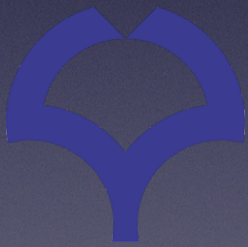
# Hadron physics with K- at J-PARC

Hiroaki Ohnishi
RIKEN/RCNP Osaka Univ.



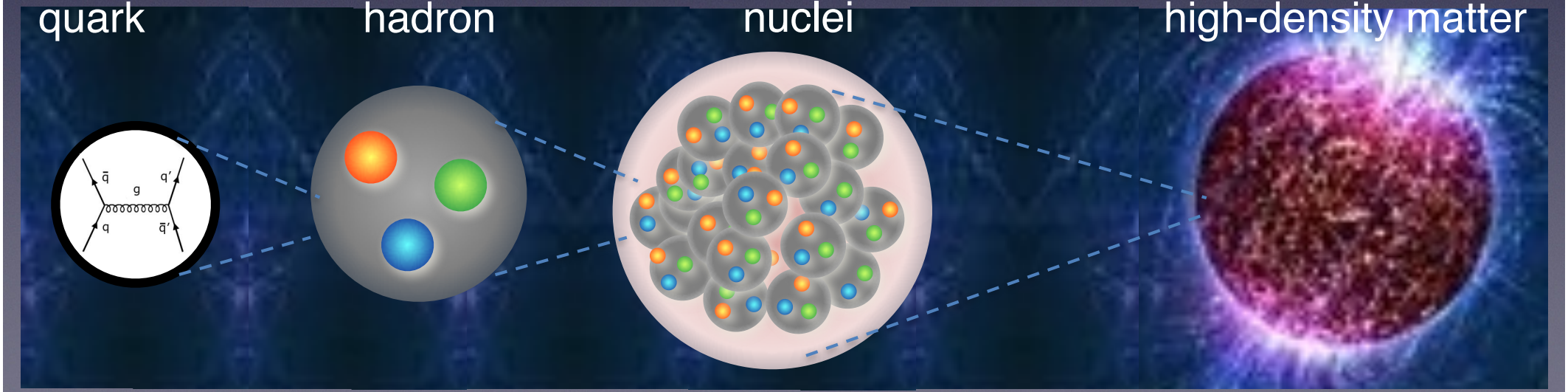


# How the matter created by QCD

QCD is the “theory” to describe strong interaction

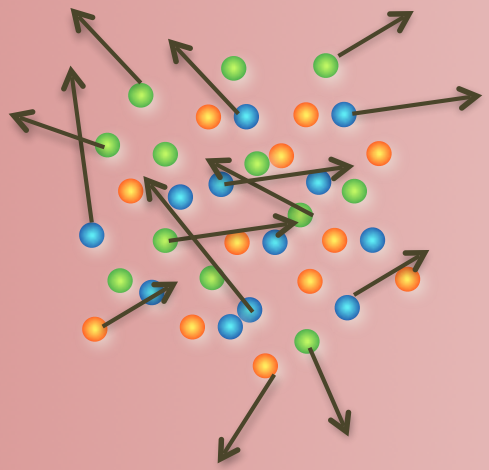
However, still many unsolved problems remains

- What is the effective degree of freedom to describe hadrons (especially for excited baryons)
- Meson property (mass, width etc.) in nuclear matter
    - Origin for hadron mass

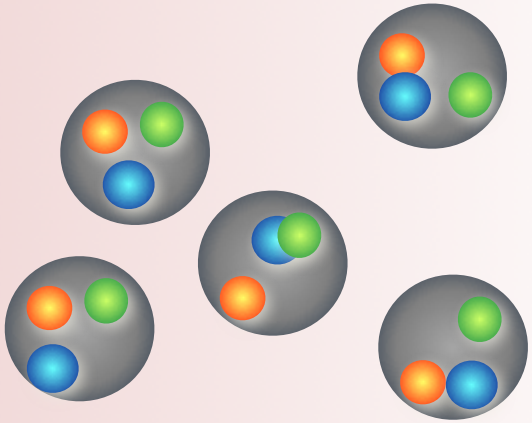


# Evolution for QCD matter "Quark to Hadron"

High Temperature
QCD matter



cool down



Hadronic matter

Spontaneous braking of Chiral symm.
Confinement

Is there any hierarchical structure btw quark and hadron

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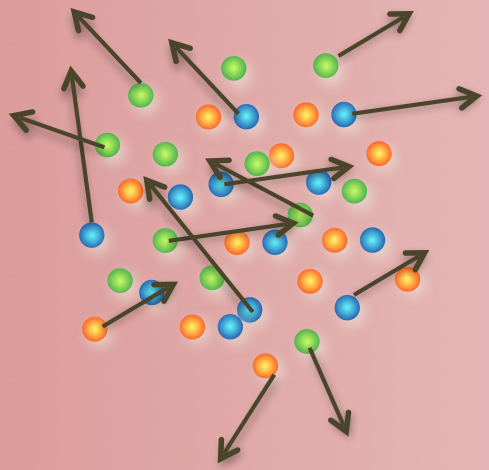

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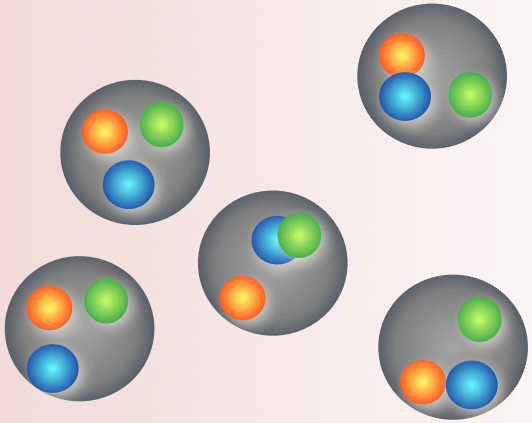


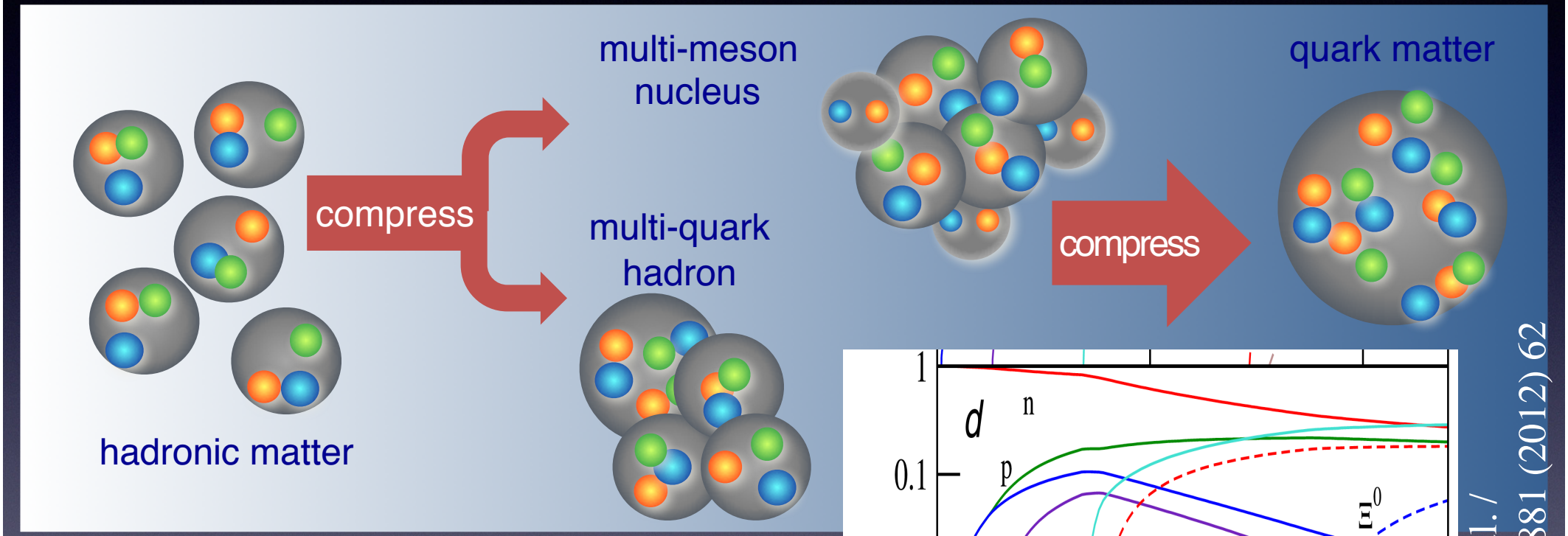
Hadronic matter

Spontaneous braking of Chiral symm.
Confinement

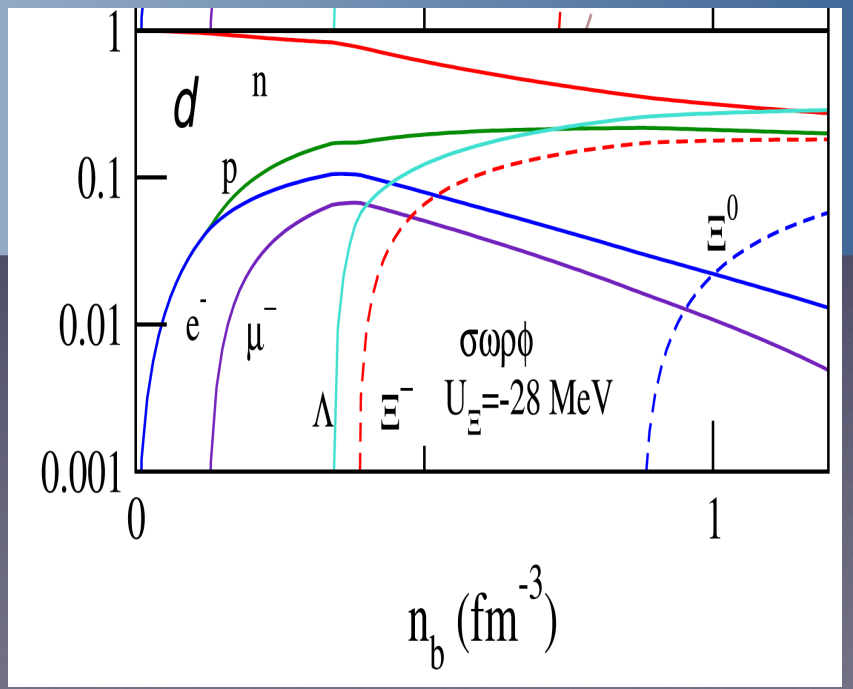
Is there any hierarchical structure btw quark and hadron

what is effective DoF to describe hadron

# Evolution for QCD matter
# “Hadron to high dense matter”




Strengeness will play
important role
in high dense matter



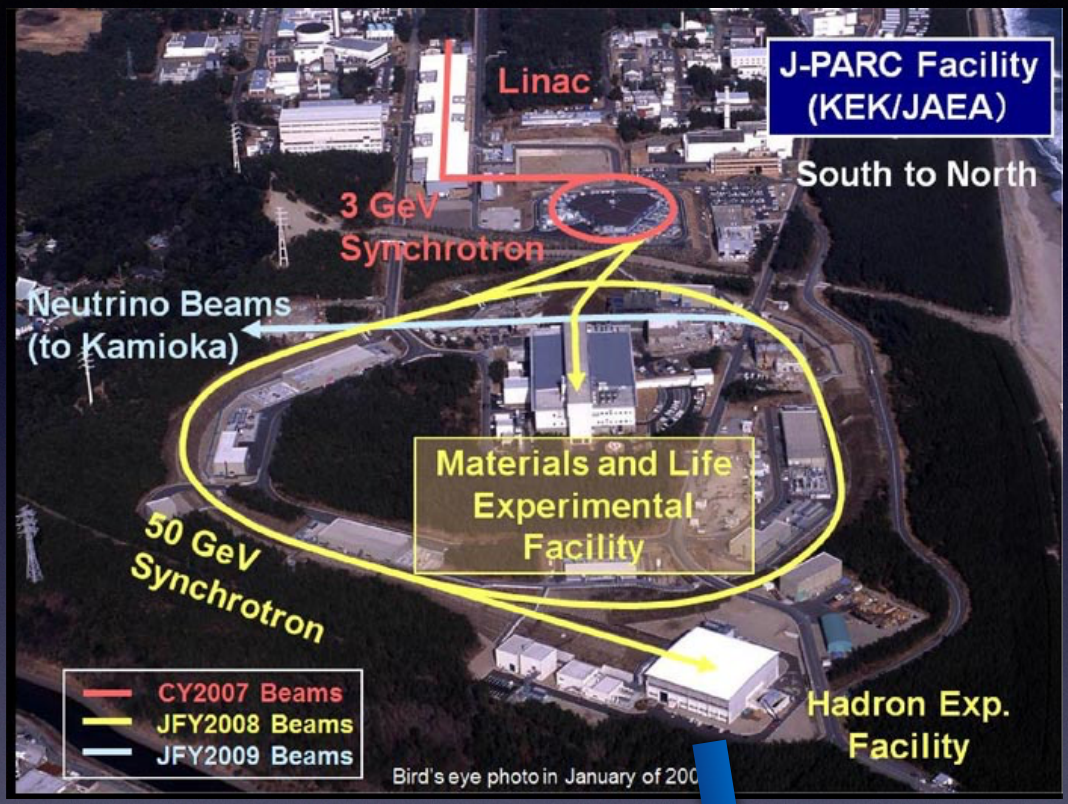

S. Weissenborn et al. /
Nuclear Physics A 881 (2012) 62

# J-PARC

Japan Proton Accelerator Research Complex

# J-PARC

## Japan Proton Accelerator Research Complex


Hadron Experimental facility

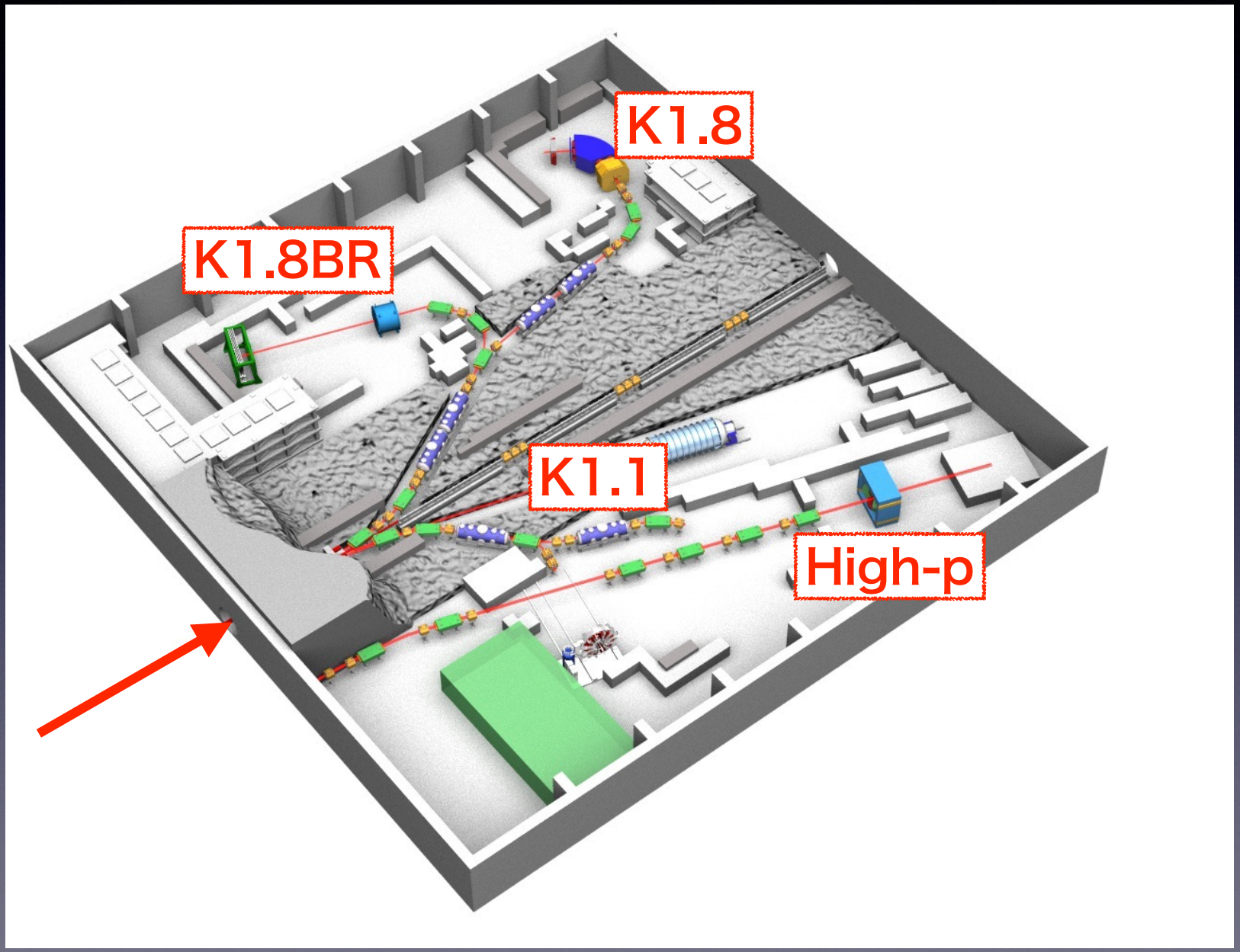
Primary beam intensity :(Dec 2015)

$48 \times 10^{12}$ proton/5.52s

( 30 GeV Proton )

# J-PARC

## Japan Proton Accelerator Research Complex



# J-PARC

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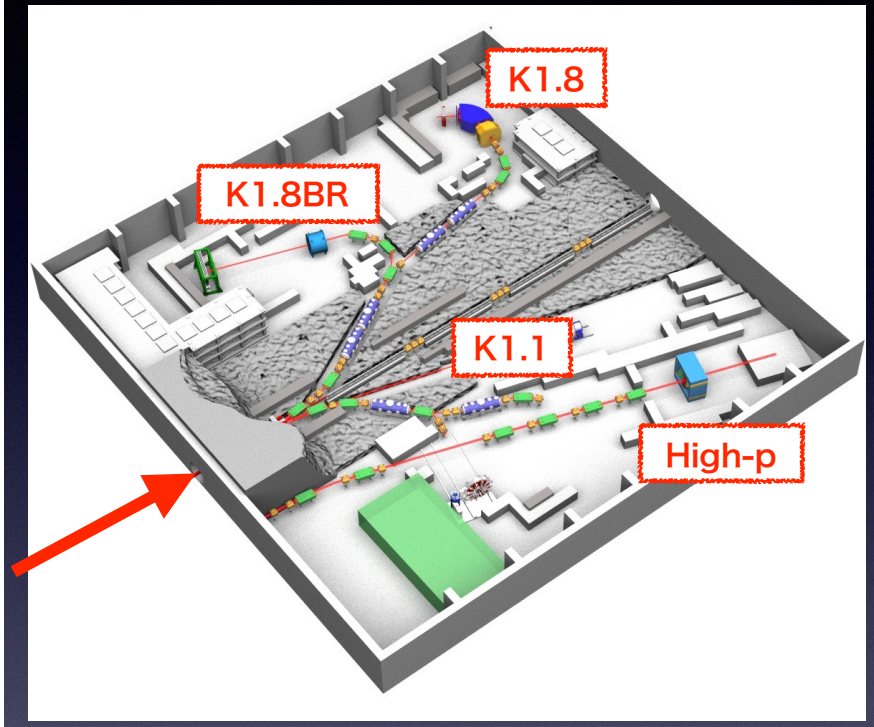

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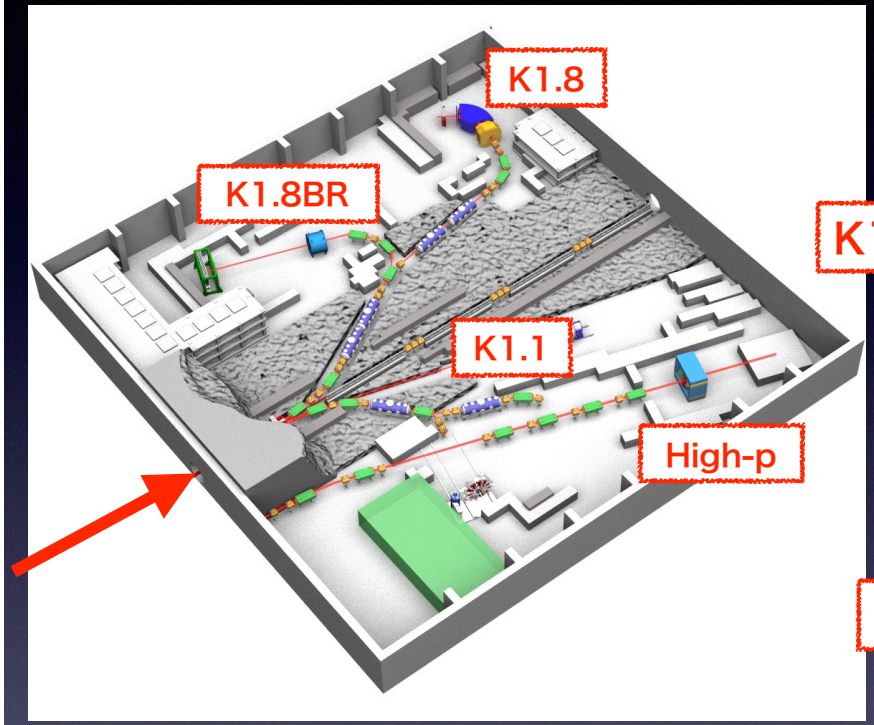


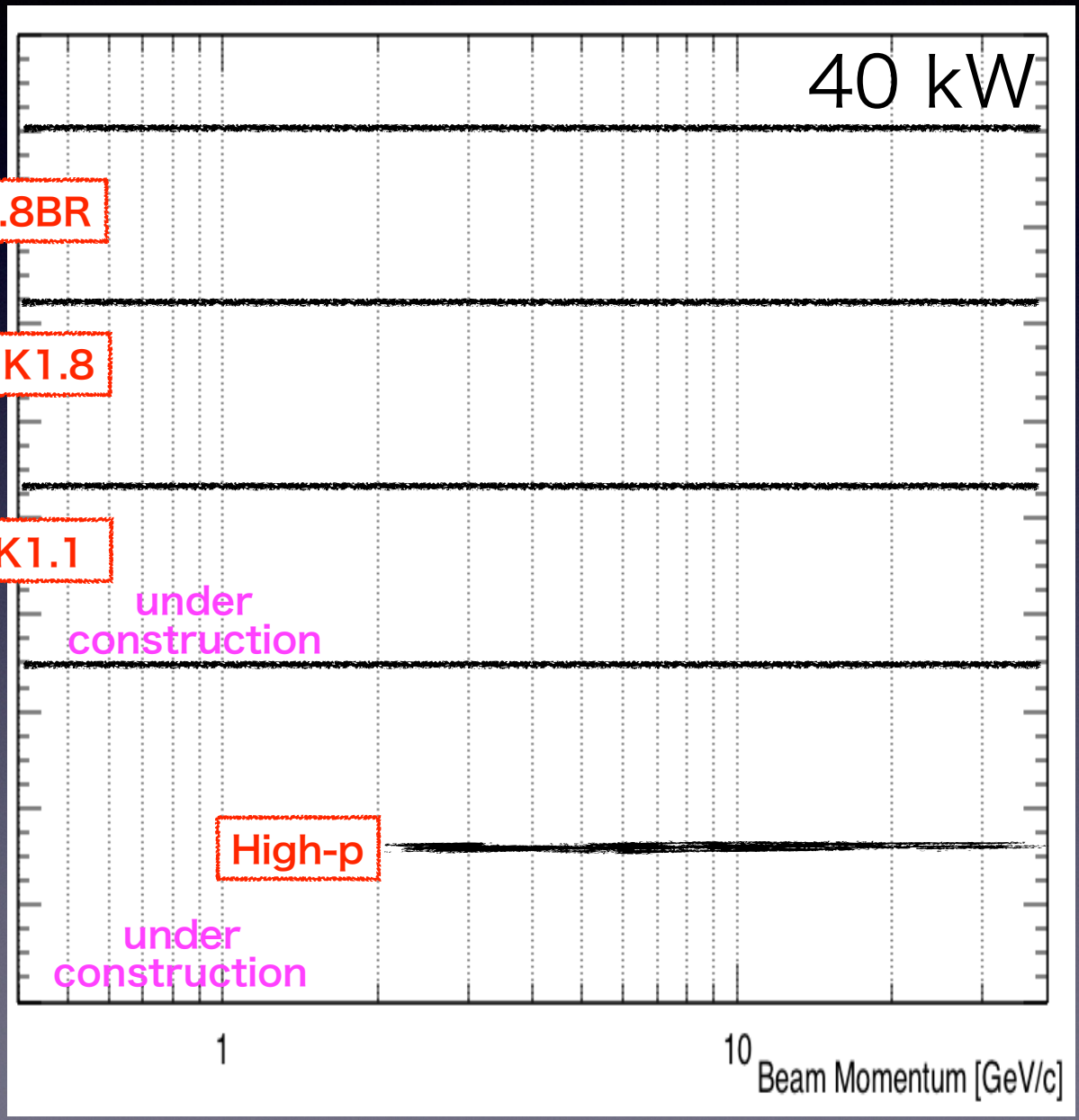

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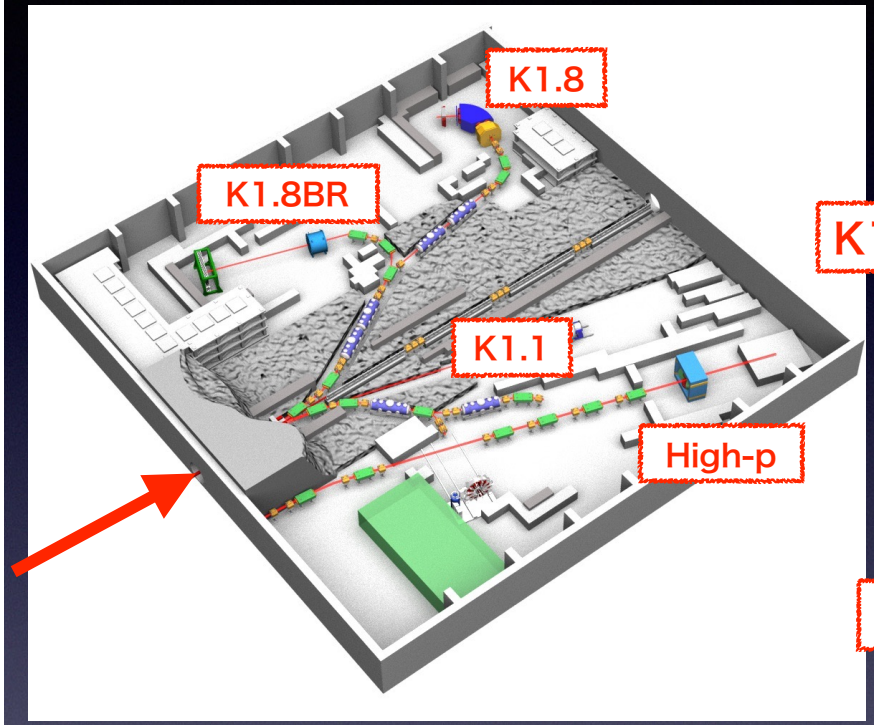
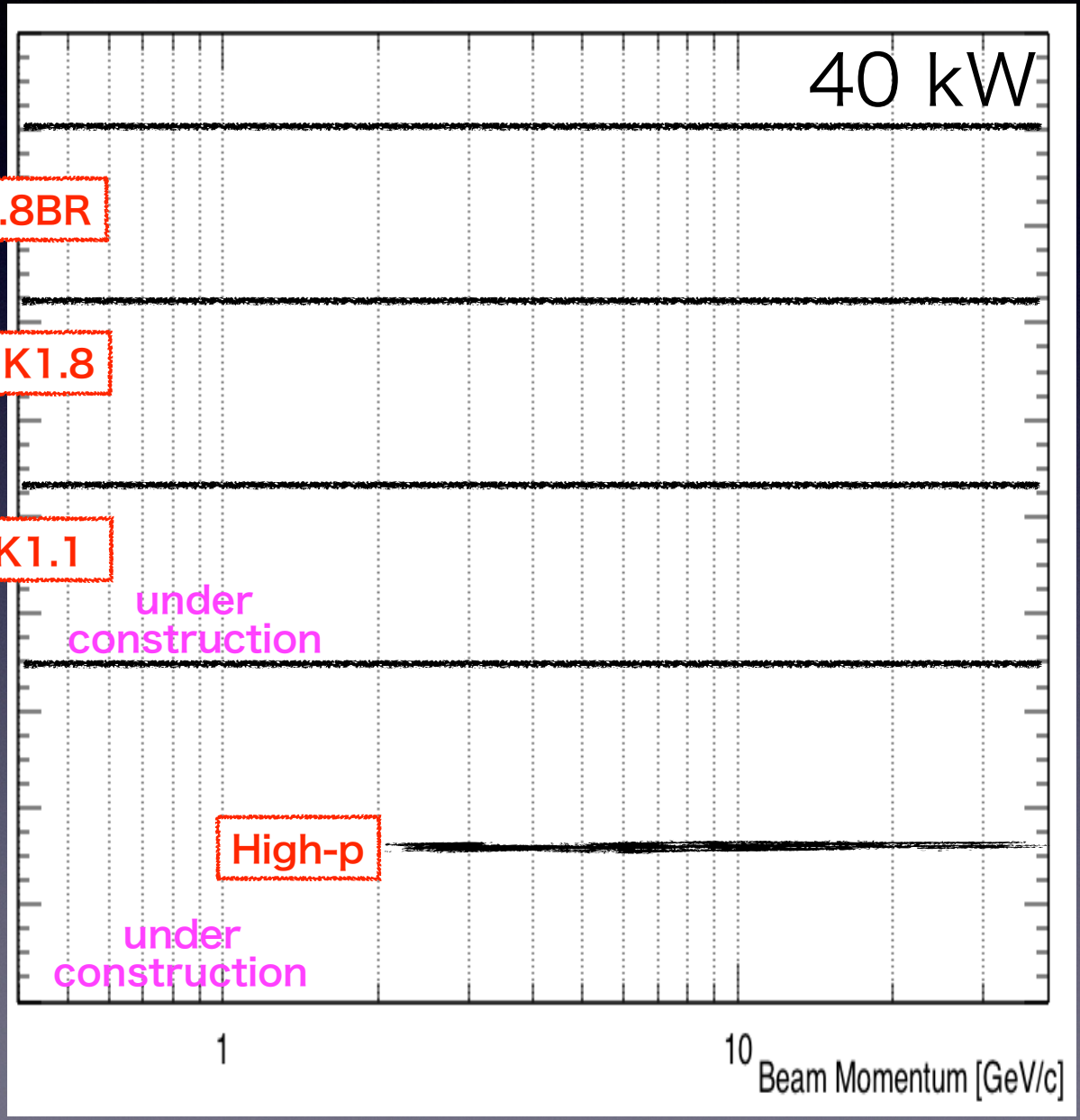



Two beam lines are under operation

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



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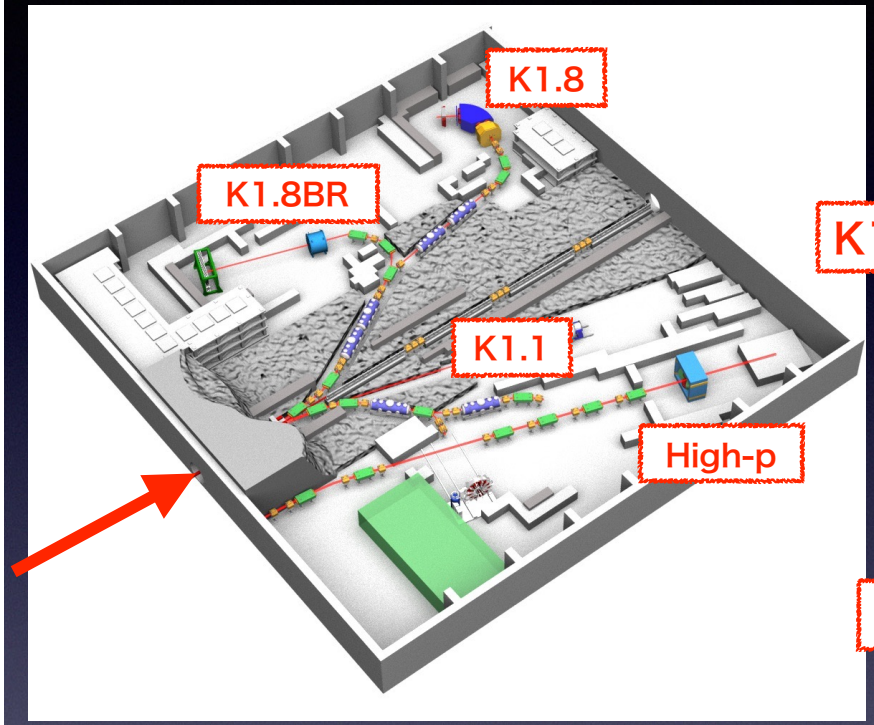


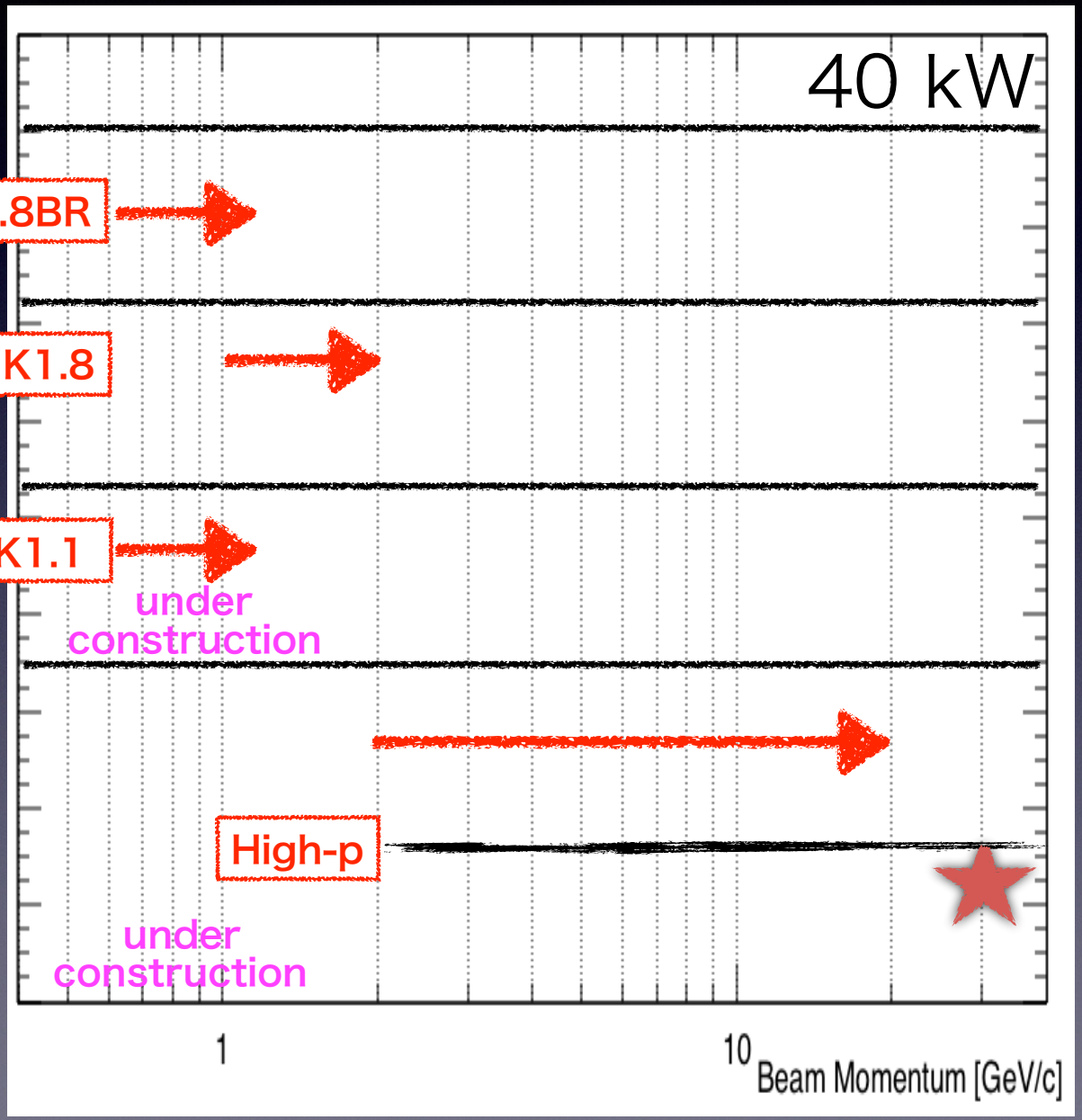


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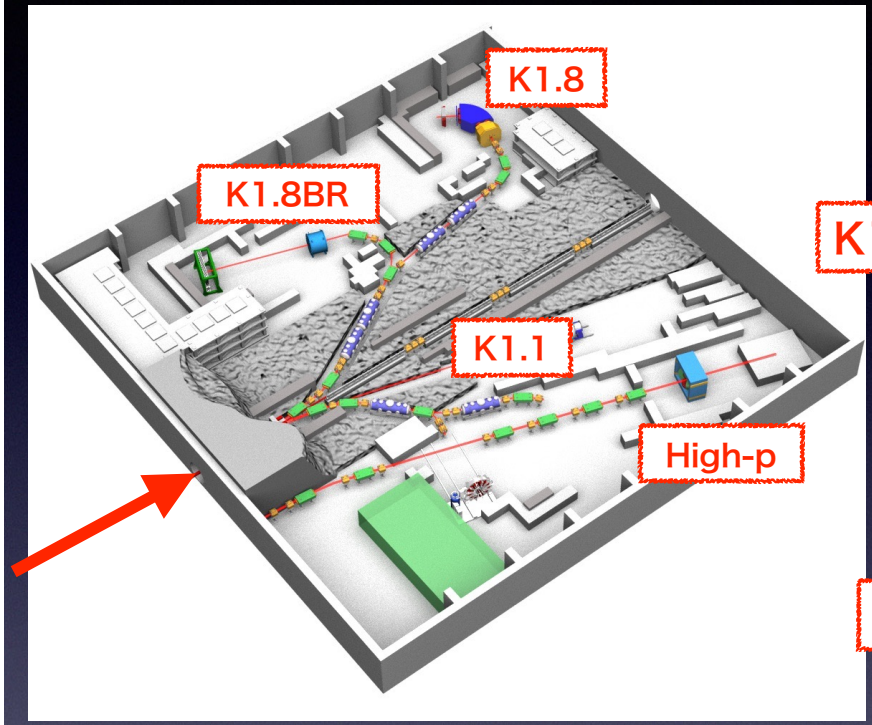


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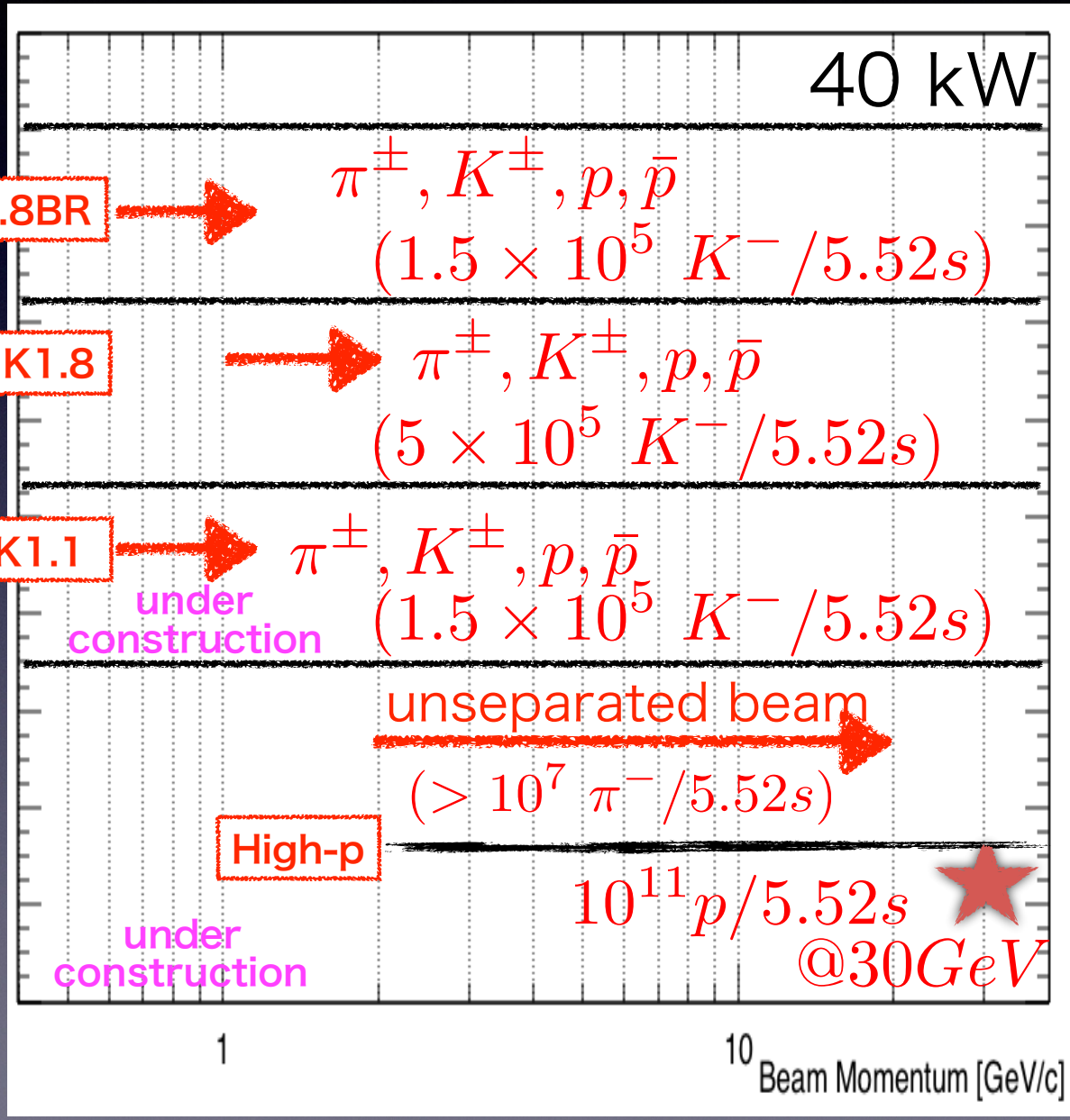

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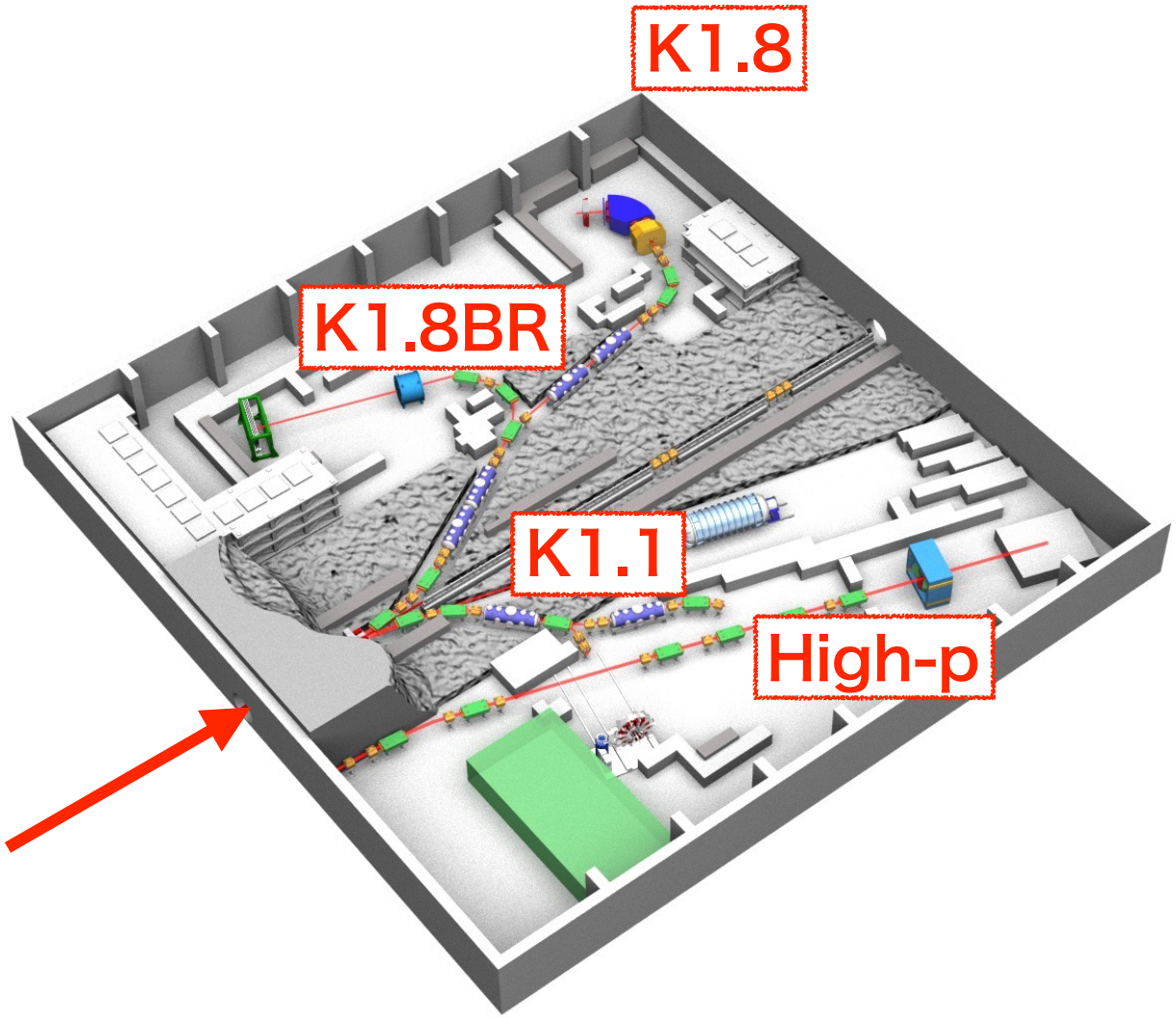


# J-PARC

## Japan Proton Accelerator Research Complex

E15/E31

Kaonic-nucleus

Λ(1405)

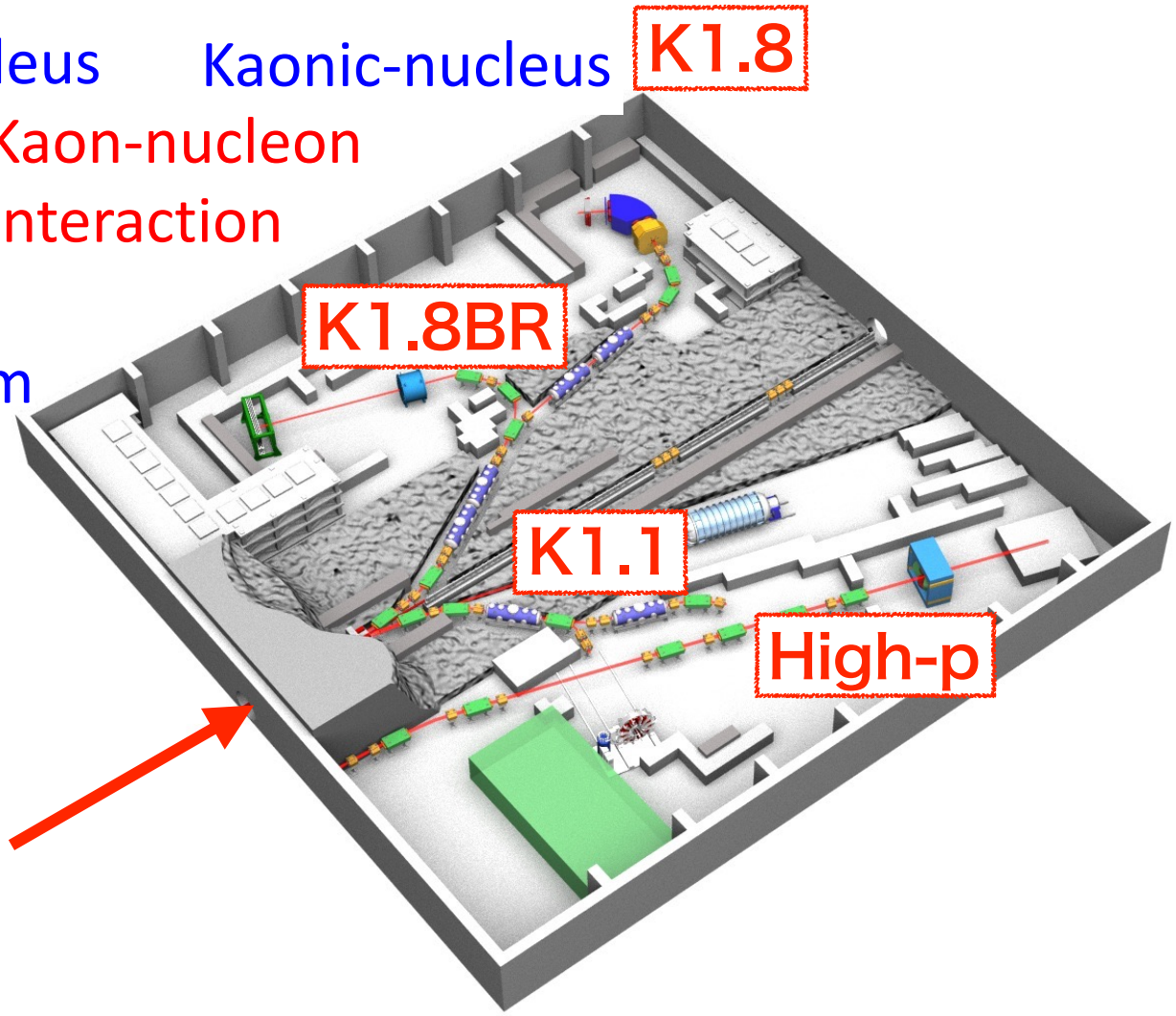
E27

Kaonic-nucleus

Kaon-nucleon interaction

E17/E57

Kaonic-atom



# J-PARC

## Japan Proton Accelerator Research Complex

E15/E31

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Λ(1405)

E27

Kaonic-nucleus

K1.8

E19

Search for Pentaquark

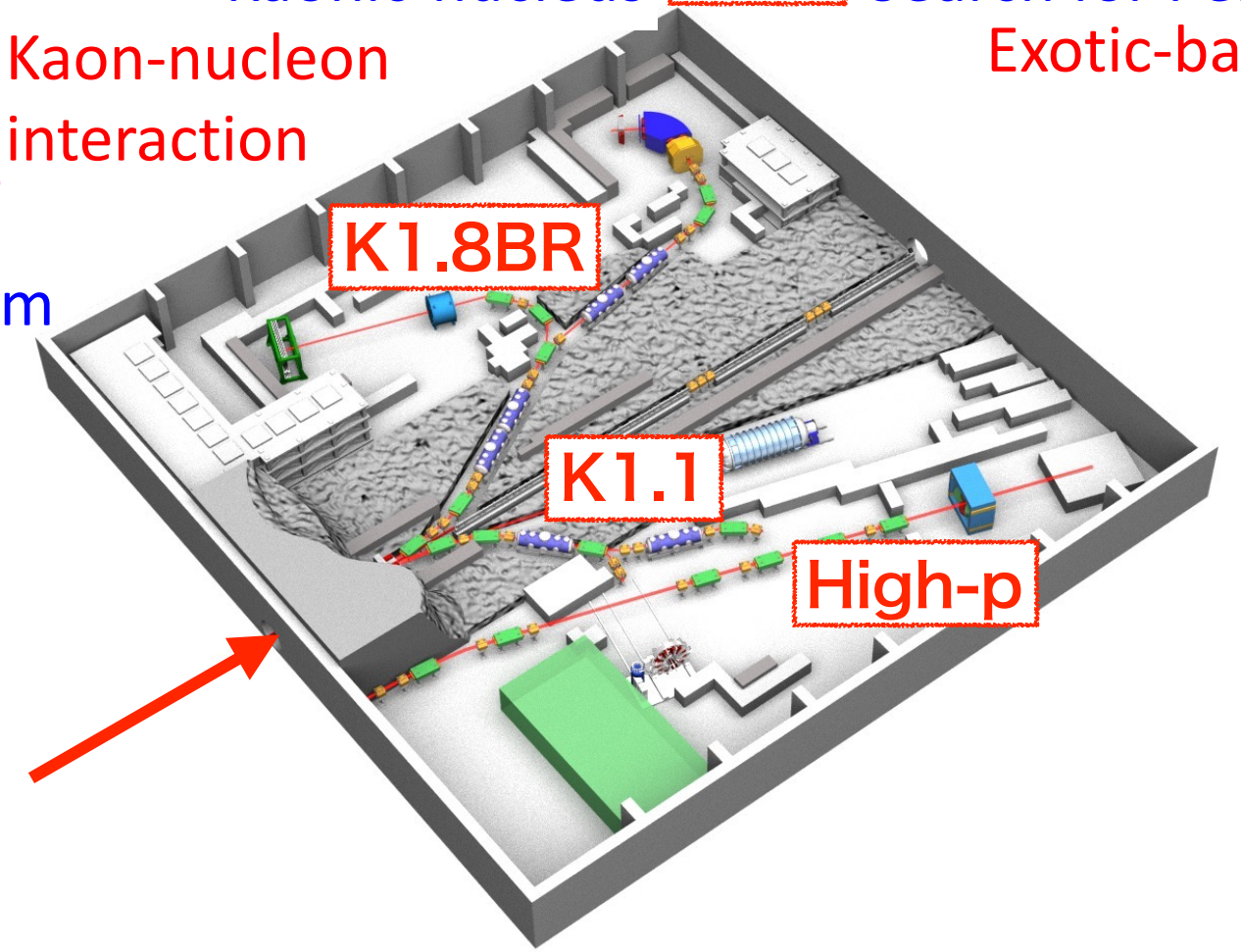
Exotic-baryon

Kaon-nucleon

interaction

E17/E57

Kaonic-atom



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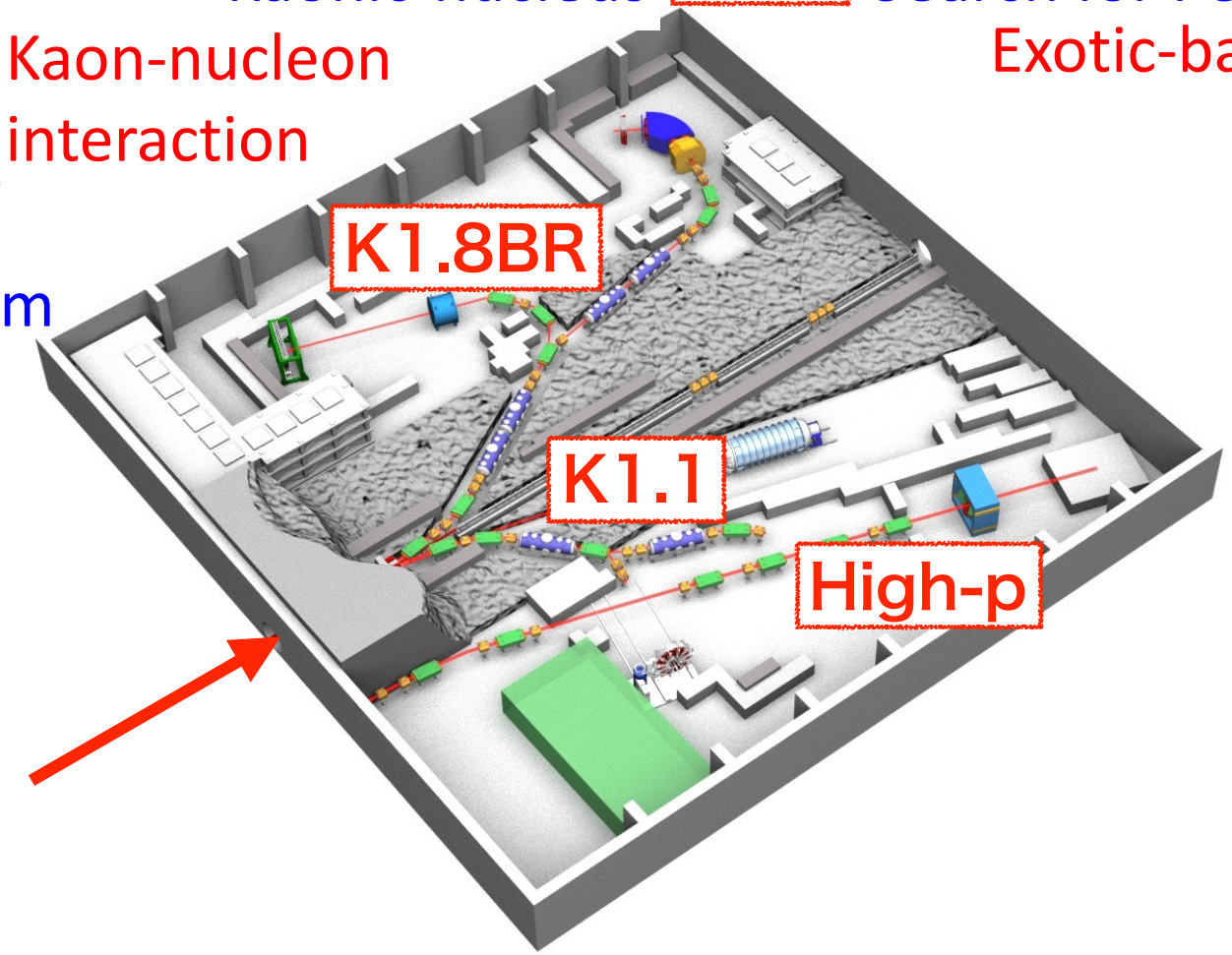


E16/E29
Φ in nucleus

Spontaneous
breaking of
Chiral symmetry

# J-PARC

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E15/E31

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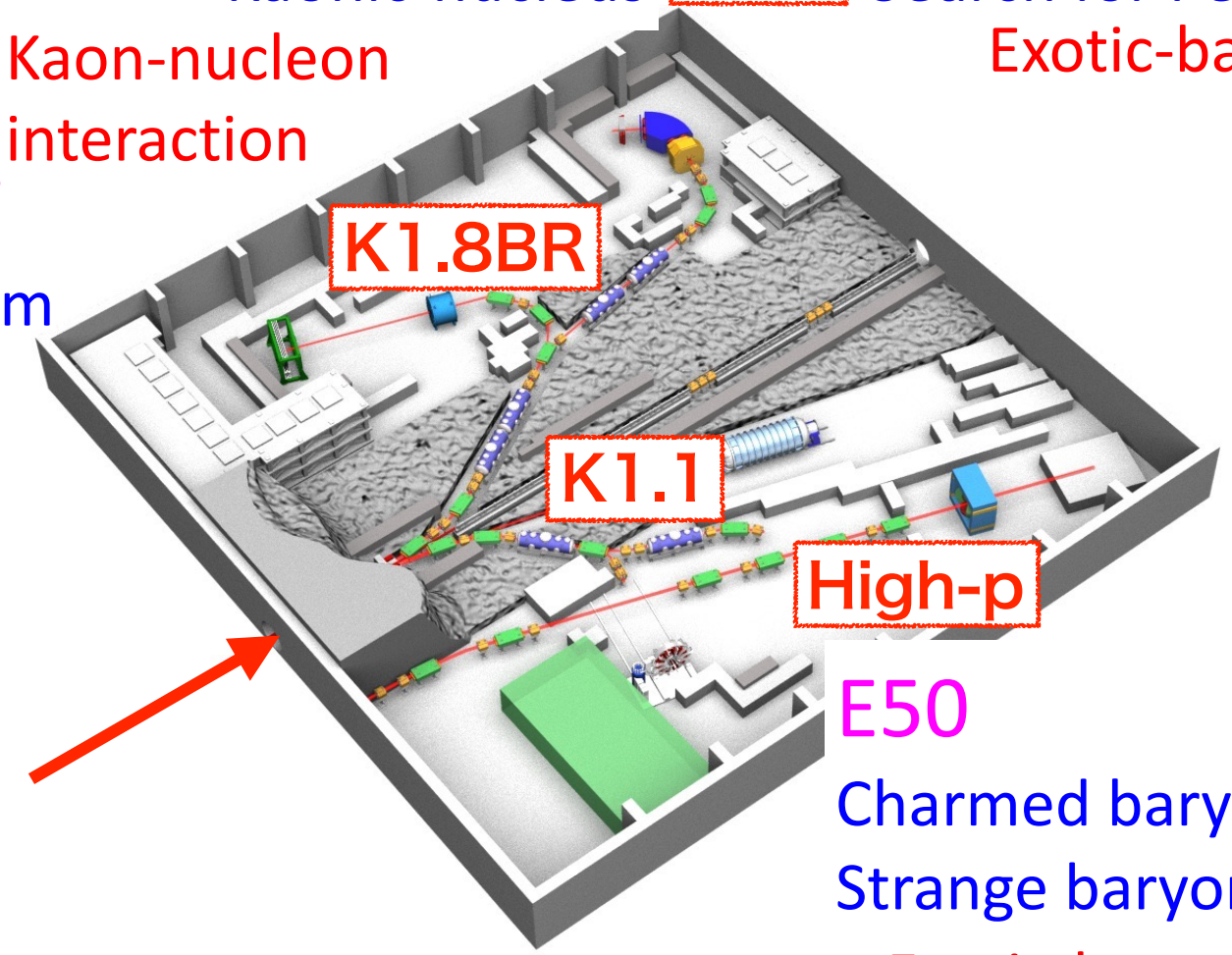



E16/E29

Φ in nucleus

Spontaneous

breaking of

Chiral symmetry

E50

Charmed baryon

Strange baryon

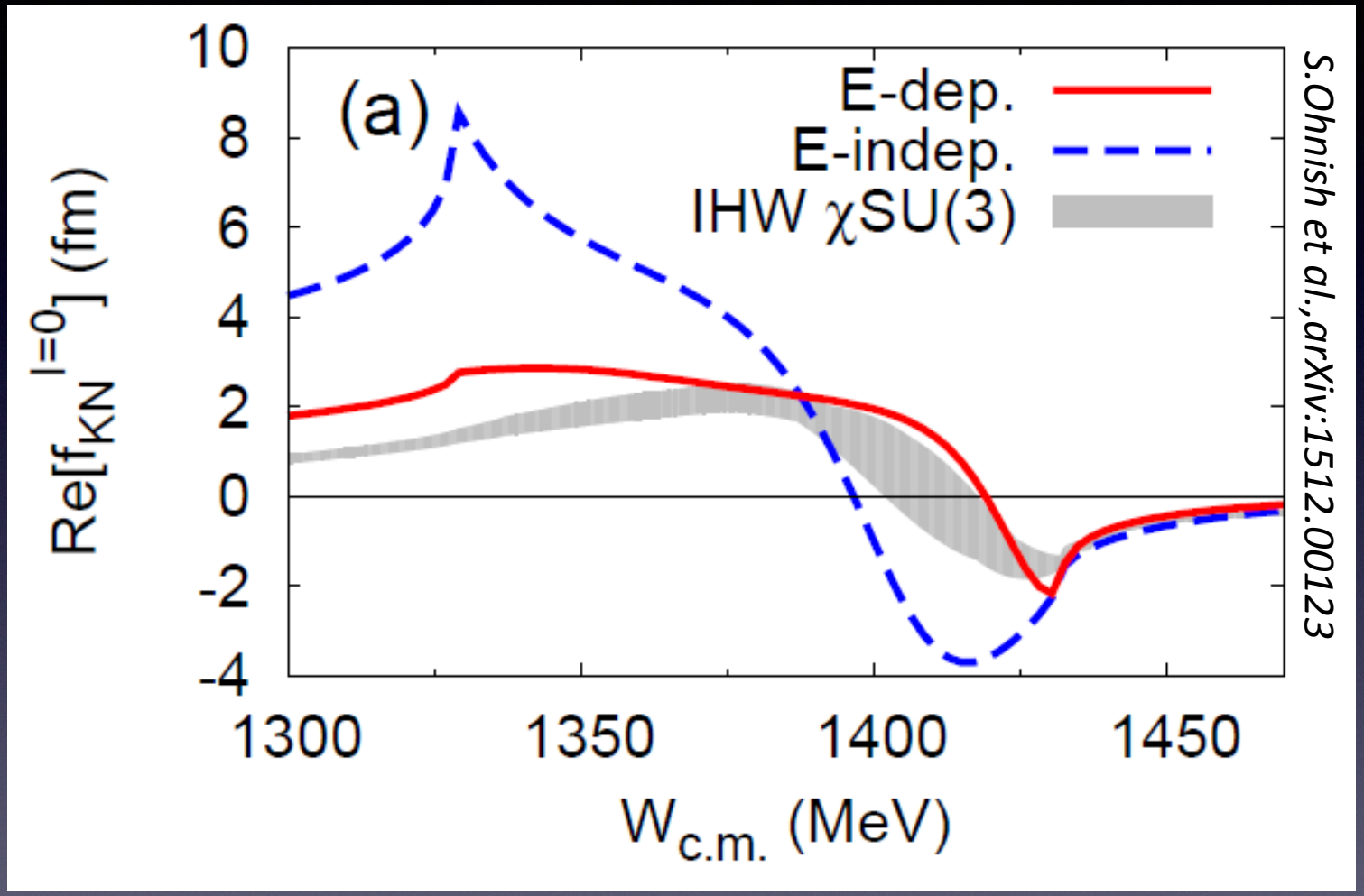
Exotic-baryon

# Hadron Physics with low momentum $K^-$

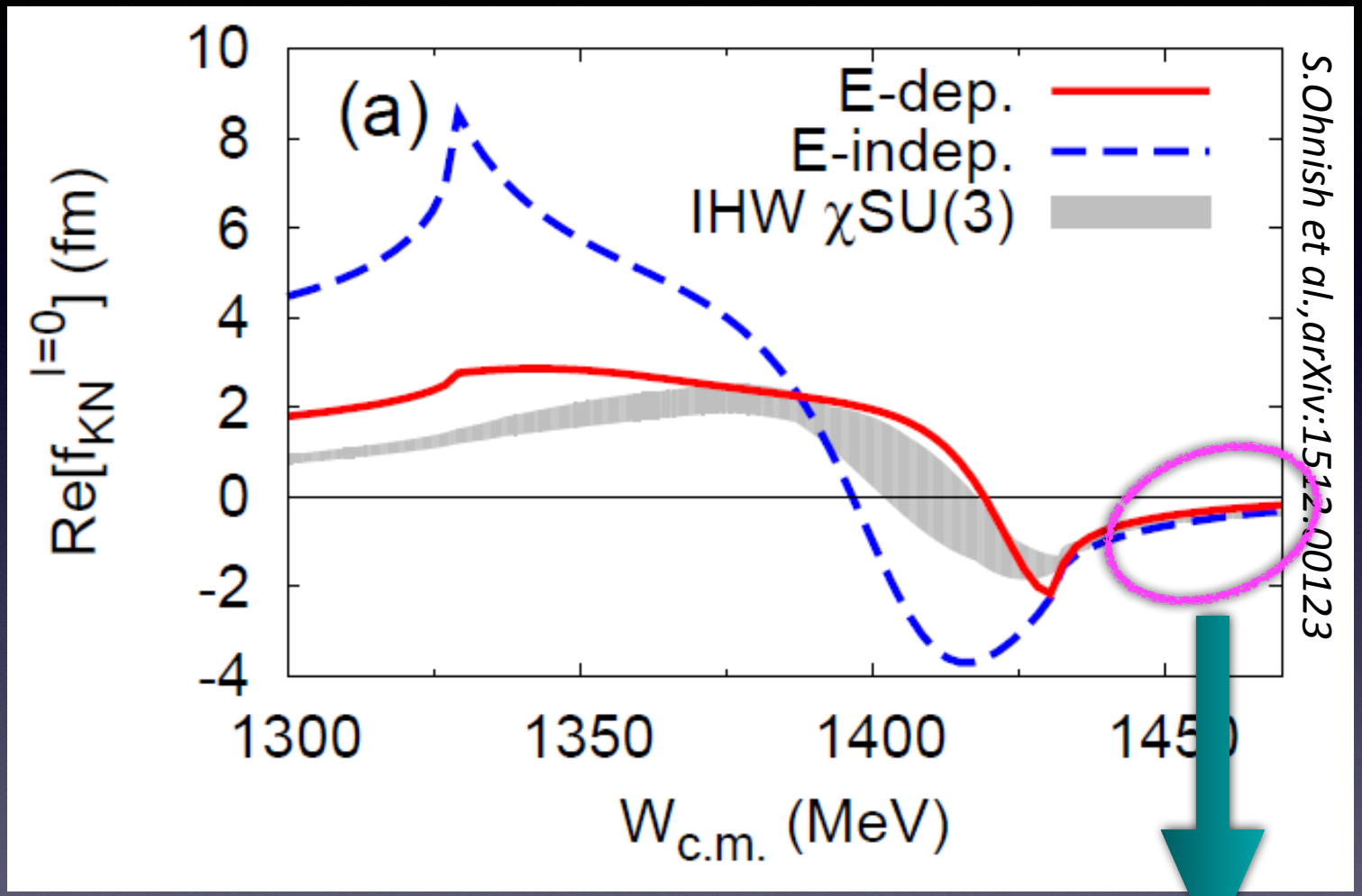
## $p < 2$ GeV/$c$

- $\bar{K}$-nucleus interaction (s=-1) at K1.8BR beam line

# $\bar{K}N$ potential



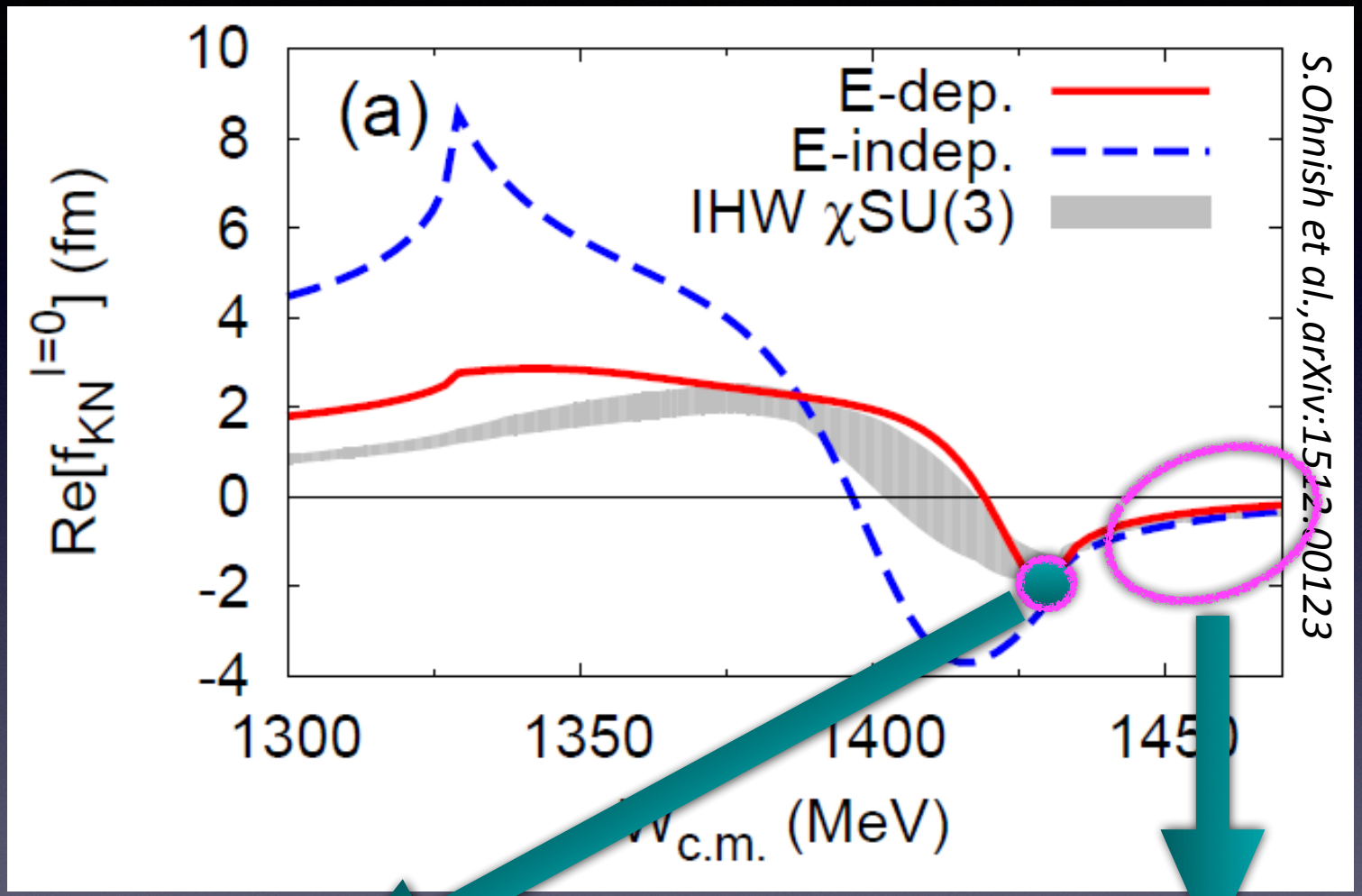
# $\bar{K}N$ potential




low energy

$\bar{K}N$scattering

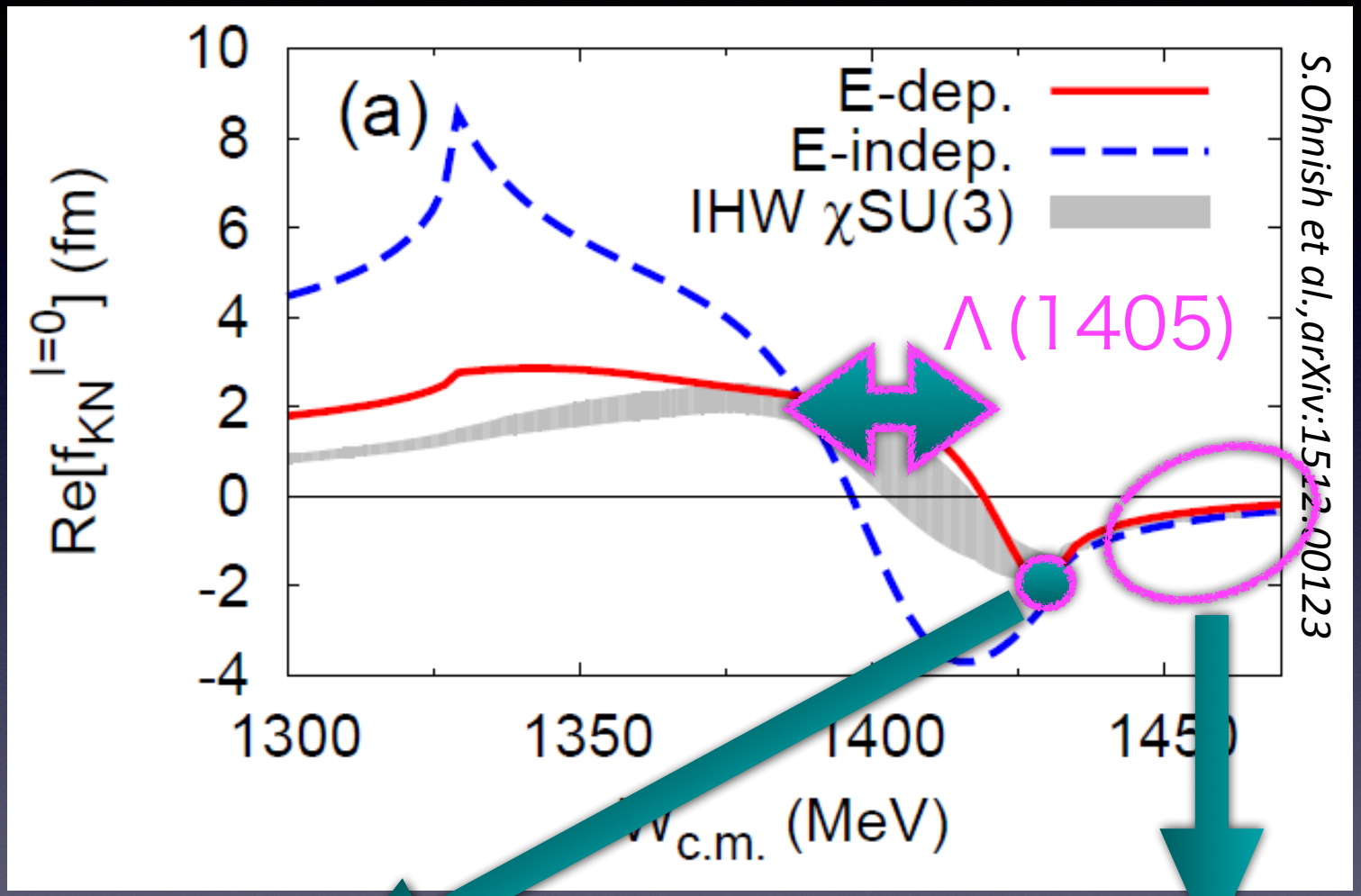
# $\bar{K}N$ potential




Kaonic atom
X-ray

low energy
$\bar{K}N$scattering

# $\bar{K}N$ potential




Kaonic atom
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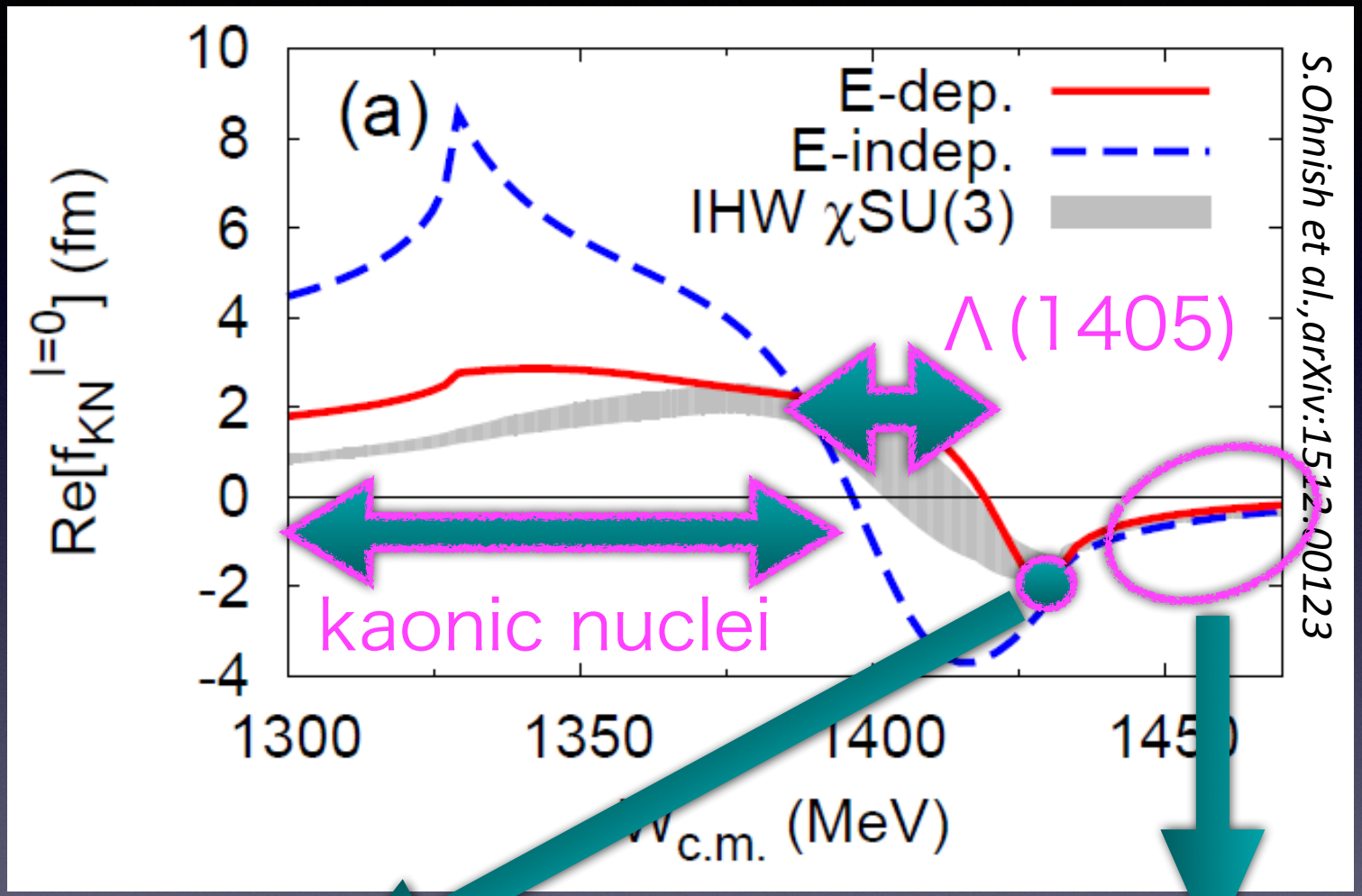


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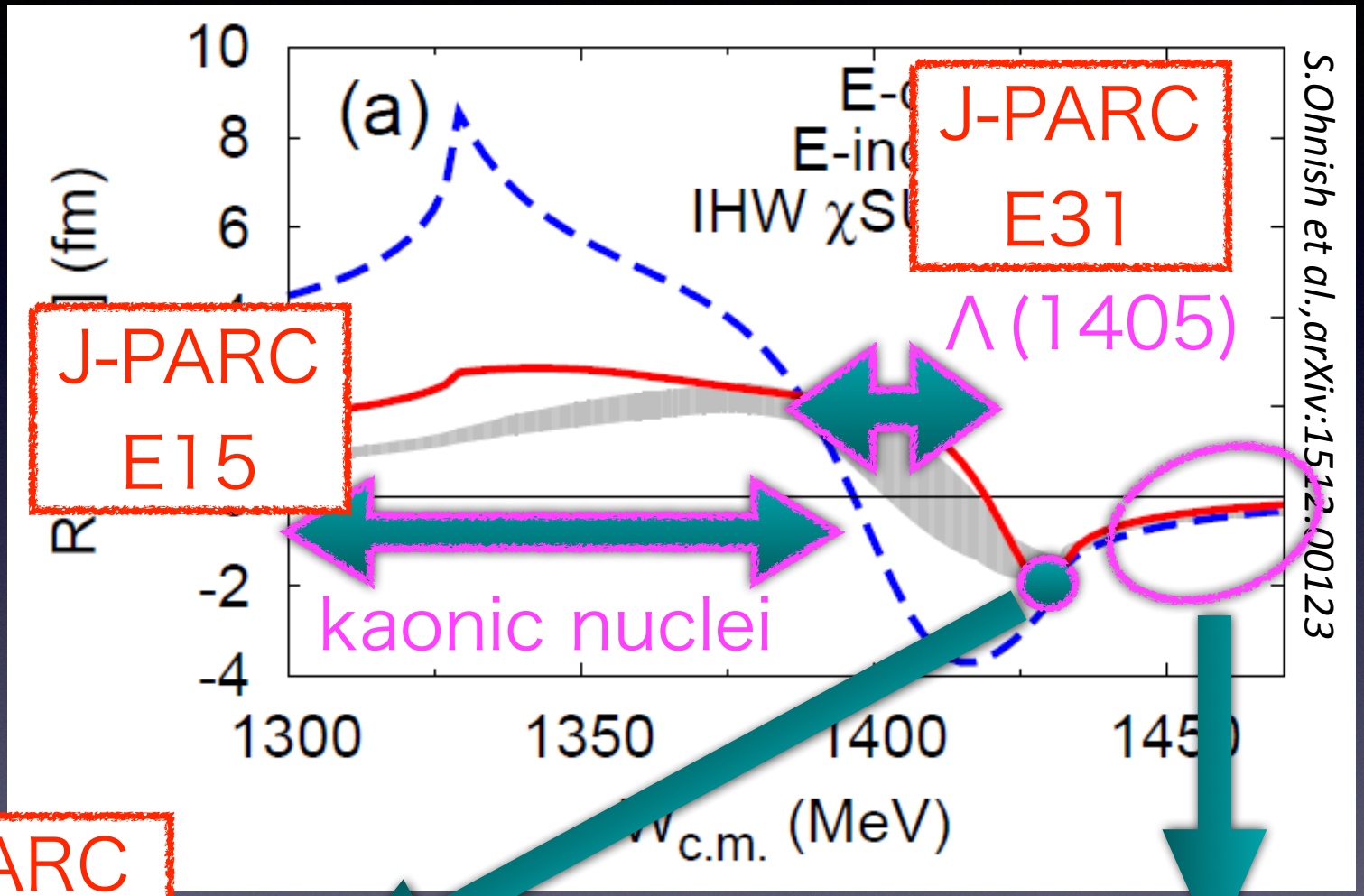



J-PARC E31

Λ(1405)

J-PARC E15

kaonic nuclei

J-PARC E17/E57

Kaonic atom X-ray

low energy $\bar{K}N$ scattering

$\bar{K}NN$

# $\bar{K}NN$:

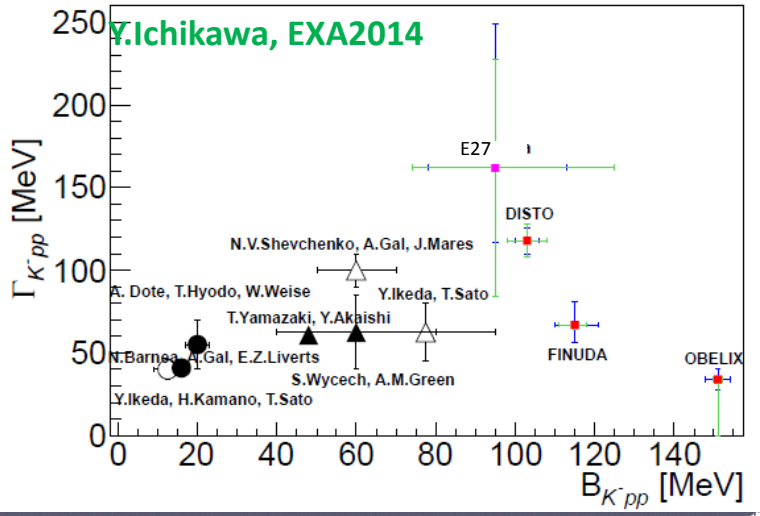
the simplest $\bar{K}$-nuclear bound state

# $\bar{K}NN$: the simplest $\bar{K}$-nuclear bound state

Calculated $K^- pp$ binding energies $B$ and widths $\Gamma$ (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 |
| $\Gamma$ | 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.

# $\bar{K}NN$: the simplest $\bar{K}$-nuclear bound state

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

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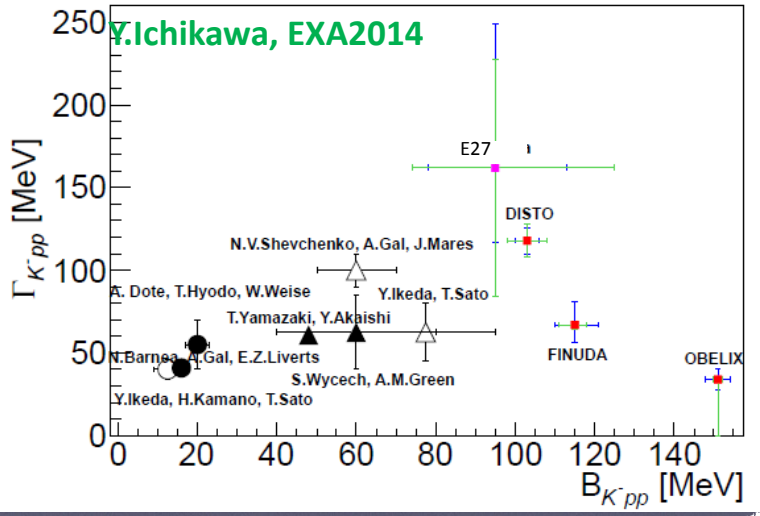
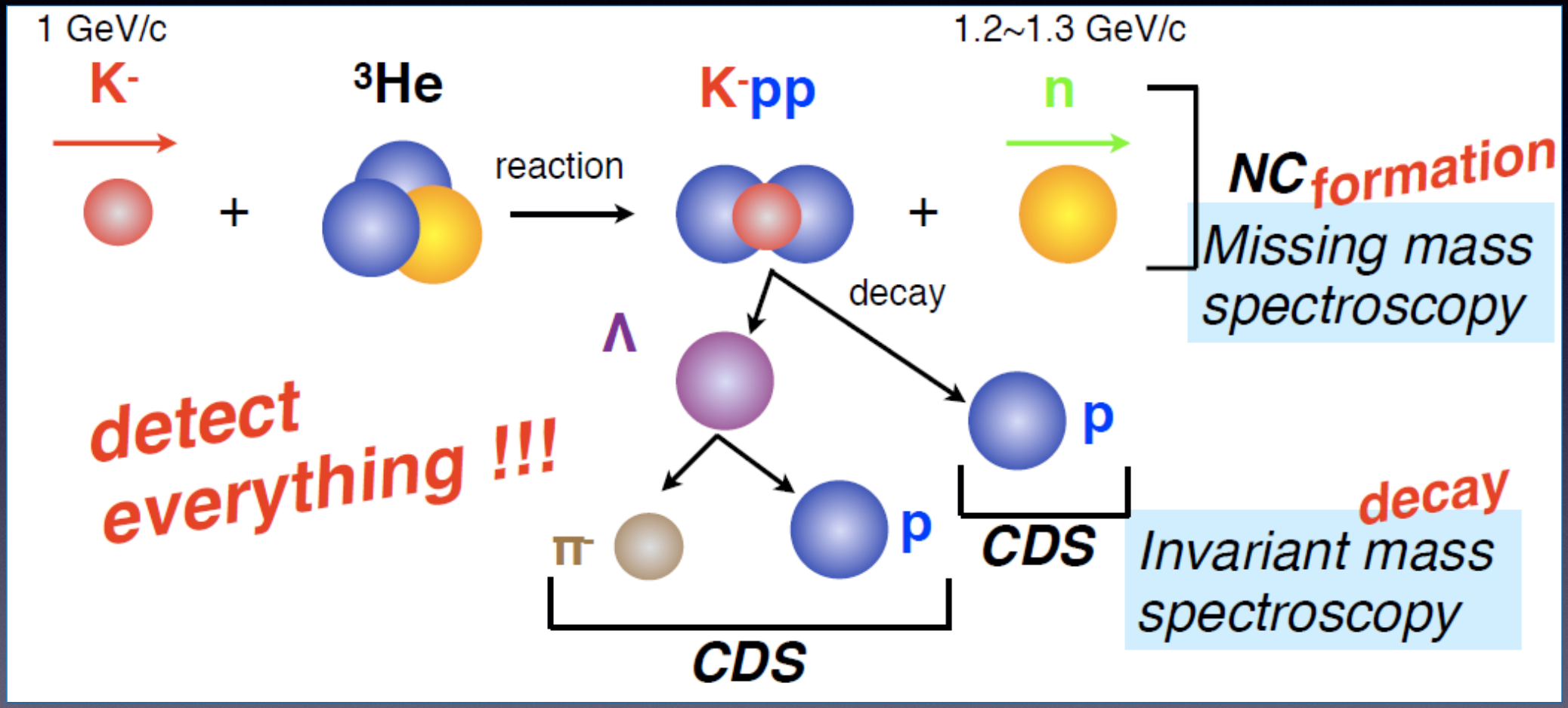



- Theoretically, existence of Kaonic nucleus is no doubt. Question is mass and width.

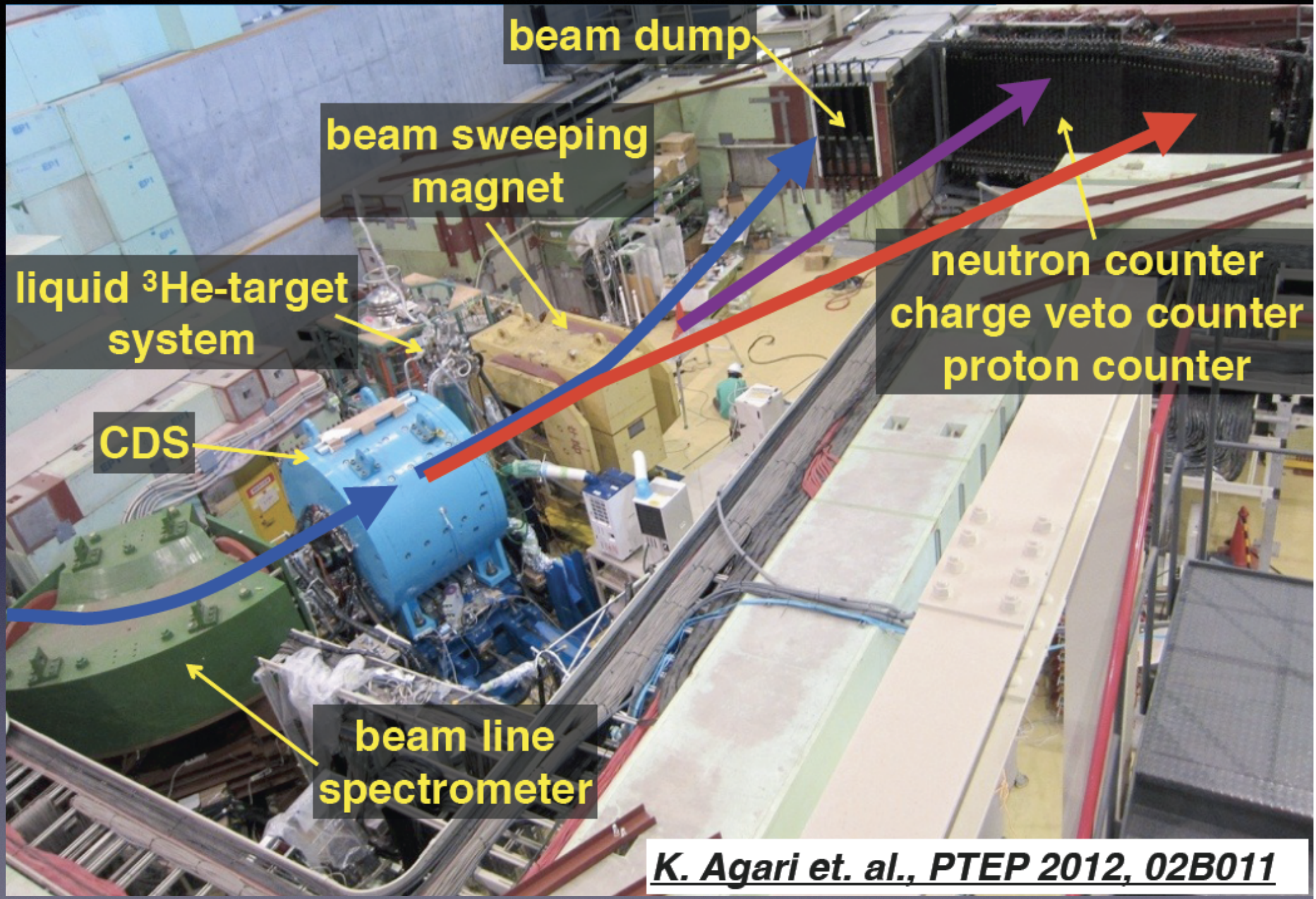
# J-PARC E15 experiment

A search for $\bar{K}NN$ via $^3$He(*in-flight* K$^-$,n) reaction




Proposal submitted to J-PARC on 2006

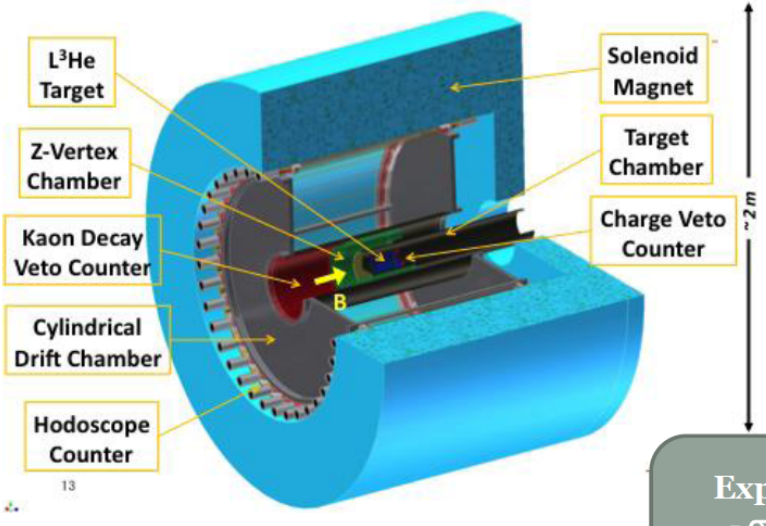
1st physics data taking on 2013

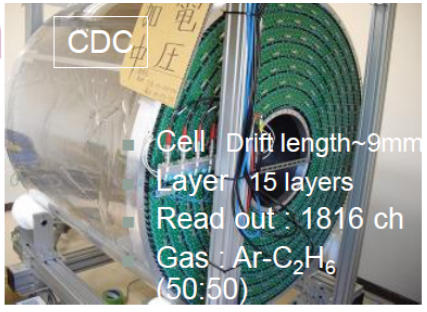

beam dump
beam sweeping magnet
liquid $^3$He-target system
CDS
neutron counter
charge veto counter
proton counter
beam line spectrometer
K. Agari et. al., PTEP 2012, 02B011

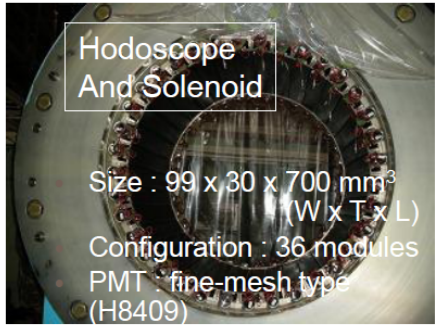
# Selected performance

## Cylindrical Detector System

- To detect the decay particles from $^3$HeTarget
  - Momentum reconstruction
  - Particle identification

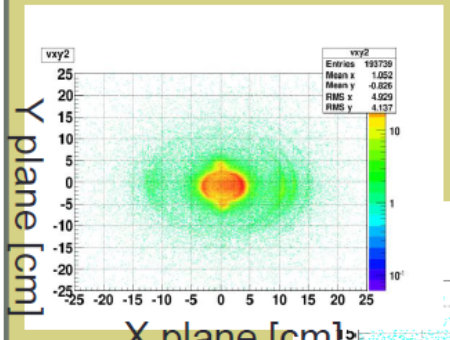


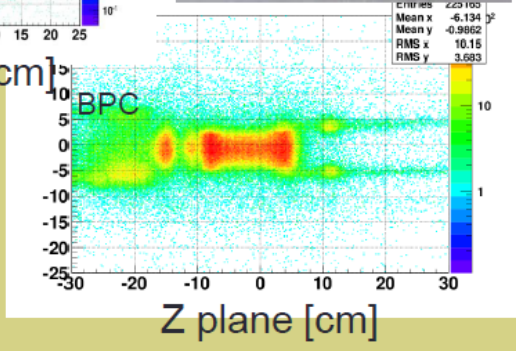



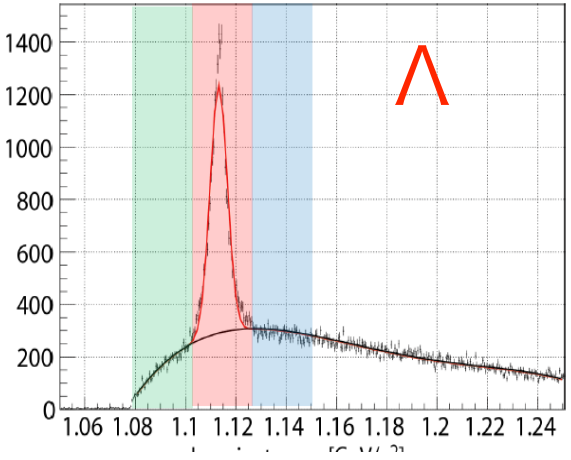

**Expected mass resolution :**
**- σ ~ 3.6 MeV/c² for Λ**
**- σ ~ 10 MeV/c² for K⁻pp**
**( $\sigma_{cdc}$ = 200 μm / Field : 0.7 T)**

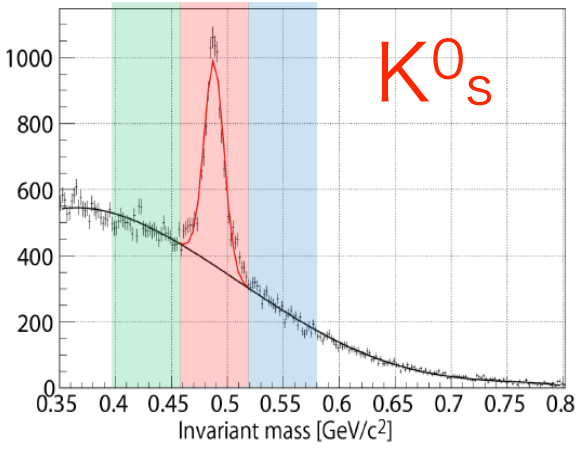
## Target image

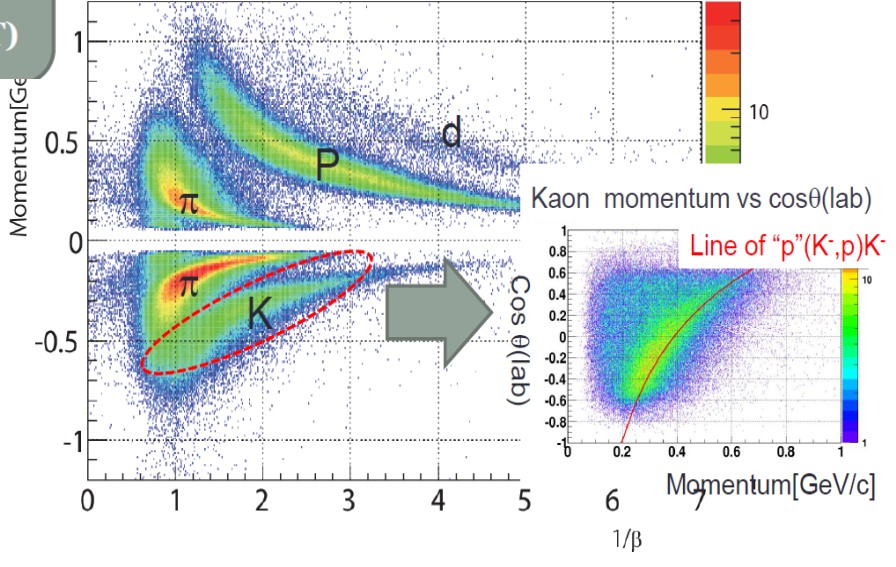


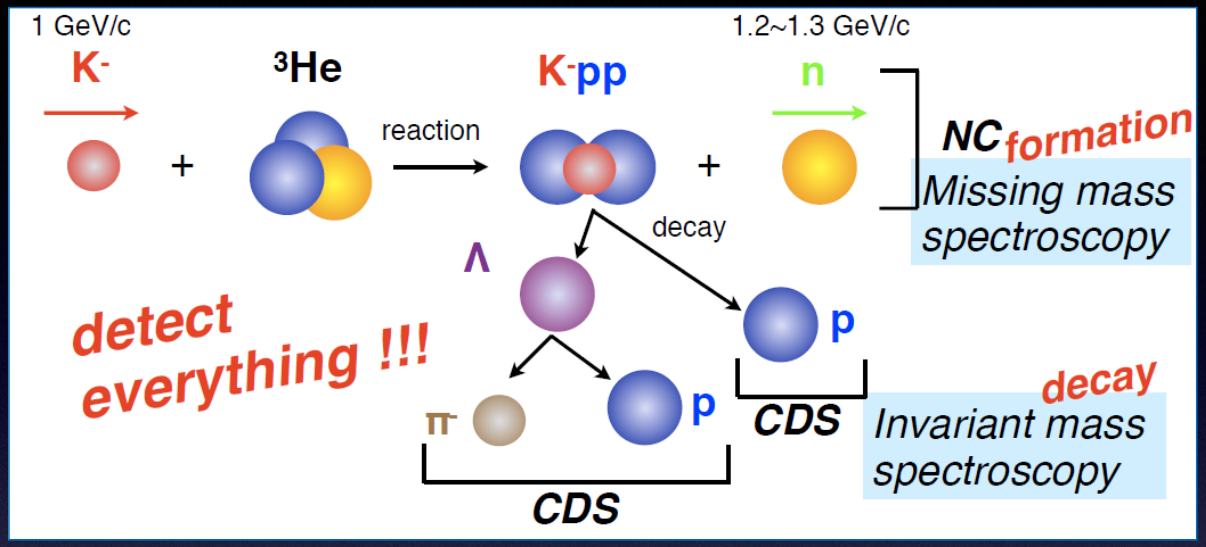

- Pi beam data
- DC of CDC 2track(pion)



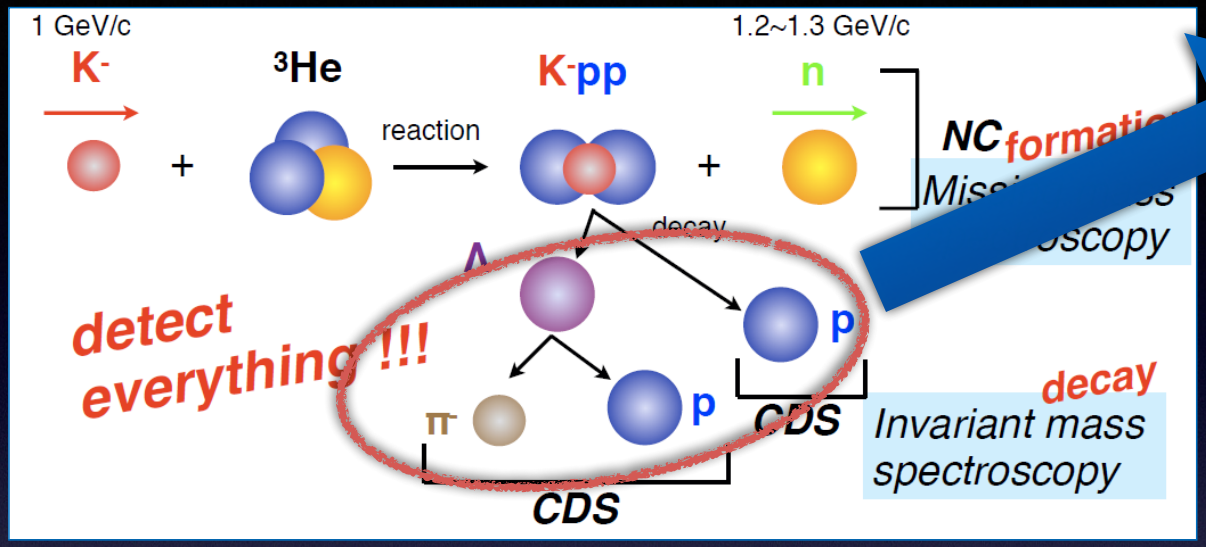



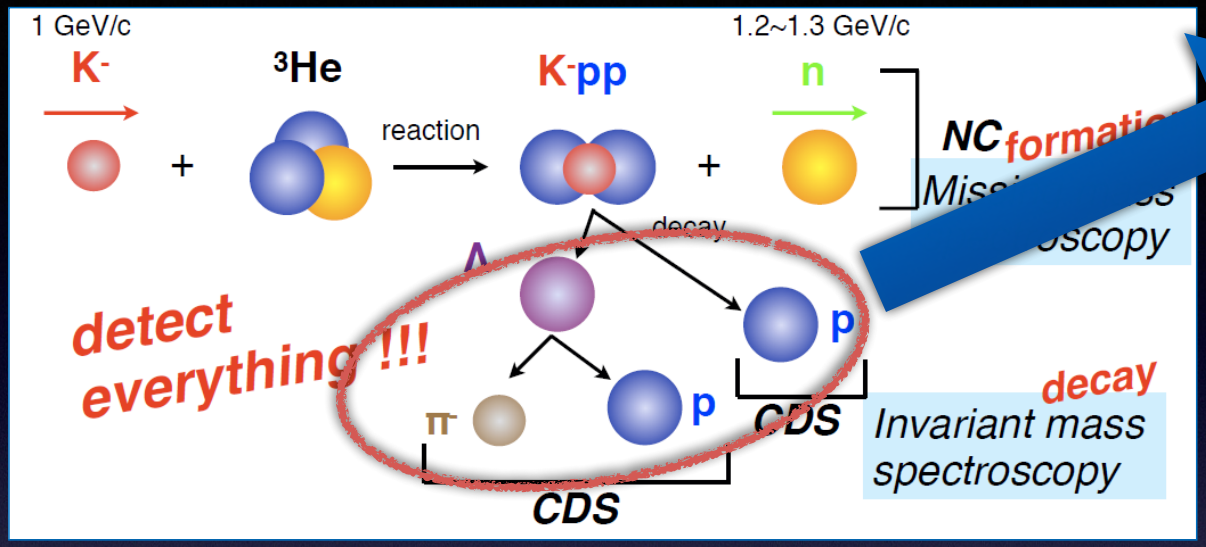
# Results : Λpn final state



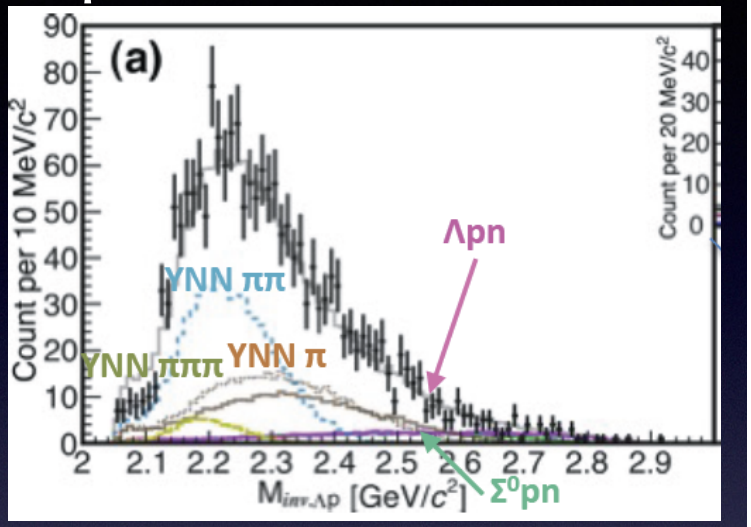
# Results : Λpn final state



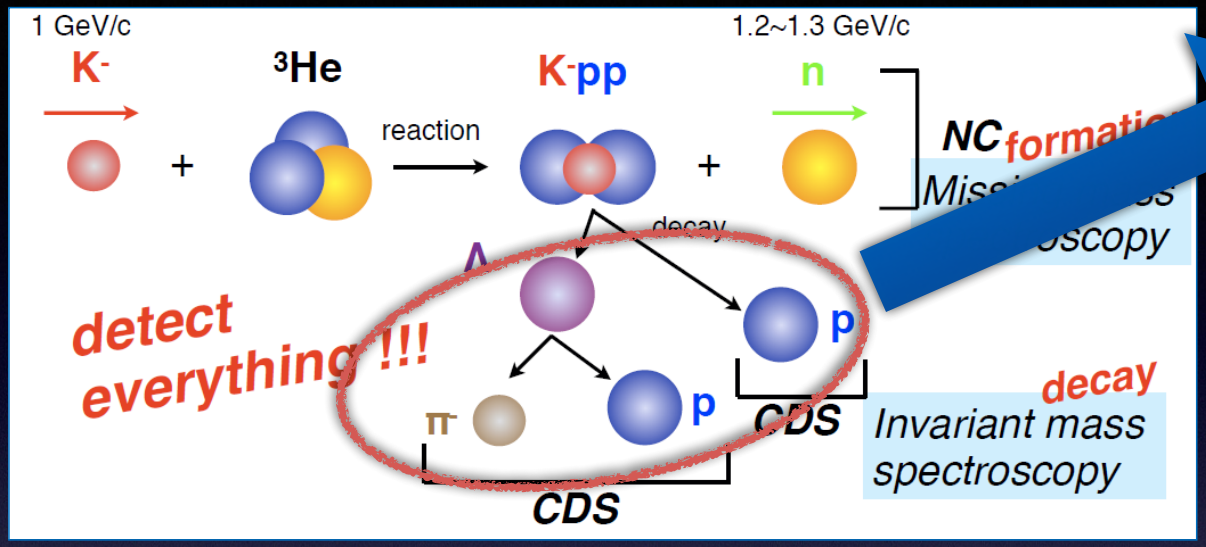
# Results : Λpn final state



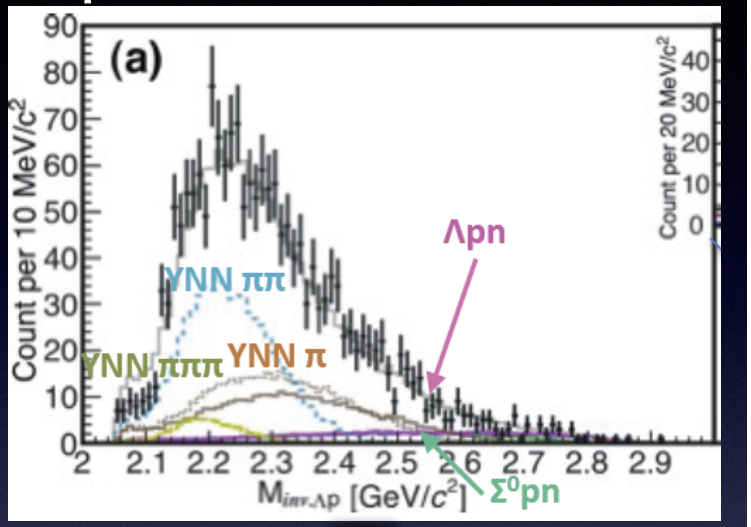

Λp invariant mass



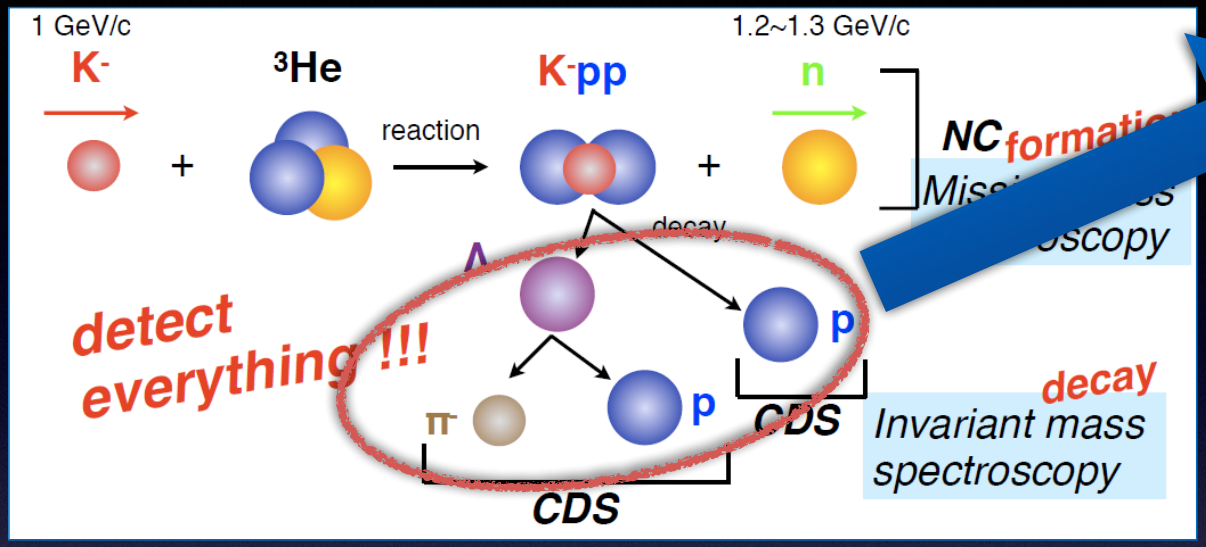
# Results : Λpn final state



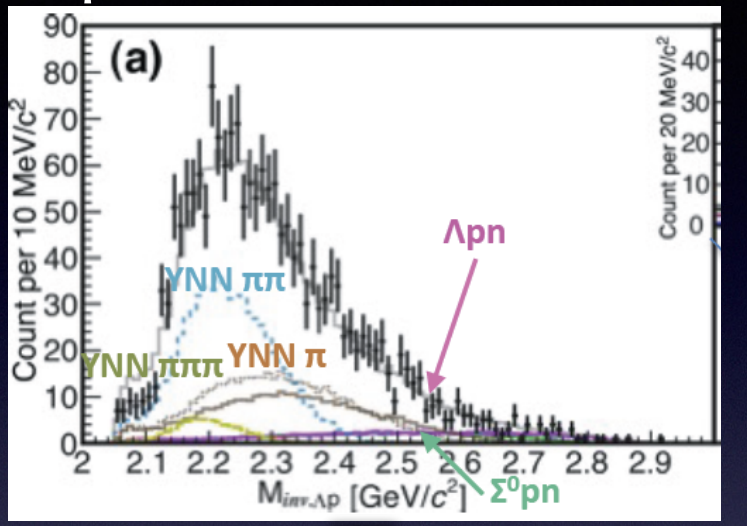

Λp invariant mass



# Results : Λpn final state

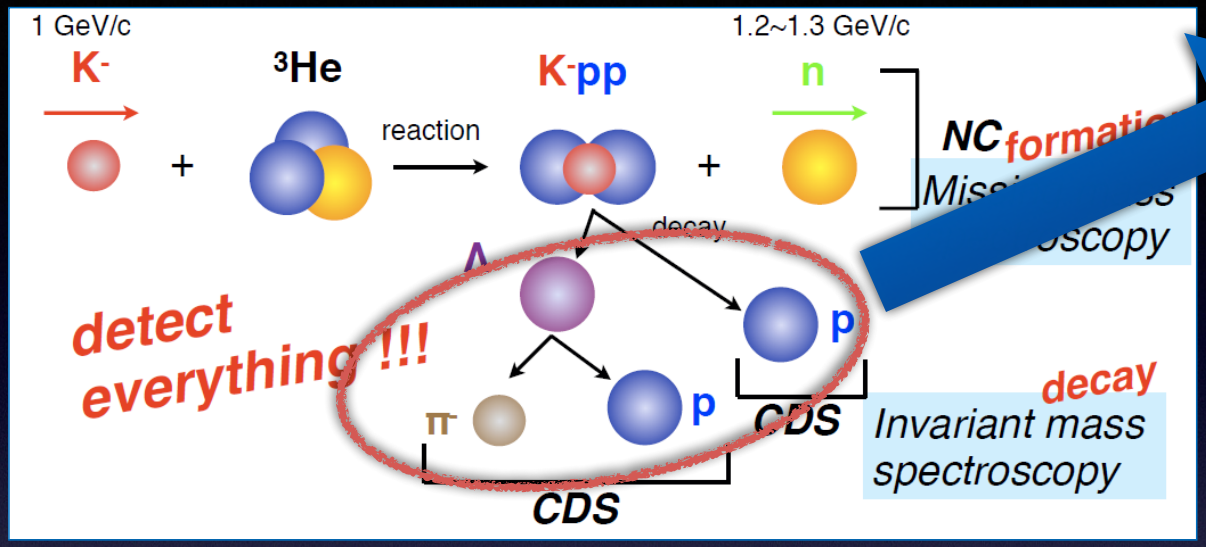



Λp invariant mass

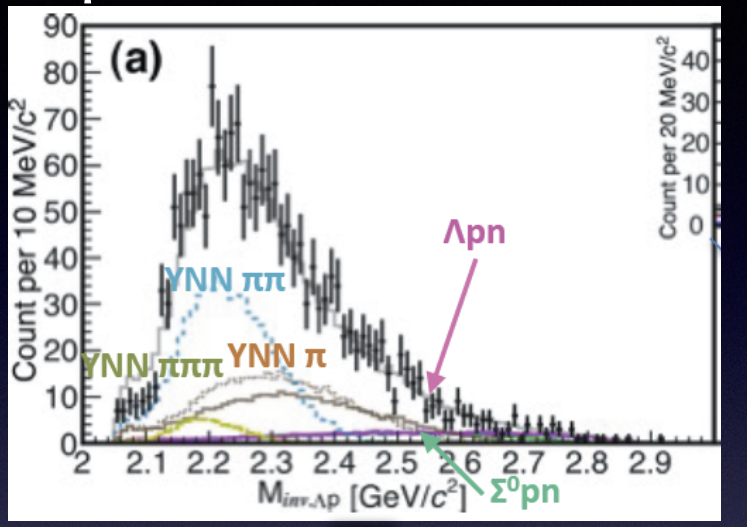



missing mass

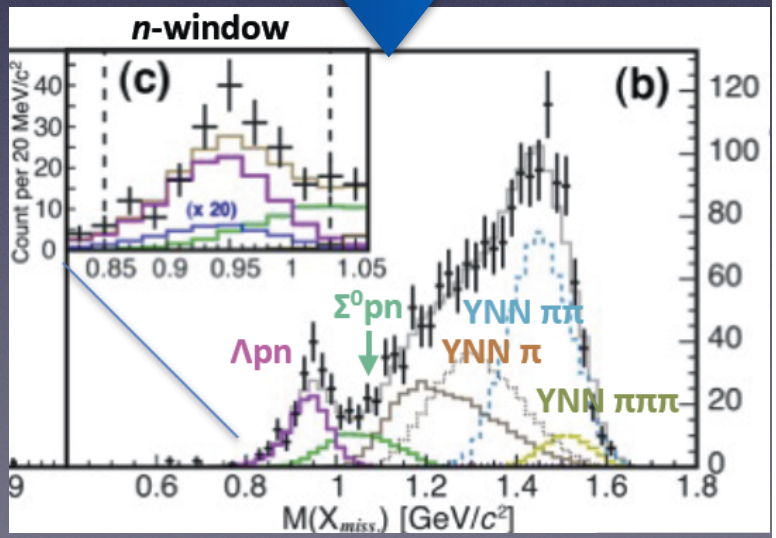
# Results : Λpn final state



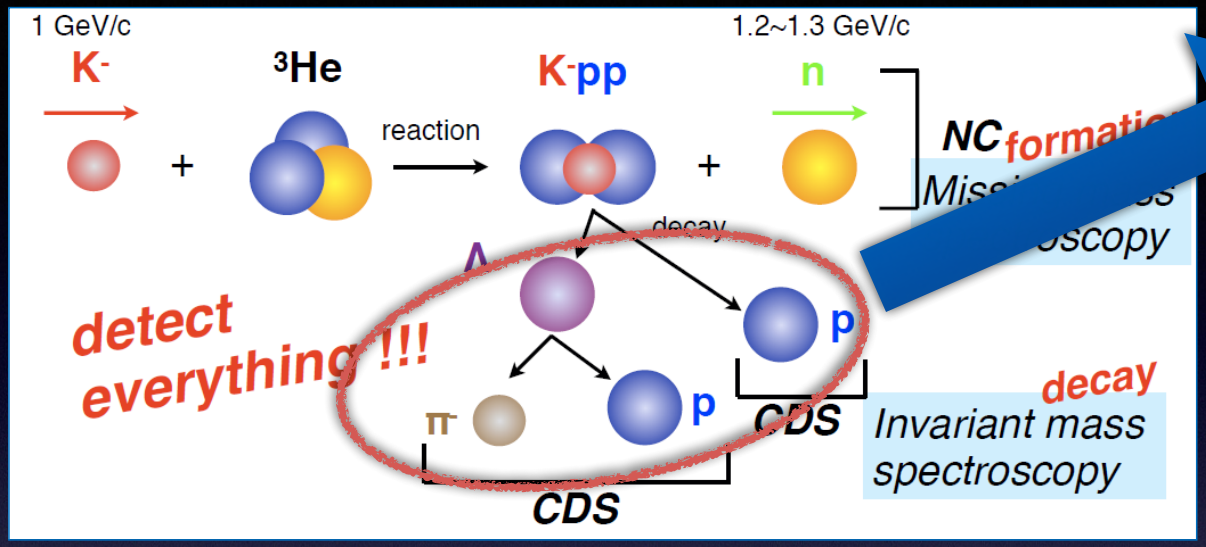

## Λp invariant mass



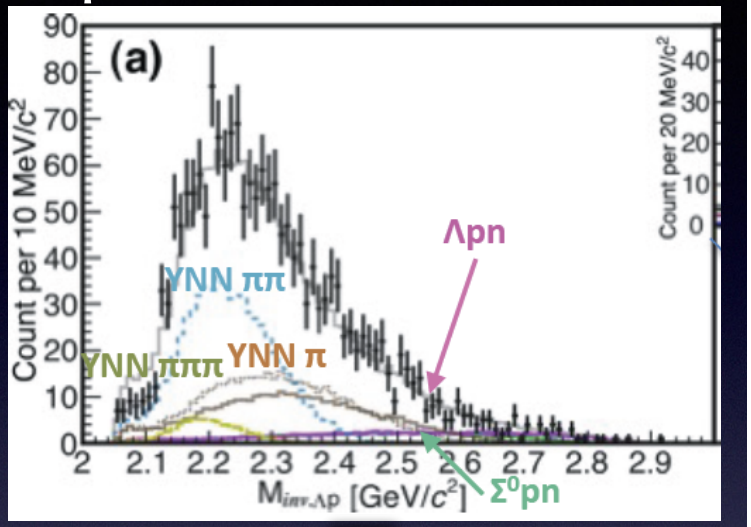

## missing mass



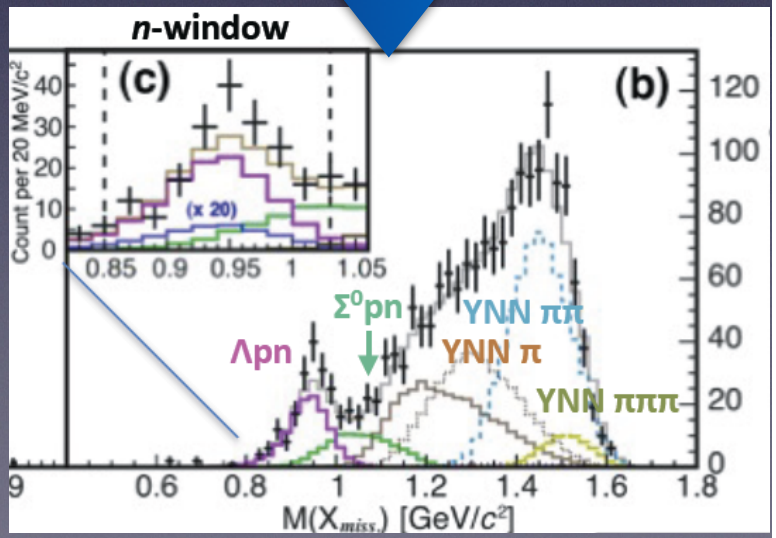
# Results : Λpn final state




Λp invariant mass




missing mass

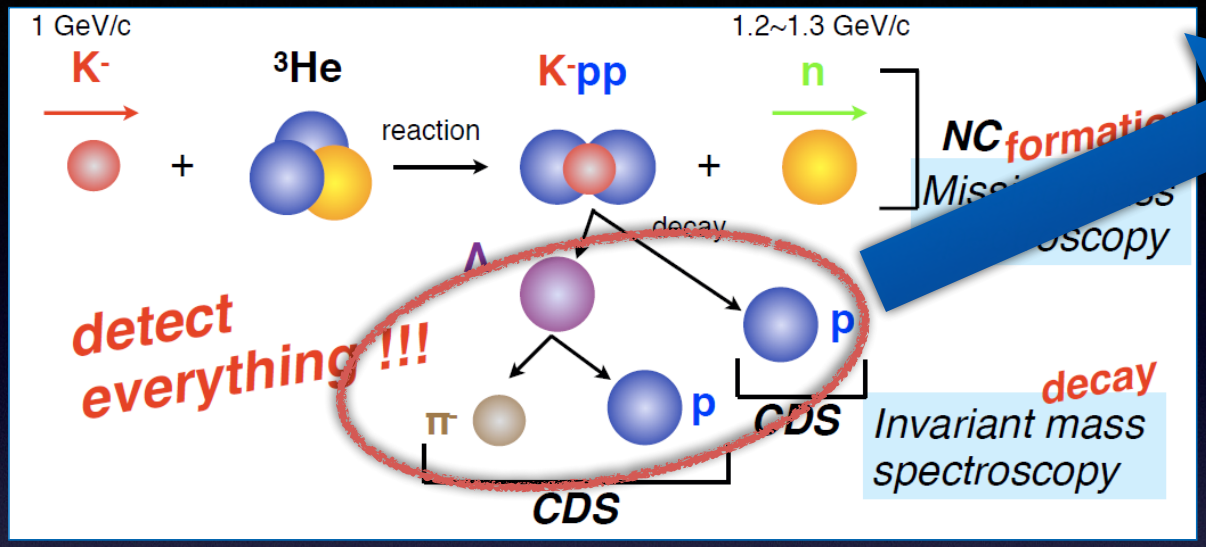



✦ neutron is identified kinematically

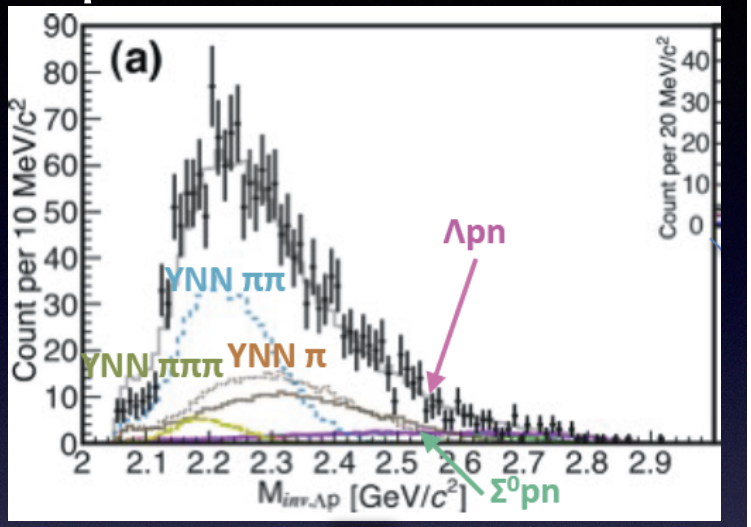
$$K^- + {}^3He \rightarrow \Lambda + p + n_{missing}$$

we can cover large solid angle

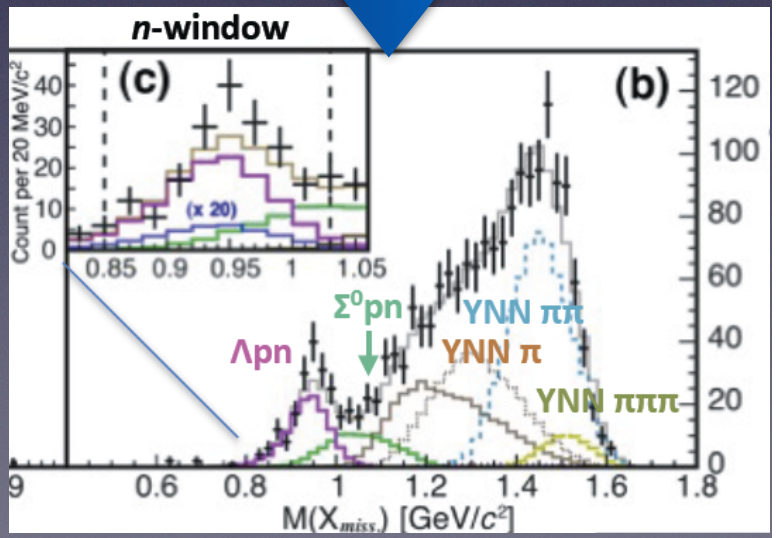
# Results : Λpn final state




Λp invariant mass




missing mass

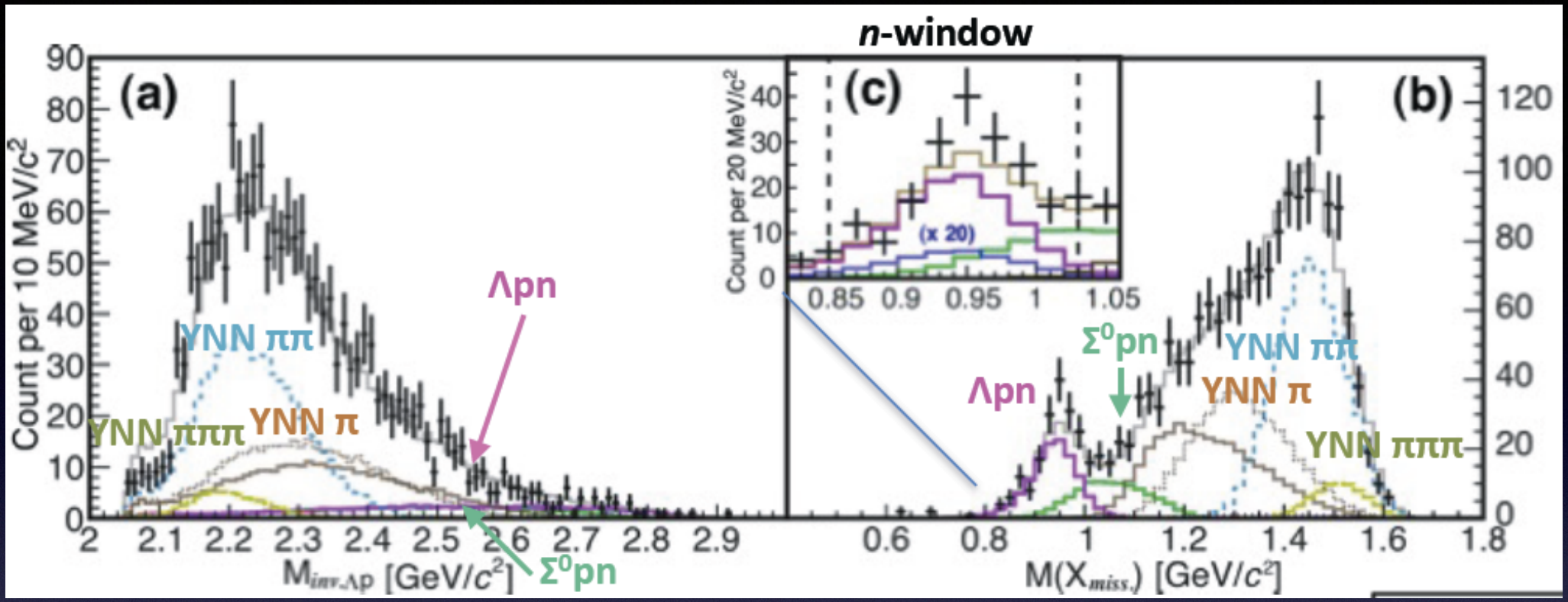


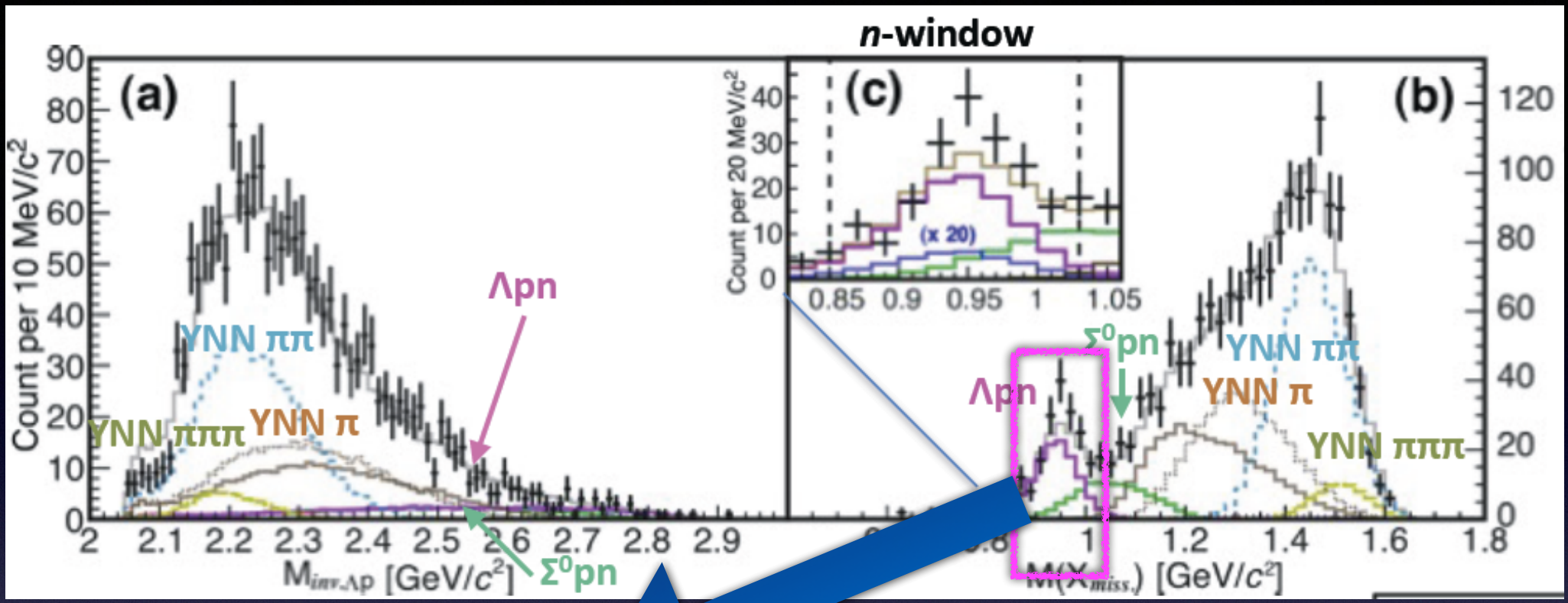

✦ neutron is identified kinematically

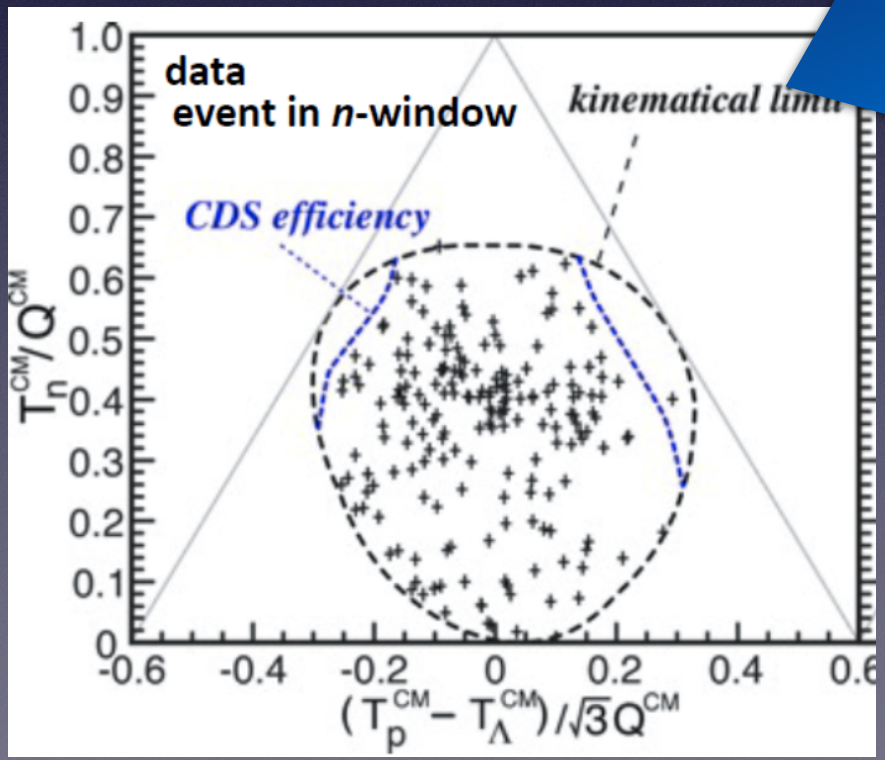
$$K^- + {}^3He \rightarrow \Lambda + p + n_{missing}$$

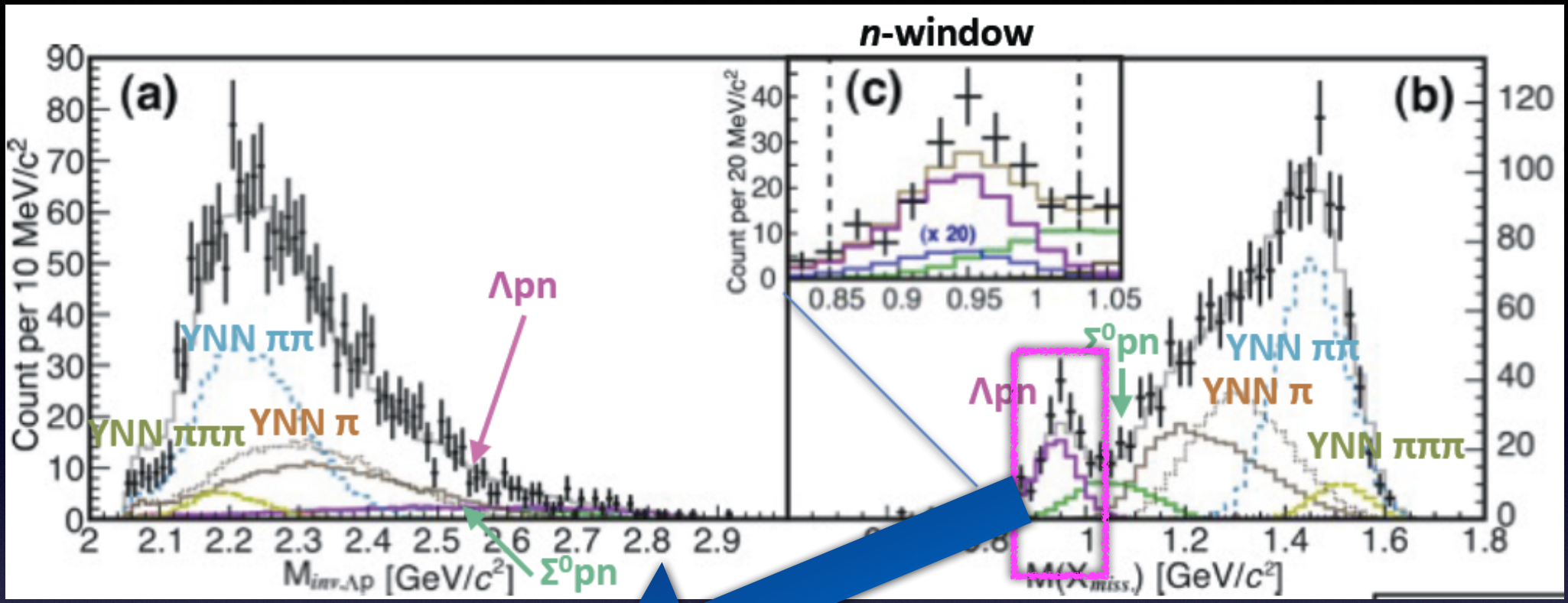
we can cover large solid angle

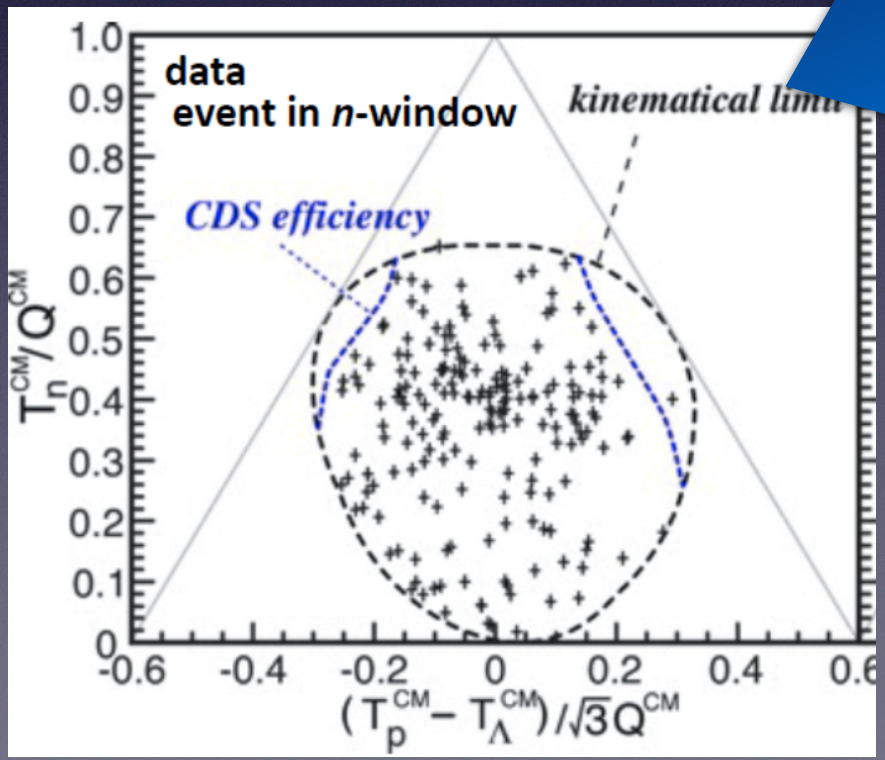
✦ to identify the contribution,
global fit performed on
Λp missing mass & invariant mass
simultaneously


n-window
(a)
(b)
(c)
Count per 10 MeV/c²
Count per 20 MeV/c²
(x 20)
M_inv-Λp [GeV/c²]
M(X_miss.) [GeV/c²]
Λpn
Σ⁰pn
YNN ππ
YNN π
YNN πππ


n-window
(a)
(b)
(c)
Count per 10 MeV/c²
Count per 20 MeV/c²
(x 20)
Λpn
Σ⁰pn
YNN ππ
YNN π
YNN πππ
M_inv-Λp [GeV/c²]
M(X_miss.) [GeV/c²]

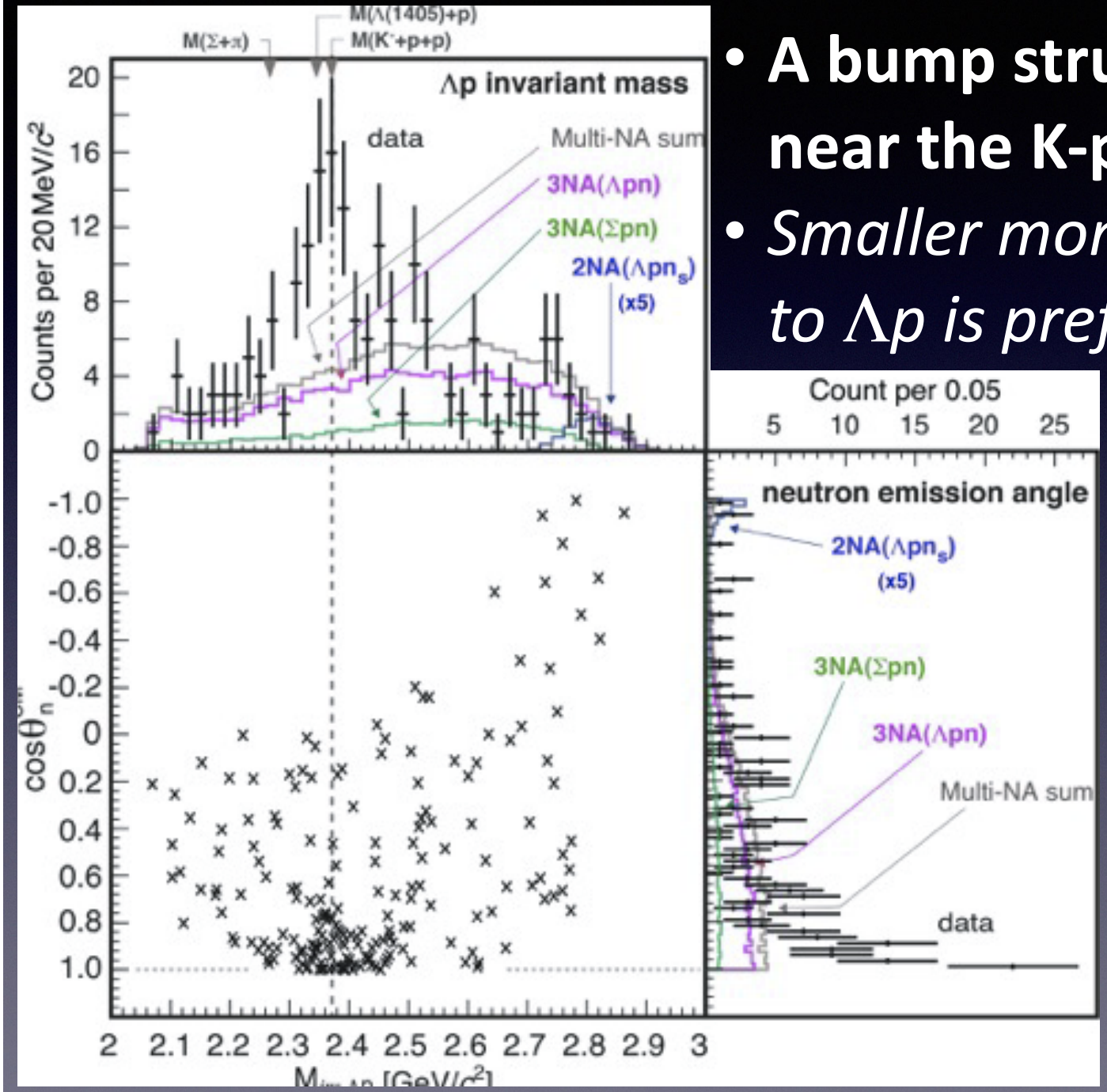

data
event in n-window
kinematical limit
CDS efficiency
T_n^CM/Q^CM
(T_p^CM − T_Λ^CM)/√3Q^CM




- The events widely distribute in the phase space → Kaon absorption by three nucleons are dominant
- Event concentration is seen at $T^{CM}_n/Q^{CM}$~0.4

# Bound state?




- **A bump structure exists near the K-pp threshold**
- *Smaller momentum transfer to Λp is preferred (0.8<cos$\theta^{CM}_n$)*

neutron→forward
kaon→backward

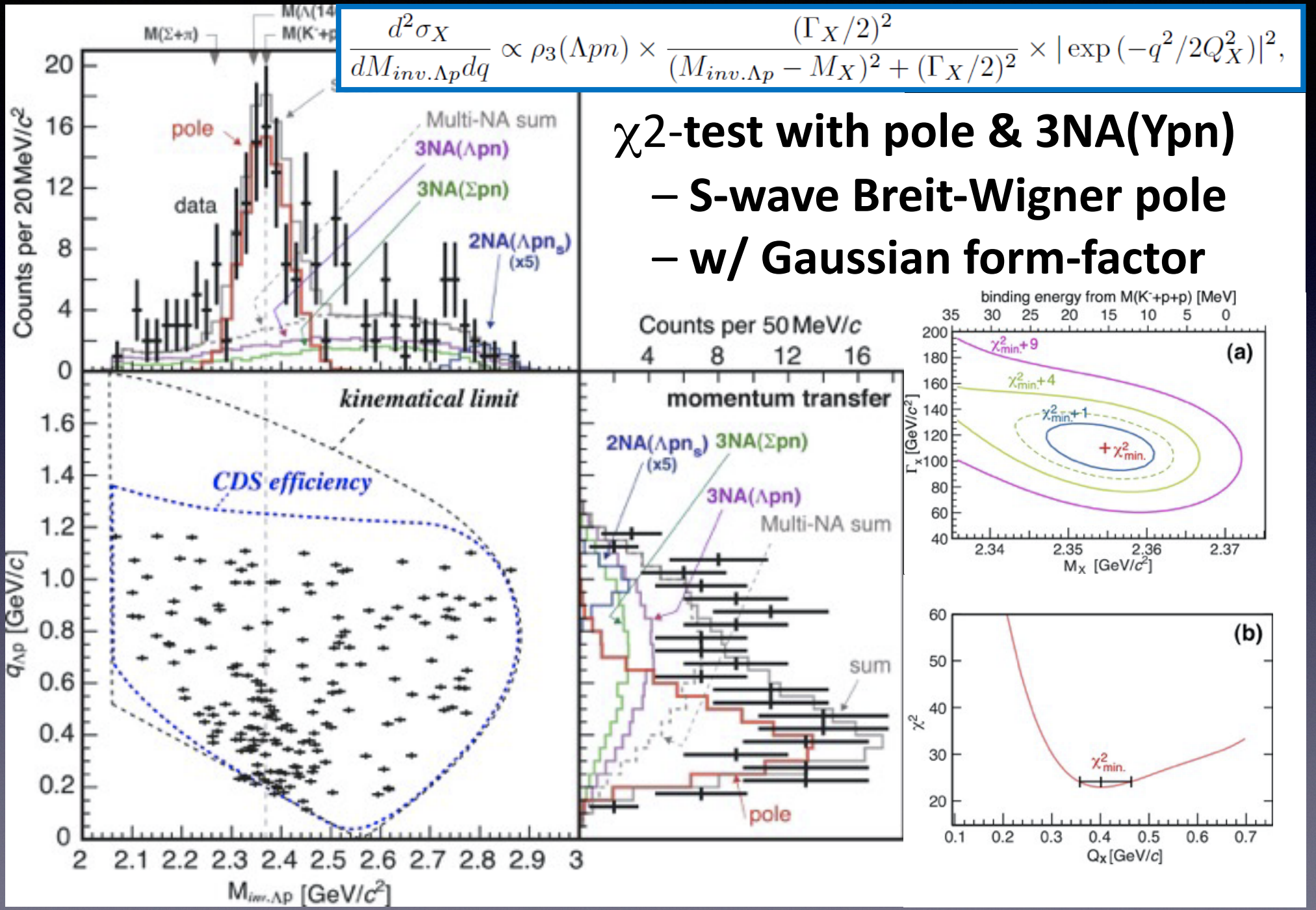
Something happened
Slow Kaon produced
near by nucleus

# Bound state?

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

**$\chi$2-test with pole & 3NA(Ypn)**

- **S-wave Breit-Wigner pole**
- **w/ Gaussian form-factor**



# Bound state?



Nuclear Experiment

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

J-PARC E15 Collaboration: Y. Sada, S. Ajimura, M. Bazzi, G. Beer, H. Bhang, M. Bragadireanu, P. Buehler, L. Busso, M. Cargnelli, S. Choi, C. Curceanu, S. Enomoto, D. Faso, H. Fujioka, Y. Fujiwara, T. Fukuda, C. Guaraldo, T. Hashimoto, R. S. Hayano, T. Hiraiwa, M. Iio, M. Iliescu, K. Inoue, Y. Ishiguro, T. Ishikawa, S. Ishimoto, T. Ishiwatari, K. Itahashi, M. Iwai, M. Iwasaki, Y. Kato, S. Kawasaki, P. Kienle, H. Kou, Y. Ma, J. Marton, Y. Matsuda, Y. Mizoi, O. Morra, T. Nagae, H. Noumi, H. Ohnishi, S. Okada, H. Outa, K. Piscicchia, A. Romero Vidal, A. Sakaguchi, F. Sakuma, M. Sato, A. Scordo, M. Sekimoto, H. Shi, D. Sirghi, F. Sirghi, K. Suzuki, S. Suzuki, T. Suzuki, K. Tanida, H. Tatsuno, M. Tokuda, D. Tomono, A. Toyoda, K. Tsukada, O. Vazquez Doce, E. Widmann, B. K. Wuenschek, T. Yamaga, et al. (4 additional authors not shown)

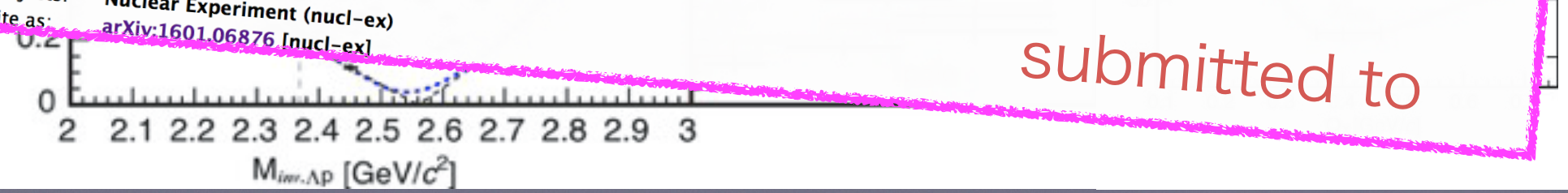
*(Submitted on 26 Jan 2016)*

To search for an S= −1 di-baryonic state which decays to $\Lambda p$, the $^3\mathrm{He}(K^-,\Lambda p)n_{missing}$ reaction was studied at 1.0 GeV/$c$. Unobserved neutrons were kinematically identified from the missing mass $M_X$ of the $^3\mathrm{He}(K^-,\Lambda p)X$ reaction in order to have a large acceptance for the $\Lambda pn$ final state. The observed $\Lambda pn$ events, distributed widely over the kinematically allowed region of the Dalitz plot, establish that the major component comes from a three nucleon absorption process. A concentration of events at a specific neutron kinetic energy was observed in a region of low momentum transfer to the $\Lambda p$. To account for the observed peak structure, the simplest S-wave pole was assumed to exist in the reaction channel, having Breit-Wigner form in energy and with a Gaussian form-factor. A minimum $\chi^2$ method was applied to deduce its mass $M_X = 2355\ ^{+6}_{-8}$ (stat.) ±12 (syst.) MeV/c$^2$, and decay-width $\Gamma_X = 110\ ^{+19}_{-17}$ (stat.) ±27 (syst.) MeV/c$^2$, respectively. The form factor parameter $Q_X \sim$ 400 MeV/$c$ implies that the range of interaction is about 0.5

Comments: 11pages, 8 figures
Subjects: **Nuclear Experiment (nucl-ex)**
Cite as: arXiv:1601.06876 [nucl-ex]



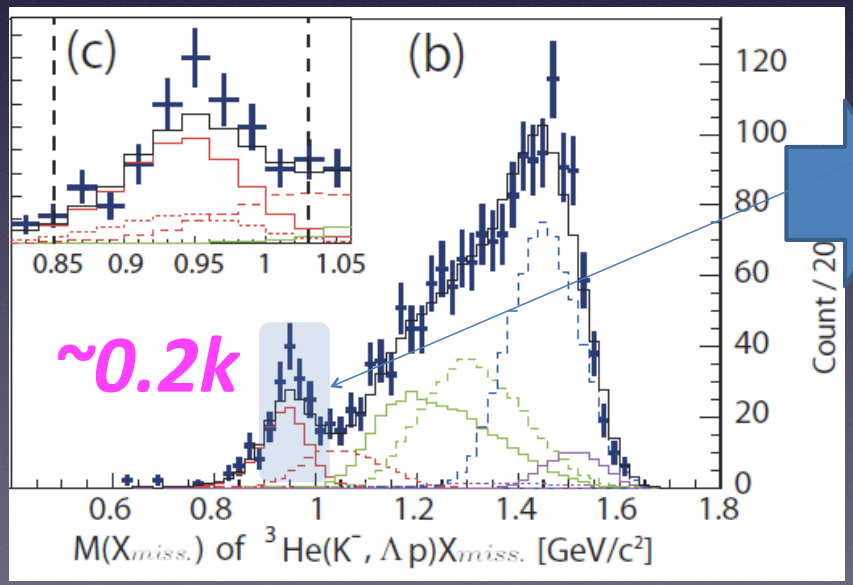
submitted to



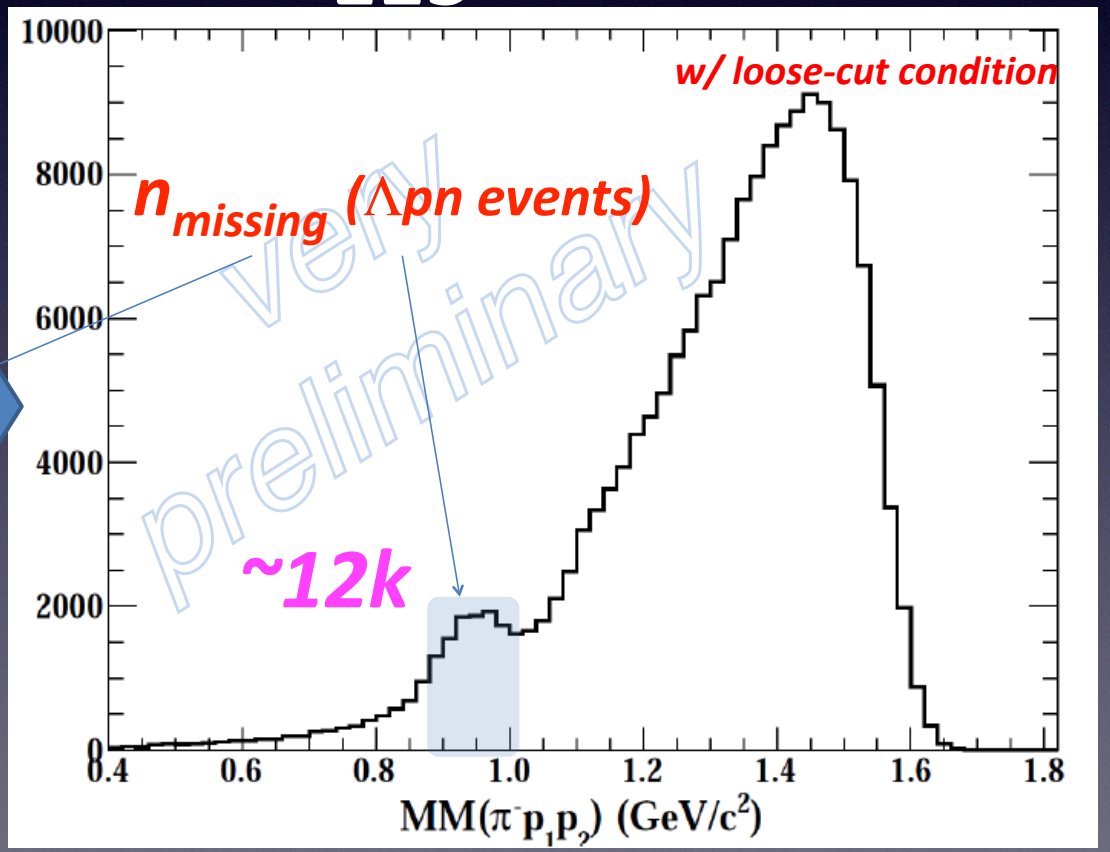
# New data

- ✦ We took new data during Nov-Dec/2015
- ✦ ~ 50 times more $K^-$+3He→ΛpnΛpn events are accumulated

**E15$^{1st}$**




**E15$^{2nd}$**




- Data analysis is in progress

# Hadron Physics with high momentum $K^-$ $p > 2$ GeV/$c$

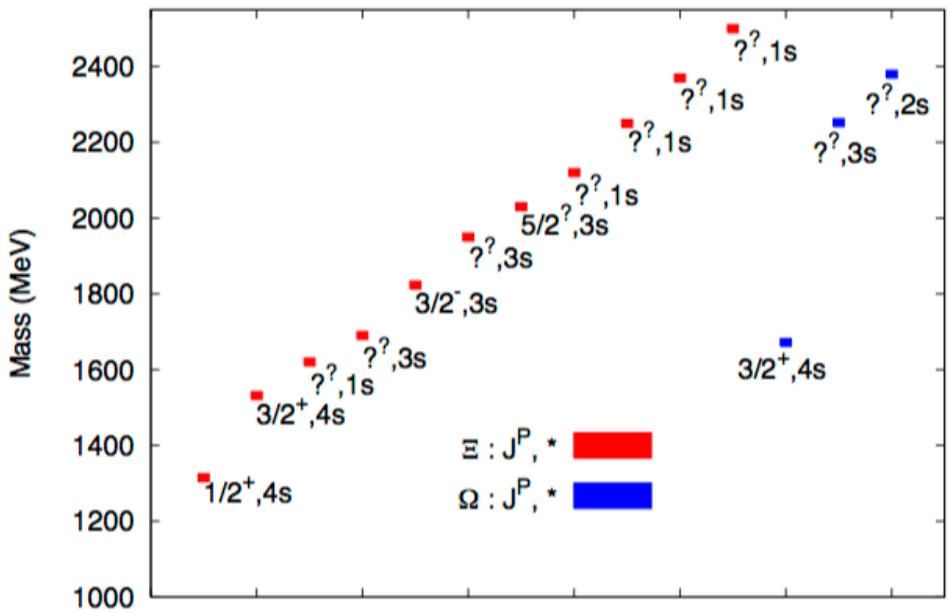
# Hadron Physics with high momentum $K^-$

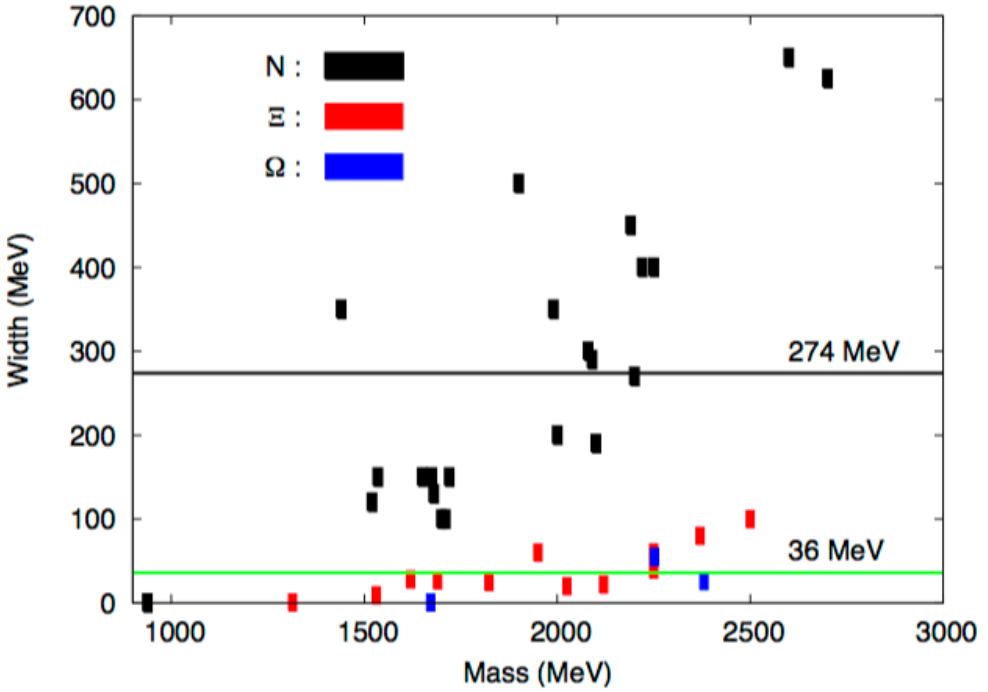
$p > 2$ GeV/$c$

Multi-strange Baryon spectroscopy

# Baryon Mass and width

Copy from PoS: LATTICE2008:125,2008



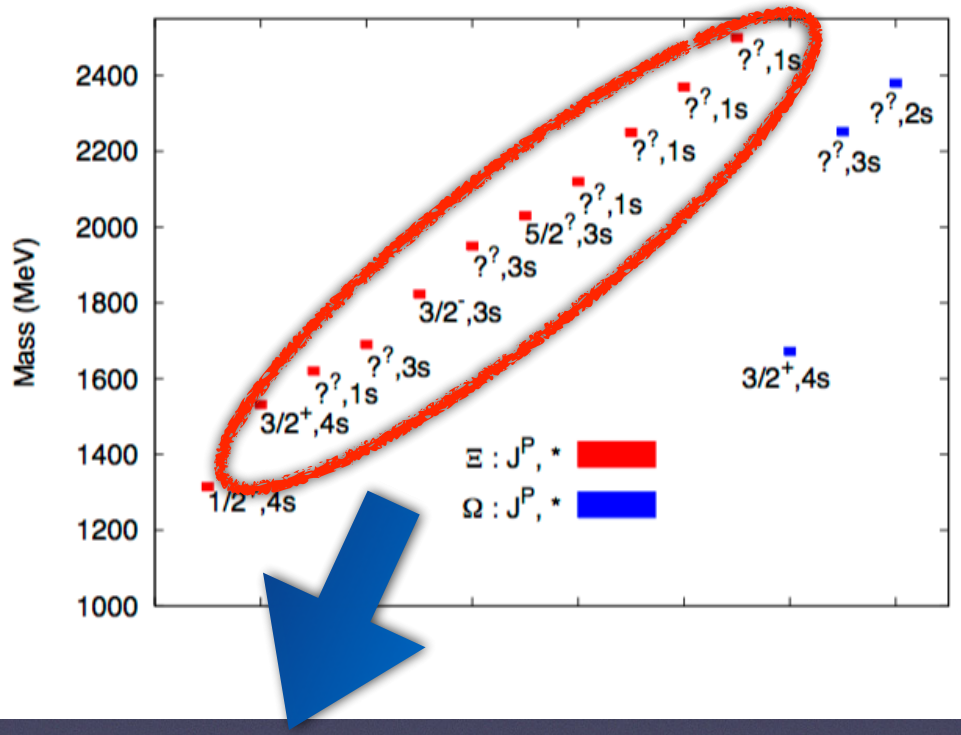

Excited state of Ξ,Ω baryon are not well established

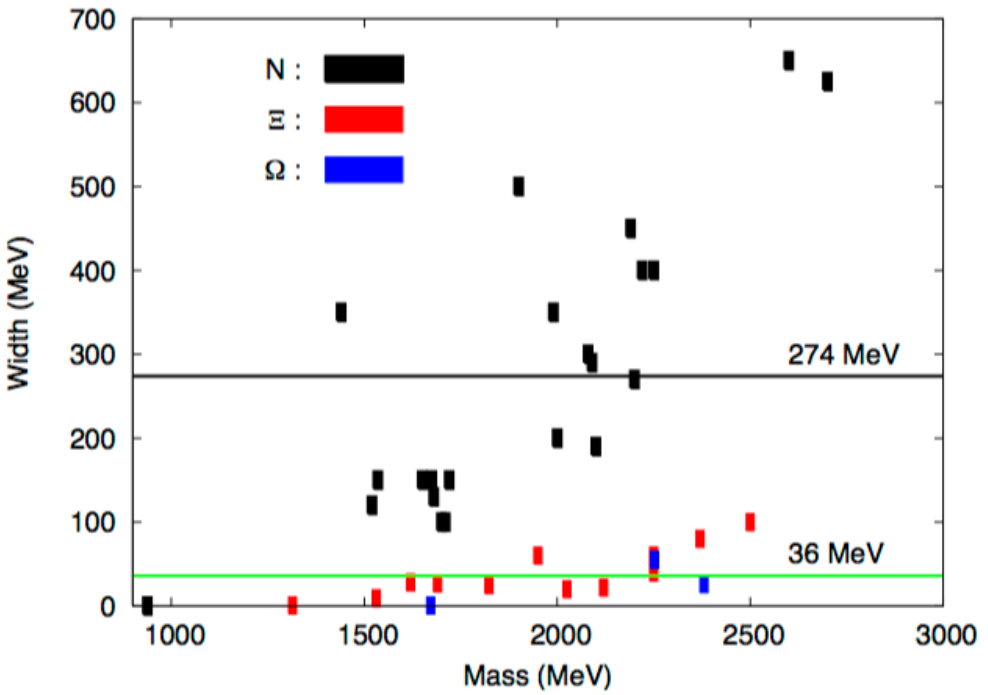
Width of excited states for Ξ,Ω seems narrow compared with nucleon resonances

we may have a chance to find it by experiment!

# Baryon Mass and width

Copy from PoS: LATTICE2008:125,2008




$K^-p \rightarrow \Xi^{0*}(1530)\pi^-K^+$; $p_{th}$= 1.835 GeV/c

$K^-p \rightarrow \Xi^{-*}(1950)K^+$; $p_{th}$= 2.536 GeV/c

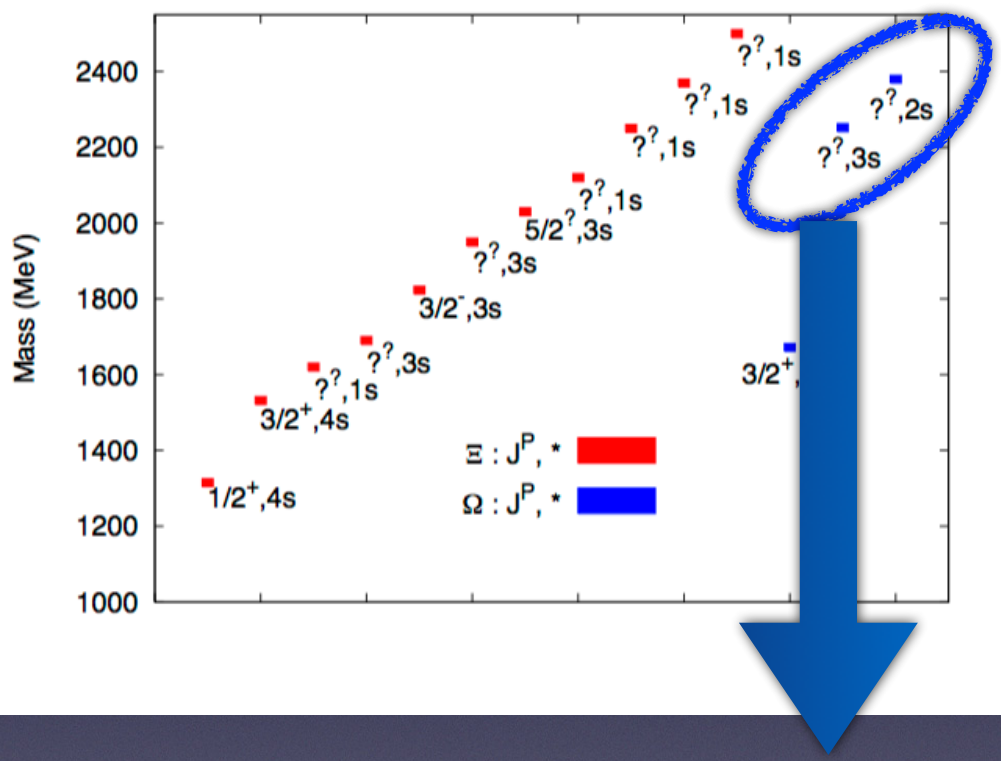
$K^-p \rightarrow \Xi^{--}(1860)\pi^+K^+$; $p_{th}$= 2.668 GeV/c

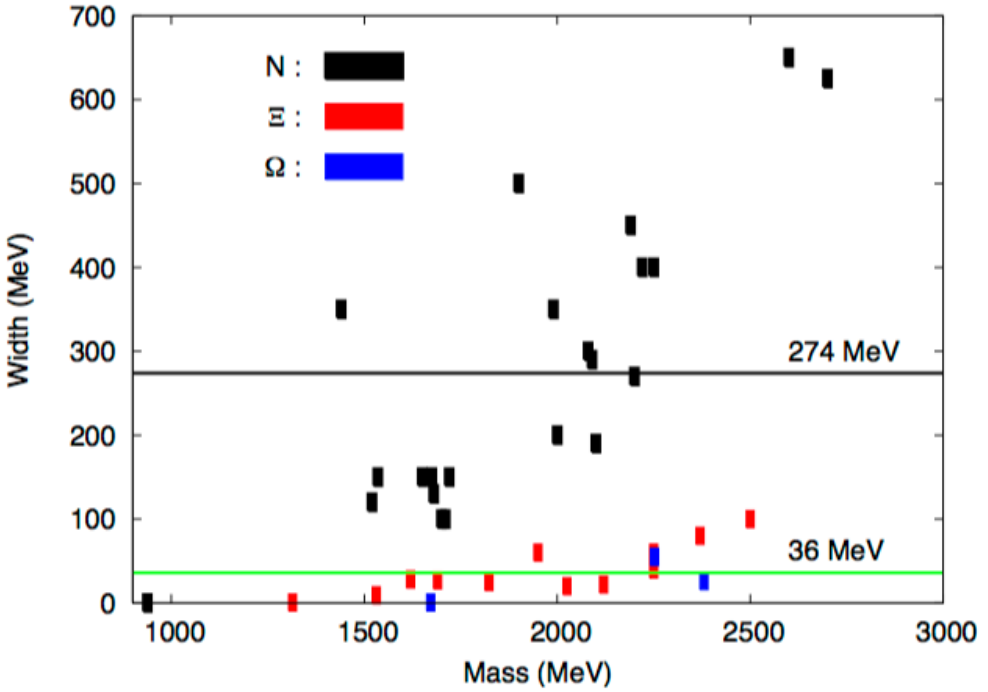
$K^-p \rightarrow \Xi^{-*}(2500)K^+$; $p_{th}$= 2.687 GeV/c

Production cross section ~ a few $\mu$b

# Baryon Mass and width

Copy from PoS: LATTICE2008:125,2008



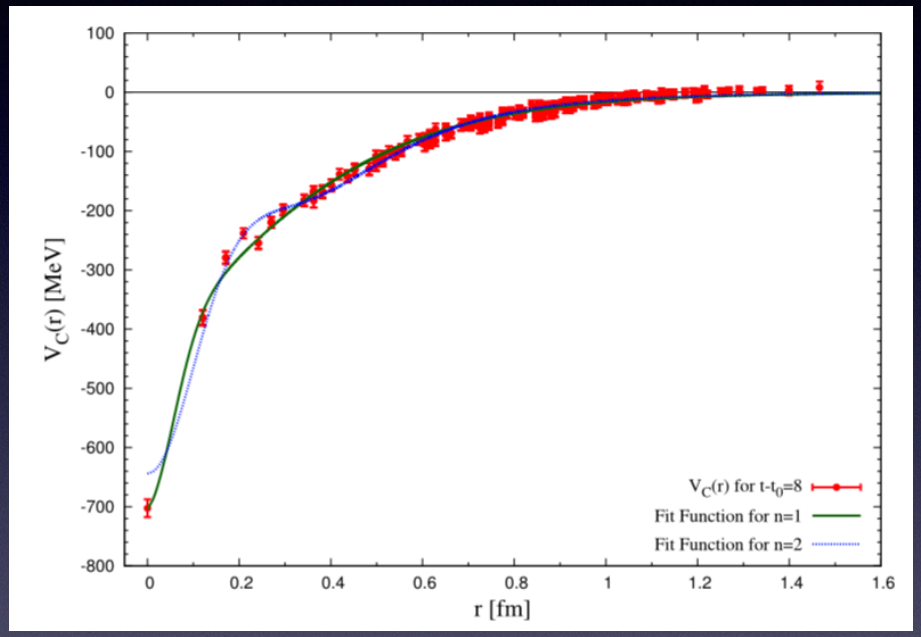

Ω production : (very little information are available so far)

Ω(2250) ~ 0.63μb @11 GeV/c

Ω(2470) ~ 0.29μb @11 GeV/c

High intensity & High momentum K- beam is needed

# ΩN bound state?
# (spin-2 dibaryon)




Nucl. Phys. A928(2014)89 HAL QCD Coll.

Lattice QCD calculation predict that existence of ΩN bound state

$$B_{N\Omega} = 18.9(5.0)(^{+12.1}_{-1.8})\ \mathrm{MeV},$$
$$a_{N\Omega} = -1.28(0.13)(^{+0.14}_{-0.15})\ \mathrm{fm},$$
$$(r_e)_{N\Omega} = 0.499(0.026)(^{+0.029}_{-0.048})\ \mathrm{fm}.$$

$m_\pi$ = 875(1) MeV and $m_K$ = 916(1) MeV

need detail investigation using Ω-N interaction!

via $K^- + p \rightarrow K^+ K^0 \Omega$ reaction on nuclear target!

need high intensity $K^-$ > 3 GeV/*c* beam

# Multi-strange baryon spectroscopy

- Ξ* spectroscopy can be started and made at High-p beam line (unseparated beam).

# LOI submitted to J-PARC on April 14/2014

## Ξ Baryon Spectroscopy with High-momentum Secondary Beam

M. Naruki and K. Shirotori
*Department of Physics, Kyoto University, Kyoto, 606-8502, Japan and*
*Research Center for Nuclear Physics (RCNP), 10-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan*
(Dated: April 14, 2014)

We express our interest in performing the Ξ baryon spectroscopy with high-momentum secondary beams. The experimental information on the excited states of Ξ baryon is largely lacking. The physics cases and possibilities to investigate $\Xi^*$ states using the high-momentum beam line is discussed. The enough sensitivity is expected to determine the excited state up to 2 GeV/$c^2$ systematically with a reasonable beam time in both kaon and $\pi$ induced reactions. The high intense secondary beam provide an opportunity to investigate an unknown field of $\Xi^*$ baryons.

detail will be discussed in Prof. Noumi's talk

# Multi-strange baryon spectroscopy

- Ξ* spectroscopy can be made at High-p beam line (unseparated beam).
- However, for detail analysis, we need high intensity K- beam.
- For Ω* spectroscopy, daintily need high energy and high intensity K- beam.

# Multi-strange baryon spectroscopy

- Ξ* spectroscopy can be made at High-p beam line (unseparated beam).
- However, for detail analysis, we need high intensity K- beam.
- For Ω* spectroscopy, daintily need high energy and high intensity K- beam.

High intensity-high momentum-separated beam line is needed to proceed projects above

# Missing pieces

Missing pieces

high momentum

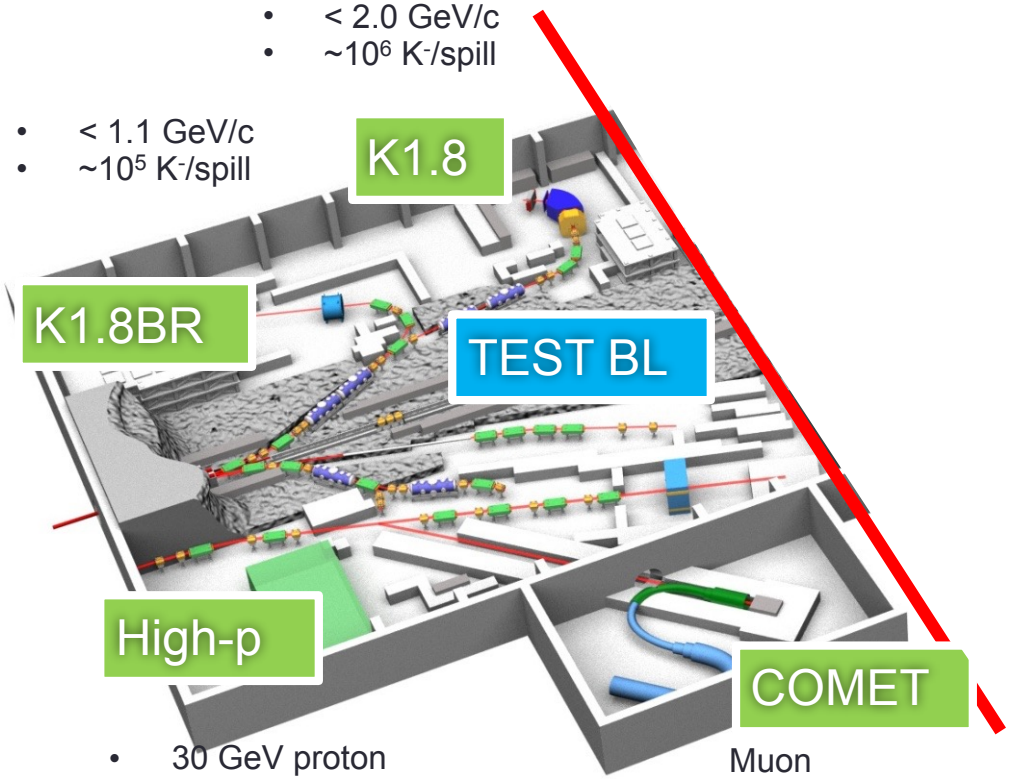
high intensity

separated beam

# J-PARC Hadron hall extension

- < 2.0 GeV/c
- ~$10^6$ $K^-$/spill

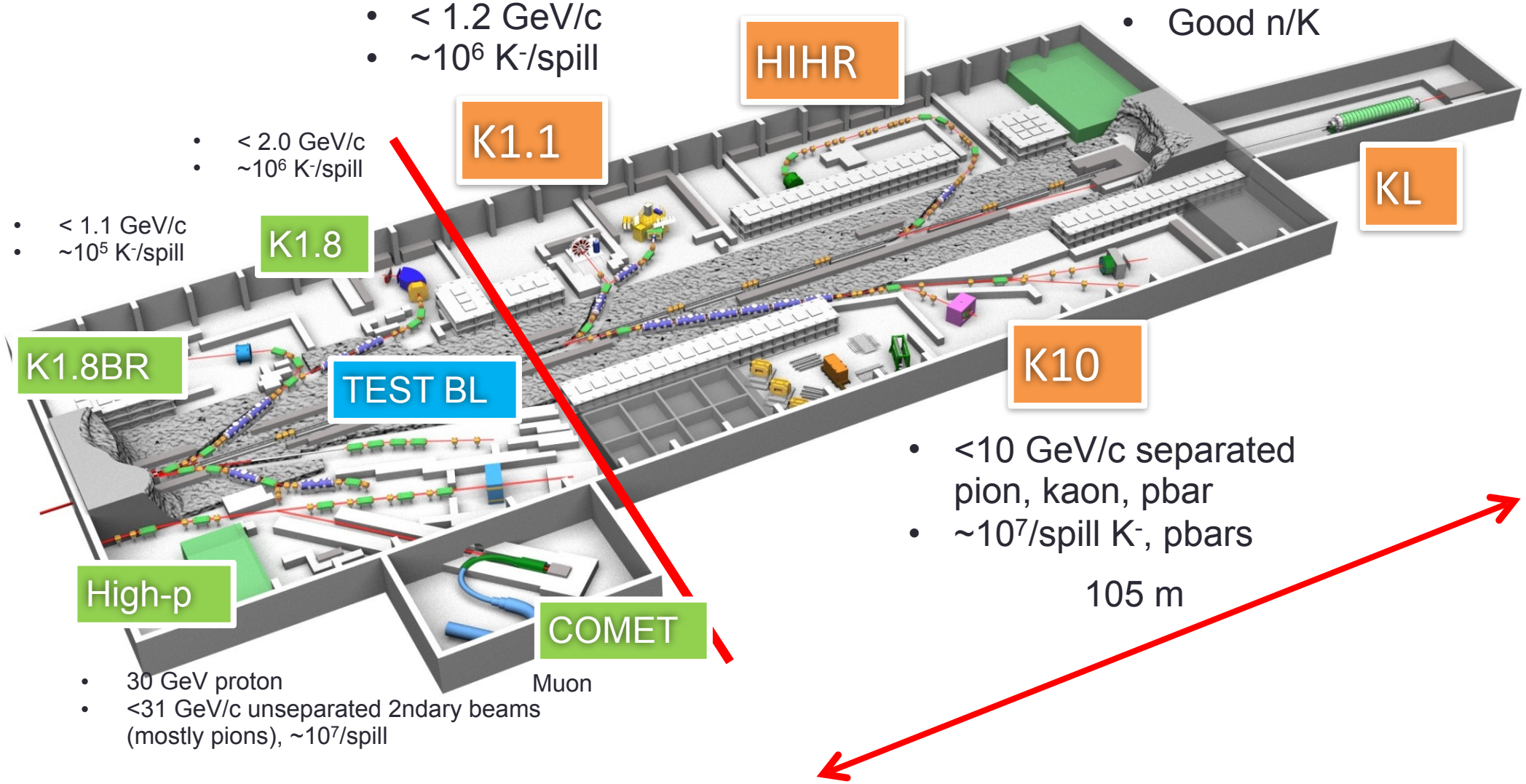
- < 1.1 GeV/c
- ~$10^5$ $K^-$/spill



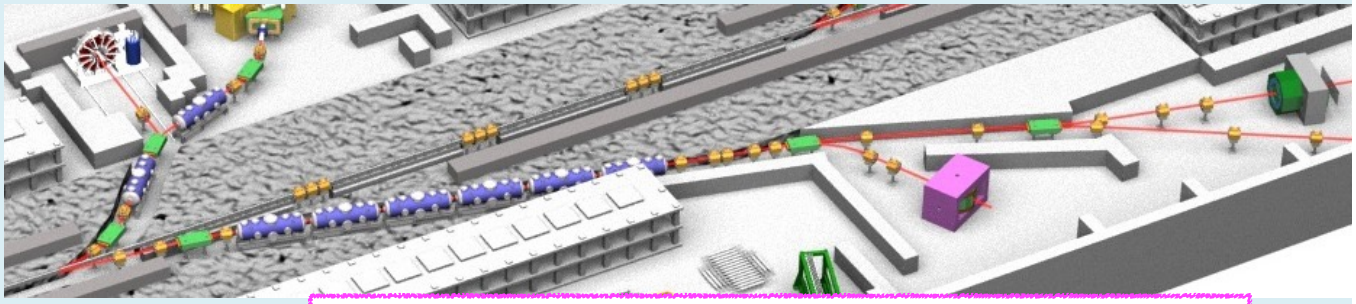

- 30 GeV proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~$10^7$/spill

Muon

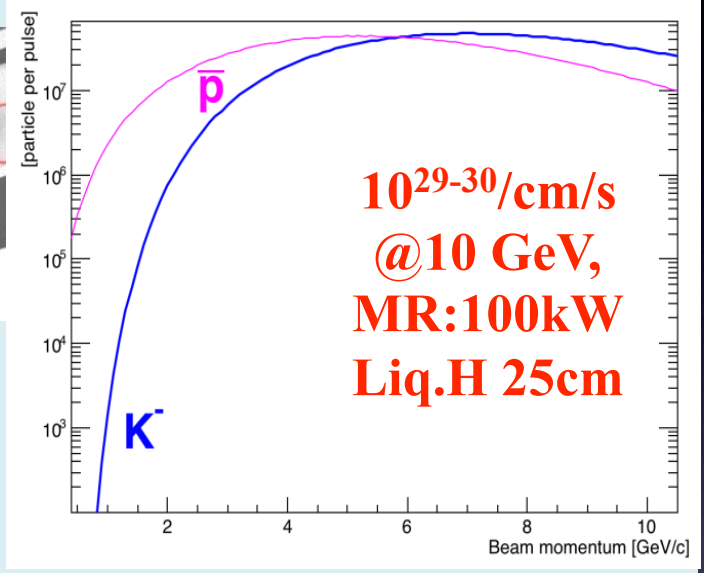
# J-PARC Hadron hall extension



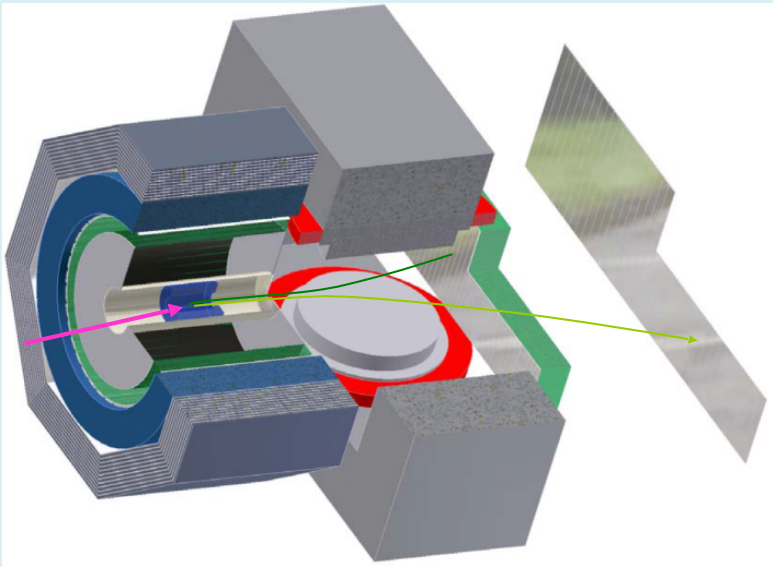
# High momentum high intensity beam line (K10)



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

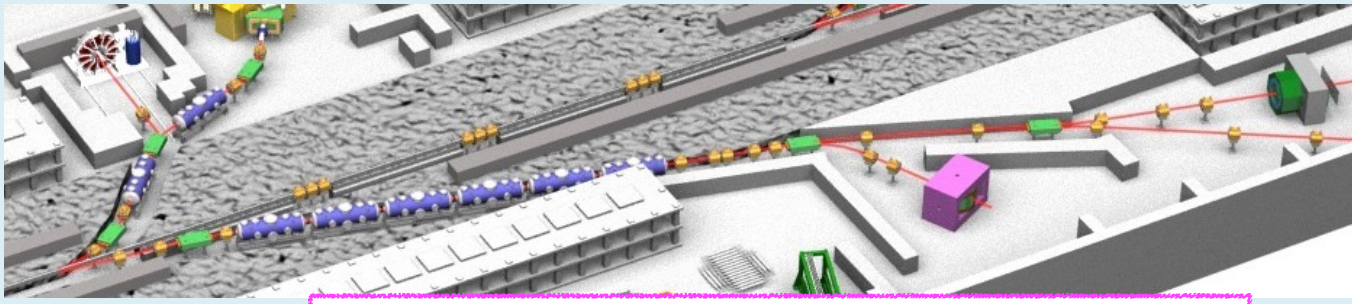



- Typical beam intensity
  - $K^-$ : 10 M/6s @ 4-6 GeV/c
  - pbar : 10 M/6s @ 10 GeV/c

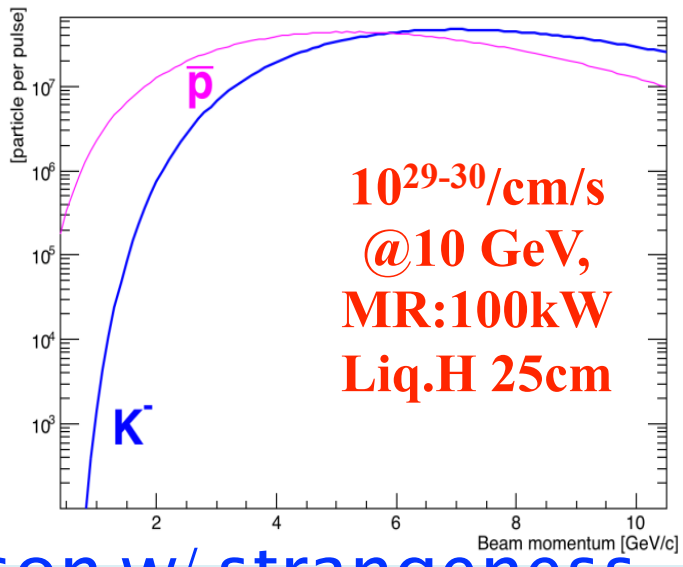


Design for the detector has been started.
→ Large solid angle spectrometer
(large solenoid + Dipole in forward)

# High momentum high intensity beam line (K10)

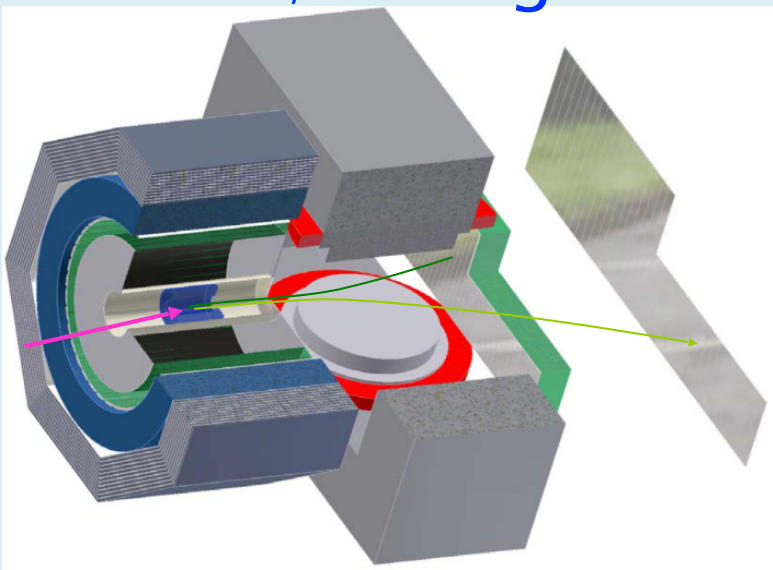


long beam line (~ 70m)
beam intensity as high as we can



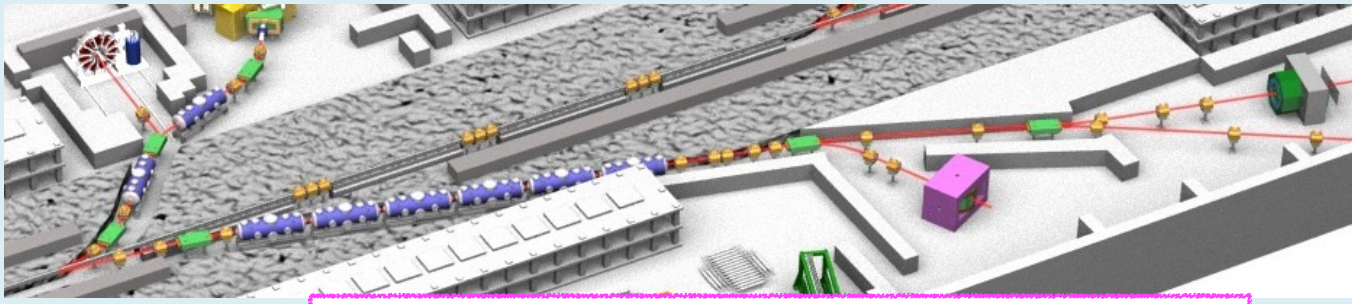

- Typical beam intensity
  - $K^-$ : 10 M/6s @ 4-6 GeV/c
  - pbar : 10 M/6s @ 10 GeV/c

$\Xi^*$ / $\Omega$ / scalar meson w/ strangeness

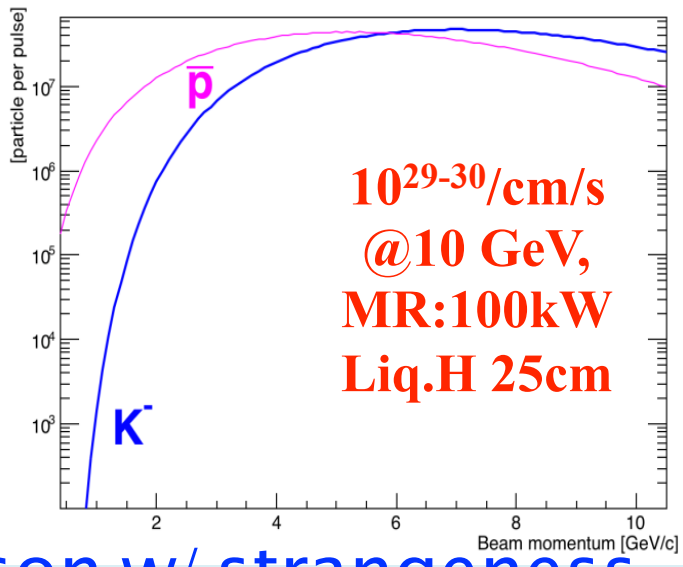


Design for the detector has been started.
→ Large solid angle spectrometer
(large solenoid + Dipole in forward)

# High momentum high intensity beam line (K10)



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

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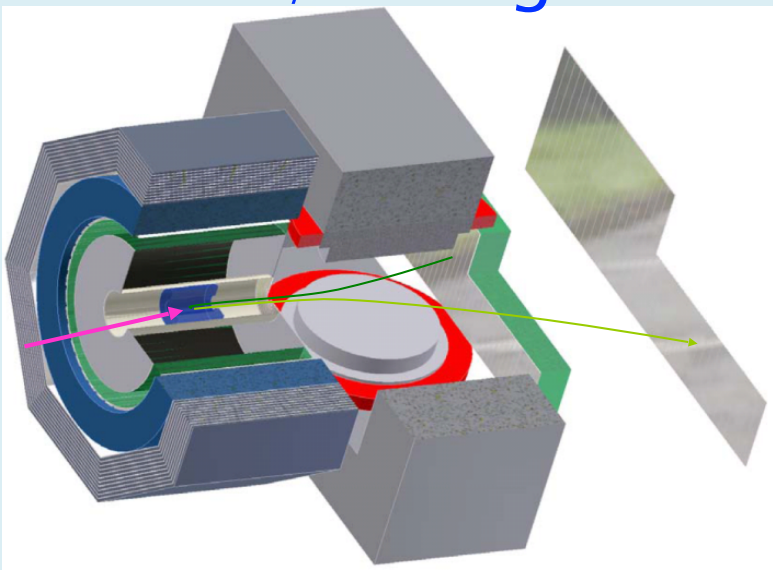

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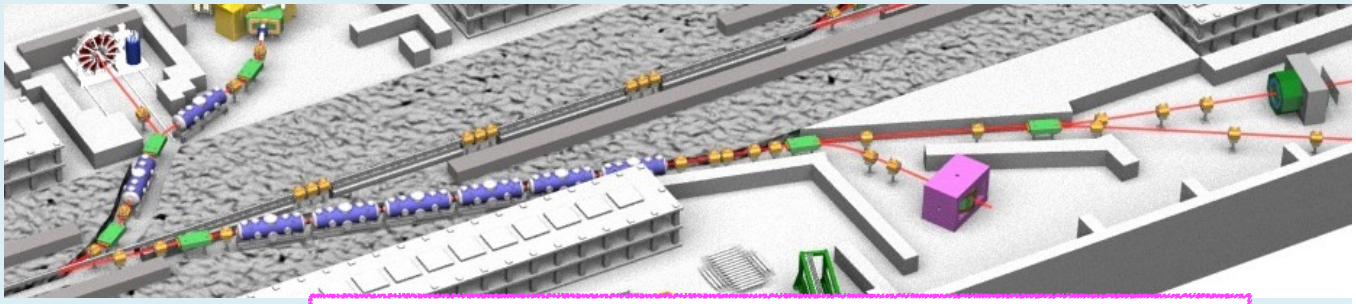

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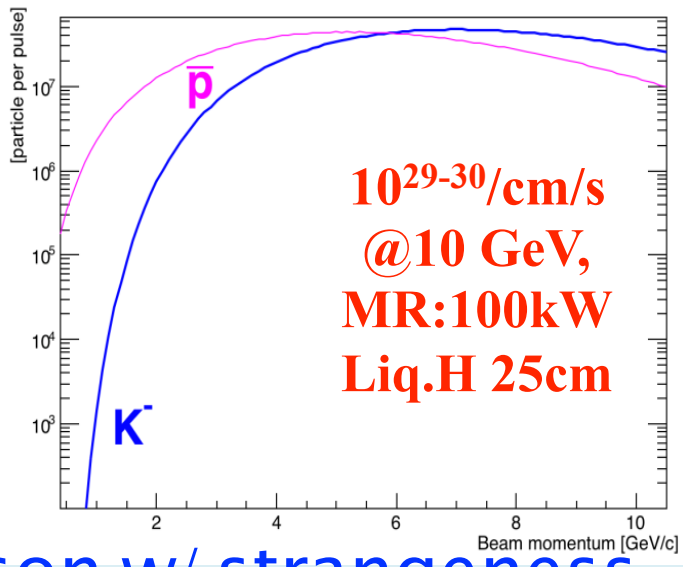


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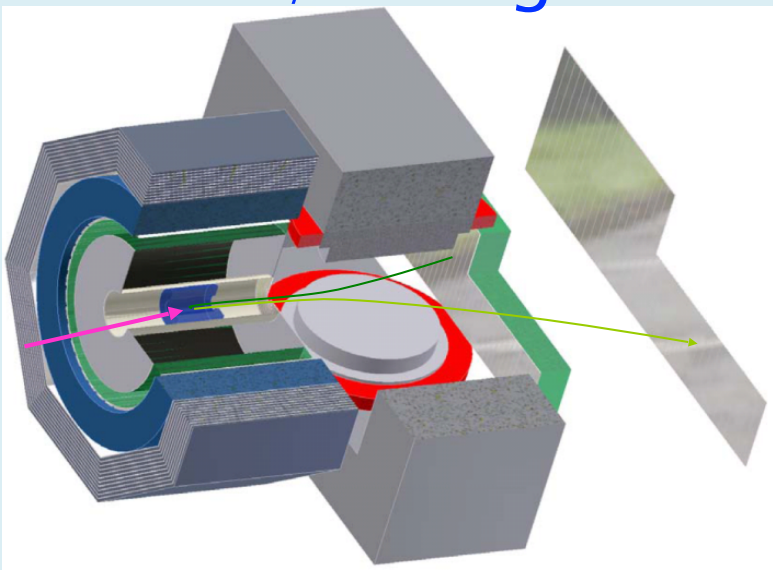

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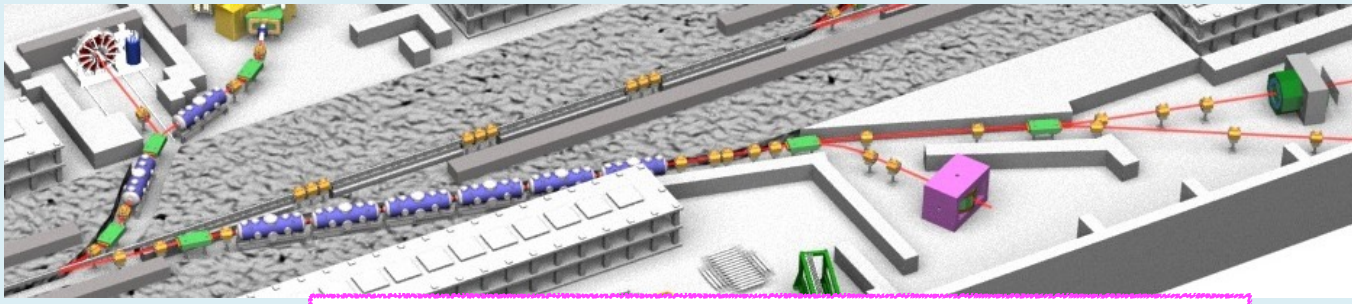

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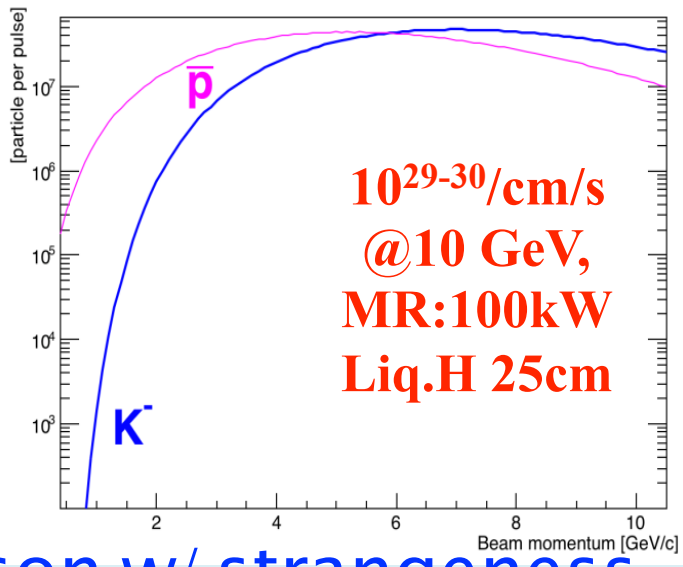


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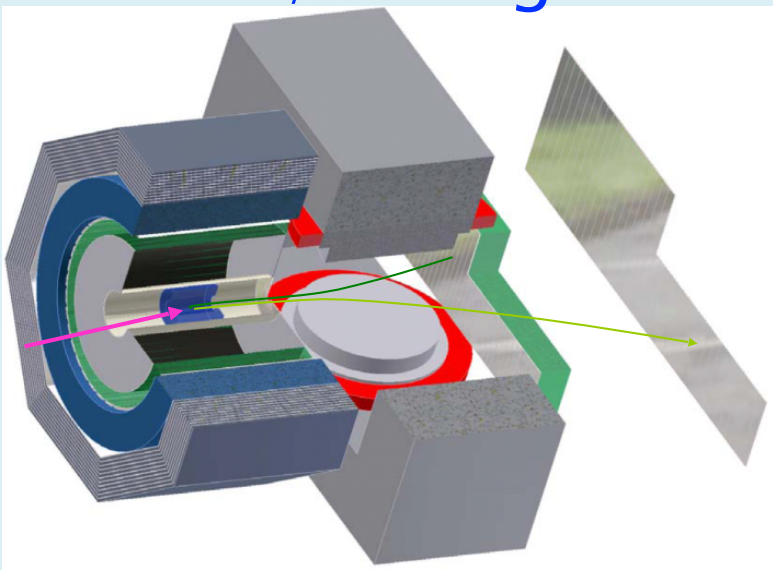
$\Xi^*$ / $\Omega$ / scalar meson w/ strangeness

charmed meson in nucleus



Design for the detector has been started.

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

# Summary

- Hadron physics programs with strangeness at J-PARC are reviewed
  - $\bar{K}N$ interaction( $\bar{K}NN$ ) and multi-strangeness baryon, $\Xi^*$, spectroscopy
- New opportunity will be opened with high intensity high momentum separated beam ( $\pi$,K±,pbar ) which will be realize with hadron hall extension (under discussion)
  - $\Omega^*$ spectroscopy
  - charmed hadron in nucleus

# International workshop on physics at the extended hadron experimental facility of J-PARC

5-6 March 2016
KEK Tokai Campus
Asia/Tokyo timezone



We have been discussing time to time on a future plan to extend the hadron experimental facility (HEF) of the Japan Proton Accelerator Research Complex (J-PARC) among the J-PARC users since the construction of J-PARC started or even before.
Now, we are pleased to inform that the extension of HEF has been listed in "Roadmap 2014", a basic plan of large-scale academic research projects to be promoted, which has been drawn recently by the working group on large-scale academic research projects under the science council of MEXT (Monbukagaku-cho).
At this occasion, we would like to have an international workshop to discuss this project further among current and potential users over the world.
In particular, we will discuss the following issues.
(1) physics issues to be attacked at the extended hadron physics
(2) new experimental ideas to be accommodated in the project
(3) floor plan of the extended HEF

Organized by Hadron Hall Users' Association (HUA)

Organizers:
Takeshi KOMATSUBARA (KEK), Hajime NANJO (Kyoto), Hiroyuki NOUMI (RCNP, Osaka), Shinya SAWADA (KEK), Mayumi SUEHIRO (KEK), Toshiyuki TAKAHASHI (KEK), Kiyoshi TANIDA (JAEA)

Contact: HDExt-WS@ml.j-parc.jp

https://kds.kek.jp/indico/event/20472/overview


# MENU2016@Kyoto

July 25-30

(Scientific program will start from 26, 9am)

Abstract submission dead line : April/25

If you plan to attend MENU2016, we advice to reserve hotel room as soon as possible!

Because

(a) July-August is just on the highest seasons for tourist in japan

(b) The climax of one of the famous Japanese festival “Gion Matsuri” will hold on July 24.

Thank you very much