Kaonic nuclei search via the in-flight (K^-, n) reaction on helium-3

1. Introduction
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3. Semi-inclusive $^3He(K^-, n)X$ analysis
4. Exclusive $^3He(K^-, \Lambda p)n$ analysis
5. Future prospect
6. Summary

Tadashi Hashimoto
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J-PARC E15 collaboration

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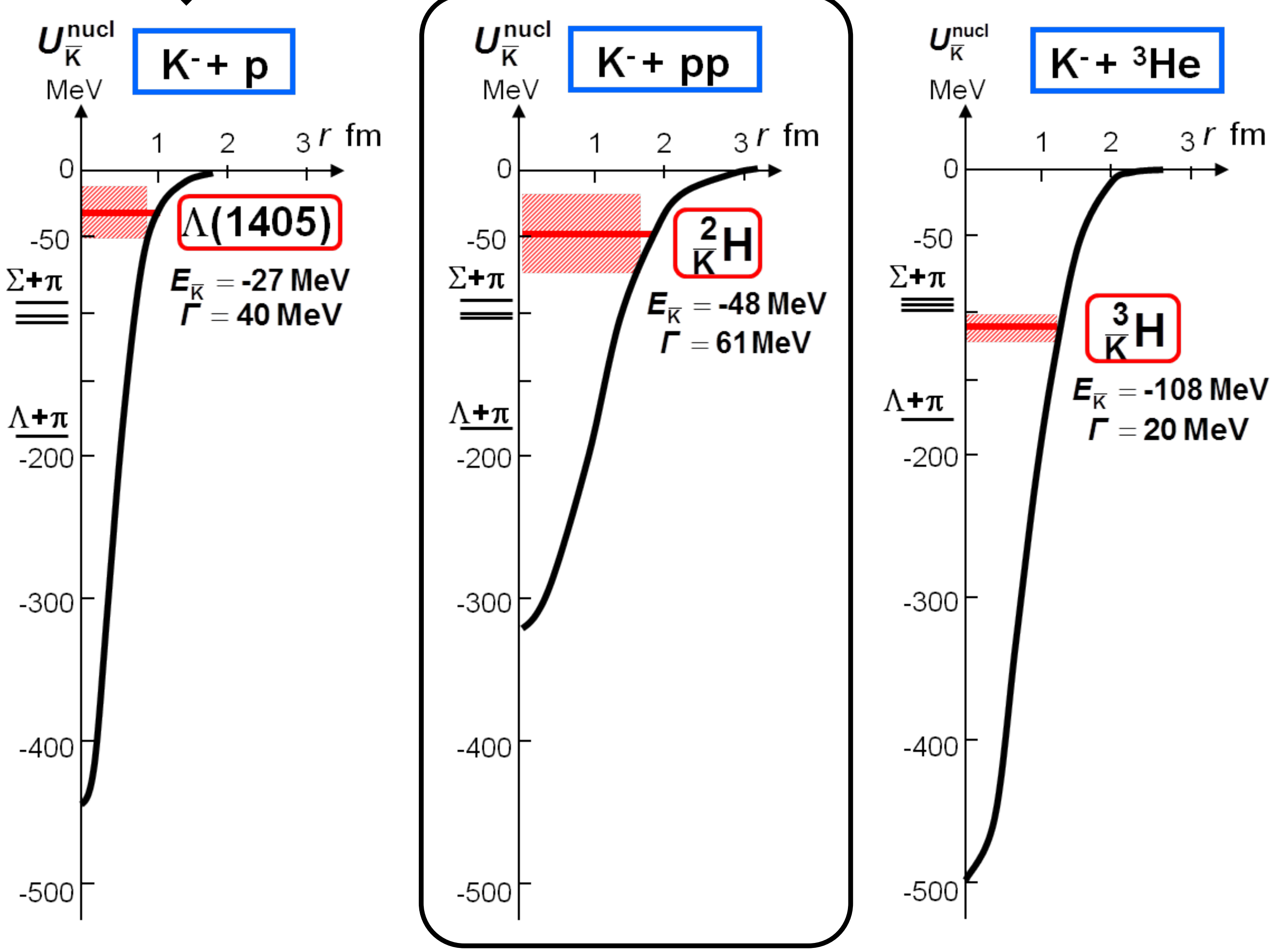
Kaonic nuclear bound state

Anti-kaon might be bound to a nucleus

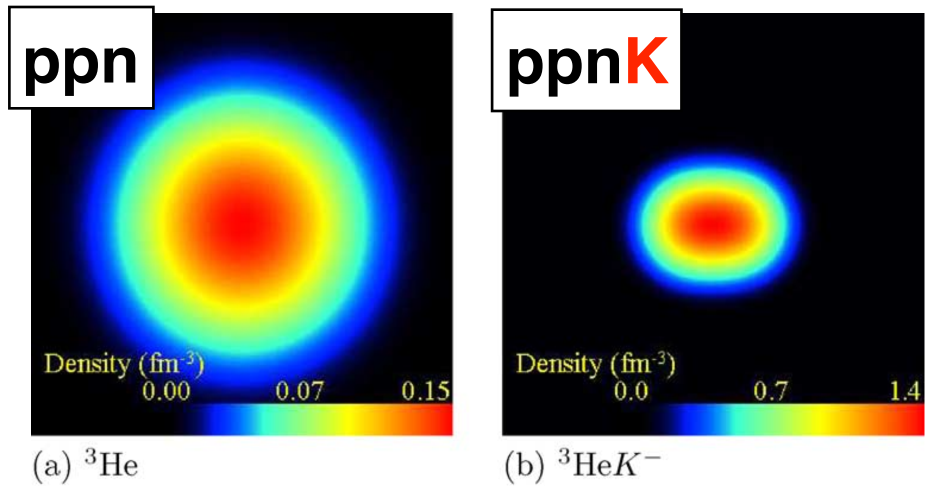
due to the strongly attractive $K^{bar}N$ interaction in I=0

Assumption

1.Y. Akaishi and T. Yamazaki. *Phys. Rev. C* **65,** 044005 (2002).
2.T. Yamazaki and Y. Akaishi. *Physics Letters B* **535,** 70–76 (2002).

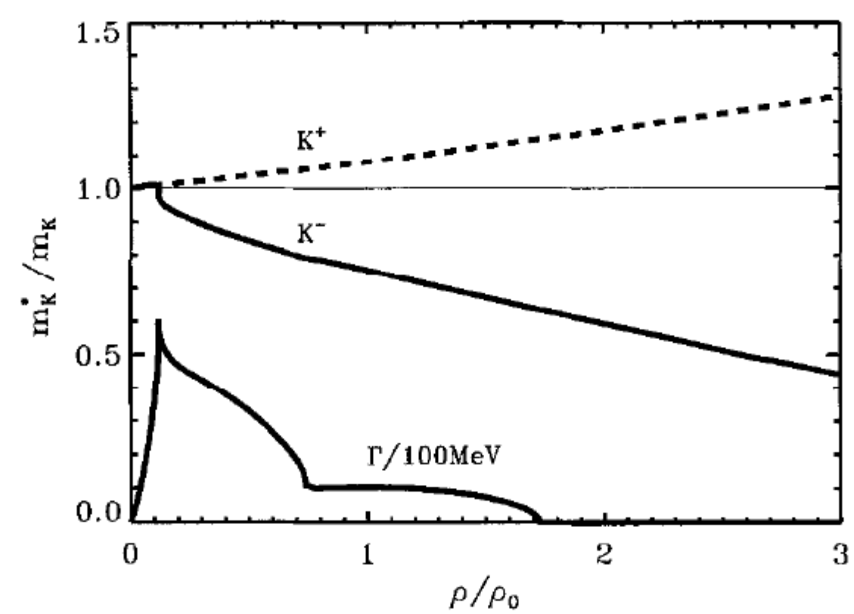


dense nuclei are predicted



A. Dote, H. Horiuchi, Y. Akaishi and T. Yamazaki, Phys. Lett. B 590 (2004) 51

Kaon mass in nuclear medium?



1.T. Waas *et al. Physics Letters B* **379,** 34–38 (1996).

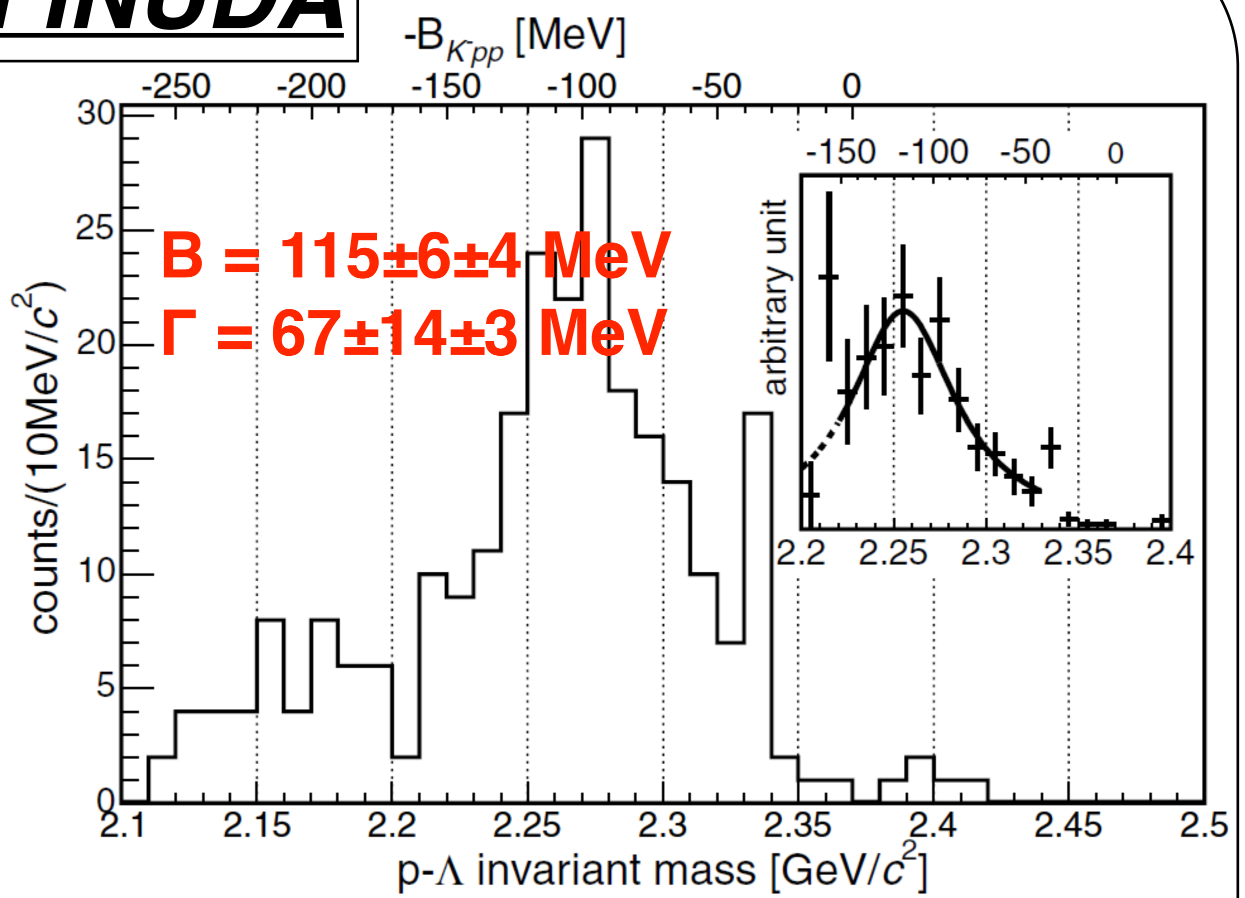
the lightest kaonic nucleus

"K-pp" : $[K^{bar}(NN)_{I=1,S=0}]_{I=1/2}, J^{\pi}=0^-$

“K⁻pp” candidates

FINUDA

B = 115±6±4 MeV
Γ = 67±14±3 MeV



1.M. Agnello *et al. Phys. Rev. Lett.* **94,** 212303 (2005).

back-to-back Λp pair
from stopped K^- on ^{6}Li, ^{7}Li, ^{12}C

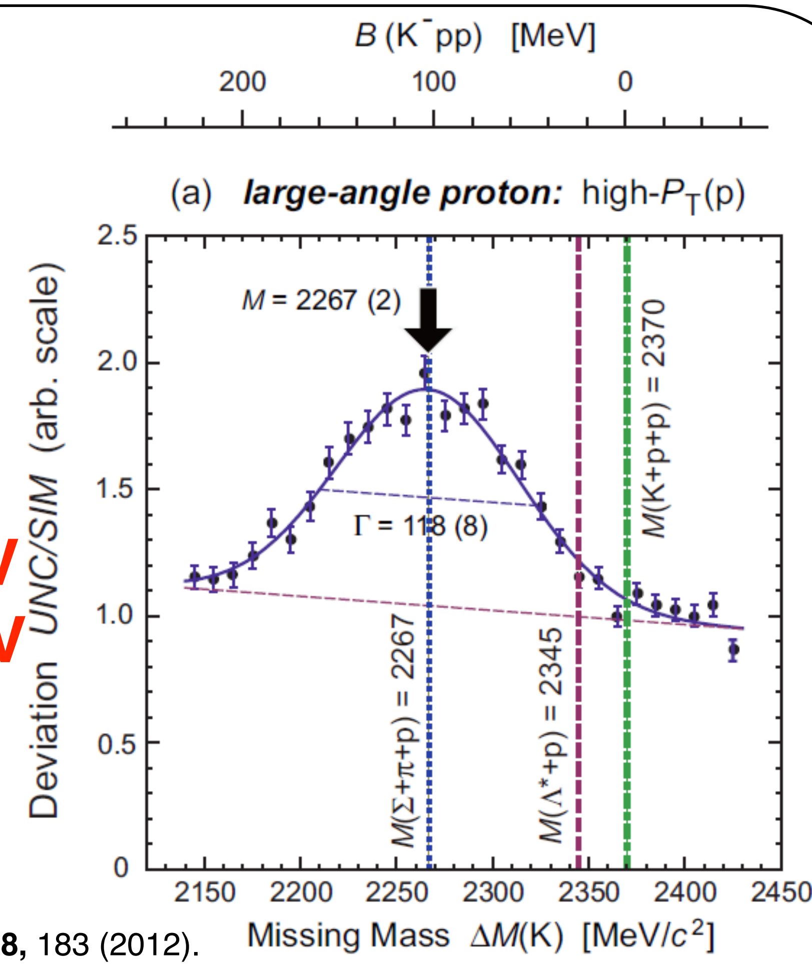
2NA contributions?

$$K^-\text{"}NN\text{"} \to \Sigma^0 p, \quad \Sigma^0 \to \Lambda\gamma \qquad K^-\text{"}NN\text{"}N \to \Sigma NN, \quad \Sigma N \to \Lambda N$$

DISTO

@T_p=2.85 GeV

B = 105±2±5 MeV
Γ = 118±8±10MeV



1.P. Kienle *et al. Eur. Phys. J. A* **48,** 183 (2012).
2.T. Yamazaki *et al. Phys. Rev. Lett.* **104,** 132502 (2010).

Exclusive pp→(“K⁻pp”K⁺)→ΛpK⁺ channel
larger cross section than Λ*

Consistency with HADES@T_p=3.5 GeV ?

N* contribution? $$p + p \to p + N^*, \quad N^* \to K^+\Lambda$$

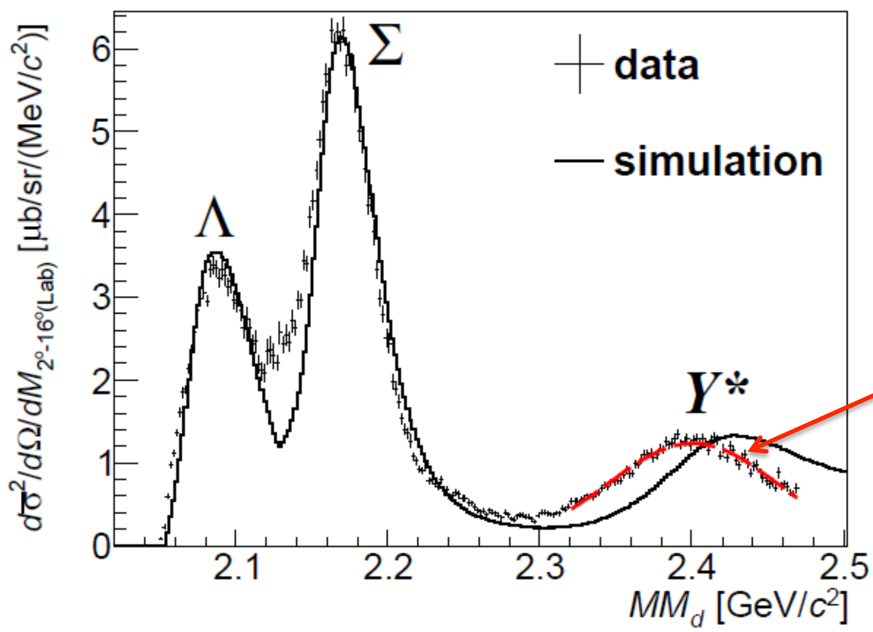
Interpretations are still arguable…

J-PARC E27

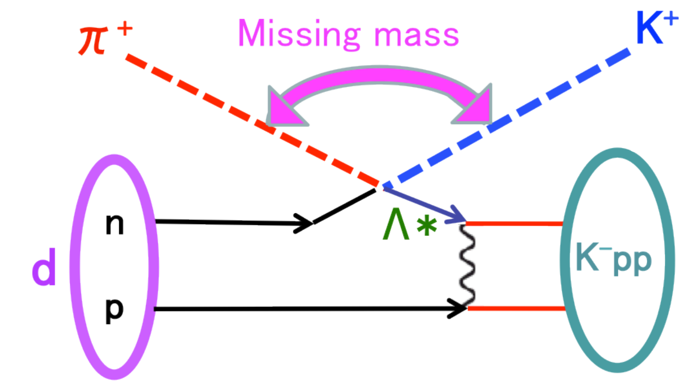
from Y. Ichikawa's slides
@ strangeness workshop on 20150803

d(π^+, K^+) at 1.69 GeV/*c* (Inclusive spectrum)

*Y** peak; data = 2400.6 ± 0.5(stat.) ± 0.6(syst.) MeV/c^2
sim = 2433.0 $^{+2.8}_{-1.6}$ (syst.) MeV/c^2
``shift'' = −32.4 ± 0.5(stat.) $^{+2.9}_{-1.7}$ (syst.) MeV/c^2



- Sticking probability of the Λ(1405) (Elementary: 36.9 μb/sr)
  - $(d\sigma/d\Omega_{\text{``}K^-pp\text{''}\to\Sigma^0p})/(d\sigma/d\Omega_{\Lambda(1405)})$ = 8.2 %
  - $(d\sigma/d\Omega_{\text{``}K^-pp\text{''}\to\Lambda p})/(d\sigma/d\Omega_{\Lambda(1405)})$ = 6.0 %
  - $(d\sigma/d\Omega_{\text{``}K^-pp\text{''}})/(d\sigma/d\Omega_{\Lambda(1405)}) \gtrsim$ 14.2 % (for the *Y**: $\gtrsim$ 3.1 %)
  - Theoretical value is about 1%.



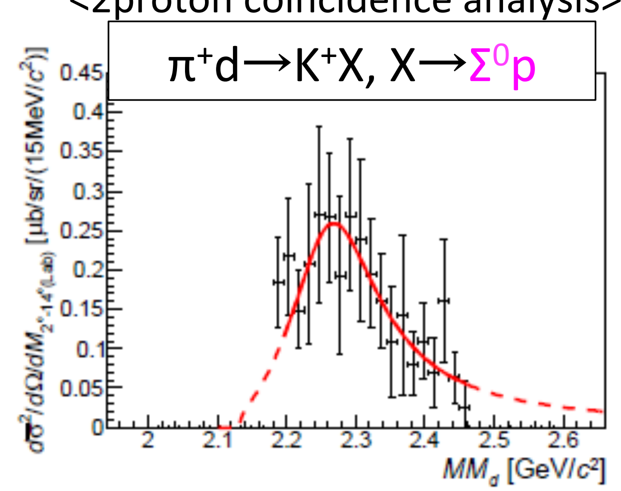
``K^-pp''-like structure(coincidence)

- Broad enhancement ~2.28 GeV/c^2 has been observed in the Σ^0p spectrum.
  - Mass: $2275\ ^{+17}_{-18}$ (stat.) $^{+21}_{-30}$ (syst.) MeV/c^2 (BE: $95\ ^{+18}_{-17}$ (stat.) $^{+30}_{-21}$ (syst.) MeV)
  - Width: $162\ ^{+87}_{-45}$ (stat.) $^{+66}_{-78}$ (syst.) MeV
  - $d\sigma/d\Omega_{\text{``}K^-pp\text{''}\to\Sigma^0p}$ = 3.0 ± 0.3 (stat.) $^{+0.7}_{-1.1}$ (syst.) μb/sr

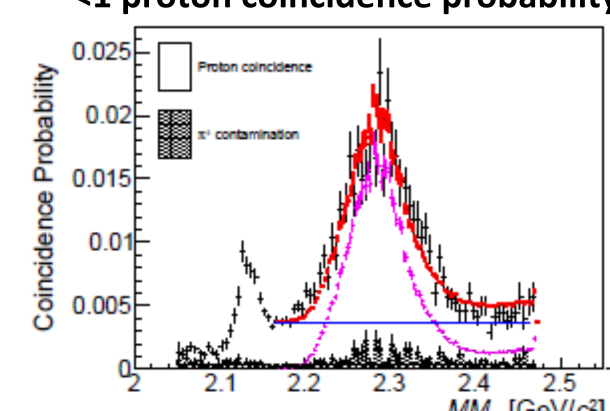
T. Sekihara, D. Jido and Y. Kanada-En'yo, PRC **79**, 062201(R) (2009).

  - $\Gamma_{\Lambda p}/\Gamma_{\Sigma^0 p} = 0.92\ ^{+0.16}_{-0.14}$ (stat.) $^{+0.60}_{-0.42}$ (syst.). [Theoretical value: ~1.2]

<2proton coincidence analysis>



<1 proton coincidence probability>

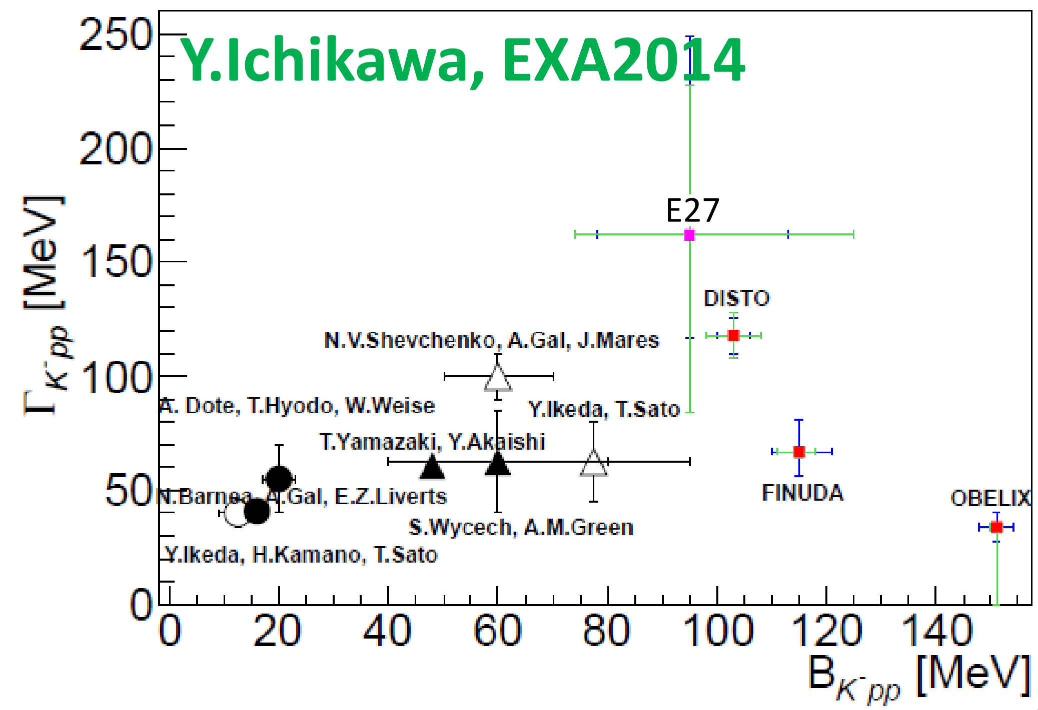


Theoretical calculations

Calculated $K^- pp$ binding energies B and widths Γ (in MeV). **A.Gal, NPA914(2013)270**

	Chiral, energy dependent			Non-chiral, static calculations			
	var. [7]	var. [8]	Fad. [9]	var. [10]	Fad [11]	Fad [12]	var. [13]
B	16	17–23	9–16	48	50–70	60–95	40–80
Γ	41	40–70	34–46	61	90–110	45–80	40–85

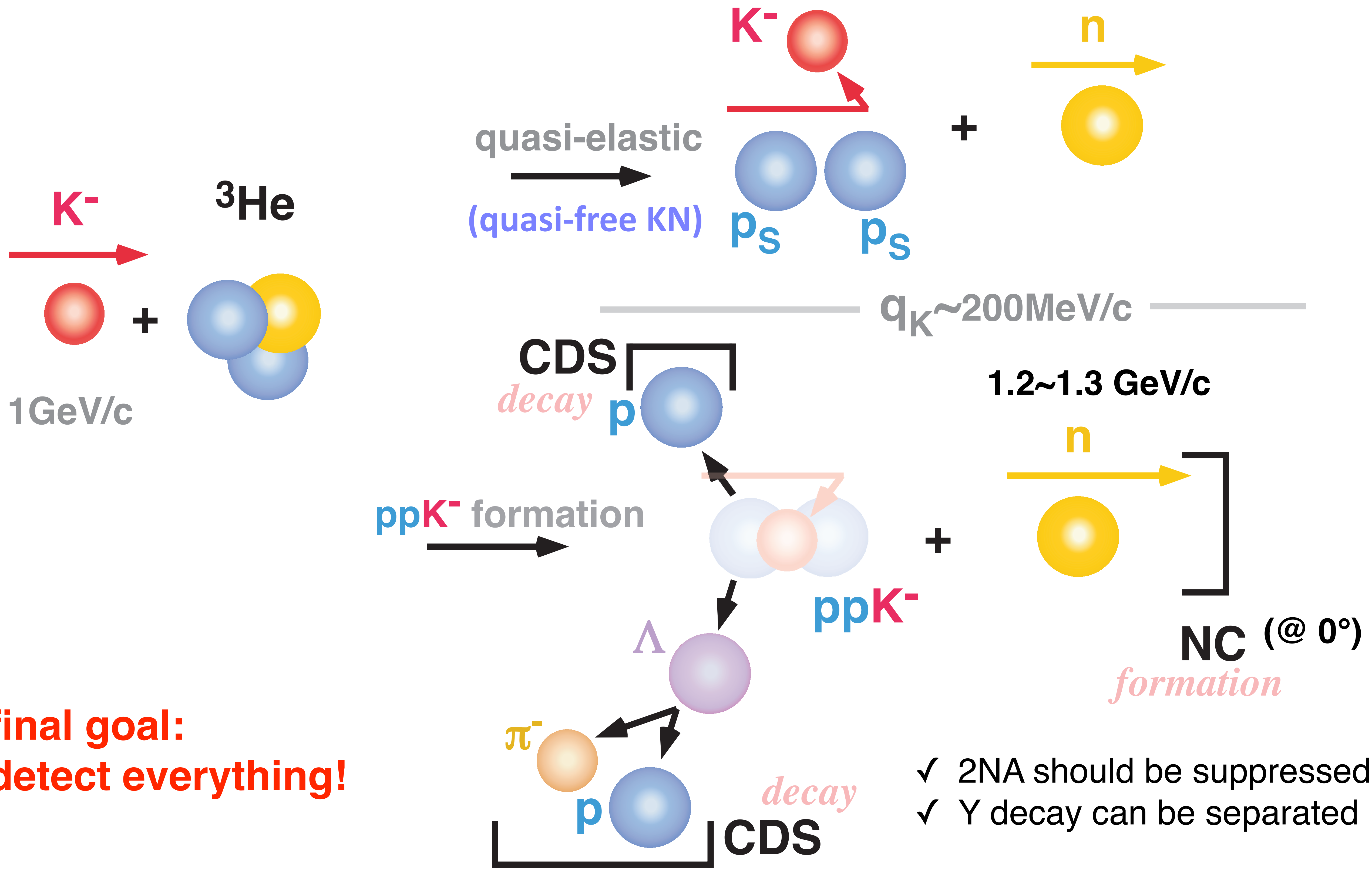
[7] N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132.
[8] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804 (2008) 197;
A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79 (2009) 014003.
[9] Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124 (2010) 533.
[10] T. Yamazaki, Y. Akaishi, Phys. Lett. B 535 (2002) 70.
[11] N.V. Shevchenko, A. Gal, J. Mareš, Phys. Rev. Lett. 98 (2007) 082301;
N.V. Shevchenko, A. Gal, J. Mareš, J. Revai, Phys. Rev. C 76 (2007) 044004.
[12] Y. Ikeda, T. Sato, Phys. Rev. C 76 (2007) 035203;
Y. Ikeda, T. Sato, Phys. Rev. C 79 (2009) 035201.
[13] S. Wycech, A.M. Green, Phys. Rev. C 79 (2009) 014001.



- All theoretical studies predict existence of the “K⁻pp”
- Experimental observation cannot be explained

Further experimental information with different reaction channels is important

In-flight K^- reaction on ^3He



final goal:
detect everything!

✓ 2NA should be suppressed
✓ Y decay can be separated

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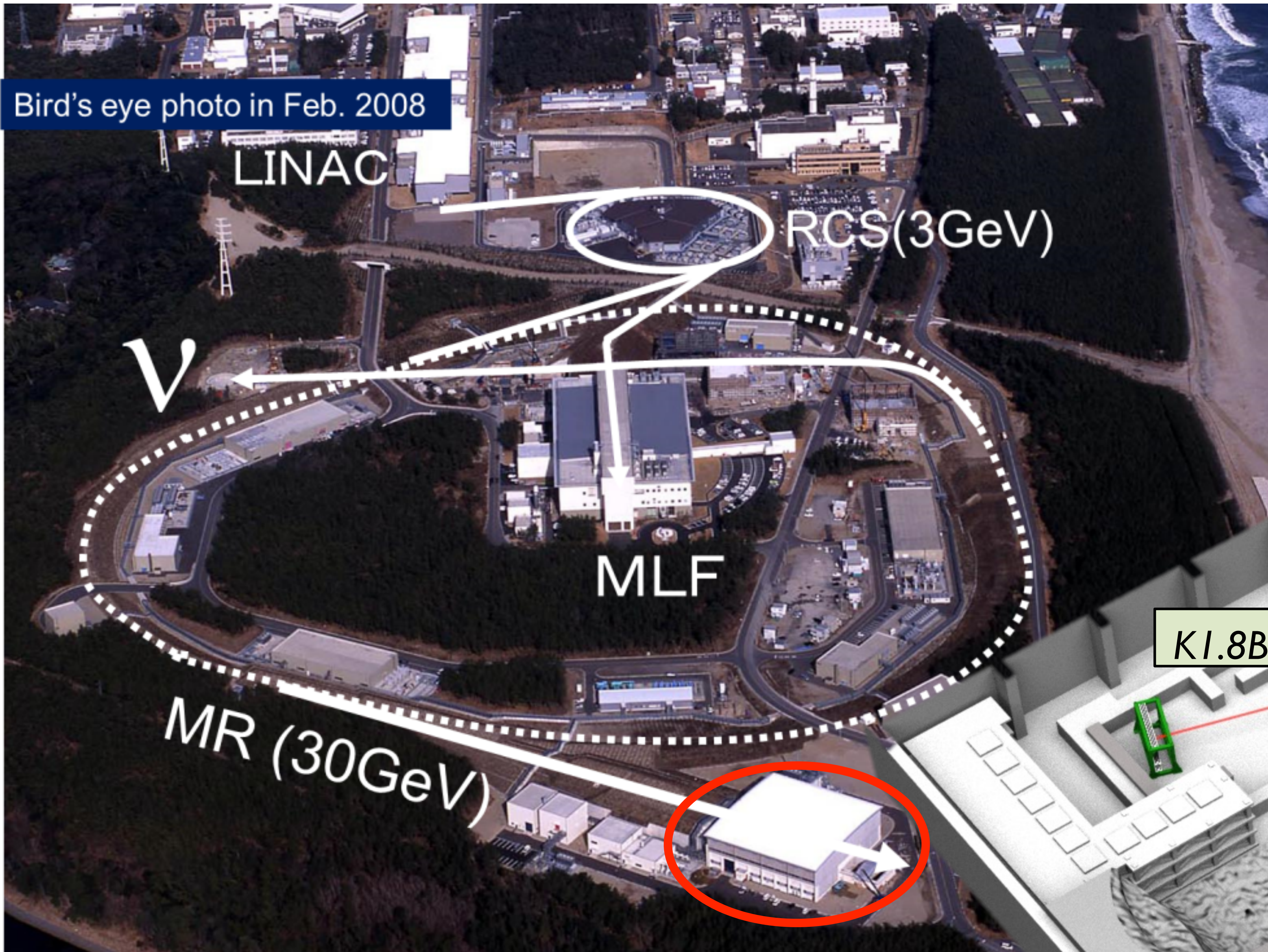
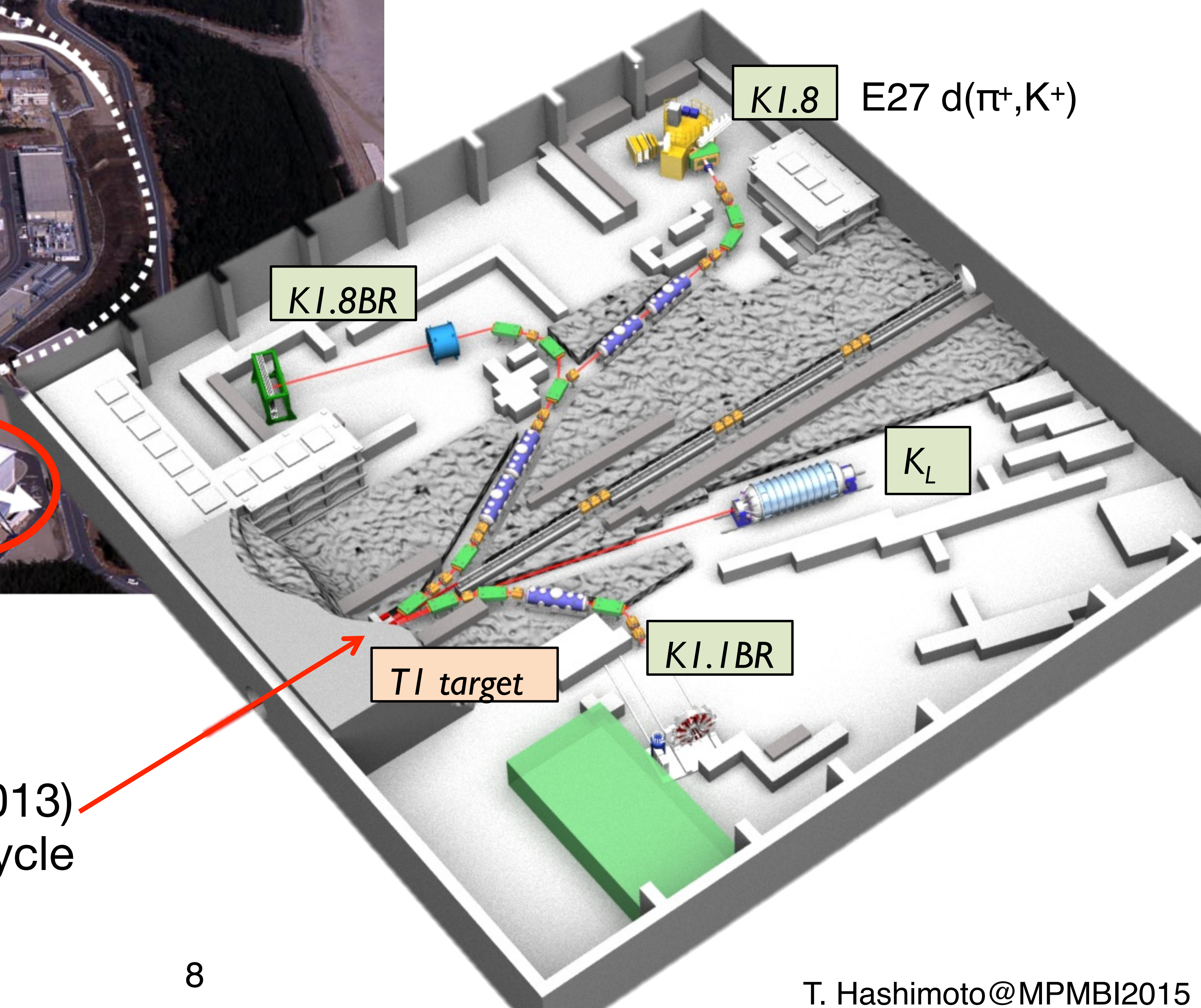
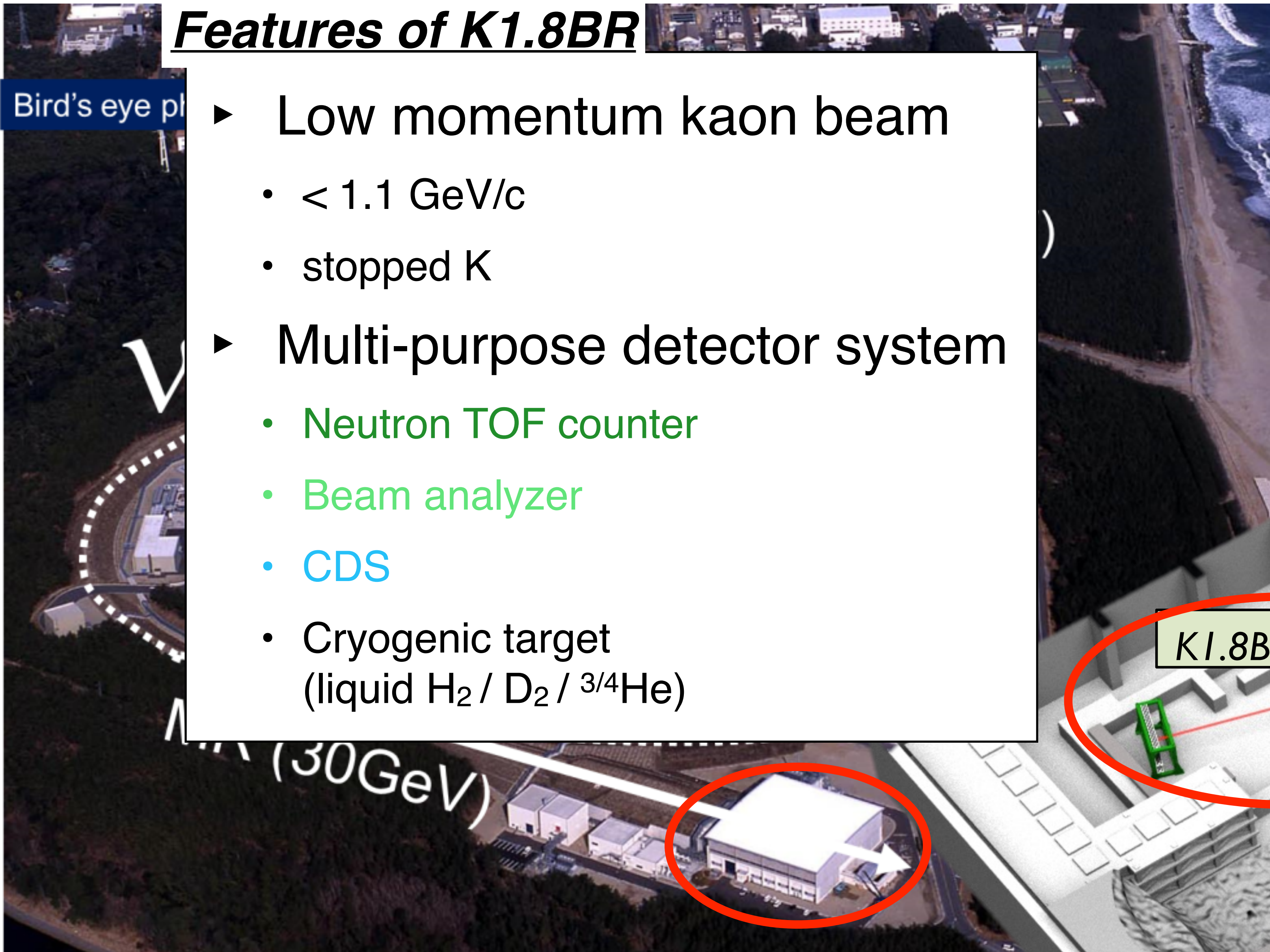
J-PARC hadron hall





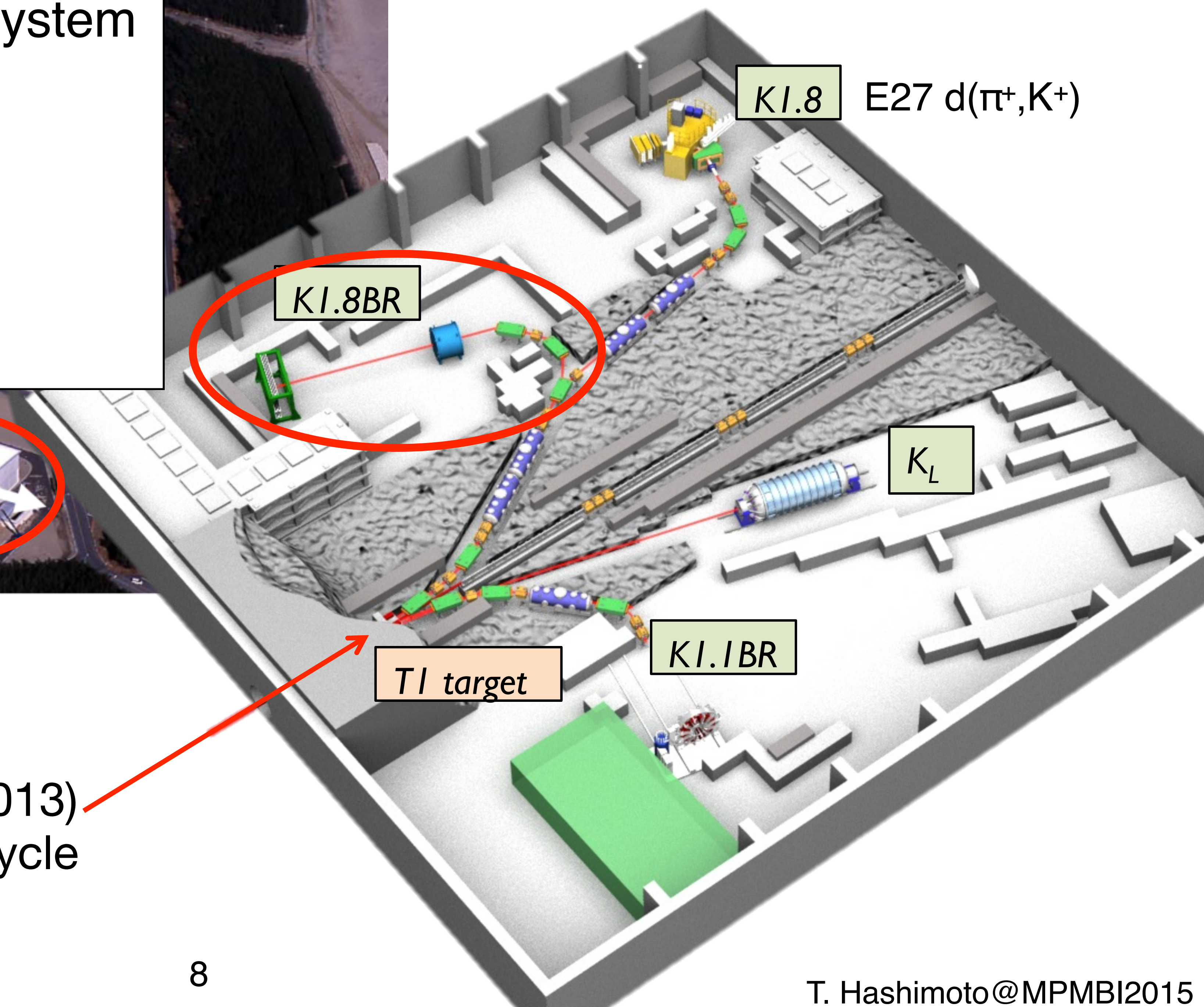
Primary proton beam: (as of May. 2013)
24 kW, 30 Tppp with 6s repetition cycle
2s spill length, ~45% duty factor

J-PARC hadron hall



Features of K1.8BR

- Low momentum kaon beam
  - < 1.1 GeV/c
  - stopped K
- Multi-purpose detector system
  - Neutron TOF counter
  - Beam analyzer
  - CDS
  - Cryogenic target (liquid H_2 / D_2 / $^{3/4}He$)

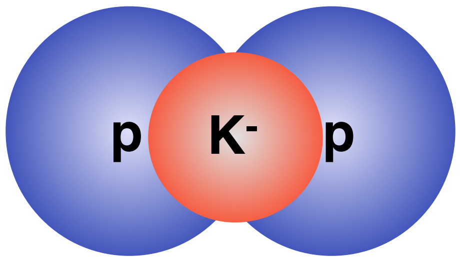


Primary proton beam: (as of May. 2013)
24 kW, 30 Tppp with 6s repetition cycle
2s spill length, ~45% duty factor

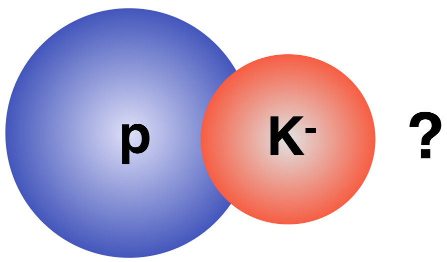
Experiments at K1.8BR

- **All approved experiments investigate the *$K^{bar}N$* interaction**

- E15: Search for $K^{-}pp$ via $^{3}He(K^{-}, n)$

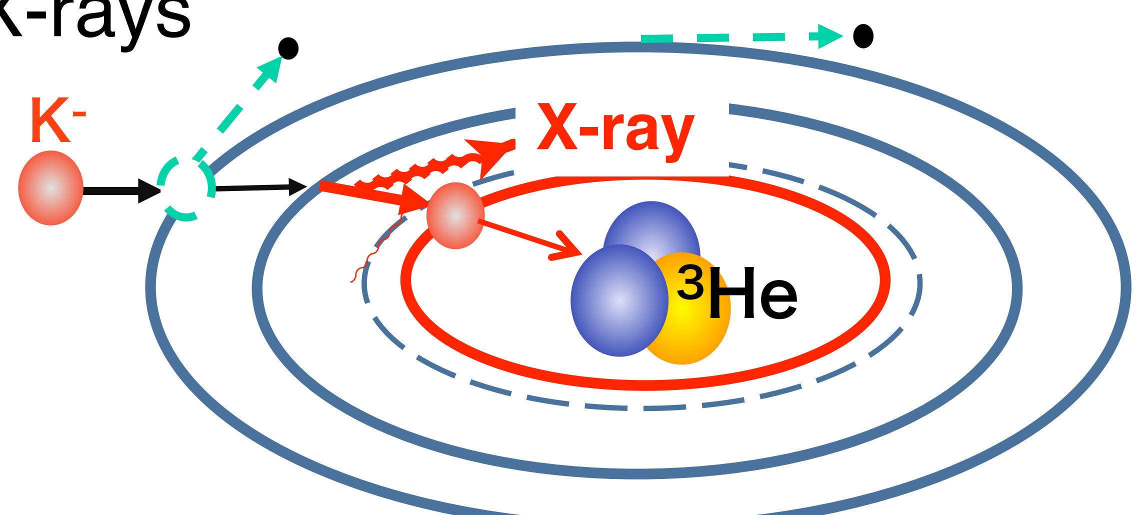


- E31: Spectroscopic study of Λ(1405) via d(K^{-},n)

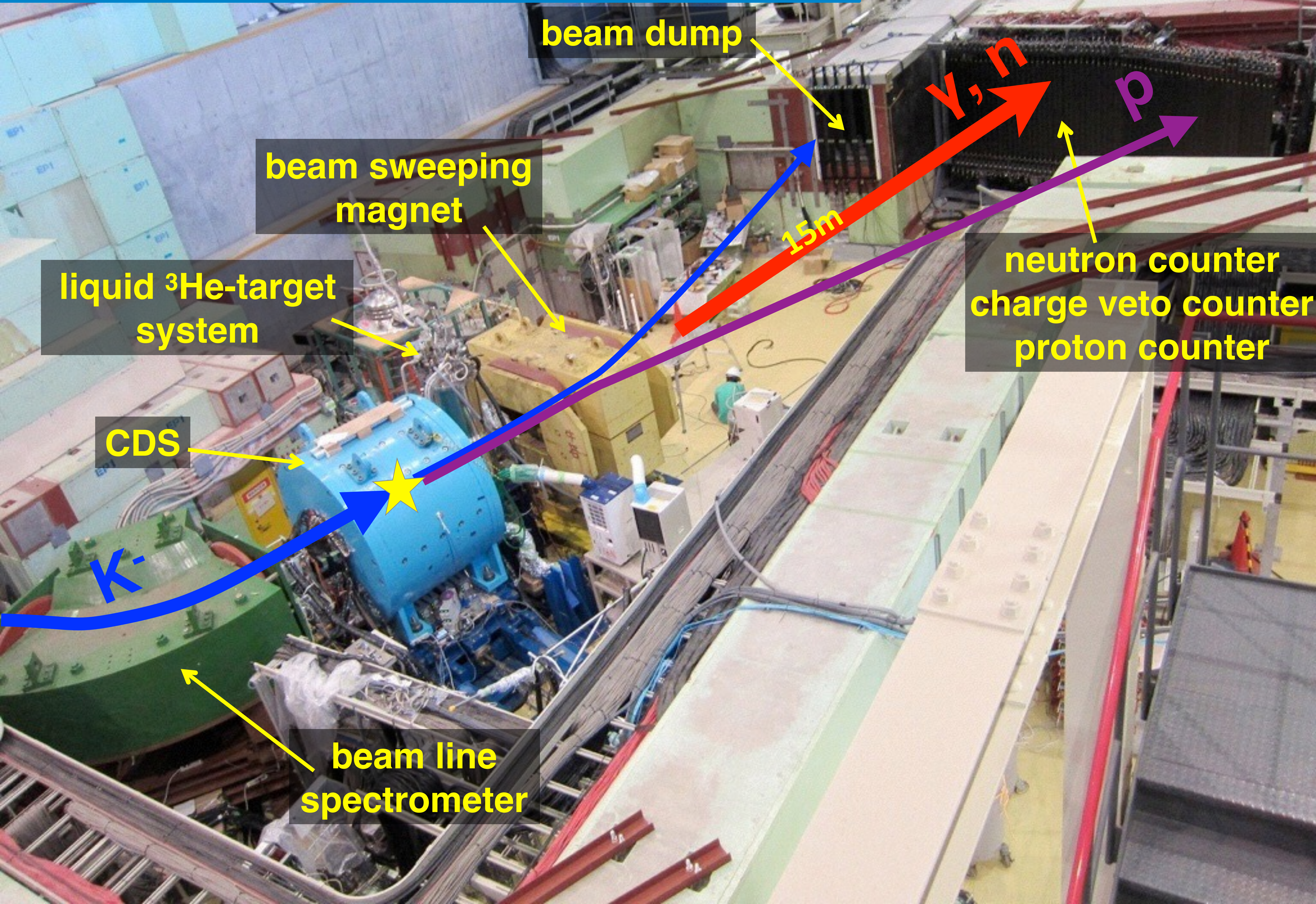


- E17(→E62) : Kaonic $^{3}He/^{4}He$ atom X-rays

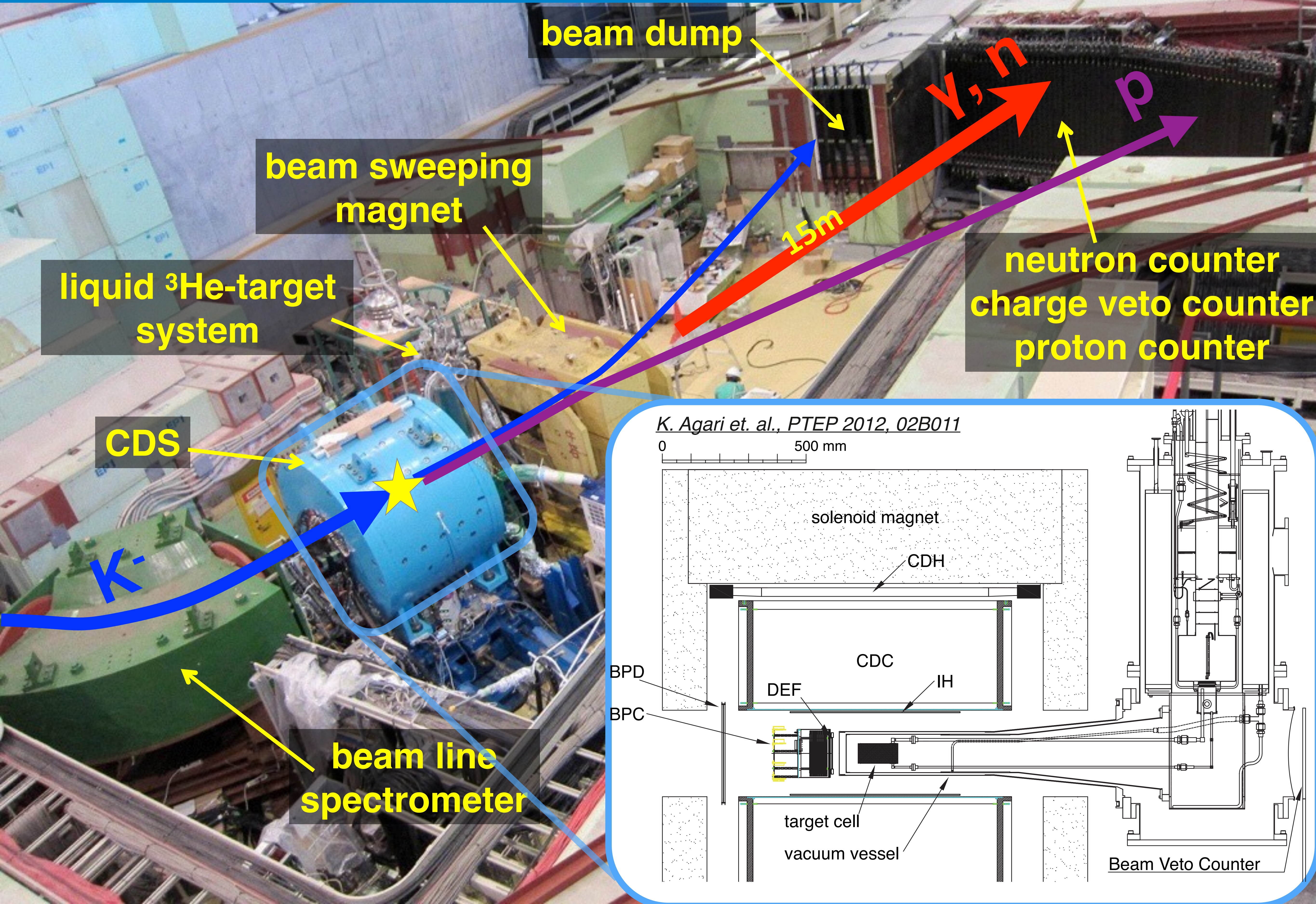
- E57: K-p, K-d X-rays



J-PARC K1.8BR spectrometer



J-PARC K1.8BR spectrometer



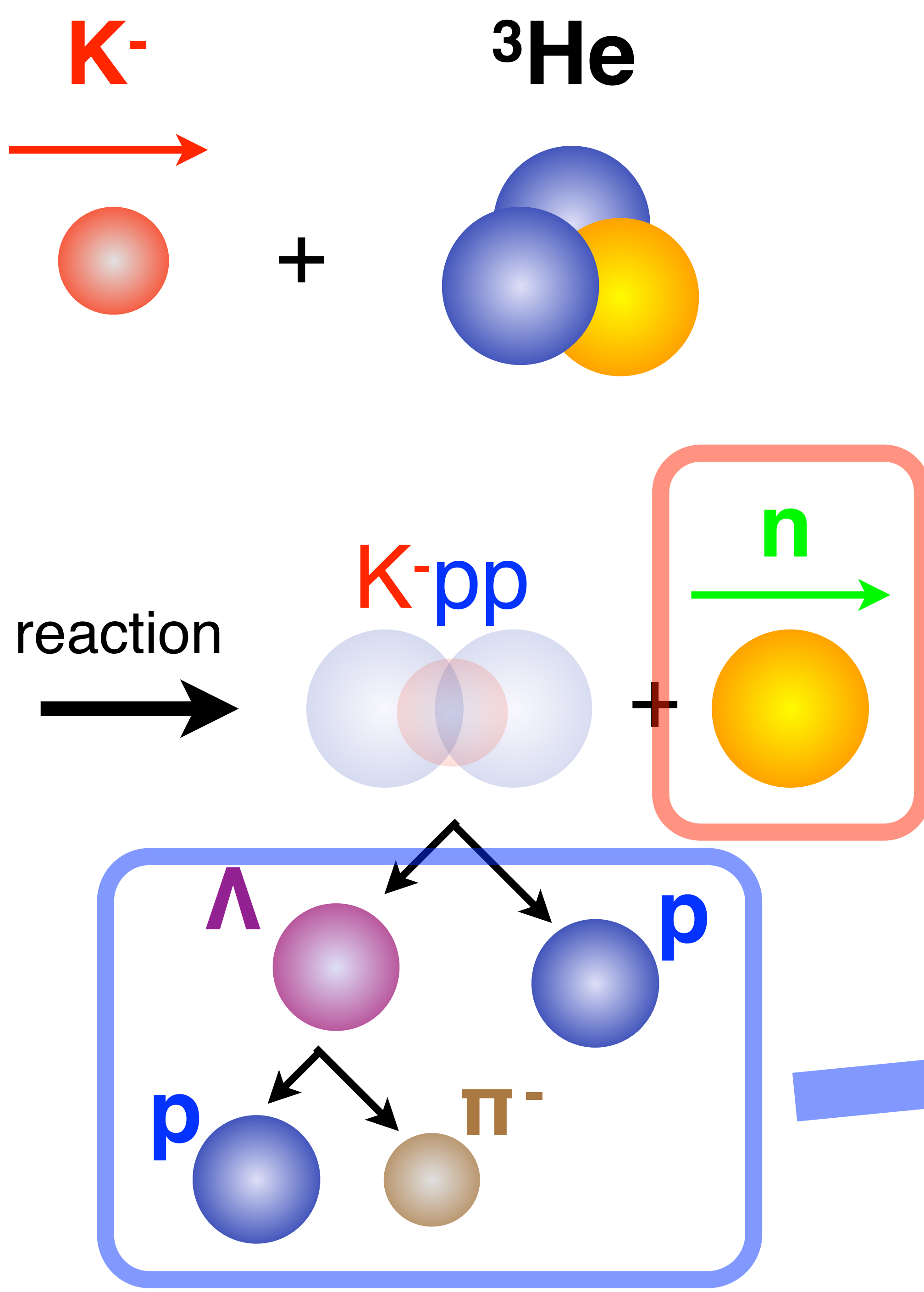
Status of J-PARC E15

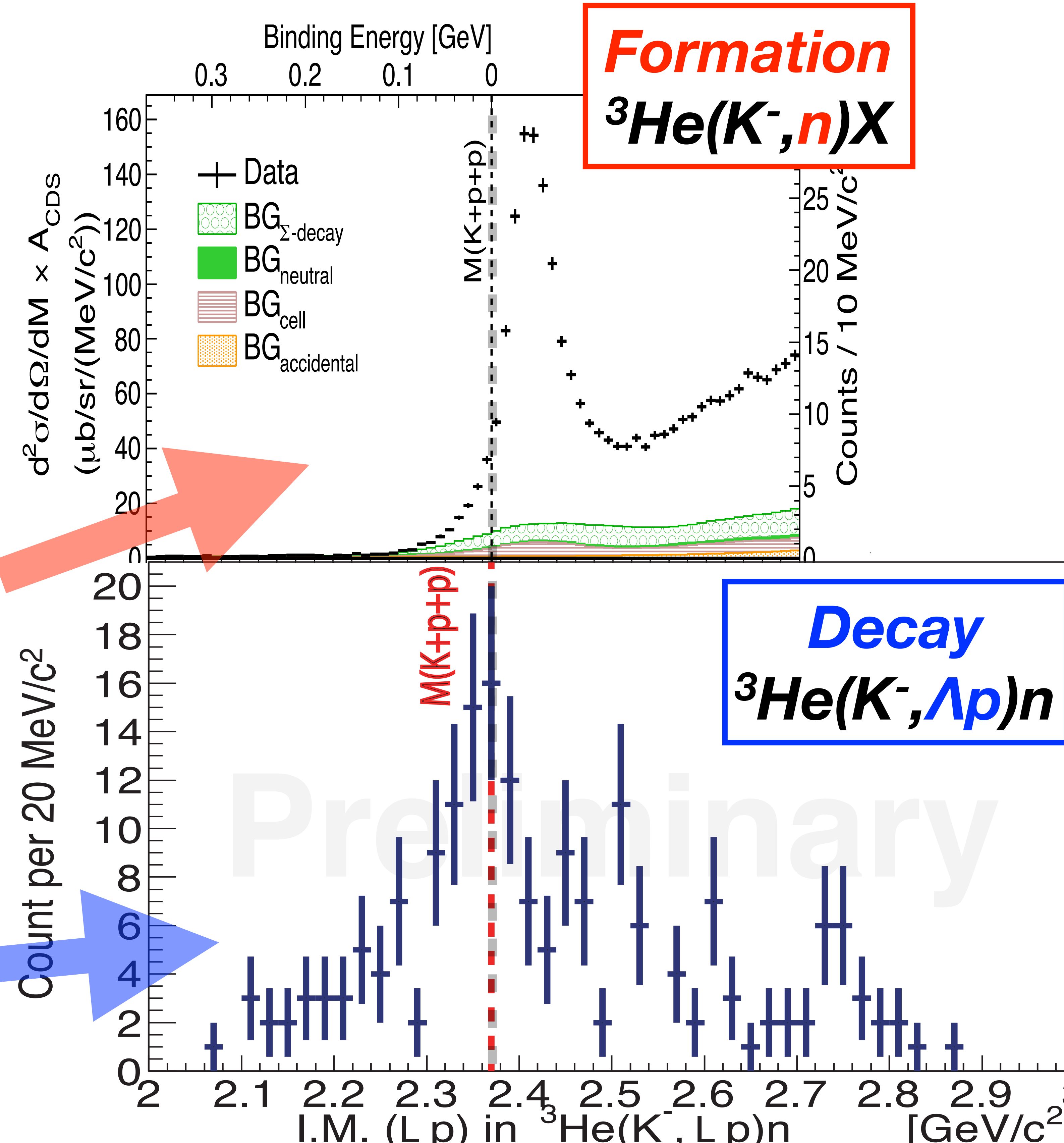
- Production run of ***~1% of the approved proposal*** was successfully carried out in 2013.
- **2^{nd} physics run will be performed in the autumn of 2015**

	Exp. Target	Primary-beam intensity	Secondary-kaon intensity	Duration	Kaons on target (w/ tgt selection)
May, 2013 (Run#49c)	**$E15^{1st}$** ^{3}He	24 kW (30 Tppp, 6s)	140 k/spill	88 h	5.3×10^9
Apr-May, 2015 (Run#62)	**calibration** H_2	26.5 kW (33 Tppp, 6s)	130 k/spill	73 h	3.7×10^9
Apr-May, 2015 (Run#62)	**calibration** D_2	26.5 kW (33 Tppp, 6s)	130 k/spill	53 h	2.8×10^9
Autumn, 2015	**$E15^{2nd}$** ^{3}He	40 kW (50 Tppp, 6s)	200k/spill	26d	50×10^9

J-PARC E15 1st stage experiment

5 x 10^9 kaons
(~ 1% of full proposal)





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

PTEP
Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

Letter

Search for the deeply bound $K^{-}pp$ state from the semi-inclusive forward-neutron spectrum in the in-flight K^{-} reaction on helium-3

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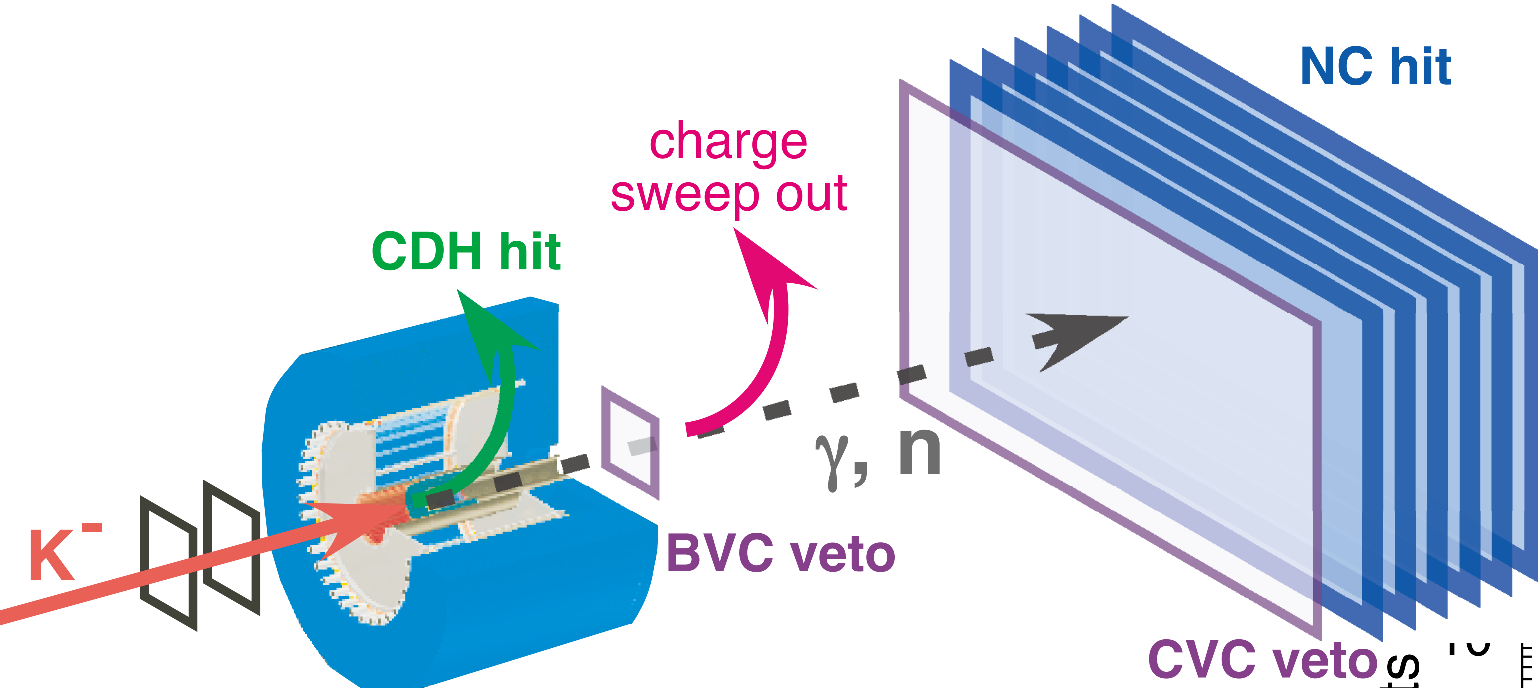
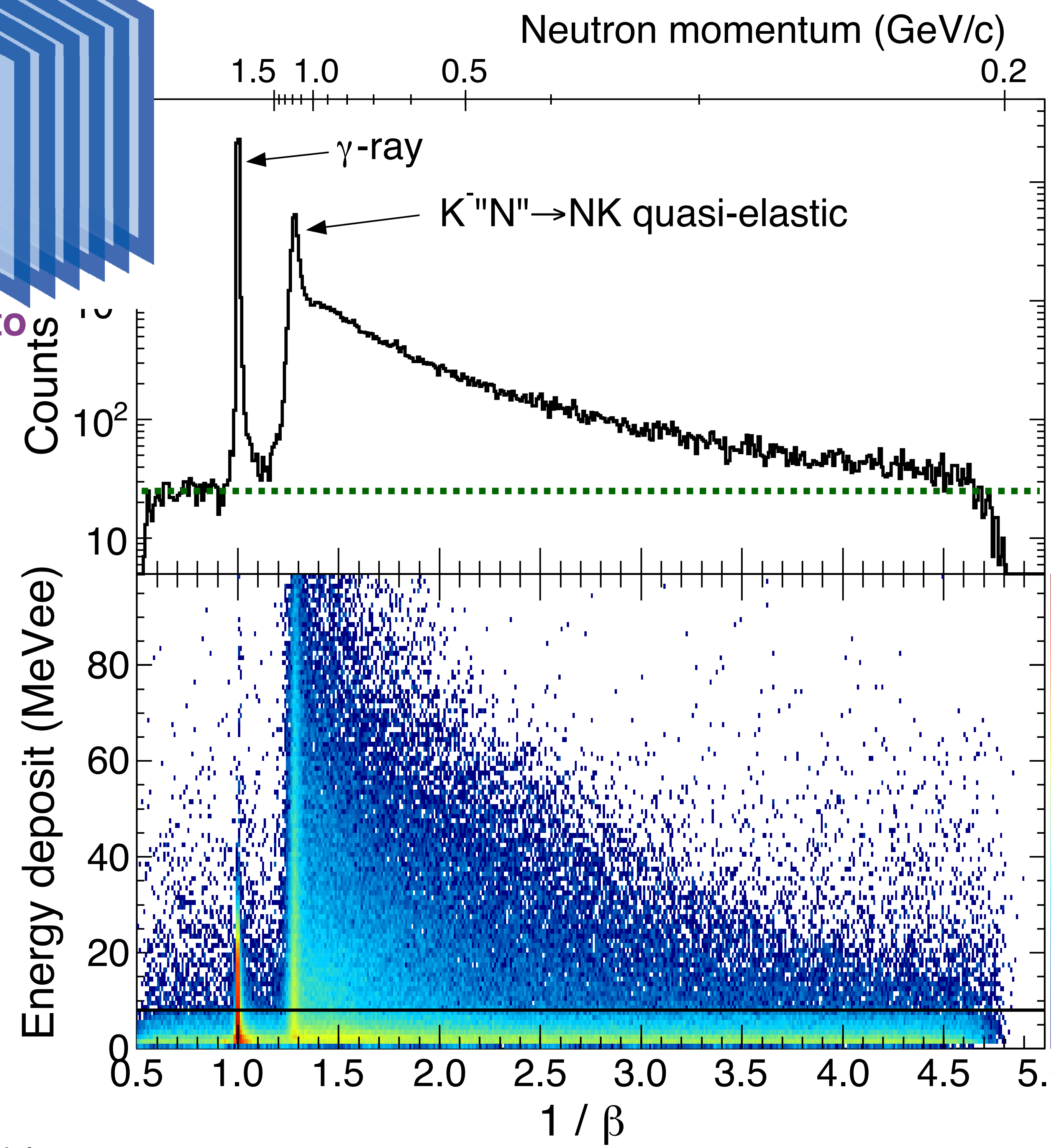
Neutron analysis





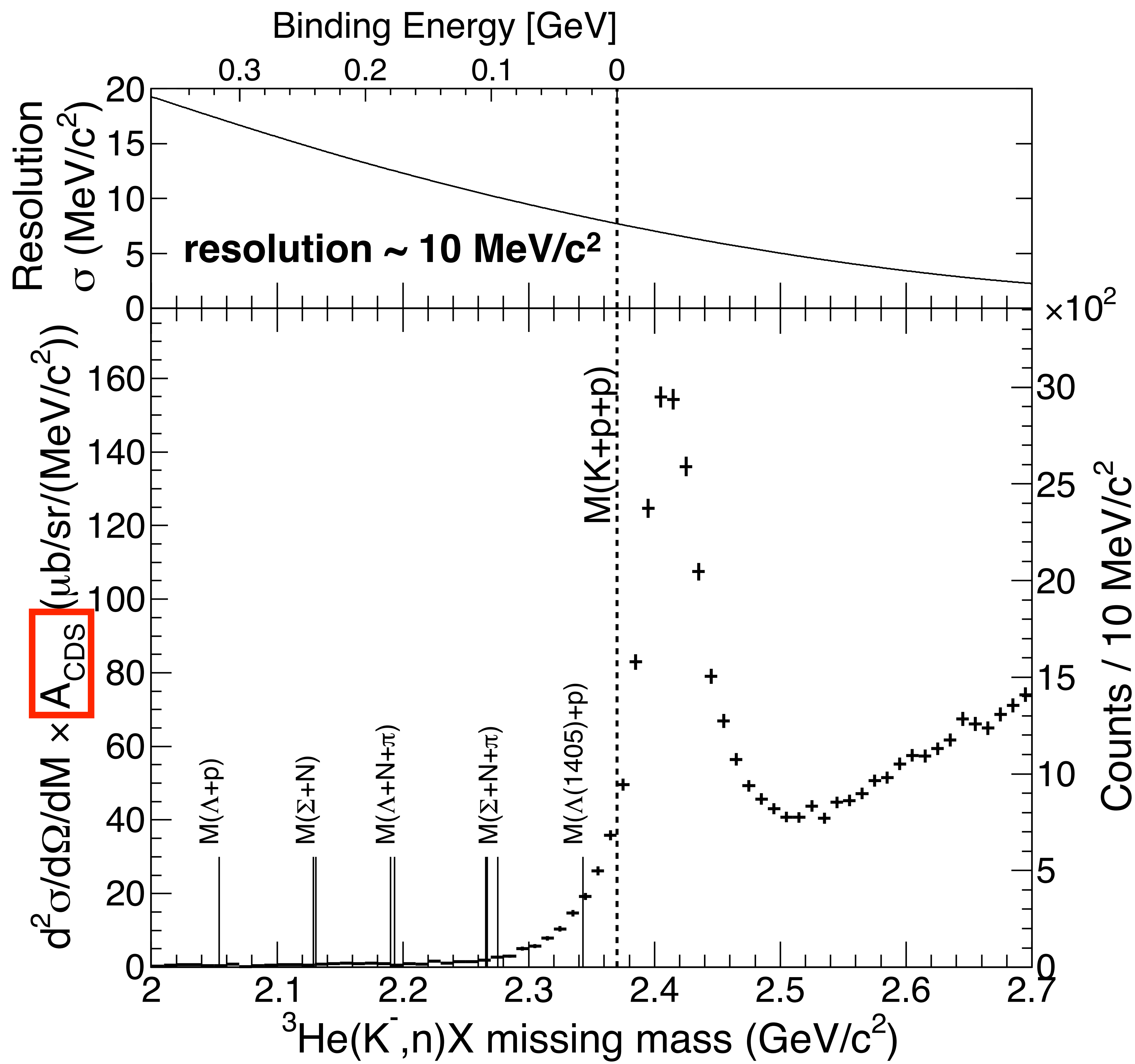
θ^{lab}= 0° @ p_K= 1 GeV/c

minimum-bias by a request of charged track(s) in the CDS

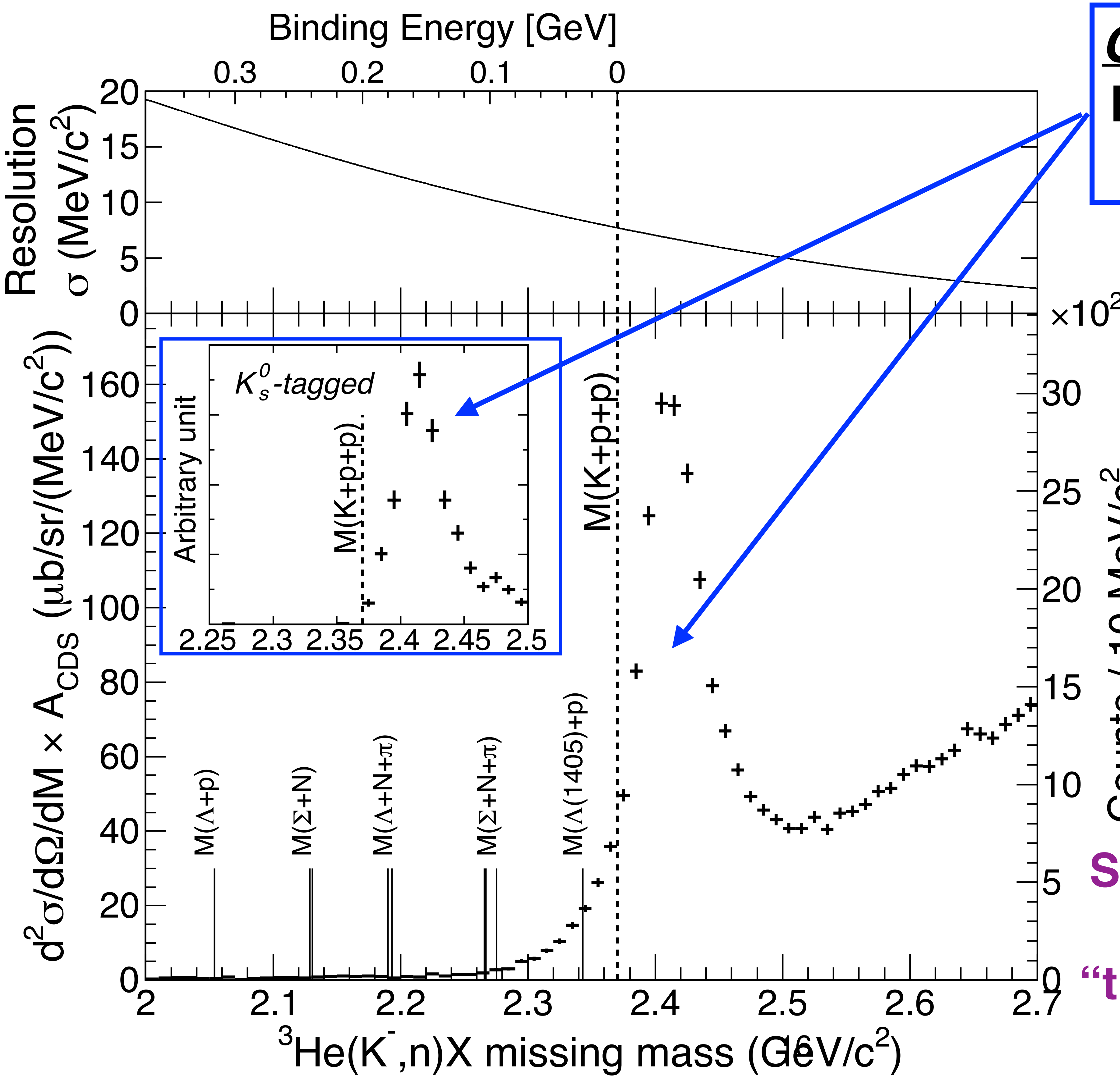
- ✓ *select helium-3 region*
- ✓ *determine the neutron flight length*

- ✓ Low background
- ✓ Clear γ - neutron separation
- ✓ 150 ps TOF resolution (σ) at the γ-ray peak

Semi-inclusive spectrum



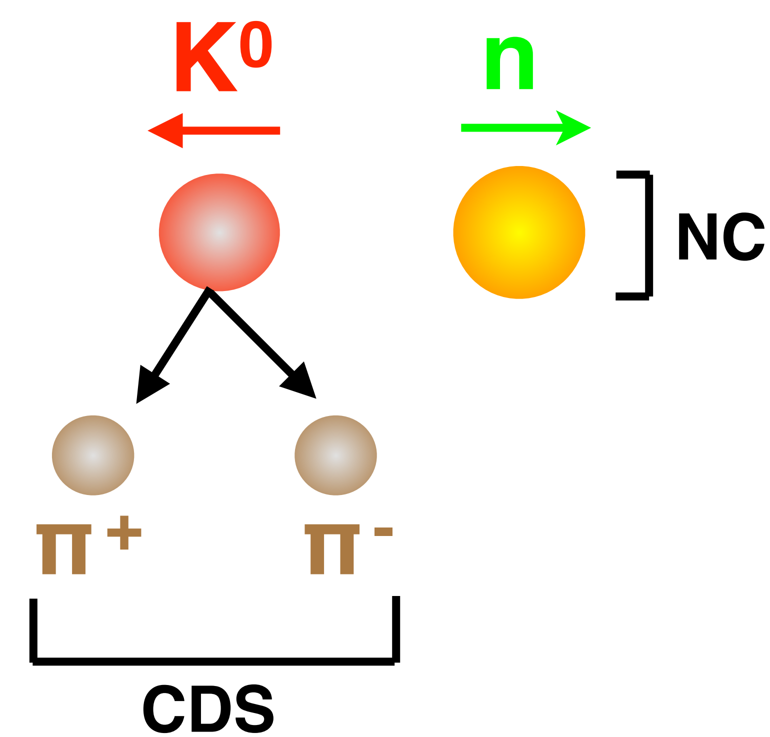
Semi-inclusive spectrum



Charge-exchange

$K^- + {}^3He \rightarrow K^0 + d_s + n$

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



Sub-threshold structure is not due to "the detector resolution"

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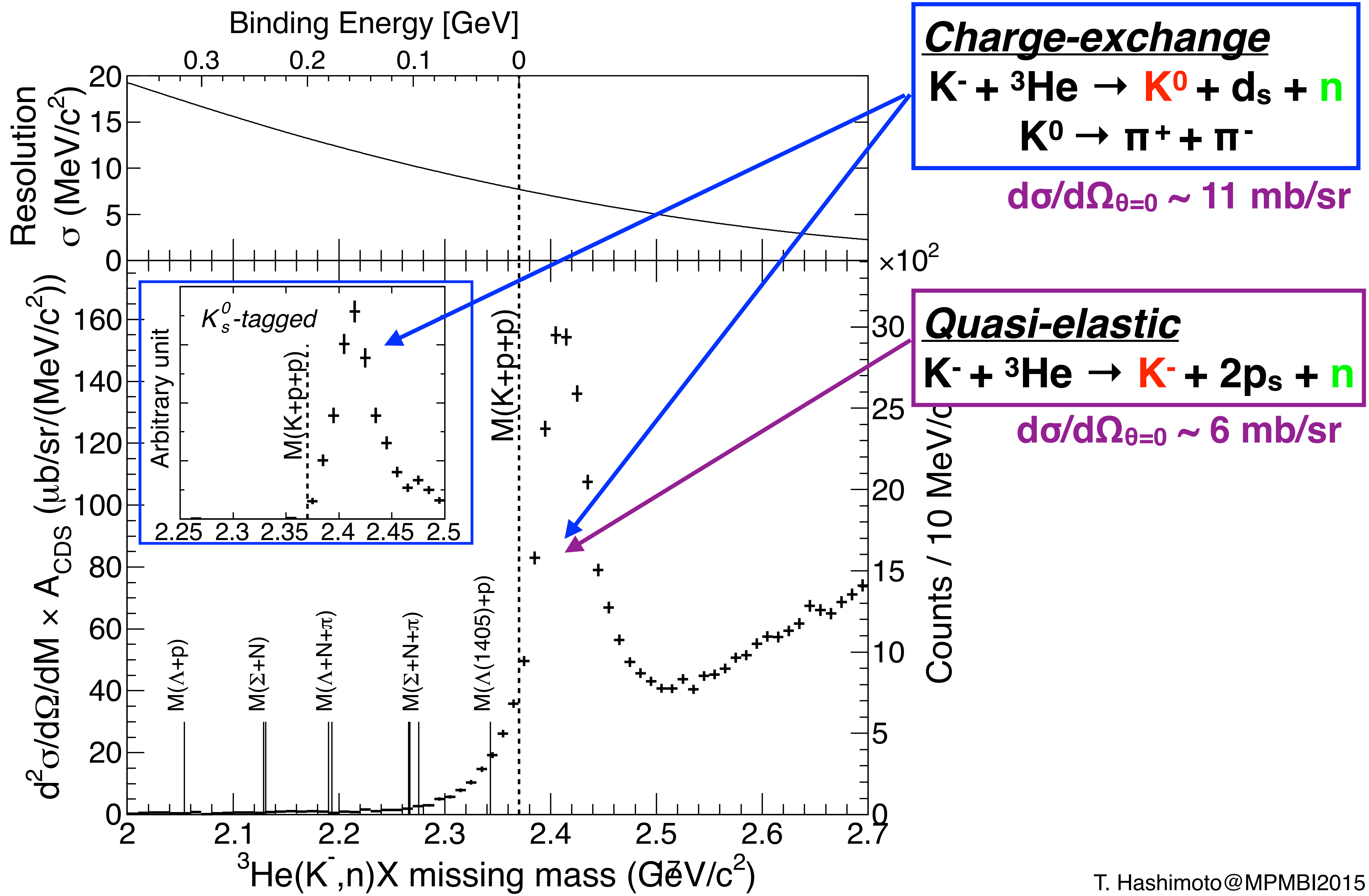
Semi-inclusive spectrum



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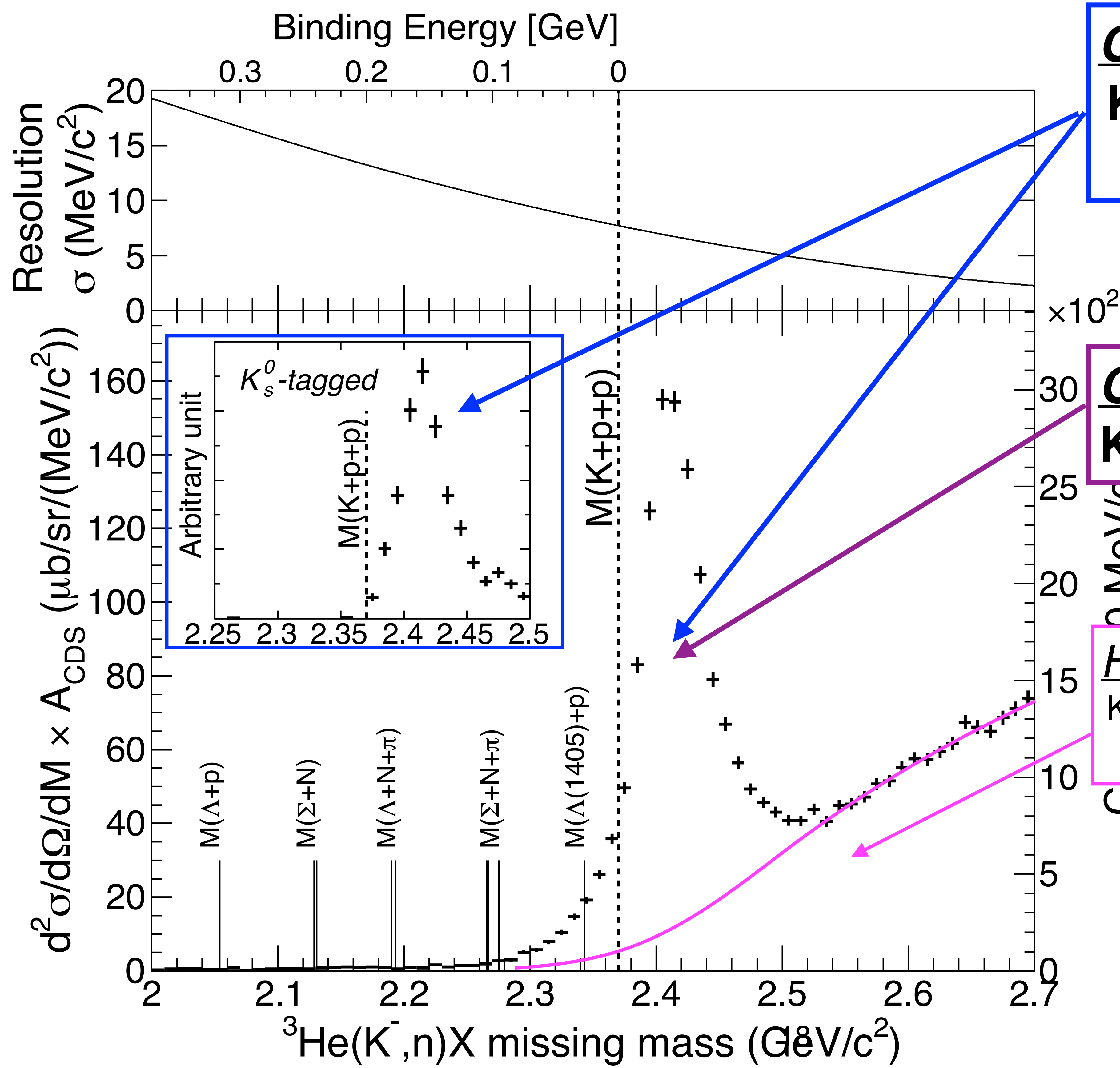
Semi-inclusive spectrum



Charge-exchange

$K^- + {}^3He \rightarrow K^0 + d_s + n$

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

$d\sigma/d\Omega_{\theta=0} \sim 11$ mb/sr

Quasi-elastic

$K^- + {}^3He \rightarrow K^- + 2p_s + n$

$d\sigma/d\Omega_{\theta=0} \sim 6$ mb/sr

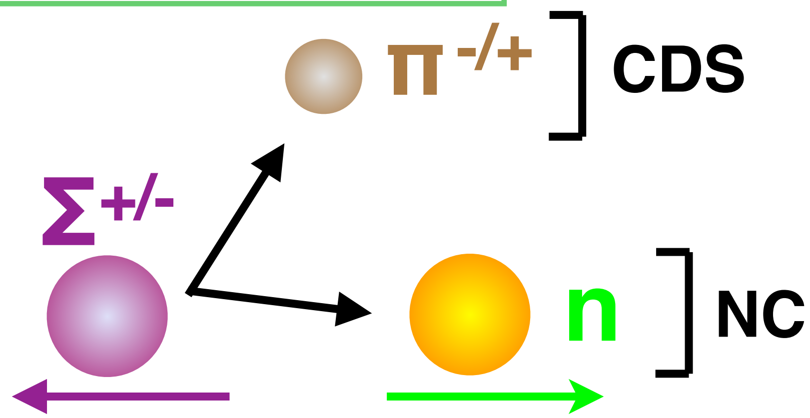
Hyperon decay

$K^- + {}^3He \rightarrow Y + \pi(\pi)(\pi) + 2N_s$

$Y \rightarrow n + \pi$

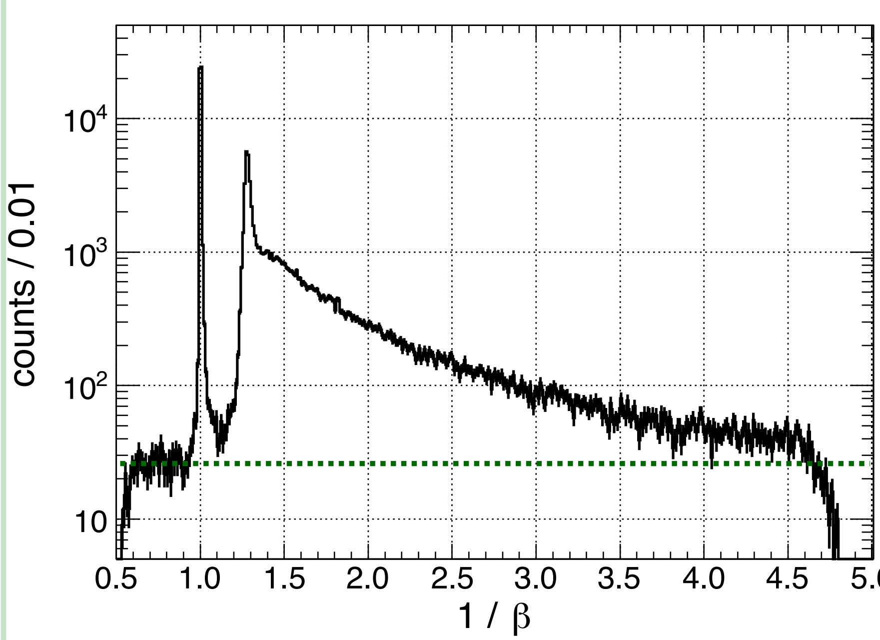
Background evaluation

$K^- + \text{“N”} \rightarrow \Sigma + \pi$



~ 90% can be reconstructed

very small acceptance for KN→Λπ

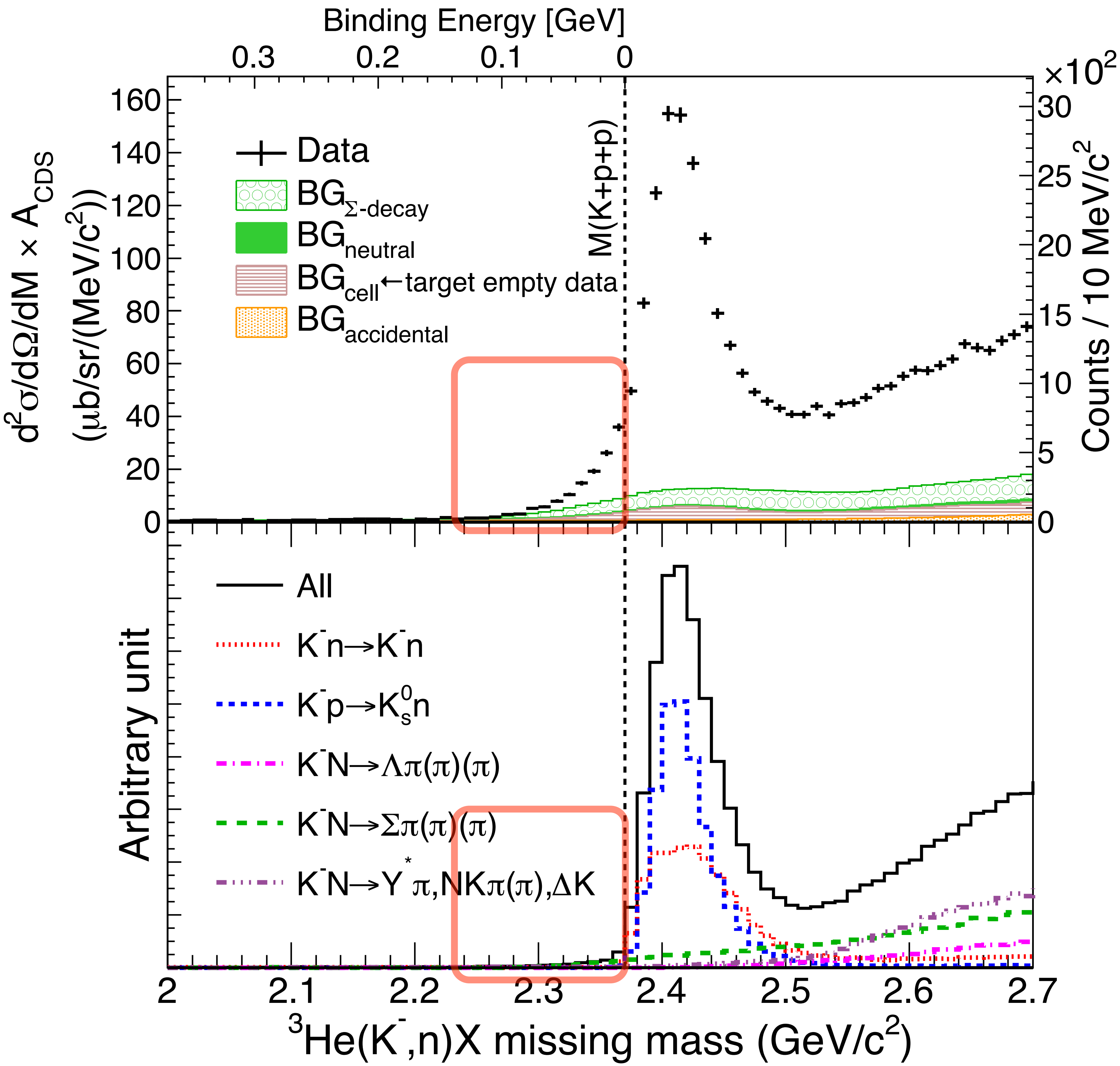


+

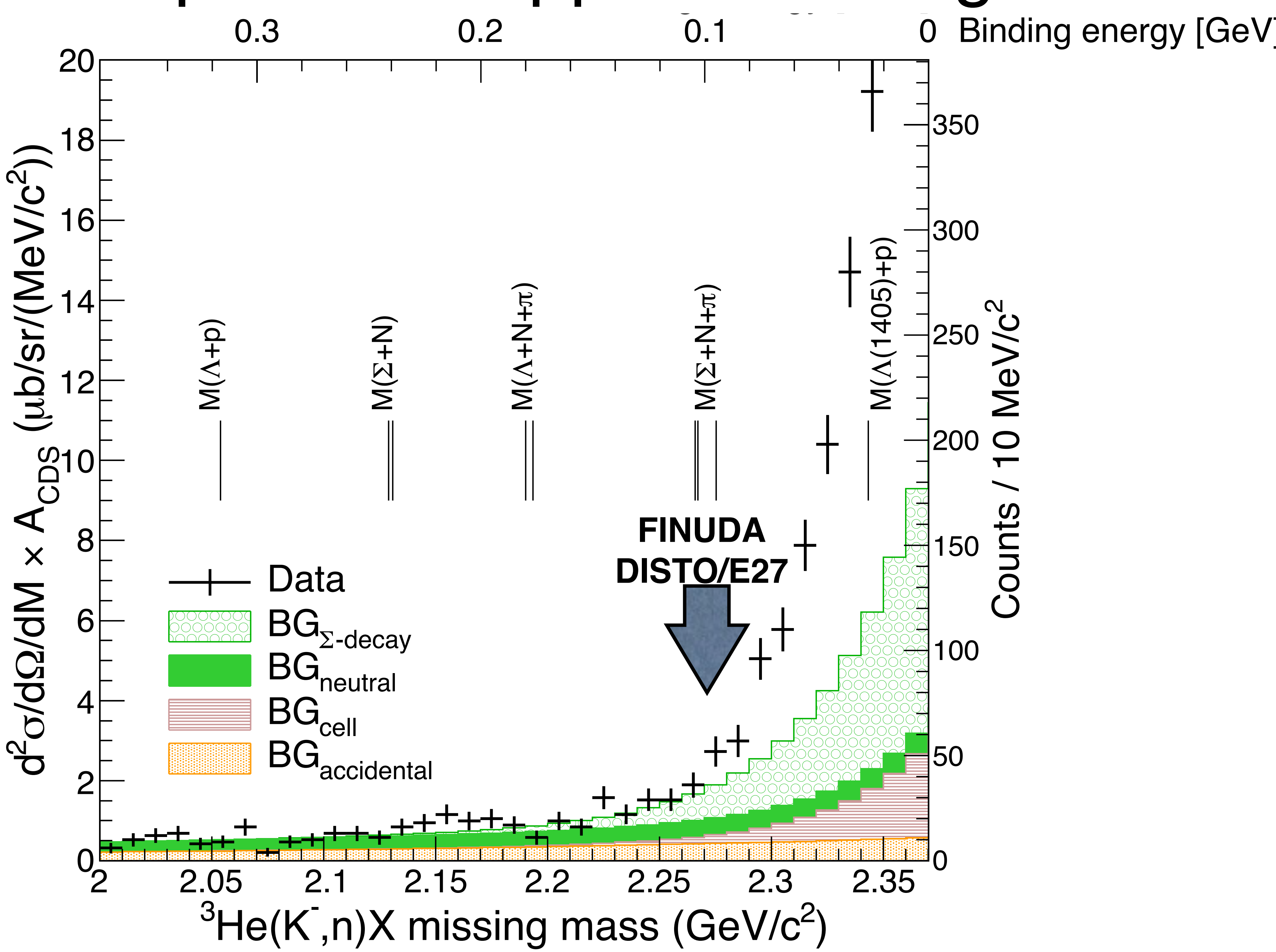
$Y \rightarrow N\pi^0$, $\pi^0 \rightarrow 2\gamma$

K_L decay&reaction in the NC

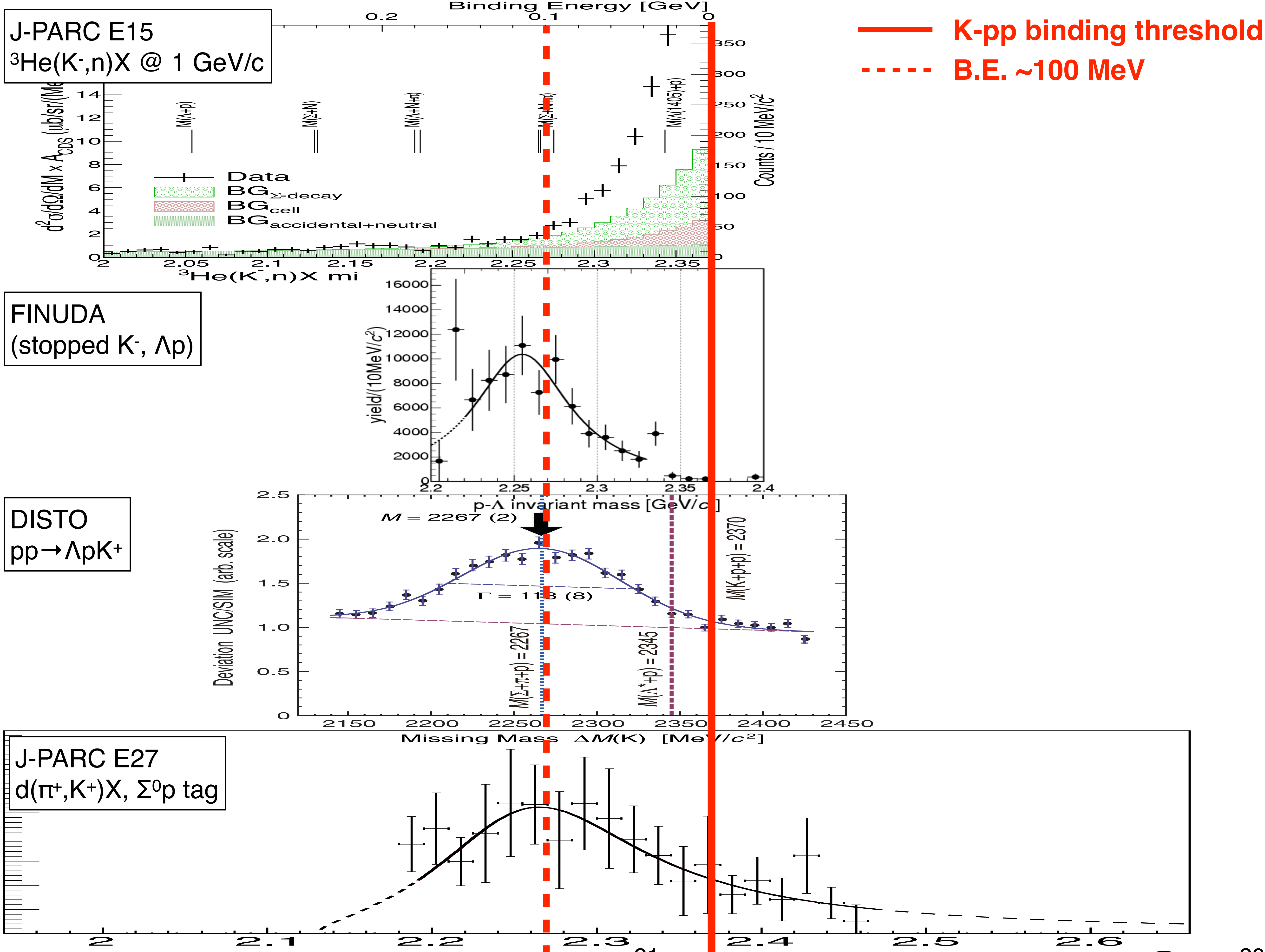
(evaluated with MC)



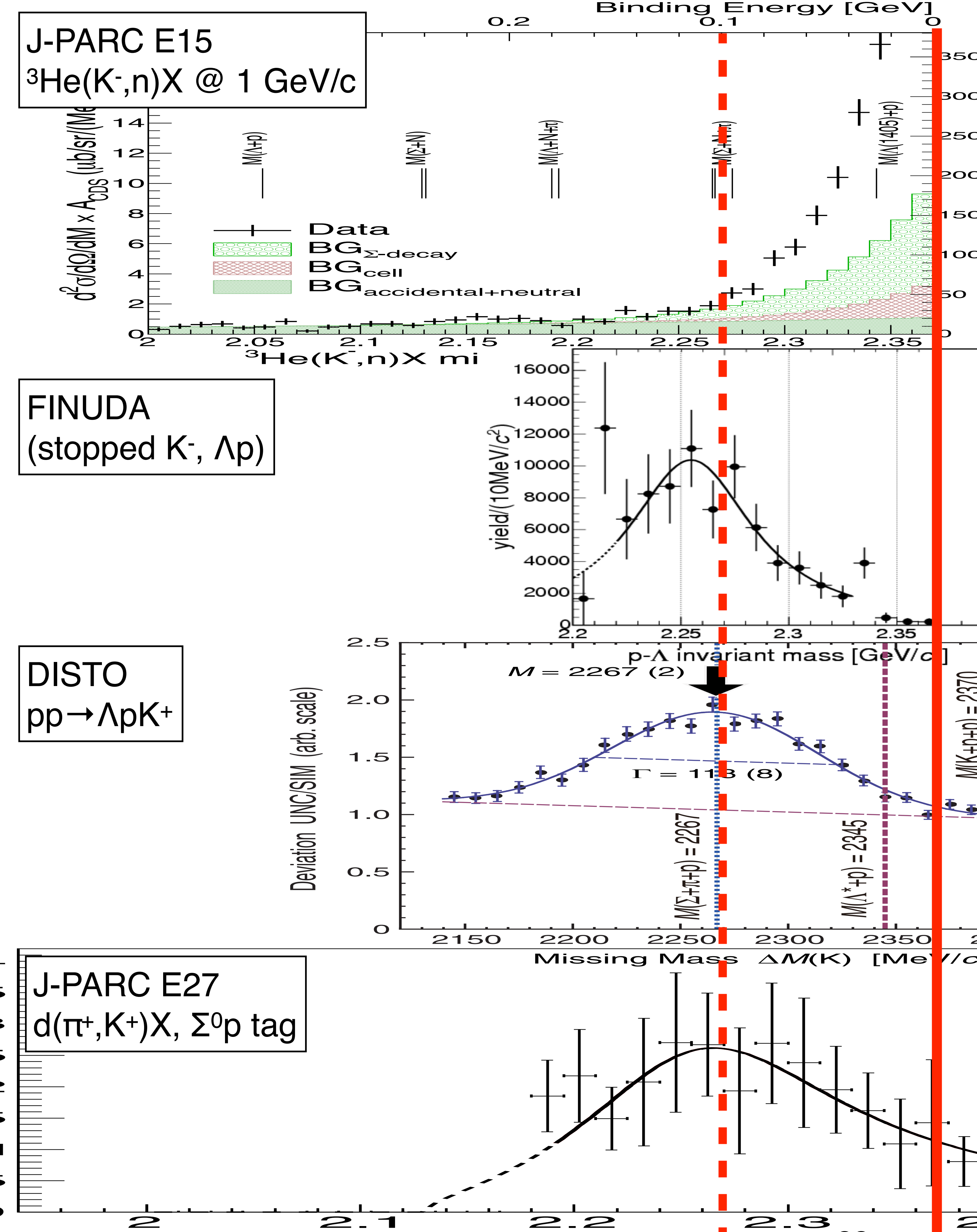
Close-up view: “K-pp” bound region

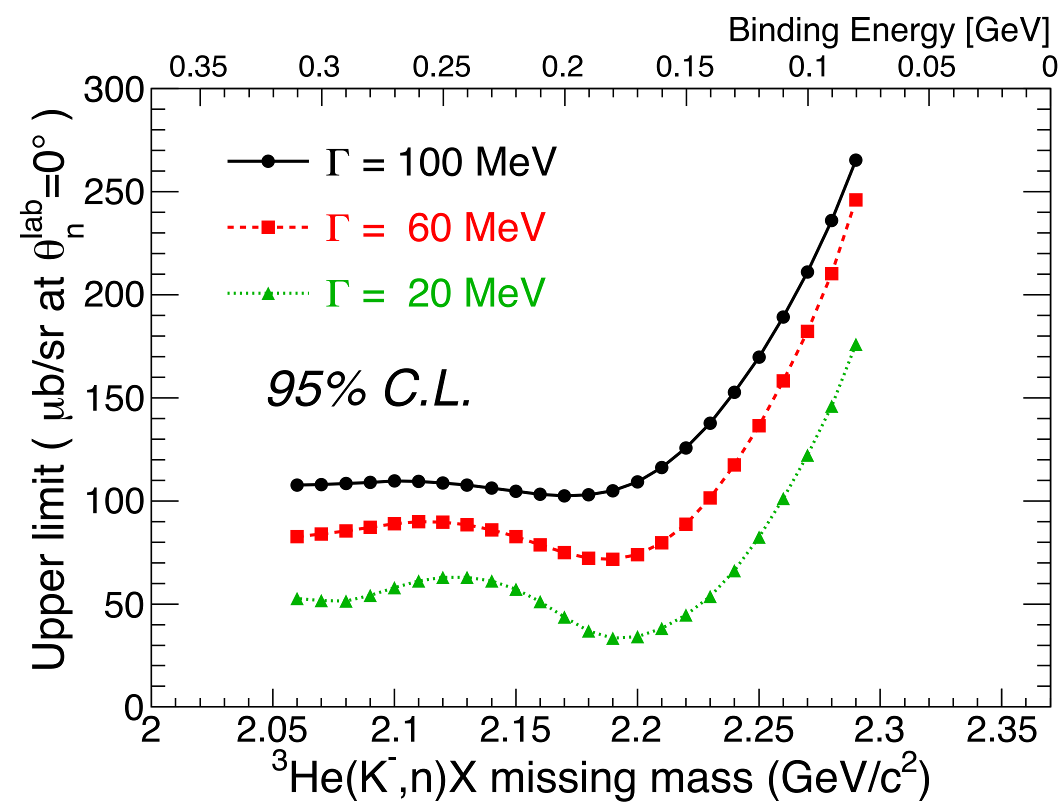


1. **Deeply-bound region: no significant structure**
2. **Just below the K-pp threshold: excess of the yield**


K-pp binding threshold
B.E. ~100 MeV
J-PARC E15
^{3}He(K$^-$,n)X @ 1 GeV/c
Binding Energy [GeV]
0.2
0.1
0
Data
BG$_{\Sigma\text{-decay}}$
BG$_{cell}$
BG$_{accidental+neutral}$
M(Λ+p)
M(Σ+N)
M(Λ+N+π)
M(Σ+N+π)
M(Λ(1405)+p)
Counts / 10 MeV/c^2
^{3}He(K$^-$,n)X mi
FINUDA
(stopped K$^-$, Λp)
yield/(10MeV/c^2)
DISTO
pp→ΛpK$^+$
p-Λ invariant mass [GeV/c]
M = 2267 (2)
Γ = 118 (8)
M(Σ+π+p) = 2267
M(Λ*+p) = 2345
M(K+p+p) = 2370
Deviation UNC/SIM (arb. scale)
Missing Mass ΔM(K) [MeV/c^2]
J-PARC E27
d(π$^+$,K$^+$)X, Σ^{0}p tag
MM_d [GeV/c^2]

2014



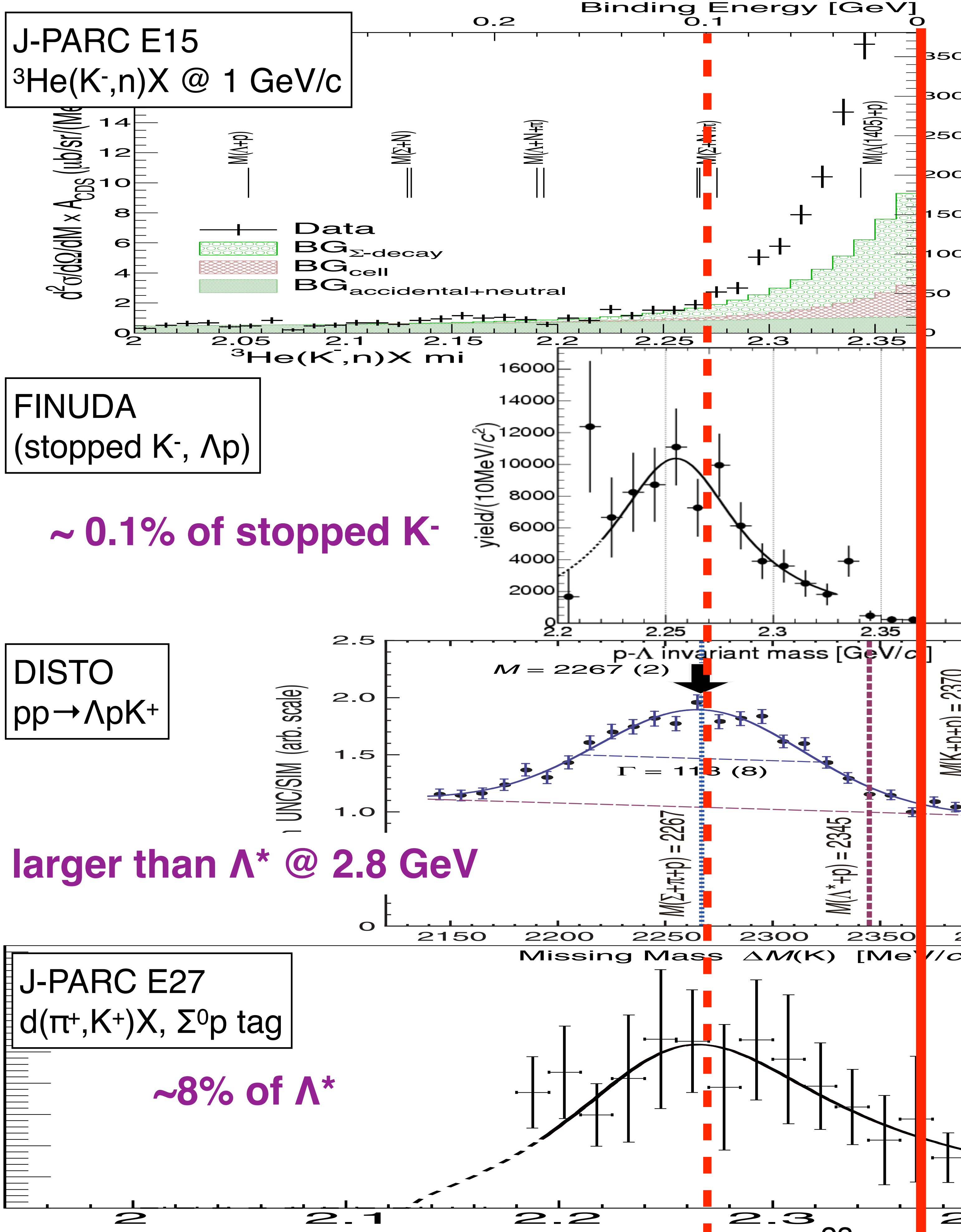


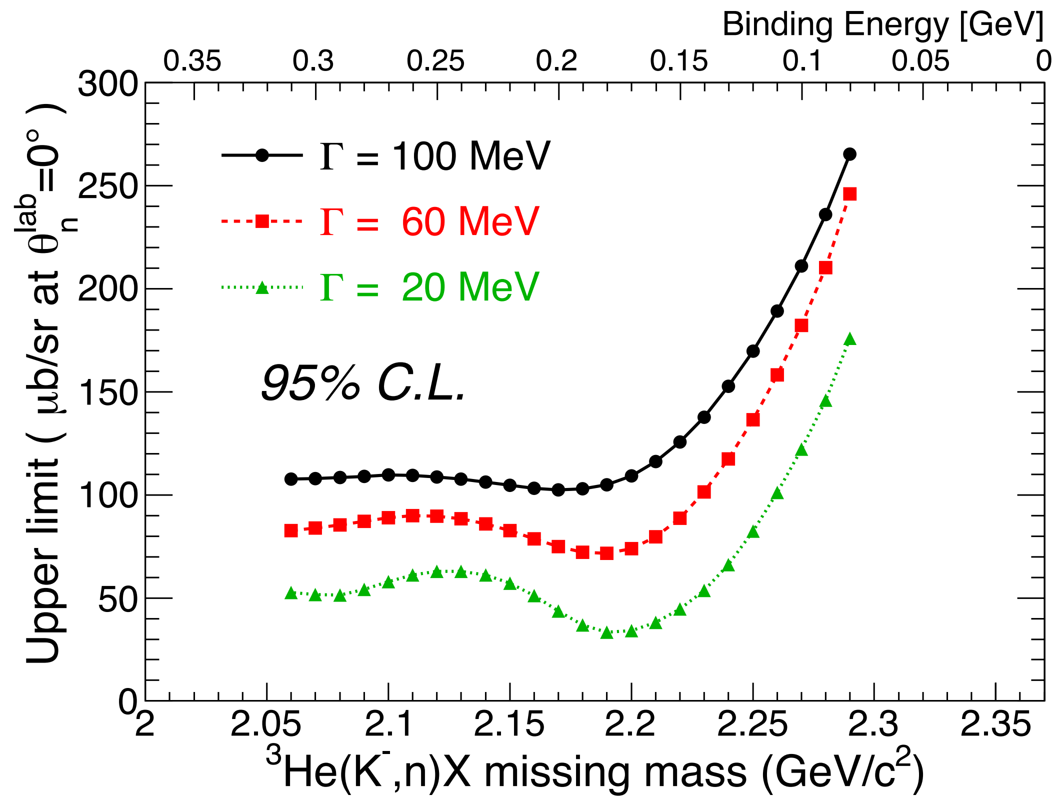
Assumptions

Intrinsic peak shape: Breit-Wigner

Decay mode: **K⁻pp→Λp 100%** (isotropic decay)

- **J-PARC E15 (U.L.)**
  30 ~ 300 μb/sr @ 0 deg.
  0.5 - 5% of quasi-elastic
  smaller than usual hypernucleus sticking





Assumptions

Intrinsic peak shape: Breit-Wigner

Decay mode: **$K^-pp \rightarrow \Lambda p$ 100%** (isotropic decay)

- **J-PARC E15 (U.L.)**
  30 ~ 300 μb/sr @ 0 deg.
  0.5 - 5% of quasi-elastic
  smaller than usual hypernucleus sticking

- **LEPS (γ+d) (U.L.)**
  1.5-26% of $\gamma N \rightarrow K^+\pi^- Y$

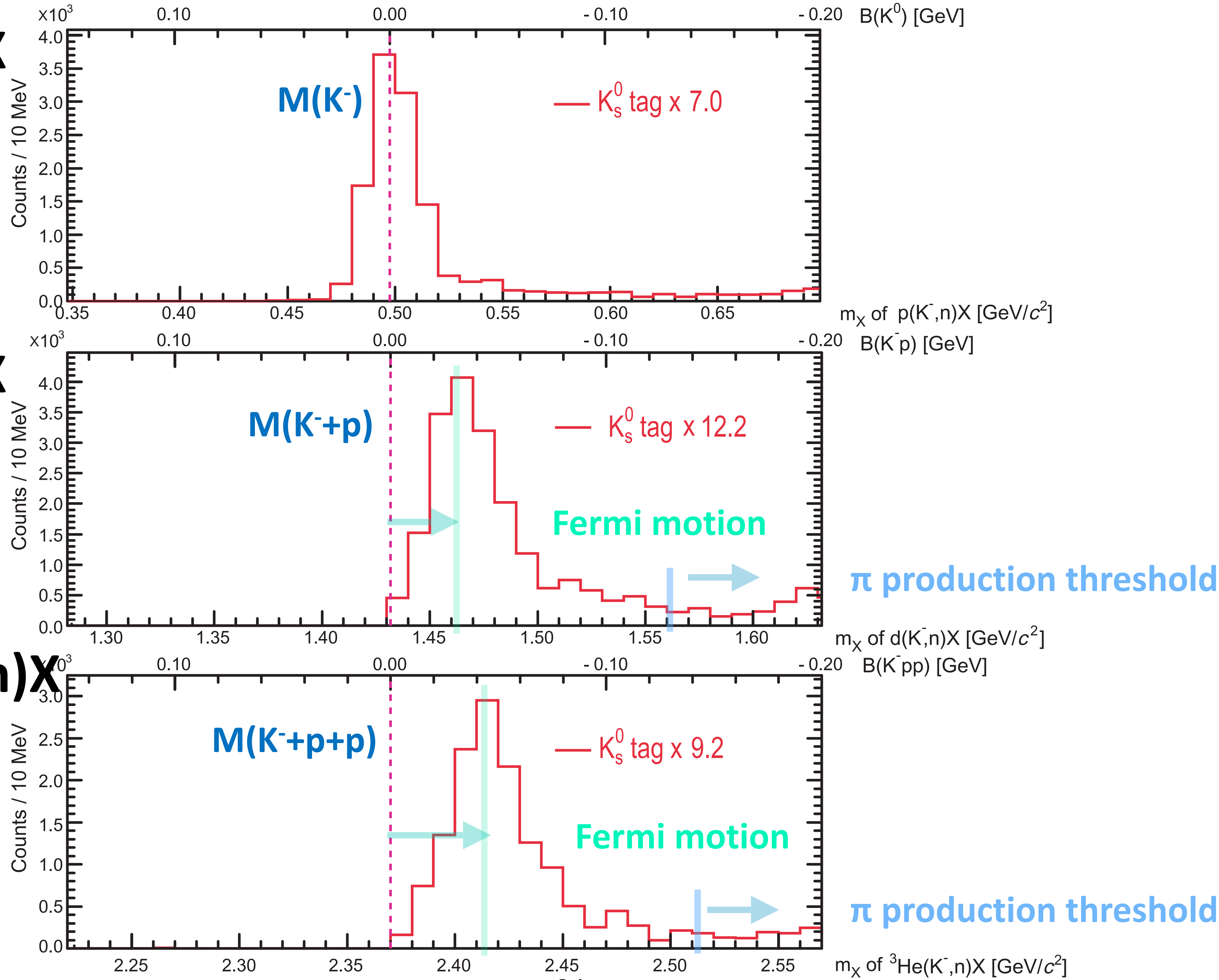
- **HADES (pp @ 3.5 GeV)**
  0.7-4.2 μb (Λ* ~ 10 μb)

Forward neutron specta on p/d/^{3}He

p(K$^-$,n)X

d(K$^-$,n)X

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



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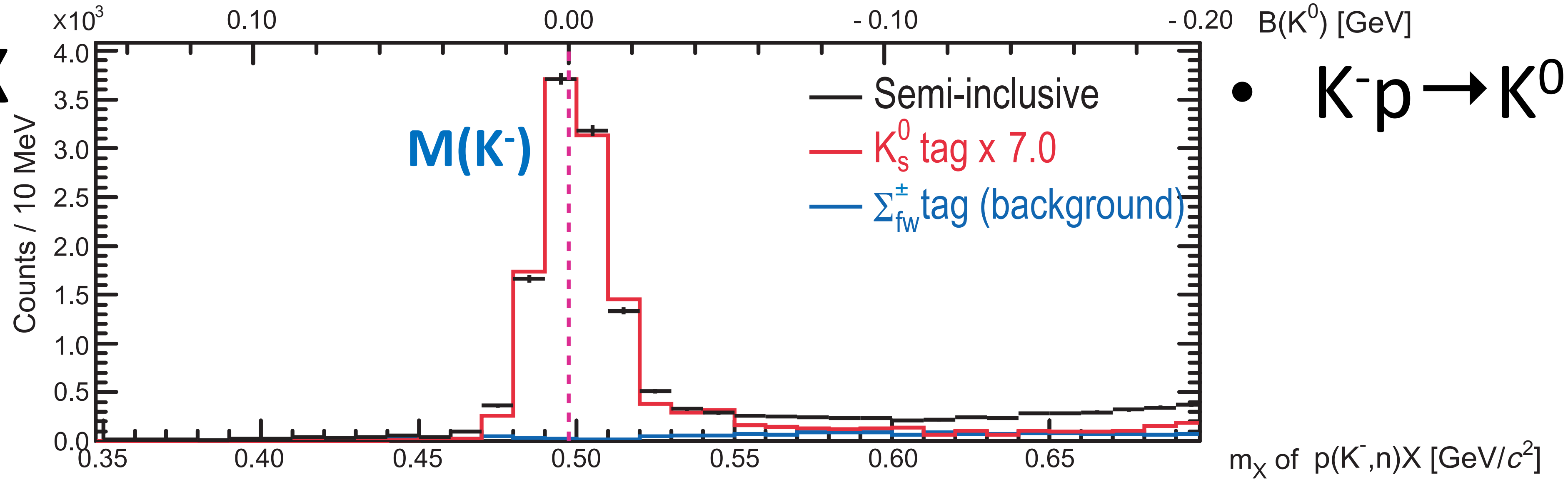
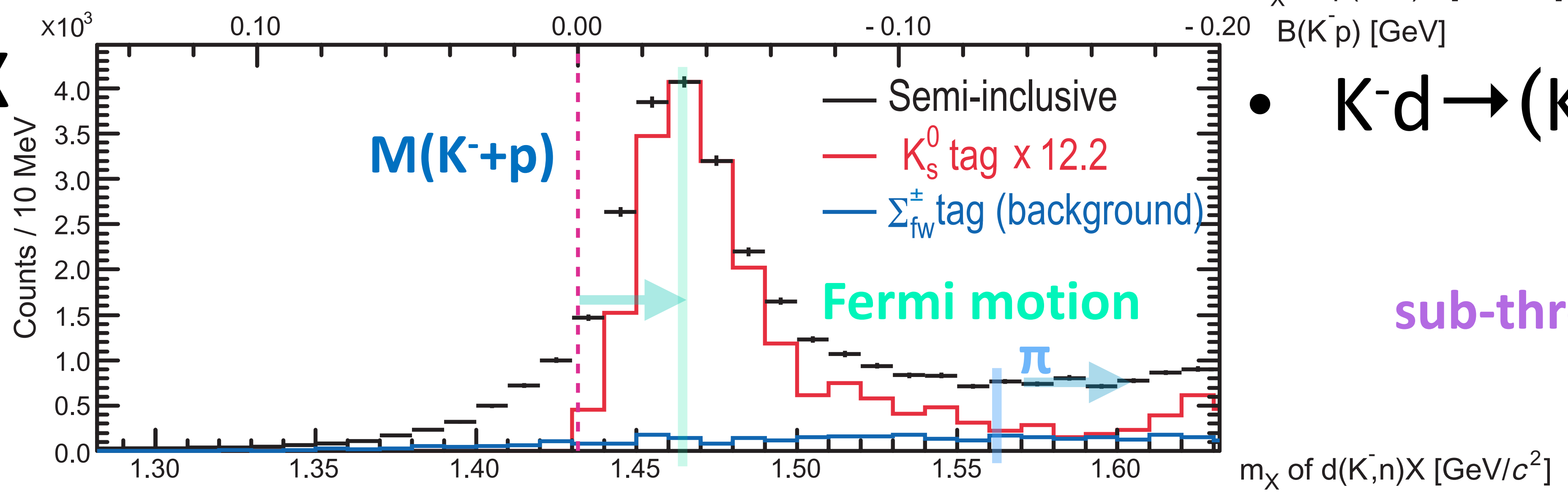
Forward neutron specta on p/d/^{3}He

p(K$^-$,n)X



- $K^-p \rightarrow K^0 + n_{fw}$

d(K$^-$,n)X



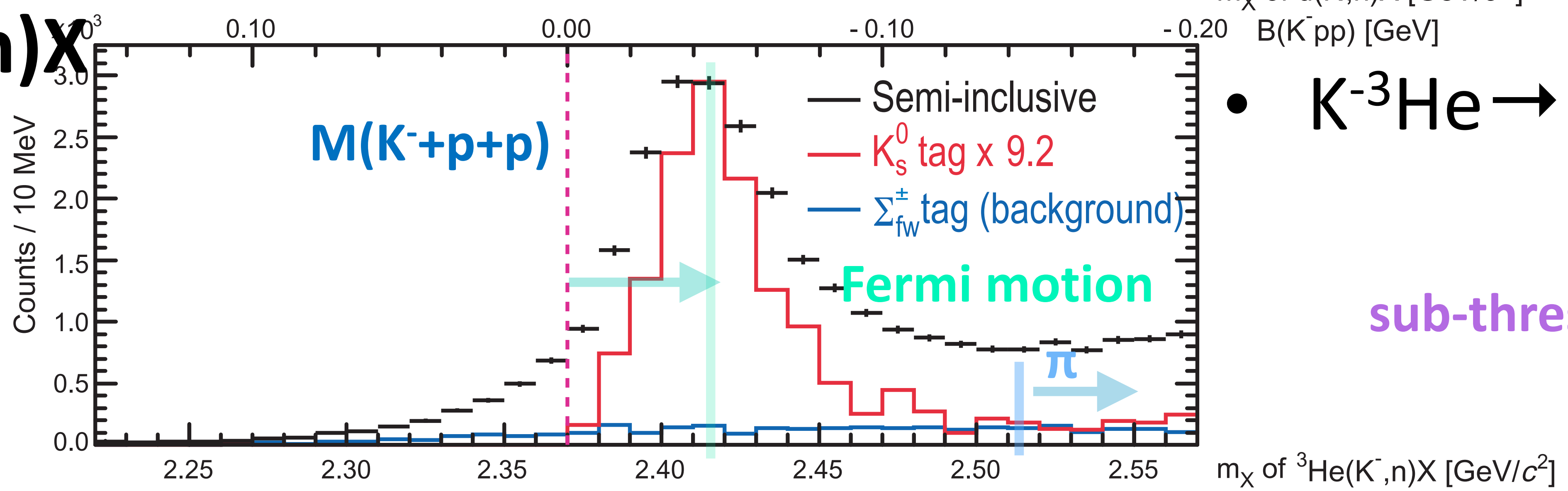
- $K^-d \rightarrow (K^-p) + n_{fw}$

  Y*

  sub-threshold excess!

  cf. E31

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



- $K^{-3}He \rightarrow (K^-pp) + n_{fw}$

  Y*N

  sub-threshold excess!

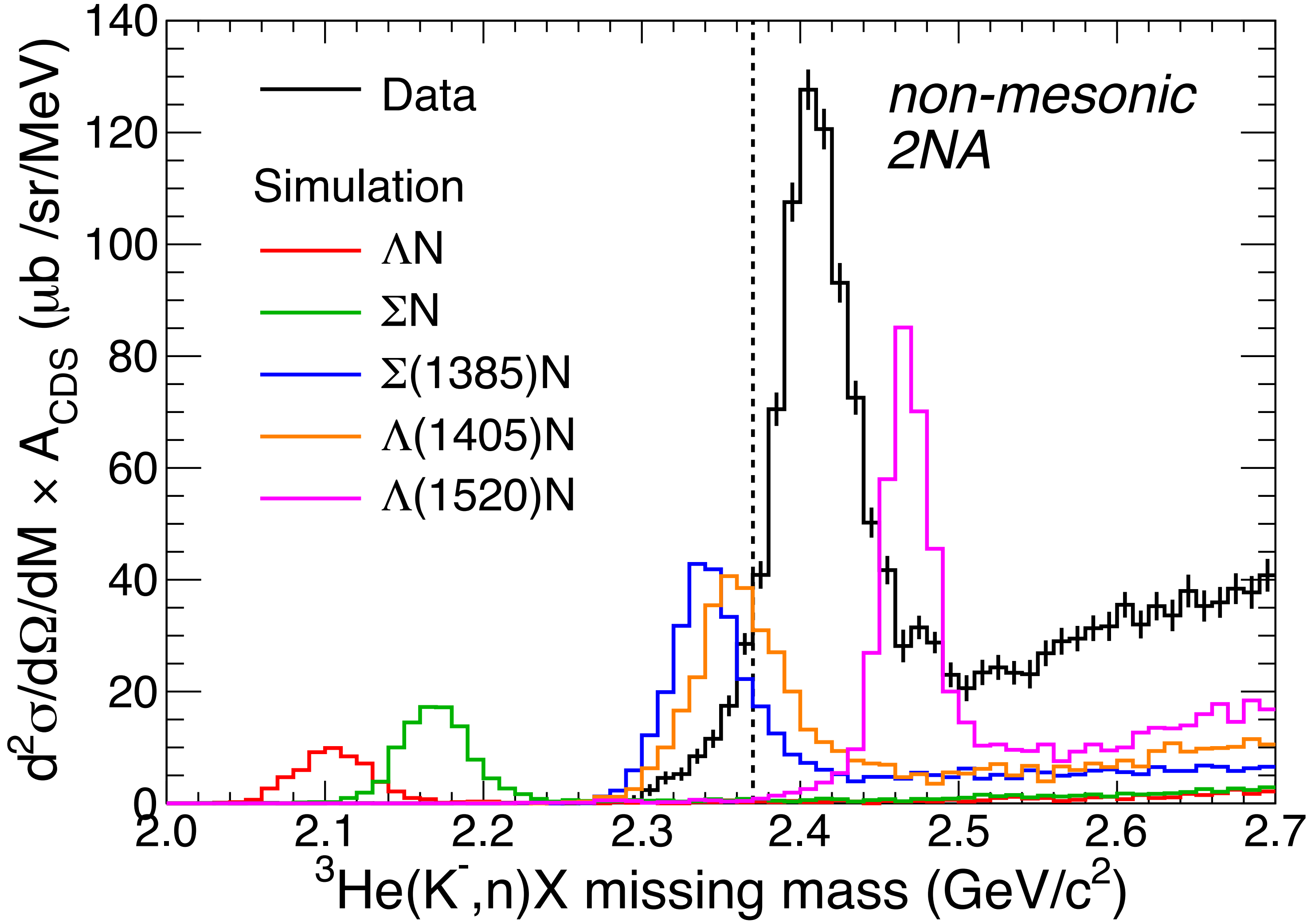
What is the origin of the excess?

naively understood by attractive & absorptive potential

other possibilities are…

1. non-mesonic two-nucleon absorption: Λ(1405)n branch

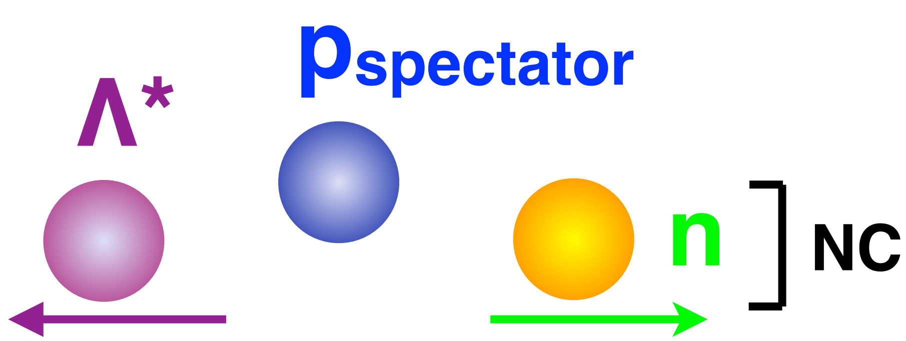
- rather large cross-section ~ 5 mb/sr
- U.L. of deeply bound states: 1 ~ 10% of Λ*n branch?



20 mb/sr @ θ=0

***Breit-Wigner** with PDG mass&width*

$$K^- + ^3\text{He} \rightarrow Y^{(*)} + \boxed{N} + N_s.$$



ΛN/ΣN branches are negligibly small

Λ(1520)n branch < 2 mb/sr

What is the origin of the excess?

naively understood by attractive & absorptive potential

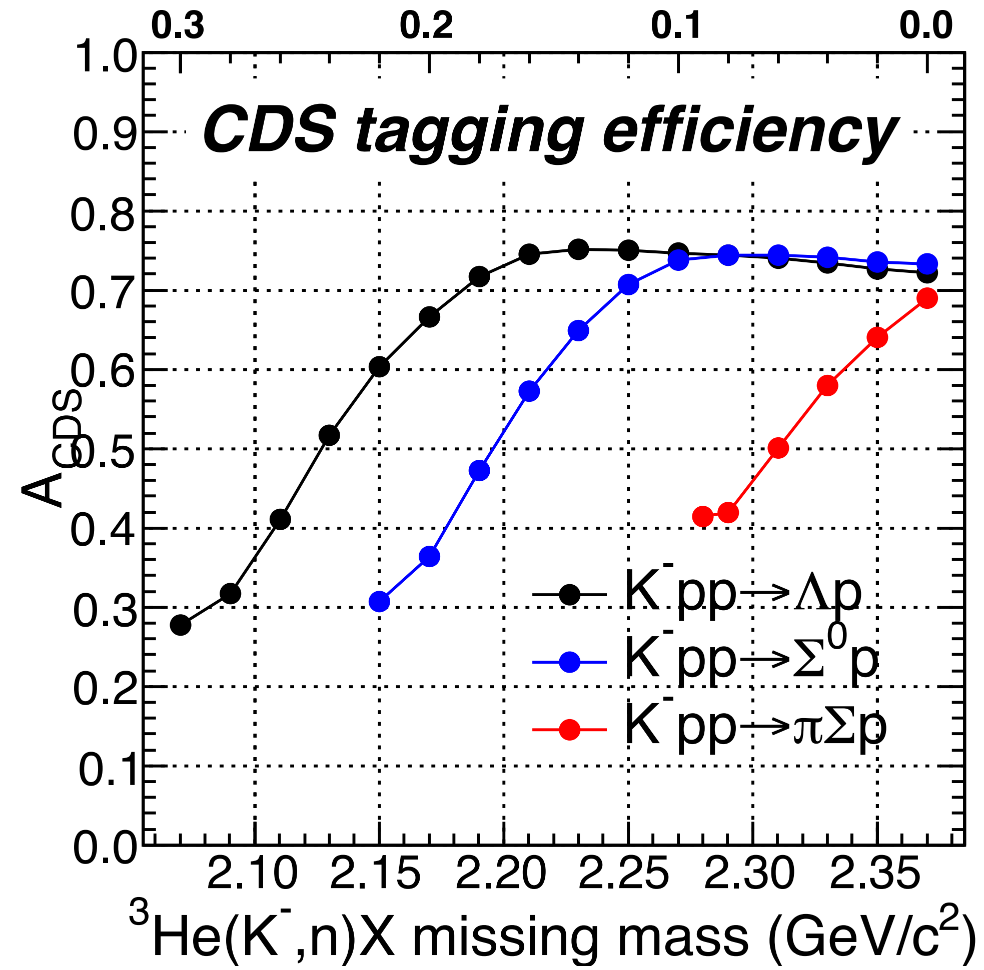
other possibilities are…

1. non-mesonic two-nucleon absorption: Λ(1405)n branch

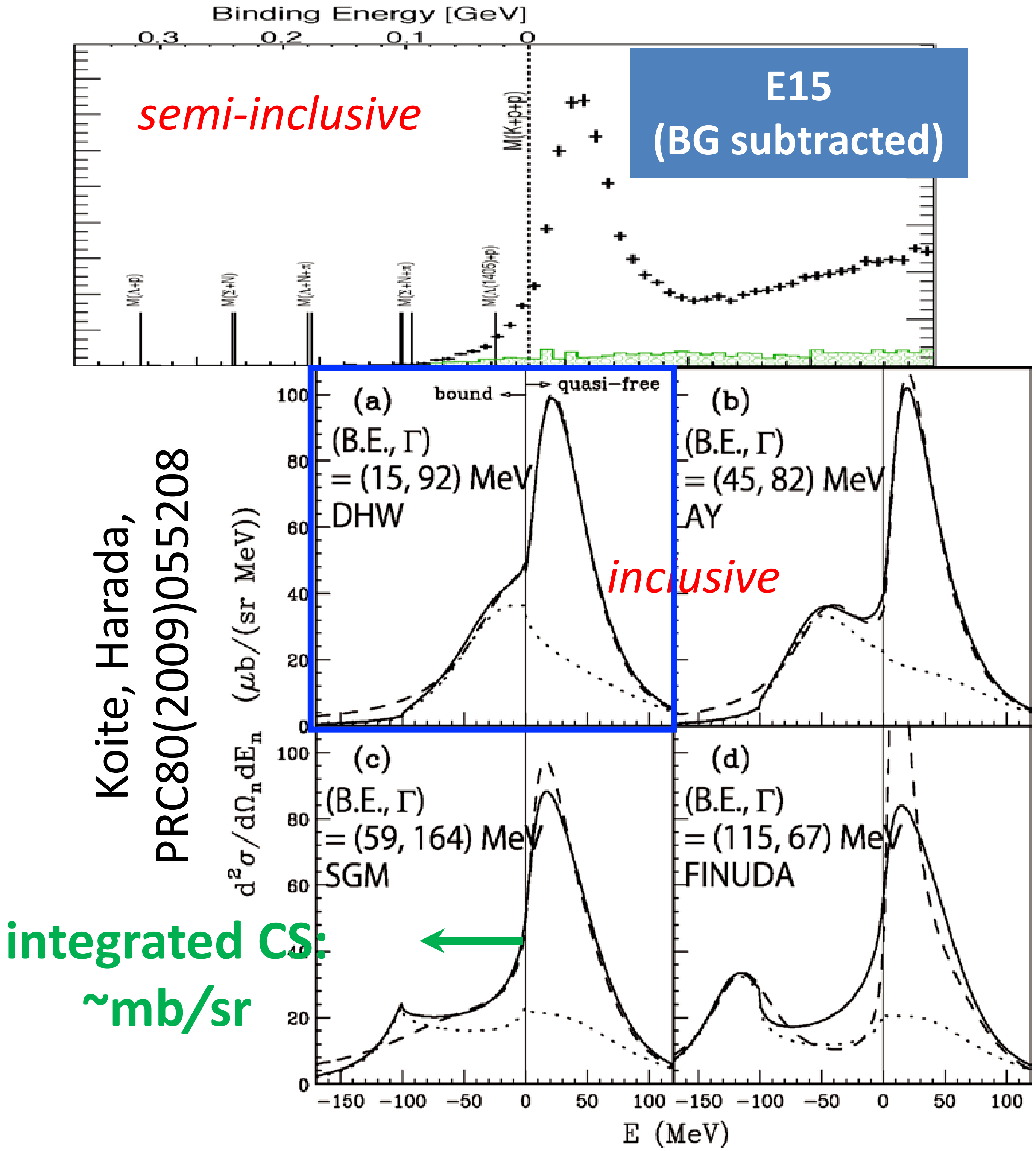
- rather large cross-section ~ 5 mb/sr
- U.L. of deeply bound states: 1 ~ 10% of Λ*n branch?

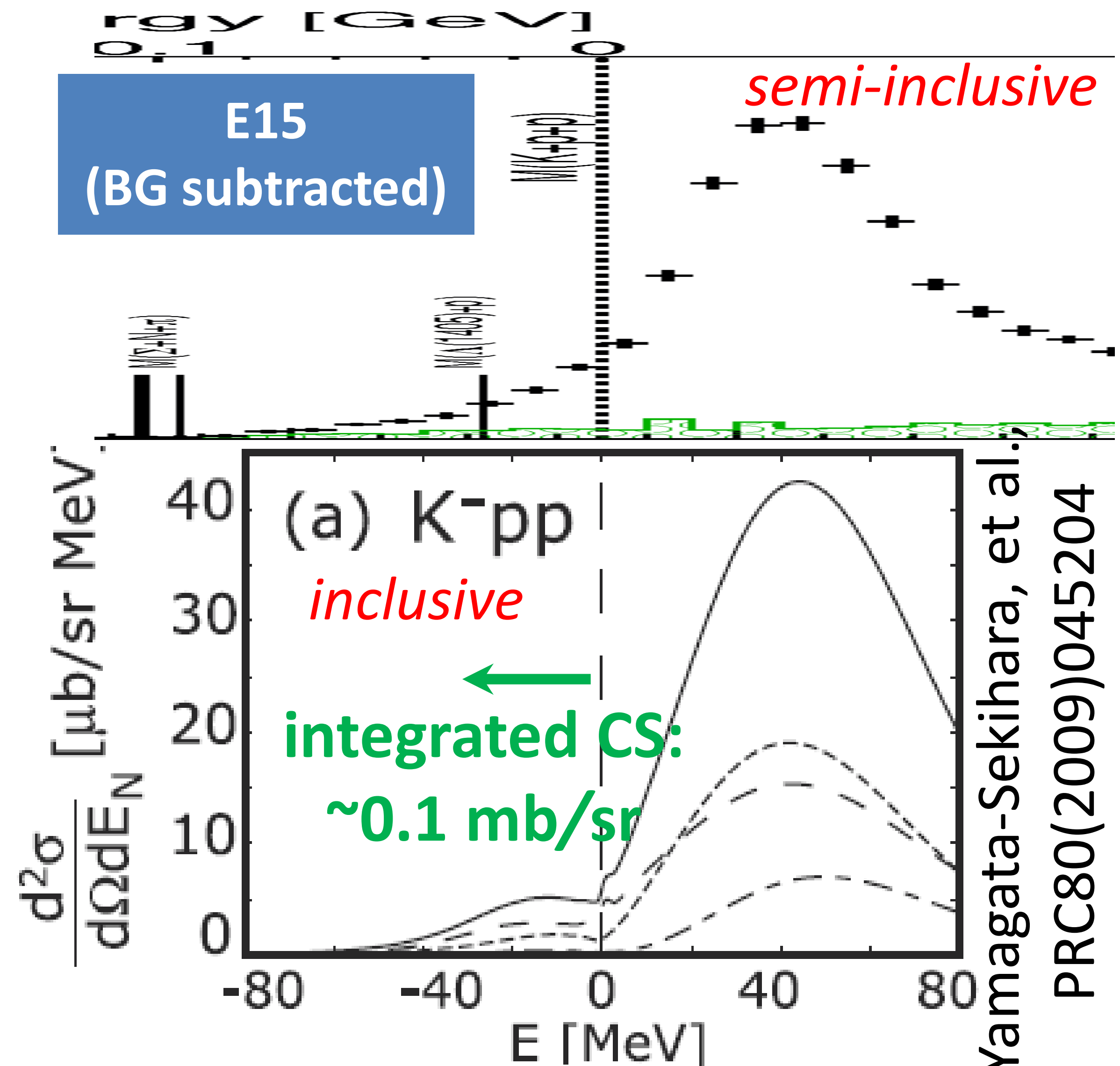
2. Loosely-bound "K^-pp" state

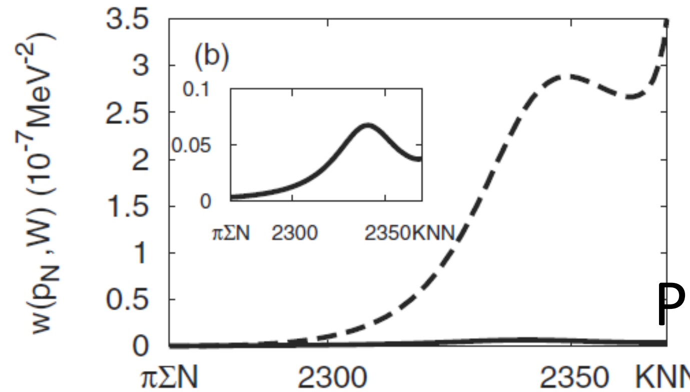
- The excess corresponds to 1~2 mb/sr
  - ~ 10% of quasi-elastic peak
- Assumptions
  - Fully attributed to the K^-pp state
  - isotropic decay $K^-pp \rightarrow \Lambda p/\Sigma p/\pi\Sigma p$



Comparison with theoretical spectral functions







S.Ohnishi, et al.,
PRC88(2013)025204

Experimental spectrum is similar to theoretical predictions with a loosely-bound state.
(Λ(1405) production is not considered)

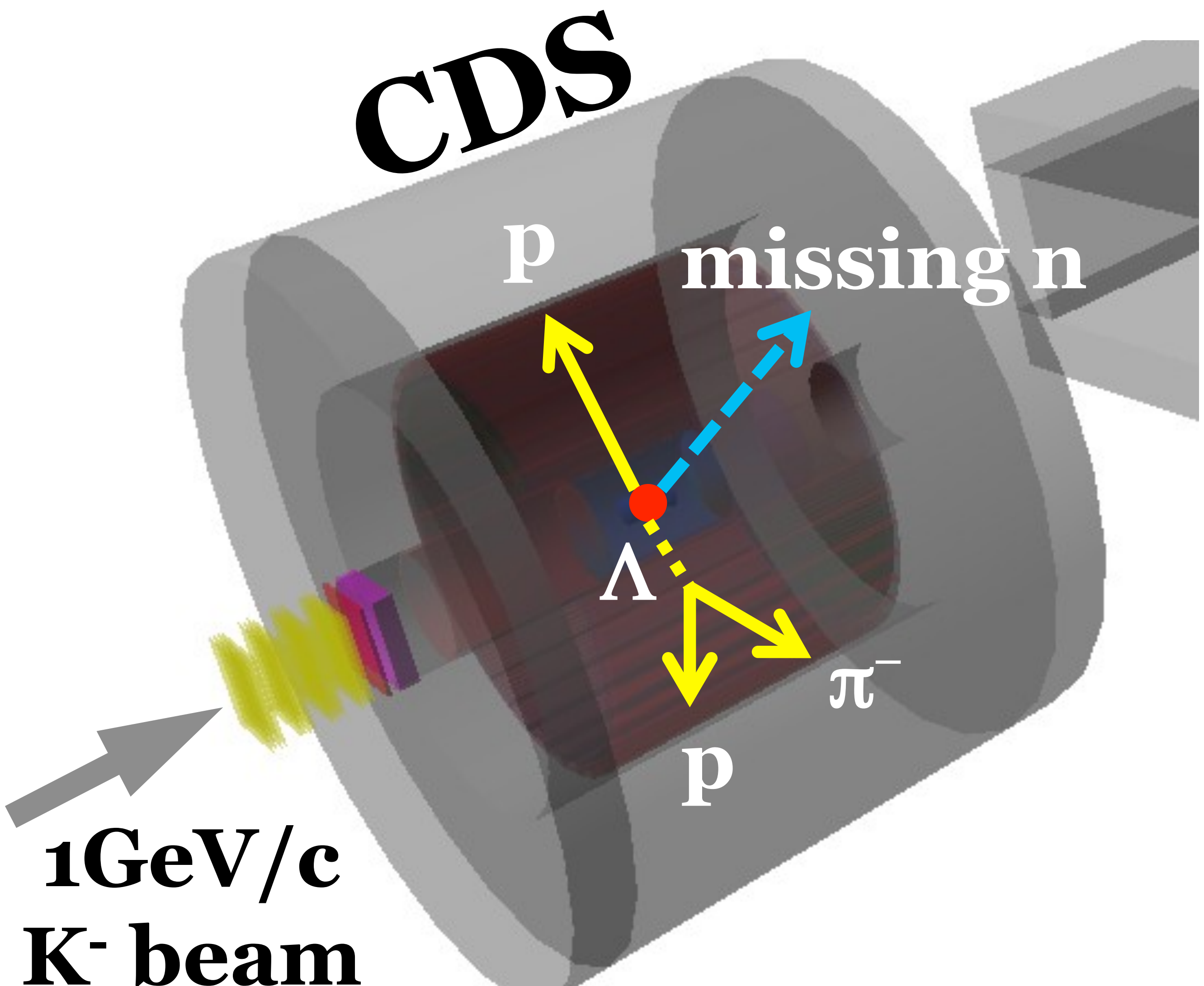
Decay channel
Exclusive $^{3}He(K^{-}, \Lambda p)n$

PTEP
Prog. Theor. Exp. Phys. **2015**, 00000 (12 pages)
DOI: 10.1093/ptep/0000000000

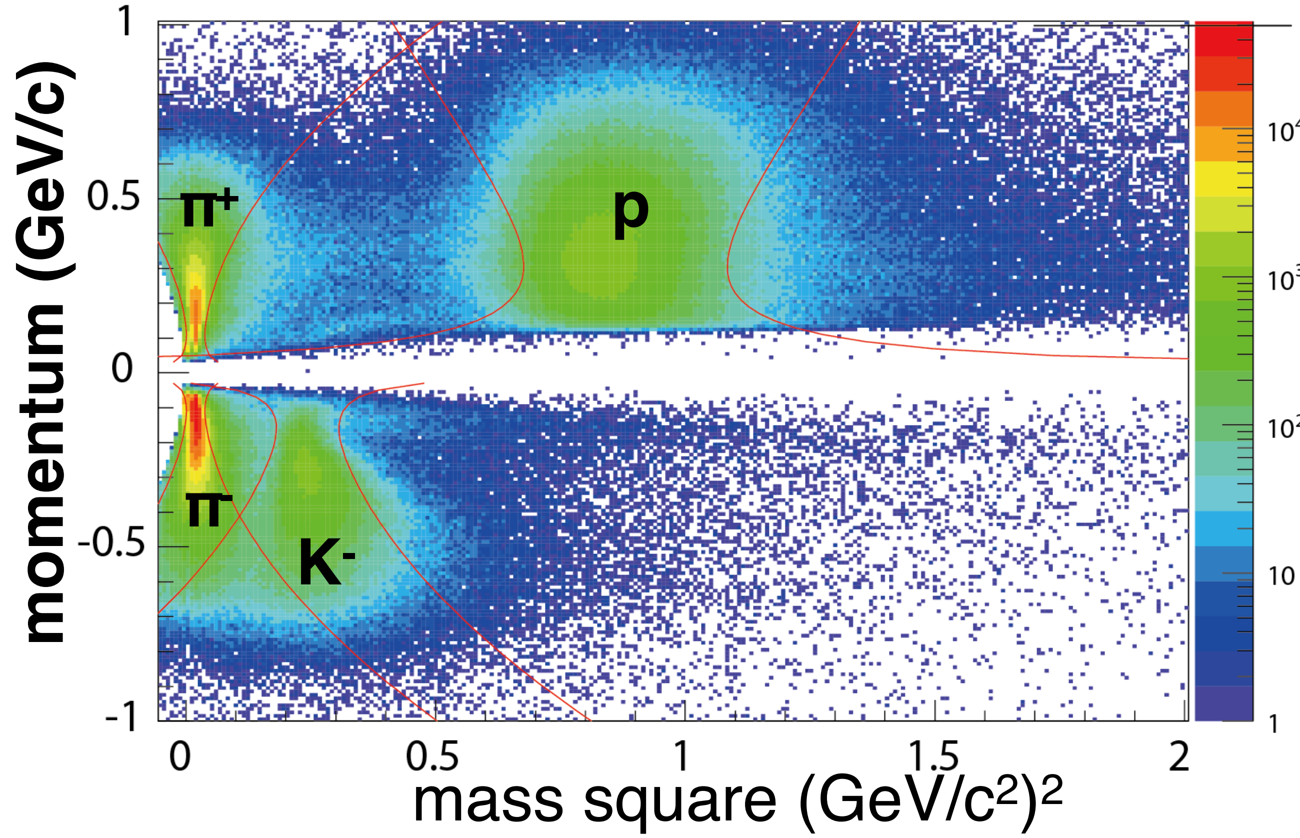
Search for S=-1 di-baryonic state on $K^{-}pp$ threshold

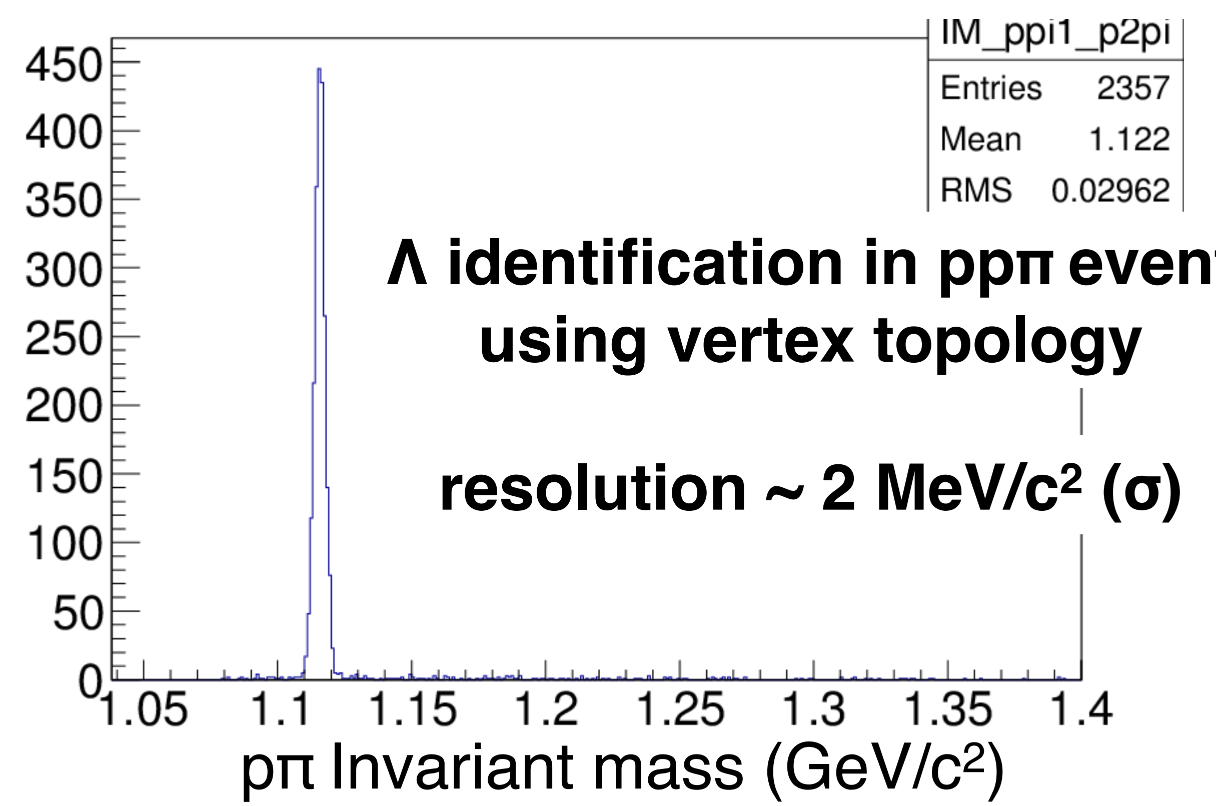
Y. Sada[1], S. Ajimura[1], G. Beer[2], H. Bhang[3], M. Bragadireanu[4], P. Buehler[5], L. Busso[6,9], M. Cargnelli[5], S. Choi[3], C. Curceanu[7], S. Enomoto[8], D. Faso[6,9], H. Fujioka[10], Y. Fujiwara[11], T. Fukuda[12], C. Guaraldo[7], T. Hashimoto[11], R. S. Hayano[11], T. Hiraiwa[1], M. Iio[8], M. Iliescu[7], K. Inoue[13], Y. Ishiguro[10], T. Ishikawa[11], S. Ishimoto[8], T. Ishiwatari[5], K. Itahashi[14], M. Iwai[8], M. Iwasaki[15,14], Y. Kato[14], S. Kawasaki[13], P. Kienle[16], H. Kou[15], Y. Ma[14], J. Marton[5], Y. Matsuda[17], Y. Mizoi[12], O. Morra[6], T. Nagae[10], H. Noumi[1], H. Ohnishi[14], S. Okada[14], H. Outa[14], K. Piscicchia[7], M. Poli Lener[7], A. Romero Vidal[7], A. Sakaguchi[13], F. Sakuma[14], M. Sato[14], A. Scordo[7], M. Sekimoto[8], H. Shi[18], D. Sirghi[18], F. Sirghi[18], K. Suzuki[18], S. Suzuki[8], T. Suzuki[11], K. Tanida[3], H. Tatsuno[7], M. Tokuda[15], D. Tomono[14], A. Toyoda[8], K. Tsukada[18], O. Vazquez Doce[7,19], E. Widmann[5], B. K. Wuenschek[5], T. Yamaga[13], T. Yamazaki[11,14], H. Yim[20], Q. Zhang[14], and J. Zmeskal[5]

Λp identification

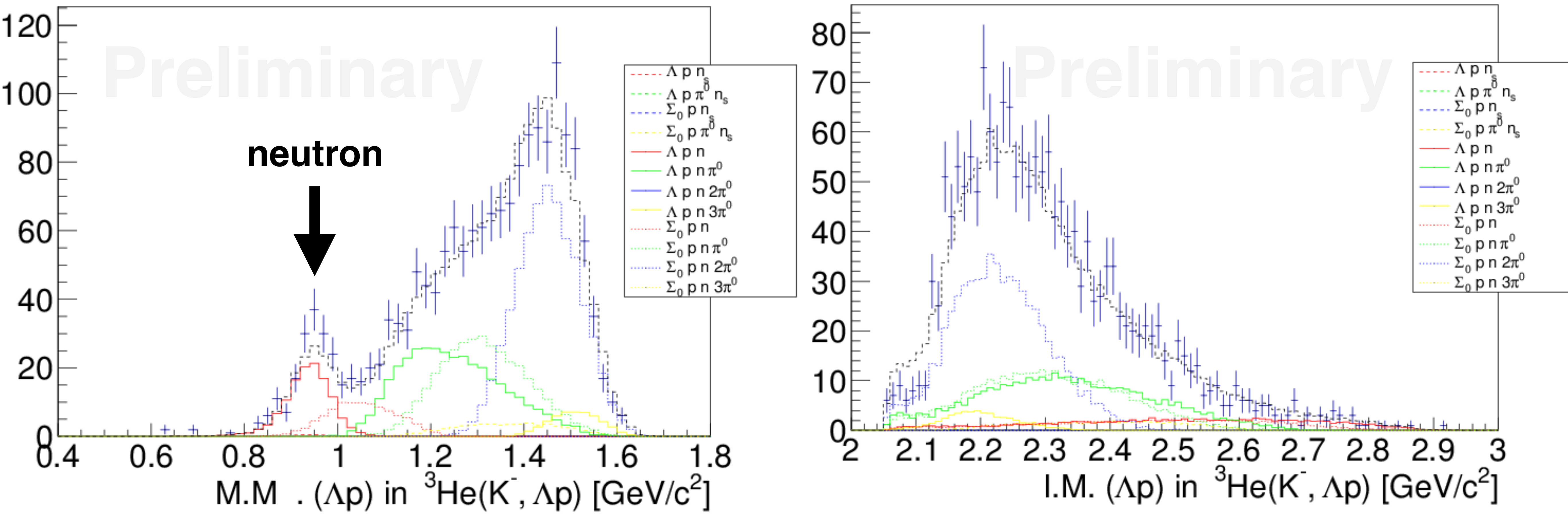


PID by TOF and track curvature



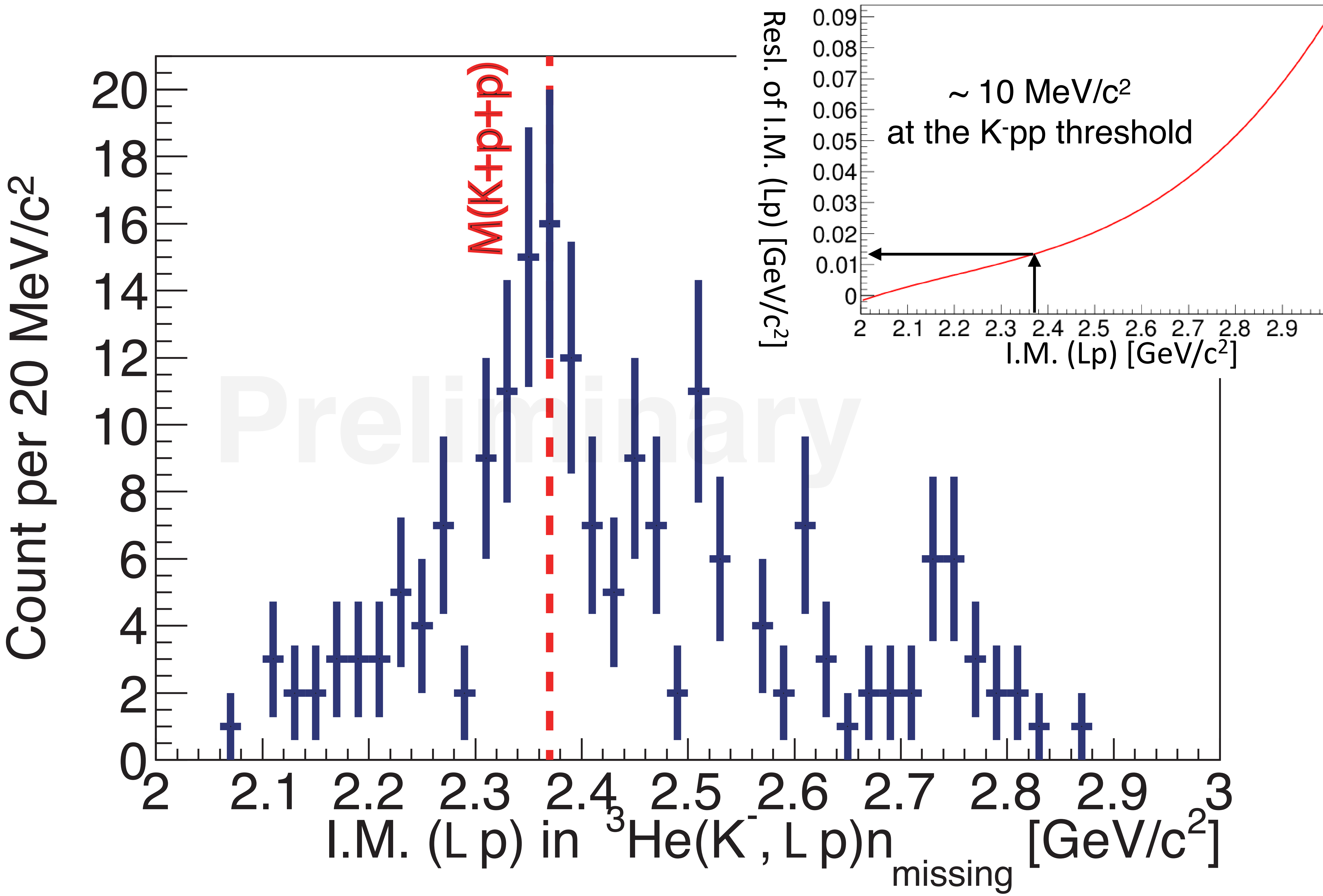


missing neutron ID



- Simultaneous fit of M.M.(Λp) & I.M.(Λp)
- Events with π are dominant
- Λpn ~ 200 events
  - contamination of Σ^0pn: ~20%

Exclusive spectrum



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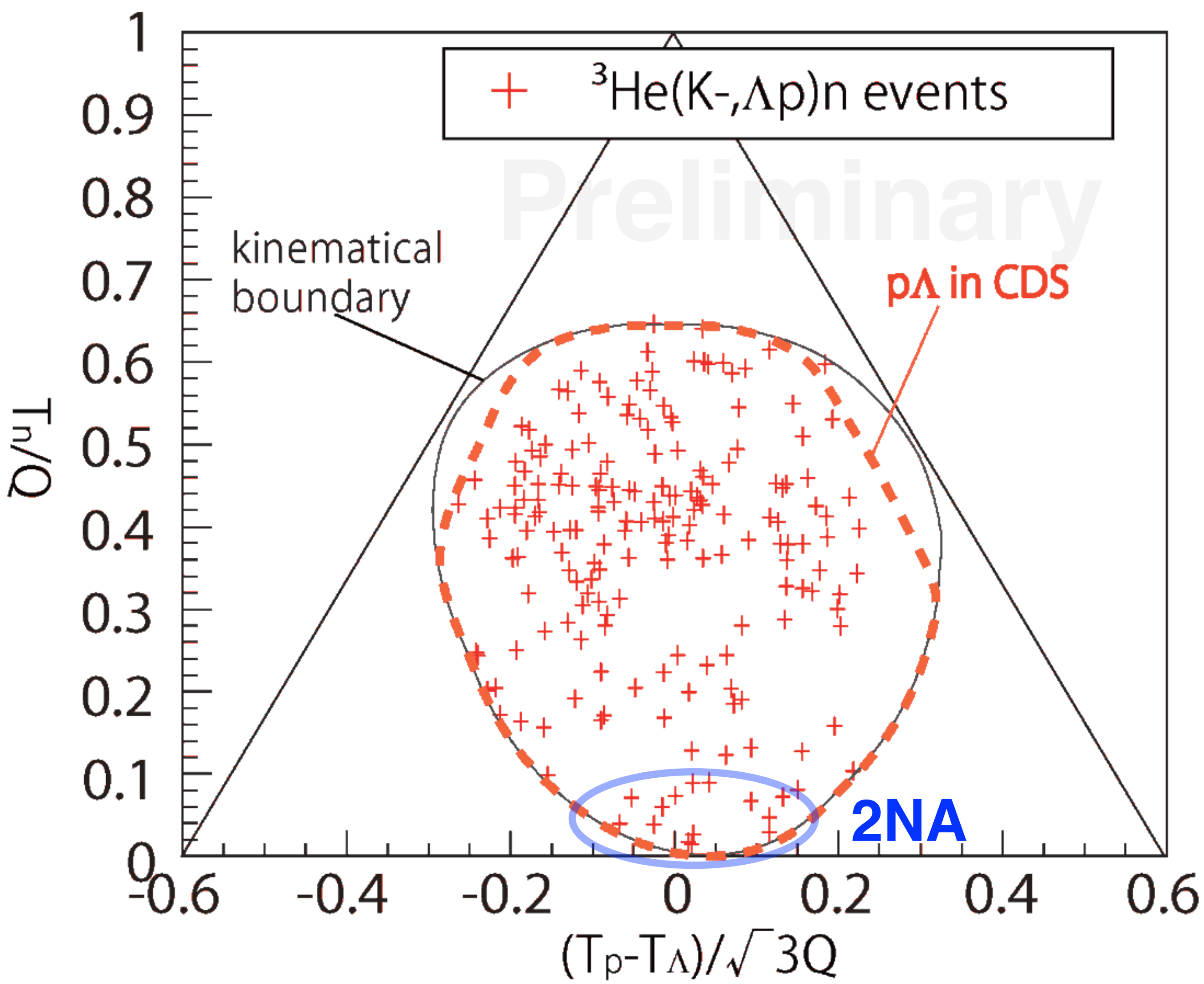
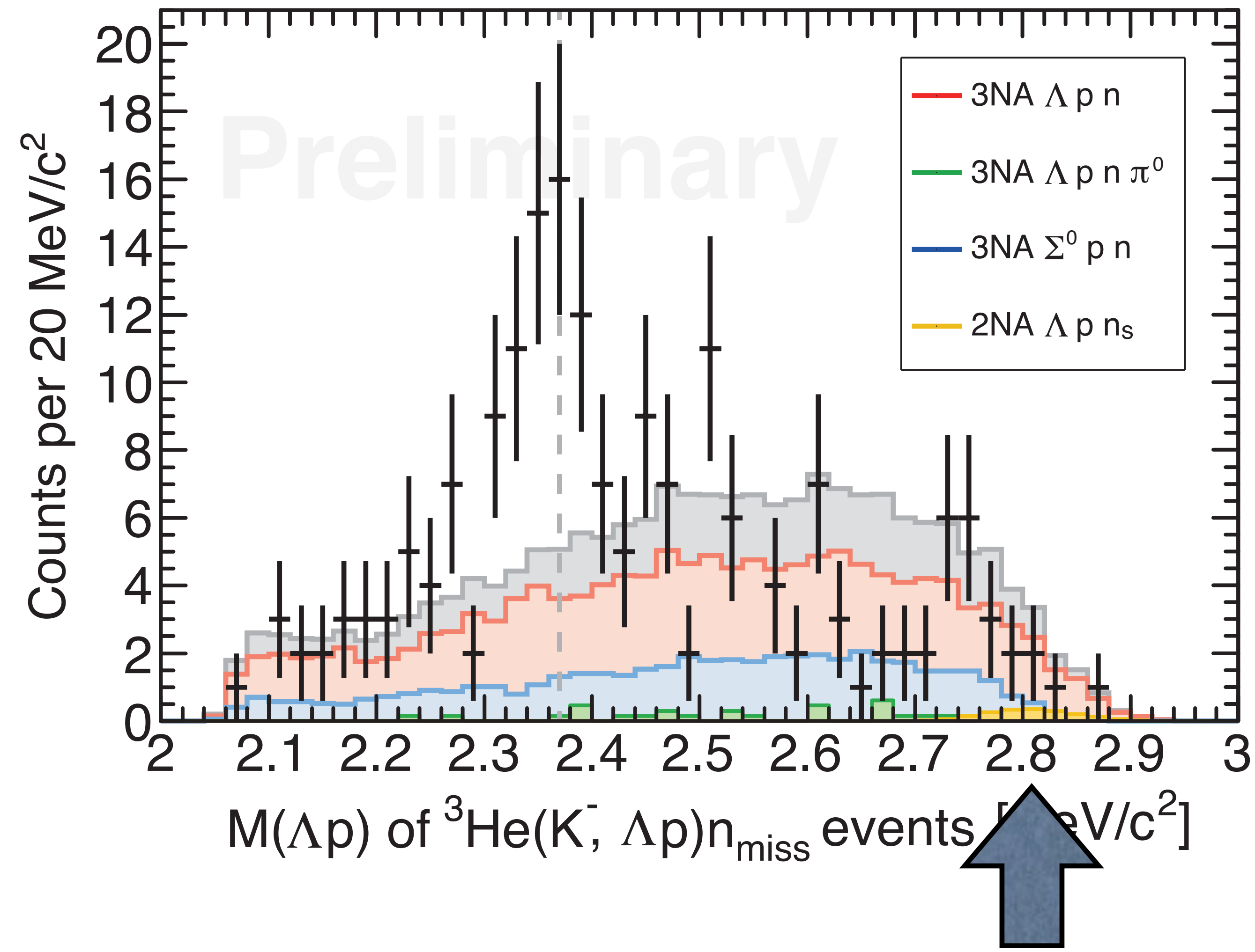
Comparison with Phase space

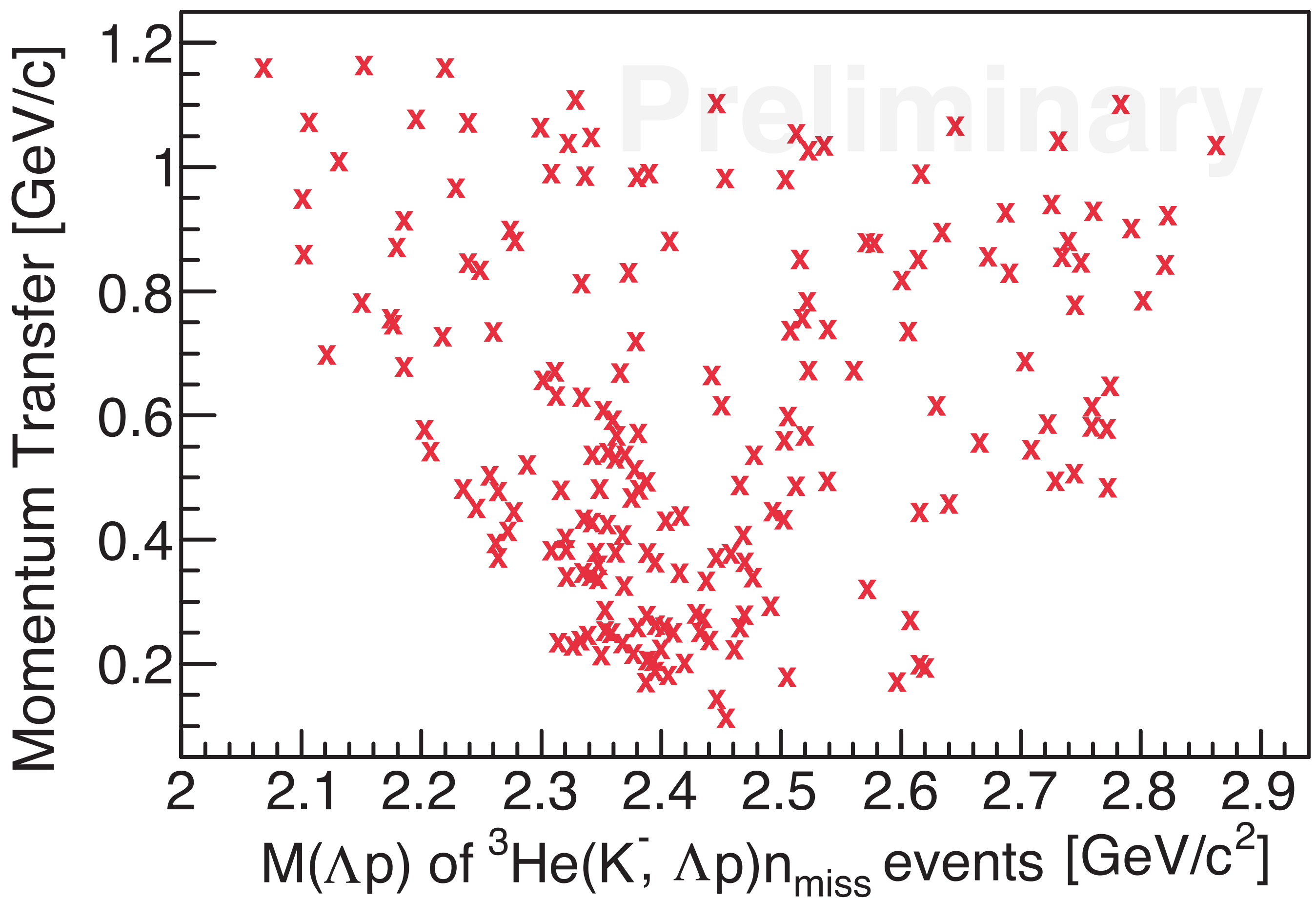




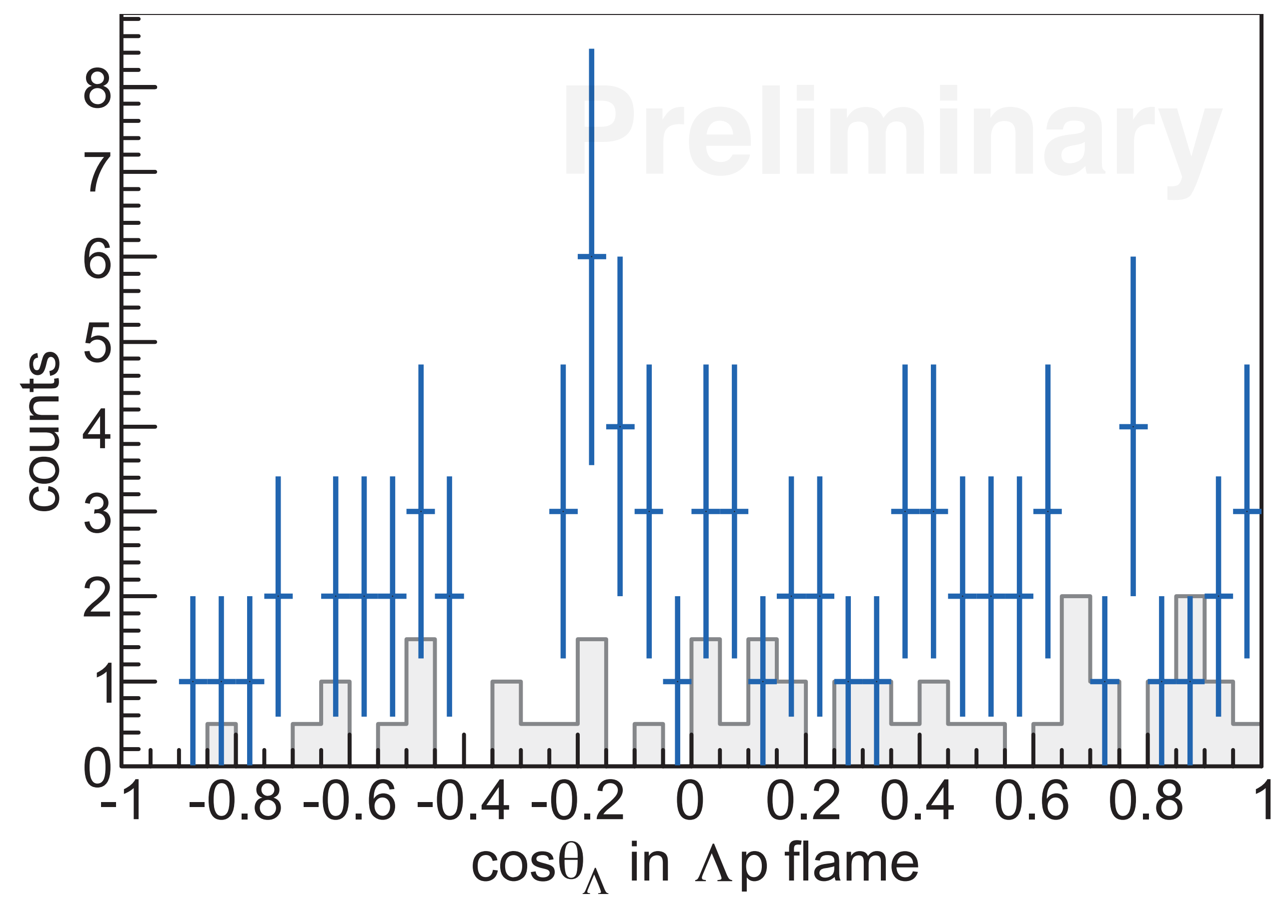
- **2NA reaction $K^- + {}^3He \rightarrow \Lambda + p + n_s$ seem to be very weak**
  - c.f.) stop K^- reaction: 10 ~ 20% of total events
- **3NA reaction $K^- + {}^3He \rightarrow \Lambda + p + n$ seem to exist**
  - ~ 40 μb, (10^{-4}~10^{-3} of $K^- + {}^3He$ total cross section)
- **Enhancement around the K^-pp threshold**

Kinematics of the structure

Mom. Trans vs. IM(Λp)



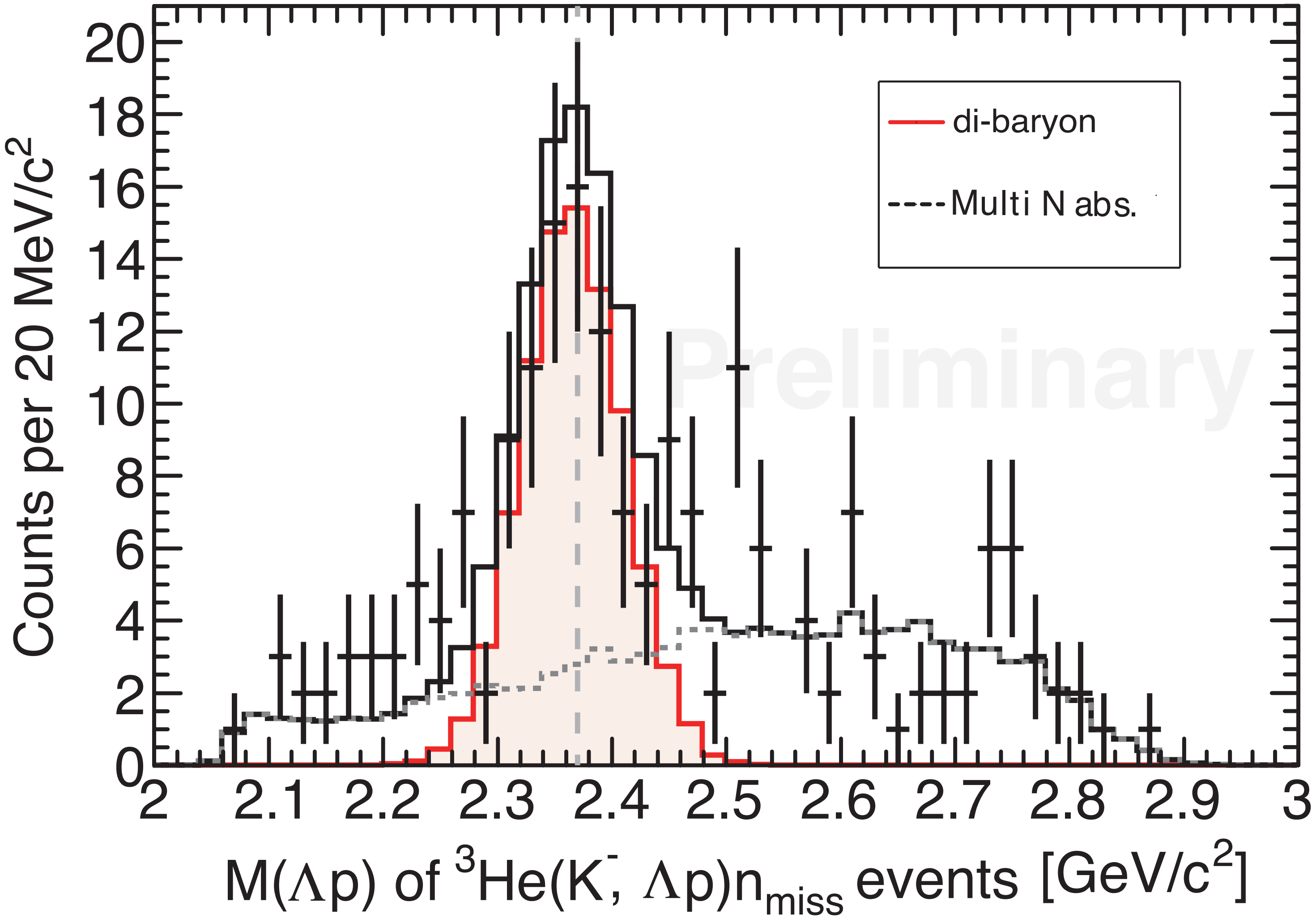
Λp decay-angle in CM



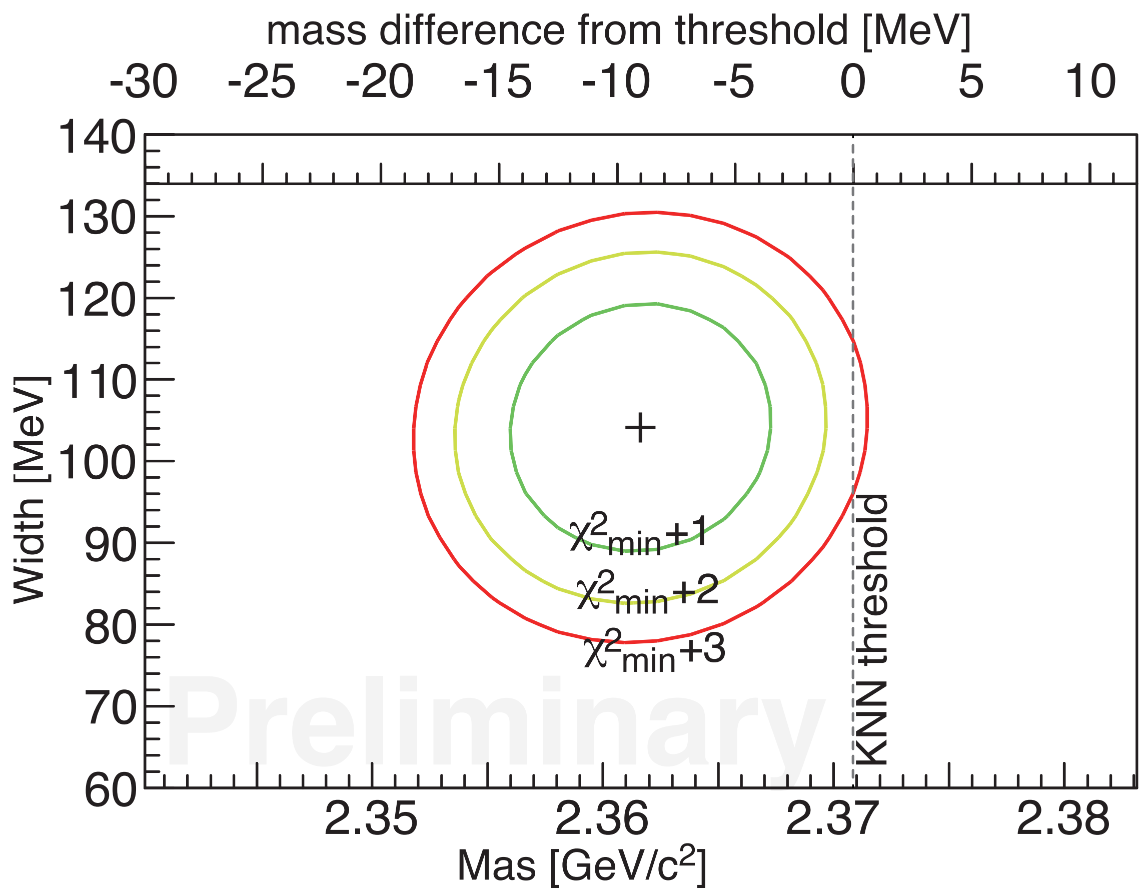
$\cos\theta_\Lambda = 1$ relative to the Λp frame

- low-momentum transfer is enhanced
- isotropic decay?

Assuming Breit-Wigner

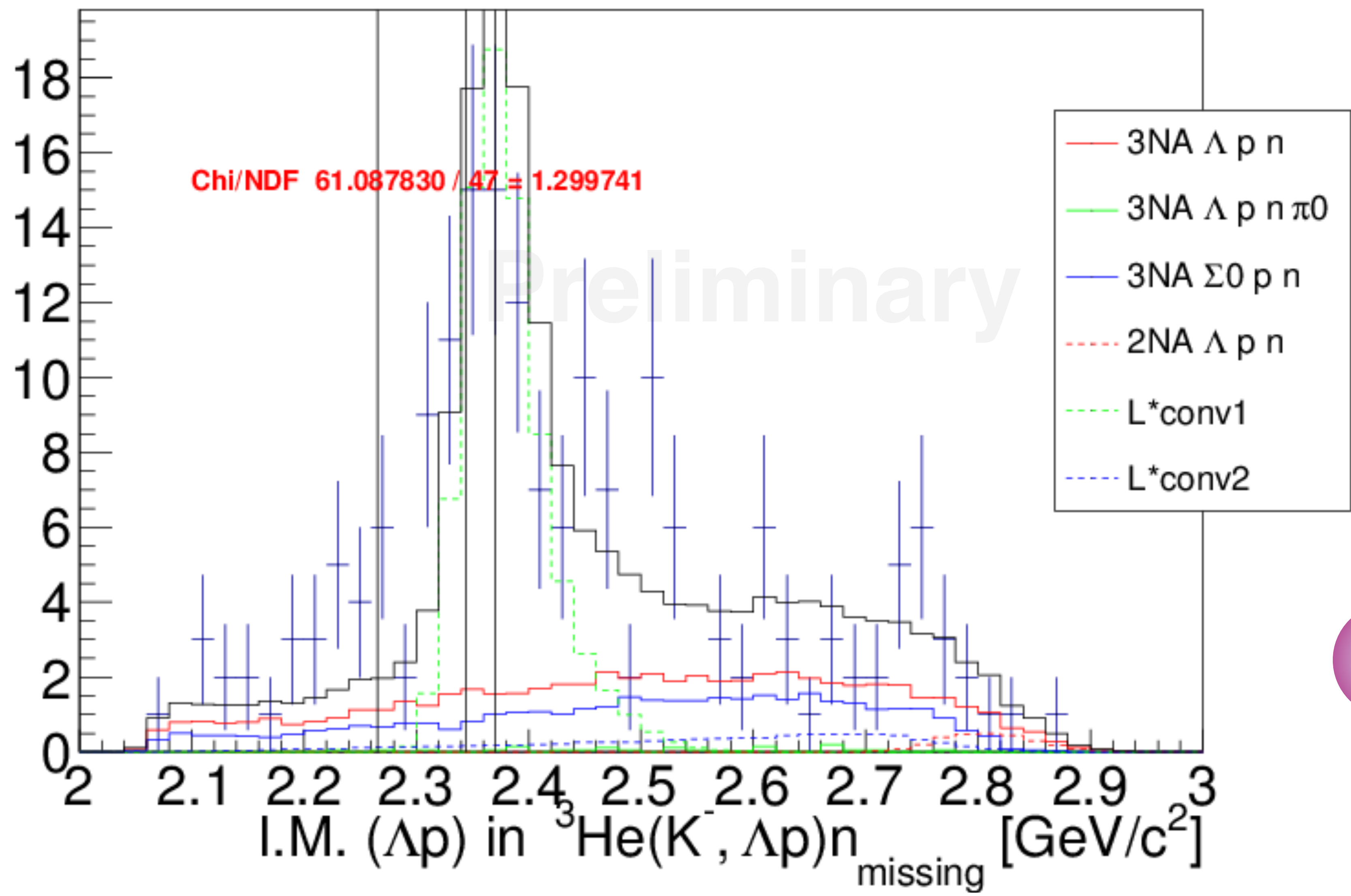


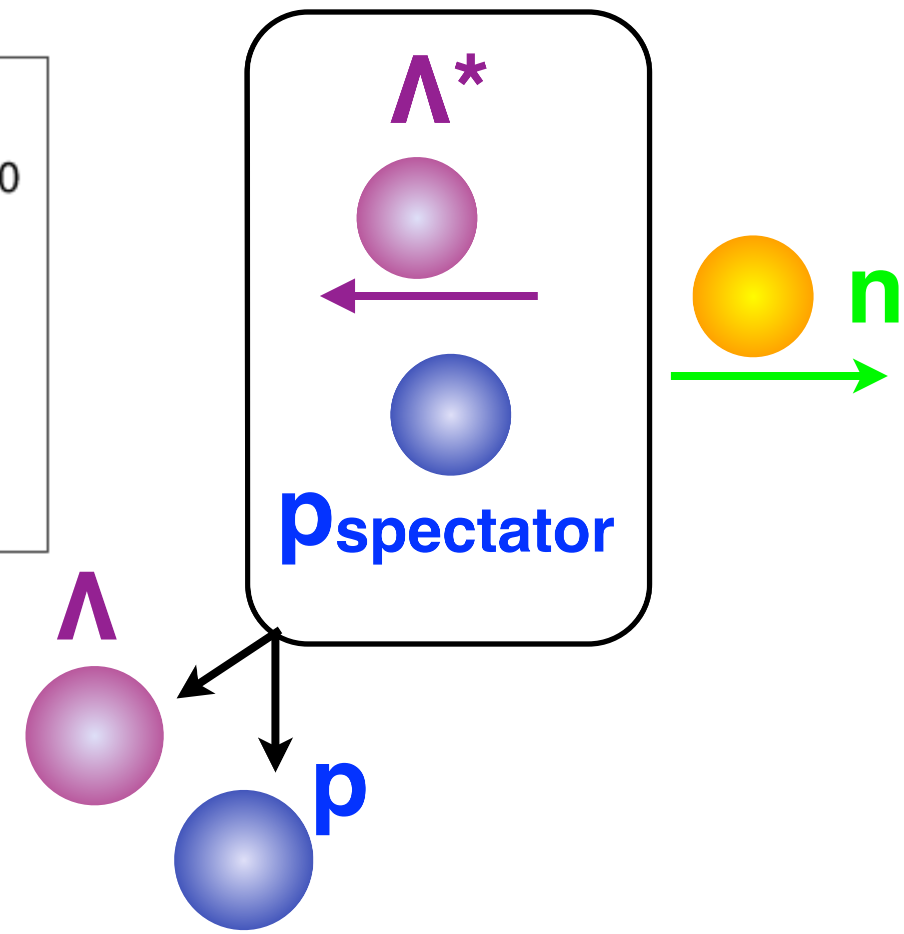
χ2/NDF=62.3 /49



- **χ^2-test with Breit-Wigner and 3NA backgrounds**
  - assume isotropic Λp decay as a function of mass and width
- **~ 15 μb, a few μb/sr at θ_n=0**
  - not contradict with the forward neutron analysis
    - < 1~2 mb/sr excess in semi-inclusive neutron spectrum
    - theories suggest K-pp→Λp << K-pp→πΣp

$\Lambda(1405)p_s \rightarrow \Lambda p$ conversion





- **Difficult to distinguish from the “K-pp” experimentally.**
- **Should be compared with quasi-free Λ*N**
  - < 5 mb/sr from forward neutron analysis
  - ~ 0.5 mb/sr from theoretical calc. on K-d
  - a few percent conversion probability?

further studies are ongoing…

Outlook - E15^{2nd} & near future plan@K1.8BR

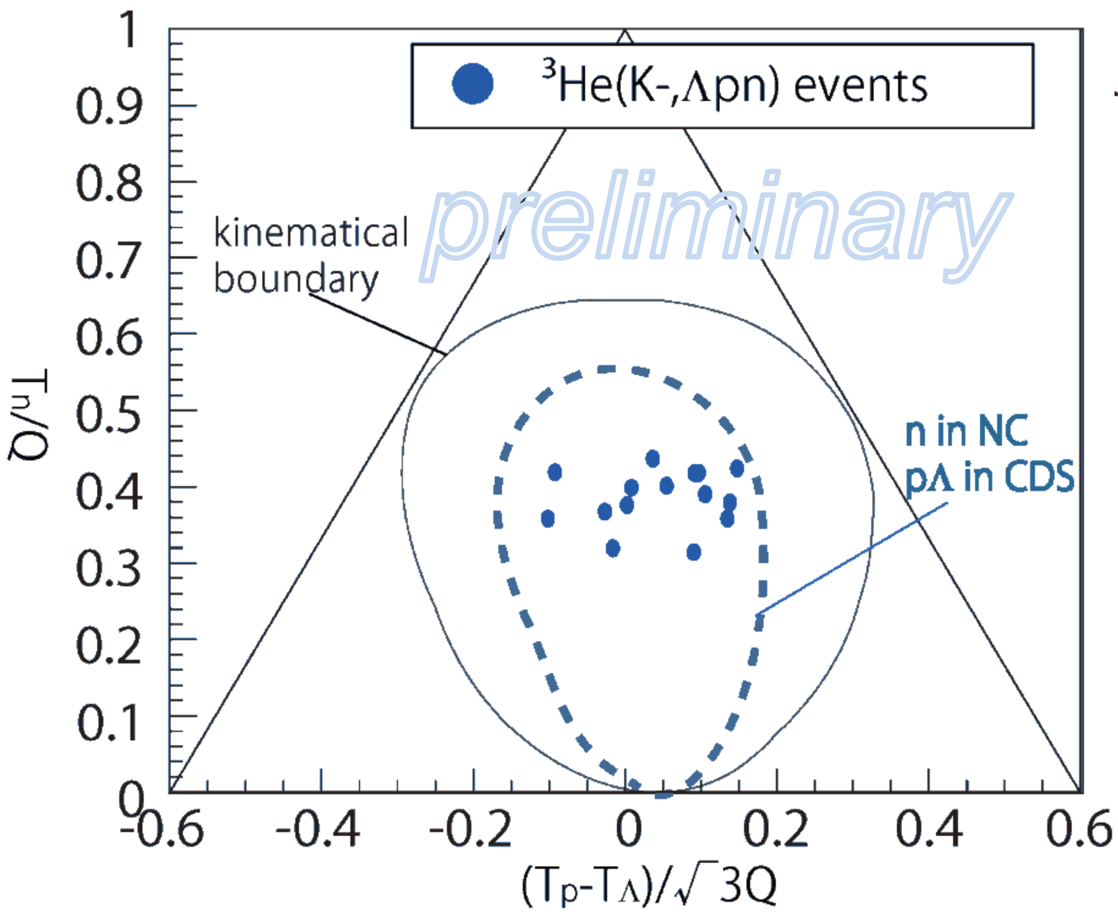
- **E15 2nd-stage physics run**
  - x10 statistics, ~10% of full proposal
  - Exclusive analysis
  - Kinematically complete measurement of ^{3}He(K$^-$,**Λpn**)
- **E31 pilot run (D2-target)**
- **E17→E62: K$^-$He x-ray measurement with TES**
  - TES: novel cryogenic detector, ~5 eV FWHM@6 keV
  - Feasibility test was successfully performed at PSI
- **E57: K$^-$d x-ray measurement with SDDs**

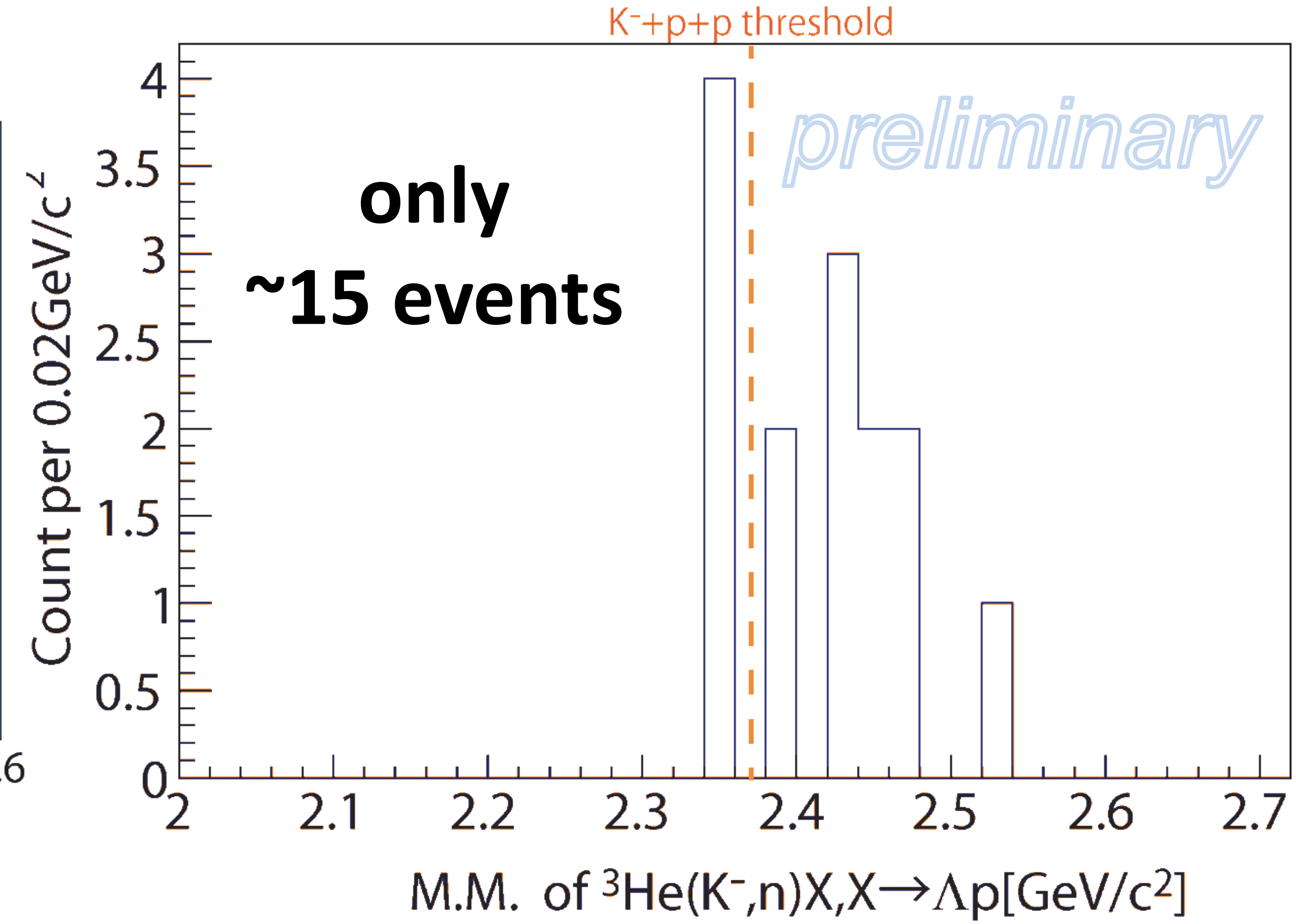
2015

2016

2017 ~ ?

Kinematically complete measurement





- Minimum momentum transfer of the $^3He(K^-,n)$ reaction
  → would enhance the S=-1 di-baryon production
- **x100 beam time is required**

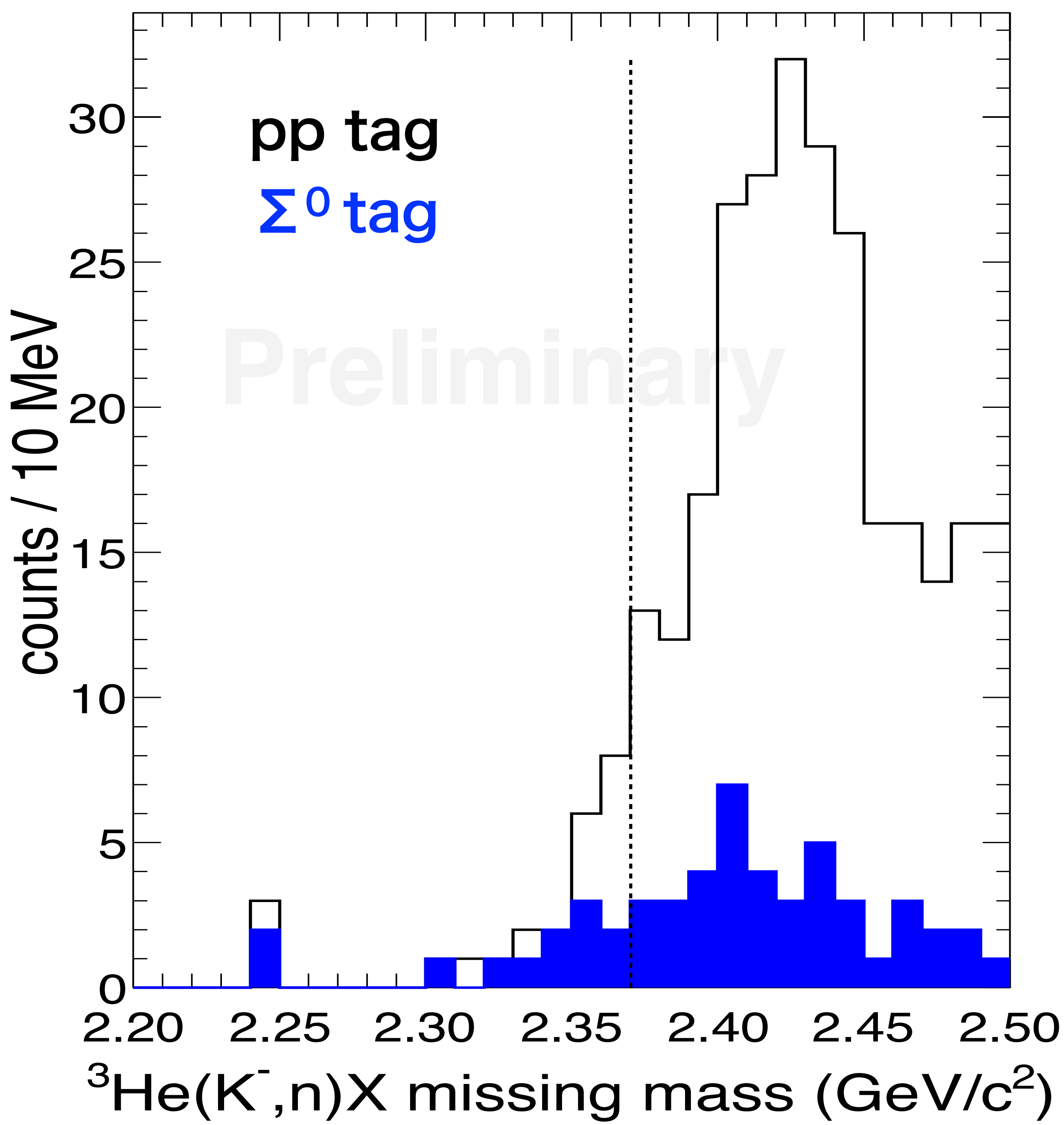
21

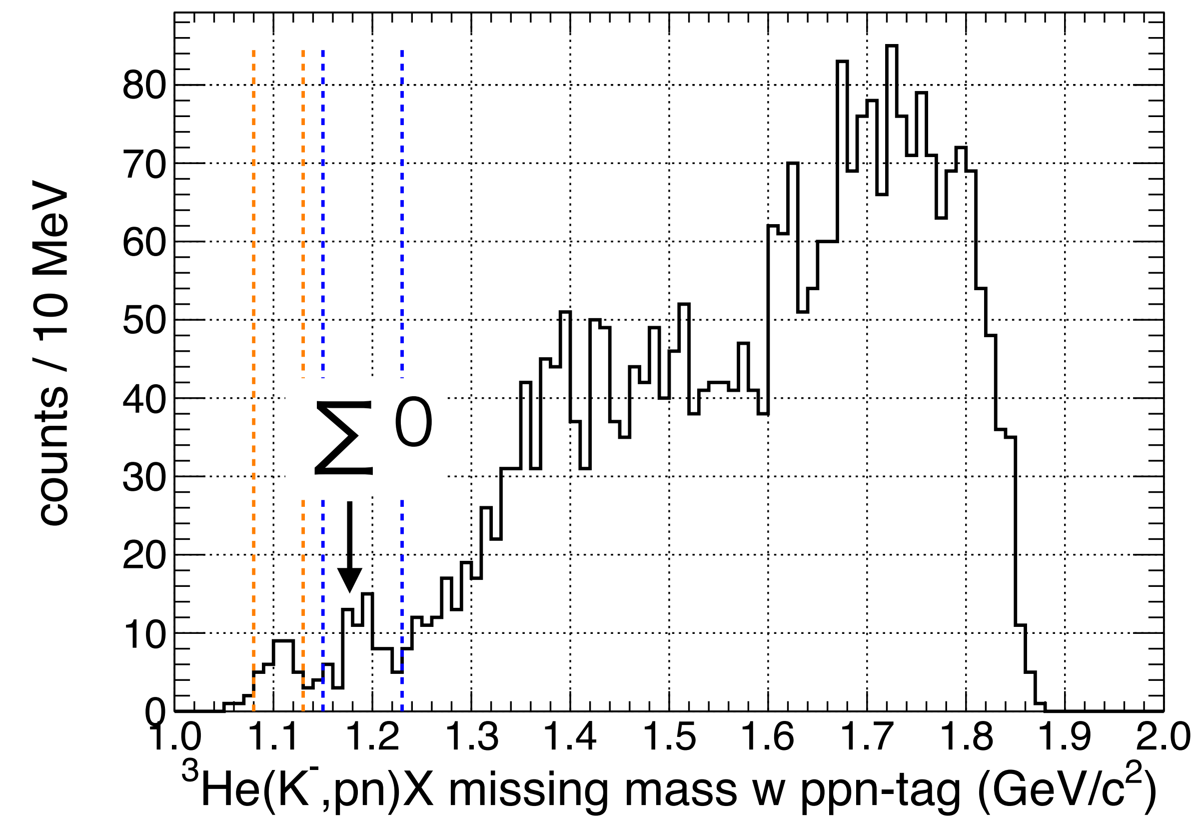
CDS
NC

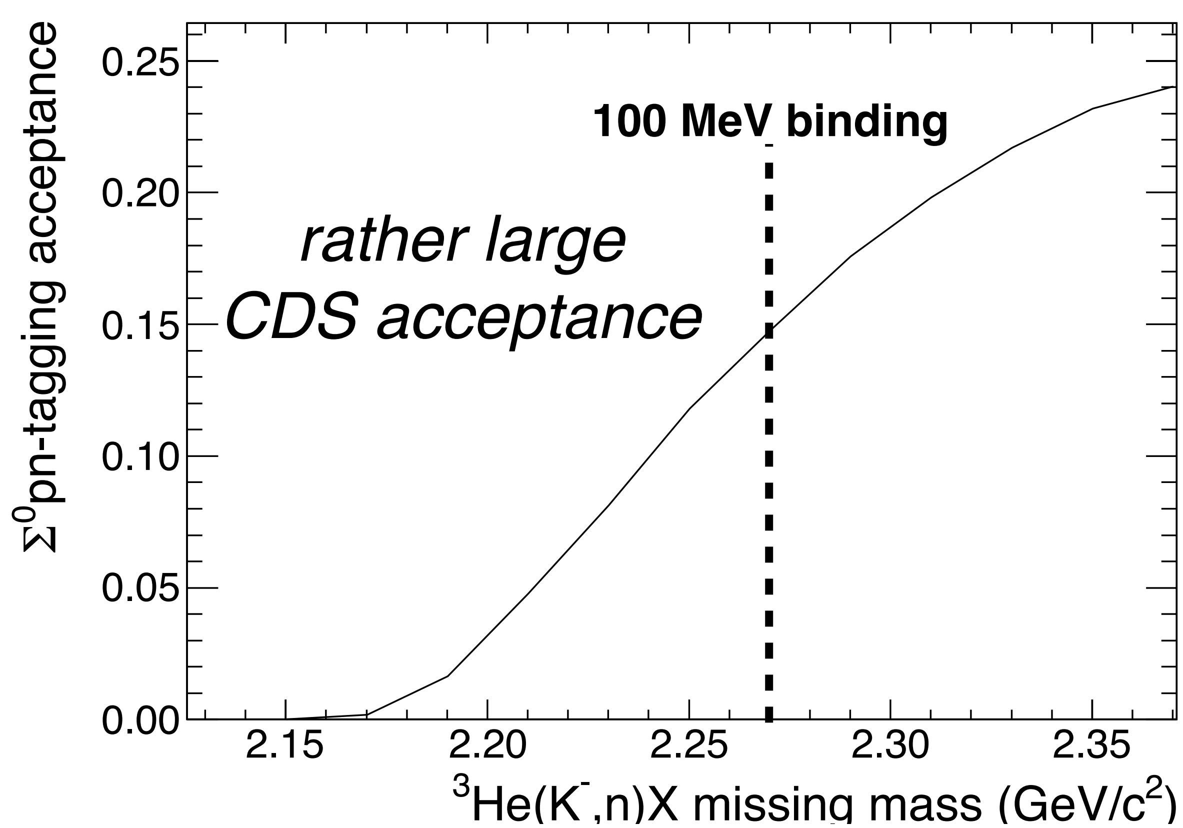
“K-pp”→Σ^0p decay

$K^- + {}^3He \rightarrow (\Sigma^0 + p) + n$

$\Sigma^0 \rightarrow \Lambda\gamma \rightarrow p + \pi$







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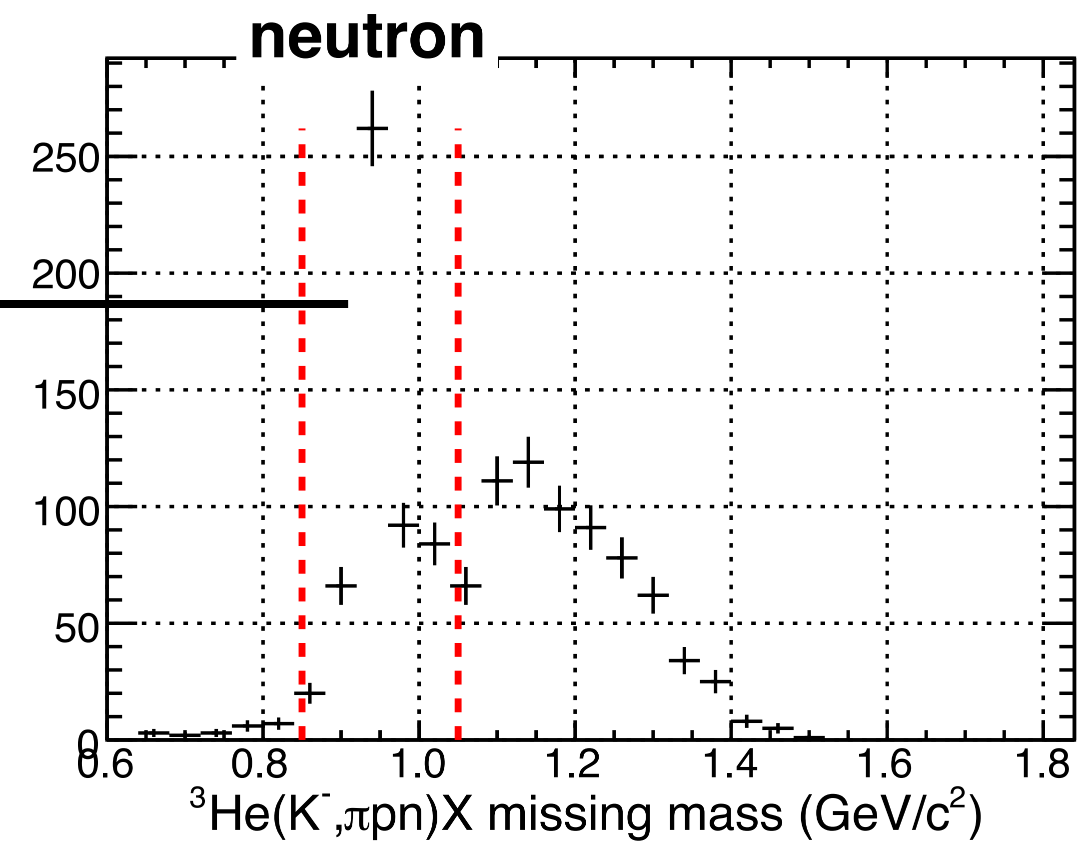
“K-pp”→$(\pi\Sigma)^0 p$ decay

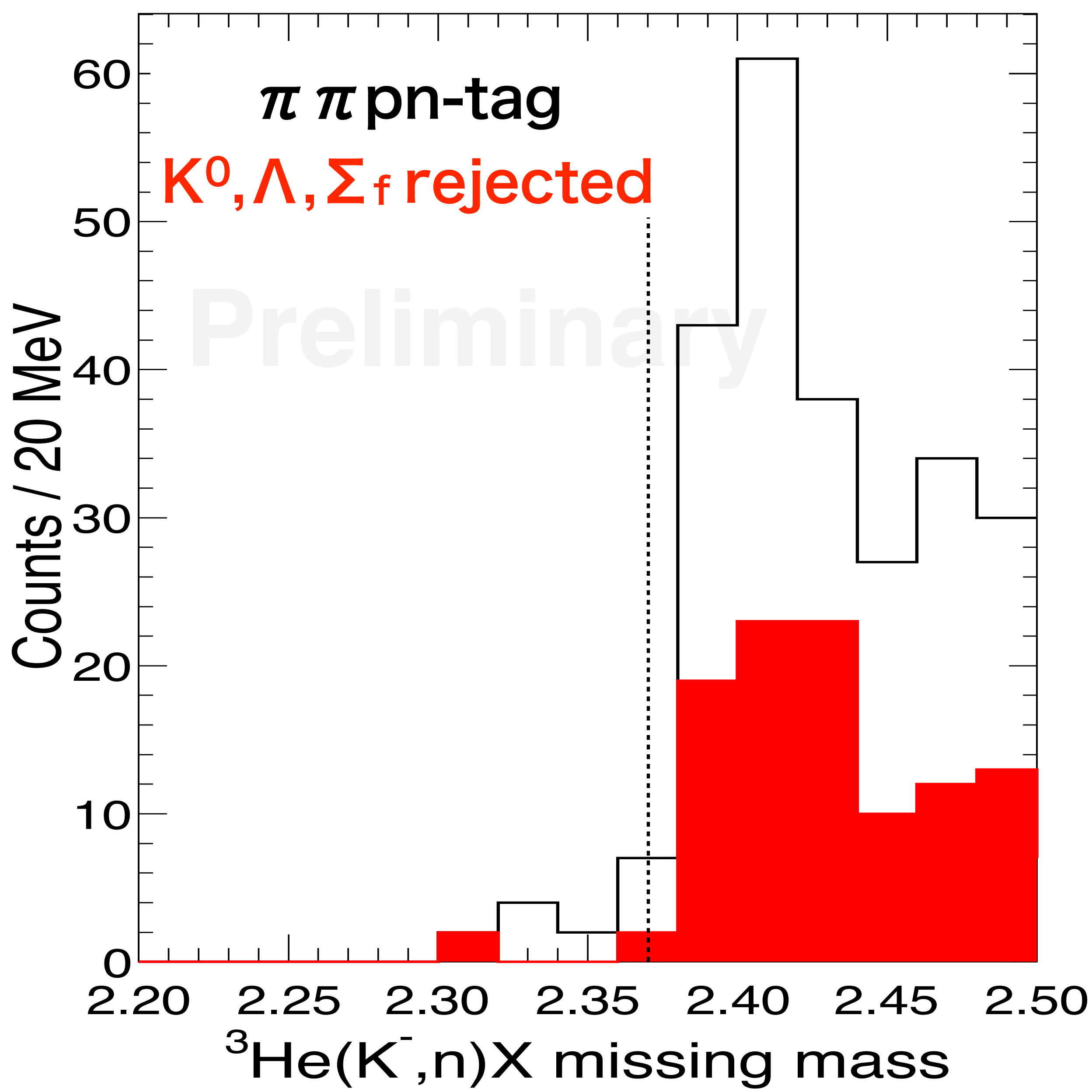
CDS

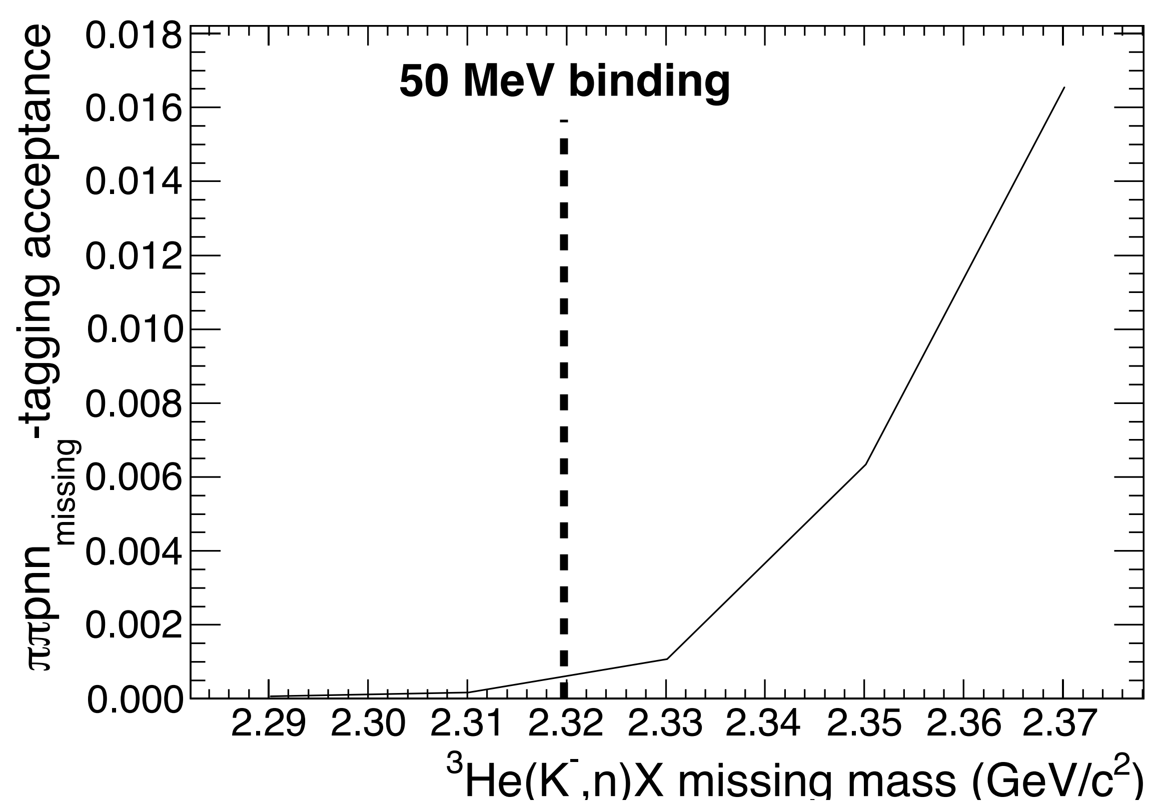
NC

$K^- + {}^3He \rightarrow (\Sigma + \pi + p) + n$

$\Sigma \rightarrow \pi + (n)$



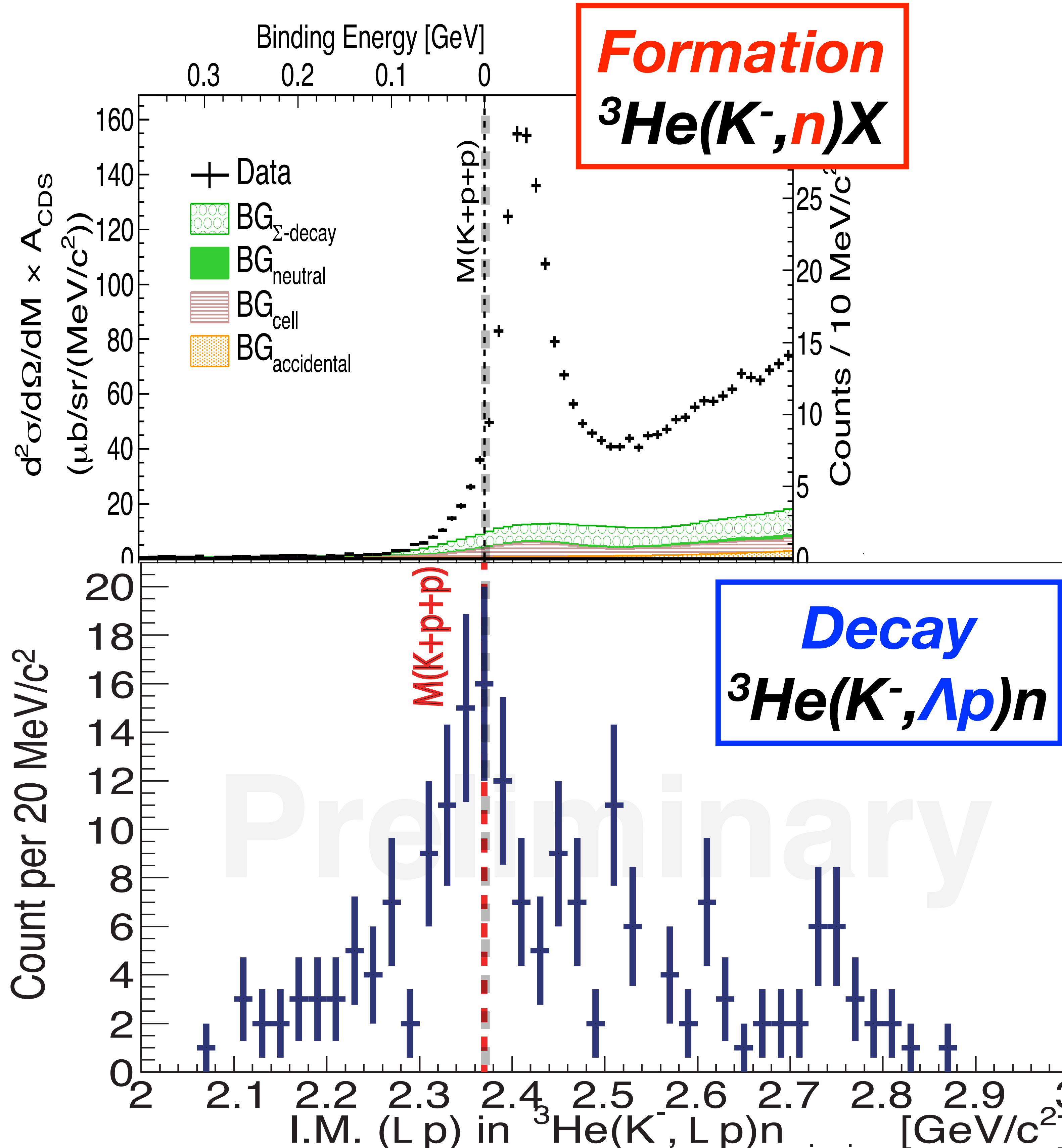


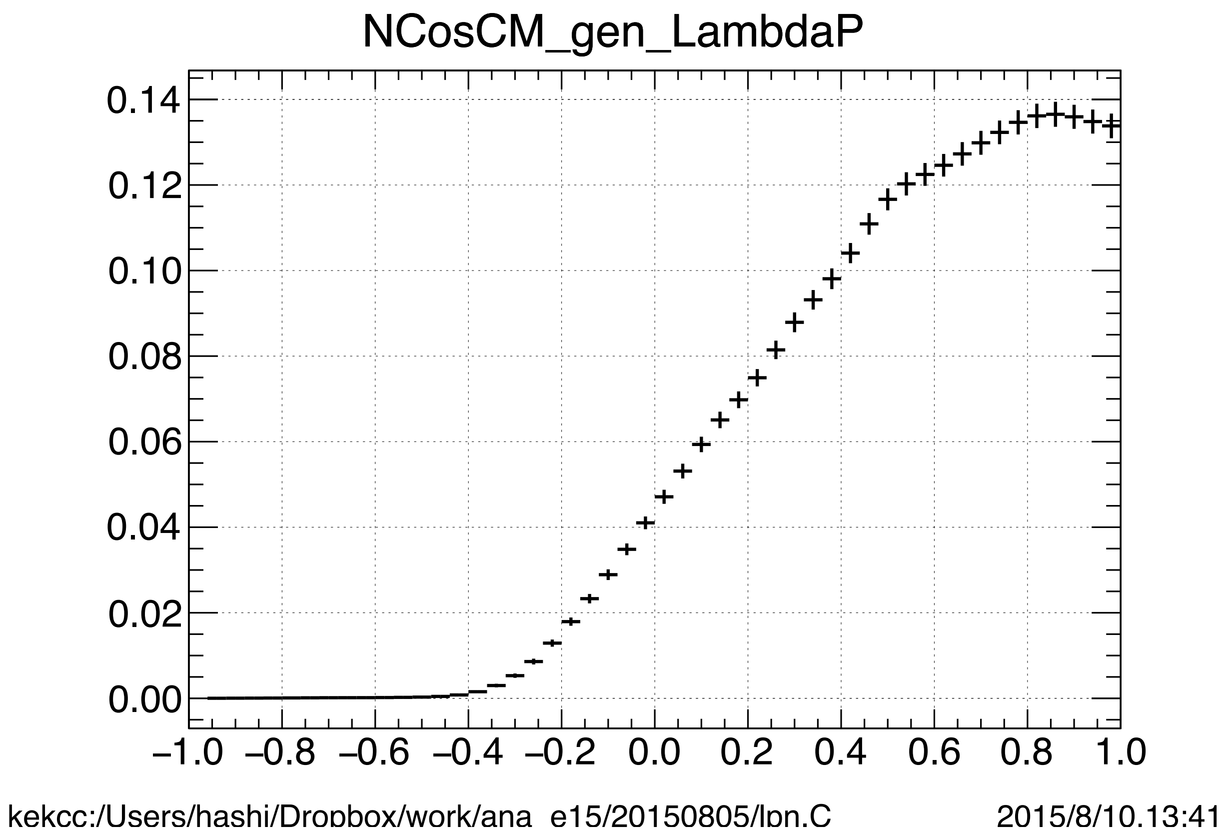


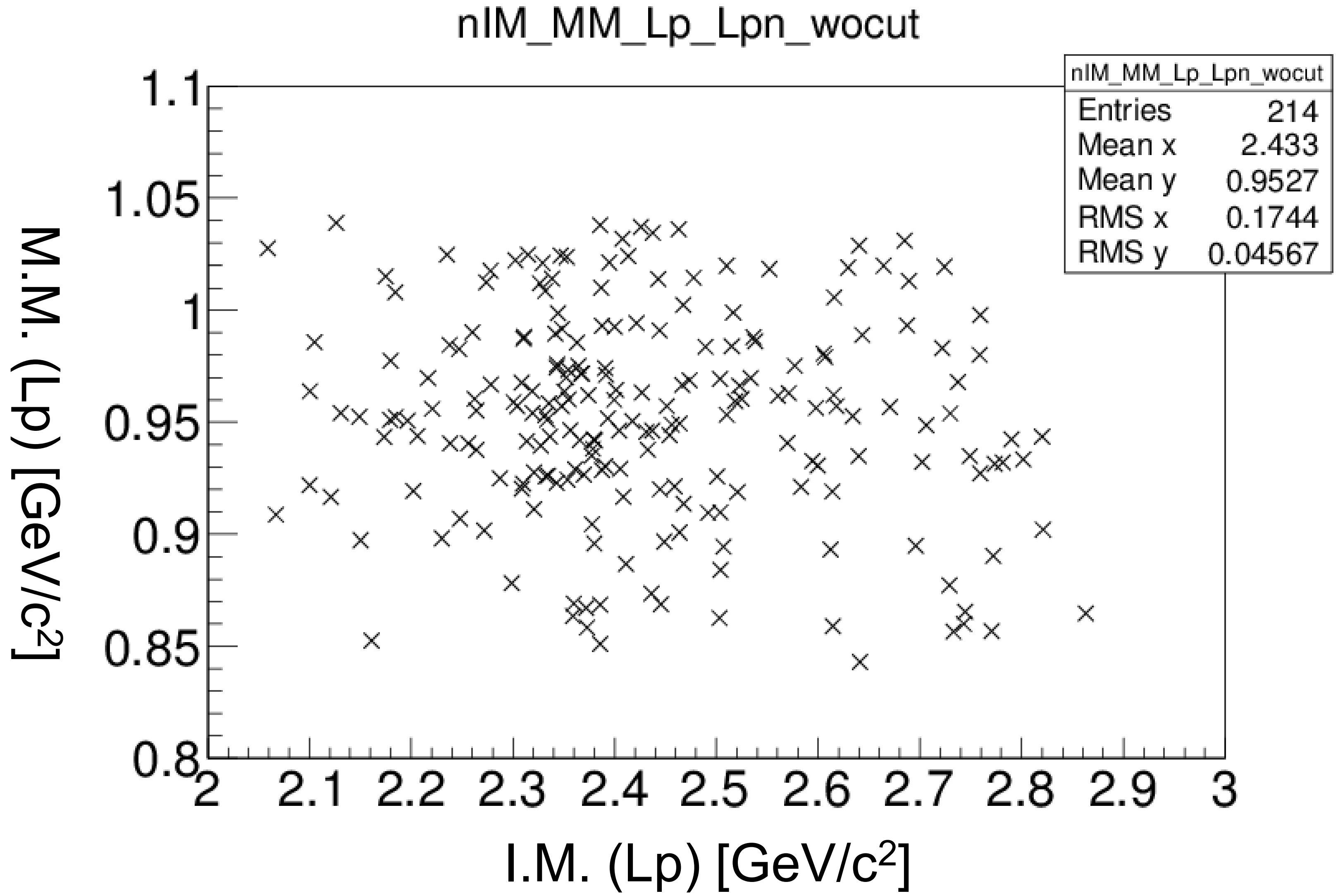
CDS acceptance limited…

Summary

- **Deeply-bound region**
  - bump-structure reported by FINUDA/DISTO/E27, has **NOT** been observed
  - reaction channel dependence?
- **Around the threshold**
  - Some structure has been seen both in formation- and decay-channel
  - Hint of S=-1 di-baryon state?
  - explained by Λ(1405)?
- **x10 statistics data coming soon !**
  - exclusive analysis to reveal the origin of the sub-threshold structure

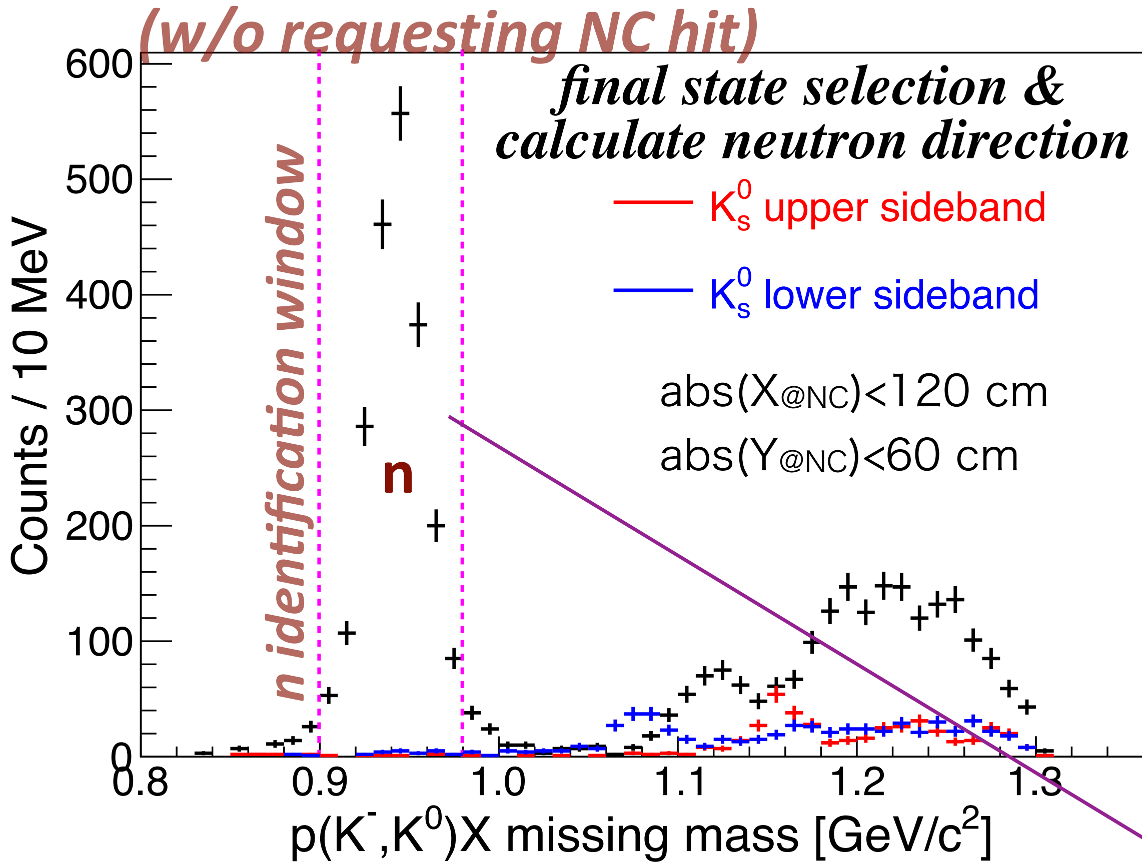


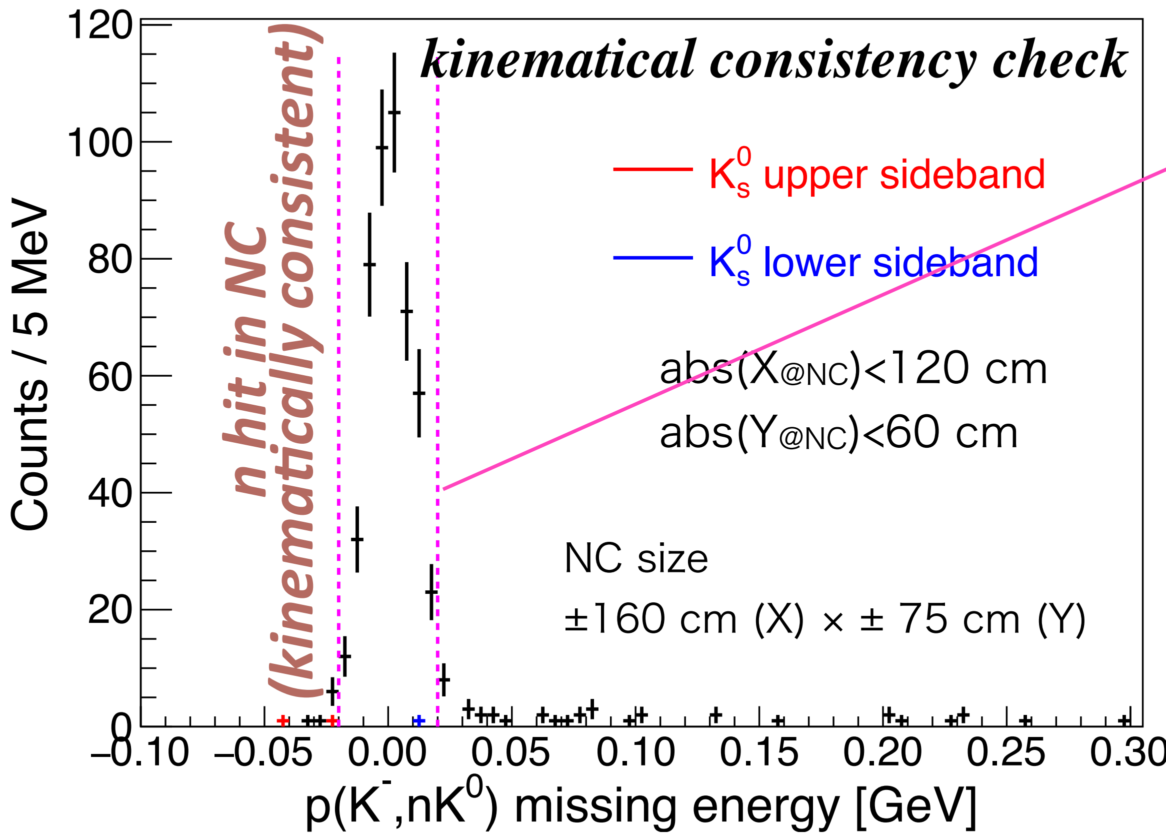

NCosCM_gen_LambdaP
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
–1.0 –0.8 –0.6 –0.4 –0.2 0.0 0.2 0.4 0.6 0.8 1.0
kekcc:/Users/hashi/Dropbox/work/ana_e15/20150805/lpn.C
2015/8/10.13:41



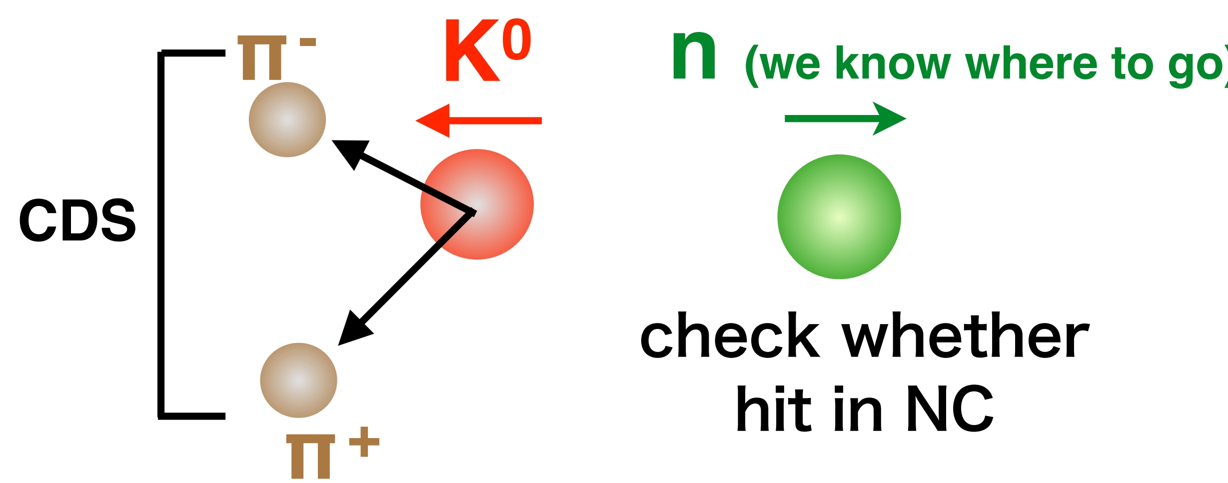
nIM_MM_Lp_Lpn_wocut
nIM_MM_Lp_Lpn_wocut
Entries 214
Mean x 2.433
Mean y 0.9527
RMS x 0.1744
RMS y 0.04567
M.M. (Lp) [GeV/c2]
I.M. (Lp) [GeV/c2]
1.1
1.05
1
0.95
0.9
0.85
0.8
2
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3

NC efficiency evaluation





"neutron direction" can be calculated by incoming K^- & K^0 decay



$$\frac{N^{K^0_s}_{neutron} - N^{sideband}_{neutron}}{\left(N^{K^0_s}_{missN} - N^{sideband}_{missN}\right) \times R_{onNC} \times \epsilon^{BVC\&CVC}_{overveto}}$$

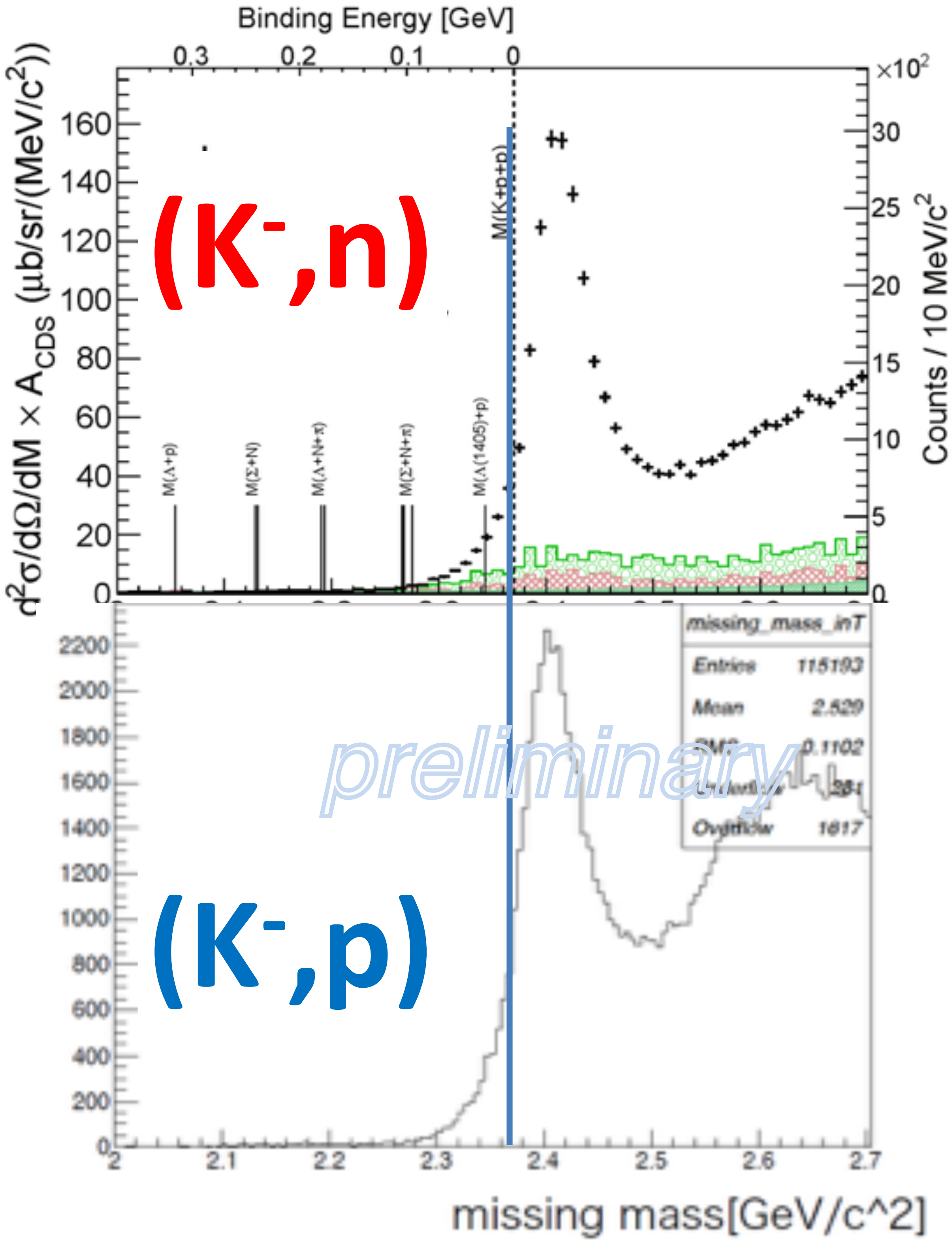
R_{onNC}: estimated by MC
~ 0.9 @ H_2
~ 0.6 @ ^3He

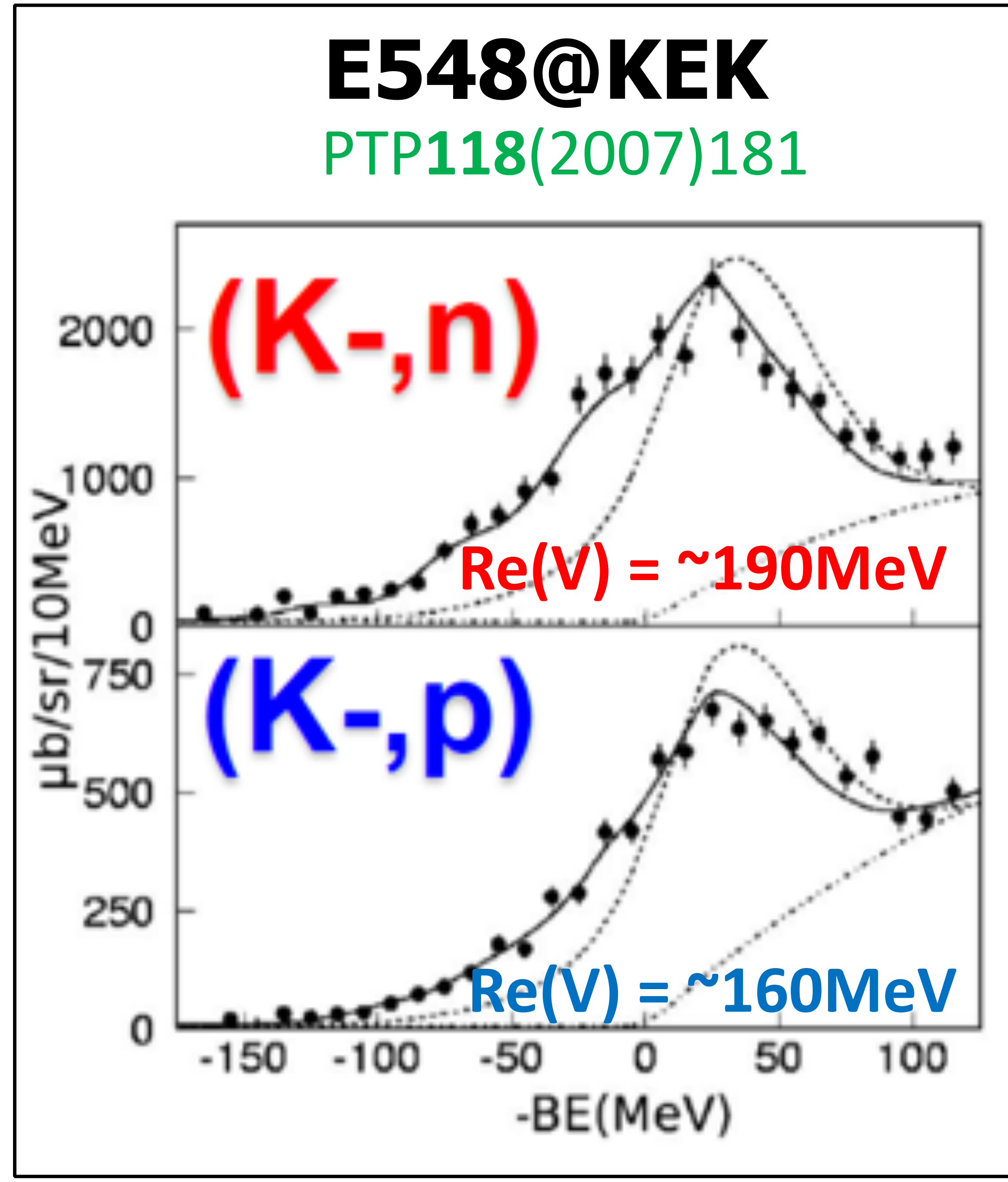
$\epsilon^{BVC\&CVC}_{overveto}$: ~ 0.9

NC detection efficiency can be evaluated at the precision of ~1%

c.f.) 23 ± 4% @ ^3He target

Semi-Inclusive ^{3}He(K^{-},n/p)X M.M. spectrum





- ^{3}He(K^{-},p) spectrum looks similar to (K^{-},n)