A search for deeply-bound kaonic nuclear states by in-flight $^{3}He(K^{-}, n)$ reaction at J-PARC

F. Sakuma, RIKEN

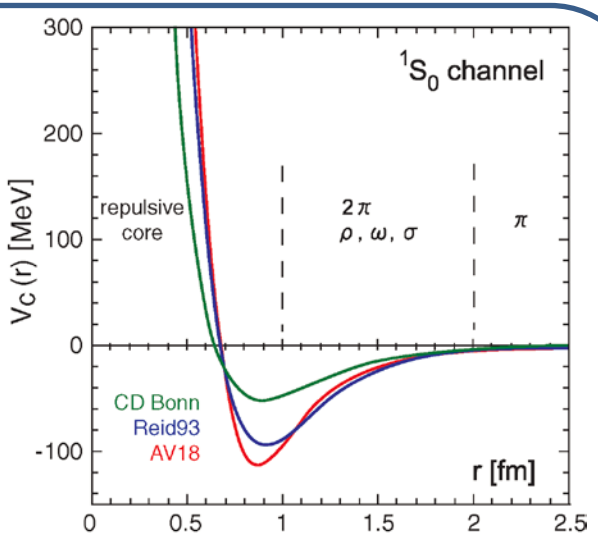
for the J-PARC E15 collaboration

- Introduction
- The J-PARC E15 experiment
- Preliminary results of 1st physics run
- Summary

II International Symposium on Mesic Nuclei, Jagiellonian University Cracow, September 22 - 25, 2013

Motivation: Embedding K^- in Nucleus

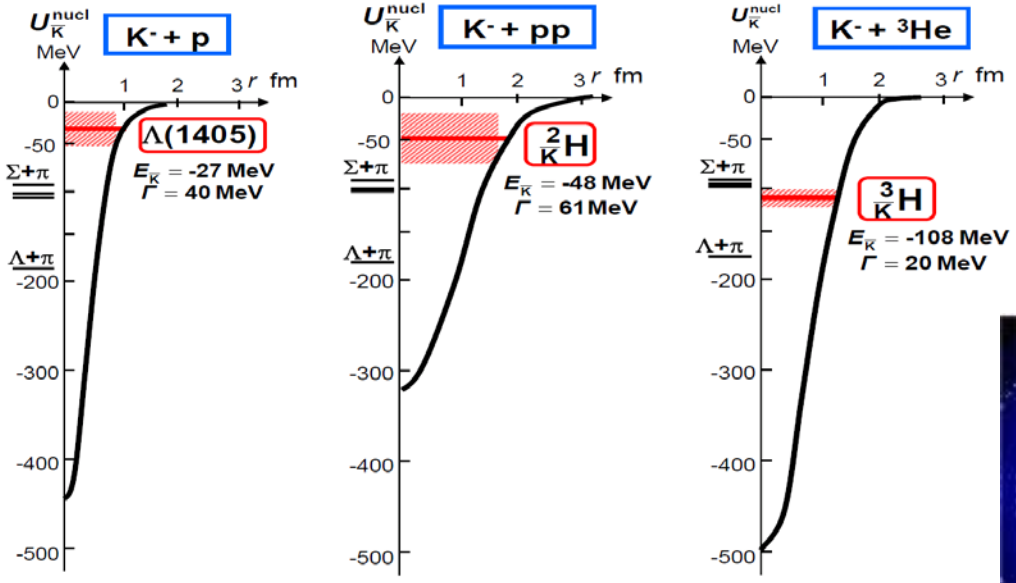
- Light mesons
  - **π-N interaction is attractive**
  - play an important role in a nucleus as “glue”



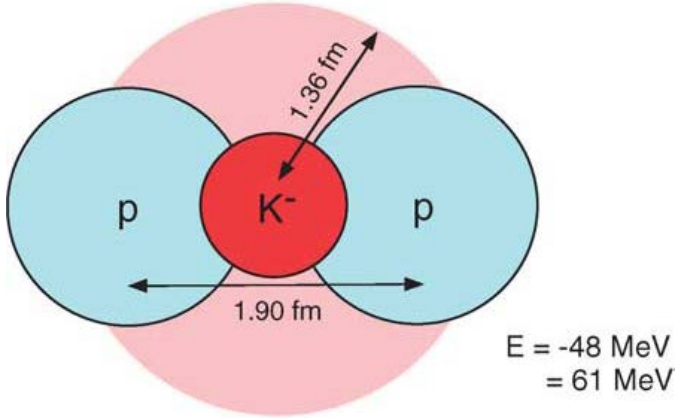
- Light S=-1 mesons?
  - Kaonic-atom experiments (KpX@KEK, DEAR/SIDDHARTA@DAΦNE) clarified ***strongly*** **attractive K^{bar}-N interaction**
  - What will happen when K^{bar} is embedded in nucleus?
    - K^{bar}-nucleus bound state?
    - high density?

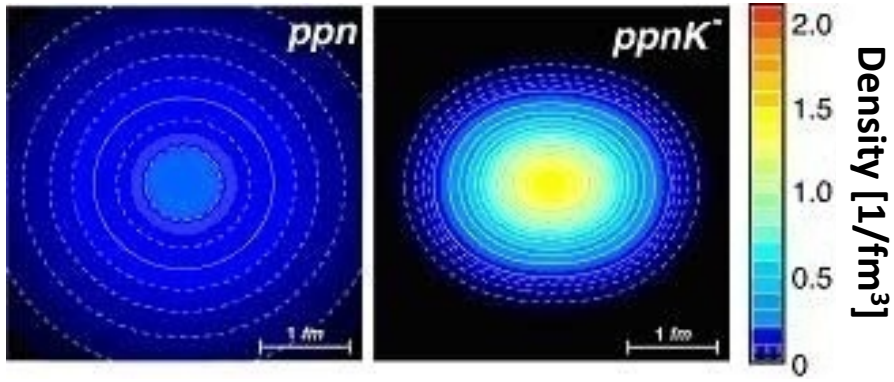
Kaonic Nuclei

Kaonic nucleus is a bound state of nucleus and anti-kaon ($K^{bar}NN$, $K^{bar}NNN$, $K^{bar}K^{bar}NN$, ...)



Y.Akaishi & T.Yamazaki, PLB535, 70(2002).





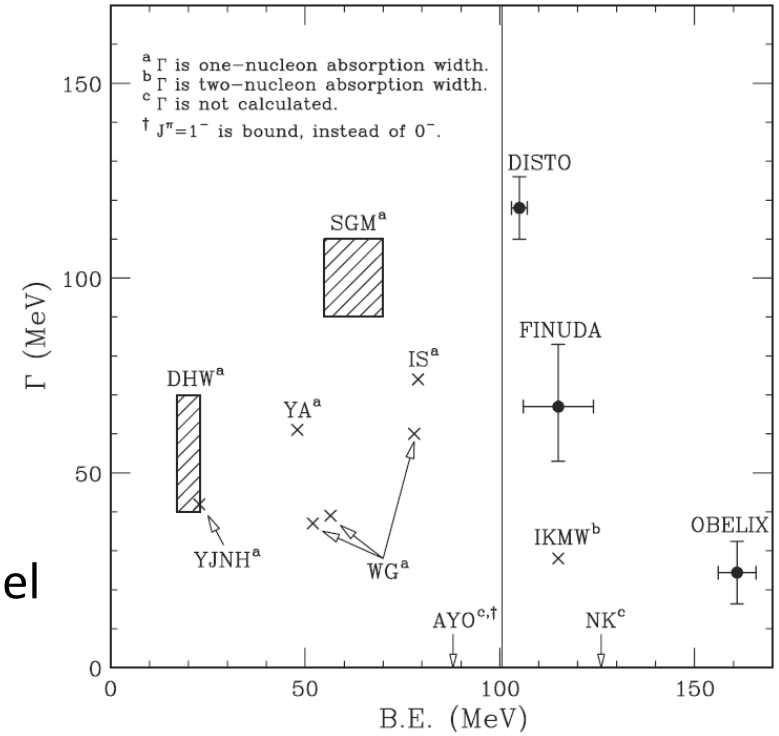
T.Yamazaki, A.Dote, Y.Akiaishi, PLB587, 167 (2004).

Theoretical Situation

K^-pp : the simplest K^{bar}-nuclear state

- **Akaishi, Yamazaki [AY]**
  - ATMS with phenomenological model
- **Dote, Hyodo, Wise [DHW]**
  - Variational with chiral-SU(3) model
- **Ikeda, Sato [IS]**
  - Faddeev with chiral-SU(3) model
- **Shevchenko, Gal, Mares [SGM]**
  - Faddeev with phenomenoligical model
- **Wycech, Green [YG]**
  - Variational with phenomenological model
- **Arai, Yasui, Oka [AYO]**
  - Λ^* model

Koike and Harada, PRC80(2019)055208

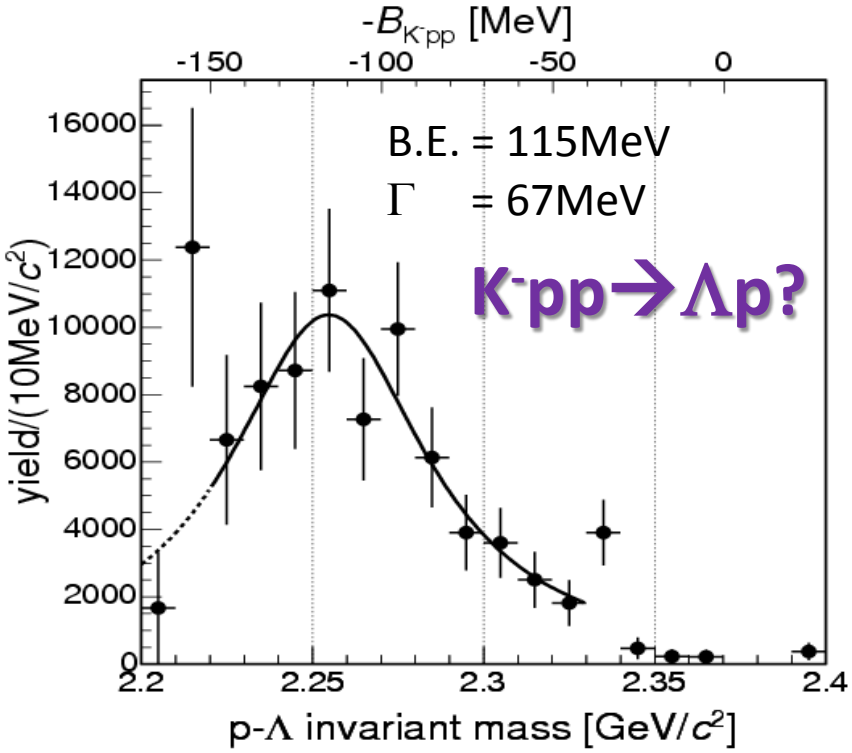


All studies predict existence of the K^-pp

→ However, B.E. and Γ are controversial

Experimental Situation

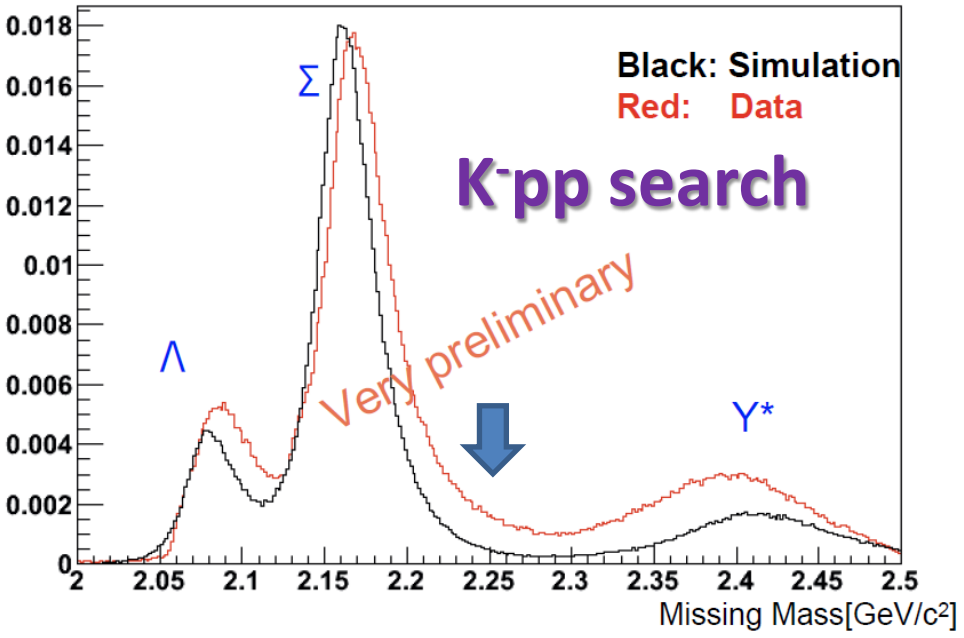
K^-/π^+ induced experiments



FINUDA@DAΦNE

PRL**94**(2005)212303

A(*stopped* K^-, Λp)



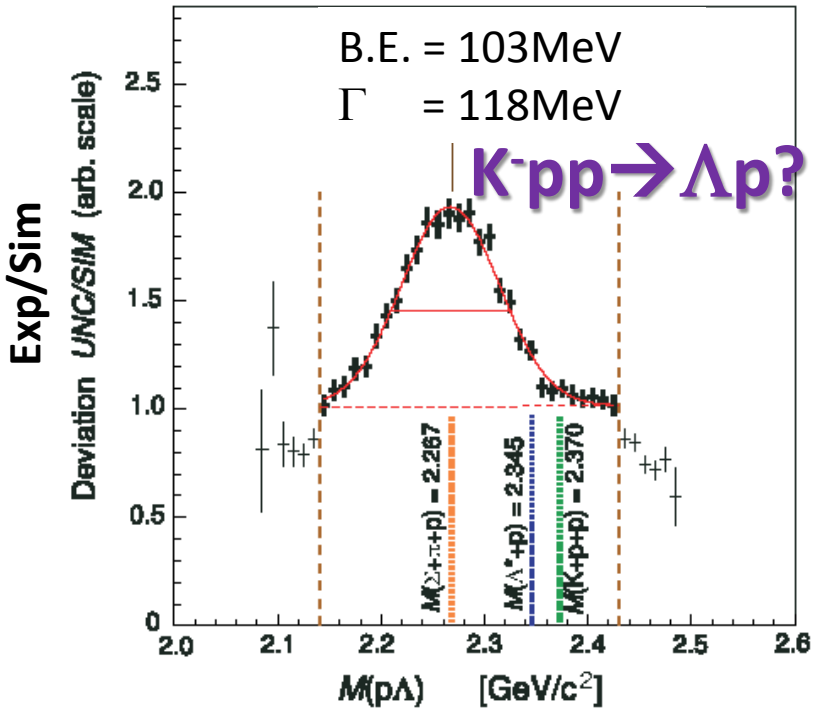
E27@J-PARC

FB20 conference (2012)

d(π^+, K^+) @ 1.7GeV/c

Experimental Situation [Cont'd]

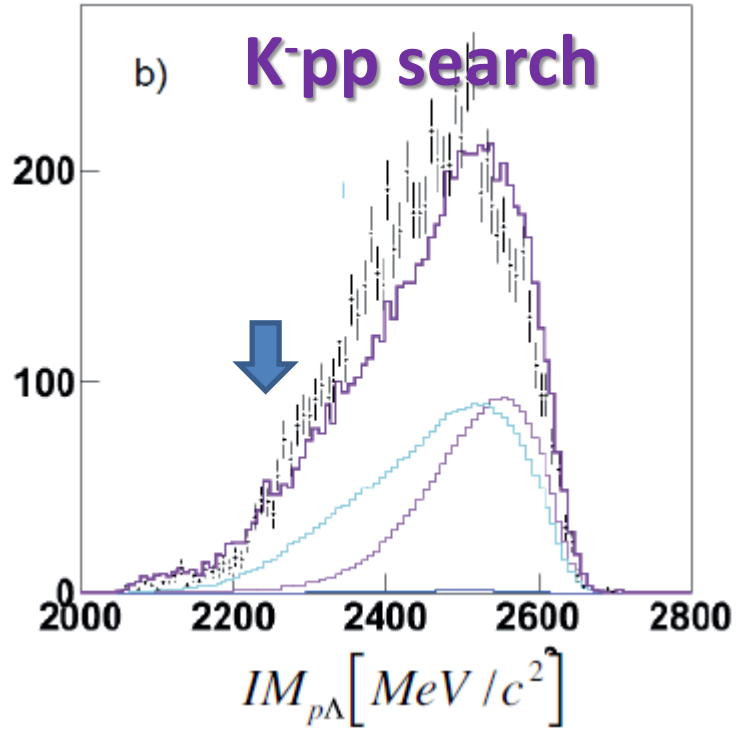
p induced experiments



DISTO@SATURNE

PRL**104**(2010)132502

p + p → (Λ + p) + K⁺ @ 2.85GeV



HADES@GSI

NP**A914**(2013)60

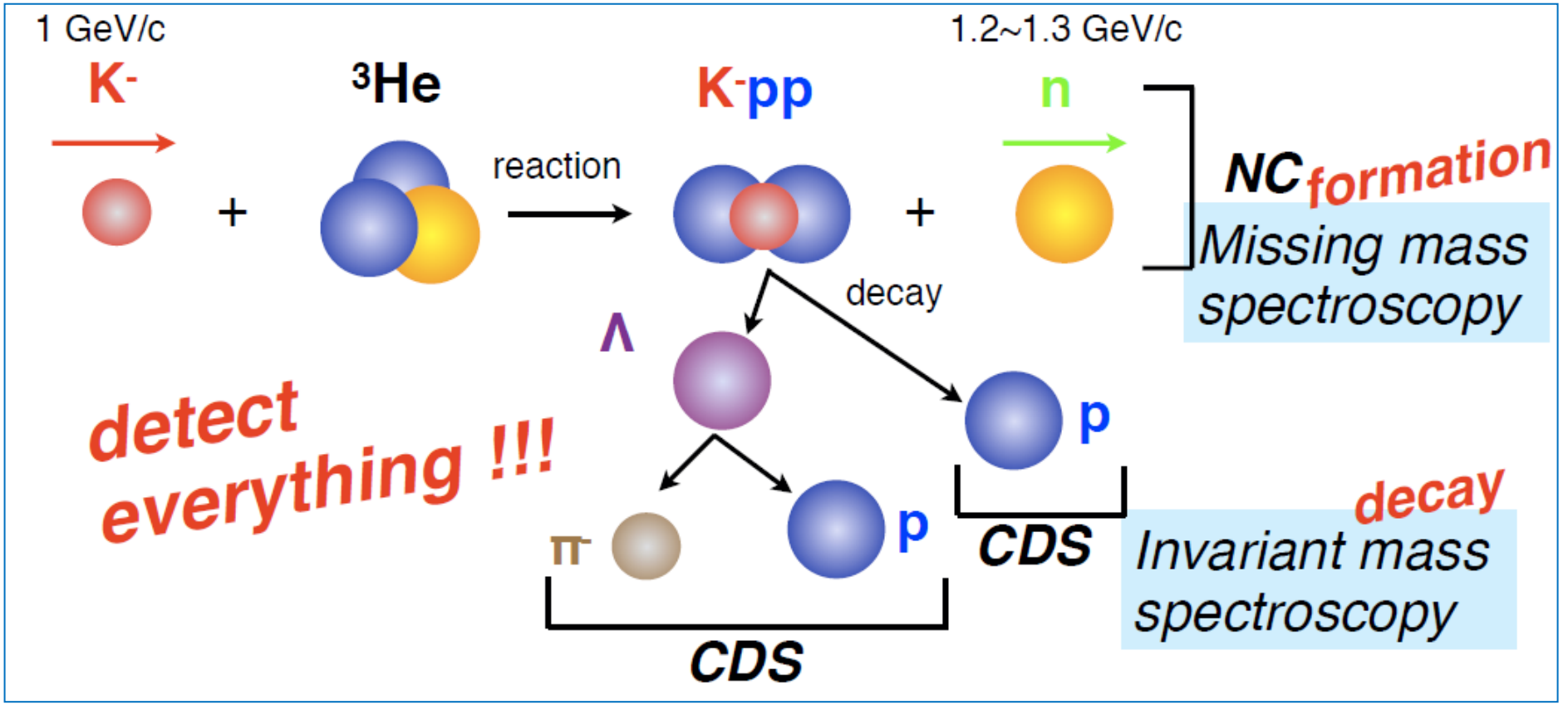
p + p → (Λ + p) + K⁺ @ 3.5GeV

We need more studies in various channels!

The J-PARC E15 Experiment

Experimental Principle

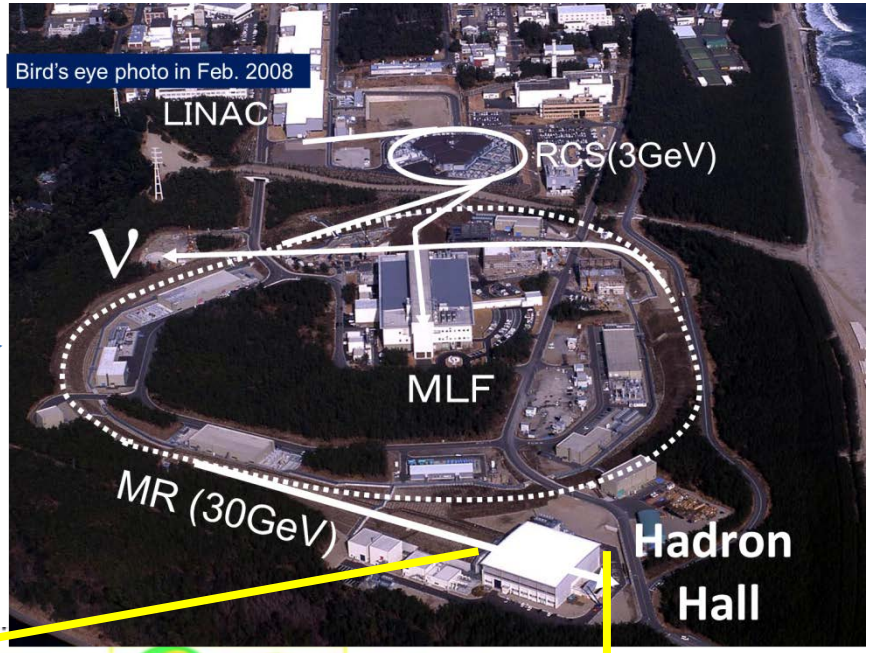
A search for the simplest kaonic nucleus, K^-pp, using ^3He(*in-flight* K^-,n) reaction



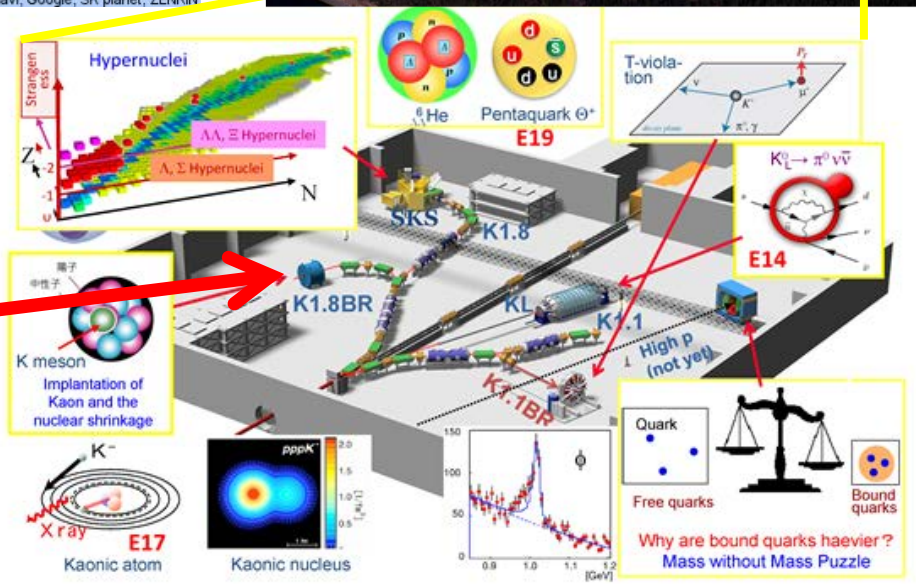
- two-nucleon absorption
- hyperon decays

} CAN be discriminated kinematically

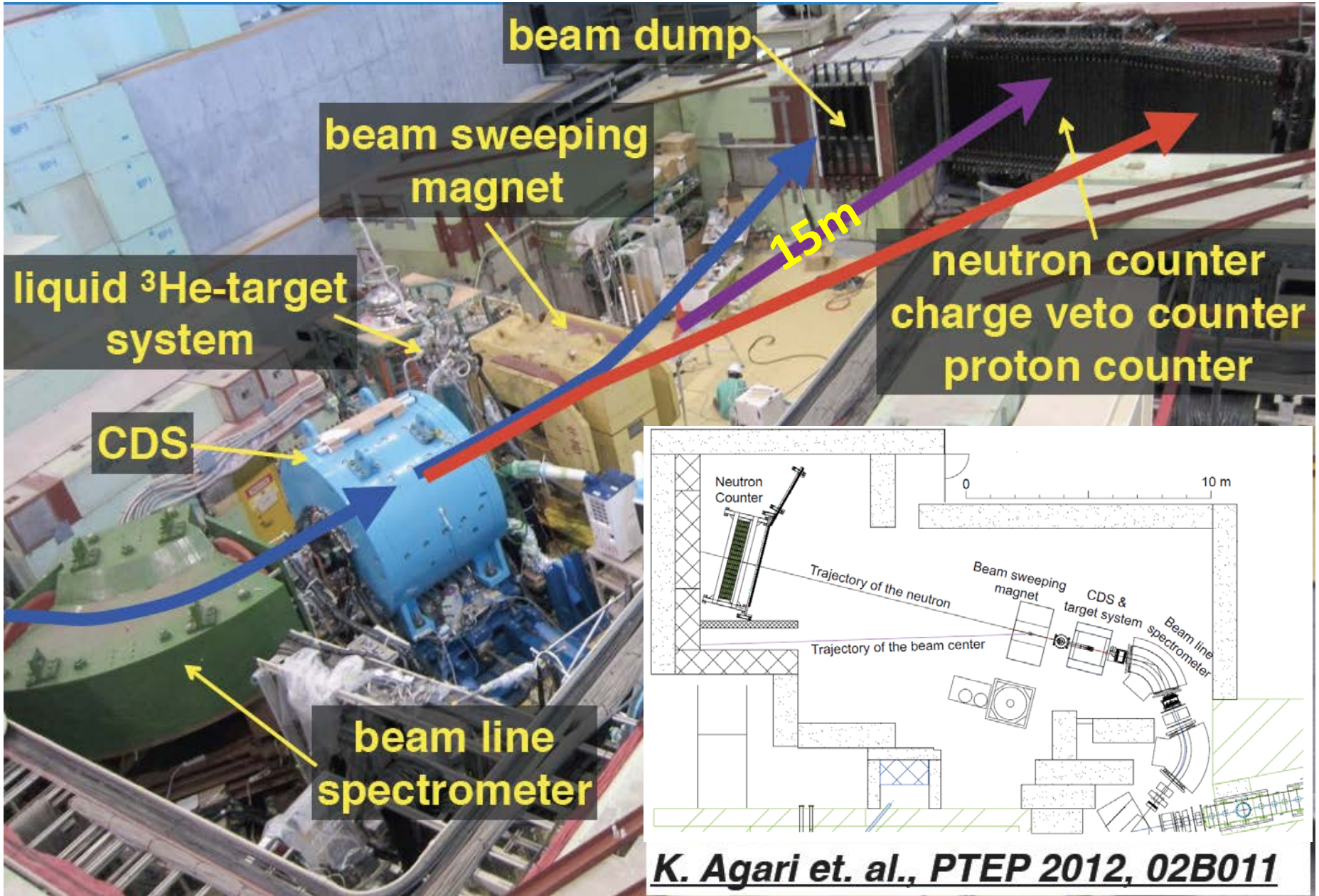
J-PARC (Japan Proton Accelerator Research Complex)



K1.8BR
E15/E17/E31



Experimental Setup



K. Agari et. al., PTEP 2012, 02B011

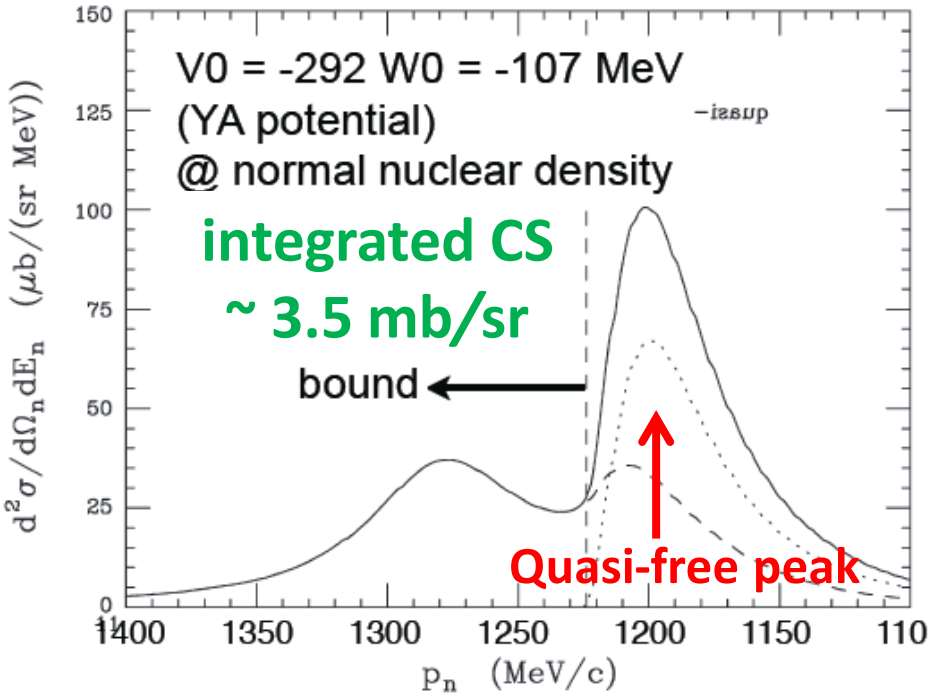
The Goal of E15

- **To investigate the kaonic nuclei**
  - **① Semi-Inclusive ^{3}He(K^-,n)**
  - **② Inclusive ^{3}He(K^-,Λp)**
  - **③ Exclusive ^{3}He(K^-,Λpn)**
  - Semi-Inclusive ^{3}He(K^-,p)
- Multi-nucleon absorption process
  - Hits of exotic production?
- Hyperon production
  - Nuclear dependence of Y* production

1: Semi-Inclusive ^{3}He(K$^-$,n)

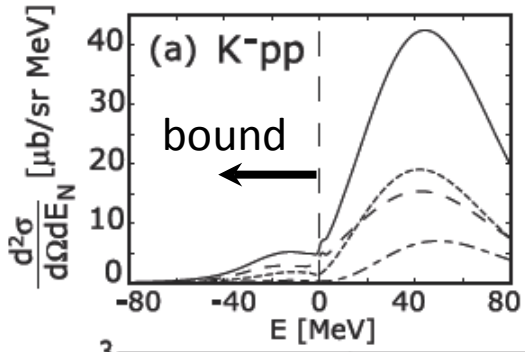
Calculated formation-spectra for ^{3}He(in-flight K-,n)

$K^- + {}^3He \rightarrow$ "K$^-$pp" + n @ P_K=1GeV/c, θ=0°

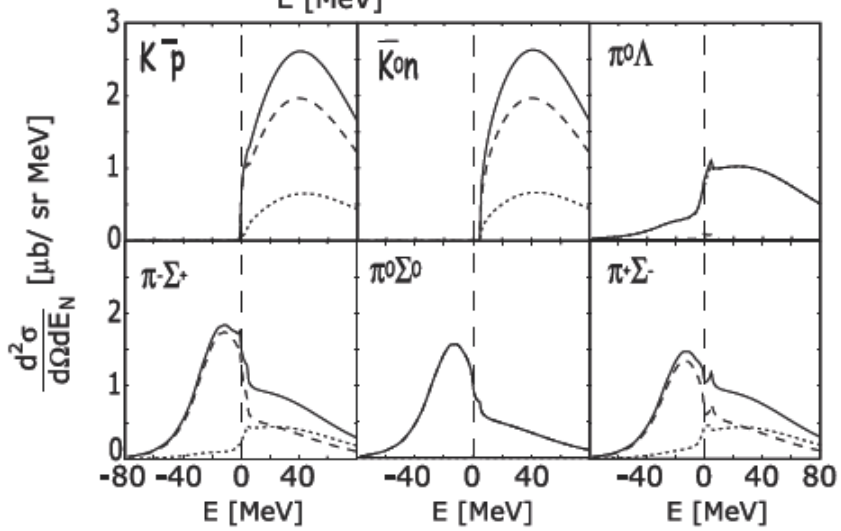


T.Koike and T.Harada. , PLB652 (2007) 262

If right, we can measure the bound structure!



Σ tag enhances the bound structure



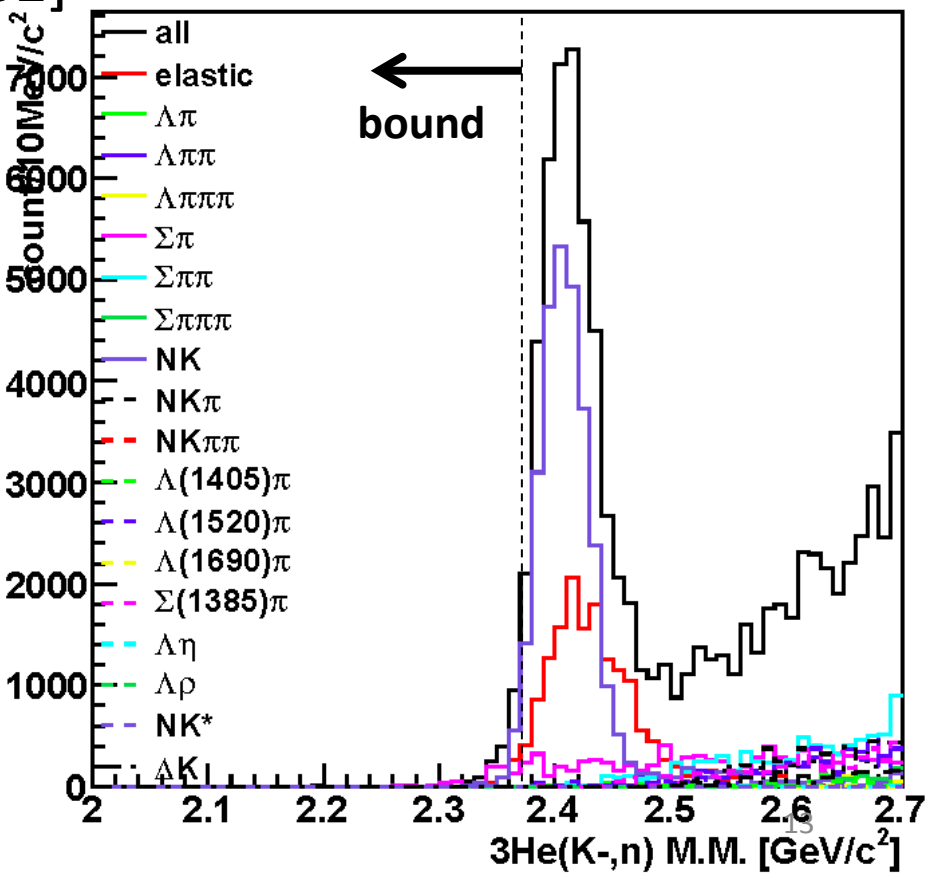
J. Yamagata-Sekihara et. al., Phys. Rev. C 80, 045204 (2009)

1: Semi-Inclusive ^{3}He(K$^-$,n) [Cont'd]

Expected spectrum from MC (Geant4)

- All known K$^-$N interactions are considered:
  - Cross-section [CERN-HERA-83-02]
  - Fermi-motion
  - Angular distribution
- Simple assumptions:
  - $\sigma_{tot} = 2*\sigma_{K\text{-}p} + \sigma_{K\text{-}n}$ (~150mb)

^{3}He(K$^-$,n) M.M. spectrum w/ 1-charged tag in the CDS



1: Semi-Inclusive ^{3}He(K$^-$,n) [Cont'd]

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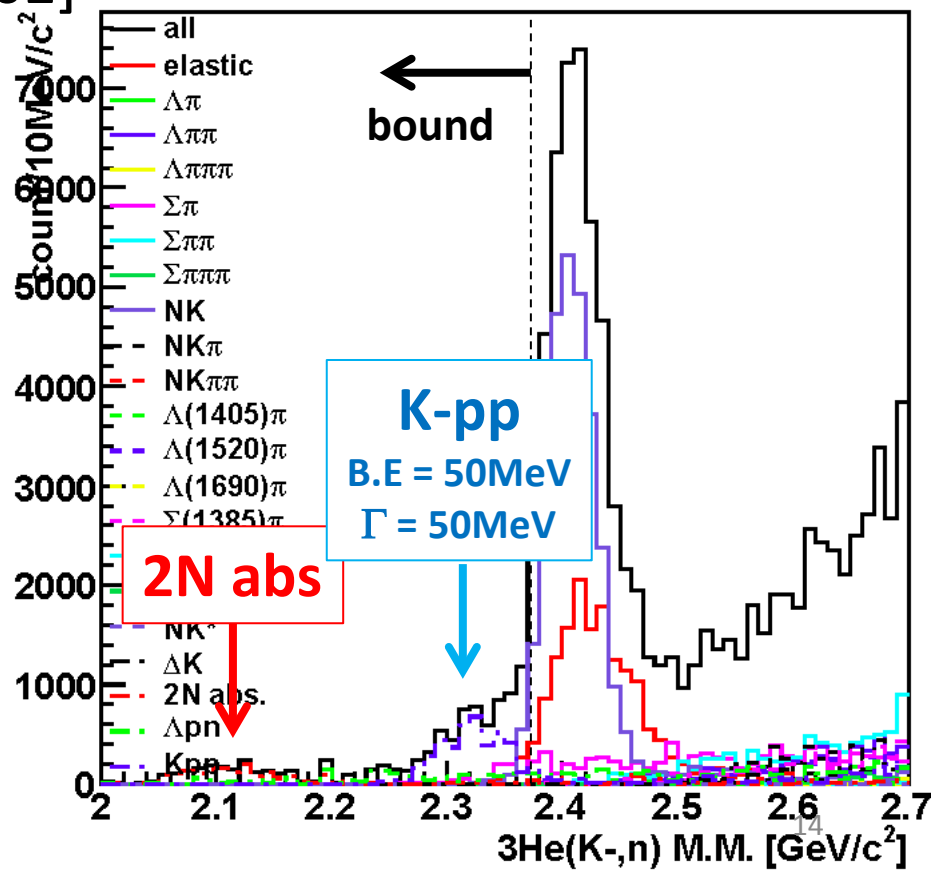
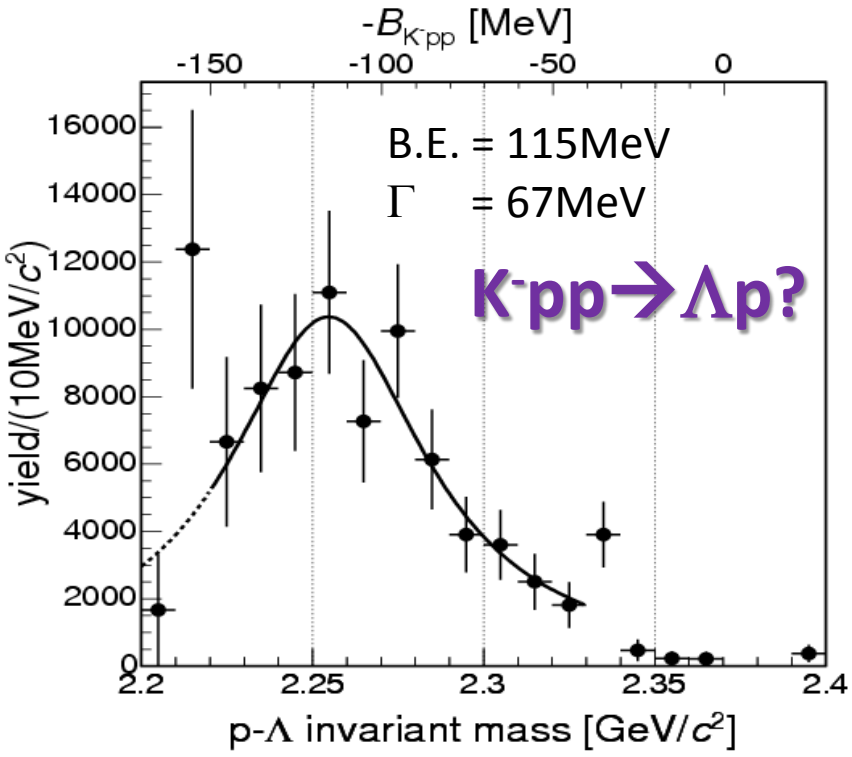
- Simple assumptions:
  - $\sigma_{tot} = 2*\sigma_{K-p} + \sigma_{K-n}$ (~150mb)
  - 2N abs.: K$^-$ ^{3}He → Λ n p_s
    - $\sigma/d\Omega$=1mb/sr, isotropic
  - **K$^-$pp prod.: K$^-$ ^{3}He → K$^-$pp n**
    - **$d\sigma/d\Omega$=1mb/sr, isotropic**
    - **K$^-$pp →Λp(25%), Σ^0p(25%), πΣp(50%)**

^{3}He(K$^-$,n) M.M. spectrum w/ 1-charged tag in the CDS



2: Inclusive ^{3}He(K^-,Λp)



FINUDA@DAΦNE

PRL**94**(2005)212303

A(*stopped* K^-, Λp)

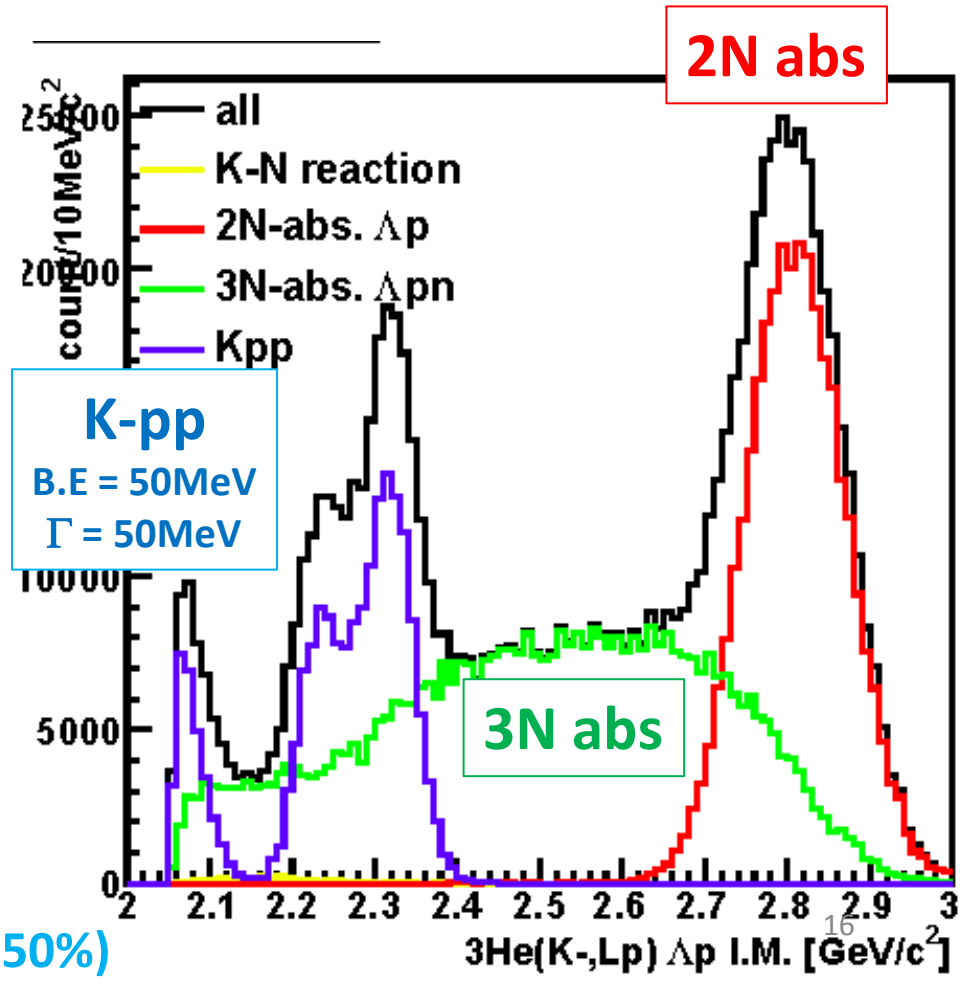
- **FINUDA: stopped K^-**
  - Back-to-back Λp correlation
  - BG from multi-N absorption? / 2-step processes?
- **E15: in-flight K^-**
  - Λp correlation is NOT so simple
  - Give some hints of multi-N absorption and the K^-pp production

2: Inclusive ^{3}He(K^-,Λp) [Cont'd]

Expected (simplified) spectrum from MC (Geant4)

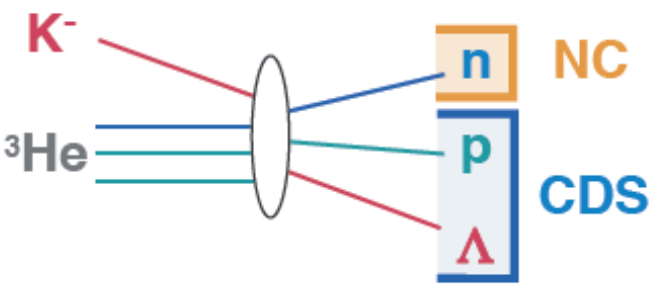
- All known K^-N interactions are considered:
  - Cross-section [CERN-HERA-83-02]
  - Fermi-motion
  - Angular distribution
- Simple assumptions:
  - $\sigma_{tot} = 2*\sigma_{K-p} + \sigma_{K-n}$ (~150mb)
  - 2N abs.: $K^- {}^3He \rightarrow \Lambda$ p n_s
    - $\sigma/d\Omega$=1mb/sr, isotropic
  - 3N abs.: $K^- {}^3He \rightarrow \Lambda$ p n
    - $d\sigma/d\Omega$=1mb/sr, isotropic
  - **K^-pp prod.: $K^- {}^3He \rightarrow K^-$pp n**
    - **$d\sigma/d\Omega$=1mb/sr, isotropic**
    - **K^-pp $\rightarrow \Lambda$p(25%), Σ^0p(25%), $\pi\Sigma$p(50%)**

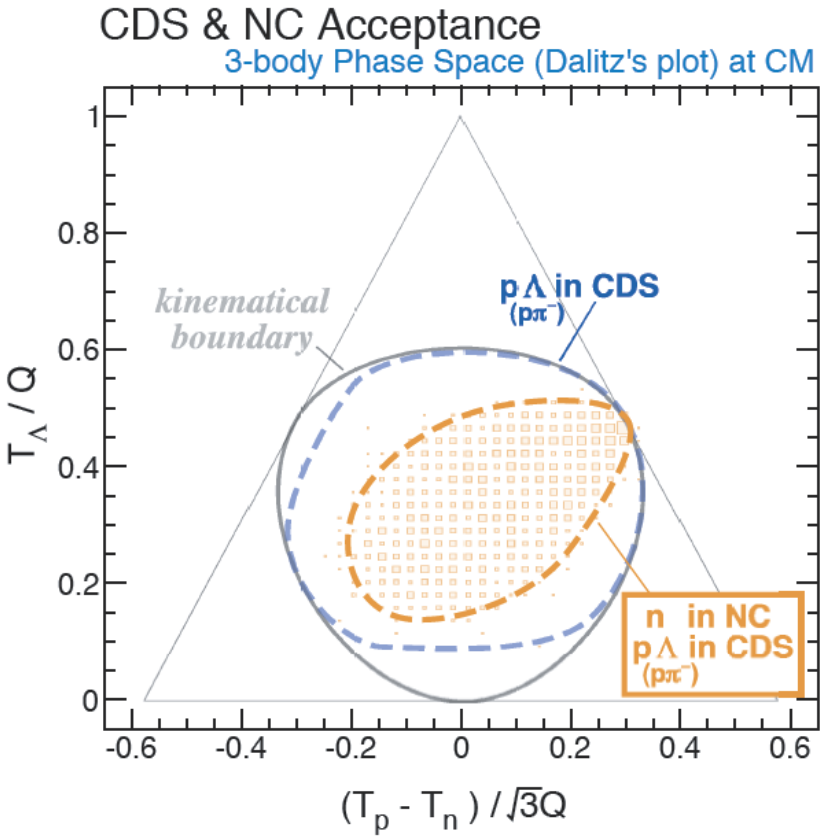
Λp invariant mass spectrum



3: Exclusive ^{3}He(K^-,Λpn)

- **The main goal of the E15 measurement**
  - Will pin down the signature of the K^-pp
  - *large statistics , i.e., large beam-time is needed!!!*
- Dalitz plot analysis helps us to investigate particle correlation





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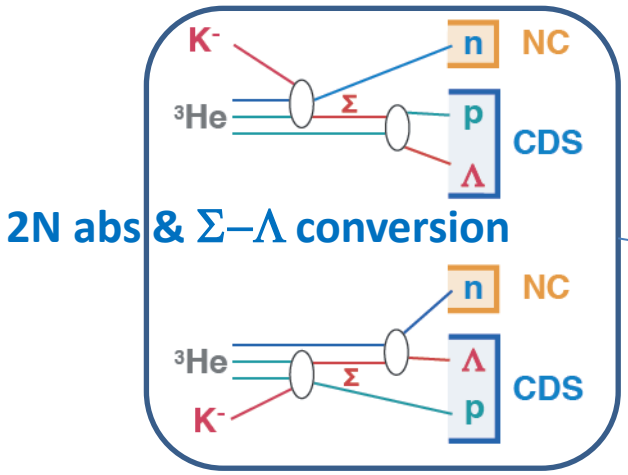
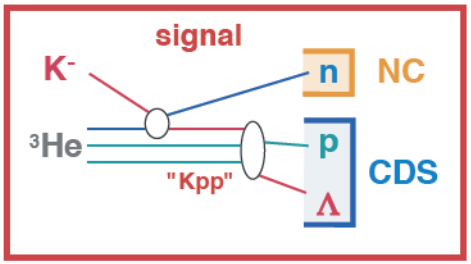
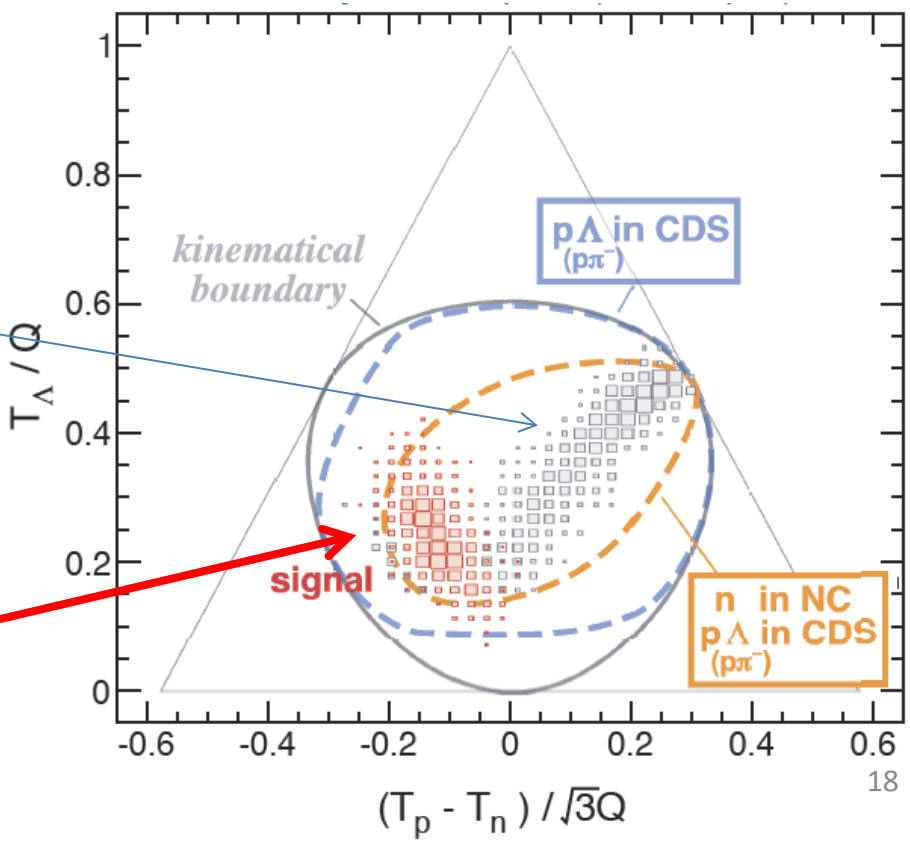






Preliminary Results of 1st Physics Run

1st Stage Physics Run

Jun.2006	**proposed and approved @ 1st PAC**
Feb 2009	first beam transportation to K1.8BR
Mar.11 2011	the earthquake
May 2012	completion of spectrometer construction
May 2013	**1st physics run**
May.23 2013	the accident

- Accumulated data in the 1st stage physics run
  - ~1% of original proposal

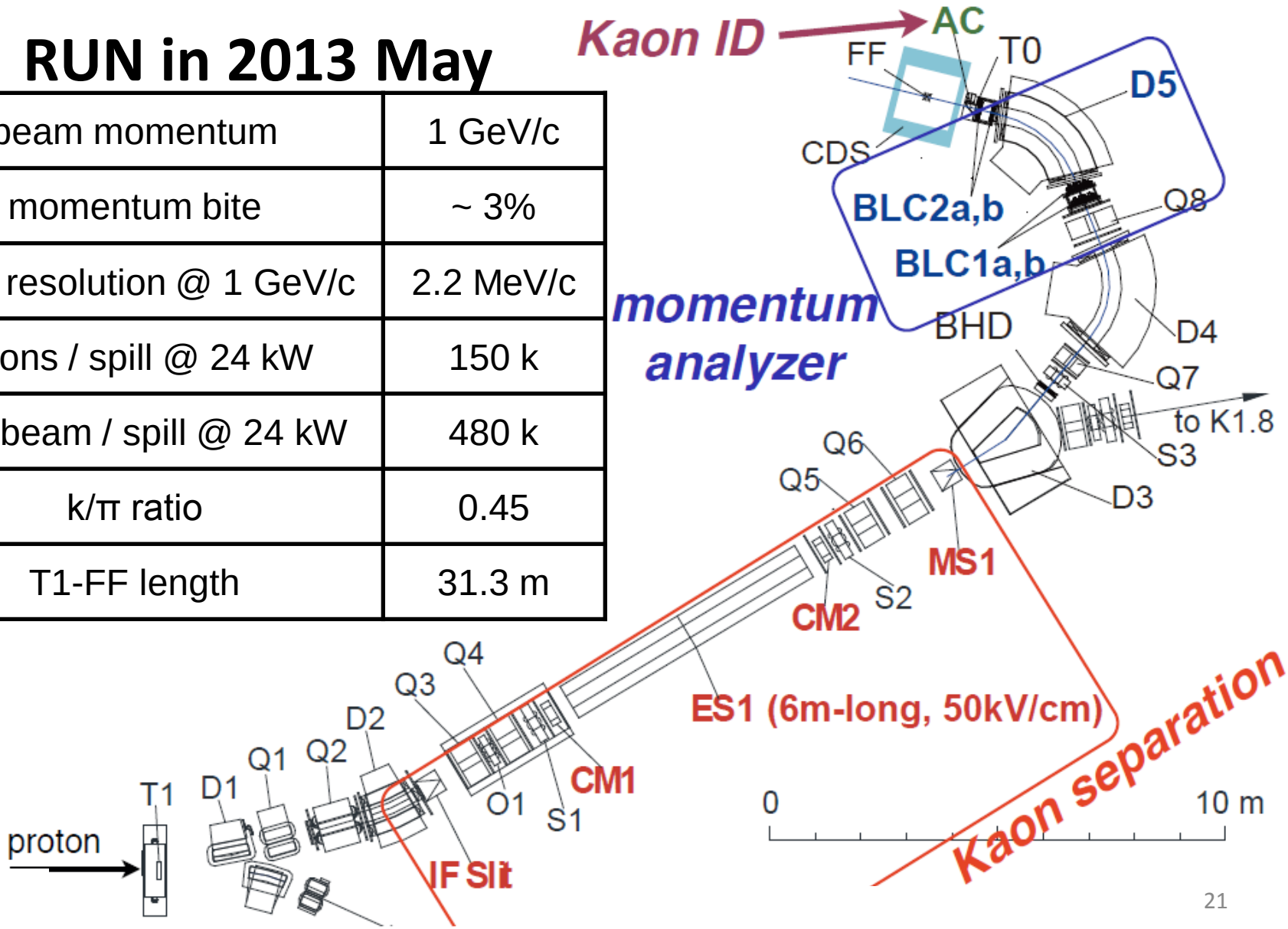
period	primary beam intensity	duration	Kaons on target
March, 2013	14.5 kW (18 Tppp, 6s cycle)	30 hours	0.9×10^9
May, 2013	24 kW (30 Tppp, 6s cycle)	88 hours	4.0×10^9

production target: Au 50% loss, spill length: ~2s, spill duty factor: ~45%

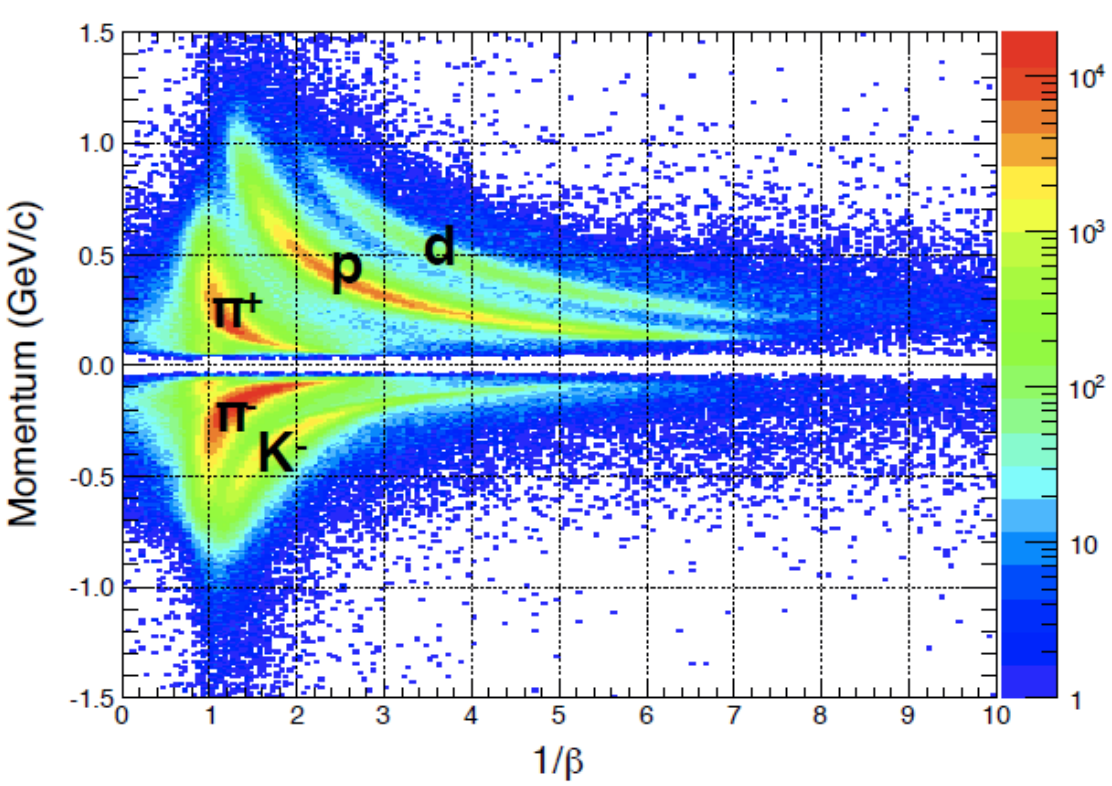
Kaon-Beam Spectrometer

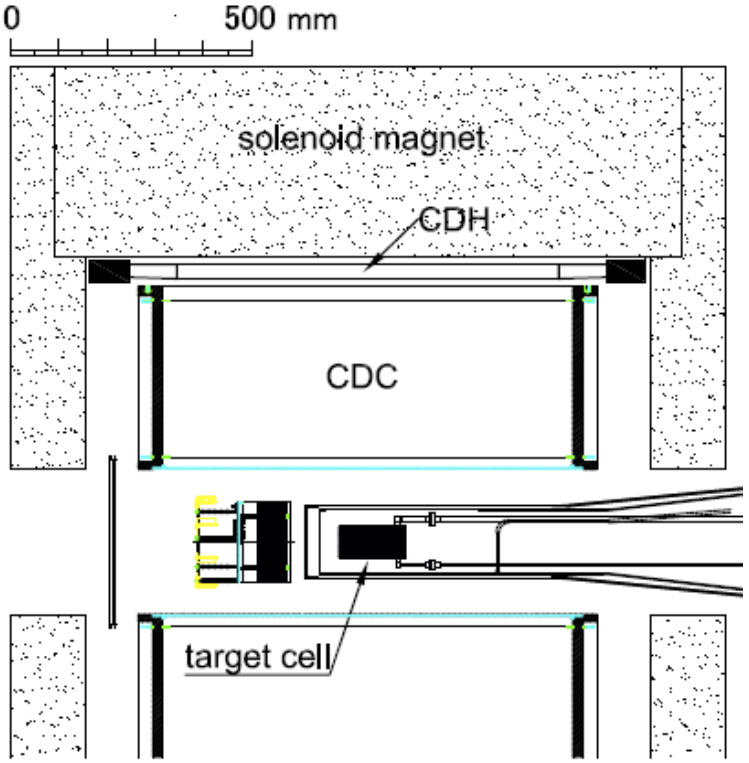
RUN in 2013 May

beam momentum	1 GeV/c
momentum bite	~ 3%
mom resolution @ 1 GeV/c	2.2 MeV/c
Kaons / spill @ 24 kW	150 k
total beam / spill @ 24 kW	480 k
k/π ratio	0.45
T1-FF length	31.3 m



Cylindrical Detector System: pID

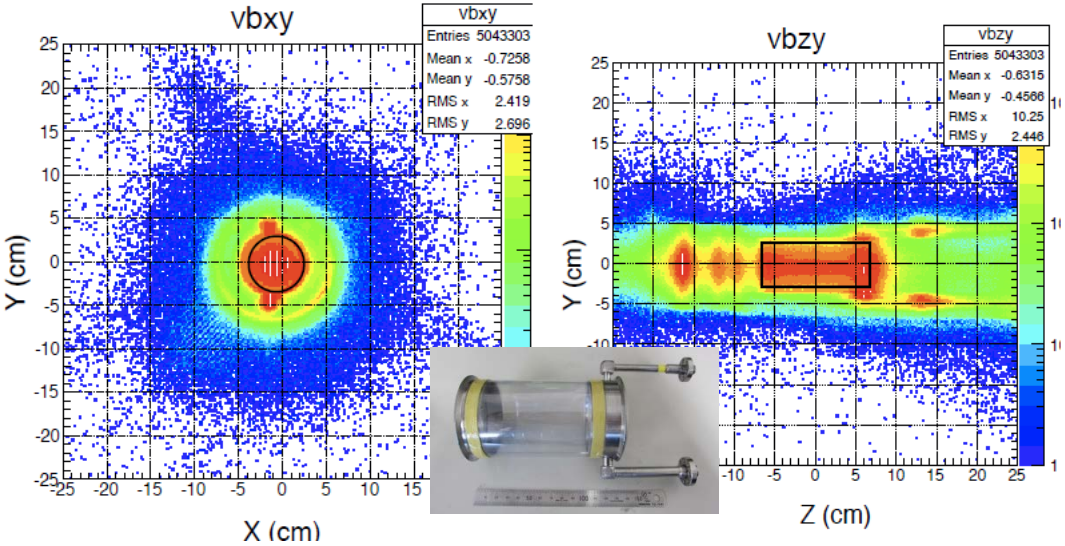




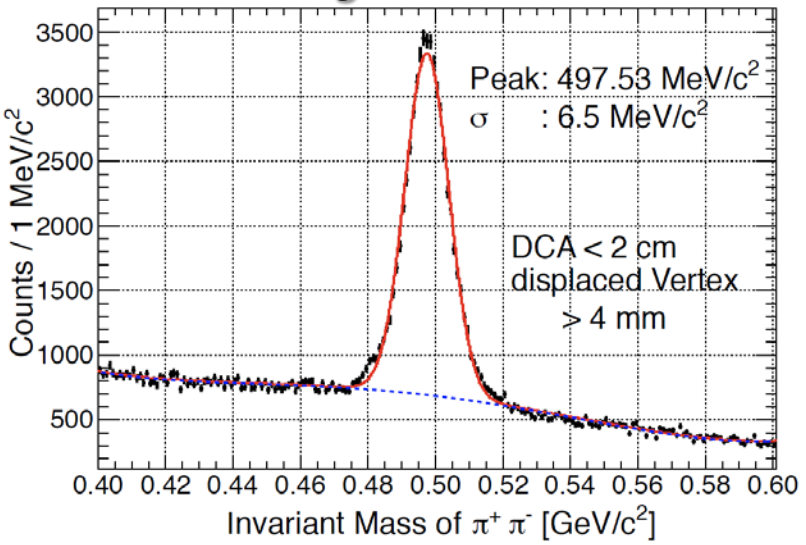
- CDC (15 layers, 1816ch) + CDH (36 seg) + 0.7T
  - solid angle: 60% of 4π
- **π/K/p/d are clearly separated**

Cylindrical Detector System: Tracking

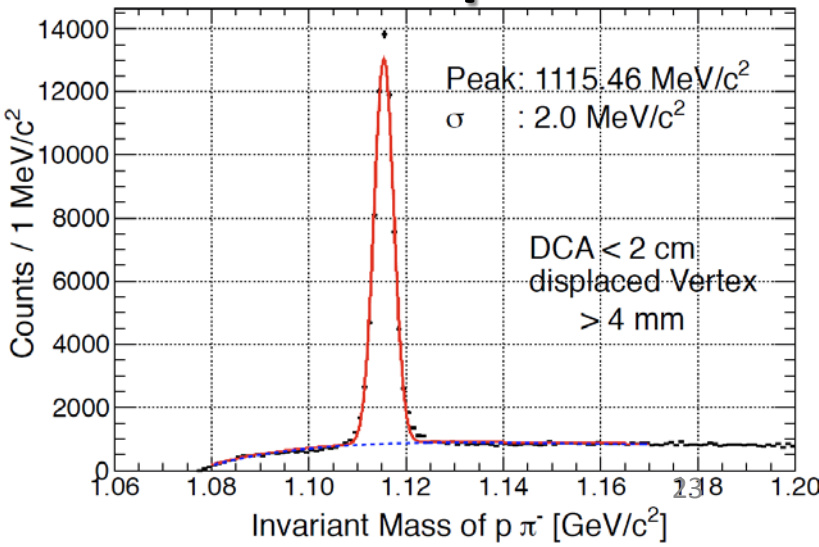
target image



$K^0_S \rightarrow \pi^+\pi^-$



$\Lambda \rightarrow p\pi^-$

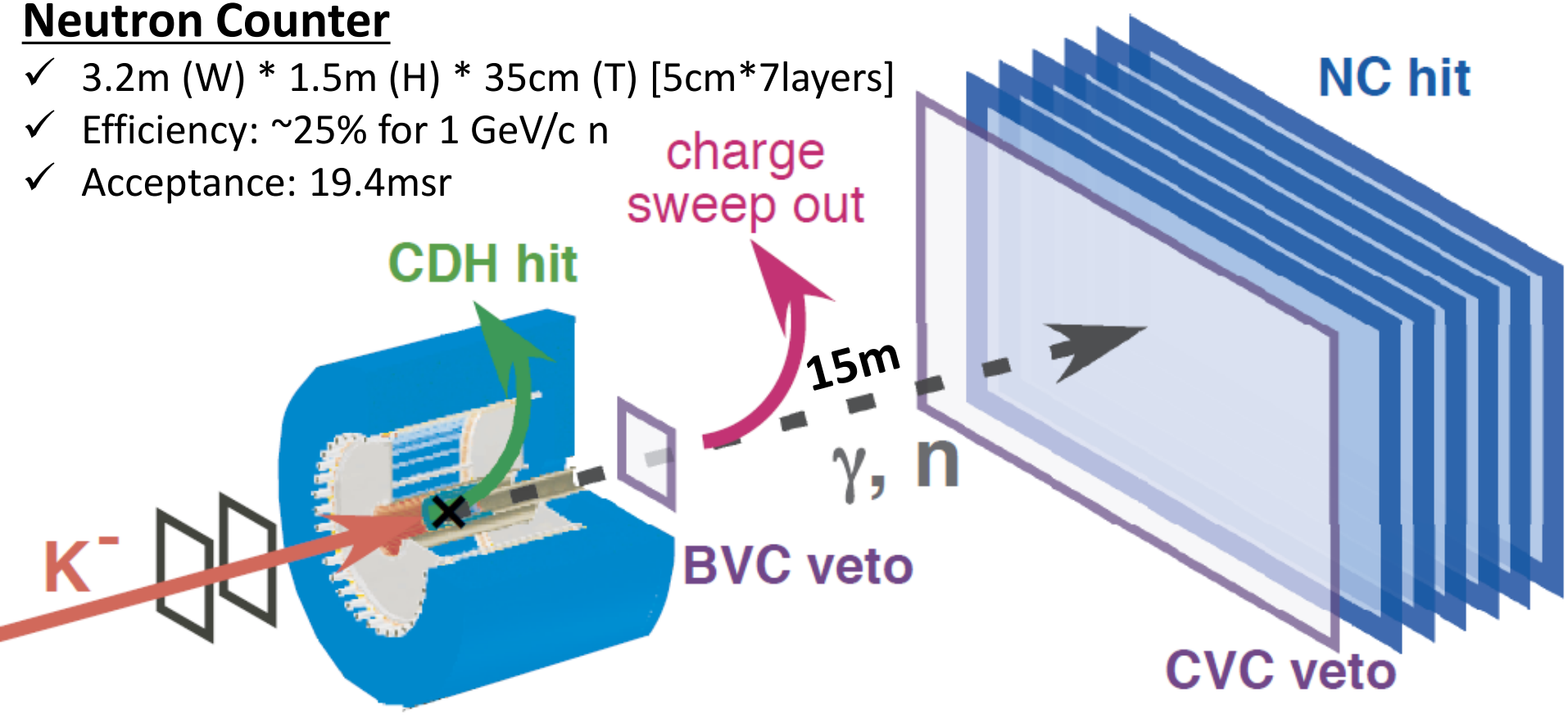


- Designed performance was achieved
  - K^0/Λ are reproduced by the MC
- **Resolution for $K^-pp \rightarrow \Lambda p$ reconstruction: ~10MeV/c²**

Forward Neutral Particles

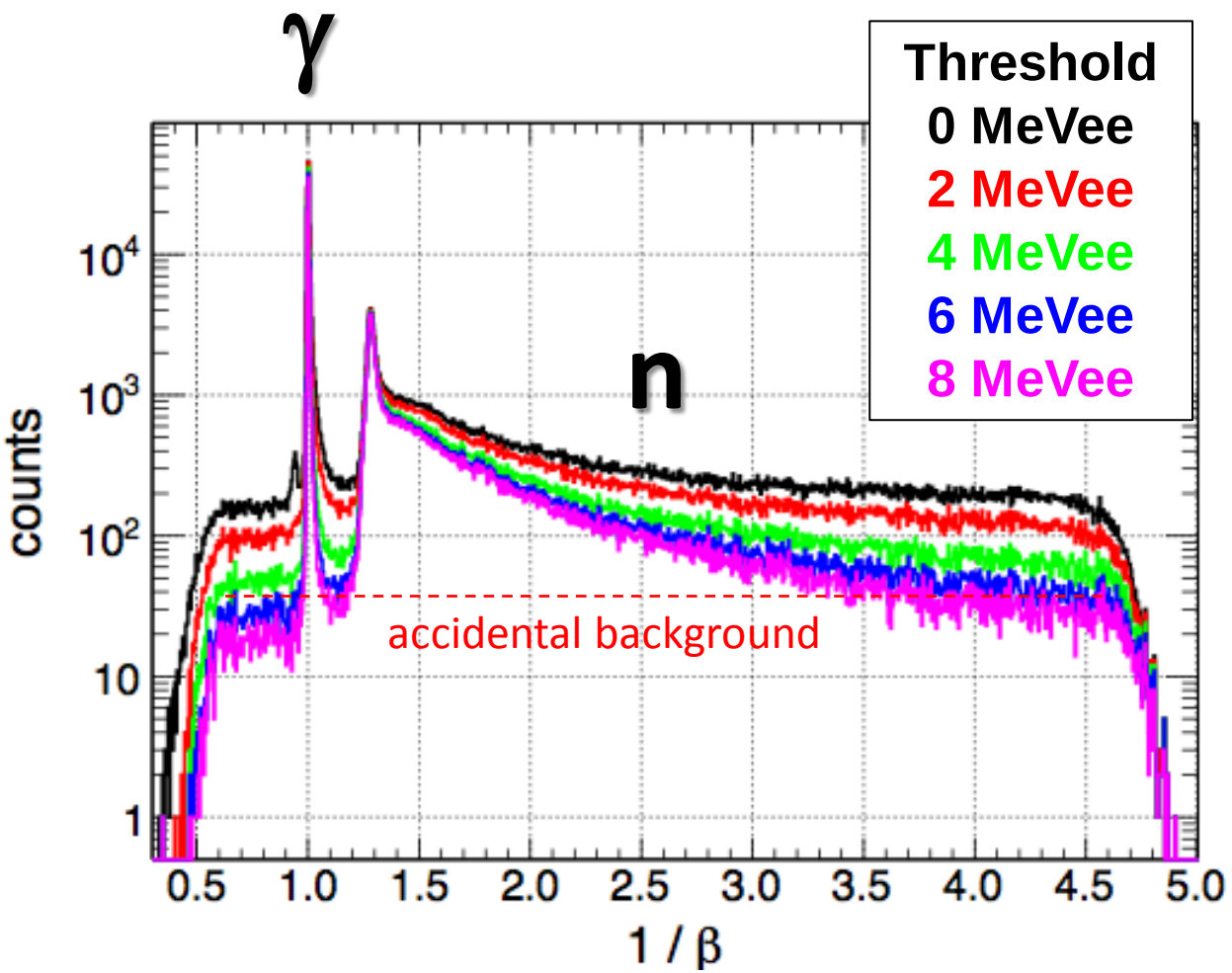
Neutron Counter

- ✓ 3.2m (W) * 1.5m (H) * 35cm (T) [5cm*7layers]
- ✓ Efficiency: ~25% for 1 GeV/c n
- ✓ Acceptance: 19.4msr



- Neutron momentum is determined by TOF method
- require at least 1 track in CDC to reconstruct the reaction vertex→ flight length

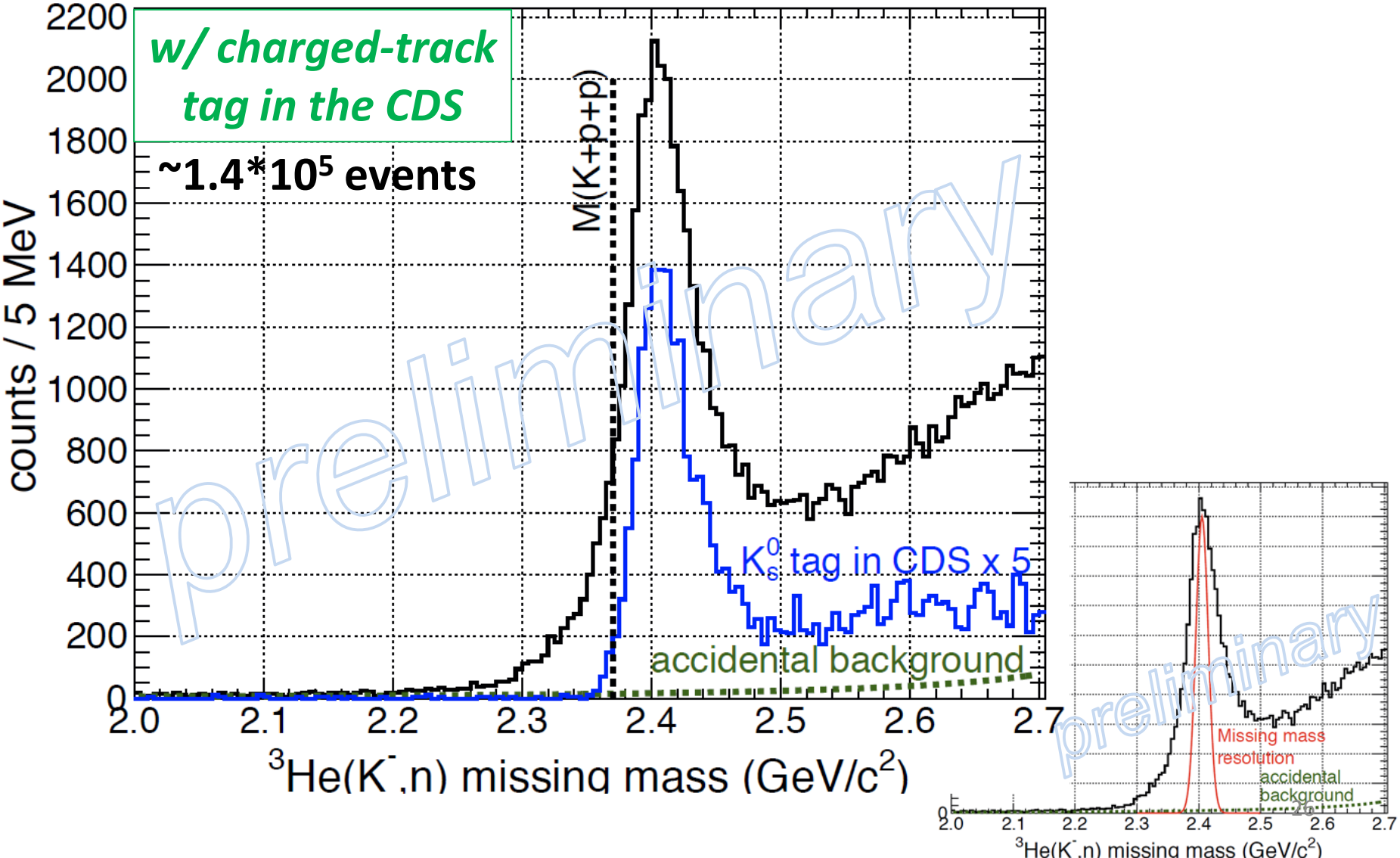
Forward Neutral Particles [Cont'd]



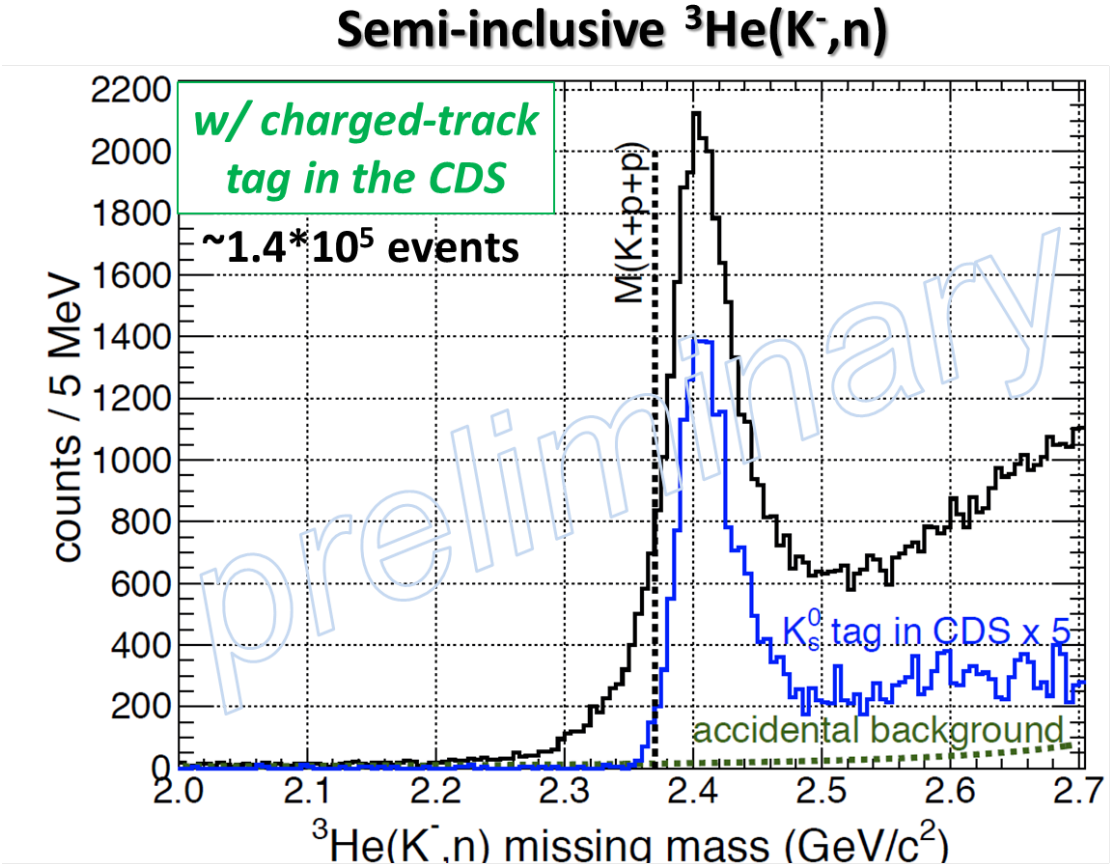
- ✓ **Set threshold to 5 MeVee**
- ✓ good S/N ratio of ~100 @ QF neutron peak
- ✓ **σ_{TOF} ~ 160ps → $\sigma_{M.M.}$ ~ 10MeV/c^2 for 1GeV/c n**

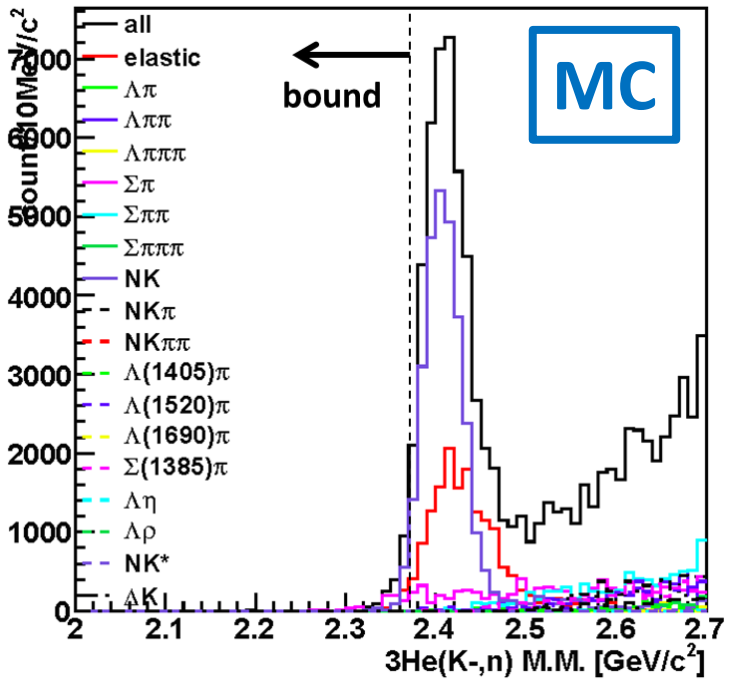
Preliminary Result 1: ^{3}He(K$^-$,n)

Semi-inclusive ^{3}He(K$^-$,n)



Preliminary Result 1: ^{3}He(K$^-$,n)

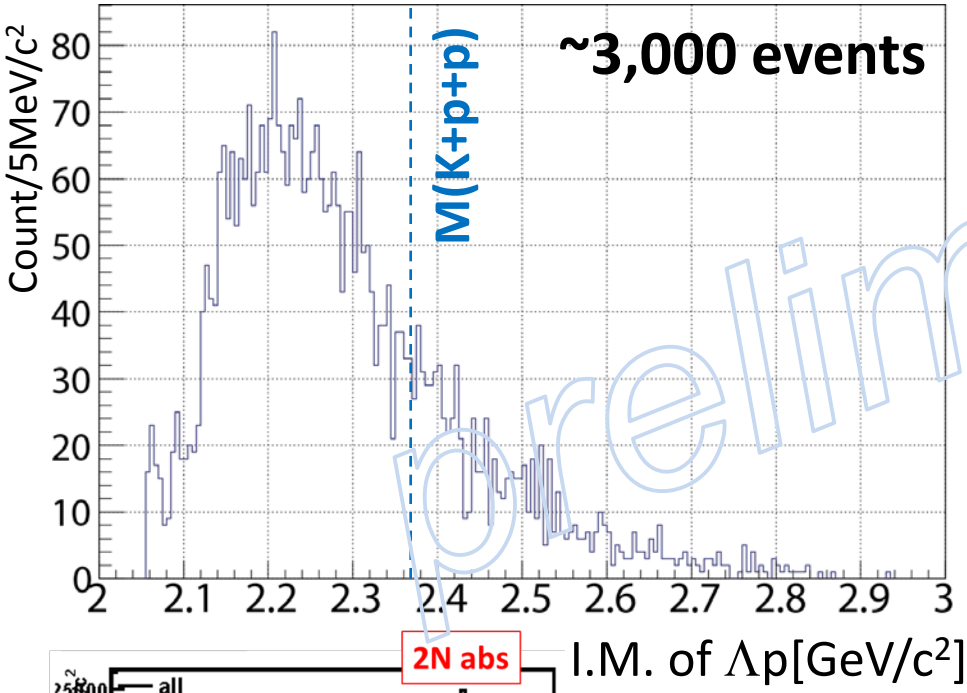




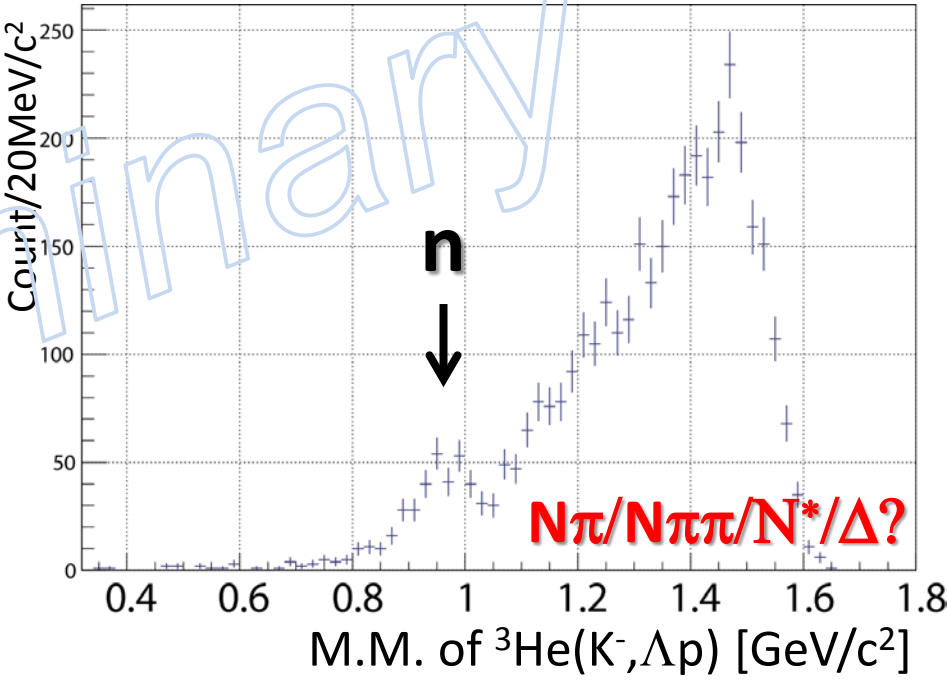
- Global shape is roughly understood by known processes.
- Tail component is very interesting.
  - Careful analysis is in progress
  - Can be reproduced by known processes?

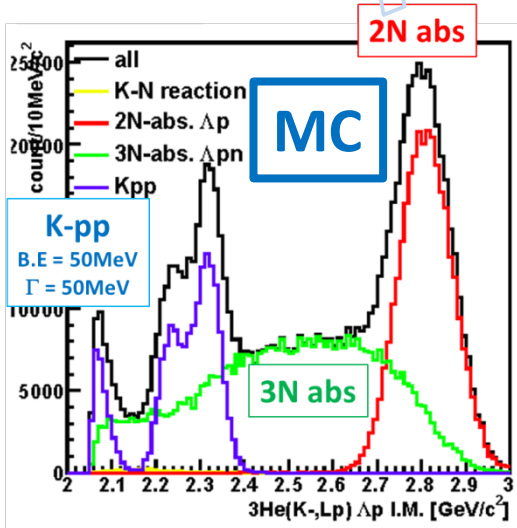
Preliminary Result 2: ^{3}He(K$^-$,Λp)

Λp invariant mass



^{3}He(K$^-$,Λp) missing mass





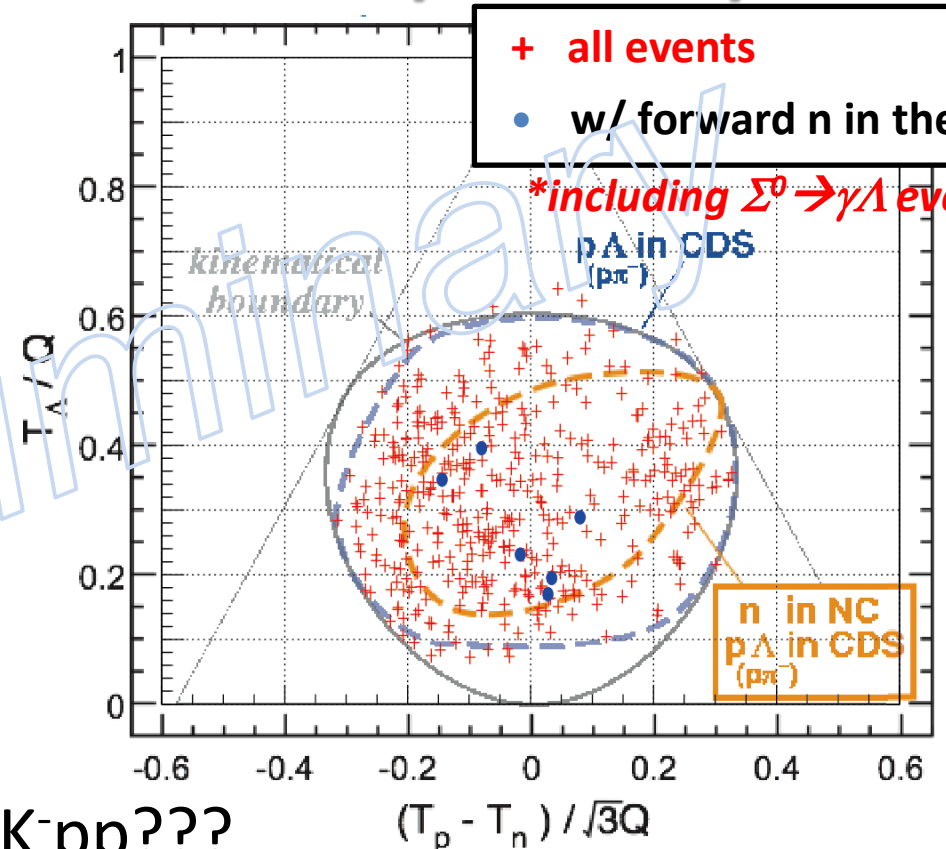
- Multi-N absorption processes exist.
- **Spectrum shape is NOT understood yet.**
  - 2N/3N-abs.?
  - 2N-abs with multi-π?

Preliminary Result 3: ^{3}He(K$^-$,Λpn)

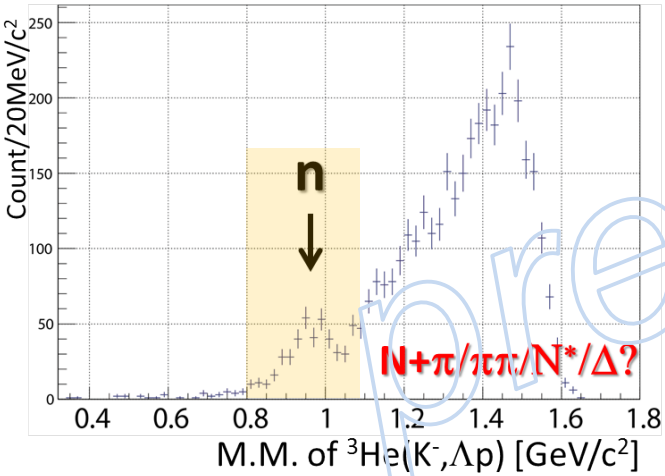
Dalitz plot of Λpn

+ all events
• w/ forward n in the NC

**including $\Sigma^0 \rightarrow \gamma\Lambda$ events*



^{3}He(K$^-$,Λp) missing mass

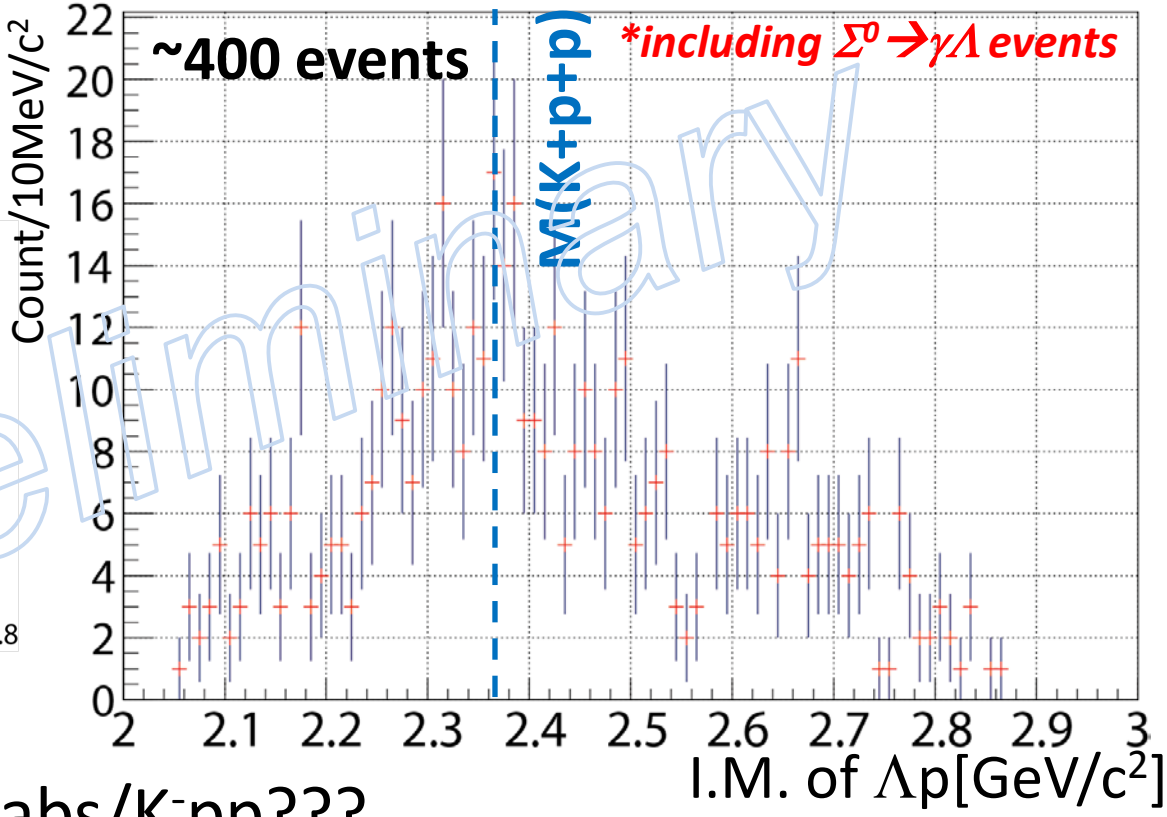


- Some hints of 3N-abs/K$^-$pp???

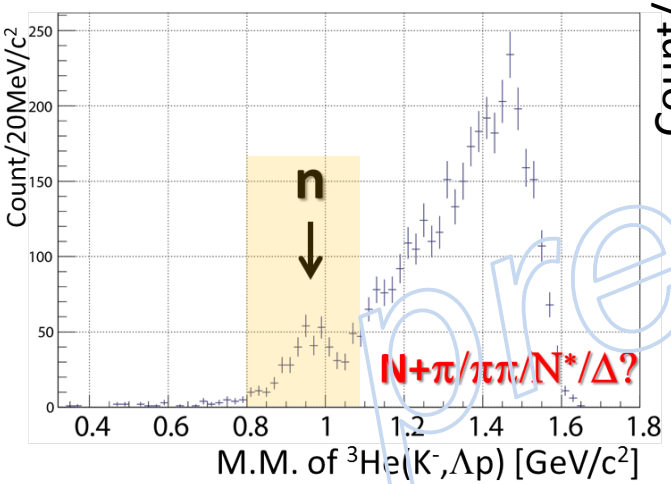
- Number of **n** in the NC & **Λp** in the CDS events is less than 10
- We need more beam-time!

Preliminary Result 3: ^{3}He(K$^-$,Λpn)

Λp invariant mass w/ missing n



^{3}He(K$^-$,Λp) missing mass



- Some hints of 3N-abs/K$^-$pp???
- Further analysis is ongoing.
  - Opening angle of Λp,
  - Momentum/Angular dist., etc.

- Number of **n** in the NC & **Λp** in the CDS events is less than 10
- We need more beam-time!

Summary

- **We have performed 1st physics run of the J-PARC E15 experiment to search for the K^-pp bound-state**
  - ~$4*10^9$ kaons were incident on ^{3}He
    - ^{3}He(K^-,n) : ~$1.4*10^5$ events
    - ^{3}He(K^-,Λp) : ~3,000 events with the CDS
    - ^{3}He(K^-,Λpn) : <10 events with the CDS & the NC
- **Further analyses will be reported soon**
  - Finalization of the ^{3}He(K^-,n) spectrum
  - Detailed analysis of exclusive Λpn events
  - Comparison of ^{3}He(K^-,n/p) spectra
  - …

The J-PARC E15 Collaboration

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