スレショールドカスプの実験的同定と今後の研究計画

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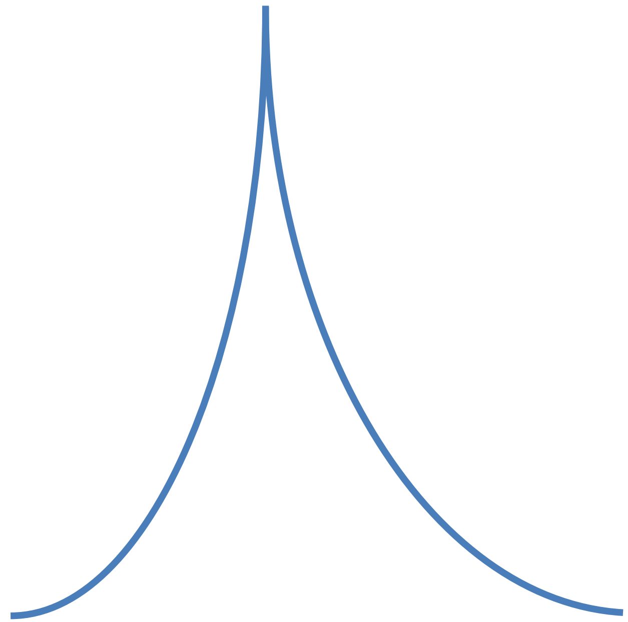
Threshold cusp

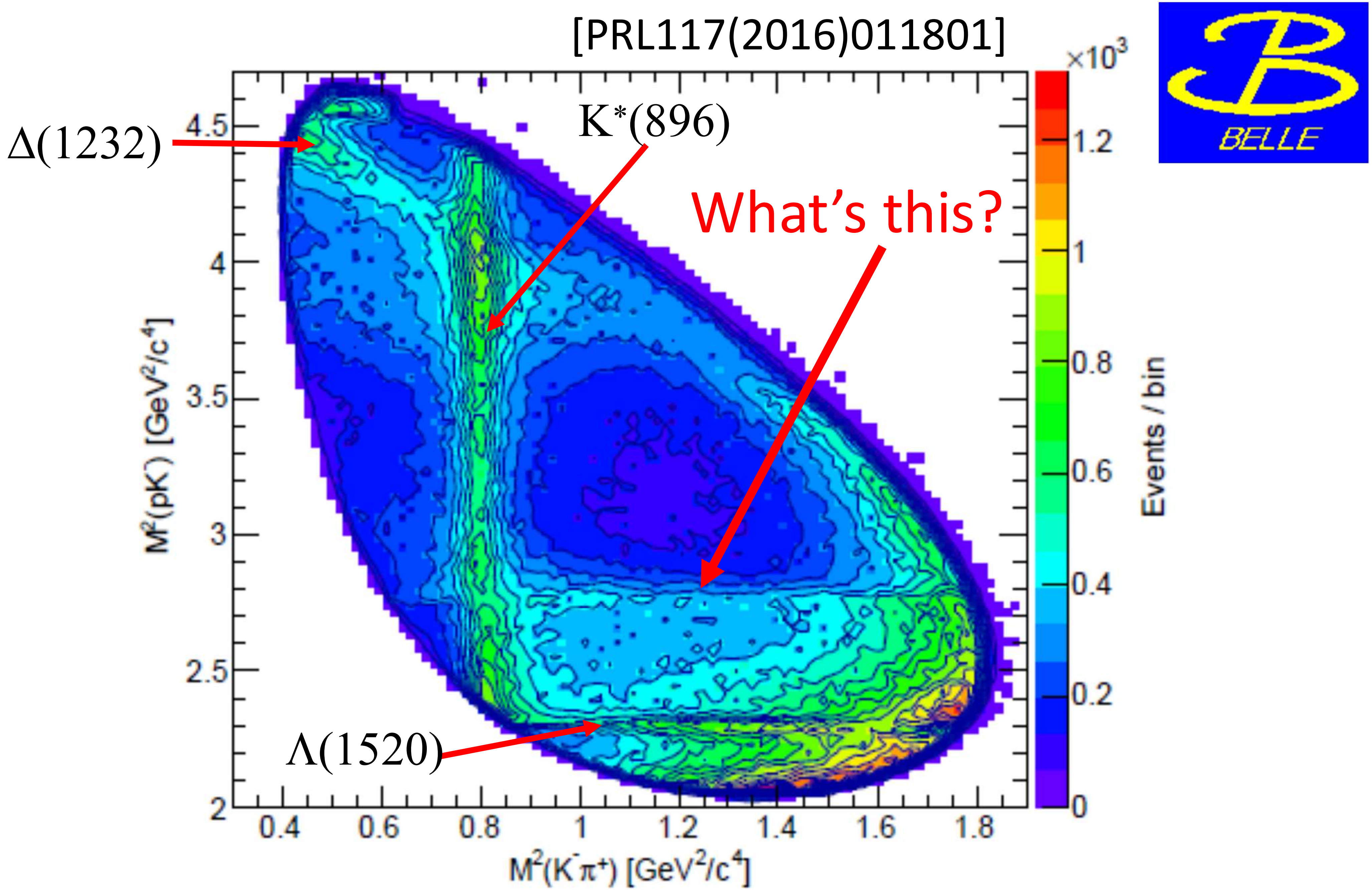
- Jump in strength ($|amp|^2$) in the (L+1)th derivative
  - In the widest sense, cusp ALWAYS appears at thresholds.
- Practically, cusp appears only in S-wave
- Interesting case is the 1st derivative changes sign, especially from positive to negative
  - Cusp in the narrow sense.
  - In principle, can be distinguished from usual peak by the derivative at the top, but practically there is experimental resolution.
  - Very few identified cases



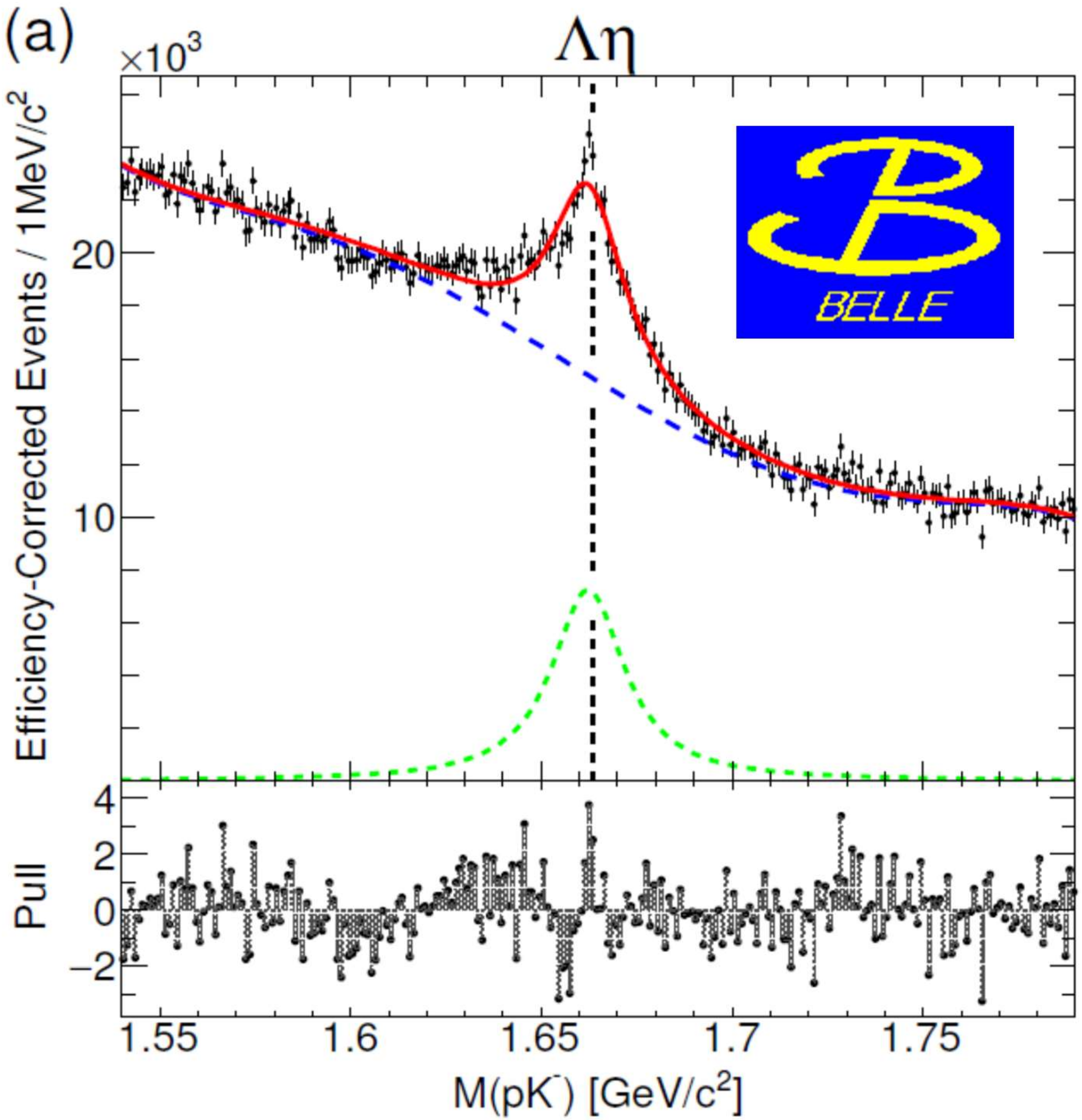
Belle results:

1. $\Lambda_c \rightarrow pK^-\pi^+$ at the $\Lambda\eta$ threshold
2. At the $\overline{\mathrm{K}}\mathrm{N}(\mathrm{I}=1)$ threshold

1. Peak structure in $\Lambda_c \to pK^-\pi^+$



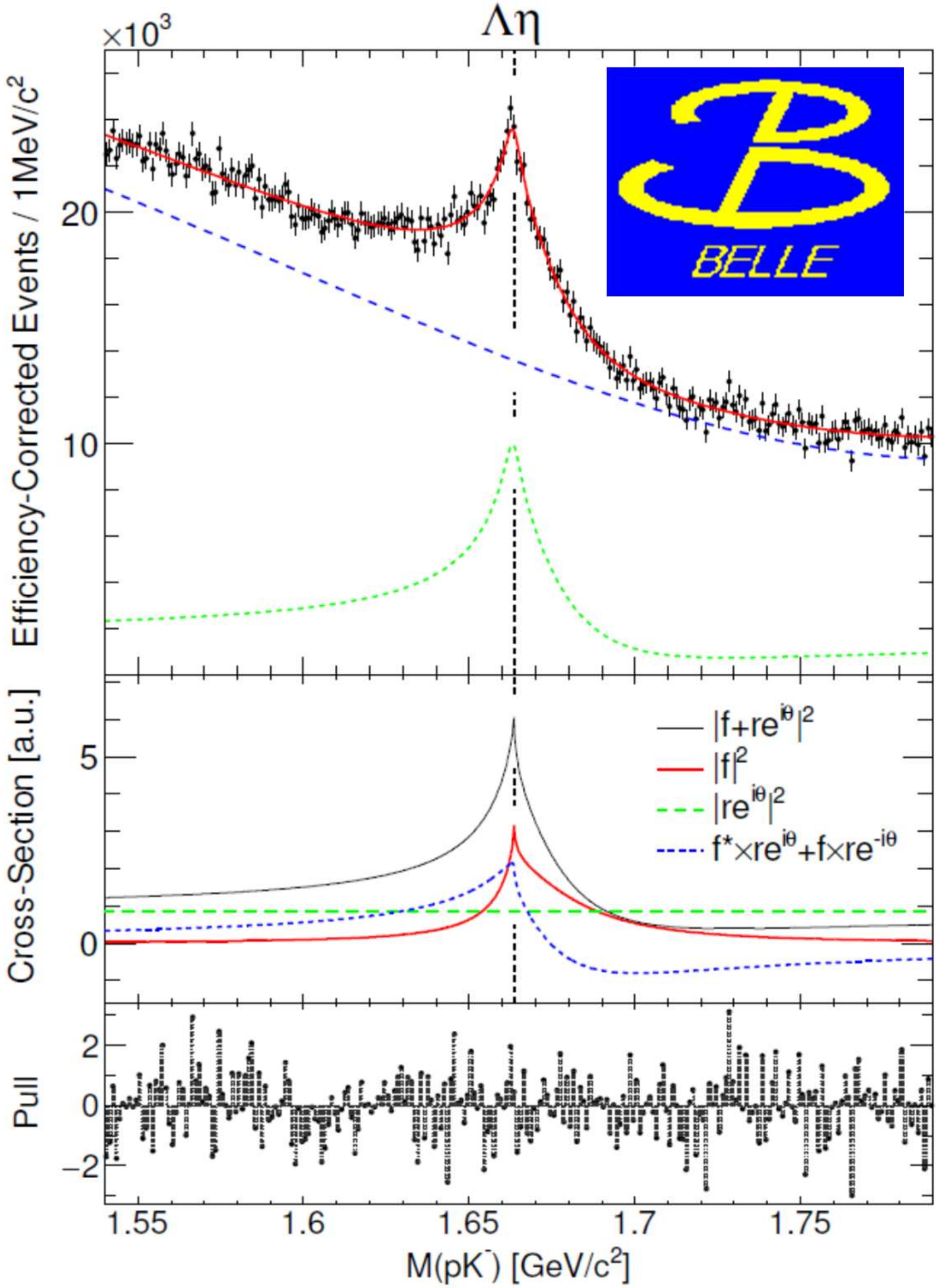
Fit to Breit-Wigner



- Not very good especially near the peak.
- Best χ^2/DOF: 308/243

[arXiv:2209.00050, submitted to PRL]

Fit to Flatte



$$\frac{dN}{dm} \propto |f(m) + re^{i\theta}|^2$$

f(m): non-relativistic Flatte

$$\frac{1}{m - m_f + \frac{i}{2}(\Gamma' + \bar{g}_{\Lambda\eta} k)}$$

- Improved near the peak
- Best χ^2/DOF: 257/243
  - Better than BW by 7σ

Threshold cusp

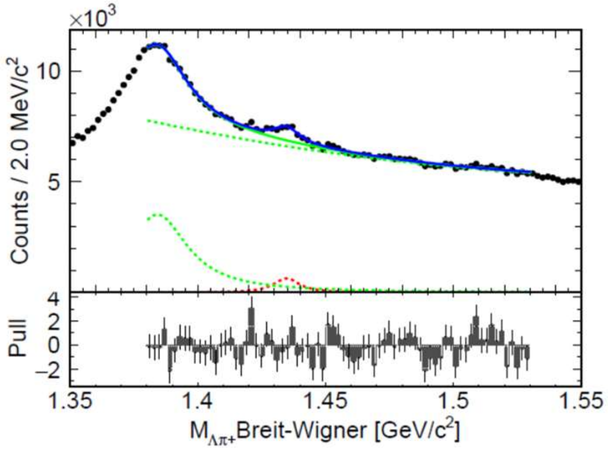
- The fit explains the peak as a threshold cusp with nearby $\Lambda(1670)$
  → **First identification of a threshold cusp from the spectrum shape**
- Obtained $\Lambda(1670)$ parameters are consistent with those measured in $\Lambda_c \to \Lambda\eta\pi^+$ [Belle, PRD103 (2021) 052005]

	Present result	**$\Lambda\eta\pi^+$ mode**
Mass	1674.4	$1674.3 \pm 0.8 \pm 4.9$
Width	$50.3 \pm 2.9^{+4.2}_{-4.0}$	$36.1 \pm 2.4 \pm 4.8$

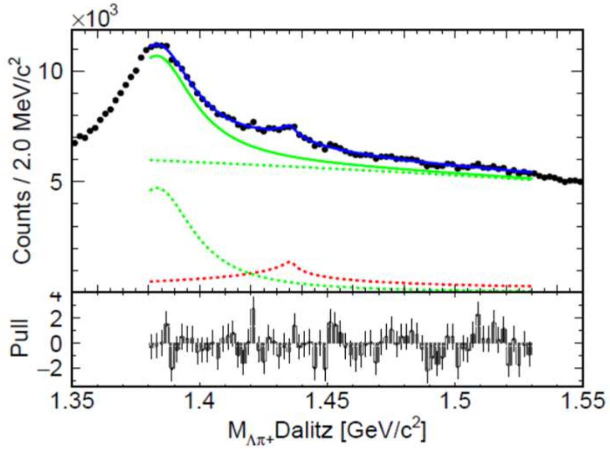
- How about other near-threshold exotic hadrons?
  – **They may be actually threshold cusps!**

2. $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$

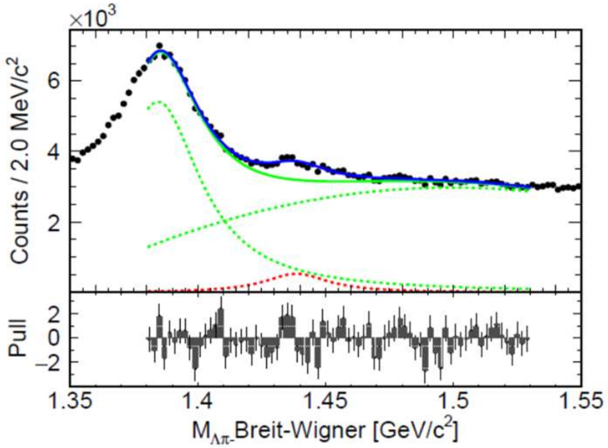
- Cusp candidates are observed in $\Lambda\pi^{\pm}$ invariant mass spectra, especially from Λ_c decay in Belle ([arXiv:2211.11151] just submitted to PRL)

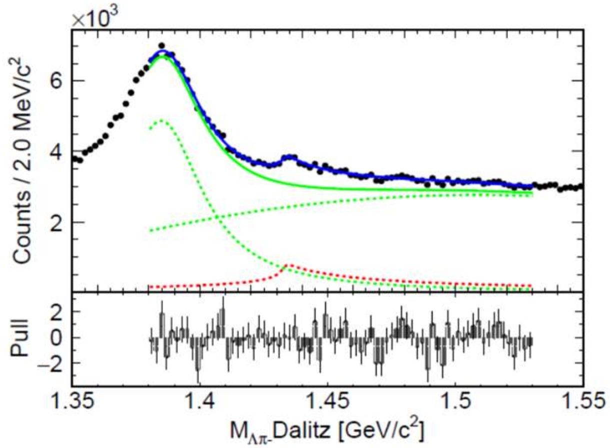


(a)

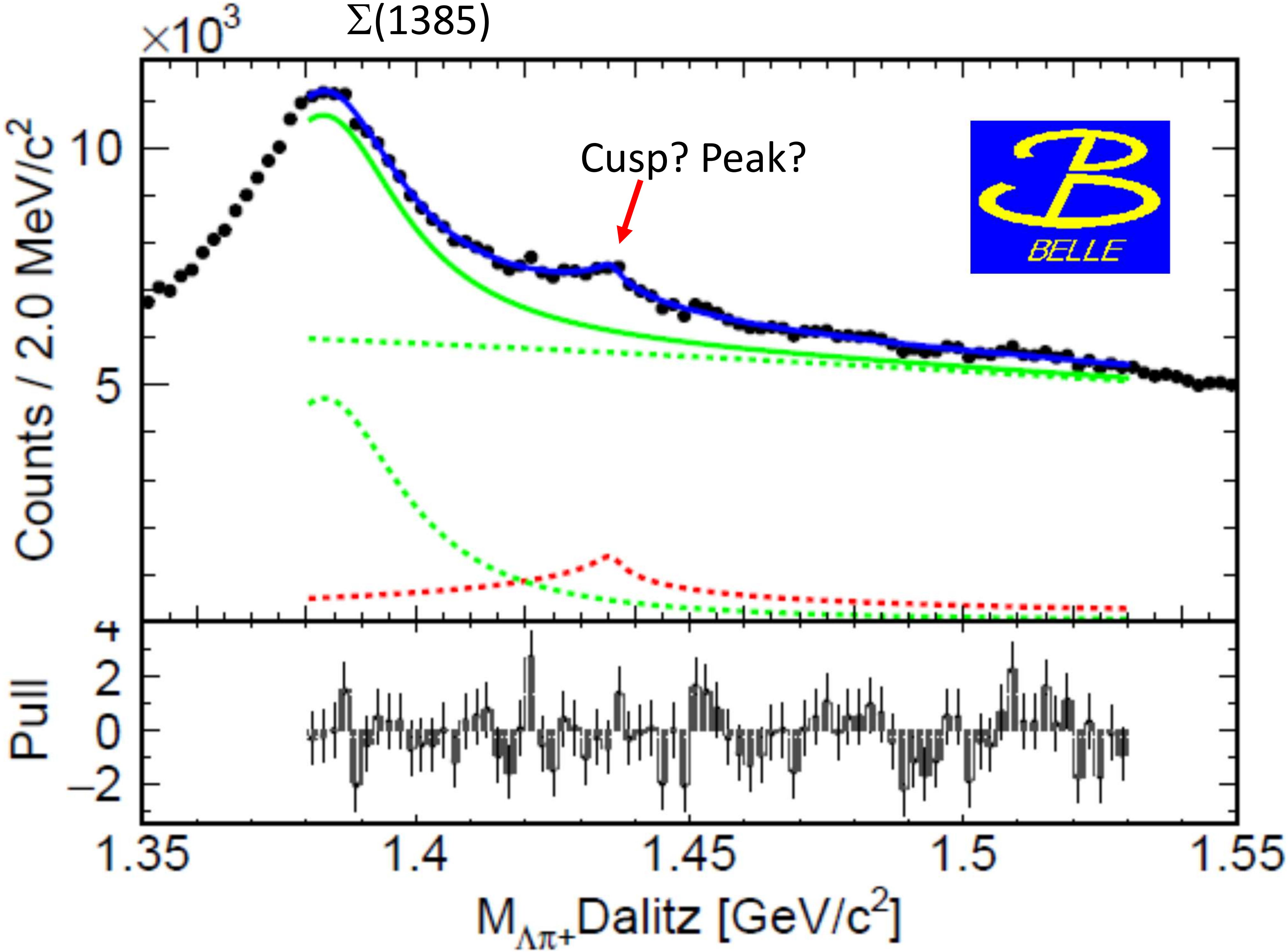


(a)





Σ(1385)



×10³
Cusp? Peak?
BELLE
10
5
Counts / 2.0 MeV/c²
4
2
0
−2
Pull
1.35
1.4
1.45
1.5
1.55
M_Λπ+ Dalitz [GeV/c²]

2 fitting models

1. Standard Breit-Wigner

$$f_{BW} = \frac{\Gamma/2}{(E - E_{BW})^2 + \Gamma^2/4},$$

2. Dalitz model (cusp) [Czech. J. Phys. B**32**, 1021 (1982)]
   For $\bar{K}N(I=1)$ scattering length A=a+ib and decay momentum k/κ(=|k| below the threshold)

$$f_D = \frac{4\pi b}{(1+kb)^2 + (ka)^2}, E > m_{\bar{K}N}$$
$$= \frac{4\pi b}{(1+\kappa a)^2 + (\kappa b)^2}, E < m_{\bar{K}N},$$

   neglecting decay form factor

Fitting results

1. Breit-Wigner

Mode	E_{BW} [MeV/c^2]	Γ [MeV/c^2]	χ^2 / NDF
$\Lambda\pi^+$	1434.3 ± 0.6	11.5 ± 2.8	$74.4/68$
$\Lambda\pi^-$	1438.5 ± 0.9	33.0 ± 7.5	$92.3/68$

2. Dalitz model (cusp)

Mode	a[fm]	b[fm]	χ^2 / NDF
$\Lambda\pi^+$	0.48 ± 0.32	1.22 ± 0.83	$68.9/68$
$\Lambda\pi^-$	1.24 ± 0.57	0.18 ± 0.13	$78.1/68$

Dalitz model gives slightly better χ^2, but the difference is not significant.

Results & discussions

1. Breit-Wigner

   Mass +: $1434.3 \pm 0.6^{+0.9}_{-0.0}$ MeV/c²

   –: $1438.5 \pm 0.9^{+0.2}_{-2.5}$ MeV/c²

   Width +: $11.5 \pm 2.8^{+0.1}_{-5.3}$ MeV

   –: $33.0 \pm 7.5^{+0.1}_{-23.6}$ MeV

- Significance 7.5(6.2)σ
- This interpretation suggests an existence of an exotic state, Σ(1435).

Results & discussions

2. Dalitz (cusp)

   a +: $0.48 \pm 0.32^{+0.38}_{-0.01}$ fm

   –: $1.24 \pm 0.57^{+1.56}_{-0.16}$ fm

   b +: $1.22 \pm 0.83^{+2.54}_{-0.18}$ fm

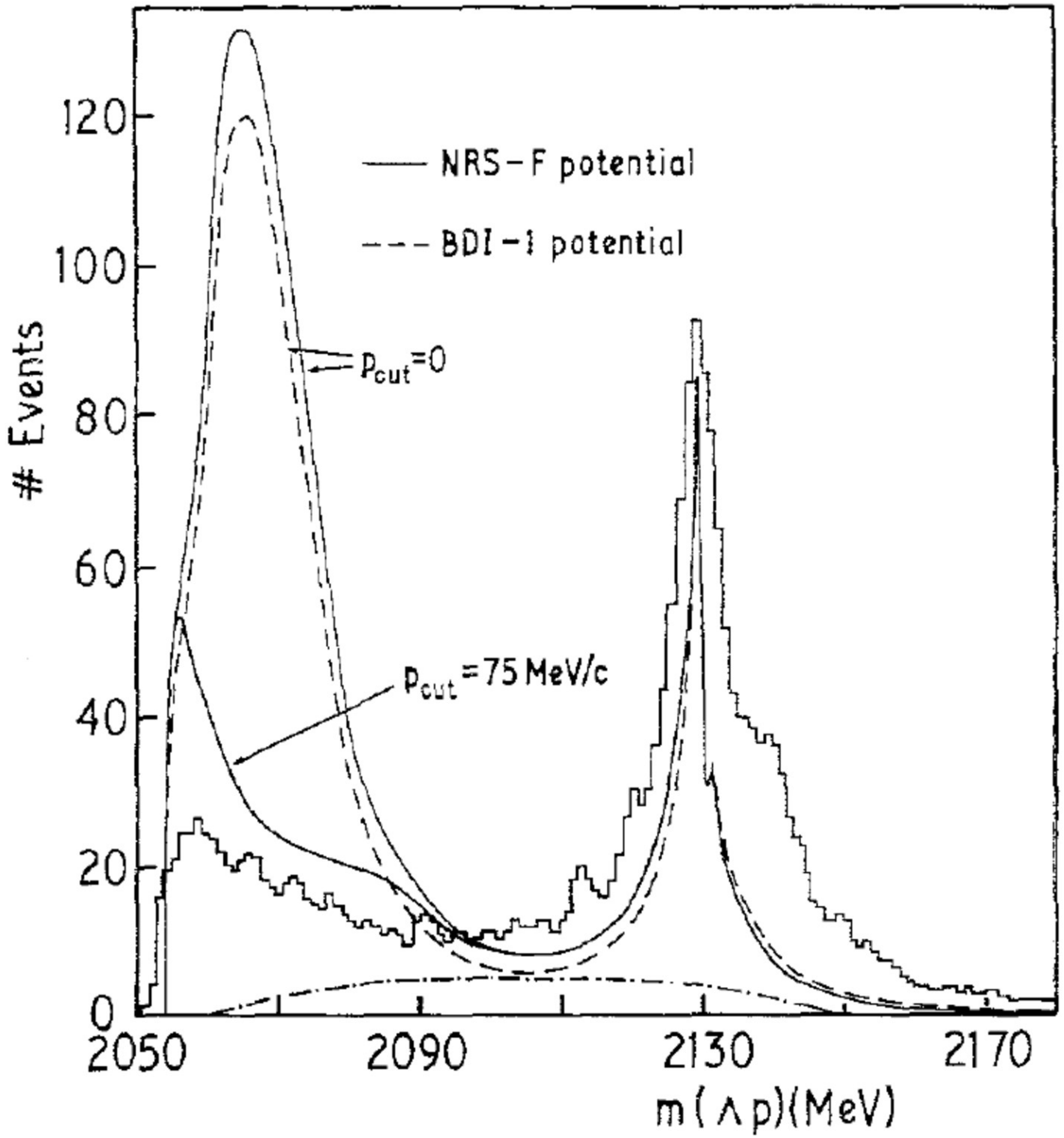
   –: $0.18 \pm 0.13^{+0.00}_{-0.20}$ fm

- Many theories predict a cusp here.
- Obtained scattering lengths are larger than most theories, but with large uncertainties
  (Also, form factor is ignored.)

Future plans at J-PARC

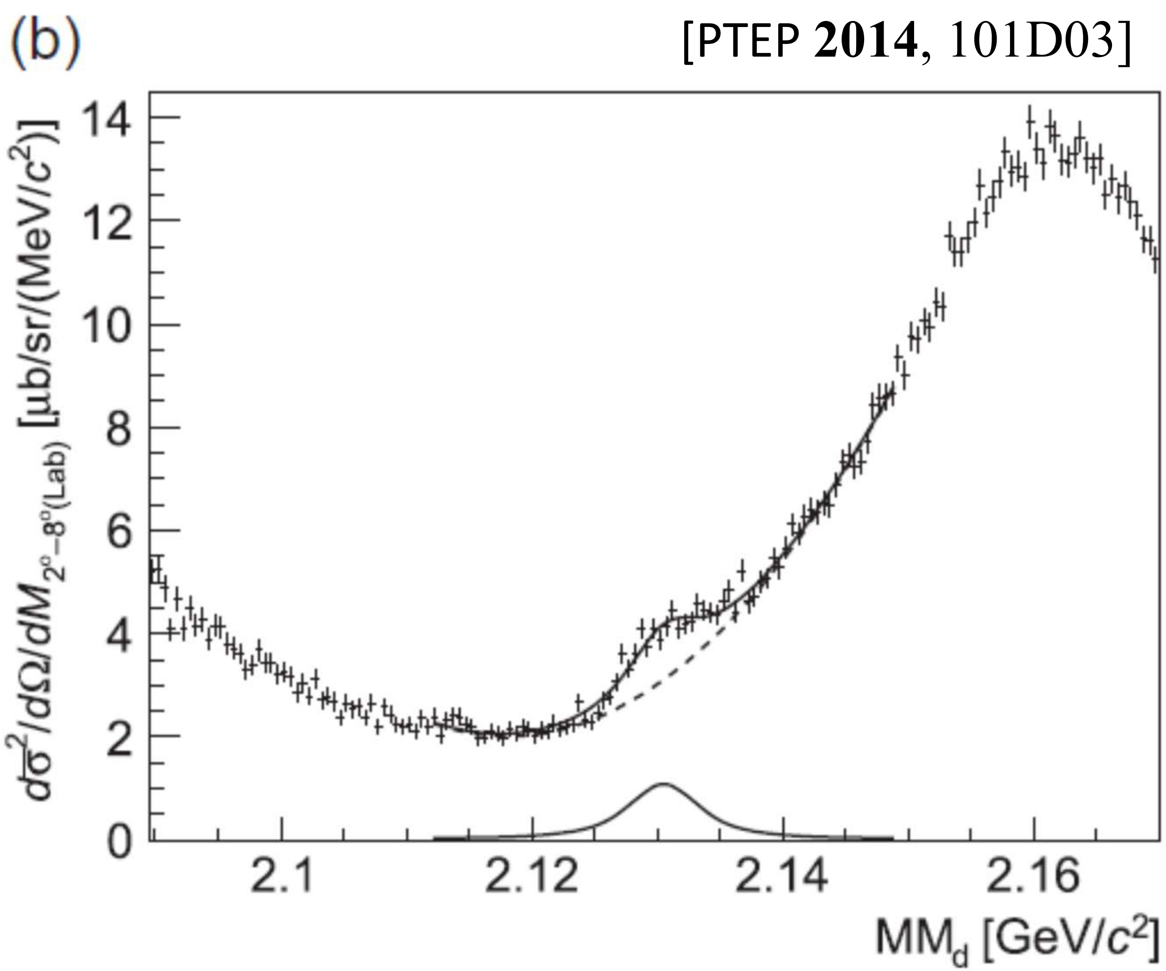
E90 for ΣN interaction & Further possibilities

ΣN cusp



- K^-(stopped)+d $\rightarrow \Lambda p \pi^-$
- Maybe the cleanest cusp ever seen, but not confirmed.
  - Because the resolution is not enough

J-PARC E27 result



- d(π^+,K^+) reaction at 1.69 GeV/c
- Cannot distinguish "cusp" from usual peak

- Fit with Breit-Wigner (Resolution: $\sigma = 1.4$ MeV)

$$\Gamma = 5.3^{+1.4+0.6}_{-1.2-0.3}\ \mathrm{MeV}$$

What should we do?

- Try even higher resolution
  - 1 MeV (FWHM) would be enough to see the cusp shape
- Tagging of the final state is necessary
  - Must be ΛN to derive ΣN (I=1/2) scattering length
  - ΣN (I=3/2) contaminate if not tagged
- J-PARC E90
  - 1 MeV resolution with d(K^-,p) reaction at $p_K \sim 1.4$ GeV/c Thanks to the high resolution of S-2S spectrometer,.
  - Tagging of decay particles by the Hyperon Spectrometer → 4π acceptance

ΣN(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

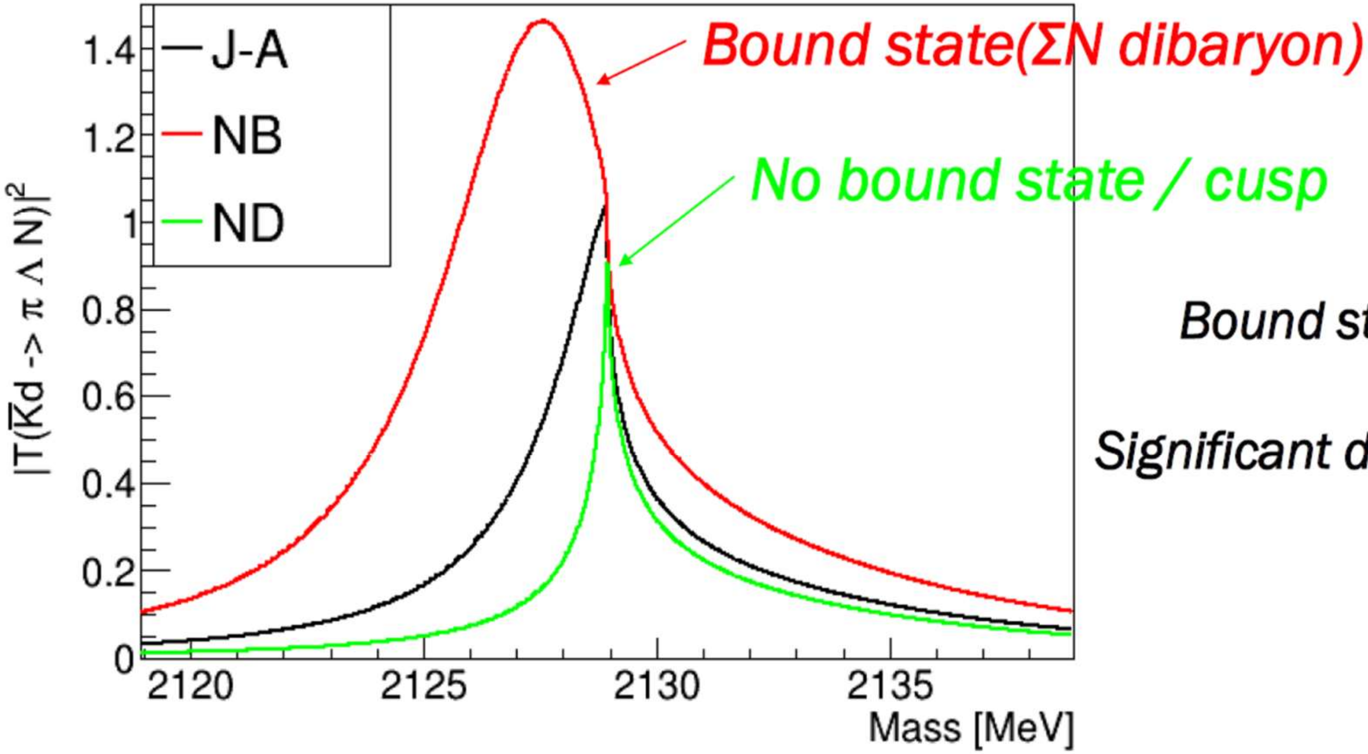
Large ambiguity!!

- Possibility of a bound state
  - Like deuteron. Could be called as dibaryon
  - Cusp could appear even if the state is bound. ← due to source size effect.

Spectrum shape with Dalitz model

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

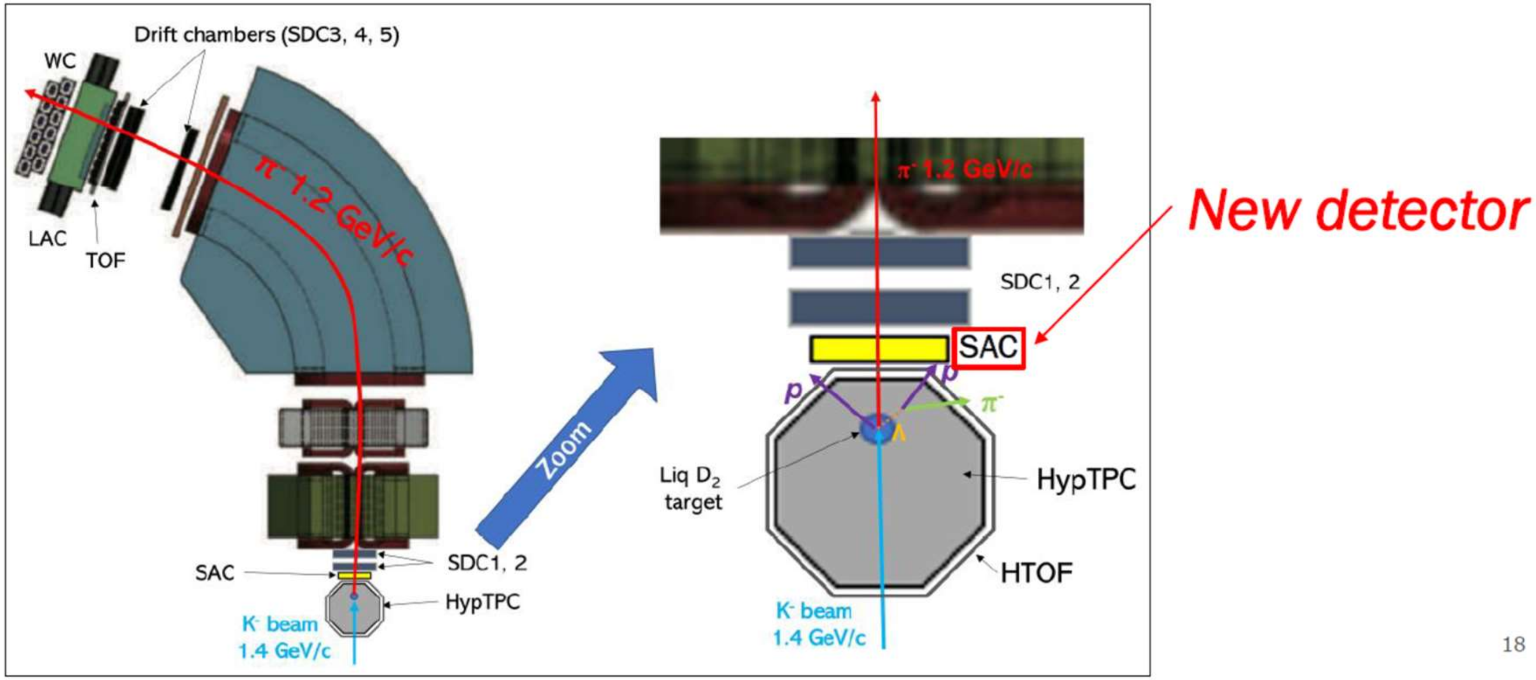
Bound state (deuteron like dibaryon) or not?
Significant difference in the spectrum shape

E90 setup

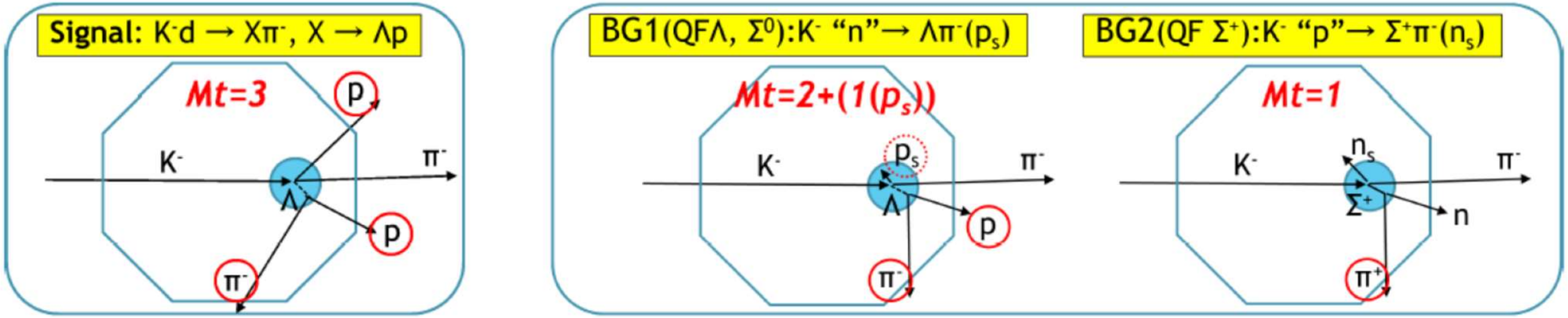
SET UP

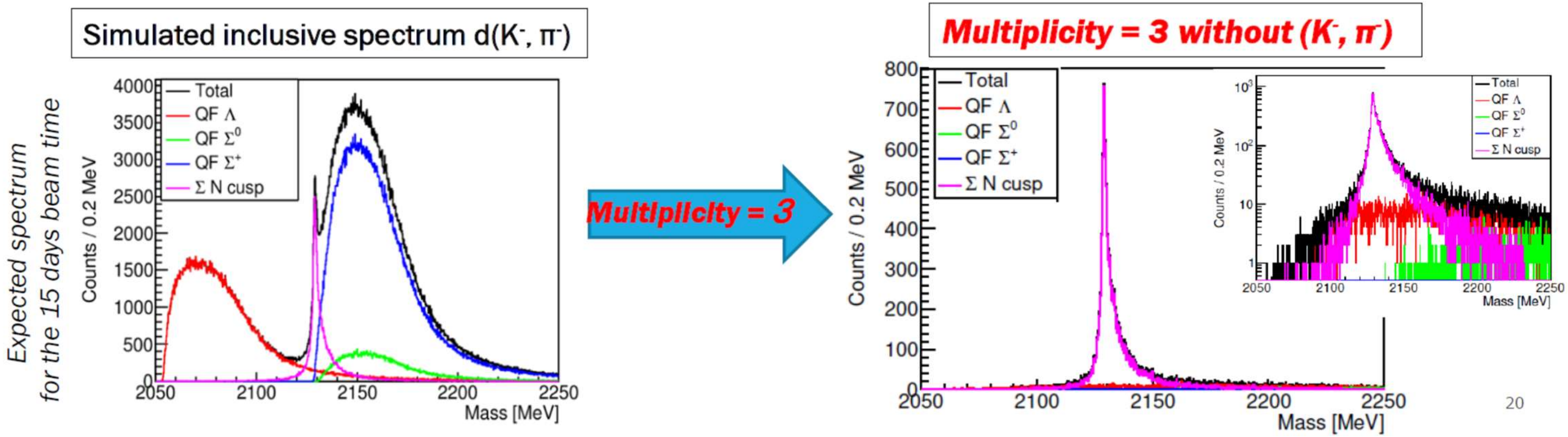
- **Reaction: $K^-d \to \Lambda p \pi^-$ at 1.4 GeV/c**
- **S-2S(developed for E70): π^- measurements → measurement of missing mass spectrum**
  - **Good mass resolution: ΔM ~ 0.4 MeV (σ), (Δp/p(K18)=3.3×10^{-4}(FWHM), Δp/p(S-2S)=6.0×10^{-4}(FWHM))**
- **HypTPC(developed for E42): Final state (Λp) restriction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

Momentum transfer ~ 200 MeV/c

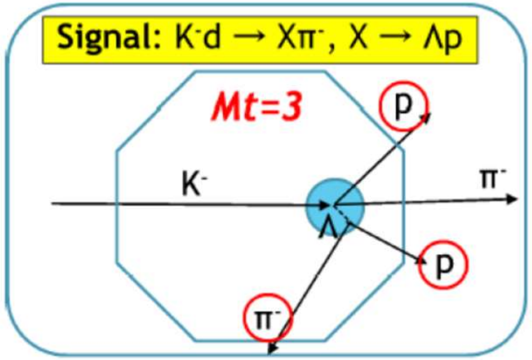


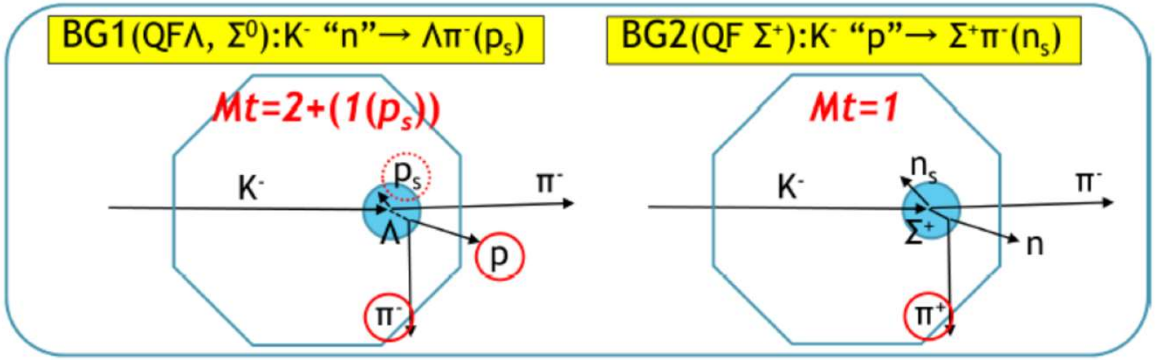
QF BACKGROUND SUPPRESSION BY HYPTPC





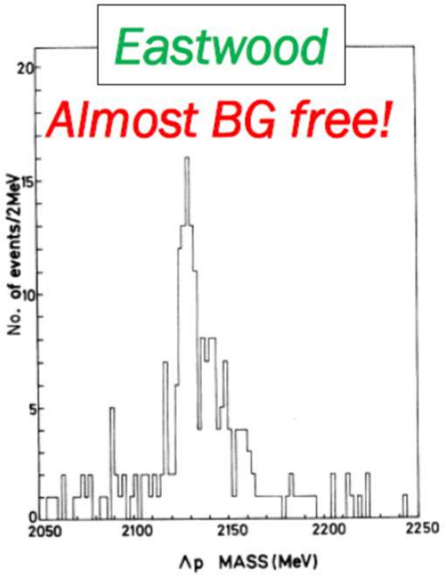
QF BACKGROUND SUPPRESSION BY HYPTPC

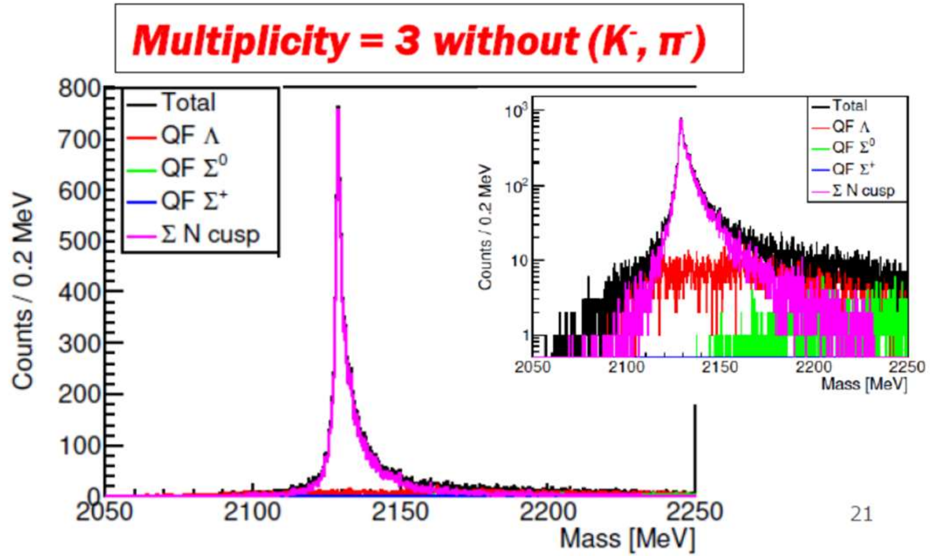




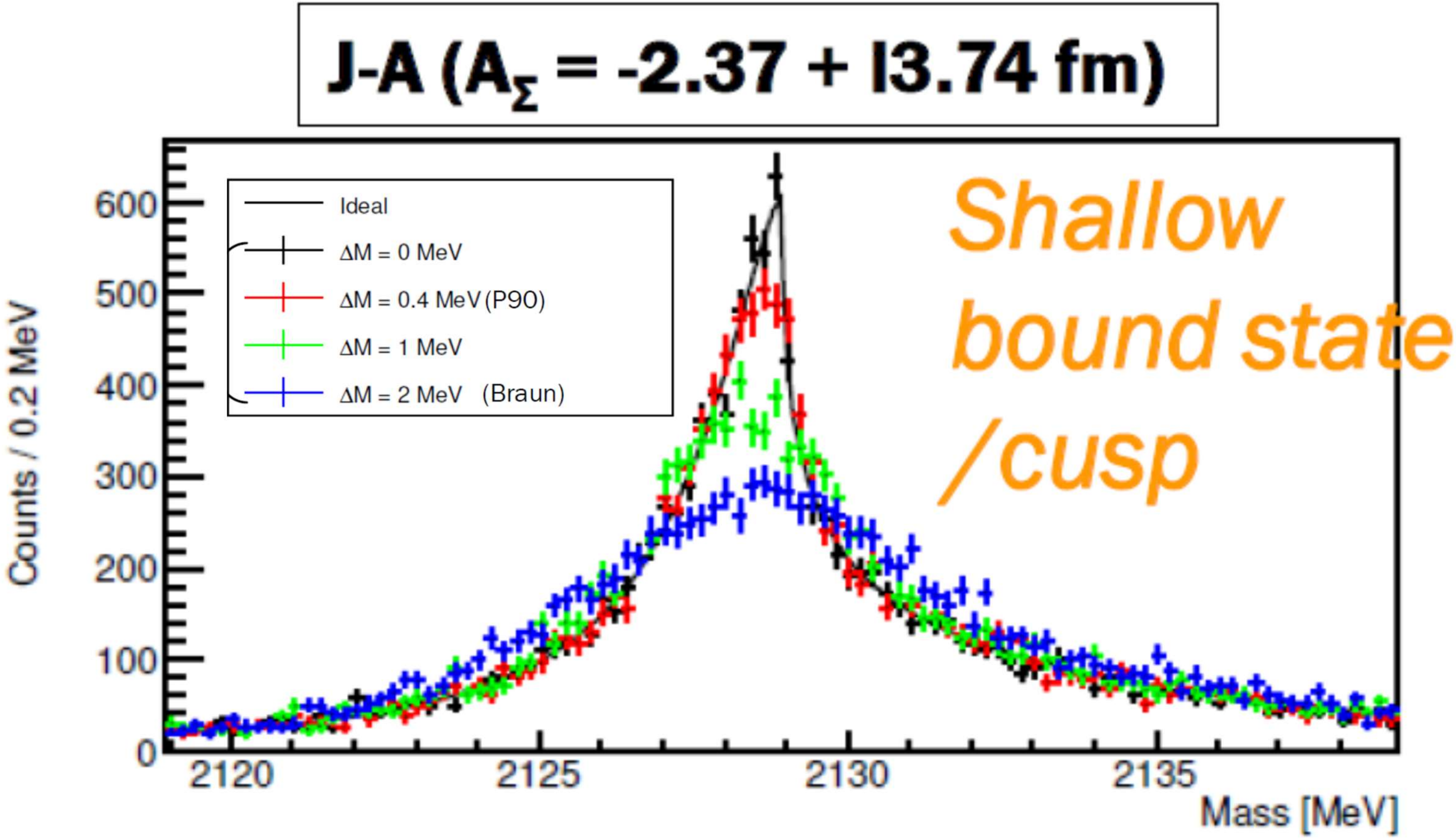
$K^- d \rightarrow \Lambda p \pi^-$
@1.45 and 1.65 GeV/c
(Bubble chamber)

$\cos\theta_{CM} > 0.9$
$p_{proton} > 150$ MeV/c



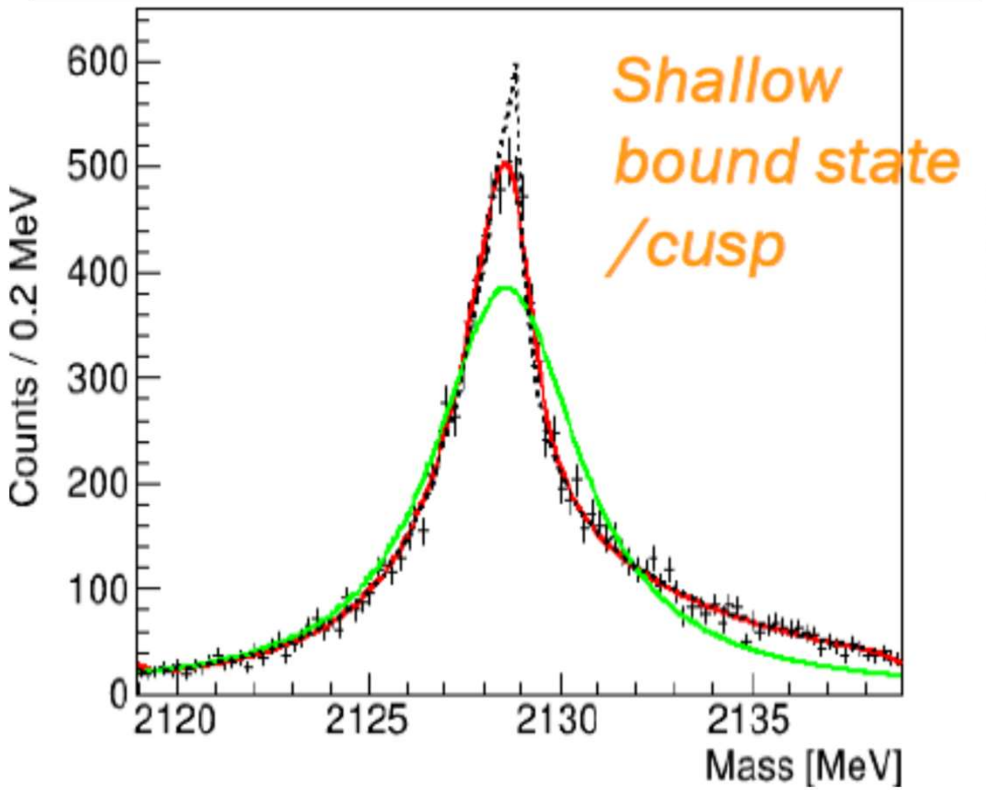


Importance of resolution

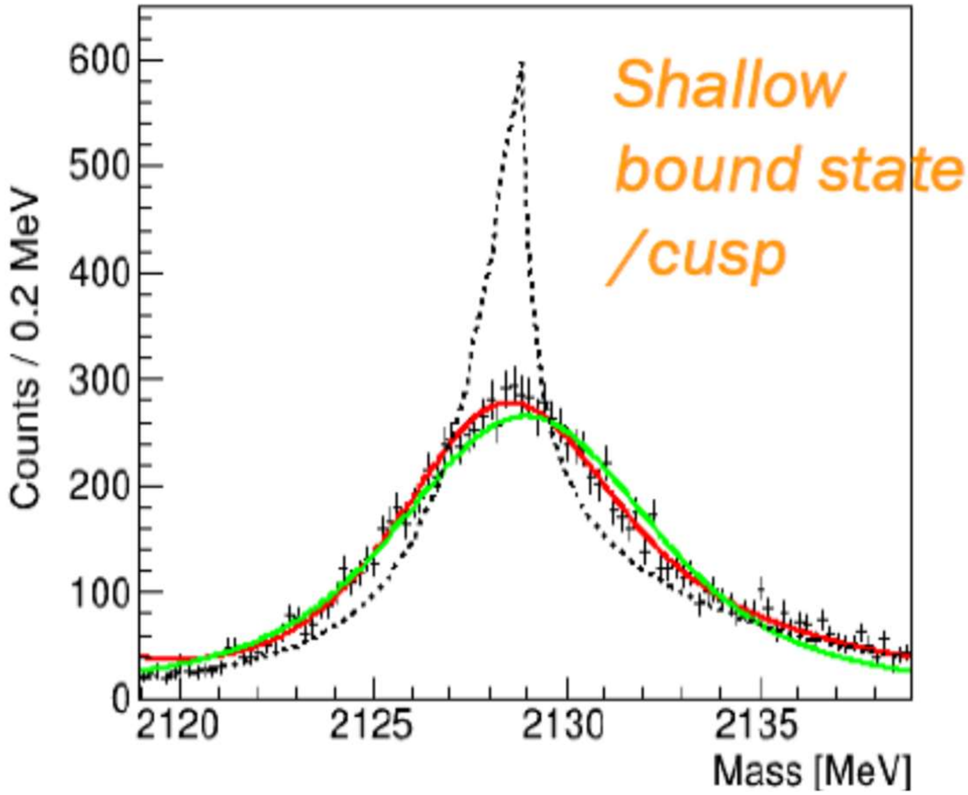


Can identify cusp?

σ＝0.4 MeV



σ＝2 MeV



Possible with σ＝0.4 MeV, but not with 2 MeV

Other possibilities?

- Many
- Any peak near a threshold could be a cusp
  - X(3872), Ξ(1620), Ξ(1690), …
  - We are studying X(3872) case at Belle (II) with treating J/ψππ and D*D channels at the same time.
- At J-PARC
  - E72 can study Λη threshold more precisely in various channels ($K^- p$, $\bar{K}^0$n, $\pi^\pm \Sigma^\mp$, …)
  - $\eta^{(\prime)}$N cusp with π^-p (→ $\eta^{(\prime)}$n) → π^-p elastic scattering as a byproduct of E45
  - Dedicated experiment for $\Lambda\pi - \bar{K}N(I = 1)$ cusp.
  - And More

Summary

- Threshold cusp
  - A peak-like structure at a threshold
  - Shape is (mostly) determined by scattering length
    → A new method to determine scattering length
- In Belle
  - $\Lambda\eta$ cusp is identified in $\Lambda_c \to pK^-\pi^+$
  - Another candidate found in $\Lambda\pi$ at the $\bar{K}N$ threshold
- Plan at J-PARC
  - ΛN-ΣN cusp study for ΣN interaction. Bound state?
- **Many other possibilities!!**
  - Any near-threshold peaks could be threshold cusps