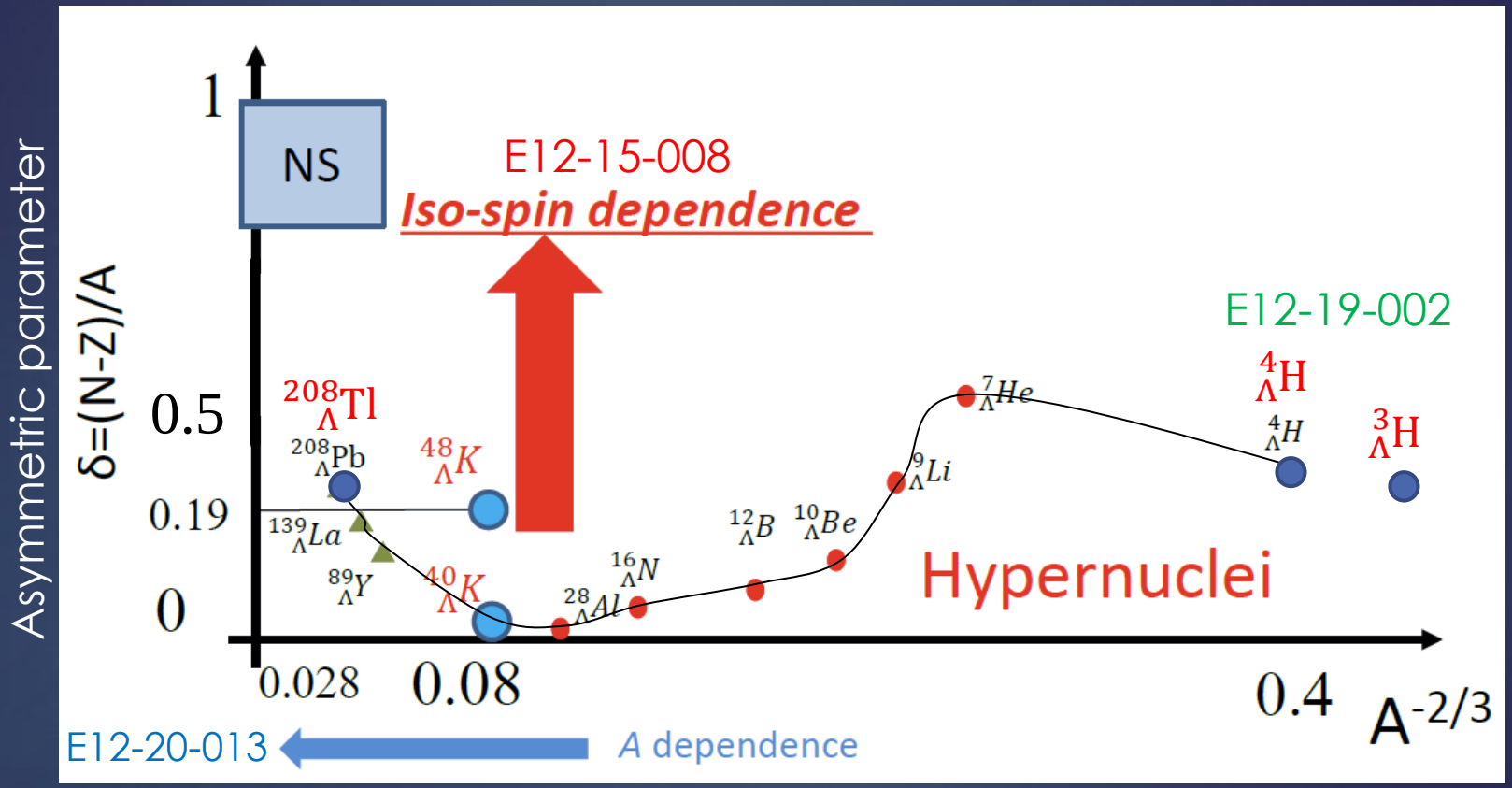
2 $M_\odot$ Neutron Stars

Additional Force to make EOS stiff

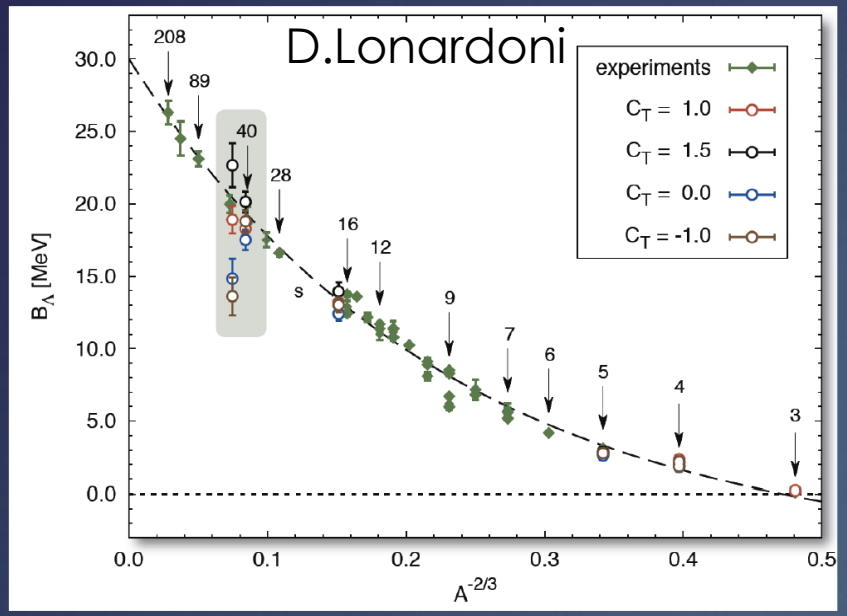
AFDMC by Lonardoni et al. PRL114 (2015) 092301, updated (2016)

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

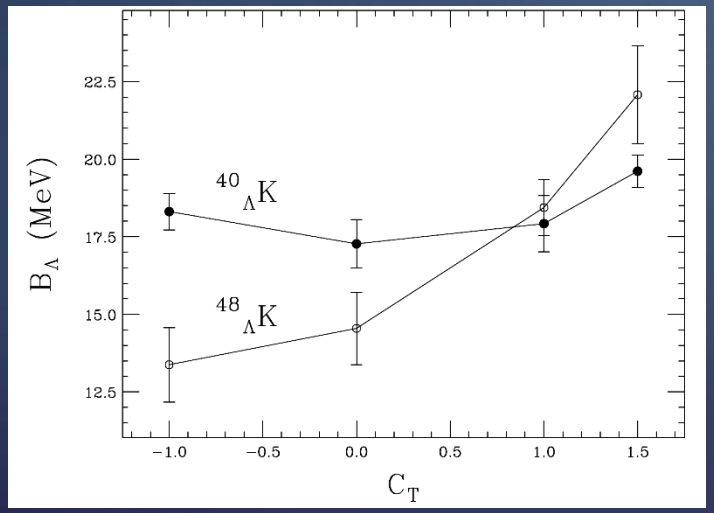
From hypernuclei to NS



Phenomenological 3 BRF+AFDMC



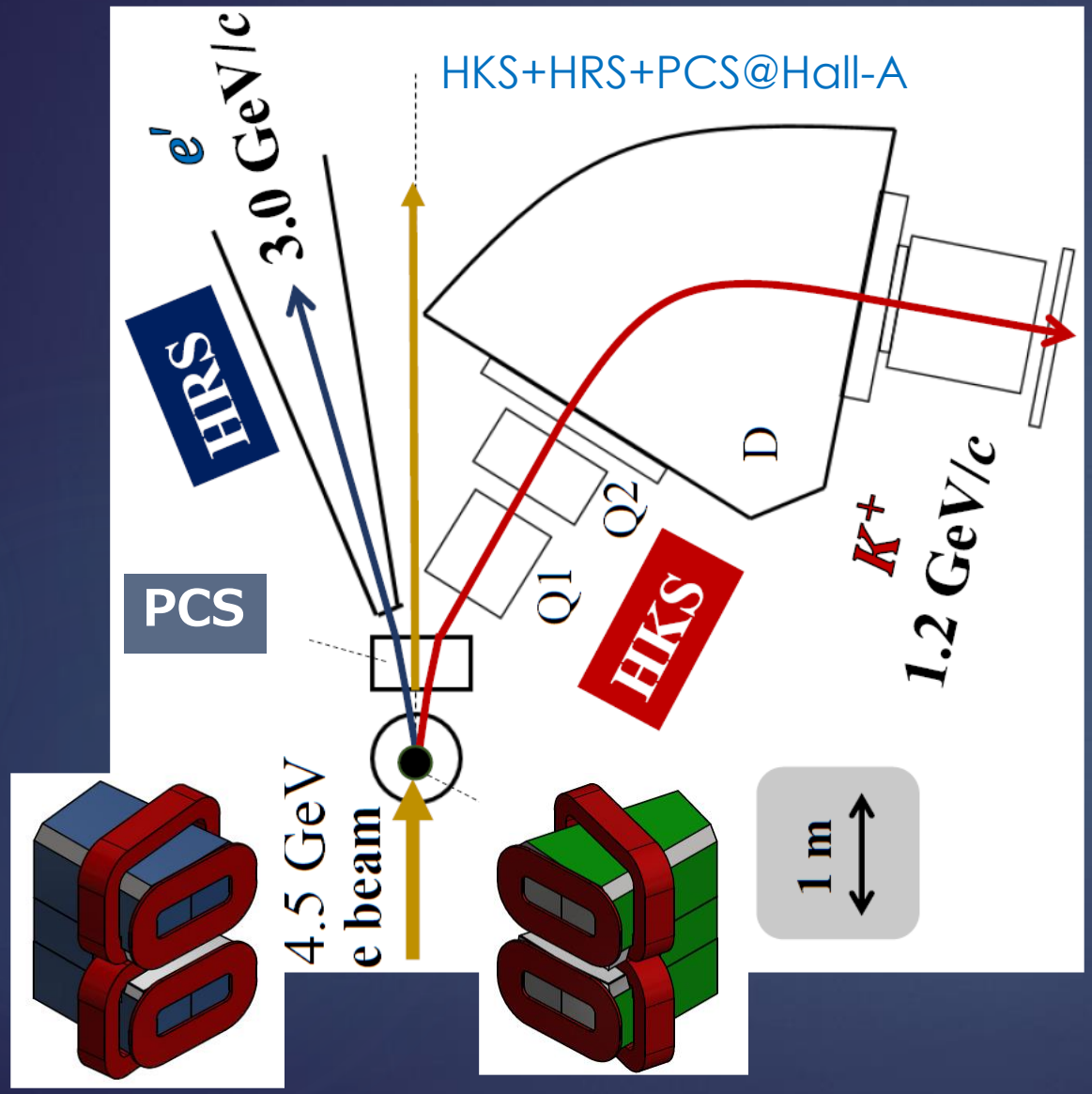
C_T :Parameter to gauge Λnn contribution in ΛNN potential



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

E12-15-008
accepted with GRADE A.

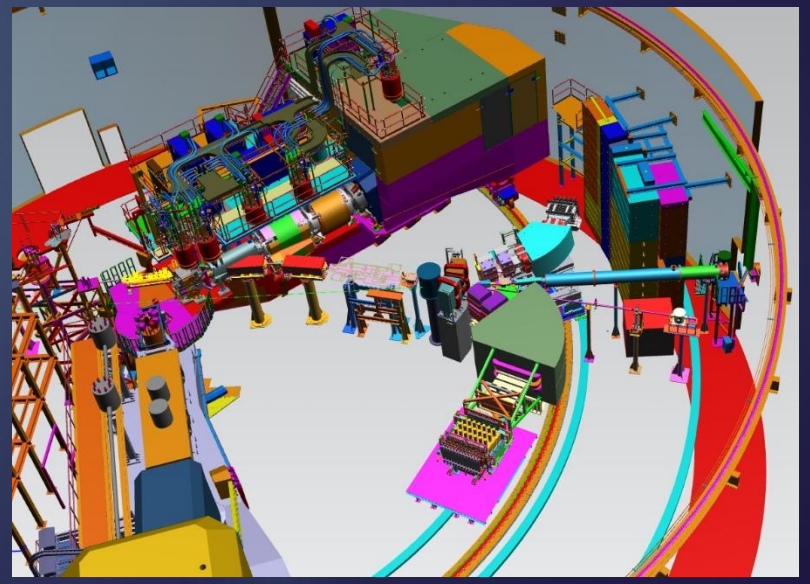
E12-15-008 ($^{40,48}_{\Lambda}$Ca), E12-20-013 ($^{208}_{\Lambda}$Pb)



2020/3/13 @ TOKIN (SENDAI)

New Pair Charge Sep. Mag.
^{40,48}Ca targets

HKS+HES+PCS@Hall-C



From T.Gogami JLab PAC49

Hypertriton ($^{3}_{\Lambda}$H) puzzle

Small B_Λ **vs.** **Short Lifetime**

J-PARC new exp. Talk by Dr. Ma

$B_\Lambda = 0.13 \pm 0.05$ MeV (emulsion[1])
$B_\Lambda = 0.41 \pm 0.12 \pm 0.11$ MeV (STAR[2])

$\tau = (0.5 \sim 0.92)\ \tau_\Lambda$
(HypHI, STAR, ALICE)

RMS radius, $\sqrt{< r^2 >} \cong \frac{\hbar}{\sqrt{4\mu B_\Lambda}}$

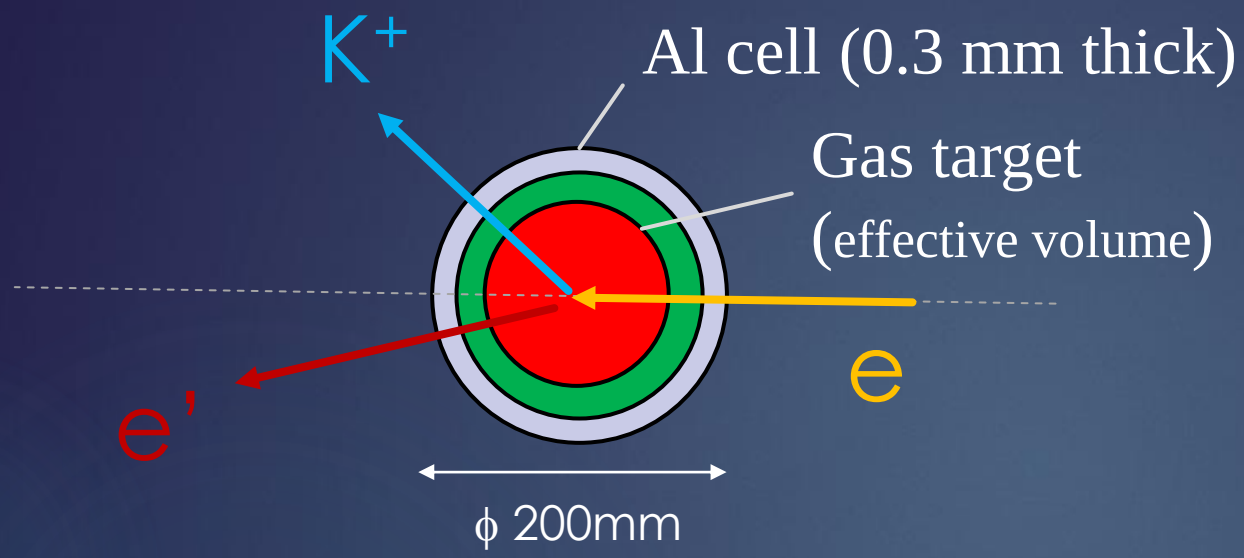
Fadeev calcuation with realistic NN/YN interactions
→ $\tau = 0.97\ \tau_\Lambda$
(H. Kamada *et al.*, *Phys. Rev. C* **57**, 4 (1998))

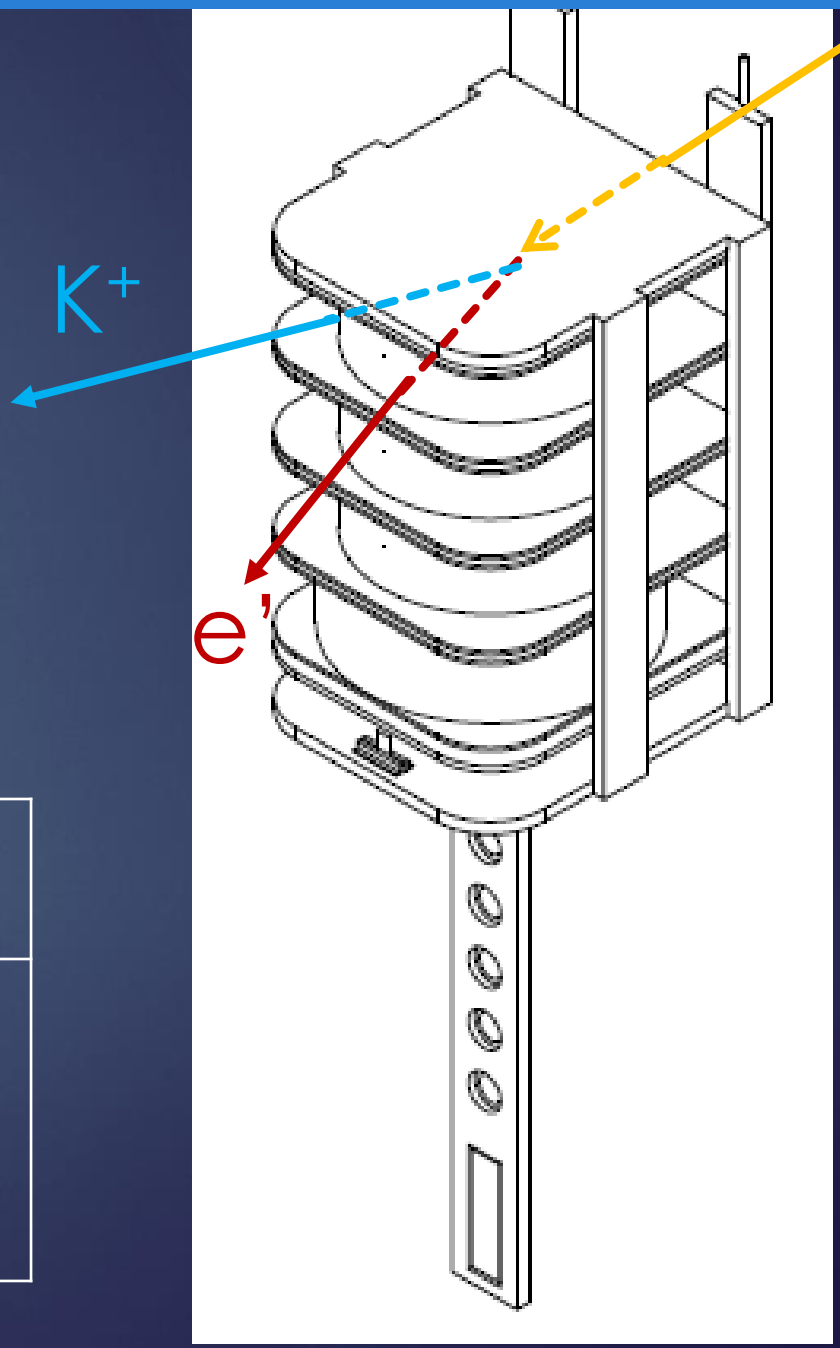
[1] M. Juric *et al.*, *Nucl. Phys. B* **52**, 1-30 (1973).
[2] The STAR Collaboration, *Nature Physics* (2020); https://doi.org/10.1038/s41567-020-0799-7

JLab E12-19-002 (newly approved)

Cryogenic gaseous targets

$|\Delta B^{\text{stat.}}| = 20$ keV, $|\Delta B^{\text{sys.}}| = 55$ keV





Target	Density [/(g/cm^3)]	Temperature [/K]	Pressure [/atm]
^{3}He	9.5	12	3
^{4}He	13.1		
$^1H_2$	2.8	30	

Hyperon Puzzle

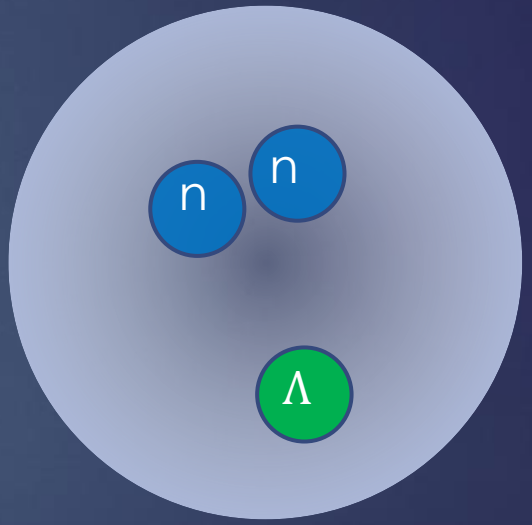
Two solar mass neutron stars

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

E12-19-002 Light targets

E12-18-013 ^{208}Pb targets

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

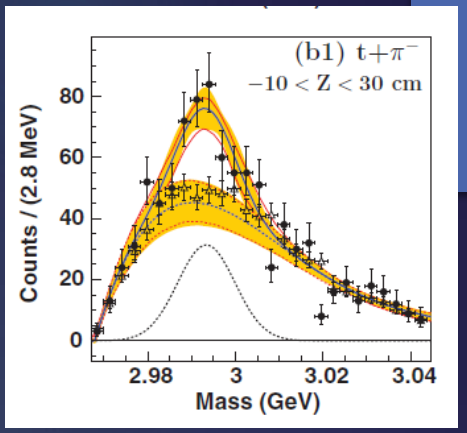


E12-17-003 ^{3}H target

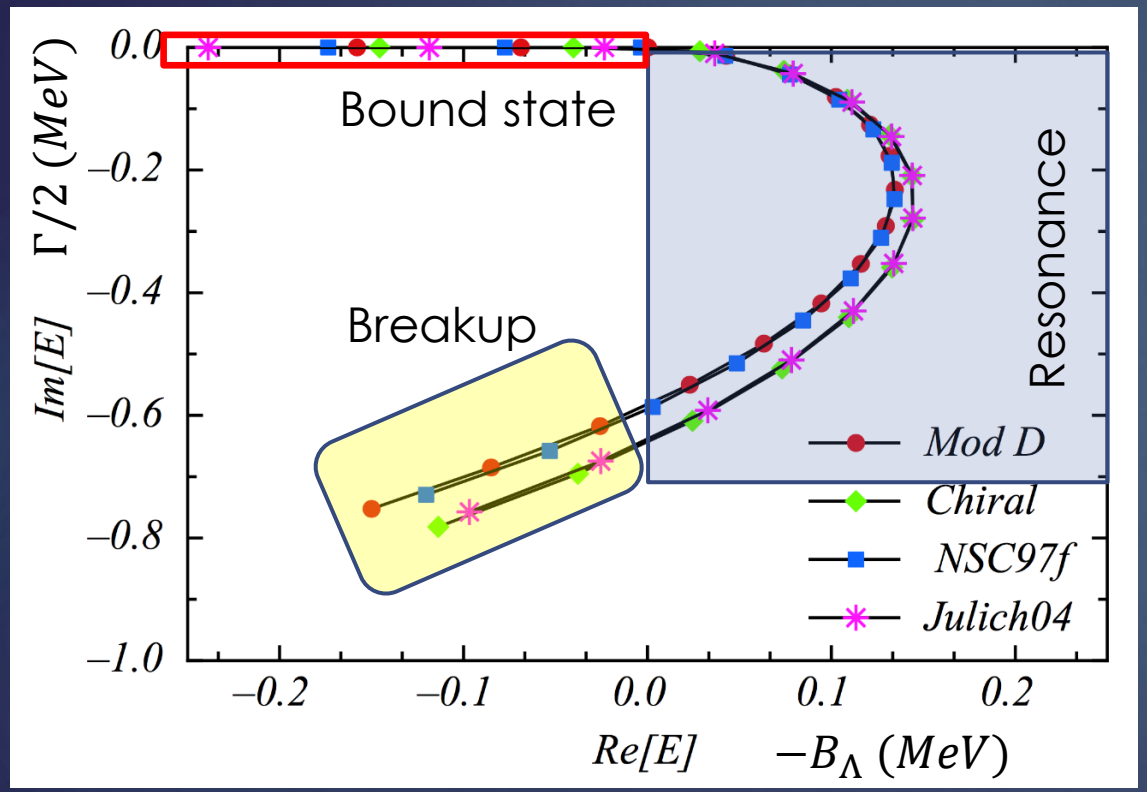
JLab E12-17-003

Λn interaction study by investigation of Λnn resonance

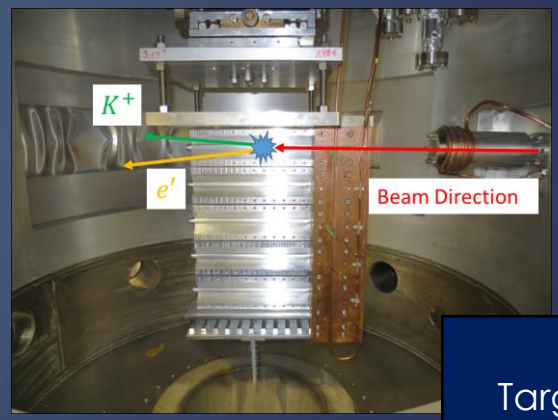
Jlab PAC45 approved as "High-Impact" exp.



C.Rappold et al.
PRC 88041001(R) (2013)



$^{3}H(e, e'K^{+})nn\Lambda$



Target	Thickness [mg/cm^2]	Number of incident electrons
^{3}H	84.8	1.0×10^{20}
^{1}H	70.8	3.0×10^{19}

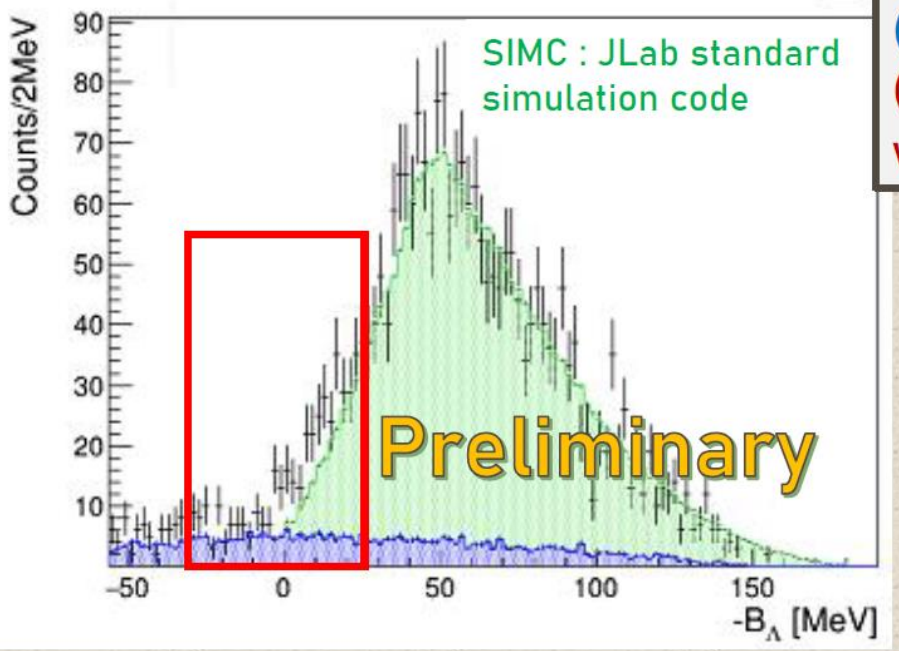
I.R.Afnan and B.F.Gibson, PRC 92, 054608 (2015)

Very preliminary result

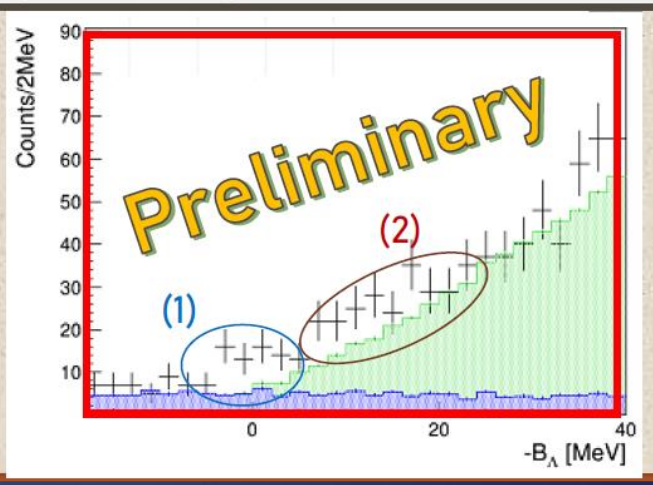
Difference between data and simulation

QF−Λ distribution with JLab standard simulation code (SIMC)

Physics : fermi momentum, spectral function, kaon decay, radiative correlations



(1) some events around threshold exist.
(2) there are excess events($0 < -B_\Lambda < 20$ MeV) which are not explained by SIMC.

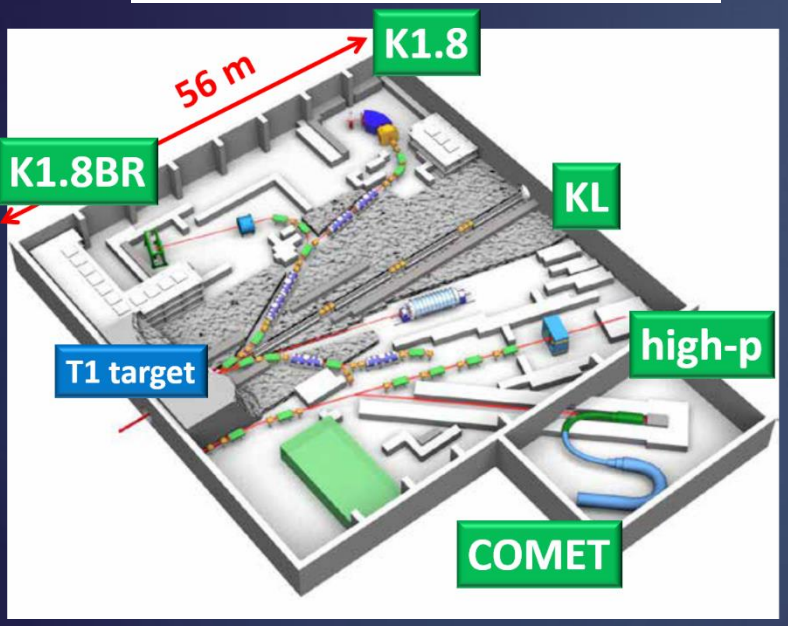


Possible FSI effects

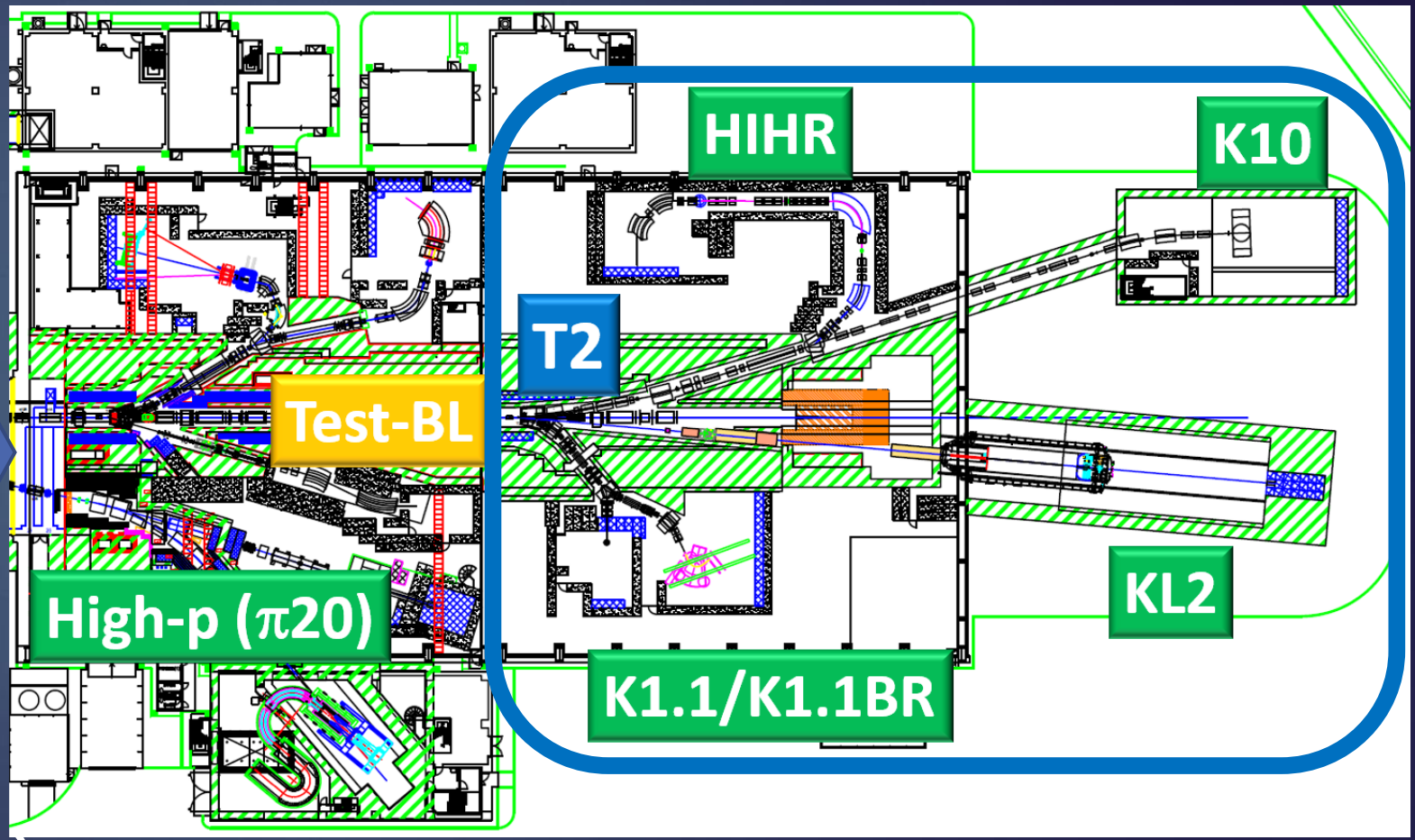
From K.Itabashi, APFB2020

Hadron Experimental Facility eXtension (HEF-ex) Project @J-PARC

Present facility

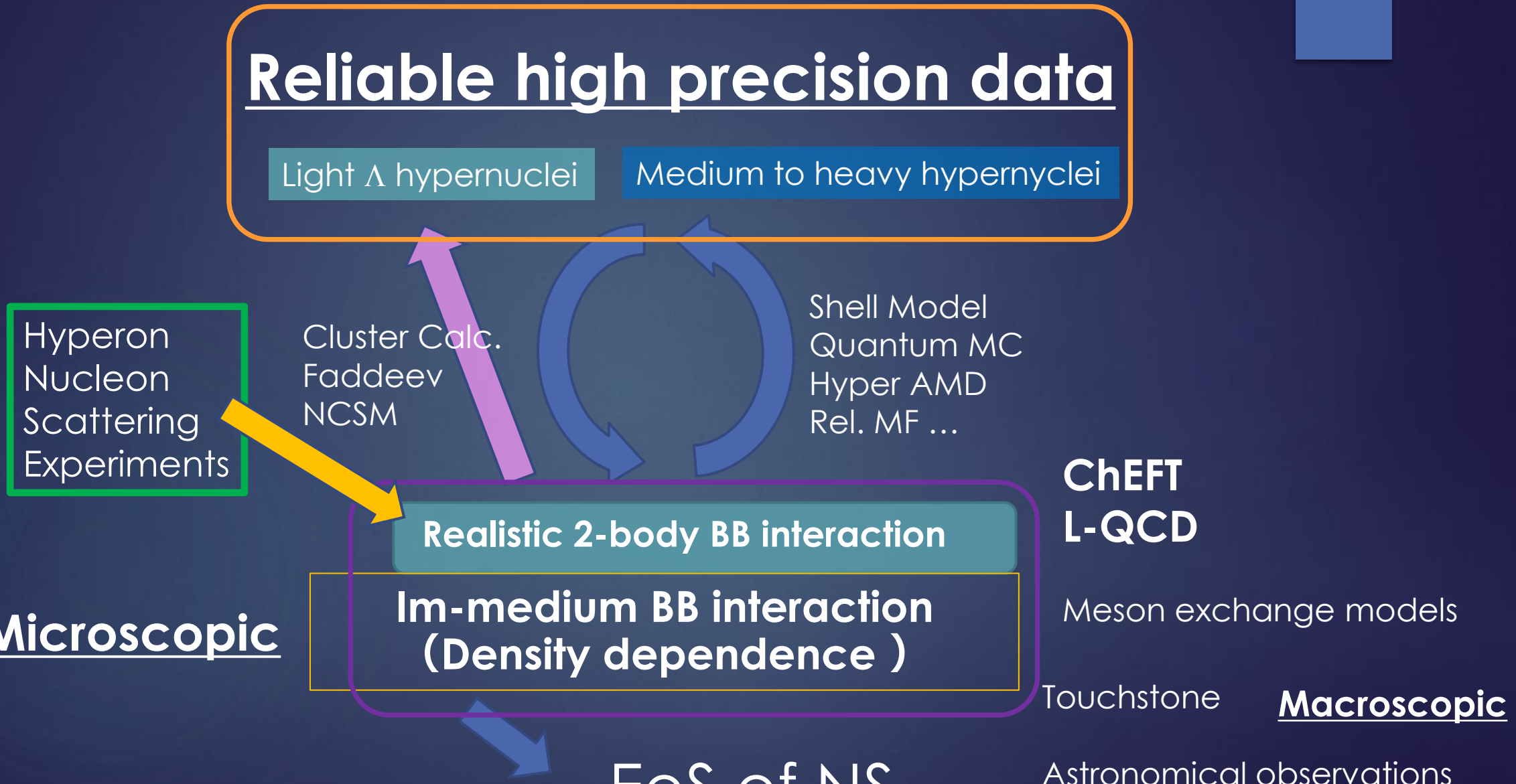


1 production target (T1) +
charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



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



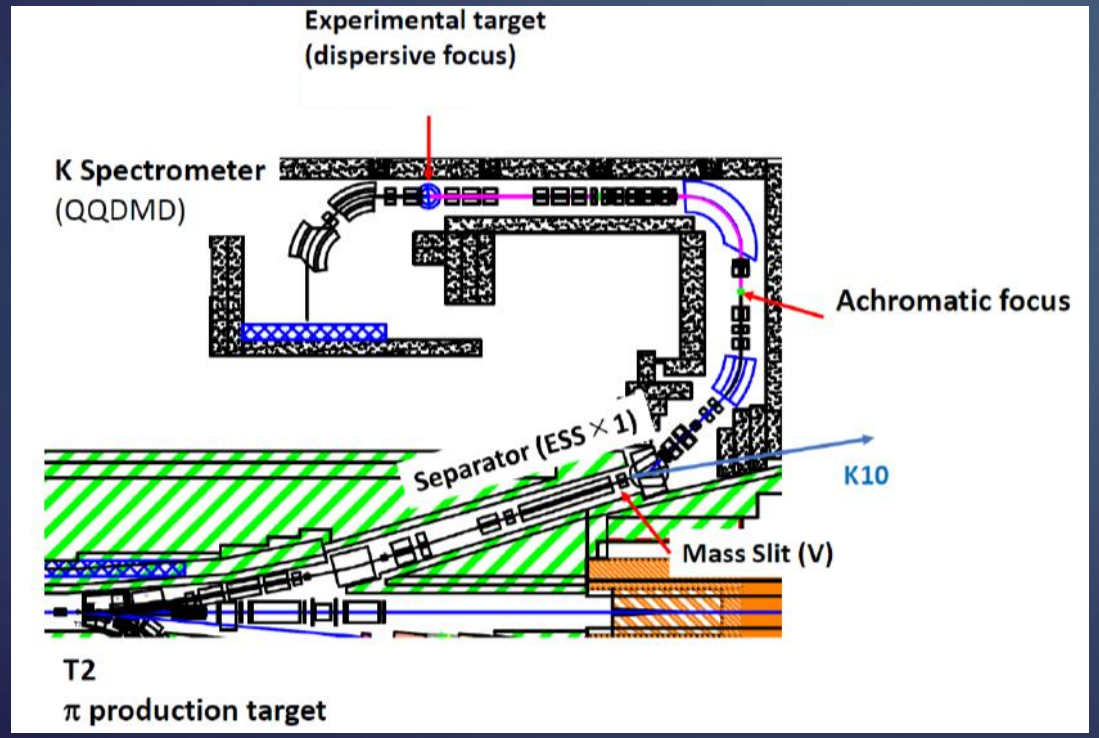
HIHR

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

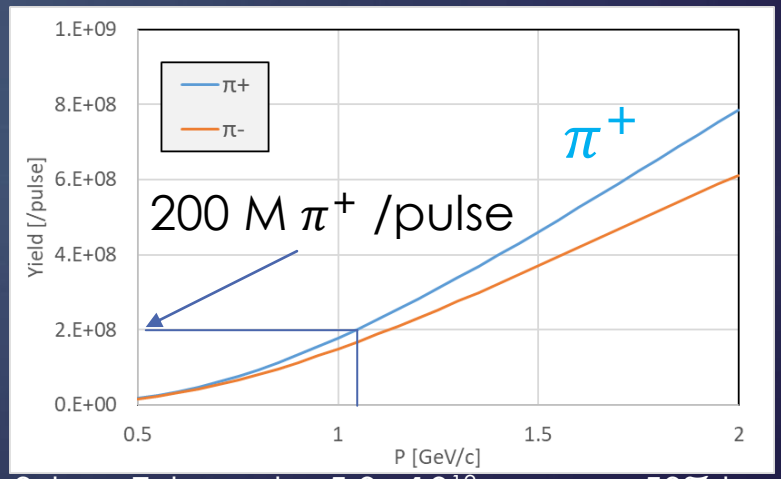
    no beam tracking = **NO limit for π rate** from detectors

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

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

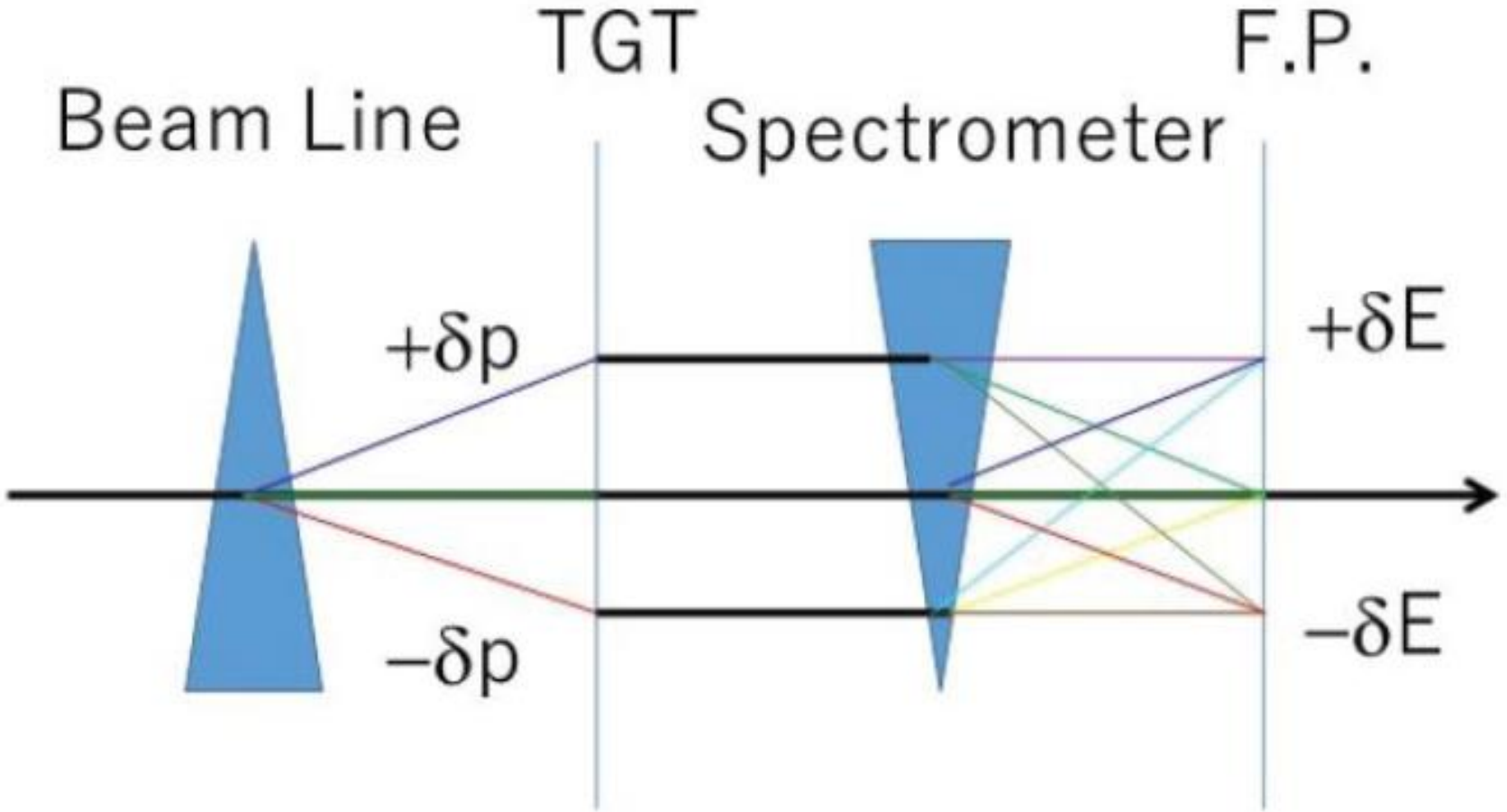


HR beamline (P_{max} = 2 GeV/c)
+ High Res. Kaon sectrometer



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



Momentum Matching Parameters and Conditions

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

T : TGT cosine, Q : Excitation Energy,

θ : Scattering Angle, $\theta_1 = b_{21}x_0 + b_{22}\theta_0 + \delta_0 b_{26}$

$K : (\partial p_{scat} / \partial\theta)(1/p_{scat})$ ……Scattering Angle Correction Coefficient

$C : (\partial p_{scat} / \partial p_{beam})(p_{beam} / p_{scat})$ …Incident Momentum Correction Coefficient

$D : (\partial p_{scat} / \partial Q)(1/p_{scat})$ ……Excitation Energy Correction Coefficient

Momentum Matching Condition :

$x_f = (\partial x_f / \partial x_0)x_0 + (\partial x_f / \partial\theta_0)\theta_0 + (\partial x_f / \partial\delta_0)\delta_0 + (\partial x_f / \partial\theta)\theta + s_{16} * DQ$

$\partial x_f / \partial x_0 = s_{11} * b_{11} * T + s_{12} * b_{21}$: total magnification → *minimize*,

$\partial x_f / \partial\theta_0 = s_{11} * b_{12} * T + s_{12} * b_{22}$: point-to-point focus → 0,

$\partial x_f / \partial\delta_0 = s_{11} * b_{16} * T + s_{12} * b_{26} + s_{16} * C$: momentum matching → 0,

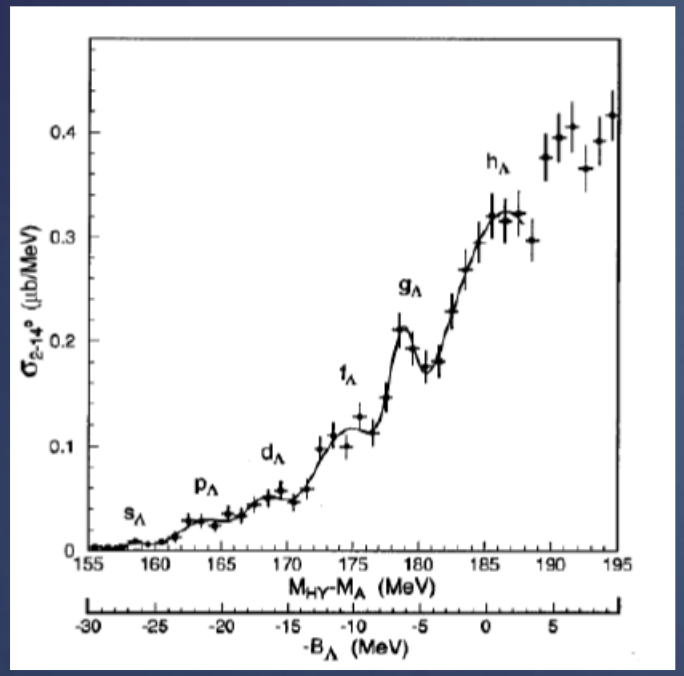
$\partial x_f / \partial\theta = s_{12} + s_{16} * K$: kinematical correction (finite scatt. angle) → 0

$s_{16} * DQ$: a position shift by the excitation energy

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

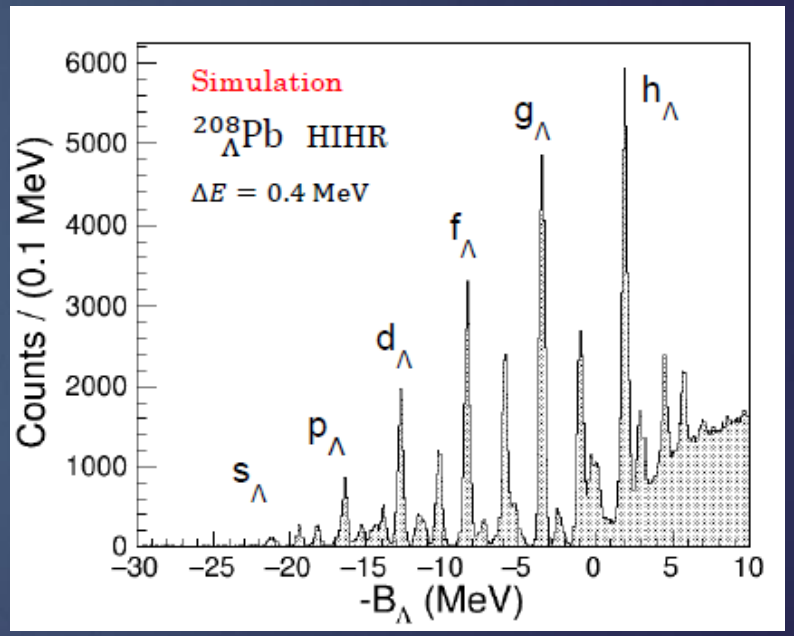
KEK-PS E369 with SKS



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)

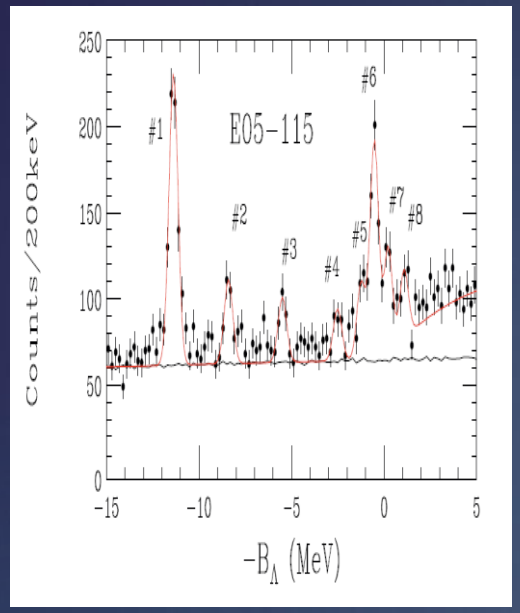
Expected at HIHR beamline



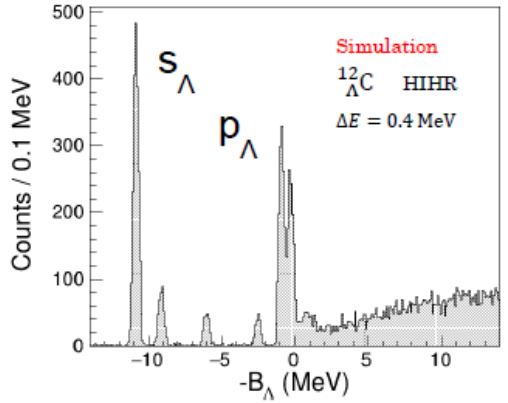
60 days × 200M π/spill @ HIHR

ΔE~**0.4 MeV(FWHM)**

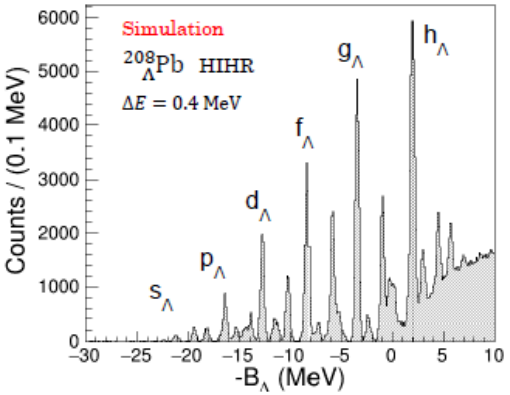
Expected spectra



$^{12}_{\Lambda}$B @ JLab E05 − 115

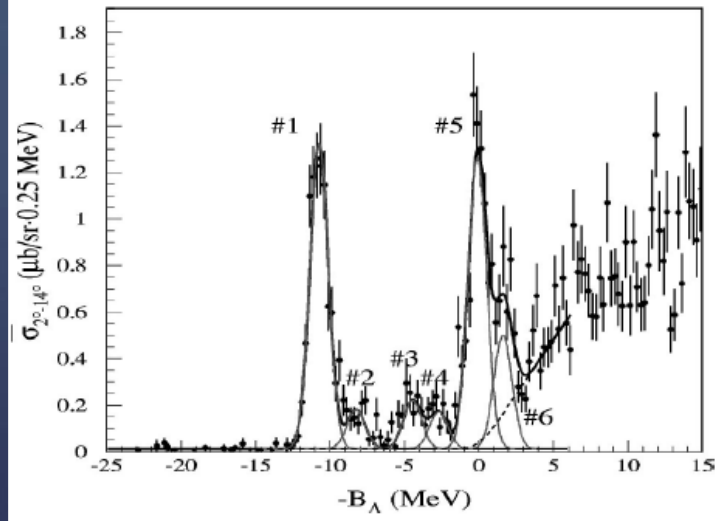


$^{12}_{\Lambda}$C @ HIHR Simulation

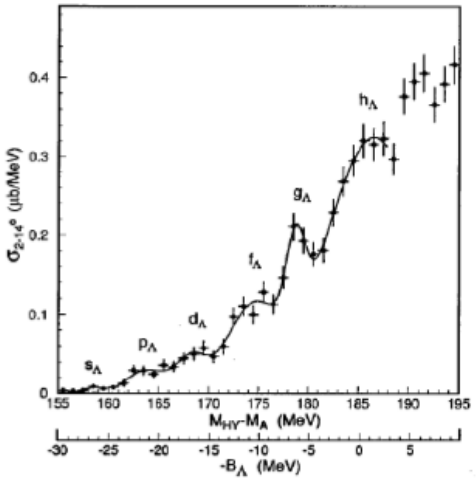


$^{208}_{\Lambda}$Pb @ HIHR Simulation

KEK-SKS
ΔE = 1.45 MeV



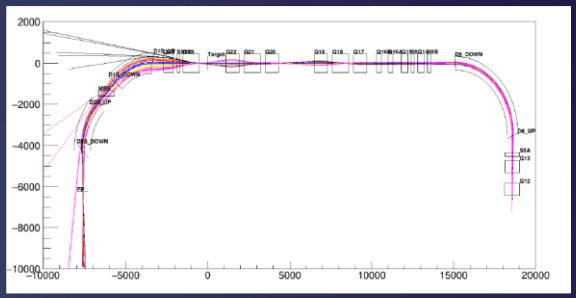
KEK-SKS
ΔE = 2.3 MeV

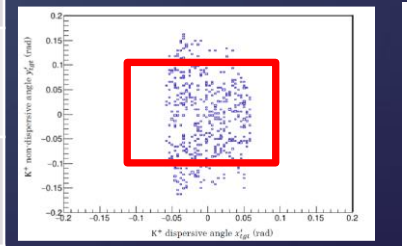


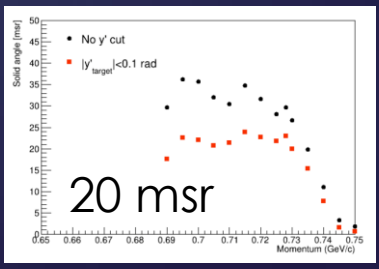
Expected Yield of Hypernulclei

	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

Summary

- (e,e'K^+) opens a door of sub-MeV spectroscopy of Λ hypernuclei at JLab.
- Experiment of $^3\mathrm{H}(e, e'K^+)X$: Consistency check of analysis in progress.
- New programs: Hypertriton puzzle and CSB study (${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$),

  Isospin dependence (${}^{40}_{\Lambda}\mathrm{K}$, ${}^{48}_{\Lambda}\mathrm{K}$),

  Heaviest hypernuclei (${}^{208}_{\Lambda}\mathrm{Tl}$)

- 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