Result of pentaquark search experiment at J-PARC

M. Moritsu

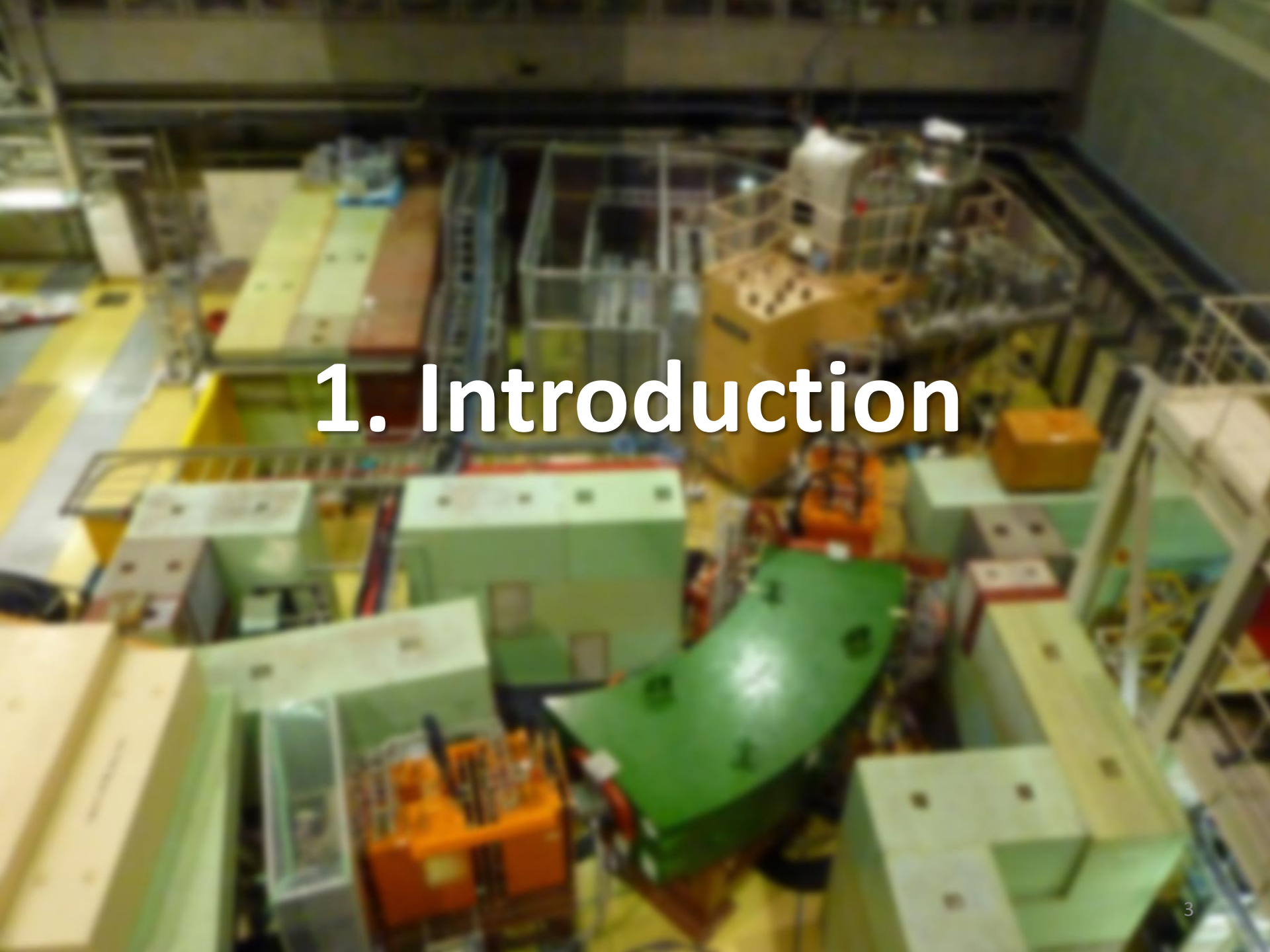
(RCNP, Osaka University)

for the J-PARC E19 collaboration

Hadron Square 11th @ Nagoya Univ., 2014/03/12

Contents

1. Introduction
2. J-PARC E19 experiment
3. Analysis and Result
4. Discussion on Θ^+ decay width
5. Summary

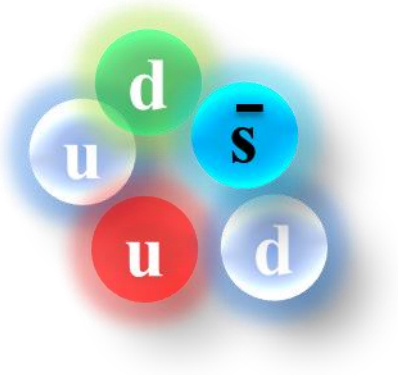


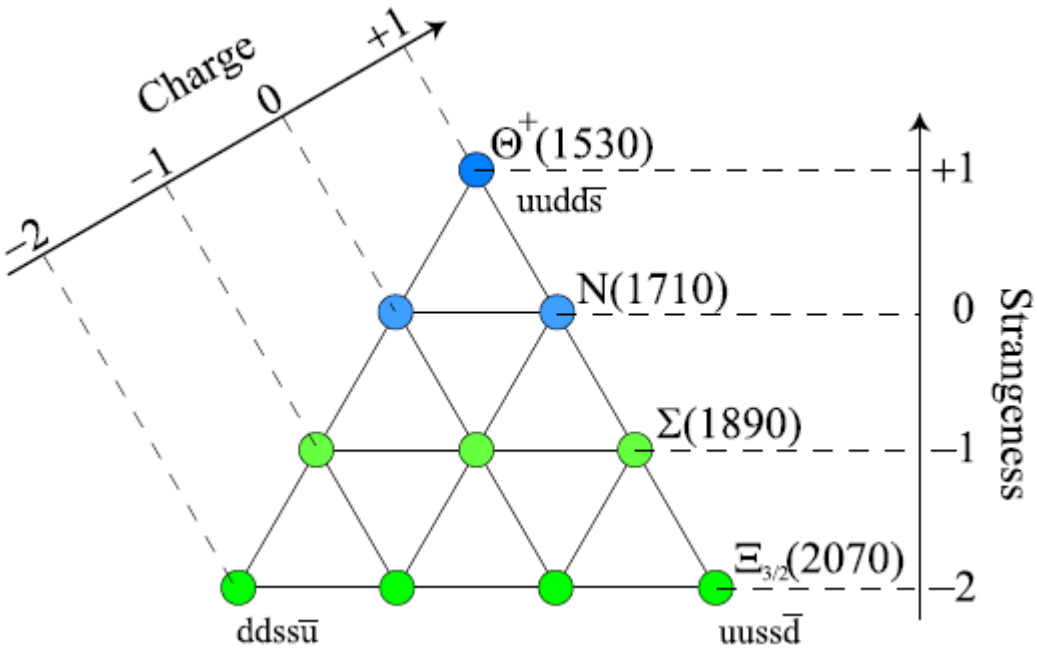
1. Introduction

Pentaquark

Pentaquark Θ^+

- **Genuine exotic hadron (*uudds^{bar}*)**
- **M = ~1540 MeV/c^2 (decay Θ^+ → KN)**





- **Θ^+ pentaquark was first predicted by Diakonov, Petrov and Polyakov in 1997.**
- **Θ^+ appears as one of antidecuplet members calculated by chiral soliton model.**
- **They said Θ^+ could have narrow width less than 15 MeV.**

✓ **Its narrow width is a key !!**

Diakonov et al., Z. Phys. A 359, 305 (1997).

Primary motivation

Frank Wilczek said

"a discovery of exotic pentaquarks was unlikely to require introducing new interactions of modifying QCD as basic theory of the strong interaction.

However, such measurements would offer us a golden opportunity to sharpen and expand our understanding of **QCD itself**."

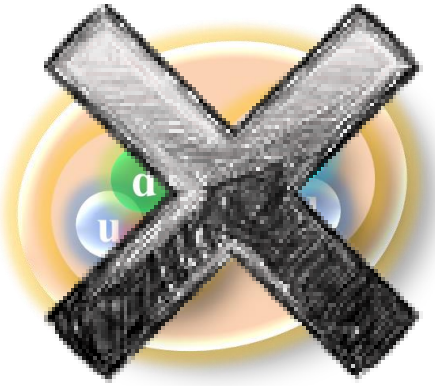
R. Jaffe and F. Wilczek, Eur. Phys. J. C 33, s38 (2004).

Physics motivation

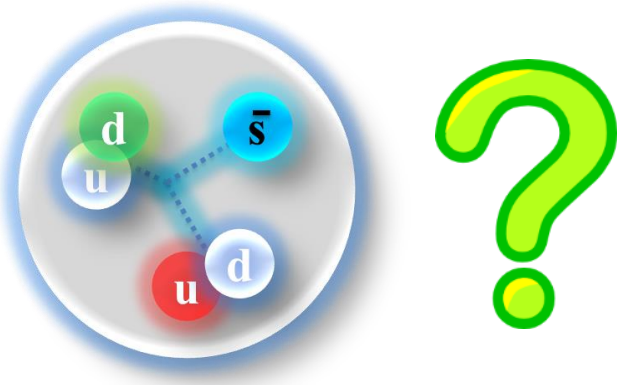
- **Distinctive feature of Θ^+ pentaquark**

Narrow Width **(< a few MeV)**

  - **Need some mechanism to suppress decay.**



Meson-Baryon molecule

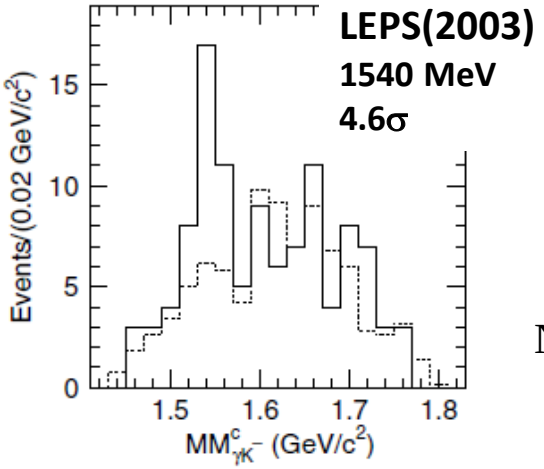


Diquark structure
(Need quark rearrangement for KN decay)
R.Jaffe, F.Wilczek (2003)

Useful tool to understand low energy QCD dynamics !!

Experimental search

- **SPring8/LEPS group reported the first evidence for Θ^+ in 2003.**

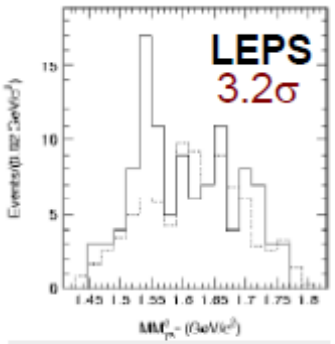


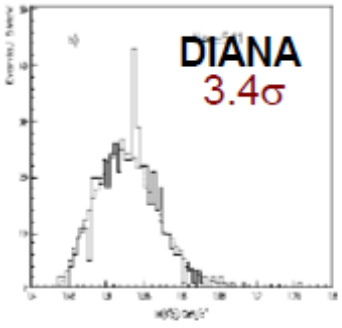
γ "n" $\rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$

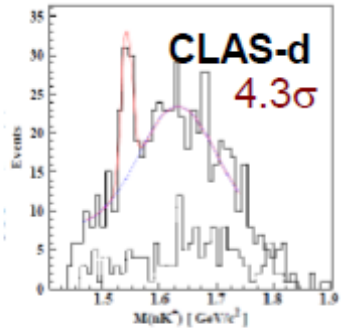
Nakano et al., PRL 91, 012002 (2003).

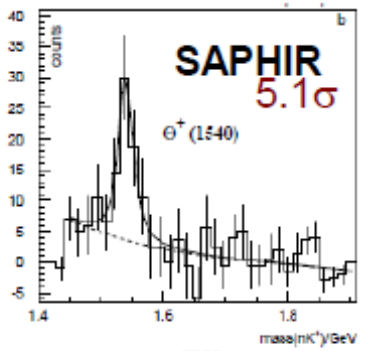
Experimental search

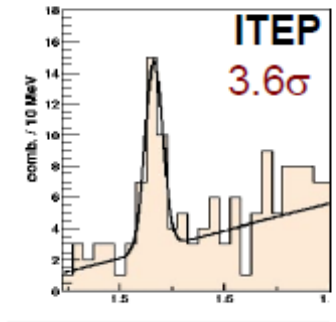
- SPring8/LEPS group reported the first evidence for Θ^+ in 2003.
- Dozen experimental groups published supporting evidence for the Θ^+.

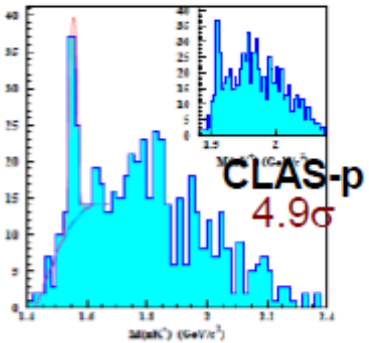


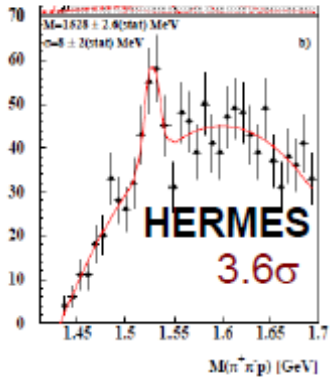


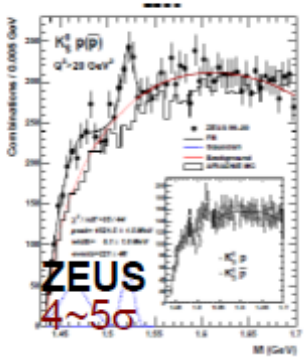


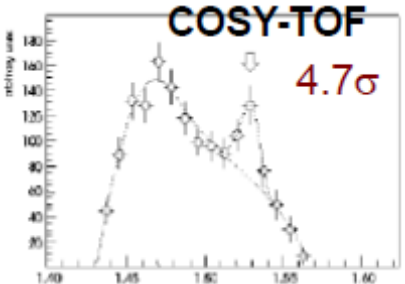


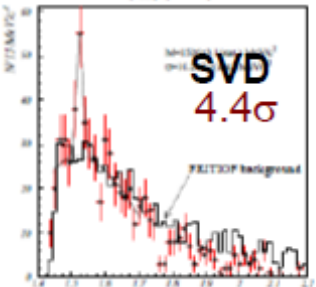








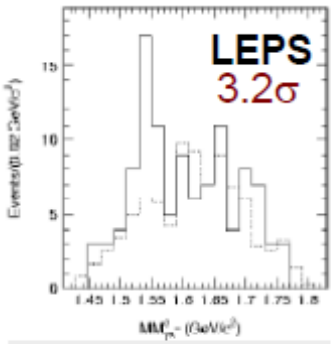


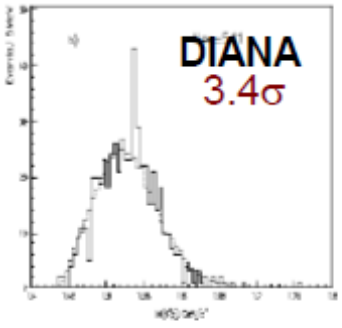


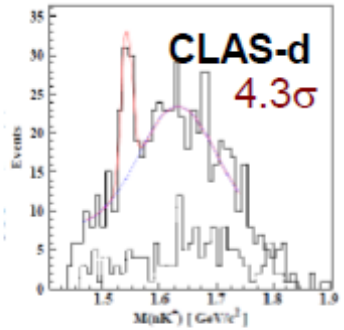
[CAUTION]
Significances ware recalculated by
significance = S/√(S+B) or S/dS

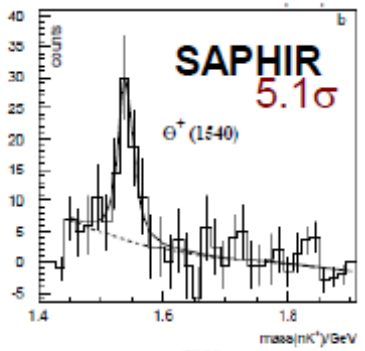
Experimental search

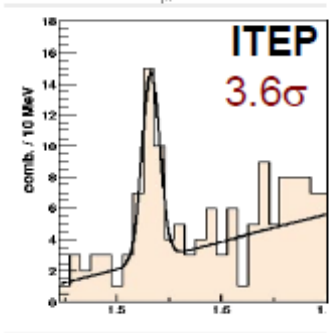
- SPring8/LEPS group reported the first evidence for Θ^+ in 2003.
- Dozen experimental groups published supporting evidence for the Θ^+.
- ded out.

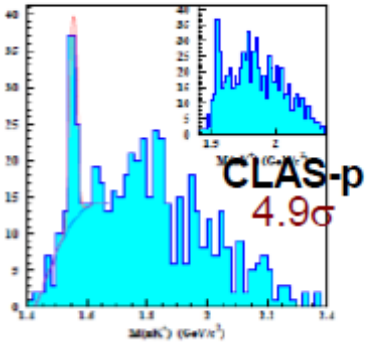


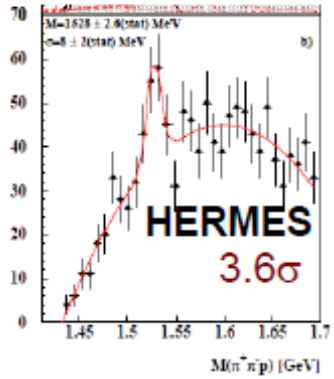


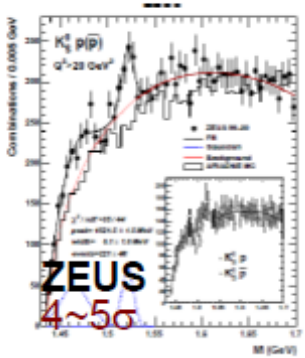


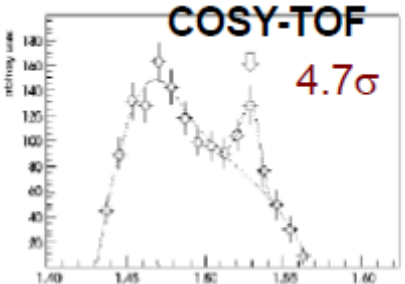


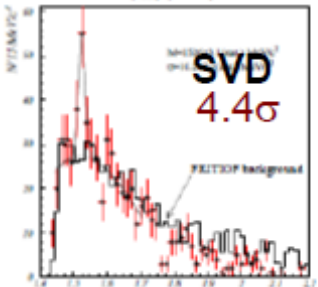












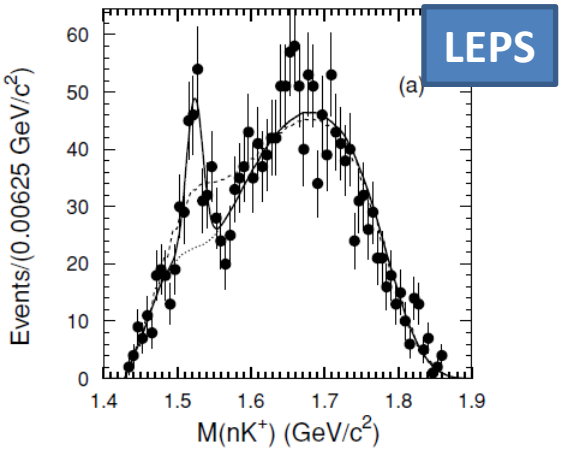
[CAUTION]
Significances ware recalculated by
significance = S/√(S+B) or S/dS

2
4

Experimental search

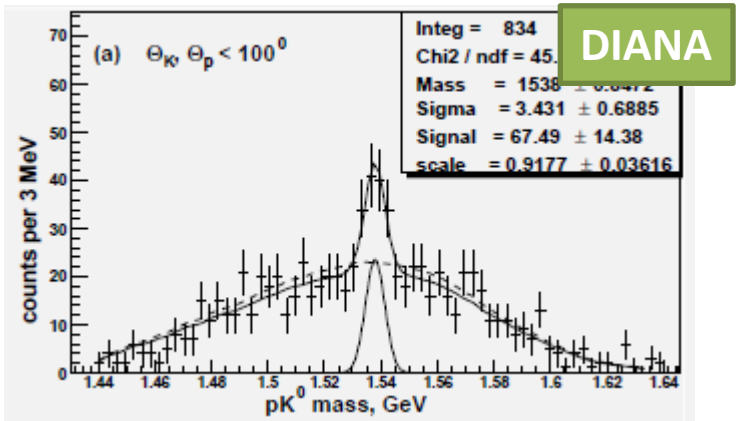
- **SPring8/LEPS group reported the first evidence for Θ⁺ in 2003.**
- **Dozen experimental groups published supporting evidence for the Θ⁺.**
- **Some reconfirmed their evidence, but many others disappeared or faded out.**

LEPS Collaboration,
PRL 91, 012002 (2003),
PRC 79, 025210 (2009), ... next ?



- $\gamma d \rightarrow K^- K^+ pn$
- 5.1 σ
- M = 1524 ± 2 + 3 GeV

DIANA Collaboration,
Phys. Atom. Nucl. 66, 1715 (2003),
70, 35 (2007), 73, 1168 (2010), arXiv:1307.1653

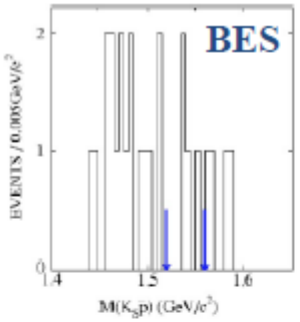


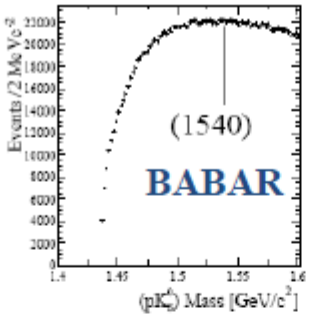
- $K^+ Xe \rightarrow K^0 pXe'$
- 6.3 σ
- M = 1538 ± 2 MeV
- Γ = 0.36 ± 0.11 MeV

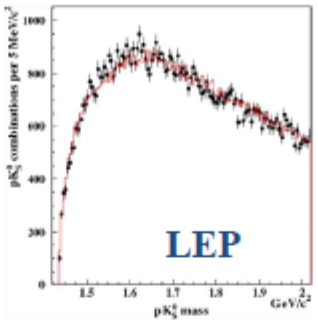
$$\Gamma_{\Theta^+} = \frac{N_{\Theta^+}}{N^{\mathrm{ch}}} \frac{\sigma^{\mathrm{ch}}}{107\ \mathrm{mb}\, B_i\, B_f} \Delta m,$$

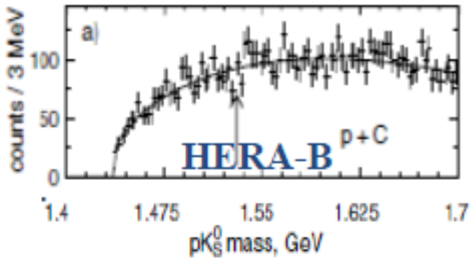
Experimental search

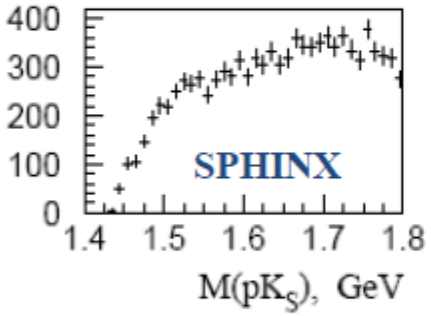
- **There are also many non-observation experiment. It is noted that some of them may have no sensitivity, because of Θ^+ production mechanism or kinematics.**

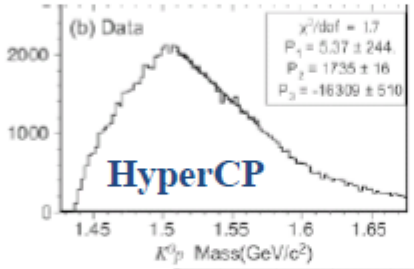


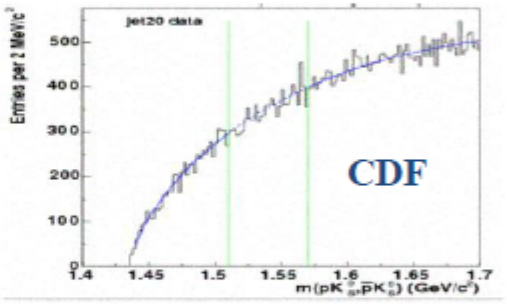


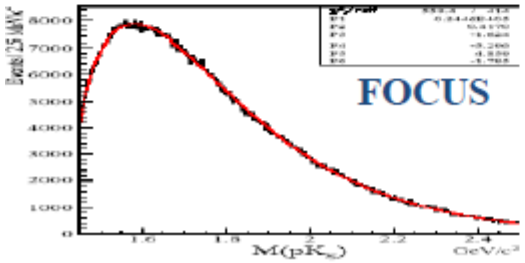


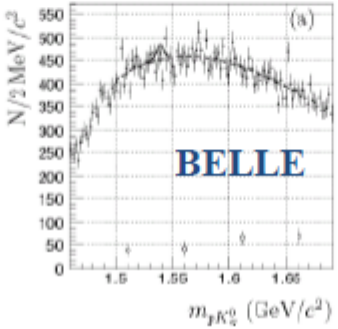


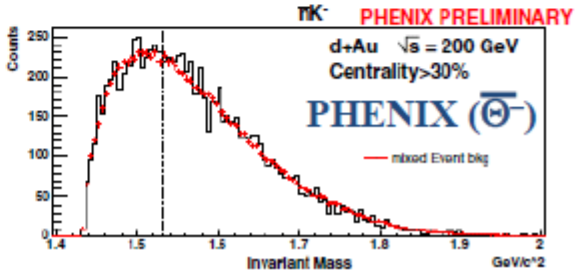








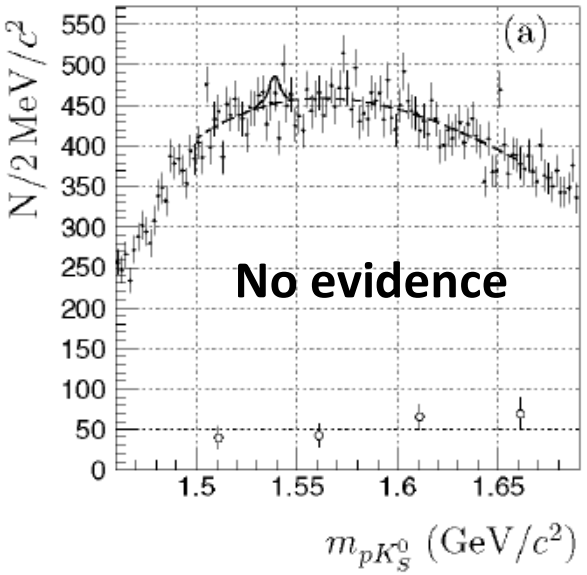




Experimental search

R. Mizuk et al. (Belle Collaboration), Phys. Lett. B 632, 173 (2006).

- Kaon secondary interactions in detector material. $K^+n \to \Theta(1540)^+ \to pK^0_S$

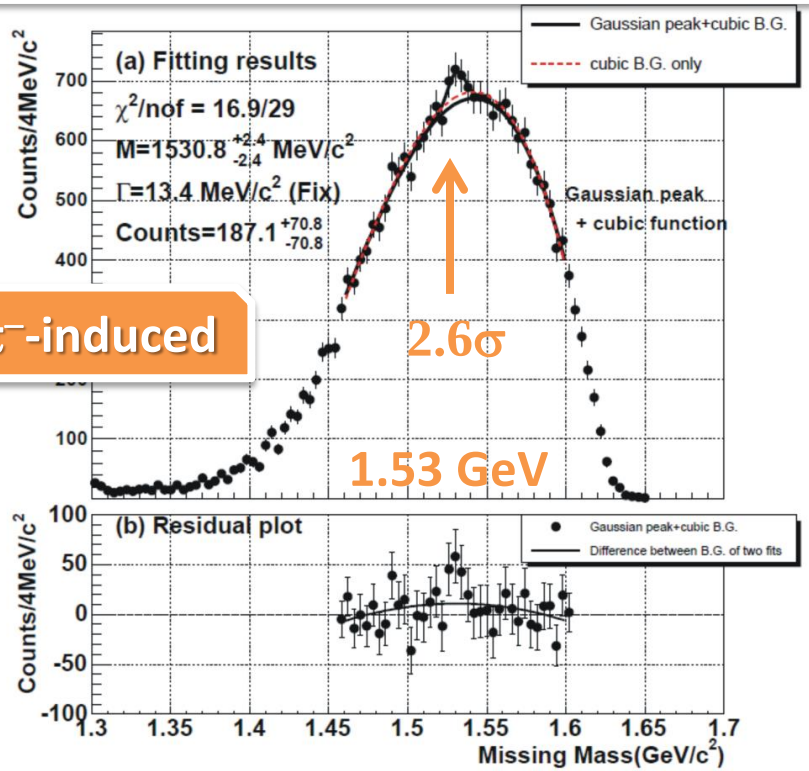


$$\frac{\sigma(KN \to \Theta(1540)^+ X)}{\sigma(\bar{K}N \to \Lambda(1520)X)} < 2.5\% \text{ at the 90\% C.L.}$$

$$\Gamma\left(K^+n \to \Theta(1540)^+ \to pK^0_S\right) < 0.64 \text{ MeV at the 90\% C.L.}$$

Previous experiments at KEK-PS

E522 : π^- p → K^- Θ^+ @ 1.92 GeV/c

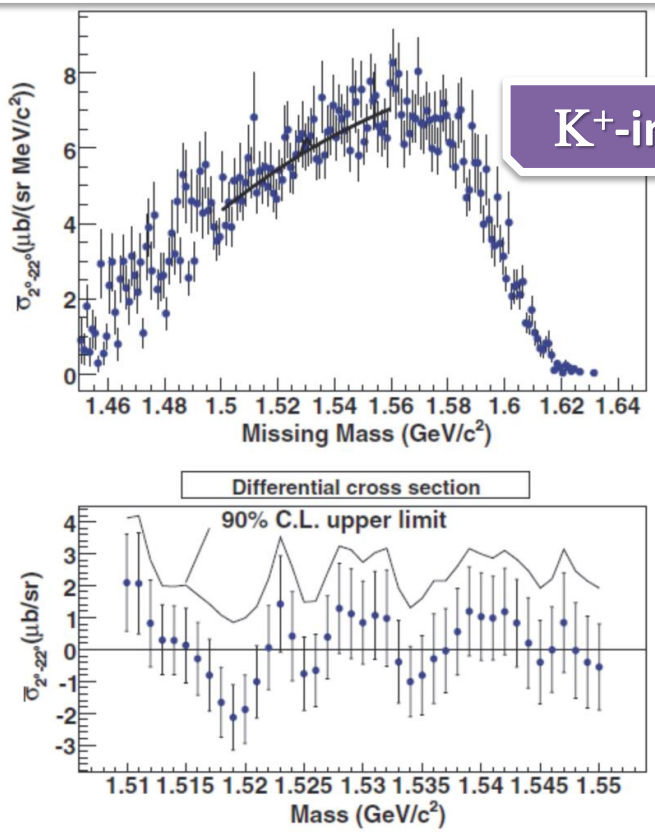


π^--induced

K. Miwa *et al.*, PLB 635, 72 (2006).

- Bump structure (2.6σ)
  - ➔ Not enough to claim the existence
- Upper limit: σ < 3.9 μb (90% C.L.)

E559 : $K^+p \rightarrow \pi^+ \Theta^+$ @ 1.20 GeV/c



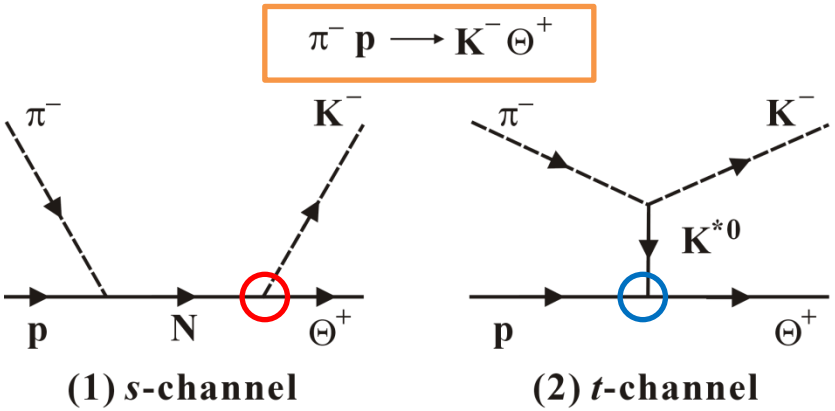
K^+-induced

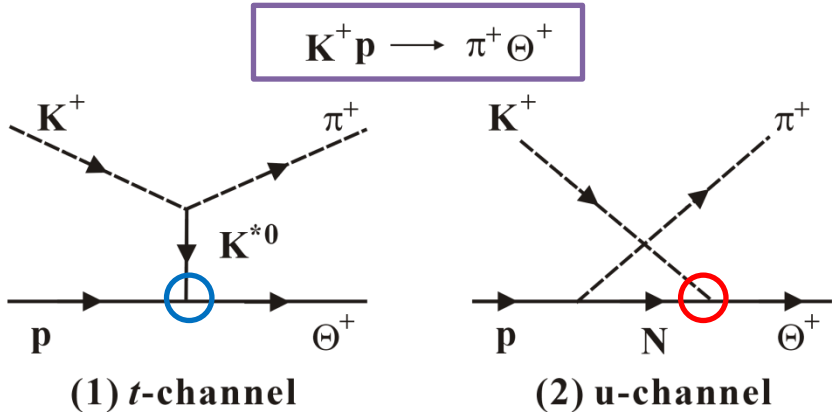
K. Miwa *et al.*, PRC 77, 045203 (2008).

- No peak structure
- Upper limit: σ < 3.5 μb/sr (90% C.L.)

Hadronic production

Diagrams for calculation





Unknown coupling constants

$g_{KN\Theta}$ & $g_{K^*N\Theta}$

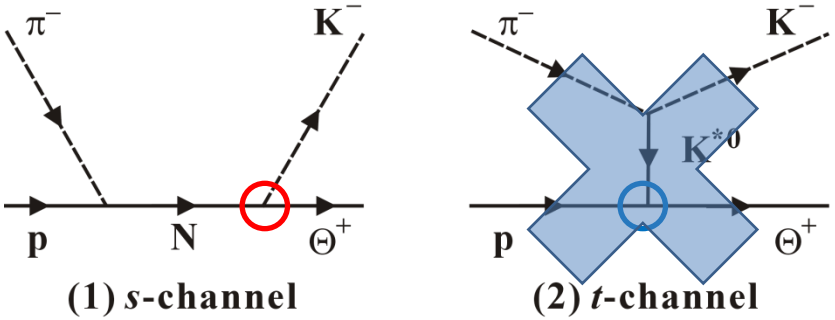
⇒**No experimental information**

⇒**Parameters in calculation**

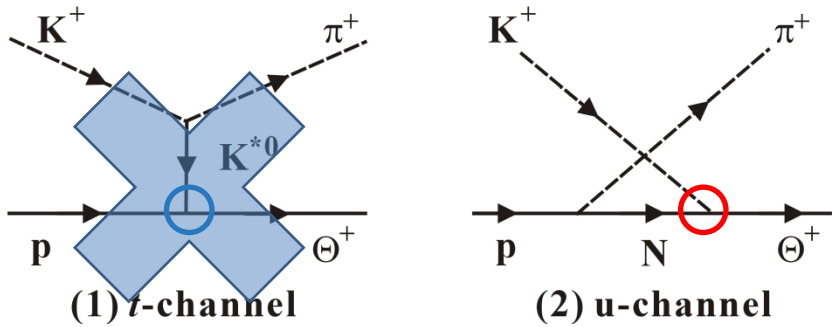
Hadronic prod

Diagrams for calculation

$\pi^- p \longrightarrow K^- \Theta^+$

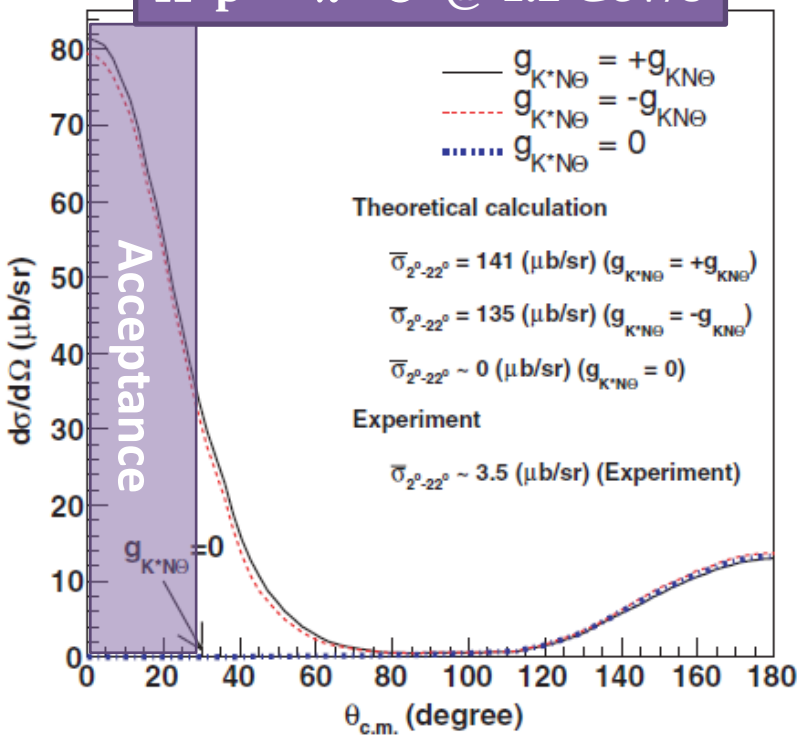


$K^+ p \longrightarrow \pi^+ \Theta^+$



Backward peak

Differential cross section
$K^+ p \rightarrow \pi^+ \Theta^+$ @ 1.2 GeV/c



Oh *et al.* PRD 69, 074016 (2004)

✓ $K^+ p \rightarrow \pi^+ \Theta^+$: $\sigma < 3.5$ μb/sr

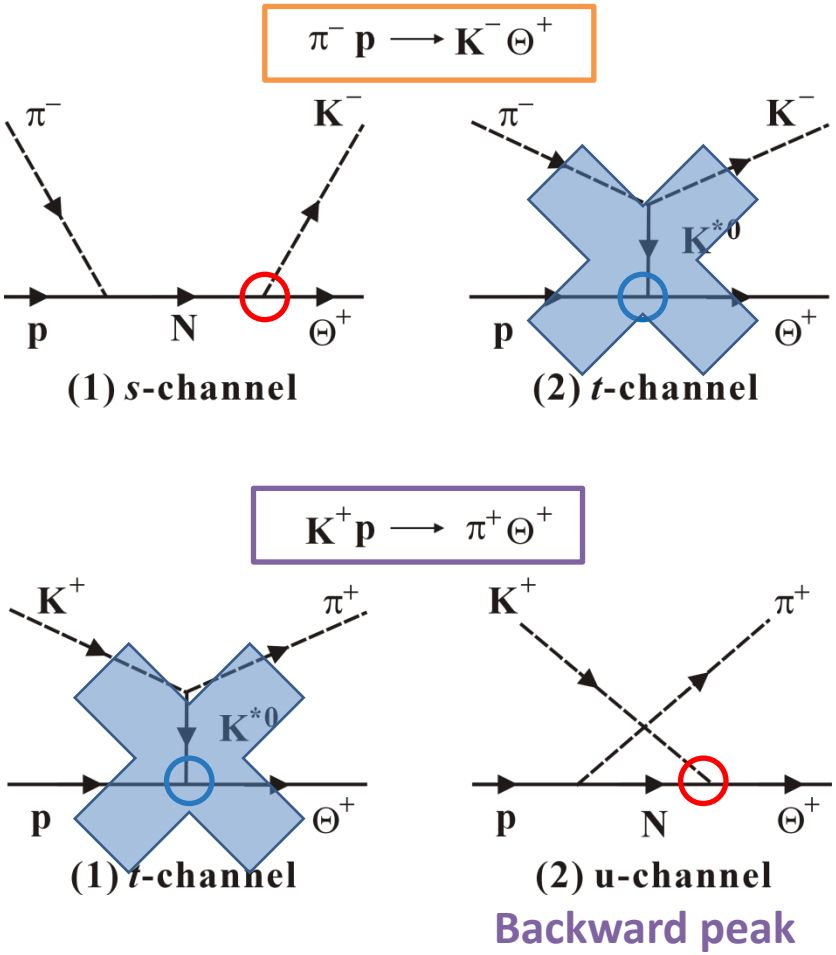
– Low backward sensitivity

➔ small K* coupling:

$g_{K^*N\Theta} \sim 0$

Hadronic production

Diagrams for calculation



✓ $\pi^- p \rightarrow K^- \Theta^+ : \sigma < 3.9\ \mu b$

– s-channel dominance

➔ $g_{KN\Theta}$ is also small.

– $\Gamma_\Theta \propto g^2_{KN\Theta}$

➔ Very narrow width

2. J-PARC E19 experiment

Our Approach (J-PARC E19)

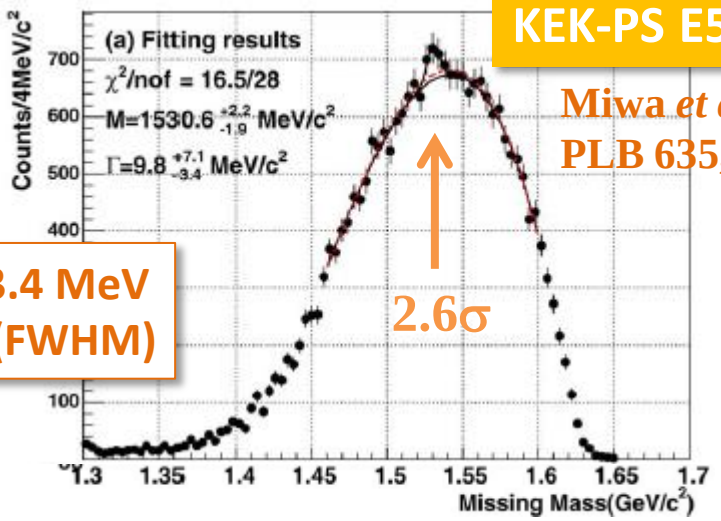
1. **Pion induced reaction** $\pi^- + p \rightarrow K^- + \Theta^+$
   - Complementary to photo-production (LEPS/CLAS).
   - Expect sizable production cross section. => High statistics

2. **High resolution missing ma**
   - K1.8 beam line & SKS : $\Delta M =$

Previous experiment

KEK-PS E522

Miwa *et al.*, PLB 635, 72.



ΔM ~ 13.4 MeV (FWHM)

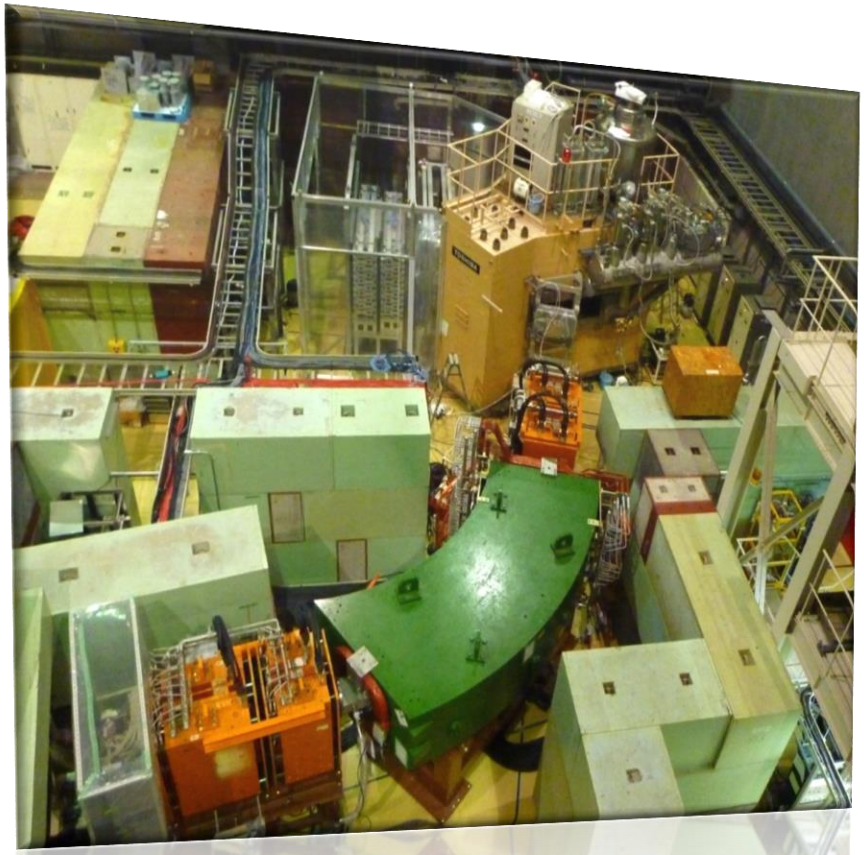
Our Approach (J-PARC E19)

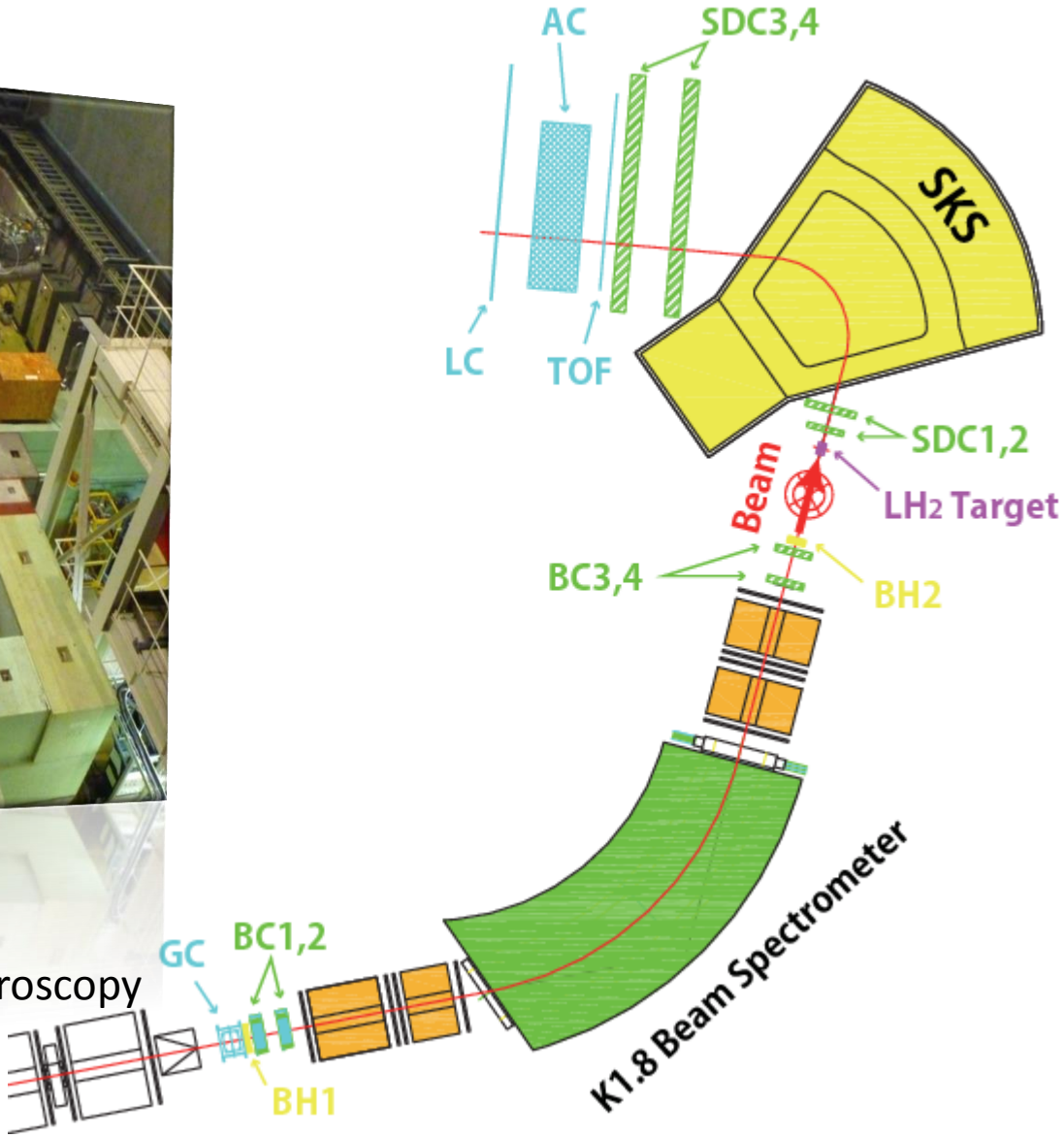
1. **Pion induced reaction** $\pi^- + p \rightarrow K^- + \Theta^+$
   - Complementary to photo-production (LEPS/CLAS).
   - Expect sizable production cross section. => High statistics

2. **High resolution missing mass spectroscopy**
   - K1.8 beam line & SKS : ΔM = 2 MeV (FWHM)

Conclusive result by higher sensitivity !!

Experimental setup





J-PARC K1.8

Dedicated to the (π,K) reaction spectroscopy

π^- beam
1.92/2.00 GeV/c

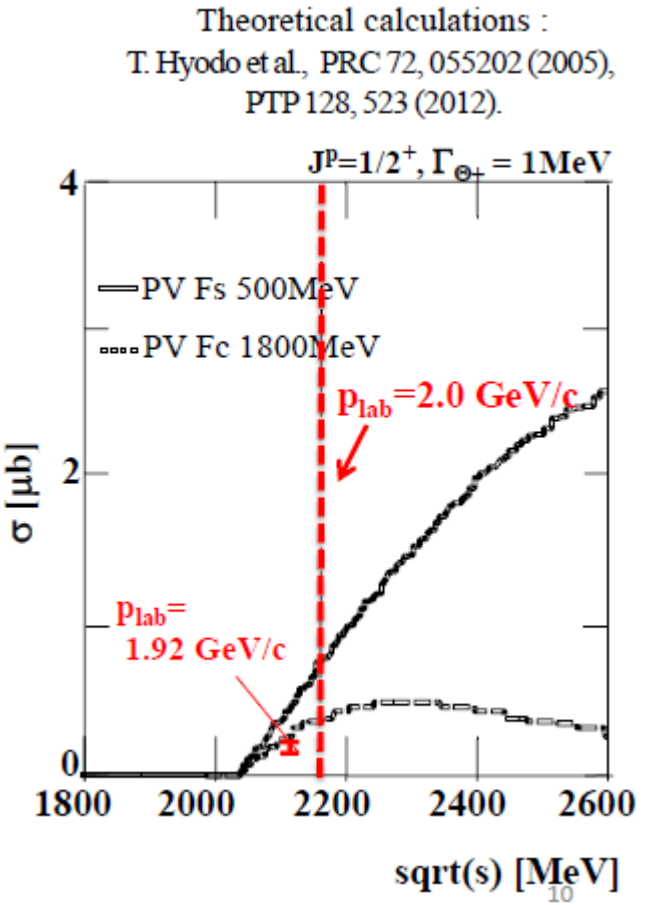
History of E19

	Comment	Beam Momentum	Beam intensity	π's on Target
2009/10 ~	K1.8 beam line & detector commissioning start			
2010/10-11 1st RUN	**examine the 2.6σ bump structure observed in E522**	**1.92 GeV/c**	**1.0 M /spill**	**7.8 x 10^{10}**
2012/02 2nd RUN	**new data at the highest beam momentum at K1.8**	**2.00 GeV/c**	**1.7 M /spill**	**8.1 x 10^{10}**

We reconstructed the setup between 1st and 2nd run because of the earthquake. 2 Setups are a little different.

History of E19

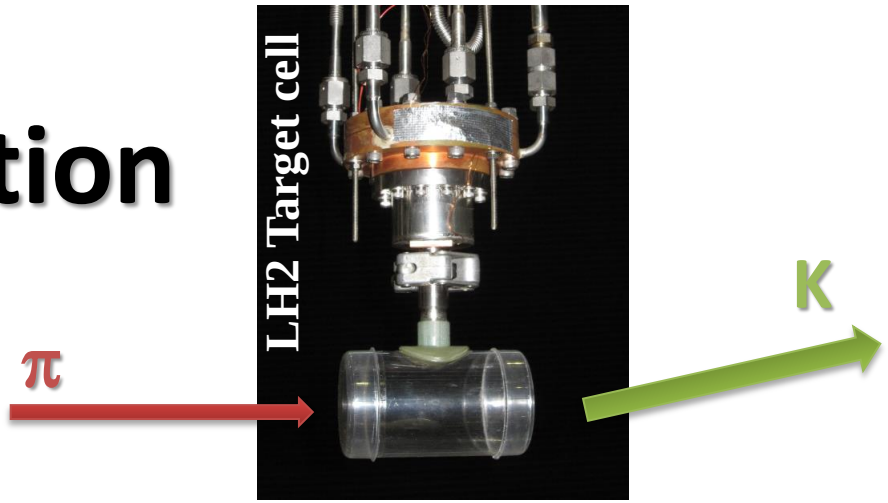
	Comment	Beam Mome
2009/10 ~	K1.8 beam line & detector commissioning start	
2010/10-11 1st RUN	**examine the 2.6σ bump structure observed in E522**	**1.92 GeV/**
2012/02 2nd RUN	**new data at the highest beam momentum at K1.8**	**2.00 GeV/**



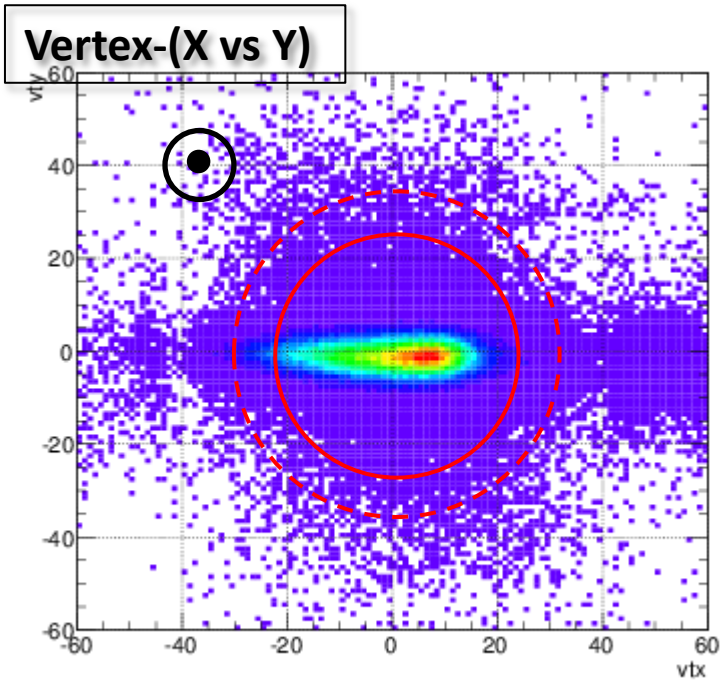
We reconstructed the setup between 1st and 2nd run because of the earthquake. 2 Setups are a little different.

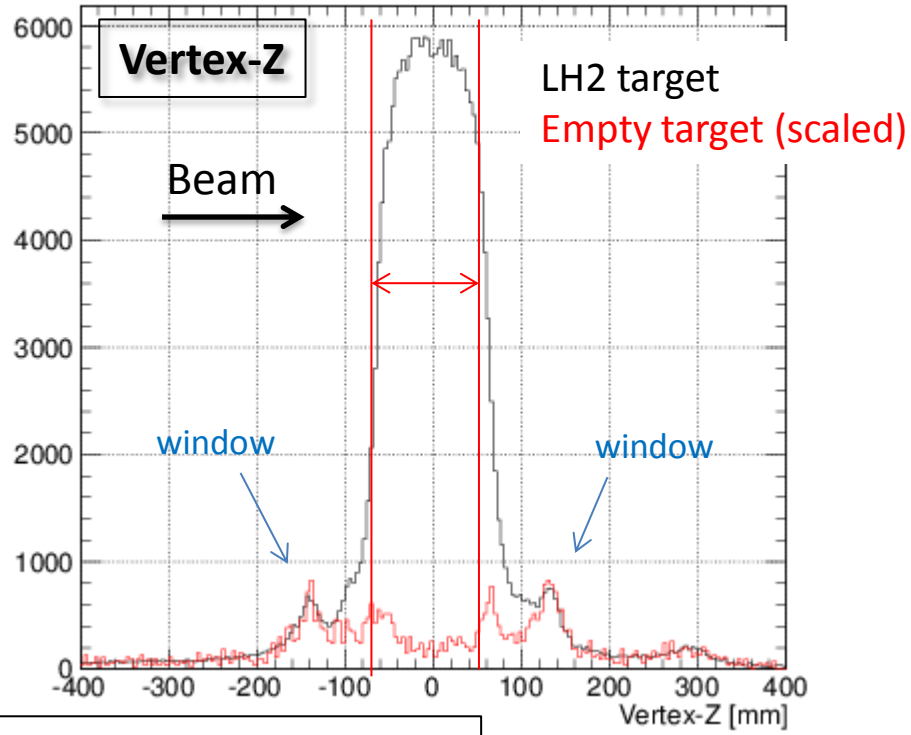
3. Analysis and Result

Vertex Reconstruction



$\phi 67.8 \times 120$ mm





Vertex cut efficiency : 84.8 %
Contamination from other materials : < 2.9 %

Calibration processes

1. $\pi^{\pm} + p \rightarrow K^{+} + \Sigma^{\pm}$
2. Beam-through runs

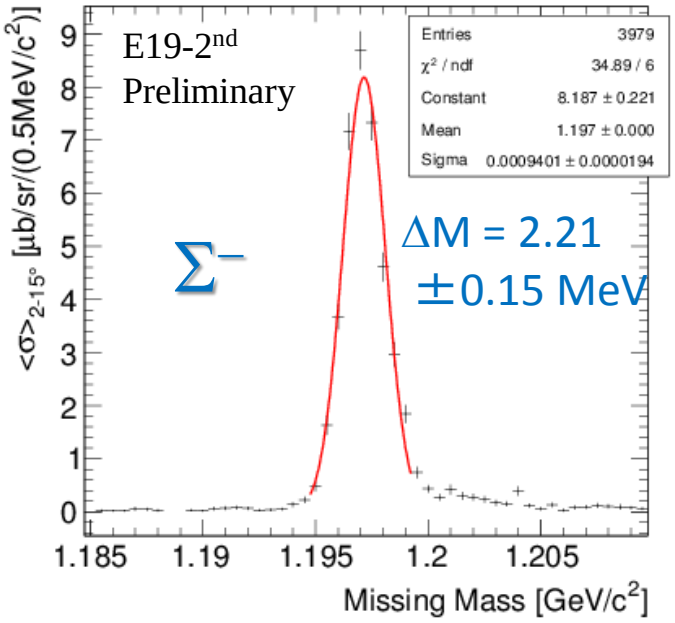
- **Estimated missing mass resolution:**

$\Delta M_{\Theta} = 2.13 \pm 0.15$ MeV (FWHM)

- **Absolute mass scale uncertainty :**

± 1.4 MeV for Θ^{+} region

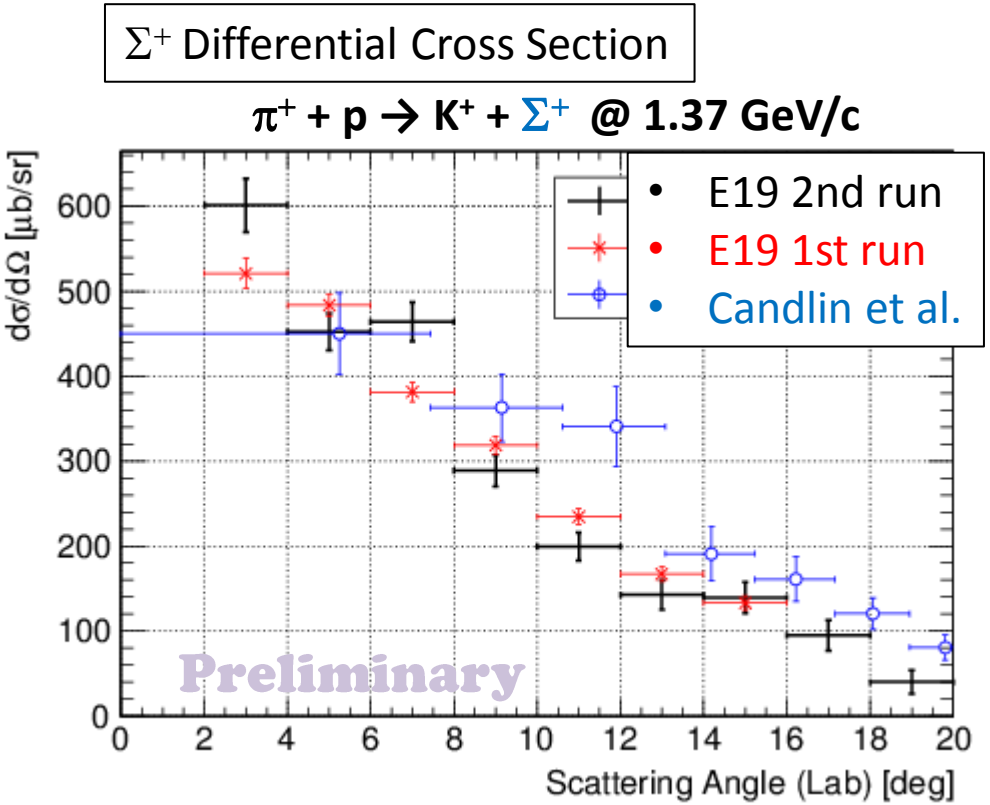
$\pi^{-} + p \rightarrow K^{+} + \Sigma^{-}$ @ 1.45 GeV/c



If we would observe Θ^{+}, the peak should be very sharp with good mass precision.

Consistency check with previous exp.

- ✓ $\pi^+ + p \rightarrow K^+ + \Sigma^+$ @ 1.37 GeV/c
- ✓ Differential cross section
  - Consistent with each other.
  - Good understanding of efficiencies and acceptance.

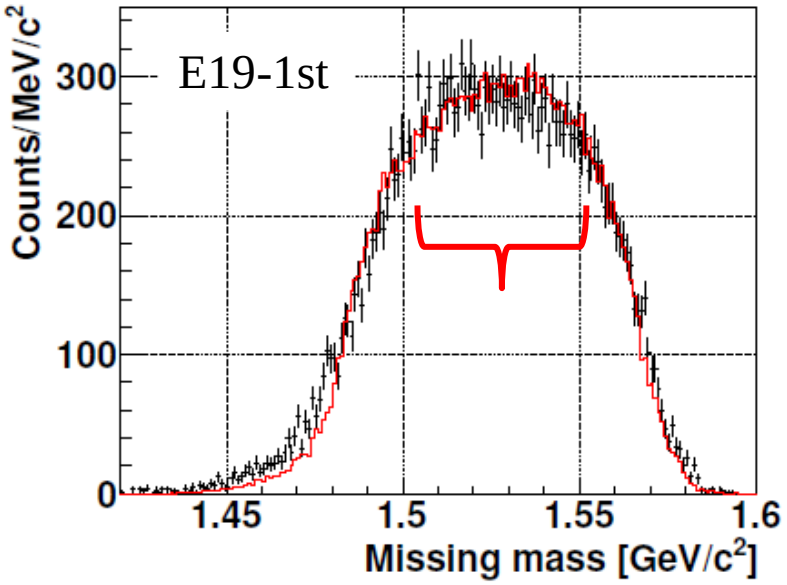


Consistency Check → OK

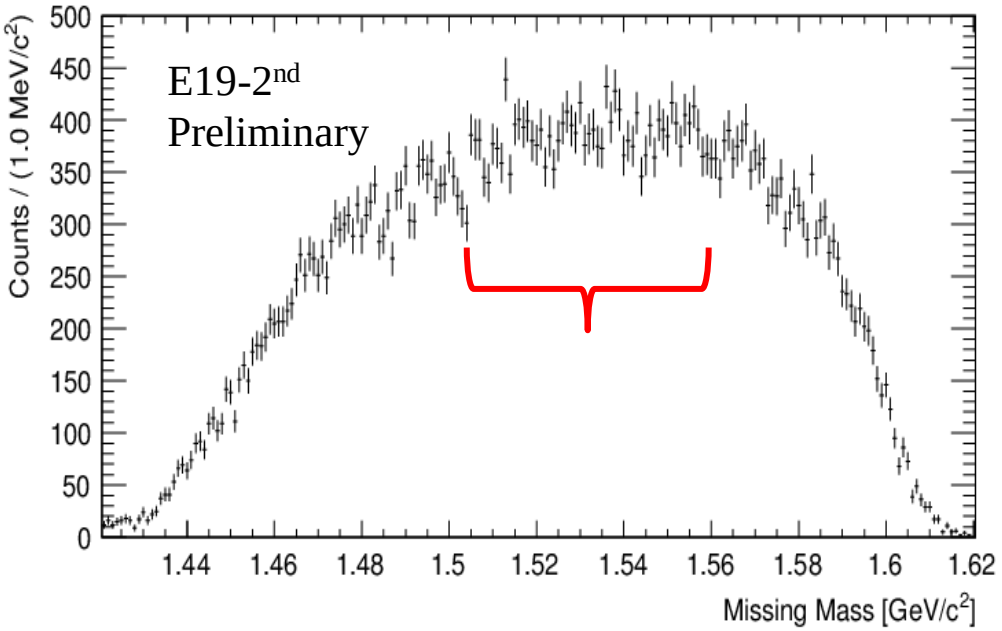
Result

$\pi^- + p \rightarrow K^- + X$

p_π = 1.92 GeV/c



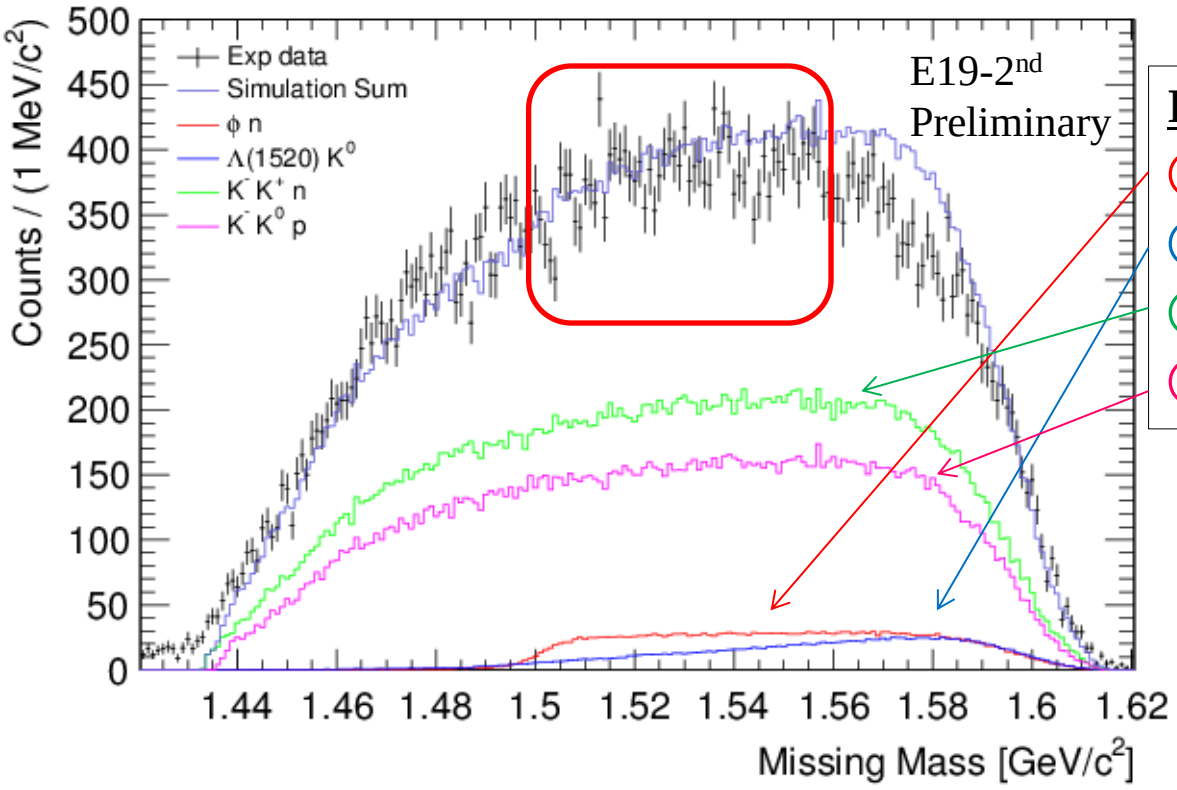
p_π = 2.01 GeV/c



Shirotori et al., PRL 109, 132002 (2012).

- **Missing mass of (π,K) @ scattering angle: 2—15 deg (Lab)**
- **No peak structure was observed.**
- **2nd run has wider acceptance than 1st run.**

Comparison with BG simulation



BG processes

① $\pi^- p \rightarrow \phi n \rightarrow K^- K^+ n$

② $\pi^- p \rightarrow \Lambda(1520) K^0 \rightarrow K^- K^0 p$

③ $\pi^- p \rightarrow K^- K^+ n$ (nonresonant)

④ $\pi^- p \rightarrow K^- K^0 p$ (nonresonant)

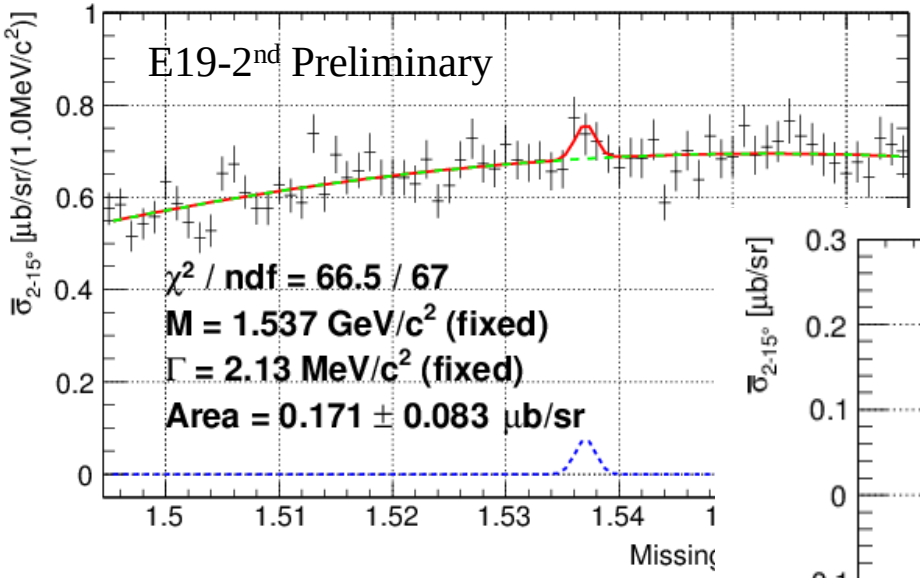
Cross sections and angular distributions of ①② are referred from precedent exp.
Scale of ③④ was normalized to exp. data.

O.I. Dahl et al., PR 163, 1377 (1967)
H. Courant et al., PRD 16, 1 (1977)

- **Data can be reproduced by BG simulation.**
- **BG distribution has no structure in Θ^+ sensitive region: 1.50—1.56 GeV.**

Upper limit for Θ^+ production cross section

An example of fitting result

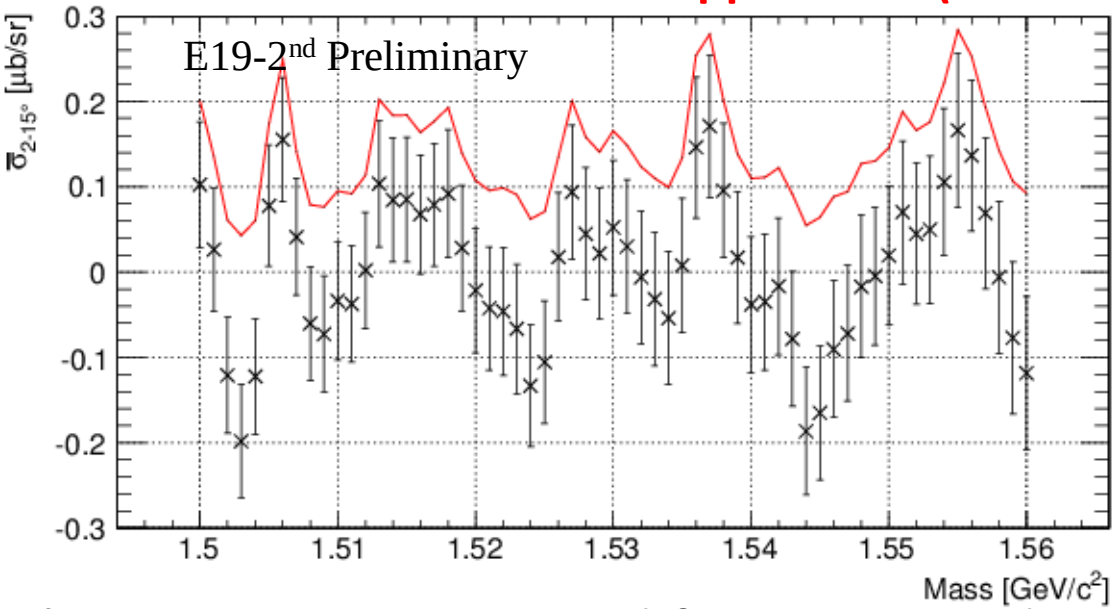


Signal: Gaussian with fixed experimental width.

B.G.: 2nd order polynomial

Fitting results of each mass

Upper Limit (90%C.L.)



☐ Upper limit for differential cross section averaged from 2 to 15 deg:

< 0.28 μb/sr @ 1.50 – 1.56 GeV/c²

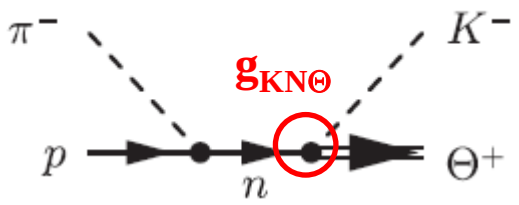
✓ **This limit is an order of magnitude smaller than that of KEK-E522.**

4. Discussion on Θ^+ decay width

Theoretical calculation of meson-induced Θ^+ production

T. Hyodo et al., PTP 128, 523 (2012).

- **Effective Lagrangian approach**
- **Less ambiguous than photoproduction**



$\Gamma_\Theta \propto g^2_{KN\Theta} \propto \sigma$

✓ **Theoretical uncertainty**

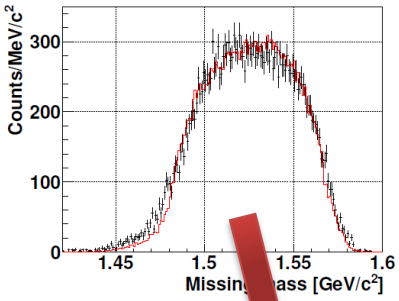
- Coupling scheme: PS/PV
- Form factor: static/covariant
- Form factor cutoff value was determined by hyperon prod.
- Θ^+ mass dependence was considered; 1.510—1.550 GeV

There are some ambiguity,

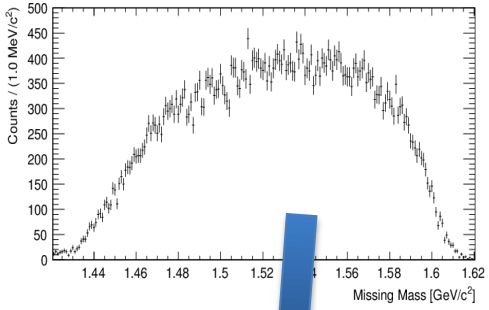
But we took all variations into account and adopted the "most conservative" case. This is confident for "upper limit estimation".

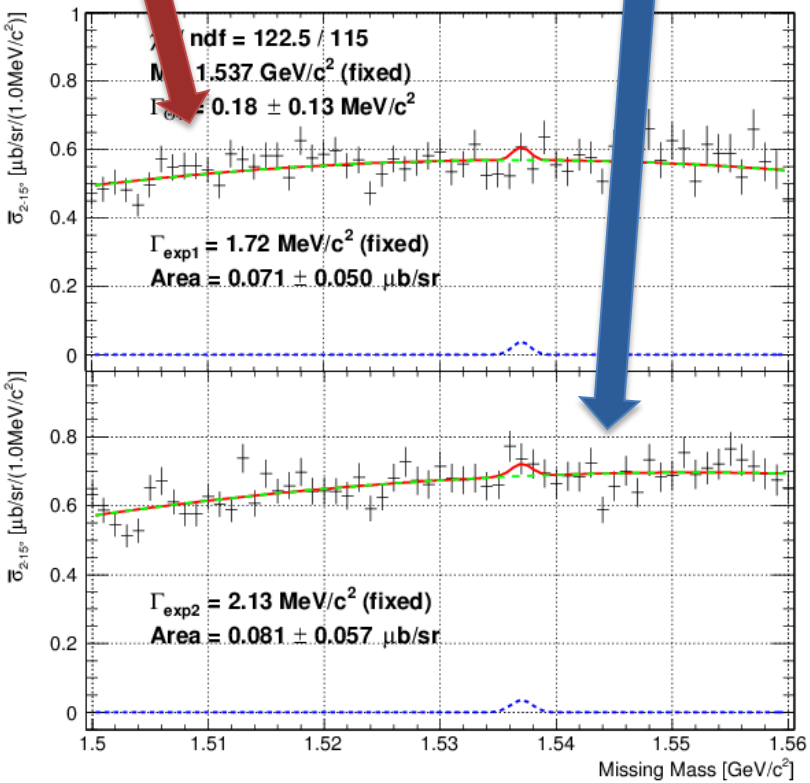
Combined Analysis of 1st and 2nd run

1st run @ 1.92 GeV/c



2nd run @ 2.01 GeV/c

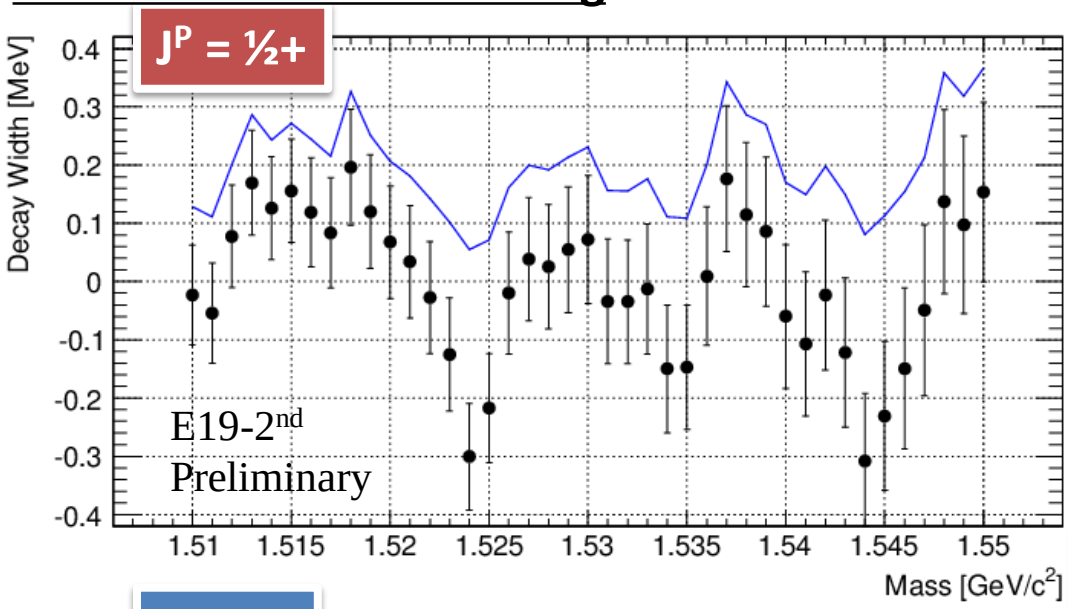




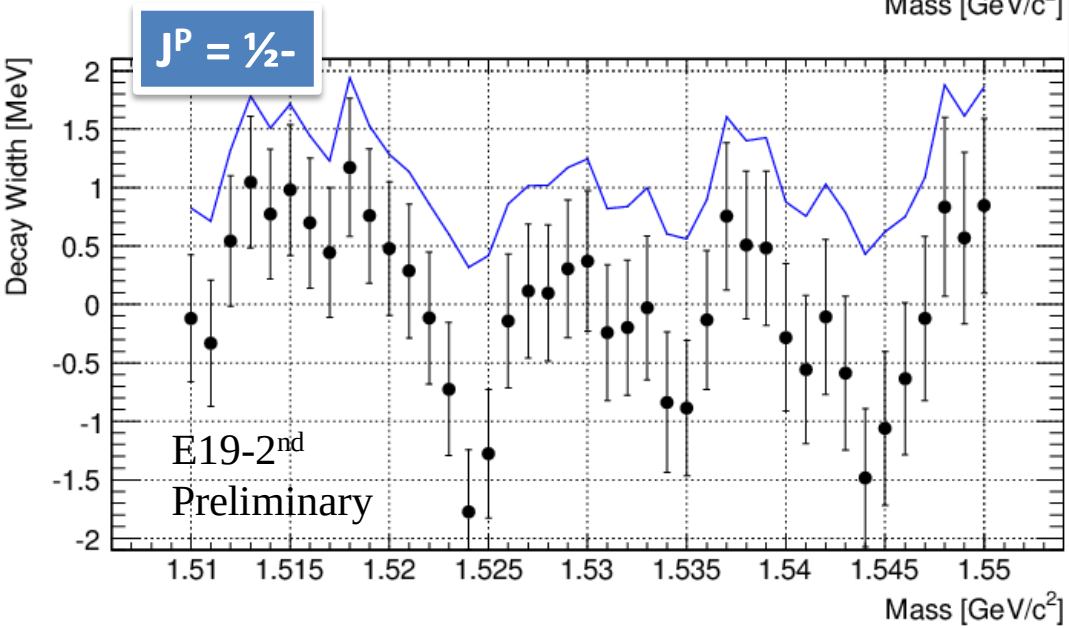
- Now, we obtained results at 2 kinds of initial momentum: 1.92 and 2.01 GeV/c.
- We performed a combined analysis based on the theoretical calculation, considering about these momentum dependence.
- $\Gamma_{\Theta+}$ is an unique parameter.

Upper limit on decay width

Results of combined fitting



← Upper Limit (90%C.L.)



In mass region 1.51—1.55 GeV/c^2
Upper limit on Γ_Θ

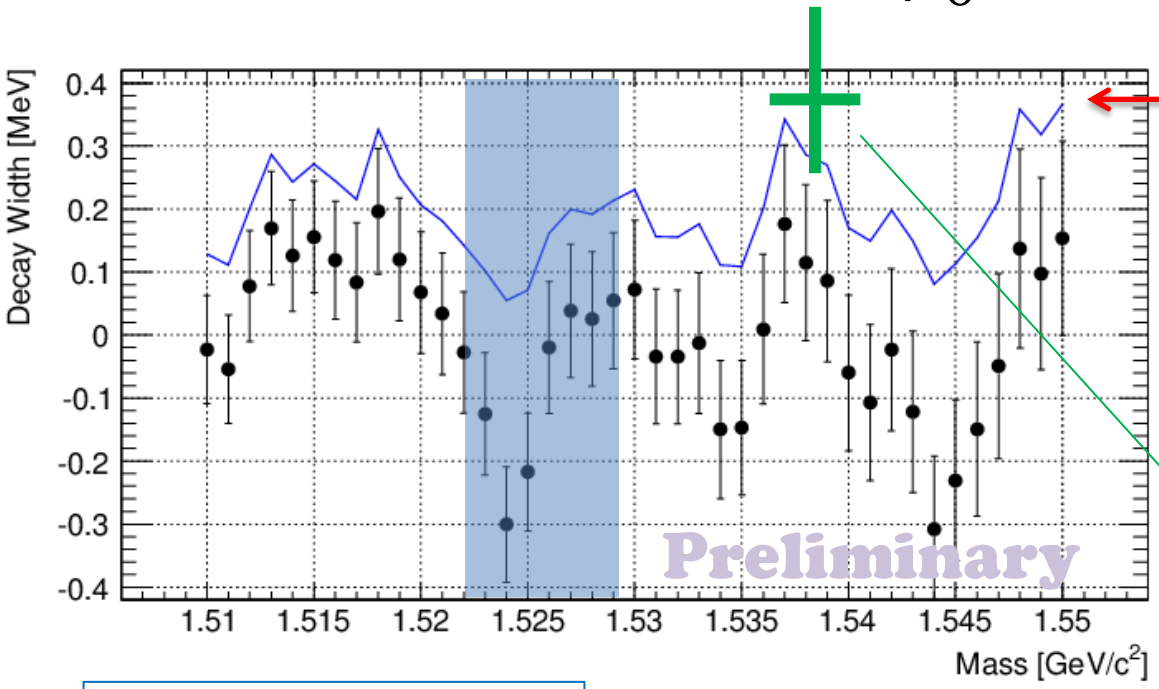
- **< 0.37 MeV for ½+**
- **< 1.9 MeV for ½-**

½+ means P-wave resonance.
½- means S-wave one.

Discussion (for ½+) comparison with other experiment

✓ **Our U.L. overcame the U.L. from Belle (Γ_Θ < 0.64 MeV).**

R.Mizuk et al., PLB 632, 173 (2006)



U.L. in mass region of 1.51--1.55 GeV
→ **Γ_Θ < 0.37 MeV**

DIANA:
M = 1538±2 MeV
Γ = 0.36±0.11 MeV
arXiv:1307.1653

LEPS:
M = 1524±2 + 3 MeV
PRC 79, 025210 (2009).

For LEPS region, Γ < 0.22 MeV.

For DIANA region,
Our U.L. is comparable to their width.

Summary

- J-PARC E19 is a pentaquark Θ^+ search experiment with high statistics and high resolution.
  - $\pi^- p \rightarrow K^- \Theta^+$ reaction
  - J-PARC K1.8 B.S. and SKS
- Result of E19-1st and 2nd run was presented.
  - No peak structure was observed in MM spectrum.
  - Upper limit for Θ^+ production cross section was obtained to be 0.28 μb/sr @ 1.50 – 1.56 GeV/c^2
- Upper limit on Θ^+ decay width was also discussed.
  - Comparing with theoretical calculation, at most decay width should be less than 0.37 and 1.9 MeV for J^P = ½+ and ½-, respectively.
  - This is extremely small as width of hadron resonance.