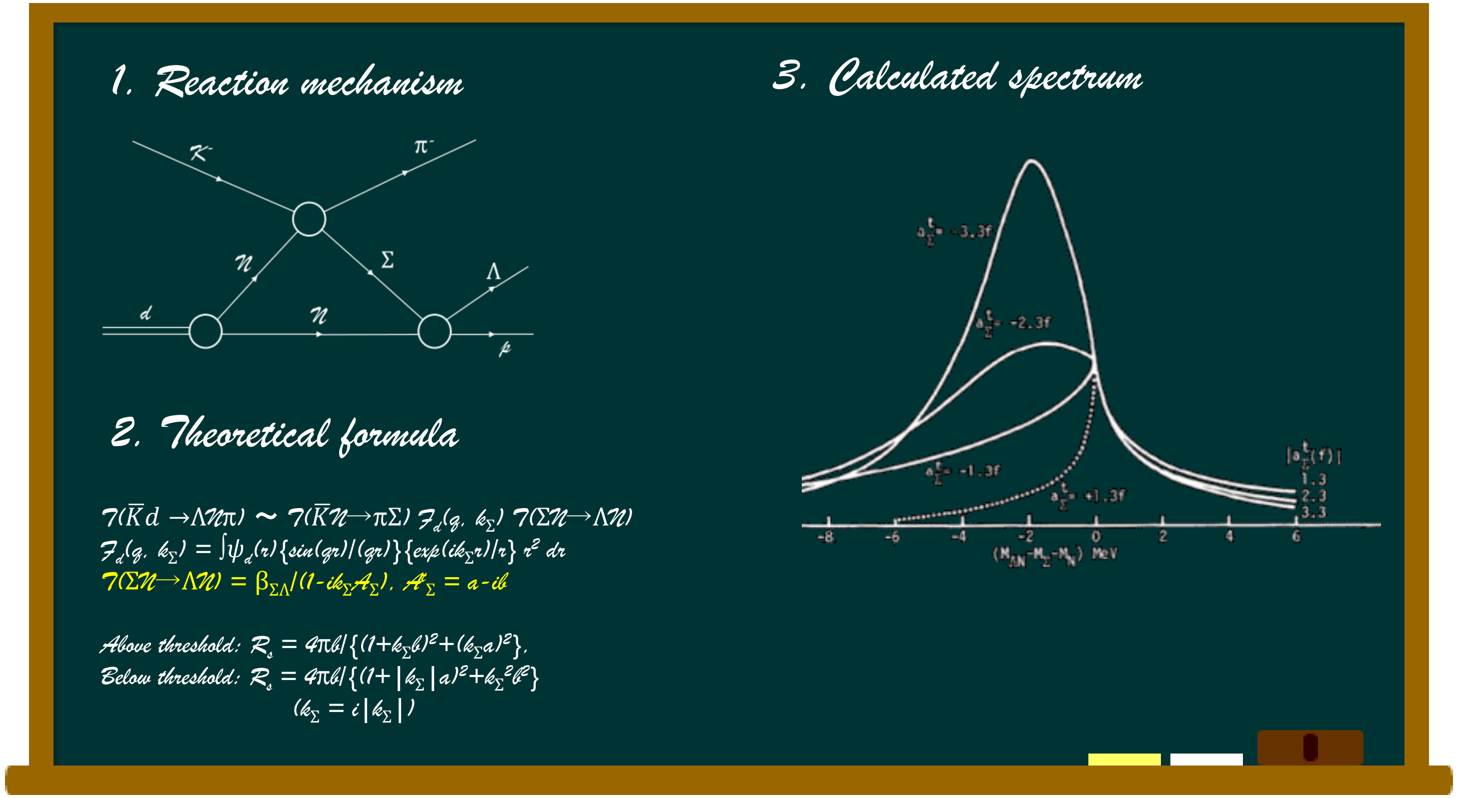
J-PARC P90: HIGH RESOLUTION SPECTROSCOPY OF THE ΣN CUSP BY USING $d(K^{-},\pi^{-})$ REACTION

YUDAI ICHIKAWA (JAEA)

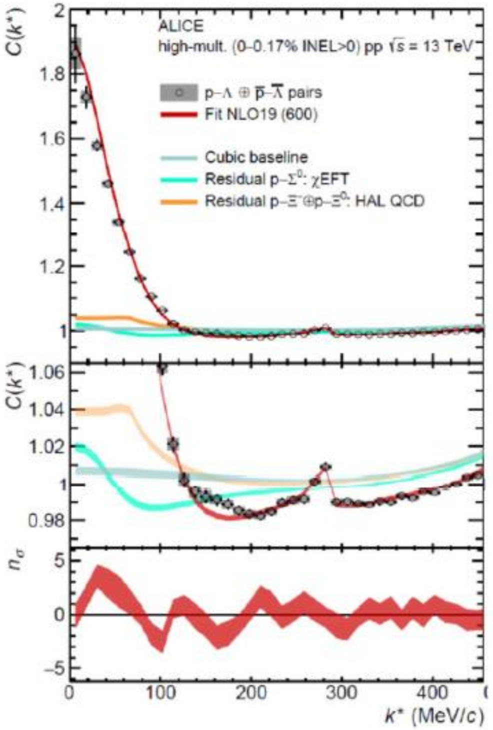
JOINT THEIA-STRONG2020 AND JAEA/MAINZ REIMEI WEB-SEMINAR *2022/01/26*



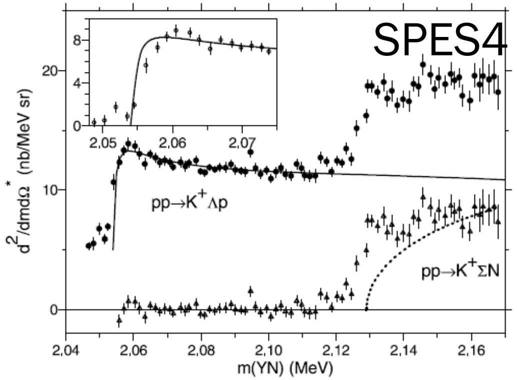
“ΣN CUSP”

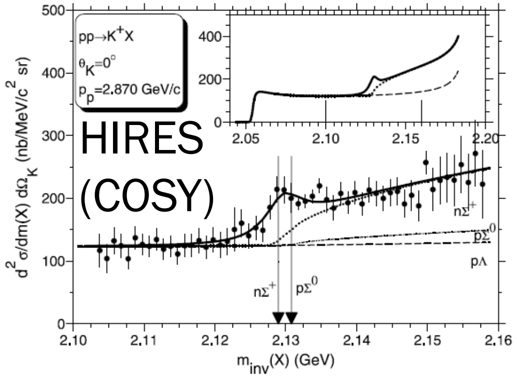
Clear enhancement around ΣN threshold (~2.13 GeV/c²)

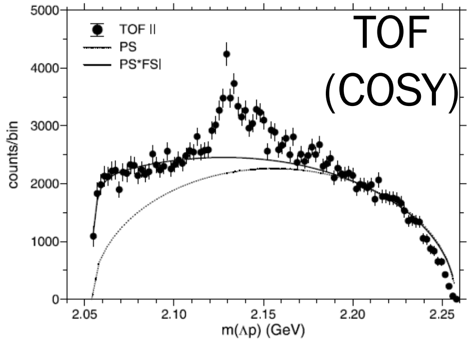
ALICE(*pp@13TeV*)



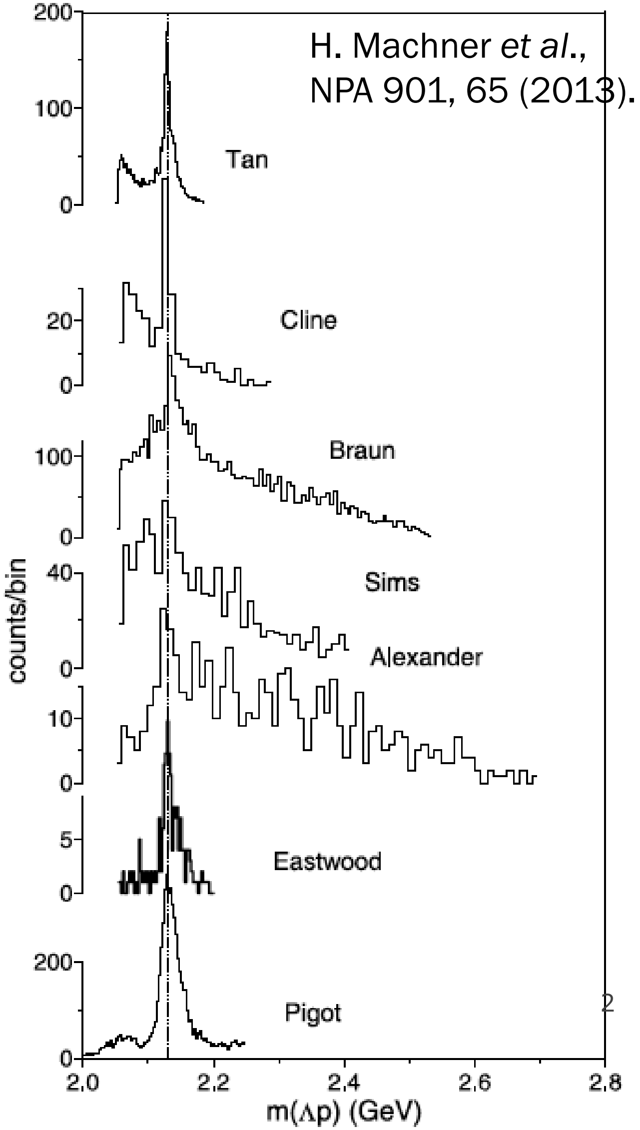
pp → ΛpK⁺



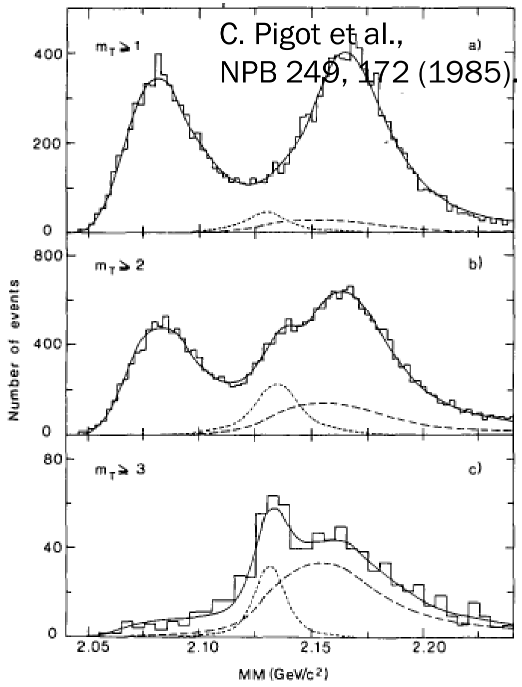


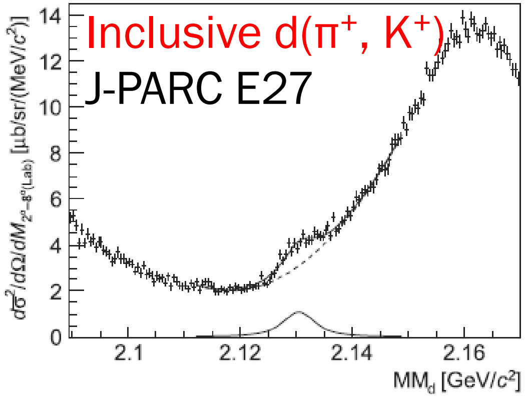


K⁻d → Λpπ⁻



π⁺d → ΛpK⁺





PURPOSE OF THE PROPOSED EXPERIMENT

- Deduce the ΣN scattering length of (T, S) = (1/2, 1) channel by fitting "ΣN cusp" spectrum shape observed in the missing mass of the d(K^-, π^-) reaction.
  - Unstable bound state (ΣN dibaryon)? or Virtual state?

The key of this experiment is the excellent missing-mass resolution thanks to the S-2S spectrometer (used in E70) and high statistics.
We will be able to achieve the best resolution of 0.4 MeV in σ, which is two times better than the past experiment (HIRES at COSY).

ΣN INTERACTION

- ΣN interaction is one of the key to understand B_8B_8 interaction in SU(3)
- Relation with E40 (ΣN scattering experiment)
  - E40: ΣN scattering (p_Σ > 470 MeV/c) → Short range interaction

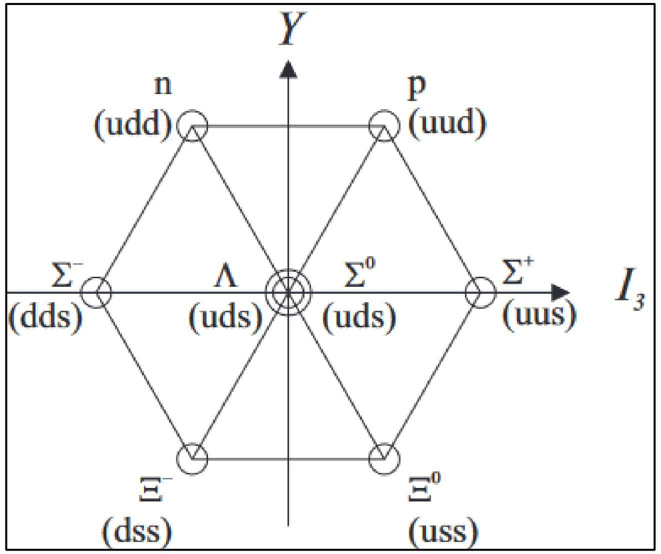
    *ΣN scattering experiment in lower momentum is difficult
  - P90: "ΣN cusp" → ΣN scattering length (0 energy interaction)
  - ΣN scattering length: $A_\Sigma = a + ib$
  - **a(real part)** → Important for the Σ-hypernuclei
  - **b(imaginary part)** → ΛN-ΣN coupling strength

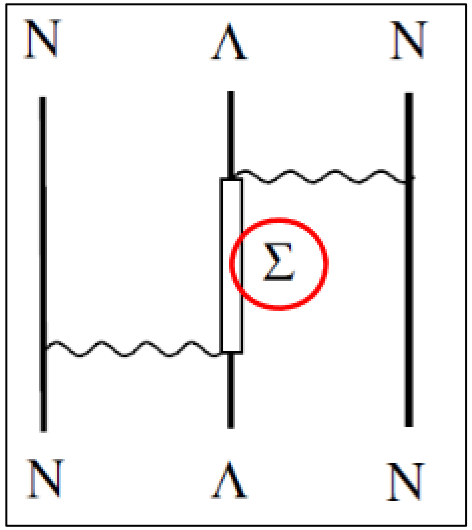
    ↓

    Important for the Λ-hypernuclei

Complementary

Octet baryon





THRESHOLD CUSP

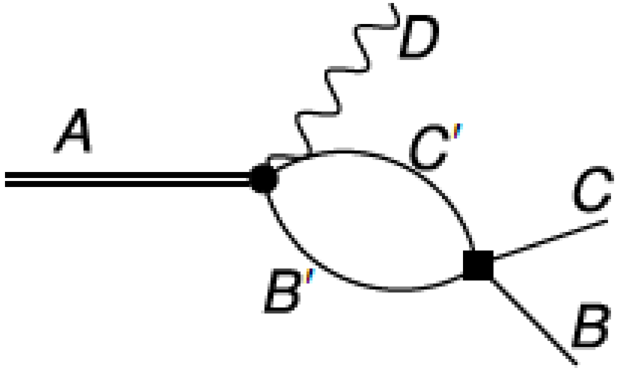
Cusp structure can be expressed by the scattering length (for B'C'), A = a + ib

- **B'C'→BC amplitude**
  - $f_{B'C',BC} \sim \frac{\sqrt{b}}{1-ikA}$, **Pole position**: $k \sim -\frac{i}{A}$

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

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

- **(Two body scattering amplitude)**
  - $f = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\, e^{i\delta_l} \sin\delta_l \, P_l(\cos\theta)$
  - →(s-wave) $f = \frac{1}{k} e^{i\delta_0} \sin\delta_0 = \frac{1}{k\cot\delta - ik} \rightarrow \frac{a}{1-ika}$
    - $k\cot\delta = \frac{1}{a} - \left(\frac{r_{eff}}{2}\right)k^2 + \cdots$



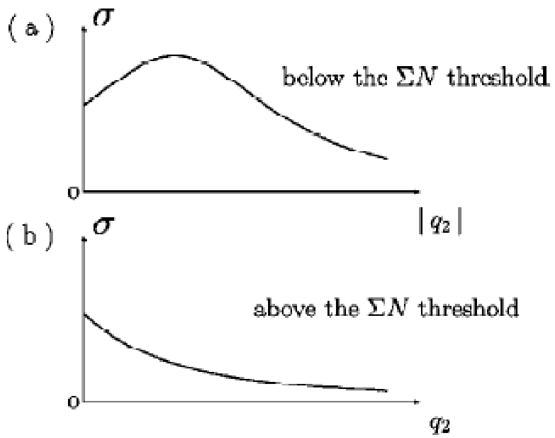
- **Reaction rate (R) :** $\frac{d\sigma^2}{d\Omega dE} \propto |f_{B'C',BC}|^2$
  - **Above threshold:** $\mathrm{R} = \frac{4\pi b}{\{(1+kb)^2+(ka)^2\}}$
  - **Below threshold:** $\mathrm{R} = \frac{4\pi b}{\{(1+\kappa a)^2+(\kappa b)^2\}}$, $k = i\kappa$ **(due to analytic continuation)**

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

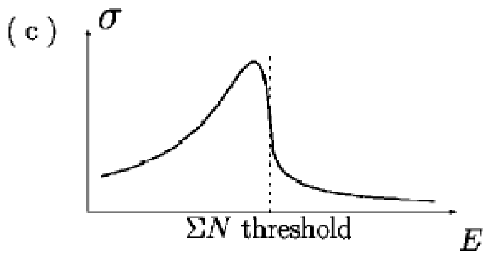
POLE POSITION vs CROSS SECTION (dσ/dE)

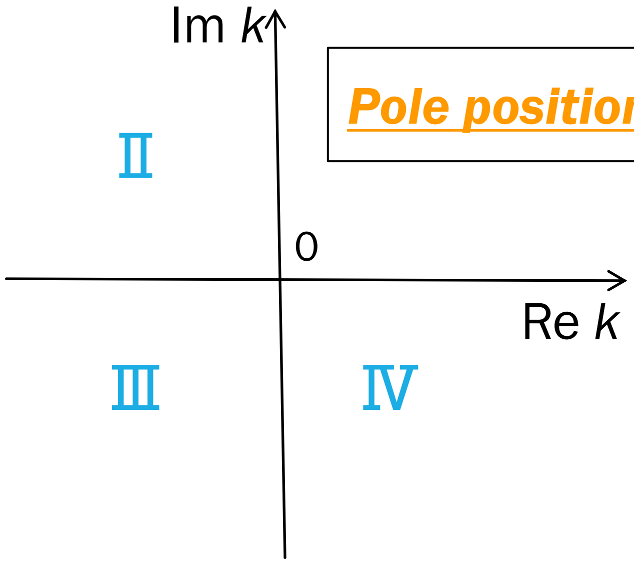
K. Miyagawa and H. Yamamura, PRC 60, 024003 (1999).

- Pole in (Ⅱ) quad



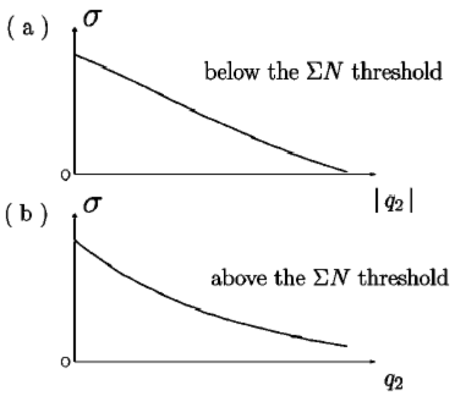
Bound state



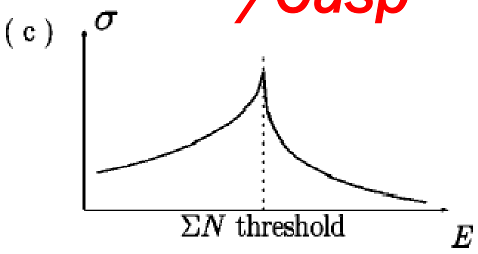


Pole position: $k \sim -\frac{i}{A}$

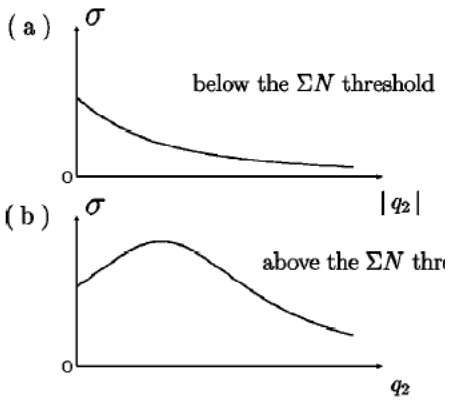
- Pole in (Ⅲ) quad



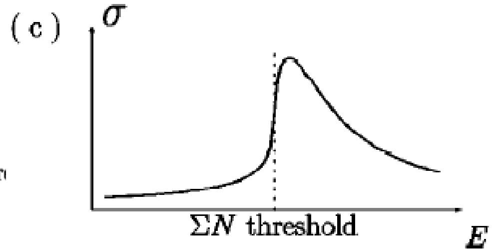
Virtual state /Cusp



- Pole in (Ⅳ) quad



Resonance



THRESHOLD CUSP

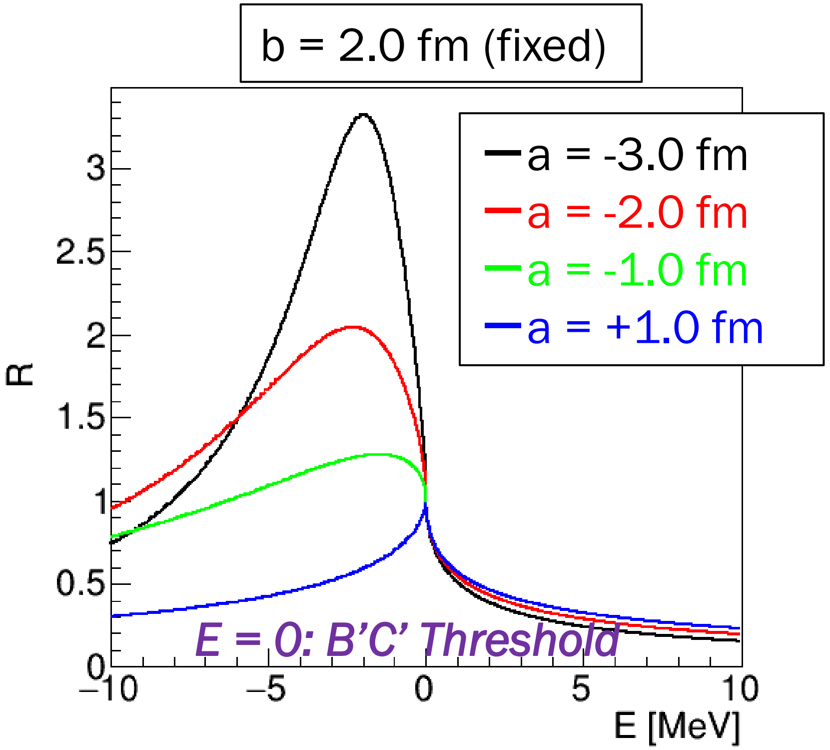
Cusp structure can be expressed by the scattering length (for B'C'), A = a + ib

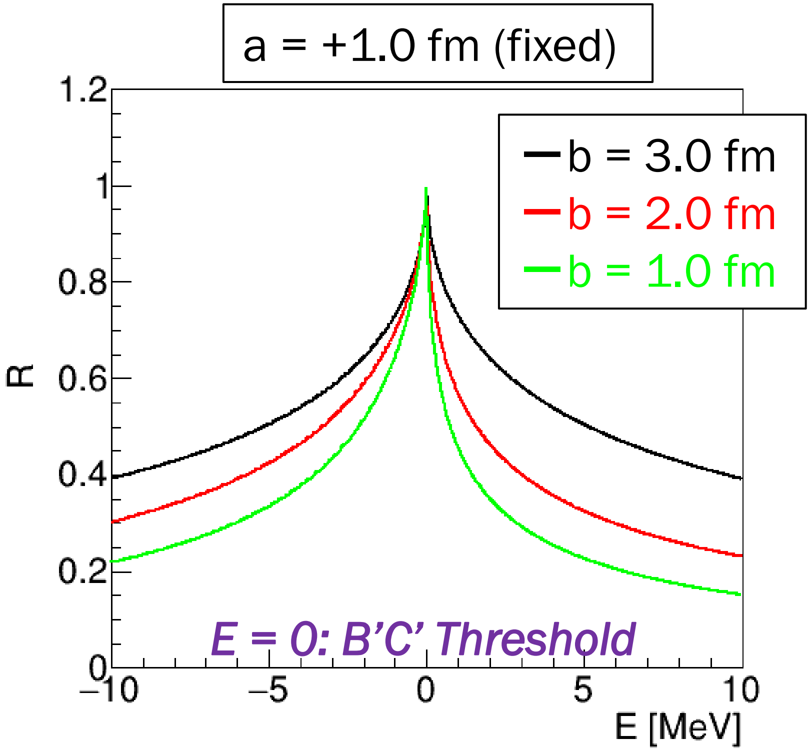
- **Above threshold:** $R = \frac{4\pi b}{\{(1+kb)^2+(ka)^2\}} \sim 1 - 2kb + O(k^2)$
- **Below threshold:** $R = \frac{4\pi b}{\{(1+\kappa a)^2+(\kappa b)^2\}} \sim 1 - 2\kappa a + O(\kappa^2),\ k = i\kappa$

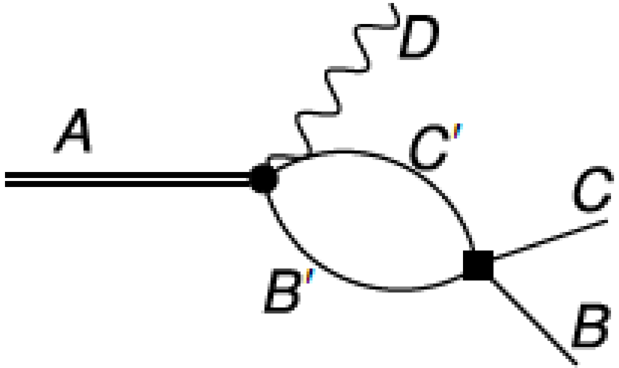
Reduced mass

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

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



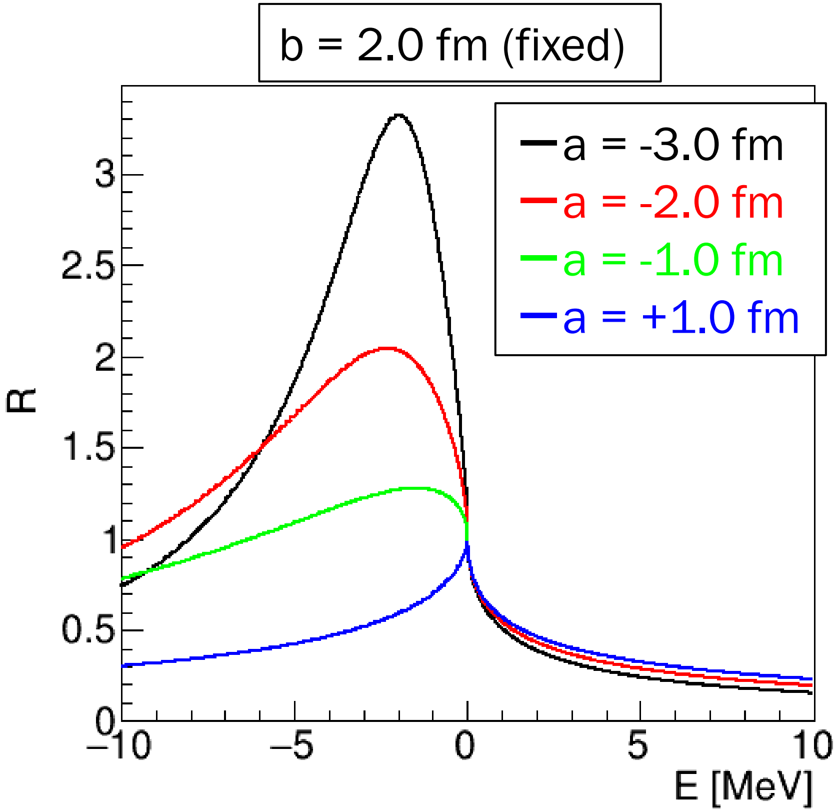




For the "ΣN cusp", B'=Σ, C'=N, B=Λ, C=N

"ΣN CUSP"

- "ΣN cusp" is measured by $K^{-}d \rightarrow \pi^{-}\Lambda p$ reaction etc..
  - T: T = ½ (Λp final state)
  - S: $^{3}S_{1}$ is favored, D-target; observed in forward angles



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

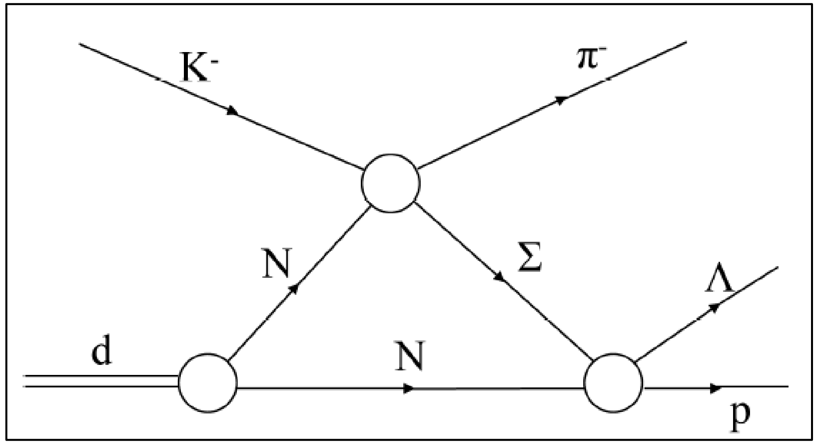
Below threshold: $R = \frac{4\pi b}{\{(1+\kappa a)^2+(\kappa b)^2\}} \sim 1 - 2\kappa a + O(\kappa^2),\ \ k = i\kappa$

$(k \sim \sqrt{2\mu E})$

"ΣN Cusp" can be expressed by the ΣN scattering length ($A_{\Sigma}=a+ib$) of the (T, S) = (1/2, $^{3}S_{1}$) channel!!

R.H. Dalitz, Nucl. Phys. A354, 101 (1981).

"ΣN cusp" $K^-d \to \pi^-\Lambda p$ reaction



Amplitude of the elementary reaction

- $f(\theta) \propto T(\bar{K}d \to \Lambda N\pi) \sim T(\bar{K}N \to \pi\Sigma)\, F_d(\vec{Q}_\Sigma, k_\Sigma)\, T(\Sigma N \to \Lambda N)$

Deuteron factor

$$F_d(Q_\Sigma, k_\Sigma) = \int \frac{e^{ik_\Sigma r}}{r} e^{i\vec{Q}_\Sigma \cdot \vec{r}} \psi_d(r) d^3 r$$

$$\vec{Q}_\Sigma = \vec{q} m_N / (m_N + m_\Sigma)$$

$\psi_d(r)$: deuteron wave function

Amplitude of ΣN⟶ΛN reaction (Important term)

$T(\Sigma N \to \Lambda N) \propto \frac{\sqrt{b}}{1 - ikA}$

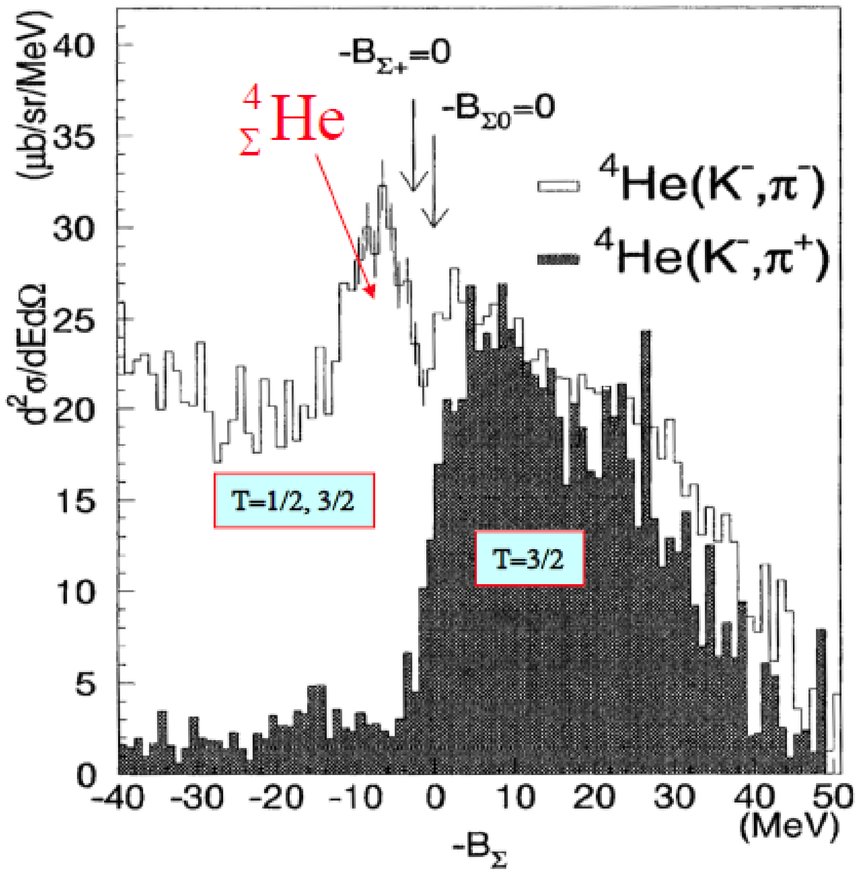
Above threshold: $R = \frac{4\pi b}{\{(1+kb)^2 + (ka)^2\}} \sim 1 - 2kb + O(k^2)$

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

$(k \sim \sqrt{2\mu E})$

"ΣN Cusp" can be expressed by the ΣN scattering length ($A_\Sigma = a + ib$) of the (T, S) = (1/2, $^3S_1$) channel!!

IMPORTANCE OF (T, S) = (1/2, 1) CHANNEL IN $^4_\Sigma$He



ΣN interaction has strong T and S dependence.
$V_{T=3/2, S=1}$ and $V_{T=1/2, S=0}$ are expected to be repulsive due to quark Pauli-blocking effect.
→ No Σ-hypernuclei in large A system.

ΣN cusp channel: $V_{T=1/2, S=1}$
(expected to be attractive potential and origin for the $^4_\Sigma$He bound state)

ΣNNN (4body) system

ΣN(2body) system

	T	S	$\overline{V}_{\Sigma N}$ (V_{TS})			
^{4}He(K⁻, π⁺):	$\frac{3}{2}$	0	$\frac{5}{18}V_{\frac{3}{2}0}$	$+\frac{1}{2}V_{\frac{3}{2}1}$	$+\frac{2}{9}V_{\frac{1}{2}0}$	
^{4}He(K⁻, π⁻):	$\frac{1}{2}$	0	$\frac{4}{9}V_{\frac{3}{2}0}$		$+\frac{1}{18}V_{\frac{1}{2}0}$	$+\frac{1}{2}V_{\frac{1}{2}1}$

$\Sigma N(T=1/2, {}^3S_1)$ SCATTERING LENGTH (THEORY), $A_\Sigma = a + ib$

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

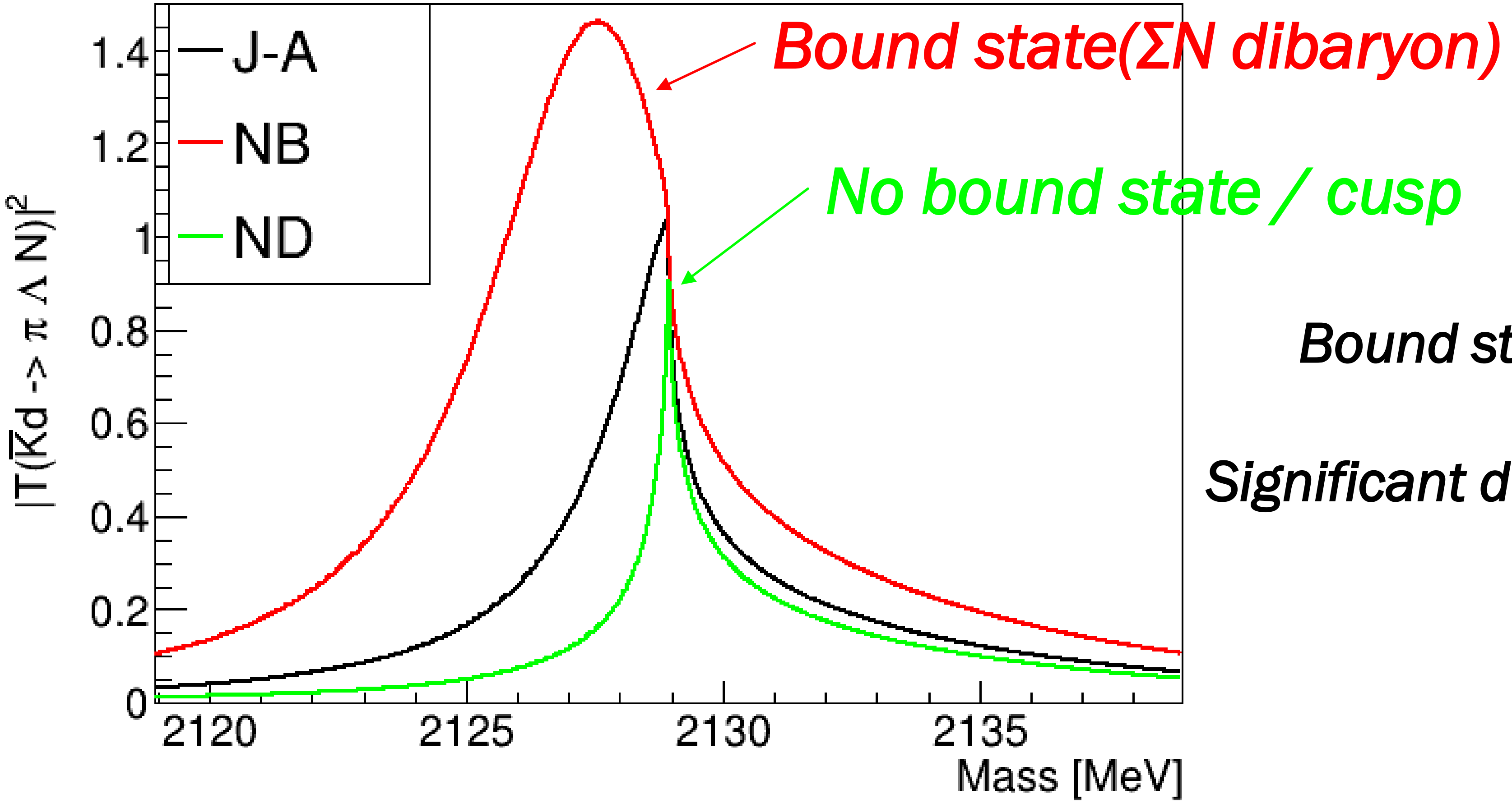
a > 0: Attractive

a < 0: Bound state

Large ambiguity!!

ΣN(T=1/2, $^3S_1$) SCATTERING LENGTH (THEORY)

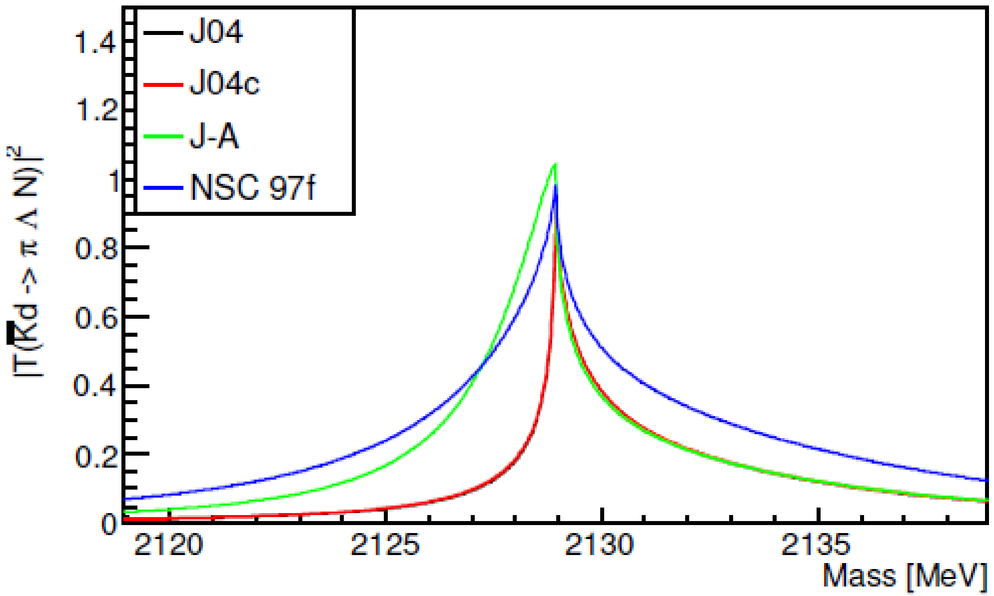
Shallow bound state/cusp: e.g. J-A (A_Σ = -2.37 + i3.74 fm)
Deeply bound state (~BW): e.g. NB (A_Σ = -3.00 + i1.8 fm)
No bound state/cusp: e.g. ND (A_Σ = 2.06 + i4.64 fm)

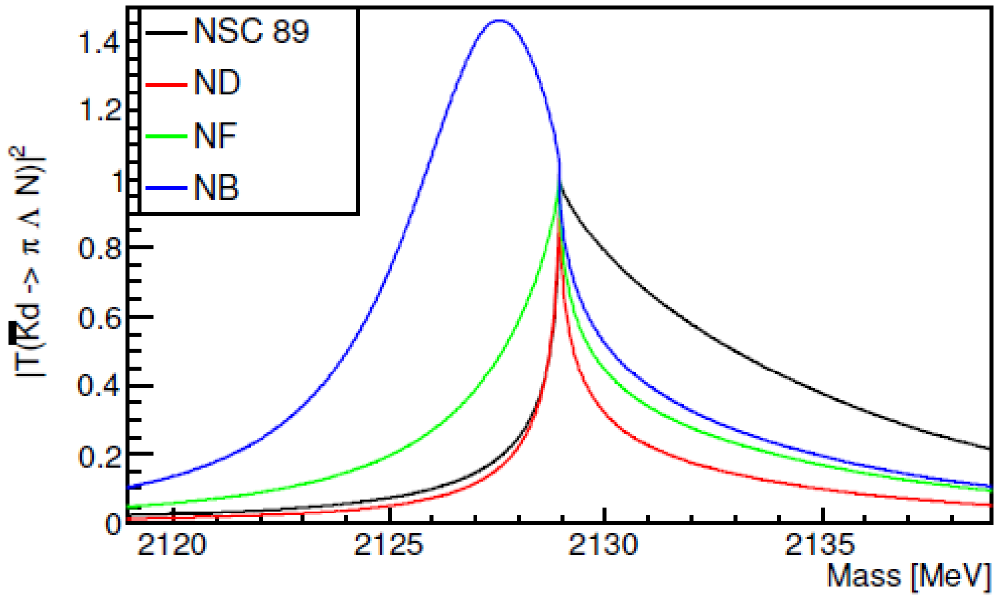


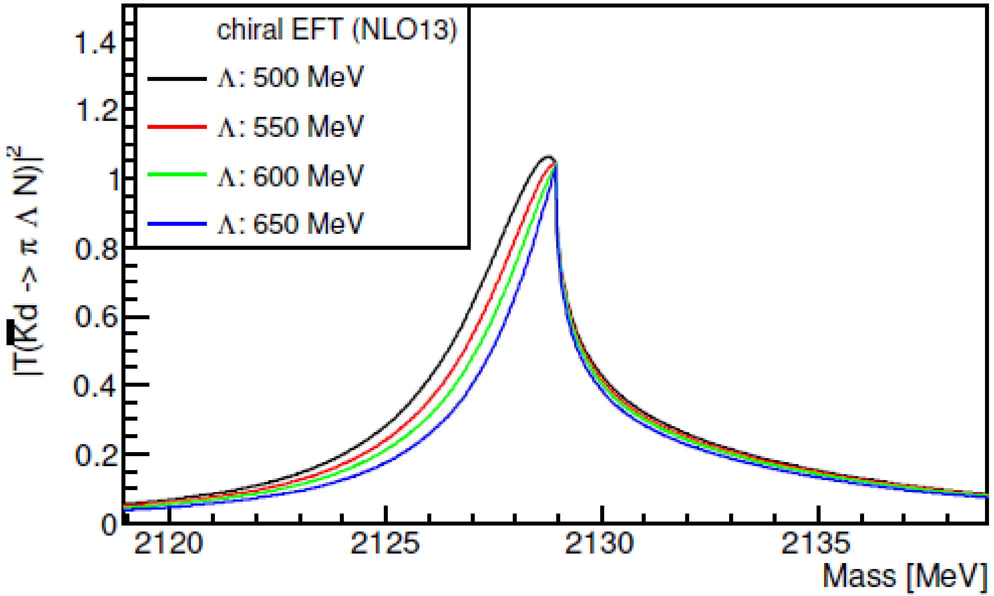
Pole position: $k \sim -i/A_\Sigma$

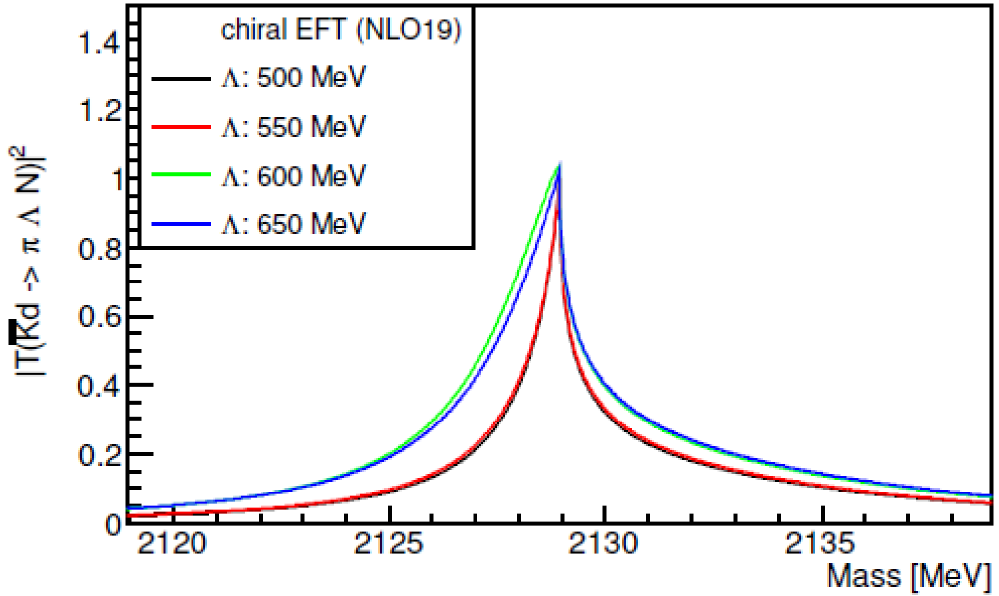
Bound state (deuteron like dibaryon) or not?
Significant difference in the spectrum shape

$\Sigma N(T=1/2, {}^3S_1)$ SCATTERING LENGTH (THEORY)



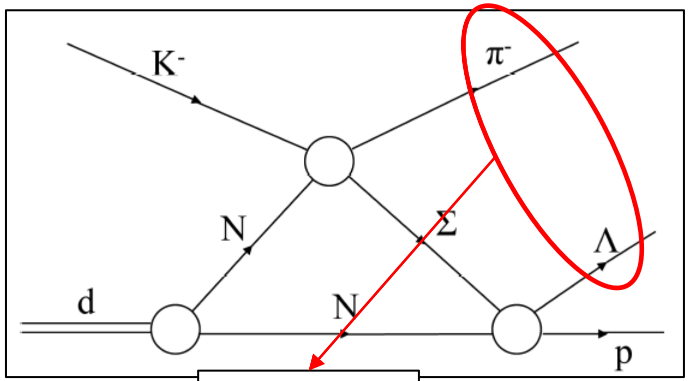


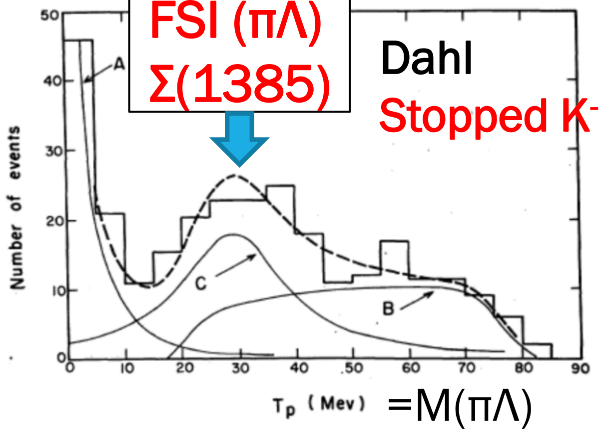




REQUIREMENTS FOR THE "ΣN CUSP" EXPERIMENT

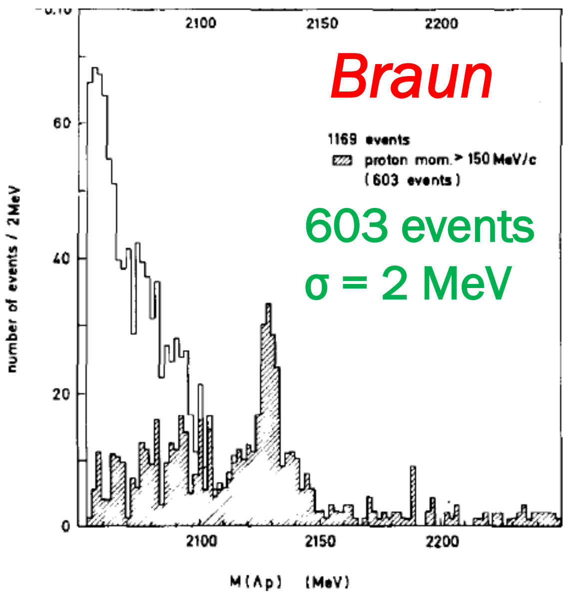
- Good energy resolution (σ < 1 MeV)
- High statistics (> 10^4 events)
- Good Signal / Noise (S/N) ratio
- Avoid FSI **except for the ΣN**
  - × **Stopped** $K^- d \rightarrow \Lambda p \pi^-$ reaction ($p_\pi \sim p_\Lambda \sim p_p$)
    FSI: **πΛ, πp**, **YN (YN FSI = ΣN cusp signal)**
  - ○ **In-flight** $K^- d \rightarrow \Lambda p \pi^-$ reaction ($p_K \sim p_\pi >> p_\Lambda \sim p_p$)
    FSI: **YN (YN FSI = ΣN cusp signal),** ○**impulse approximation**
- Decompose $^1S_0$ and $^3S_1$ contribution
  ($K^- d \rightarrow \Lambda p \pi^-$ reaction: extract only $^3S_1$ contribution by D-target property)

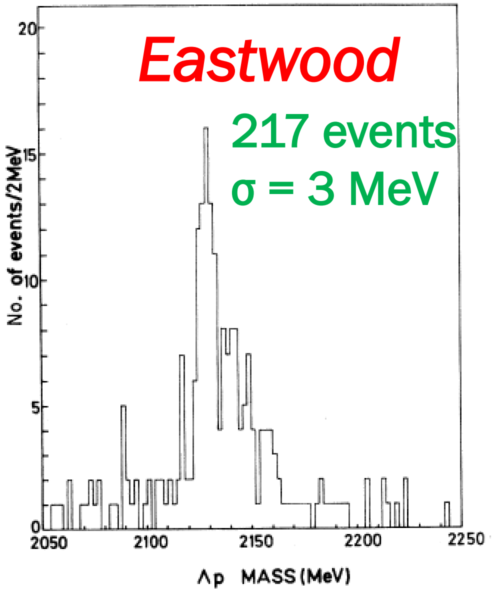


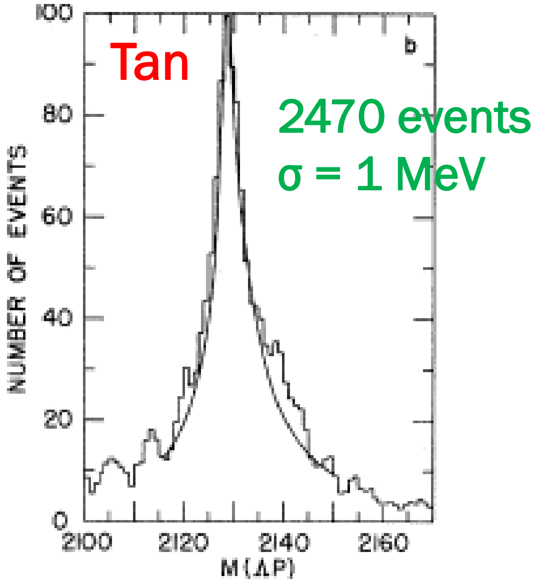


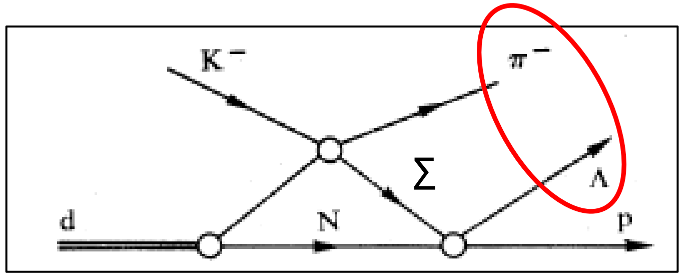
There was no experiment to satisfy these requirements!!

		Reaction	Comments	Statistics	Resolution
Bubble chamber	Braun	Inflight d(K^-, π^-)Λp 680 – 840 MeV/c	Low statistic, worse resolution	603 events (cosθ>0.9, momcut)	2 MeV
	Eastwood	Inflight d(K^-, π^-)Λp 1450, 1650 MeV/c	Low statistic worse resolution	217 events (cosθ>0.9, momcut)	3 MeV
	Tan	stopped d(K^-, π^-)Λp	Large FSI	2470 events	1 MeV
	Pigot	Inflight d(K^-, π^-), d(π^+, K^+)	Poor resolution	Uncertain	9.1 MeV (d(K^-, π^-) 1.4 GeV/c)
	pp→ΛpK^+ (COSY etc)	pp→ΛpK^+	$^1S_0$ + $^3S_1$ admixture Worse SN	High	0.8 MeV
	ALICE	pp (Femtoscopy)	$^1S_0$ + $^3S_1$ admixture	High	No description
	J-PARC E27	d(π^+, K^+) (Inclusive)	Worse SN (inclusive)	High	1.4 MeV









Stopped K^- reaction

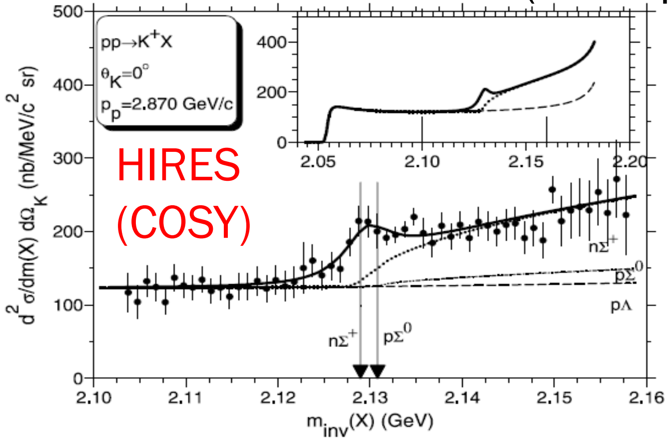
- Multiple K^- scattering
- FSI:πΛ, πp ($p_\pi \sim p_\Lambda \sim p_p$) [YN FSI = Signal]

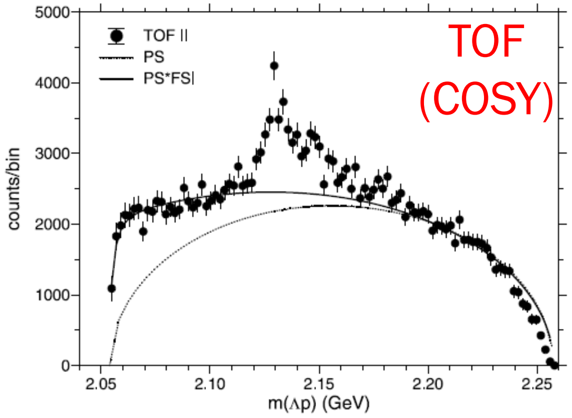
Bubble chamber

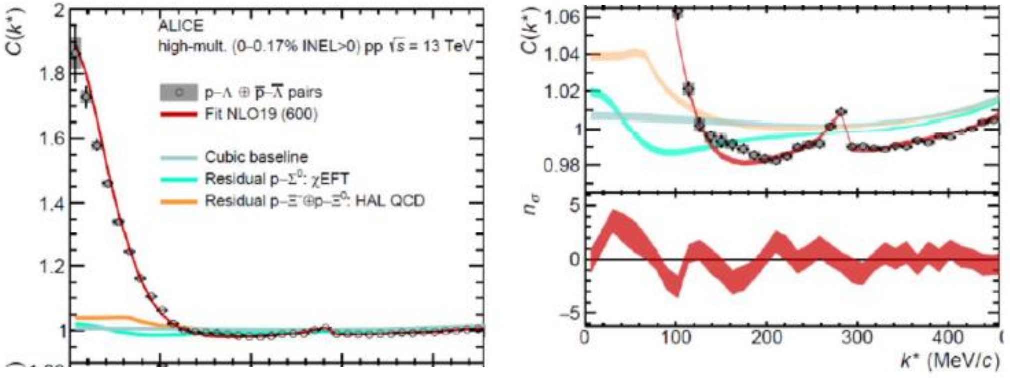
	Reaction	Comments	Statistics	Resolution
Braun	Inflight d(K⁻, π⁻)Λp 680 – 840 MeV/c	Low statistic, worse resolution	603 events (cos θ >0.9, momcut)	2 MeV
Eastwood	Inflight d(K⁻, π⁻)Λp 1450, 1650 MeV/c	Low statistic worse resolution	217 events (cos θ >0.9, momcut)	3 MeV
Tan	stopped d(K⁻, π⁻)Λp	Large FSI	2470 events	1 MeV
Pigot	Inflight d(K⁻, π⁻), d(π⁺, K⁺)	Poor resolution	Uncertain	9.1 MeV (d(K⁻, π⁻) 1.4 GeV/c)
pp→ΛpK⁺ (COSY etc)	pp→ΛpK⁺	$^1S_0 + {}^3S_1$ admixture Worse SN	High	0.8 MeV
ALICE	pp (Femtoscopy)	$^1S_0 + {}^3S_1$ admixture	High	No description
J-PARC E27	d(π⁺, K⁺) (Inclusive)	Worse SN (inclusive)	High	1.4 MeV

pp→ΛpK⁺: Good resolution, Worse SN, $^1S_0+{}^3S_1$ mixed,
Complicated reaction mechanism (via N*, Δ*)
→PWA (with Spin observable)

ALICE(*pp*@13TeV, Femtoscopy)
$^1S_0+{}^3S_1$ mixed→Spin observable





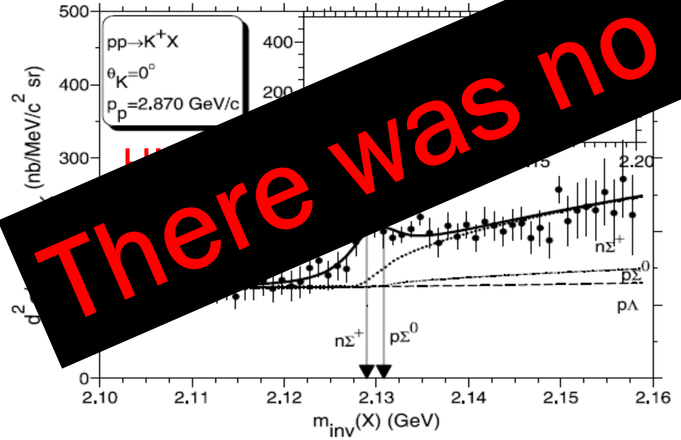


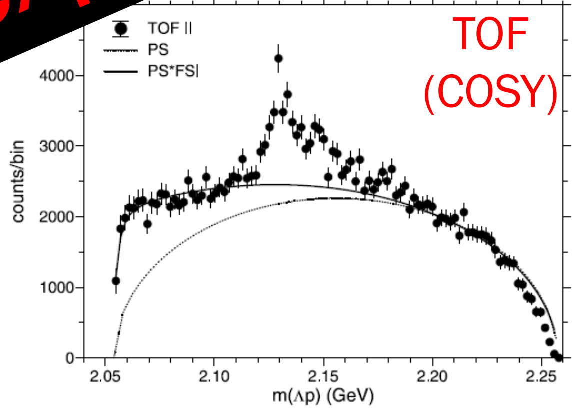
Bubble chamber

	Reaction	Comments	Statistics	Resolution
Braun	Inflight d(K^-, π^-)Λp 680 – 840 MeV/c	Low statistic, worse resolution	603 events (cos θ >0.9, momcut)	2 MeV
Eastwood	Inflight d(K^-, π^-)Λp 1450, 1650 MeV/c	Low statistic worse resolution	217 events (cos θ >0.9, momcut)	3 MeV
Tan	stopped d(K^-, π^-)Λp	Large FSI	2470 events	
Pigot	Inflight d(K^-, π^-), d(π^+, K^+)	Poor resolution	Un	.1 MeV (d(K^-, π^-) 1.4 GeV/c)
pp→ΛpK^+ (COSY etc)	pp→ΛpK^+	$^1S_0$ + $^3S_1$ admixt Worse		0.8 MeV
ALICE	pp (Femtoscopy)	^1S	High	No description
J-PARC E27	d(π^+, K^+) (Inclusive)	clusive)	High	1.4 MeV

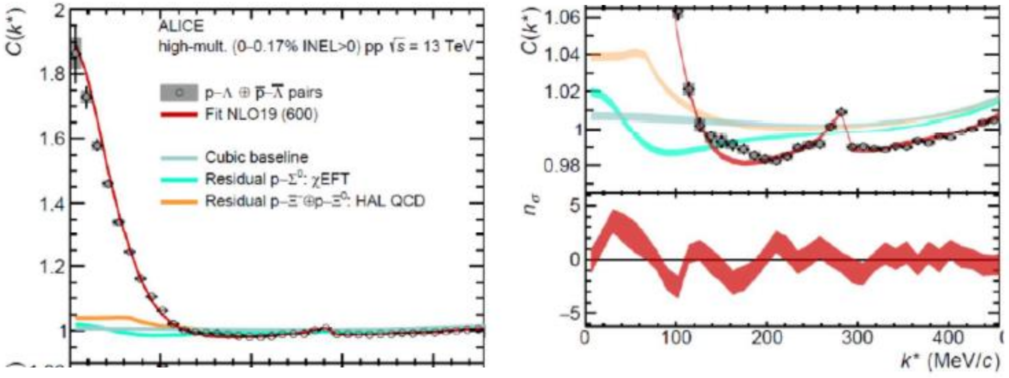
There was no experiment to satisfy the requirements!!

pp→ΛpK^+: Good resolution, Worse ... d,
Complicated rea ... via N*, Δ*)
→PWA(wi ... c)



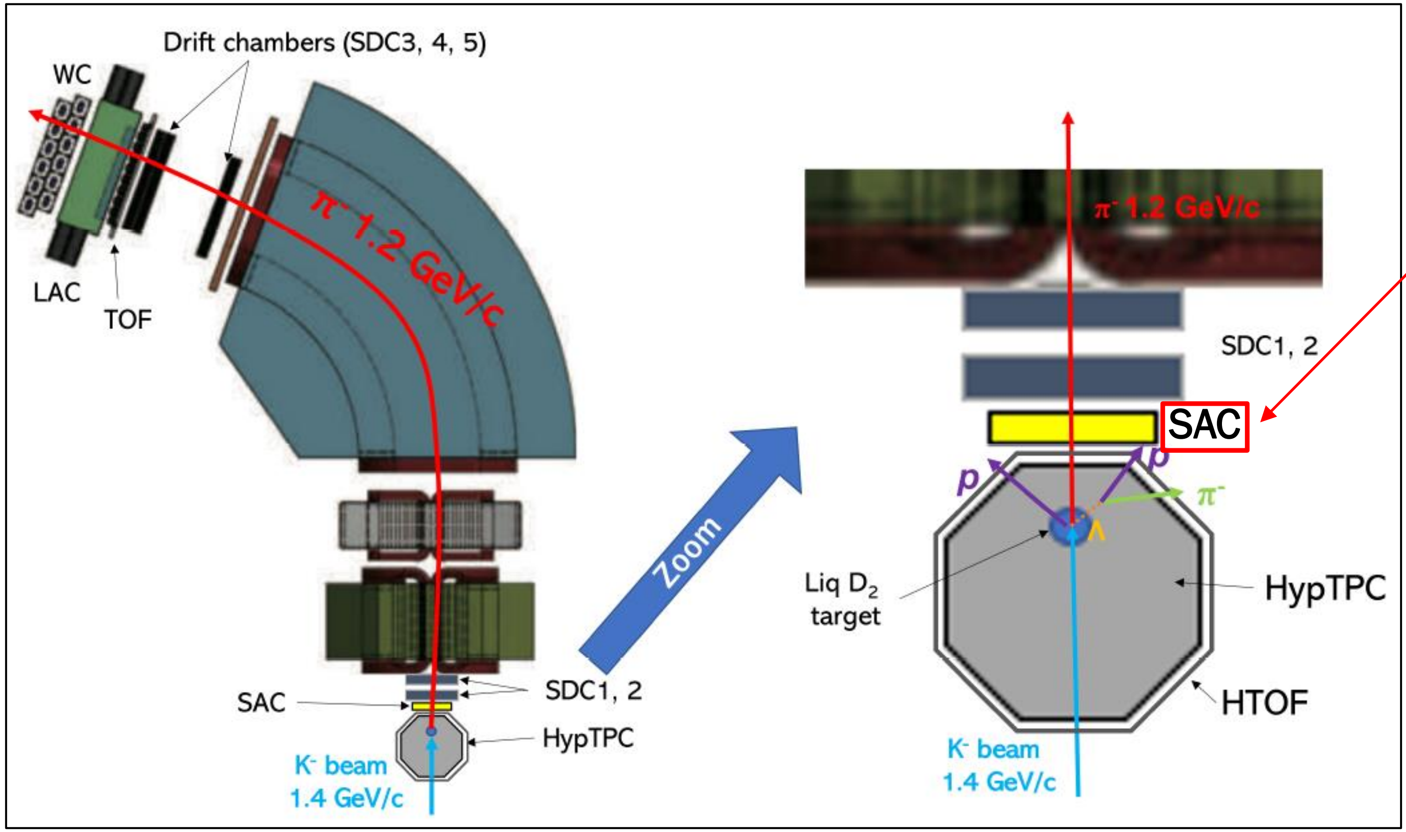


ALICE(*pp*@13TeV, Femtoscopy)
$^1S_0$+$^3S_1$ mixed→Spin observable



SET UP

- **Reaction: $K^-d \rightarrow \Lambda p \pi^-$ at 1.4 GeV/c**
- **S-2S(developed for E70): π^- measurements → measurement of missing mass spectrum**
  - **Good mass resolution: ΔM ~ 0.4 MeV (σ), (Δp/p(K18)=3.3×10^{-4}(FWHM), Δp/p(S-2S)=6.0×10^{-4}(FWHM))**
- **HypTPC(developed for E42): Final state (Λp) restriction and background suppression**



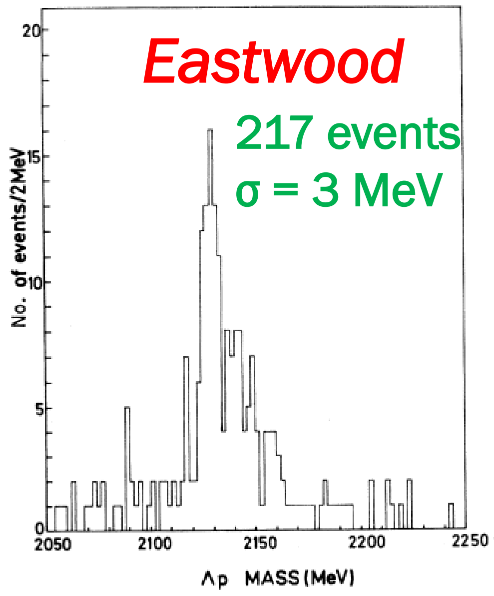
New detector

Momentum transfer ～200 MeV/c

YIELD ESTIMATION

$$N = (\frac{d\sigma}{d\Omega}) \times d\Omega_{S2S} \times (\frac{N_{beam} \times N_A \times (\rho x)}{A}) \times \epsilon.$$

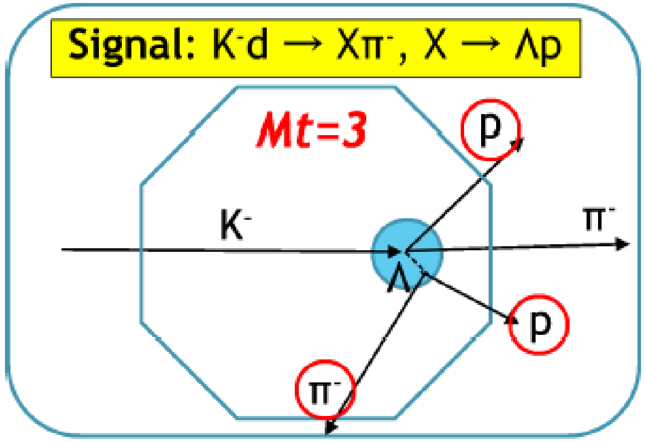
- $d\sigma/d\Omega$ = 127 ub/sr in Lab (D. Eastwood et al., Phys. Rev. D 3 (1971) 2603.)
- $d\Omega$ = 50 msr
- N_A = 6.02×1e23;
- ρx = 0.54 g/cm by taking into account the beam size, σ_x = 23 mm
- N_{beam} = 0.5M K^-/4sec, 90%Acc eff
- A = 2.
- ε = 0.5 （including decay factor and DAQ eff）

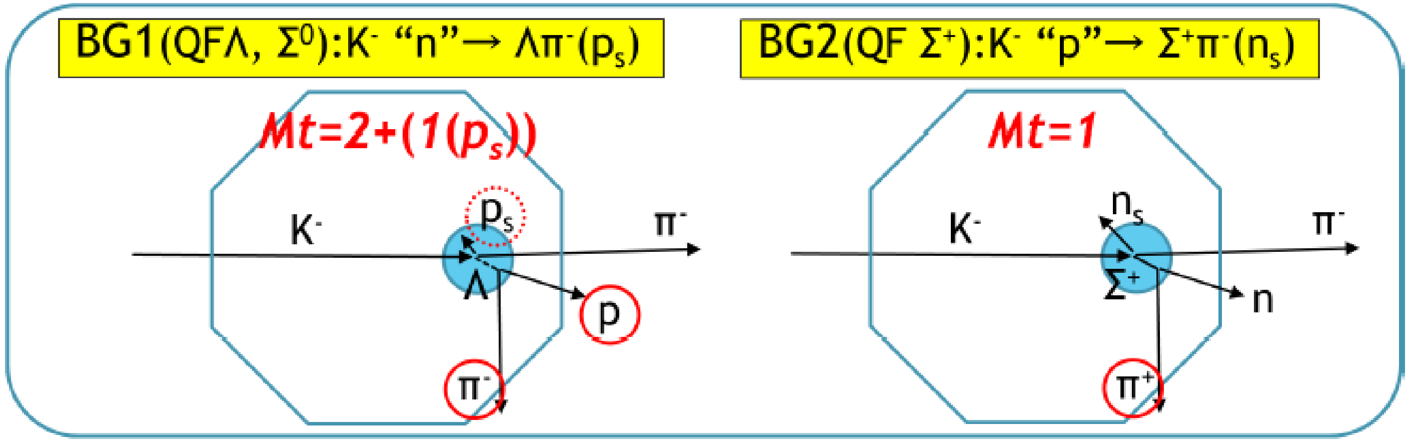


Inclusive: 7.6×10⁴ events for 15 days beam time

Exclusive: 1.4×10⁴ events for 15 days beam time

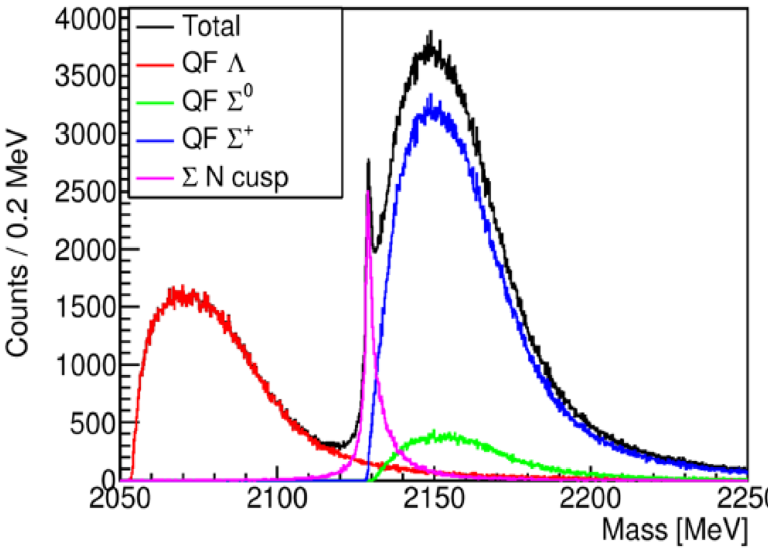
QF BACKGROUND SUPPRESSION BY HYPTPC





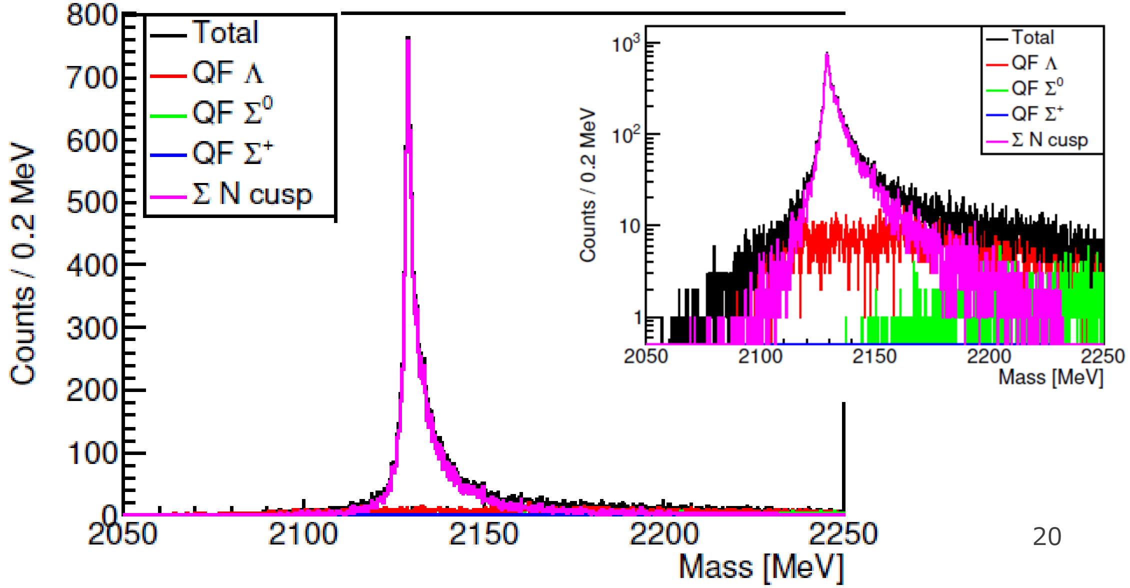
Simulated inclusive spectrum d(K^-, π^-)

Expected spectrum
for the 15 days beam time

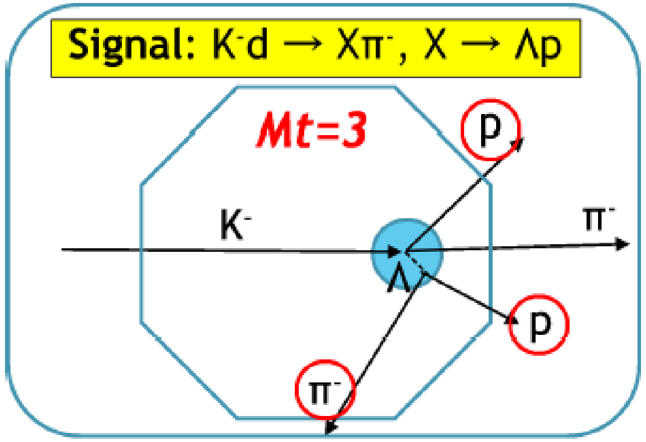


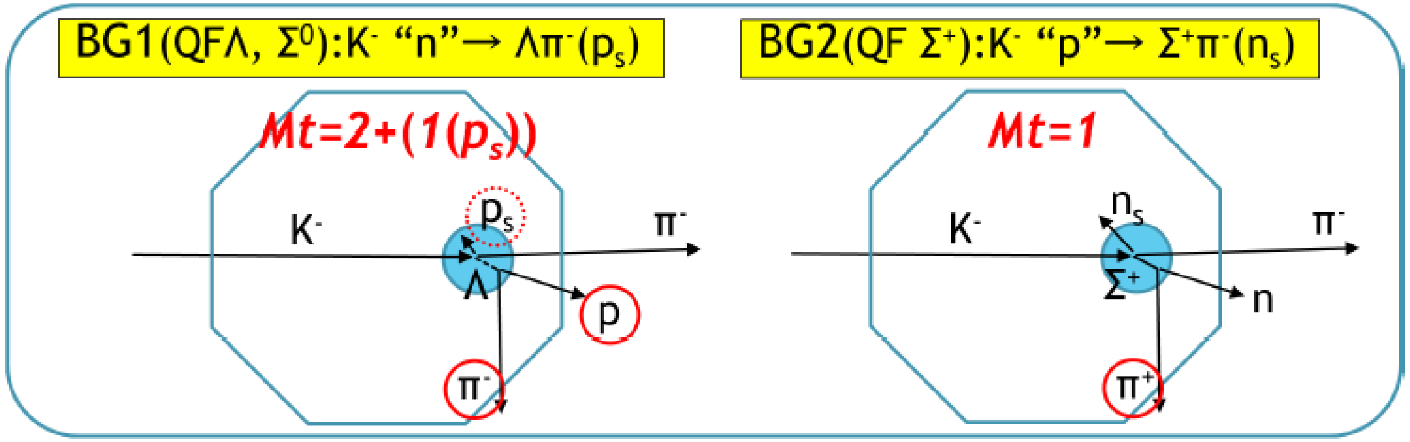
Multiplicity = 3

Multiplicity = 3 without (K^-, π^-)



QF BACKGROUND SUPPRESSION BY HYPTPC





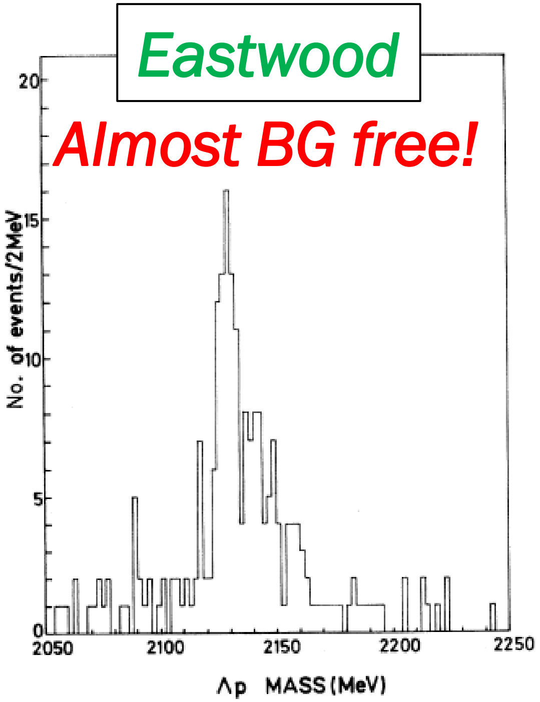
$K^- d \rightarrow \Lambda p \pi^-$

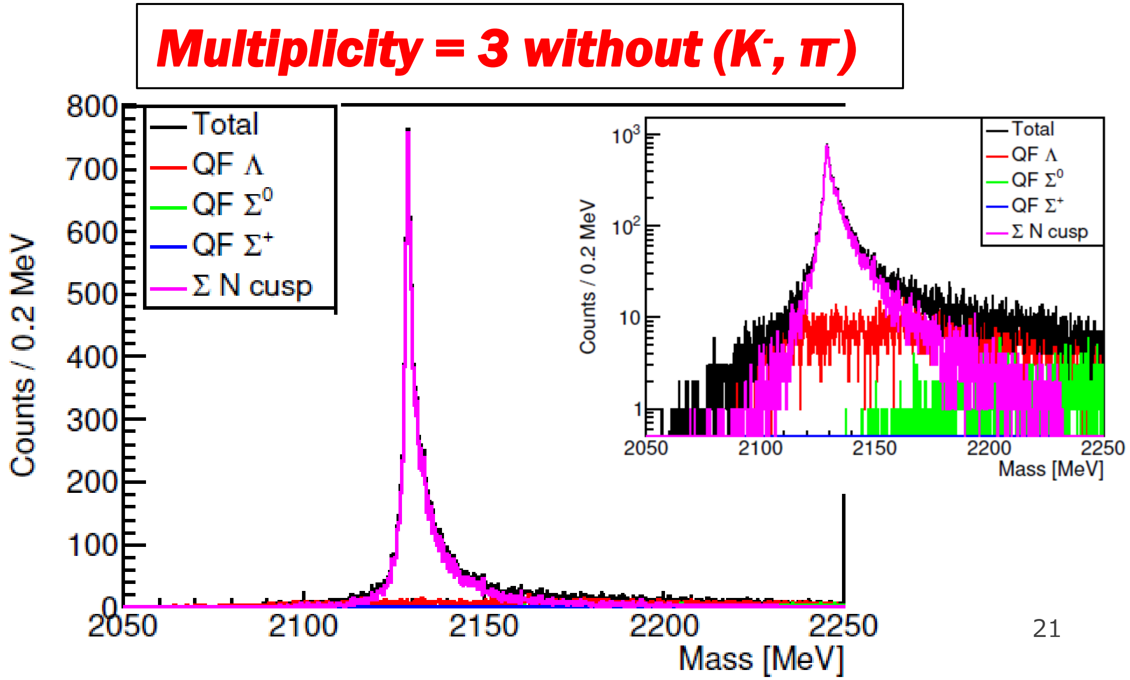
@1.45 and 1.65 GeV/c

(Bubble chamber)

$\cos\theta_{CM} > 0.9$

$p_{proton} > 150$ MeV/c

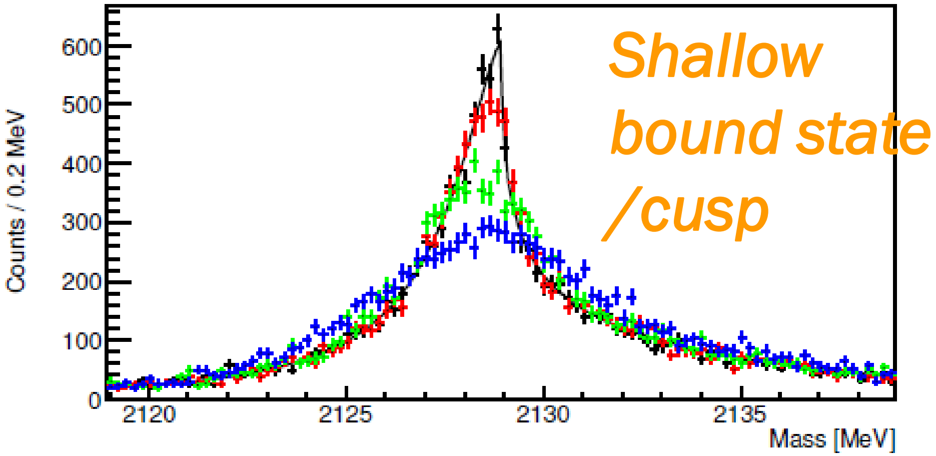




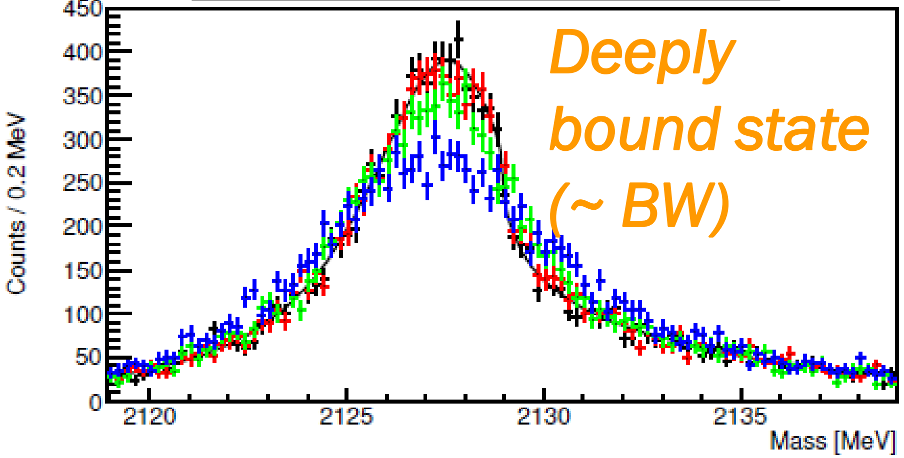
EXPECTED SPECTRA (RESOLUTION EFFECT)

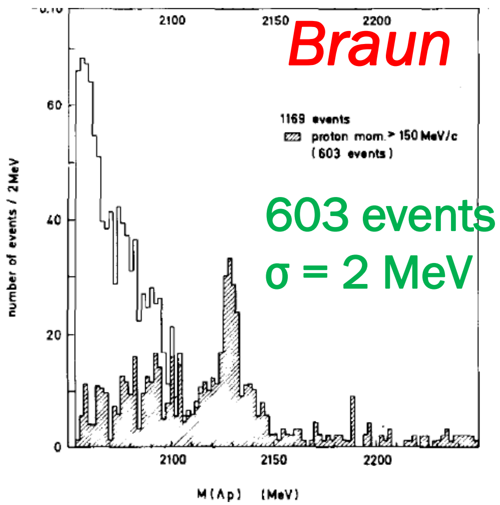
Good energy resolution is necessary to discuss the cusp shape!!

J-A (A_Σ = -2.37 + i3.74 fm)

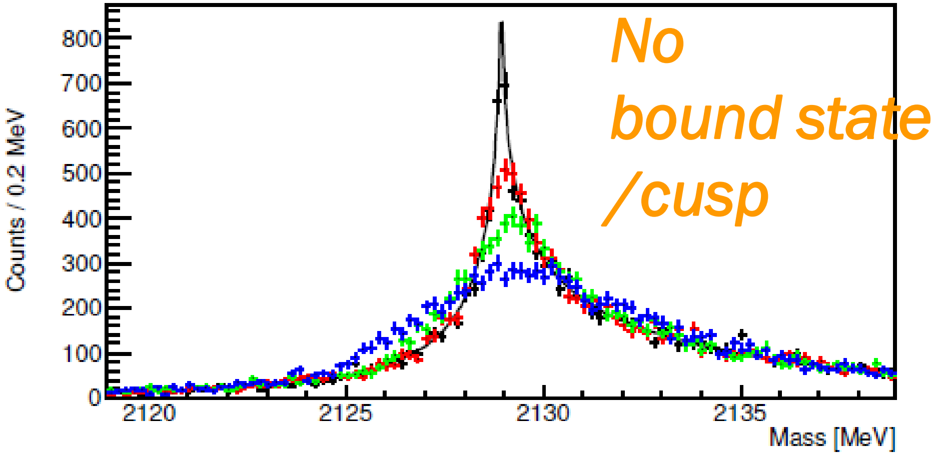


NB (A_Σ = -3.00 + i1.8 fm)



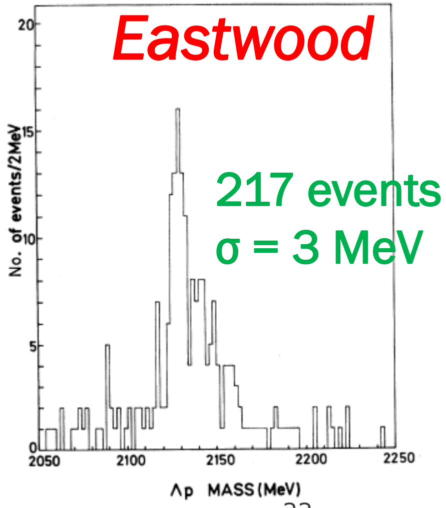


ND (A_Σ = 2.06 + i4.64 fm)



1.4×10^4 Events (P90)

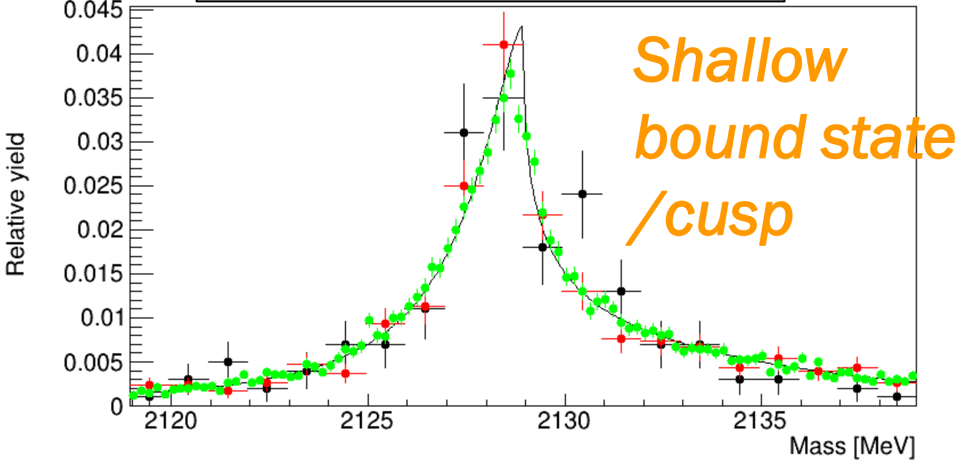
Line	Label
Ideal	Ideal
black	ΔM = 0 MeV
red	ΔM = 0.4 MeV (P90)
green	ΔM = 1 MeV
blue	ΔM = 2 MeV (Braun)



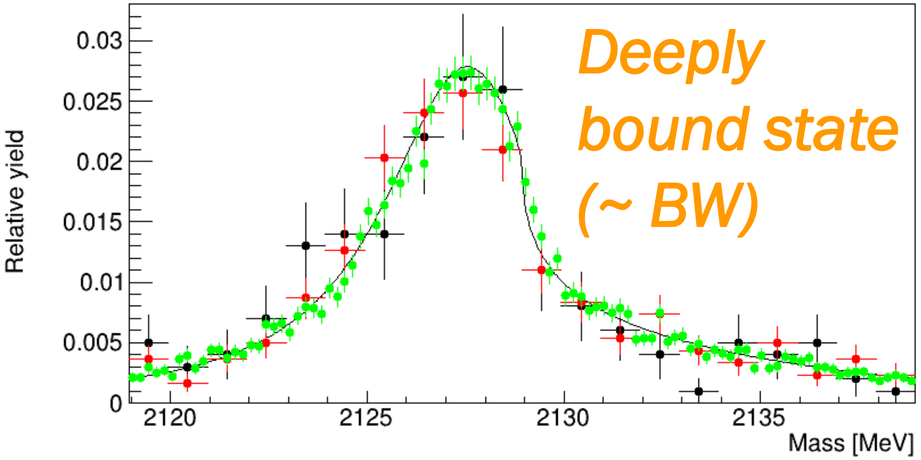
EXPECTED SPECTRA (STATISTICAL EFFECT)

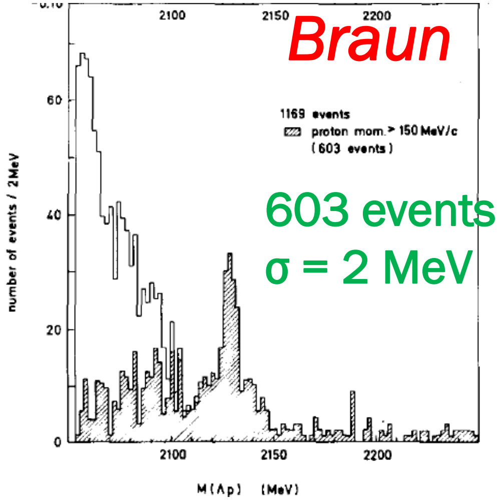
>10^4 statistics is necessary!!

J-A (A_Σ = -2.37 + i3.74 fm)

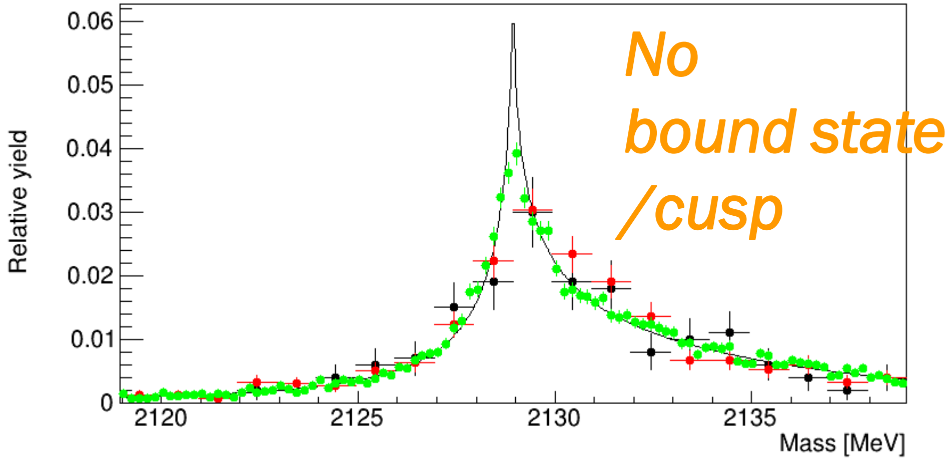


NB (A_Σ = -3.00 + i1.8 fm)

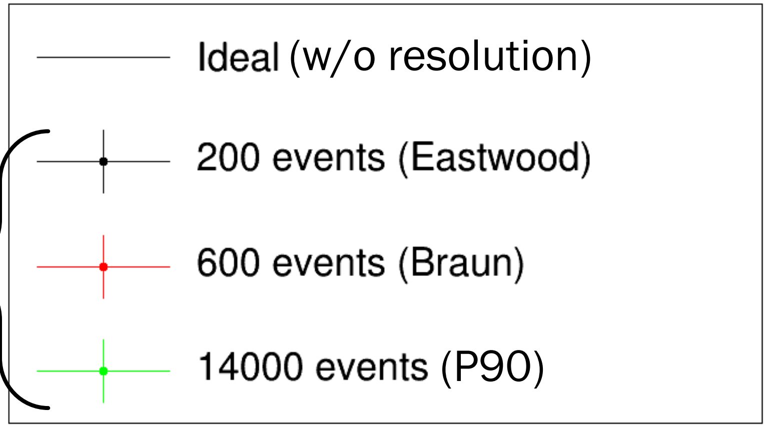


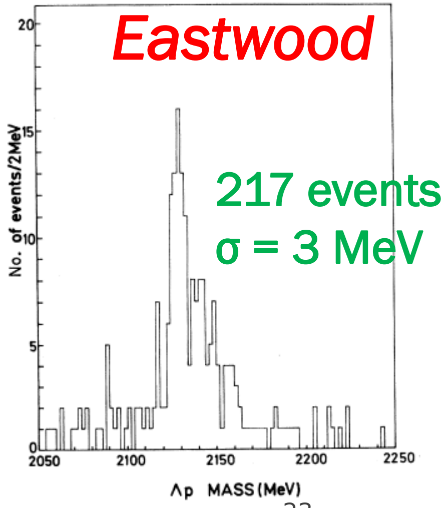


ND (A_Σ = 2.06 + i4.64 fm)



ΔM = 0.4 MeV (P90)





SCATTERING LENGTH FIT VS BREIT-WIGNER FIT

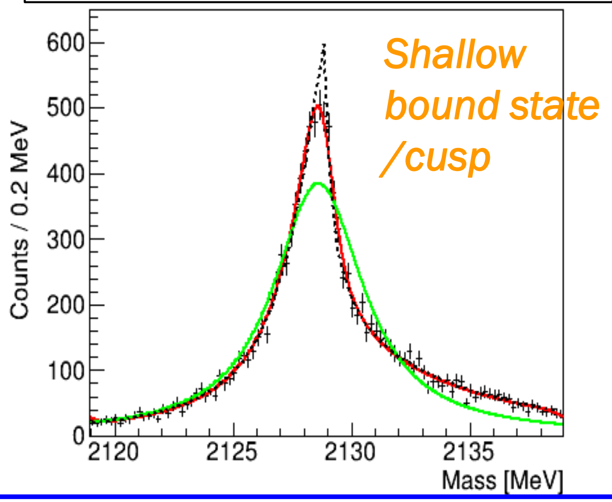
Significant difference between scattering length fit and Breit-Wigner fit in ΔM = 0.4 MeV!!

Statistical error for the scattering length ($A_\Sigma = a + ib$) determination is < 0.3 fm.

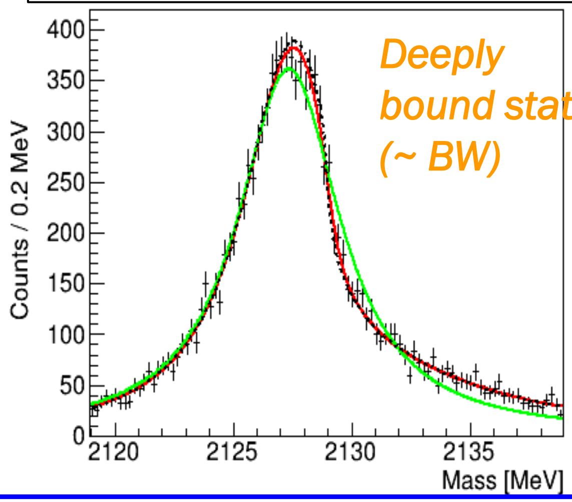
+ Data points
--- Ideal w/o resolution
— Scattering length fit
— Breit Wigner fit

ΔM : 0.4 MeV (P90)

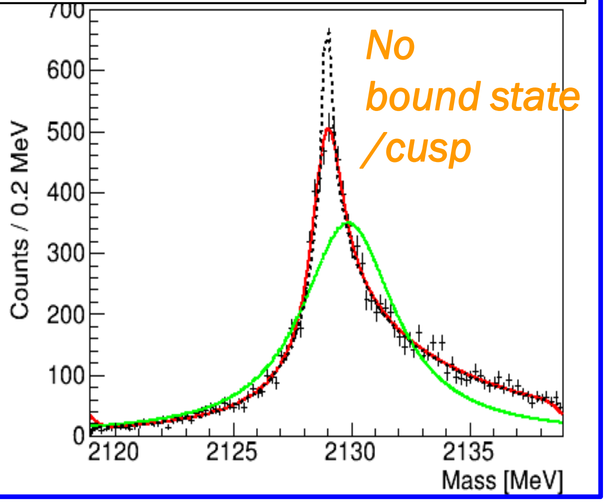
J-A (A_Σ = -2.37 + i3.74 fm)



NB (A_Σ = -3.00 + i1.8 fm)



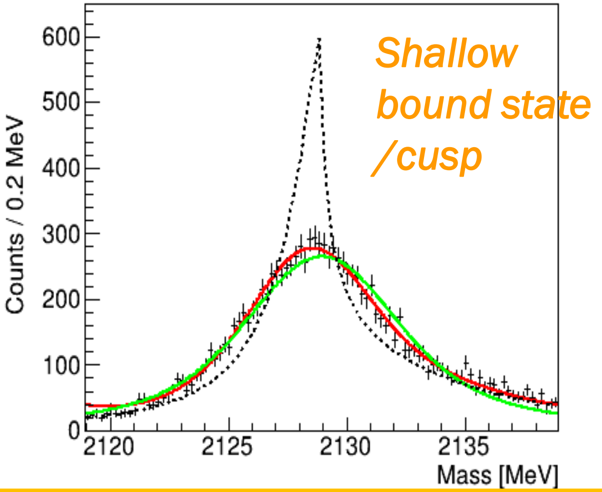
ND (A_Σ = 2.06 + i4.64 fm)



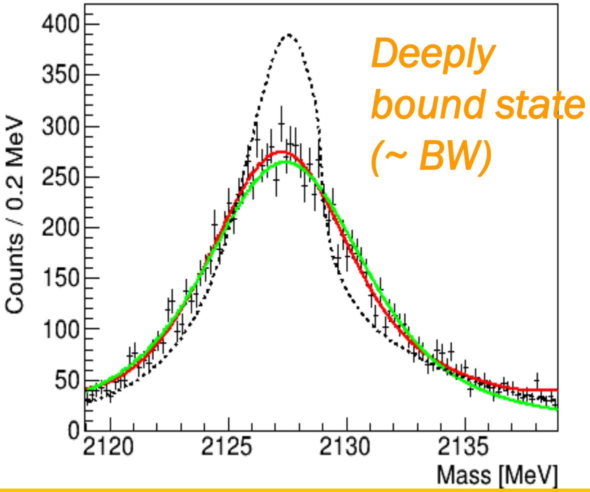
+ Data points
--- Ideal w/o resolution
— Scattering length fit
— Breit Wigner fit

ΔM : 2.0 MeV (Braun)

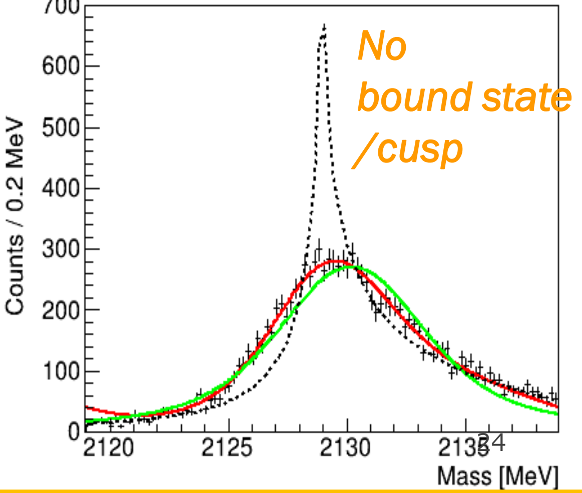
J-A (A_Σ = -2.37 + i3.74 fm)



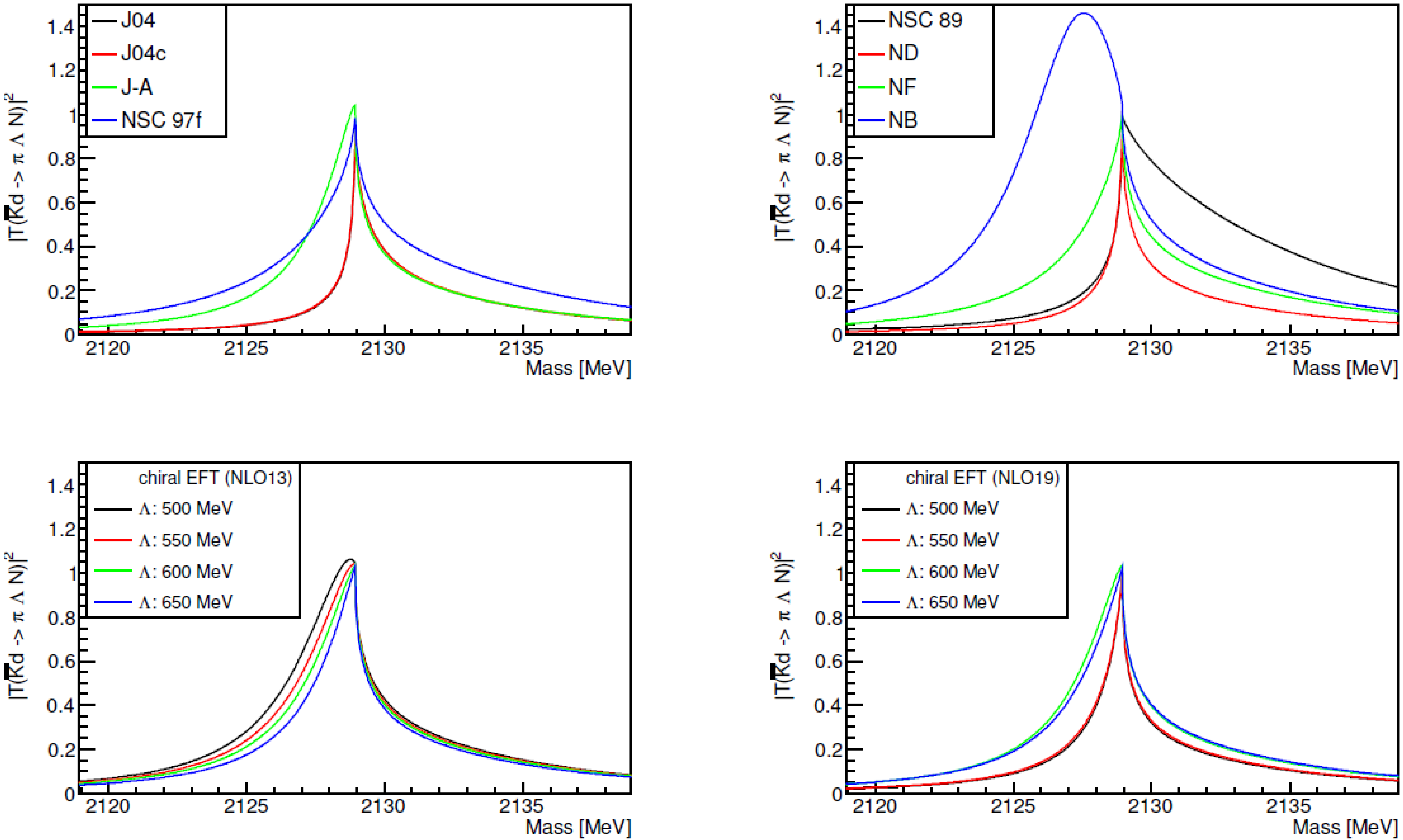
NB (A_Σ = -3.00 + i1.8 fm)



ND (A_Σ = 2.06 + i4.64 fm)

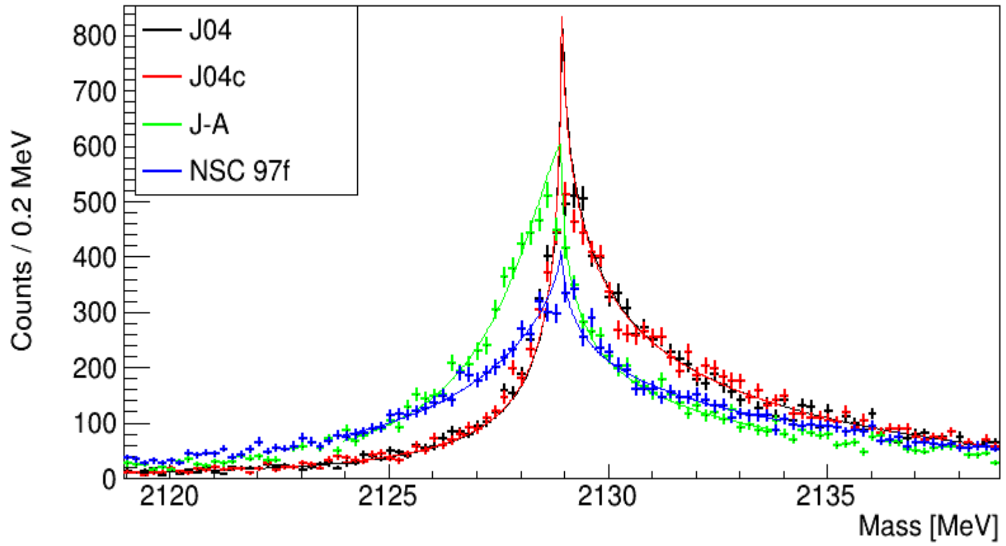


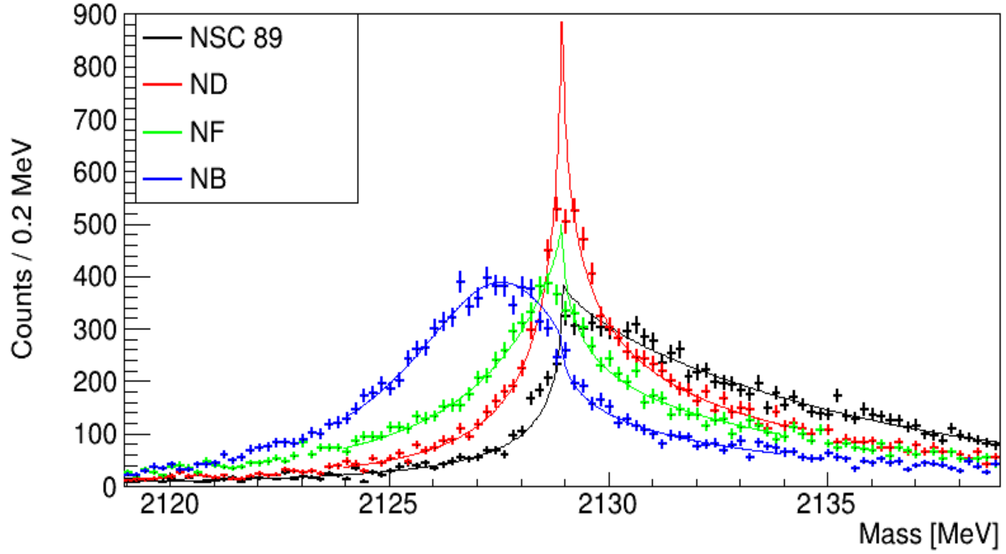
$\Sigma N(T=1/2,\ ^3S_1)$ SCATTERING LENGTH (THEORY)

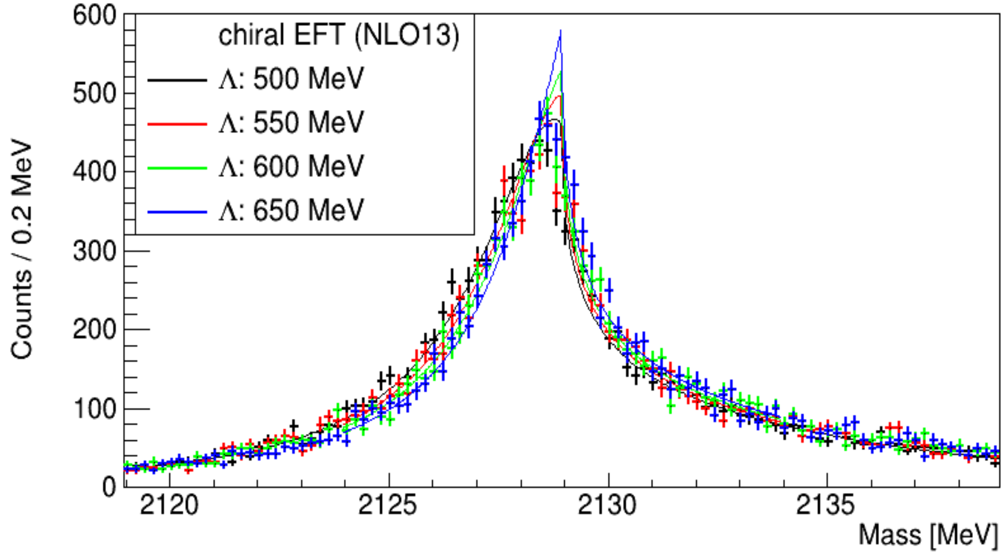


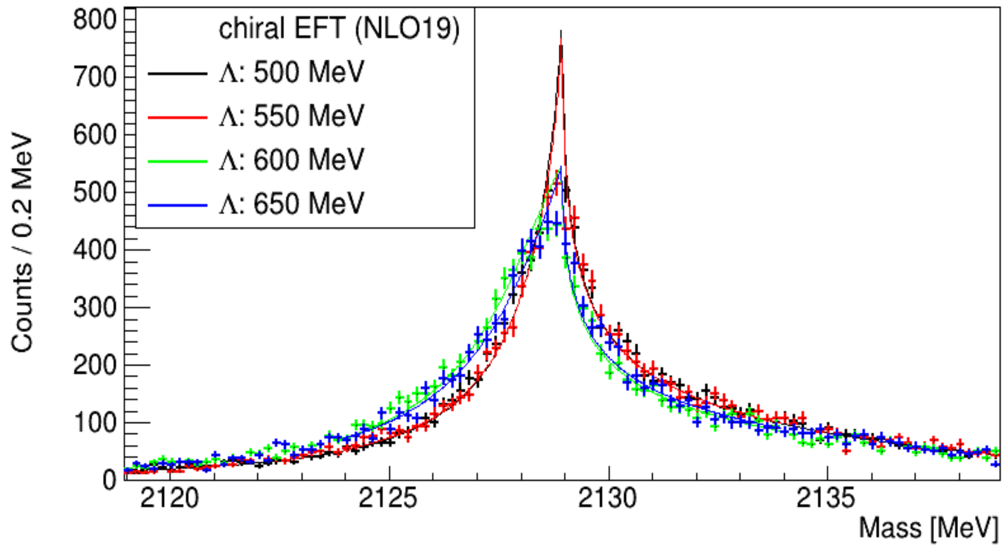
EXPECTED SPECTRA WITH P90 QUALITY

ΔM = 0.4 MeV, 1.4 × 10^4 events



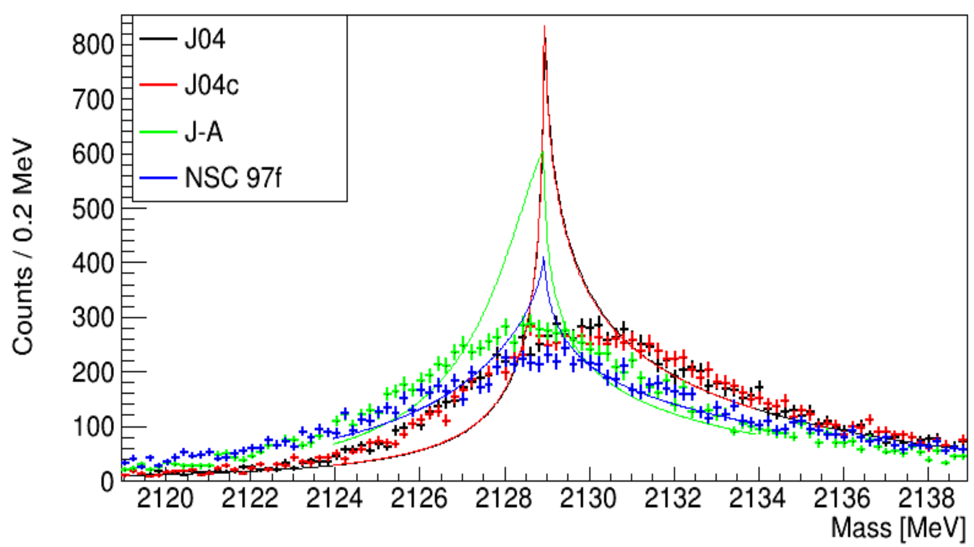


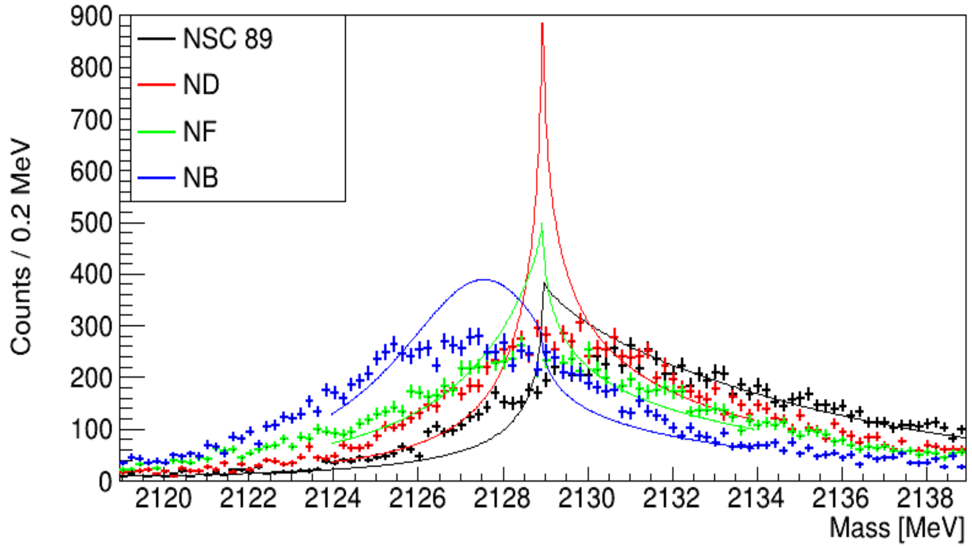


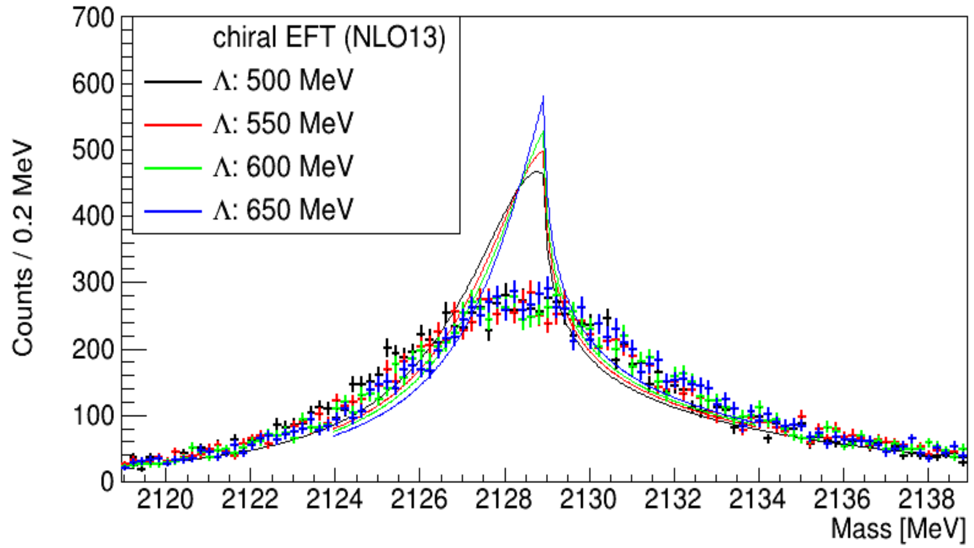


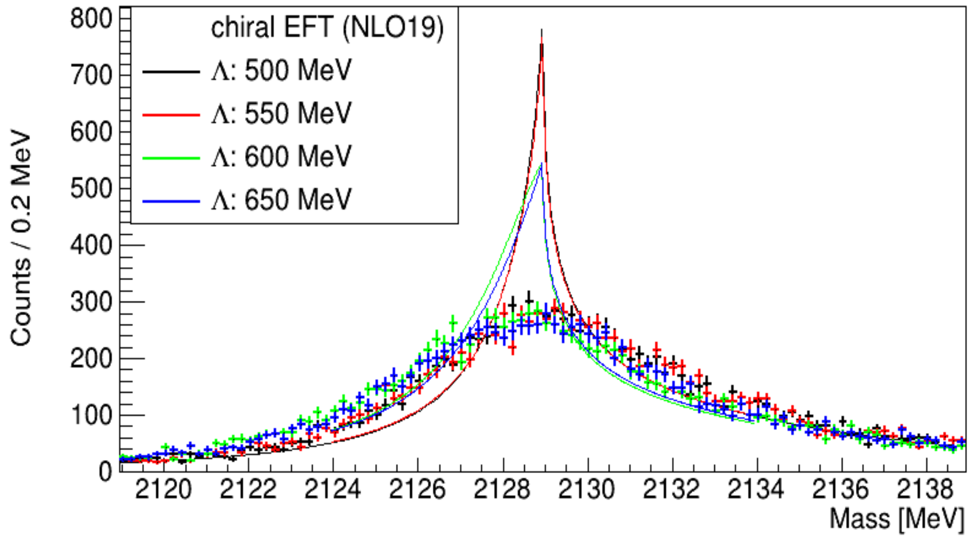
EXPECTED SPECTRA WITH WORSE RESOLUTION

ΔM = 2 MeV, 1.4×10^4 events



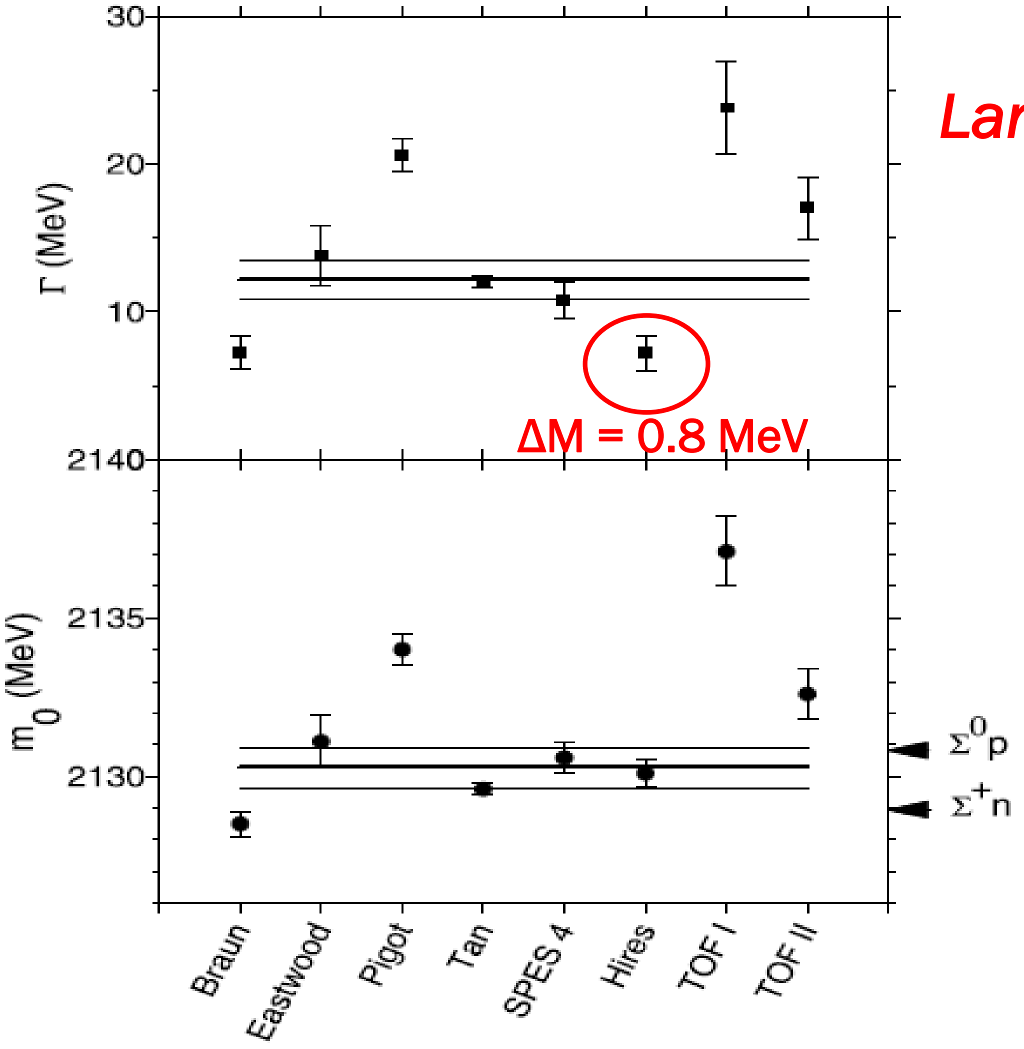






COMPARISON OF M_0 , Γ(1 BW FIT)

H. Machner *et al.*, NPA 901, 65 (2013).



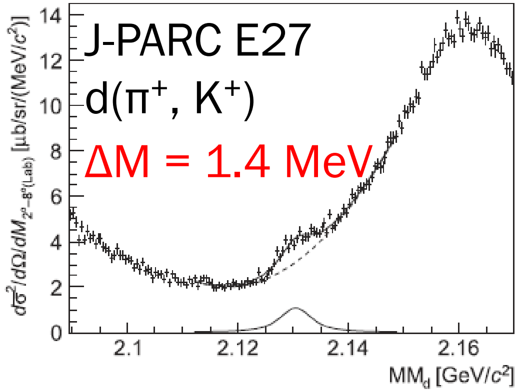
Large width may be come from the worse resolution.

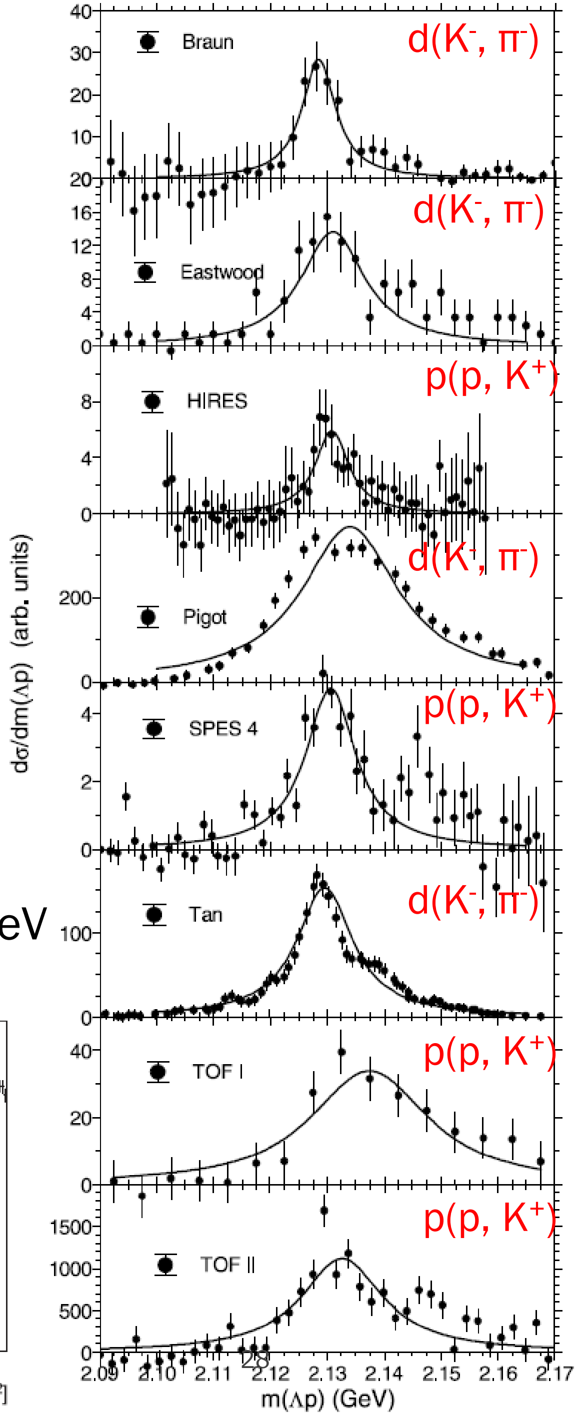
↓

P90 is essential!!

E27: M = 2130.5±0.4(stat.) ±0.9(syst) MeV

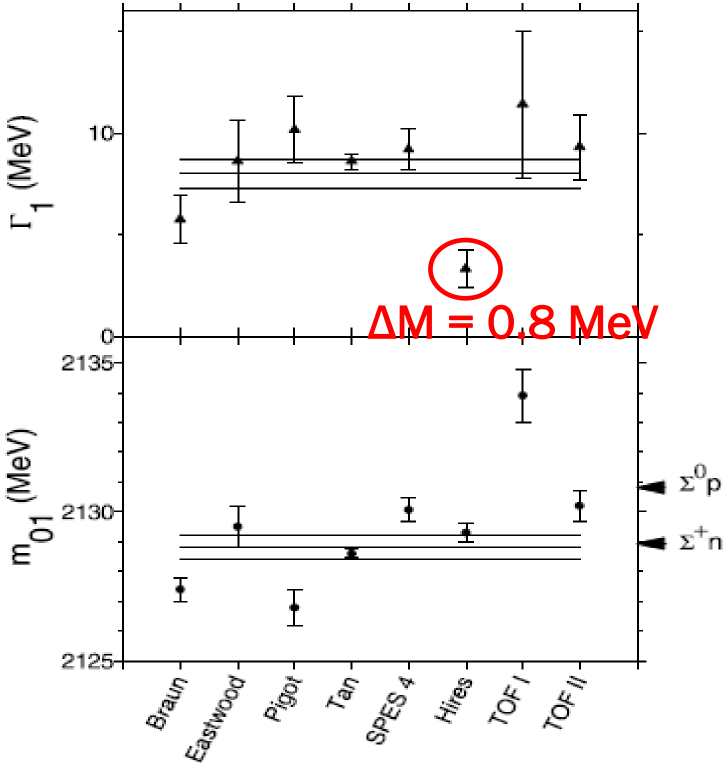
Γ = 5.3 $^{+1.4}_{-1.2}$ (stat.) $^{+0.6}_{-0.3}$(syst.) MeV

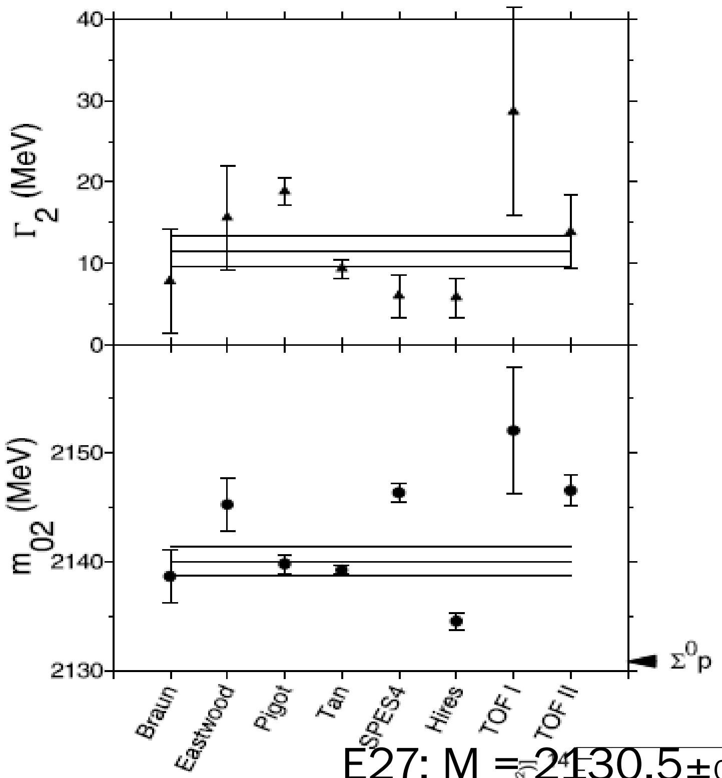


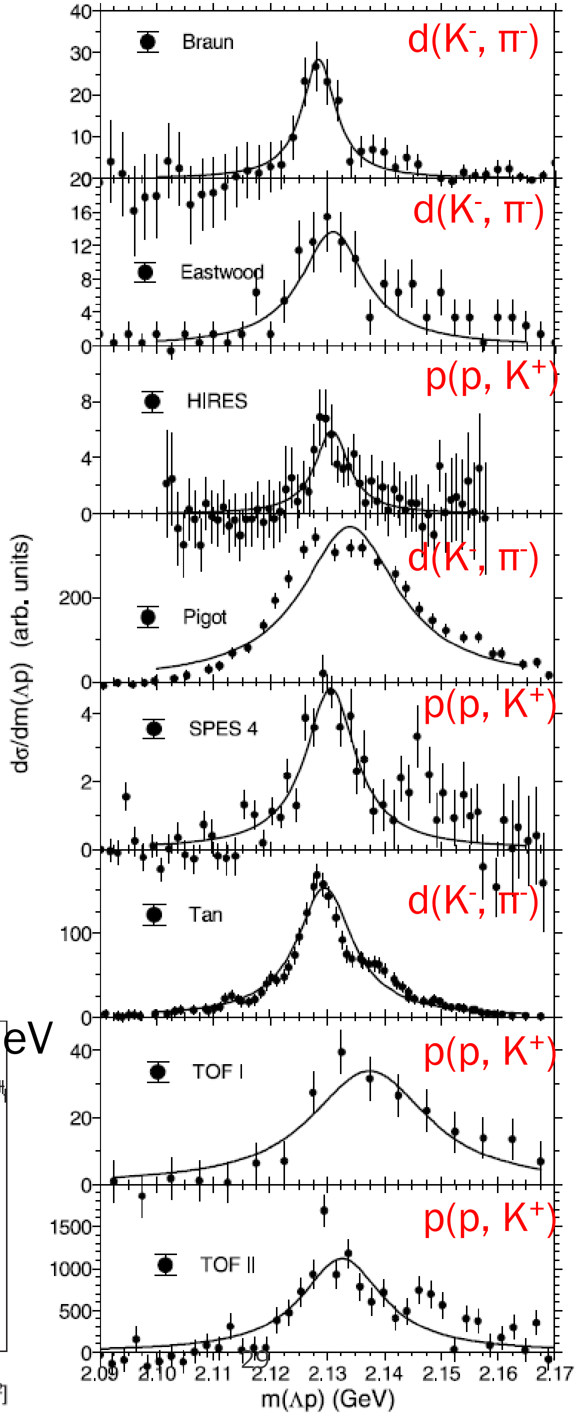


COMPARISON OF M_0 , Γ(2 BW FIT)

H. Machner *et al.*, NPA 901, 65 (2013).

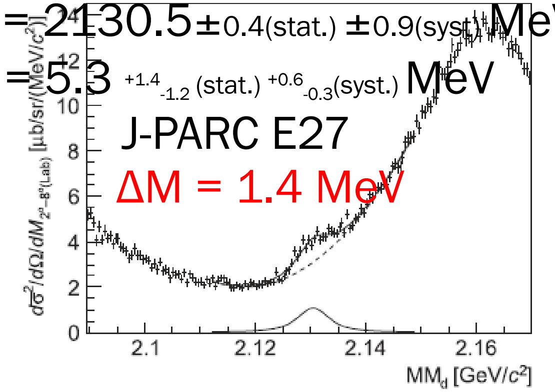






E27: M = 2130.5±0.4(stat.) ±0.9(syst.) MeV

Γ = 5.3 $^{+1.4}_{-1.2}$ (stat.) $^{+0.6}_{-0.3}$(syst.) MeV



Large width may be come from the worse resolution.

↓

P90 is essential!!

SUMMARY

- ΣN interaction is the important key of the B_8B_8 interaction and (Λ, Σ)hypernclei.
- "ΣN cusp" can be expressed by the ΣN interaction (scattering length).
  - There are a lot of past experiments to measure the "ΣN cusp" .
    However, the origin of the "ΣN cusp" remains unclear yet. ΣN dibaryon or not?
  - Inflight d(K^-, π^-) reaction has advantage to dedicate (T=1/2, $^3S_1$) channel.
- P90 will investigate the nature of "ΣN cusp" with the world's best quality.
  - K1.8 Beam line, S-2S for π- measurement, and HypTPC for BG suppression.
  - 1.4×10^4 ΣN cusp events are expected in 15 days beam time.
  - 0.4 MeV (σ) mass resolution will be achieved, 2 times better than past exp.
  - We can deduce scattering length with the statistical error less than 0.3 fm.

→ We will be ready to install by the end of JFY 2023. [SAC, TPC stands]