Feb. 10, 2014
at Tokai

Experiments on Strangeness nuclear physics

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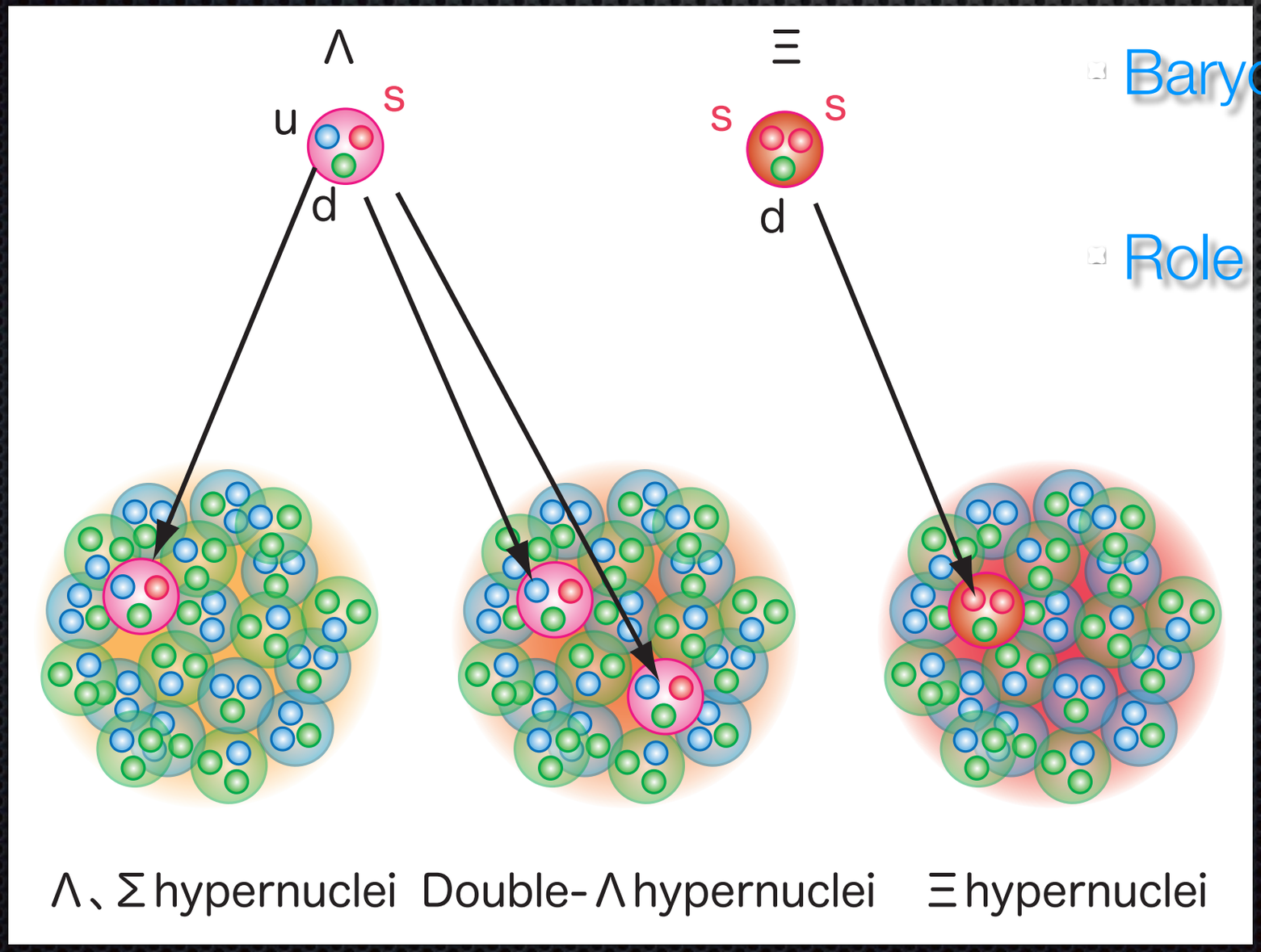
Kyoto University

Contents

- Introduction to Strangeness Nuclear Physics
- Hadronic Systems with Strangeness
  - S=-1 Baryon : Λ, Σ
  - S=-2 Baryon : Ξ
  - S=-1 Meson : K
- Summary

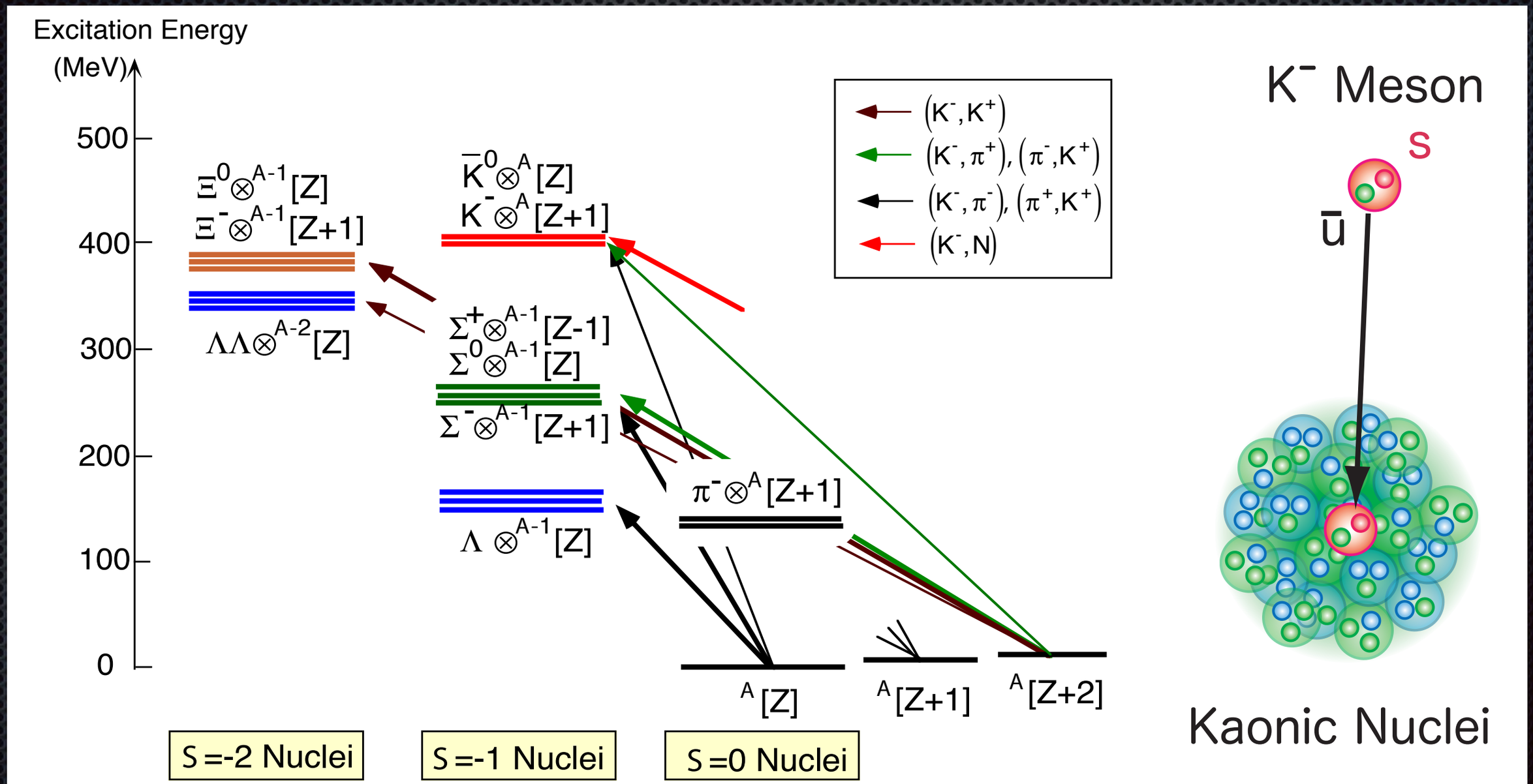
“Hypernuclei”

- Hadron Many-Body systems with Strangeness
- Hyperons(Λ, Σ, Ξ) in Nuclei

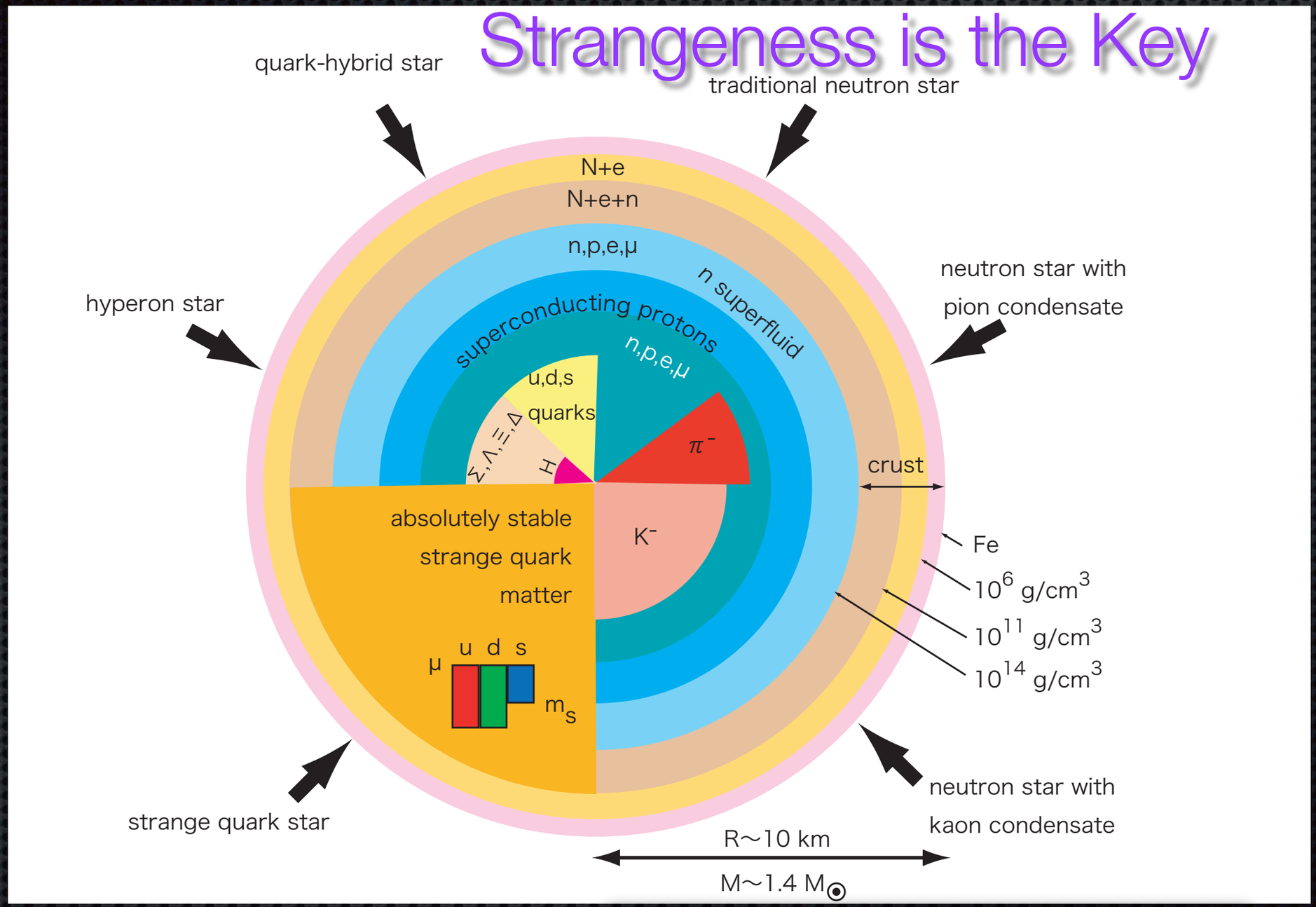


- Baryon-Baryon Interactions in $SU_F(3)$
- Role of Strangeness in Dense Matter

- Strange Mesons ($\bar{K}$, K) in nuclei



What's in the Neutron Star Core ?



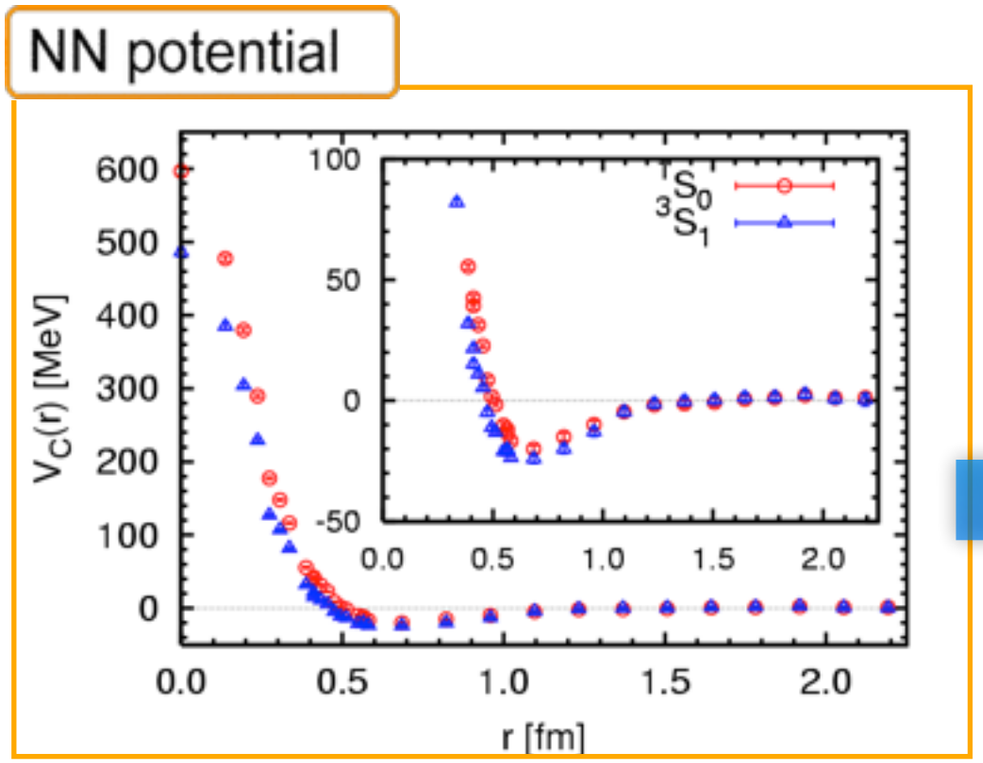
By F. Weber

- Chemical Potential:

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

Modern Picture of Baryon-Baryon Interactions

- Nuclear Force from Lattice QCD

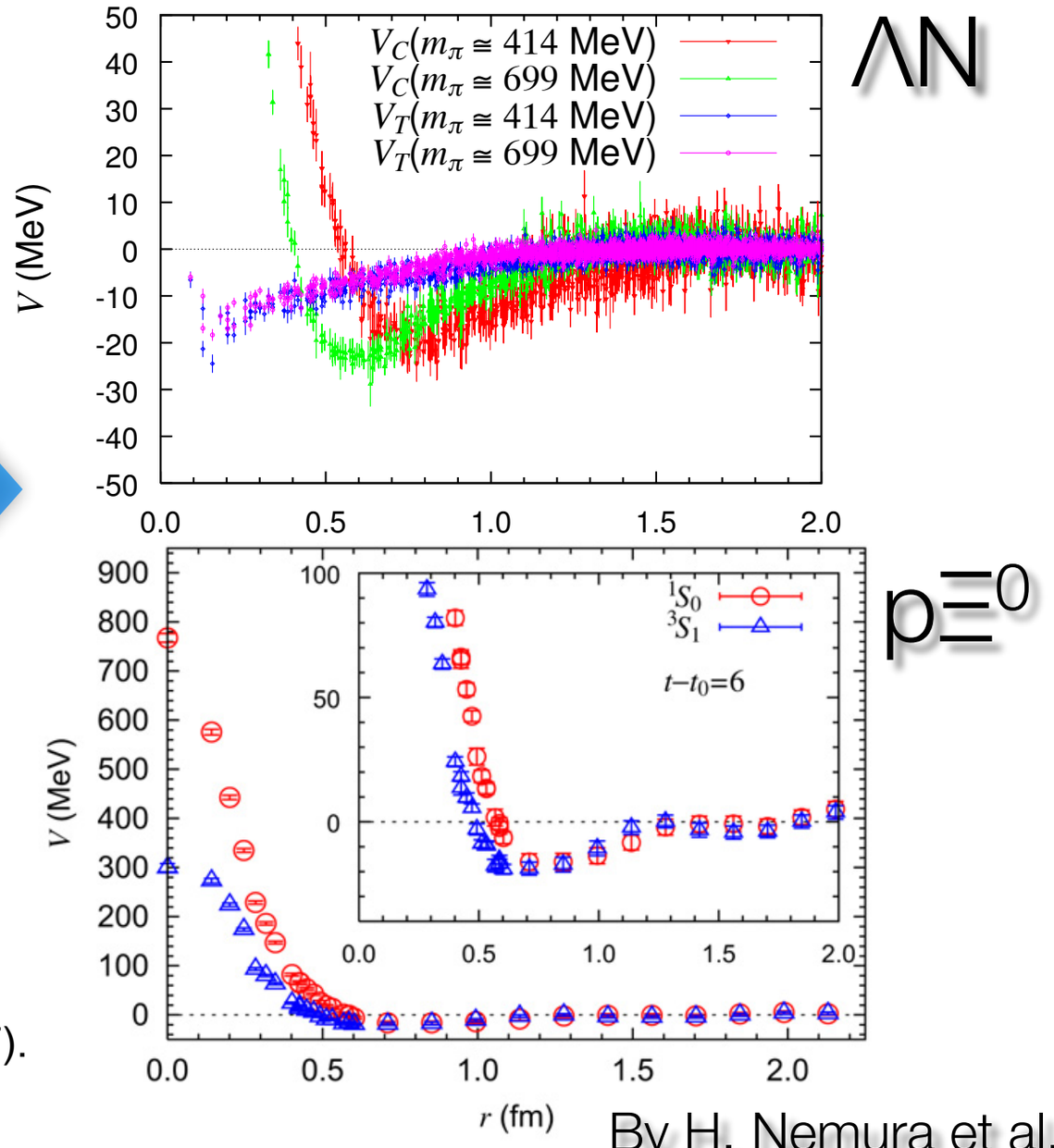


Long-range attraction

+

Repulsive Hard-core

N.Ishii, S.Aoki, T.Hatsuda, Phys.Rev.Lett.99,022001 (2007).



By H. Nemura et al.

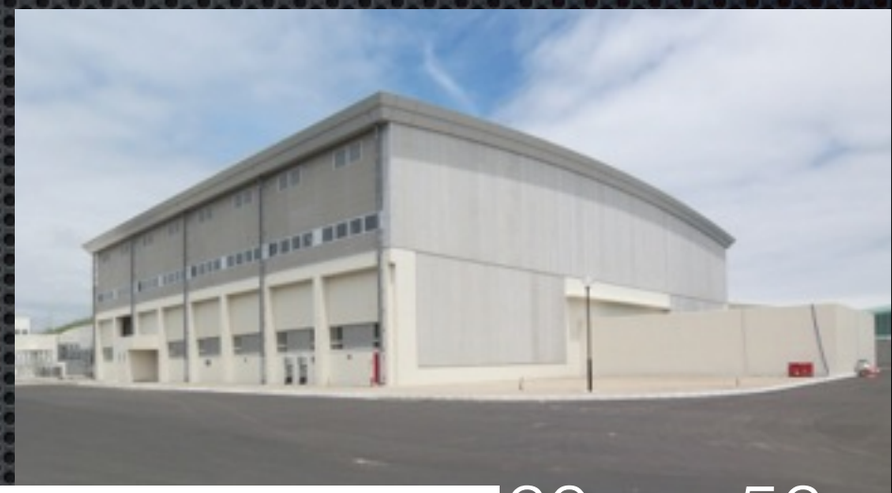
World Facilities in the 21st Century

For Strangeness Nuclear Physics

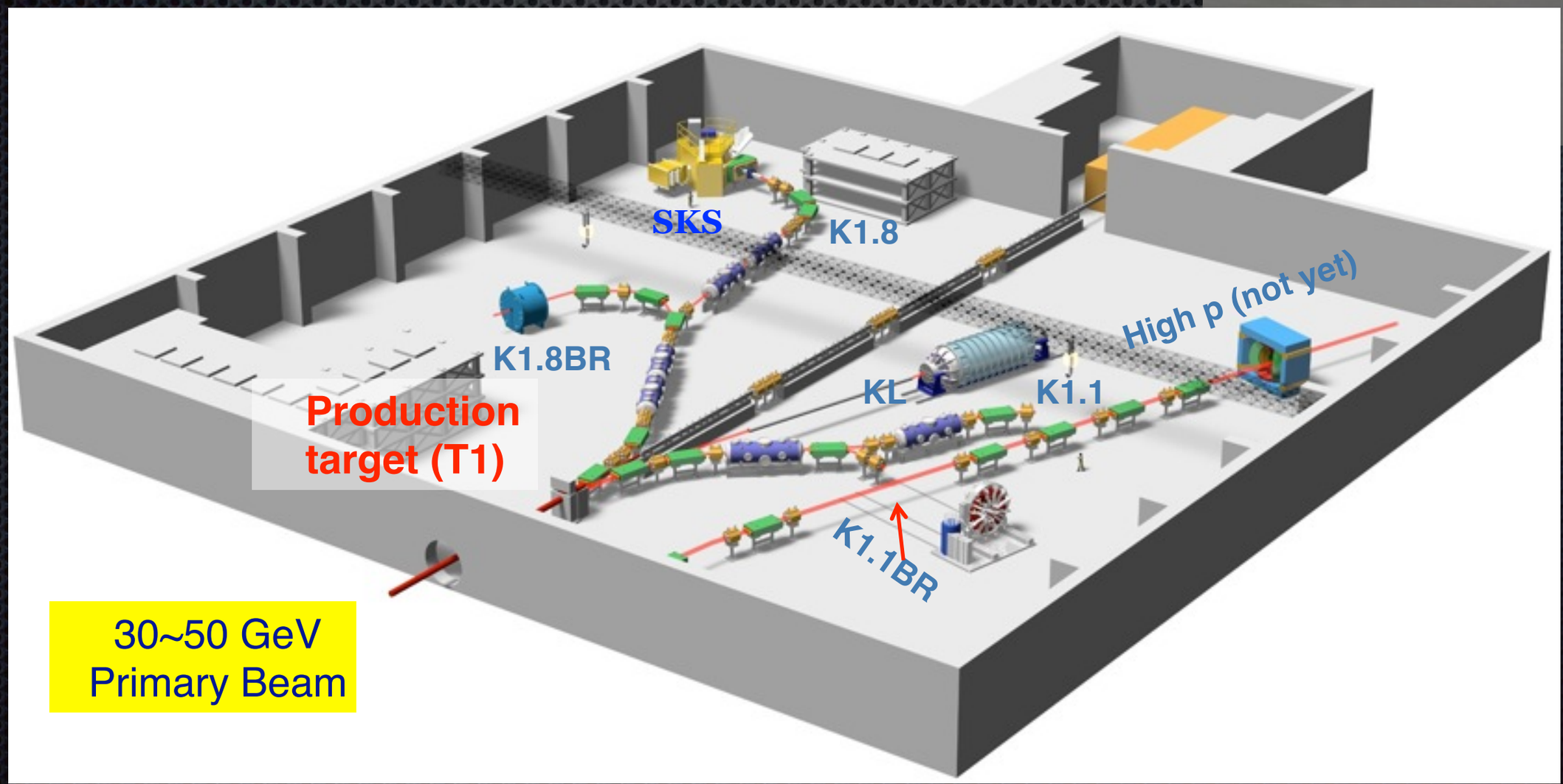
Hadron Experimental Hall

World highest intensity Kaon beams !

First beam in Feb. 2009

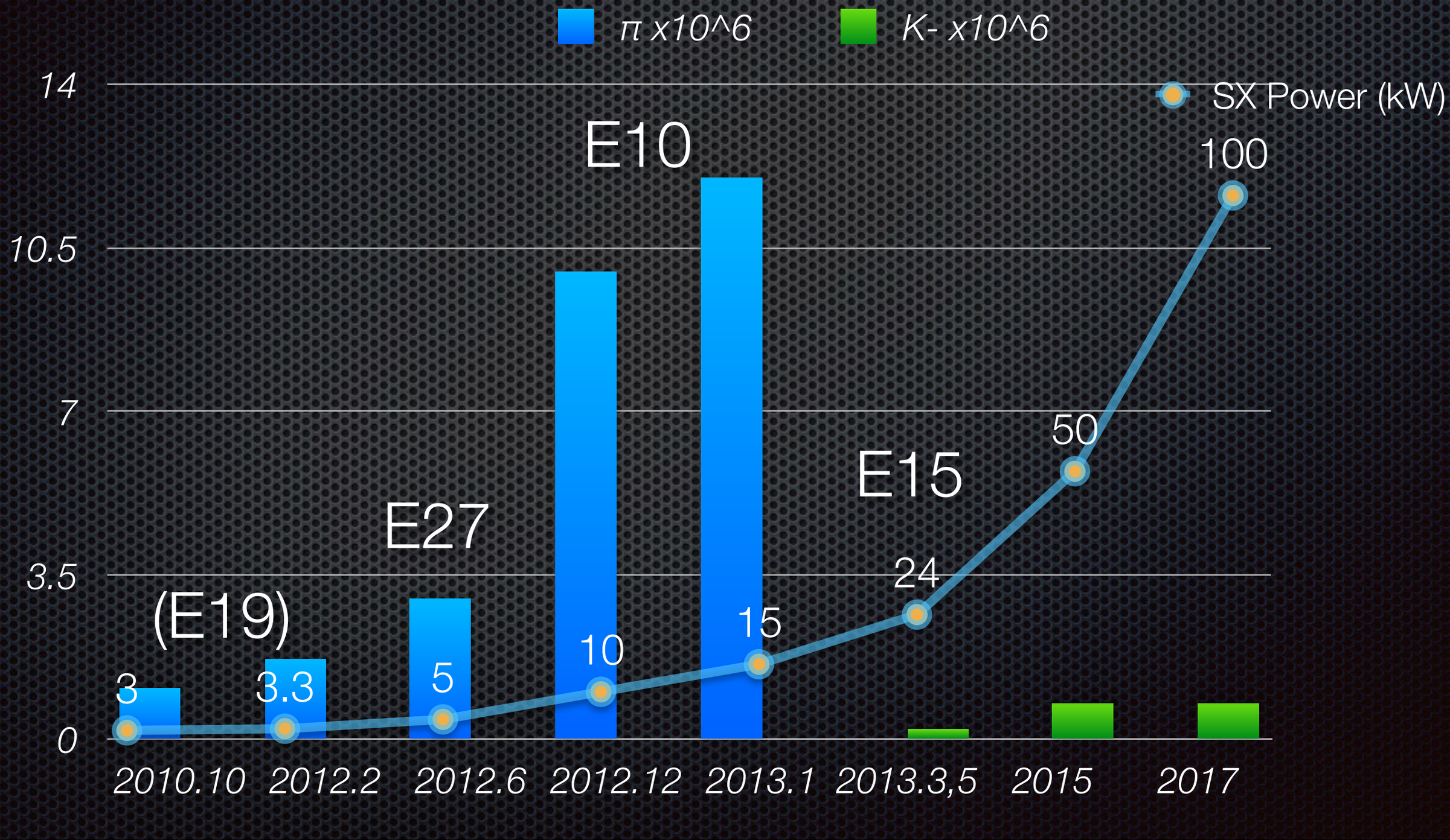


60m x 56m



30~50 GeV Primary Beam

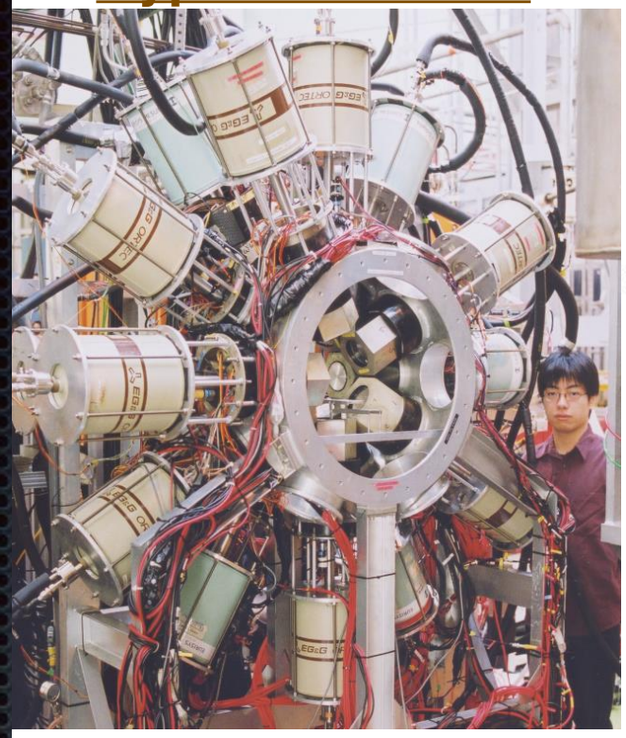
J-PARC Beam time: $\pi^{\pm} \rightarrow K^{-}$



S≡-1 Baryon Systems

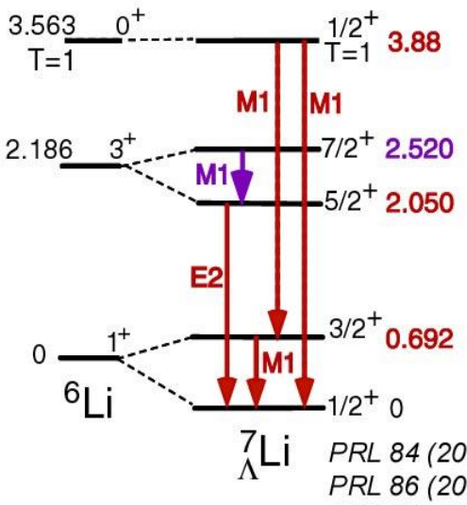
Hypernuclear Gamma-rays

Hyperball 1998~



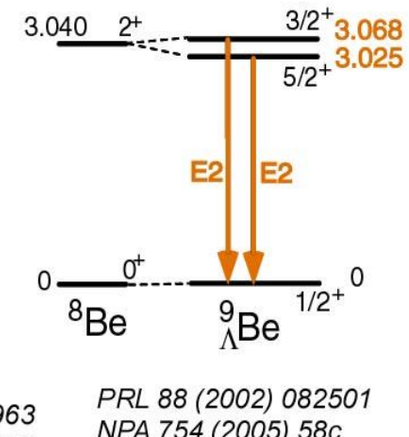
Hypernuclear γ-ray data (2012)

^{7}Li (π^+,$K^+\gamma$) KEK E419



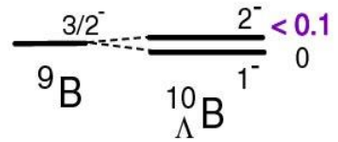
PRL 84 (2000) 5963
PRL 86 (2001) 1982
PLB 579 (2004) 258
PRC 73 (2006) 012501

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



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

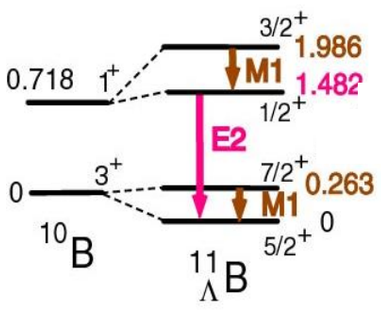
^{10}B (K^-,$\pi^-\gamma$) BNL E930('01)



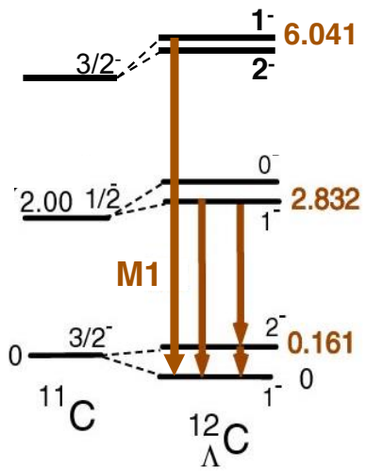
NPA 754 (2005) 58c

^{12}C (π^+,$K^+\gamma$) KEK E566

^{11}B (π^+,$K^+\gamma$) KEK E518

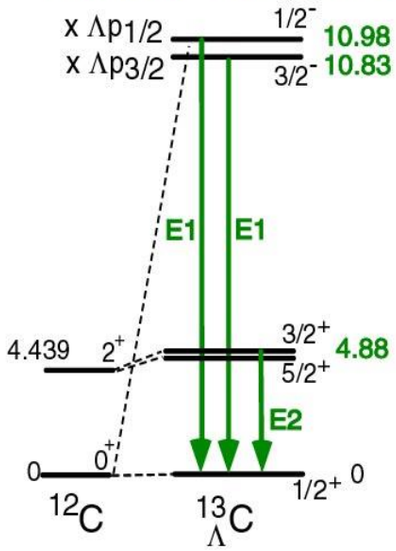


NPA 754 (2005) 58c



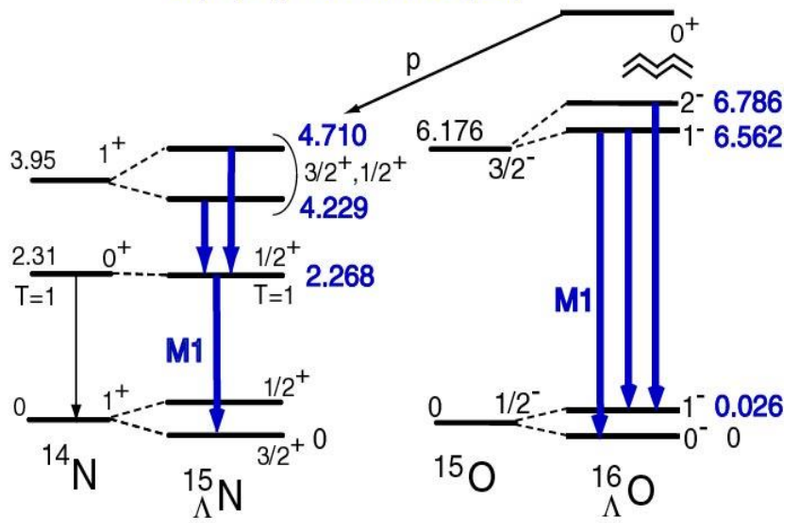
EPJ A33 (2007) 243
NPA835 (2010) 422

^{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

by D.J. Millener

Gamma-ray Spectroscopy of Light Hypernuclei

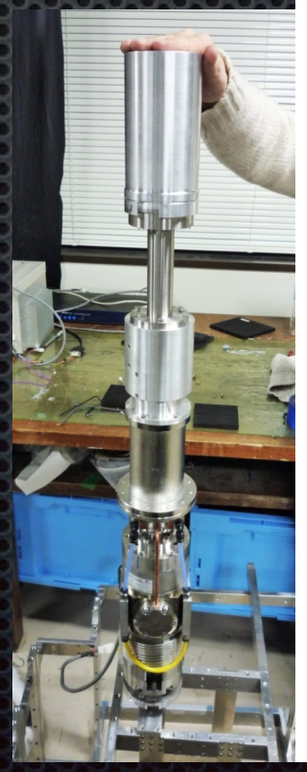
J-PARC E13
H. Tamura et al.

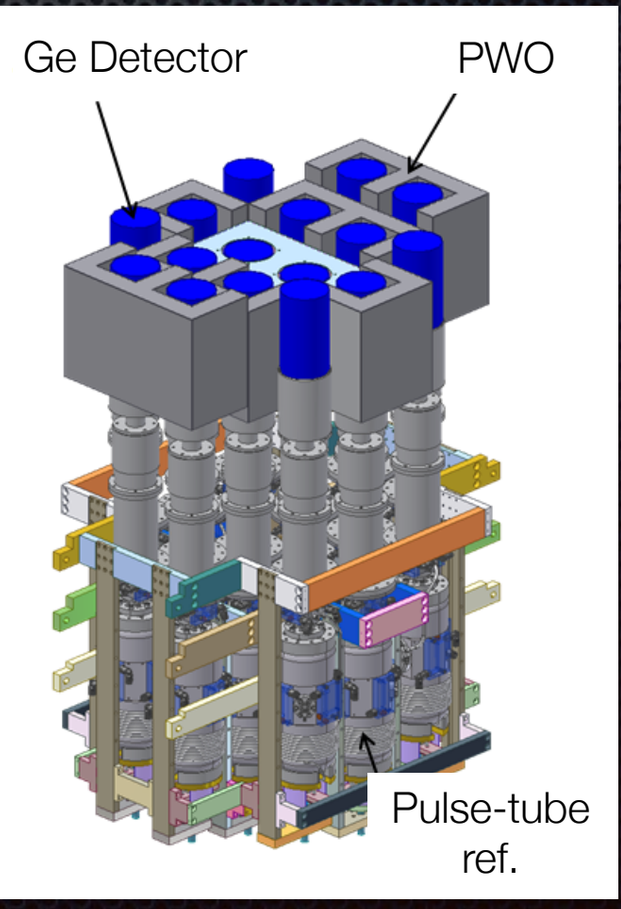
- ΛN interaction in sd-shell hypernuclei : $^{19}_{\Lambda}$F
- Spin-flip B(M1) measurement for g_Λ in nuclei

Hyperball-J

  - ^{7}Li(K^-,$\pi^-\gamma$)$^{7}_{\Lambda}$Li at 1.1 GeV/c: M1($3/2^+ \rightarrow 1/2^+$)
- various hypernuclear gamma-rays
  - $^{4}_{\Lambda}$He, $^{10}_{\Lambda}$B, etc.

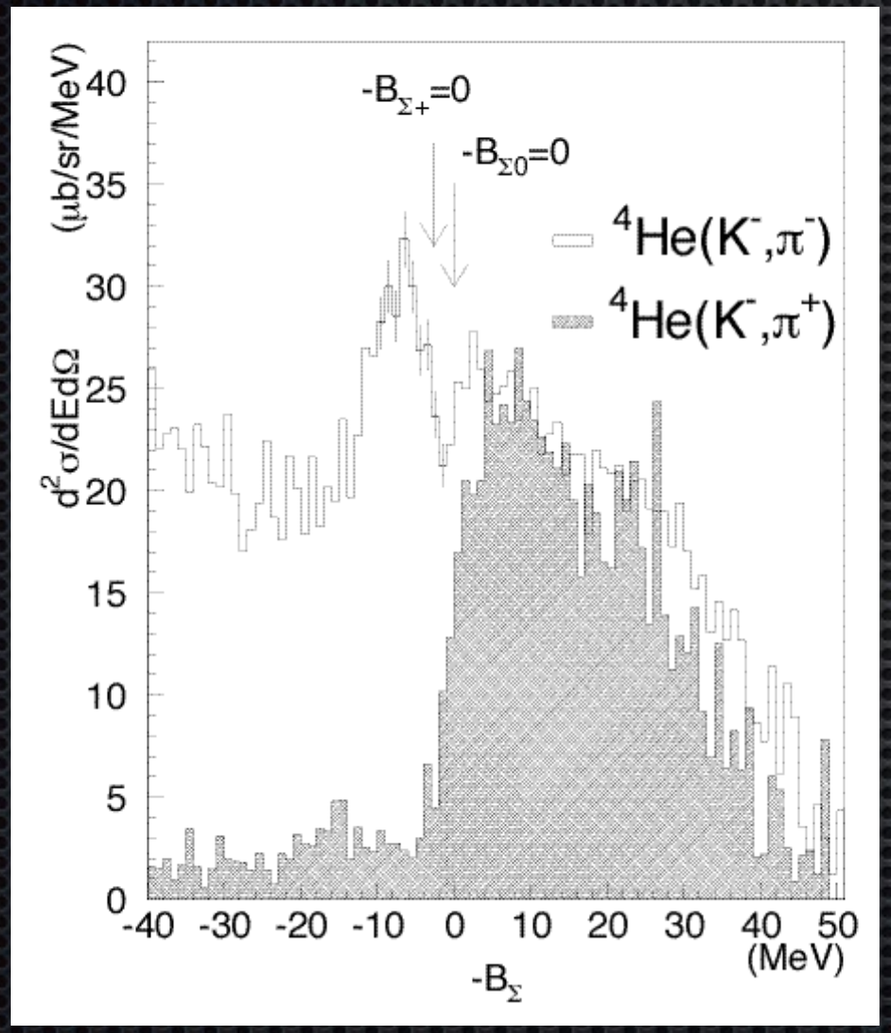
Ge x32; ε~6% at 1 MeV
→ γ-γ coincidence





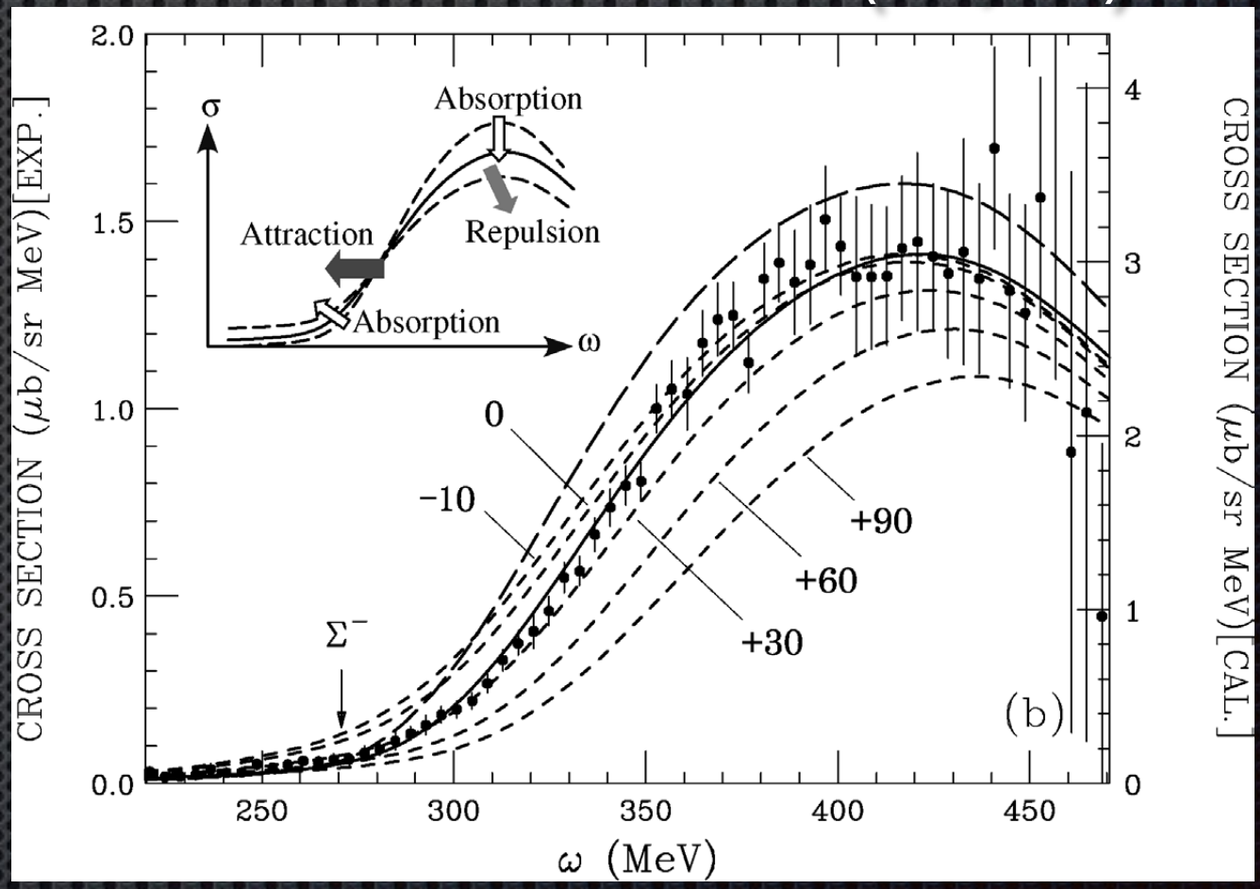
Σ-Hypernuclei

- One bound state observed: $^{4}_{\Sigma}$He



T. Nagae et al., PRL 80 (1998) 1605.

^{28}Si(π$^-$,K$^+$)

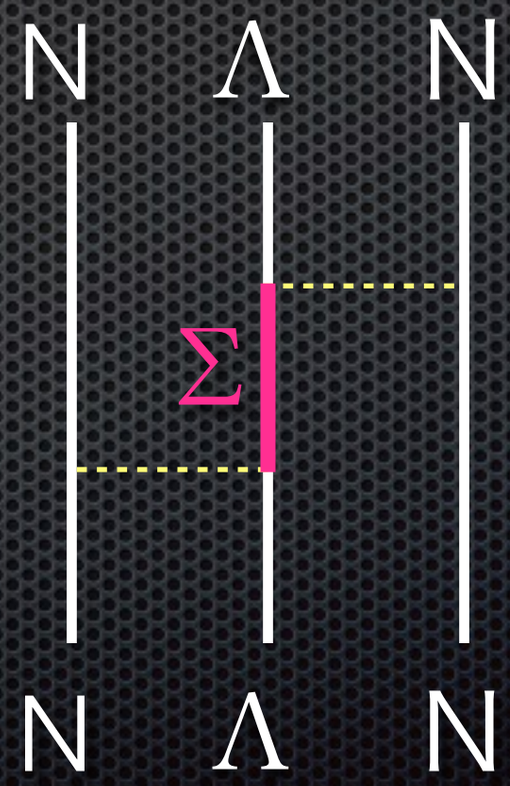


Σ^--Nucleus potential: Repulsive

T. Harada and Y. Hirabayashi, NPA 759 (2005) 143.

ΛN-ΣN coupling

- Strong coupling through one-pion exchange
- Large mixing in neutron-rich(N>Z) hypernuclei
- ΛNN three-body force→High density matter EOS



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

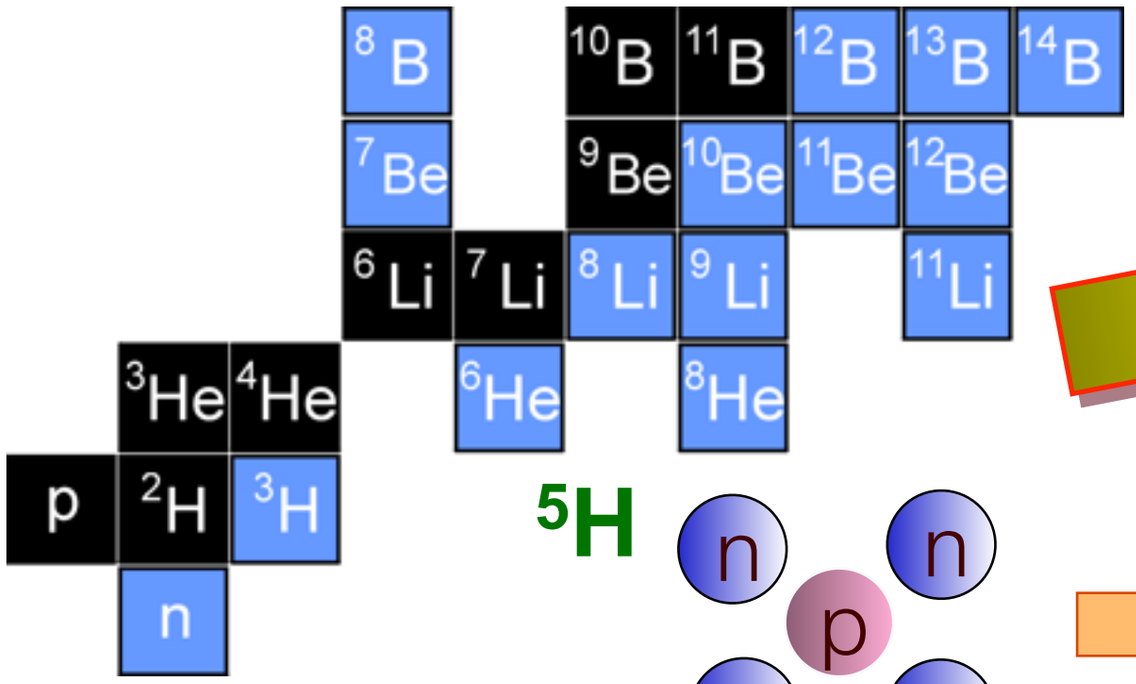
J-PARC E10
A. Sakaguchi et al.

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



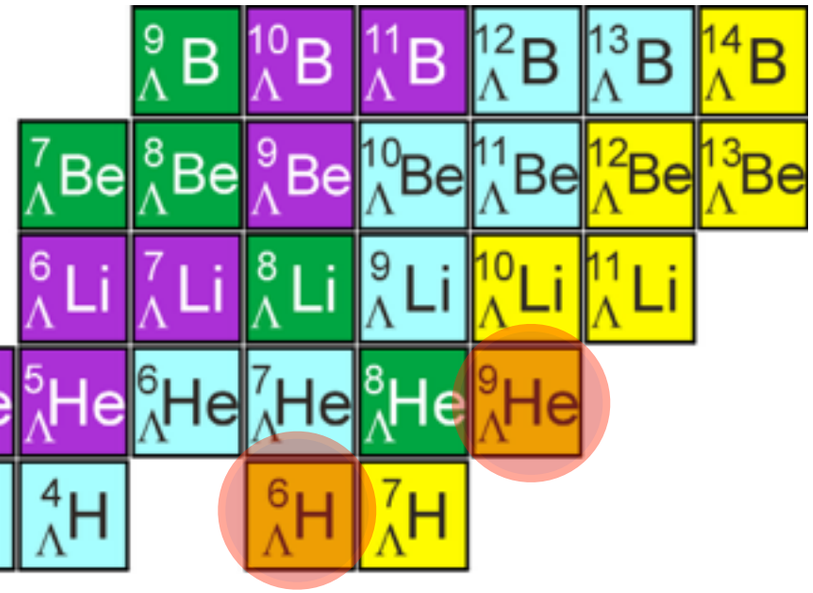
NCX

SCX

DCX

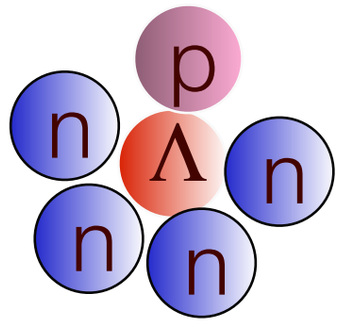
Λ

Λ-hypernuclei



^{5}H

unbound



$^6_\Lambda$H

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

"Hyperheavy hydrogen": deeply bound

S=-2 Baryon Systems

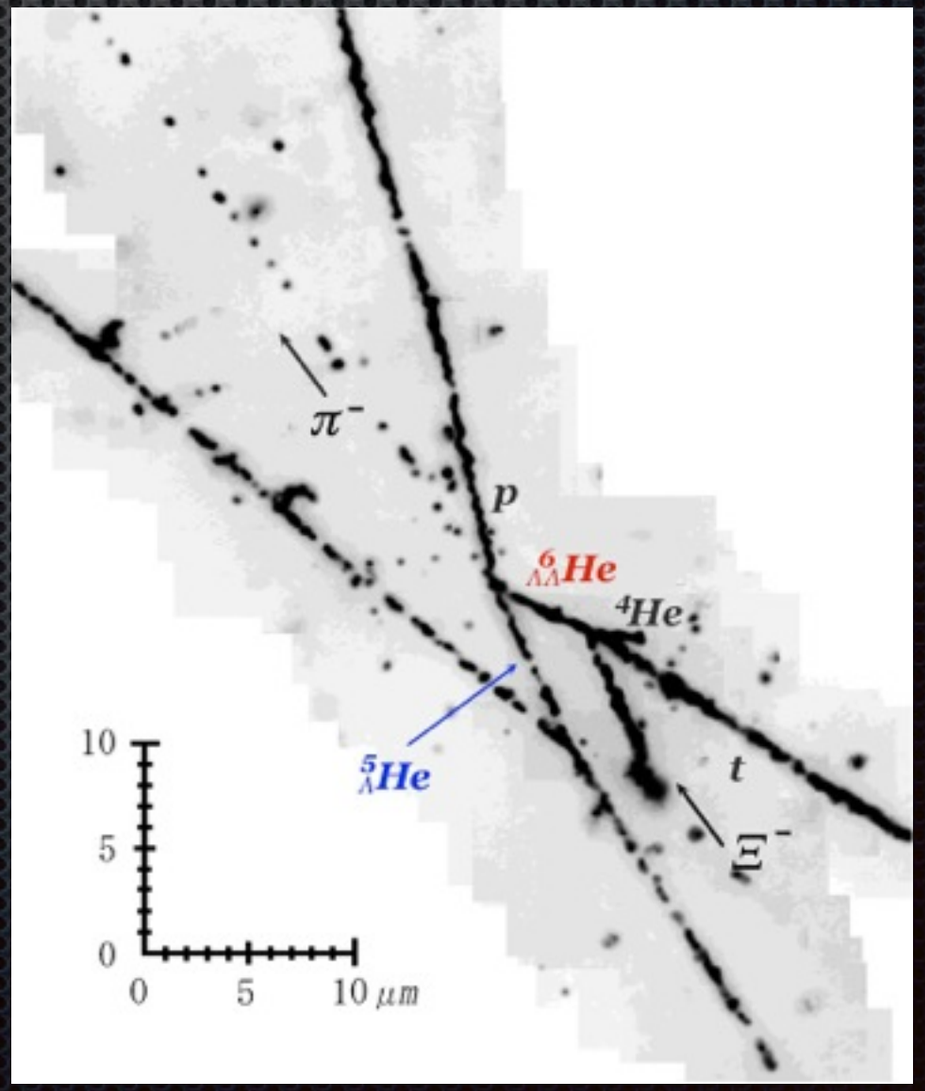
Double-Λ Hypernuclei

- "Nagara" event; ${}^{\Lambda\Lambda}{}^{6}\mathrm{He}$
  - Uniquely identified
  - $\Delta B_{\Lambda\Lambda}$=0.67±0.17 MeV

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

  - smaller than before (~4 MeV)

KEK E373



H. Takahashi et al., PRL87, (2001) 212502.

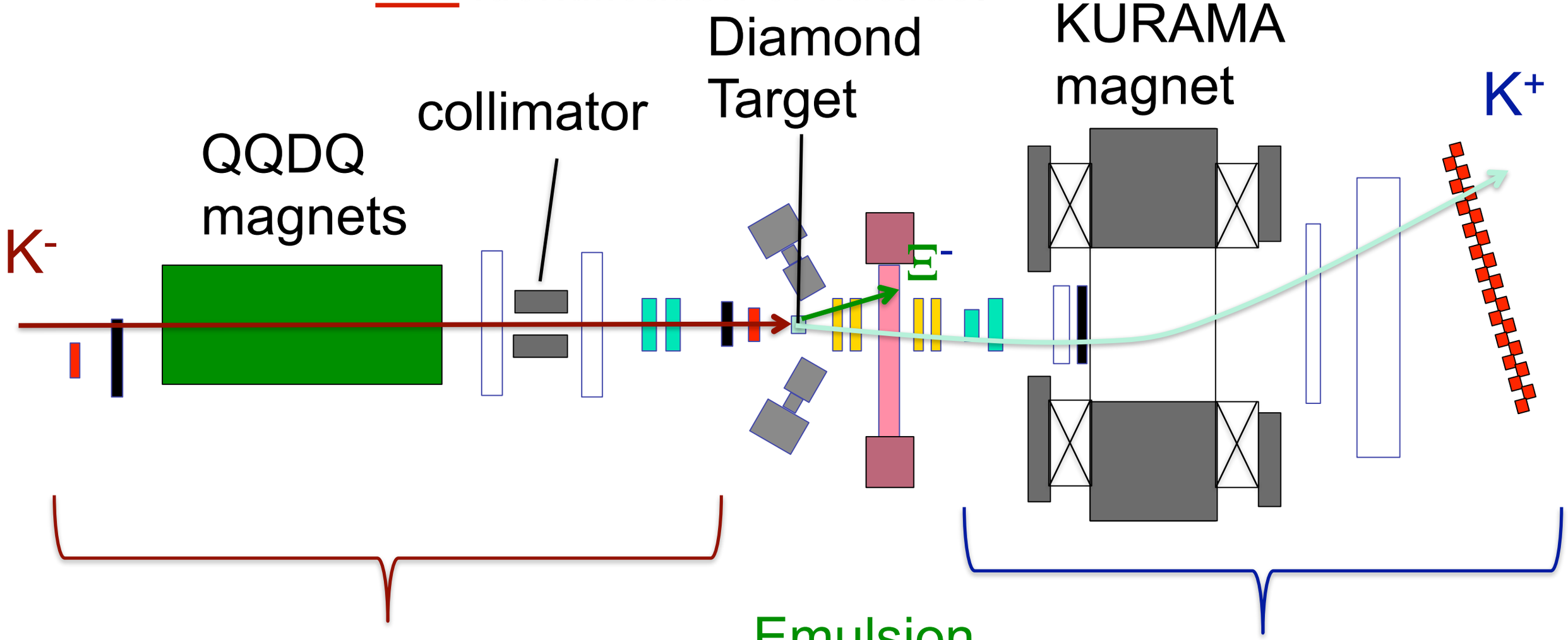
J-PARC E07: Hybrid-Emulsion Exp.

K. Nakazawa et al.

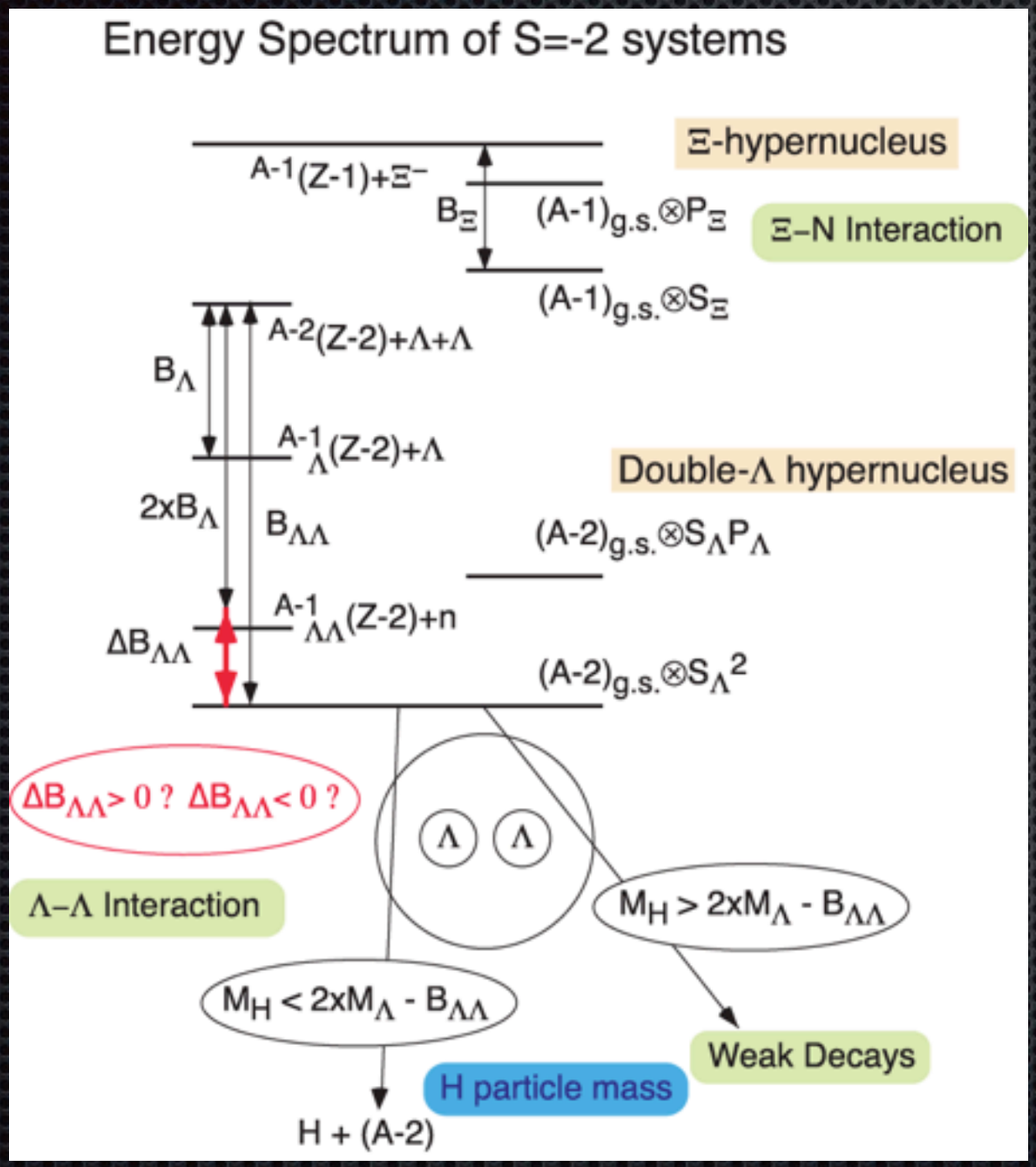
- 10 times' statistics of E373 (KEK-PS) ⇔ **10^4** Ξ-stop

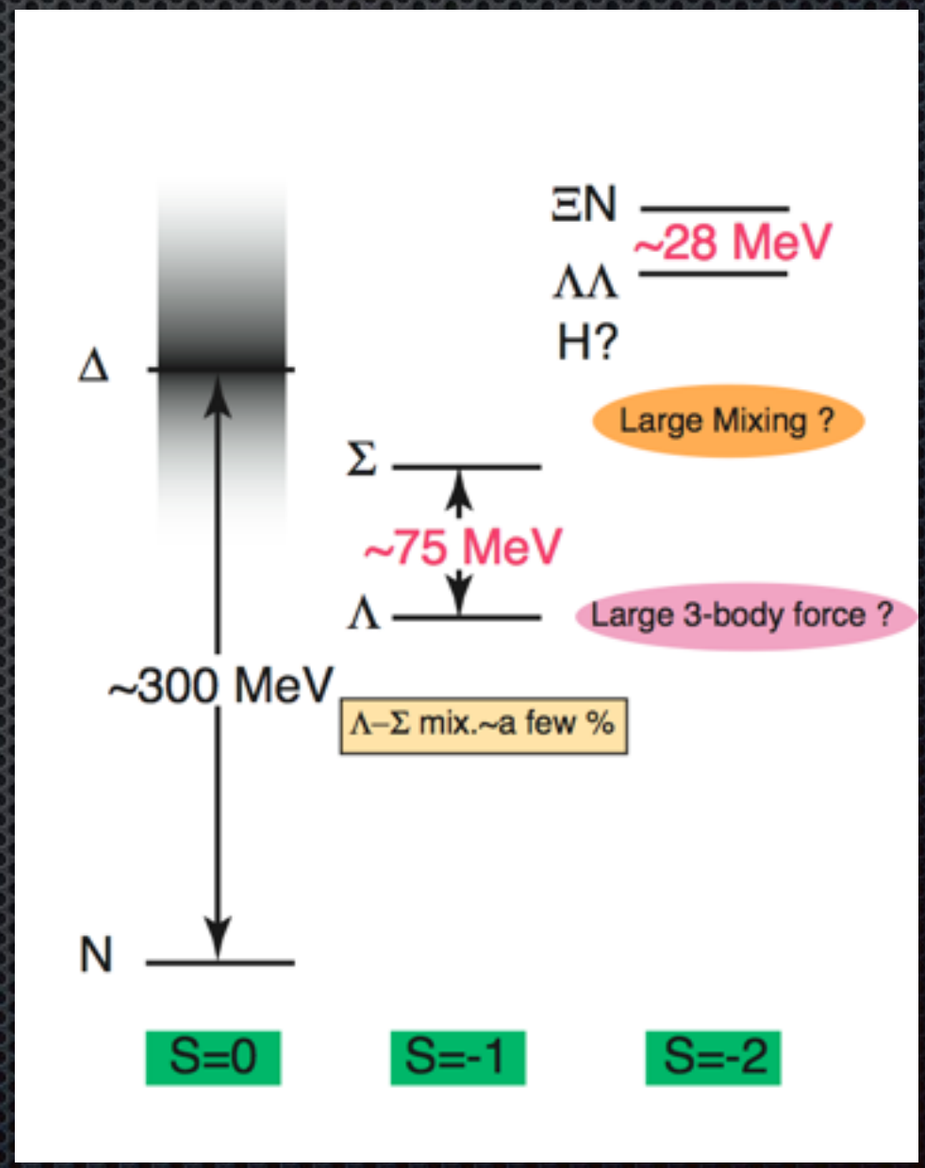
  ➔ **~10^2** double hypernuclei,

  ~10 identification of nuclide.



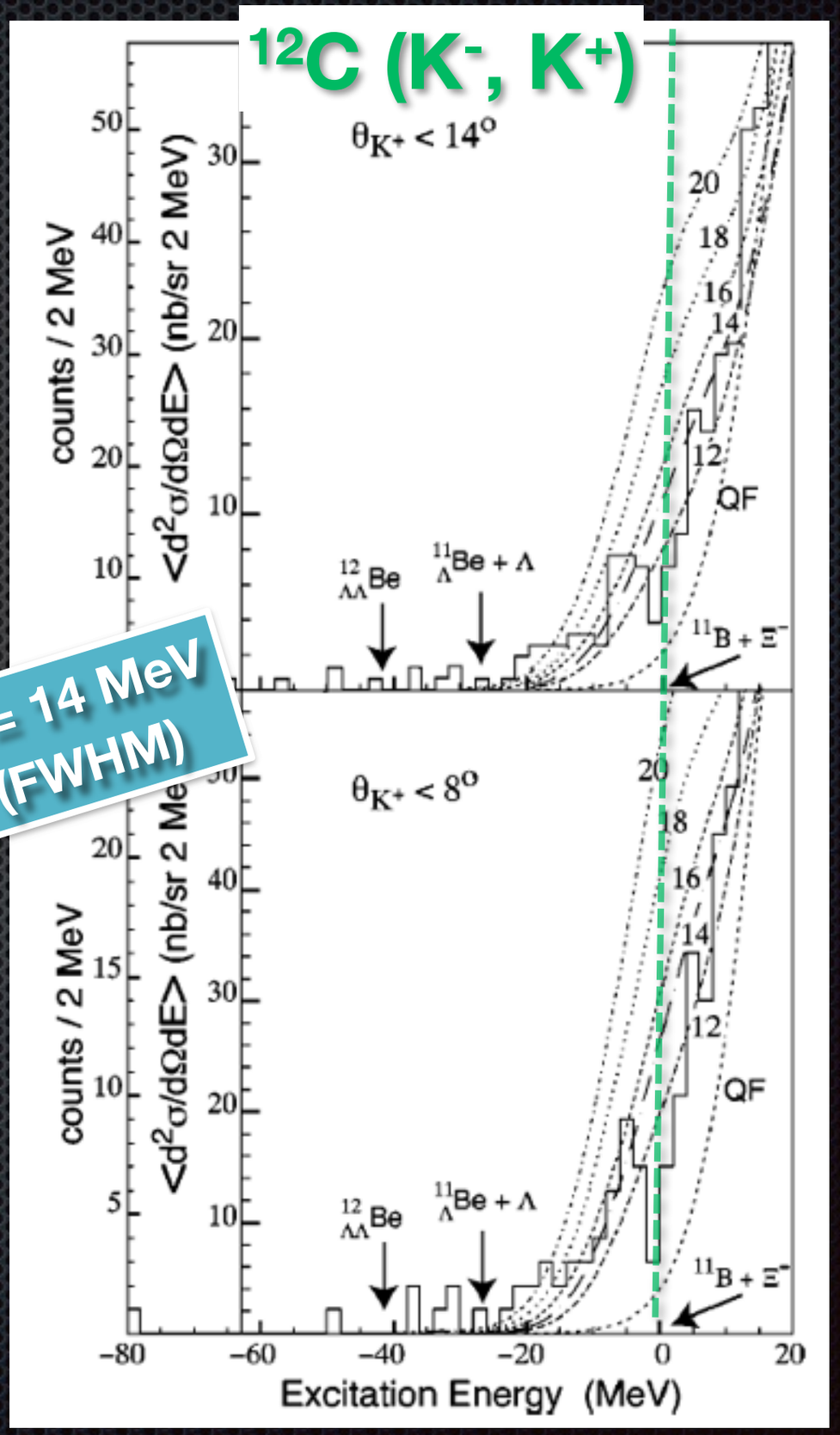
S=-2 World


Energy Spectrum of S=-2 systems
Ξ-hypernucleus
A-1(Z-1)+Ξ⁻
BΞ
(A-1)g.s.⊗PΞ
Ξ–N Interaction
(A-1)g.s.⊗SΞ
A-2(Z-2)+Λ+Λ
BΛ
A-1Λ(Z-2)+Λ
Double-Λ hypernucleus
2xBΛ
BΛΛ
(A-2)g.s.⊗SΛPΛ
A-1ΛΛ(Z-2)+n
ΔBΛΛ
(A-2)g.s.⊗SΛ2
ΔBΛΛ> 0 ? ΔBΛΛ< 0 ?
Λ Λ
Λ–Λ Interaction
MH > 2xMΛ - BΛΛ
MH < 2xMΛ - BΛΛ
Weak Decays
H particle mass
H + (A-2)


ΞN
~28 MeV
ΛΛ
H?
Large Mixing ?
Δ
Σ
~75 MeV
Λ
Large 3-body force ?
~300 MeV
Λ–Σ mix.~a few %
N
S=0
S=-1
S=-2

Ξ hypernuclei

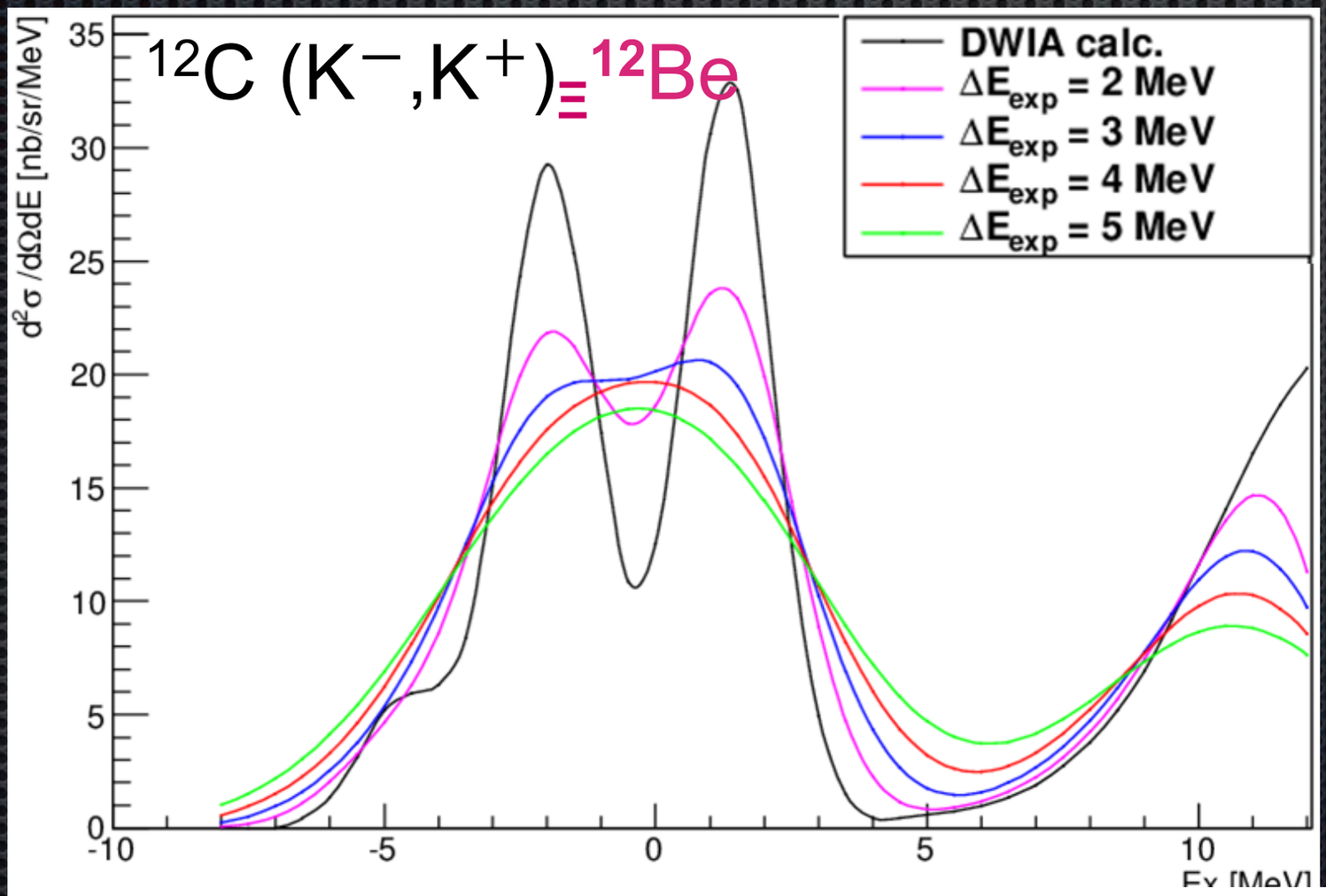
- Previous measurements : BNL E885
  - $^{12}C(K^-, K^+)$ at 1.8 GeV/c
  - $\Delta E = 14\ MeV_{FWHM}$
  - Events in the bound region : 89±14 nb/sr (<8deg.); 42±5 nb/sr (<14deg.)
  - $V_\Xi \sim 14$ MeV (weakly attractive)



P.Khaustov et al., PRC61(2000)054603

Better resolution !

- 60 msr, Δp/p=0.05% → ΔM=1.5 MeV



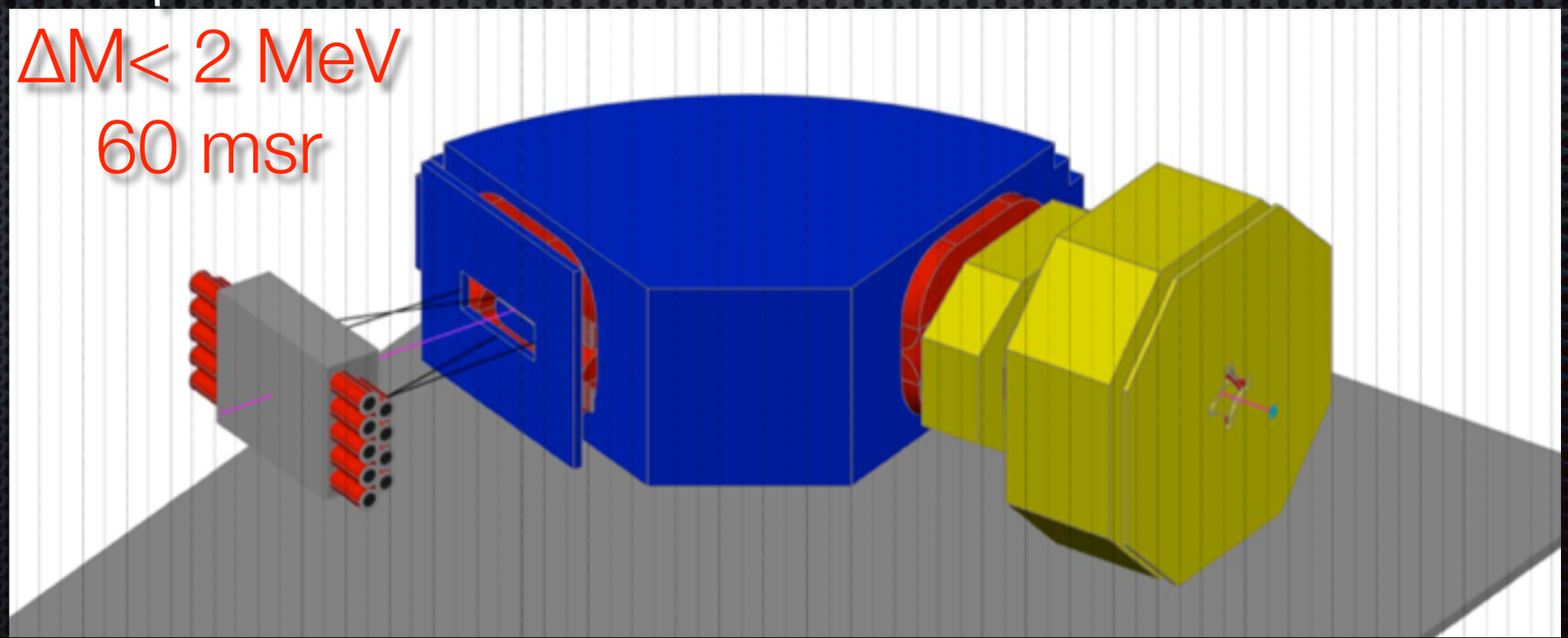
T. Motoba and S. Sugimoto, Nucl. Phys. A 835, 223 (2010)

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

J-PARC E05
T. Nagae et al.

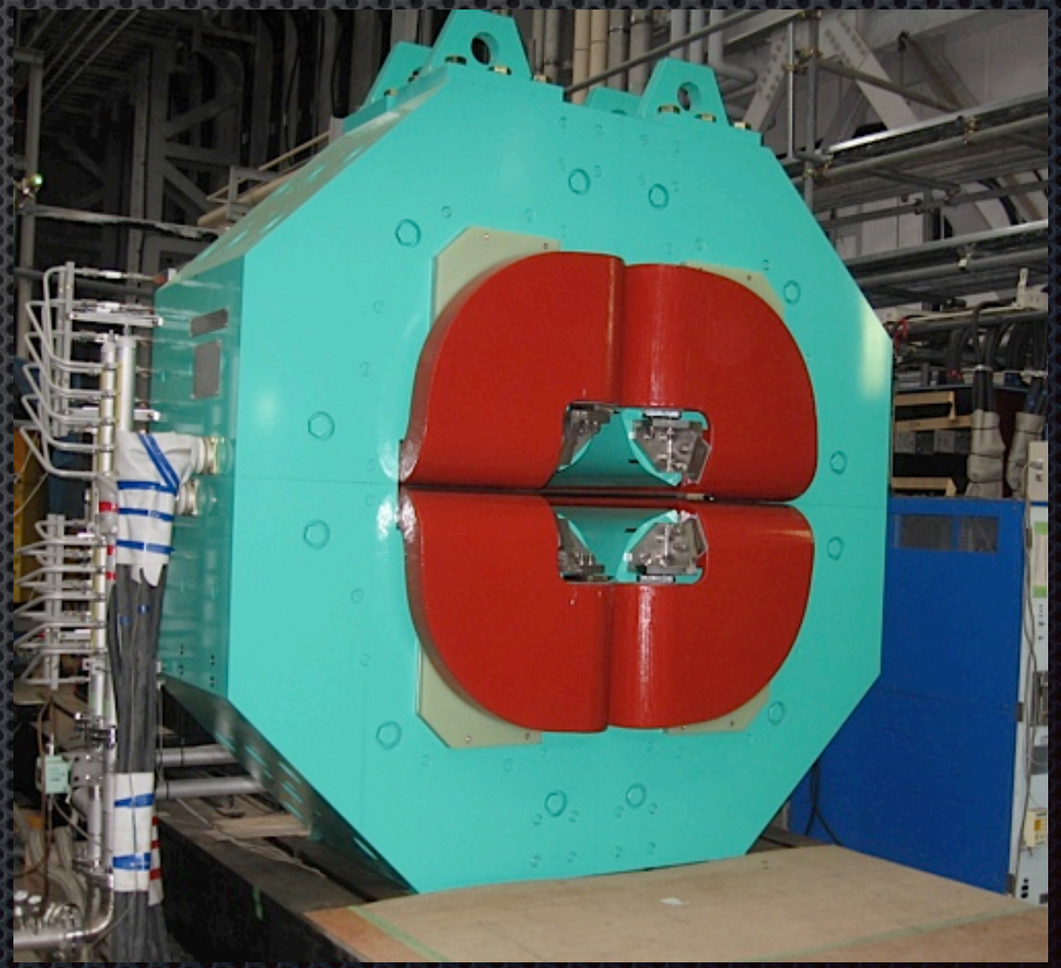
- Discovery of Ξ-hypernuclei
- Measurement of Ξ-nucleus potential depth and width of $^{12}_{\Xi}$Be S=-1 → S=-2 (Multi-Strangeness System)

"S-2S" spectrometer



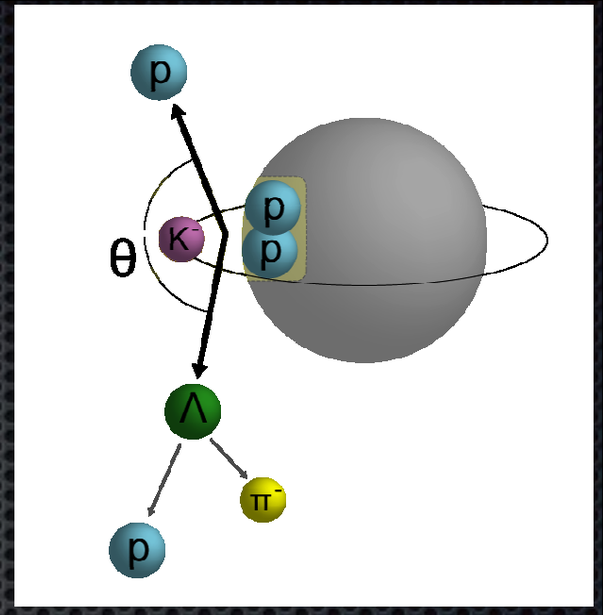
Q1 Construction in 2012

- 2.4 m x 0.88 m, 37 ton



Kaonic Nuclei

Experiments on K^-pp

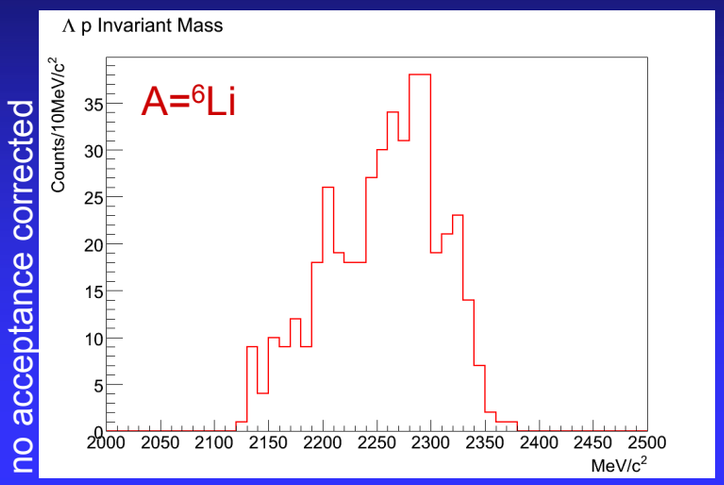


- First evidence of K^-pp with $^6Li+^7Li+^{12}C$

B=115+6/-5+3/-4 MeV
Γ= 67+14/-11+2/-3 MeV

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

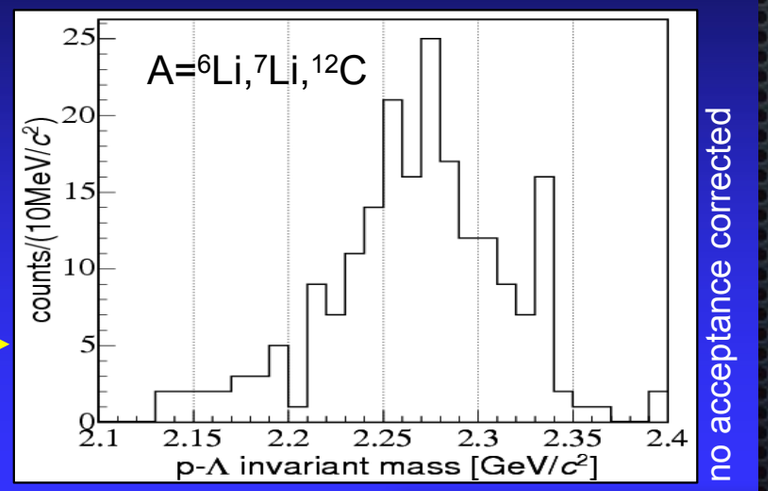
- Confirmed for ^6Li only, with better statistics S. Piano@Hyp-X



New
inv mass spectra
compatible with
published one

New data — Old data

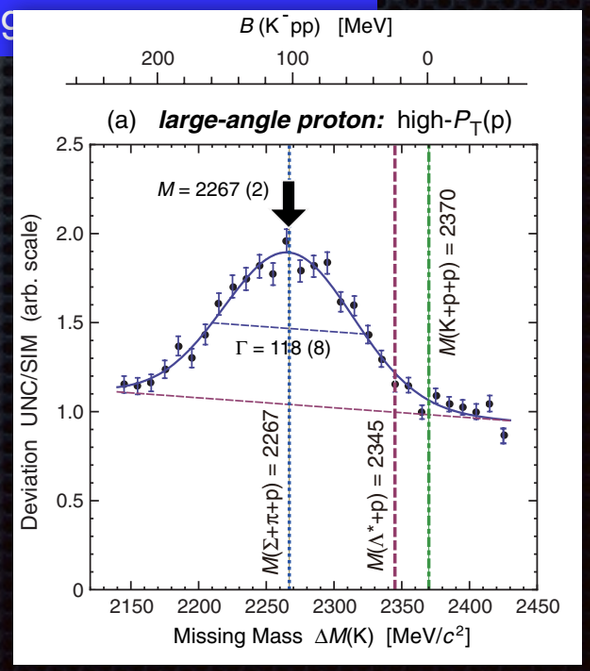
Same cuts applied



FINUDA Coll., PRL 9

- DISTO data: p+p→K^-pp + K^+ at 2.85 GeV
  - M=2267±3±5 MeV/c^2
  - Γ= 118±8±10 MeV

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



Theoretical work on K^-pp

- K^-pp does exist !!

...but maybe broad (consistent with FINUDA)

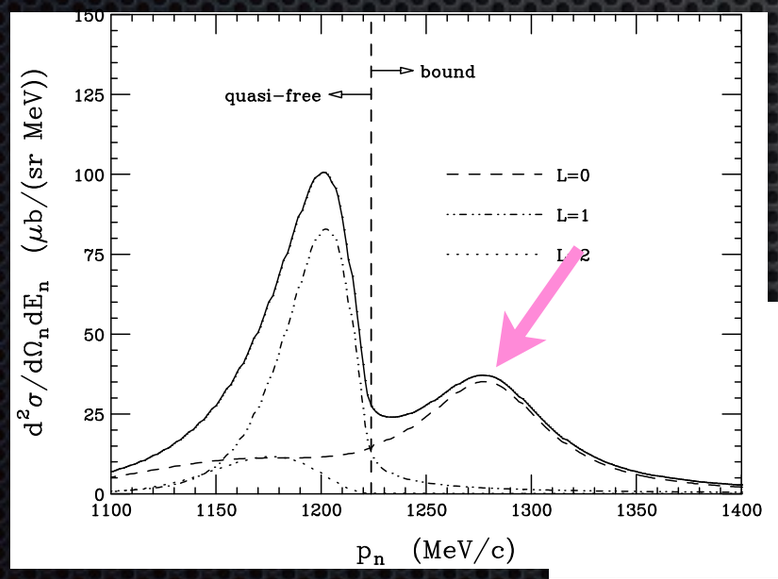
	ATMS	Variational	Faddeev	Faddeev	Variational
(MeV)	Yamazaki & Akaishi, PLB535 (2002) 70.	Dote, Hyodo, Weise, PRC79 (2009) 014003.	Shevchenko, Gal, Mares, PRL98 (2007) 082301.	Ikeda & Sato, PRC79 (2009) 035201.	Wycech & Green, PRC79 (2009) 014001.
B	48	17-23	50-70	60-95	40-80
Γ	61	40-70	90-110	45-80	40-85

- FSI effects ? ; V.K. Magas et al., PRC 74 (2006) 025206.
- Λ*N bound state ? ; T. Uchino et al., NPA 868-869 (2011) 53.

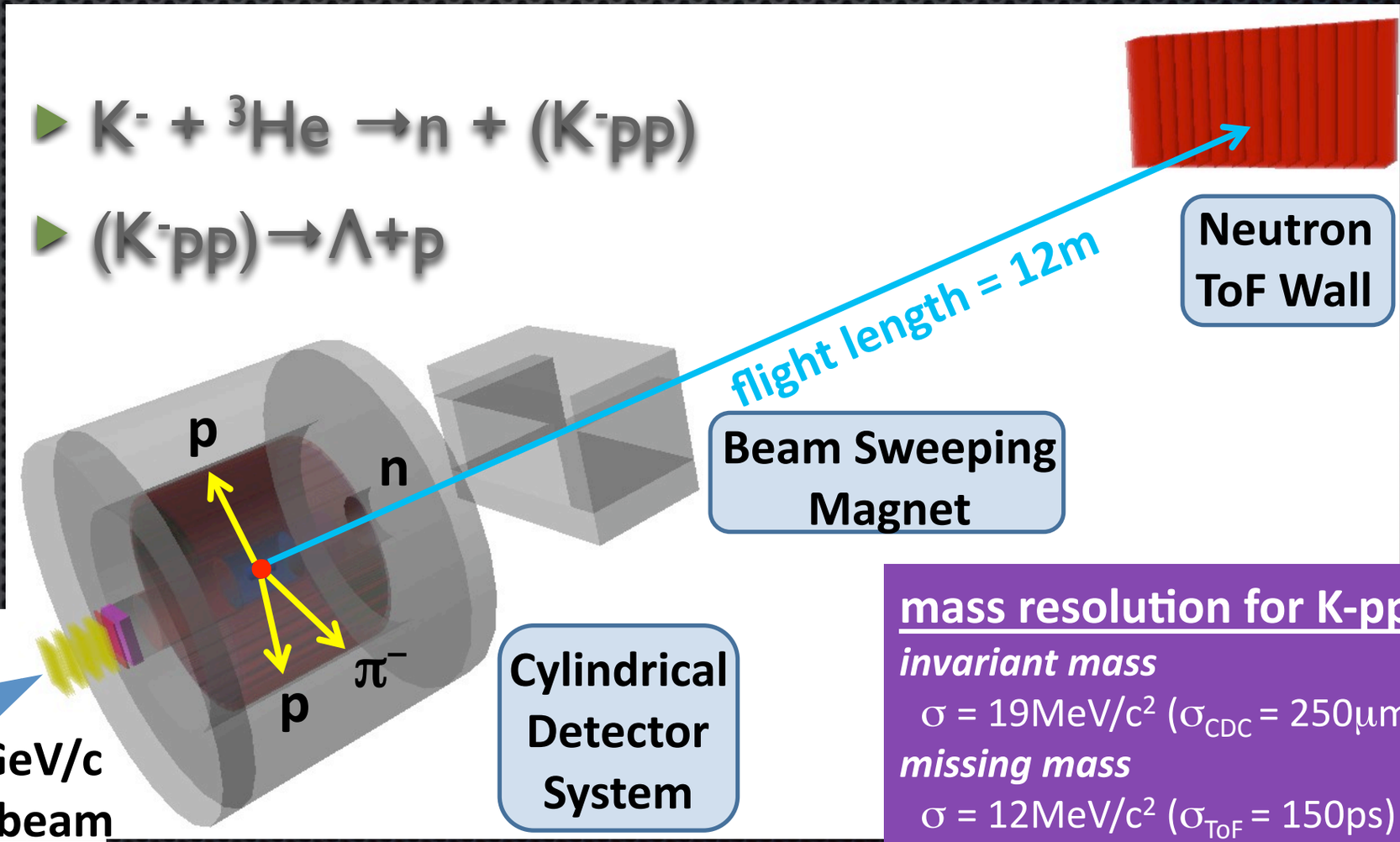
K^-pp search experiments at J-PARC

- ^{3}He(K^-,n) reaction at 1 GeV/c: E15

M. Iwasaki et al.



- $K^- + {}^3He \rightarrow n + (K^-pp)$
- $(K^-pp) \rightarrow \Lambda + p$



mass resolution for K-pp

invariant mass

$\sigma = 19\text{MeV}/c^2$ ($\sigma_{CDC} = 250\mu m$)

missing mass

$\sigma = 12\text{MeV}/c^2$ ($\sigma_{ToF} = 150ps$)

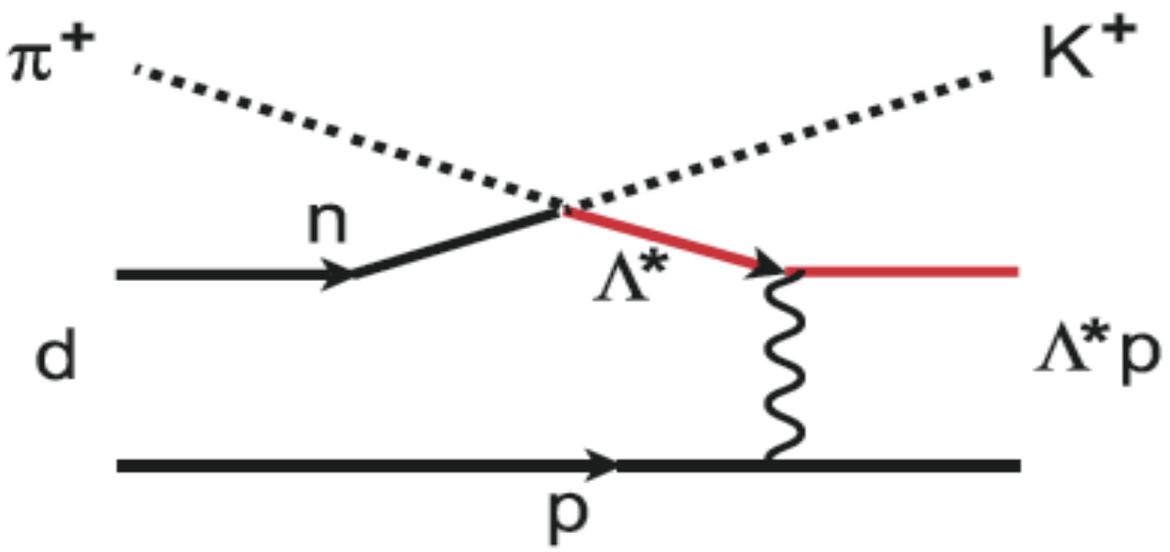
FIG. 1. The calculated inclusive spectra of the ^{3}He(in-flight K^-,n) reaction at p_{K^-} = 1.0 GeV/c and θ_{lab} = 0° as a function of the neutron momentum, using the YA optical potential with (1) B_{K^-pp} = 100 MeV, Γ_{K^-pp} = 70 MeV, (2) B_{K^-pp} = 0 MeV, Γ_{K^-pp} = 70 MeV. The vertical dashed line indicates the corresponding neutron momentum at p_n = 1220 MeV/c at the K^- emitted threshold. The contributions of partial waves

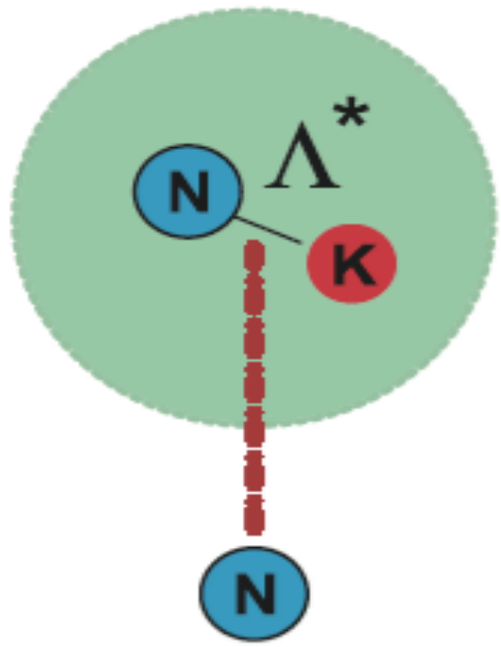
E27: *d*(π^+,K^+) reaction

π^+ + "n" --> "Λ^*" + K^+

"Λ^*" + "p" --> bound K^-pp ***minor***

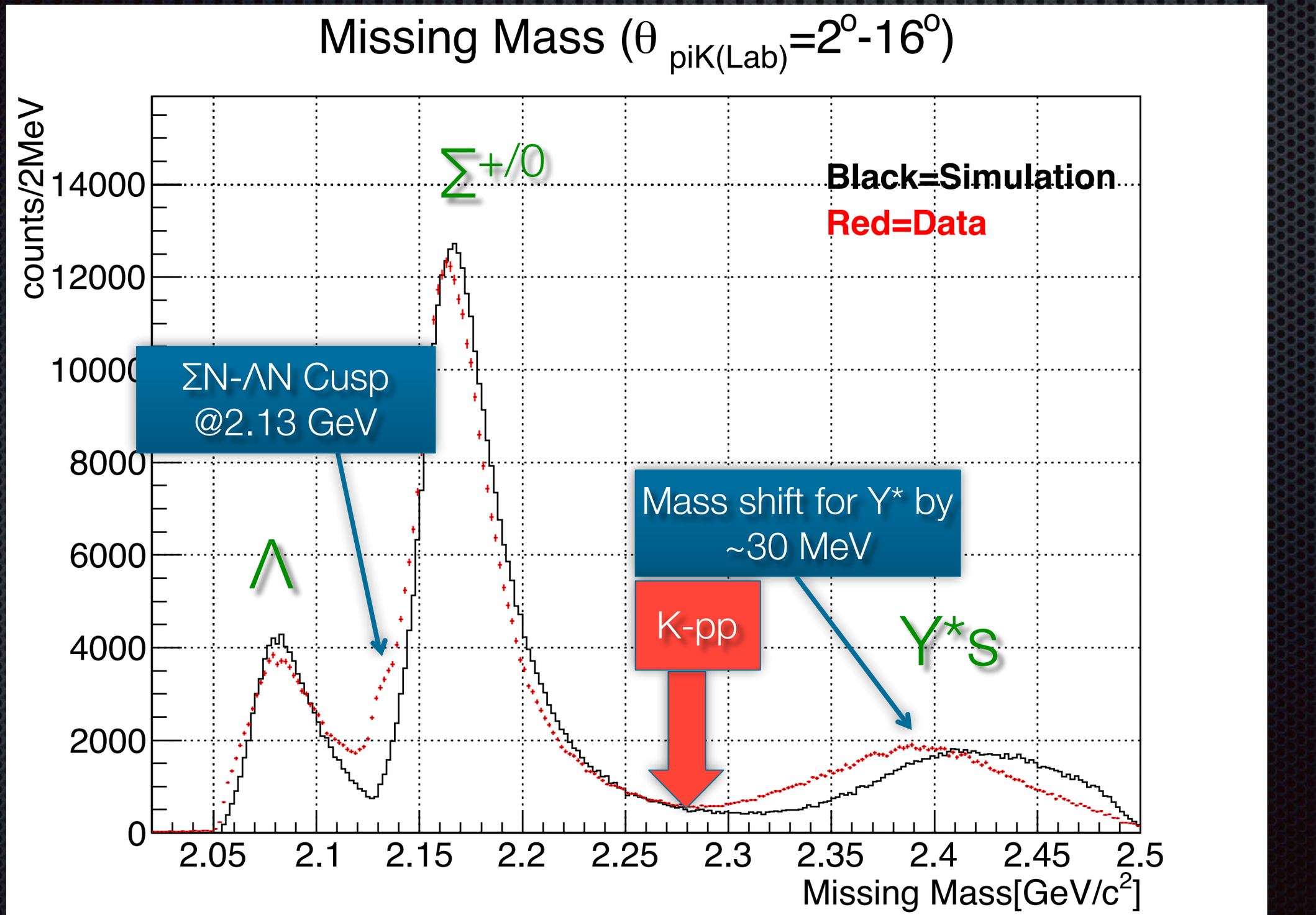
--> quasi-free Λ^* ***dominant***





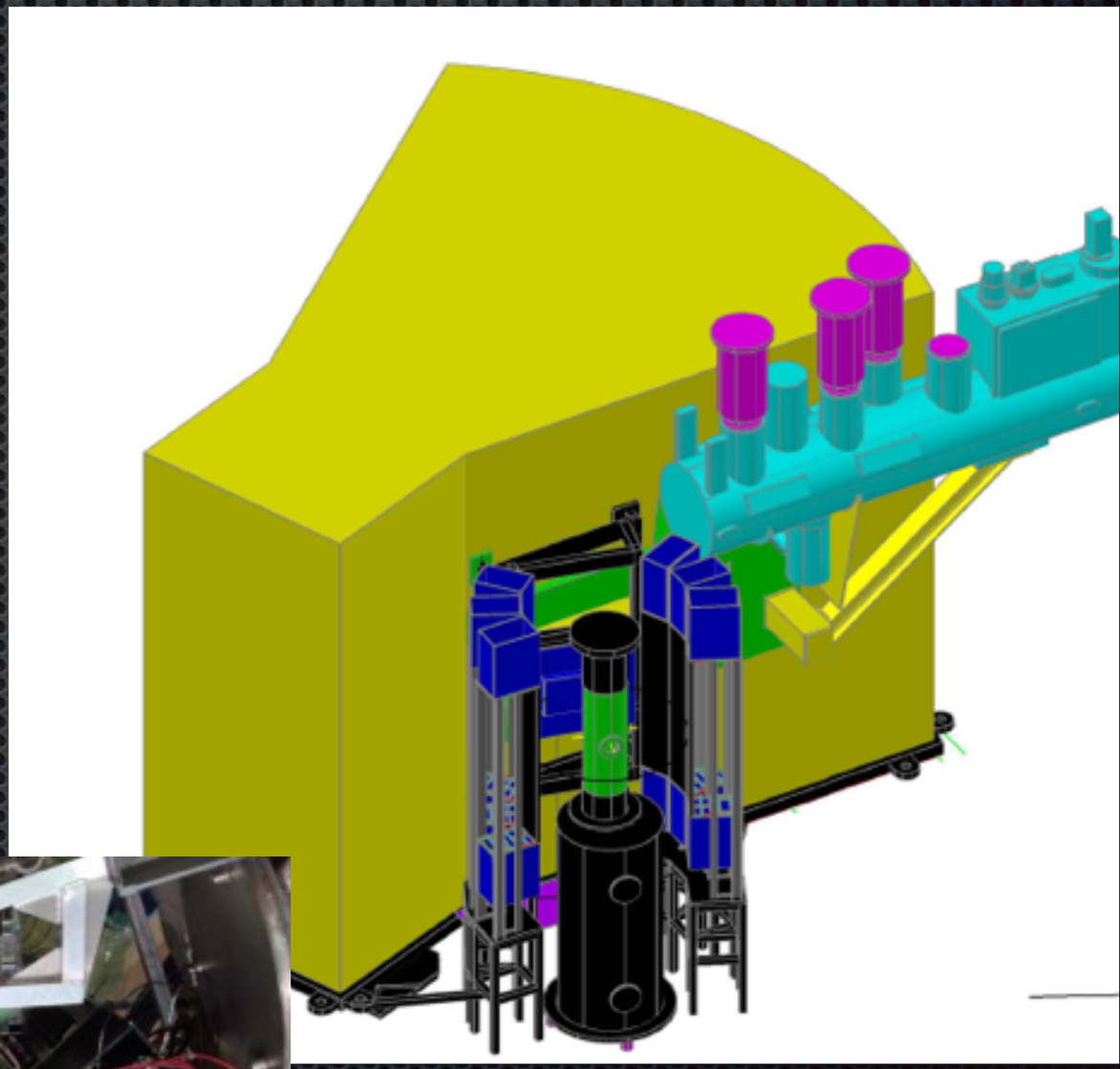
Yamazaki & Akaishi, Phys. Rev. C76 (2007) 045201.

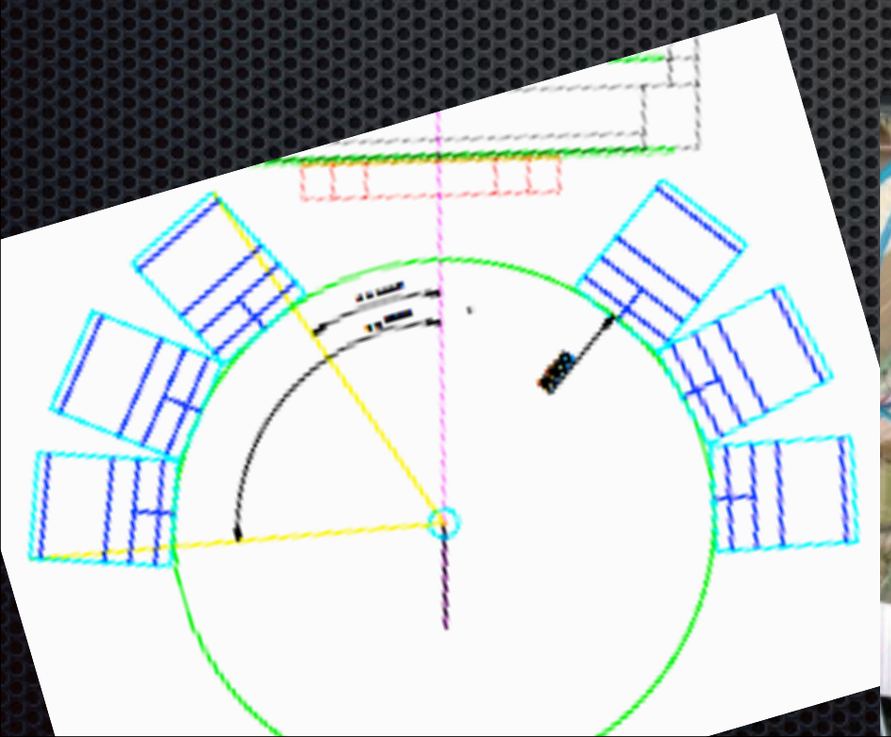
d(π⁺, K⁺) @1.7GeV/c

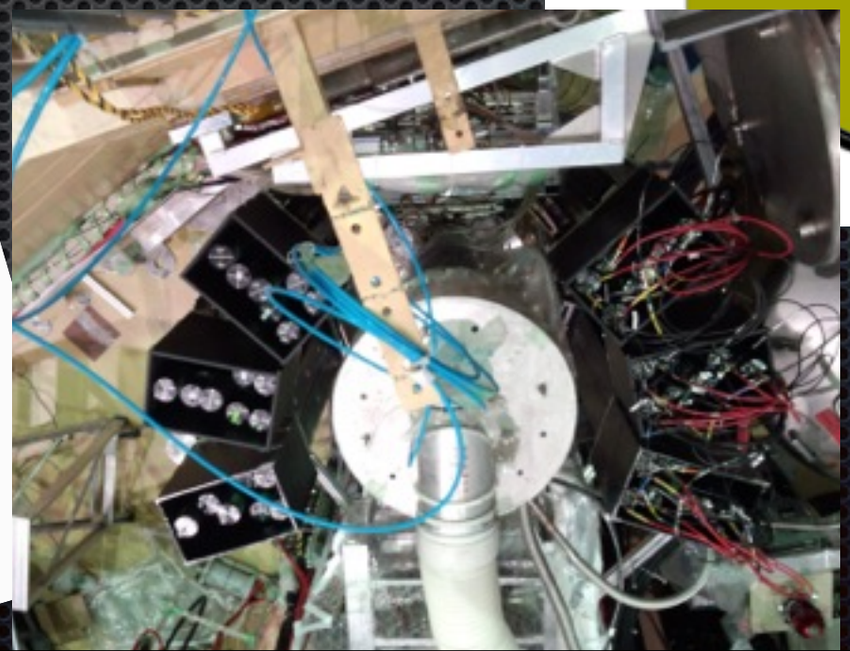

Missing Mass (θ piK(Lab)=2°-16°)
counts/2MeV
14000
12000
10000
8000
6000
4000
2000
0
2.05
2.1
2.15
2.2
2.25
2.3
2.35
2.4
2.45
2.5
Missing Mass[GeV/c²]
Σ+/0
Λ
ΣN-ΛN Cusp
@2.13 GeV
Black=Simulation
Red=Data
Mass shift for Y* by
~30 MeV
K-pp
Y*s

Range Counter System for E27

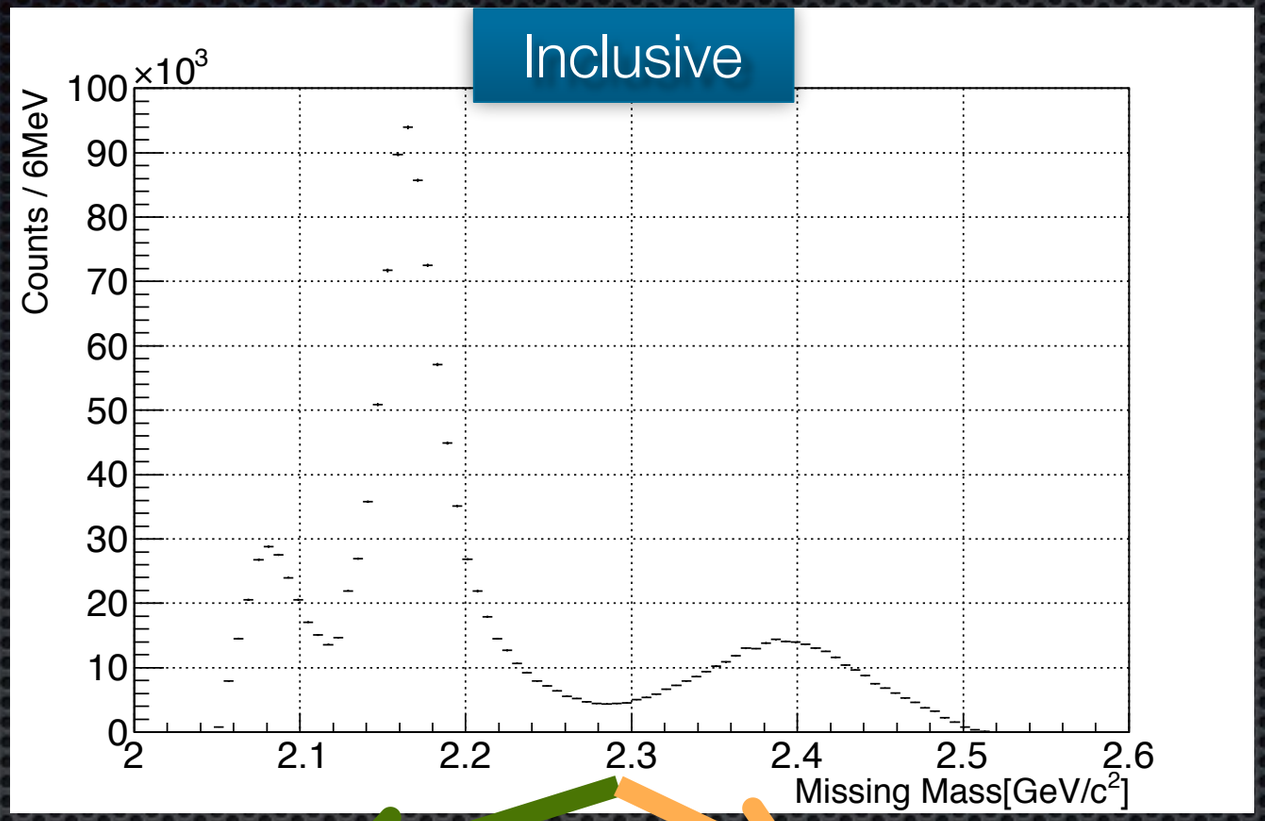
- 5 layers (1+2+2+5+2 cm) of plastic scinti.
- 39 - 122 degrees(L+R)
- 50 cm TOF





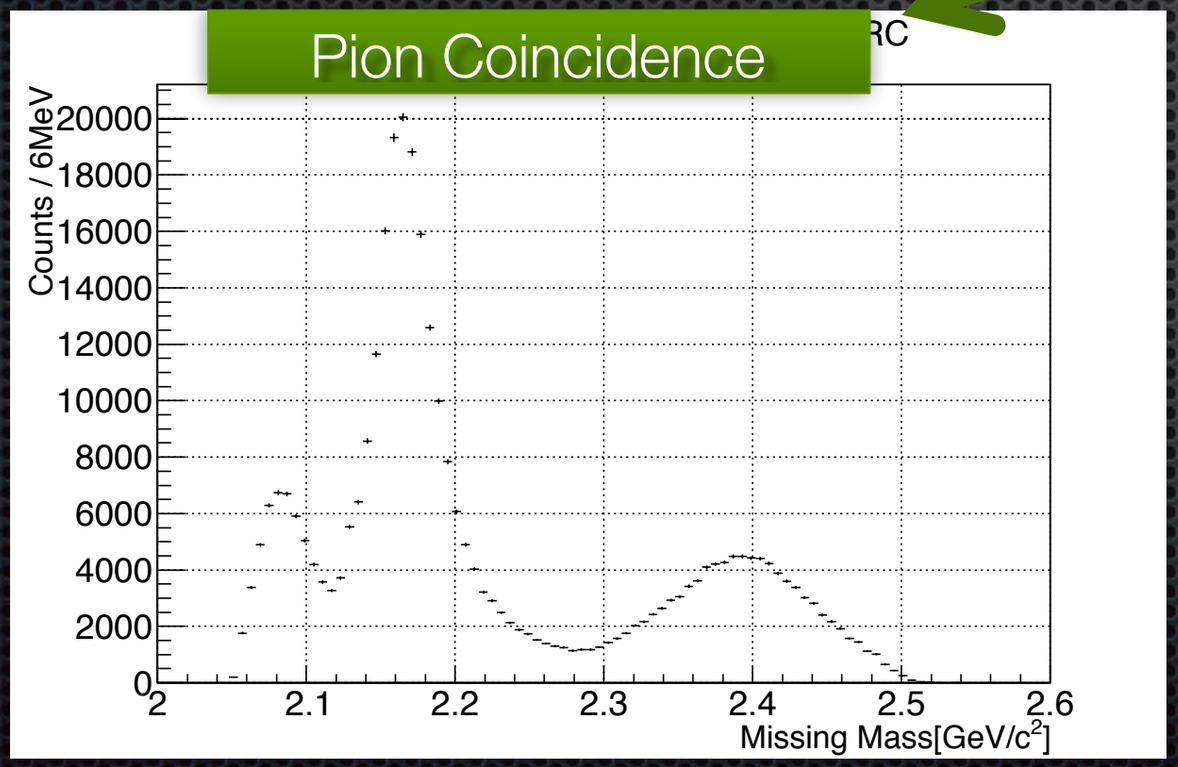


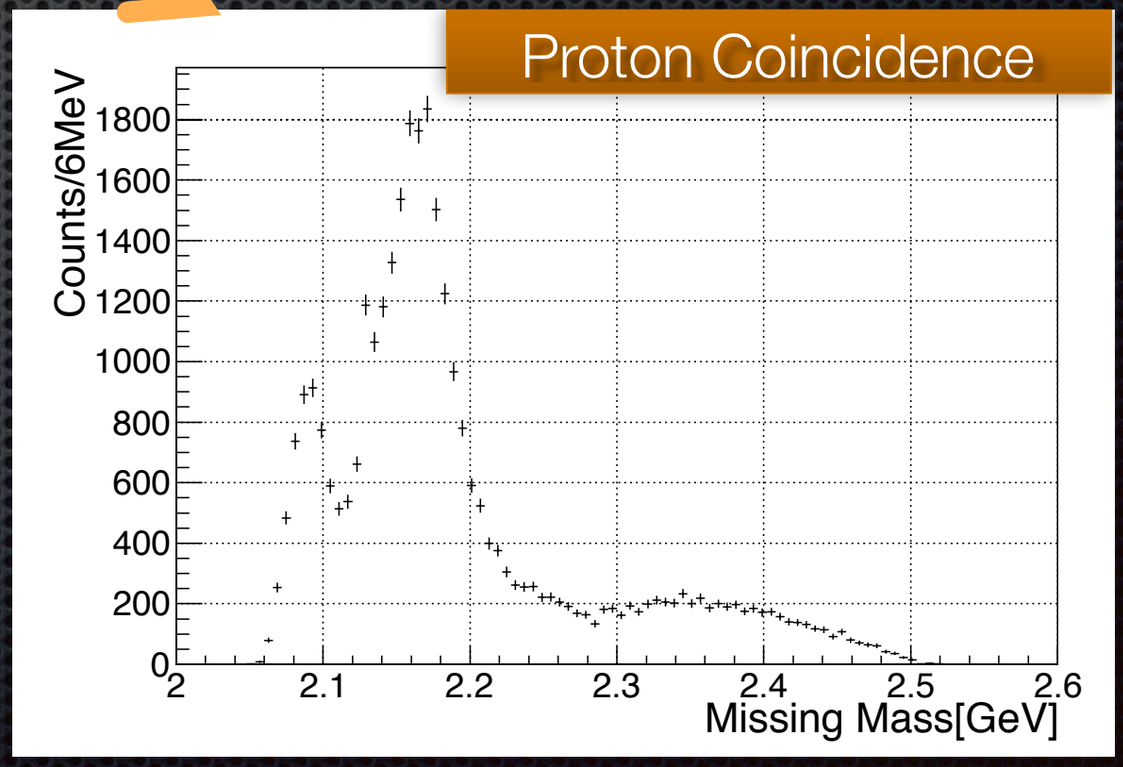
Coincidence study



"pion"=π or slow p

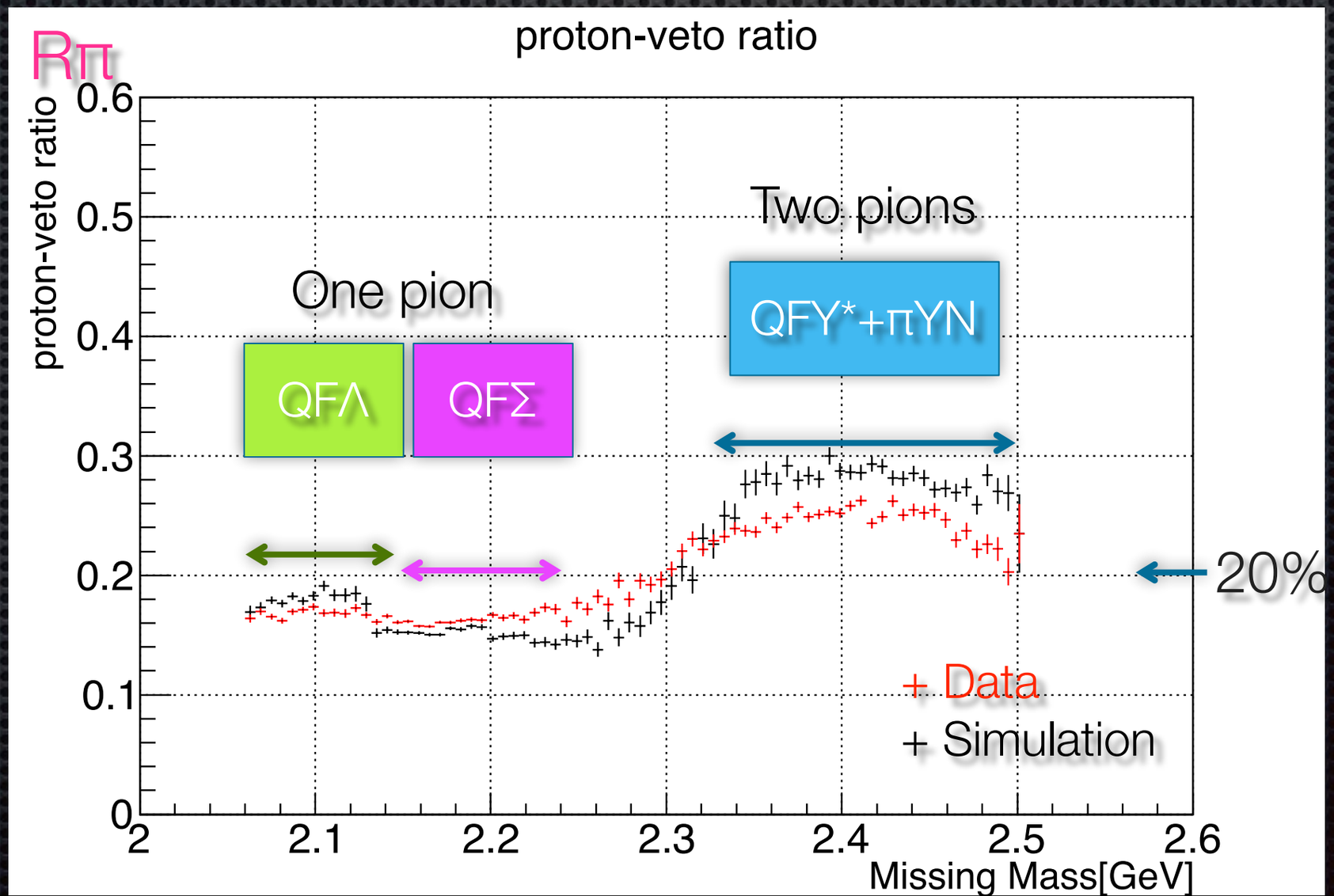
"proton"=p>280 MeV/c



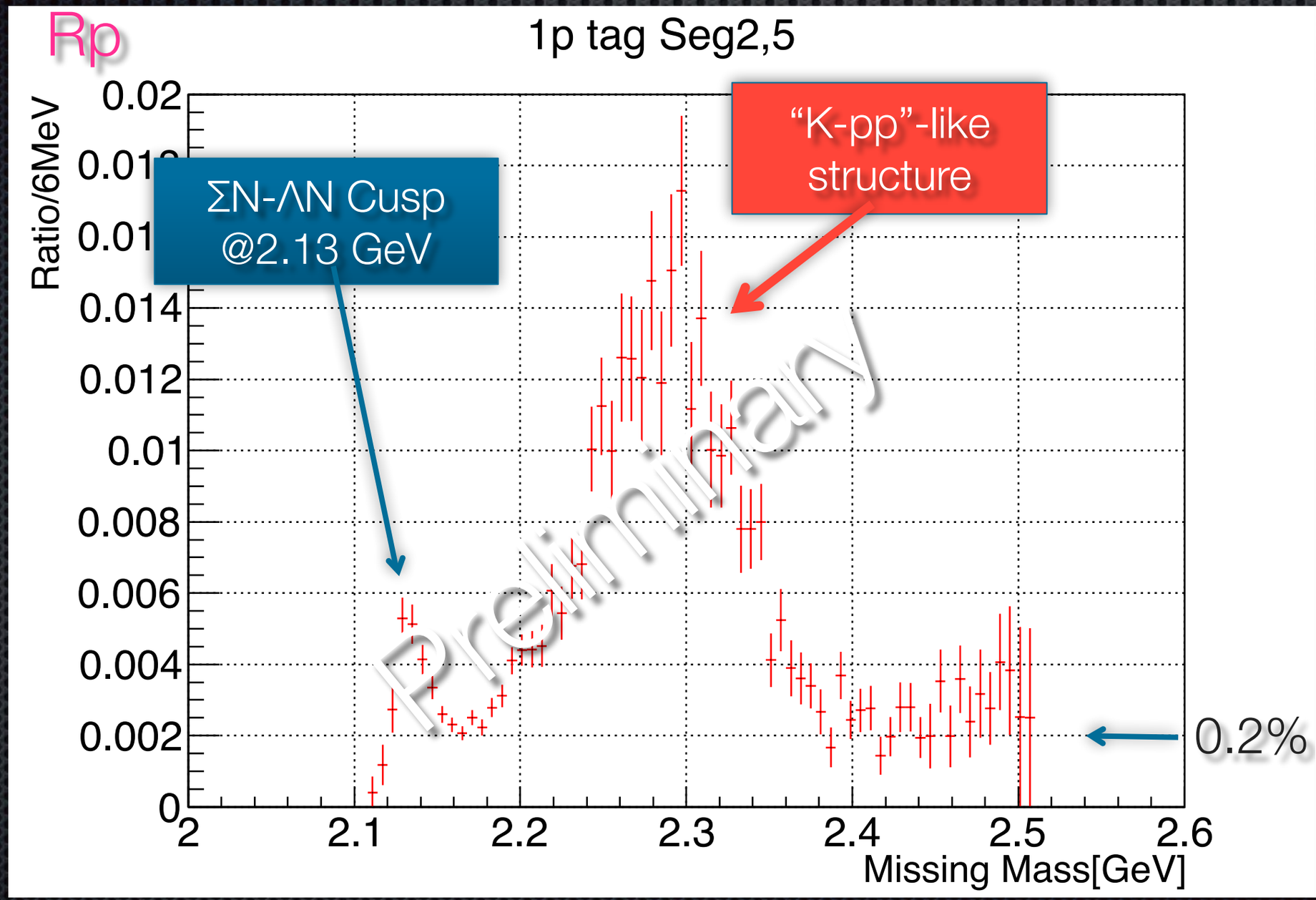


Pion Coincidence Rate

- R_π = (Pion coincidence spectrum)/(Inclusive spectrum)
- $R_\pi \propto$ (π emission BR)x(π detection efficiency)



Proton Coincidence Rate

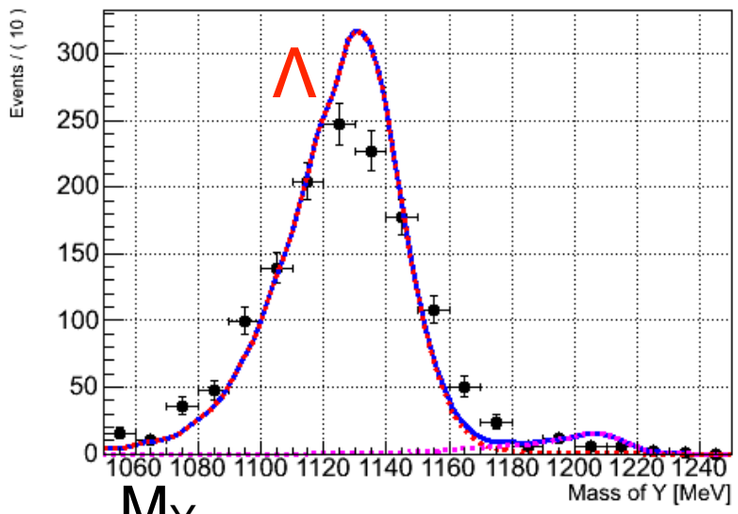


Hyperon mass with two protons

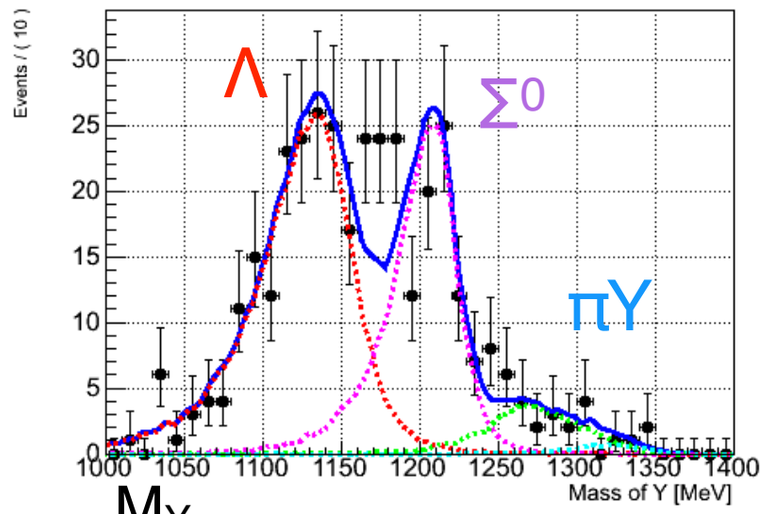
- $d(\pi^+,K^+)K^-pp$; $K^-pp \rightarrow Y+p$, $Y \rightarrow \pi+p(+\pi)$
  - $M_Y^2 = (E_\pi+M_d-E_{K^-}-E_p)^2-(p_\pi-p_{K^-}-p_p)^2$

Black: Data , Red: Λp, Pink: Σ^0p, Green: Λπ^0p, Sky: $\Sigma^+\pi^-$p, Blue: All component

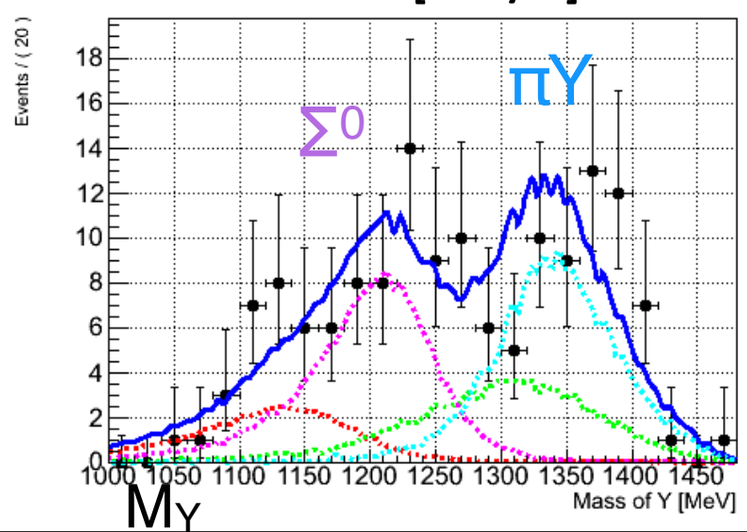
2.1<MM<2.22[GeV/c²]

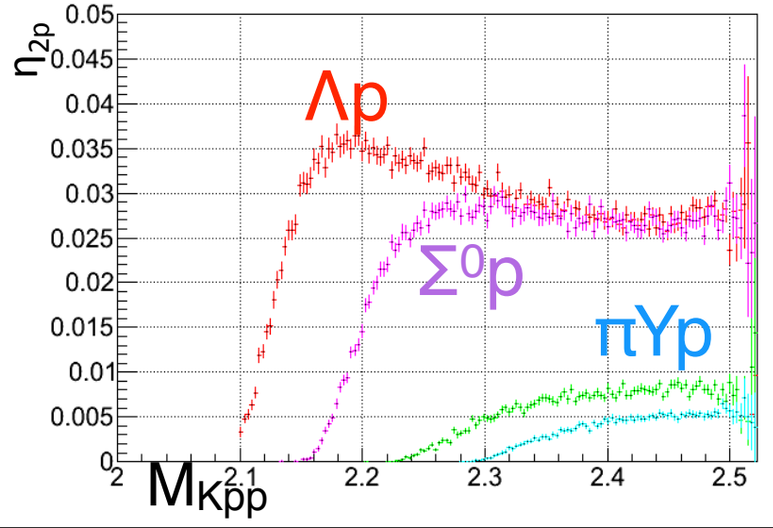


2.22<MM<2.35[GeV/c²]



MM>2.35 ¡[GeV/c²]





Summary

- Λ -Hypernuclei
  - E10: Neutron-rich hypernuclei; $^{6}_{\Lambda}$H
  - E13: Hypernuclear γ-ray spectroscopy; $^{19}_{\Lambda}$F, $^{4}_{\Lambda}$He
- $\Lambda\,\Lambda$ -Hypernuclei
  - E07: Hybrid-emulsion experiment
- Ξ -Hypernuclei
  - E05: (K^-,K^+) spectroscopy with S-2S
- Kaonic Nuclei (*K^-pp* bound state)
  - E15: ^{3}He(K^-,n)
  - E27: d(π^+,K^+)