"Excited Hyperons in QCD Thermodynamics at Freeze-Out"
Jefferson Lab - 2016/11/16-11/17

Recent results of the experiment to search for $\bar{K}NN$ bound state at J-PARC

Hiroaki Ohnishi
RIKEN/RCNP Osaka Univ.
for
the E15 collaboration

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Recent results of the experiment to search for $\bar{K}NN$ bound state at J-PARC

Di-baryon with s=-1

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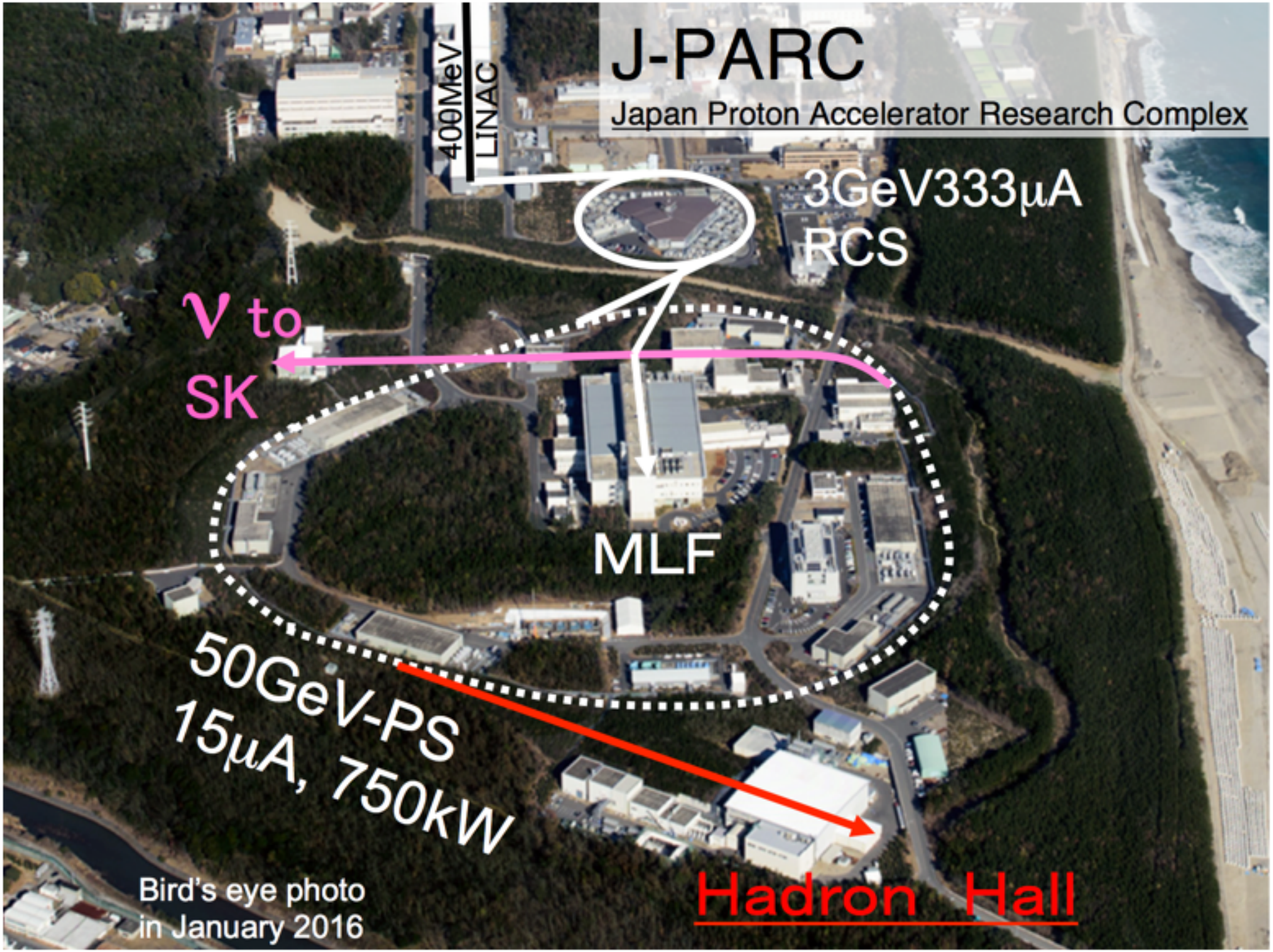
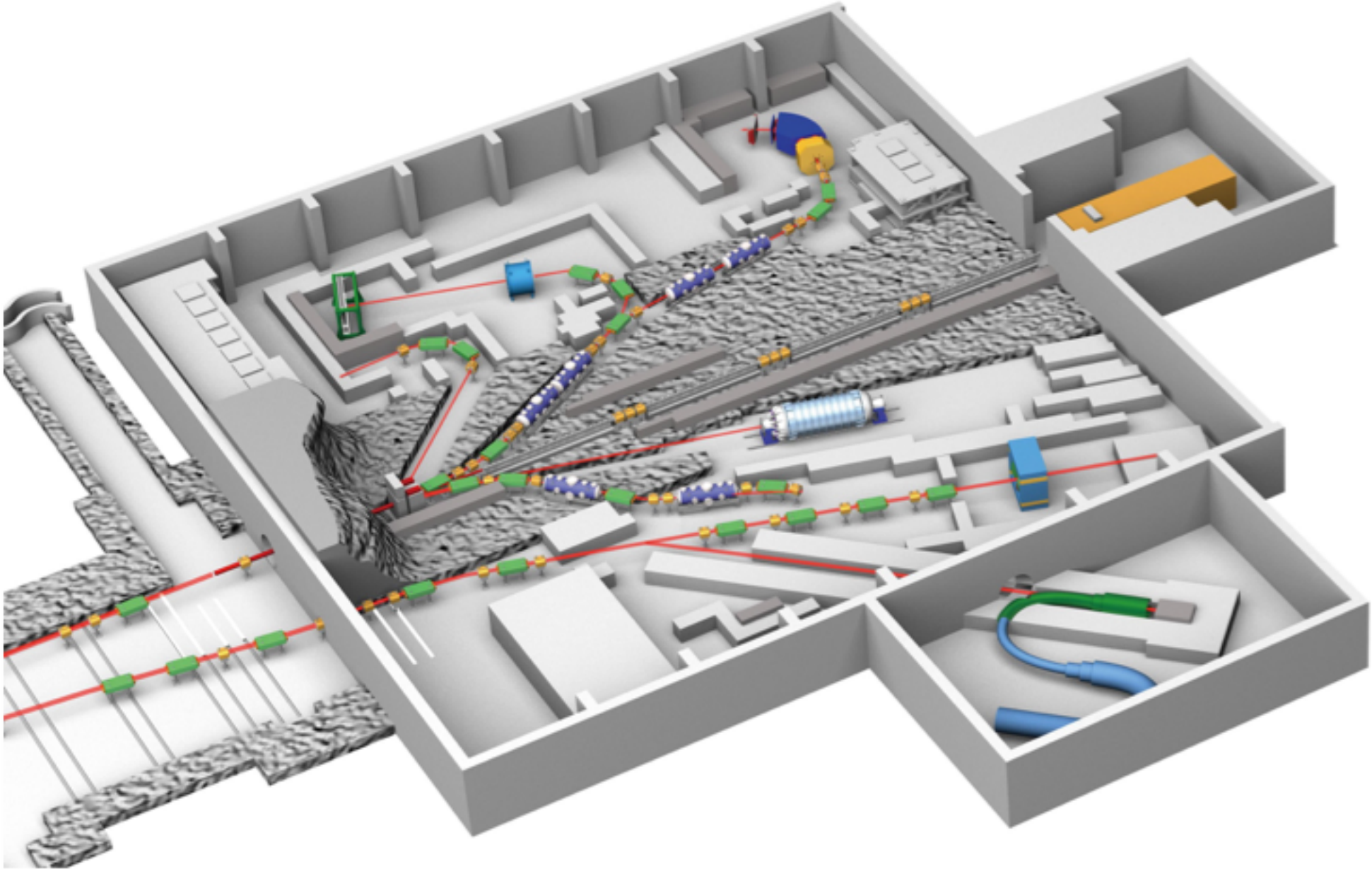
J-PARC

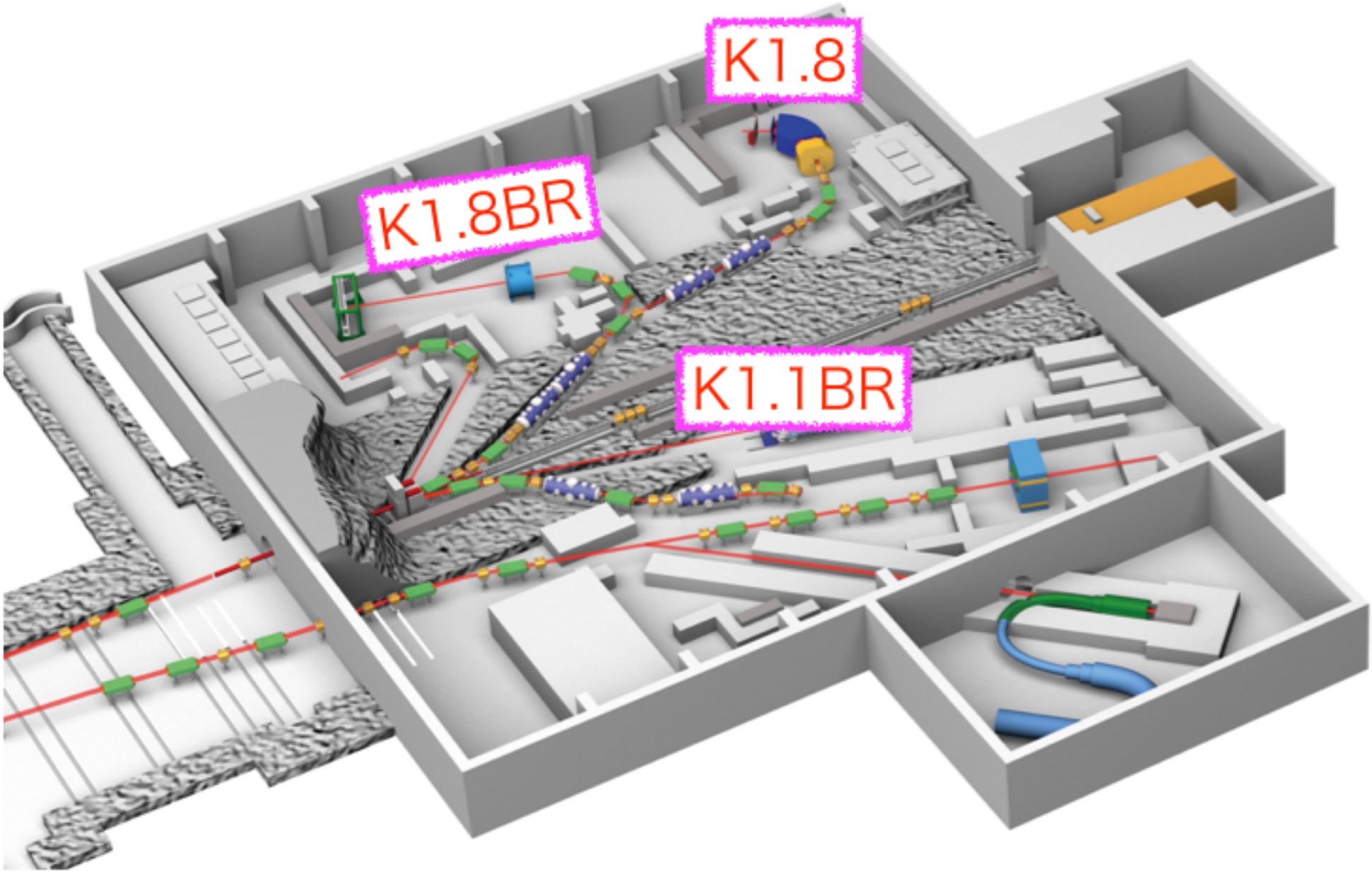
Japan Proton Accelerator Research Complex


J-PARC
Japan Proton Accelerator Research Complex
400MeV-LINAC
3GeV333μA
RCS
ν to
SK
MLF
50GeV-PS
15μA, 750kW
Hadron Hall
Bird's eye photo
in January 2016

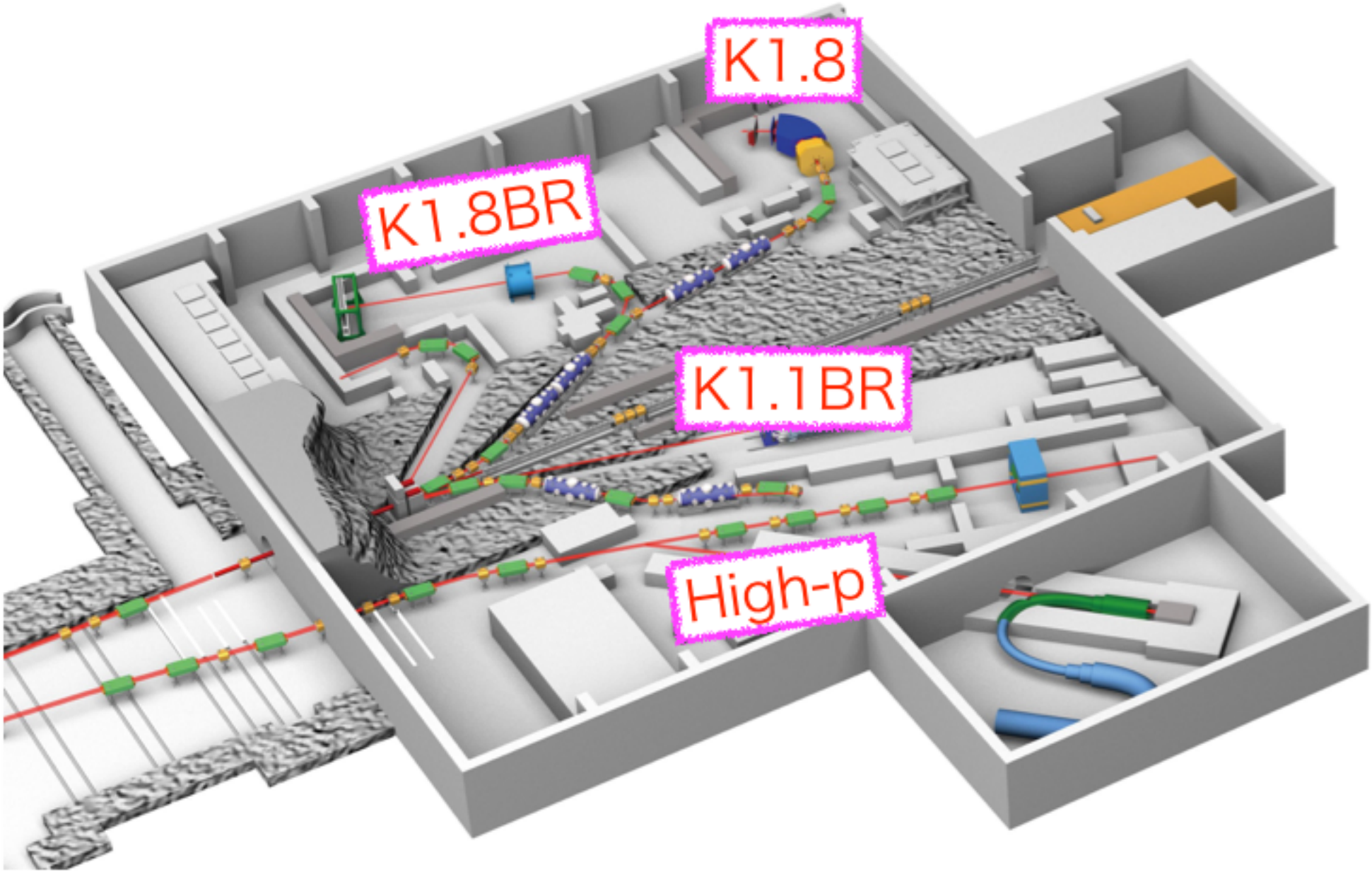
J-PARC hadron hall



J-PARC hadron hall



J-PARC hadron hall



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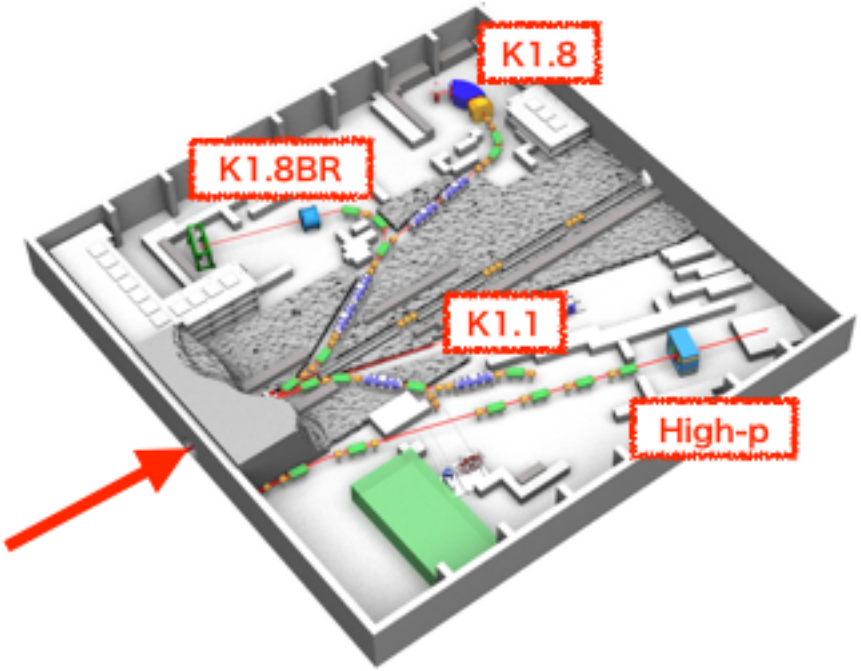

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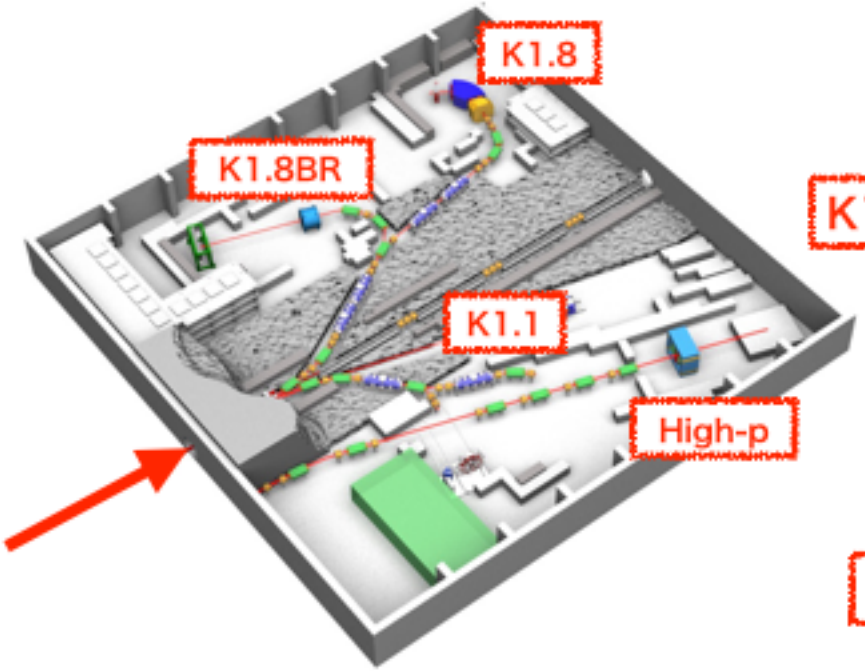

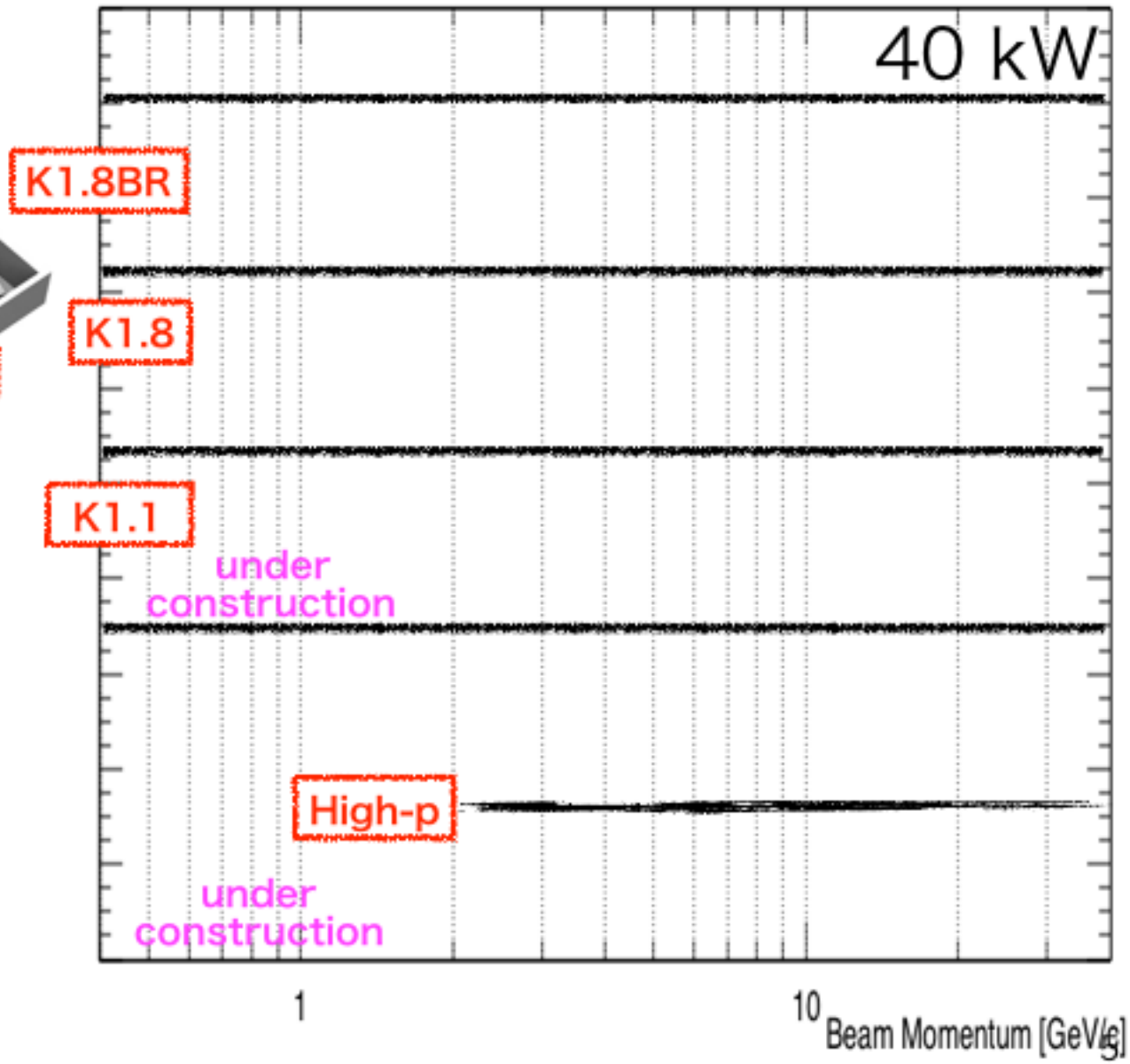

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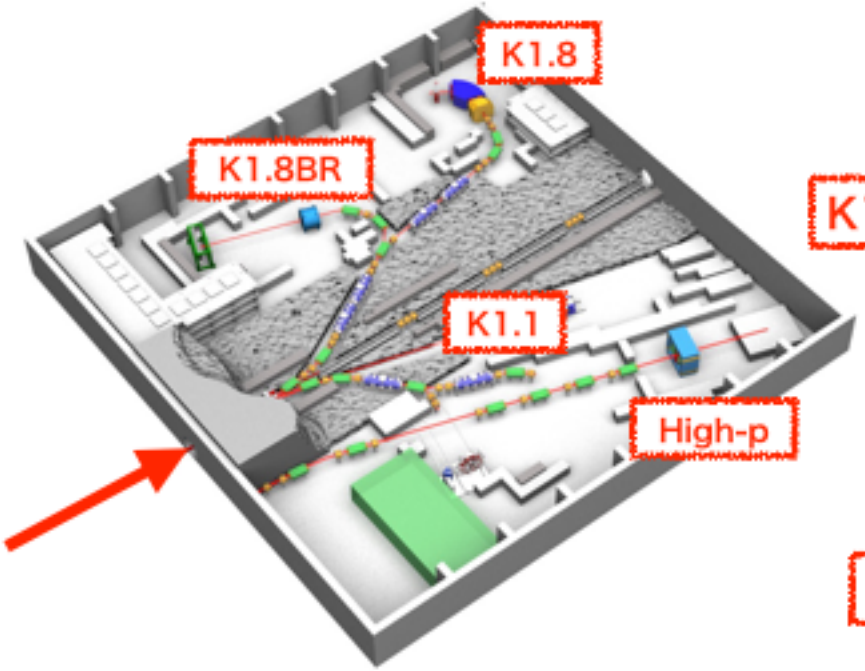

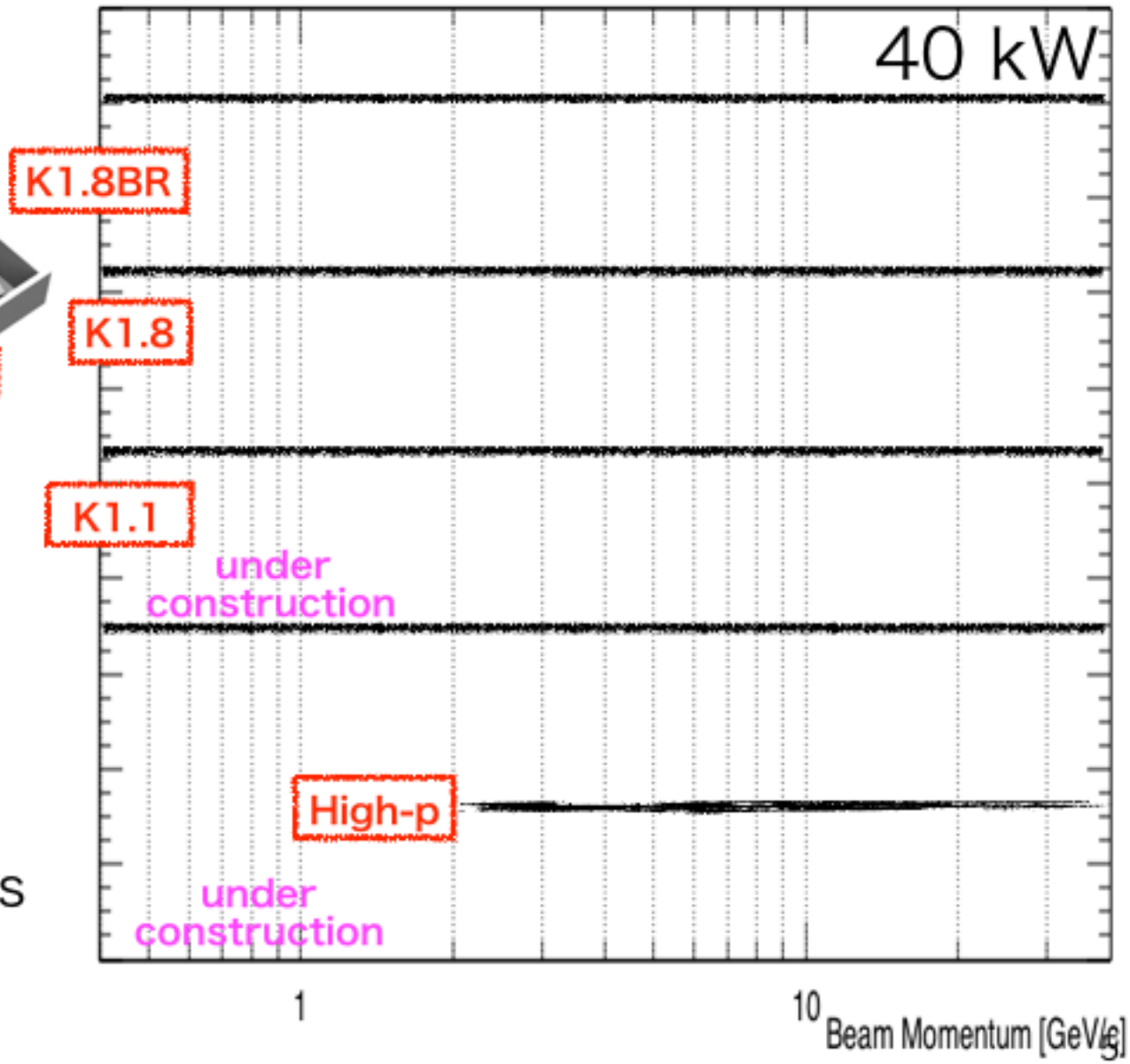

Two beam lines are under operation

K1.1 & High-p beam lines are under construction

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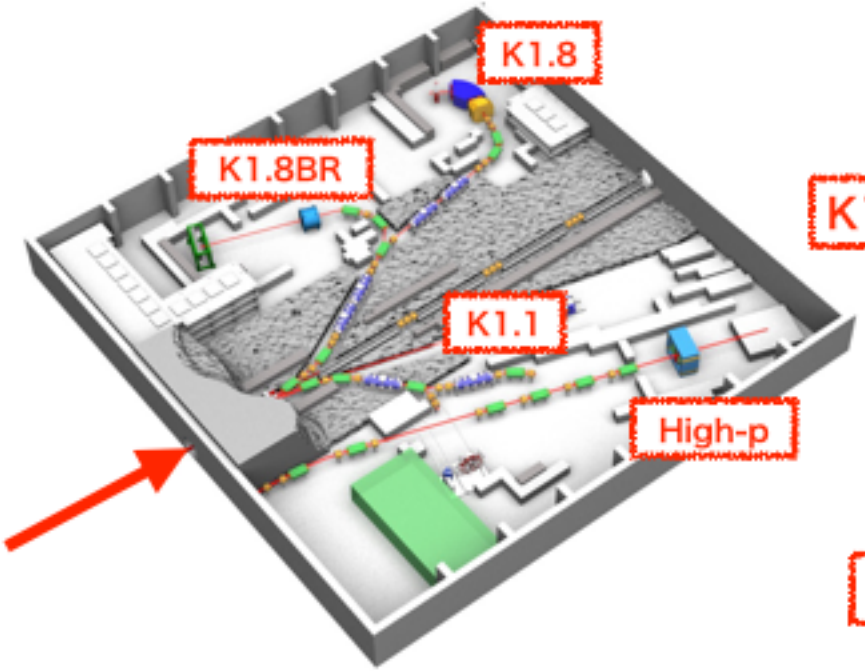

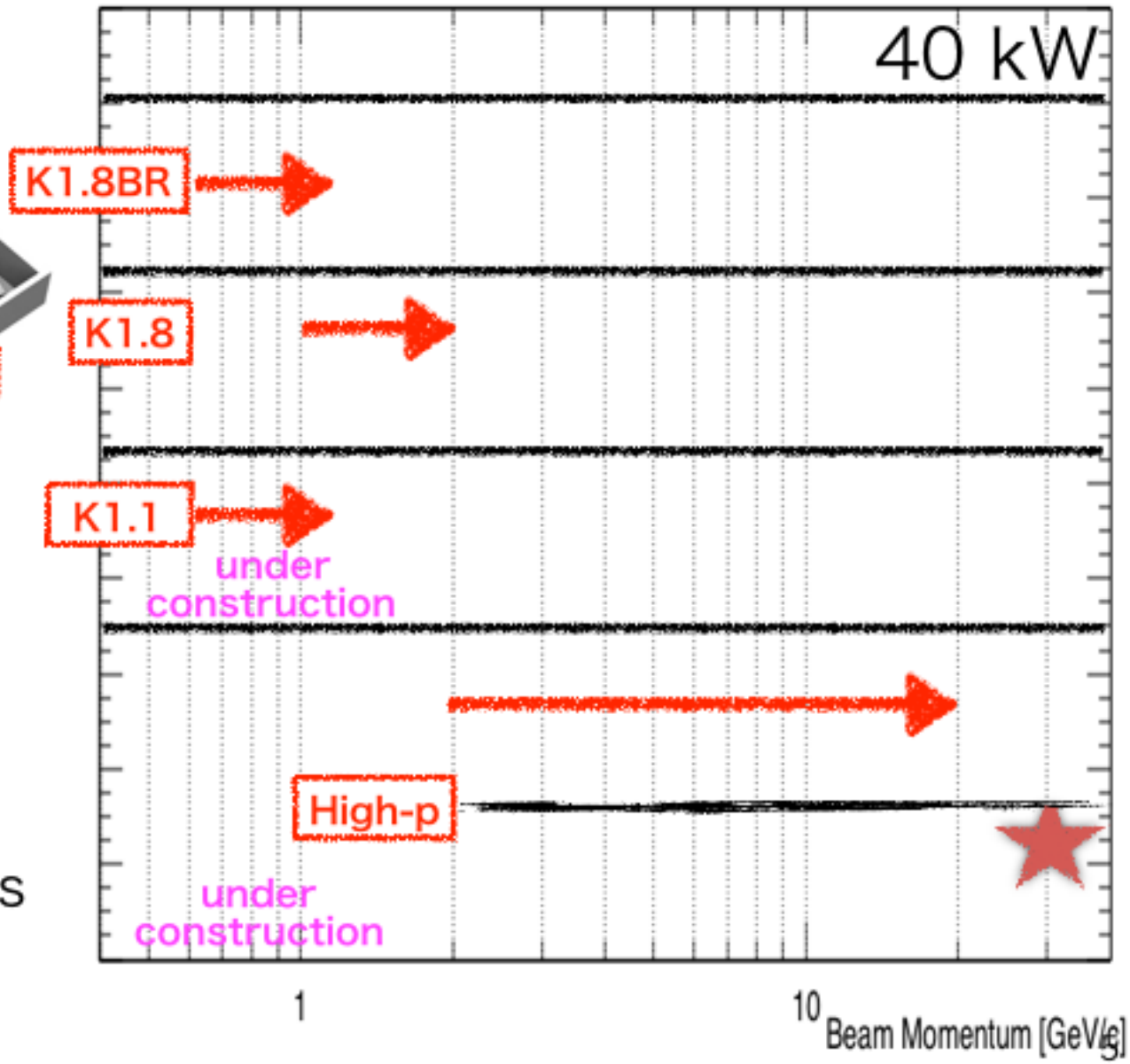

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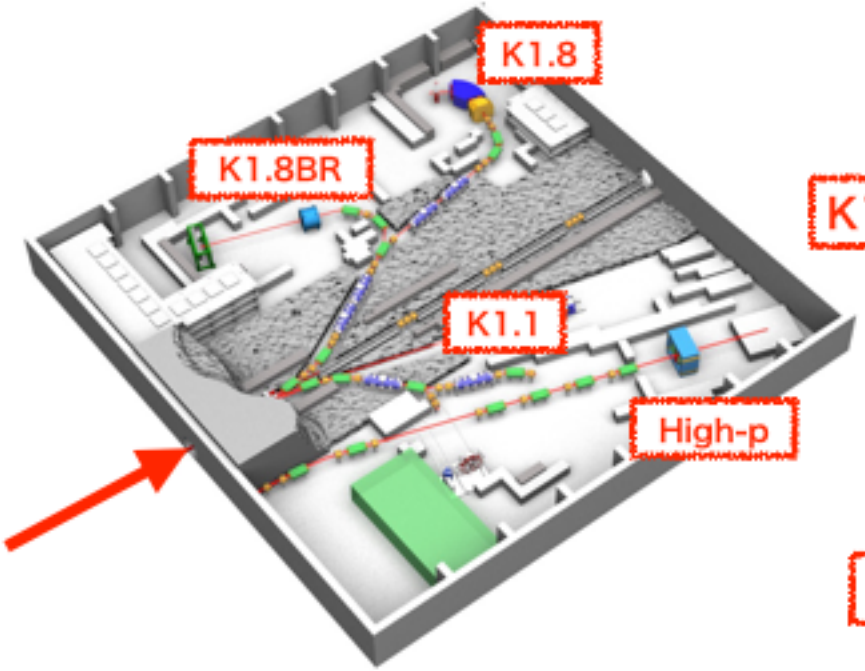

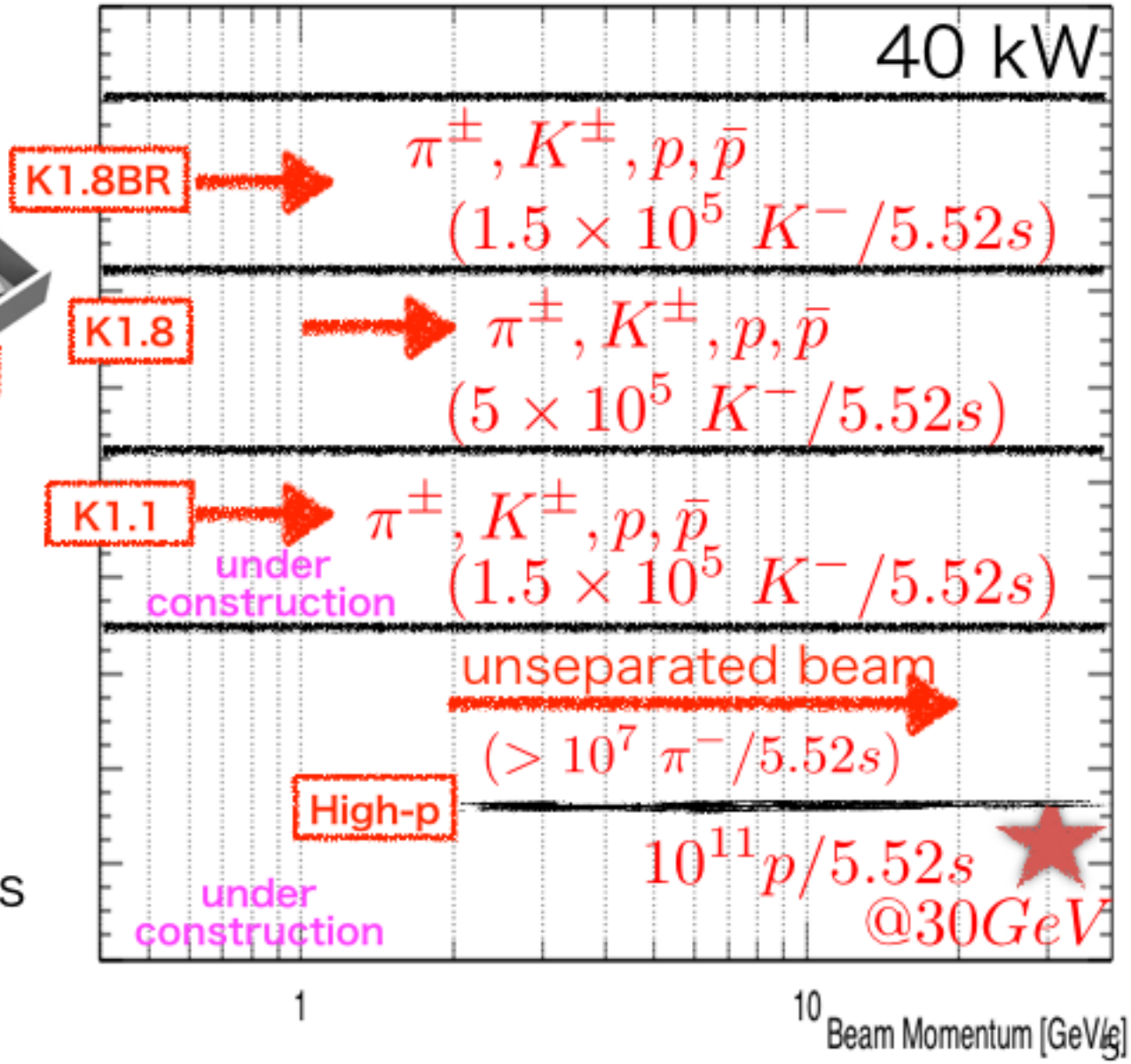

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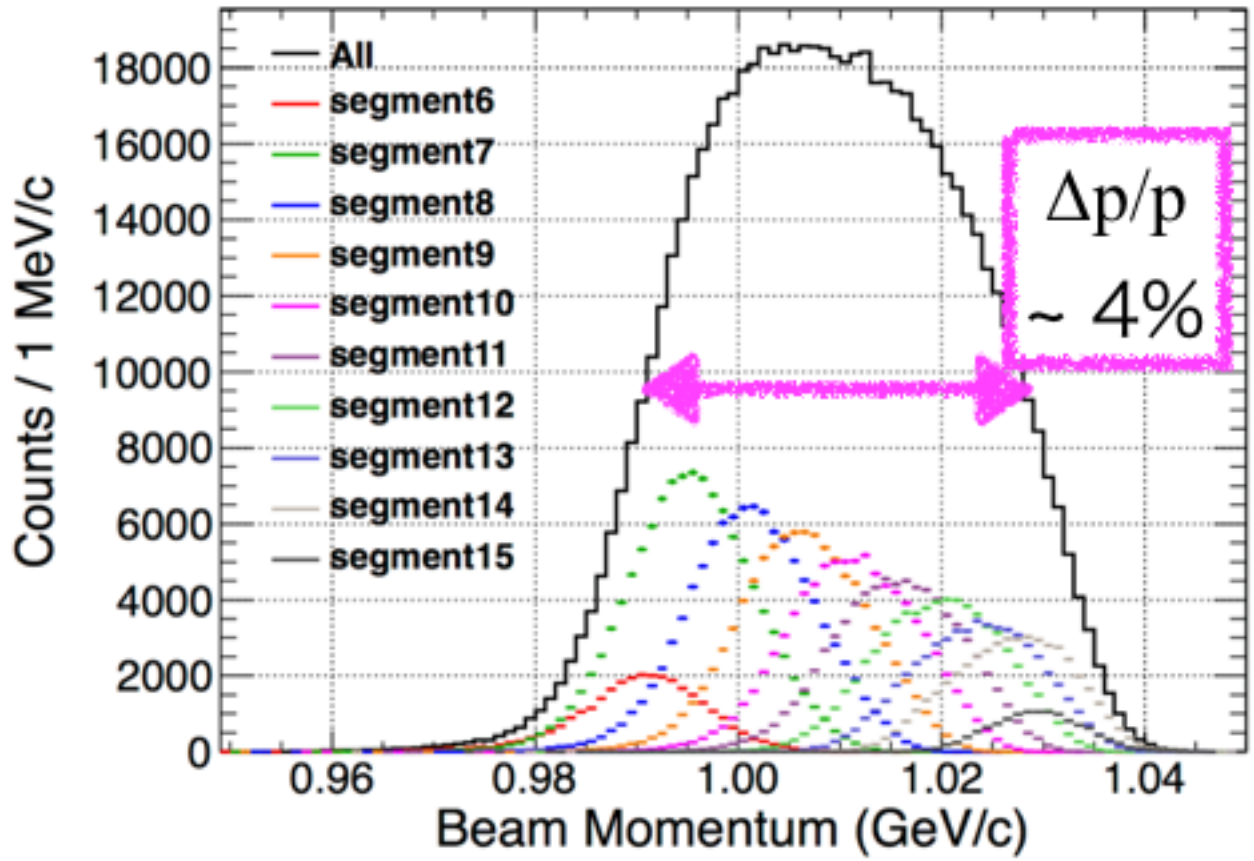
For example :@K1.8BR

spectrometer setting : 1GeV/c



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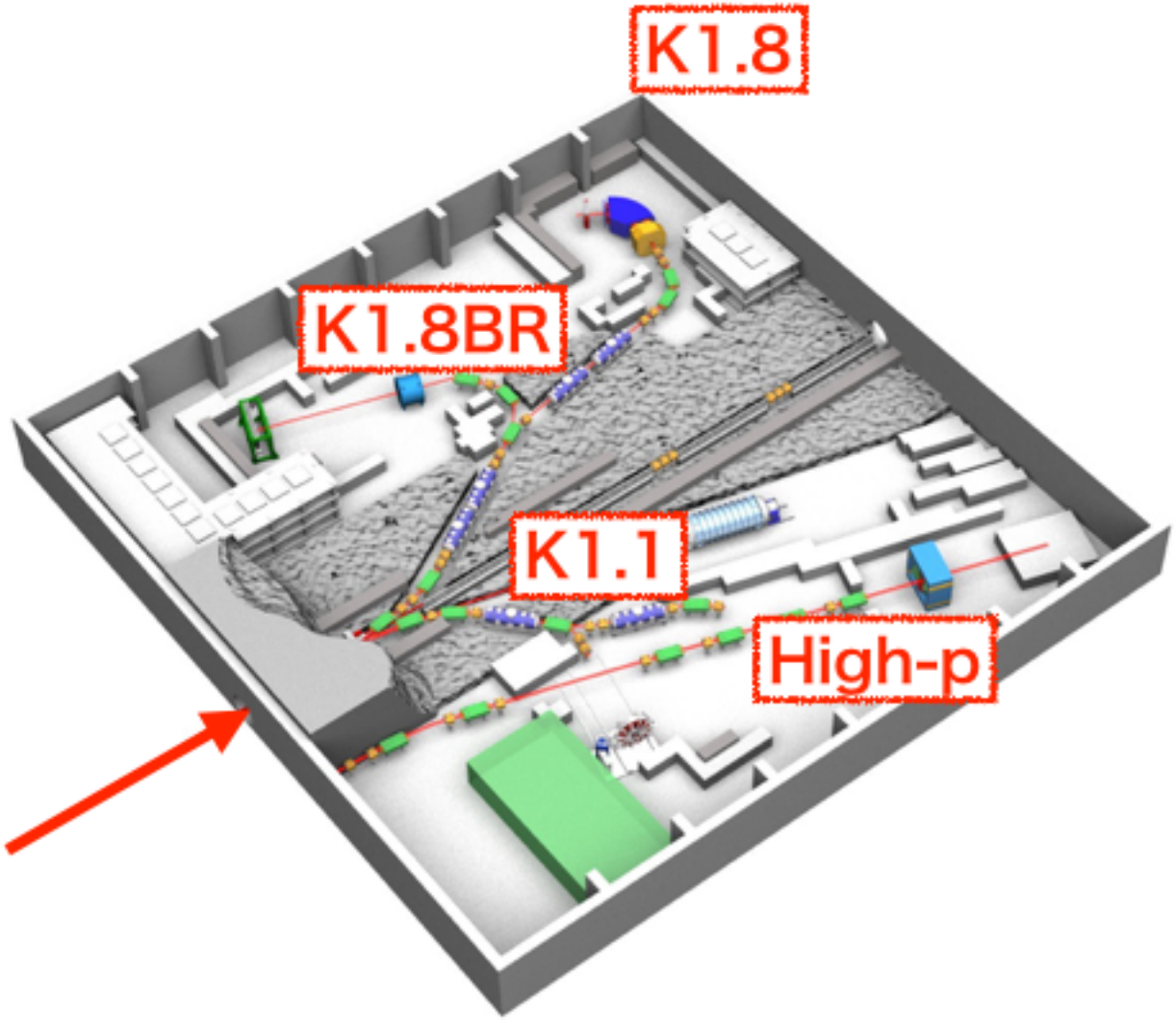

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E15/E31

Kaonic-nucleus

Λ(1405)

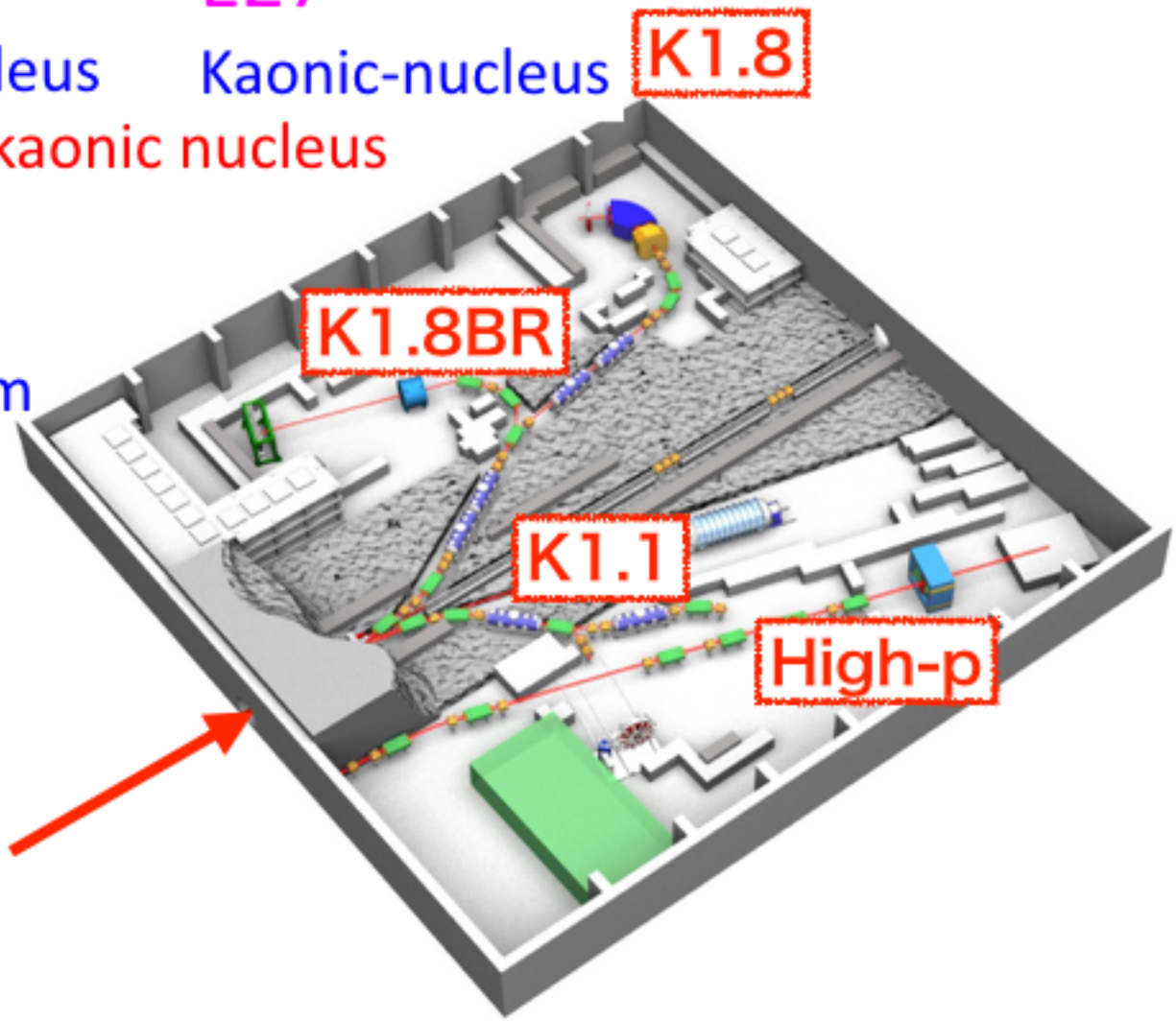
E27

Kaonic-nucleus

kaonic nucleus

E17/E57

Kaonic-atom



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E19

Search for Pentaquark

s=+1

Exotic baryon

E17/E57

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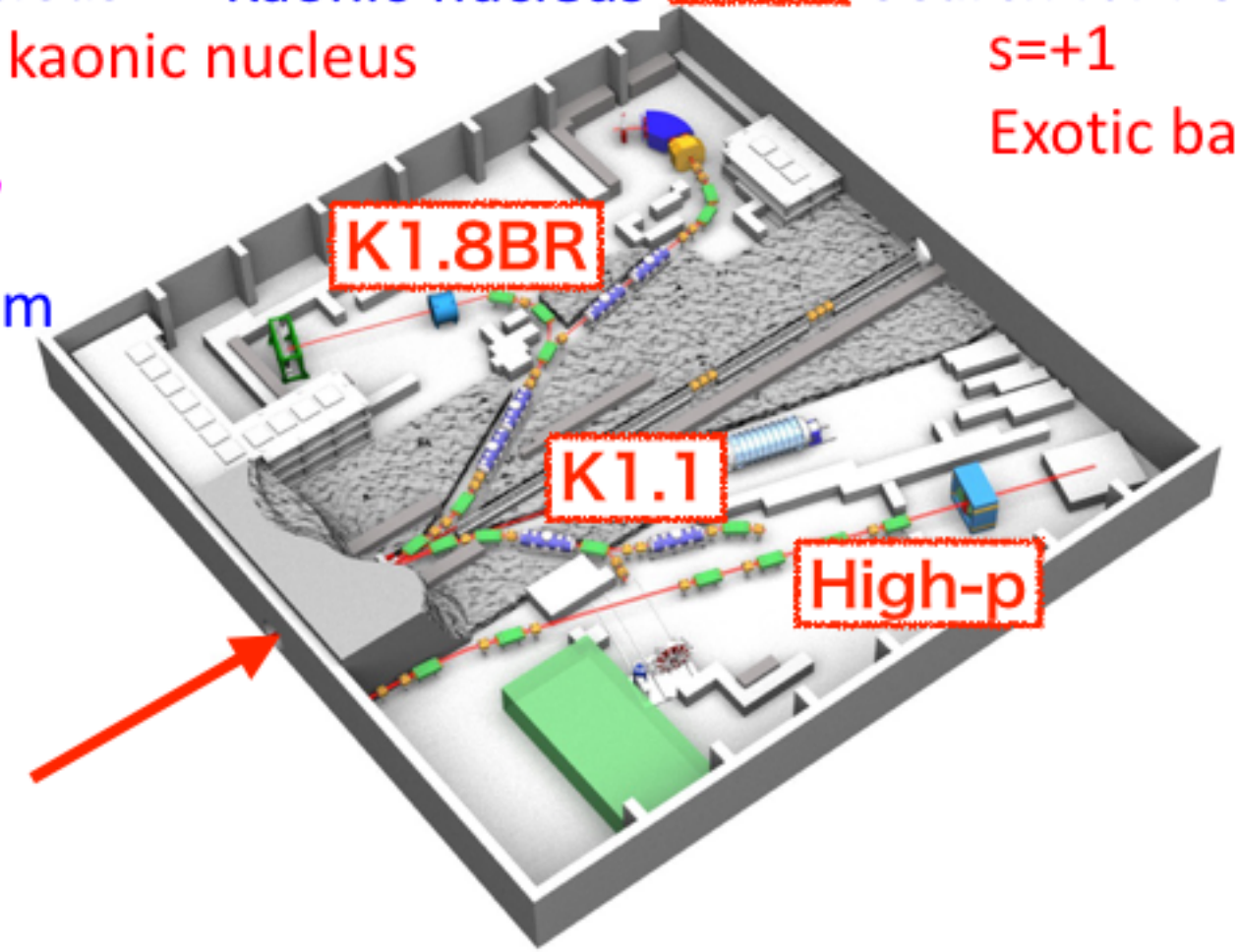

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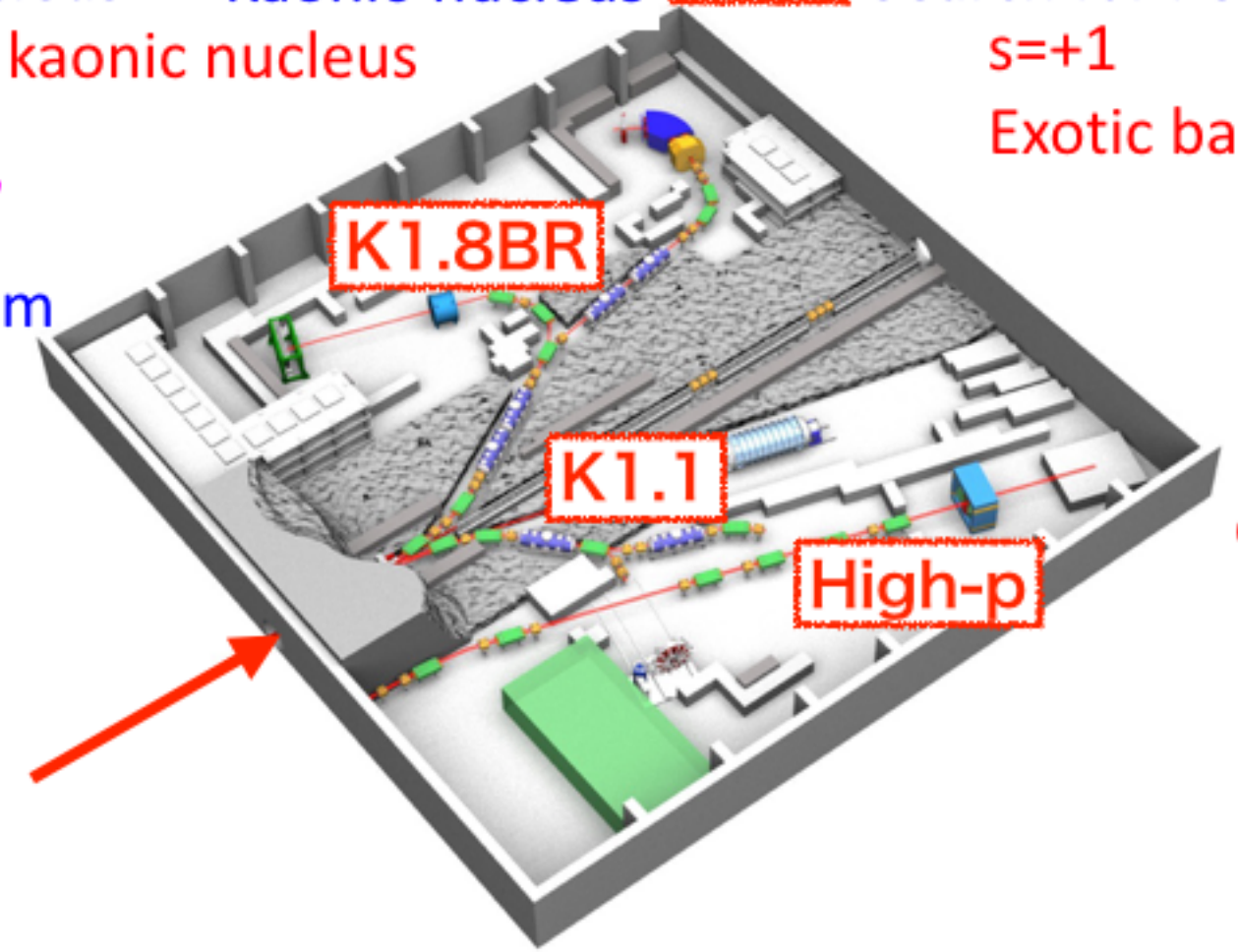

E16/E29

Φ in nucleus

chiral symm.

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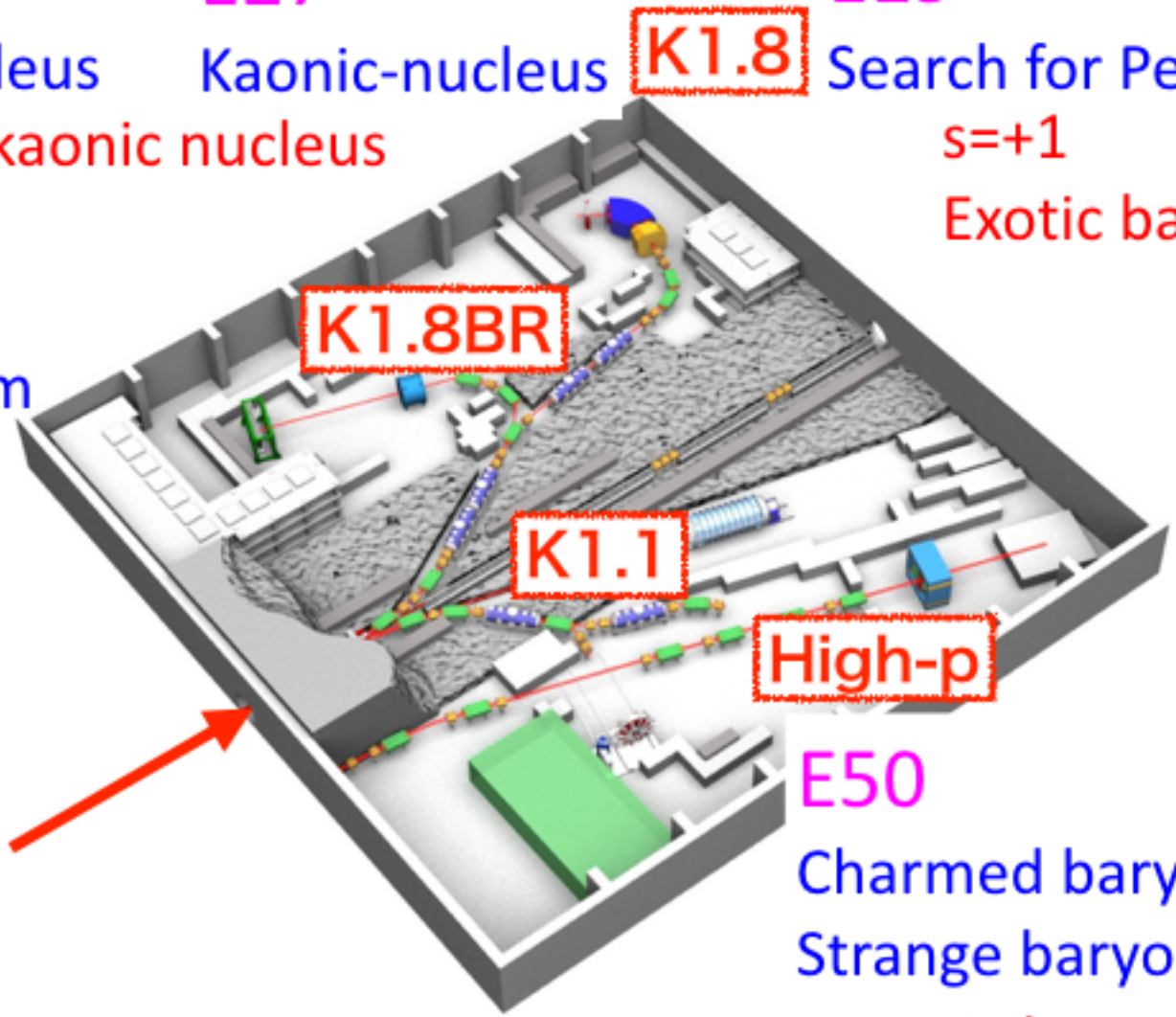


E16/E29
Φ in nucleus
chiral symm.

E50
Charmed baryon
Strange baryon
exotic baryons

Goal for hadron physics

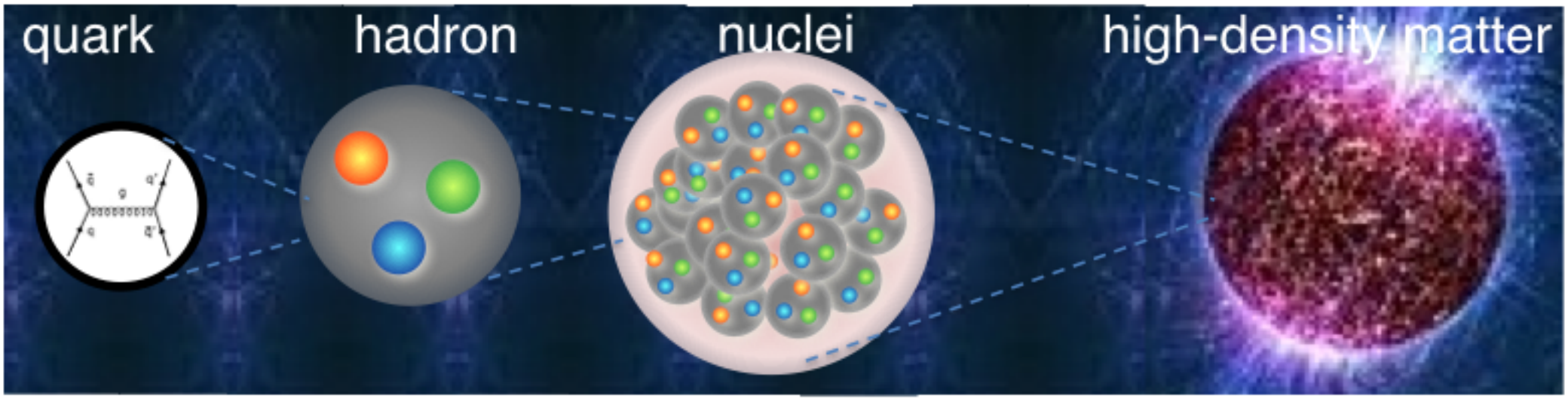
QCD Lagrangian is known as

$$\mathcal{L}_{QCD} = \overline{\psi_i}(i(\gamma_\mu D_\mu)_{ij} - m\delta_{ij})\psi_i - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

Question is How hadrons are created from QCD?

How nucleus are created?

What is happened inside neutron star
(hadron in high density matter)



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Question is How hadrons are created from QCD?

and

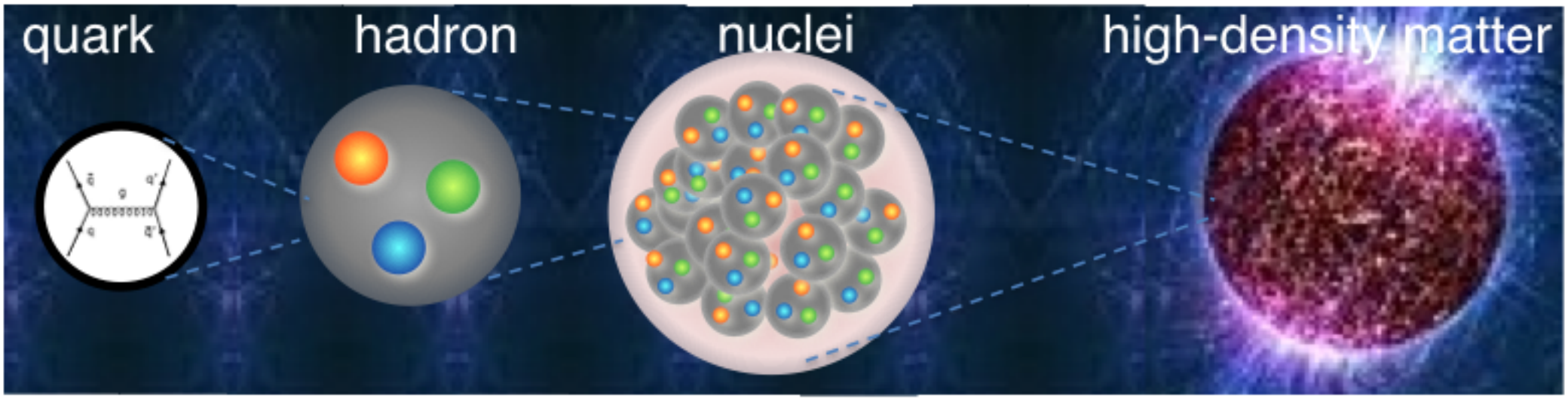
How nucleus are created?

relation btw

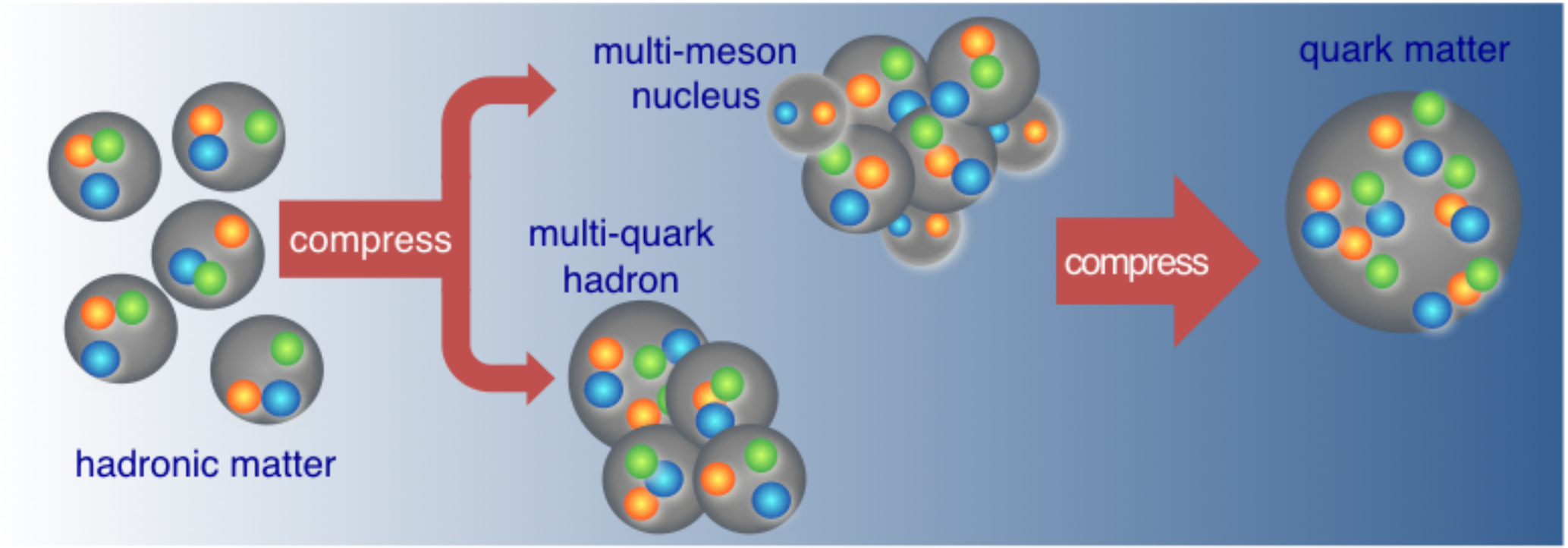
What is happened inside neutron star

each other

(hadron in high density matter)



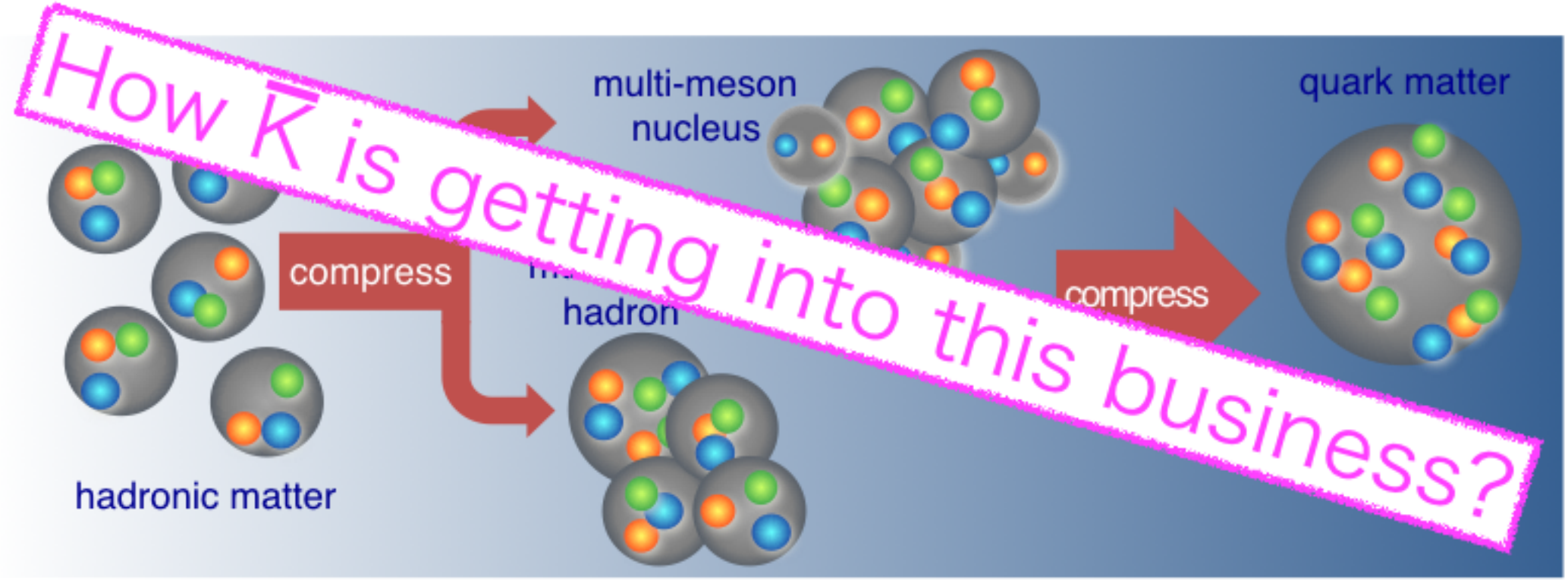
Transition from Low density to high density



meson in nucleus might have vary important role on the way to high density nuclear matter

Transition from

Low density to high density



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Interaction between $\overline{K}$ and nucleon

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- $\bar{K}N$ interaction

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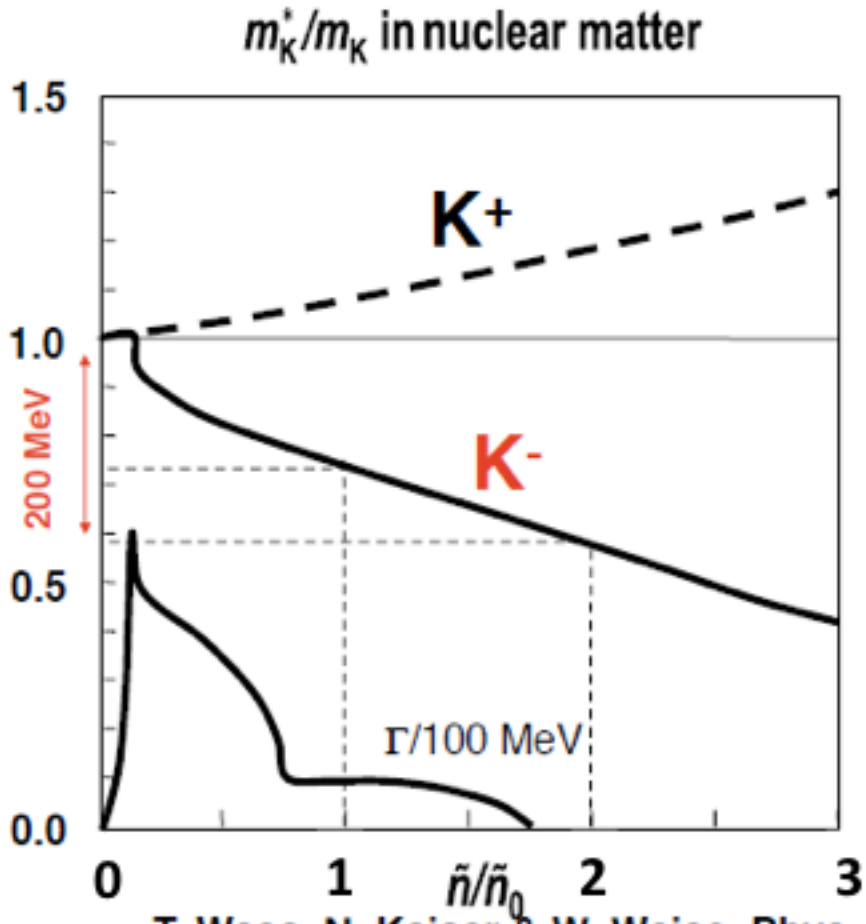


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

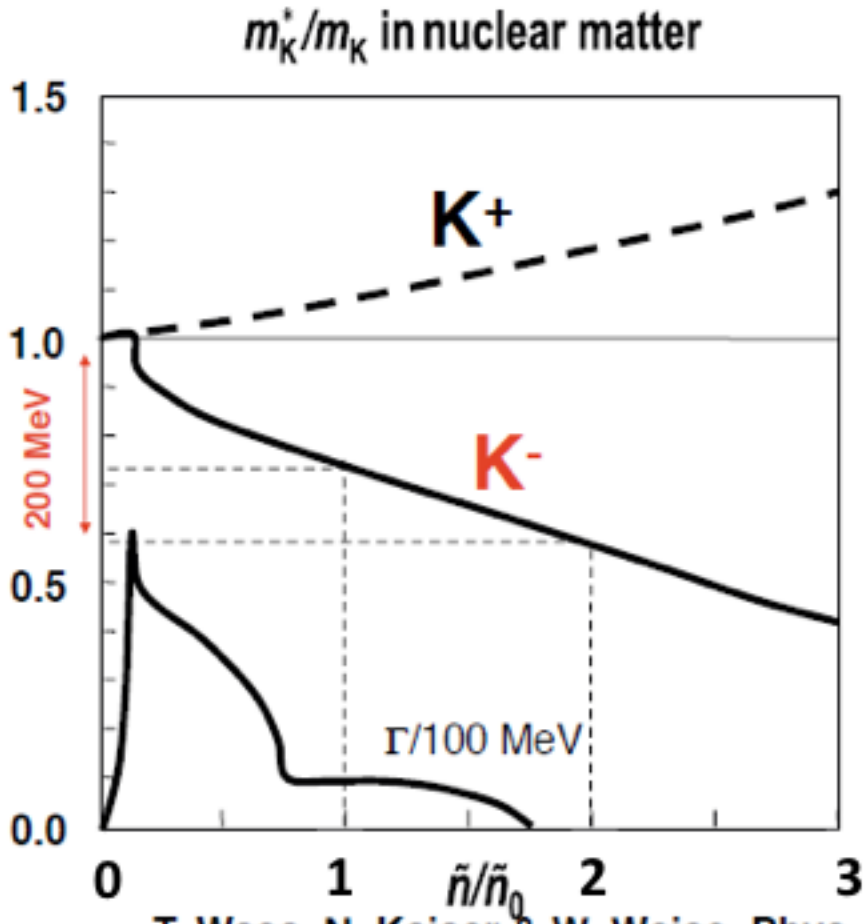
Interaction between $\bar{K}$ and nucleon

- $\bar{K}N$ interaction
  - → strongly attractive
- $\Lambda(1405)$: s=-1, I=0, $J^P=1/2^-$
  - → Mass is just above $\bar{K}N$ threshold

$m_{\bar{K}N}$ ····· 1432 MeV

Only 27 MeV

$m_{\Lambda(1405)}$ ····· 1405.1 MeV



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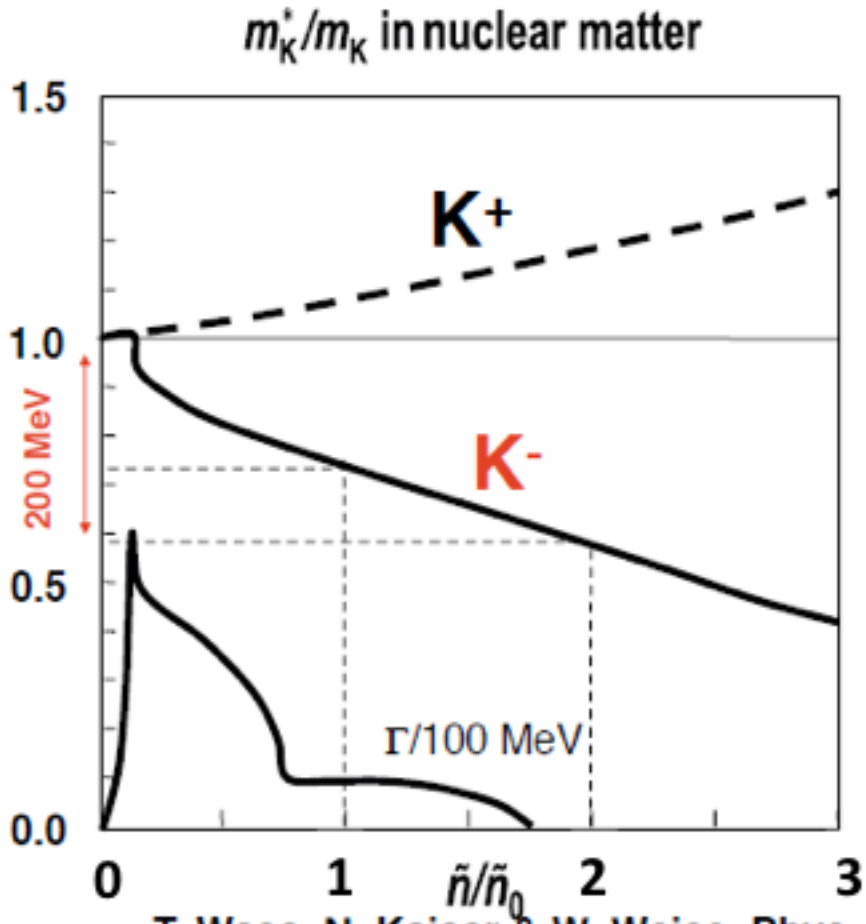

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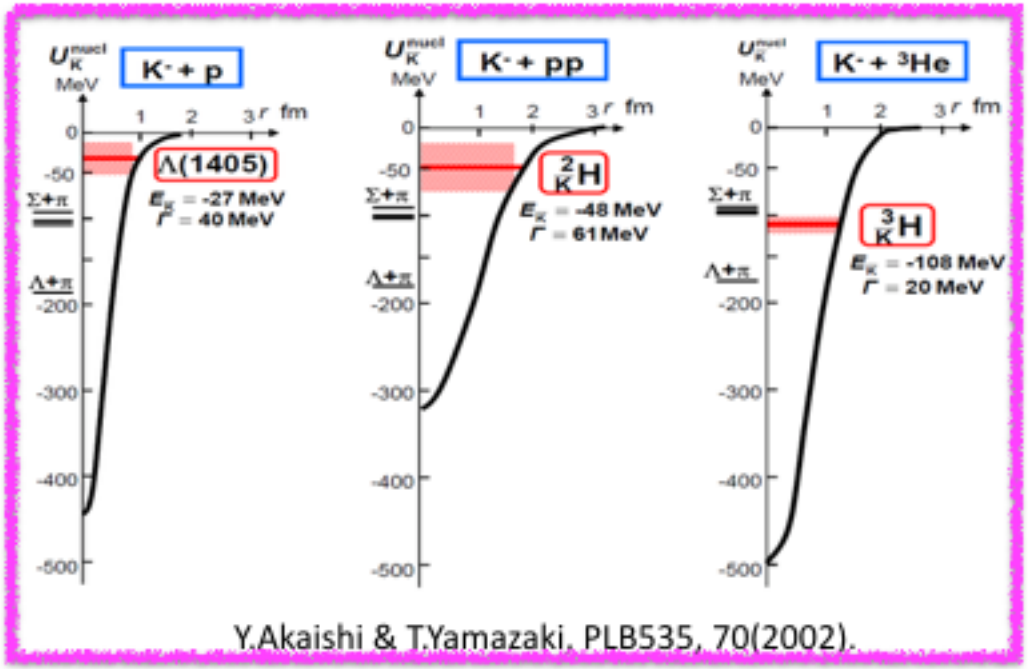
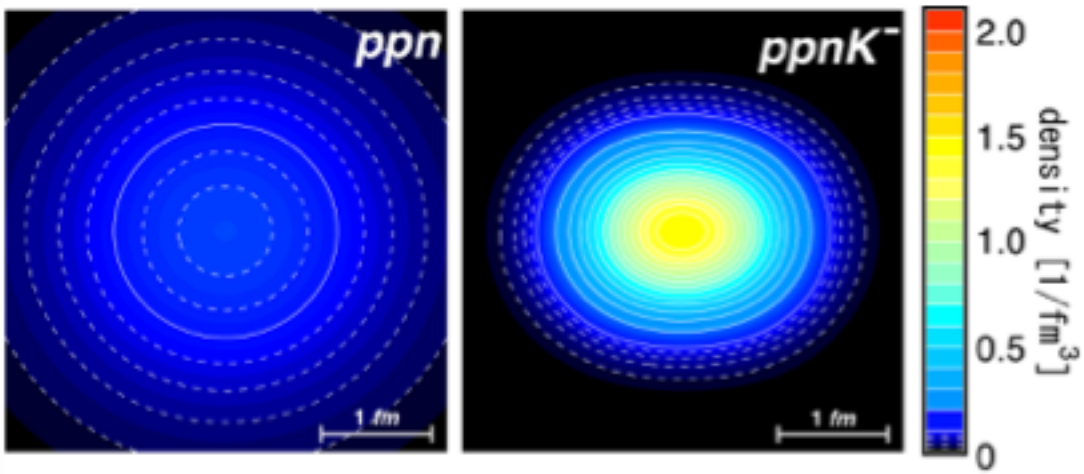
$\Lambda(1405)$: Bound state of $\bar{K}N$?

What will happen if $\bar{K}$ placed in nucleus?

- If attraction btw $\bar{K}N$ is strong enough, Kaonic nuclear bound state might be formed



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



A. Dote *et al.* : PLB 590 (2004) 51

$\rho \gg \rho_0$

- High density matter may realize inside nucleus, due to strong attraction btw $\bar{K}N$

Search for Kaonic nuclear cluster

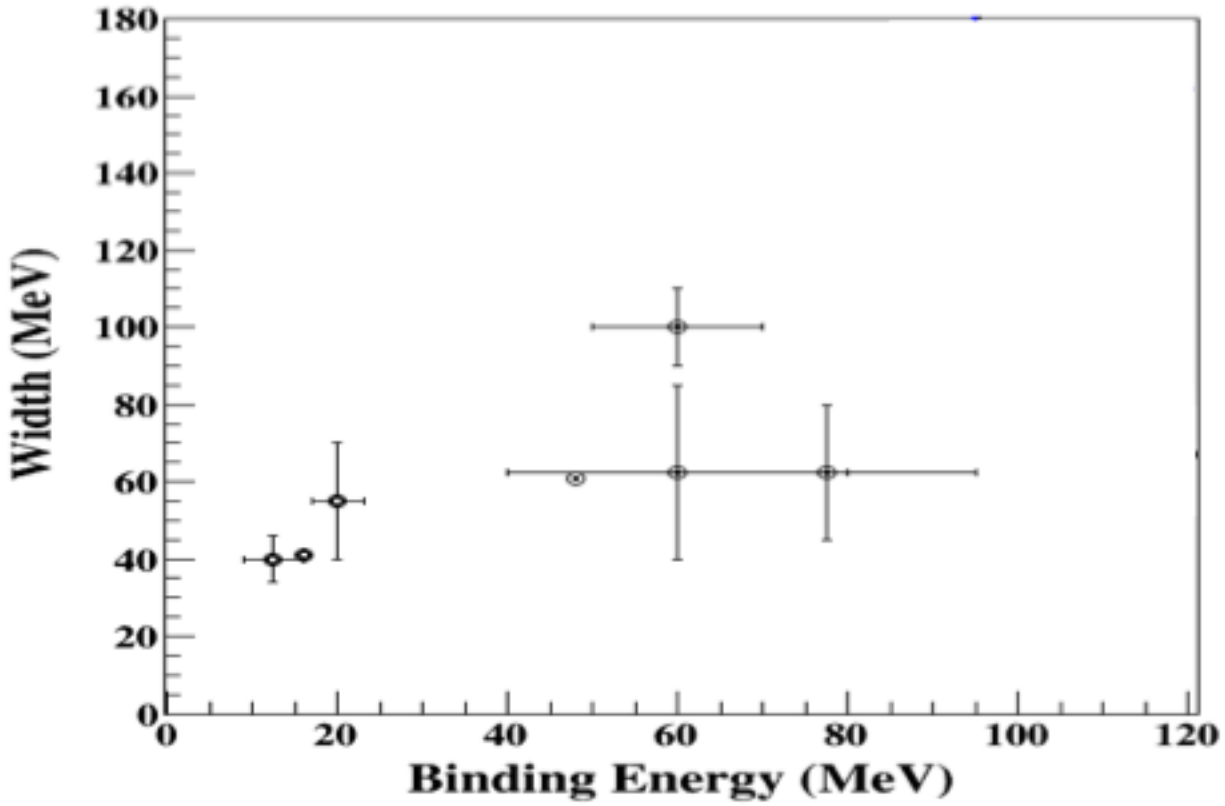
- We started from simplest Kaonic cluster, *i.e.* K^-pp (one K^- with two protons)
- Several experimental challenges have been made various facilities
  - DAΦNE / FINUDA : $K^-_{stopped}$ on Li→Λp
  - DISTO / Saclay : $p+p \rightarrow K^+\Lambda p$ (2.85 GeV)
  - LEPS / SPring-8 : $\gamma+d \rightarrow K^+\pi^-X$
  - E27, E15 / J-PARC : $d(\pi^+,K^+)$ X | 3He(K-,n)Λp
  - HADES / GSI : $p+p \rightarrow K^+\Lambda p$ (3.5 GeV)

Theoretical Calculations on $\bar{K}NN$

$K^{bar}N$ int.	Chiral SU(3) (energy dependent)			Phenomenological (energy independent)			
	Variational		Faddeev	Variational		Faddeev	
Method	Barnea, Gal, Liverts	Dote, Hyodo, Weise	Ikeda, Kamano, Sato	Yamazaki, Akaishi	Wyceck, Green	Shevchenko, Gal, Mares	Ikeda, Sato
B (MeV)	16	17-23	9-16	48	40-80	50-70	60-95
Γ (MeV)	41	40-70	34-46	61	40-85	90-110	45-80

- **$K^{bar}N$ interaction model:**
  - Chiral SU(3) [energy dependent] → **B.E. ~ 20 MeV**
  - Phenomenological [energy independent] → **B.E. ~ 40-70 MeV**
- **Calculation method:**
  - Almost the same results = *depending on $K^{bar}N$ interaction*

$\bar{K}NN$ bound state



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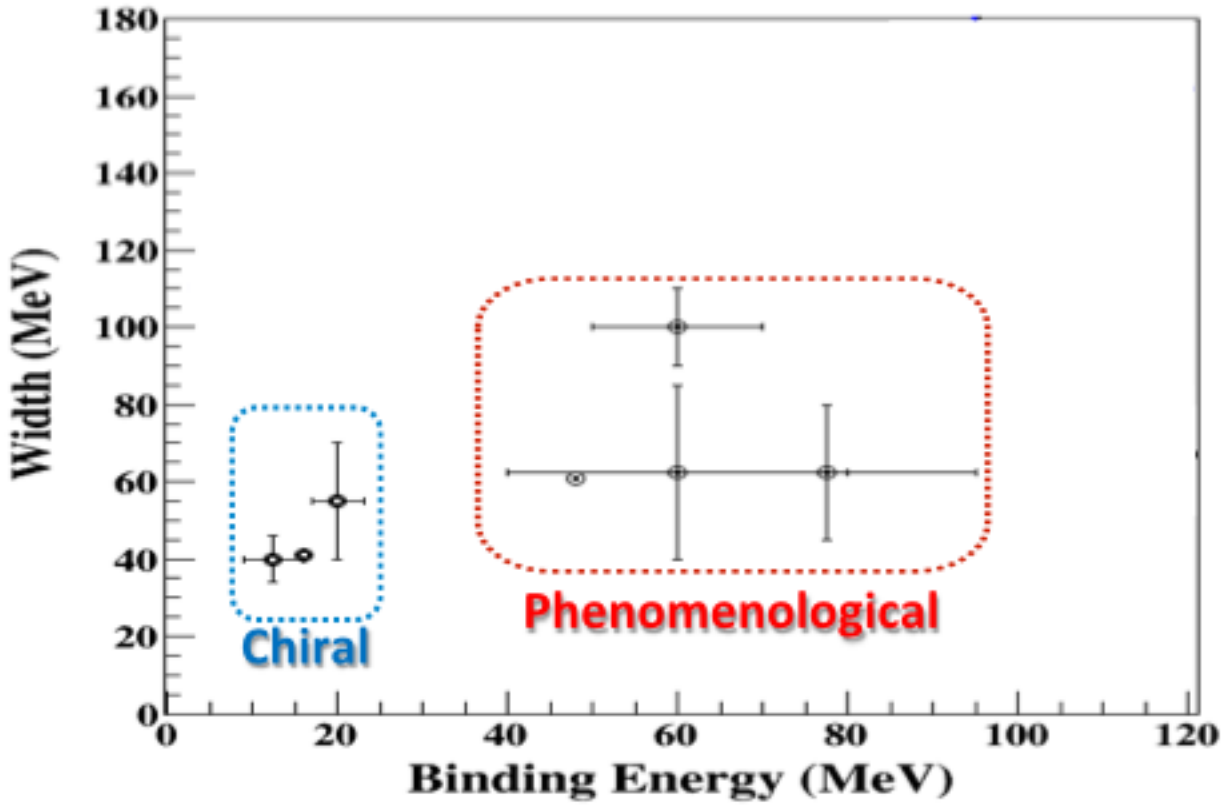

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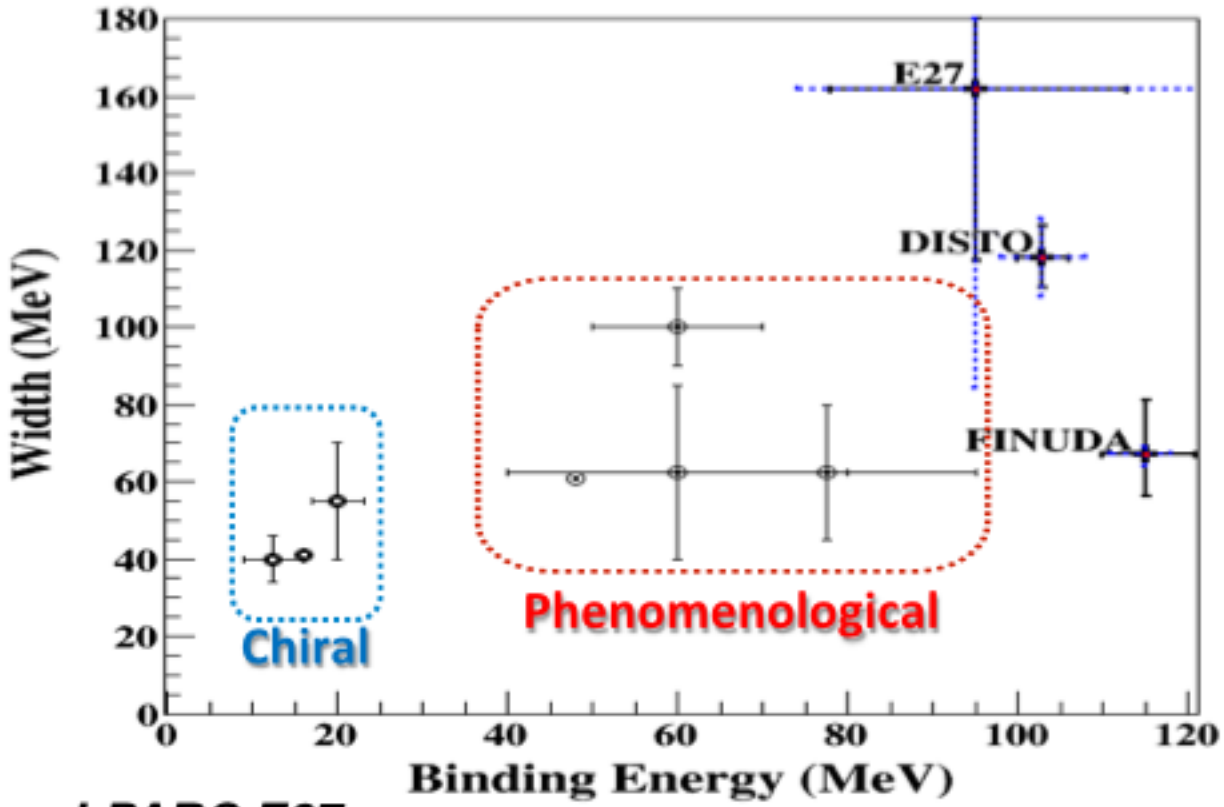
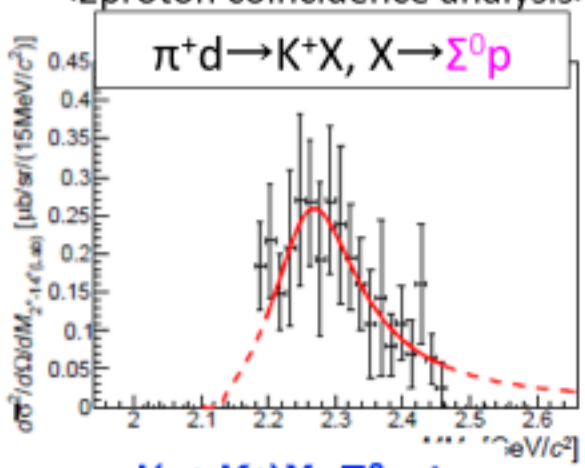


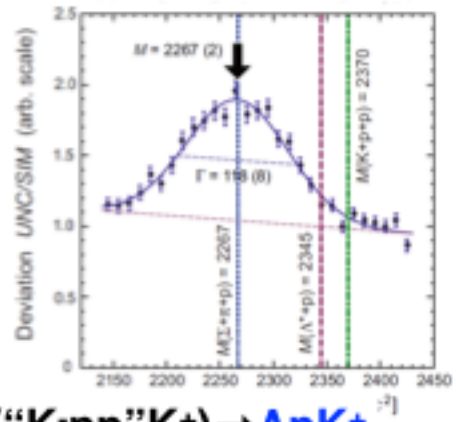
J-PARC E27

<2proton coincidence analysis>



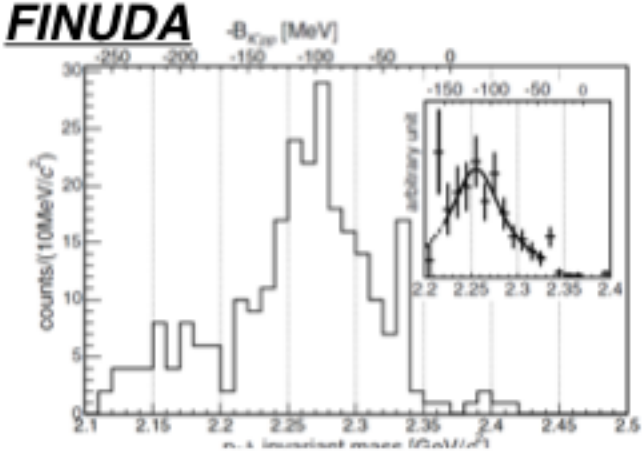
$d(\pi^+,K^+)X$, Σ^0p-tag

DISTO



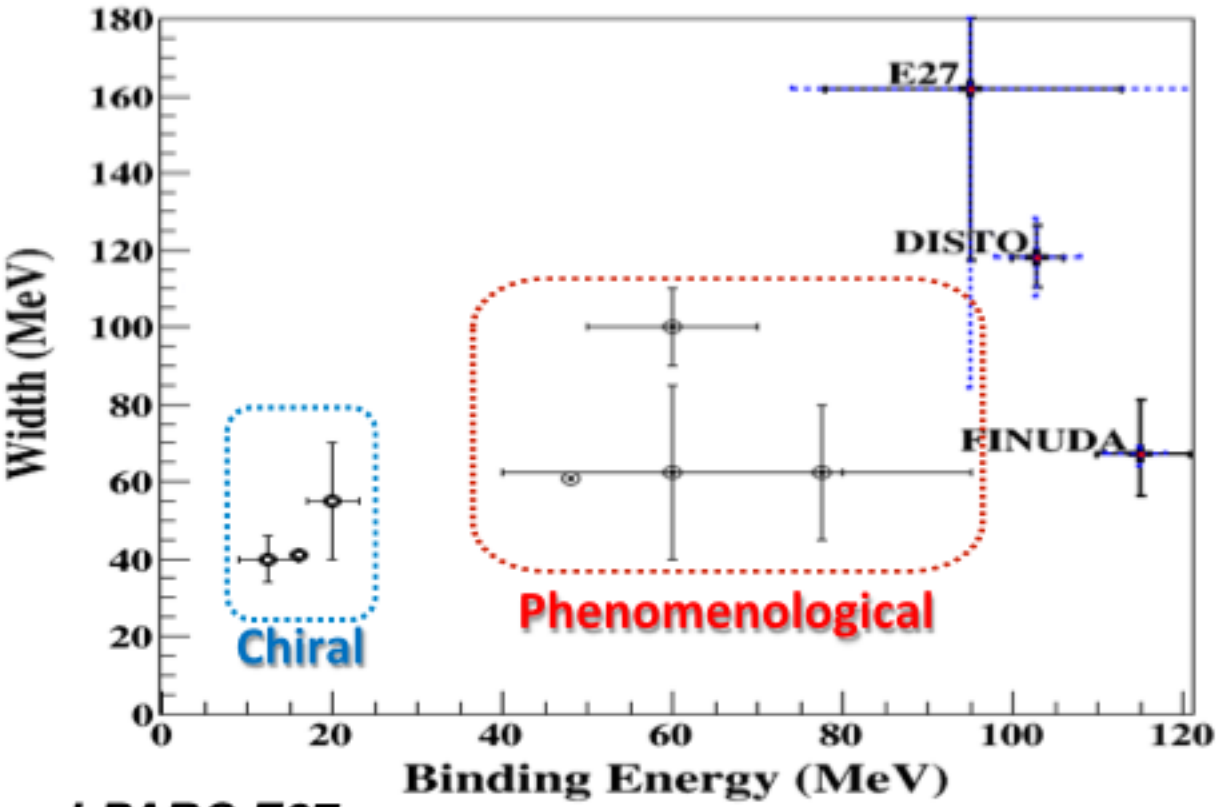
$pp \rightarrow$ ("K^-pp"K^+) $\rightarrow \Lambda p K^+$
@T_p=2.85 GeV

FINUDA



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

$\bar{K}$NN bound state



No signal observed
(upper limit are claimed)

- HADES/FOPI
  (p-p collisions)
- LEPS
  (photo- production)

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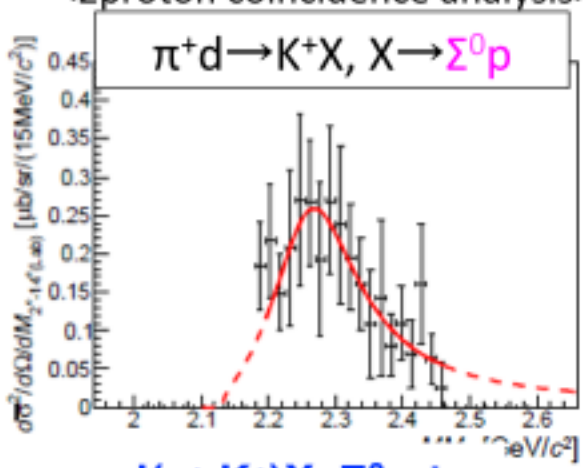

d(π⁺,K⁺)X, Σ⁰p-tag

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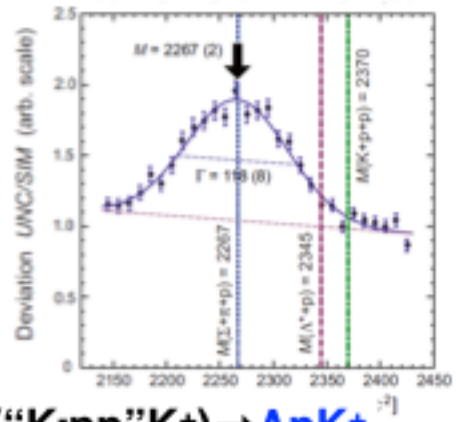

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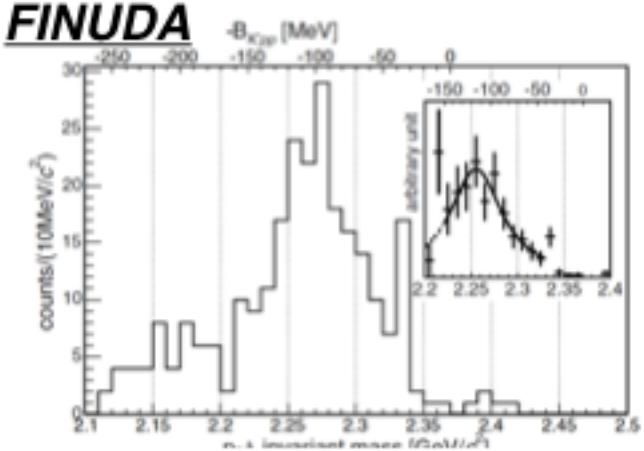

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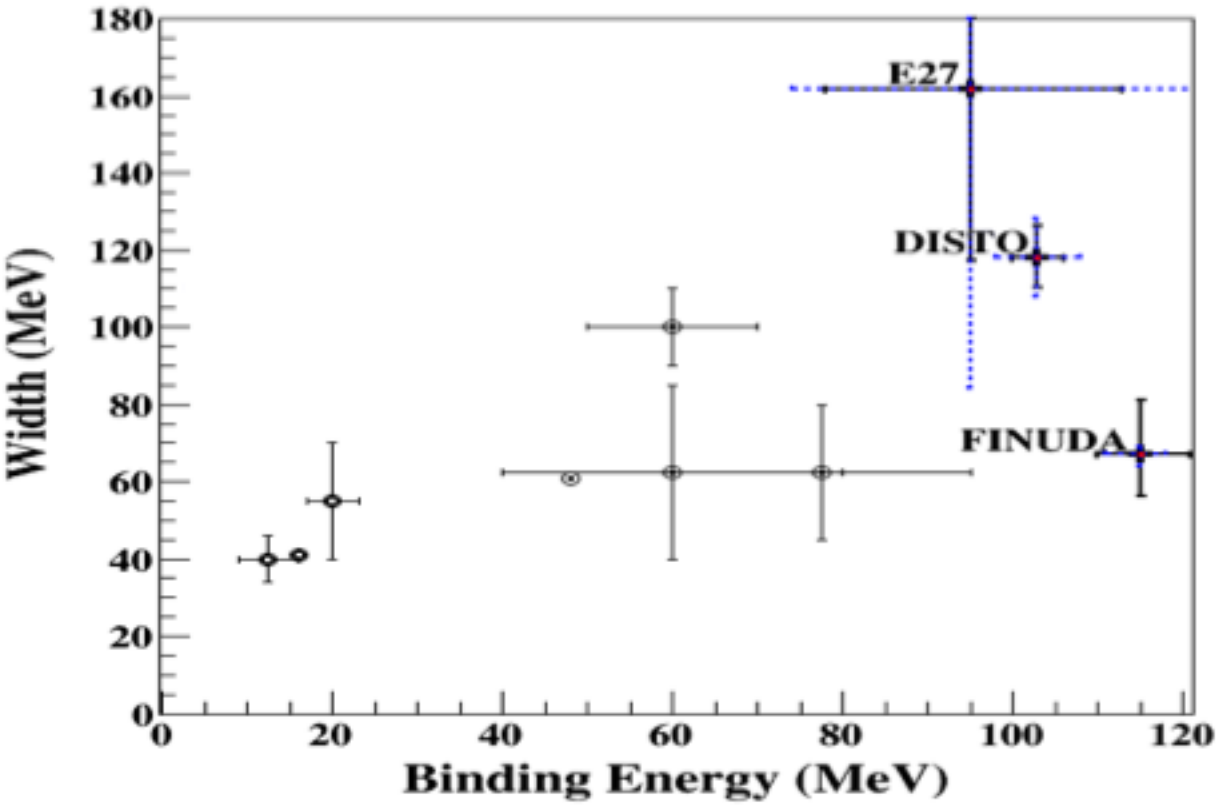

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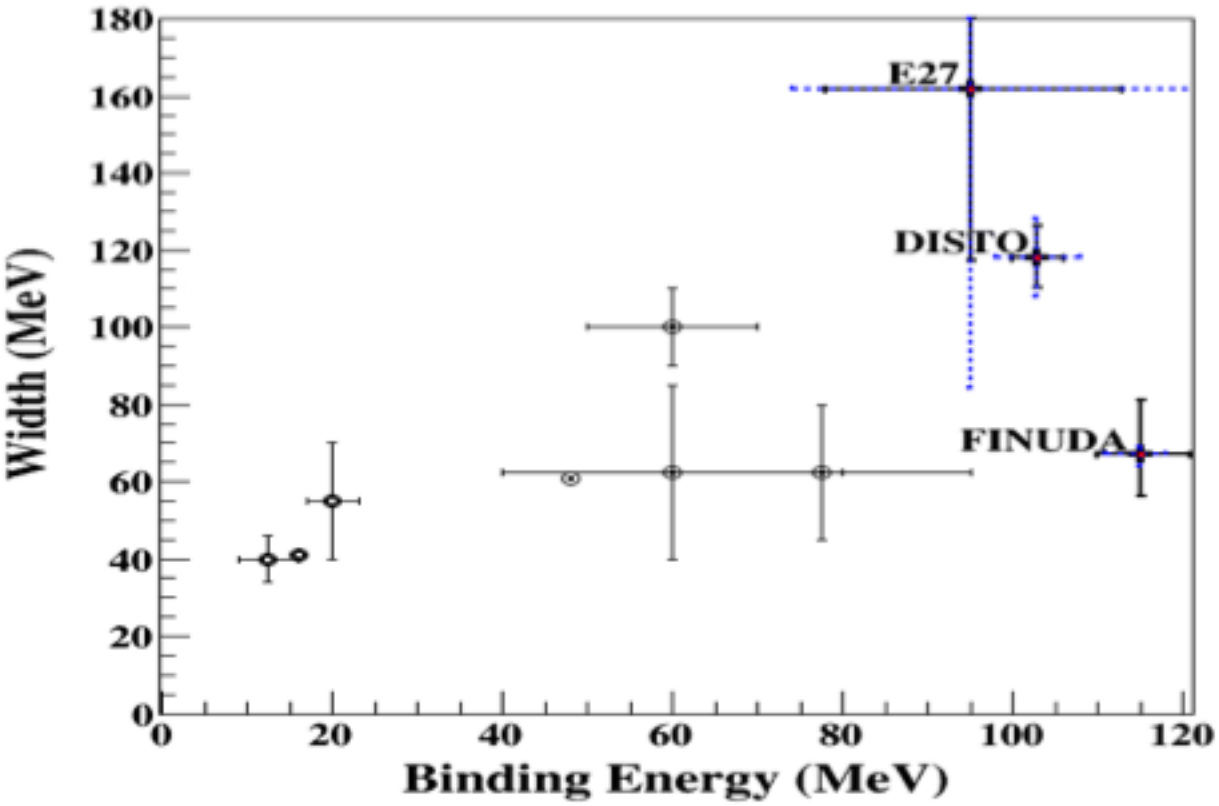

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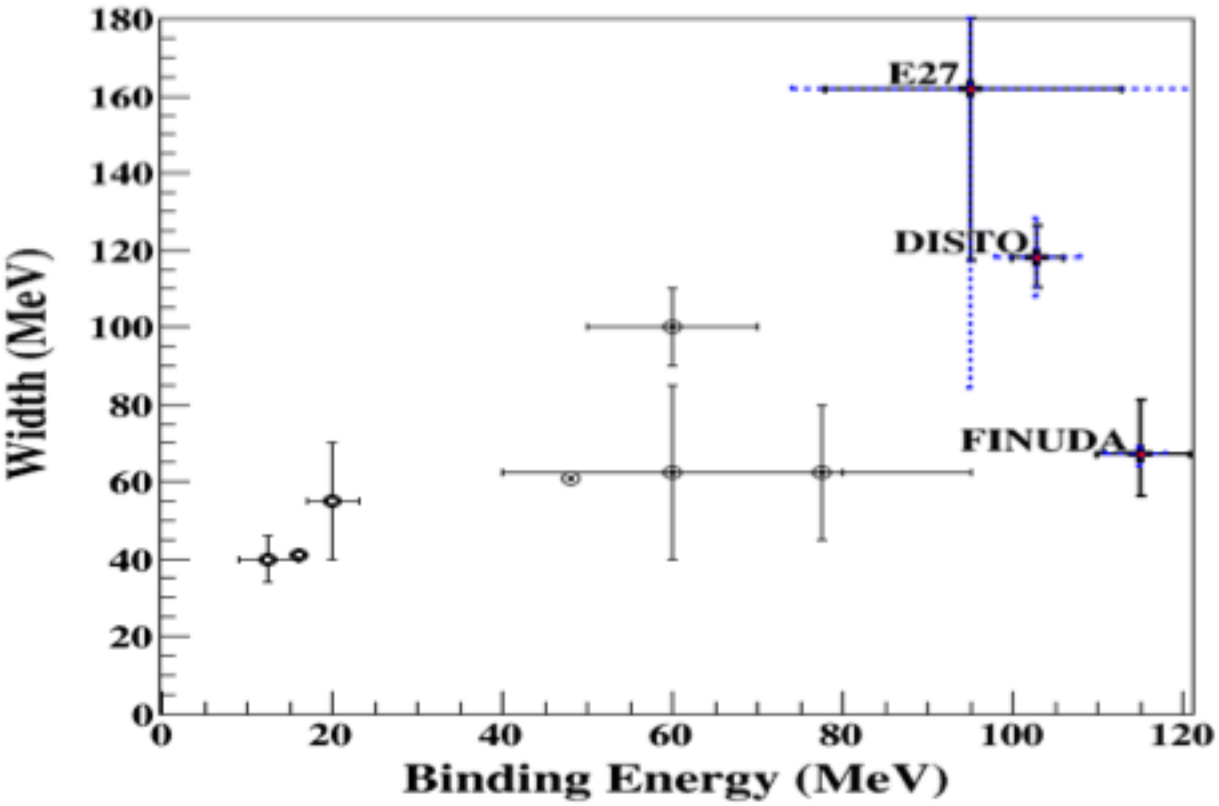
- Two messages:
  - Existence for the $\bar{K}$NN would be no question, but width would be wide due to strong $\bar{K}$ absorption
  - However only deeply bound state has been observed?

$\bar{K}$NN bound state



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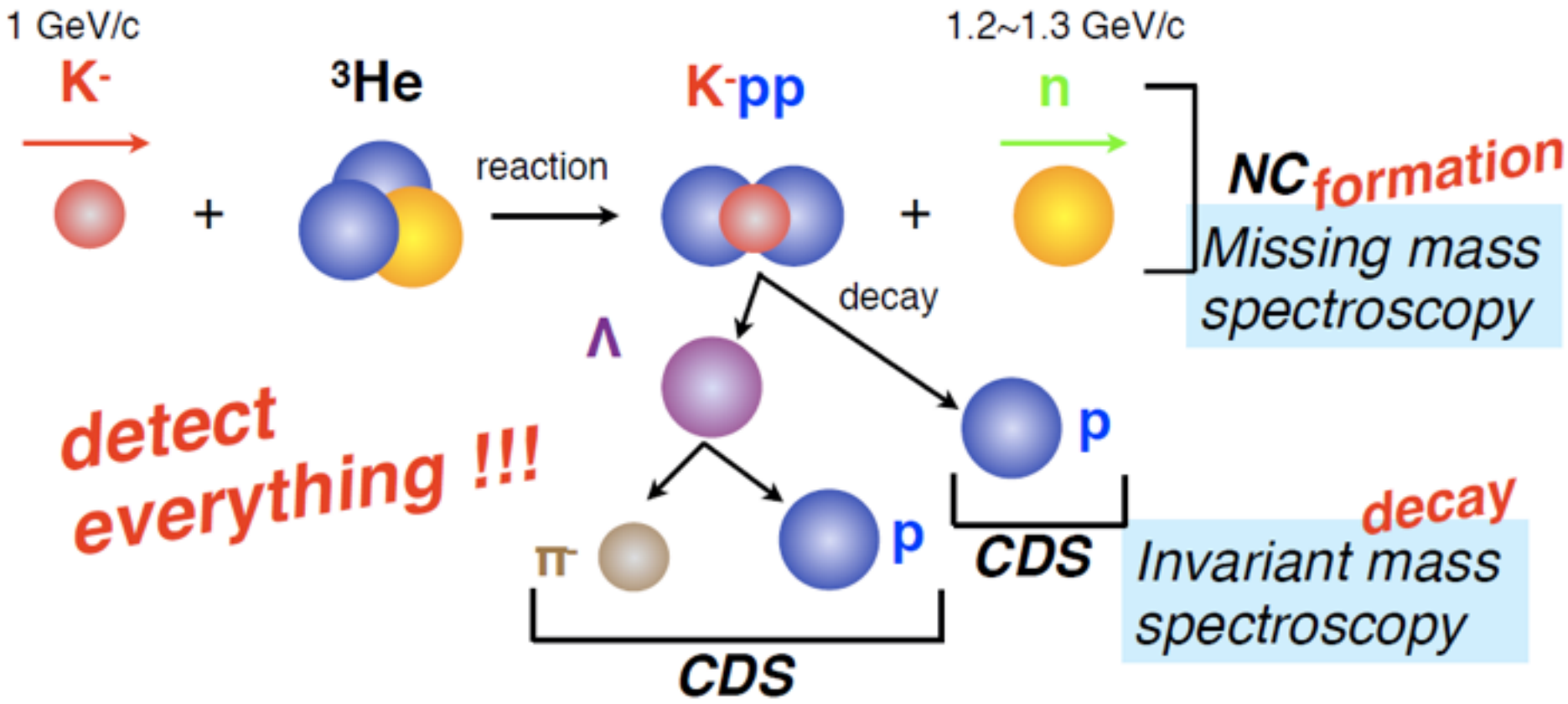
How do we understand the situation?

Kaonic nucleus at K1.8BR/J-PARC

Concept for the J-PARC E15 Experiment

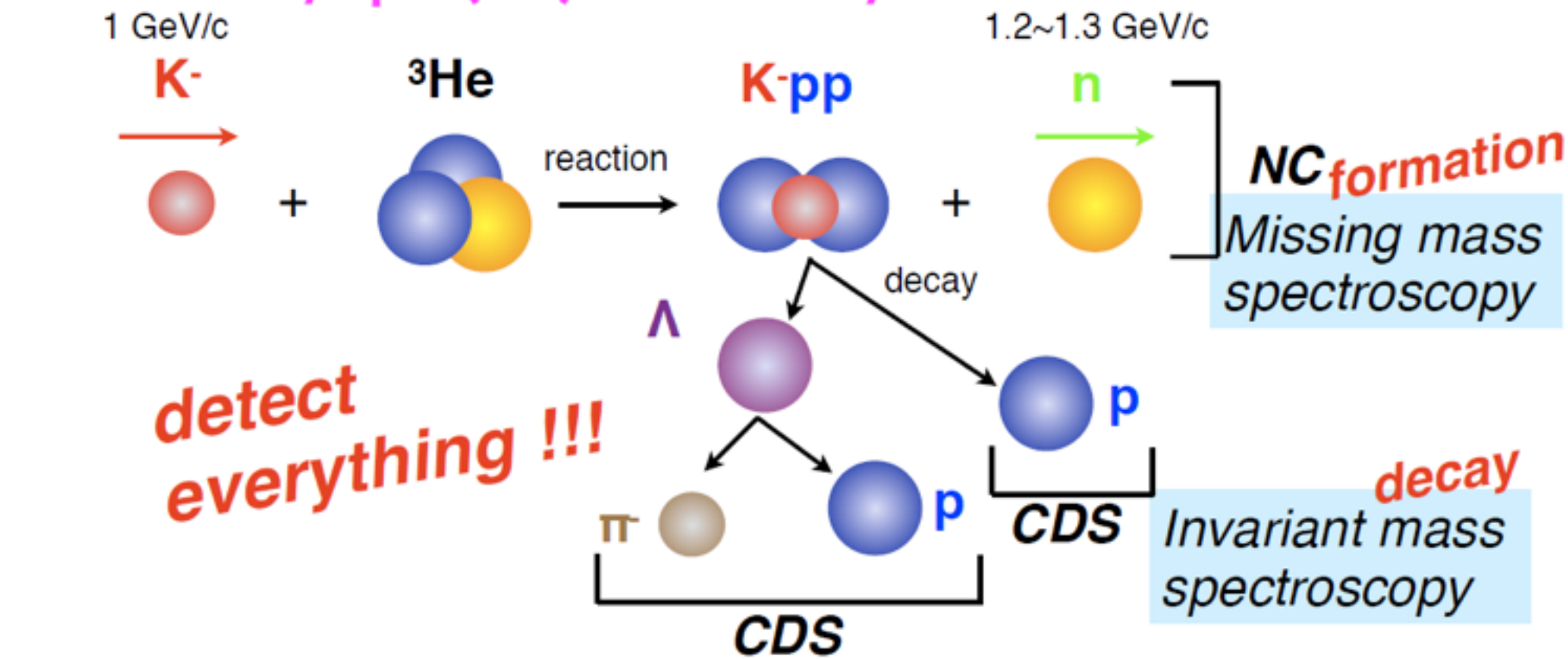


- two-nucleon absorption
- hyperon decays

} CAN be discriminated kinematically

Concept for the J-PARC E15 Experiment

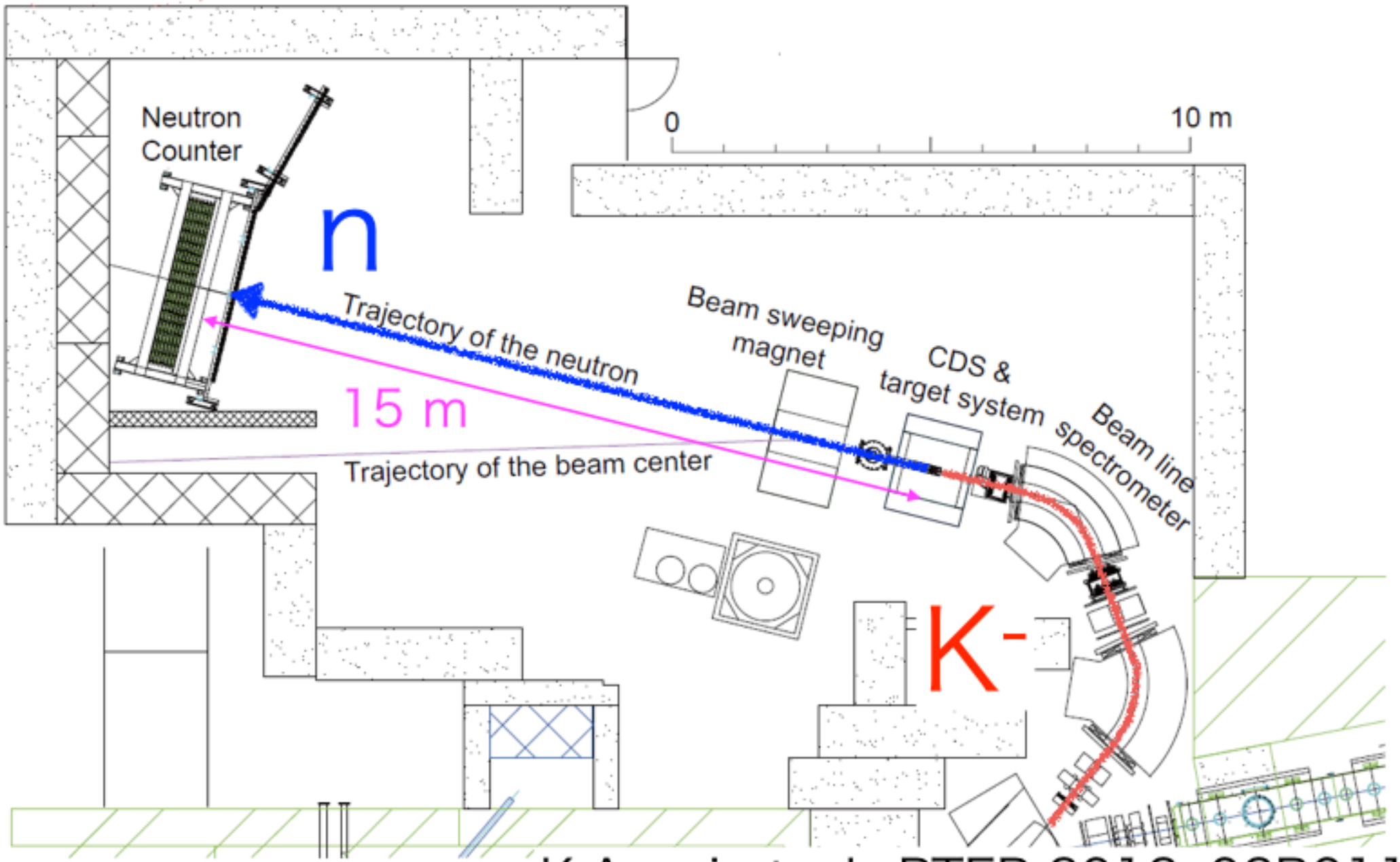
~200k K^- /spill(6s) @ 1 GeV/c



- two-nucleon absorption
- hyperon decays

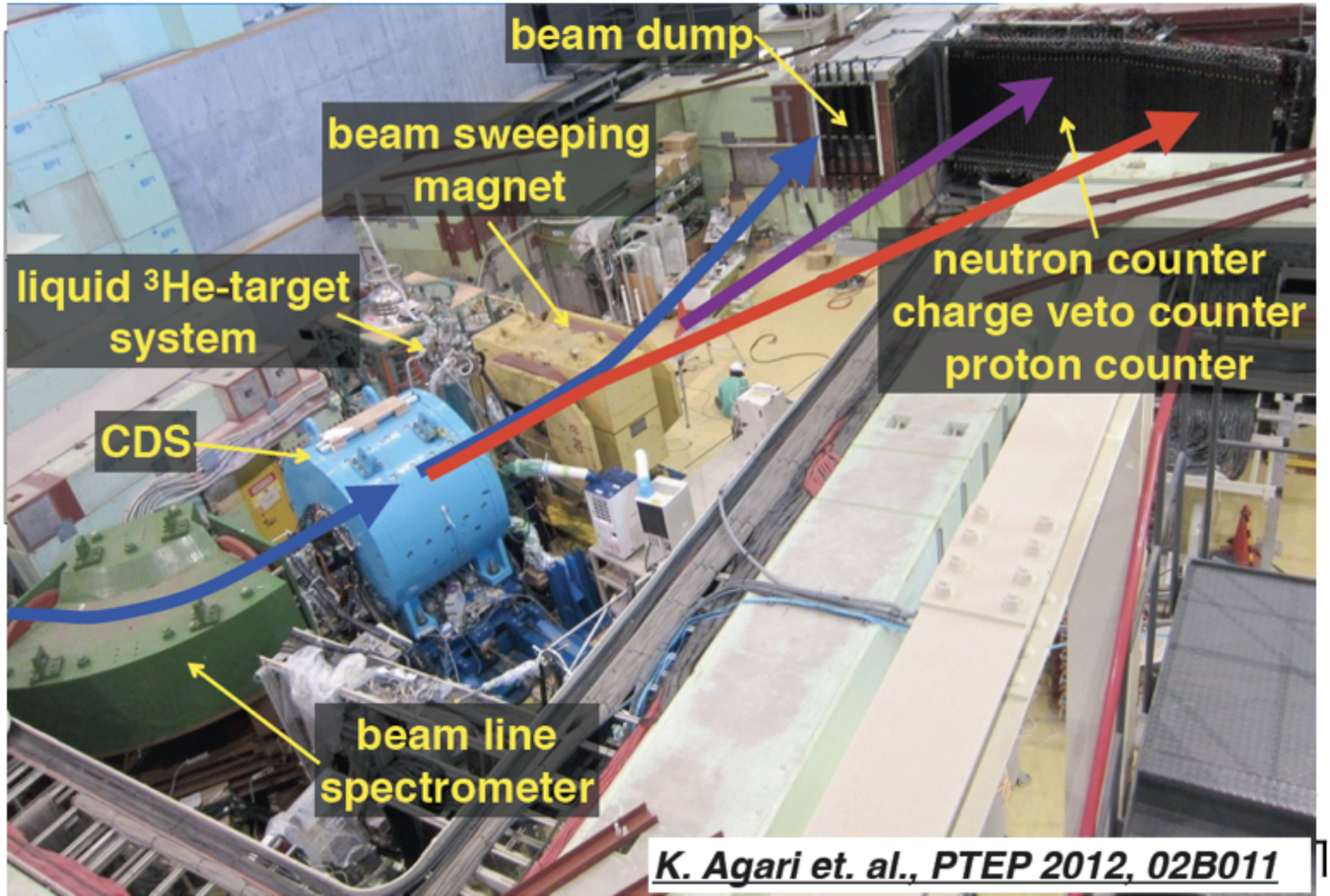
} CAN be discriminated kinematically

Apparatus for the Experiment



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

Apparatus for the Experiment



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

Formation Channel, inclusive $^3He(K^-,n)$ reaction

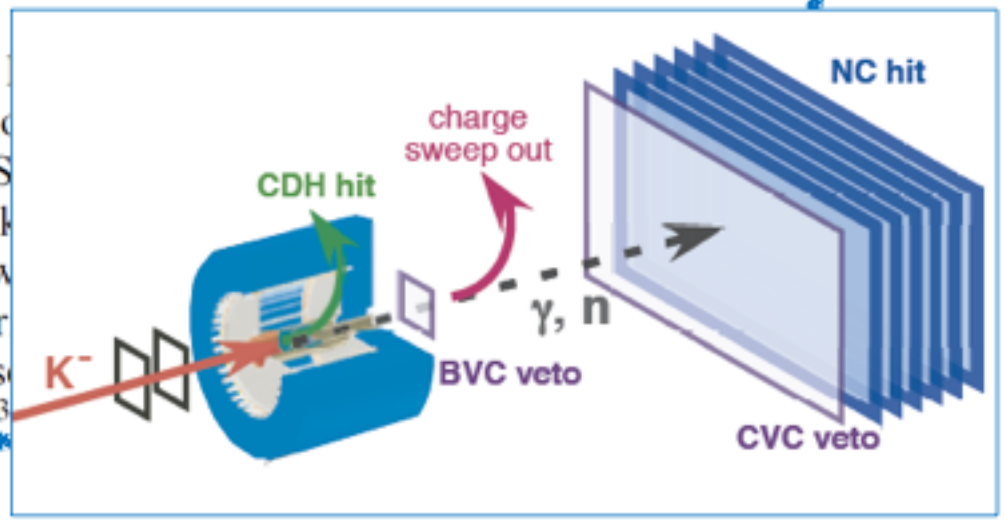
PTEP

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

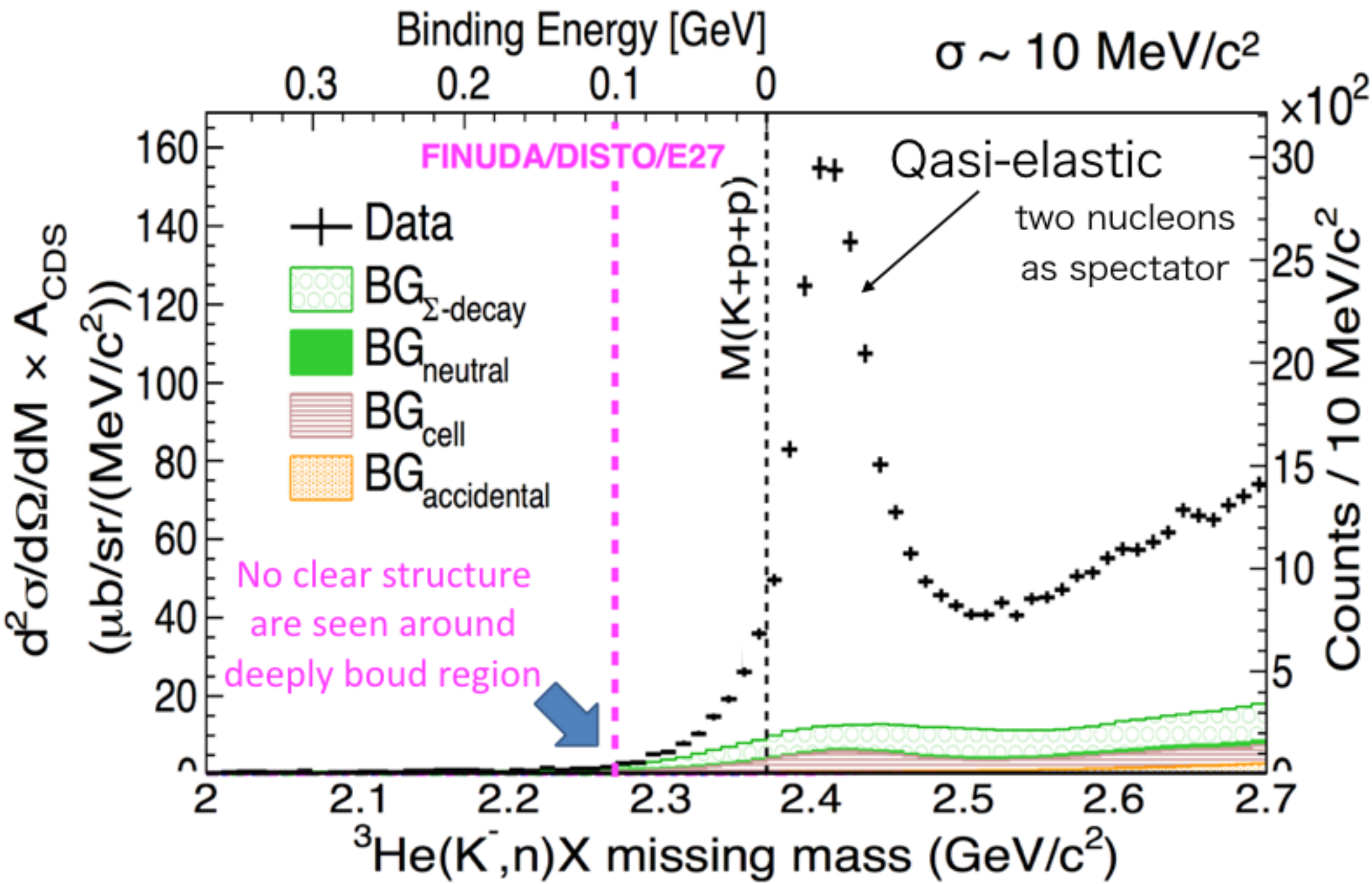
Letter

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

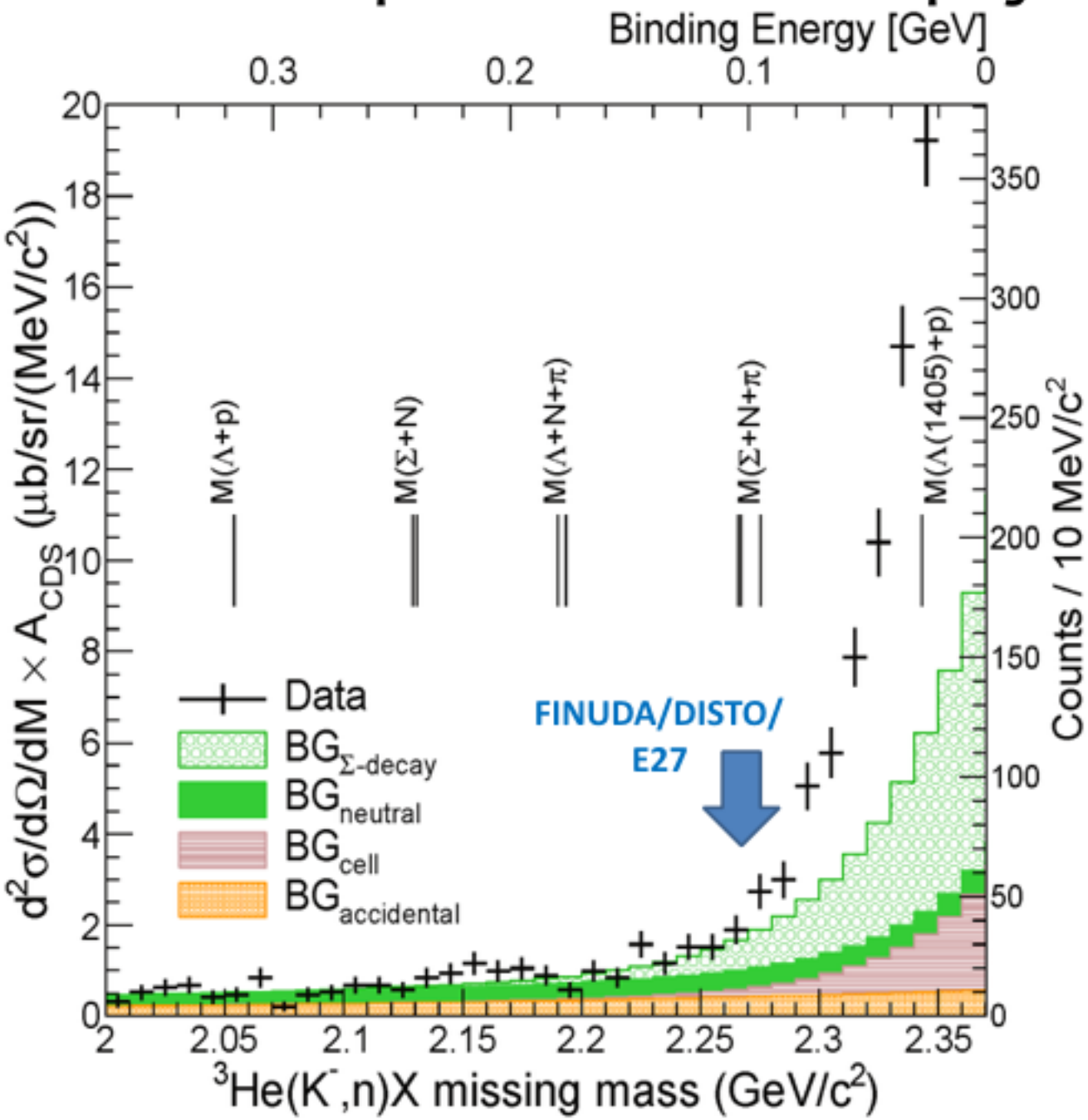
J-PARC E15 Collaboration
T. Hashimoto[1,*,†], S. Ajimura[2], G. Beer[3], H.
M. Cargnelli[8], S. Choi[4], C. Curceanu[9], S. Enc
Y. Fujiwara[1], T. Fukuda[11], C. Guaraldo[9], R. S
M. Iliescu[9], K. Inoue[13], Y. Ishiguro[10], T. Ishik
M. Iwai[12], M. Iwasaki[14,15], Y. Kato[14], S. Kaw
J. Marton[8], Y. Matsuda[17], Y. Mizoi[11], O. Mor
H. Ohnishi[14,2], S. Okada[14], H. Outa[14], K. Pis
A. Romero Vidal[9], Y. Sada[10], A. Sakaguchi[13]

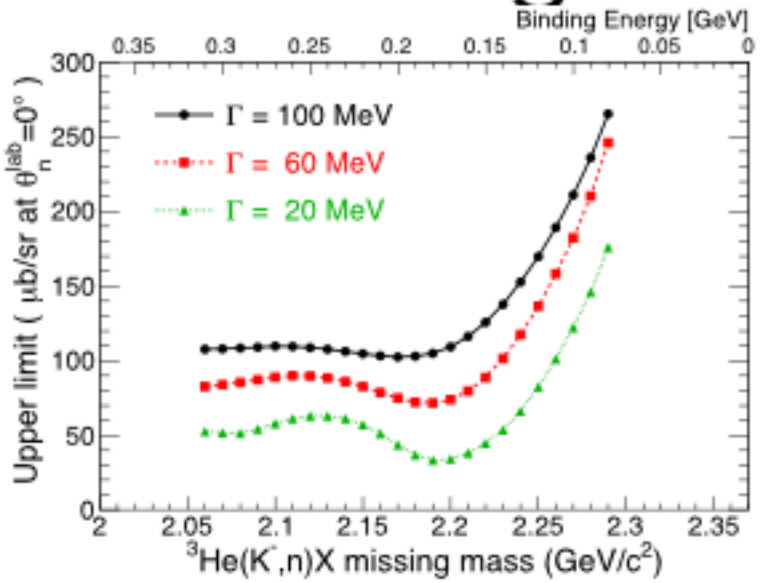


Semi-inclusive $^3He(K^-,n)$ at $\theta_n = 0$



Close-Up of the Deeply-Bound Region





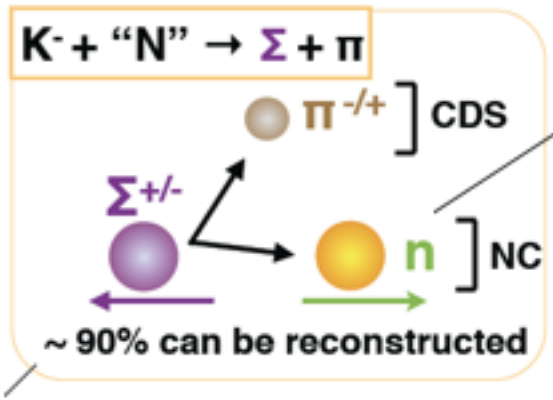
Intrinsic peak shape: Breit-Wigner
Decay mode: **K$^-$pp→Λp 100%** (isotropic decay)

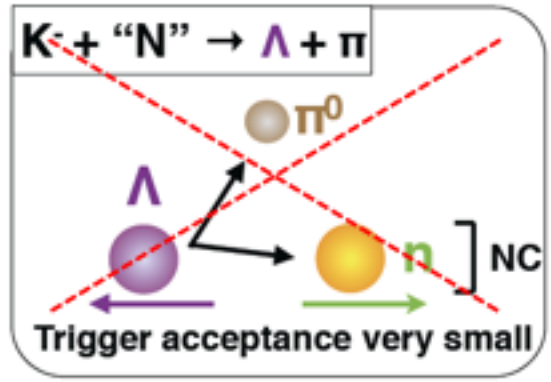
- **J-PARC E15 (U.L.)**
  30 ~ 300 μb/sr @ 0 deg.
  0.5 - 5% of quasi-elastic

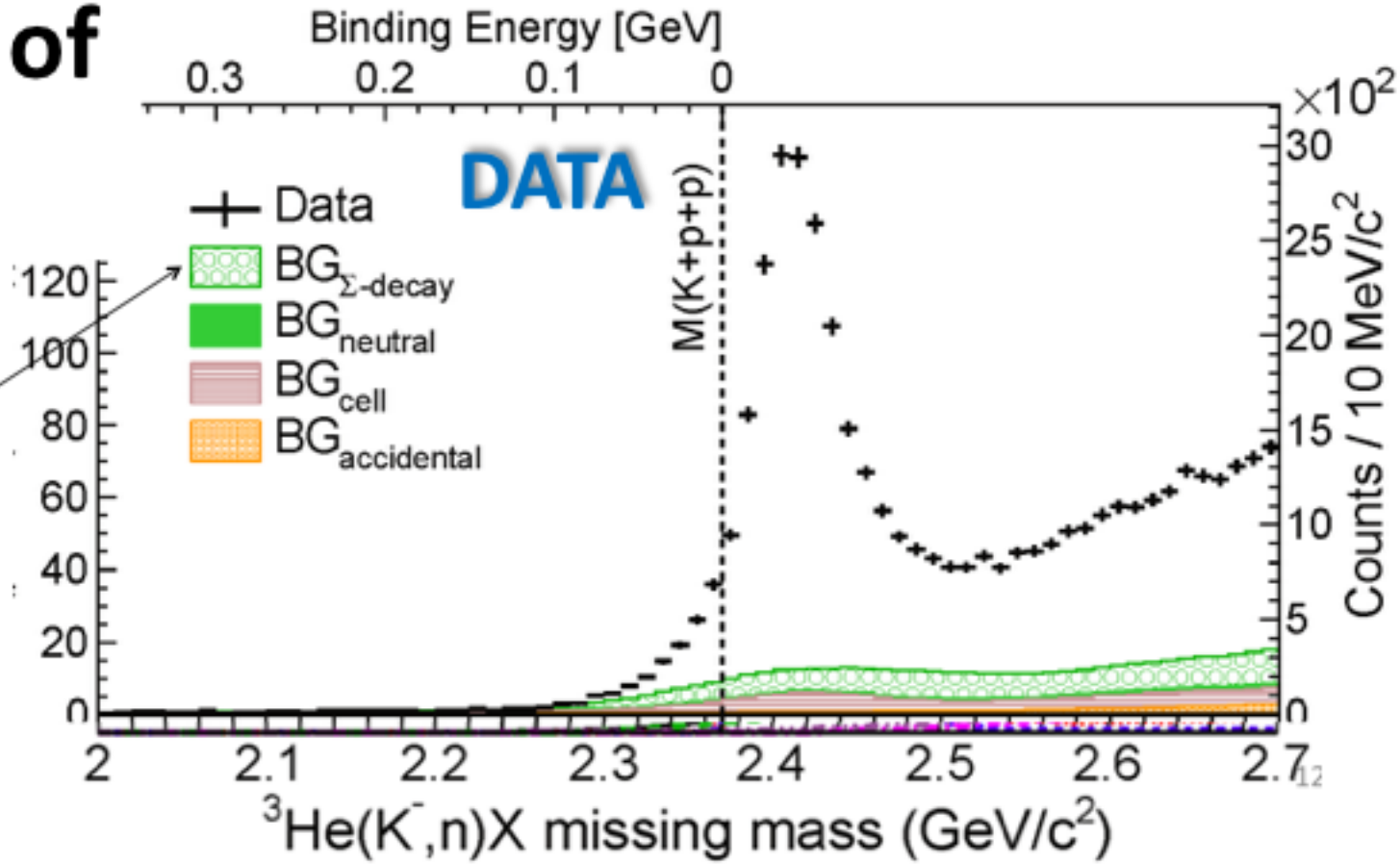
smaller than usual hypernucleus sticking

- **LEPS (γ+d) (U.L.)**
  1.5-26% of γN→K$^+$π$^-$Y
- **HADES (pp @ 3.5 GeV) (U.L.)**
  0.7-4.2 μb (Λ* ~ 10 μb)

Comparison of $^3He(K^-,n)X$







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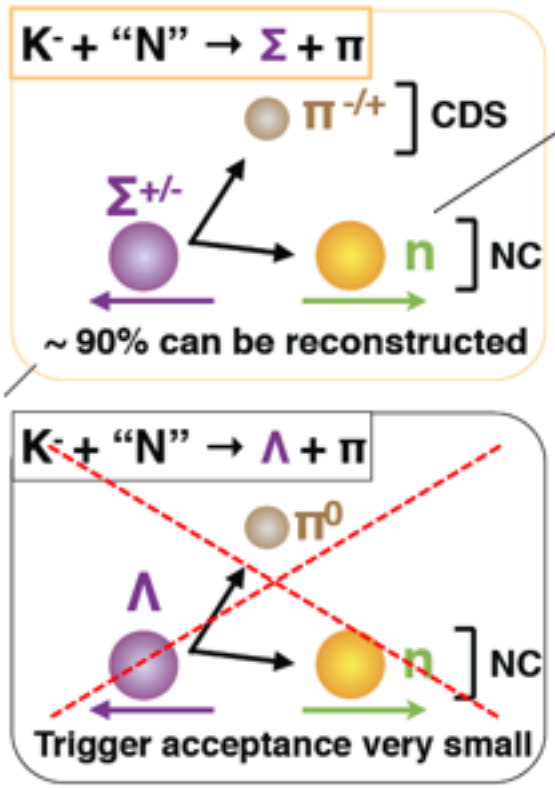

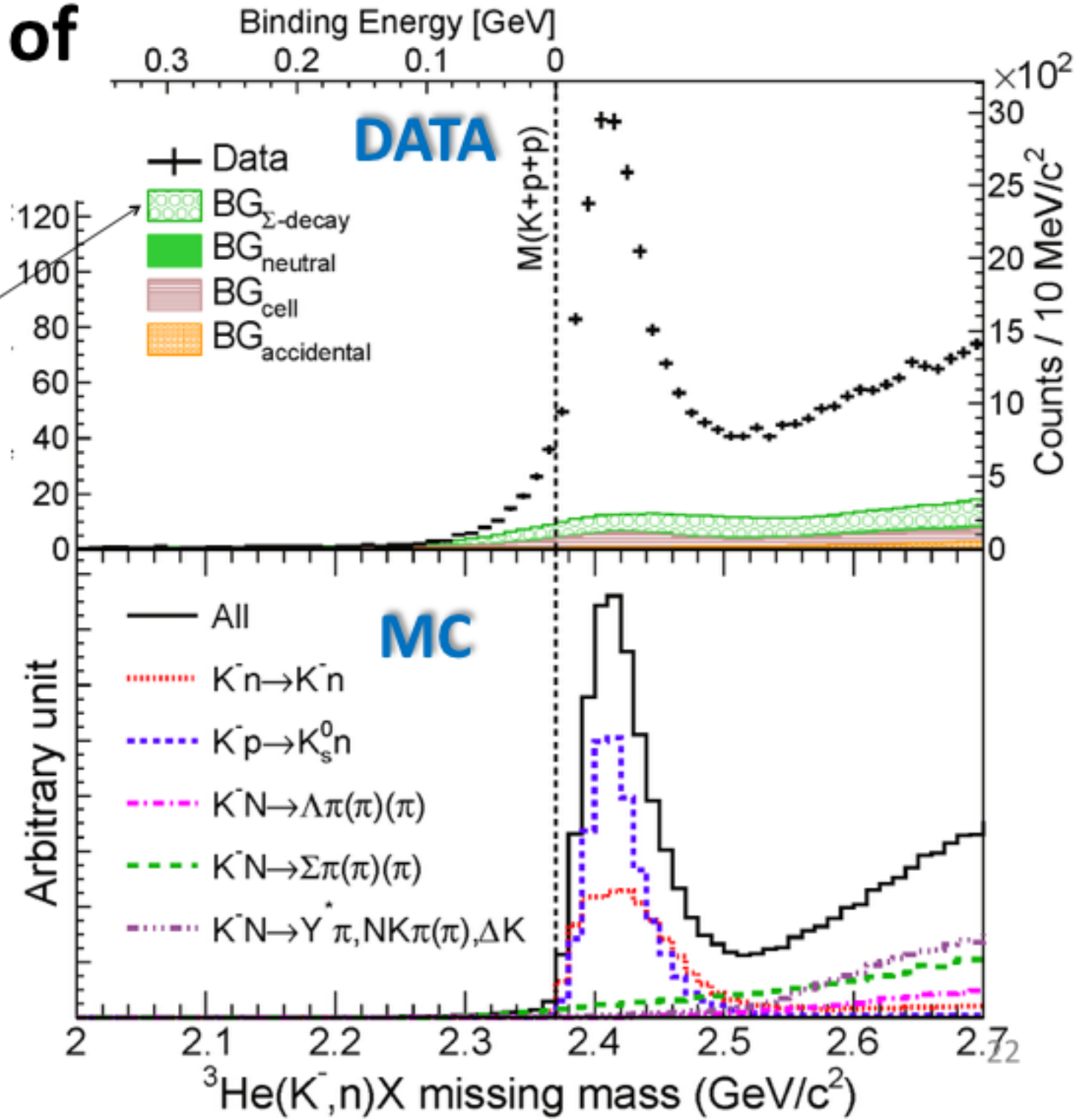

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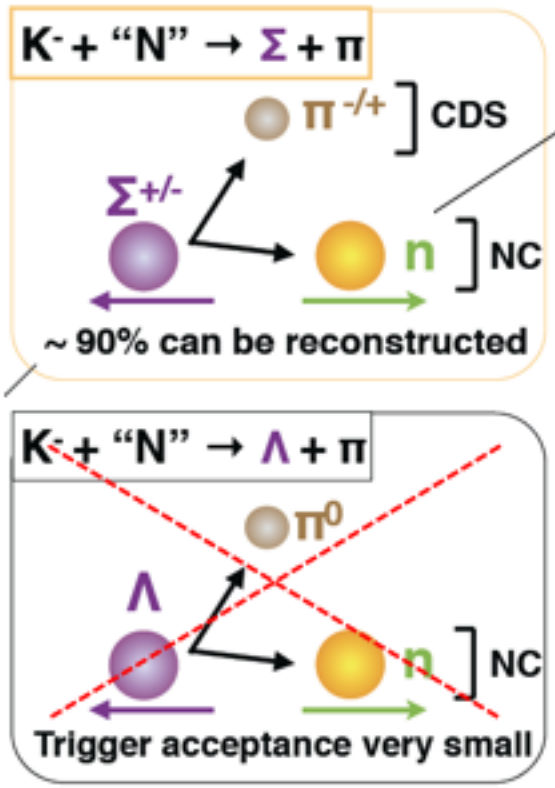
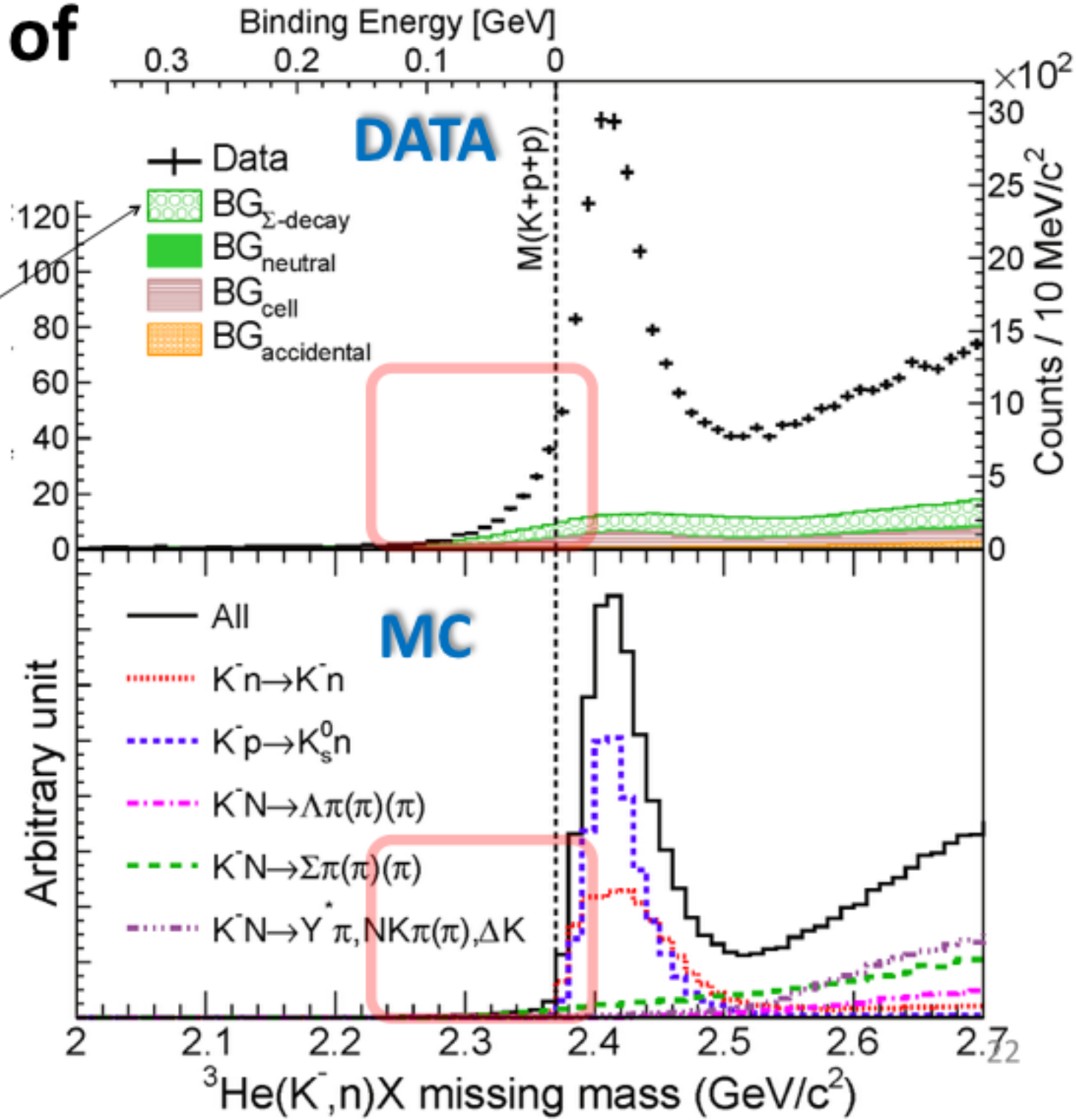
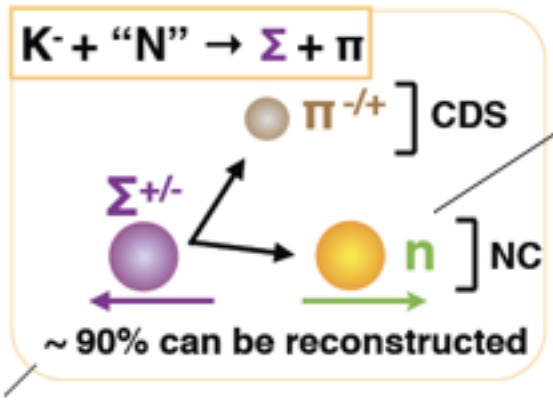
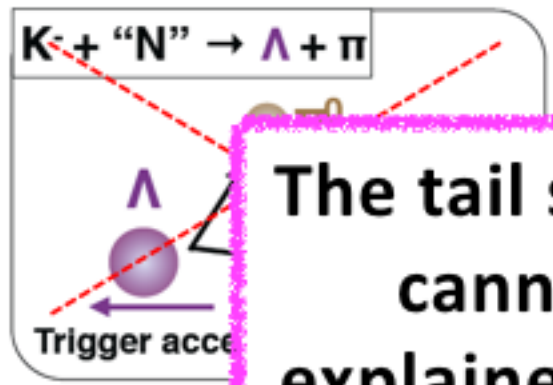
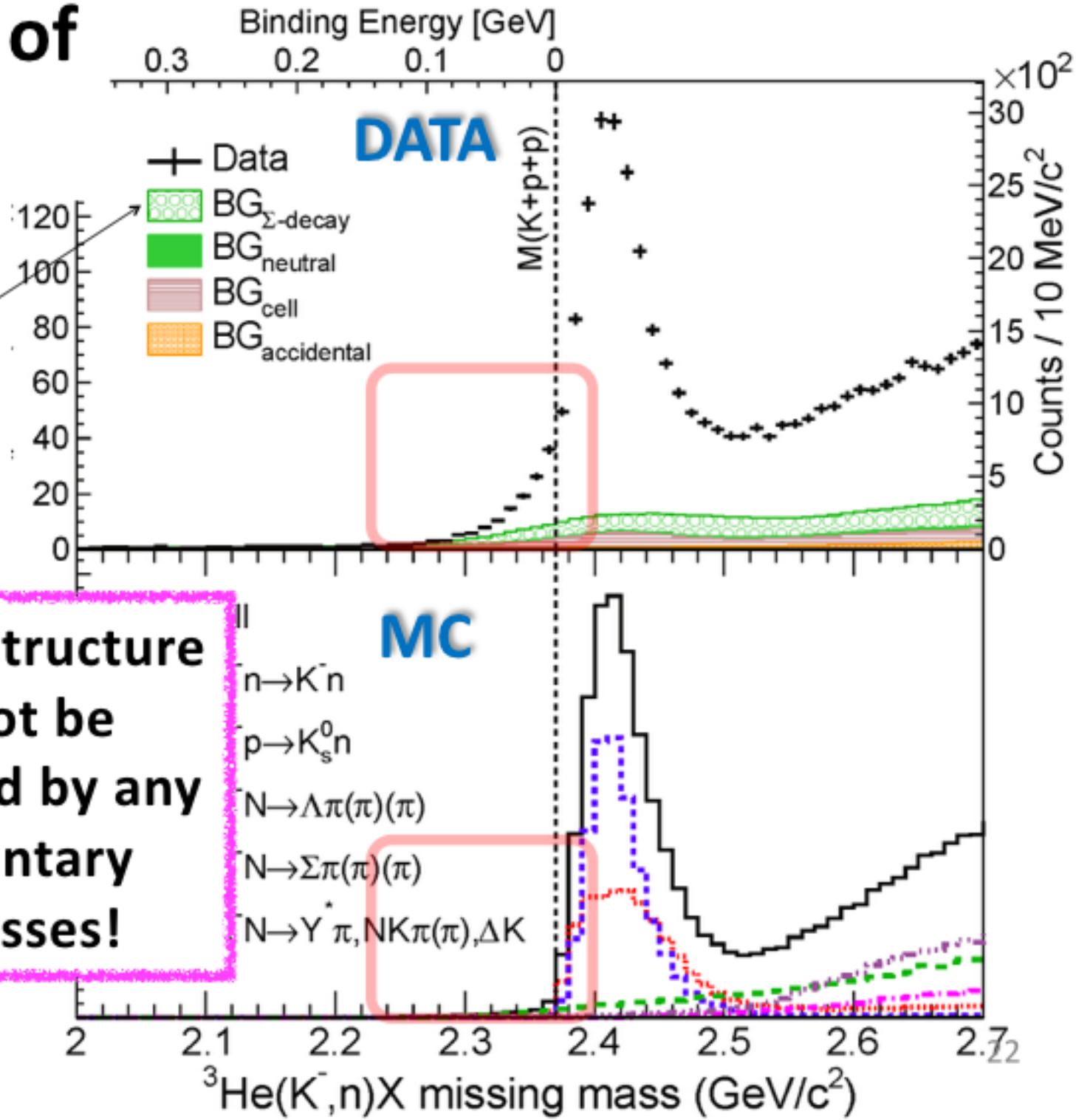




Comparison of $^3He(K^-,n)X$



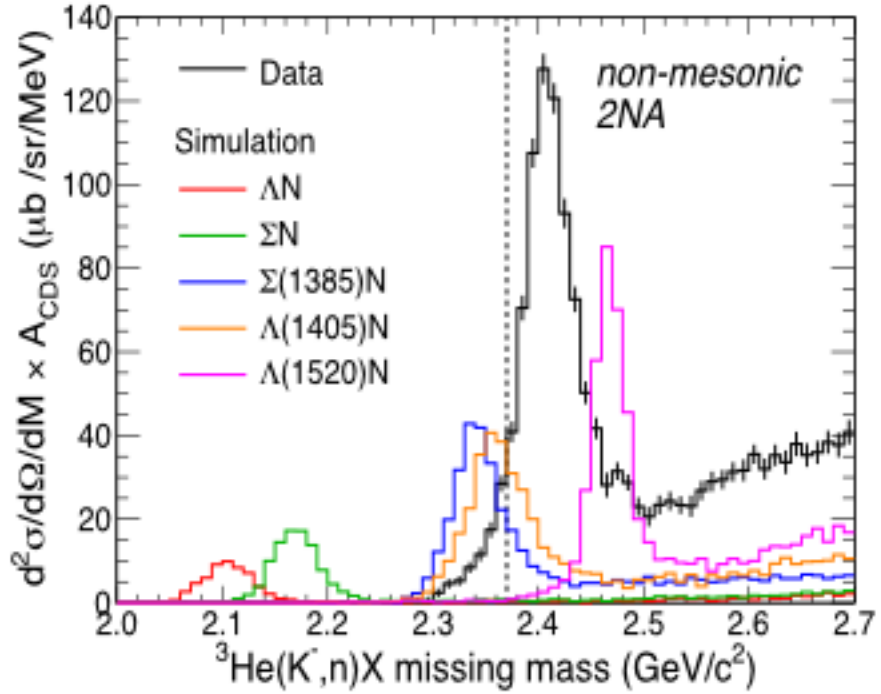




The tail structure cannot be explained by any elementary processes!

Source of tail structure

- Are there due to only the attractive nature of $\bar{K}N$ potential and its absorption?
- Other possibilities? → *i.e.* no-mesonic two nucleon absorption of $\Lambda(1405)$
- To explain all excess by due to $\Lambda(1405)$, we need to assume rather large $\Lambda(1405)$ production cross section (~ 5 mb!!!)



Probably, we need to understand the production of $\Lambda(1405)$ on nucleus

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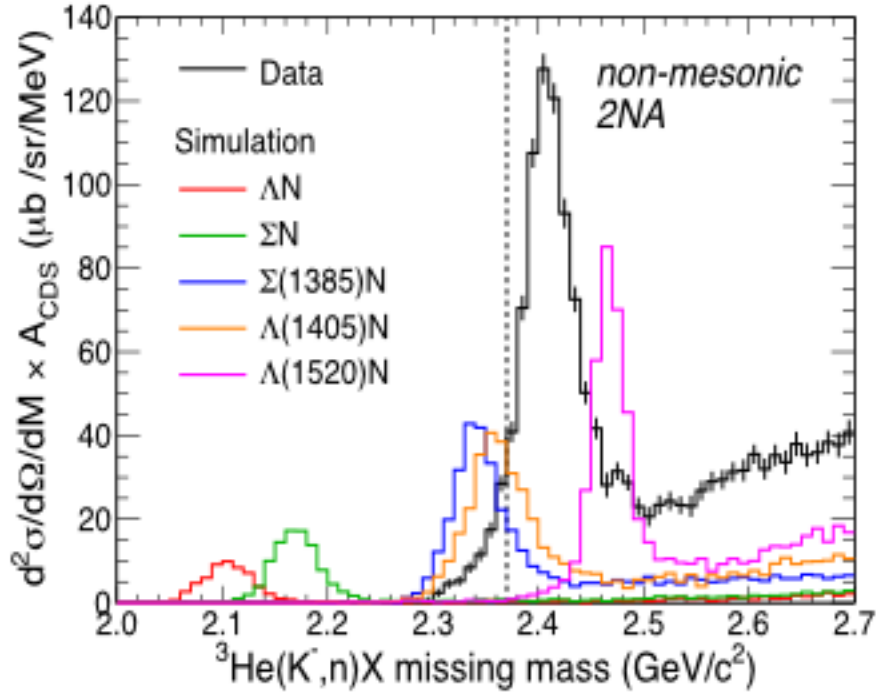


Probably, we need to understand the production of $\Lambda(1405)$ on nucleus

This issue will be discussed by Prof.Noumi later

Exclusive ^{3}He(K^-, Λp)n

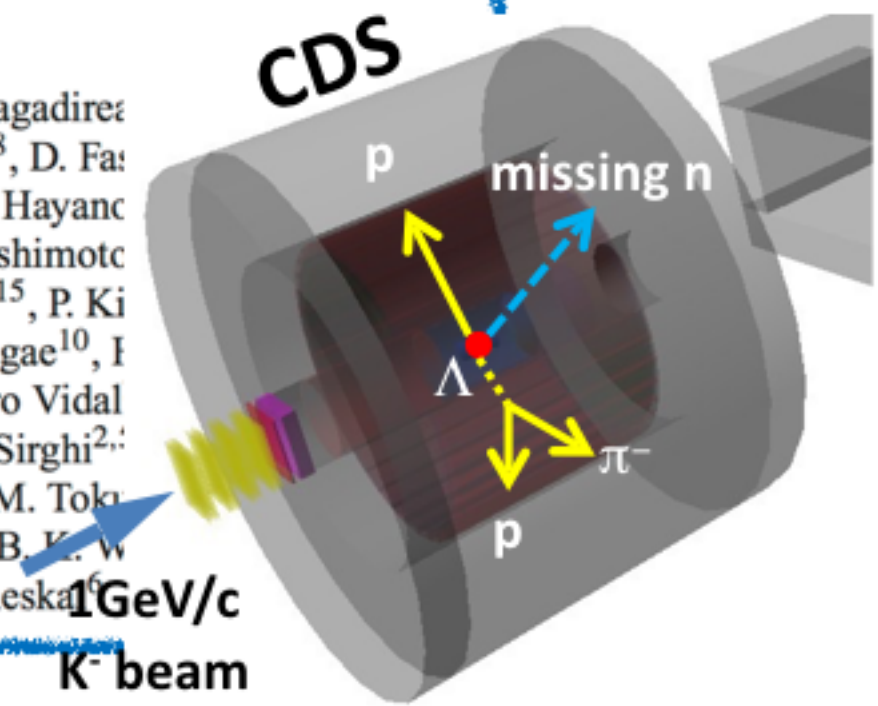
PTEP

Prog. Theor. Exp. Phys. **2016**, 051D01 (11 pages)
DOI: 10.1093/ptep/ptw040

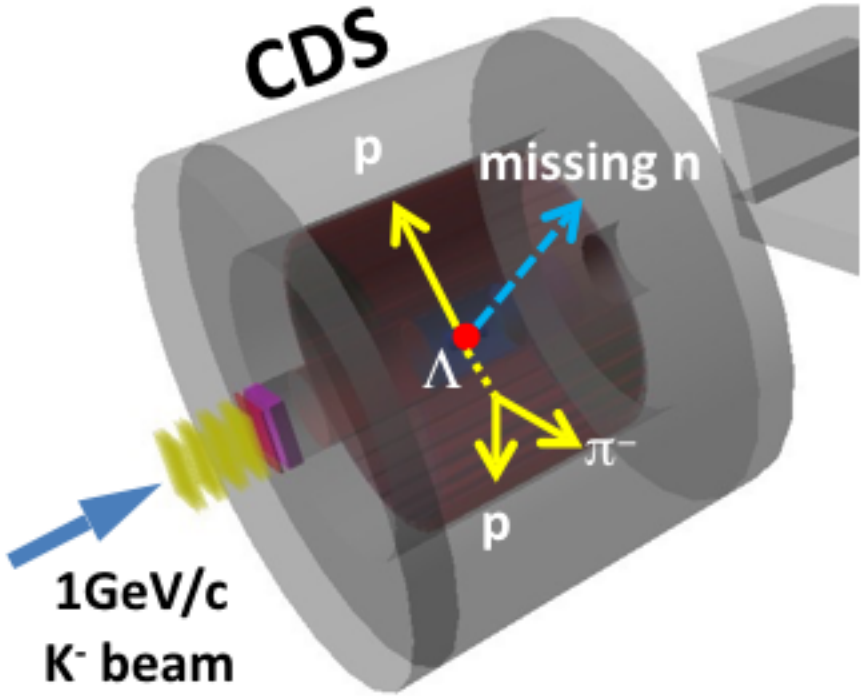
Letter

Structure near the $K^- + p + p$ threshold in the in-flight ^{3}He(K^-, Λp)n reaction

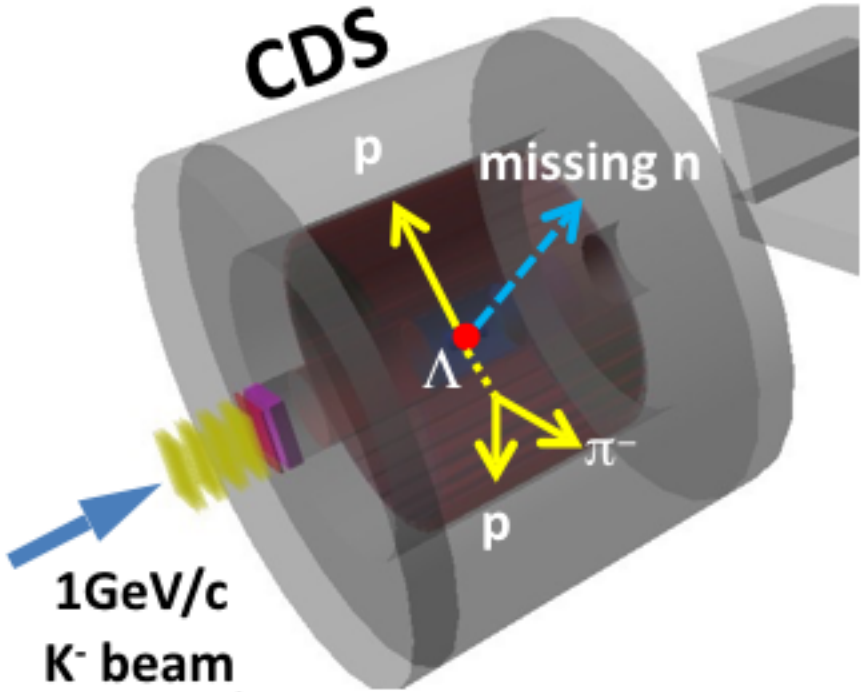
J-PARC E15 Collaboration
Y. Sada[1,*], S. Ajimura[1], M. Bazzi[2], G. Beer[3], H. Bhang[4], M. Bragadirea
L. Busso[7,9], M. Cargnelli[6], S. Choi[4], C. Curceanu[2], S. Enomoto[8], D. Fa
Y. Fujiwara[11], T. Fukuda[12], C. Guaraldo[2], T. Hashimoto[13], R. S. Hayanc
M. Iio[8], M. Iliescu[2], K. Inoue[1], Y. Ishiguro[10], T. Ishikawa[11], S. Ishimotc
K. Itahashi[13], M. Iwai[8], M. Iwasaki[13,14], Y. Kato[13], S. Kawasaki[15], P. Ki
Y. Ma[13], J. Marton[6], Y. Matsuda[17], Y. Mizoi[12], O. Morra[7], T. Nagae[10], I
H. Ohnishi[13,1], S. Okada[13], H. Outa[13], K. Piscicchia[2], A. Romero Vidal
F. Sakuma[13], M. Sato[13], A. Scordo[2], M. Sekimoto[8], H. Shi[2], D. Sirghi[2,
K. Suzuki[6], S. Suzuki[8], T. Suzuki[11], K. Tanida[18], H. Tatsuno[19], M. Tok
A. Toyoda[8], K. Tsukada[20], O. Vazquez Doce[2,21], E. Widmann[6], B. K. W
T. Yamaga[15], T. Yamazaki[11,13], H. Yim[22], Q. Zhang[13], and J. Zmeska[6]

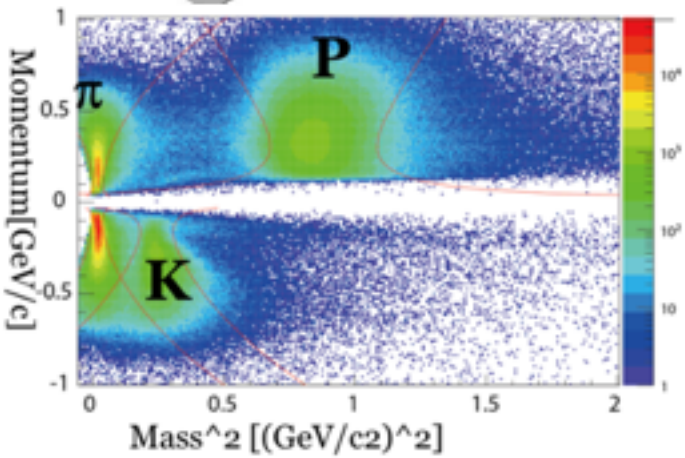


Exclusive $^3He(K^-, \Lambda p)n$ events



Exclusive $^3He(K^-, \Lambda p)n$ events





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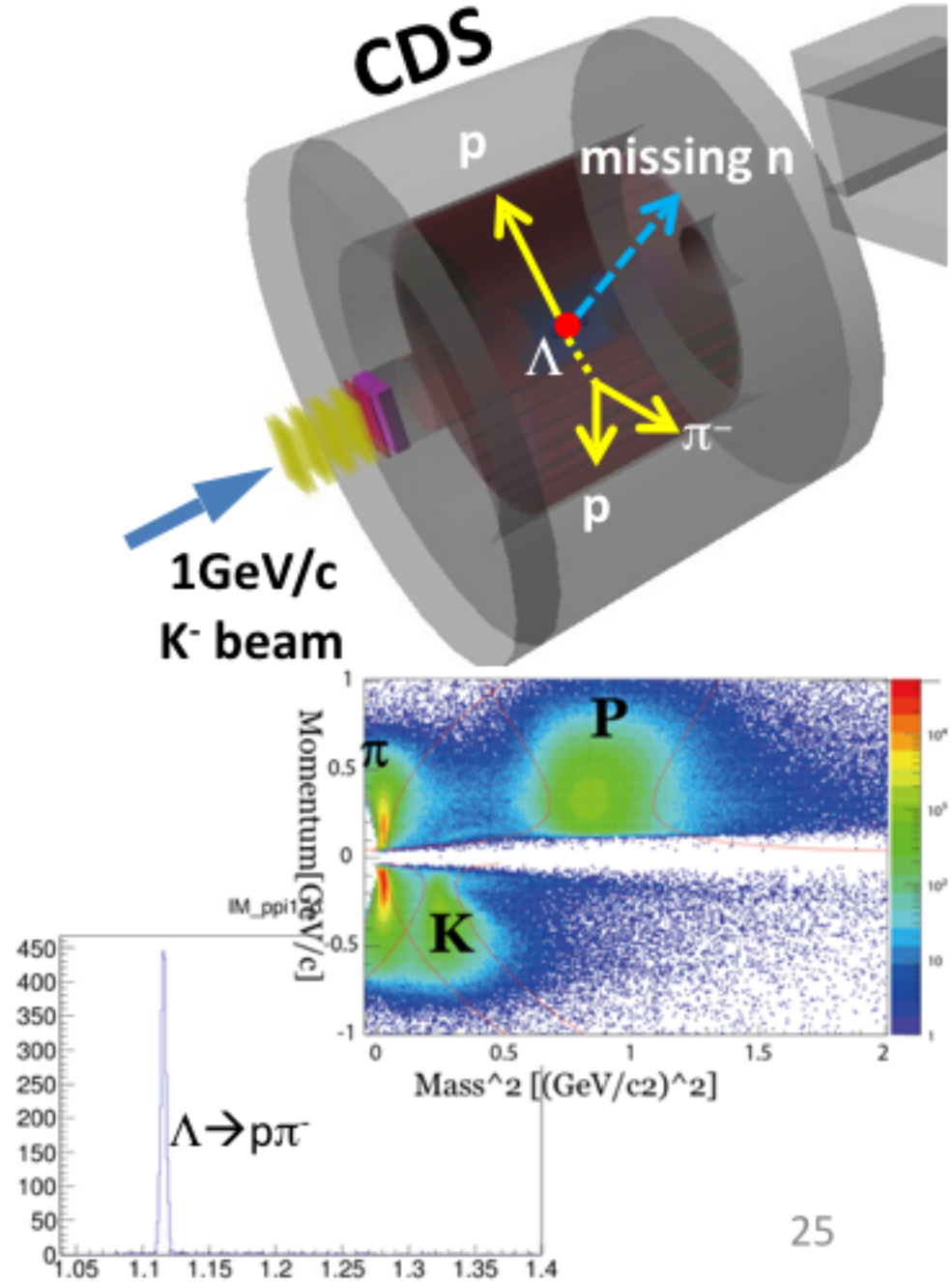

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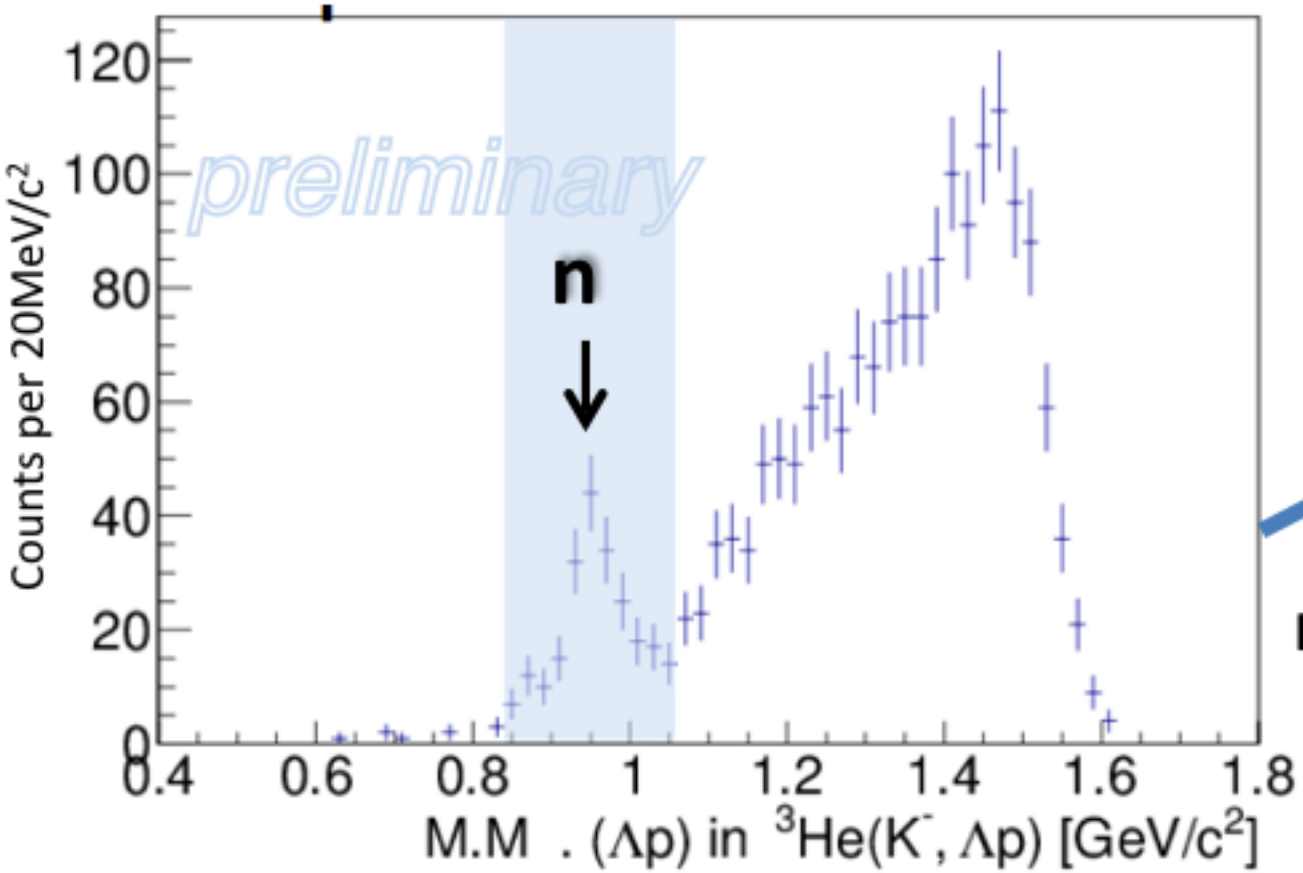
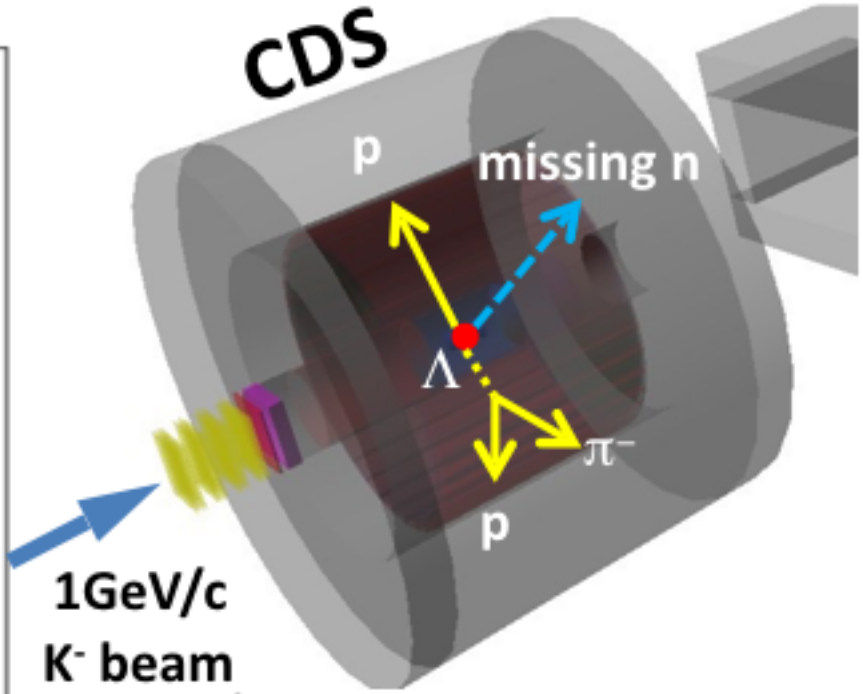
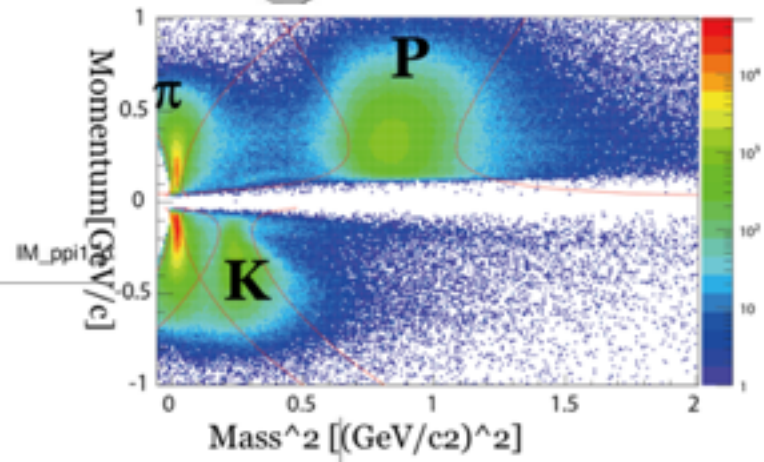
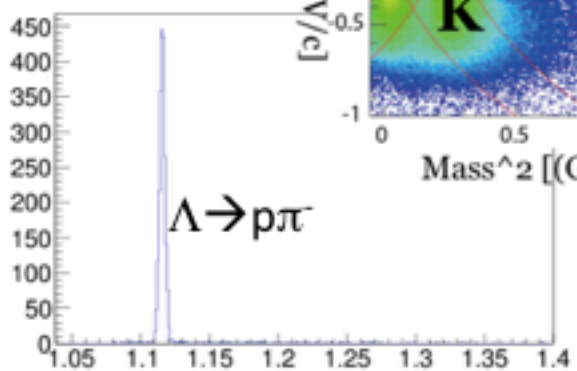
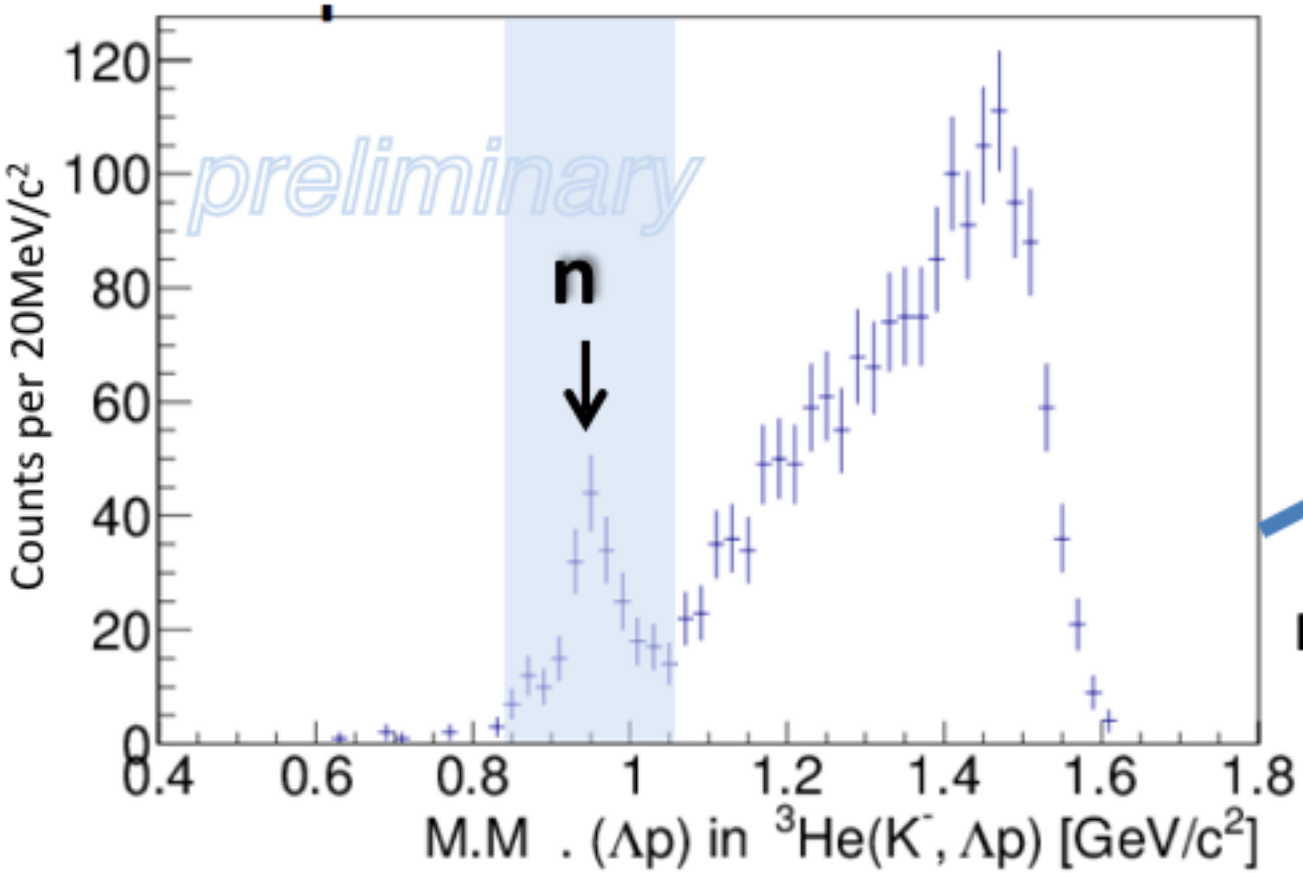


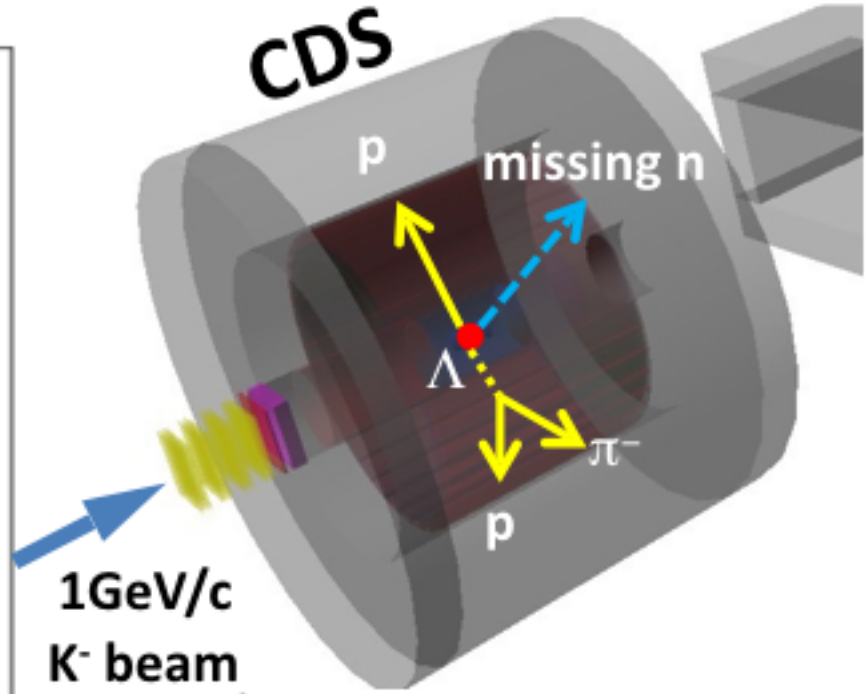


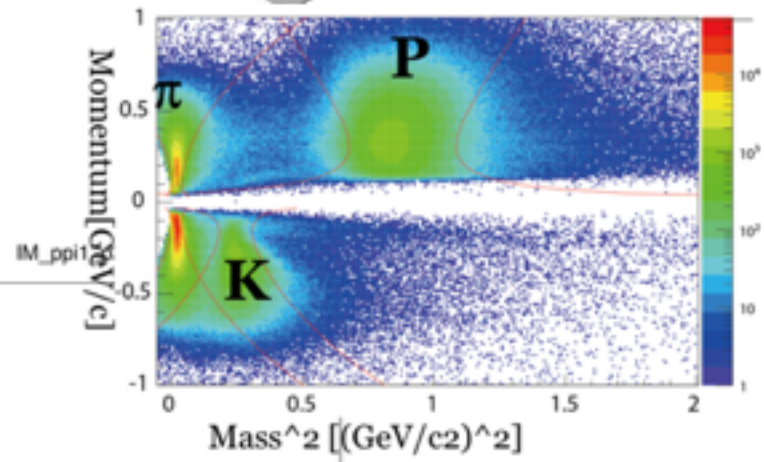


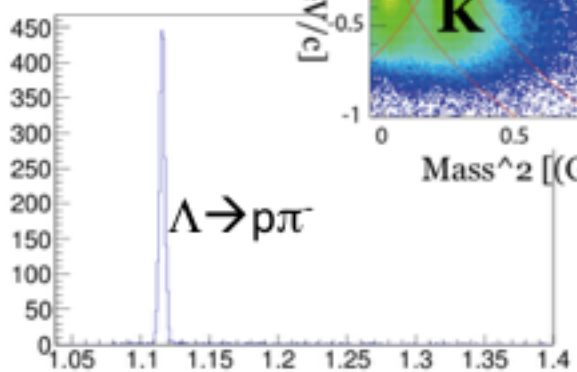


Exclusive ^{3}He(K$^-$, Λp)n events



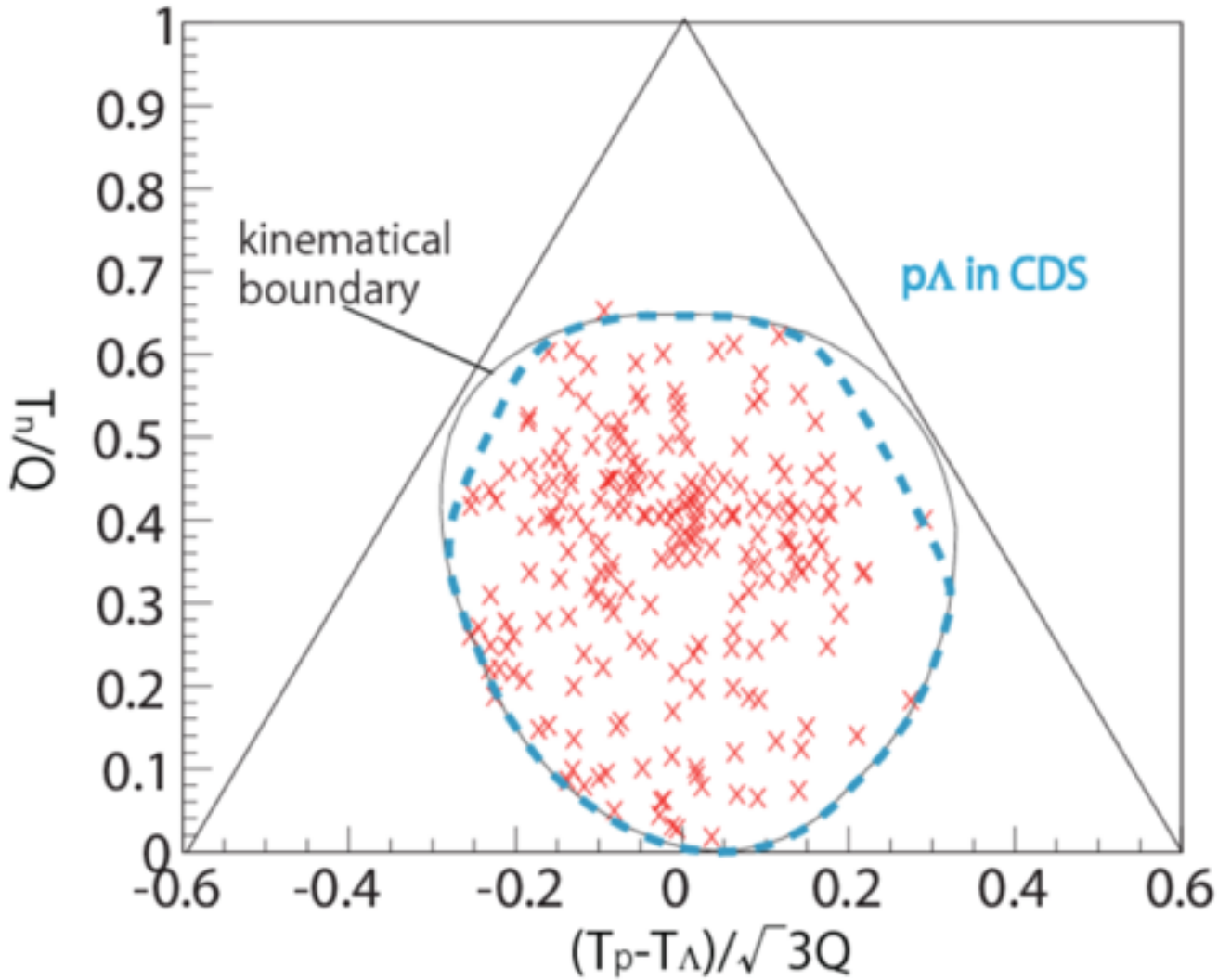




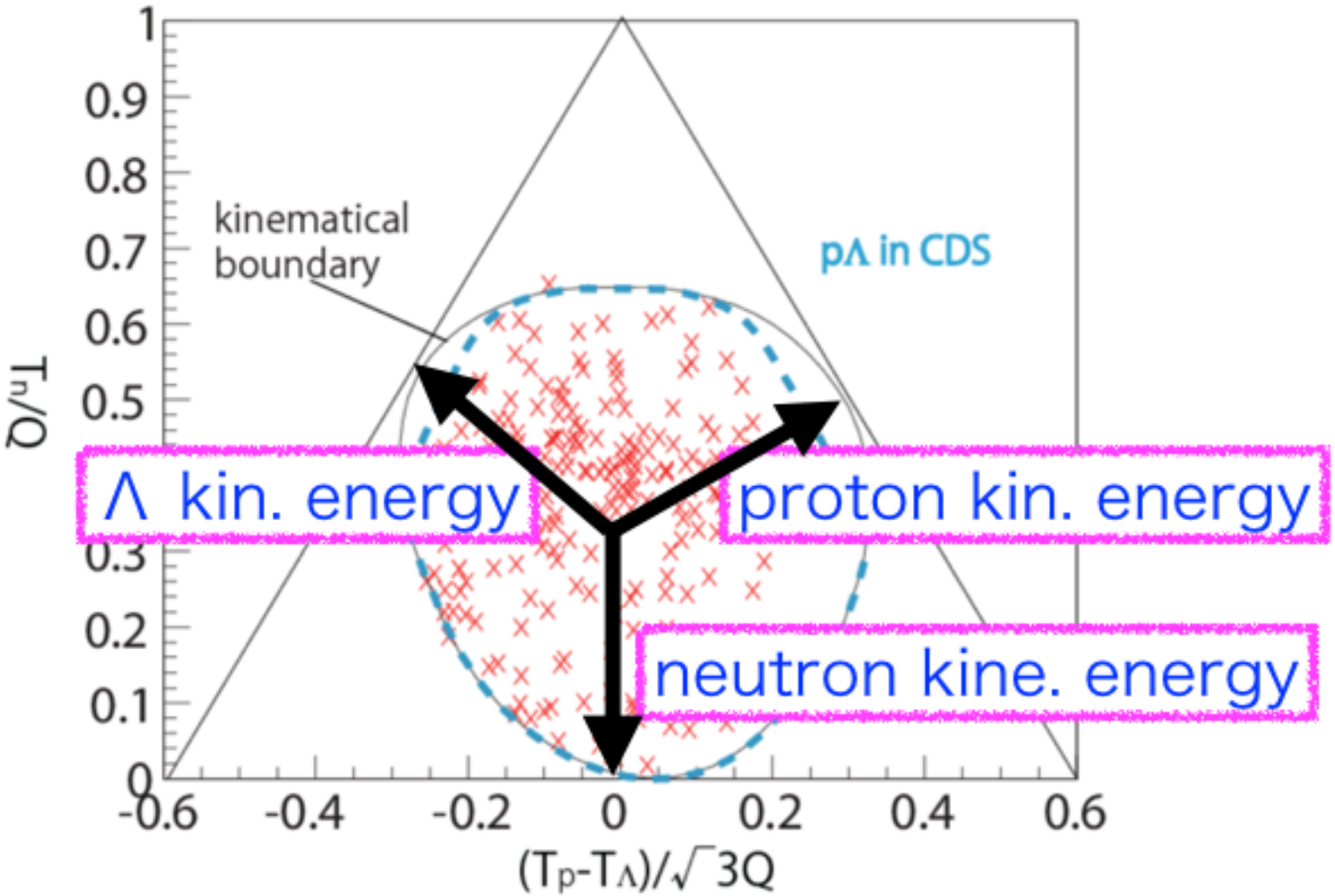


- **K$^-$^{3}He→Λ(Σ^0)pn events can be identified exclusively**
  - # of Λ(Σ^0)pn events: ~200
    - Σ^{0}pn contamination: ~20%

Kinematical distribution of Λpn final state



Kinematical distribution of Λpn final state



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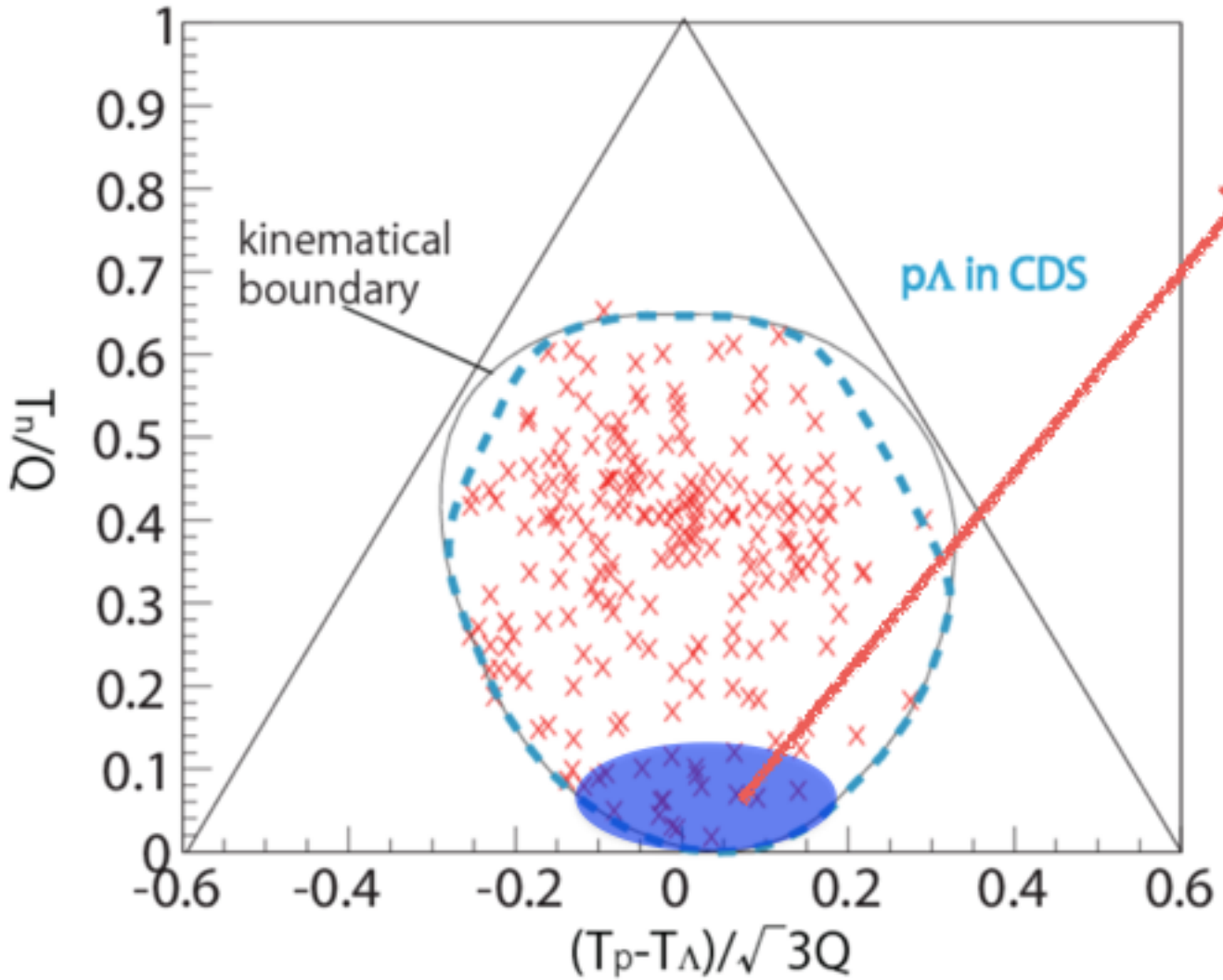
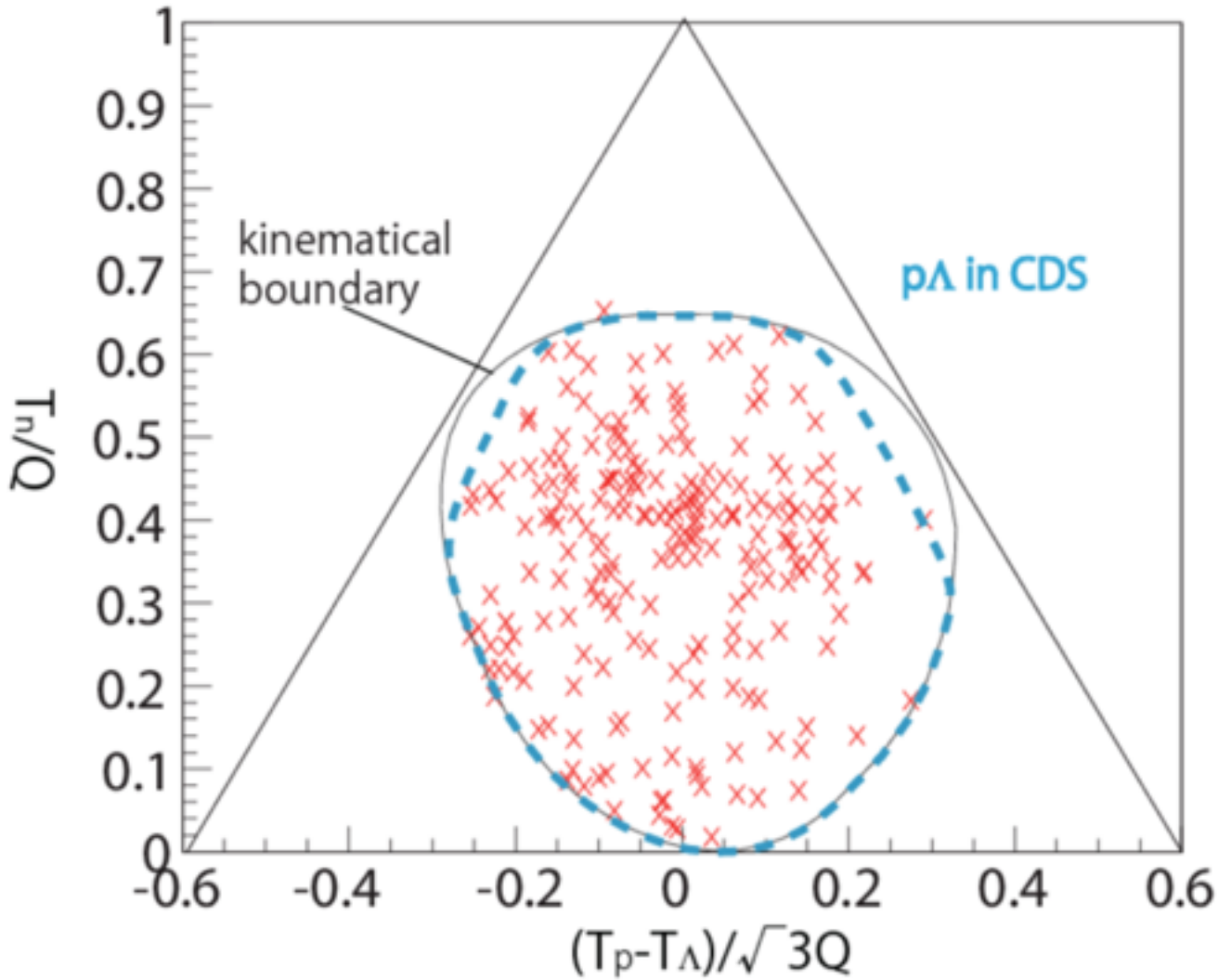


neutron spectator event (2NA) will be appeared here!

we have good acceptance for neutron spectator 2NA events

Kinematical distribution of Λpn final state



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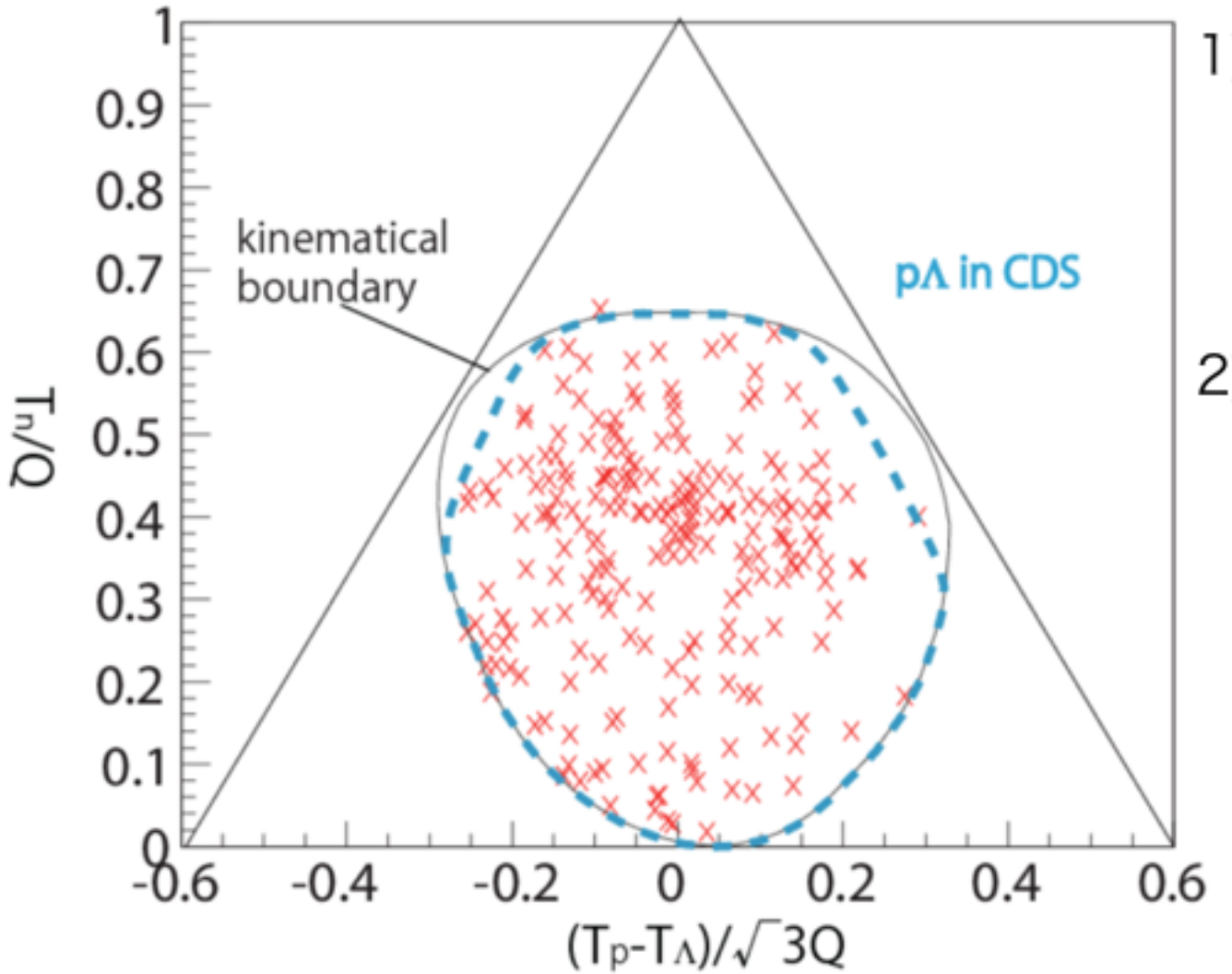
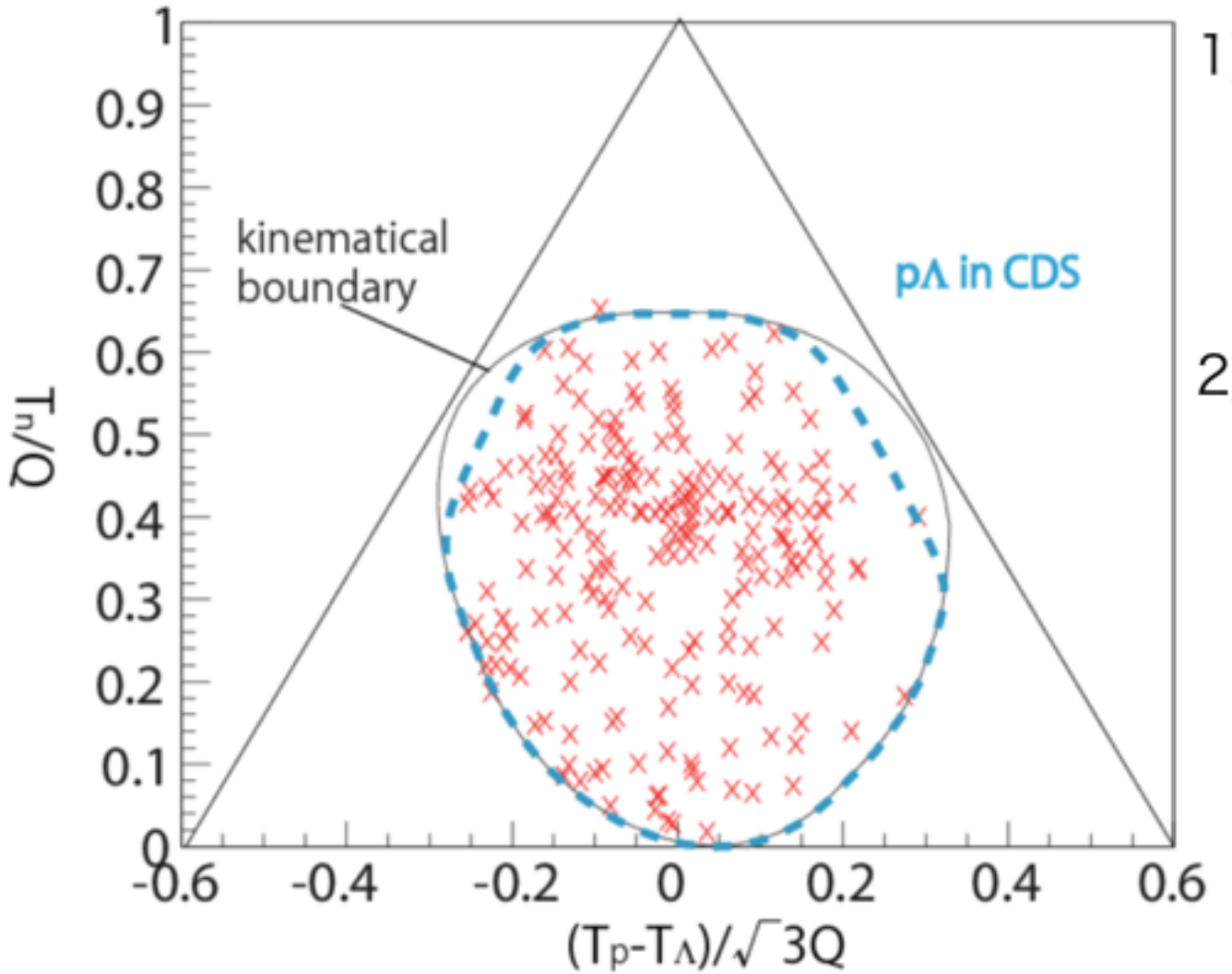


1) event widely distributed
   -> energy for kaon is equally distributed to 3 nucleons
2) 2NA absorption is not observed clearly
   (it was one of the major contribution in a kaon at rest)

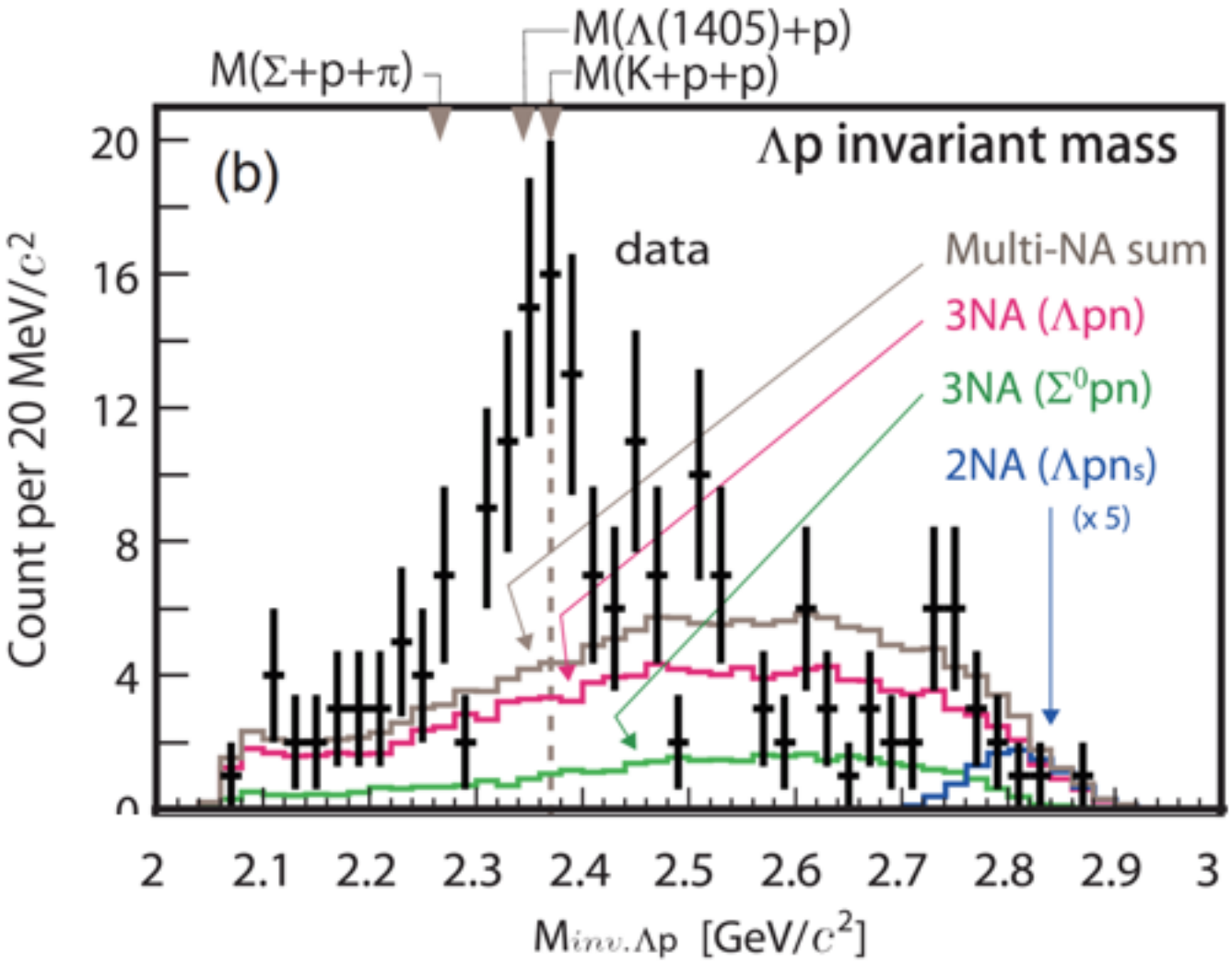
Kinematical distribution of Λpn final state



1) event widely distributed
   -> energy for kaon is equally distributed to 3 nucleons
2) 2NA absorption is not observed clearly
   (it was one of the major contribution in a kaon at rest)

Can we see any structure?

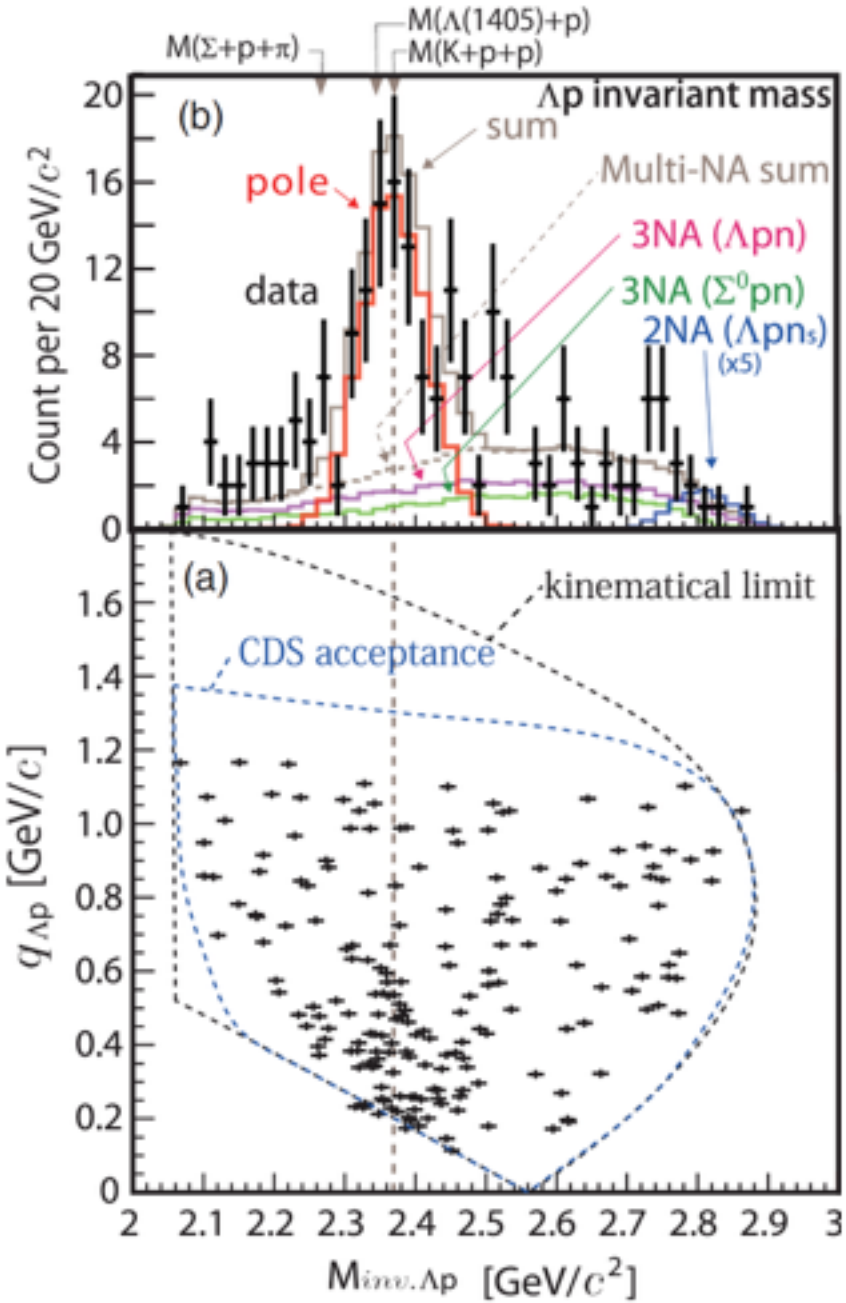
Exclusive ^{3}He(K$^-$,Λp)n can be described by 3NA?



- contribution from 2NA seems very minor
- The spectrum CANNOT be reproduced by only 3NA
- Clear structure is seen around the threshold

Momentum Transfer of (K^-,n) reaction

Mom. Trans. of (K^-,n) vs. IM(Λp)



- **low-momentum transfer seems to be enhanced around the threshold**

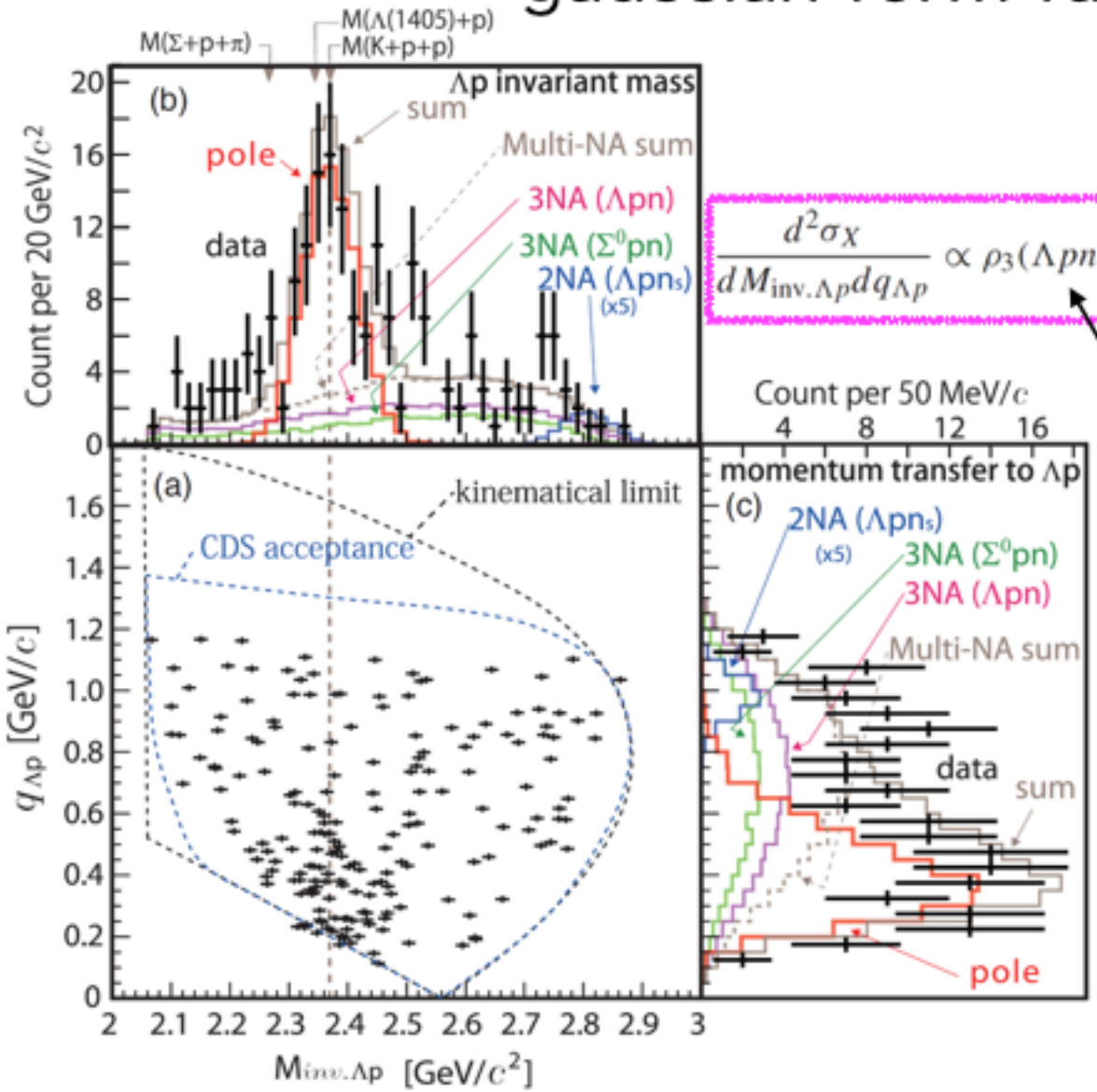
possible candidates

- Λ(1405) production in 2NA followed by $\Lambda^* p_s \rightarrow \Lambda p$?
- S=-1 di-baryon state of $X \rightarrow \Lambda p$?

Could the structure be a di-baryon?

assume

- single pole resonance with Breit-Wigenr line shape (Mx, Γx)
- gaussian form factor (with Qx)



Breit-Wigenr

$$\frac{d^2\sigma_X}{dM_{\mathrm{inv.}\Lambda p}\,dq_{\Lambda p}} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{\mathrm{inv.}\Lambda p}-M_X)^2+(\Gamma_X/2)^2} \times \left|\exp\left(-q_{\Lambda p}^2/2Q_X^2\right)\right|^2$$

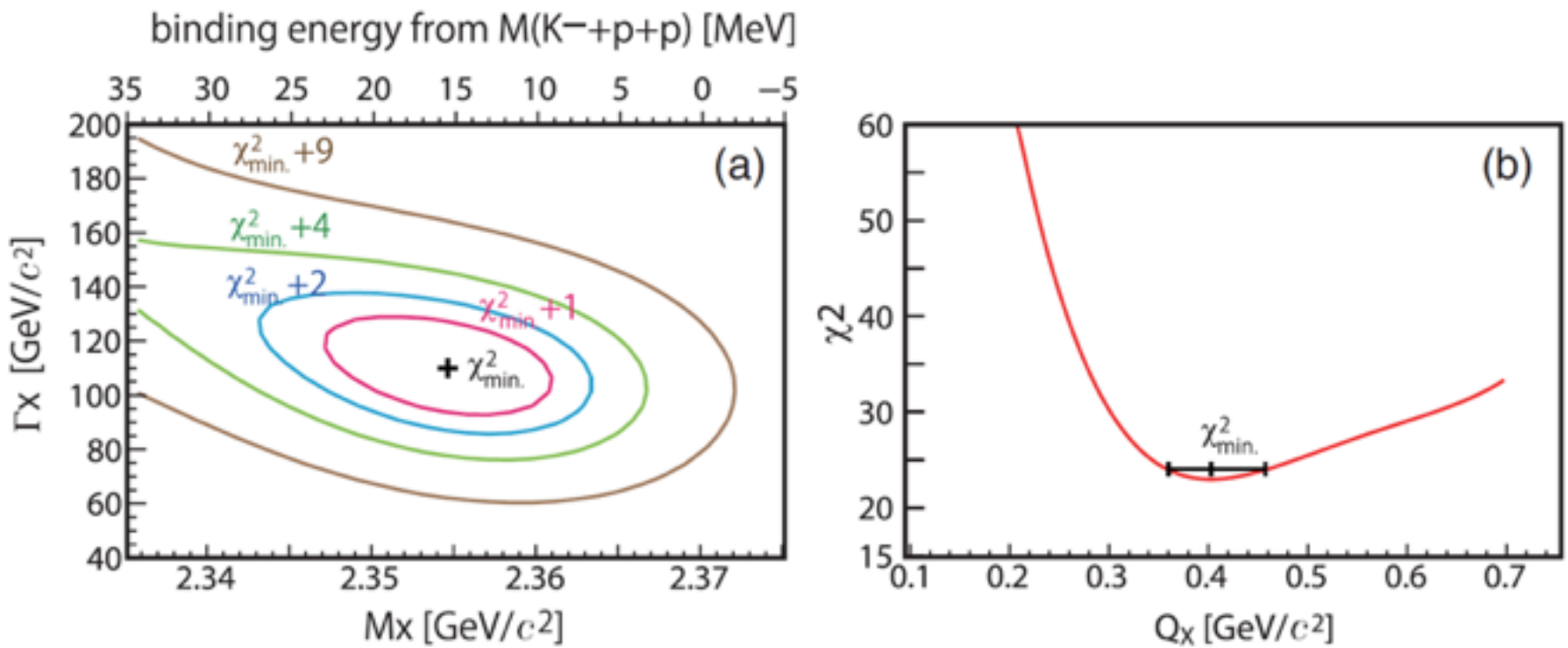
Lorentz invariant phase-space

Form factor

$\chi 2$ test have been performed including processes like 2NA and 3NA reaction

Could the structure be a di-baryon?

$$\frac{d^2\sigma_X}{dM_{\mathrm{inv.}\Lambda p}dq_{\Lambda p}} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{\mathrm{inv.}\Lambda p}-M_X)^2+(\Gamma_X/2)^2} \times \left|\exp\left(-q^2_{\Lambda p}/2Q^2_X\right)\right|^2$$



$$M_X = 2355^{+6}_{-8}(stat.) \pm 12(syst.)\ \mathrm{MeV/c^2}$$

$$\Gamma_X = 110^{+19}_{-17}(stat.) \pm 27(syst.)\ \mathrm{MeV/c^2}$$

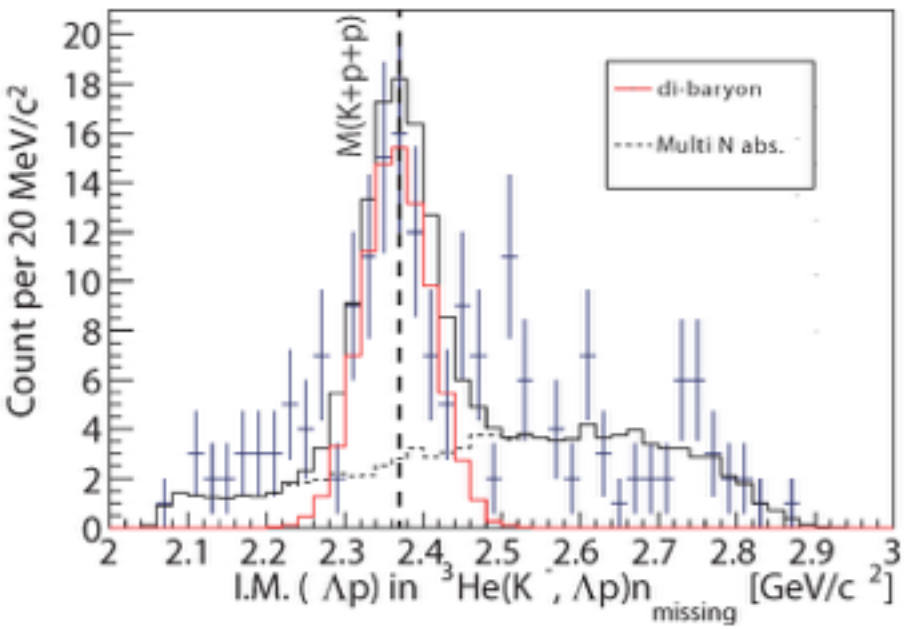
$$Q_X = 400^{+60}_{-40}\ \mathrm{MeV/c}$$

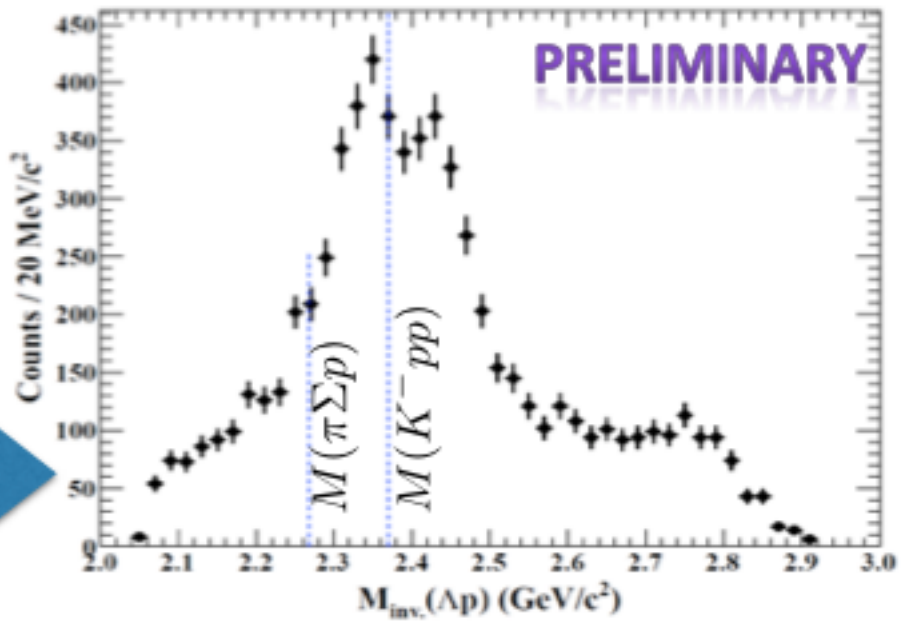
→ $B_X \sim 15\ \mathrm{MeV/c^2}$
shallow potential?

→ 0.5 fm?
compact system?

Detail analysis to investigate structure near K-pp threshold is in progress

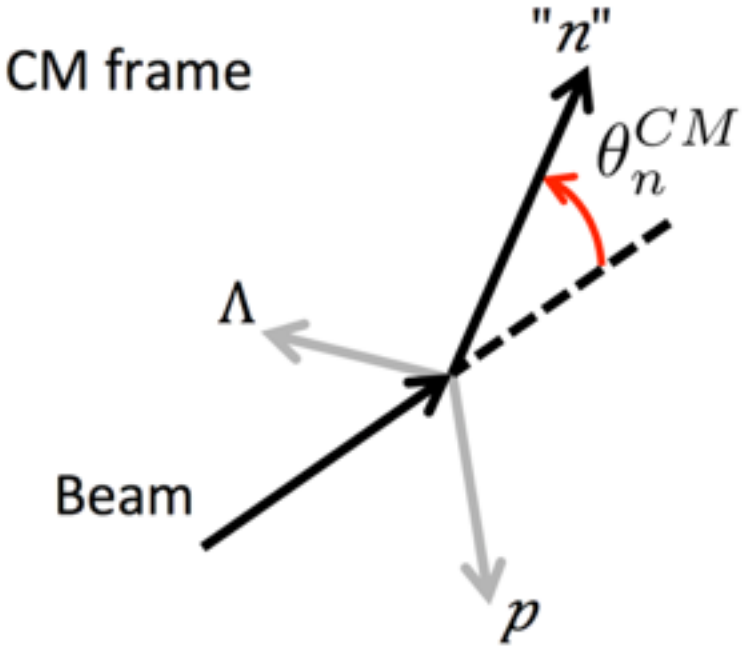
30 times more data are taken in 2015

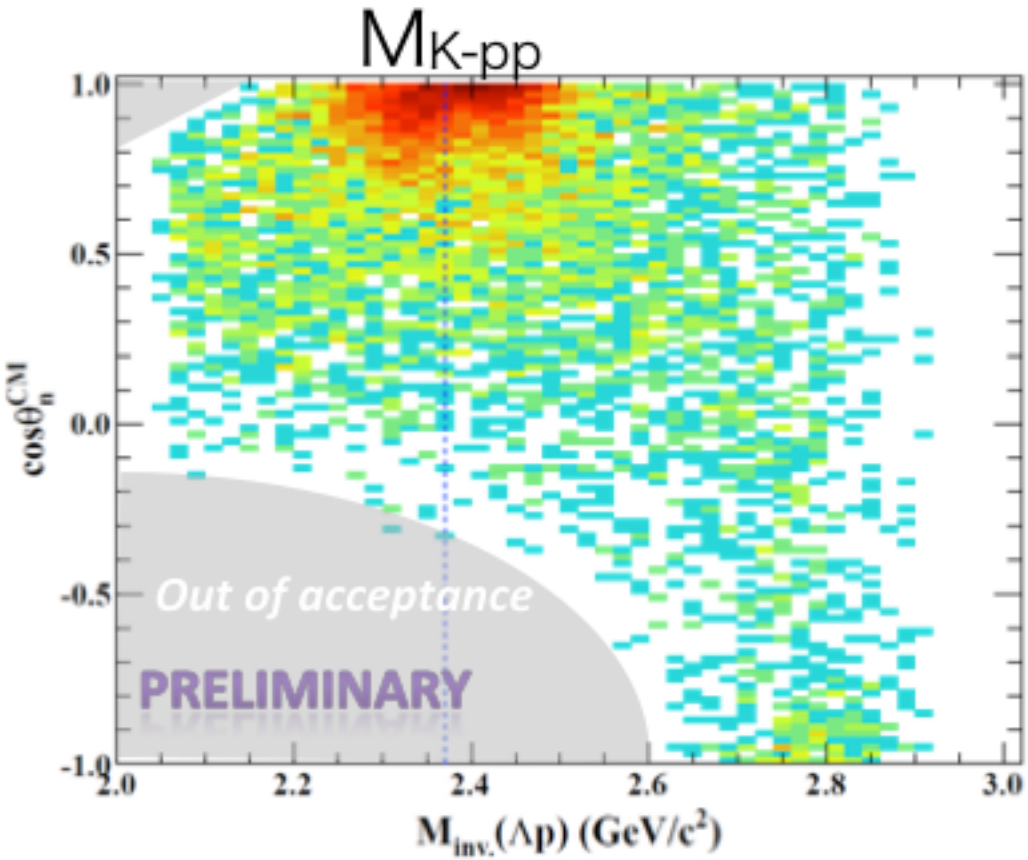




Global structure seems to be confirmed

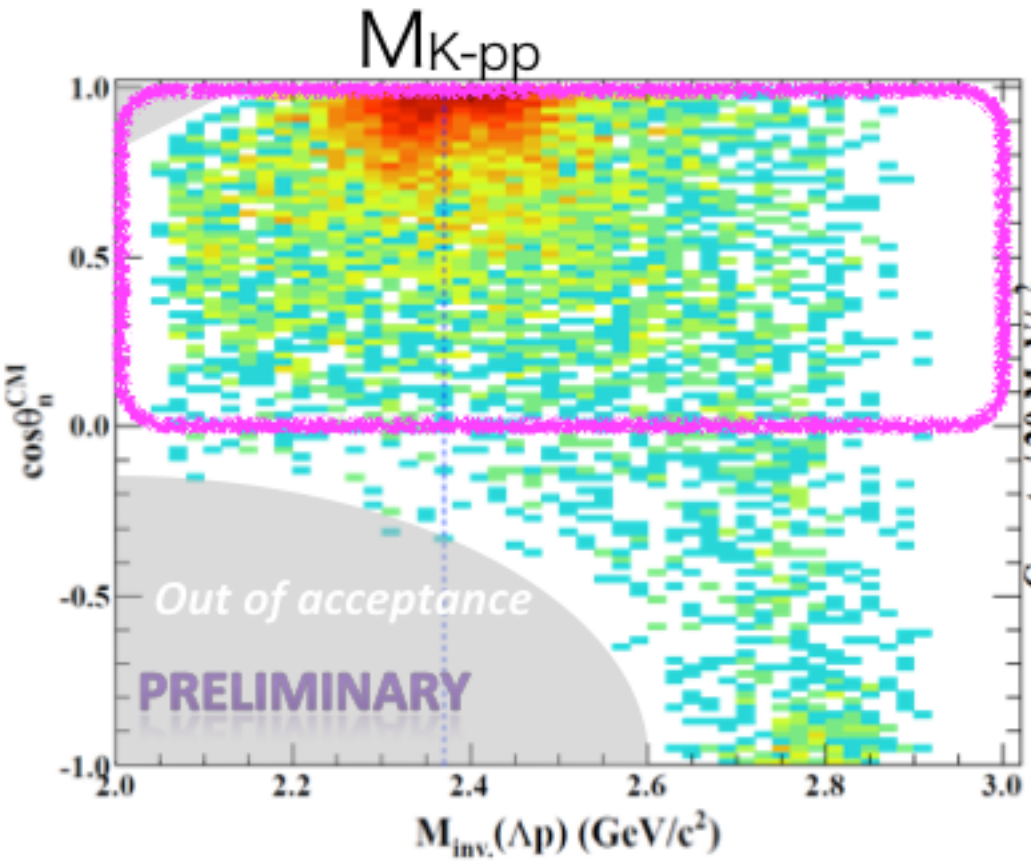
Λp invariant mass v.s. neutron emission angle

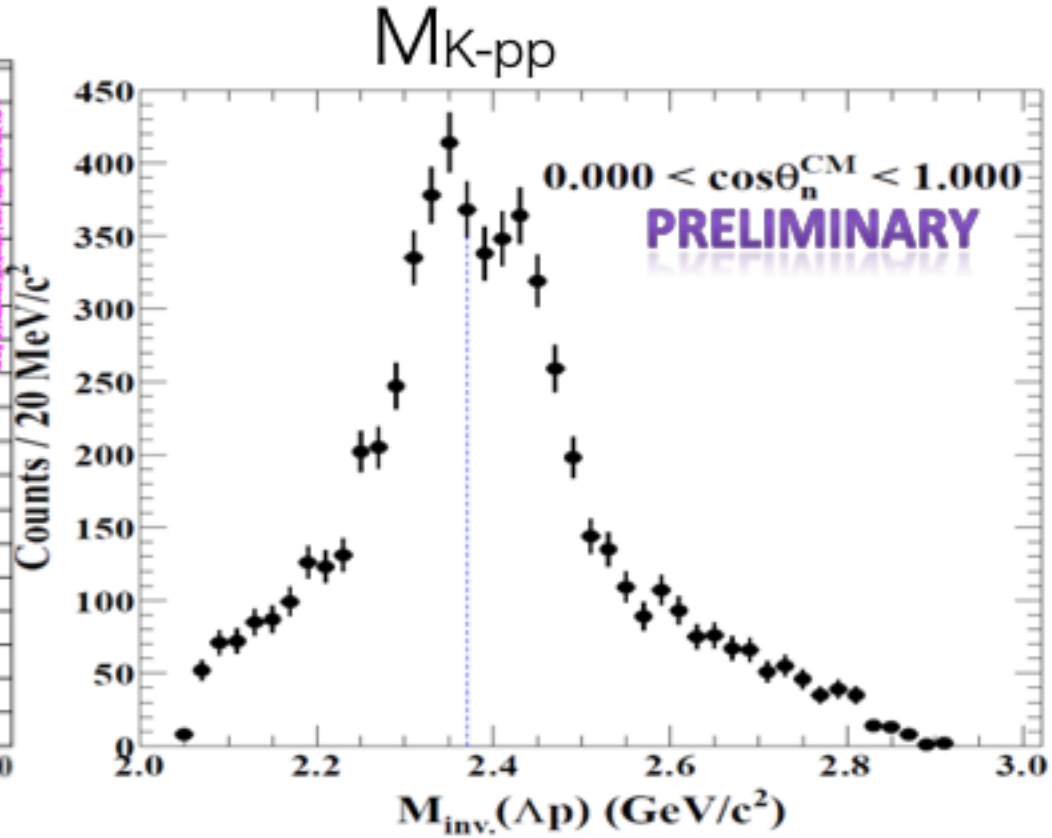




Events clearly concentrated around K⁻pp threshold when neutron emitted to forward direction

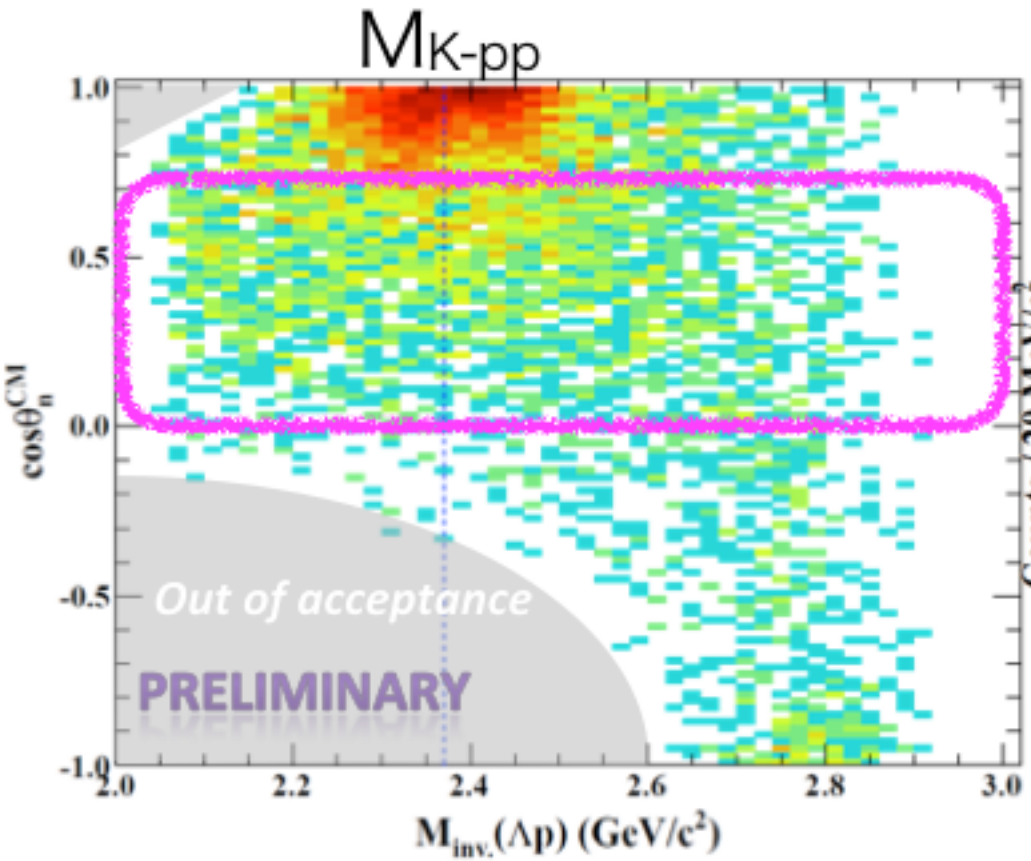
Invariant mass as a function of $\cos(\theta_n)$

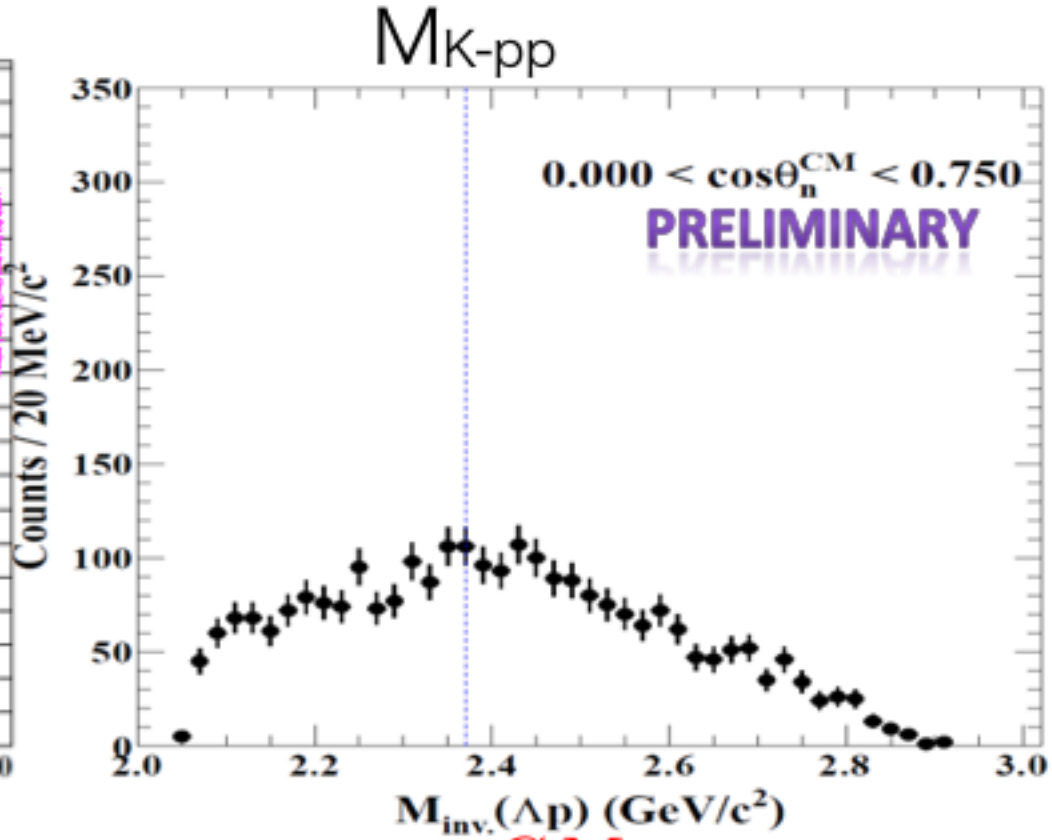




$$0 < \cos(\theta_n^{CM}) < 1.0$$

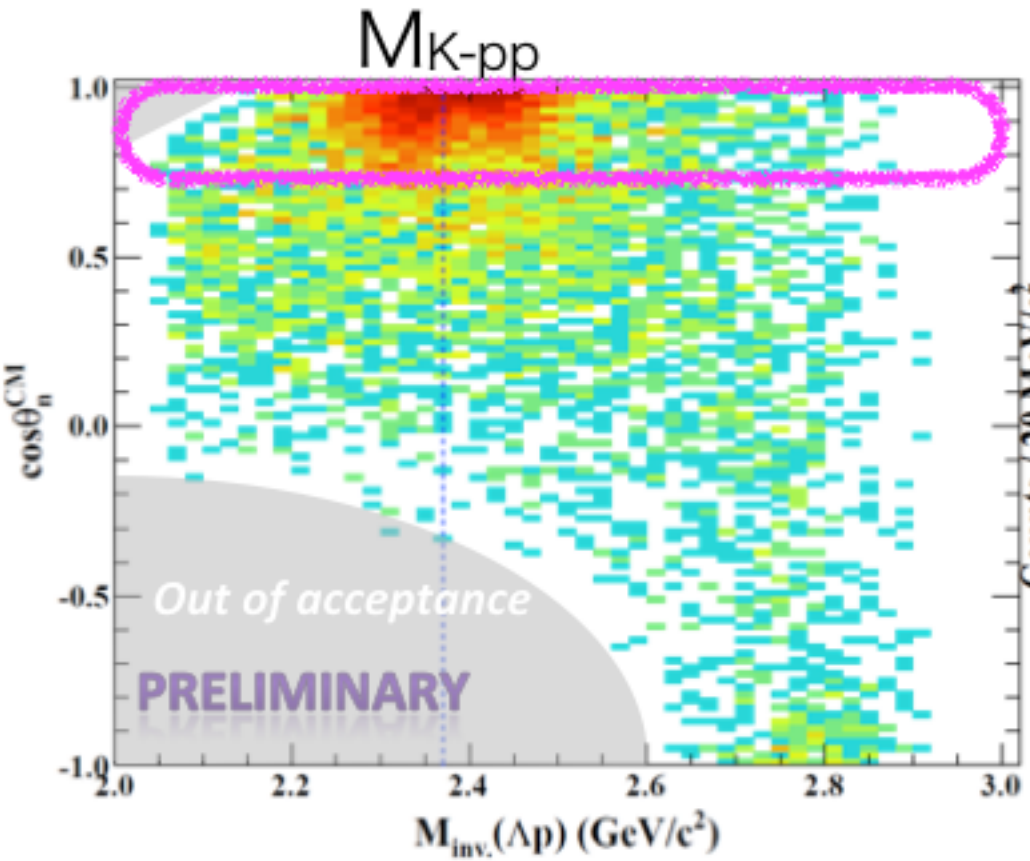
Invariant mass as a function of $\cos(\theta_n)$

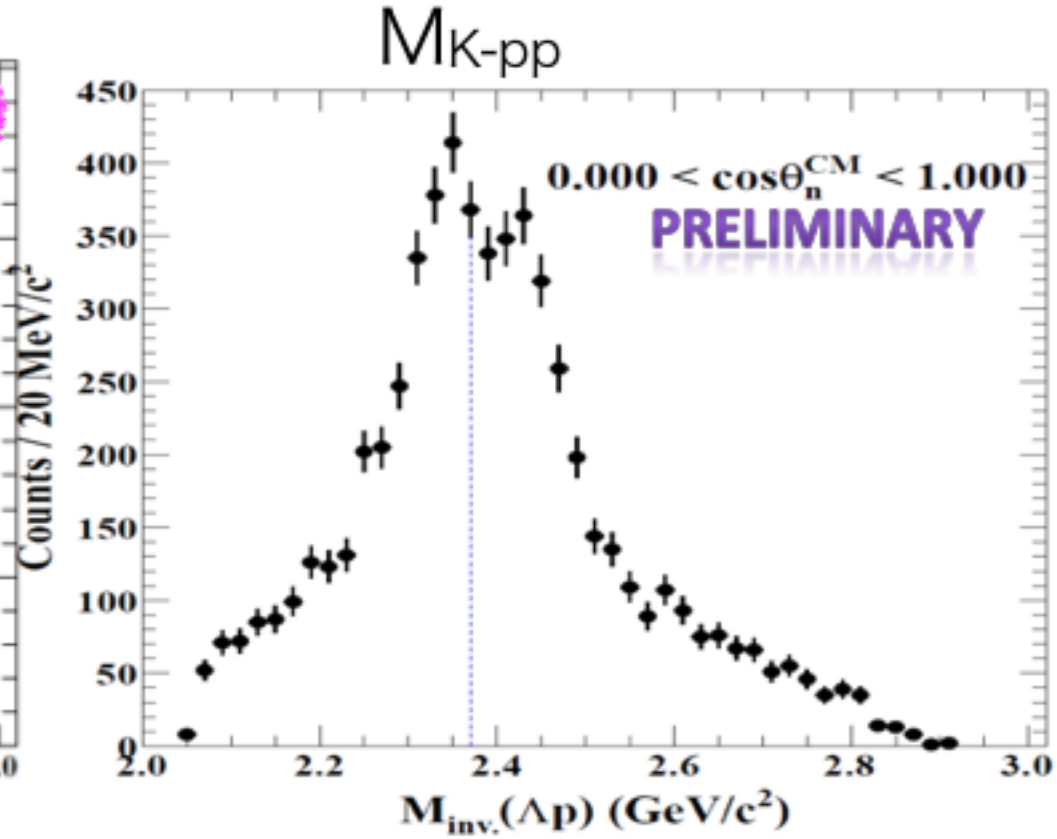




$$0 < \cos(\theta_n^{CM}) < 0.75$$

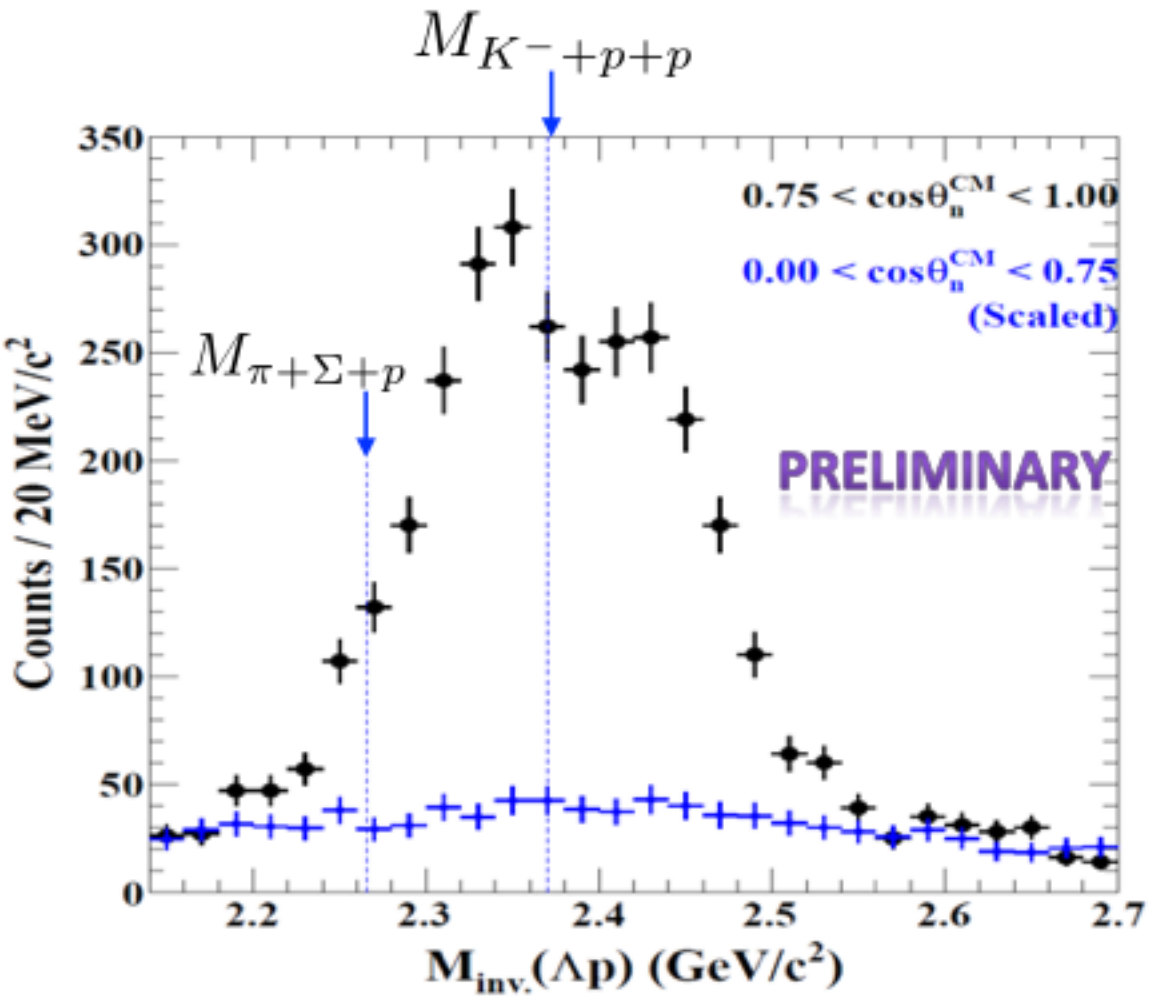
Invariant mass as a function of $\cos(\theta_n)$



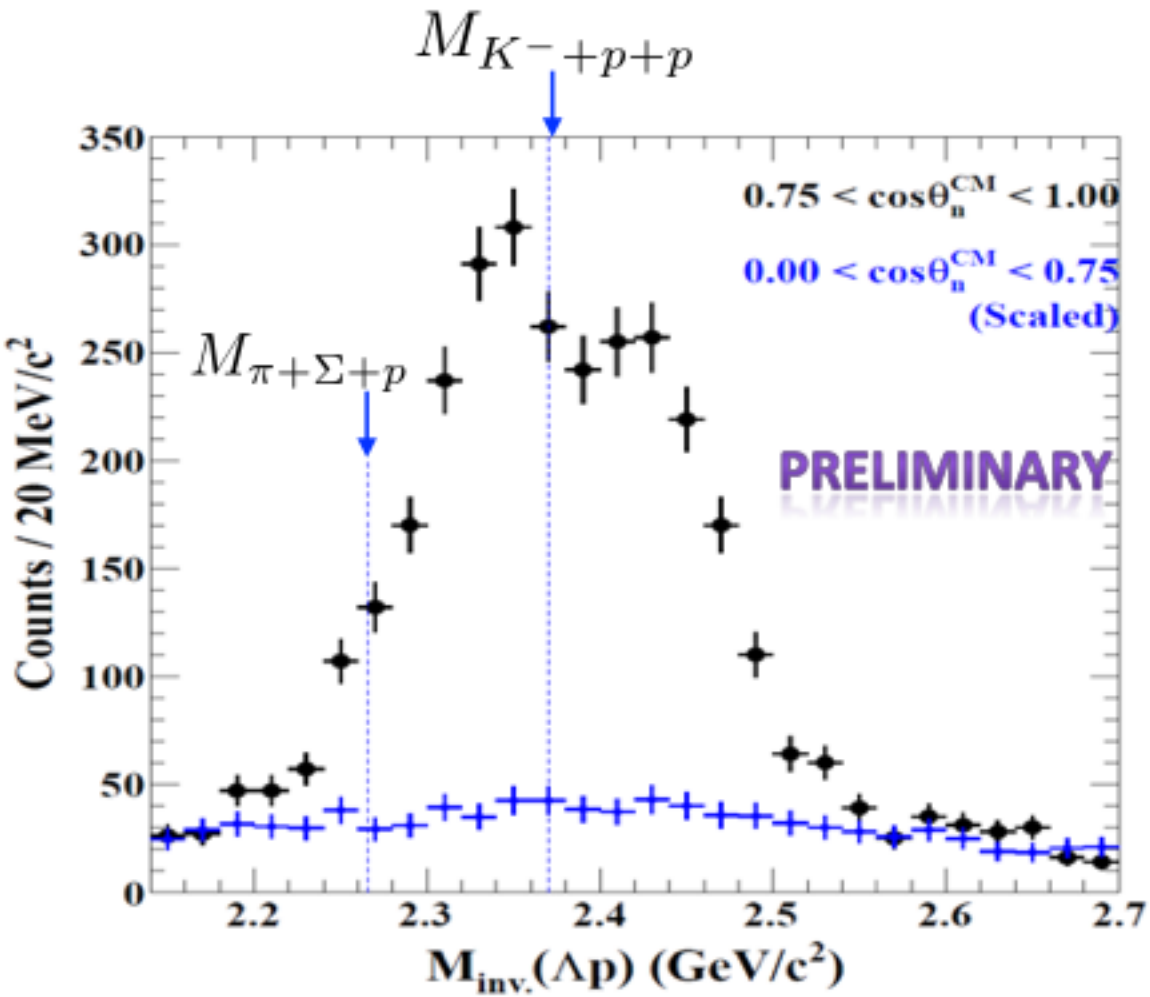


$$0.75 < \cos(\theta_n^{CM}) < 1.0$$

Λp invariant mass

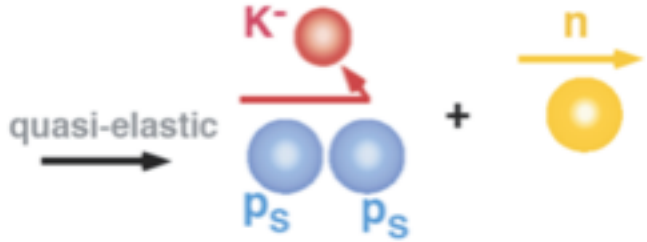


Λp invariant mass



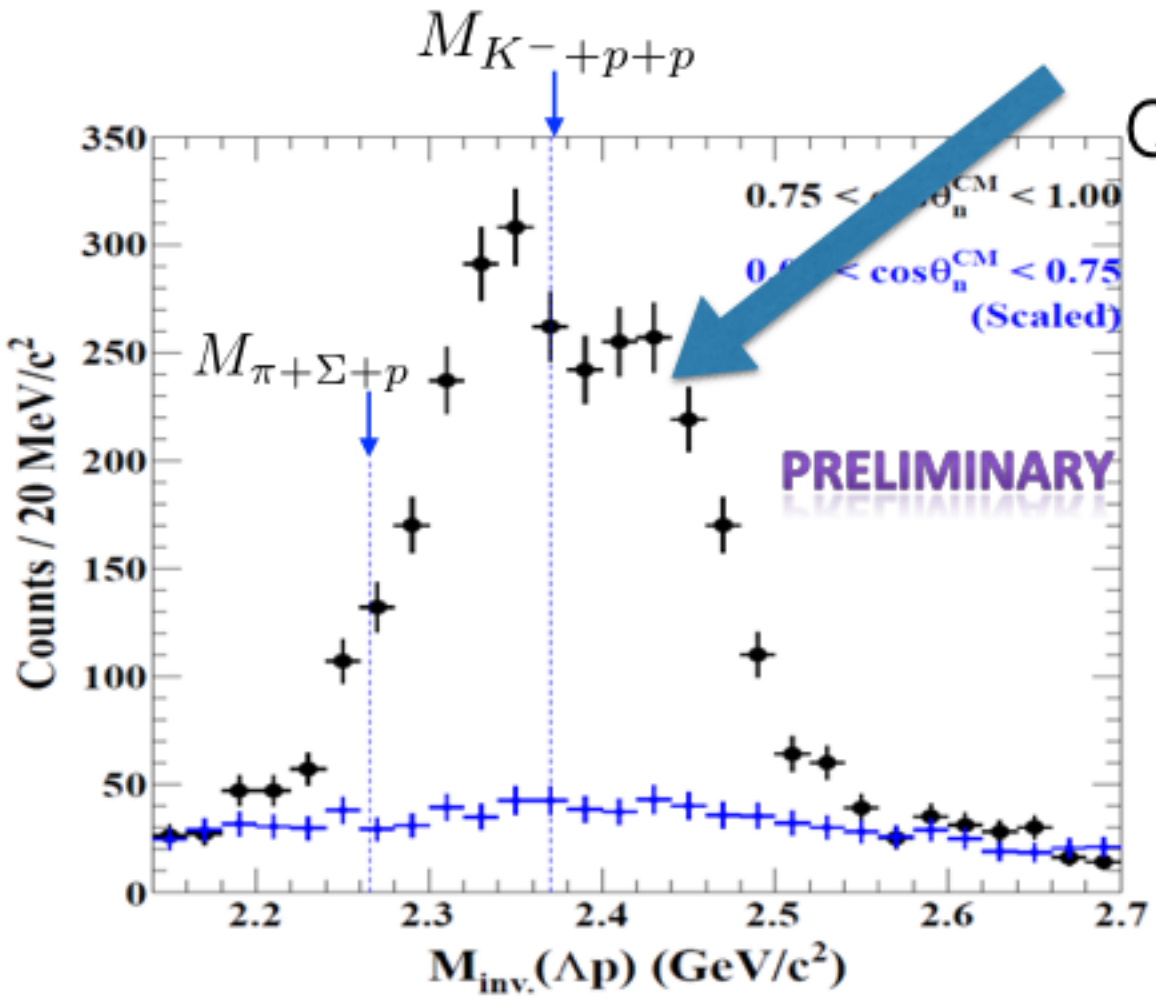
Two components may exist

Λp invariant mass



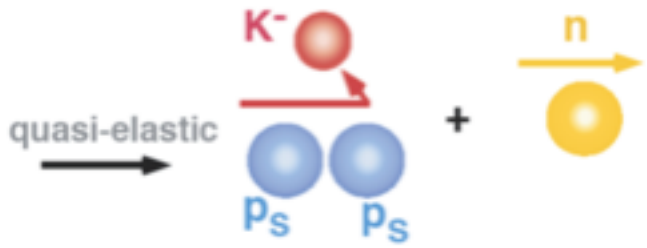
un bound :

Quasi-elastic?



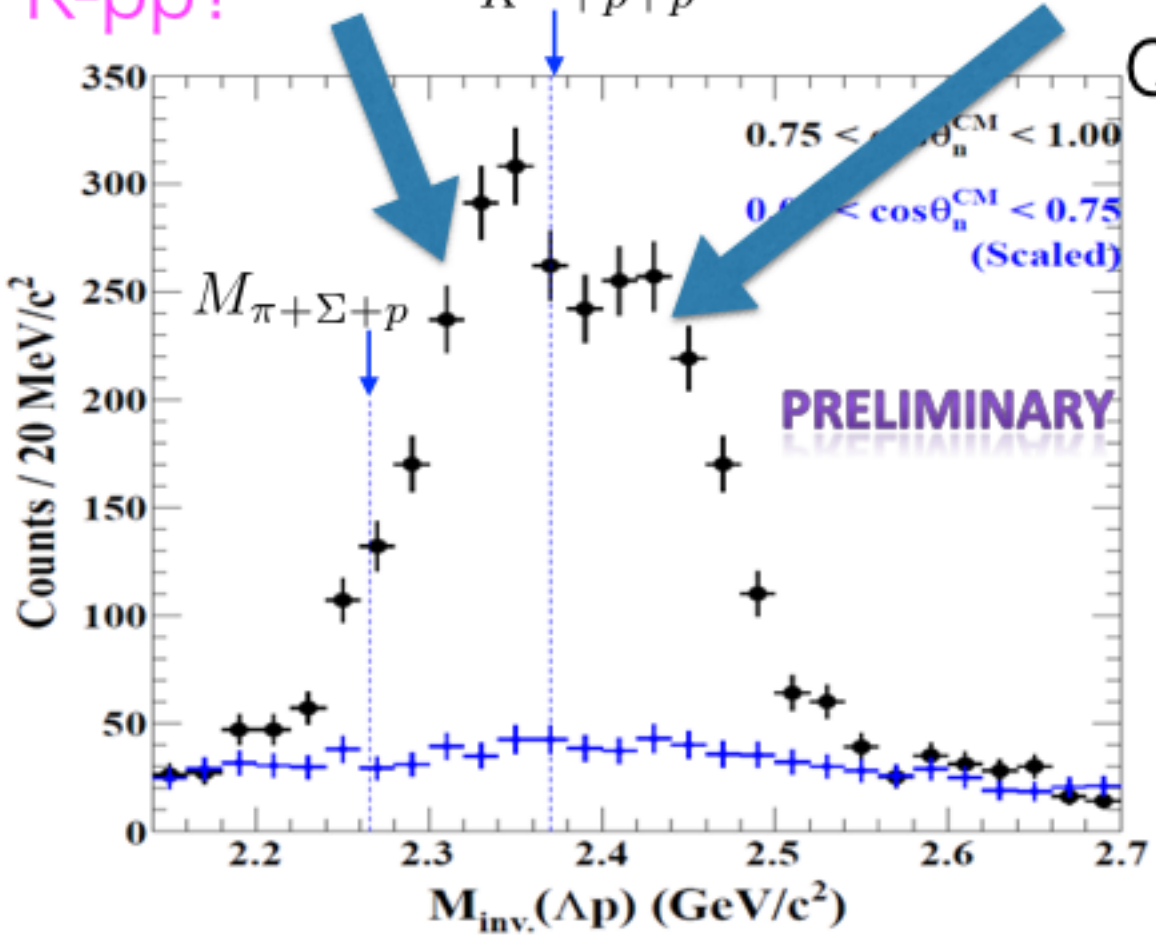
Two components may exist

Λp invariant mass



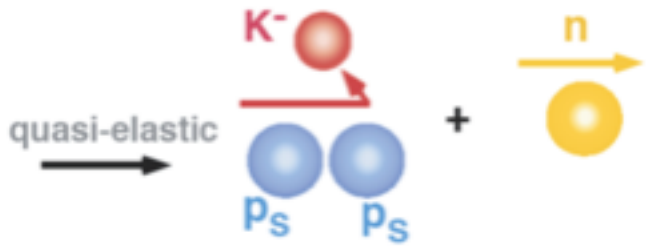
Signal from K-pp?

un bound : Quasi-elastic?



Two components may exist

Λp invariant mass

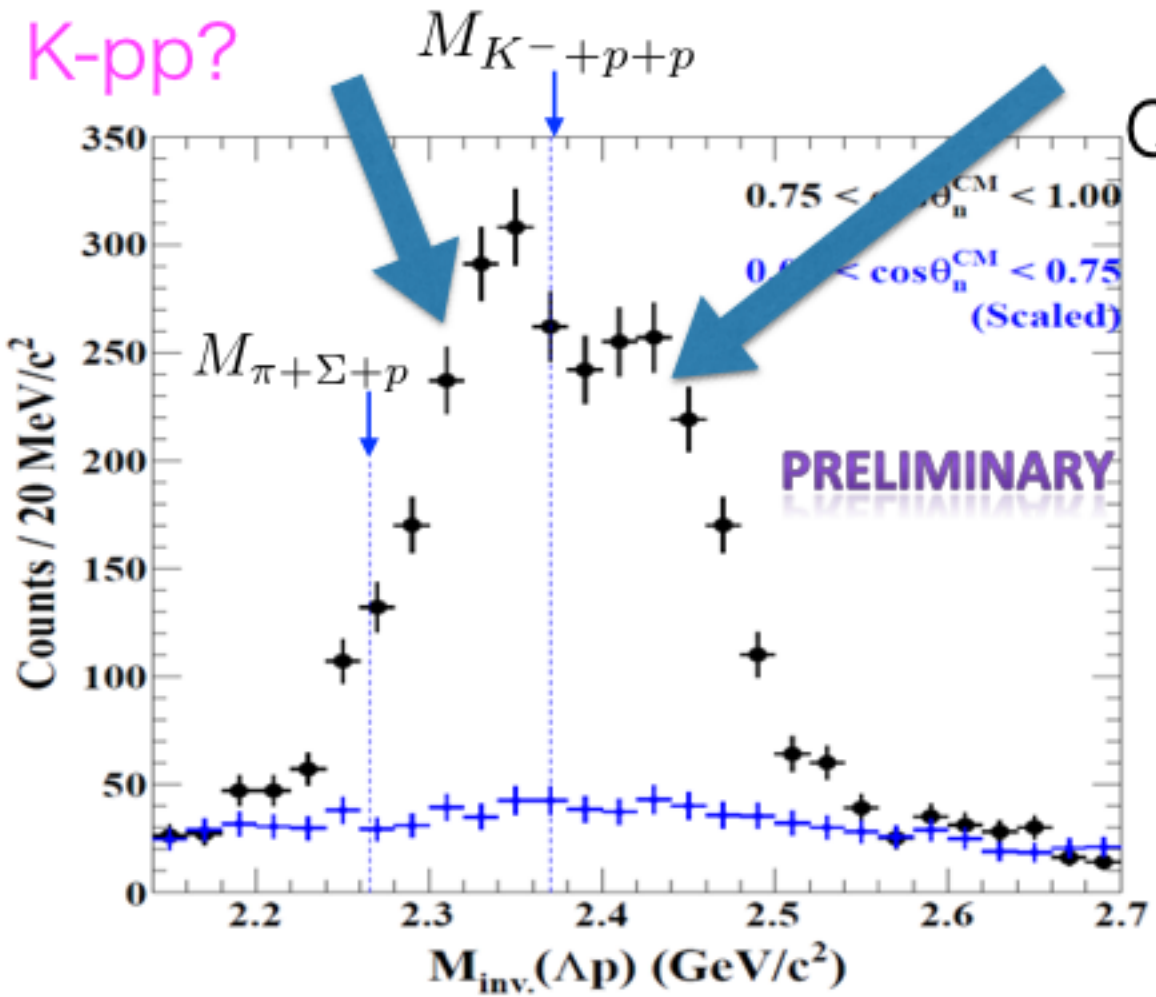


un bound :

Quasi-elastic?

Signal from

K-pp?



Two components may exist

Further detail analysis is in progress

Summary

- Interesting structure found in Λp invariant mass spectra on the K-pp production threshold via $^{3}He(K^{-},\Lambda p)n$ reaction
- The structure may strongly related with S=-1 dibaryon state

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$Mx \sim 2355\ MeV/c^2$, $\Gamma x \sim 100 MeV/c^2$

- Detail investigation on the structure with high statistics is in progress

The J-PARC E15 Collaboration

S. Ajimura[a], G. Beer[b], H. Bhang[c], M. Bragadireanu[e], P. Buehler[f], L. Busso[g,h], M. Cargnelli[f], S. Choi[c], C. Curceanu[d], S. Enomoto[i], D. Faso[g,h], H. Fujioka[j], Y. Fujiwara[k], T. Fukuda[l], C. Guaraldo[d], T. Hashimoto[k], R. S. Hayano[k], T. Hiraiwa[a], M. Iio[o], M. Iliescu[d], K. Inoue[i], Y. Ishiguro[j], T. Ishikawa[k], S. Ishimoto[o], T. Ishiwatari[f], K. Itahashi[n], M. Iwai[o], M. Iwasaki[m,n*], Y. Kato[n], S. Kawasaki[i], P. Kienle[p], H. Kou[m], Y. Ma[n], J. Marton[f], Y. Matsuda[q], Y. Mizoi[l], O. Morra[g], T. Nagae[j$], H. Noumi[a], H. Ohnishi[n], S. Okada[n], H. Outa[n], K. Piscicchia[d], M. Poli Lener[d], A. Romero Vidal[d], Y. Sada[j], A. Sakaguchi[i], F. Sakuma[n], M. Sato[n], A. Scordo[d], M. Sekimoto[o], H. Shi[k], D. Sirghi[d,e], F. Sirghi[d,e], K. Suzuki[f], S. Suzuki[o], T. Suzuki[k], K. Tanida[c], H. Tatsuno[d], M. Tokuda[m], D. Tomono[n], A. Toyoda[o], K. Tsukada[r], O. Vazquez Doce[d,s], E. Widmann[f], B. K. Weunschek[f], T. Yamaga[i], T. Yamazaki[k,n], H. Yim[t], Q. Zhang[n], and J. Zmeskal[f]

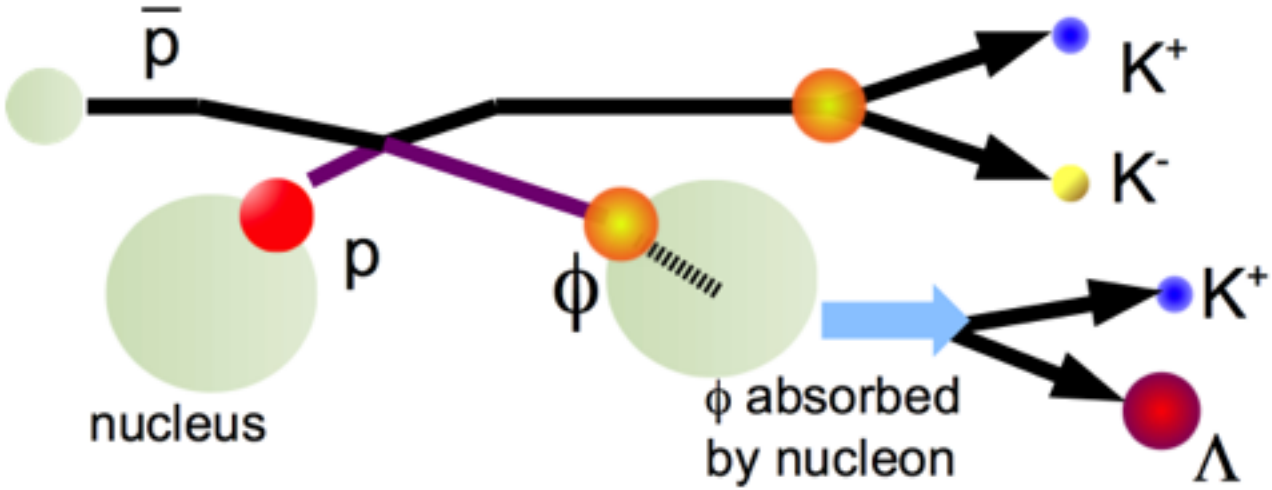
(a) Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan
(b) Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
(c) Department of Physics, Seoul National University, Seoul, 151-742, South Korea
(d) Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
(e) National Institute of Physics and Nuclear Engineering – IFIN HH, Romania
(f) Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria
(g) INFN Sezione di Torino, Torino, Italy
(h) Dipartimento di Fisica Generale, Universita' di Torino, Torino, Italy
(i) Department of Physics, Osaka University, Osaka, 560-0043, Japan
(j) Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
(k) Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
(l) Laboratory of Physics, Osaka Electro-Communication University, Osaka, 572-8530, Japan
(m) Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
(n) RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
(o) High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
(p) Technische Universität München, D-85748, Garching, Germany
(q) Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
(r) Department of Physics, Tohoku University, Sendai, 980-8578, Japan
(s) Excellence Cluster Universe, Technische Universität München, D-85748, Garching, Germany
(t) Korea Institute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea

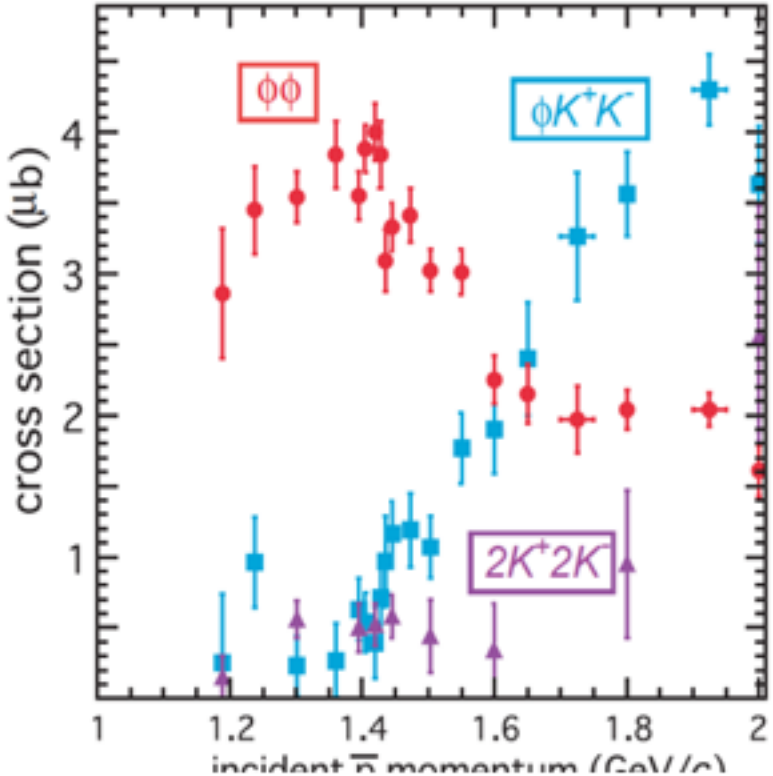
(*) Spokesperson
($) Co-Spokesperson

Future direction about Kaonic nucleus

- if existence of K-pp state is established
  - Can we determine quantum numbers? (spin and parity)
  - How about K^- in heavier nucleus? (K^-pp / K^-pp / K^-C)
  - double K^- nucleus
  - How about meson other than K^- i.e. η', ϕ etc.

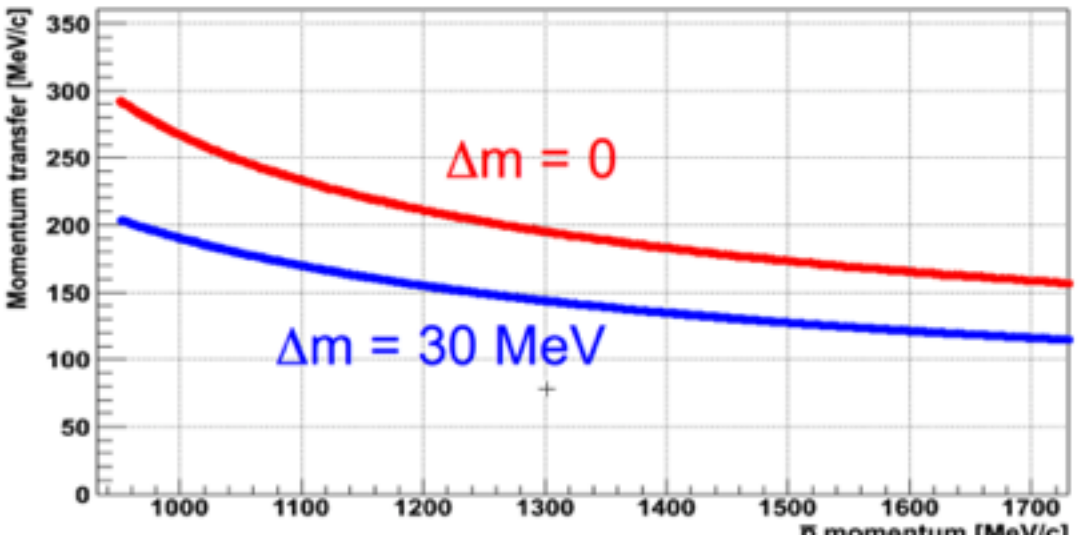
φ in nucleus : J-PARC E29



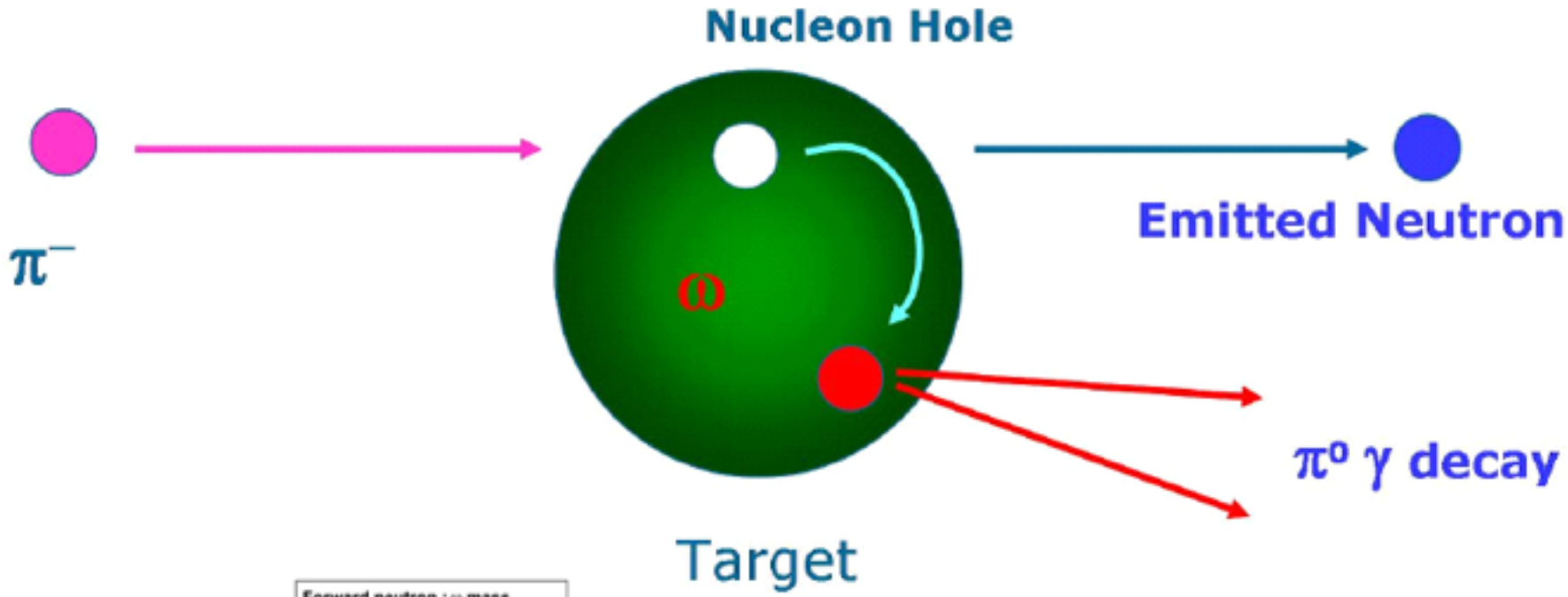


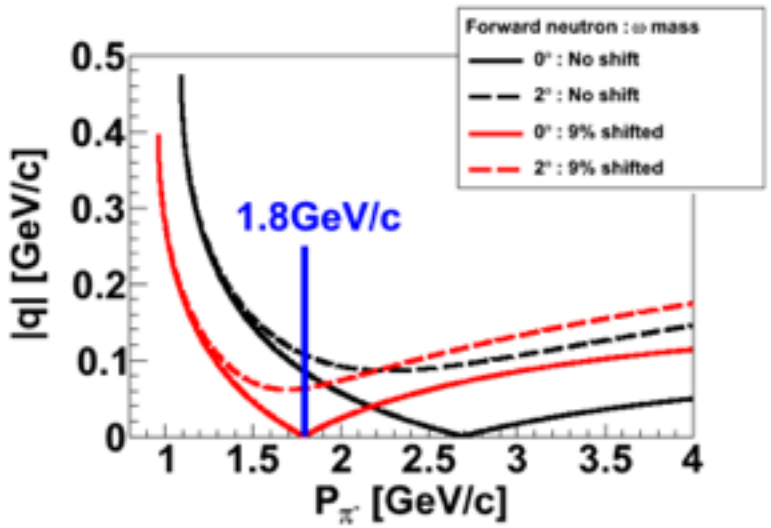
using $p(p,\phi)\phi$ reaction

antiproton beam with
1.0 – 1.1 GeV/c



ω in nucleus : J-PARC E29





detecting forward going neutron and $\pi 0\gamma \rightarrow \gamma\gamma\gamma$ simultaneously

New opportunities with new facility

New opportunities with new facility

J-PARC hadron hall extension

New opportunities with new facility

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Hadron physics with single Strangeness
to
multi-strangeness and charm physics

New opportunities with new facility

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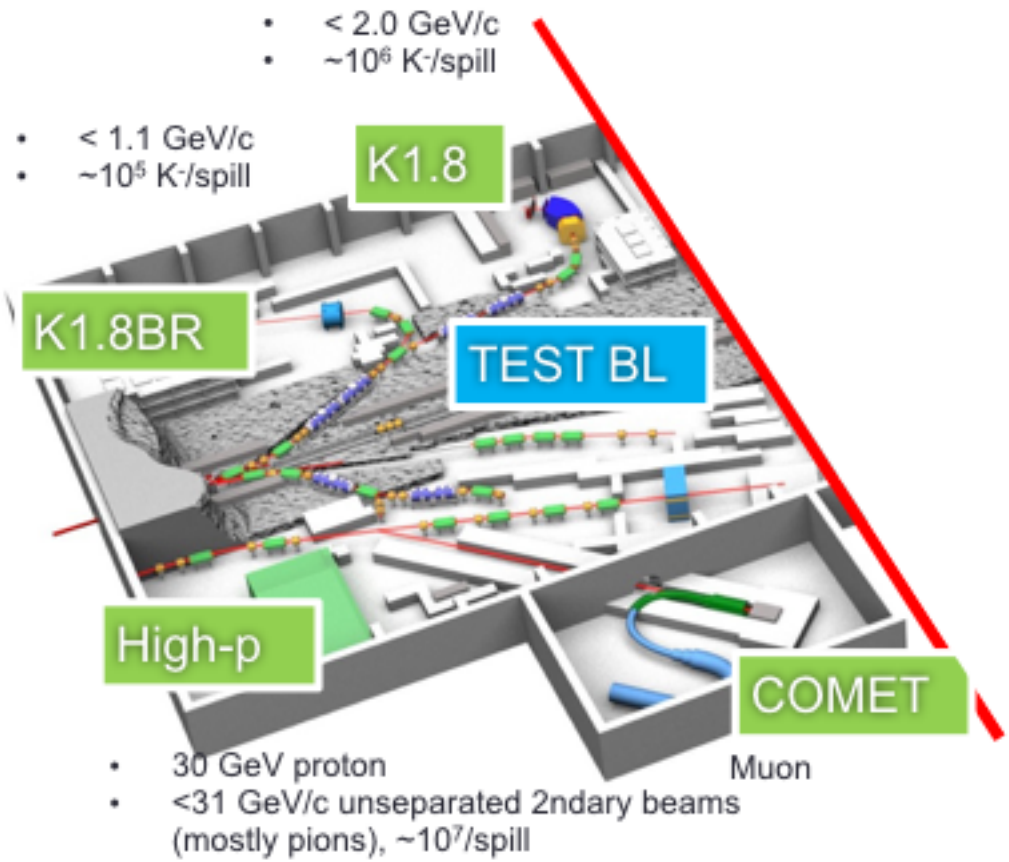
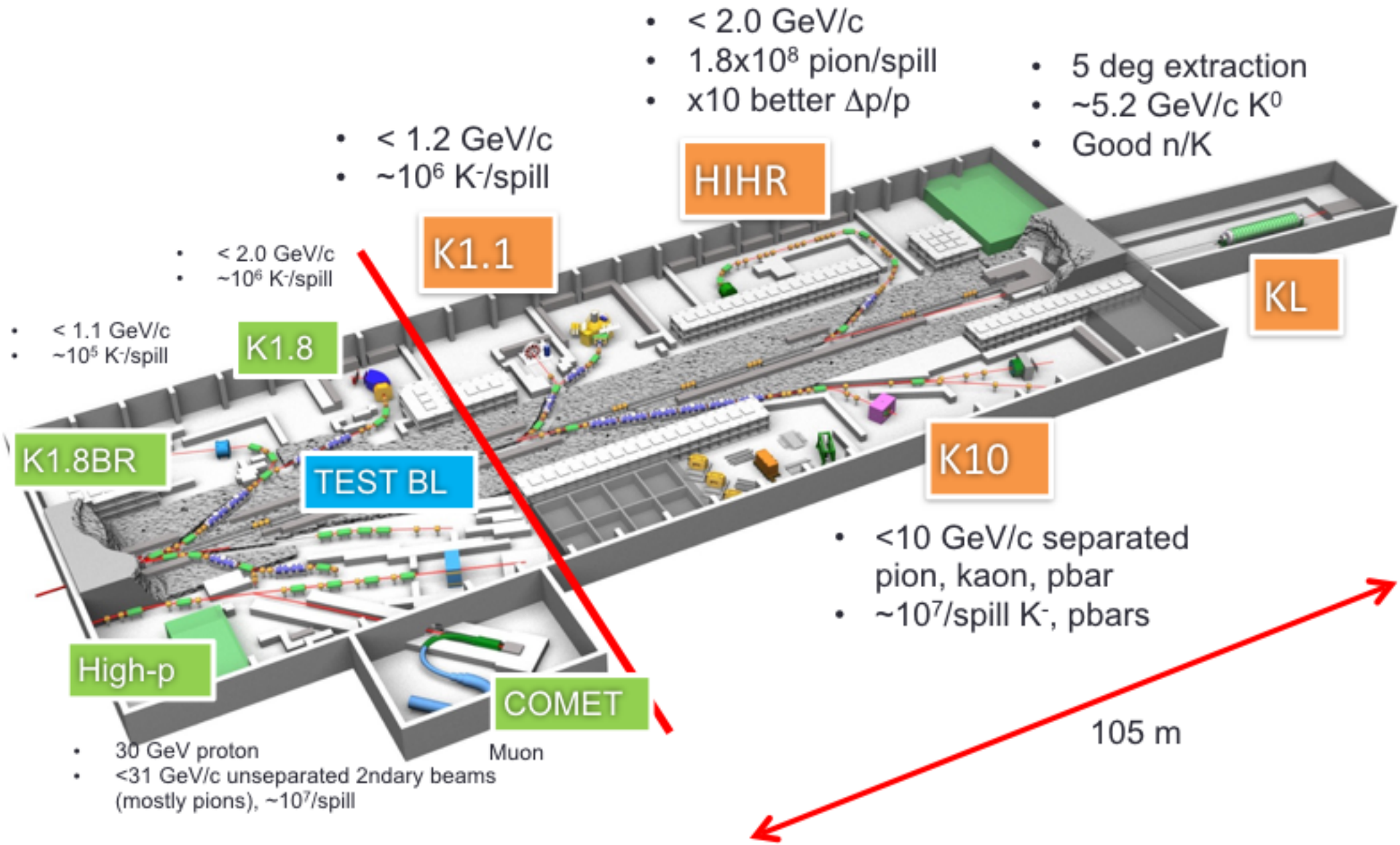
Physics with flavor frontier

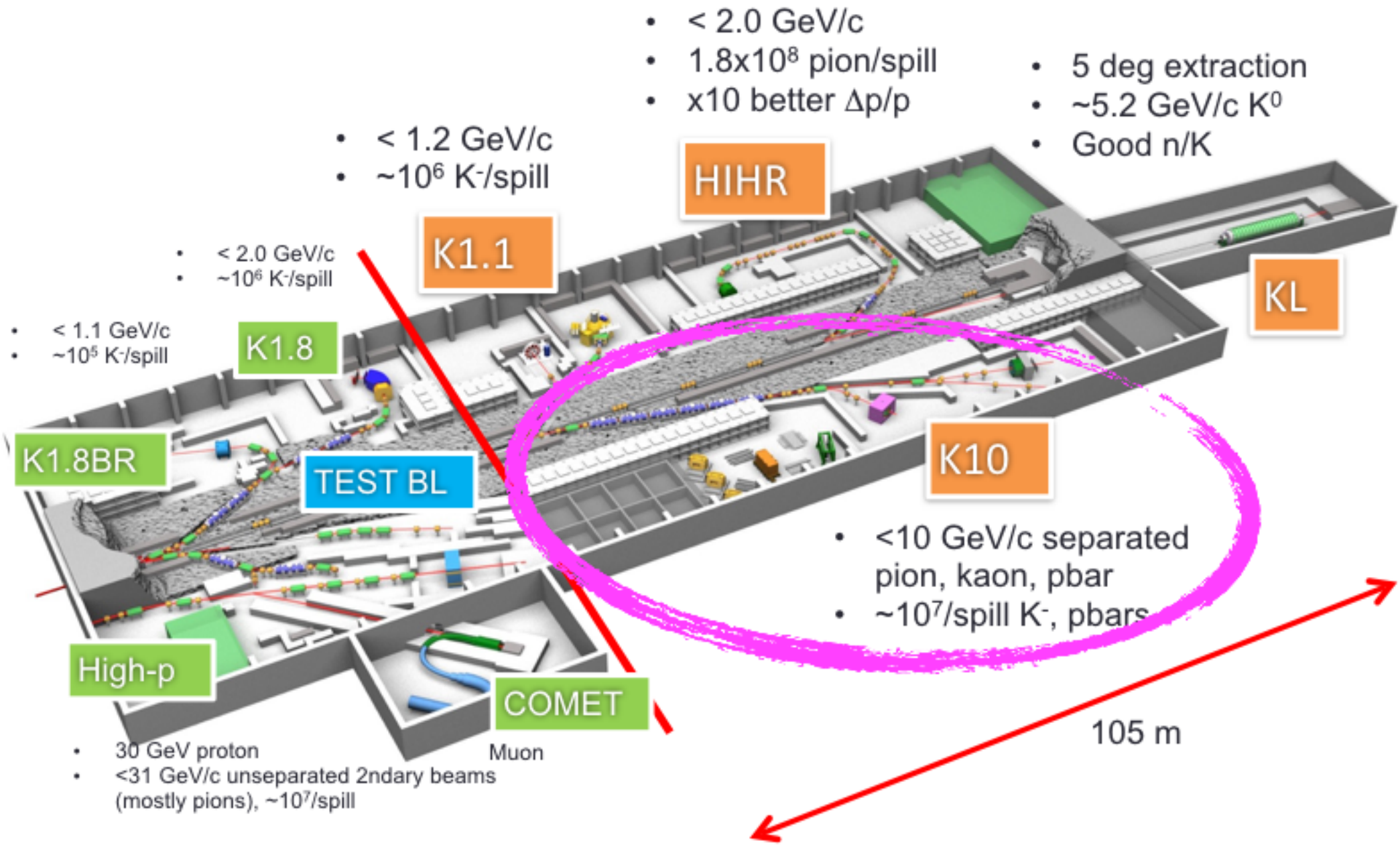
J-PARC Hadron hall extension



J-PARC Hadron hall extension

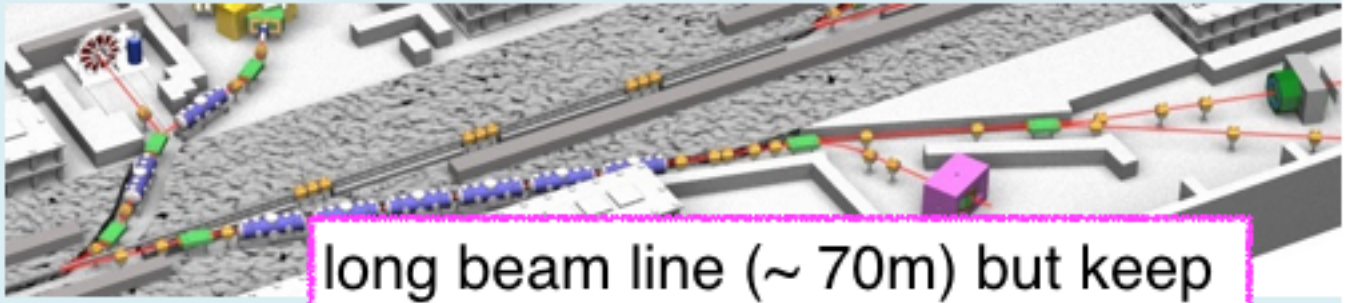


J-PARC Hadron hall extension

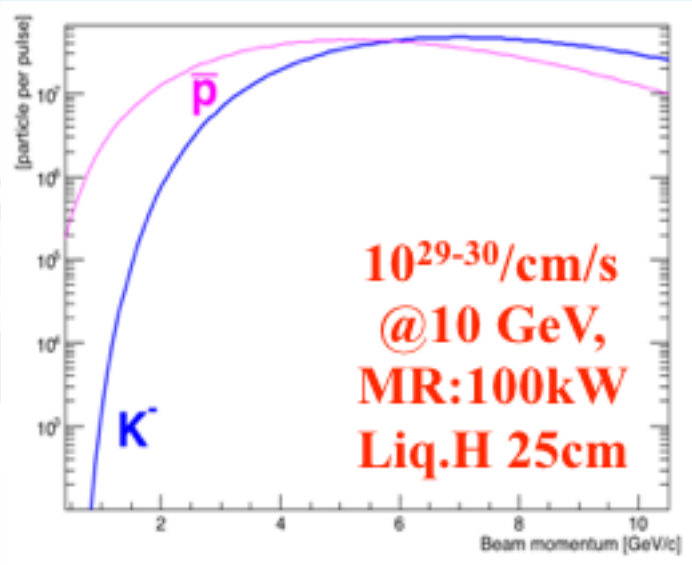


Physics at K10

- Anti-proton beam up to 10 GeV/c will open the new window to explore charm physics at J-PARC
- Design for the beam line is in progress.



long beam line (~ 70m) but keep beam intensity as high as we can



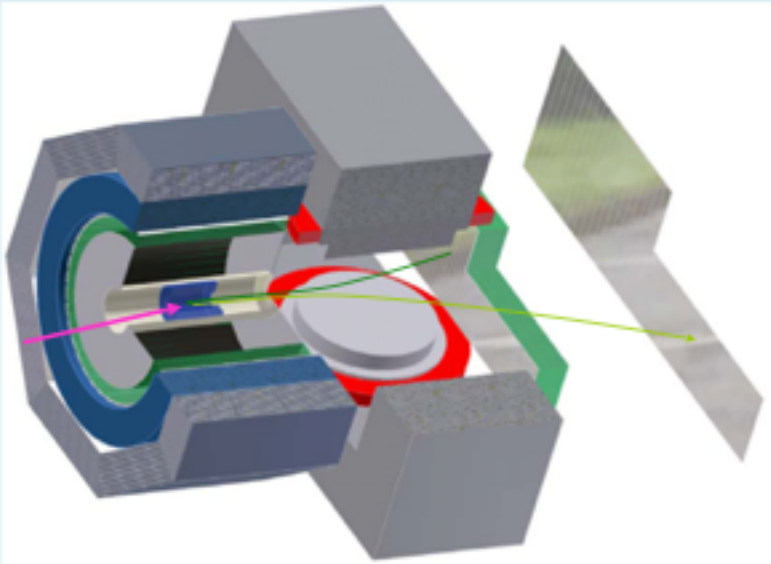
- Typical beam intensity
  - K^- : 10 M/6s @ 4-6 GeV/c
  - pbar : 10 M/6s @ 10 GeV/c

Ξ^* / Ω / scalar meson w/ strangeness

charmed meson in nucleus

Design for the detector has been started.

→ Large solid angle spectrometer
(large solenoid + Dipole in forward)



Hadron hall extension

- New physics opportunity will be open by this project.
  - wide range Ξ^* / Ω^* baryon spectroscopy
  - charmed meson in nucleus
  - Probably many others! now under discussion !!
- Those programs will be complimentary subjects with physics programs at KL beam @ J-Lab

Hadron hall extension

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  - wide range Ξ^* / Ω^* baryon spectroscopy
  - charmed meson in nucleus
  - Probably many others! now under discussion !!
- Those programs will be complimentary subjects with physics programs at KL beam @ J-Lab

Most aggressive scenario:

we expected to have first beam in 2021/2022

Thank you very much