軽いK中間子原子核の系統的測定
Systematic Investigation of the Light Kaonic Nuclei

F. Sakuma, RIKEN

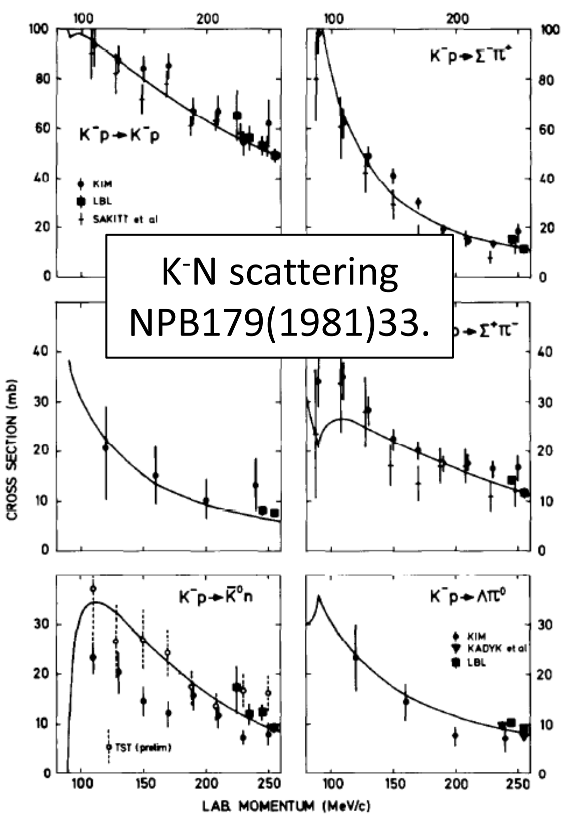
on behalf of the J-PARC P80 collaboration

Physics Goal

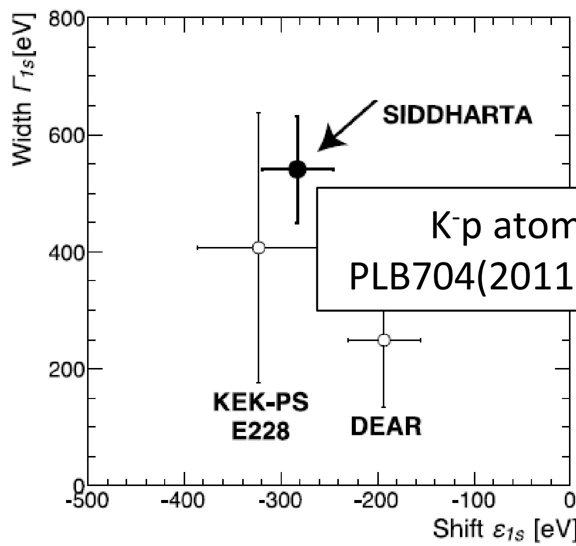
Reveal the meson properties inside nuclei
via **the $\bar{K}N$ interaction**

A powerful probe to understand low energy QCD

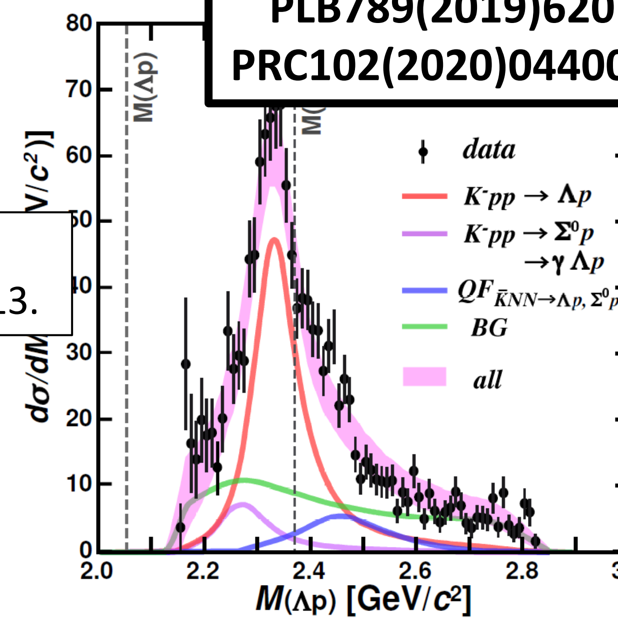
Strongly attractive in I=0 from extensive measurem… **→ Kaonic Nuclei**



K⁻N scattering
NPB179(1981)33.



K⁻p atom
PLB704(2011)113.



"K⁻pp" @ E15
PLB789(2019)620.
PRC102(2020)044002.

Many Questions to be Answered

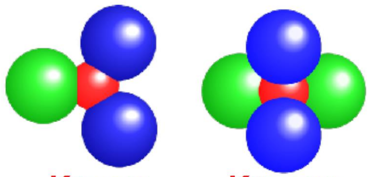
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K⁻pp"?
  - Really compact and dense system?

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

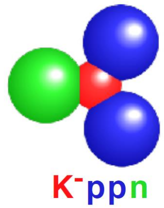
- **More heavier kaonic nuclei?**
  - Mass number dependence?



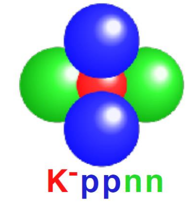
K^-ppn K^-ppnn

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

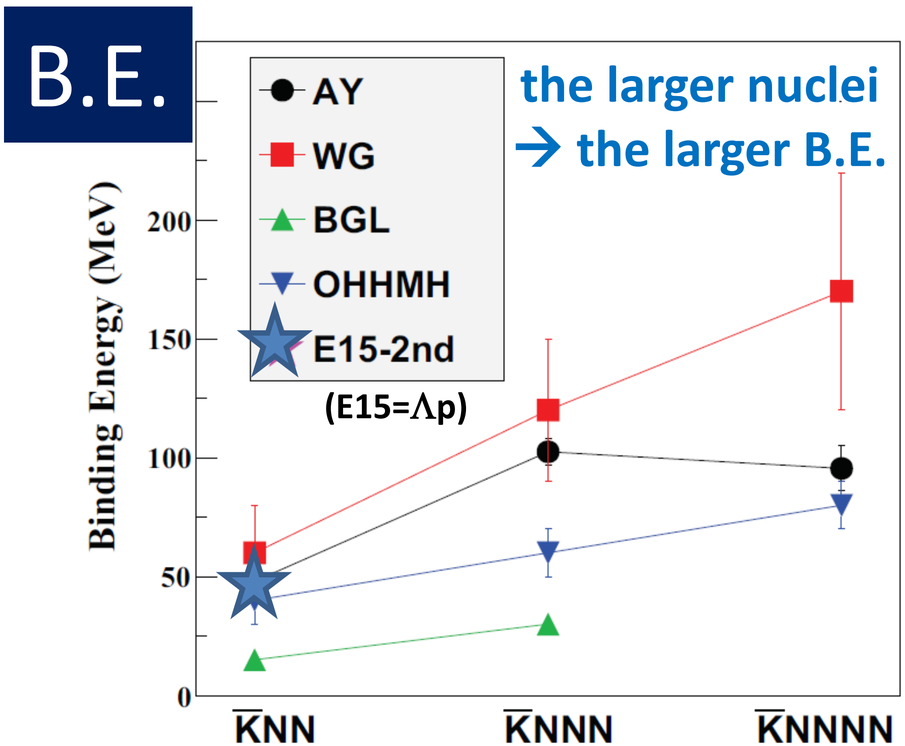
K^-K^-pp

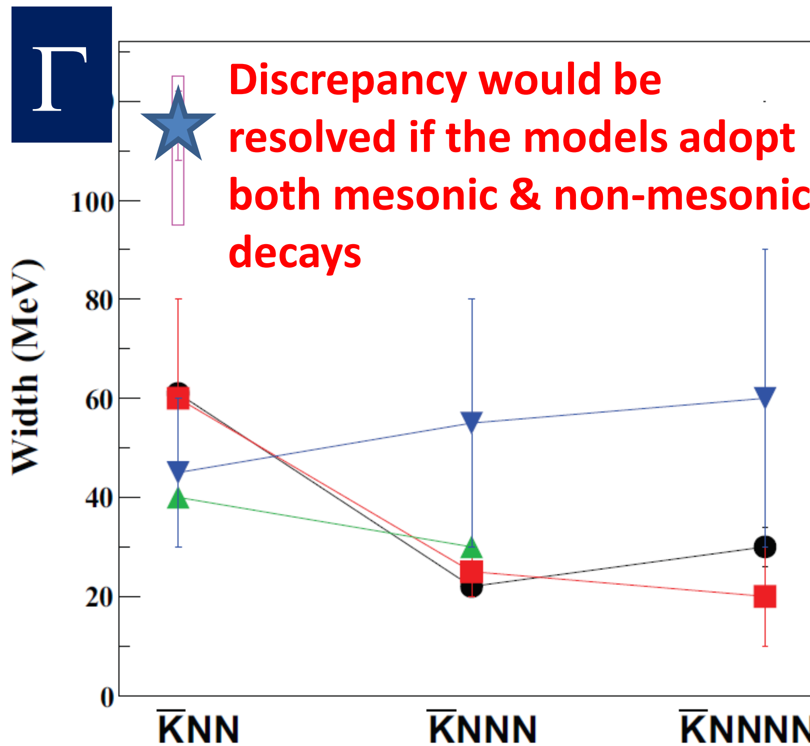


$\bar{K}NNN$ and $\bar{K}NNNN$

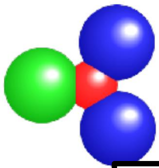


- More heavier system must be explored to provide more conclusive evidence of the kaonic nuclei

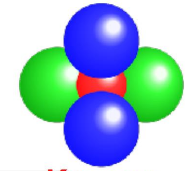




➢ The $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration

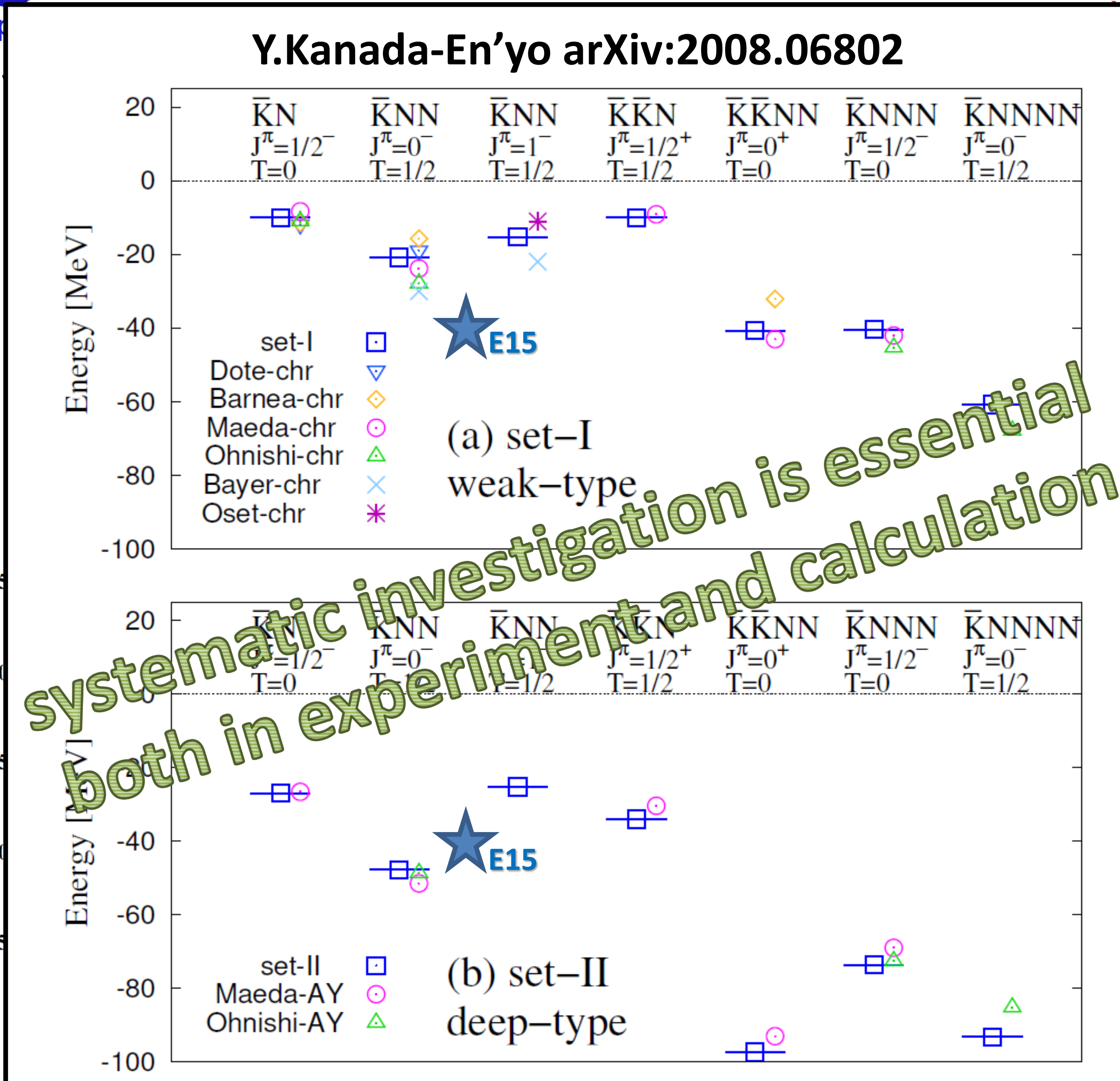


$\bar{K}NNN$ and $\bar{K}NNNN$



K⁻pp ... ppnn

- Be... ust
  be...
  - ✓ ... to be
    ... e



if

onic

NNNN

New Project @ J-PARC

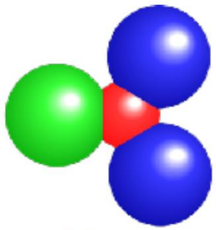
-- systematic investigation of the light kaonic nuclei --

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*



$K^{-}ppn$

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

via $^{4}He(1\ GeV/c\ K^{-}, n)$ reaction

Goals of the proposed experiment:

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

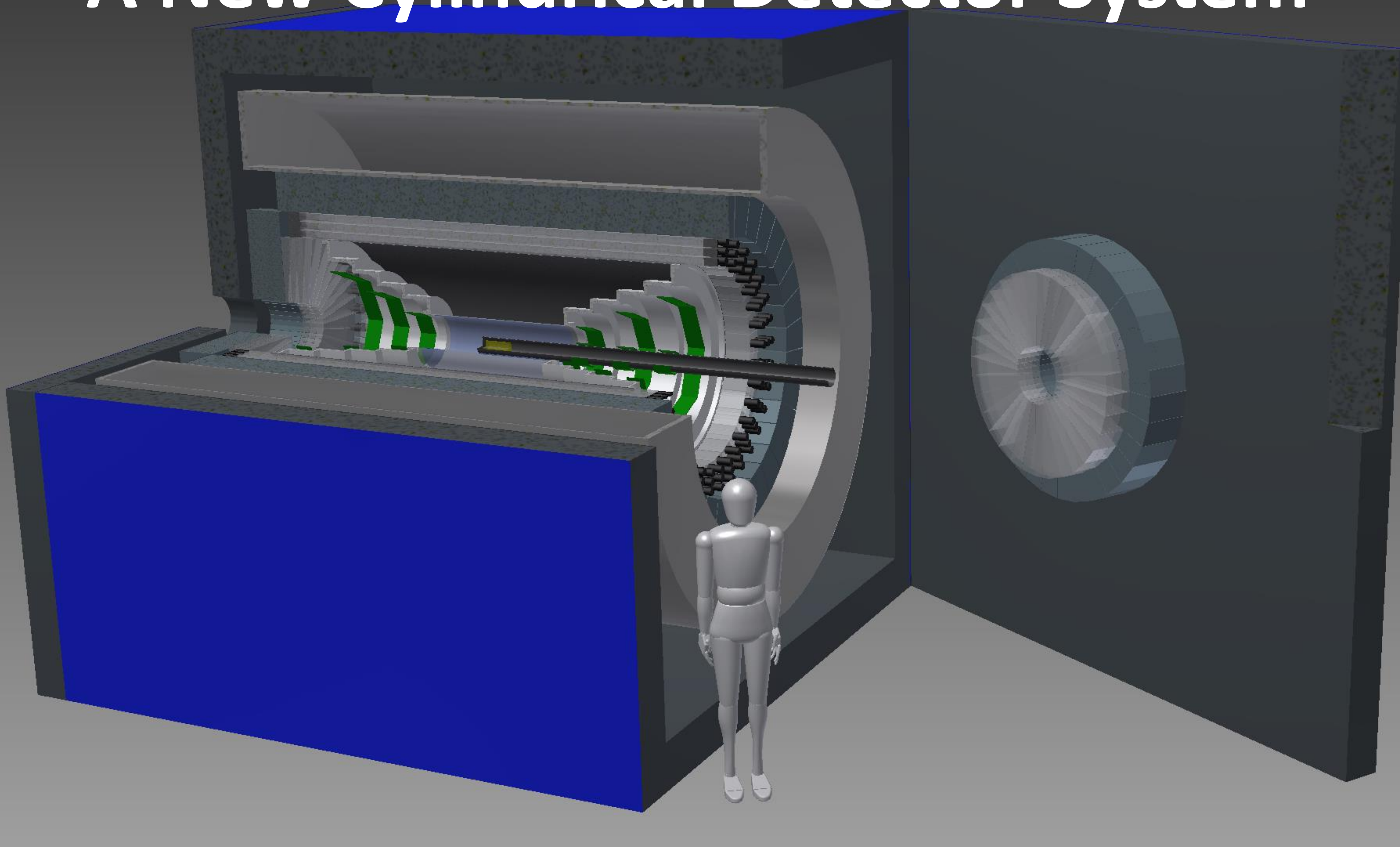
- Establish the existence of the kaonic nuclei

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

- As a feasibility study to access heavier system

- **Feasibility study of proton spin-direction measurement**
  - *e.g.*, by installing a prototype module of a polarimeter

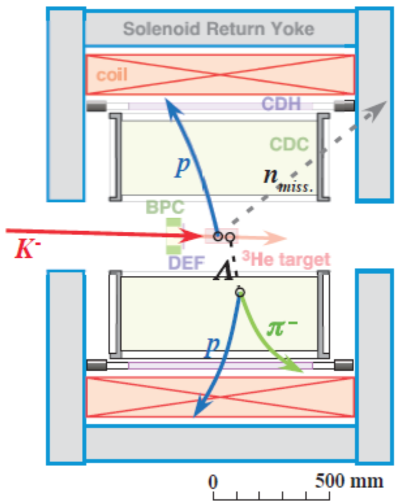
A New Cylindrical Detector System

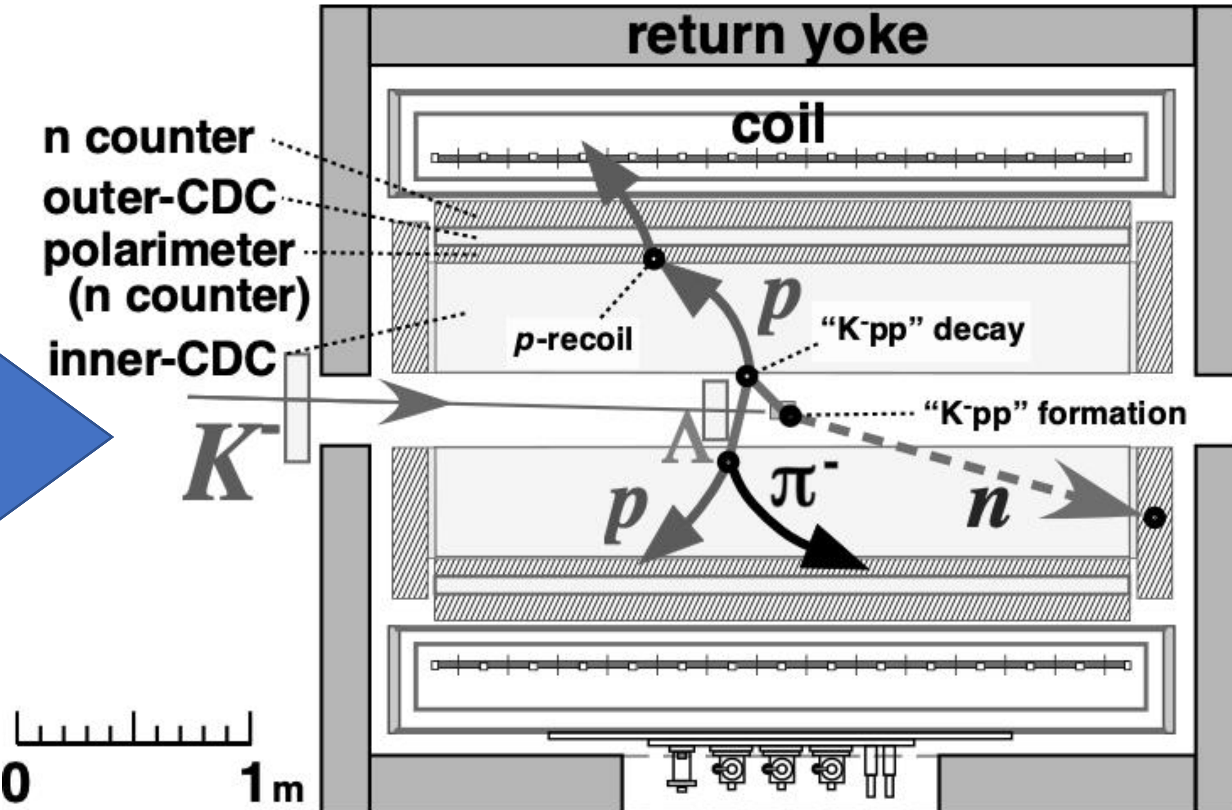


A new 4π spectrometer with n/γ detection capability

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)

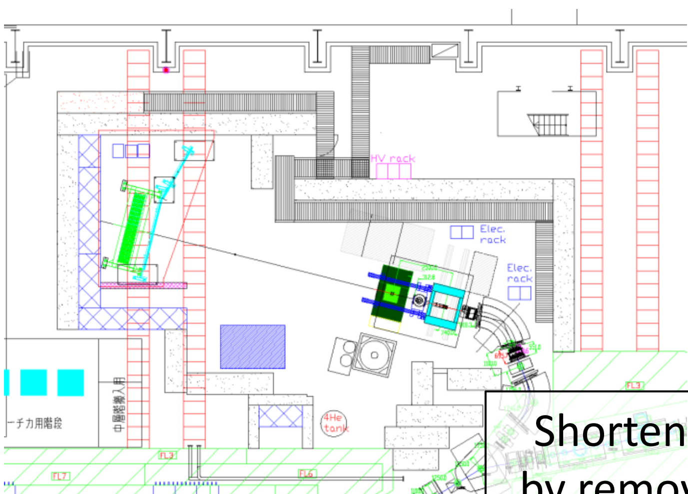
Solid angle: ~x1.5 (~90%)

Neutron detection capability: ~x10

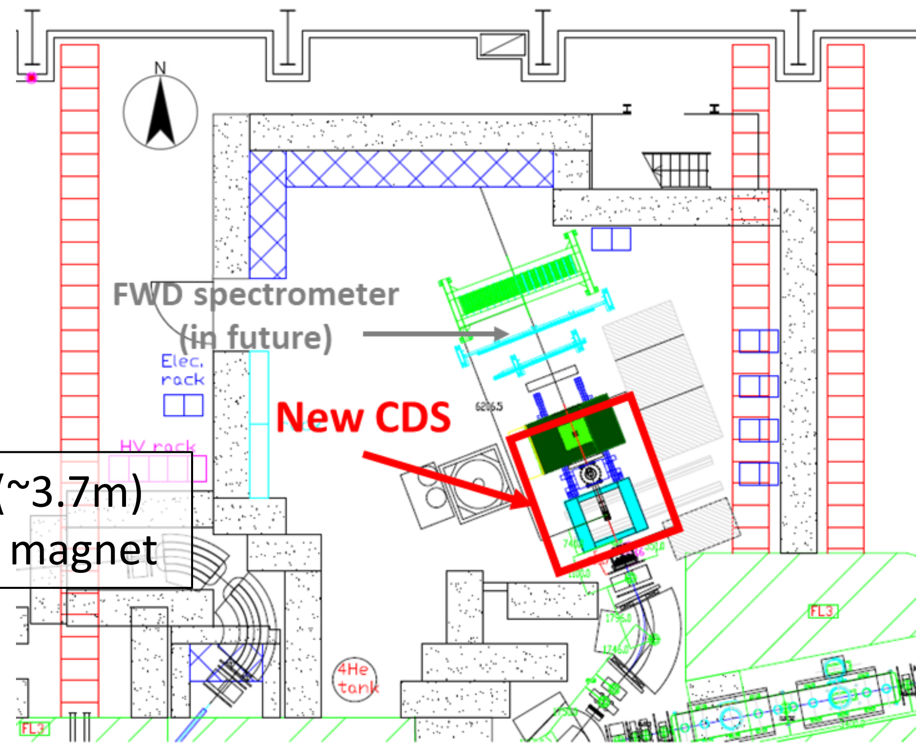
(~1.5x15%)

Improvement of Kaon Intensity

K1.8BR beamline



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



- **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 $\bar{K}NNN$

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

- assume the K^-ppn cross section of

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

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

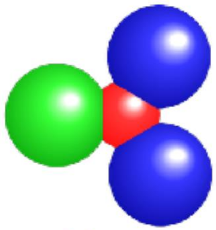
  - ◆ The same CS of "K-pp"→Λp in E15
  - ◆ *As for Λd decay, we refer to the absorption of stopped K^- on ^4He*

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

absorption of stopped K^- on ^4He

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
$\to \Sigma^+\quad nnn$	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
$\to \Sigma^-\quad pd$	1.6±0.6
$\to \Sigma^-\quad ppn$	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
$\to \Lambda\ (\Sigma^0)\quad (pnn)$	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



K$^-$ppn

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

B_{Kppn} ~ 40 MeV

Γ_{Kppn} ~ 100 MeV

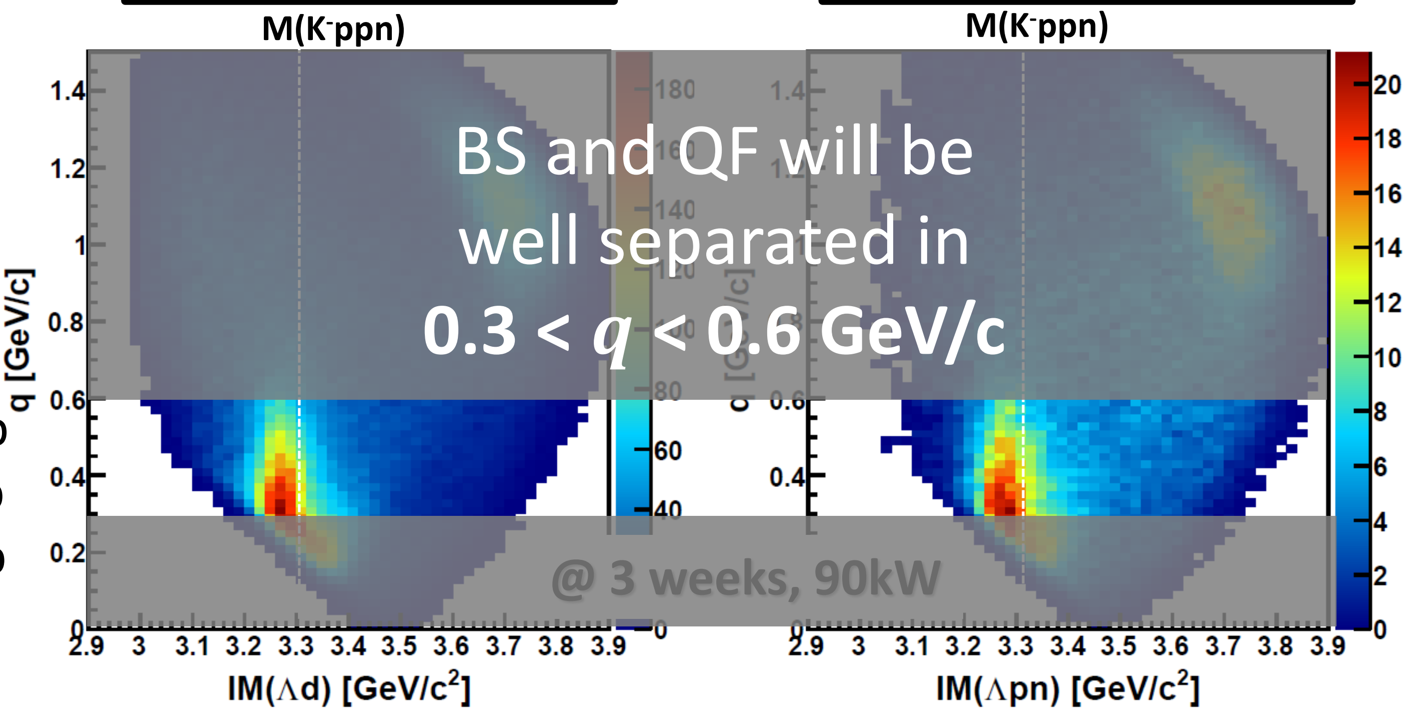
Q_{kppn} ~ 400 MeV/c

σ(K$^-$ppn)*Br ~ 10 μb

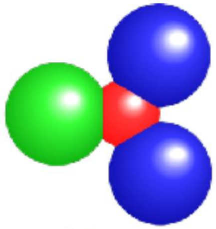
σ(QF) ~ 10 μb

σ(BG) ~ 20 μb

K^-+^{4}He→Λd+n | **K^-+^{4}He→Λpn+n**



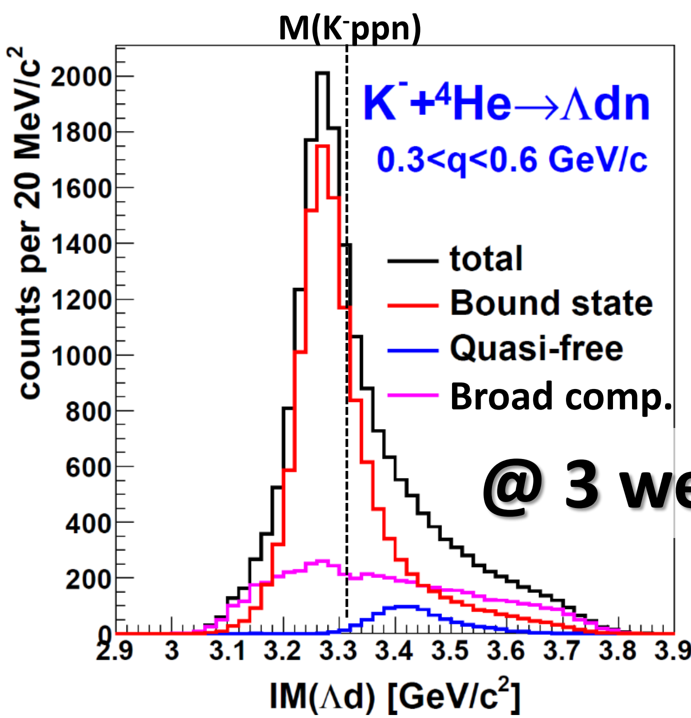
- Similar parameters obtained with the K^-+^{3}He→Λpn (PRC102(2020)044002.) are adopted to K$^-$ppn/QF/BG shapes
- **K-ppn signal [<u>q-independent</u>] will be seen clearly**



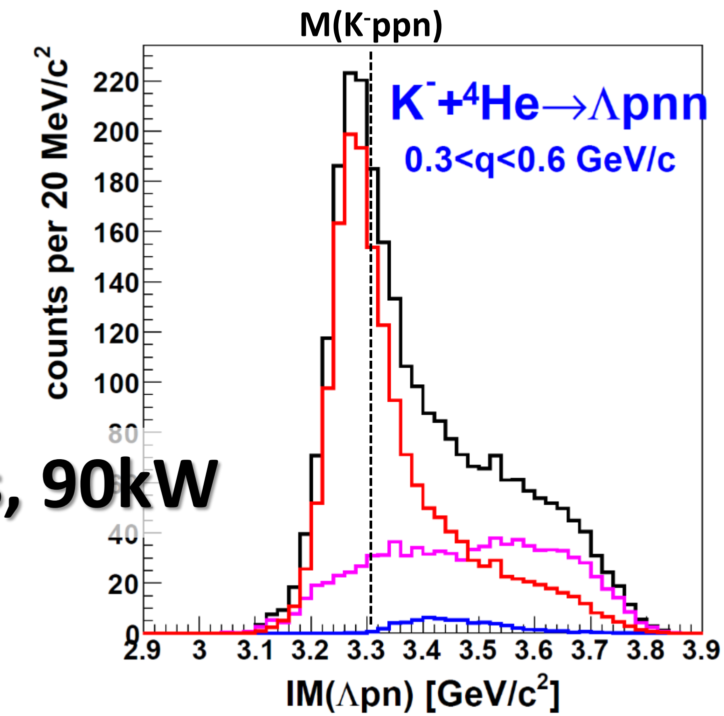
K^-ppn

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

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



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



@ 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 $^3He(K^-,\Lambda p)n$**
  - ✓ 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:
  - **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

J-PARC P80 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. Hashimoto
Japan Atomic Energy Agency (JAEA), Ibaraki [illegible]1195, Japan

M. Iio, S. Ishimoto, K. Ozawa, S. Suzuki
High Energy Accelerator Research Organization (KEK), Ibaraki [illegible], Japan

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

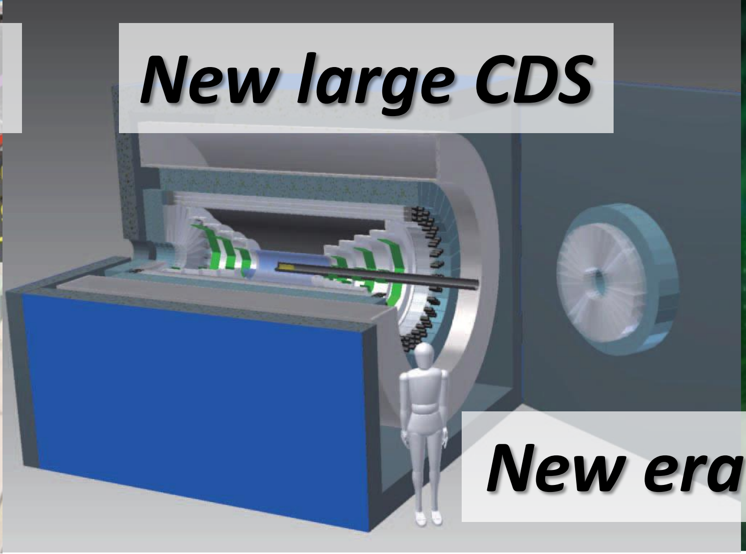
T. Nagae
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan

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

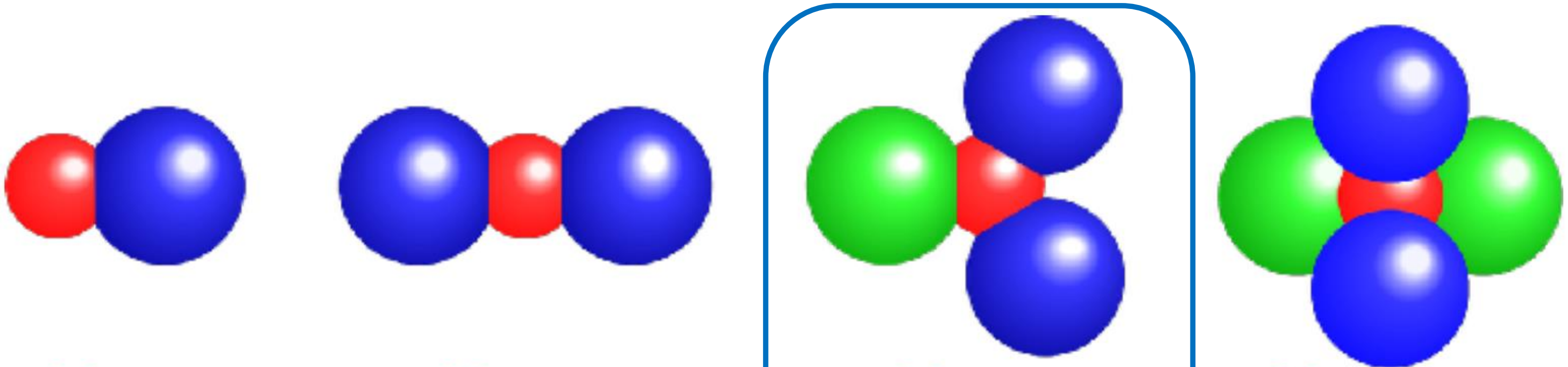
P. Buehler, M. Simon, E. Widmann, J. Zmeskal
Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria

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 $^4He(K^-,N)$

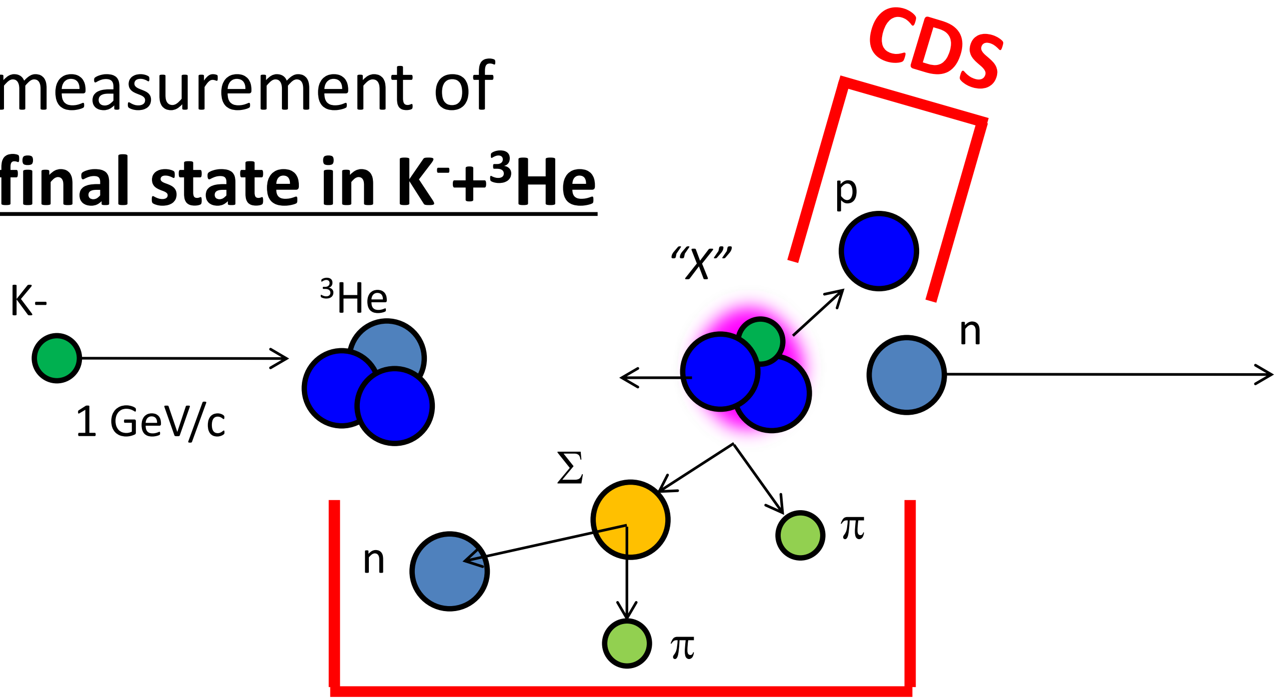
Many Questions to be Answered

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

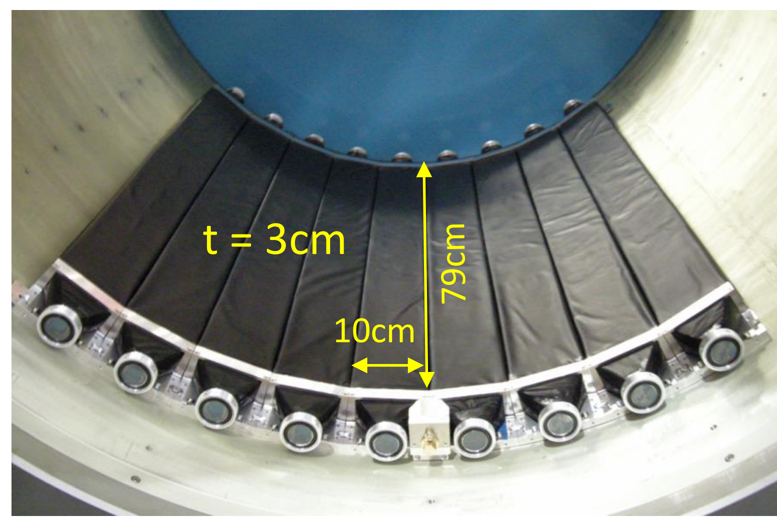
- **$\pi\Sigma N$ mesonic decay**
  - expected to be the dominant channel
    - only YN non-mesonic decays were reported
- **Reaction mechanism**
  - relation between $\Lambda(1405)$="K^-p" & "K^-pp"
    - "K^-pp" is expected to be produced via $\Lambda(1405)+p\rightarrow$"$K^-pp$" door-way process

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

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



CDS

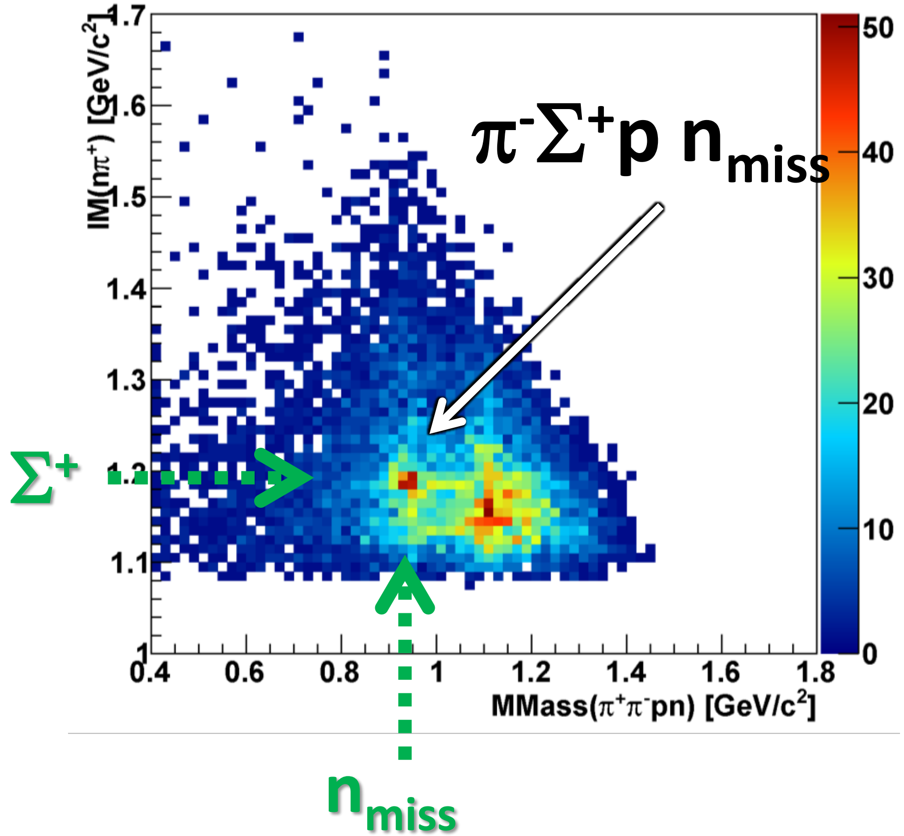


- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

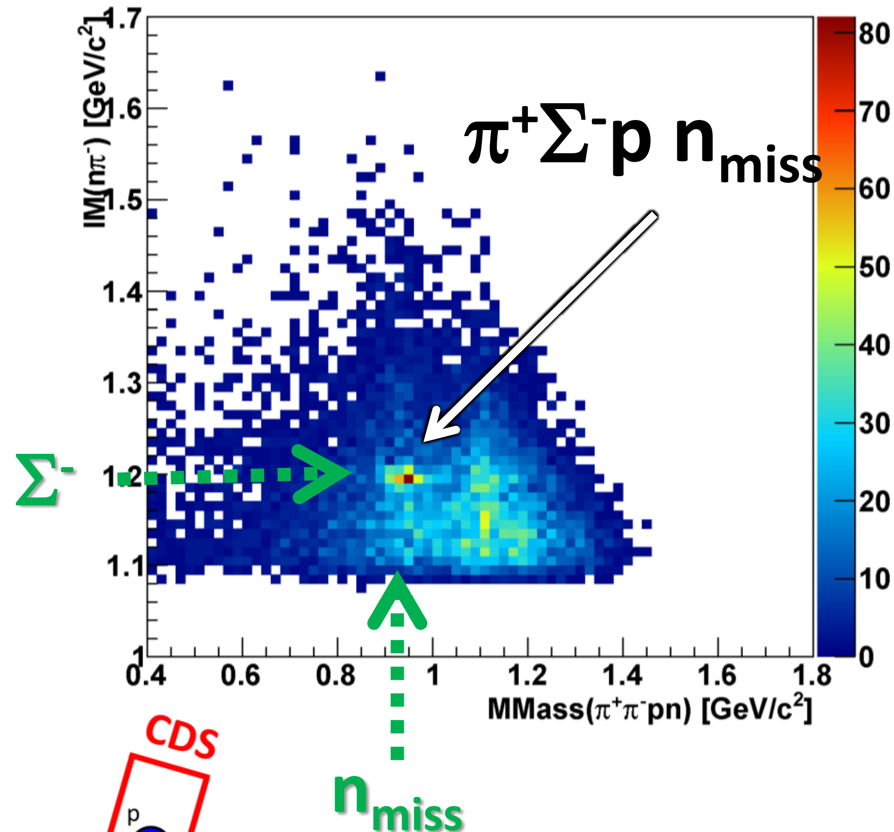
  n detection efficiency ~ 3-10%

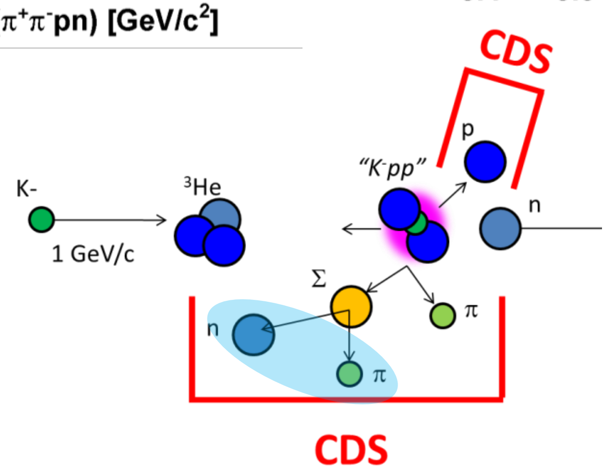
πΣpn Events

IM(nπ+) vs MM(π+π-pn)

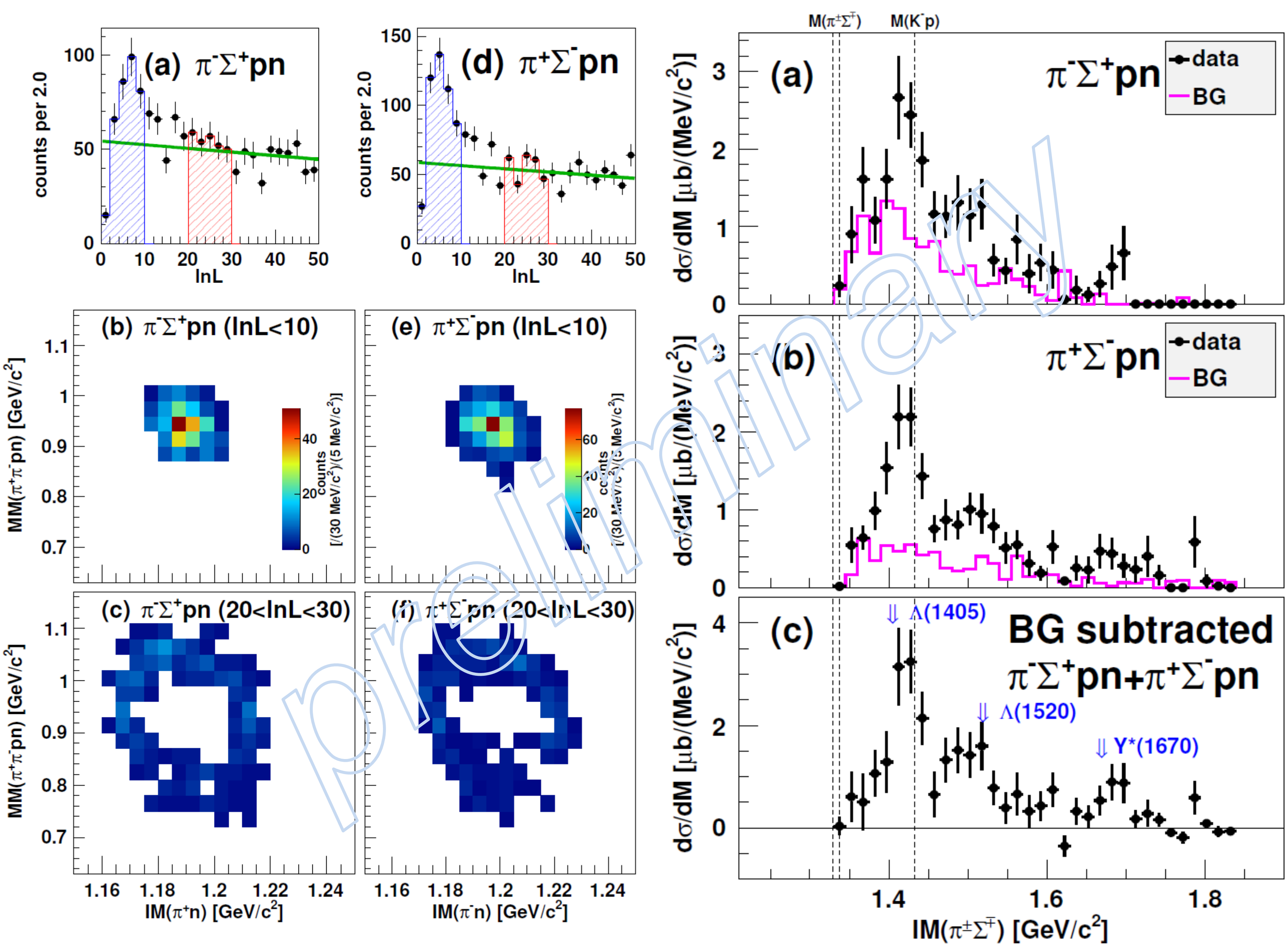


IM(nπ-) vs MM(π+π-pn)



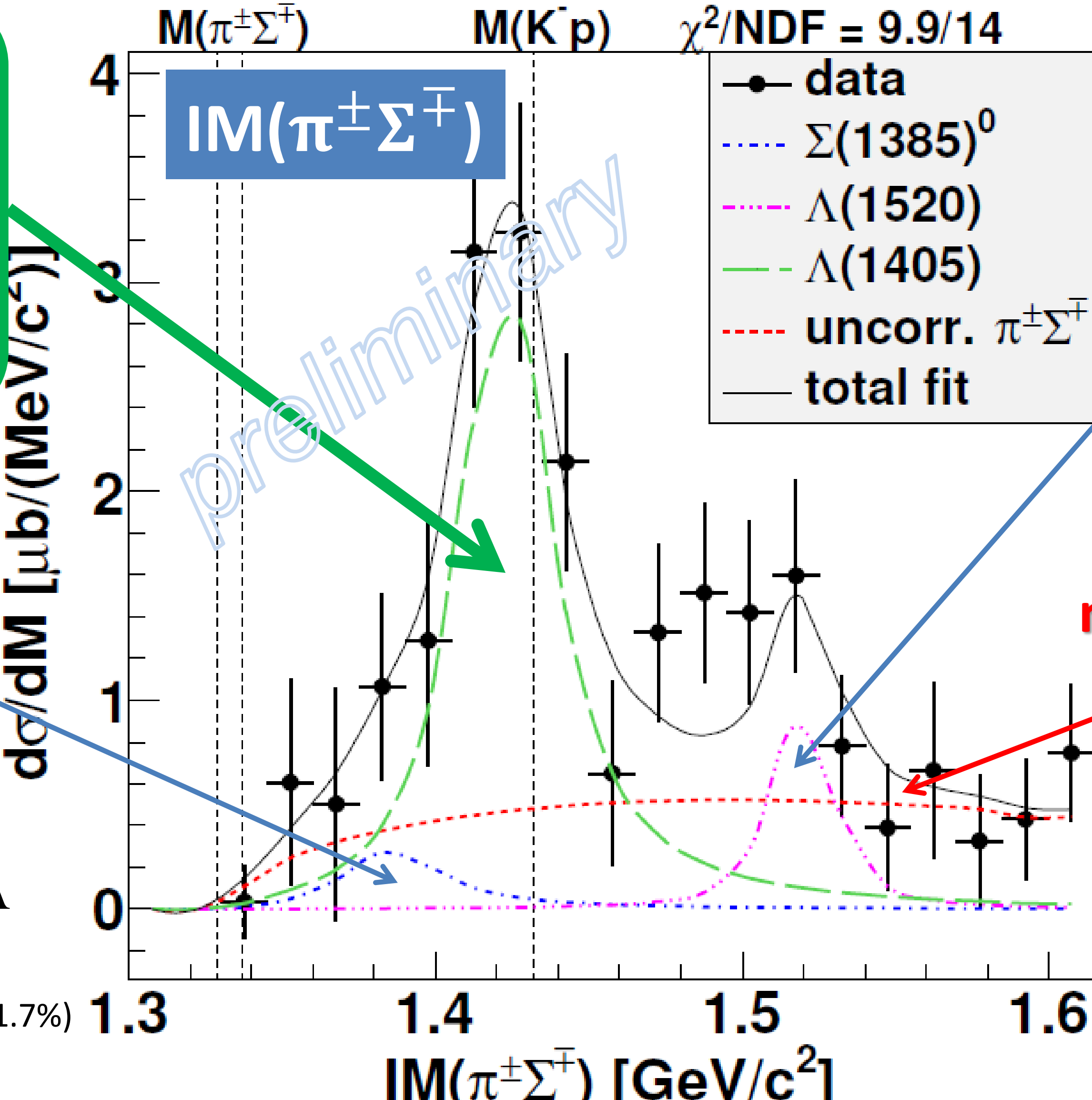


BG Subtracted IM($\pi^{\pm}\Sigma^{\mp}$) in $\pi^{\pm}\Sigma^{\mp}pn$



$Y^{*}pn$ Final State

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



Λ(1520)
~ 100 μb

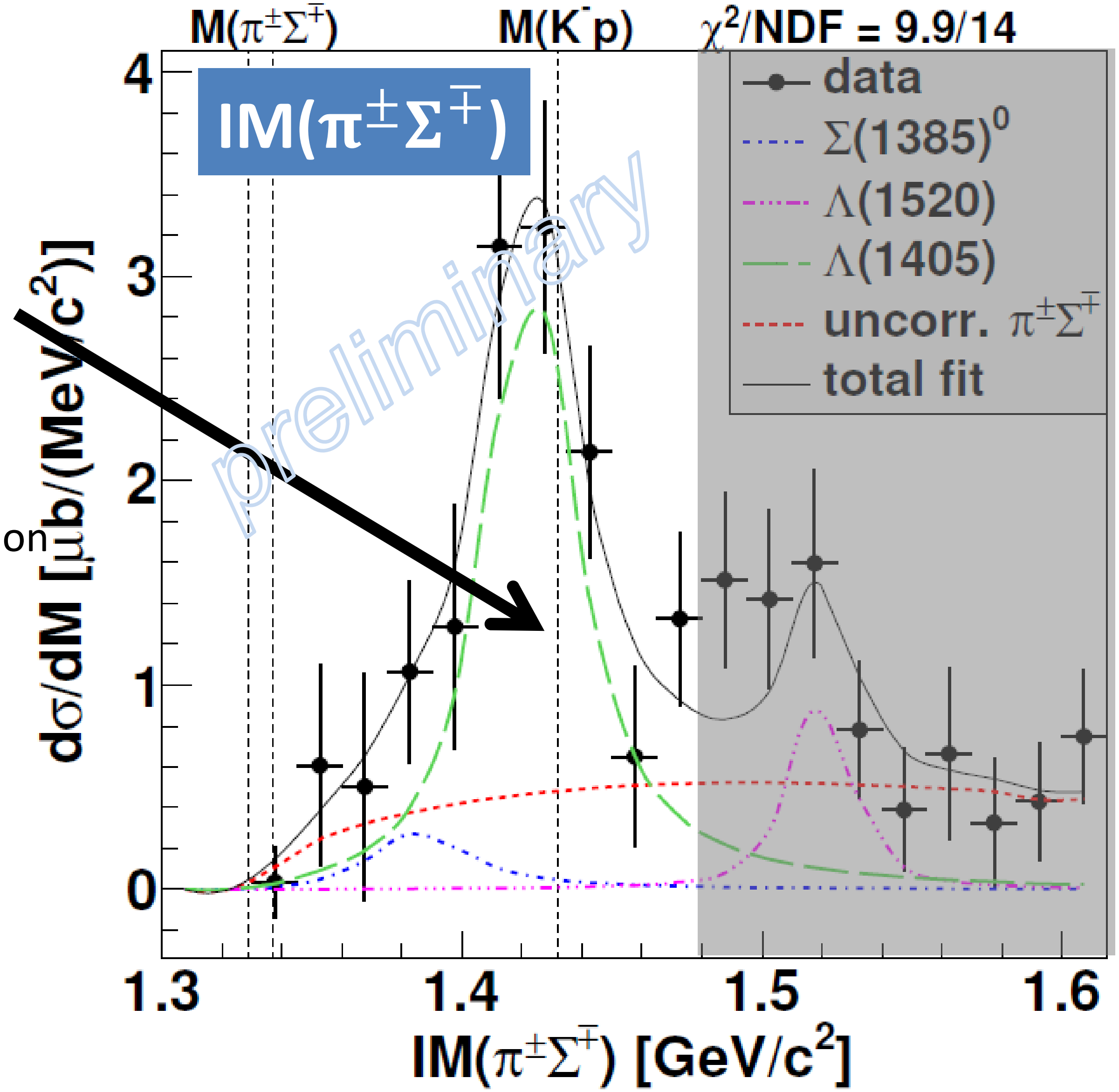
πΣpn non-resonant

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

$\Lambda(1405)pn$ Final State Selection

Select $\Lambda(1405)$ region

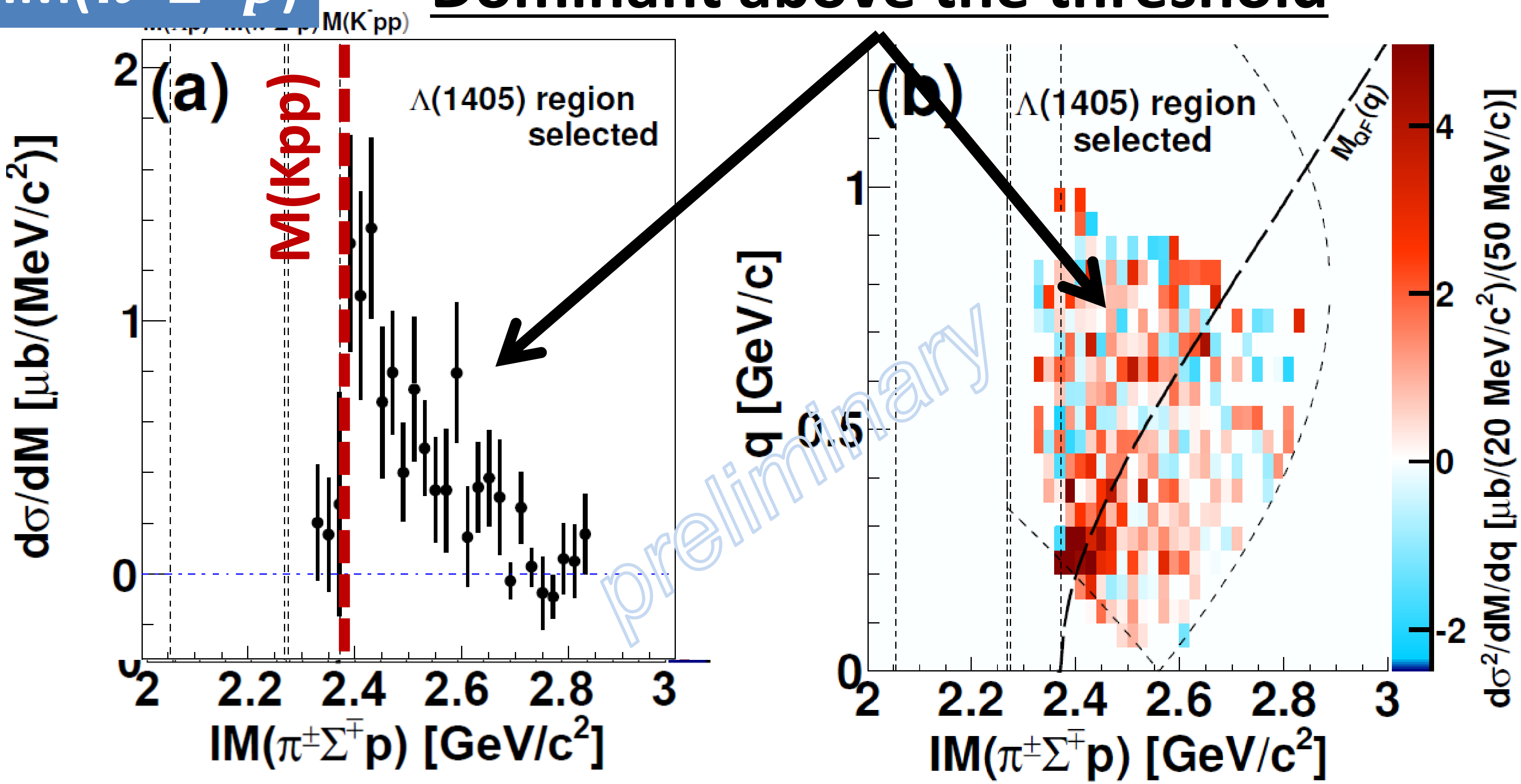
- Below $\Lambda(1520)$
- Small contribution from $\Sigma(1385)$



IM(πΣp) in Λ(1405)pn Final State

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

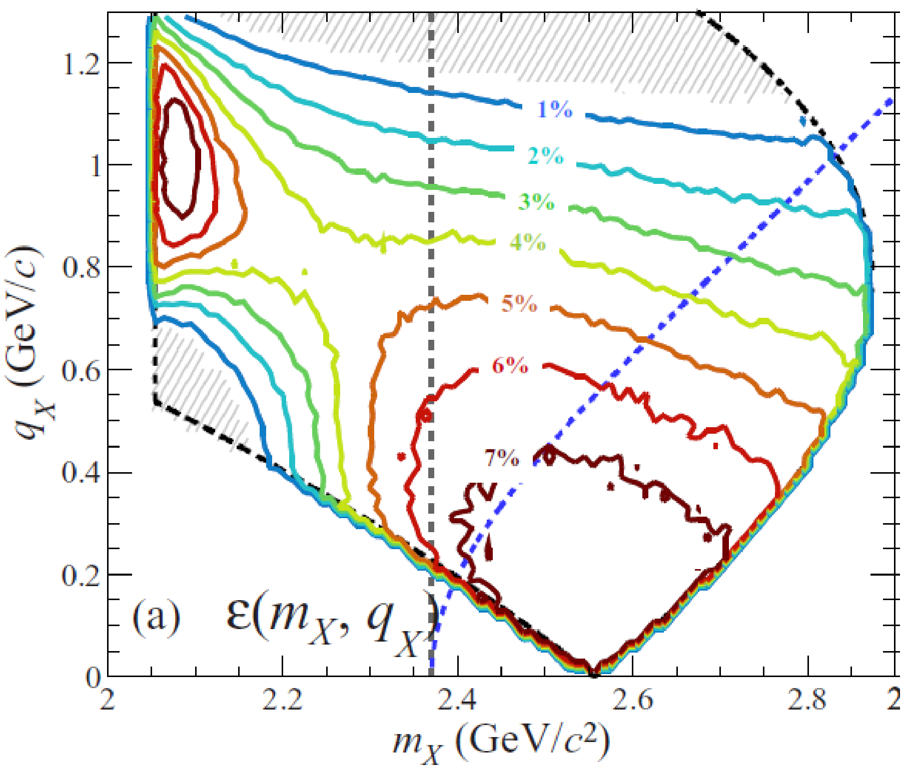
Dominant above the threshold



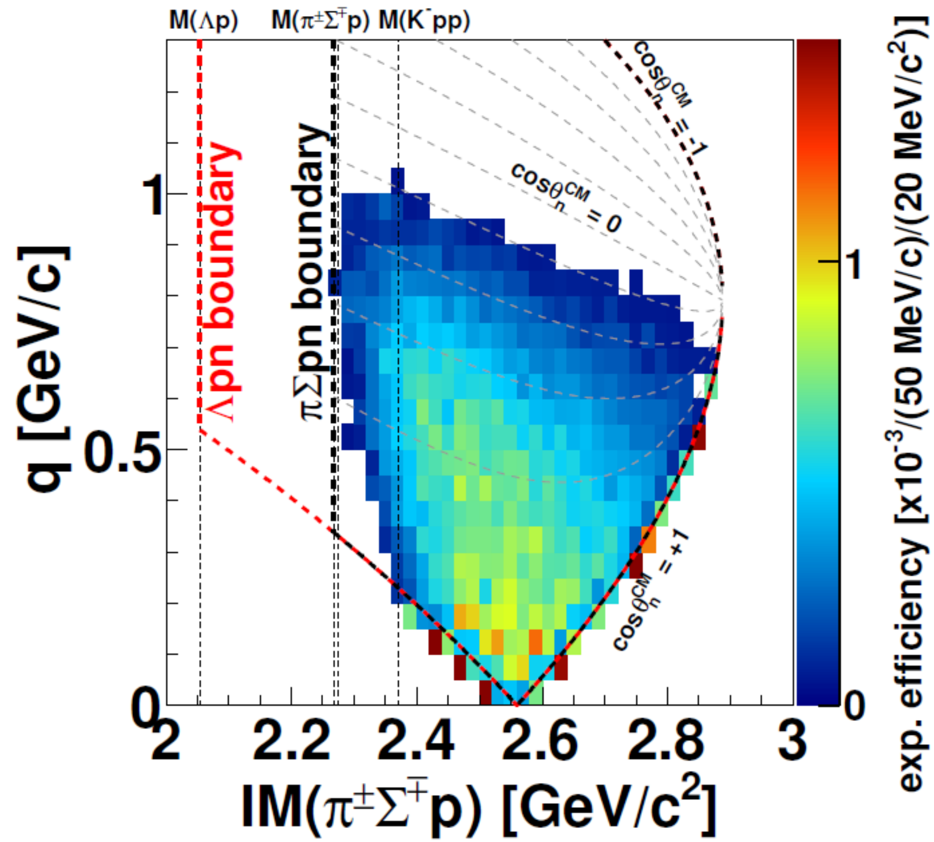
- IM(Λ(1405)p) distributes above the M(Kpp)
- QF $K^{-}N \rightarrow K^{bar}n$ followed by $K^{bar}NN \rightarrow \Lambda(1405)p$

Detector acceptances of Λpn and πΣpn

Λp



πΣp



Σ*N bound state? Other possibilities?

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

$\Sigma(1385)$ 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-$\pi\Sigma$N-$\pi\Lambda$N coupled channel system, where the $\pi\Lambda$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

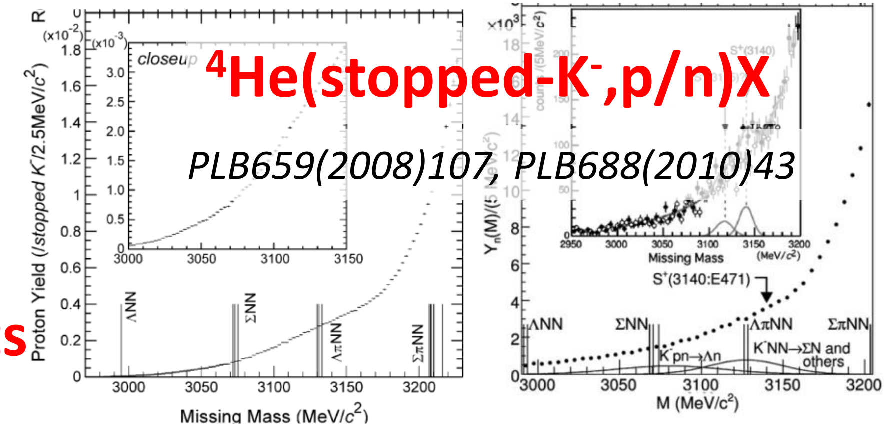
- A few candidates have been reported in ***inclusive*** measurements

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

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

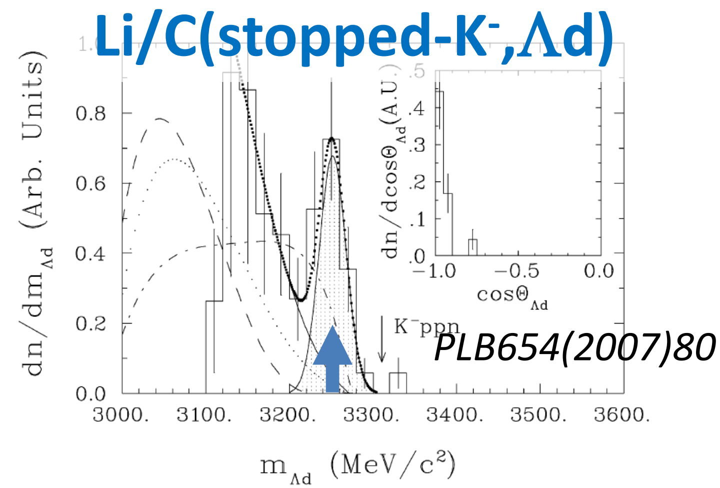
◆ **FOPI@GSI** ← **Observed?**
- – Λd in Ni+Ni

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



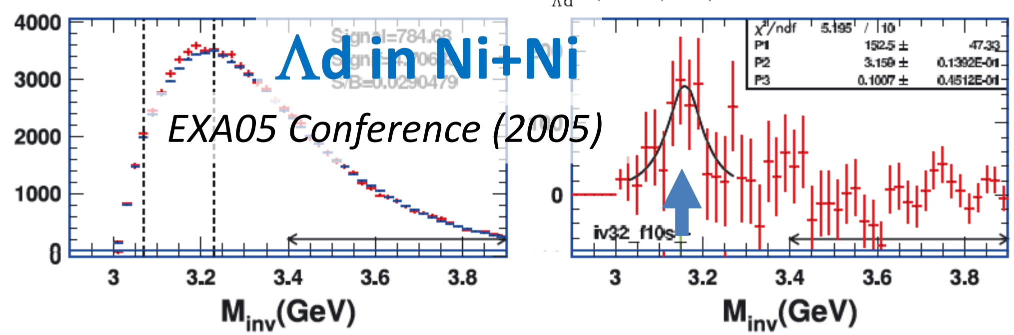
^{4}He(stopped-K$^-$,p/n)X

PLB659(2008)107, PLB688(2010)43



Li/C(stopped-K$^-$,Λd)

PLB654(2007)80



Λd in Ni+Ni

EXA05 Conference (2005)

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 2024
    - 3.2 x 10^5 K- on target / spill @ 1.0 GeV/c
  - **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***