Light kaonic nuclei at J-PARC

F. Sakuma, RIKEN

on behalf of the J-PARC E15/E80 collaborations

Strangeness Nuclear Physics Workshop, 2021

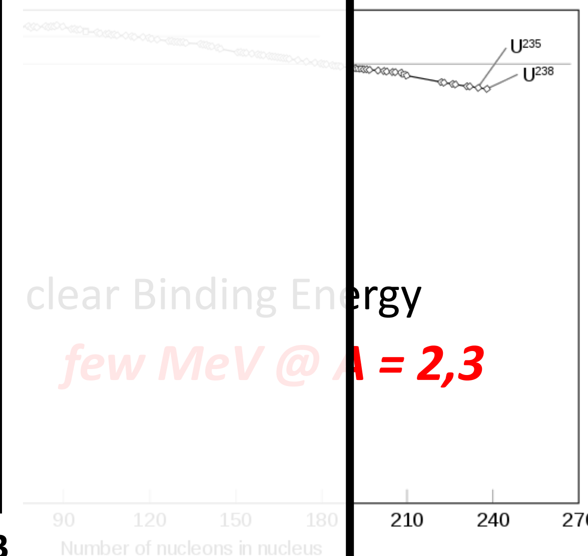
18-19 December 2021, Online

Kaonic Nuclei

Predicted from … action in I=0

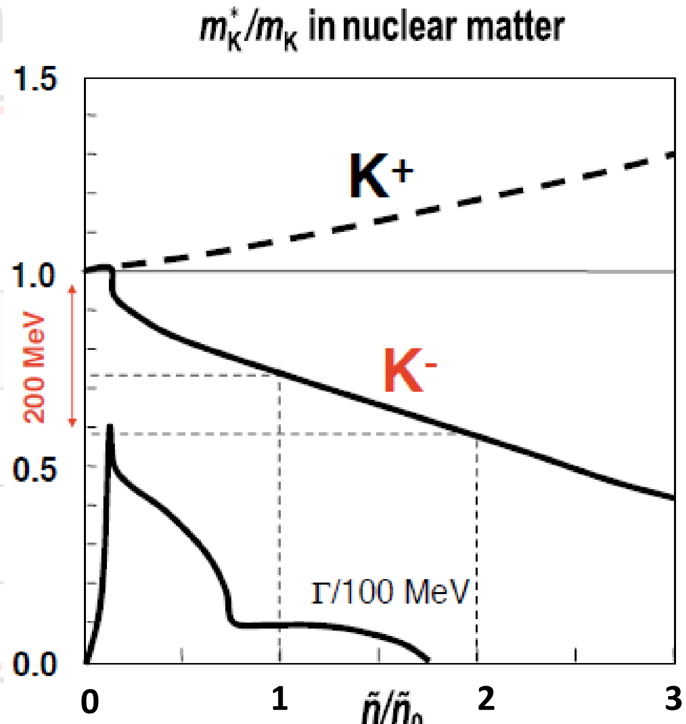
… 88., PRC65(2002)044005., etc.

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

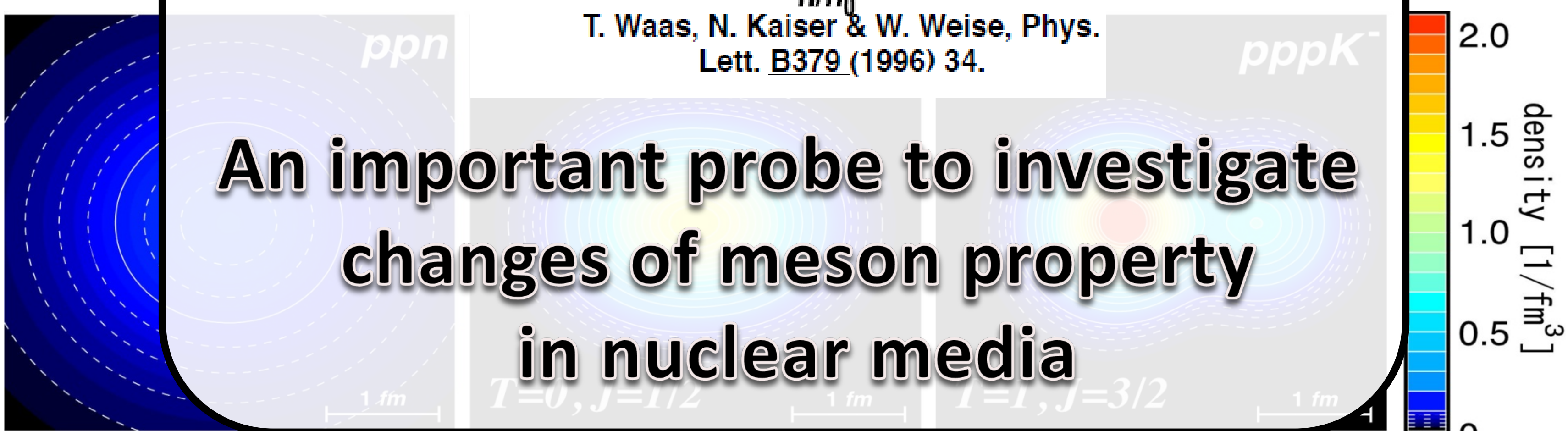


… clear Binding Energy

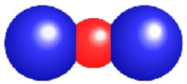
few MeV @ A = 2,3



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



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



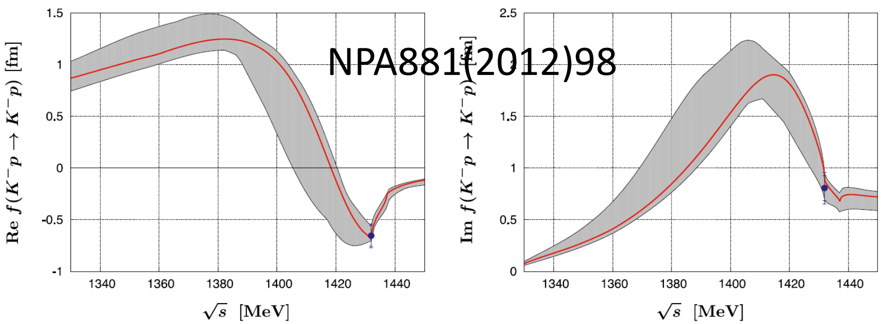
Theoretical Calculations on "K^-pp"

K^-pp

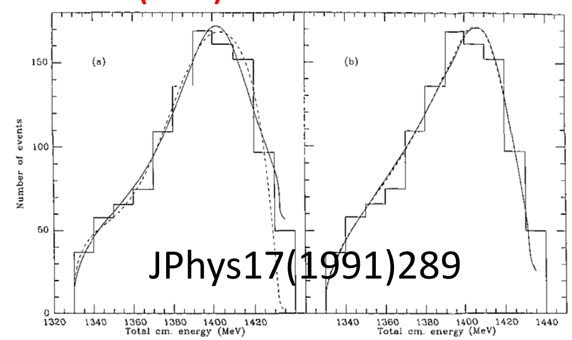
The simplest kaonic nuclei, $\bar{K}NN$ ($J^P=0^-$, $I=1/2$)

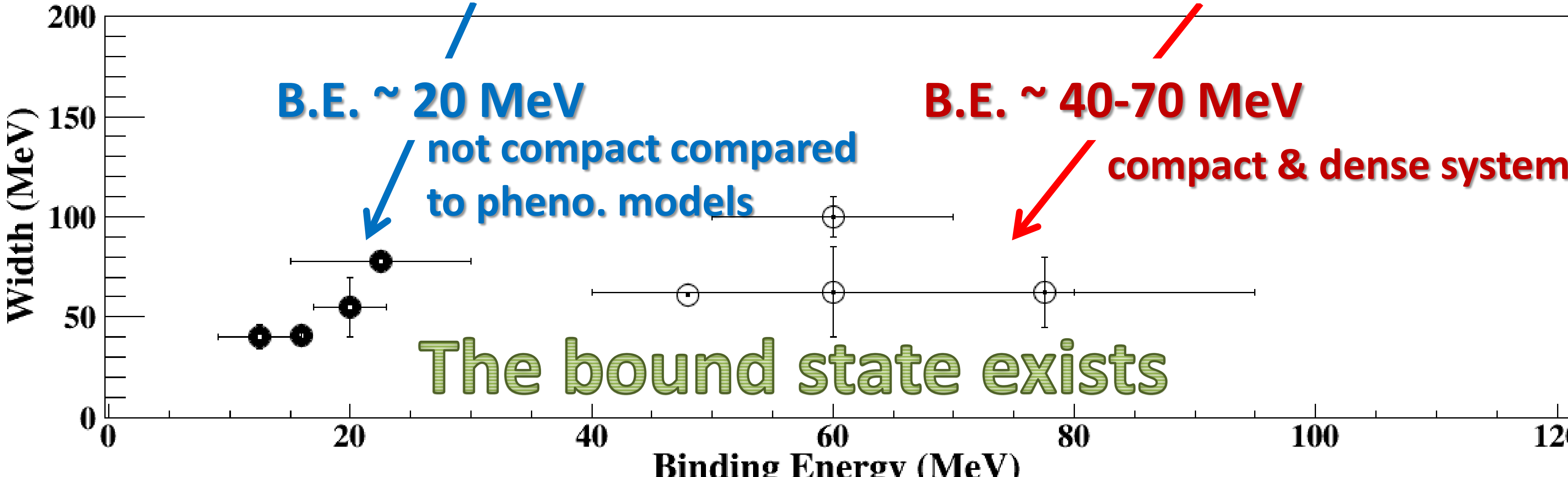
$\bar{K}N$ int.	Chiral SU(3) (energy dependent)	Phenomenological (energy independent)

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



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





B.E. ~ 20 MeV

not compact compared to pheno. models

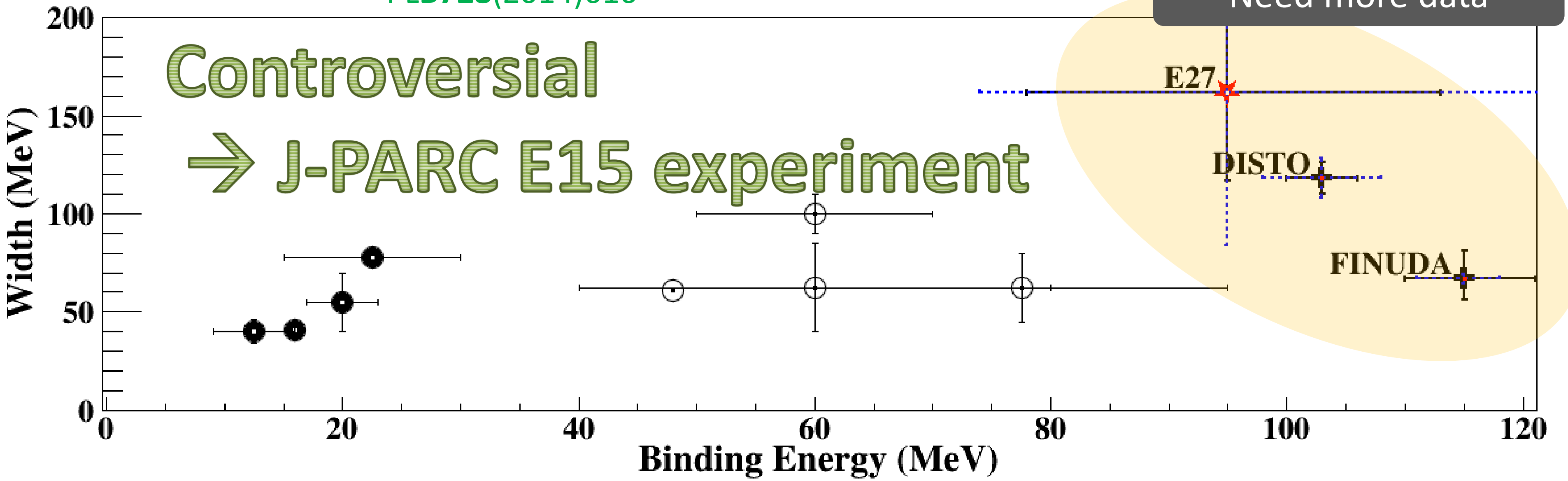
B.E. ~ 40-70 MeV

compact & dense system

The bound state exists

Experimental Situation "before E15"

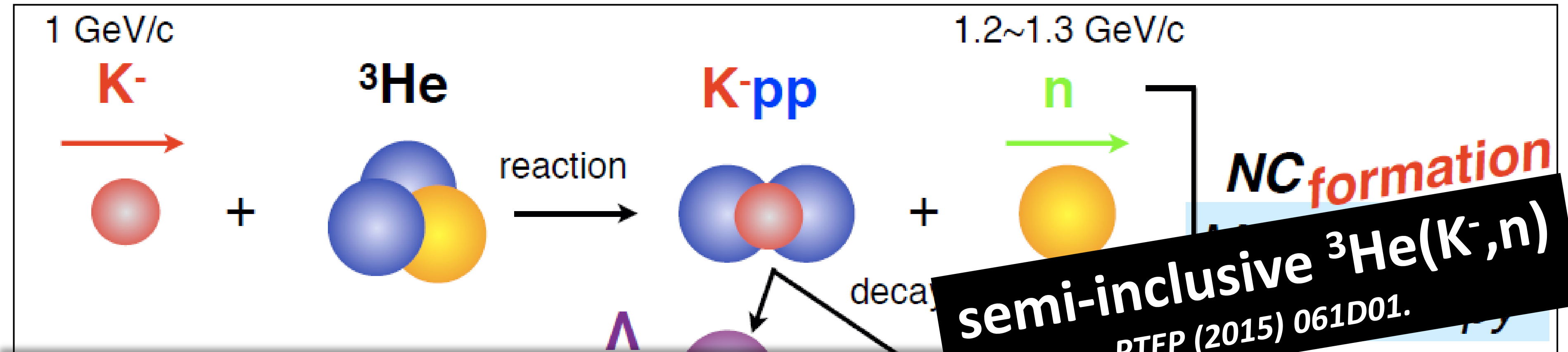
Negative results		Positive results	
AMADEUS@DAΦNE $^{12}C(K^-_{stopped}, \Lambda p)$ EPJ**C79**(2019)190	↔	**FINUDA@DAΦNE** PRL**94**(2005)212303 $^{6}Li/^{7}Li/^{12}C(K^-_{stopped}, \Lambda p)$	Multi-NA processes?
HADES@GSI $p + p \rightarrow (\Lambda + p) + K^+$ @ 3.5GeV PLB**742**(2015)242	↔	**DISTO@SATURNE** PRL**104**(2010)132502 $p + p \rightarrow (\Lambda + p) + K^+$ @ 2.85GeV	Intermediate $N^* \rightarrow pK^+$?
LEPS@SPring-8 $d(\gamma, \pi^- K^+)X$ @ 1.5-2.4 GeV PLB**728**(2014)616	↔	**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
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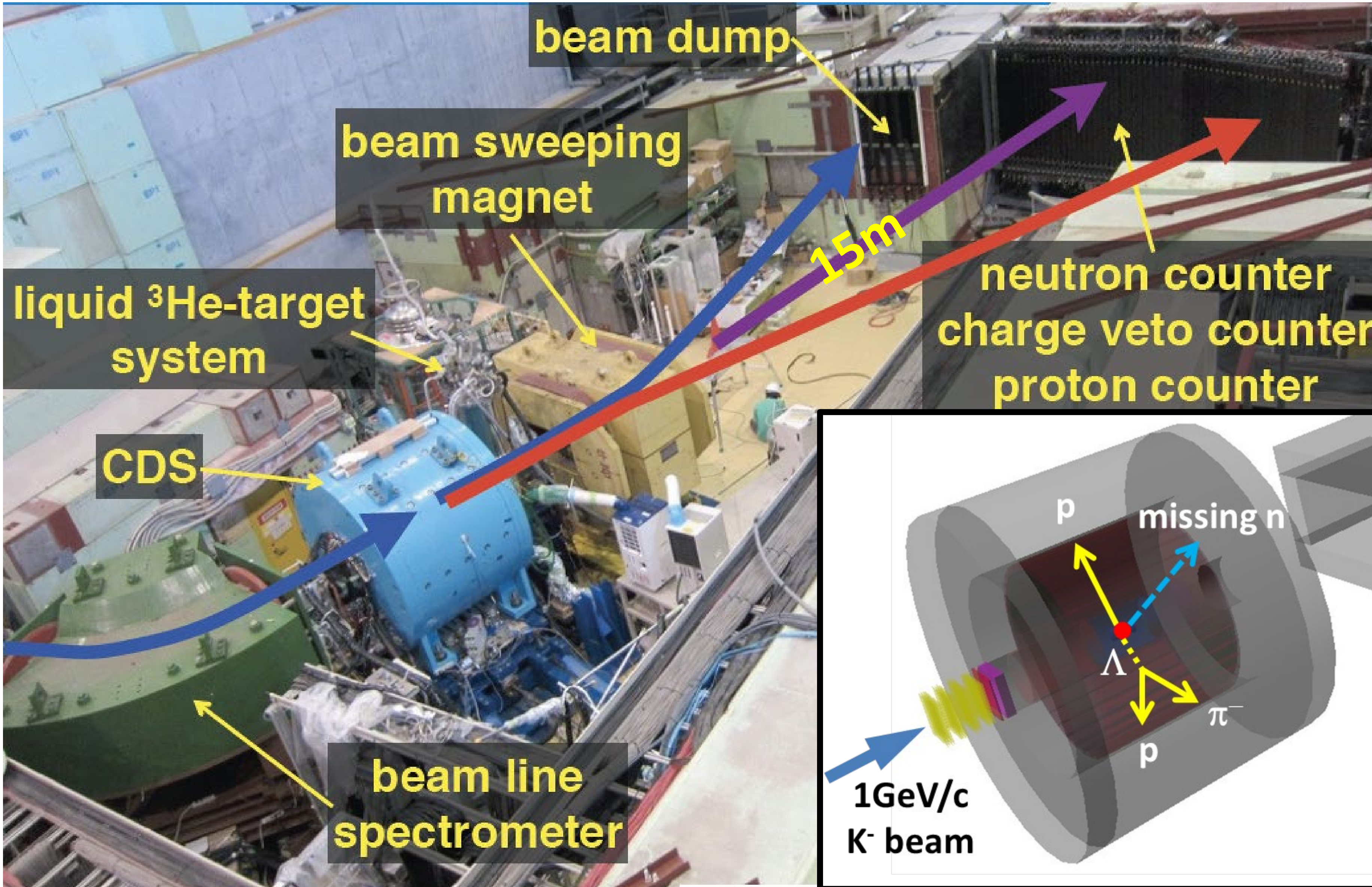
O. Vazquez Doce,[9,16] E. Widmann,[6] T. Yamazaki,[12,1] H. Yim,[19] Q. Zhang,[1] and J. Zmeskal[6]
(J-PARC E15 Collaboration)

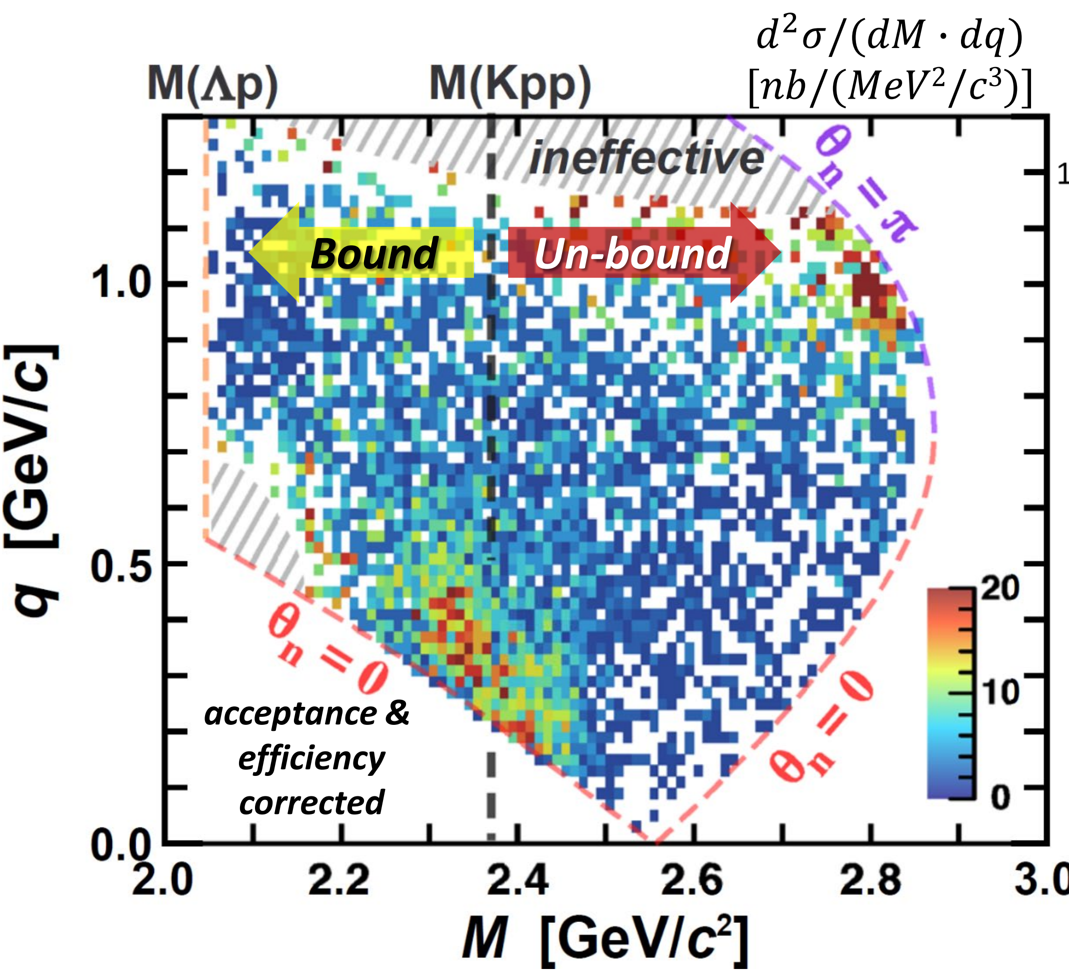
Experimental Setup @ K1.8BR

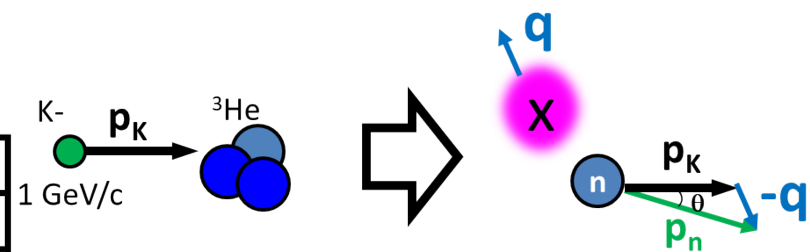


K. Agari et. al., PTEP 2012, 02B011

Exclusive ^{3}He(K$^-$,Λp)n

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



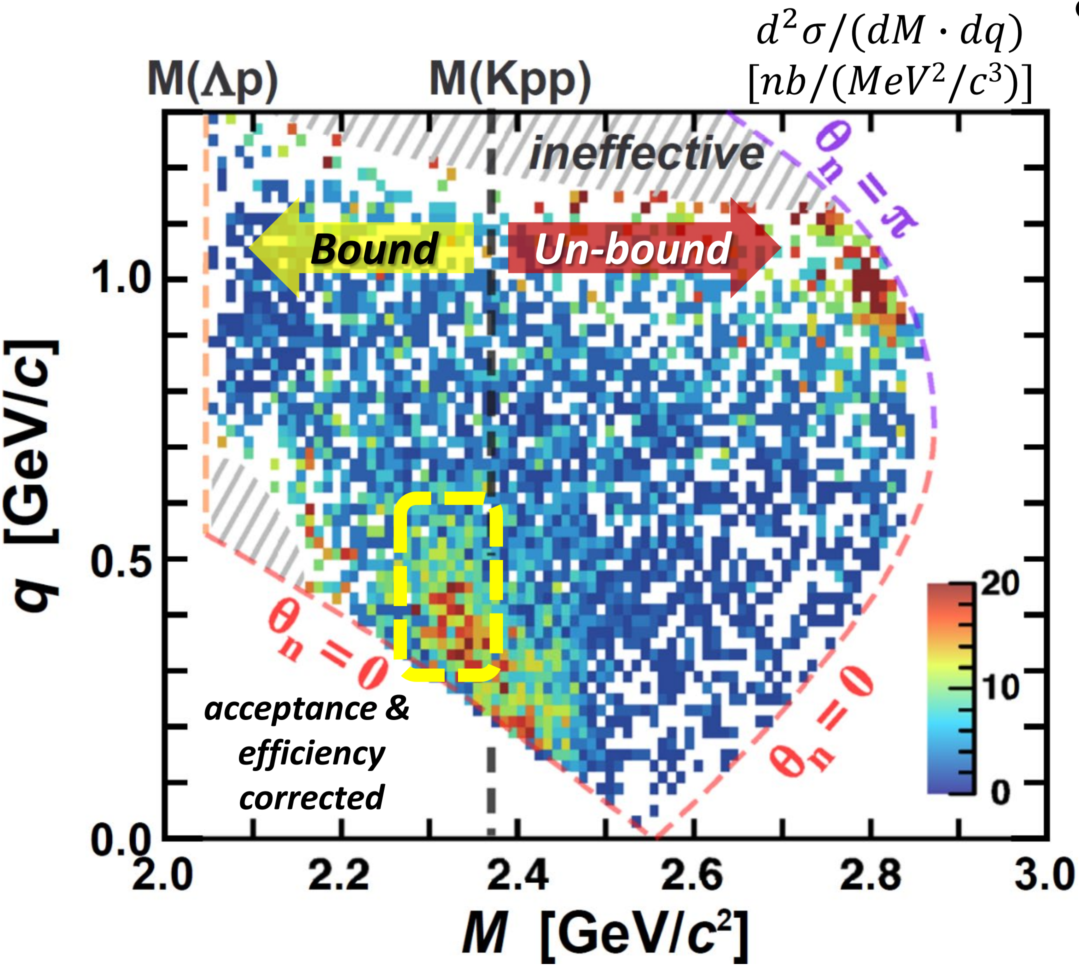


- **Momentum transfer analysis using the (K$^-$,n) reaction**
  - ✓M(Λp) vs. q
  - ✓give a clear information on reaction processes

q : *momentum transfer of (K-,n)*
M : *invariant mass of Λp*

Exclusive ^{3}He(K^-,Λp)n

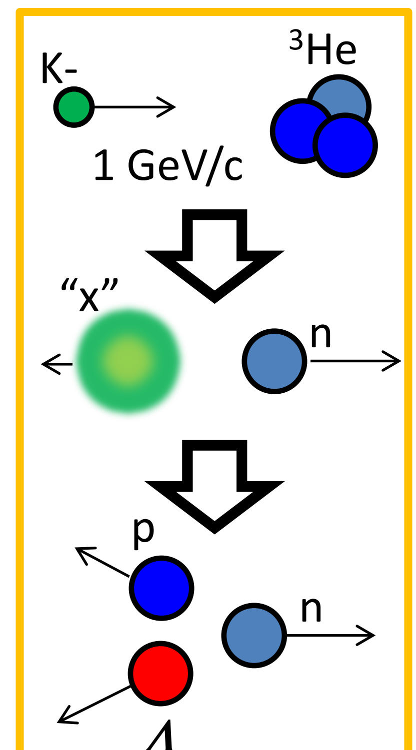
T.Yamaga et. al., PRC102(2020)044002.



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

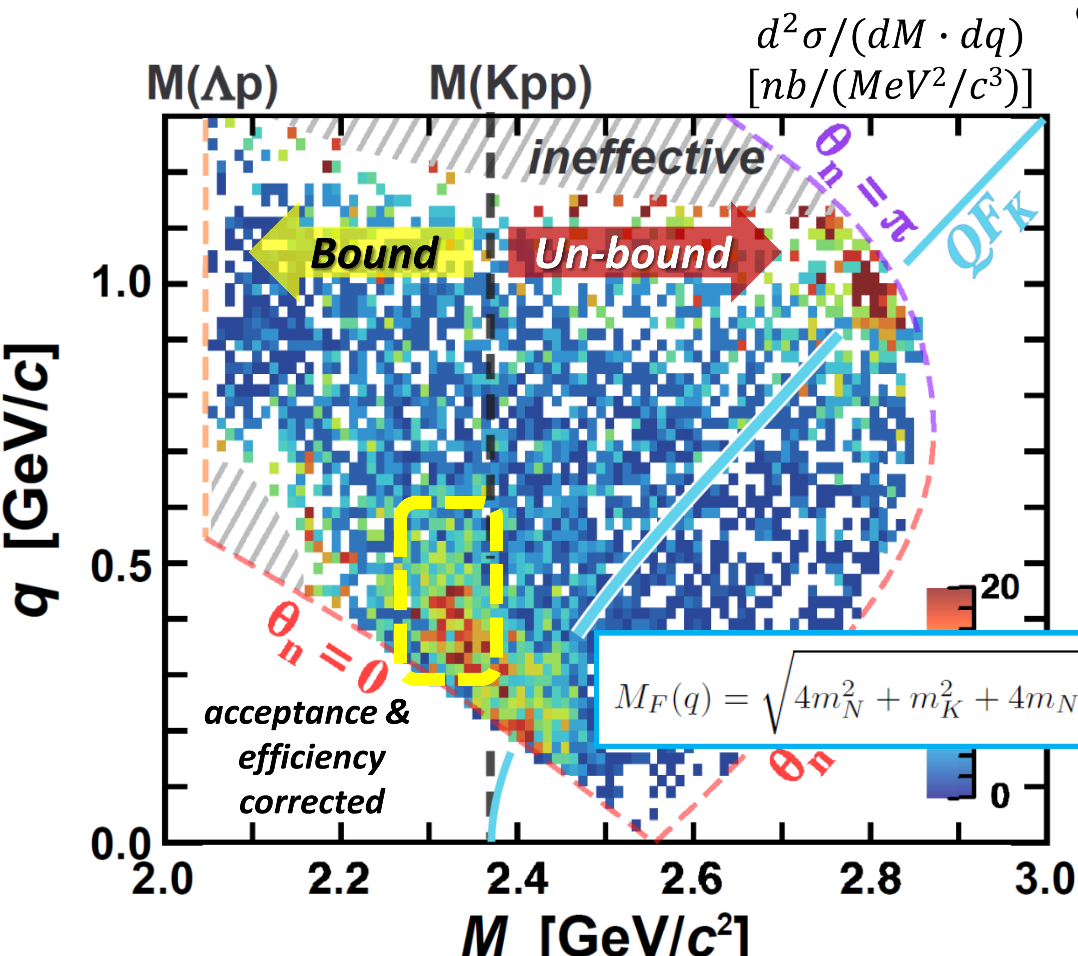
M *: invariant mass of Λp*

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



Exclusive ^{3}He(K$^-$,Λp)n

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

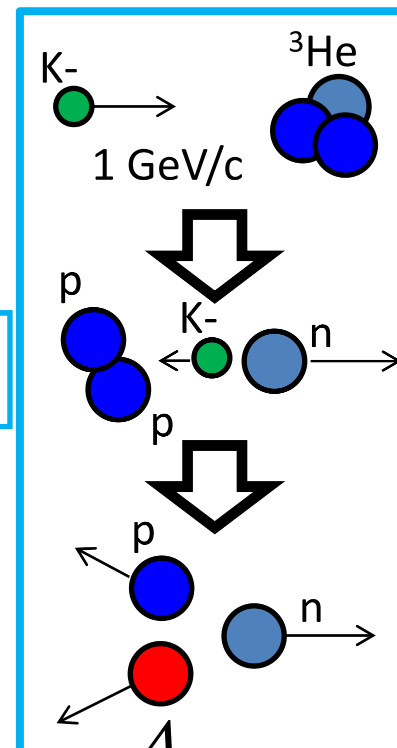


$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

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

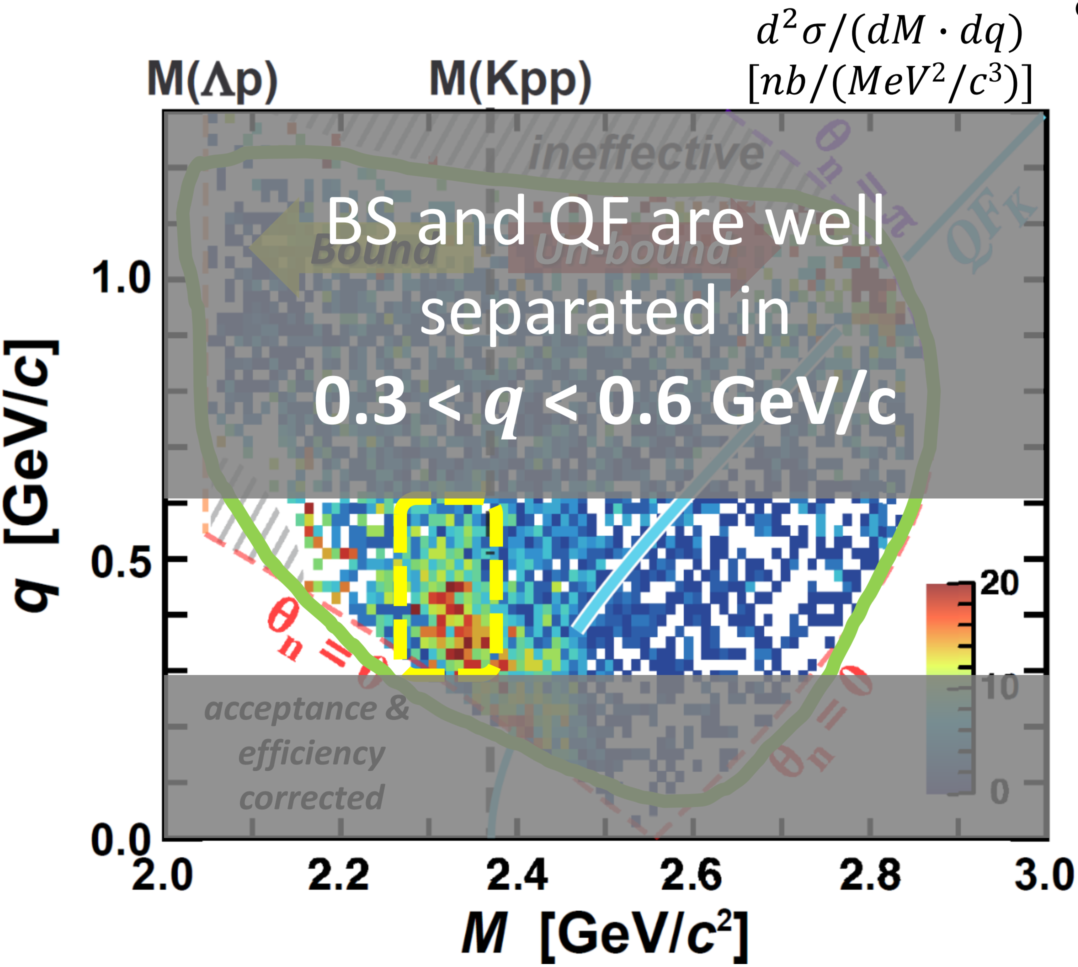
M : *invariant mass of Λp*

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



Exclusive ^{3}He(K$^-$,Λp)n

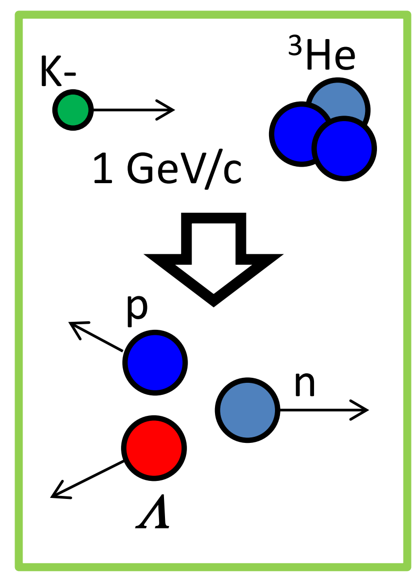
T.Yamaga et. al., PRC102(2020)044002.



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

M *: invariant mass of Λp*

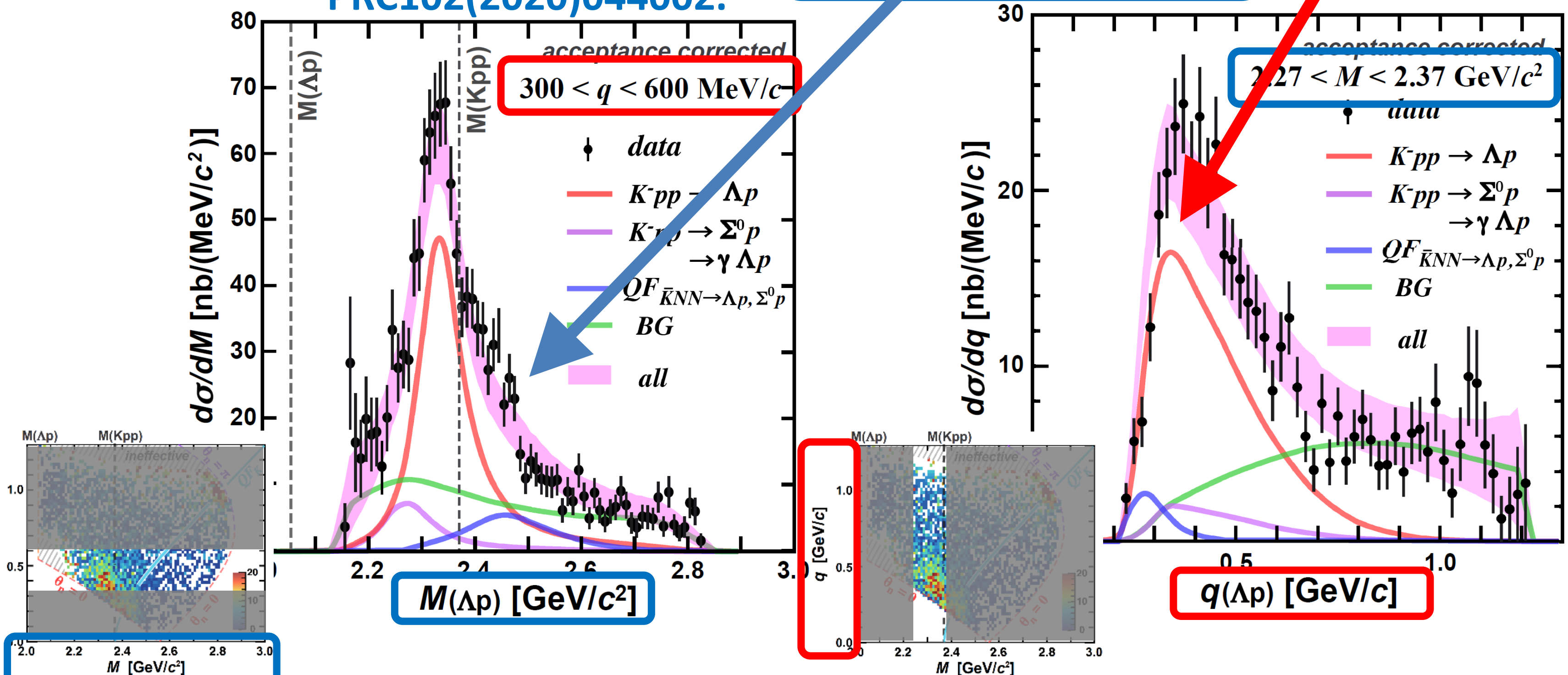
- **Broad Component**
  - ✓3NA reaction?
  - ✓Further investigations are ongoing



"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*

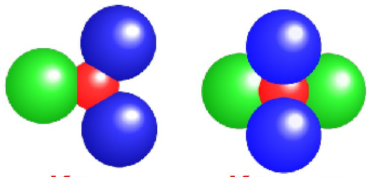
→ suggest the "K⁻pp" is quite compact

Many Questions to be Answered

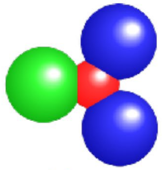
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K^-pp"?
  - Really compact and dense system?

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

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

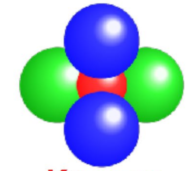


- **Double kaonic nuclei?**
  - Much compact and dense system?



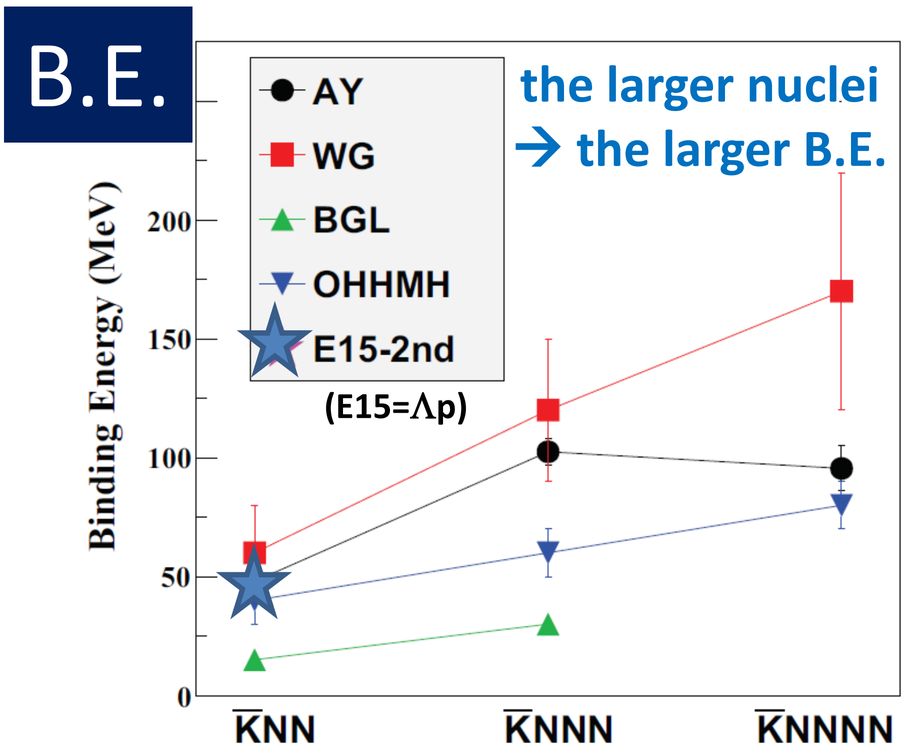
K⁻ppn

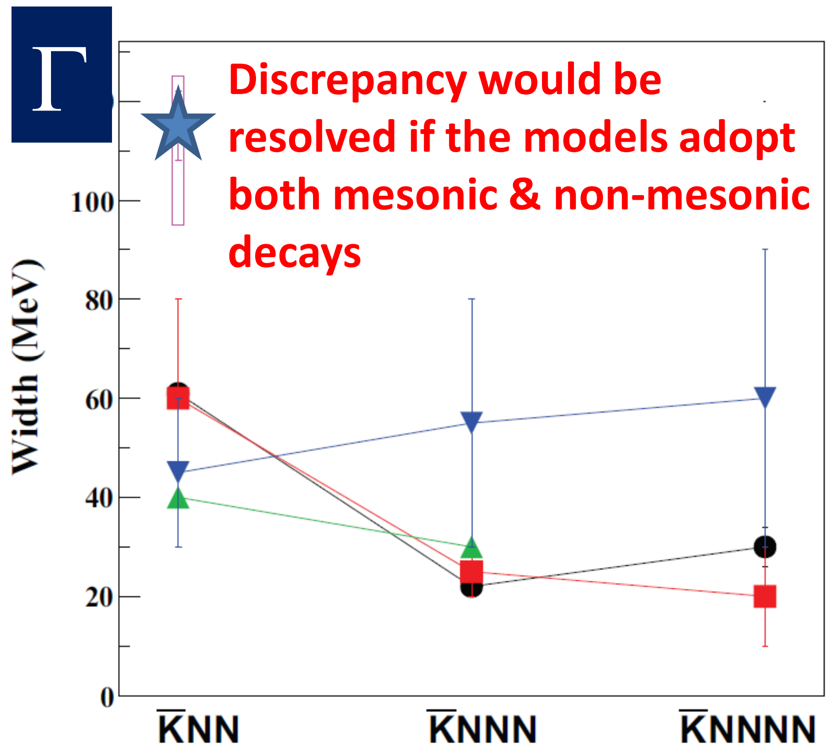
$\bar{K}NNN$ and $\bar{K}NNNN$



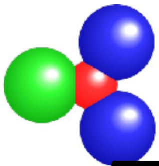
K⁻ppnn

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

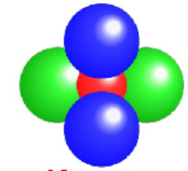




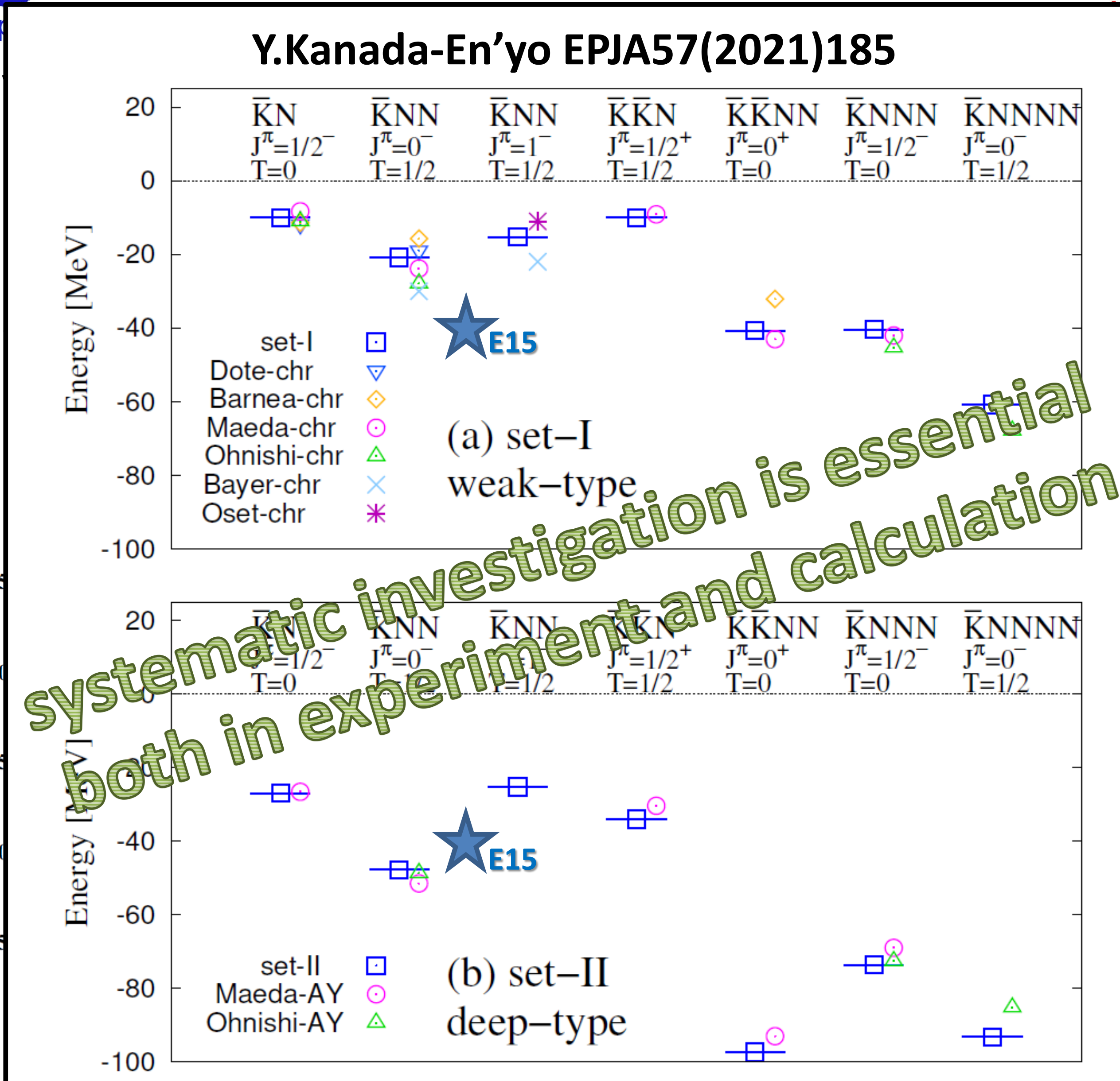
- ➢ The $\bar{K}NNNN$ system is expected to be the most compact system due to an α particle configuration



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



- Be… …ust be…
  - ✓ … to be … e



systematic investigation is essential both in experiment and calculation

New Project @ J-PARC

-- systematic investigation of the light kaonic nuclei --

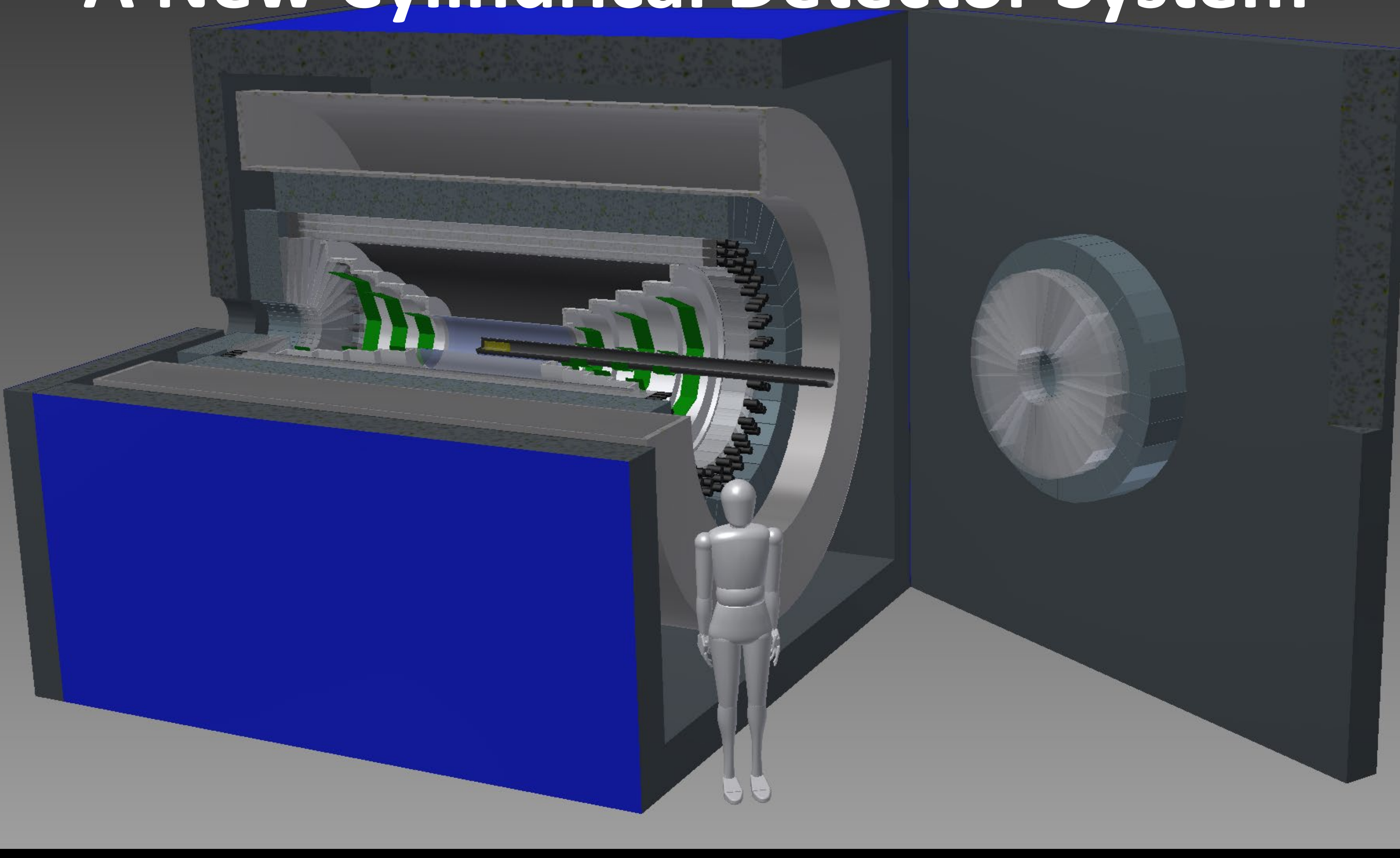
Strategy of the New Project

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

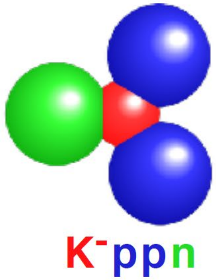
	Reaction	Decays	Key
$\bar{K}N$	d(K$^-$,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$	F-factor → n/γ identification
$\bar{K}NN$	^{3}He(K$^-$,N)	Λp/Λn	J^P → polarimeter
$\bar{K}NNN$	^{4}He(K$^-$,N)	Λd/Λpn	large acceptance **← A first step**
$\bar{K}NNNN$	*^{6}Li(K$^-$,d)*	*Λt/Λdn/Λpnn*	*many body decay*
$\bar{K}\bar{K}NN$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

B_{Kppn} ~ 40 MeV

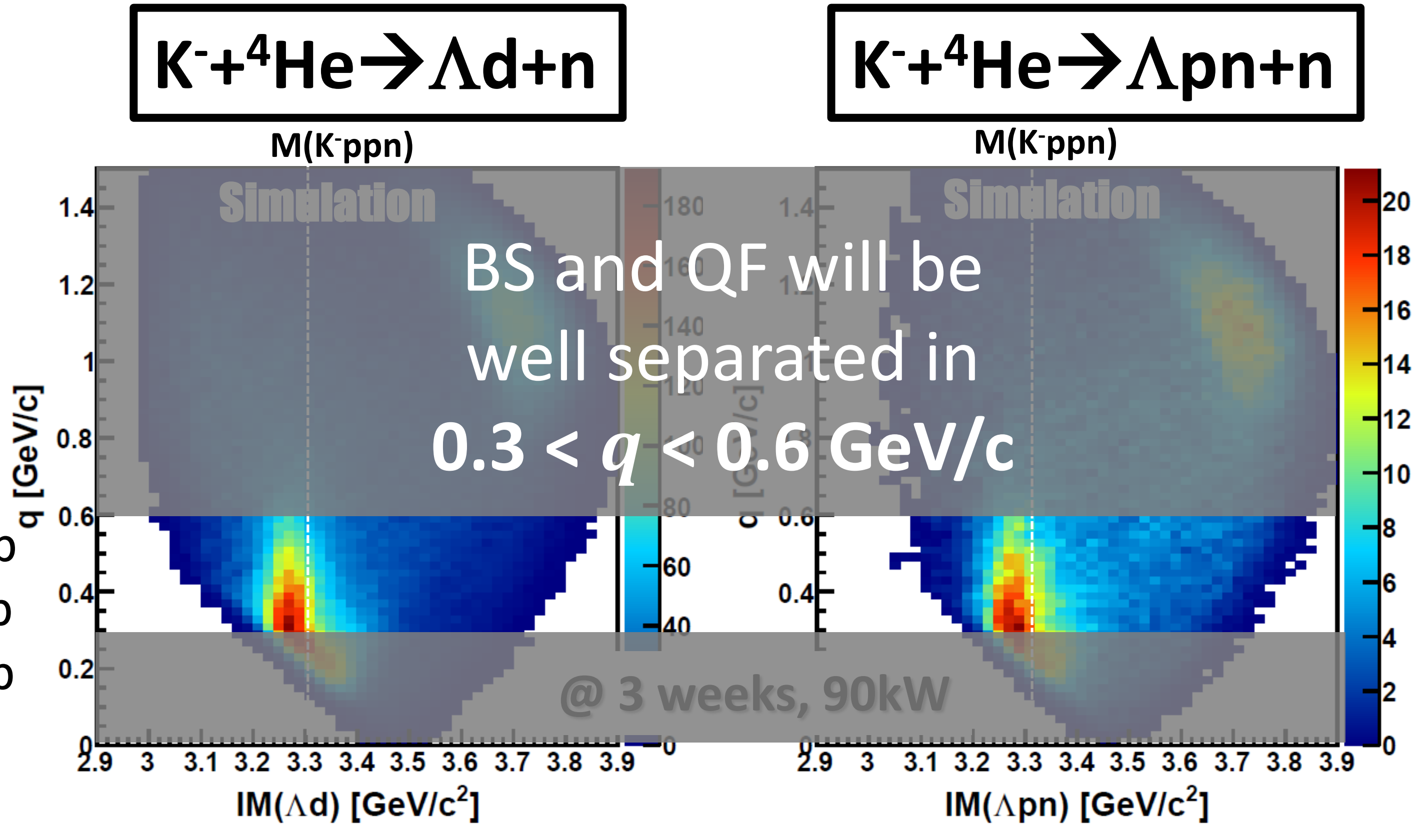
Γ_{Kppn} ~ 100 MeV

Q_{kppn} ~ 400 MeV/c

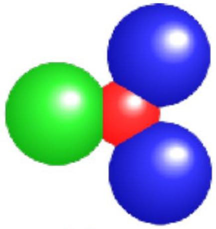
σ(K$^-$ppn)*Br ~ 10 μb

σ(QF) ~ 10 μb

σ(BG) ~ 20 μb



- 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**

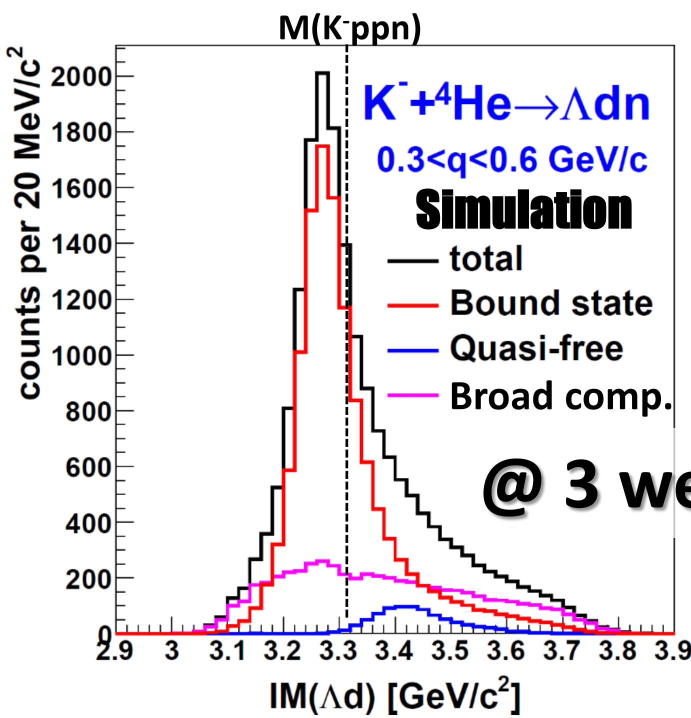


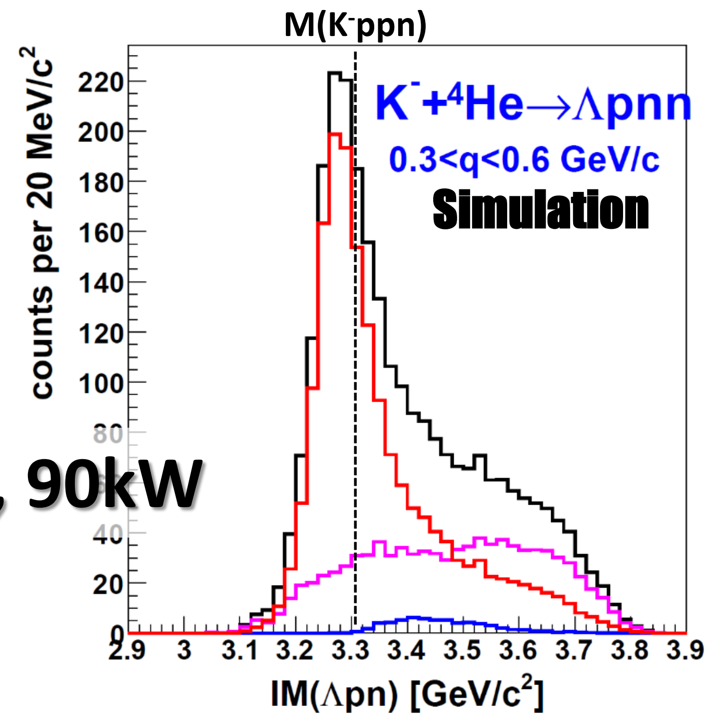
K⁻ppn

Expected $\bar{K}NNN$ 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 $^{3}He(K^{-},\Lambda p)n$**

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

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J-PARC E80 Collaboration

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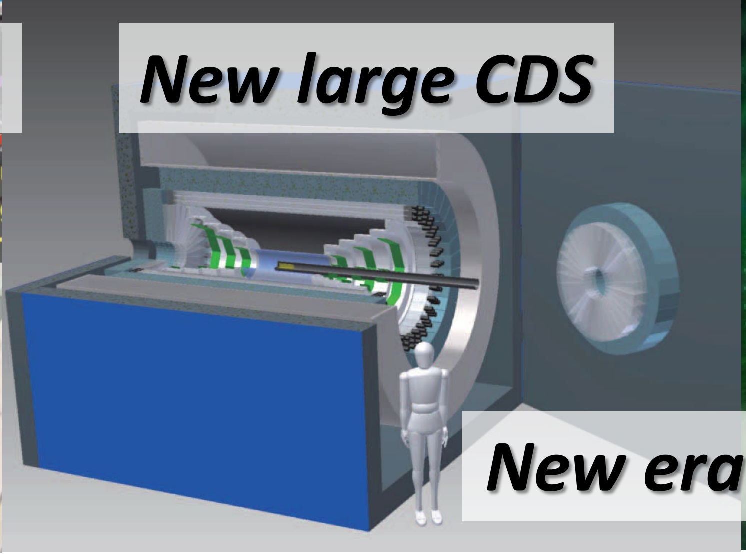
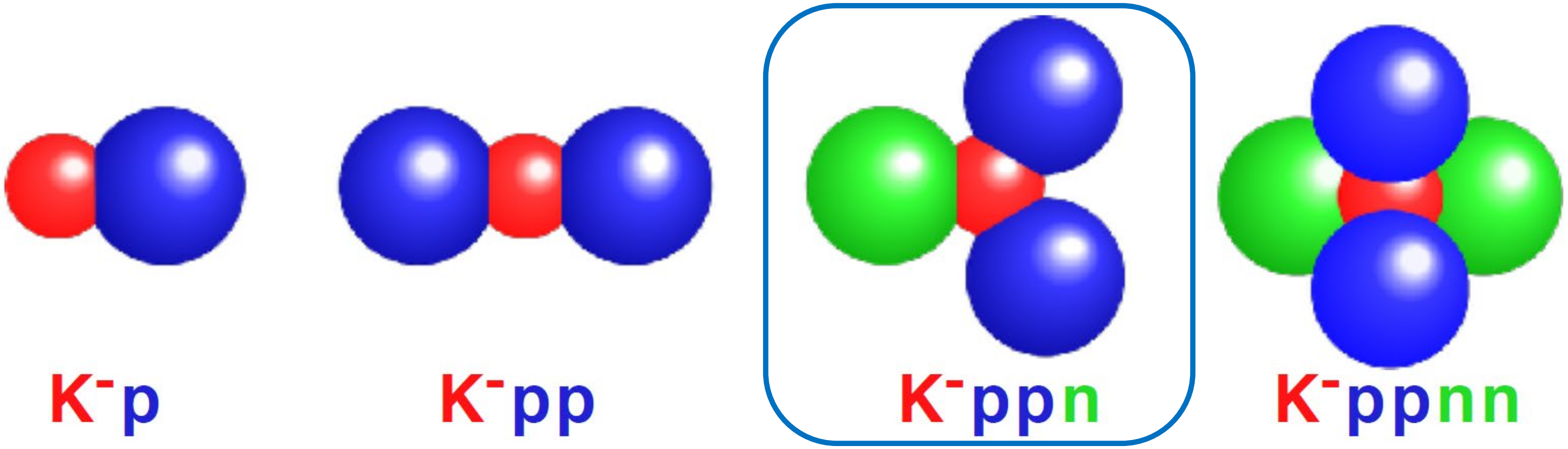
We're looking for new collaborators!



Thank you for your attention!

A first step of the new project



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

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

J-PARC P89

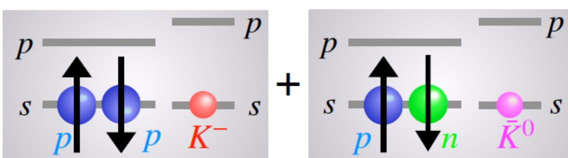
J-PARC P89

Internal structure & spin-parity

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

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

$J^P = 0^-$

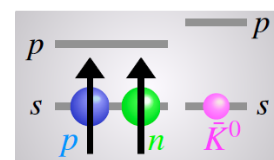


$$\frac{|I_{\bar{K}N} = 0|}{|I_{\bar{K}N} = 1|} = \frac{3}{1}$$

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.*

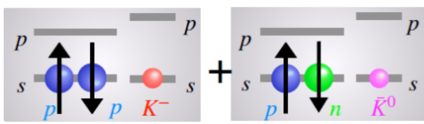
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

How to determine J^P

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

$J^P = 0^-$



To make negative parity from Λp

$L_{\Lambda p} = 1$

To be $J = 0$

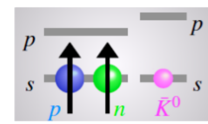
$S_{\Lambda p} = 1$

↓

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

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

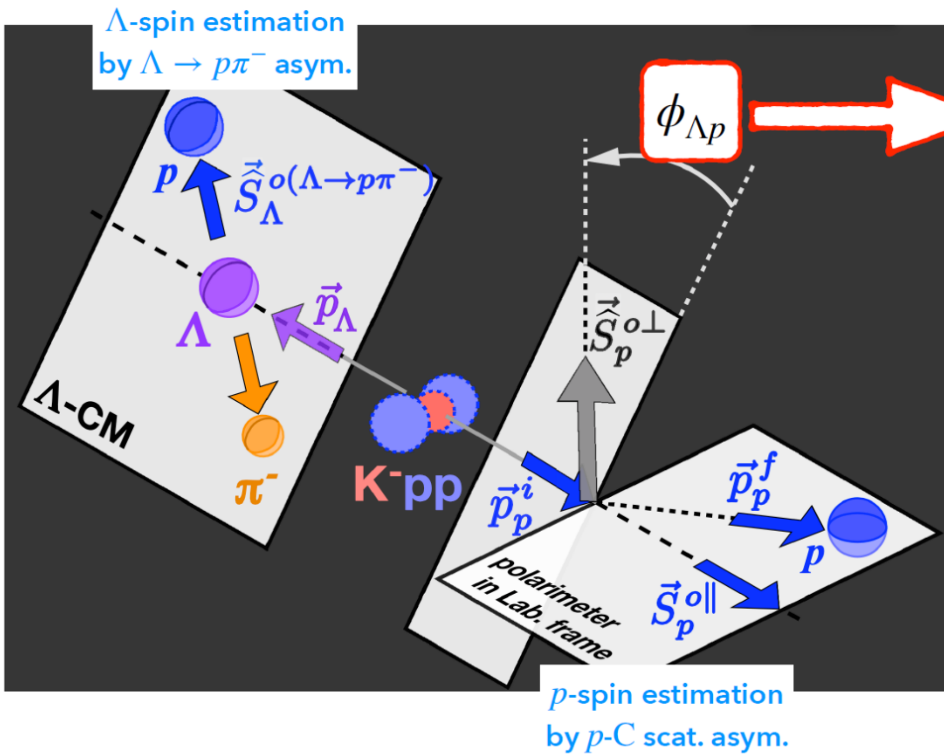
We can deduce J^P from $\alpha_{\Lambda p}$ measurement.

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 $\Lambda \rightarrow p\pi^-$ & 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;

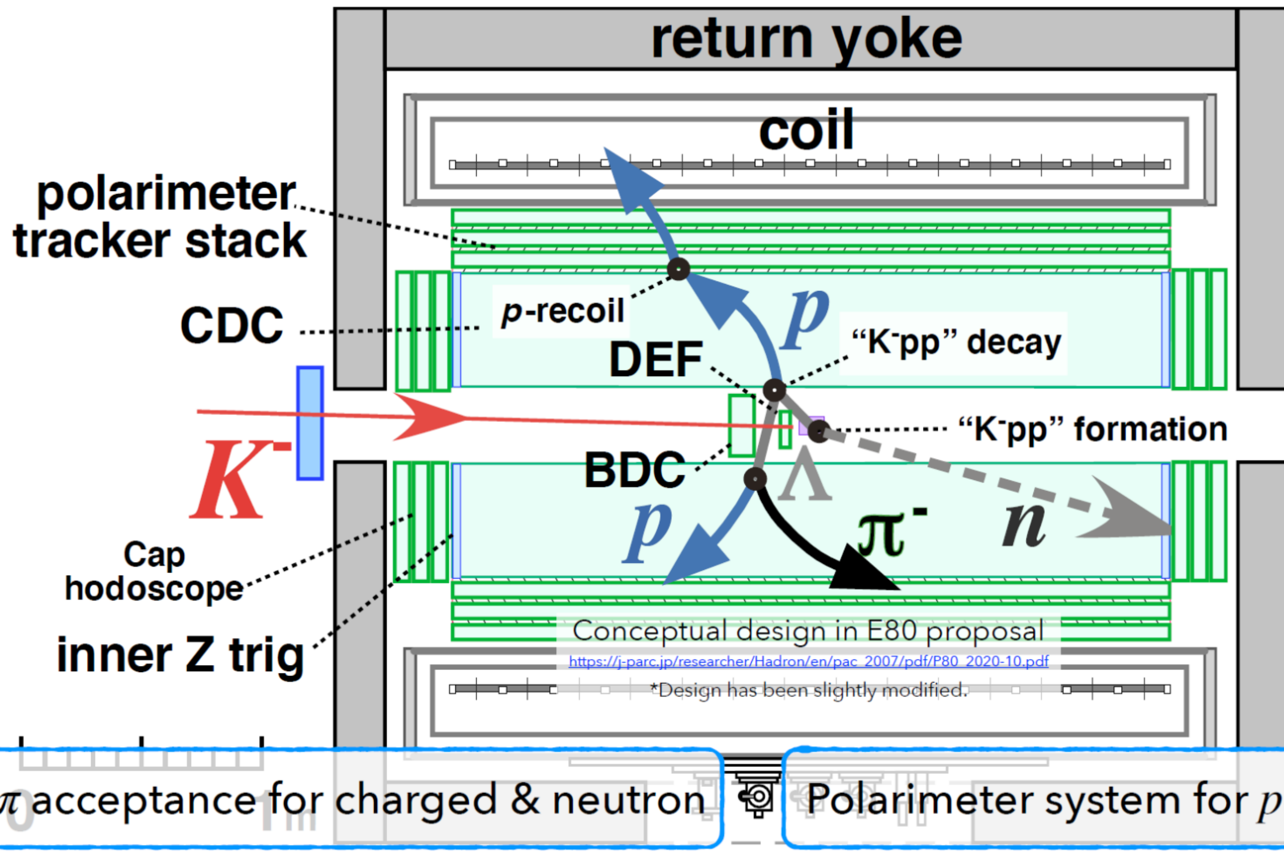
α_- : Λ asym. parameter	B : Magnetic field
A_{pC} : Analyzing power	$B_{\bar{K}}$: Binding energy
$f_{\vec{S}_\Lambda}$: Spin distribution	q : Momentum transfer

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



~ 4π acceptance for charged & neutron

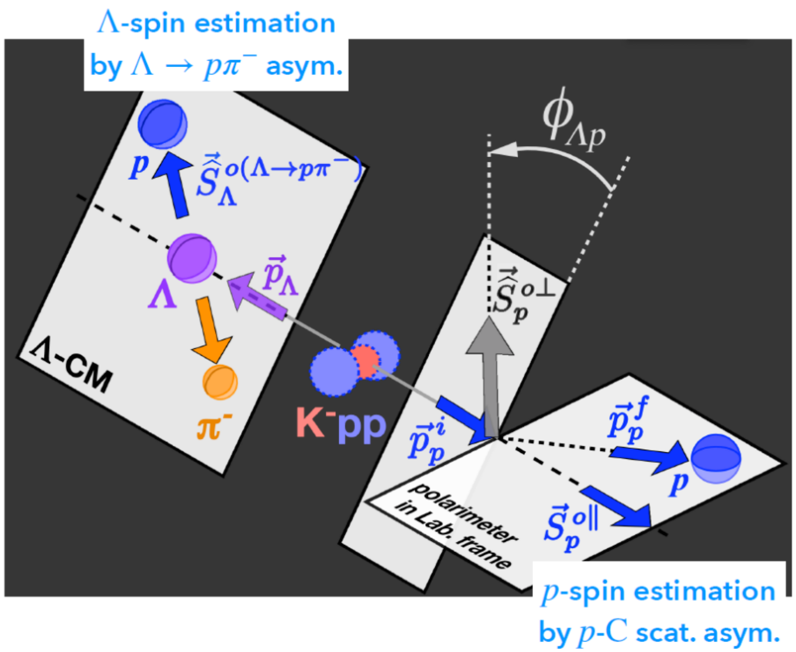
Polarimeter system for p-spin measurement

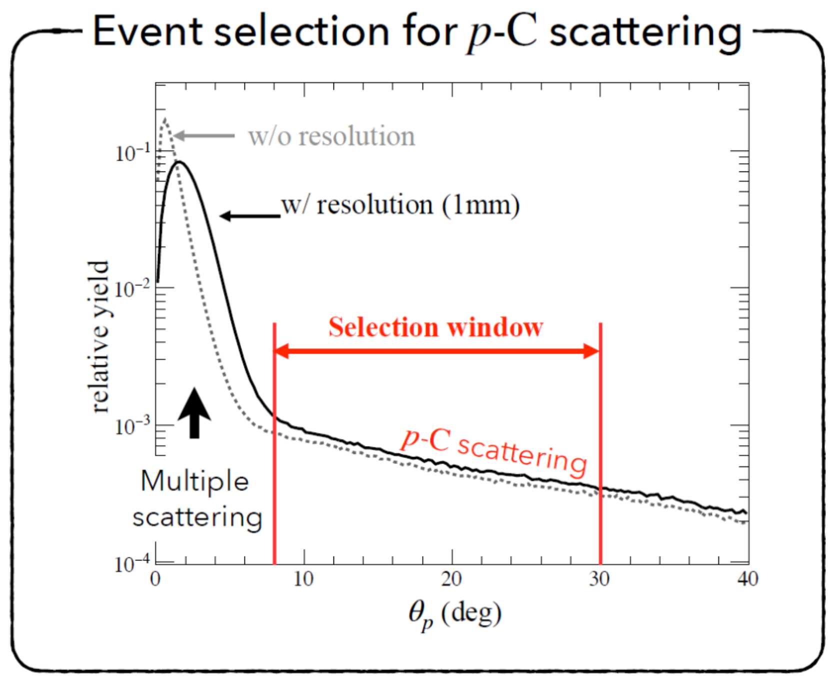
T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

Expected spectra

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



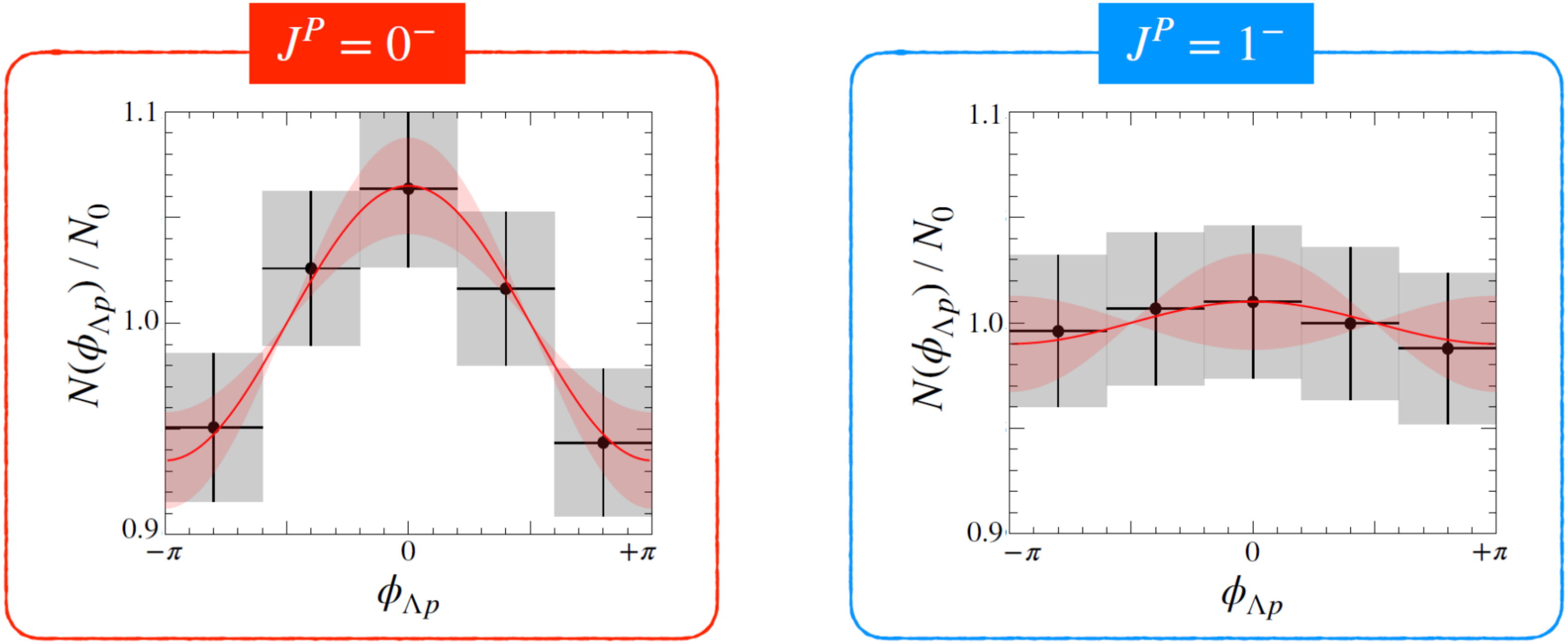


T. Yamaga (RIKEN), 32nd J-PARC PAC meeting, Jul.14-16, https://kds.kek.jp/event/38719/

J-PARC P89

Expected spectra

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



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*

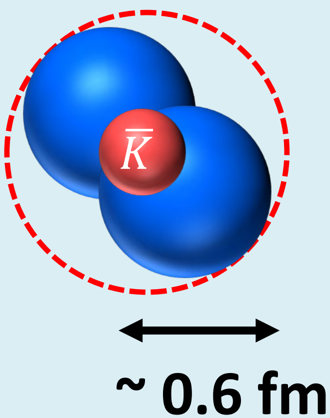
suggest the "K⁻pp" is quite compact (R_{Kpp} ~ 0.6 fm)

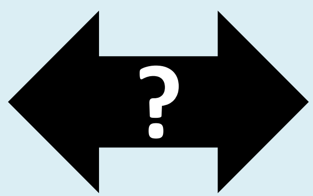
→ *Need more realistic theoretical calculations*

a whole new probe to reveal
the structure of a nucleon

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

Radius of "K⁻pp"

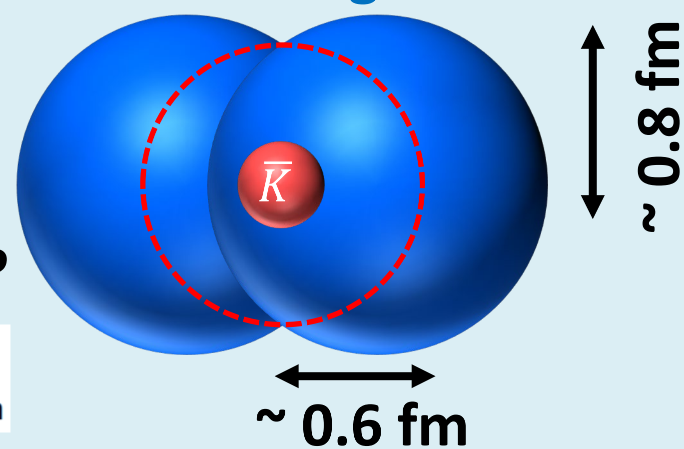




& effect of K size?

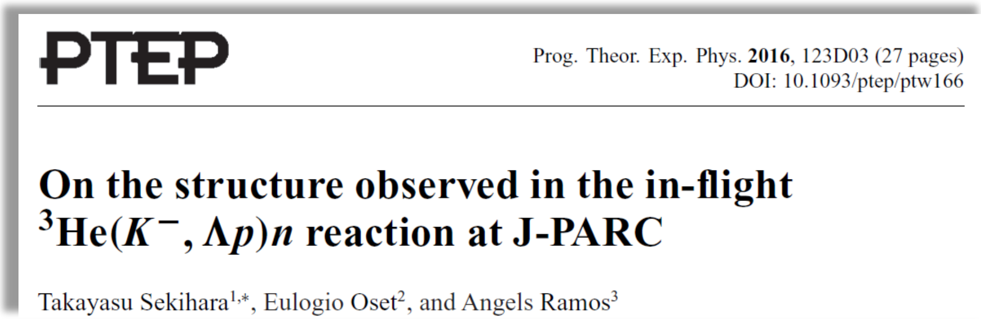
Charge radius
$\langle r \rangle = 0.560 \pm 0.031$ fm

Interaction range of "K⁻"



A Theoretical Interpretation

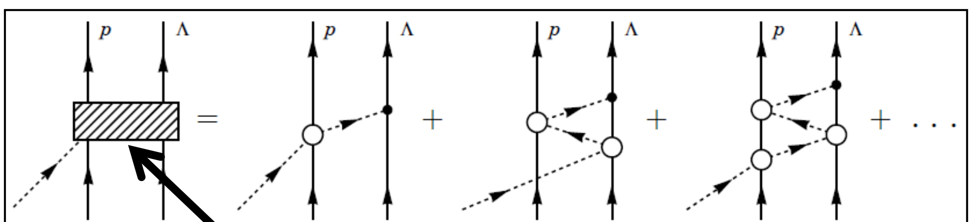
- A calculation with chiral unitary approach reproduces the mass spectrum with the $\bar{K}NN$

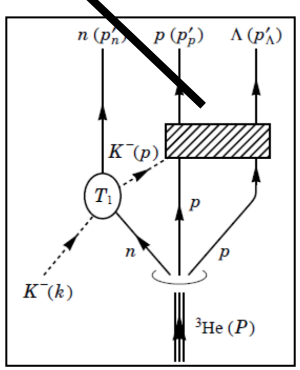

PTEP

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

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

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

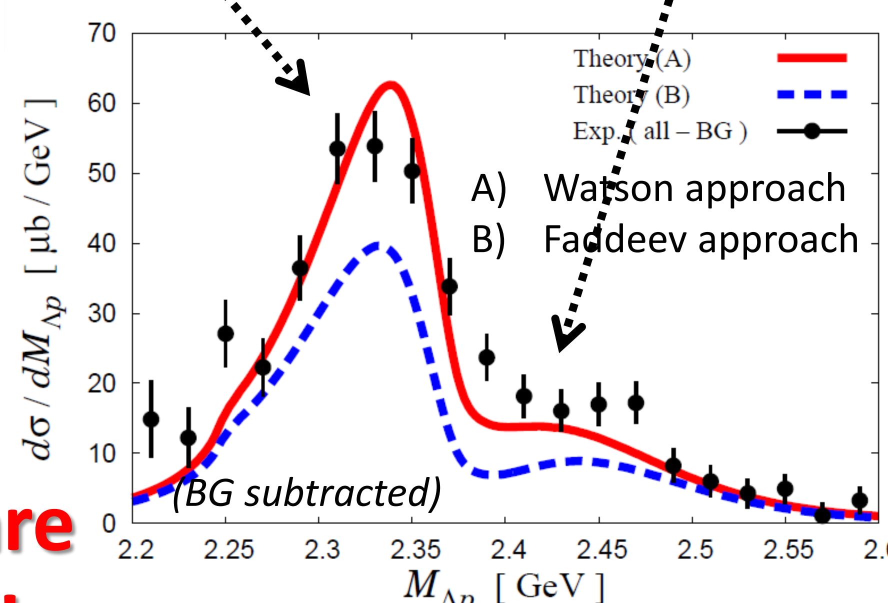




Theoretical investigations are indispensable!

K^bar NN bound-state

quasi-elastic kaon scattering



JPS Conf. Proc.26(2019)023009.

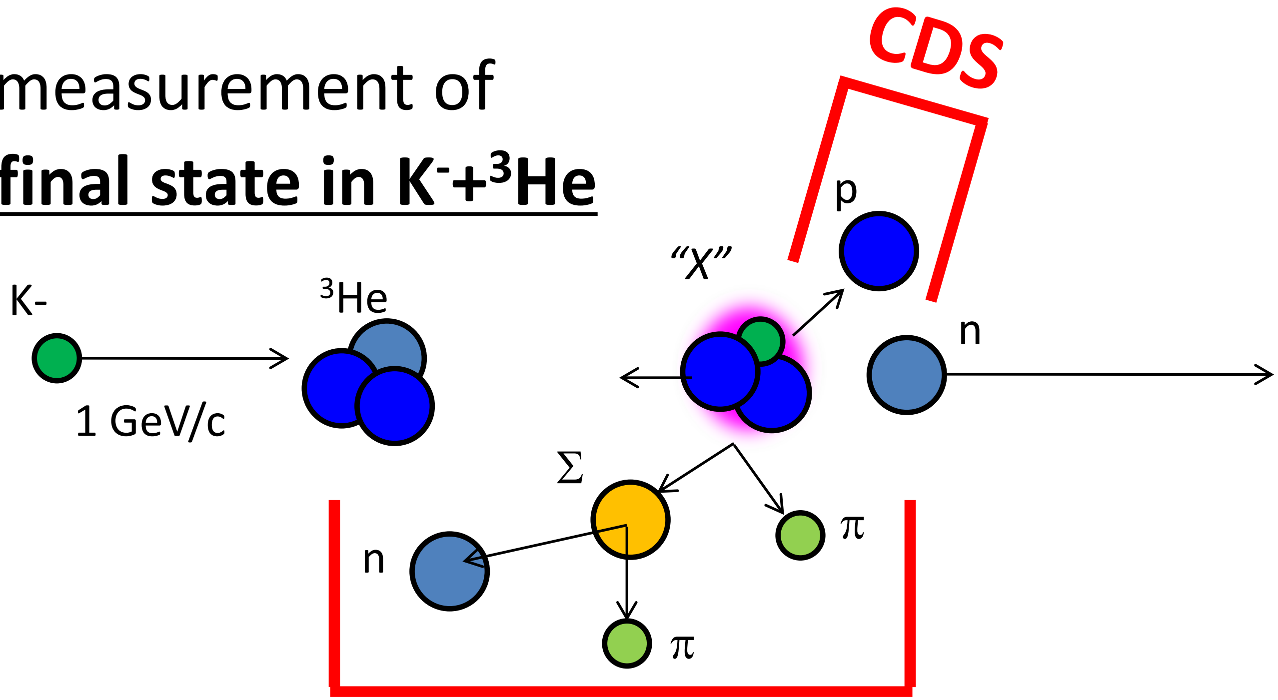
Many Questions to be Answered

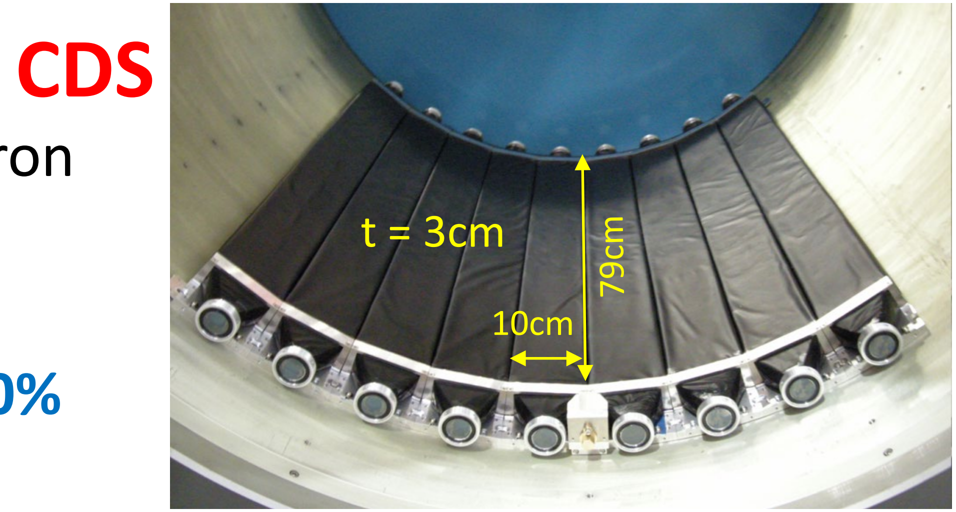
- **Further details of the $\bar{K}NN$**
  - Spin and parity of the "K$^-$pp"?
  - Really compact and dense system?
  - Other decay modes?

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

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



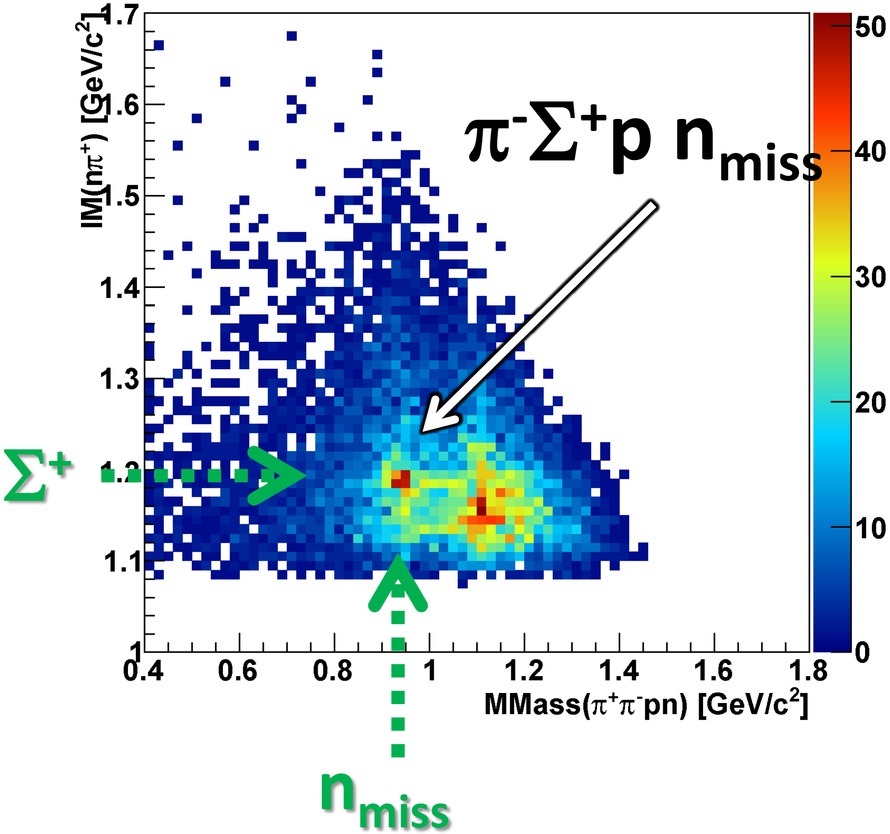


- **Experimental challenge** of neutron detection with thin scintillation counter (t=3cm)

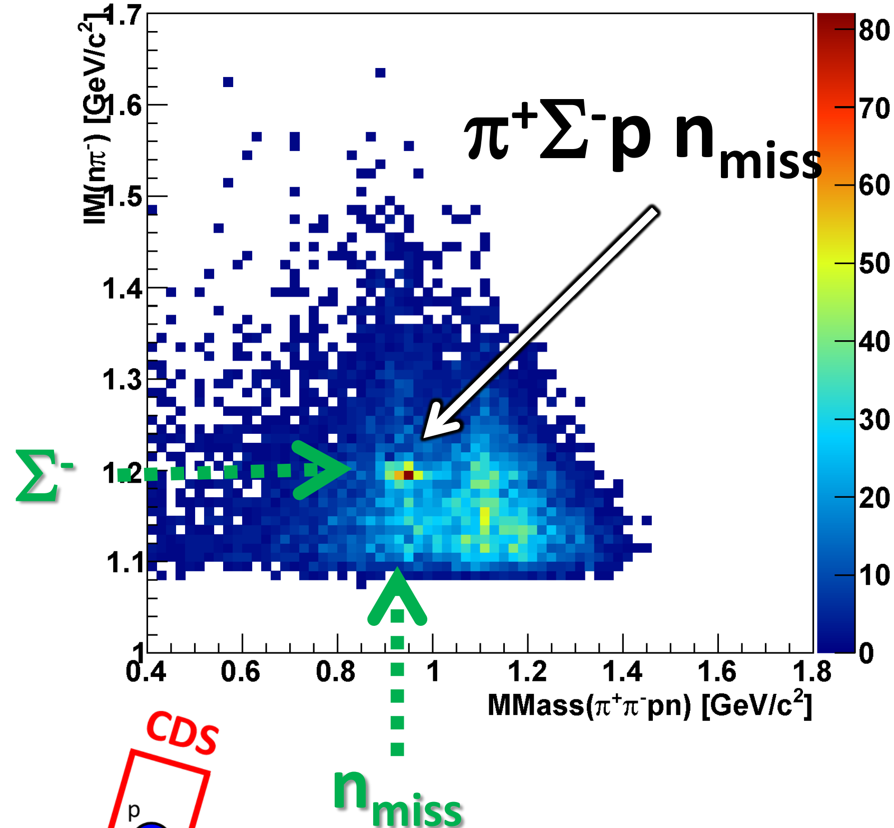
n detection efficiency ~ 3-10%

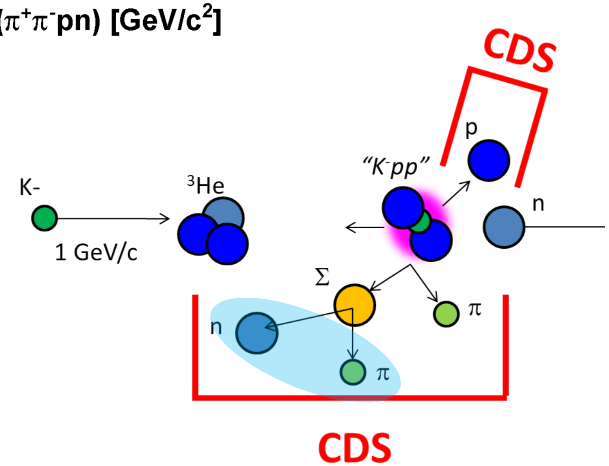
πΣpn Events

IM(nπ⁺) vs MM(π⁺π⁻pn)

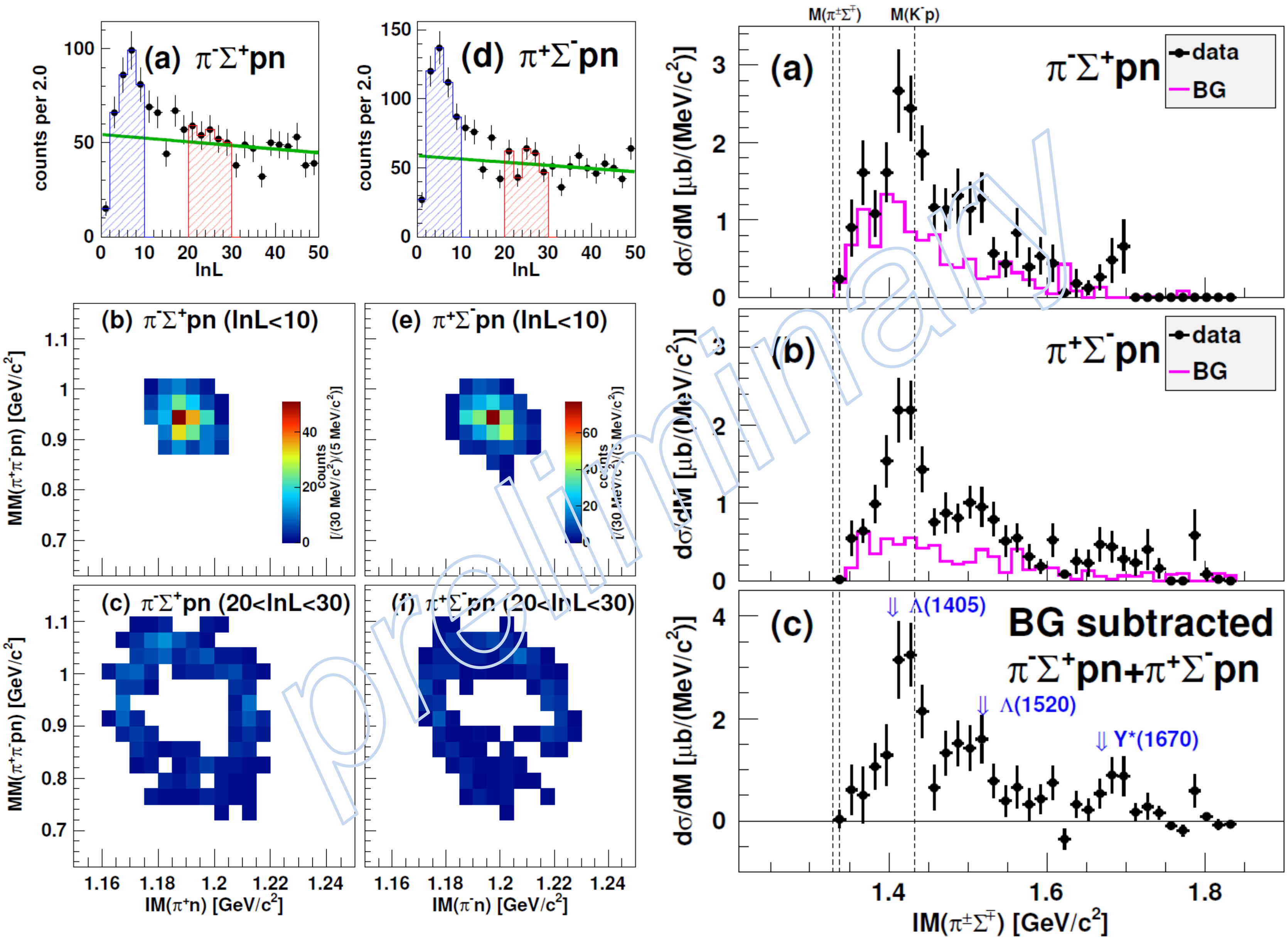


IM(nπ⁻) vs MM(π⁺π⁻pn)



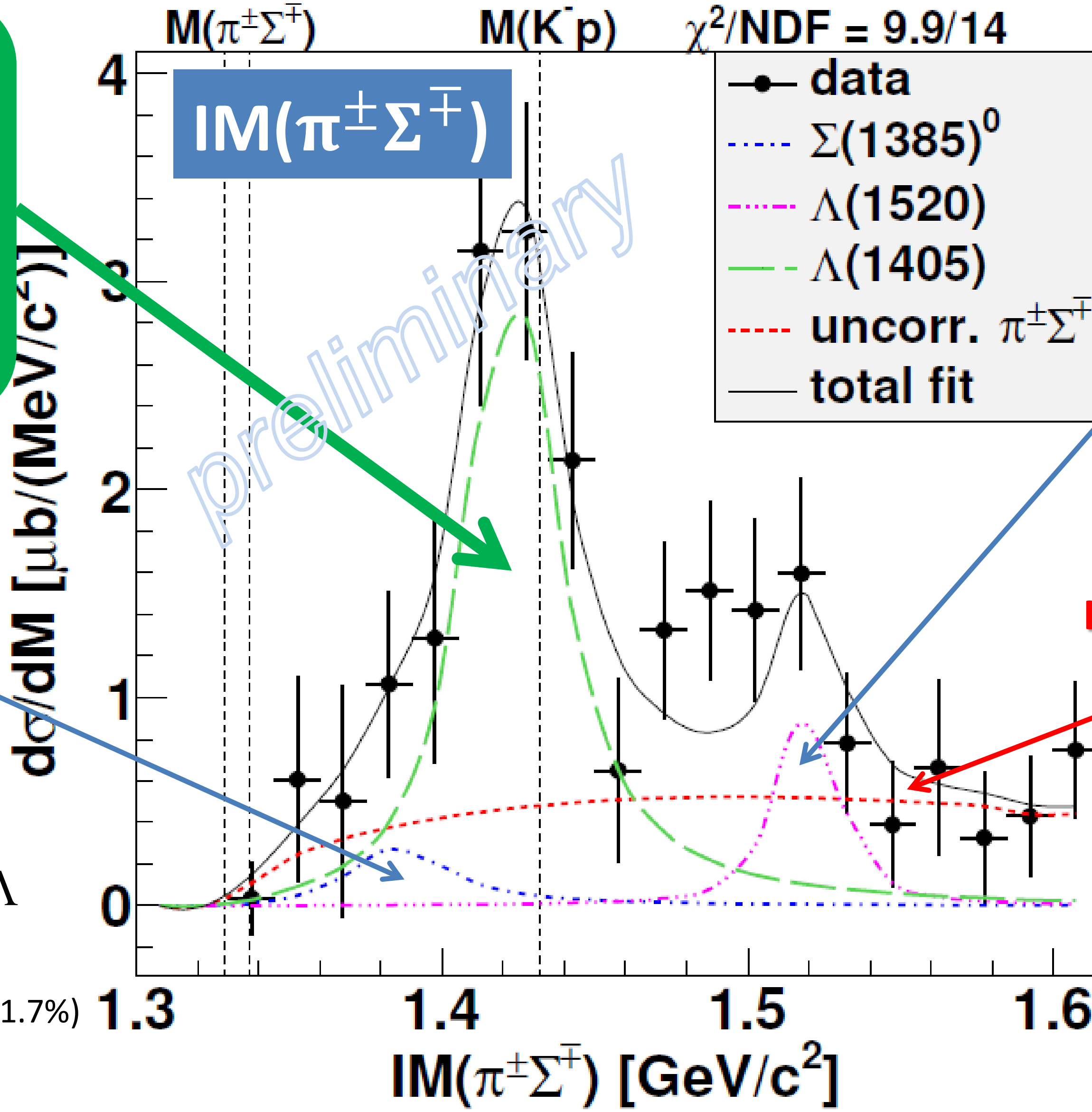


BG Subtracted IM($\pi^{\pm}\Sigma^{\mp}$) in $\pi^{\pm}\Sigma^{\mp}pn$



$Y^{*}pn$ Final State

$\Lambda(1405)$
~ 250 μb
Fit with BW:
M ~ 1422 MeV
Γ ~ 40 MeV



$\Lambda(1520)$
~ 100 μb

πΣpn non-resonant

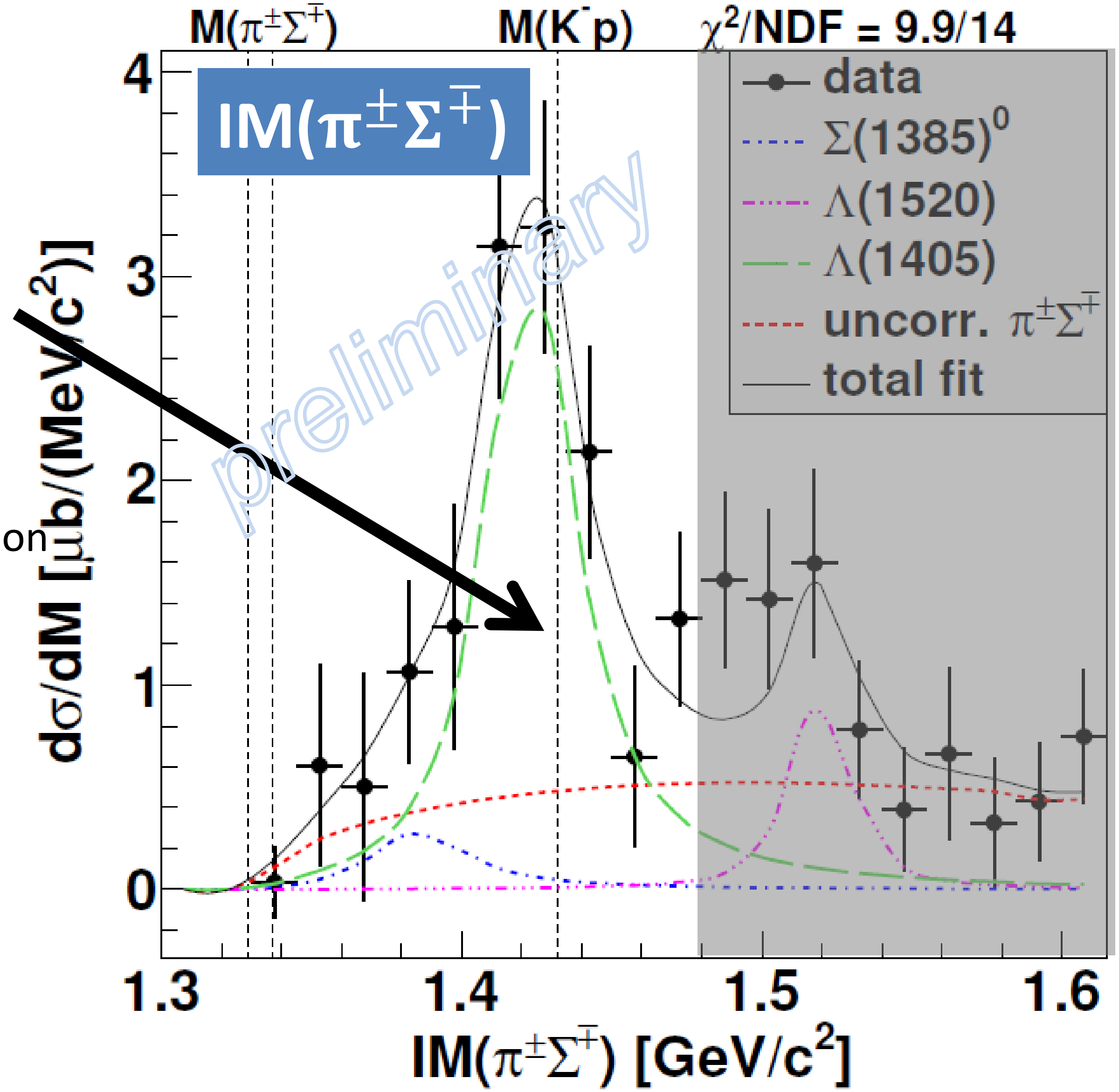
$\Sigma(1385)^0$
~ 100-150 μb
[evaluated from $\Sigma(1385)^{+/-} \rightarrow \pi^{+/-}\Lambda$ measurement]

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

$\Lambda(1405)pn$ Final State Selection

Select $\Lambda(1405)$ region

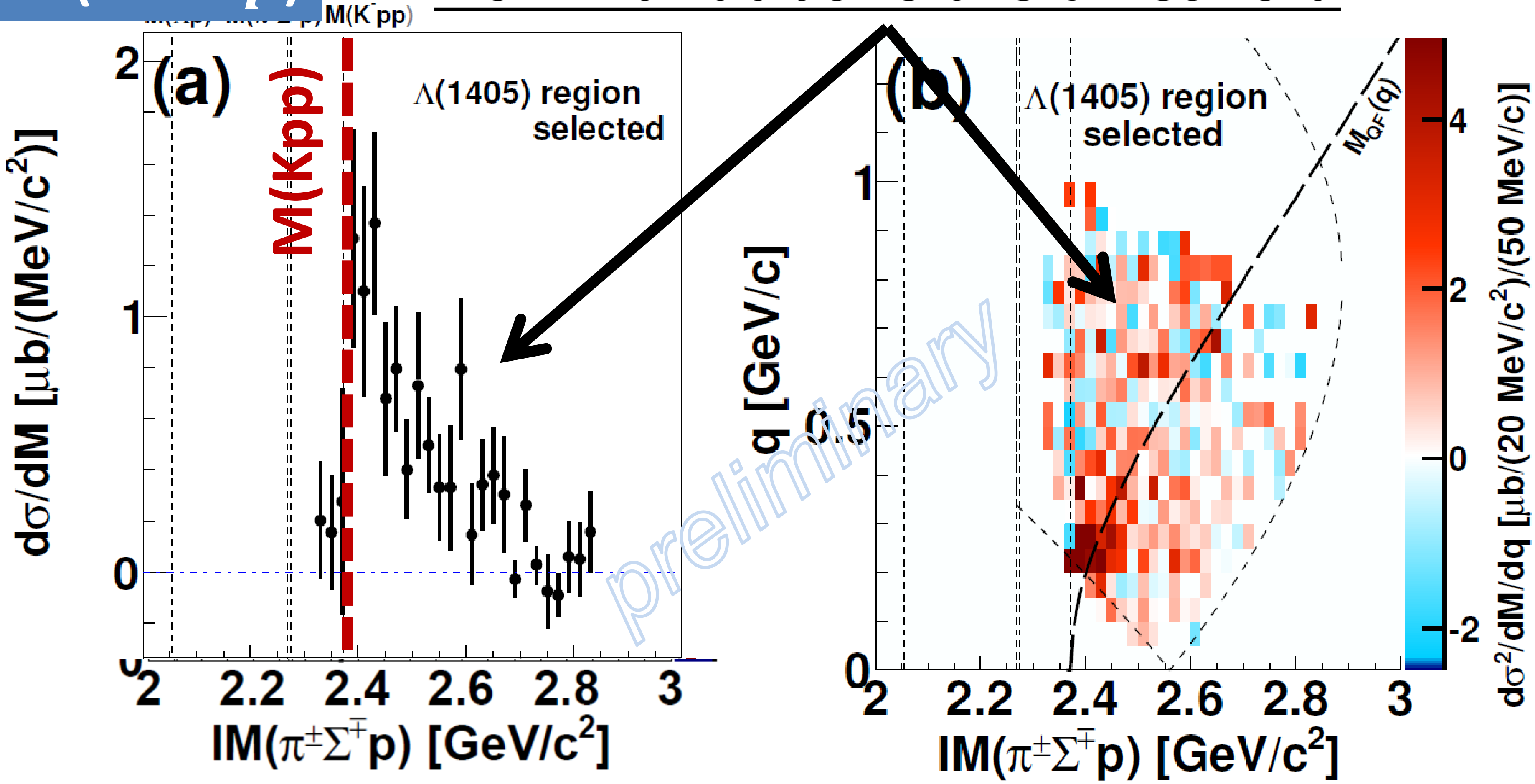
- Below $\Lambda(1520)$
- Small contribution from $\Sigma(1385)$



IM(πΣp) in Λ(1405)pn Final State

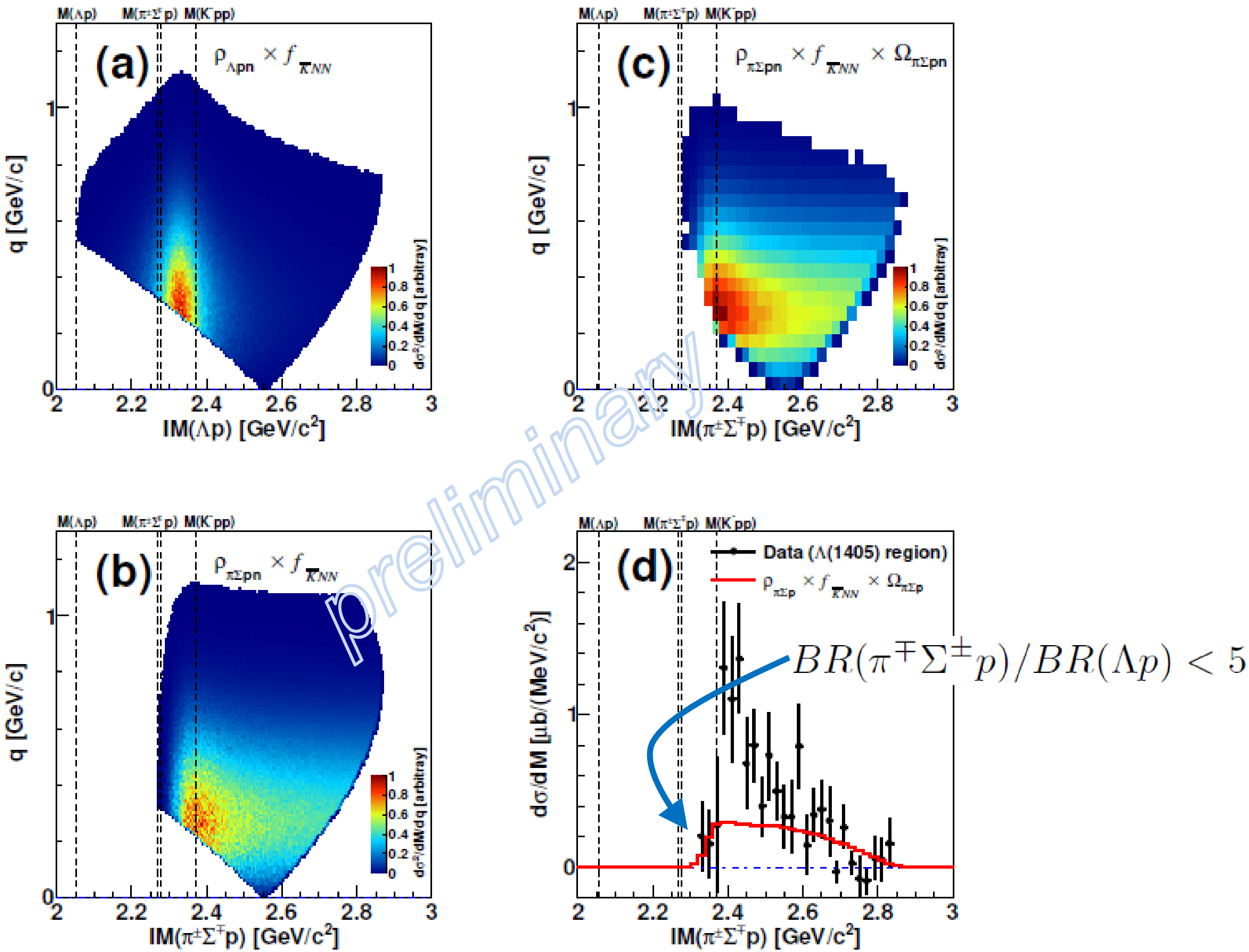
IM($\pi^{\pm}\Sigma^{\mp}p$)

Dominant above the threshold



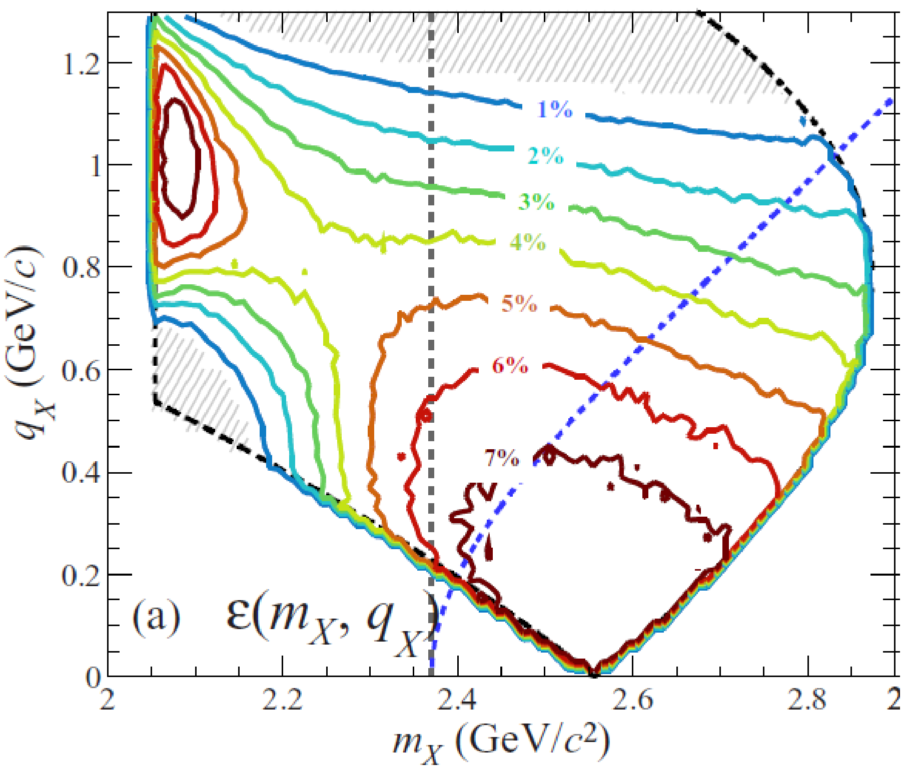
- IM(Λ(1405)p) distributes above the M(Kpp)
- QF $K^{-}N \rightarrow K^{bar}n$ followed by $K^{bar}NN \rightarrow \Lambda(1405)p$

Investigation of K⁻pp → πΣp decay

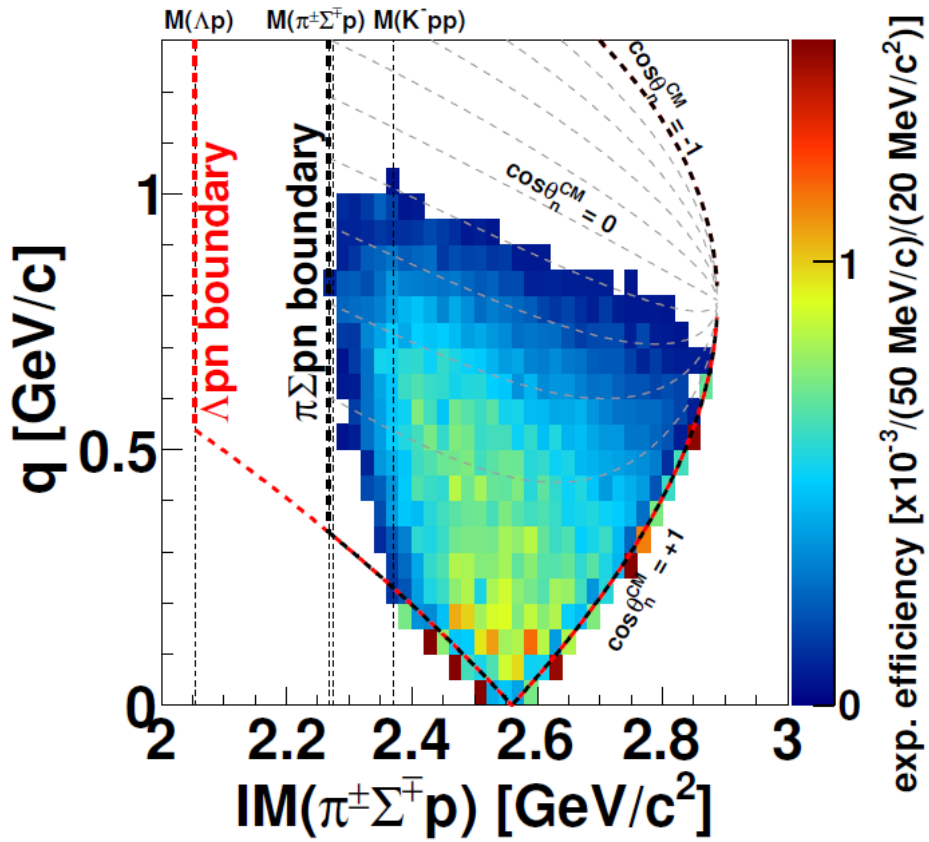


Detector acceptances of Λpn and πΣpn

Λp

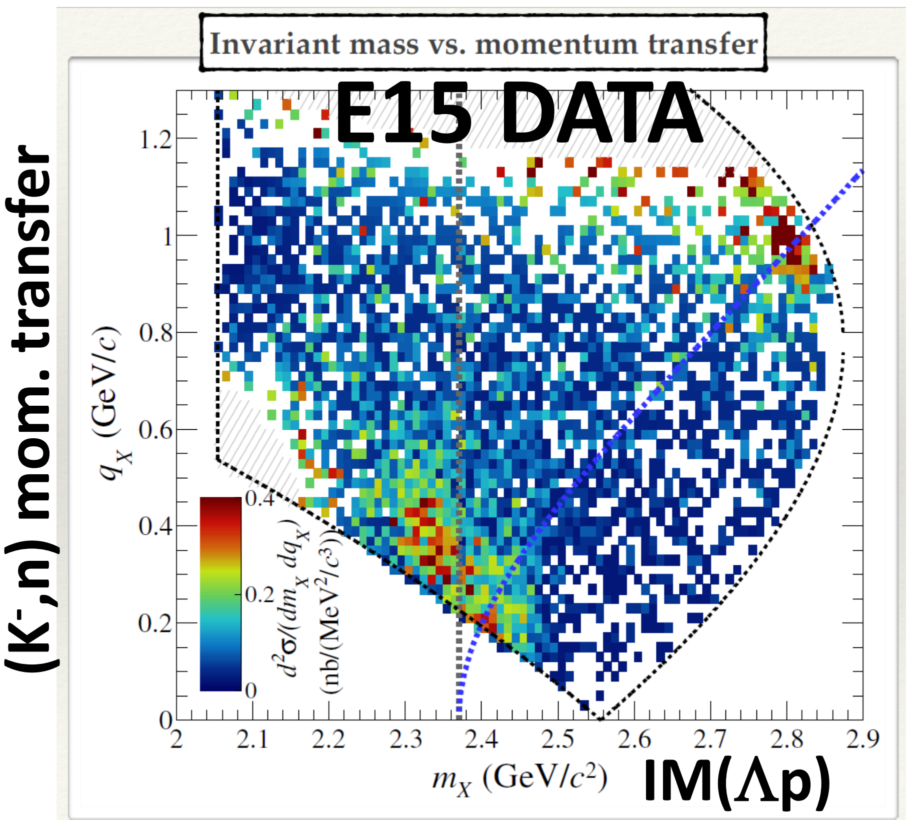


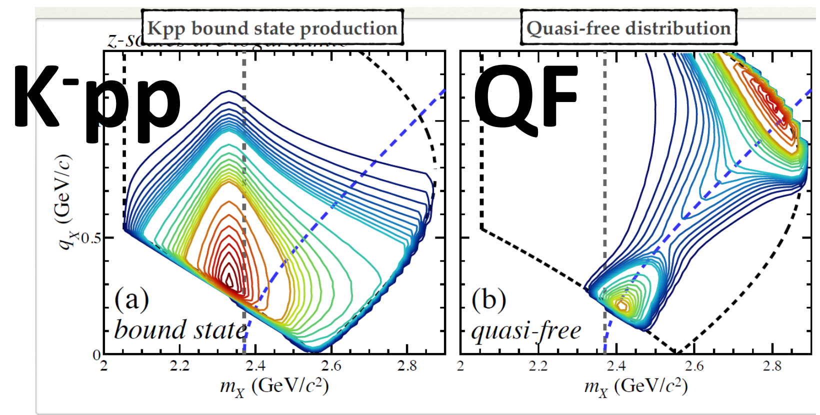
πΣp

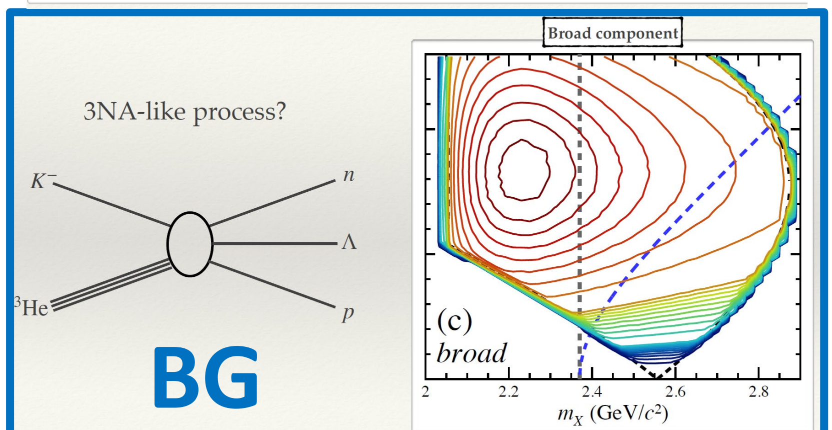


Recent progress of the E15 analysis

- 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

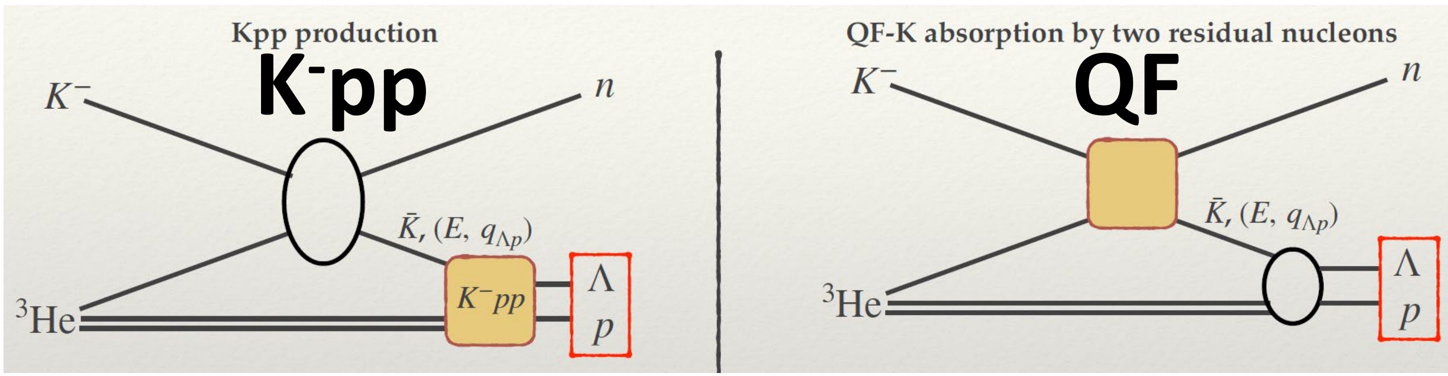




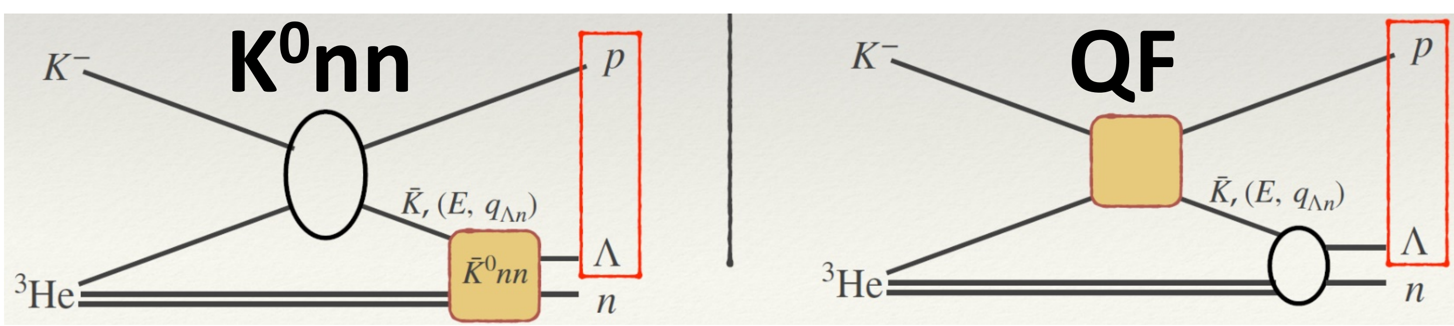


Recent progress of the E15 analysis

- 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 $K^{-}pp$ ($=K^{0}nn$) is also generated

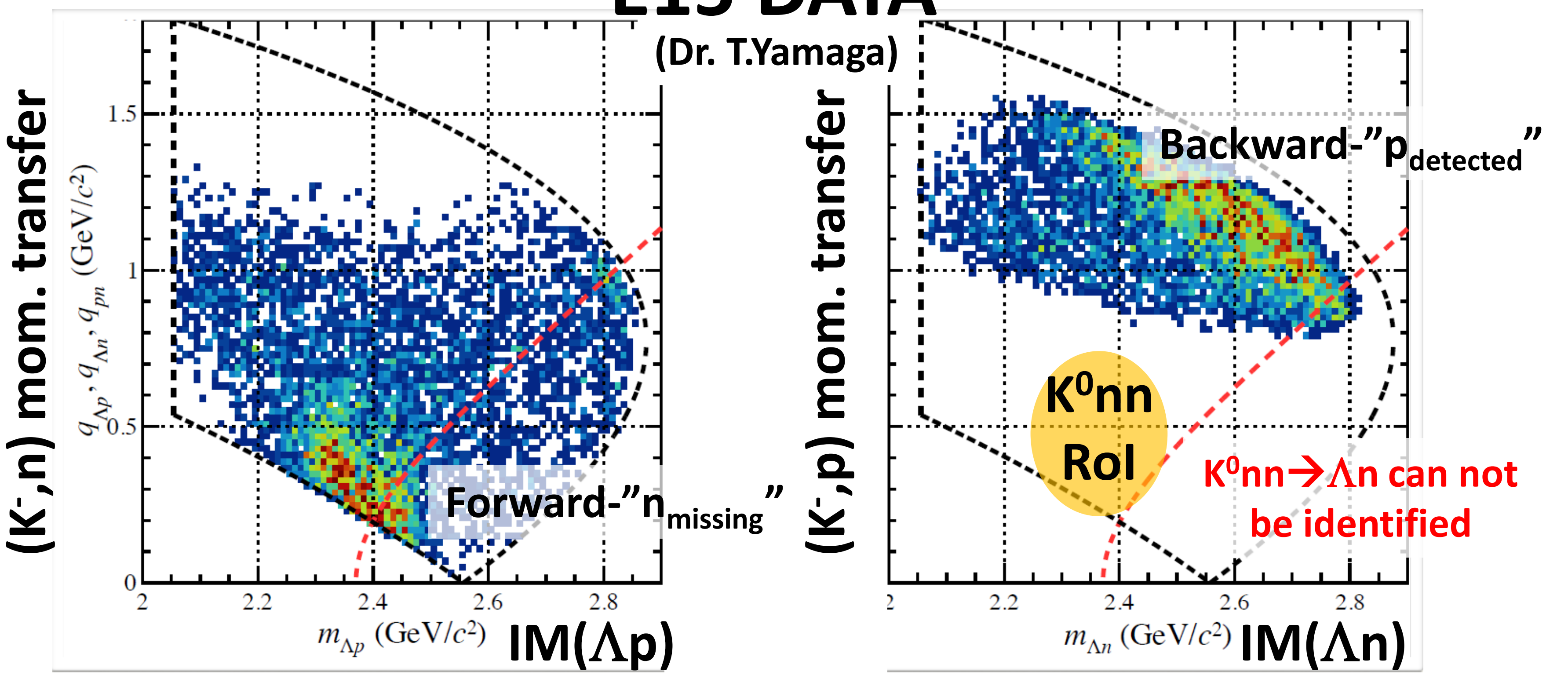


Recent progress of the E15 analysis

- 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

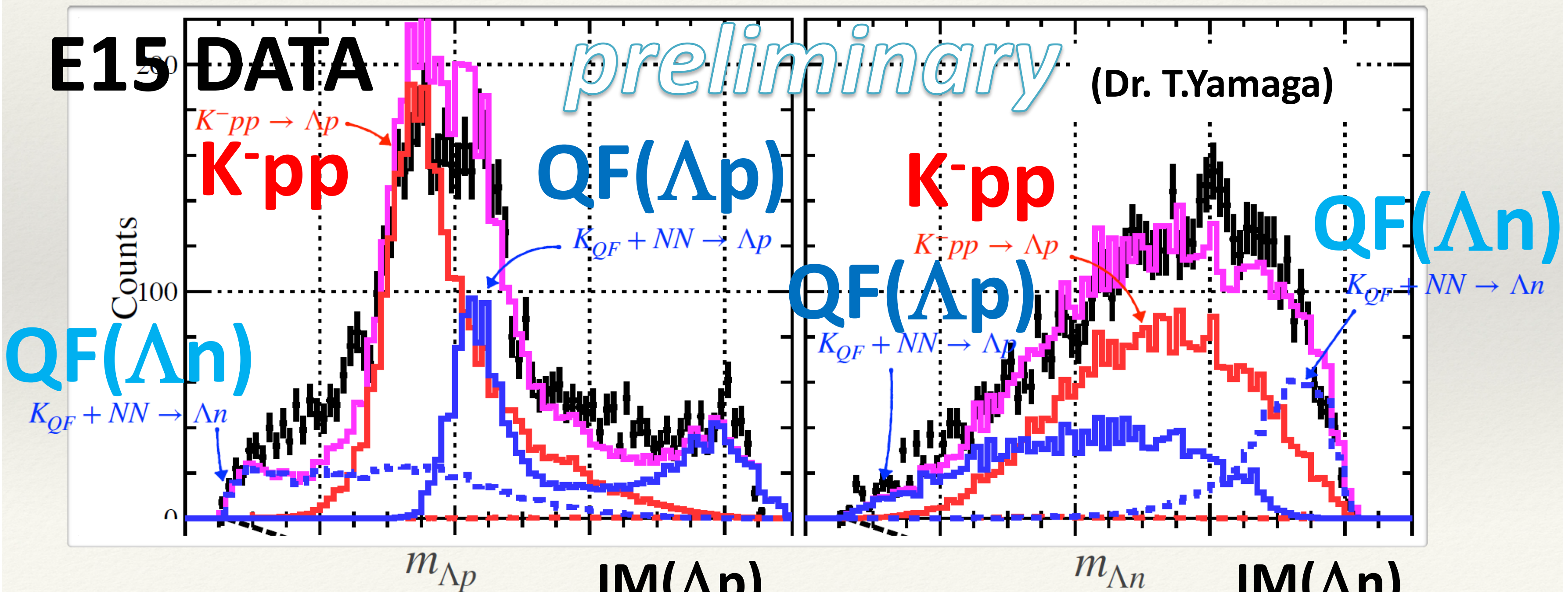
(Dr. T.Yamaga)



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 $K^{bar}NN$-πΣN-πΛN coupled channel system, where the πΛN 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 "$\pi\Lambda$N-$\pi\Sigma$N 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 $\pi\Lambda$N resonance with **Σ*N-$\Delta\Sigma$** 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 "$\pi\Lambda$N-$\pi\Sigma$N dibaryon"

"K⁻ppn" Candidates so far

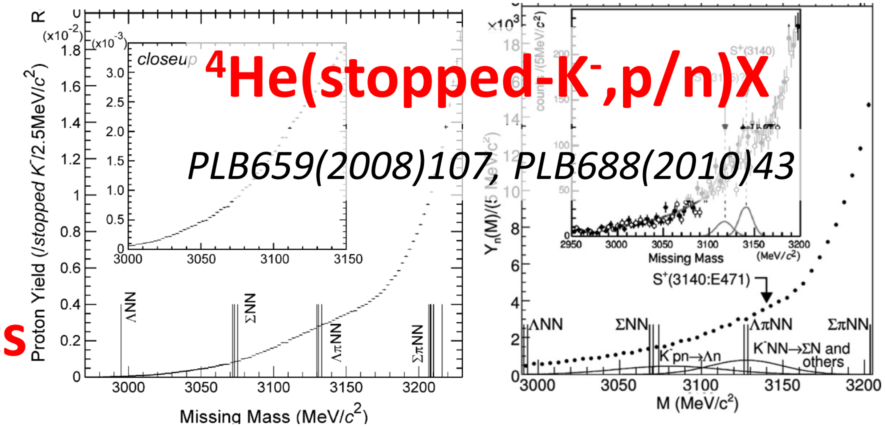
- A few candidates have been reported in ***inclusive*** measurements

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

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

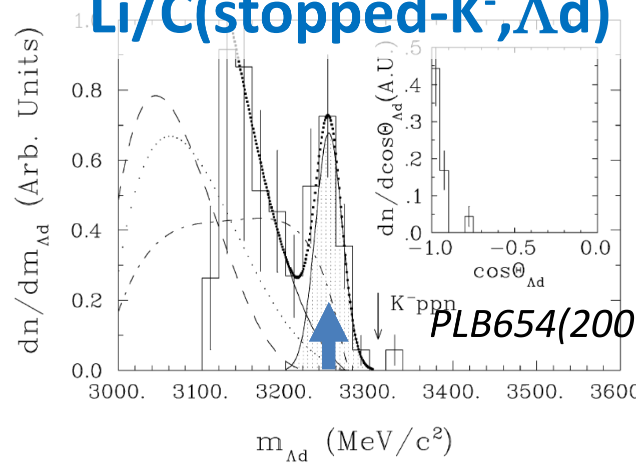
◆ **FOPI@GSI** ← **Observed?**
  - Λd in Ni+Ni

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



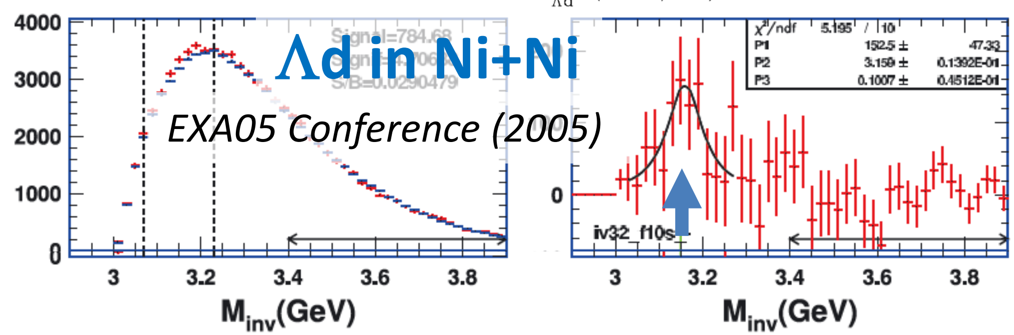
^{4}He(stopped-K^{-},p/n)X

PLB659(2008)107, PLB688(2010)43



Li/C(stopped-K^{-},Λd)

PLB654(2007)80

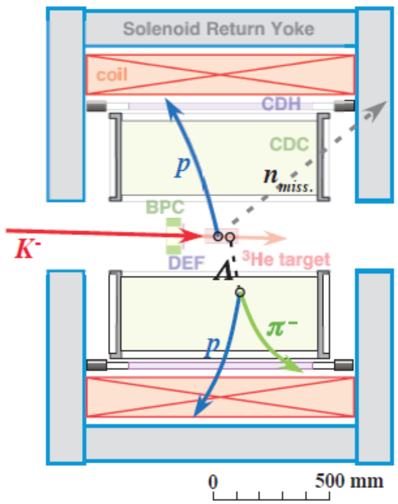


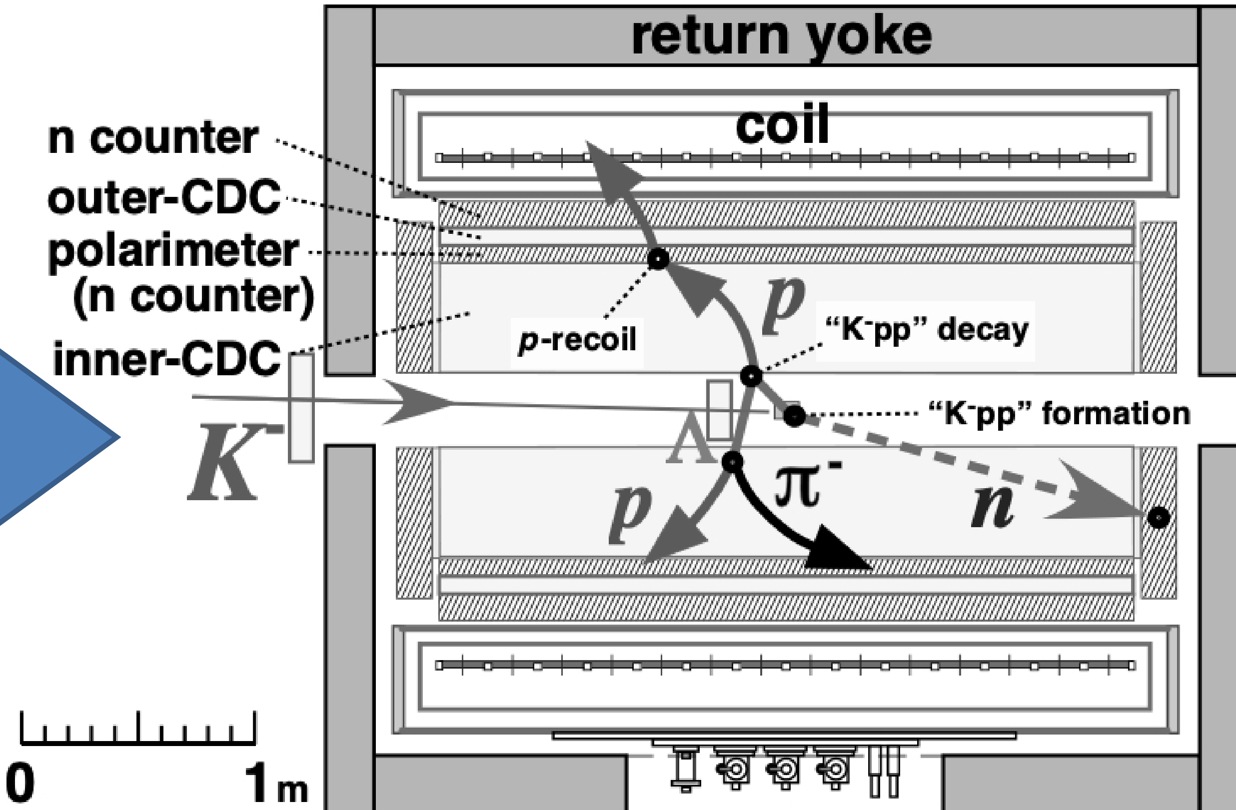
Λd in Ni+Ni

EXA05 Conference (2005)

A New Cylindrical Detector System

present setup





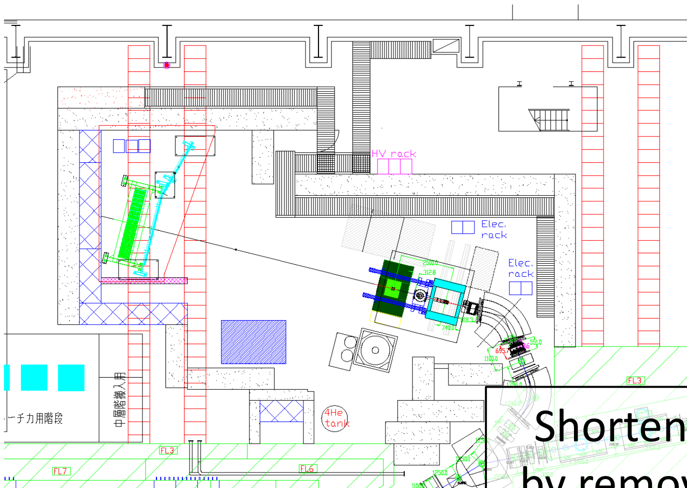
- **SC Solenoid Magnet**
- **Cylindrical Drift Chamber**
- **Neutron Counter**
- FWD/BWD Drift Chambers
- Vertex Fiber Tracker
- Electromagnetic Calorimeter (constructed in 2nd-stage)

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

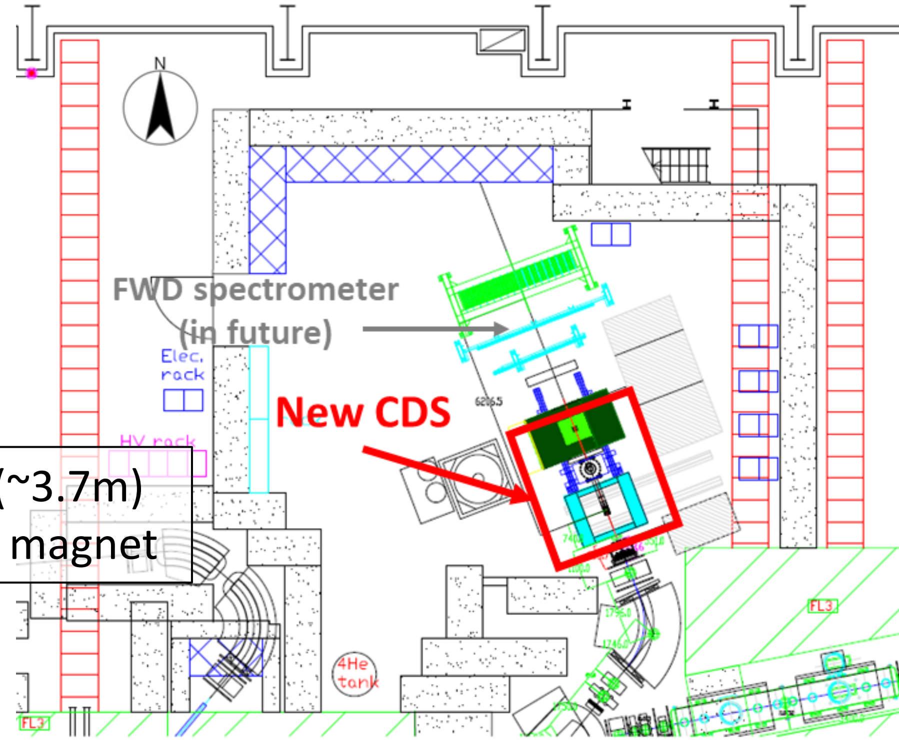
Neutron detection capability: ~x10 (~1.5x15%)

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

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

  - ◆ 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
$\to \Sigma^+\ \ nnn$	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 $= \Lambda + \Sigma = (100_{-7}^{+0})\%$	

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Expected Yield of $\bar{K}NNN$

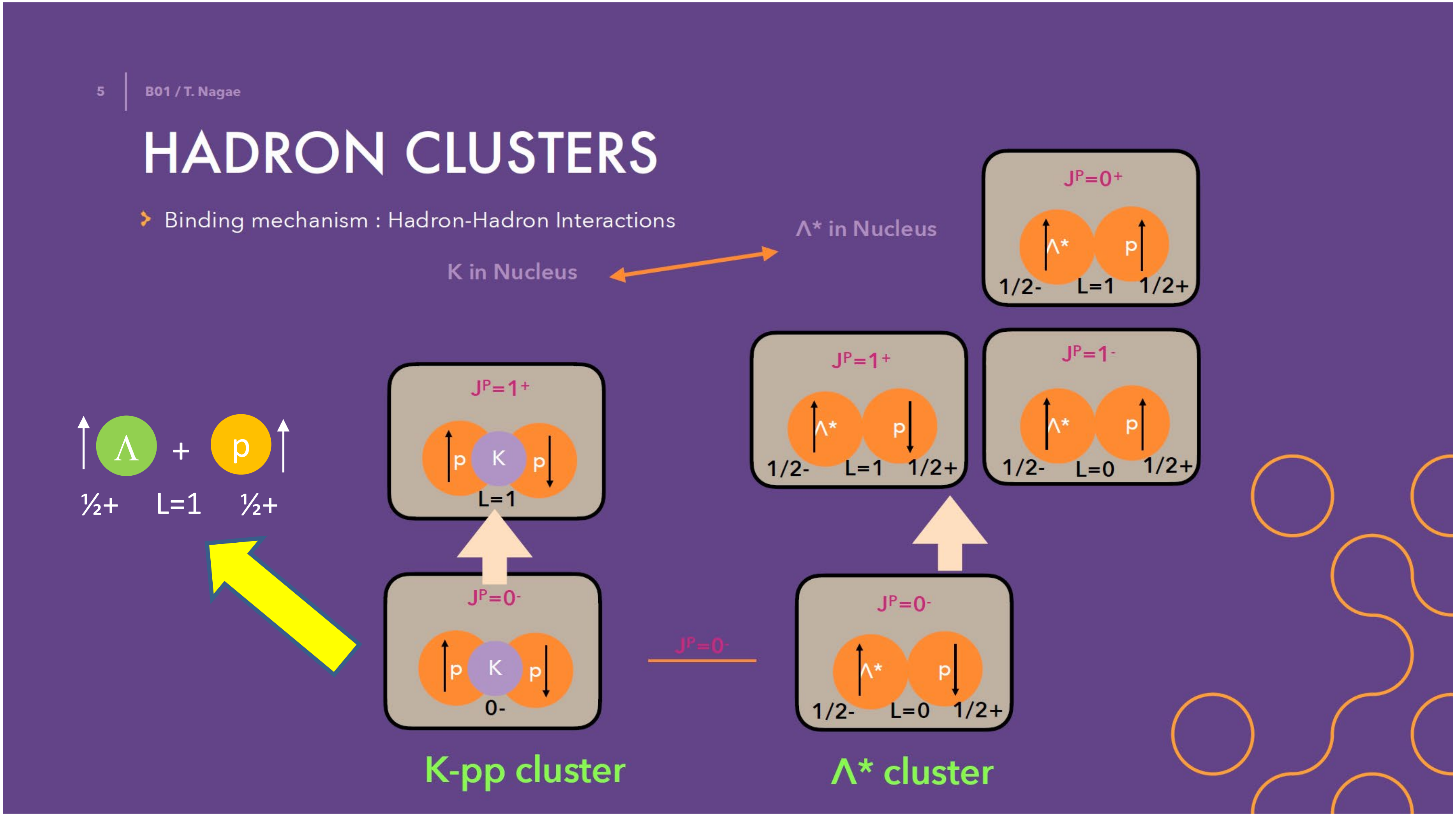
$$
\begin{aligned}
N &= \sigma \times N_{beam} \times N_{target} \times \epsilon, \\
\epsilon &= \epsilon_{DAQ} \times \epsilon_{trigger} \times \epsilon_{beam} \times \epsilon_{fiducial} \times \Omega_{CDS} \times \epsilon_{CDS},
\end{aligned}
$$

- N_{beam} = **100 G** K- on target
  - under the MR beam power of **90 kW** with **5.2 s** repetition cycle.
    - 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

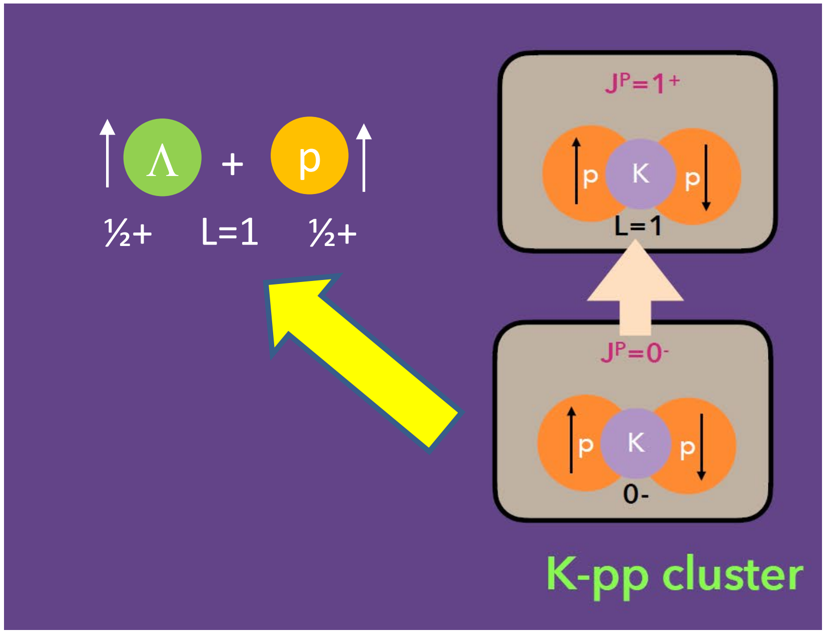
**** improved from E15***

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

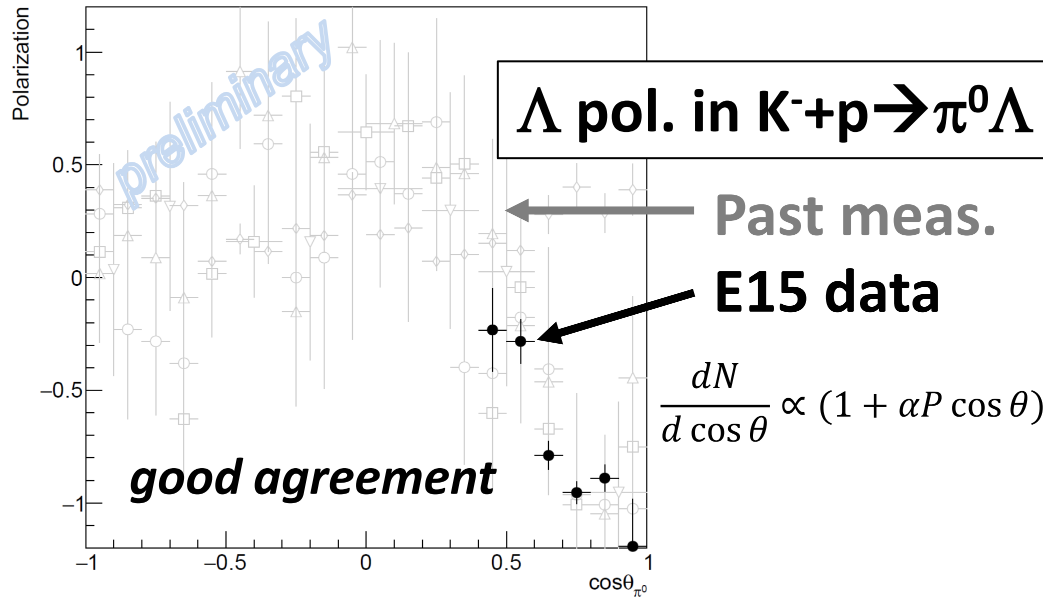


T.Nagae, "The 4th Symposium on Clustering as a window on the hierarchical structure of quantum systems", May 28th, 2020

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

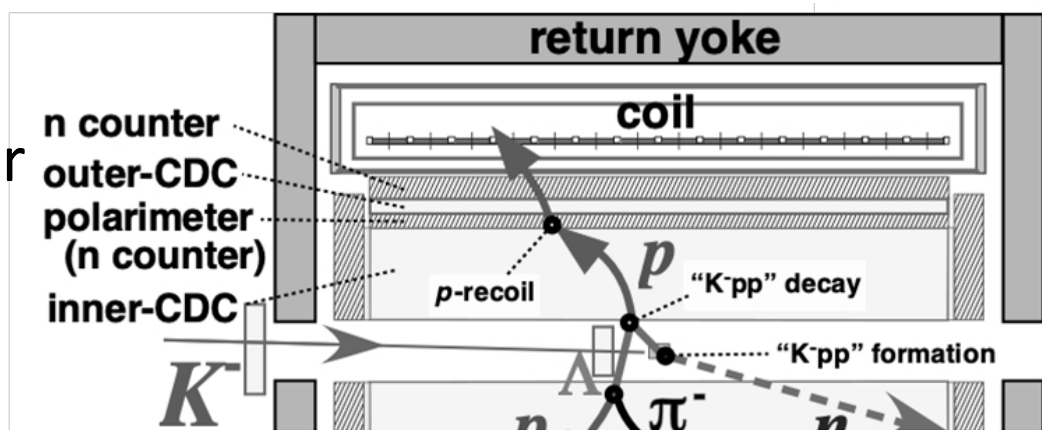


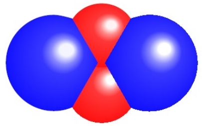
- **Λ polarization** can be measured via π⁻p decay



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

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

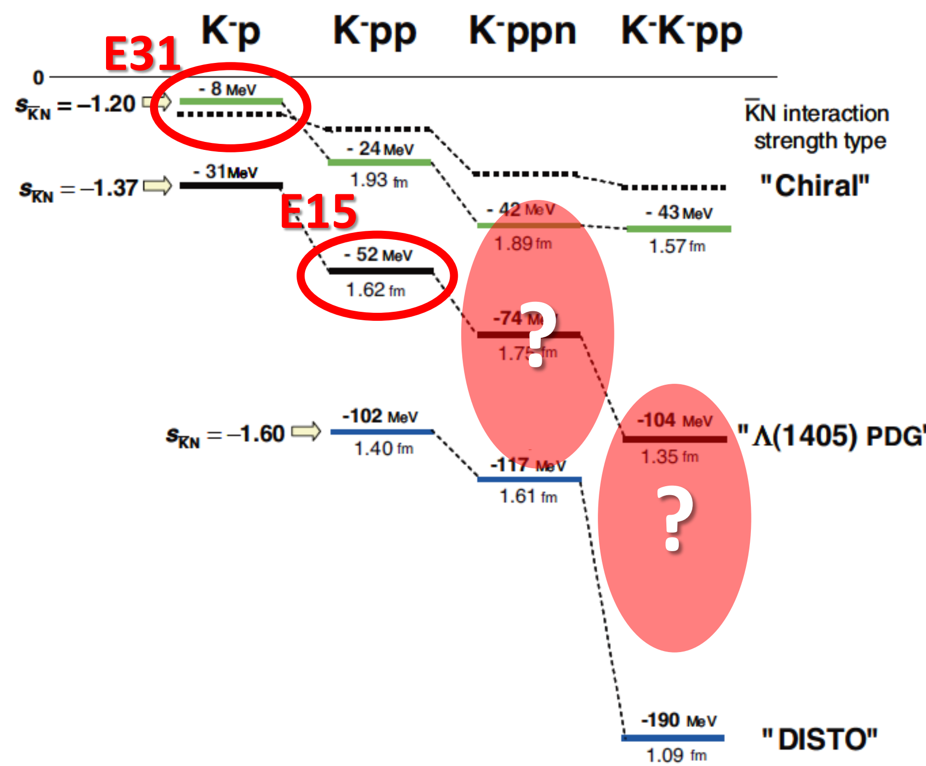




K^-K^-pp

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 $\bar{K}NN$