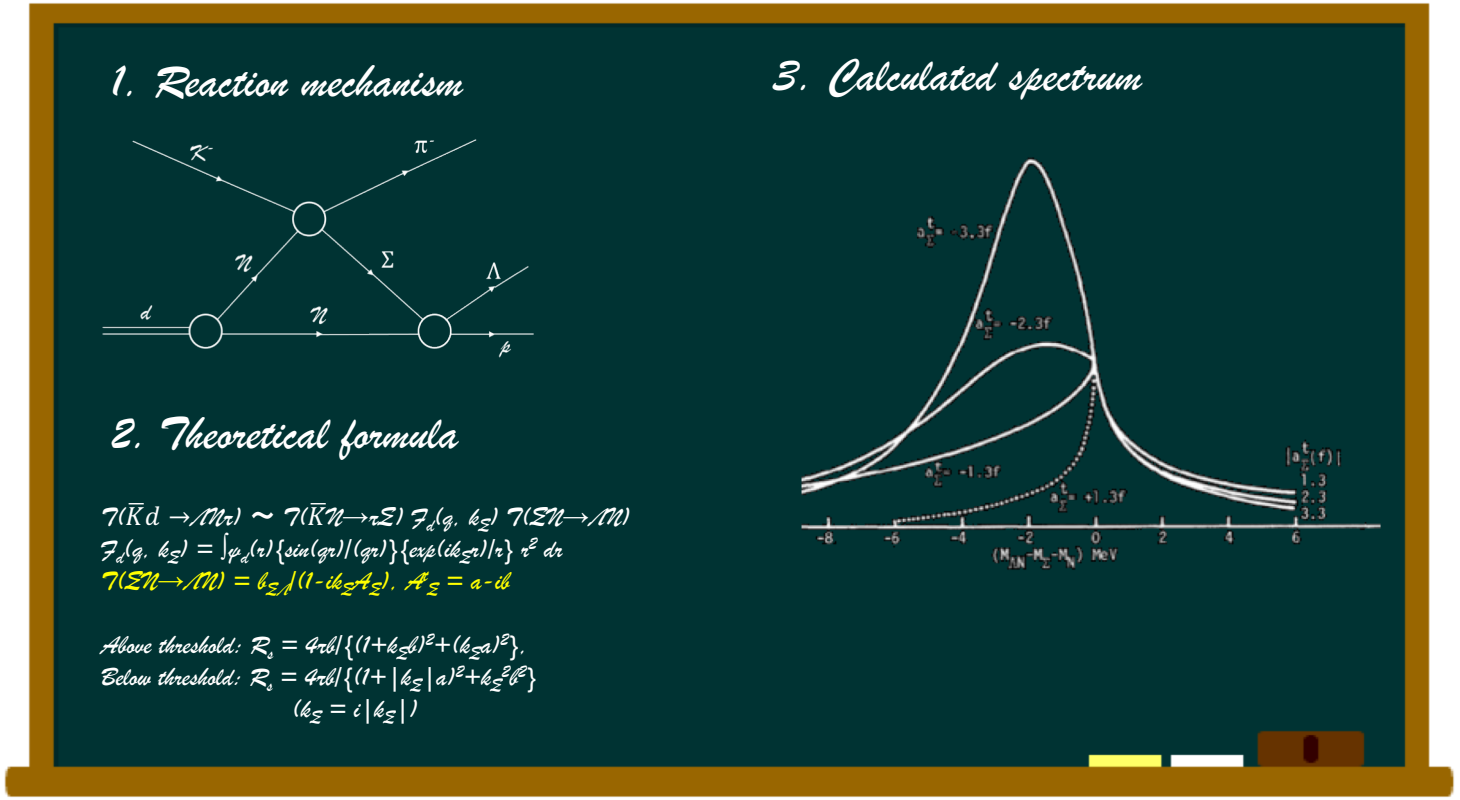
STUDY OF HADRON CLUSTER USING HYPTPC

YUDAI ICHIKAWA (JAEA)

第8回クラスター階層領域研究会 (2023/2/9-11, 大阪大学)

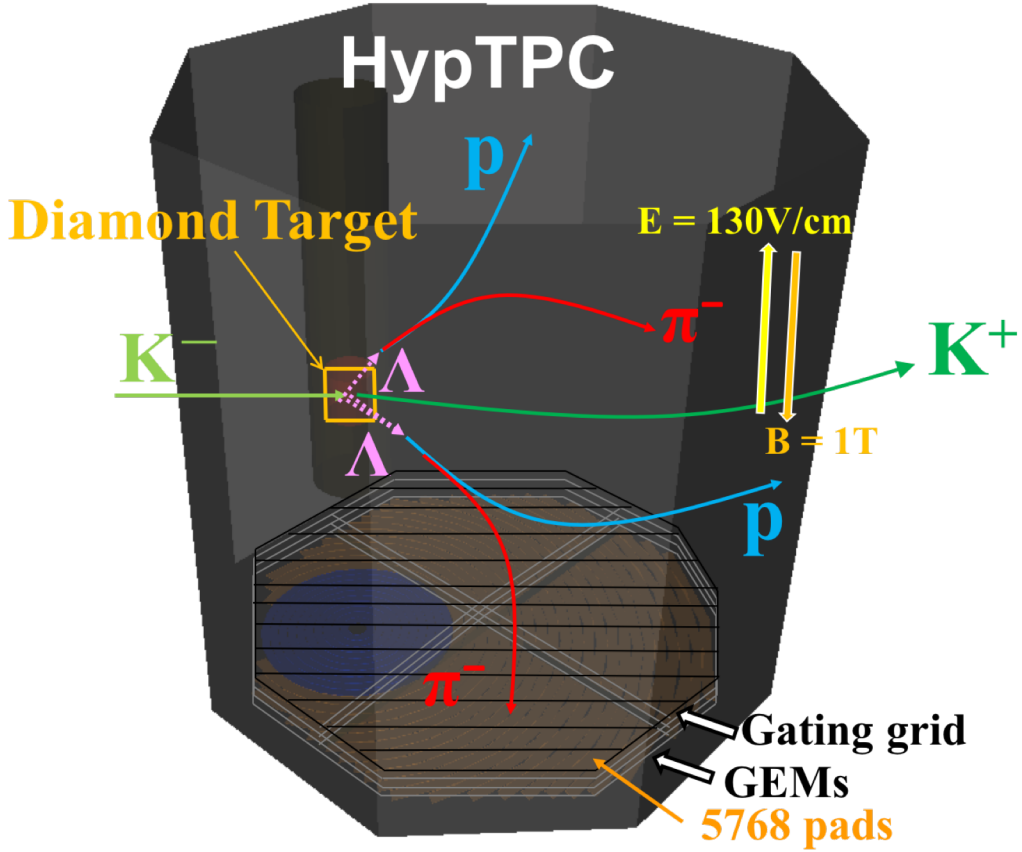


HypTPC (GEM based TPC)

Large acceptance, High-rate capability up to 10^6 Hz

E42: H-dibaryon search by $^{12}C(K^-, K^+)$ reaction
E45: N* and Δ* spectroscopy by p(π, 2π) reaction

E72: Λ* search by $p(K^-, \Lambda)\eta$ reaction
E90: ΣN cusp by $d(K^-, \pi^-)\Lambda p$ reaction

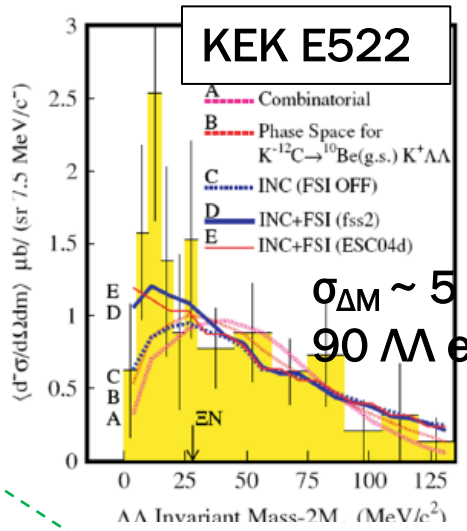


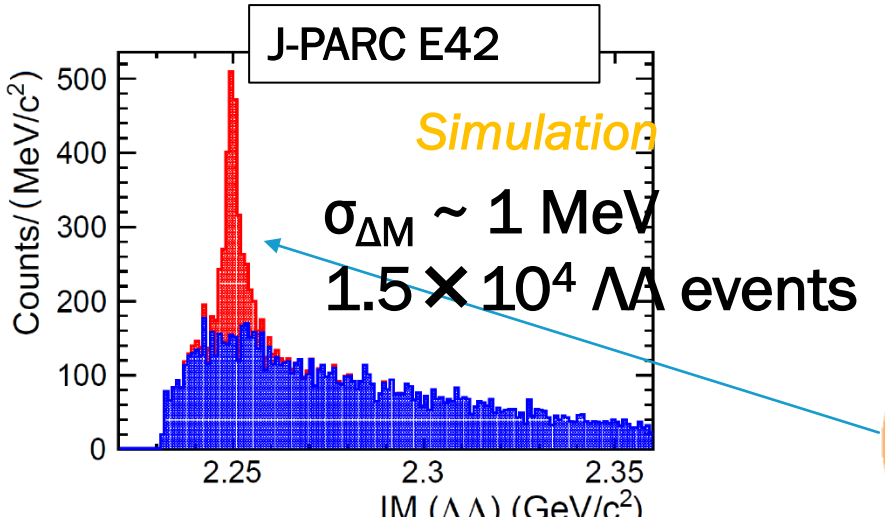
J-PARC E42 EXPERIMENT

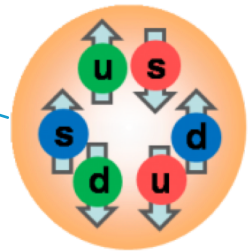
E42 Completed June 29, 2021

$K^- + \text{“pp”} \rightarrow H\,K^+,\ H \rightarrow \Lambda\Lambda, \Lambda p\pi^-, \Xi^- p$ (invariant-mass spectroscopy)

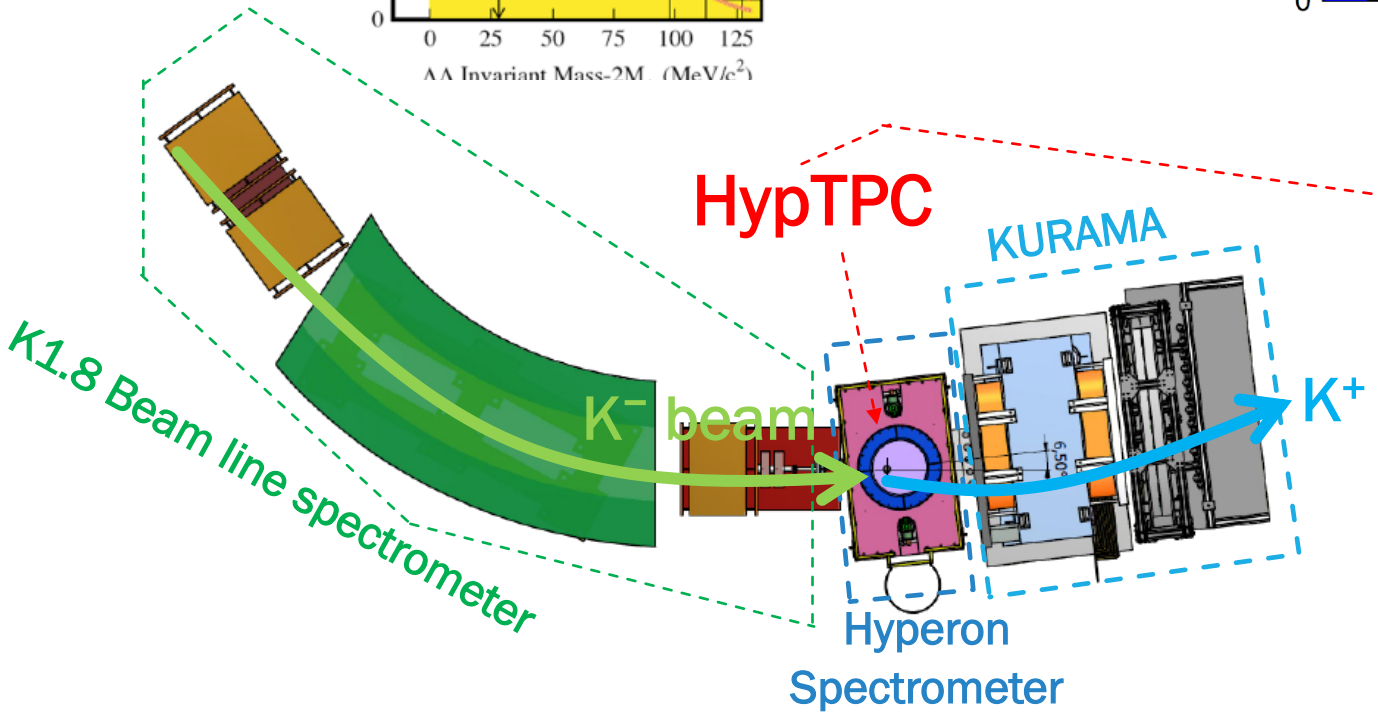
$^{12}C(K^-, K^+)$ reaction

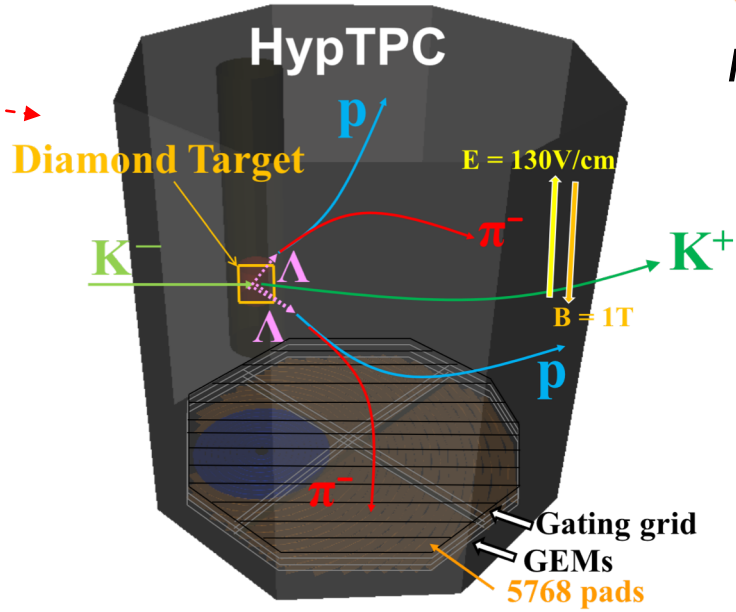






H dibaryon



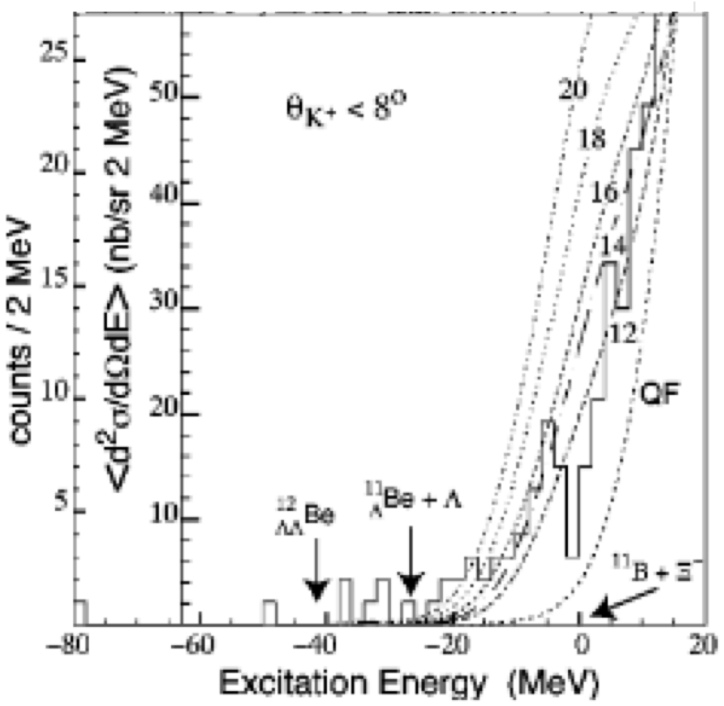


PHYSICS OUTPUT FROM E42 (EXCERPT)

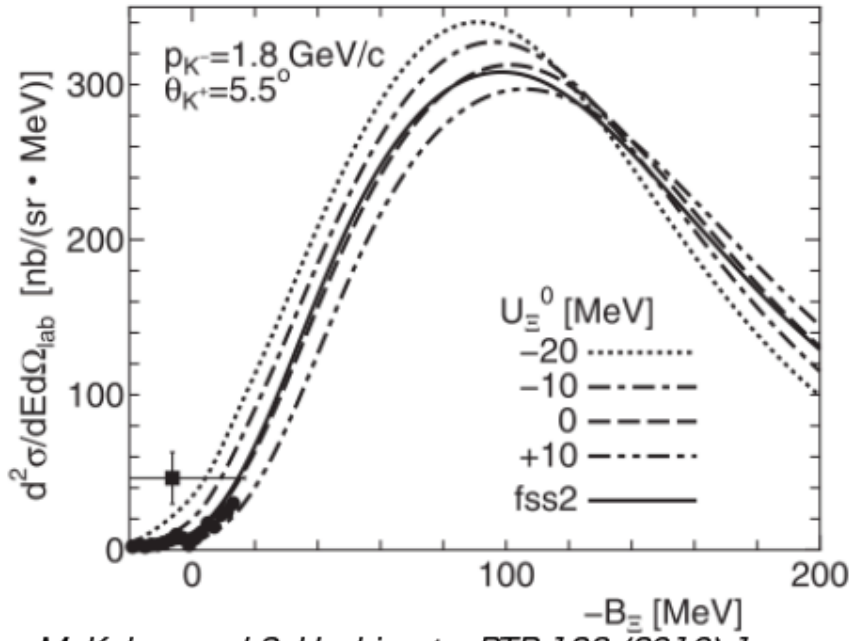
- (Main)H-dibaryon search
  - K^- + “pp”→H K^+, H → ΛΛ, Λpπ$^-$, Ξ^- p (invariant-mass spectroscopy)
- Ξ-A interaction (later slide)
  - Spectrum fit of $^{12}C(K^-, K^+)$ missing mass with (V_0, W_0) parameters
  - By using HypTPC, we can decompose Escape(Ξ-) and Conversion(ΛΛ) spectra → Sensitivity to determine W_0 parameter (Imaginary part)
- Kaonic nuclear search via $^{12}C(K^-, p)$ reaction (later slide)
  - Coincidence measurement to improve the S/N with $^{12}C(K^-, p)$Λp requirement
  - Invariant-mass spectroscopy (Λp, Λpp) of Kaonic nuclei (fragment production)
- Ξ^- polarization of K^-+p → Ξ^-+K^+ reaction
- K* invariant mass measurement via $^{12}C(K^-, p)$ reaction

E42 BYPRODUCT
Ξ-A POTENTIAL STUDY BY $^{12}C(K^-, K^+)$ SPECTRUM

- BNL-E885
  - ΔE ~14 MeV (FWHM)
  - $d\sigma/d\Omega$~42nb/sr (θ<14deg, −20<E<0 MeV)
  - Suggested V_Ξ~ −14 MeV???
    - from just a "visual inspection"
    - assuming imaginary part = 0



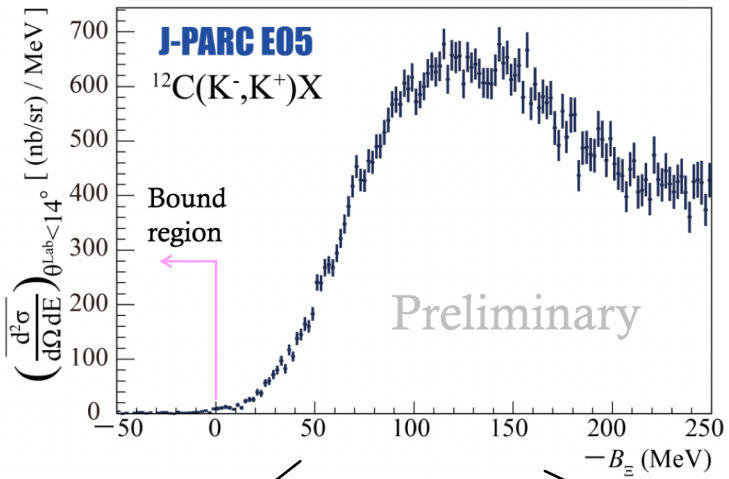
BNL-E885 spectrum can be explained with V_Ξ =0 MeV, Γ =4 MeV (with imaginary part W_0)



M. Kohno and S. Hashimoto, PTP 123 (2010) 1

E42 BYPRODUCT
Ξ-A POTENTIAL STUDY BY $^{12}C(K^-, K^+)$ SPECTRUM

$^{12}C(K^-, K^+)$Inclusive spectrum



E42 can decompose the inclusive spectrum to escape and conversion spectra.

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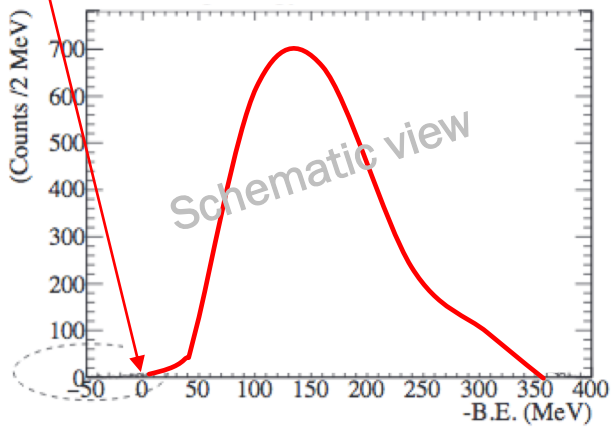
Should have much more sensitivity of W_0 determination!

E42: Decompose

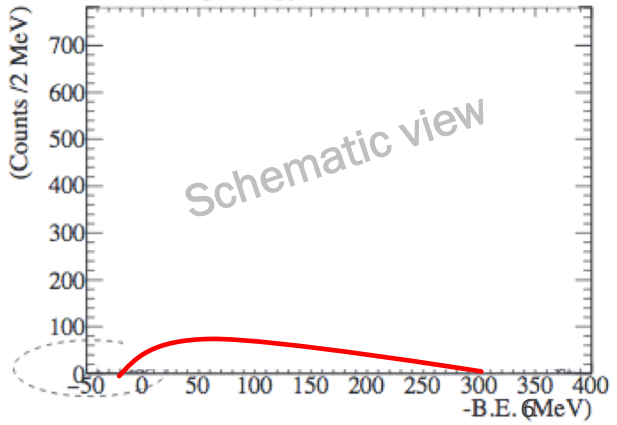
(Ξ⁻) Escape spectrum

The cross section at B.E. ≧ 0 should be 0



(ΛΛ) Conversion spectrum

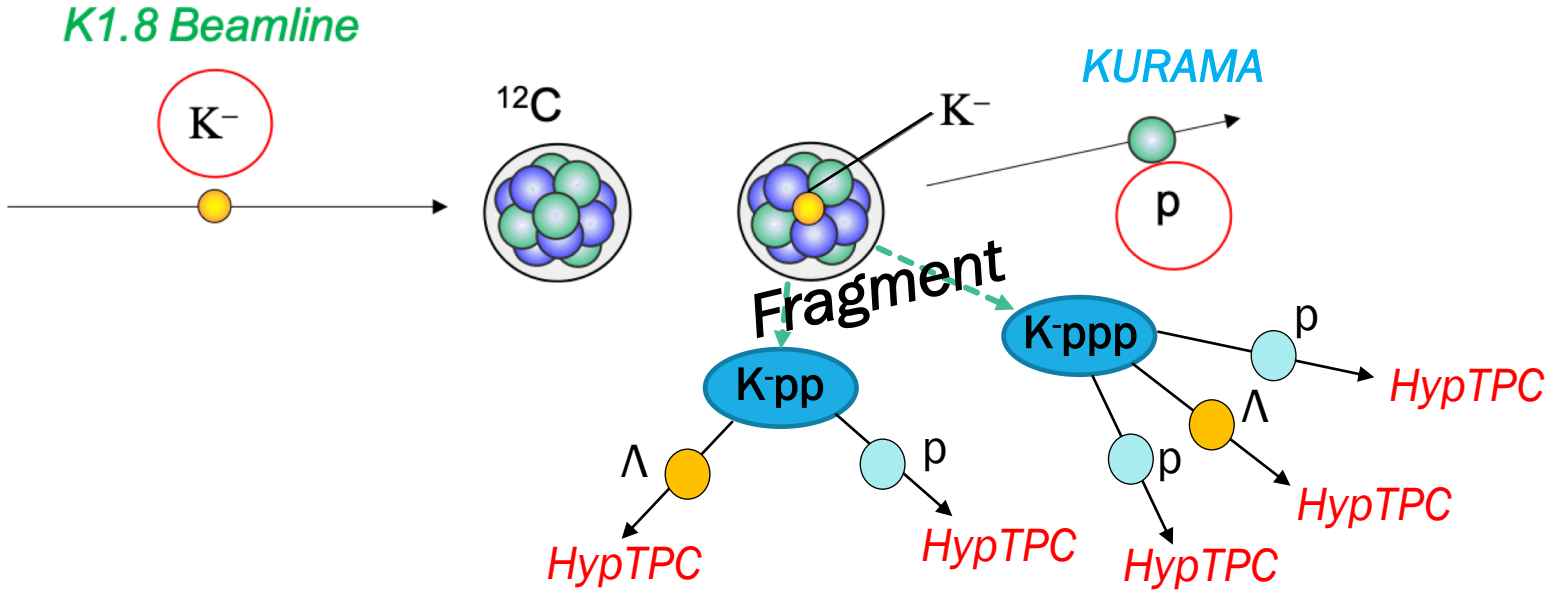
The strength (yield) also has the information of imaginary part



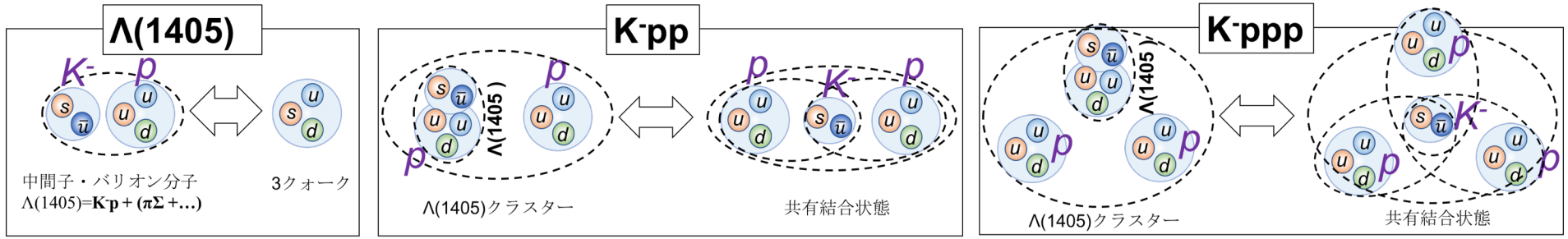
E42 BYPROCUT: K⁻pp and K⁻ppp SEARCH

K⁻pp: Λp invariant mass, K⁻ppp: Λppp invariant mass by selecting $^{12}C(K^-, p)$ reaction (fragment production)

公募研究



P. Kienle et al. / Physics Letters B 632 (2006) 187–191

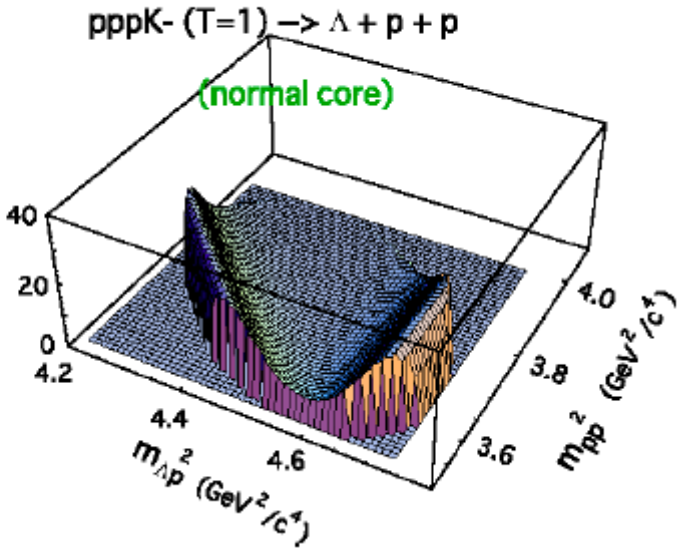


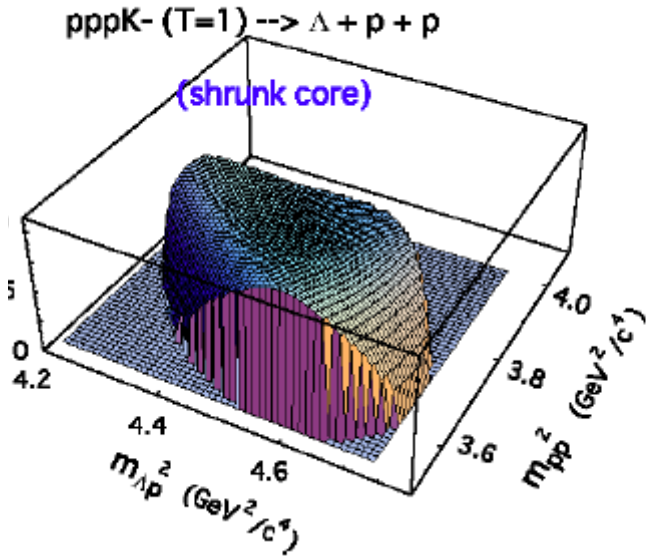
E42 BYPROCUT: K^-pp and K^-ppp SEARCH

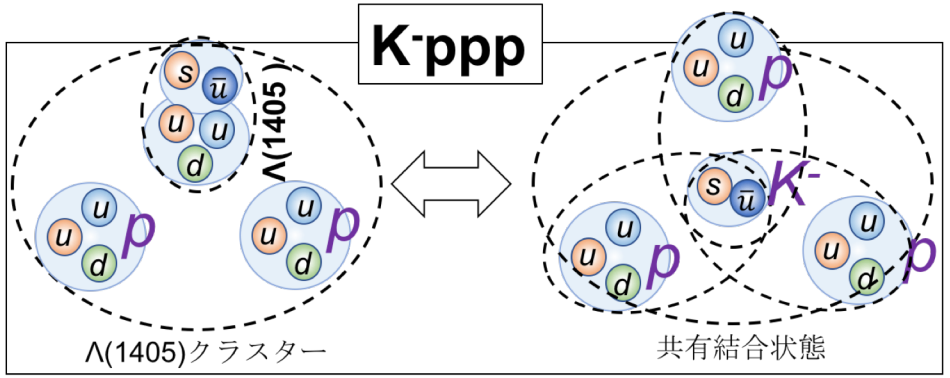
K^-pp: Λp invariant mass, K^-ppp: Λppp invariant mass
by selecting $^{12}C(K^-, p)$ reaction (fragment production)

P. Kienle et al. / Physics Letters B 632 (2006) 187–191

公募研究



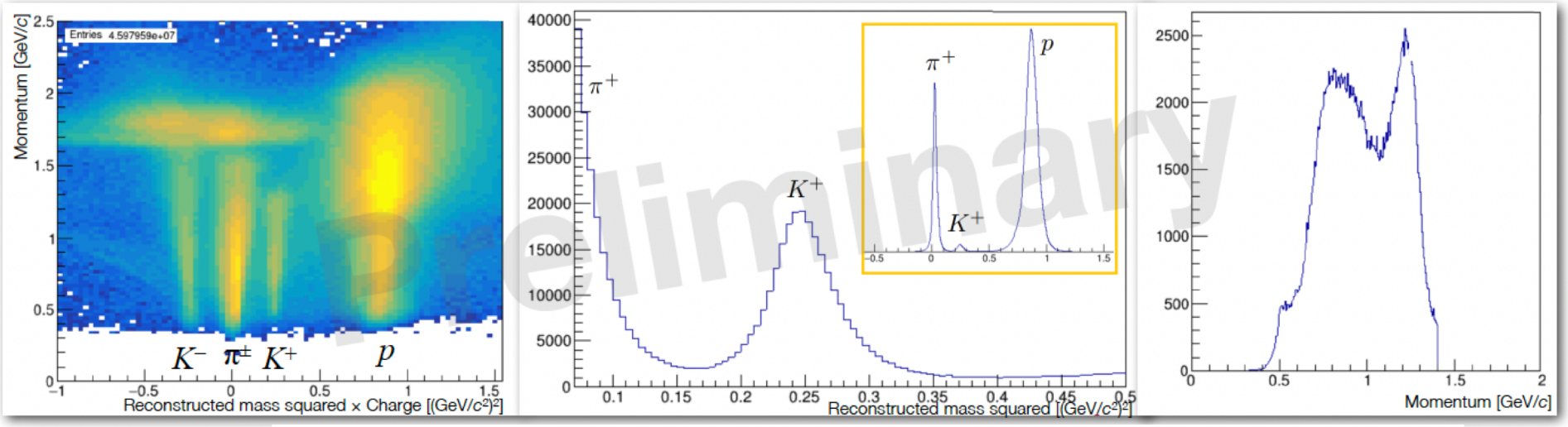




PRELIMINARY ANALYSIS（KURAMA）

Scattered particles

K^+: 0.5-1.4 GeV/c

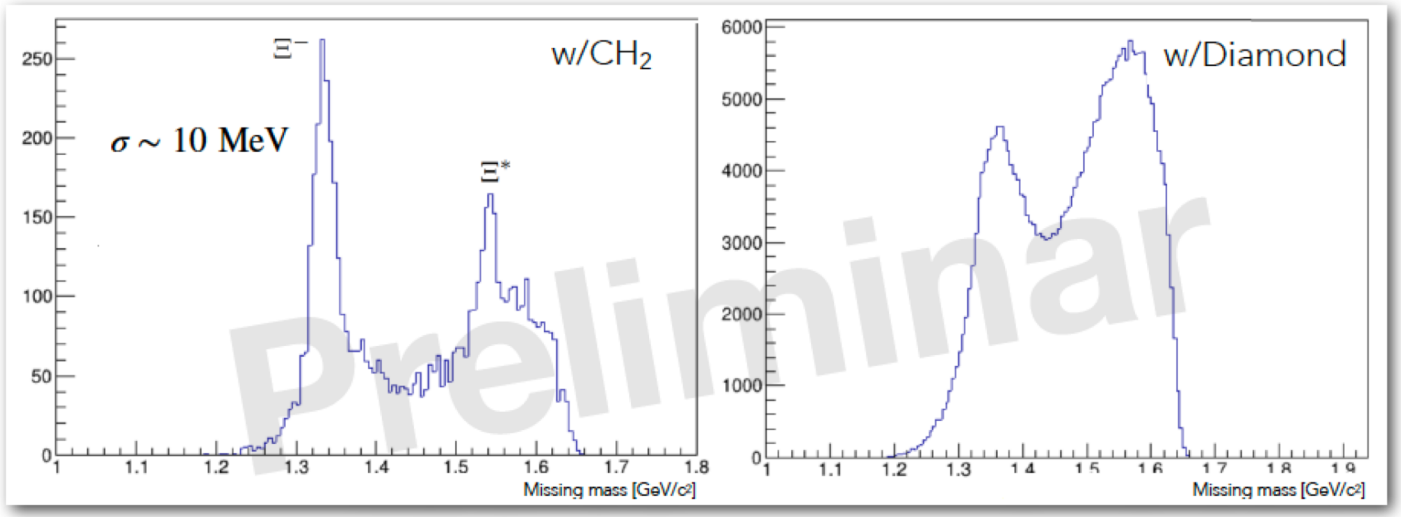


$^{12}C(K^-, K^+)$

3×10⁵ events

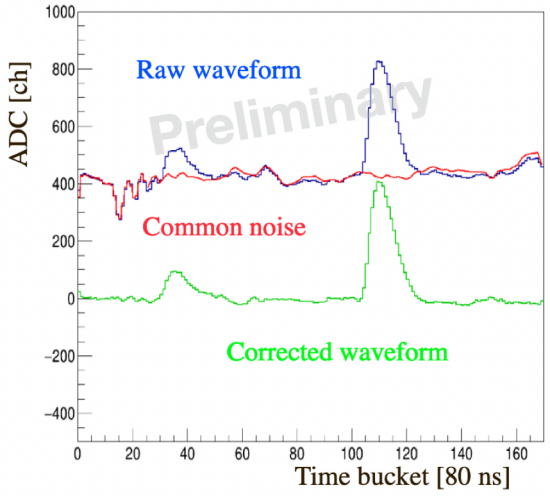
(KEK E522 : 45934 events)

Missing mass



PRELIMINARY ANALYSIS (HYPTPC1)

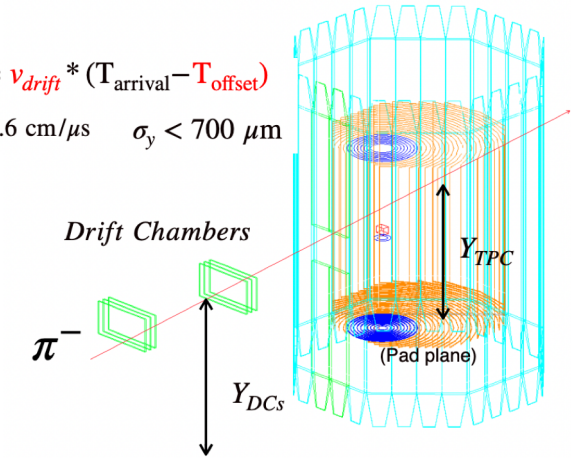
Flash ADC analysis (BG subtraction)



π^- beam-through data w/o B-field

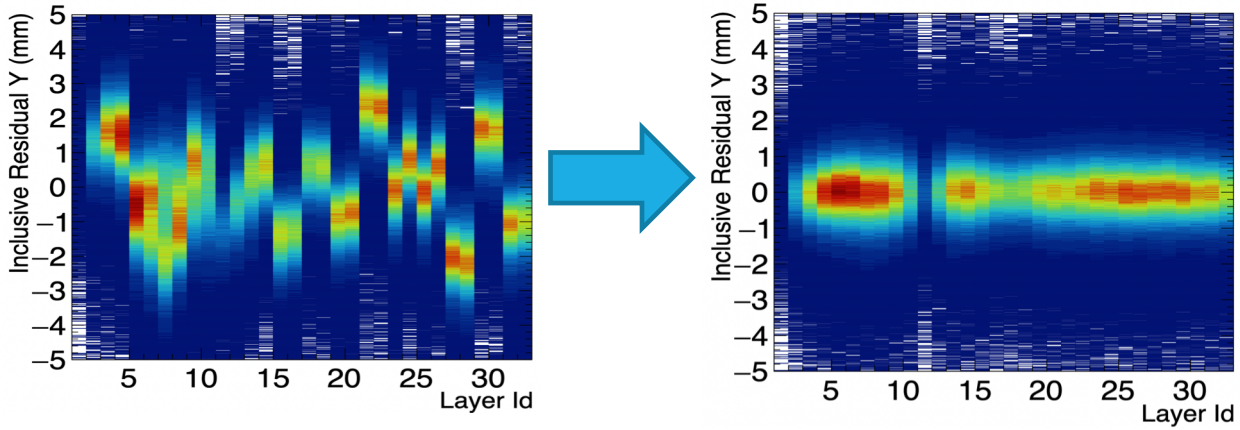
$Y_{TPC} = v_{drift} * (T_{arrival} - T_{offset})$

$v_{drift} \sim 5.6$ cm/μs $\sigma_y < 700$ μm

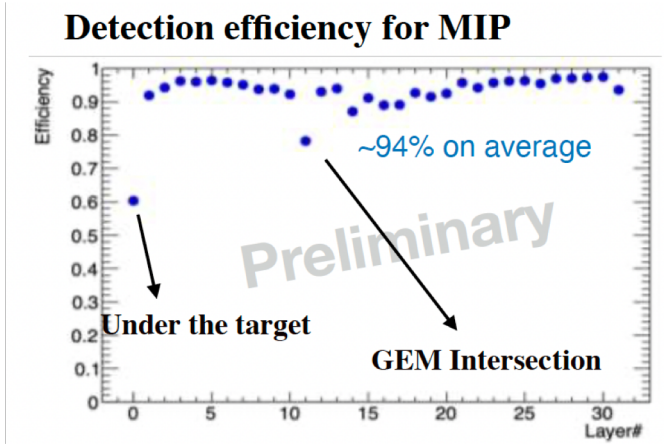


Time offset adjustment by using beam-through data analysis

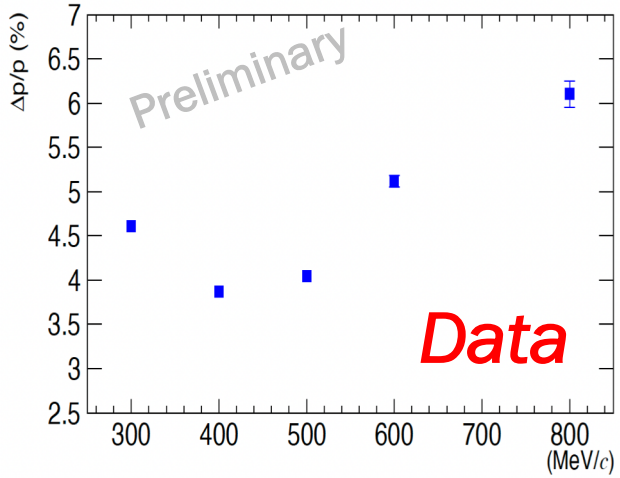
Y residual distribution(Beam through)

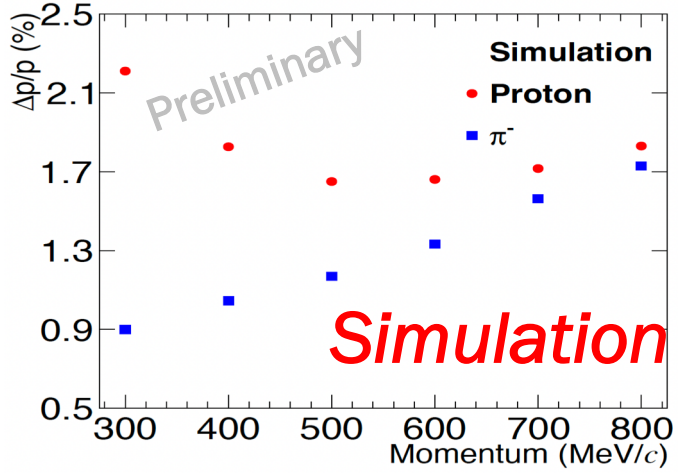


Estimation of hit efficiency



Momentum resolution



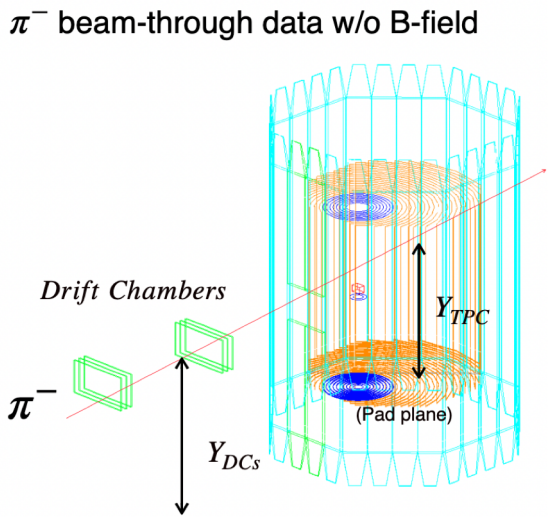


Worse than simulation

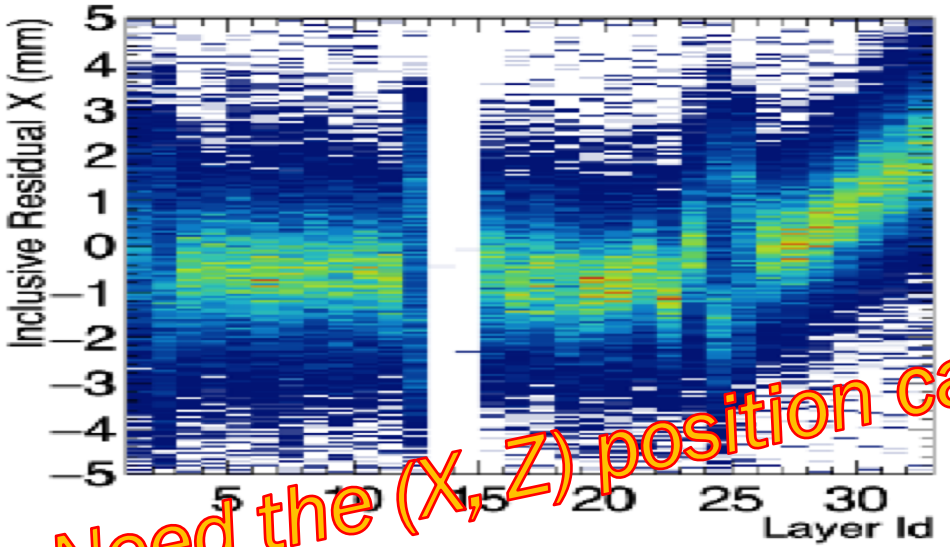
↓

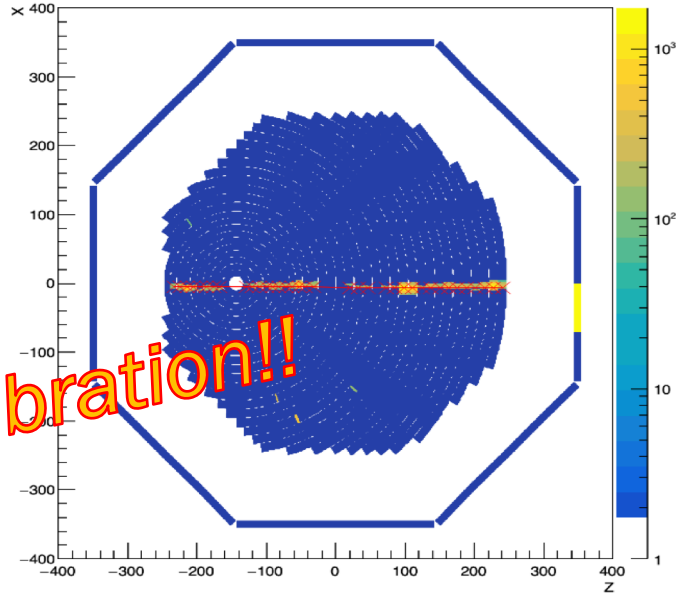
Position correction (on-going)

PRELIMINARY ANALYSIS (HYPTPC1)

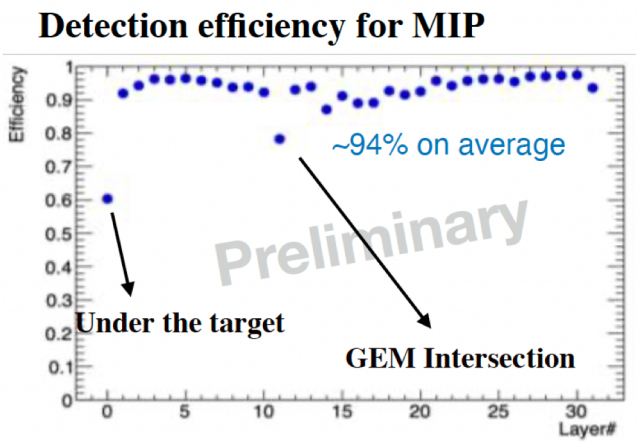


X residual distribution(Beam through)

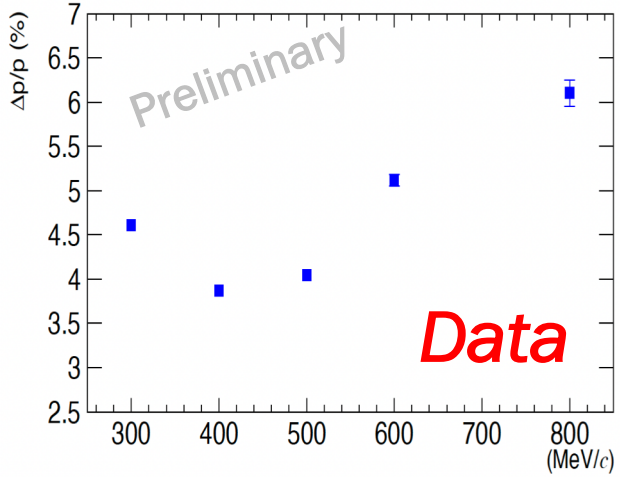


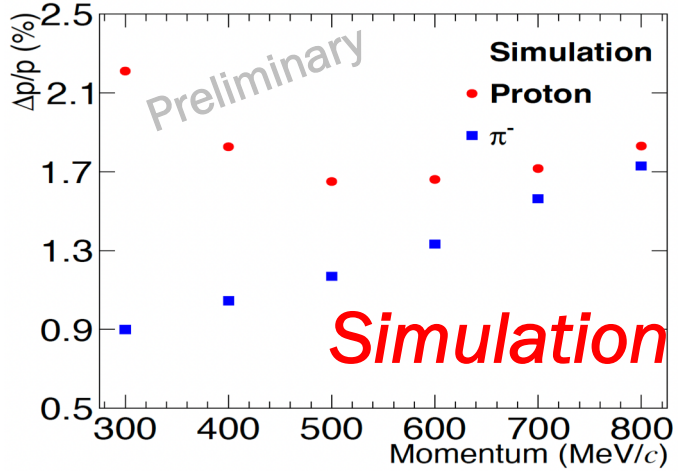


Estimation of hit efficiency



Momentum resolution



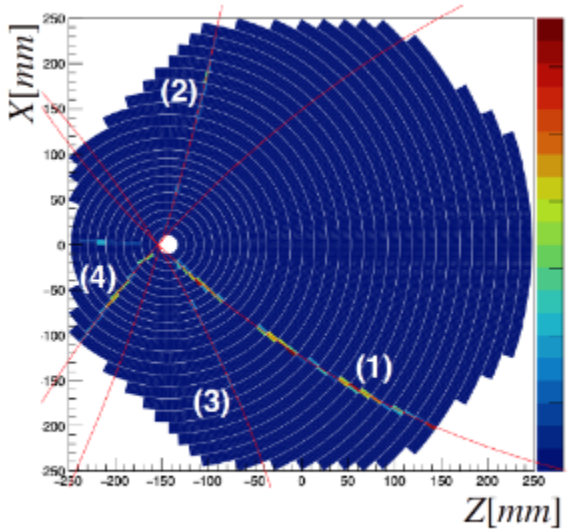


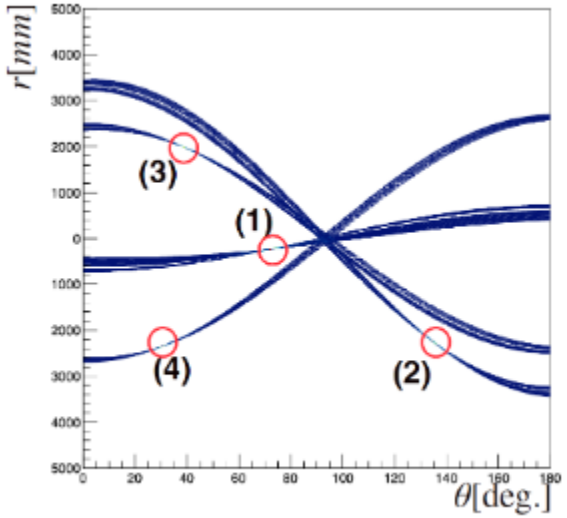
Worse than simulation

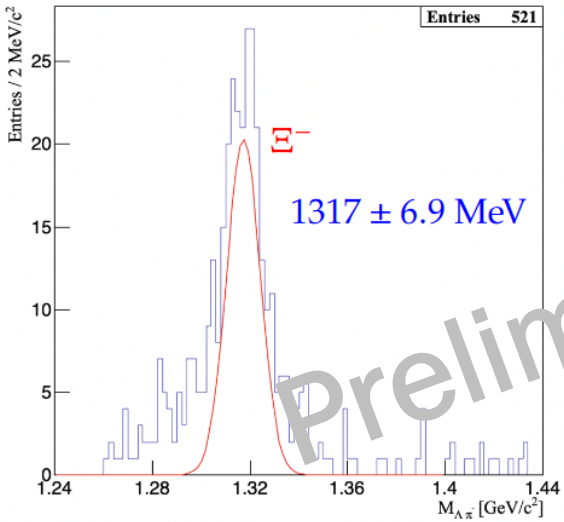
↓

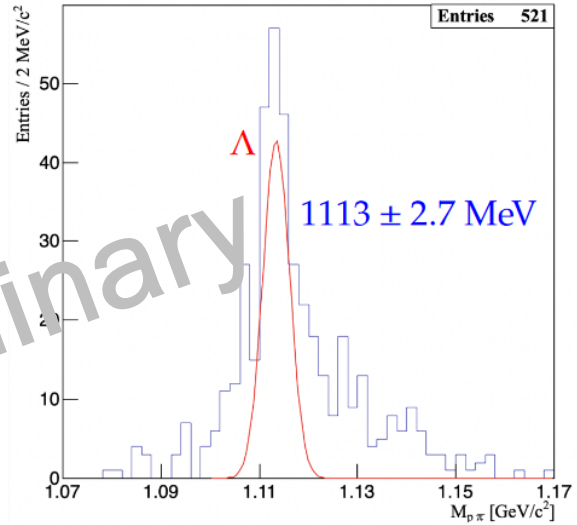
Position correction (on-going)

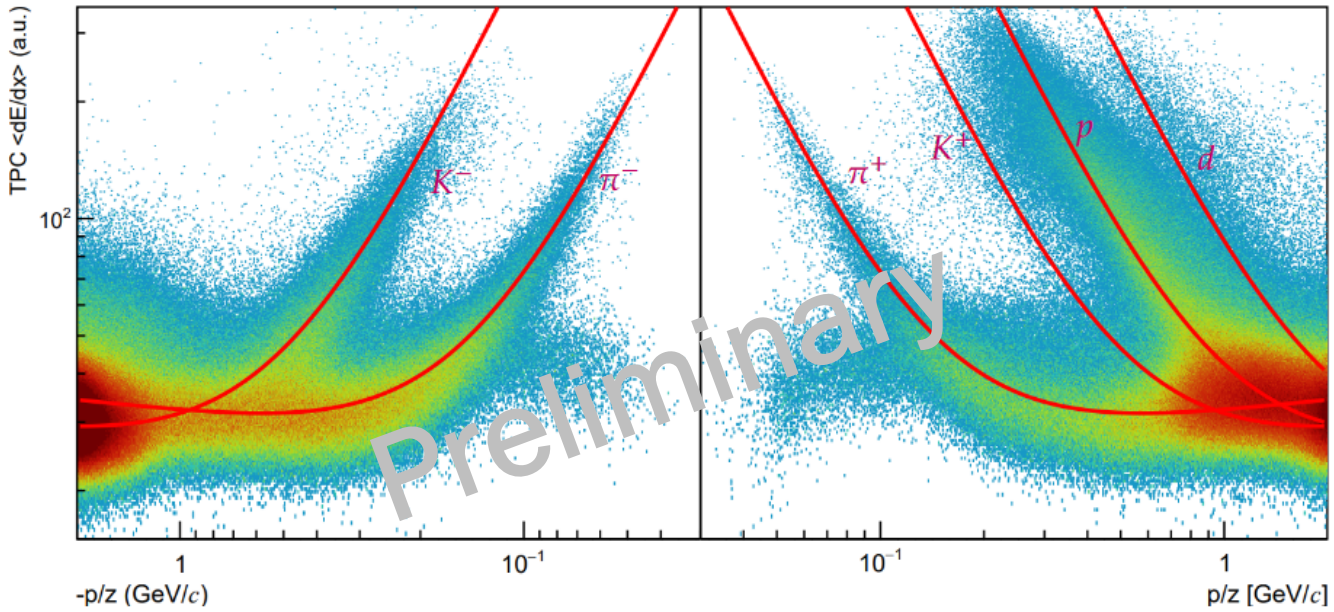
PRELIMINARY ANALYSIS (HYPTPC2)

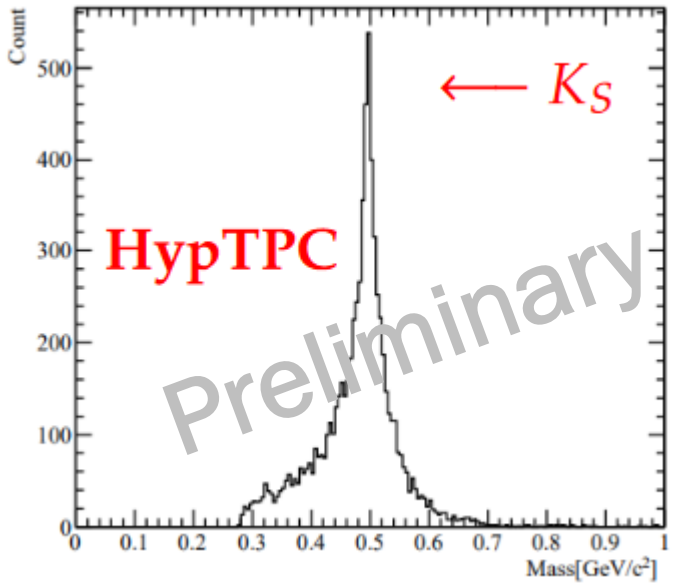






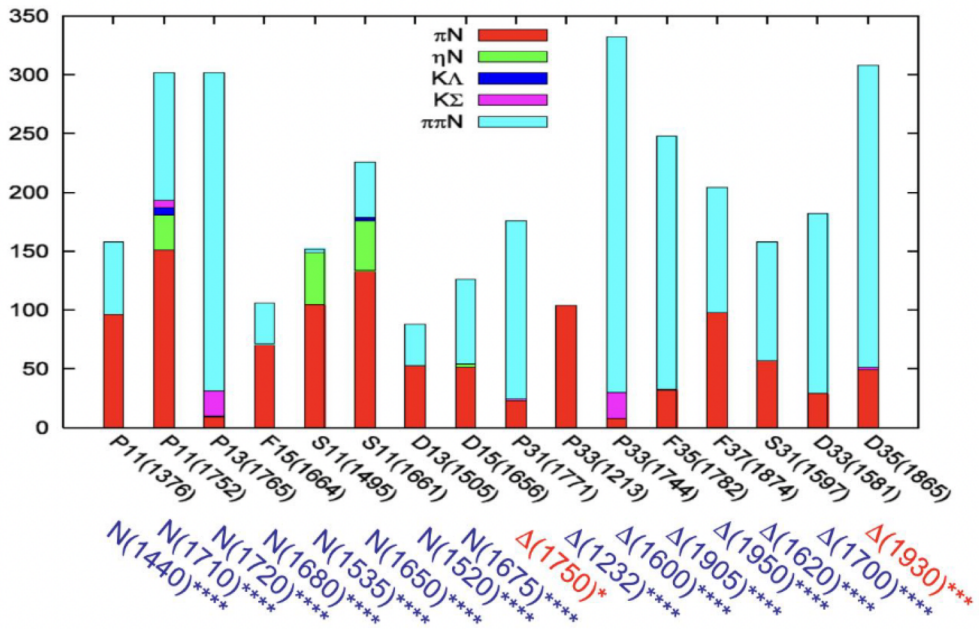






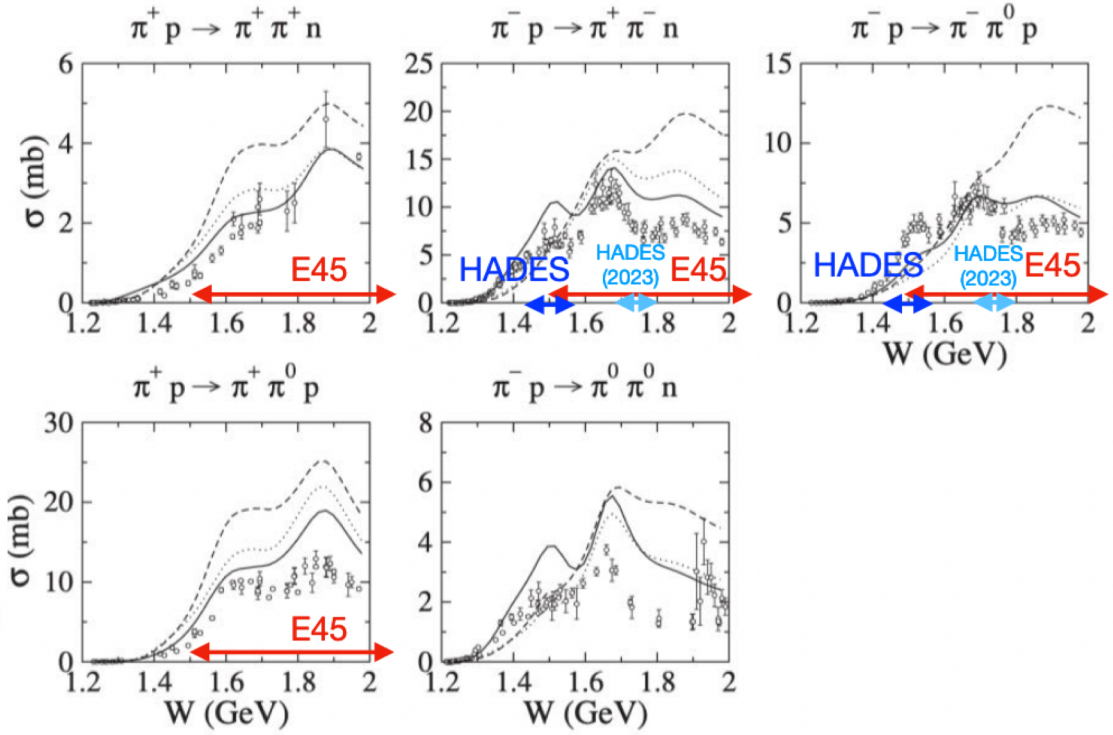
J-PARC E45 EXPERIMENT

- N*/Δ* spectroscopy with the πp→ππN and πp→KY reactions in the wide energy range of 1.5 - 2.15 GeV (p=0.73 - 2.0 GeV/c)
- Updates on the world database (πp→ππN)
  - 240k events measured in1970's → x100 higher statistics



There are many N* and Δ* resonances which couple to ππN dominantly

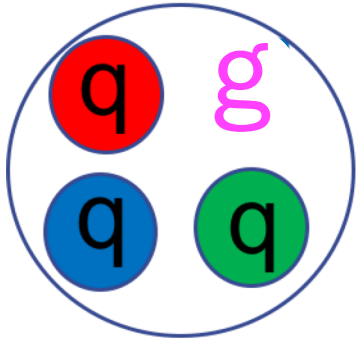
H. Kamano, et al. PRC 79 025206 (2009)



HADES, PRC 102, 024001 (2020)

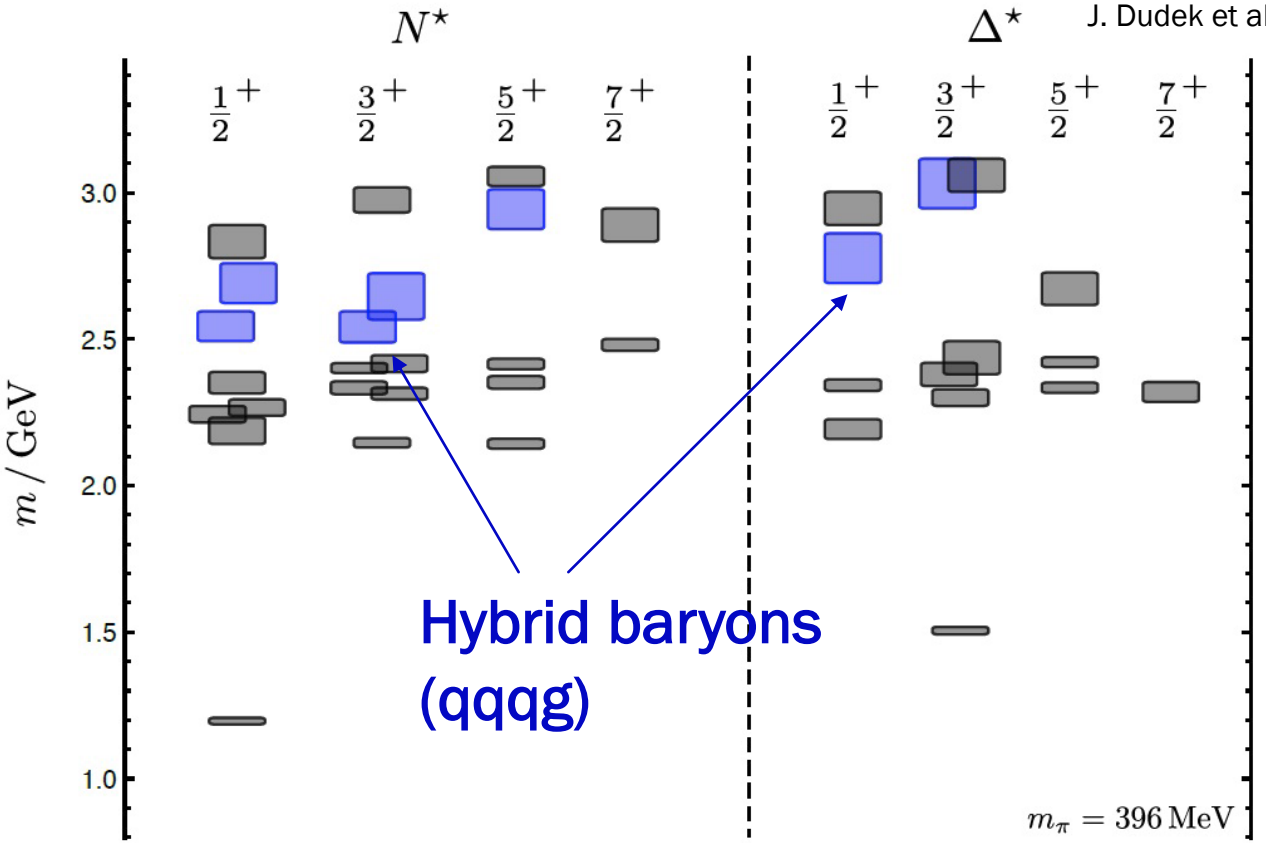
H. Kamano et al., PRC 79, 025206 (2009)

J-PARC E45 EXPERIMENT



Hybrid baryons are predicted by Lattice QCD

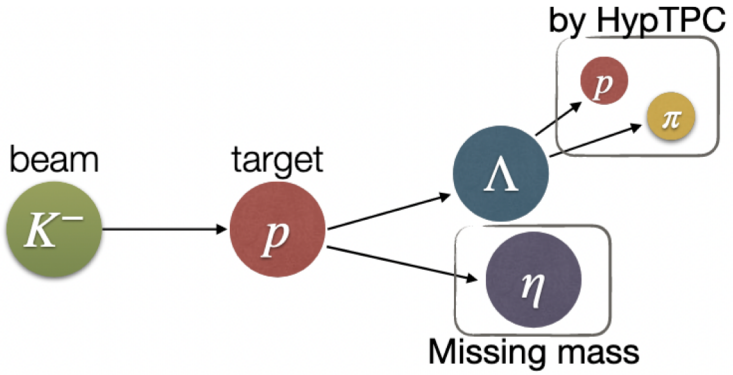
J. Dudek et al., PRD 85 054016(2012).



J-PARC E72 EXPERIMENT

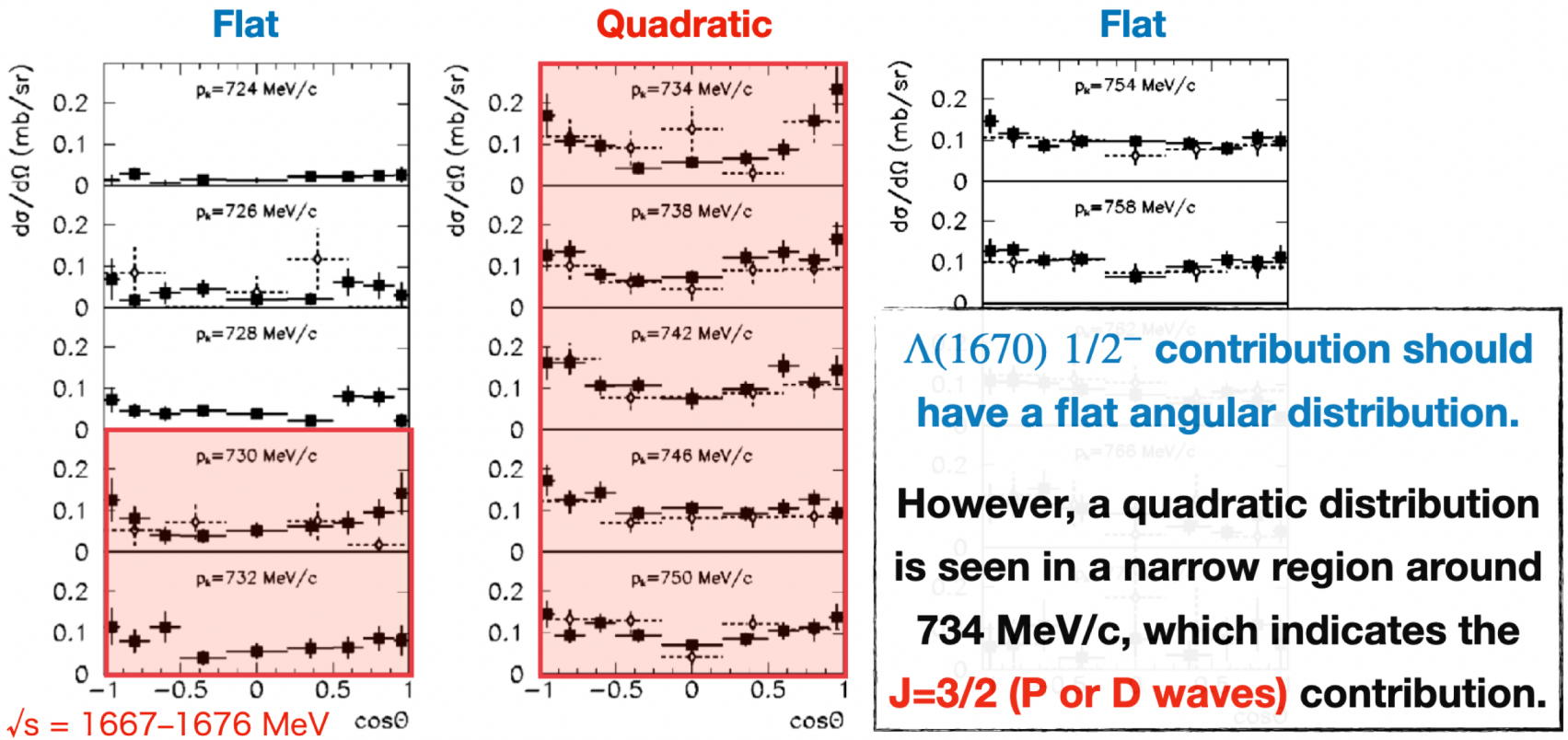
E72 aims to established narrow J = 3/2 Λ* and to determine its parity

- The Kp⟶Λη reaction with pK = 735 MeV/c (±2% FWHM)
- K^- momentum resolution: δp/p ~1.5 MeV/c (Γ~1 MeV)
- Angular distribution⟶ spin, Λ polarization ⟶ parity



[Crystal Ball, PRC 64 (2001) 055205]

■ : $\eta \to \gamma\gamma$
□ : $\eta \to 3\pi^0$



Λ(1670) 1/2⁻ contribution should have a flat angular distribution.

However, a quadratic distribution is seen in a narrow region around 734 MeV/c, which indicates the J=3/2 (P or D waves) contribution.

J-PARC E72 EXPERIMENT

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- The Kp⟶Λη reaction with pK = 735 MeV/c (±2% FWHM)
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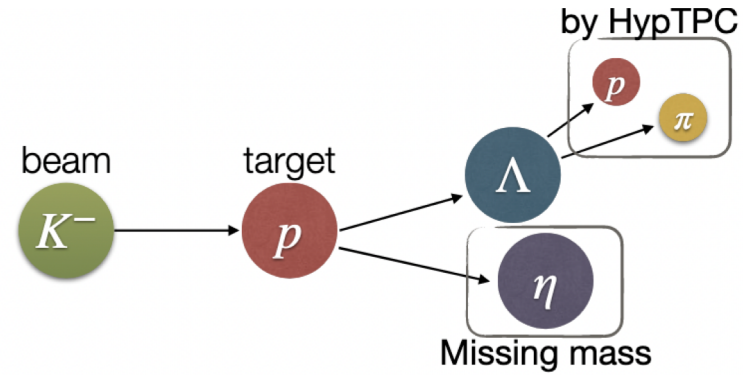
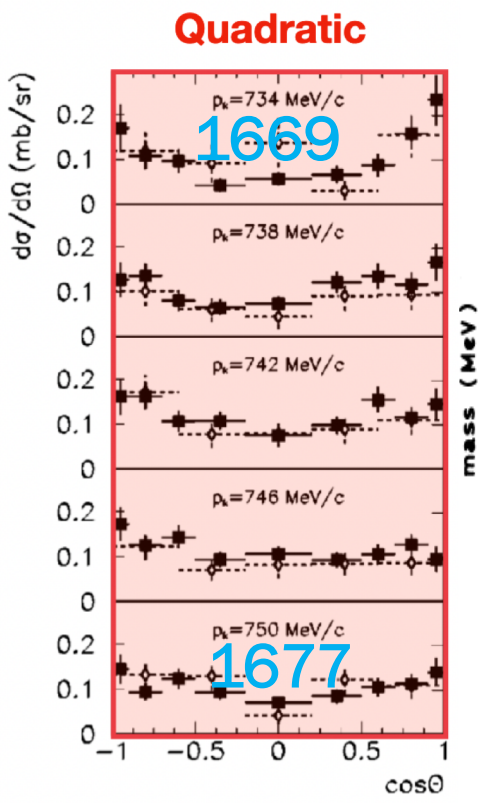
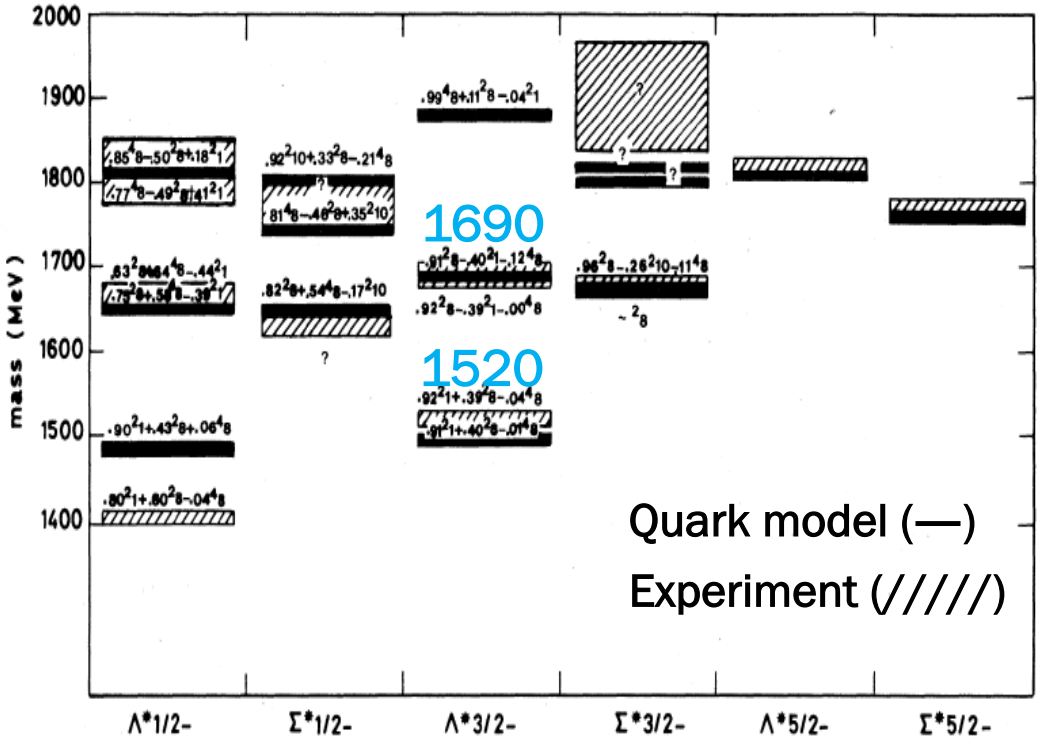
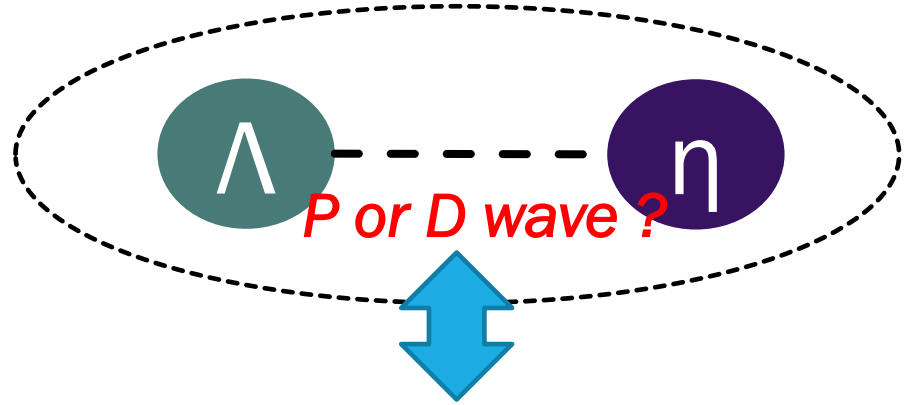




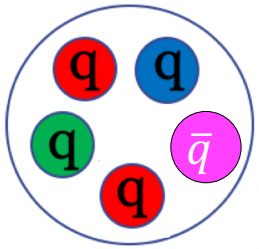
No J=3/2 state around 1670 MeV



Meson-Baryon molecule?

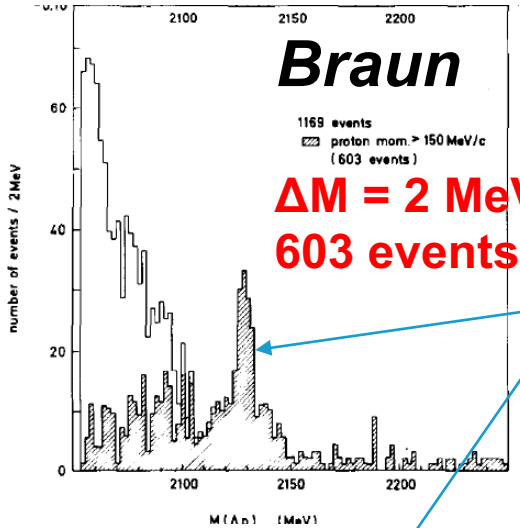


Penta-quark?

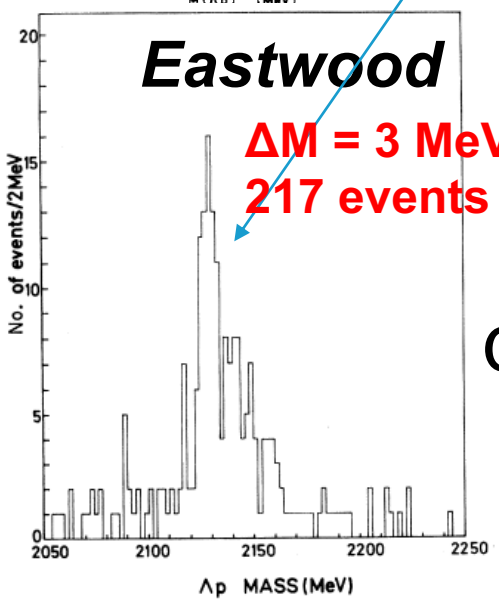


E90: “ΣN cusp” using HypTPC +S2S

Old bubble chamber
$d(K^-, \pi^-)\Lambda p$



ΔM = 2 MeV
603 events



ΔM = 3 MeV
217 events

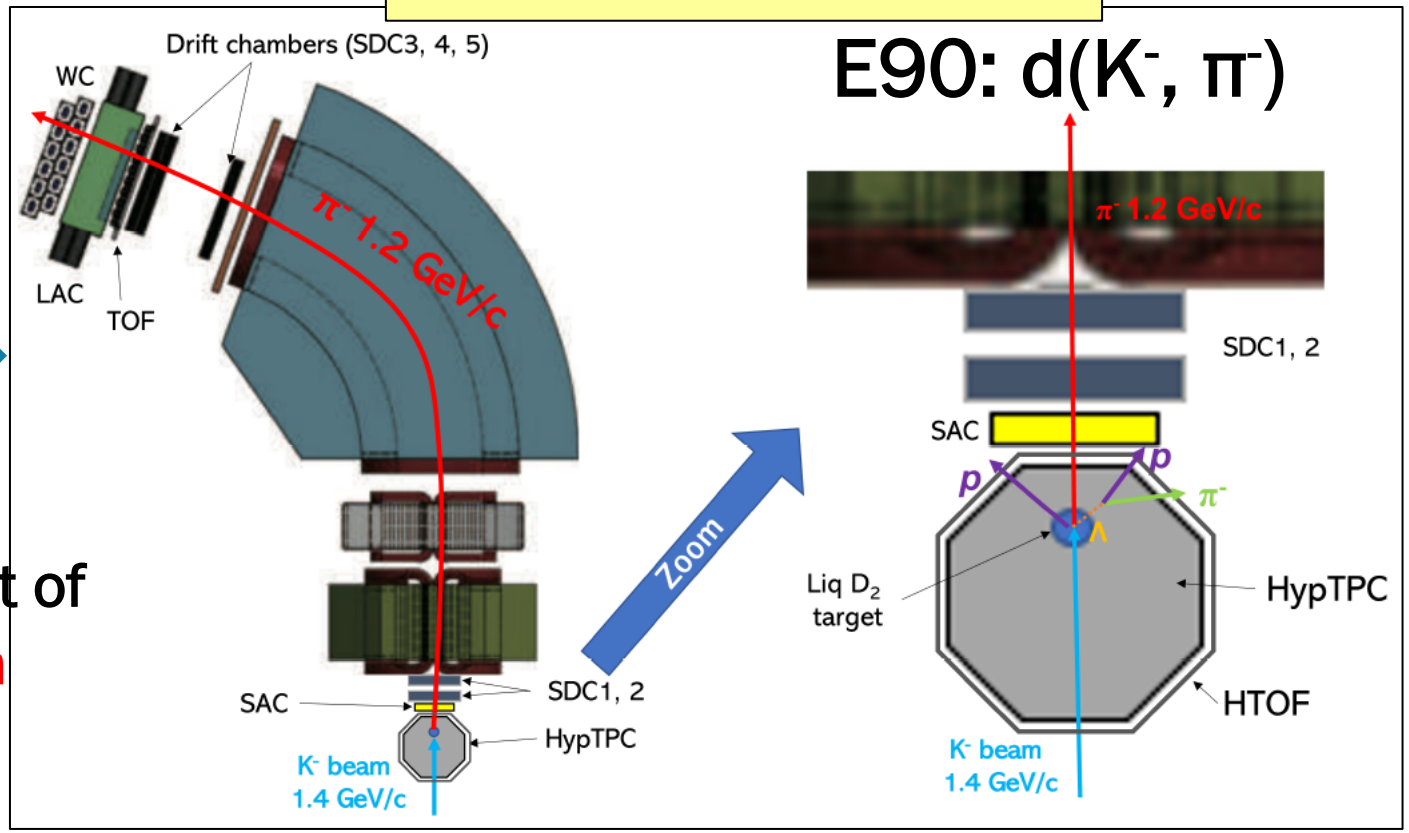
“ΣN cusp”
Near ΣN threshold

E90

Great improvement of
mass resolution
and statistics

(K^-, π^-) measurement: (K18 + S2S)
Decay particles: HypTPC

ΔM = 0.4 MeV (σ)
1.4×10^4 events



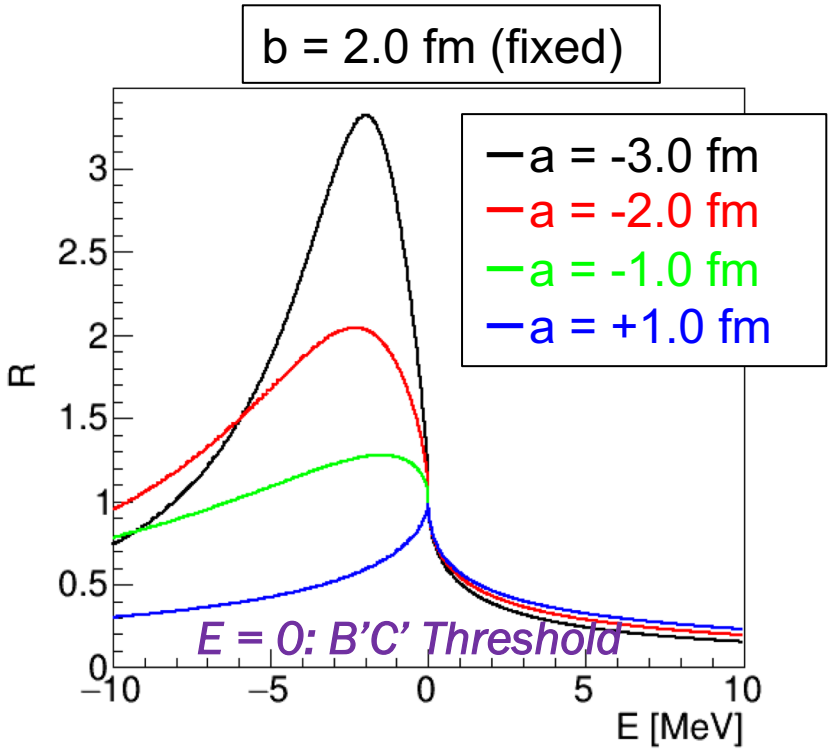
THRESHOLD CUSP

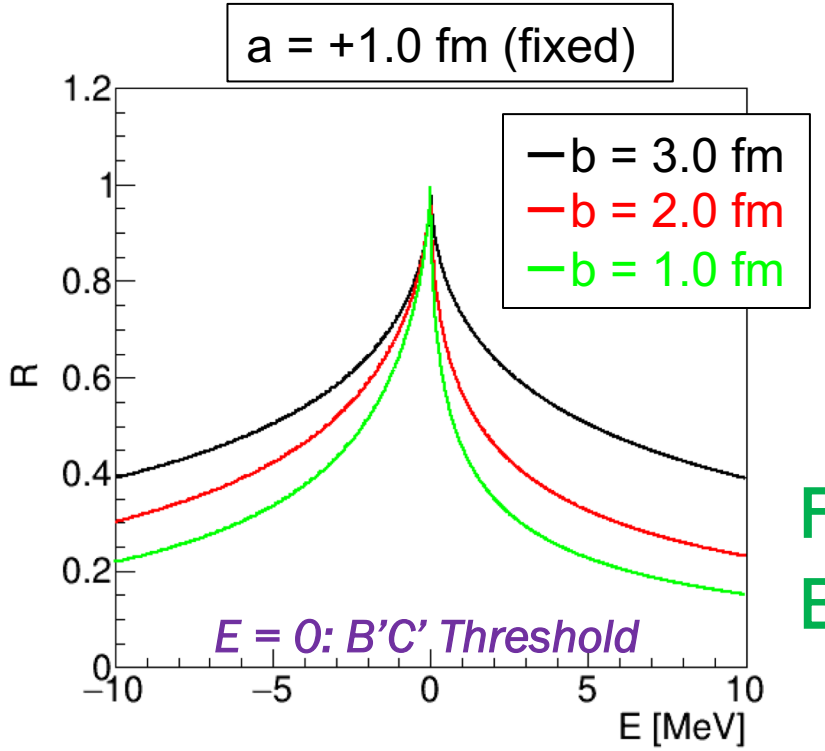
Cusp structure can be expressed by the scattering length (for B'C'), A = a + ib

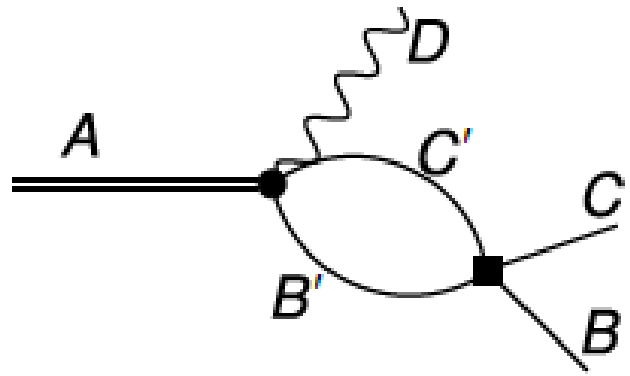
- Above threshold: $\mathrm{R} = \frac{4\pi b}{\{(1+kb)^2+(ka)^2\}} \sim 1 - 2kb + O(k^2)$
- Below threshold: $\mathrm{R} = \frac{4\pi b}{\{(1+\kappa a)^2+(\kappa b)^2\}} \sim 1 - 2\kappa a + O(\kappa^2),\ k = i\kappa$

Reduced mass
$\mu = m_{B'}m_{C'}/(m_{B'}+m_{C'})$

k(relative momentum for B'C') ~ $\sqrt{2\mu E}$







For the "ΣN cusp",
B'=Σ, C'=N, B=Λ, C=N

Key of E90: High resolution ΔM = 0.4 MeV

Theoretical Value of ΣN scattering length ($T=1/2$, $^3S_1$)

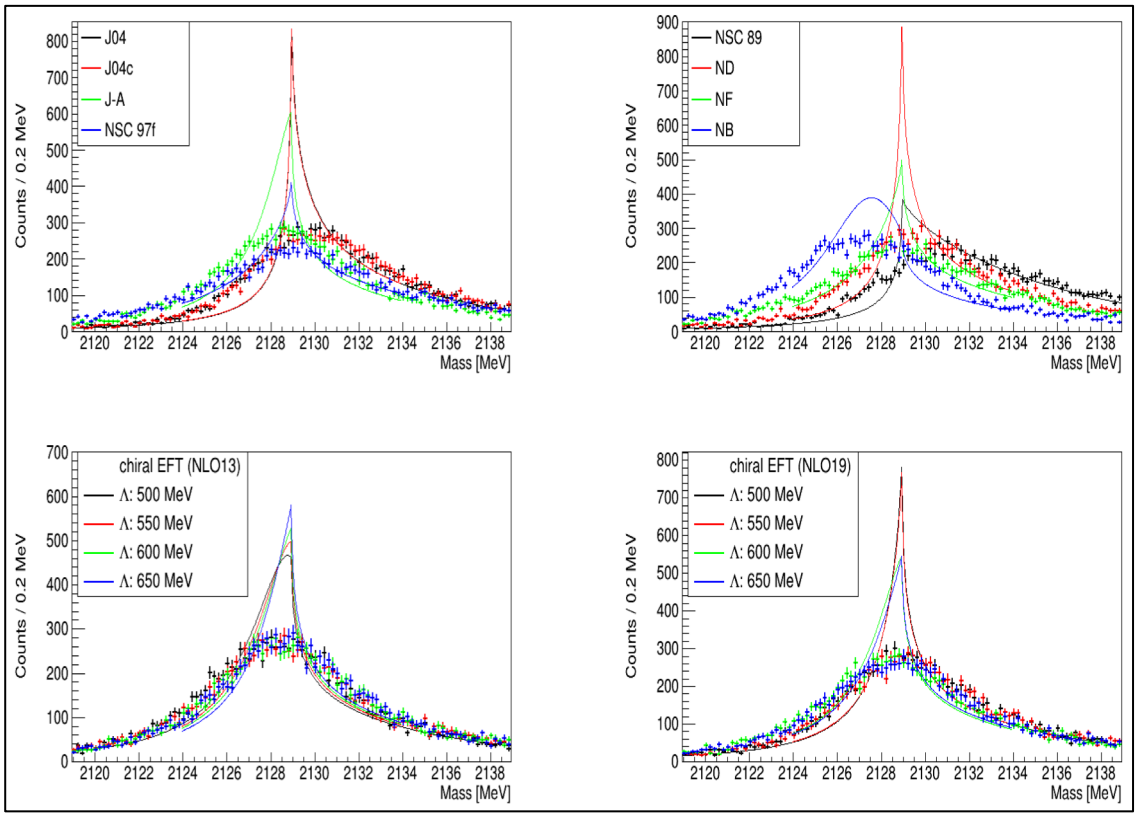
Model	J04	J04c	J–A	NSC 97f	NSC 89	ND	NF	NB
a [fm]	3.83	3.63	-2.37	-1.03	2.54	2.06	-1.29	-3.0
b [fm]	3.01	3.09	3.74	2.41	0.26	4.64	3.02	1.8

Model	chiral EFT (NLO13)				chiral EFT (NLO19)			
Λ [MeV]	500	550	600	650	500	550	600	650
a [fm]	-2.61	-2.44	-2.27	-2.06	-0.95	-0.98	-2.29	-1.95
b [fm]	2.89	3.11	3.29	3.59	4.77	4.59	3.39	3.38

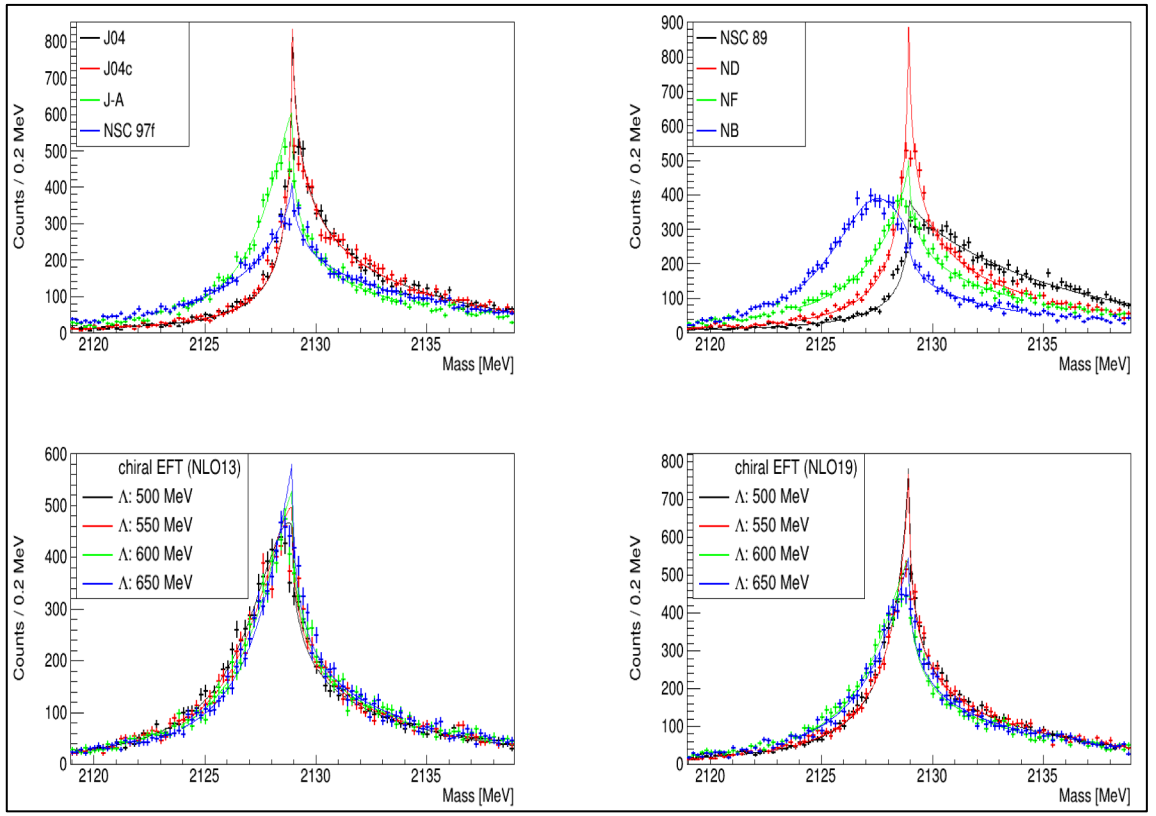
a < 0: Bound state
a > 0: attractive

ΣN-dibaryon !?

Sensitivity of past experiment（ΔM = 2 MeV）



Sensitivity of E90（ΔM = 0.4 MeV）



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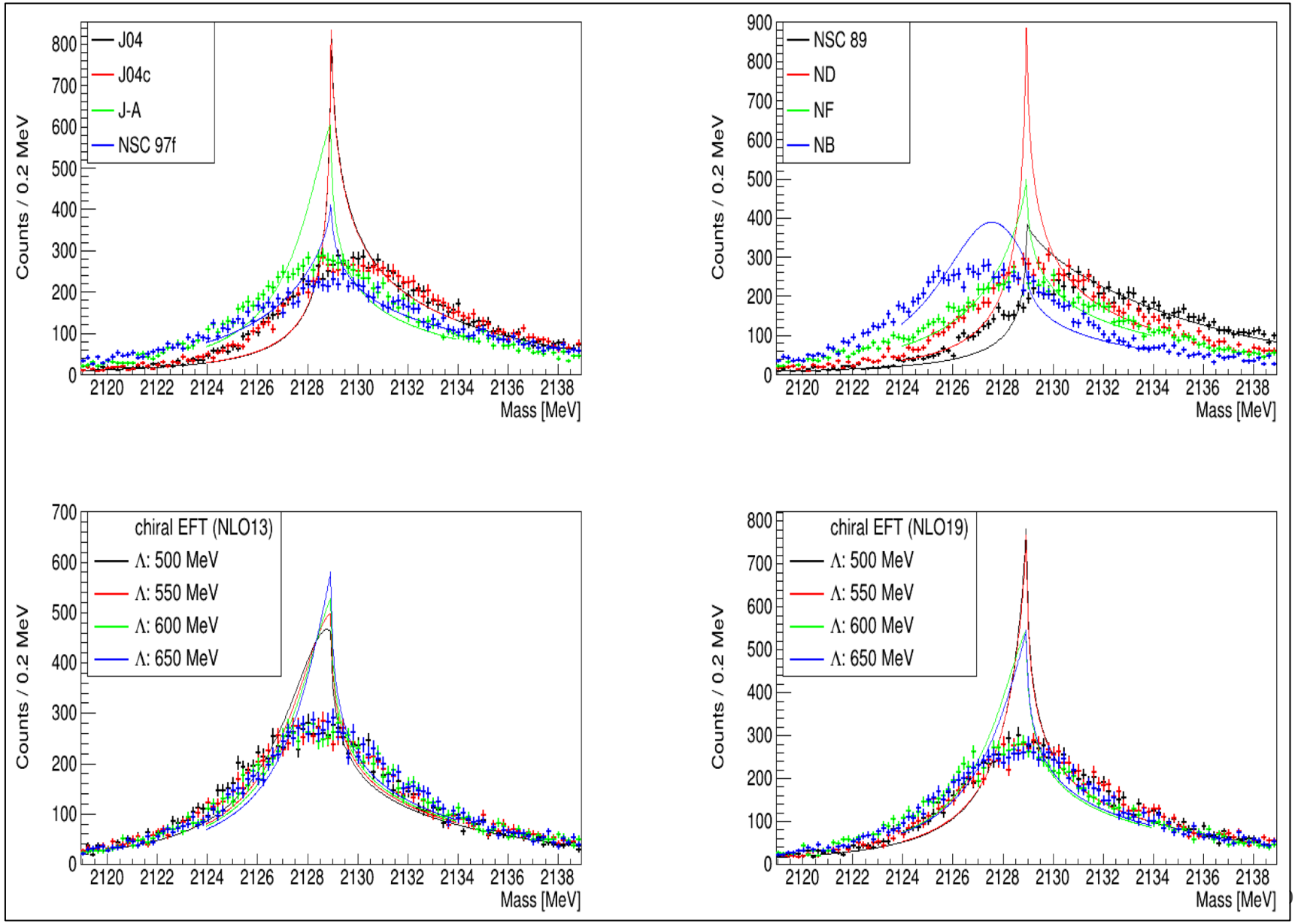
Model	chiral EFT (NLO19)			
Λ [MeV]	500	550	600	650
a [fm]	-0.95	-0.98	-2.29	-1.95
b [fm]	4.77	4.59	3.39	3.38

with E90 statistics
(1.4×10^4 events)

Old bubble chamber
: < 10^3 events



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with E90 statistics
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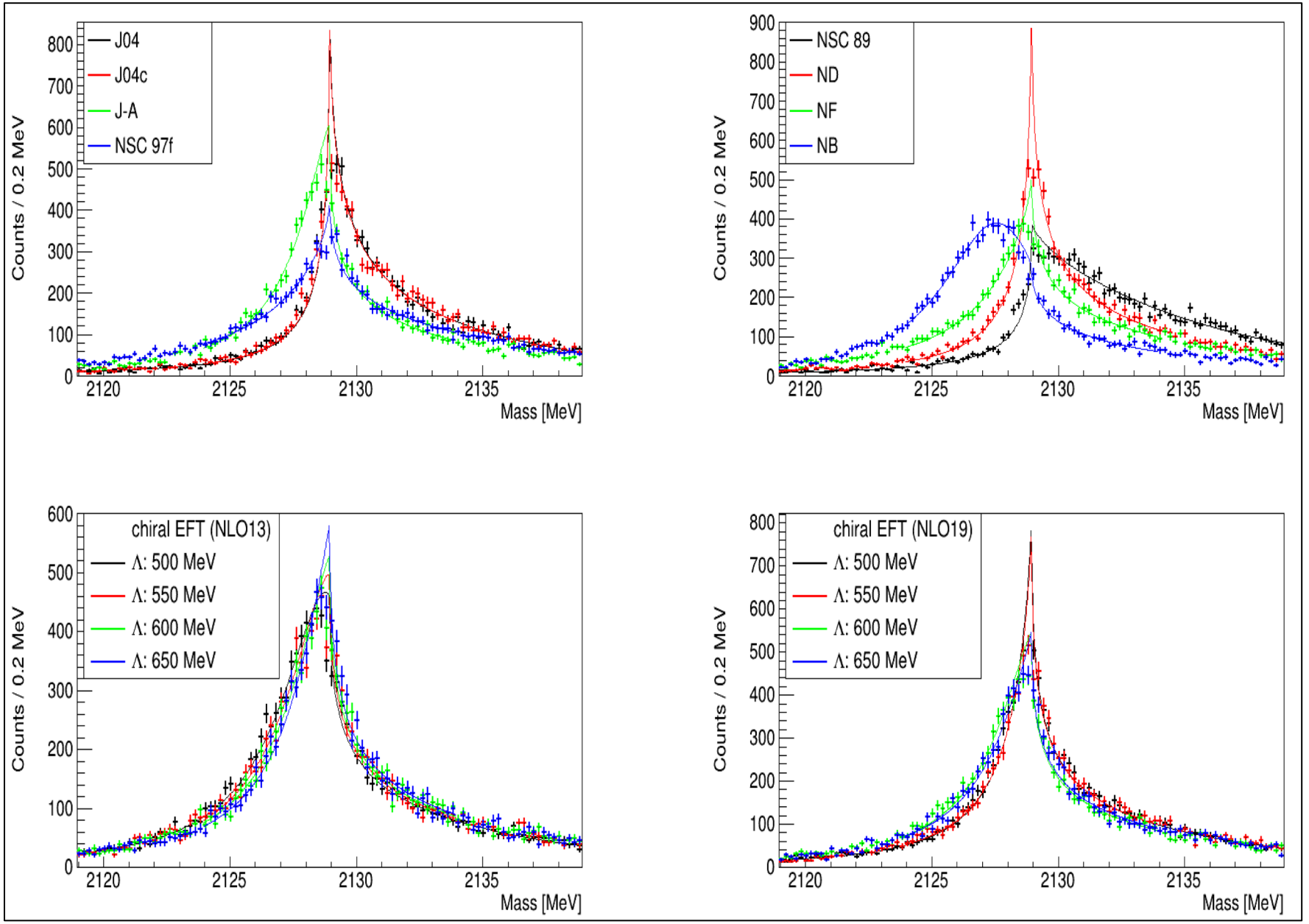
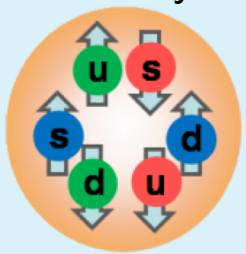
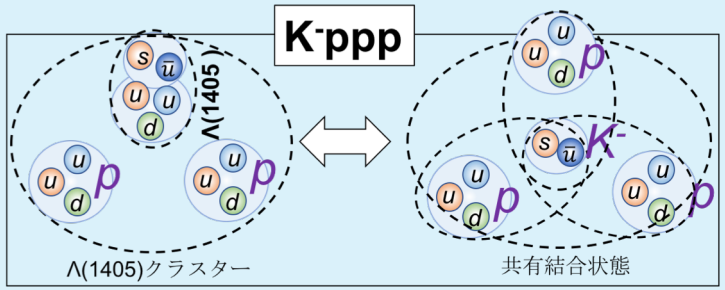


HADRON CLUSTERS STUDIED BY HYPTPC
HYPTPC = “EXOTIC DETECTOR”

E42

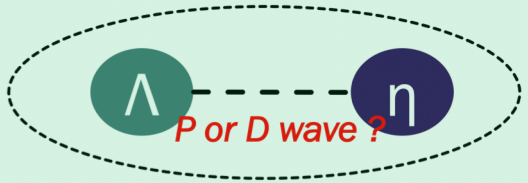
H-dibaryon



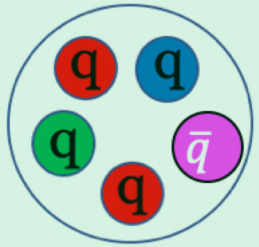


E72

Λ-η molecule?

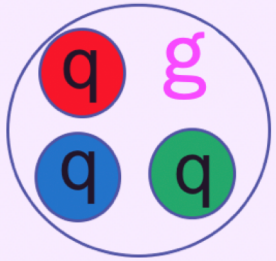


Penta quark?



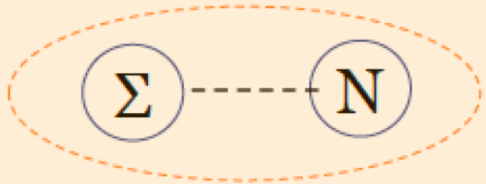
E45

Hybrid-baryon



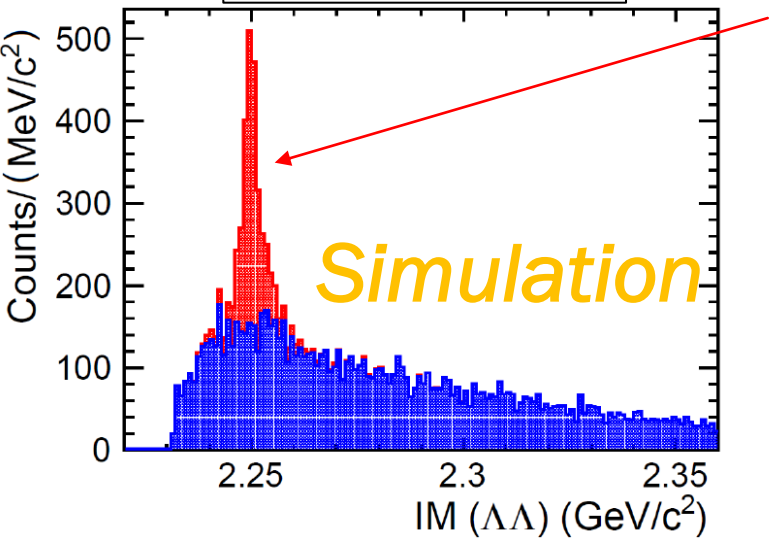
E90

ΣN dibaryon

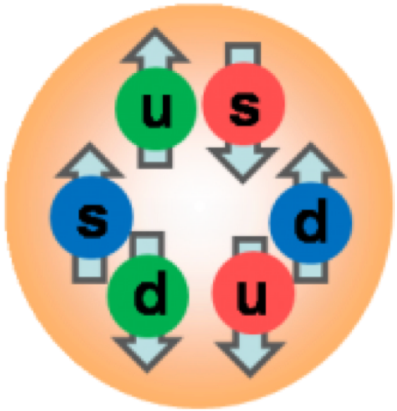


COMPOSITENESS (X) OF H-DIBARYON

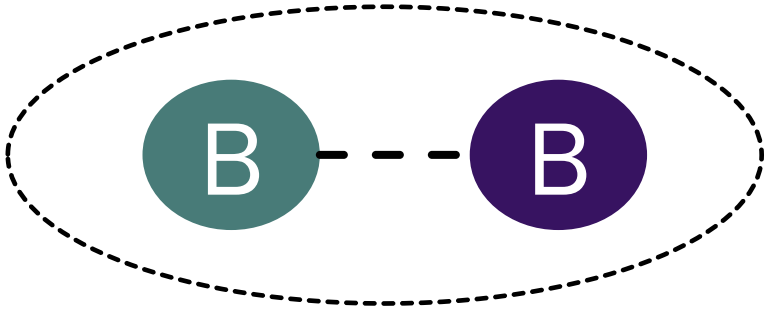
J-PARC E42



H-dibaryon(6 quarks)? or B-B bound state (2 baryons) ?



Λ-Λ, ΞN, ΣΣ



Compositeness(X) X = 0 X = 1

Hadron wave function

$$|\Psi\rangle = \sqrt{X}\,|\text{hadronic molecule}\rangle + \sqrt{1-X}\,|\text{others}\rangle$$

Compositeness (weight of hadronic molecule)

COMPOSITENESS (X) OF H-DIBARYON

Weak-binding relation

$$a_0 = R\left\{\frac{2X}{1+X} + \mathcal{O}\left(\frac{R_{\rm typ}}{R}\right)\right\}$$

S. Weinberg, Phys. Rev. 137, B672 (1965);
Y. Kamiya and T. Hyodo, PTEP 2017, 023D02 (2017).

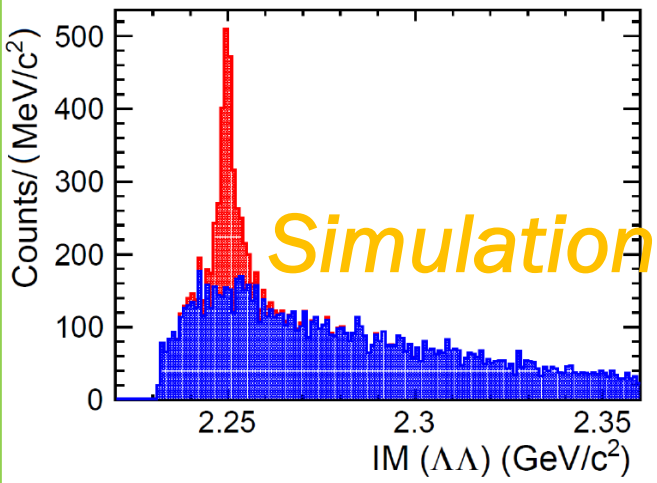
a_0 (scattering length) $R_{\rm typ}$(interaction range)

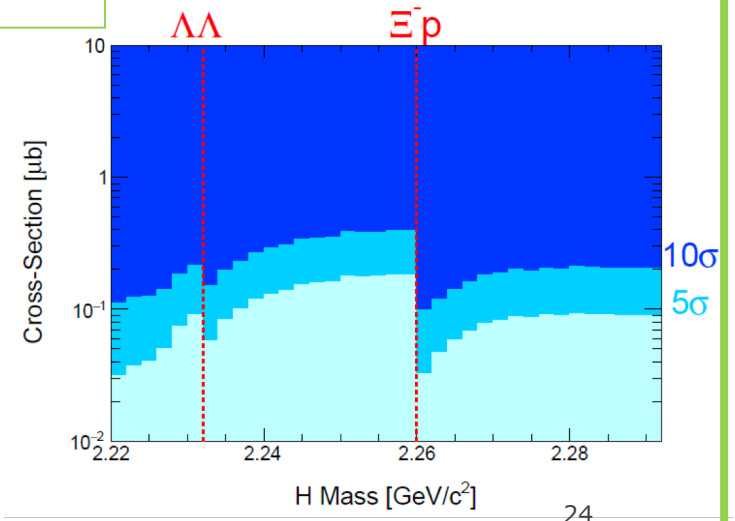
$R \equiv (2\mu B)^{-1/2}$, B (binding energy)

(ΛΛ, ΞN, ΣΣ) scattering length
- Femtoscopy
- ΞN scattering
- Ξ⁻p atom (X-ray)

$$H = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma + \sqrt{\frac{4}{8}}\Xi N$$

E42





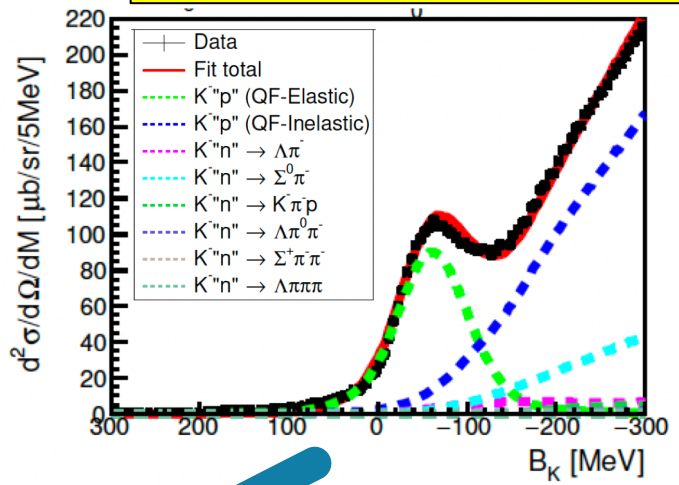
SUMMARY

- We have 4 J-PARC experiments by using HypTPC detector.
  - E42: H-dibaryon search by using $^{12}C(K^-, K^+)$ reaction.
  - E45: N* and Δ* spectroscopy by using p(π, 2π) reaction.
  - E72: Λ* search by using $p(K^-, \Lambda)\eta$ reaction
  - E90: High resolution spectroscopy of "ΣN cusp" by using $d(K^-, \pi^-)$ reaction
- The analysis of E42 experiment is on going.
- HypTPC will hunt the "exotic hadron clusters"!!

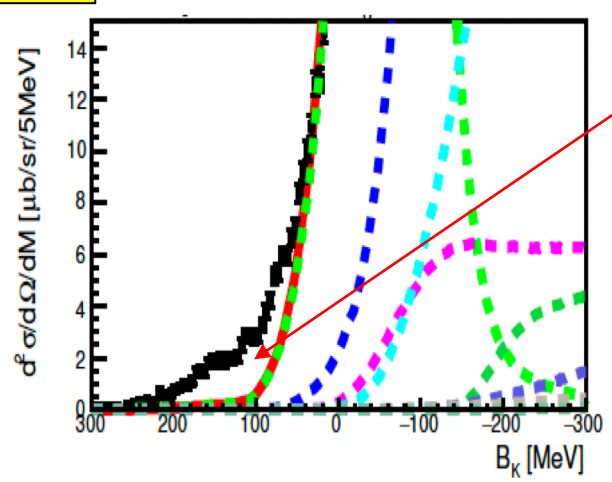
BACK UP

E42 BY PRODUCT: KAONIC NUCLEUS SEARCH BY $^{12}C(K^-, P)$

J-PARC E05 data (Inclusive)



Enlarged view



Motivation:

To observe the excess as a distinct peak!

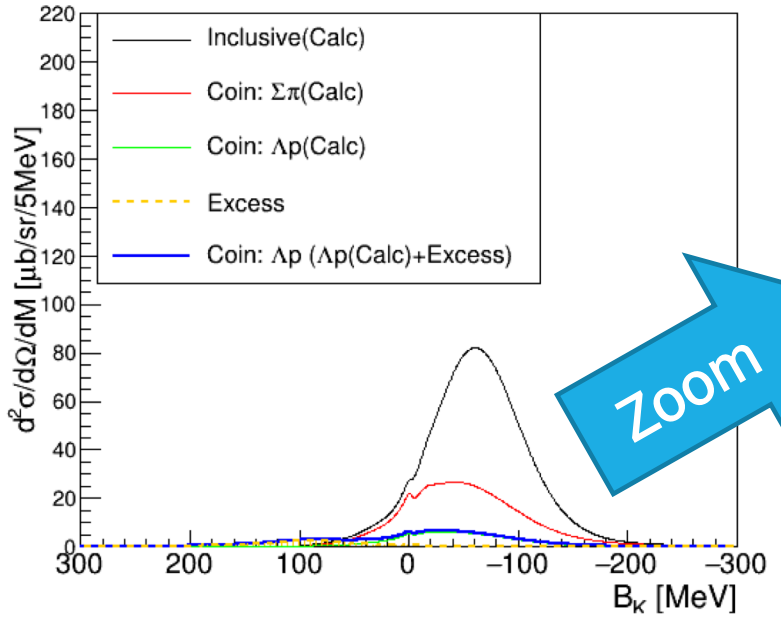
Method:

$^{12}C(K^-, p)\Lambda p$ measurement

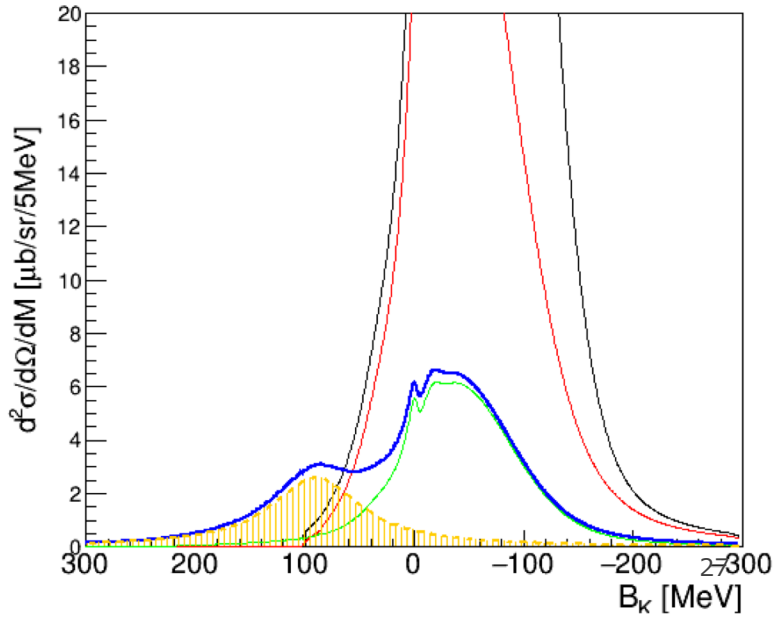
Inclusive → Exclusive

(E05) (E42)

Expected spectrum of $^{12}C(K^-, p)\Lambda p$ [Conversion spectrum]



Zoom



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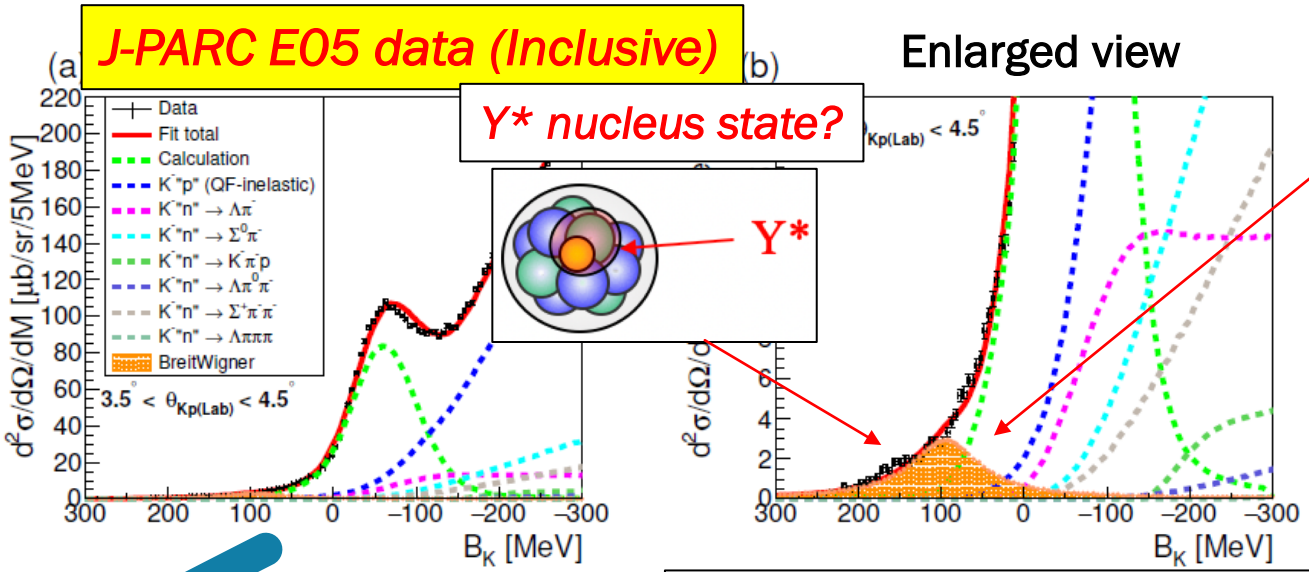

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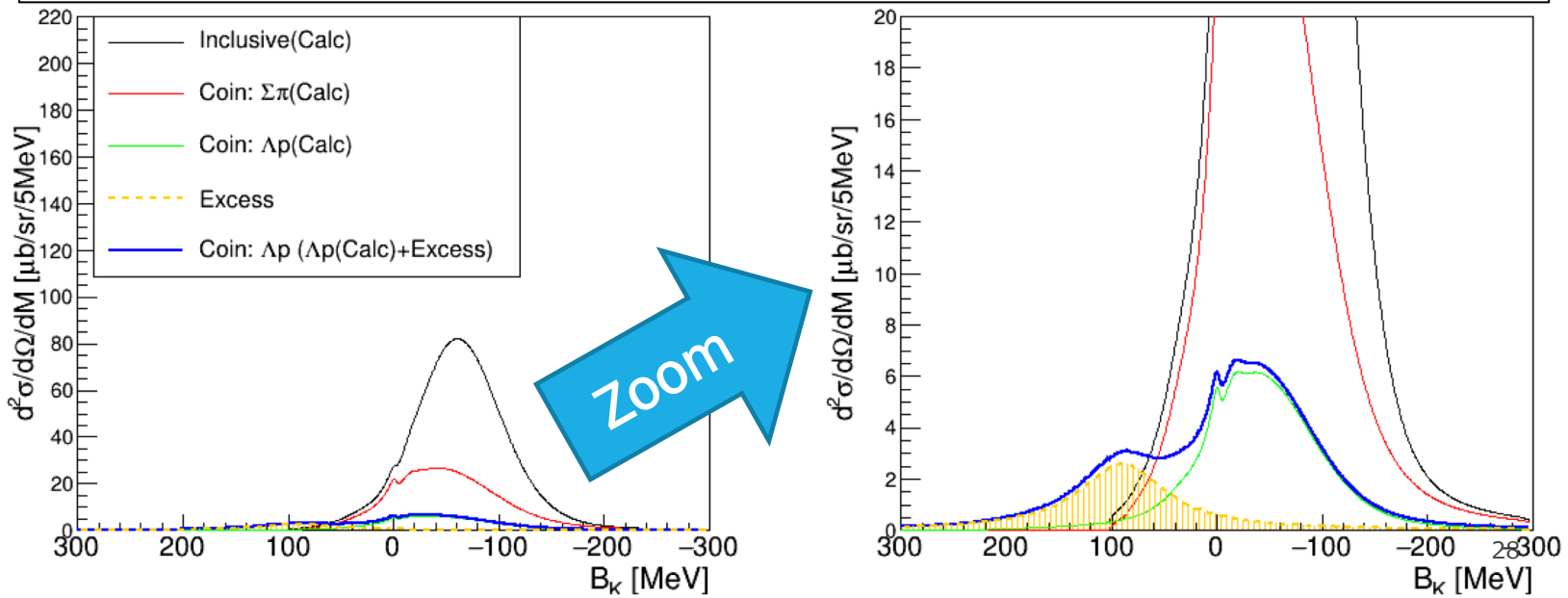

E45/E72 SETUP