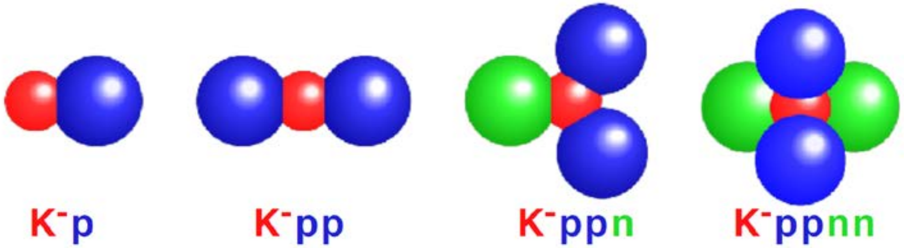
Systematic Investigation of the Light Kaonic Nuclei

– from the $\bar{K}N$ *to* $\bar{K}NNNN$ *systems –*

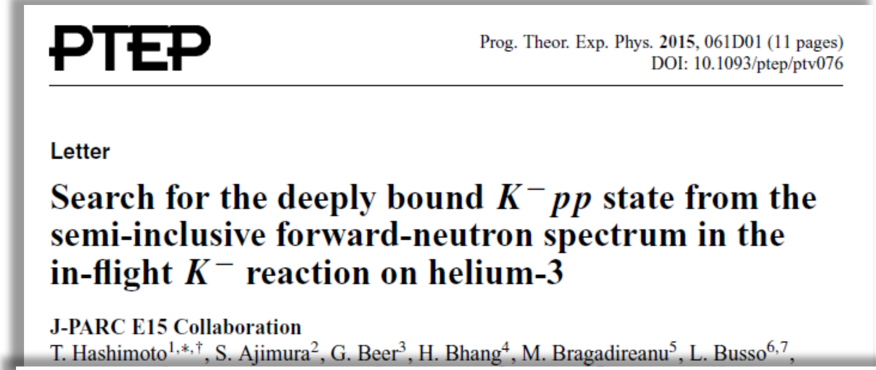


F. Sakuma, RIKEN

on behalf of
the J-PARC P80 collaboration

30th J-PARC PAC meeting, Jul 20-22, 2020

This proposal aims to <u>expand</u> the physics successfully developed by the J-PARC <u>E15</u> experiment



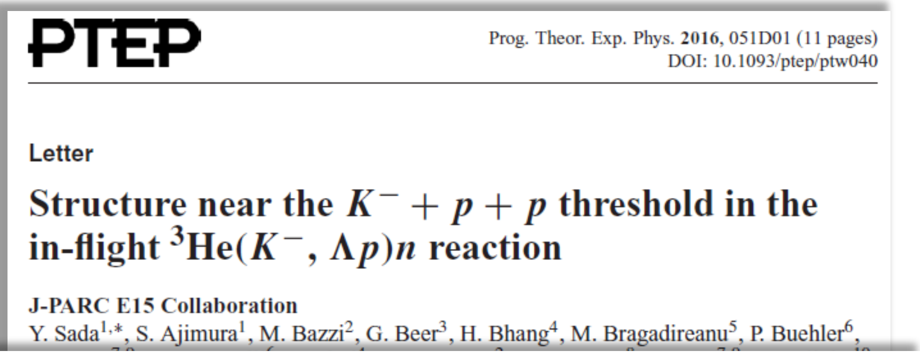
PTEP

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. Bhang[4], M. Bragadireanu[5], L. Busso[6,7],



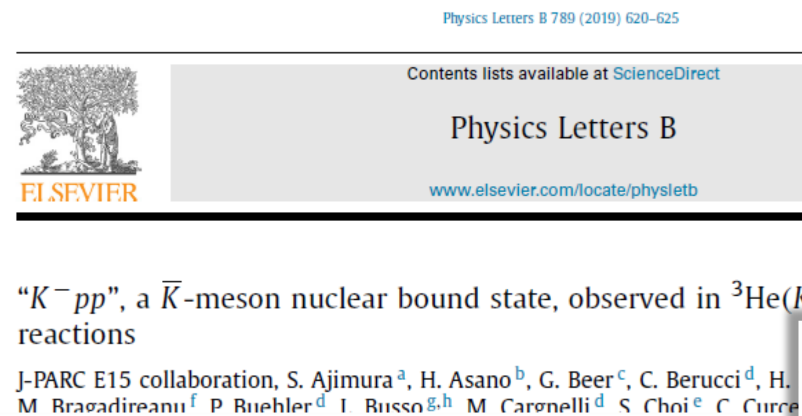
PTEP

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$(K^-, \Lambda p)n$ reaction

J-PARC E15 Collaboration
Y. Sada[1,*], S. Ajimura[1], M. Bazzi[2], G. Beer[3], H. Bhang[4], M. Bragadireanu[5], P. Buehler[6],



Physics Letters B 789 (2019) 620–625

Contents lists available at ScienceDirect

Physics Letters B

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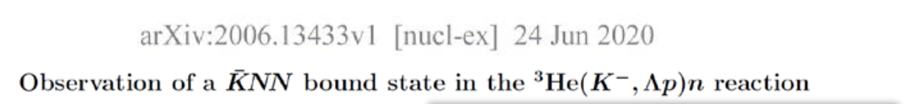
ELSEVIER

"K^-pp", a $\bar{K}$-meson nuclear bound state, observed in ^{3}He$(K^-, \Lambda p)n$ reactions

J-PARC E15 collaboration, S. Ajimura[a], H. Asano[b], G. Beer[c], C. Berucci[d], H.
M. Bragadireanu[f], P. Buehler[d], L. Busso[g,h], M. Cargnelli[d], S. Choi[e], C. Curce



arXiv:2006.13433v1 [nucl-ex] 24 Jun 2020

Observation of a $\bar{K}NN$ bound state in the ^{3}He$(K^-, \Lambda p)n$ reaction

T. Yamaga[1,*] S. Ajimura[2], H. Asano[1], G. Beer[3], H. Bh

Submitted to PRC

Ministry of Foreign Affairs in Italy

Giappone, team internazionale scopre nuova forma materia

Data: 30/01/2019

Un nuovo tipo di 'materia strana', che potrebbe fornire nuove informazioni sull'origine della massa nell'universo dopo il Big Bang, è stata scoperta dagli scienziati di un team internazionale in Giappone, in parte finanziato dal Ministero degli Affari Esteri e Cooperazione Internazionale. L'esperimento E15 del Japan Proton Accelerator Research Complex di Tokai in Giappone ha riguardato i mesoni K, (o kaoni) particelle quantistiche diventate di recente un importante argomento di ricerca, che potrebbe fornire spunti su misteri quali l'origine della massa e il fenomeno quantistico di "confinamento del colore". Il contributo italiano è avvenuto nell'ambito del Protocollo esecutivo di cooperazione scientifica e tecnologica Italia–Giappone.

Newspaper in Romania

O nouă formă de materie NUCLEARĂ STRANIE descoperită în Japonia! Toată omenirea într-un DEGETAR?

Autor: CătălinaCurceanu
10 februarie 2019

Un grup de cercetatori din care face parte si autoarea acestui articol a descoperit o noua forma de materie „stranie" in cadrul unui experiment efectuat la acceleratorul J-PARC in Japonia. Aceasta descoperire ne va ajuta sa intelegem mai bine originea masei imediat dupa Big Bang si inima stelelor de neutroni

boli infecțioase

5:00 - The New York Times: Deceniul chinez

4:30 - Școlarizarea gratuită pentru studenții UE va fi eliminată în Scoția

4:00 - USA Today: Partidul Republican este tot mai dezbinat în privința lui Trump

3:00 - Financial Times: Gove anunță un pachet de măsuri menit să întărească granițele după Brexit

2:30 - Londra nu va participa la programul european de vaccinuri

2:00 - Arestări și controale în urma votului din Rusia privind reforma constituțională

1:41 - Venus, primul leagăn al omenirii?! HOROSCOPUL LUI DOM' PROFESOR

1:00 - ABC: Italia va prelungi starea de urgență până în decembrie

0:30 - Cum și-a speriat Antonia fanii. Ce a pățit într-un club...

0:06 - Bulgaria redeschide cluburile de noapte, la trei zile după ce a decis să le închidă

29.01.2019 12:29 | WISSEN

KAON STATT NEUTRON

Physiker erzeugen in Japan neue Materieform

Newspaper in Austria

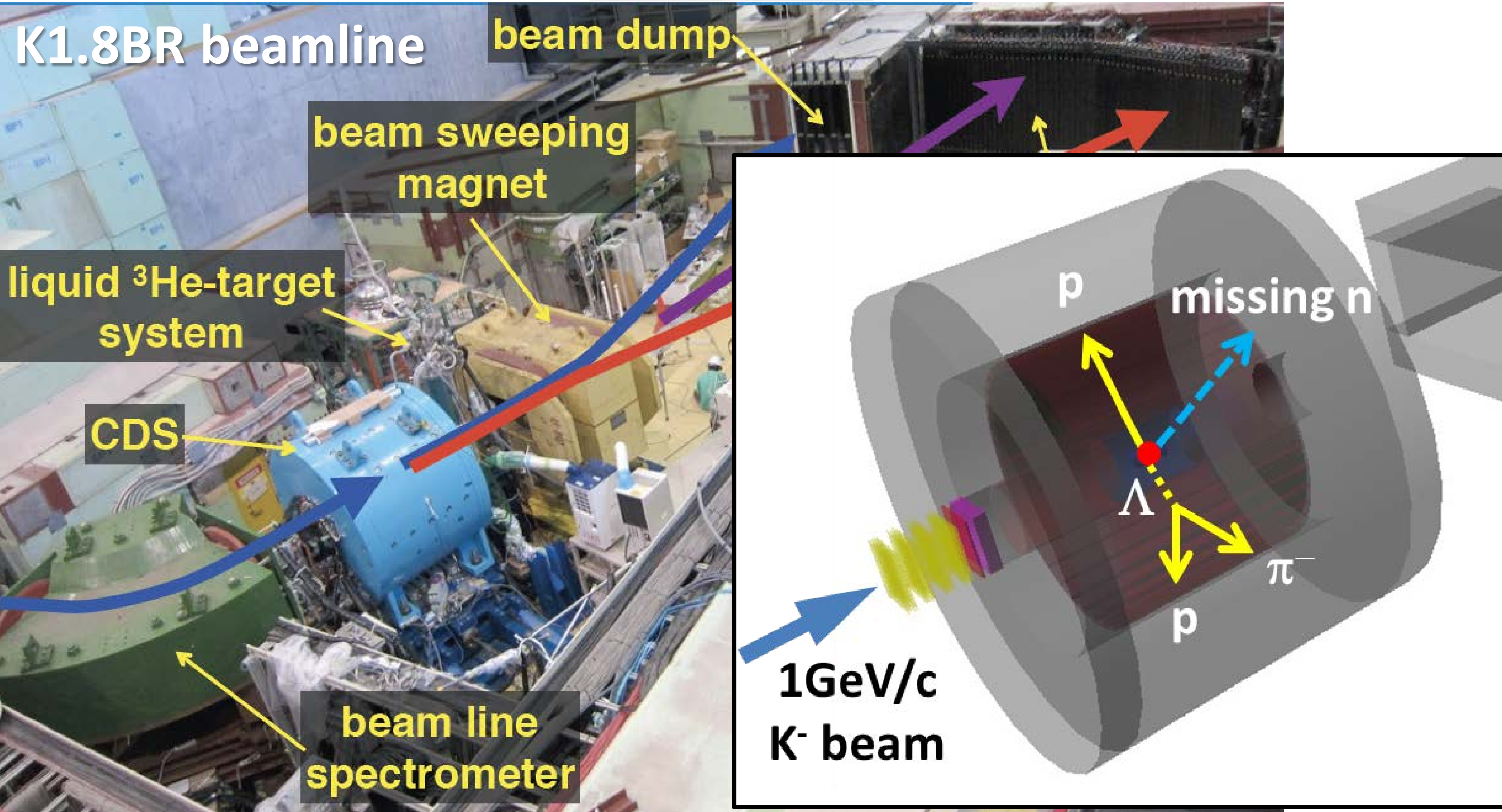
(Bild: OAW/Harald Ritsch, J-PARC/Flickr/PatrickDep, krone.at-Grafik)

Am japanischen Teilchenbeschleunigerzentrum J-PARC (Japan Proton Accelerator Research Complex) nahe Tokio ist es unter Mitwirkung der Österreichischen Akademie der Wissenschaften gelungen, erstmals eine neue Form von äußerst dichter Materie mit Anti-Kaonen nachzuweisen. Die Forscher hoffen, dass das Verständnis dieser Materie neue Antworten auf grundlegende Fragen der modernen Physik eröffnen wird.

What We Did

- Experimental Search for the $\bar{K}NN$ -

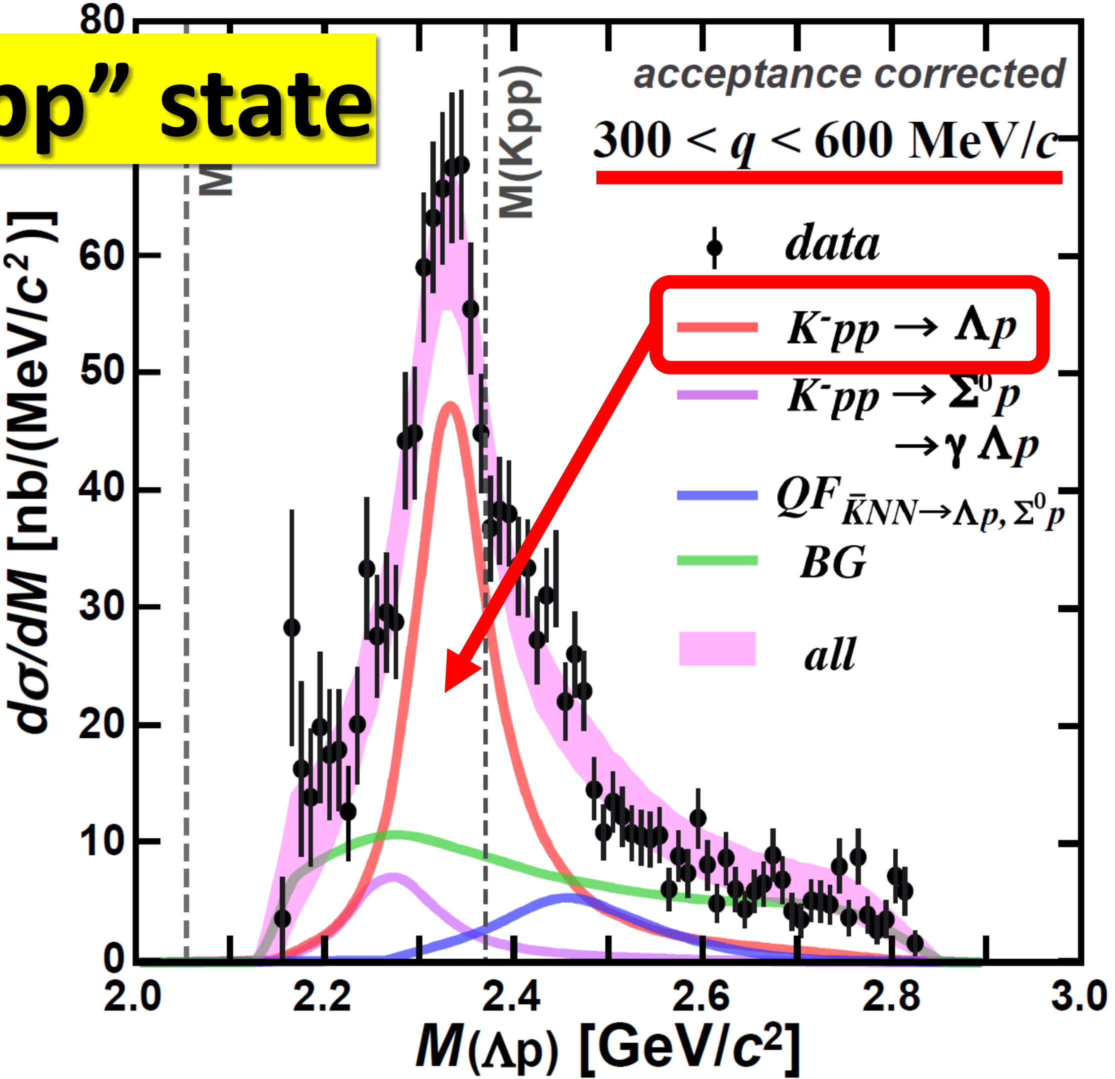
- We measured the **^{3}He(K$^-$,Λp)n** reaction



What We Observed

PLB789(2019)620.

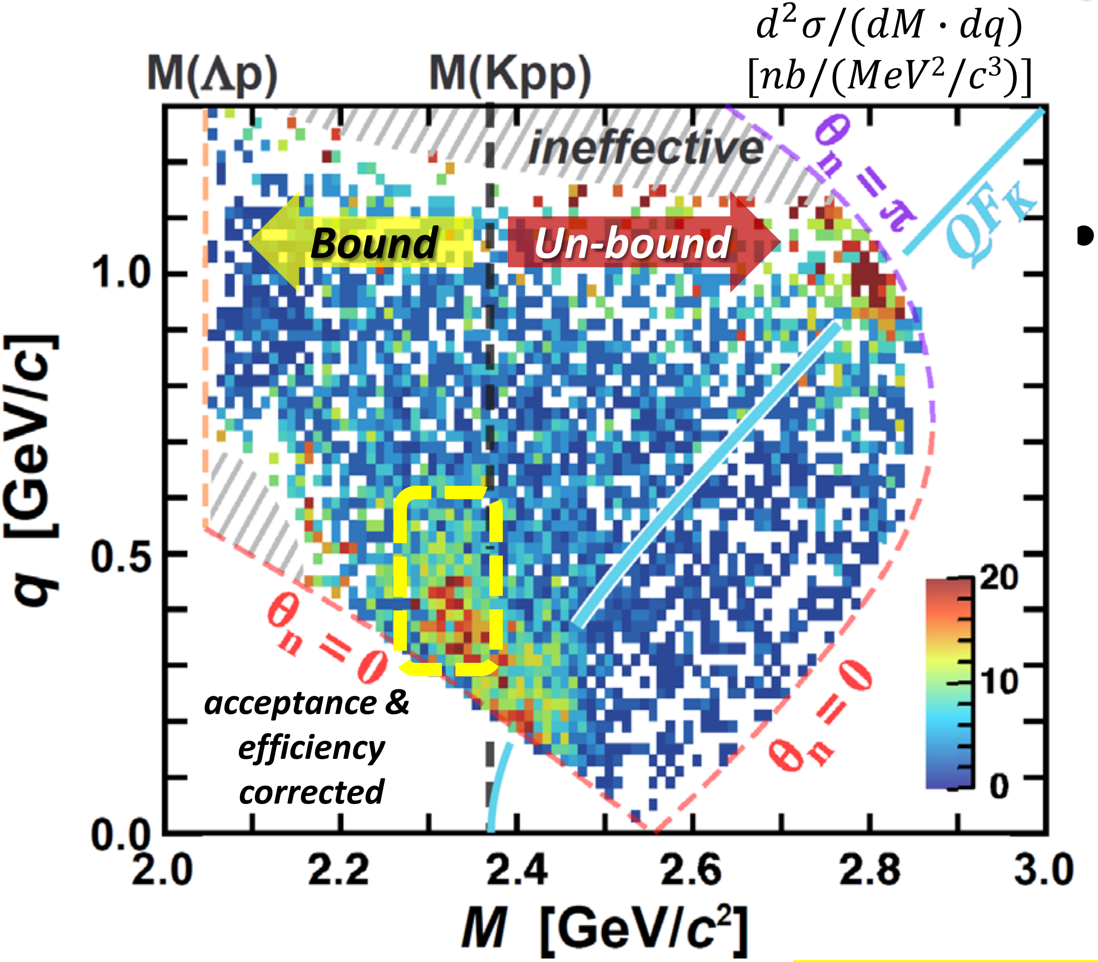
arXiv:2006.13433 submitted to RPC



“K-pp” state

What We Have Learned

T.Yamaga et. al., arXiv:2006.13433



q : momentum transfer of (K-,n)

M : invariant mass of Λp

- **"K⁻pp" bound state exists**
  - ✓q-independent
- **QF followed by 2NA** shows Λpn FS can be generated from 2-step processes via (K⁻,n)
  - ✓q-dependent

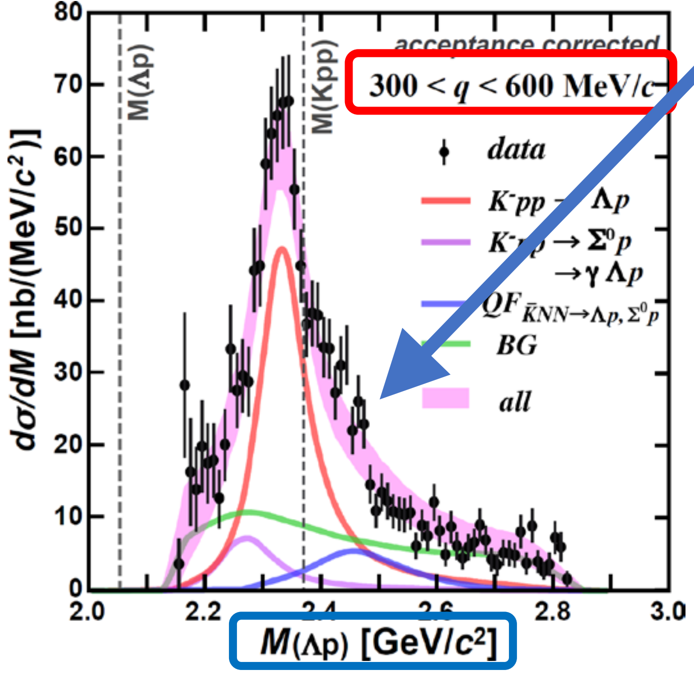
→ quite important to understand the production mechanism of the "K⁻pp" bound state

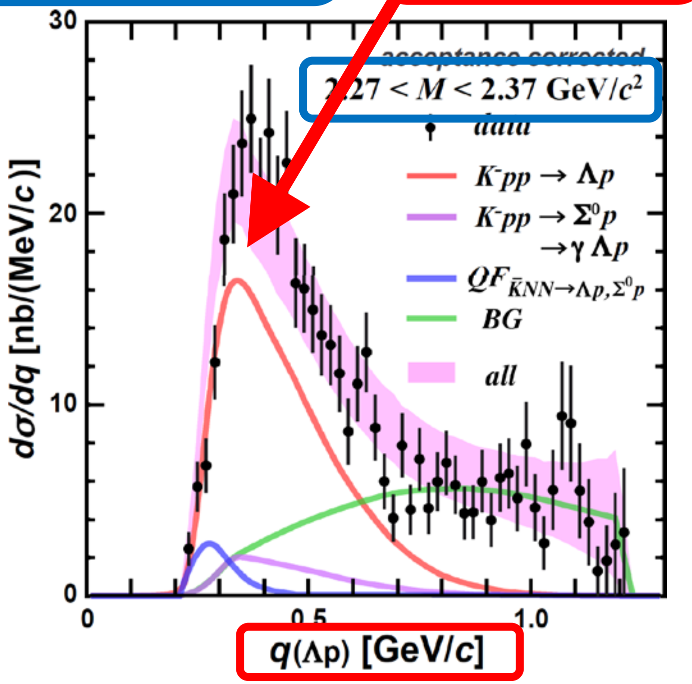
2D analysis in (M,q) is essential

What We Have Learned

Fit with PWIA $\sigma(M,q) \propto \rho(M,q) \times \boxed{\frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}} \times \boxed{exp\left(-\frac{q^2}{Q_{Kpp}{}^2}\right)}$

arXiv:2006.13433





B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV
→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)
→ *wide momentum transfer*

The results suggest the "K^-pp" is quite compact

Size of “K⁻pp”

Fit with PWIA $$\sigma(M,q) \propto \rho(M,q) \times \frac{(\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2} \times exp\left(-\frac{q^2}{{Q_{Kpp}}^2}\right)$$

B_{Kpp} ~ 40 MeV
→ *large binding energy*

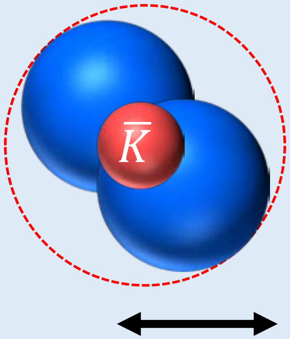
Q_{kpp} ~ 400 MeV
→ *wide momentum transfer*

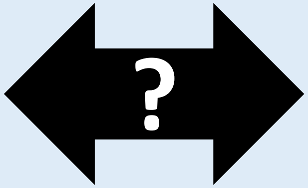
suggest the “K⁻pp” is quite compact (R_{Kpp} ~ 0.6 fm)

→ Need more realistic theoretical calculations

Still an open question ($\bar{K}N$ = strong force)

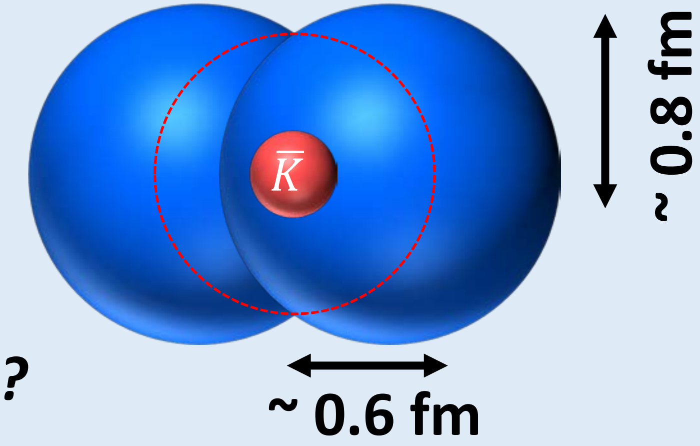
Radius of “K⁻pp”





In addition, effect of K size?

Interaction range of “K⁻”

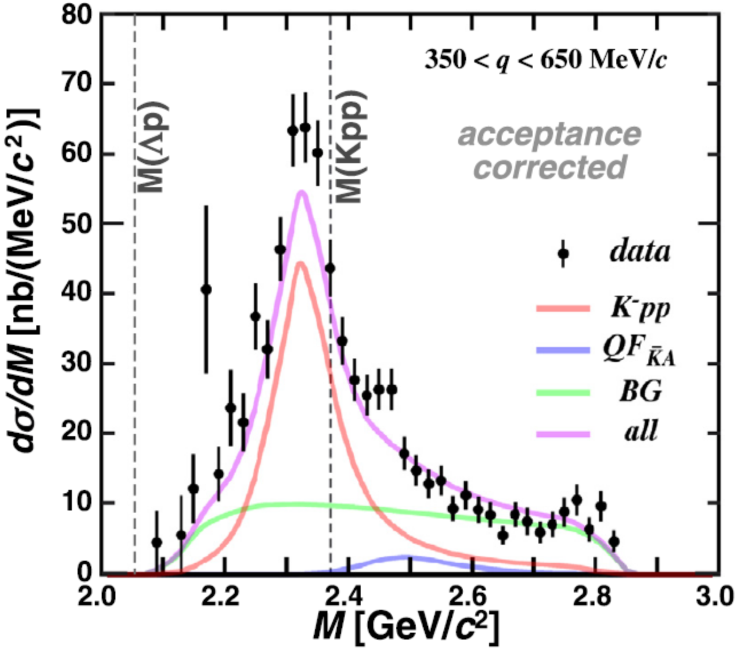


What We Have Learned with Theorists

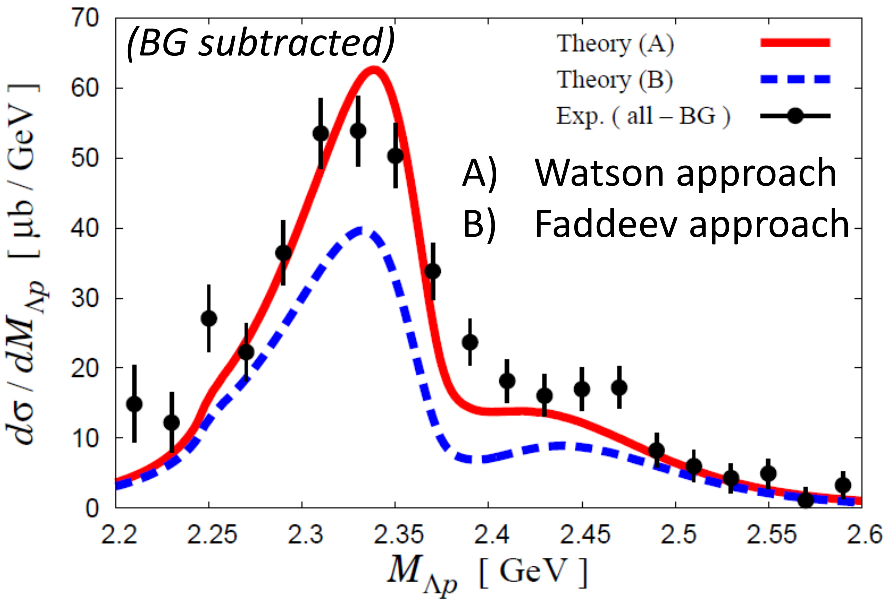
- A theoretical calculation in chiral unitary approach reproduces the mass spectrum with the $\bar{K}NN$

→ Theoretical investigations for experimental results are indispensable

PLB789(2019)620.

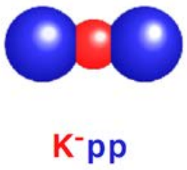


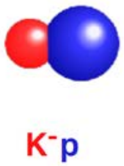
PTEP2016(2016)123D03.
JPS Conf. Proc.26(2019)023009.

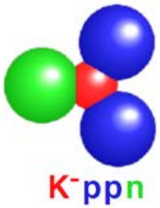


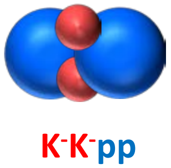
Many Questions to be Answered

- **Further details of the $\bar{K}NN$**
  - Spin and parity of the “K^-pp”?
  - Strength of $\bar{K}N$ interaction?
  - Really compact and dense system?
- **Λ(1405) state**
  - $\bar{K}N$ molecular state as considered?
  - Size?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?
- **More heavier kaonic nuclei?**
  - Mass number dependence?
- **Double kaonic nuclei?**
  - Much compact and dense system?



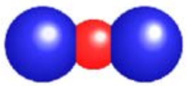




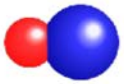


Experimental Task for the New Project

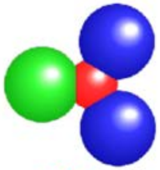
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K$^-$pp"?
  - Strength of $\bar{K}N$ interaction?
  - Really compact and dense system?
- **Λ(1405) state**
  - $\bar{K}N$ molecular state as considered?
  - Size?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?
- **More heavier kaonic nuclei?**
  - Mass number dependence?
- **Double kaonic nuclei?**
  - Much compact and dense system?



K$^-$pp

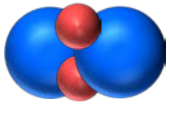


K$^-$p



K$^-$ppn

K$^-$ppnn



K$^-$K$^-$pp

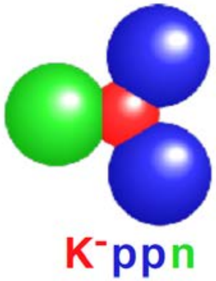
Strategy of the New Project

- for systematic study from the $\bar{K}N$ to $\bar{K}NNNN$ systems -

	Reaction	Decays	Key	
$\bar{K}N$	d(K⁻,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	n/γ identification	
$\bar{K}NN$	^{3}He(K⁻,N)	Λp/Λn	polarimeter	← **Feasibility study**
$\bar{K}NNN$	^{4}He(K⁻,N)	Λd/Λpn	large acceptance	← **A first step**
$\bar{K}NNNN$	*^{6}Li(K⁻,d)*	*Λdn/Λpnn*	*many body decay*	← **Feasibility study**
$\bar{K}\bar{K}NN$	*$\bar{p}$ + ^{3}He*	*ΛΛ*	*$\bar{p}$ beam yield*	

*We take a **step-by-step** approach*

- To realize the systematic measurements, we utilize
  - ☐ **a large acceptance spectrometer**
    - detect/identify all particles to specify the reaction
  - ☐ **high-intensity kaon beam**
    - more K⁻ yield than the existing beamline



A First Step: Search for $\bar{K}NNN$

Goals of the proposed experiment:

① **Observe the K^-ppn state via 2-body Λd decay**

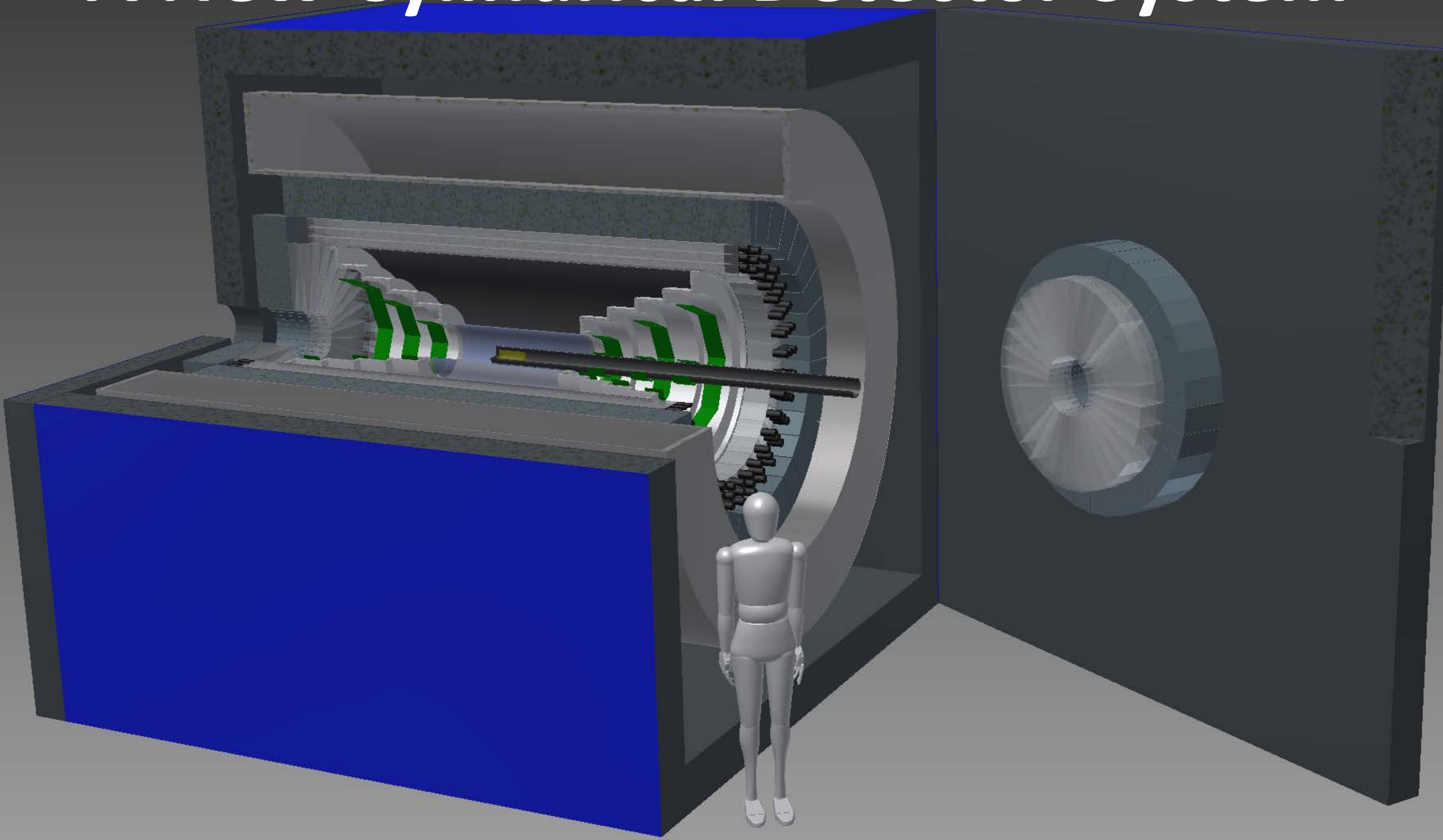
- Establish the existence of the kaonic nuclei

② **Reconstruct the K^-ppn state via 3-body Λpn decay**

- As a feasibility study to access heavier system

- **Feasibility study of the polarization measurement**
  - *e.g.*, by installing a prototype module of the polarimeter

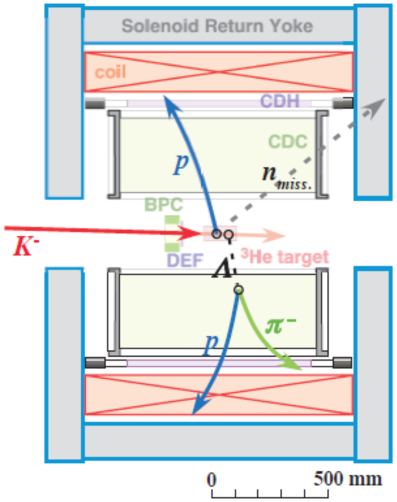
A New Cylindrical Detector System

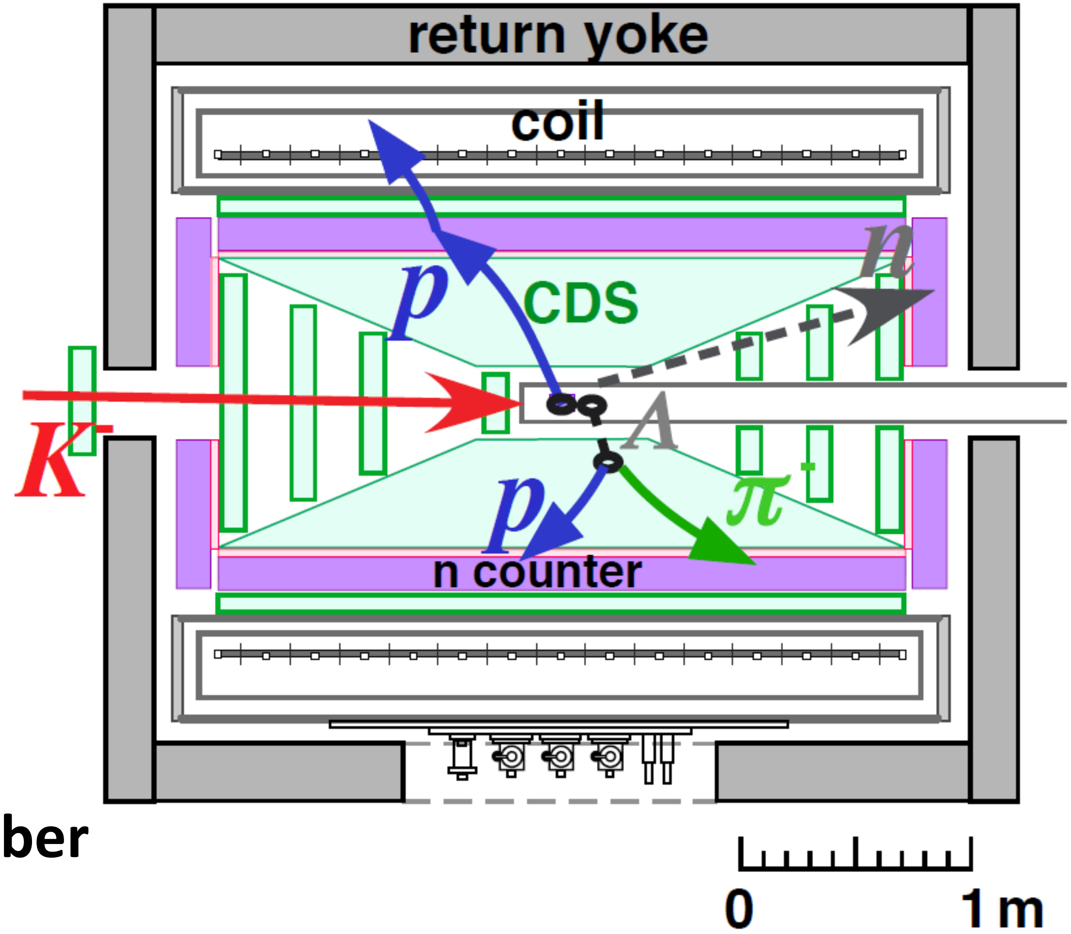


A new 4π spectrometer with n/γ detection capability

A New Cylindrical Detector System

present setup





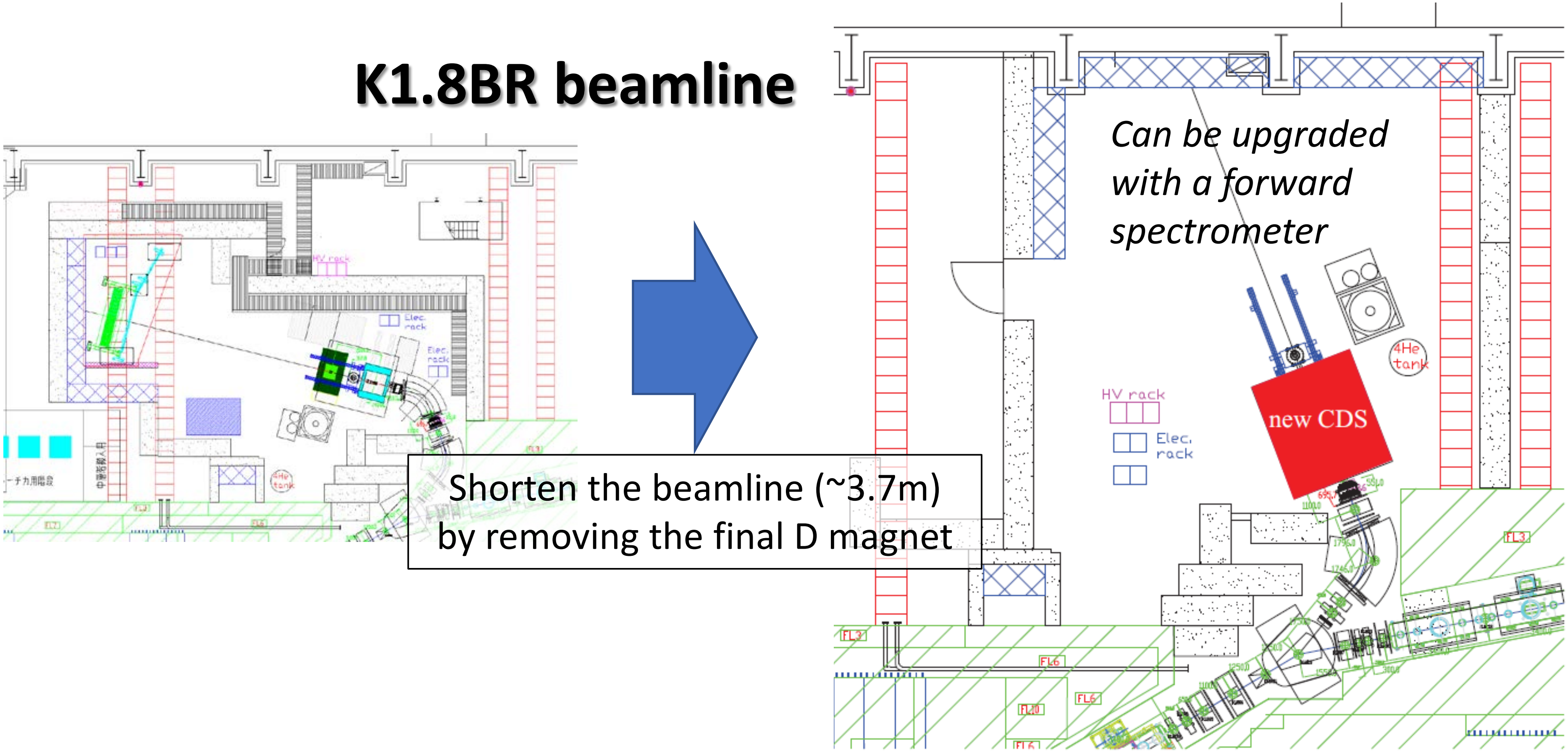
- **SC Solenoid Magnet**
- **Cylindrical Drift Chamber**
- **Neutron Counter**
- FWD/BWD Drift Chambers
- Vertex Fiber Tracker
- Electromagnetic Calorimeter (constructed in 2nd-stage)

Solid angle: ~x1.5 (~90%)

Neutron detection capability: ~x10

(~1.5x15%)

Improvement of Kaon Intensity



K1.8BR beamline

Shorten the beamline (~3.7m) by removing the final D magnet

Can be upgraded with a forward spectrometer

- **We propose a new configuration of the beamline**
  - K- yield is expected to increase by **~ 1.4 times @ 1.0 GeV/c**

Expected Yield of $\bar{K}NNN$

$$\begin{aligned} N &= \sigma \times N_{beam} \times N_{target} \times \epsilon, \\ \epsilon &= \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS}, \end{aligned}$$

- We assume the K^-ppn cross section of

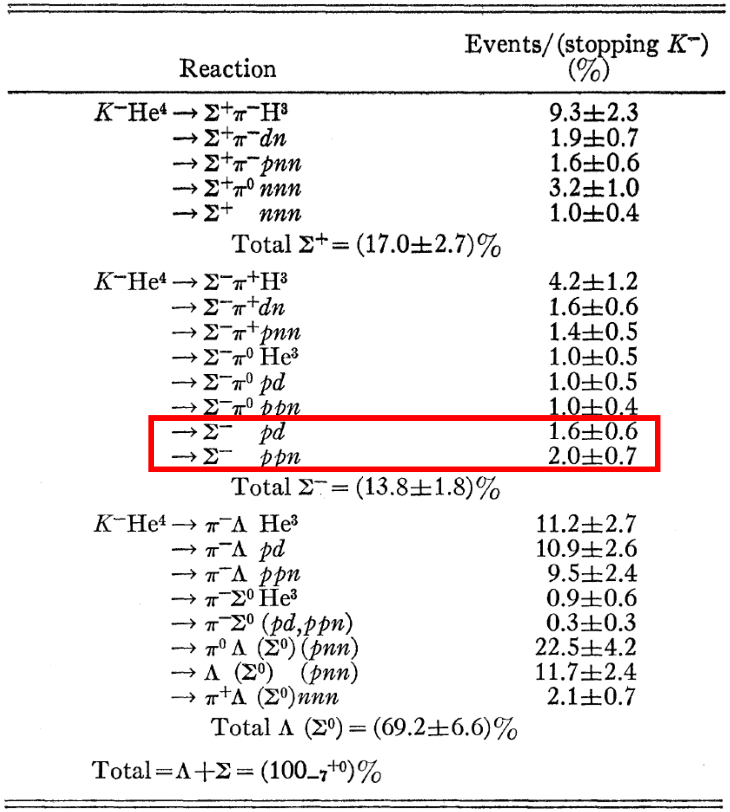
$$\boldsymbol{\sigma(K^-ppn) \cdot Br(\Lambda d) \sim 10\ \mu b}$$
$$\boldsymbol{\sigma(K^-ppn) \cdot Br(\Lambda pn) \sim 10\ \mu b}$$

◆ The same CS of "K-pp"→Λp in E15

◆ *As for Λd decay, we refer to the absorption of stopped K^- on ^{4}He*

→decay fraction to Σ^-pd : Σ^-ppn ~ 1 : 1

absorption of stopped K^- on ^{4}He



Reaction	Events/(stopping K^-) (%)
$K^-He^4 \rightarrow \Sigma^+\pi^-H^3$	9.3±2.3
$\rightarrow \Sigma^+\pi^-dn$	1.9±0.7
$\rightarrow \Sigma^+\pi^-pnn$	1.6±0.6
$\rightarrow \Sigma^+\pi^0\, nnn$	3.2±1.0
$\rightarrow \Sigma^+\quad nnn$	1.0±0.4
Total $\Sigma^+ = (17.0\pm2.7)\%$	
$K^-He^4 \rightarrow \Sigma^-\pi^+H^3$	4.2±1.2
$\rightarrow \Sigma^-\pi^+dn$	1.6±0.6
$\rightarrow \Sigma^-\pi^+pnn$	1.4±0.5
$\rightarrow \Sigma^-\pi^0\, He^3$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\, pd$	1.0±0.5
$\rightarrow \Sigma^-\pi^0\, ppn$	1.0±0.4
$\rightarrow \Sigma^-\quad pd$	1.6±0.6
$\rightarrow \Sigma^-\quad ppn$	2.0±0.7
Total $\Sigma^- = (13.8\pm1.8)\%$	
$K^-He^4 \rightarrow \pi^-\Lambda\ He^3$	11.2±2.7
$\rightarrow \pi^-\Lambda\ pd$	10.9±2.6
$\rightarrow \pi^-\Lambda\ ppn$	9.5±2.4
$\rightarrow \pi^-\Sigma^0\, He^3$	0.9±0.6
$\rightarrow \pi^-\Sigma^0\, (pd, ppn)$	0.3±0.3
$\rightarrow \pi^0\,\Lambda\ (\Sigma^0)\,(pnn)$	22.5±4.2
$\rightarrow \Lambda\ (\Sigma^0)\quad (pnn)$	11.7±2.4
$\rightarrow \pi^+\Lambda\ (\Sigma^0)nnn$	2.1±0.7
Total $\Lambda\ (\Sigma^0) = (69.2\pm6.6)\%$	
Total $= \Lambda + \Sigma = (100_{-7}^{+0})\%$	

PRD1(1970)1267

Expected Yield of $\bar{K}NNN$

$$\begin{aligned} N &= \sigma \times N_{beam} \times N_{target} \times \epsilon, \\ \epsilon &= \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS}, \end{aligned}$$

- N_{beam} = **100 G** K- on target
  - under the MR beam power of **90 kW** with **5.2 s** repetition cycle. around 2023
    - 3.2 x 10^5 K- on target / spill @ 1.0 GeV/c
  - **3 weeks** data taking (90% up-time)

- **N(K$^-$ppn→Λd) ~ 1.9 x 10^4**
- **N(K$^-$ppn→Λpn) ~ 2.8 x 10^3**
  - c.f. 1.7 x 10^3 "K$^-$pp"→Λp accumulated in E15-2nd (40 G K$^-$)

	Λd / Λpn
σ(K$^-$ppn)*Br	10 μb
N(K$^-$ on target)	100 G
N(target)	2.65 x 10^{23}
ε(DAQ)	0.9
ε(trigger)	0.93
ε(beam)	0.55
Ω(CDC)	0.27 / 0.077
ε(CDC)	0.6 / 0.3
N(K$^-$ppn)	19 k / 2.8 k

**** improved from E15***

Expected Spectrum of K^-+^{4}He

@ 3 weeks, 90kW

B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

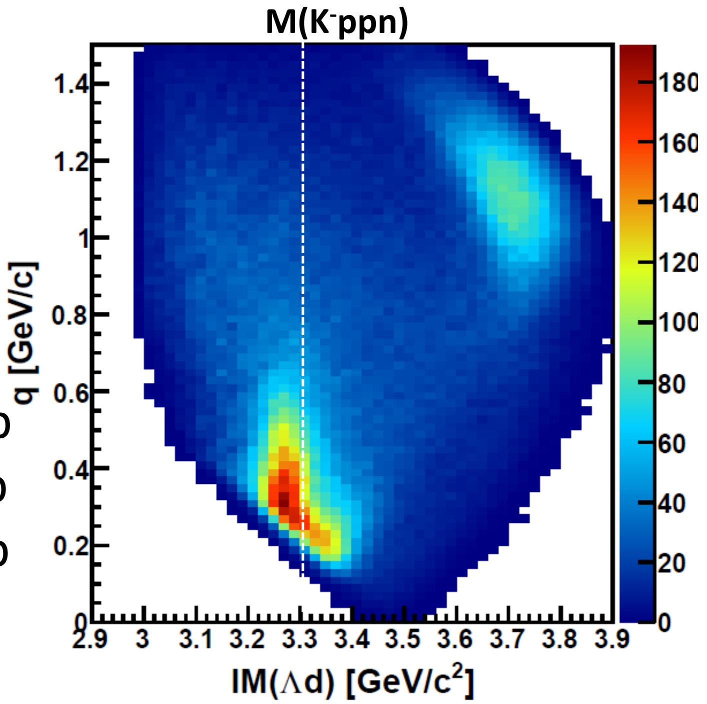
Q_{kppn} ~ 400 MeV/c

$\sigma(K^-ppn)*Br$ ~ 10 μb

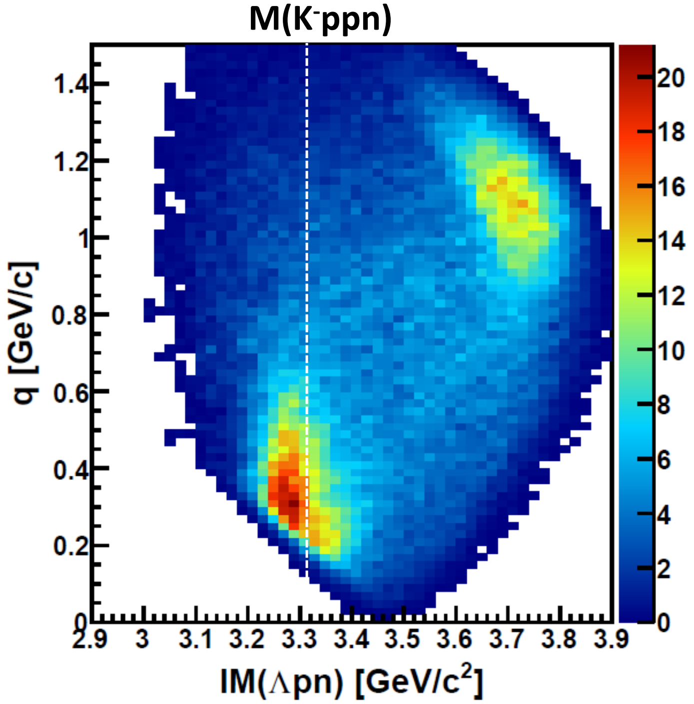
$\sigma(QF)$ ~ 10 μb

$\sigma(BG)$ ~ 20 μb

K^-+^{4}He→Λd+n



K^-+^{4}He→Λpn+n



- Similar parameters obtained with the K^-+^{3}He→Λpn (arXiv:2006.13433) are adopted to K^-ppn/QF/BG shapes
- **K-ppn signal [q-independent] can be seen clearly**

Expected Spectrum of $K^{-}+{}^{4}He$

@ 3 weeks, 90kW

$K^{-}+{}^{4}He \rightarrow \Lambda d+n$

$K^{-}+{}^{4}He \rightarrow \Lambda pn+n$

B_{Kppn} ~ 40 MeV

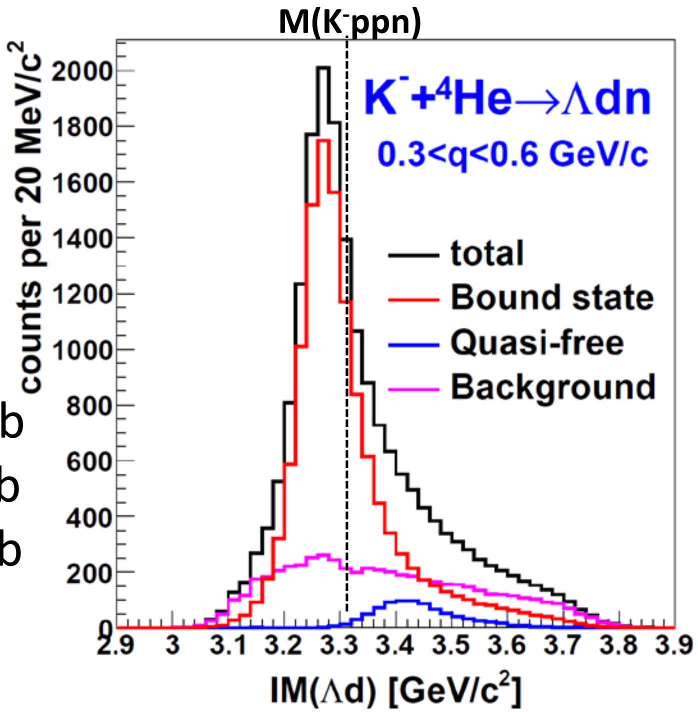
Γ_{Kppn} ~ 100 MeV

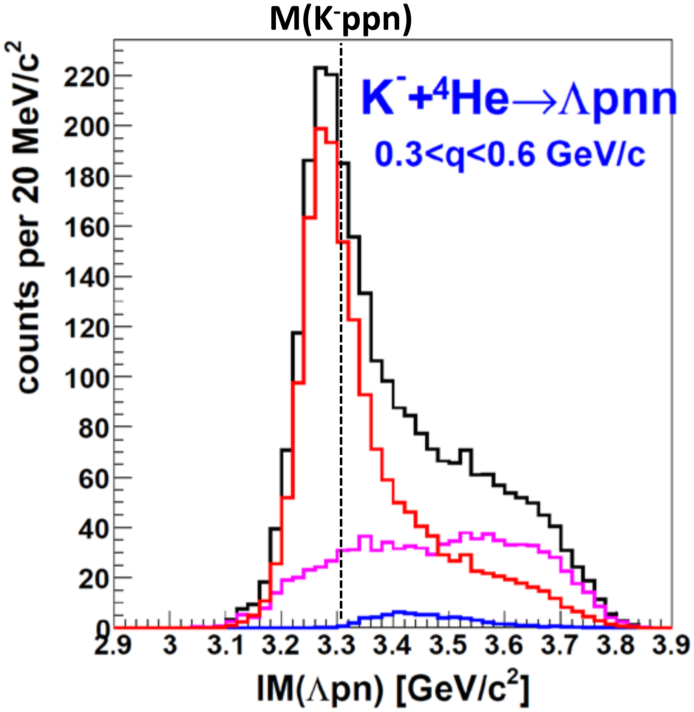
Q_{kppn} ~ 400 MeV/c

$\sigma(K^{-}ppn)$*Br ~ 10 μb

$\sigma(QF)$ ~ 10 μb

$\sigma(BG)$ ~ 20 μb



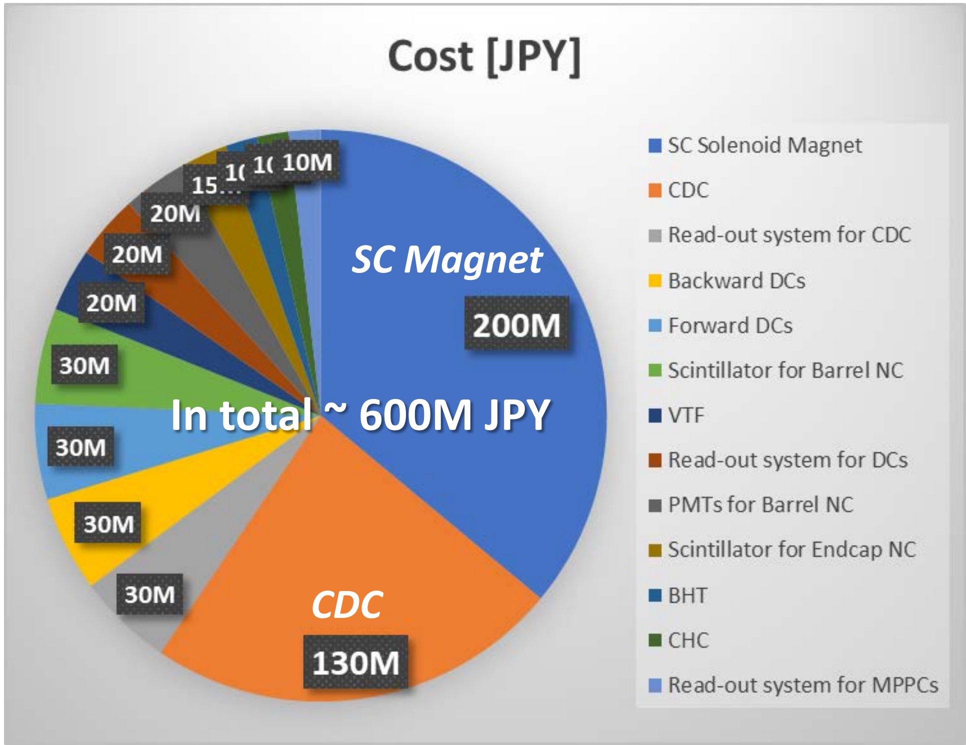


- The signals can be enhanced by selecting $0.3 < q < 0.6$ GeV/c
- **The $K^{-}ppn$ signal will be observed if the $\sigma(K^{-}ppn)$*Br is more than ~ μb**

Schedule & Cost

- We would like to perform the proposed experiment **around 2023**
  - ☐ Design & construction: ~2022
  - ☐ Commissioning run : 2023
  - ☐ Performance run followed by Physics run : 2023~

- Most of the construction cost will be covered by “MEXT Grant-In-Aid” and “RIKEN internal budget”
  - ✓ We are now applying “Specially Promoted Research (特推)”



Summary of the New Project

- **The new project aims to reveal the properties of the light kaonic nuclei from the $\bar{K}N$ to $\bar{K}NNNN$**
  - ➢ a powerful probe to understand low energy QCD
  - ➢ the best approach to cold & high-density nuclear matter

- We take a step-by-step approach:
  - **a $\bar{K}NNN$ search via 4He(K-,N) reactions as a first step**
  - followed by a spin/parity measurement of the $\bar{K}NN$ soon
  - experimental challenges of $\bar{K}N$, $\bar{K}NNNN$, and $\bar{K}\bar{K}NN$ will also be followed

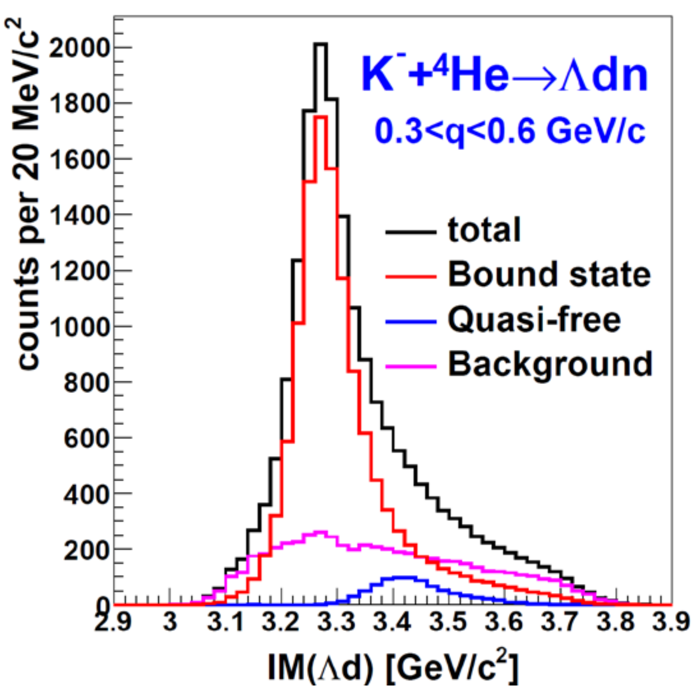
- We realize the systematic measurements with
  - ☐ a new 4π cylindrical detector system (CDS)
  - ☐ the improved K1.8BR beamline spectrometer

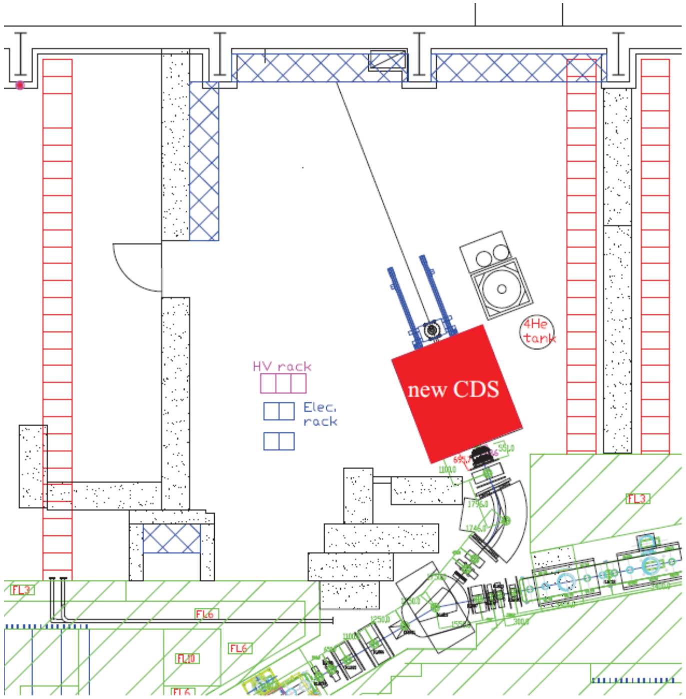
Requests to PAC

1. stage-1 approval of **“the $\bar{K}NNN$ search via ^{4}He(K$^-$,N) reactions”**

2. Endorse of **“the K1.8BR beamline upgrade”**

We would like to perform the upgrade during the long shutdown in 2021-22





Collaboration of the New Project

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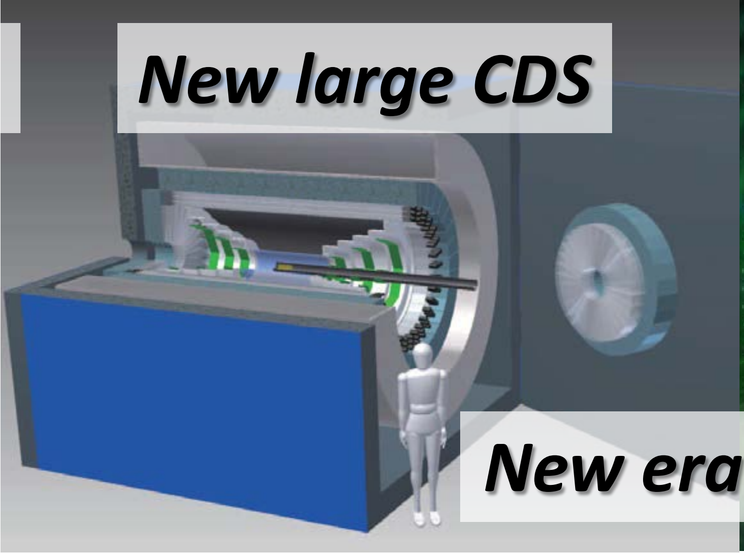
High intense K beam

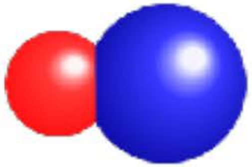

New large CDS

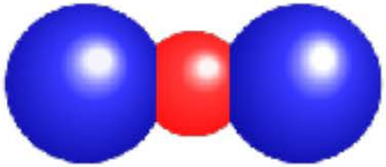

ÖWA/Harald Ritsch

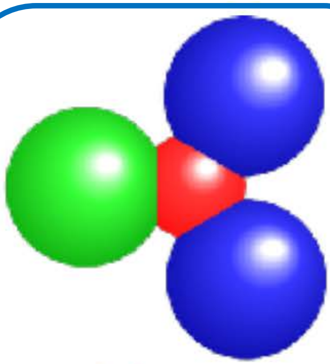
New era of kaonic nuclei

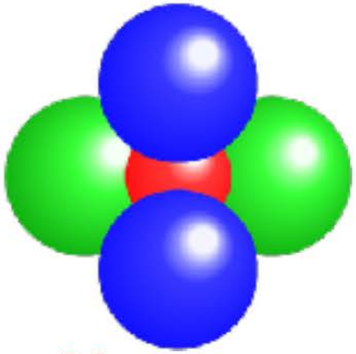
Thank you for your attention!

A first step of the project


K^-p


K^-pp


K^-ppn


K^-ppnn

via in-flight $^4He(K^-,N)$

Appendix

Physics Background

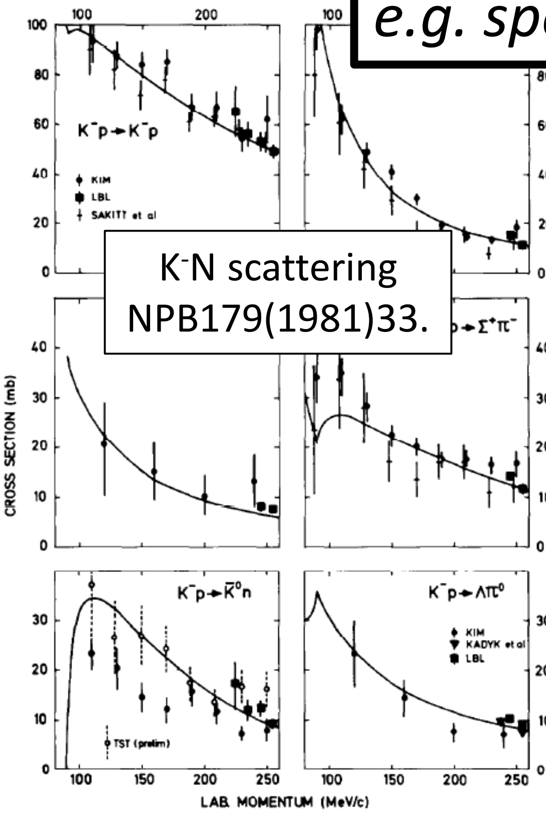
Physics Goal

Reveal the $\bar{K}$ meson property inside nuclei via **the $\bar{K}N$ interaction**

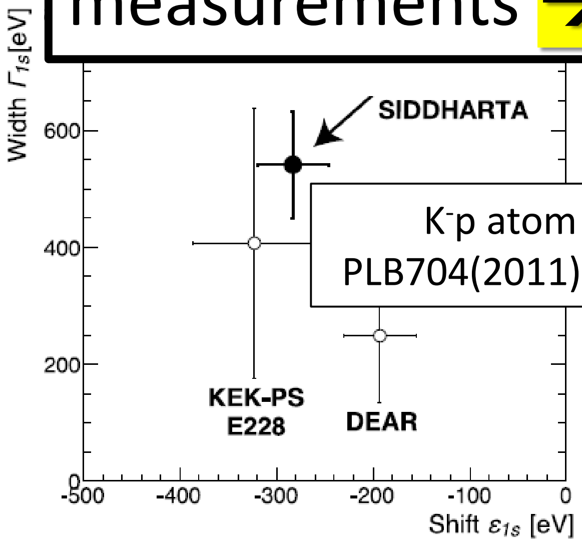
A powerful probe to understand low energy QCD

e.g. spontaneous and explicit chiral symmetry breaking

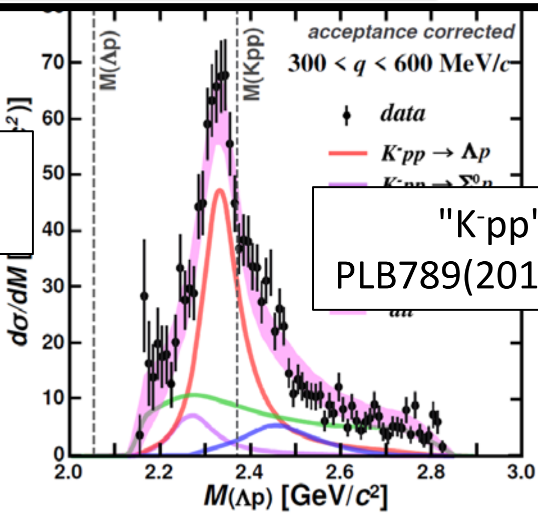
Strongly attractive in I=0 from extensive measurements **→ kaonic nuclei**



K^-N scattering
NPB179(1981)33.



K^-p atom
PLB704(2011)113.



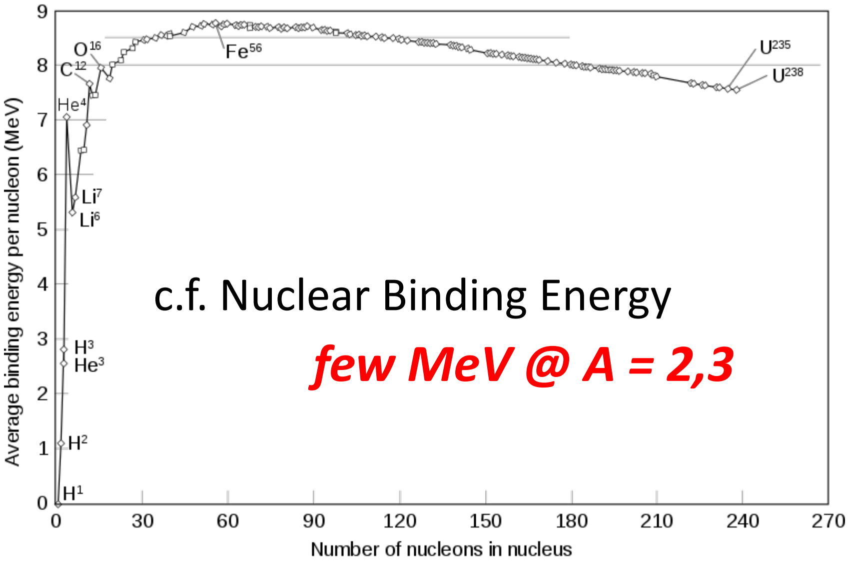
"K^-pp"
PLB789(2019)620.

Kaonic Nuclei

Predicted from **attractive $\bar{K}N$ interaction in I=0**

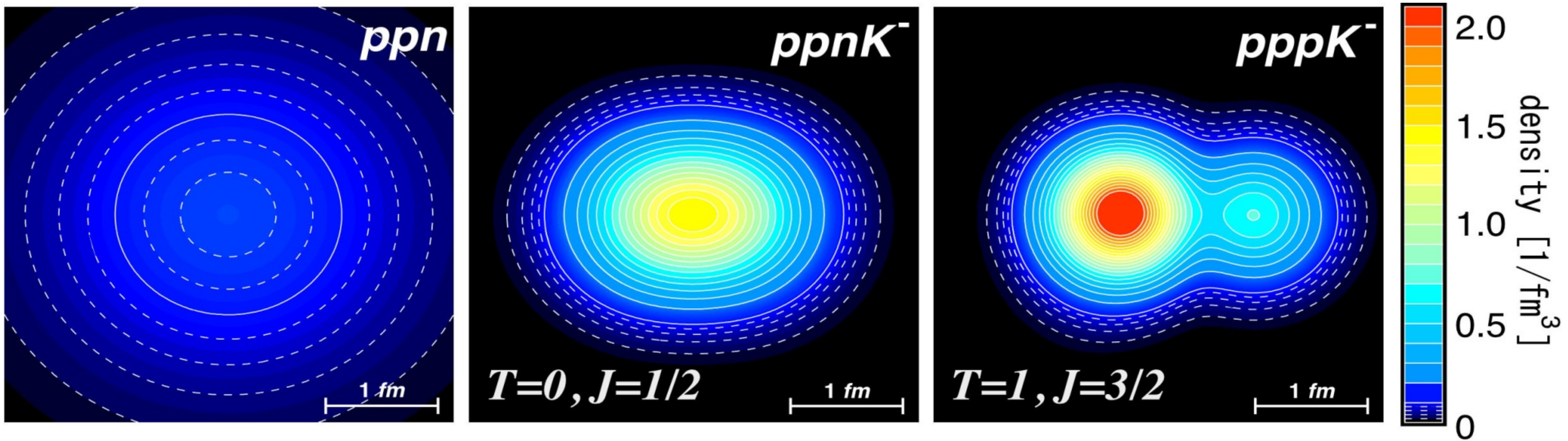
Kaonic Nuclei	**Binding Energy [MeV]**	**Width [MeV]**
Λ(1405) = K^-p	27	40
K^-pp	48	61
K^-ppp	97	13
K^-ppn	118	21

PL7(1963)288., PRC65(2002)044005., etc.



c.f. Nuclear Binding Energy

few MeV @ A = 2,3

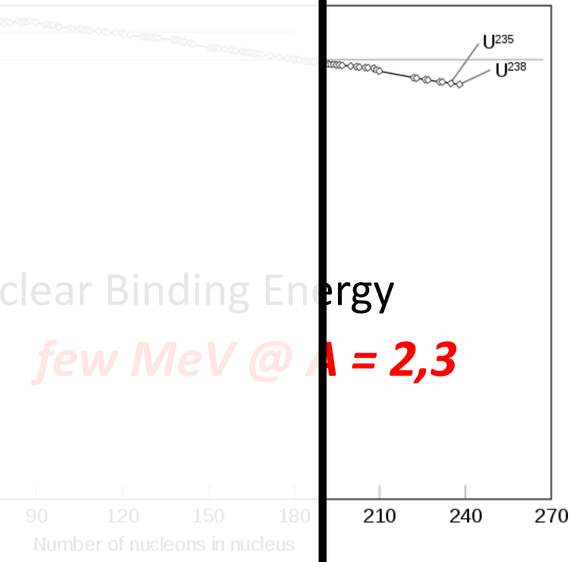


Kaonic Nuclei

Predicted from … action in I=0

Kaonic Nuclei	Binding Energy [MeV]
Λ(1405) = K⁻p	27
K⁻pp	48
K⁻ppp	97
K⁻ppn	118

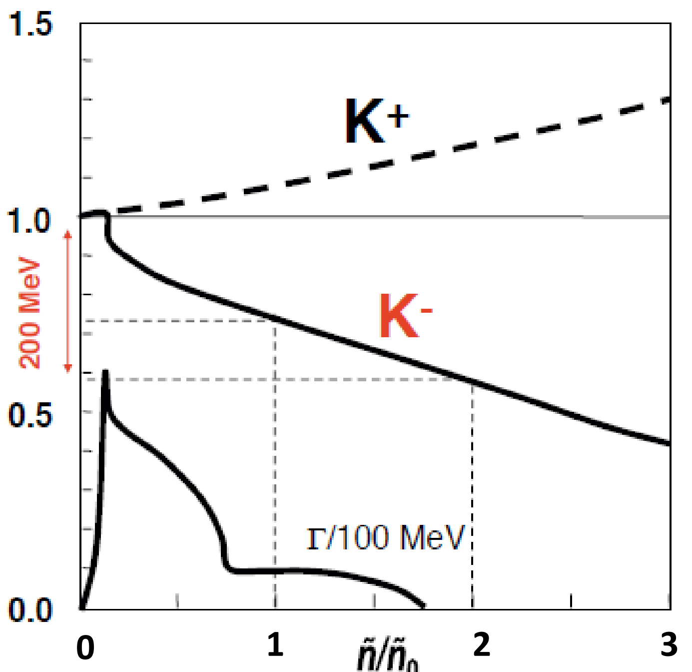
…88., PRC65(2002)044005., etc.



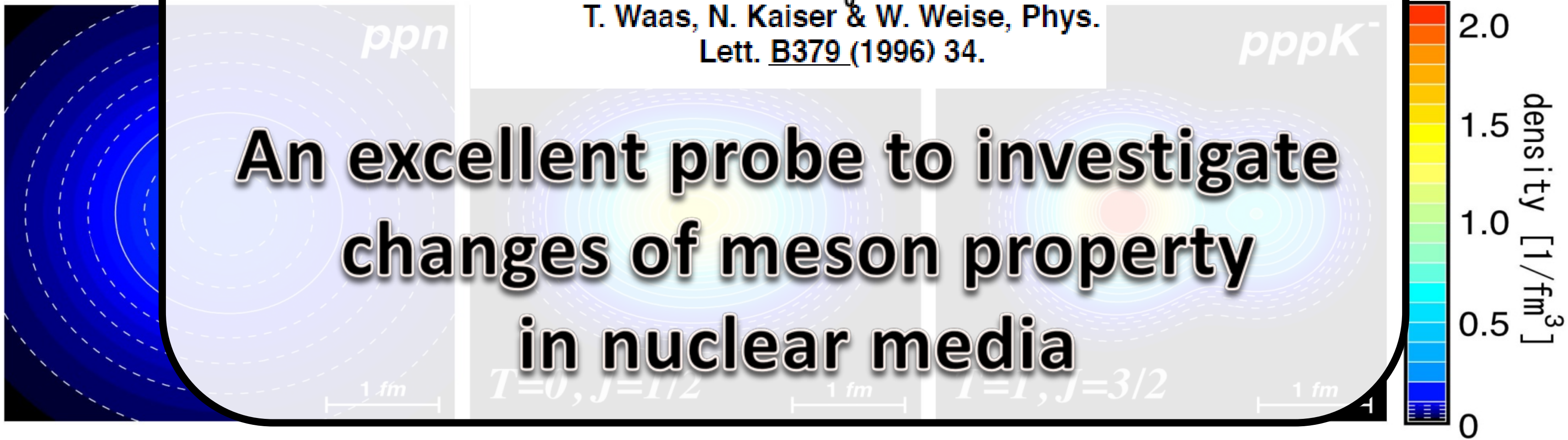
…clear Binding Energy

few MeV @ A = 2,3

m_K^*/m_K in nuclear matter



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



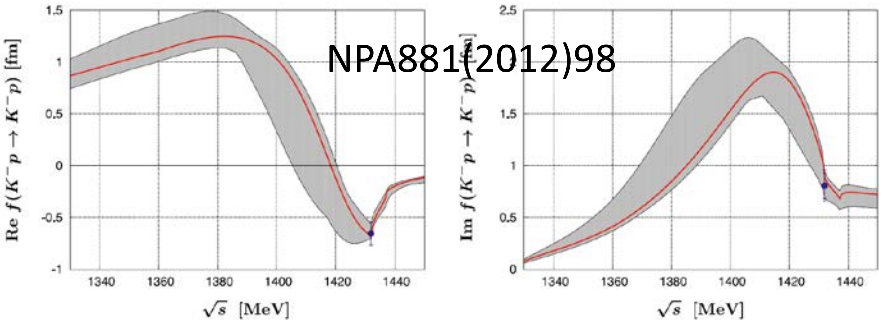
An excellent probe to investigate changes of meson property in nuclear media

Are Kaonic Nuclei Really Compact?

In the case of the $\bar{K}NN$ system ($J^P=0^-$)

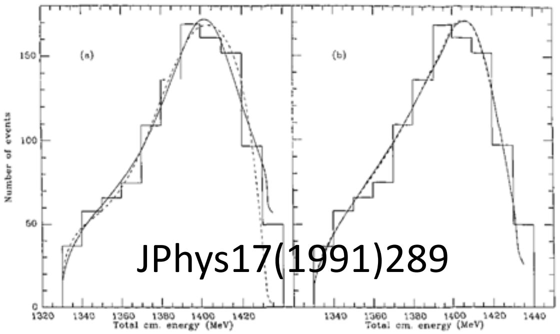
$K^{bar}N$ int.	Chiral SU(3) (energy dependent)	Phenomenological (energy independent)

$M_{\Lambda(1405)}$~1420, double pole

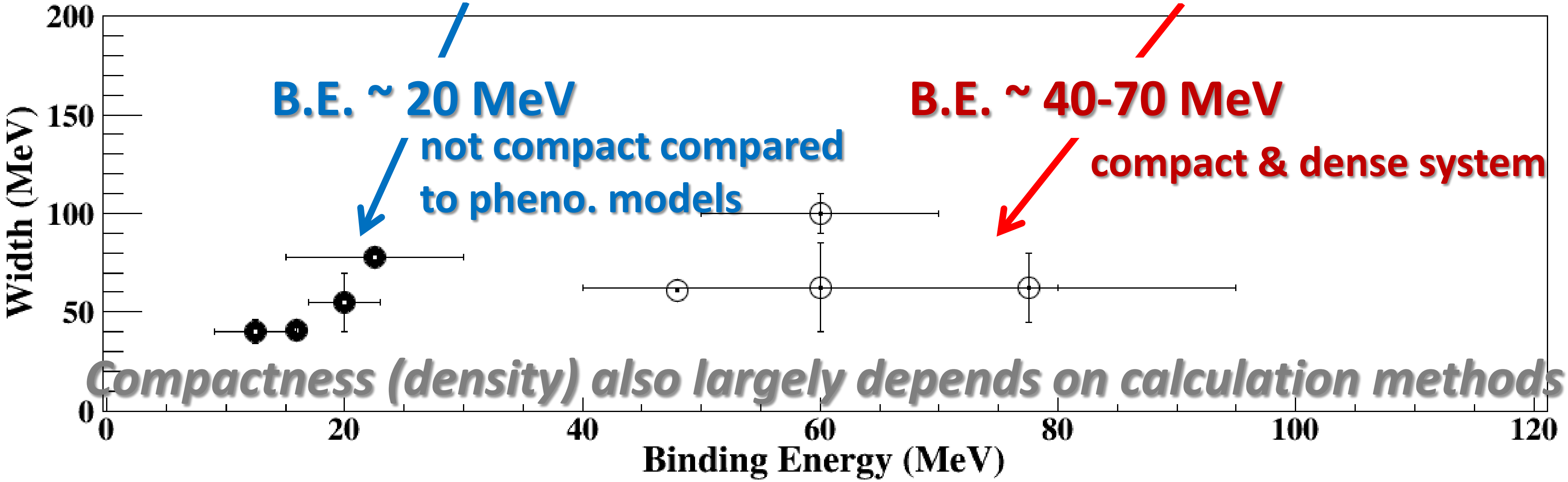


NPA881(2012)98

$M_{\Lambda(1405)}$~1405, single pole



JPhys17(1991)289



B.E. ~ 20 MeV

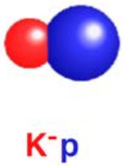
not compact compared to pheno. models

B.E. ~ 40-70 MeV

compact & dense system

Compactness (density) also largely depends on calculation methods

New Project

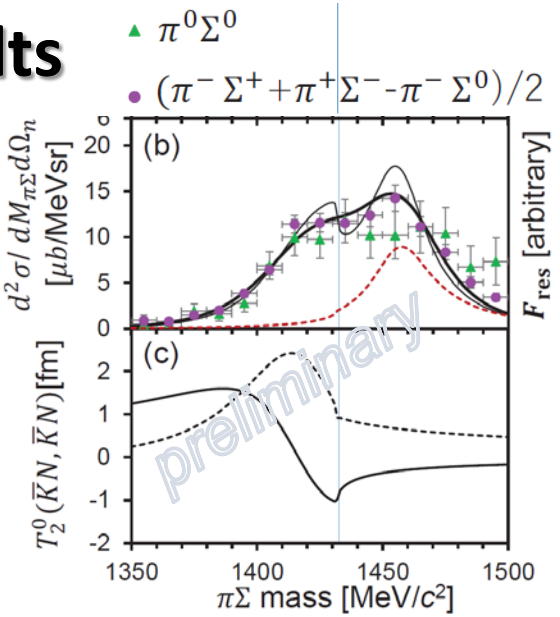


Task for $\bar{K}N$

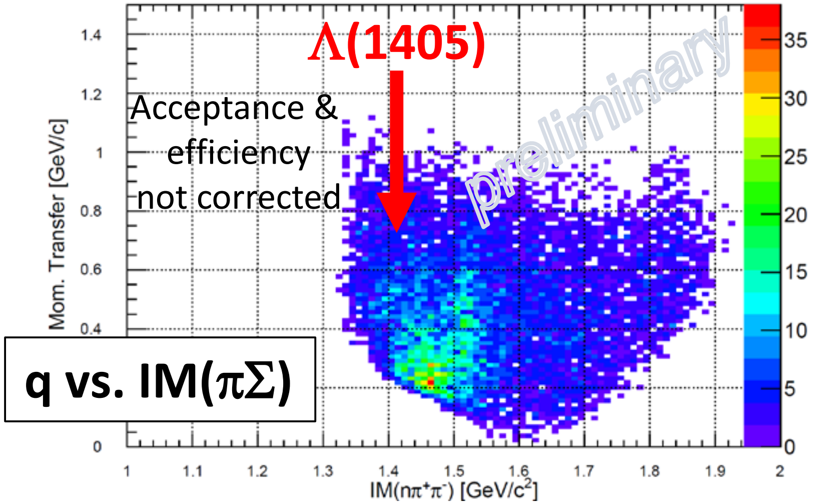
- Theoretically, Λ(1405) is consider to be the $\bar{K}N$ quasi-free bound state
- We have revealed the line shape of the $\bar{K}N \rightarrow \pi\Sigma$ channel via the (K⁻,n) reaction at θ_n=0° in E31

E31 results

$\bar{K}N \rightarrow \bar{K}N$ Amplitude in I=0



Exploratory analysis at E31



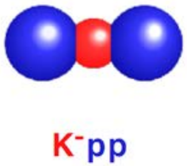
Acceptance & efficiency not corrected

q vs. IM(πΣ)

- Size of the Λ(1405) is still important subject to be determined

  → Clarify the picture whether a baryonic state or a $\bar{K}N$ molcuer

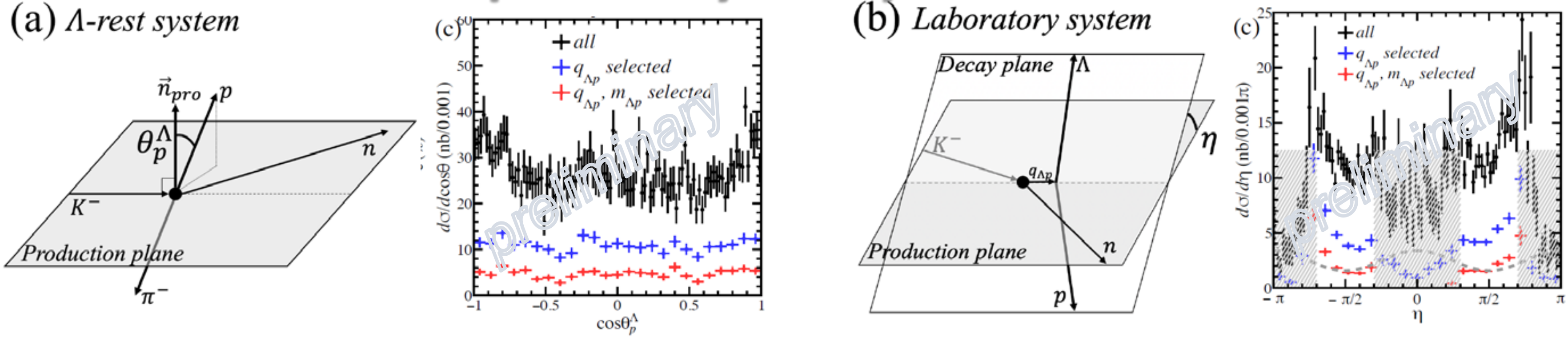
- **We deduce the Λ(1405) size via form factor measurement in a wide range of *q***



Task for $\bar{K}NN$

- The $\bar{K}NN$ system is expected to have $J^P = 0^-$
- To determine the spin/parity, **“topological analysis of decay particles”** ***or*** **“direct measurement of decay particle polarization”** is essential

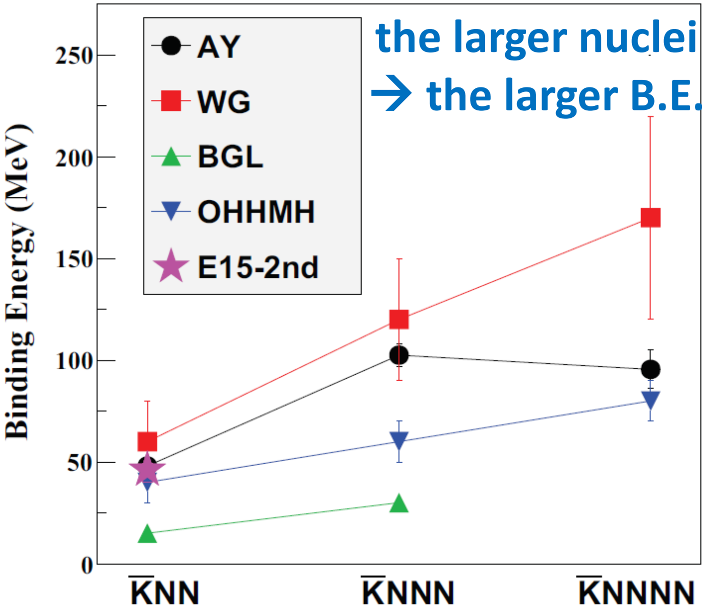
Exploratory analysis at E15



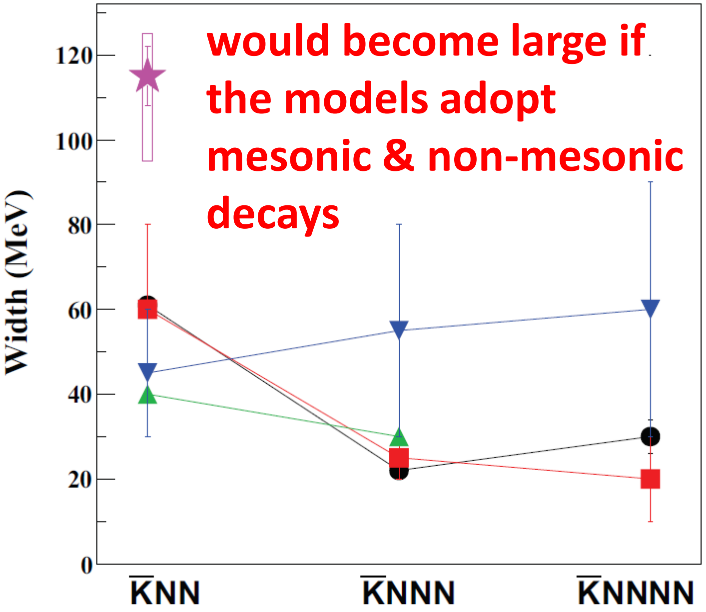
- **We determine the spin/parity of the system via its Λp decay**
  - by introducing a polarimeter composed of a hodoscope and a tracker
- **We precisely deduce the system size**
  - with more statistical data in corporation with theoretical analyses

Task for $\bar{K}NNN$ and $\bar{K}NNNN$

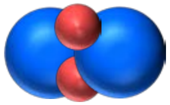
- Beyond the $\bar{K}NN$, more heavier system must be explored to establish the kaonic nuclei
  - ✓In particular, the $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration
- **We reveal the mass number dependence of the binding energy, decay width, and system size**



the larger nuclei
→ the larger B.E.

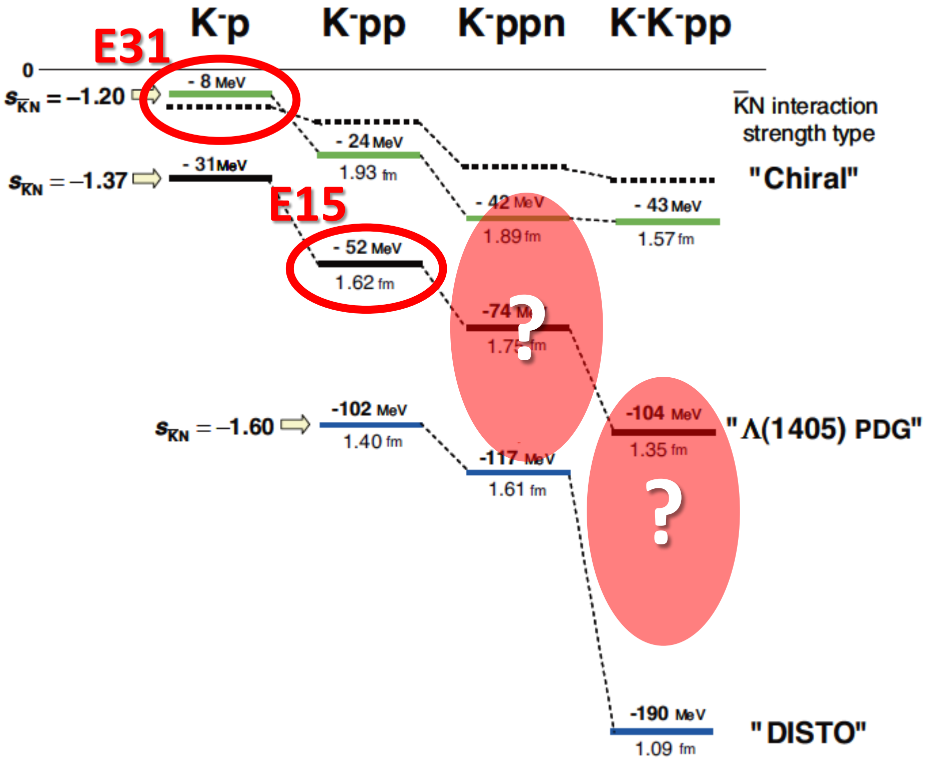


would become large if the models adopt mesonic & non-mesonic decays



Toward $\bar{K}\bar{K}NN$

- **We also wish to access the S = −2 kaonic nuclei such as the theoretically predicted "K$^-$K$^-$pp" state**
  - ✓as previously submitted LoI
  - ✓A good probe to the $\bar{K}N$ int.



Proc. Jpn. Acad., **B89** (2013) 418.

- The $\bar{K}\bar{K}NN$ system could give us a chance to access much higher density than the S = −1 kaonic nuclei

The $\bar{K}\bar{K}NN$ production cross section would be quite small
→ roughly 1/1000 of that of the $\bar{K}NN$

“K^-ppn” Candidates so far

- A few candidates have been reported in ***inclusive*** measurements

◆**E471/E549@KEK** ← **NULL results**

  - ^{4}He(stopped-K^-,p/n)X

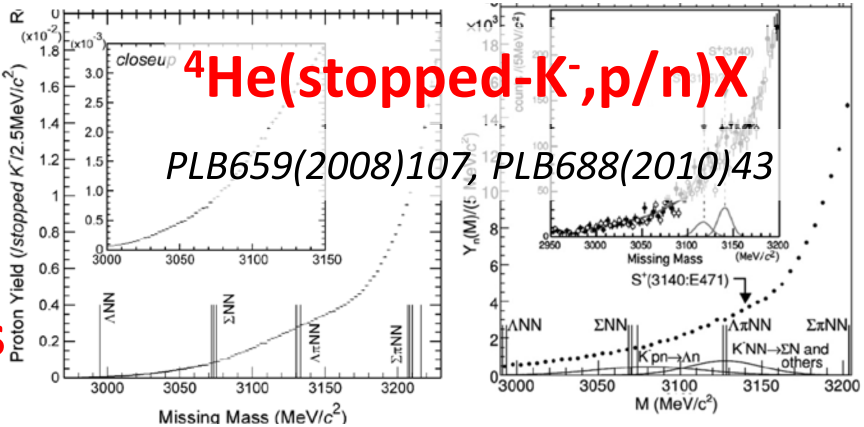
◆**FINUDA@DAΦNE** ← **Observed?**

  - Li/C(stopped-K^-,Λd)

◆**FOPI@GSI** ← **Observed?**

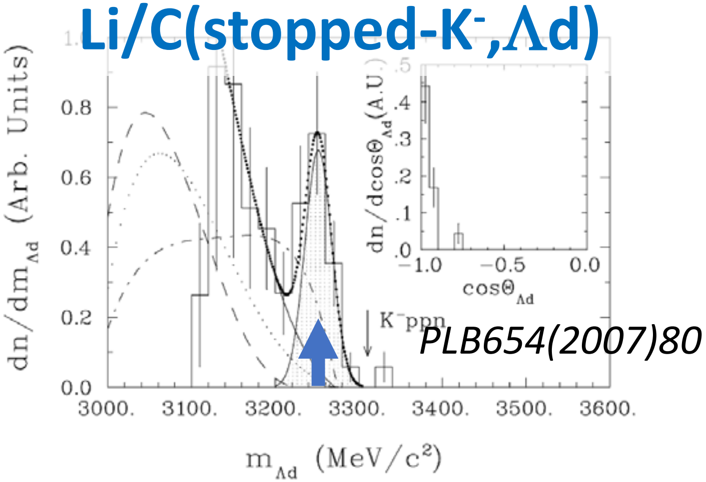
  - Λd in Ni+Ni

- **Exclusive measurement using a simple reaction (in-flight & light nuclei) is crucial**



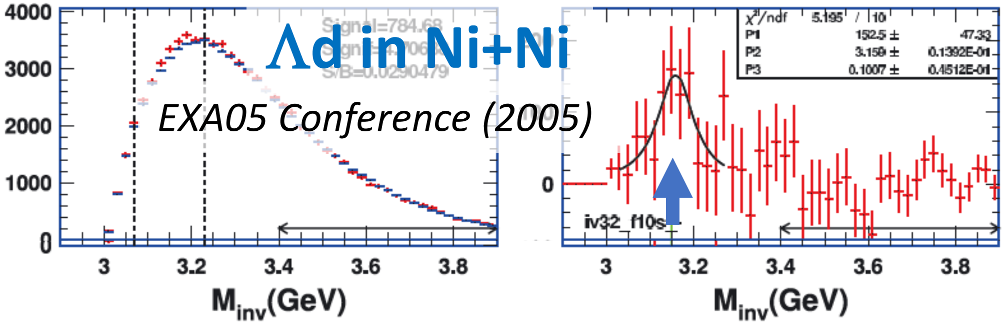
^{4}He(stopped-K^-,p/n)X

PLB659(2008)107, PLB688(2010)43



Li/C(stopped-K^-,Λd)

PLB654(2007)80



Λd in Ni+Ni

EXA05 Conference (2005)

Schedule of Preparation

<table>
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<tr><td>Magnet</td><td>design</td><td colspan="2">purchase (S.C. wires)</td><td colspan="3"></td><td colspan="3"></td><td colspan="2"></td><td colspan="2" rowspan="9">comm. run</td><td colspan="4" rowspan="9">physics run</td><td colspan="2" rowspan="9">analysis, publication</td></tr>
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<tr><td>Forward DC</td></tr>
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<tr><td>BHT</td><td colspan="2" rowspan="2">construction</td><td colspan="4" rowspan="2">test and commisioning</td></tr>
<tr><td>CHC</td></tr>
<tr><td>NC</td><td>design</td><td colspan="2">purchase</td><td colspan="3">assembly</td><td colspan="3">test and commisioning</td><td colspan="2"></td></tr>
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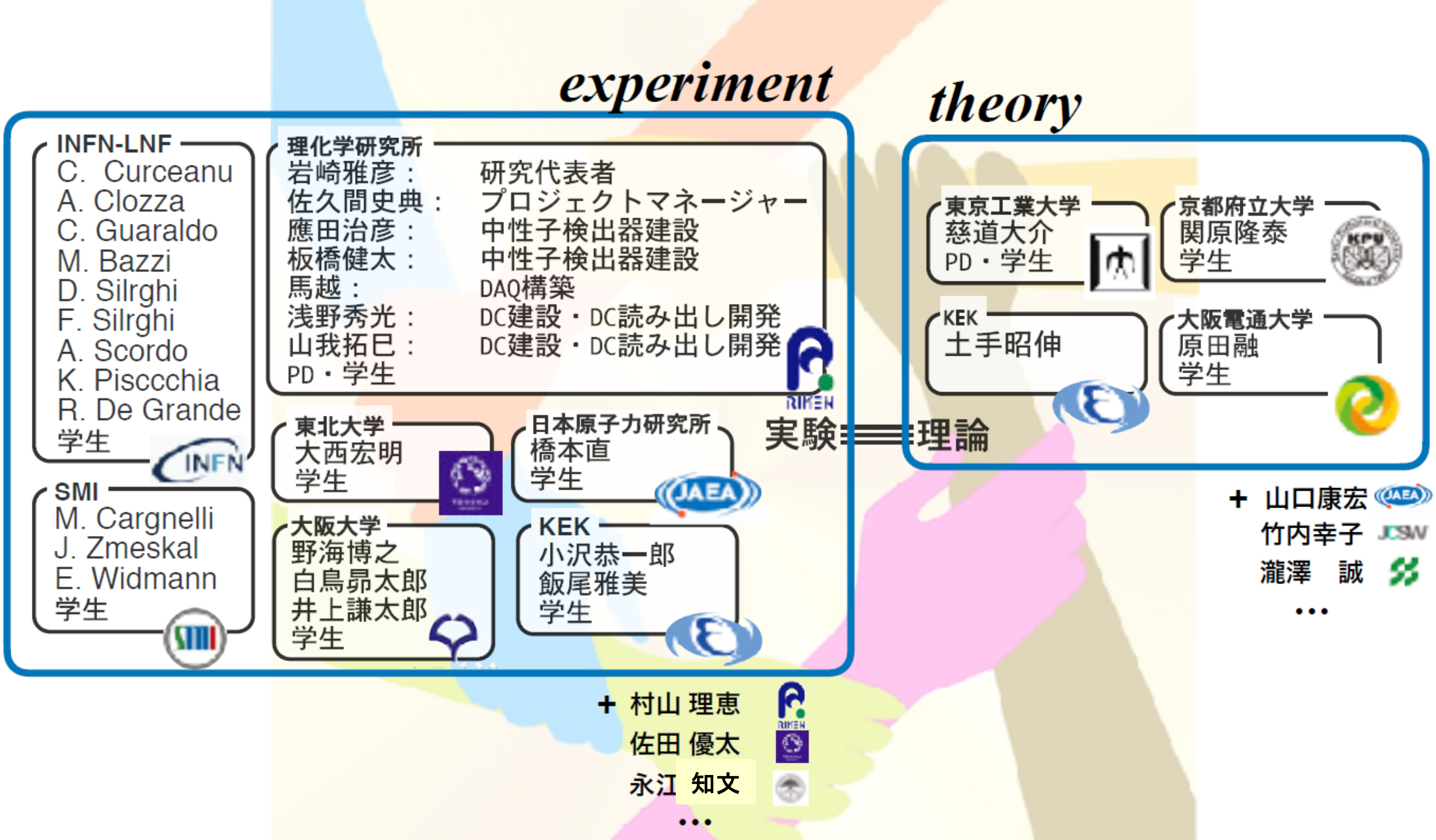
Summary of the Experiment for $\bar{K}NNN$

Beamline	K1.8BR
Primary beam	30 GeV, 90 kW (5.2 s spill interval)
Secondary beam	1.0 GeV/c K^-
Beam intensity	3.2×10^5 K^- on target per pulse
Detectors	Improved K1.8BR beamline spectrometer, New cylindrical detector system (CDS)
Target	Liquid ^{4}He
Beam time	1 week for commissioning run, 1 week for performance study run with LH_2, 3 weeks for physics run with L^4He
Expected yield	1.9×10^4 $K^-ppn \rightarrow \Lambda d$, 2.8×10^3 $K^-ppn \rightarrow \Lambda pn$

around 2023

Collaboration with Experimental & Theoretical Group



experiment

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板橋健太：	中性子検出器建設
馬越：	DAQ構築
浅野秀光：	DC建設・DC読み出し開発
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KEK
小沢恭一郎
飯尾雅美
学生

+ 村山 理恵
佐田 優太
永江 知文
…

実験═══理論

theory

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慈道大介
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京都府立大学
関原隆泰
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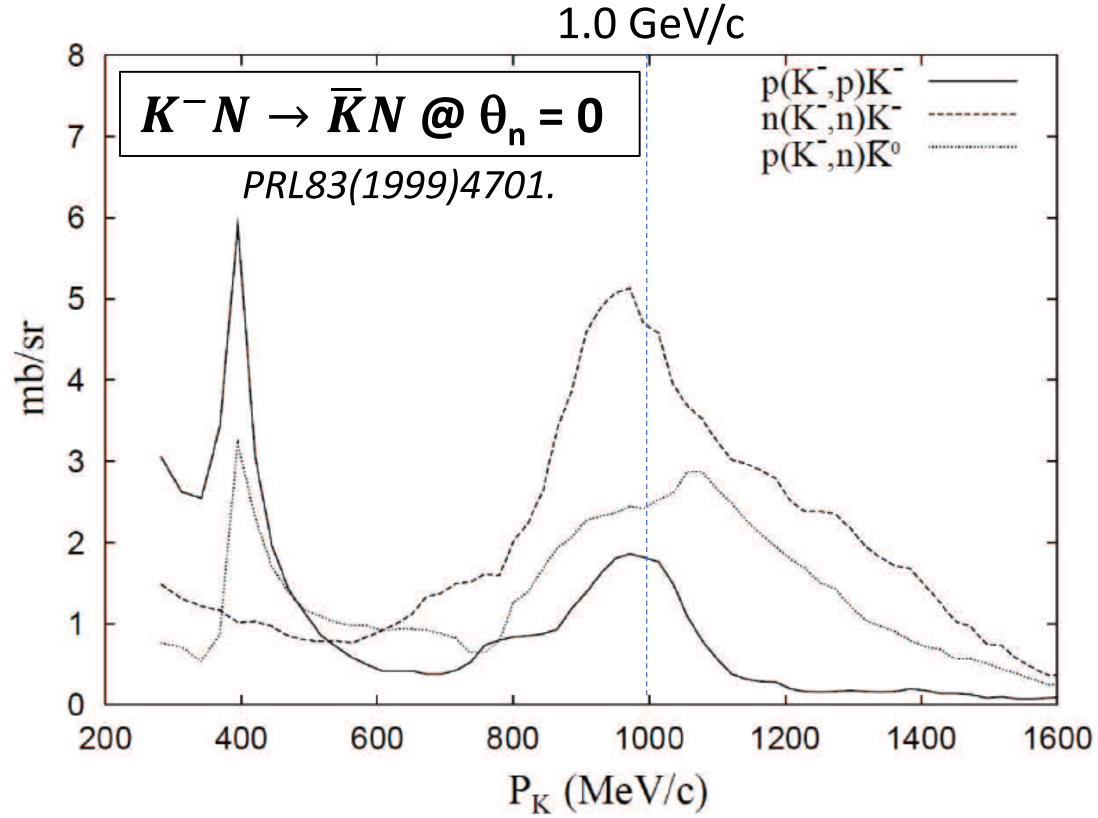
KEK
土手昭伸

大阪電通大学
原田融
学生

+ 山口康宏
竹内幸子
瀧澤　誠
…

Apparatus

Kaon Beam Momentum



1.0 GeV/c

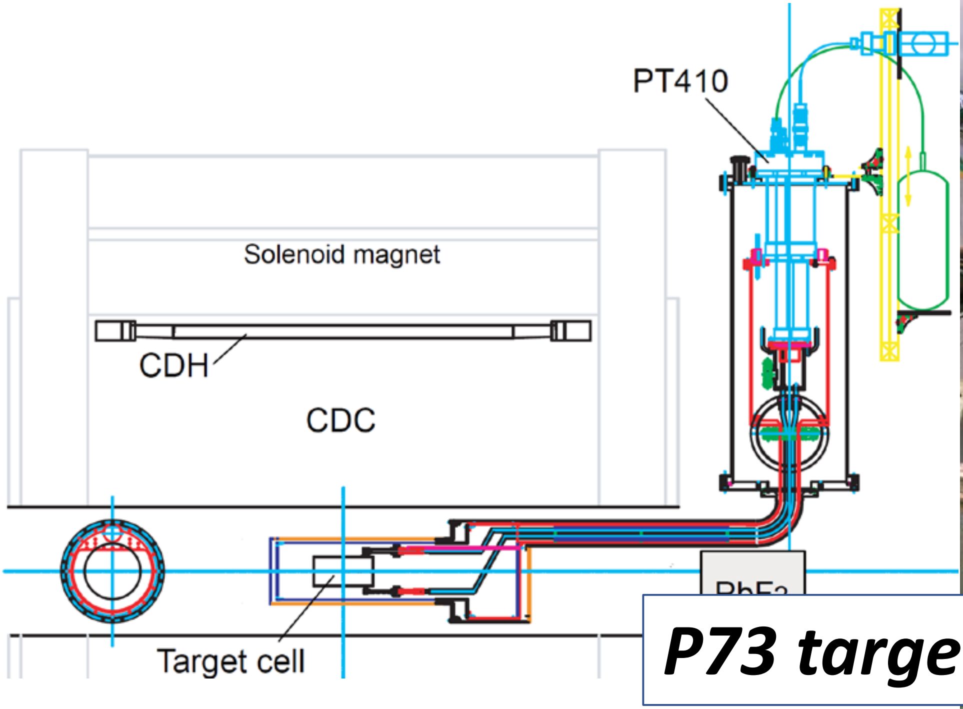
$K^{-}N \rightarrow \bar{K}N$ @ θ_n = 0

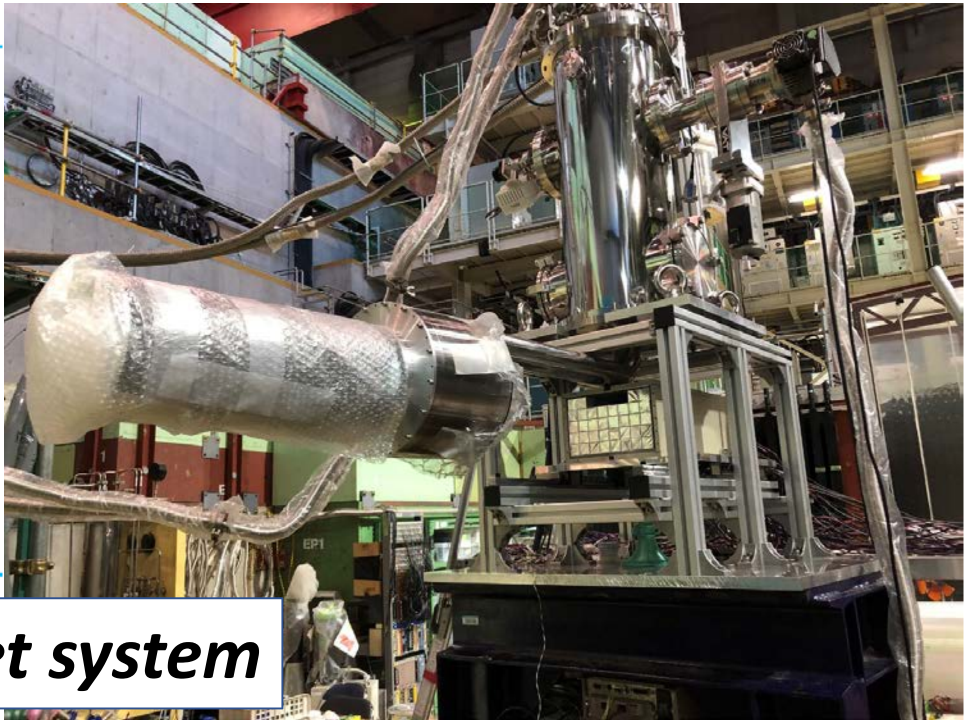
PRL83(1999)4701.

- **Use 1.0 GeV/c K^{-} beam ($\sqrt{s}$ = 1.8 GeV)**
  - $K^{-}N \rightarrow \bar{K}N$ reactions have the maximum cross section
    - Due to the intermediate state of Y*(1800)
  - low-momentum back-scattered kaon as a ‘off-shell kaon’ beam
- We also plan to perform momentum scan (0.9-1.15 GeV/c) in the near future

Target System

- Pulse tube refrigerator system developed for P73
- Liquefy all types of $H_2/D_2/^3He/^4He$ gases
- Pure Be target cell developed for E15
- **System has been successfully operated**





P73 target system

SC Solenoid Magnet

- The same design of the "**COMET Detector-Solenoid**"
  - developed by the **KEK Cryogenic Science Center**
- Solenoidal magnetic field of 0.7T is used (max ~1T)
- external dimensions:

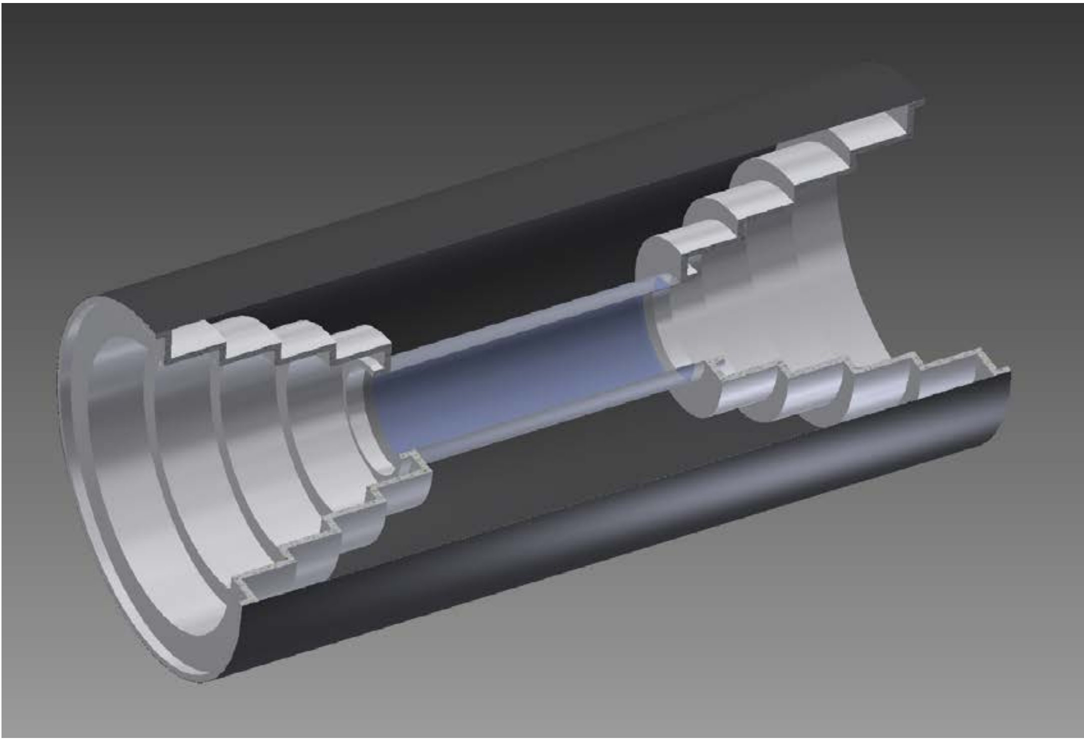
  3.4m × 3.4m × 3.9m (25t)
  - No need to dig the floor of the HD hall

Vacuum vessel of SC coil

図 3　真空容器鳥瞰図（内筒のレール台座、補強等は表示されていない）

CDC

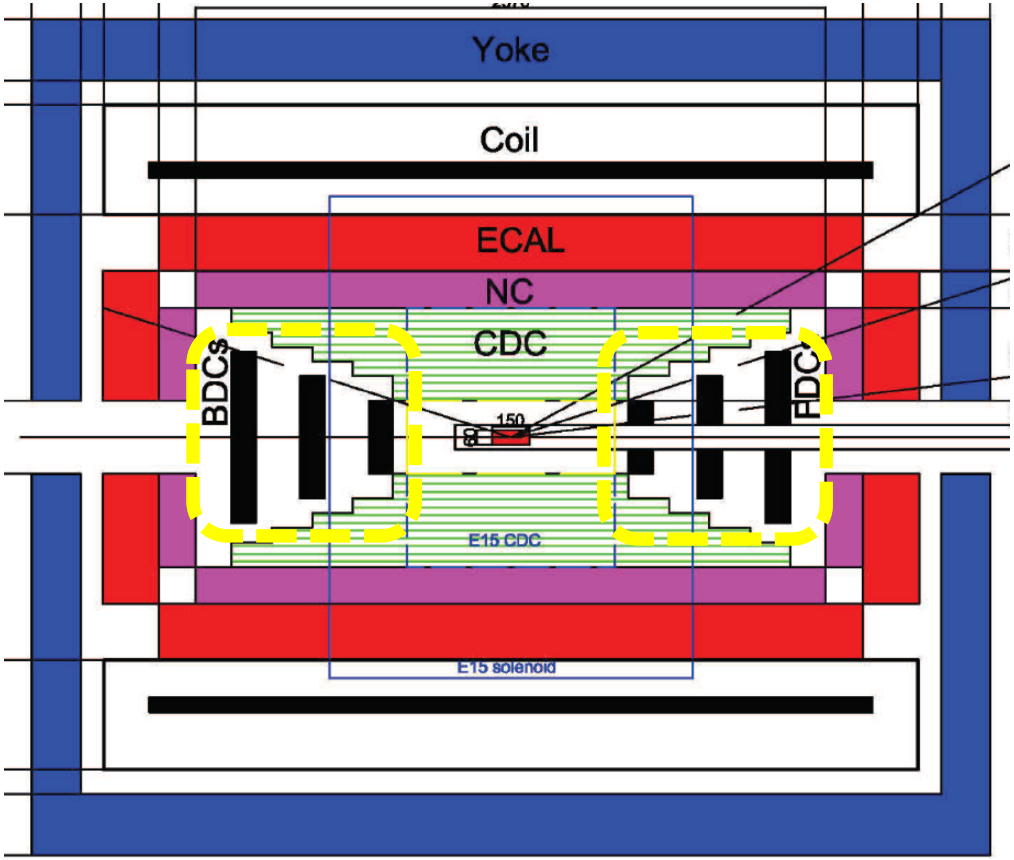
- Conical-shaped end-plates
  - $29^o < \theta < 151^o$
  - 15cm < r < 50cm
  - wire support: feed-though
  - longest wire length: 2.2m
- readout channels is ~2,150
  - existing ASD preamps and HUL boards



Super layer	Layer	Wire direction	Radius (mm)	Cell width (degree)	Cell width (mm)	Stereo angle (degree)	Signal channel per layer
A1	1, 2, 3	X, X' X	190 - 230	5.00	~ 18.0	0	72
U1	4, 5	U, U'	250 - 300	3.60	~ 18.5	$\sim \pm 3.5$	100
V1	6, 7	V, V'					
A2	8, 9, 10	X, X' X	320 - 360	3.00	~ 18.0	0	120
U2	11, 12	U, U'	380 - 430	2.25	~ 17.0	$\sim \pm 3.5$	160
V2	13, 14	V, V'					
A3	15, 16, 17	X, X' X	450 - 490	2.00	~ 16.5	0	180

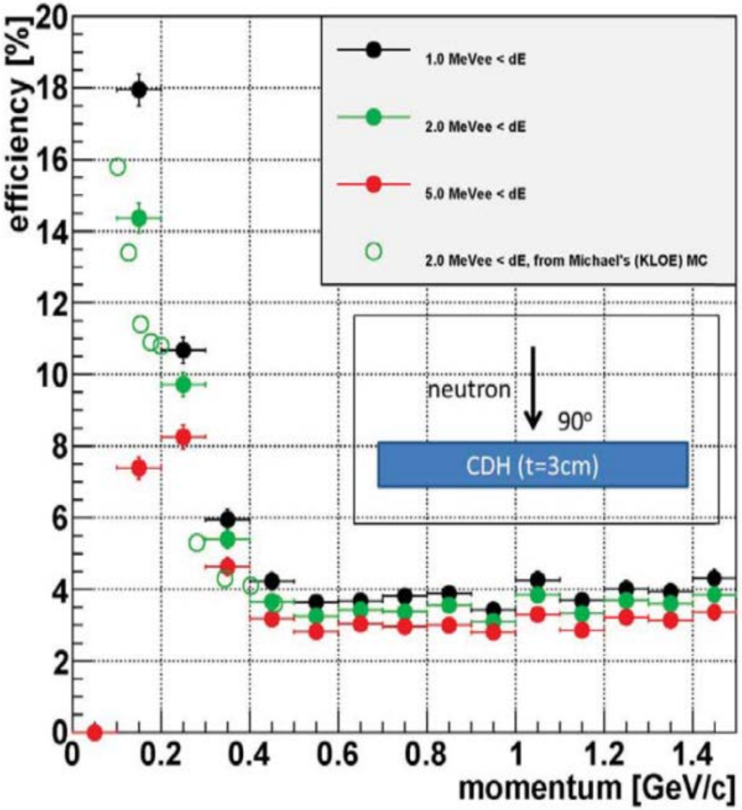
BDC/FDC

- Planner chambers
  - XX’YY’XX’YY’ config.
- BDC/FDC: 3/3 modules
  - placed at 0.5 m, 0.8 m, and 1.1m up/down-stream
  - 30 cm, 50 cm, and 70 cm inscribed circle diameters
- ~3,072 channels
  - ~(32*8, 64*8, 96*8)*2
- We plan to construct DCs in stages



NC

- **Aiming to detect low-p neutron ranging from 100 to 500 MeV/c**
- 15cm plastic scintillator divided by ~3 layers & ~32 segments
  - **Neutron detection eff. = 15~45%** depending on momentum
- FM-PMT and MPPC readout for barrel and end-cap, respectively
  - Barrel NC has ~ 2.5m length



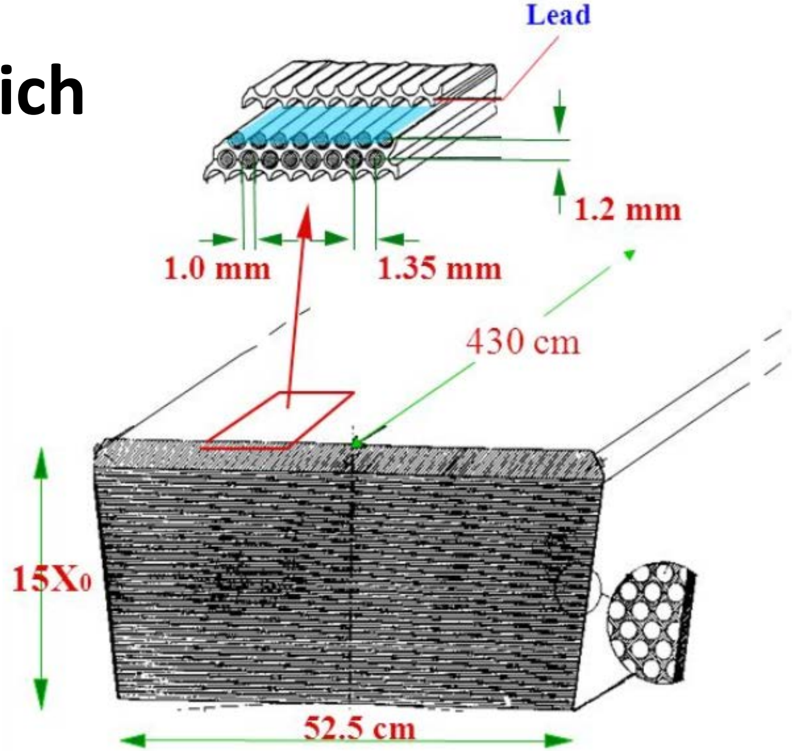
Neutron eff. / 3cm

- NC is used for trigger counters together with CHC (Charge Hodoscope Counter)
  - 3mm plastic scintillator with MPPC readout
  - Charged/neutral-trigger are generated using combination of CHC/NC hits

ECAL

- A sampling-type calorimeter
  - ~15 radiation length is required
- **KLOE** type or **conventional sandwich** type
  - KLOE type
    - Lead - scintillating-fiber
    - **Excellent performance**
      - $\sigma_E/E = 5.7\%/\mathrm{sqrt}(E(\mathrm{GeV}))$
      - $\sigma_t = 54/\mathrm{sqrt}(E(\mathrm{GeV})) + 50$ ps
    - Quite expensive: ~ 700M JPY
  - sandwich type
    - Lead - scintillator-slab with wave-length shifting fibers
    - **Rather low cost**: < 100M JPY

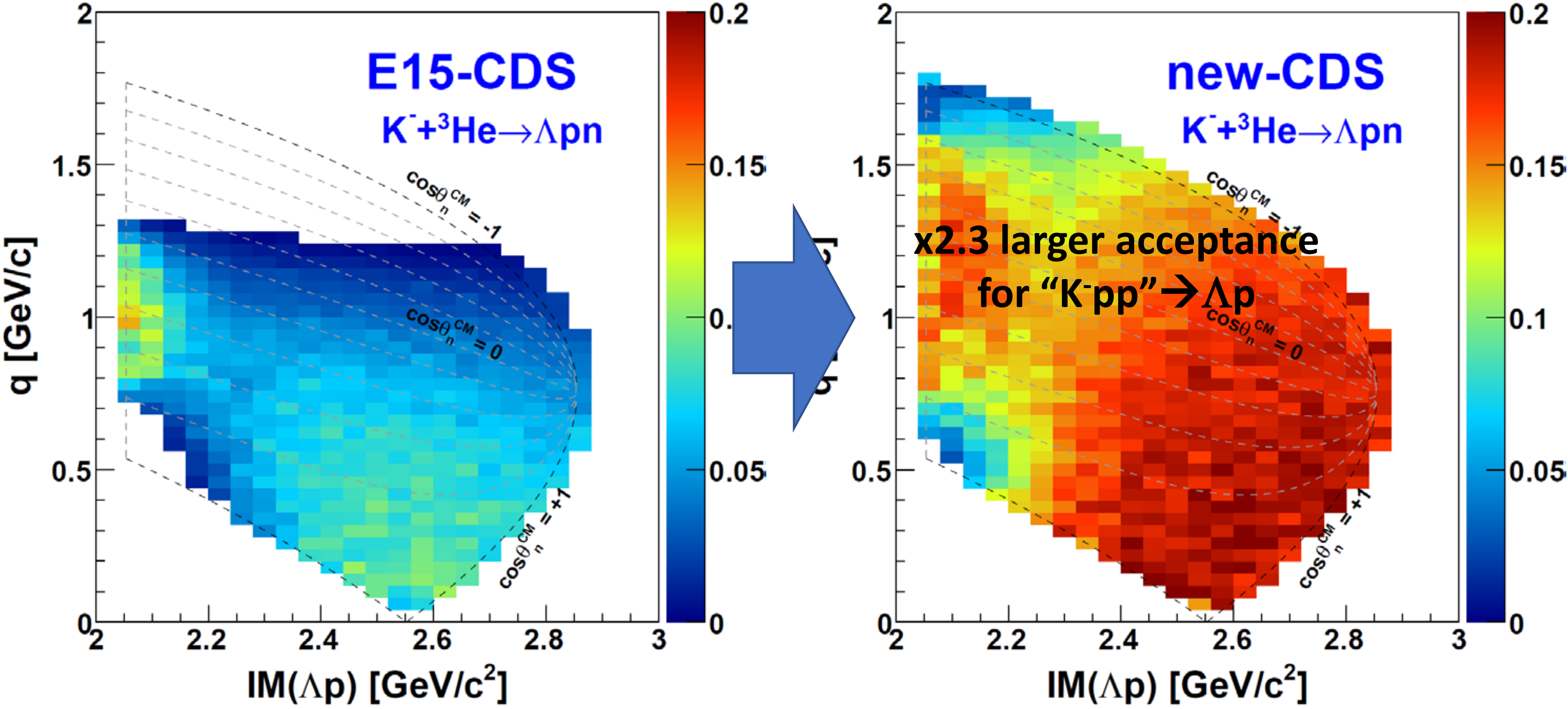
KLOE EM-CAL



→ The second stage of the project

Improved Acceptance of the New CDS

e.g. $\bar{K}NN \rightarrow \Lambda p$***, which has been well studied in E15***



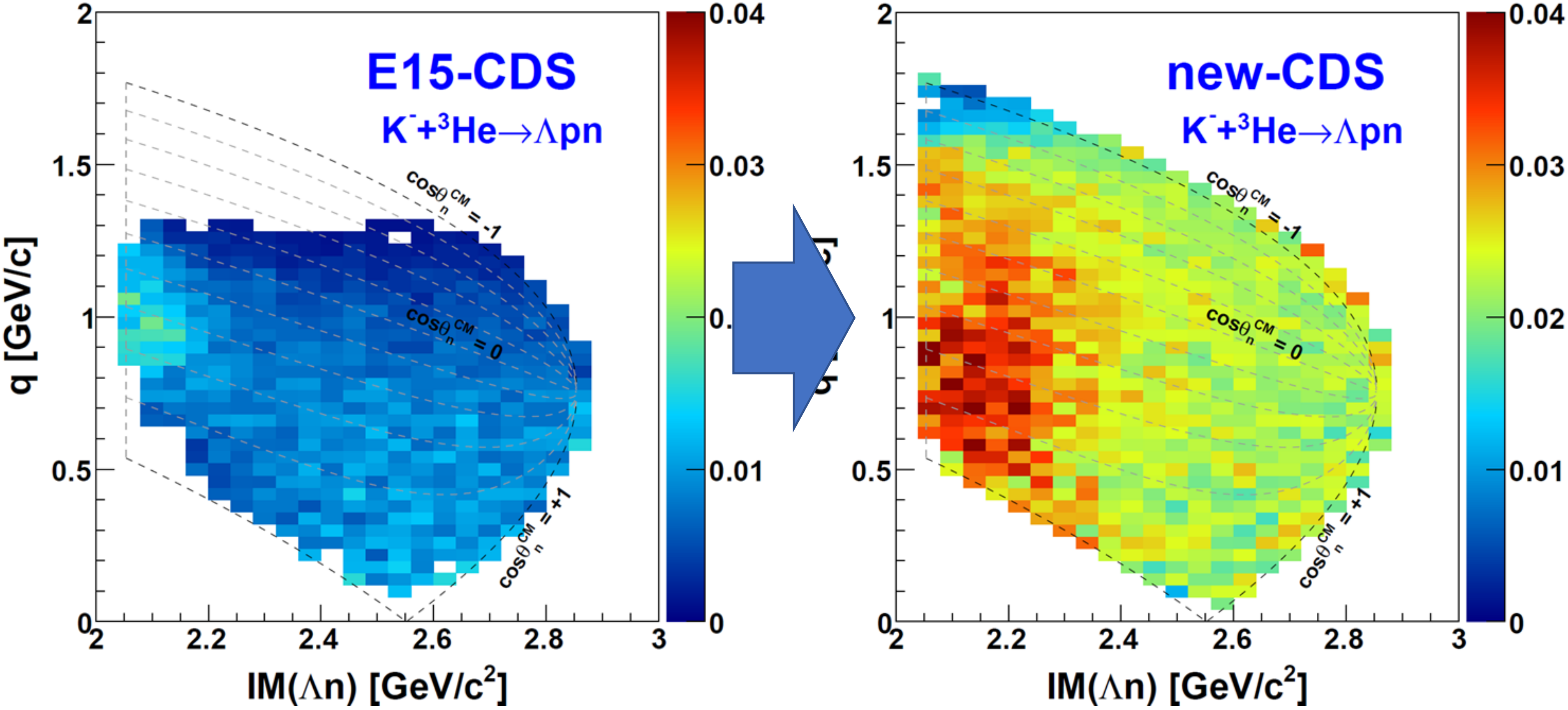
x2.3 larger acceptance for "K$^-$pp"→Λp

Drastically improved!

→ enables us to specify the reaction channel unambiguously

Improved Acceptance of the New CDS

e.g. $\bar{K}NN \rightarrow \Lambda n$***, which cannot be seen in E15***



Drastically improved!

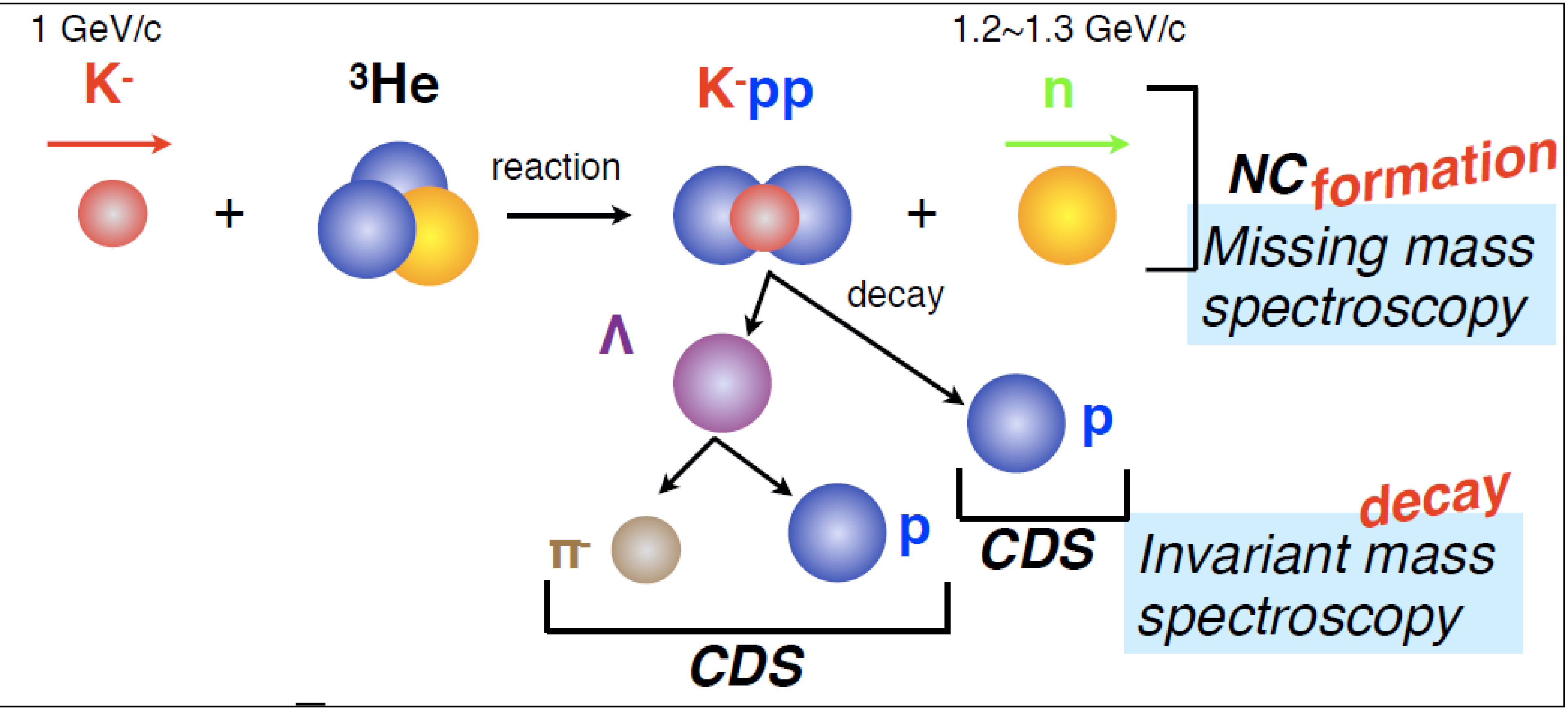
→ enables us to specify the reaction channel unambiguously

Results of E15

What We Did in E15

- experimental search for the $\bar{K}NN$ -

- via the **^{3}He(*in-flight* K$^-$,n)** reaction @ 1.0 GeV/c

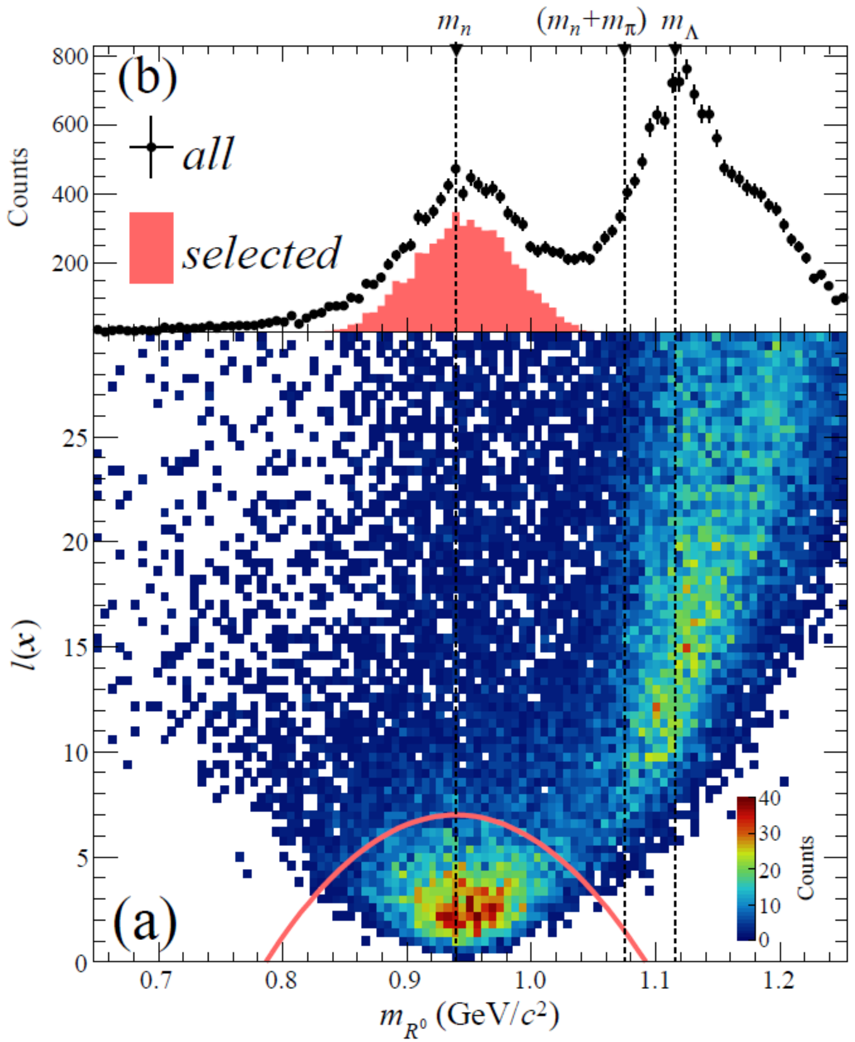


- $K^- N \rightarrow \bar{K} N$ reactions have the maximum cross section
- **low-momentum back-scattered kaon as a 'off-shell kaon' beam**

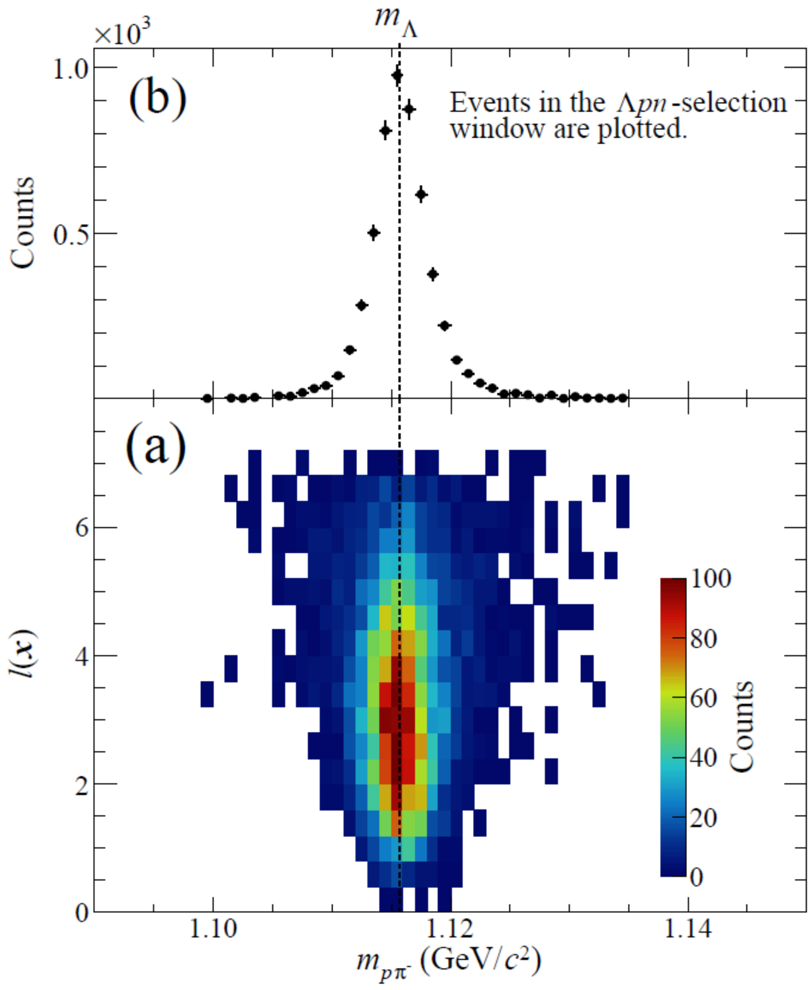
Identification of Λpn Final State

arXiv:2006.13433

Missing-n identification

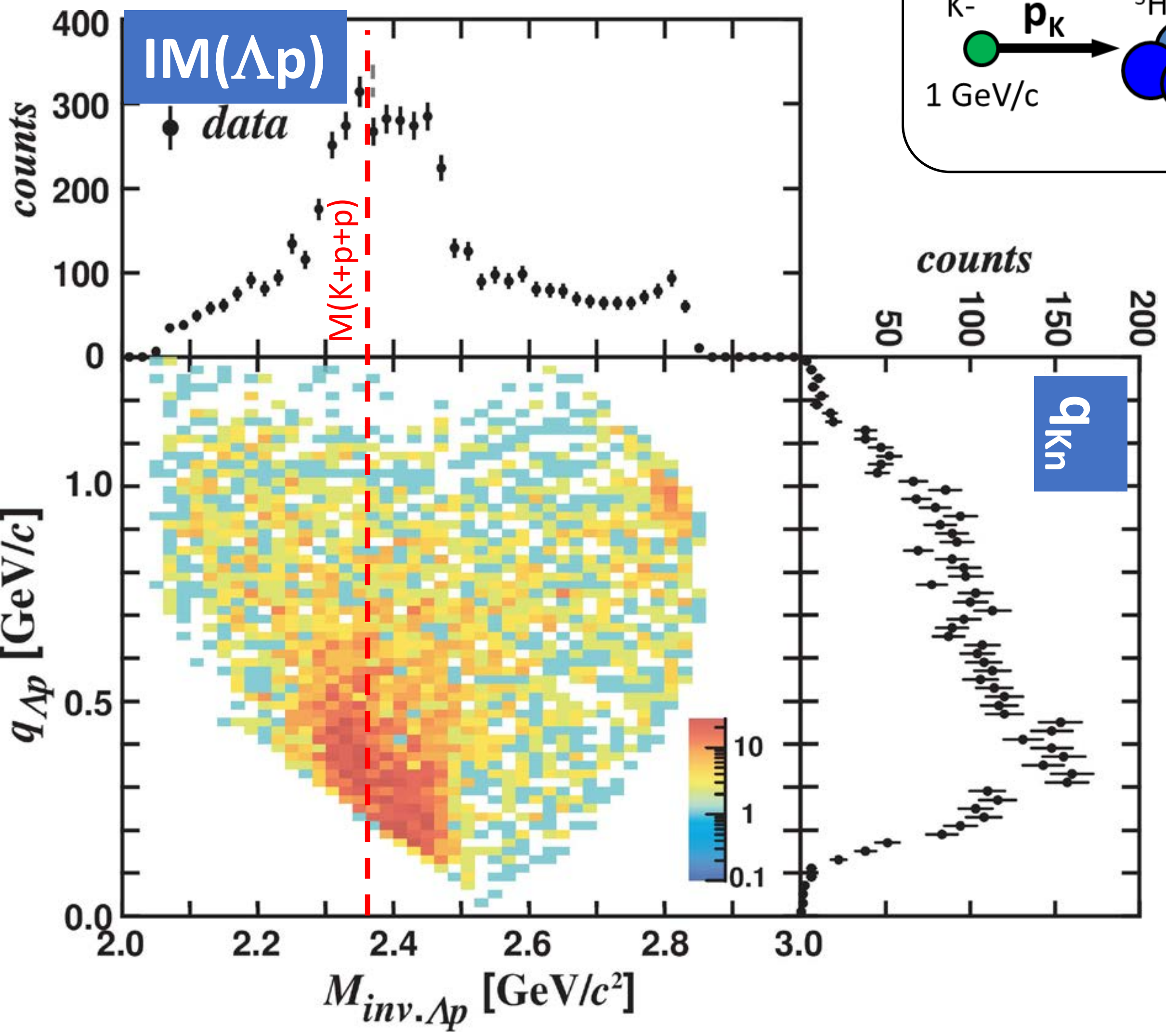


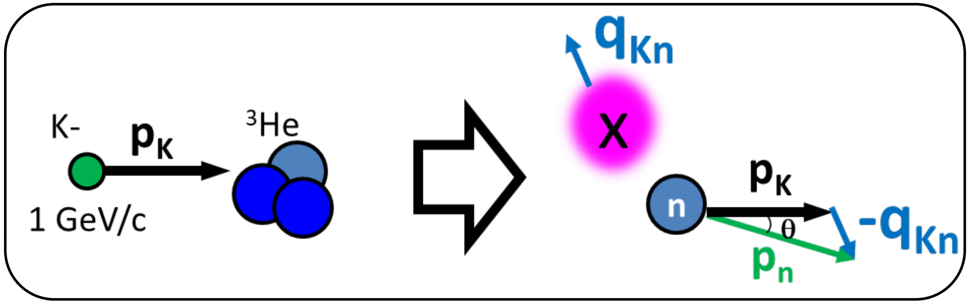
Λ reconstruction



IM(Λp) vs. Momentum Transfer q_{Kn}

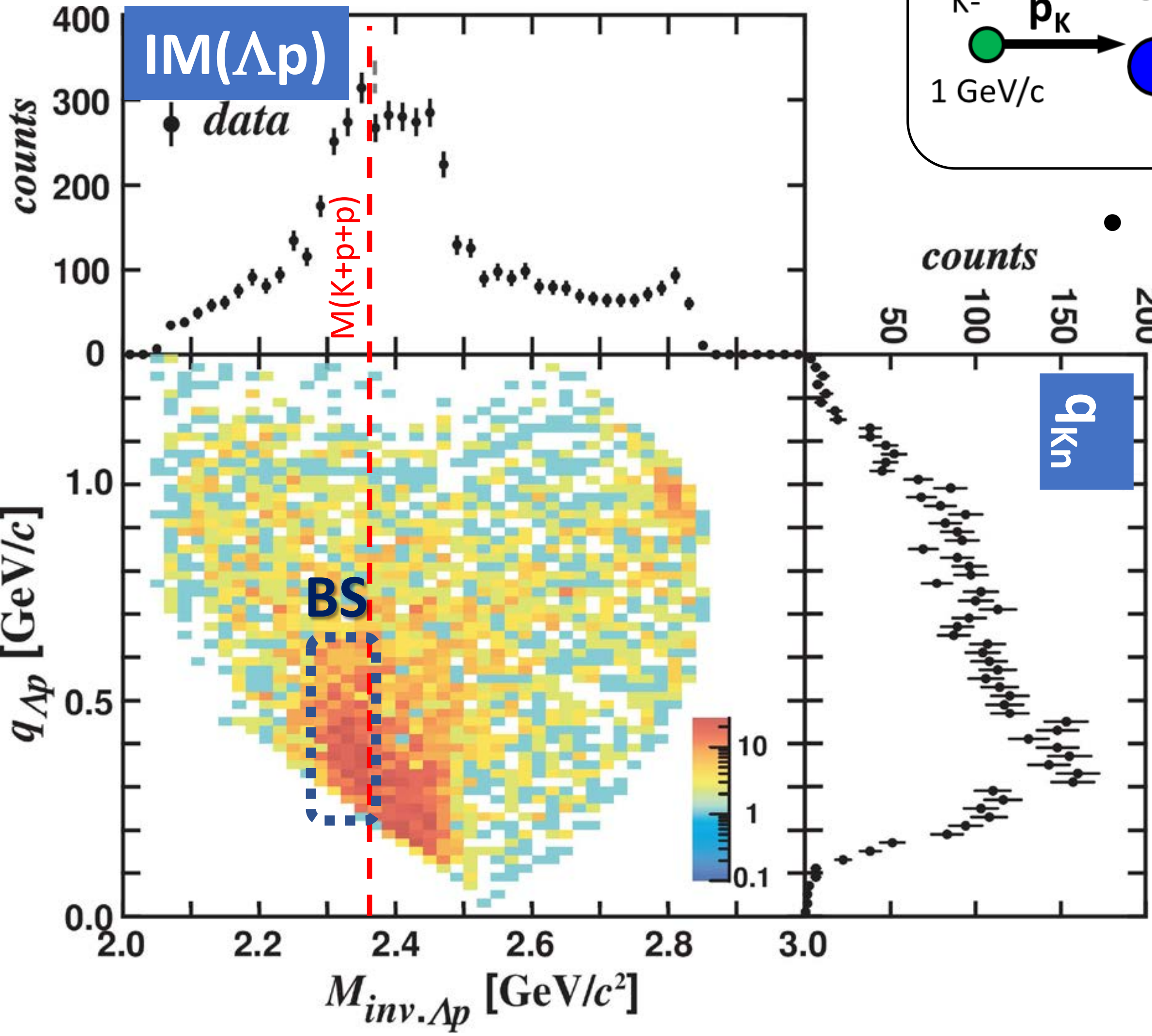
E15 collab., PLB789(2019)620.

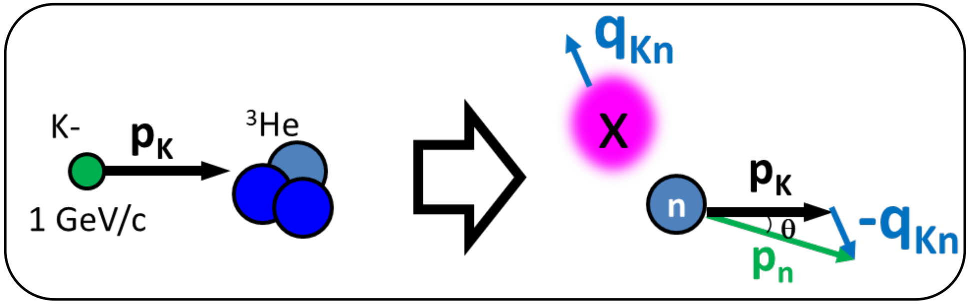




IM(Λp) vs. Momentum Transfer q_{Kn}

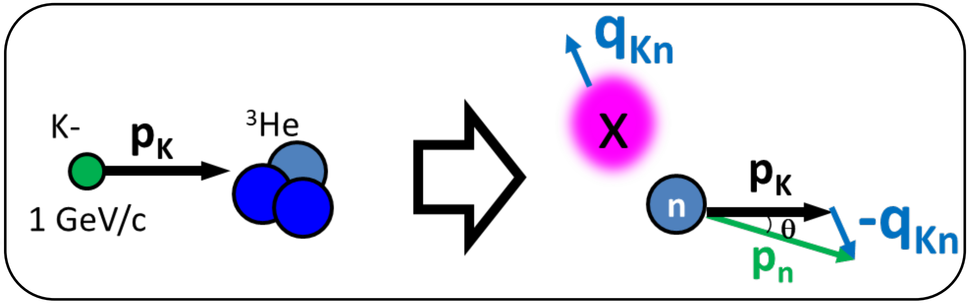
E15 collab., PLB789(2019)620.



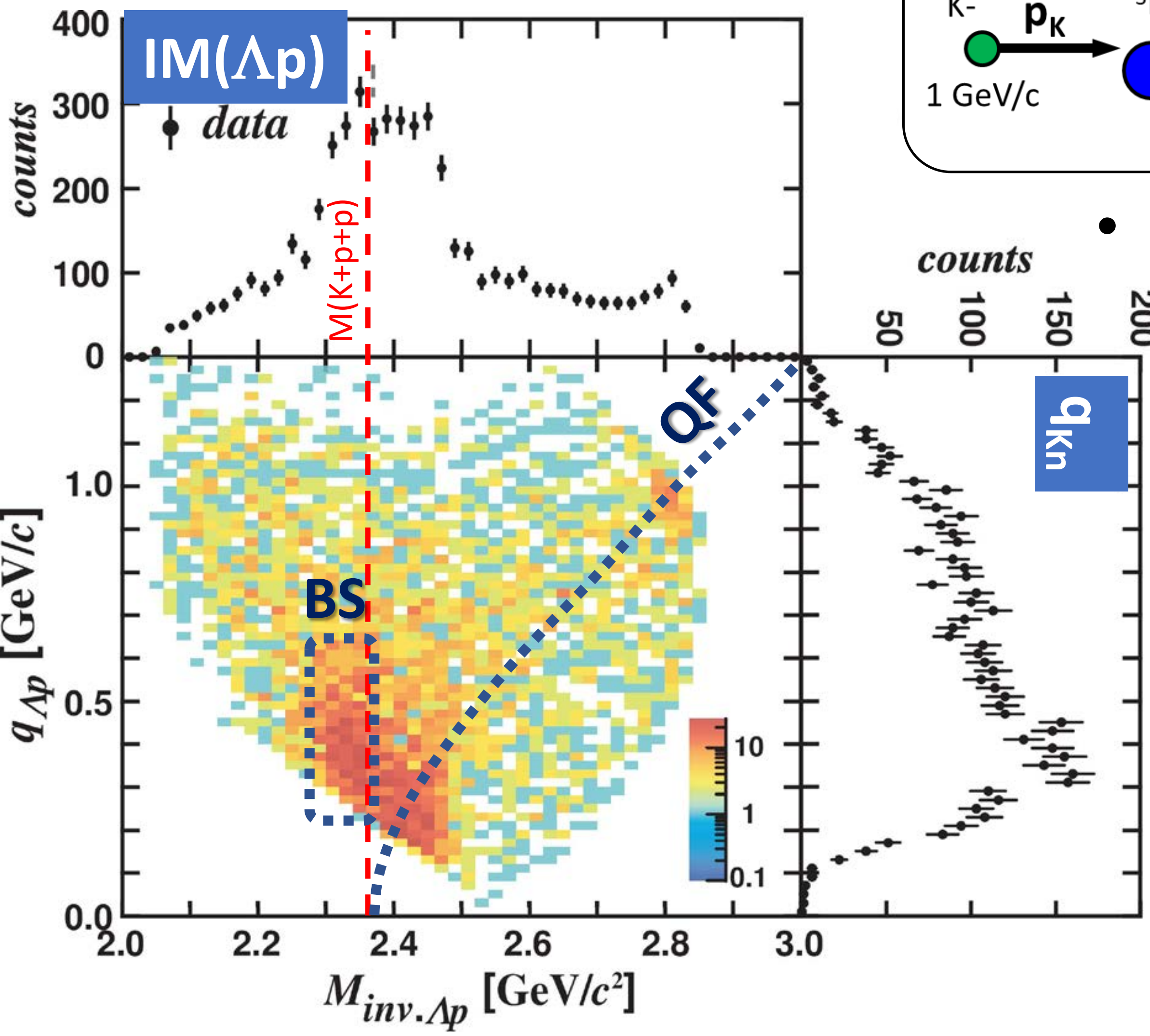


- Can be interpreted as 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**

IM(Λp) vs. Momentum Transfer q_{Kn}



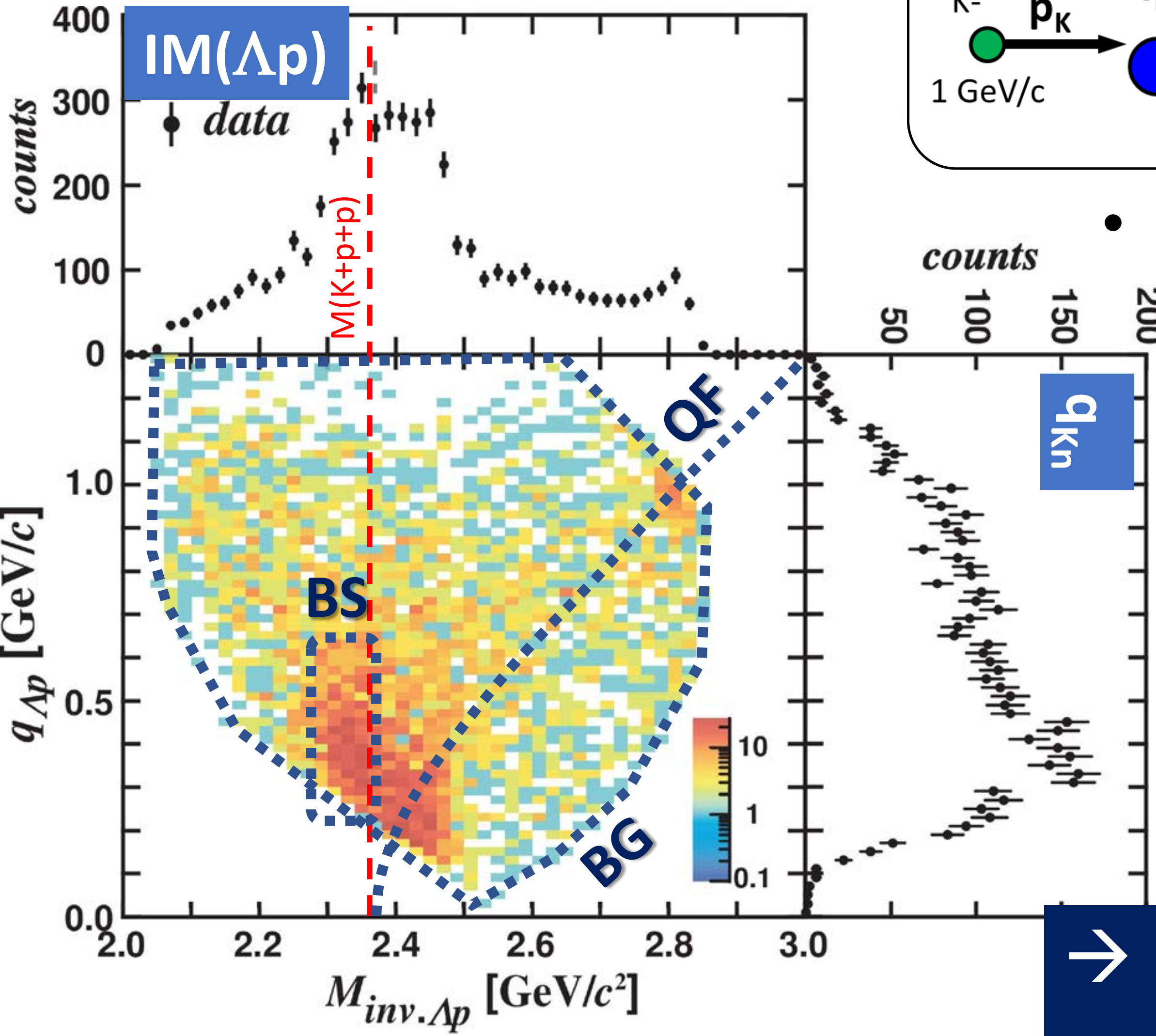
E15 collab., PLB789(2019)620.

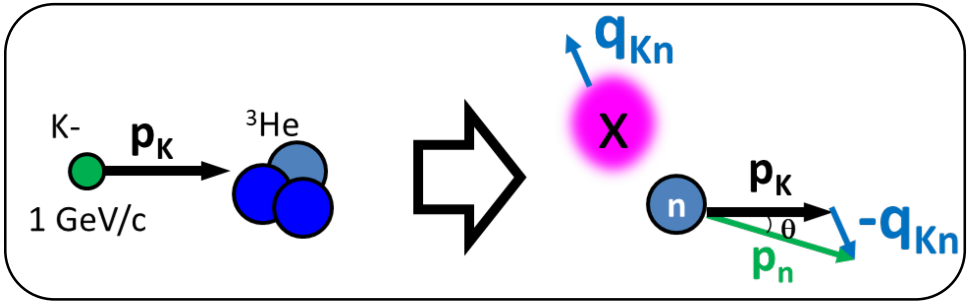


- Can be interpreted as 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**
  - **Quasi-elastic K^- abs.**
    - **centroid depends on q_{Kn}**

IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.

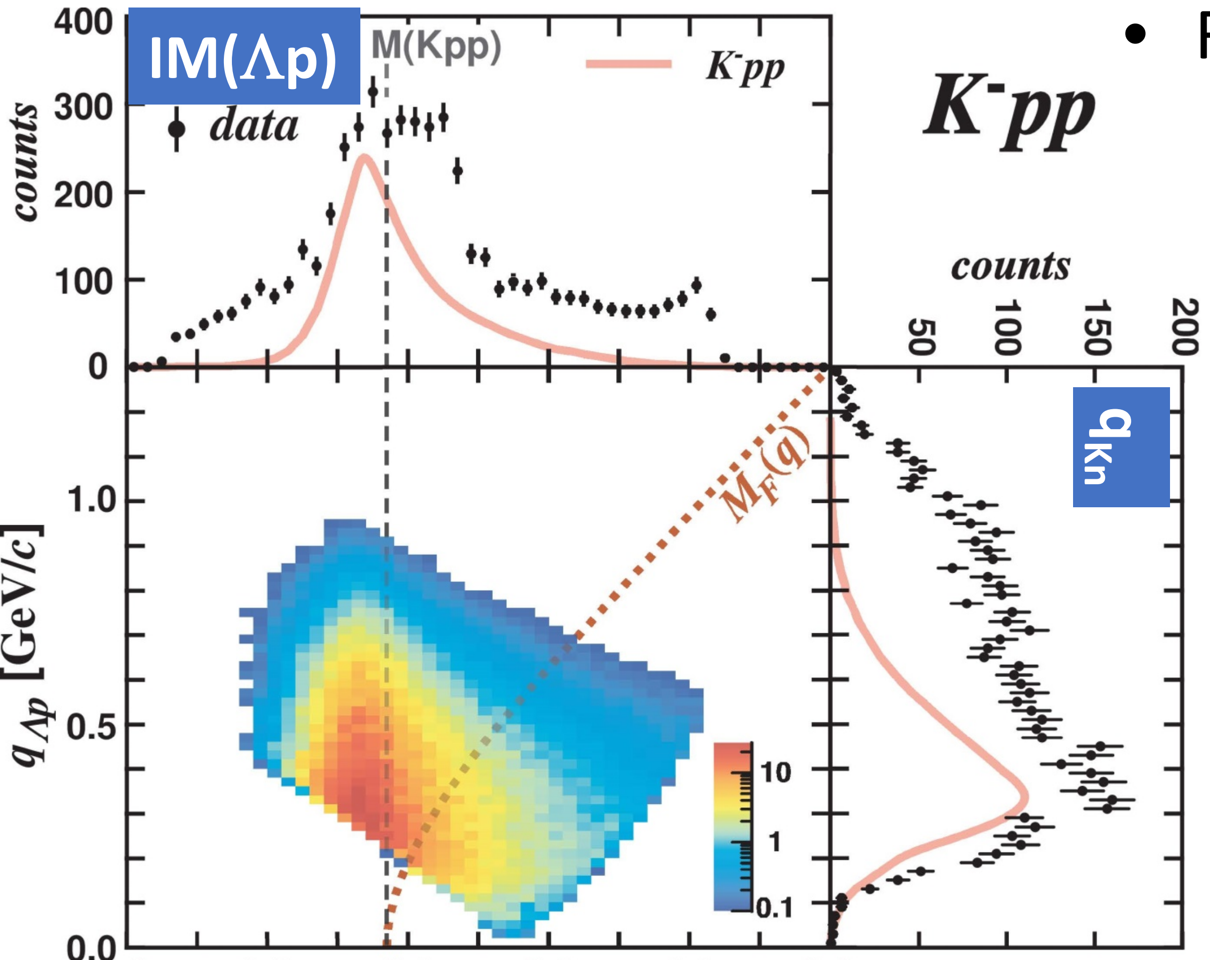




- Can be interpreted as 3 components
  - **Bound state**
    - centroid DOES NOT depend on q_{Kn}
  - **Quasi-elastic K^- abs.**
    - centroid depends on q_{Kn}
  - **Background**
    - Broad distribution

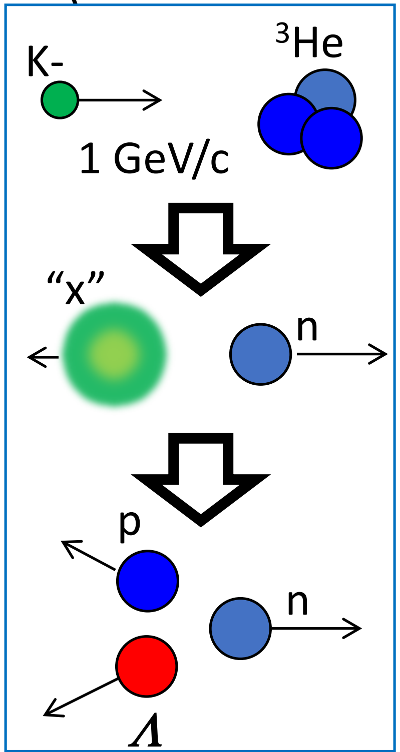
→ Fit the spectrum with 3 components

IM(Λp) vs. Momentum Transfer q_{Kn}



E15 collab., PLB789(2019)620.

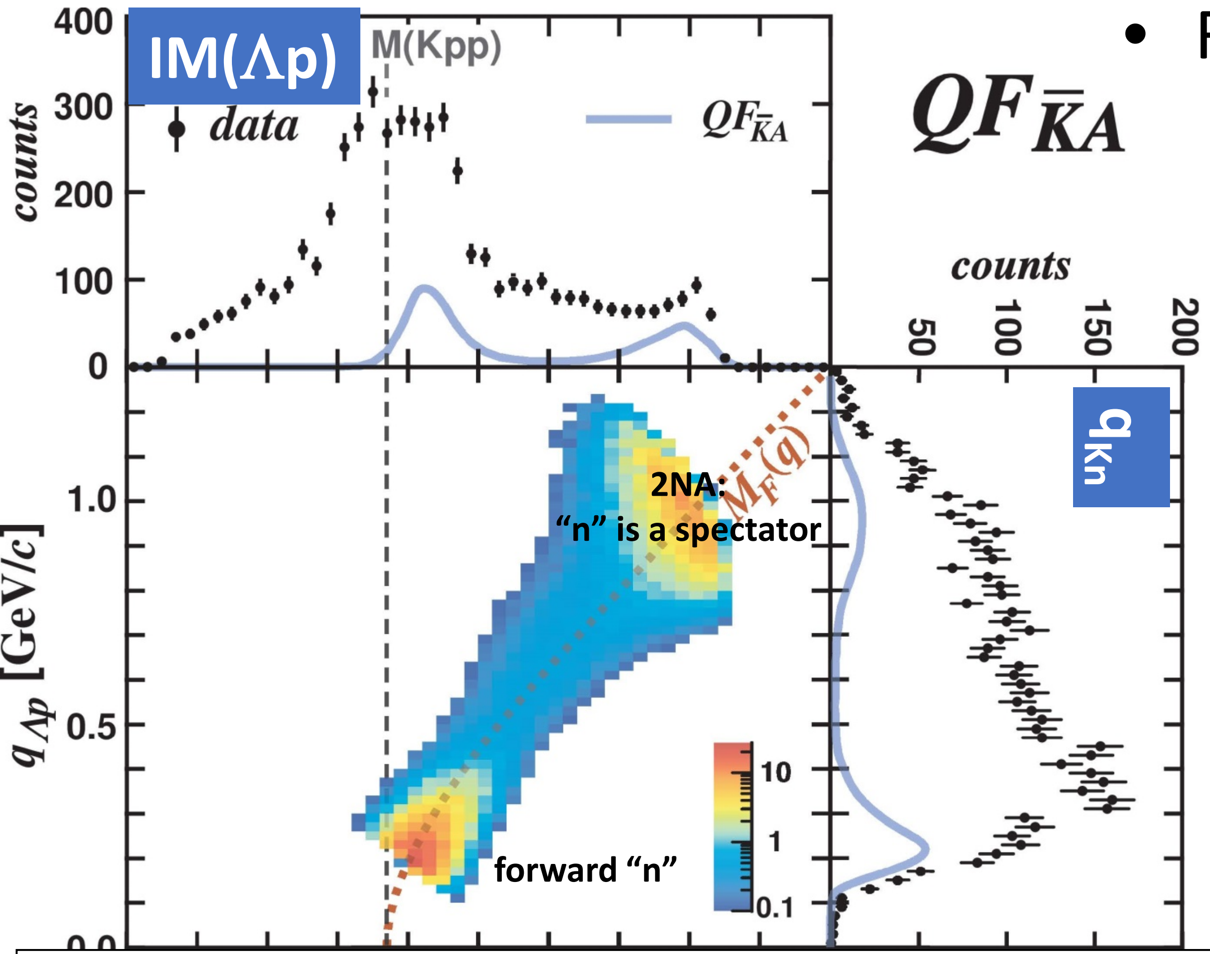
- Fit with 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**
    - BW*(Gauss form-factor)



$$f_{\{Kpp\}}(M,q) = \frac{A_{Kpp}\,(\Gamma_{Kpp}/2)^2}{(M - M_{Kpp})^2 + (\Gamma_{Kpp}/2)^2}\, e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

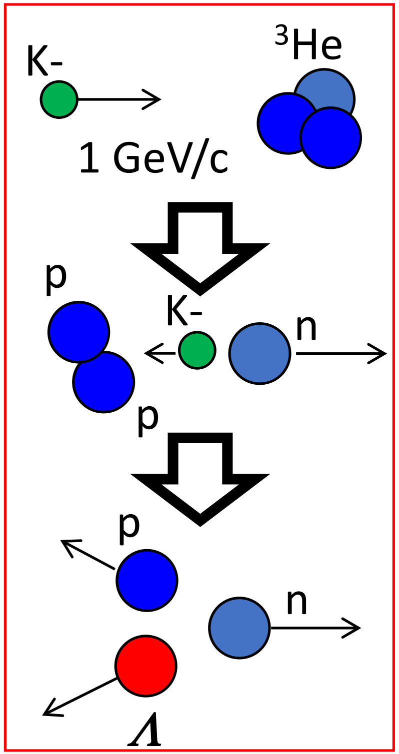
IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.



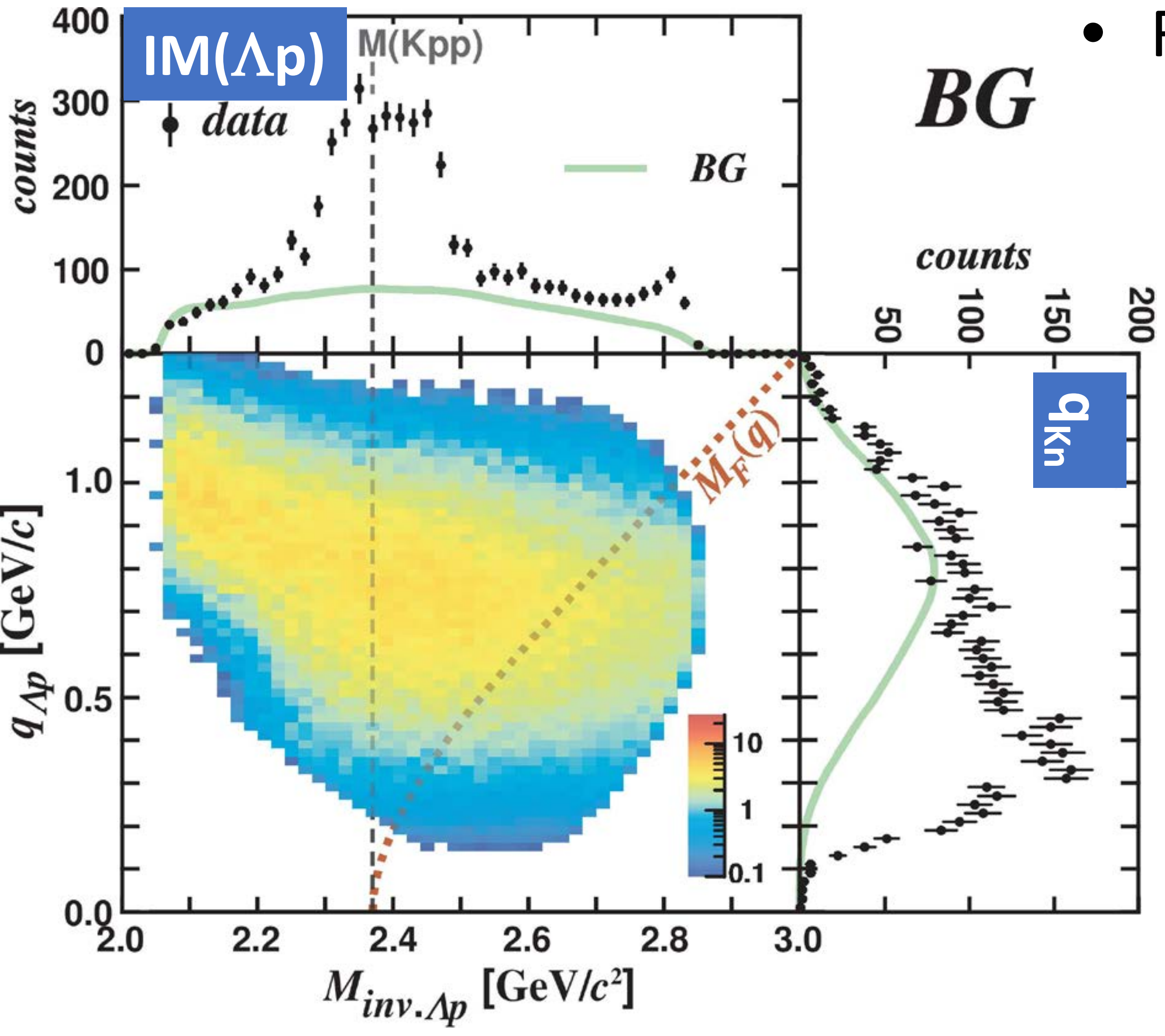
$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

- Fit with 3 components
  - **Quasi-elastic K^- abs.**
    - **centroid depends on q_{Kn}**
    - Followed by Λp conversion

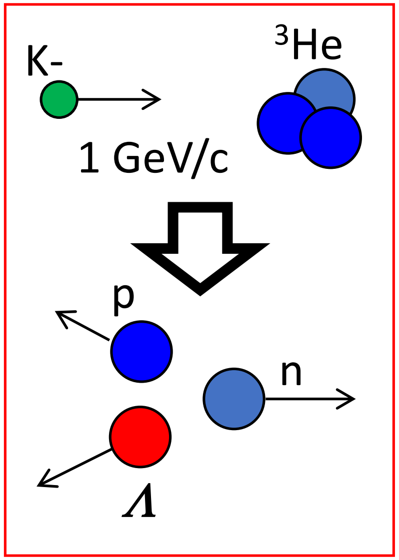


IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.

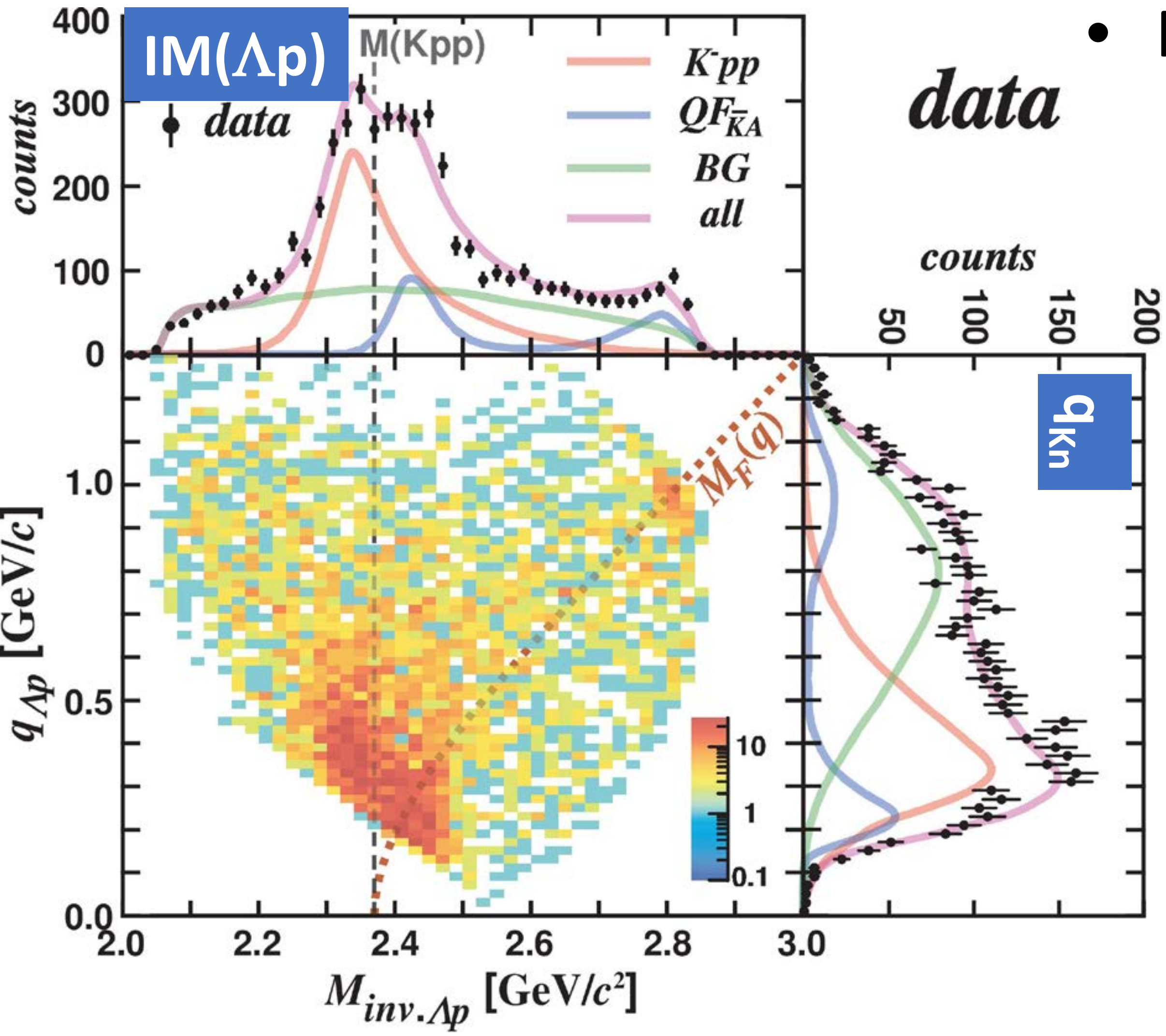


- Fit with 3 components
  - **Background**
    - Broad distribution



IM(Λp) vs. Momentum Transfer q_{Kn}

E15 collab., PLB789(2019)620.



- Fit with 3 components
  - **Bound state**
    - **centroid DOES NOT depend on q_{Kn}**
    - BW*(Gauss form-factor)

$$f_{\{Kpp\}}(M,q)=\frac{A_{Kpp}\ (\Gamma_{Kpp}/2)^2}{(M-M_{Kpp})^2+(\Gamma_{Kpp}/2)^2}\,e^{-\left(\frac{q}{Q_{Kpp}}\right)^2},$$

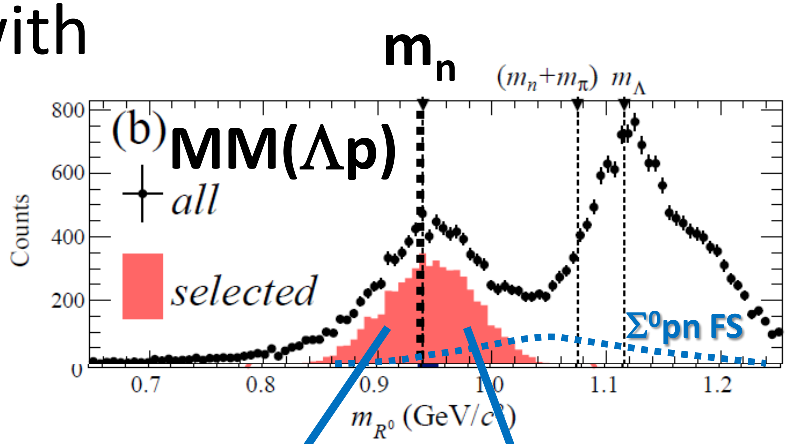
  - **Quasi-elastic K⁻ abs.**
    - **centroid depends on q_{Kn}**
    - Followed by Λp conversion

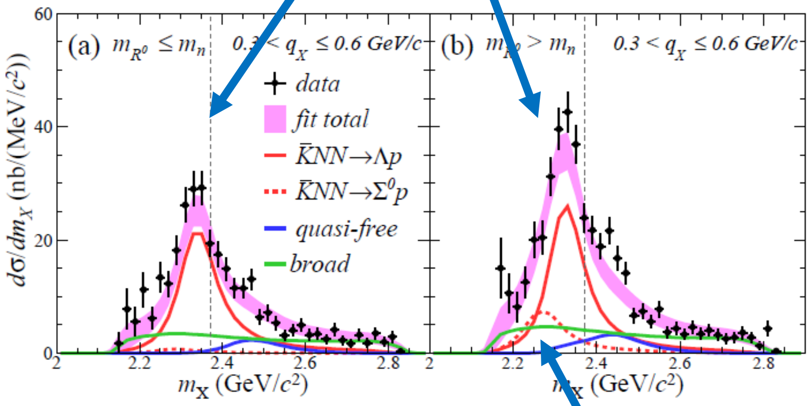
$$M_F(q)=\sqrt{4m_N^2+m_K^2+4m_N\sqrt{m_K^2+q^2}},$$

  - **Background**
    - Broad distribution

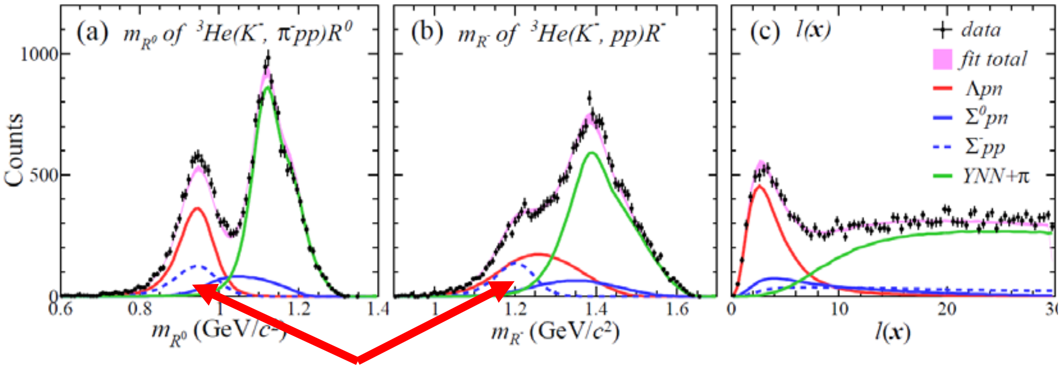
arXiv:2006.13433 (submitted to PRC)

- We have improved the analysis with
  - $\Sigma^0 pn$ channel
  - $\Sigma^- pp$ background
- Parameters have been updated
  - consistent with previous values



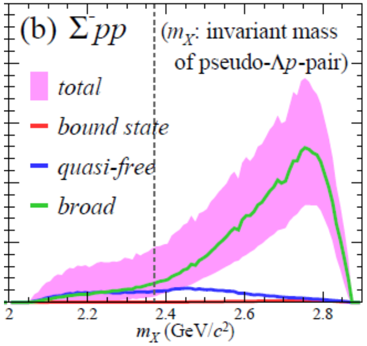


$\Sigma^0 pn$ FS



$\Sigma^- pp$ FS

No structure below M(Kpp)

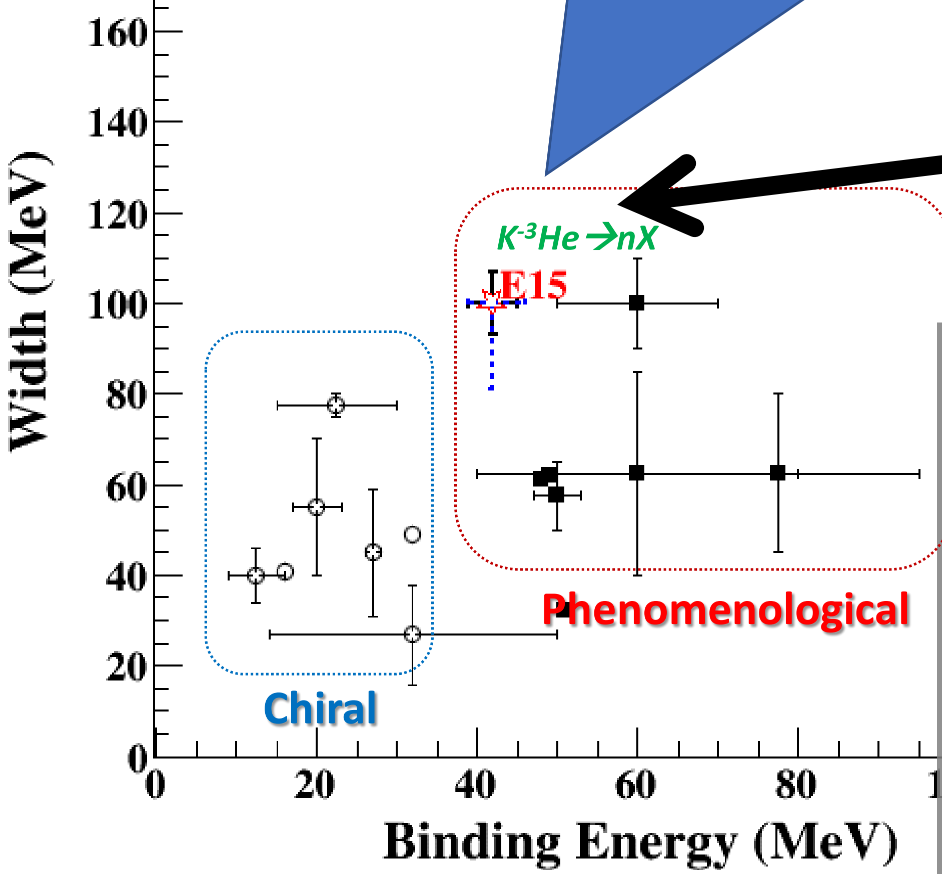


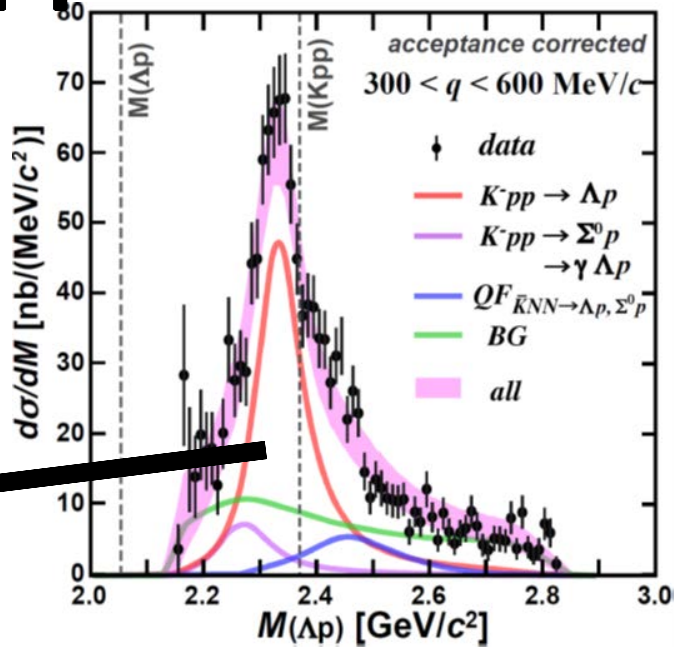
Spectrum above m_n in MM(Λp) is well reproduced with inclusion of the Σ^0pn channel

Observed “K$^-$pp”

the most reliable observation

- simple K- induced reaction
- exclusive measurement
- good BG separation from 2NA





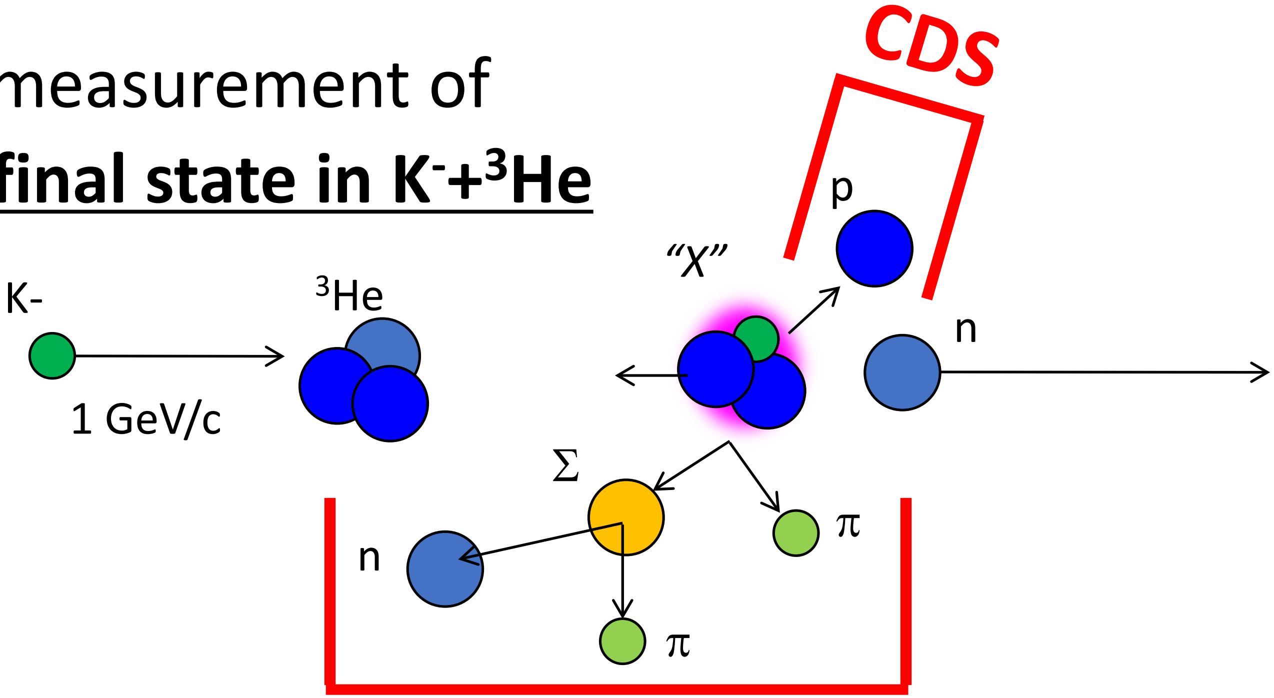
- **Binding energy: ~40 MeV**
  - Deeper than chiral-SU(3) based theoretical predictions
- **Width: ~100 MeV**
  - Seems to be larger than theoretical calculations (mesonic πY decays only)

We need further understanding

- **Spin/Parity of the “K^-pp”**
  - *New 4π detector system is needed*
- **Other decay channels** $K^-\ {}^3He \rightarrow \pi\Sigma pn$
  - **$\pi\Sigma$N mesonic decay** is theoretically expected to be the dominant channel
    - Only YN non-mesonic decays were reported
- **Reaction mechanism**
  - Relation between Λ(1405) & “K^-pp”
    - Λ(1405) has been considered as **“K^-p”**
    - Theoretically, “K^-pp” is expected to be produced via **Λ(1405)+p→”K^-pp” door-way process**

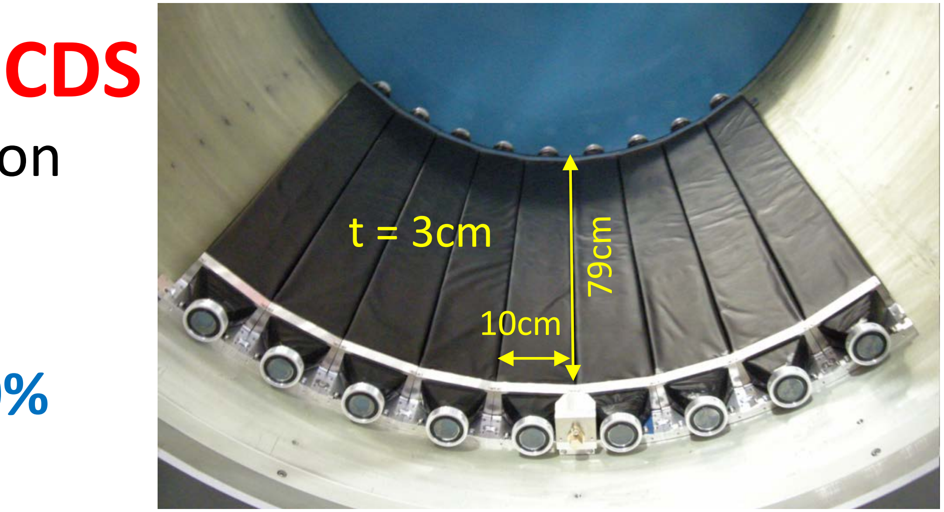
$K^{-}\ {}^{3}He \rightarrow \pi\Sigma pn$ Measurement

- Exclusive measurement of **$\pi^{\pm}\Sigma^{\mp}pn$ final state in $K^{-}+{}^{3}He$**



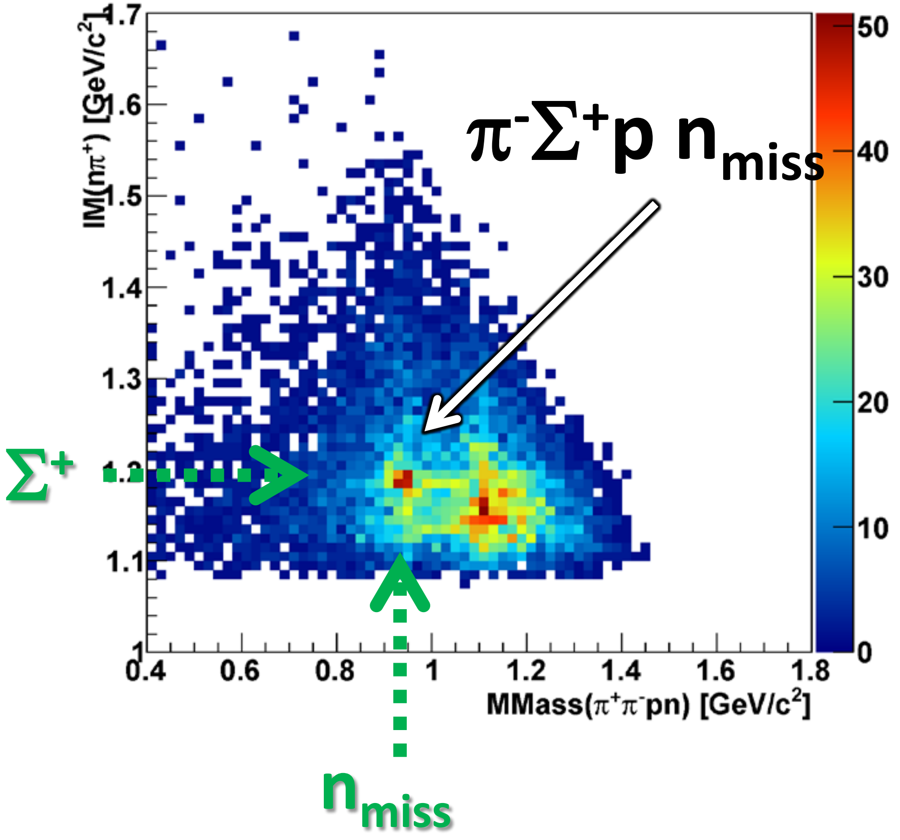
- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

  n detection efficiency ~ 3-10%

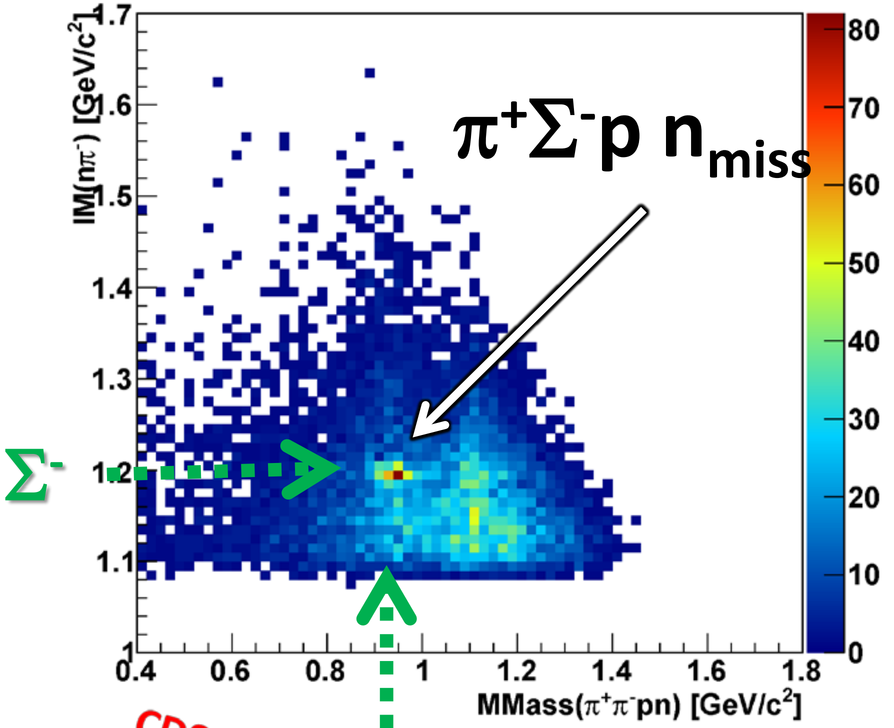


$\pi\Sigma pn$ Events

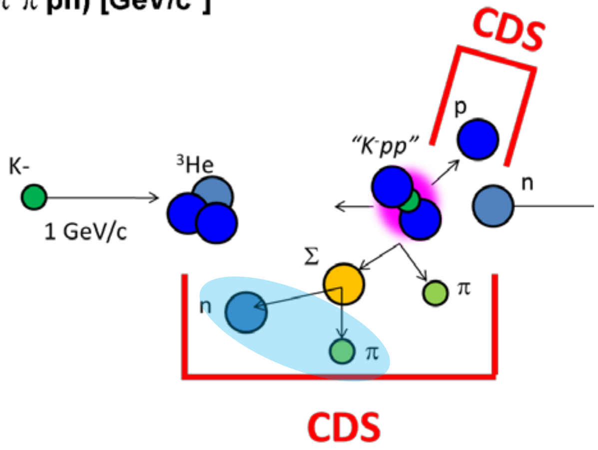
IM($n\pi^+$) vs MM($\pi^+\pi^-pn$)



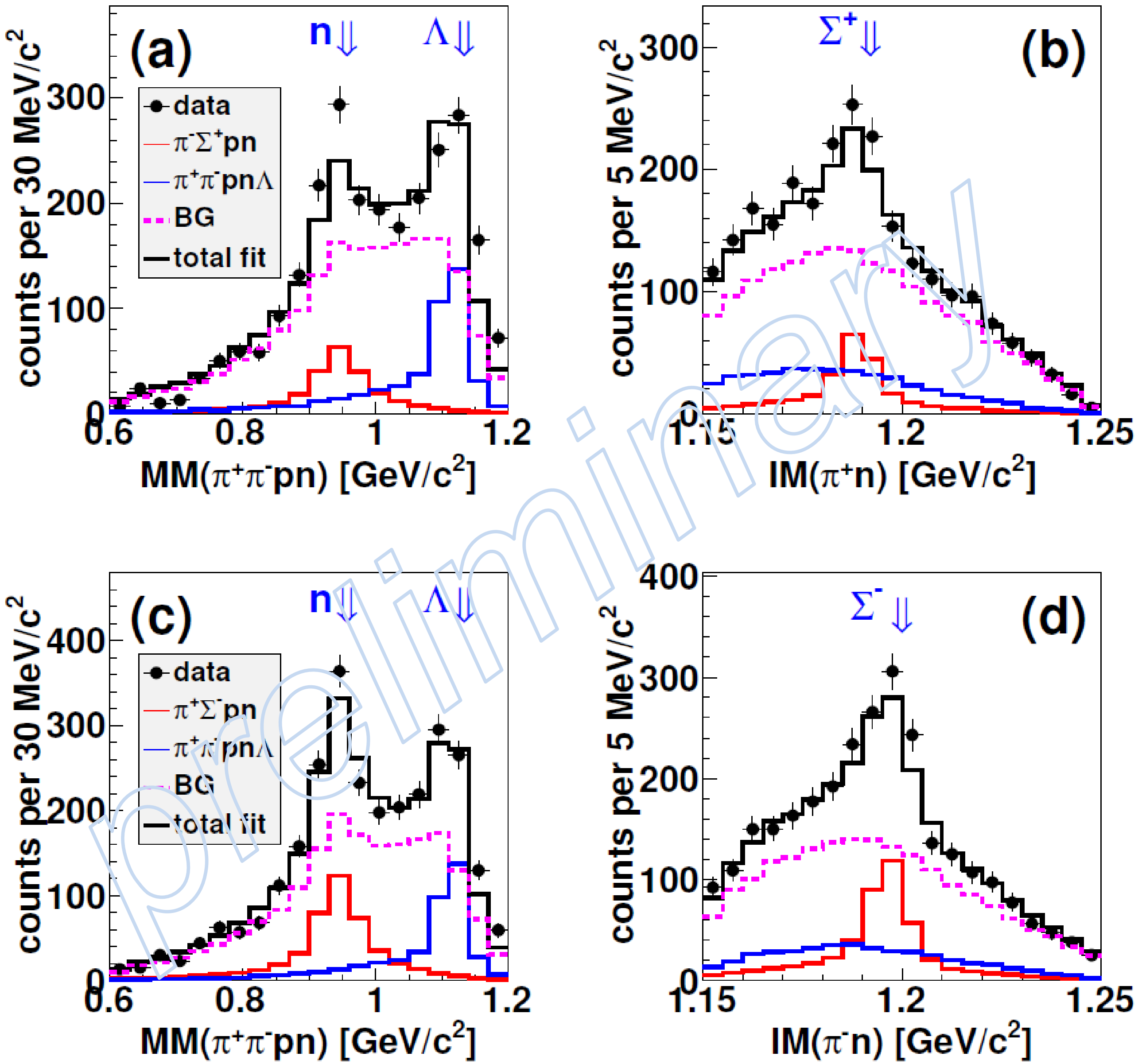
IM($n\pi^-$) vs MM($\pi^+\pi^-pn$)



n_{miss}



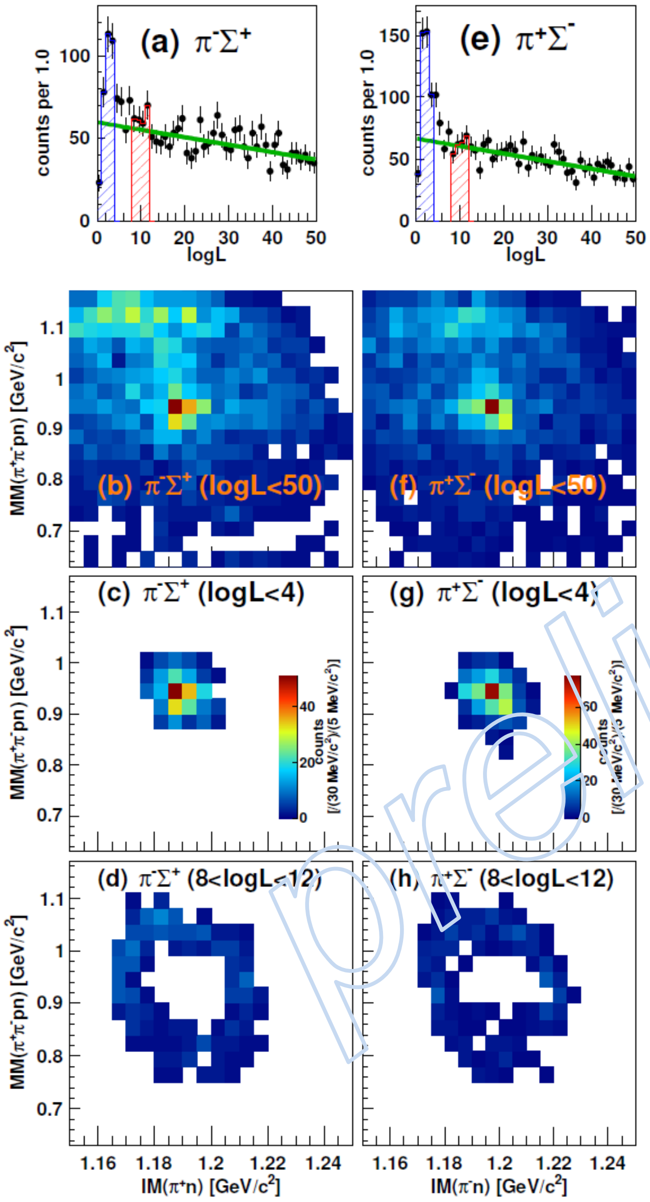
$\pi\Sigma pn$ Identification

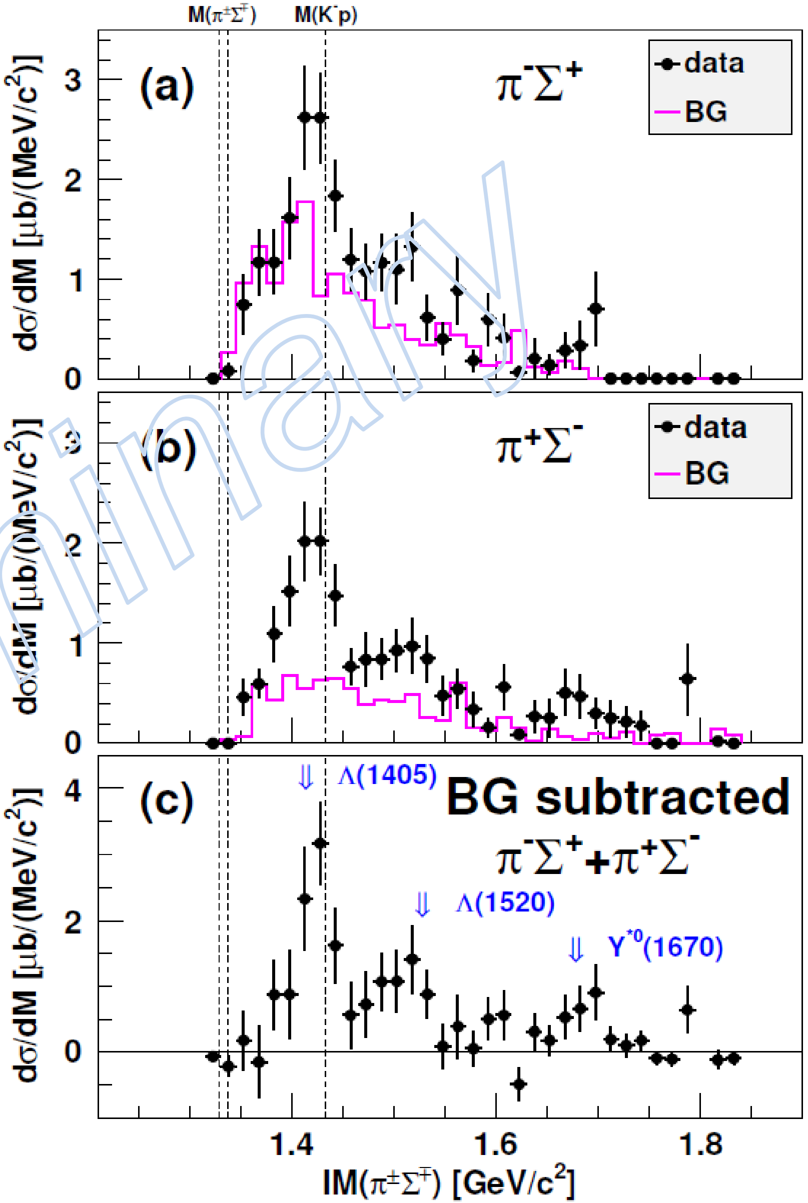


$\pi^-\Sigma^+p\ n_{miss}$

$\pi^+\Sigma^-p\ n_{miss}$

BG Subtracted IM($\pi^{\pm}\Sigma^{\mp}$) in $\pi^{\pm}\Sigma^{\mp}pn$



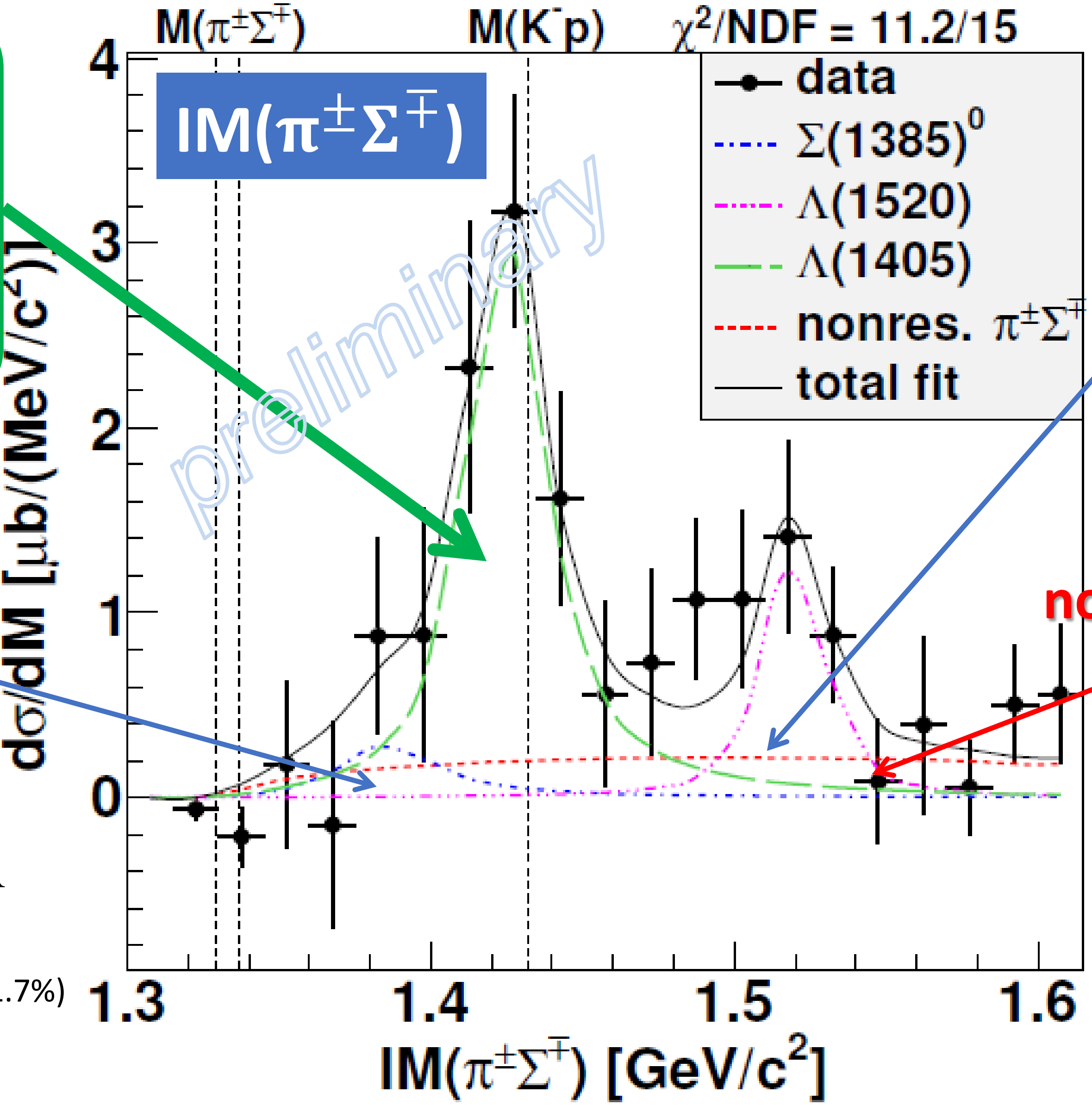


$Y^{*}pn$ Final State

$\Lambda(1405)$

~ 200 μb

Fit with BW:
M ~ 1425 MeV
Γ ~ 30 MeV



$\Lambda(1520)$

~ 100 μb

πΣpn non-resonant

$\Sigma(1385)^{0}$

~ 90-160 μb

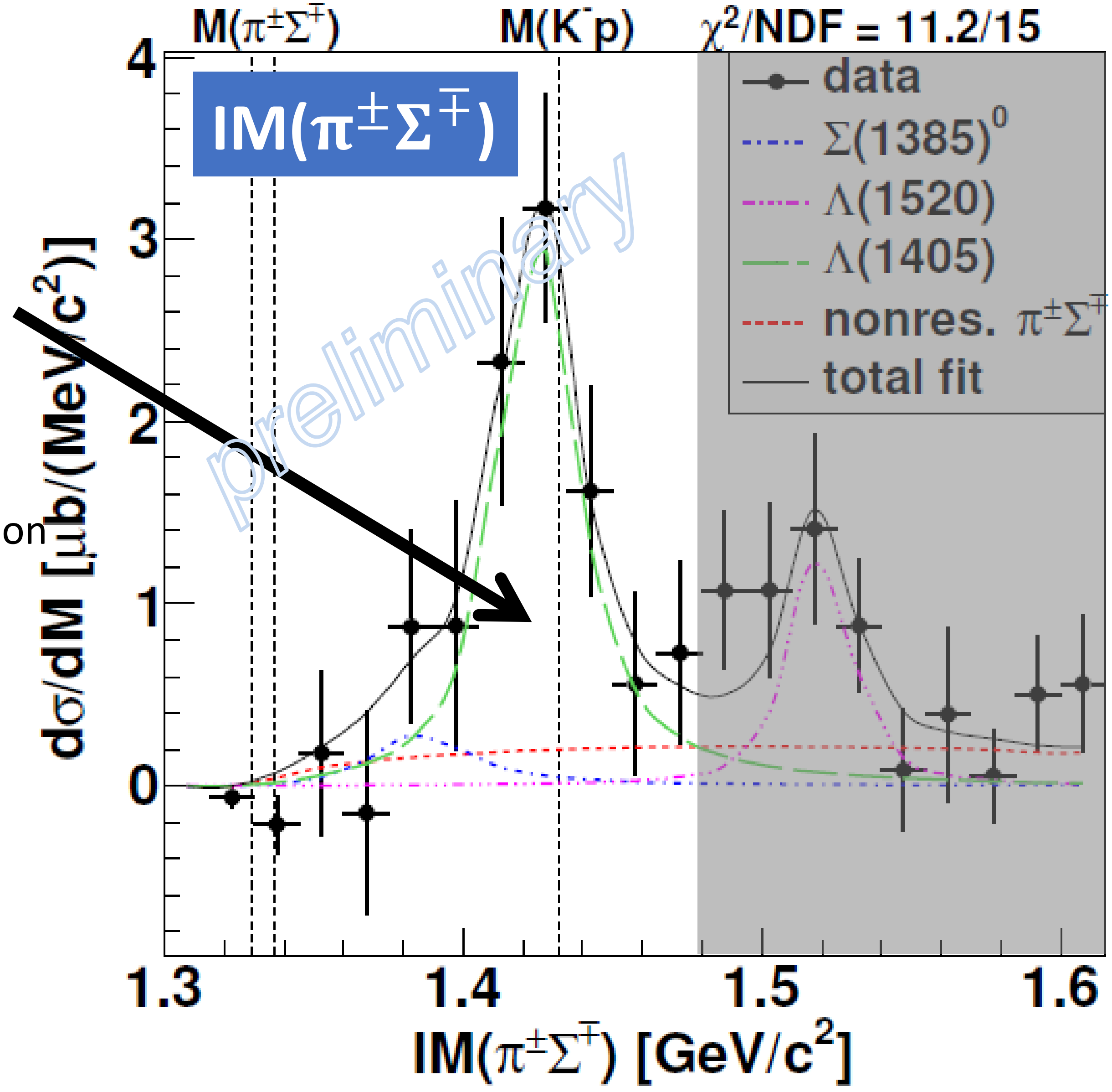
[evaluated from $\Sigma(1385)^{+/-} \rightarrow \pi^{+/-}\Lambda$ measurement]

($\Sigma(1385) \rightarrow \pi\Lambda/\pi\Sigma$: 87.0/11.7%)

$\Lambda(1405)pn$ Final State Selection

Select $\Lambda(1405)$ region

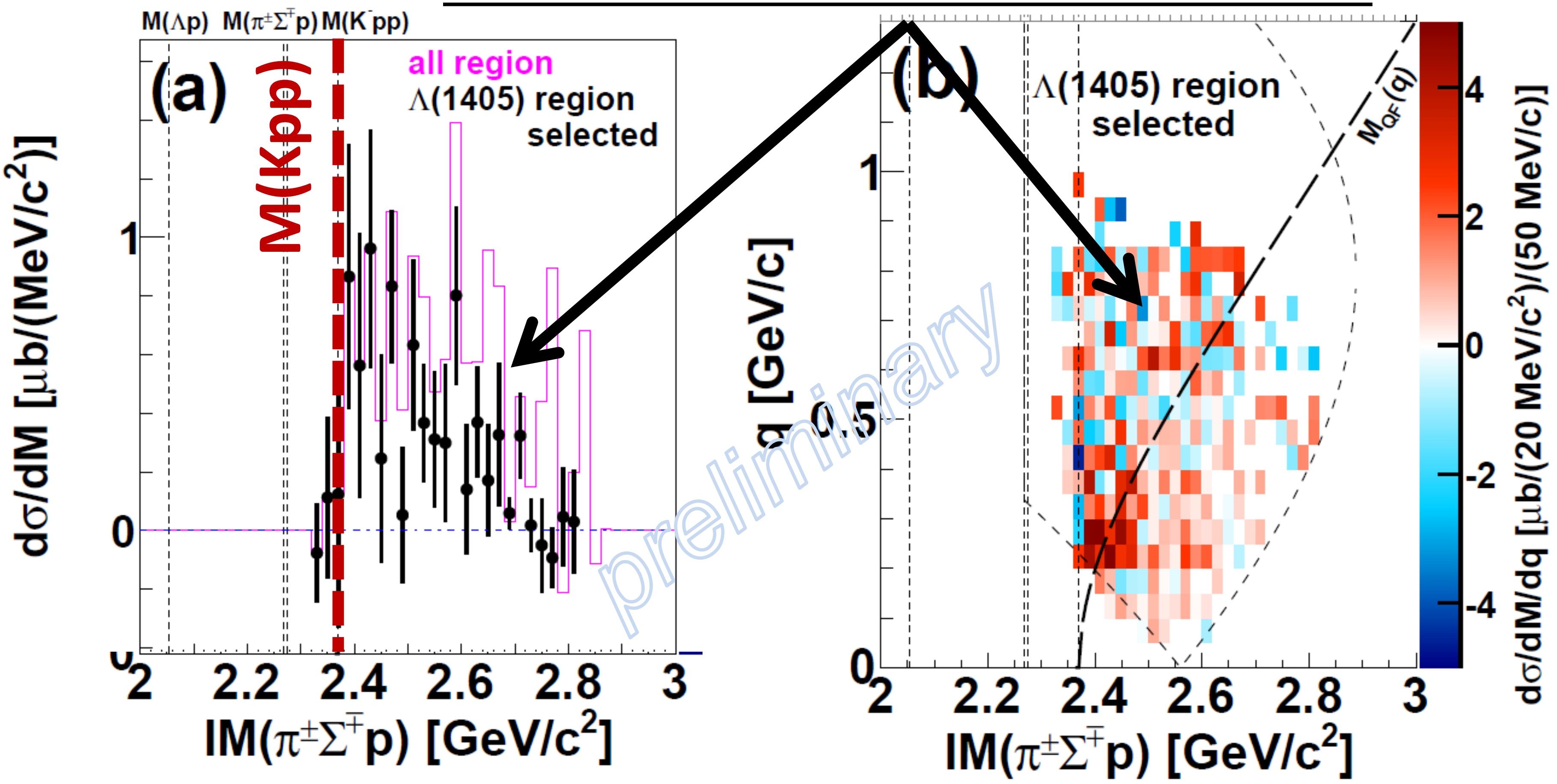
- Below $\Lambda(1520)$
- Small contribution from $\Sigma(1385)$



IM(πΣp) in Λ(1405)pn Final State

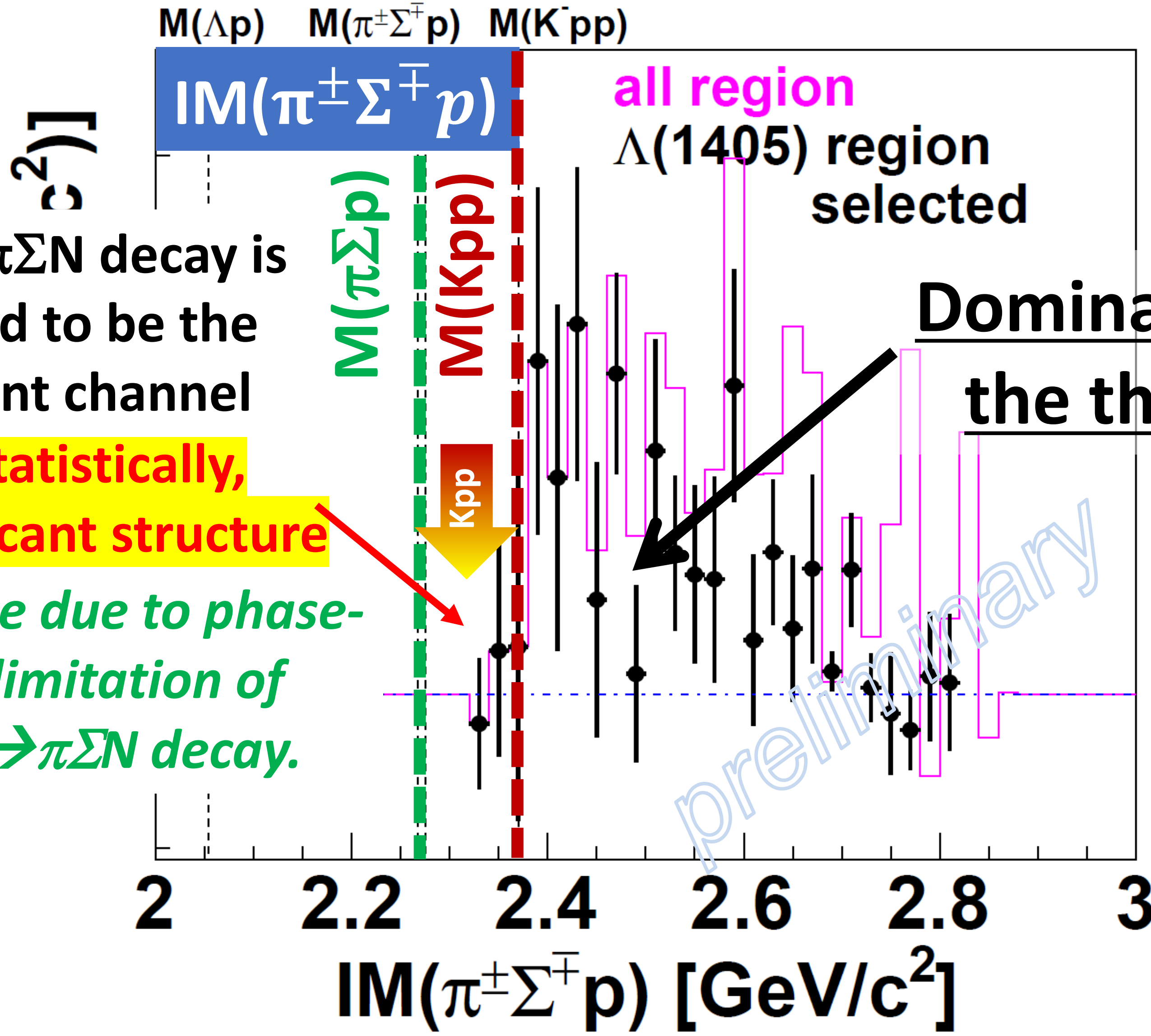
IM($\pi^{\pm}\Sigma^{\mp}p$)

Dominant above the threshold



- IM(Λ(1405)p) distributes above the M(Kpp)
- QF $K^{-}N \rightarrow K^{bar}n$ followed by $K^{bar}NN \rightarrow \Lambda(1405)p$

“Kpp”→πΣp Decay?



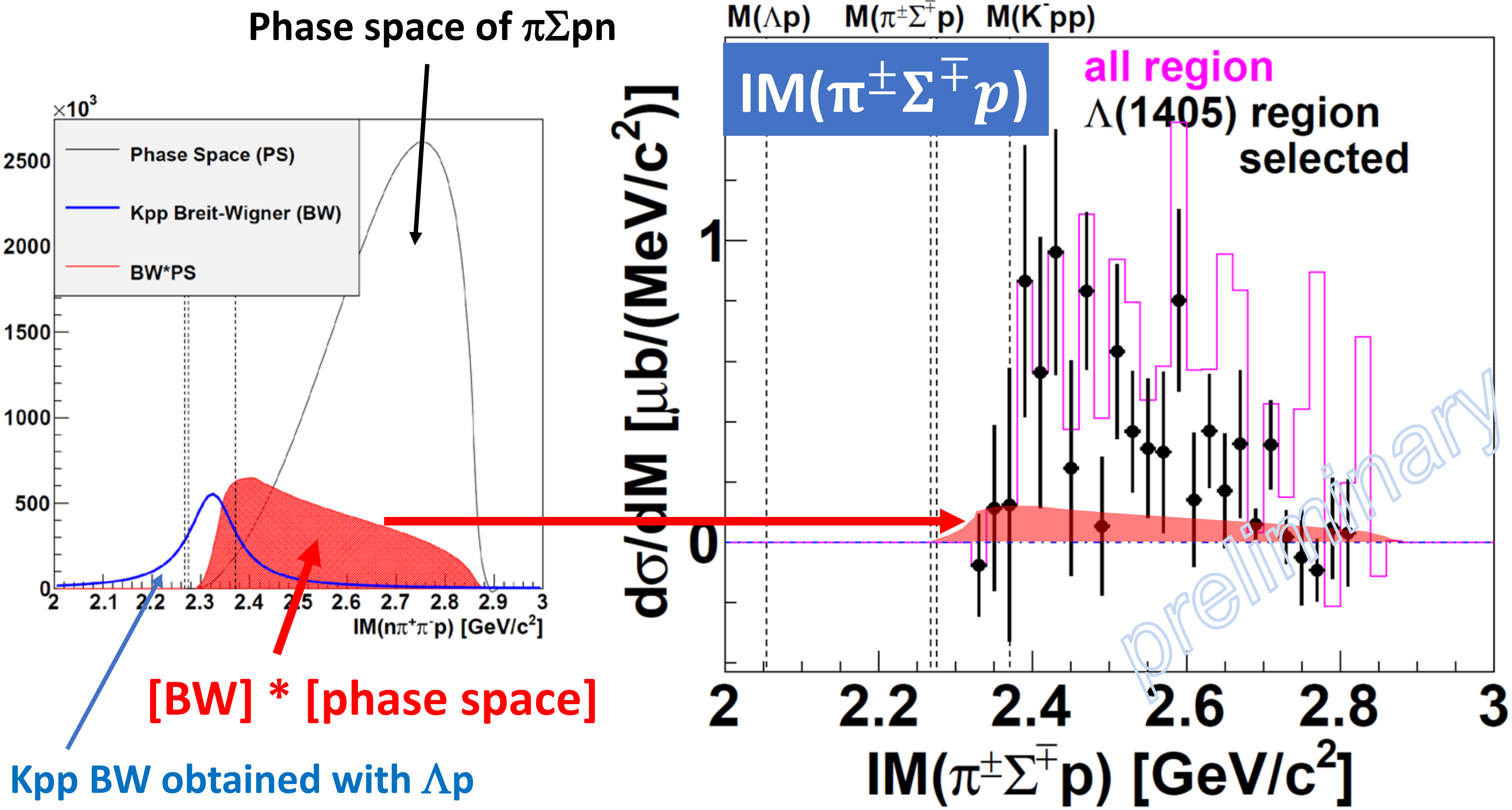
“Kpp”→πΣN decay is expected to be the dominant channel

BUT, statistically,
NO significant structure

This will be due to phase-space limitation of “K⁻pp”→πΣN decay.

Dominant above the threshold

PS Limitation of “K⁻pp”→πΣp Decay

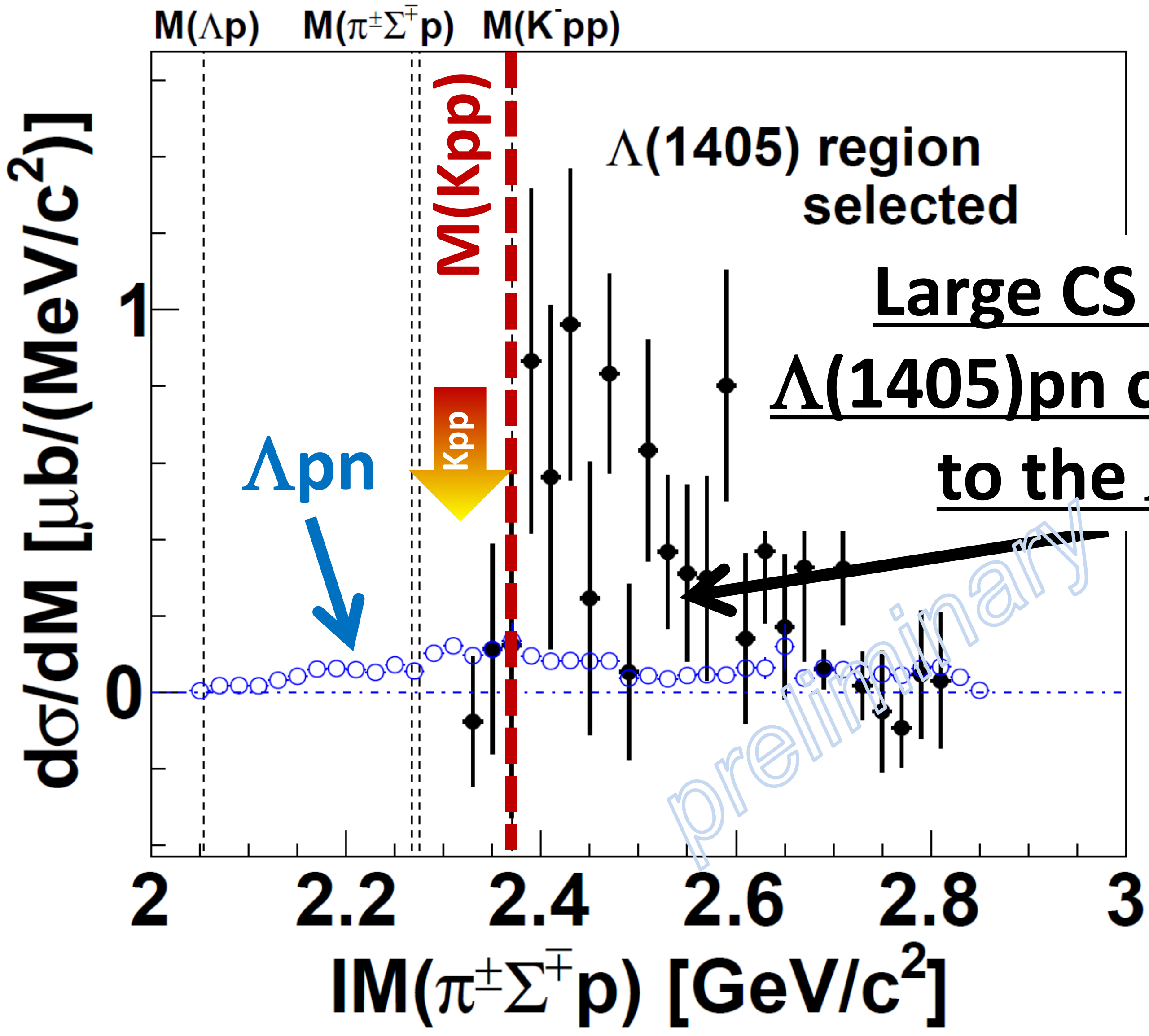


Phase space of πΣpn

[BW] * [phase space]

Kpp BW obtained with Λp

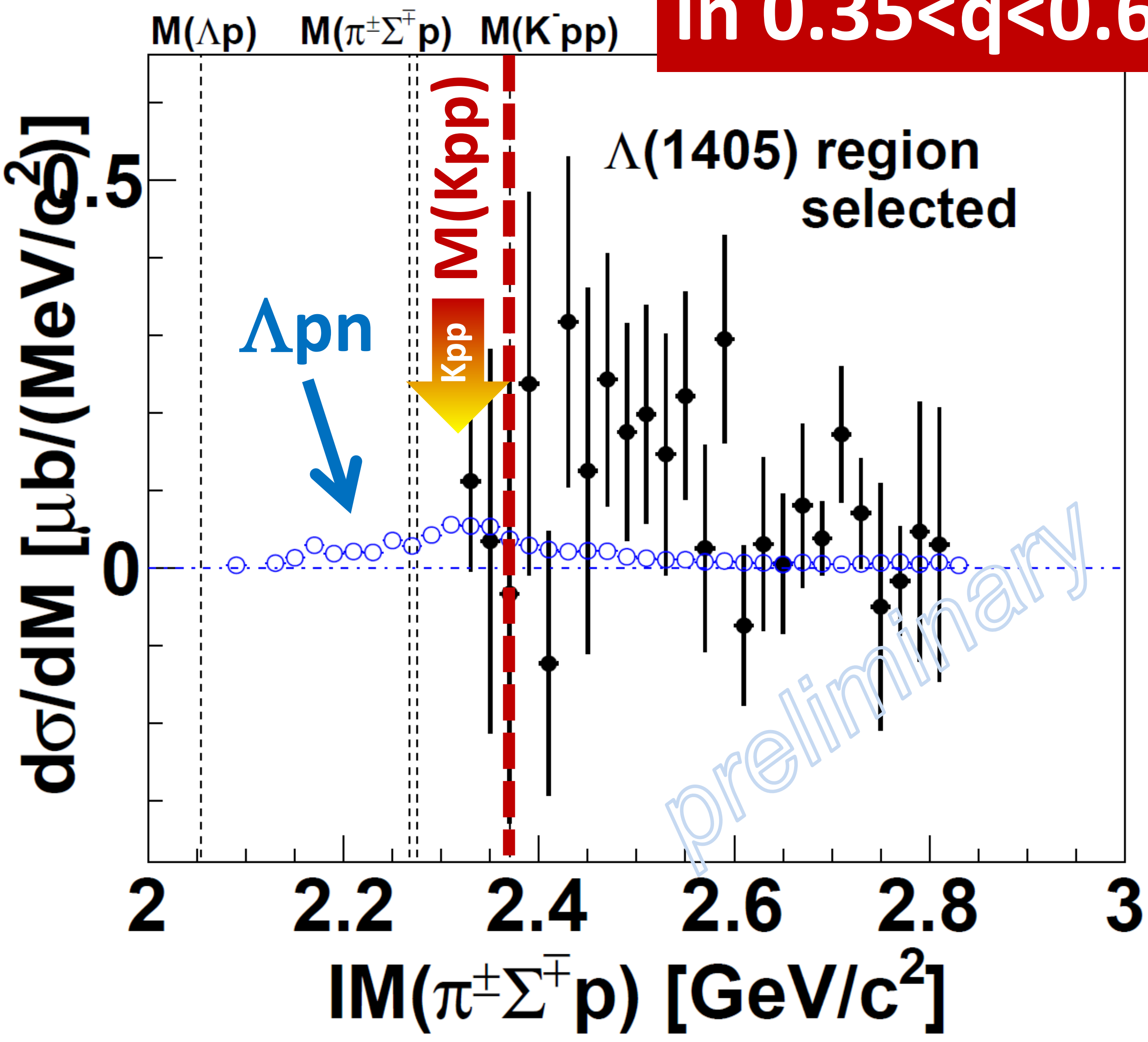
Comparison of Λpn & Λ(1405)pn



Large CS of the Λ(1405)pn compared to the Λpn

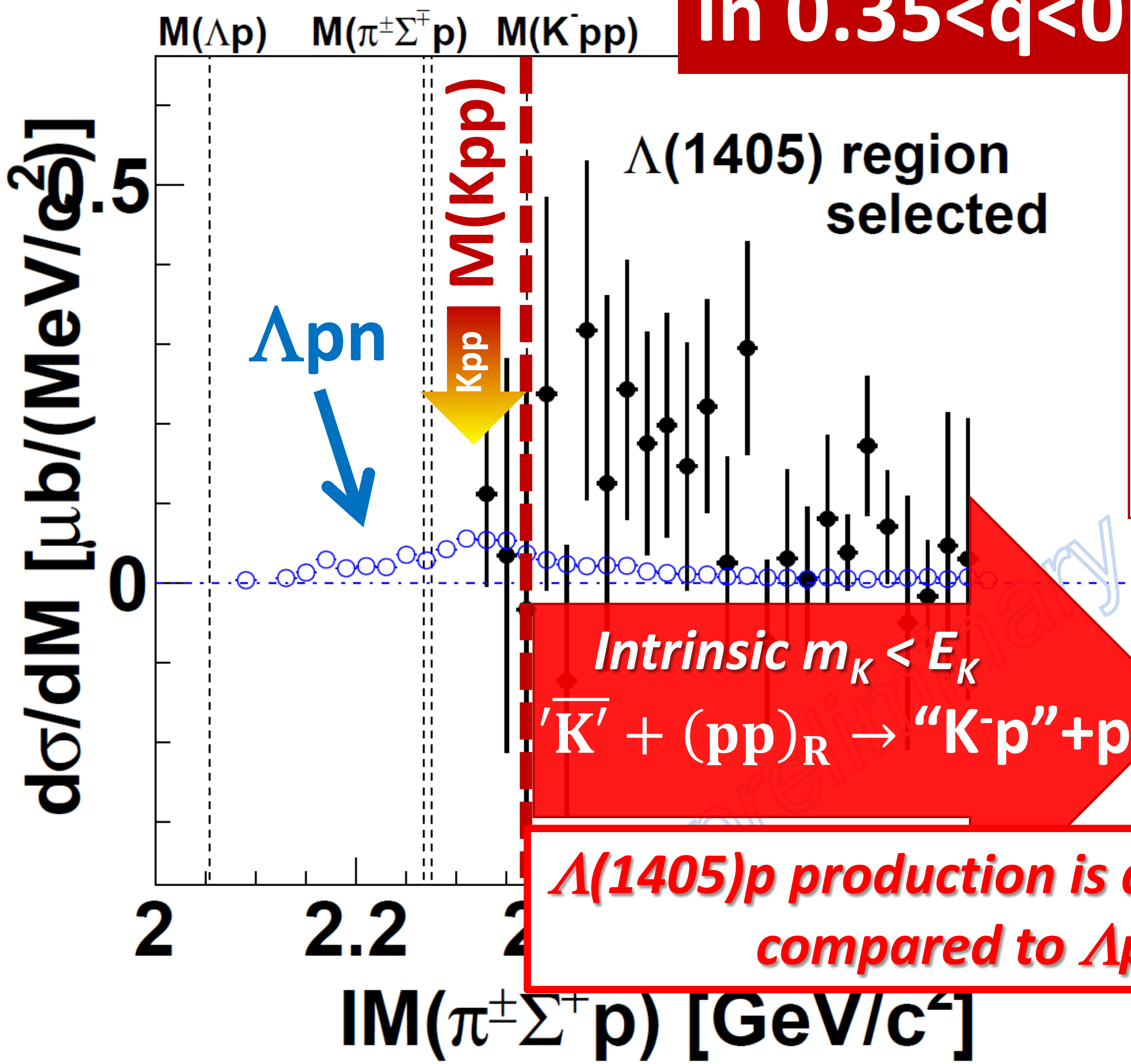
Comparison of Λpn & Λ(1405)pn

in 0.35<q<0.65 GeV/c



Comparison of Λpn & Λ(140

in 0.35<q<0

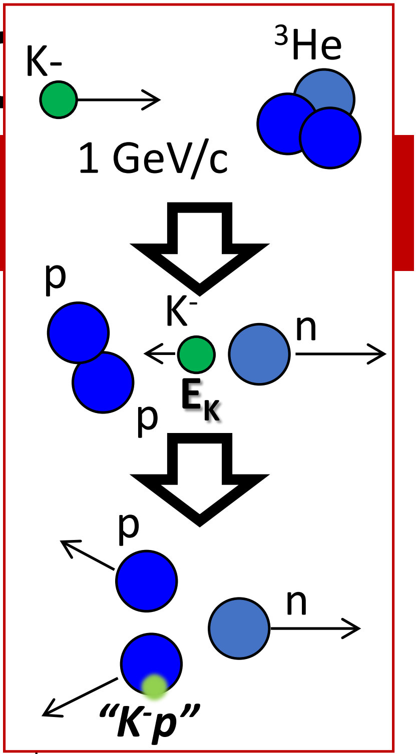


Λ(1405) region selected

Intrinsic $m_K < E_K$

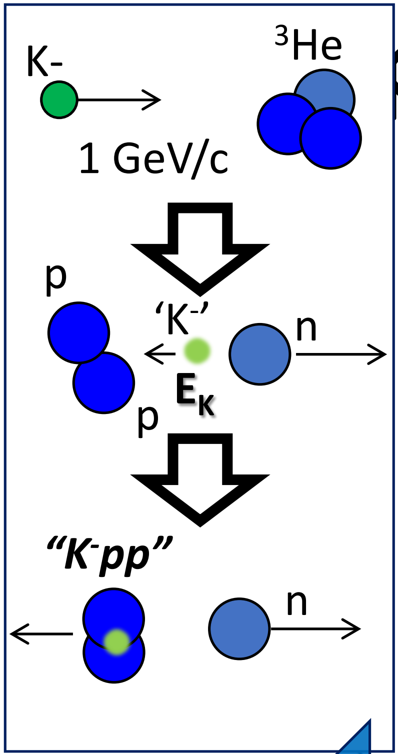
$'\overline{K}' + (pp)_R \rightarrow$ "K⁻p"+p

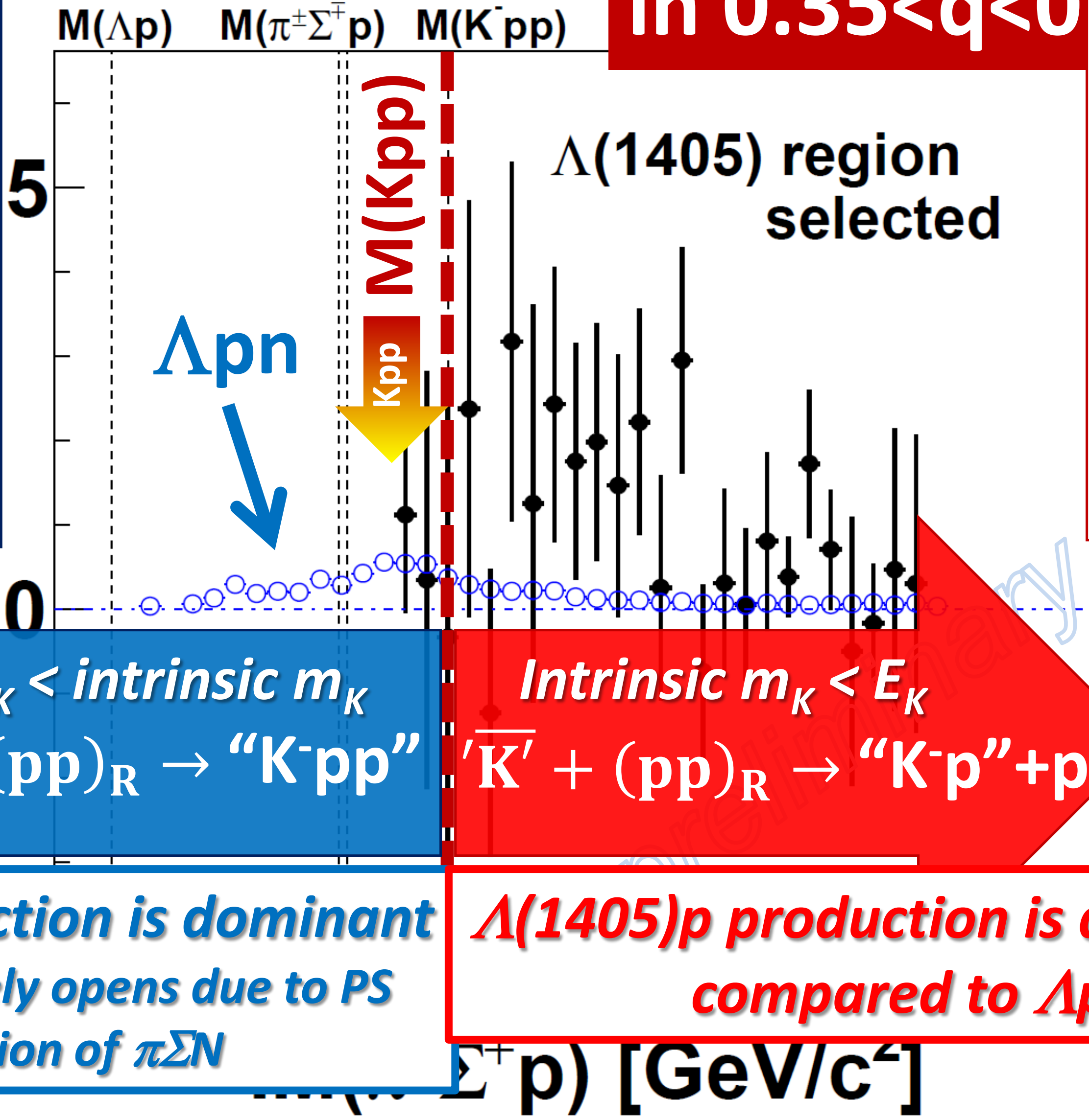
Λ(1405)p production is dominant compared to Λp

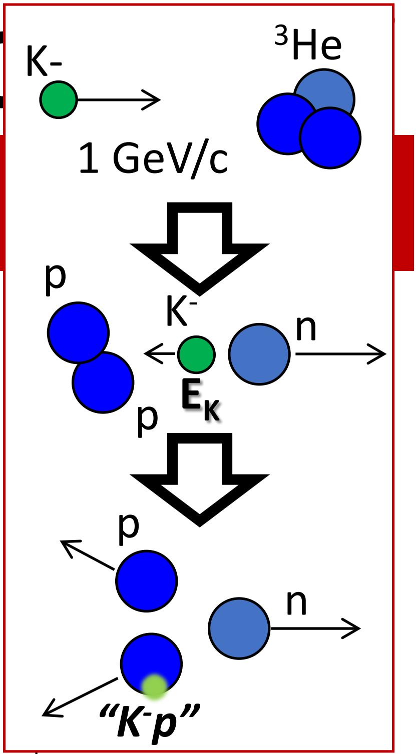


parison of Λpn & Λ(140

in 0.35<q<0







E_K < intrinsic m_K

$'\overline{K}' + (pp)_R \rightarrow$ "K-pp"

Intrinsic m_K < E_K

$'\overline{K}' + (pp)_R \rightarrow$ "K-p"+p

"K-pp" production is dominant

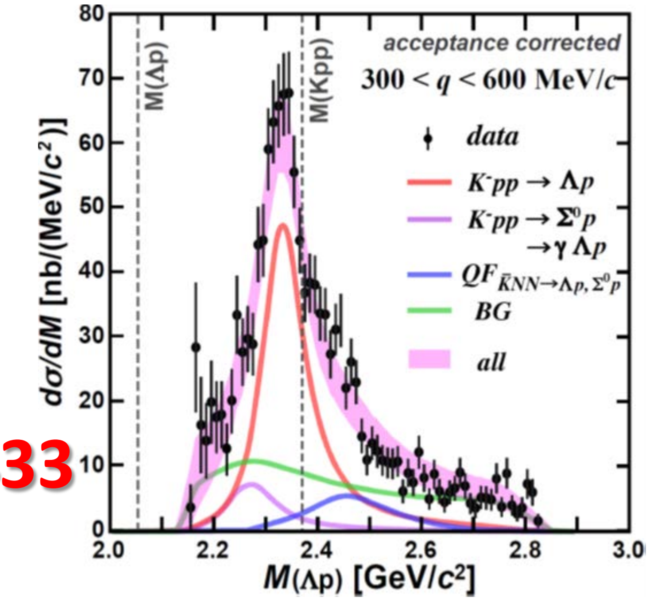
Λp decay widely opens due to PS limitation of πΣN

Λ(1405)p production is dominant compared to Λp

Conclusion

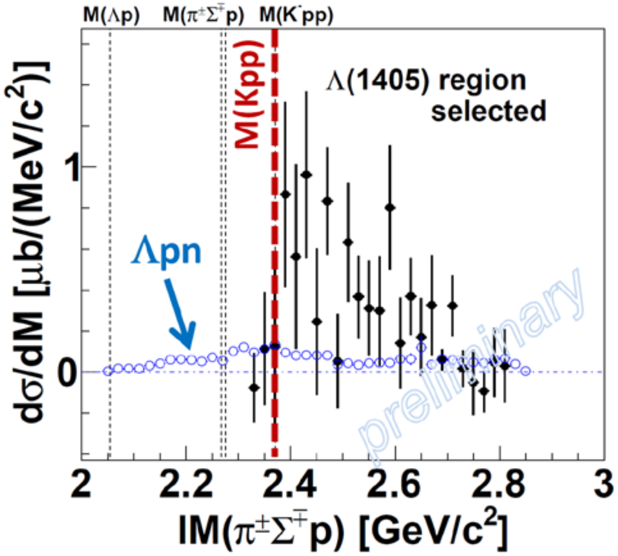
- **We observed the “K$^-$pp” bound state in ^{3}He(K$^-$,Λp)n**
  - Binding energy: ~40 MeV
  - Width: ~100 MeV

← PLB789(2019)620./arXiv:2006.13433



- **We found large CS of the Λ(1405)p formation compared to the “K$^-$pp”**
  - quite important information on the production mechanism of the “K$^-$pp”

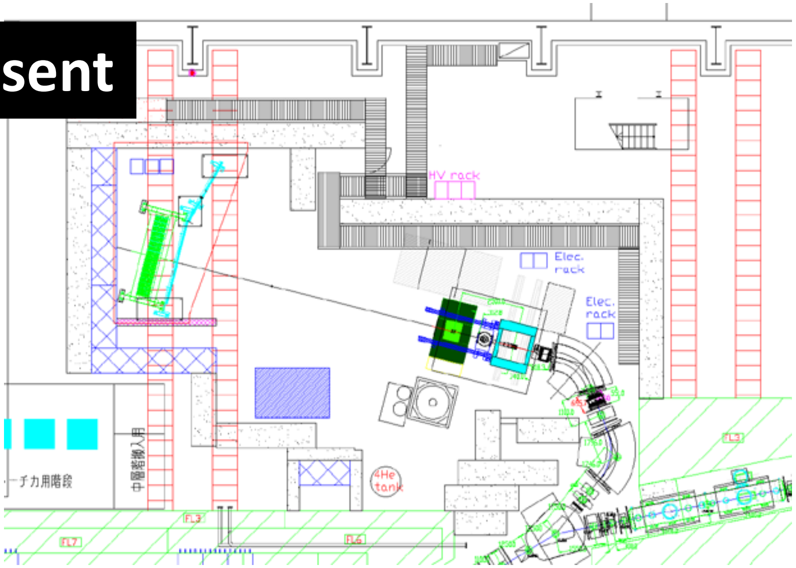
← paper in preparation



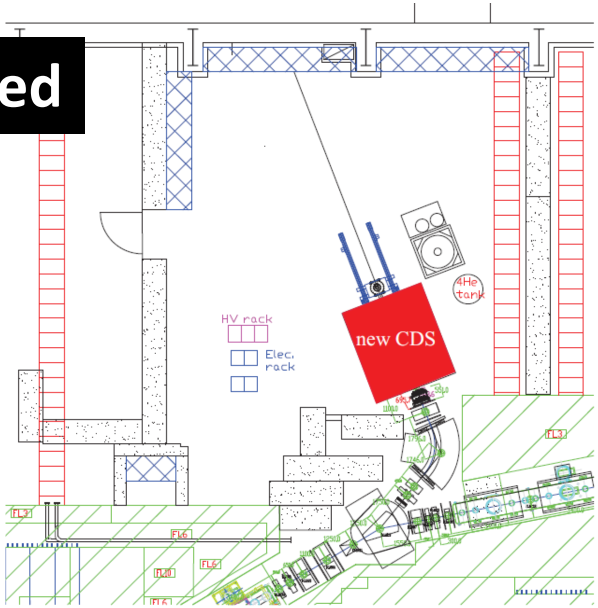
Added Materials

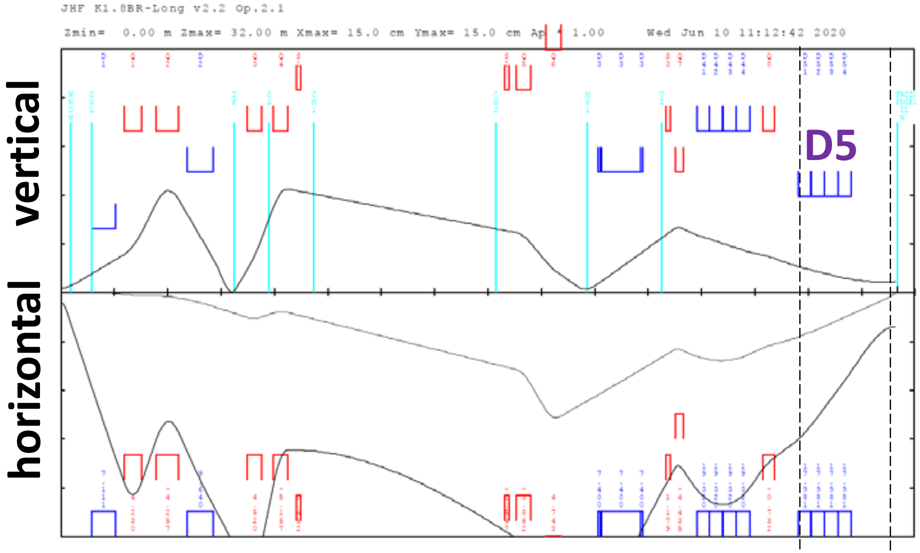
K1.8BR Beamline Optics

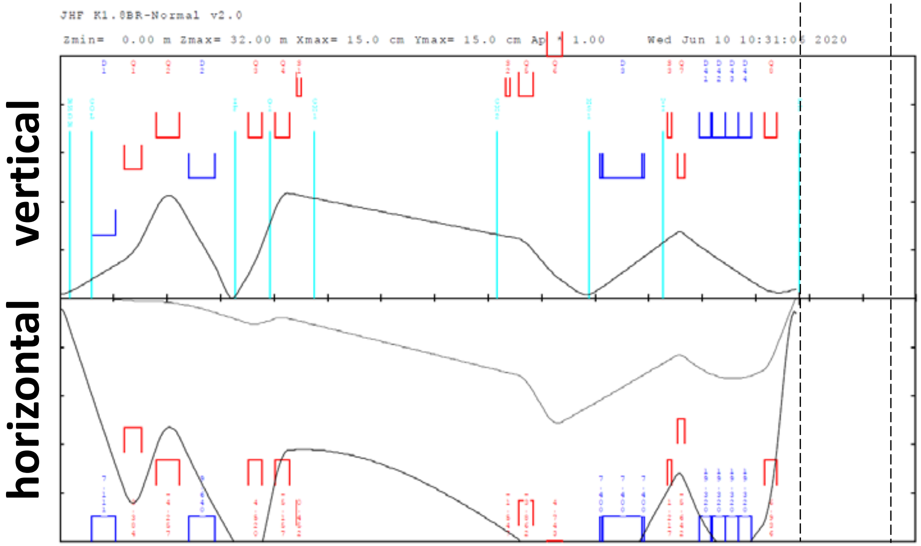
Present



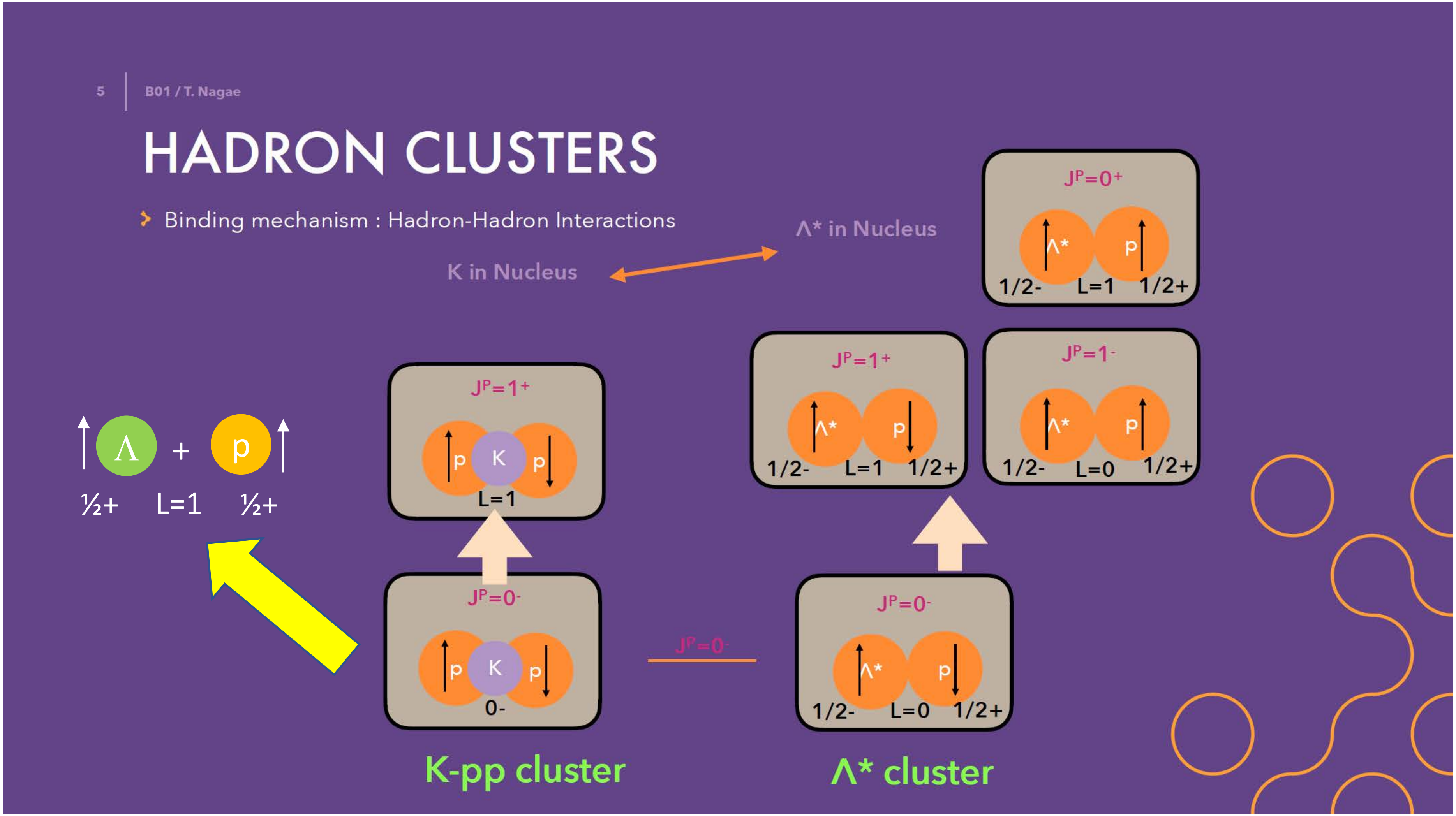
Modified







Spin-Parity of $\bar{K}NN$



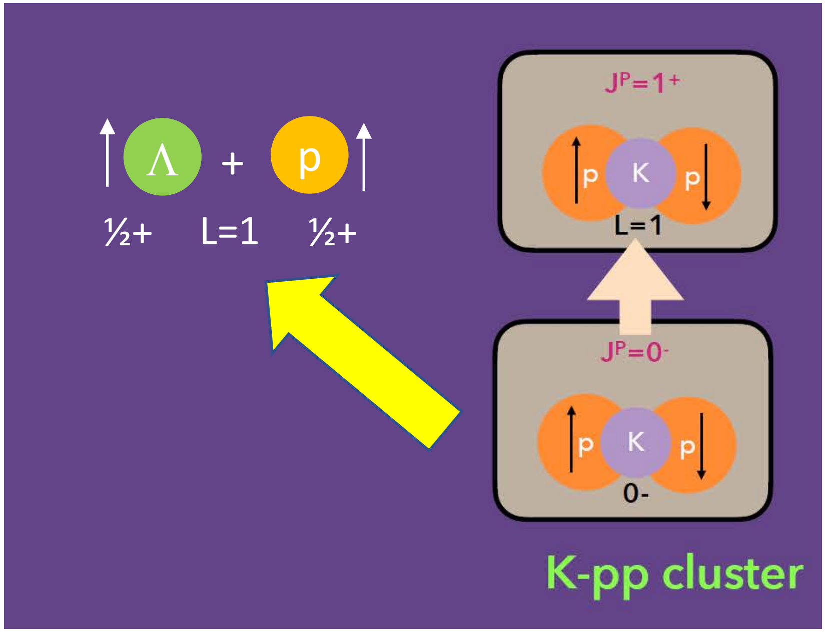
5 | B01 / T. Nagae

HADRON CLUSTERS

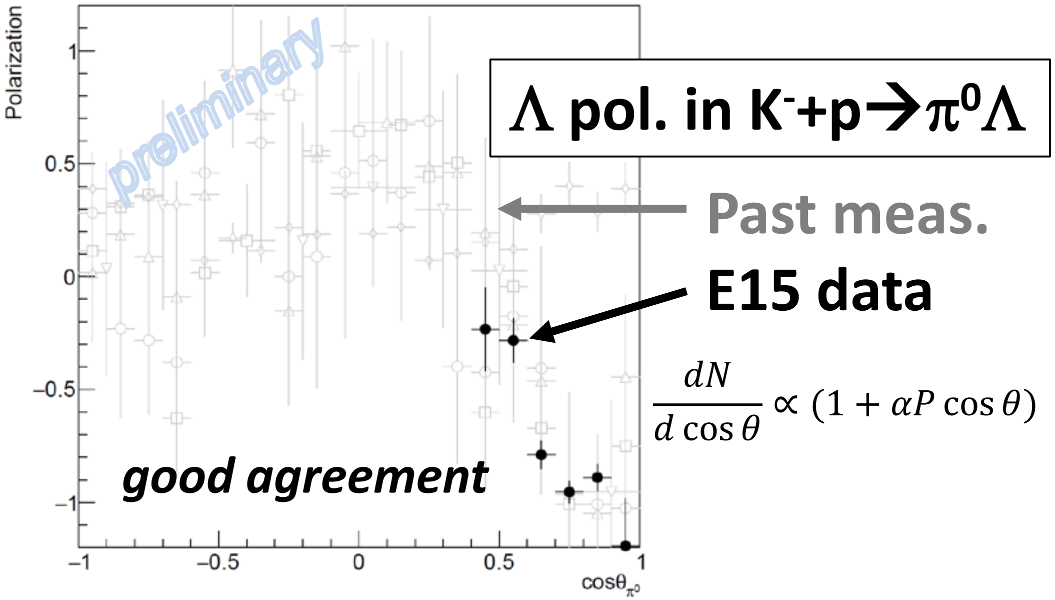
- Binding mechanism : Hadron-Hadron Interactions

T.Nagae, “The 4th Symposium on Clustering as a window on the hierarchical structure of quantum systems”, May 28th, 2020

Spin-Parity of $\bar{K}NN$



- **Λ polarization** can be measured via π^-p decay



$$\frac{dN}{d\cos\theta} \propto (1 + \alpha P \cos\theta)$$

- **Proton polarization** is measured with a polarimeter
  - Tracking system
  - Plastic scintillator