Forefront Research Program (b)

New forms of hadronic nuclei

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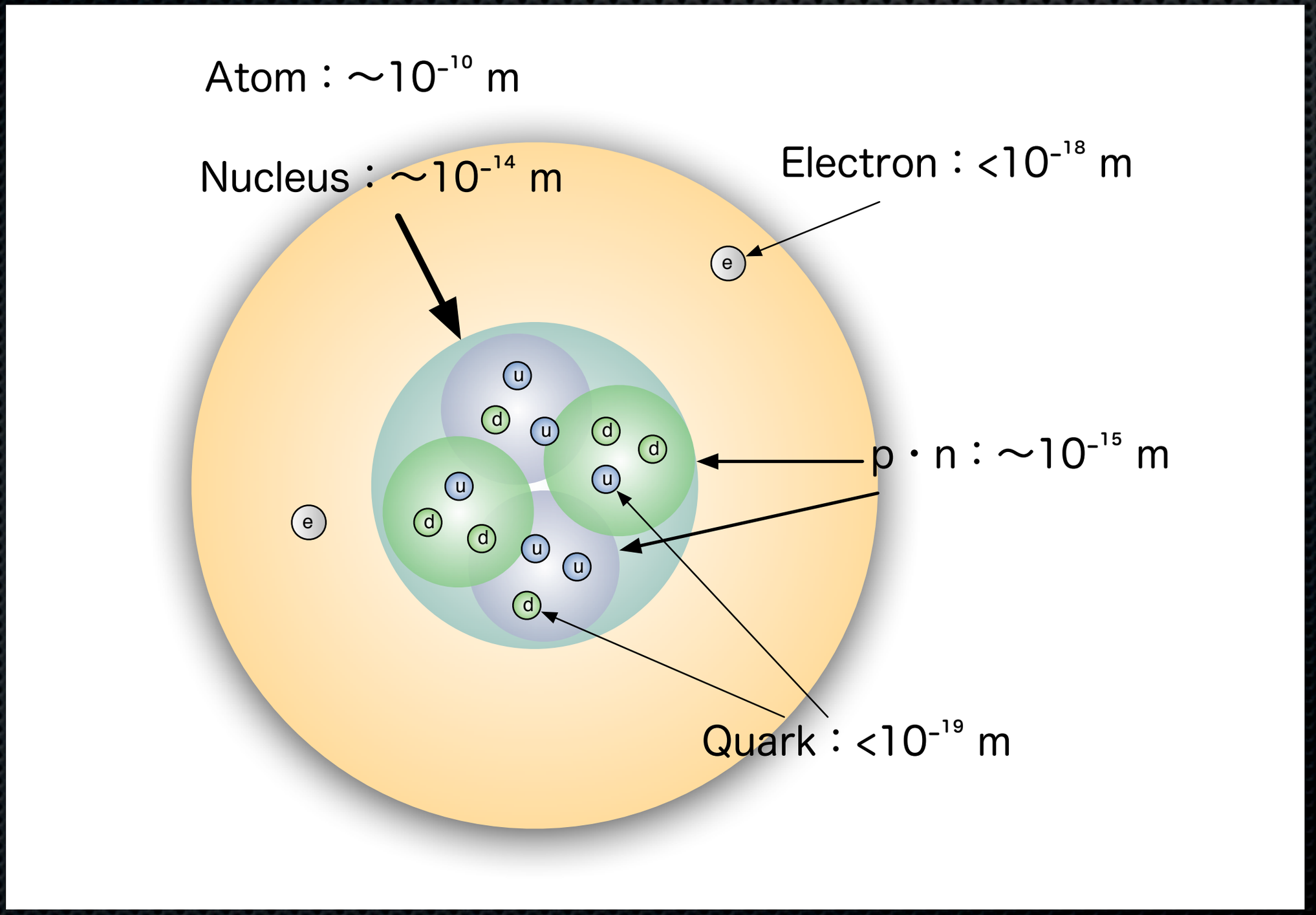
Kyoto University

GCOE Sympo.,
Kyoto,
12-Feb.-2013

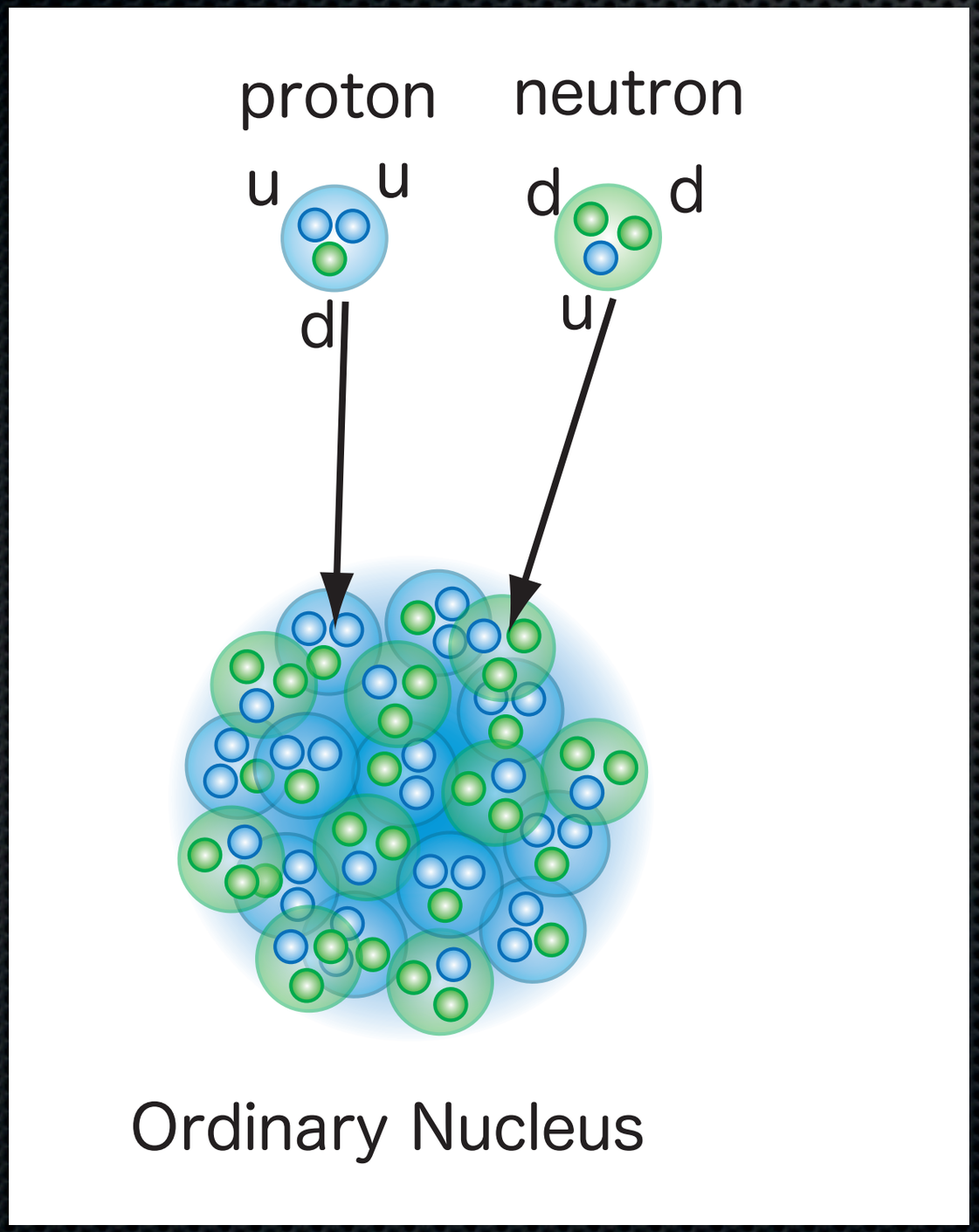
Contents

- Introduction of Hadronic Nuclei
- Recent topics in Strangeness Nuclear Physics
- Strangeness Nuclear Physics program at J-PARC
  - E19, E27,
  - ..., E15, E10, E05
- Summary

Normal Nuclei



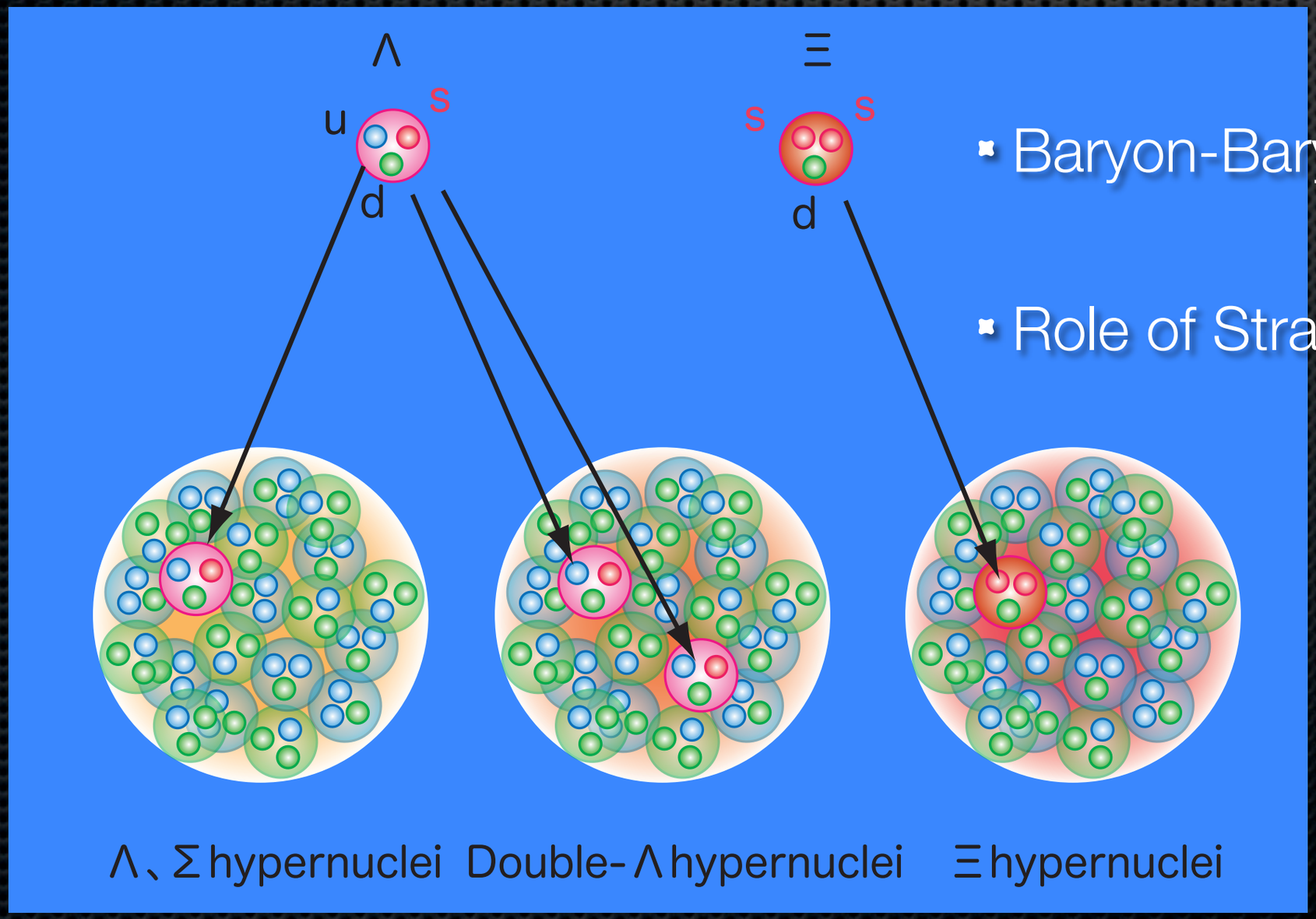
Normal Nuclei



+2/3e	-1/3e
Up 3	Down 6
Charm 1,250	Strange 100
Top 174,300	Bottom 4,300

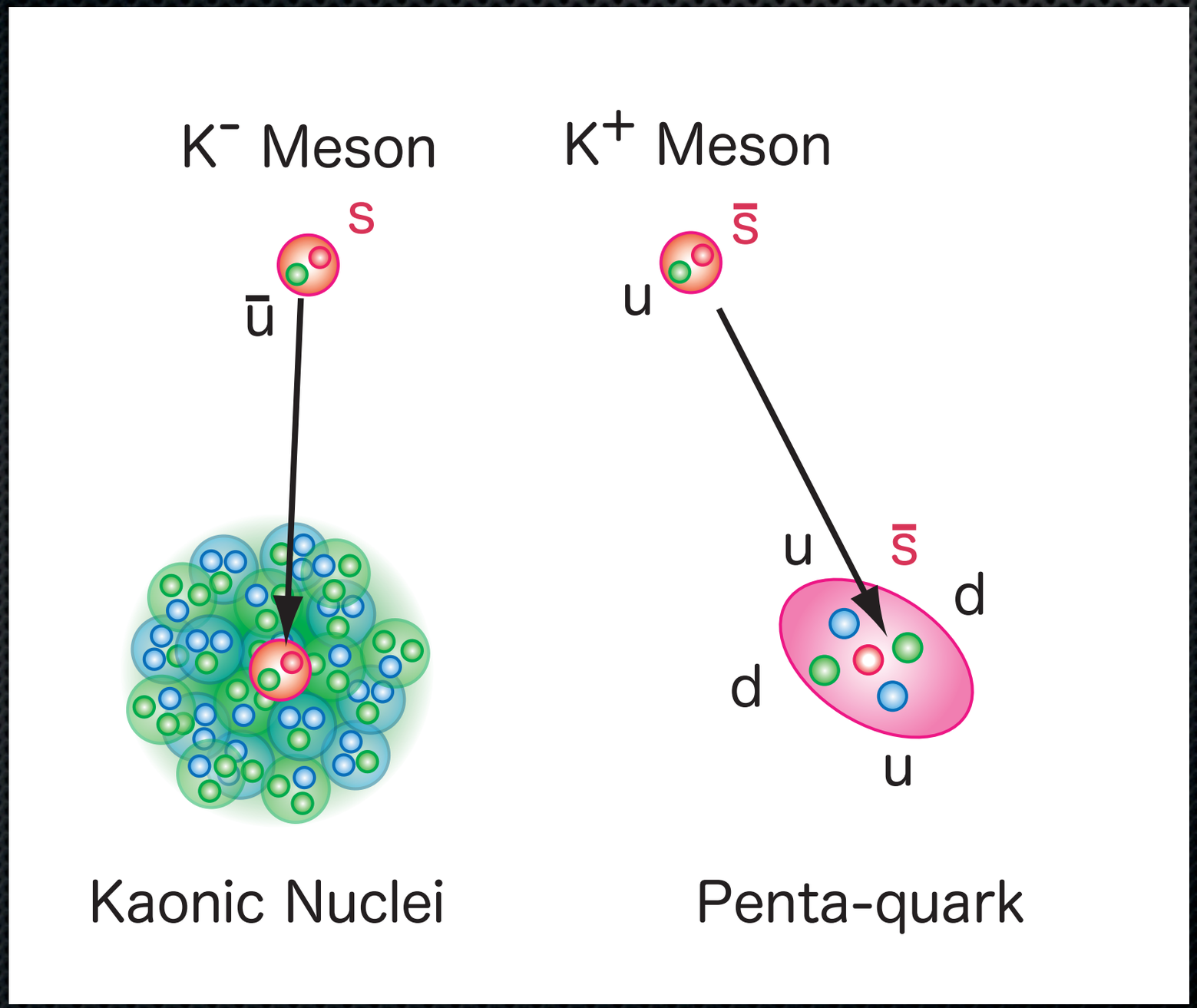
Hadronic Nuclei with Strangeness

- Hypernuclei : Hyperons(Λ, Σ, Ξ) in Nuclei



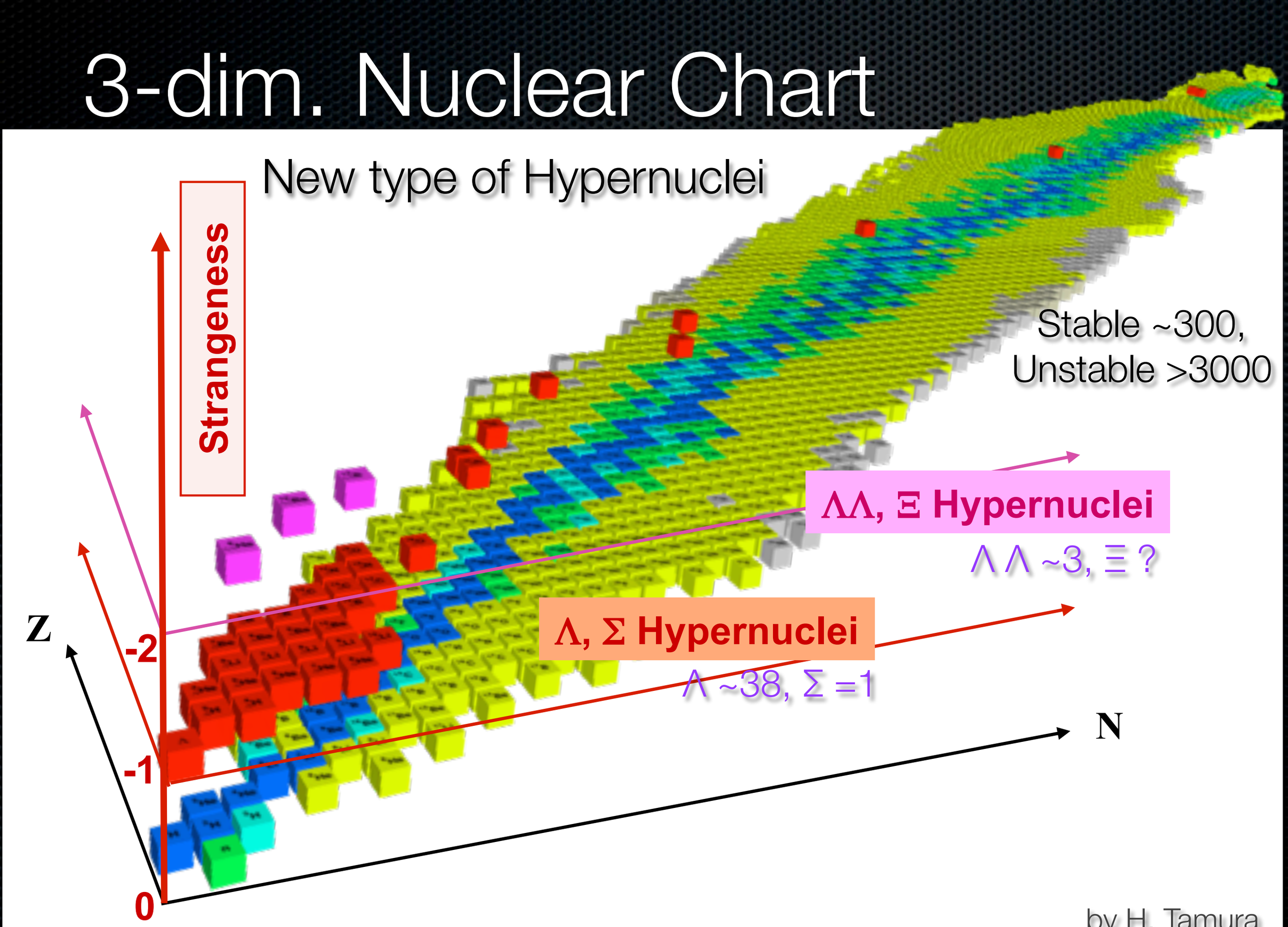
- Baryon-Baryon Interactions in $SU_F(3)$
- Role of Strangeness in Dense Matter

Exotic Systems



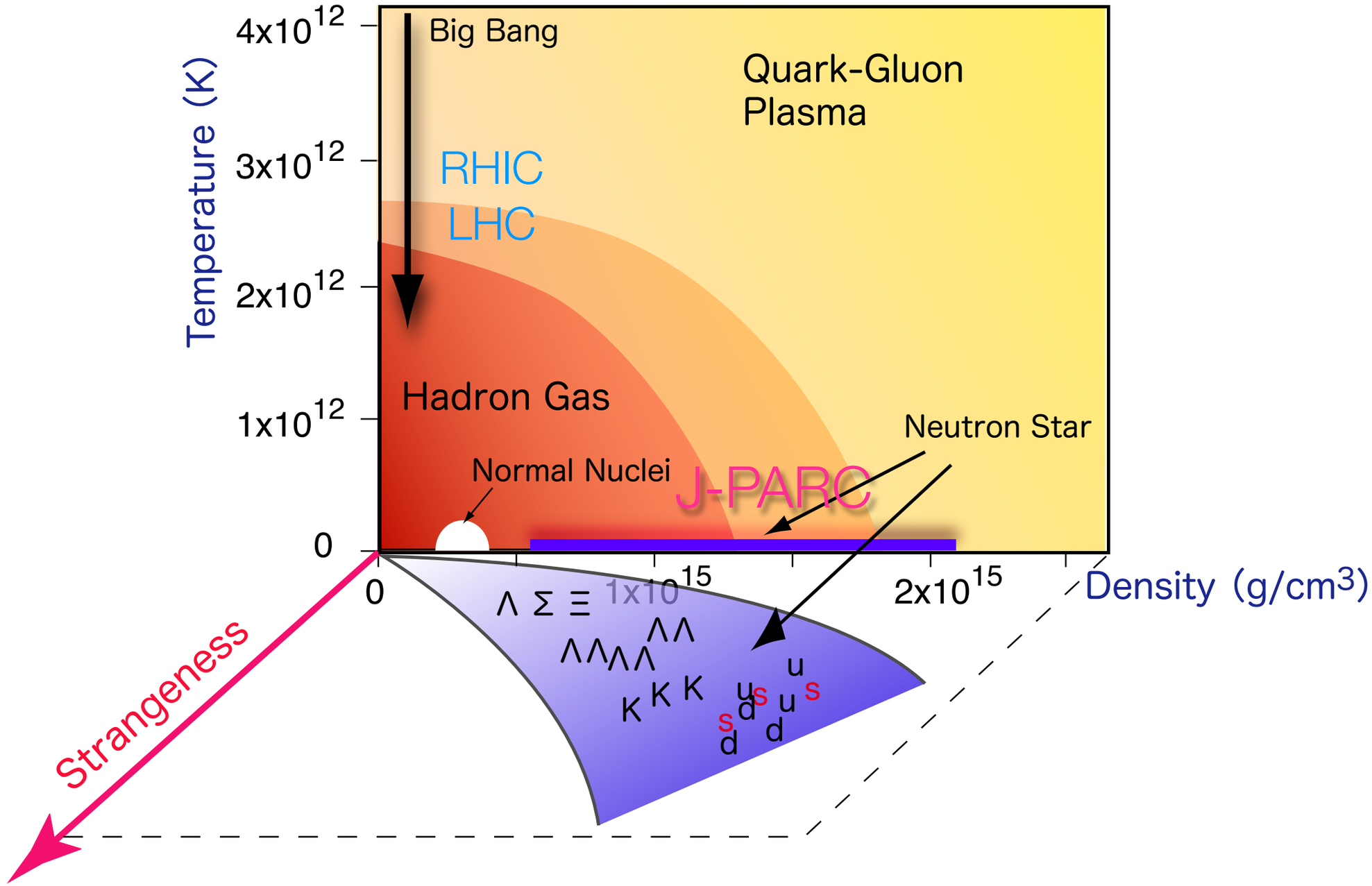
3-dim. Nuclear Chart

New type of Hypernuclei



by H. Tamura

Role of strangeness in dense matter



From 1974 Nobel Lecture by A. Hewish , “Pulsars and High Density Physics”,

- At yet deeper levels the neutron-neutron interaction may result in the creation of a solid neutron lattice, although this possibility is under debate, and finally there is the question of a material composed of stable hyperons

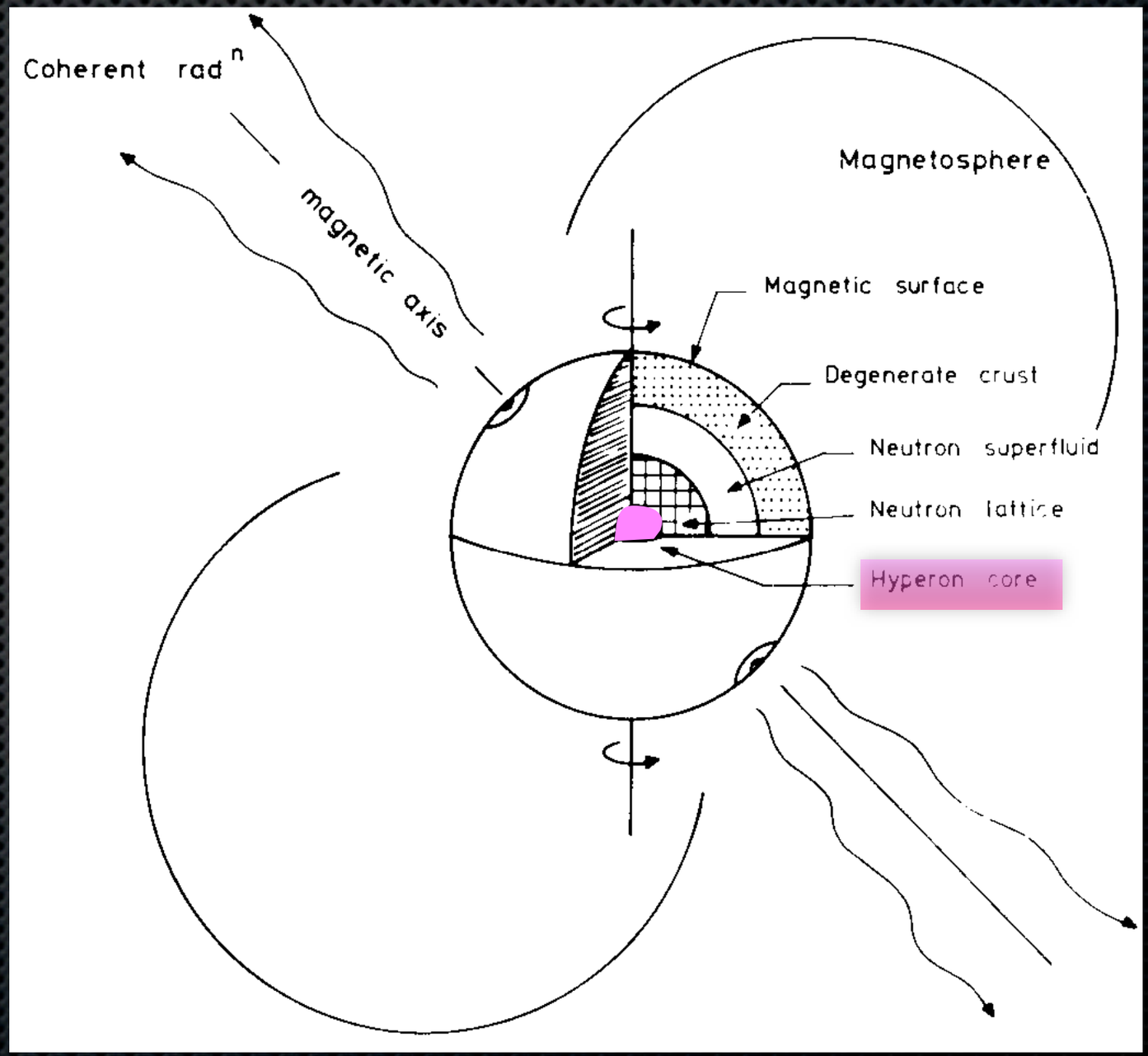
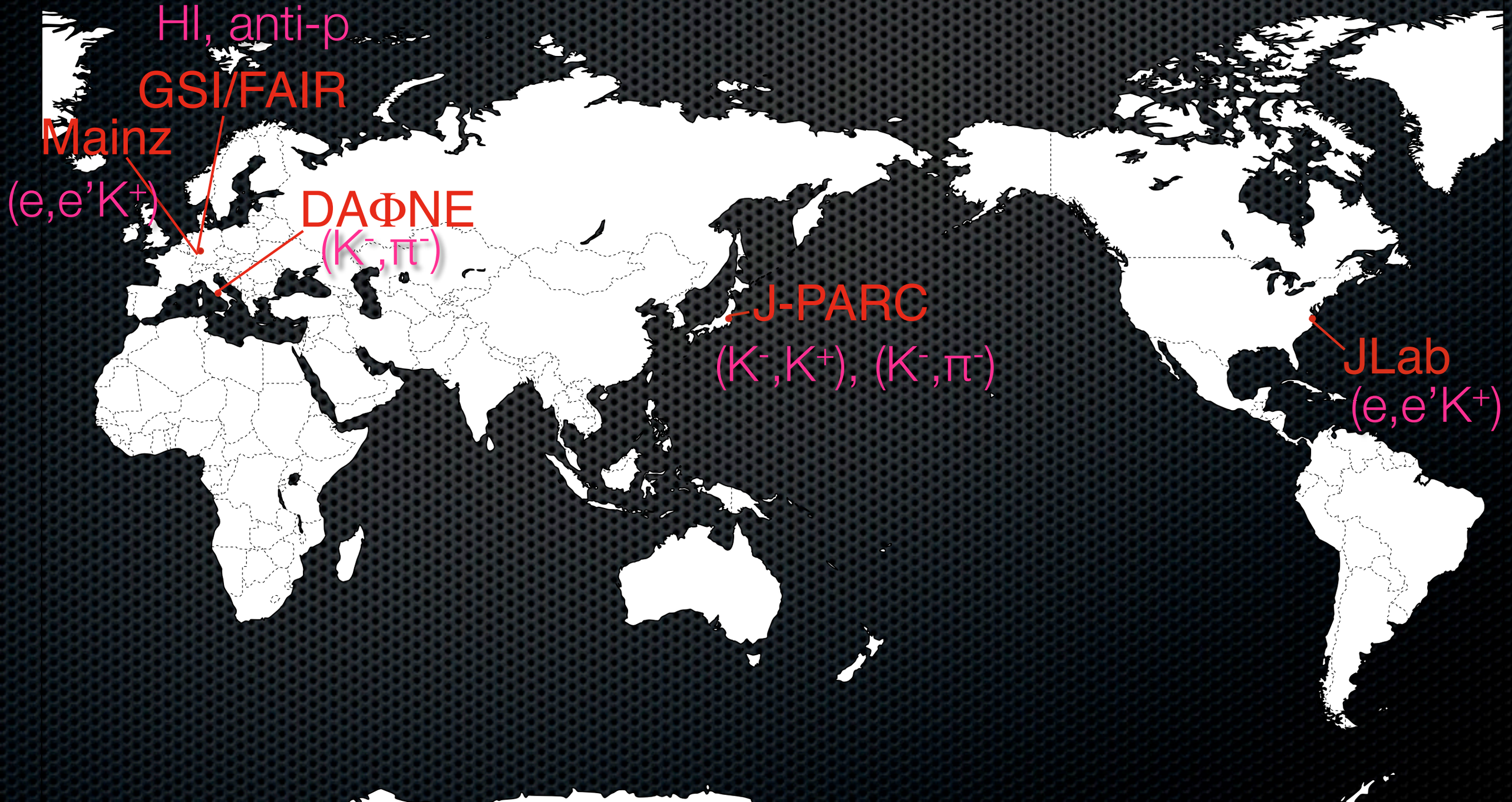
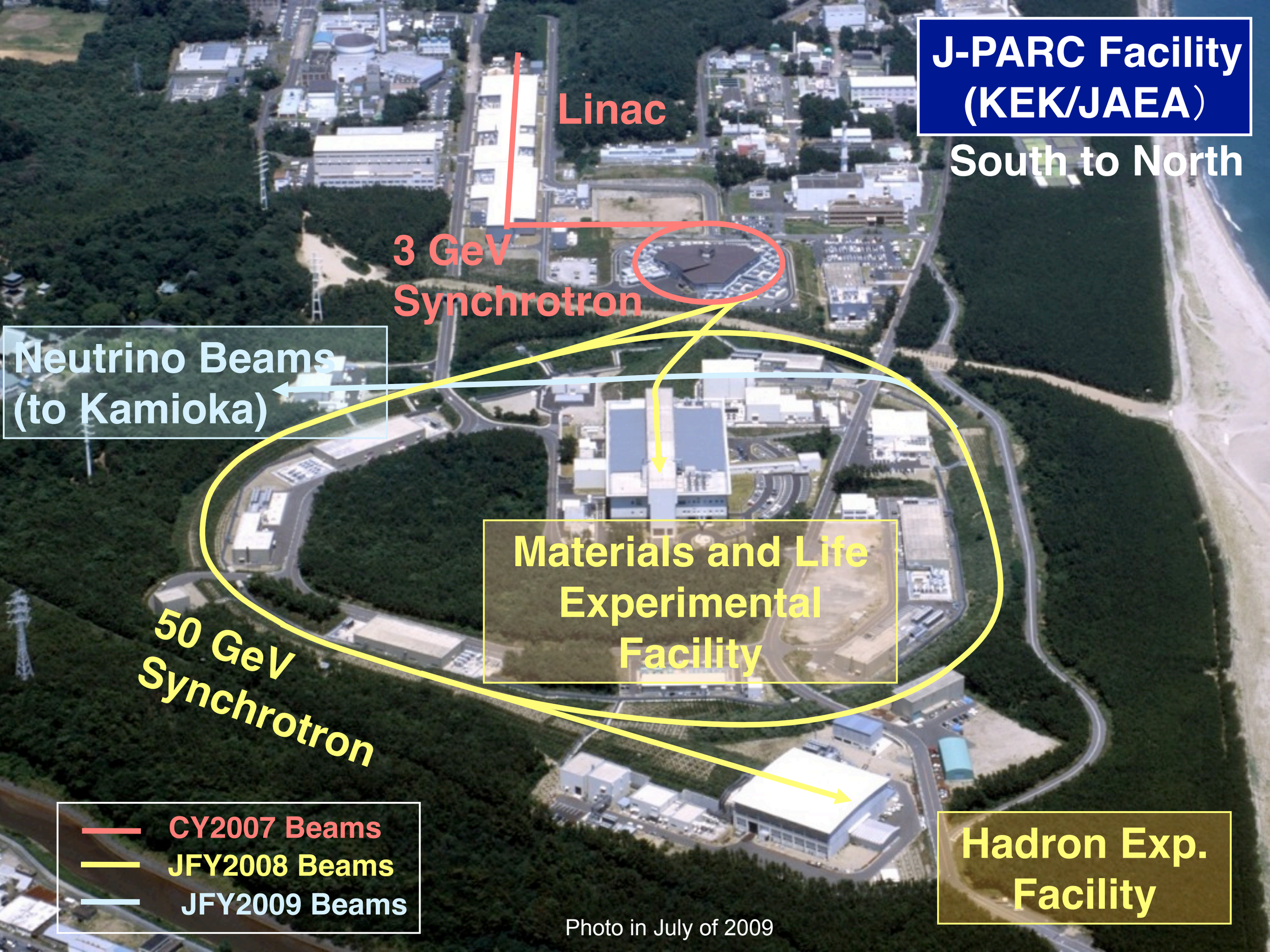


Fig. 5. Model of a neutron star

Strangeness nuclear physics can have an answer

World Facilities in the 21st Century




J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Hadron Exp.
Facility
Photo in July of 2009

Recent topics
In Strangeness Nuclear Physics

${}^{6}_{\Lambda}$H in FINUDA

M. Agnello et al.,
PRL 108 (2012) 042501.

- Produced in the ^{6}Li(K^-_{stop},π^+) reaction

Glue-like role of Λ

$$K^-_{\text{stop}} + {}^{6}\text{Li} \rightarrow {}^{6}_{\Lambda}\text{H} + \pi^+ (p_{\pi^+} \sim 252\ \text{MeV}/c)$$

$${}^{6}_{\Lambda}\text{H} \rightarrow {}^{6}\text{He} + \pi^- (p_{\pi^-} \sim 134\ \text{MeV}/c)$$

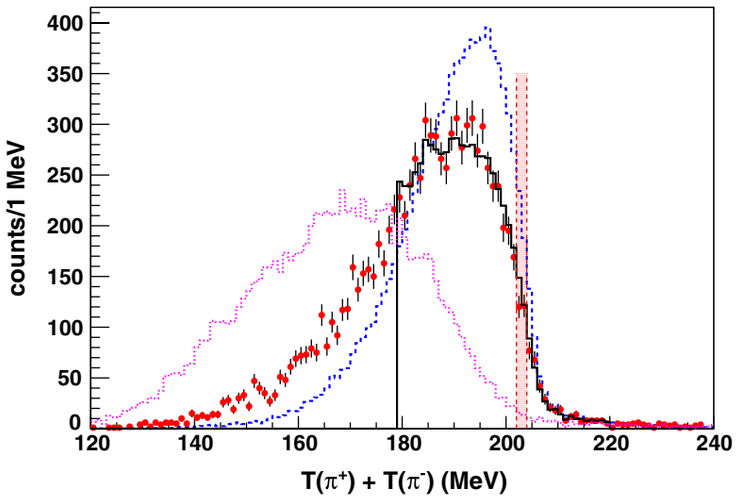
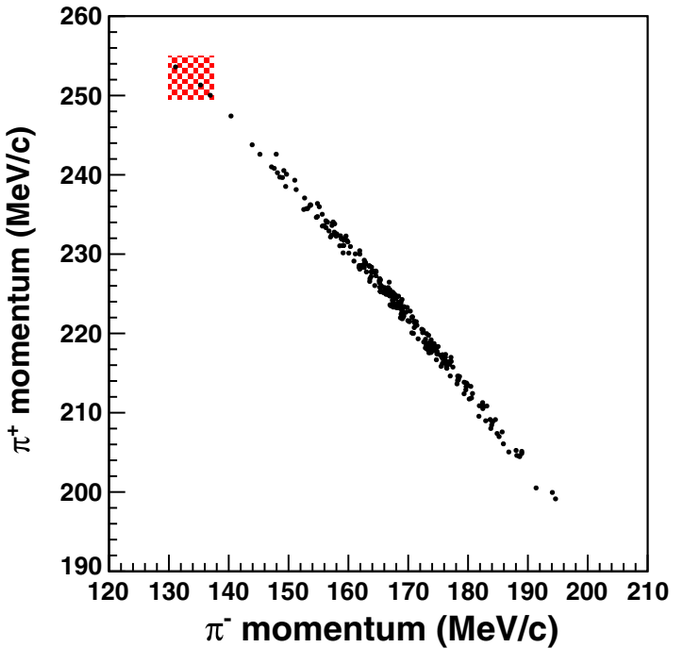


FIG. 1 (color online). Distribution of raw total kinetic energy $T_{\text{sum}} \equiv T(\pi^+) + T(\pi^-)$ for $\pi^{\pm}$ pair coincidence events from ^{6}Li targets. The vertical (red) bar represents the cut $T_{\text{sum}} =$ 202–204 MeV. The dashed (blue) histogram is a quasifree simulation of $K^-_{\text{stop}} + {}^{6}\text{Li} \rightarrow \Sigma^+ + {}^{4}\text{He} + n + \pi^-; \Sigma^+ \rightarrow n + \pi^+$ background, and the dotted (violet) histogram is a four-body phase space simulation of the same background. Their best fit to the data is shown by the solid (black) histogram; see the text.



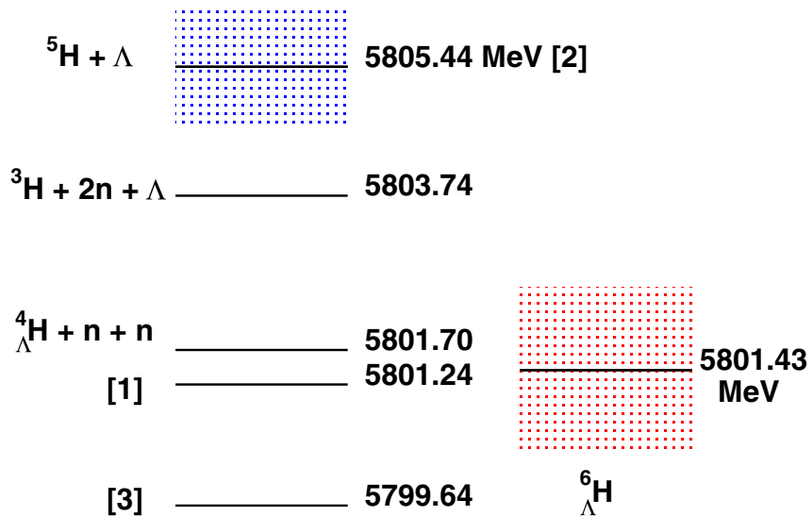
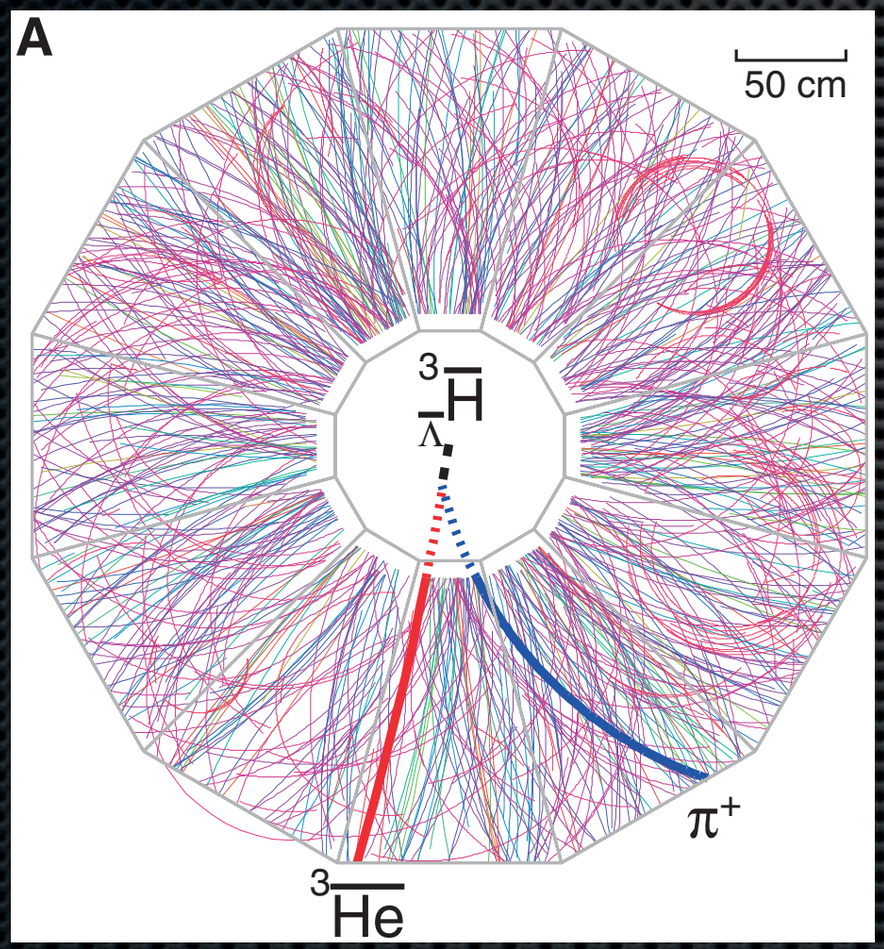


FIG. 3 (color online). ${}^{6}_{\Lambda}$H mass (RHS) from three ${}^{6}_{\Lambda}$H candidate events, as related to several particle stability thresholds and theoretical predictions (LHS).

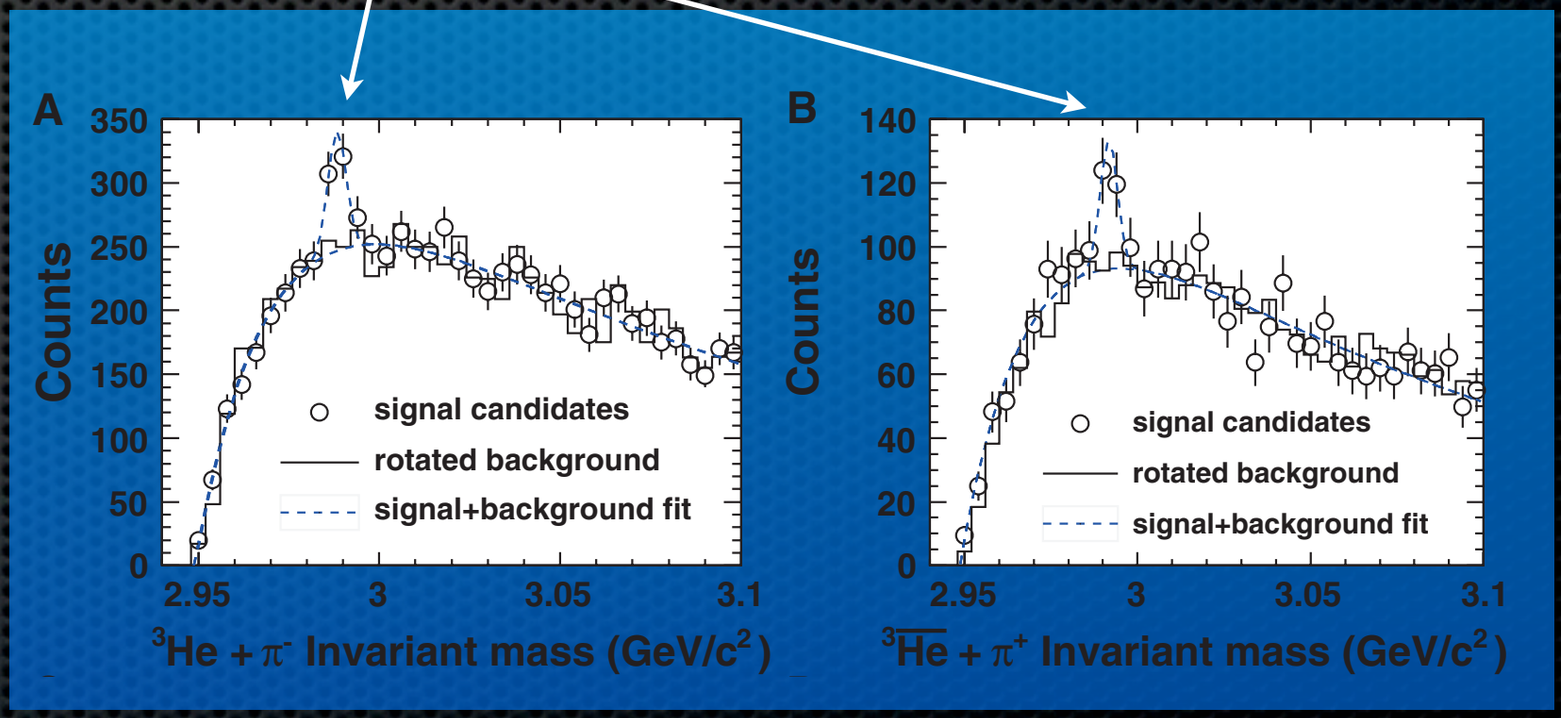
Anti-Hypernucleus at RHIC

The STAR Collaboration, Science 328 (2010) 58.

$$\overline{{}^{3}_{\Lambda}\mathrm{H}} \rightarrow \pi^{+} + \overline{{}^{3}\mathrm{He}}$$

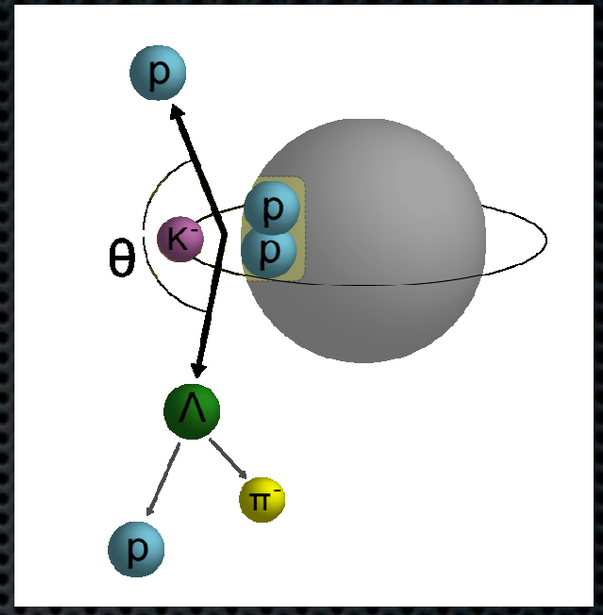


$$\overline{{}^{3}_{\Lambda}\mathrm{H}}/{}^{3}_{\Lambda}\mathrm{H} = 0.49 \pm 0.18 \pm 0.07$$



Life time($^{3}_{\Lambda}$H)=182+89/-45±27 ps

Recent data on K^-pp



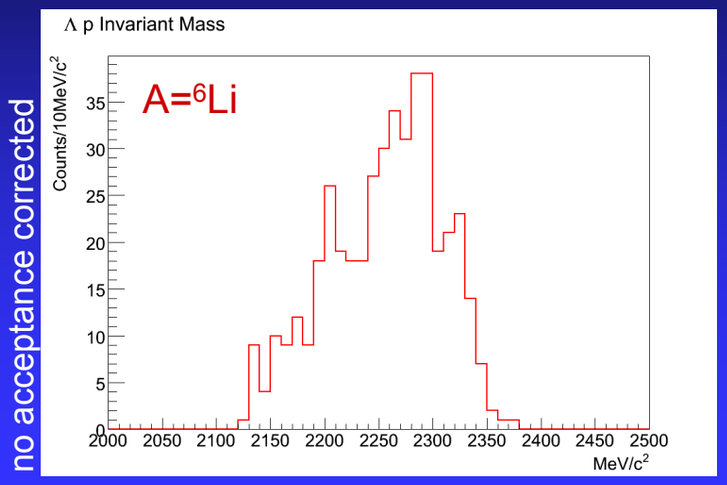
- First evidence of K^-pp with ^{6}Li+^{7}Li+^{12}C

  B=115+6/-5+3/-4 MeV

  Γ= 67+14/-11+2/-3 MeV

  M. Agnello et al., PRL94, (2005) 212303

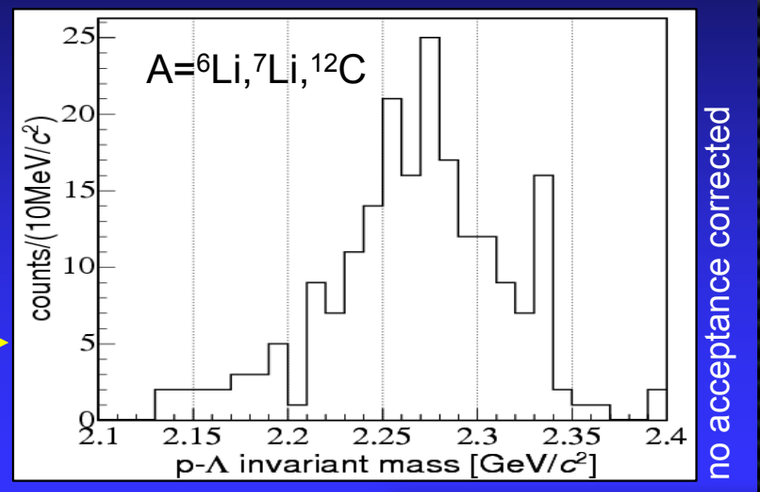
- Confirmed for ^{6}Li only, with better statistics S. Piano@Hyp-X



New
inv mass spectra
compatible with
published one

New data ◄——► Old data

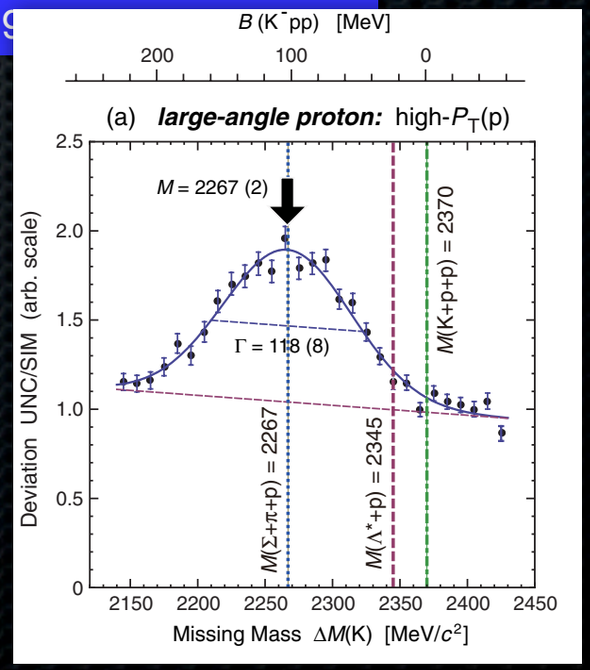
Same cuts applied



FINUDA Coll., PRL 9

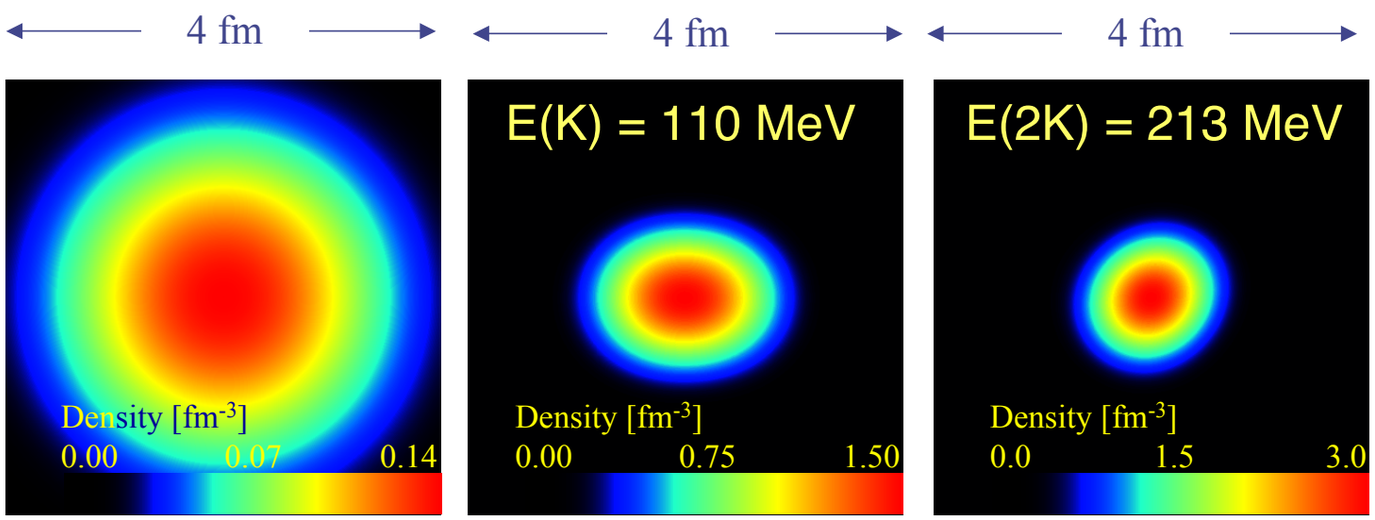
- DISTO data: p+p→K^-pp + K^+ at 2.85 GeV
  - M=2267±3±5 MeV/c²
  - Γ= 118±8±10 MeV

T. Yamazaki et al., PRL 104 (2010) 132502.



Formation of High Density State

- Formation of Cold(T=0) and Dense($\rho > 5\ \rho_0$) nuclear matter
- Chiral symmetry restoration
- Kaon condensation



ppn

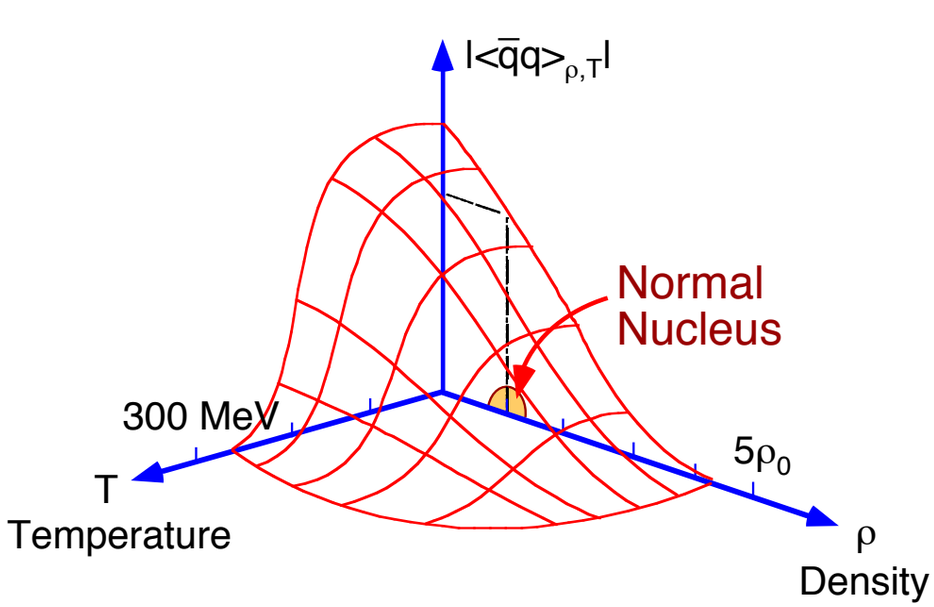
total B.E. = 6.0 MeV
central density = 0.14 fm^{-3}
R_{rms} = 1.59 fm

ppnK⁻

total B.E. = 118 MeV
central density = 1.50 fm^{-3}
R_{rms} = 0.72 fm

ppnK⁻K⁻

total B.E. = 221 MeV
central density = 3.01 fm^{-3}
R_{rms} = 0.69 fm



$\rho > \rho_0 \times 10$!?

Dote et al.

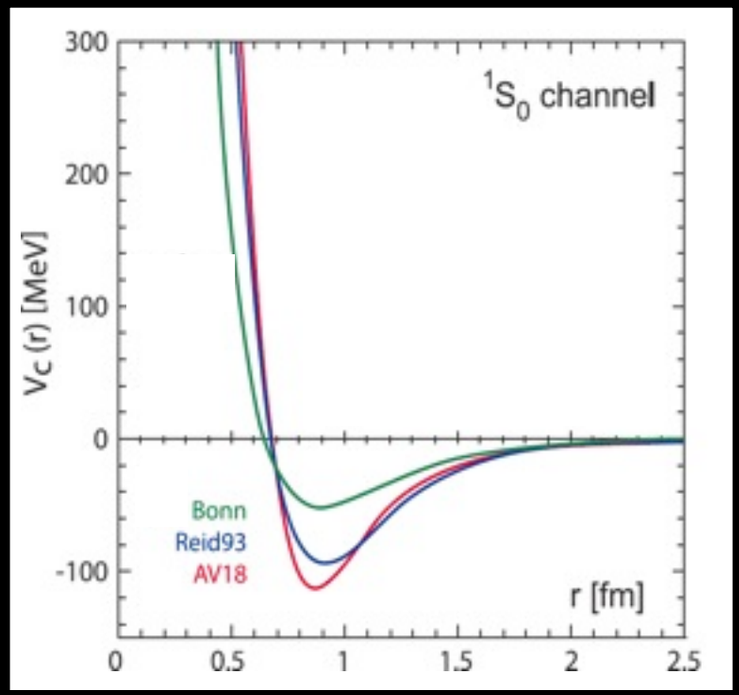
T. Hatsuda and T. Kunihiro, Phys. Rev. Lett. **55** (1985) 158.
W. Weise, Nucl. Phys. **A443** (1993) 59c.

Baryon force: From phenomenology to 1st principle

- NN int.: about 4500 np and pp scatt. data

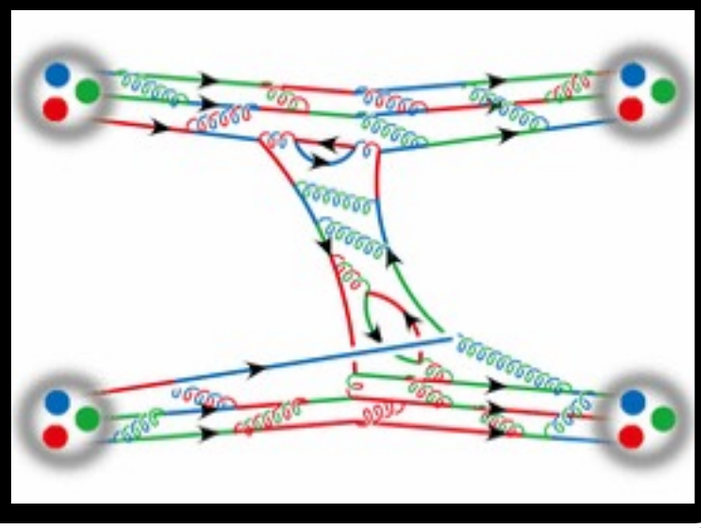
"high precision" NN interactions		# of parameters
CD Bonn	(p space)	38
AV18	(r space)	40
EFT in N^{3}LO	(nπ+contact)	24

R. Machleidt, arXiv:0704.0807 [nucl-th]



- NNN, YN, YY : data very limited
- YNN, YYN, YYY : none

QCD has only four parameters :
m_u, m_d, m_s, Λ_{QCD}



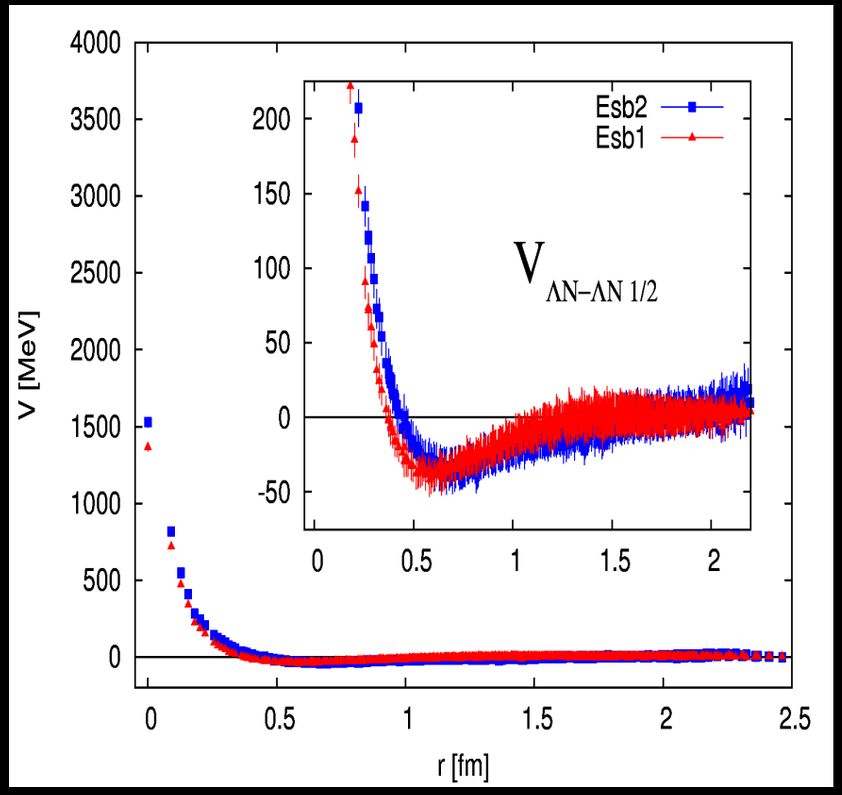
SU(3) breaking: coupled channel LQCD

Sasaki et al.
[HAL QCD Coll.] (2012)

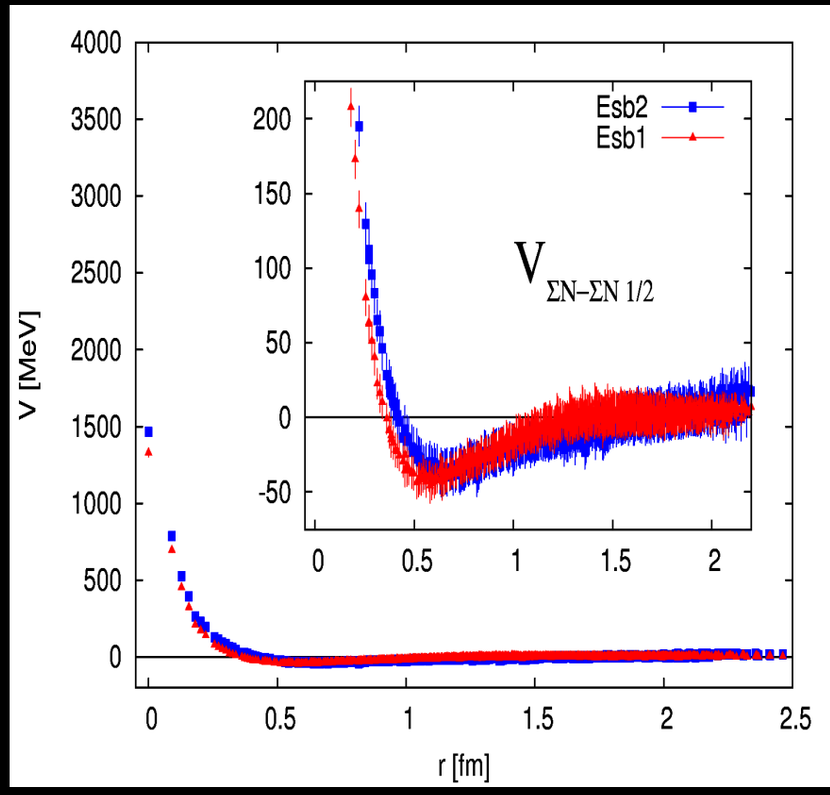
$$\left(k_n^2 + \nabla^2\right) \phi_n^{\alpha}(\vec{r}, t) = \int U(\vec{r}, \vec{r}')^{\alpha\beta} \phi_n^{\beta}(\vec{r}', t) d^3 r'$$

Example: S=-1, $^3S_1$, I=1/2 (m_π/m_K=0.89, 0.8)

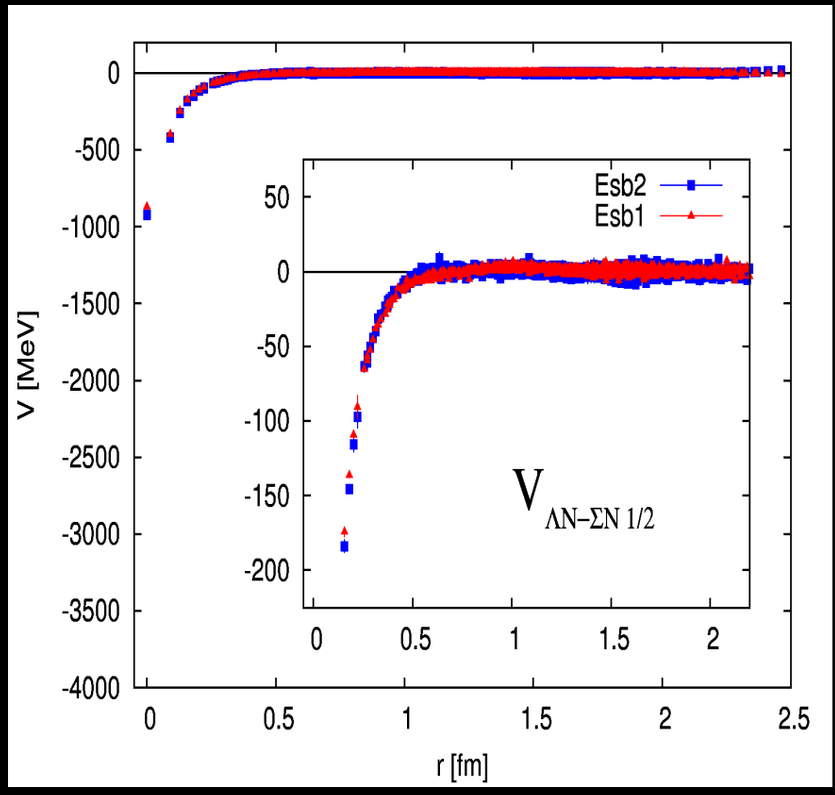
ΛN-ΛN



ΣN-ΣN



ΛN-ΣN



PACS-CS (2+1)-flavor config.
L=2.9 fm

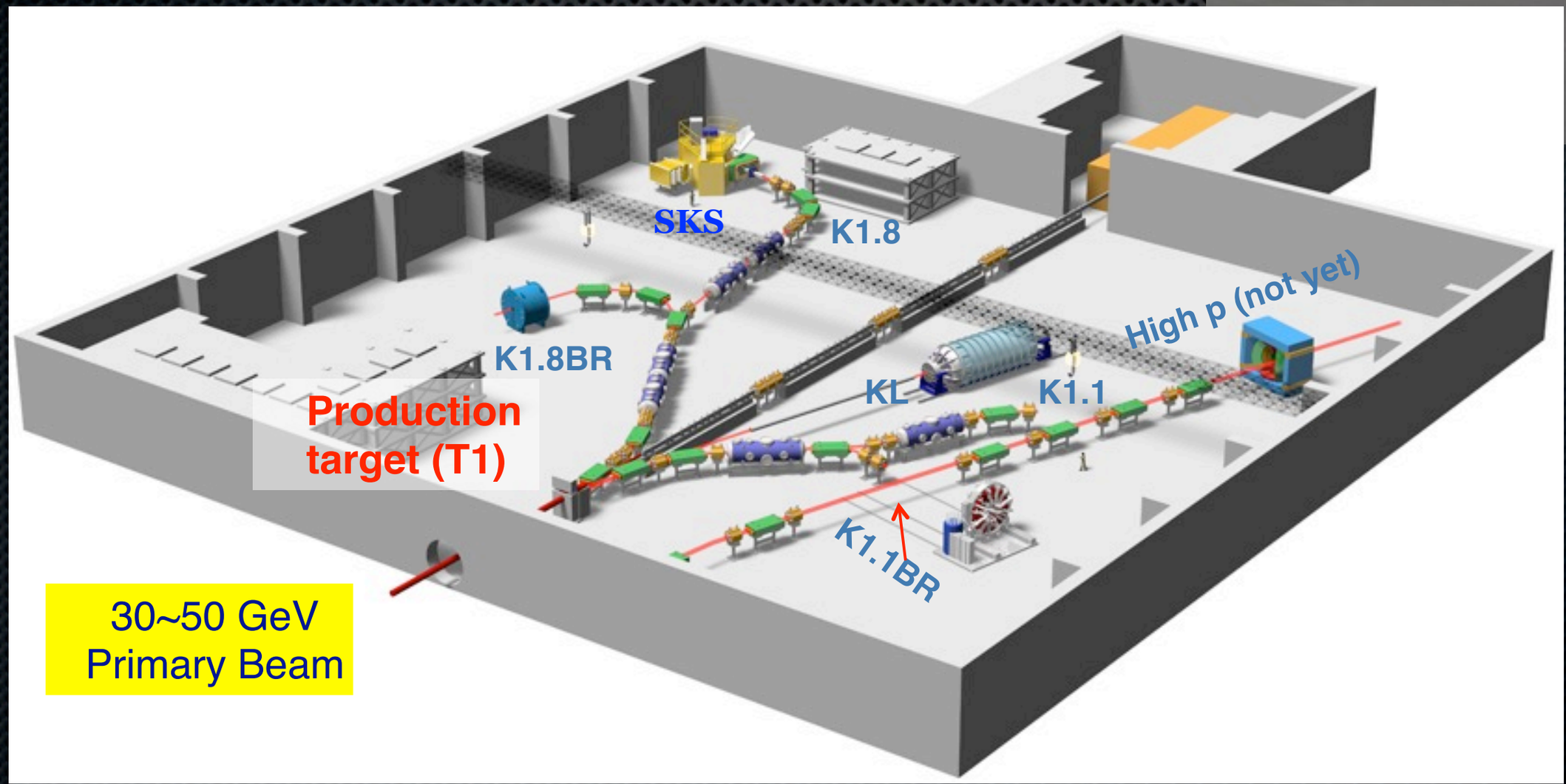
SNP Program at J-PARC

Hadron Experimental Hall

World highest intensity Kaon beams !

First beam in Feb. 2009

60m x 56m



SNP Program Schedule

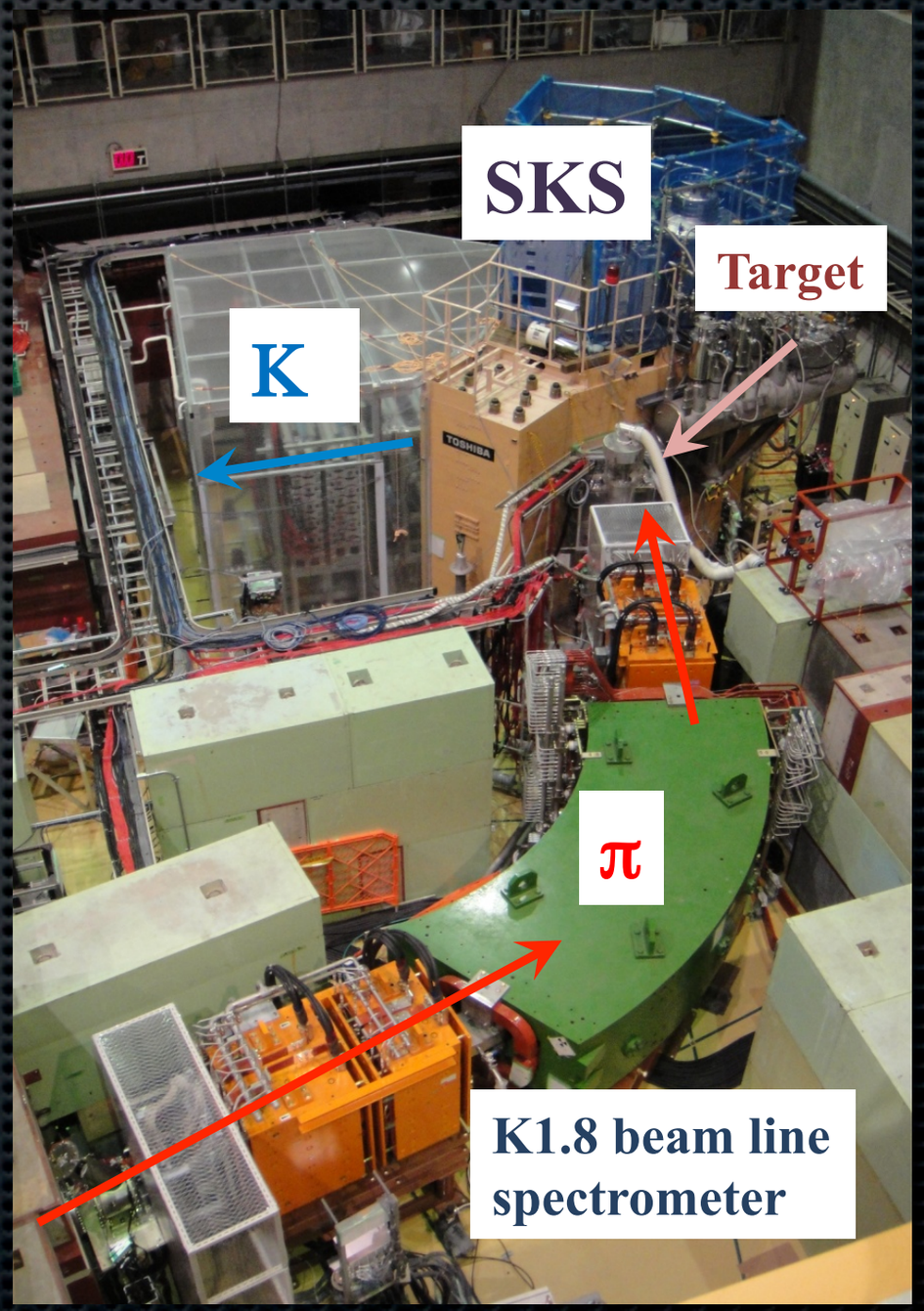
- 2010: Oct.-Nov.
  - E19: Penta-quark search in $\pi^- p \rightarrow K^- X$ at 1.92 GeV/c
    - *First physics data taking in Hadron Hall*
- 2012: Feb. , *after the Earthquake*
  - E19: $\pi^- p \rightarrow K^- X$ at 2 GeV/c
- 2012: June
  - E27: $d(\pi^+, K^+)$ for $K^- pp$, *a pilot run* 5 kW / 270 kW

SNP Program Schedule

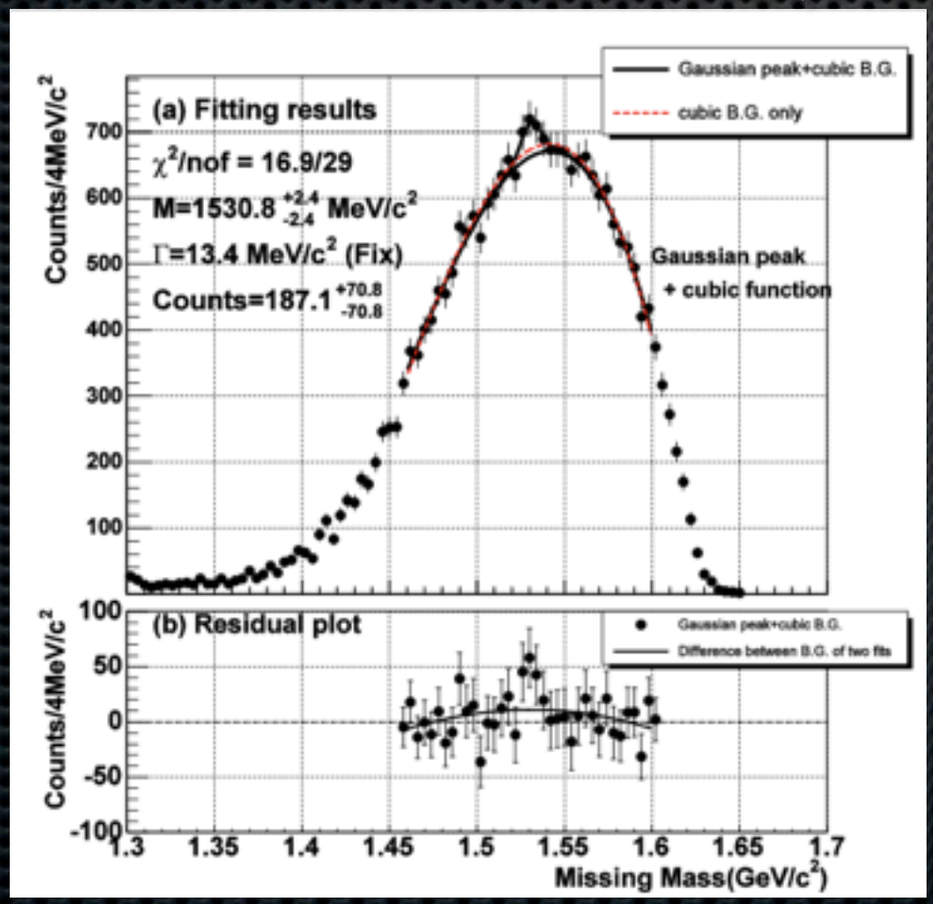
- In near future...
- 2012: Dec. 10 kW
  - E10: $(\pi^-,K^+)^6_\Lambda H$
- 2013: March - June > 10 kW
  - E15: $^3He(K^-,n)$ for *K^-pp*
  - E13: Hypernuclear γ-ray spectroscopy; $^4_\Lambda He$, $^{19}_\Lambda F$
  - E05: Ξ hypernuclei; $^{12}C(K^-,K^+)$

High-resolution search for Θ^+ in $\pi^- p \to K^- X$ reaction: E19 M. Naruki et al.

- $\pi^- p \to K^- \Theta^+$ at 1.92 GeV/c
  - SKS Spectrometer at K1.8
    - ΔE=13.4 MeV → 1.4 MeV



KEK PS E522: K. Miwa et al., PLB635 (2006) 72.

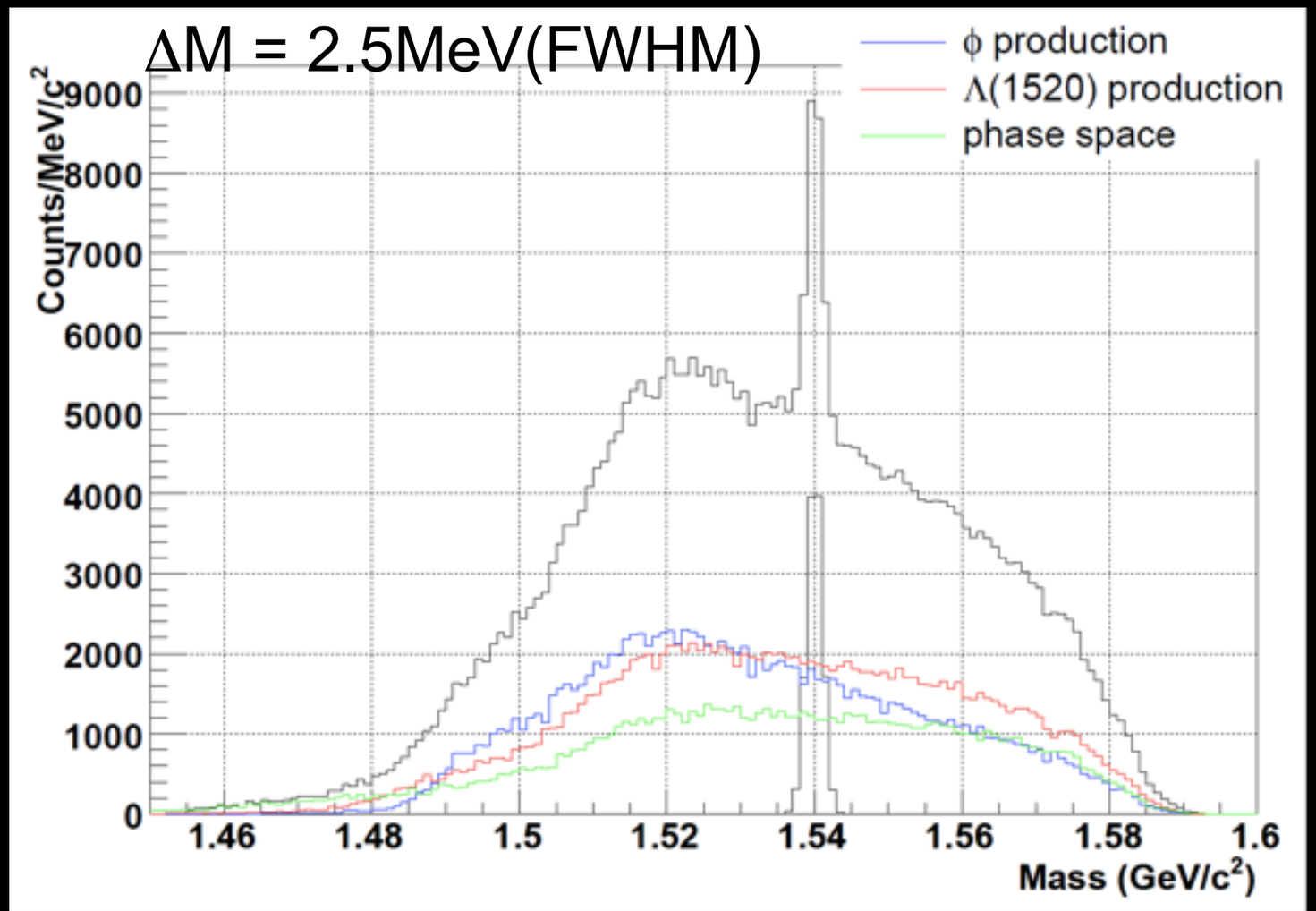


S/N=2.5 σ

dσ/dΩ=1.9μb/sr, if true.

Expected Missing Mass Spectrum

assuming $d\sigma/d\Omega$ = 1.9μb/sr (lab)



we aim to;

- confirm Θ^+ with high statistics
- study momentum dependence of cross section

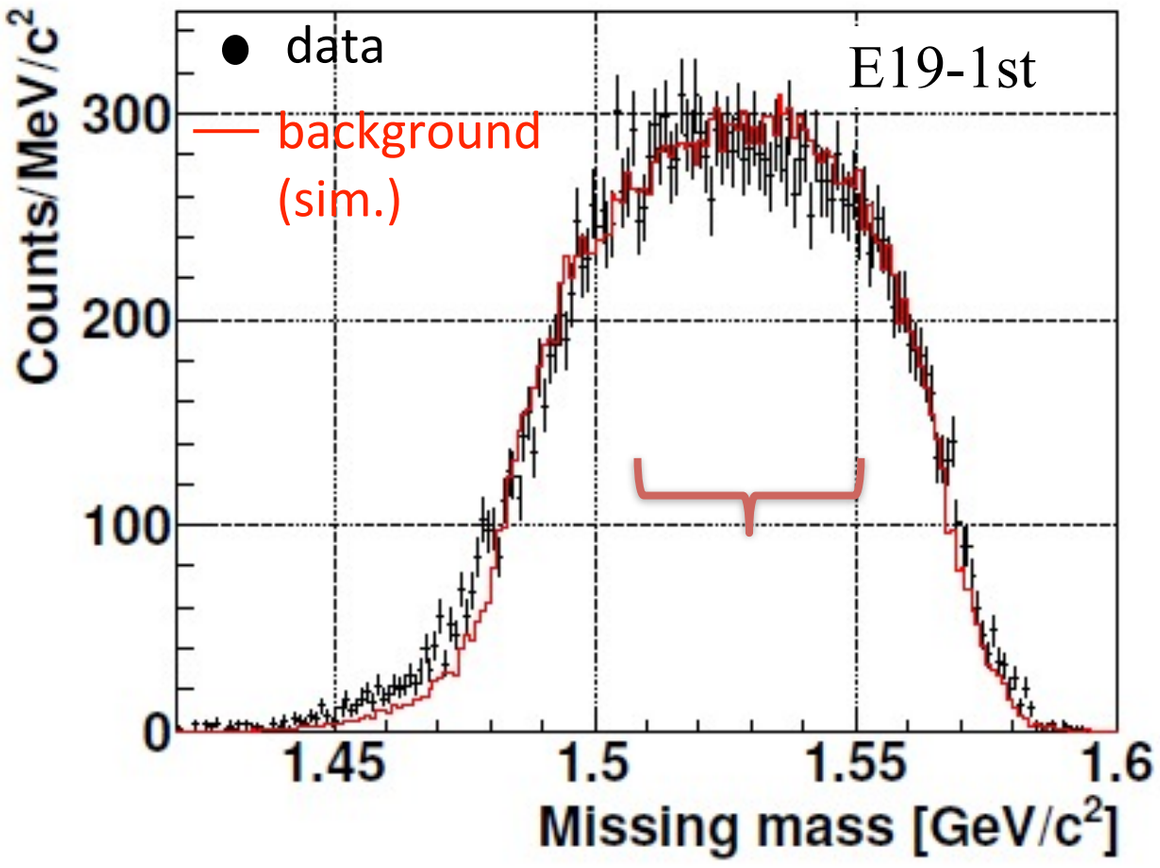
Background sources

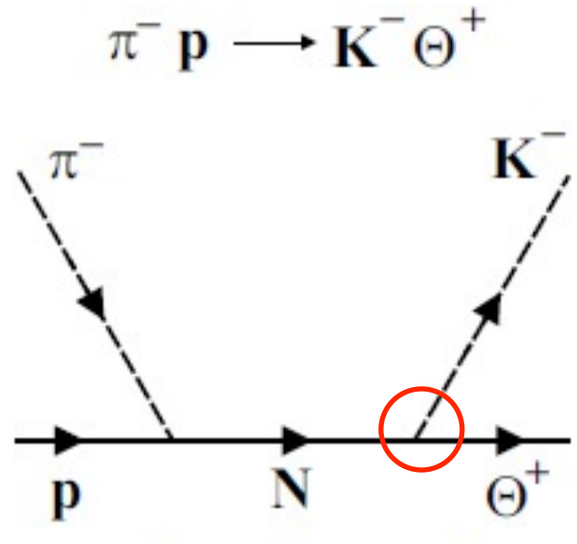
φ	$\phi n \rightarrow K^+K^-n$	30.0±8.0 μb
Λ	$\Lambda(1520)K^0 \rightarrow K^-K^0p$	20.8±5.0 μb
phase space	K^-KN	26 μb

1st run result of E19

$\pi^- + p \rightarrow K^- + X$ @ 1.92 GeV/c

Shirotori et al., PRL 109, 132002 (2012).





- **No prominent peak structure**
- **Upper limit:** **< 0.26 μb/sr**
  @ 1.51–1.55 GeV/c²

✓ **s-channel dominance**

✓ $\Gamma_\Theta \propto g^2_{KN\Theta} \propto \sigma_{tot}$

➔ **Upper limit of decay width**

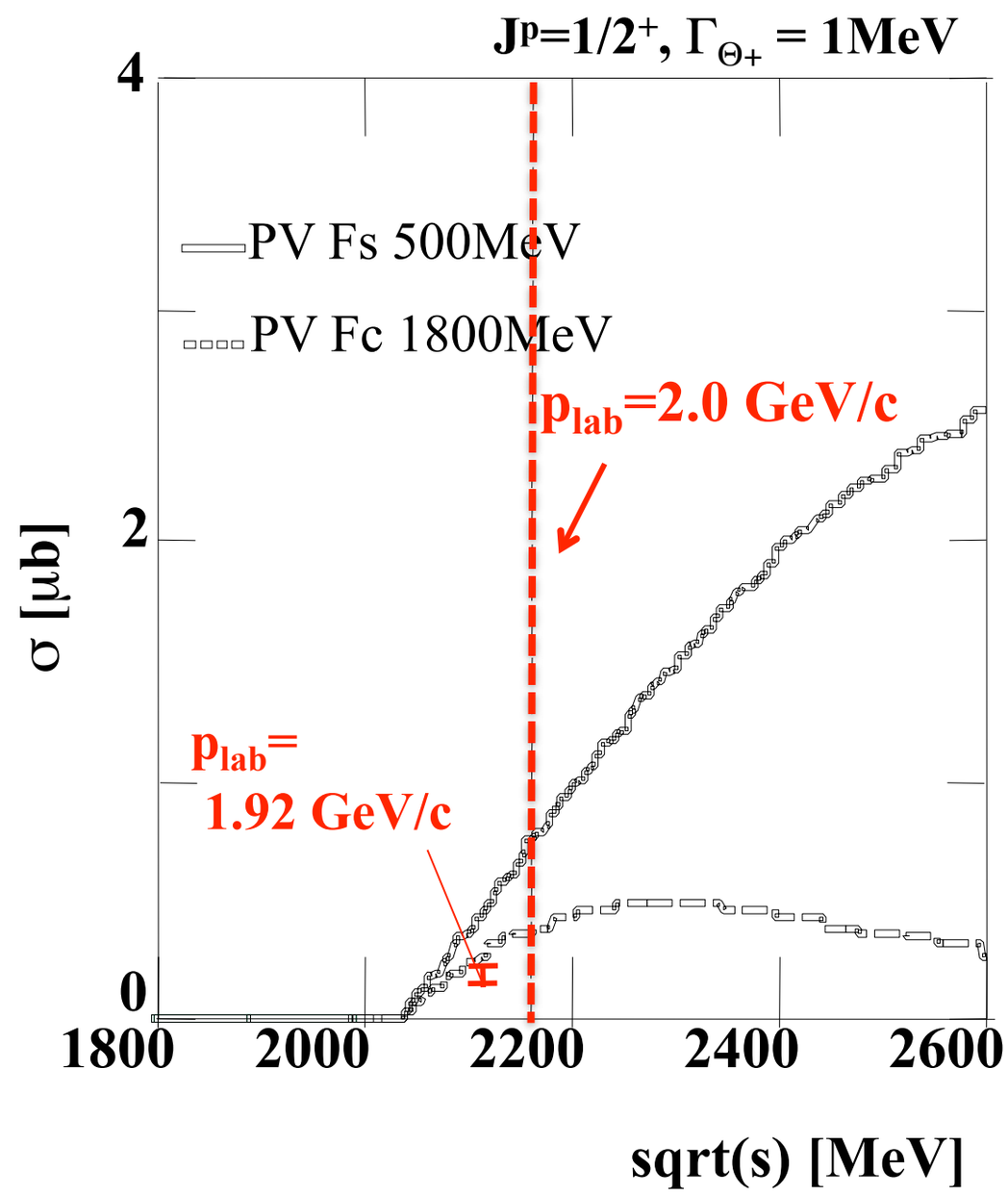
- **0.72 MeV for ½+**
- **3.1 MeV for ½-**

2nd run of E19

- **Beam time: 2012/Feb**
- **Higher beam momentum**
  2.0 GeV/c (= Max. of K1.8 B.L.)
- **Expecting increased cross section**
  ➔ higher sensitivity

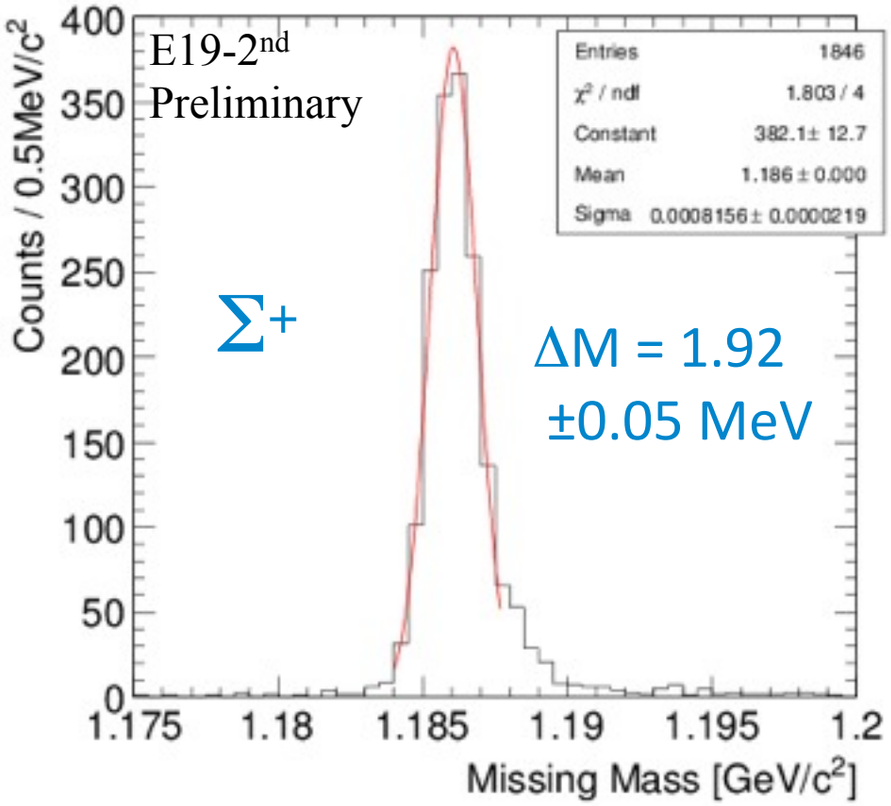
➔ Stringent restriction on the Θ+ decay width.

Theoretical calculations :
Hyodo, Hosaka, PRC 72, 055202 (2005).

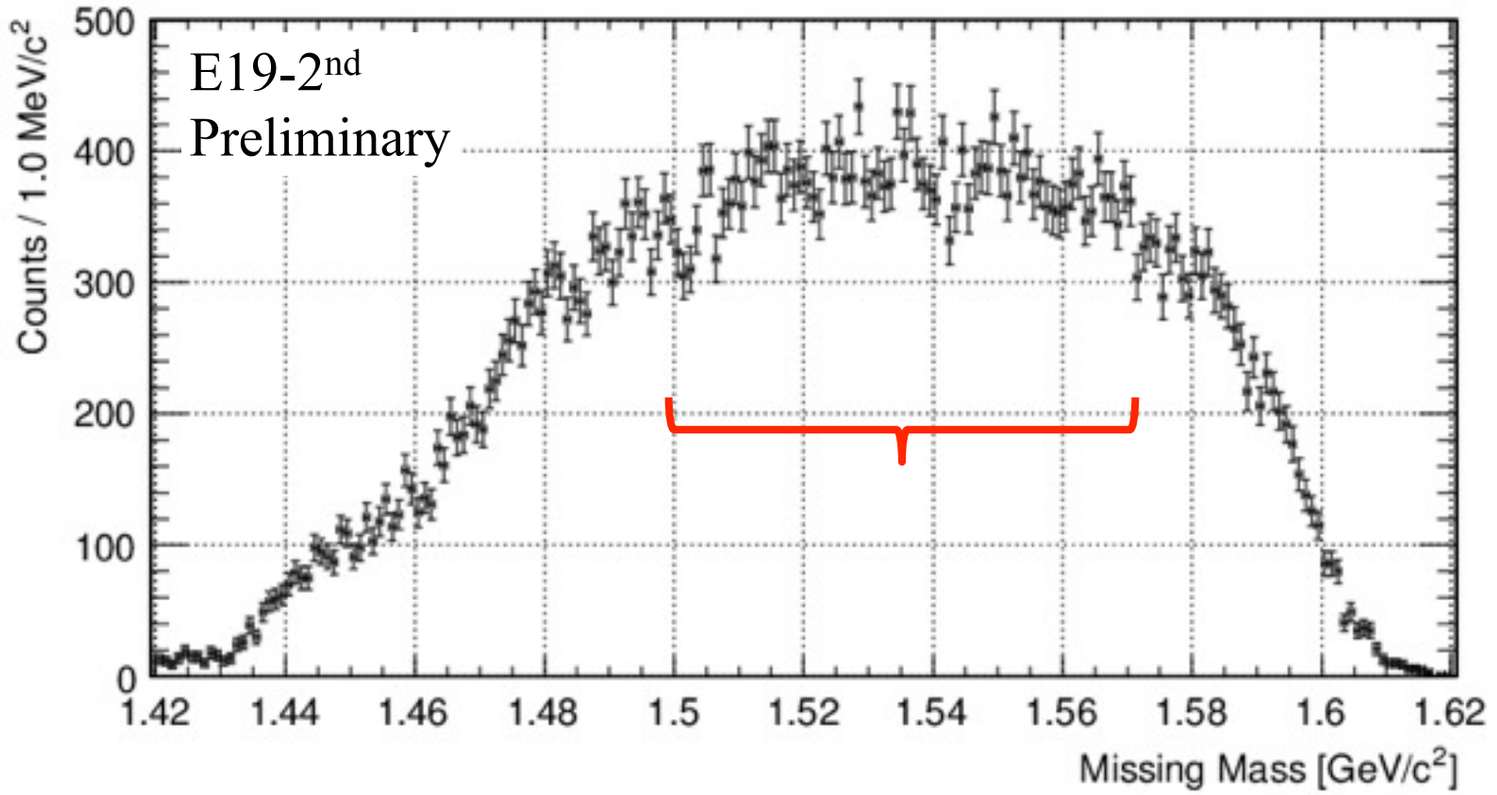


Analysis Result of E19-2nd run

$\pi^+ + p \rightarrow K^+ + \Sigma^+$ @ 1.37 GeV/c



$\pi^- + p \rightarrow K^- + X$ @ p_π = 2.0 GeV/c



- Enough spectrometer performance was achieved.
- No peak structure was observed in Θ^+ run.
- Analysis is now under finalizing.
- Upper limit of decay width will be derived soon.

M. Moritsu (Kyoto)

Search for K^-pp in the $d(\pi^+,K^+)$ reaction

E27

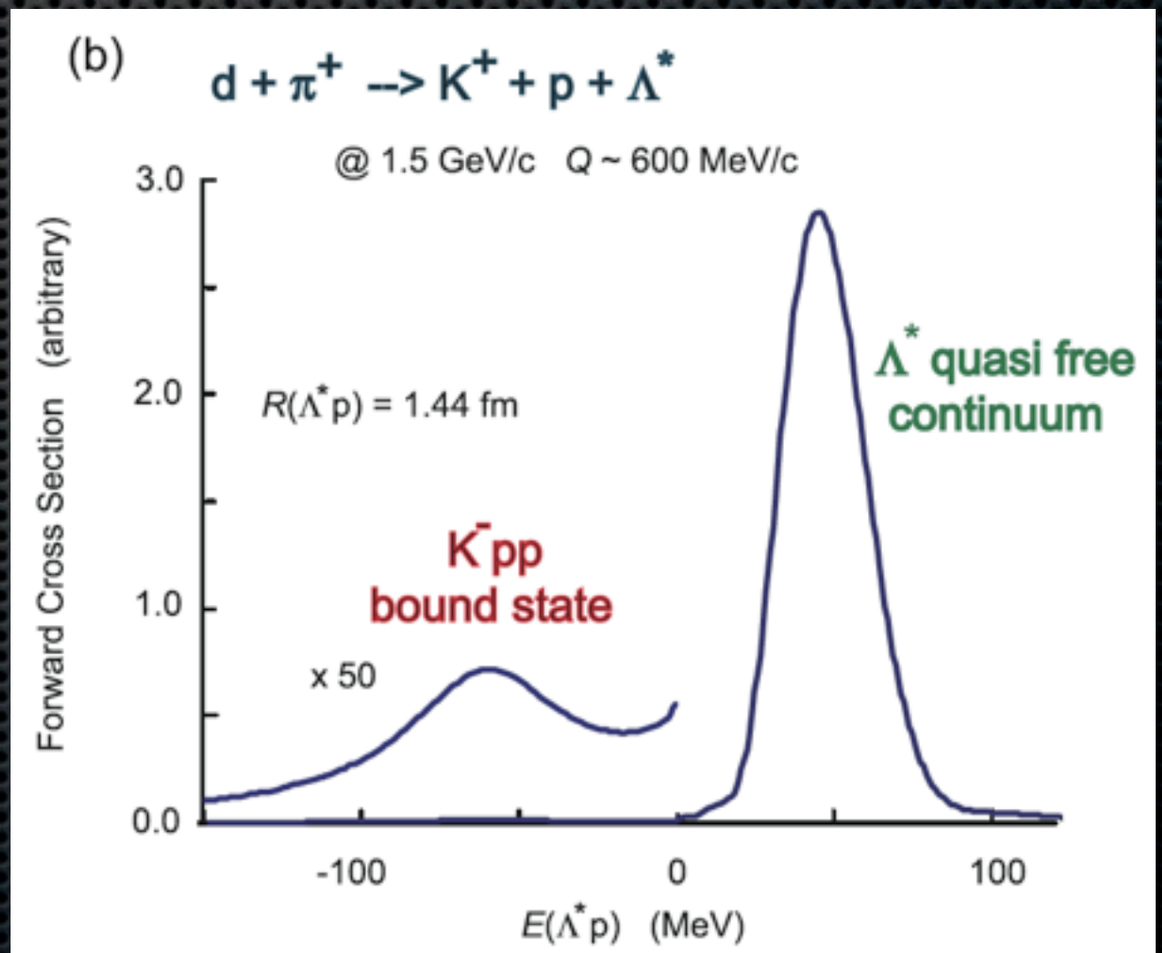
T. Nagae et al.

Y. Ichikawa, H. Ekawa (Kyoto)

$\pi^+ + \text{"n"} \rightarrow \text{"}\Lambda^*\text{"} + K^+$

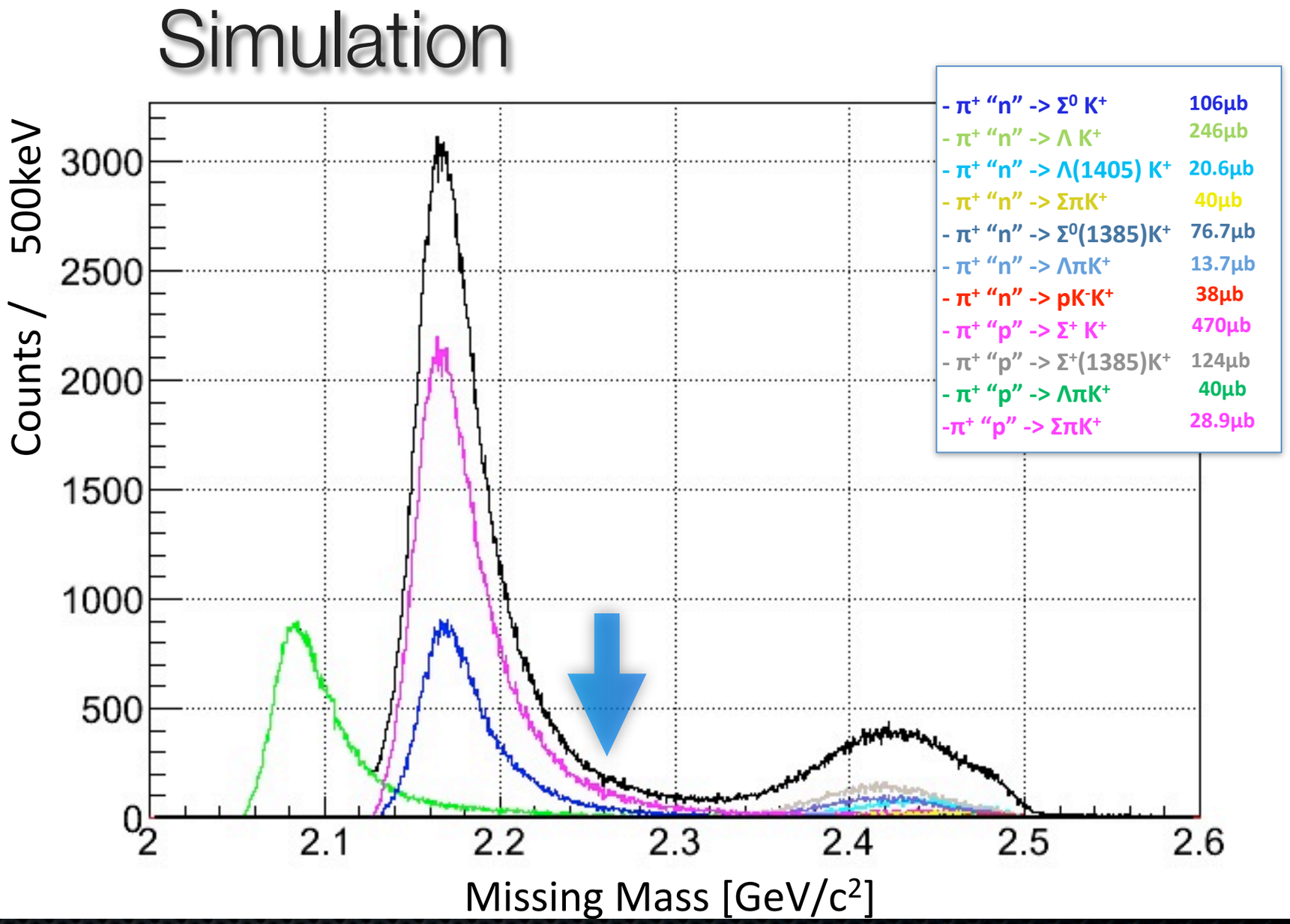
$\text{"}\Lambda^*\text{"} + \text{"p"} \rightarrow$ bound K^-pp *minor*

$\rightarrow$ quasi-free Λ^* *dominant*

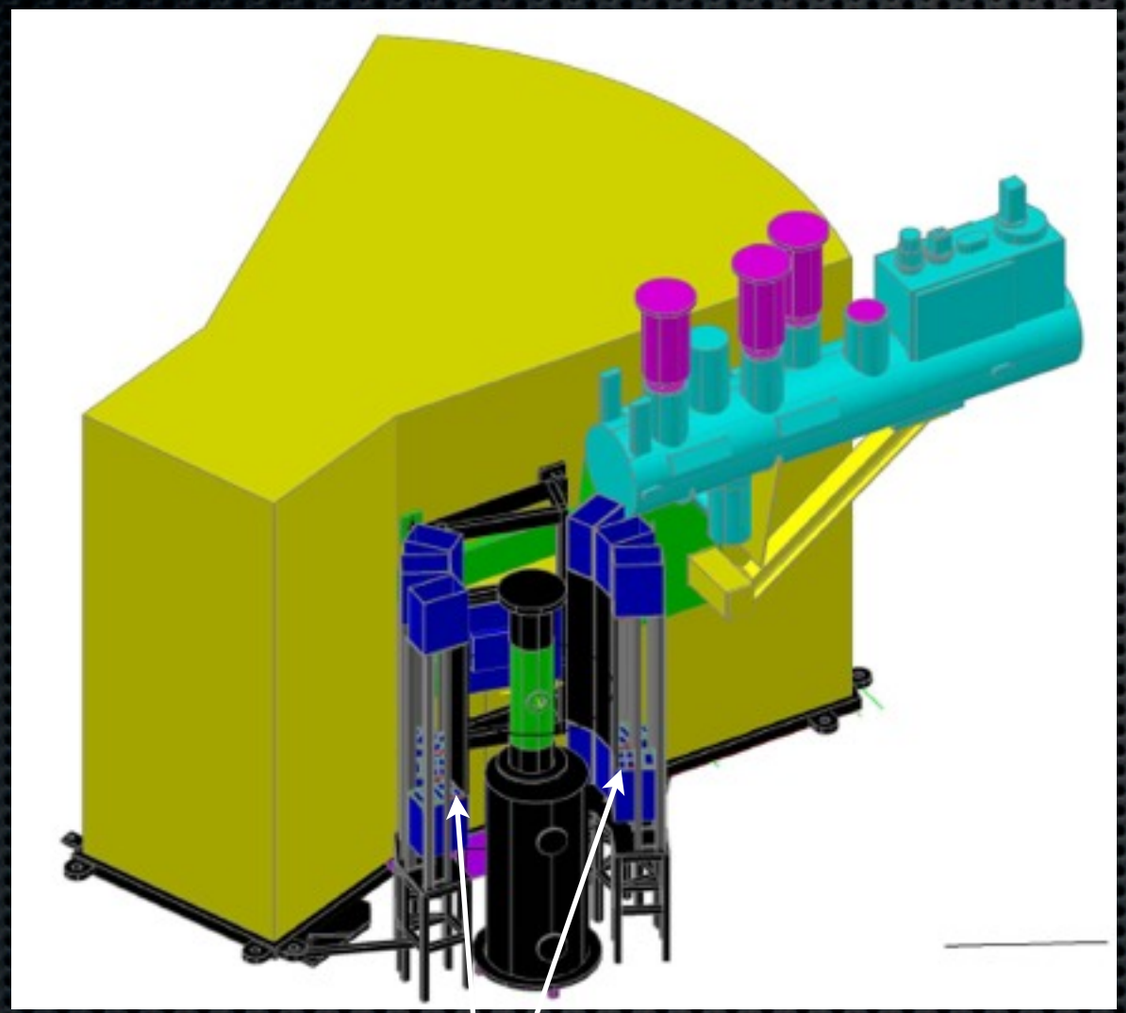


Yamazaki & Akaishi, Phys. Rev. C76 (2007) 045201.

Expected inclusive spectrum

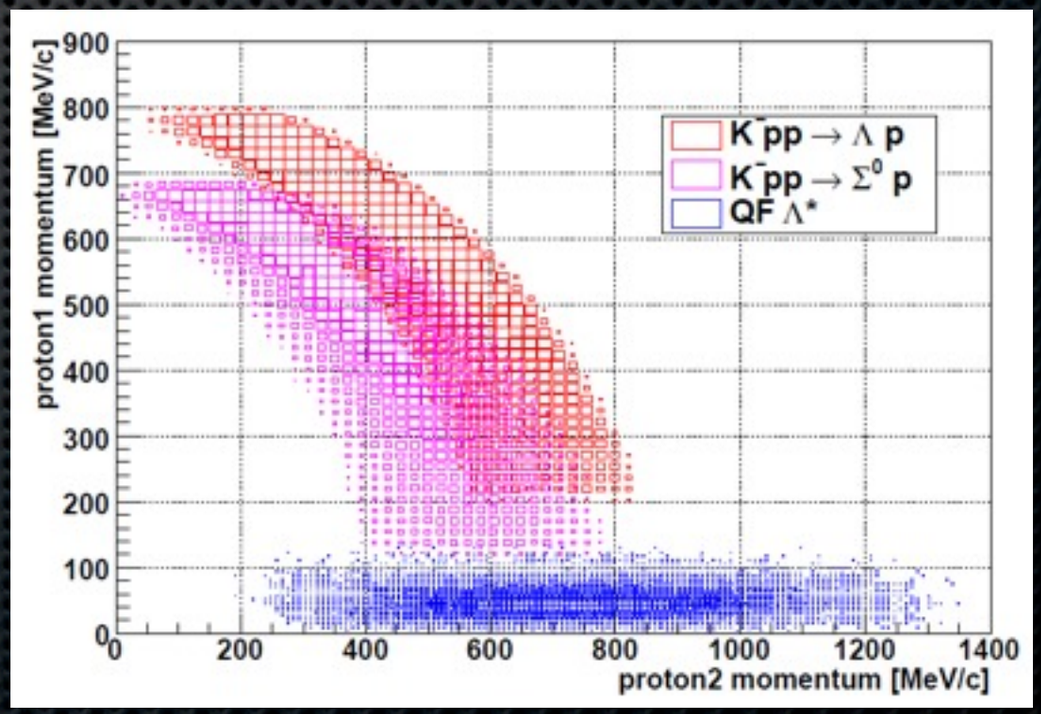


Proton tagging



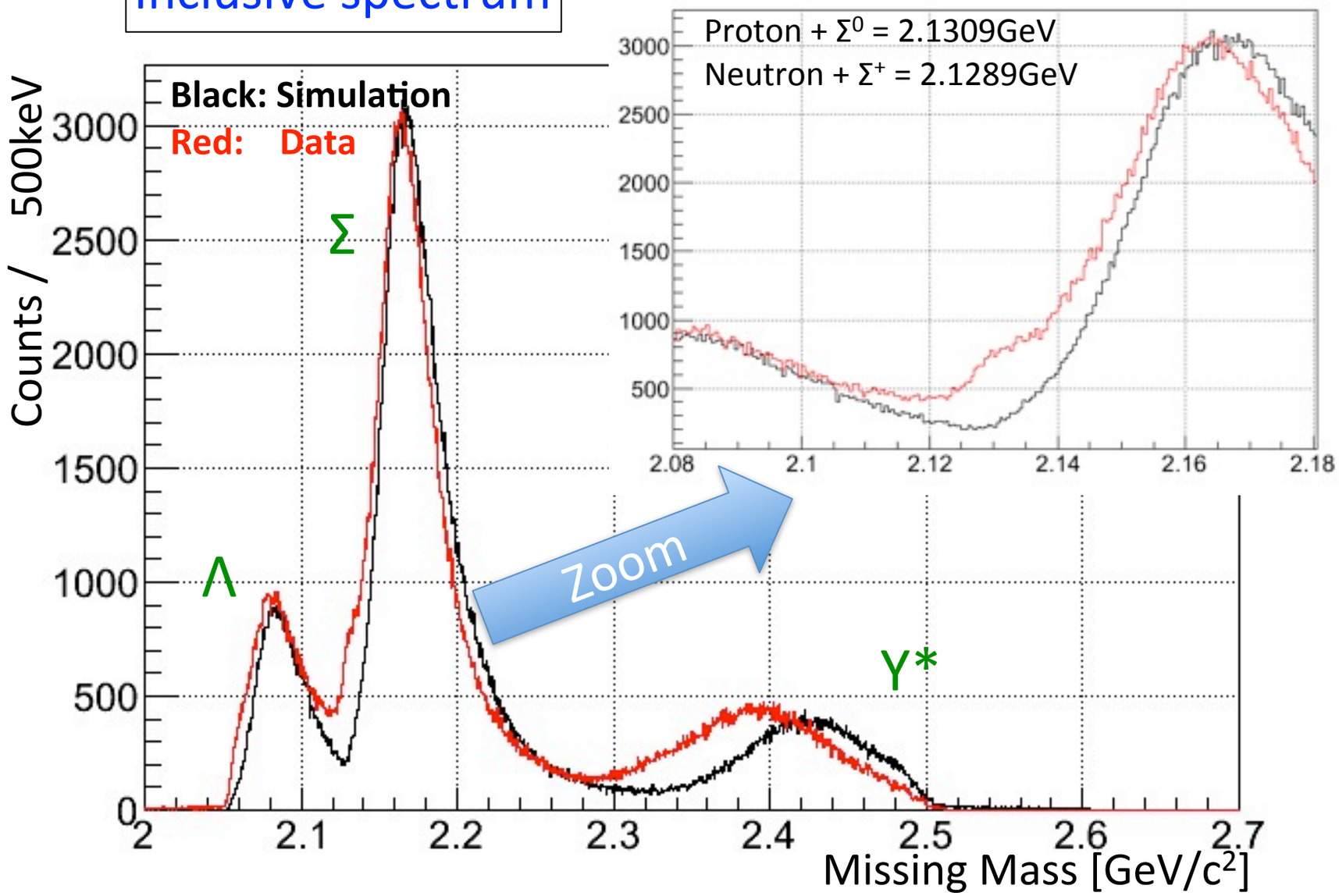
- Quasifree backgrounds

- $\pi^+ d \rightarrow \Lambda + K^+ + p_s$
- $\rightarrow \Sigma^0 + K^+ + p_s$
- $\rightarrow \Sigma^+ + K^+ + n_s$
- $\pi^+ d \rightarrow \Lambda + \pi + K^+ + N_s$
- $\rightarrow \Sigma + \pi + K^+ + N_s$



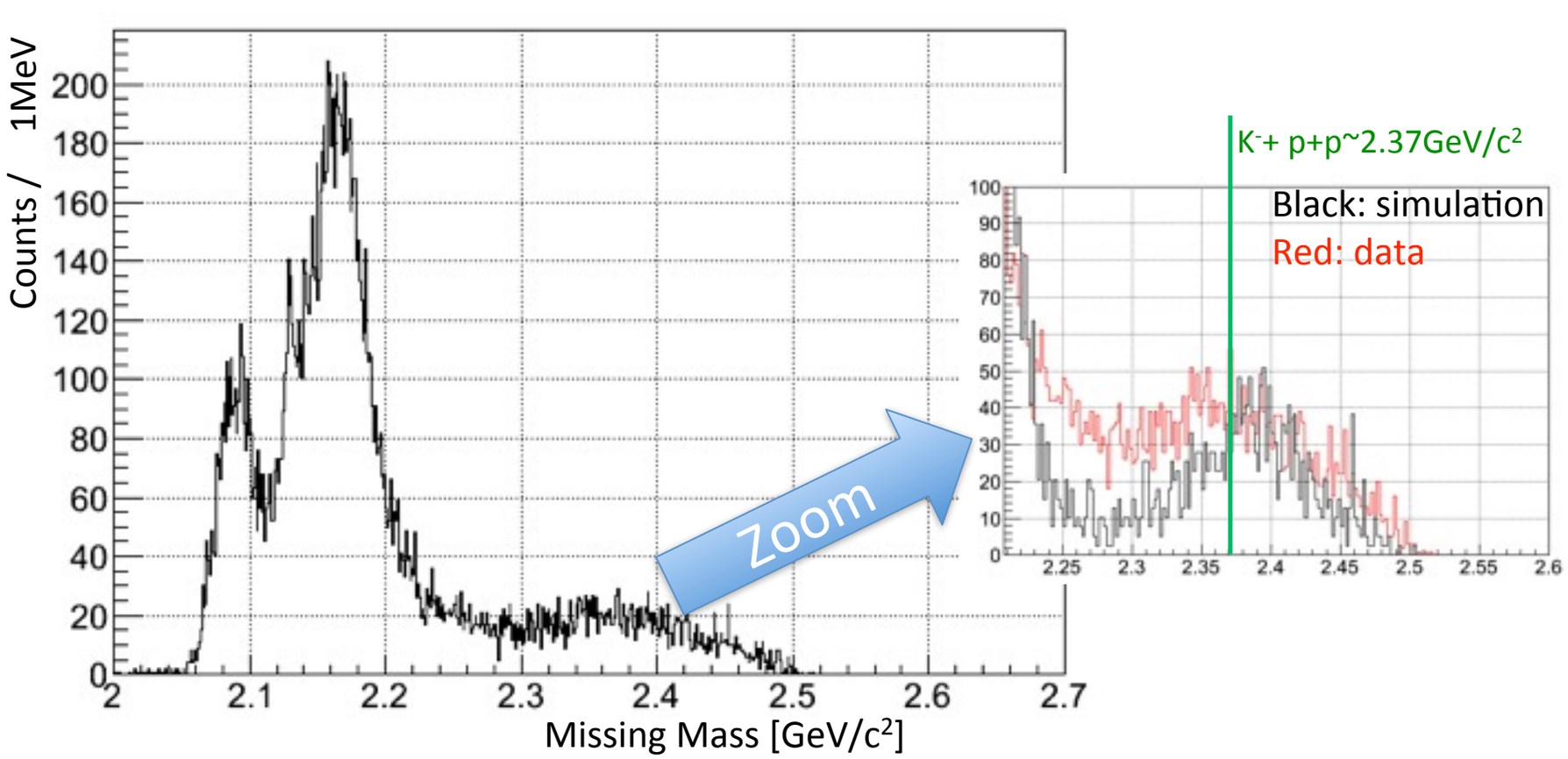
$d(\pi^+,K^+)$ at 1.7 GeV/c

Inclusive spectrum



$d(\pi^+,K^+)$ with one proton

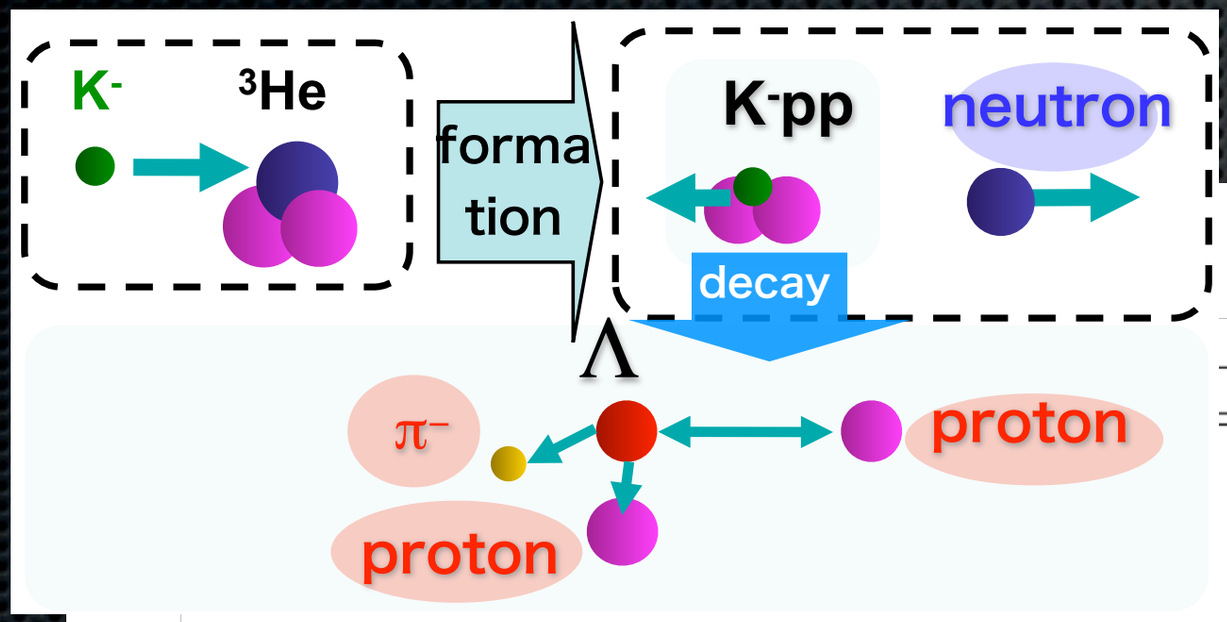
Mom_{proton} > 0.3GeV/c

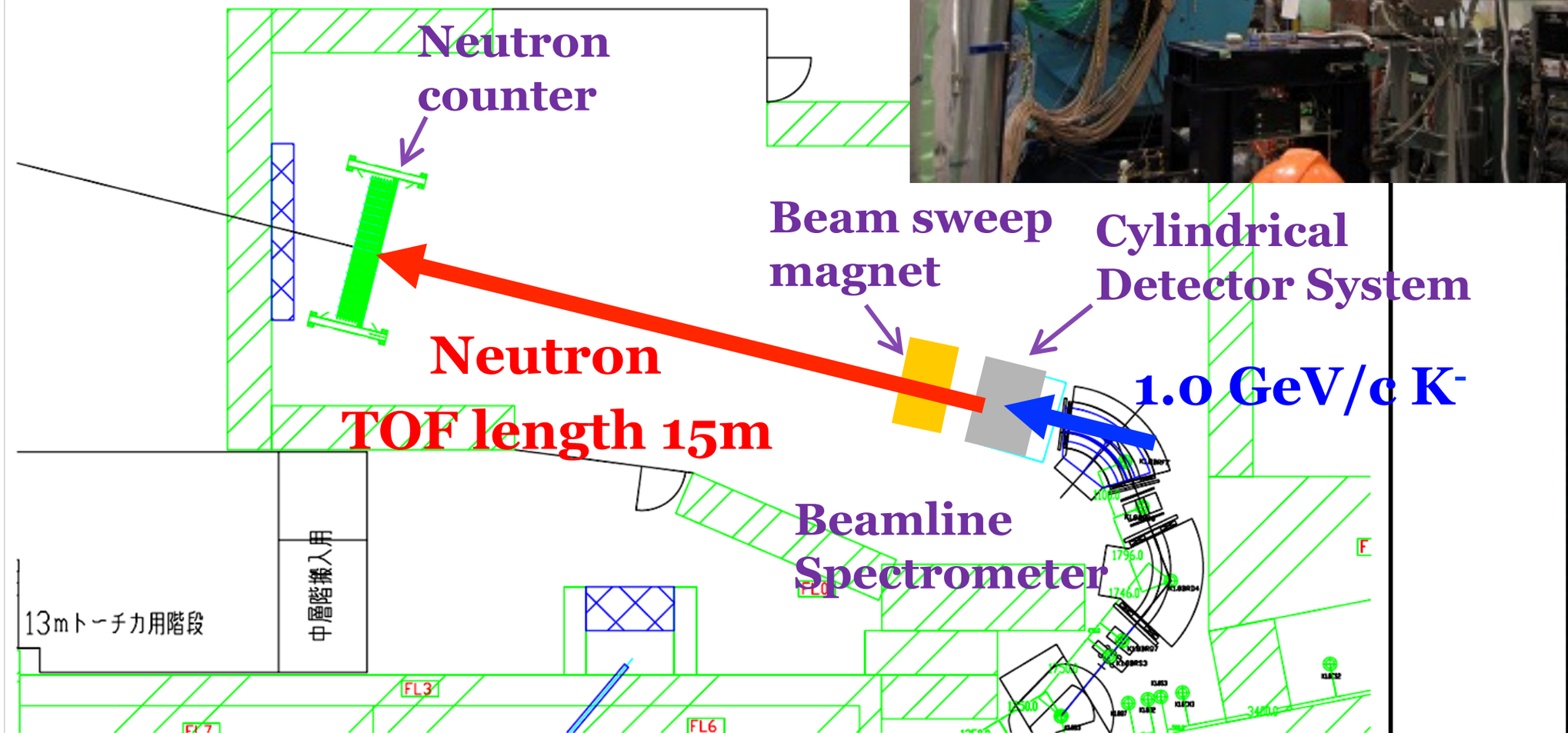


A Search for deeply-bound kaonic nuclear states by in-flight ^{3}He(K^{-},n) reaction at 1 GeV/c

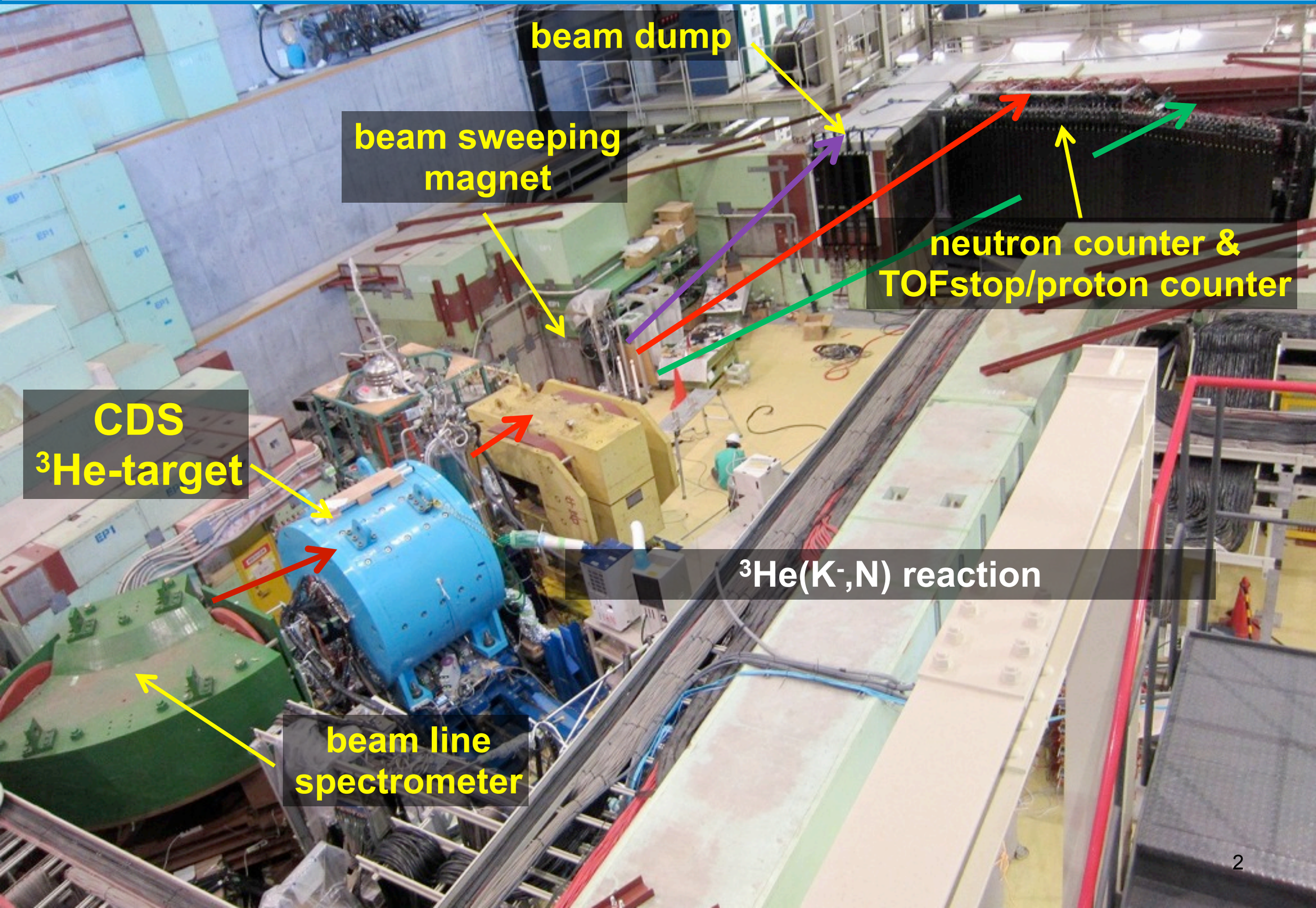
E15

M. Iwasaki et al.

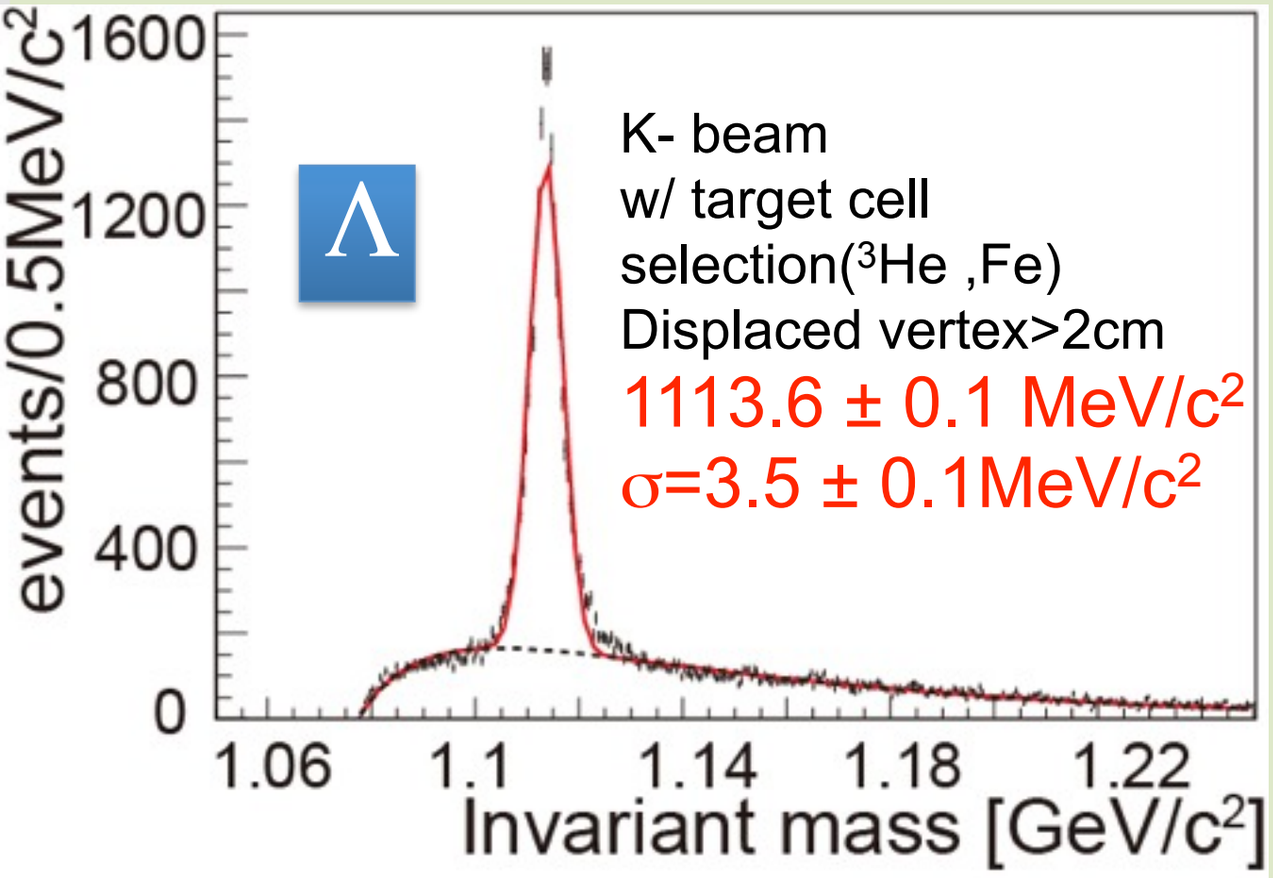




J-PARC K1.8BR beam line[Jun. 2012]



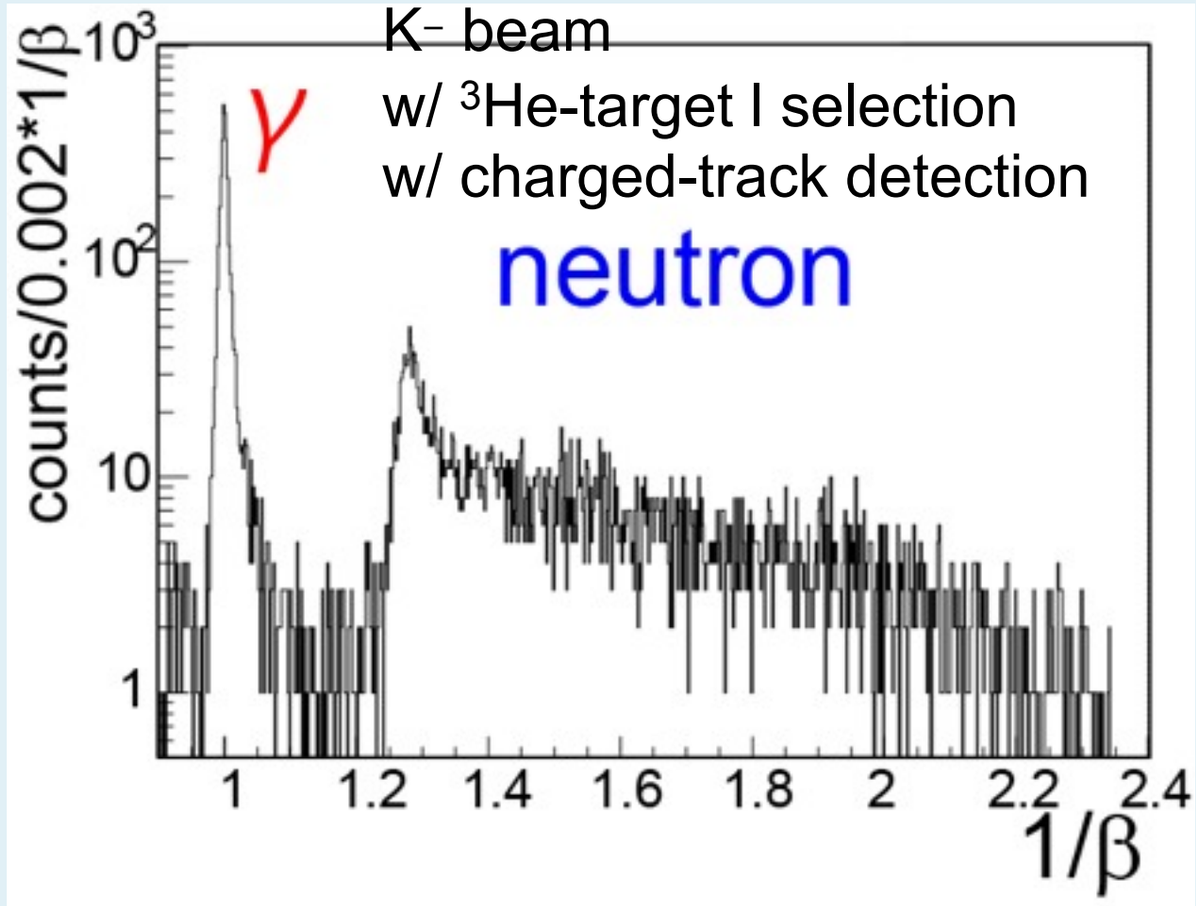
p π⁻ invariant mass spectra



- We successfully reconstructed Λ
- σ and center of mass is consistent to Simulation=> Achieved designed value(CDS resl. 200μm)

invariant mass resolution(Kpp) =10MeV/c² (with simulation)

Forward Neural Particle spectra



- Typical TOF resl. =150psec (T0-NC)
- QF peak of neutron is clear

Missing mass resolution (Kpp) =10MeV/c²

Neutron-rich Hypernuclei with (π^-,K^+) reaction

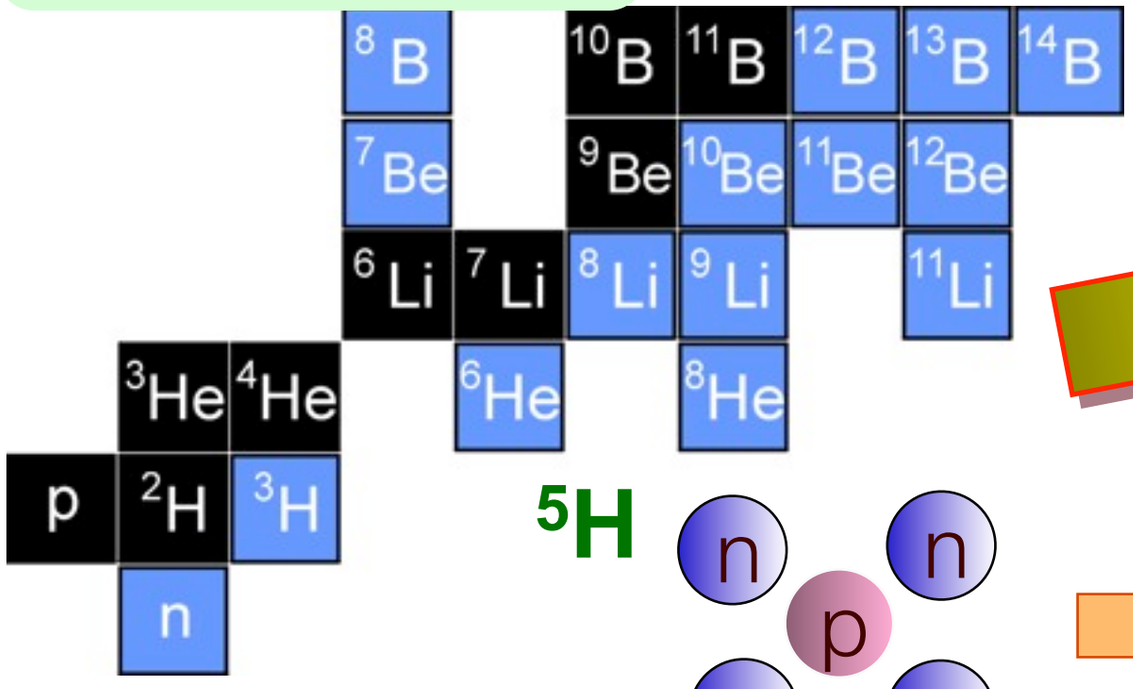
J-PARC E10
A. Sakaguchi et al.

NCX: (K^-,π^-), (π^+,K^+) reaction

SCX: $(e,e'K^+)$, (K^-,π^0), (π^-,K^0) reaction

DCX: (K^-,π^+), (π^-,K^+) reaction

ordinary nuclei



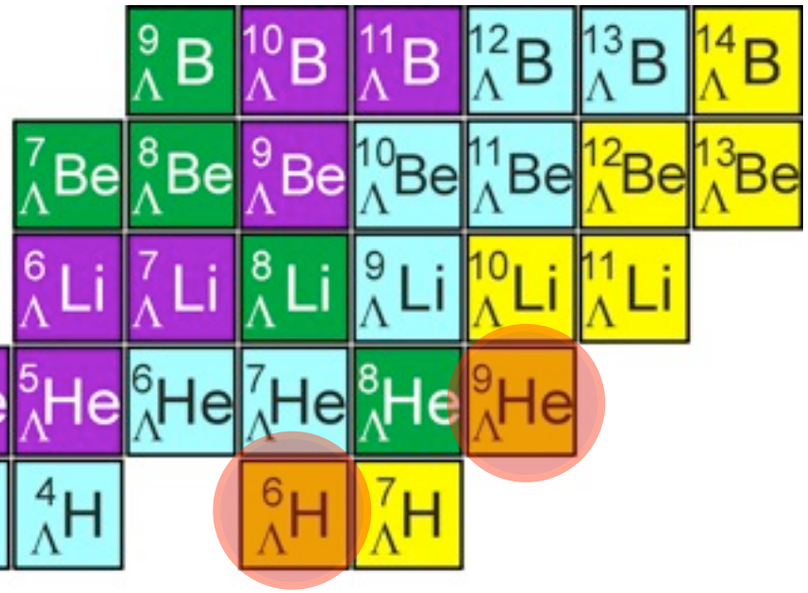
NCX

SCX

DCX

Λ

Λ-hypernuclei

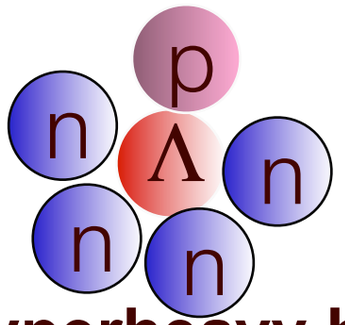


Akaishi:
Glue-like role of Λ
(B_Λ=4.4 MeV)
+
ΛNN coherent coupling (+1.4 MeV)

^{5}H

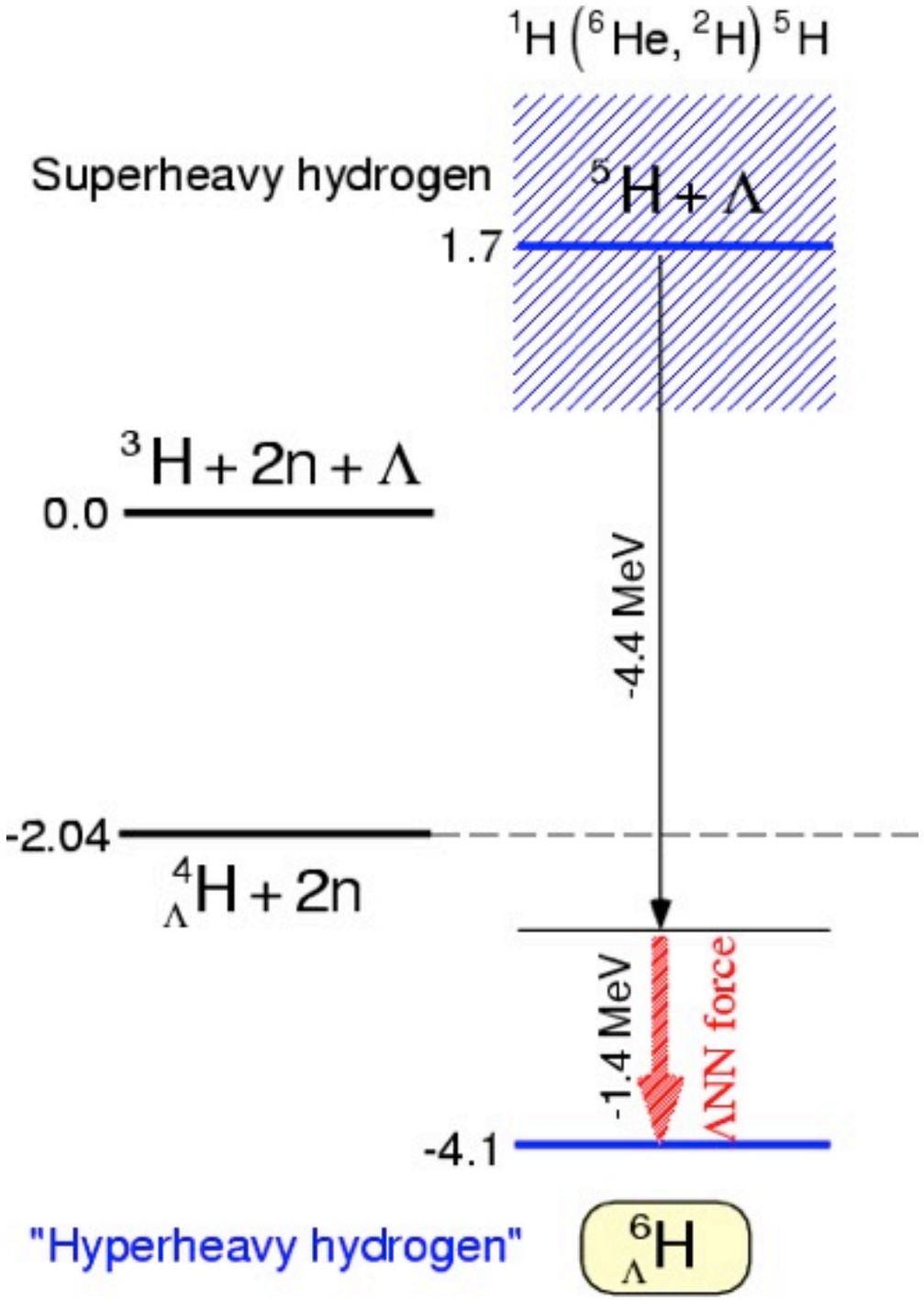
unbound

$^6_\Lambda$H



"Hyperheavy hydrogen": deeply bound

ΛN-ΣN Mixing in Neutron-rich Hypernuclei (theoretical approach)



Y. Akaishi et al. Frascati Phys. Ser. XVI (1999) 59

Coherent ΛN-ΣN mixing

originally introduced to explain A=3-5 hypernuclei

Normal ΛN interaction

$B_Λ$ ~ 4.4 MeV

Coherent ΛN-ΣN mixing effect

$B_Λ$ ~ 4.4 + 1.4 MeV

Precise measurement of B.E.

→ Estimation of mixing effect

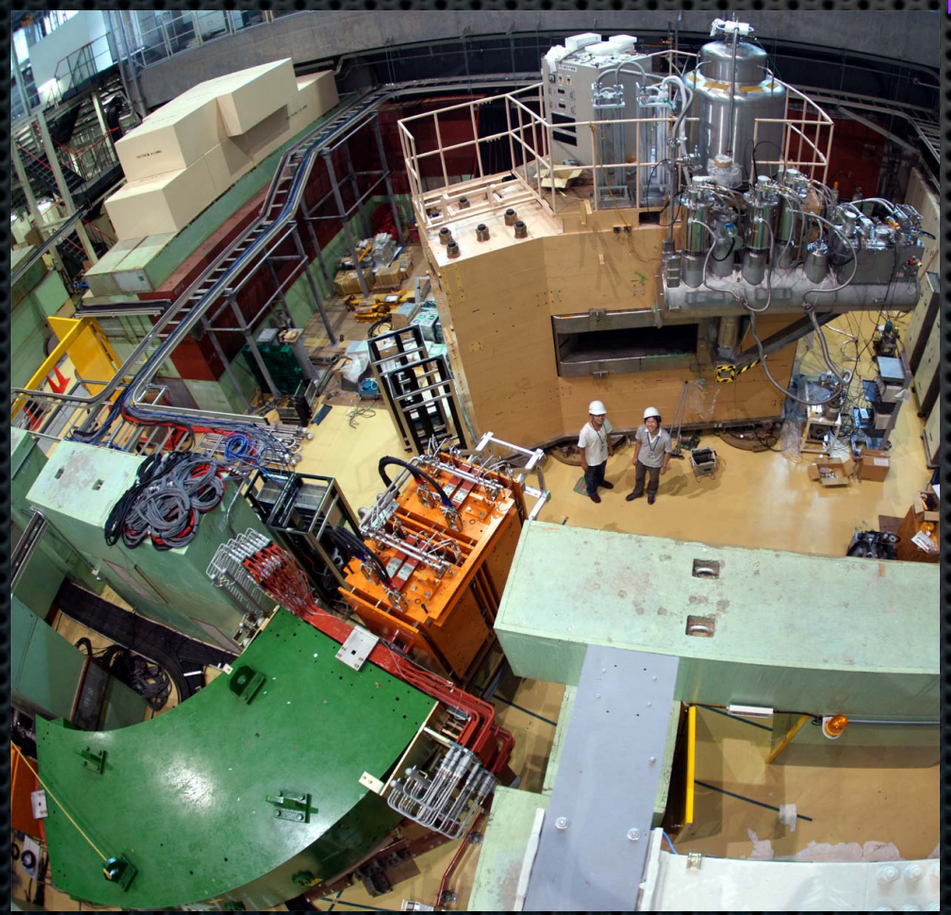
H. Sugimura (Kyoto)

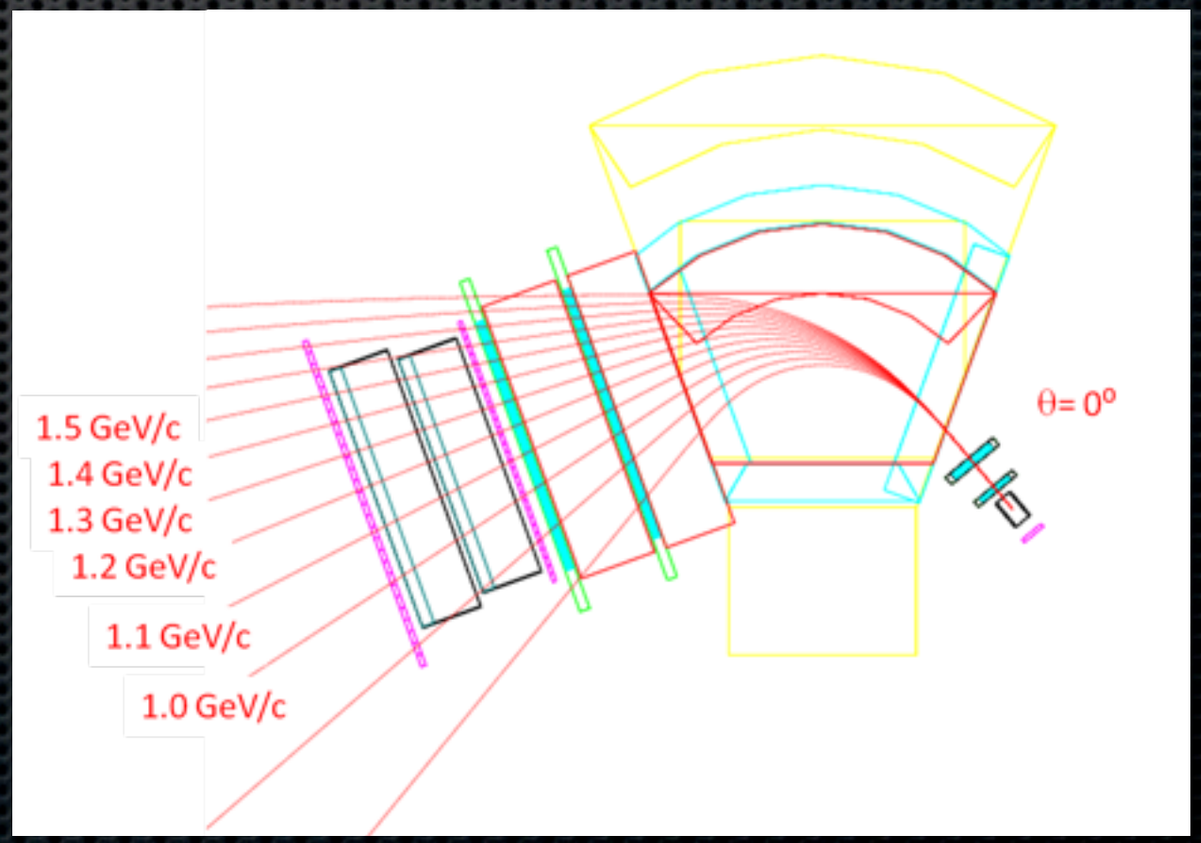
Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-,K^+) Reaction

J-PARC E05
T. Nagae et al.

- Discovery of Ξ-hypernuclei
- Measurement of Ξ-nucleus potential depth and width

of $^{12}_{\Xi}$Be S=-1 → S=-2 (Multi-Strangeness System)

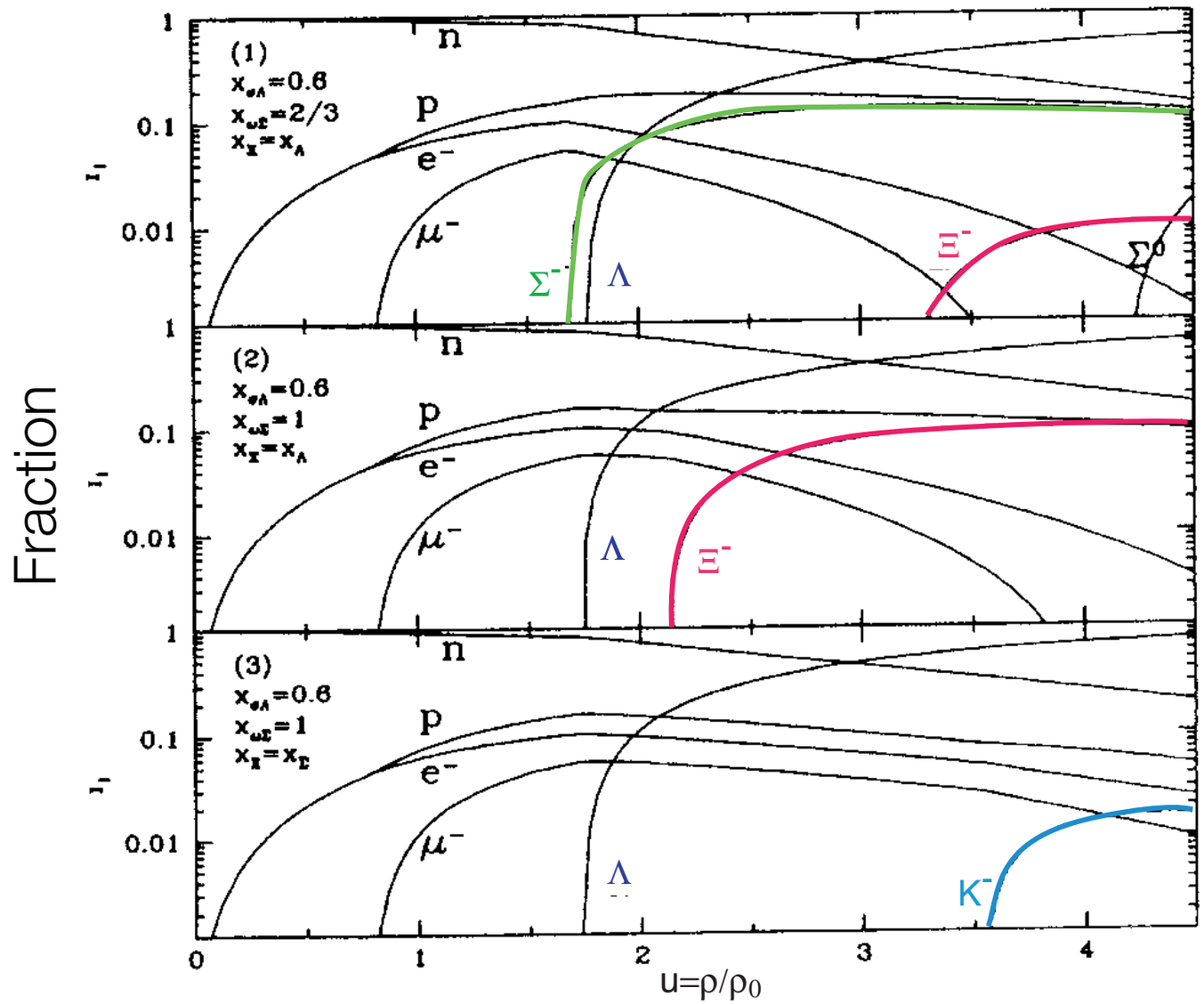




Ξ-Nucleus potential ?

- Chemical Potential:

$$\mu_B = m_B + \frac{{k_F}^2}{2m_B} + U(k_F)$$



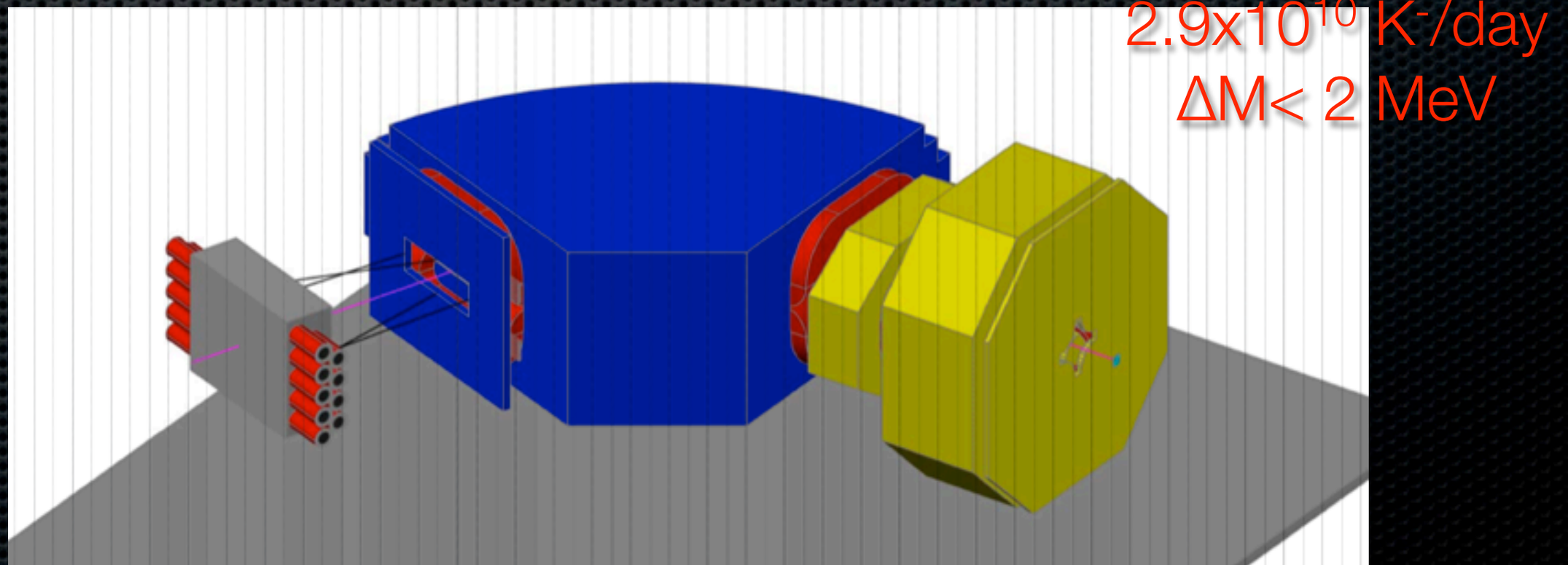
U Σ <0, U Ξ <0

U Σ >0, U Ξ <0

U Σ >0, U Ξ >0

E05 Phase 2 with S-2S

- Grant-In-Aid for Specially promoted research: 2011 – 2015
- 60 msr, Δp/p=0.05% → ΔM=1.5 MeV
- Construction of S-2S(QQD): ~3 years
  - Installation in 2014
- Data taking in 2015 with > 150 kW !!



S. Kanatsuki (Kyoto)

Summary

- J-PARC Beam recovery after the earthquake: Feb. 2012
- Day-1 Experiments; data-taking in progress
  - E19: penta-quark search; 2nd run completed.
  - E27: K-pp search in $d(\pi^+,K^+)$; pilot run finished.
  - E10: Neutron-rich hypernuclei
  - E15: K^-pp search in ^{3}He(K^-,n) reaction
  - E05: Ξ hypernuclei
  - etc.