8th July 2021
International WS on the Extension Project for
the J-PARC Hadron Experimental Facility

Supra-precision (π^+,K^+) spectroscopy ($S\pi K$) of Λ hypernuclei at the High Intensity High Resolution beamline

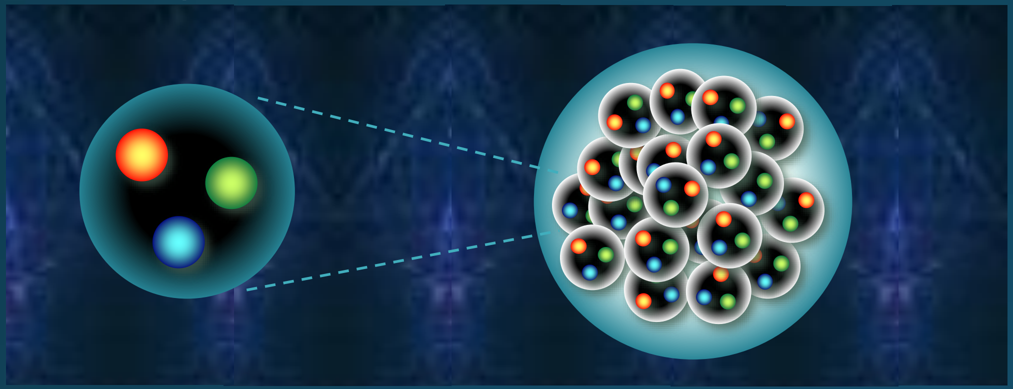
HIHR Hypernuclear Collaboration
Satoshi N. Nakamura (Tohoku Univ.)

Nuclear Physics :

Study of quantum many-body system governed by the strong interaction

Baryon

(Hyper) Nucleus



10^{-15} m

Nucleon-nucleon (baryon-baryon) interaction

Many-body problems

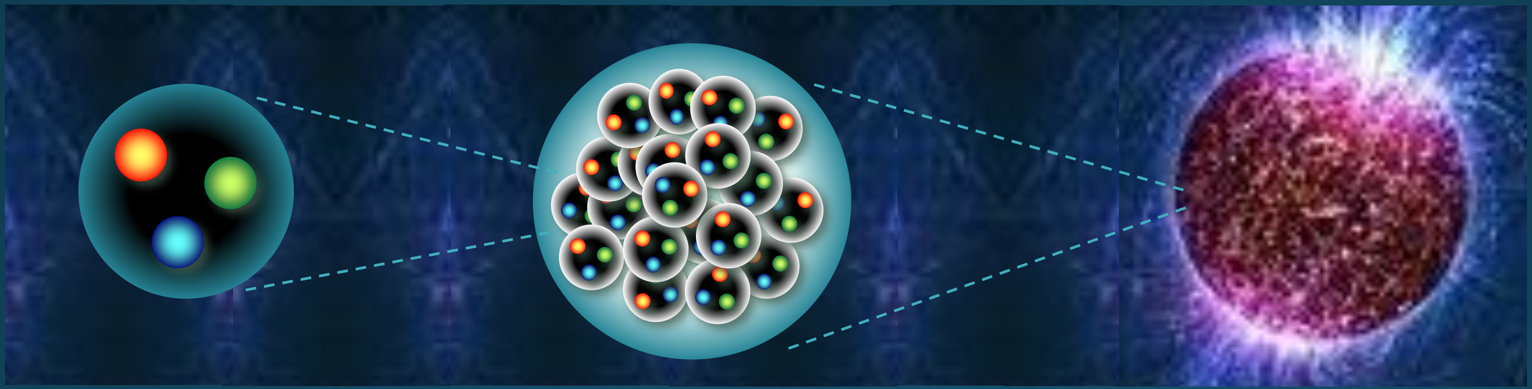
Nuclear Physics :

Study of quantum many-body system governed by the strong interaction

Baryon

(Hyper) Nucleus

Neutron Star



10^{-15} m

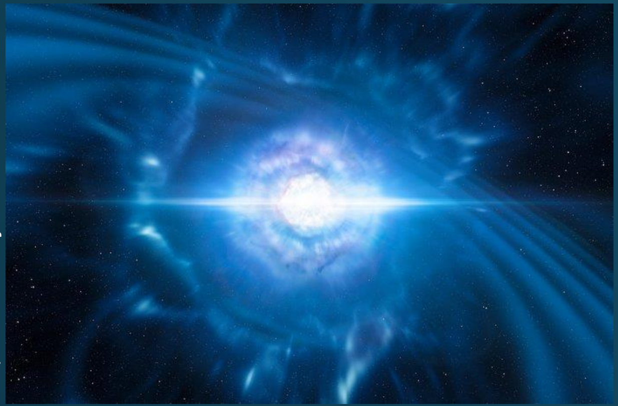
10^{4} m

Terrestrial experiments

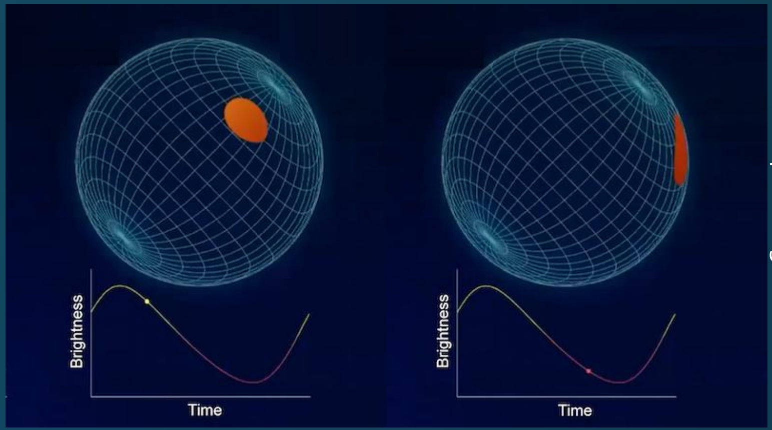
New information from astronomical observation

Understand these systems in the same framework.

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

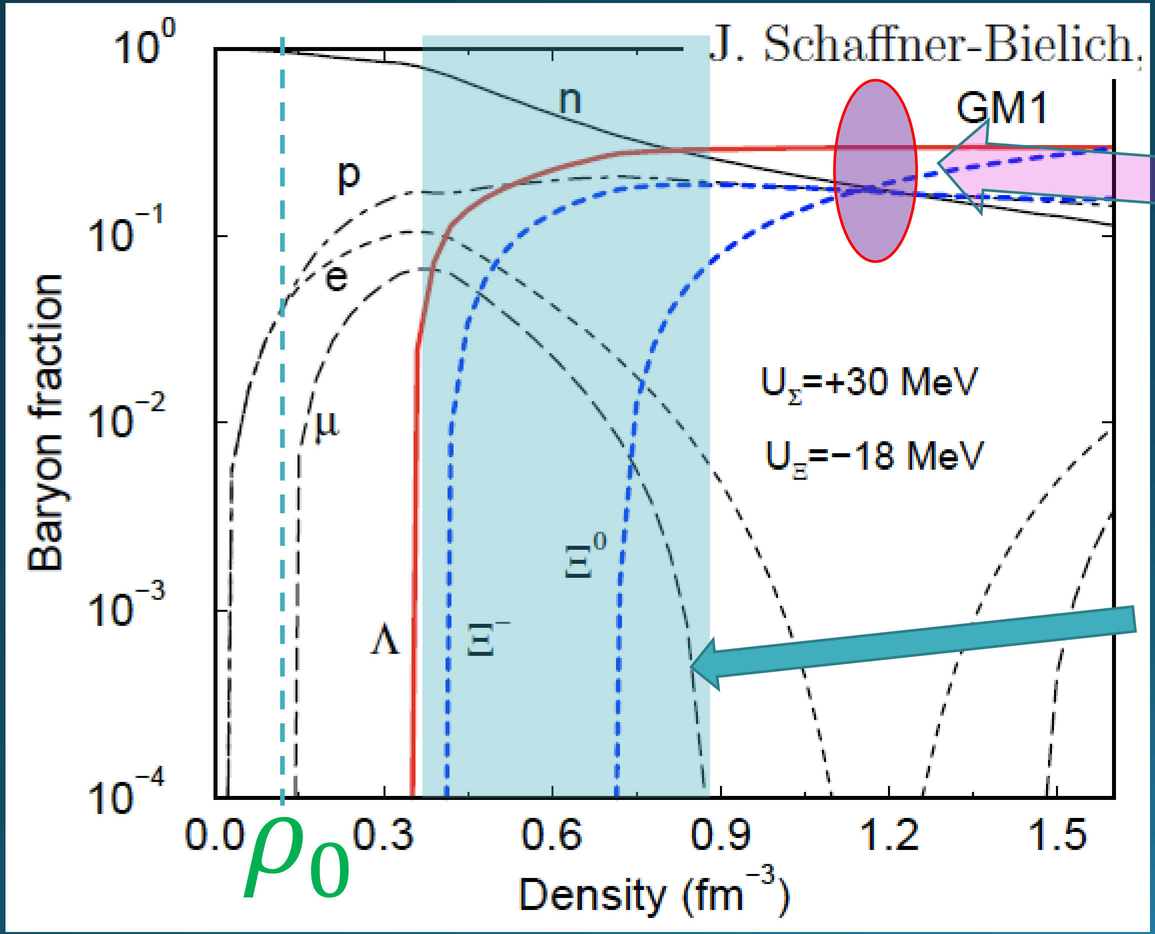
⇩

Microscopic understanding
becomes more important!

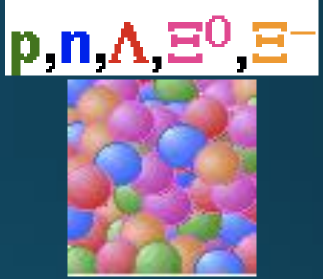
Neutron star and Strange hadronic matter

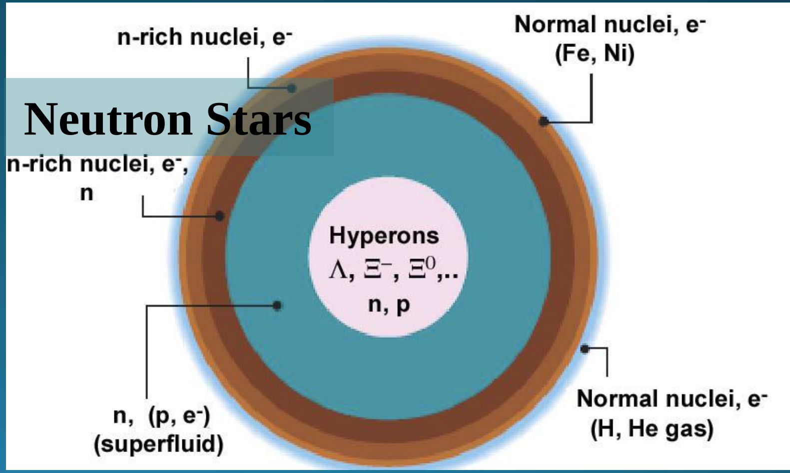
Sym. Nucl. Matter : Limit for size (due to Coulomb force)

Asym. Nucl. Matter : Neutron Stars, Strange Hadronic Matter



Nu ~ Nd ~ Ns

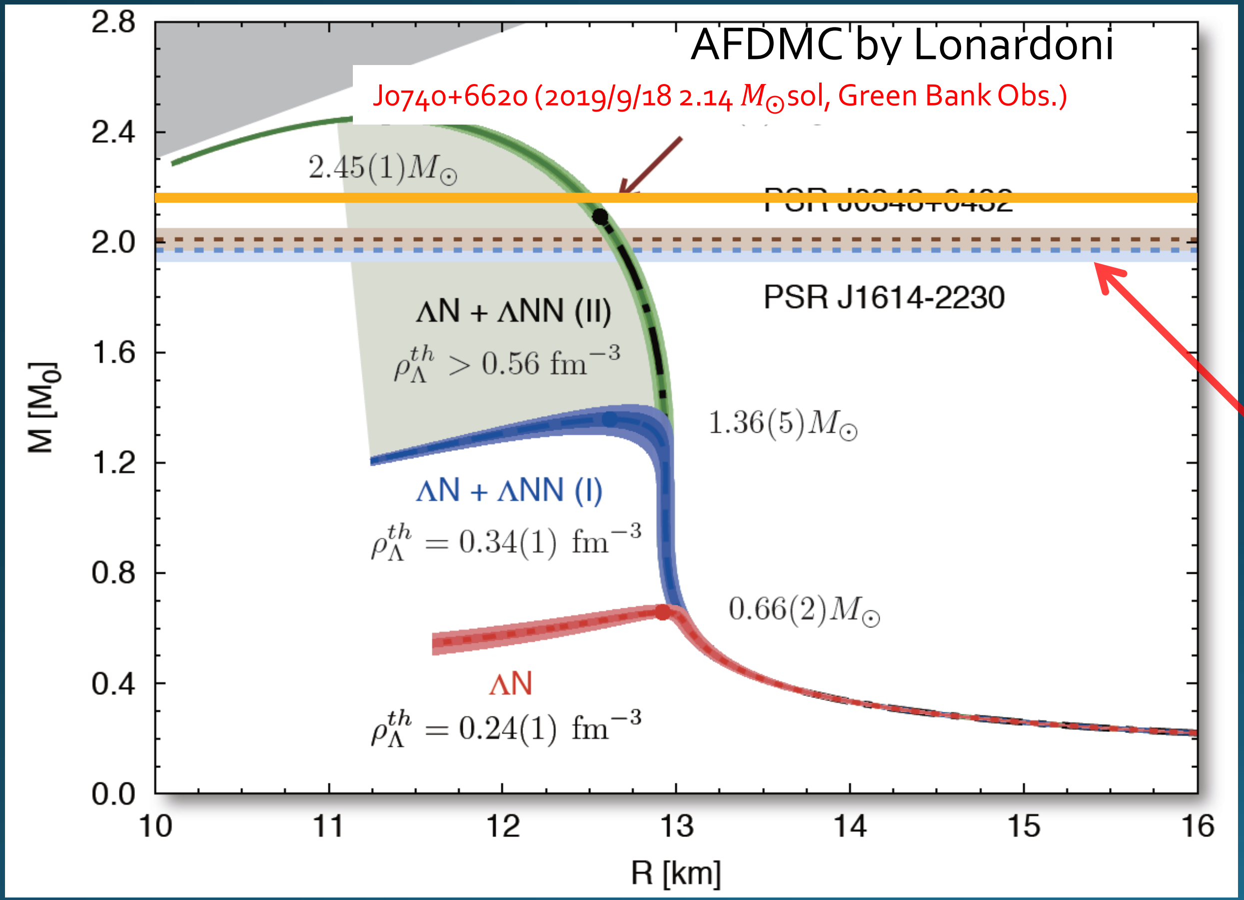




Hyperon Puzzle

Based on our knowledge on Baryonic Force:

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



Too Soft EOS

Contradict to observation

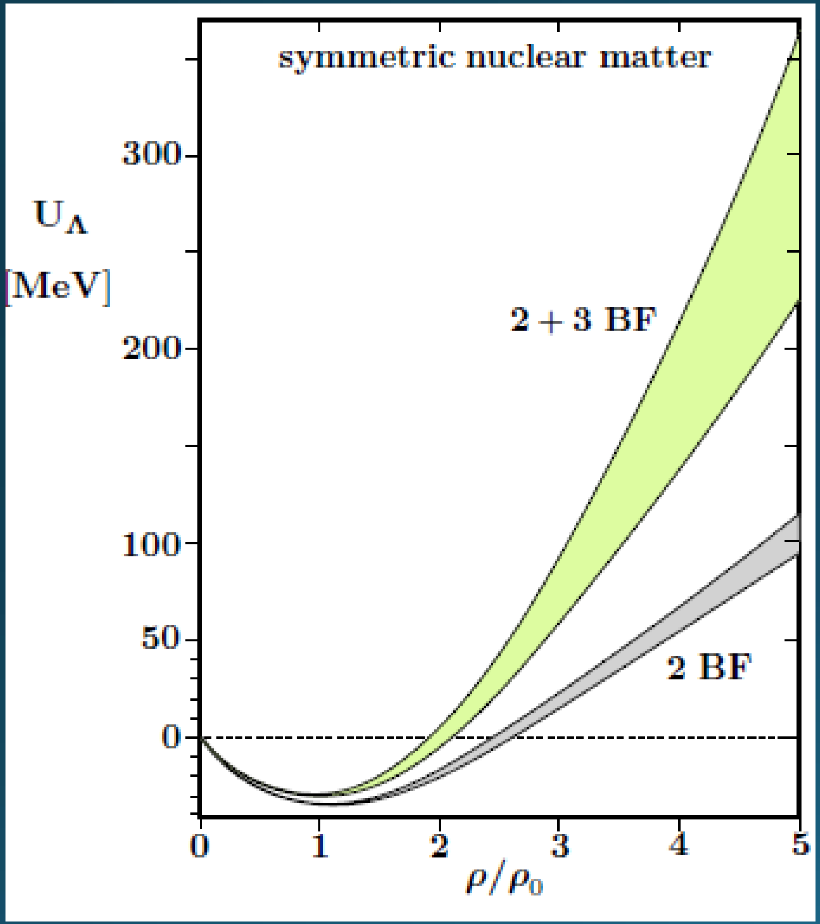
2 $M_\odot$ Neutron Stars

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



With 3BRF
recover stiffness

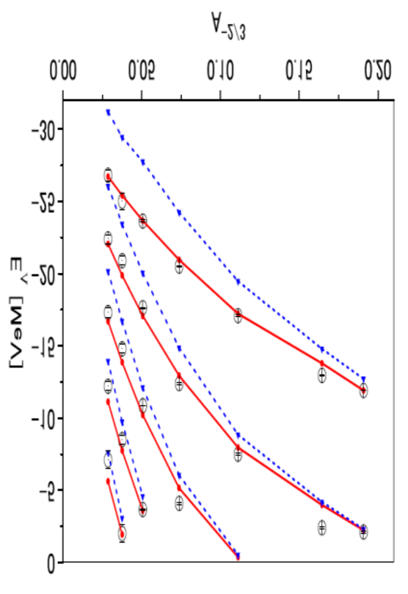
With Hyperon
too Soft

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

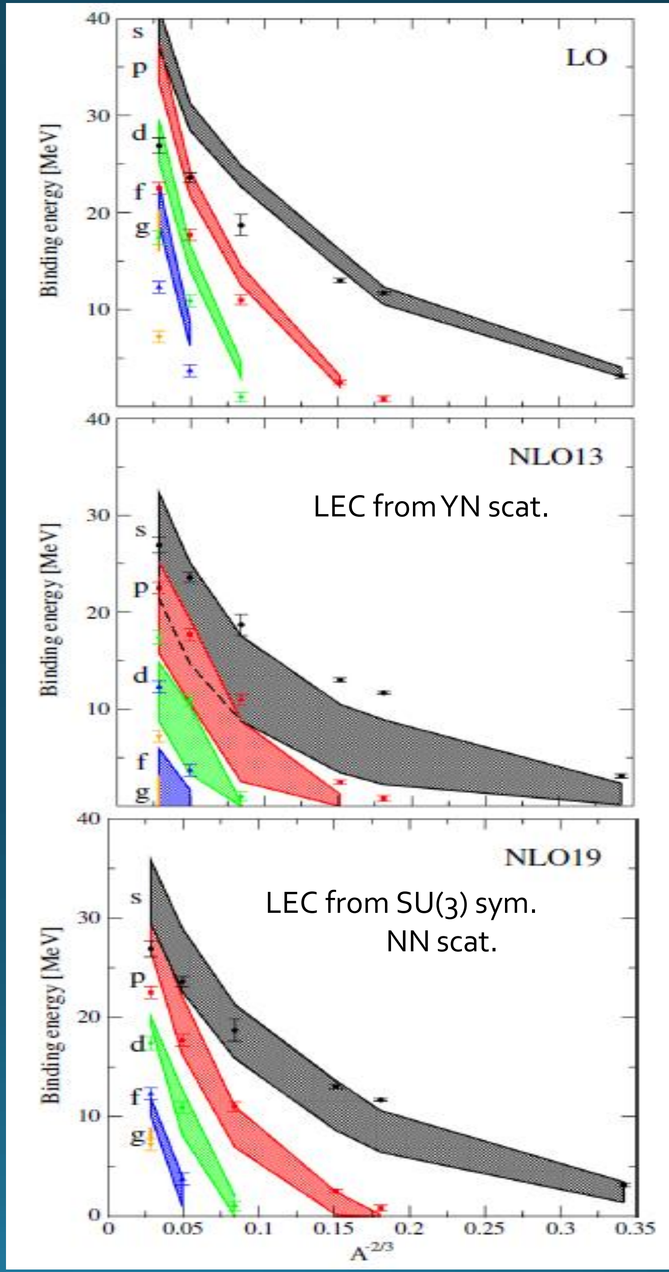
ChEFT(NLO: Saturation Decuplet)+Brueckner-Bethe-Goldstone eq.+ΛN-ΣN,ΛNN-ΣNN coupled channels

Λ Single Particle Energies of Λ Hypernuclei by Various Calculations

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

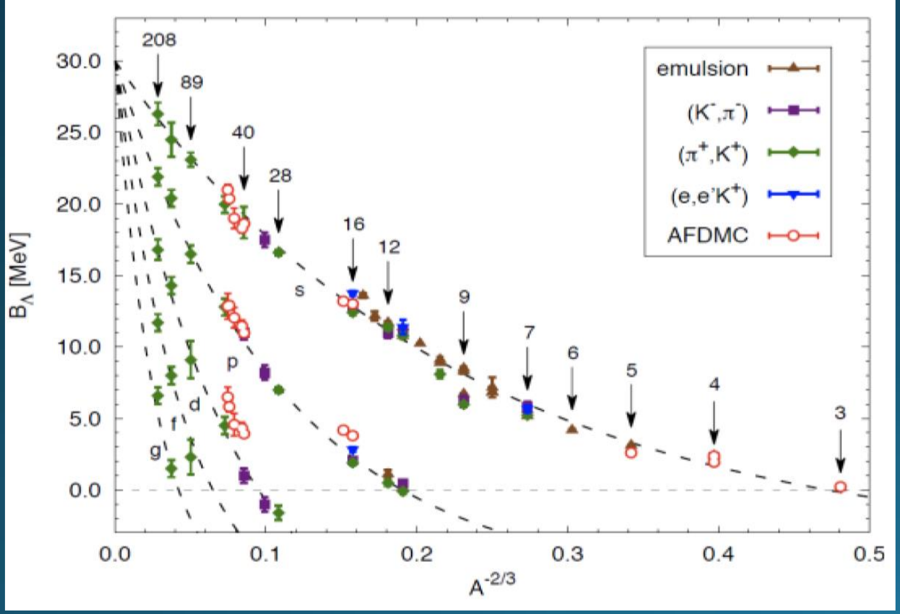


ESC16
ESC16+ (Inc. 3BF)
G-matrix



ChEFT

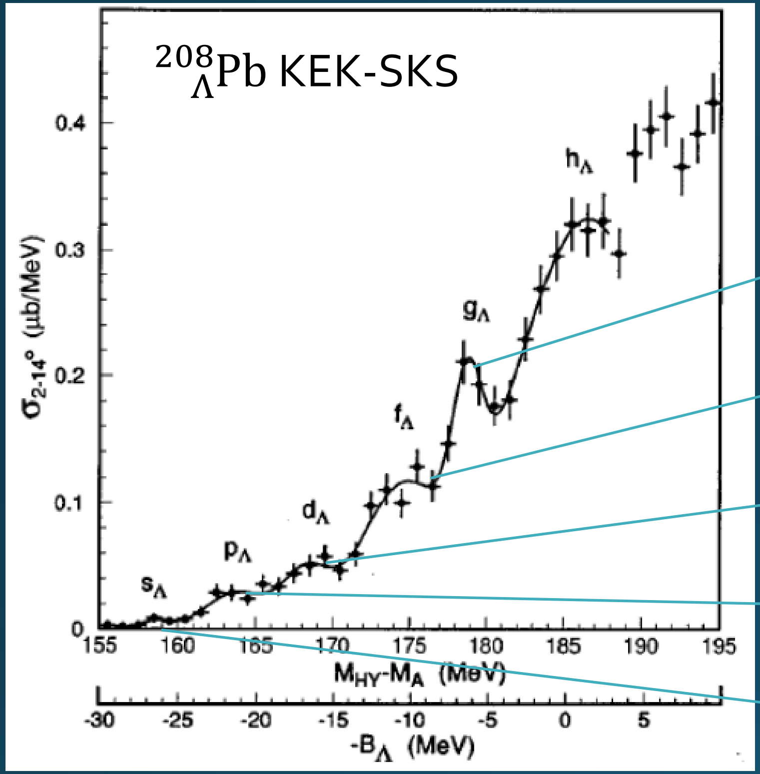
AFDMC

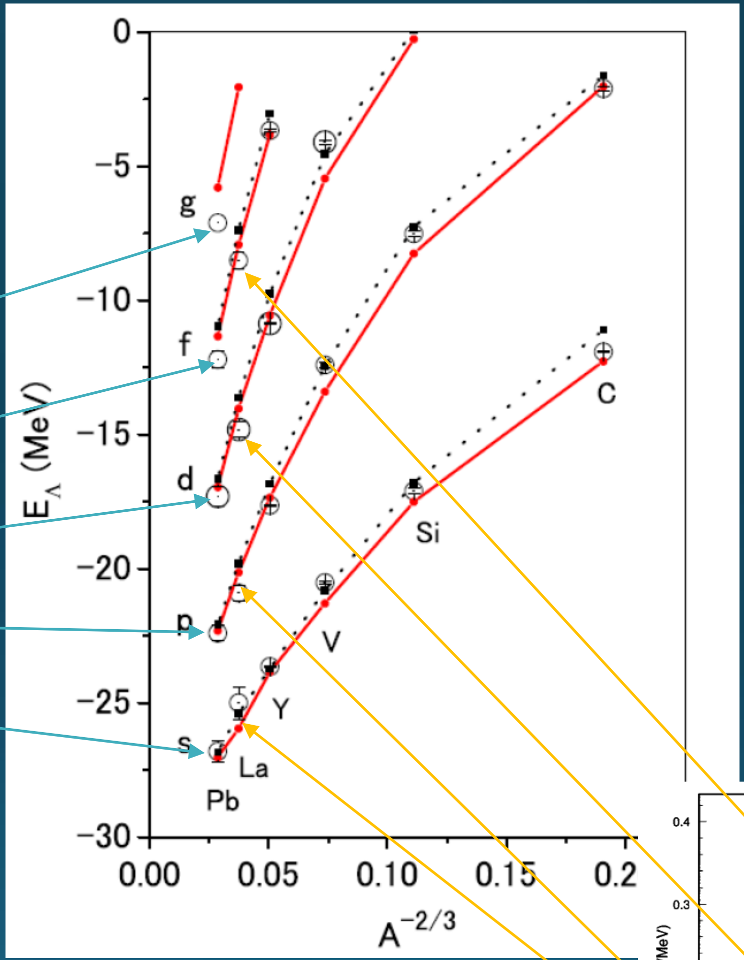


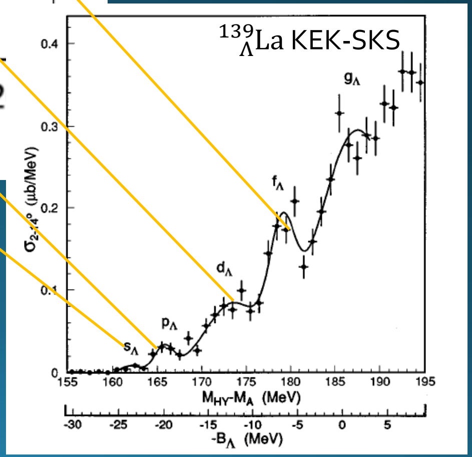
D.Lonardoni and F. Pederiva, arXiv:1711.07521.

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

Measurement of B_Λ of Λ hypernuclei

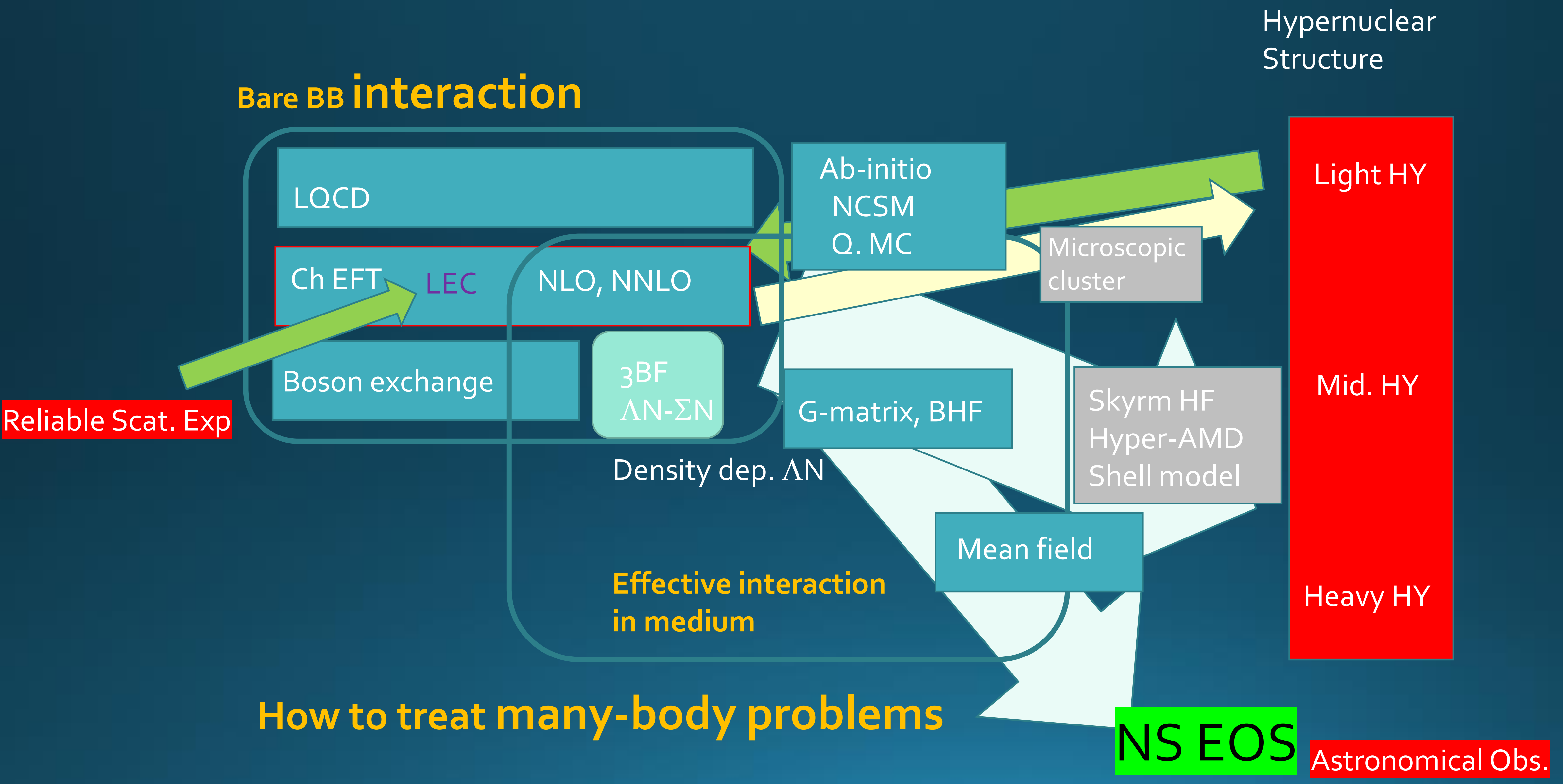




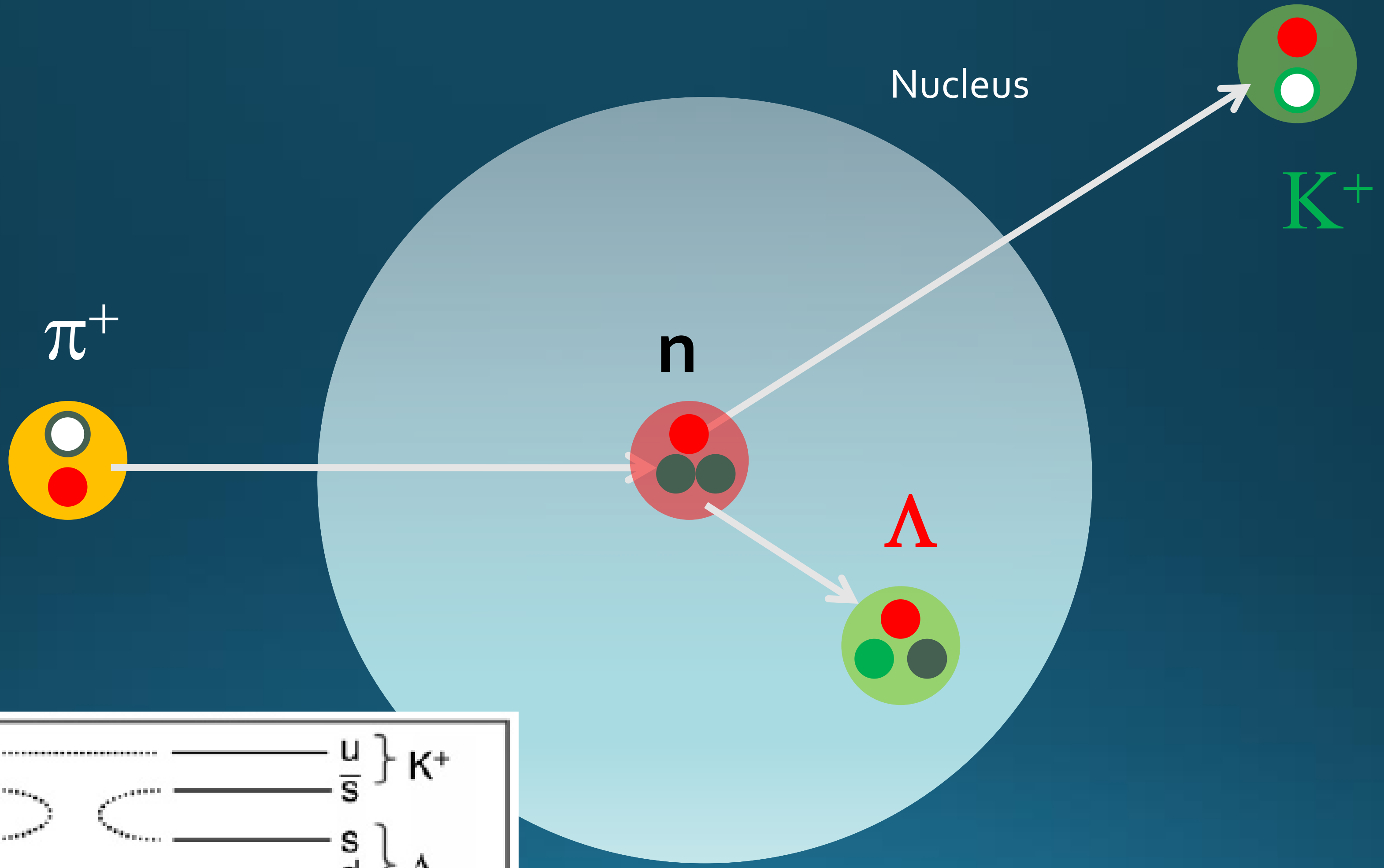


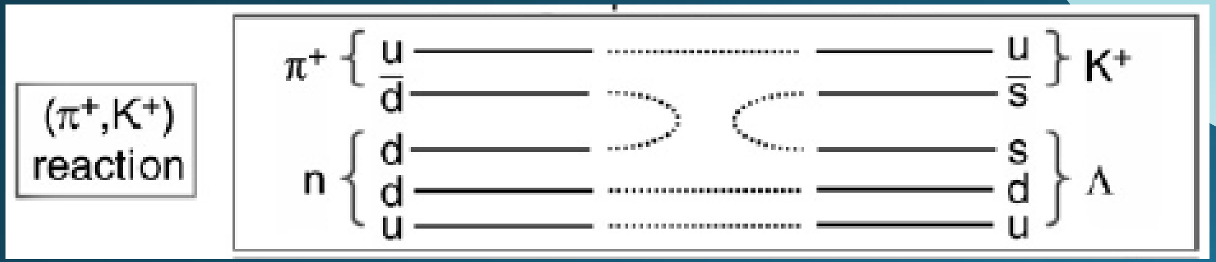
Y.Yamamoto et al., PRC 90 (2014) 045805

Understand Hypernuclei and extend to Neutron Stars



Spectroscopic study of Λ hypernuclei with the (π^+, K^+) reaction

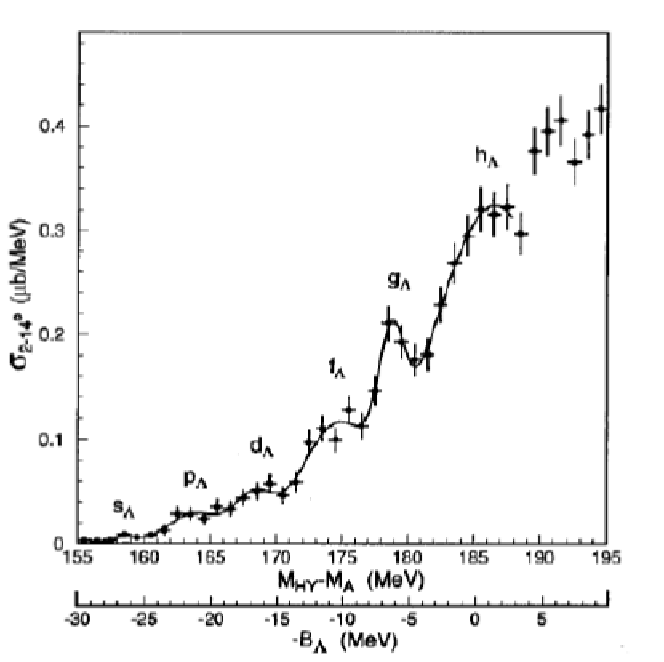




High Resolution, High Intensity (π^+,K^+) spectroscopy

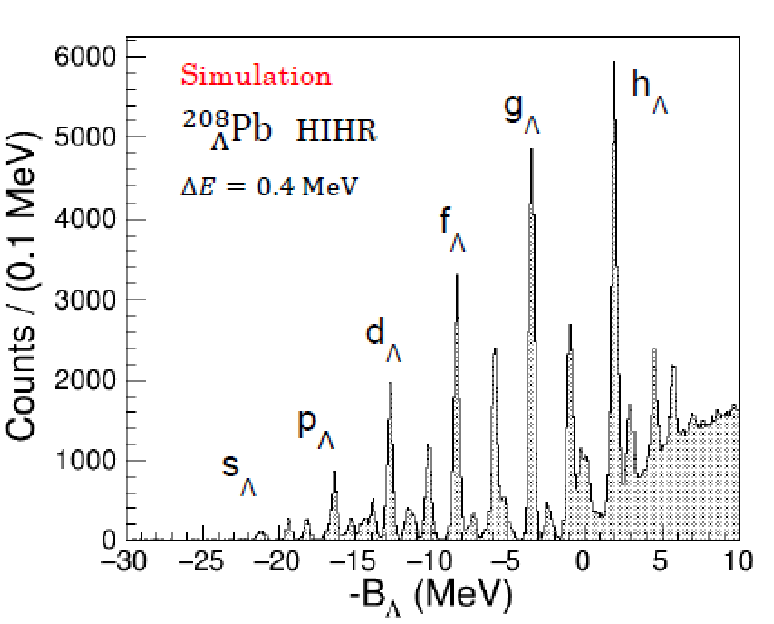
^{12}C, $^{6,7}Li$, ^{9}Be, $^{10,11}B$, ^{28}Si, ^{40}Ca, ^{51}V, ^{89}Y, ^{139}La, ^{208}Pb

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

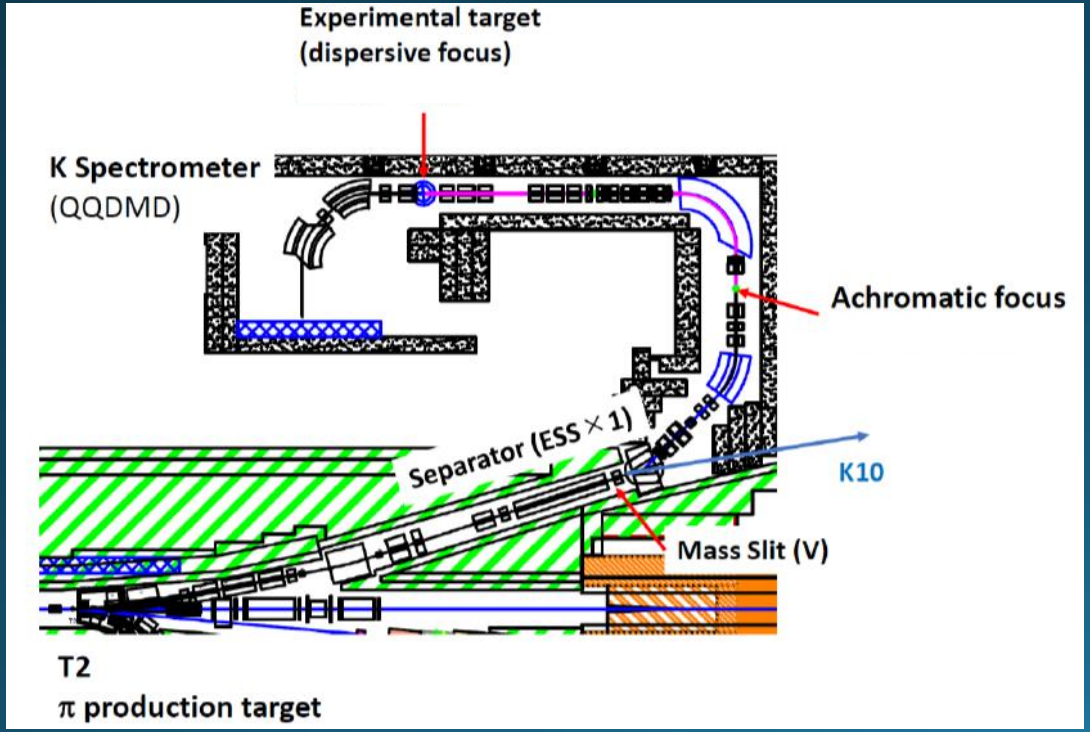
ΔE~0.4 MeV(FWHM)

HIHR

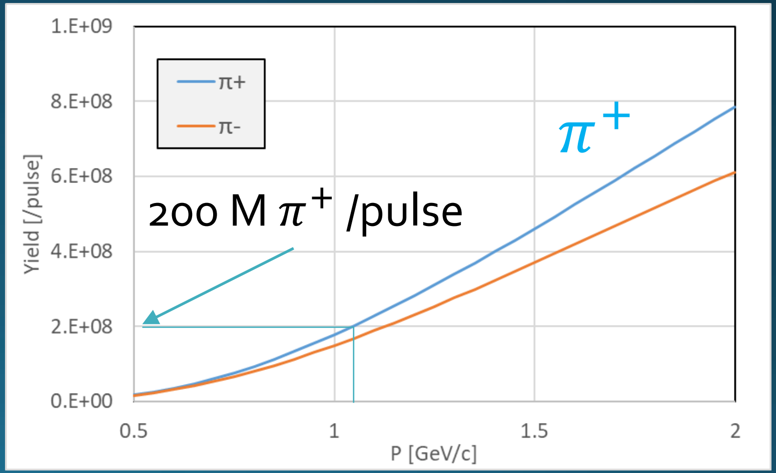
- High-Intensity High-Resolution Beamline for High Precision (π^+, K^+) Spectroscopy
  - Dispersion matching ; NO limit of beam intensity
  - Well established technique for GR, SHARAQ, but first challenge for GeV meson beams

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



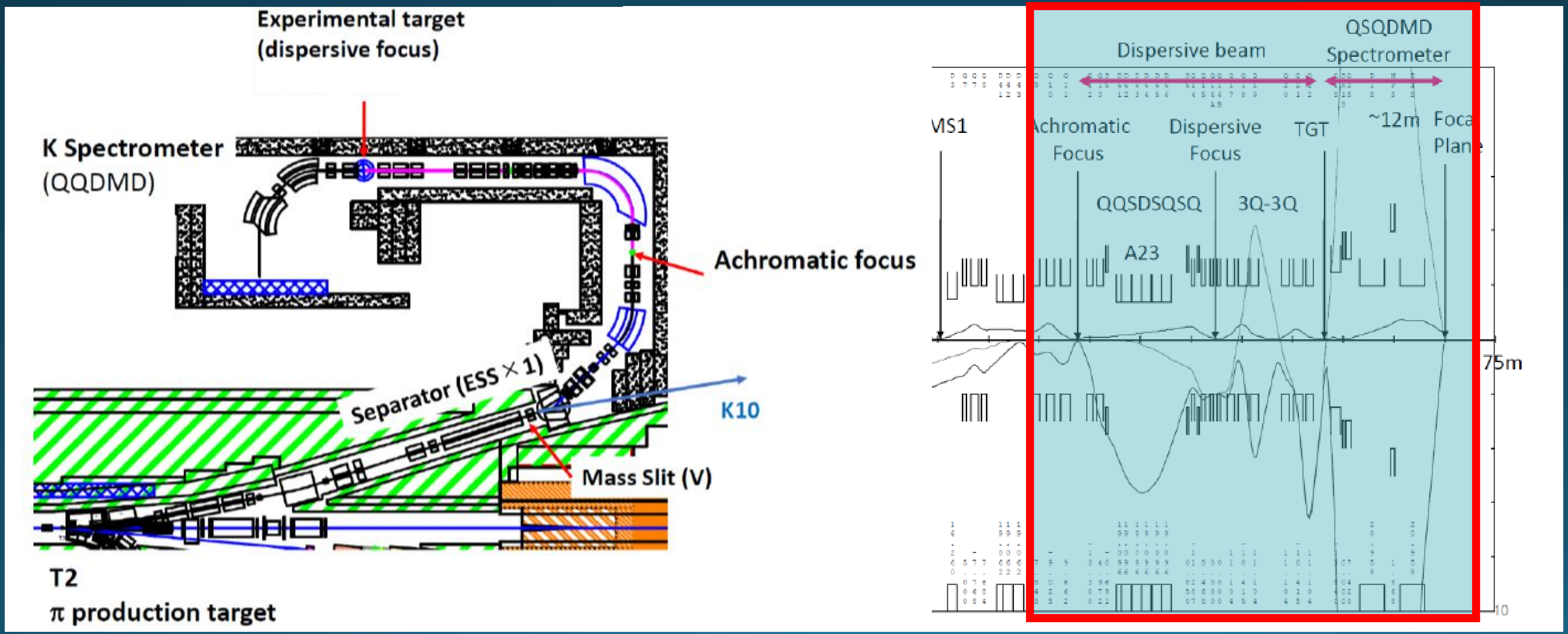
3deg. Ext. angle, 5.0×10^{13} ppp on 50% loss target
(T2) 46kW, 5.2s (92kW on T1)
1.4msr%, (Updated by T. Takahashi)

HIHR

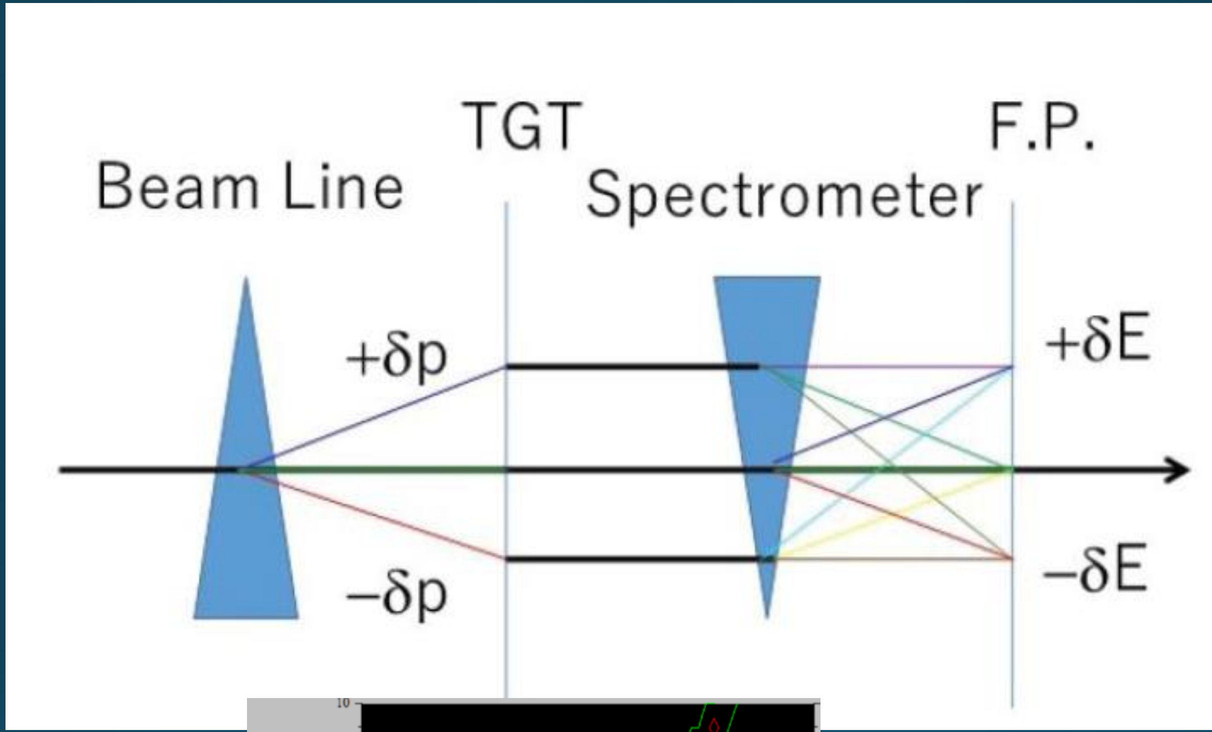
Present beamlines:
~10^6 pions/pulse,
$\Delta p/p$ ~ 1/1000

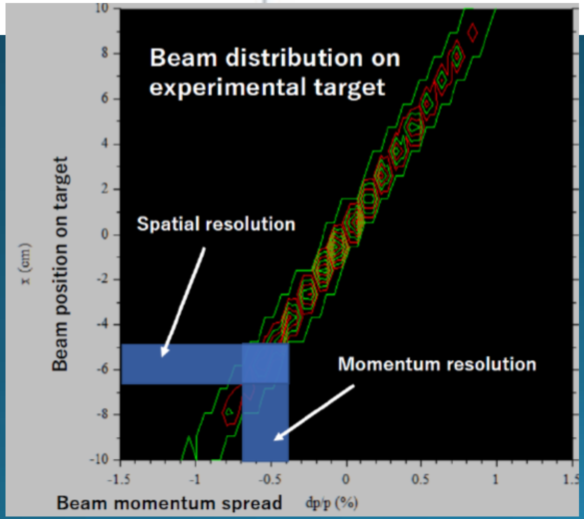
- High-Intensity High-Resolution Beamline for High Precision (π^+, K^+) Spectroscopy
  - Dispersion matching ; NO limit of beam intensity
  - Well established technique for GR, SHARAQ, but first challenge for GeV meson beams

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



Momentum dispersion match





Momentum Matching Parameters and Conditions

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

$T : TGT\ cosine,$ $Q : Excitation\ Energy,$

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

$K : (\partial p_{scat} / \partial\theta)(1/p_{scat})$ ....*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 $\rightarrow$ *minimize*,

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

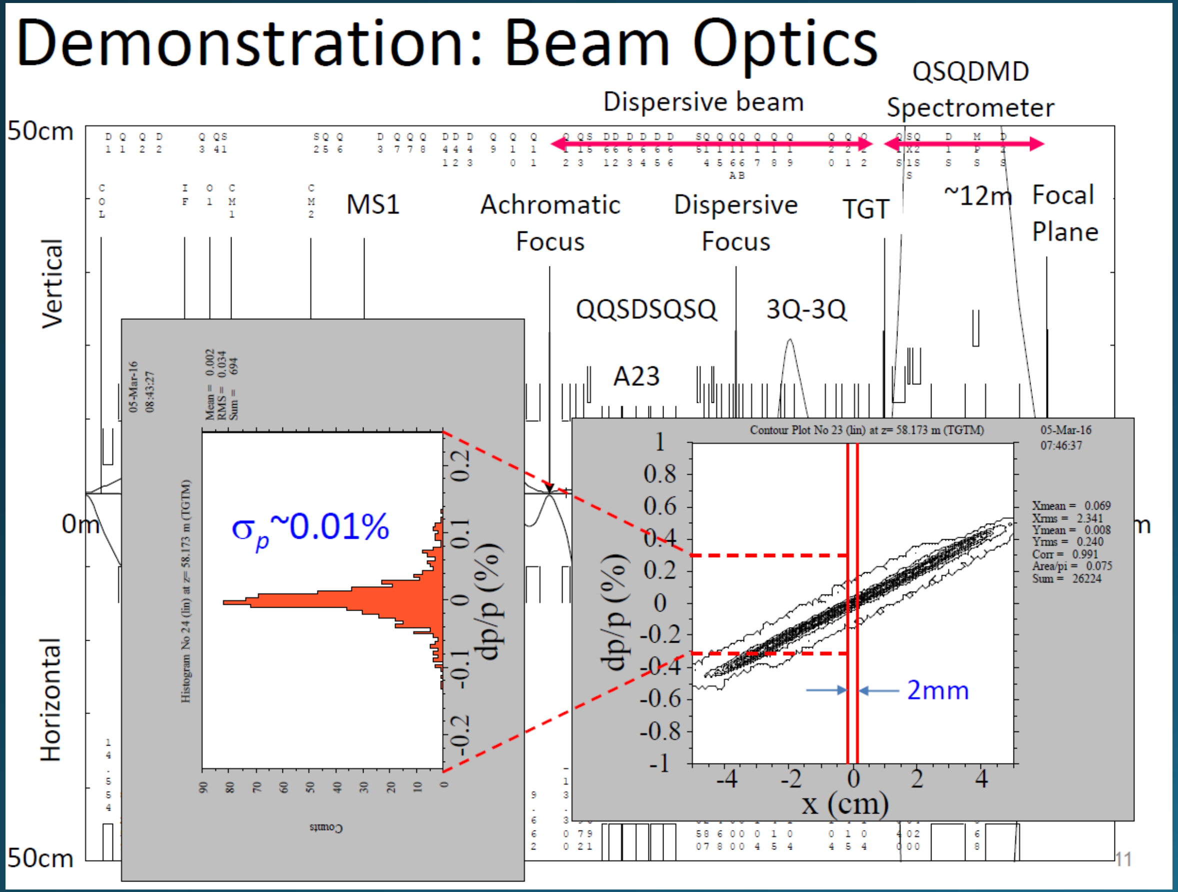
$\partial x_f / \partial\delta_0 = s_{11}{*}b_{16}{*}T + s_{12}{*}b_{26} + s_{16}{*}C$: momentum matching $\rightarrow 0$,

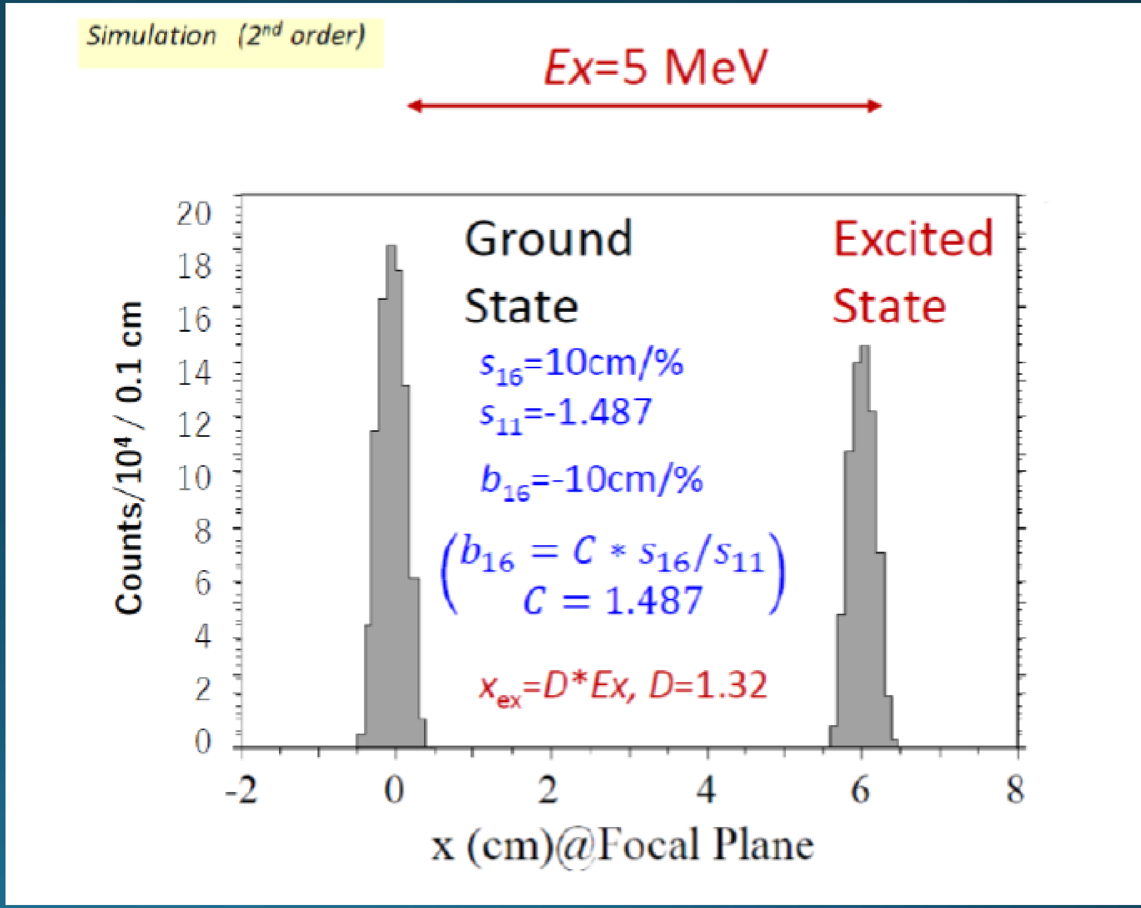
$\partial x_f / \partial\theta = s_{12} + s_{16}{*}K$: kinematical correction (finite scatt. angle) $\rightarrow 0$

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

From H.Noumi, HIHR/K1.1 Domestic WS

Resolution study (TRANSPORT)

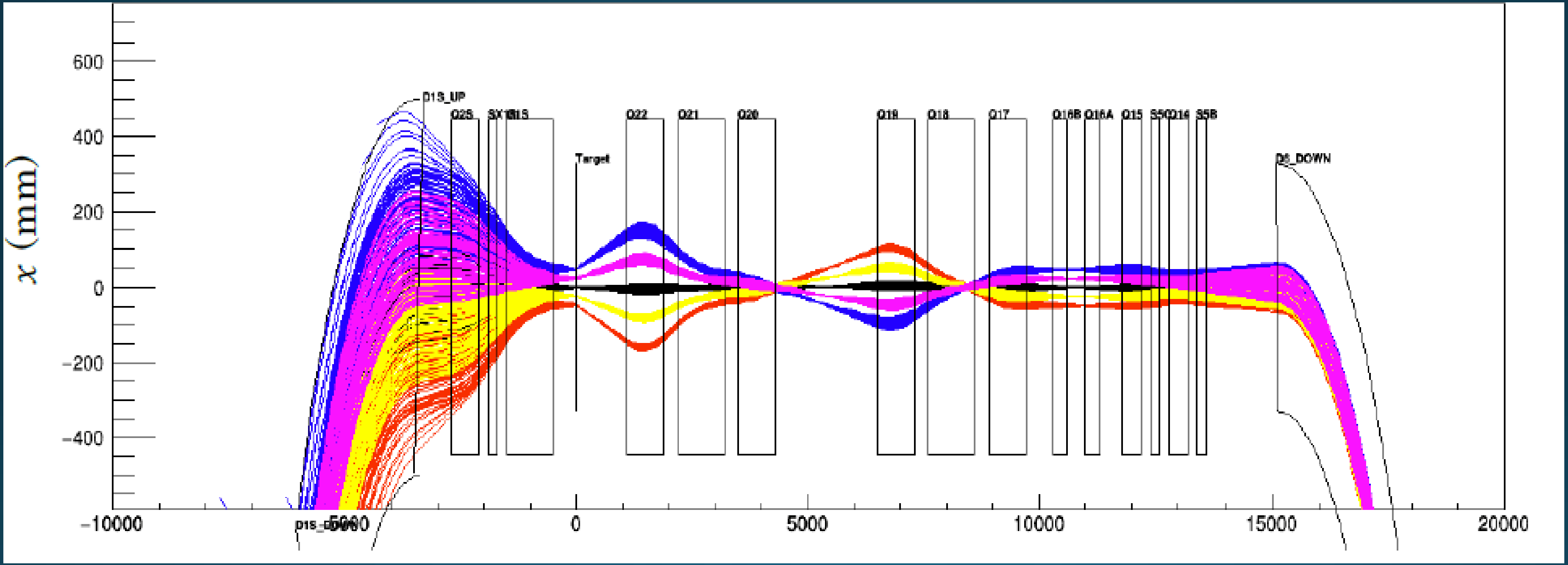




Expected Resolution based on optical design

	HIHR @J-PARC Ex. 1.1GeV/c π^+
Reaction	$^{12}\mathrm{C}(\pi^+, K^+)^{12}_{\Lambda}\mathrm{C}$
Beam Momentum Resolution	0.25 MeV/c
Scattered Particle Momentum Resolution	0.37 MeV/c
Mass Resolution (Beam Optics)	**0.32 MeV (Mom. Dis. Match)**
Straggling in Target	**0.09 MeV ($100\ mg/cm^2$)**
Total Energy Resolution	**0.33 MeV (FWHM)**

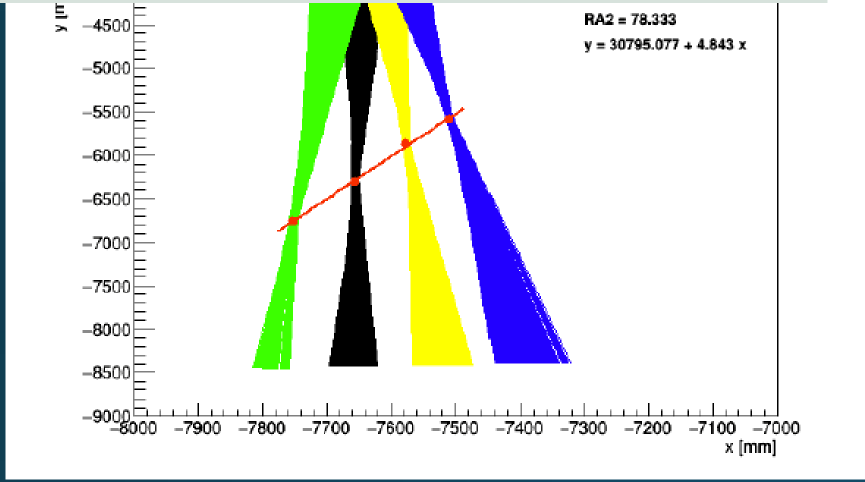
Resolution study (GEANT4)

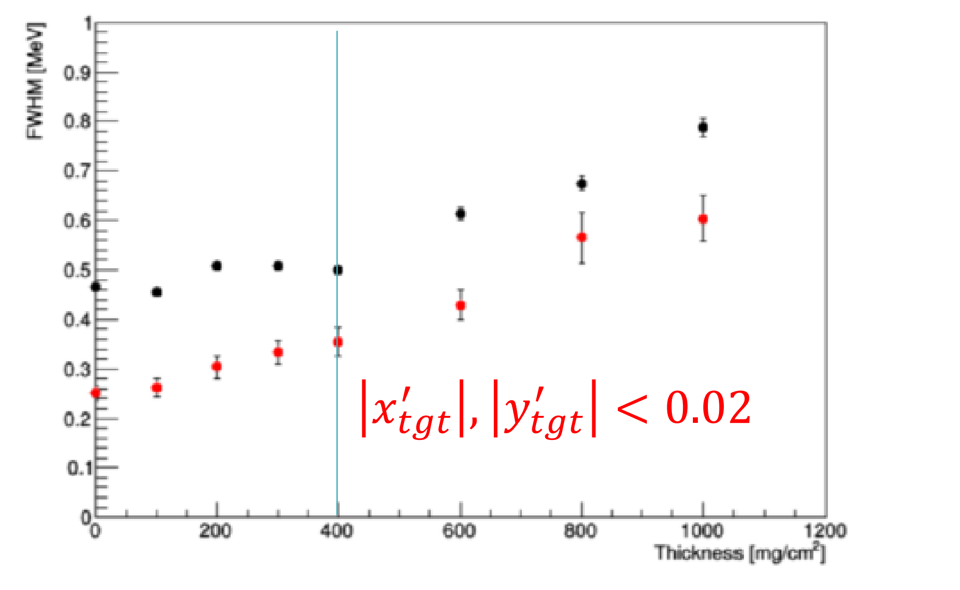


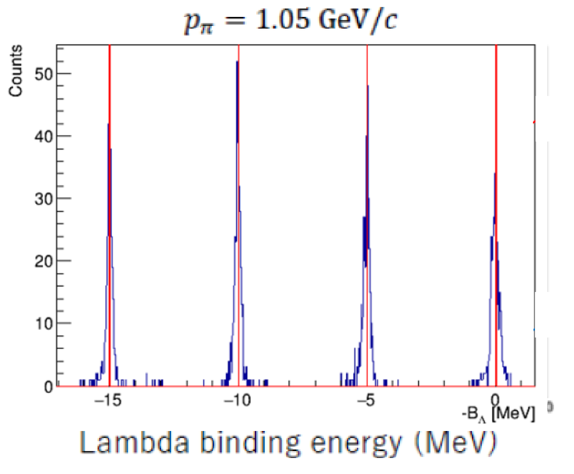
Beam momentum spread -> Position spread on target

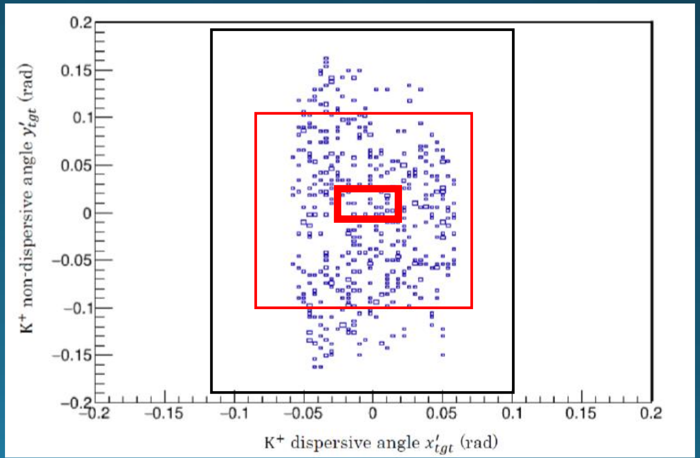
Resolution study (GEANT4)

Position corresponds to excitation energies.





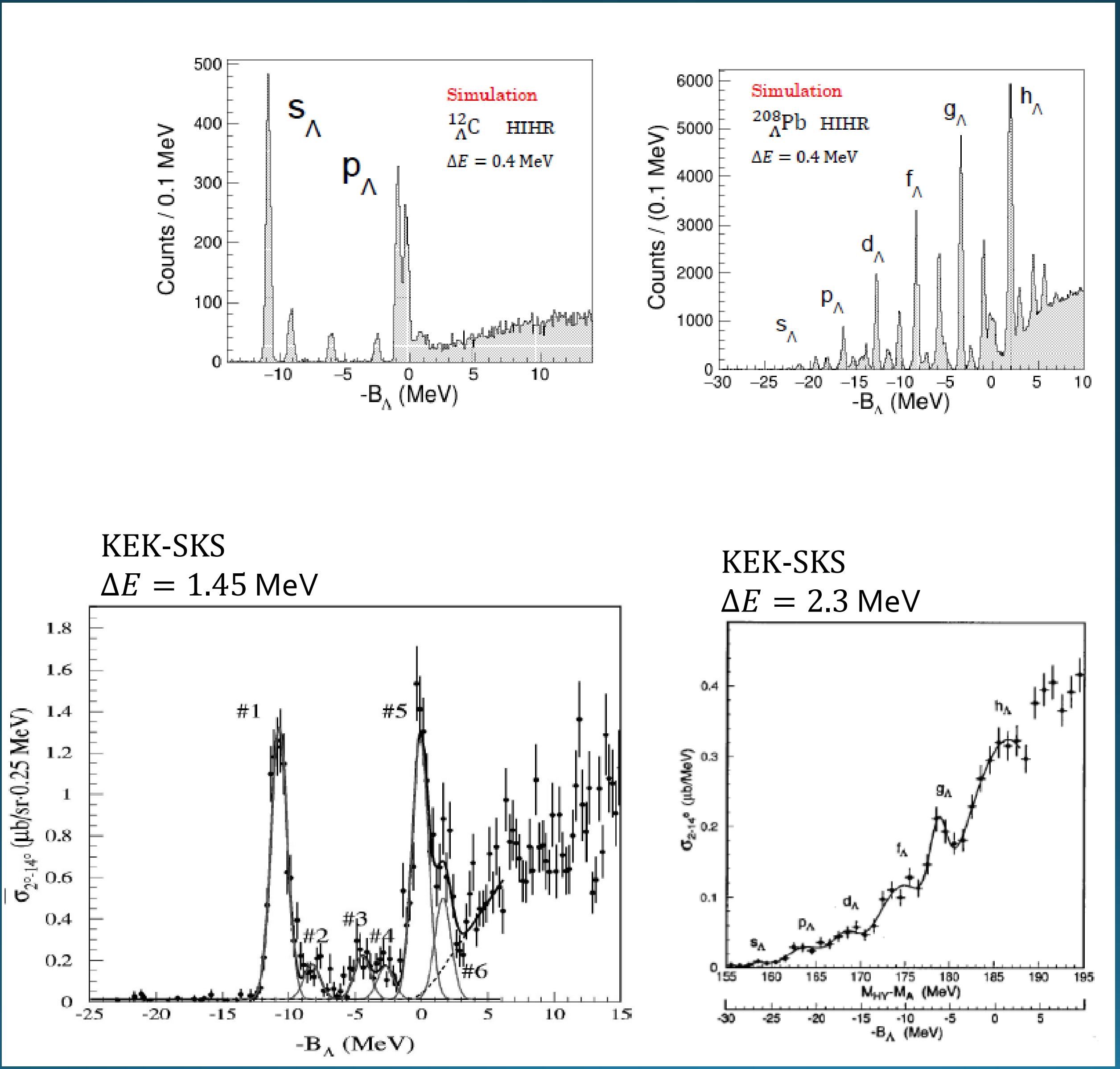




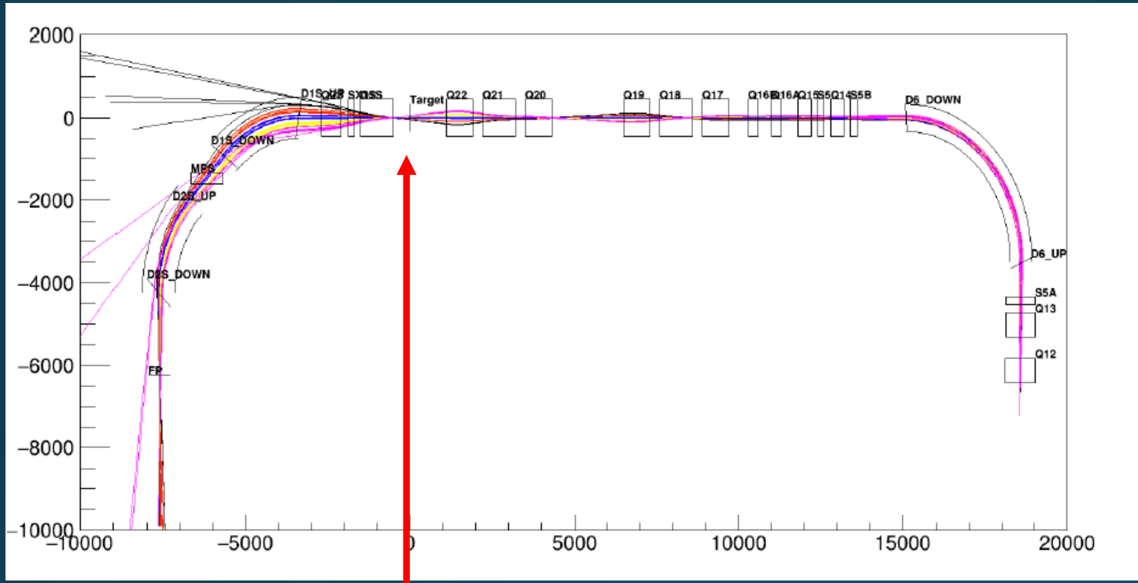
Res < 360 keV (FWHM)

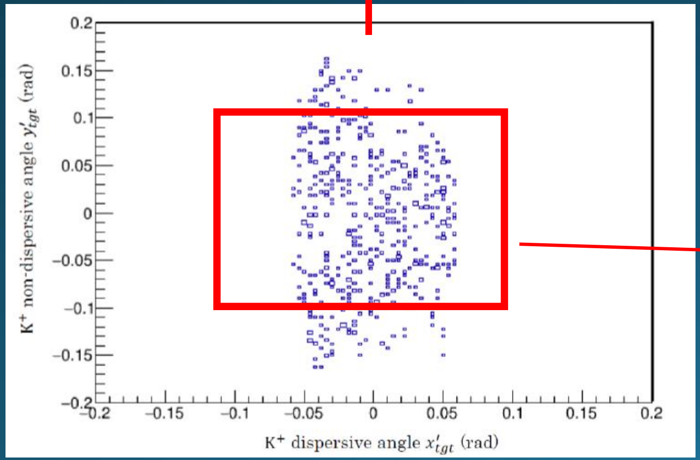
$$-B_{\Lambda}rec=\Sigma a_{ijkl}x_{FP}^{i}y_{FP}^{j}u_{FP}^{k}v_{FP}^{l}$$

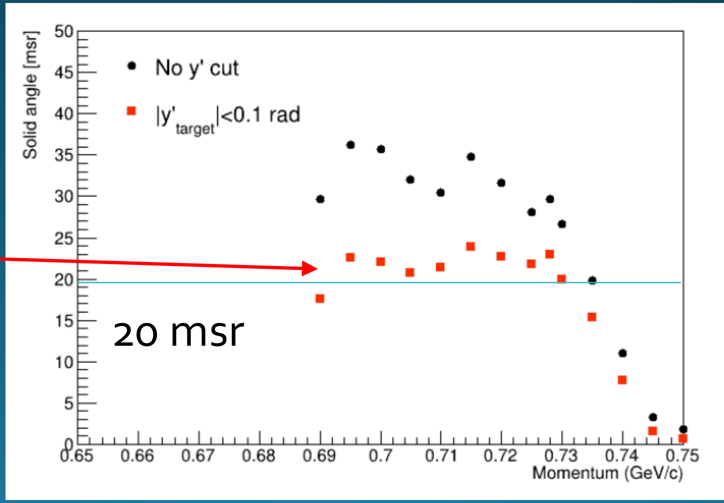
Expected spectra



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 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

Beamtime requirement

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 (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 heavy targets

104 days for total

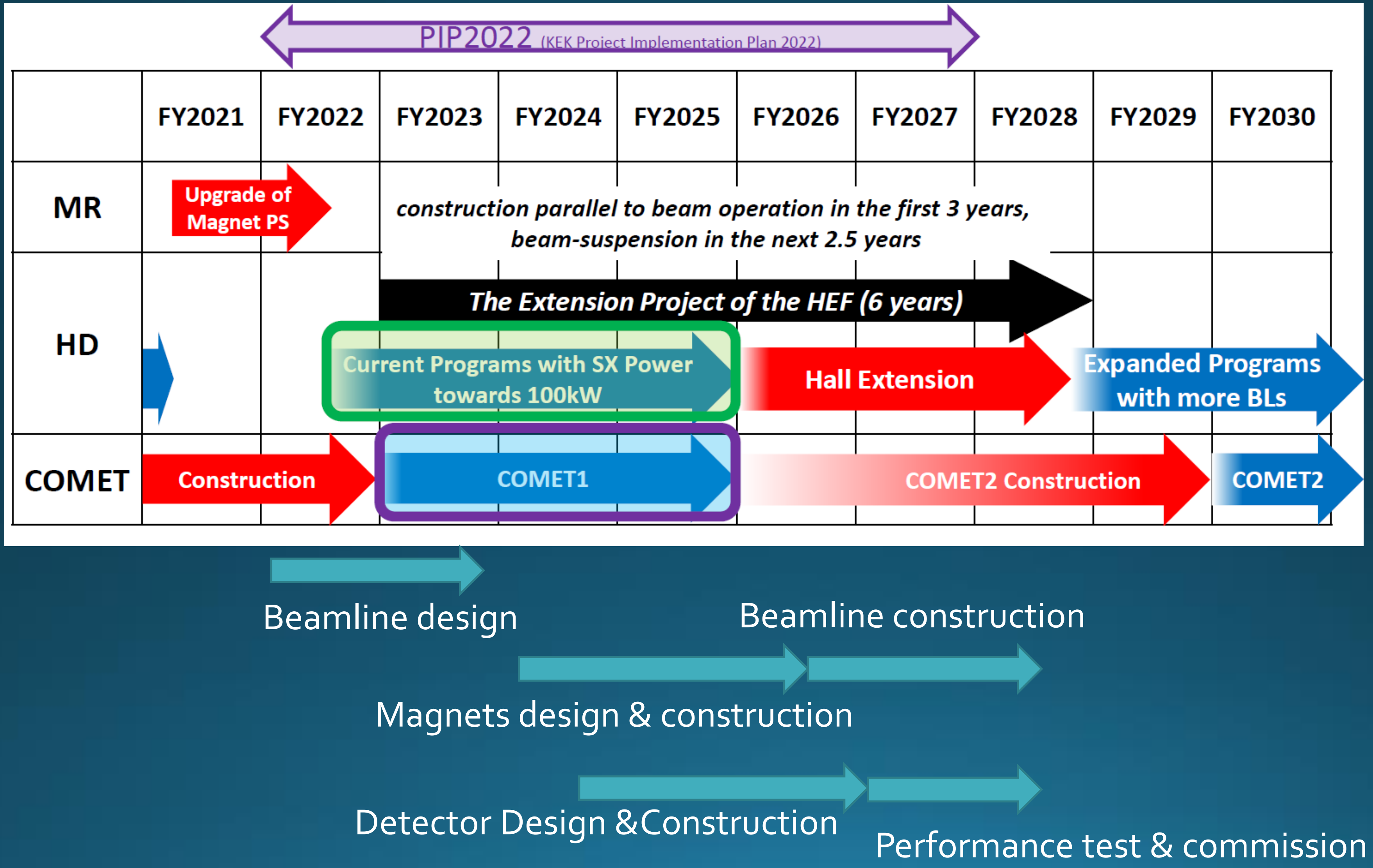
International competition for High-resolution (π^+, K^+) spectroscopy at HIHR

Jefferson Lab and Mainz are possible competitors.

Highly competitive but simultaneously complementary

	HIHR	JLab	Mainz
Reaction	(π^+, K^+)	$(e, e'K^+)$	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	△ ${}^{12}_{\Lambda}\mathrm{C}$ $p(\pi^-, K^+)\Sigma^-$ Decay π	◎ $p(e, e'K^+)\Lambda, \Sigma^0$	○ Elastic *e* scattering

Schedule


PIP2022 (KEK Project Implementation Plan 2022)
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
FY2029
FY2030
MR
Upgrade of Magnet PS
construction parallel to beam operation in the first 3 years, beam-suspension in the next 2.5 years
HD
The Extension Project of the HEF (6 years)
Current Programs with SX Power towards 100kW
Hall Extension
Expanded Programs with more BLs
COMET
Construction
COMET1
COMET2 Construction
COMET2
Beamline design
Beamline construction
Magnets design & construction
Detector Design &Construction
Performance test & commission

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)
- Beamtime request
  - 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.