Recent Developments in Quark-Hadron Sciences,
11-15 June, 2018

YKIS2018

STRANGENESS NUCLEAR PHYSICS IN J-PARC EXPERIMENTS

Tomofumi NAGAE,

Kyoto University

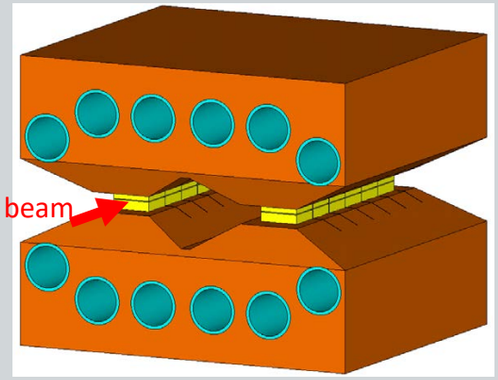
YKIS2018

CONTENTS

STATUS IN NUCLEAR PHYSICS

YKIS2018

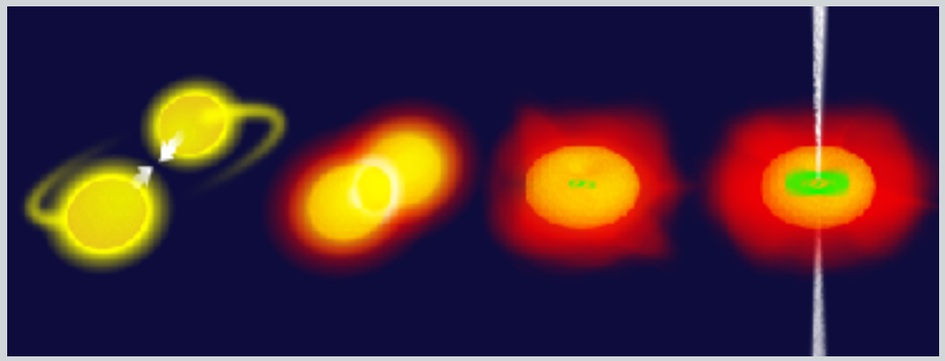
- Beam Power : reached at 50 kW,
  many thanks to the Accelerator people.



- Next target: waiting for a 90-kW target;
  - Essential for E70 (Ξ Hyp.), E03 (Ξ atom X), E57 (KdX),
    E42(H), … *High-Intensity Kaon Era !!*
- Role of Strangeness in High-density matter
- GW170817: Binary NS merger ! (finally)

> a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

B.P. About et al., DOI: 10.1103/PhysRevLett.119.161101



R_{BNS}=1540+3200/-1220 $Gpc^{-3}yr^{-1}$

6-120 BNS mergers/yr

Rather high rate !

HIGH DENSITY HADRONIC MATTER

Core of Neutron Star (NS)

||

Test ground of High Density Matter

Nuclear Many-Body Theory

Hypernuclear Data

ΔE=1 MeV

YN Scattering Data

Limited statistics

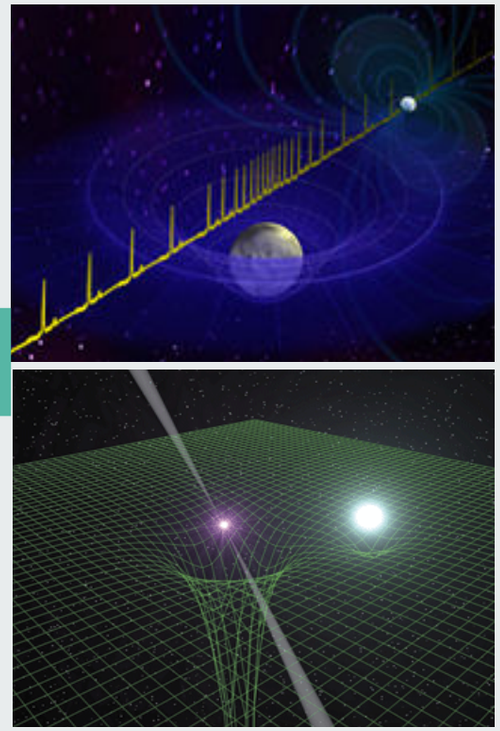
Hyperon Puzzle !

$M_{max}<1.5M_\odot$? $M_{max}>2M_\odot$

Hyperons should appear !

Astronomical Observation challenges the Standard Nuclear Physics.

Observation of $2M_\odot$ NS



Nature 467 (2010) 1081-83.
Science 340 (2013) 6131.

S=-1 SYSTEMS

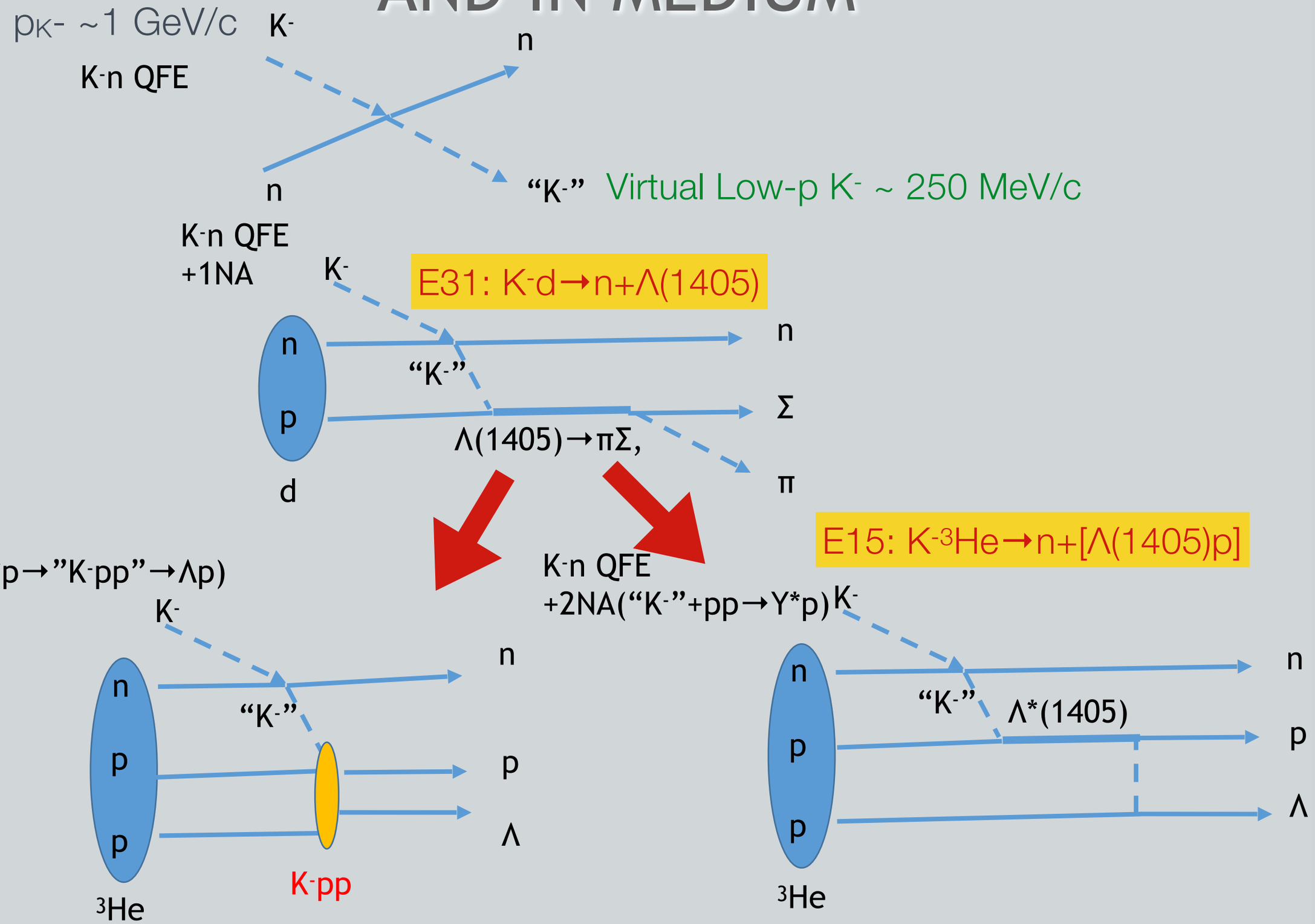
Λ(1405) and Kaonic Nuclei,

Λ-Hypernuclear γ-rays,

Σp Scattering

E15+E31:Λ(1405) IN VACUUM AND IN MEDIUM

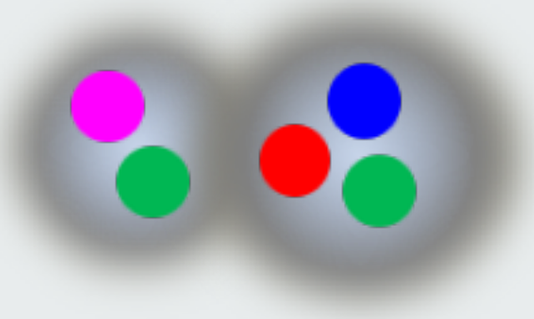
YKIS2018

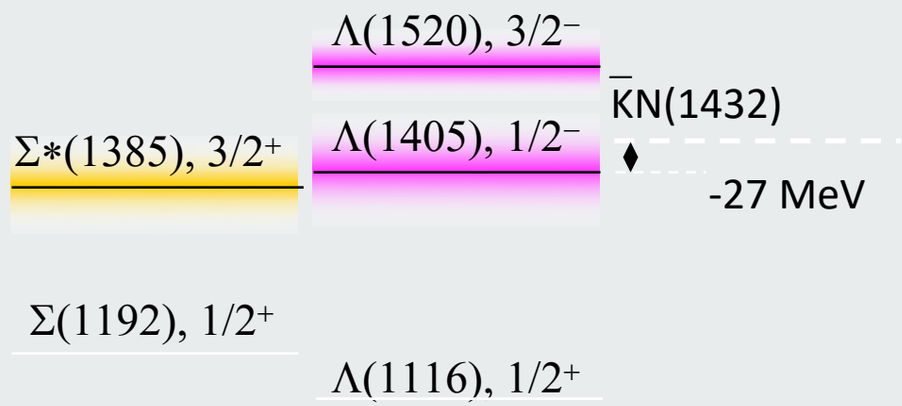


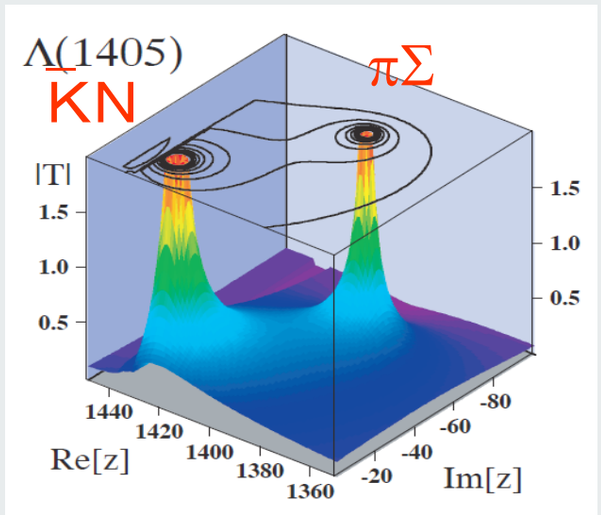
E31: STRUCTURE OF Λ(1405), QQQ BARYON OR K^{BAR}N MOLECULE ?

Λ(1405) : Double pole ?

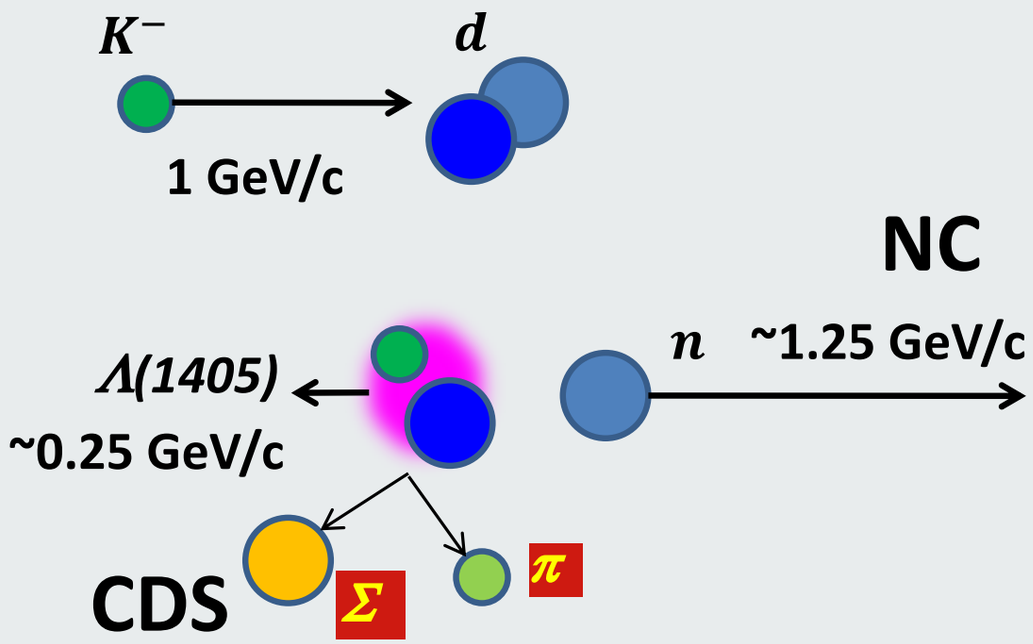
- *$\Sigma\pi$ mass spectrum below $M_{\bar{K}N}$ reveals its structure.*





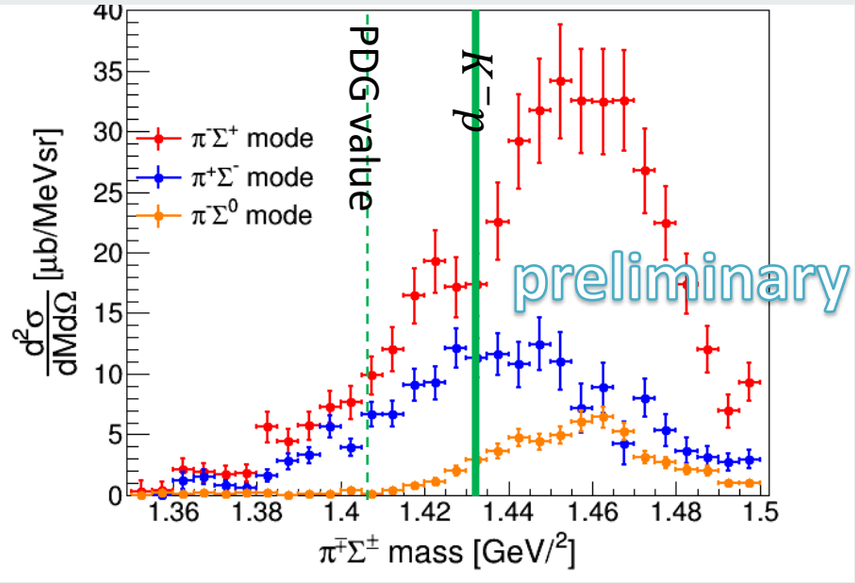


ChU model, T. Hyodo

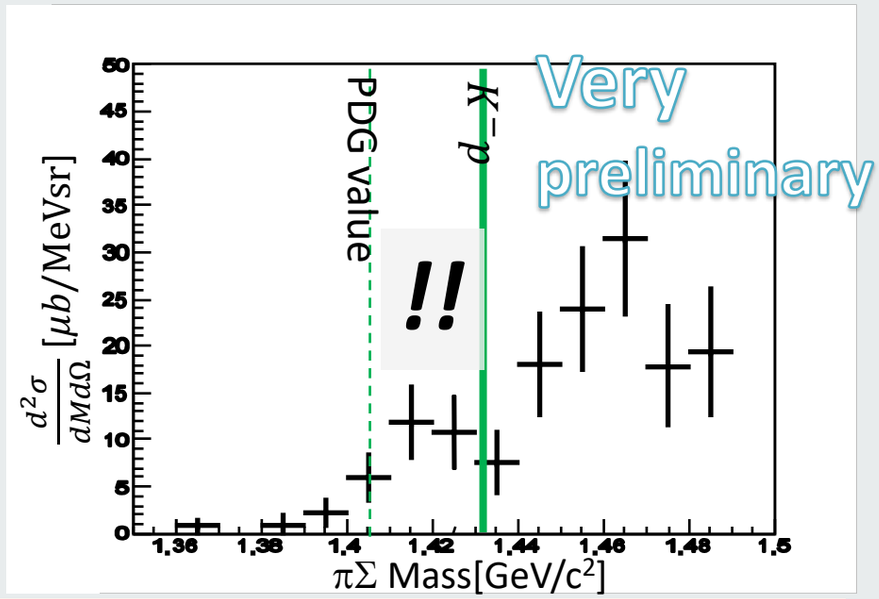


E31 1st Run Results

$\pi^+\Sigma^-/\pi^-\Sigma^+$ Mode ($I = 0, 1$)



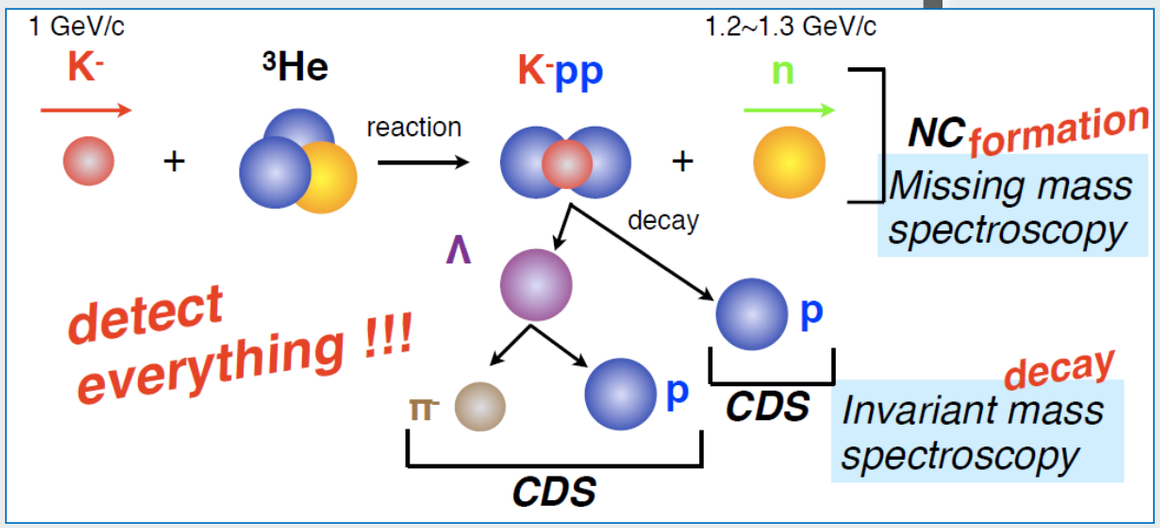
$\pi^0\Sigma^0$ Mode ($I = 0$)



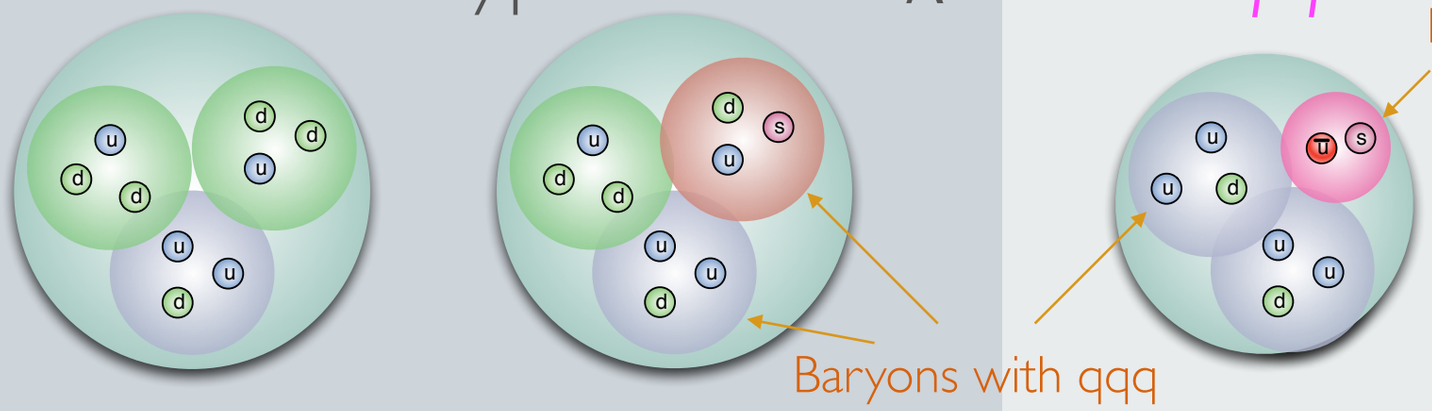
2nd Run finished with 3 times more statistics.

E15: $K^- + {}^3He \rightarrow n + \Lambda p$

- Kaonic Nuclei



Triton ^3H Hyper-Triton $^3_\Lambda H$ K^-pp



Nuclei (p+n+n)

Baryon with two quark flavors

Hyper Nuclei (p+n+Λ)

Baryon with three quark flavors

Kaonic Nuclei (p+p+K)

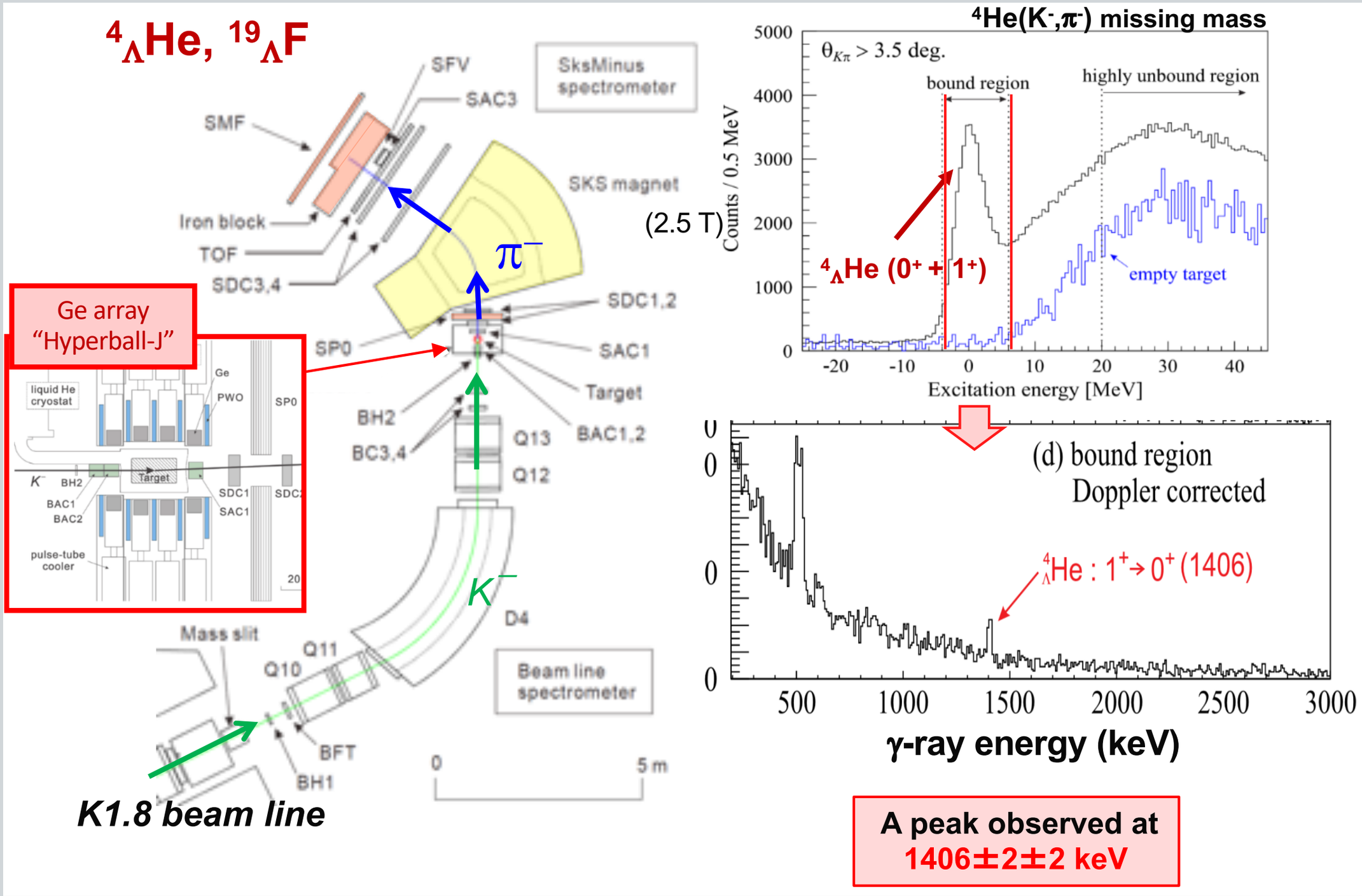
Total Binding Energy：

8.48 MeV 2.33 MeV 40~100 MeV

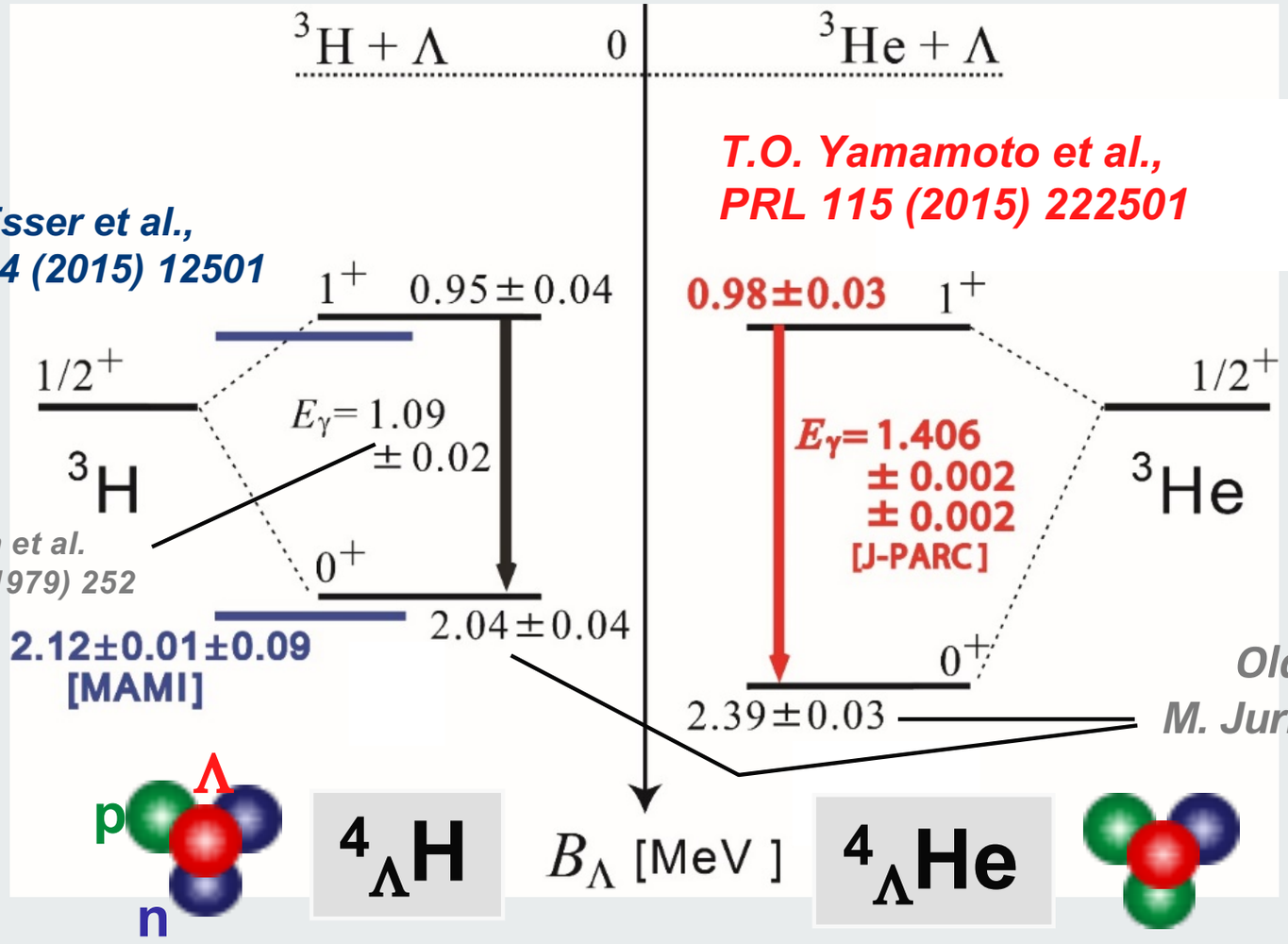
E13:γ-ray spectroscopy

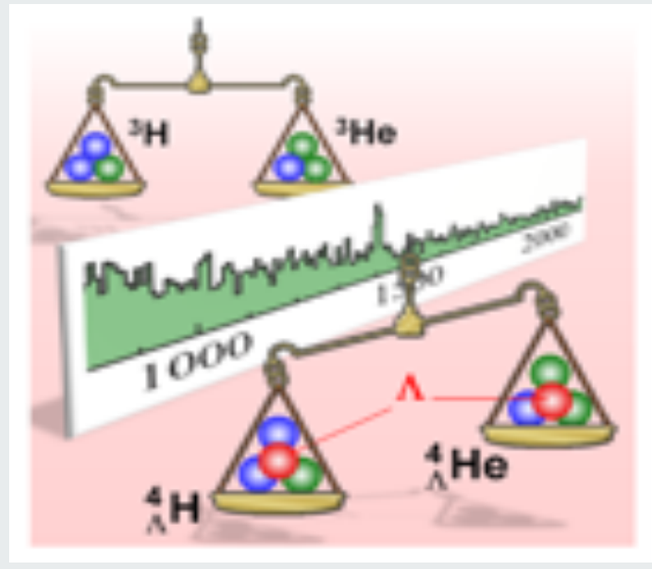
YKIS2018

T.O. Yamamoto et al., Phys. Rev. Lett. 115 (2015) 222501.



CSB (Charge Symmetry Breaking) in A=4 hypernuclei





A <u>large</u> CSB effect in ΛN force (pΛ ≠ nΛ) confirmed.
<u>Spin dependence</u> in CSB effect

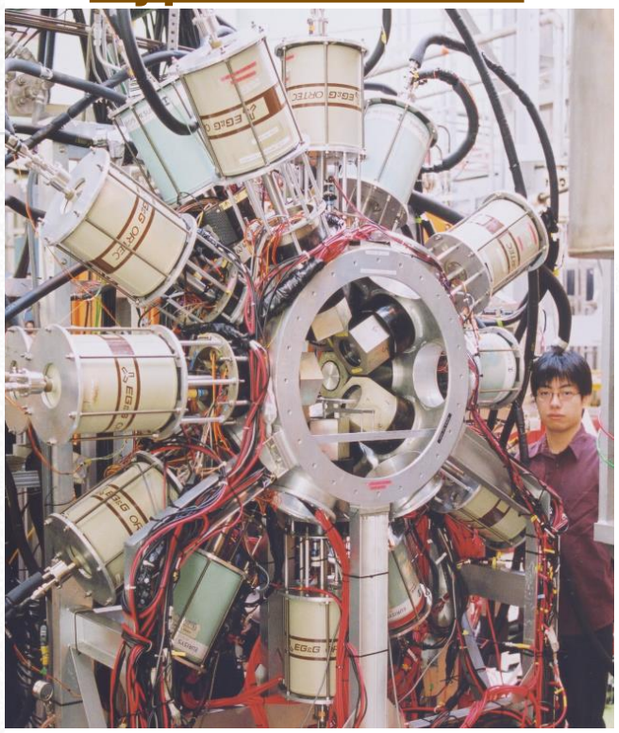
cf. B(^{3}H) - B(^{3}He) – EM effect ~70 keV

All the previous theoretical works failed to understand it.
Recent suggestion: Σ–Λ coupling is a key to solve the puzzle.

A. Gal, PLB 744 (2015) 352, D. Gazda and A. Gal, PRL 116 (2016) 122501

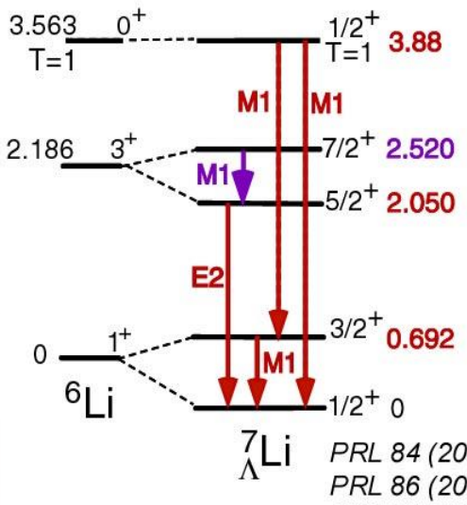
Hypernuclear Gamma-rays

Hyperball 1998~



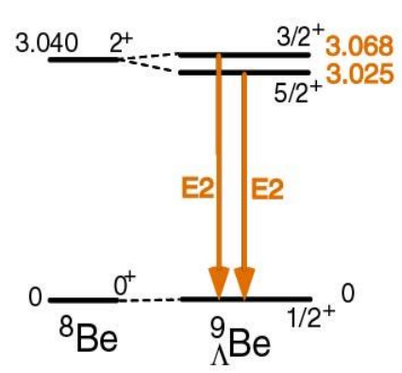
Hypernuclear γ-ray data (2012)

^{7}Li (π^+,$K^+\gamma$) KEK E419



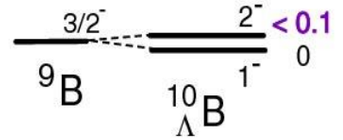
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

^{9}Be (K^-,$\pi^-\gamma$) BNL E930('98)



PRL 88 (2002) 082501
NPA 754 (2005) 58c

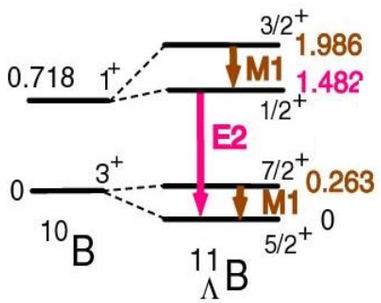
^{10}B (K^-,$\pi^-\gamma$) BNL E930('01)



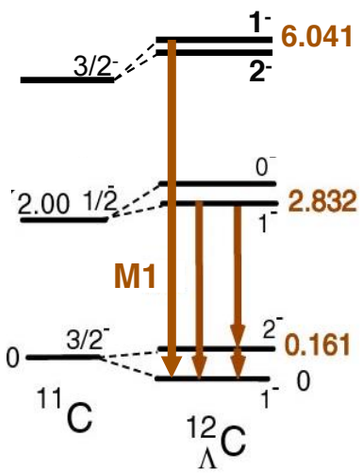
NPA 754 (2005) 58c

^{12}C (π^+,$K^+\gamma$) KEK E566

^{11}B (π^+,$K^+\gamma$) KEK E518

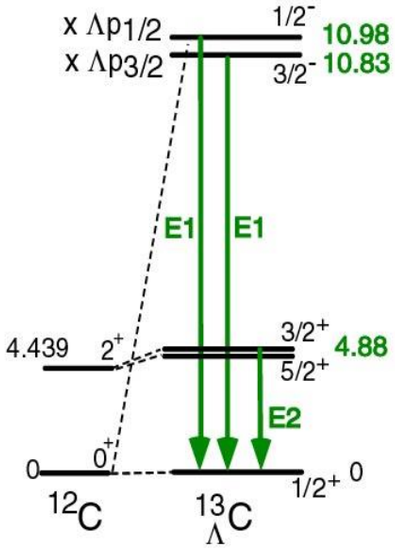


NPA 754 (2005) 58c



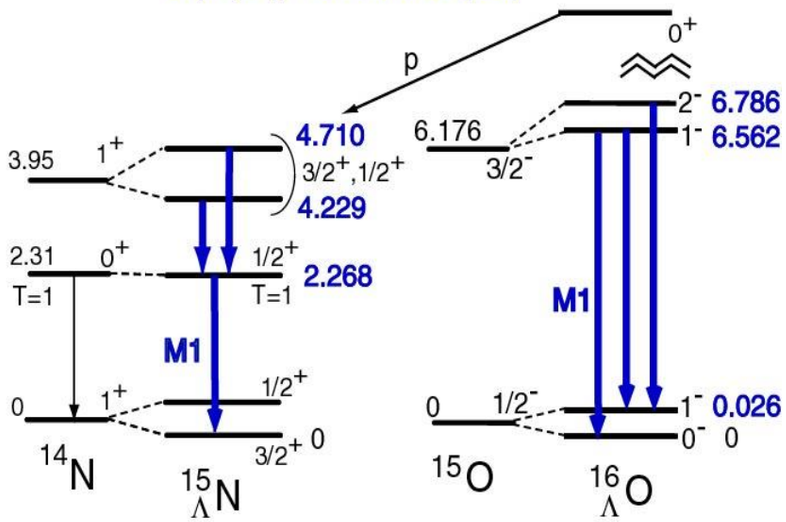
EPJ A33 (2007) 243
NPA835 (2010) 422

^{13}C (K^-,$\pi^-\gamma$) BNL E929 (NaI)



PRL 86 (2001) 4255
PRC 65 (2002) 034607

^{16}O (K^-,$\pi^-\gamma$) BNL E930('01)



PRC 77 (2008) 054315

PRL 93 (2004) 232501
EPJ A33 (2007) 247

by H. Tamura

ΛN Effective Interaction

$$V_{\Lambda N}^{eff} = V_0(r) + V_\sigma(r)\vec{s_\Lambda}\vec{s_N} + V_\Lambda(r)\vec{\ell}_{\Lambda N}\vec{s_\Lambda} + V_N(r)\vec{\ell}_{\Lambda N}\vec{s_N} + V_T(r)S_{12}$$

Δ S_Λ S_N T

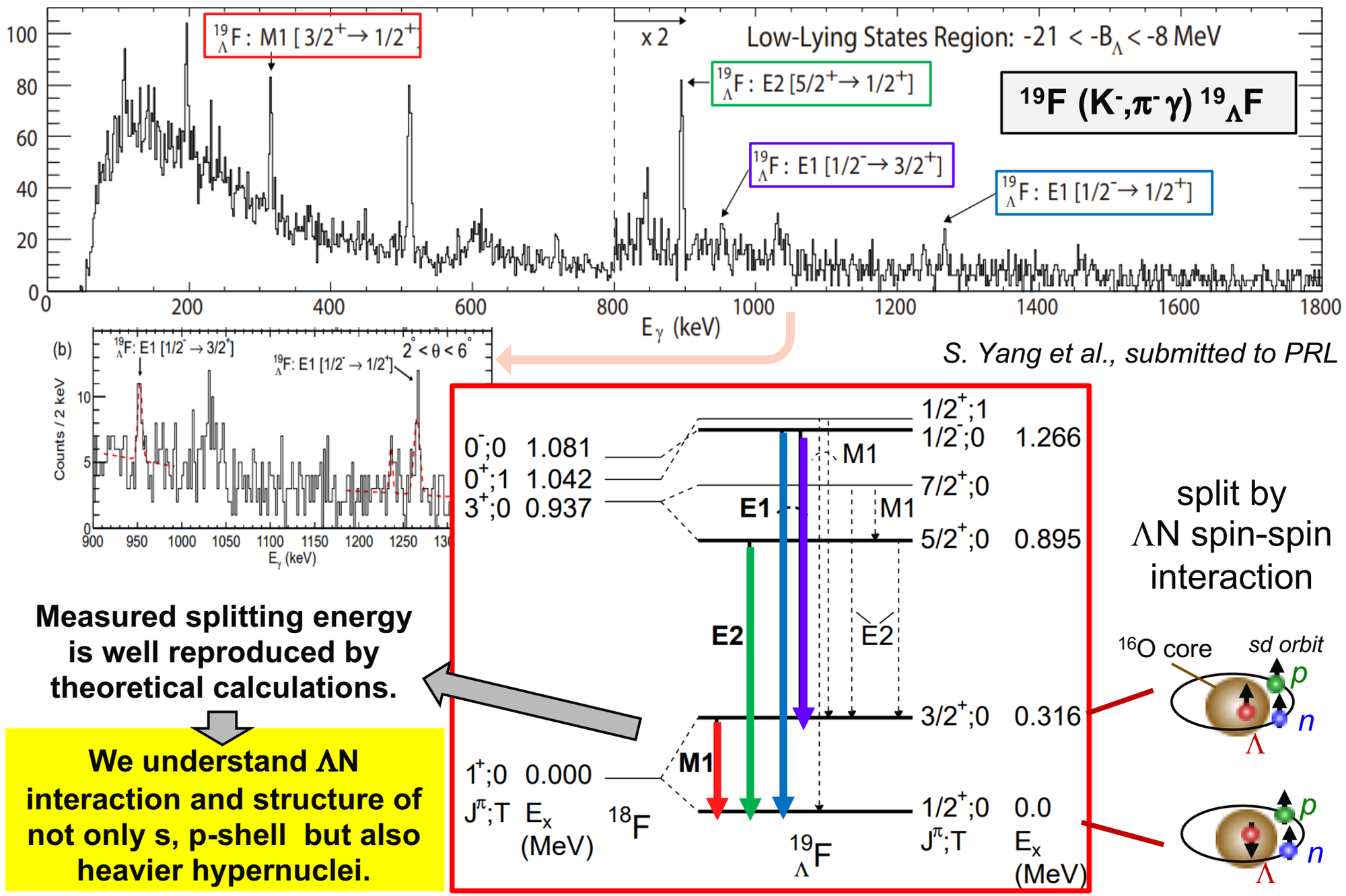
Parameters in MeV

	Δ	S_Λ	S_N	T
$A = 7-$?	0.430	−0.015	−0.390	0.030
$A = 11 - 16$	0.330	−0.015	−0.350	0.024

Very small LS

$^{19}_{\Lambda}$F:First *sd*-shell hypernuclei

S.B. Yang et al., Phys. Rev. Left. 120 (2018) 132505.



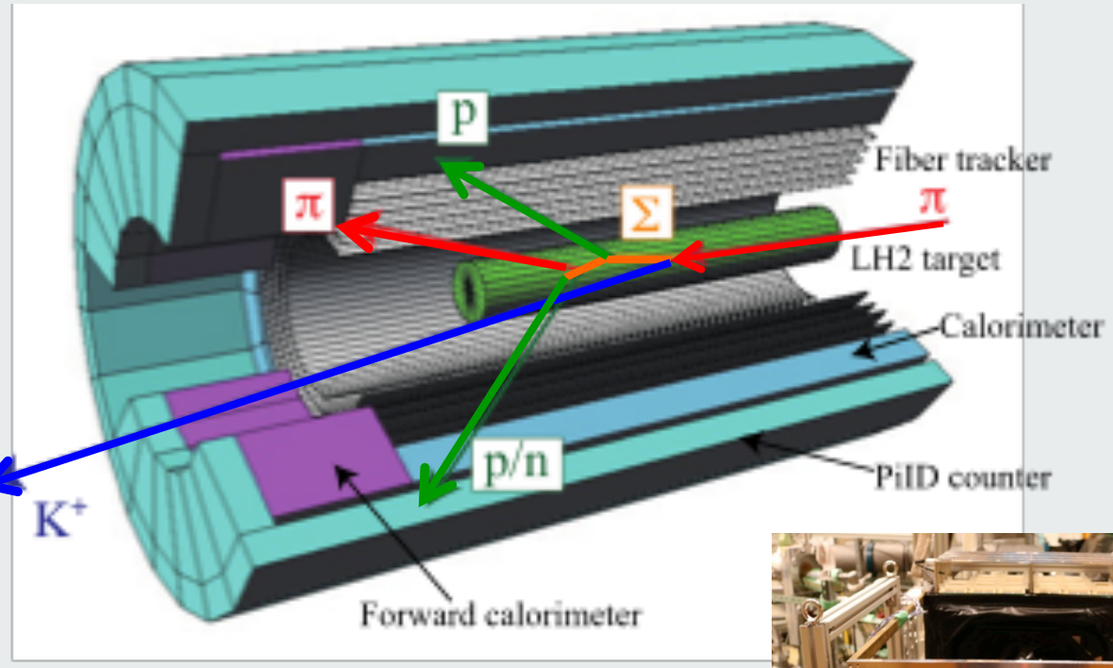
Measured splitting energy is well reproduced by theoretical calculations.

We understand ΛN interaction and structure of not only s, p-shell but also heavier hypernuclei.

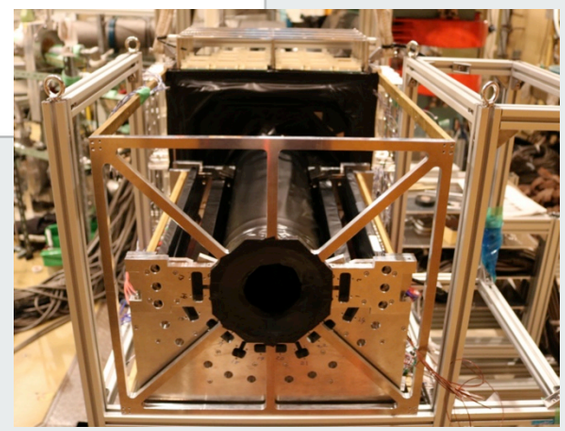
E40: $\Sigma^{\pm}p$ scattering

- $d\sigma/d\Omega$ for 10,000 events
  - $\Sigma^{+}p$ elastic
    $\pi^{\pm}p \rightarrow K^{+}+\Sigma^{\pm}$, $\Sigma^{\pm}p \rightarrow \Sigma^{\pm}p$
  - $\Sigma^{-}p$ elastic+inelastic

Ready for Run in 2018 !!



Kinematical Identification with LH_2 target and Large acceptance detector(CATCH)

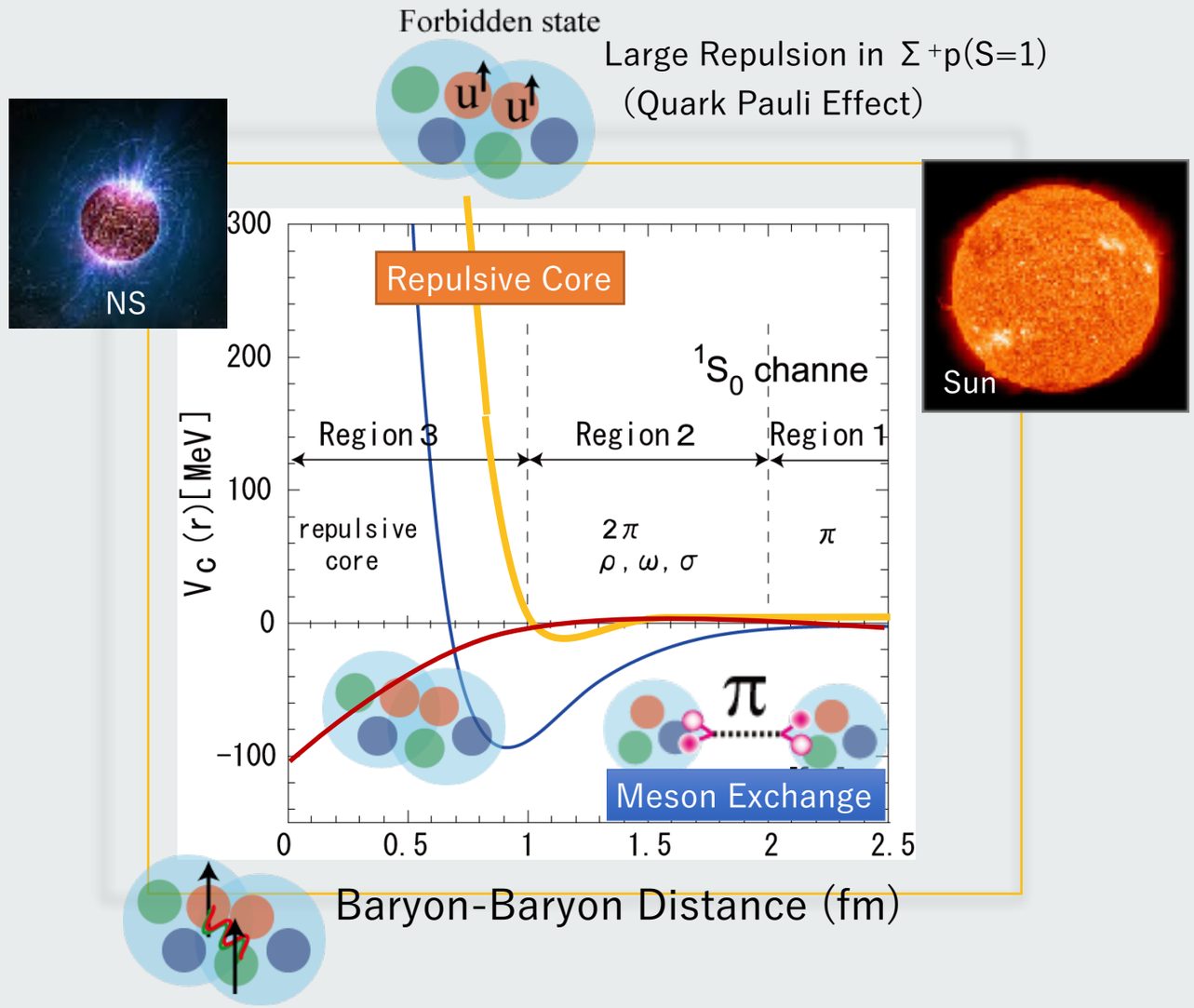


- Understanding the Repulsive core at short distance

Quark Pauli Effect in $\Sigma^{+}p$ channel ??

REPULSIVE CORE AT SHORT DISTANCE

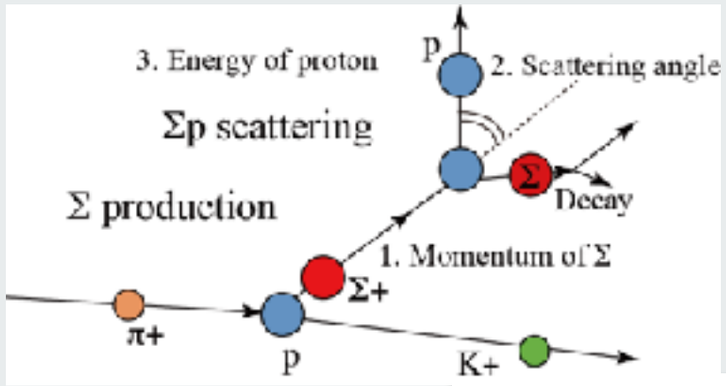
- Meson Exchange Model:
  - Successful in Long-range Attraction.
  - Phenomenology for Short-range
- Quark Picture:
  - Quark Pauli Effect
  - Color-Magnetic Force



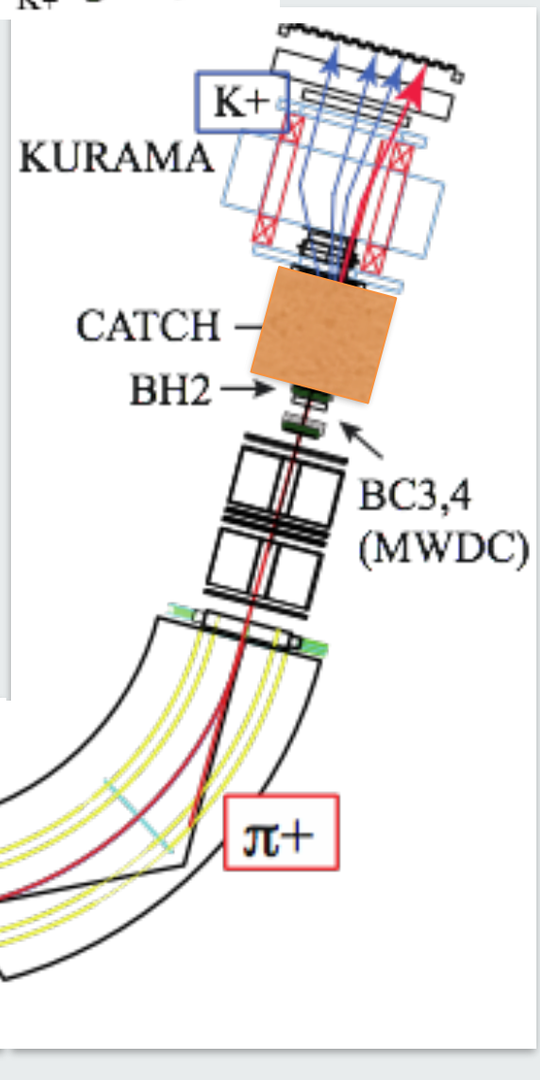
Attraction from Color-Magnetic Interaction (H dibaryon?)

E40 experimental Setup

Two successive two-body reactions

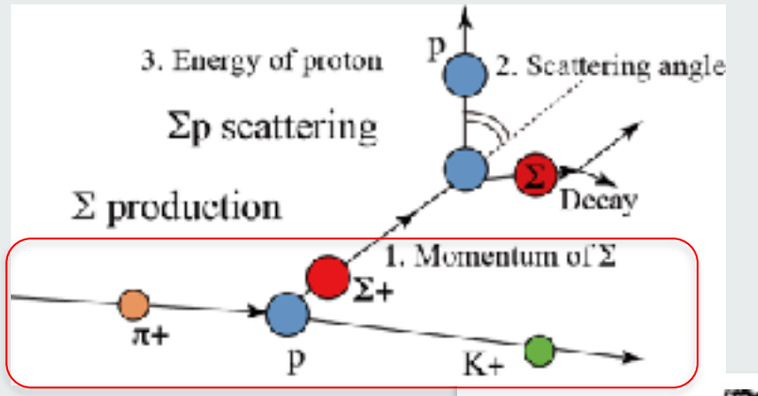


Detection of Σp scattering event
by CATCH detector

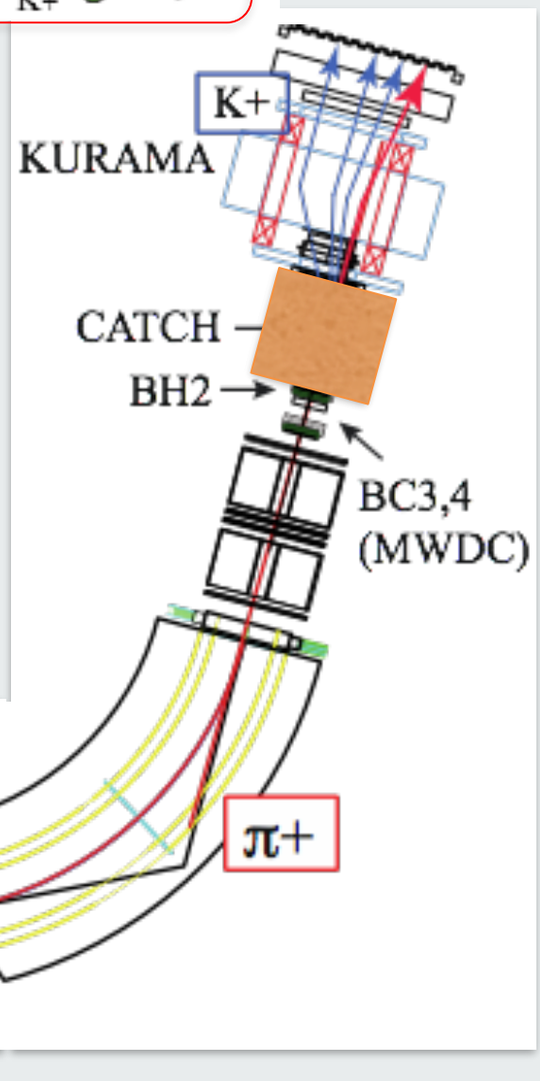


E40 experimental Setup

Two successive two-body reactions

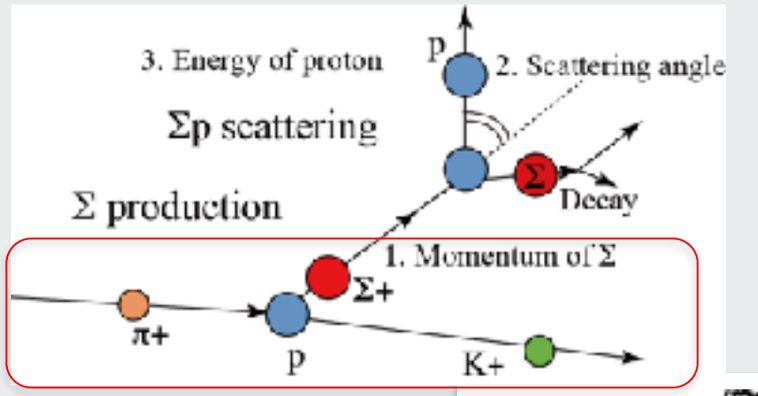


Detection of Σp scattering event
by CATCH detector

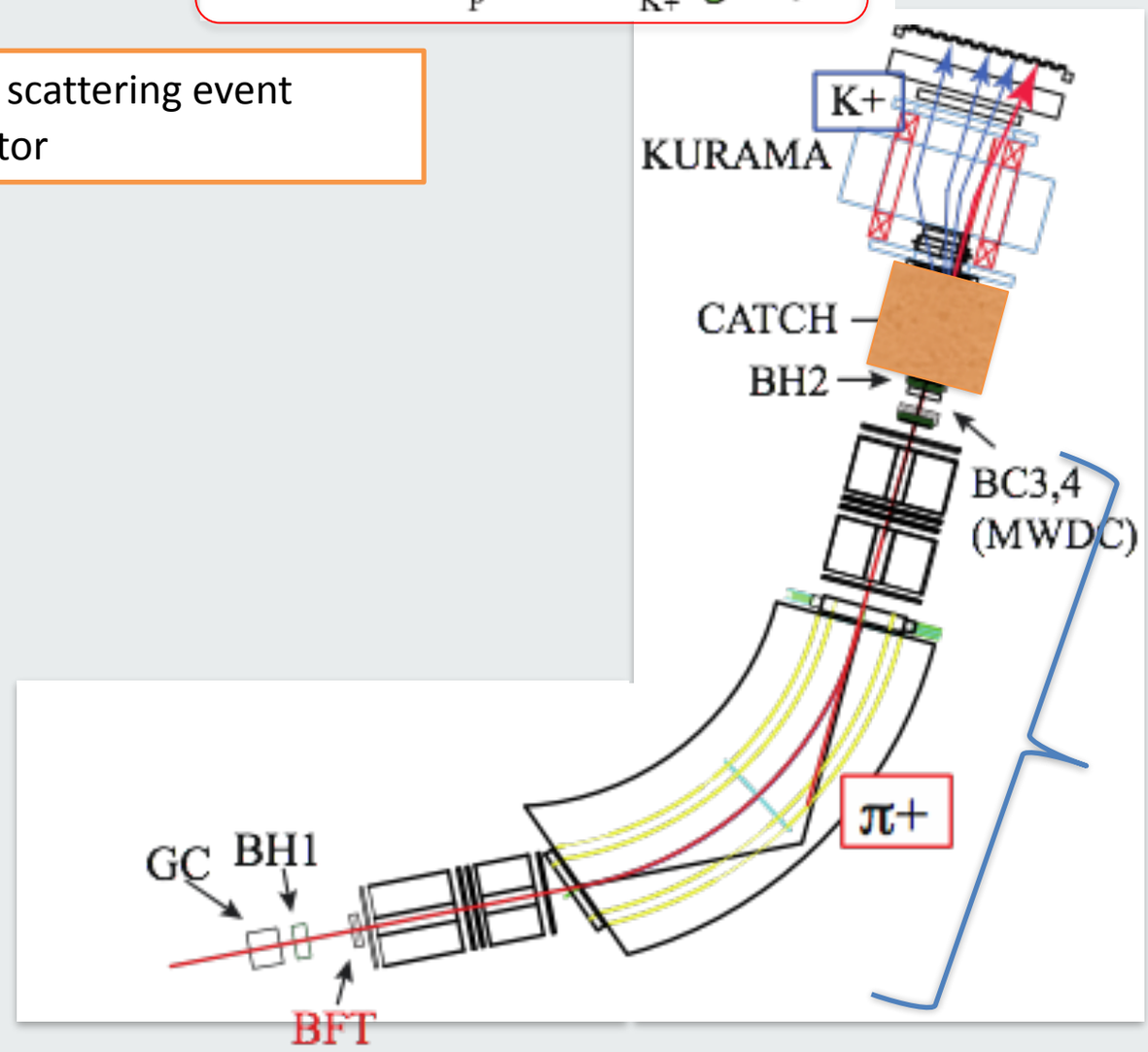


E40 experimental Setup

Two successive two-body reactions



Detection of Σp scattering event
by CATCH detector

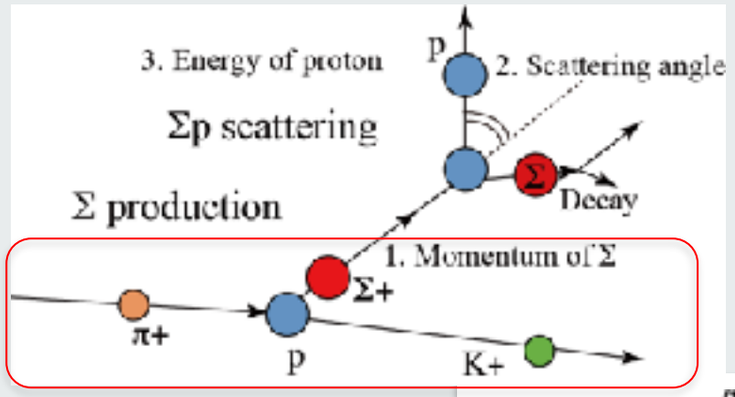


Beamline spectrometer

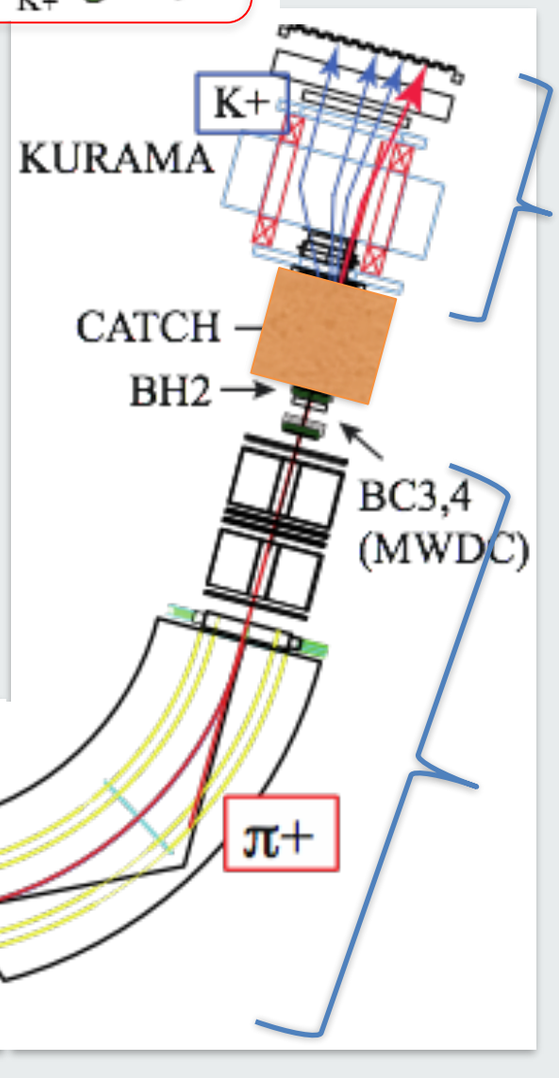
- Momentum analysis of π beam

E40 experimental Setup

Two successive two-body reactions



Detection of Σp scattering event
by CATCH detector

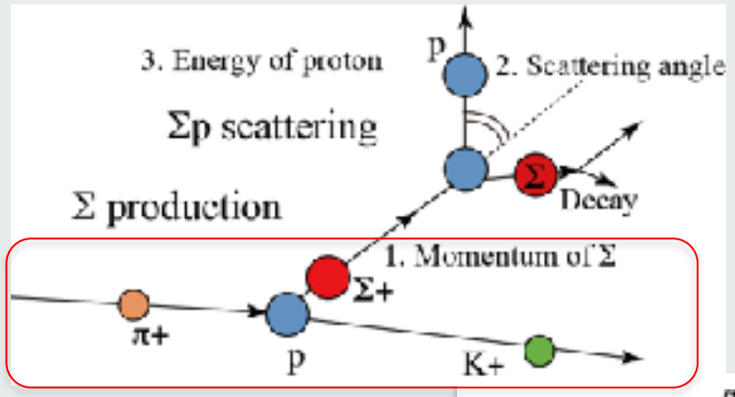


KURAMA spectrometer
- Identification of K^+
- Momentum analysis

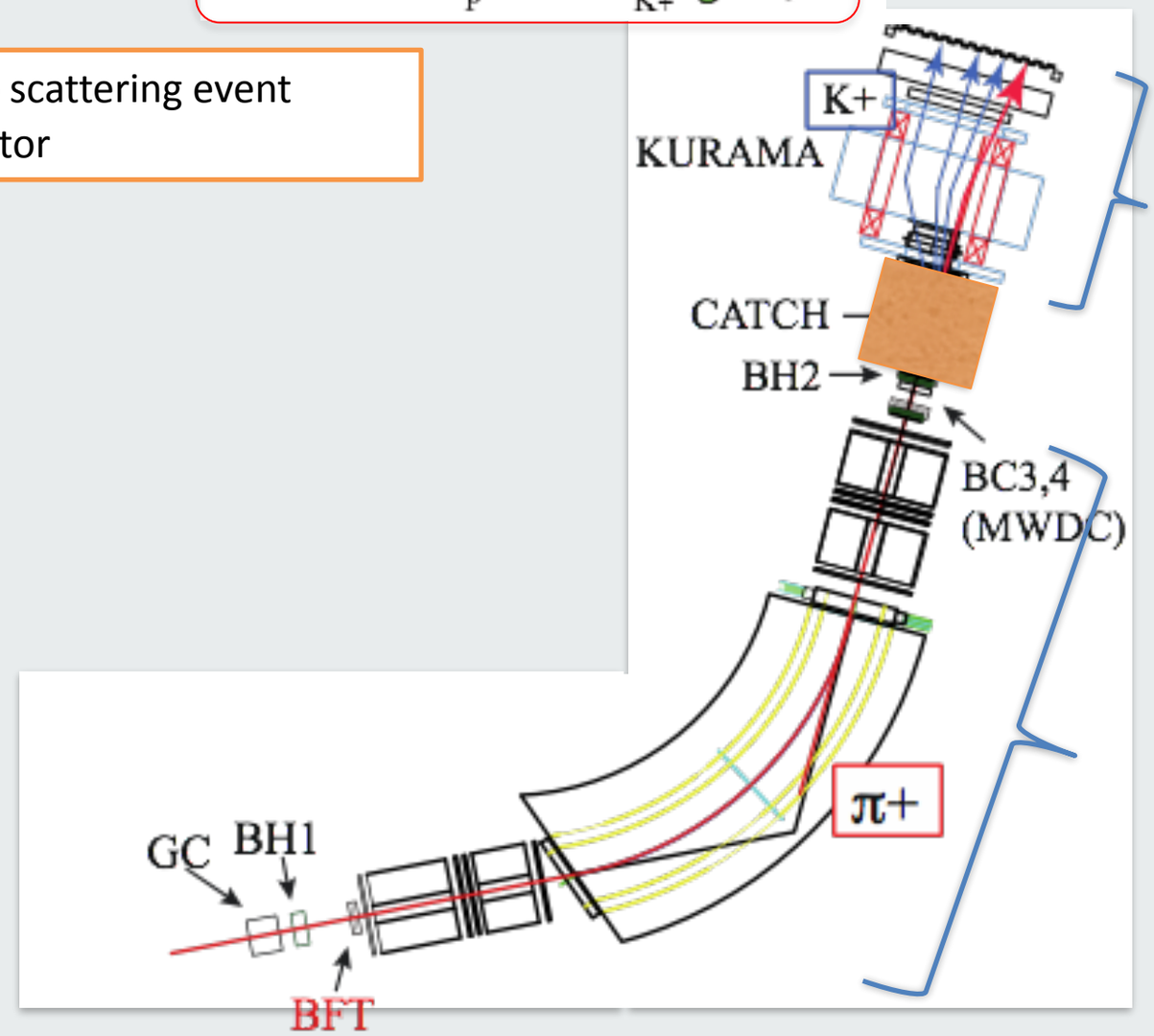
Beamline spectrometer
- Momentum analysis of π beam

E40 experimental Setup

Two successive two-body reactions



Detection of Σp scattering event
by CATCH detector



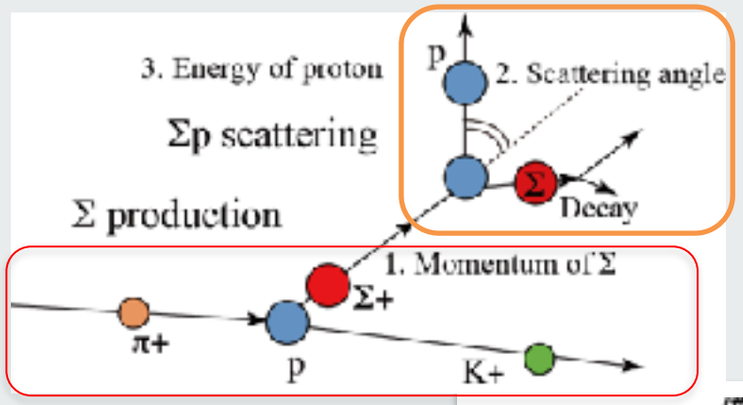
KURAMA spectrometer
- Identification of K^+
- Momentum analysis

Momentum reconstruction
of Σ beam

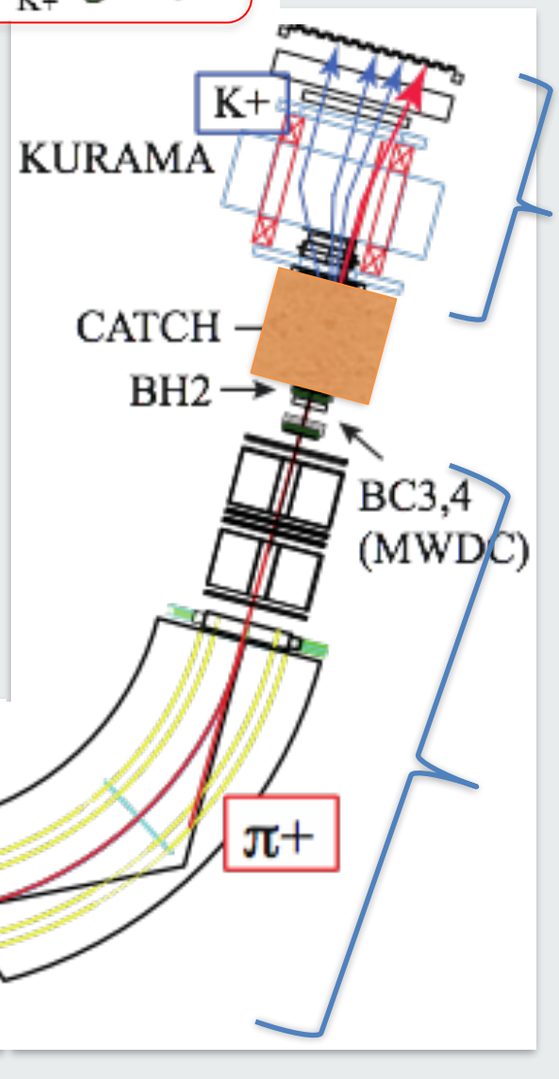
Beamline spectrometer
- Momentum analysis of π beam

E40 experimental Setup

Two successive two-body reactions



Detection of Σp scattering event
by CATCH detector



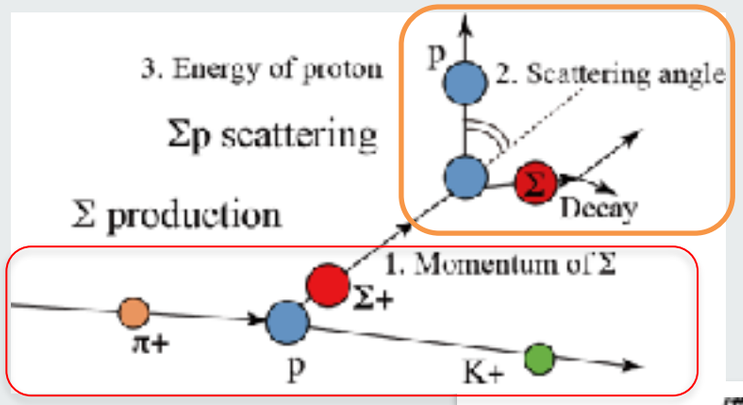
KURAMA spectrometer
- Identification of K^+
- Momentum analysis

Momentum reconstruction
of Σ beam

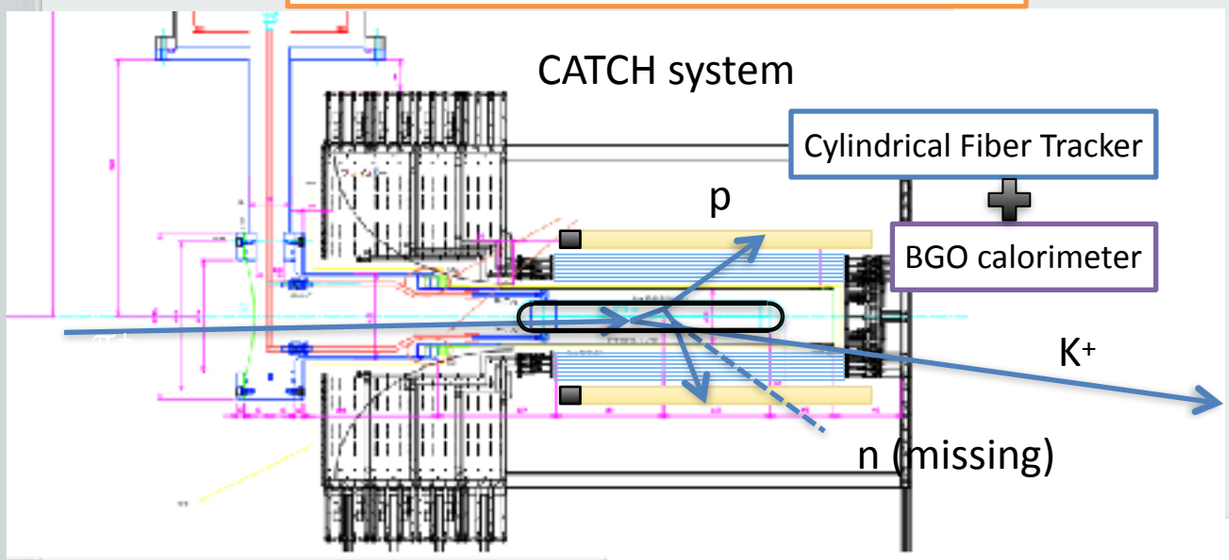
Beamline spectrometer
- Momentum analysis of π beam

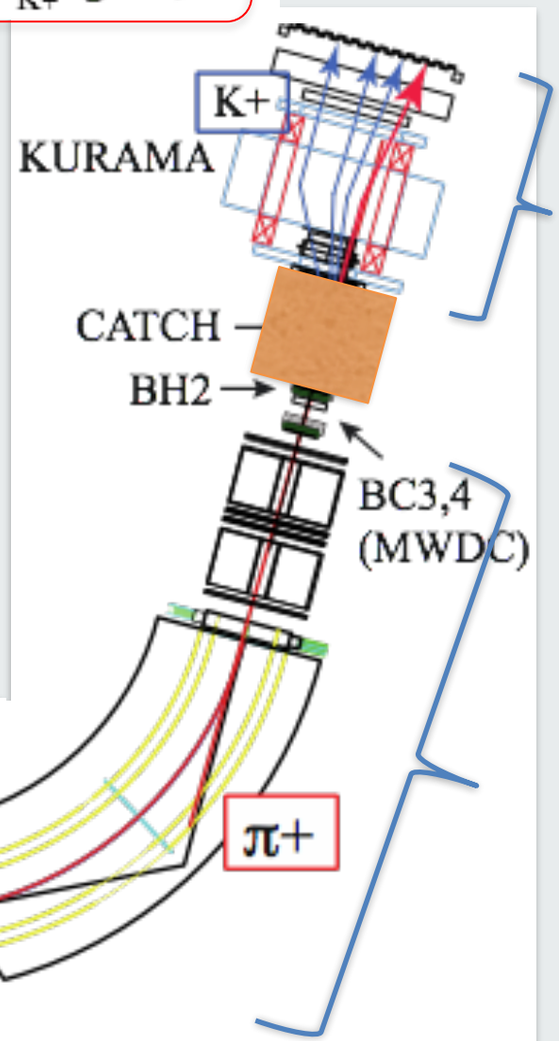
E40 experimental Setup

Two successive two-body reactions



Detection of Σp scattering event
by CATCH detector





KURAMA spectrometer
- Identification of K^+
- Momentum analysis

Momentum reconstruction of Σ beam

Beamline spectrometer
- Momentum analysis of π beam

S=-2 SYSTEMS

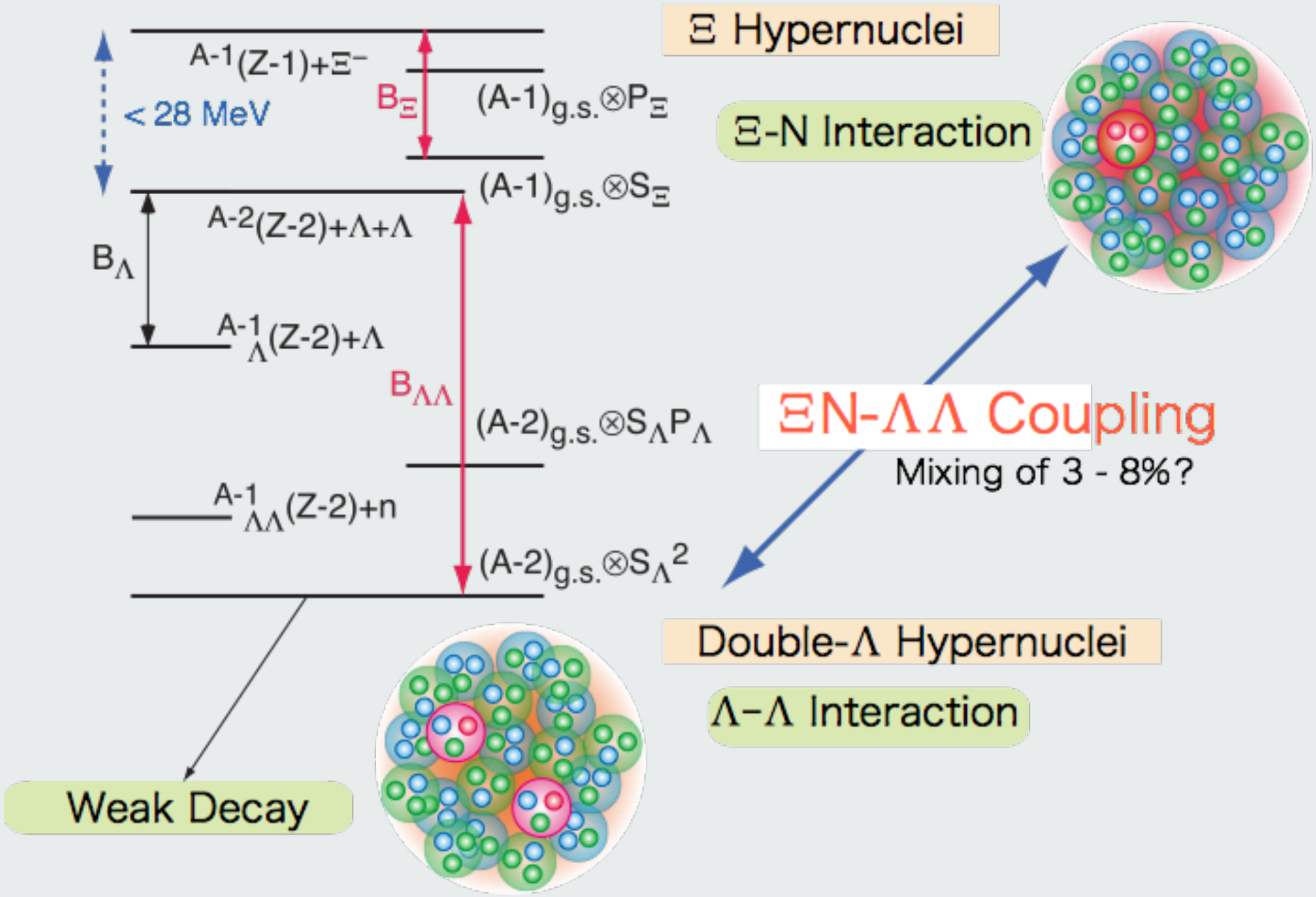
Ξ hypernuclei

Double-Λ Hypernuclei

H dibaryon

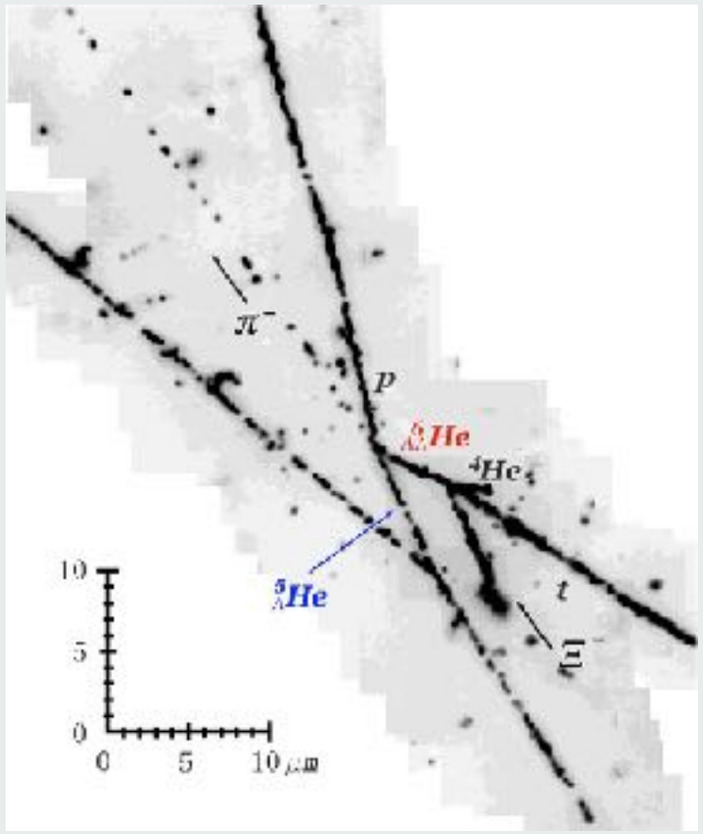
S=-2 WORLD

Energy Spectrum of S=-2 systems



KEK E373

- Double-Λ hypernuclei
- Nagara Event; ${}^{\Lambda\Lambda}{}^{6}\mathrm{He}$
  - $\Delta B_{\Lambda\Lambda}=0.67\pm0.17$ MeV

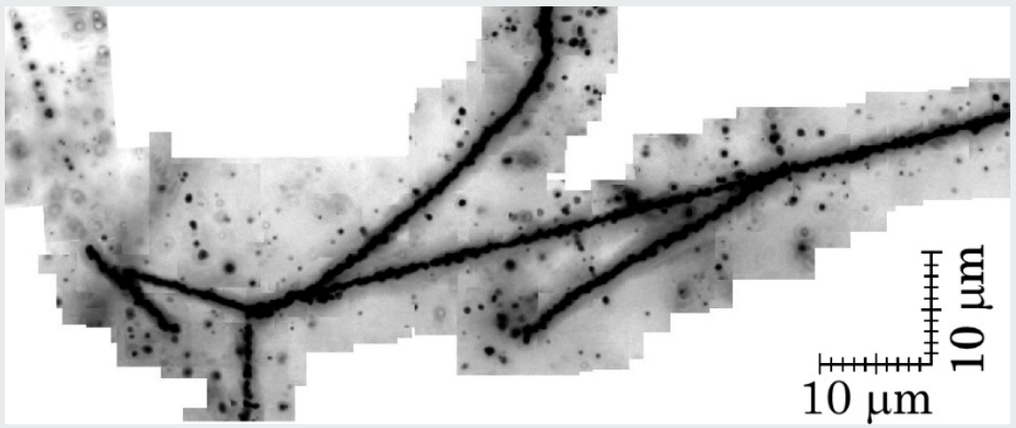


J.K. Ahn et al., PRC 88 (2013) 014003.

- Kiso Event; Ξ^{-}-${}^{14}\mathrm{N}$
- $\Xi^{-}+{}^{14}\mathrm{N}\rightarrow{}^{10}_{\Lambda}\mathrm{Be}+{}^{5}_{\Lambda}\mathrm{He}$

$B_{\Xi}=1.03$ or 3.87 MeV $\pm\Gamma/2$

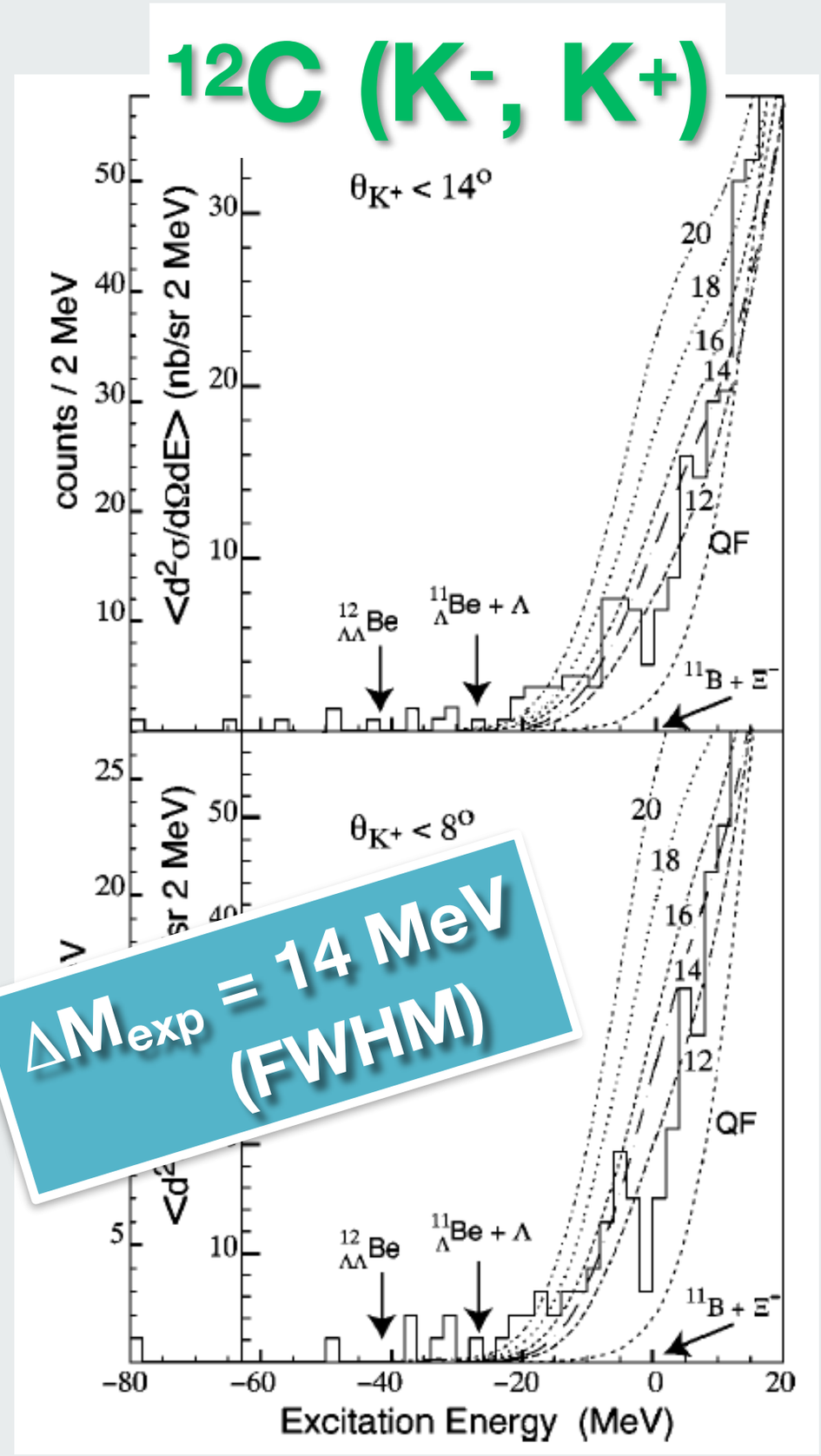
well beyond the atomic binding of 0.17 MeV



K. Nakazawa et al., PTEP (2015) 033D02

BNL E885

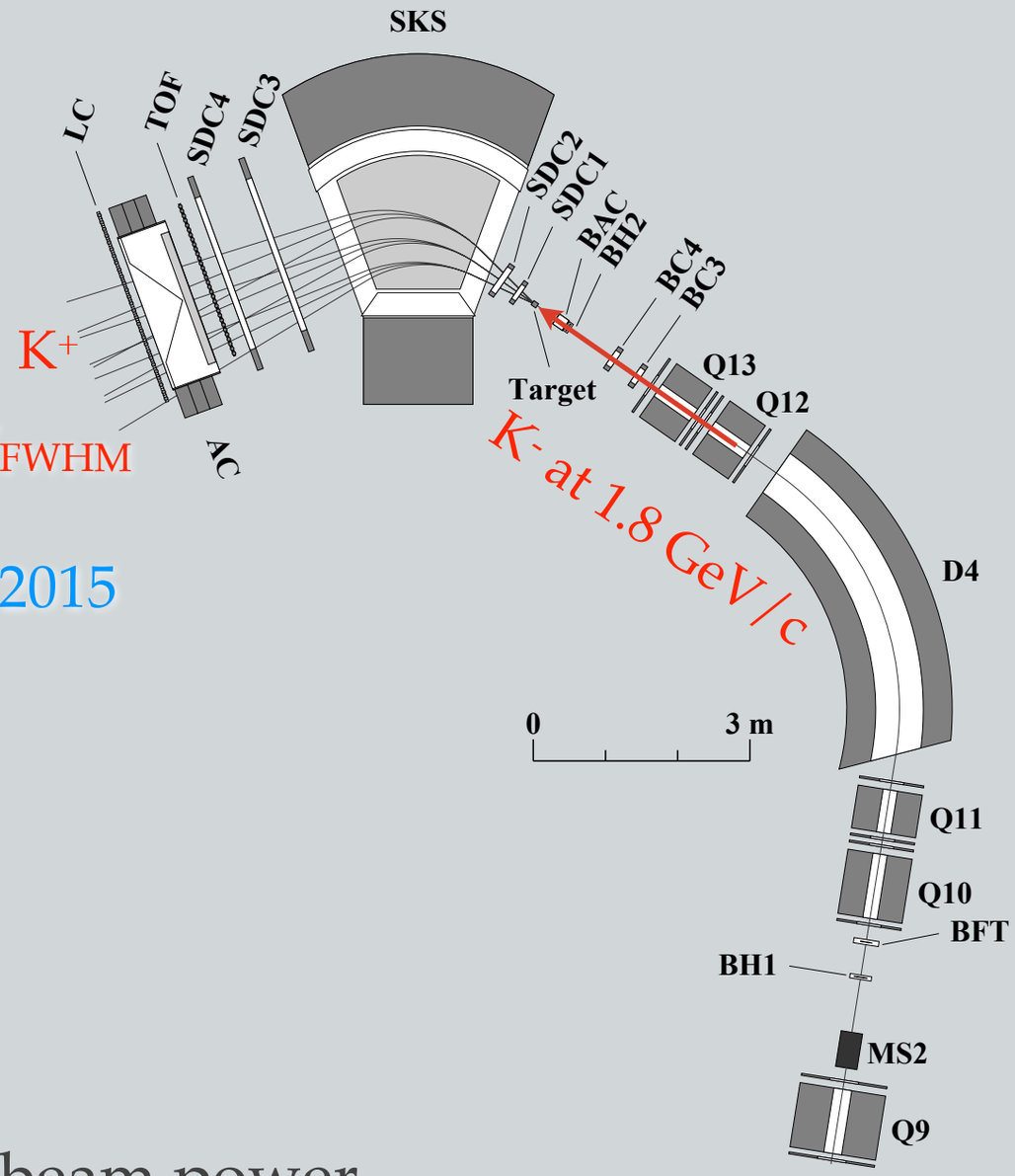
- $^{12}C(K^-,K^+)$ at 1.8 GeV/c
- no clear evidence of Ξ-hypernuclear bound state.
  - because of the limited mass resolution of 14 MeV_{FWHM}
- suggested weakly attractive potential of -14 MeV depth. (B_Ξ~4.5 MeV)
  - by shape analysis and counts in bound region, compared with DWIA calc.
- 89±14 nb/sr (<8deg. 42 events);
  42±5 nb/sr (<14deg. 67 events)



YKIS2018

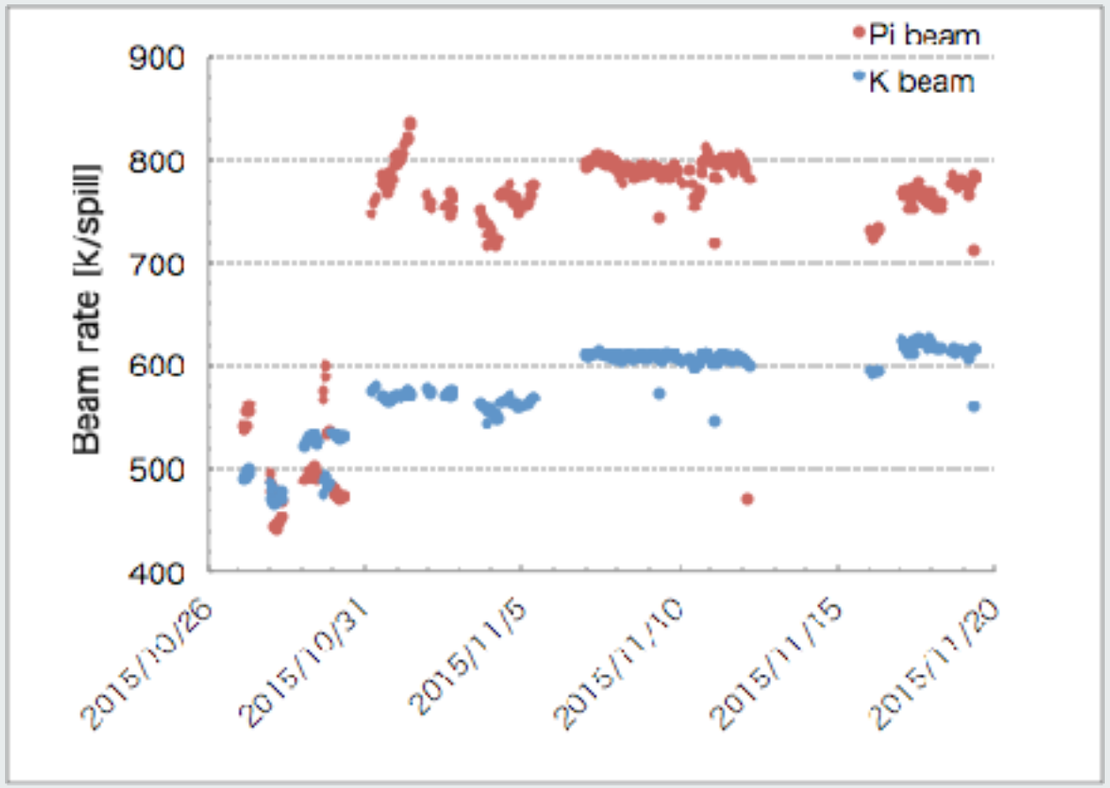
E05: $^{12}C(K^-,K^+)^{12}_{\Xi}Be$

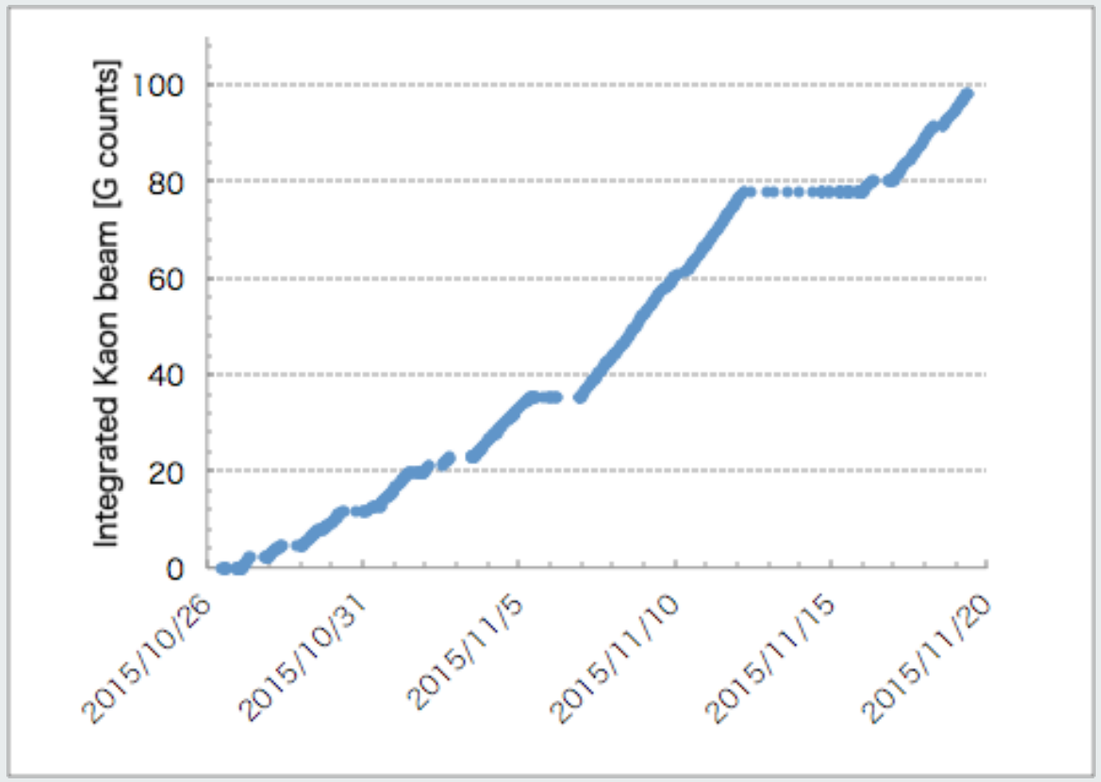
- K1.8 beam line with SKS' (110 msr)
  - AC + LC for π^+, p veto in trigger
  - $CH_2(K^-,K^+)$ 9.54g/cm^2 → ΔE=5.4 MeV$_{FWHM}$
- Two weeks of beam time ; Oct.26 - Nov.19, 2015
  - Detector tuning 1 day
  - $p(K^-,K^+)\Xi^-$@1.5-1.9 GeV/c 2 days
  - $^{12}C(K^-,K^+)$ 9.36g/cm^2 10 days
- 600k K^-/spill was achieved for 39 kW beam power.



K^- beam intensity

- 600k K^-/spill was achieved for 39 kW beam power.

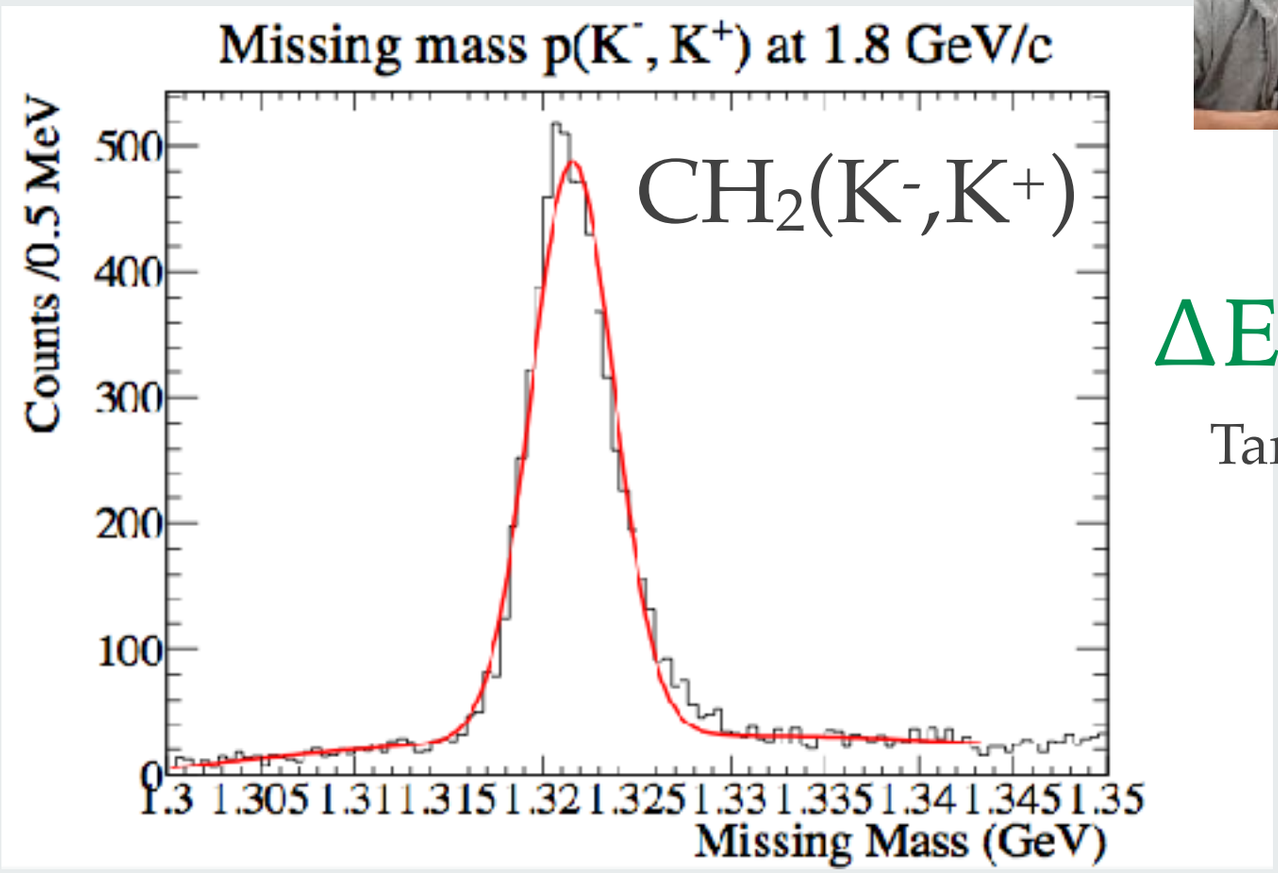




- Integrated K^- intensity reached 100 G !!

$K^- P \rightarrow K^+ \Xi^-$

- Ξ^- at J-PARC !!
  - 6000 Ξ^-/day



$\Delta E \sim 5.4$ MeV fwhm

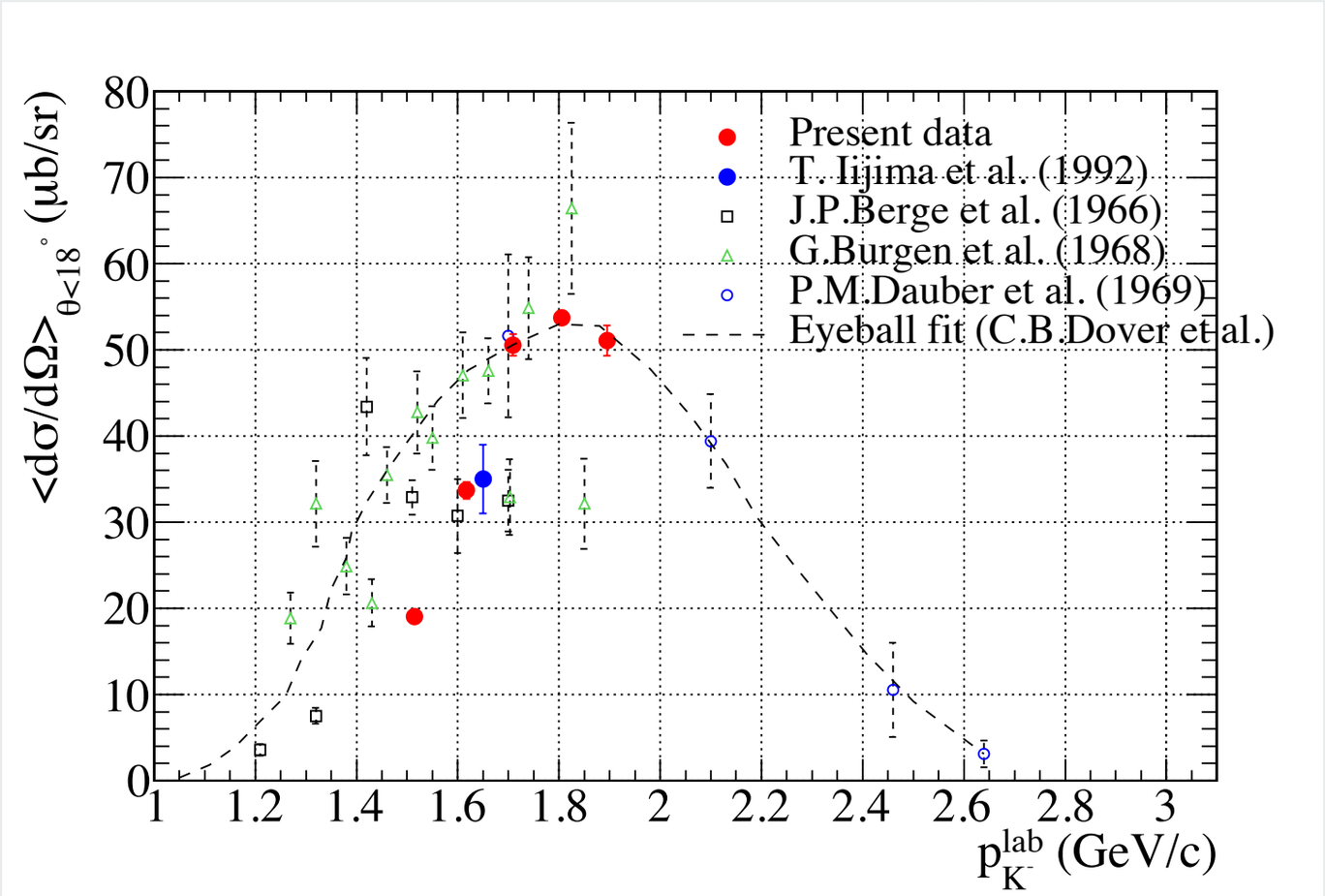
Target energy loss straggling limited.
10 MeV_{FWHM} at BNL

OPTIMUM MOMENTUM

- Yield maximum at 1.8 GeV/c suggested by Dover & Gal.

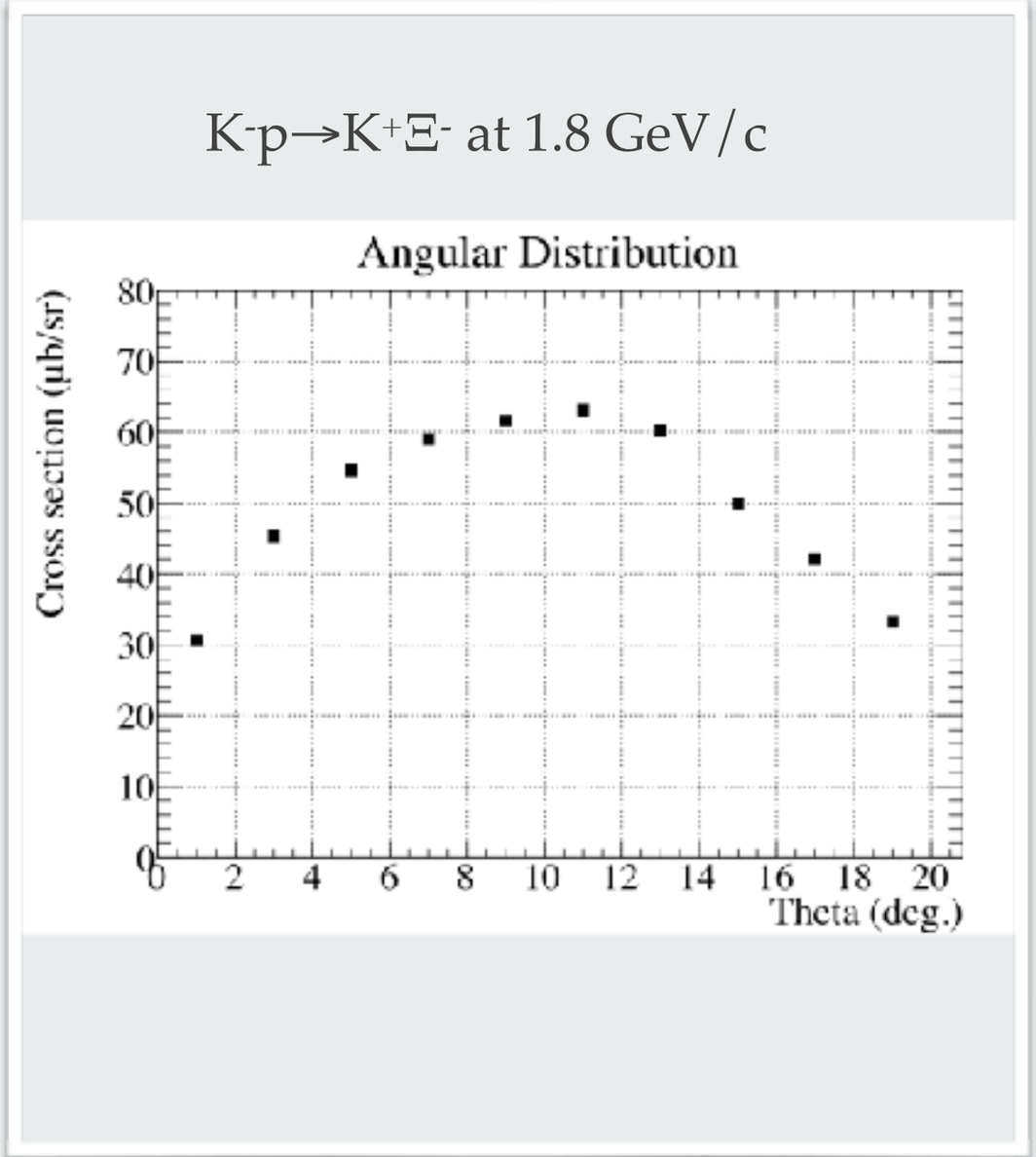
C.B.Dover and A.Gal, Ann. Phys. 146 (1983) 309.

  - New data from 1.5 to 1.9 GeV/c.
  - Two orders better statistics.
  - Max. at 1.8 GeV/c is confirmed !

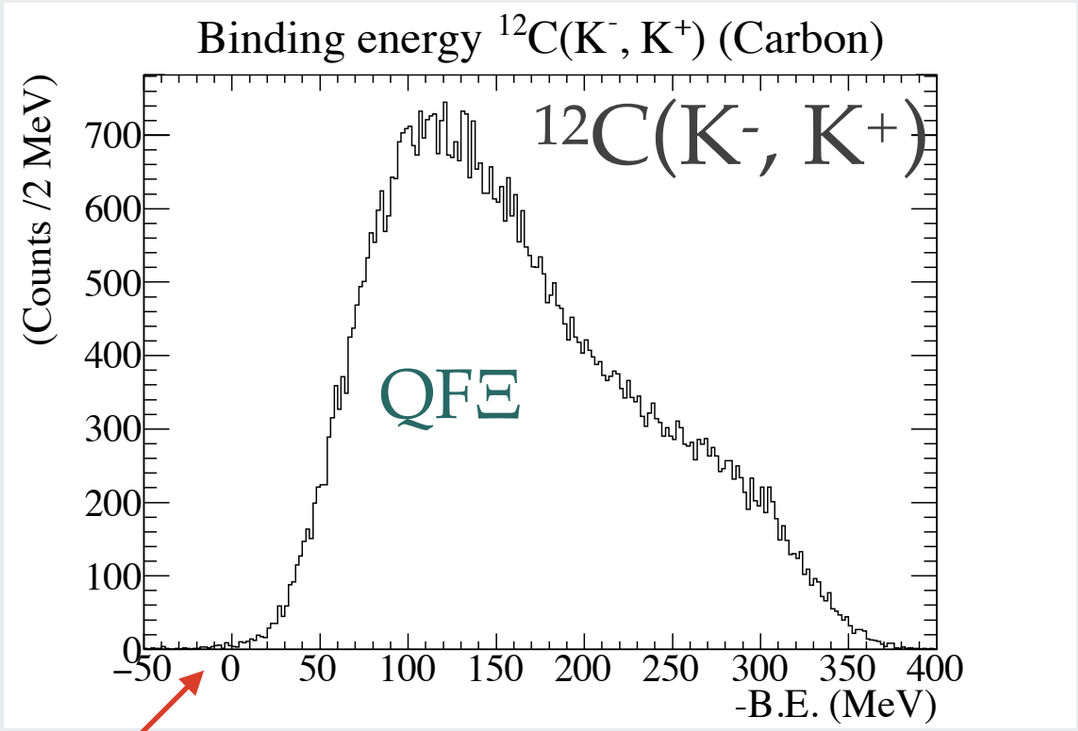


ANGULAR DISTRIBUTION OF $K^-P \rightarrow K^+ \Xi$

- Differential cross section at 1.8 GeV/c

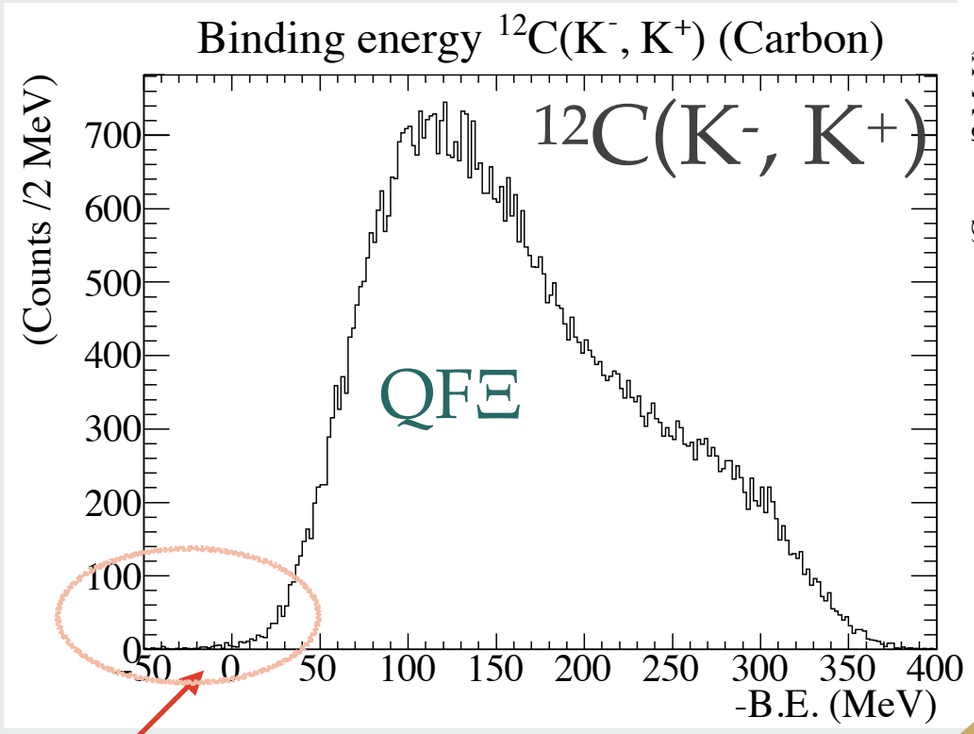


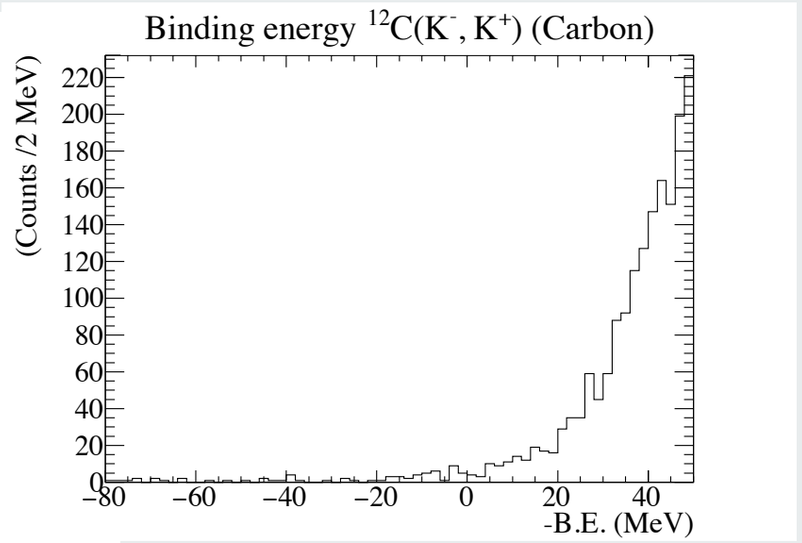
- 80 G K^- incident on ^{12}C(9.3 g/cm^2)



Focus on this part.

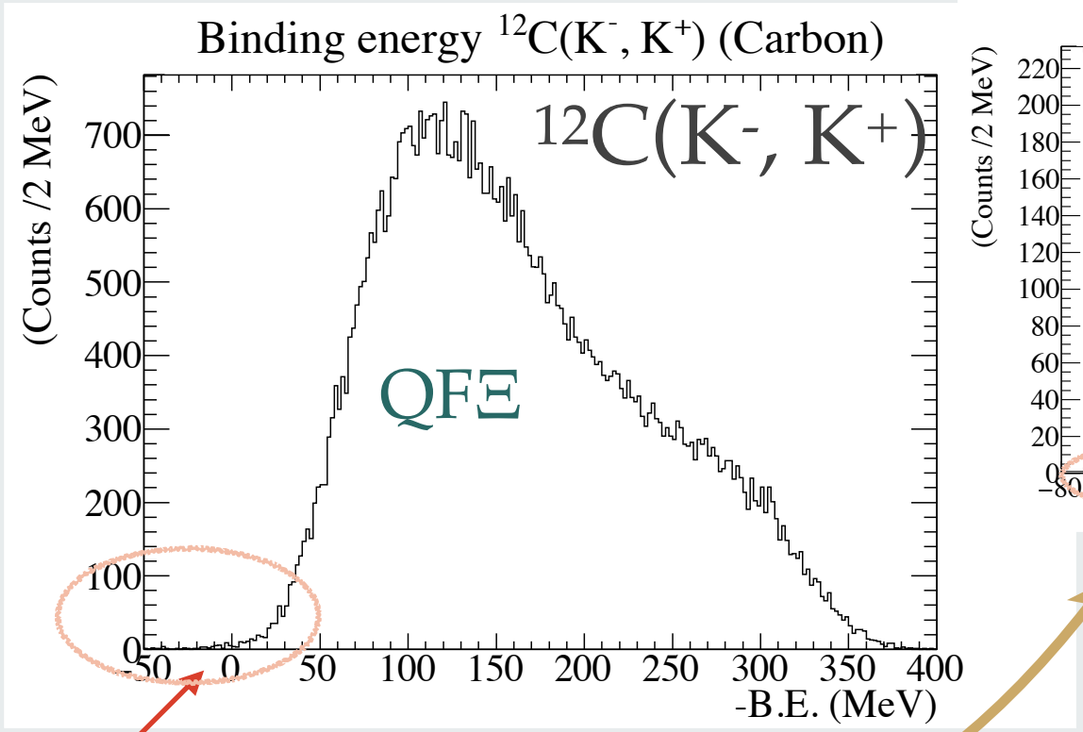
- 80 G K^- incident on ^{12}C(9.3 g/cm^2)

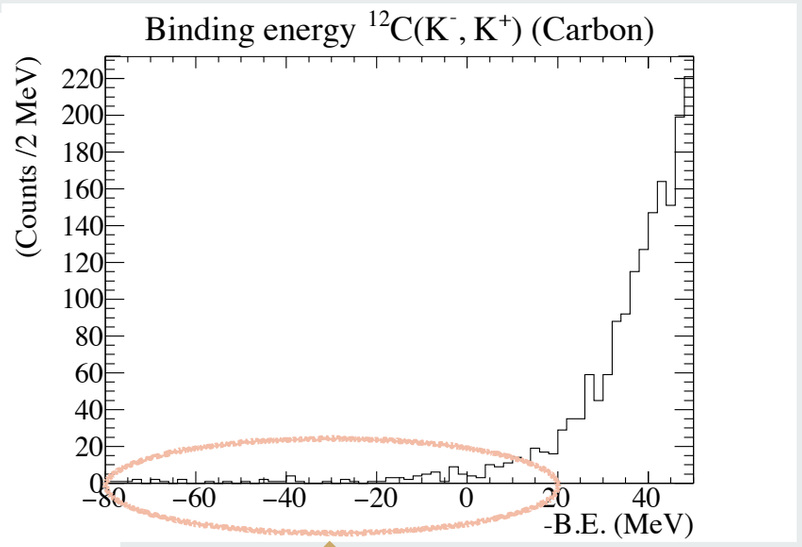




Focus on this part.

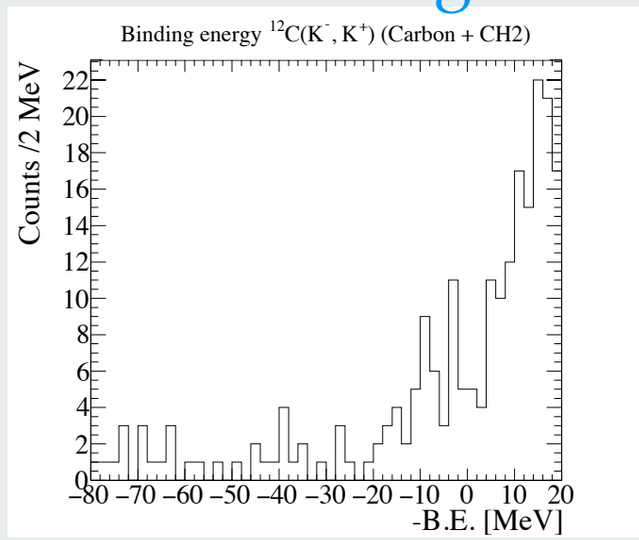
- 80 G K^- incident on $^{12}C(9.3\ g/cm^2)$



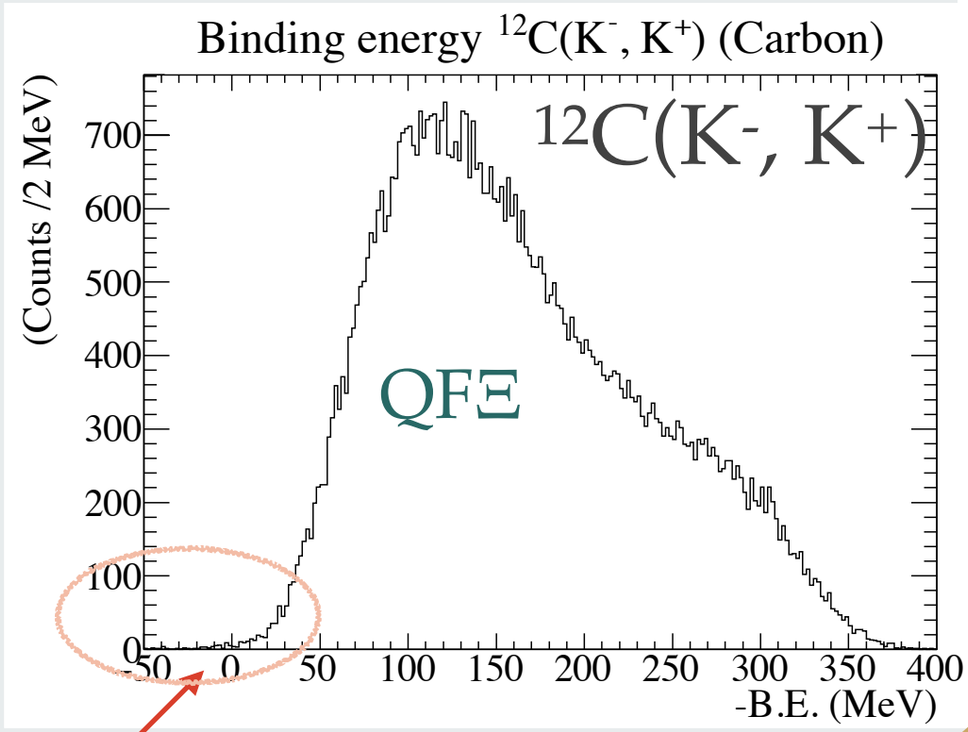


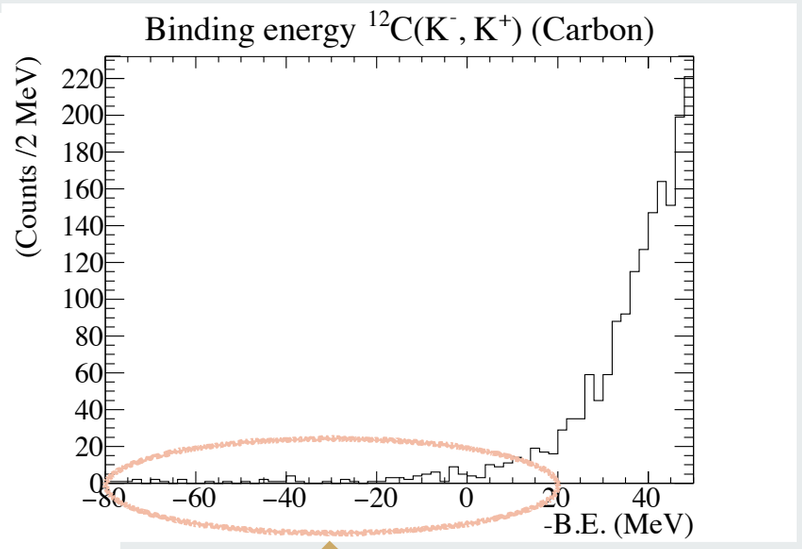
Focus on this part.

Ξ Bound Region

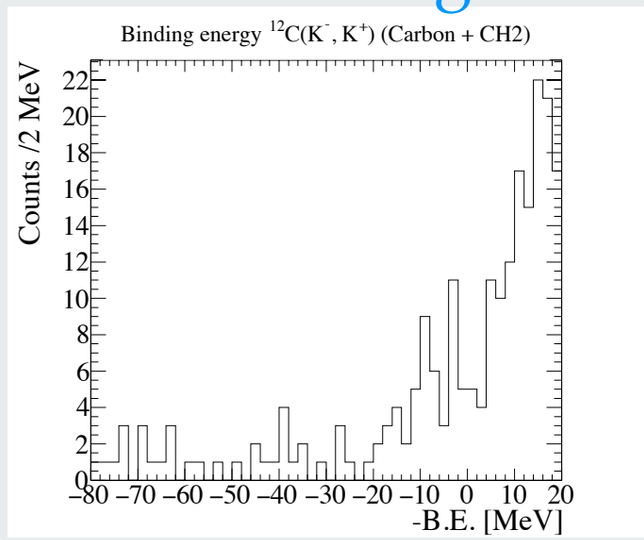


- 80 G K^- incident on ^{12}C(9.3 g/cm^2)

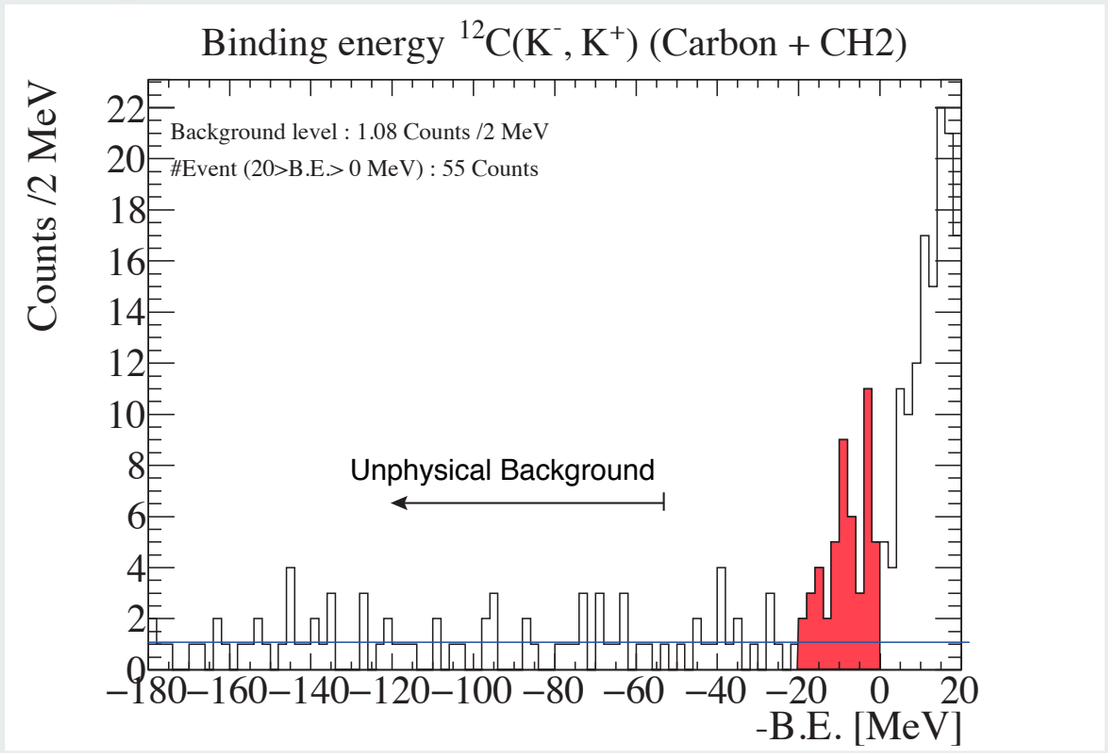




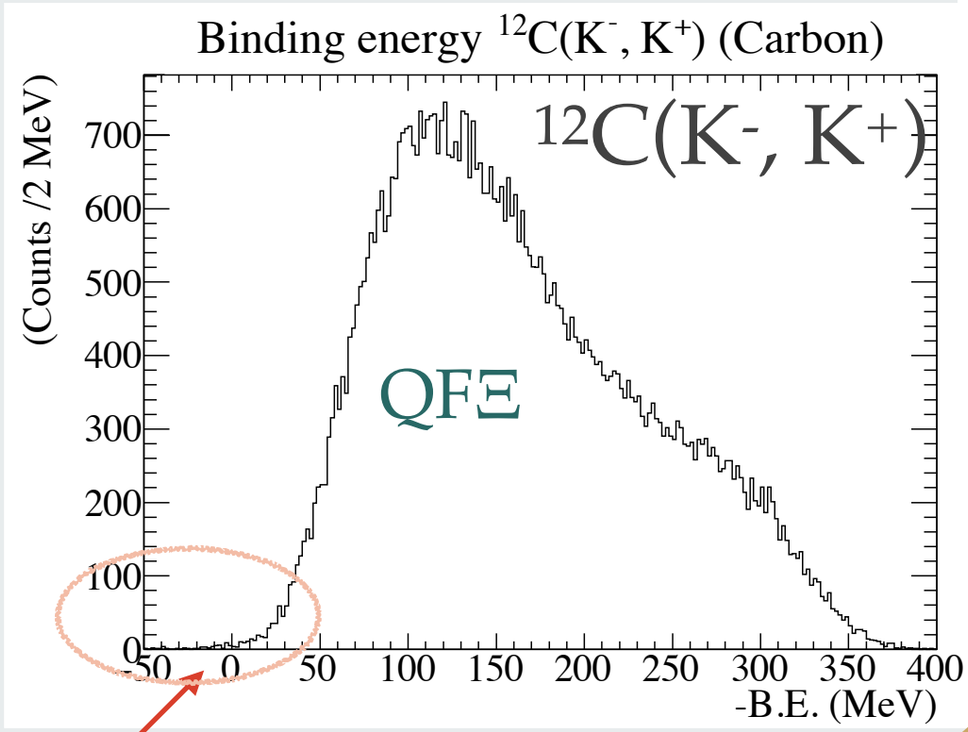
Ξ Bound Region

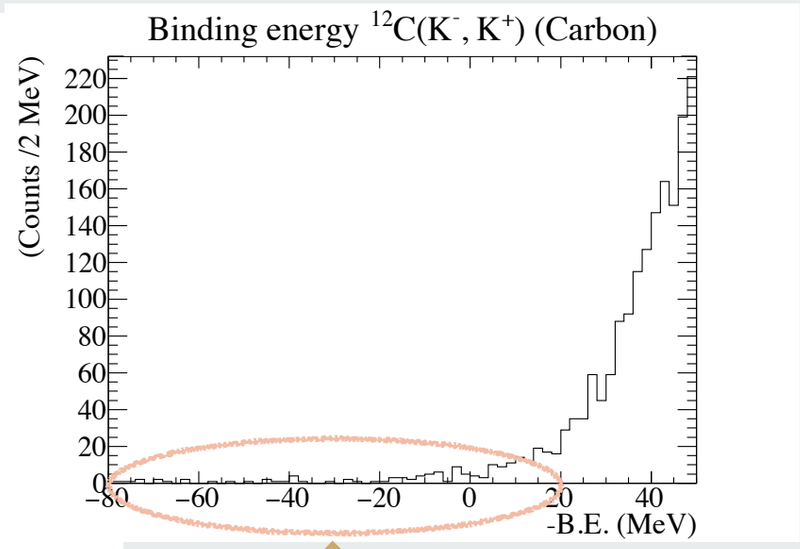


Focus on this part.

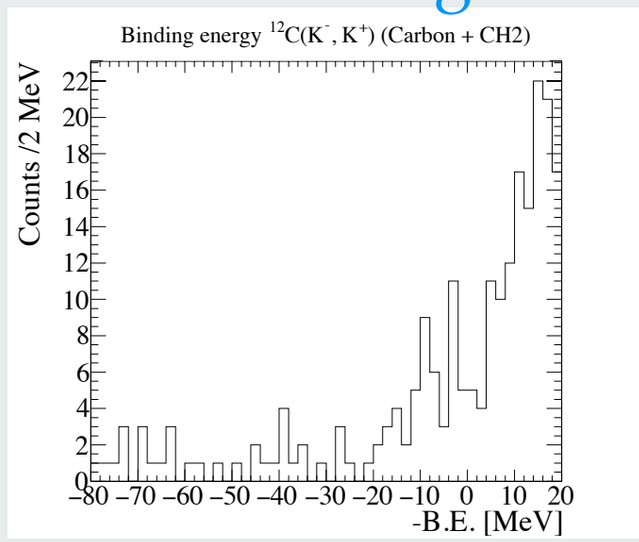


- 80 G K^- incident on $^{12}C(9.3\ g/cm^2)$

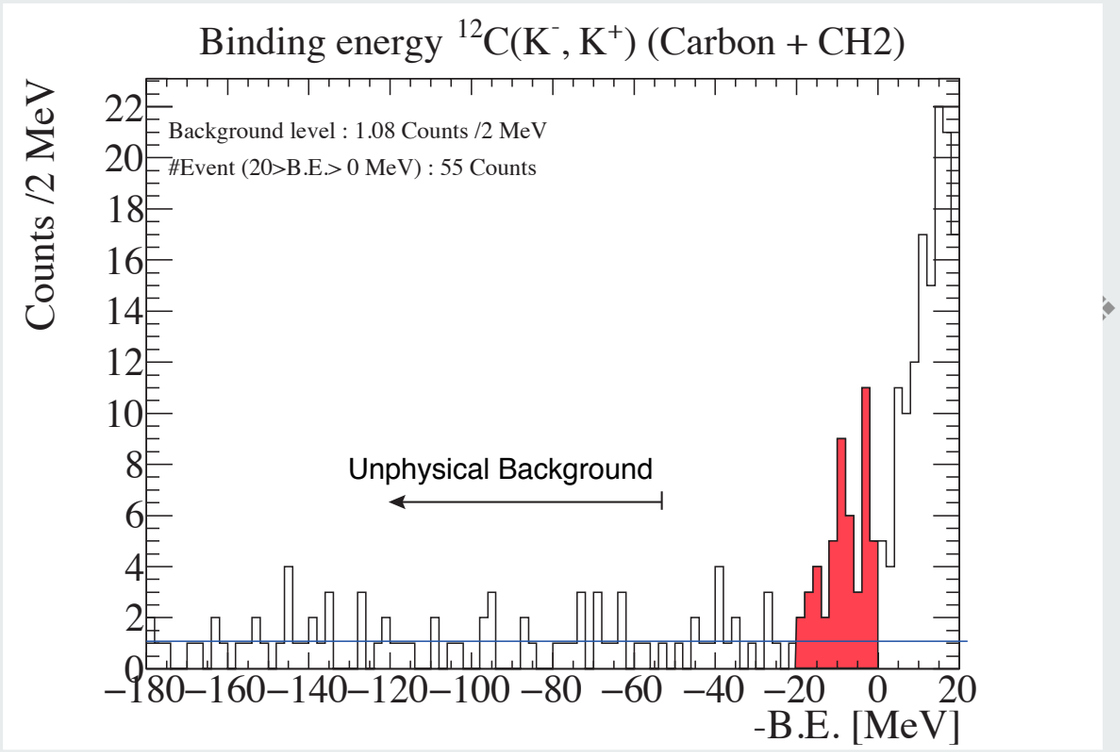




Ξ Bound Region

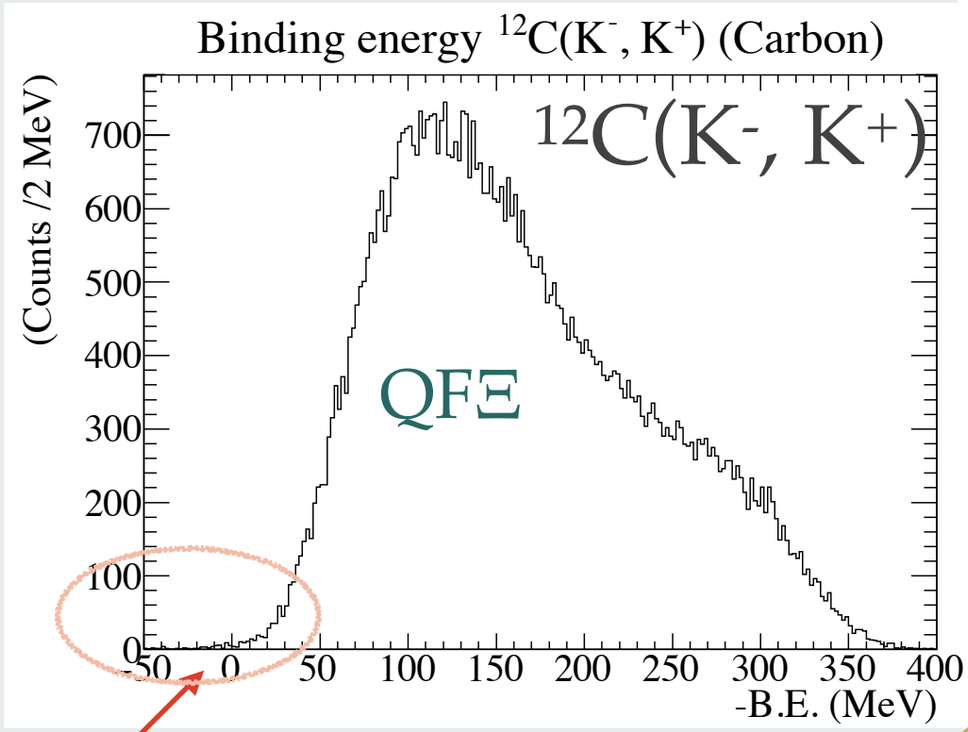


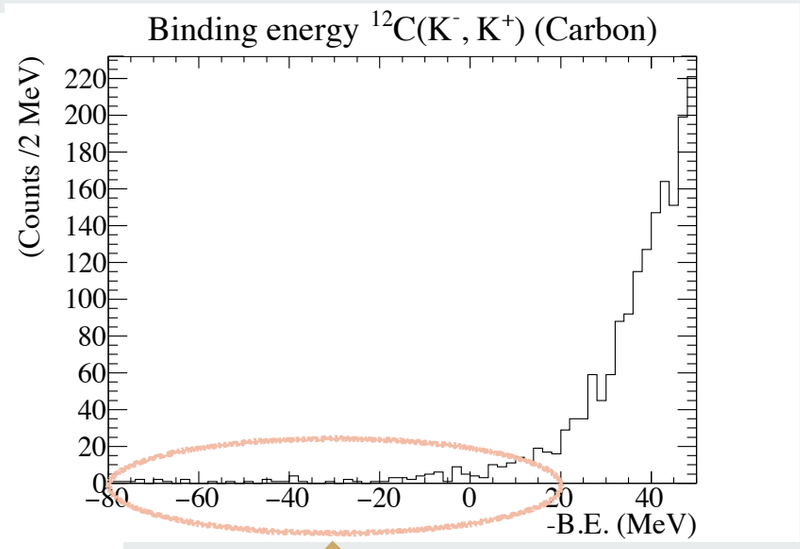
Focus on this part.



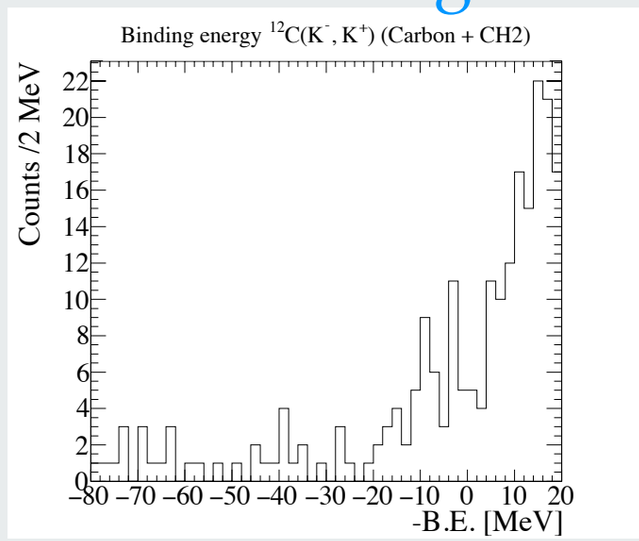
- -20<-BE<0 (MeV)
  T=S+B=55 counts
  B=10.8 counts S/ΔS=5.5

- 80 G K^- incident on $^{12}C(9.3\ g/cm^2)$

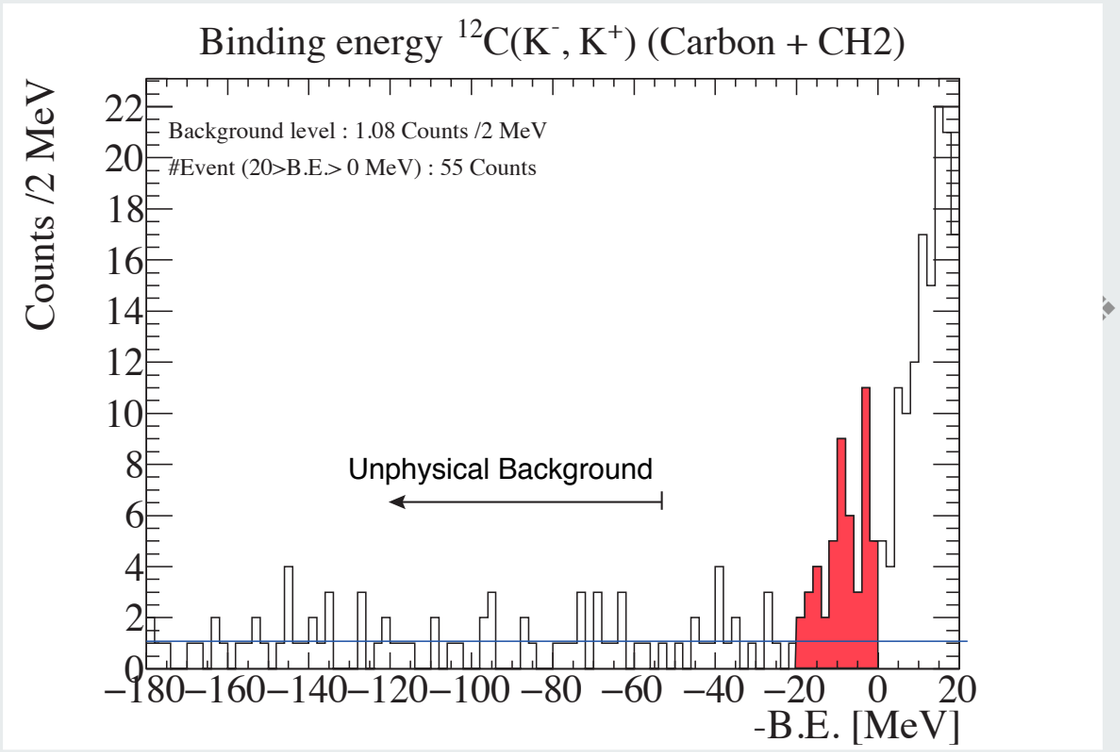




Ξ Bound Region



Focus on this part.



- -20<-BE<0 (MeV)
  T=S+B=55 counts
  B=10.8 counts → S/ΔS=5.5

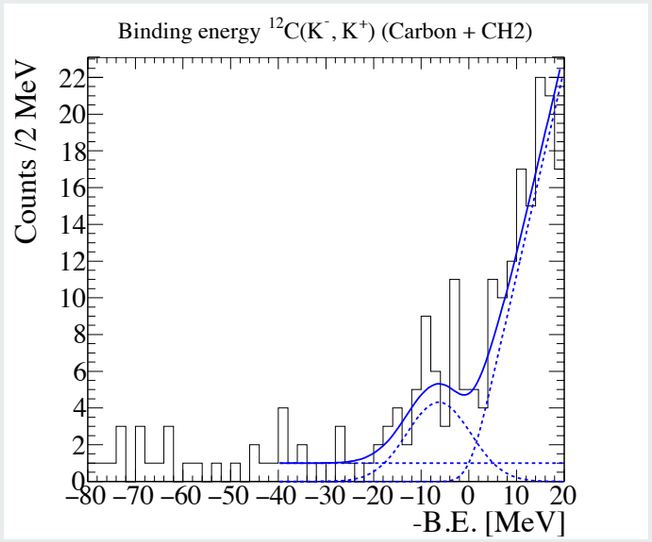
PEAK FITTING

- QFΞ(linear)+Background(Flat)

  +

- One Gaussian (all free)

- B_{Ξ}=6.3 MeV, ΔB_{FWHM}=15.7 MeV



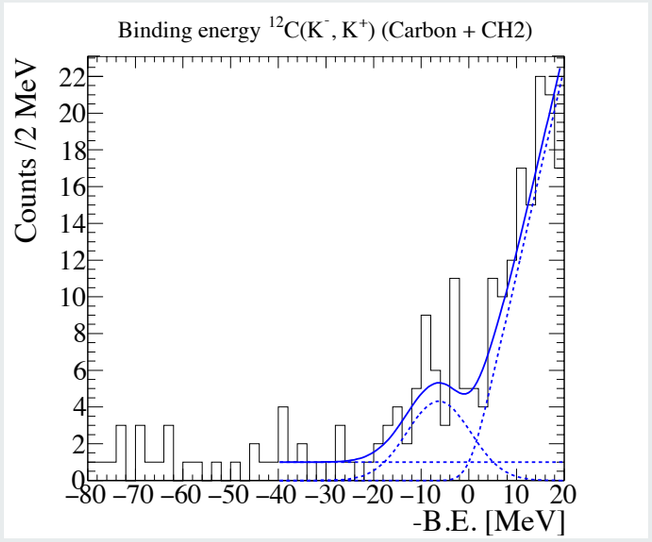
PEAK FITTING

- QFΞ(linear)+Background(Flat)

+

- One Gaussian (all free)

- B_{Ξ}=6.3 MeV, ΔB_{FWHM}=15.7 MeV

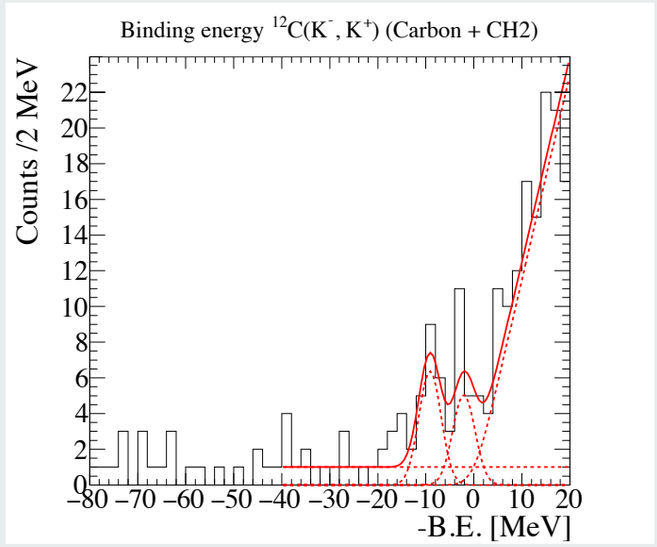


- QFΞ(linear)+Background(Flat)

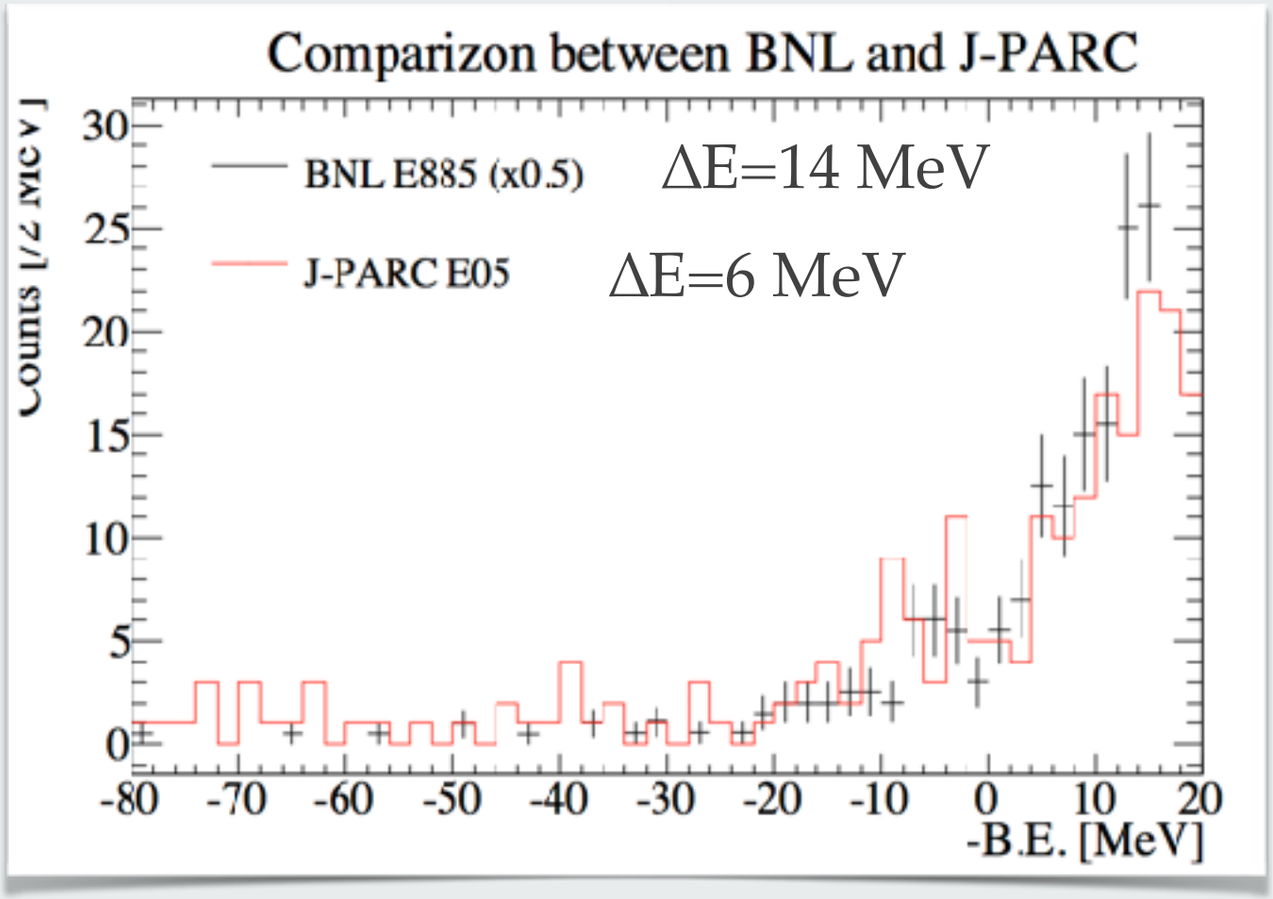
+

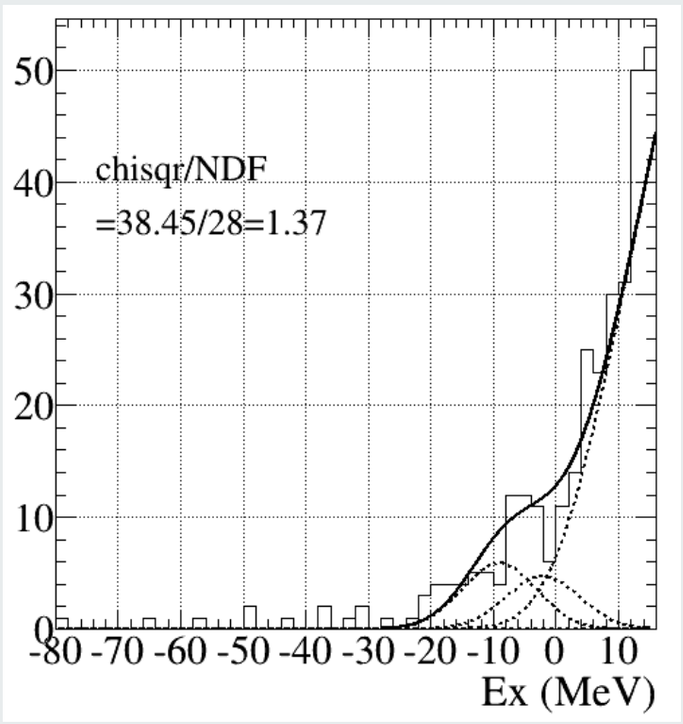
- Two Gaussians (fixed width=5.4 MeV)

- B_{Ξ}=9.1 MeV and 2.1 MeV



COMPARISON WITH BNL E885

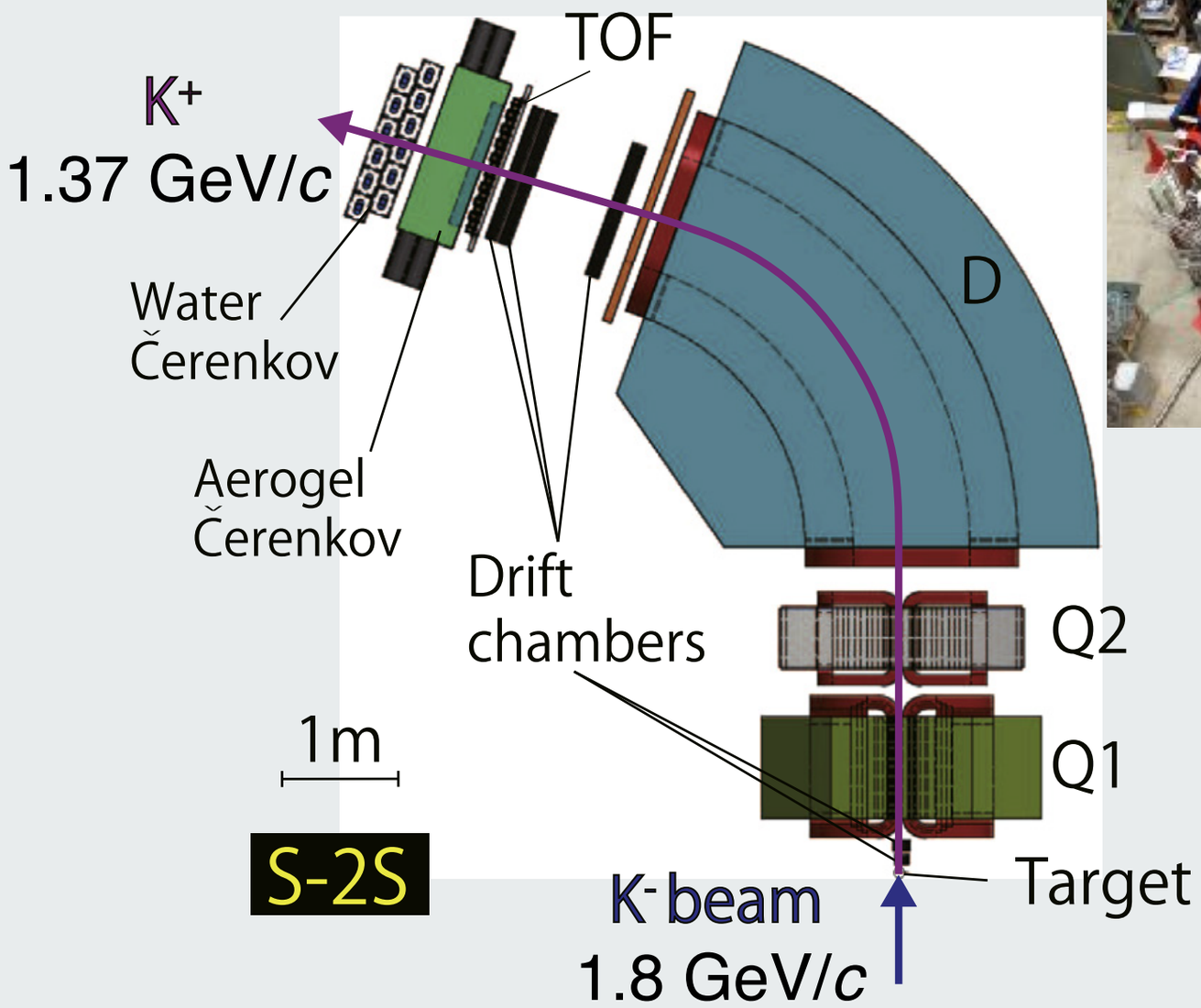


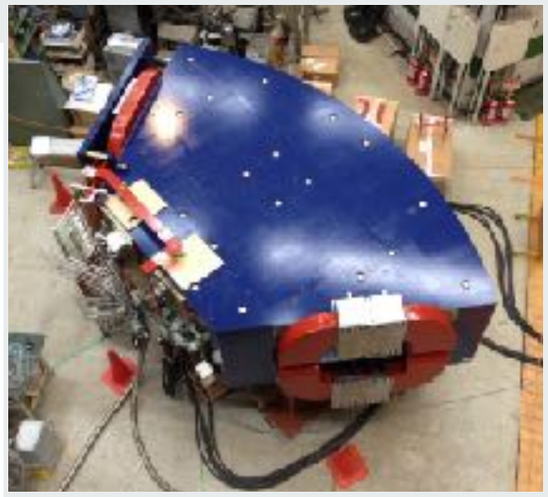


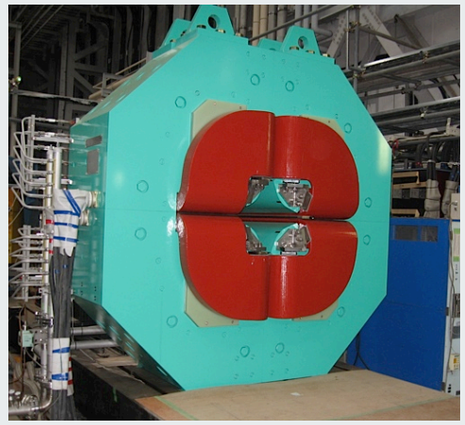
Two peak fit with ΔE=14 MeV

S-2S spectrometer

- SKS' in the pilot run → S-2S
  110 msr, 5.4 MeV 55 msr, 2 MeV

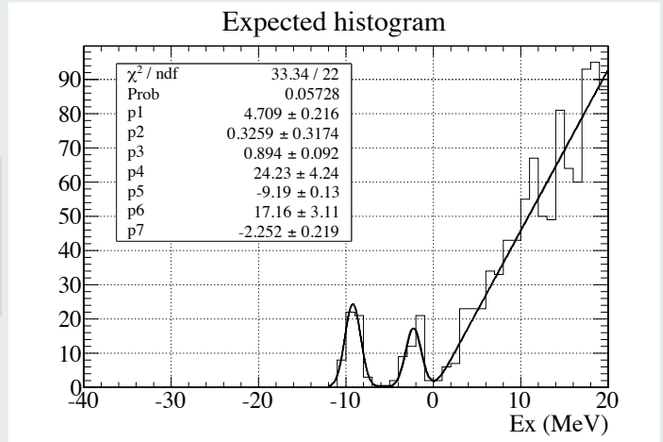


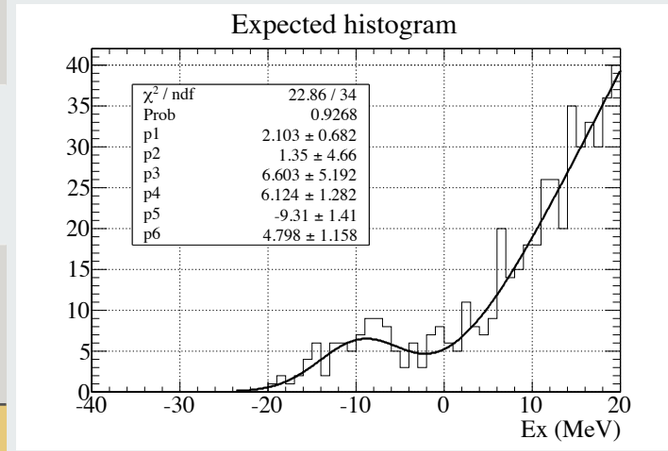




E70

Run Conditions	E05	E70
K^- intensity (M/spill)	0.6	1.31
MR beam power (kW)	39	85
Spill cycle (s)	5.52	4.7
Target thickness (g/cm^2)	9.3	10
Spectrometer acceptance (msr)	110	55
Missing-mass resolution (FWHM)	6	< 2
Signal events/days of running	40/10 days	~110/20 days



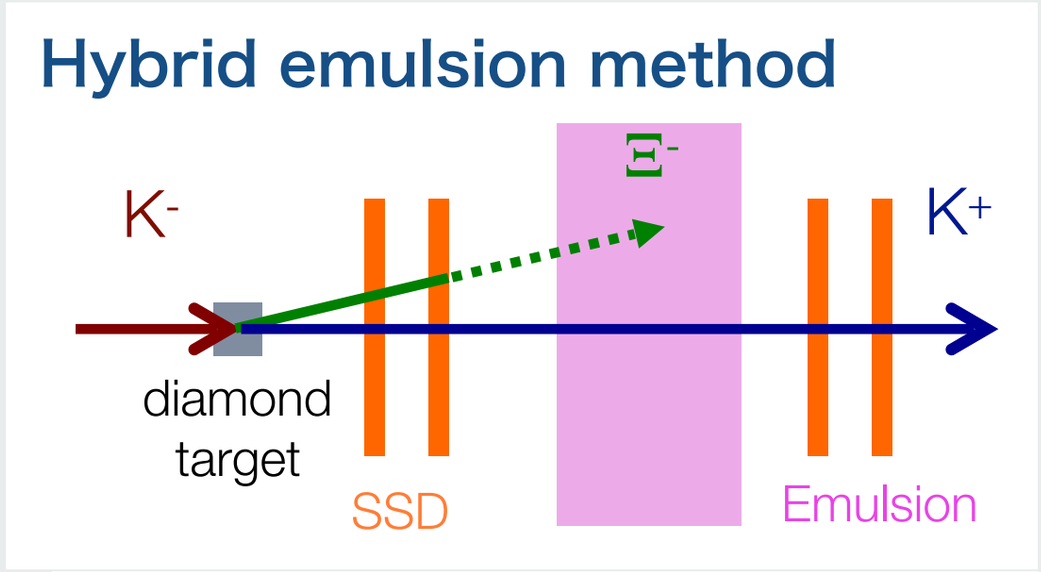


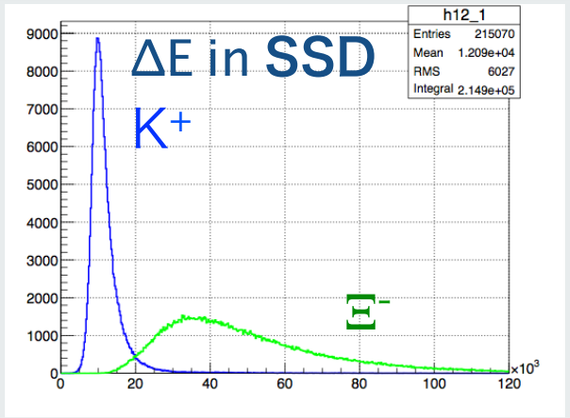
E07: Hybrid Emulsion experiment

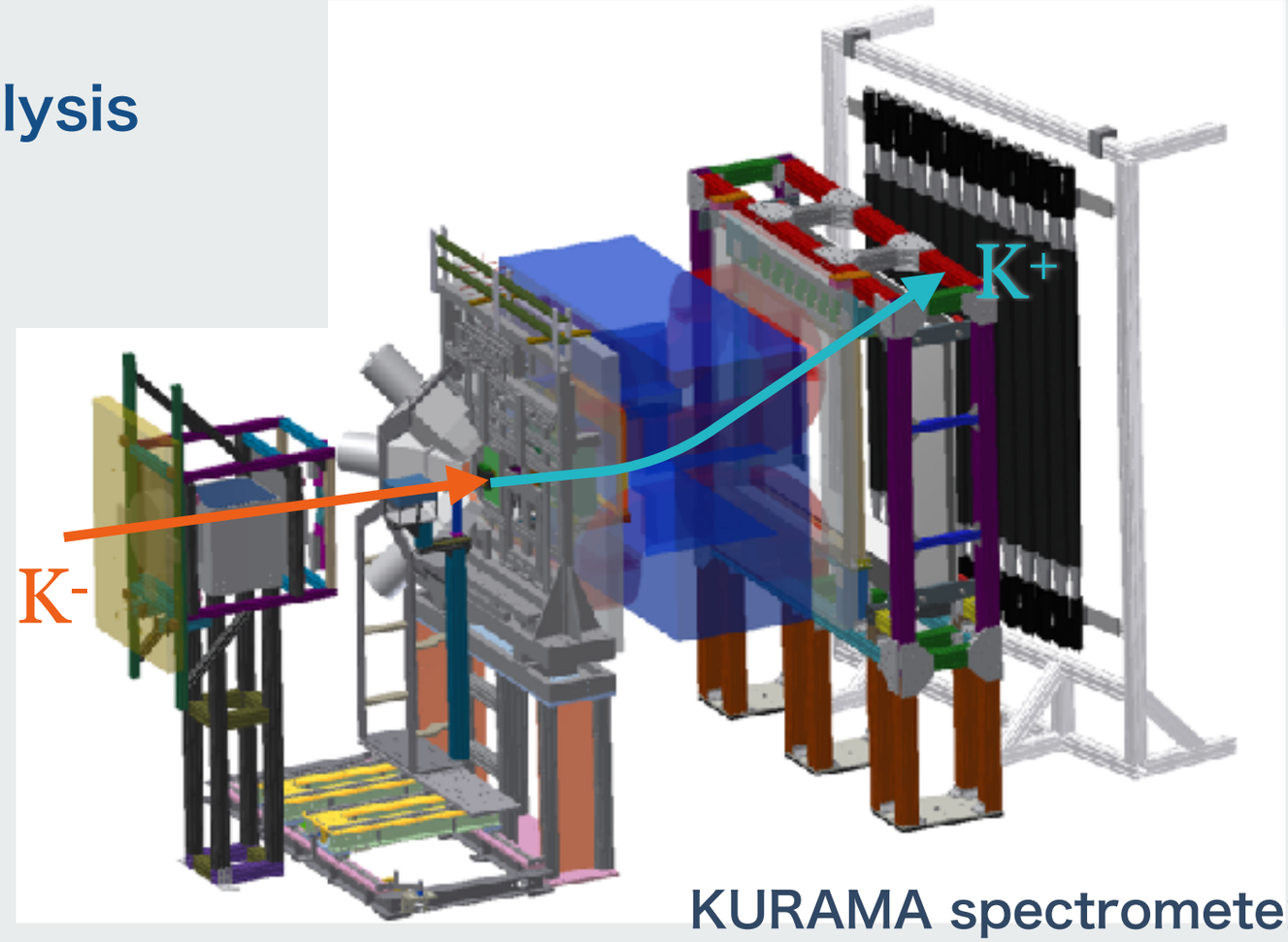
- Beam Exposure completed in June, 2017.
- Photographic Development completed.

Ξ⁻ statistics in spectrometer analysis

	stack	Ξ⁻ event	Ξ⁻ stop (simulation)
2016	18	27.9 k	1.13 k
2017	100	216 k	11.9 k



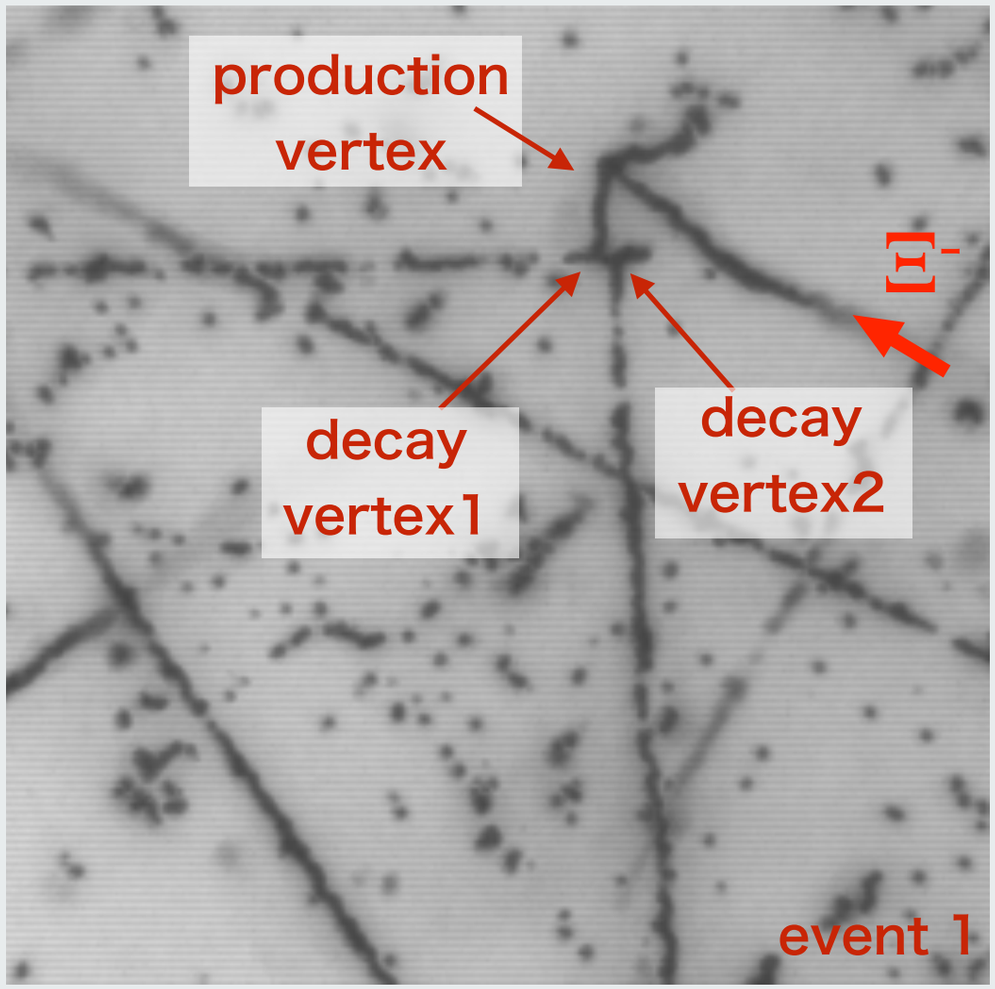




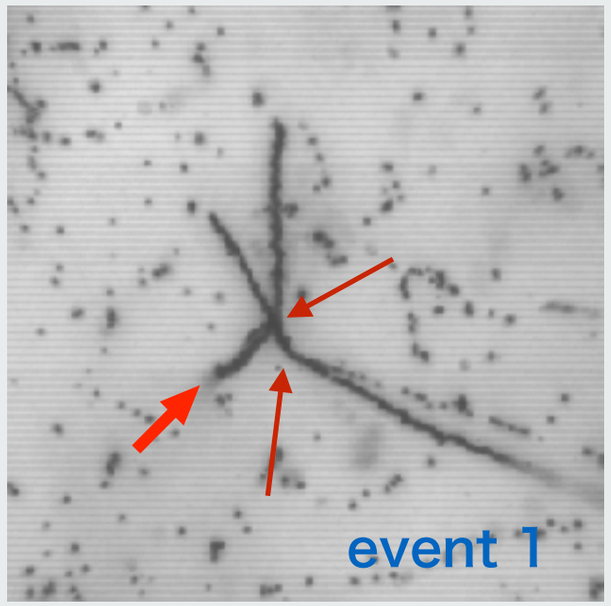
KURAMA spectrometer

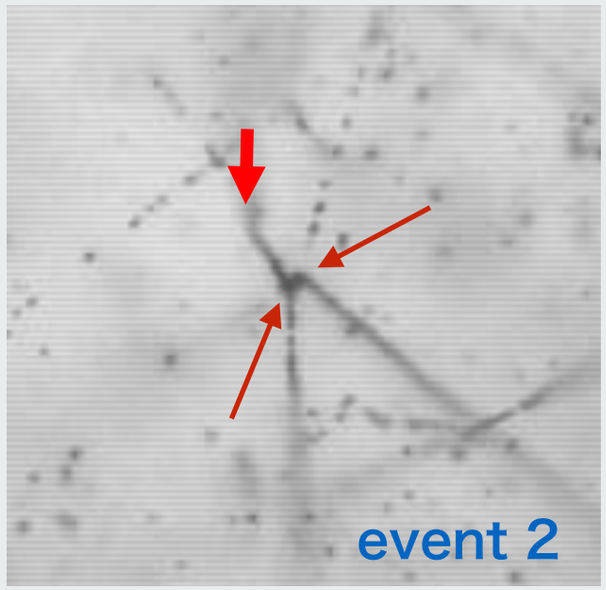
Scanning in progress

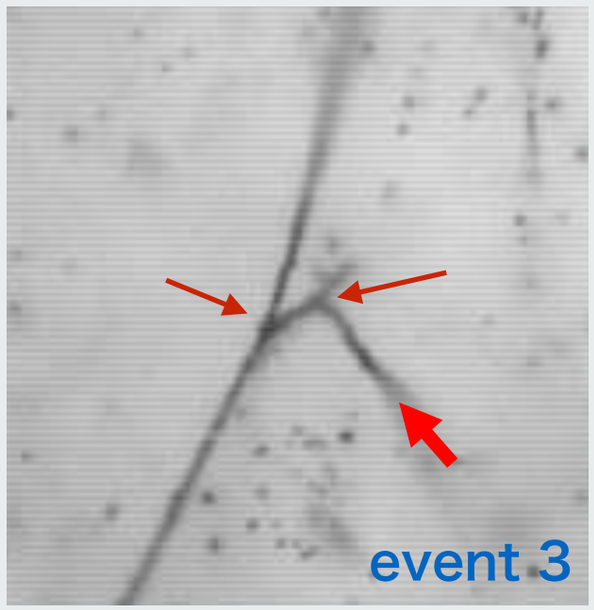
3 vertex event

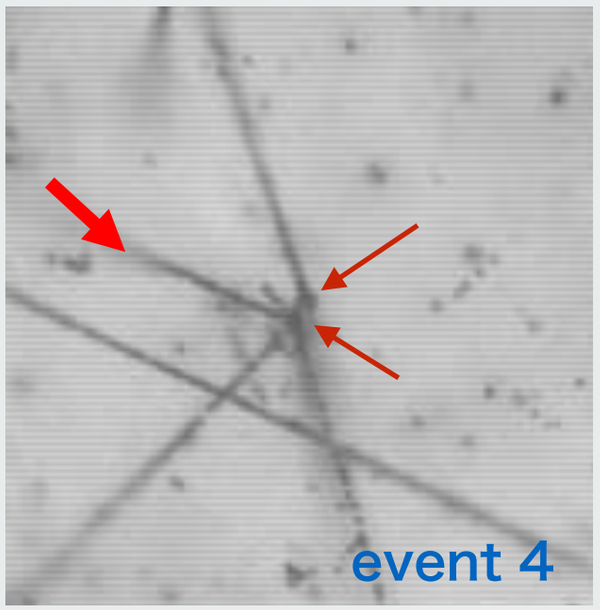


2 vertex events





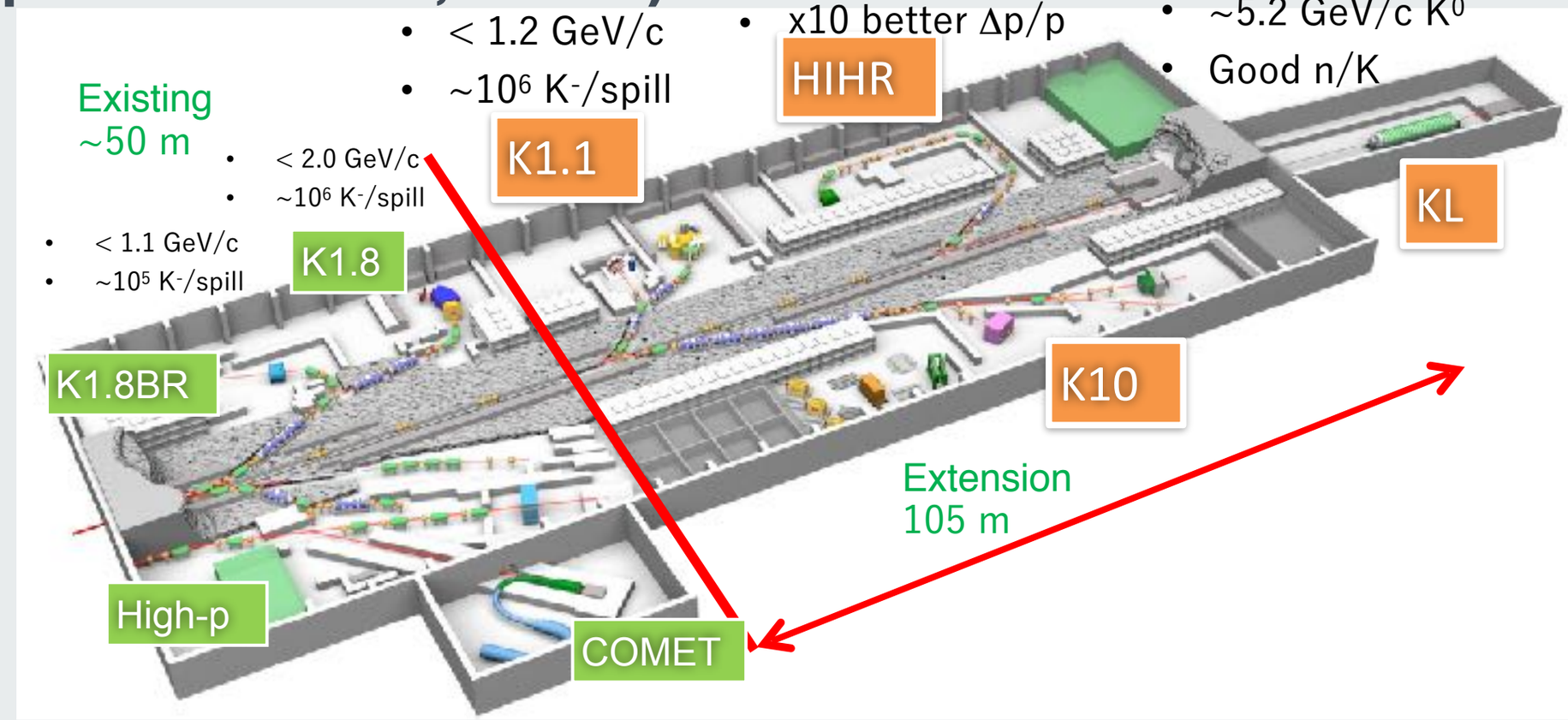




Several Hyper-fragments have been observed.

1 year for fast scanning of all the emulsions.

Hadron Hall Extension Plan (proposed for SCJ, MEXT)

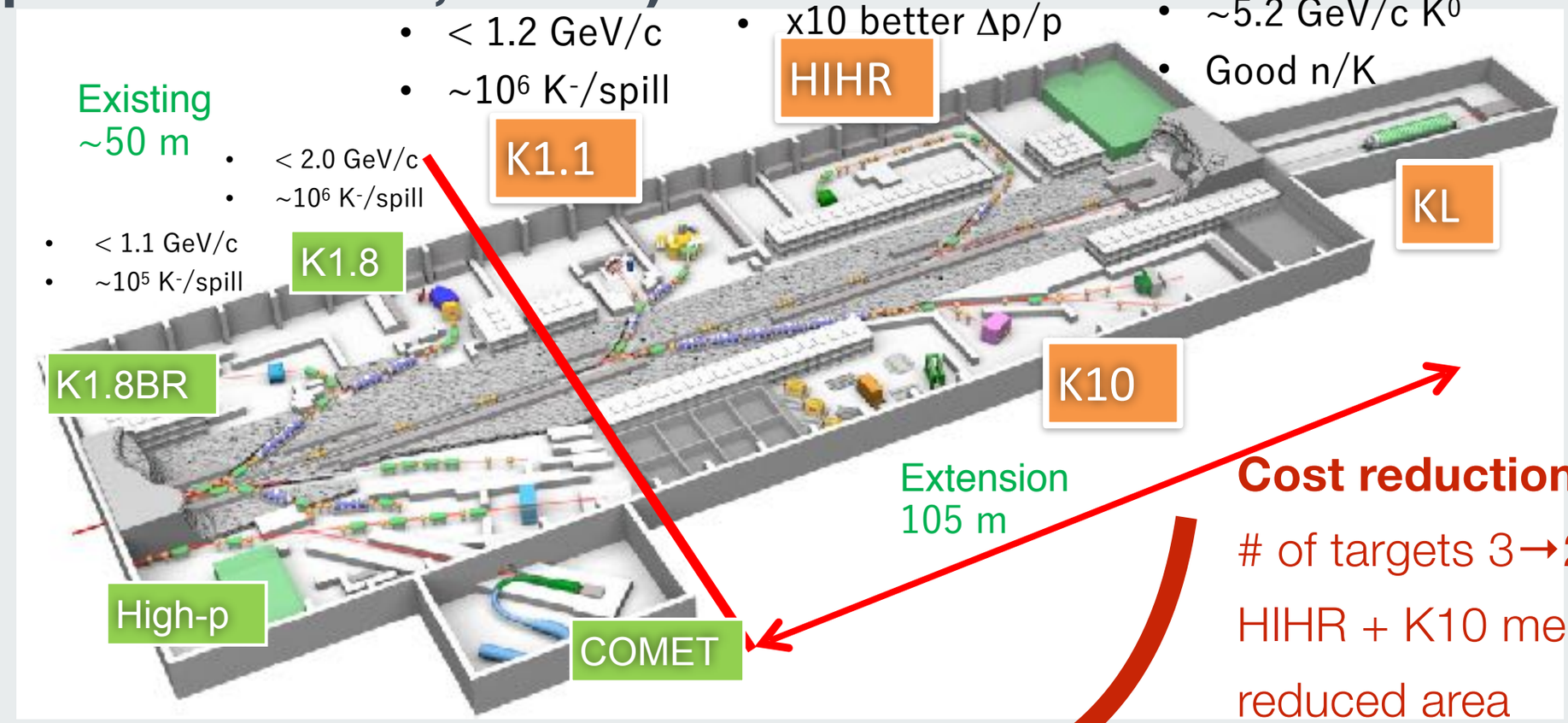


Hadron Hall Extension Plan (proposed for SCJ, MEXT)

- < 2.0 GeV/c
- 1.8x10⁸ pion/spill
- x10 better Δp/p

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

- < 1.2 GeV/c
- ~10⁶ K^-/spill

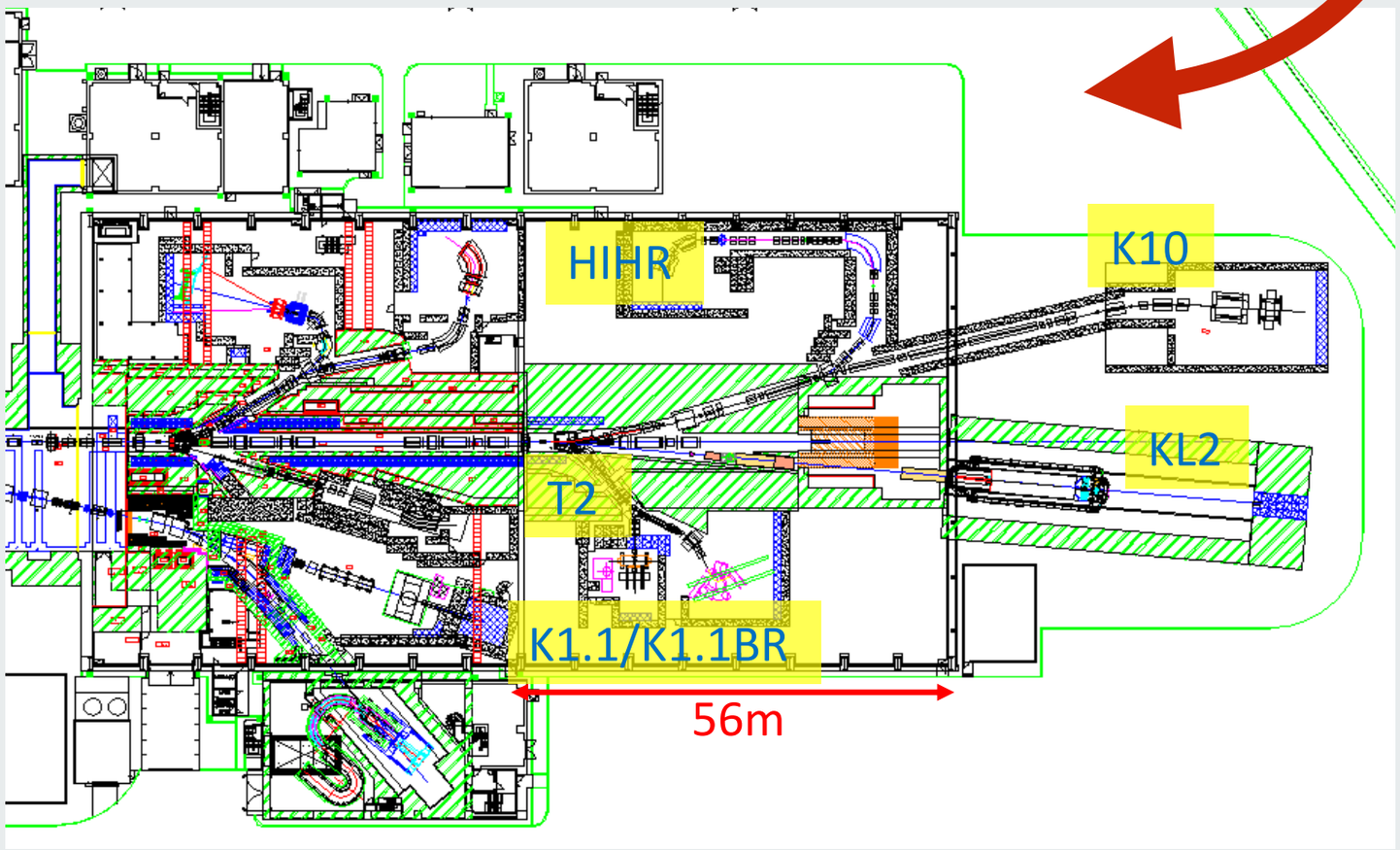


Cost reduction:

# of targets 3→2

HIHR + K10 merged

reduced area

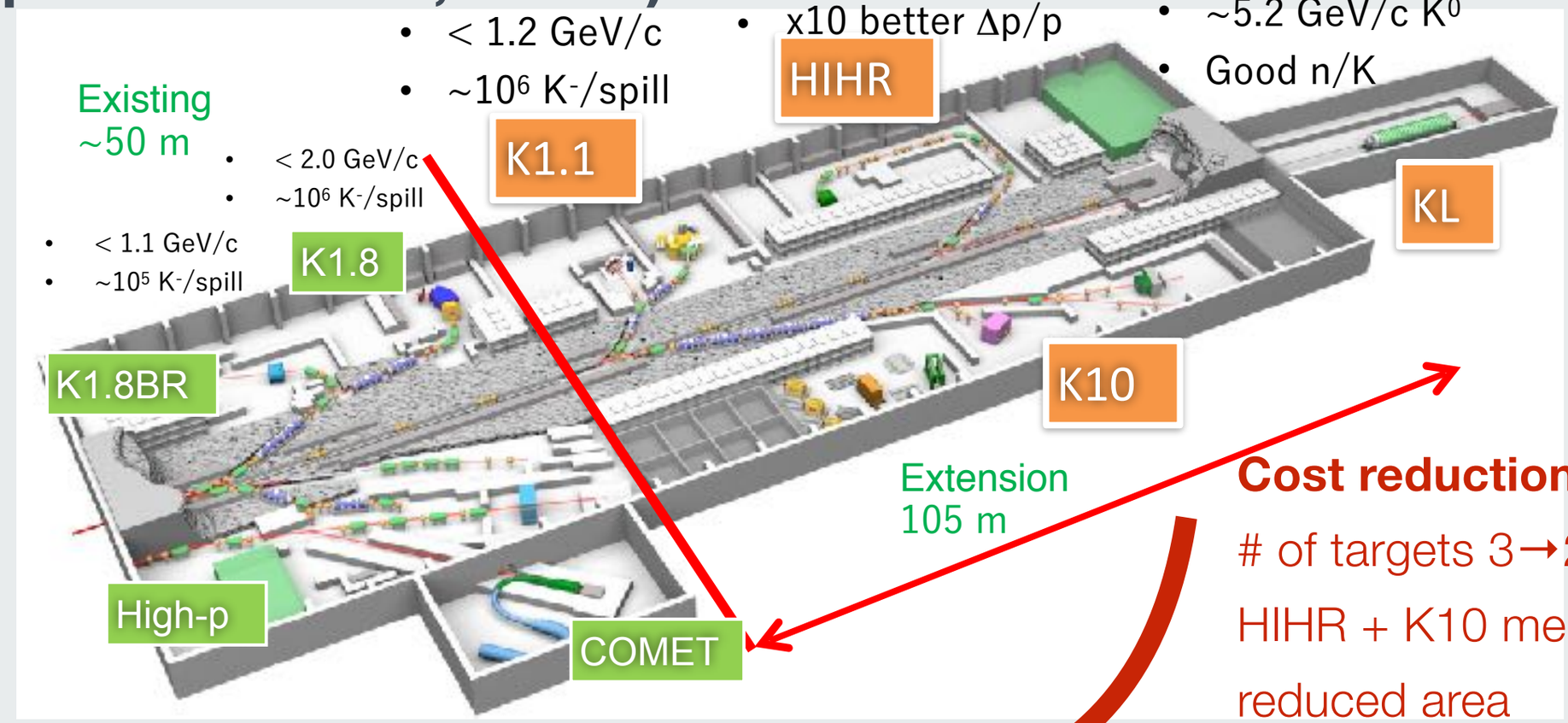


Hadron Hall Extension Plan (proposed for SCJ, MEXT)

- < 2.0 GeV/c
- 1.8×10^8 pion/spill
- x10 better $\Delta p/p$

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

- < 1.2 GeV/c
- ~10^6 K^-/spill

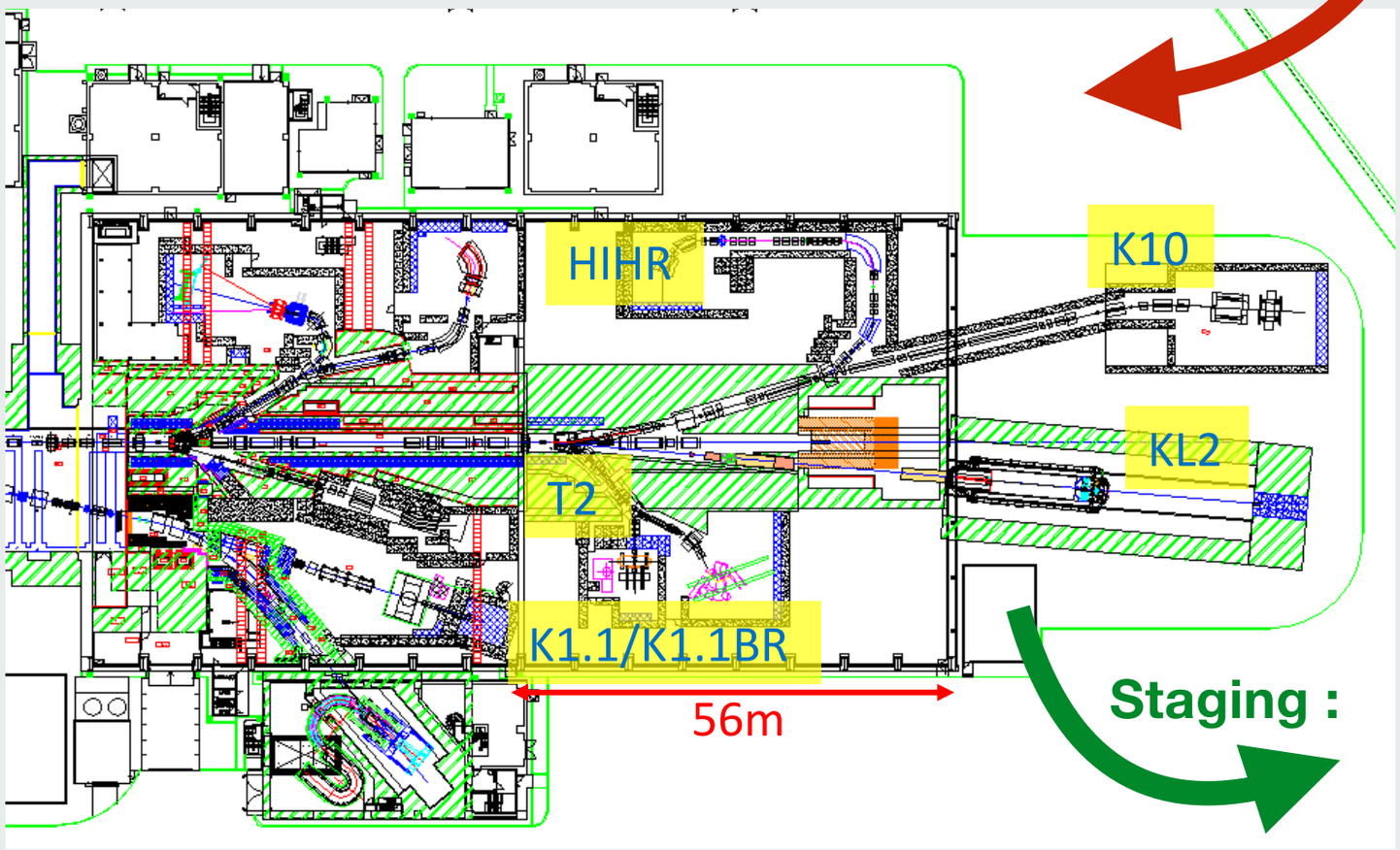


Cost reduction:

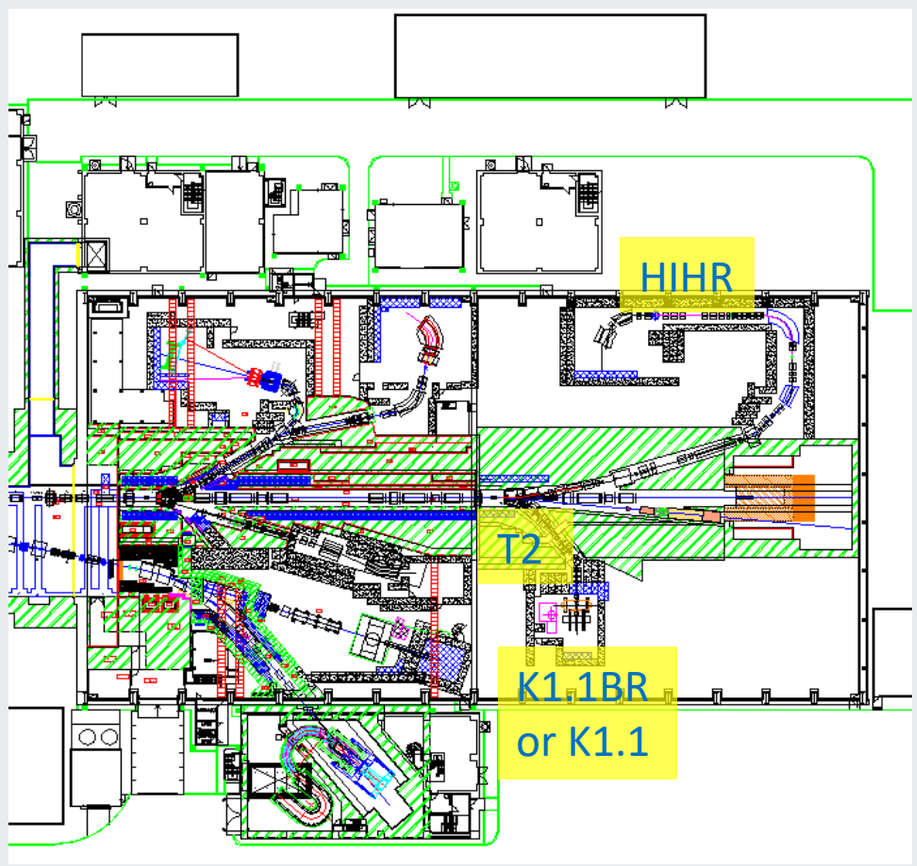
# of targets 3→2

HIHR + K10 merged

reduced area



Staging :

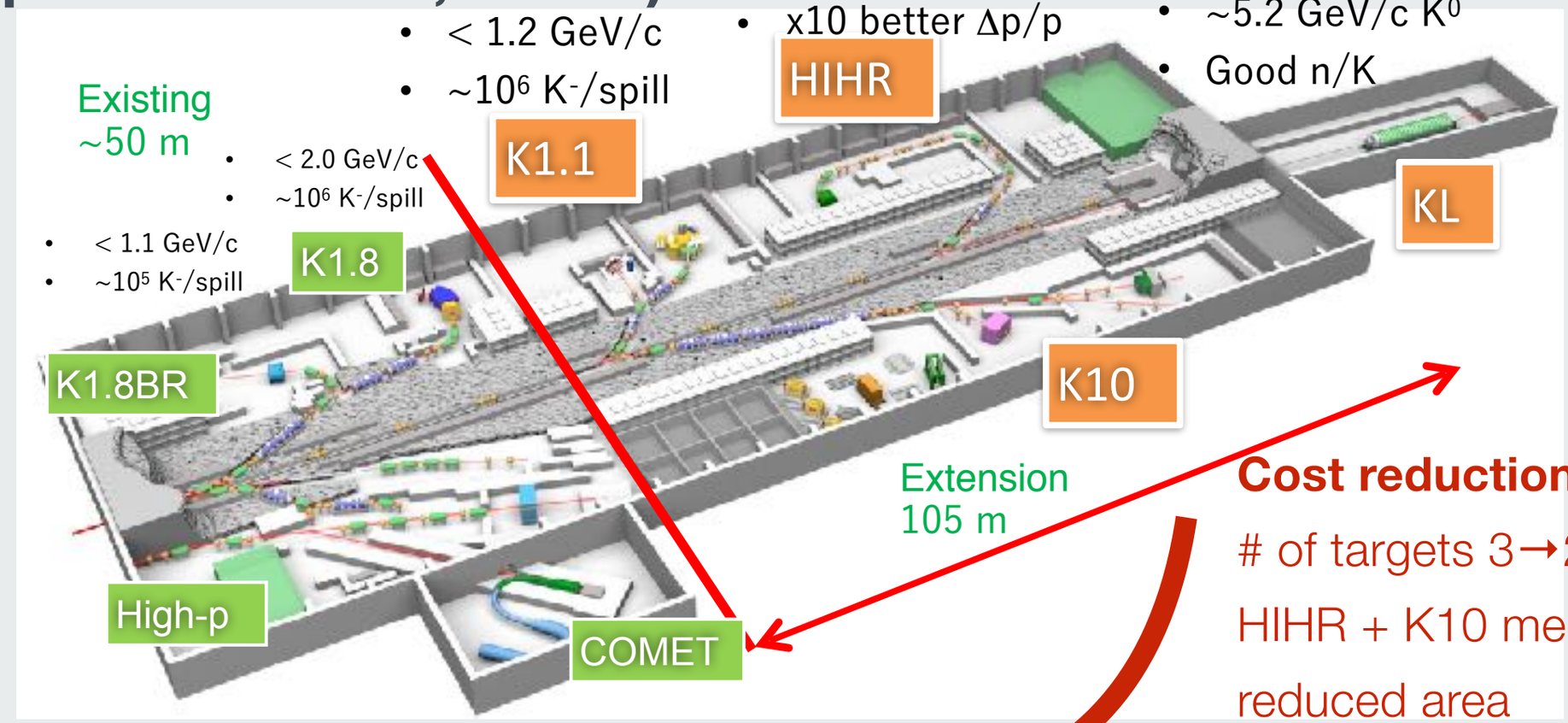


Hadron Hall Extension Plan (proposed for SCJ, MEXT)

- < 2.0 GeV/c
- 1.8×10^8 pion/spill
- x10 better $\Delta p/p$

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

- < 1.2 GeV/c
- ~10^6 K^-/spill

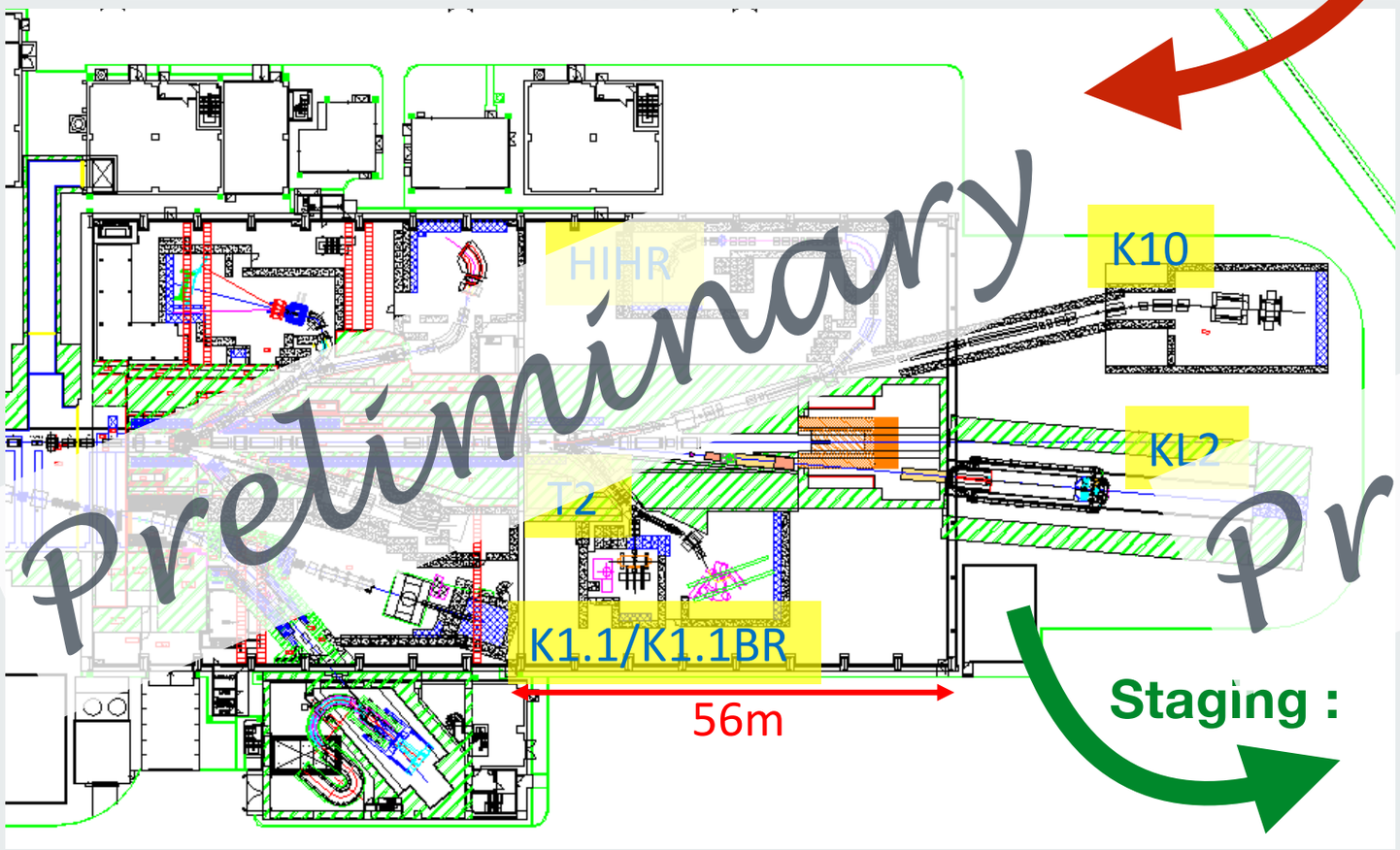


Cost reduction:

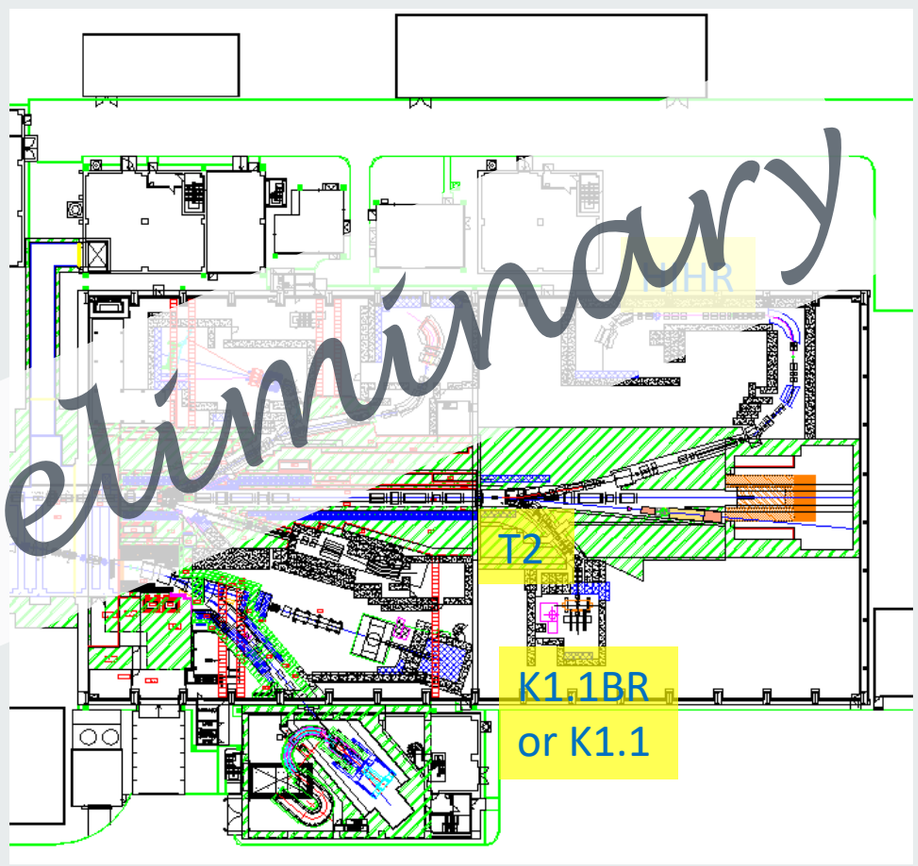
# of targets 3→2

HIHR + K10 merged

reduced area



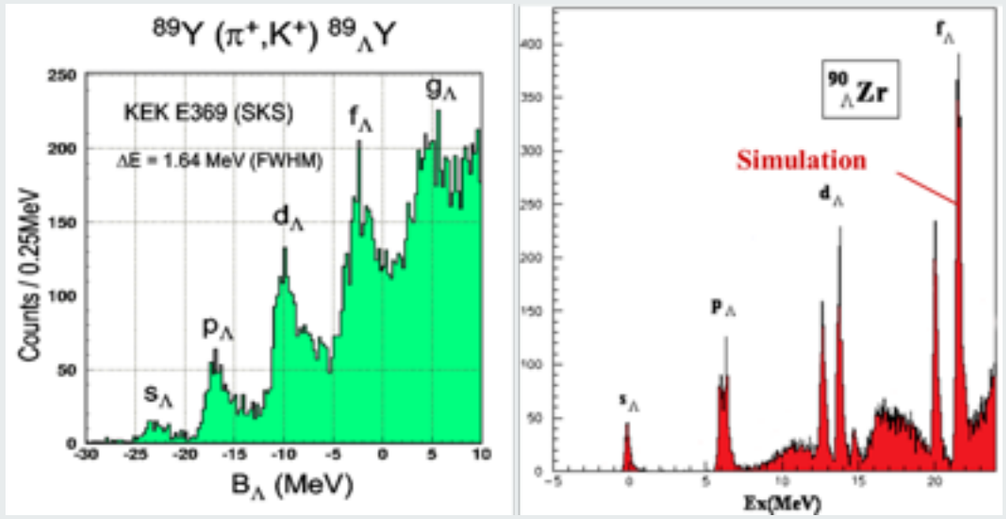
Staging :



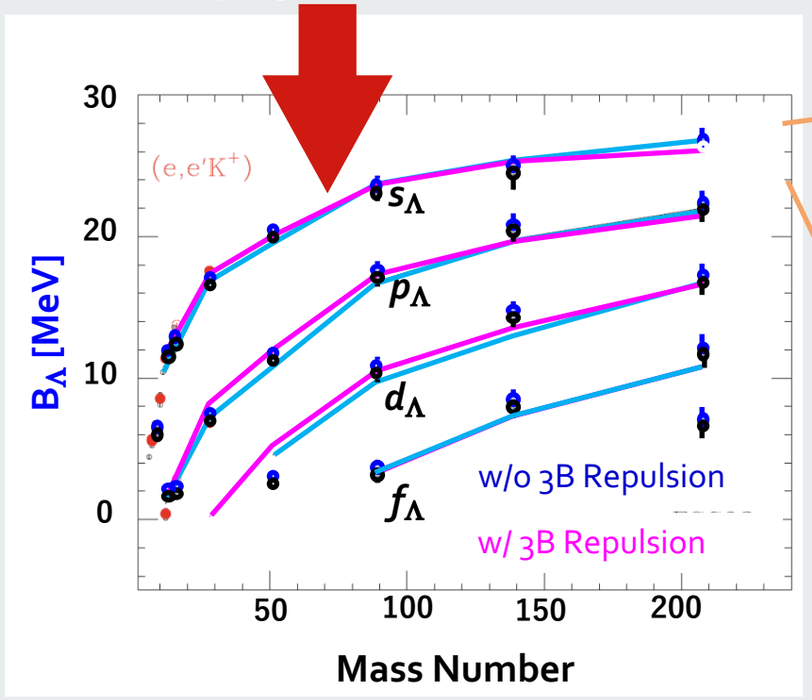
SπK spectroscopy

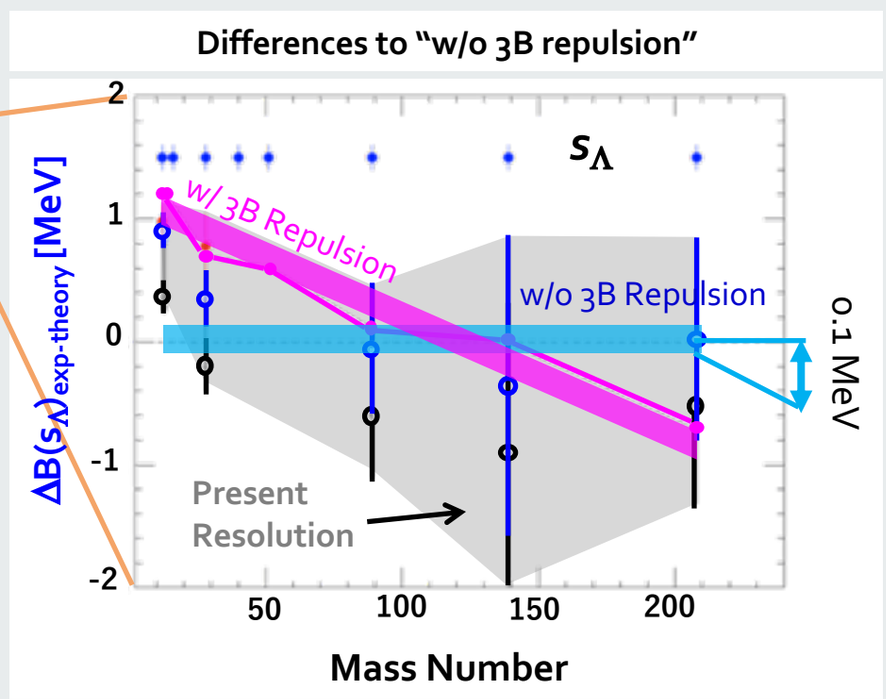
- Supra-precision (π,K) spectroscopy to probe 3-body YNN force with ΔE~0.1 MeV

KEK-PS E369 with SKS → Expected at HIHR beam line



~60 days @ 3M π⁺/spill ~30 days @ 180M π⁺/spill



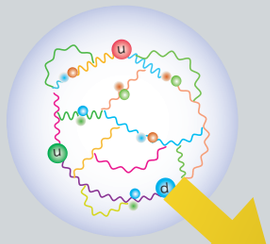


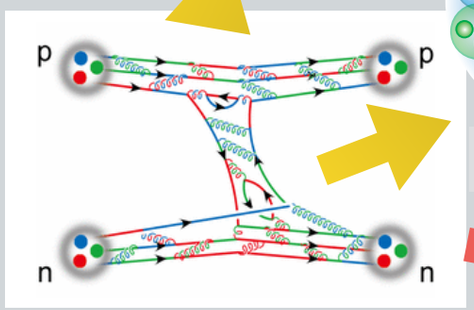
Verification of 3-body repulsion can be a solution to the Hyperon Puzzle.

Science Goal

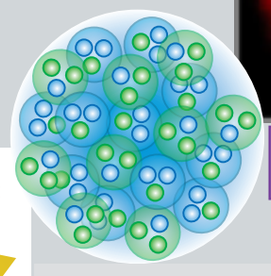
YKIS2018

A=1
Quark Confinement

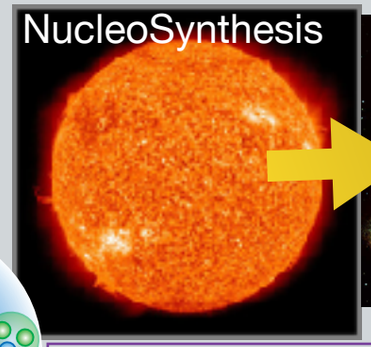


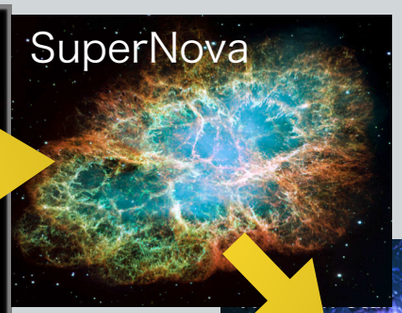


A=2
Baryon Interactions (Nuclear Force)



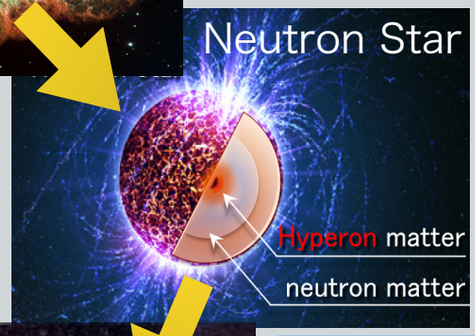
Ordinary Nuclei

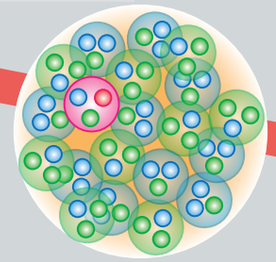




u, d-quark World

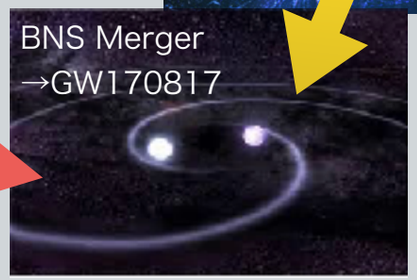
Heavy Nuclei ?





Λ, Σ Hypernuclei

u, d, s-quark world



Dense Matter Physics
r-Process Site

A=∞

Science Goal

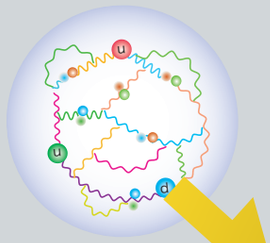
YKIS2018

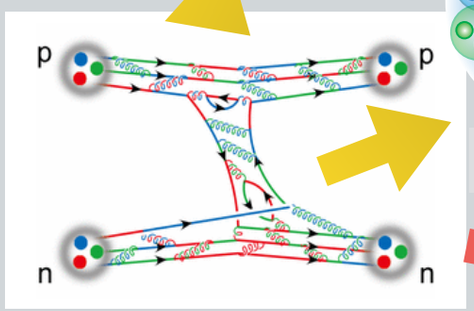
LatticeQCD

HAL QCD

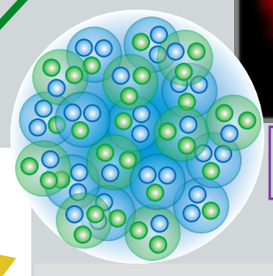
Numerical Relativity simulation

A=1
Quark Confinement

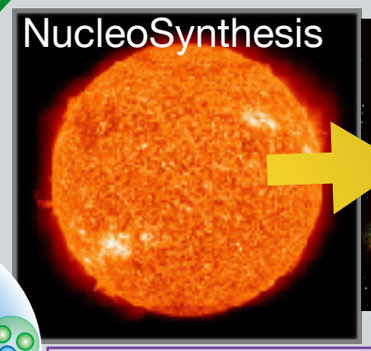




A=2
Baryon Interactions (Nuclear Force)

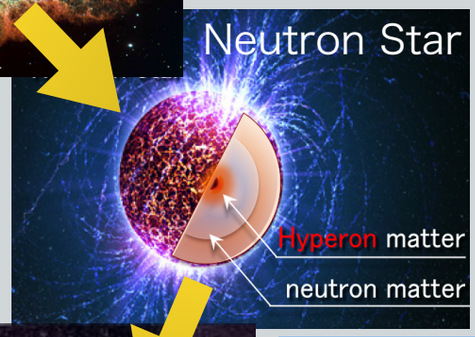


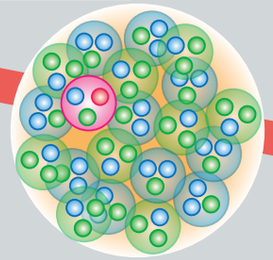
Ordinary Nuclei



u, d-quark World

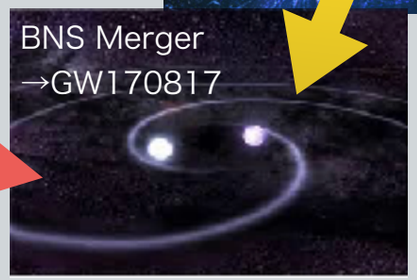
Heavy Nuclei ?





Λ, Σ Hypernuclei

u, d, s-quark world



Dense Matter Physics
r-Process Site

A=∞

Science Goal

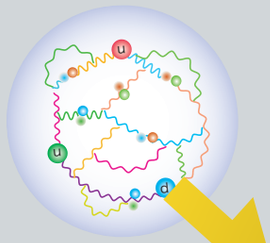
YKIS2018

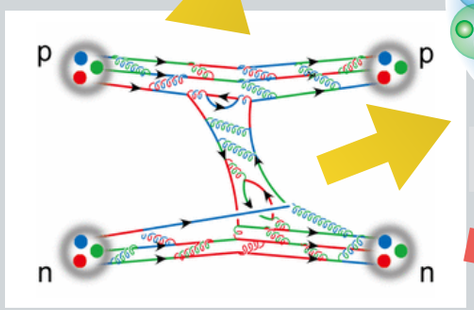
LatticeQCD

HAL QCD

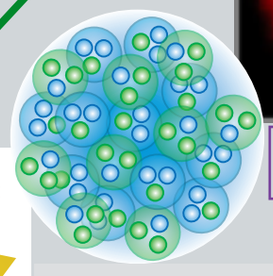
Numerical Relativity simulation

A=1
Quark Confinement

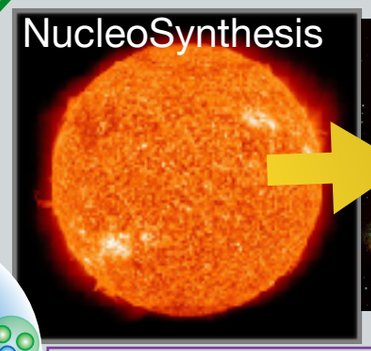




A=2
Baryon Interactions (Nuclear Force)

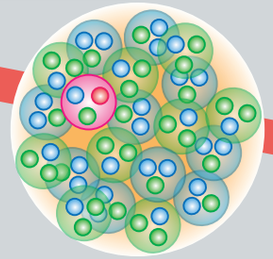


Ordinary Nuclei



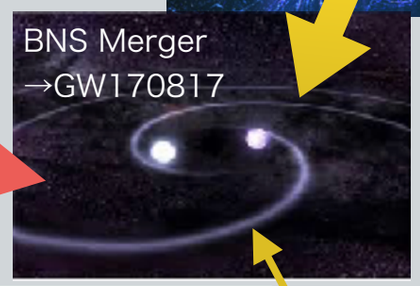
u, d-quark World

Heavy Nuclei ?



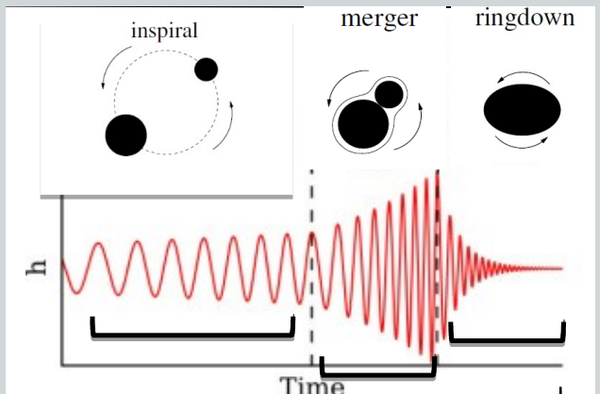
Λ, Σ Hypernuclei

u, d, s-quark world



Dense Matter Physics
r-Process Site

A=∞



SUMMARY

YKIS2018

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

- Strong evidence for Ξ-Hypernuclei in E05 together with the “Kiso” event.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

- Strong evidence for Ξ-Hypernuclei in E05 together with the “Kiso” event.

- E07 completed the emulsion exposure in 2017, and under scanning.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

- Strong evidence for Ξ-Hypernuclei in E05 together with the “Kiso” event.

- E07 completed the emulsion exposure in 2017, and under scanning.

- Data taking on E31, E40, are on-going in 2018 with 50 kW.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

- Strong evidence for Ξ-Hypernuclei in E05 together with the “Kiso” event.

- E07 completed the emulsion exposure in 2017, and under scanning.

- Data taking on E31, E40, are on-going in 2018 with 50 kW.

- New 90 kW target to be installed in 2019 for conducting S=-2 experiments.

SUMMARY

YKIS2018

- GW170817; Binary NS merger
  → New era of Dense matter physics

- New insight on Λ(1405) in E31.

- Large Charge-Symmetry Breaking in A=4 hypernuclei

- $^{19}_{\Lambda}$F γ-rays are measured in sd-shell, for the first time.

- Strong evidence for Ξ-Hypernuclei in E05 together with the “Kiso” event.

- E07 completed the emulsion exposure in 2017, and under scanning.

- Data taking on E31, E40, are on-going in 2018 with 50 kW.

- New 90 kW target to be installed in 2019 for conducting S=-2 experiments.

- Hadron Hall Future Plan: cost reduction and staging options are in discussion, focusing on Dense matter physics.