24th Nov. 2021

THEIA-Strong, REIMEI seminar

Precise spectroscopy of Lambda hypernculei At High Intensity High Resolution beamline

SATOSHI N. NAKAMURA

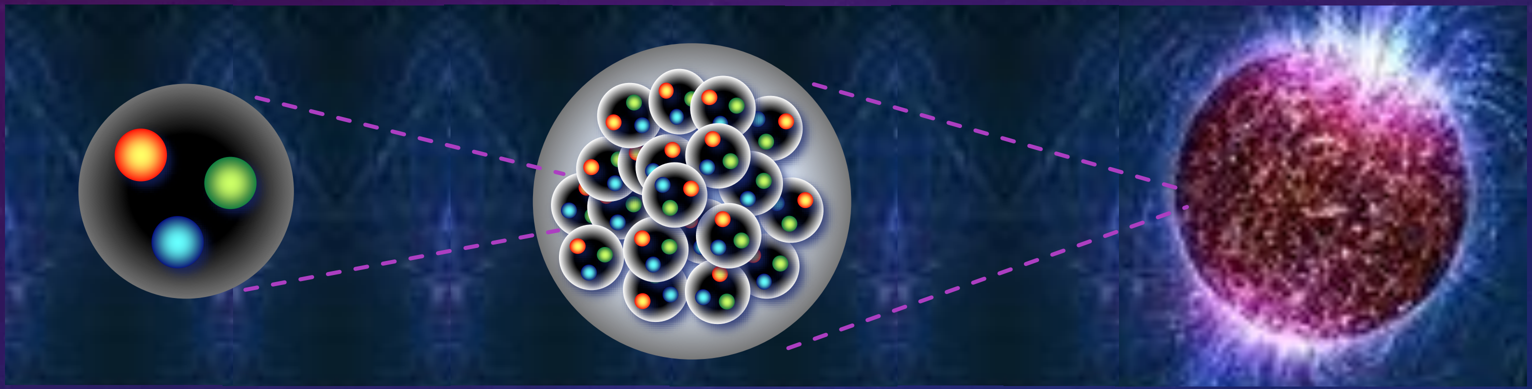
TOHOKU UNIVERSITY

NUCLEAR PHYSICS :
STUDY OF QUANTUM MANY-BODY SYSTEM GOVERNED BY THE STRONG INTERACTION

Baryon

(Hyper)
Nucleus

Neutron Star



10^{-15} m

10^{4} m

Terrestrial experiments

New information from astronomical observation

Understand these systems in the same framework.

Experimental Inputs, Check of Models

High-Quality Λ Hypernuclear Data

Wide variety

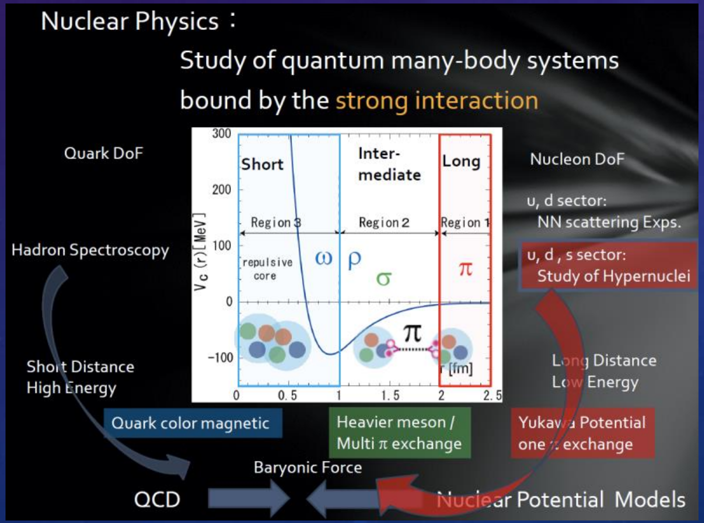
High-resolution

Extreme conditions

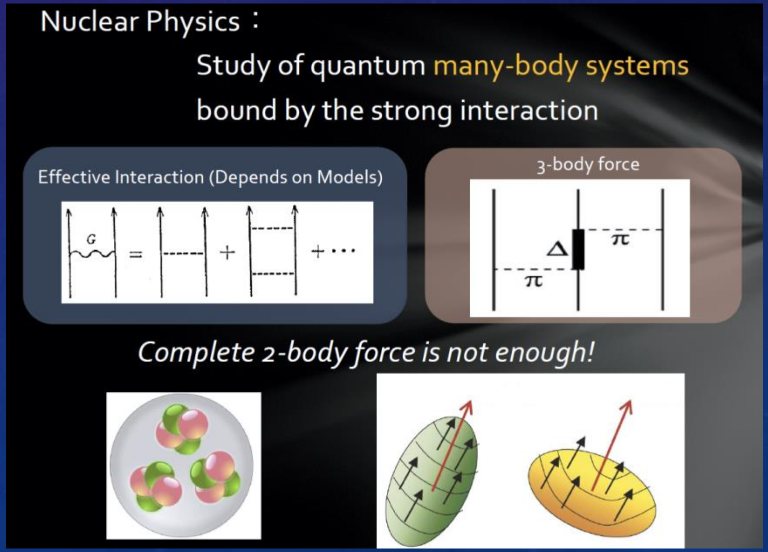
Single experiment
Is NOT enough,
systematic study
necessary

Theoretical Models

Baryonic Force based on QCD

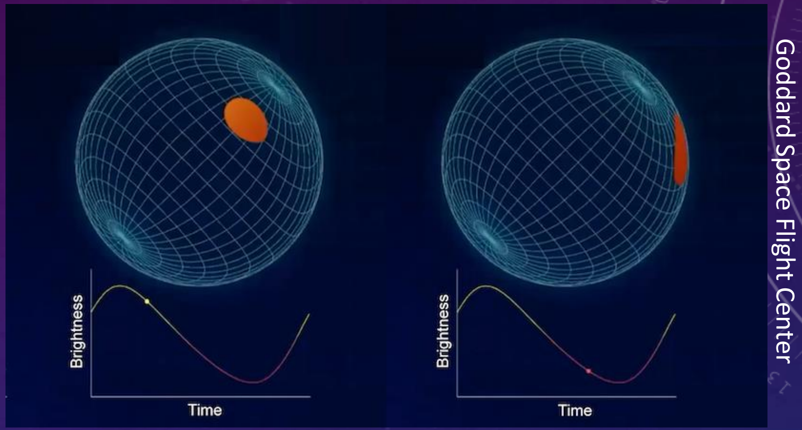


Many-body systems



New Astronomical Observations of NS

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



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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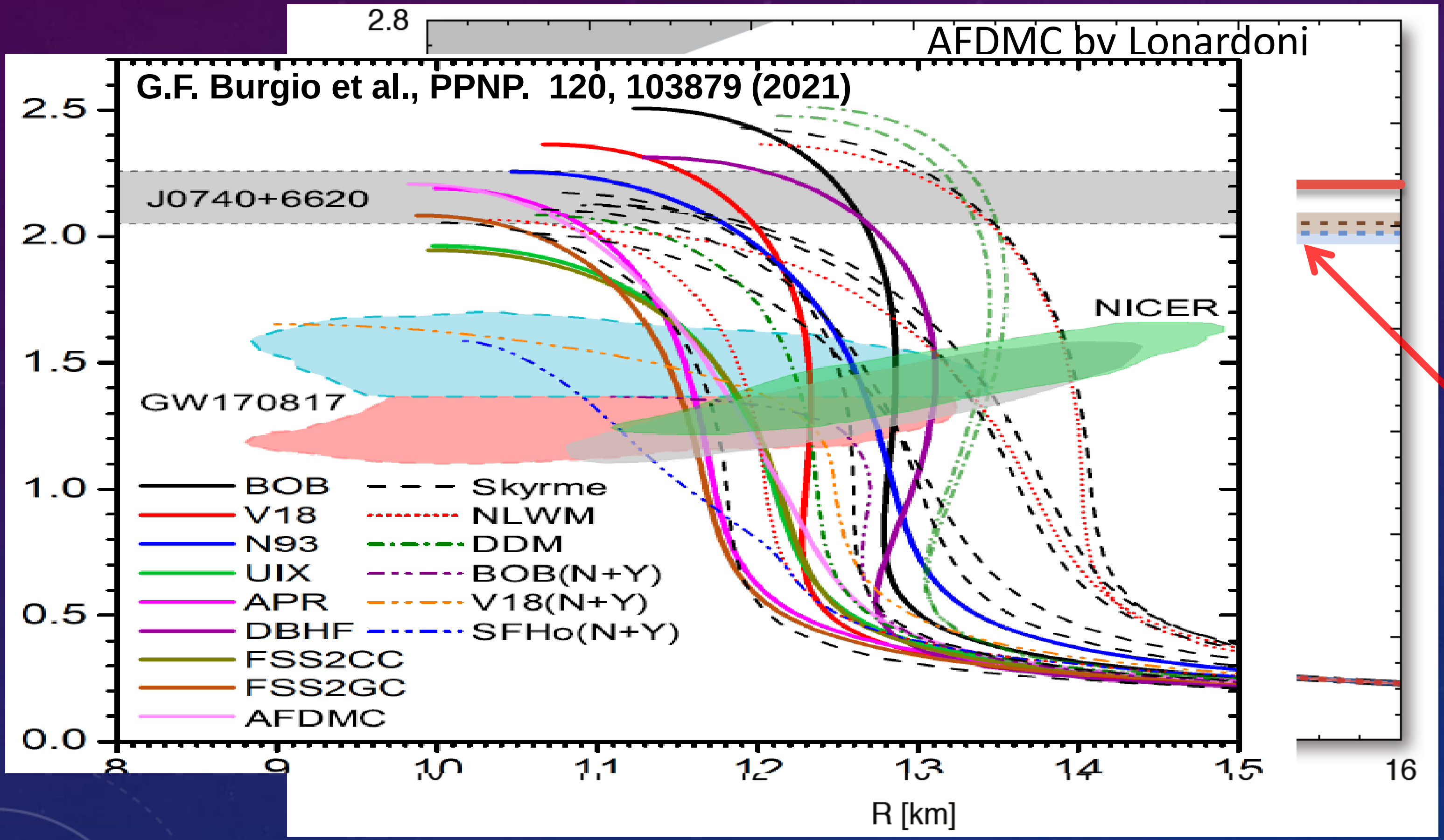
HYPERON PUZZLE

Based on our knowledge on Baryonic Force:

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



Too Soft EOS

Contradict to observation

2 $M_\odot$ Neutron Stars

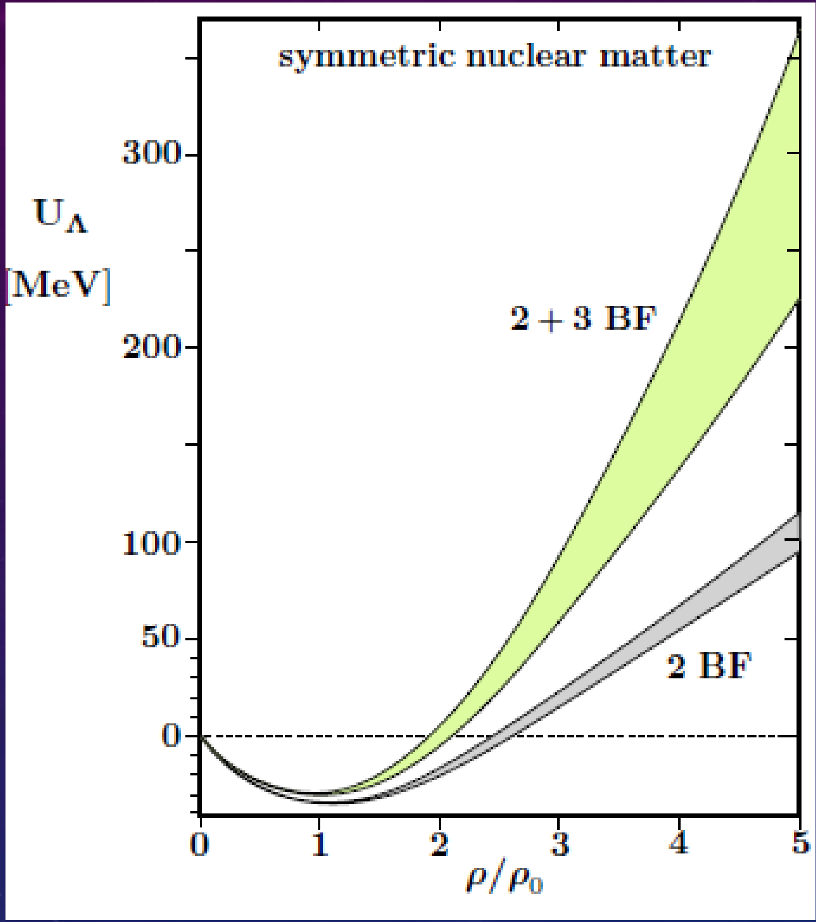
Additional Force to make EOS stiff

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

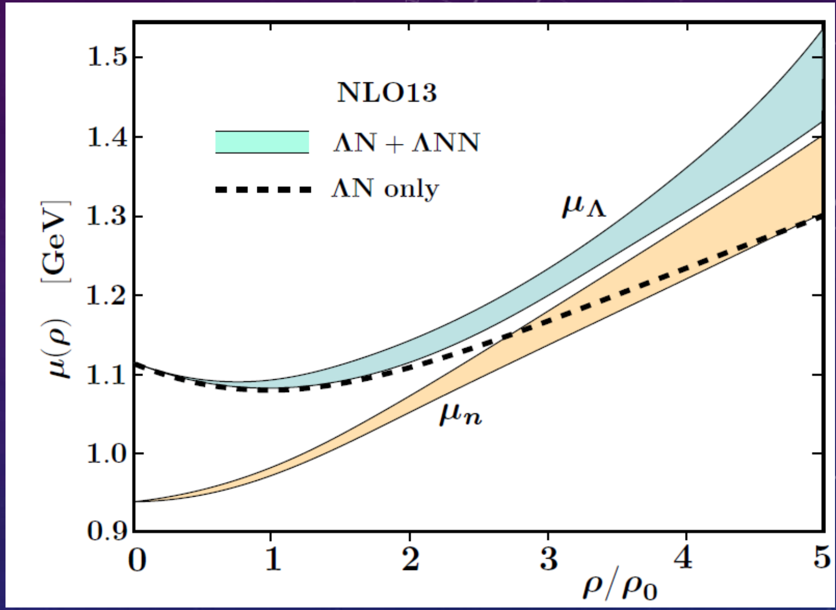
3BF recovers stiffness



D.Gerstung et al., Eur. Phys. J. A (2020) 56:175.

With 3BRF
recover stiffness

With Hyperon
too Soft



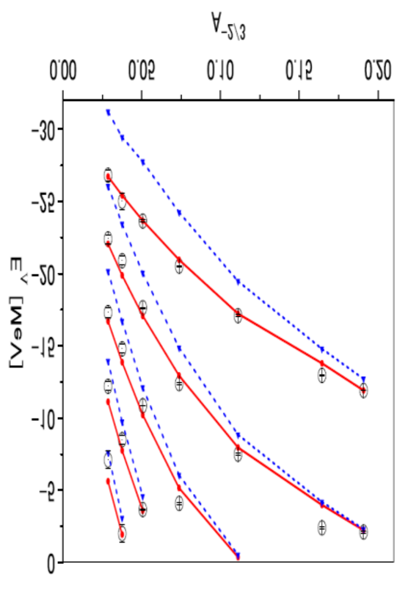
ChEFT(NLO: Saturation Decuplet)

3BF → Density Dep. Effective 2BF

Brueckner-Bethe-Goldstone eq.

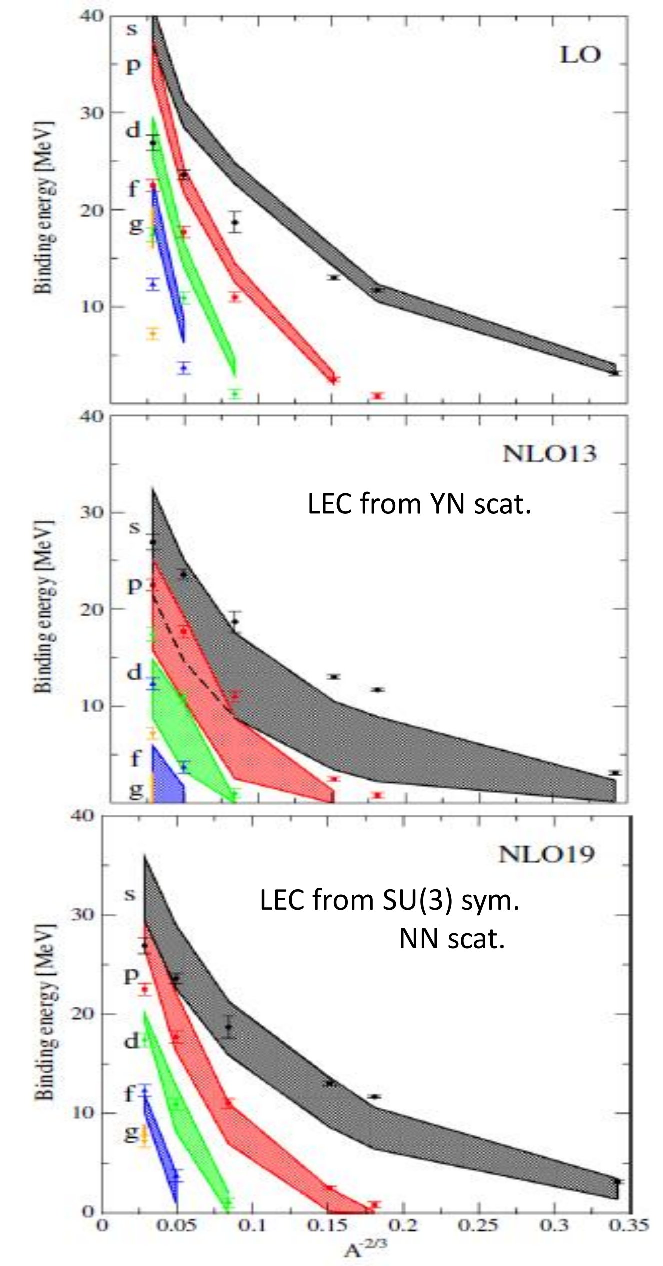
ΛN-ΣN,ΛNN-ΣNN coupled channels

Λ Single Particle Energies of Λ Hypernuclei by Various Calculations



M.M. Nagels et al., PRC 99 (2019) 044003.

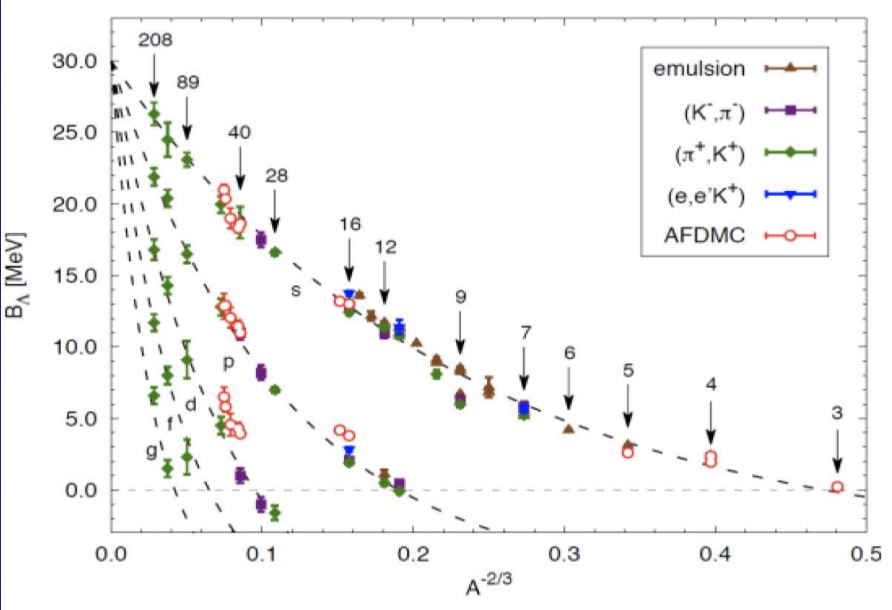
ESC16
ESC16+ (Inc. 3BF)
G-matrix



ChEFT

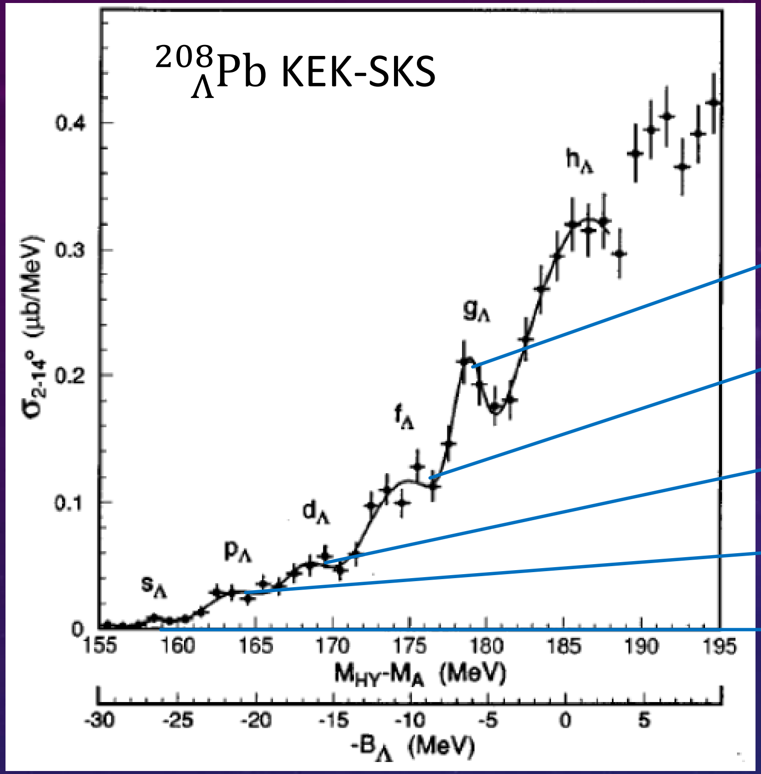
J.Haidenbauer, I.Vidana, EPJA (2020) 56:55.

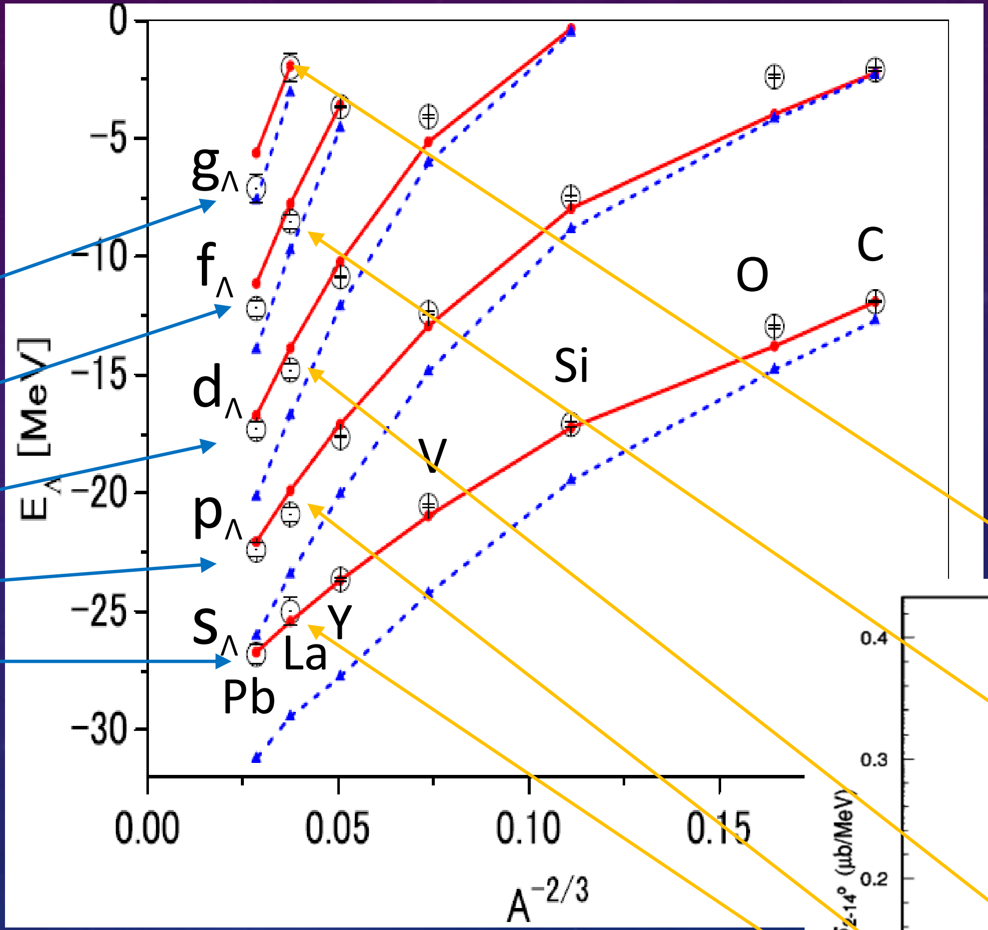
AFDMC

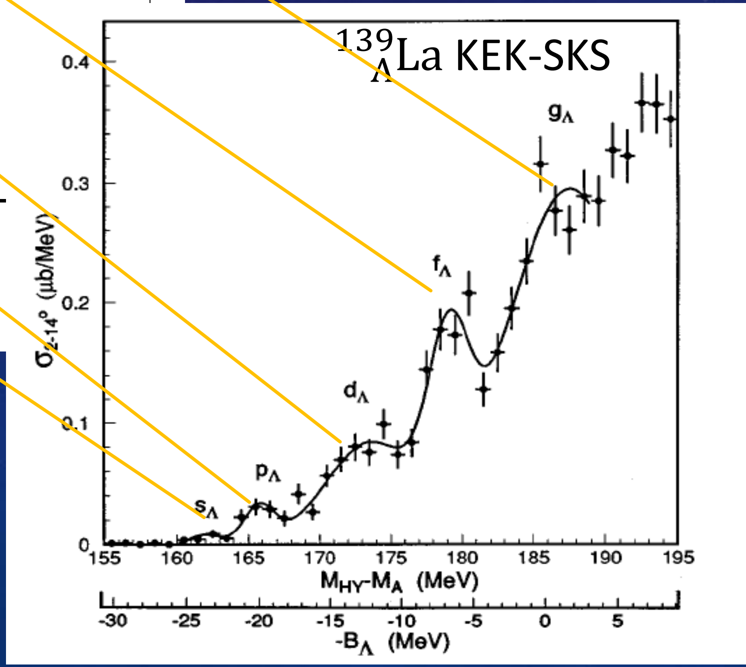


D.Lonardoni and F. Pederiva, arXiv:1711.07521.

Precise measurement of various B_Λ







M.M.Nagels, et al., Phys. Rev. C 99 (2019) 044004

ESC16 (+MPP + TBA)

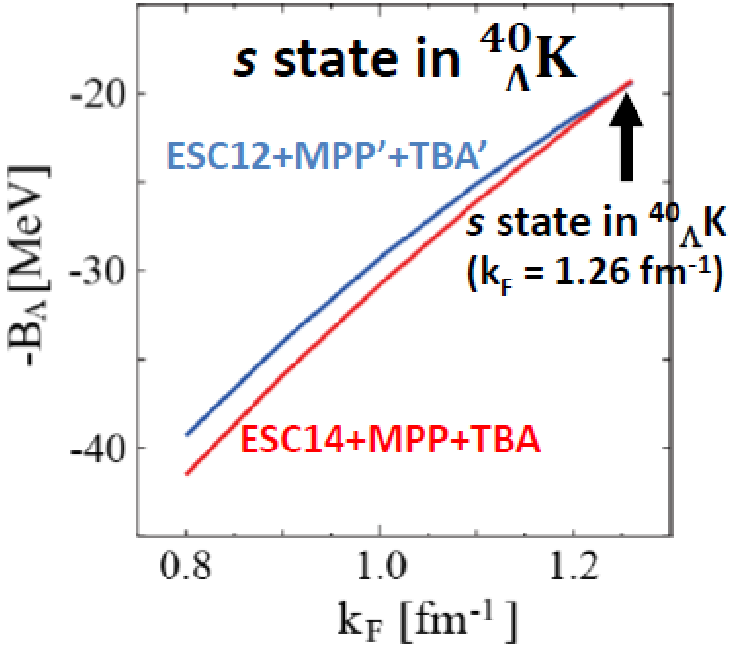
Λ in various orbits

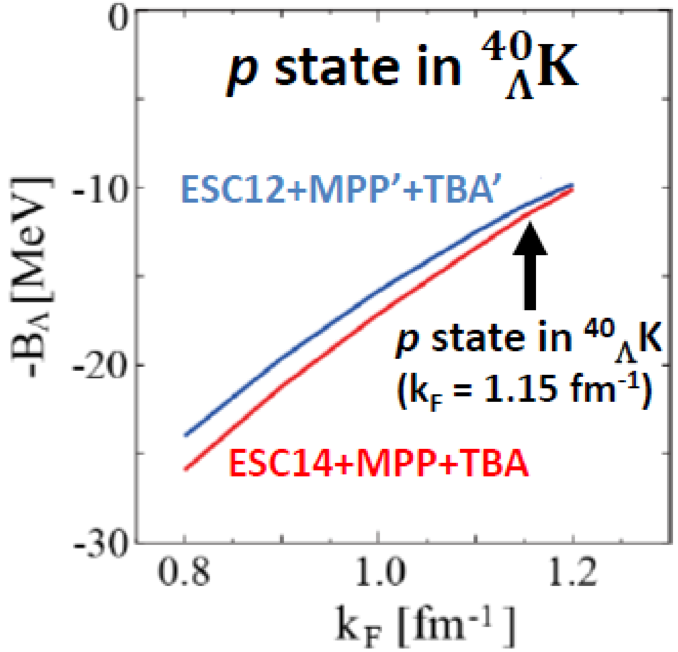
Results : Difference in k_F dependence

- **Comparison between ESC14+MPP+TBA and ESC12+MPP'＋TBA'**

(MPP: original) (MPP': weakened)

Example: $^{40}_{\Lambda}$K





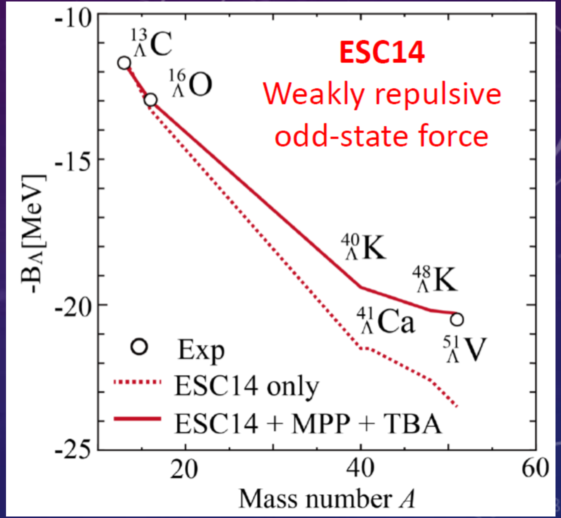
k_F from ADA

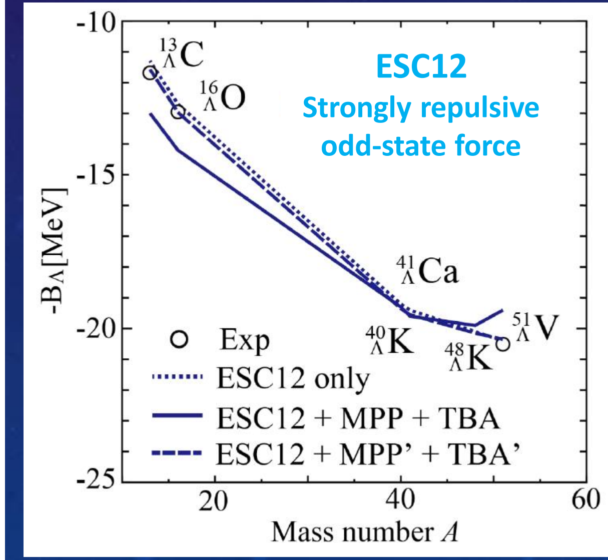
$^{40}{}_{\Lambda}$K(s): k_F = 1.26 fm^{-1}

$^{40}{}_{\Lambda}$K(p): k_F = 1.15 fm^{-1}

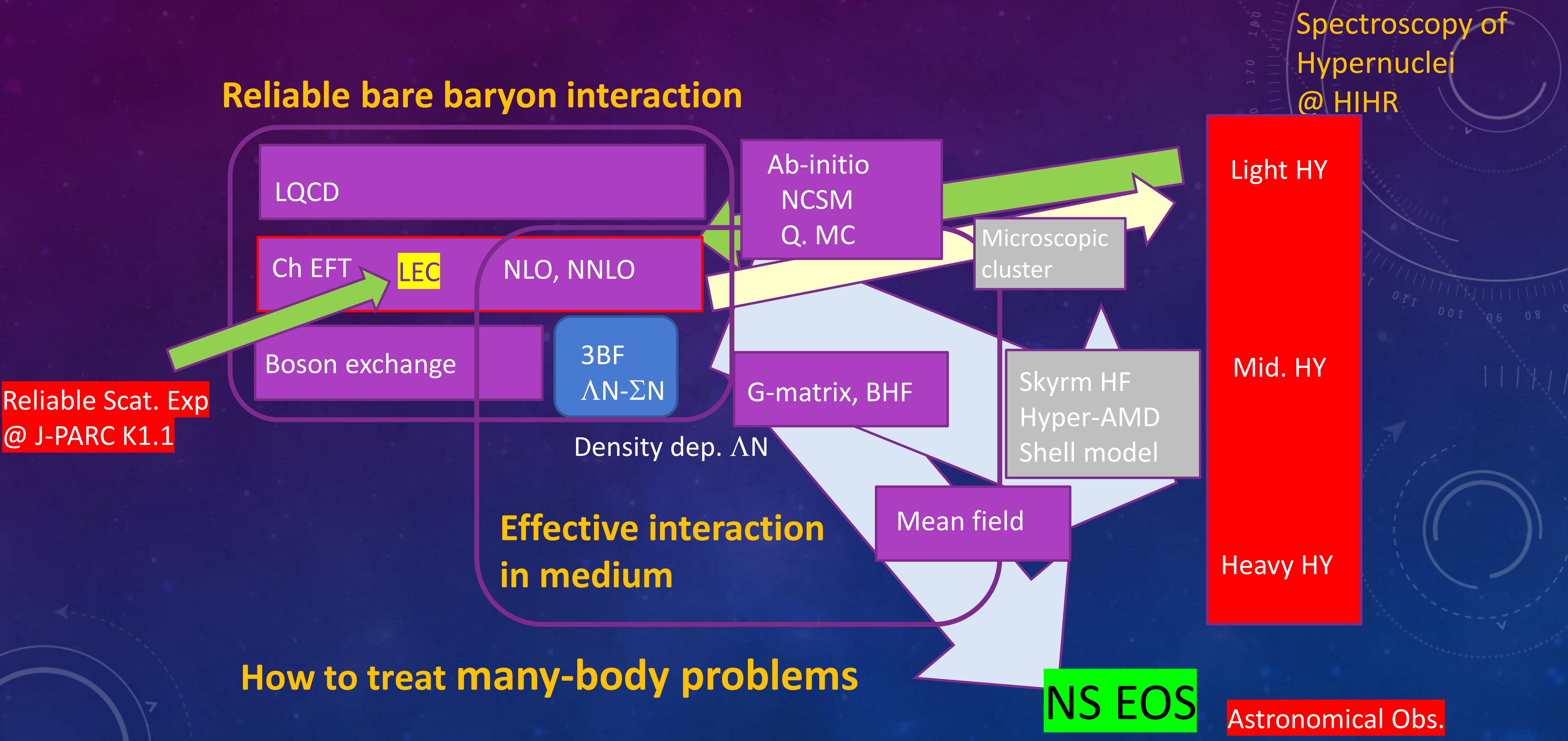
$^{40}{}_{\Lambda}$K(d): k_F = 1.02 fm^{-1}

Calculated B_Λ values can be different in *p* states and *d* states





Understand Hypernuclei and extend to Neutron Stars



Various spectroscopic methods of Λ hypernuclei

	Resolution (MeV;FWHM)	Abs. Energy	Cross sec. (μb/sr)	Momentum Transfer	
Reaction spectroscopy					
(K^-, π^-)	>2	○	◎ 1000	Small	$n \to \Lambda$
(π^+, K^+)	**<0.4**	○	◎ 10	**Large**	$\boldsymbol{n \to \Lambda}$
$(e, e'K^+)$	**~0.5**	◎	△ 0.1	**Large**	$\boldsymbol{p \to \Lambda}$
Decay Spectroscopy					
$\gamma - ray$	~0.003	×	-	-	
$decay\ \pi^-$	~0.1	◎ (only gs)	-	-	Fragments

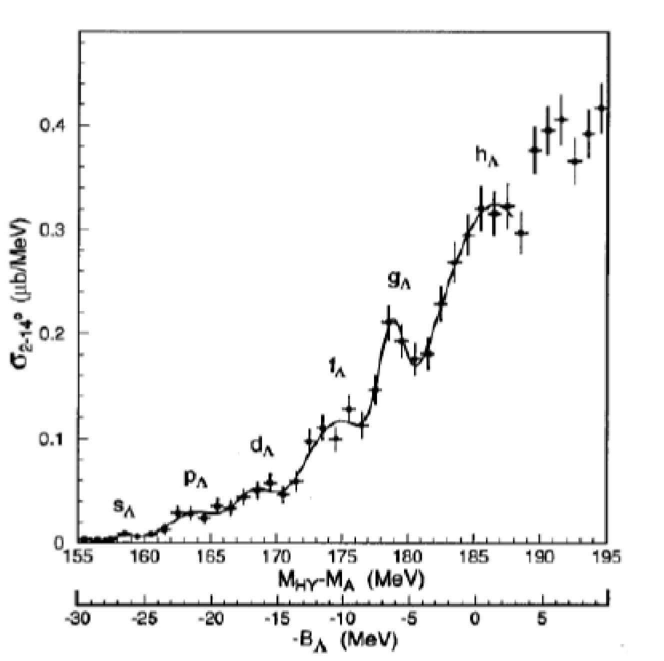
Mirror HY

High Intensity High Resolution beamline at J-PARC Extended Hadron Hall

High Resolution, High Intensity (π^+,K^+) spectroscopy

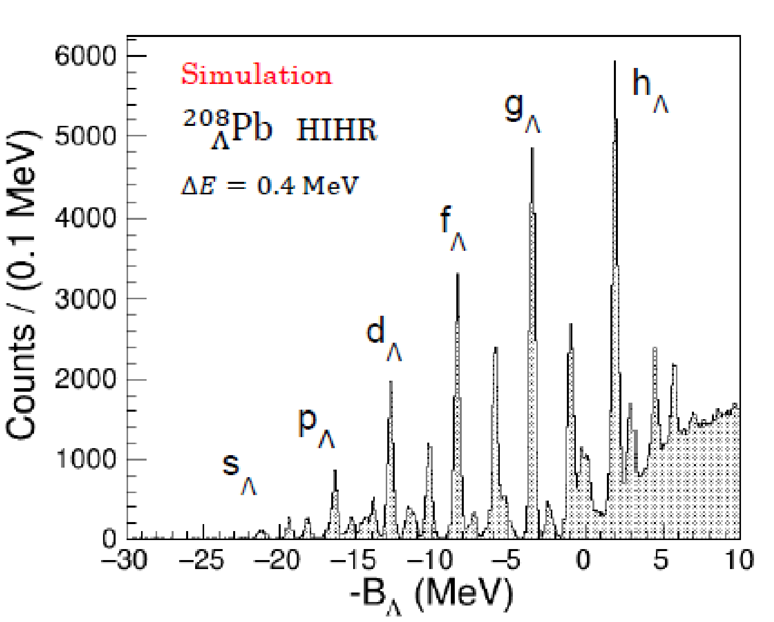
^{12}C, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, ^{28}Si, ^{40}Ca, ^{51}V, ^{89}Y, ^{139}La, ^{208}Pb

KEK-PS E369 with SKS → Expected at HIHR beamline



60 days × 3M π/spill @ KEK K6

ΔE~2.3 MeV(FWHM)



60 days × 200M π/spill @ HIHR

ΔE~0.4 MeV(FWHM)

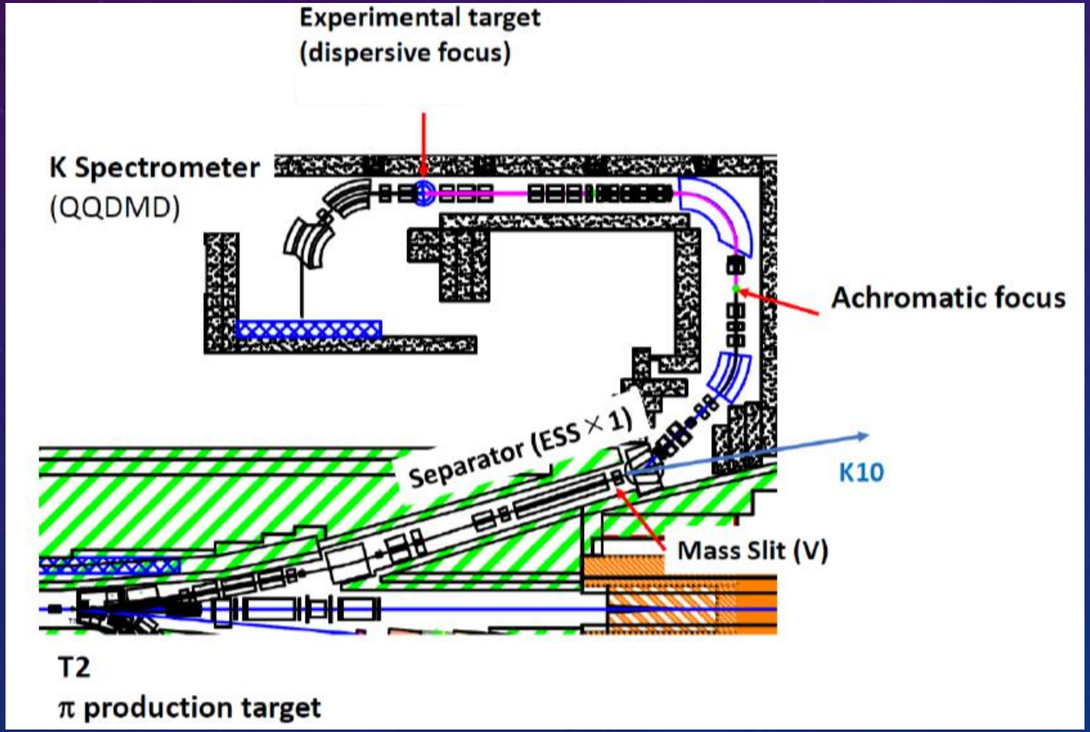
HIHR

- High-Intensity High-Resolution Beamline for High Precision (π^+, K^+) Spectroscopy
  - Dispersion matching ; NO limit of beam intensity
  - Well established technique for GR, SHARAQ,

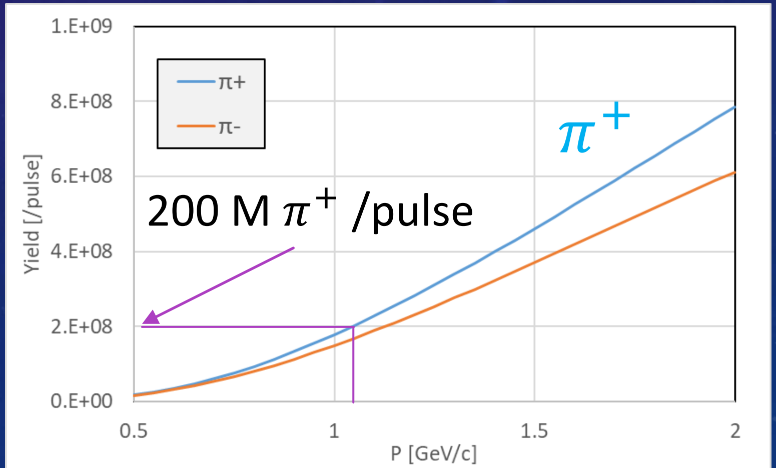
    but first challenge for GeV meson beams

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

HIHR:
~2 x 10^8 pions/pulse,
$\Delta p/p$ ~ 1/10000



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



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

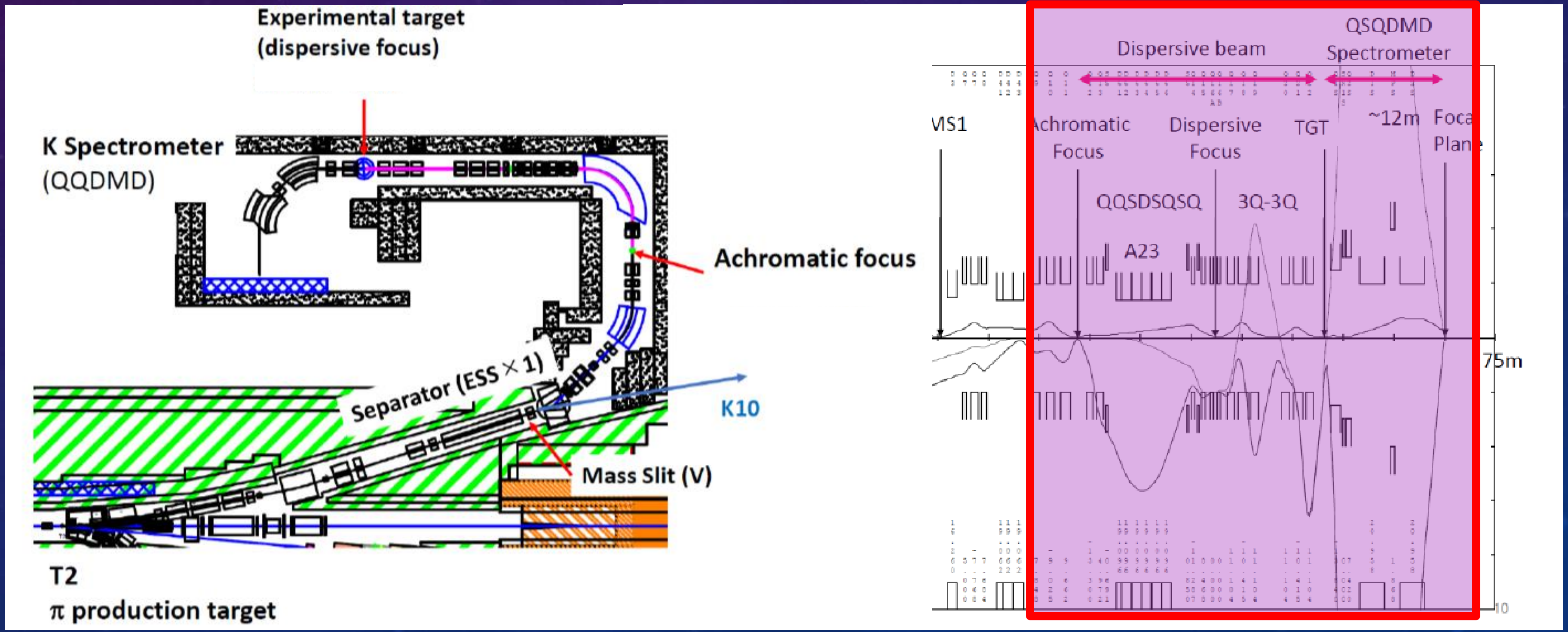
HIHR

- High-Intensity High-Resolution Beamline for High Precision (π^+, K^+) Spectroscopy
  - Dispersion matching ; NO limit of beam intensity
  - Well established technique for GR, SHARAQ,

    but first challenge for GeV meson beams

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

HIHR:
~2 x 10^8 pions/pulse,
$\Delta p/p$ ~ 1/10000



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

$x_f = (\cancel{s_{11}b_{11}T + s_{12}b_{26}})x_0$ -------- total magnification → minimize

$+(\cancel{s_{11}b_{12}T + s_{12}b_{22}})\theta_0$ -------- point-to-point focus → 0

$+(\cancel{s_{11}b_{16}T + s_{12}b_{26} + s_{16}C})\delta_0$ --- momentum matching → 0

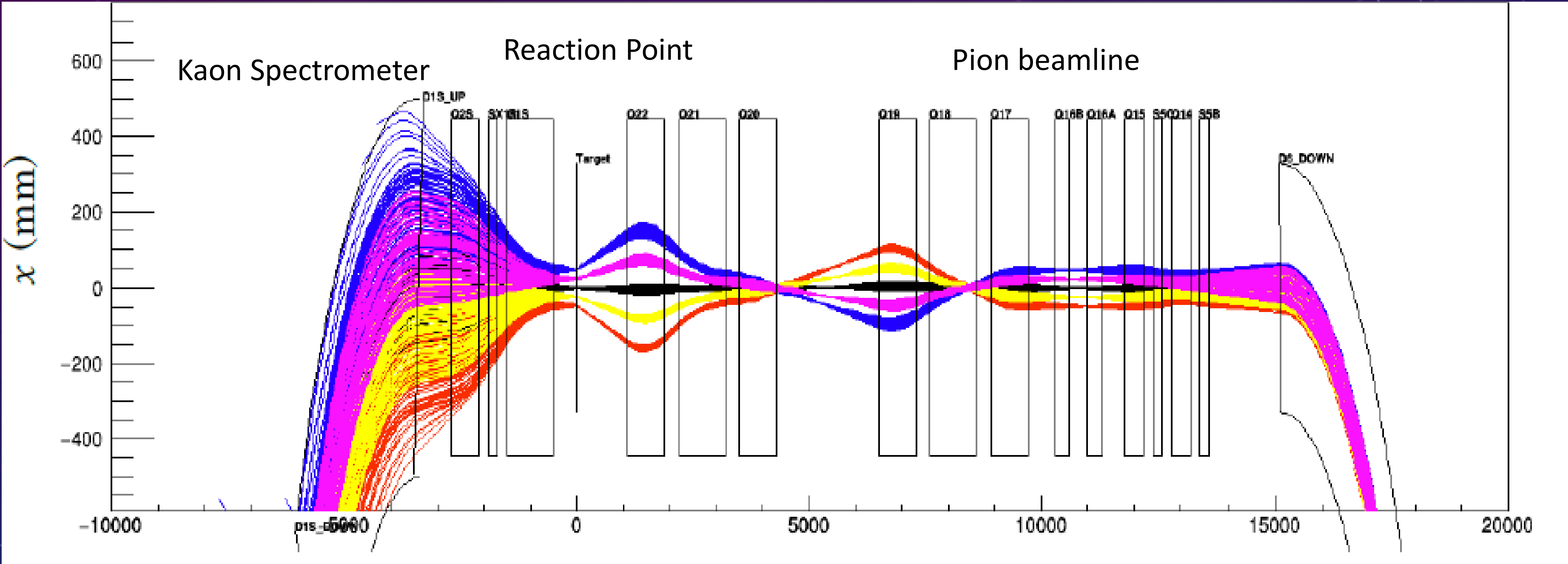
$+(\cancel{s_{1s} + s_{16}K})\theta$ -------- kinematical correction → 0

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

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

Resolution study (GEANT4)

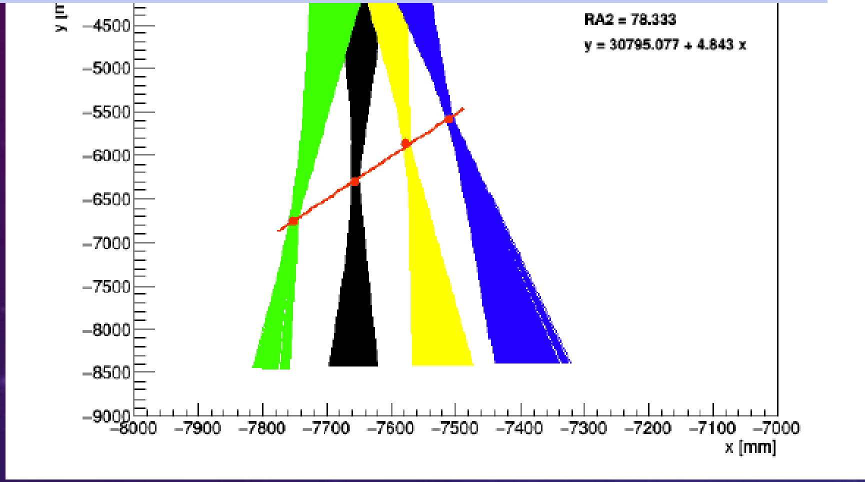
$$\begin{pmatrix} x_f \\ \theta_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} & s_{16} \\ s_{21} & s_{22} & s_{26} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} T & 0 & 0 \\ 0 & \theta/\theta_1 + 1 & 0 \\ 0 & 0 & (K\theta + DQ)/\theta_0 + C \end{pmatrix} \begin{pmatrix} b_{11} & b_{12} &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

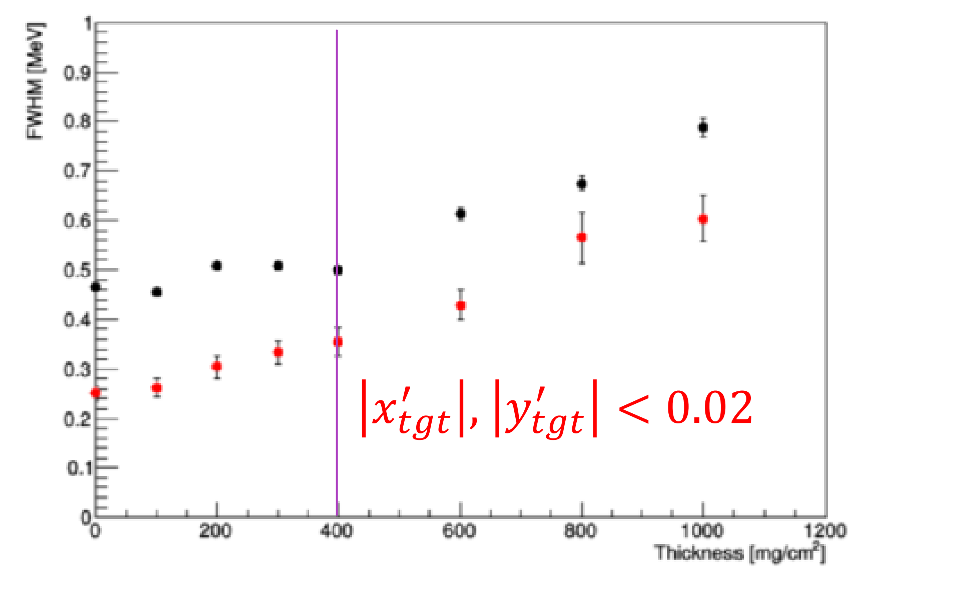


Beam momentum spread -> Position spread on target

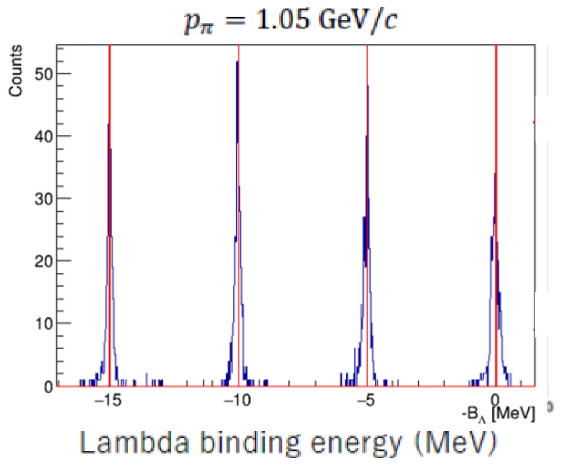
Resolution study (GEANT4 Simulation)

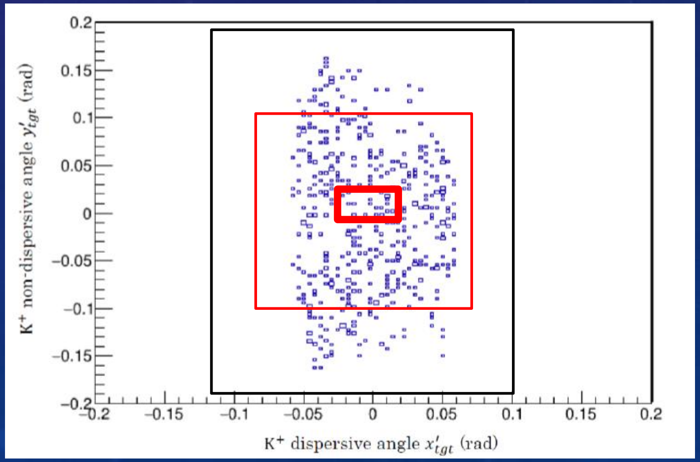
Position corresponds to excitation energies.





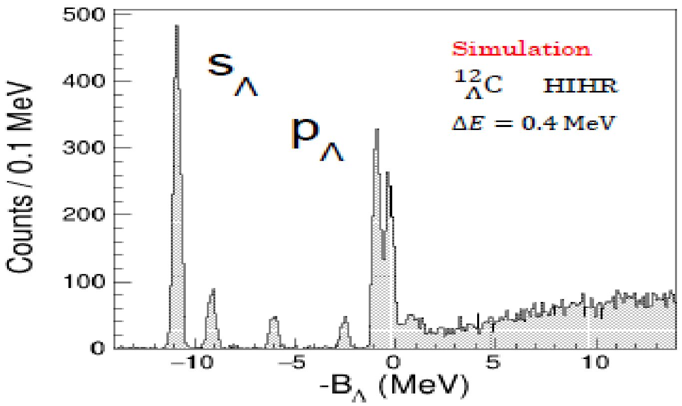
Res < 360 keV (FWHM)

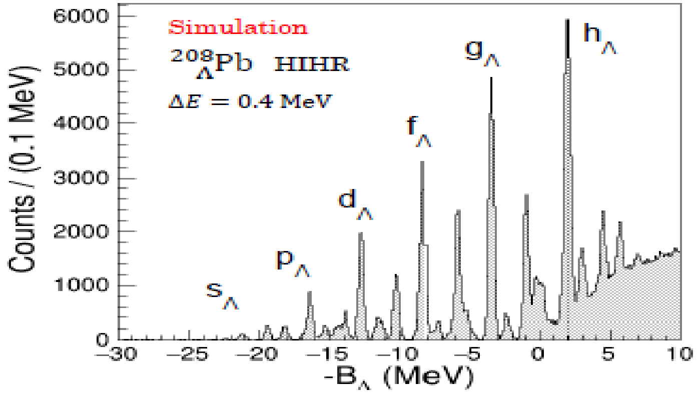




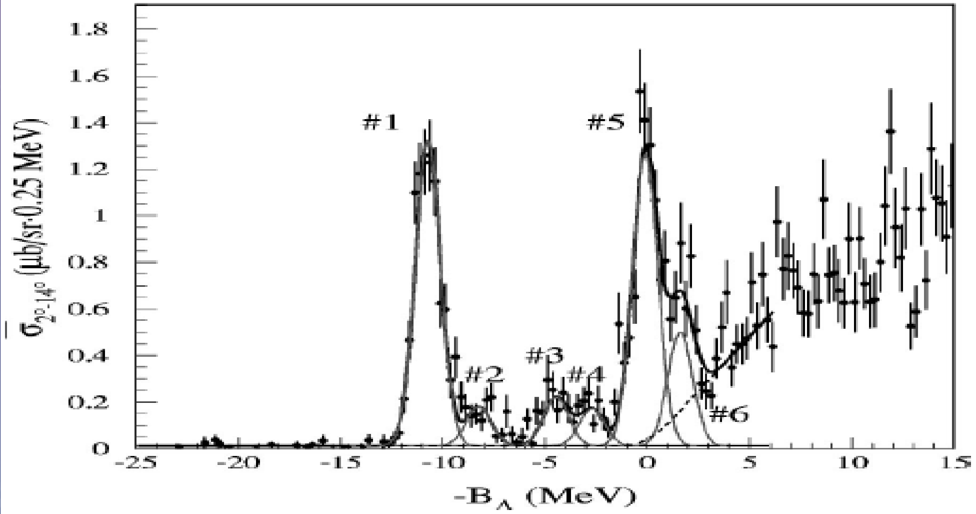
$$-B_{\Lambda}rec=\Sigma a_{ijkl}x_{FP}{}^{i}y_{FP}{}^{j}u_{FP}{}^{k}v_{FP}{}^{l}$$

EXPECTED SPECTRA

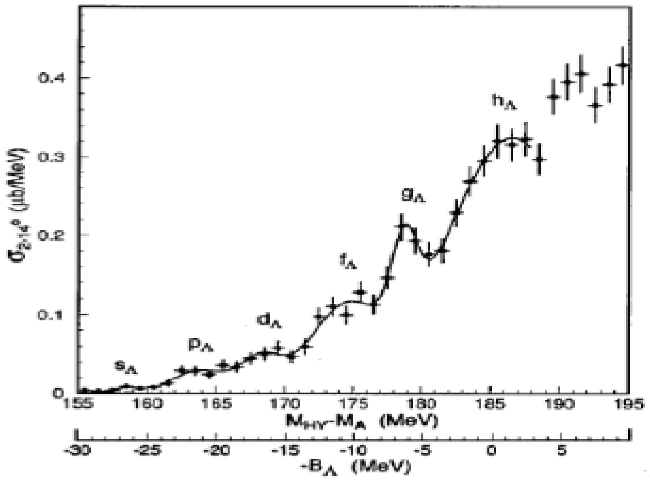




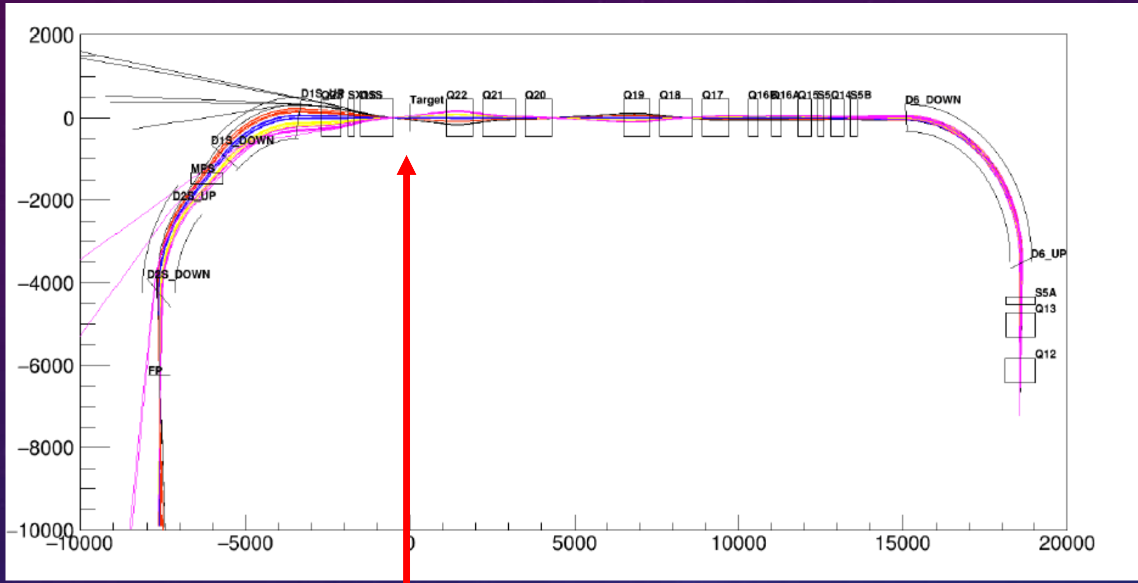
KEK-SKS
$\Delta E = 1.45$ MeV

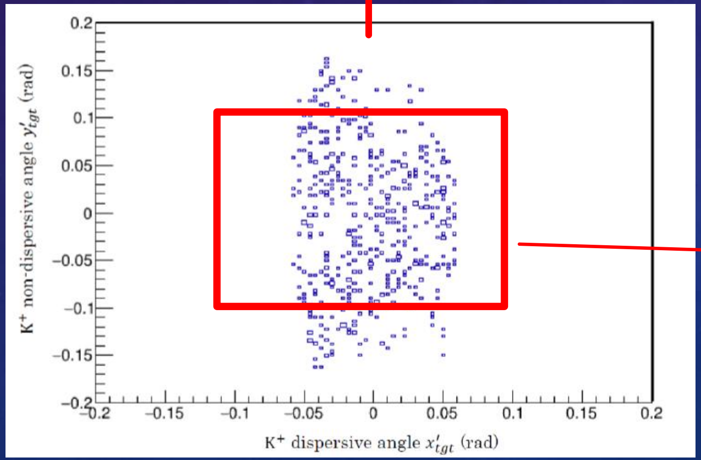


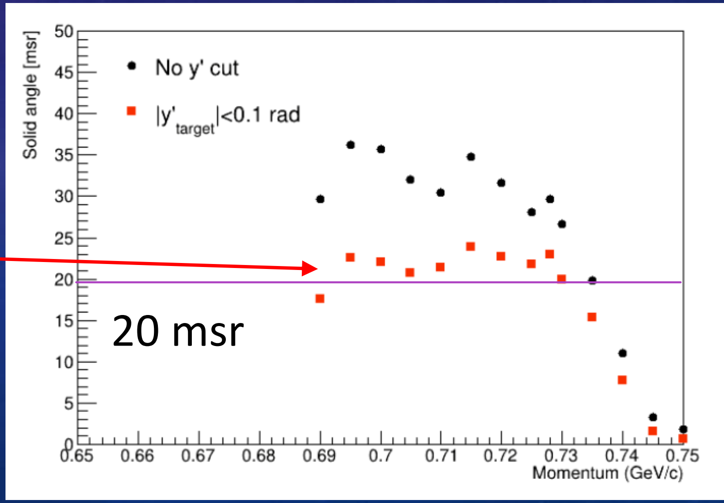
KEK-SKS
$\Delta E = 2.3$ MeV



Yield study with GEANT4







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)	$3.85 \times 10^7\ \pi^+$ **(200 M/spill, 50kW)**
Target Thick (mg/cm^2)	**400** **(1.8 g/cm^3 × 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**

First Campaign Experiment

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/cm²)	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 light targets

GOAL :

Resolution < 400 keV (FWHM)

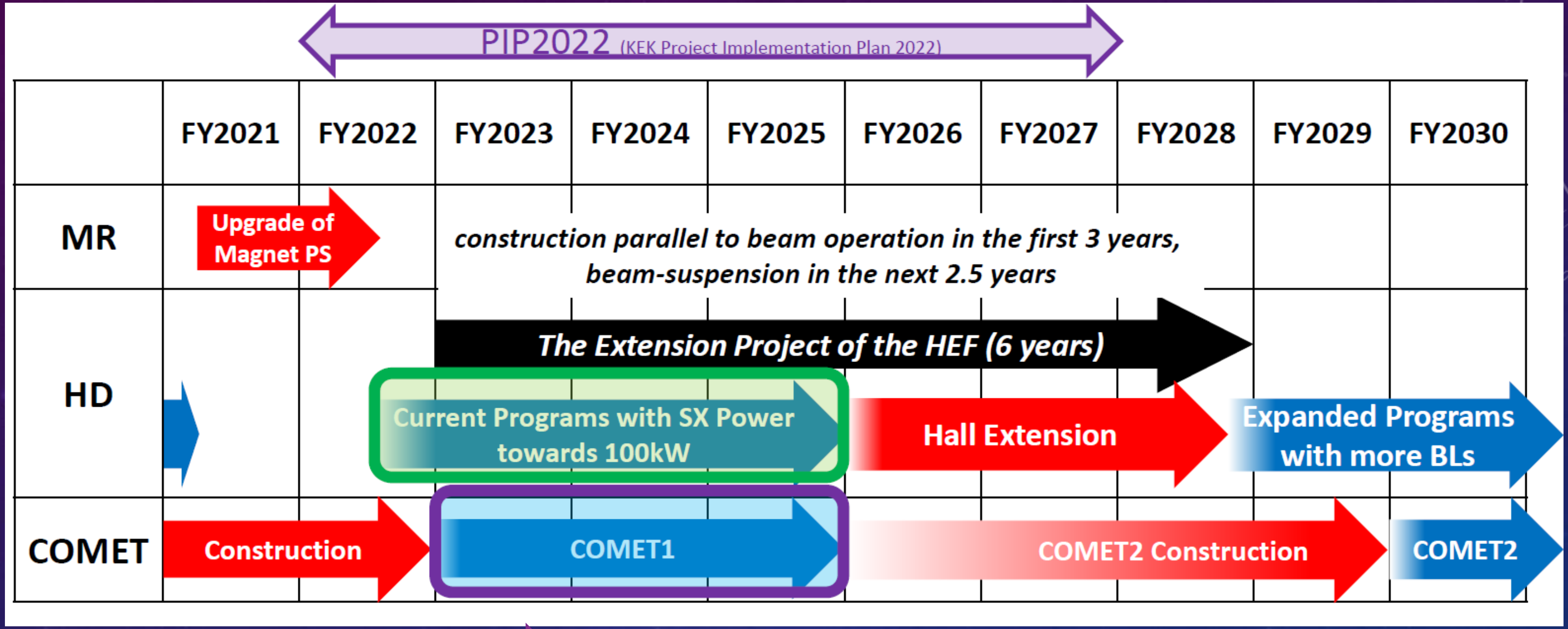
Peak determination precision 40 keV ($\sigma \sim$ 17 keV)

$^{139}_{\Lambda}La$	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 heavy targets

104 days for total

SCHEDULE



Beamline design

Beamline construction

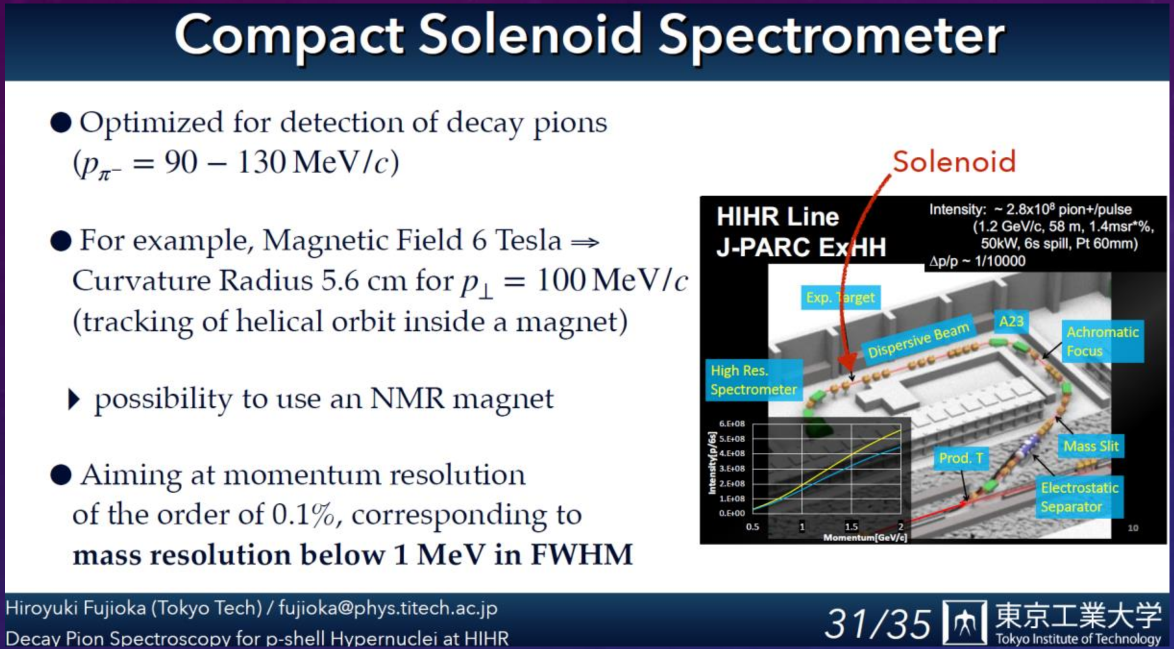
Magnets design & construction

Detector Design &Construction

Performance test & commission

New ideas

Decay pion spectroscopy for p-shell hypernuclei



$${}^{A}_{\Lambda}Z_{\mathrm{g.s.}} \rightarrow {}^{A}(Z+1) + \pi^-$$

H. Fujioka @Strangeness in NS – Physics at J-PARC HIHR/K1.1 (2021/6/18)

ArXiv:2110.04462, the White Paper

Double Charge Exchange for neutron rich hypernuclei ${}^{A}Z(\pi^-, K^+){}^{A}_{\Lambda}(Z-2)$

ΣN Cusp study $d(\pi^+, K^+)$

η, η' nuclear bound states ${}^{12}\mathrm{C}(\pi^+, p)$

Tetra neutron ${}^{4}\mathrm{He}(\pi^-, \pi^+)\,{}^{4}\mathrm{n}$

SUMMARY

- Physics Motivation

  Spectroscopy of Λ hypernuclei with (π^+, K^+) reaction at HIHR beamline

  Study of ΛNN 3-body force

  Key information to solve the Hyperon Puzzle

  Systematic Study of CSB for various hypernuclei (complimentary to $(e,e'K^+)$)

  Provide standard data of Λ hypernuclei for decades

- Necessary Beam

  1.1 GeV/c π^+ beam, 2.0×10^8 / spill (50kW, Pt 60mm,extraction angle 3degrees)

  (No limit for π beam intensity. Stronger beam is welcome)

- 1st Campaign of the experiments

  30 days run for ^{12}C, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{28}Si, ^{40}Ca, ^{51}V, ^{89}Y

  73 days run for ^{139}La, ^{208}Pb

  Total 104 days

HIHR will be a unique **hypernuclear factory** which provides various high precision data to construct a reliable baryonic interaction model and to deepen our understanding of quantum many-body systems.