NSmatter@YITP,
Oct. 25, 2013

Baryon-Baryon Interactions obtained from Hypernuclear studies

Tomofumi NAGAE
Kyoto University

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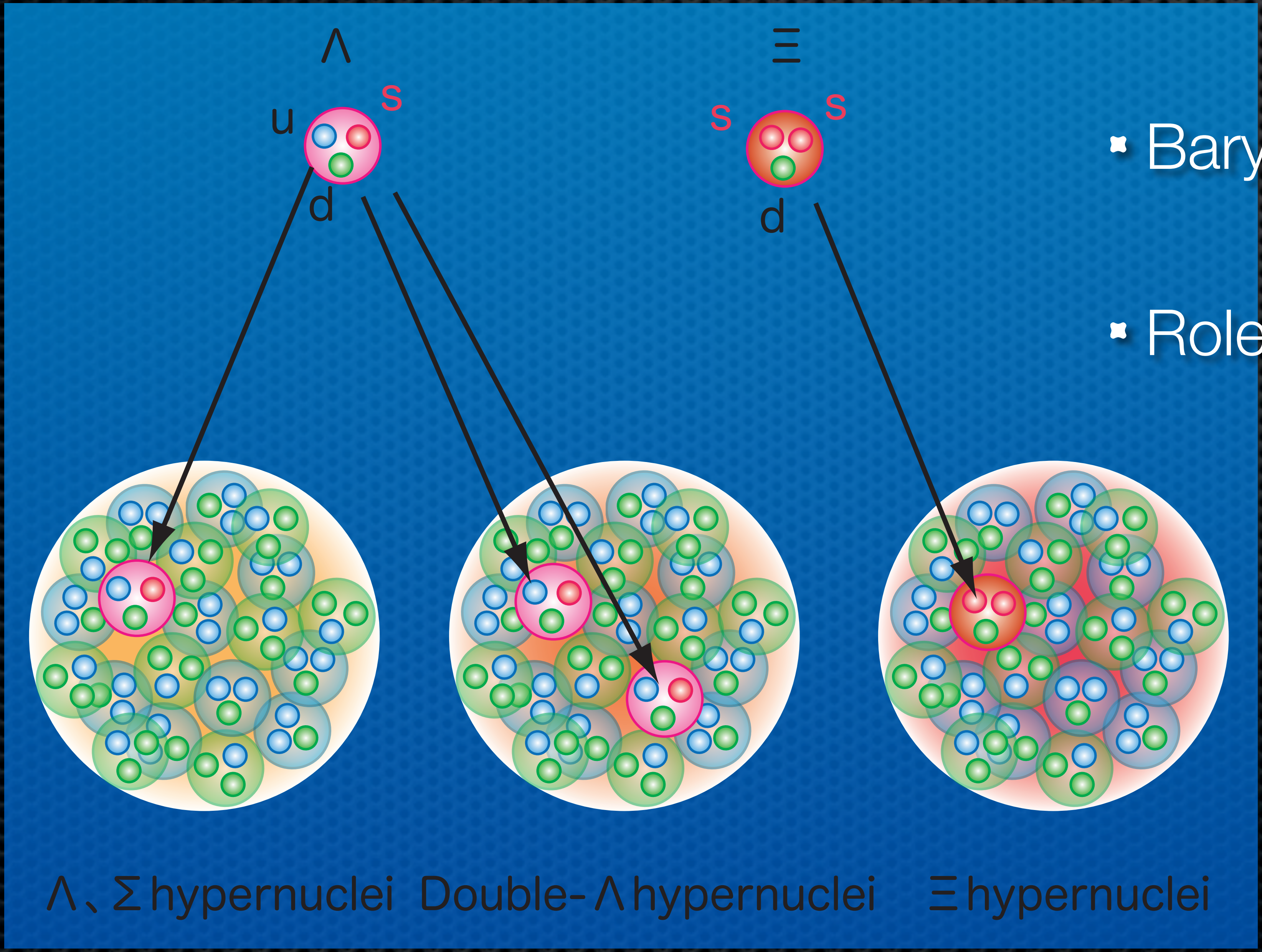
- Introduction to Strangeness Nuclear Physics
- Baryon-Baryon Interactions
    - S=-1 Baryon Systems
    - S=-2 Baryon Systems
    - Kaonic Nuclei
- Summary

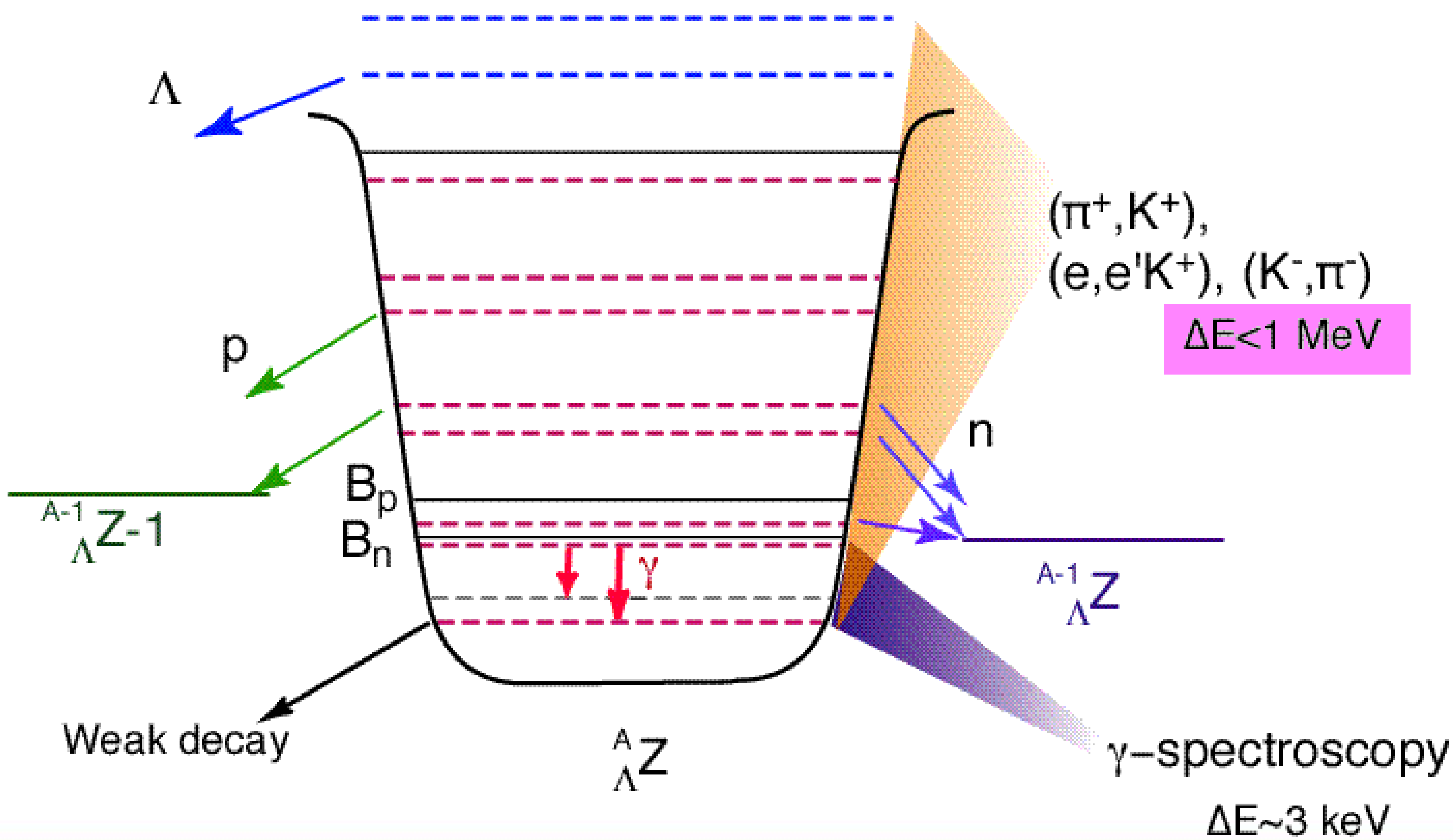
Hadron Many-Body Systems with Strangeness

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

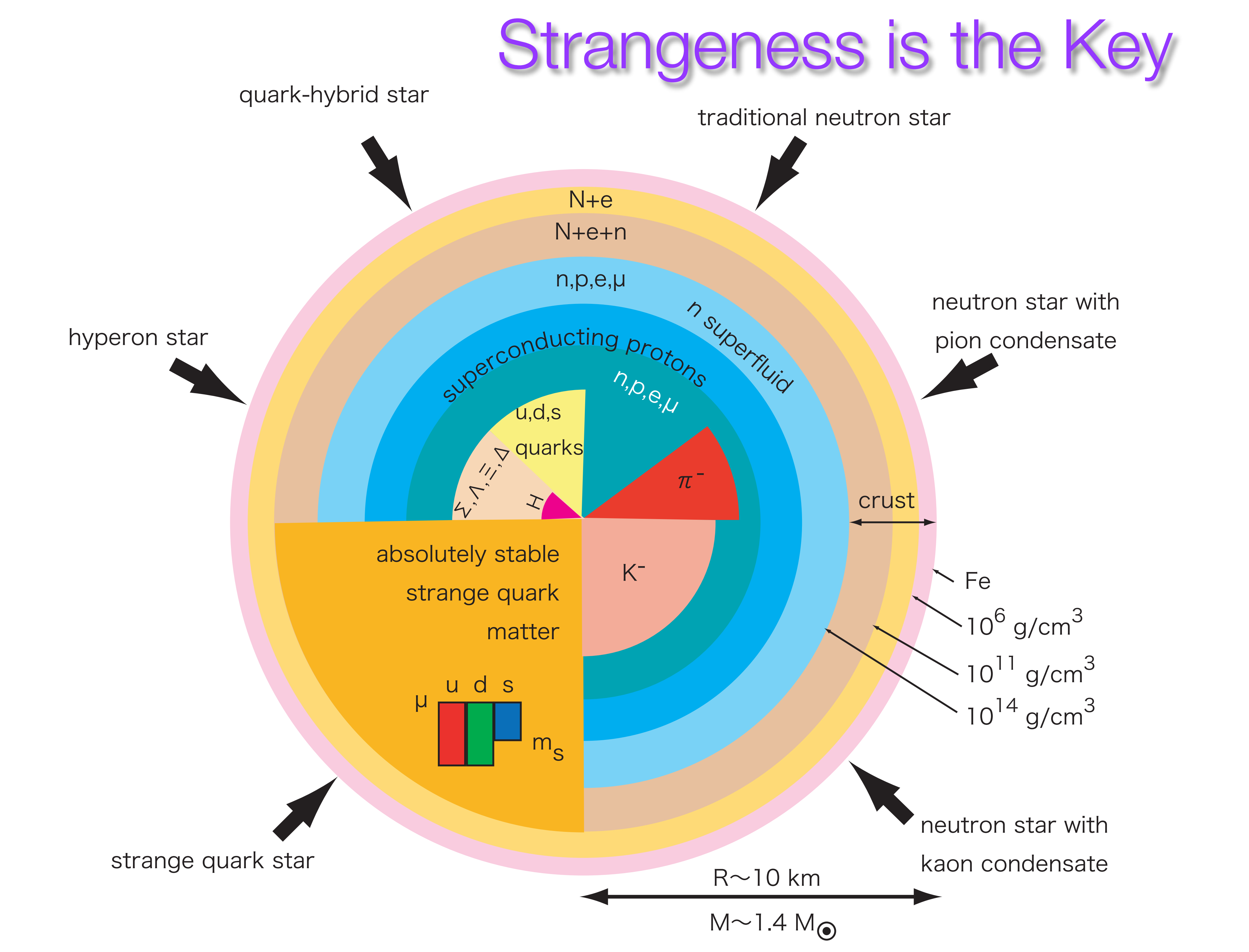


- Baryon-Baryon Interactions in $SU_F(3)$
- Role of Strangeness in Dense Matter

Excited levels of Λ-hypernuclei



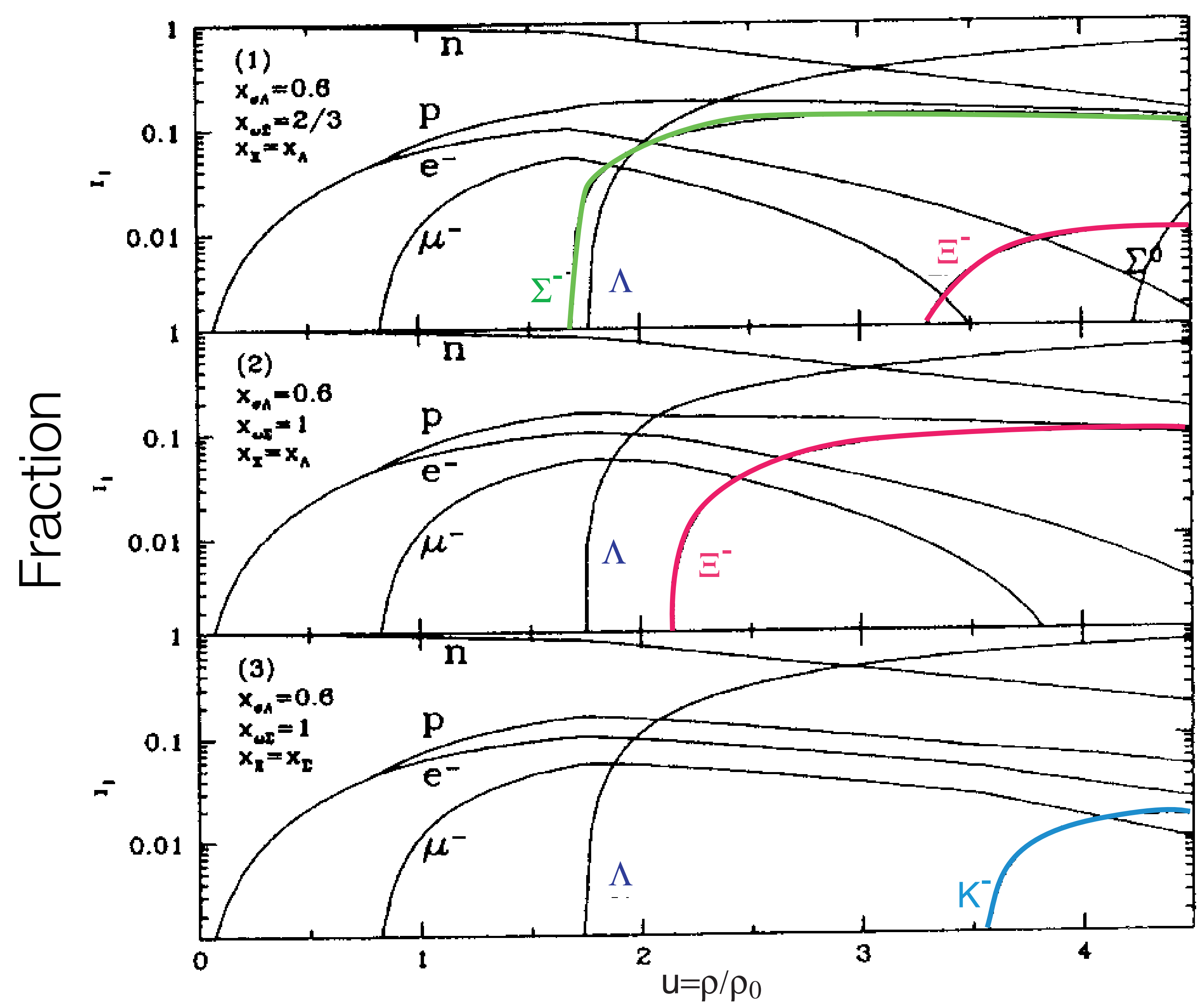
What's in the Neutron Star Core ?



By F. Weber

Ξ -Nucleus potential ?

- Chemical Potential: $$\mu_B = m_B + \frac{k_F^{\,2}}{2m_B} + \boxed{U(k_F)}$$



U Σ <0, U Ξ <0

U Σ >0, U Ξ <0

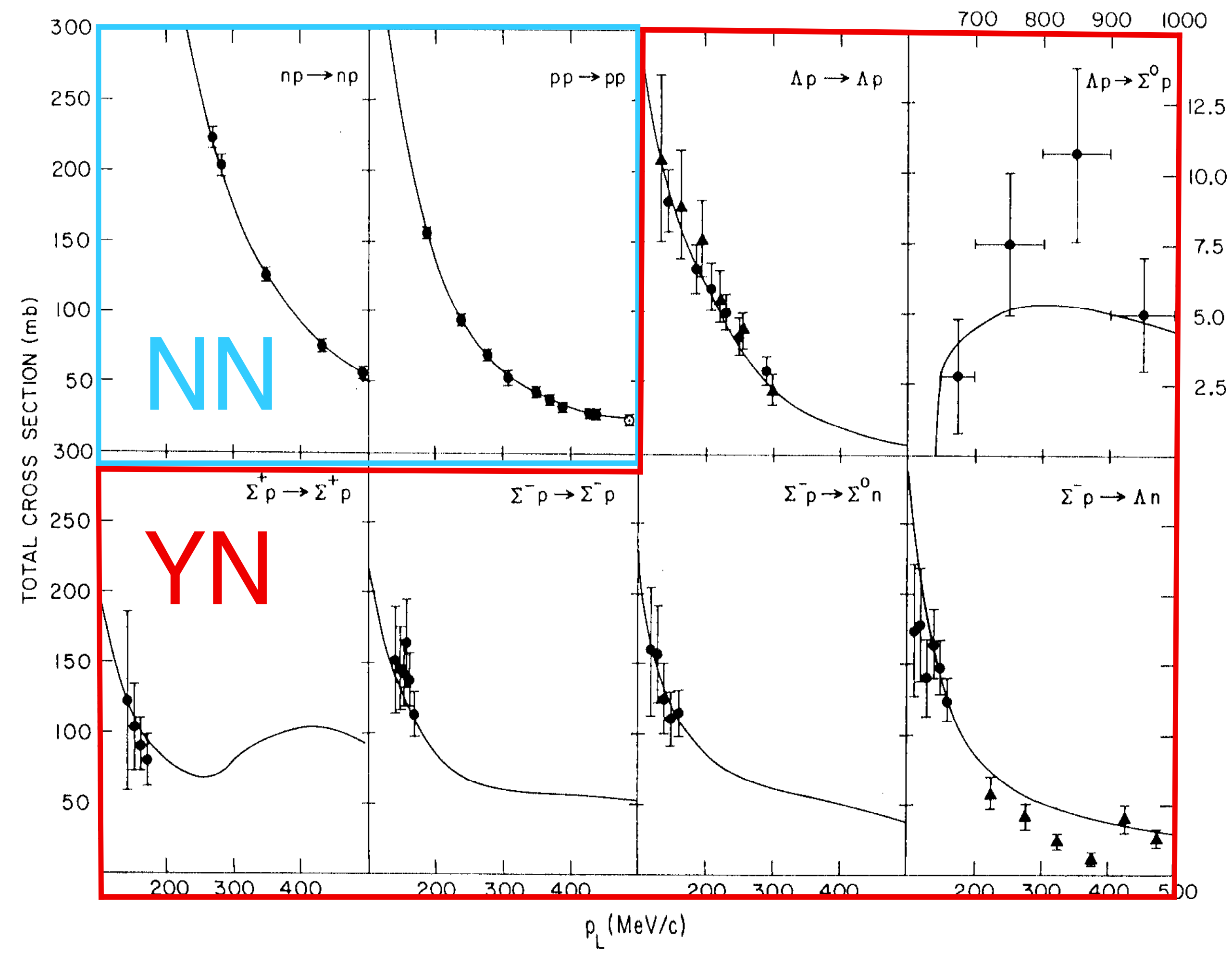
U Σ >0, U Ξ >0

Hyperon-Nucleon Scattering

$\Sigma^{\pm}p$, Λp: only 38 data points

- $\Xi^{-}p$ elastic scattering and $\Xi^{-}p \rightarrow \Lambda\Lambda$ reaction
- Asymmetry in Λp and $\Sigma^{+}p$ elastic scattering

Λ+p, Σ^{+}+p, Σ^{-}+p and Ξ^{-}+p scattering



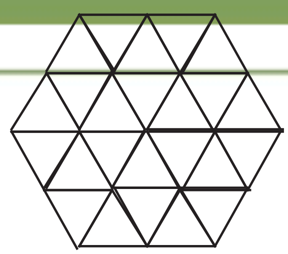
from Dover & Feshbach Ann.Phys.198(90)321

Need high quality data with high statistics

Baryon-Baryon Interaction

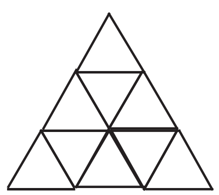
Baryon-Baryon Systems in SU(3)

27_s



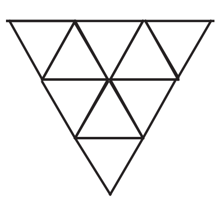
S=0 NN(T=1)
S=-1 ΣN(T=3/2)ΣN−ΛN(T=1/2)
S=-2 ΣΣ(T=2)ΞN−ΣΛ−ΣΣ(T=1)ΞN−ΣΣ−ΛΛ(T=0)
S=-3 ΞΣ(T=3/2)ΞΣ−ΞΛ(T=1/2)
S=-4 ΞΞ(T=1)

10_a



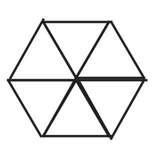
S=0 NN(T=0)
S=-1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ(T=1)
S=-3 ΞΣ(T=3/2)

10_a



S=−1 ΣN(T=3/2)
S=-2 ΞN−ΣΛ−ΣΣ(T=1)
S=-3 ΞΣ−ΞΛ(T=1/2)
S=-4 ΞΞ(T=0)

8_s



S=−1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ(T=1)ΞN−ΣΣ−ΛΛ(T=0)
S=-3 ΞΣ−ΞΛ(T=1/2)

8_a

S=−1 ΣN−ΛN(T=1/2)
S=-2 ΞN−ΣΛ−ΣΣ(T=1)ΞN(T=0)
S=-3 ΞΣ−ΞΛ(T=1/2)

1_s •

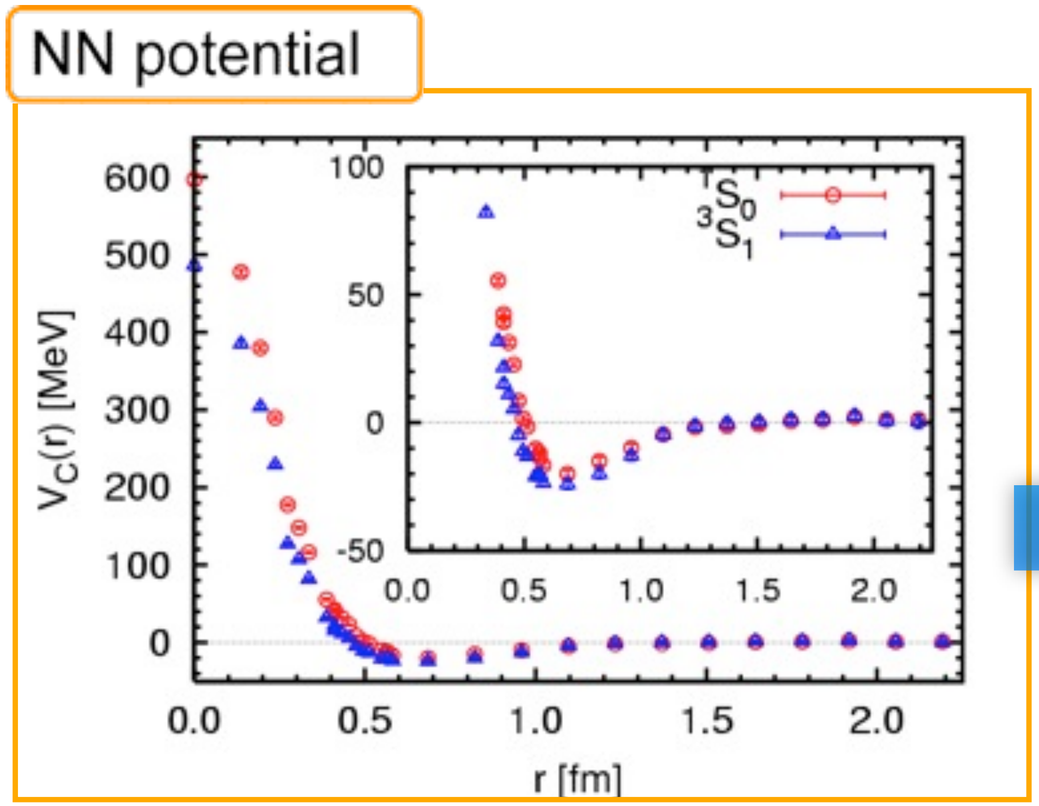
S=−2 ΞN−ΣΣ−ΛΛ(T=0)

H Dibaryon ?

- Understanding of the flavor SU(3) baryon-baryon interaction
  - Y-N, Y-Y < N-N ?
    Repulsive or Attractive ?
  - Repulsive cores in Y-N/Y-Y ?
    What’s the origin ?
  - Spin-dependent forces in Y-N/Y-Y.
  - Dibaryons

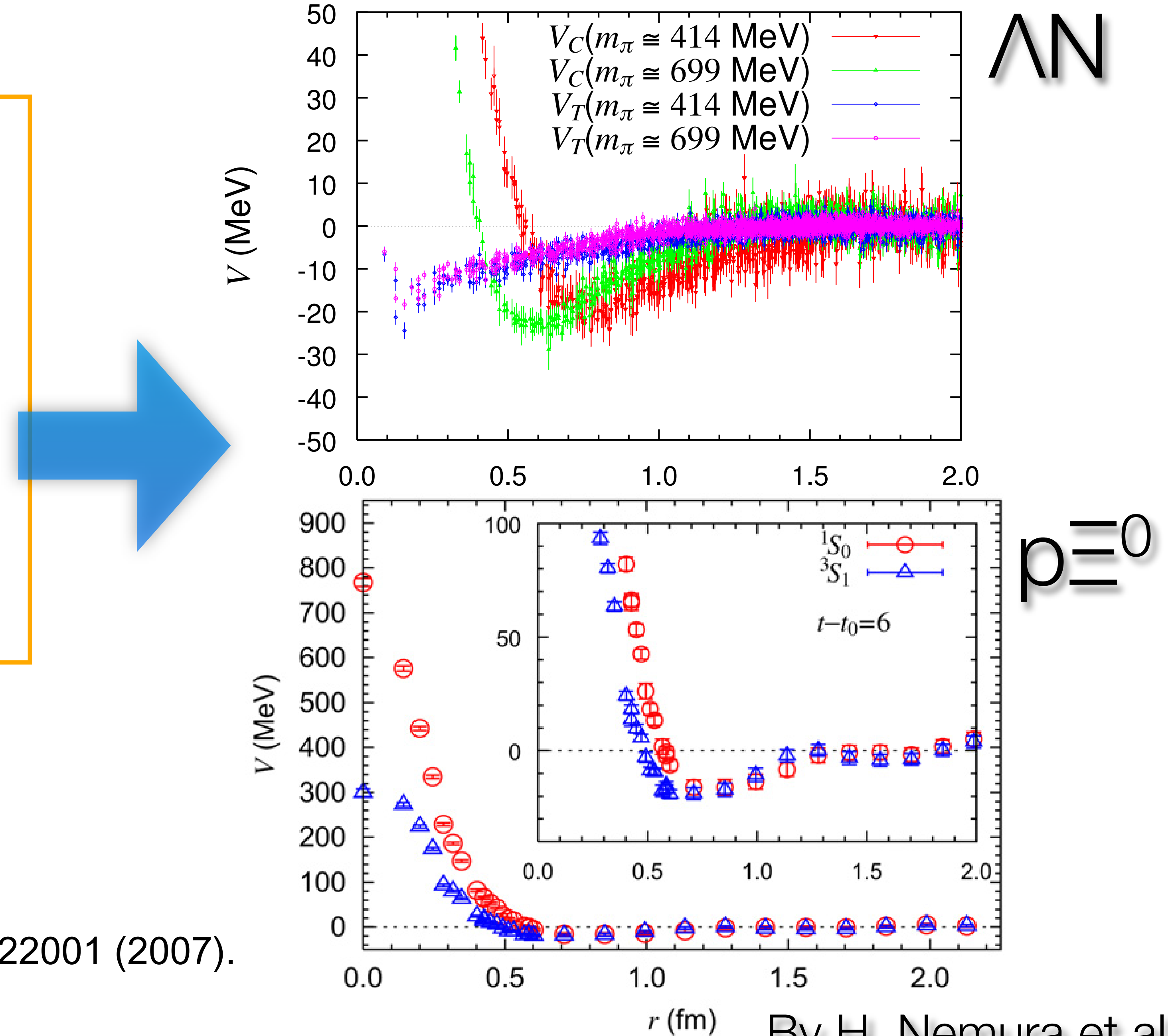
Modern Picture of Baryon-Baryon Interactions

- Nuclear Force from Lattice QCD



Long-range attraction
+
Repulsive Hard-core

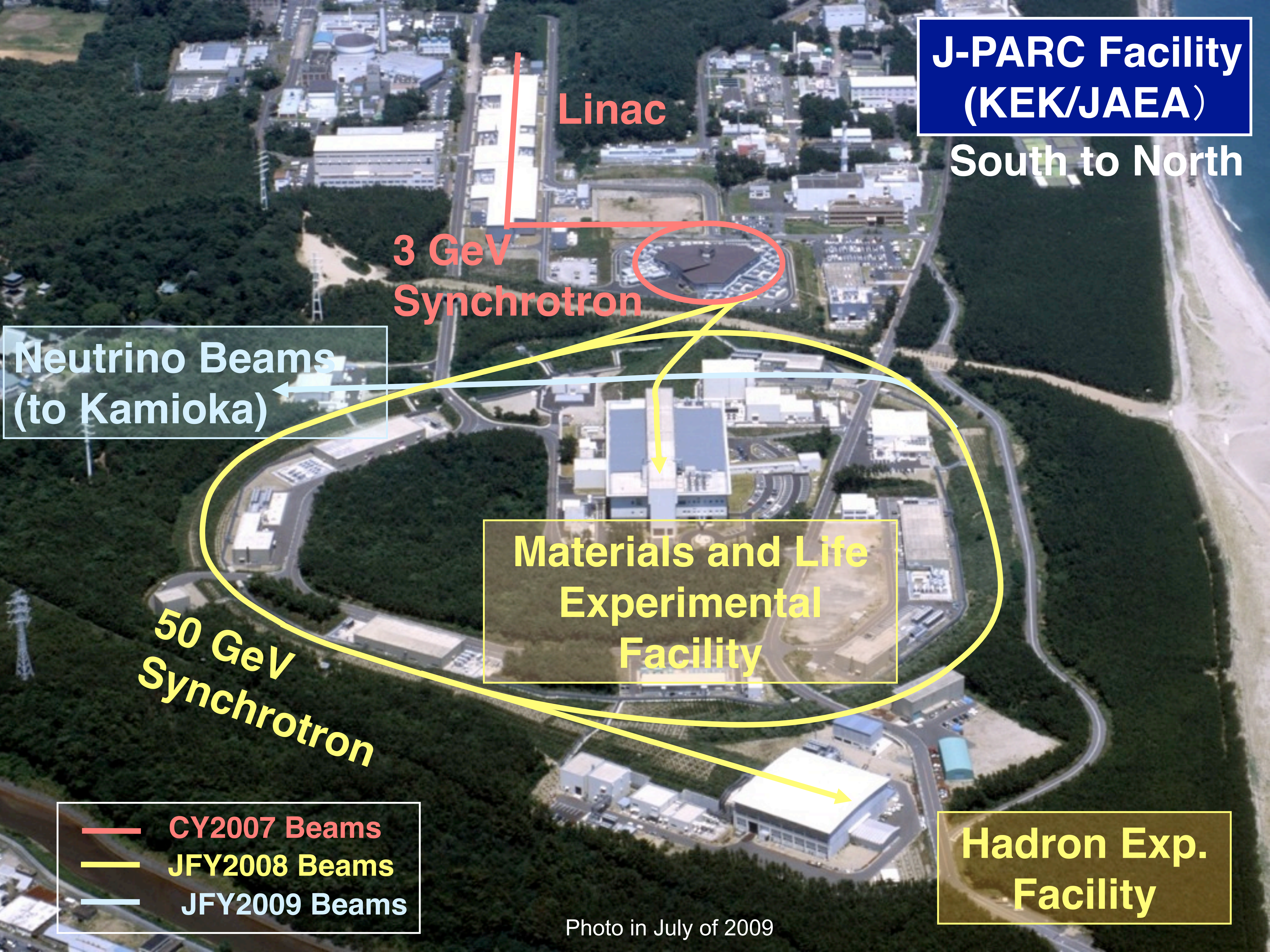
N.Ishii, S.Aoki, T.Hatsuda, Phys.Rev.Lett.99,022001 (2007).



By H. Nemura et al.

World Facilities in the 21st Century

For Strangeness Nuclear Physics

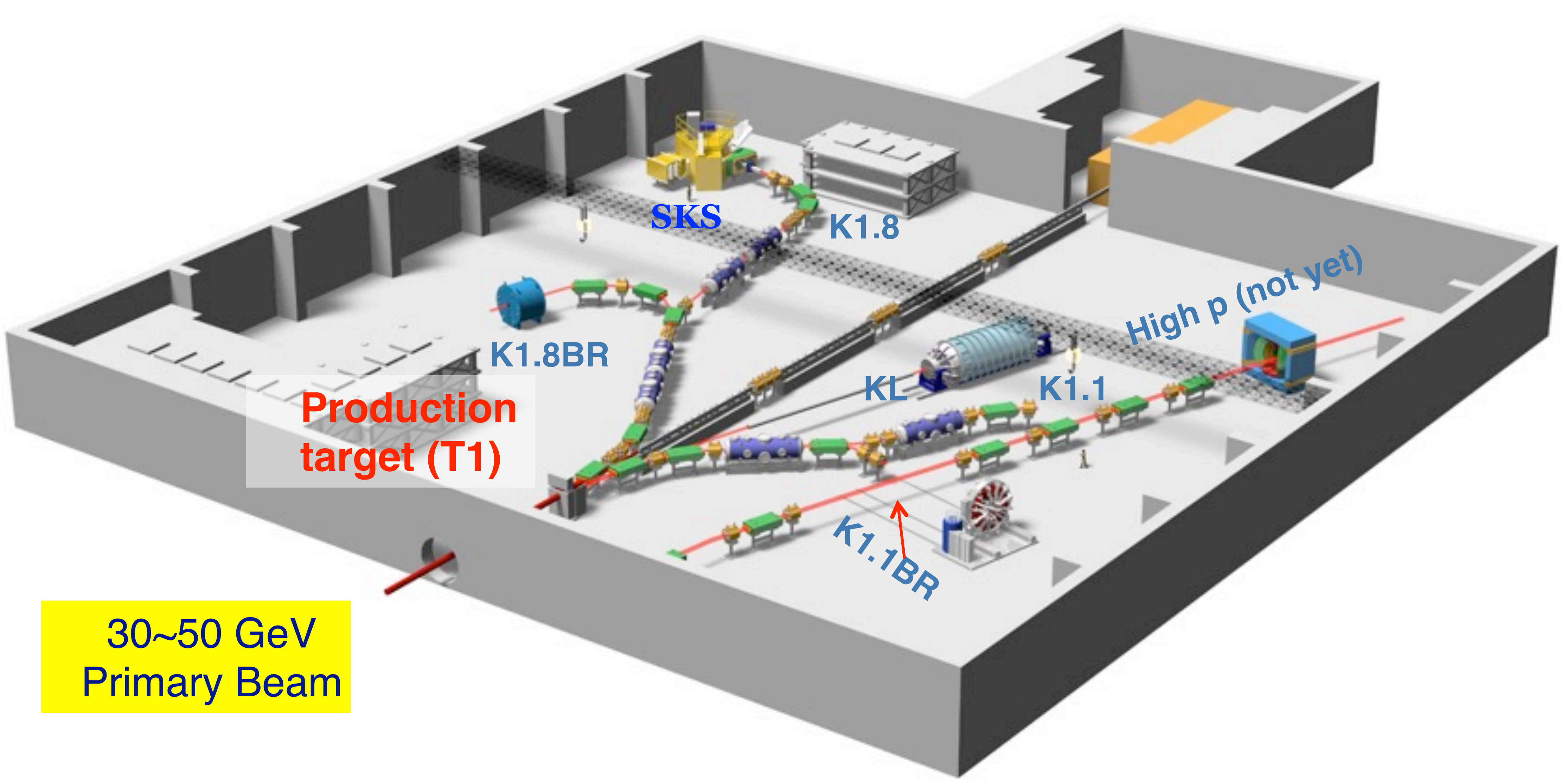

J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Photo in July of 2009

Hadron Experimental Hall

World highest intensity Kaon beams !

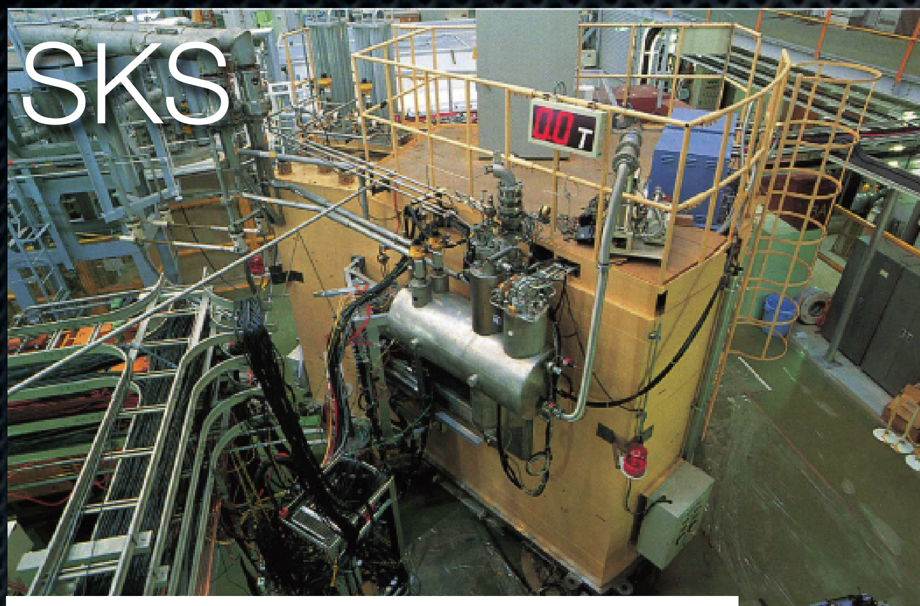
First beam in Feb. 2009

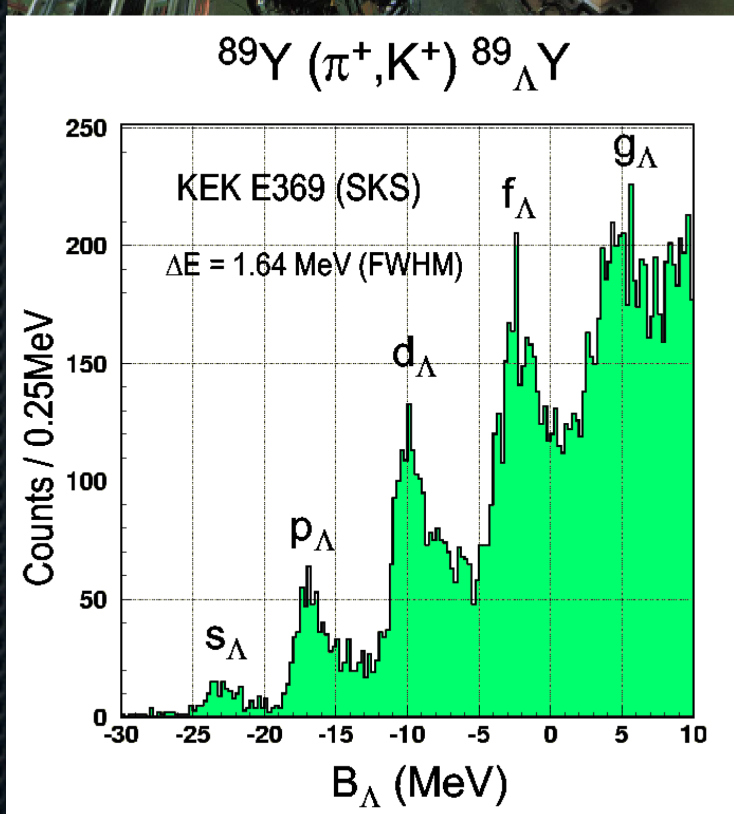
60m x 56m



S=-1 Baryon Systems

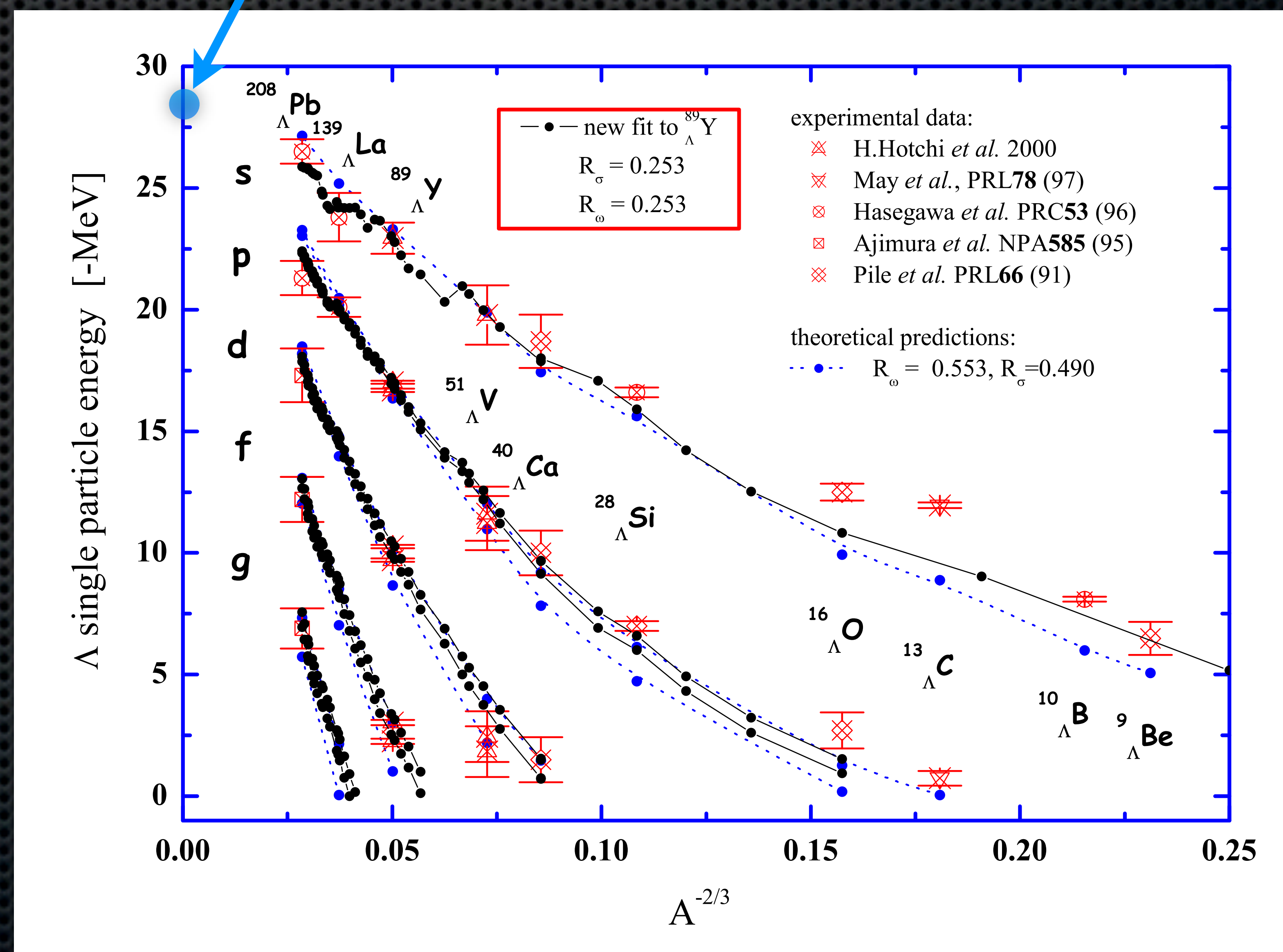
(π^+,K^+) Spectroscopy



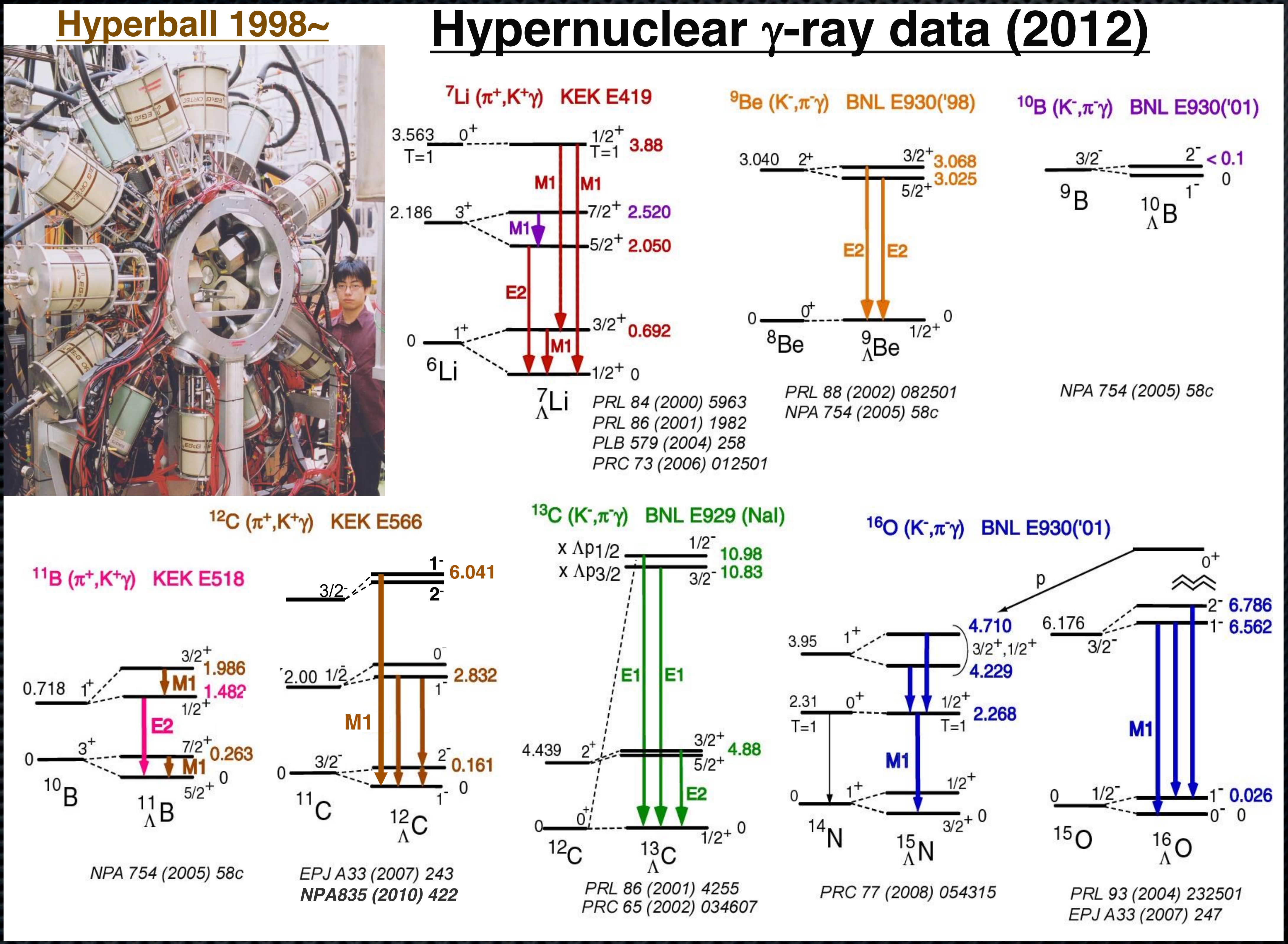


H.Hotchi et al., PRC 64, 044302(2001)

- Λ single-particle energy
  → U_Λ=28 MeV



Hypernuclear Gamma-rays



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

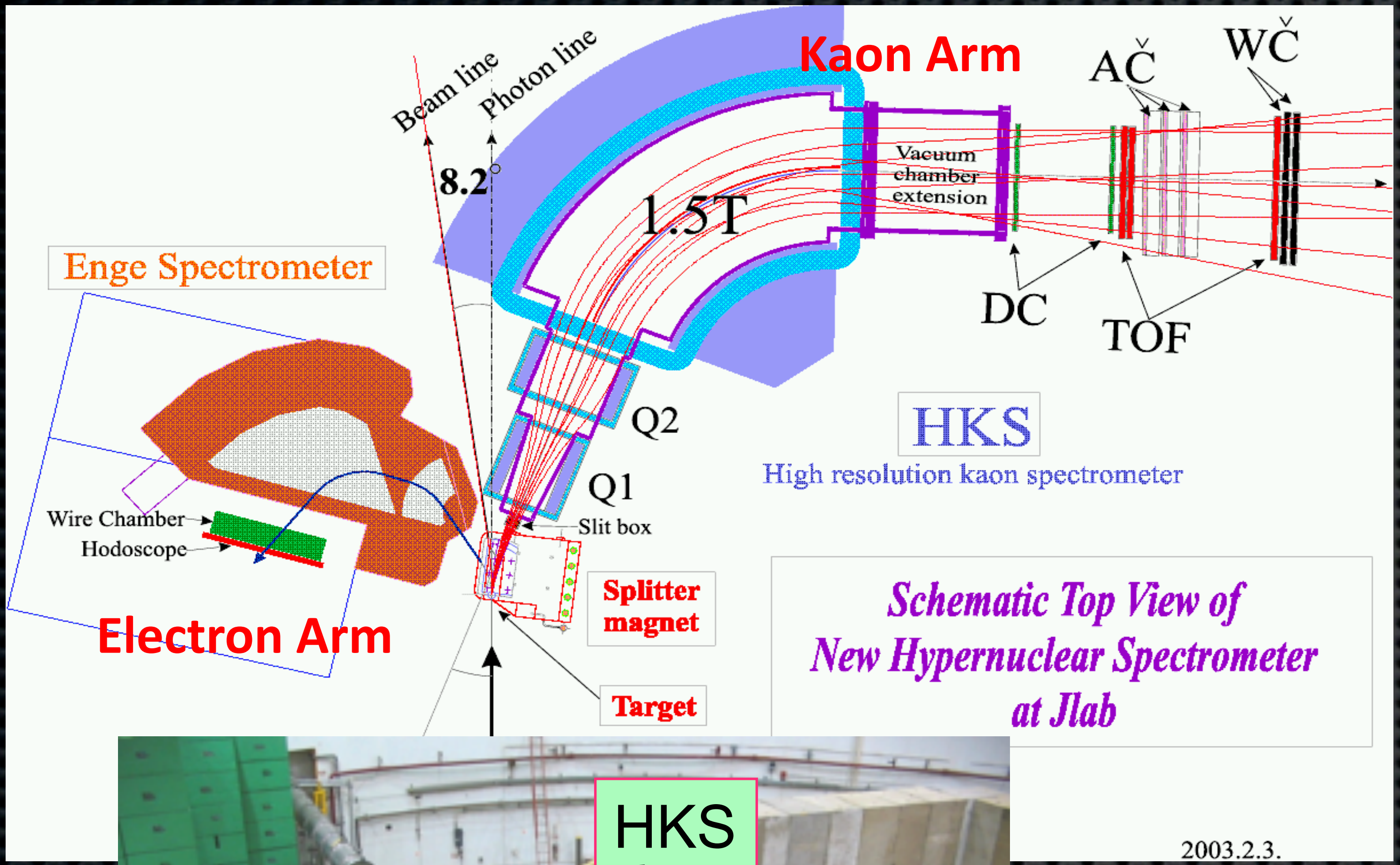
	Δ	S_Λ	S_N	T
$A = 7-\ ?$	0.430	-0.015	-0.390	0.030
$A = 11 - 16$	0.330	-0.015	-0.350	0.024

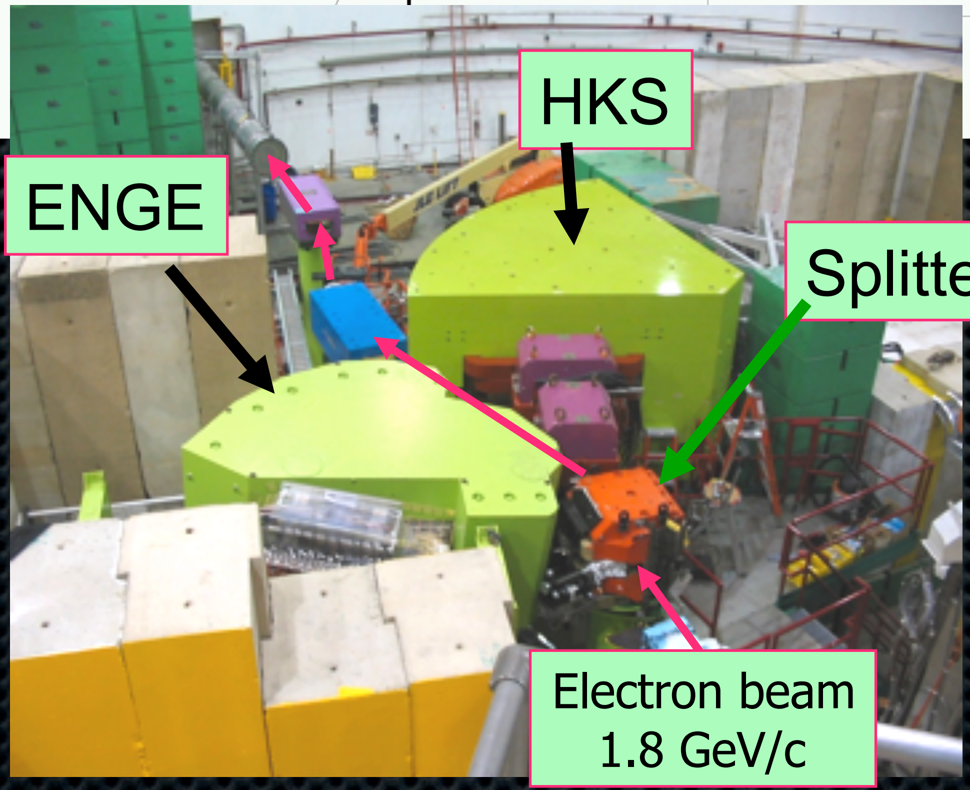
Very small LS

by D.J. Millener

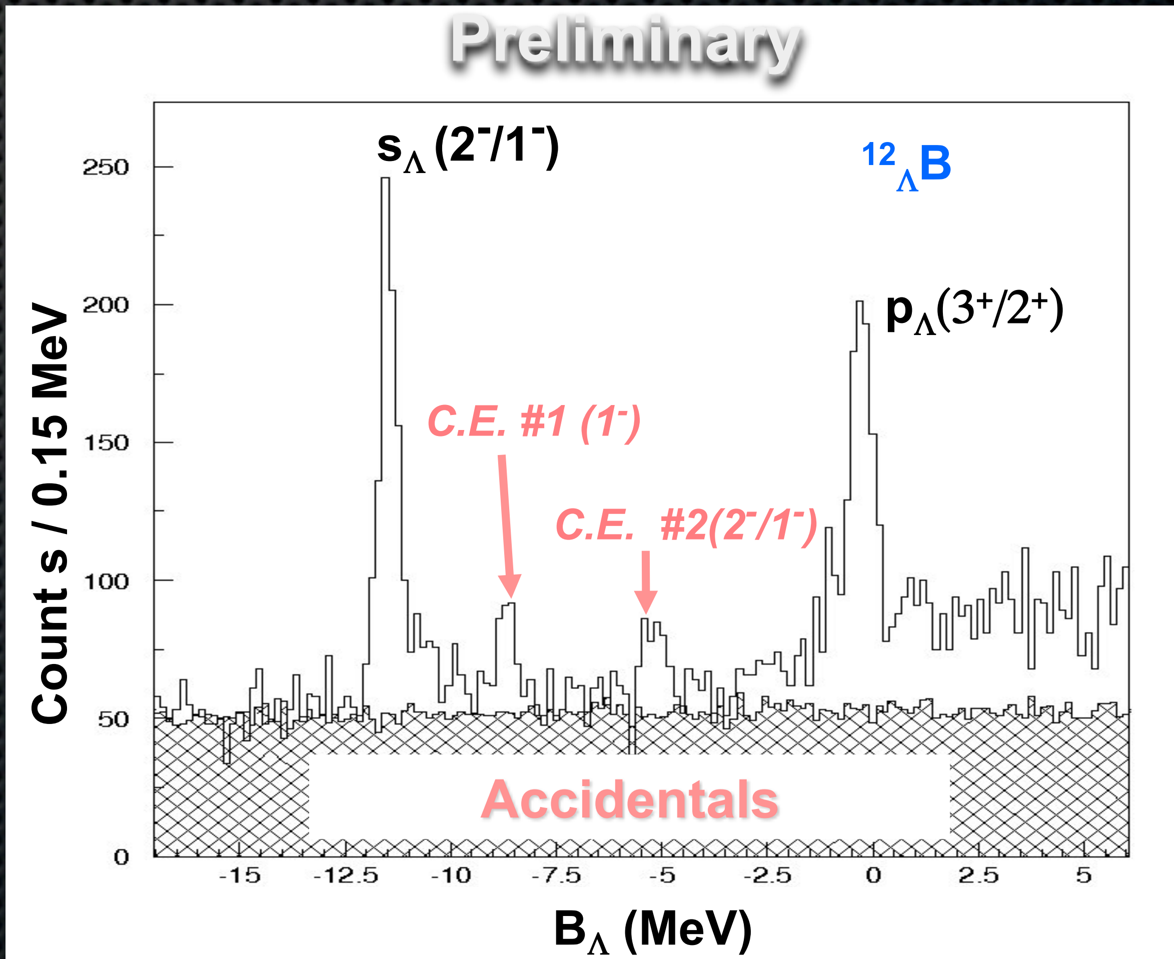
JLab: (e,e'K$^+$)

High-resolution Spectrometer in Hall-A & -C





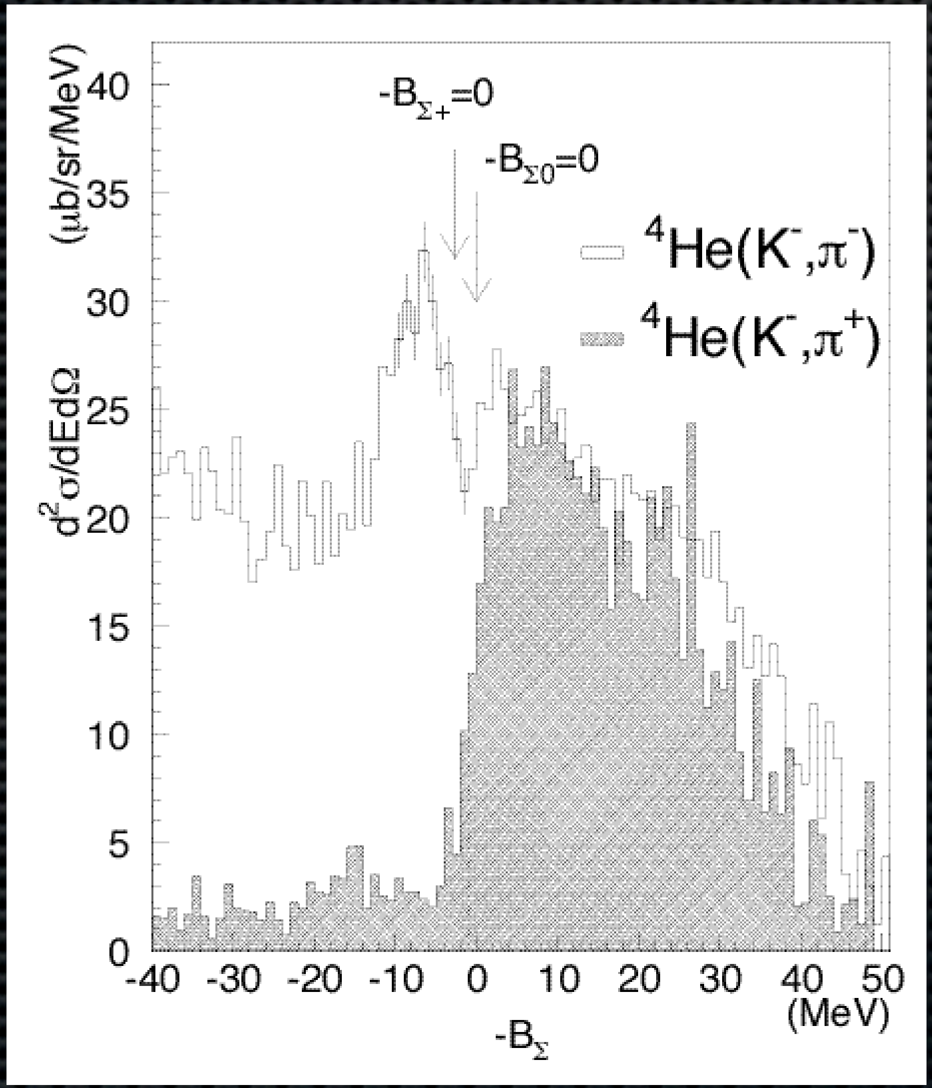
O. Hashimoto @ Hyp-X



- $^{12}{}_\Lambda B$ Ground state resolution: 465 keV FWHM

Σ -Hypernuclei

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

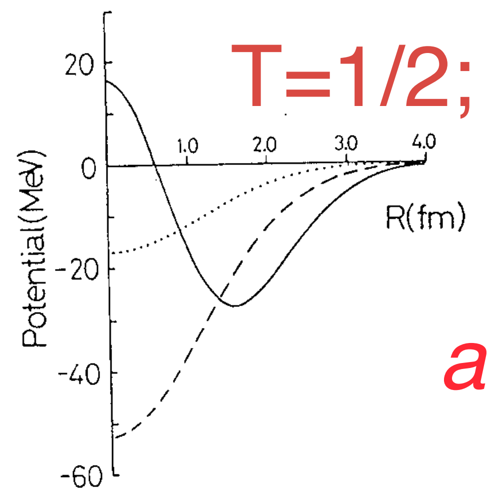


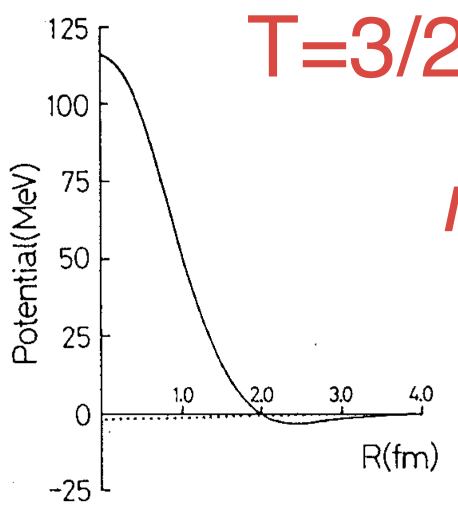
T. Nagae et al., PRL 80 (1998) 1605.

Harada and Akaishi

- ✓ Strong Isospin dependence
  - Lane term
  - $U_{C\Sigma} = U^0 + U^t T_C \cdot t_\Sigma / A$

- T. Harada et al., Nucl. Phys. A507(1990) 715.
- T. Harada, PRL 81 (1998) 5287.



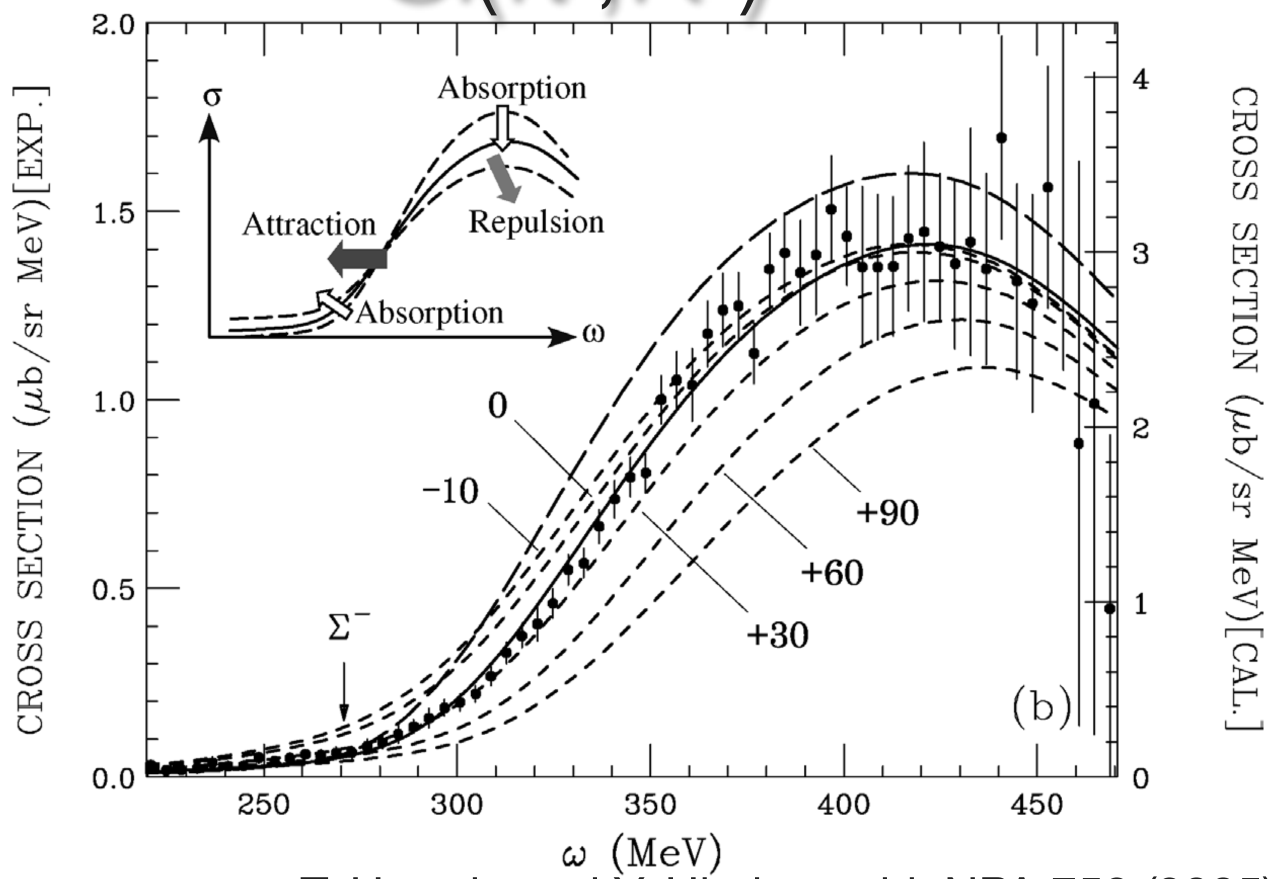


Repulsive in Medium-Heavy Nuclei

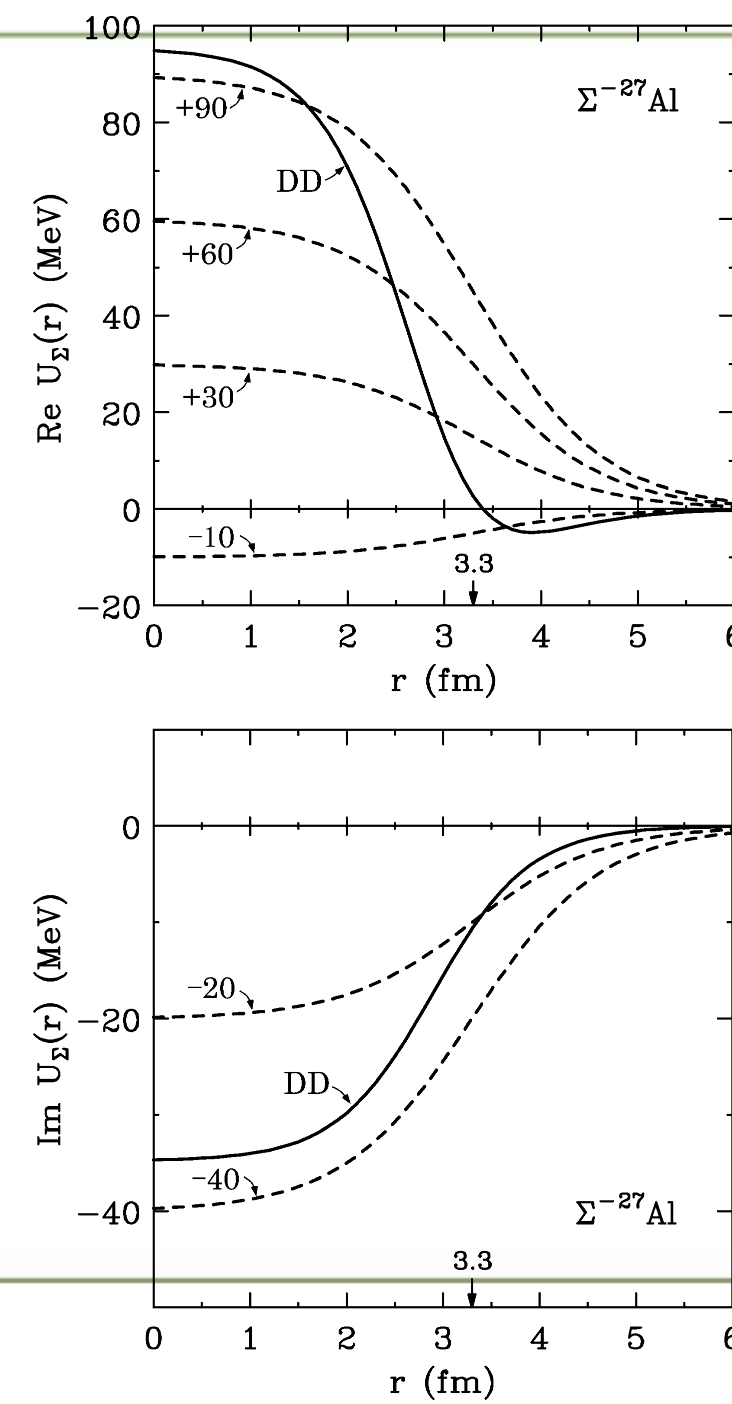
T. Harada, Y. Hirabayashi / Nuclear Physics A 759 (2005) 143–169

- V_0=+30 MeV, W_0=-40 MeV

$^{28}Si(\pi^-,K^+)$



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



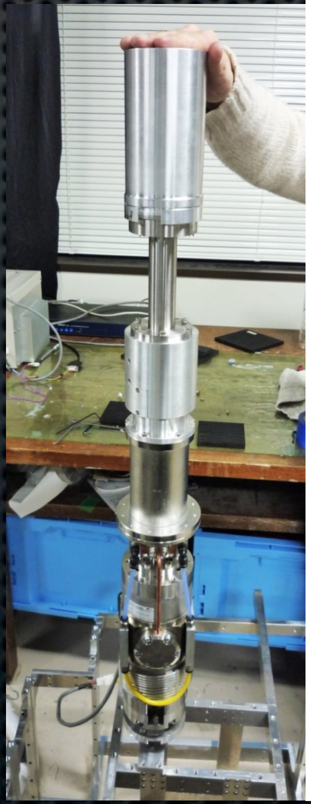
Gamma-ray Spectroscopy of Light Hypernuclei

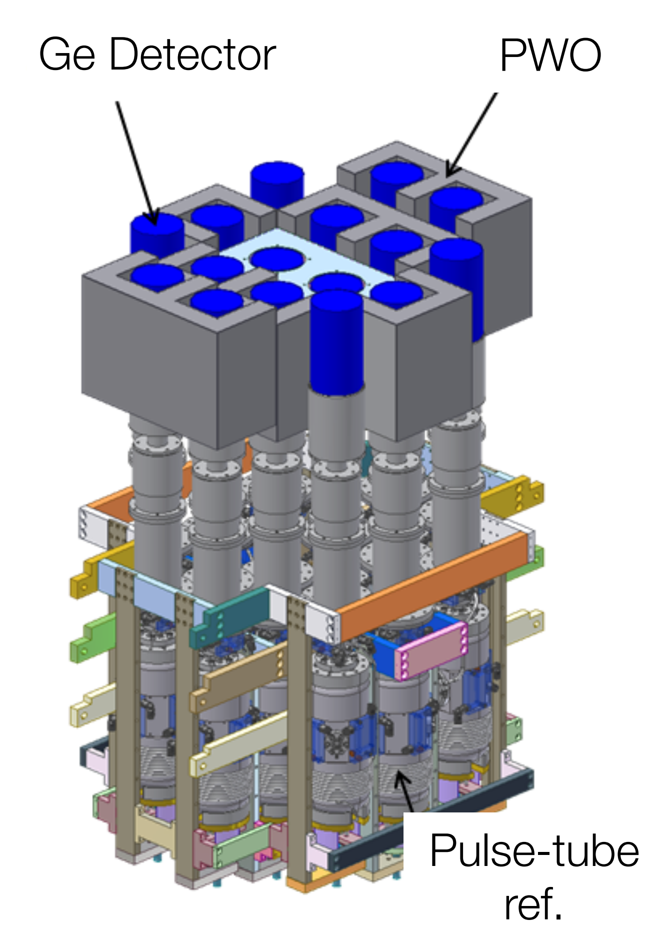
J-PARC E13
H. Tamura et al.

- Spin-flip B(M1) measurement for g_Λ in nuclei
  - ^{7}Li(K^-,$\pi^-\gamma$)${}^{7}_{\Lambda}$Li at 1.5 GeV/c: M1($3/2^+ \rightarrow 1/2^+$)
- ΛN interaction in sd-shell hypernuclei
  - ${}^{19}_{\Lambda}$F: easiest in sd-shell
- ΛN interaction in p-shell hypernuclei
  - ${}^{10}_{\Lambda}$B
- etc.

Ge x32; ε~5.8% at 1 MeV
→ γ-γ coincidence

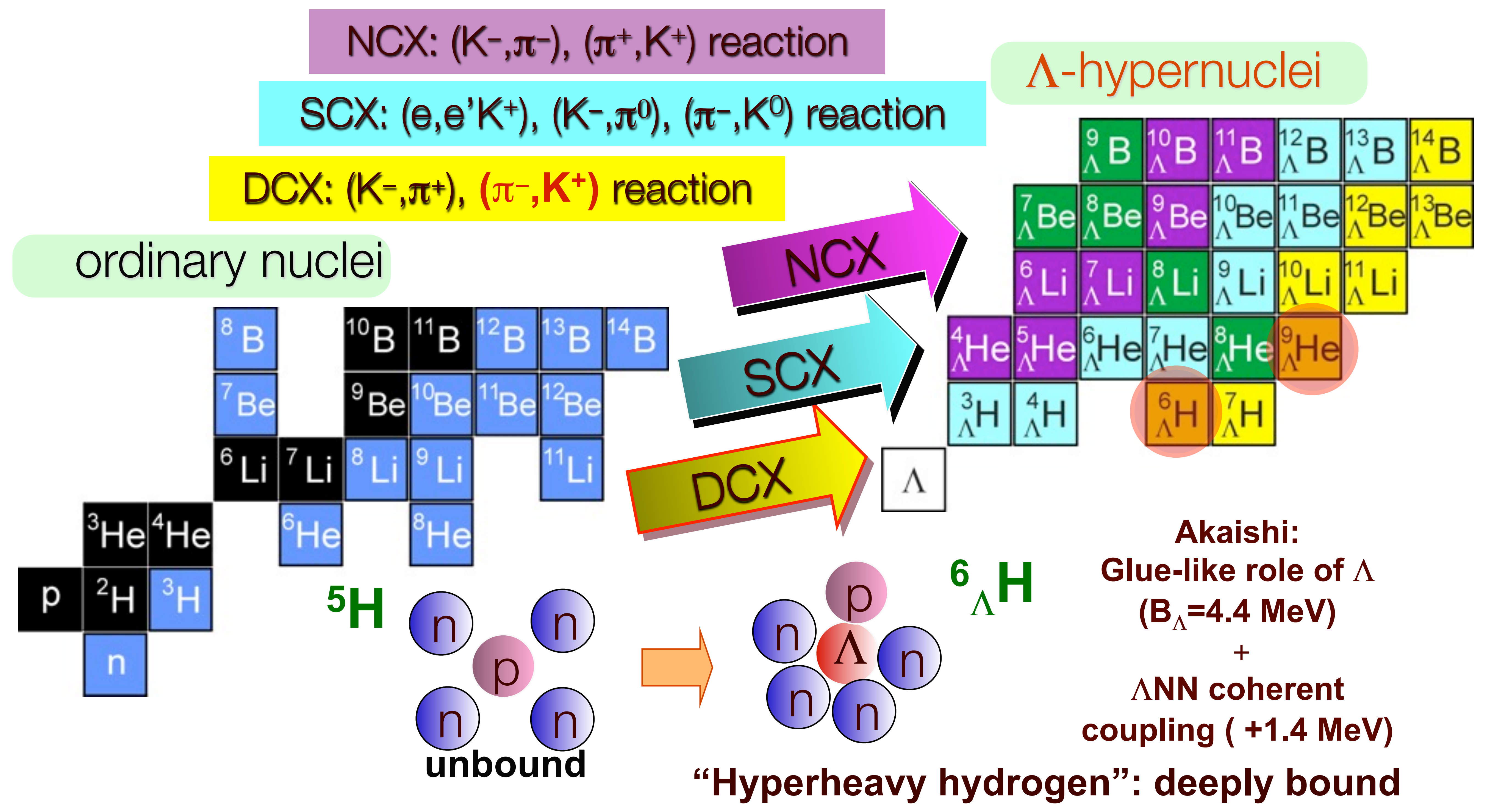
Hyperball-J





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

J-PARC E10
A. Sakaguchi et al.



S=-2 Baryon Systems

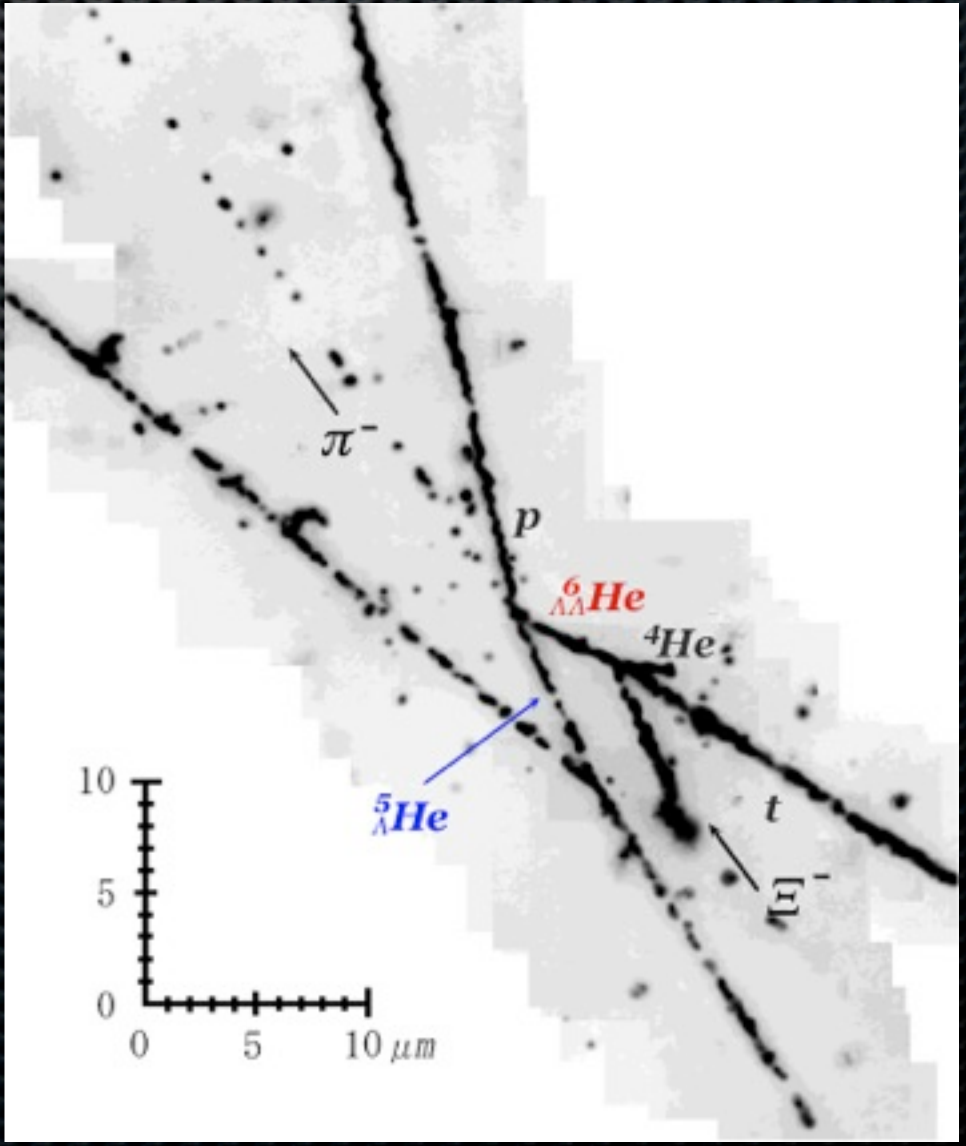
Double-Λ Hypernuclei

- "Nagara" event; $_{\Lambda\Lambda}{}^{6}\mathrm{He}$
  - Uniquely identified
  - $\Delta B_{\Lambda\Lambda}$=1.01±0.02+0.18/-0.11 MeV

    0.67±0.17 MeV
    (updated by Nakazawa@Hyp-X)

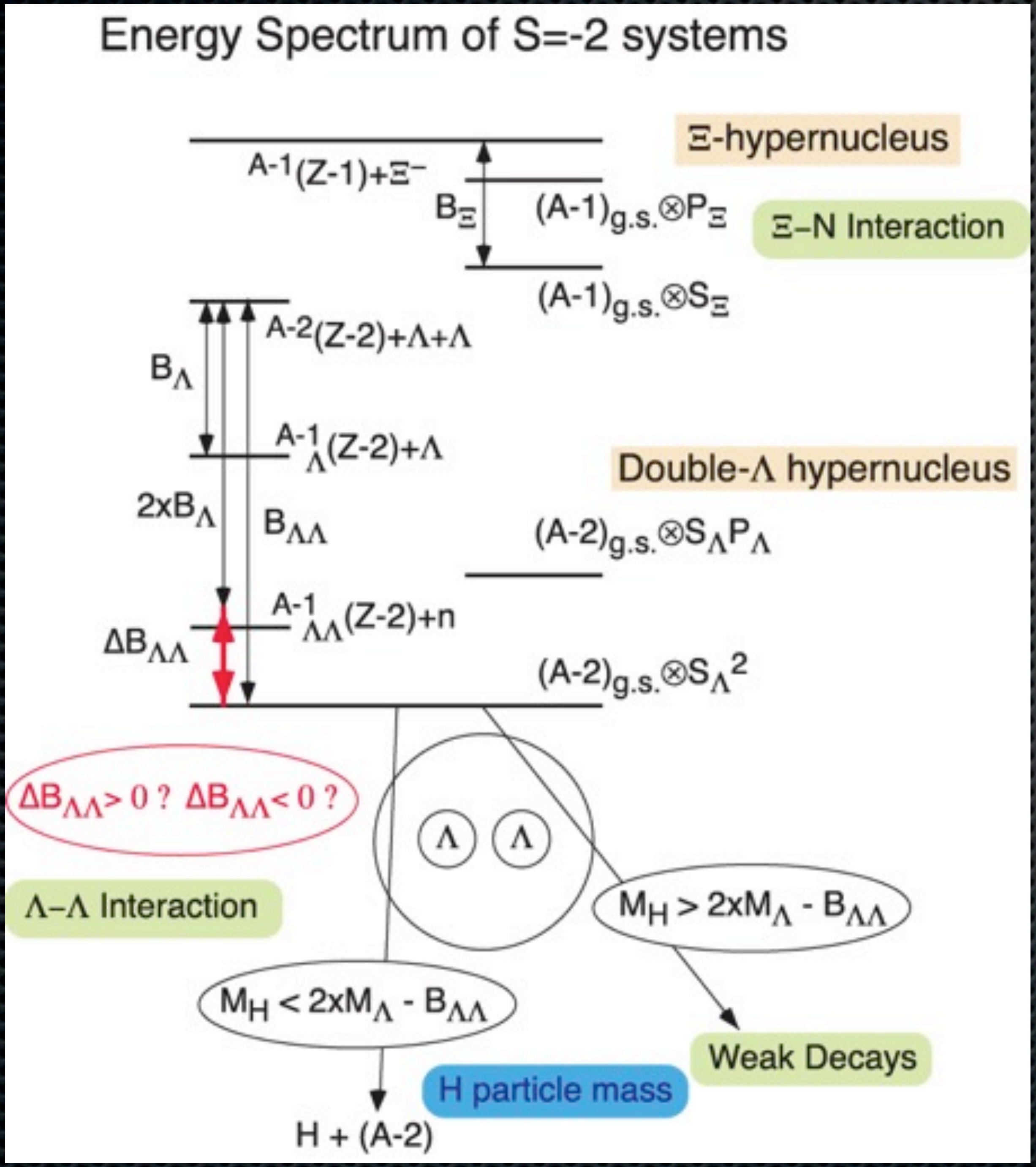
  - smaller than before (~4 MeV)

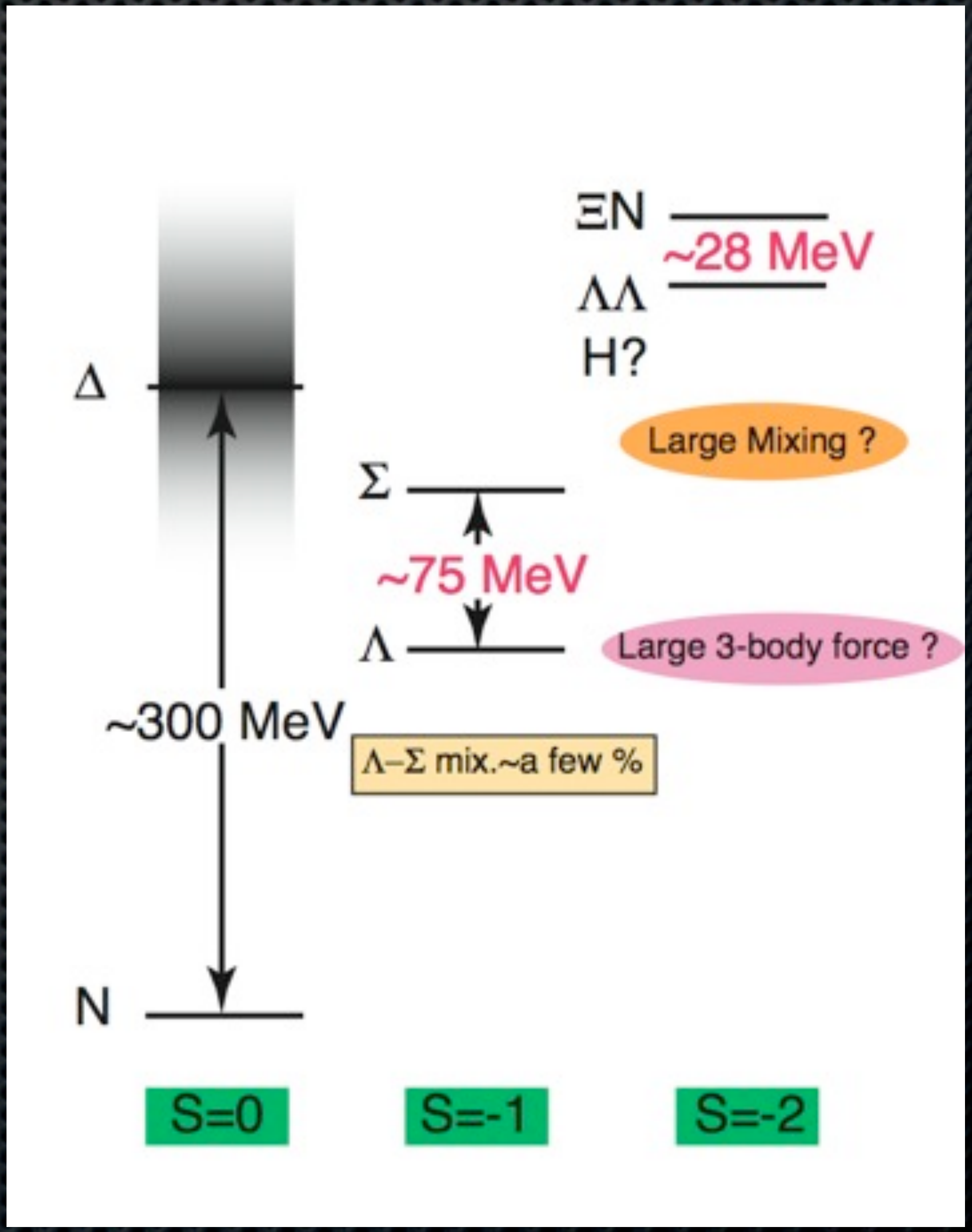
KEK E373



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

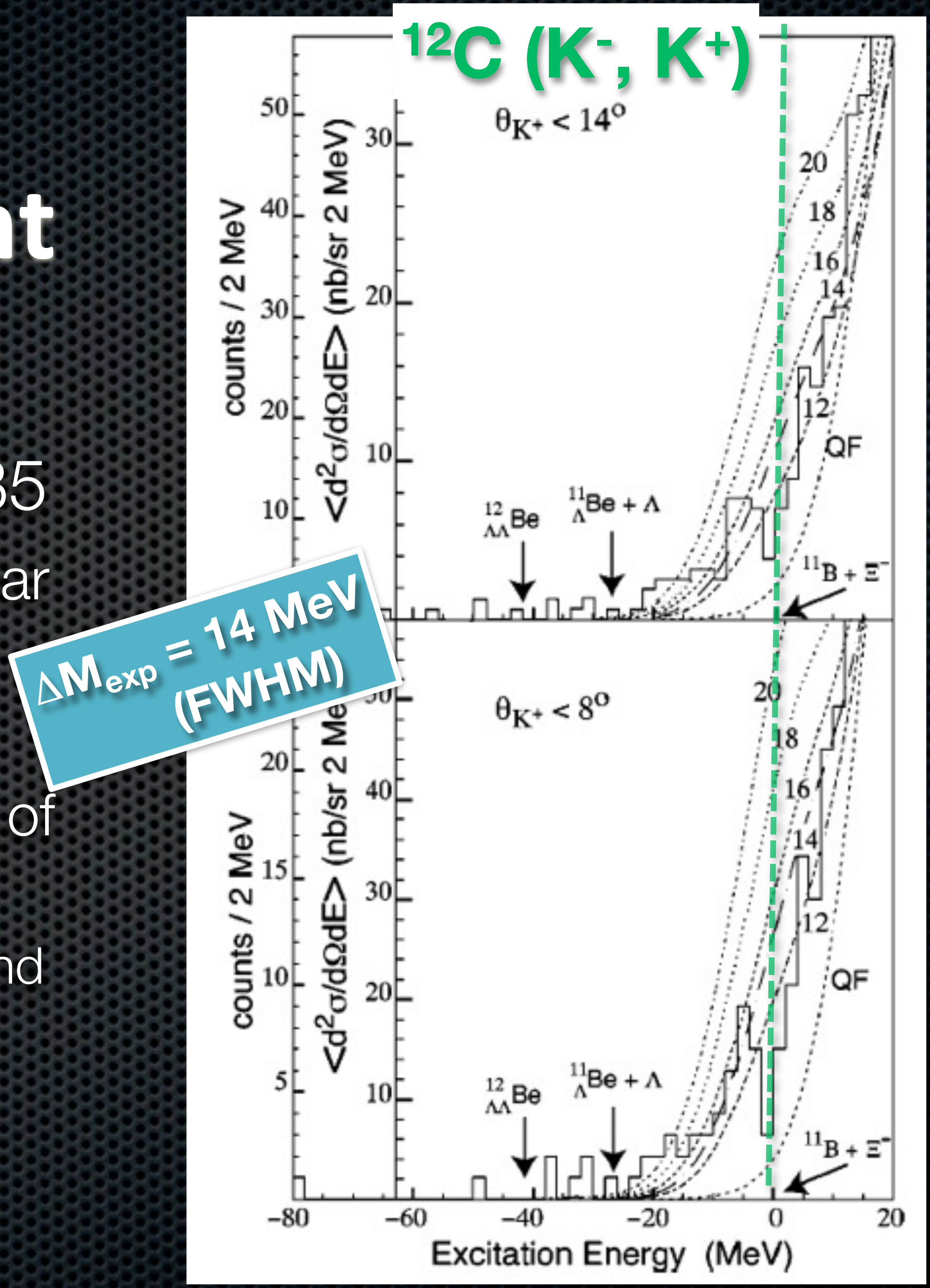
S=-2 World


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-1 Λ(Z-2)+Λ
Double-Λ hypernucleus
2xBΛ
BΛΛ
(A-2)g.s.⊗SΛPΛ
A-1 ΛΛ(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?
Δ
Large Mixing ?
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 measurement

- Previous experiment : BNL-E885
  - not clear evidence of Ξ-hypernuclear bound state.
    - because of limited mass resolution
  - suggest weakly attractive potential of -14 MeV depth.
    - by shape analysis and counts in bound region, compared with DWIA calc.
  - 89±14 nb/sr (<8deg.); 42±5 nb/sr (<14deg.)



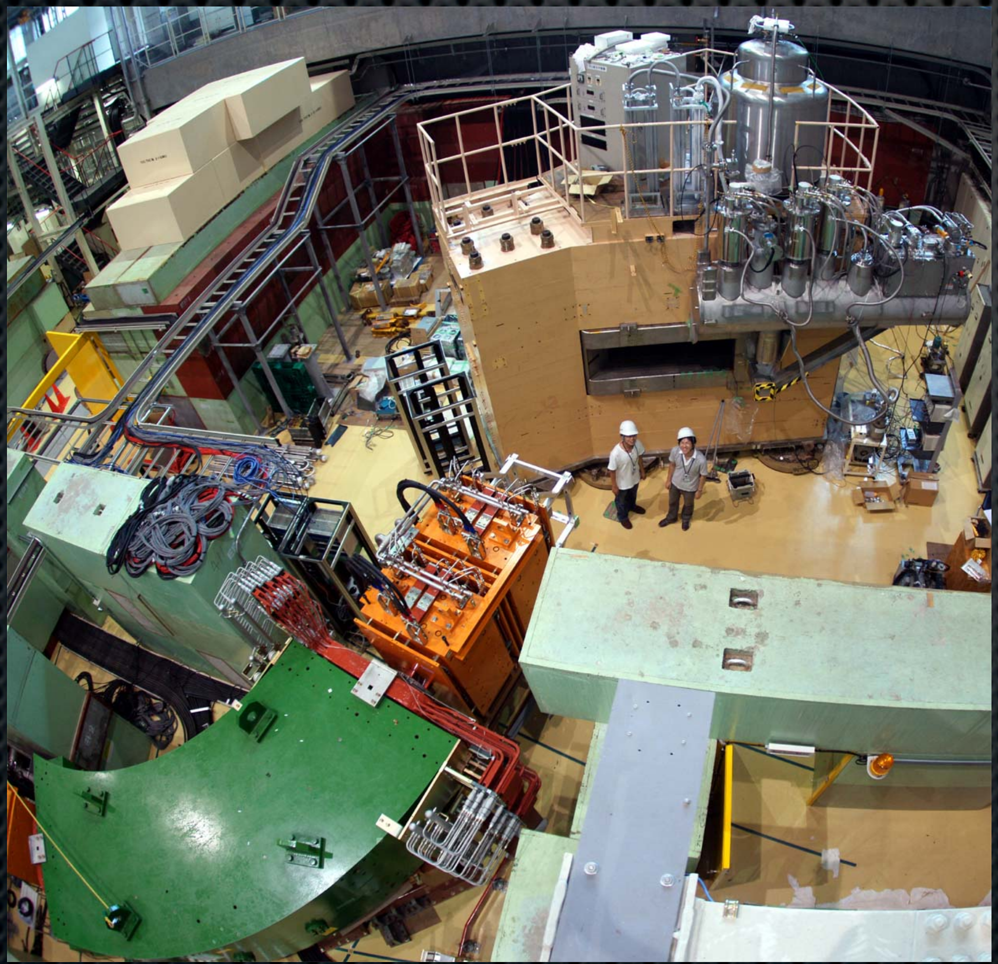
P.Khaustov et al., PRC61(2000)054603

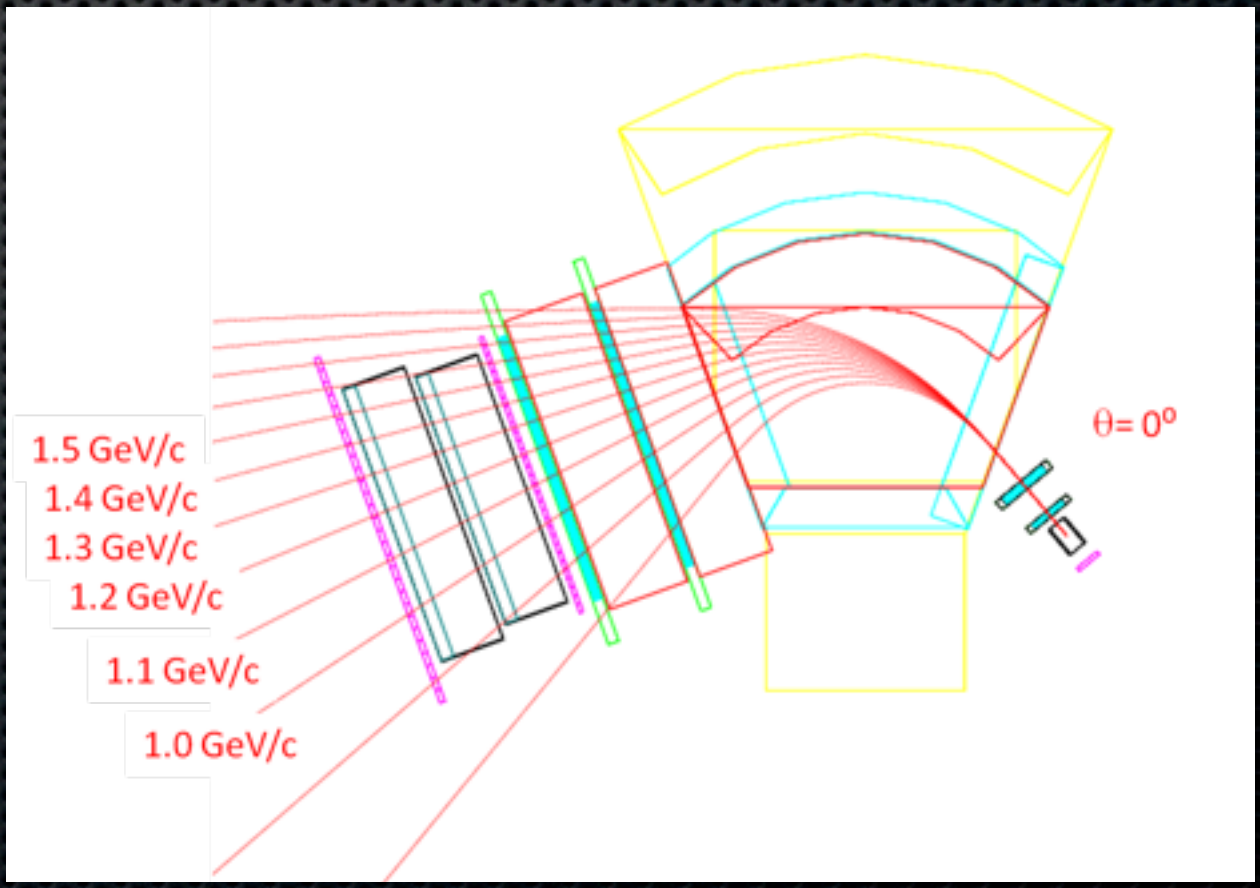
Spectroscopic Study of Ξ-Hypernucleus, $^{12}_{\Xi}$Be, via the ^{12}C(K^-,K^+) Reaction

J-PARC E05
T. Nagae et al.

- Discovery of Ξ-hypernuclei
- Measurement of Ξ-nucleus potential depth and width of $^{12}_{\Xi}$Be

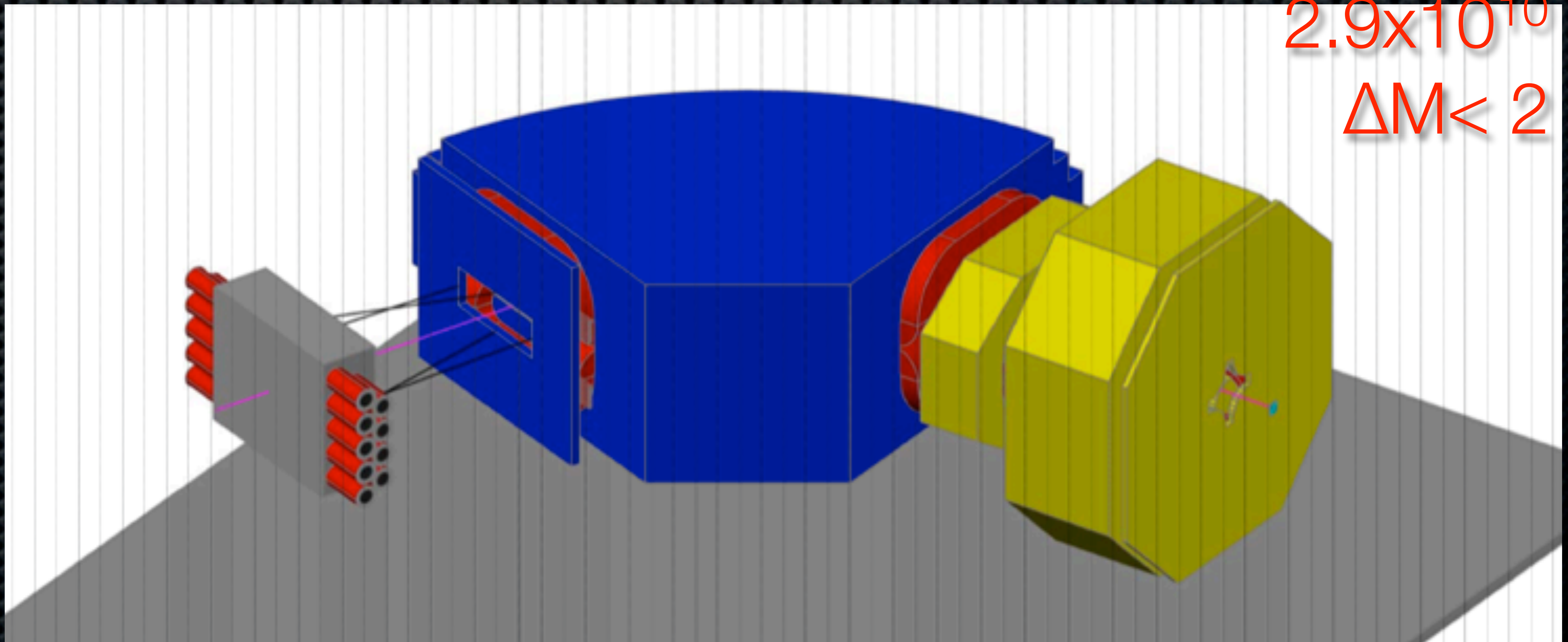
S=-1 → S=-2 (Multi-Strangeness System)



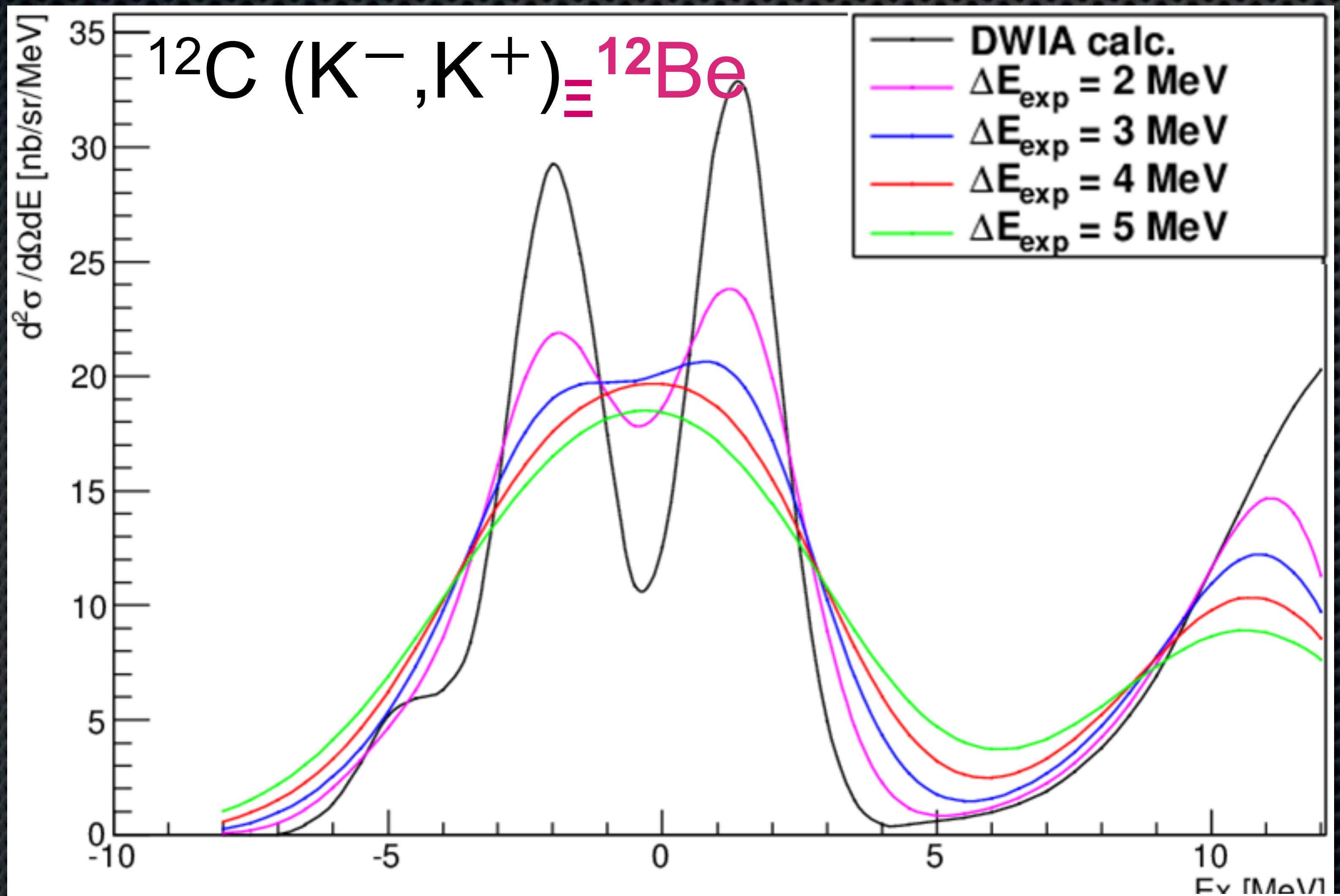


E05 Phase 2 with S-2S

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



2.9×10^{10} K^-/day
$\Delta M< 2$ MeV



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

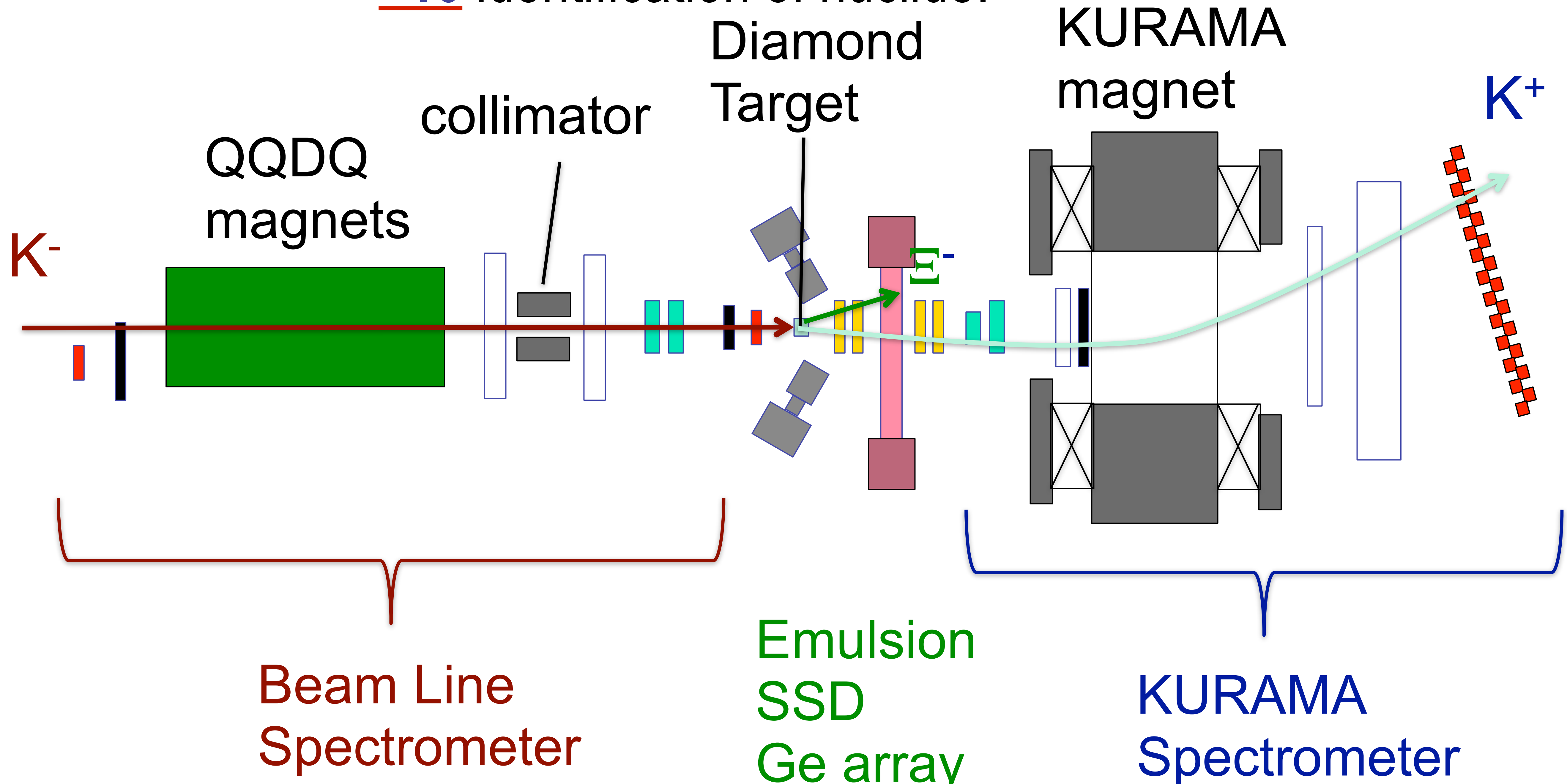
J-PARC E07: Hybrid-Emulsion Exp.

＊Detection of double hypernuclei

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

  ➔ ~10^2 double hypernuclei,

  ~10 identification of nuclide.

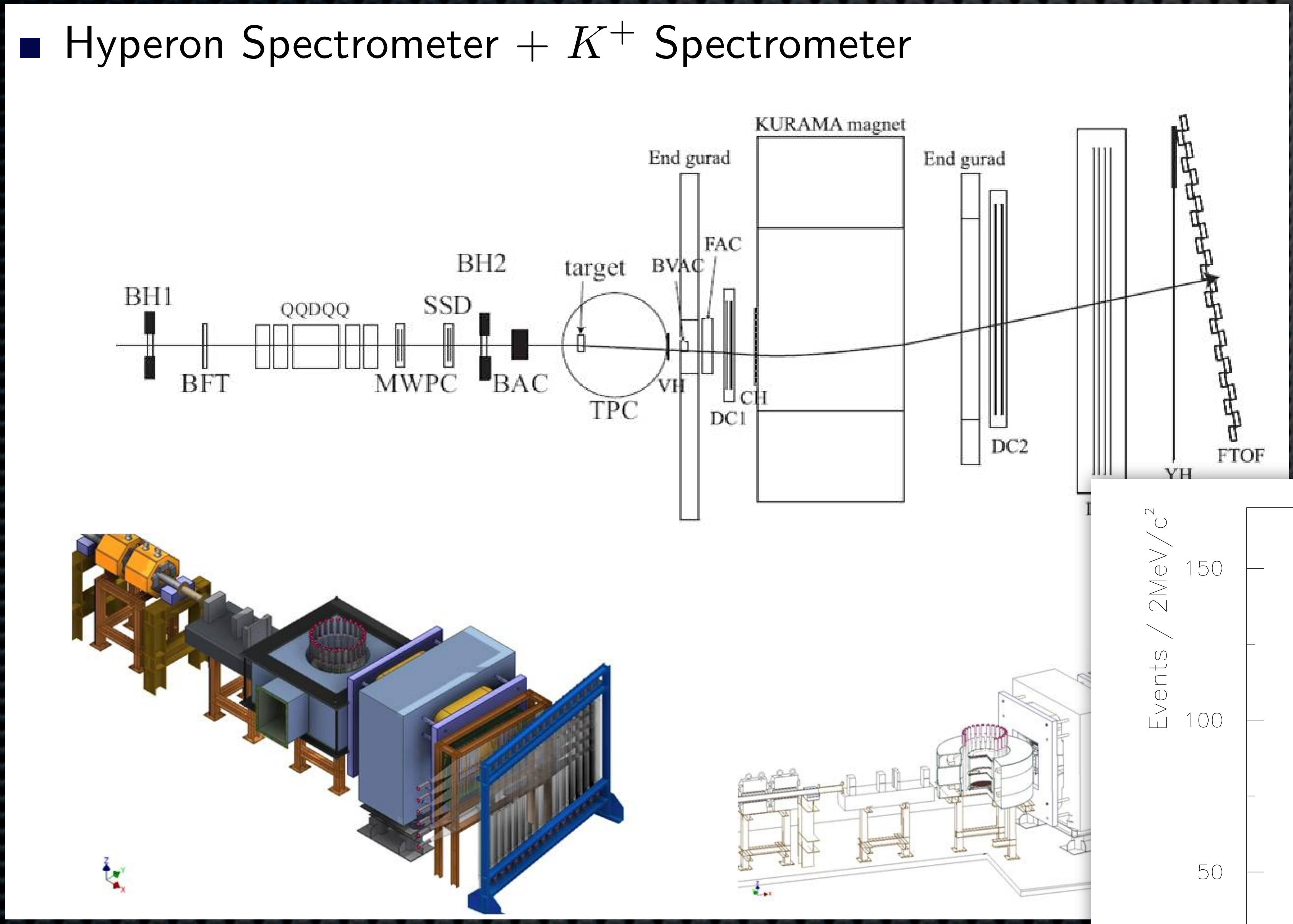


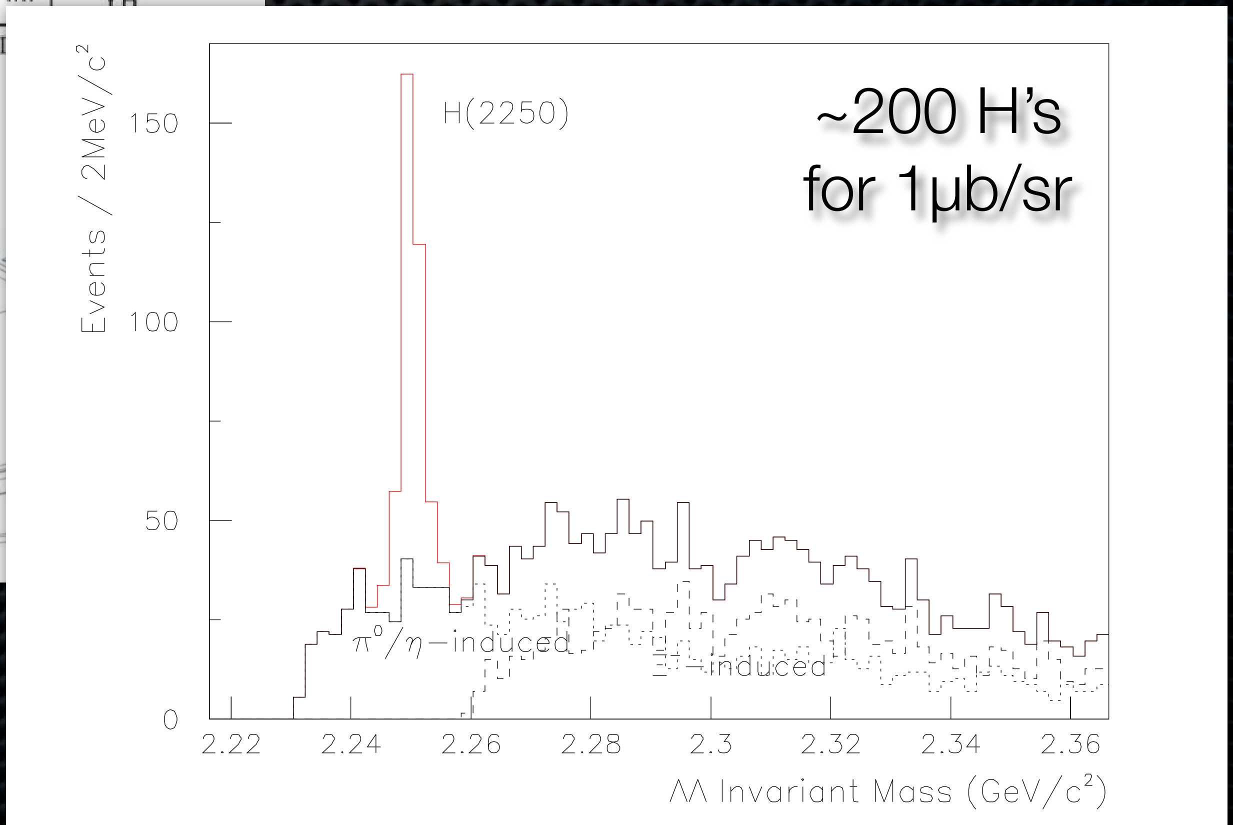
H search at J-PARC

E42

by J.K. Ahn & K. Imai et al.

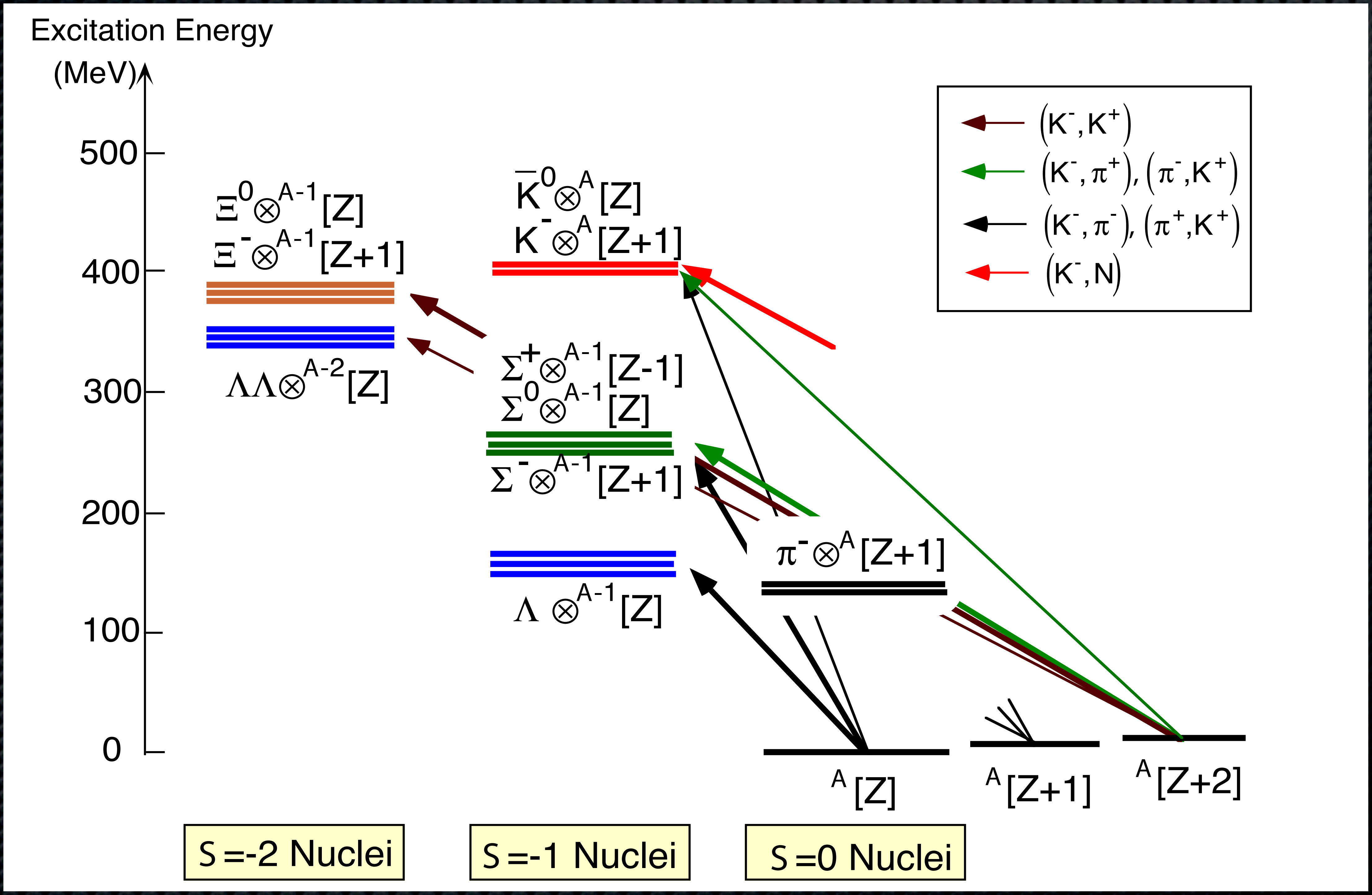
- (K⁻,K⁺) reaction



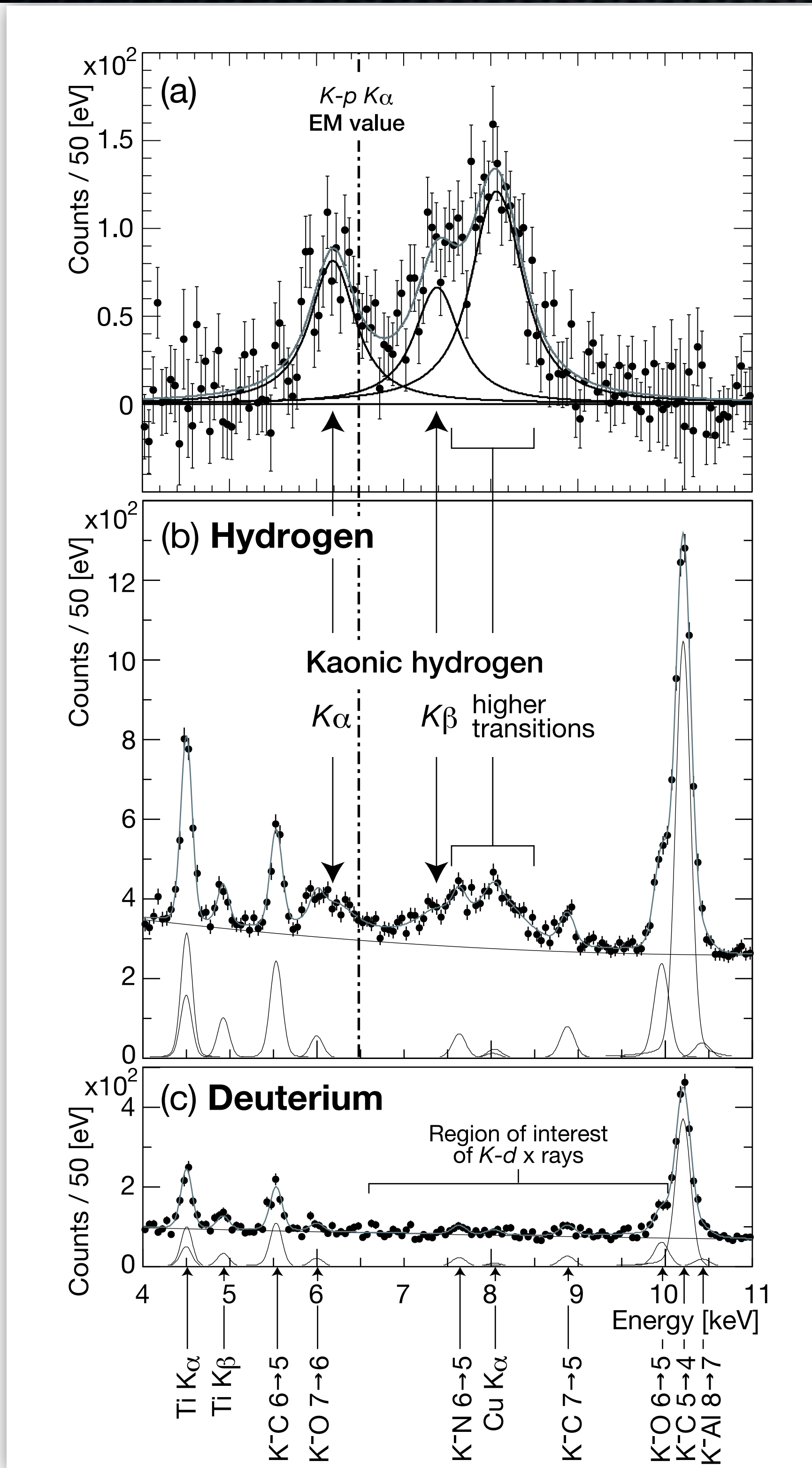


Kaonic Nuclei

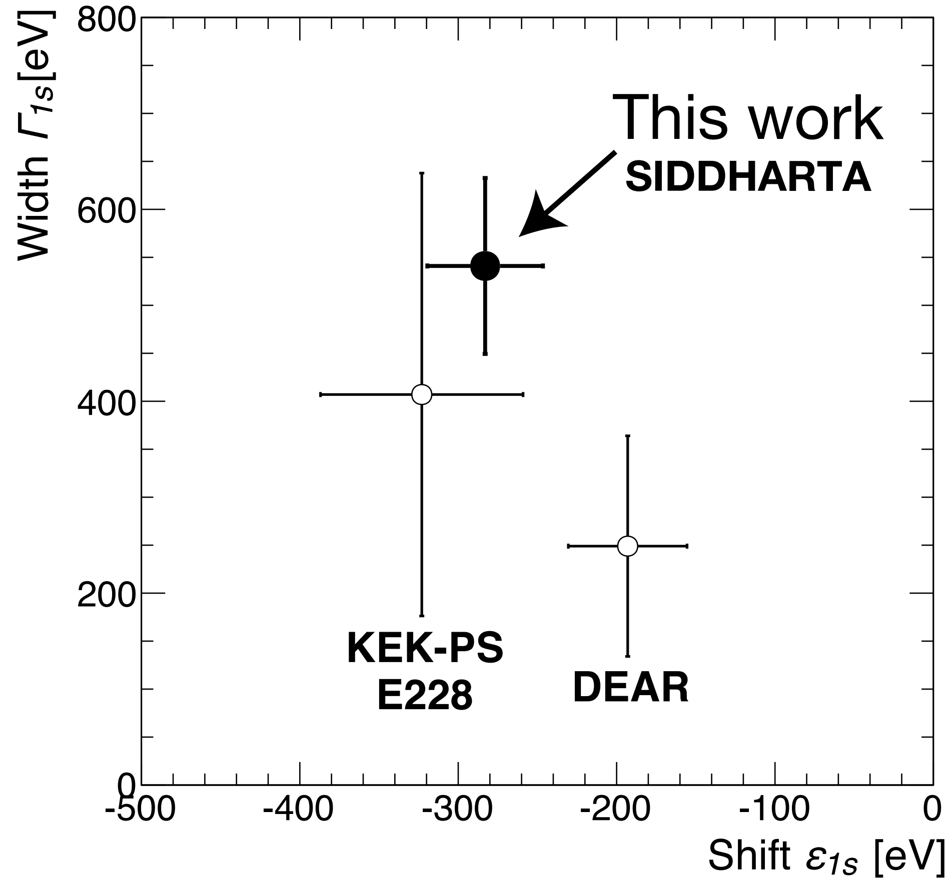
Meson-Bayon Bound Systems with Strangeness



Kaonic Hydrogen X-ray

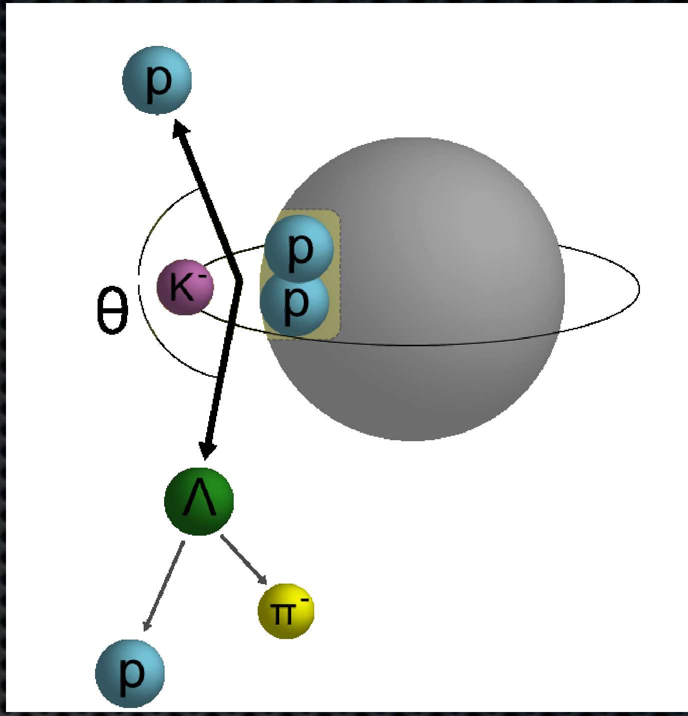


SIDDHARTA



$$\epsilon_{1s} = -283 \pm 36(\mathrm{stat}) \pm 6(\mathrm{syst})\ \mathrm{eV}$$
$$\Gamma_{1\mathrm{s}} = 541 \pm 89(\mathrm{stat}) \pm 22(\mathrm{syst})\ \mathrm{eV},$$

New FINUDA data on $K^- pp$



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

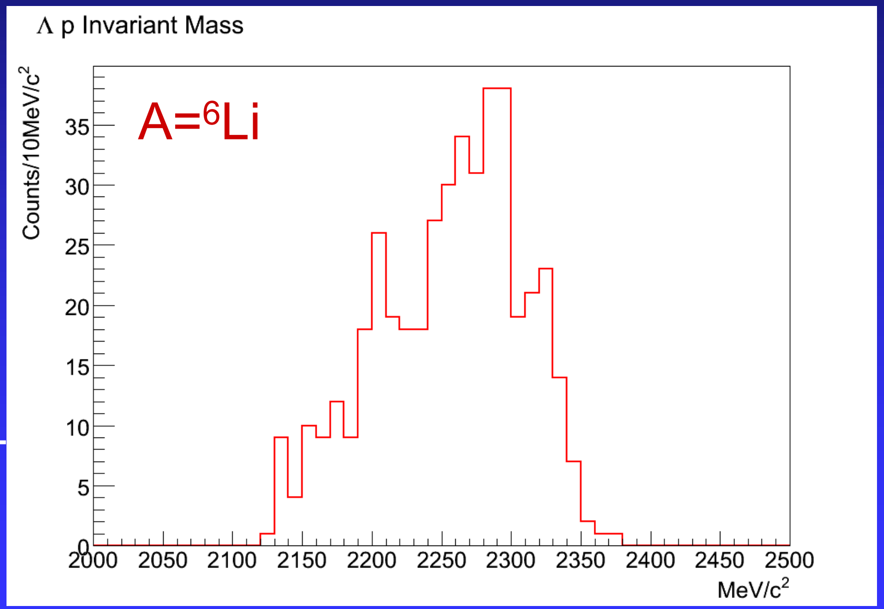
B=115+6/-5+3/-4 MeV
Γ= 67+14/-11+2/-3 MeV

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

- Confirmed for ^{6}Li only, with better statistics

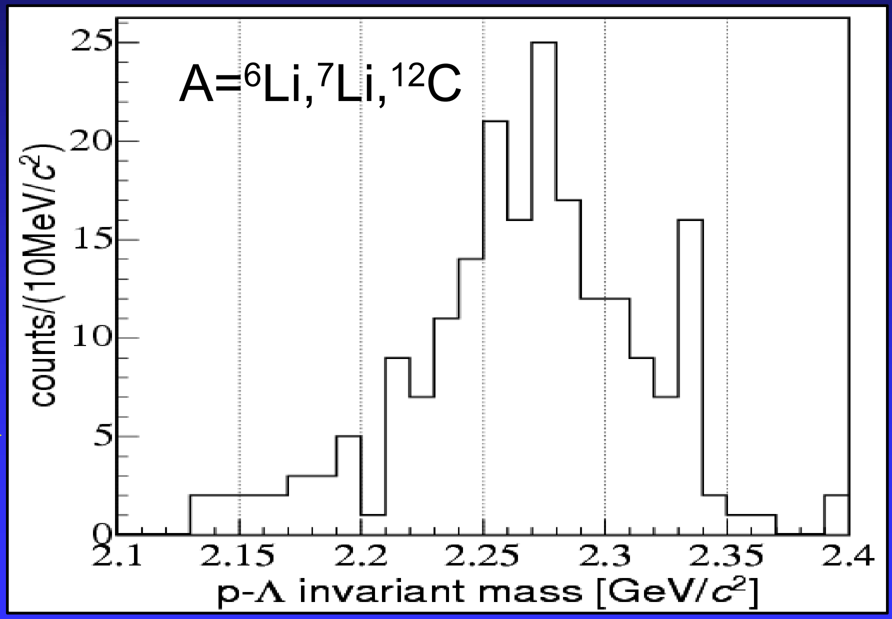
S. Piano@Hyp-X

no acceptance corrected



New
inv mass spectra
compatible with
published one

New data ⟷ Old data
Same cuts applied



no acceptance corrected

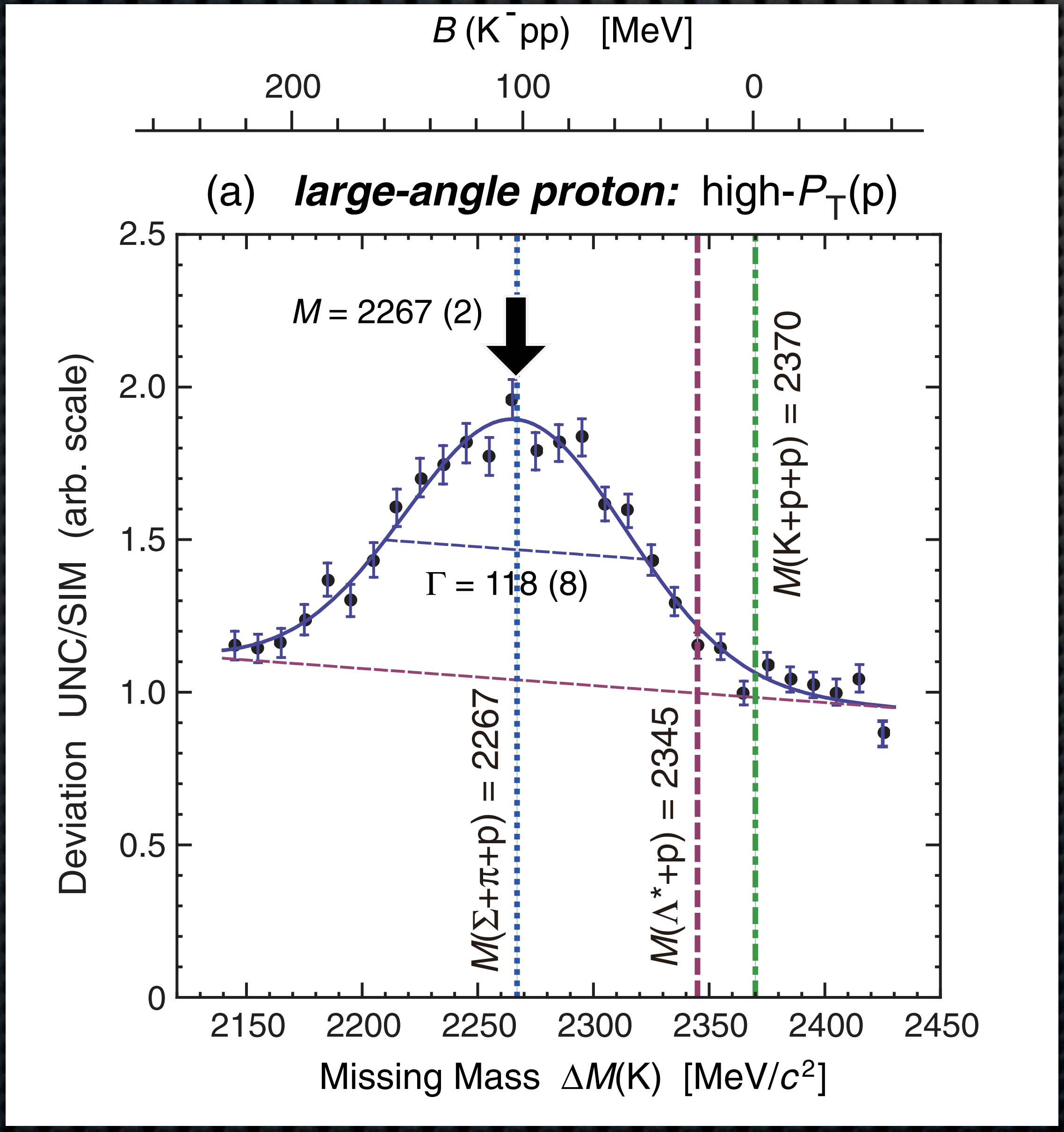
FINUDA Coll., PRL 94(2005)212303

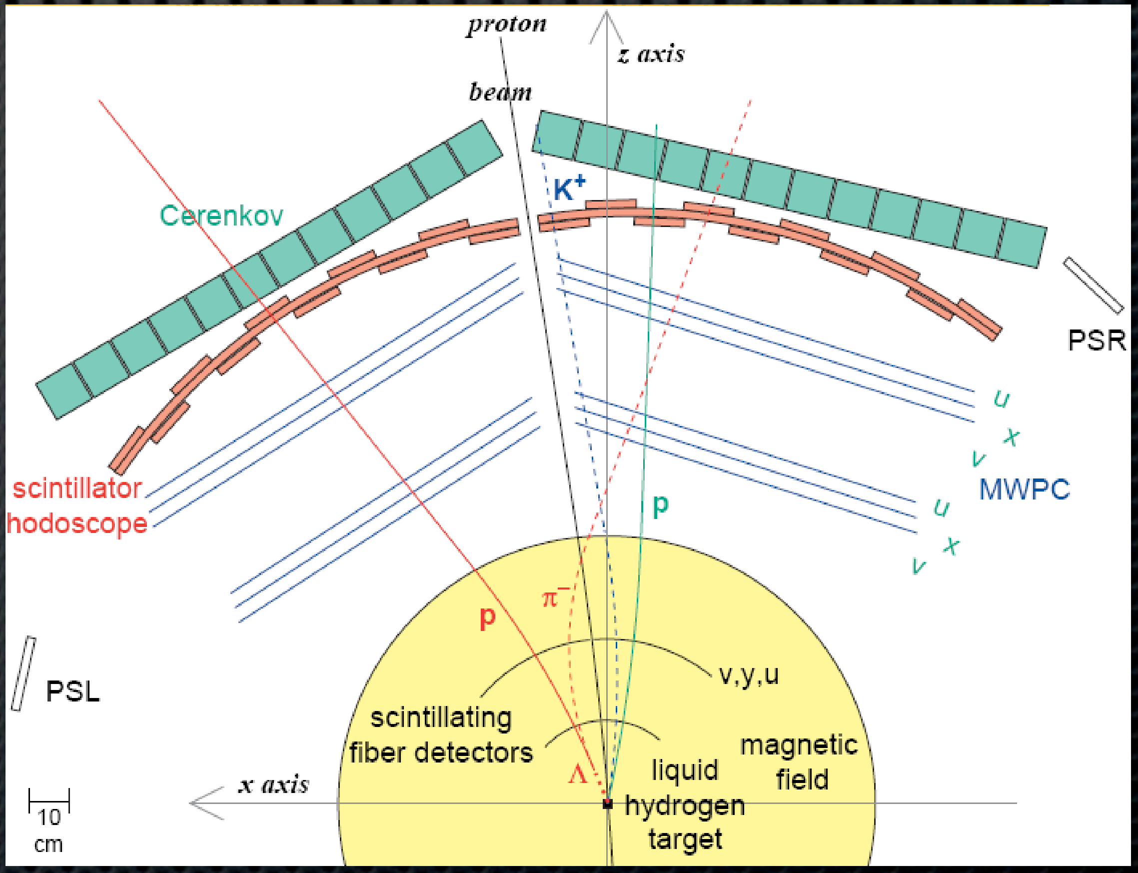
FSI, ΣN→ΛN conversion cannot explain the new data

DISTO data on $K^{-}pp$

- 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.





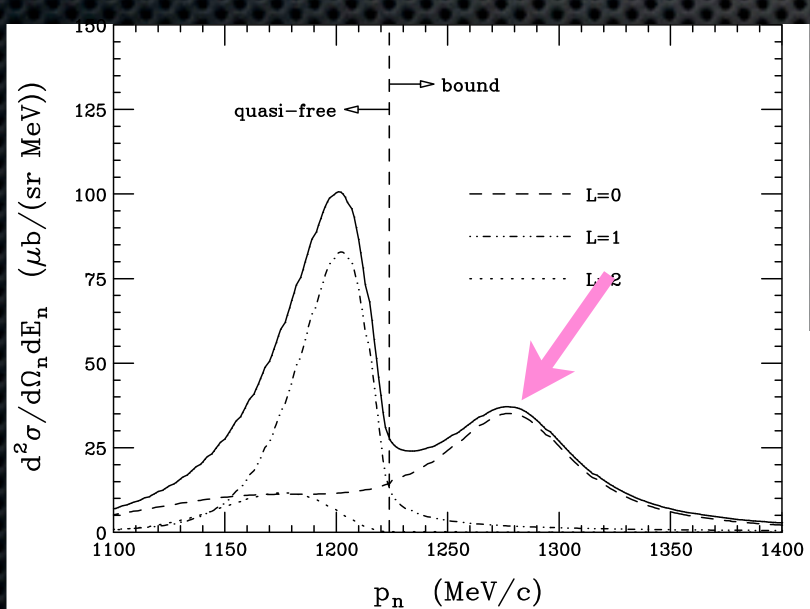
$K^{-}pp$: theoretical status

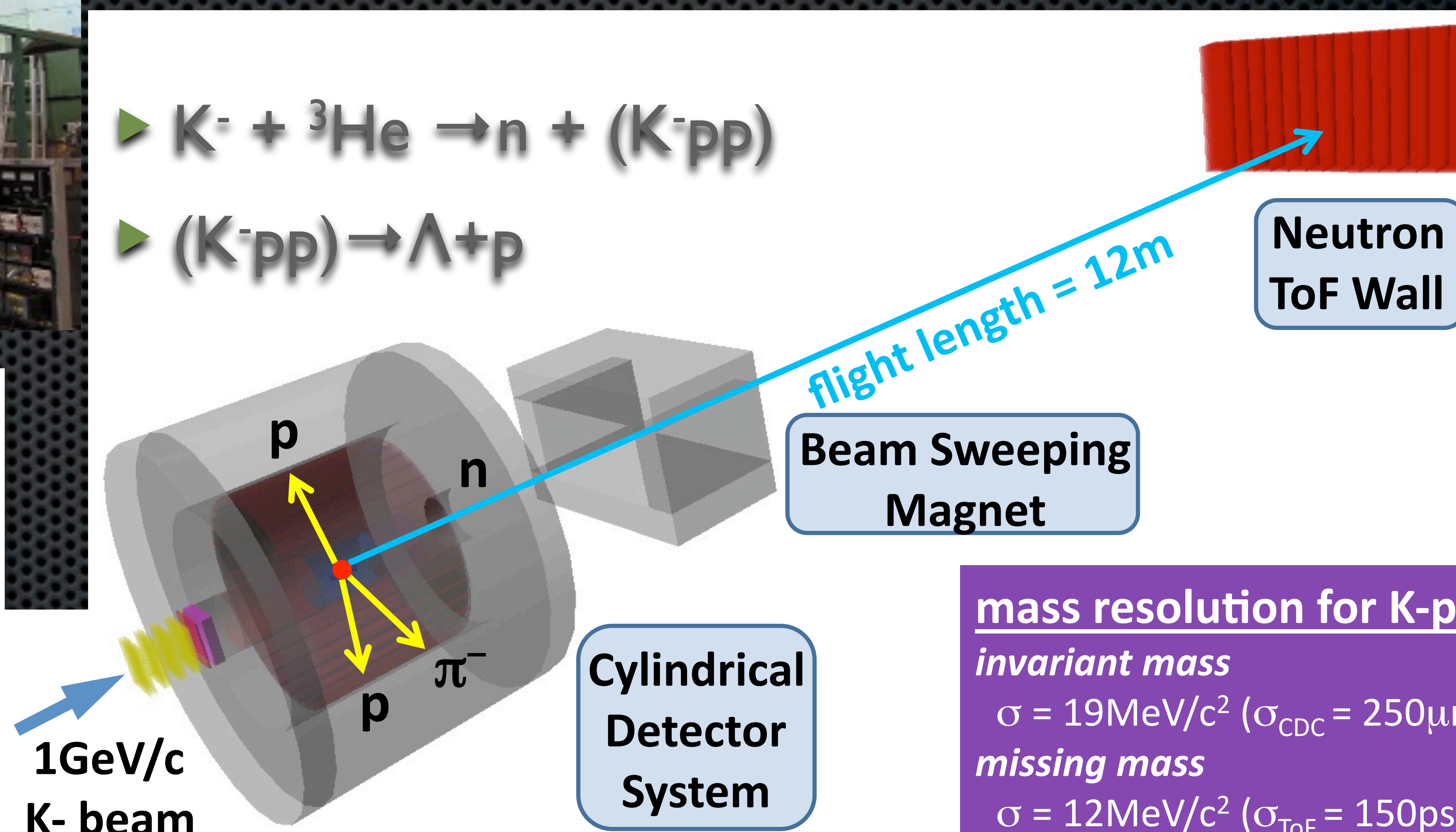
Methods	Binding Energy (MeV)	Width (MeV)
Shevchenko, Gal, Mares Faddeev	50 - 70	~100
Ikeda and Sato Faddeev	60 - 95	45 - 80
Yamazaki and Akaishi Variational (ATMS)	48	61
Dote, Hyodo, Weise Variational (AMD)	20±3	40 - 70

- *$K^{-}pp$ should exist as a bound state.*
  - Deep or Shallow ??
  - Width could be 40 – 100 MeV
- Λ(1405)-p bound state ? (Arai, Oka, and Yasui)
- FSI effects ? (Magas, Oset, Ramos, Toki)

$K^{-}pp$ search experiments at J-PARC

- ^{3}He(K^-,n) reaction at 1 GeV/c: E15
- d(π^+,K^+) reaction at 1.5 GeV/c: E27





mass resolution for K-pp

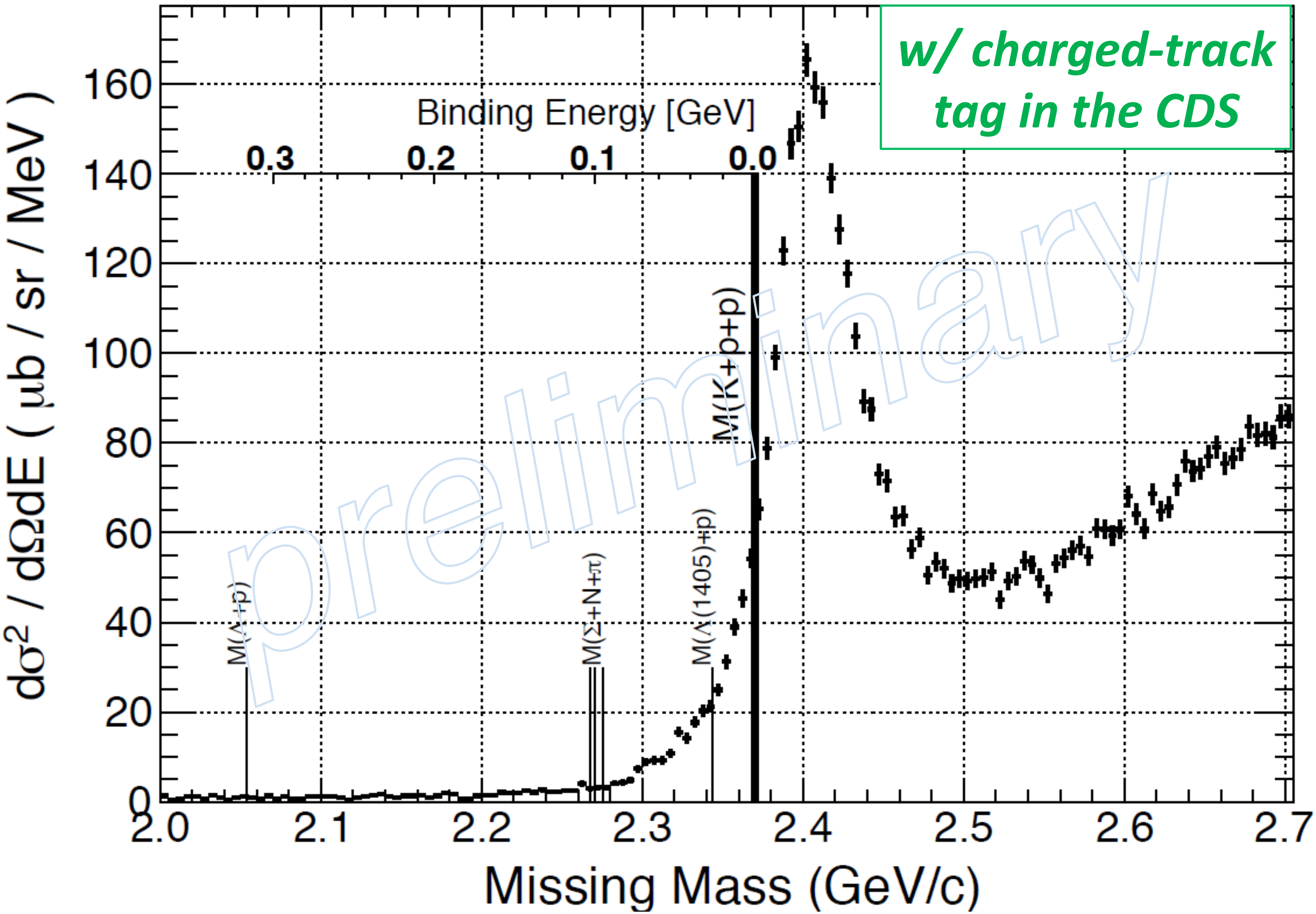
invariant mass

σ = 19MeV/c^2 (σ_{CDC} = 250μm)

missing mass

σ = 12MeV/c^2 (σ_{ToF} = 150ps)

Preliminary Result : $^{3}He(K^{-},n)$



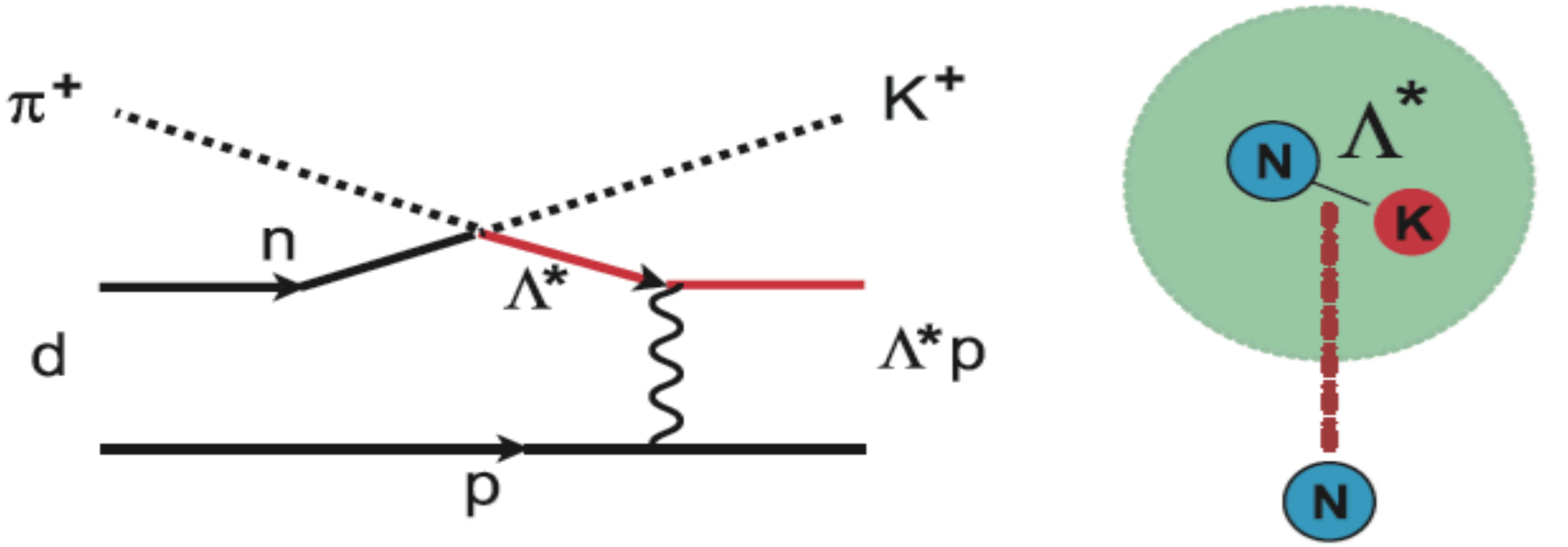
$d(\pi^+, K^+)$ reaction

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

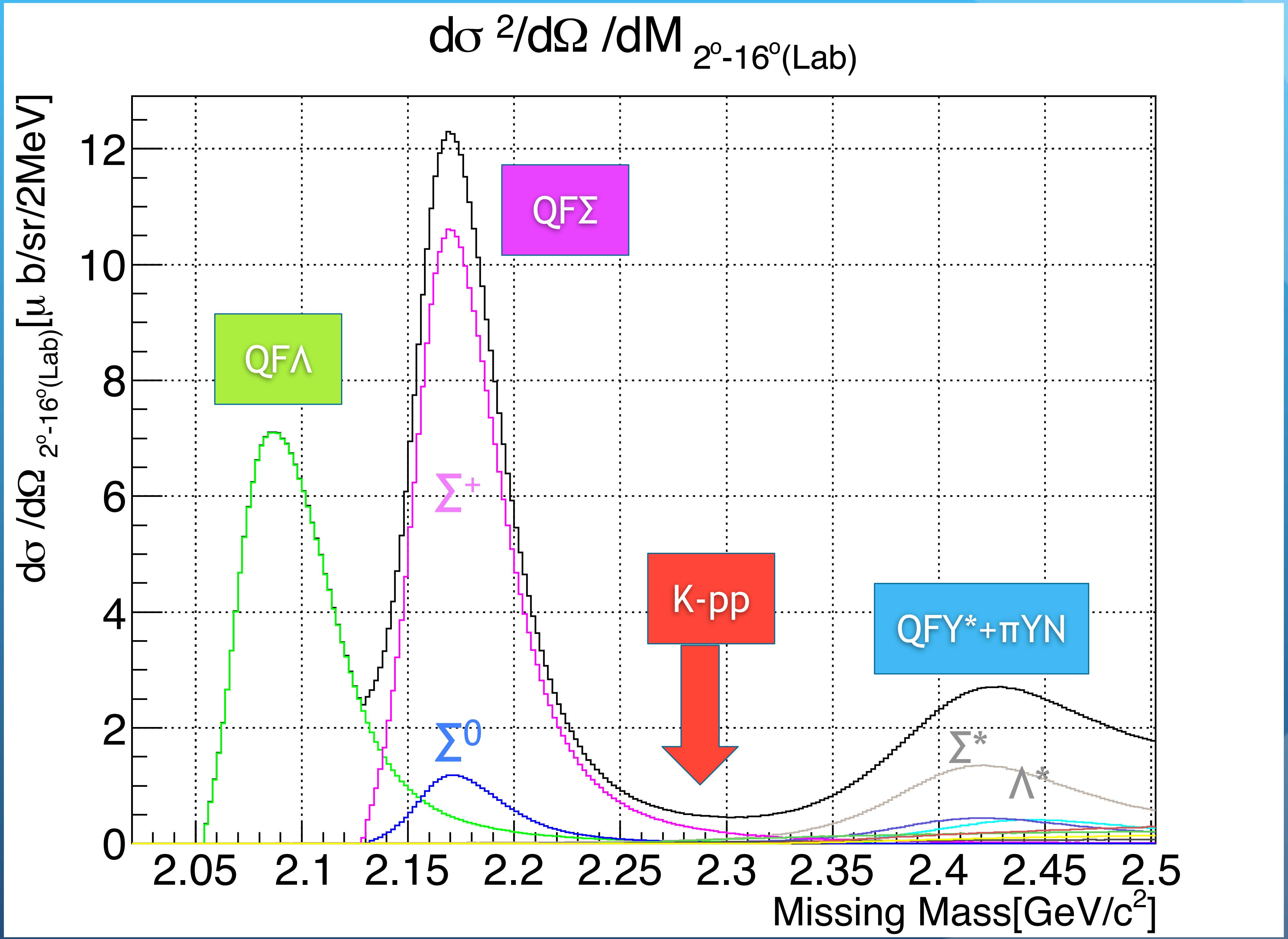
π^+ + "n" --> "Λ^*" + K^+

"Λ^*" + "p" --> bound K^-pp *minor*

--> quasi-free Λ^* *dominant*



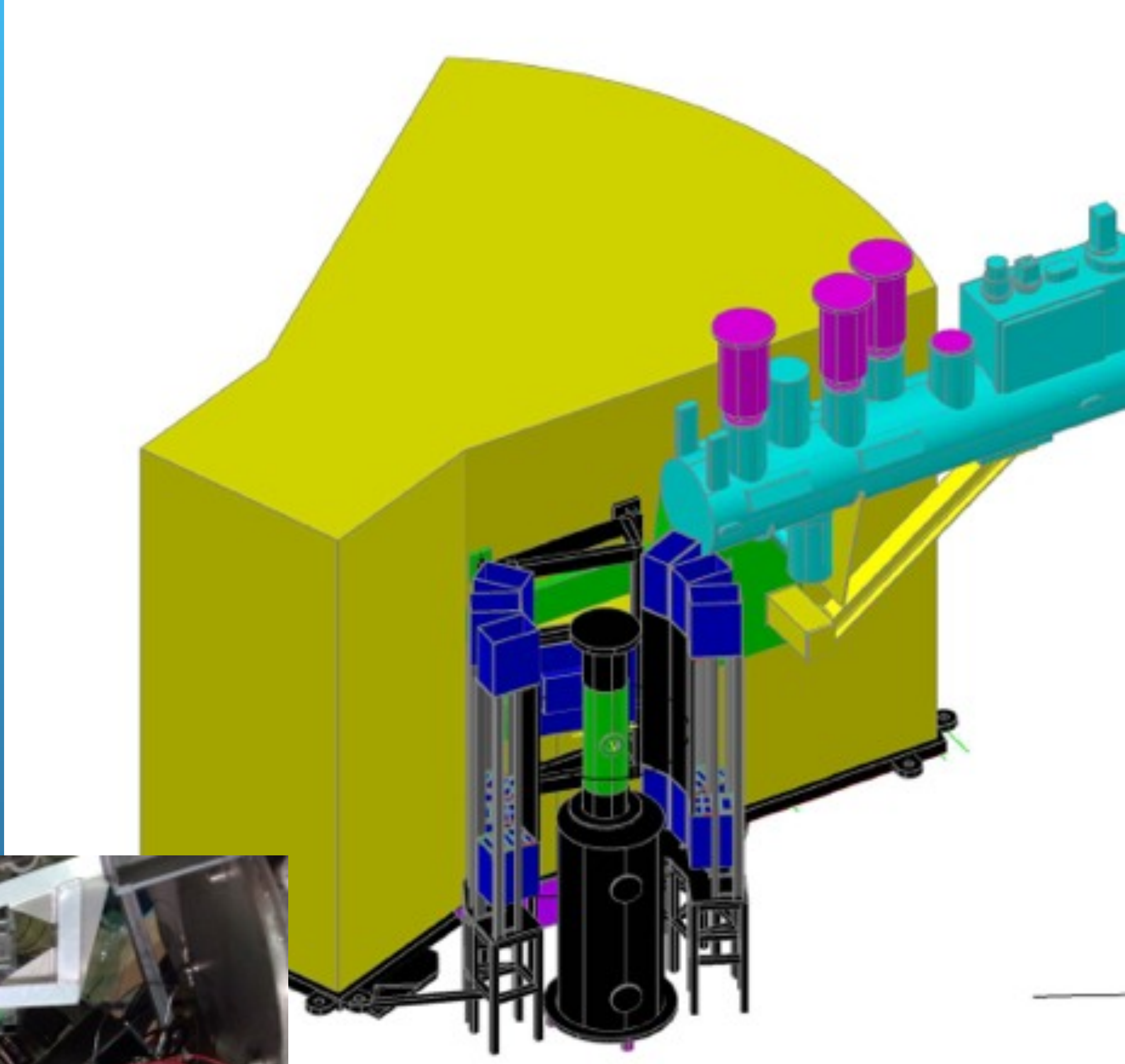
d(π^+,K^+) inclusive spectrum; in simulation

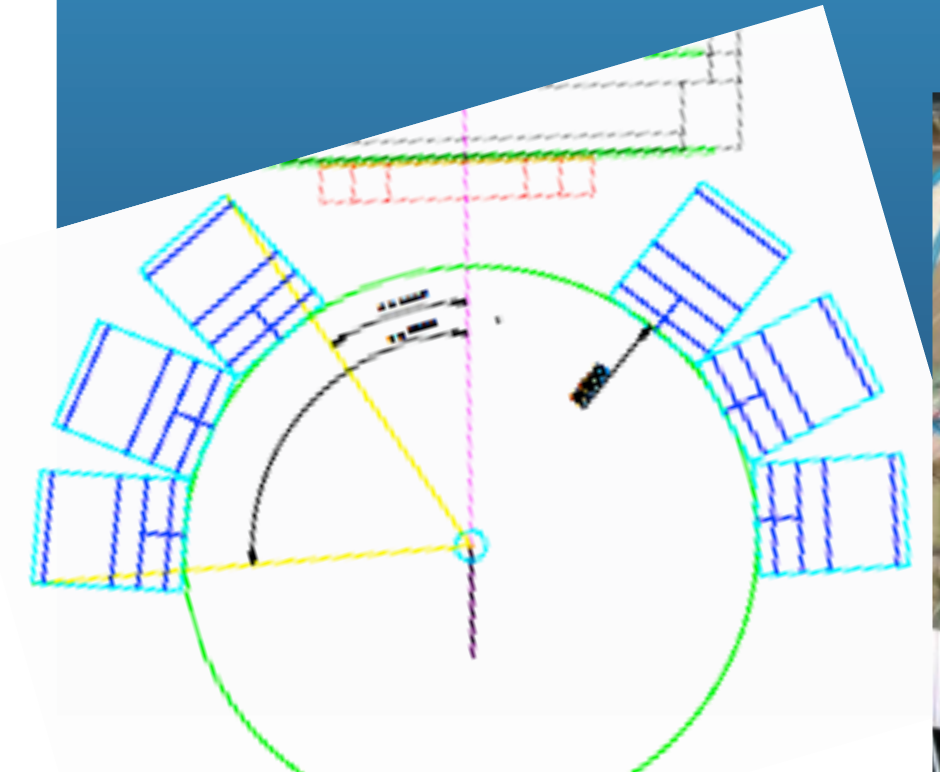


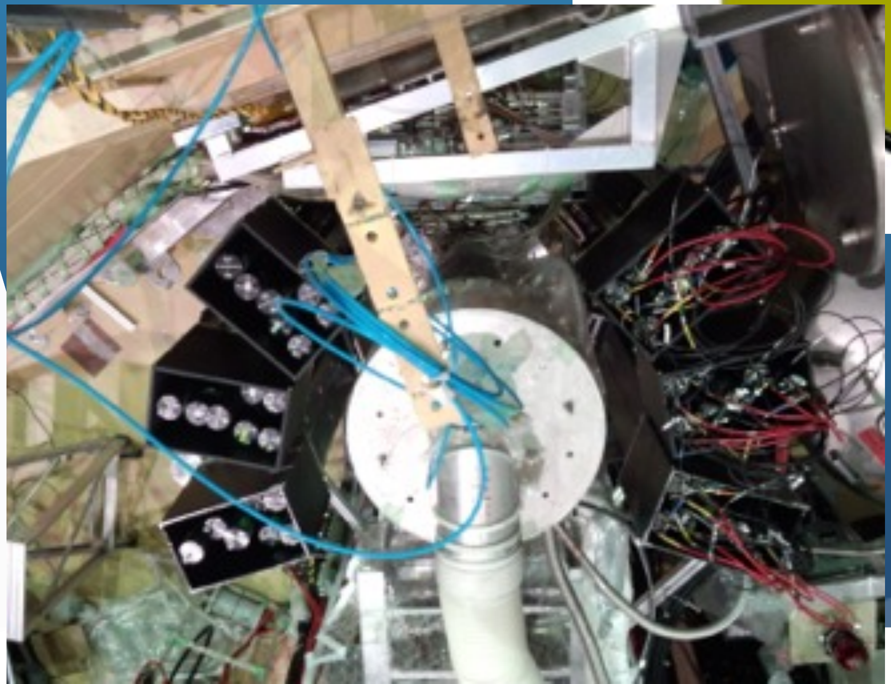
Range Counter System for E27

- 5 layers (1+2+2+5+2cm)

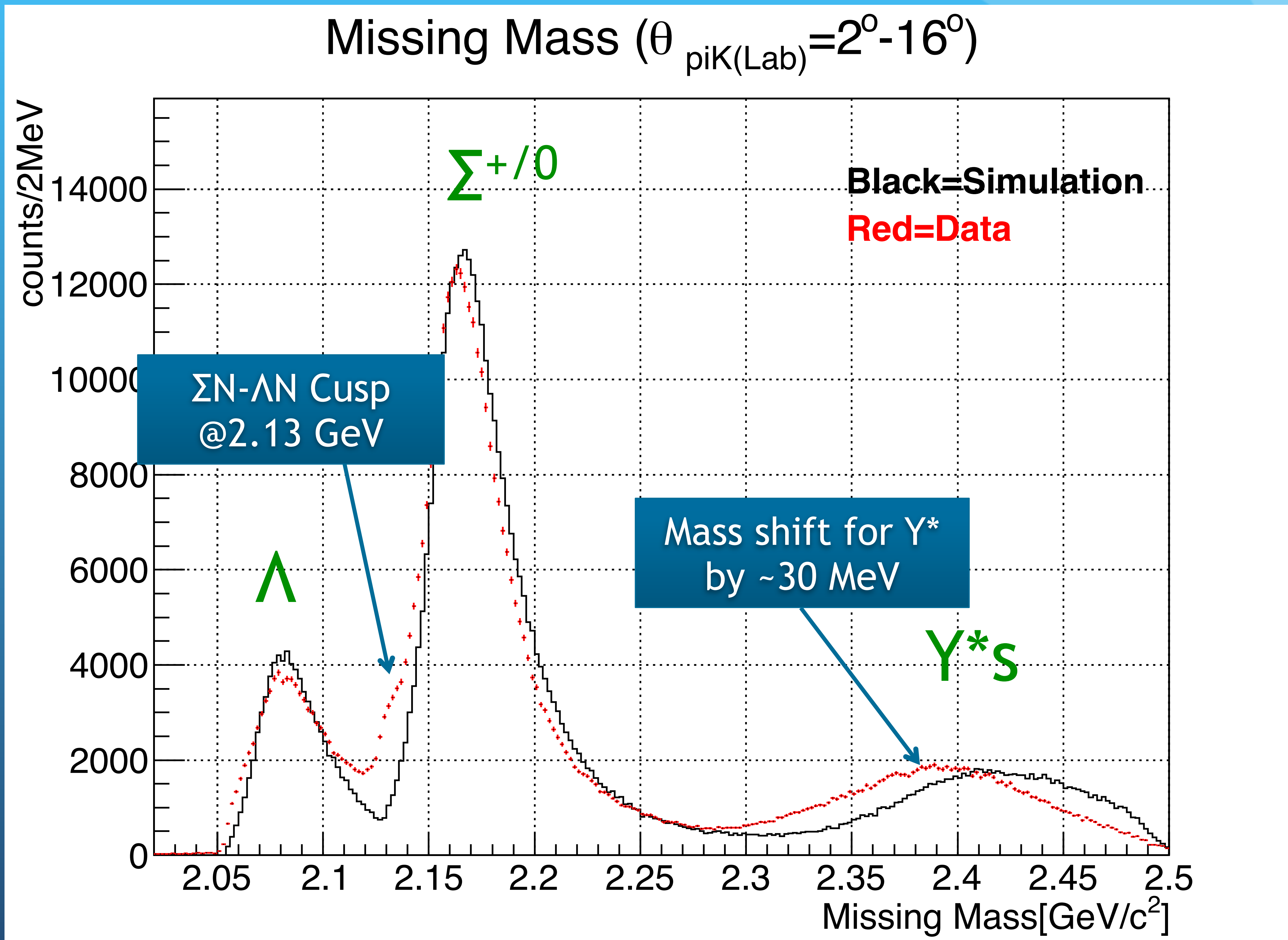
  of plastic scinti.
- 39 – 122 degrees (L+R)
- 50 cm TOF



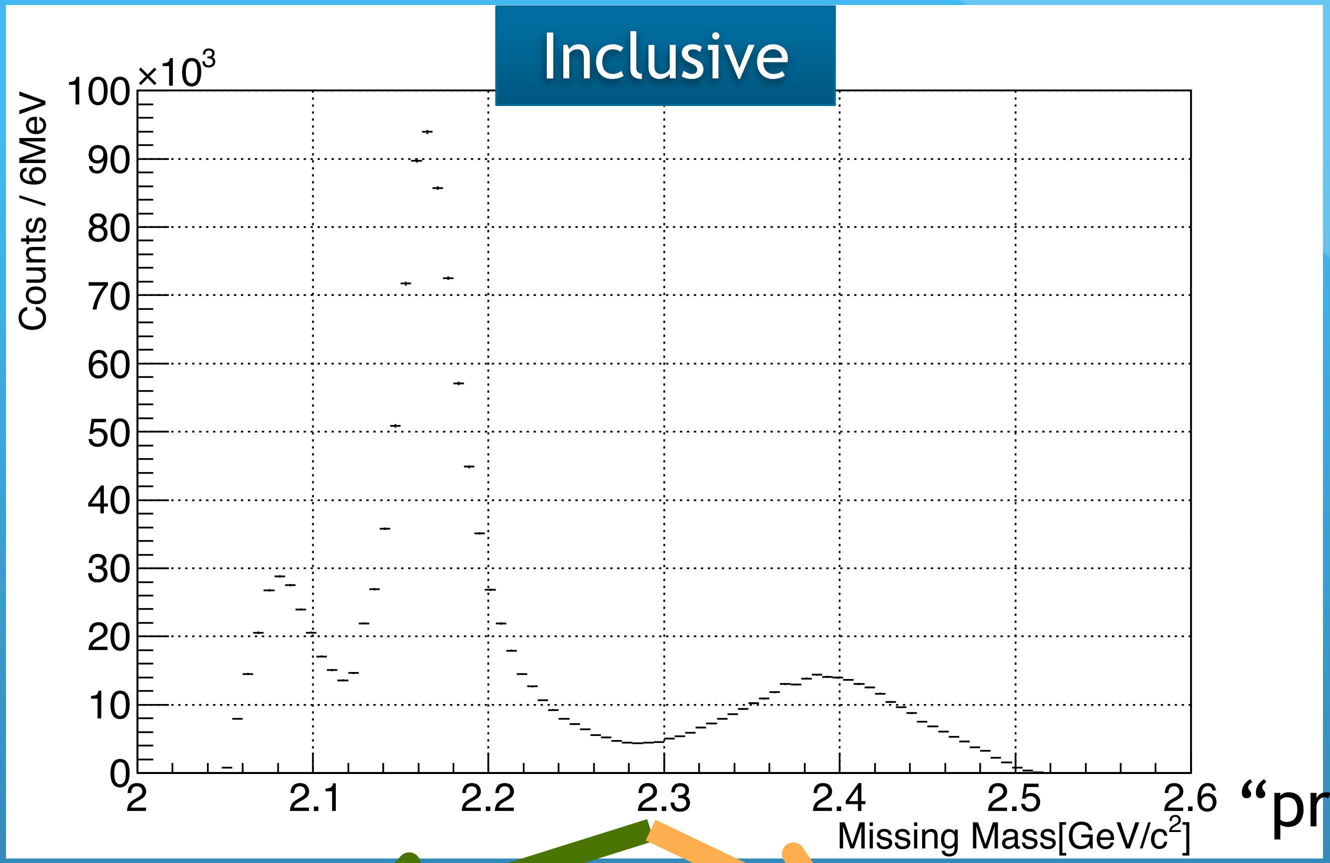




d(π^+, K^+) @1.7GeV/c

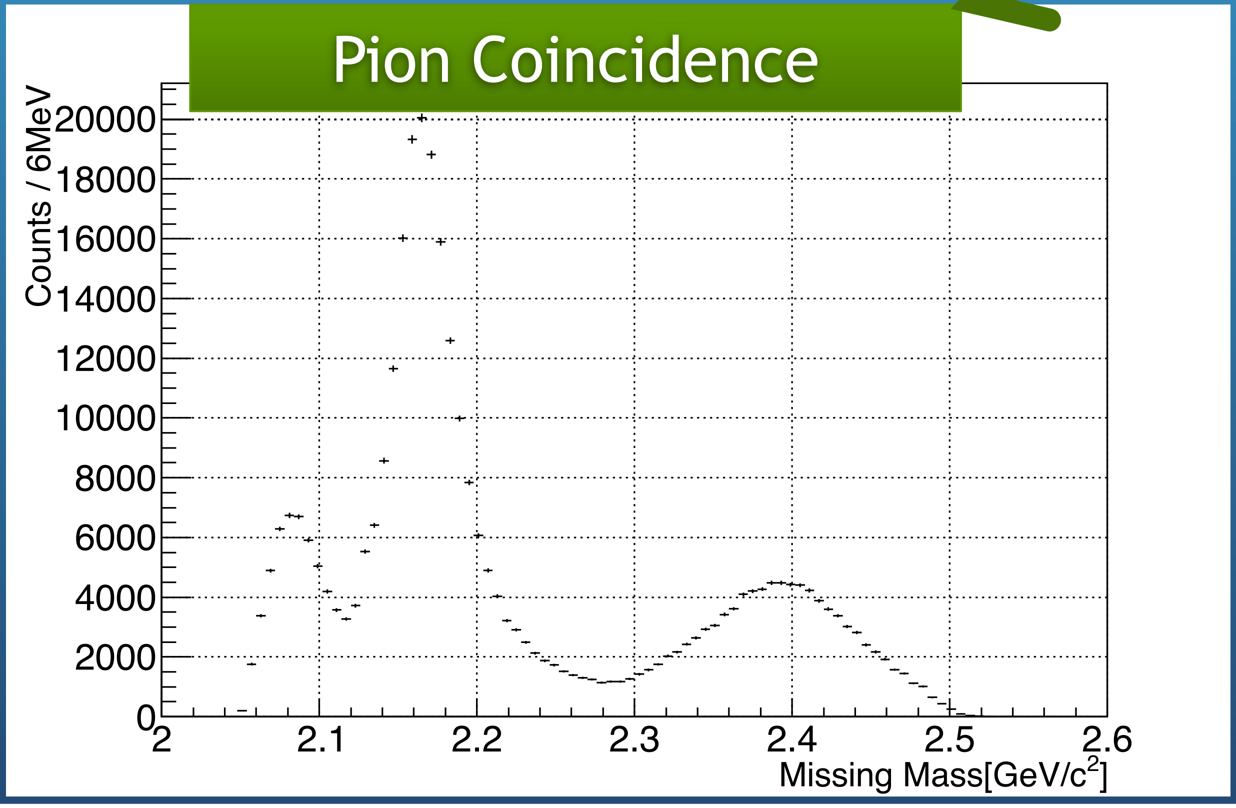

Missing Mass (θ piK(Lab)=2°-16°)
counts/2MeV
Missing Mass[GeV/c²]
0
2000
4000
6000
8000
10000
12000
14000
2.05
2.1
2.15
2.2
2.25
2.3
2.35
2.4
2.45
2.5
Σ+/0
Λ
Y*s
Black=Simulation
Red=Data
ΣN-ΛN Cusp
@2.13 GeV
Mass shift for Y*
by ~30 MeV

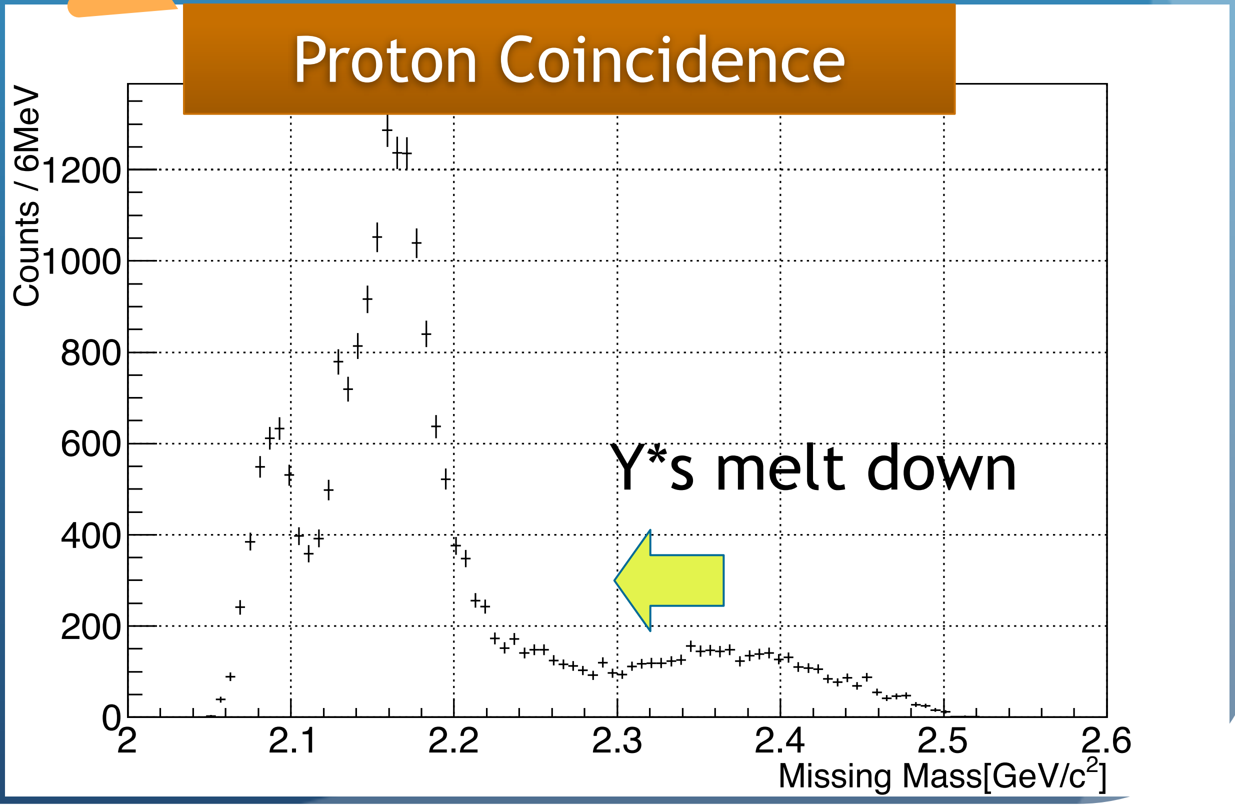
Coincidence study



“proton”=p>280 MeV/c

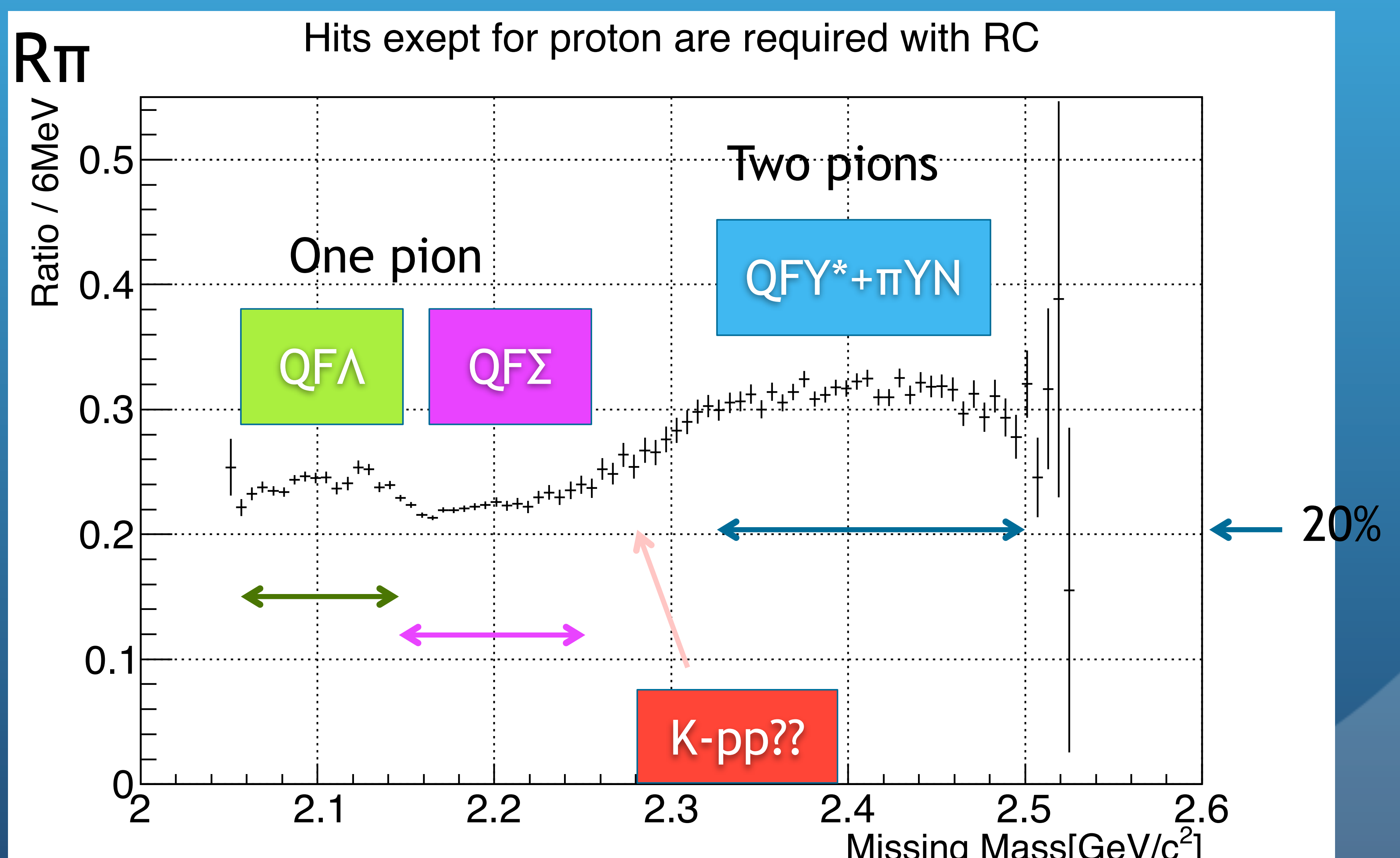
“pion”=π or
slow p



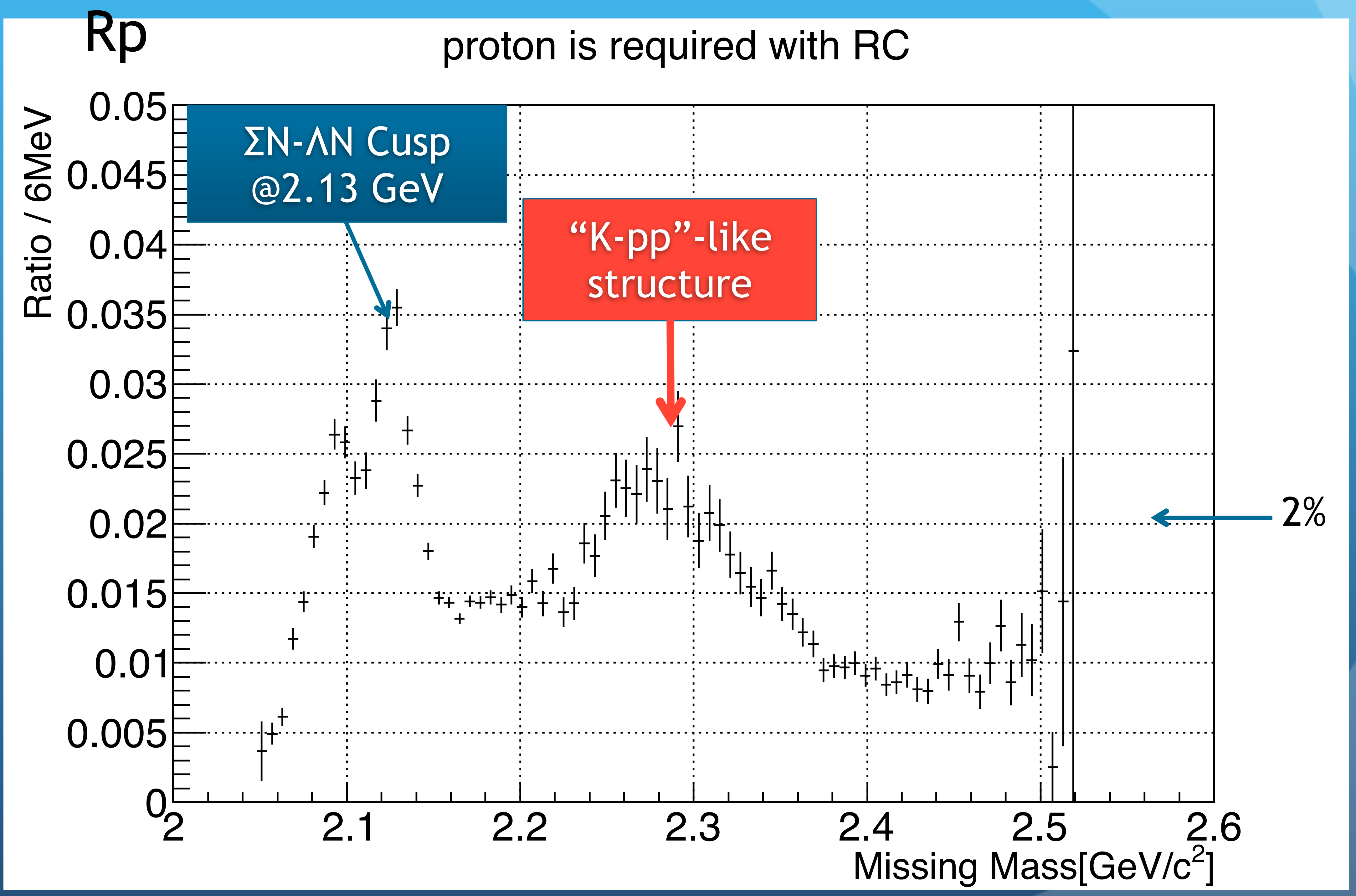


Pion Coincidence Rate

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



Proton Coincidence Rate



Summary

- Baryon-Baryon Interactions ← Hypernuclear Spectroscopy
  - Λ N Interaction
    - B_Λ = 28±1 MeV
    - Very small spin-orbit splitting
  - $\Lambda\Lambda$ Interaction; $\Delta B_{\Lambda\Lambda}$=0.67±0.17 MeV
  - Σ N Interaction
    - One bound state in $^{4}_{\Sigma}$He ←Isospin dependence
    - B_{Σ^-} ~ -30 MeV (Repulsive in medium-heavy nuclei)
  - Ξ N Interaction
    - B_Ξ~14 MeV; weakly attractive ?
  - $\bar{K}$N Interaction; Large attraction in I=0