

Satoshi N Nakamura

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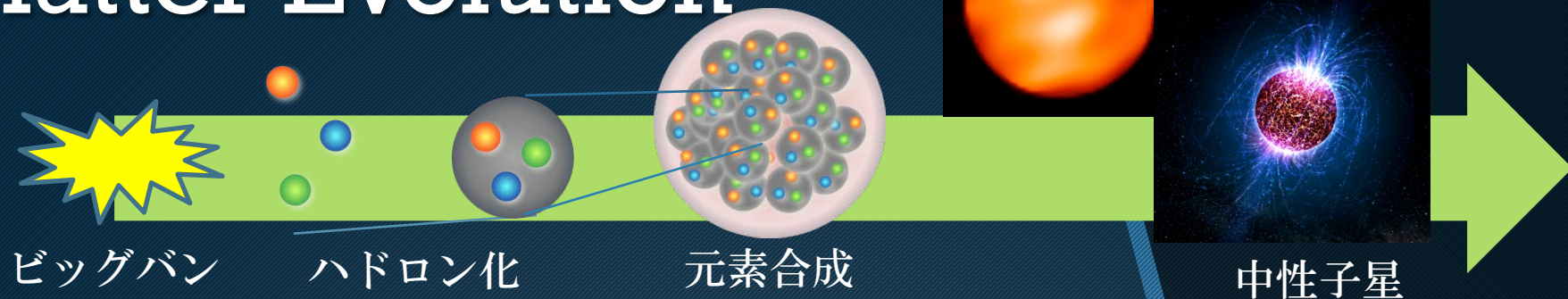
中性子星核物質ウィンタースクール

福島飯坂温泉

17 February . 2017

ストレンジネス核物理

Matter Evolution



QCD に立脚するモデル
(Lattice QCD, Effective theories of QCD)

様々な物質形態の性質

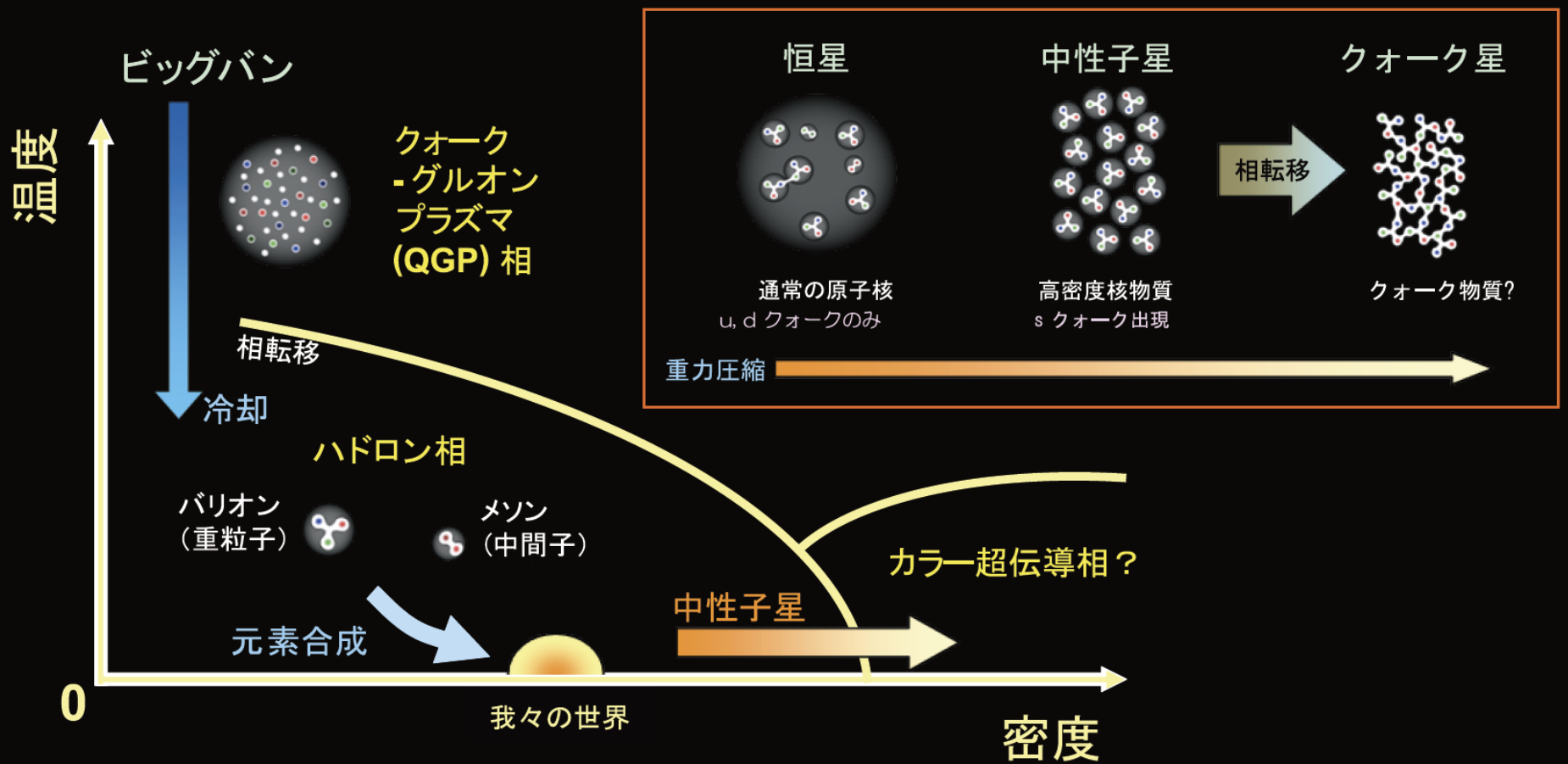
宇宙物質創成の謎の解明へ

ハドロン構造

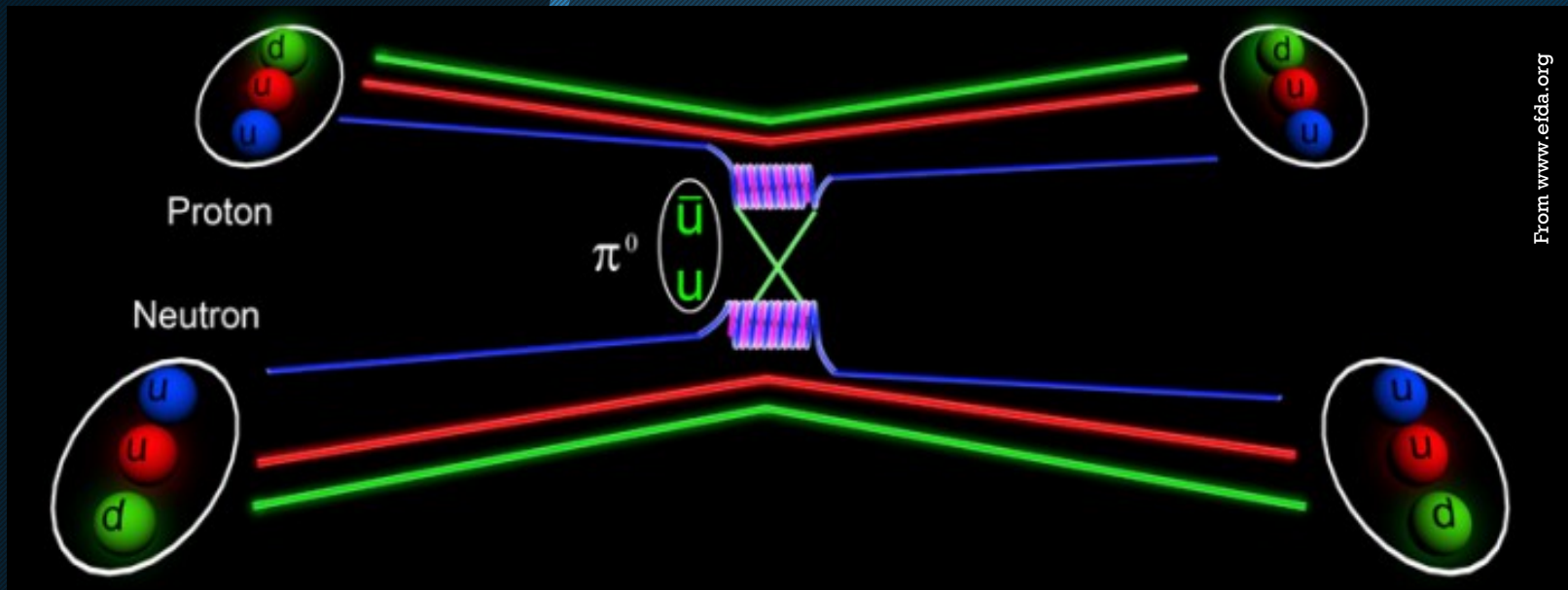
高密度ハドロン物質

物質中におけるハドロンの性質

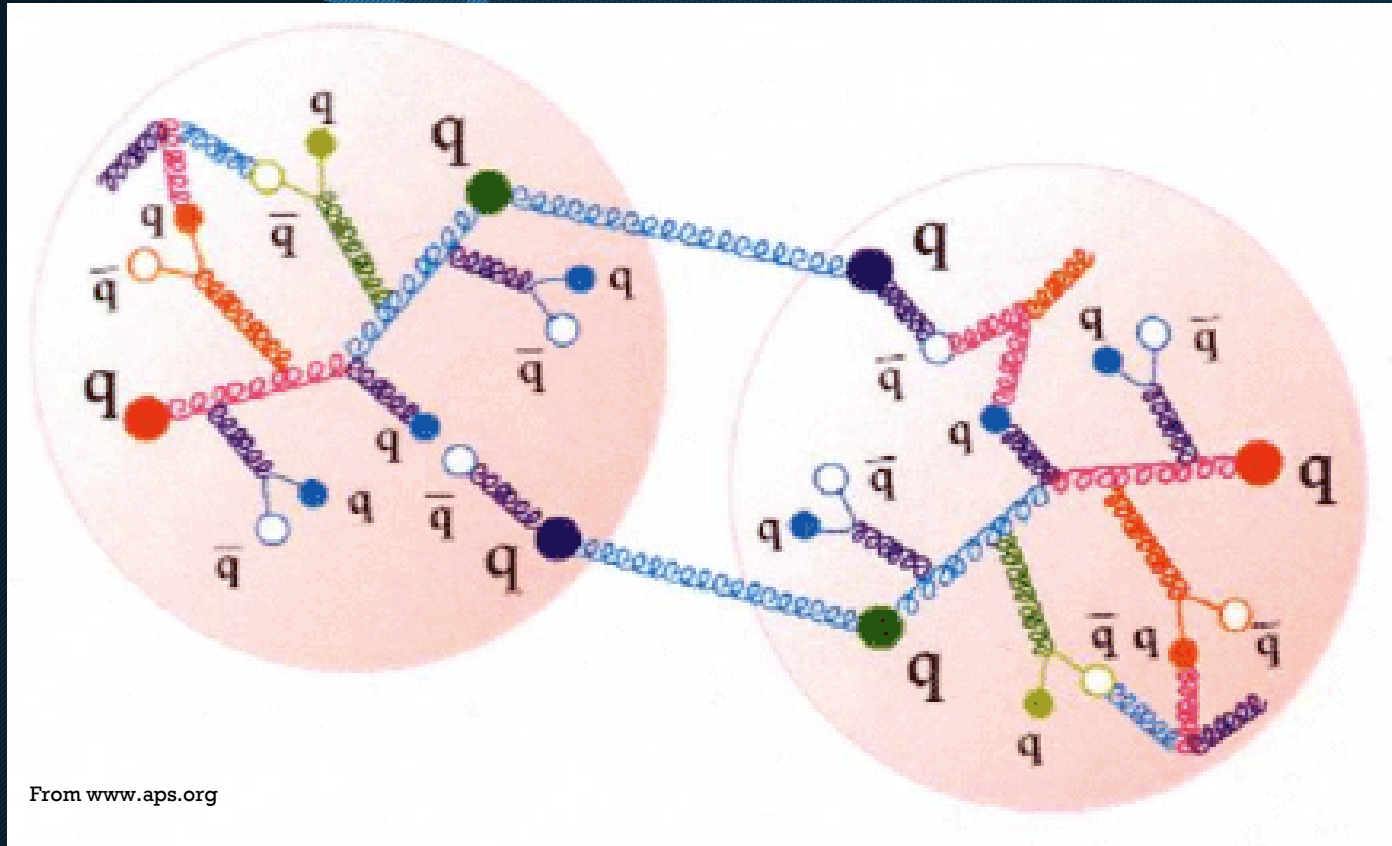
原子核物理：＝強い相互作用で束縛された量子多体系の物理



核力：低エネルギーにおける強い相互作用



離れているcolorless物体(核子)間の相互作用
one pion exchange



近づくとも quark の自由度が無視できない

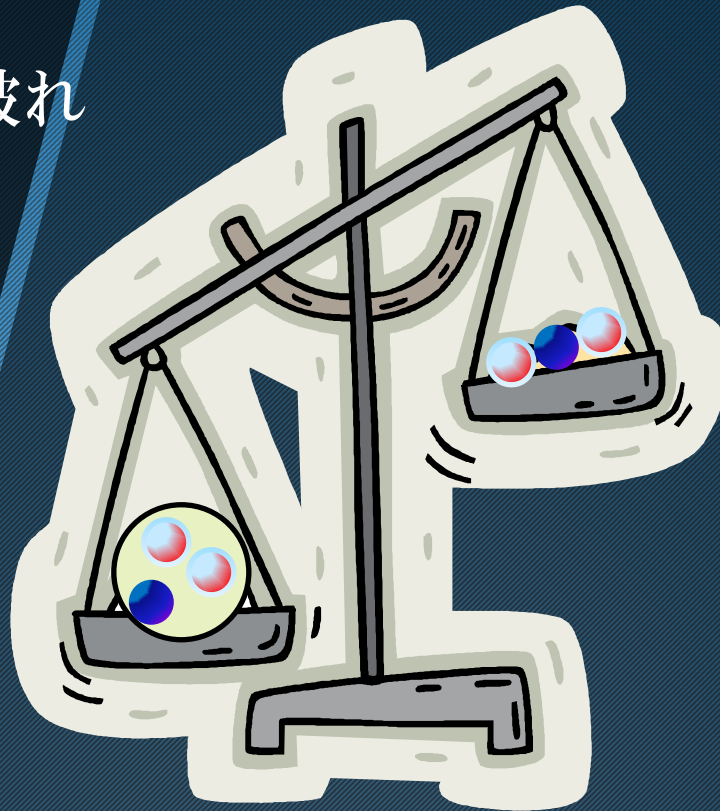
クォークと核子の質量

低エネルギーにおける強い相互作用

カイラル対称性の破れ



陽子質量
 $938.272 \text{ MeV}/c^2$



$U_p (3\text{MeV}/c^2)$
+ $U_p (3\text{MeV}/c^2)$
+ Down ($5 \text{ MeV}/c^2$)

$11\text{MeV}/c^2$



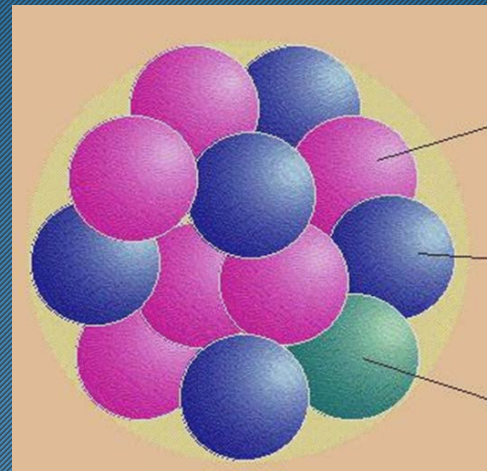
ヒッグス機構

なぜ、重い系がより安定なのか？
我々の質量の ~90%は何から生じている？

10 MeV

Λ QCD

Nuclear Force


$$R(^{208}\text{Pb}) \sim 6.6\text{fm}$$

A horizontal line with arrows at both ends, representing a logarithmic scale. Three vertical tick marks are placed along the line. Below the first tick mark is the text "0.1 fm". Below the second tick mark is the text "1 fm". Below the third tick mark is the text "10 fm".

核力

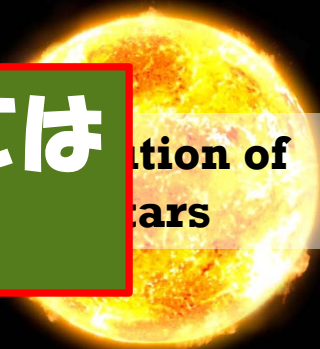
微視的核力モデル
現象論的ポテンシャル



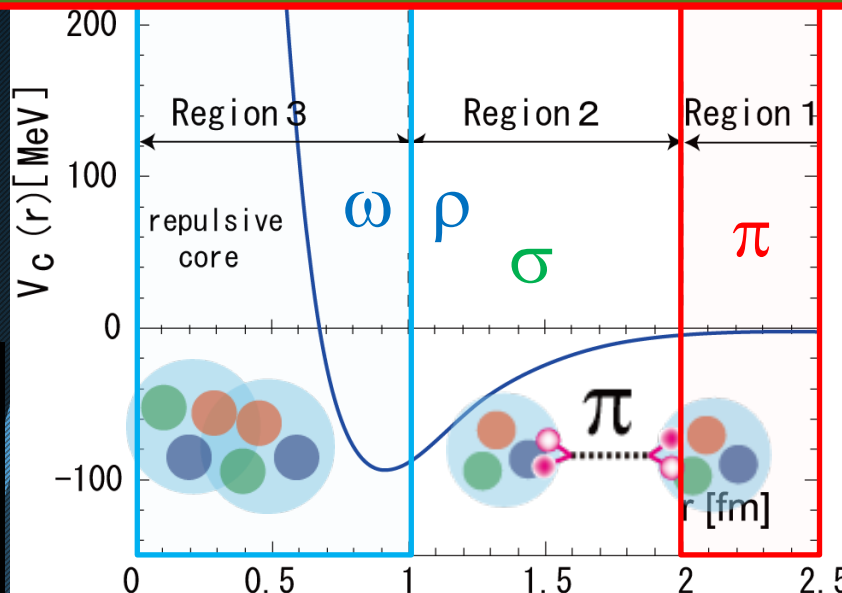
Nuclear Saturation

color magnetic
斥力芯

斥力芯、 LS 力の原因については
未だ良く分かっていない！



tion of
ars



one pion exchange
(湯川核力)
原子核を束縛

ω, σ exchange
 LS force
魔法数の原因



Supernova Explosion

Figure of Supernova Remnant: Crab Nebula (Messier 1)
Subaru Telescope, National Astronomical Observatory of Japan
Copyright © 2007 National Astronomical Observatory of Japan. All rights reserved. March 12, 2007

Nucleosynthesis
Abundance of elements

One Pion Exchange Potential (OPEP)

電磁気で

$$\phi_m = -\vec{\mu} \cdot \vec{\nabla} \left(\frac{1}{r} \right)$$

$$\vec{H} = -\vec{\nabla} \phi_m$$

$$\begin{aligned} V_m &= -\vec{\mu}_2 \cdot \vec{H}_1 \\ &= -(\mu_2 \cdot \nabla)(\mu_1 \cdot \nabla) \left(\frac{1}{r} \right) \end{aligned}$$

$$V_\pi = \frac{f^2}{3\hbar c} m_\pi c^2 (\tau_1 \cdot \tau_2) \left\{ \sigma_1 \cdot \sigma_2 + \left(1 + \frac{3}{\kappa r} + \frac{3}{(\kappa r)^2} \right) S_{12} \right\} \left(\frac{e^{-\kappa r}}{r} \right)$$

π field で

$$\phi_\pi = \frac{f}{\kappa} \vec{\sigma} \cdot \vec{\nabla} \left(\frac{e^{-\kappa r}}{r} \right)$$

$$\kappa^{-1} := \frac{\hbar}{m_\pi c}$$

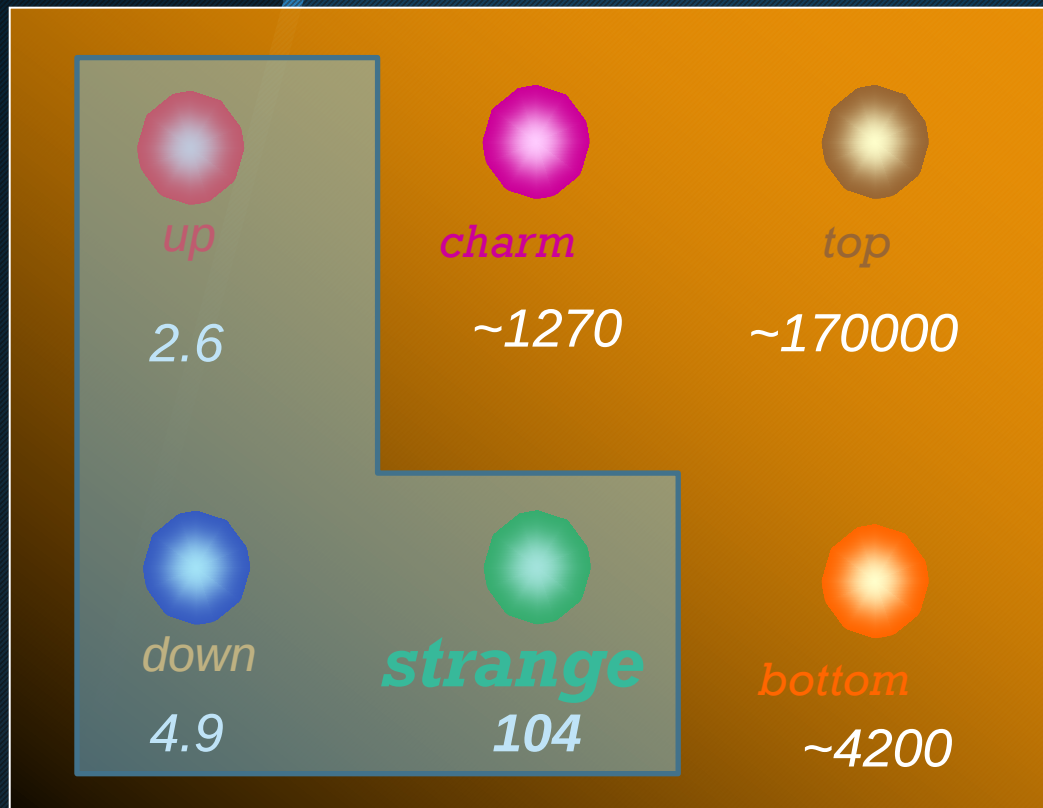
$$V_\pi = \frac{f^2}{\kappa^2} (\sigma_2 \cdot \nabla)(\sigma_1 \cdot \nabla) \left(\frac{e^{-\kappa r}}{r} \right)$$

$$S_{12} := \frac{3(\sigma_1 \cdot r)(\sigma_2 \cdot r)}{r^2} - \sigma_1 \cdot \sigma_2$$

クォーク：世界を構成する粒子

$$+\frac{2e}{3}$$

$$-\frac{e}{3}$$



Mass
(MeV/c²)

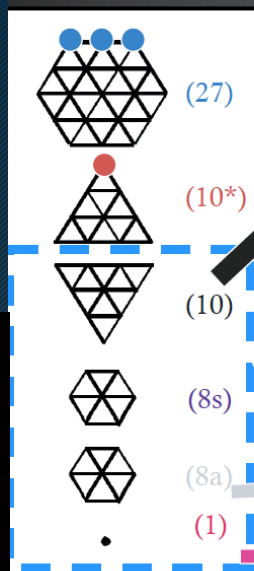
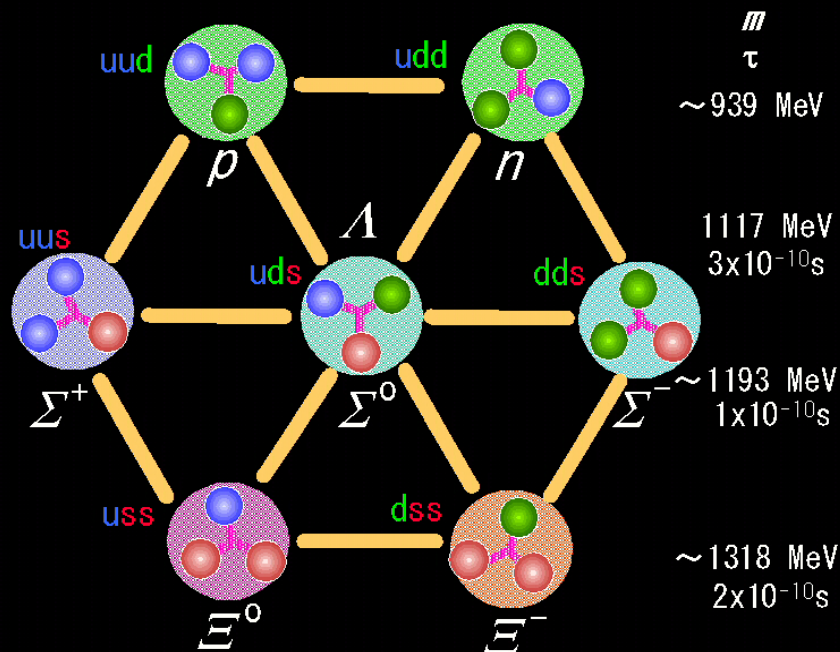
Stable

unstable
(life $\sim 10^{-10}$ s)

Very unstable
(life $< 10^{-12}$ s)

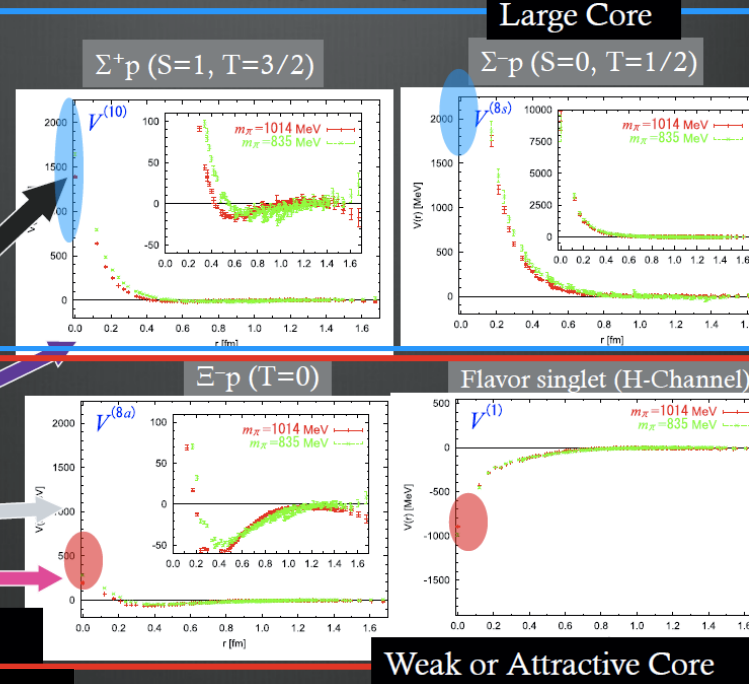
Baryon Octet (spin=1/2)

quark
● up
● down
● strange



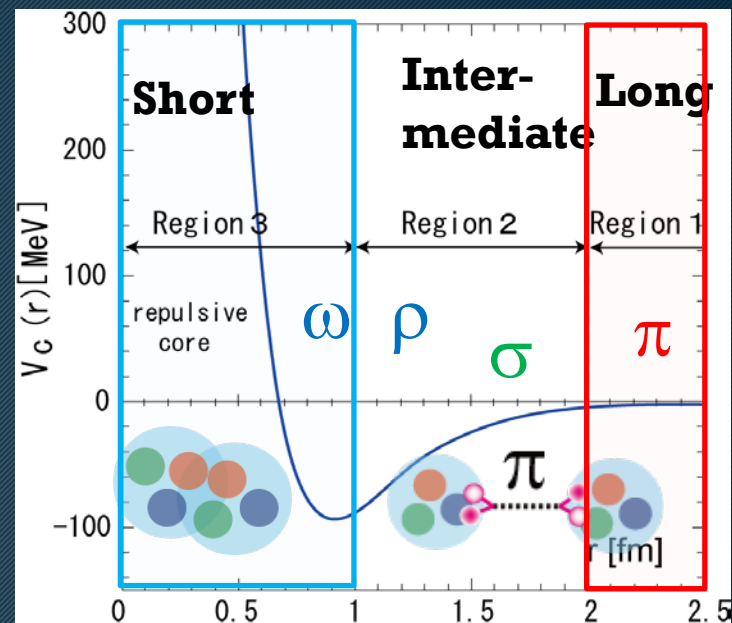
Lattice QCD,
T. Inoue et al.

Prog. Theor. Phys. 124 (2010) 591.



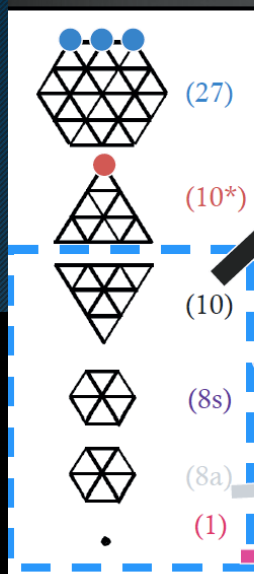
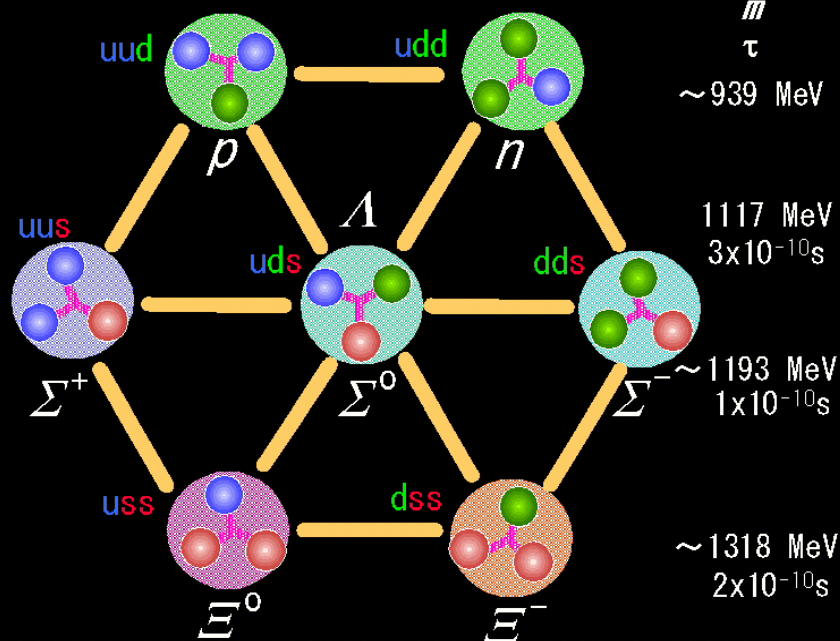
Weak or Attractive Core

Color Magnetic + **Quark Pauli** (YNで重要)



Baryon Octet (spin=1/2)

quark
● up
● down
● strange

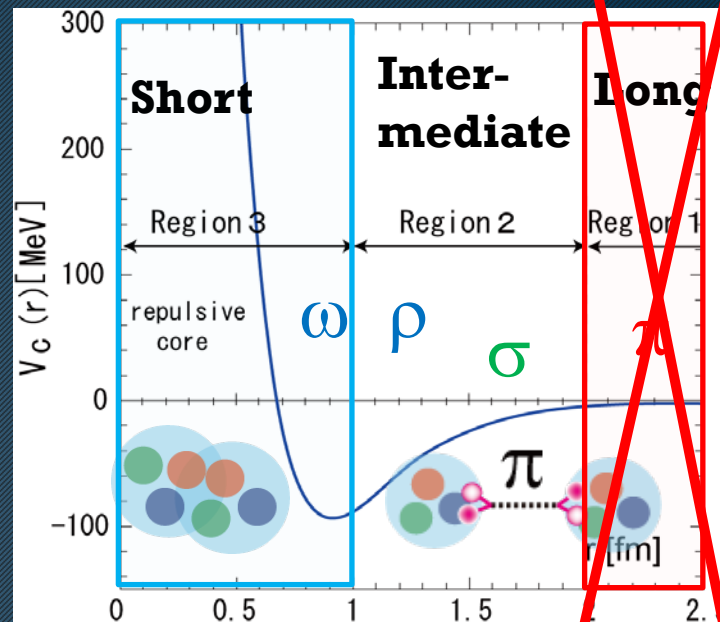
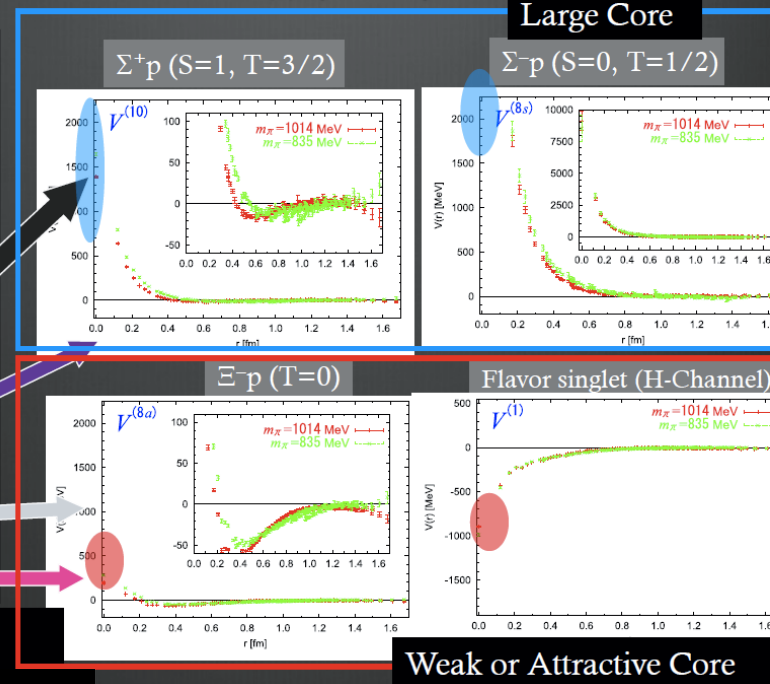


Lattice QCD,
T. Inoue et al.

Prog. Theor. Phys. 124 (2010) 591.

Color Magnetic + Quark Pauli (YNで重要)

Λ
 $T=0$



バリオン間相互作用

QCD

バリオン間相互作用

クォーク自由度
 $SU_f(3)$ 対称性

Nuclear Force

豊富な NN 散乱データ

Hyperon Force

限られた YN/YY 散乱データ

確立した理論
Cluster Model
Shell Model
Mean Field

核構造

Normal/Exotic nuclei

ハイパー核構造

Λ , $\Lambda\Lambda$, Ξ Hypernuclei

多体系

原子核物理：＝強い相互作用で束縛された
量子多体系の物理

核力

微視的核力モデル
現象論的ポテンシャル



原子核

~~単純な2体力の重ね合わせ~~

多体問題への様々なアプローチ

Ab-initio calculation

Cluster model

Shell model

Mean Field Calculation

多体系

原子核物理：＝強い相互作用で束縛された
量子多体系の物理

核力

精密核力モデル

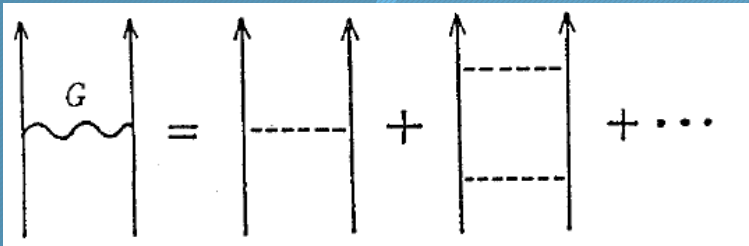
現象論的ポテンシャル



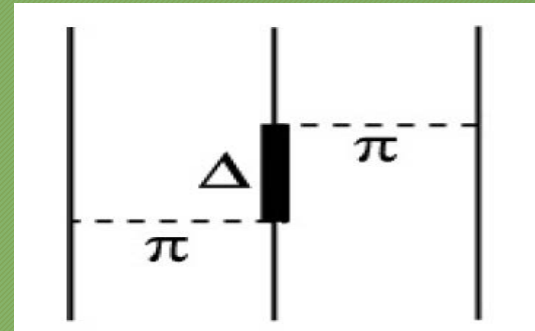
原子核

~~単純な2体力の重ね合わせ~~

有効相互作用 (モデルに依存)



3体核力

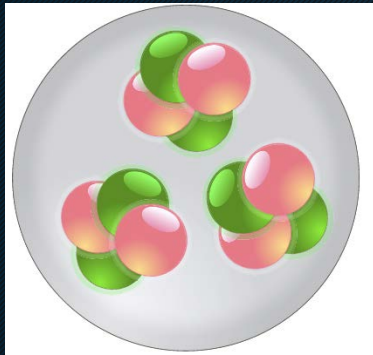


多体系

原子核物理：＝強い相互作用で束縛された
量子**多体系**の物理

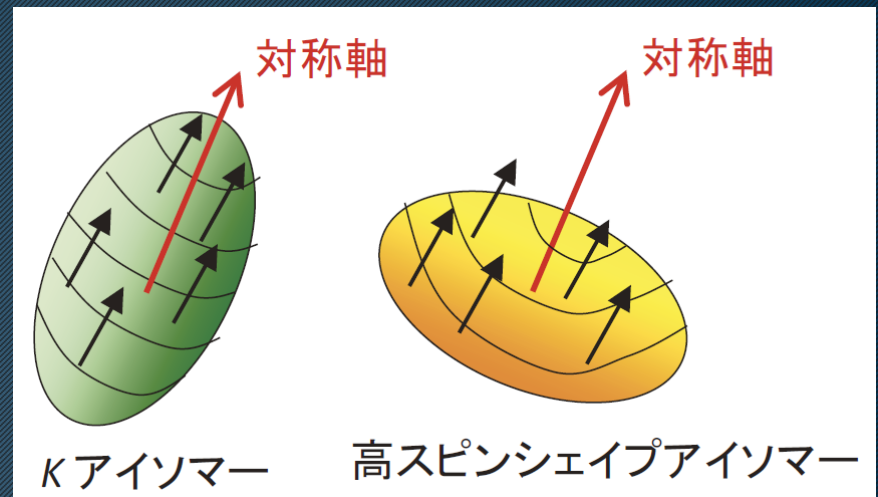
多体系だから**数種掇様が面白い**

原子核は束縛エネルギーが飽和したガスや液体みたい

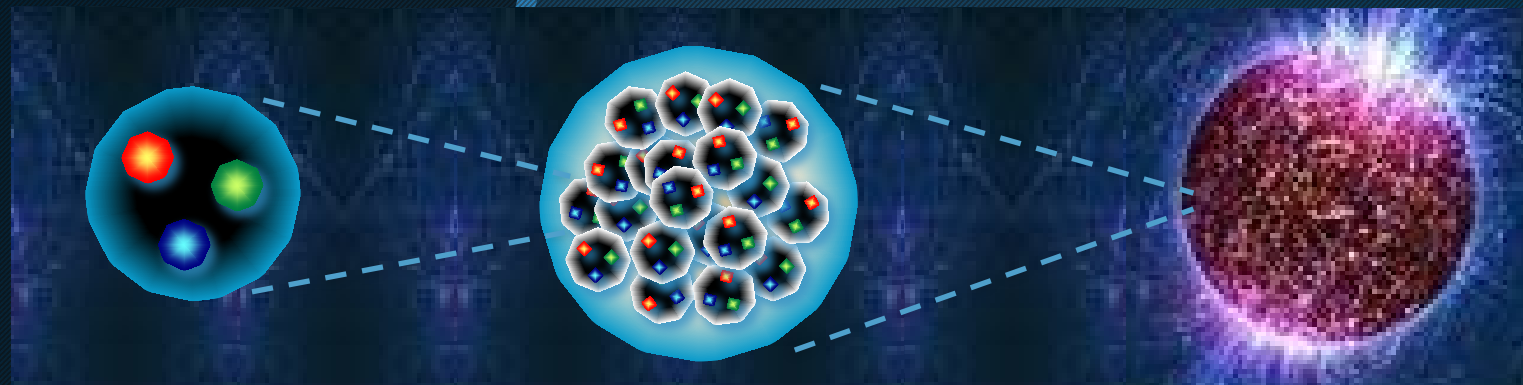


僅かなエネルギーでクラスター化

変形して寿命が延びる



フェルミガスモデルと中性子星



10^{-15} m

10^4 m

強い相互作用が重要な量子多体系

フェルミガスモデル

核内で核子は自由

核子はフェルミオン(パウリ排他律に従う！)

原子核をガスとしてモデル化

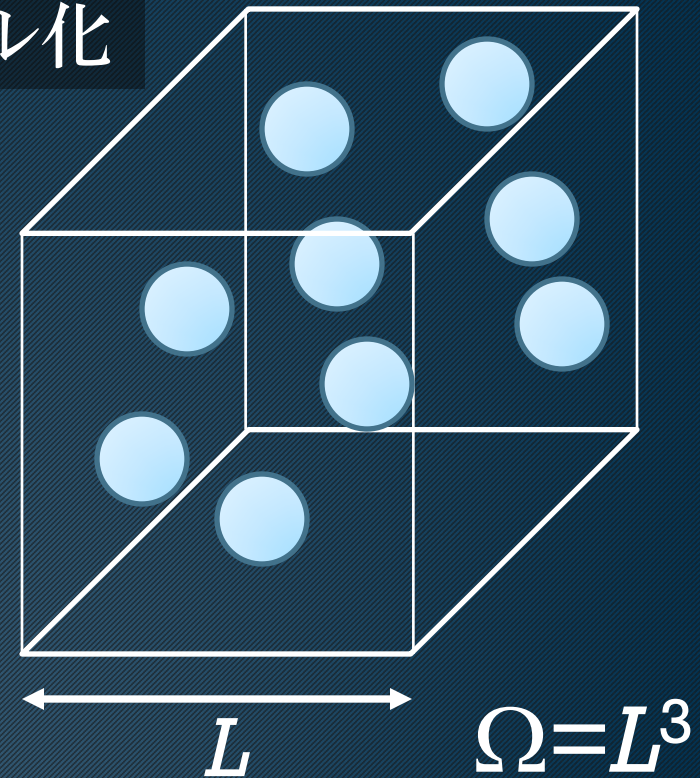
$$\varphi = \frac{1}{\sqrt{\Omega}} e^{i\mathbf{k} \cdot \mathbf{r}} \times Spin \times Isospin$$

From B.C.

$$k_i = \frac{2\pi}{L} n_i$$

of States for Neutron

$$\frac{dn}{dk_n} dk_n = 2 \left(\frac{L}{2\pi} \right)^3 4\pi k_n^2 dk_n$$



フェルミガスモデル

中性子数: N

$$N = \int_0^{k_F} \frac{dn}{dk_n} dk = \frac{1}{3\pi^2} \Omega k_F^3$$

$$k_F = \left(3\pi^2 \frac{N}{\Omega} \right)^{1/3}$$

$$E_{nF} = \frac{(\hbar k_F)^2}{2M} = \frac{(9\pi^4)^{1/3} \hbar^2}{2M} \left(\frac{N}{\Omega} \right)^{2/3}$$

Let $N = Z = A/2$, $\Omega = A/0.17$ [fm³]

$$\hbar k_F \sim 1.3 \text{ fm}^{-1} \cdot \hbar = 250 \text{ MeV}/c$$

$$E_F \sim 33 \text{ MeV}$$

太陽を半径10kmまで押しつぶす

$$M_{\odot} \sim 2 \times 10^{33} [\text{g}] \rightarrow n \sim \frac{\{2 \times 10^{33} \cdot 6 \times 10^{23}\}}{\left(\frac{4\pi}{3}\right)(10^4)^3} \sim 0.286 [\text{fm}^{-3}]$$

$$n_p = n_e$$

$$n_n + n_p = 0.286 [\text{fm}^{-3}]$$

$$n \leftrightarrow p + e^- + 0.8 \text{MeV}$$

$$\mu_{nF} \simeq 200 [\text{MeV}] \cdot n_n^{\frac{2}{3}} + 940 [\text{MeV}]$$

$$\mu_{pF} \simeq 200 [\text{MeV}] \cdot n_p^{\frac{2}{3}} + 940 [\text{MeV}]$$

$$\mu_{eF} \simeq 400 [\text{MeV}] \cdot n_e^{\frac{1}{3}}$$

$$\mu_{nF} = \mu_{pF} + \mu_e + 0.8 [\text{MeV}]$$

$$\frac{n_p}{n_n} \sim 0.025$$

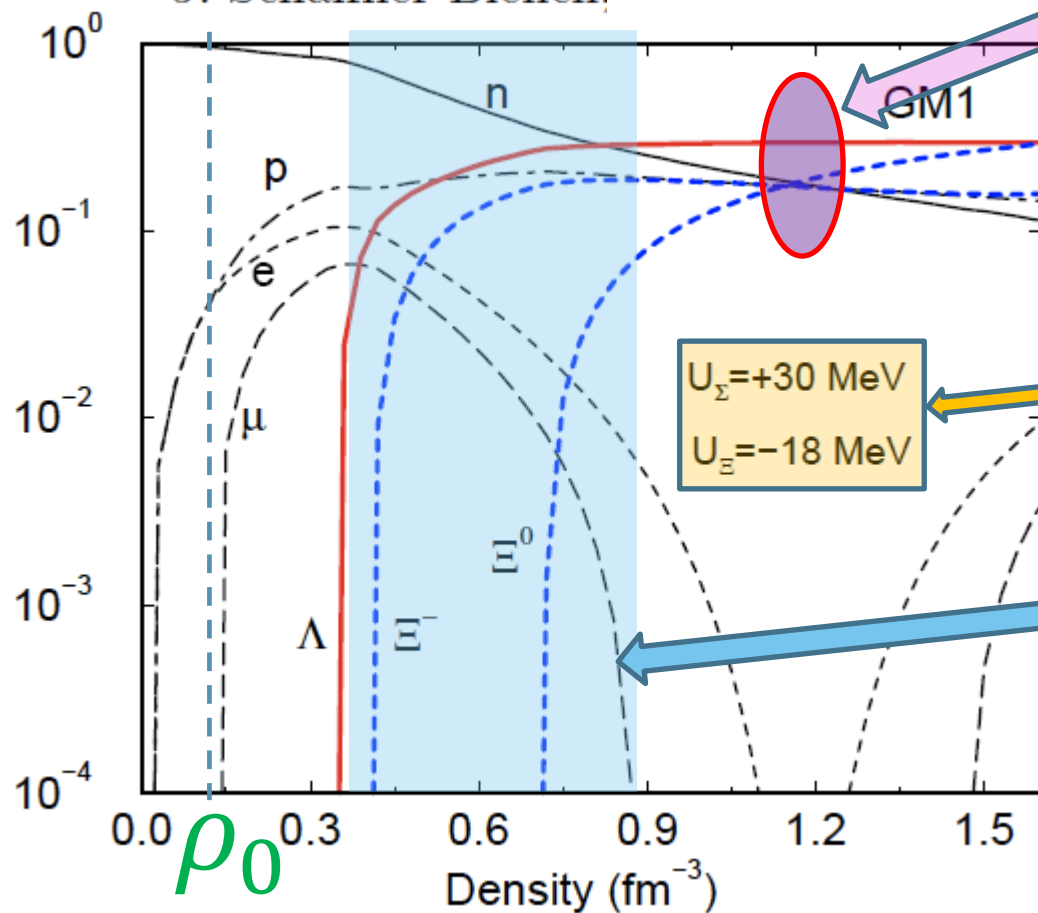
中性子星

中性子星内部はまだまだ理解が足りない！

対称核物質：クーロン力が巨大化を阻害

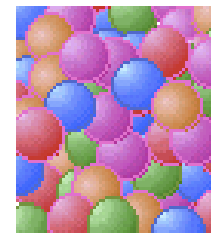
非対称核物質：中性子星

J. Schaffner-Bielich



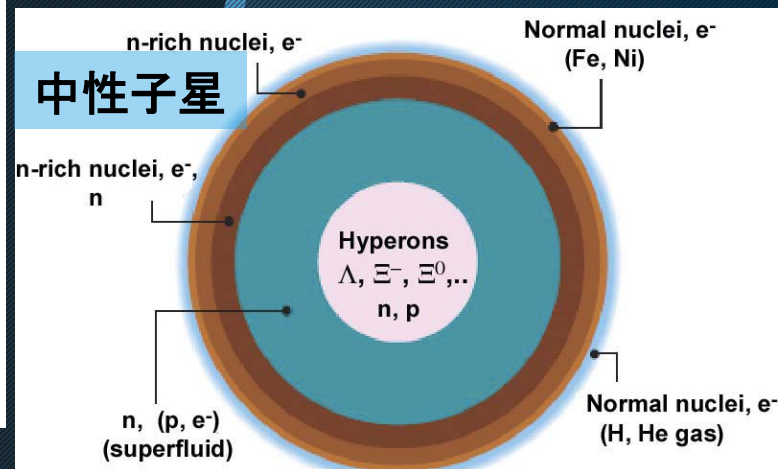
Strange hadronic matter

$Nu \sim Nd \sim Ns$



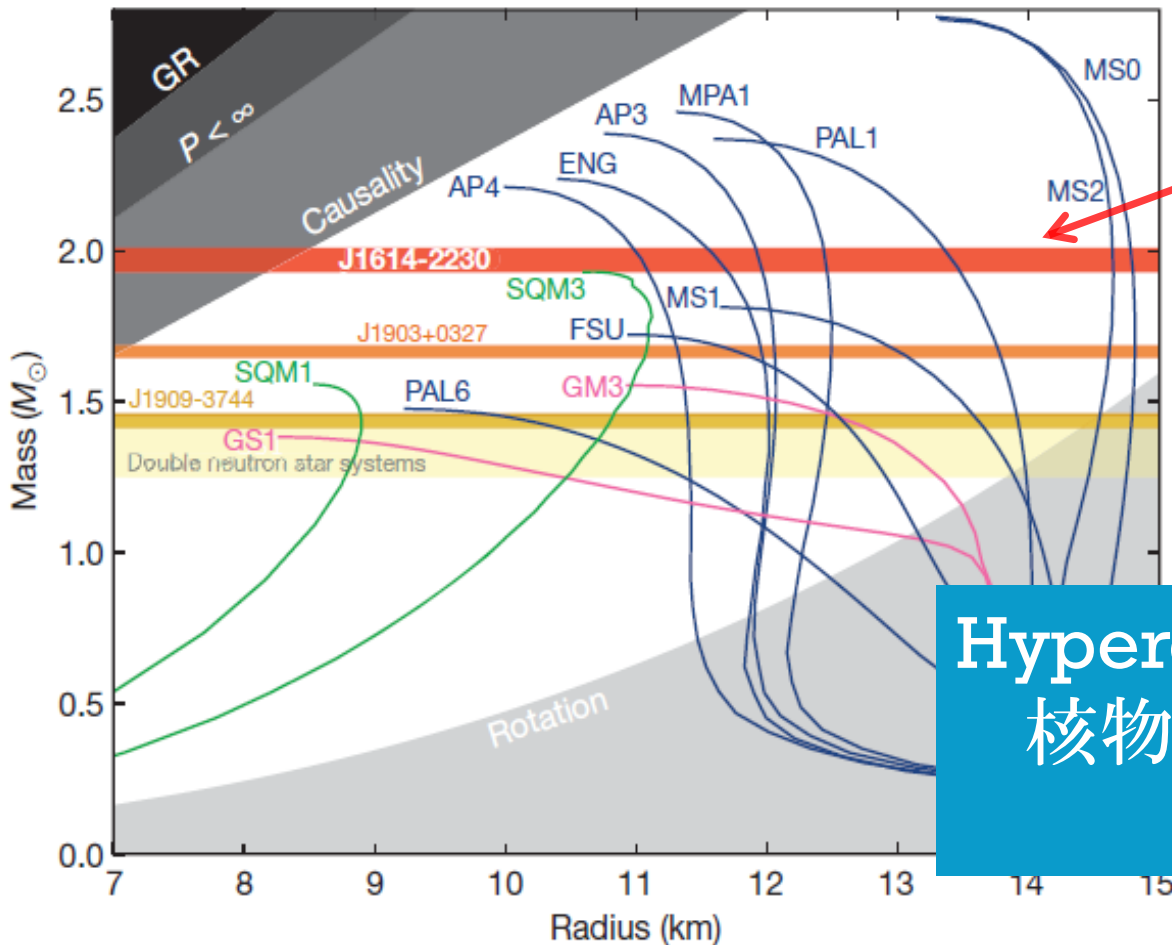
$p, n, \Lambda, \Xi^0, \Xi^-$

ハイペロン力の理解が本質的に重要



Hyperon Puzzle

現在の我々の知識（原子核＋ハイパー核）：
高密度（ $\rho=2\sim 3\rho_0$ ）でハイペロンが発生しなくてはならない

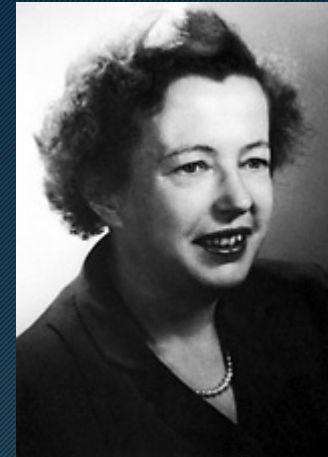
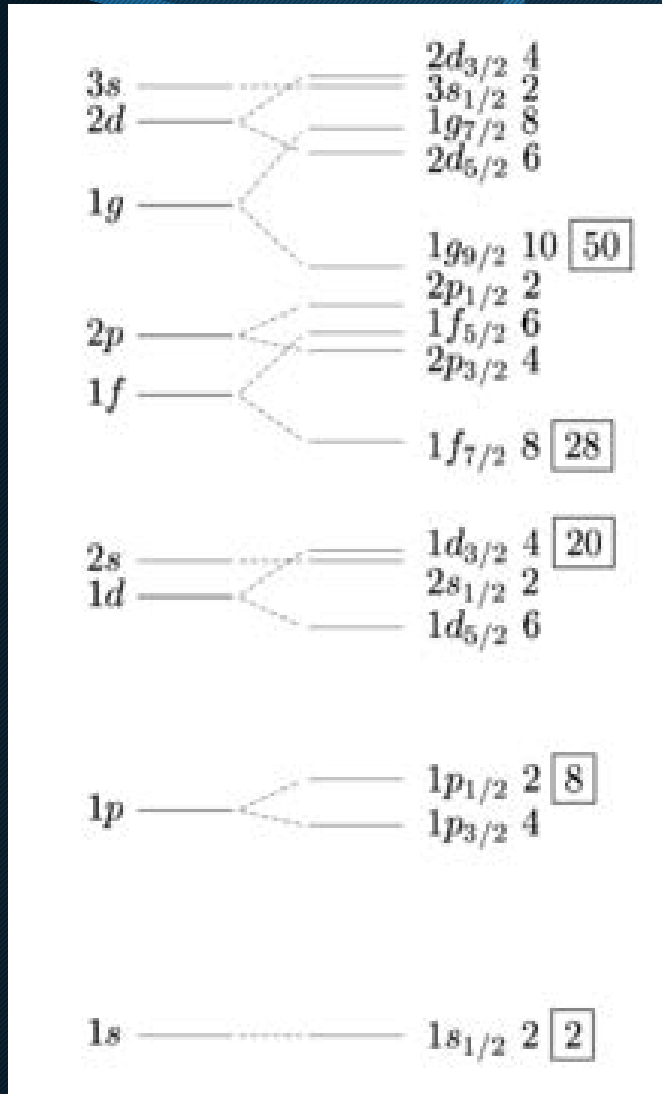


2 M_{solar} 質量中性子星

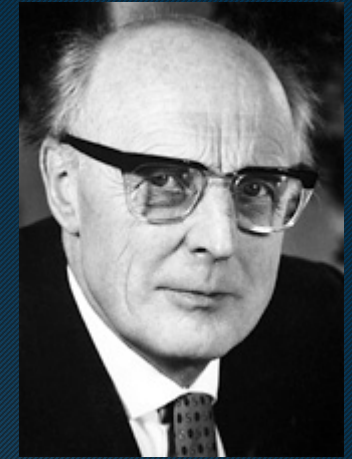
重大な知識の欠陥が露呈
Soft すぎる EOS

Hyperon Puzzle の解決
核物理の最重要課題の
一つ

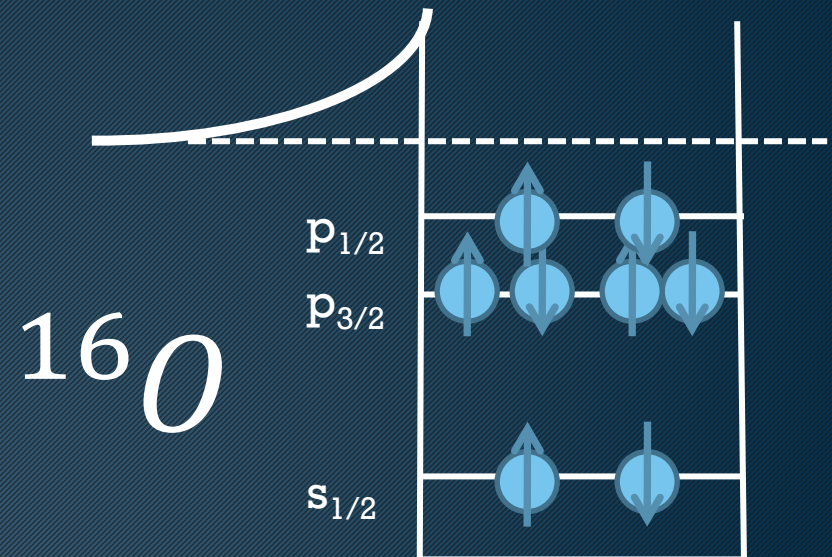
原子核深部はどうなっている？



Maria G. Mayer

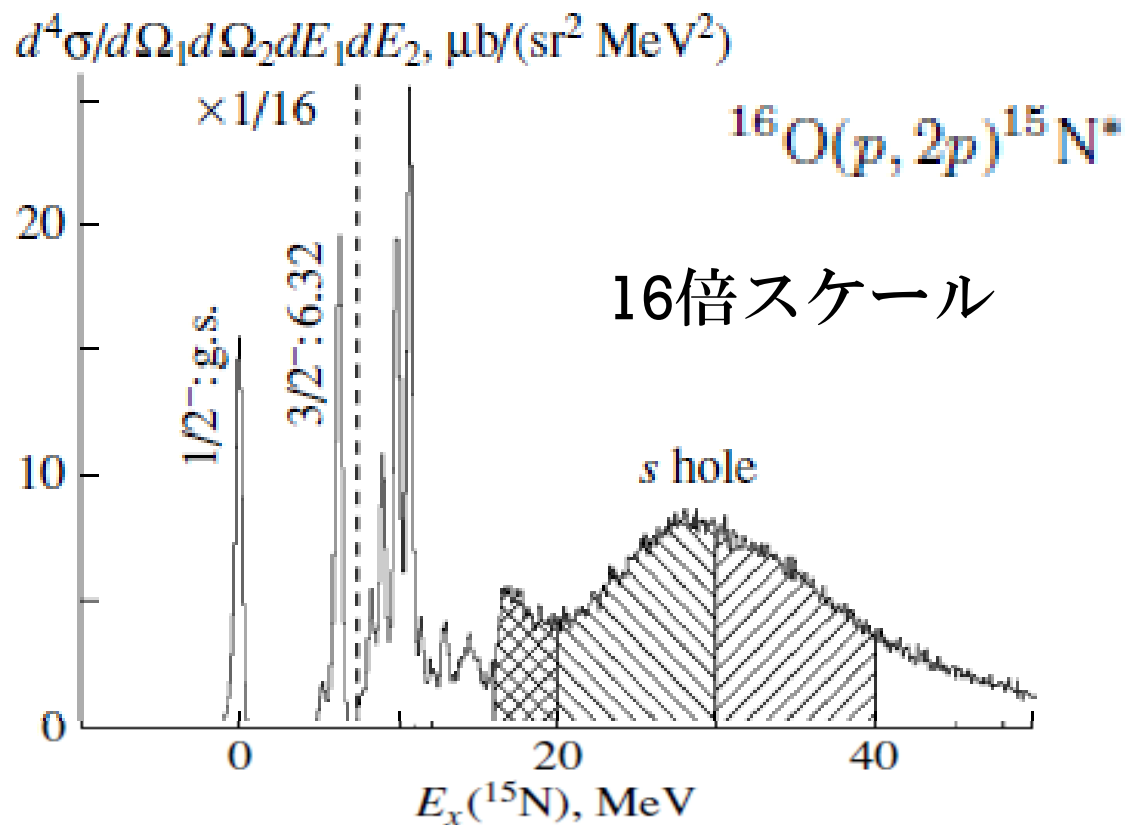


J. Hans D. Jensen

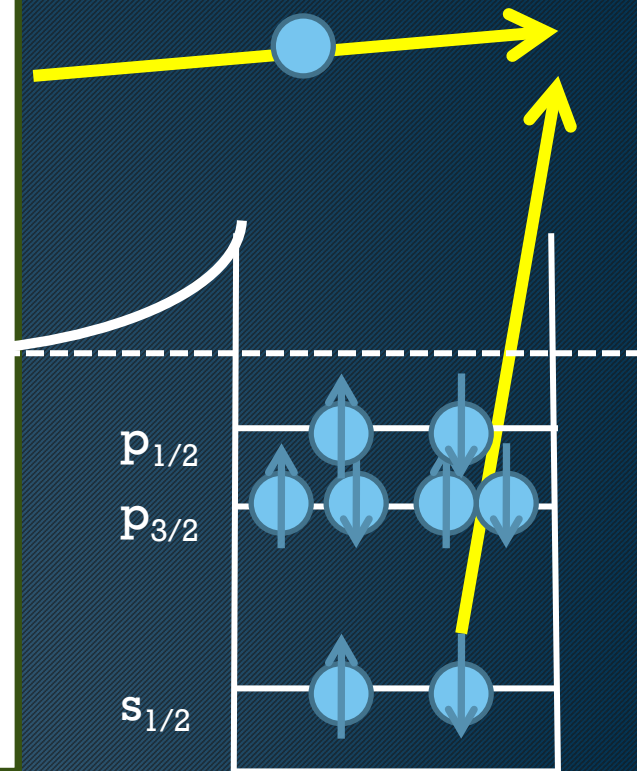


シェルモデル (1963 Nobel Prize in Physics)

原子核深部はどうなっている？



M.Yosoi et al. *Physics of Atomic Nuclei*, Vol. 67, No. 10, 2004, pp. 1810–1817



Λ 粒子：最も軽いハイペロン

PDG (2013)



(uds)

$I(J^P) = 0(\frac{1}{2}^+)$ Status: ****

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Λ MASS

The fit uses Λ , Σ^+ , Σ^0 , Σ^- mass and mass-difference measurements.

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1115.683$\pm$0.006				OUR FIT
1115.683$\pm$0.006				OUR AVERAGE

Λ MEAN LIFE

Measurements with an error $\geq 0.1 \times 10^{-10}$ s have been omitted altogether, and only the latest high-statistics measurements are used for the average.

VALUE (10^{-10} s)	EVTS	DOCUMENT ID	TECN	COMMENT
2.631$\pm$0.020				OUR AVERAGE

Error includes scale factor of 1.6. See the ideogram below.

Λ DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$p\pi^-$	(63.9 $\pm$ 0.5) %
Γ_2	$n\pi^0$	(35.8 $\pm$ 0.5) %
Γ_3	$n\gamma$	(1.75 $\pm$ 0.15) $\times 10^{-3}$

$\tau \sim 260$ ps

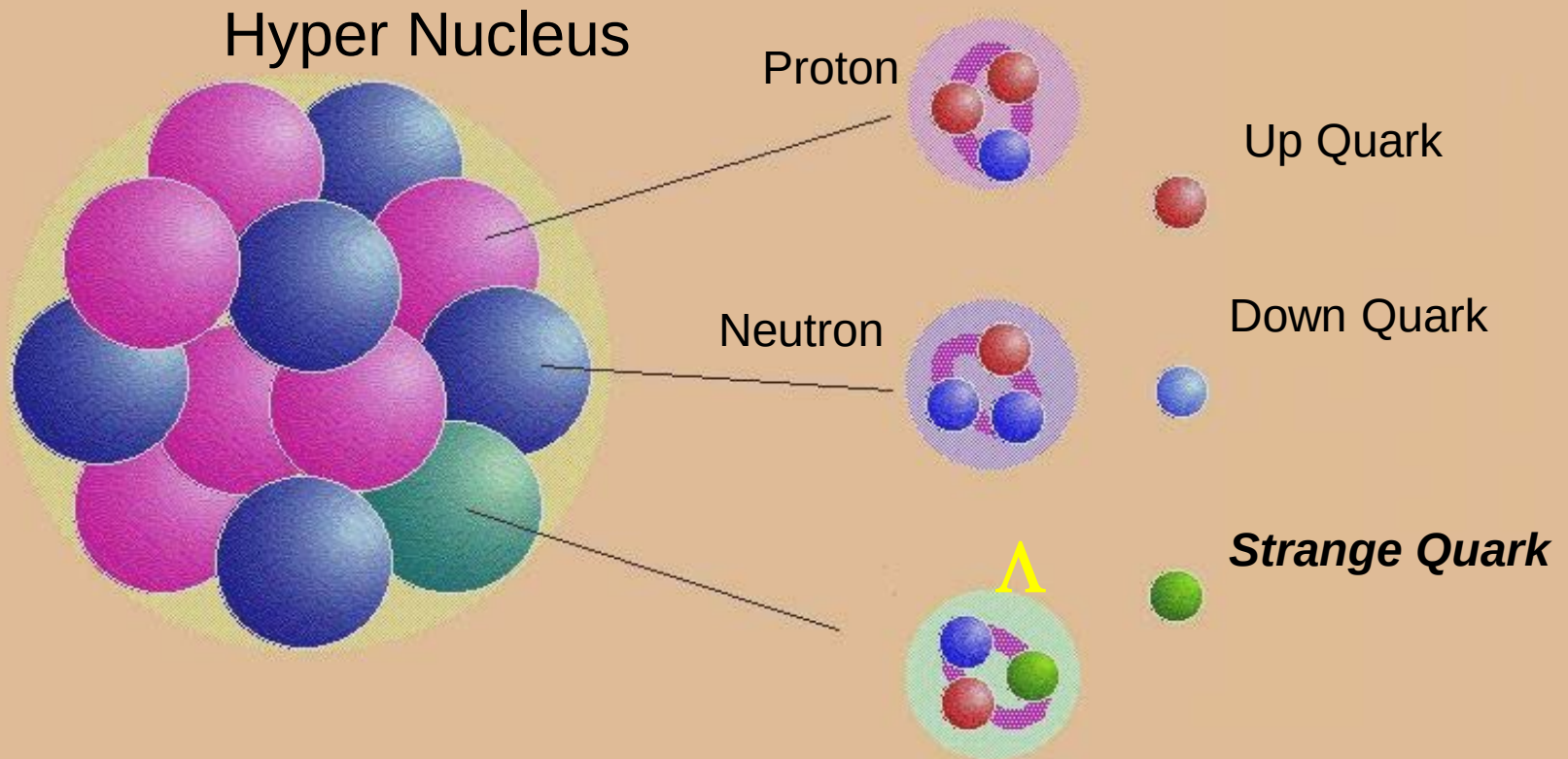
$c\tau \sim 8$ cm

散乱実験は困難

束縛状態は作れる

ラムダハイパー核

地上で作れる中性子星の欠片



原子核に Λ を入れると...

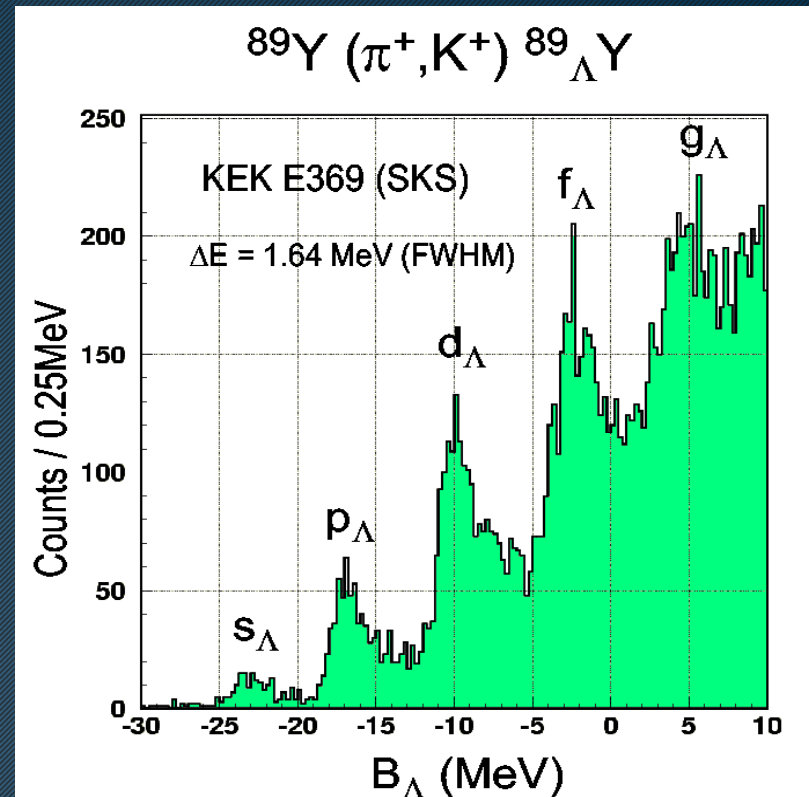
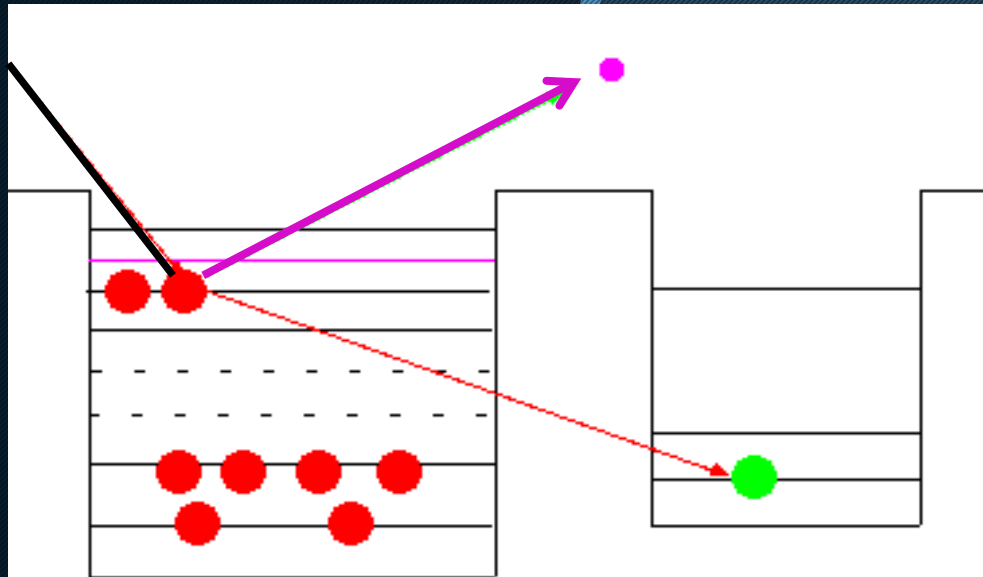
BB相互作用

NN相互作用

原子核構造

Λ は核子からの
パウリ排他律を受けない

ハイパー核構造
単一粒子描像



原子核に Λ を入れると...

BB相互作用

NN相互作用

原子核構造

Λ は核子からの
パウリ排他律を受けない

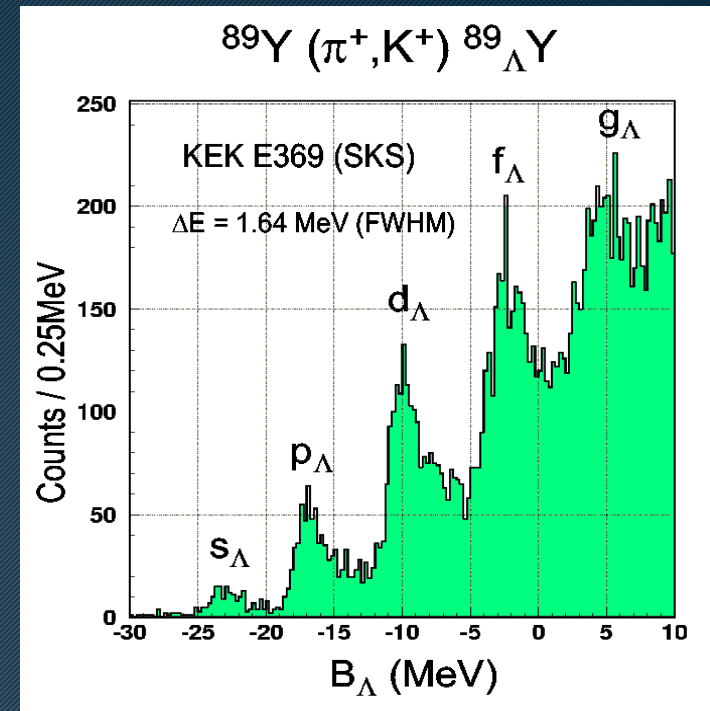
精密分光が可能！

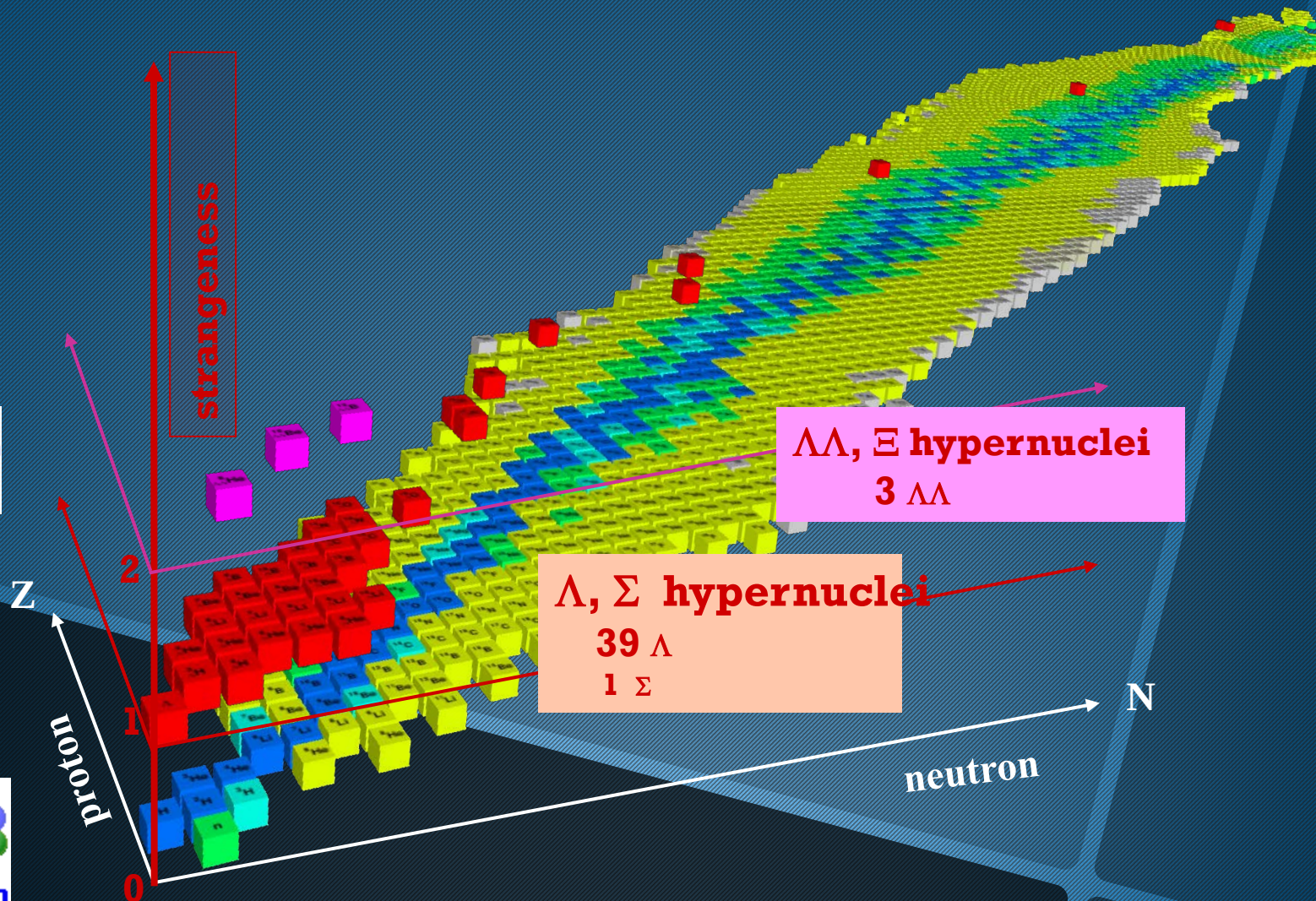
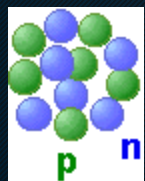
ハイパー核構造
単一粒子描像

原子核深部のプローブ

核媒質中でのハドロンの性質変化

不純物により核の構造が変化





Notation of hypernuclei

A
 Λ Z

A : Number of Baryons

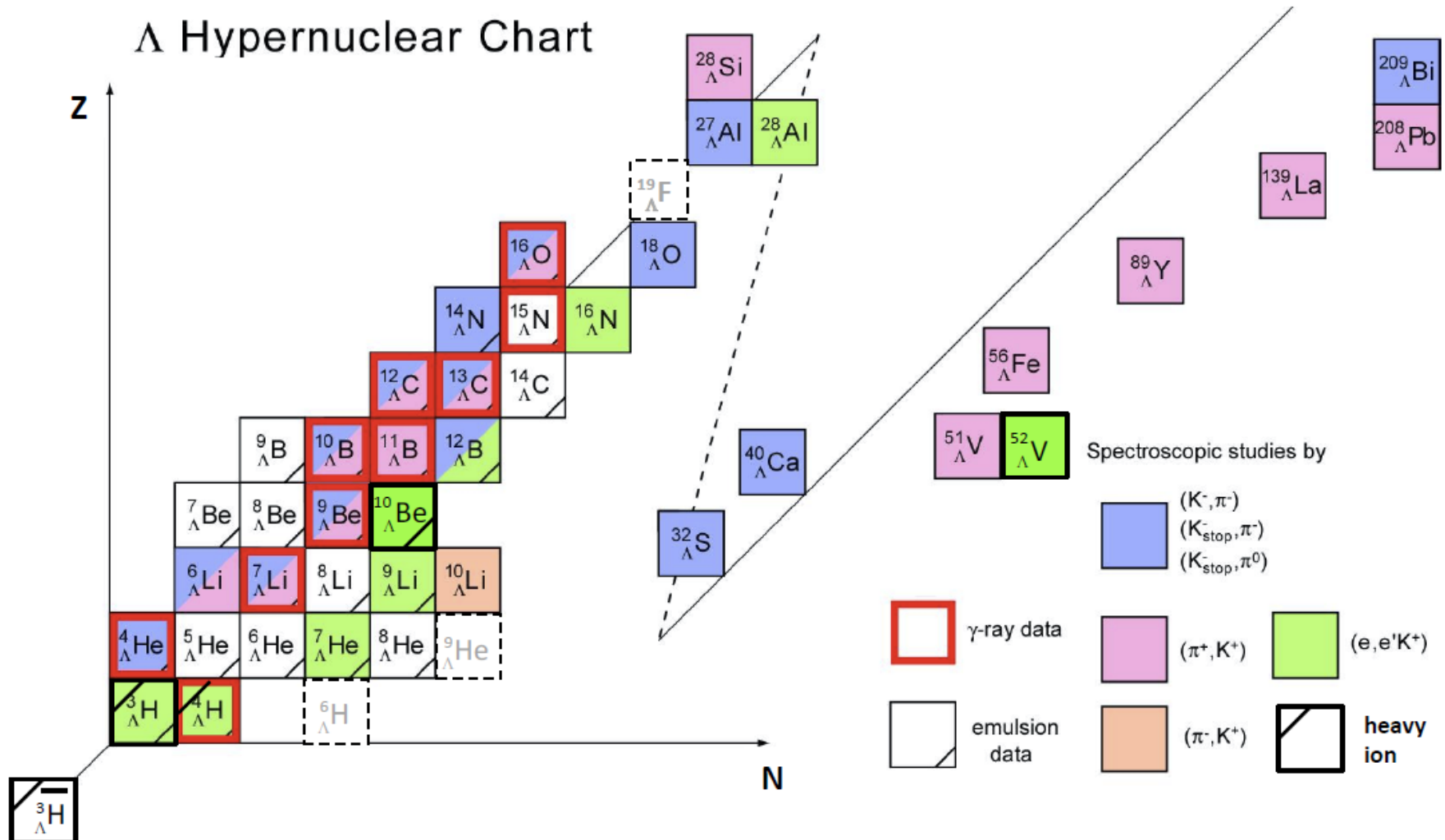
Z : Charge of nucleus

${}_{\Lambda}^{12}\text{C}$

$(p \times 6 + n \times 5) + \Lambda$

Λ ハイパー核分光これまでの成果

Λ Hypernuclear Chart



Λ ハイパー核生成反応

Secondary beam

➤ Intensity $< 10^6$ Hz



Mirror



Energy scale calibration

Primary beam

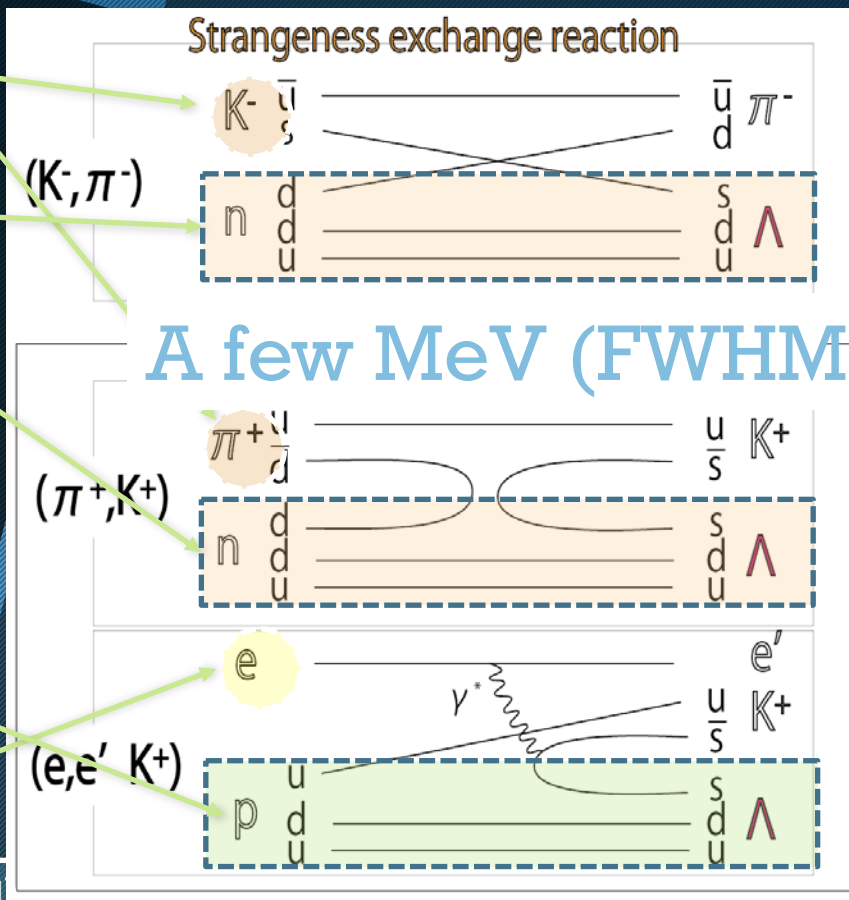
Small Emittance ($2\mu\text{m} \cdot \text{mrad}$)

High intensity ($\sim 10^{14}$ Hz)

$\Delta E/E < 10^{-4}$

Thinner target

($0.1 \text{ g/cm}^2 \Leftrightarrow \text{a few g/cm}^2$)



Cross
section
[$\mu\text{b/sr}$]

Recoil
Momentum
[MeV]

10^2

< 100

10^0

> 300

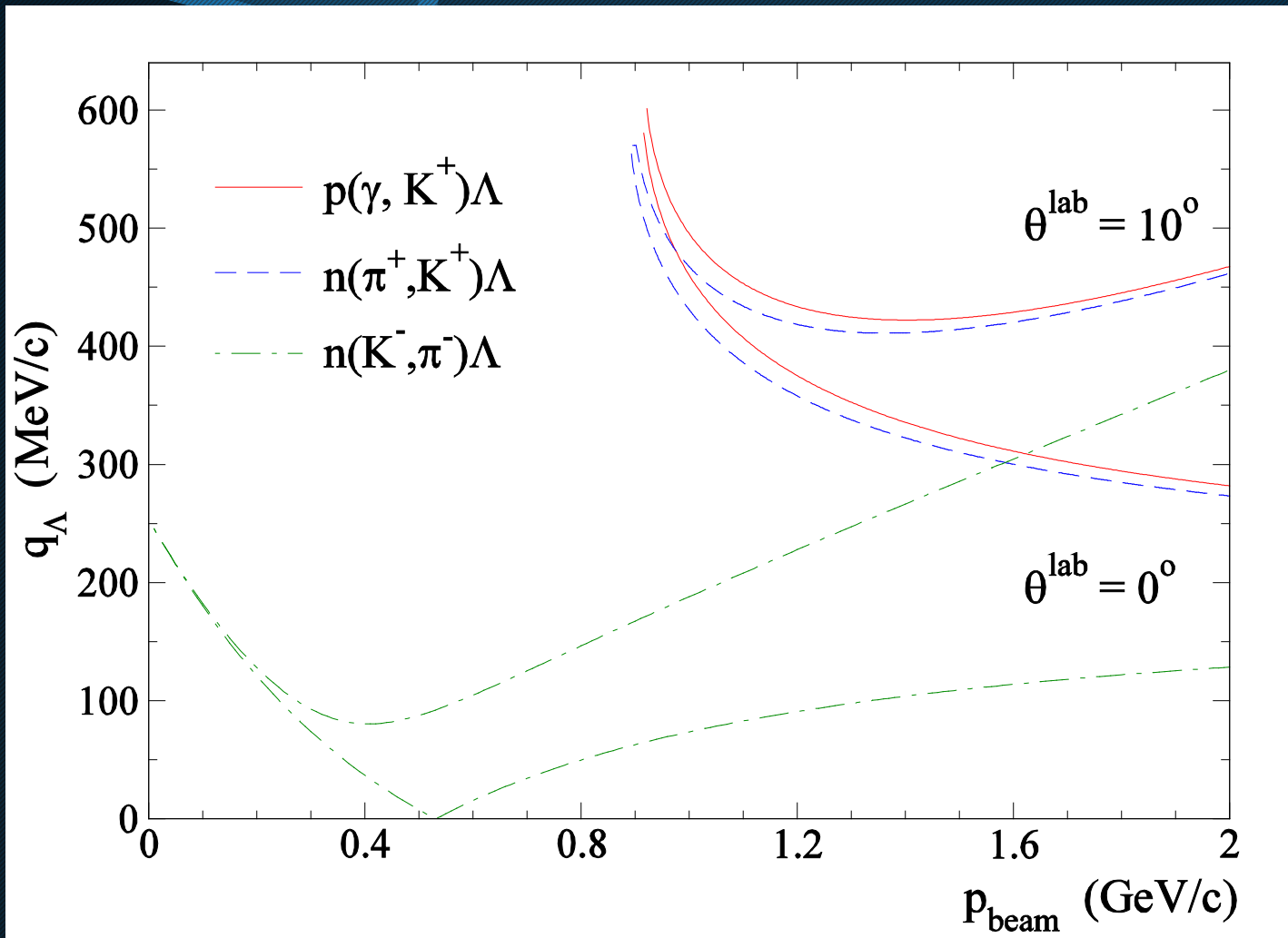
10^{-1}

> 300

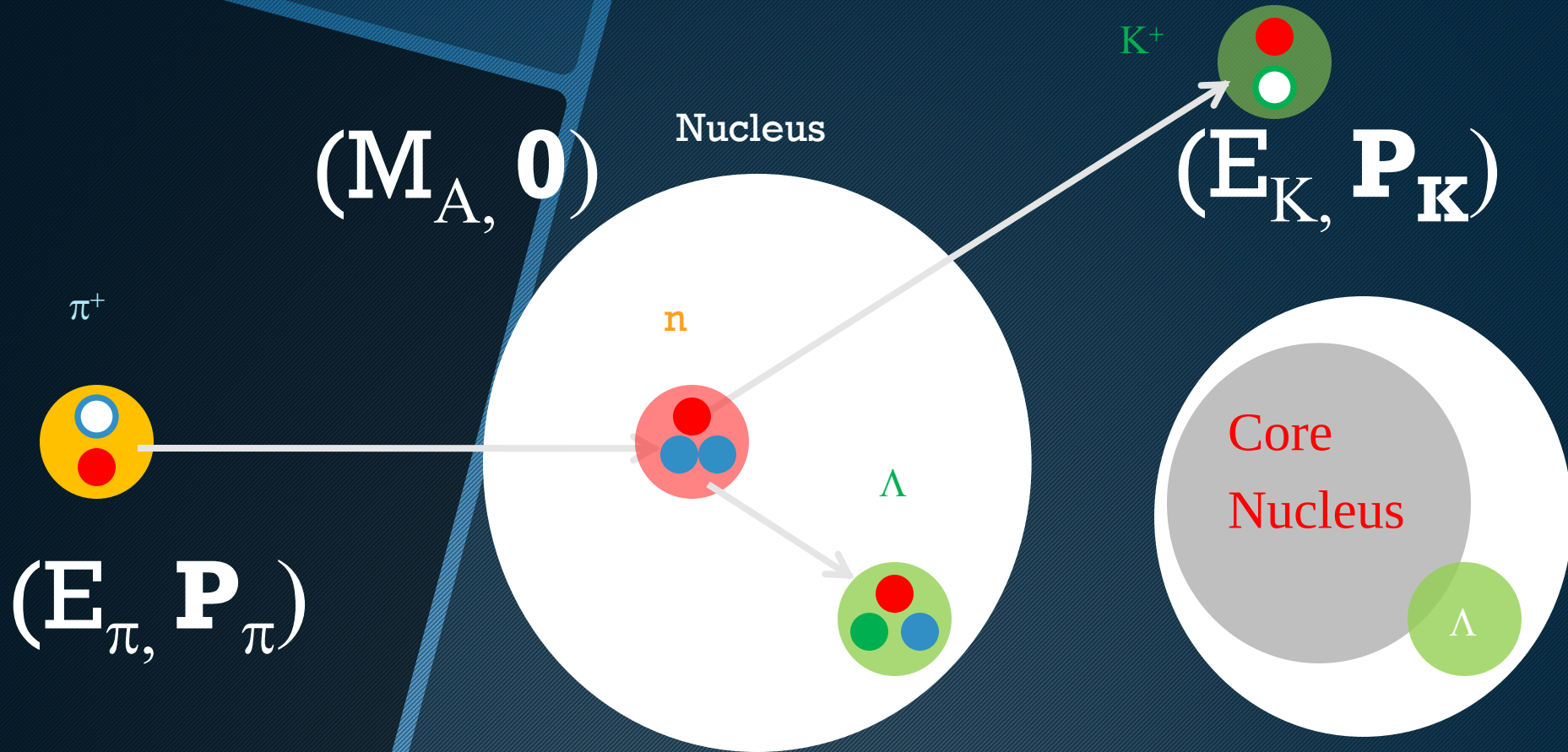
Sub-MeV (FWHM)

$e'K^+$ coincidence exp.
Huge background

Recoil momentum



Missing Mass Spectroscopy



$$M_{HYP} = \sqrt{(E_\pi + M_A - E_K)^2 - (\mathbf{p}_\pi - \mathbf{p}_K)^2}$$

$$-B_\Lambda = M_{HYP} - (M_{Core} + m_\Lambda) \quad \text{Binding energy } \Lambda \text{ separation ene.}$$

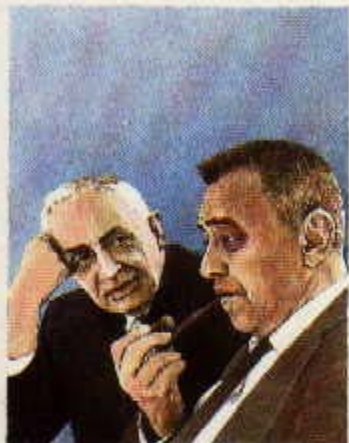
最初のハイパー核の発見

1953 原子核乾板+宇宙線

M.Danysz and J.Pniewski

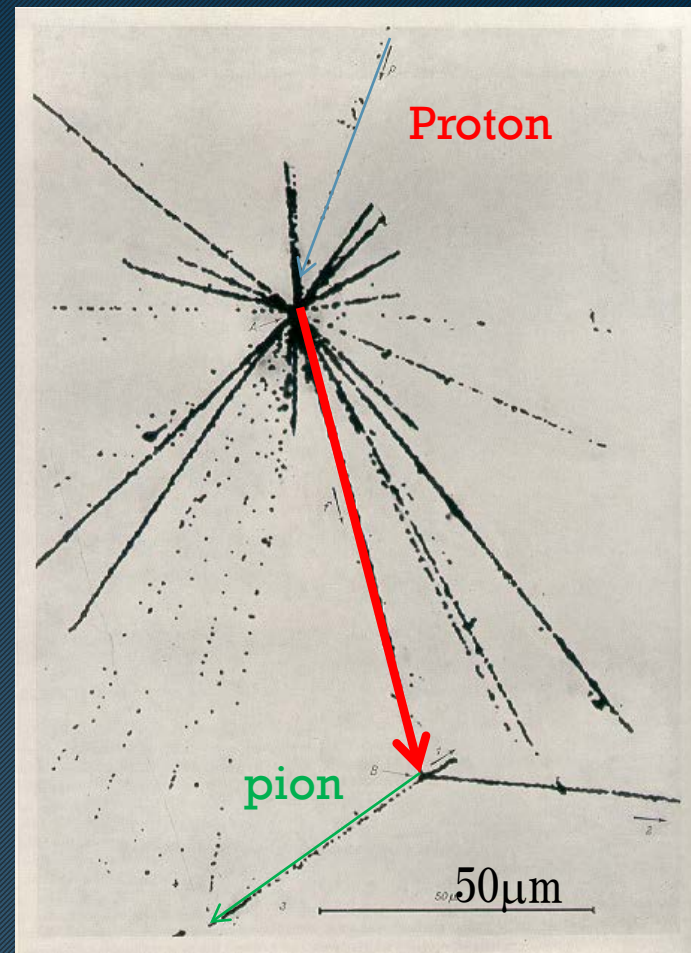
KARTKA POCZTOWA. cena 2000 zł

40 ROCZNICA ODKRYCIA
MATERII HIPERJĄDROWEJ



Profesor Marian Danysz (1909-1983)
Profesor Jerzy Pniewski (1913-1989)

POCZTA POLSKA - V 1993 r. Nakład 200.000 Proj. Maciej Jędrzyński



Phil. Mag. 44 (1953) 348

ハイパー核研究の歴史

1953 Danysz and Pniewskiによるハイパー核発見

1970s CERN, BNLにおける K 中間子ビームによるカウンター実験

$A(K^-, \pi^-)_{\Lambda} A$ reaction

Limitation by K intensity

ハイパー核研究の歴史

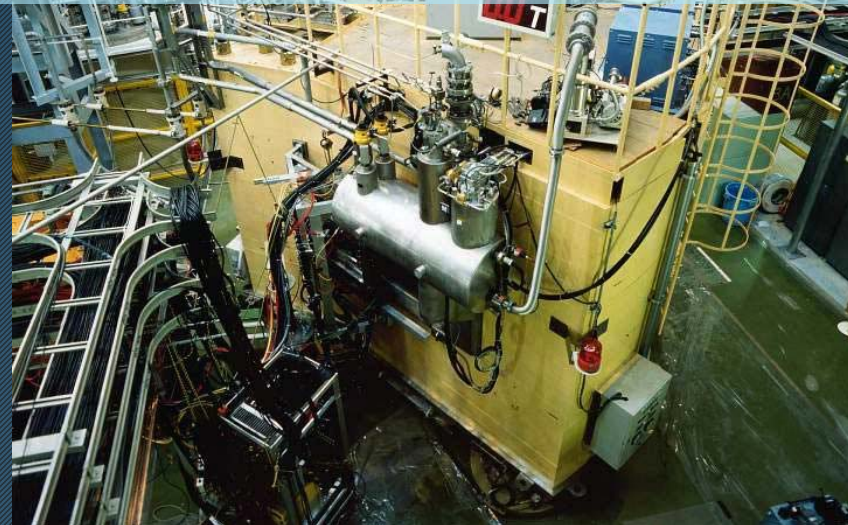
1953 Danysz and Pniewskiによるハイパー核発見

1970s CERN, BNLにおける K 中間子ビームによるカウンター実験

1980s BNL-AGS, KEK-PS における K/ π ビームを用いた実験

$A(K^-, \pi^-)_\Lambda A$, $A(\pi^+, K^+)_\Lambda A$ reaction

Superconducting Kaon Spectrometer (SKS)
@KEK-PS



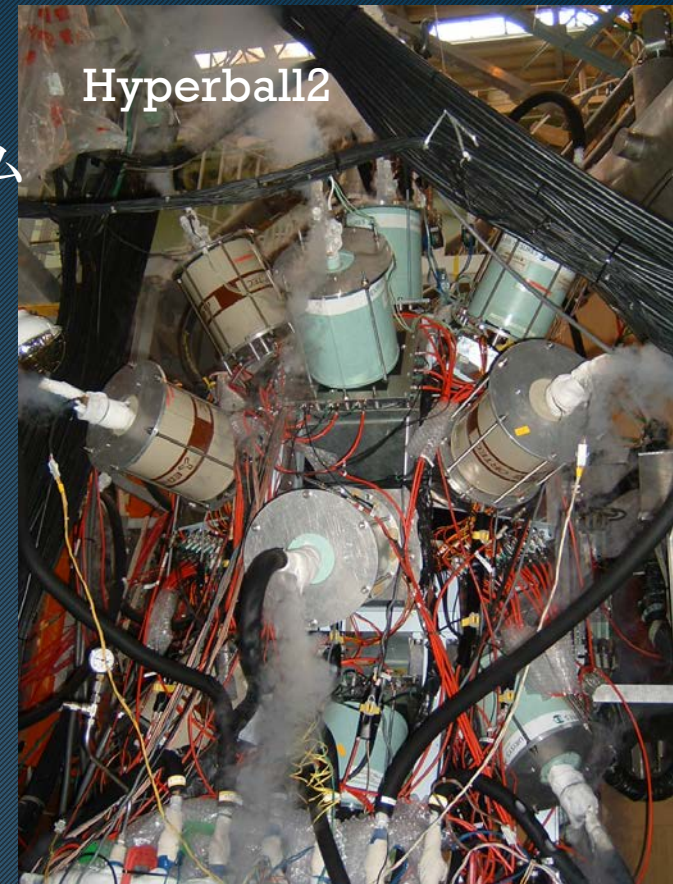
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1998- ハイパーボールによる γ -線分光



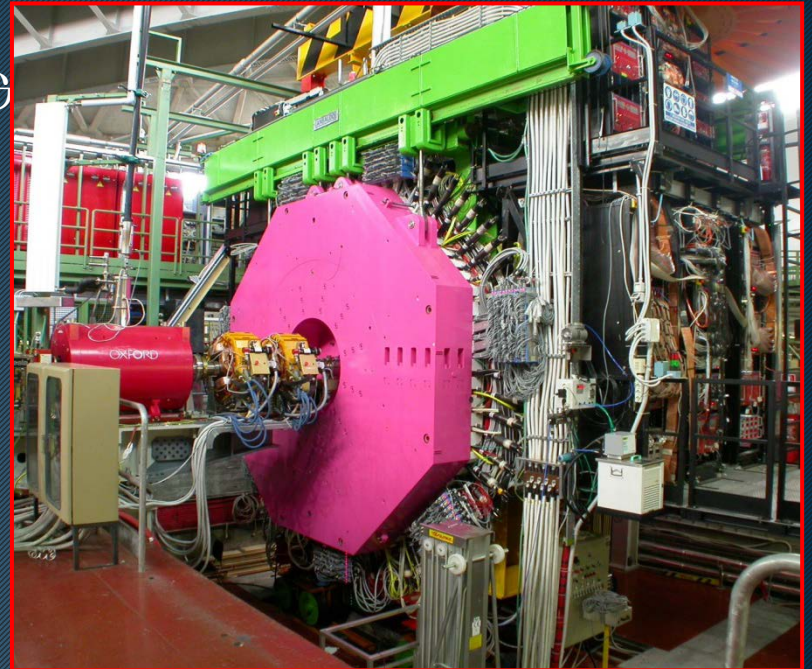
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を用いた実験

1998- ハイパーボールによる γ -線分光
FINUDA at DAΦNE
 $\Phi \rightarrow K^+ K^-$ (49%)



ハイパー核研究の歴史

1953 Danysz and Pniewskiによる

1970s CERN, BNLにおける K によるカウンター実験

1980s BNL-AGS, KEK-PS における K を用いた実験

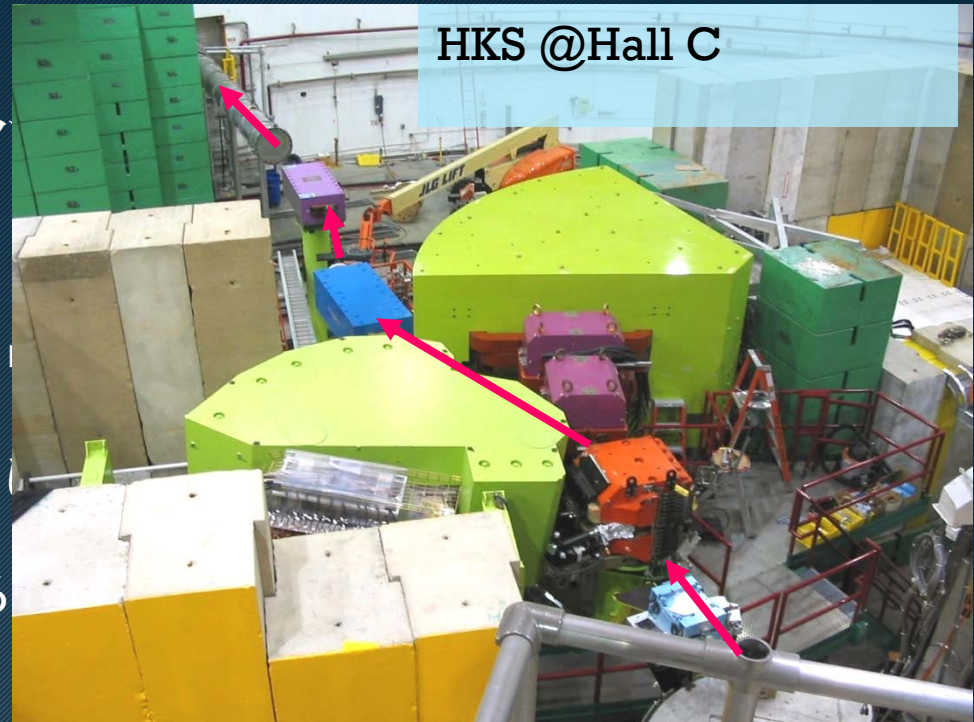
1998- ハイパーボールによる

2000~

$(e, e'K^+)$ 反応分光 @ JLab

$Z(e^-, e'K^+)_{\Lambda}(Z-1)$ 反応

大強度中間子ビーム実験 @ J-PARC



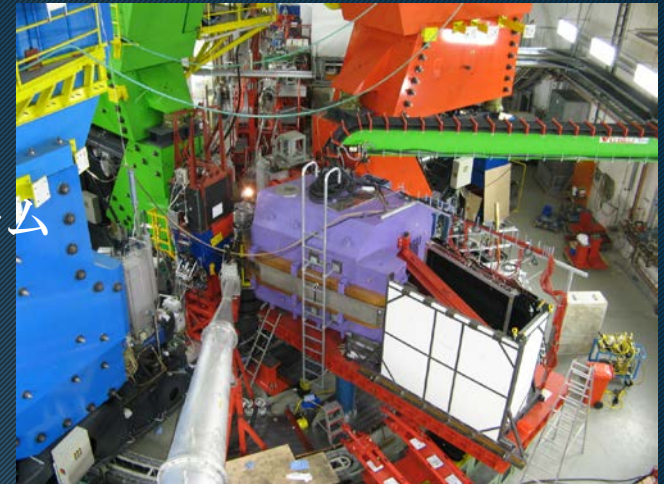
ハイパー核研究の歴史

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$Z(e^-, e'K^+)_{\Lambda}(Z-1)$ 反応

大強度中間子ビーム実験 @ J-PARC

崩壊 π 中間子分光 @ MAMI

Summary of P a r t 1

原子核物理：＝強い相互作用＋量子多体系

u,d quark + s quark：通常の核力では見られない多彩な振る舞い

量子多体系の多様な構造

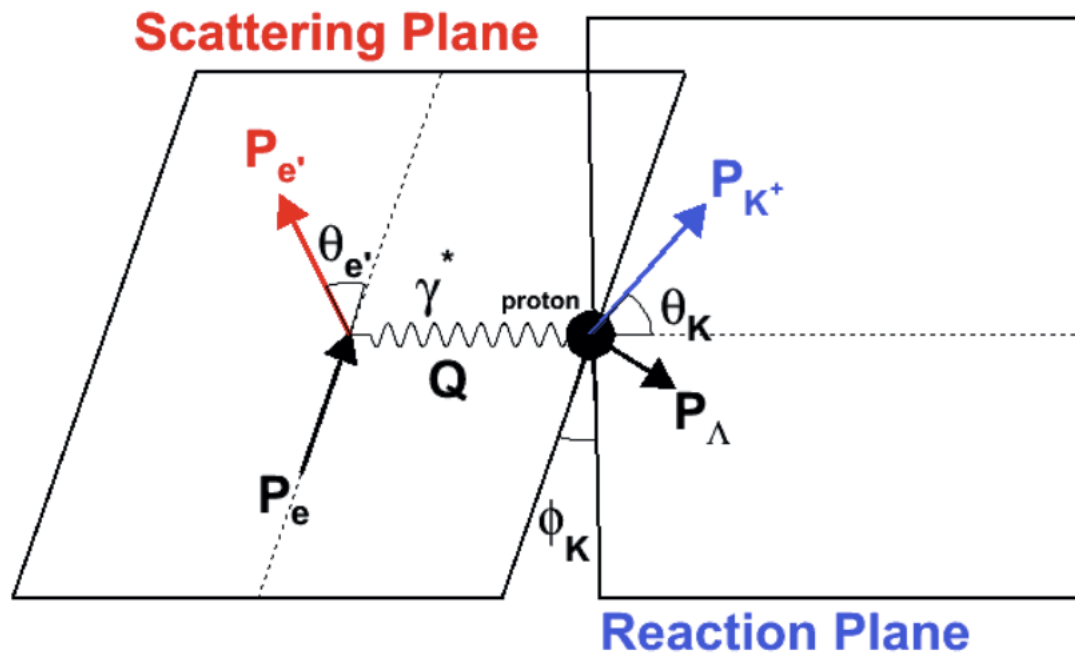
ハイパー核を通したバリオン相互作用の研究

ハイパー核を使った原子核深部探索

P a r t 2 . ストレンジネス電磁生成

ストレンジネス電子生成素過程 Kinematic Parameters

$$e(p_e) + p(p_p) \rightarrow e(p_{e'}) + \Lambda(p_\Lambda) + K^+(p_K)$$



One-photon-approx.



electron と hadron を分離
仮想光子(VP)による光生成

$$Q^2 = -q^\mu q_\mu > 0$$

$$Q^2 = 0 \quad : \text{real photon}$$

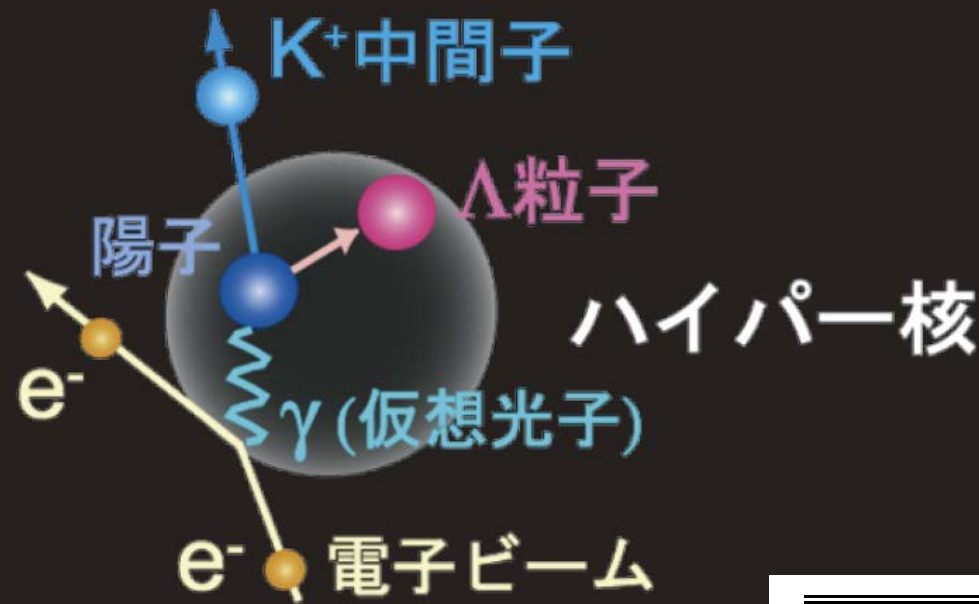
$$\begin{aligned} \omega &= E_e - E_{e'} \\ \vec{q} &= \vec{p}_e - \vec{p}_{e'} \end{aligned}$$

$$q^\mu = (\omega, \vec{q})$$

Mass less approx.

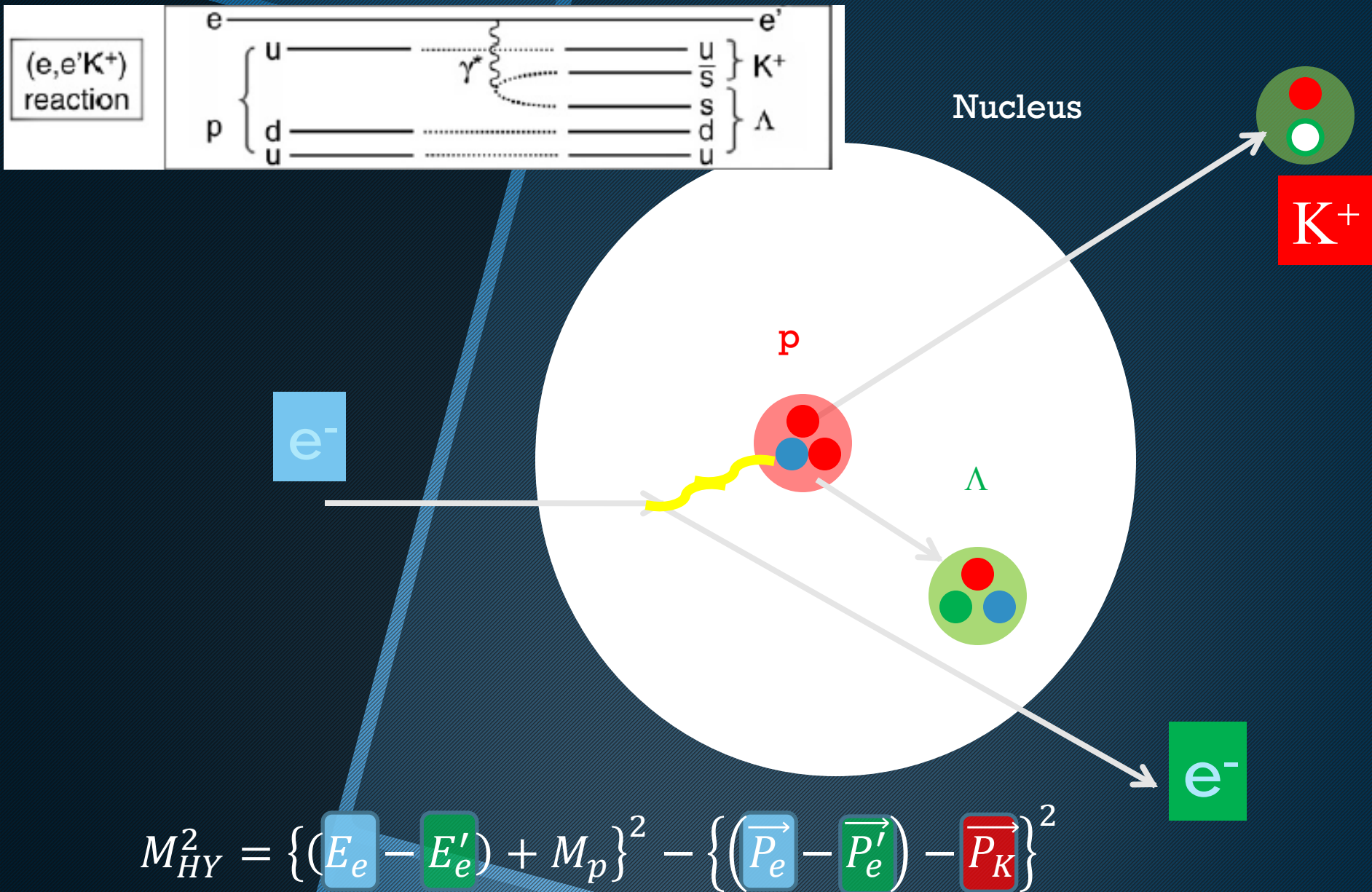
$$Q^2 \simeq 4E_e E_{e'} \sin^2 \frac{\theta}{2}$$

ハイペロン電子生成の threshold energy



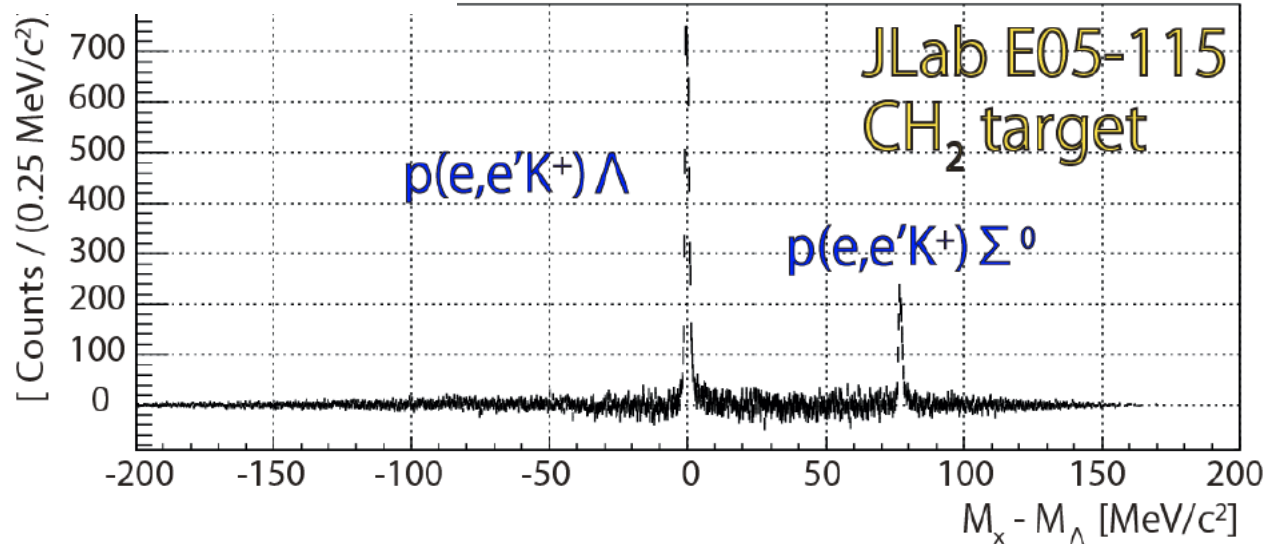
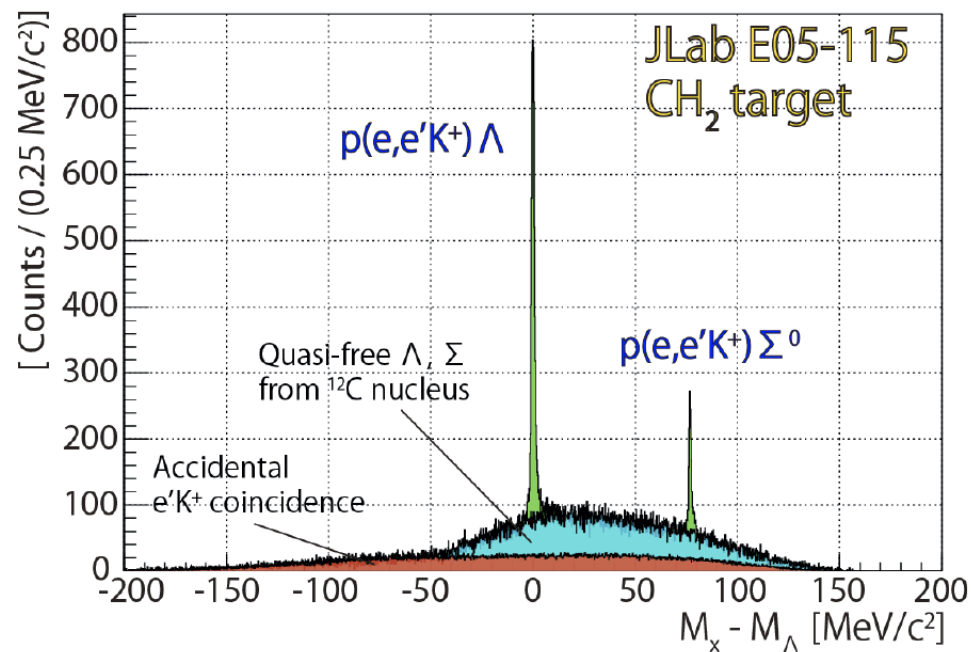
Reaction Channel	Threshold Energy E_γ [MeV]
$\gamma + p \rightarrow K^+ + \Lambda$	911.1
$\gamma + p \rightarrow K^+ + \Sigma^0$	1046.1
$\gamma + n \rightarrow K^+ + \Sigma^-$	1052.1
$\gamma + n \rightarrow K^0 + \Lambda$	915.3
$\gamma + n \rightarrow K^0 + \Sigma^0$	1050.6
$\gamma + p \rightarrow K^0 + \Sigma^+$	1047.5

ハイパー核電子生成反応



$p(e, e' K^+) \Lambda, \Sigma^0$

T.Gogami 博士論文(2014)東北大

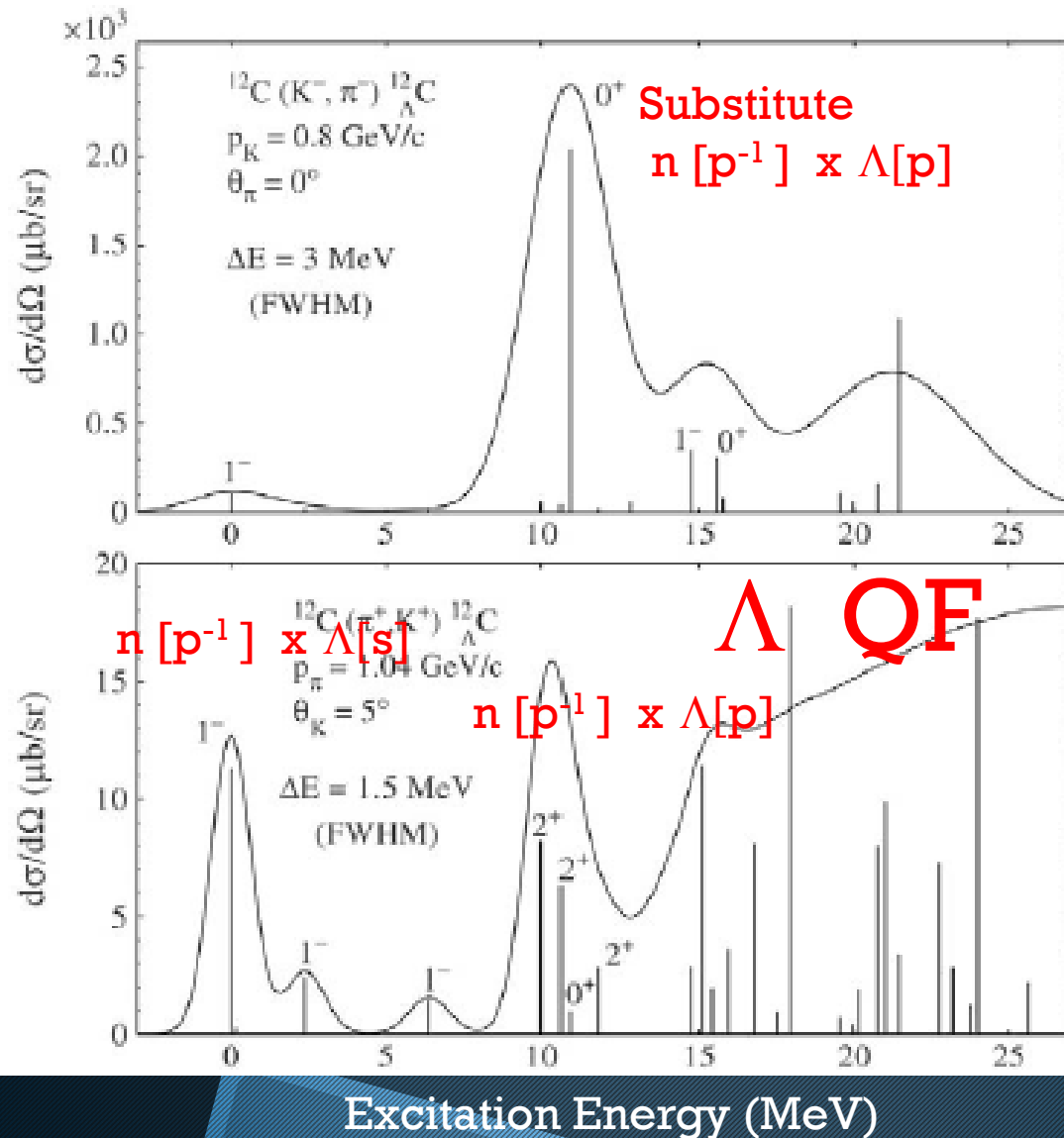


様々なハイパー核分光方法

Method	Resolution	Absolute E	Yield	comments
(e,e'K ⁺)	0.5 MeV	◎	× 100nb/sr	$p \rightarrow \Lambda$
(π^+ ,K ⁺)	1.5 – 2 MeV	○ (norm $^{12}_{\Lambda}\text{C}$)	○ 10 μ b/sr	$n \rightarrow \Lambda$
(K ⁻ , π^-)	~2 MeV	○ (norm $^{12}_{\Lambda}\text{C}$)	◎ 10mb/sr	$n \rightarrow \Lambda$
γ -ray	0.003 MeV	×	-	-
Decay π	0.1 MeV	○ (only g.s.)	-	Fragments

全ての手法は相補的で、どれも重要。

(K^-, π^-) , (π^+, K^+) 反応分光法



Λ production

X

Λ trapped
in nucleus



Λ hypernucleus

X1/100

➤ 電磁相互作用

ハイパー核電磁生成分光

➤ 陽子を Λ へ:

(π, K), (K, π) 反応とは別のハイパー核

束縛エネルギー絶対値校正 (Λ, Σ^0)

➤ 高品質一次ビーム

($E > 1.5 \text{ GeV}$, 高強度 $100 \mu\text{A} = 6 \times 10^{14}/\text{s}$, 高分解能 $\Delta p/p \sim 10^{-5}$)

高分解能 ($< 1 \text{ MeV}$)

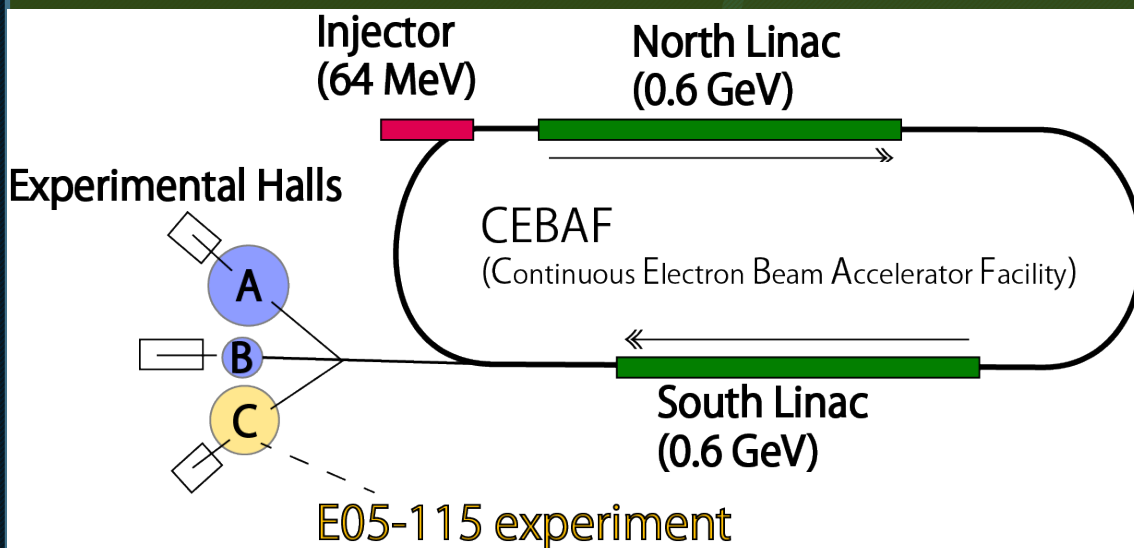
薄いエンリッチ標的 ($\sim 100 \text{ mg/cm}^2$)

実験が可能な場所はハイパー核: JLab と MAMI-C のみ

ストレンジネス電磁生成だと ELPH でも可能

(e,e'K⁺) 反応分光実験 at ジェフアーソン国立研究所 (JLab)

Continuous Electron Beam Accelerator Facility (CEBAF)



Requirements

Beam energy $\gtrsim 1.5$ GeV

Energy spread $\Delta E/E < 10^{-4}$

Small emittance ($2\mu\text{m} \cdot \text{mrad}$)

High intensity (a few 100 μA)

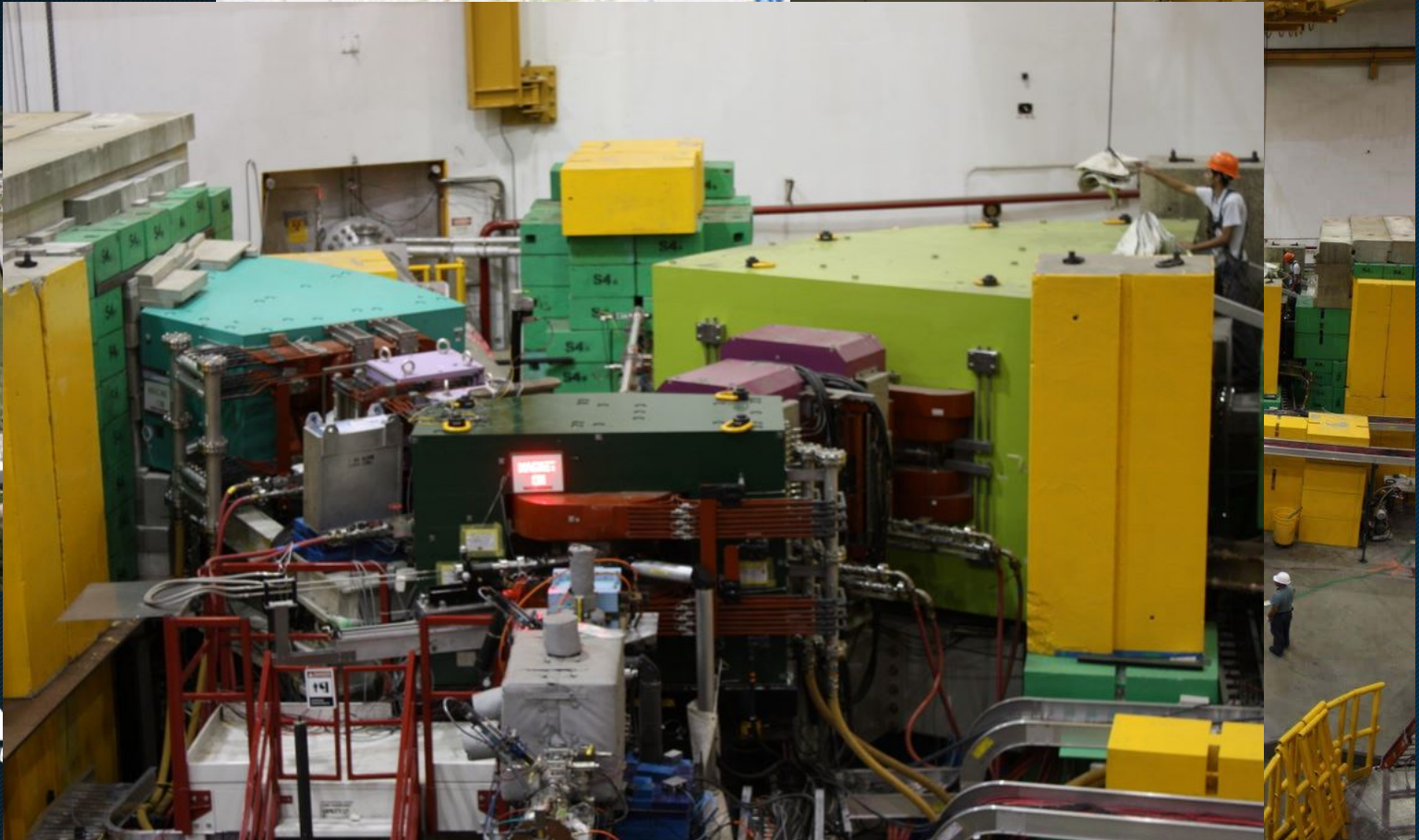
Duty factor $\simeq 100\%$

$6.25 \times 10^{14}/\text{sec}$

1 周 = 約 1 マイル



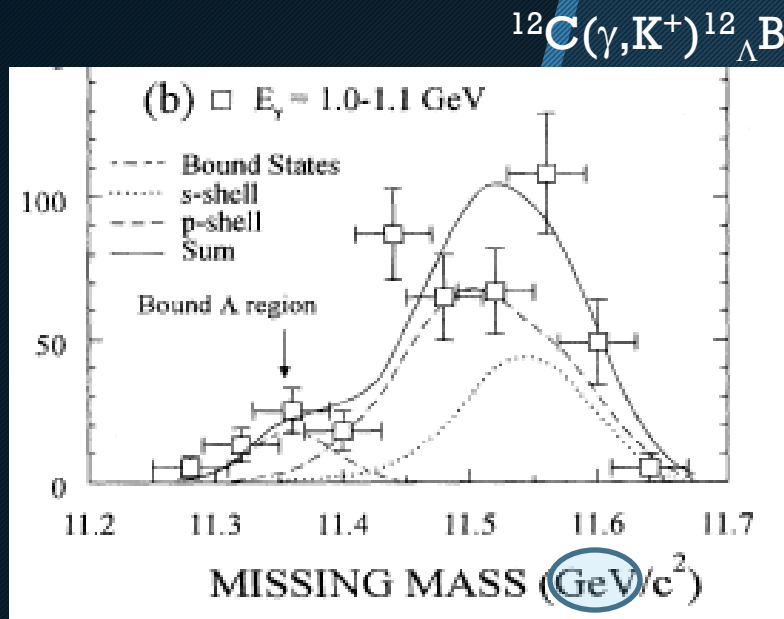
Thomas Jefferson National Accelerator Facility (JLab)



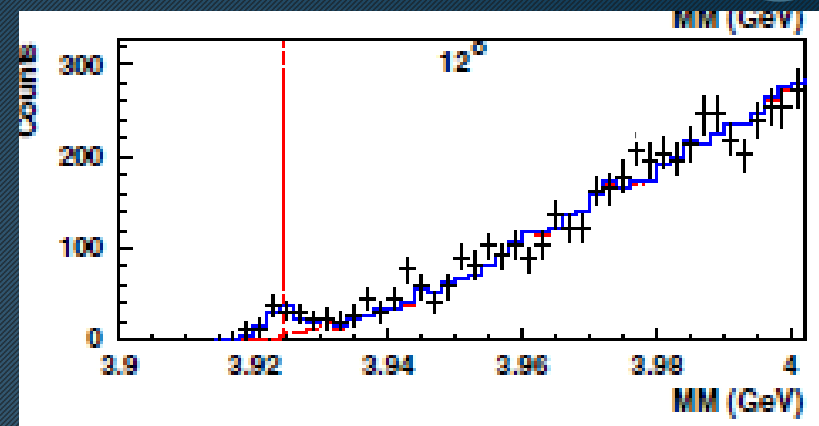
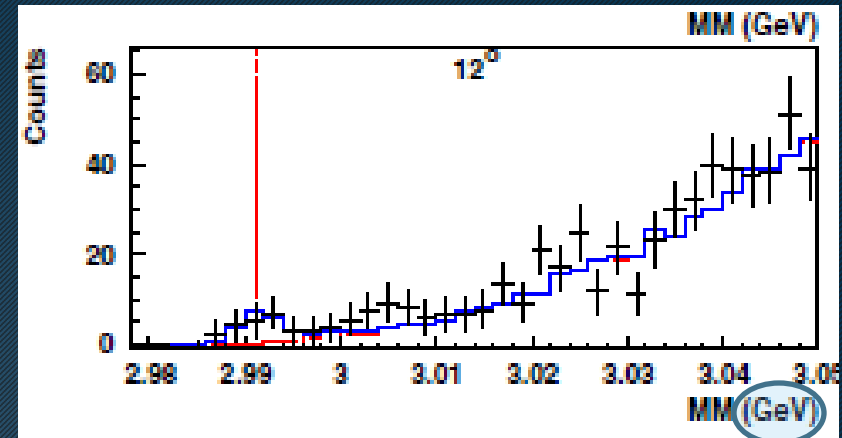
Jefferson
EXPLORING THE NAT



Early works : EM production of Λ Hypernucleus



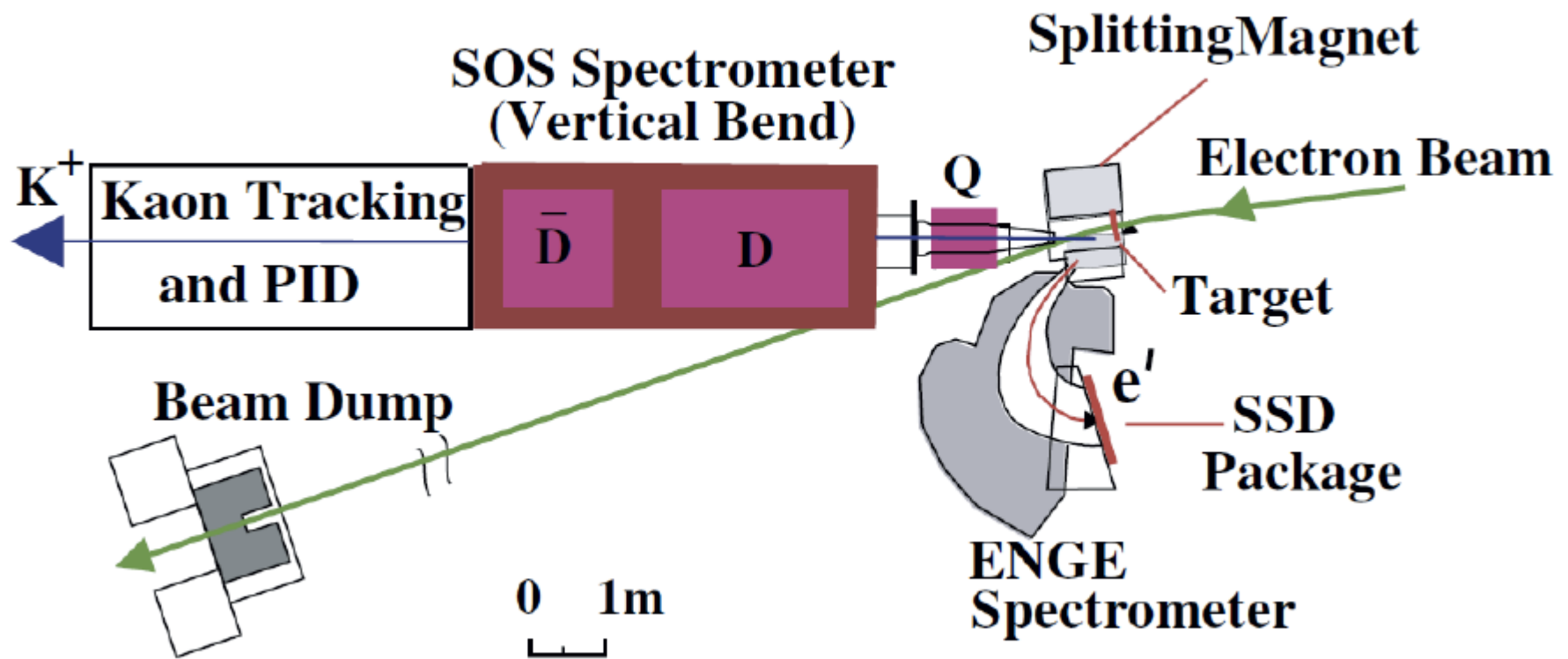
ES132 @INS-TAGX, PRC 52 (1995) 1157.



E91-016 @ JLab-HallC , PRL 93(2004)242501

*NEXT STEP: Spectroscopy with
mass resolution of sub-MeV*

JLab E89-009 実験セットアップ (pilot 実験)

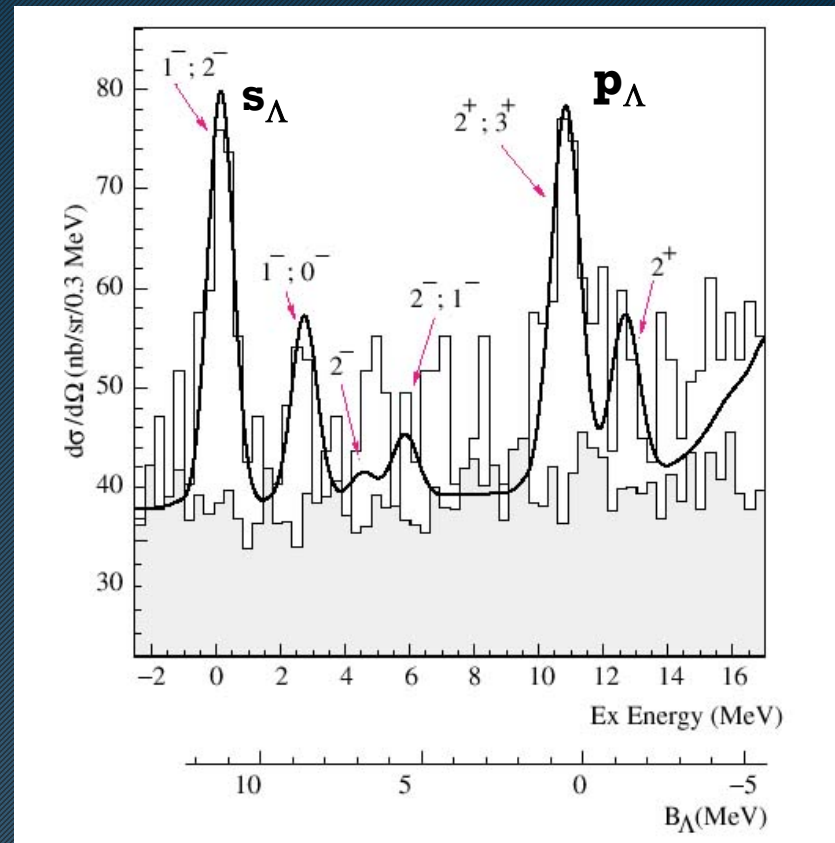


The first $(e,e'K^+)$ hypernuclear experiment (E89-009, HNSS)

$$^{12}\text{C}(e,e'K^+) ^{12}_{\Lambda}\text{B}$$

Demonstrated that :
the $(e,e'K)$ hypernuclear
spectroscopy is
possible!

Sub-MeV energy
resolution
<800 keV (FWHM)

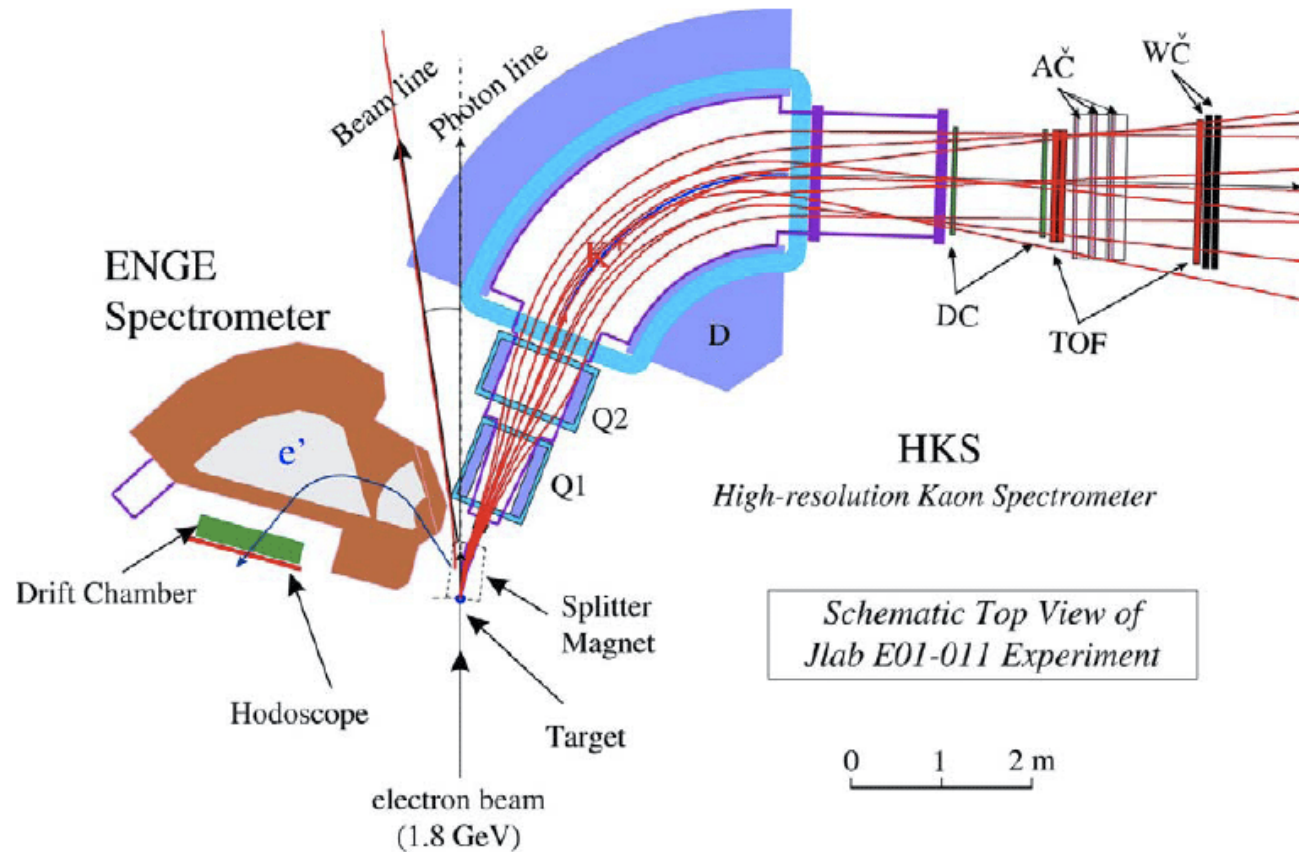
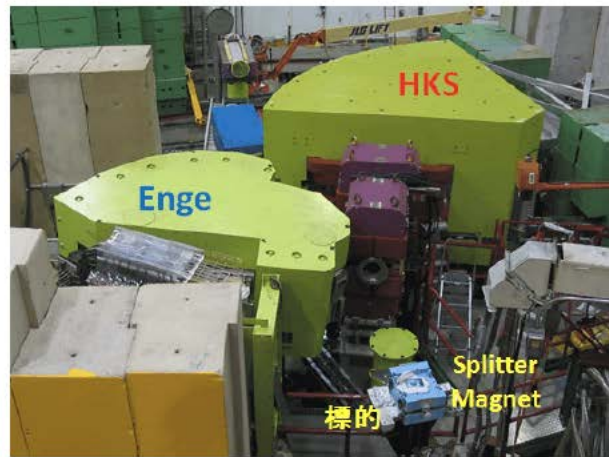


ハイパー核電磁生成分光の困難点

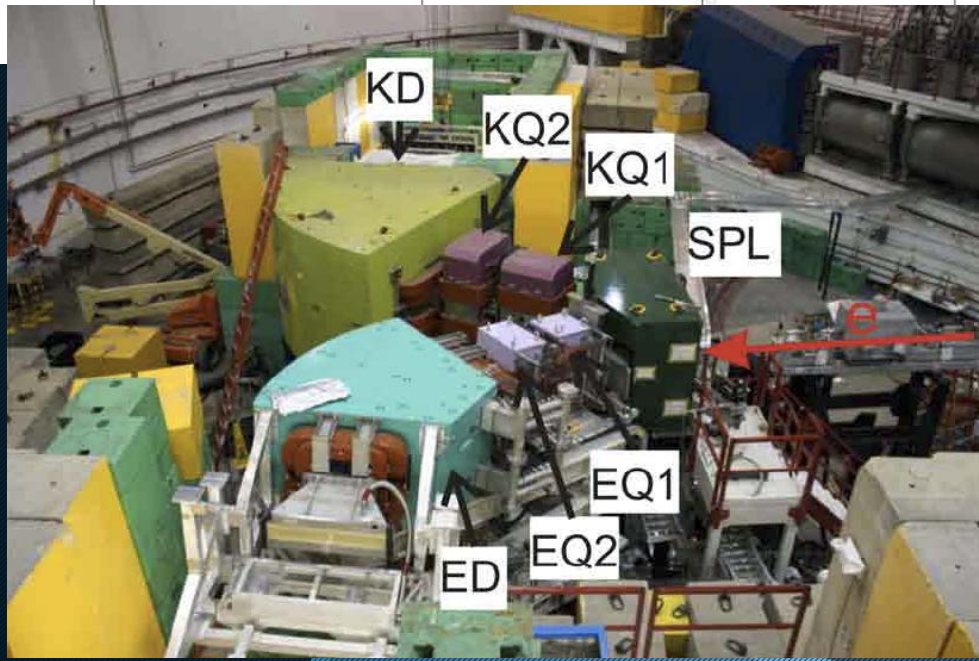
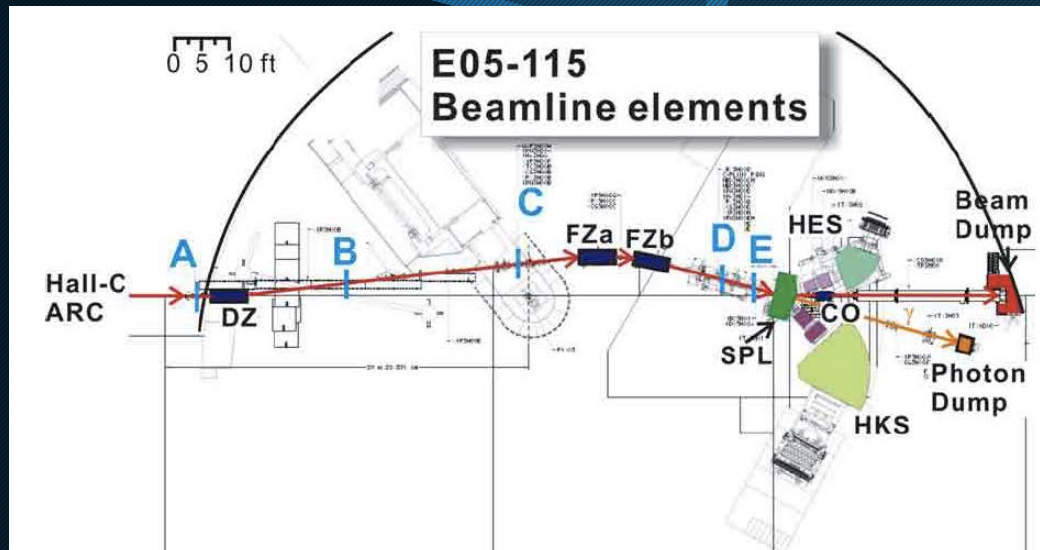
- 大量の e' バックグラウンド（制動放射、メラー散乱）
Signal/Noise, 高計数率下で動作する検出器
- 小さな生成断面積
- (e', K^+) 同時計数実験
統計量の制限、連続ビーム

高品質な電子ビームが必須！

E01-011



E05-115 setup



Beam condition

Beam energy	2.344 GeV
Beam momentum stability	$< 1 \times 10^{-4}$

HKS

Configuration	QQD (KQ1+KQ2+KD, horizontal bend)
Central momentum	1.2 GeV/c
Momentum acceptance	$\pm 12.5\%$
Momentum resolution ($\Delta p/p$)	2×10^{-4}
Solid Angle	$P/\Delta P = 5000$ 10 msr with a SPL 30 msr without a SPL
Angular acceptance	-30 mrad to -230 mrad (horizontal) -70 mrad to 70 mrad (vertical)
Flight path length	10 m

HES

Configuration	QQD (EQ1+EQ2+ED, horizontal bend)
Central momentum	0.844 GeV/c
Momentum acceptance	$\pm 17.5\%$
Momentum resolution ($\Delta p/p$)	3×10^{-4}
Solid Angle	10 msr with a SPL
Angular acceptance	-200 mrad to 200 mrad (horizontal) 30 mrad - 90 mrad (vertical)

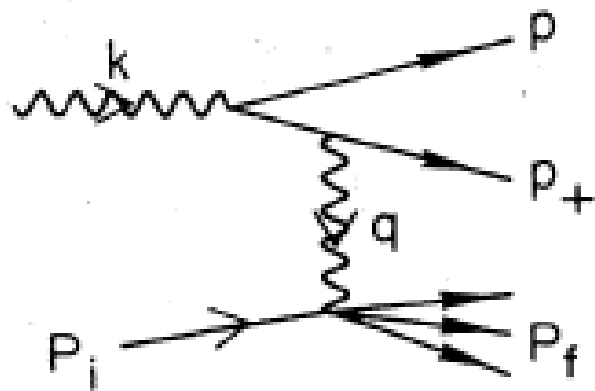
制動放射とMoller散乱

Review of Modern Physics, Vol. 46, No. 4, October 1974

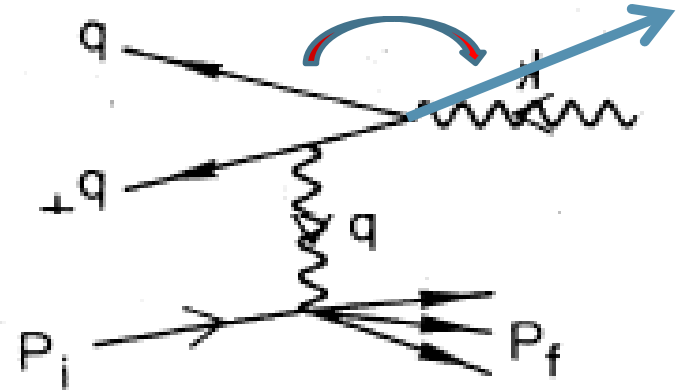
Pair production and bremsstrahlung of charged leptons*

Yung-Su Tsai

Stanford Linear Accelerator Centers, Stanford University, Stanford California 94305

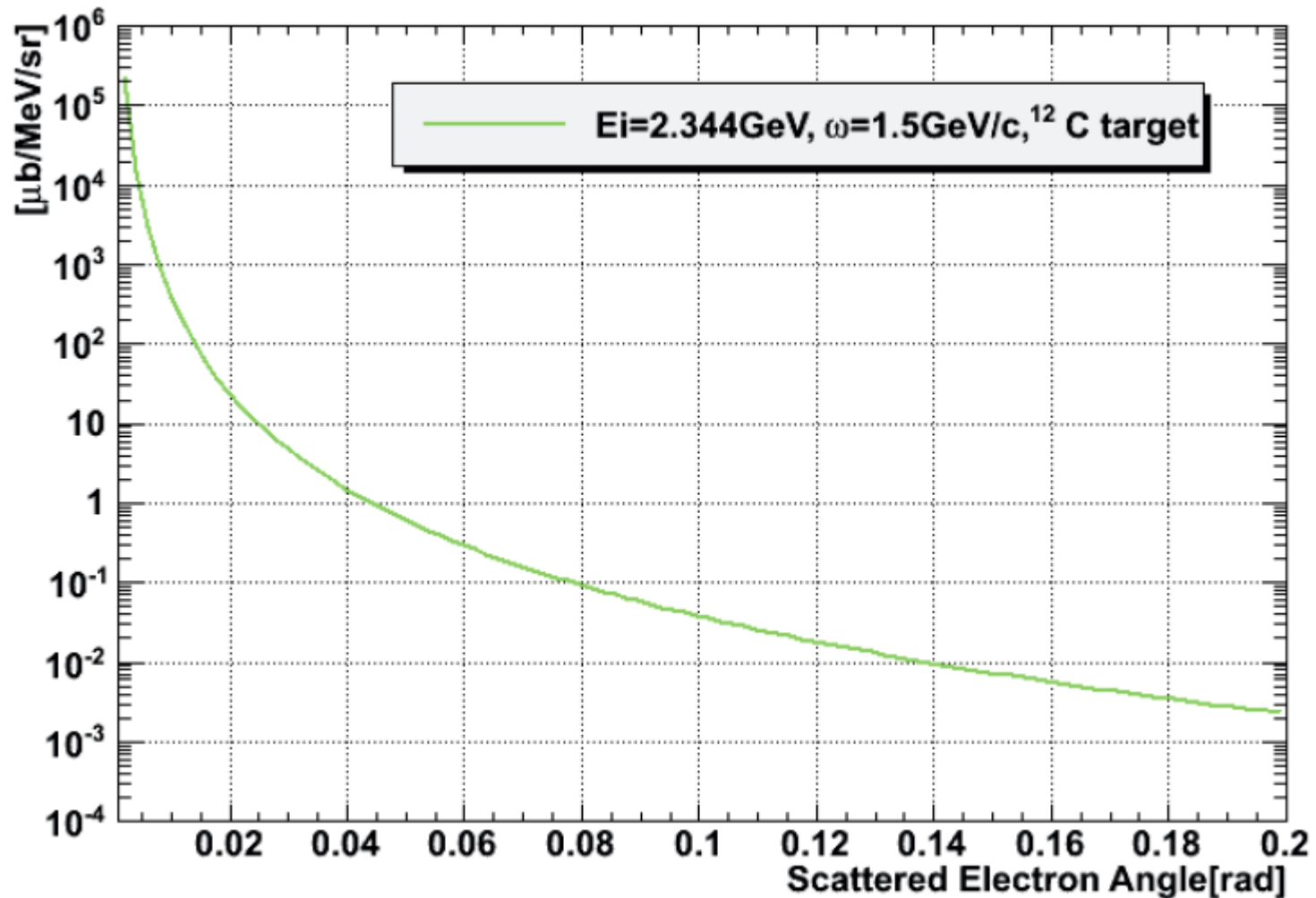


Pair production

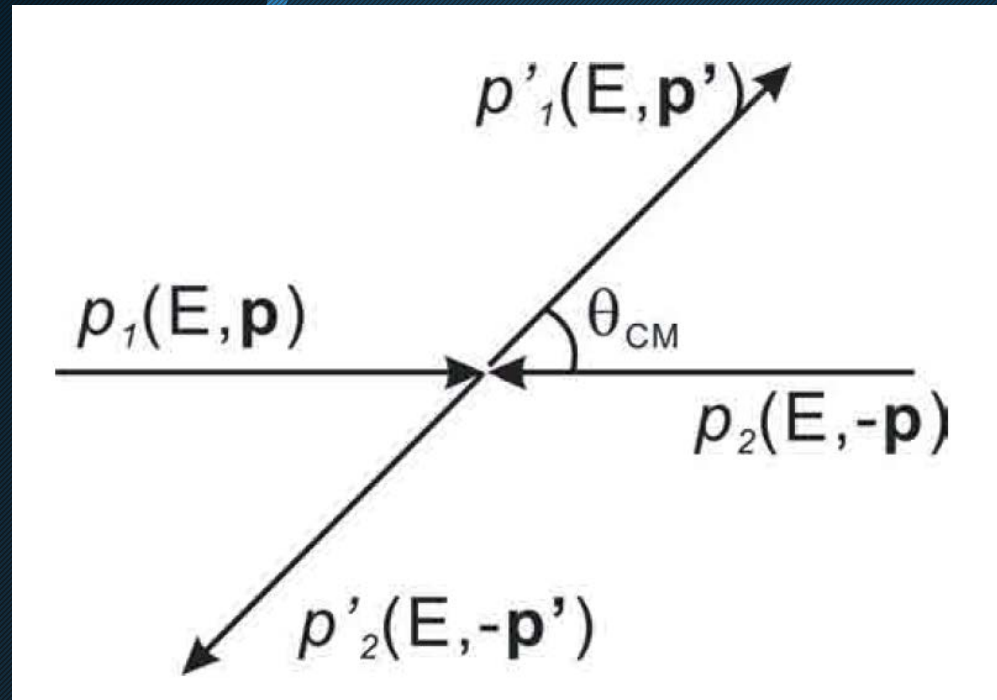


Bremsstrahlung

Bremsstrahlung の角分布

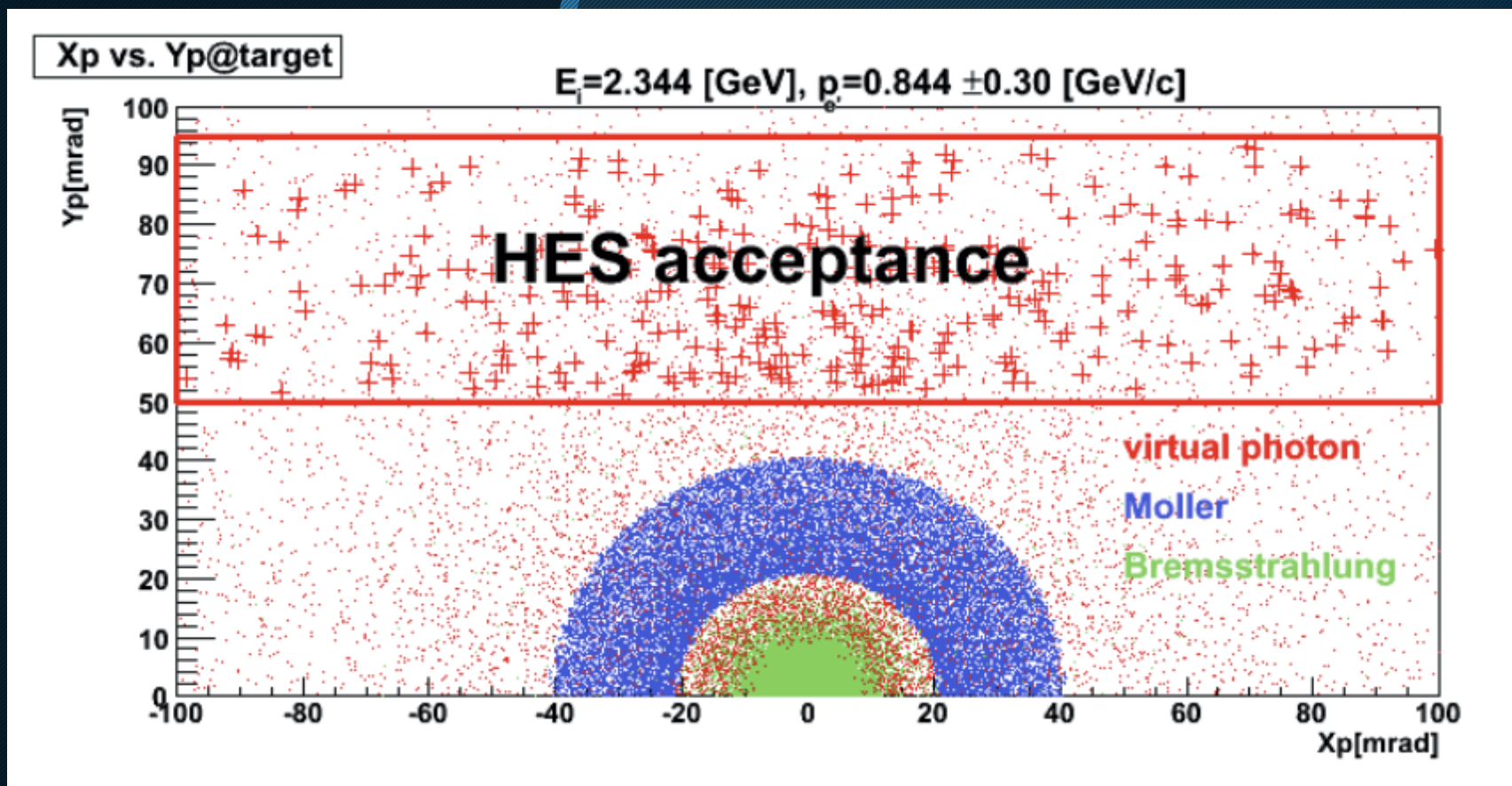


Moller 散乱



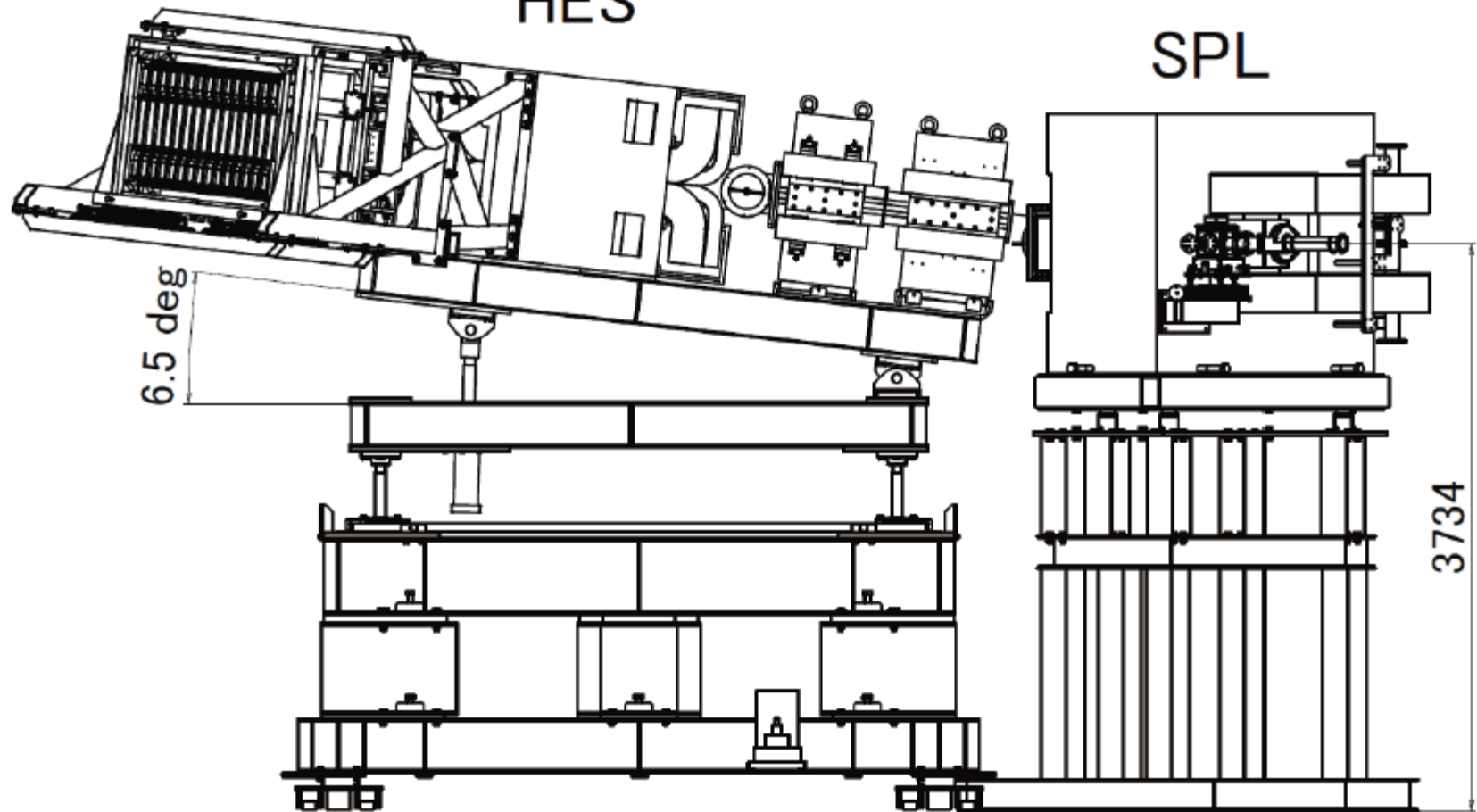
$$\left(\frac{d\sigma_m}{d\Omega} \right)_{CM} = \frac{\alpha^2 (2E_{CM}^2 - m_e^2)^2}{4E_{CM}^2 (E_{CM}^2 - m_e^2)^2} \left[\frac{4}{\sin^4 \theta_{CM}} - \frac{3}{\sin^2 \theta_{CM}} + \frac{(E_{CM}^2 - m_e^2)^2}{(2E_{CM}^2 - m_e^2)^2} \left(1 + \frac{4}{\sin^2 \theta_{CM}} \right) \right]$$

BGは1/10000以下



HES

SPL



HKS

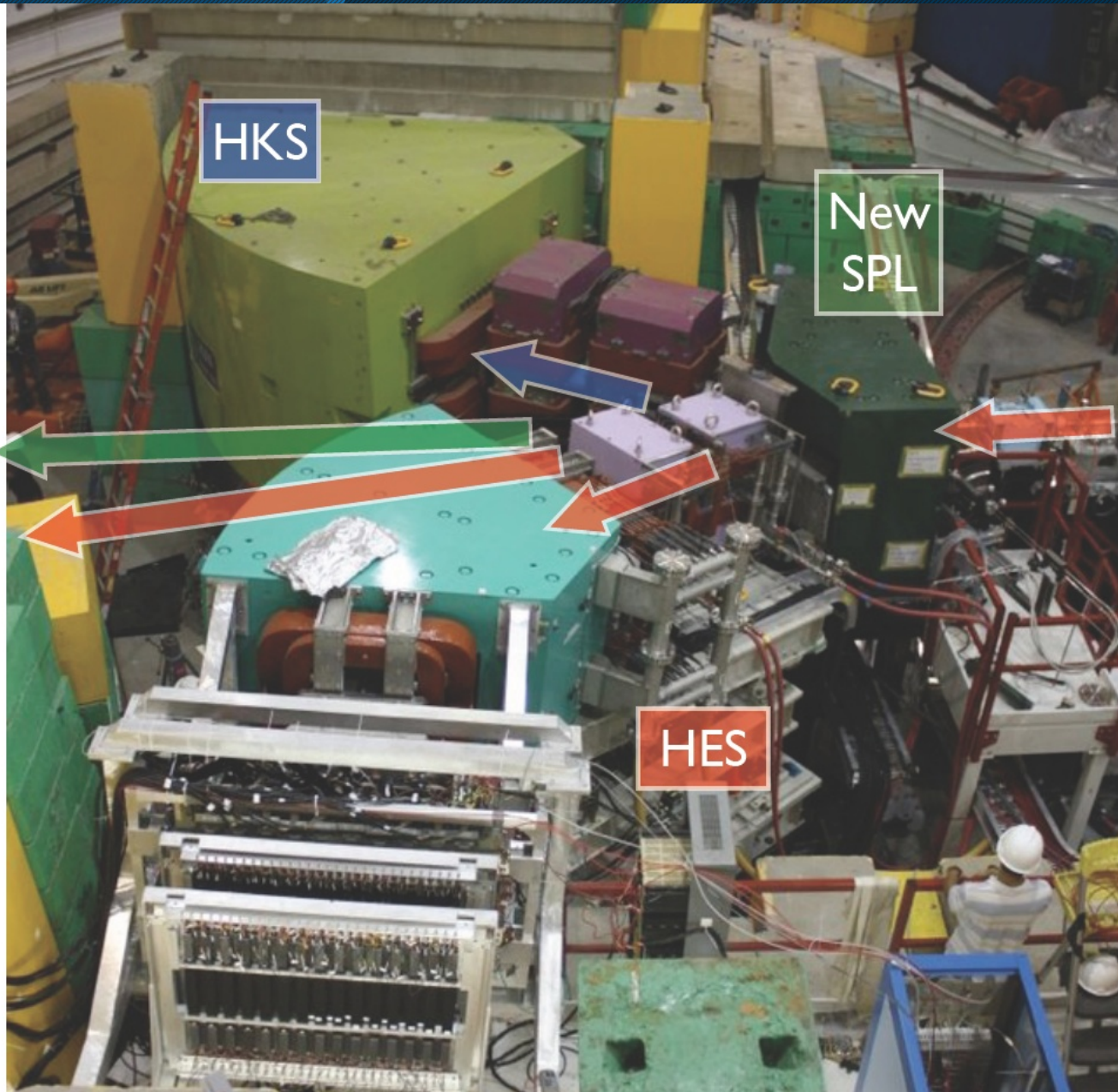
New
SPL

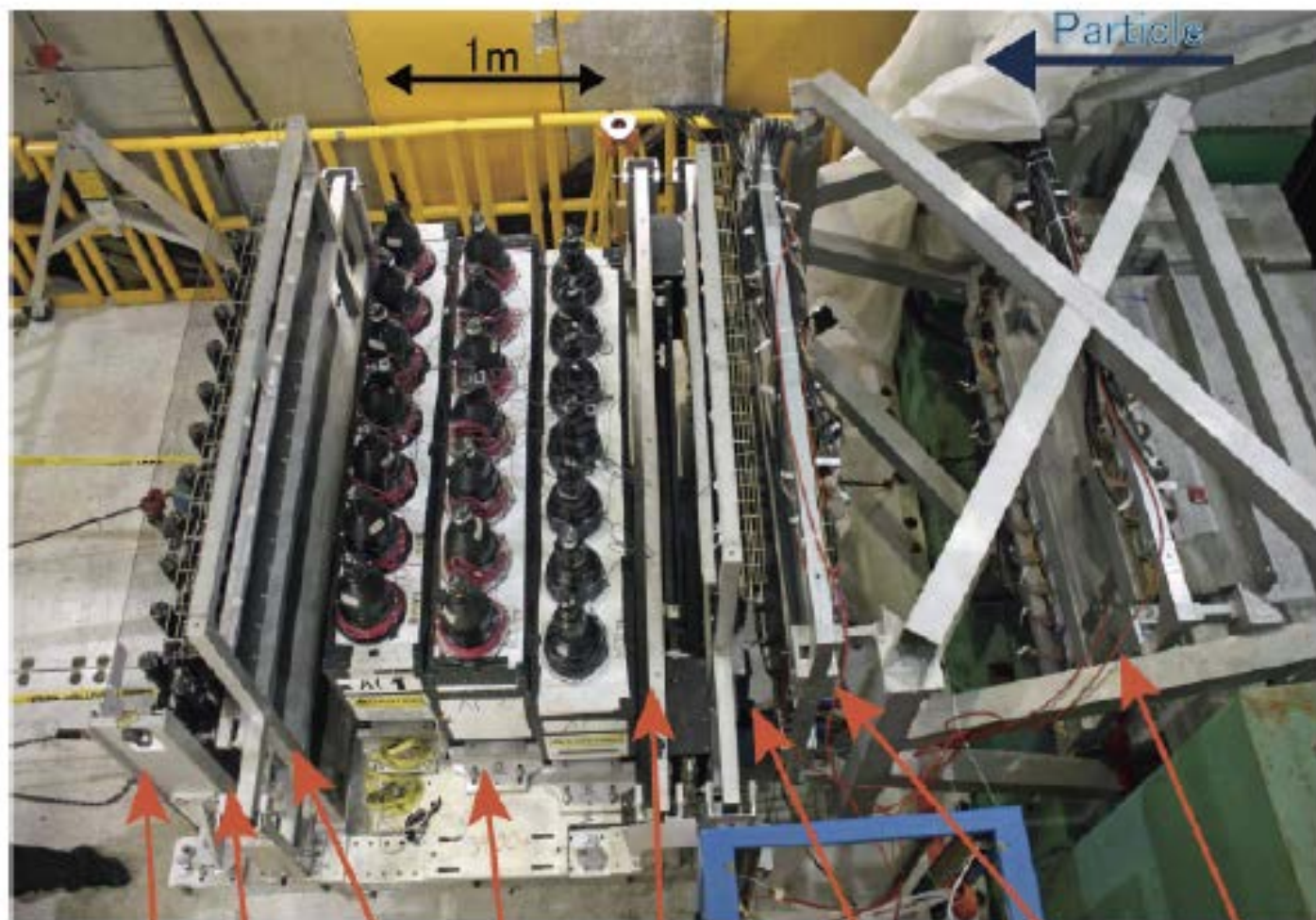
To Photon
dump

To beam
dump

Beam

HES





KTOF2Y

WC

KTOF2X

AC

KTOF1Y

KTOF1X

KDC2

KDC1

SPL : One entrance, Four exits!



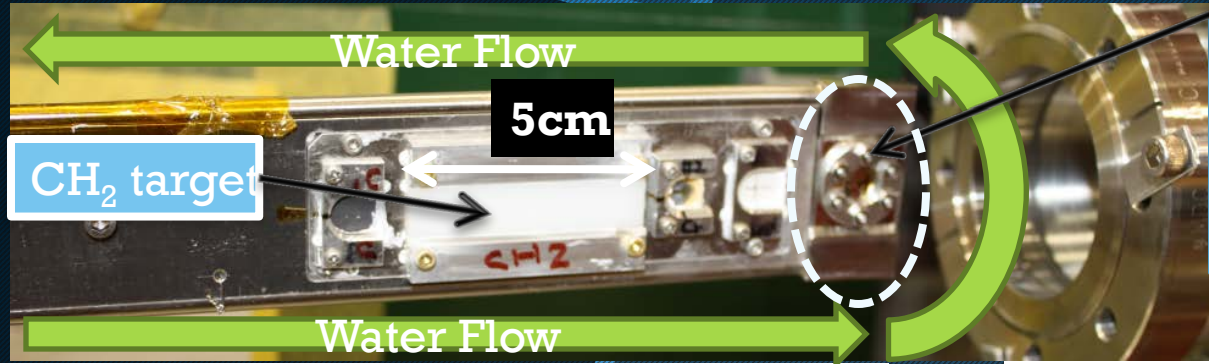
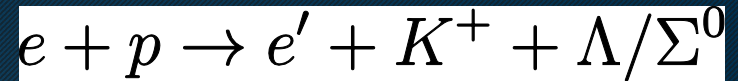
$2 \text{ GeV} \times 50 \mu\text{A} = 100 \text{ kW}$

Beam size $< \Phi 100 \mu\text{m}$

1.3 GW/cm^2

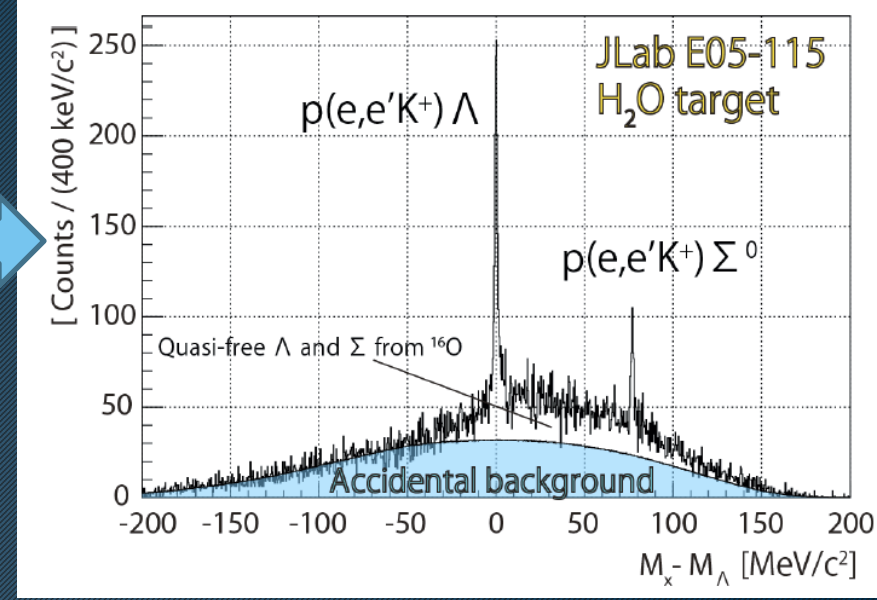
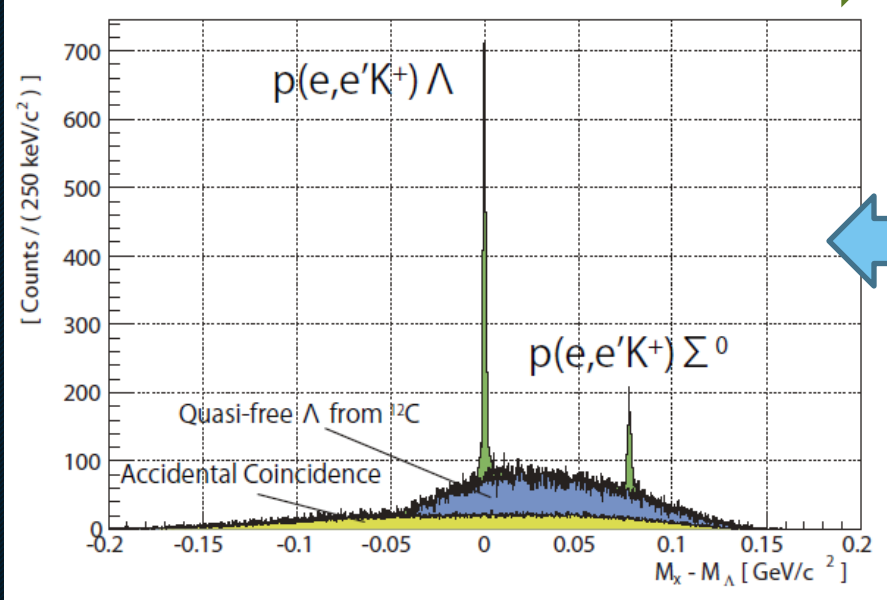


Energy Scale Calibration $-\Lambda, \Sigma^0$ peak-



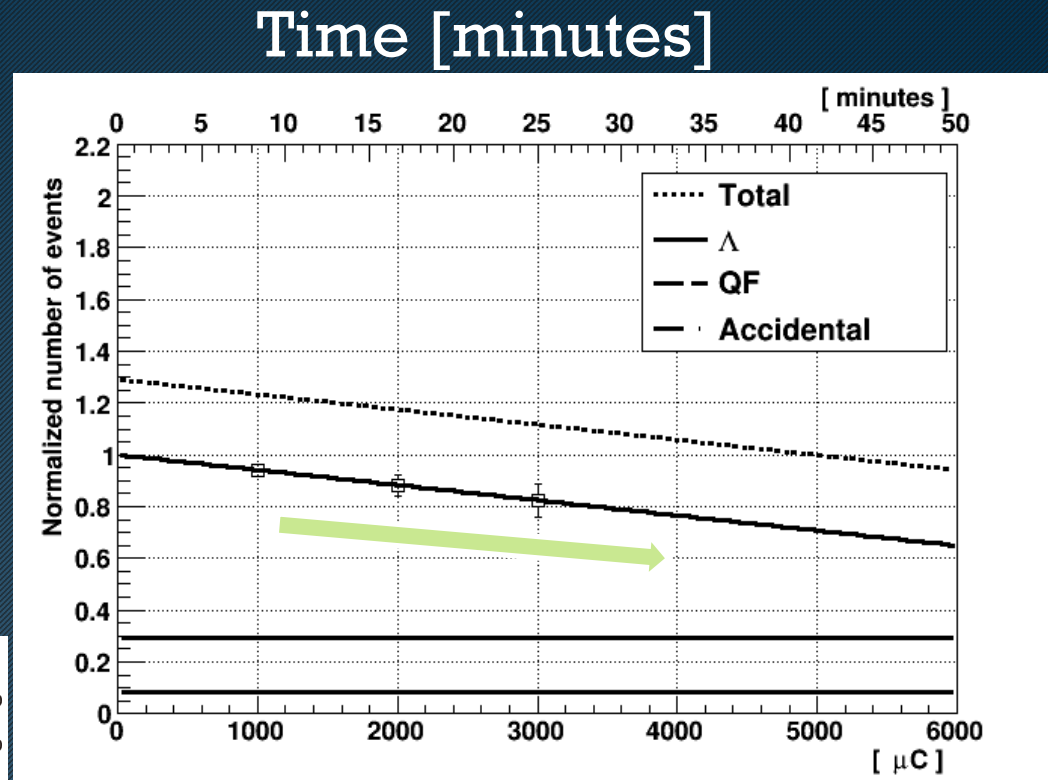
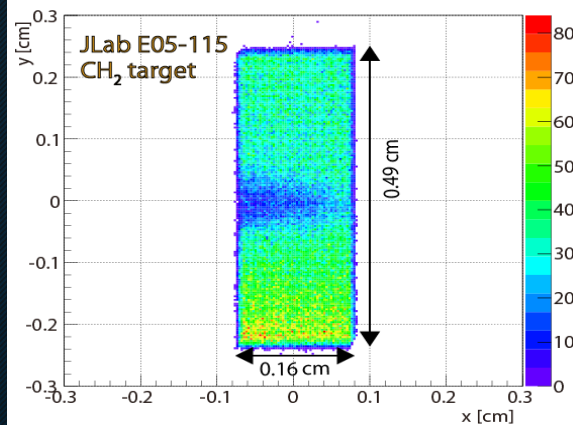
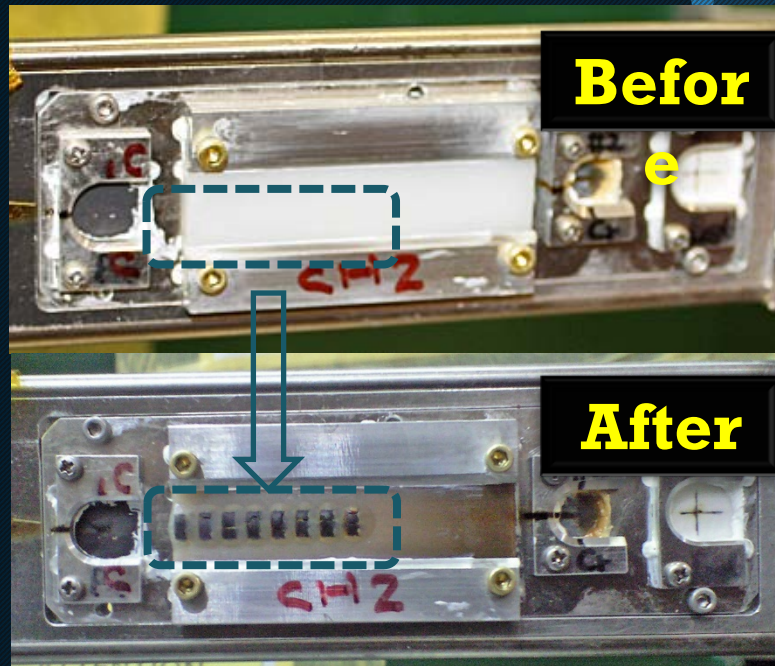
Water Cell target

Havar foil ($25\mu\text{m} \times 2$)
 -> background source
higher rate than CH_2 data



Calibration for high-multiplicity data

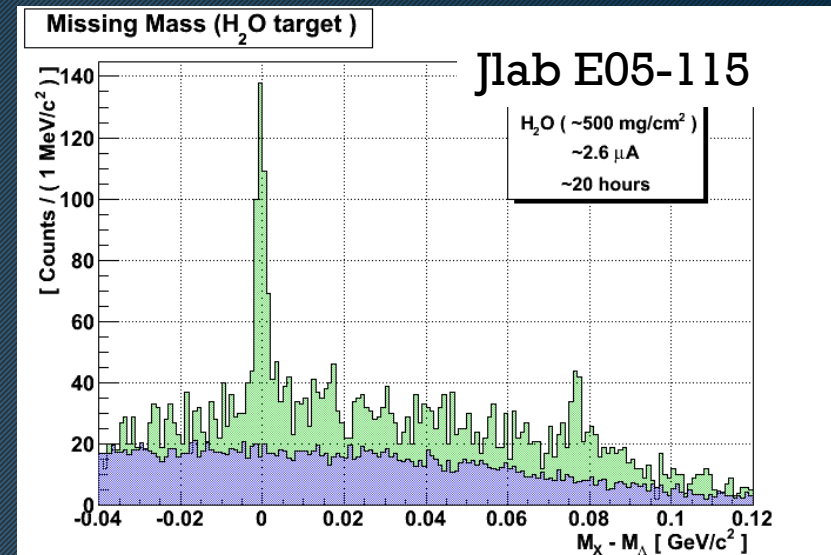
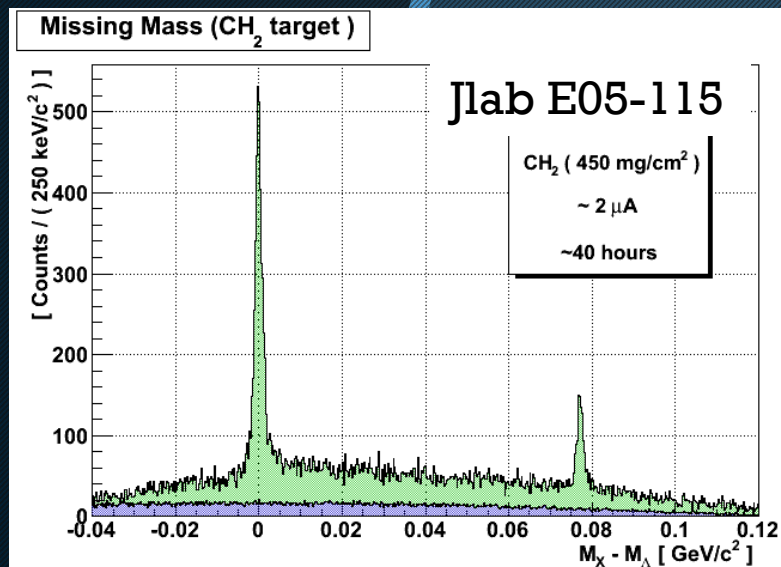
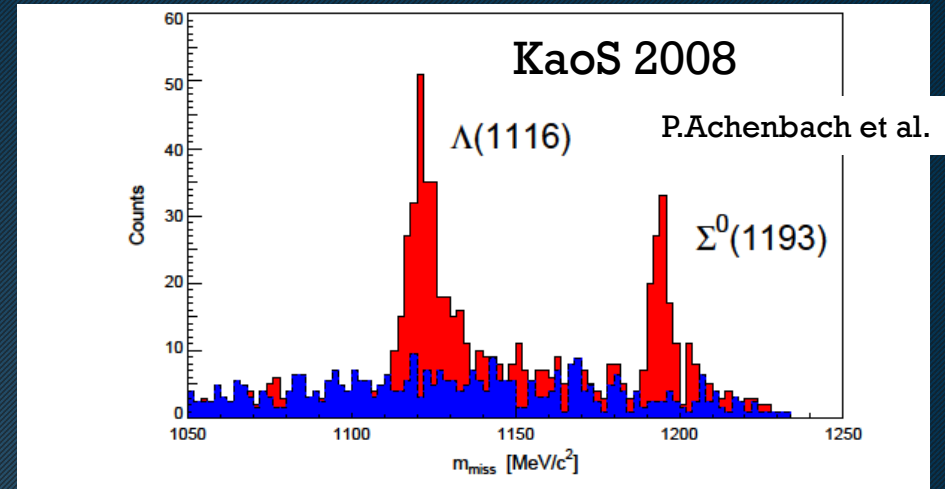
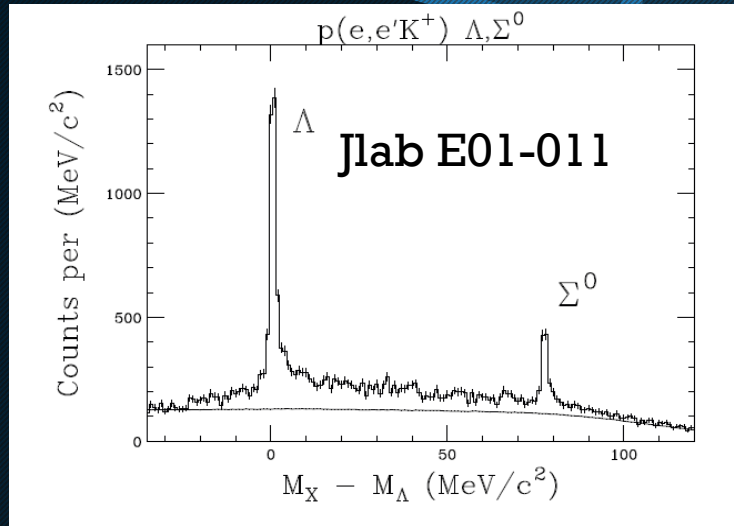
ポリエチレン標的から水素が逃げる



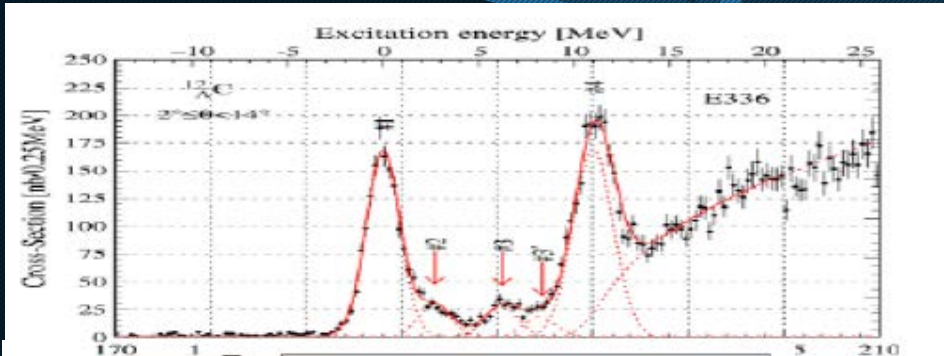
beam charge [μC]

Hydrogen escaped
due to the heat

$p(e, e'K^+) \Lambda, \Sigma^0$: Elementary Process

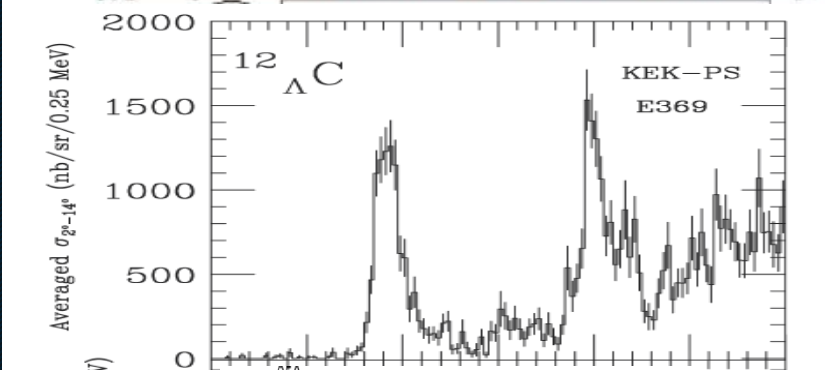


$^{12}\text{C}(\pi^+, \text{K}^+)^{12}_{\Lambda}\text{C}$ @ BNL-AGS, KEK-PS $^{12}\text{C}(e, e'\text{K}^+)^{12}_{\Lambda}\text{B}$ @ JLab Hall C

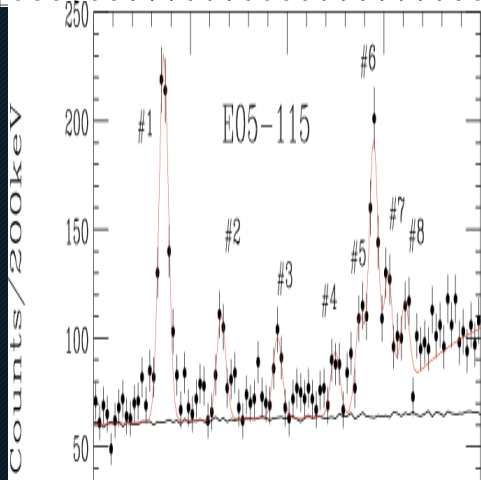


Resolution ~ 2 MeV

Excitation energy
(gs energy from emulsion)



Resolution ~ 1.6 MeV



JLab E05-115
 $^{12}\text{C}(e, e'\text{K}^+)^{12}_{\Lambda}\text{B}$

Resolution ~ 0.5 MeV

Absolute binding energy

$^{12}\text{C}(e,e'\text{K}^+)^{12}_{\Lambda}\text{B}$

0.5 MeV (FWHM)

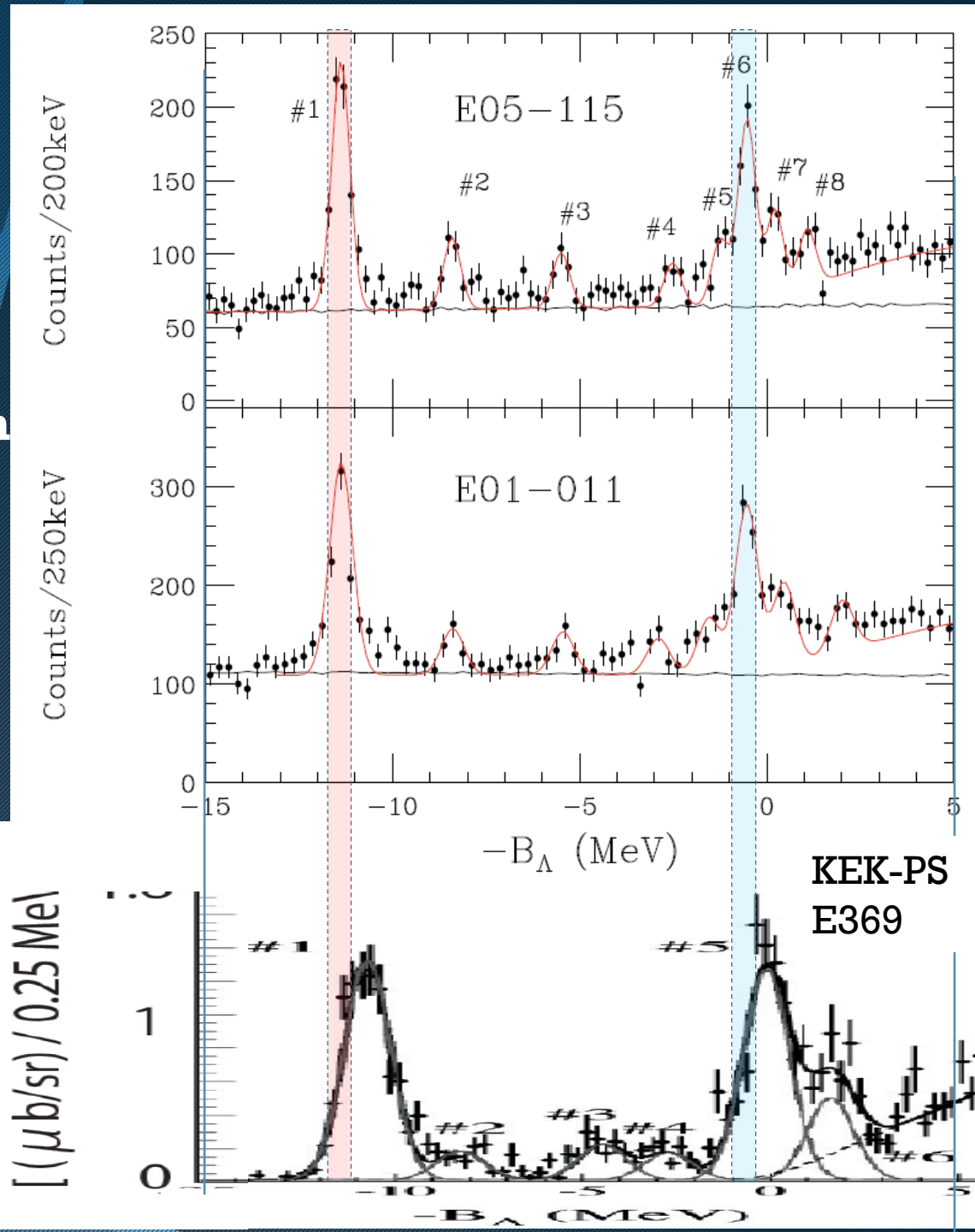
Absolute MM calibration

0.7 MeV (FWHM)

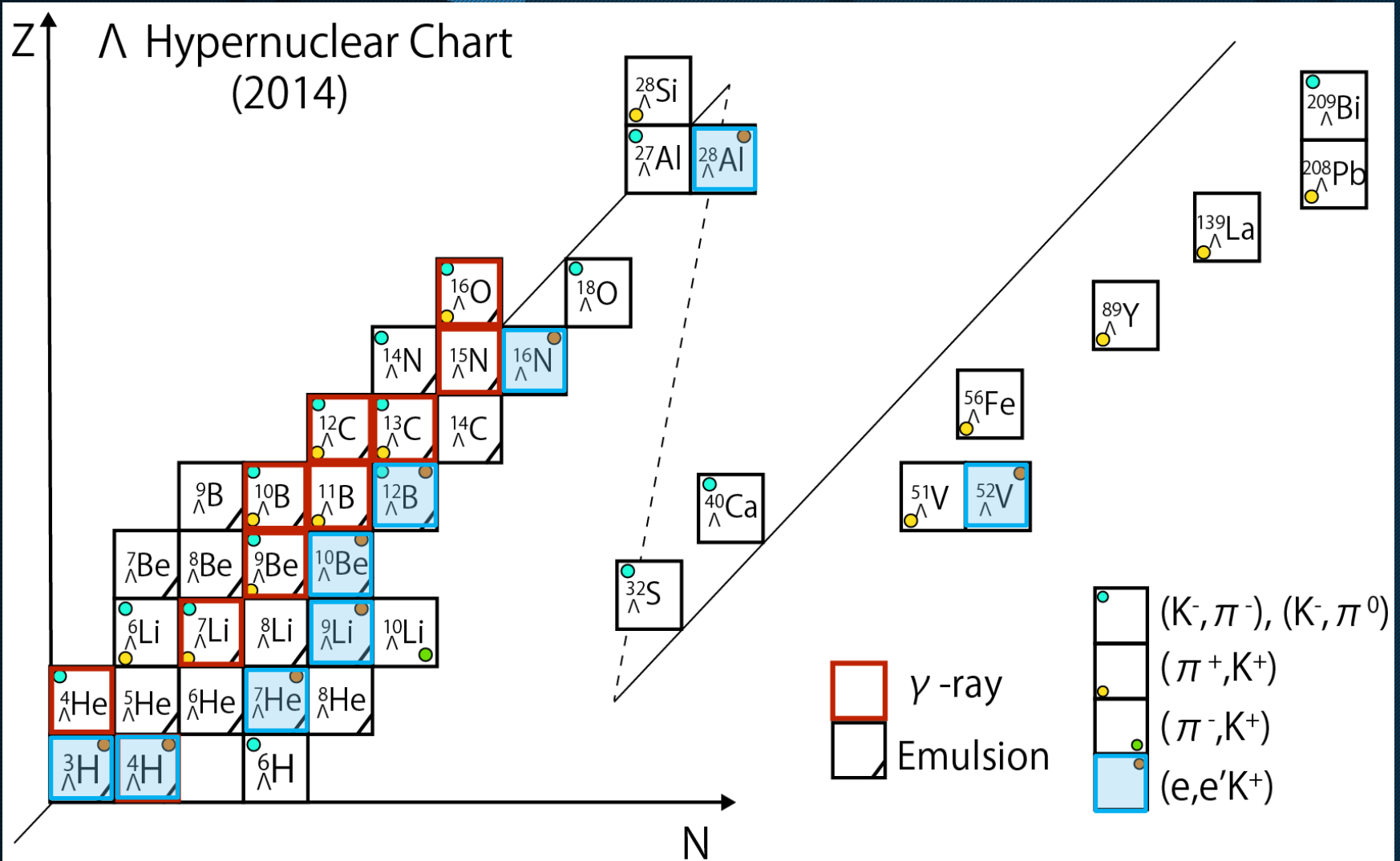
$^{12}\text{C}(\pi^+, \text{K}^+)^{12}_{\Lambda}\text{C}$

1.45 MeV (FWHM)

$^{12}_{\Lambda}\text{C}_{\text{gs}}$ energy
from old emulsion



Present Status of Λ Hypernuclear Spectroscopy

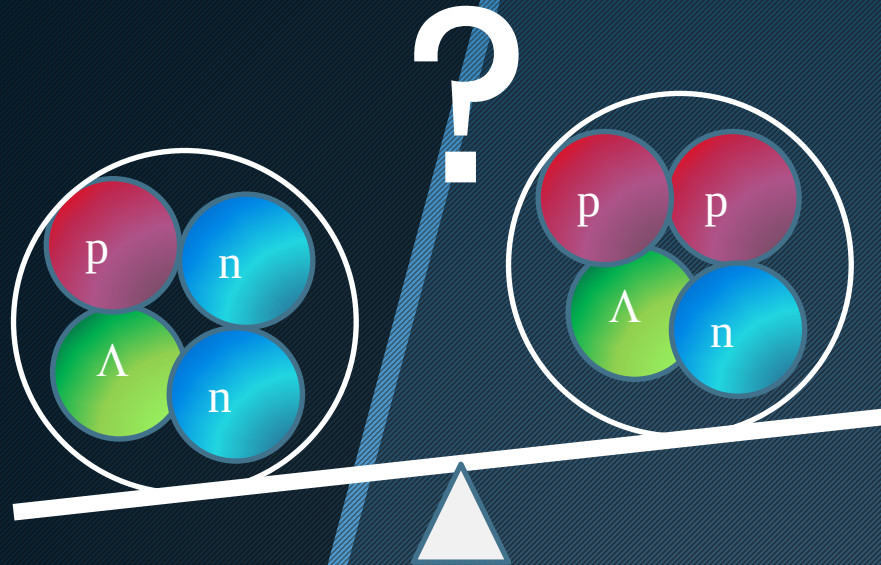


Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Recent

Mysteries in Hypernuclear Physics

Large CSB for $A=4$ hypernuclei



Hyperon Puzzle

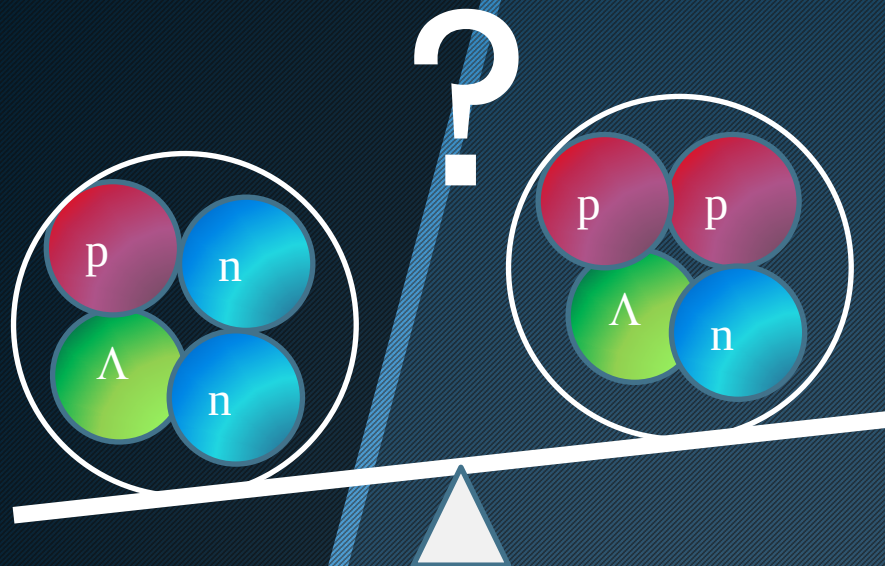


Two solar mass neutron stars

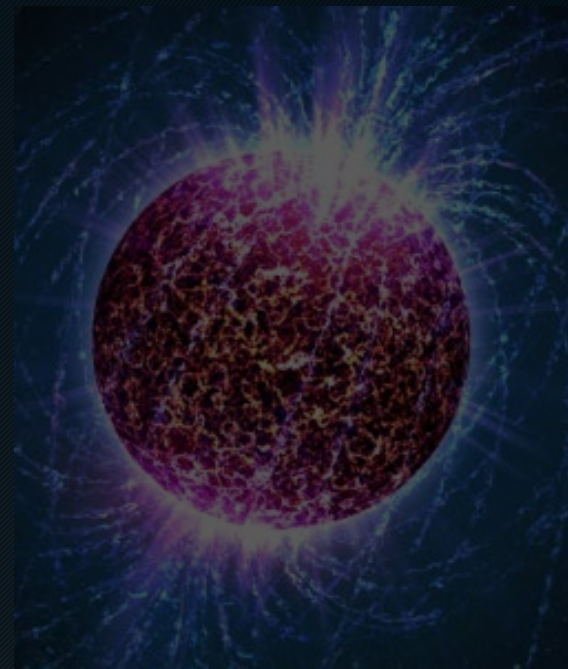
Recent

Mysteries in Hypernuclear Physics

Large CSB for $A=4$ hypernuclei



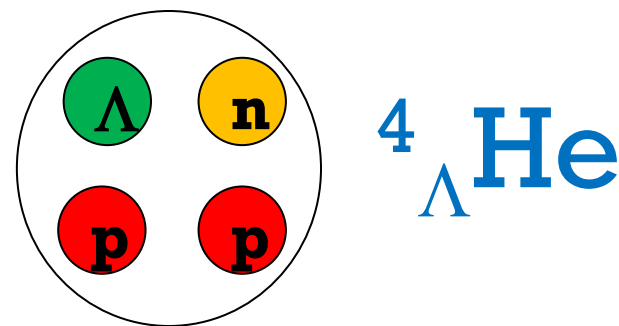
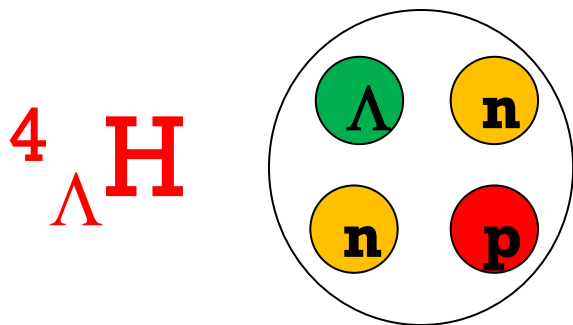
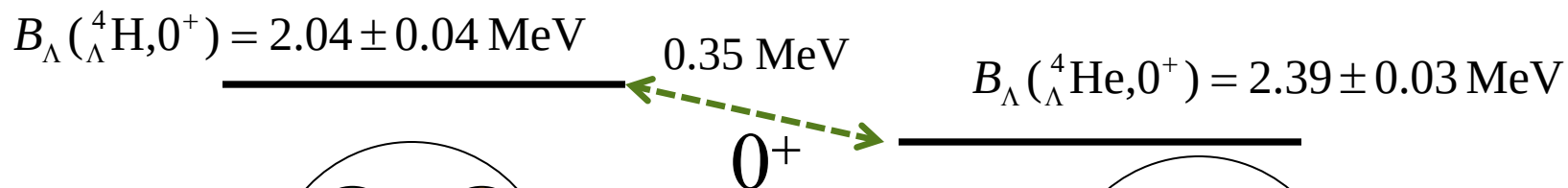
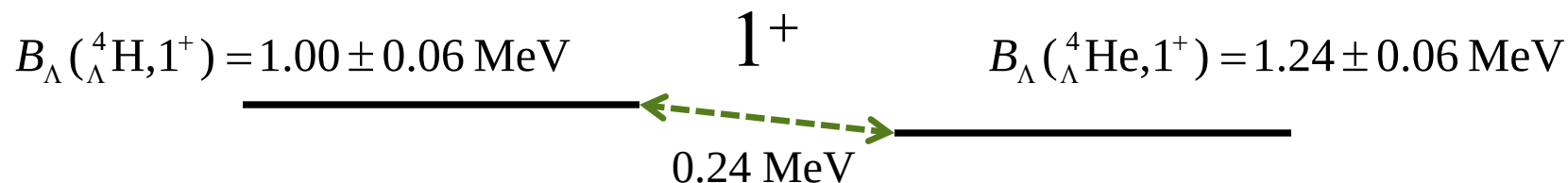
Hyperon Puzzle



Two solar mass neutron stars

Charge Symmetry Breaking Effect of ΛN interaction

Before 2015



Coulomb effect is small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

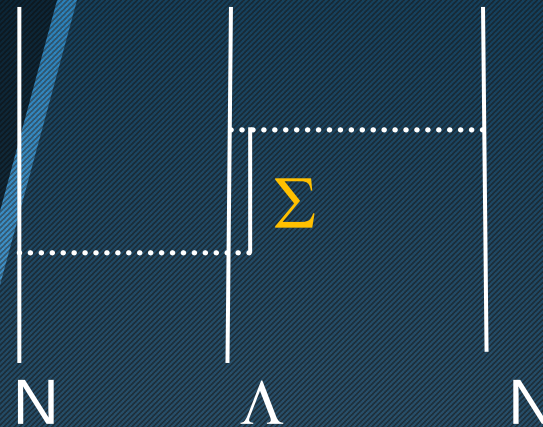
$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

Charge Symmetry Breaking

$$\text{cf) } B({}^3\text{H}) - B({}^3\text{He}) - \Delta B_c = 764 - 693 = 71 \text{ keV}$$

Three-body Λ NN force

Modern Yakubovsky and ChPT-NLO calculations were performed but they cannot explain $A=4, T=1/2$, hypernuclei. (A.Nogga, HYP2012)



$\Lambda\Sigma$ mass difference ~ 80 MeV

$<$

$N\Lambda$ mass difference ~ 300 MeV

$$M(\Sigma^+) < M(\Sigma^0) < M(\Sigma^-), \quad \Delta M(\Sigma^- - \Sigma^+) \sim 8 \text{ MeV}$$

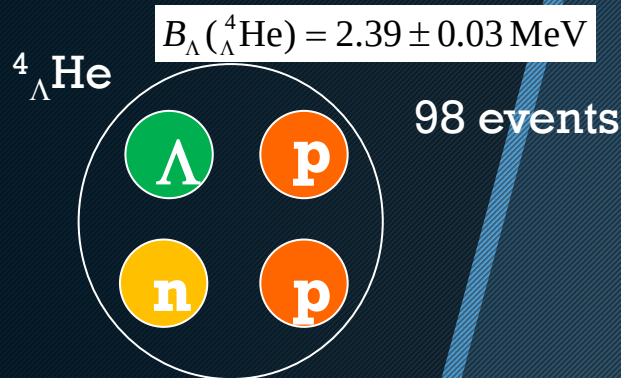
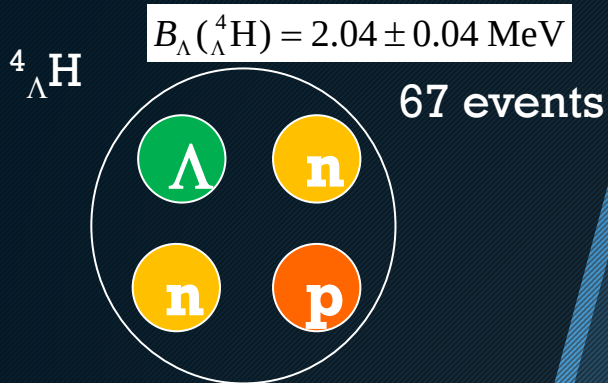
~~Consistent understanding of $0^+, 1^+$ of ${}^4_{\Lambda}\text{H}, {}^4_{\Lambda}\text{He}$~~

Phenomenological potential :

A.R.Bodmer & Q.N.Usmani, PRC 31(1985)1400.

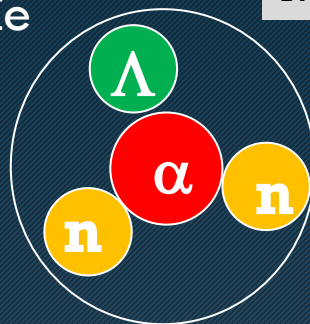
$$V^{\text{CSB}} = -\tau_3 T_{\pi^8}^2 \left[(0.568\Delta B_{\Lambda} + 0.756\Delta B_{\Lambda}^*) \right. \\ \left. + (0.568\Delta B_{\Lambda} - 0.756\Delta B_{\Lambda}^*)\sigma_{\Lambda} \cdot \sigma_N \right]$$

B_{Λ} of light hypermultiplets



${}^7_{\Lambda}\text{He}$

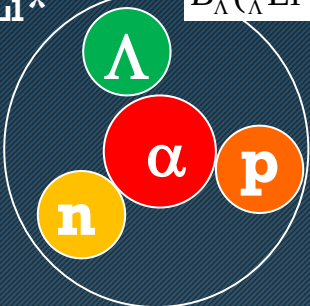
No reported B_{Λ}



${}^7_{\Lambda}\text{Li}^*$

$B_{\Lambda}({}^7_{\Lambda}\text{Li}^*) = 5.26 \pm 0.03 \text{ MeV}$

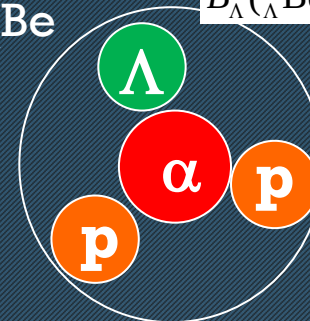
167 events



${}^7_{\Lambda}\text{Be}$

$B_{\Lambda}({}^7_{\Lambda}\text{Be}) = 5.16 \pm 0.08 \text{ MeV}$

15 events



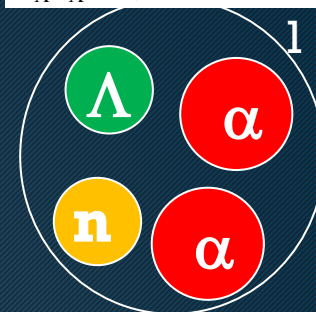
Exp. Data : Emulsion

Nuclear Physics B52 (1973) 1-30.

${}^{10}_{\Lambda}\text{Be}$

$B_{\Lambda}({}^7_{\Lambda}\text{Li}^*) = 9.11 \pm 0.22 \text{ MeV}$

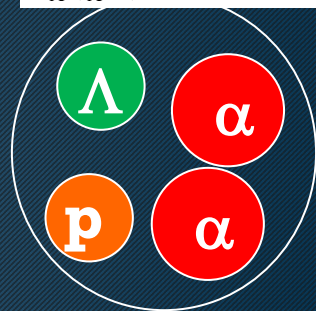
1 event



${}^{10}_{\Lambda}\text{B}$

$B_{\Lambda}({}^{10}_{\Lambda}\text{B}) = 8.89 \pm 0.12 \text{ MeV}$

10 events

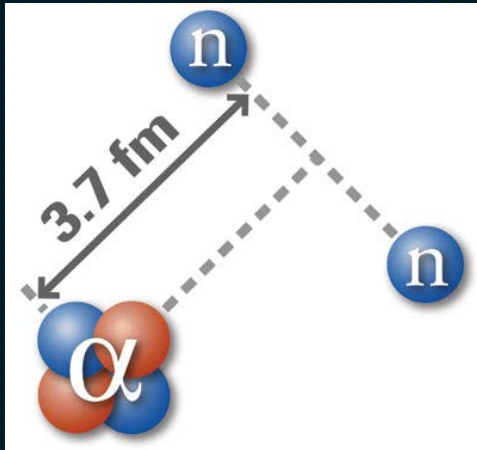


Experimental B_{Λ} $\rightarrow$ Δ_{CSB}

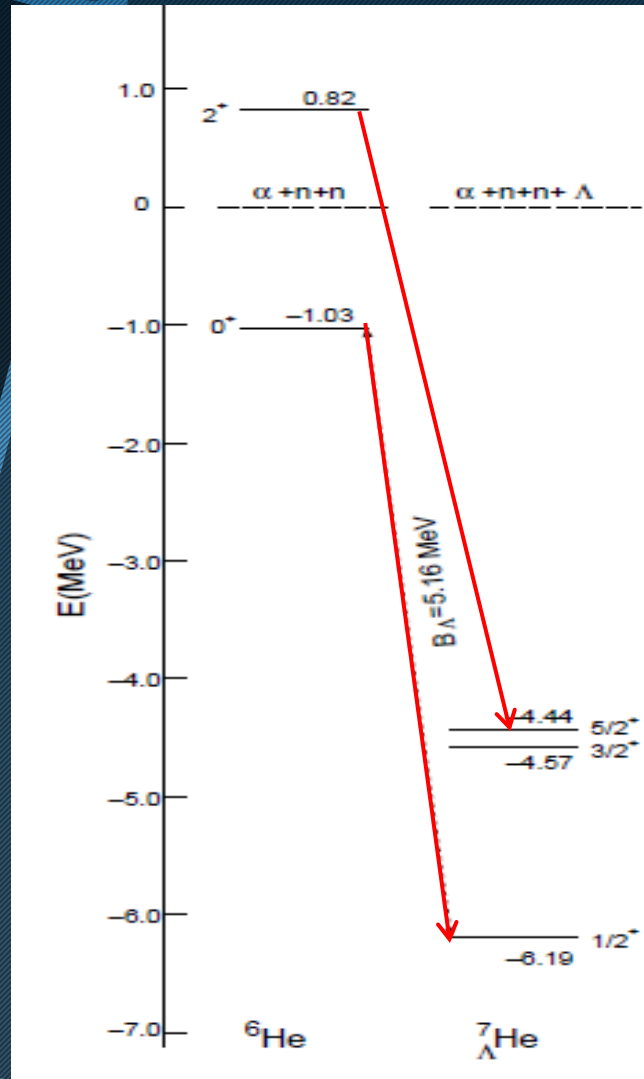
Hiyama et al. PRC80.054321

PTP 128 (2012) 105.

$${}^7_{\Lambda}\text{He} = {}^6\text{He} + \Lambda$$

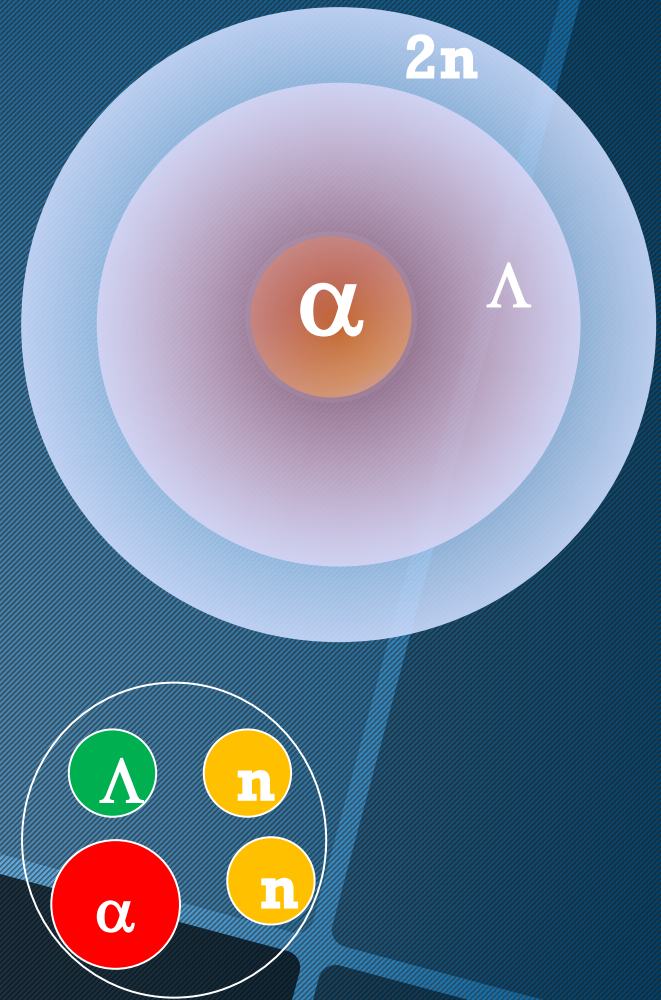
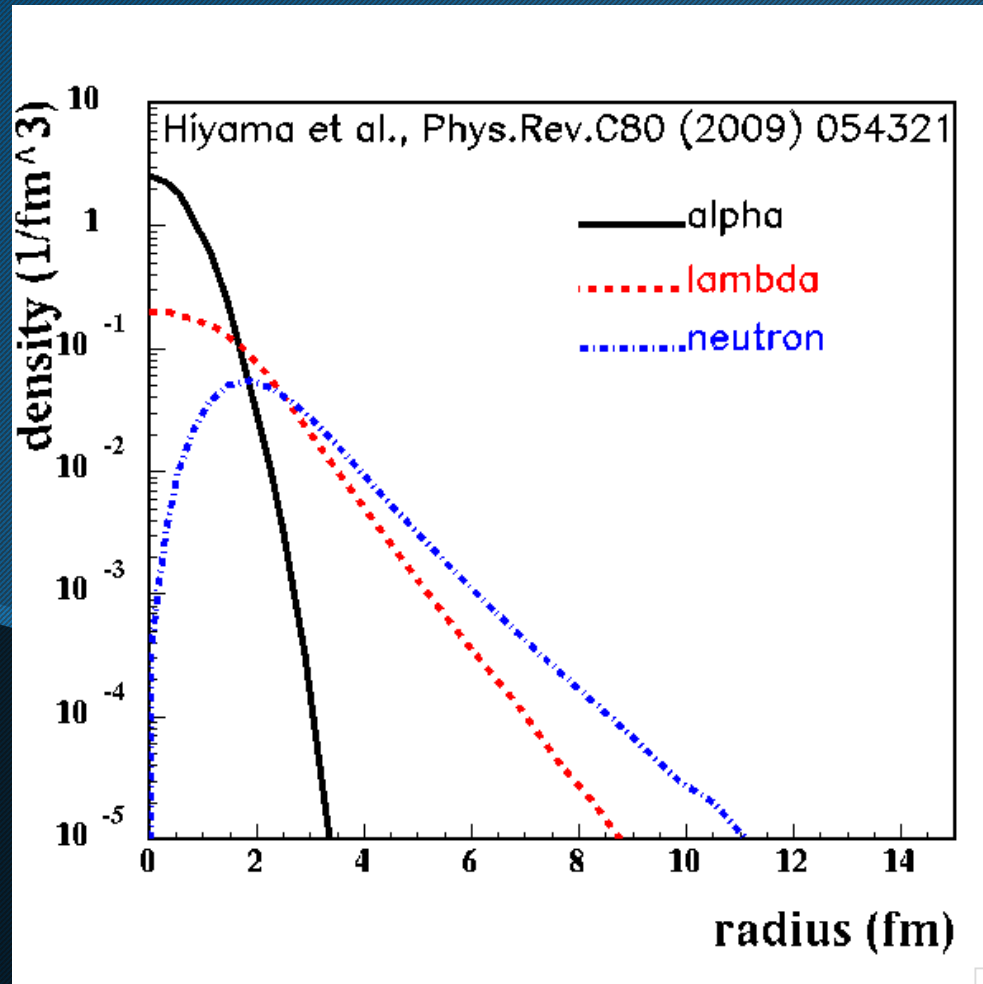


${}^6\text{He}$: 2n halo



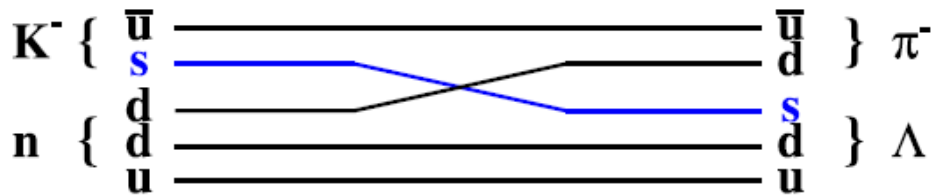
Λ behaves like glue

${}^7_{\Lambda}\text{He}$ Density Distributions

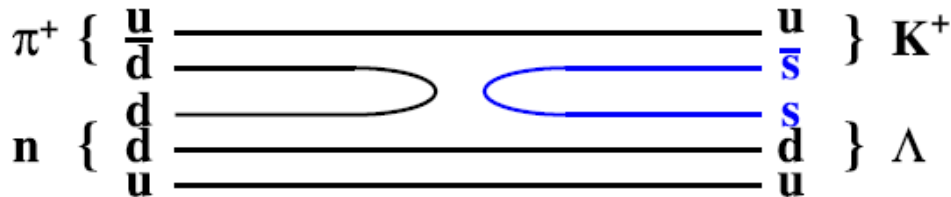


Production of Hypernuclei

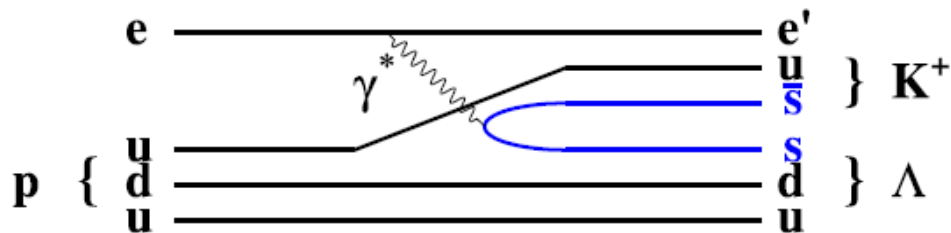
s-quark exch.
(K^- , π^-)



s,sbar pair cre.
(π^+ , K^+)



($e, e' K^+$)



n to Λ

No ${}^7\text{He}$ target

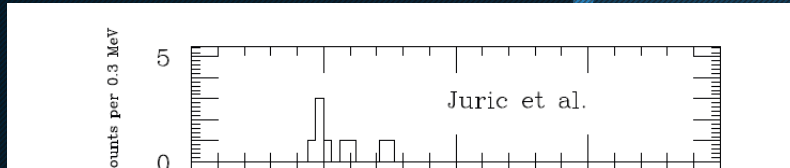
~~${}^7\text{He}(K^-, \pi^-) {}^7_{\Lambda}\text{He}$
 ${}^7\text{He}(\pi^+, K^+) {}^7_{\Lambda}\text{He}$~~

p to Λ

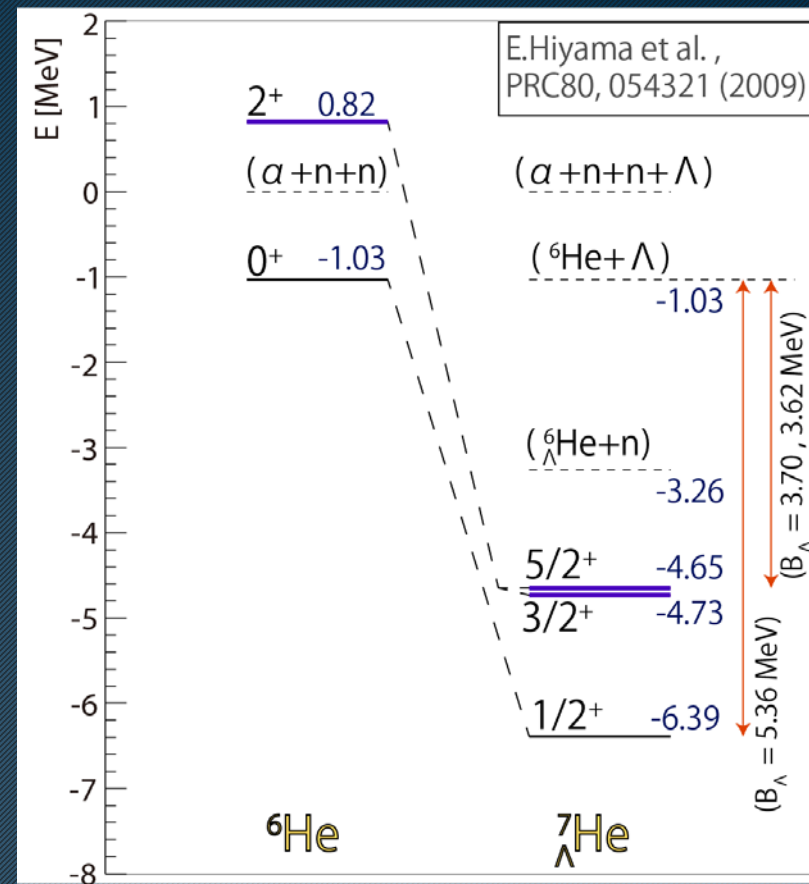
${}^7\text{Li}(e, e' K) {}^7_{\Lambda}\text{He}$

${}^7_{\Lambda}\text{He}$ spectrum

Juric et al., Nucl. Phys. A484 (1988) 520

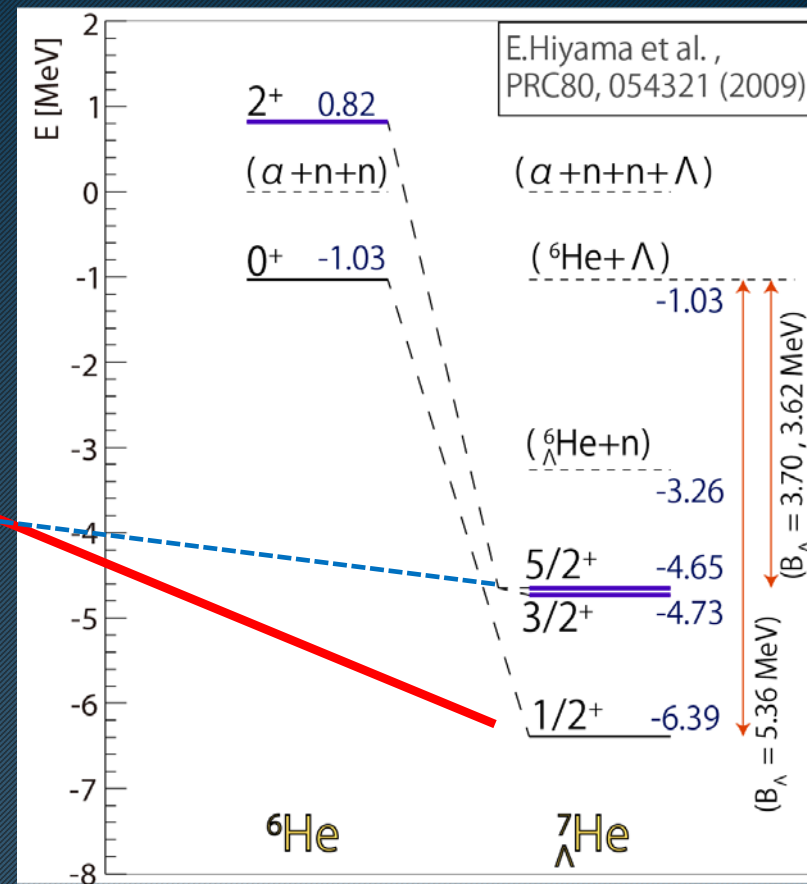
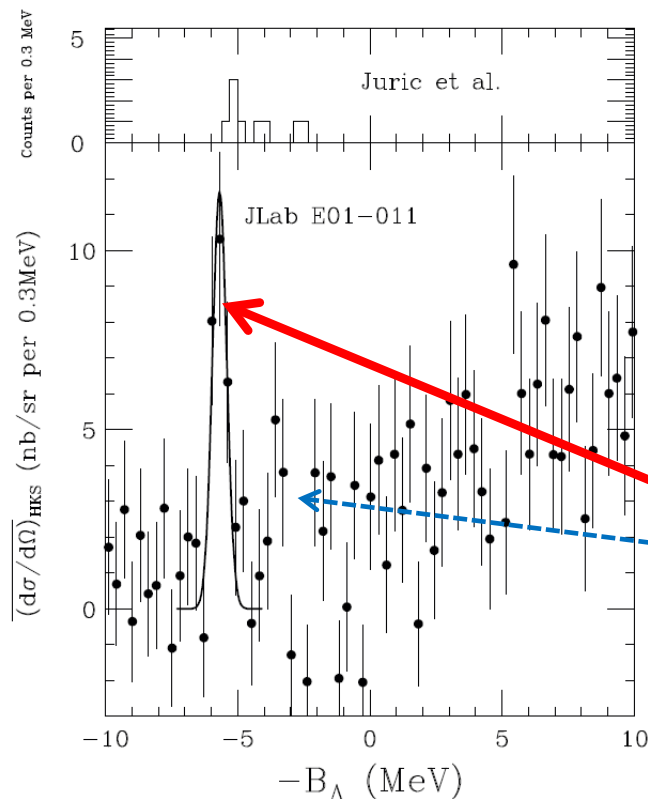


No B_{Λ} was obtained.

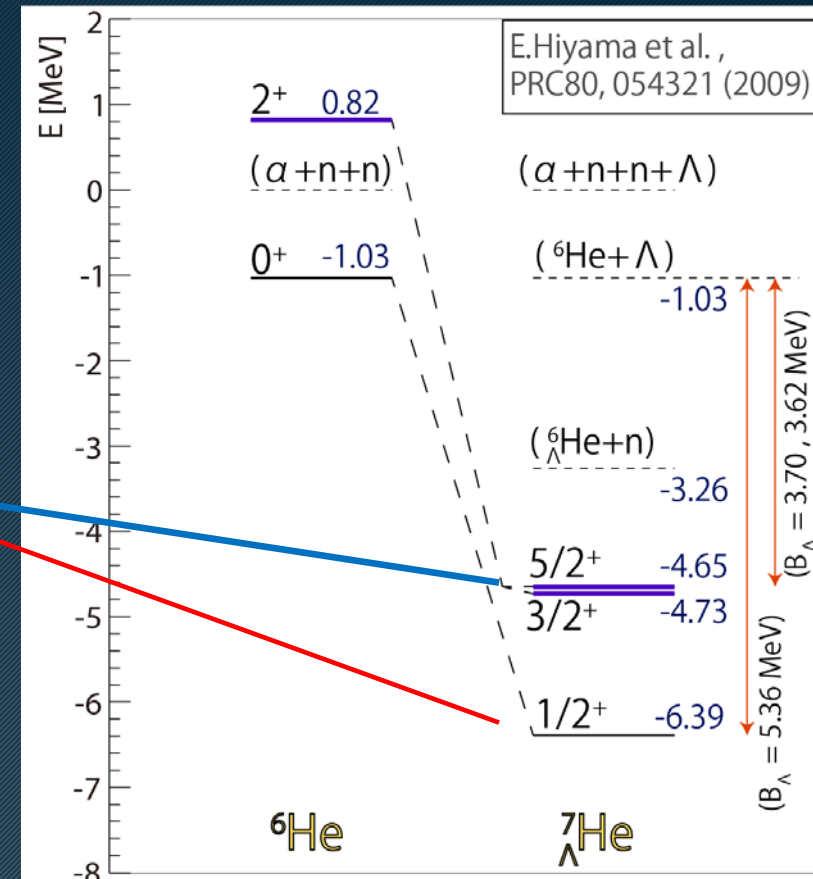
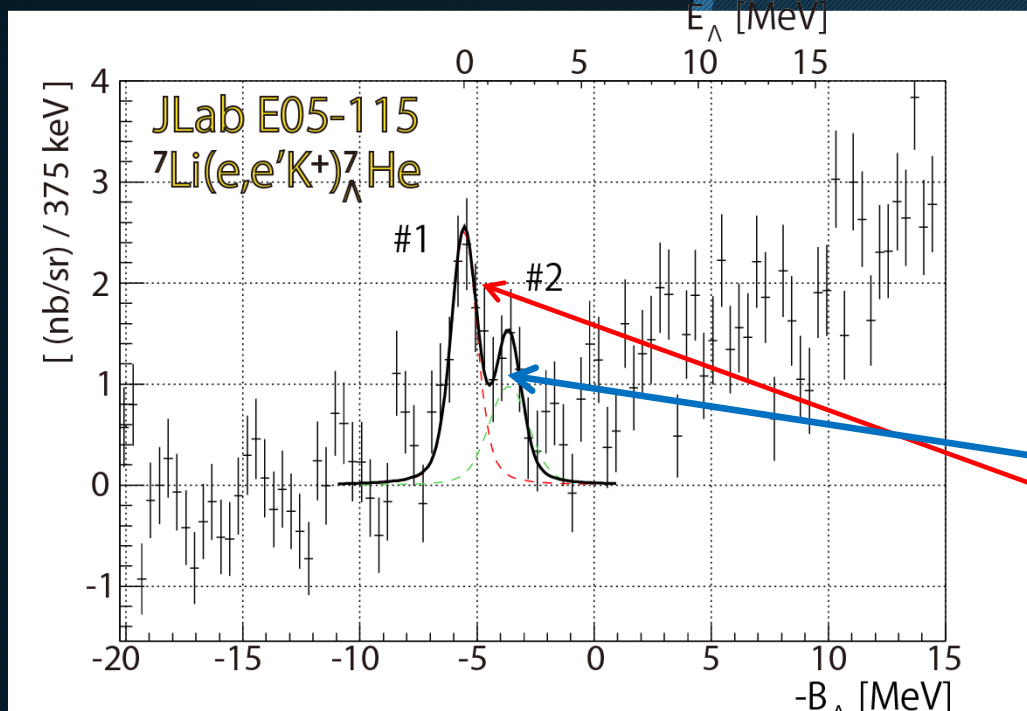


${}^7_{\Lambda}\text{He}$ spectrum of E01-01

SNN et al., PRL 110, 012502 (2013)



${}^7_{\Lambda}\text{He}$ spectrum of E05-115



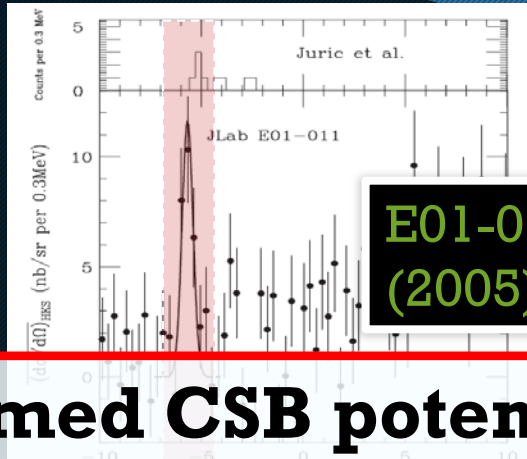
E01-011(HKS) 90 counts

E05-115(HKS-HES) >500 counts

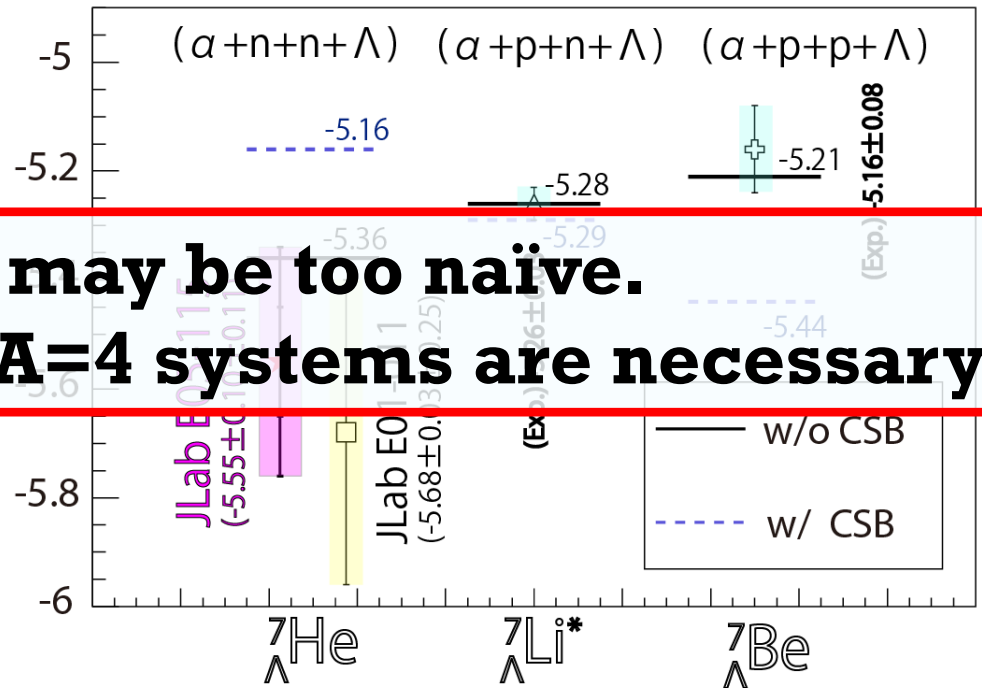
unbound ${}^6\text{He}$ excited state + Λ = bound ${}^7_{\Lambda}\text{He}$ excited state

CSB Interaction test in $A=7$ iso-triplet comparison

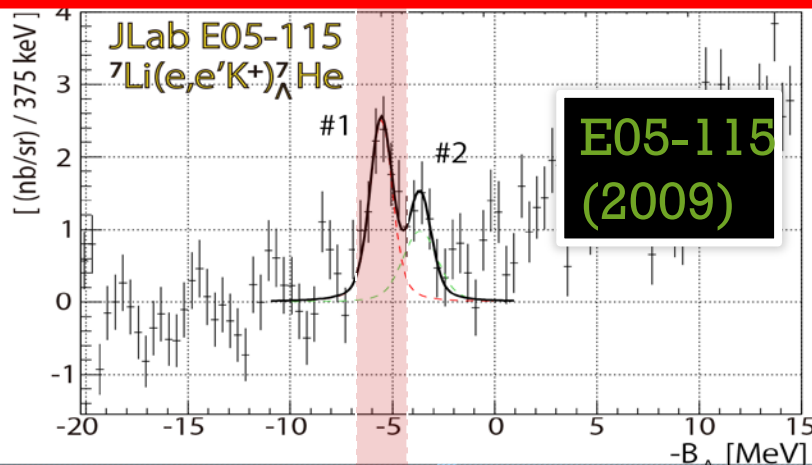
SNN et al., PRL 110, 012502 (2013)



Prediction by E.Hiyama et al.
PRC80, 054321 (2009)



**Assumed CSB potential may be too naïve.
New measurements on $A=4$ systems are necessary.**

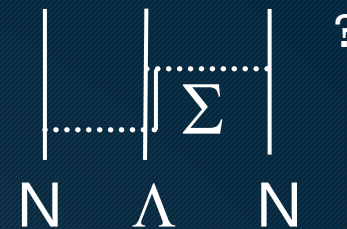


T. Gogami, Doctor Thesis (2014) Tohoku Univ.

T. Gogami et al. PHYSICAL REVIEW C 94, 021302(R) (2016)

$A=4$ system

Before 2015

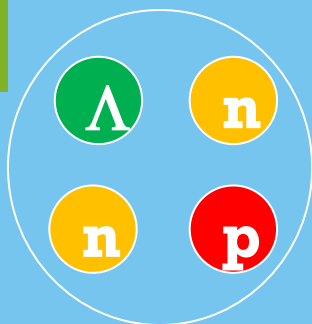


$$B_{\Lambda}({}^4_{\Lambda}\text{H}, 1^+) = 1.00 \pm 0.06 \text{ MeV}$$

${}^4\text{He}(e, e'K^+) {}^4_{\Lambda}\text{H}(1^+)$

$$B_{\Lambda}({}^4_{\Lambda}\text{H}, 0^+) = 2.04 \pm 0.04 \text{ MeV}$$

Decay π



1^+

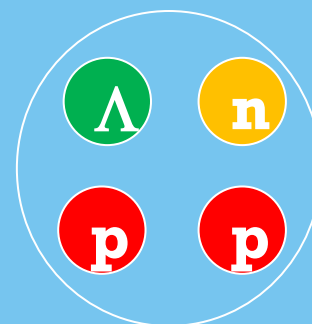
$$B_{\Lambda}({}^4_{\Lambda}\text{He}, 1^+) = 1.24 \pm 0.06 \text{ MeV}$$

J-PARC E13

$$B_{\Lambda}({}^4_{\Lambda}\text{He}, 0^+) = 2.39 \pm 0.03 \text{ MeV}$$

0.24 MeV
0.35 MeV

0^+



A.R.Bodmer & Q.N.Usmani, PRC 31(1985)1400.

Coulomb effect is very small.

$$-\Delta B_c = 0.050 \pm 0.02 \text{ MeV},$$

$$-\Delta B_c^* = 0.025 \pm 0.015 \text{ MeV}$$

$$V^{\text{CSB}} = -\tau_3 T_{\pi}^2 \frac{1}{8} [(0.568 \Delta B_{\Lambda} + 0.756 \Delta B_{\Lambda}^*) \\ + (0.568 \Delta B_{\Lambda} - 0.756 \Delta B_{\Lambda}^*) \sigma_{\Lambda} \cdot \sigma_N]$$

Plans for re-examination of $A=4$ system

${}^4_{\Lambda}\text{H}$: ${}^4\text{He}(e,e'\text{K}^+) {}^4_{\Lambda}\text{H}$ (gs &) excited states (res. 500keV)

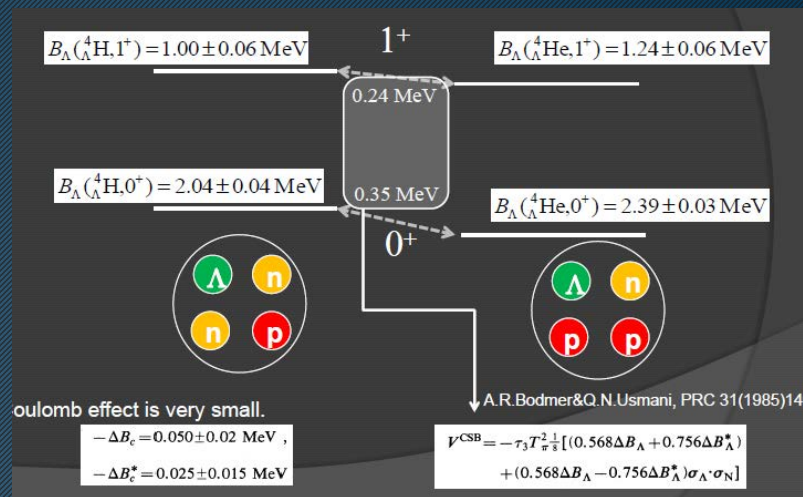
Decay π spectroscopy @ JLab, Mainz

Absolute mass of ${}^4_{\Lambda}\text{H}$ (gs) ($< 100\text{keV}$)

${}^4_{\Lambda}\text{He}$: ${}^4\text{He}(\text{K}^-, \pi^-) {}^4_{\Lambda}\text{He}$

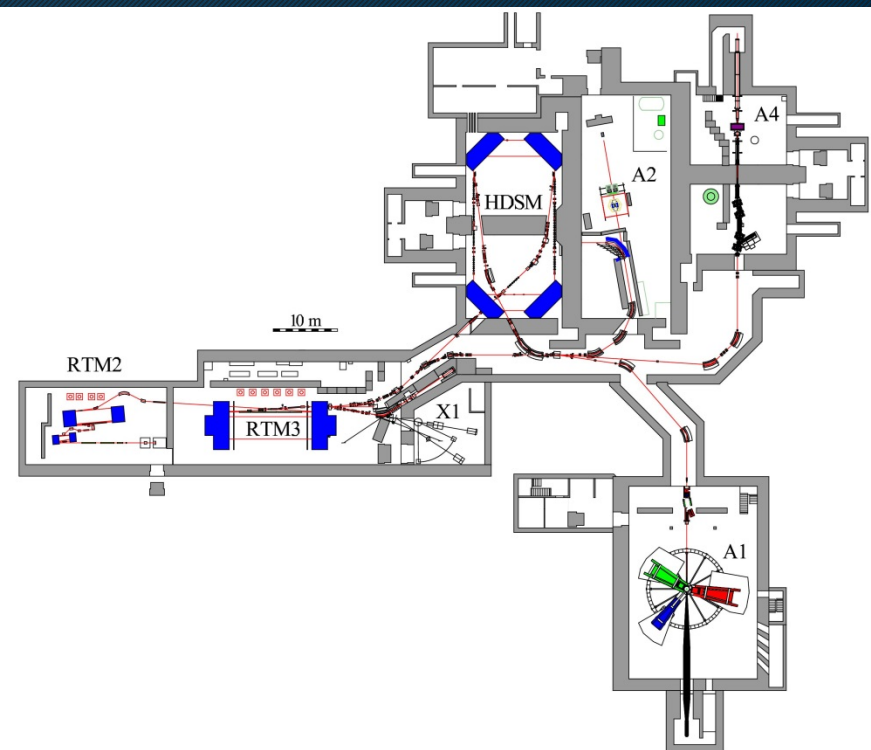
γ measurements @ J-PARC

Ex(1^+) ... (res: a few keV)

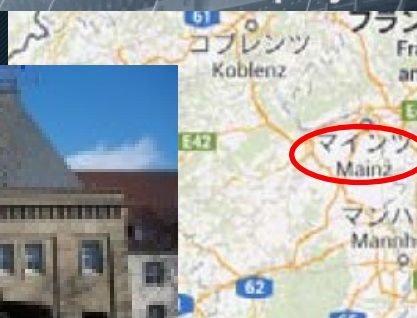


P a r t 3 . 崩壊 π 中間子分光

Mainzer Mikrotron (MAMI) Johannes Gutenberg Universität Mainz



Institut für Kernphysik



日本物理学会誌

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2013 VOL 68 NO.

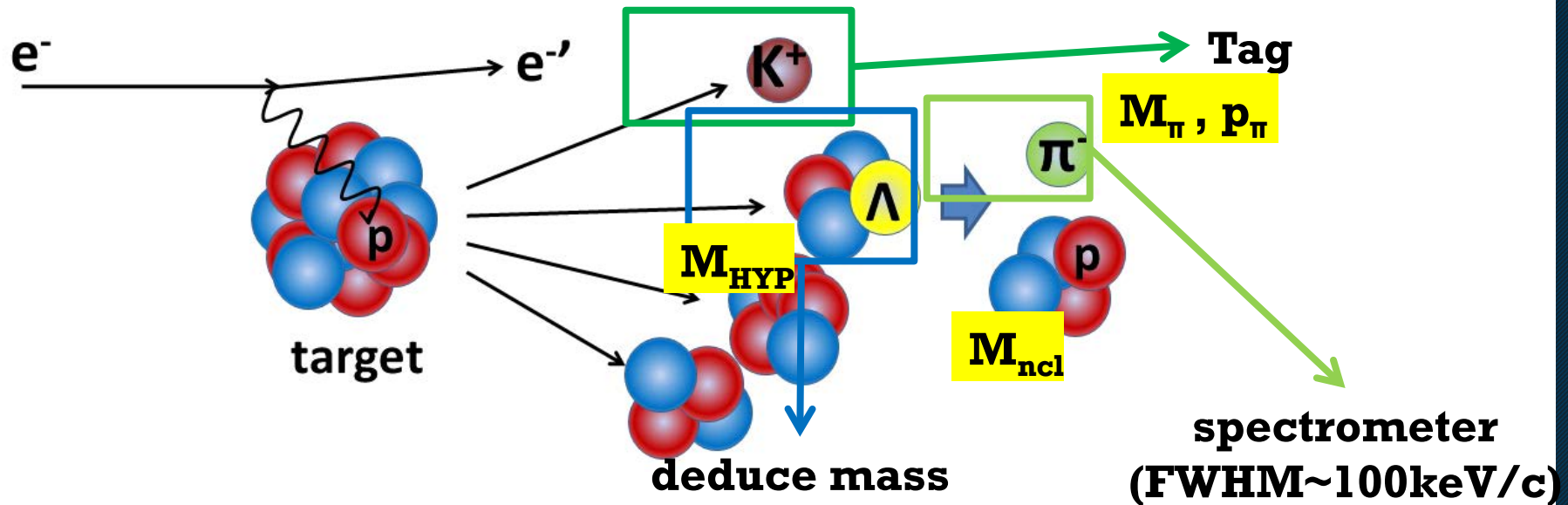
9



<http://www.jps.or.jp/>



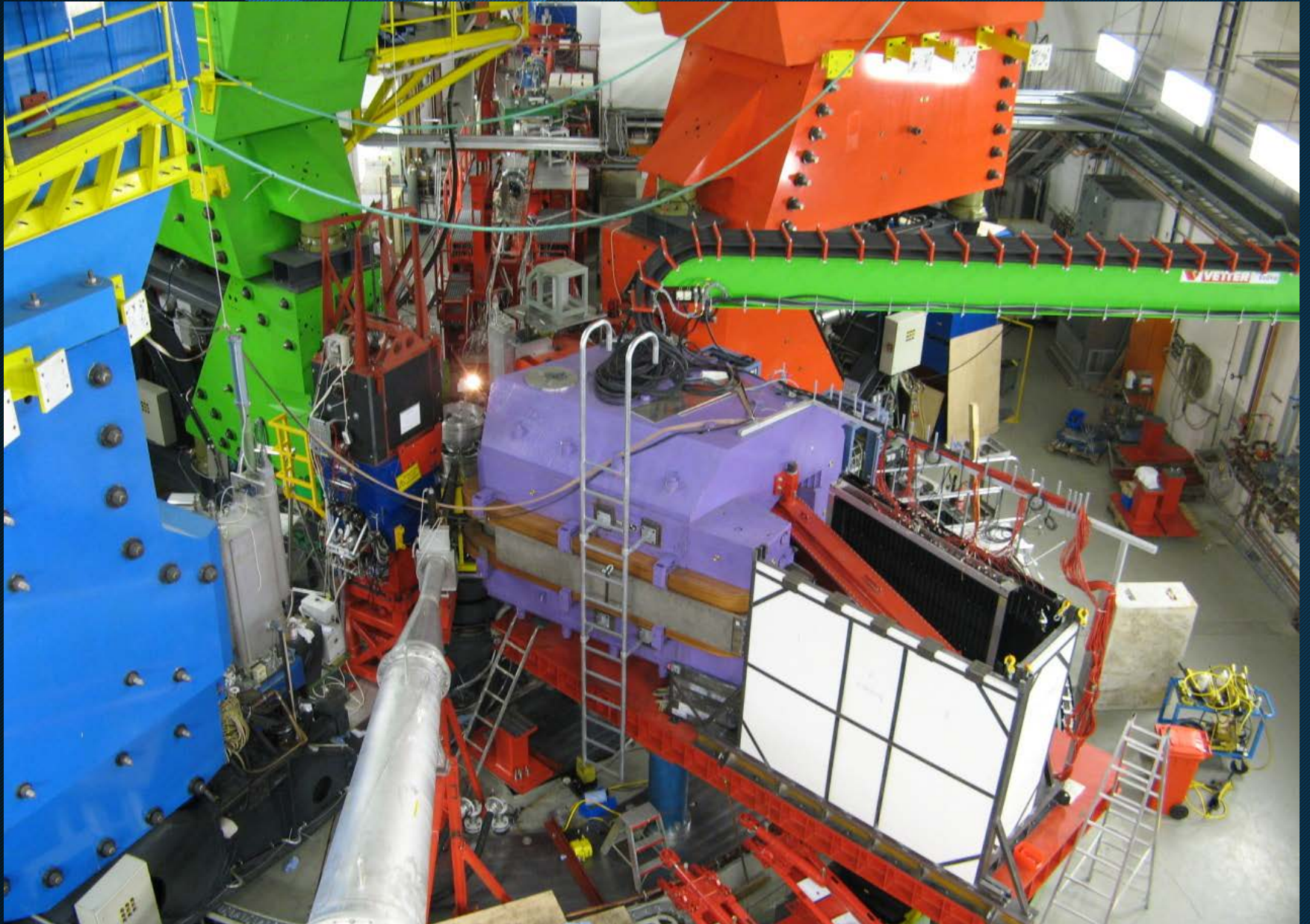
Principle of decay π spectroscopy



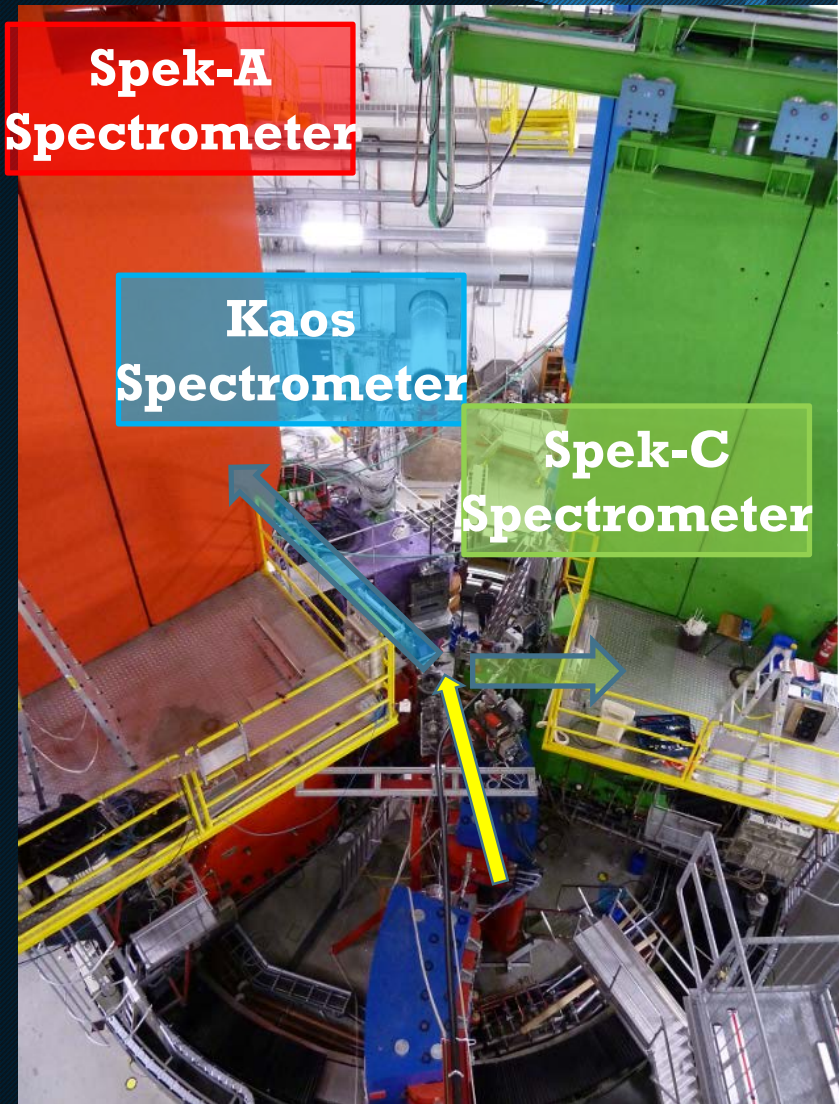
$$M_{HYP} = \sqrt{M_{ncl}^2 + p_\pi^2} + \sqrt{M_\pi^2 + p_\pi^2}$$

Simple single π measurement with K^+ tagging

KaOS at MAMI-C (Mainz Univ.)



Setup of decay pion spectroscopy in MAMI-C



	Kaos	Spek-C	Spek-A
central mom.	1000 MeV/c	125 MeV/c	130 MeV/c
mom. acceptance	50 %	25 %	
solid angle	12 msr	28 msr	
dispersive angle	2 deg	-126 deg	90 deg
path length	5.3 m	10 m	
mom. resolution	10^{-3}	10^{-4}	

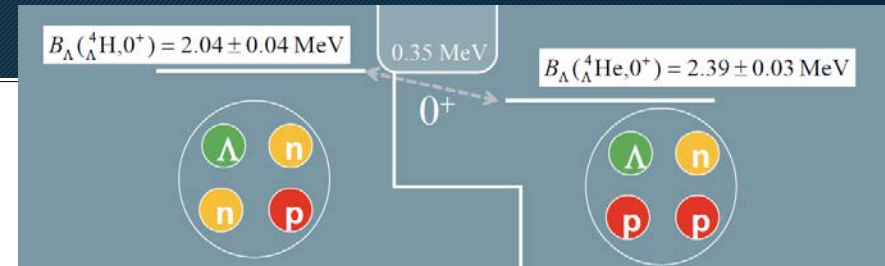
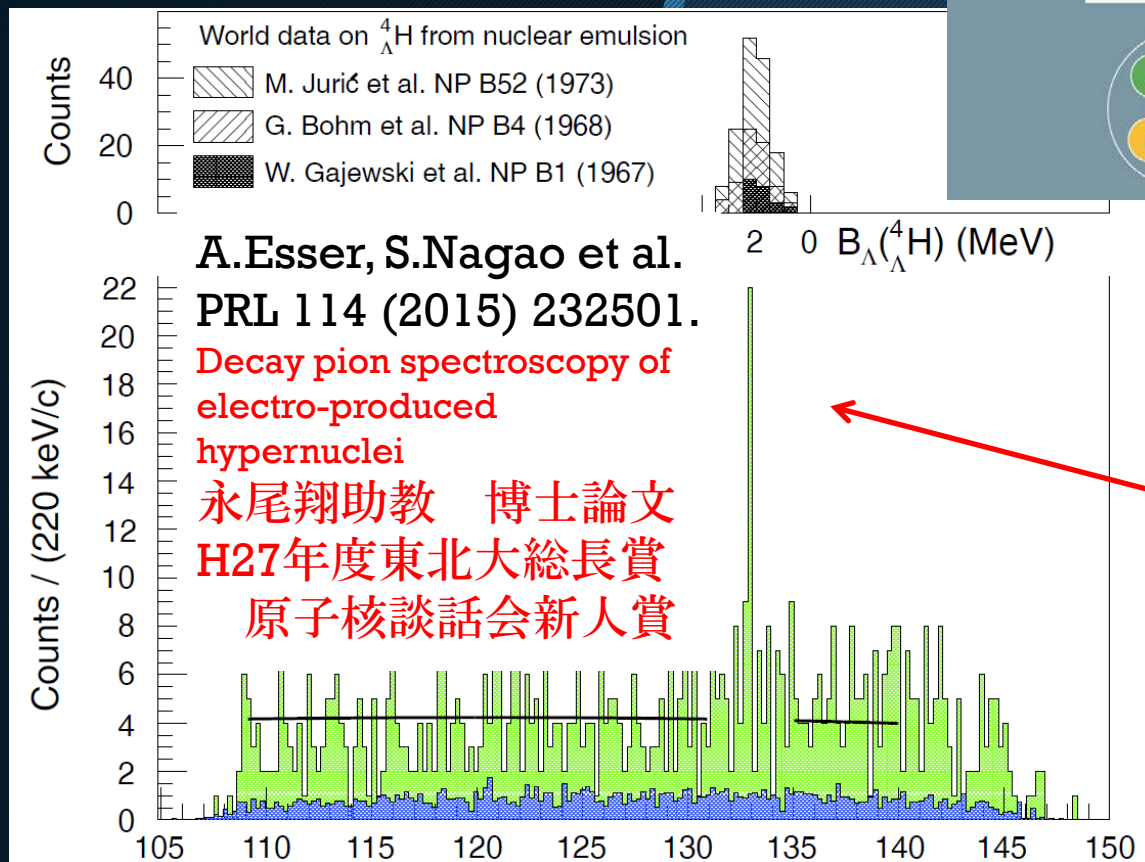
target : material : ^9Be
 thickness : $125\text{ }\mu\text{m}$ (22 mg/cm^2)
 tilt angle : 54 deg

electron beam : energy : 1.5 GeV
 current : $\sim 2\text{ }\mu\text{A}$

Data summary of pilot runs (2 0 1 2)

	First beam time	Second beam time
Term	24 May ~ 14 June	19 July ~ 1 August
Typical current	1.5 μA – 2.0 μA	2.0 μA
Total charge	0.68 C	0.74 C
K ⁺ spectrometer	Kaos	
π^- spectrometer	Spek-C	Spek-A + C
No. of π^- peak (assumption)	~10 counts	~20 counts

π^- spectrum tagged by K^+

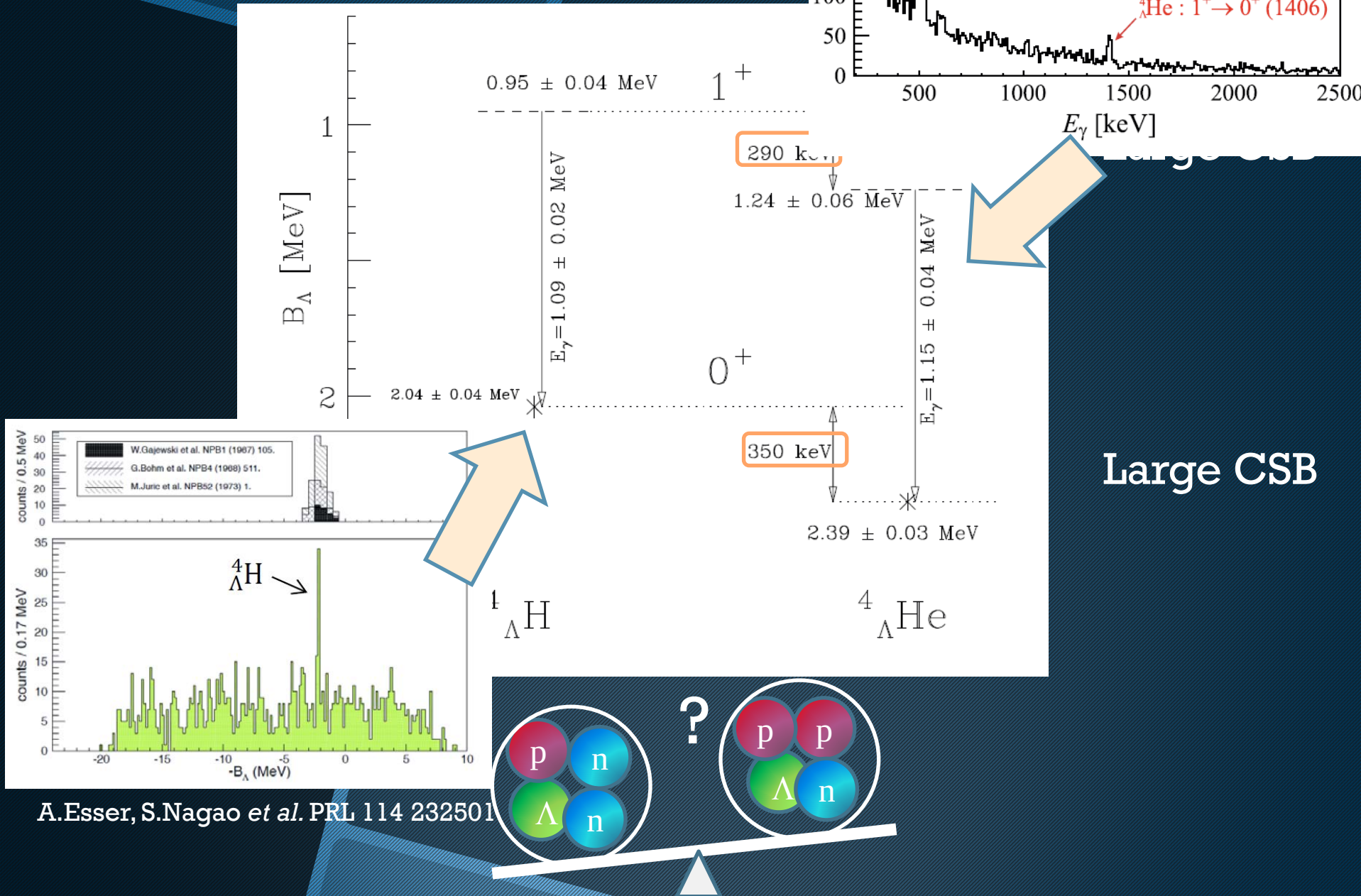


$$B_{\Lambda} = 2.12 \pm 0.01 \pm 0.09 \text{ MeV}$$

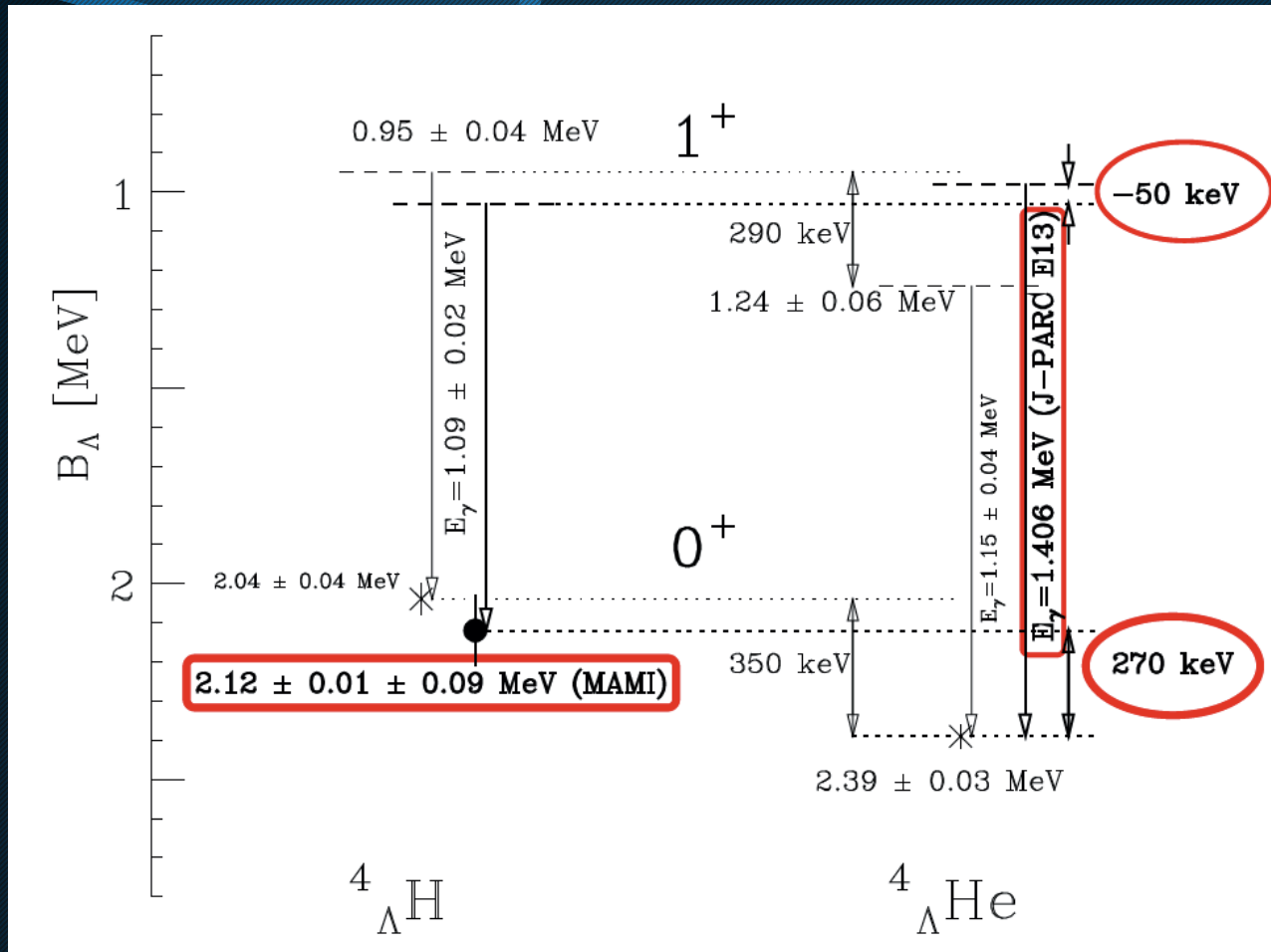
ハイパー核崩壊 π 中間子分光実験の
 系統誤差改善に向けた精密磁場測定
 富田翔子 修士論文
 H28年度 物理学専攻賞

Kaos + Spek-C (2011,2012) Pion momentum (MeV/c)

New Measurements in 2015

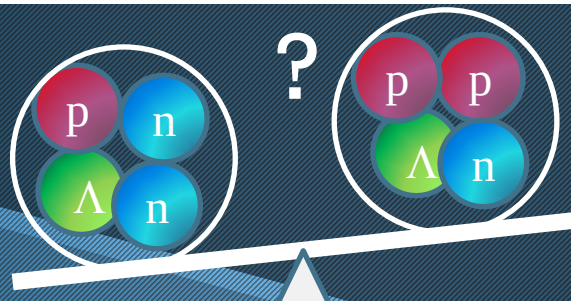


CSB for $A=4$ hypernuclei : *Current situation*

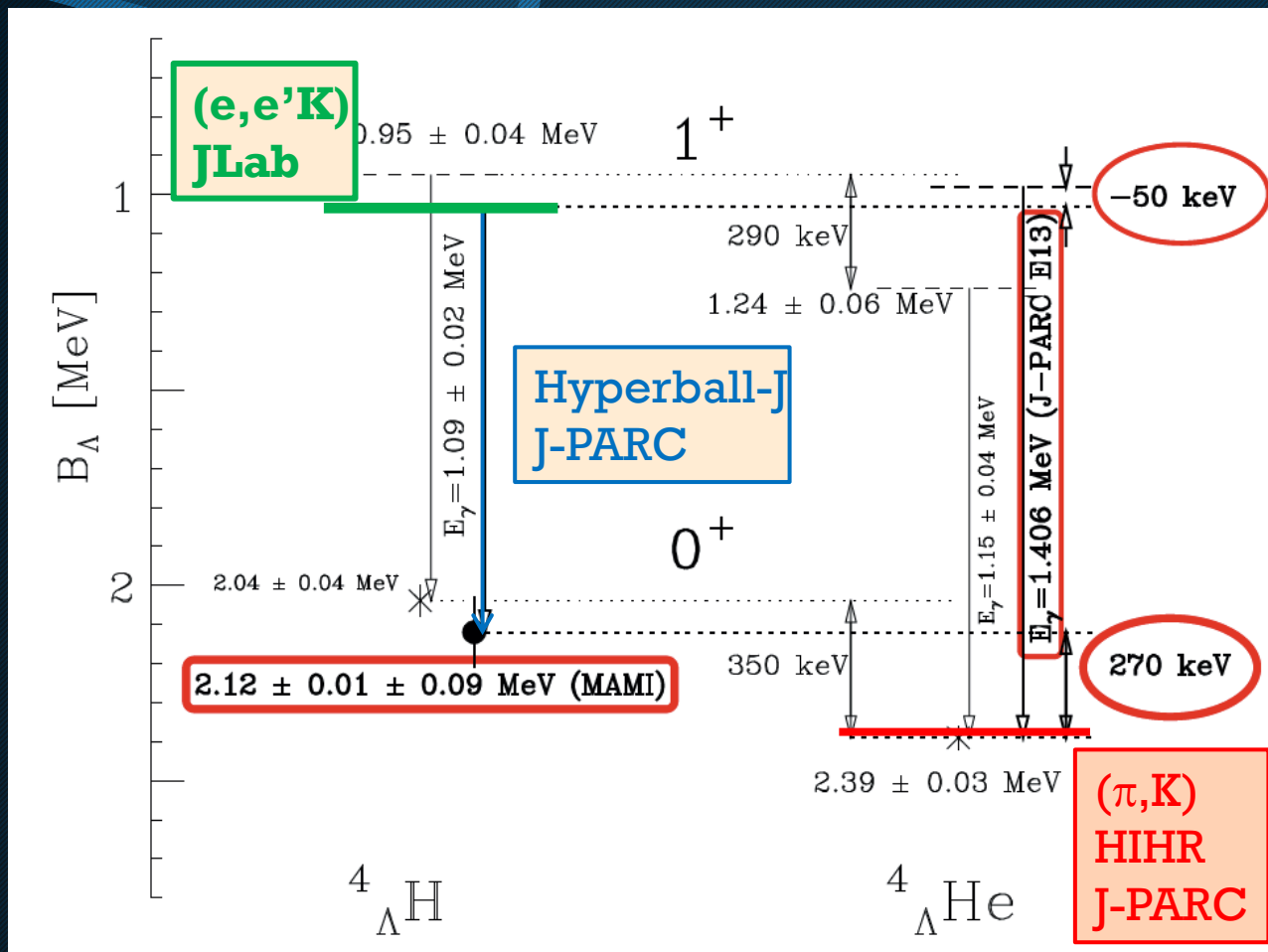


Small CSB

Large CSB

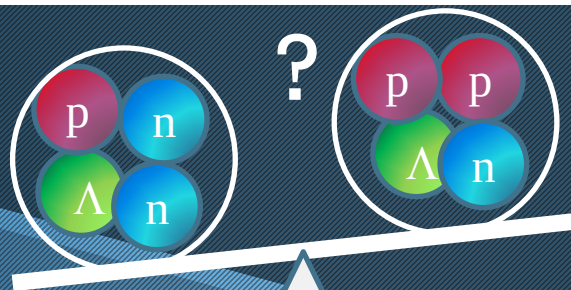


CSB for $A=4$ hypernuclei : *Future* Measurements



Small CSB

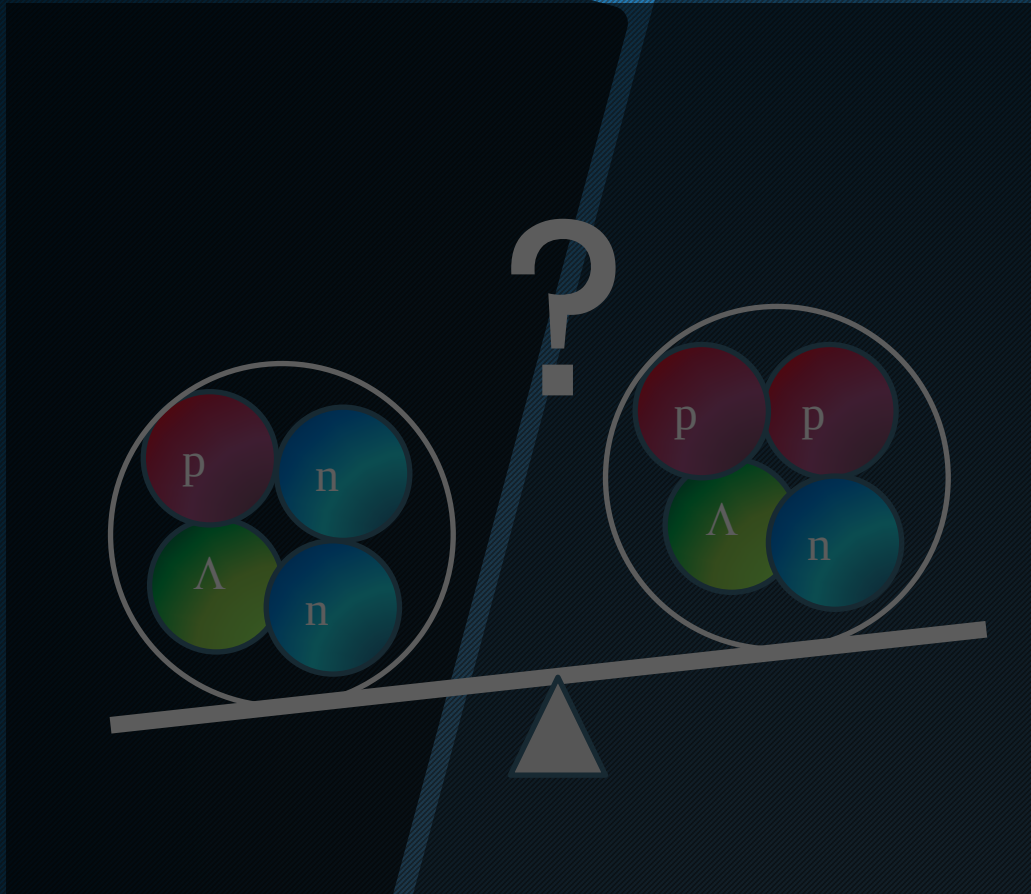
Large CSB



$\Lambda\text{N}-\Sigma\text{N}$ coupling
is a key

Recent

Mysteries in Hypernuclear Physics



Hyperon Puzzle

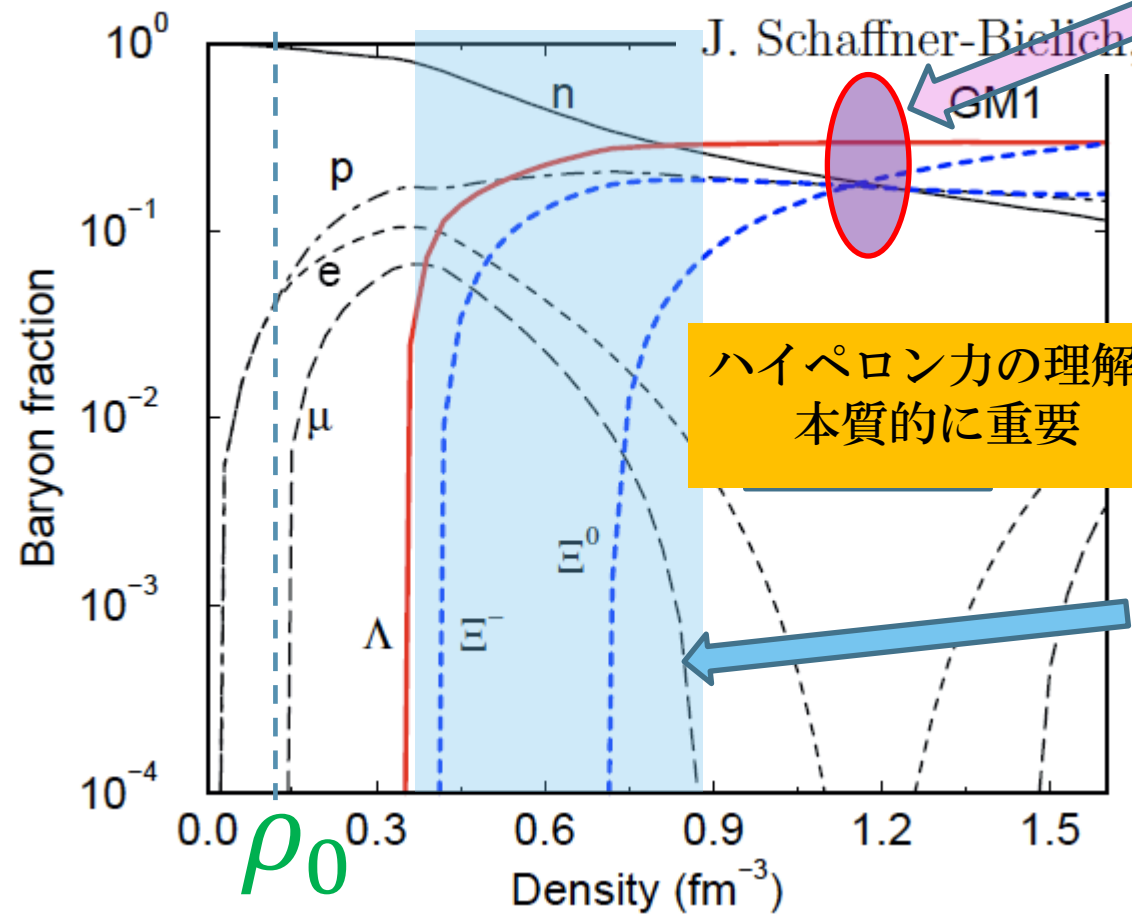


Two solar mass neutron stars

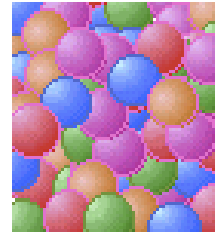
中性子星内部の理解は不十分！

対称核物質：クーロン力が障害

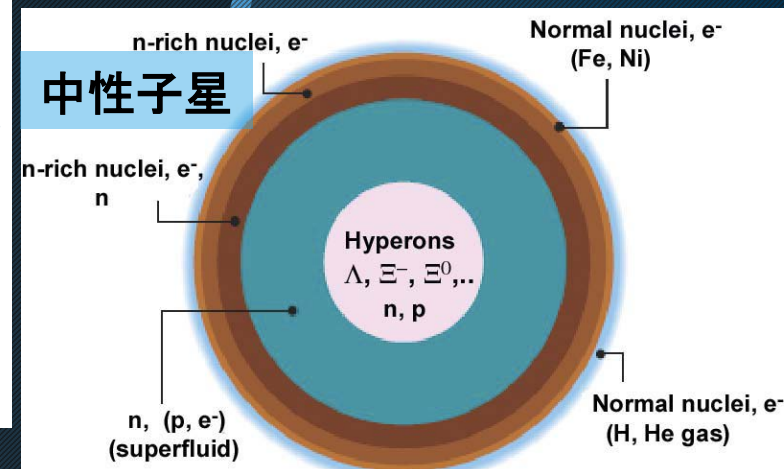
非対称核物質：中性子星



$N_u \sim N_d \sim N_s$

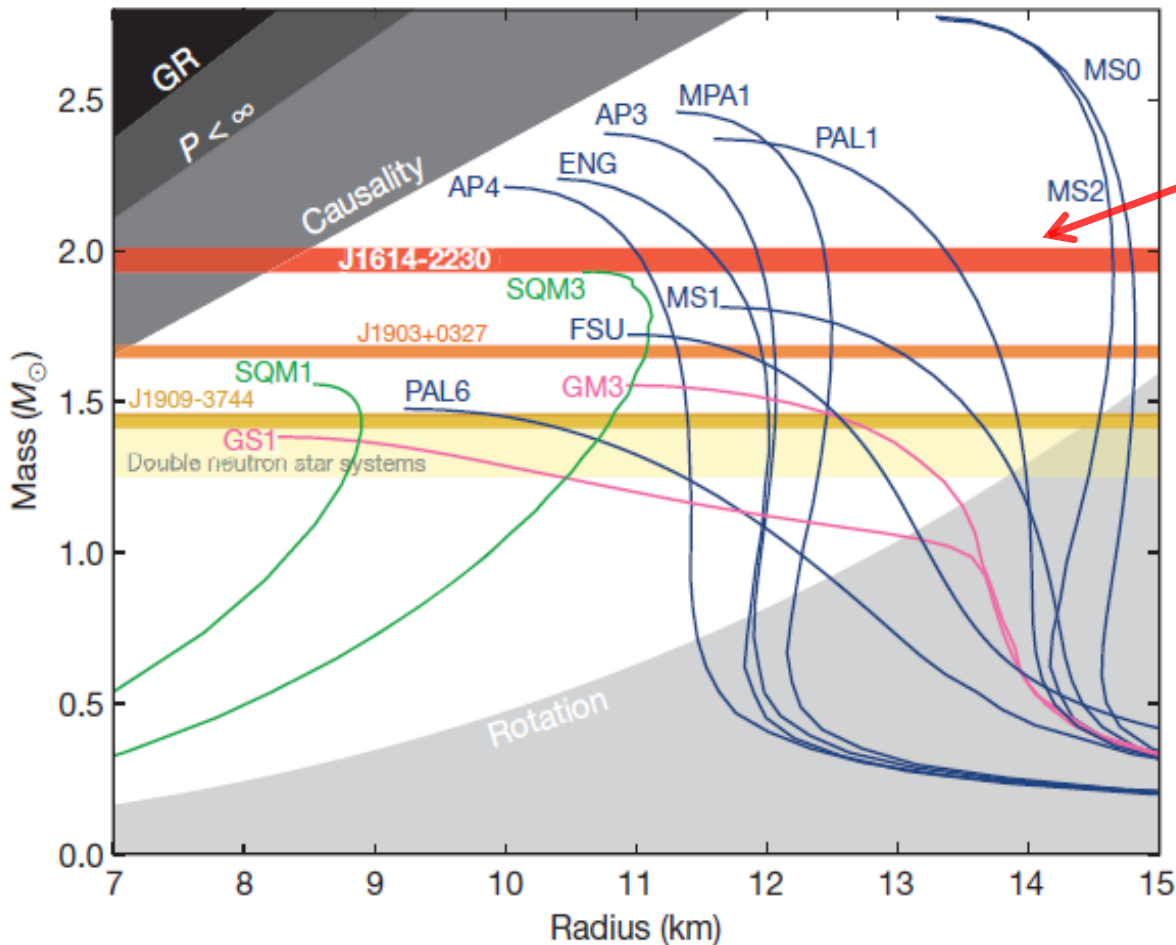


$p, n, \Lambda, \Xi^0, \Xi^-$



Hyperon Puzzle 核物理の最重要課題の一つ

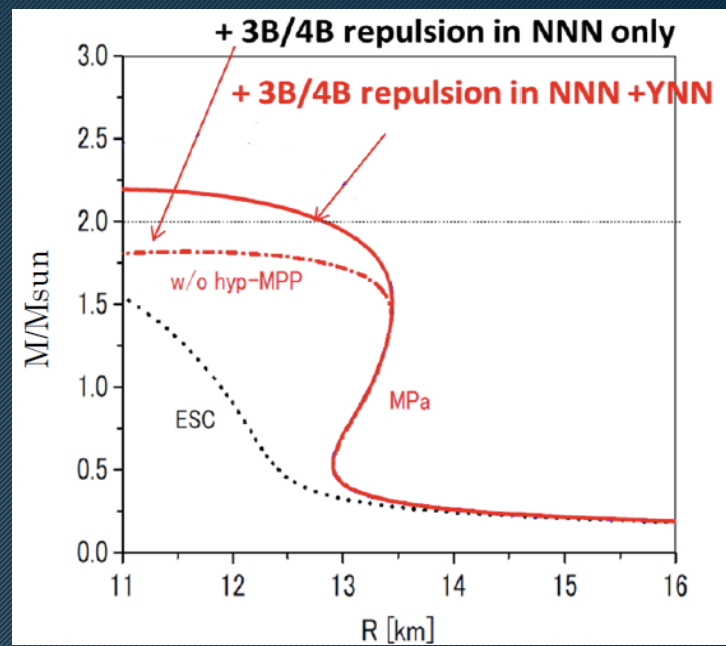
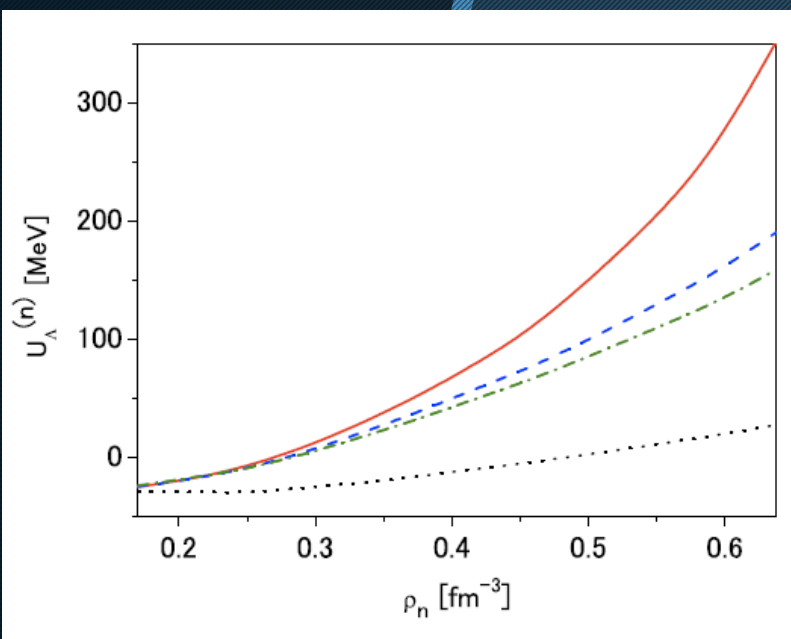
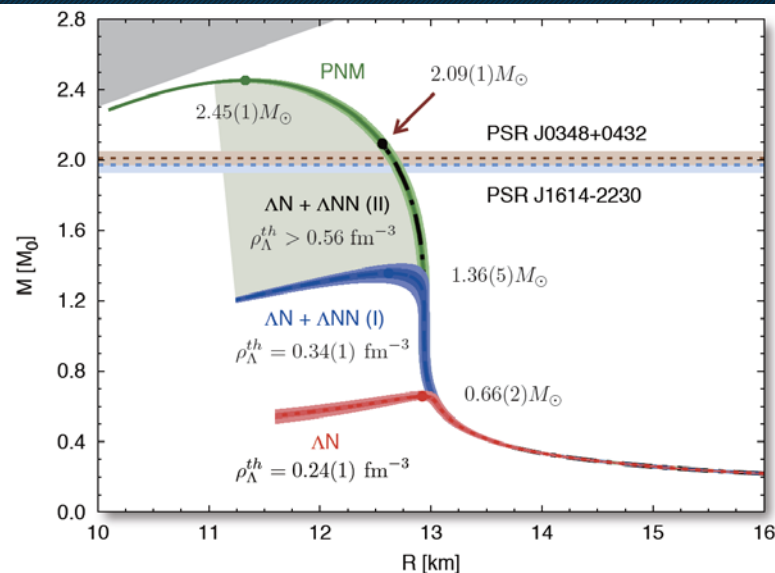
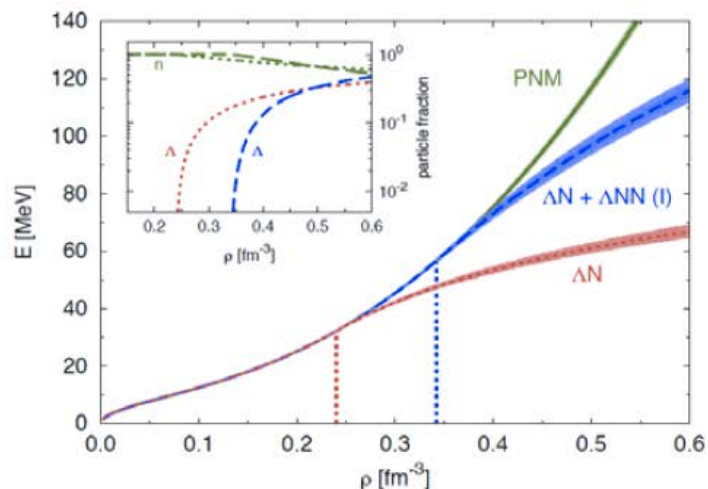
現在の我々の知識（原子核＋ハイパー核）：
高密度（ $\rho=2\sim 3\rho_0$ ）でハイペロンが発生しなくてはならない



$2 M_{\text{solar}}$ 質量中性子星

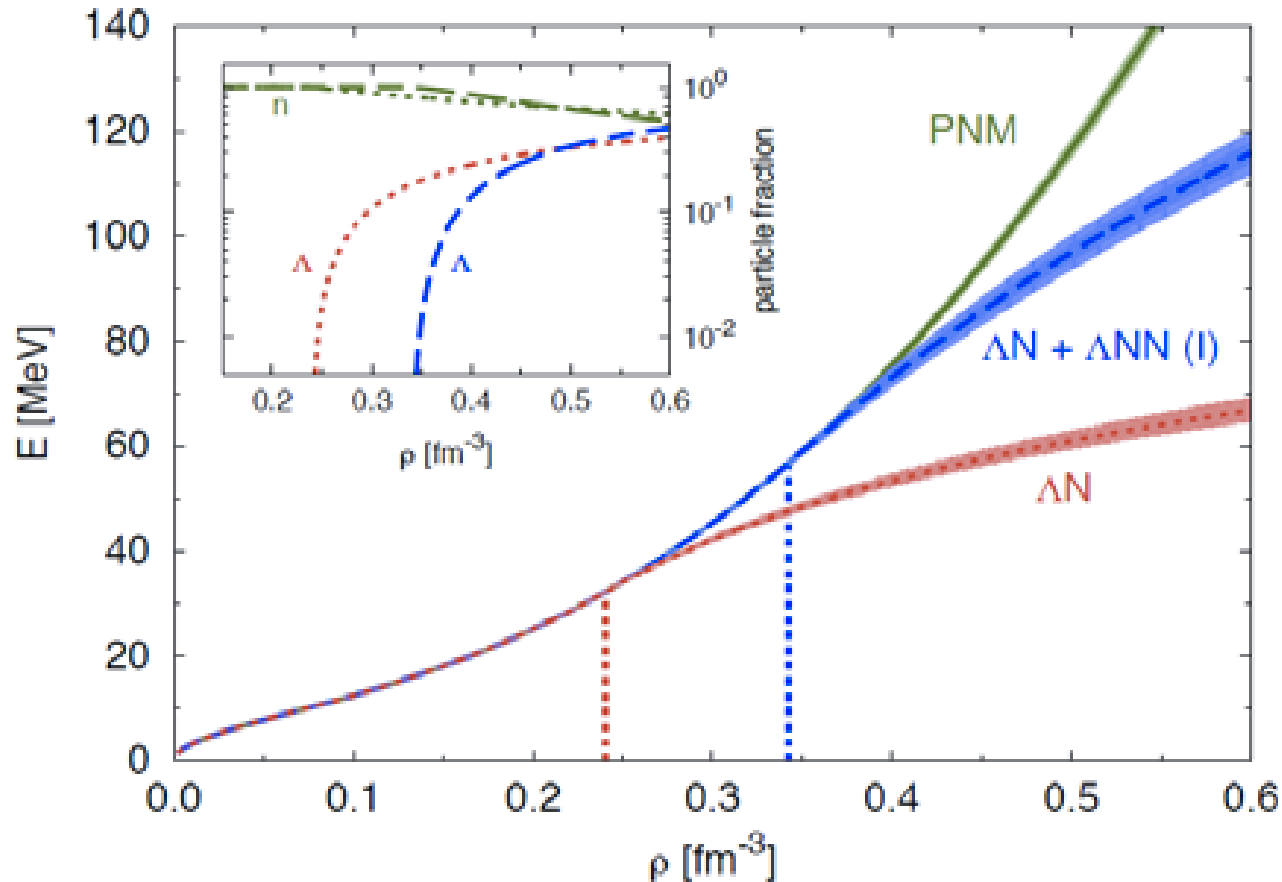
重大な知識の欠陥が露呈
Soft すぎる EOS

AFDMC by Lonardoni et al. PRL 114 (2015) 092301, updated (2016)



ESC08c + 3B/4B RF : G-Matrix Calc. by Yamamoto et al., PRC 90 (2014) 045805.

NS EOS with hyperon and 3BRF

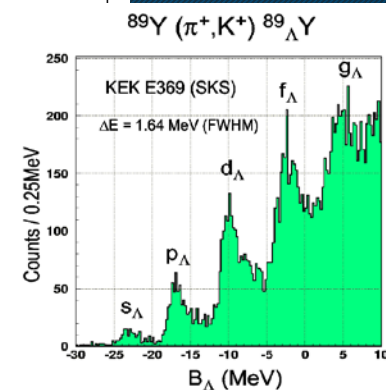
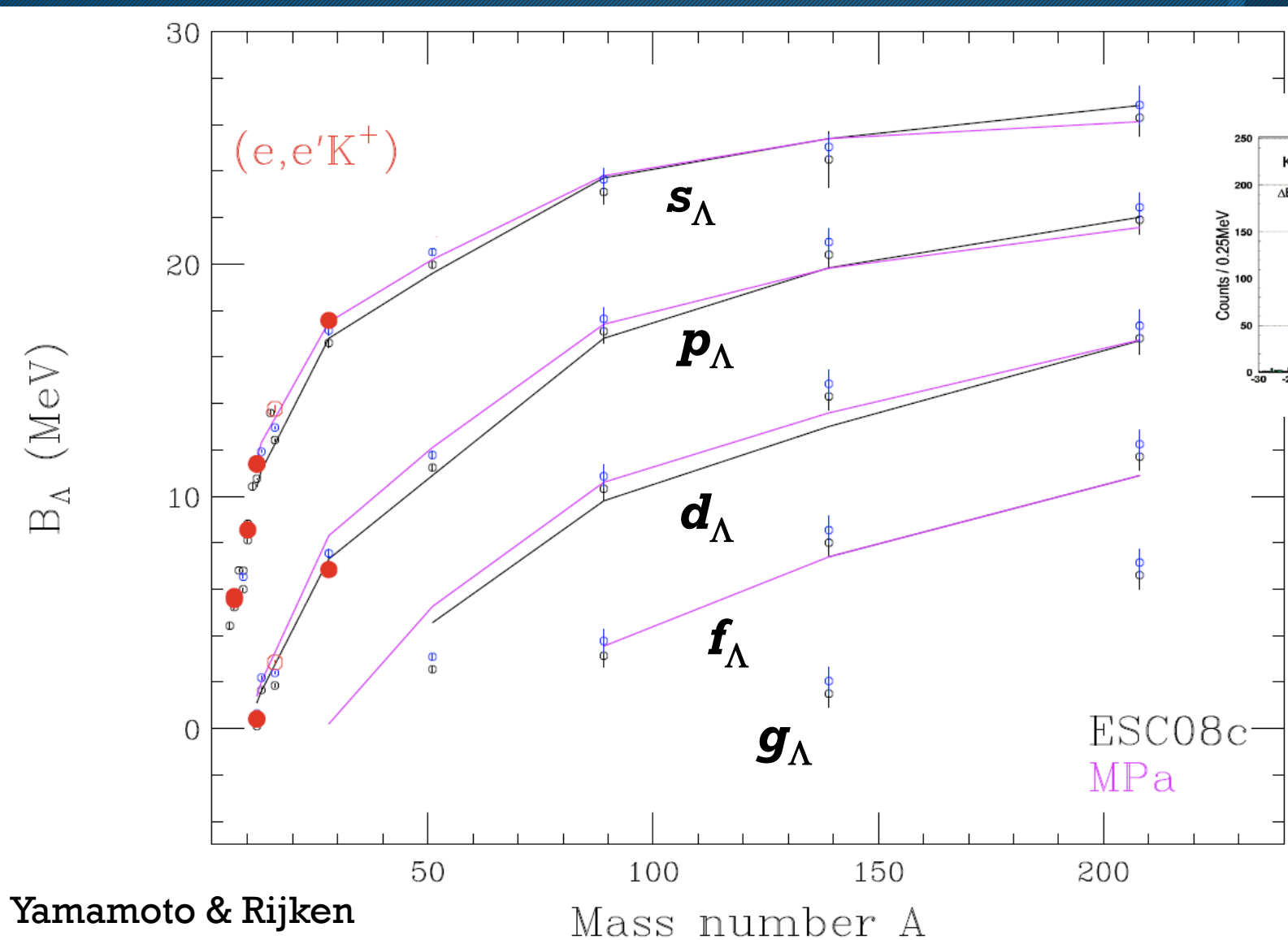


PNM

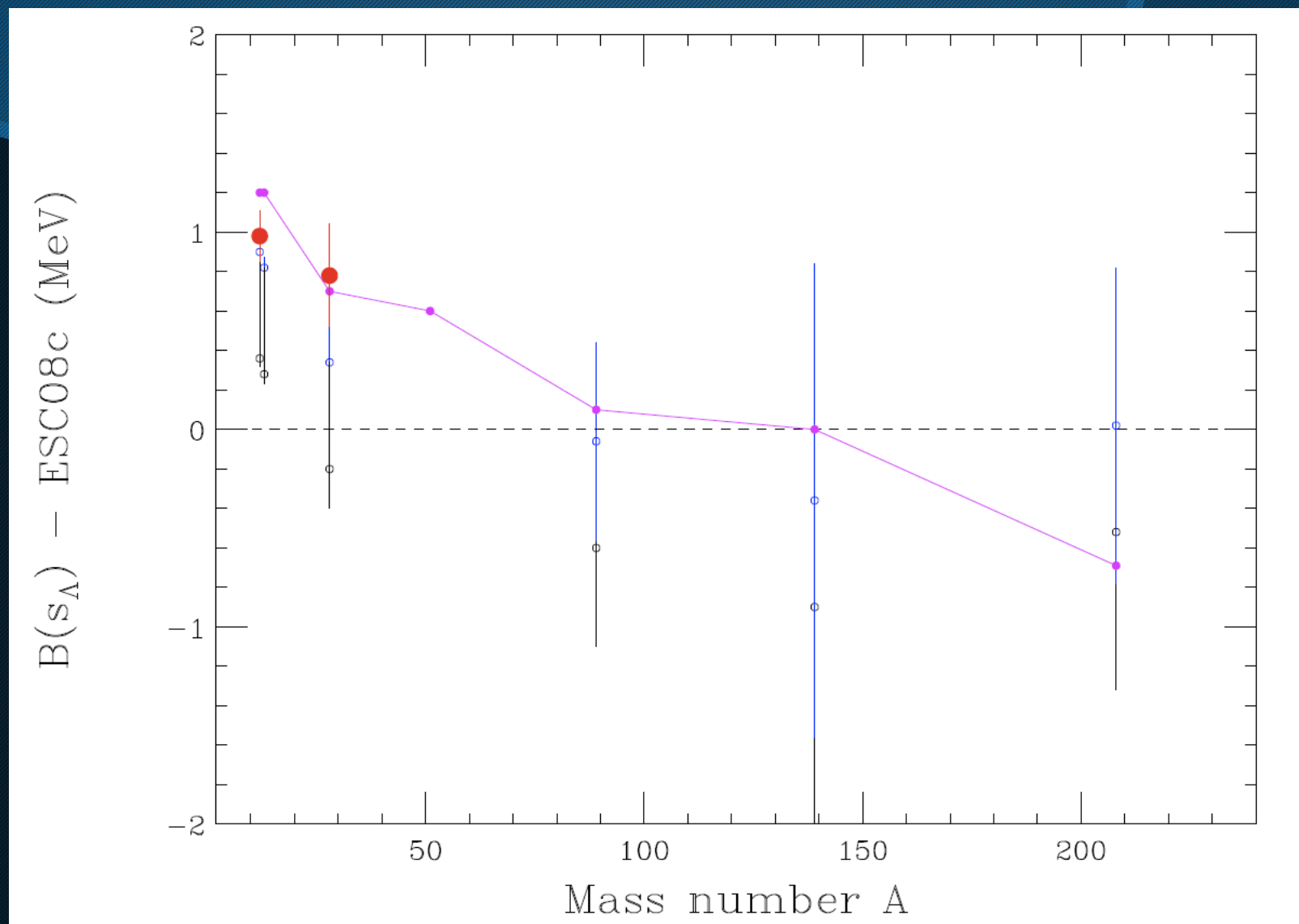
With 3BRF
recover stiffness

With Hyperon
too Soft

ハイパー核 B_Λ 測定実験結果と理論予想

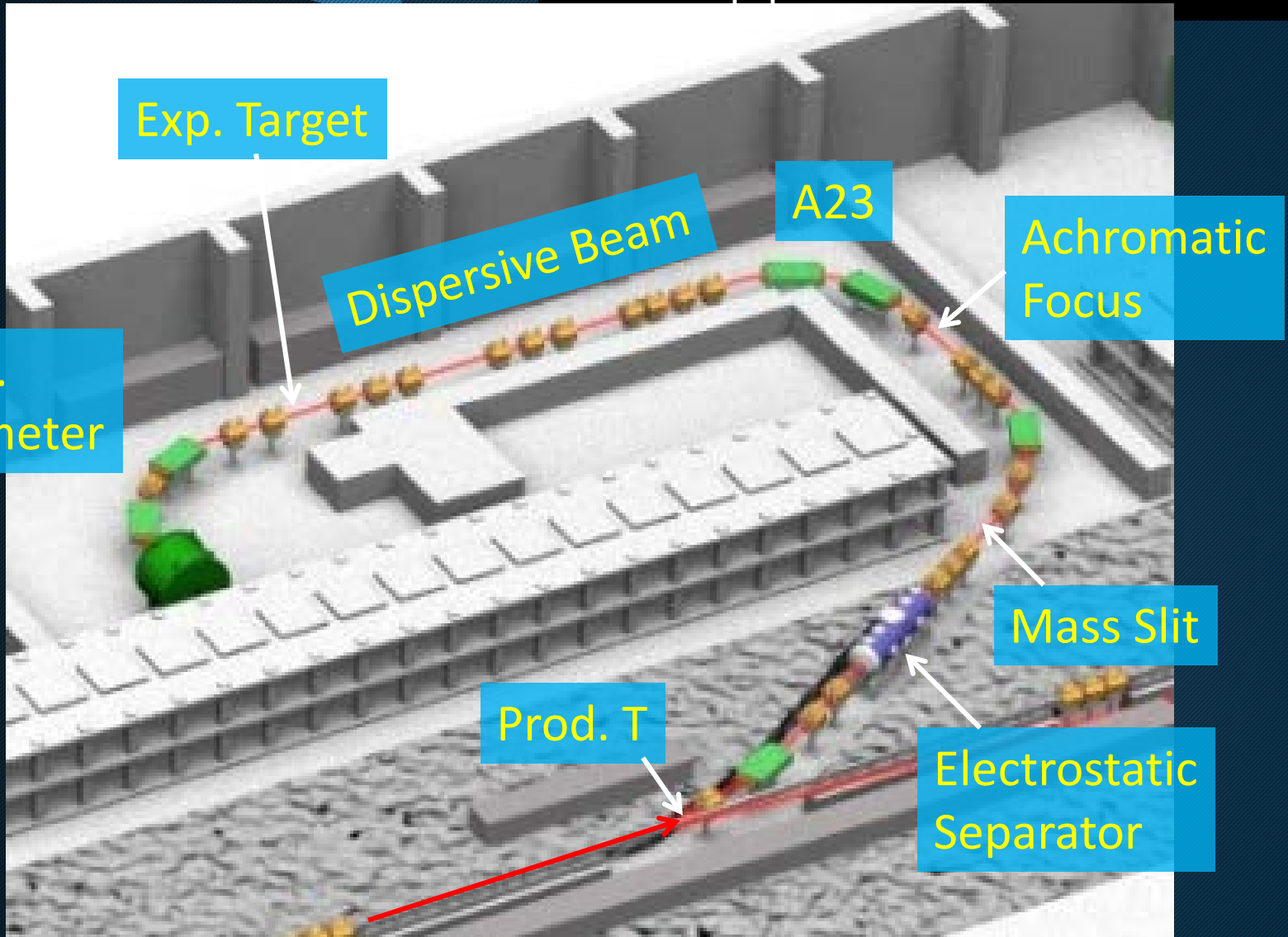


ハイパー核 B_{Λ} の実験結果と理論予想

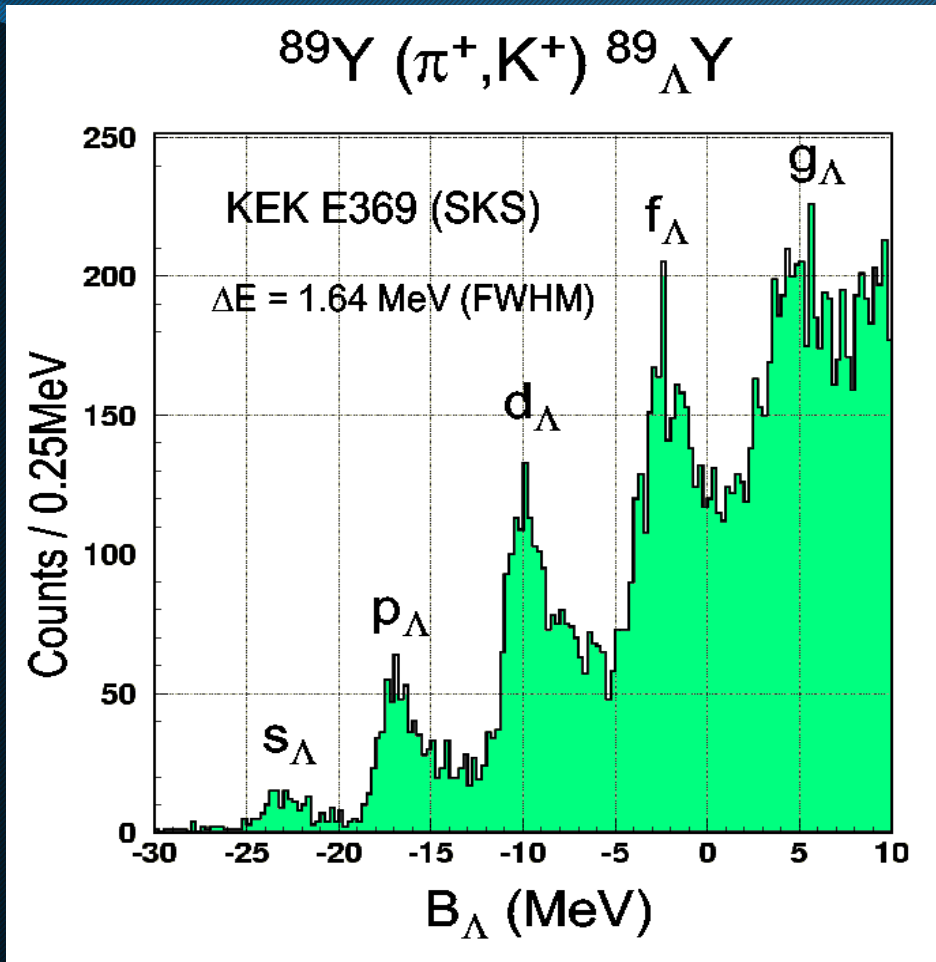


HIHR Line J-PARC ExHH

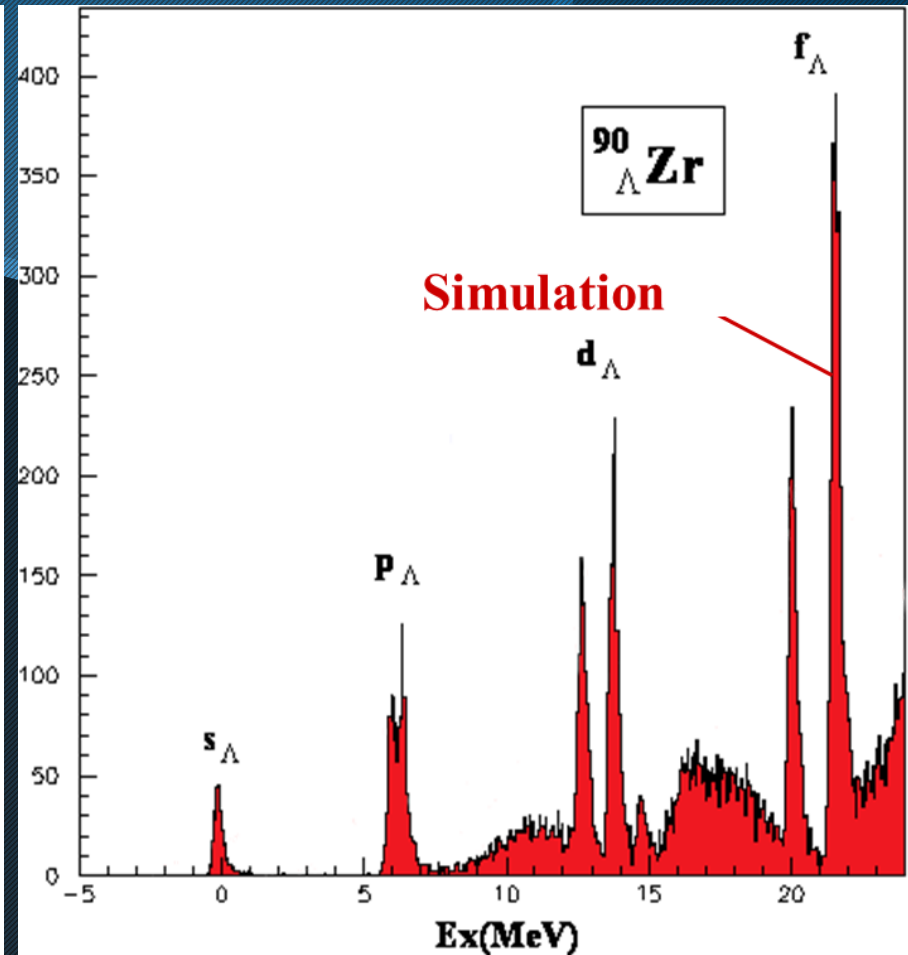
Intensity: $\sim 1.8 \times 10^8$ pion/pulse
(1.2 GeV/c, 58m, 1.4 msr*%,
100kW, 6s spill, Pt 60mm)
 $\Delta p/p \sim 1/10000$



Spectra of B_Λ with π beams KEK-PS K6 vs. Future J-PARC HIHR

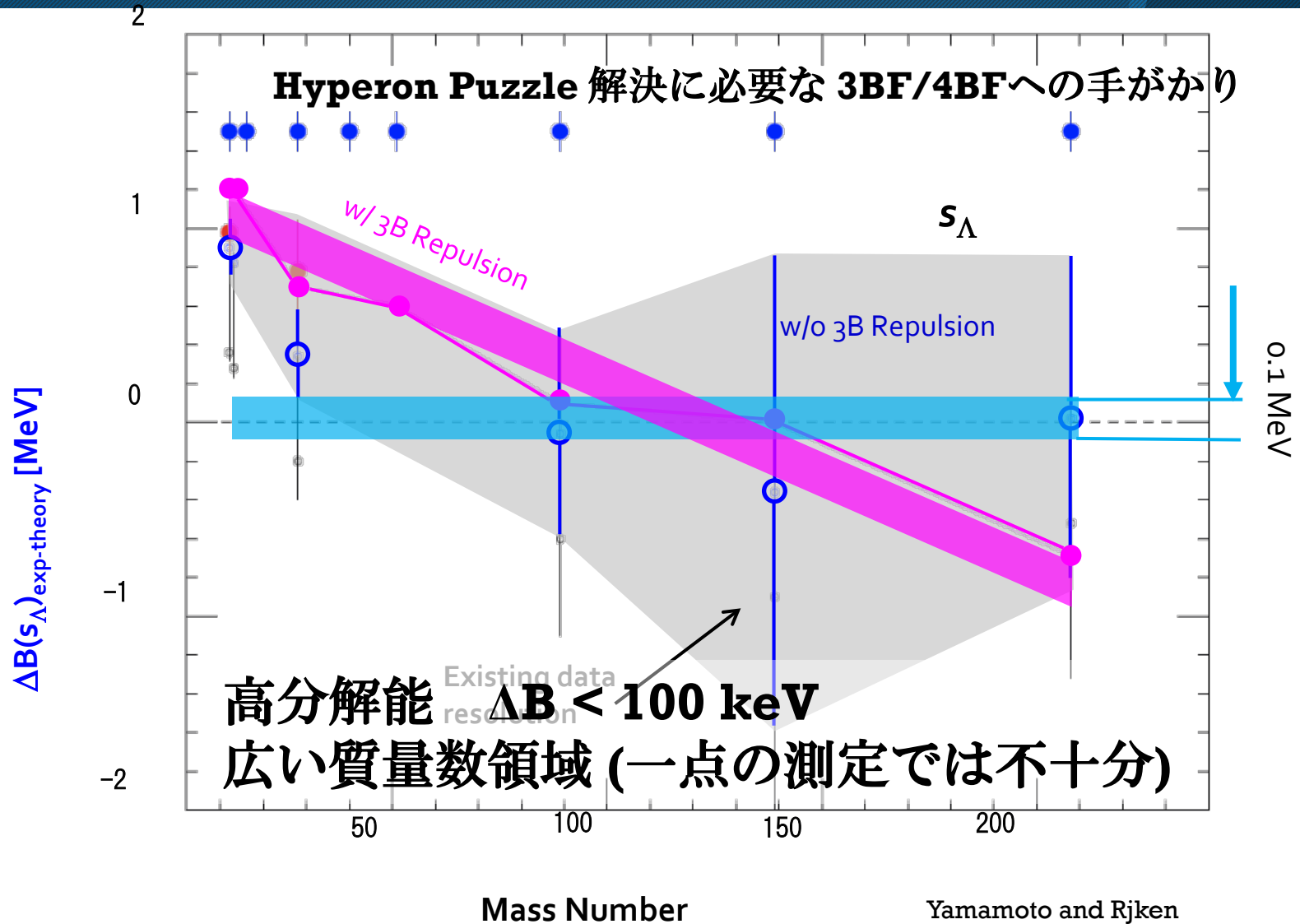


KEK-PS E369 (SKS)

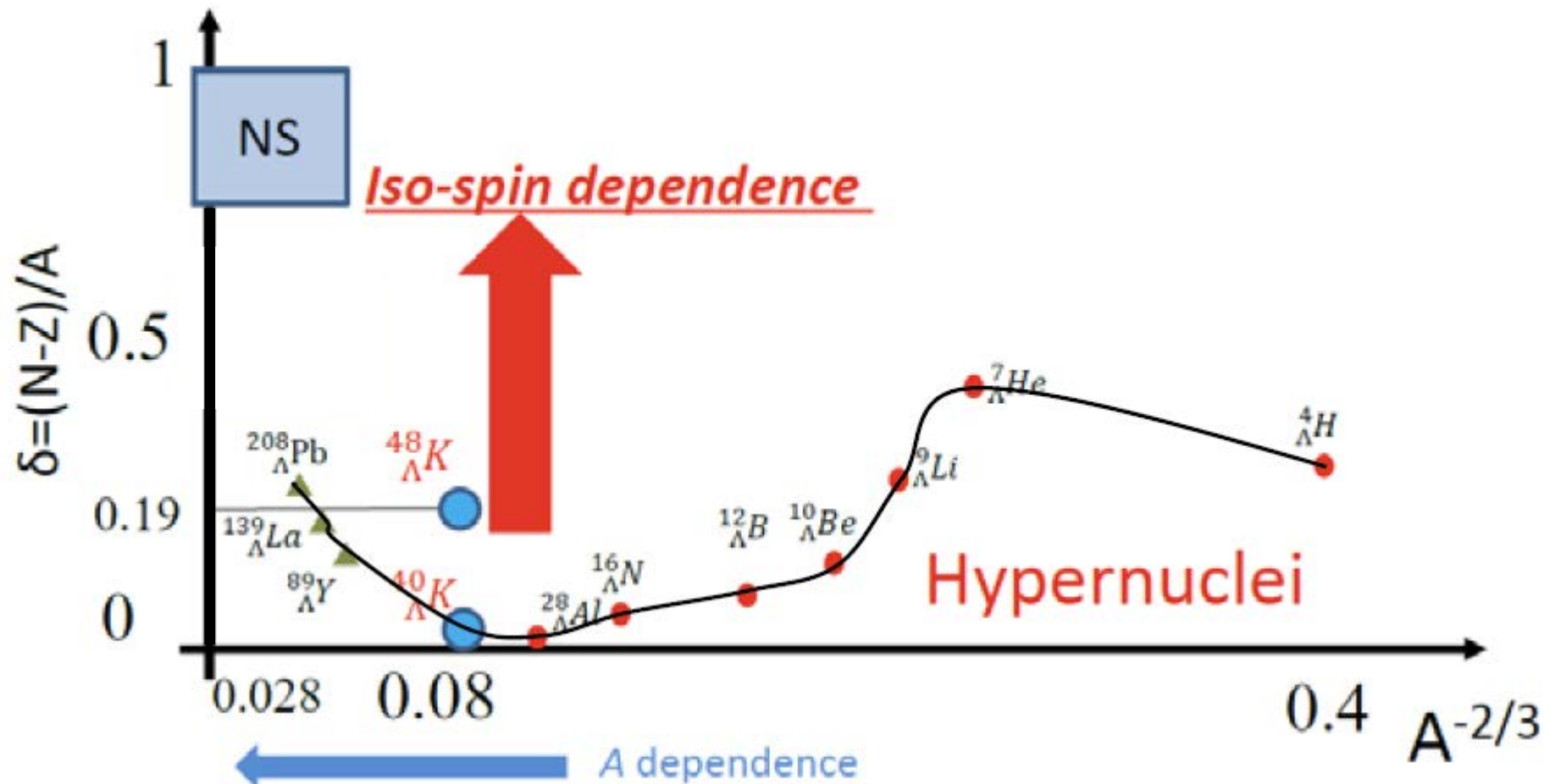


Expected Spectrum for J-PARC ExHD

ハイパー核 B_Λ の実験結果と理論予想



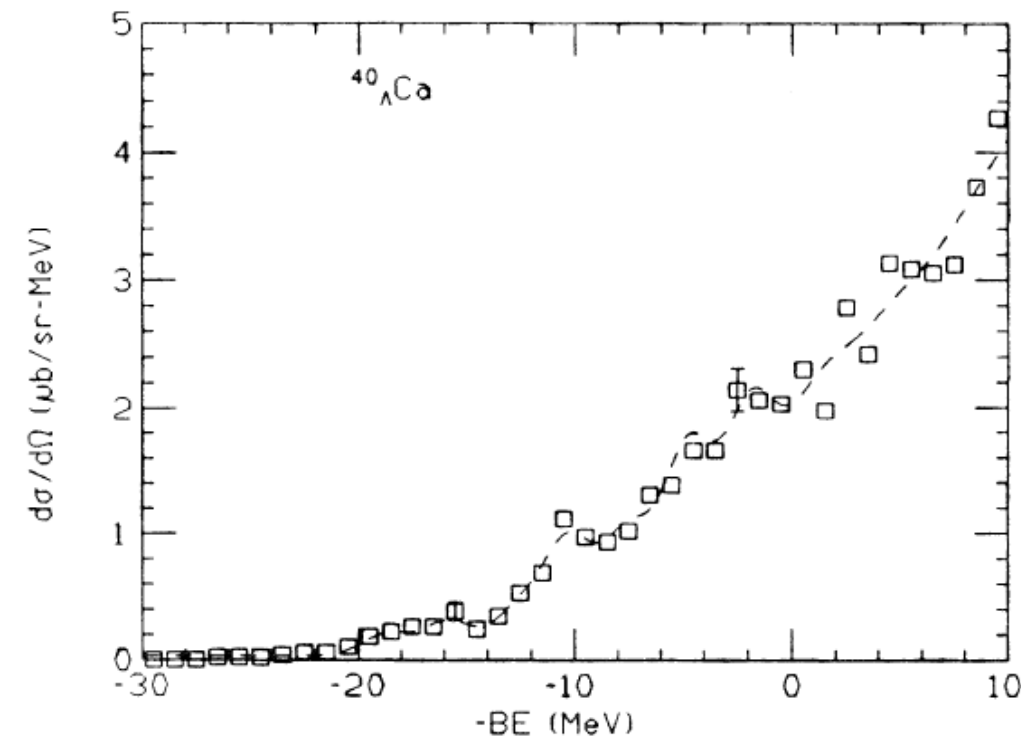
NS EOS with hyperon and 3BRF



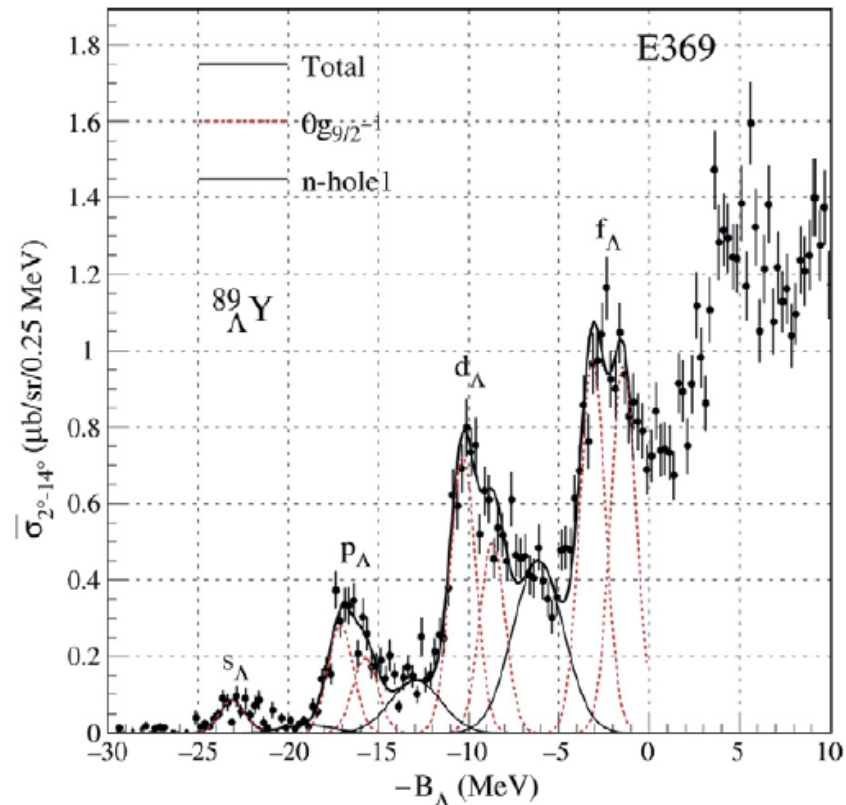
Key issues : A Dependence
Iso-spin Dependence of 3BRF

So far, NO experimental inputs for iso-spin dependence in mid-heavy HY

Mid-heavy data from ($\pi, \mathbf{K}$) exp.

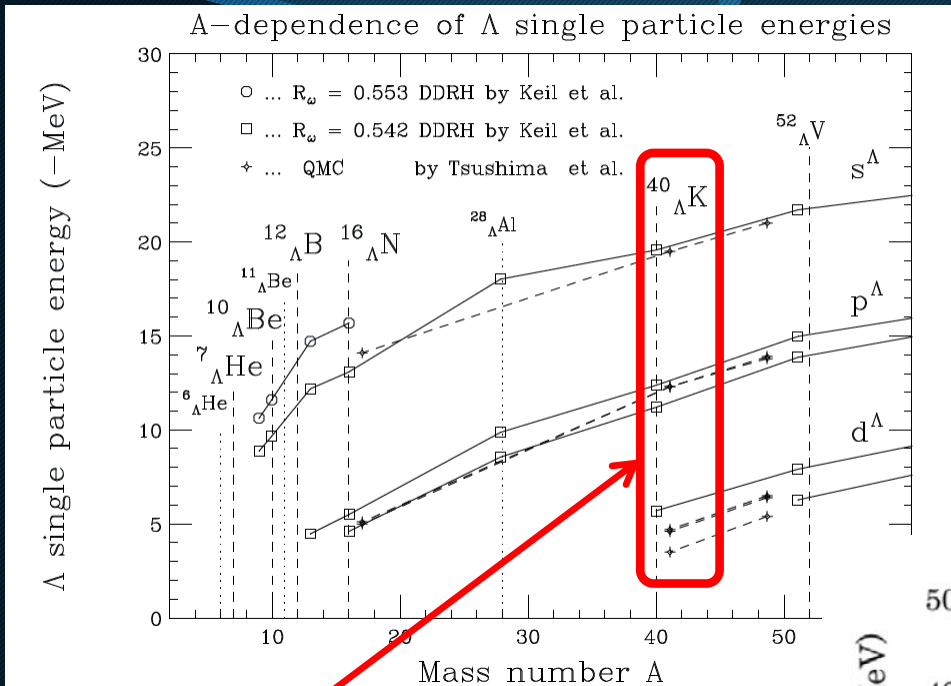


P.H.Pile et al. PRL 20 (1991) 2585.



H.Hotchi et al. PRC 64 (2001) 044302.

Ca (e,e'K⁺) Λ K

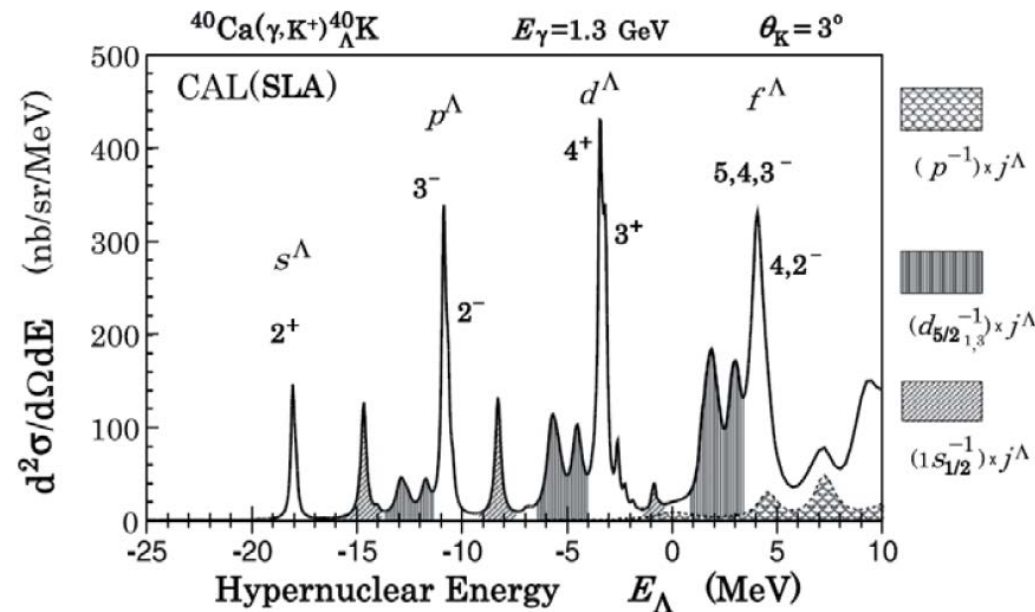


Missing in (e,e'K) data
Complete A dependence of
 Λ S.P. Energy

Clean Spectrum

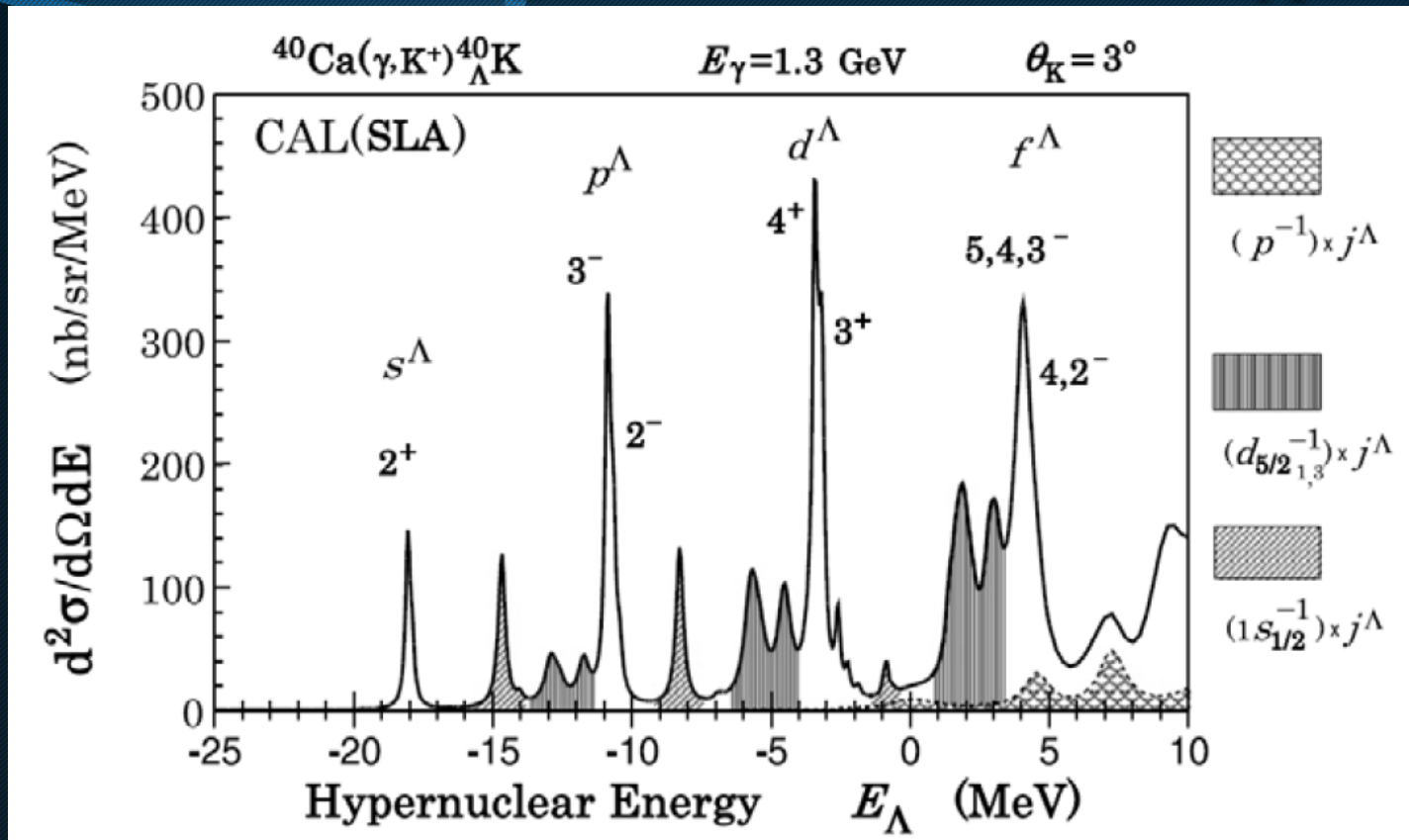
P. Bydzovsky et al. NPA881 (2012)199.

Doubly LS closed ^{40}Ca target



isotope effect of core nuclei: ^{40}Ca , ^{48}Ca targets

Expected spectrum for $^{40}_{\Lambda}\text{K}$



0.3 MeV (FWHM) resolution assumed.

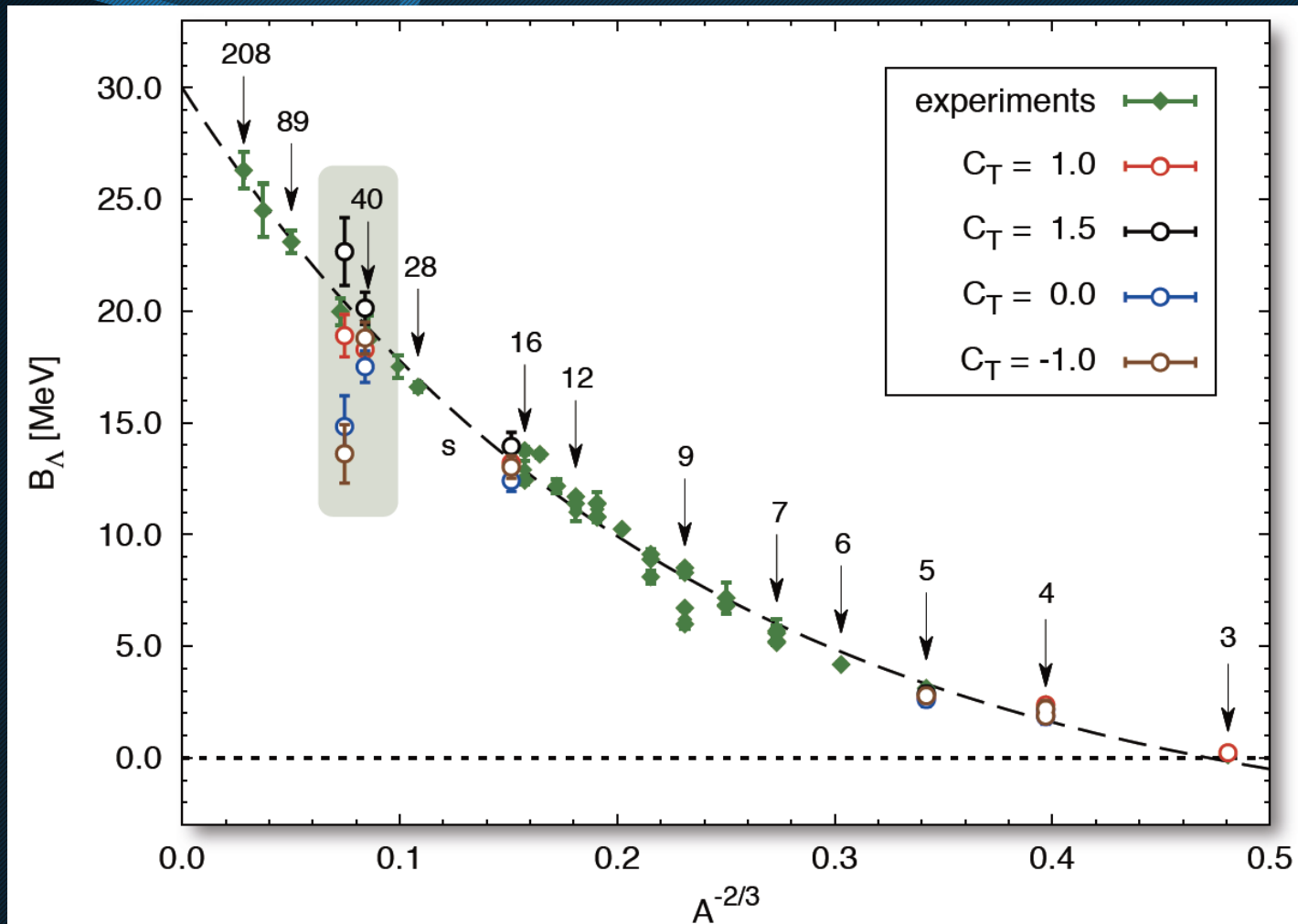
P. Bydzovski et al. NPA881 (2012) 199.

$(e, e' K^+)$ reaction

Reliable absolute energy calibration.
Excellent energy resolution.

<100 keV accuracy
Determination of B_{Λ}

$\Lambda_{nn}/\Lambda_{np}$ dependence of B_Λ



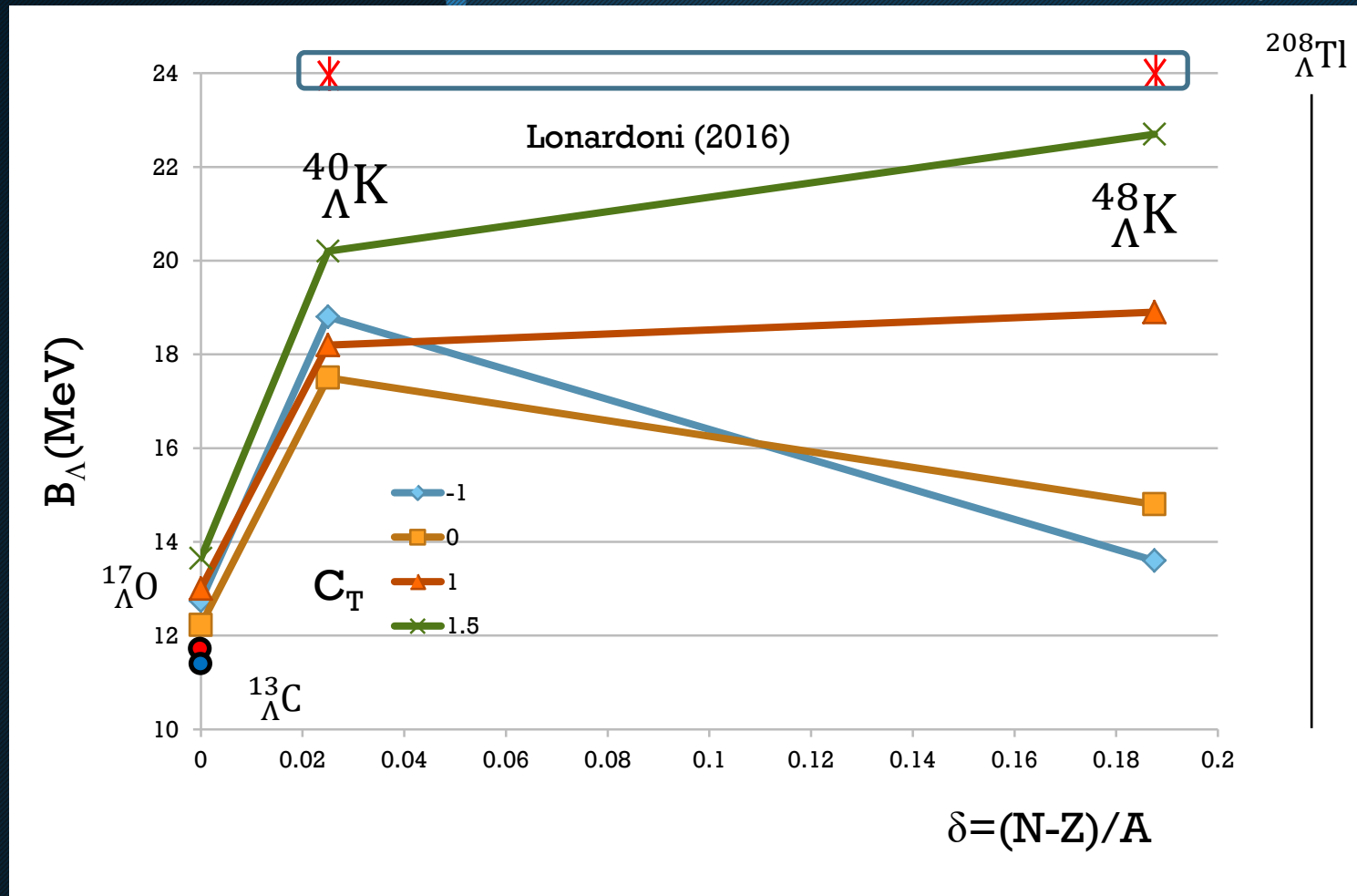
Introduced ΛNN potential

$$\tau_i \cdot \tau_j = -3p^{T=0} + C_T p^{T=1}$$

C_T gauges strength and sign of Λ_{nn} to Λ_{np} 3B force.

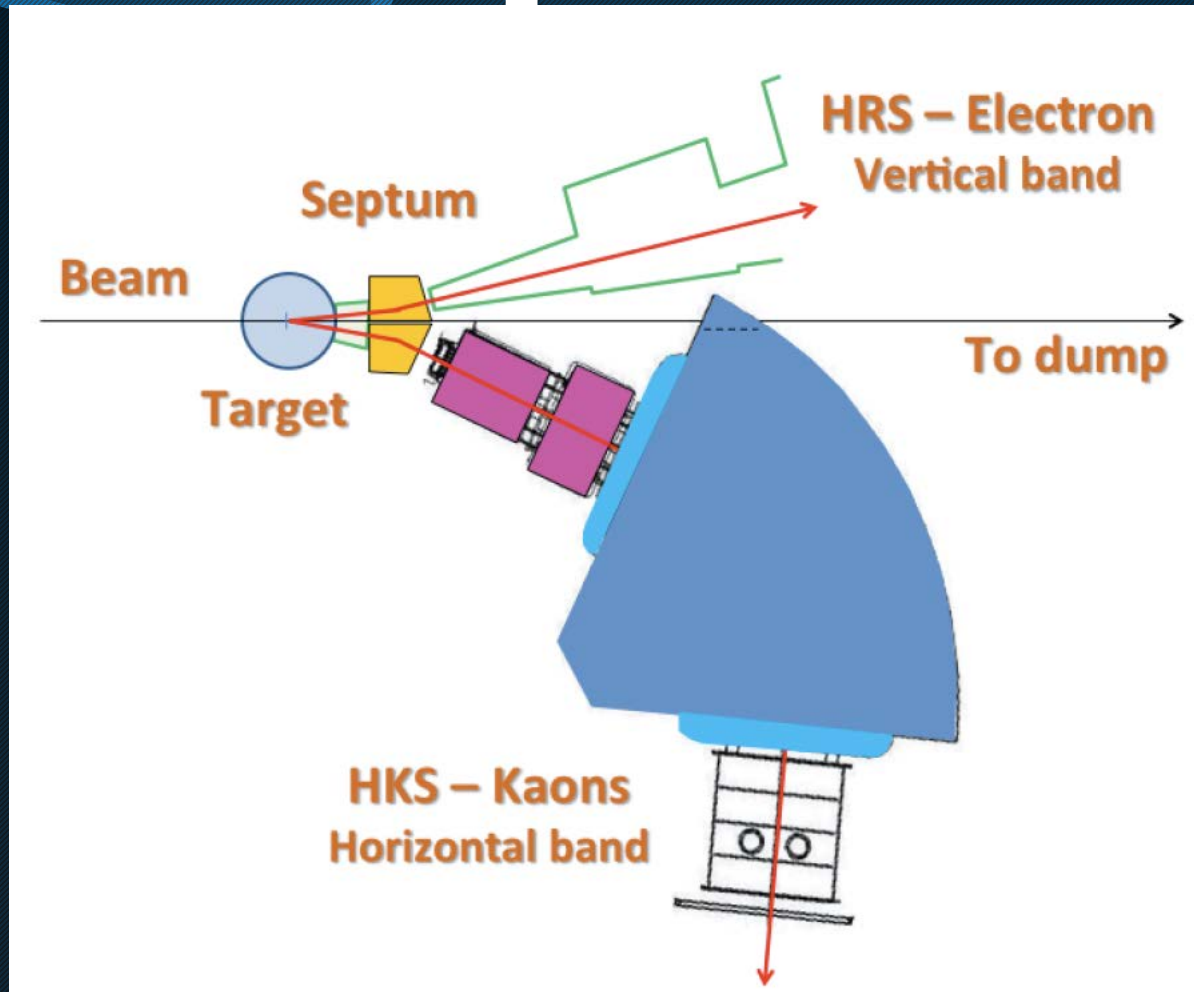
$\Lambda_{nn}/\Lambda_{np}$ dependence of B_Λ

Could be determined with an accuracy of $<100\text{keV}$ at JLab



Proposed Setup

E12-15-008



$K(\text{HKS}) \times \text{HRS} (e')$

Only JLab : Beam + Spectrometers for $(e, e'K^+)$

中重～重ハイパー核分光実験

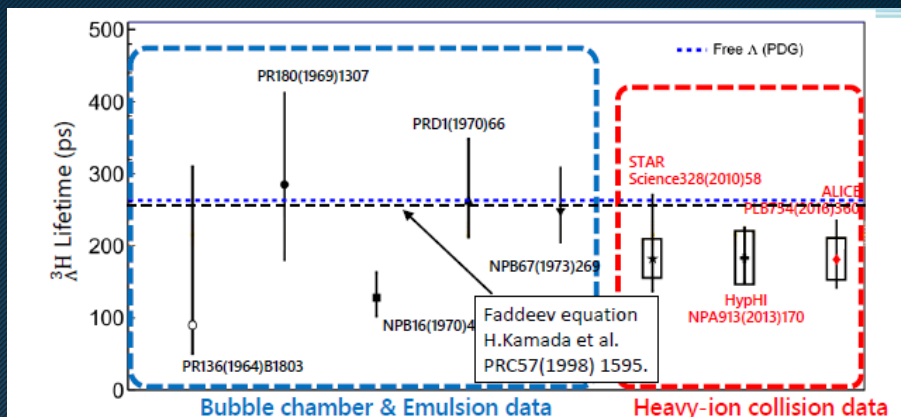
Ca targets : 二重閉殻 ^{40}Ca ^{48}Ca

高密度核物質の理解のためには
ハイペロン物質の理解が必要 (広質量域 $^{40}_{\Lambda}\text{K} \sim ^{208}_{\Lambda}\text{Tl}$)

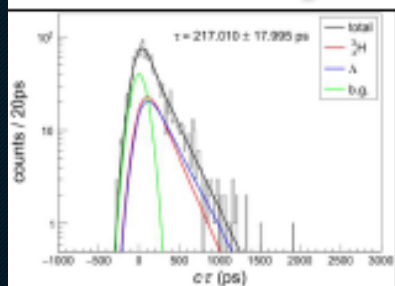
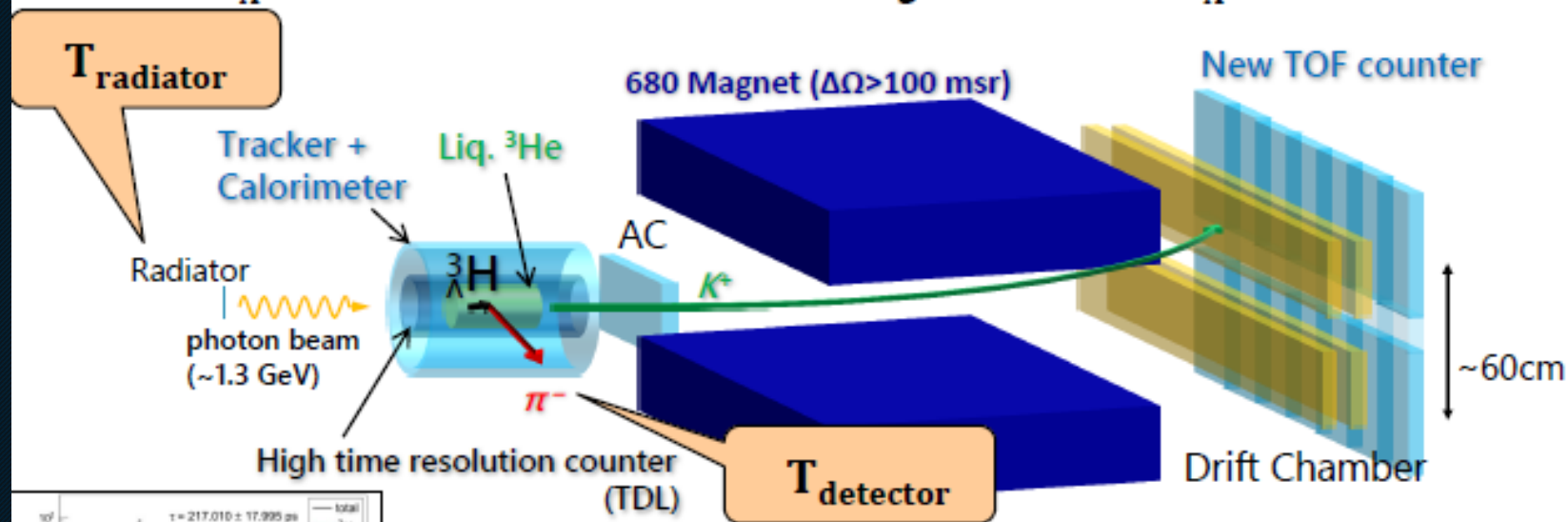
Systematic study of Λ SPE with <100 keV accuracy

アイソスピン依存性のデータは軽いハイパー核のみ
JLab E12-15-008 で $^{40}_{\Lambda}\text{K}$, $^{48}_{\Lambda}\text{K}$ を測定する。

$^3_\Lambda\text{H}$ 寿命測定実験



$^3_\Lambda\text{H}$ lifetime measurement detecting π^- time from $^3_\Lambda\text{H} \rightarrow \pi^- + ^3\text{He}$



500 H3L events in 2.5 month

Good timing resolution detector is necessary.
Suppression of e^+e^- events is important.

今後の展開と全体のSummary

JLab

Established ($e, e'K^+$)

$\Lambda, \Sigma^0, {}^7_\Lambda\text{He}, {}^9_\Lambda\text{B}, {}^{10}_\Lambda\text{Be}, {}^{12}_\Lambda\text{B}, {}^{16}_\Lambda\text{N}, {}^{28}_\Lambda\text{Al}, {}^{51}_\Lambda\text{V}$

New exp.
 ${}^{40}_\Lambda\text{K}, {}^{48}_\Lambda\text{K}$

Hyperon Puzzle
 ΛN CSB
other interesting topics

J-PARC

γ spectroscopy

New (π^+, K^+) @ HIHR

ELPH ΛN interaction
 ${}^4_\Lambda\text{H}$ lifetime

Mainz

Established decay π
 ${}^4_\Lambda\text{H}$

New exp.
 ${}^3_\Lambda\text{H}$

Other Facilities

GSI, FAIR, LHC, RHIC ...

Study of HY with HI beams

Complementary research at JLab, MAMI, ELPH and J-PARC
should progress in timely manner