J-PARC K1.8ビームラインにおけるペンタクォーク探索実験

白鳥 昂太郎
for the E19 collaboration

日本原子力研究開発機構 (JAEA)
先端基礎研究センター (ASRC)
ハドロン物理研究グループ

KEK Theory Center
J-PARC Hadron Salon
2011/9/29

E19 collaboration

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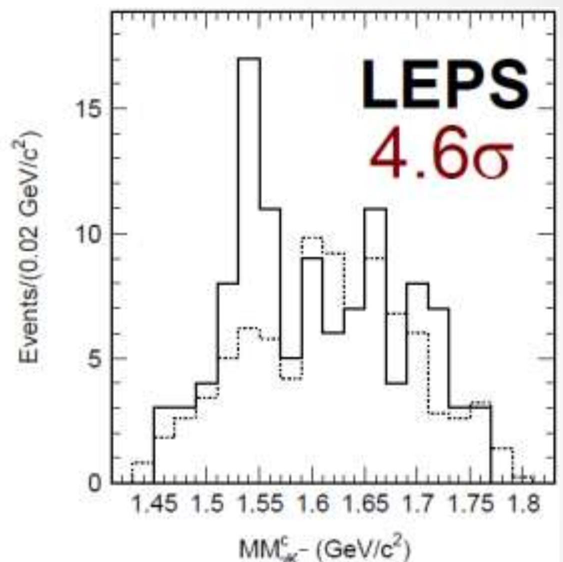
Collaborator :~70 people. Students: 1/3

Contents

Introduction

Θ^+ pentaquark baryon

T. Nakano *et al.*,
Phys. Rev. Lett., 91:012002, 2003.



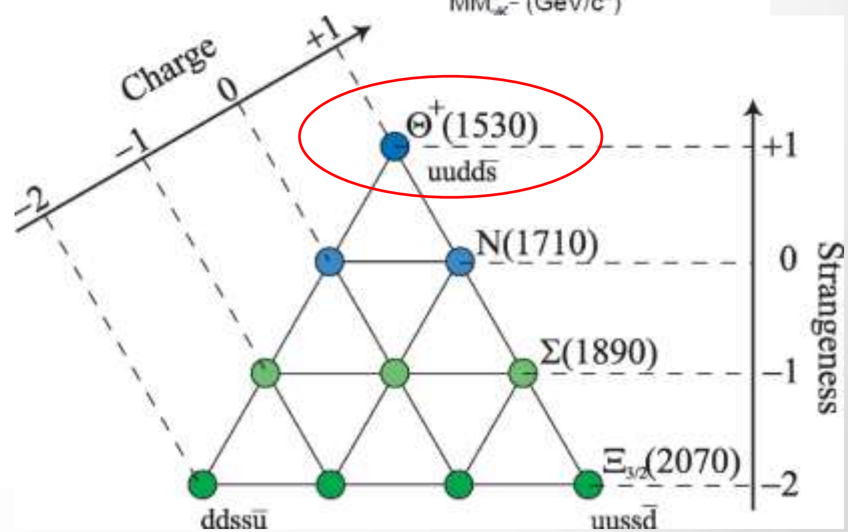
Θ^+ : First reported by the LEPS collaboration

- **$S = +1$ (uudd$\bar{s}$)**
- **$\gamma\, n \rightarrow K^- \Theta^+ \rightarrow K^- K^+ n$**
- **$M = 1540 \pm 10$ MeV/c^2**
- **$\Gamma < 25$ MeV/c^2 (Experimental resolution)**

Θ^+ : Predicted by Diakonov *et al.*

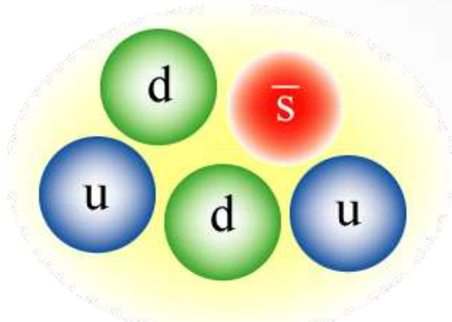
- **Anti-decuplet**
- **$M \sim 1530$ MeV/c^2, $\Gamma < 15$ MeV/c^2**

Good agreement
between theory and experiment
⇒Triggered investigation
of the Θ^+ pentaquark



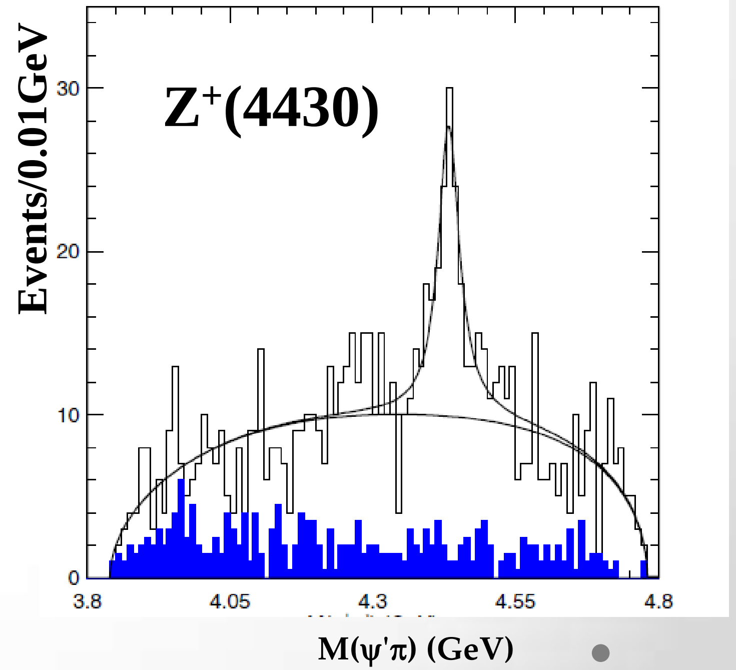
What can we lean from pentaquark ?

QCD : Hadrons to be a color singlet,
not restrict the number of quarks
⇒Exotic hadron can exist.



Pentaquark (Θ^+)

S.-K. Choi *et al.*,
Phys. Rev. Lett., 100, 142001 (2008)



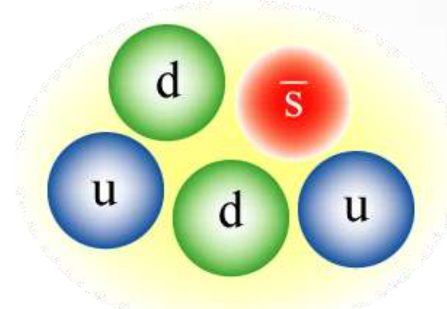
Exotic hadrons with heaver quark
(tetraquark) by Belle

X(3872), X(3940), Y(4260), $Z^+(4430)$, Z_b….

∗ Hadron multi-quark components

What can we lean from pentaquark ?

QCD : Hadrons to be a color singlet, not restrict the number of quarks
⇒Exotic hadron can exist.

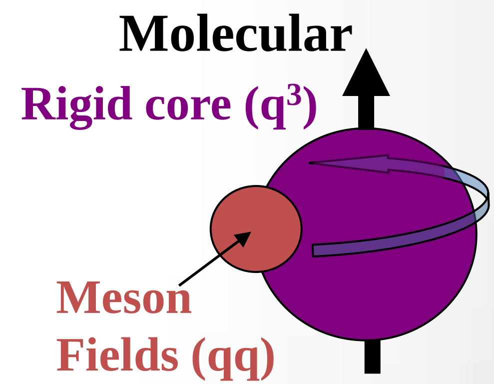


Pentaquark (Θ^+)

Θ^+ property (if exist)

- Very narrow decay width
  Γ ~a few MeV ? ⇔ Γ ~ several 10 MeV

⇒Some mechanism to suppress decay
  Internal configuration change of quarks ?

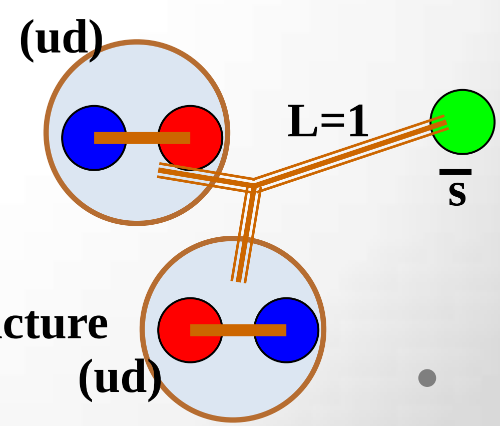


∗ What is the building block of exotic hadron ?

- Molecular : Baryon + meson : n(udd)+K^+($u\bar{s}$)
  c.f. Λ(1405)
- Di-quark : (u-d) + (u-d) + $\bar{s}$

(Jaffe *et al.*, Phys. Rev. Lett. 91, 232003 (2003).)

Exotic hadron ⇒ General property of hadron



Di-quark picture

Θ^+ : To be OR not to be

Present status of Θ^+

Θ^+ status : Many <u>positive</u> results & Many <u>negative</u> results

Present status of Θ^+

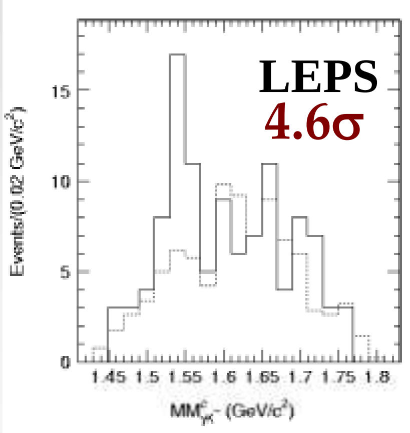
Group	Reaction	Mass (MeV)	Width (MeV)	Statistical significance (σ)
LEPS	$\gamma C \to K^+K^-(n)$	1540 ± 10	<25	4.6
LEPS	$\gamma C \to K^+K^-(n)$	1524 ± 2	<25	5.1
DIANA	$K^+Xe \to K_s^0pX$	1539 ± 2	<9	4.4
DIANA	$K^+Xe \to K_s^0pX$	1538 ± 2	0.39±0.1	8
CLAS(d)	$\gamma d \to K^+K^-p(n)$	1542 ± 5	<21	(5.2)
CLAS(p)	$\gamma p \to \pi^+K^+K^-(n)$	1555 ± 10	<26	7.8
SAPHIR	$\gamma p \to K^+K_s^0nX$	1540 ± 6	<25	4.8
ITEP	$\nu A \to K_s^0pX$	1533 ± 5	<20	6.7
HERMES	$e^+d \to K_s^0pX$	1528 ± 3	12±9	4.2
COSY-TOF	$pp \to K_s^0p\Sigma^+$	1530 ± 5	<18	4.7
ZEUS	$e^+p \to e^+K_s^0pX$	1522 ± 3	8 ±4	4.6
NOMAD	$\nu A \to K_s^0pX$	1529 ± 3	2~3	4.3
SVD	$pA \to K_s^0pX$	1526 ± 5	<24	5.6
SVD	$pA \to K_s^0pX$	1523 ± 5	<14	8.0

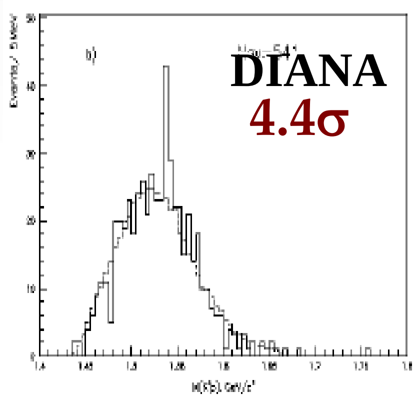
Positive results

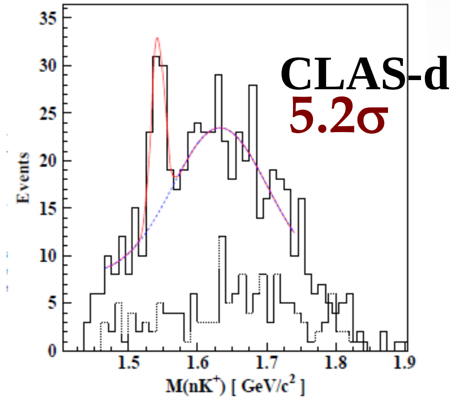
Negative results

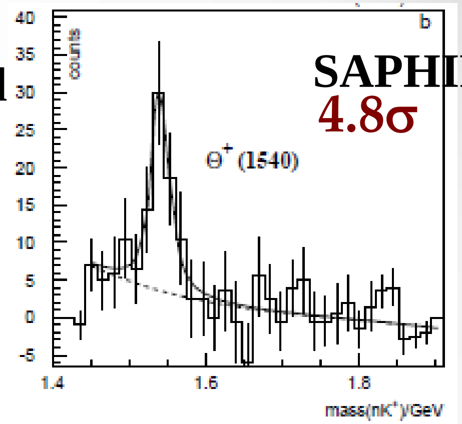
Group	Reaction	Limit
BES	$e^+e^- \to J/\Psi \to \Theta\Theta$	$< 1.1 \times 10^{-5}$ B.R. (90% C.L.)
BES	$e^+e^- \to \Psi(2S) \to \bar{\Theta}\Theta$	$< 8.4 \times 10^{-6}$ B.R. (90% C.L.)
ALEPH	$e^+e^- \to Z \to pK_s^0X$	$< 6.2 \times 10^{-4}$ B.R. (95% C.L.)
BarBar	$e^+e^- \to \Upsilon(4S) \to pK_s^0X$	$< 1.0 \times 10^{-4}$ B.R. (90% C.L.)
BarBar	$eBe \to pK_s^0X$	not given
Belle	$e^+e^- \to B^0\bar{B}^0 \to p\bar{p}K_s^0X$	$< 2.3 \times 10^{-7}$ B.R. (90% C.L.)
Belle	$K^+n \to K_s^0pX$	$\Gamma < 0.64 MeV$ (90% C.L.)
CDF	$p\bar{p} \to K_s^0pX$	$< 0.03 \times \Lambda^*$ (90% C.L.)
SPHINX	$pC \to K_s^0pX$	$< 0.1 \times \Lambda^*$ (90% C.L.)
HERA-B	$pA \to K_s^0pX$	$< 2.7\% \times \Lambda^*$ (95% C.L.)
HyperCP	$pCu \to K_s^0pX$	$< 0.3\%\ K_s^0p$
FOCUS	$\gamma BeO \to K_s^0pX$	$< 0.02 \times \Sigma^*$ (95% C.L.)
PHENIX	$dAu \to K^-\bar{n}X$	not given
WA89	$\Sigma^+A \to K_s^0pX$	$< 1.8\mu$b/A (99% C.L.)
CLAS	$\gamma p \to \bar{K}_s^0K^+n$	< 0.8 nb (95% C.L.)
CLAS	$\gamma d \to K^-pK^+n$	$< 0.15 - 3$ nb (95% C.L.)
CLAS	$\gamma d \to K^+n\Lambda$	$< 5 - 25$ nb (95% C.L.)
COSY-TOF	$pp \to \Sigma^+pK_s^0$	$< 0.15\mu$b/A (95% C.L.)
NOMAD	$\nu A \to K_s^0pX$	$< 2.13 \times 10^{-3}\nu CC$ (90% C.L.)

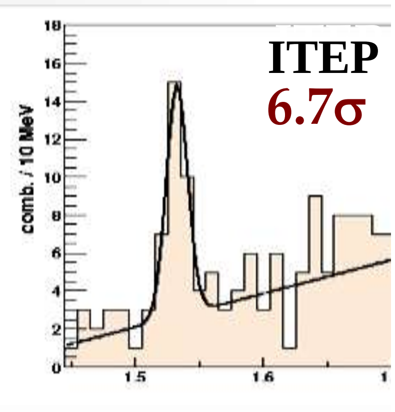
Positive Results

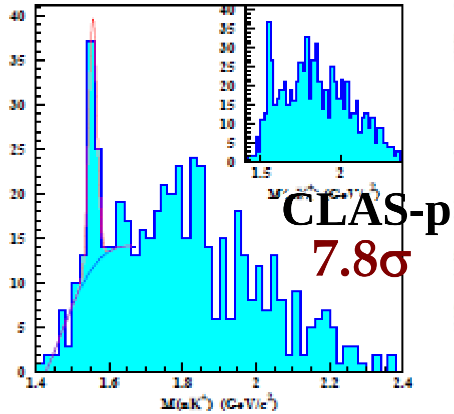


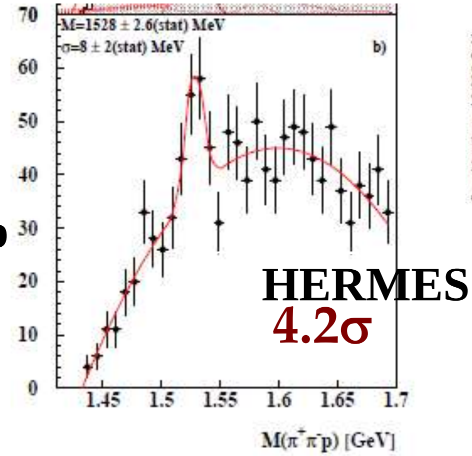


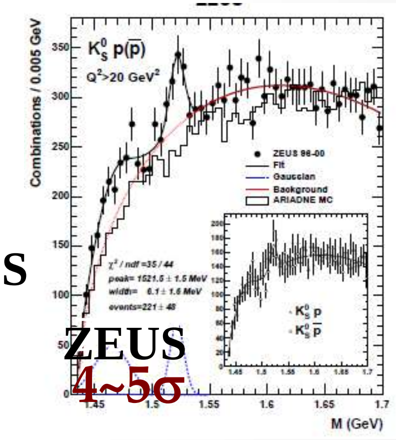


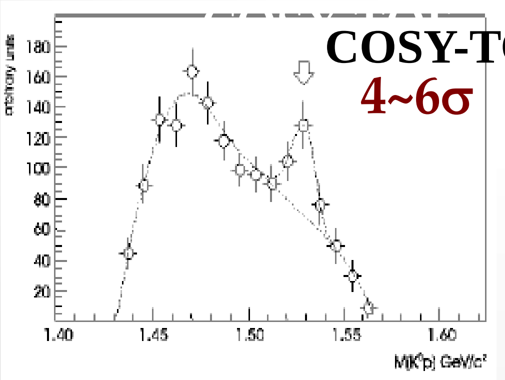


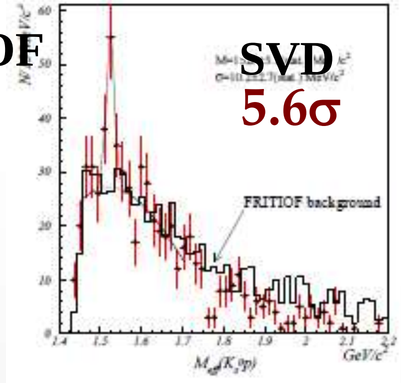










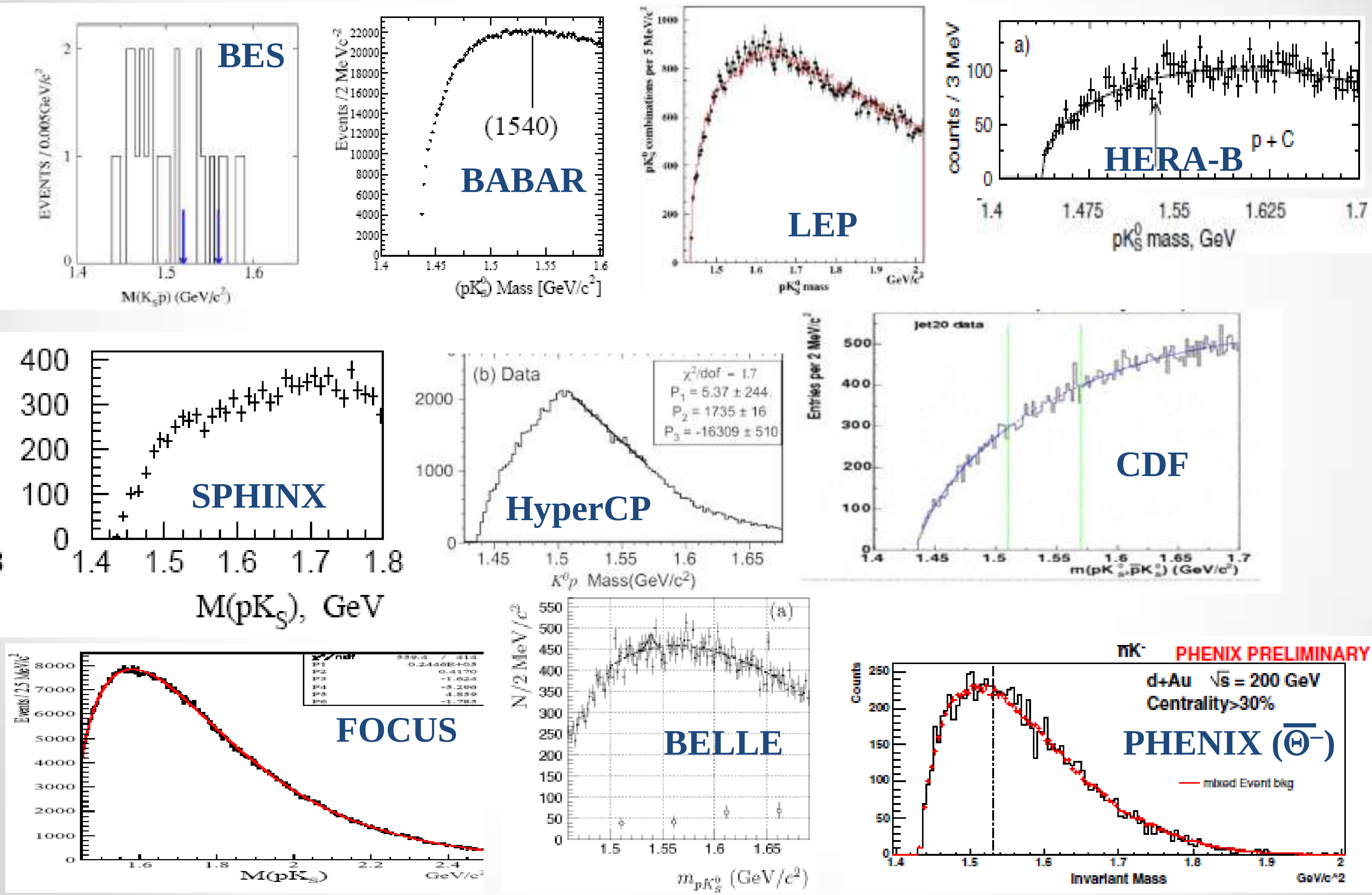


Experiments with positive evidence

Better statistics is needed

(significance ~ 5σ)

Negative Results



Present status of Θ^+

Θ^+ status : Many positive results & Many negative results

Positive results

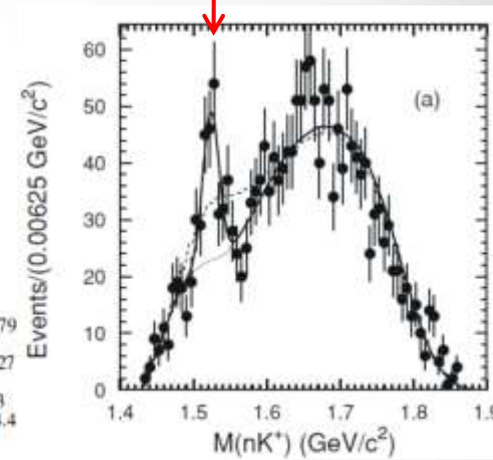
- LEPS new report : $\gamma\, d \rightarrow p\, K^- K^+ n$
- CLAS(p) : $\gamma\, p \rightarrow \pi^+ K^- \Theta^+ \rightarrow \pi^+ K^- K^+ n$
- DIANA : $K^+ n \rightarrow \Theta^+ \rightarrow K^0 p$

Negative results

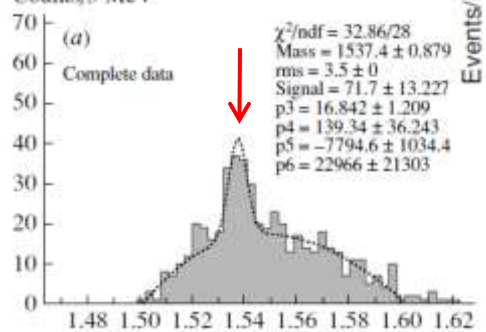
- High energy experiments
- CLAS : $\gamma\, d \rightarrow p\, K^- \Theta^+ \rightarrow p\, K^- K^+ n$
  - ∗ High statistics & high sensitivity

⇒**Controversial situation**

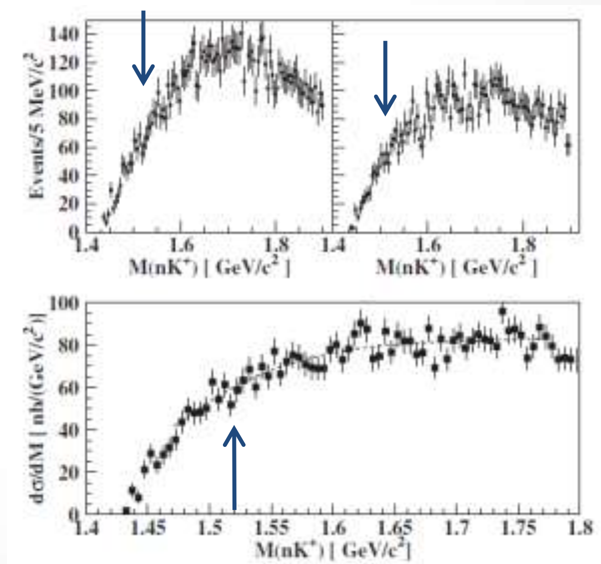
LEPS



DIANA



CLAS



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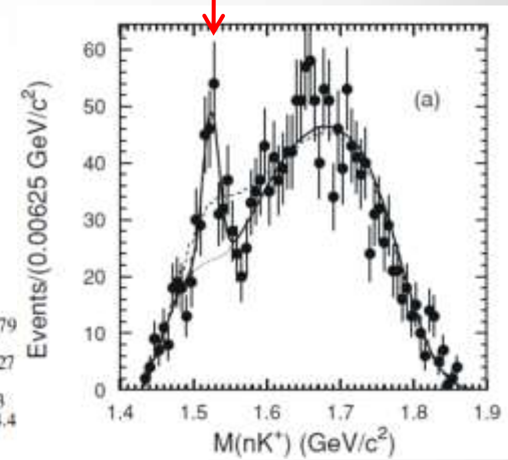
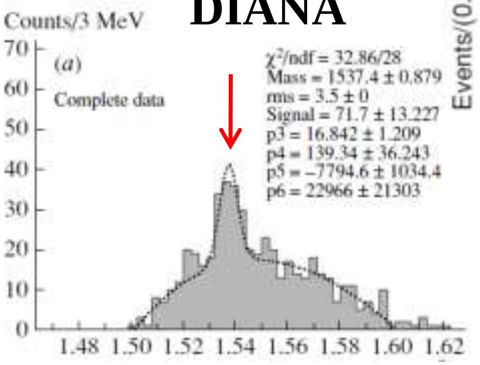
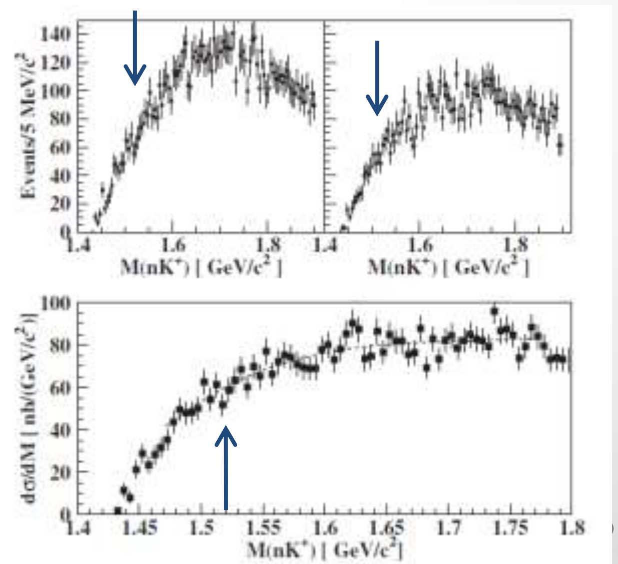
LEPS



DIANA



CLAS



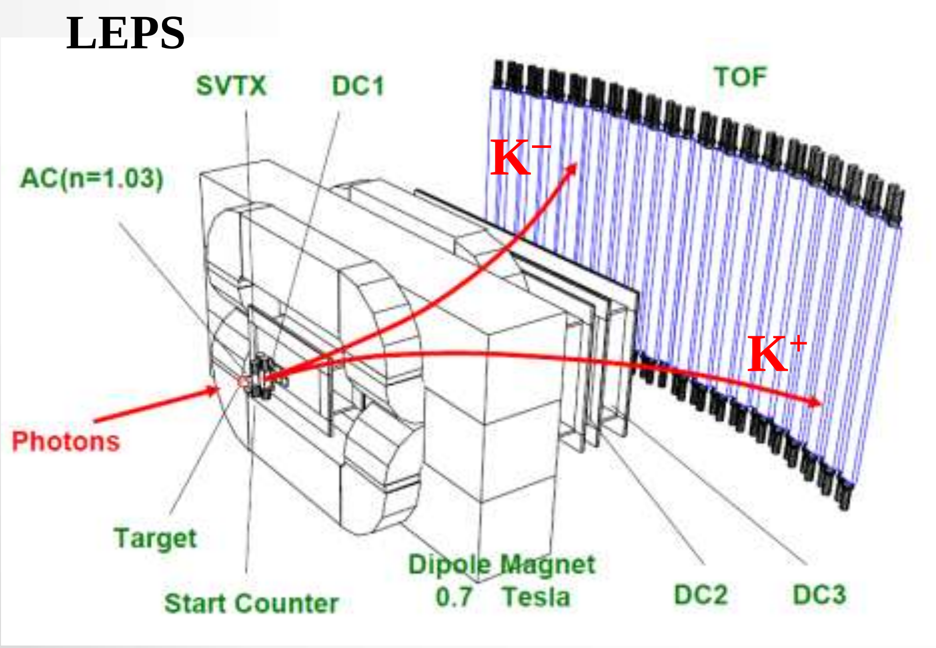
LEPS & CLAS

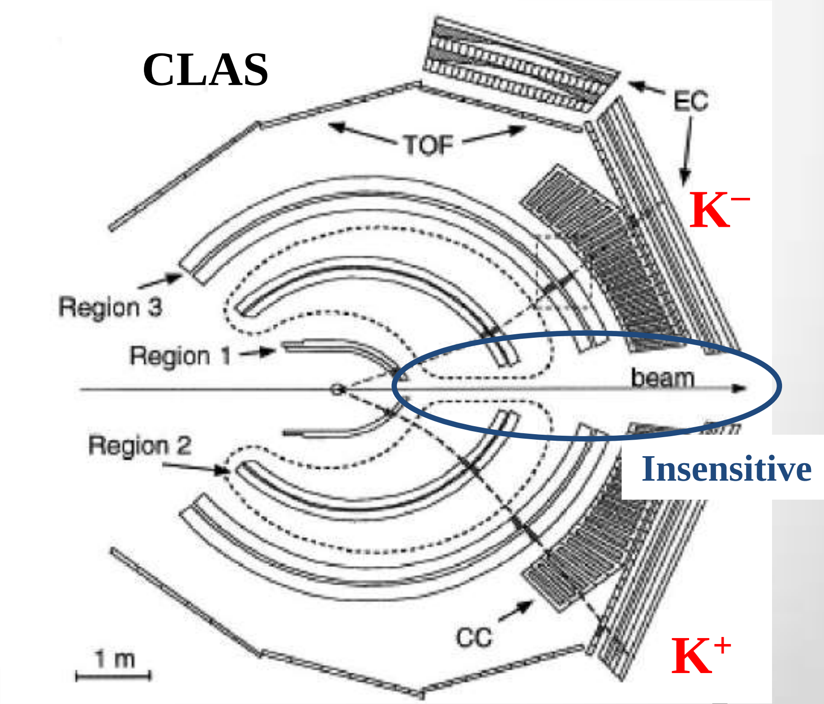
Reaction : $\gamma\, d \rightarrow p\, K^- \Theta^+ \rightarrow p\, K^- K^+ n$

Difference : $K^\pm$ detection angle

- **Forward : LEPS**
- **Backward (side) : CLAS**

∗ Detection of re-scattering proton : CLAS





LEPS & CLAS

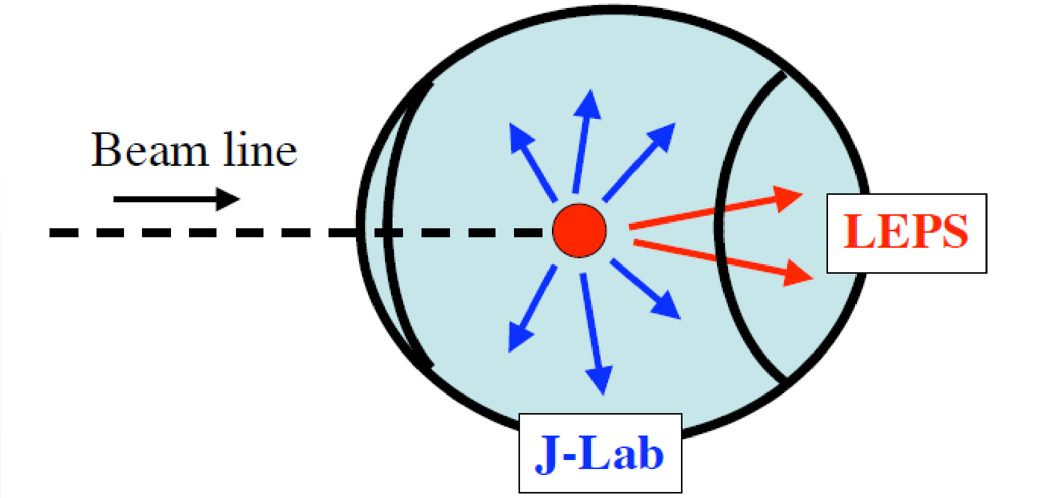
Reaction : $\gamma\, d \rightarrow p\, K^- \Theta^+ \rightarrow p\, K^-\, K^+\, n$

Difference : $K^\pm$ detection angle

- **Forward : LEPS**
- **Backward (side) : CLAS**

∗ Detection of re-scattering proton : CLAS

Explained by experimental condition
⇒Not contradicted



Present status of Θ^+

Θ^+ status : Many positive results & Many negative results

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- High energy experiments
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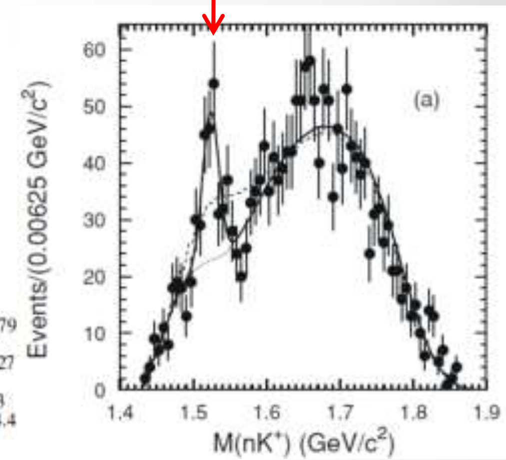
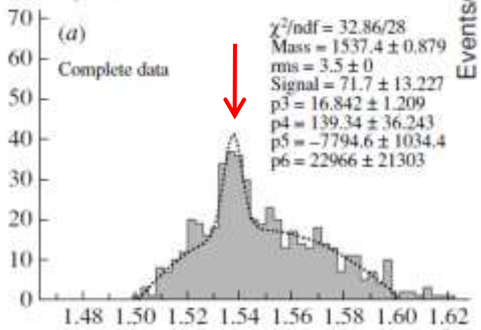
  - ✱ High statistics & high sensitivity

⇒Controversial situation

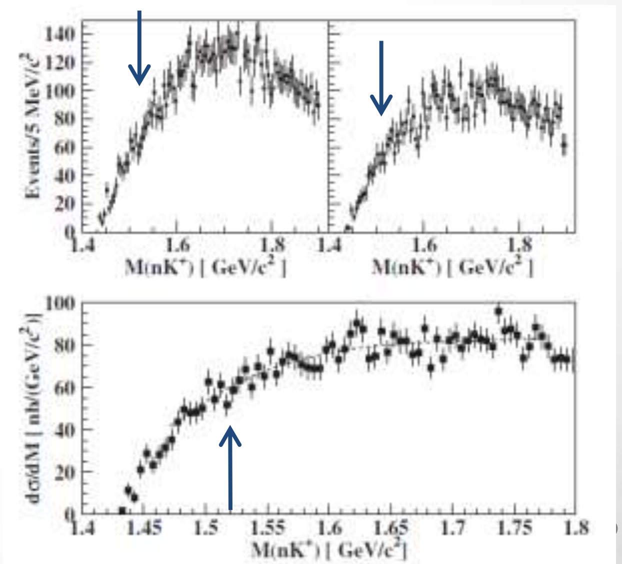
LEPS



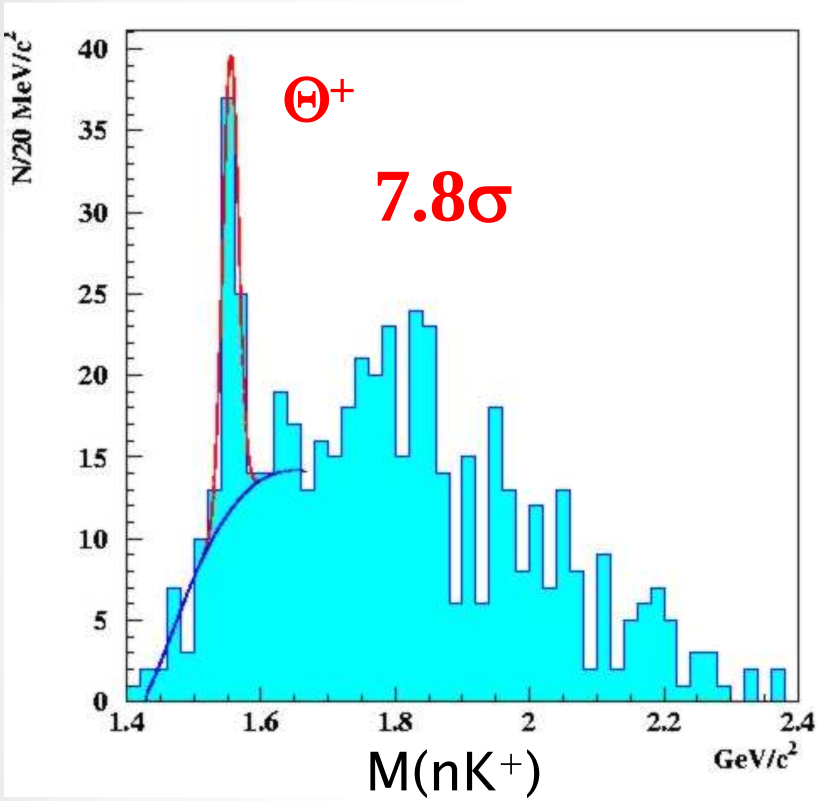
DIANA



CLAS

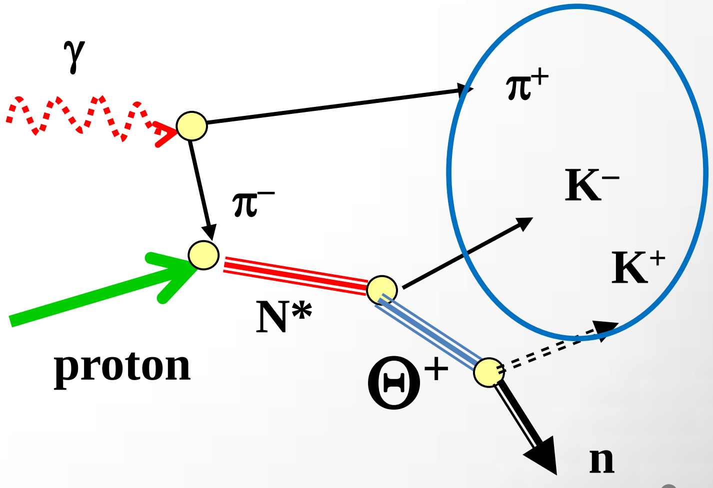


"Best" positive evidence



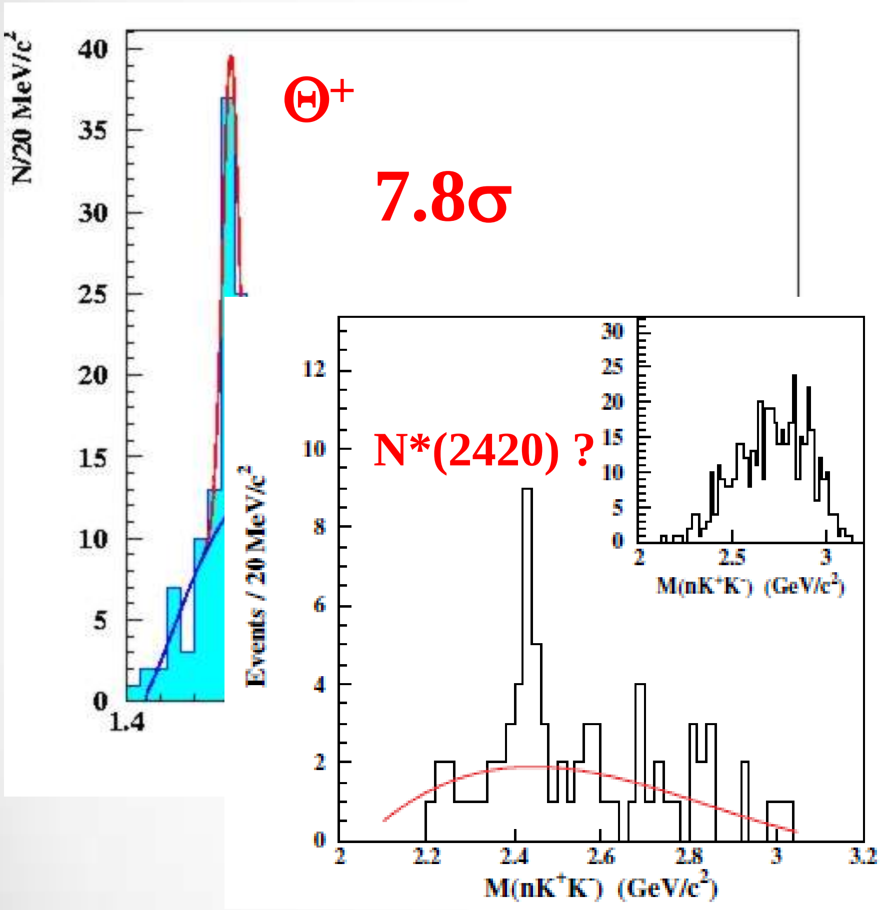
$\gamma\, p \rightarrow \pi^{+} K^{-} K^{+} (n)$

- CLAS: V. Kubarovsky *et al.* PRL 92 032001 (2004)
- Combined analysis of all CLAS data on protons for Eγ <5.5 GeV
- Cuts: forward π^{+}, backward K^{+}
- Indications of production from heavy N*(2420) ?



Eγ ~ 3.2 – 5.47 GeV

“Best” positive evidence



$E\gamma \sim 3.2 – 5.47$ GeV

$\gamma\, p \rightarrow \pi^+ K^- K^+ (n)$

- CLAS: V. Kubarovsky *et al.* PRL 92 032001 (2004)
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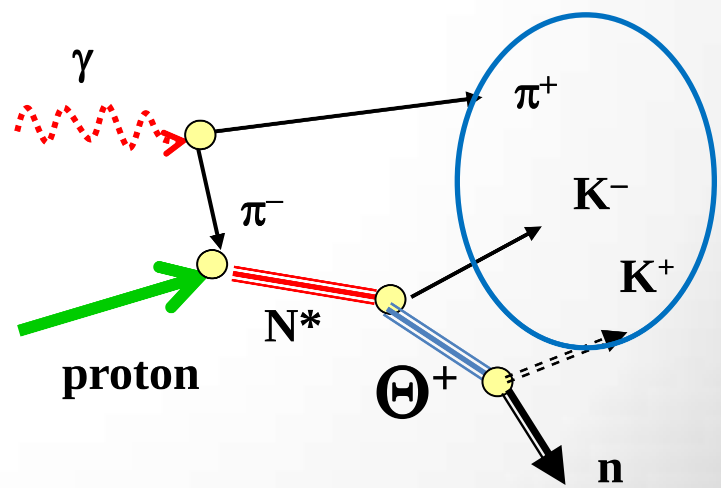


Present status of Θ^+

Θ^+ status : Many positive results & Many negative results

Positive results

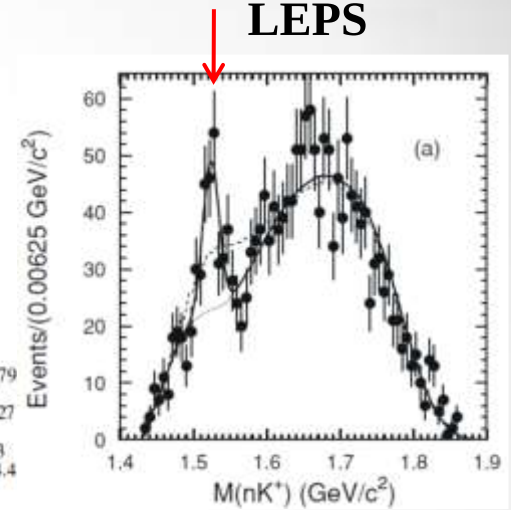
- LEPS new report : γ d $\rightarrow$p K^-K^+n
- CLAS(p) : γ p$\rightarrow\pi^+ K^- \Theta^+ \rightarrow \pi^+ K^- K^+$ n
- DIANA : K^+ n $\rightarrow\Theta^+\rightarrow K^0$ p

Negative results

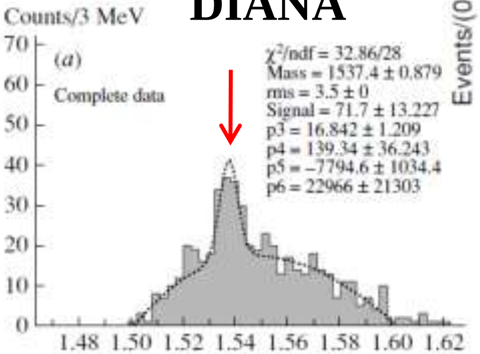
- High energy experiments
- CLAS : γ d$\rightarrow$p $K^- \Theta^+ \rightarrow$p $K^- K^+$ n
  - ＊High statistics & high sensitivity

$\Rightarrow$Controversial situation

LEPS



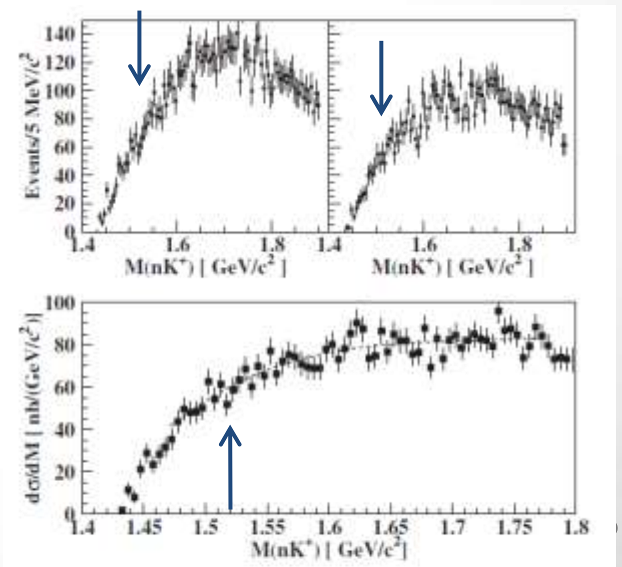
DIANA



＊Width

- DIANA : K^+ n $\rightarrow\Theta^+\rightarrow K^0$ p
  - $\Gamma = 0.39\pm0.1$ MeV/c^2
- BELLE : K^+ n $\rightarrow K^0$ pX
  - $\Gamma < 0.64$ MeV/c^2 (90% C.L.)

CLAS



＊Low energy hadron reaction (π or K beam)

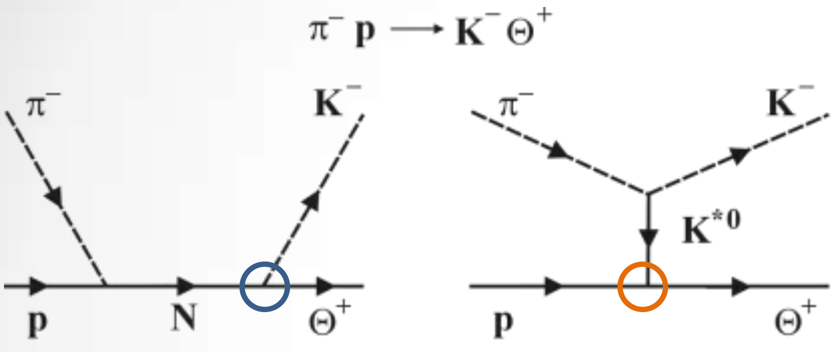
- Few data
- Expected larger production cross section

$\Rightarrow$ Essential part for the investigation of Θ^+

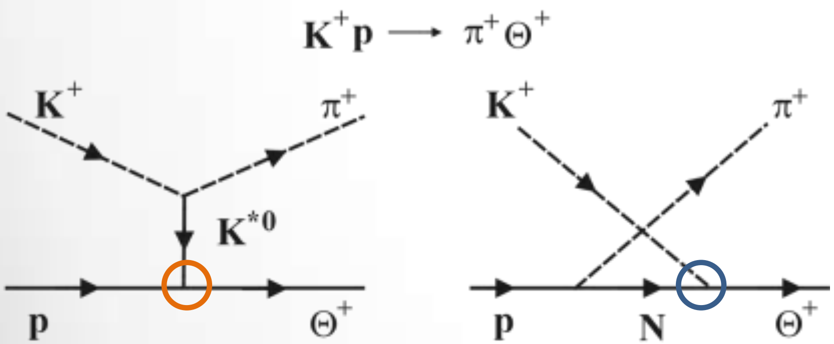
Hadronic reaction

Hadronic production

Diagrams for calculation



(1) *s*-channel (2) *t*-channel



(1) *t*-channel (2) u-channel

Unknown coupling constant

- $g_{KN\Theta}$ & $g_{K^*N\Theta}$ ($\Gamma_\Theta \propto g^2_{KN\Theta}$)

⇒No experimental information
⇒Parameters in calculation
\+ Form factor assumed from hyperon production

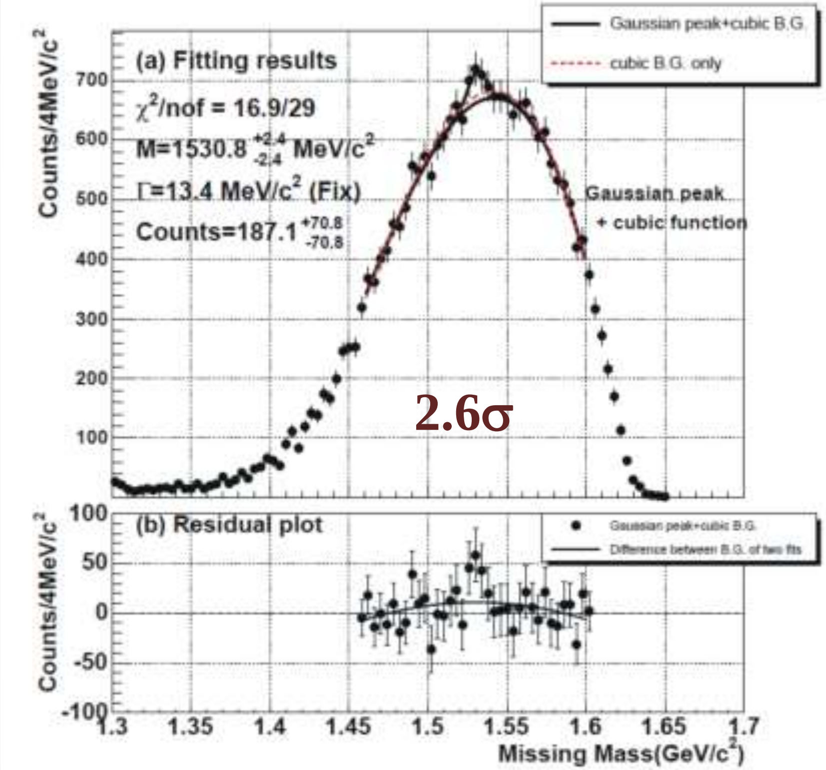
Cross section (Case of J^P_Θ =1/2⁺)

- $\pi^- + p \rightarrow K^- + \Theta^+$
  σ = 2–200 μb (Γ_Θ = 5 MeV/c^2)
  Oh *et al.*
  Phys. Rev. D 69, 014009 (2004)

- $K^+ + p \rightarrow \pi^+ + \Theta^+$
  σ > 10 μb (Γ_Θ = 1 MeV/c^2)
  Oh *et al.*
  Phys. Rev. D 69, 074016 (2004).

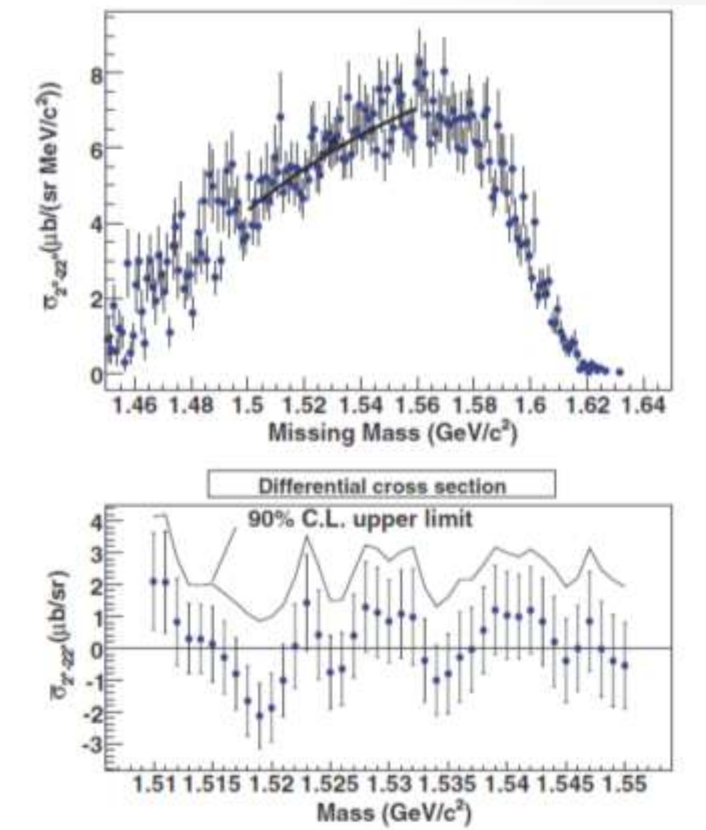
Previous experiments at KEK-PS

E522 : $\pi^- p \rightarrow K^- \Theta^+$ @ 1.92 GeV/c



K. Miwa *et al.* Phys. Lett. B635, 72, 2006.

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



K. Miwa *et al.*
Phys. Rev. C77, 045203, 2008.

Both experiment : Only upper limit of cross section

- **E522 : σ< 3.9 μb (90% C.L.) @ 1.92 GeV/c**
  (S-wave production and isotropic K^- emission)
- **E559 : σ< 3.5 μb/sr (90% C.L.)**

Present status from hadronic reactions

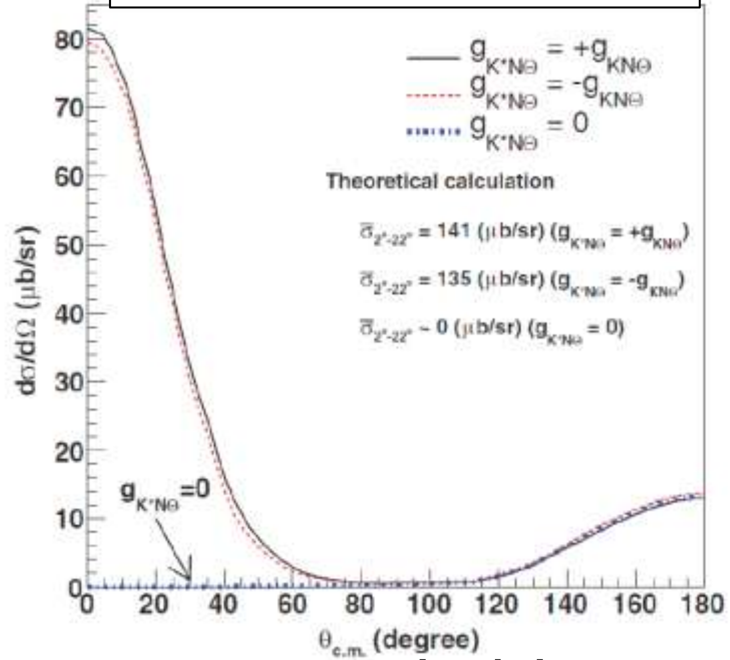
- $\pi^- p \rightarrow K^- \Theta^+$: $\sigma < 3.9\ \mu b$ (90% C.L.)
  - Both $g_{KN\Theta}$ & $g_{K^*N\Theta}$ are small.
  - $\Gamma < 10$ MeV
- $K^+ p \rightarrow \pi^+ \Theta^+$: $\sigma < 3.5\ \mu b/sr$ (90% C.L.)
  - Low backward sensitivity

  $\Rightarrow g_{K^*N\Theta} \sim 0$
- CLAS result (Photo-production)

  $\gamma p \rightarrow K^0 \Theta^+ \rightarrow K^0 K^+ n$: upper limit < 0.8 nb

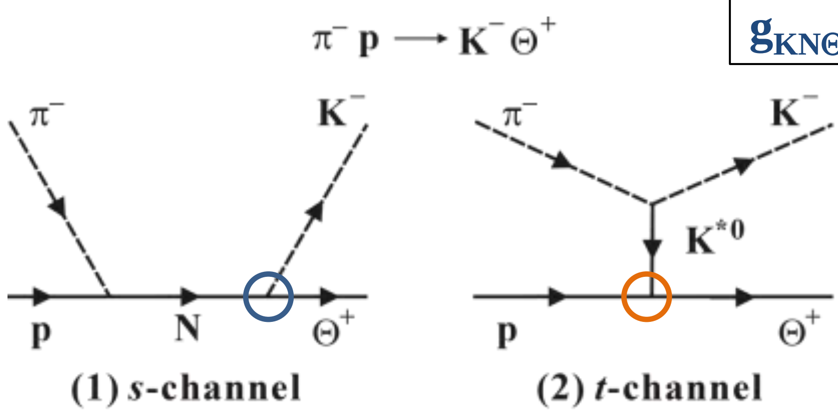
  $\Rightarrow g_{K^*N\Theta} \sim 0$

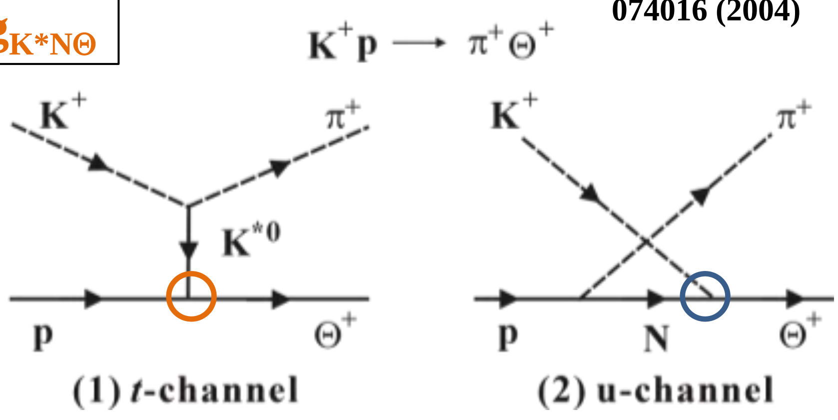
$K^+ p \rightarrow \pi^+ \Theta^+$ @ 1.2 GeV/c



Oh *et al.* Phys. Rev. D 69, 074016 (2004)

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





Present status from hadronic reactions

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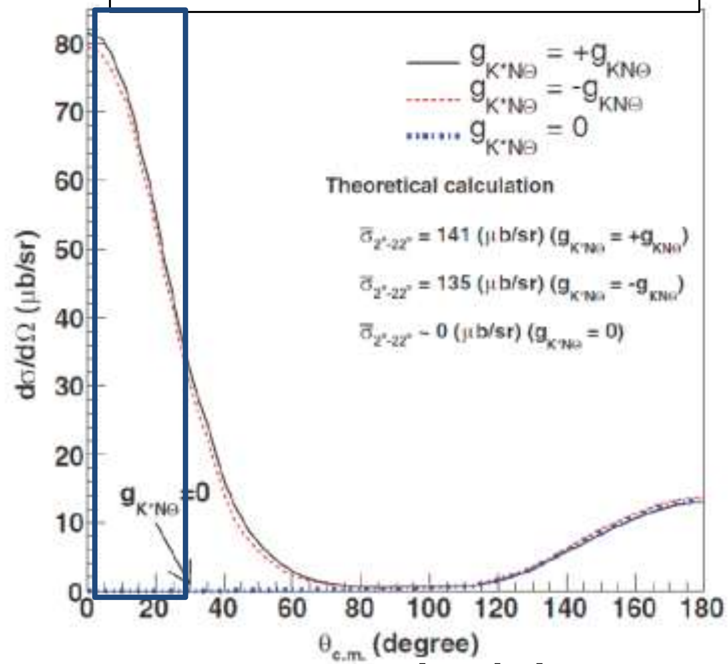
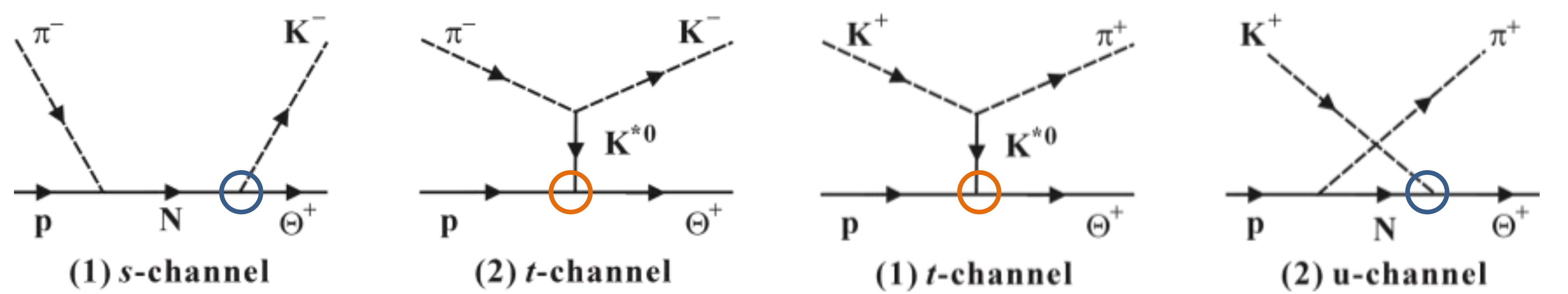


Oh *et al.* Phys. Rev. D 69, 074016 (2004)

$\pi^- p \rightarrow K^- \Theta^+$ $g_{KN\Theta}$ & $g_{K^*N\Theta}$ $K^+ p \rightarrow \pi^+ \Theta^+$



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  - Both $g_{KN\Theta}$ & $g_{K^*N\Theta}$ are small.
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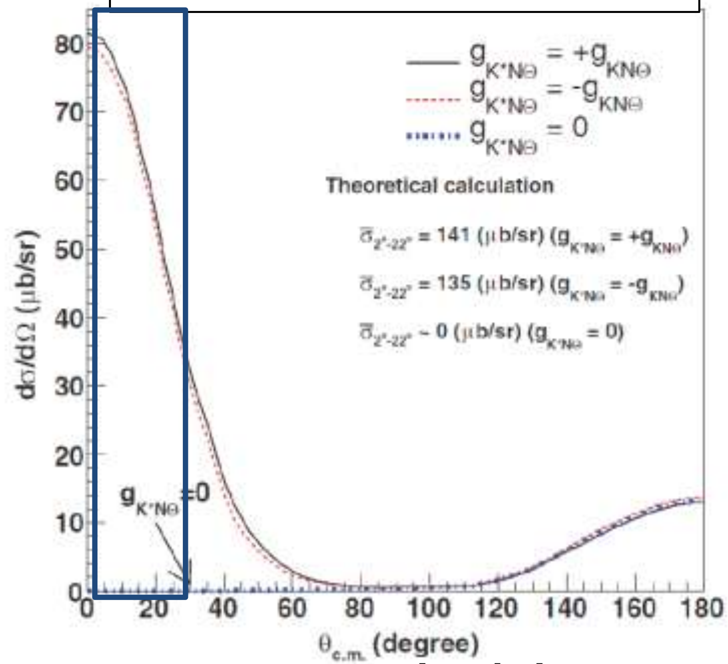
  $\gamma\, p \rightarrow K^0 \Theta^+ \rightarrow K^0 K^+ n$: upper limit < 0.8 nb

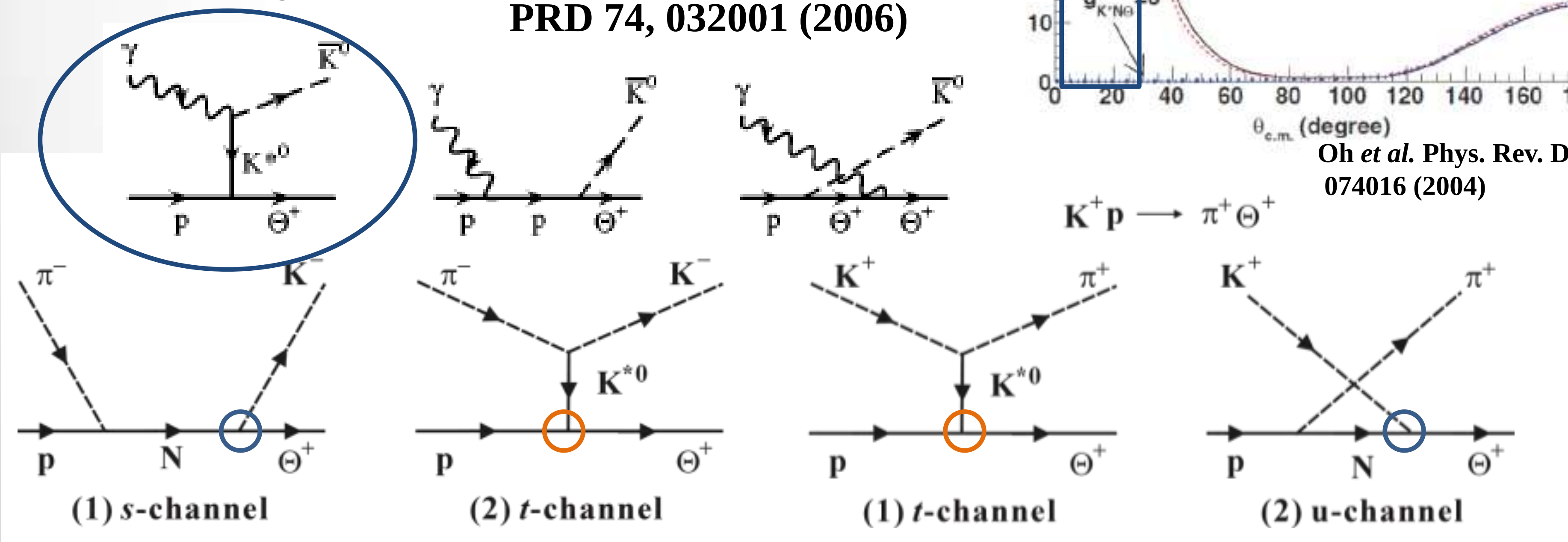
  $\Rightarrow g_{K^*N\Theta} \sim 0$

PRD 74, 032001 (2006)

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



Oh *et al.* Phys. Rev. D 69, 074016 (2004)



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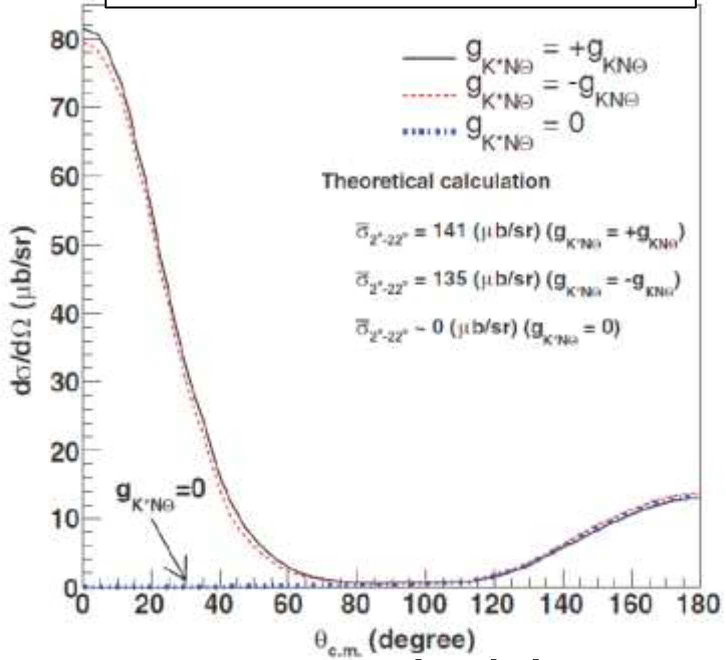


Oh *et al.* Phys. Rev. D 69, 074016 (2004)

Θ^+ production mechanism on hadron beams & property

- Small K* coupling : $g_{K^*N\Theta} \sim 0$
- s-channel dominance ($\pi^- \; p \rightarrow K^- \; \Theta^+$) ?
- Very narrow width : $\Gamma < 1$ MeV/c^2

∗ Expect small cross section : Order of 100 nb

$\Rightarrow$ Need experiment with high sensitivity

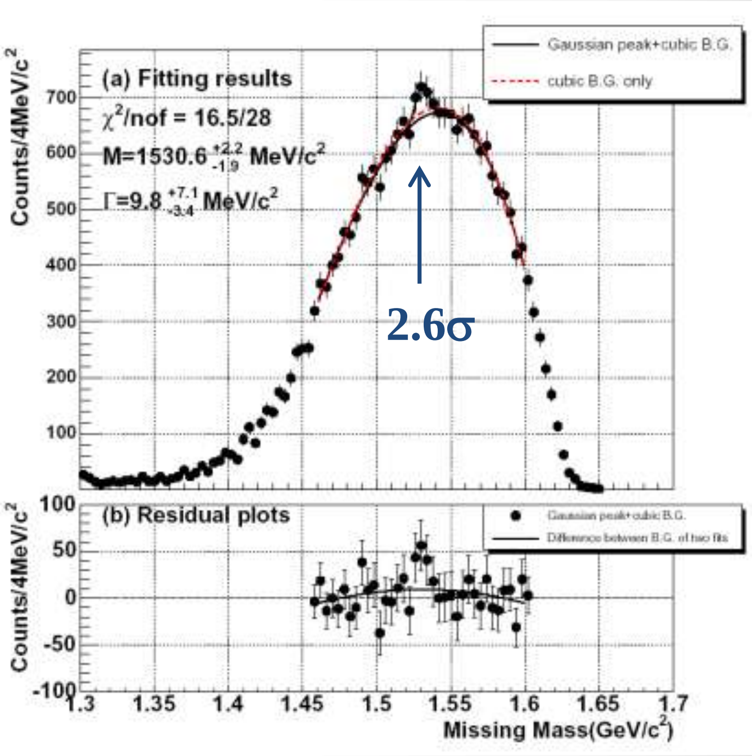
Θ^+ search by high-resolution spectroscopy via $\pi^- + p \rightarrow \Theta^+ + K^-$: J-PARC E19

Spokesperson M. Naruki

Previous E522 experiment

Reaction : $\pi^- + p \rightarrow \Theta^+ + K^-$ @ 1.92 GeV/c
Upper limit of cross section
⇔Mass resolution

- ΔM~14 MeV/c^2 (FWHM) (KURAMA spectrometer)



K. Miwa *et al*.
Phys. Lett. B, 635:72, 2006.

J-PARC E19

Reaction : $\pi^- + p \rightarrow \Theta^+ + K^-$ @ 1.92 GeV/c

- High resolution : SKS
  ∗ ΔM< 2 MeV/c^2(FWHM)
- High statistics : High intensity beam

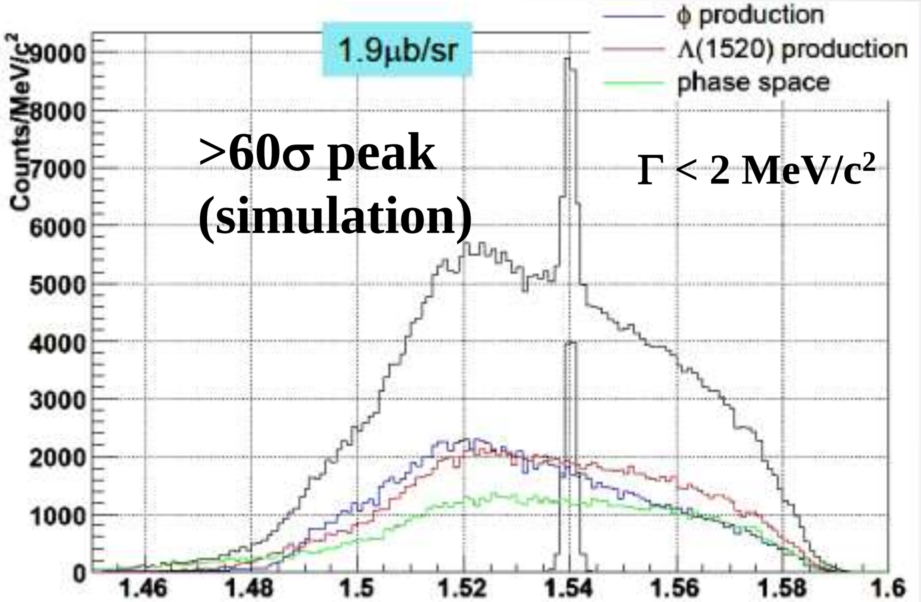
⇒ Conclusive result by higher sensitivity

The first physics run at the J-PARC hadron facility !

Goal of beam time in 2010

- Original plan : $10^7\pi^-$/ 3.6 sec × 6 days = 1.44 × $10^{12}\pi^-$
  - 3 momenta : 1.87, 1.92, 1.97 GeV/c ⇒ 4.80 × $10^{11}\pi^-$

⇒More than 60σ peak
(estimated by E522 upper limit)



- Realistic condition
  - 0.075 × $10^7\pi^-$(750 k)/ 6 sec ⇒ 133 days

    Cannot use full beam intensity due to the beam micro-structure

∗ Step 1:
  - Needs 6 days to confirm Θ^+ with 10σ @ 1.92 GeV/c
  - 0.075 × $10^7\pi^-$/ 6 sec × 6 days = 6.48 × $10^{10}\pi^-$

  (Assuming 10% duty factor)

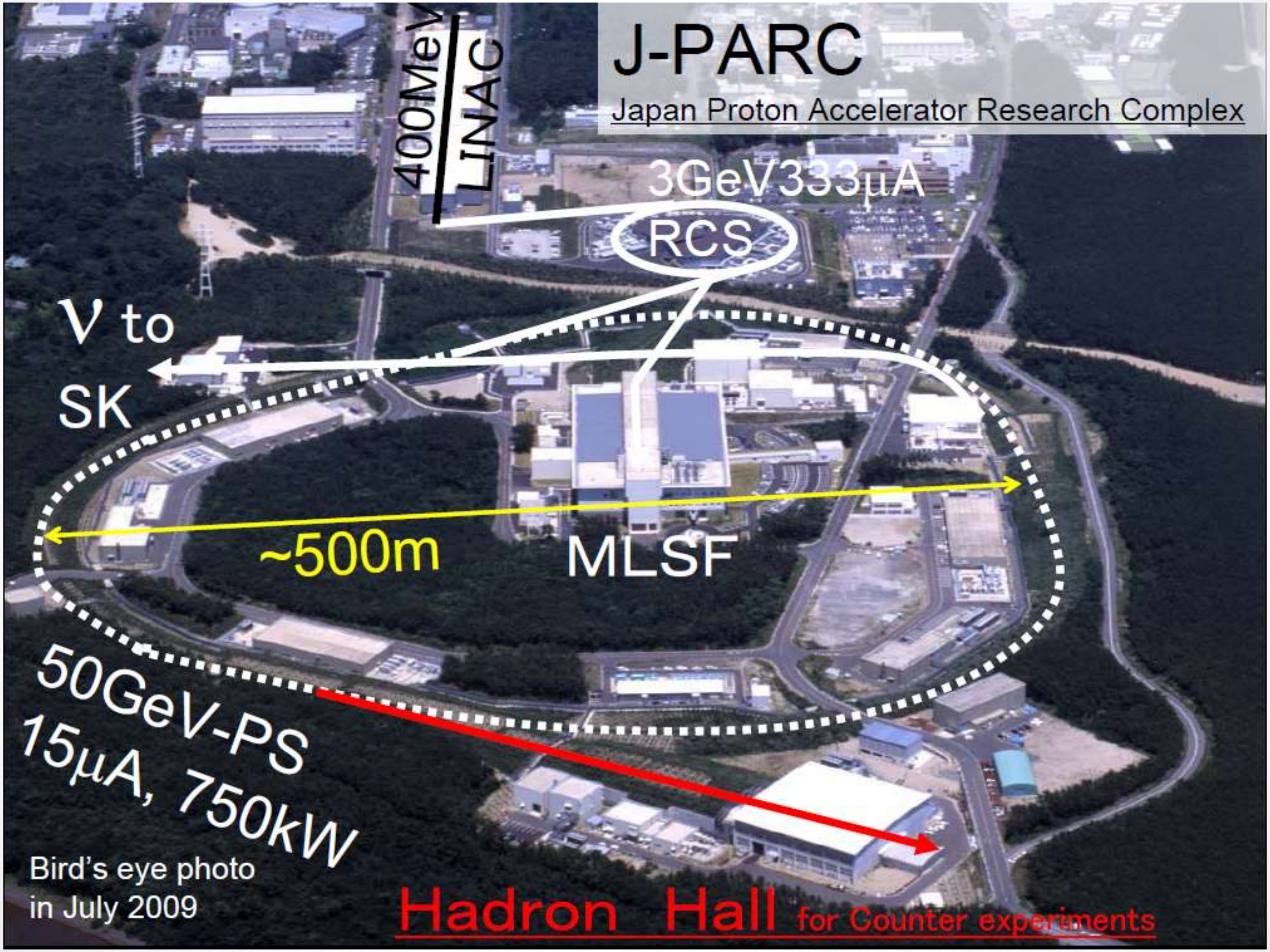
Experiment

J-PARC

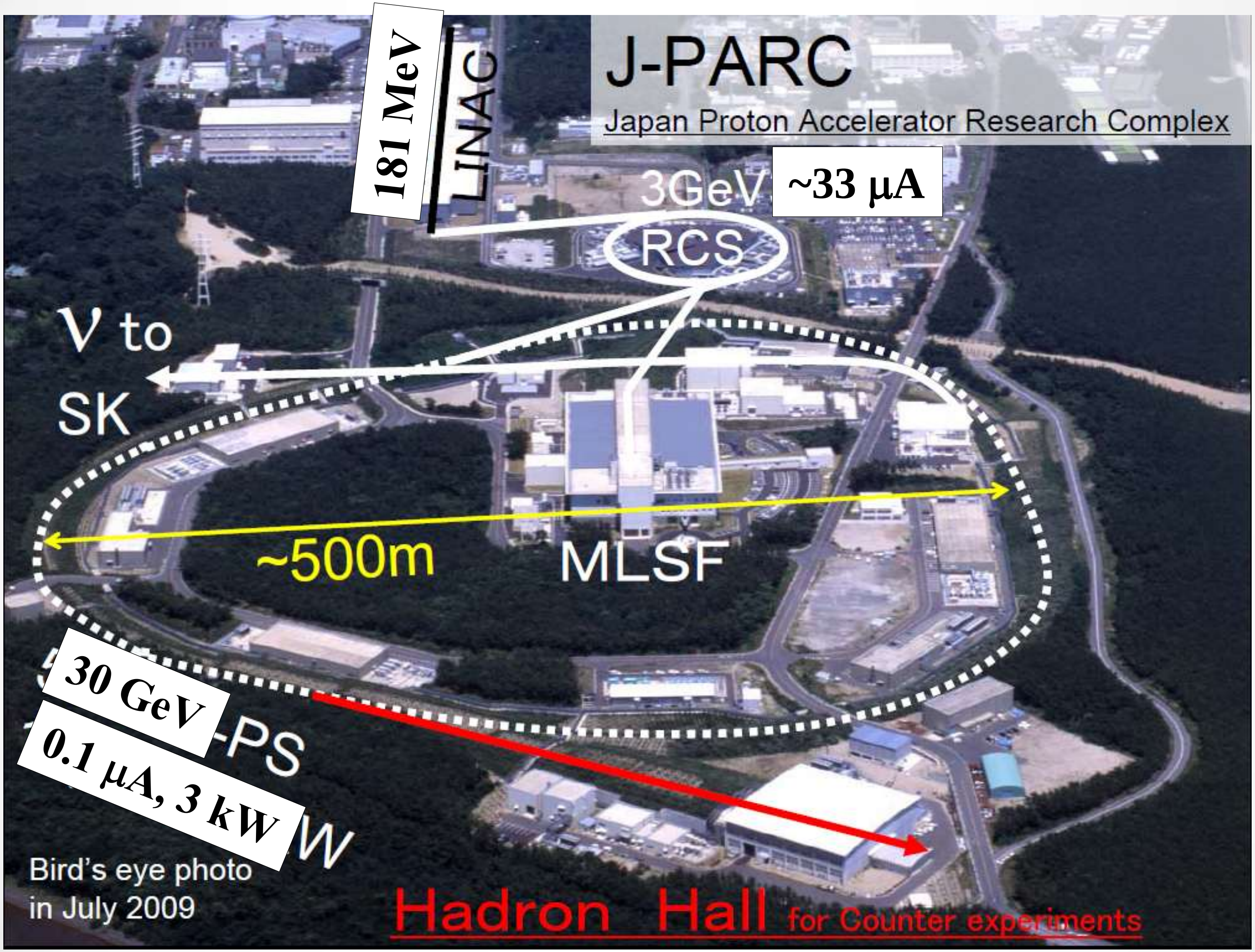
Experimental apparatus

Beam time

J-PARC & Hadron facility

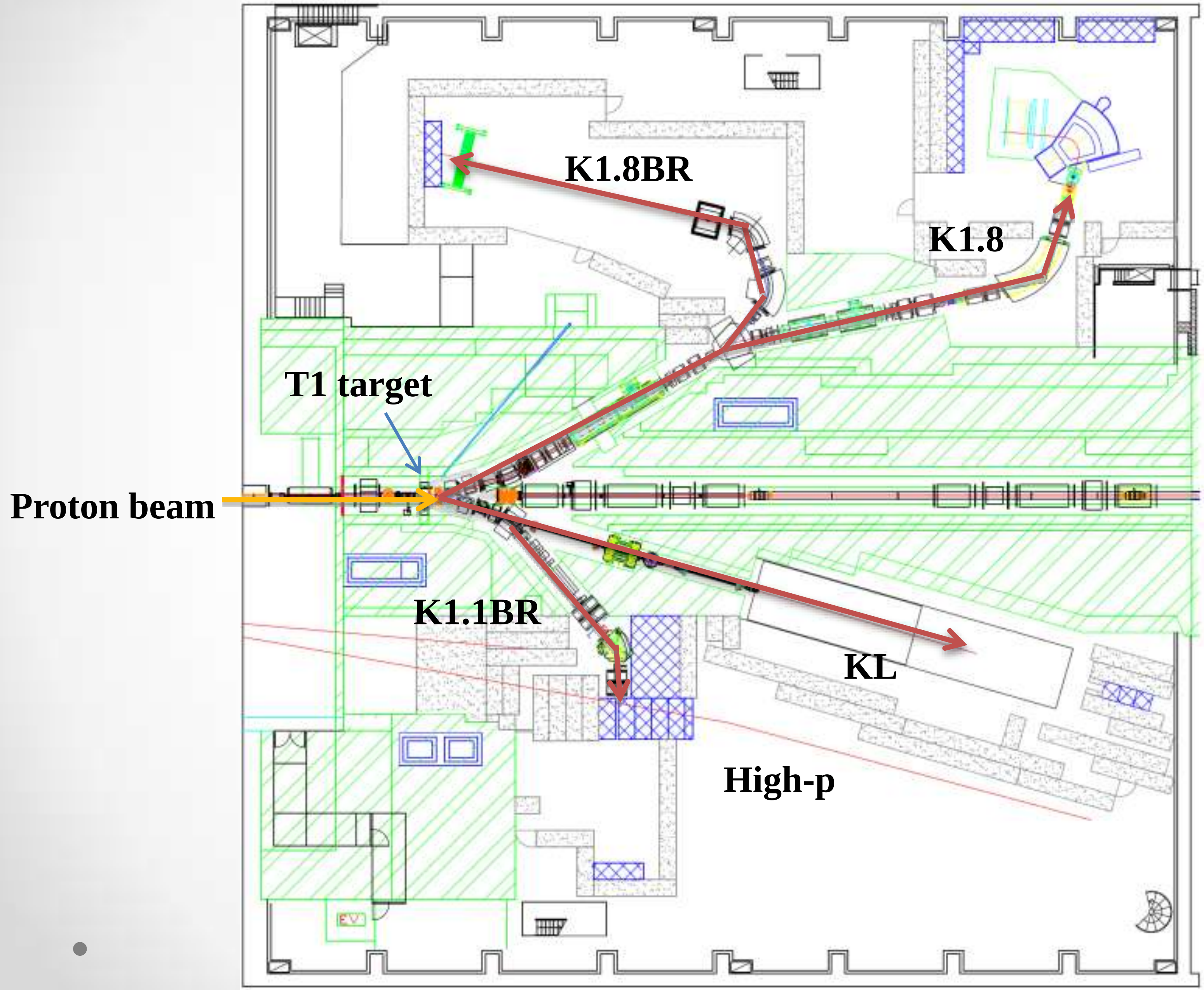


J-PARC & Hadron facility

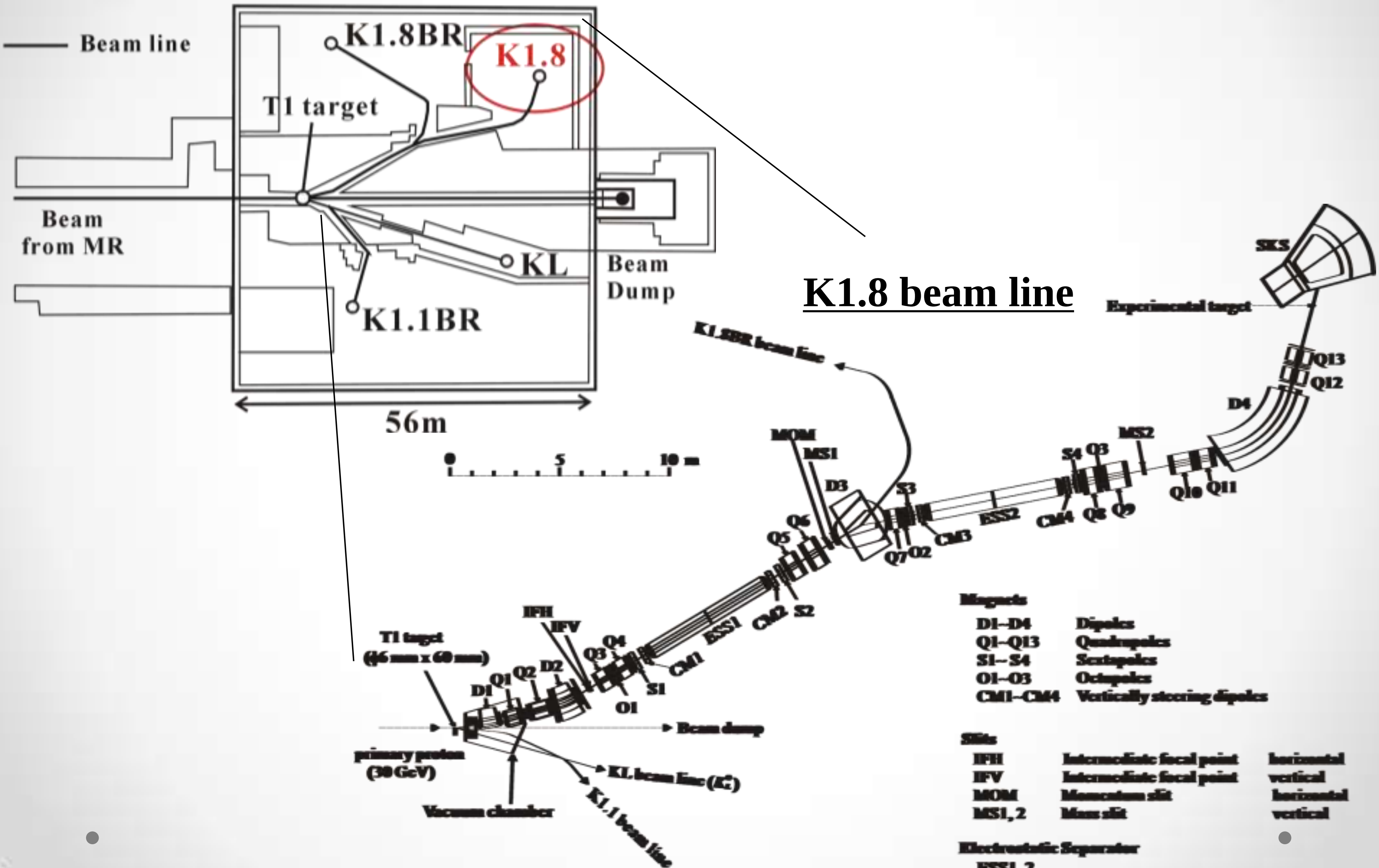


MR present operation : 30 GeV, 1/100 intensity

Hadron facility



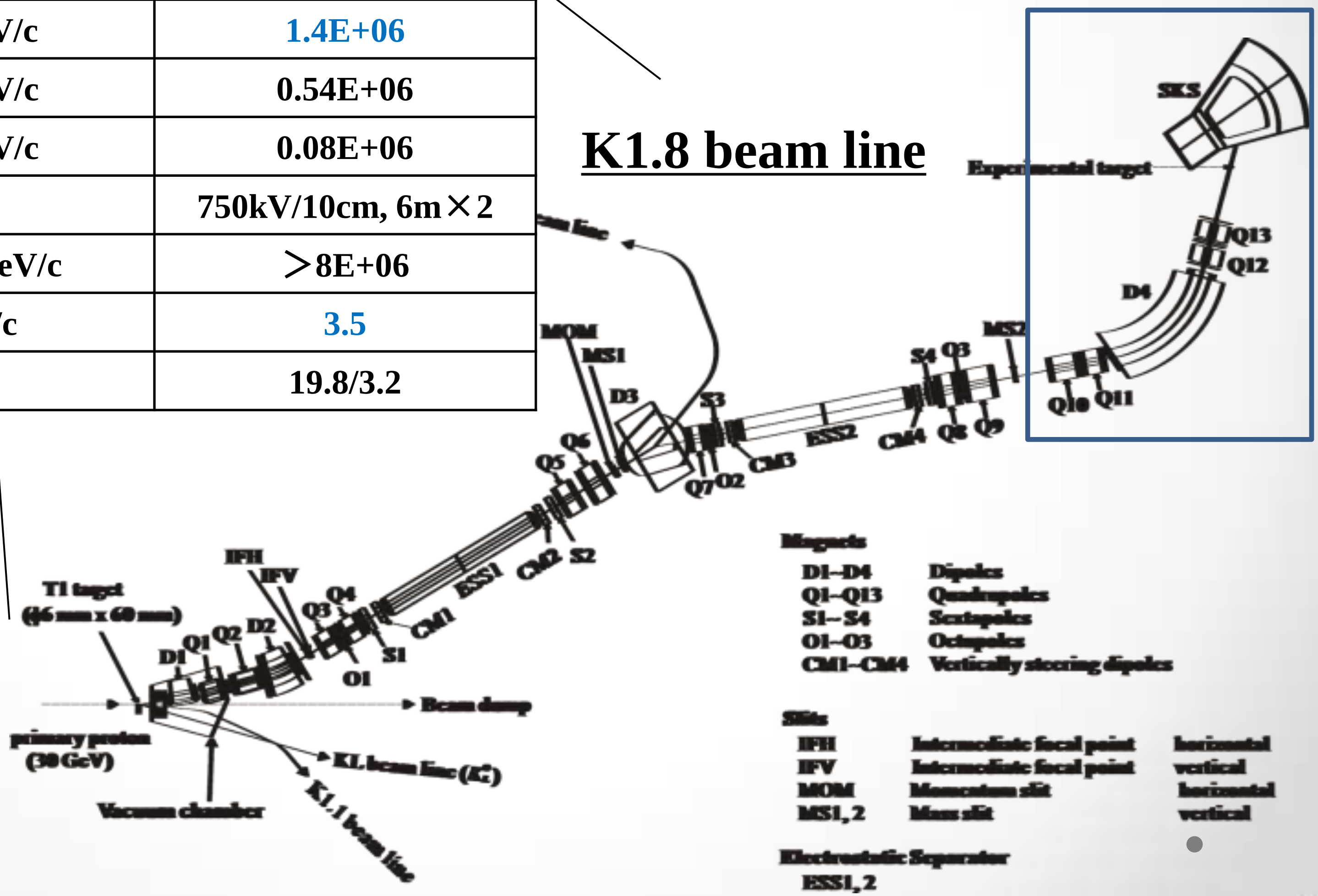
Hadron facility & K1.8 beam line



Hadron facility & K1.8 beam line

Primary proton beam (protons/spill)	30 GeV-9μA 2.0E+14
Length (m)	45.853
Acceptance (msr.%)	1.4
K^- intensity (ppp) @ 1.8 GeV/c	1.4E+06
@ 1.5 GeV/c	0.54E+06
@ 1.1 GeV/c	0.08E+06
Electrostatic separators	750kV/10cm, 6m×2
Single rate @ MS2 @ 1.8 GeV/c	>8E+06
$K^-/(\pi^-+\mu^-)$ @ FF @ 1.8 GeV/c	3.5
X/Y(rms) size @ FF (mm)	19.8/3.2

K1.8 beam line



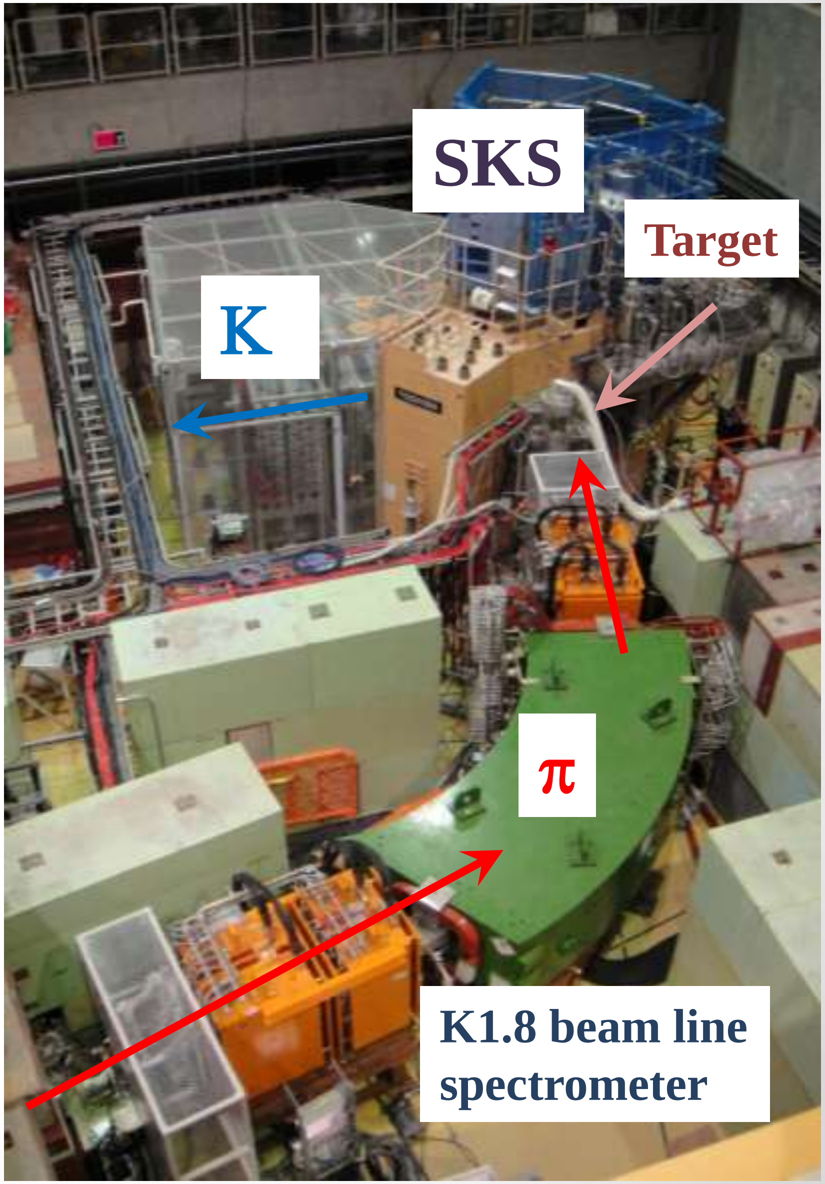
J-PARC K1.8 beam line

General-purpose mass-separated beam line

Max. momentum : 2 GeV/c

⇒Major area of hadron and hypernuclear experiment

- Exotic hadron search
- Ξ hypernuclei
- Hypernuclear γ-ray spectroscopy
- n-rich hypernuclei
- YN scattering



SKS (Superconducting Kaon Spectrometer)

SKS magnet moved from KEK

Magnetic field : 2.5T

⇒Good momentum resolution

($\Delta p \propto 1/BL^2$)

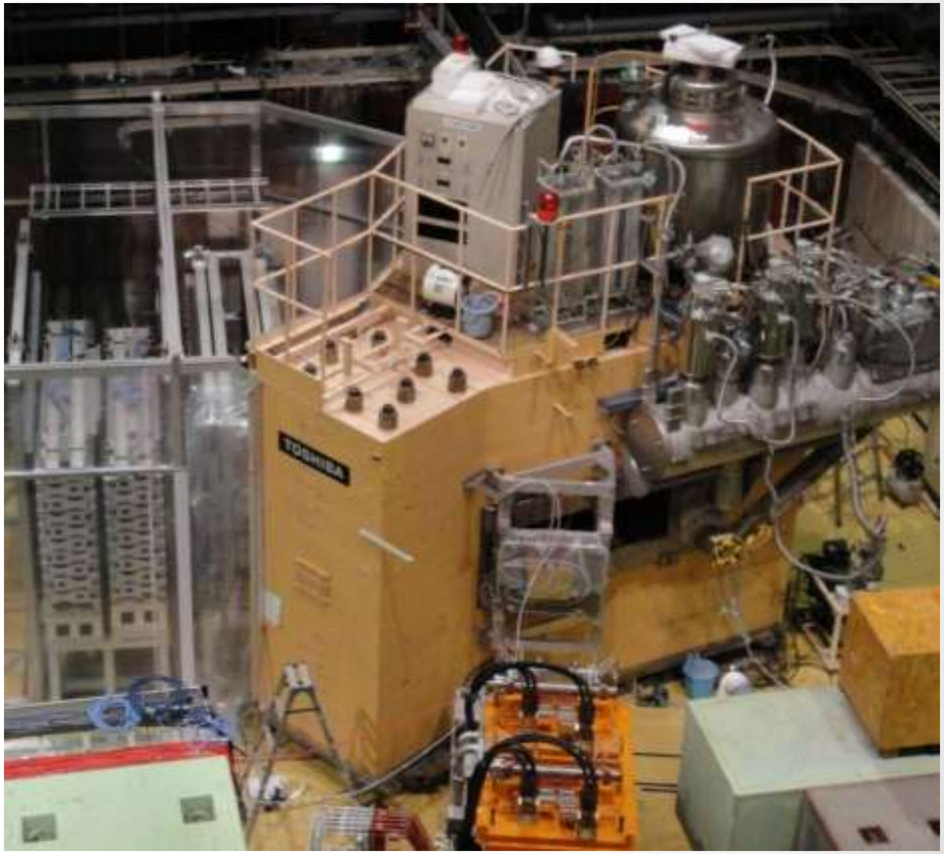
- **Small K decay : Short flight-path**
- **Large yield : Wide pole gap**

SKS performance (design value)

- **Momentum resolution :**

  $\Delta p/p \sim 2.0 \times 10^{-3}$
- **Angular acceptance : 100 msr**
- **Momentum range : 0.75-1.20 GeV/c**

Present SKS @ J-PARC



Status on Apr 2009

- No infrastructure (electricity, cooling water), beam line magnet, detectors, cables…

Construction & Working

SKS Set down at KEK : 2007

Detector construction : 2008

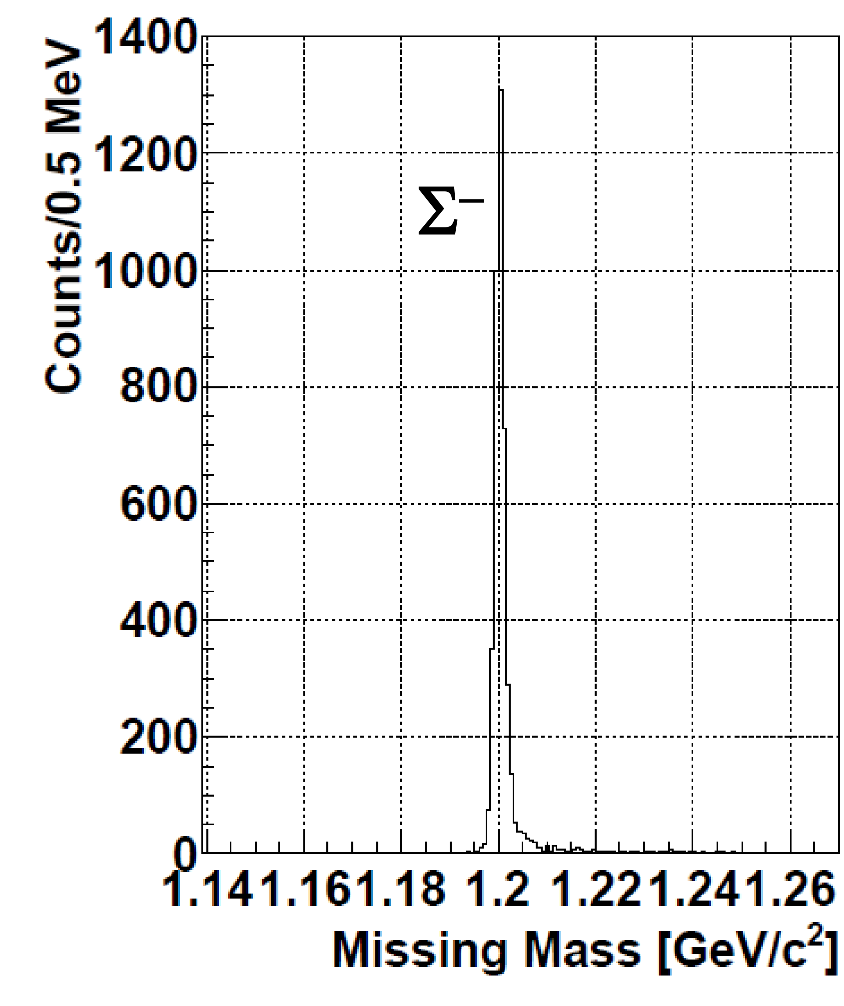
Installation : 2009/4-10

Status on Feb 2010

Commissioning 2009/10-2010/2

- **All detectors checked and ready**
- **Commissioning data taken :**
  $p(\pi^-, K^+)\Sigma^-$, $p(\pi^-, p)\pi^-$
- **E19 test data**

Status on Feb 2010



Commissioning 2009/10-2010/2

- **All detectors checked and ready**
- **Commissioning data taken :**
  $p(\pi^-, K^+)\Sigma^-$, $p(\pi^-, p)\pi^-$
- **E19 test data**

Performance of SKS
ΔM_Σ = 1.6 MeV/c^2 (FWHM)
(p_π = 1.25 GeV/c)

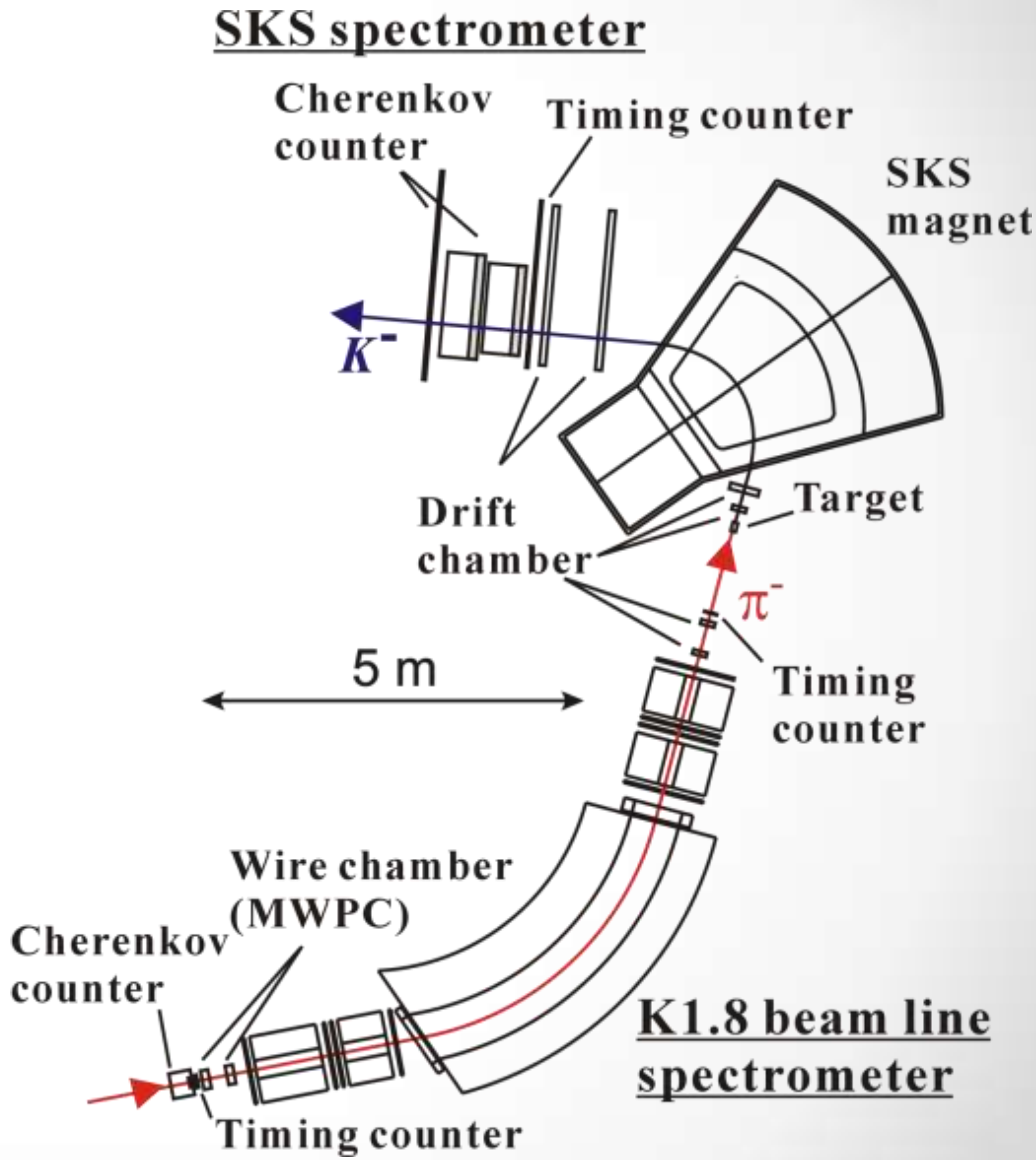
Commissioning of K1.8 system successful

K1.8 beam line setup

K1.8 beam line spectrometer & SKS
⇒Missing mass spectroscopy

- **K1.8 beam line spectrometer : p_π**
  - **PID counters**
    - Timing counters : TOF
    - Gas Cherenkov (π/e) : n=1.002
  - **Tracking**
    - MWPCs : 1 mm pitch
    - MWDCs : 3 mm pitch
- **SKS system : p_K**
  - **PID counters**
    - Timing counter
    - Aerogel Cherenkov (K/π) : n=1.05
    - Lucite Cherenkov (K/p) : n=1.49
  - **Tracking**
    - MWDCs : 3 mm pitch
    - DCs : 10 mm pitch, 2m×1m size

＊Target: Liquid hydrogen ~0.86 g/cm^2
- Free from Fermi motion effect



Data summary of E19

∗Beam time : 2010/10-11 (~250 hours)

Data

- **Empty run (no Liquid hydrogen) :**
  Check background from target materials

- **Calibration data : Check cross section, mass resolution, absolute value of missing mass**
  - **$p(\pi^-, K^+)\Sigma^-$ run @ 1.37 GeV/c**
  - **$p(\pi^+, K^+)\Sigma^+$ run @ 1.37 GeV/c**

  ∗1.37 GeV/c beam ⇒ Same as K momentum for Θ^+ run

- **Θ^+ production run : October (50 hours)/November (82 hours)**
  - **$p(\pi^-, K^-)$ @ 1.92 GeV/c**

  ⇒7.8 $\times 10^{10}$ π (E522 total beam ×10 times)

∗Beam intensity : ~1 M/spill (2.2 sec extraction period)

Due to the bad beam micro-structure

Analysis

Data spectrum

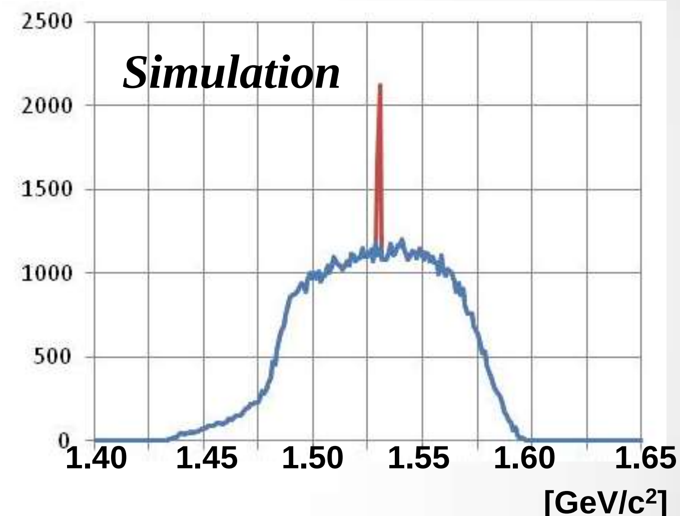
Cross section

Missing mass resolution

Physics information

Missing mass : $\pi^- + p \rightarrow \Theta^+ + K^-$ @ 1.92 GeV/c
(sqrt s = 2.14 GeV)

- Θ^+ peak + Background (associated reaction)
  - Incisive measurement



Assumed σ_Θ = 2 μb
ΔM= 2 MeV/c^2(FWHM)

- **Cross section (or upper limit)**
  - Differential CS
    - Scattering angle : 2° to ~15°
    - Mass dependence : Angular acceptance
  - Total CS : Assuming angular dependence
- **Θ^+ mass (if observed)**
  - Absolute value with a few MeV error
- **Width**
  - Direct measurement (if observed)
  - Estimated from cross section

Analysis chart

New event

↓

Trigger counter : BH1&2, TOF, LC

↓ **Time-of-flight, ADC&TDC cut**

SKS drift chamber : SDC1&2, SDC3&4 (Local tracking)

SKS tracking : Scattered particle momentum

↓ **K out selection**

K1.8 chamber : BC1&2, BC3&4 (Local tracking)

K1.8 tracking : Beam momentum

↓ **π in selection**

Vertex reconstruction : (π, K) event reconstruction

↓ **Good vertex event**

Missing mass : Cross section

Analysis chart

New event

↓ **Event selection**

Trigger counter : BH1&2, TOF, LC

↓ **Time-of-flight, ADC&TDC cut**

K event & Momentum : p_K

SKS drift chamber : SDC1&2, SDC3&4 (Local tracking)

SKS tracking : Scattered particle momentum

↓ **K out selection**

K1.8 chamber : BC1&2, BC3&4 (Local tracking)

K1.8 tracking : Beam momentum

↓ **π in selection**

Vertex reconstruction : (π, K) event reconstruction

π event & Momentum : p_π

↓ **Good vertex event**

Missing mass : Cross section

Particle identification

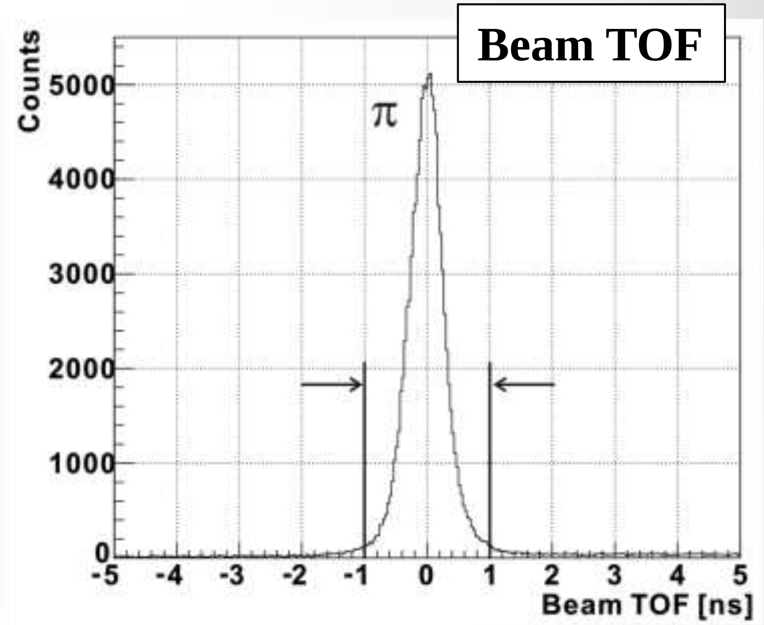
- **Beam π**
  - **Time-Of-Flight**

    Electrons rejected by GC

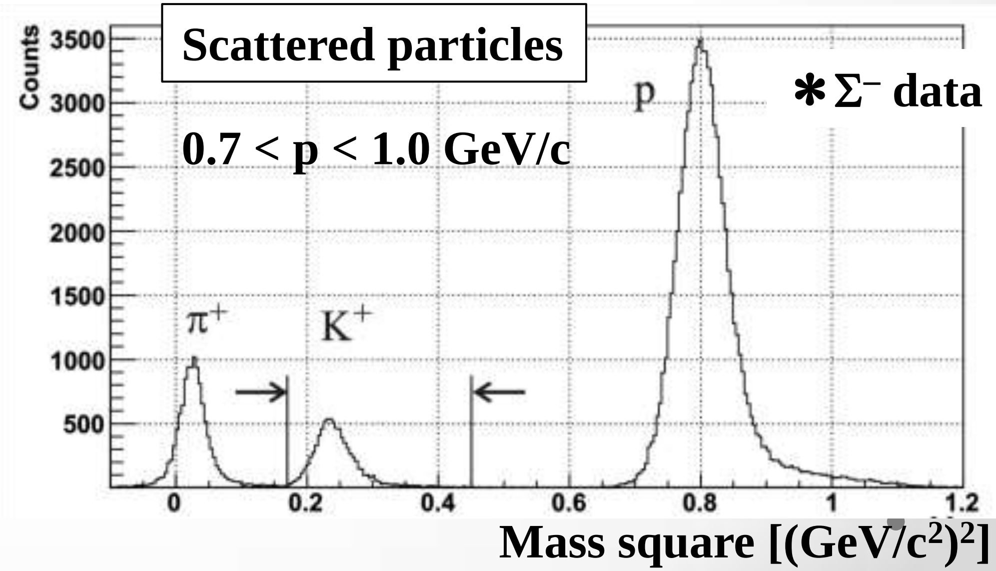
    ⇒ e/π ~ 0.0005 @ 1.92 GeV/c
- **Scattered K**
  - **TOF**

  + Path length & momentum

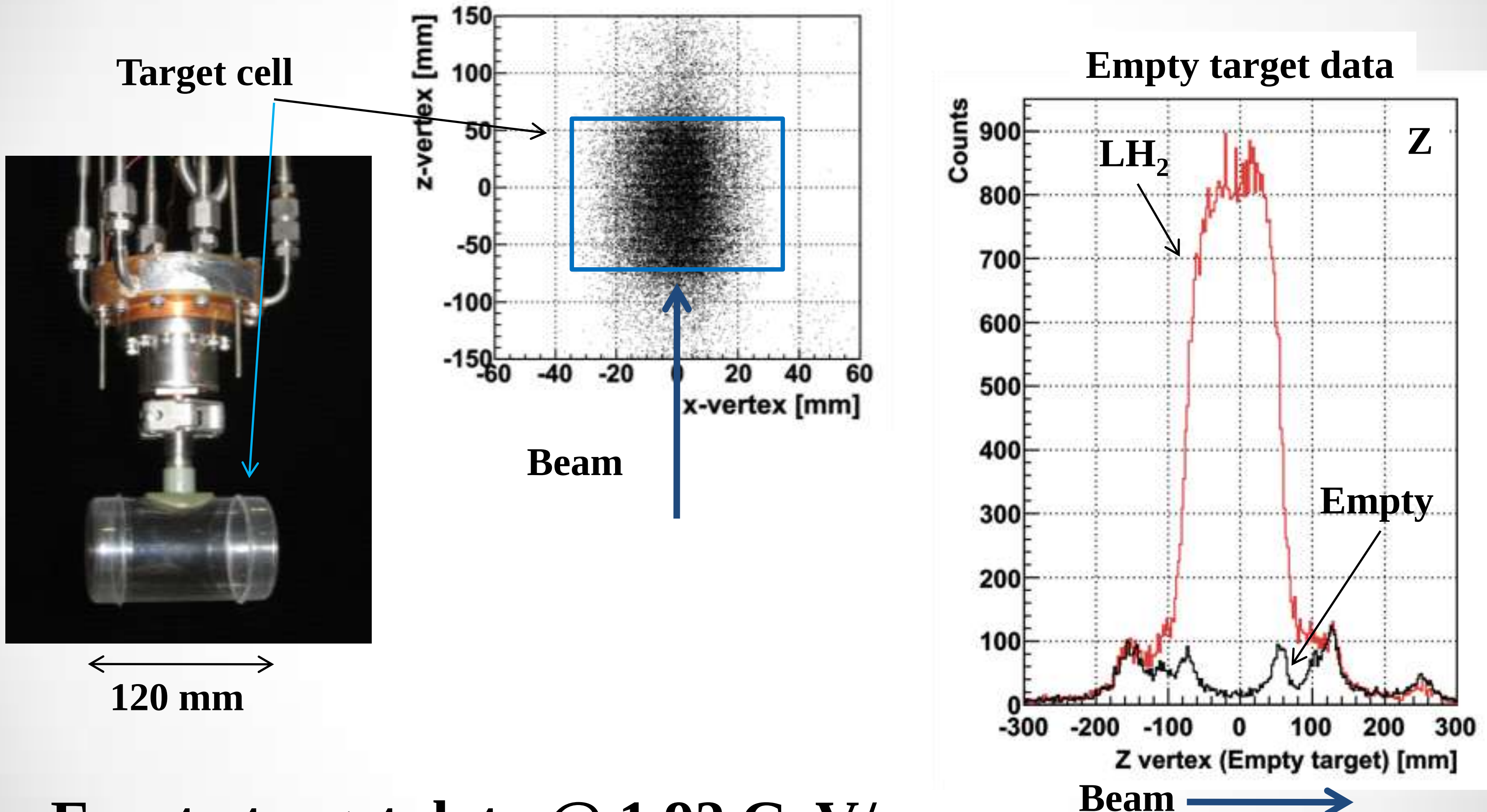
  ⇒$M^2 = p/\beta(1-\beta^2)$



Beam π and scattered K are clearly separated.



Vertex reconstruction

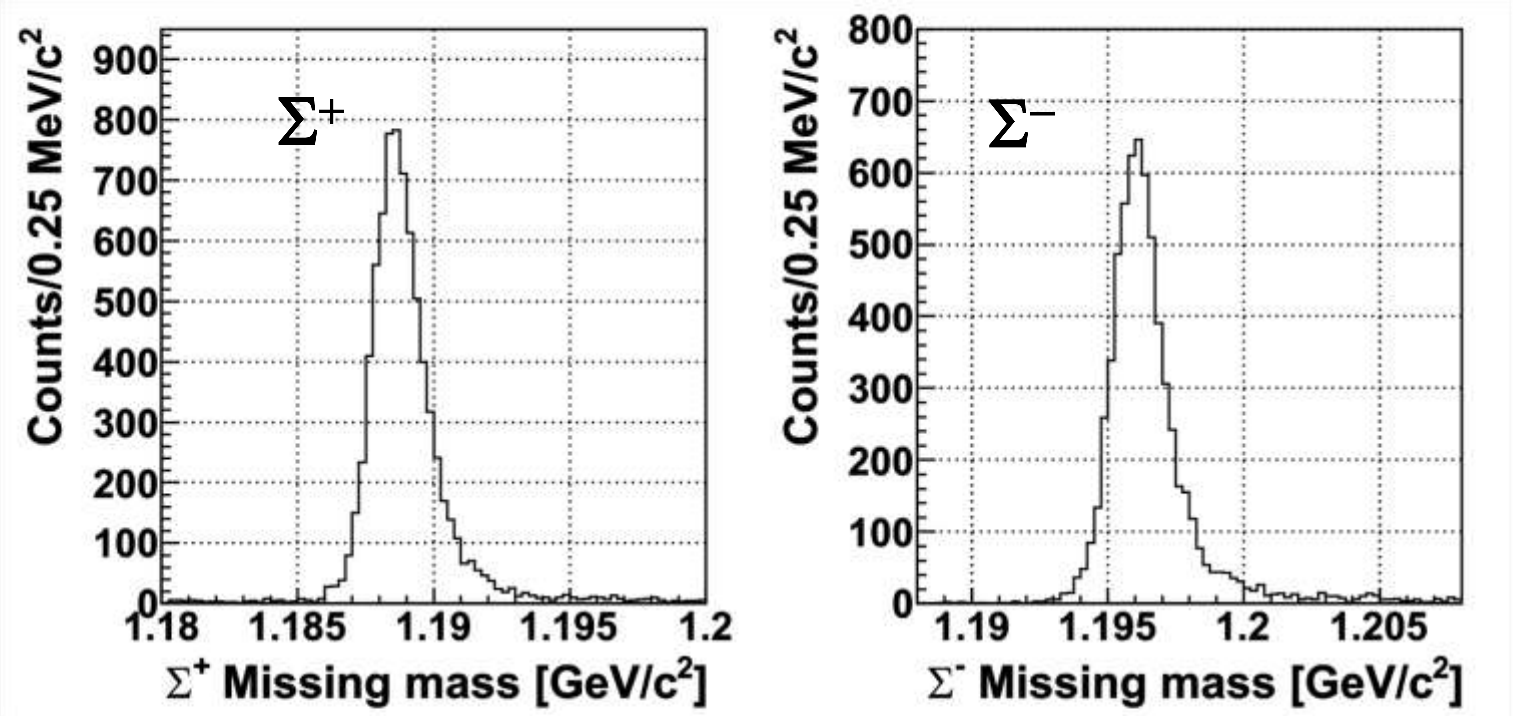


Empty target data @ 1.92 GeV/c

– ~3 % background in the selected region

Missing mass

$$M = \sqrt{(E_\pi + M_A - E_K)^2 - (p_\pi^2 + p_K^2 - 2 p_\pi p_K \cos\theta_{\pi K})}$$



$\Sigma^\pm$: ΔM_Σ = 1.9 ± 0.1 MeV/c^2 (FWHM)

⇒To estimate Θ^+ missing mass resolution

ΔM_Θ = 1.4 ± 0.1 MeV/c^2 (FWHM) ($\Delta M \propto M_{target}/M_\Theta$)

Error of the absolute mass value : ~2 MeV/c^2

Cross section

Target	Beam	Other analysis	SKS

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{1}{(\rho x)N_A} \cdot \frac{1}{N_{beam} \times f_{beam} \times \varepsilon_{K18}} \cdot \frac{1}{\varepsilon_{DAQ} \times f_{abs} \times \varepsilon_{Vertex}} \cdot \frac{N}{\varepsilon_{SKS} \times f_{Decay} \times \Delta\Omega}$$

$$\varepsilon_{K18} = \varepsilon_{BC12} \times \varepsilon_{BC34} \times \varepsilon_{K18track} \times \varepsilon_{single-track}$$

$$\varepsilon_{SKS} = \varepsilon_{SDC12} \times \varepsilon_{SDC34} \times \varepsilon_{SKStrack} \times \varepsilon_{TOF} \times \varepsilon_{LC} \times f_{AC} \times \varepsilon_{PID} \times \varepsilon_{Matrix}$$

- **Tracking part**

  BC1&2, BC3&4, SDC1&2, SDC3&4, K1.8, SKS

  Single track selection

- **Counter, PID part**

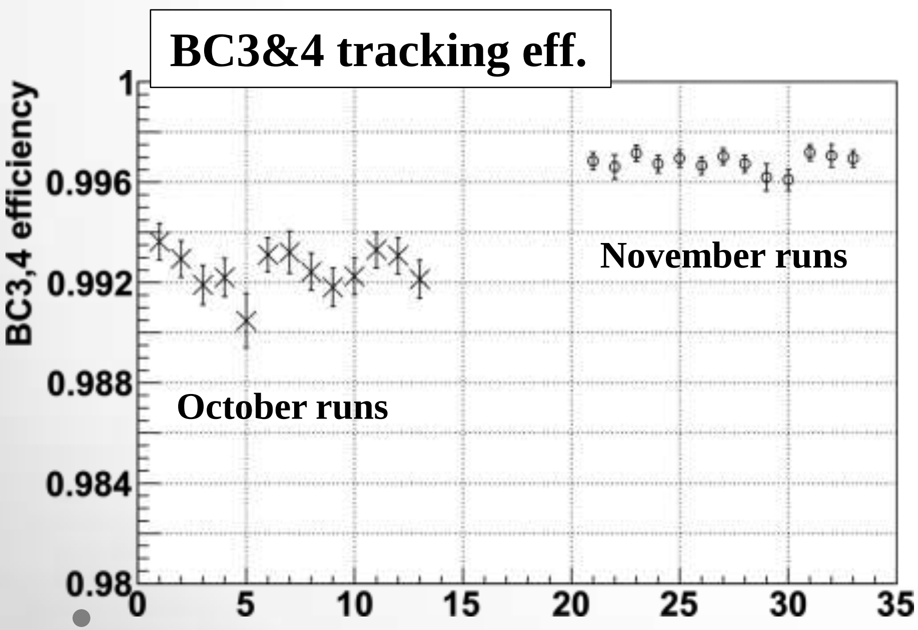
  Beam π selection, TOF, LC, AC, scattered K selection

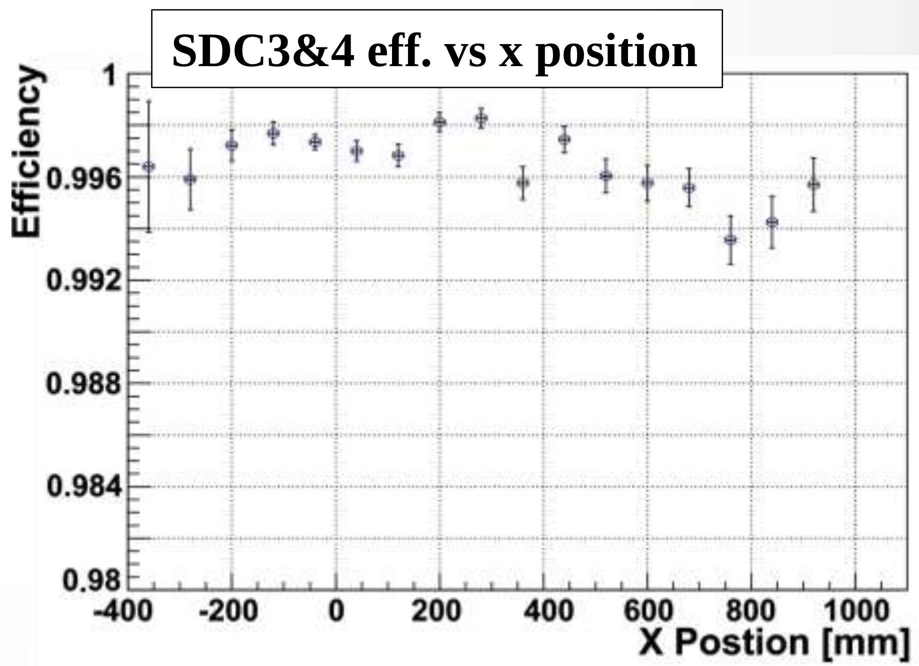
- **Other part**

  Decay, absorption, vertex, matrix trigger, acceptance

Efficiency studies

- **Beam line chambers**
  - **⇒Stability checked during the Θ^+ production run**
- **Trigger counters, SDC3&4**
  - **⇒No position dependence**
- **Absorption, K decay, beam μ contamination**
  - **⇒Simulation by realistic experimental conditions with Geant4**





Cross section

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{}{(\ldots} \ldots \frac{N}{f_{Decay} \times \Delta\Omega}$$

SKS

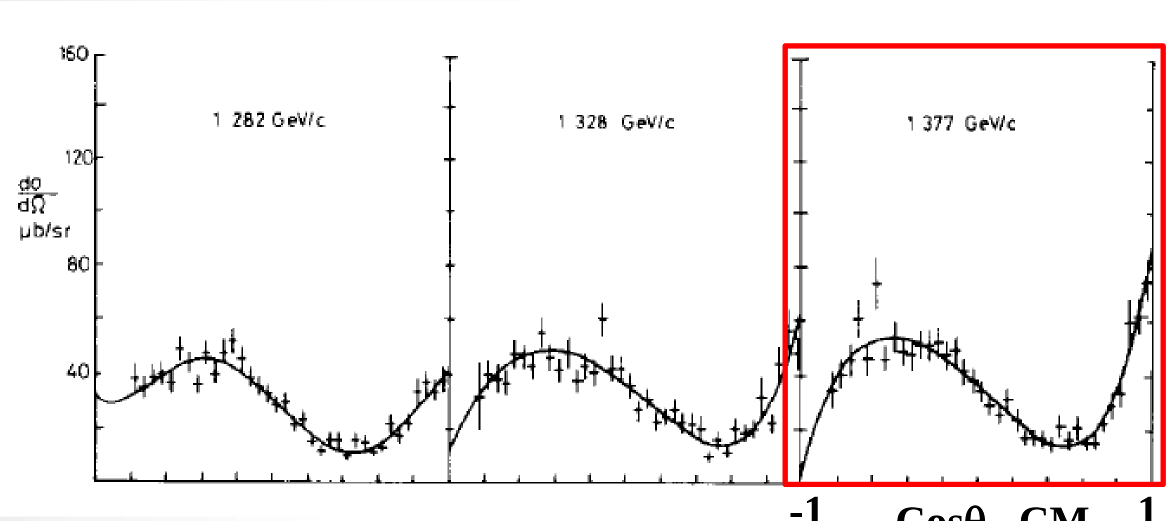
$\varepsilon_{K18} =$

$\varepsilon_{SKS} =$ … Matrix

Factors	Meaning	Values (%)
ϵ_{daq}	Data-acquisition efficiency	75.2±0.1
f_{beam}	Beam normalization factor	92.4±2.0
$\epsilon_{BC1\cdot2}$	BC1·2 efficiency	94.3±1.0
$\epsilon_{BC3\cdot4}$	BC3·4 efficiency	99.3±0.2
$\epsilon_{K1.8track}$	K1.8 tracking efficiency	93.1±0.8
$\epsilon_{single-track}$	Single track ratio	85.0±0.8
ϵ_{TOF}	TOF efficiency	99.7±0.1
ϵ_{LC}	LC efficiency	98.5±0.1
f_{AC}	AC1·2 accidental veto factor	89.8±1.2
$\epsilon_{SDC1\cdot2}$	SDC1·2 efficiency	95.6±0.2
$\epsilon_{SDC3\cdot4}$	SDC3·4 efficiency	99.8±0.2
$\epsilon_{SKStrack}$	SKS tracking efficiency	96.0±0.2
ϵ_{PID}	PID efficiency in SKS	92.9±0.5
f_{decay}	K decay factor	41.7±2.0
$f_{abs}\ (K^+)$	K^+ absorption factor	96.8±0.5
$f_{abs}\ (K^-)$	K^- absorption factor	89.4±0.5
ϵ_{vertex}	Event vertex cut efficiency	75.4±0.7
ϵ_{matrix}	The matrix trigger efficiency	99.0±0.1
	Total relative error	±6

- **Trac…**
  BC1…
  Sing…
- **Cou…**
  Bea…
- **Othe…**
  Dec…

Cross section: Σ^+

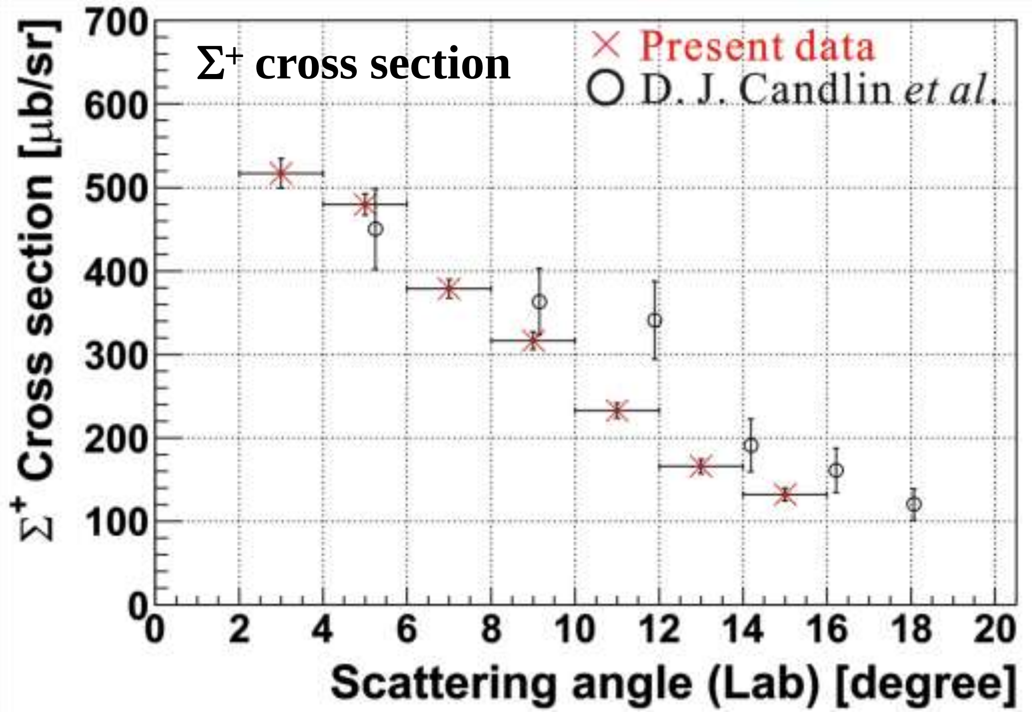


$p(\pi^+, K^+)\Sigma^+$ @ 1.377 GeV/c

D. J. Candlin *et al*.
Nucl. Phys. B226(1983)1-28

- p_π = 1.375 GeV/c @ Σ^+ run
- Old data converted to lab. frame

The present data agrees well with the previous measurements.



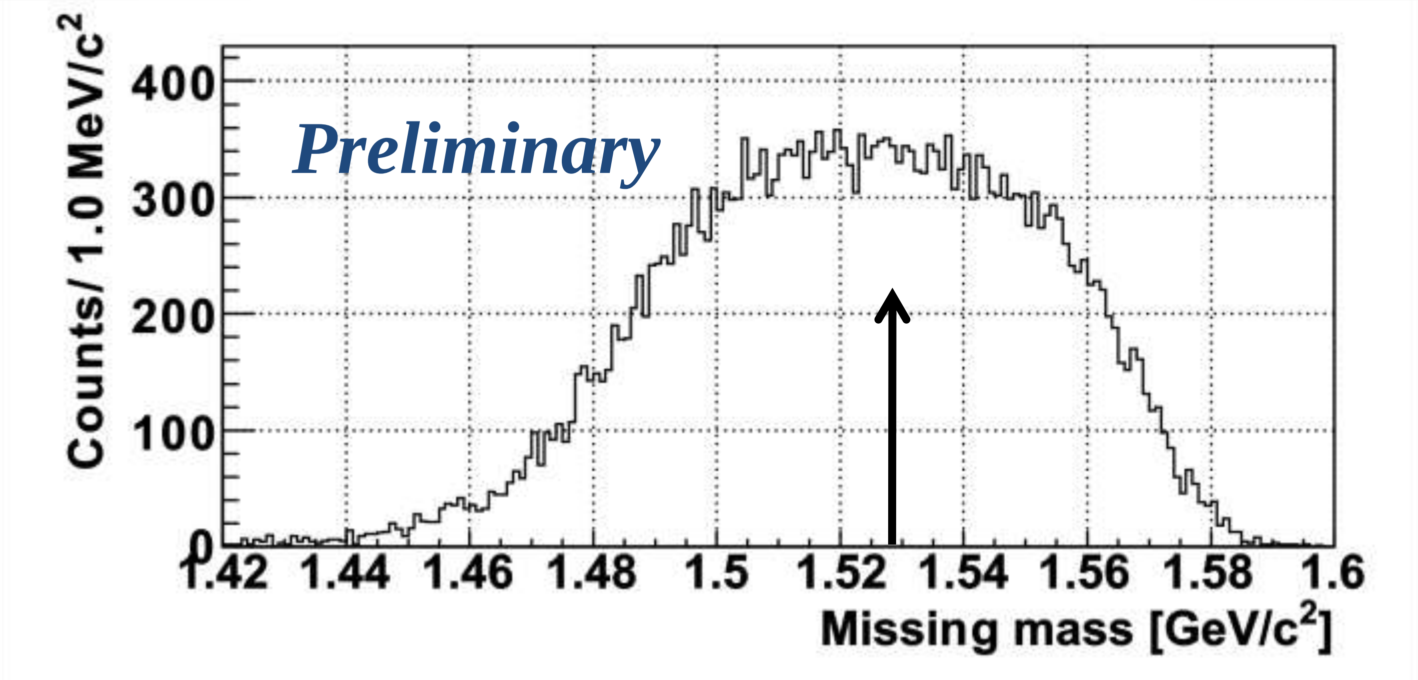
Result

Missing mass

Cross section

Missing mass spectrum

$\pi^- + p \rightarrow K^- + X$ @ 1.92 GeV/c

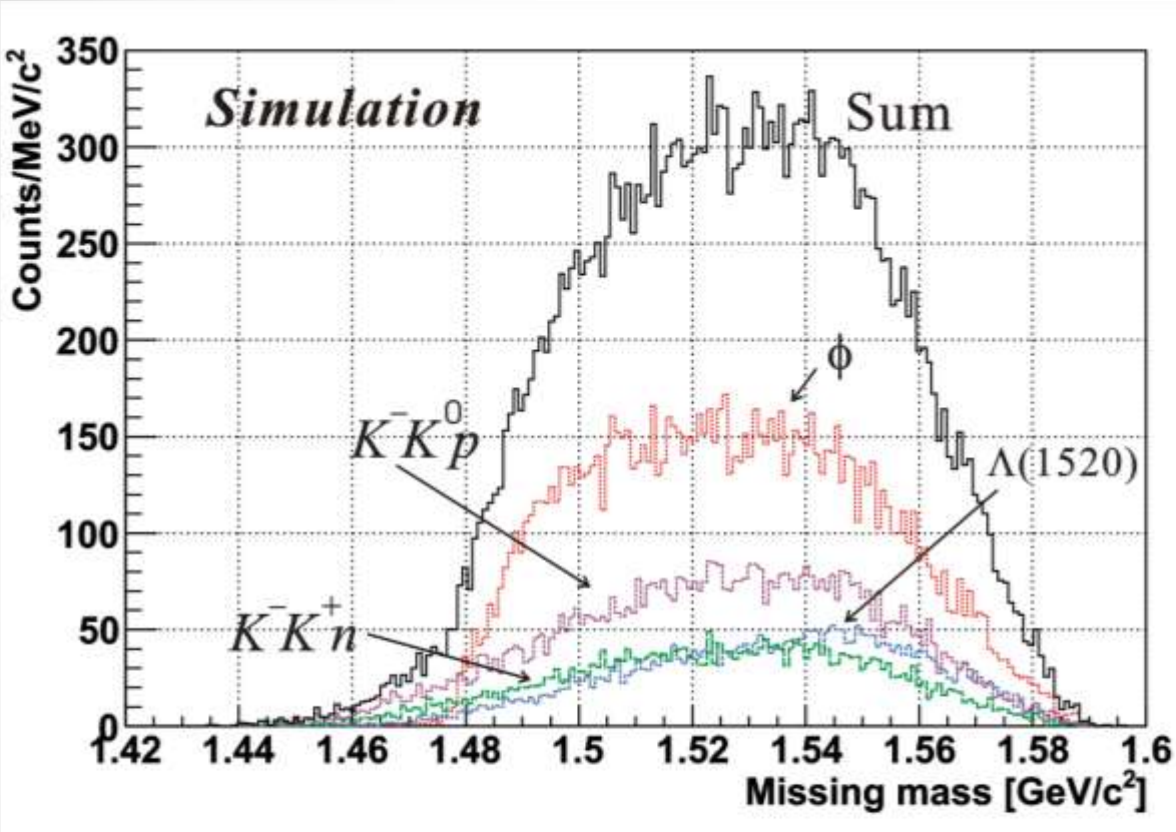


- **All event sum : 7.8×10^{10} π^-**
- **With event selection**

✱If exists
$M_\Theta \sim 1.53$ GeV/c^2

<u>No prominent peak structure observed.</u>

Comparison with background simulation



BG reactions

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

(σ = 30±8 μb)

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

$\rightarrow K^- K^0 p$

(σ = 21±5 μb)

- $\pi^- p \rightarrow K^- K^+ n$
- $\pi^- p \rightarrow K^- K^0 p$

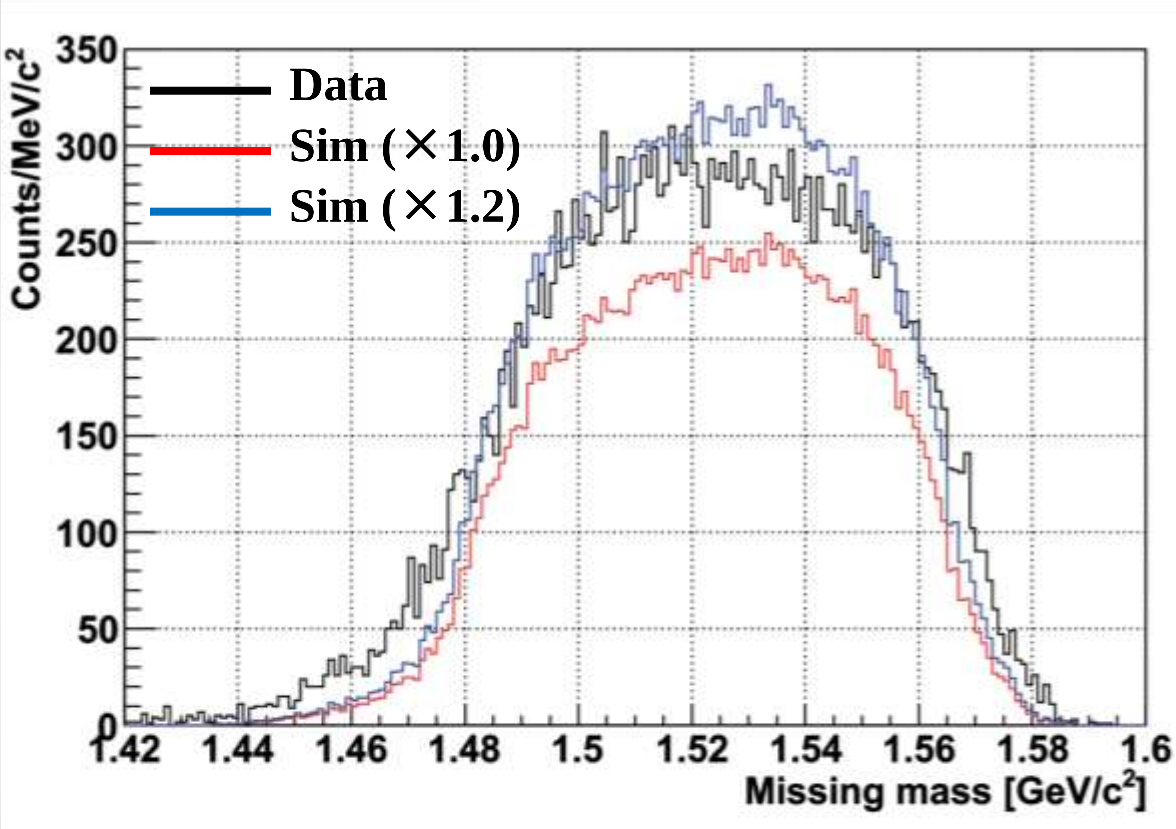
(σ ~25 μb)

O. I. Dahl *et al* .
Phys. Rev. B 163, 1377 (1967).
(Bubble chamber data)

Simulation with measured cross section using angular distributions

- ϕ production : uniform (S-wave)
- $\Lambda(1520)$: $\propto 1+\cos^2\theta_{cm}$ (D-wave)

Comparison with background simulation



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  $\rightarrow K^- K^0 p$

(σ = 21±5 μb)

- $\pi^- p \rightarrow K^- K^+ n$
- $\pi^- p \rightarrow K^- K^0 p$

(σ ~25 μb)

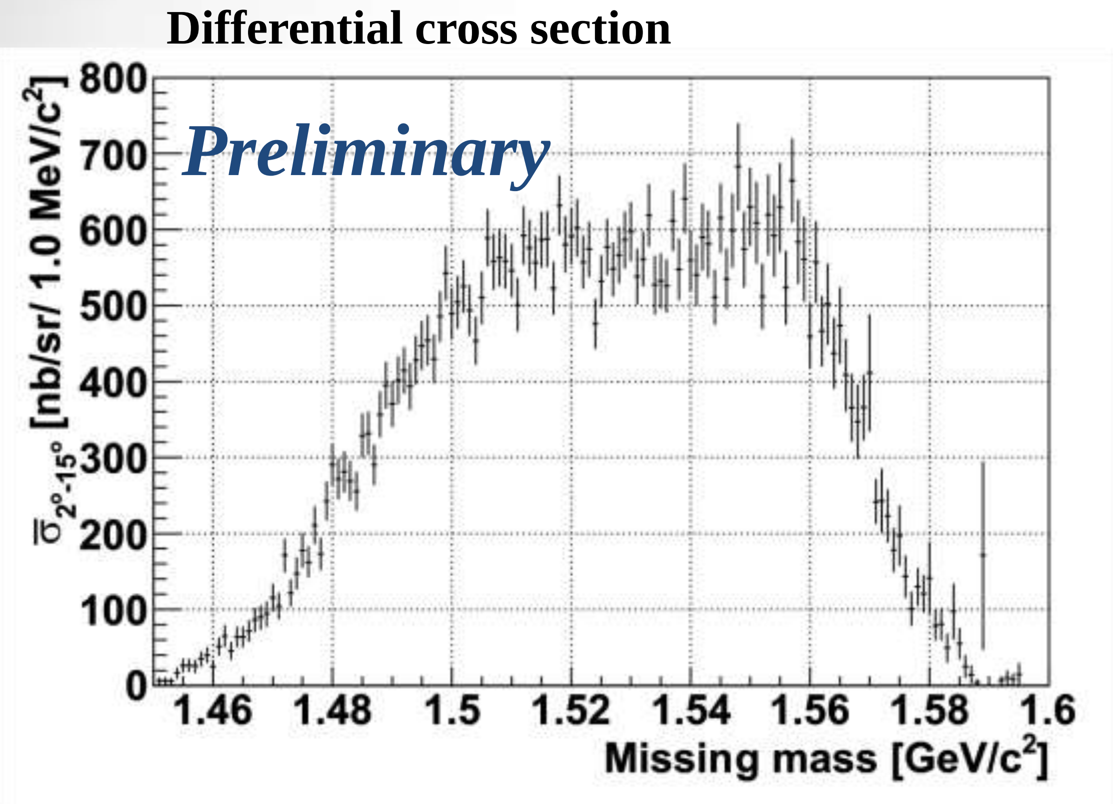
✱Agree within the error of old data : ~30%

O. I. Dahl *et al* .
Phys. Rev. B 163, 1377 (1967).
(Bubble chamber data)

Simulation with measured cross section using angular distributions

- ϕ production : uniform (S-wave)
- $\Lambda(1520)$: $\propto 1+\cos^2\theta_{cm}$ (D-wave)

Differential cross section



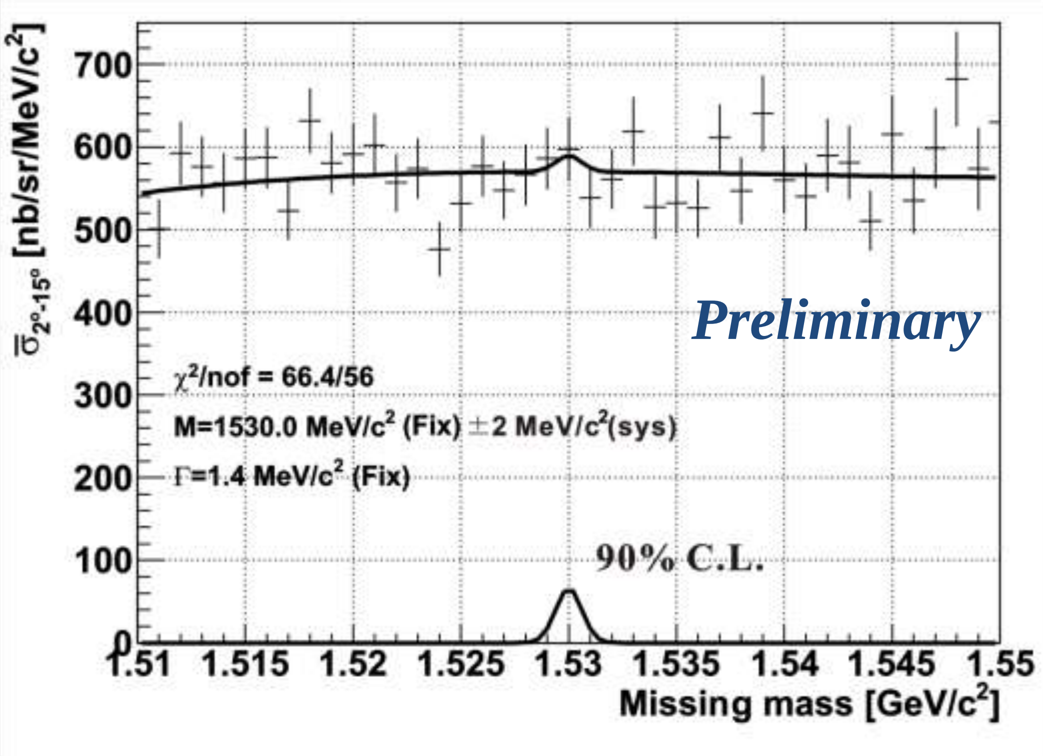
Differential cross section (Averaged 2° -15° @Lab)

⇒Obtain 90 % confidence level upper limit

Width : 1.4 MeV/c^2 fixed (Estimated Σ data)

Upper limit of cross section

Differential cross section



Scanning region
1.51-1.55 GeV/c^2

BG shape
⇒ 3rd order polynomial
Peak shape
⇒ Gaussian
(σ=1.4 MeV/c^2 fixed)

Differential cross section (Averaged 2° -15° @Lab)
⇒Obtain 90 % confidence level upper limit
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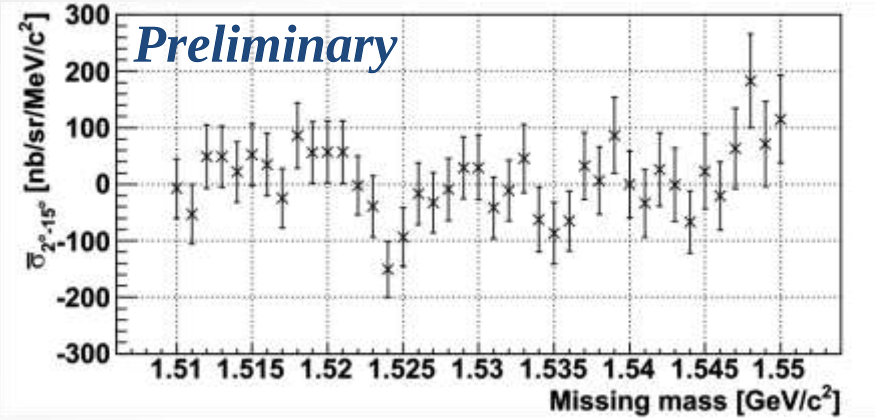
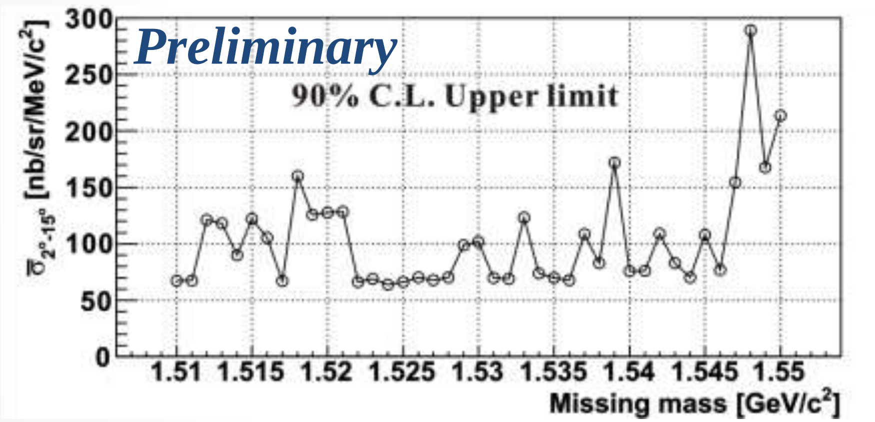




Scanning region
1.51-1.55 GeV/c^2

BG shape
⇒ 3rd order polynomial
Peak shape
⇒ Gaussian
(σ=1.4 MeV/c^2 fixed)

Assumed : Γ_Θ ~ 0 MeV/c^2

Upper limit cross section : < 300 nb/sr @ 1.51–1.55 GeV/c^2

Evaluation of systematic errors is ongoing.

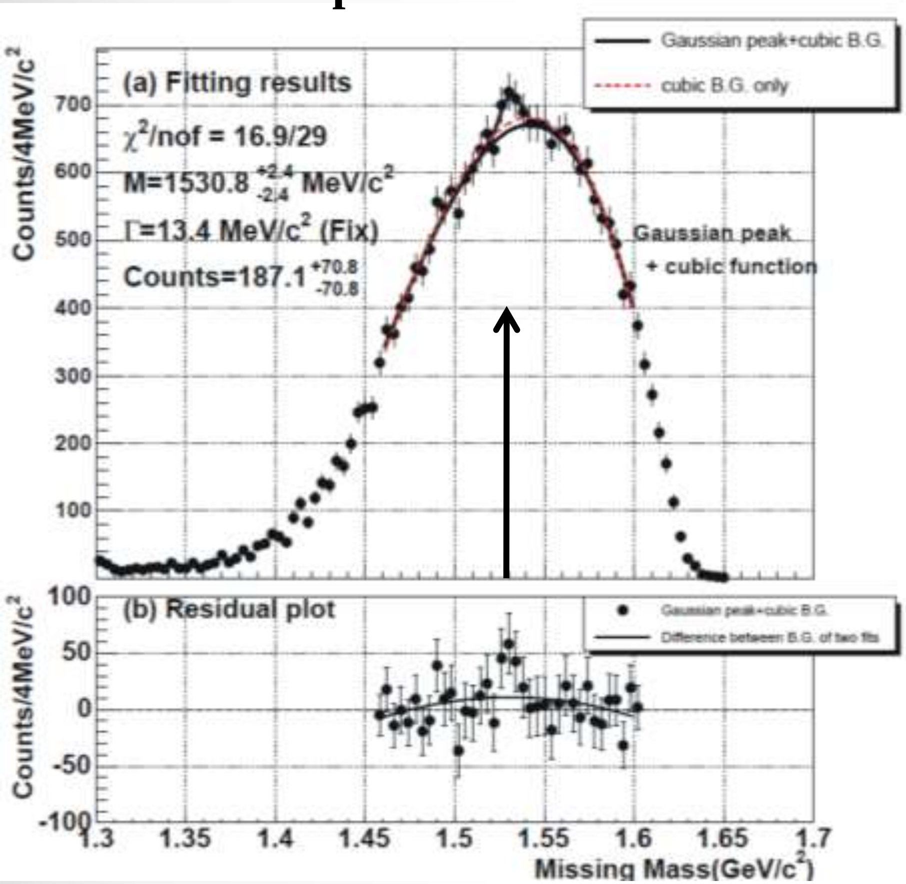
Cross section @ if M_Θ = 1.53 GeV/c^2

Differential : <u>100 nb/sr</u> (averaged 2° –15°)
Total : <u>150 nb</u>
(S-wave production and isotropic K^- emission ⇒ 8% acceptance)

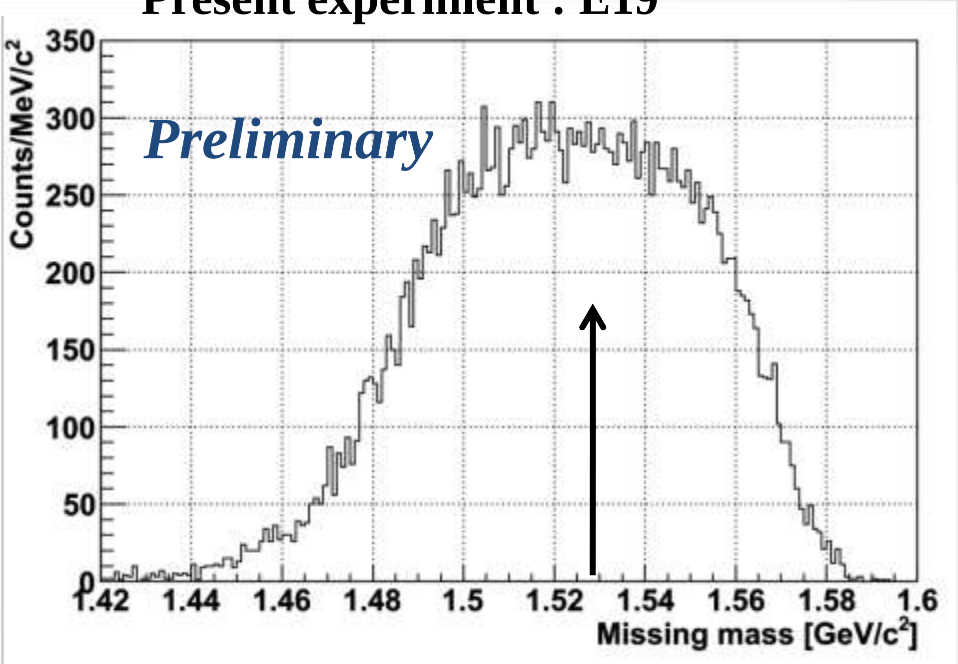
Discussion

Experiment

Previous experiment : E522



Present experiment : E19



✱If σ_{total} = 200 nb @ Γ~1 MeV/c²
⇒ > 200 counts peak

Total yield (10 times) + Resolution (13.6 MeV/c² ⇒ 1.4 MeV/c²)
⇒10 times higher sensitivity

Bump observed in E522 was not confirmed.

Theoretical calculation

Upper limit : < 0.3 μb @ 1.54 GeV/c^2

Theoretical calculations :
T. Hyodo, private communication

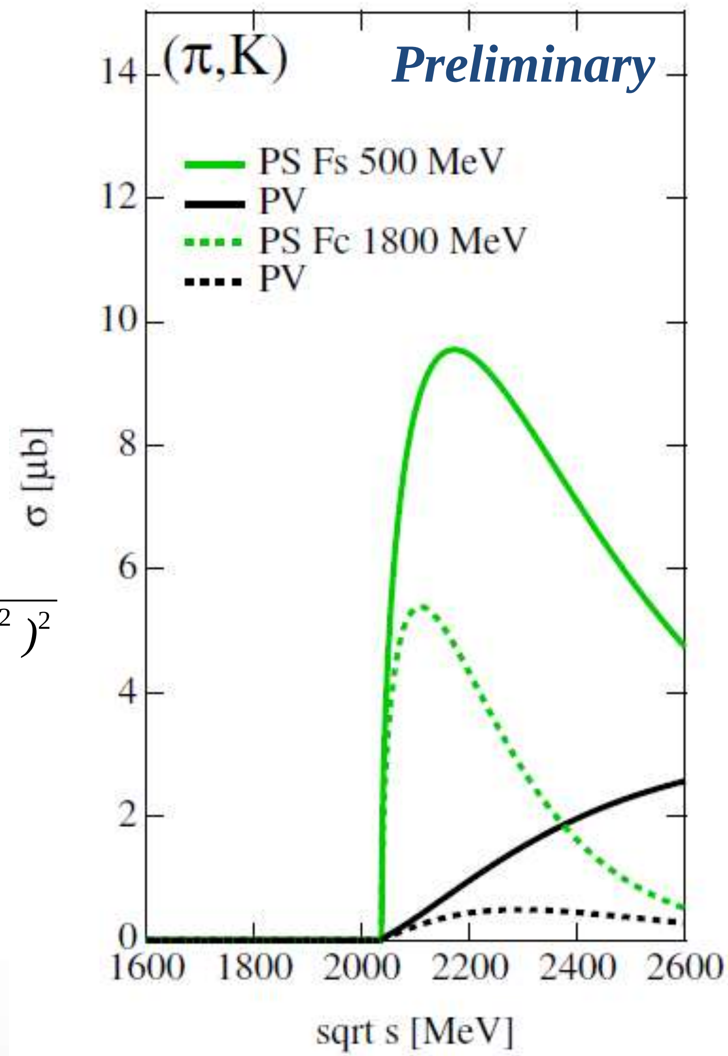
		P_{lab}= 1.92 GeV/c
PS	Fs 500MeV	9.2 μb
	Fc 1800MeV	5.3 μb
PV	Fs 500MeV	0.51 μb
	Fc 1800MeV	0.29 μb

✱Integrated over the whole solid angle

$$* Fs = \frac{\Lambda^2}{\Lambda^2 + q^2}$$

$$* Fc = \frac{\Lambda^4}{\Lambda^4 + (x - m_x{}^2)^2}$$

$J^P = 1/2^+$, $\Gamma_{\Theta+}$ = 1MeV



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	Fc 1800MeV	5.3 μb
PV	Fs 500MeV	0.51 μb
	Fc 1800MeV	0.29 μb

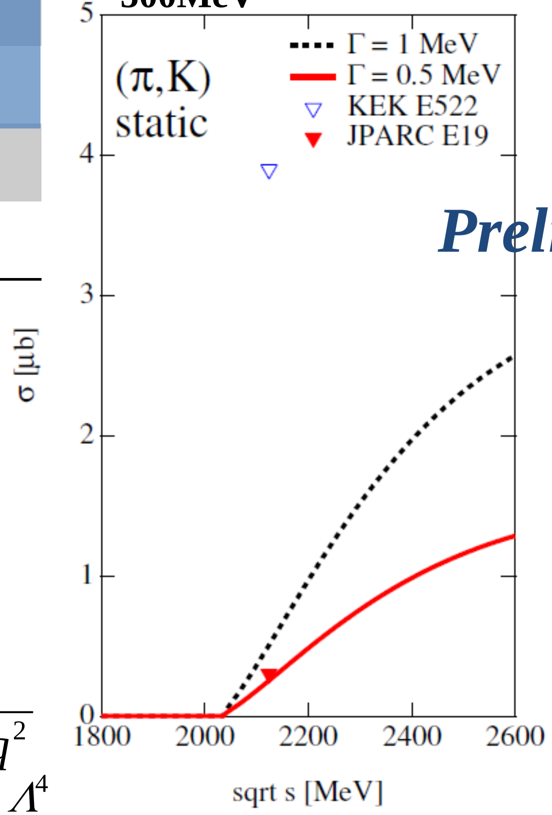
＊Integrated over the whole solid angle

＊Upper limit of width
Γ < 0.5 MeV/c^2 @ Fs
Γ < 1.0 MeV/c^2 @ Fc
@ PV scheme

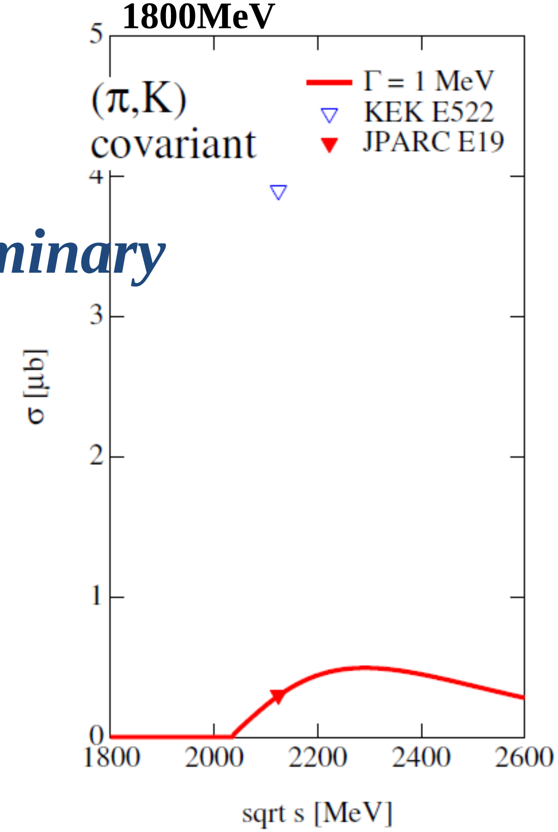
$$* Fs = \frac{\Lambda^2}{\Lambda^2 + q^2}$$

$$* Fc = \frac{\Lambda^4}{\Lambda^4 + (x - m_x{}^2)^2}$$

Fs
500MeV



Fc
1800MeV



Preliminary

↑ p_{lab}=1.92GeV/c

↑ p_{lab}=1.92GeV/c

Cross section for π & photo-induced reaction

- **Present result : < 300 nb/sr (2° -15°)**
- **LEPS result : 12±2 nb/sr (LEPS acceptance)**

Liu&Ko	PS	Fs (0.5 GeV)	5 μb	π p→K Θ
	PS	Fc (1.2 GeV)	~8 nb	γ p→K Θ
Oh	PS	w/o FF	8 nb	γ p→K Θ
	PS	Fs (0.75)	1.5 nb	γ p→K Θ
	PS	Fc(1.8)	24 nb	γ p→K Θ
	PS	w/o FF	120 μb	π p→K Θ
	PS	Fs (0.5)	9 μb	π p→K Θ
	PS	Fc (1.8)	4 μb	π p→K Θ

Cross section for π & photo-induced reaction

- Present result : < 300 nb/sr (2° -15°)
- LEPS result : 12±2 nb/sr (LEPS acceptance)

Consistency check

＊Need PV scheme calculation for comparison

+ Photo-induced reaction by changing the Θ^+ magnetic moment

γ-induced : Nam et al. PLB633,483(2006)

PV, Fc (0.75GeV), k_Q=1

- for $J^P=1/2^+$, σ=1.5 nb at $E\gamma$=2GeV
- for $J^P=3/2^+$, σ=25 nb at $E\gamma$=2GeV
- for $J^P=3/2^-$, σ=200 nb at $E\gamma$=2GeV
- for $J^P=1/2^-$, σ~0.3 nb* at $E\gamma$=2GeV

*hep-ph/0403009

π-induced : Hyodo, priv. comm.

PV, Fs (0.5GeV), $J^P = 1/2^+$

- σ=0.51 μb at p_π=1.92 GeV/c

PV, Fc (1.8GeV), $J^P = 1/2^+$

- σ=0.30 μb at p_π=1.92 GeV/c

Summary of E19

- J-PARC E19 : High-resolution search via $\pi^- p \rightarrow K^- \Theta^+$ reaction
  The first physics experiment at the J-PARC hadron facility !

- Data taking of E19 has been successfully carried out.
  - 7.8×10^{10} π^- irradiated on LH_2 target
  - Calibration data : $p(\pi^{\pm}, K^+)\Sigma^{\pm}$ @ 1.37 GeV/c
    - Θ^+ missing mass resolution : 1.4 MeV/c^2 (FWHM) (Expected)
    - Consistent $\Sigma^{\pm}$ cross section (Measured)

  ⇒More than 10 time higher sensitivity achieved.

- Preliminary experimental result
  ＊No clear Θ^+ peak structure observed
  - Differential cross section : $\sigma < 300$ nb/sr @ 1.51-1.55 GeV/c^2
    (2° -15° @ Lab, 4° -40° @ CM)
  - Total cross section : $\sigma < 300$ nb @ 1.54 GeV/c^2

  ⇔ Theoretical calculation (σ ~300-500 nb)
  - Upper limit of width : $\Gamma < 1$ MeV/c^2 @ Fc

＊1st step of J-PARC E19 successfully finished !

⇒2nd step : 2 GeV/c beam data taking at K1.8 beam line

Future plan

Θ^+ search

Other exotic hadron search

2^{nd} step beam time

Upper limit : < 0.3 μb @ 1.54 GeV/c^2

		P_{lab}= 1.92 GeV/c	P_{lab}= 2 GeV/c
PS	Fs 500MeV	9.2 μb	9.8 μb
	Fc 1800MeV	5.3 μb	4.9 μb
PV	Fs 500MeV	0.51 μb	0.75 μb
	Fc 1800MeV	0.29 μb	0.50 μb

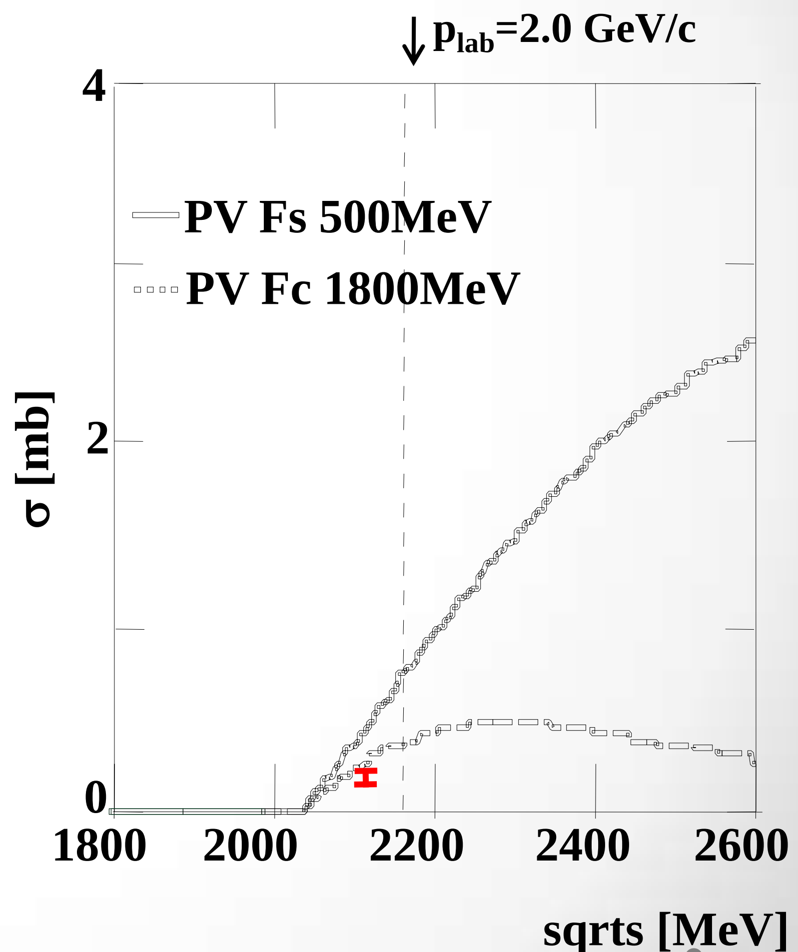
＊Integrated over the whole solid angle

2 GeV/c beam : the next step,
take data & accumulate statistics.

Sensitivity = 75 nb/sr (lab)
corresponds to an stringent limit to the decay width of Θ^+:
1 MeV × (75 nb/sr / 300 nb/sr)
< 0.2 MeV

Theoretical calculations :
T. Hyodo, private communication

$J^p=1/2^+$, $\Gamma_{\Theta+}$ = 1MeV



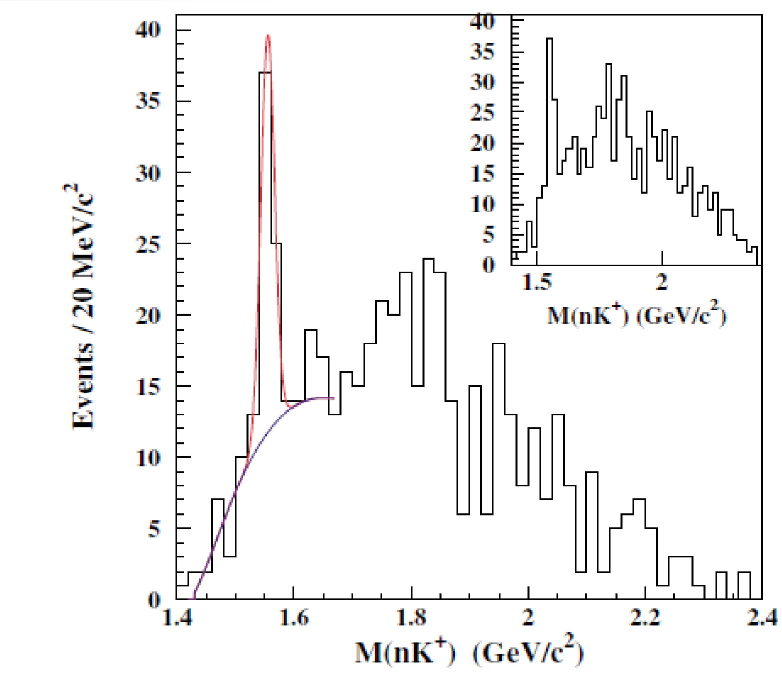
Possibility

N* coupling ($g_{KN^*\Theta}$)

CLAS data suggested : Mass ~2.4 GeV/c^2

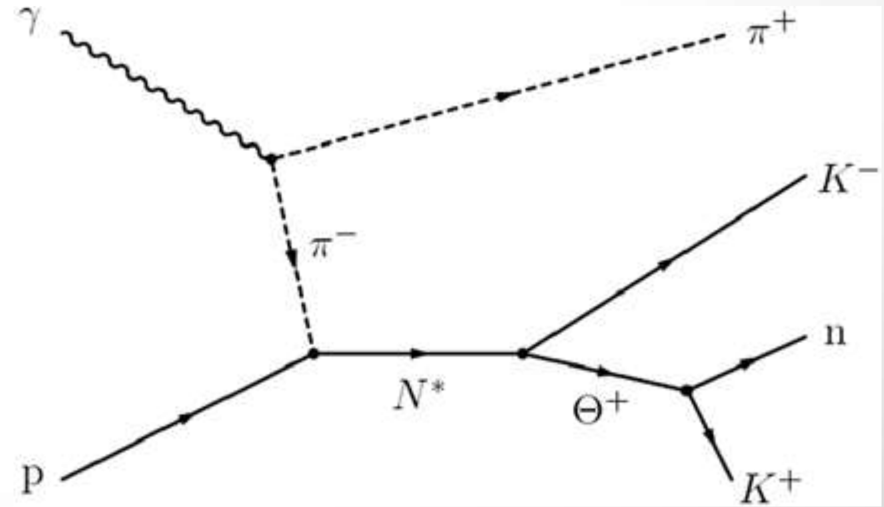
⇒Hadron beam : Threshold = p_π ~2.5 GeV/c

∗ Need **higher momentum beam** (K1.8 max: 2 GeV/c)



V. Kubarovsky *et al*.
Phys. Rev. Lett. 92(2004)032001

N * production diagram



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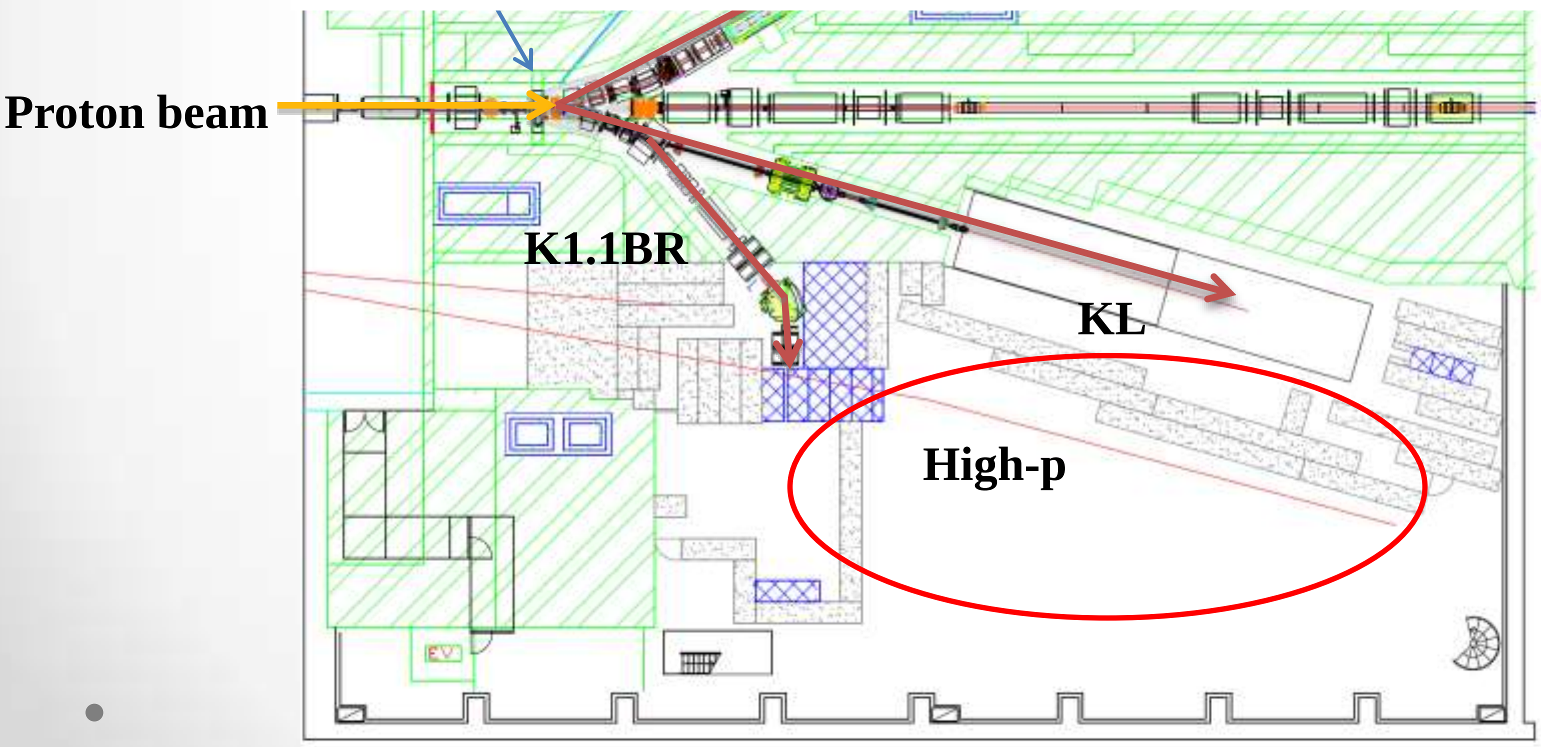


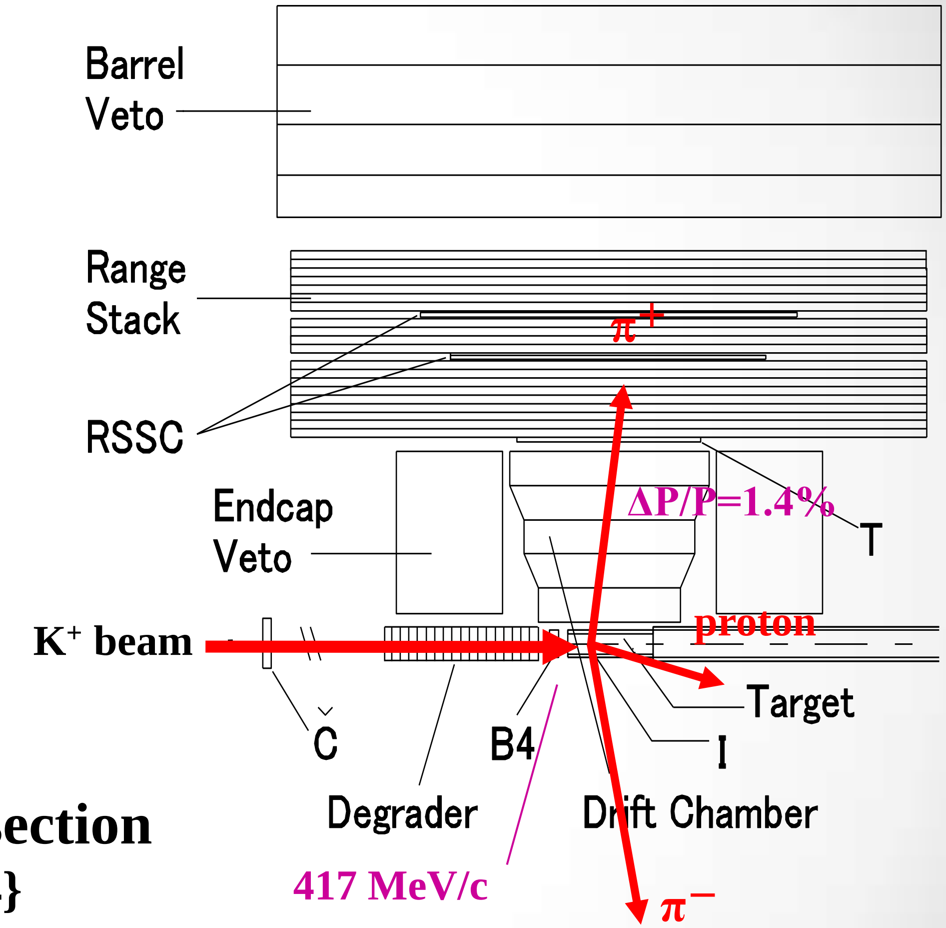
Search for Θ^+ in formation reaction

P09-LOI, T. Nakano *et al.*

- $K^+ n \rightarrow \Theta^+$
  $\rightarrow K_S^0\, p \rightarrow \pi^+ \pi^- p$
  - $p(K^+)$ = 417 (442) MeV/c
  - for M_Θ = 1.53 (1.54) GeV/c^2

⇒K1.1BR beam line w/ degrader

- π^+, π^- & proton detection with 4π spectrometer



- Determine width from cross section
  - $\sigma(E) = (\pi/4k^2)\, \Gamma^2/\{(E-m)^2+\Gamma^2/4\}$
  - σ_{tot} = 26.4 x Γ mb/MeV
- Spin measurement
  - Decay angular distribution : 1 (1/2) or $1+3\cos^2\theta$ (3/2)?

Search for Θ^+ via the (K^+, p) reaction

LOI, K. Tanida *et al.*

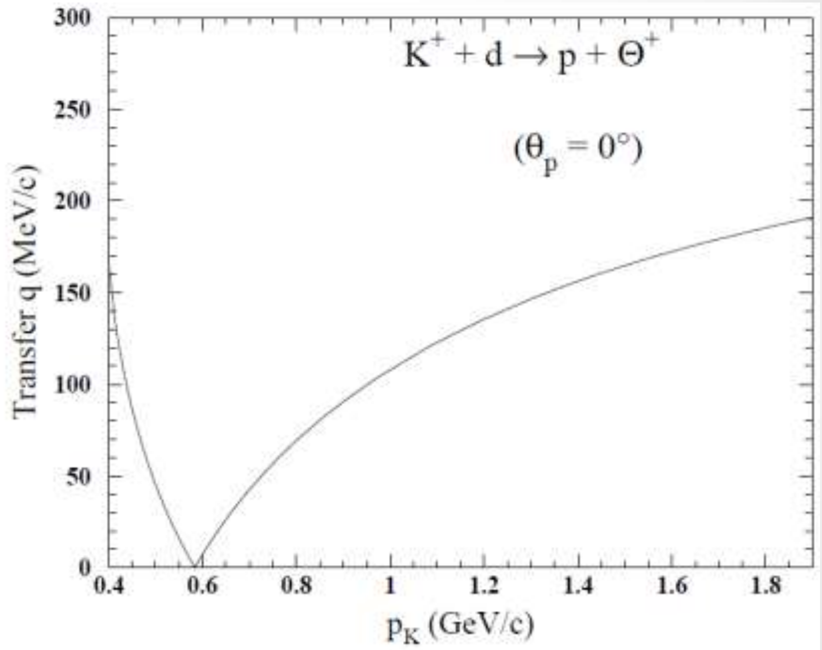
- Reaction process : $d(K^+, p)\Theta^+$ (have not been searched)
- Beam momentum : p_K ~1 GeV/c
  - p_K ~0.6 GeV/c: Magic mom
  - p_K ~1 GeV/c ⇒ q_Θ ~120 MeV/c @ 0˚ (p_p ~1.1 GeV/c)

⇒K1.1 beam line

- Detection of p: SKS
  - High resolution: ~3 MeV/c^2
- $d\sigma/d\Omega$ ~1 μb/sr (Γ_Θ ~ 1 MeV/c^2) [Nagahiro & Hosaka]
- Background process (1 GeV/c, θ_p~0˚)
  - $K^+p \rightarrow K^+p$: 5 mb/sr
  - $K^+n \rightarrow K^0p$: 1.5 mb/sr

⇒Need surrounding detector : Sideway type

To detect $\Theta^+ \rightarrow p K_s^0 \rightarrow p \pi^+ \pi^-$



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    (p_p ~1.1 GeV/c)

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  [Nagahiro & Hosaka]
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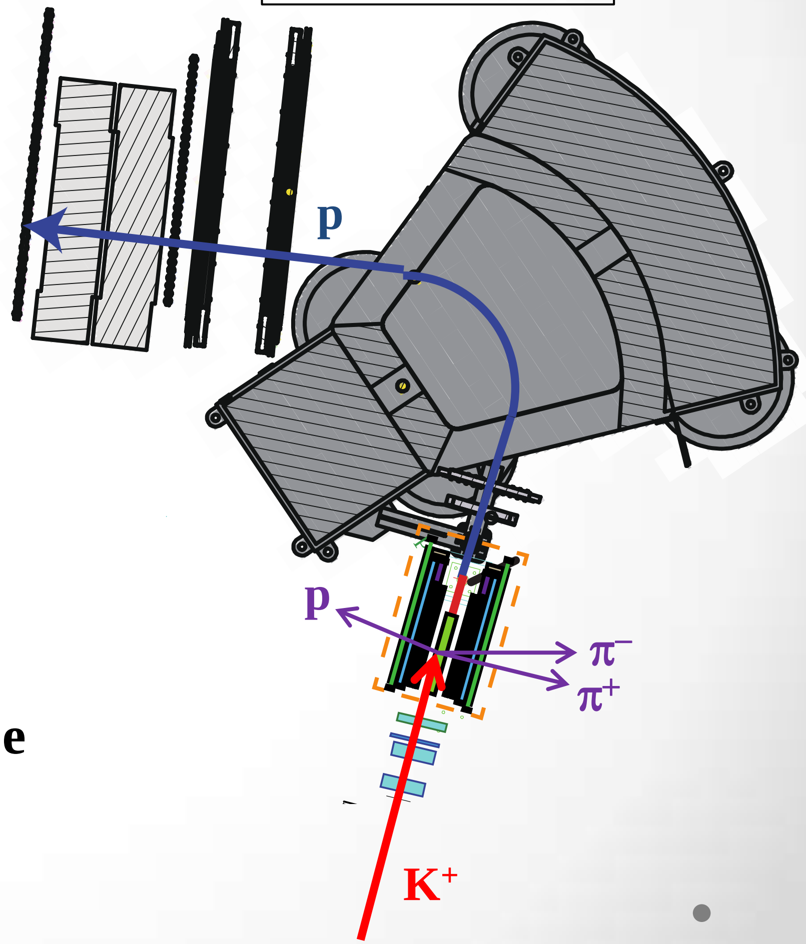
Detector image



In FUTURE…

- **Other pentaquarks**
  - **$\Xi_5^{--}(1862)$: $dds s\bar{u}$**

  via $K^- n \rightarrow \Xi^{--} K^+$ @ $p_{th} = 2.4$ GeV/c
  - **$\Theta^0_c(3100)$: $uudd\bar{c}$**

  via $p\,p \rightarrow p\,p\,\Theta^0_c\,X$ @ $p_{th} = 12.3$ GeV/c

∗ Experiment at High Momentum (Separated) beam line

⇒ For future hadron programs, we need more new beam lines and multi-purpose detector.

Thank you !

J-PARC Sunrise, last day of beam time 2010/11/16