

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

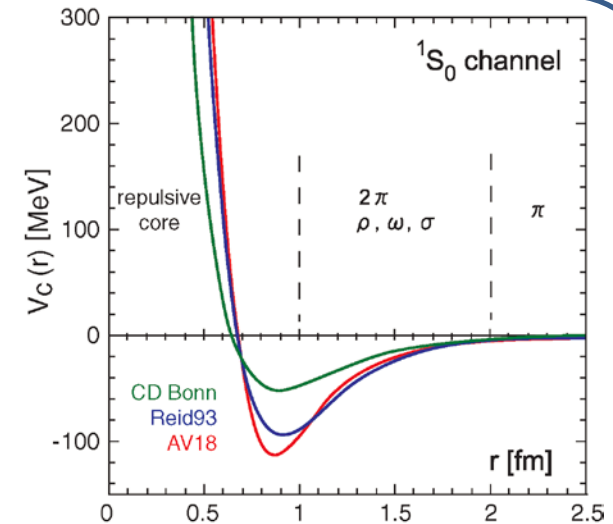
F. Sakuma, RIKEN

for the J-PARC E15 collaboration

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

Motivation: Embedding K^- in Nucleus

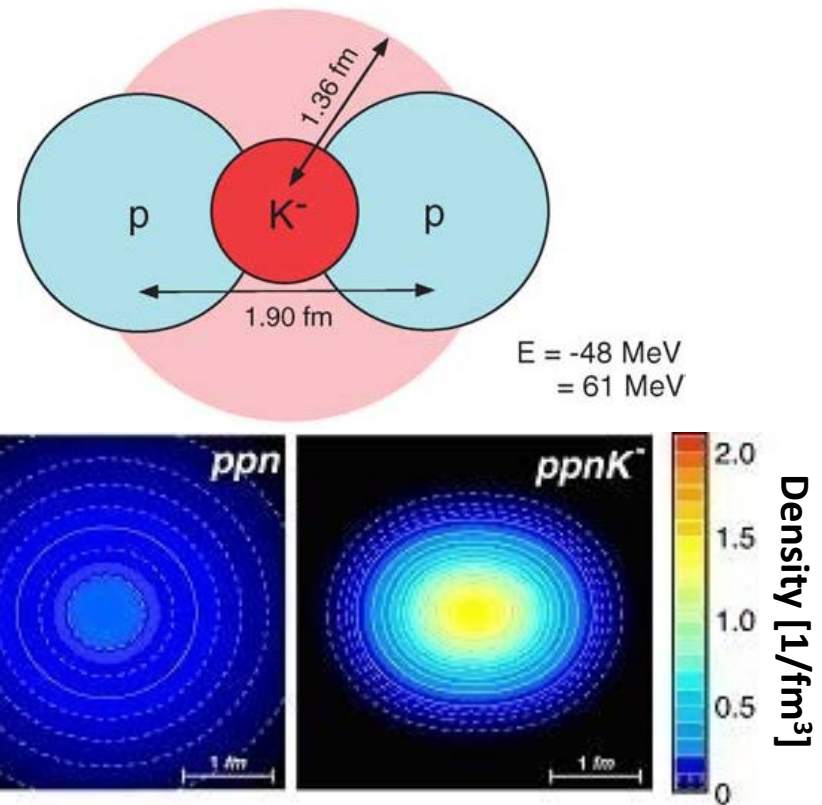
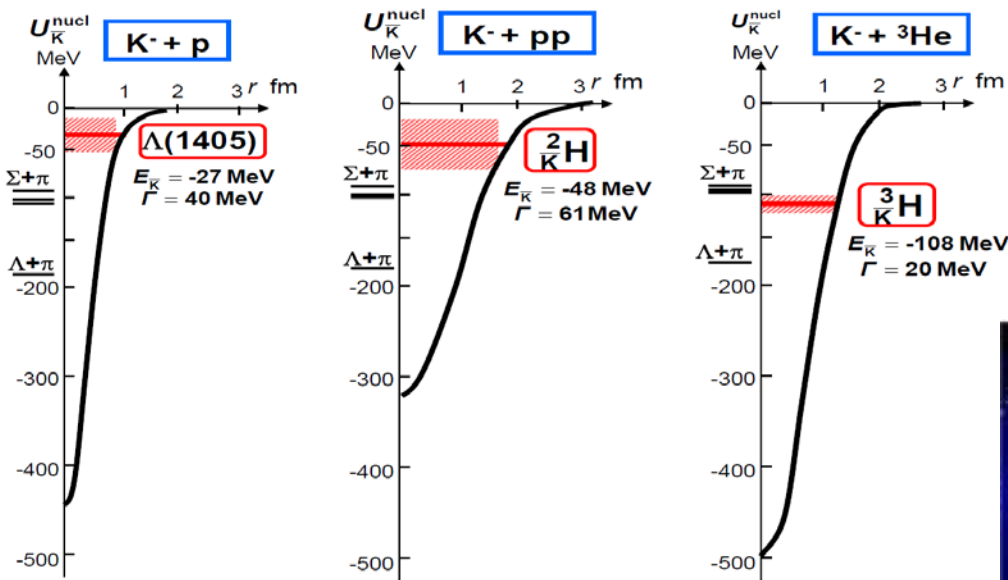
- Light mesons
 - play an important role in a nucleus as “glue”



- Light $S=-1$ mesons?
 - Kaonic-atom experiments (KpX@KEK, DEAR/SIDDHARTA@DAΦNE) clarified *strongly attractive* $K^{\text{bar}}\text{-N}$ 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 ($K^{\text{bar}}\text{NN}$, $K^{\text{bar}}\text{NNN}$, $K^{\text{bar}}K^{\text{bar}}\text{NN}$, ...)



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

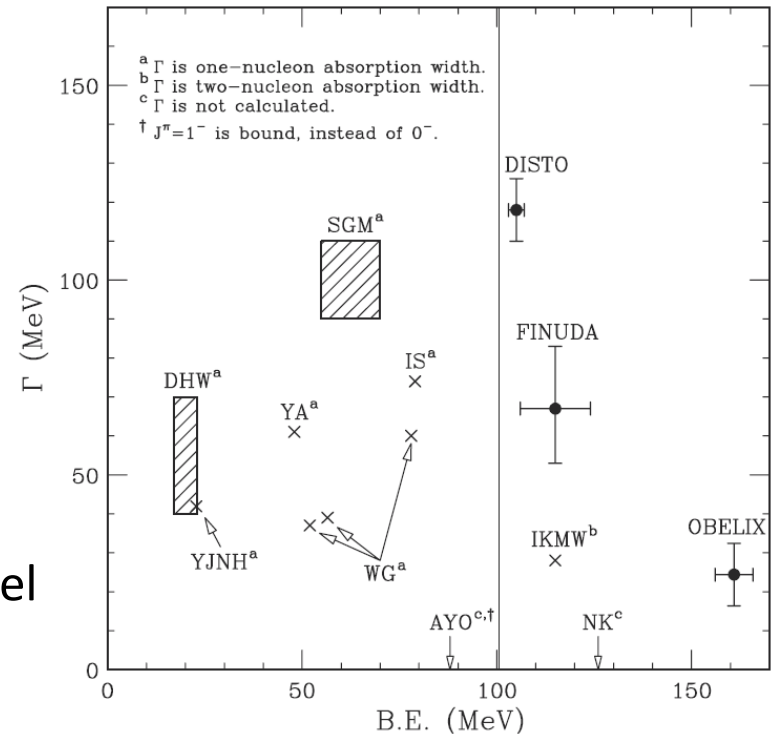
T.Yamazaki, A.Dote, Y.Akiaishi, PLB587, 167 (2004).

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 phenomenological model
- Wycech, Green [YG]
 - Variational with phenomenological model
- Arai, Yasui, Oka [AYO]
 - Λ^* model

Koike and Harada, PRC80(2019)055208

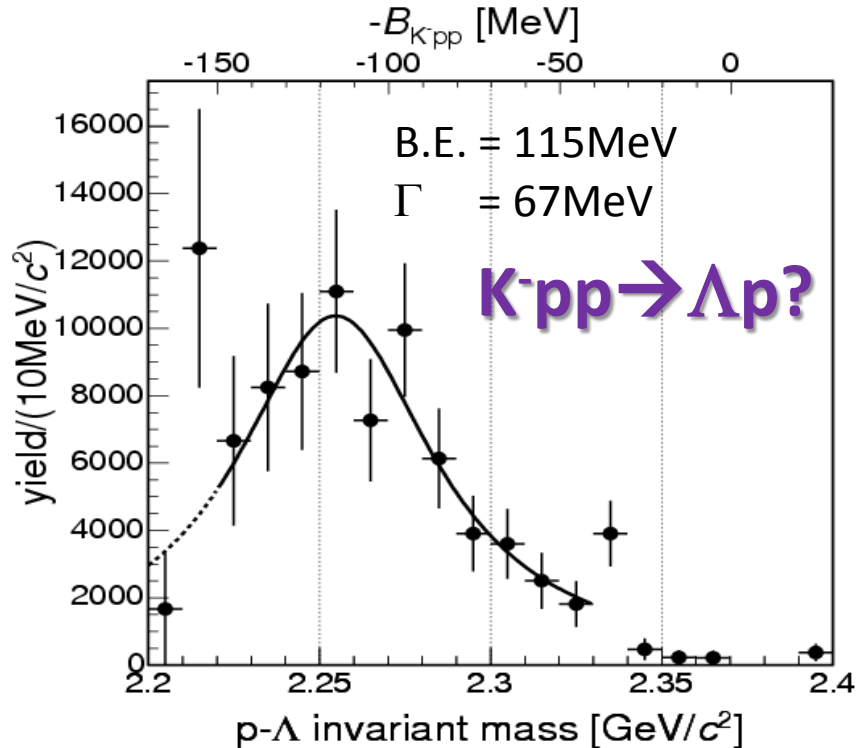


All studies predict existence of the K^-pp

→ However, B.E. and Γ are controversial

Experimental Situation

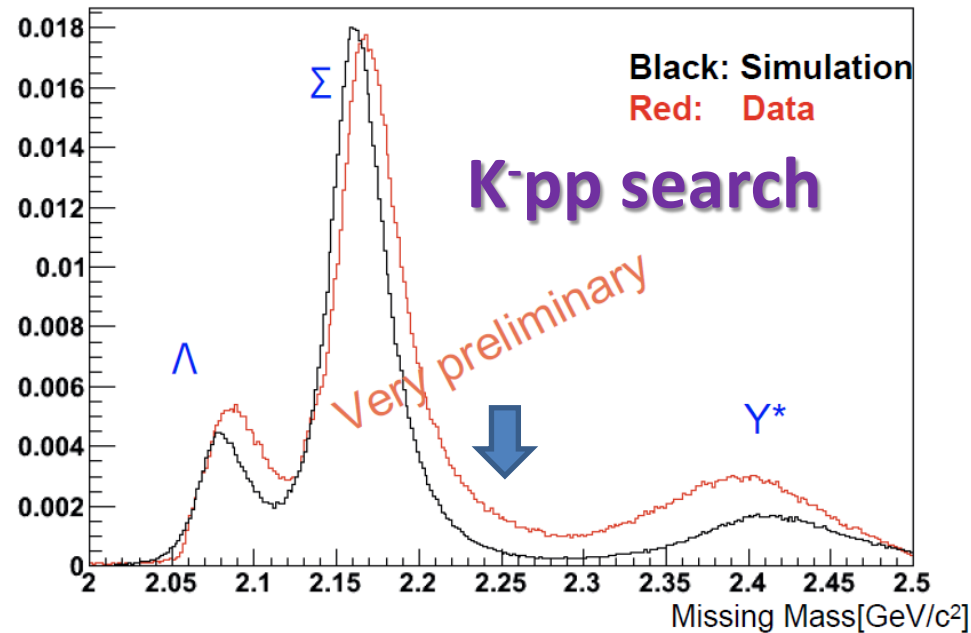
K^-/π^+ induced experiments



FINUDA@DAΦNE

PRL94(2005)212303

$\Lambda(\text{stopped } K^-, \Lambda p)$



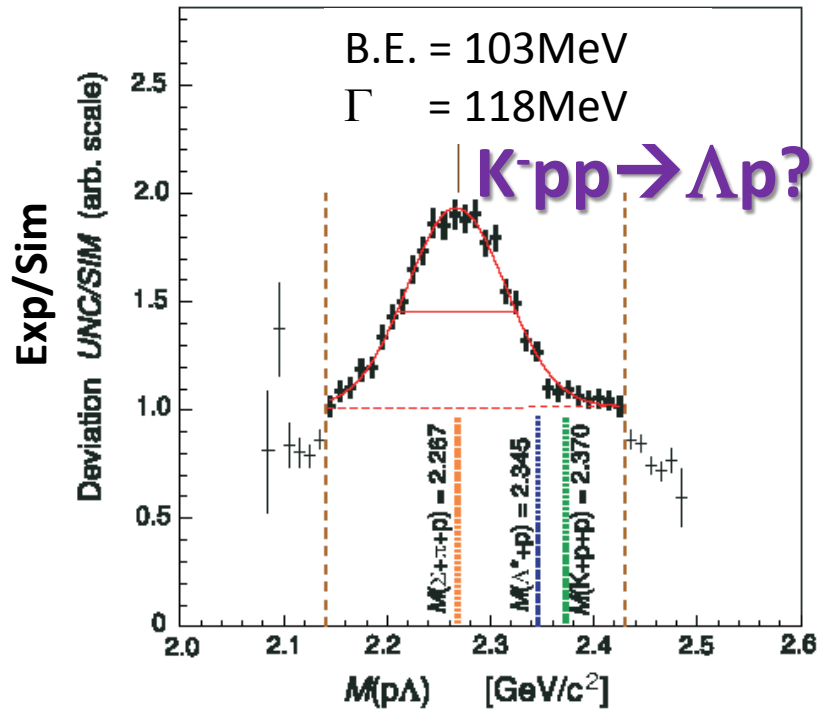
E27@J-PARC

FB20 conference (2012)

$d(\pi^+, K^+) @ 1.7\text{GeV}/c$

Experimental Situation [Cont'd]

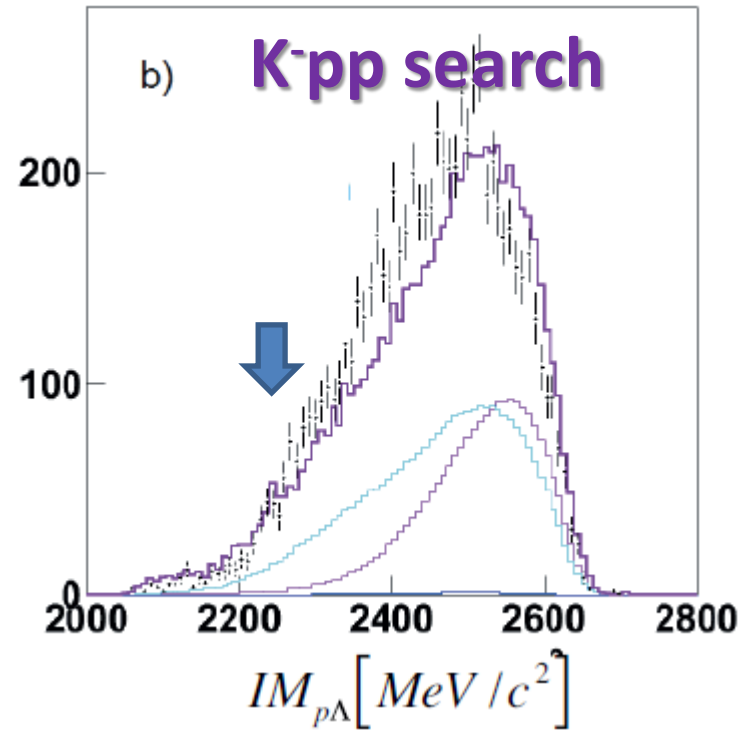
p induced experiments



DISTO@SATURNE

PRL104(2010)132502

$p + p \rightarrow (\Lambda + p) + K^+ @ 2.85\text{GeV}$



HADES@GSI

NPA914(2013)60

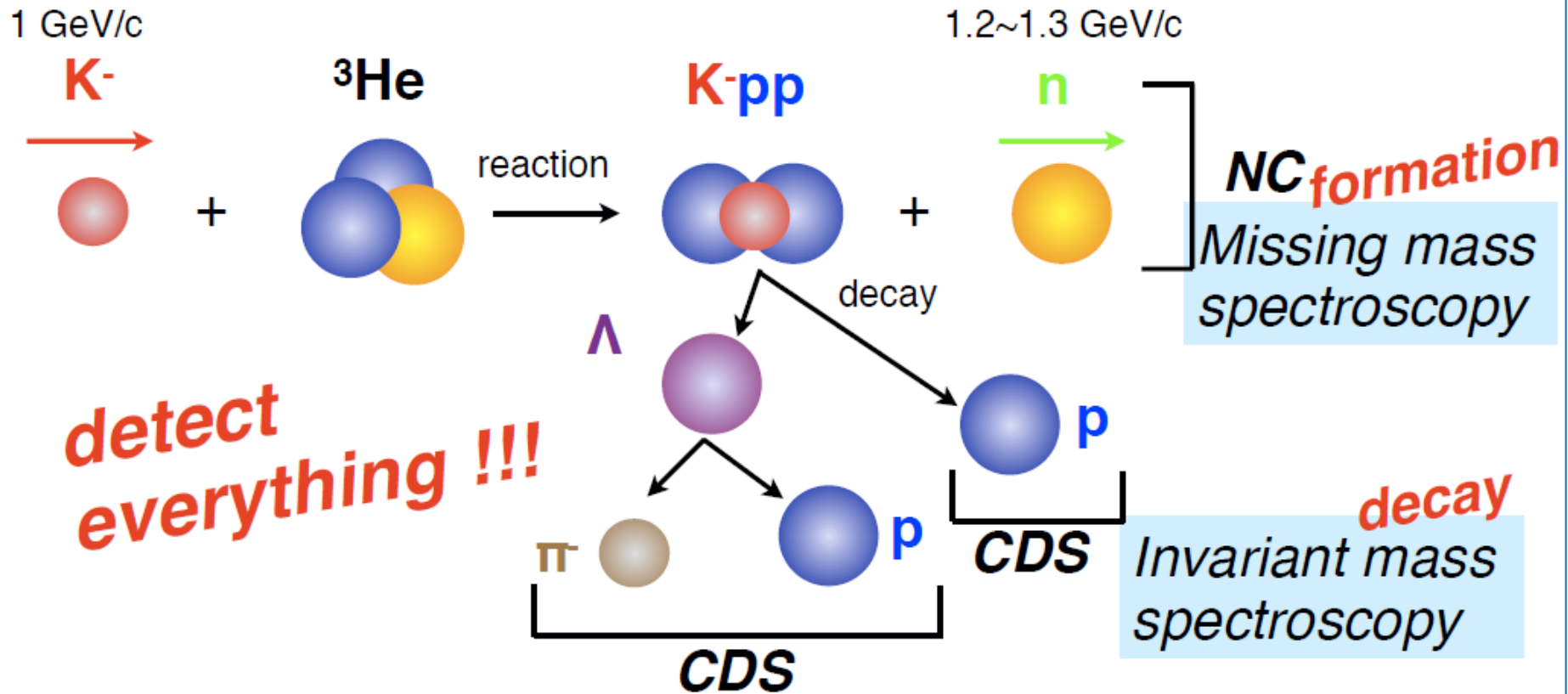
$p + p \rightarrow (\Lambda + p) + K^+ @ 3.5\text{GeV}$

We need more studies in various channels!

The J-PARC E15 Experiment

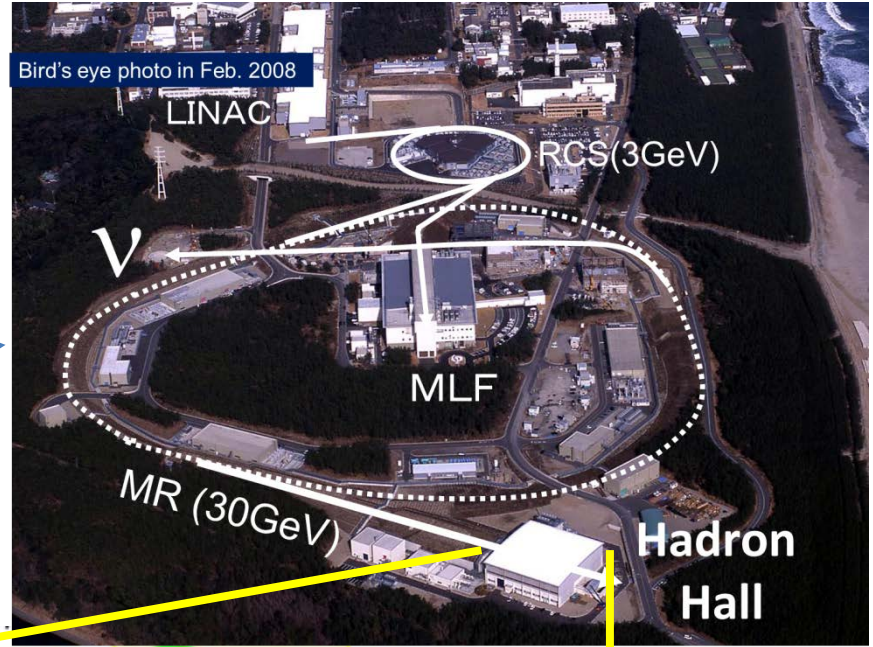
Experimental Principle

A search for the simplest kaonic nucleus, K^-pp ,
using ${}^3\text{He}(\text{in-flight } K^-, n)$ reaction

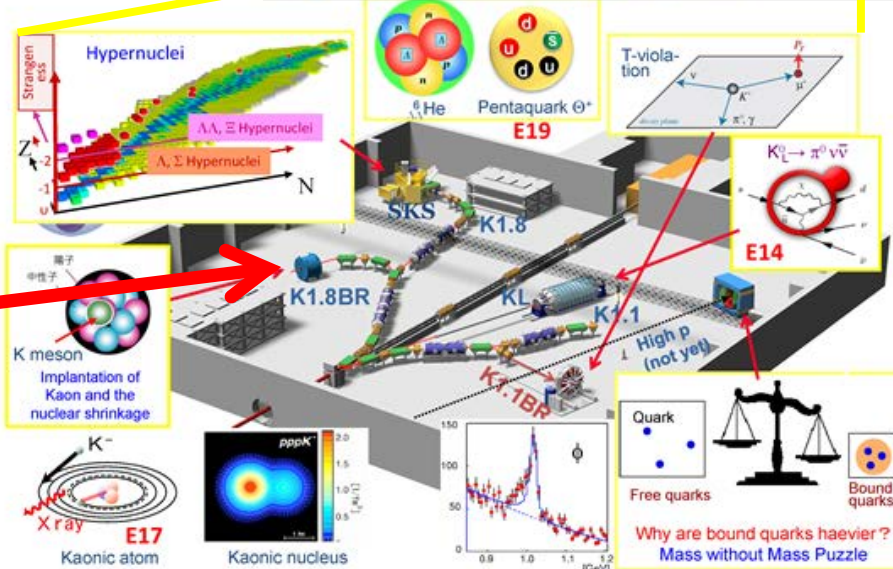


- two-nucleon absorption
 - hyperon decays
- CAN be discriminated kinematically**

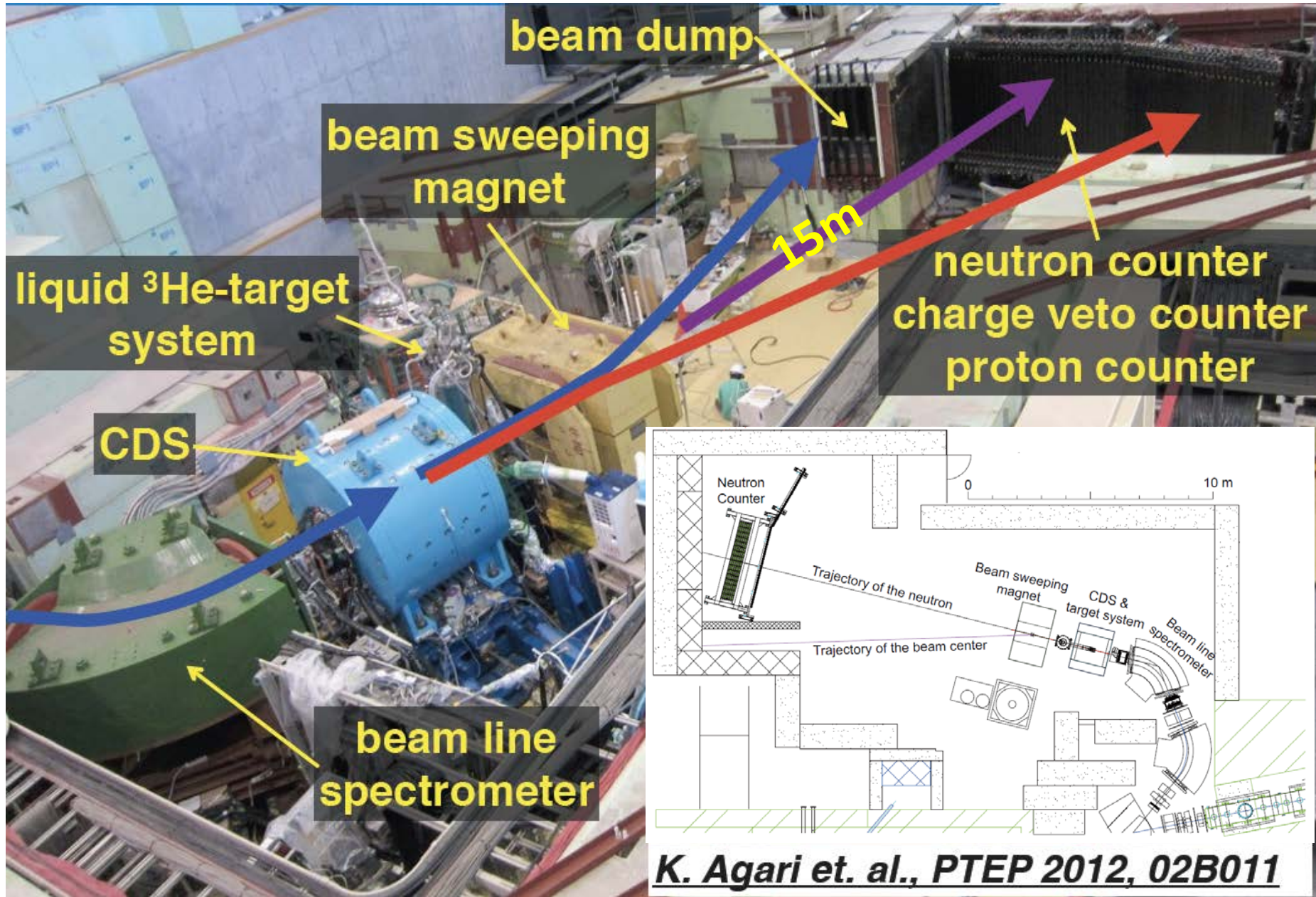
J-PARC (Japan Proton Accelerator Research Complex)



K1.8BR
E15/E17/E31



Experimental Setup

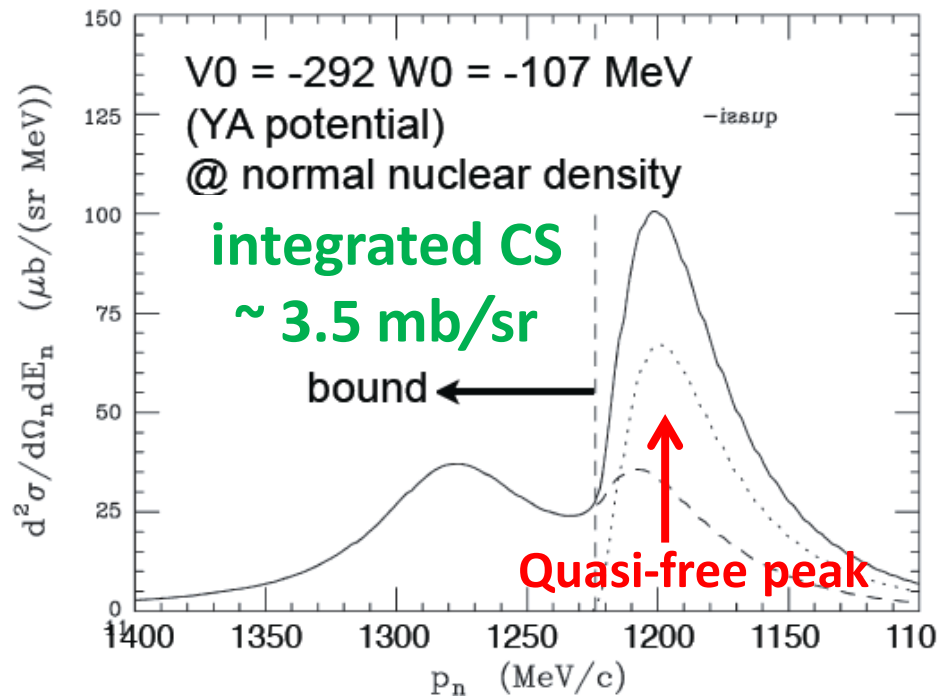


The Goal of E15

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

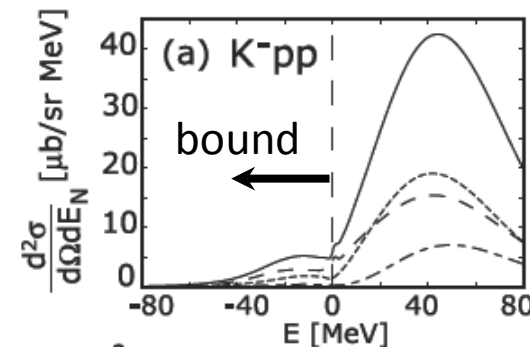
1: Semi-Inclusive ${}^3\text{He}(K^-,n)$

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

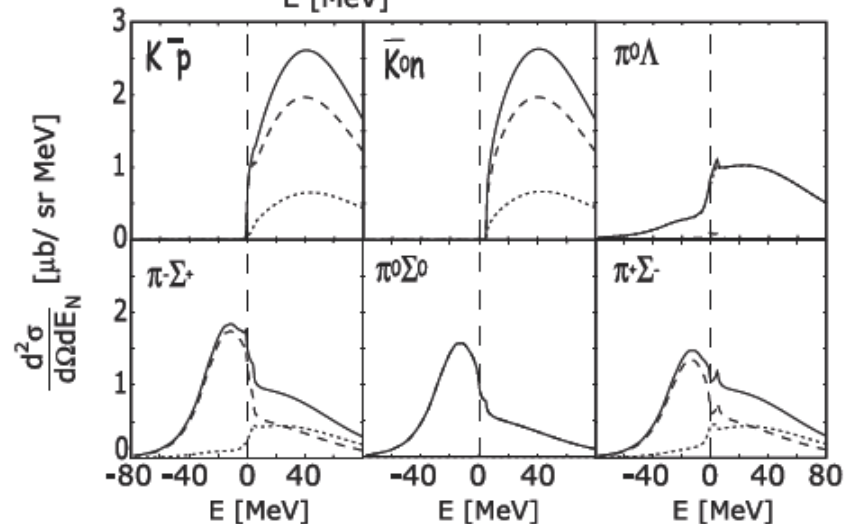


T.Koike and T.Harada. , PLB652 (2007) 262

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 $^3\text{He}(\text{K}^-, \text{n})$ [Cont'd]

Expected spectrum from MC (Geant4)

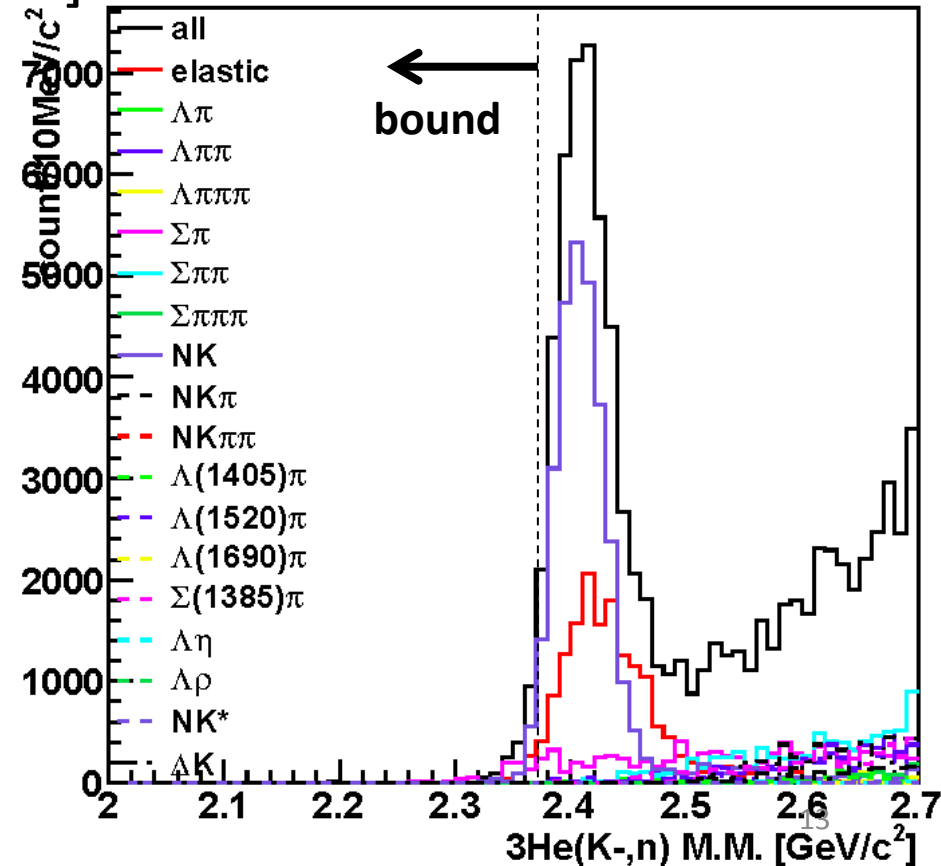
- All known K-N interactions are considered:

- Cross-section [CERN-HERA-83-02]
- Fermi-motion
- Angular distribution

- Simple assumptions:

- $\sigma_{\text{tot}} = 2 * \sigma_{\text{K-p}} + \sigma_{\text{K-n}} (\sim 150\text{mb})$

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



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

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- $\sigma_{\text{tot}} = 2 * \sigma_{\text{K-p}} + \sigma_{\text{K-n}} (\sim 150 \text{mb})$

- 2N abs.: $\text{K}^- {}^3\text{He} \rightarrow \Lambda \text{ n p}_s$

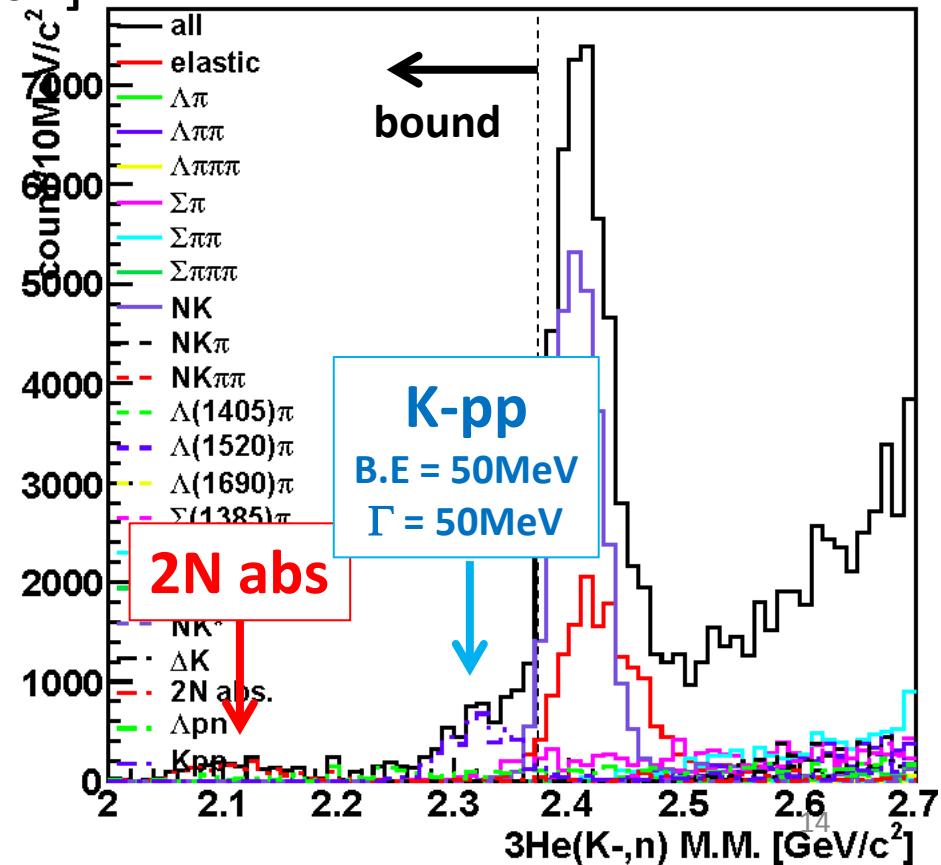
- $\sigma/\text{d}\Omega = 1 \text{mb/sr}$, isotropic

- K-pp prod.: $\text{K}^- {}^3\text{He} \rightarrow \text{K}^- \text{pp n}$

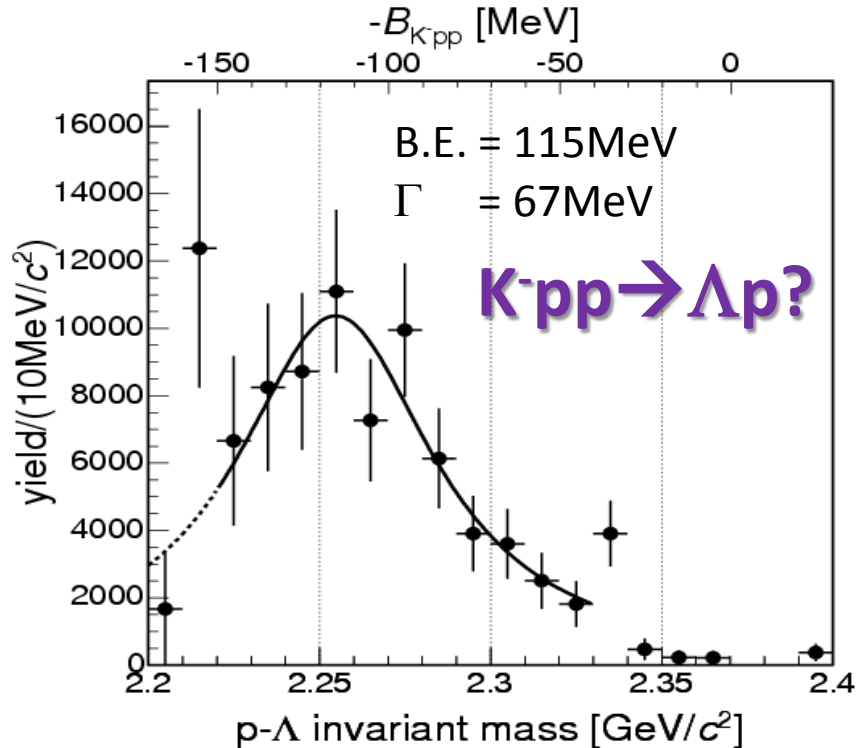
- $\text{d}\sigma/\text{d}\Omega = 1 \text{mb/sr}$, isotropic

- $\text{K}^- \text{pp} \rightarrow \Lambda \text{p}(25\%), \Sigma^0 \text{p}(25\%), \pi \Sigma \text{p}(50\%)$

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



2: Inclusive ${}^3\text{He}(\text{K}^-, \Lambda p)$



FINUDA@DAΦNE

PRL94(2005)212303

$\Lambda(\text{stopped } \text{K}^-, \Lambda p)$

- **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 ${}^3\text{He}(\text{K}^-, \Lambda p)$ [Cont'd]

Expected (simplified) spectrum from MC (Geant4)

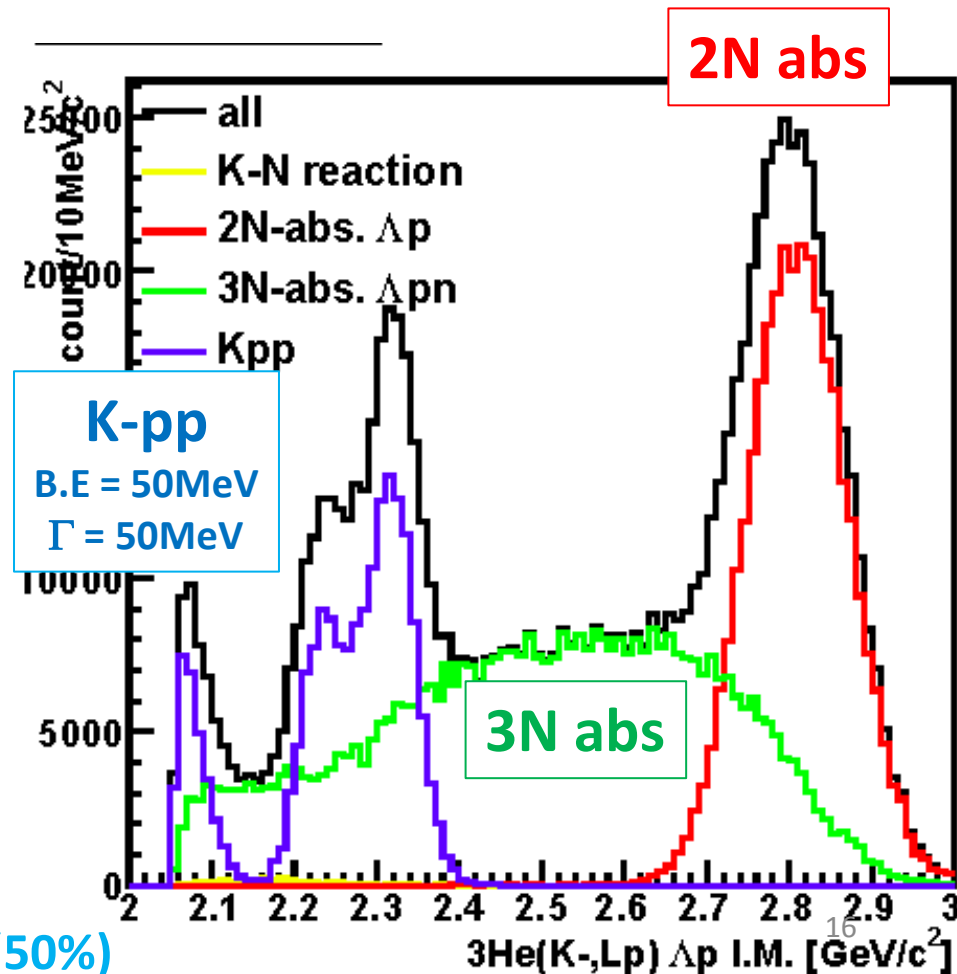
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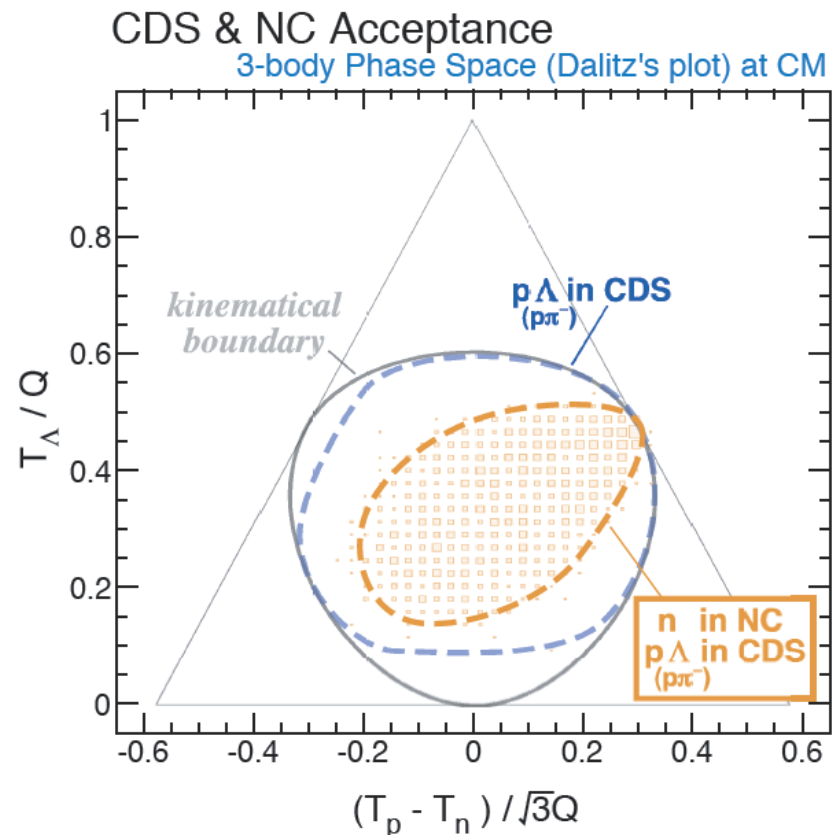
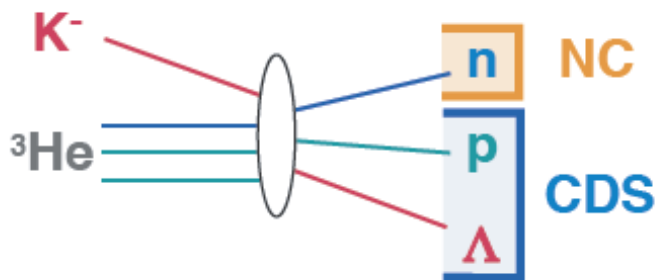
- $\sigma_{\text{tot}} = 2 * \sigma_{\text{K-p}} + \sigma_{\text{K-n}} (\sim 150 \text{mb})$
- 2N abs.: $\text{K}^- {}^3\text{He} \rightarrow \Lambda p n_s$
 - $\sigma/d\Omega = 1 \text{mb/sr}$, isotropic
- 3N abs.: $\text{K}^- {}^3\text{He} \rightarrow \Lambda p n$
 - $d\sigma/d\Omega = 1 \text{mb/sr}$, isotropic
- K⁻pp prod.: $\text{K}^- {}^3\text{He} \rightarrow \text{K}^-\text{pp} n$
 - $d\sigma/d\Omega = 1 \text{mb/sr}$, isotropic
 - $\text{K}^-\text{pp} \rightarrow \Lambda p (25\%), \Sigma^0 p (25\%), \pi \Sigma p (50\%)$

Λp invariant mass spectrum



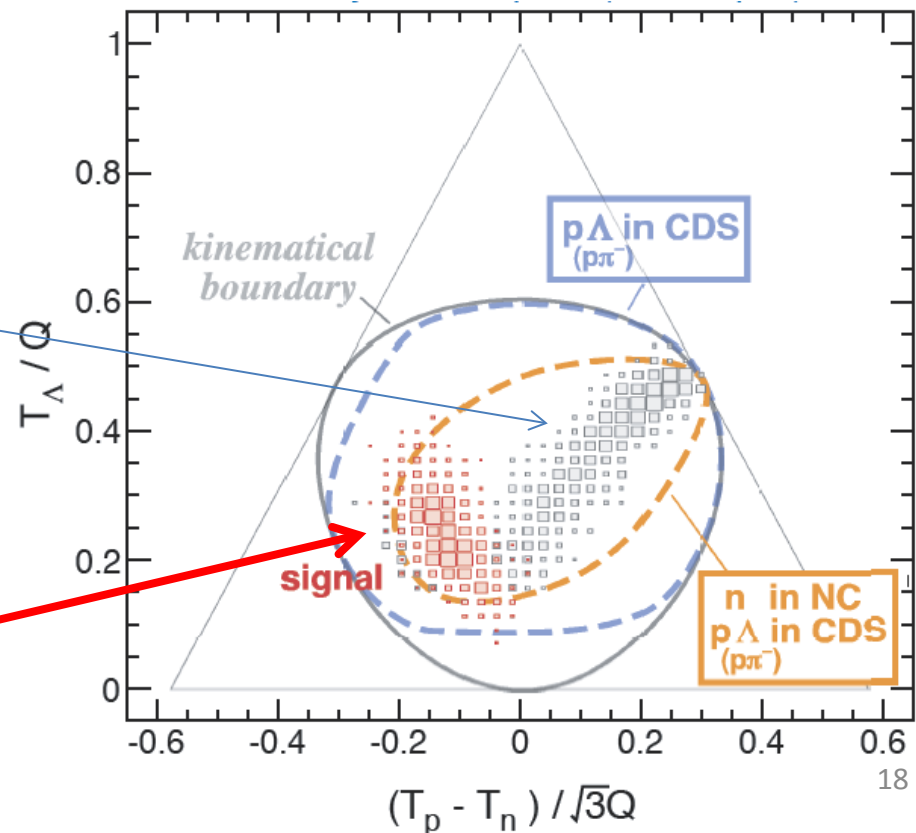
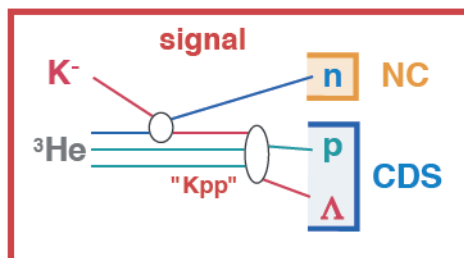
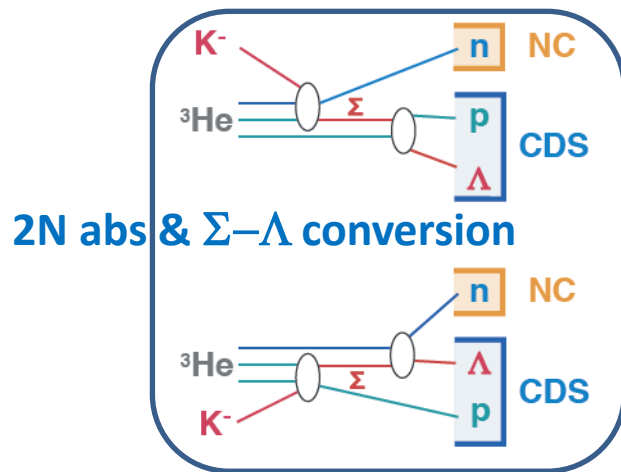
3: Exclusive $^3\text{He}(K^-, \Lambda p n)$

- 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



3: Exclusive $^3\text{He}(\text{K}^-, \Lambda \text{pn})$

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



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

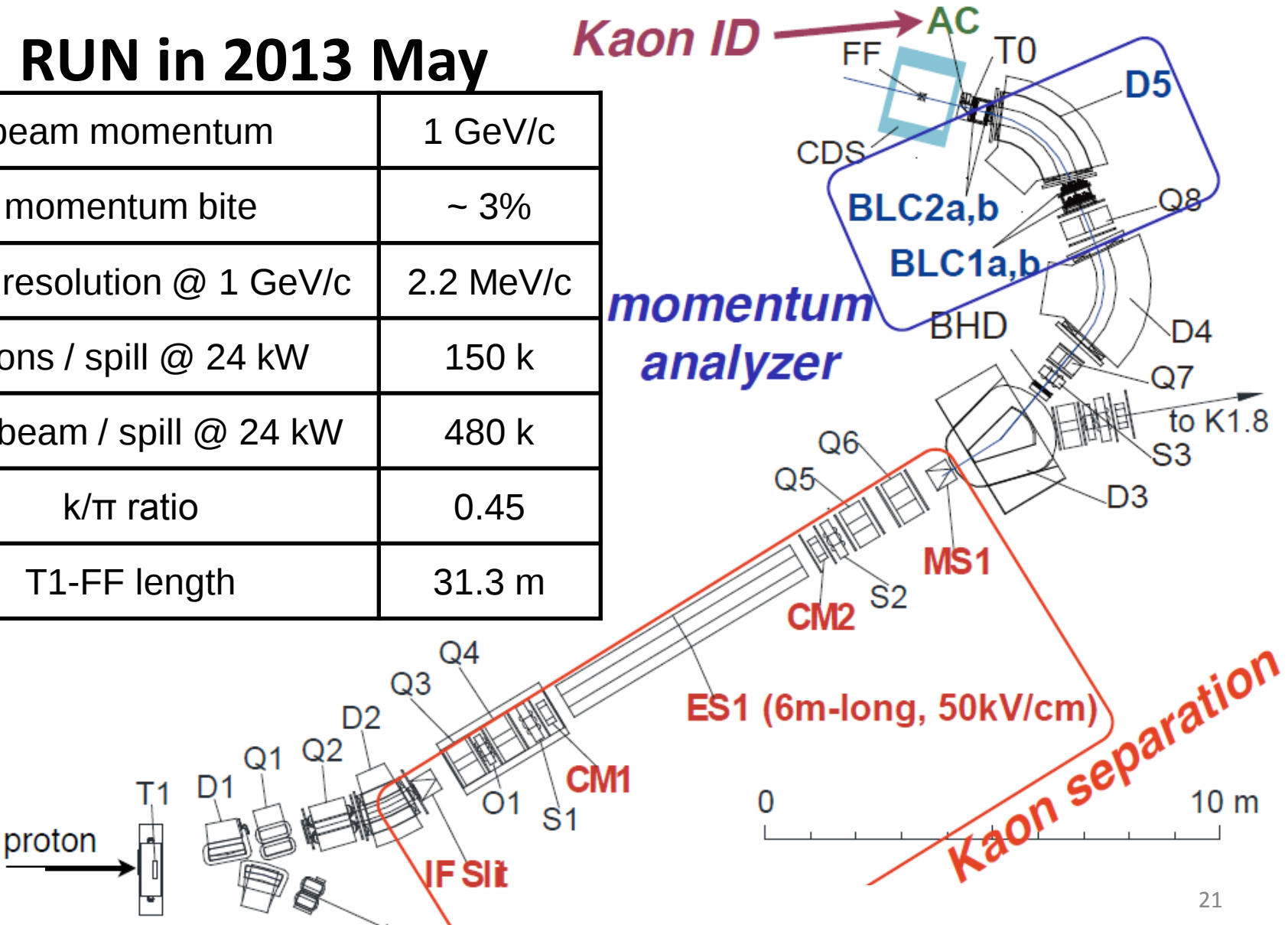
period	primary beam intensity	duration	Kaons on target
March, 2013	14.5 kW (18 Tppp, 6s cycle)	30 hours	0.9×10^9
May, 2013	24 kW (30 Tppp, 6s cycle)	88 hours	4.0×10^9

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

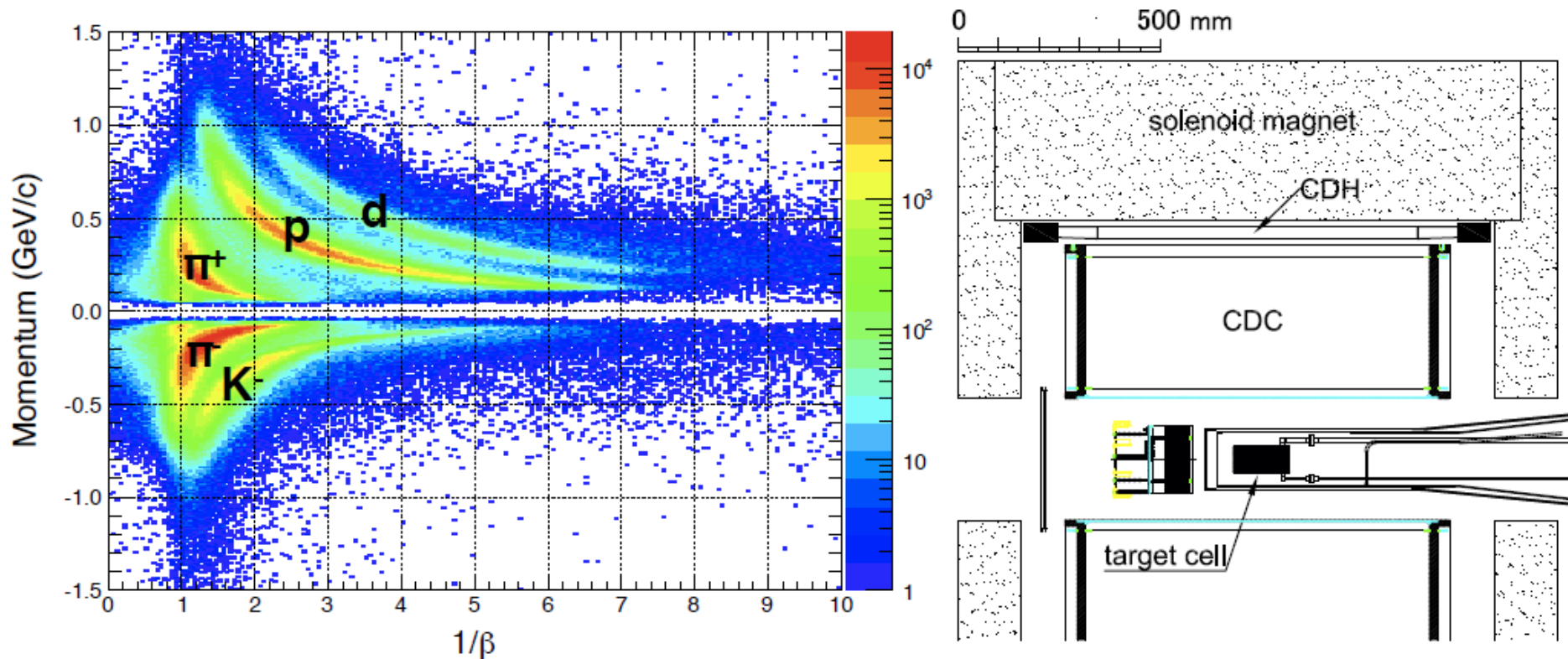
Kaon-Beam Spectrometer

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



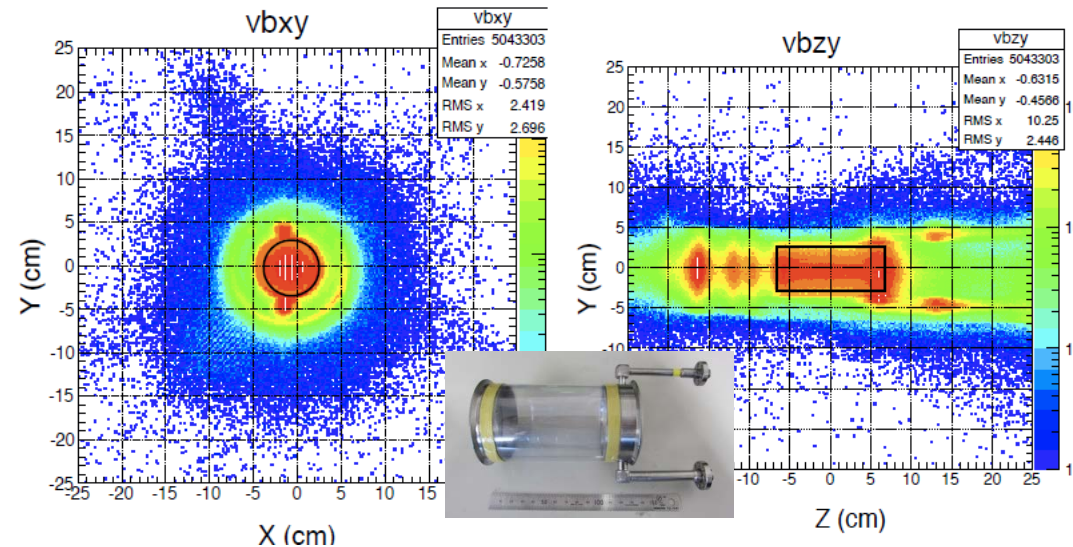
Cylindrical Detector System: pID



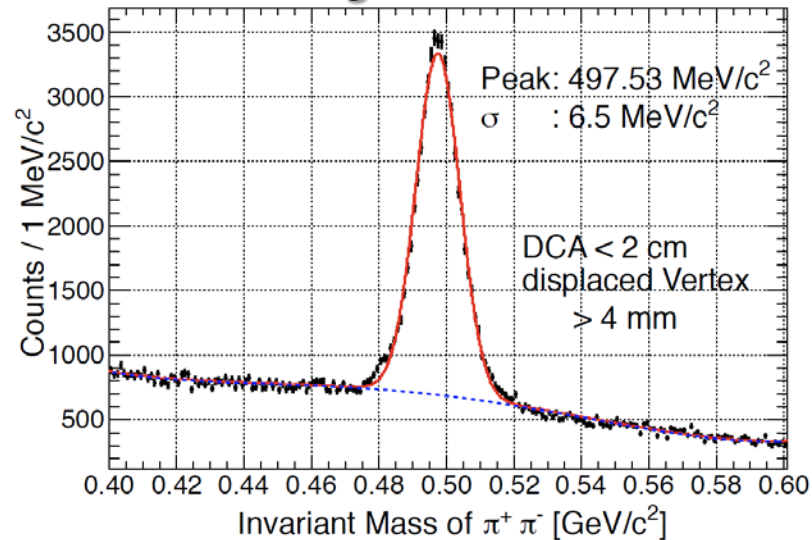
- CDC (15 layers, 1816ch) + CDH (36 seg) + 0.7T
– solid angle: 60% of 4π
- $\pi/K/p/d$ are clearly separated

Cylindrical Detector System: Tracking

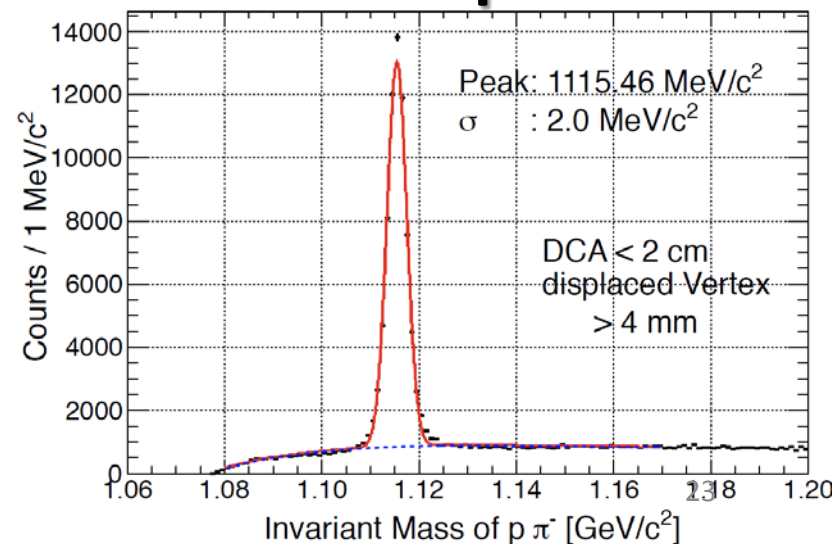
target image



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



$\Lambda \rightarrow p \pi^-$

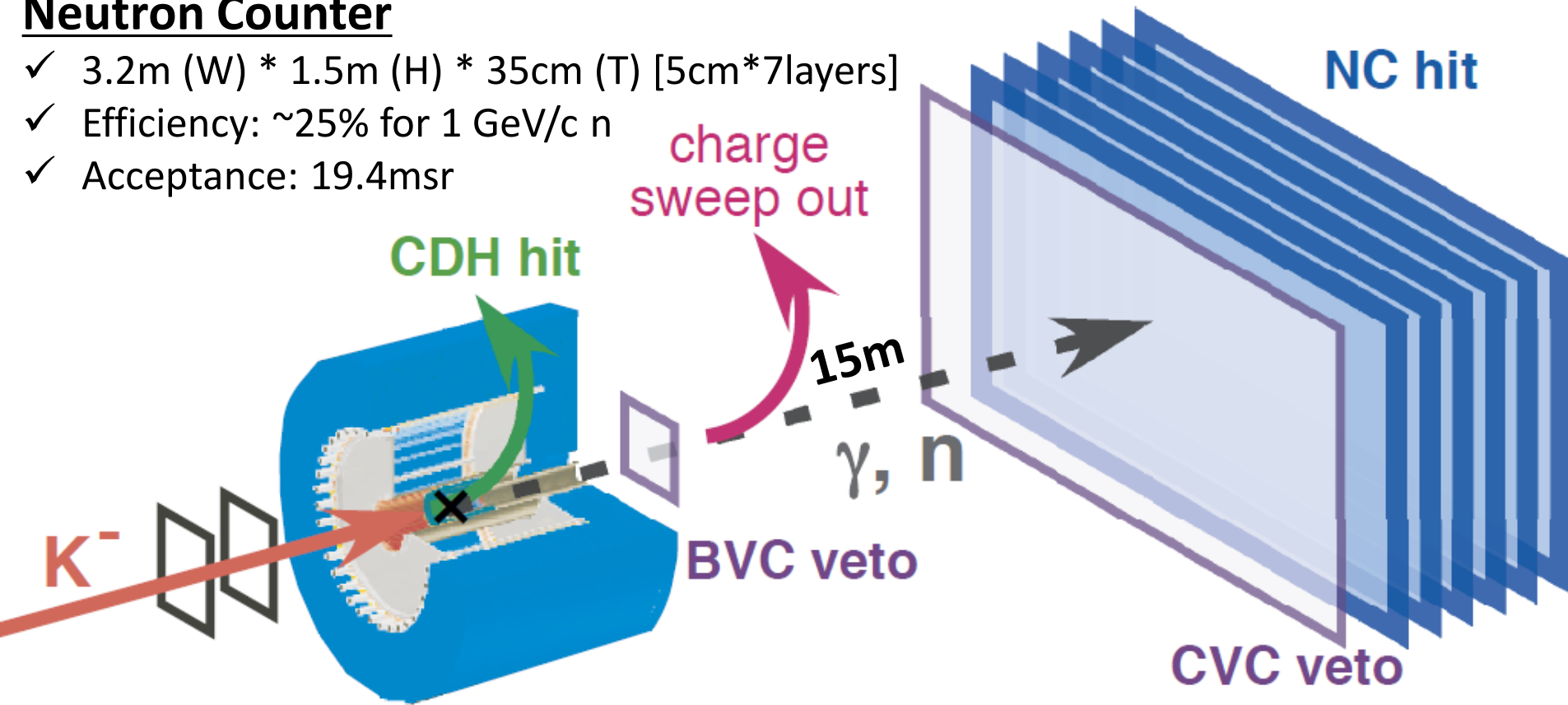


- Designed performance was achieved
 - K^0/Λ are reproduced by the MC
- Resolution for $K^- p p \rightarrow \Lambda p$ reconstruction: $\sim 10 \text{ MeV}/c^2$

Forward Neutral Particles

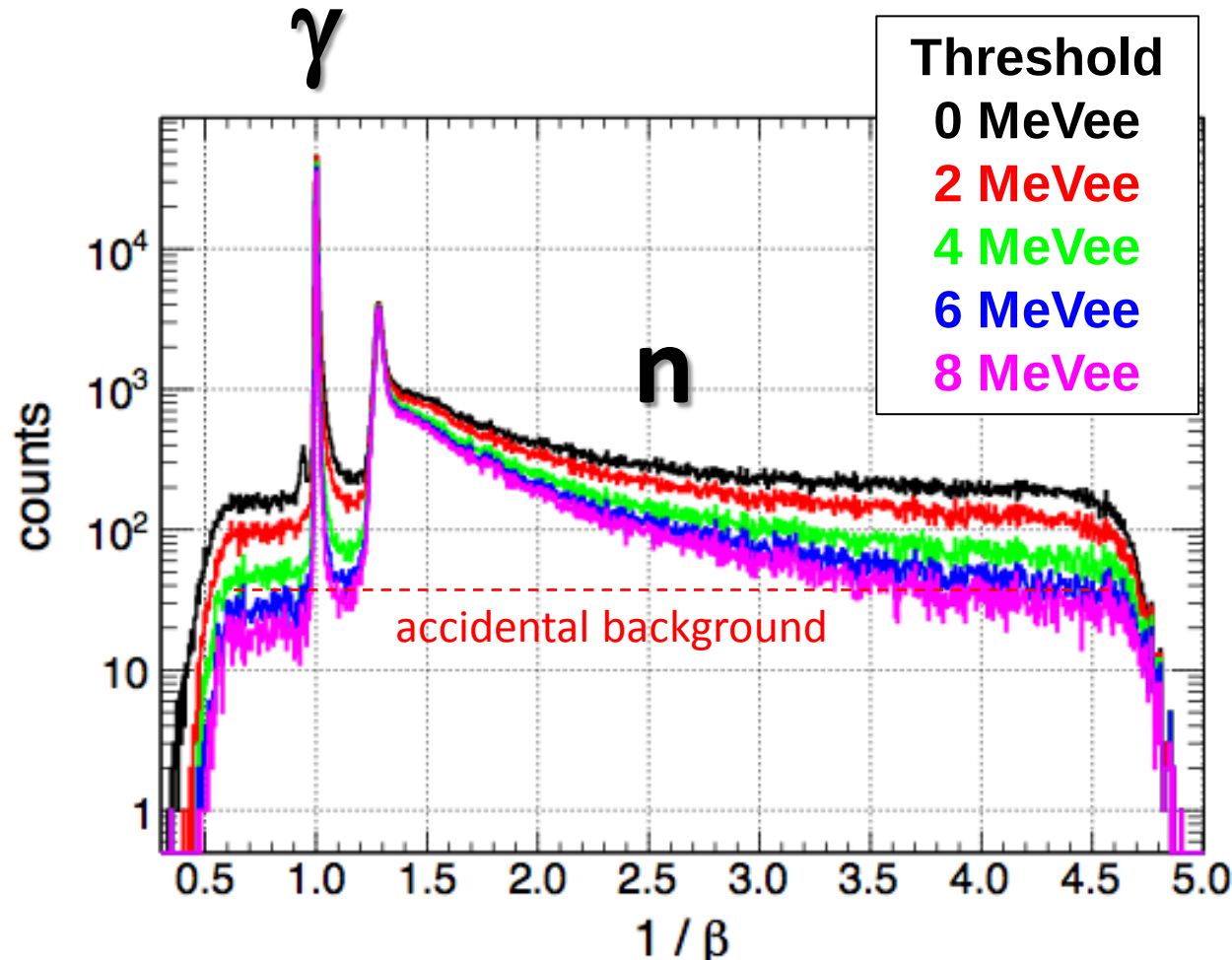
Neutron Counter

- ✓ 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

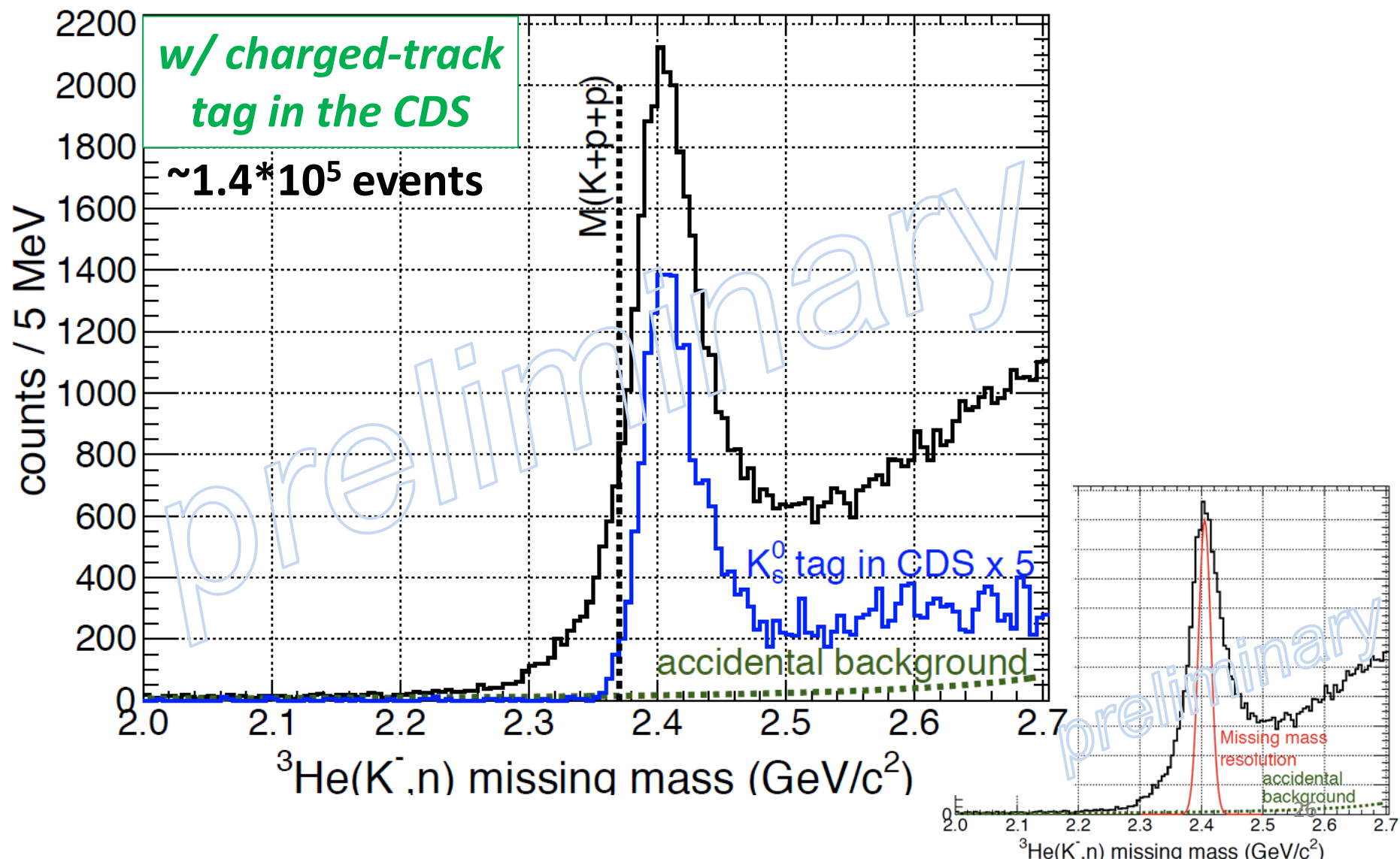
Forward Neutral Particles [Cont'd]



- ✓ Set threshold to 5 MeVee
- ✓ good S/N ratio of ~ 100 @ QF neutron peak
- ✓ $\sigma_{\text{TOF}} \sim 160\text{ps} \rightarrow \sigma_{\text{M.M.}} \sim 10\text{MeV}/c^2$ for $1\text{GeV}/c$ n²⁵

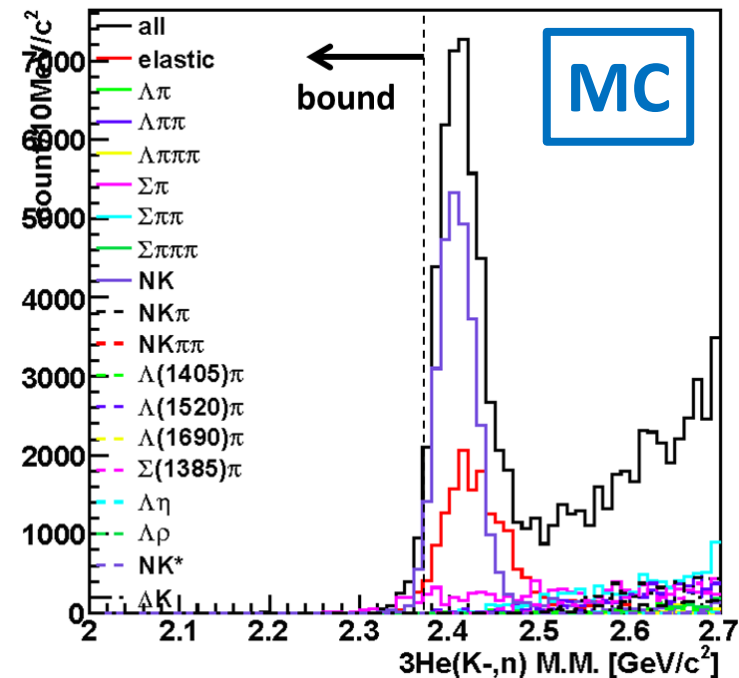
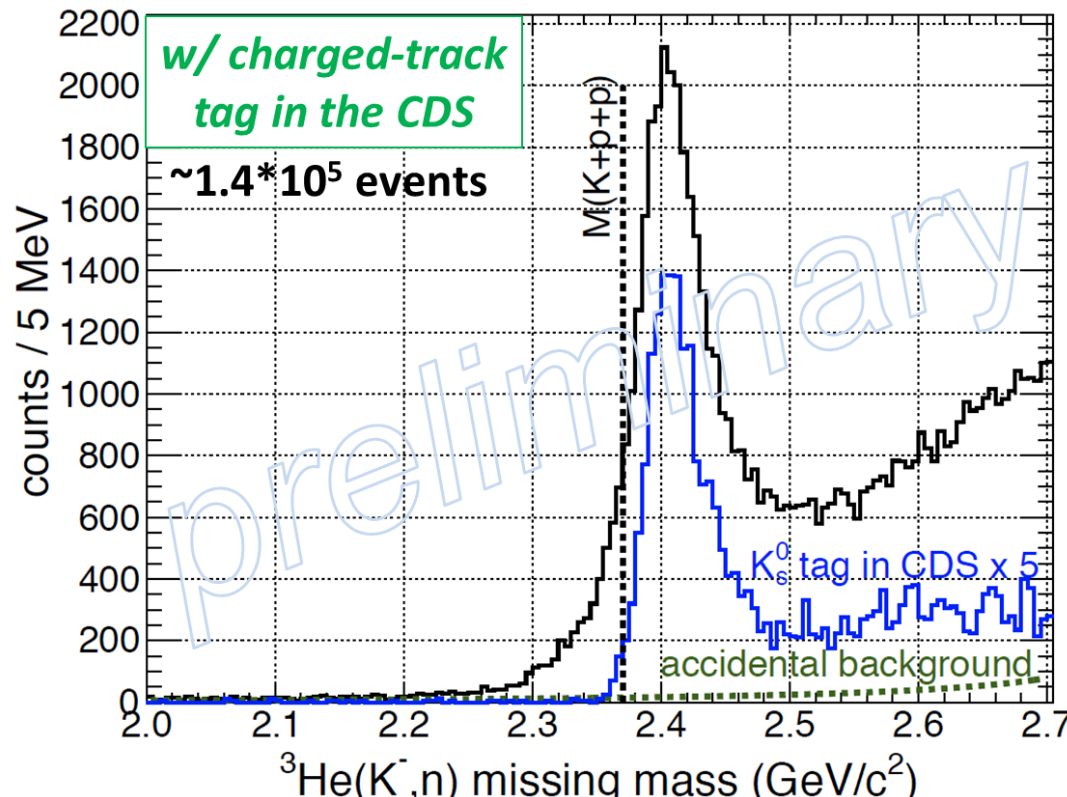
Preliminary Result 1: ${}^3\text{He}(\text{K}^-, \text{n})$

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



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

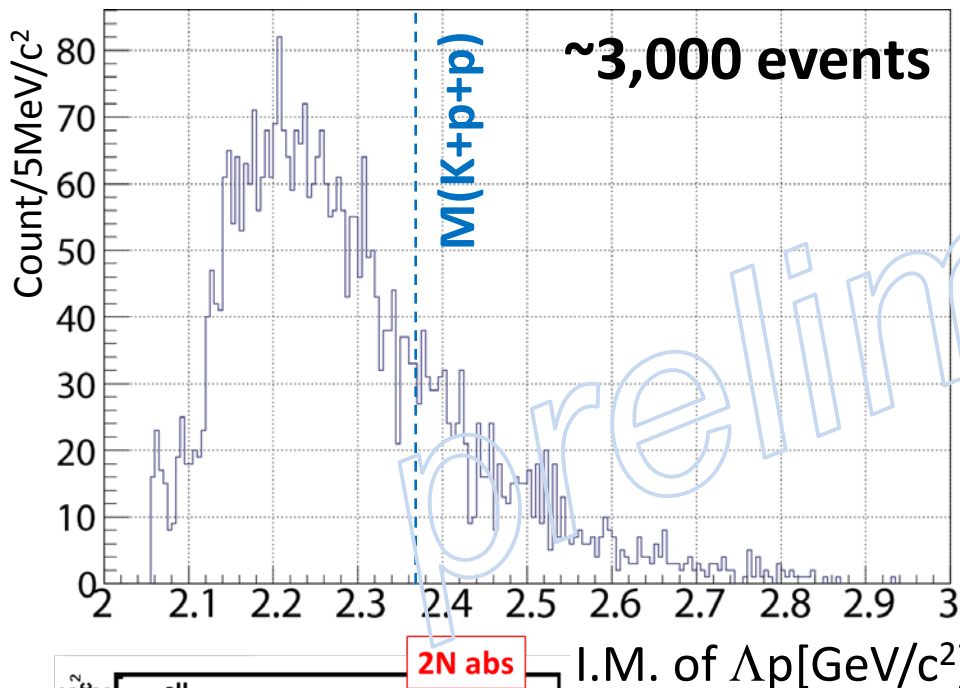
Semi-inclusive ${}^3\text{He}(\text{K}^-, \text{n})$



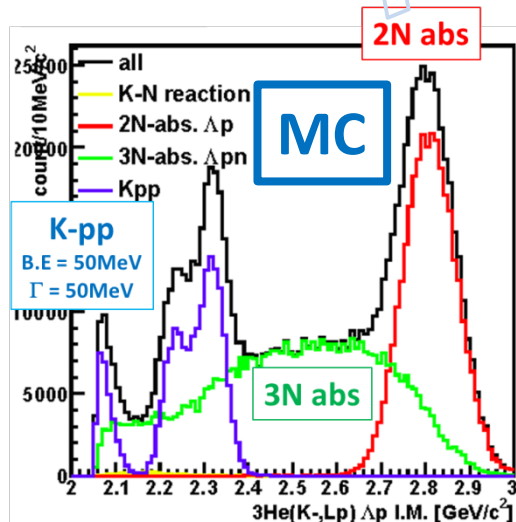
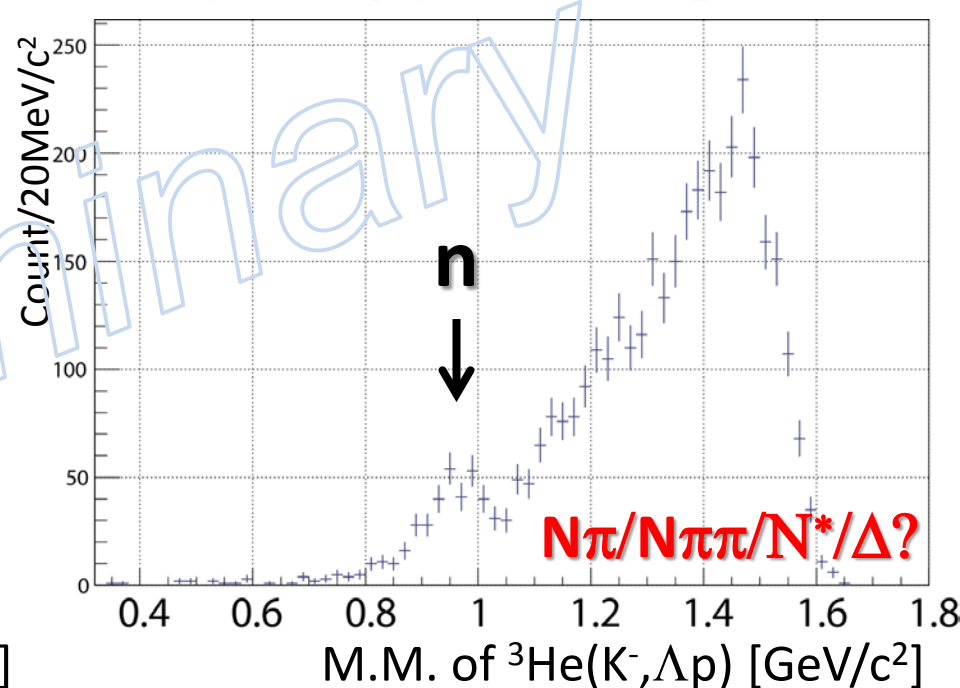
- Global shape is roughly understood by known processes.
- Tail component is very interesting.
 - Careful analysis is in progress
 - Can be reproduced by known processes?

Preliminary Result 2: $^3\text{He}(K^-, \Lambda p)$

Λp invariant mass



$^3\text{He}(K^-, \Lambda p)$ missing mass

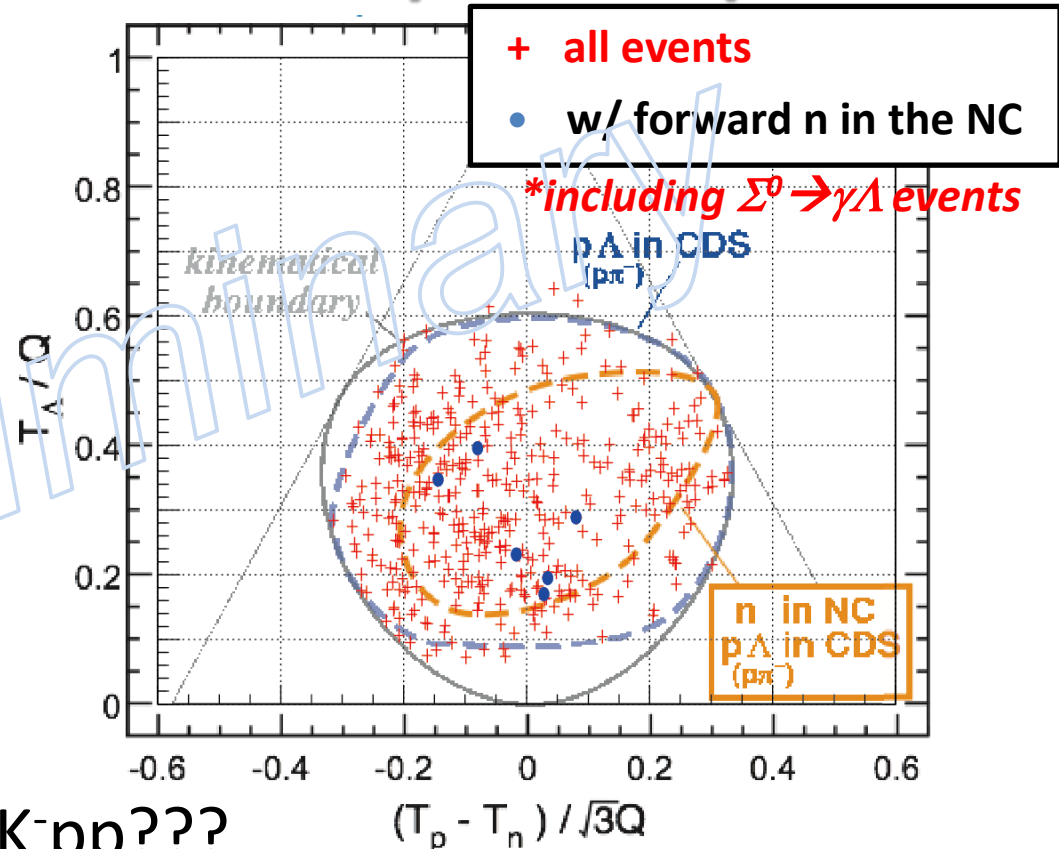
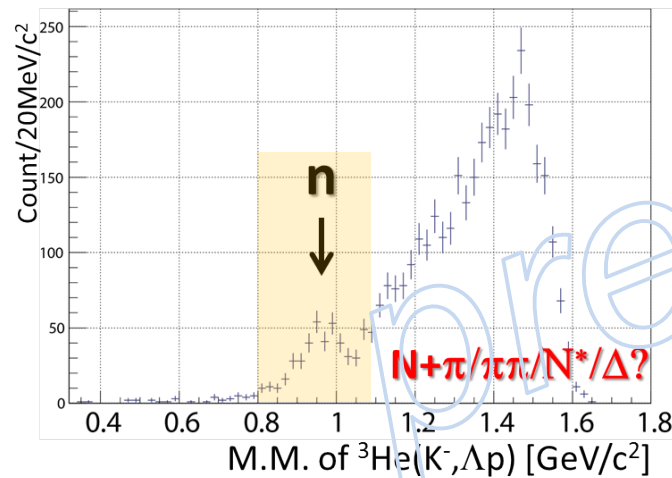


- Multi-N absorption processes exist.
- **Spectrum shape is NOT understood yet.**
 - 2N/3N-abs.?
 - 2N-abs with multi- π ?

Preliminary Result 3: ${}^3\text{He}(\text{K}^-, \Lambda \text{pn})$

Dalitz plot of Λpn

${}^3\text{He}(\text{K}^-, \Lambda \text{p})$ missing mass



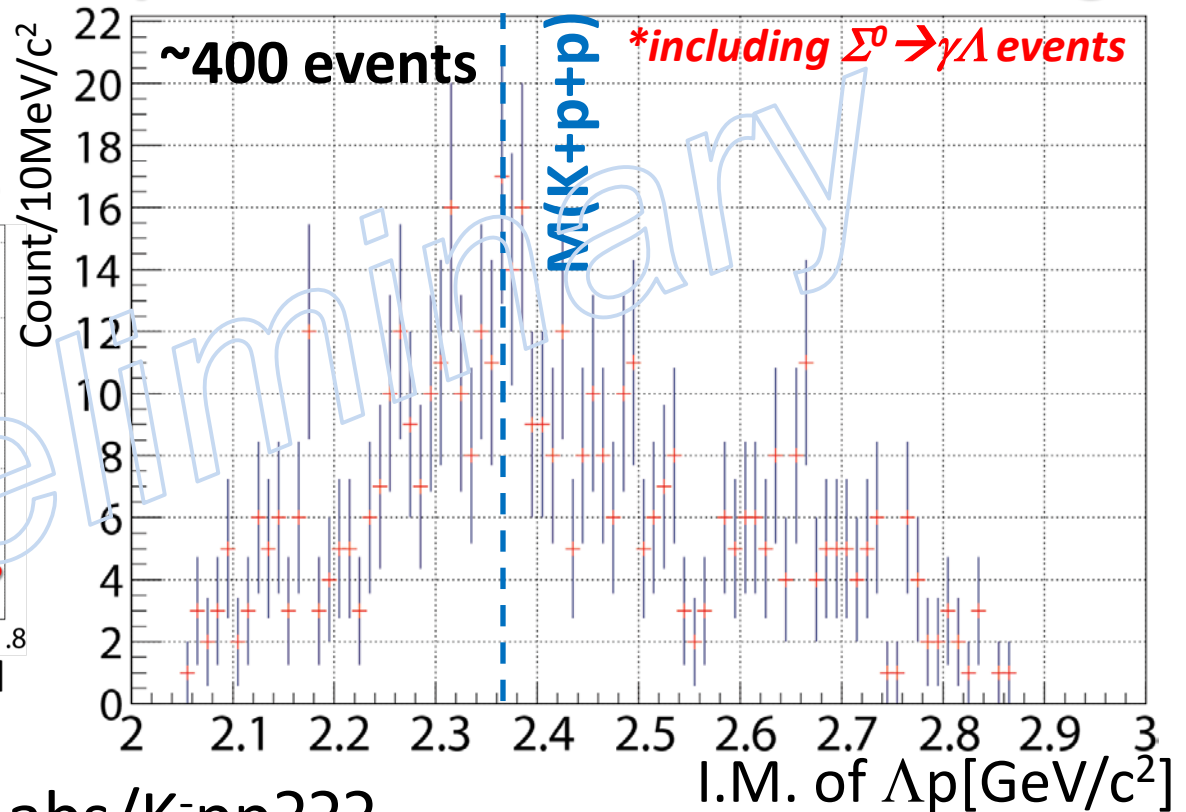
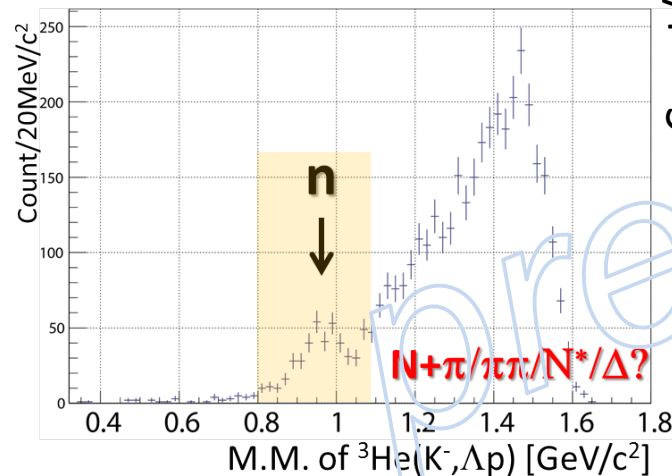
- Some hints of 3N-abs/ $\text{K}^- \text{pp}$???

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

Preliminary Result 3: ${}^3\text{He}(\text{K}^-, \Lambda \text{pn})$

Λp invariant mass w/ missing n

${}^3\text{He}(\text{K}^-, \Lambda \text{p})$ missing mass



- Some hints of $3\text{N-abs}/\text{K}^- \text{pp}???$
- 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**
 - $\sim 4 \times 10^9$ kaons were incident on ^3He
 - $^3\text{He}(K^-,n)$: $\sim 1.4 \times 10^5$ events
 - $^3\text{He}(K^-, \Lambda p)$: $\sim 3,000$ events with the CDS
 - $^3\text{He}(K^-, \Lambda pn)$: < 10 events with the CDS & the NC
- **Further analyses will be reported soon**
 - Finalization of the $^3\text{He}(K^-,n)$ spectrum
 - Detailed analysis of exclusive Λpn events
 - Comparison of $^3\text{He}(K^-,n/p)$ spectra
 - ...

The J-PARC E15 Collaboration

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