Summary of the K^-pp bound-state observation in E15 and future prospects

F. Sakuma, RIKEN

on behalf of the J-PARC E15/E80 collaborations

EXA2021

INTERNATIONAL CONFERENCE ON EXOTIC ATOMS AND RELATED TOPICS (EXA 2021),

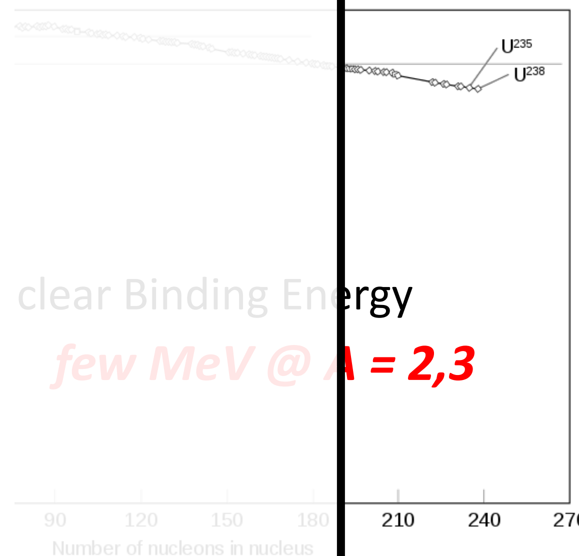
September 13-17, 2021, Online

Kaonic Nuclei

Predicted from ... action in I=0

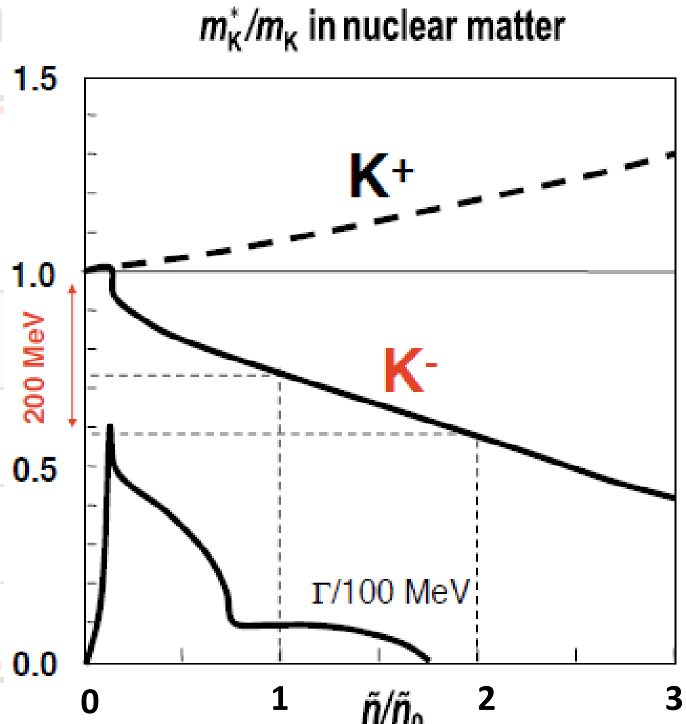
Kaonic Nuclei	Binding Energy [MeV]
Λ(1405) = K^-p	27
K^-pp	48
K^-ppp	97
K^-ppn	118

...88., PRC65(2002)044005., etc.

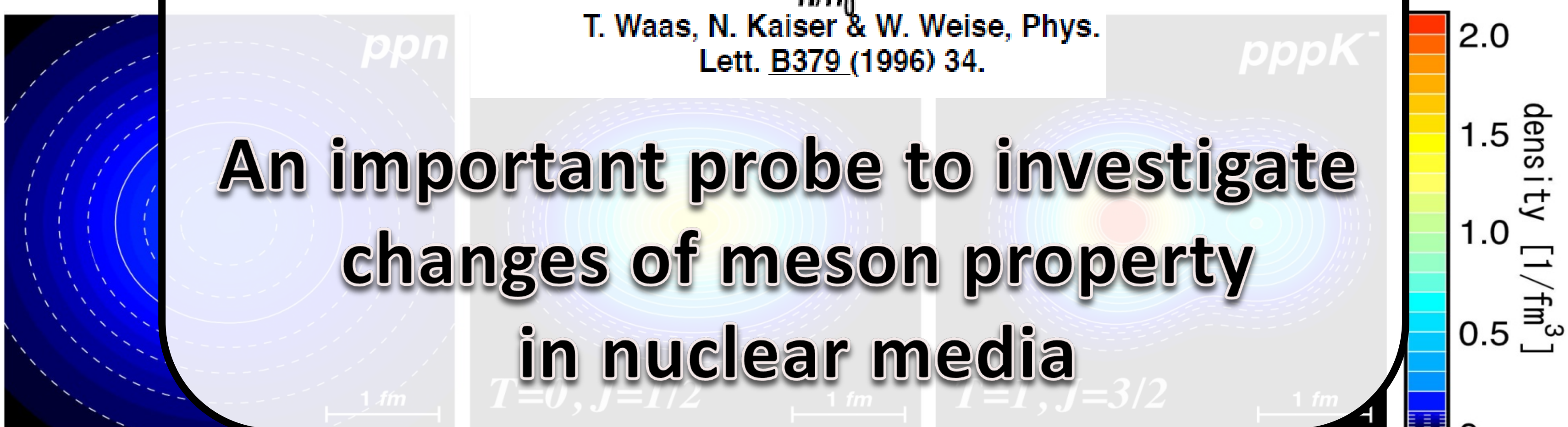


...clear Binding Energy

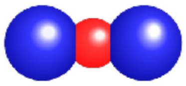
few MeV @ A = 2,3



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



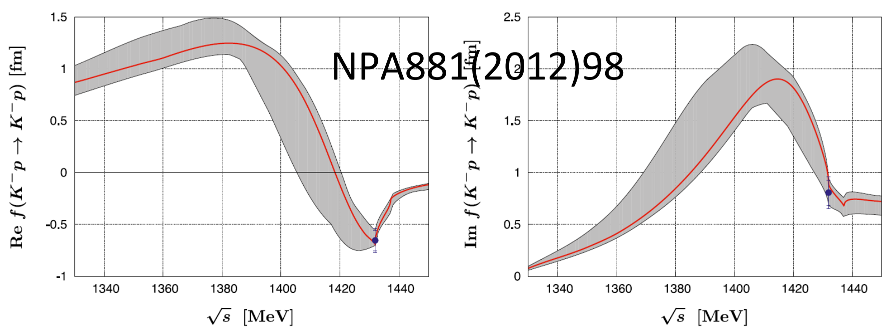
An important probe to investigate changes of meson property in nuclear media

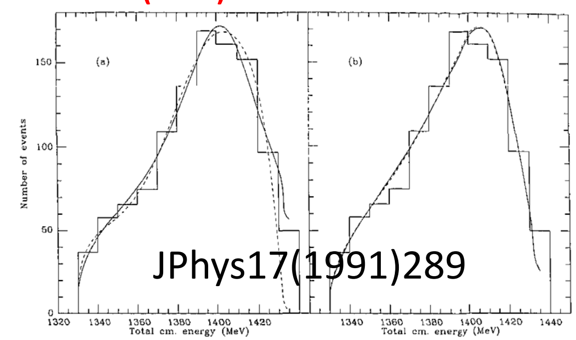


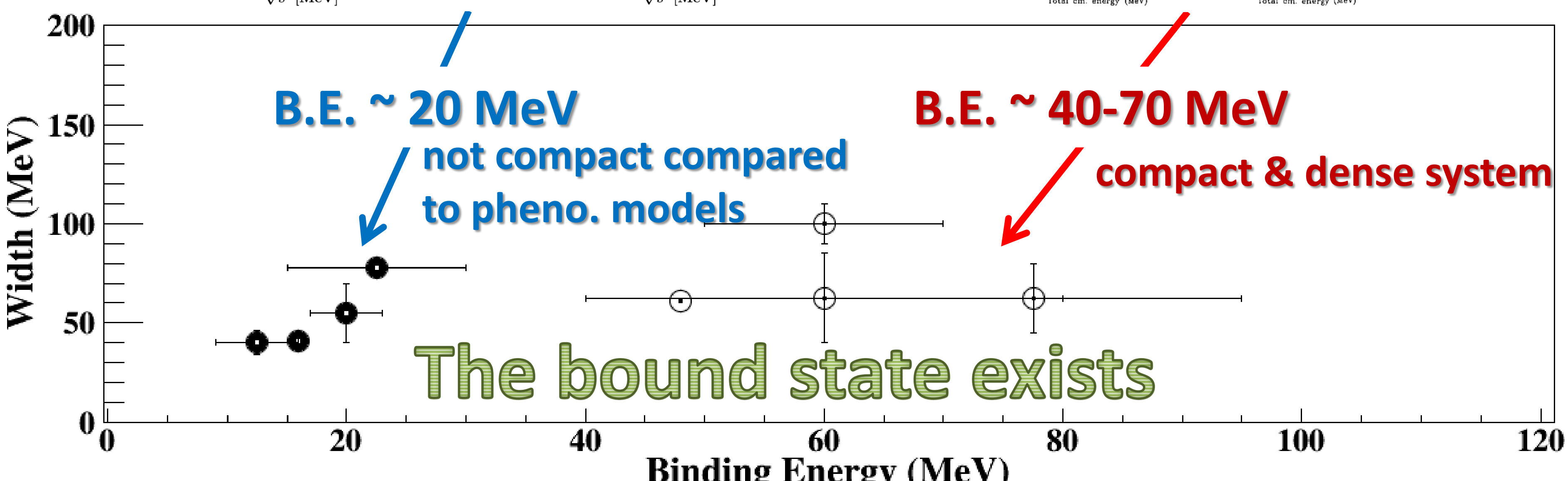
Theoretical Calculations on "K^-pp"

The simplest kaonic nuclei, $\bar{K}NN$ ($J^P=0^-$, $I=1/2$)

$\bar{K}N$ int.	Chiral SU(3) (energy dependent)	Phenomenological (energy independent)
	$M_{\Lambda(1405)}$~1420, double pole	$M_{\Lambda(1405)}$~1405, single pole







Experimental Situation "before E15"

Negative results

AMADEUS@DAΦNE
$^{12}C(K^-_{stopped}, \Lambda p)$ EPJ**C79**(2019)190

HADES@GSI
$p + p \rightarrow (\Lambda + p) + K^+$ @ 3.5GeV
PLB**742**(2015)242

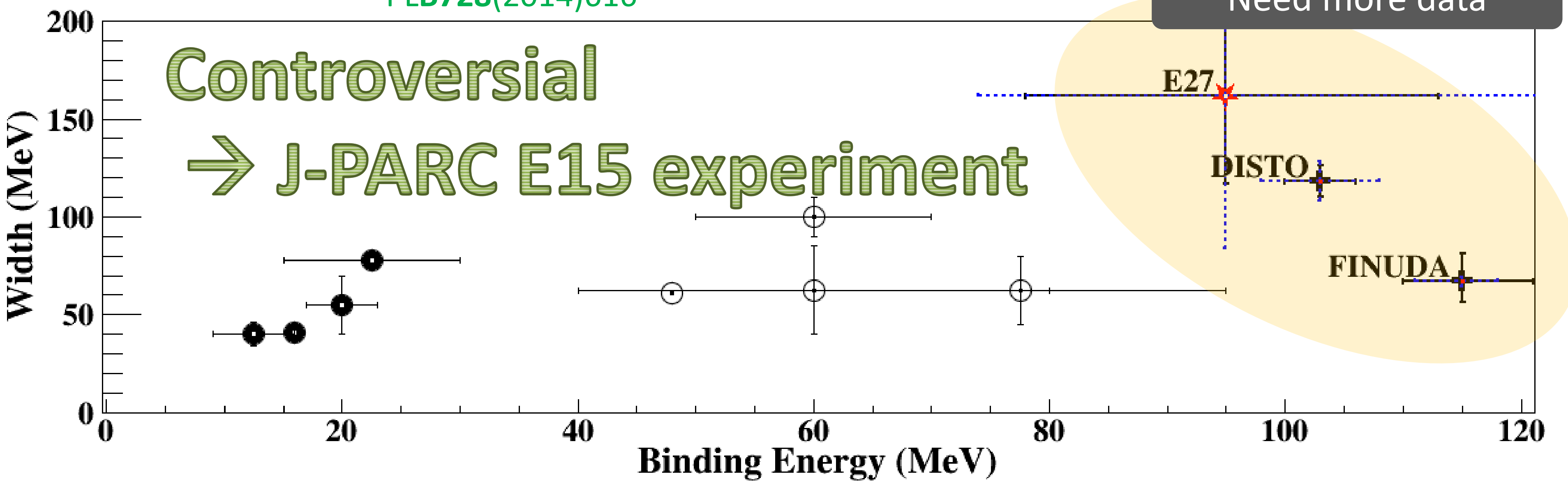
LEPS@SPring-8
$d(\gamma, \pi^- K^+)X$ @ 1.5-2.4 GeV
PLB**728**(2014)616

Positive results

FINUDA@DAΦNE PRL**94**(2005)212303
$^6Li/^7Li/^{12}C(K^-_{stopped}, \Lambda p)$
Multi-NA processes?

DISTO@SATURNE PRL**104**(2010)132502
$p + p \rightarrow (\Lambda + p) + K^+$ @ 2.85GeV
Intermediate $N^* \rightarrow pK^+$?

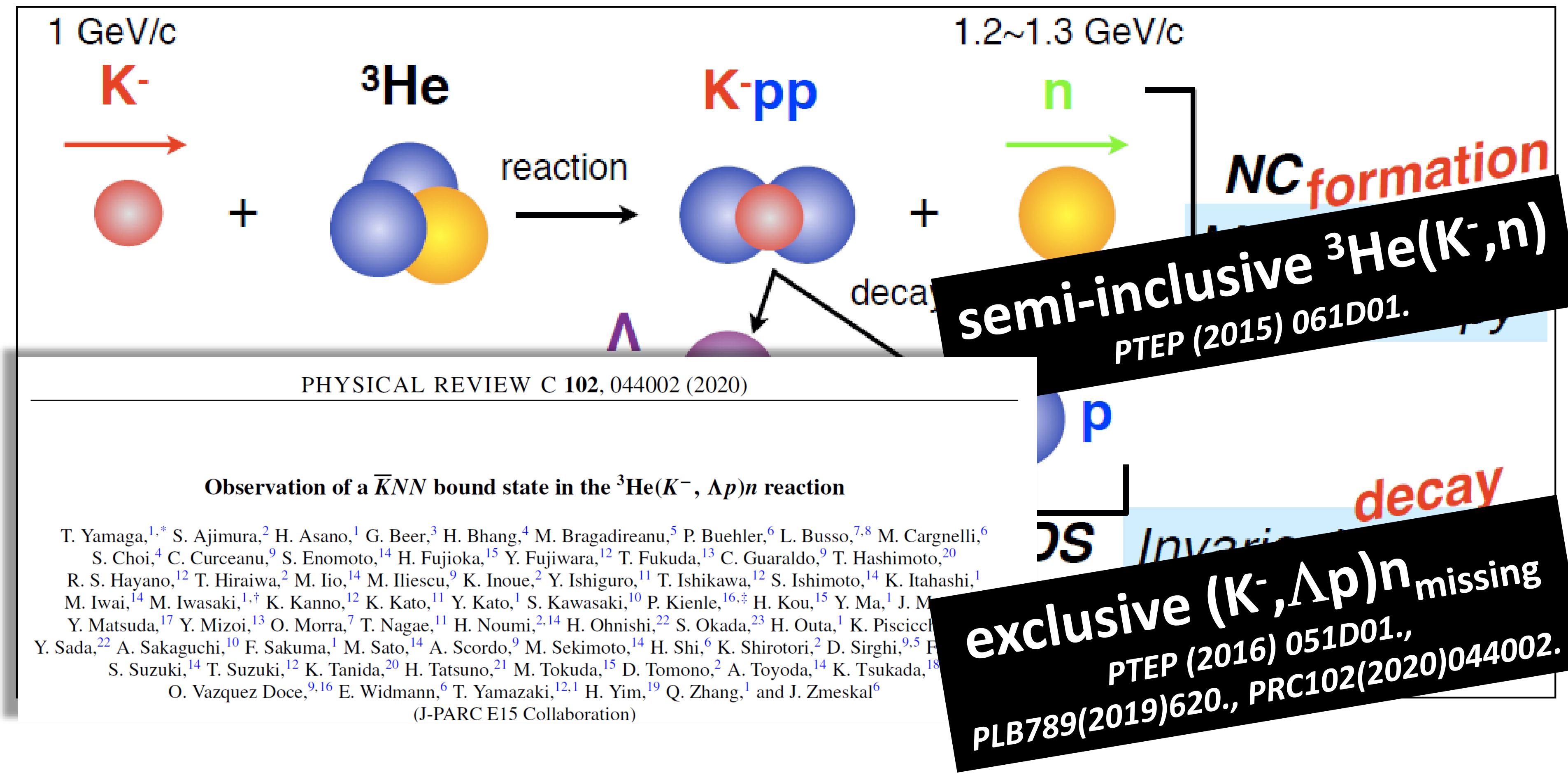
E27@J-PARC PTEP(2015)021D01.
$d(\pi^+, K^+)\Sigma^0 p$ @ 1.69 GeV/c
Need more data



J-PARC E15 Experiment

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

2NA and Y decays can be discriminated kinematically

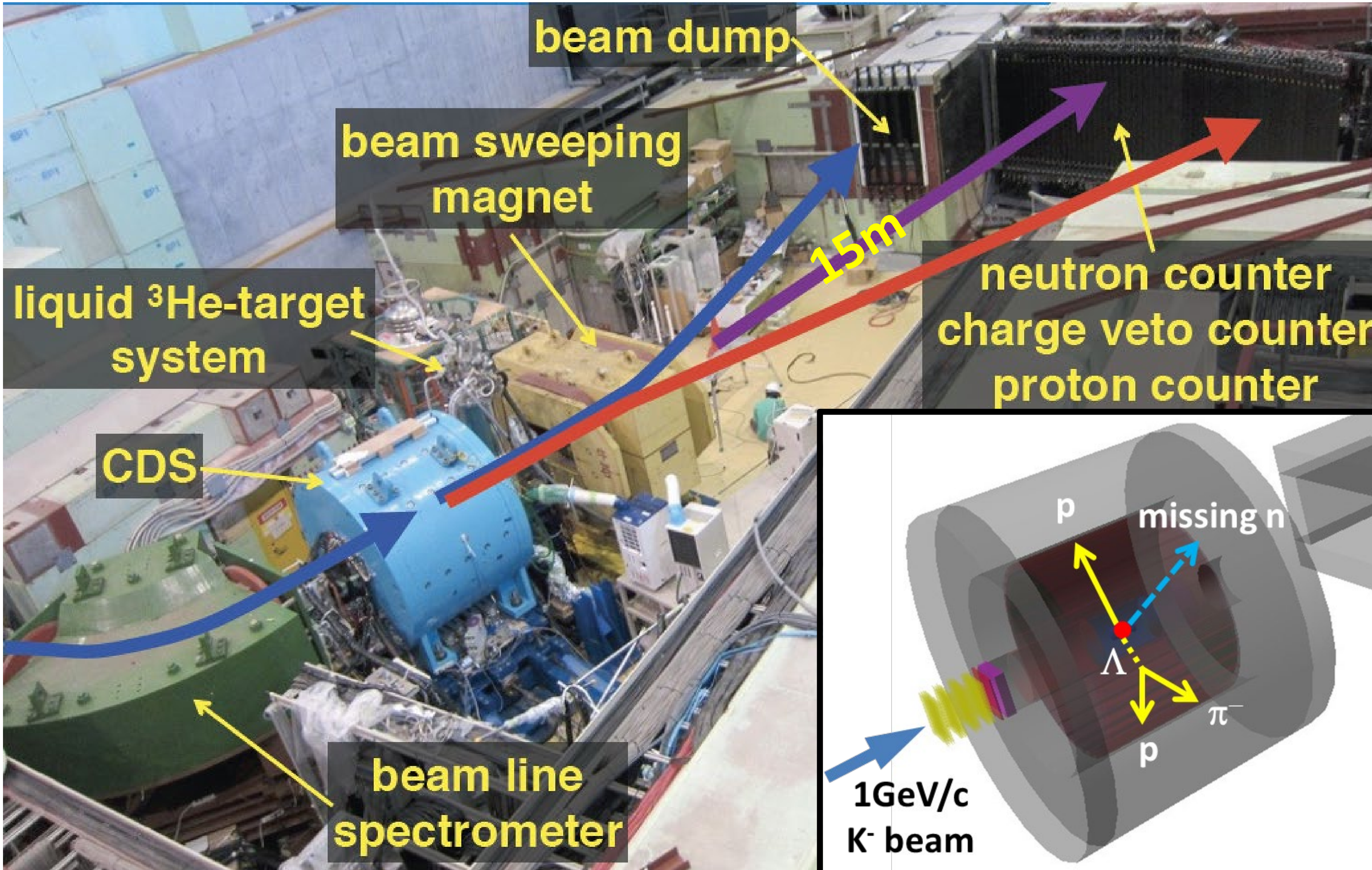


PHYSICAL REVIEW C **102**, 044002 (2020)

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

T. Yamaga,[1,*] S. Ajimura,[2] H. Asano,[1] G. Beer,[3] H. Bhang,[4] M. Bragadireanu,[5] P. Buehler,[6] L. Busso,[7,8] M. Cargnelli,[6] S. Choi,[4] C. Curceanu,[9] S. Enomoto,[14] H. Fujioka,[15] Y. Fujiwara,[12] T. Fukuda,[13] C. Guaraldo,[9] T. Hashimoto,[20] R. S. Hayano,[12] T. Hiraiwa,[2] M. Iio,[14] M. Iliescu,[9] K. Inoue,[2] Y. Ishiguro,[11] T. Ishikawa,[12] S. Ishimoto,[14] K. Itahashi,[1] M. Iwai,[14] M. Iwasaki,[1,†] K. Kanno,[12] K. Kato,[11] Y. Kato,[1] S. Kawasaki,[10] P. Kienle,[16,‡] H. Kou,[15] Y. Ma,[1] J. M Y. Matsuda,[17] Y. Mizoi,[13] O. Morra,[7] T. Nagae,[11] H. Noumi,[2,14] H. Ohnishi,[22] S. Okada,[23] H. Outa,[1] K. Piscicch Y. Sada,[22] A. Sakaguchi,[10] F. Sakuma,[1] M. Sato,[14] A. Scordo,[9] M. Sekimoto,[14] H. Shi,[6] K. Shirotori,[2] D. Sirghi,[9,5] F S. Suzuki,[14] T. Suzuki,[12] K. Tanida,[20] H. Tatsuno,[21] M. Tokuda,[15] D. Tomono,[2] A. Toyoda,[14] K. Tsukada,[18] O. Vazquez Doce,[9,16] E. Widmann,[6] T. Yamazaki,[12,1] H. Yim,[19] Q. Zhang,[1] and J. Zmeskal[6] (J-PARC E15 Collaboration)

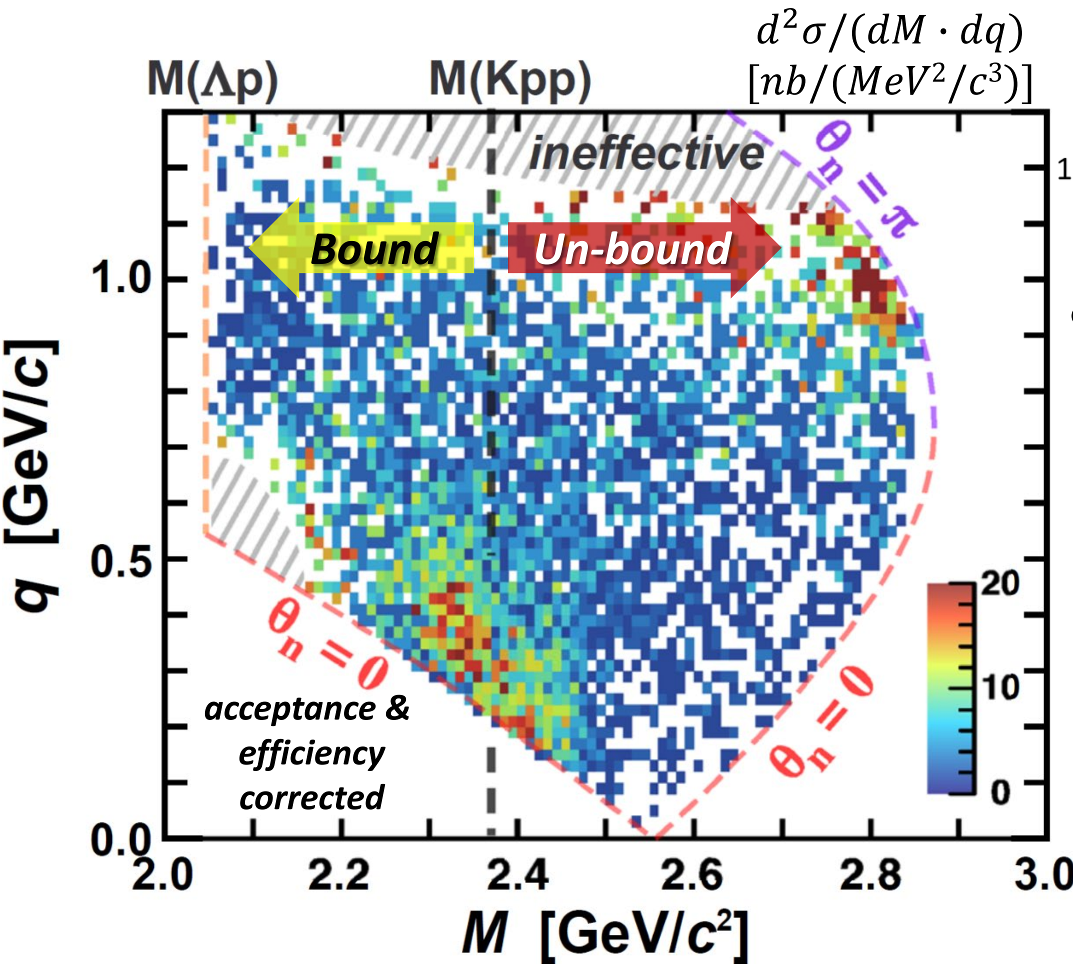
Experimental Setup @ K1.8BR

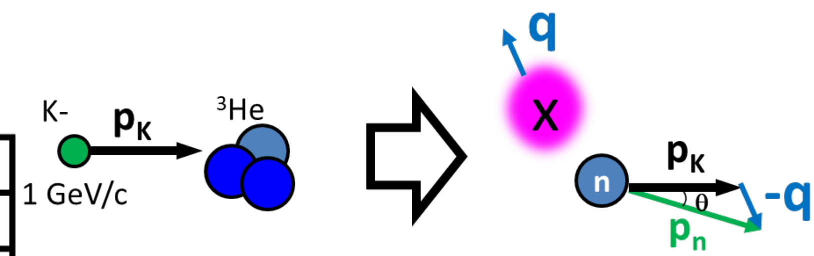


K. Agari et. al., PTEP 2012, 02B011

Exclusive ^{3}He(K^{-},Λp)n

T.Yamaga et. al., PRC102(2020)044002.





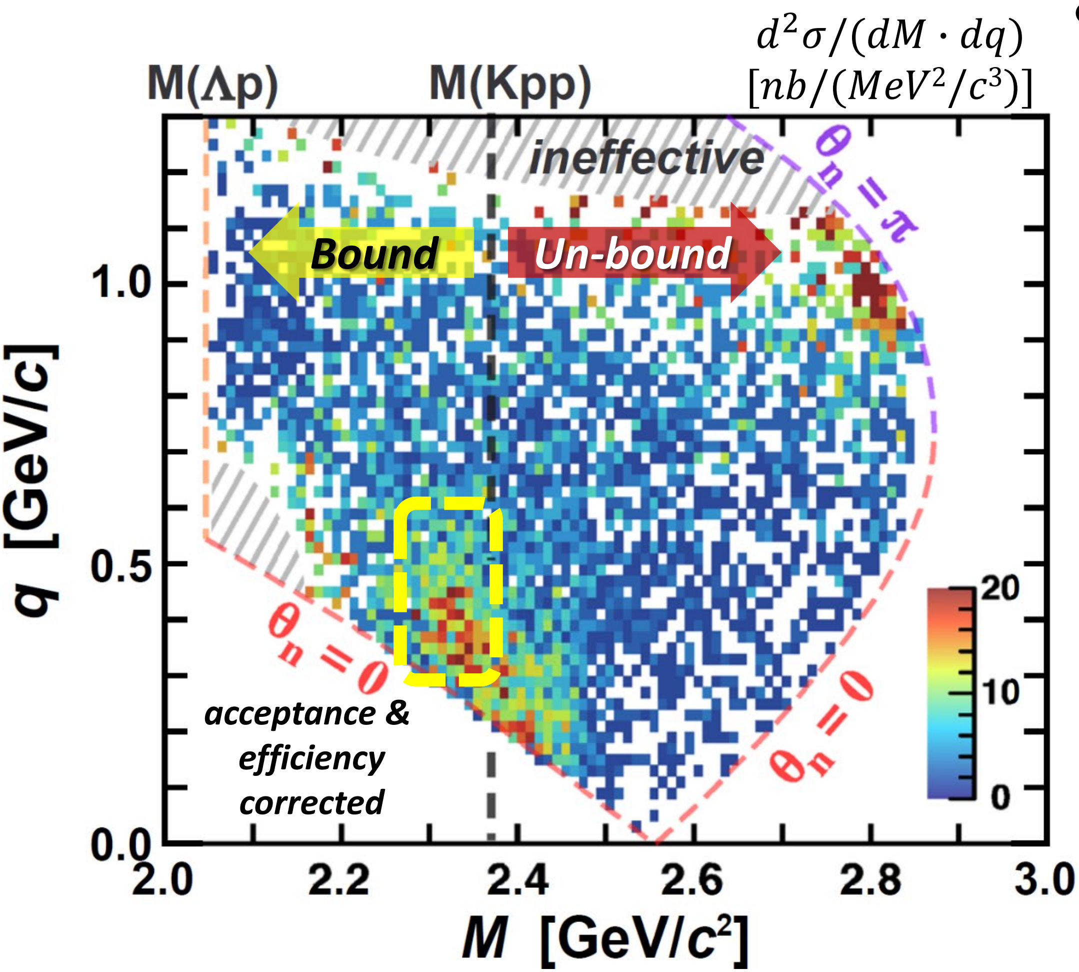
- **Momentum transfer analysis using the (K^{-},n) reaction**
  - ✓M(Λp) vs. q
  - ✓give a clear information on reaction processes

q *: momentum transfer of (K-,n)*

M *: invariant mass of Λp*

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

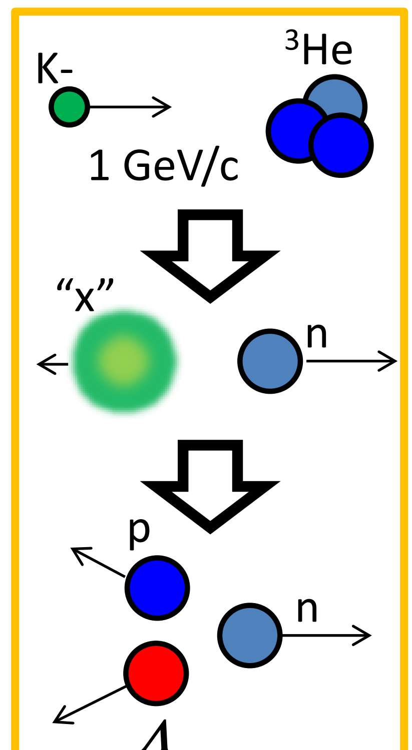
T.Yamaga et. al., PRC102(2020)044002.



q : *momentum transfer of (K-,n)*

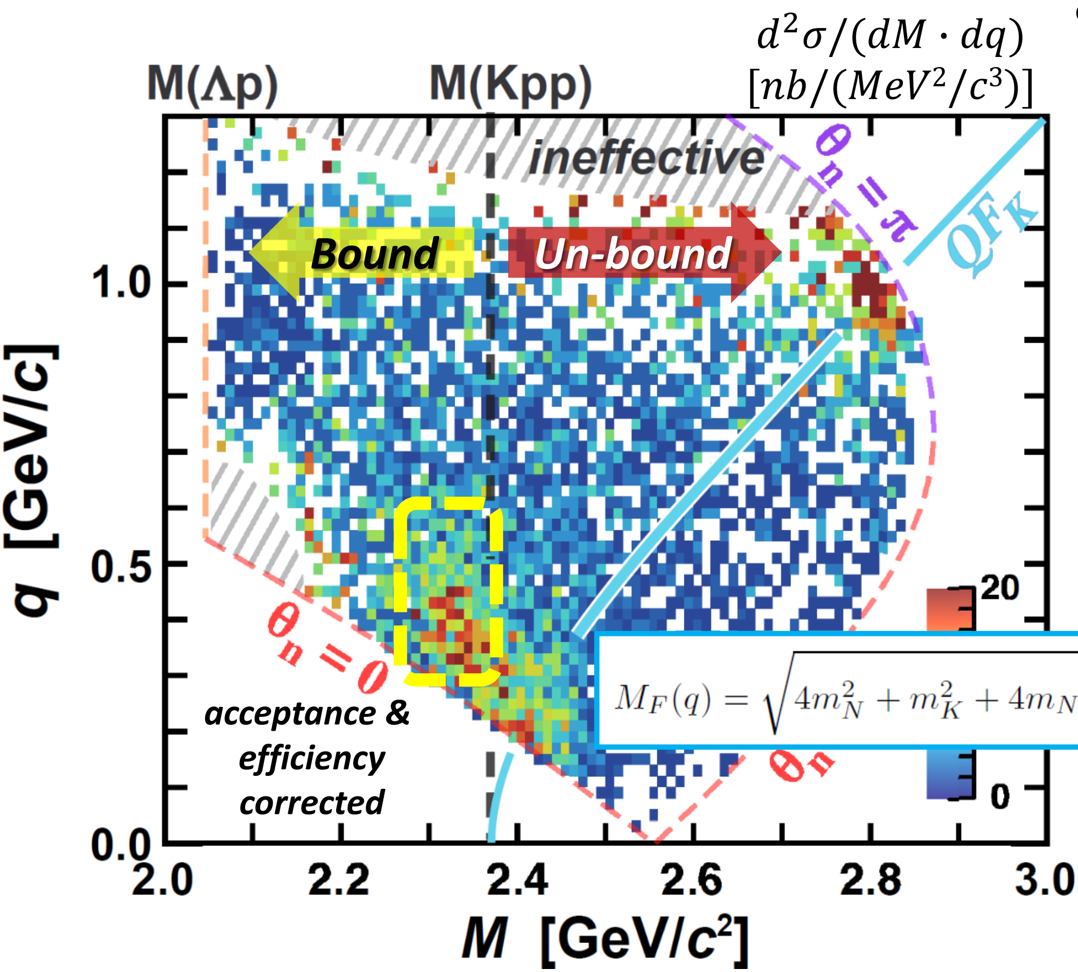
M : *invariant mass of Λp*

- **"K⁻pp" bound state exists**
  - ✓ q-independent



Exclusive ^{3}He(K$^-$,Λp)n

T.Yamaga et. al., PRC102(2020)044002.

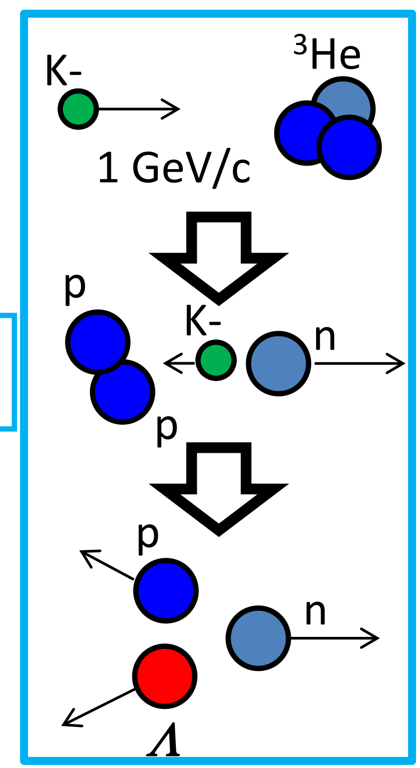


$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

q : *momentum transfer of (K-,n)*

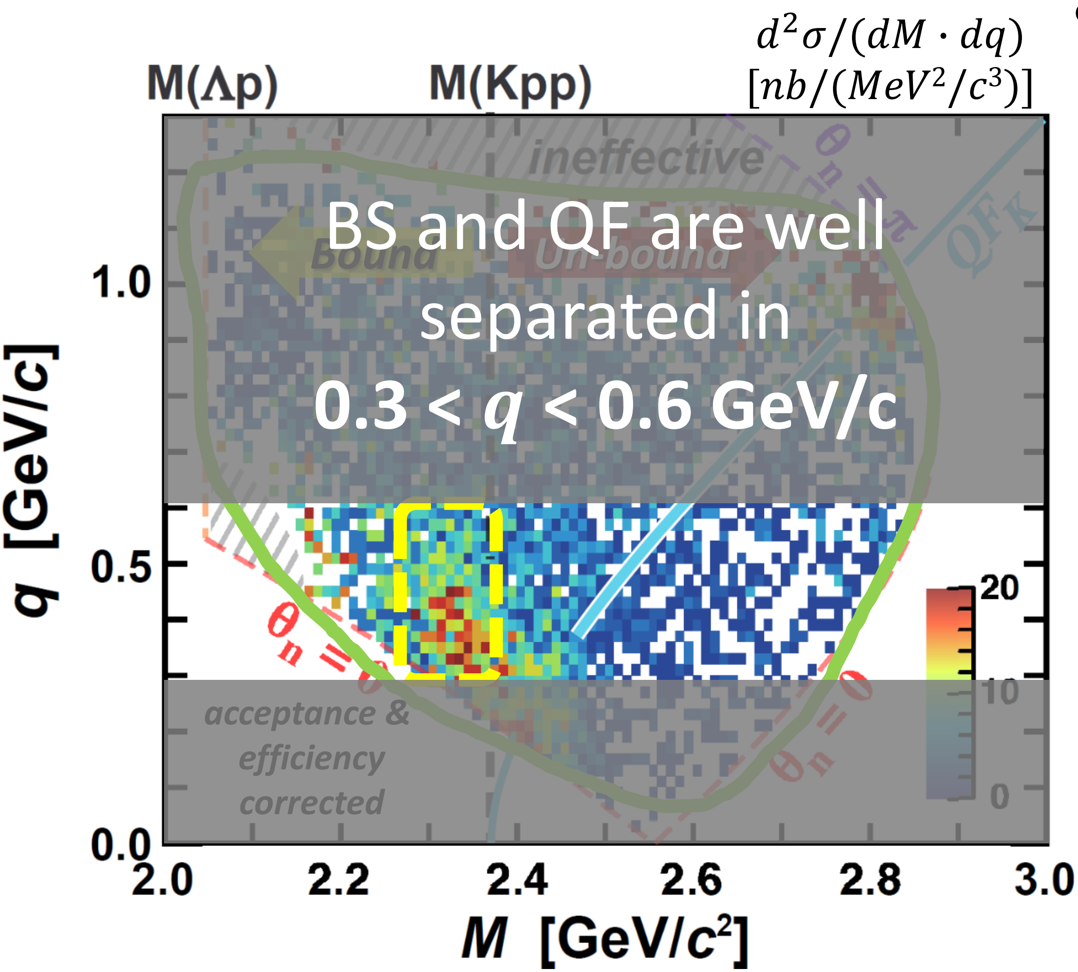
M : *invariant mass of Λp*

- **QF followed by 2NA**
  - ✓via "on-shell K$^-$"
  - ✓q-<u>dependent</u>



Exclusive ^{3}He(K$^-$,Λp)n

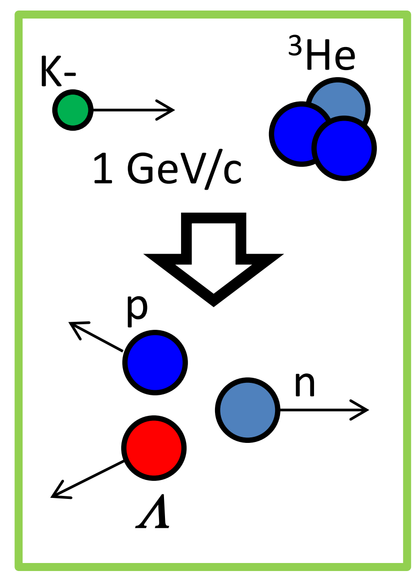
T.Yamaga et. al., PRC102(2020)044002.



q : *momentum transfer of (K-,n)*

M : *invariant mass of Λp*

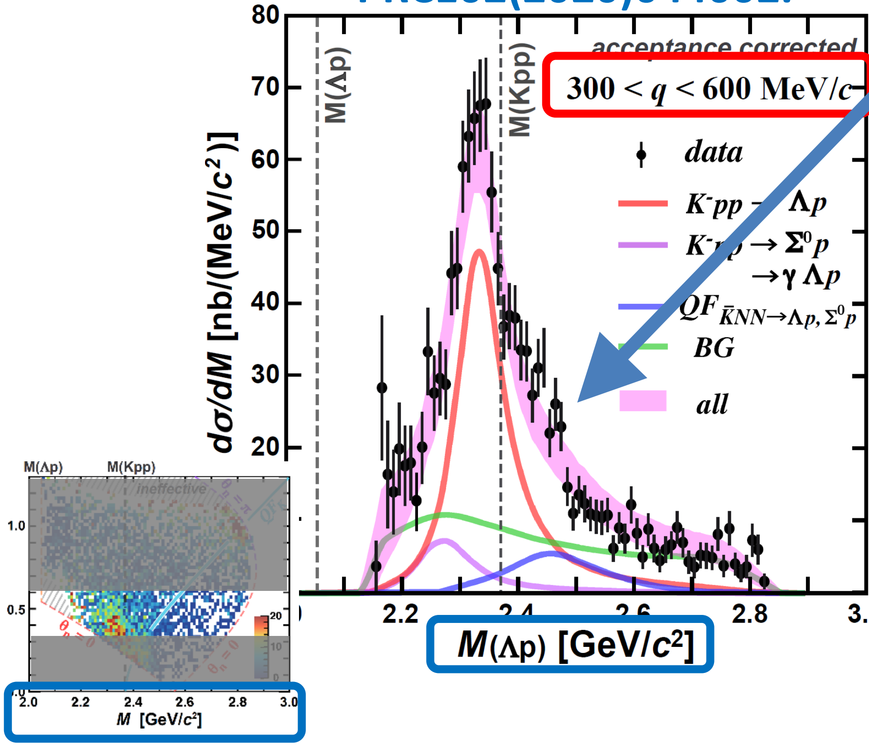
- **Broad Component**
  - ✓3NA reaction?
  - ✓Further investigations are ongoing

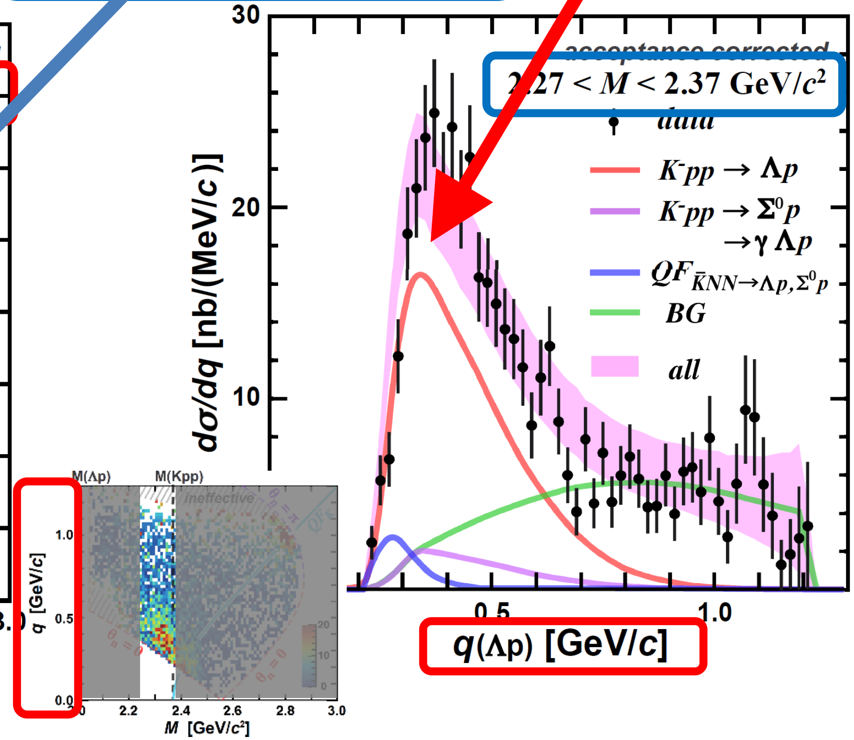


“K-pp” Bound State

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

PRC102(2020)044002.





B_{Kpp} ~ 40 MeV, Γ_{Kpp} ~ 100 MeV

→ *large binding energy*

Q_{kpp} ~ 400 MeV (c.f. Q_{QF} ~ 200 MeV)

→ *wide momentum transfer*

→ suggest the “K⁻pp” is quite compact

Many Questions to be Answered

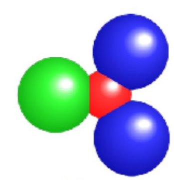
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K^-pp"?
  - Really compact and dense system?

K^-pp

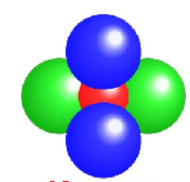
- **Λ(1405) state**
  - $\bar{K}N$ quasi-bound state as considered?
  - Size?
  - Relation between $\bar{K}N$ and $\bar{K}NN$?

K^-p

- **More heavier kaonic nuclei?**
  - Mass number dependence?



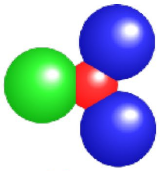
K^-ppn



K^-ppnn

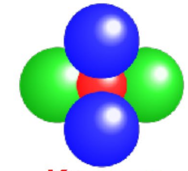
- **Double kaonic nuclei?**
  - Much compact and dense system?

K^-K^-pp



K⁻ppn

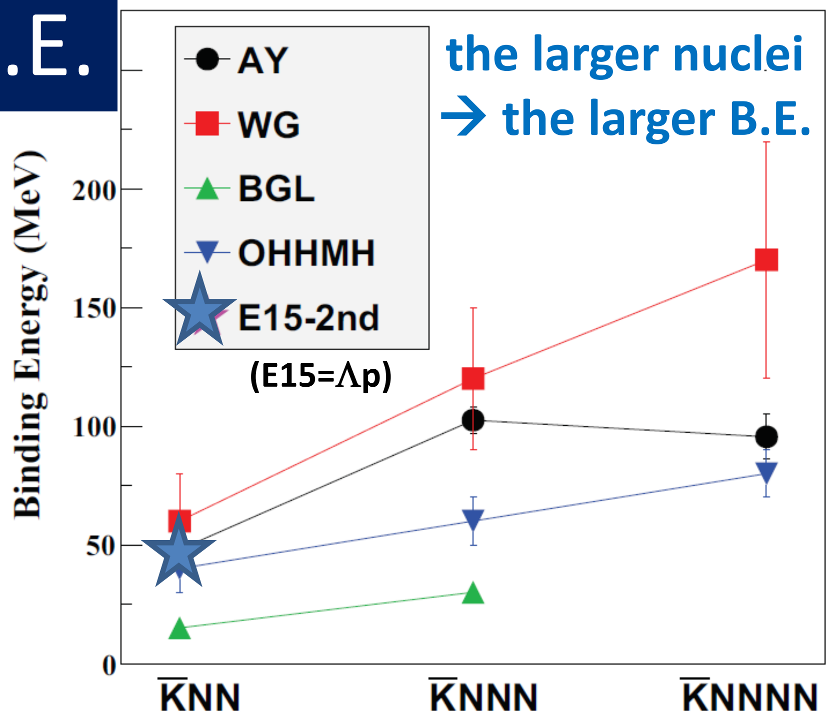
$\bar{K}NNN$ and $\bar{K}NNNN$



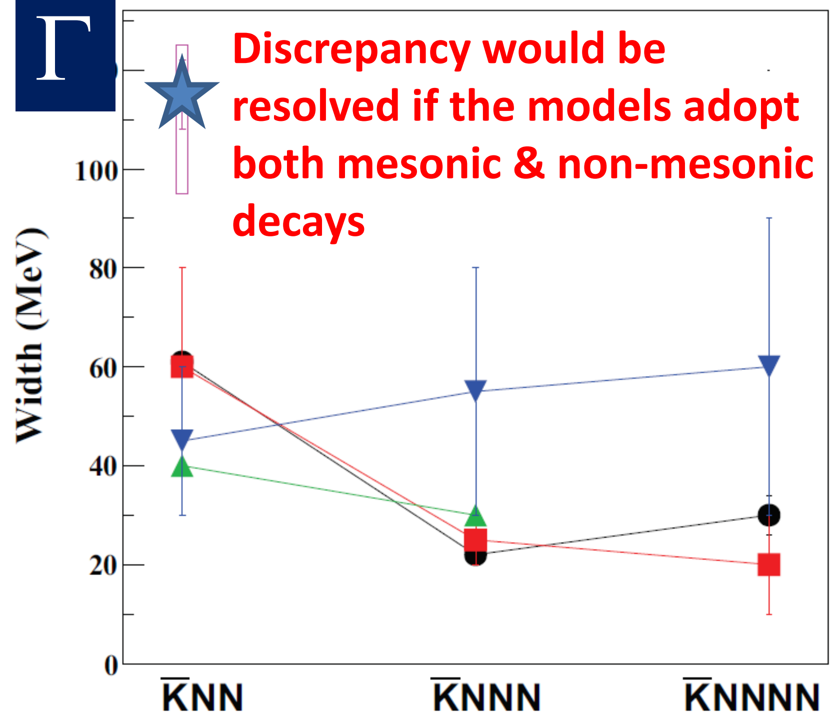
K⁻ppnn

- More heavier system must be explored to provide more conclusive evidence of the kaonic nuclei

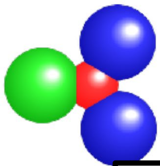
B.E.



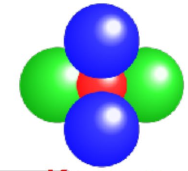
Γ



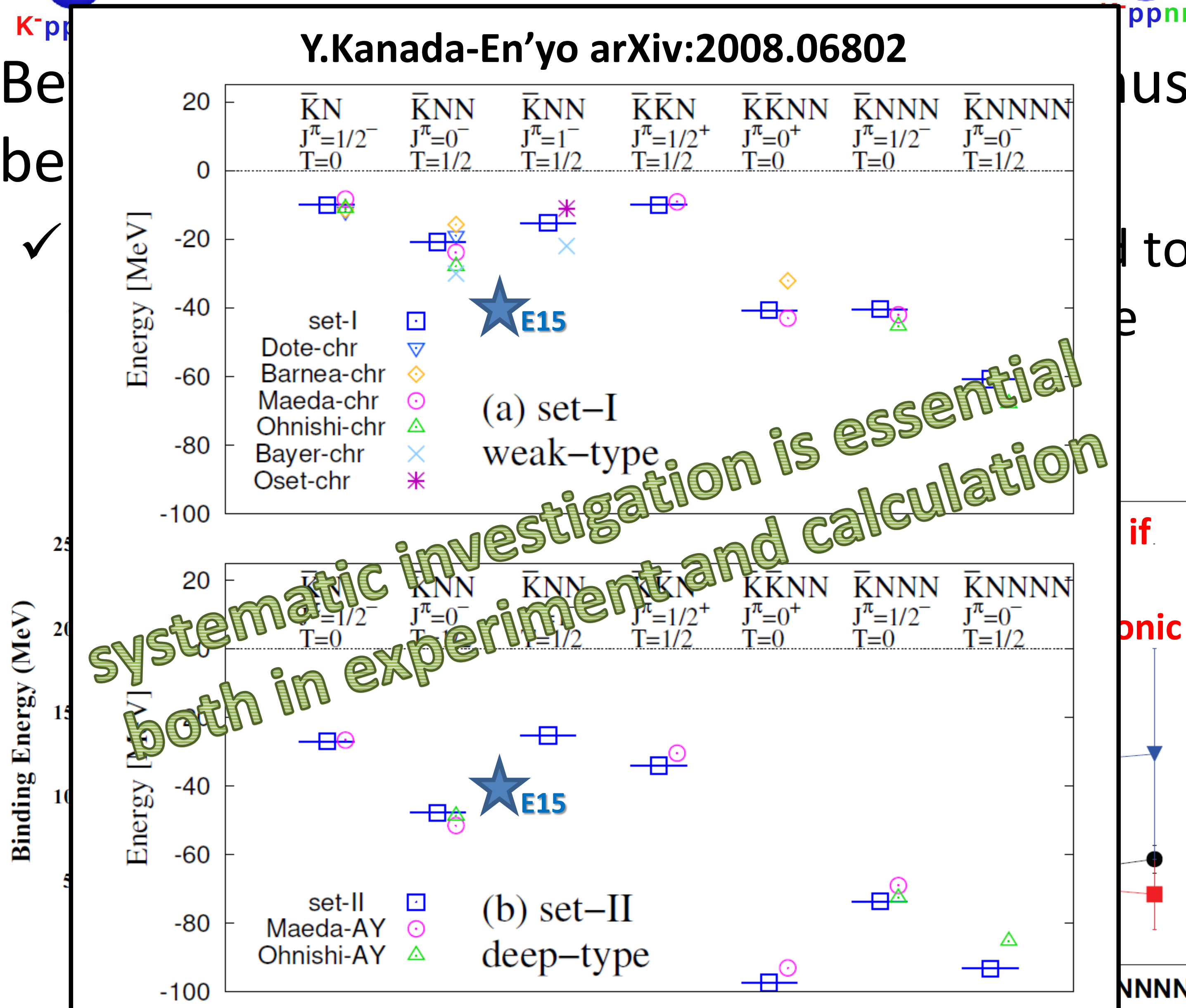
- ➢ The $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration



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



- Be… ust
  be…
  - ✓ … d to be
    … e



systematic investigation is essential both in experiment and calculation

New Project @ J-PARC

-- systematic investigation of the light kaonic nuclei --

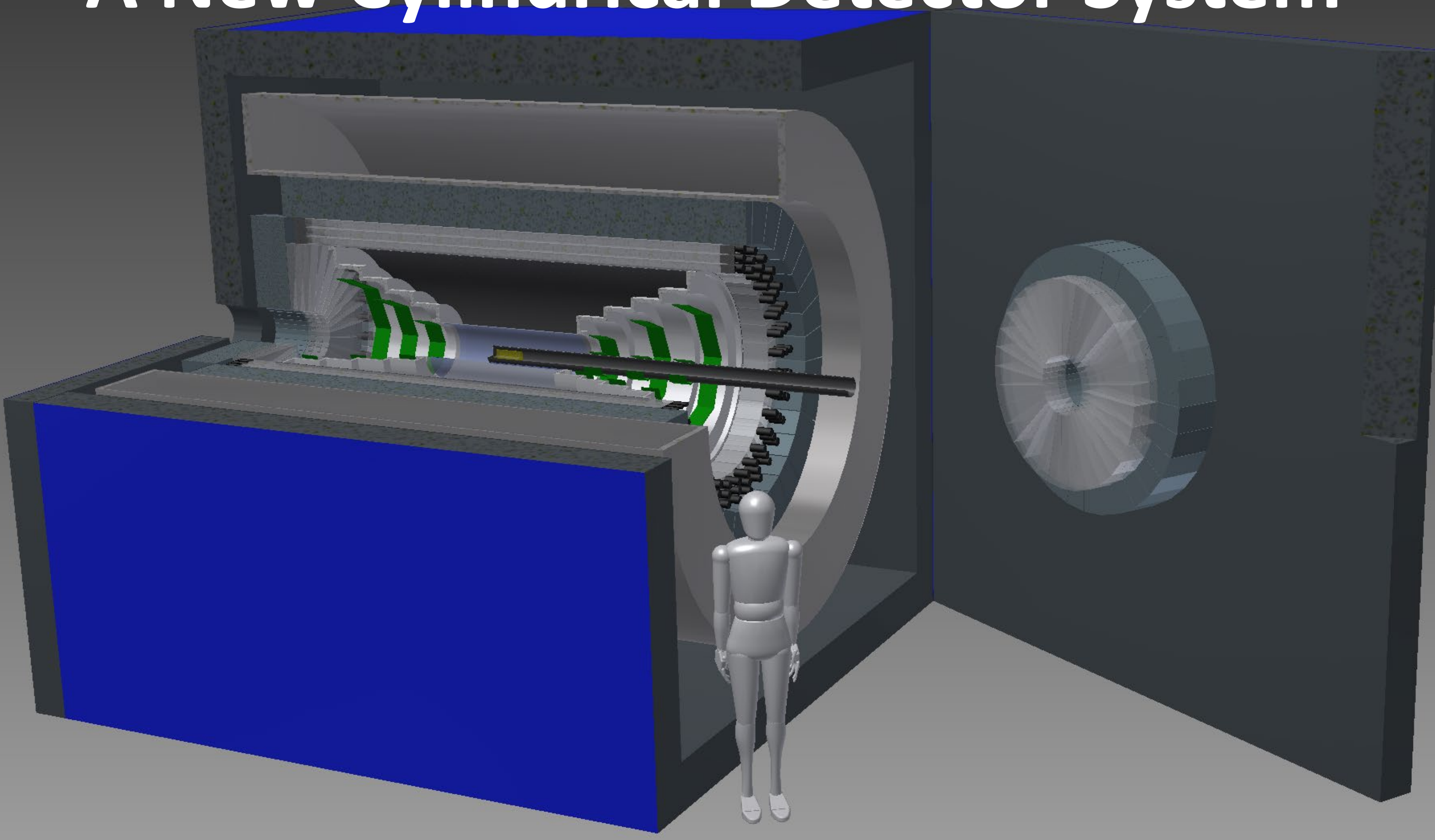
Strategy of the New Project

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

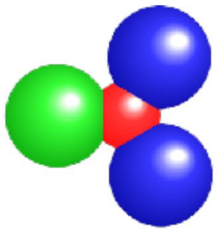
	Reaction	Decays	Key
$\bar{K}N$	d(K⁻,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	F-factor → n/γ identification
$\bar{K}NN$	^{3}He(K⁻,N)	Λp/Λn	J^P → polarimeter
$\bar{K}NNN$	^{4}He(K⁻,N)	Λd/Λpn	large acceptance **← A first step**
$\bar{K}NNNN$	*^{6}Li(K⁻,d)*	*Λt/Λdn/Λpnn*	*many body decay*
$\bar{K}\bar{K}NN$	*$\bar{p}$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

- To realize the systematic measurements, we need
  - ☐ **a large acceptance spectrometer** **← new CDS**
    - detect/identify all particles to specify the reaction
  - ☐ **high-intensity kaon beam** **← modified K1.8BR**
    - more K⁻ yield than the existing beamline
- *We take a **step-by-step** approach*

A New Cylindrical Detector System



A new 4π spectrometer with n/γ detection capability



Expected $\bar{K}NNN$ in K^-+^4He

B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

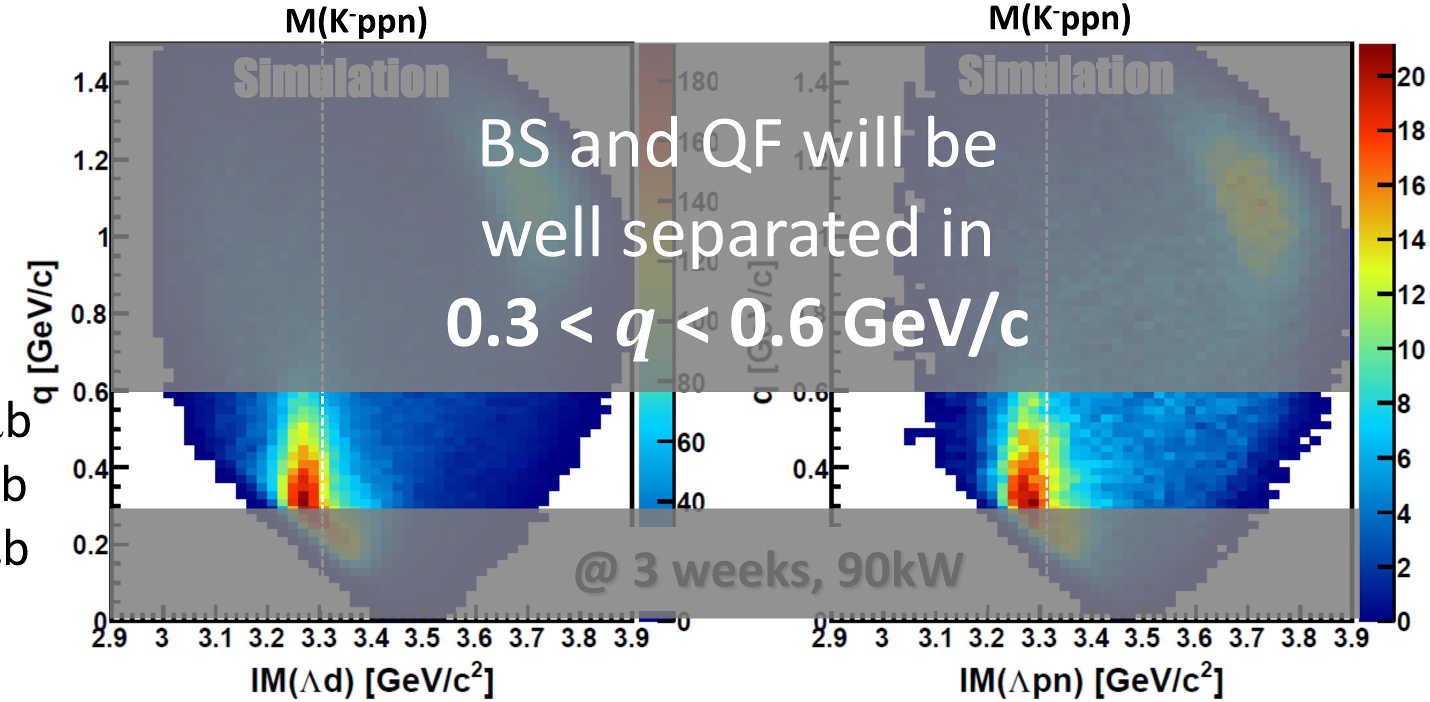
Q_{kppn} ~ 400 MeV/c

σ(K^-ppn)*Br ~ 10 μb

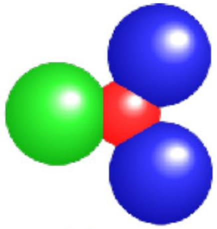
σ(QF) ~ 10 μb

σ(BG) ~ 20 μb

$K^-+^4He \rightarrow \Lambda d+n$ **$K^-+^4He \rightarrow \Lambda pn+n$**



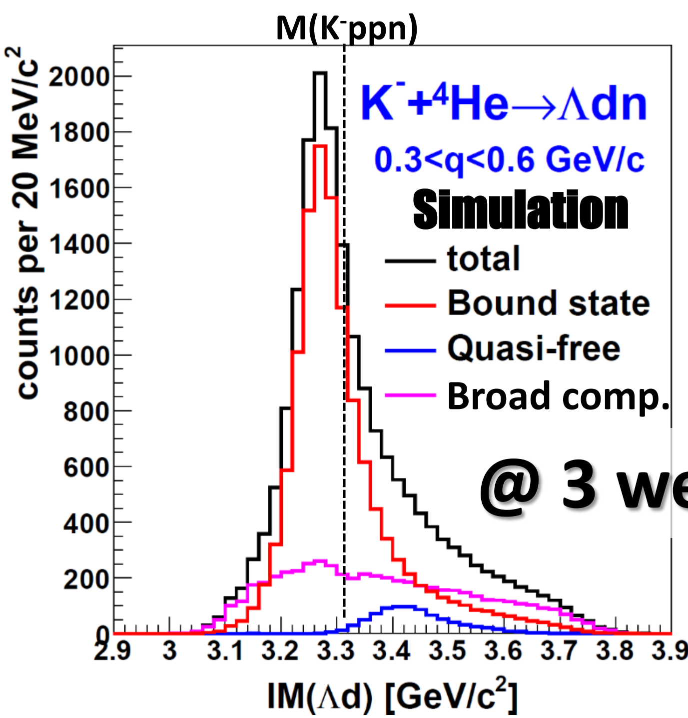
- Similar parameters obtained with the $K^-+^3He \rightarrow \Lambda pn$ (PRC102(2020)044002.) are adopted to K^-ppn/QF/BG shapes
- **"K^-ppn" signal [q-independent] will be seen clearly**



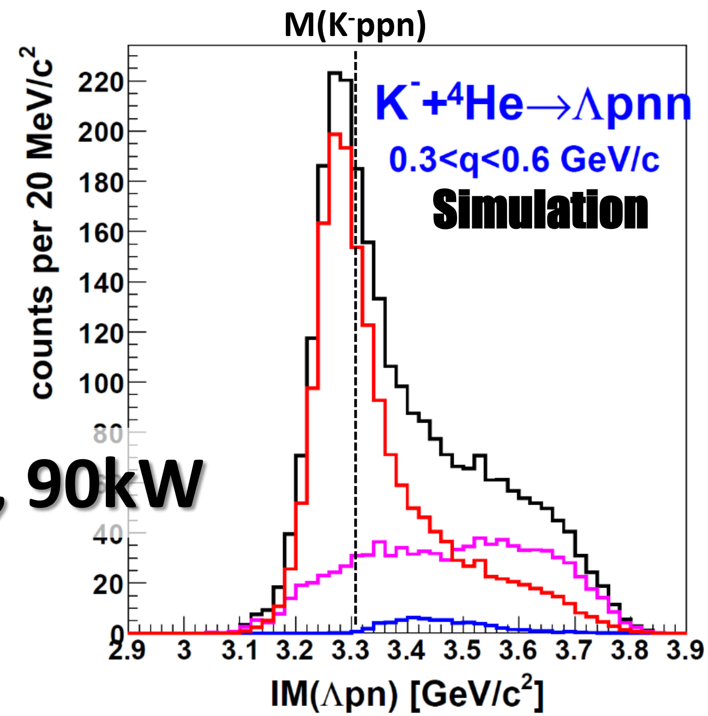
K^-ppn

Expected $\bar{K}NNN$ in $K^- + {}^4He$

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



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



@ 3 weeks, 90kW

- Assumption: similar parameters obtained at E15
- **Mass-number dependence of the kaonic nuclei will be provided for the first time.**

Summary

- **We observed the "K^-pp" bound state in $^3He(K^-,\Lambda p)n$**

J-PARC E15
✓ PLB789(2019)620., PRC102(2020)044002.

- **As the next step, the new project has been launched 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:

J-PARC E80
– **a $\bar{K}NNN$ search via $^4He(K^-,N)$ reactions as the first step**

J-PARC P89
– a spin/parity measurement of the $\bar{K}NN$ as the second step

– experimental challenges of $\bar{K}N$, $\bar{K}NNNN$, and $\bar{K}\bar{K}NN$ will also be followed

J-PARC E15 Collaboration

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

(a) Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan
(b) Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
(c) Department of Physics, Seoul National University, Seoul, 151-742, South Korea
(d) Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
(e) National Institute of Physics and Nuclear Engineering - IFIN HH, Romania
(f) Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria
(g) INFN Sezione di Torino, Torino, Italy
(h) Dipartimento di Fisica Generale, Universita' di Torino, Torino, Italy
(i) Department of Physics, Osaka University, Osaka, 560-0043, Japan
(j) Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
(k) Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
(l) Laboratory of Physics, Osaka Electro-Communication University, Osaka, 572-8530, Japan
(m) Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
(n) RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
(o) High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
(p) Technische Universität München, D-85748, Garching, Germany
(q) Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
(r) Department of Physics, Tohoku University, Sendai, 980-8578, Japan
(s) Excellence Cluster Universe, Technische Universität München, D-85748, Garching, Germany
(t) Korea Institute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea
(u) ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
(v) Department of Chemical Physics, Lund University, Lund, 221 00, Sweden
(w) Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

J-PARC E80 Collaboration

H. Asano K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma*,
T. Yamaga
RIKEN Cluster for Pioneering Research, RIKEN, Saitama, 351-0198, Japan

K. Inoue, S. Kawasaki, H. Noumi, K. Shirotori
Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan

H. Ohnishi, Y. Sada, C. Yoshida
Research Center for Electron Photon Science (ELPH), Tohoku University, Sendai, 982-0826, Japan

T. [illegible]
Japan [illegible] Energy Agency (JAEA), [illegible] 1195, Japan

M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki
High [illegible] Organization [illegible], Japan

T. Akaishi
Department of Physics, Osaka University, Osaka, 560-0043, Japan

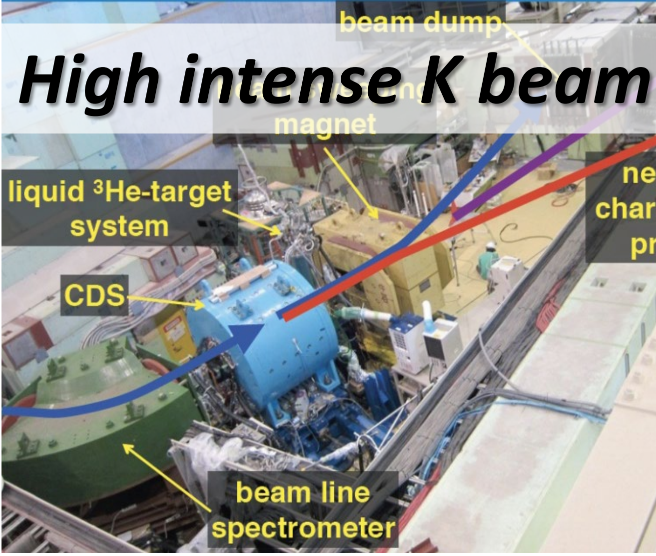
T. Nagae
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan

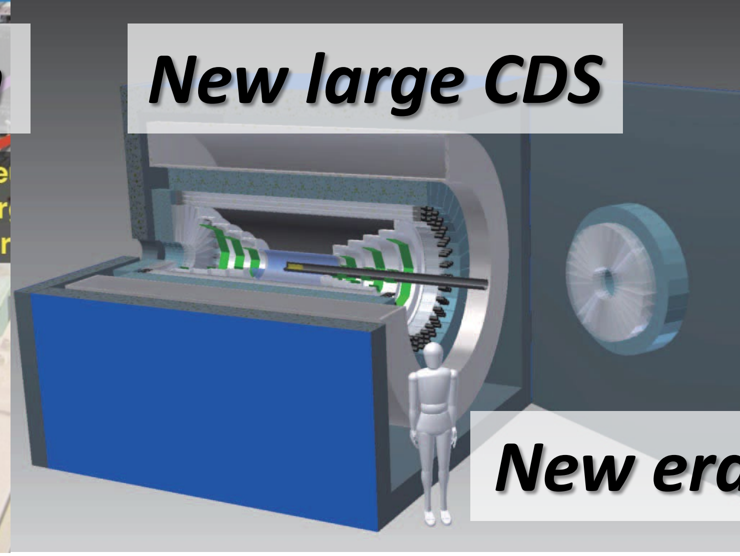
H. Fujioka
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan

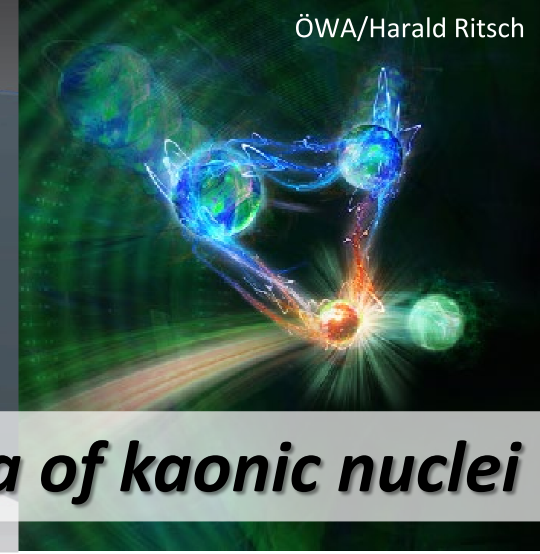
M. Bazzi, A. Clozza, C. Curceanu, C. Guaraldo, M. Iliescu, M. Miliucci, A. Scordo,
D. Sirghi, F. Sirghi
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy

P. Buehler, M. Simon, E. Widmann, J. Zmeskal
Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria

We're looking for new collaborators!

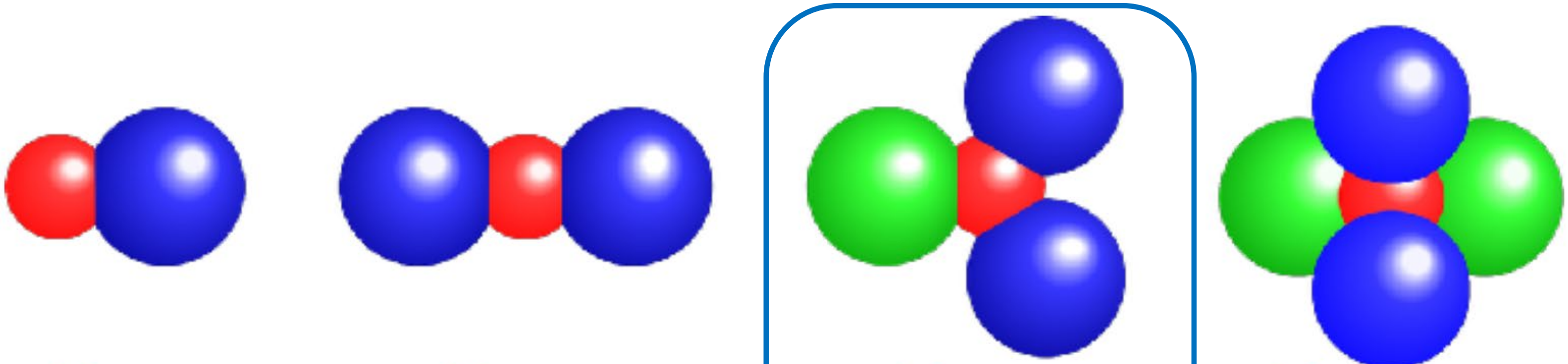






Thank you for your attention!

A first step of the new project



K^-p K^-pp K^-ppn K^-ppnn

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

Investigation of fundamental properties of the $\bar{K}NN$ state

J-PARC P89

J-PARC P89

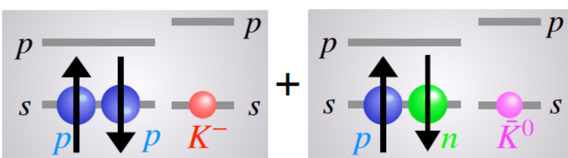
7

Internal structure & spin-parity

There are two possible J^P as for the $\bar{K}NN$ ground state.

$$" (NN)_{(I.sym \times S.asym)} \otimes \bar{K} "$$

$J^P = 0^-$

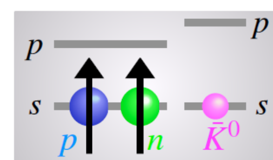


$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{3}{1}$$

Deeper bound expected

$$" (NN)_{(I.asym \times S.sym)} \otimes \bar{K} "$$

$J^P = 1^-$



$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{1}{3}$$

Shallower bound expected

** Positive parity state should be higher excited state if exist.*

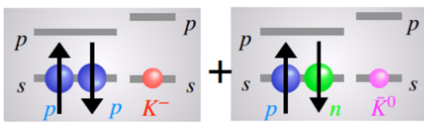
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

How to determine J^P

– Λp spin-spin correlation ($\alpha_{\Lambda p}$) in $K^- pp \rightarrow \Lambda p$ decay –

$J^P = 0^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 0$

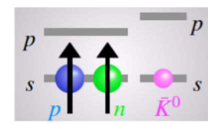
$S_{\Lambda p} = 1$

↓

$\alpha_{\Lambda p} = +1$

Spin parallel

$J^P = 1^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 1$

$BR = 1/3$ $S_{\Lambda p} = 0$ + $S_{\Lambda p} = 1$ $BR = 2/3$

↓ ↓

$\alpha_{\Lambda p} = -1$ + $\alpha_{\Lambda p} = +1$

Spin anti-parallel / Spin parallel

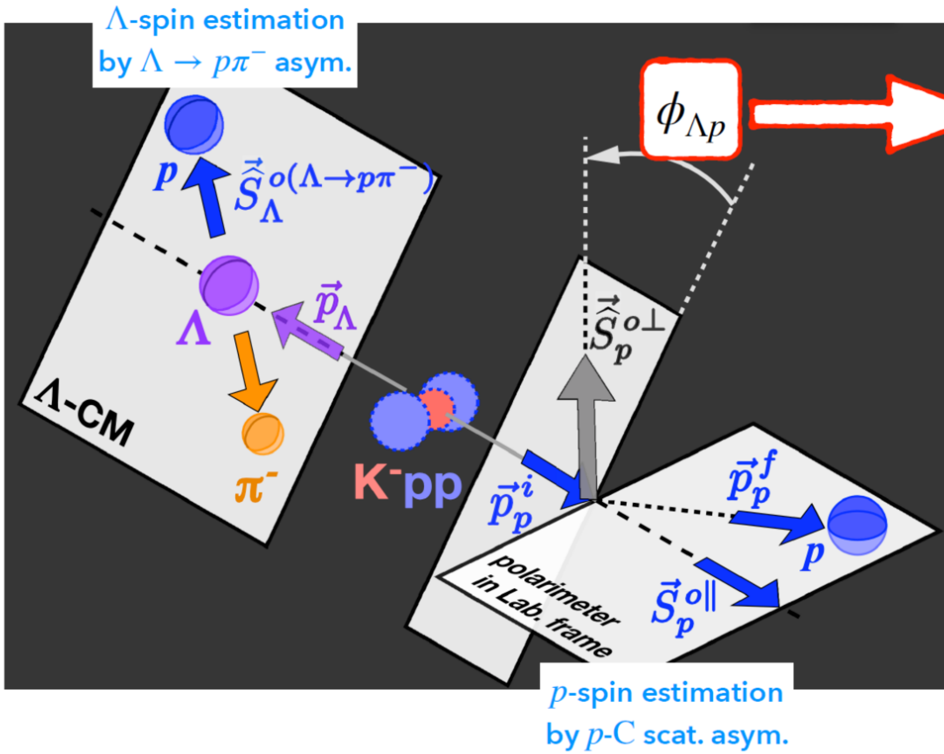
We can deduce J^P from $\alpha_{\Lambda p}$ measurement.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

How to measure spin-spin correlation

– Spin alignment measurement by $\Lambda \to p\pi^-$ & p-C scattering –



Spin-spin correlation on ϕ-asymmetry

$$N(\phi_{\Lambda p}) = N_0 \cdot (1 + r^{(J^P)} \cdot \alpha_{\Lambda p} \cos \phi_{\Lambda p})$$

$r^{(J^P)}$: asymmetry reduction factor defined by;

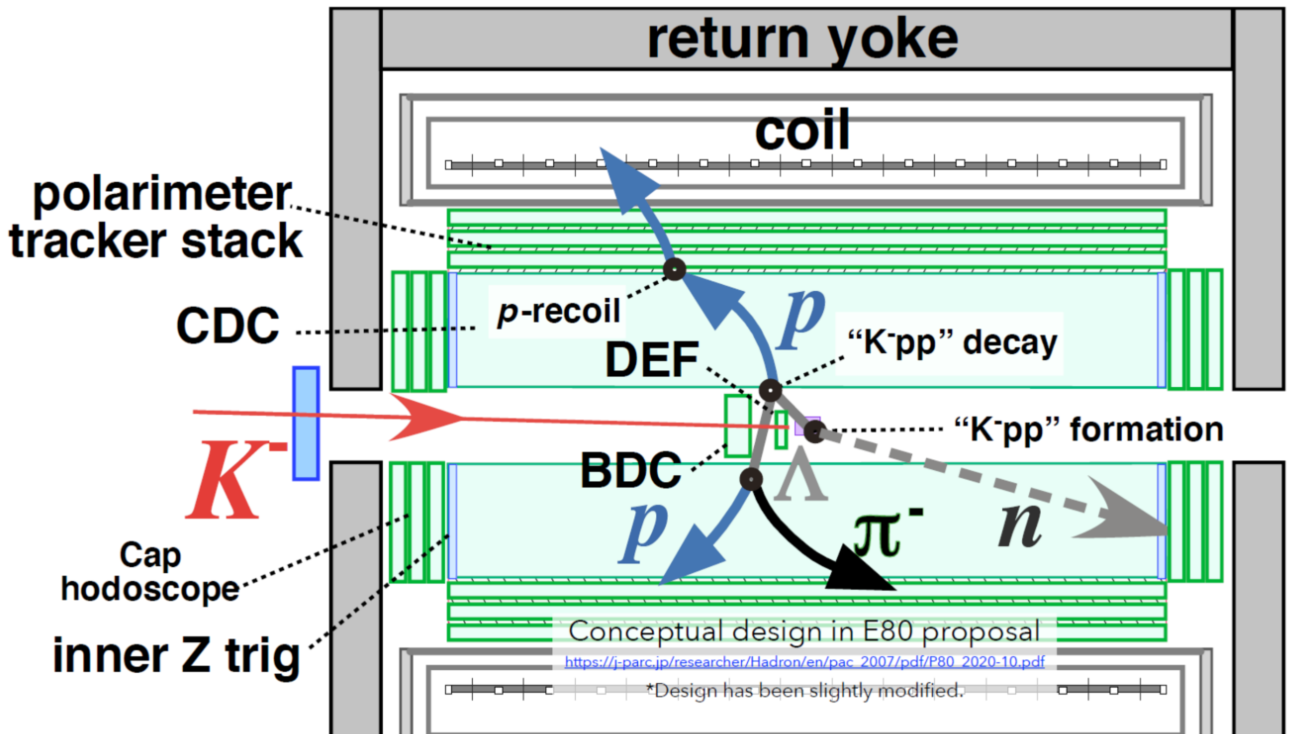
α_- : Λ asym. parameter	B : Magnetic field
$A_{p\mathrm{C}}$: Analyzing power	$B_{\bar{K}}$: Binding energy
$f_{\vec{S}_\Lambda}$: Spin distribution	q : Momentum transfer

We can observe $\alpha_{\Lambda p}$ from $\phi_{\Lambda p}$-distribution.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

Cylindrical detector system



$\sim 4\pi$ acceptance for charged & neutron

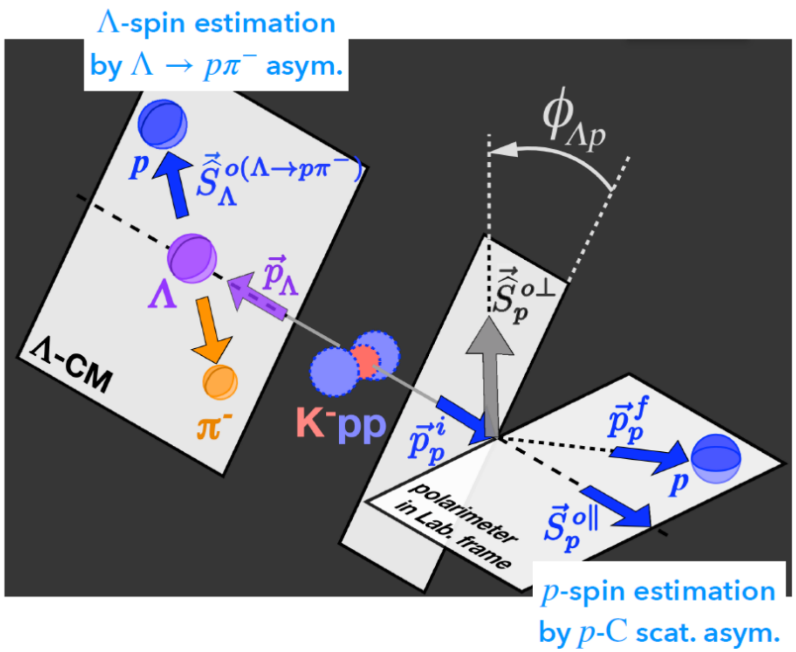
Polarimeter system for p-spin measurement

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

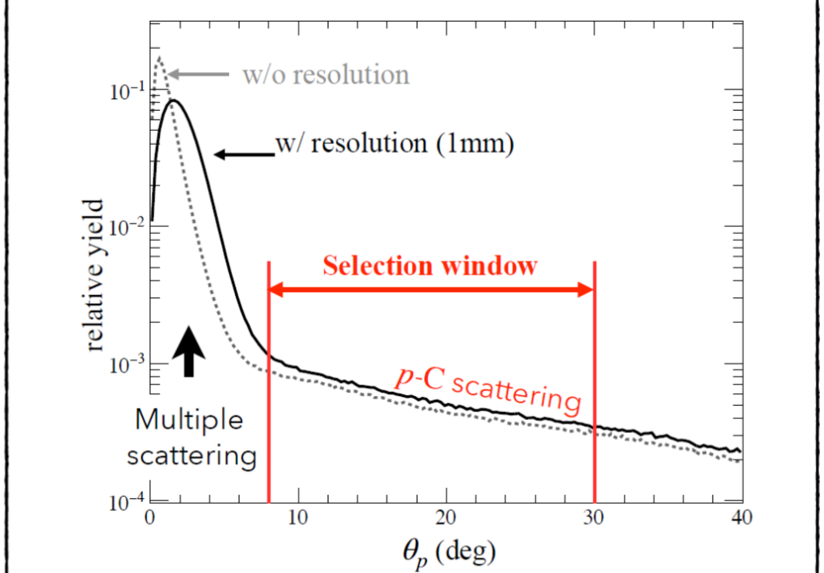
J-PARC P89

Expected spectra

– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –



Event selection for p-C scattering



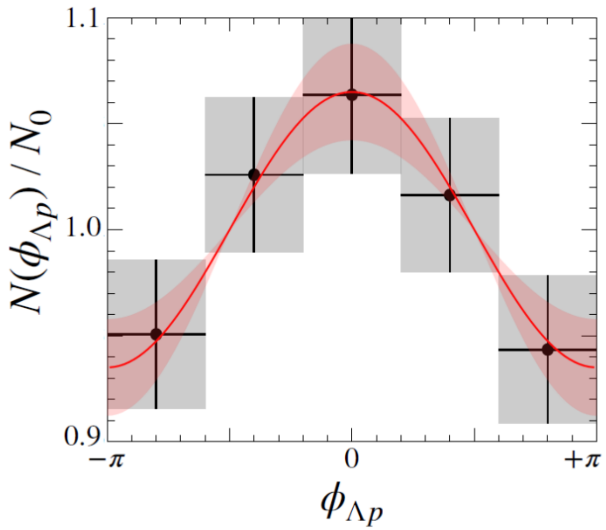
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

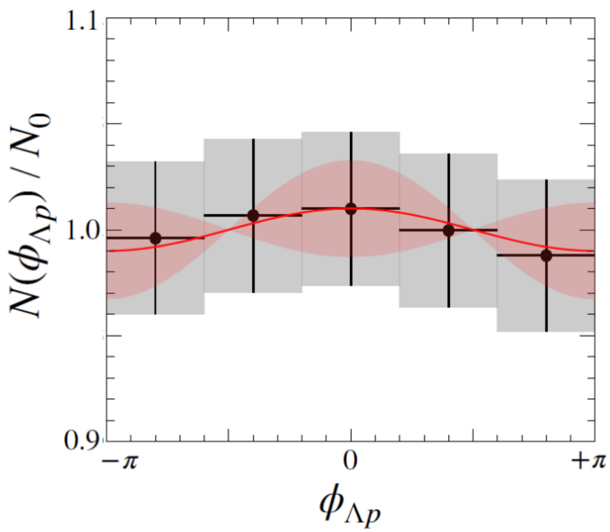
Expected spectra

– To measure $\phi_{\Lambda p}$-asymmetry for J^P determination –

$J^P = 0^-$



$J^P = 1^-$



We would exclude $J^P = 1^-$ with **95%** confidence level from **only $\phi_{\Lambda p}$-asym**.

T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

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)

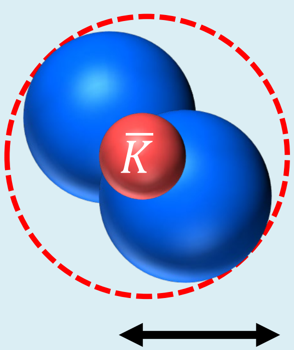
→ *Need more realistic theoretical calculations*

a whole new probe to reveal
the structure of a nucleon

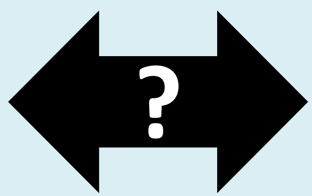
Still an open question ($\bar{K}N$ – strong force)

Radius of "K^-pp"

Interaction range of "K^-"

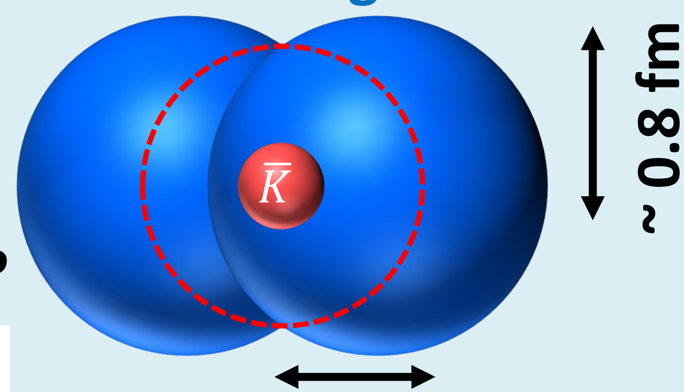


~ 0.6 fm



& effect of K size?

Charge radius
$\langle r \rangle = 0.560 \pm 0.031$ fm



~ 0.6 fm

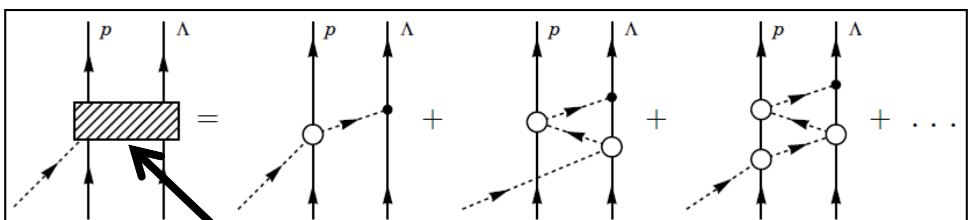
A Theoretical Interpretation

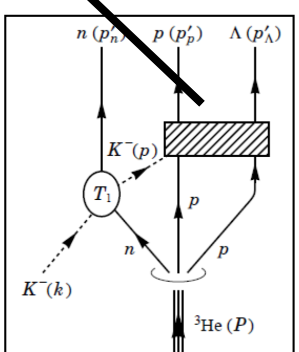
- A calculation with chiral unitary approach reproduces the mass spectrum with the $\bar{K}NN$

PTEP
Prog. Theor. Exp. Phys. 2016, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

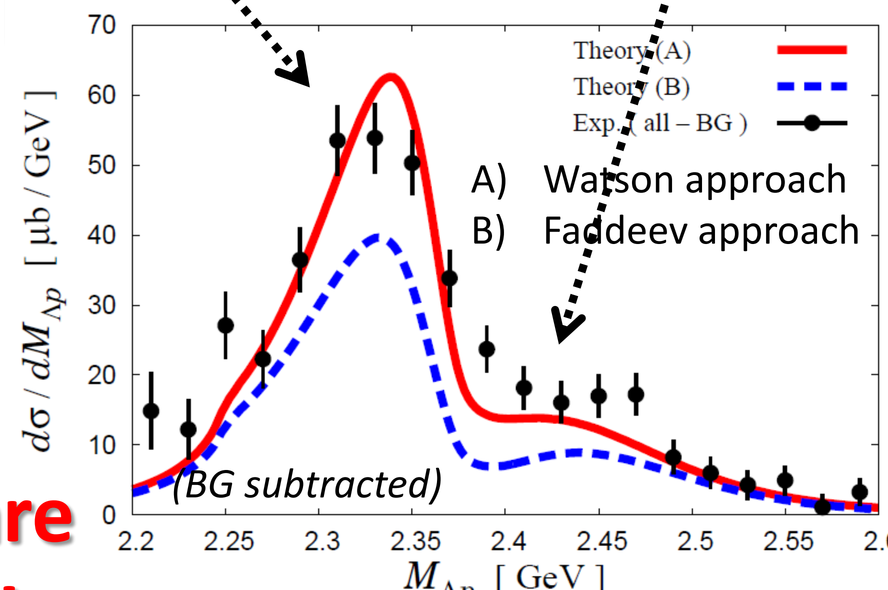
On the structure observed in the in-flight ^{3}He$(K^-, \Lambda p)n$ reaction at J-PARC

Takayasu Sekihara[1,*], Eulogio Oset[2], and Angels Ramos[3]





Theoretical investigations are indispensable!



JPS Conf. Proc.26(2019)023009.

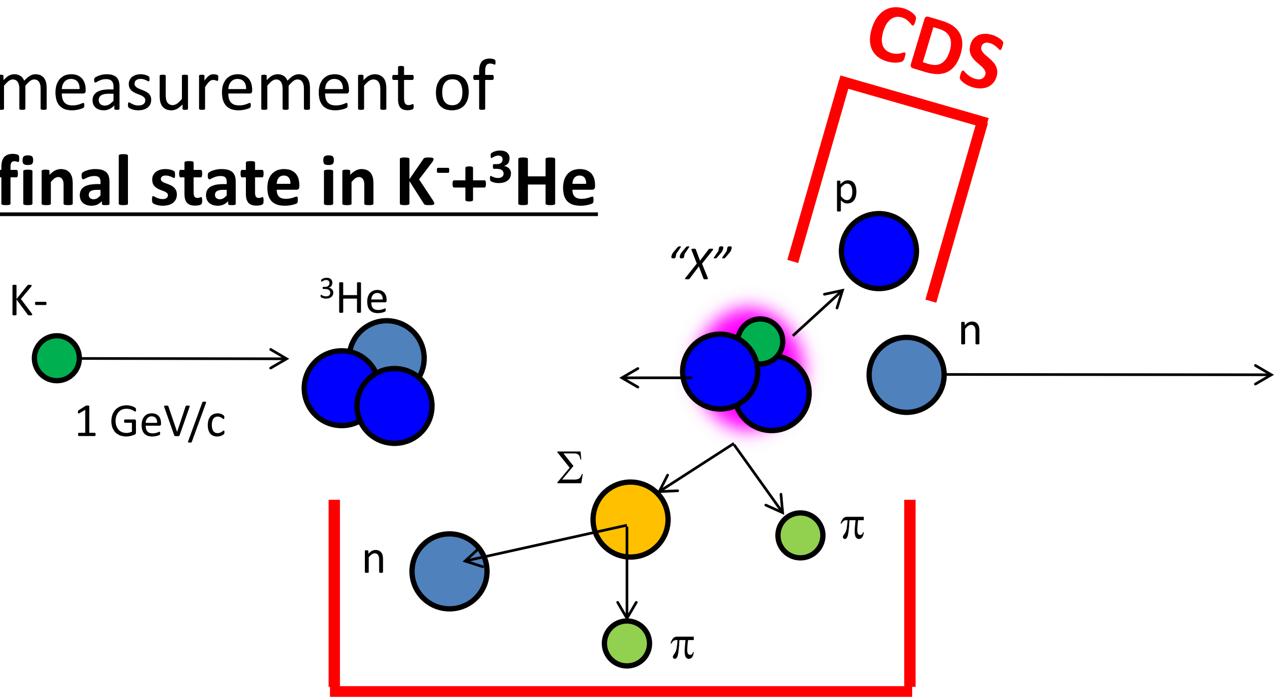
Many Questions to be Answered

- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K^-pp"?
  - Really compact and dense system?
  - Other decay modes?

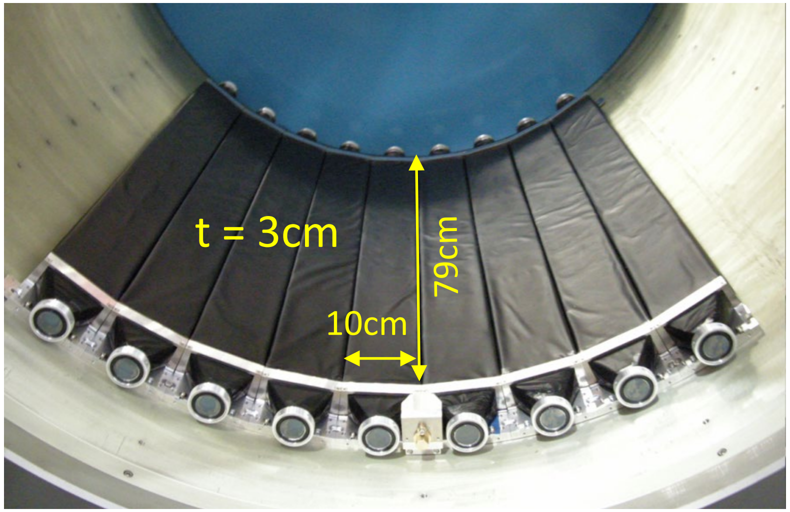
- **πΣN mesonic decay**
  - expected to be the dominant channel
    - only YN non-mesonic decays were reported
- **Reaction mechanism**
  - relation between Λ(1405)="K^-p" & "K^-pp"
    - "K^-pp" is expected to be produced via Λ(1405)+p→"K^-pp" door-way process

$K^-\ {}^3He \rightarrow \pi\Sigma pn$ @ E15

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



CDS

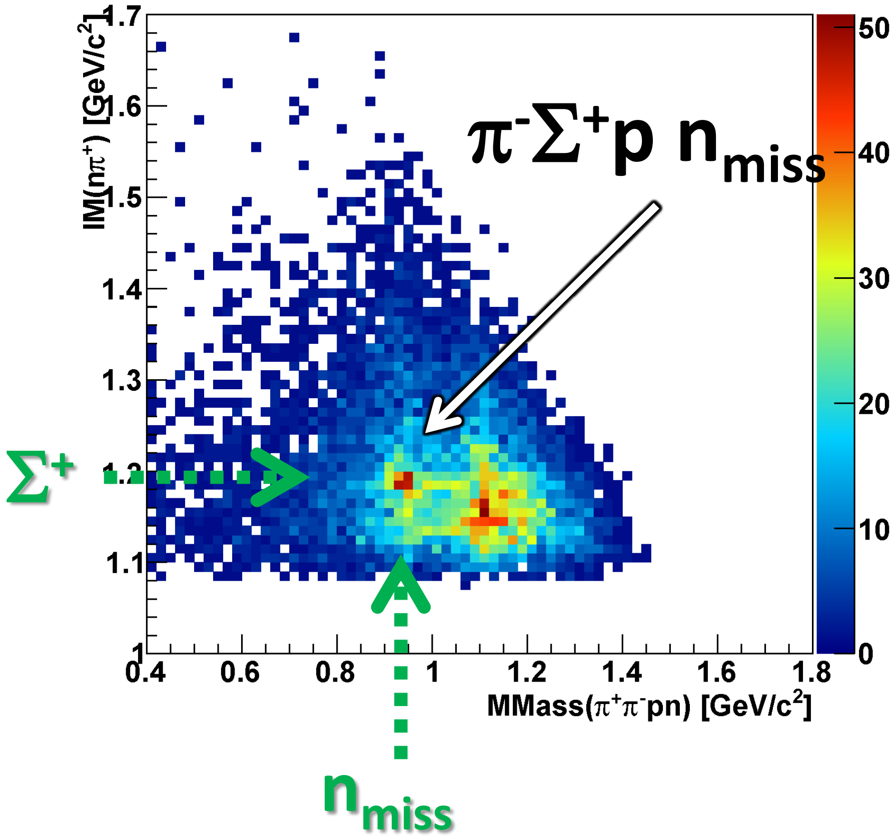


- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

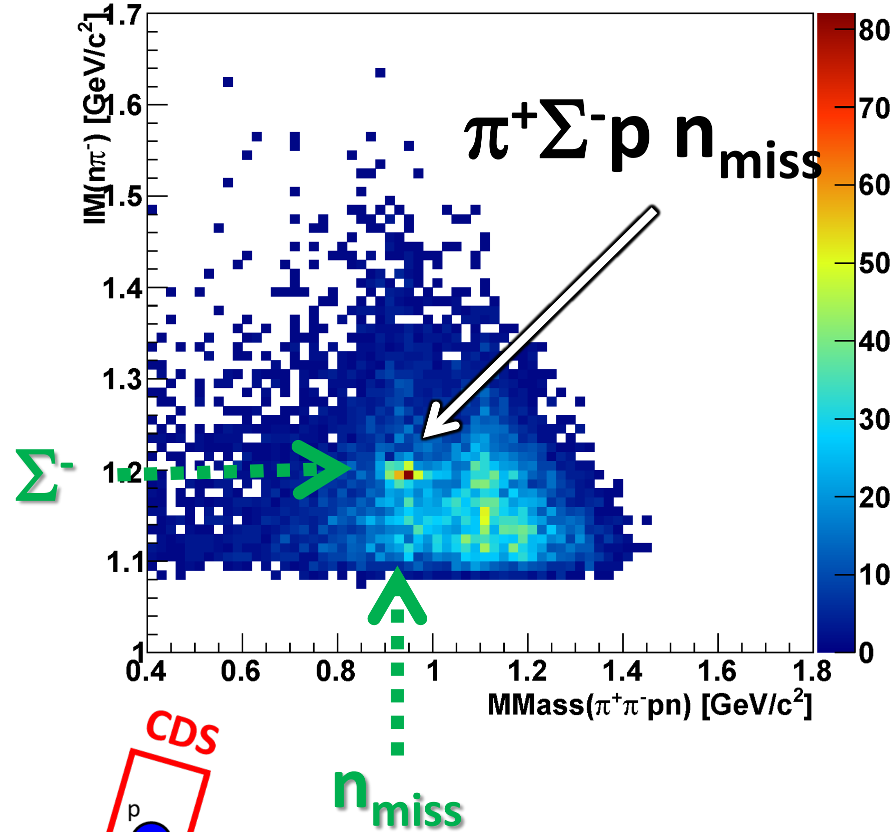
n detection efficiency ~ 3-10%

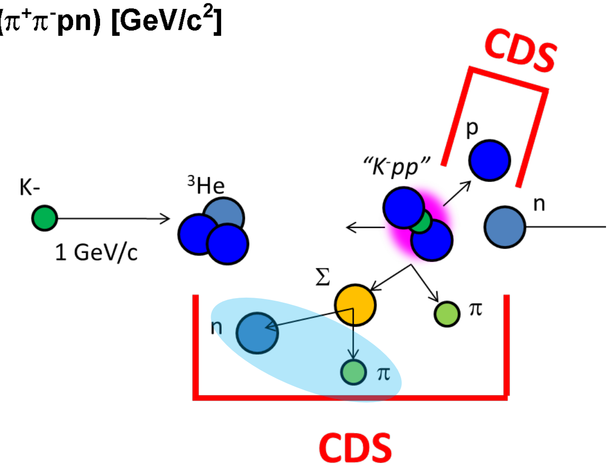
$\pi\Sigma pn$ Events

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

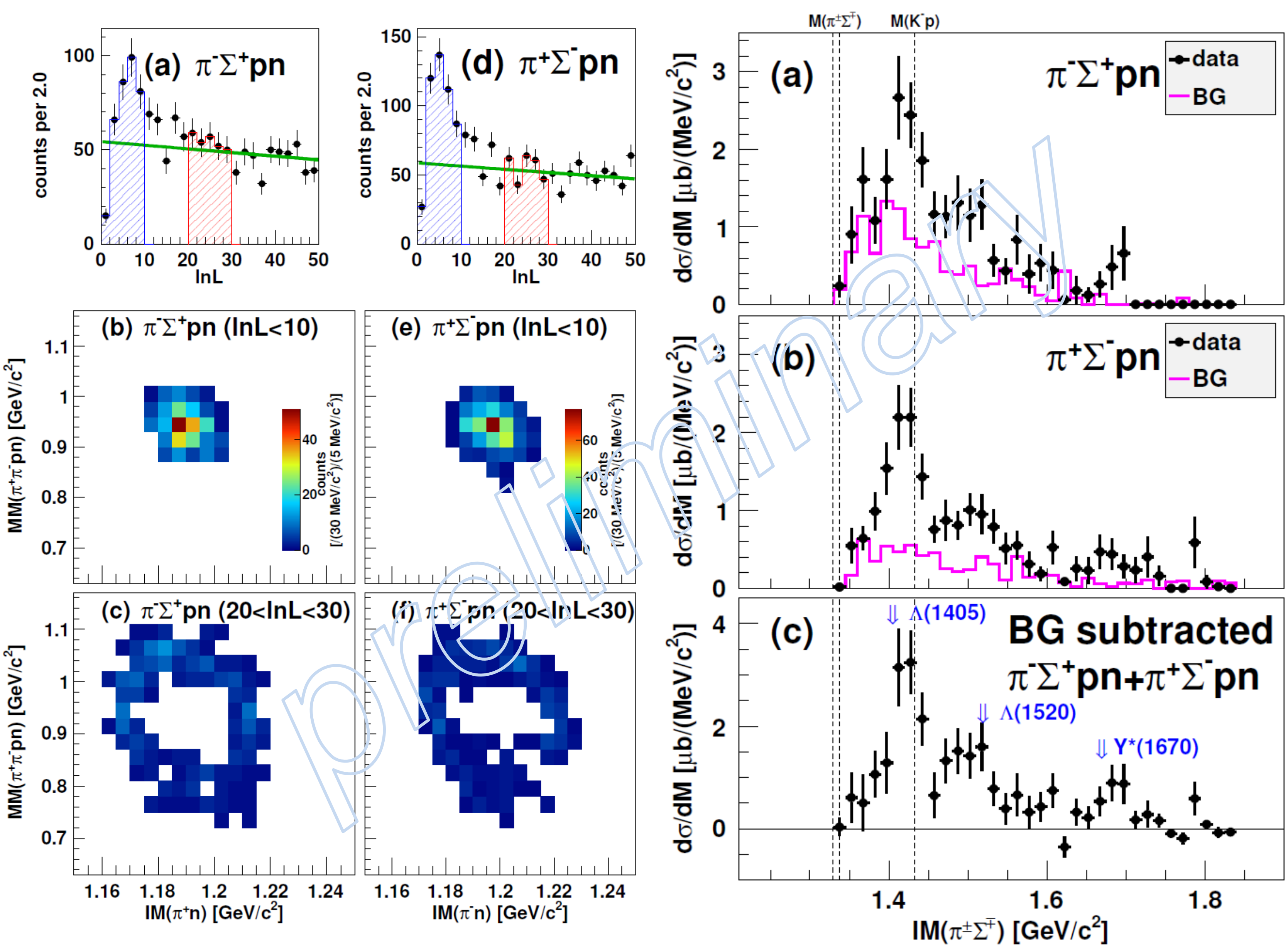


$IM(n\pi^-)$ vs $MM(\pi^+\pi^-pn)$



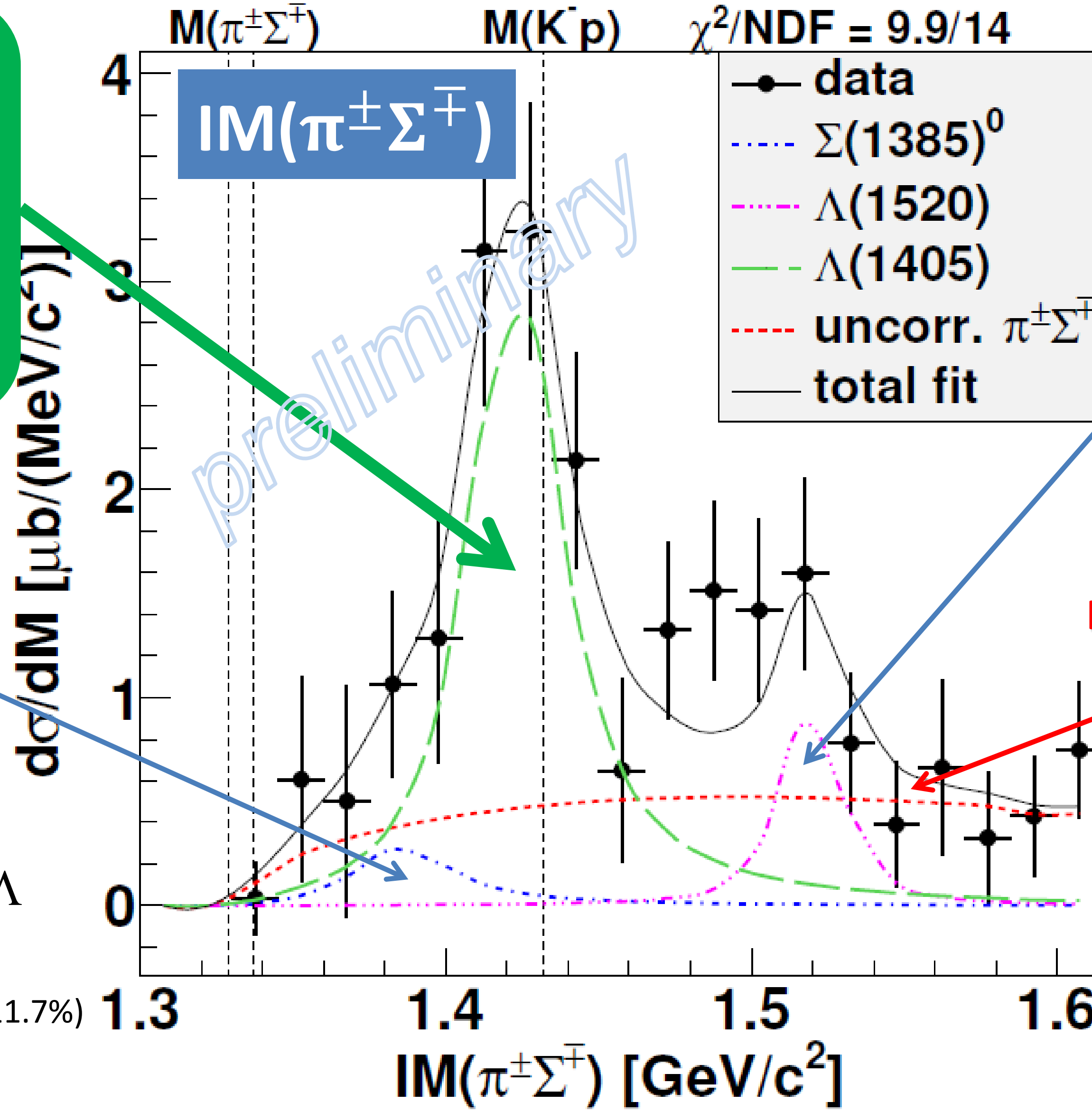


BG Subtracted IM($\pi^\pm\Sigma^\mp$) in $\pi^\pm\Sigma^\mp pn$



$Y^{*}pn$ Final State

Λ(1405)
~ 250 μb
Fit with BW:
M ~ 1422 MeV
Γ ~ 40 MeV



Σ(1385)⁰
~ 100-150 μb
[evaluated from $\Sigma(1385)^{+/-} \rightarrow \pi^{+/-}\Lambda$ measurement]
($\Sigma(1385) \rightarrow \pi\Lambda/\pi\Sigma$: 87.0/11.7%)

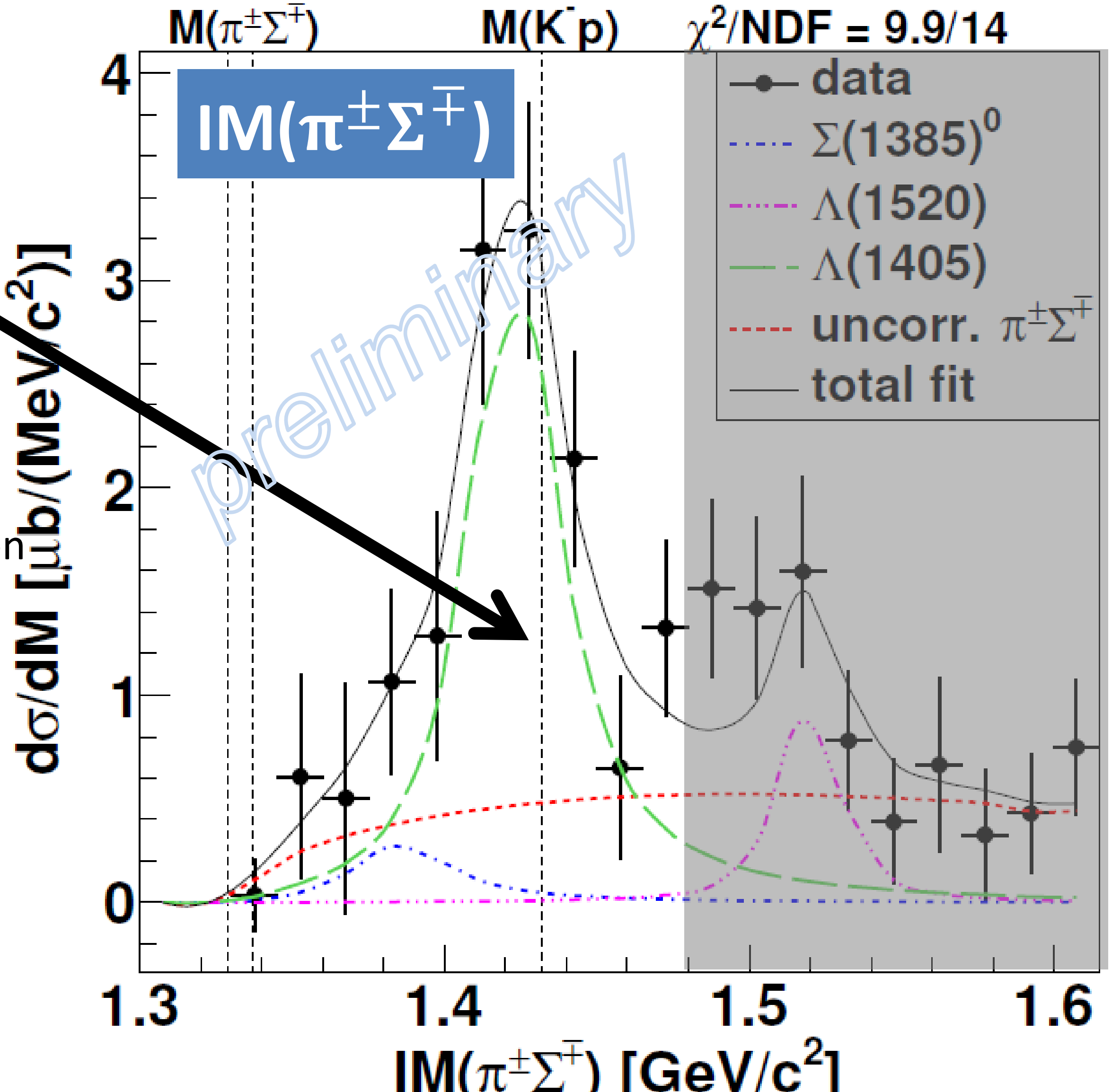
Λ(1520)
~ 100 μb

πΣpn
non-resonant

$\Lambda(1405)pn$ Final State Selection

Select $\Lambda(1405)$ region

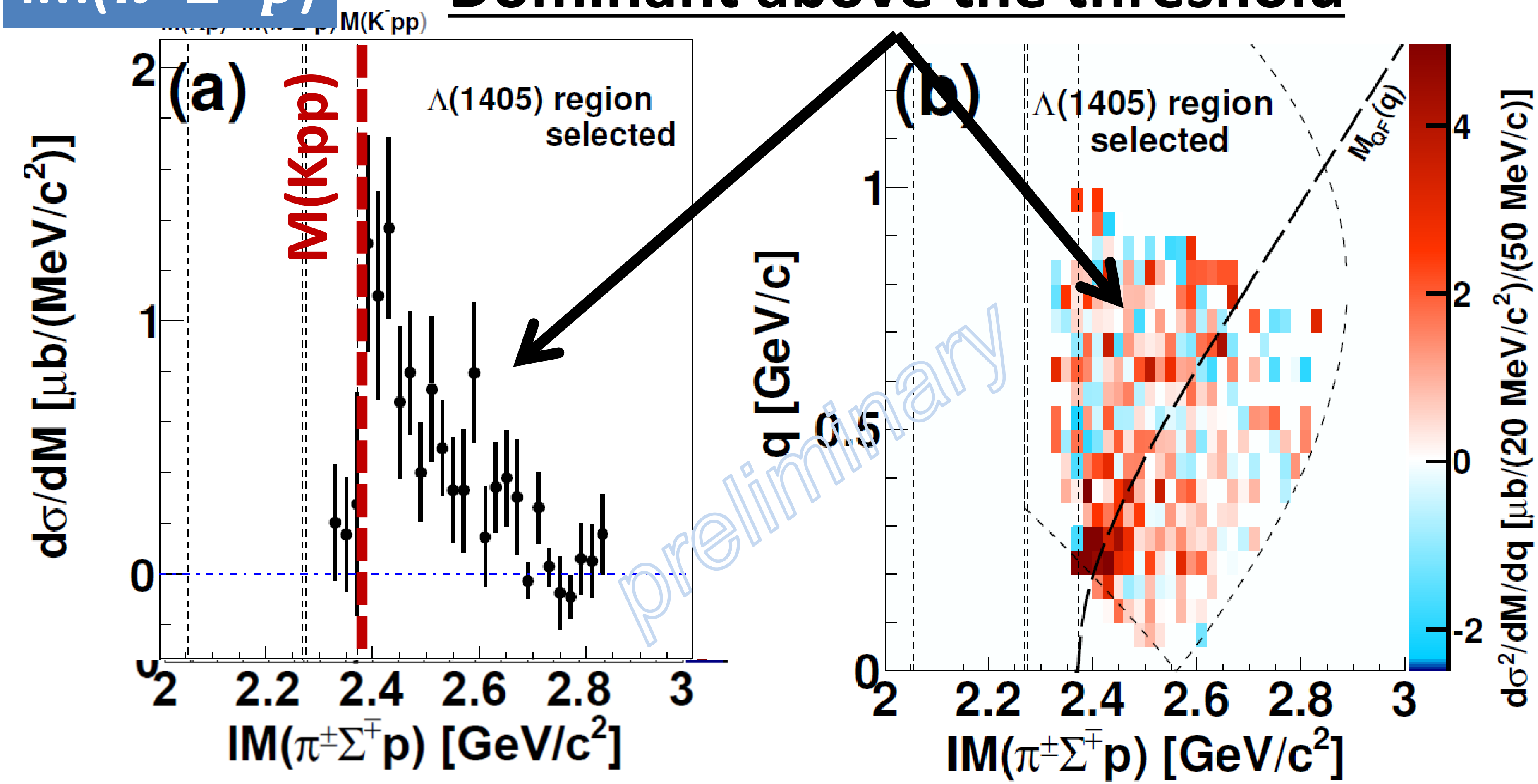
- Below $\Lambda(1520)$
- Small contribution from $\Sigma(1385)$



IM(πΣp) in Λ(1405)pn Final State

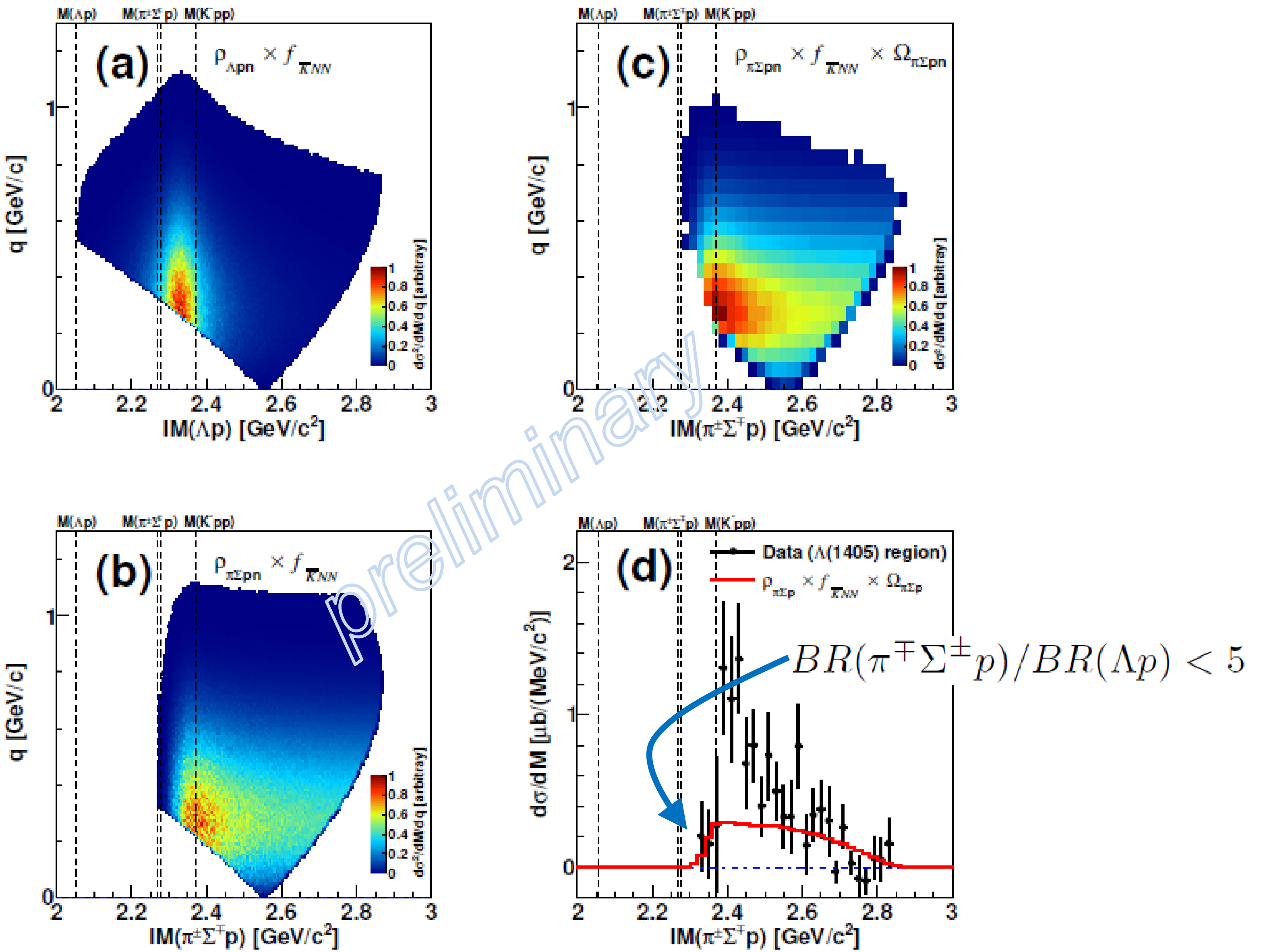
IM($\pi^{\pm}\Sigma^{\mp}p$)

Dominant above the threshold



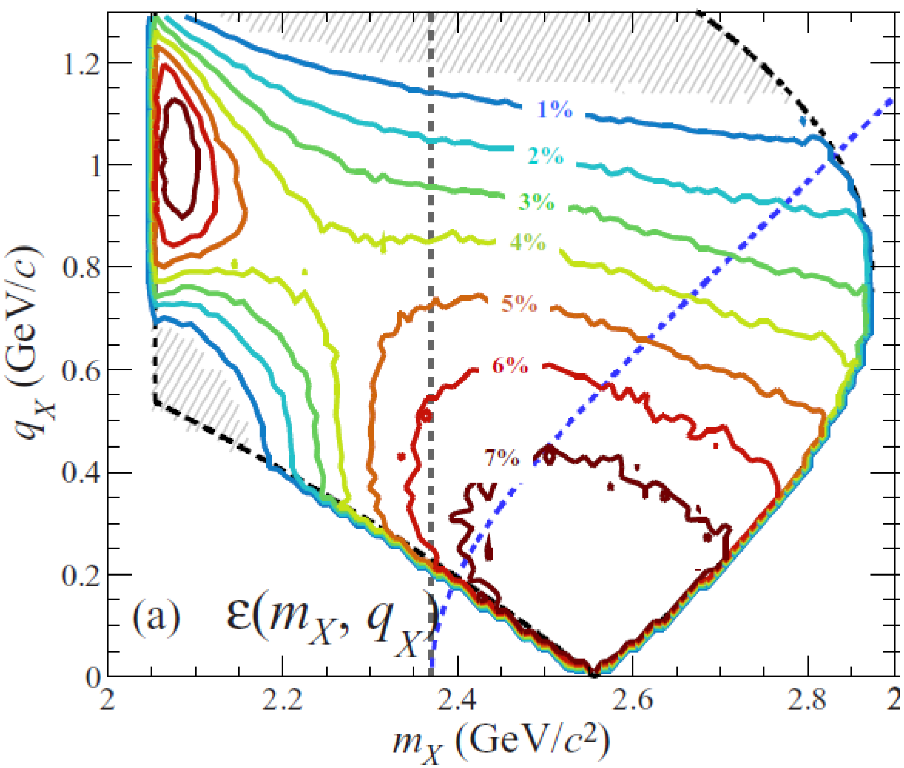
- IM(Λ(1405)p) distributes above the M(Kpp)
- QF $K^{-}N \rightarrow K^{bar}n$ followed by $K^{bar}NN \rightarrow \Lambda(1405)p$

Investigation of $K^-pp \rightarrow \pi\Sigma p$ decay

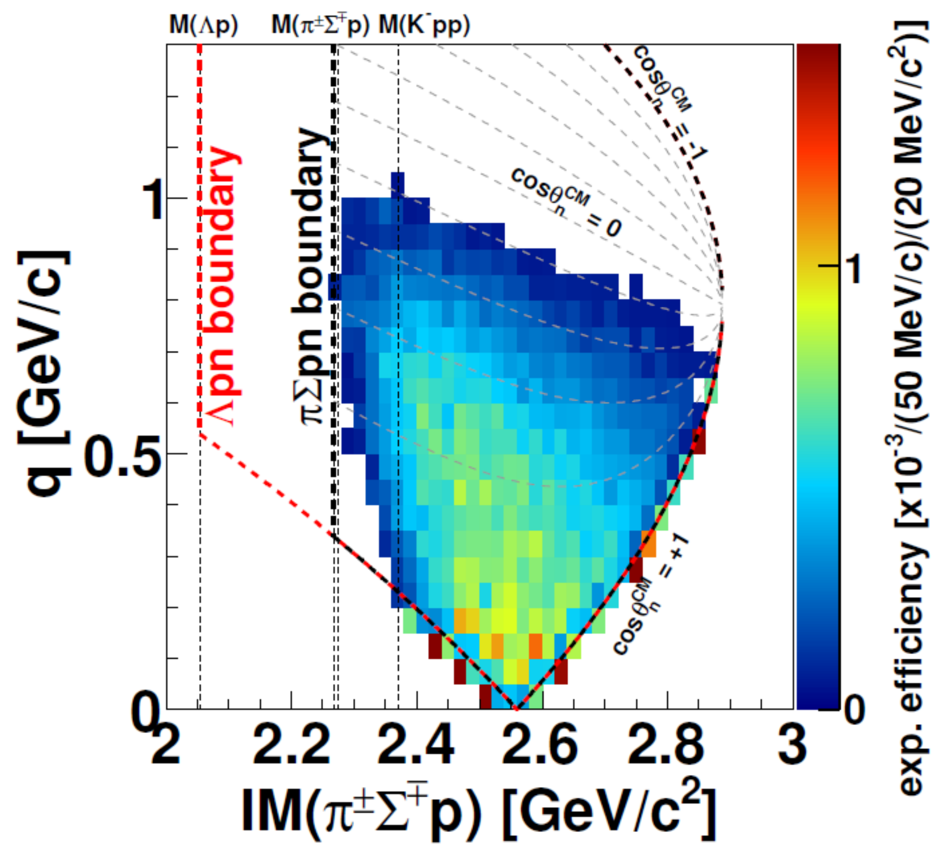


Detector acceptances of Λpn and πΣpn

Λp

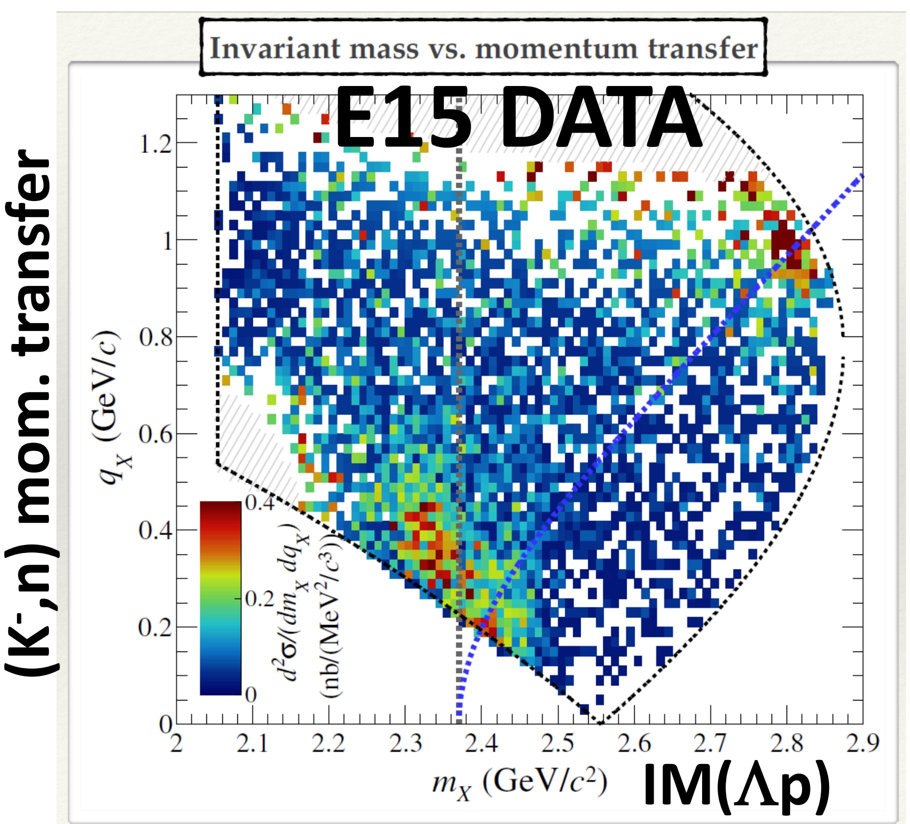


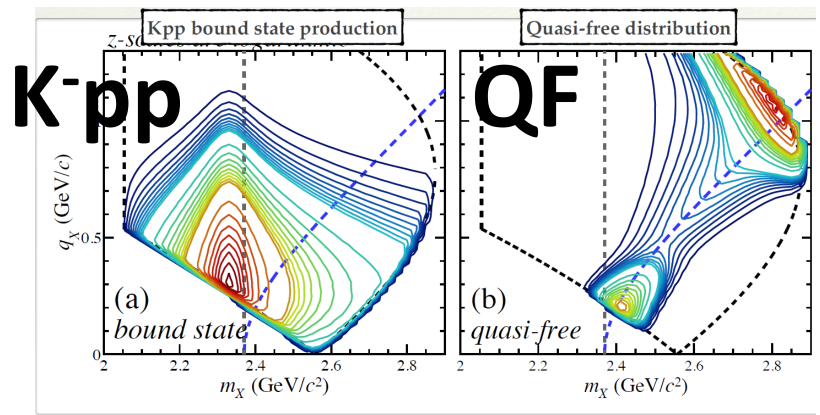
πΣp

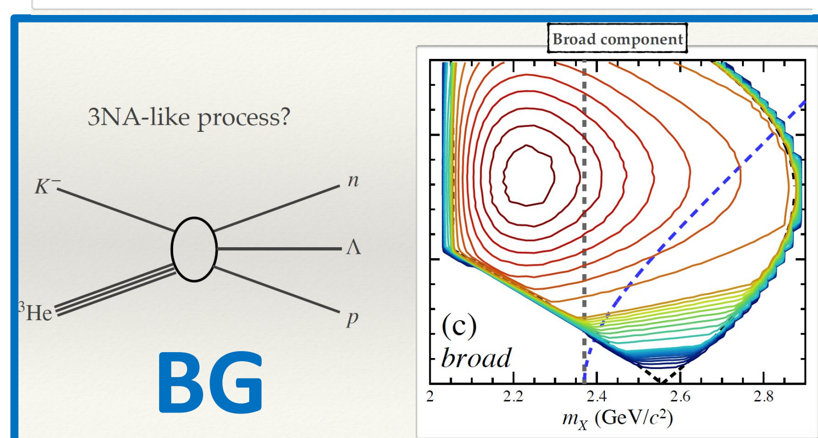


Recent progress of the E15 analysis

- In the E15 analysis so far, we assumed a point-like 3NA process for the background to explain the IM(Λp) spectrum, by parametrizing a fitting function

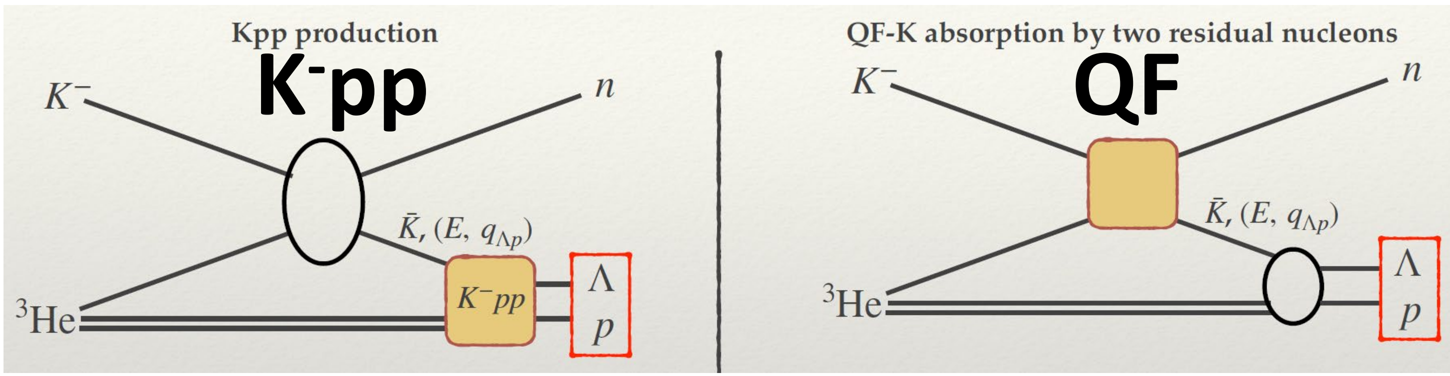




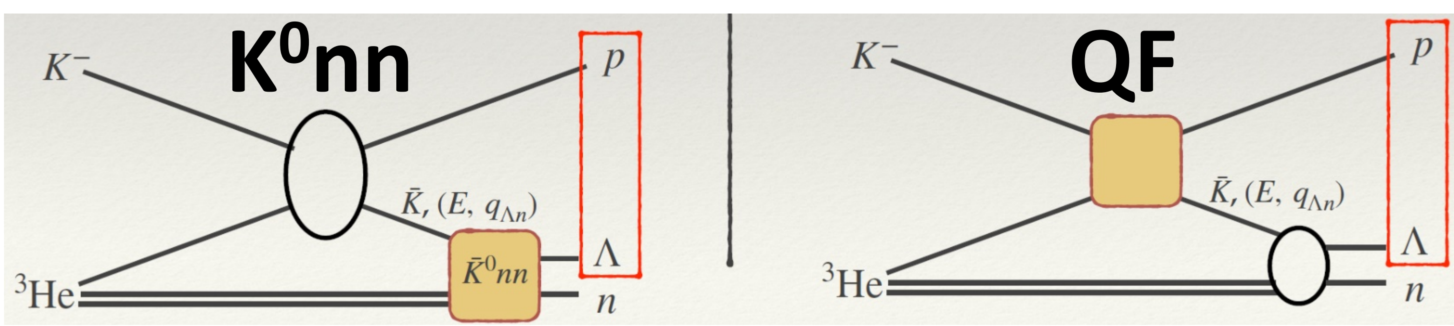


Recent progress of the E15 analysis

- For the K^-pp and QF, we assume the following processes



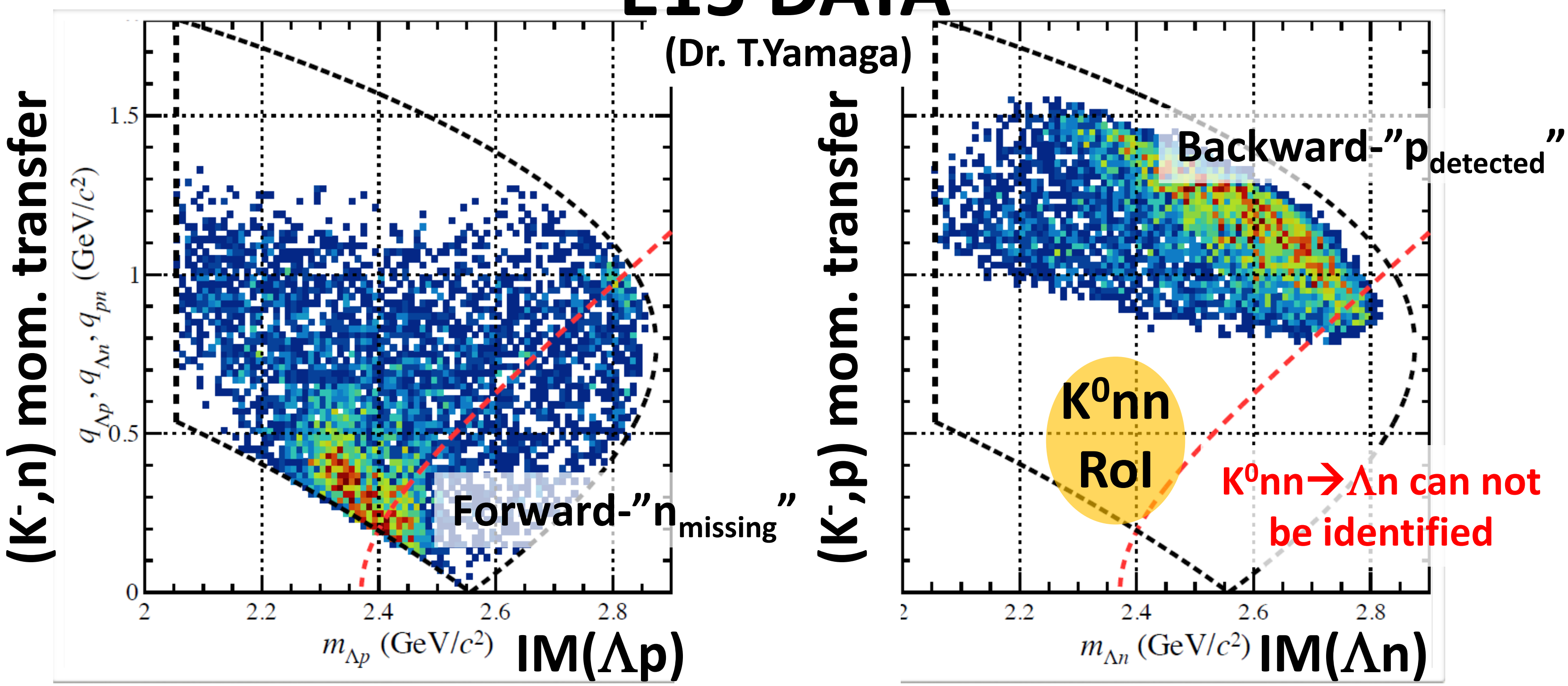
- On the other hand, "p" and "n" can be swapped in the reactions when the isospin partner of the K^-pp (=K^0nn) is also generated



Recent progress of the E15 analysis

- IM(Λp) and IM(Λn)
  - ➢ Acceptances are quite different between the "Λp" and "Λn"
  - ➢ In IM(Λn), a forward going proton is out of the acceptance

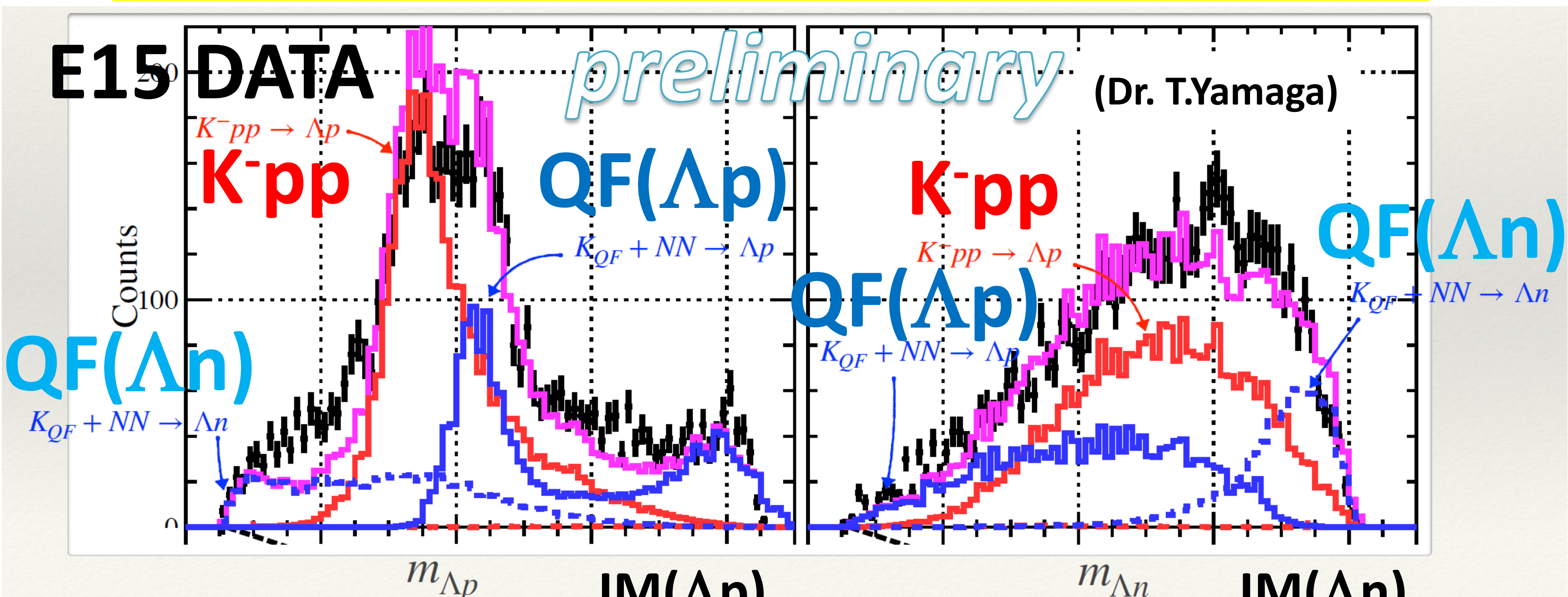
E15 DATA



Recent progress of the E15 analysis

- Both of IM(Λp) and IM(Λn) can be reproduced by the "signal" and "QFs"
  - Eye fit results → further analysis is on going

need further data with the new 4π spectrometer



(all mom. transfer region selected)

Σ*N bound state? Other possibilities?

Σ(1385) 3/2+ $I(J^P) = 1(\frac{3}{2}^+)$

Σ(1385) DECAY MODES	Fraction (Γ_i/Γ)
$\Lambda\pi$	(87.0 ±1.5) %
$\Sigma\pi$	(11.7 ±1.5) %

- Σ* coupling through K^{bar}-N channel (P-wave) would be weak
  - ✓ A.Cieply et al., PRC84(2011)045206, etc.
- Naively, Σ*N system with $1^+/2^+$ state (S-wave) could not be bound, because corresponding ΔN system (non-strangeness sector) is considered to be no-bound or quite-weakly bound
  - ✓ R. D. Mota et al., PRC59(1999)46, etc.

need J^P determination with a polarimeter

- The K^{bar}NN state (I=1/2, J^P=0$^-$) is calculated with a K^{bar}NN-□ N-□ N coupled channel system, where the □ N coupling is expected to be small
- The K^{bar}NN state with J^P=1$^-$ (K^{bar}-d like configuration) is expected to not be bound, or have small B.E.
  - ✓ S.Ohnishi et al., PRC95(2017)065202, etc.

Σ*N bound state? Other possibilities?

- One theoretical possibility is a "πΛN-πΣN dibaryon"

Nuclear Physics A 897 (2013) 167–178

Relativistic three-body calculations of a $Y = 1$, $I = \frac{3}{2}$, $J^P = 2^+$ $\pi \Lambda N$–$\pi \Sigma N$ dibaryon

H. Garcilazo [a], A. Gal [b,*]

- Calculated πΛN resonance with **Σ*N-ΔΣ** configuration is:
  - I=1/2, $J^P=2^+$: **E = -10-i52 MeV**
  - I=3/2, $J^P=2^+$: **E = -120-i2.6 MeV** with respect to M(K^{bar}NN)
- The obtained K^-pp parameter at E15 is **E=-40-i50 MeV**
- Therefore, the "observed K-pp structure" would be different from the "πΛN-πΣN dibaryon"

"K^-ppn" Candidates so far

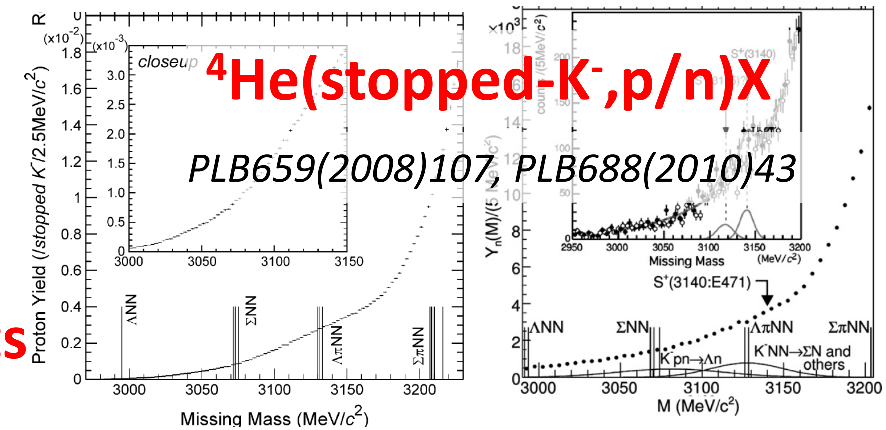
- A few candidates have been reported in ***inclusive*** measurements

◆ **E471/E549@KEK** ← **NULL results**
  - ^{4}He(stopped-K^-,p/n)X

◆ **FINUDA@DAΦNE** ← **Observed?**
  - Li/C(stopped-K^-,Λd)

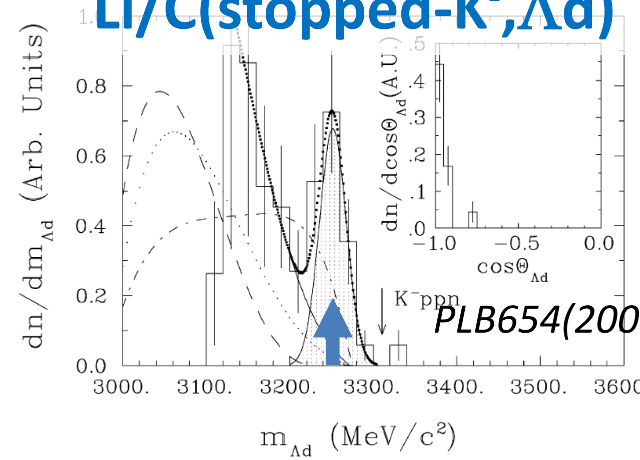
◆ **FOPI@GSI** ← **Observed?**
  - Λd in Ni+Ni

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



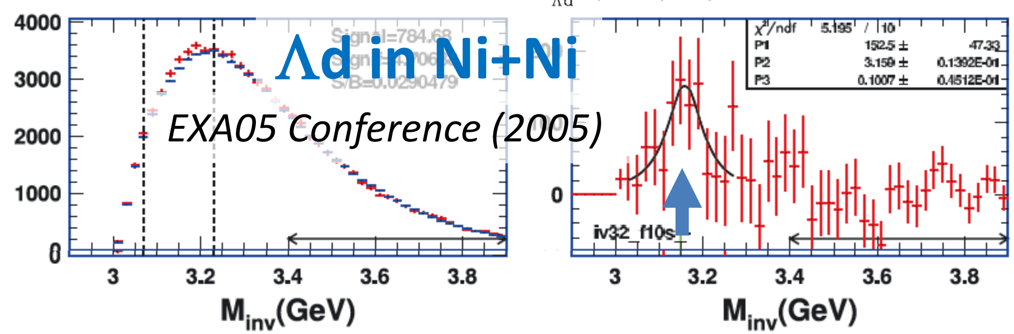
^{4}He(stopped-K^-,p/n)X

PLB659(2008)107, PLB688(2010)43



Li/C(stopped-K^-,Λd)

PLB654(2007)80

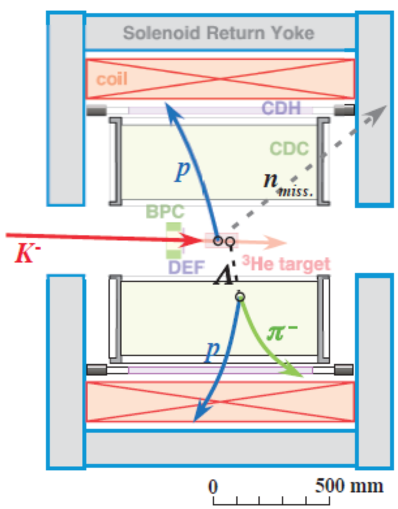


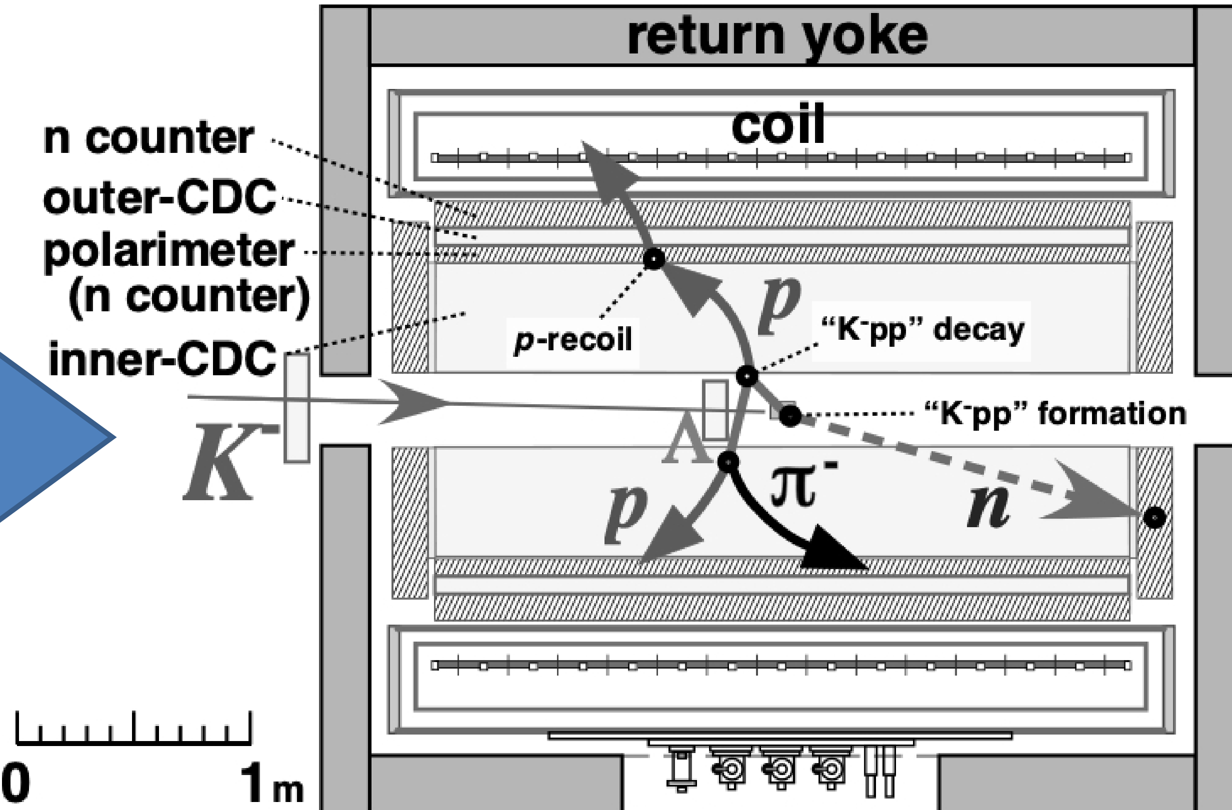
Λd in Ni+Ni

EXA05 Conference (2005)

A New Cylindrical Detector System

present setup





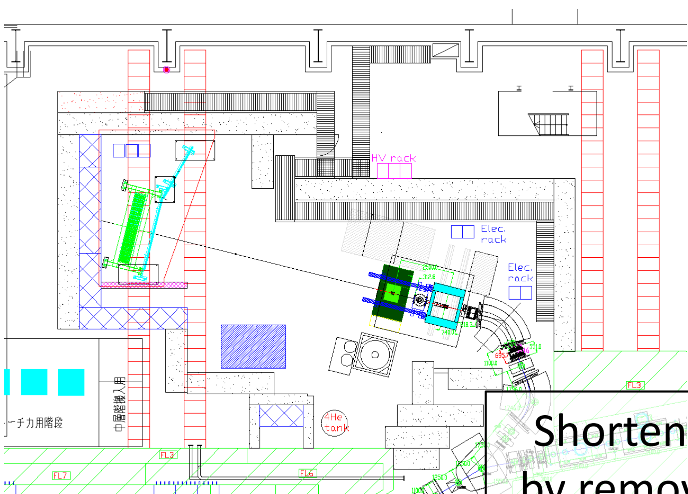
- **SC Solenoid Magnet**
- **Cylindrical Drift Chamber**
- **Neutron Counter**
- FWD/BWD Drift Chambers
- Vertex Fiber Tracker
- Electromagnetic Calorimeter (constructed in 2nd-stage)

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

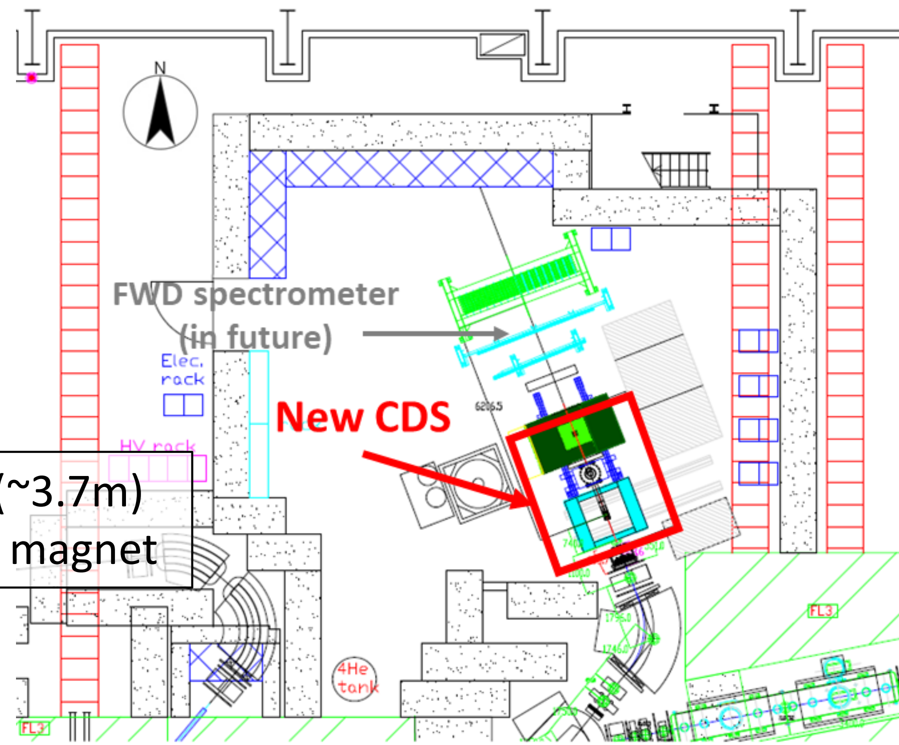
Neutron detection capability: ~x10 (~1.5x15%)

Improvement of Kaon Intensity

K1.8BR beamline



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



- **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 $\bar{K}NNN$

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

- We assume the K^-ppn cross section of

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

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

PRD1(1970)1267

Expected Yield of $\bar{K}NNN$

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

- N_{beam} = **100 G** K- on target
  - under the MR beam power of **90 kW** with **5.2 s** repetition cycle.
    - 3.2 x 10^5 K- on target / spill @ 1.0 GeV/c

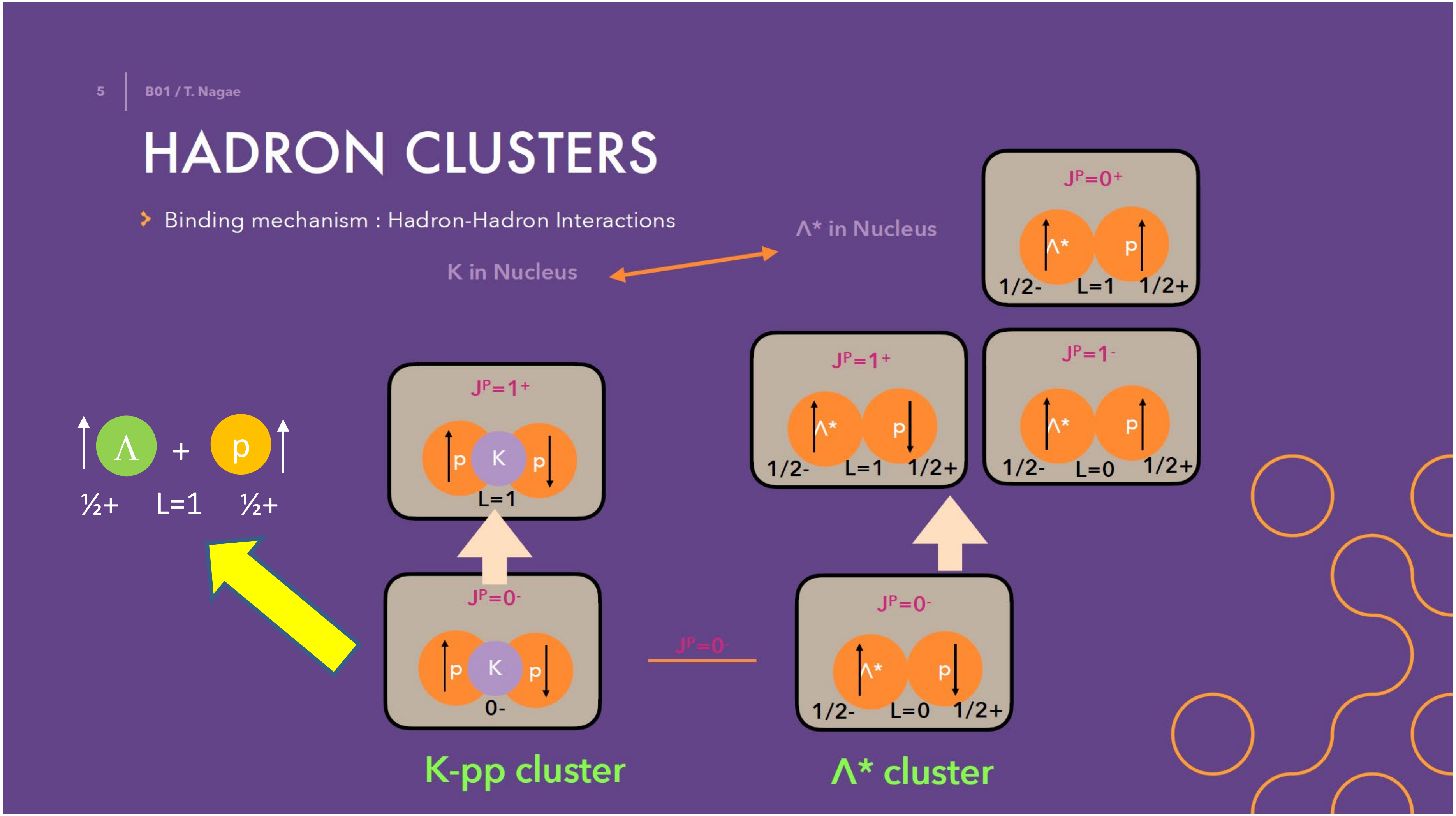
around 2024

  - **3 weeks** data taking (90% up-time)
- **N(K^-ppn→Λd) ~ 2 x 10^4**
- **N(K^-ppn→Λpn) ~ 3 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

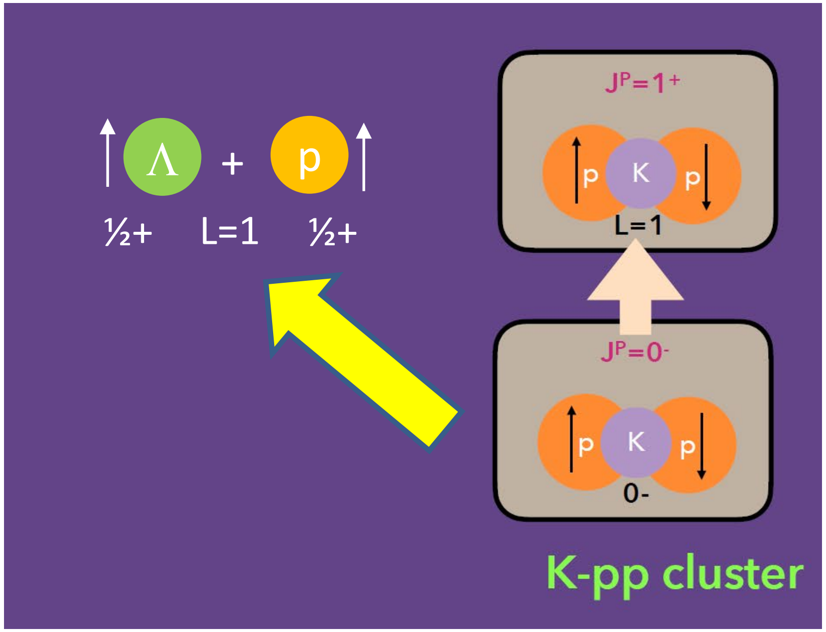
**** improved from E15***

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

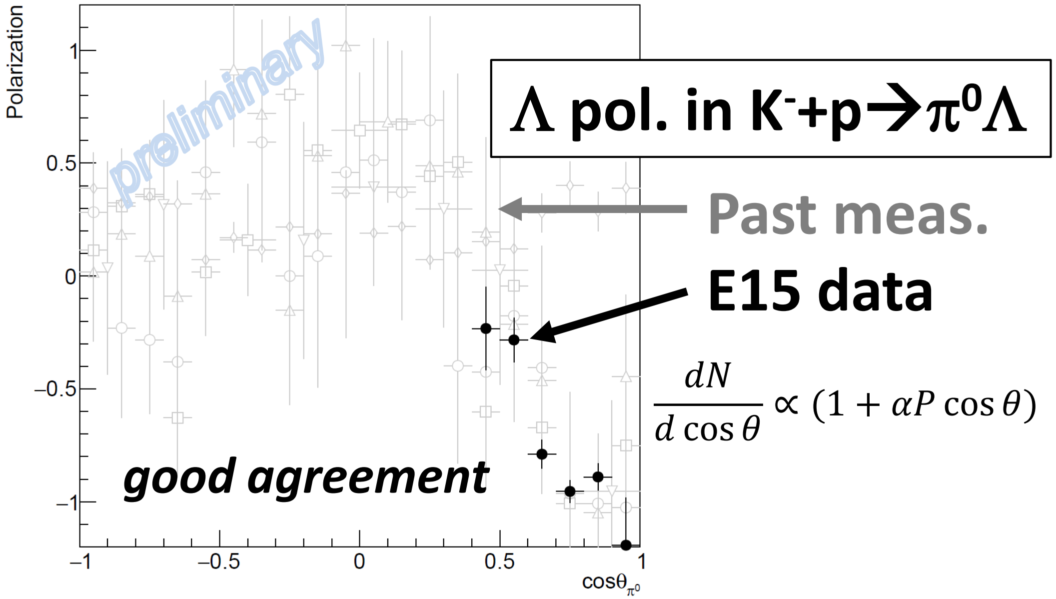


T.Nagae, "The 4th Symposium on Clustering as a window on the hierarchical structure of quantum systems", May 28th, 2020

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

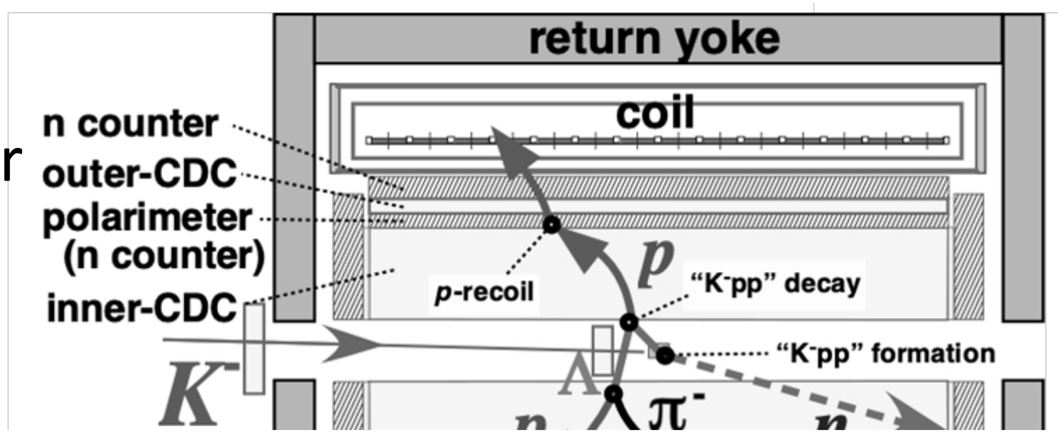


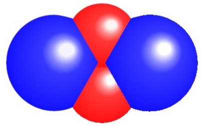
- **Λ polarization** can be measured via π^-p decay



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

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

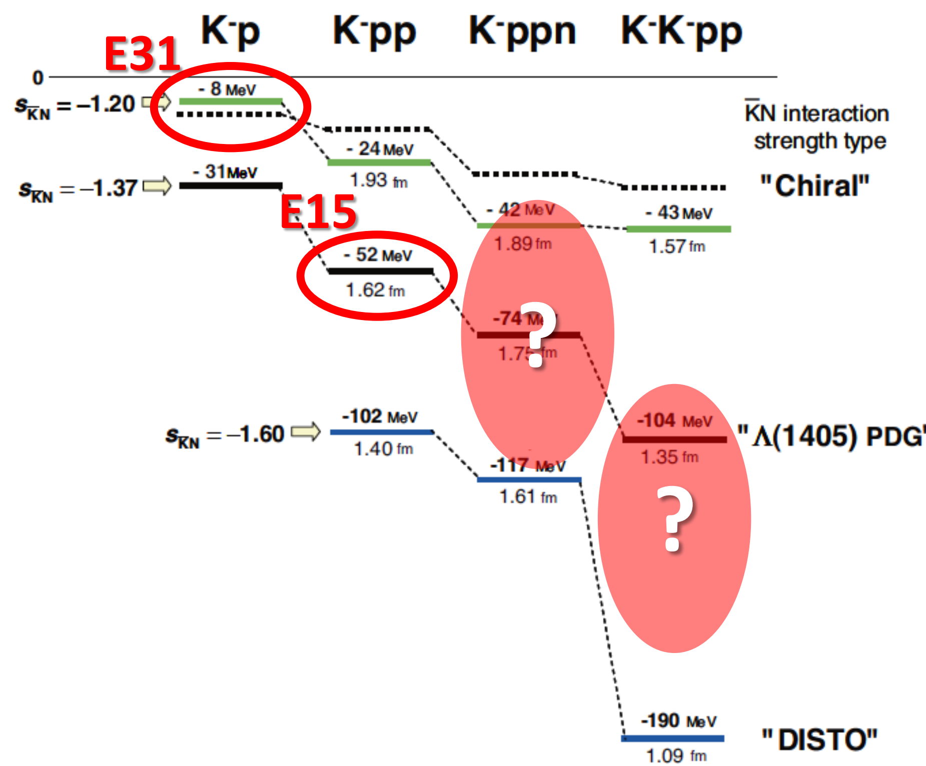




K⁻K⁻pp

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 $\bar{K}NN$