2022.6.19 HYP2022

Hypernuclear physics overview: Highlights from running experiments and perspectives

Barnea

H. Tamura

Tohoku University /JAEA

Contents:

Hypertriton and nnΛ

S=-2 systems

YN scattering

Femtoscopy

Kaonic nuclei

Future directions and Facilities

Blue text: Tamura's personal comments

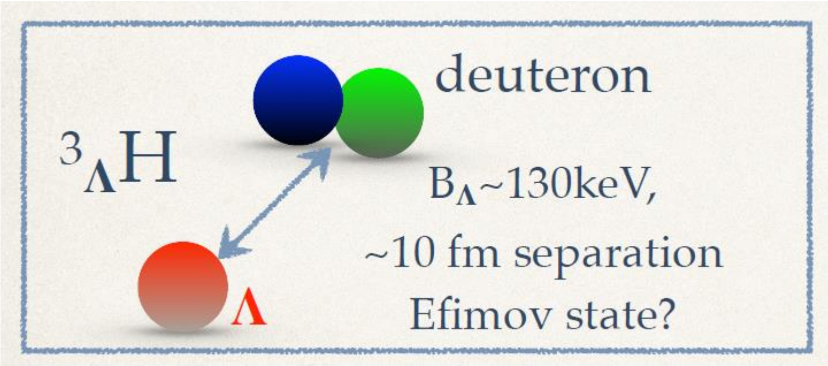
Apologies:

Experimental point of view.

Not a summary. Covering only some part of the plenary talks. Sorry.

Hypertriton and nnΛ

The smallest bound system has particular importance
Test of YN Interaction via exact calculations



We long believed:

B_{Λ}~130 keV ⇔ $\tau \sim \tau_{\Lambda(free)}$ (263 ps)

looks consistent

High quality hypertriton data are MUST for our field, but it was not seriously recognized (by experimentalists) before.

Importance is noticed since HypHI /STAR reported shorter lifetimes (2013)

Topical sessions in HYP2015@Sendai
Hypertriton lifetime
YN scattering

Hypertriton: New data (after 2018) and prospect

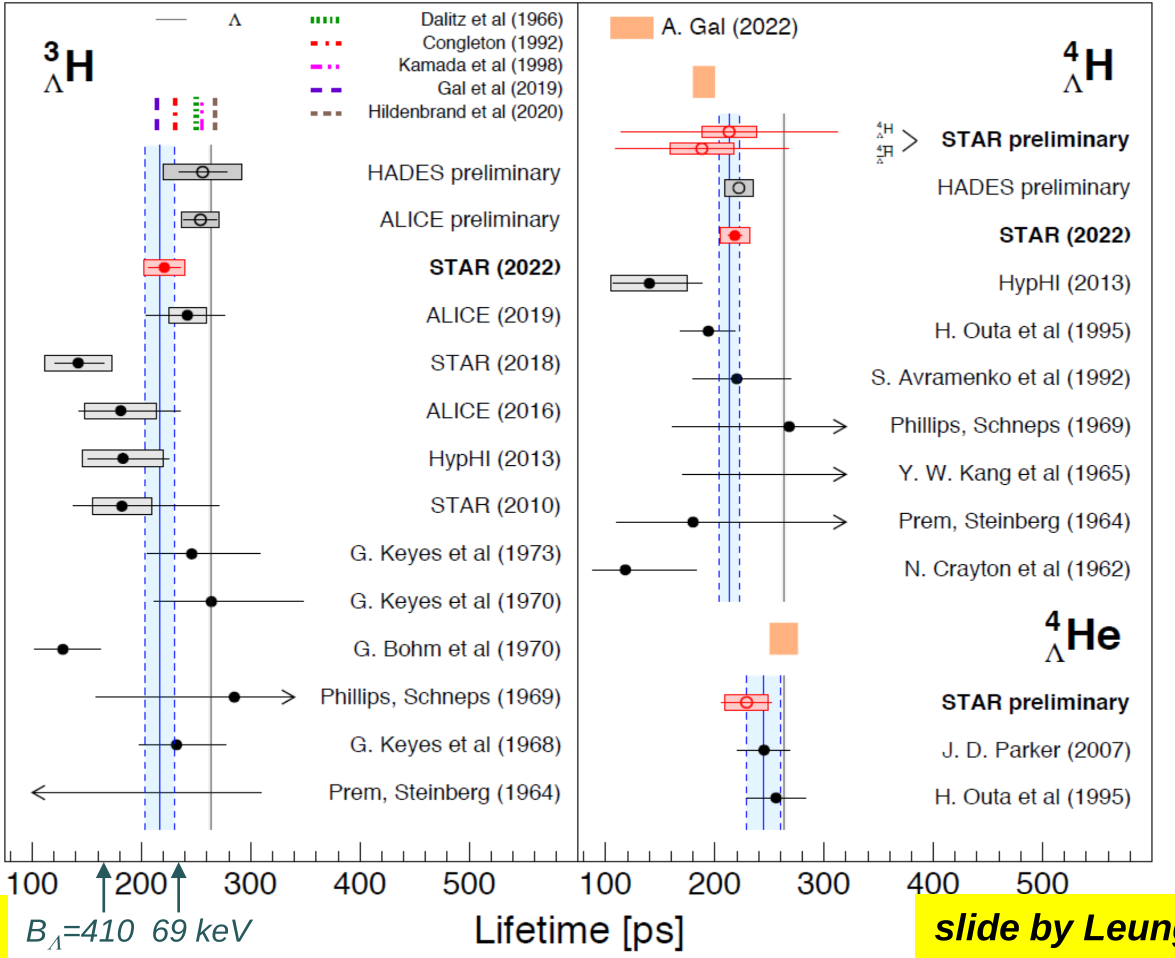
Experiment	Reaction	Measurement	τ ($^{3}_{\Lambda}$H)	τ ($^{4}_{\Lambda}$H)	B_Λ($^{3}_{\Lambda}$H)
Leung/Kisel STAR	HI (Au+Au) $\sqrt{s}$=3GeV	decay length inv. mass	$142^{+24}_{-21}\pm29$ $221\pm15\pm19$	$218\pm6\pm13$	$0.41\pm0.12\pm0.11$ under analysis
Puccio ALICE	HI (Pb+Pb) $\sqrt{s}$=5TeV	decay length inv. mass	$242^{+34}_{-38}\pm17$ New data (prel)	preliminary	preliminary ~ 0.05
Spies HADES	HI (Ag+Ag) $\sqrt{s}$=2.55GeV	decay length	$256\pm22\pm36$ (preliminary)	$222\pm8\pm13$ (preliminary)	
Saito WASA-FRS	HI (^{6}Li+^{12}C) 2GeVA	decay length	under analysis	under analysis	under analysis
Ma J-PARC E73	^{3}He(K^{-},π^{0})	decay time	test data taken run soon later	$190\pm8\pm$?? (preliminary)	-
Eckert MAMI	^{7}Li(e,K^{+})	decay pion momentum	-	-	run soon $\Delta M\sim\pm0.02$
Saito J-PARC E07	K^{-} on emulsion	decay time decay energy	under analysis	later	under analysis
Nakamura JLab E12-19-002	^{3}He(e,e'K^{+})	missing mass	-	-	approved

Present status of lifetimes

Great efforts to improve the data.

Psychological bias may comes in…
All experimentalists should be very careful .

Precise data via different methods than HI are necessary.



Gazda

slide by Leung

[A. Pérez-Obiol, DG, E. Friedman, A. Gal, Phys. Lett. B 811, 135916 (2020)]

Puccio

$B_\Lambda({}^3_\Lambda H)$

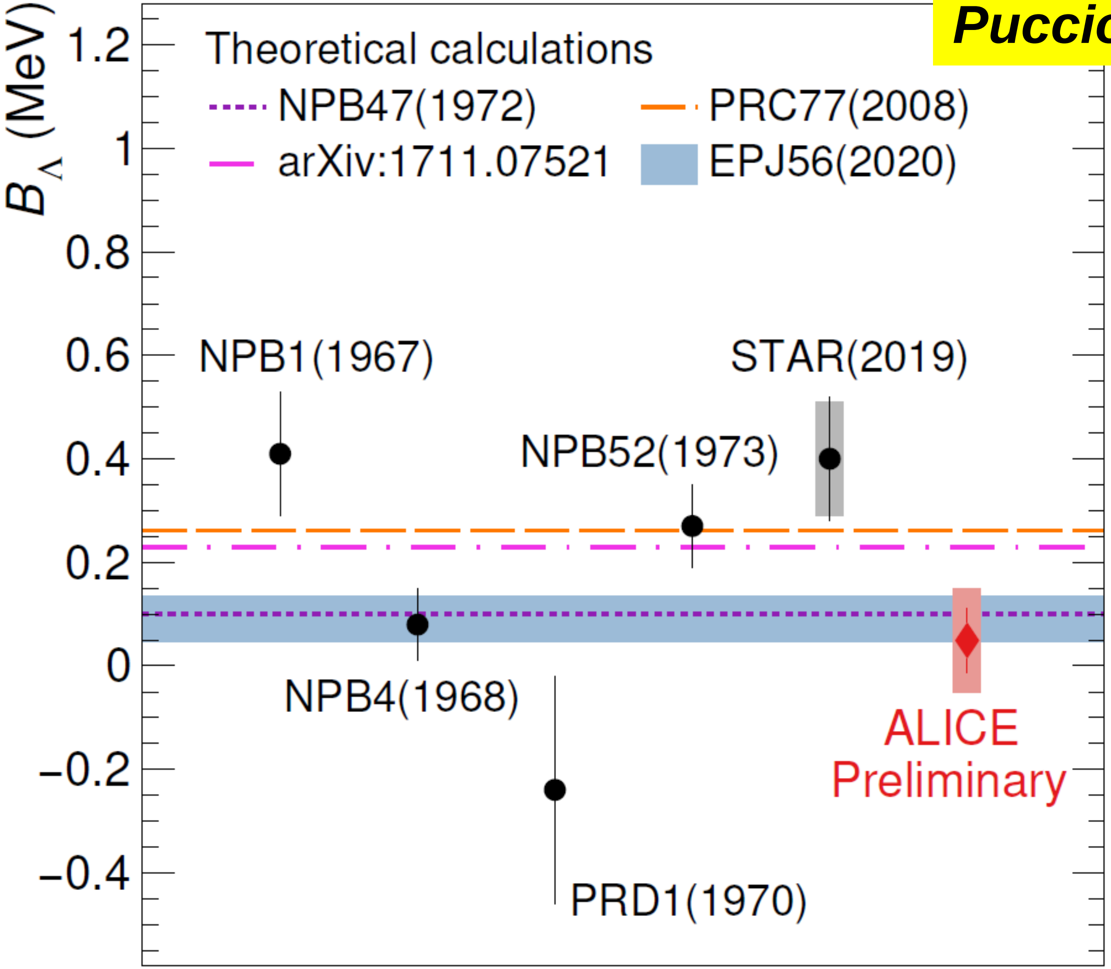
Still unclear

May be difficult to go down to a sub 100keV systematic error in the invariant mass method

Decay pion at MAMI

Emulsion analysis from J-PARC E07

seem promising.



Paper out in few weeks!

ALI-PREL-486370

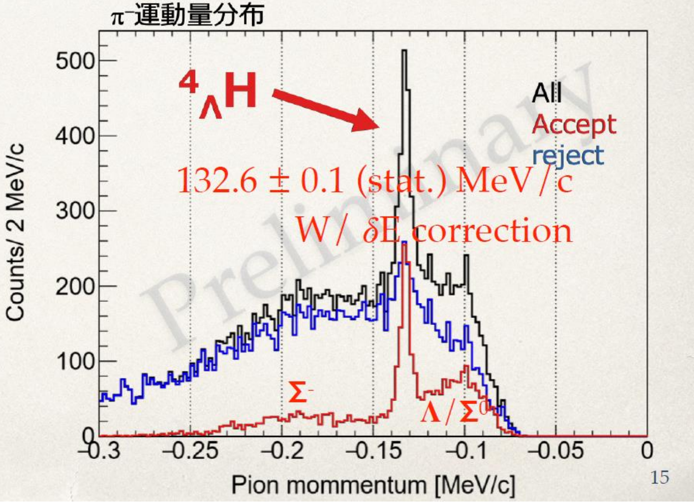
Ma

Direct timing measurement
J-PARC E73

$K^- + {}^4He \to {}^4_\Lambda H + \pi^0$

slows down inside ⁴He target and decays at rest

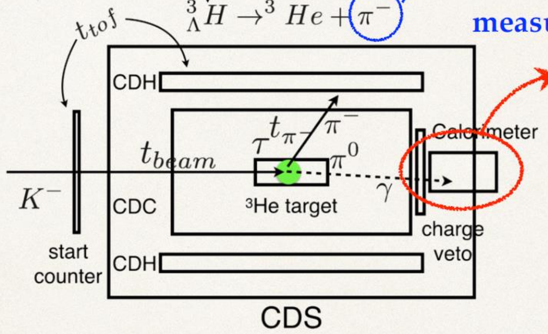
${}^4_\Lambda H \to {}^4He + \pi^-$ 132.9 MeV/c



$K^- + {}^3He \to {}^3_\Lambda H + \pi^0$ — very forward $\pi 0$ projectile; tagged with decayed high energy γ

slows dow inside ³He target and decays at rest

${}^3_\Lambda H \to {}^3He + \pi^-$ — mono-energetic, ~114MeV/c; measured with CDS

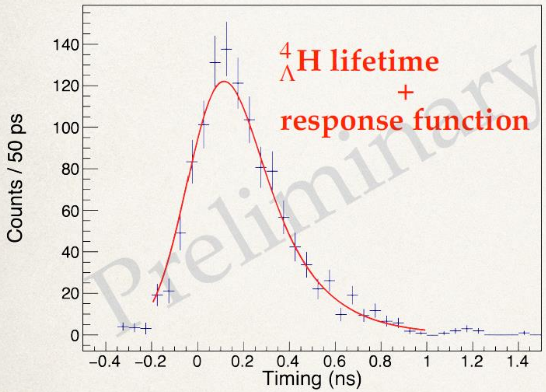


5x8 PbF2 Cherenkov Calo *R&D has been completed*

$^3{}_\Lambda$H decay time can be derived by TOF and CDS tracking

The idea of ***direct measurement***: $T_{CDH}-T_0=t_{beam}+t_{\pi^-}+\tau$;

190 ± 8(stat.)±??(sys.) ps



194^{+24}_{-26} ps @ KEK stop K-

H. Outa, et al., Nucl. Phys. A 547, (1992), 109c-114c

218 ± 6(stat.) ± 13(sys.) ps @ STAR, Au-Au collision

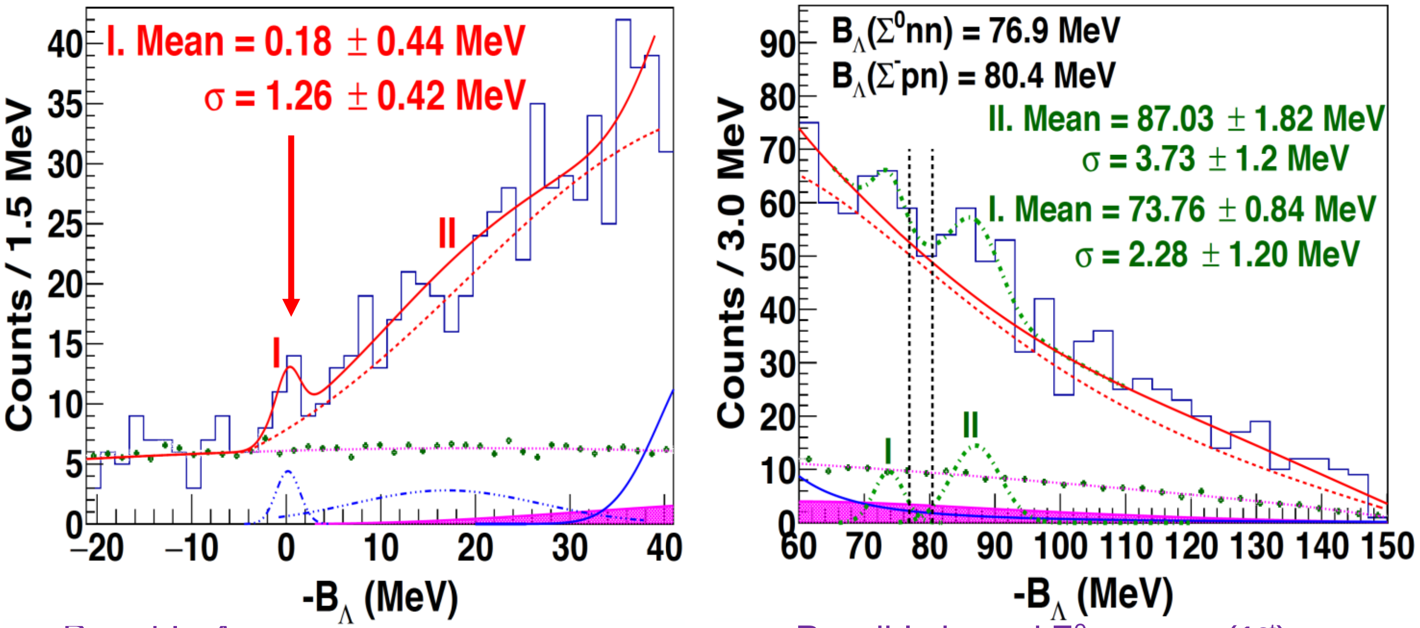
arXiv:2110.09513

Test data for 3LH was also shown

Tang

^{3}H(e, e'K$^+$) "Λnn" at JLab Hall A (E12-17-003)

Λnn state? Not significant but a re-measurement is necessary.



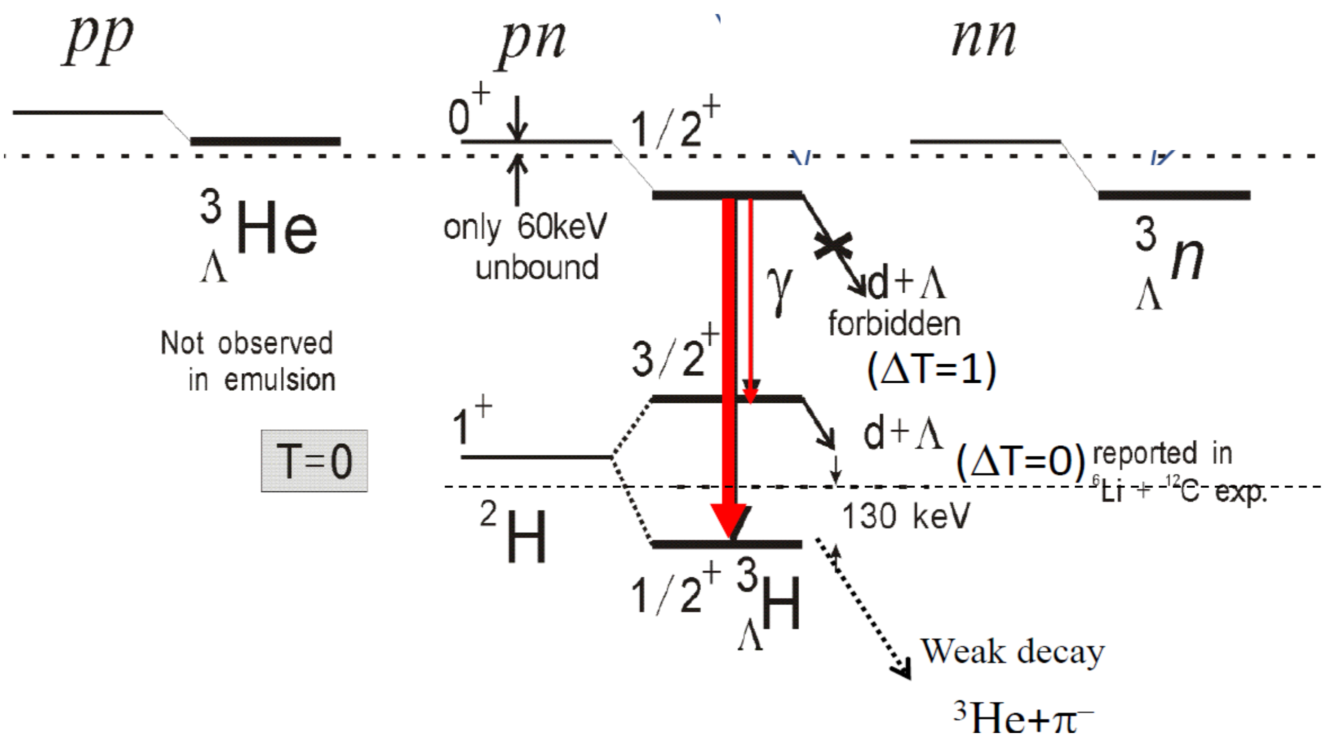
- Possible *Λnn* resonance:
  $-B_\Lambda = 0.18 \pm 0.44\ (stat) \pm 0.4\ (sys)$
  $\Gamma/2 = 0.35 \pm 0.42\ (stat) \pm 0.5\ (sys)$
- Significance: ~2.2. If real, cross section ≈ 10 nb/sr)

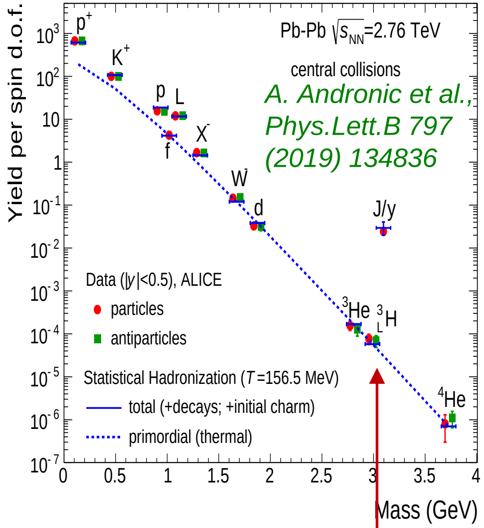
- Possible bound Σ^0*nn* state (1st):
  $-B_{\Sigma 0nn} = -3.14 \pm 0.84\ (stat) \pm 0.4\ (sys)$
- 2nd peak is about 13 MeV away
- Cross sections (1st/2nd) ≈ 20/45 nb/sr

Ukai

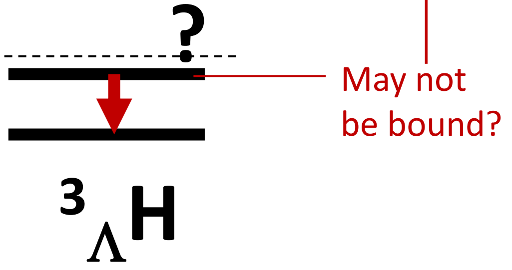
Possible γ-rays from pnΛ(T=1,0)

J-PARC E63





A. Andronic et al., Phys.Lett.B 797 (2019) 134836

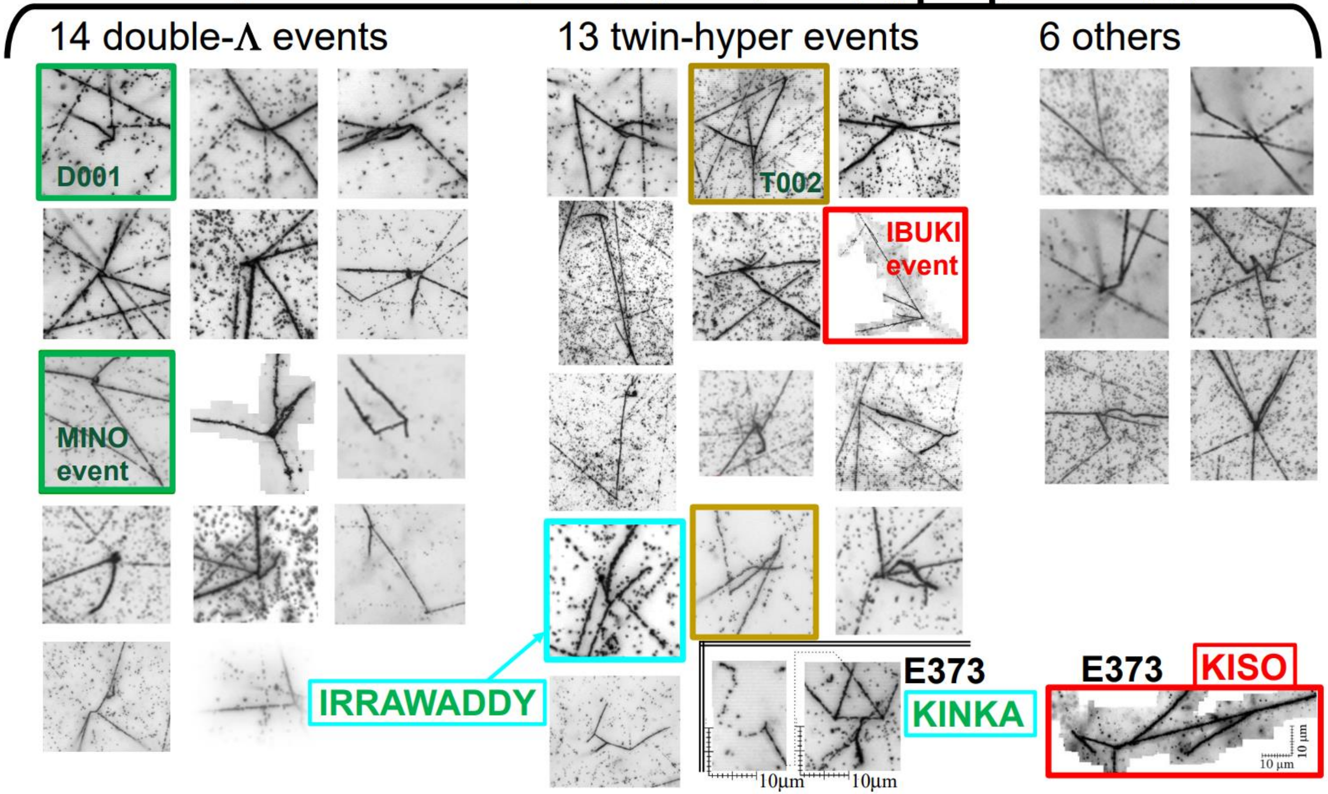


$S=-2$ systems

List of detected events in E07 (Jun., 2022)

Nakazawa

	KEK-PS E176	E373	J-PARC E07
Searching period	~10 years	~7 years	2 years (Apr., 2018 ~)
S=-2 system	**4** (1+2+[1])	**10** (4+3+[3])	$\boxed{\textbf{33}}$ (14+13+[6]) => **47**



X-ray microscope for a better track resolution.

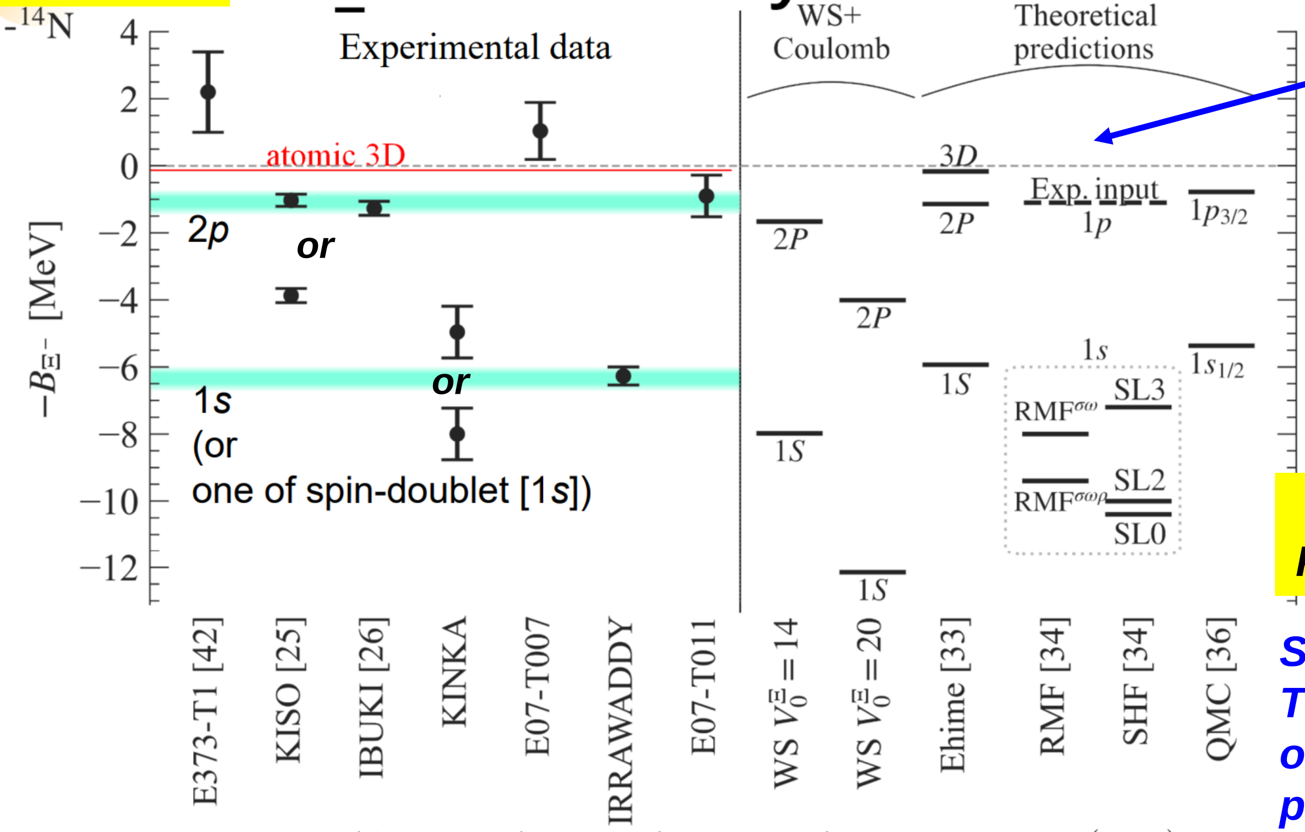
Saito

Overall scan with machine learning has been developed.

Ξ hypernuclei

Nakazawa

B_{Ξ^-} of Ξ^--^{14}N system



M. Yoshimoto, et al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

Caution: Theories seem to agree with the data, but they used the BNL suggestion of $U_{\Xi} \sim -15$MeV.

Ξ survives until it cascades down to the 0s orbit ??

Hiyama, Schulze, Friedman(Gal), Tanimura

S=-2 data are still limited. Theoretical interpretations of the data and theoretical predictions are quite important.

More efforts for Ξ-nuclear systems

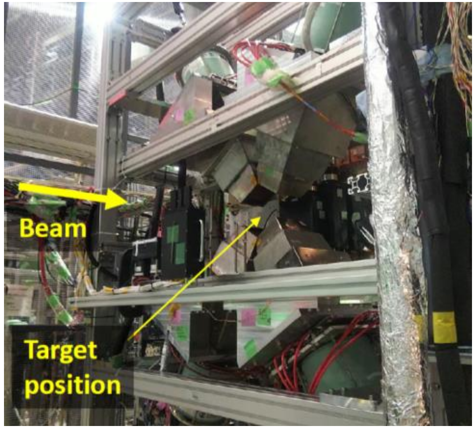
Yamamoto

Ξ-atomic X-ray measurements started.

E07: Ξ-Ag/Br with emulsion

E03: Ξ-Fe

---X-rays not observed yet.



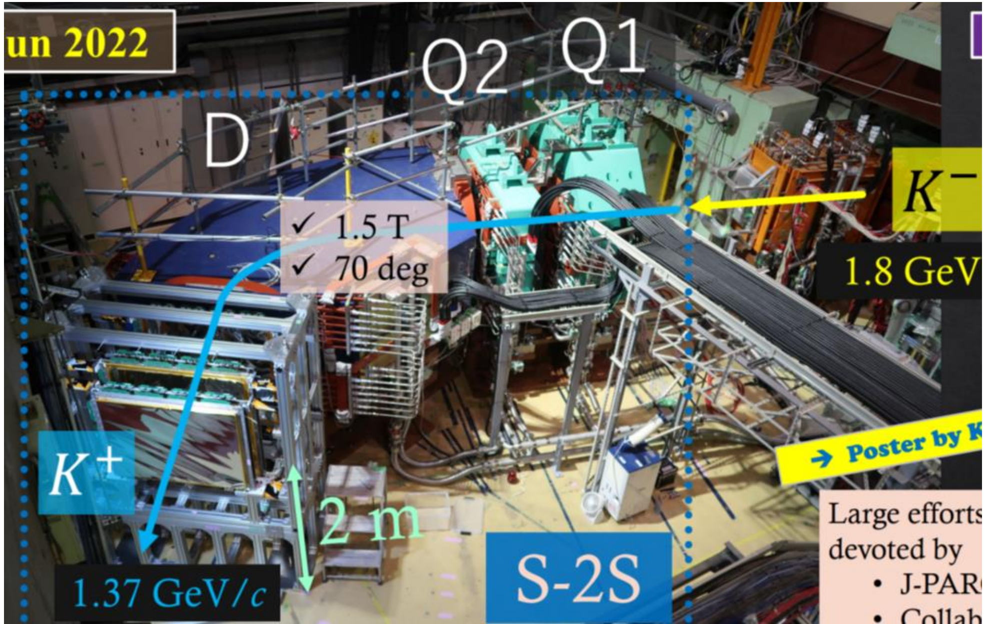
Gogami, Fujioka

Ξ-hypernuclei via (K-,K+) reaction

E70: $^{12}C(K^-,K^+)^{12}_{\Xi}Be$

E75: $^{7}Li(K^-,K^+)^{7}_{\Xi}H$

A new dedicated spectrometer
S-2S has been installed.
Run soon.



YN scattering

High quality YN scattering data have been long awaited, but now a new era has come!

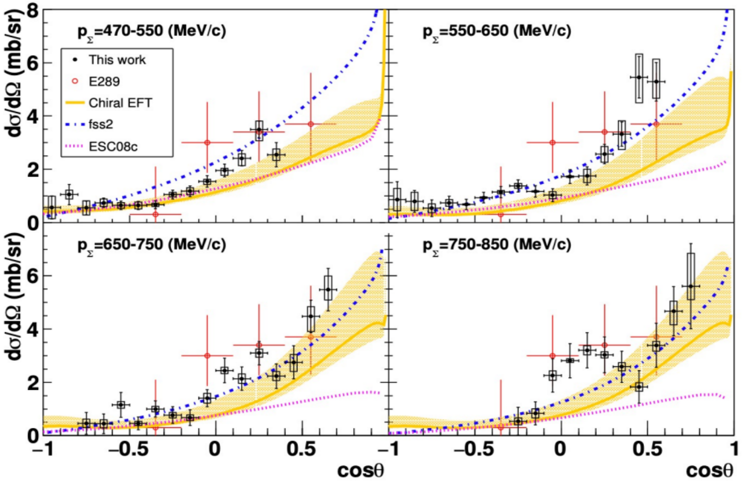
$\Sigma^{\pm}p$ scattering at J-PARC

$\Sigma^- p$ elastic

Miwa

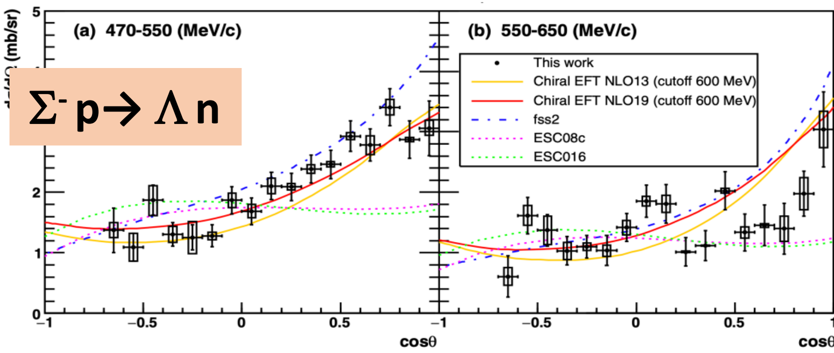
Σ^-p elastic scattering

K. Miwa et al., PRC 104, 045204 (2021)



K. Miwa et al., PRL 128, 072501 (2022)

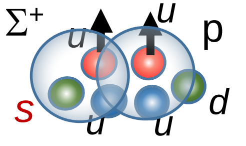
Σ^-p→Λn inelastic scattering



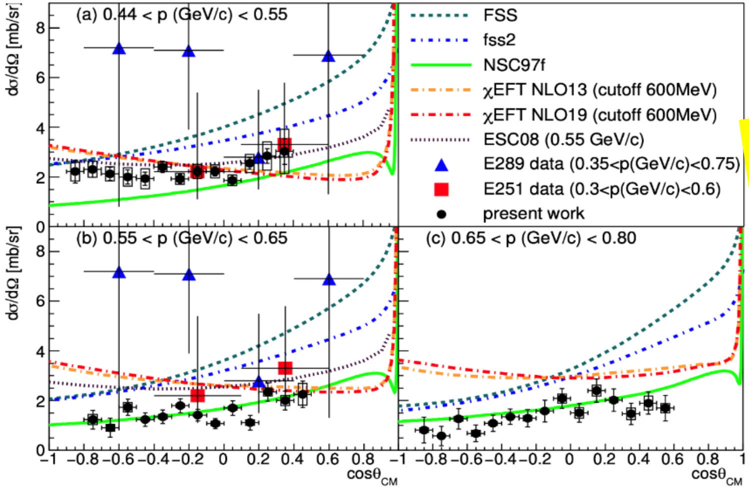
Moderate forward peaking dependence

$\Sigma^+ p$ elastic

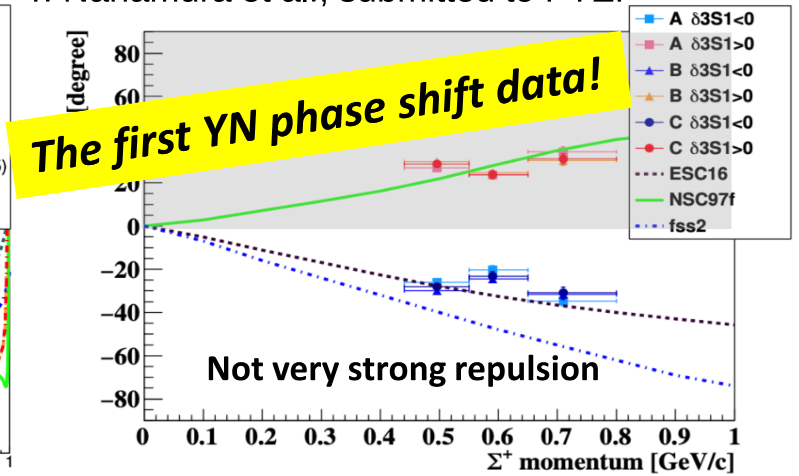
Σ^+-p (spin=1)



Strong repulsion by quark Pauli ??



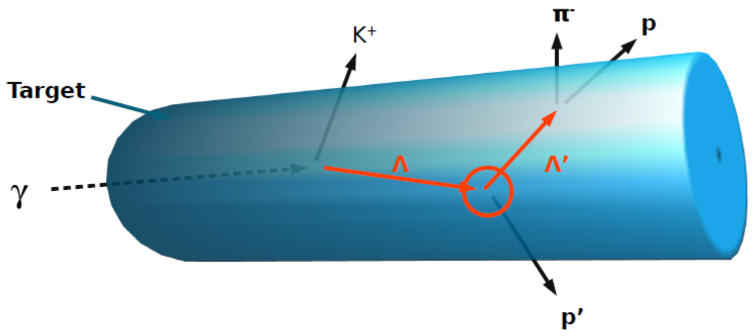
T. Nanamura et al., submitted to PTEP



Zachariou

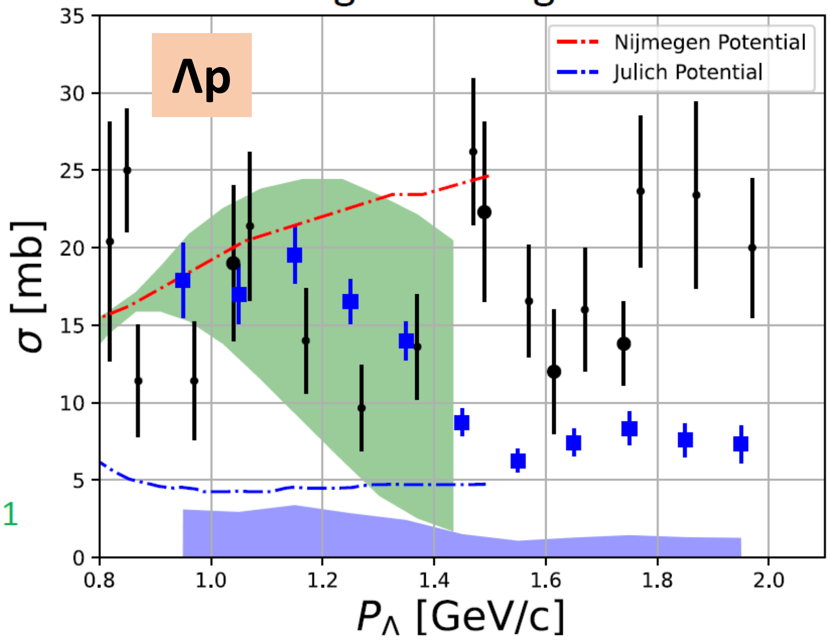
Λp scattering at JLab（CLAS）

J. Rowley *et al.*, Phys. Rev. Lett. **127**, 272303



- Σp scattering
- Λp polarization observables
- Λd scattering
- Ξp scattering in future

Order of magnitude higher statistics



J. Haidenbauer and U.-G. Meißner, Phys. Rev. C 72, 044005 (2005)

T. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59, 21 (1999).

Comparison b/w YN scattering /correlation experiments

	how to produce hyperons	*hyperon momentum*	*merits*
J-PARC	**p ($\pi^{\pm}$,K^{+}) $\Sigma^{\pm}$** **p (π^{-},K$_s^0$) Λ**	p_Y = 0.4—0.8 GeV/c	*large Λ polarization* *-> spin observables*
JLab	**p (γ, K^{+}) Λ**	p_Y = 0.7—2 GeV/c	*beam polarization* *-> polarization observables*
ALICE etc.	**Femtoscopy (pp)** **Λp, Σp, Ξp, $\Lambda\Lambda$, …**	p_Y < 0.4 GeV/c	*multi strange systems*

These three methods are complementary

High quality experiments are changing the game!

Essential to solve the hyperon puzzle.

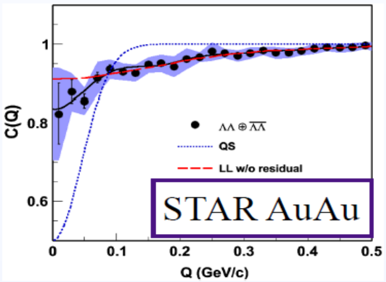
Femtoscopy

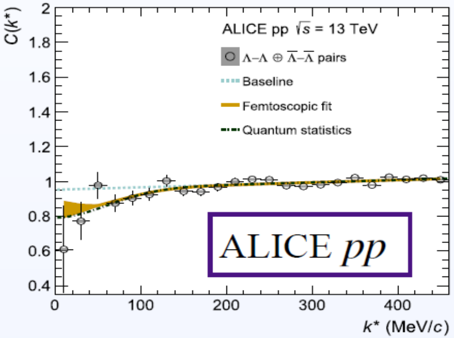
Femtoscopy first appeared in HYP2018.
Now it has grown up to be a “big business”.

Mihaylov, Zbroszczyk, Lalik, Singh, Pawlowska, Serksnyte, Lea, Vazquez Doce, …

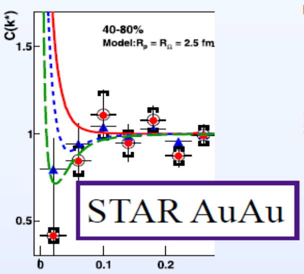
Various new data with high statistics have been reported.
Established as a standard tool to study hadron-hadron interaction

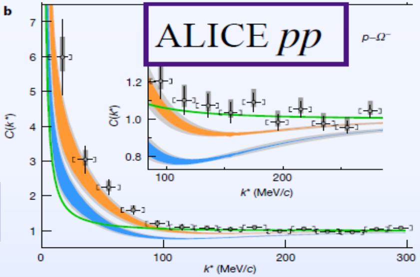
- $\Lambda\Lambda$ STAR AuAu: PRL 114,022301(2015)
  ALICE *pp*: PLB 797 (2019) 134822
  PbPb: PRC99, 024001 (2019)



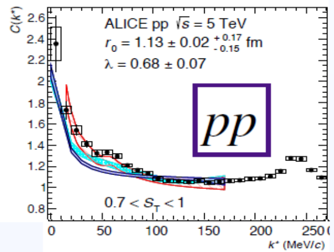


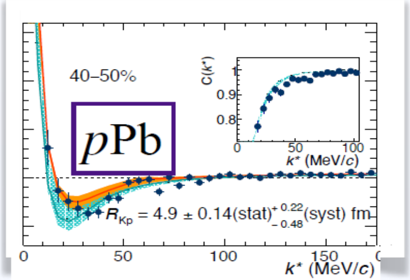
- $p\Omega$ STAR AuAu: PLB 790, 490 (2019)
  ALICE *pp*: Nature 588 (2020) 232



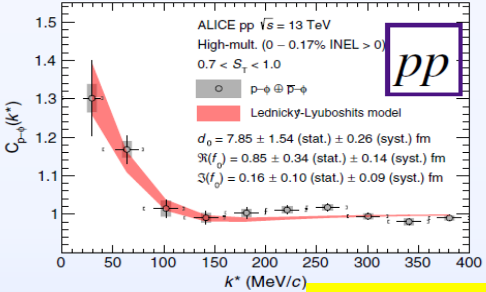


- K^-p ALICE *pp*: PRL 124 (2020) 9, 092301
  PbPb: PLB 822 (2021) 136708
  STAR AuAu: NPA 982 (2019) 359





- $p\phi$ ALICE *pp*: PRL 127 (2021) 17, 172301



Slide by Kamiya

Slide by Lea

Two-particle momentum correlation measured with ALICE at the LHC

- **KN** and **$\bar{K}$N** interaction
  - ALICE Collaboration PRL 124 (2020) 9, 092301
  - ALICE Collaboration PLB 822 (2021) 136708
  - ALICE Collaboration arXiv: 2205.15176

- **and other interactions:**
  - pp, pΛ, $\Lambda\Lambda$: ALICE Collaboration PRC 99(2019)
  - $\Lambda\Lambda$: ALICE Collaboration PLB 797 (2019) 134822
  - pΞ: ALICE Collaboration PRL 123 (2019) 134822
  - pΣ^0:ALICE Collaboration PLB 805 (2020) 135419
  - pΩ: ALICE Collaboration Nature 588 (2020) 232-238
  - pϕ: ALICE Collaboration PRL 127 (2021) 172301
  - B-$\bar{B}$:ALICE Collaboration PLB B 829 (2022) 137060
  - pΛ: ALICE Collaboration arXiv:2104.04427
  - pD: ALICE Collaboration arXiv:2201.05352
  - $\Lambda\Xi$: ALICE Collaboration arXiv:2204.10258
  - ppp and ppΛ: ALICE Collaboration arXiv:2206.03344

In 2018, I never though that such channels can be experimentally investigated.

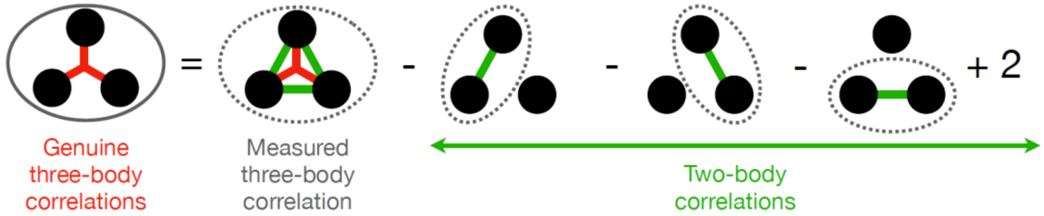
Serksnyte

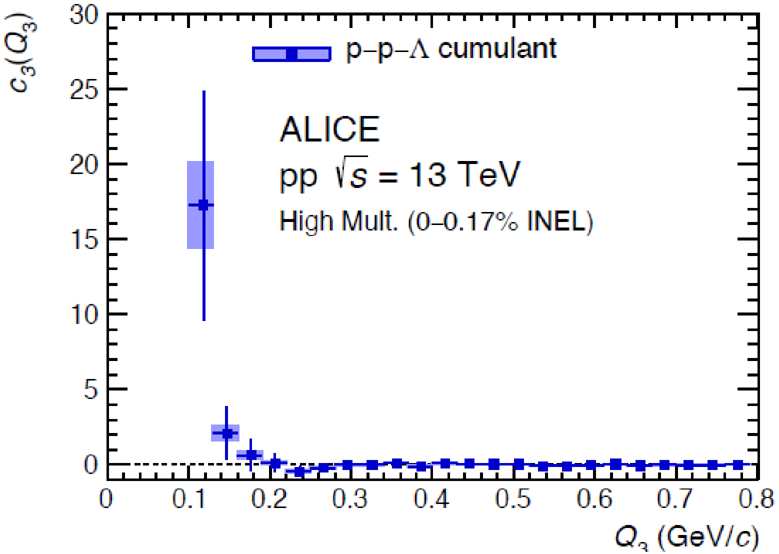
Three-body correlation

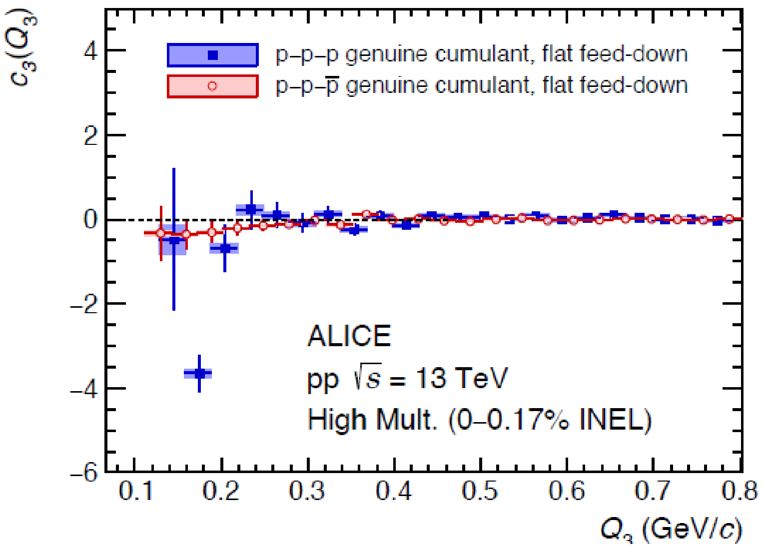
Three-particle correlation function:

$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1)\,P(\mathbf{p}_2)\,P(\mathbf{p}_3)} = \mathcal{N}\,\frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$







Kamiya

Progress in correlation function

Coupled channel

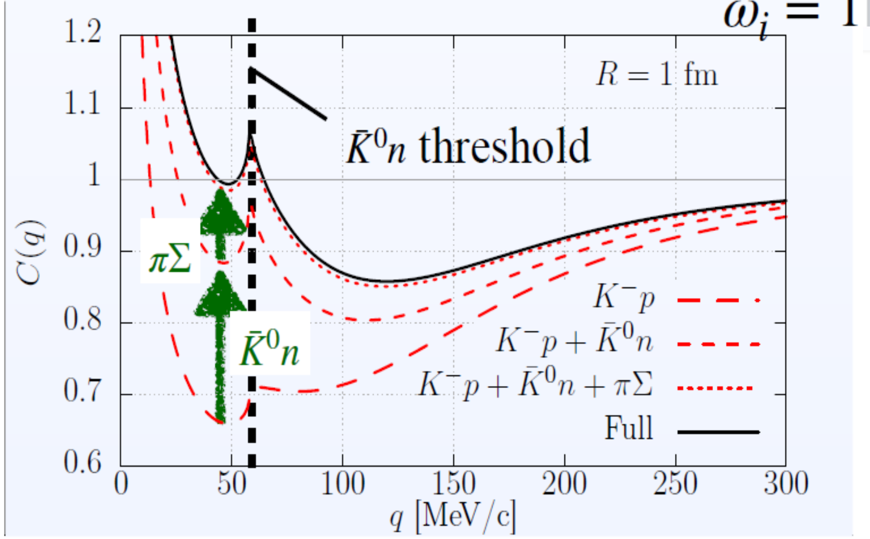
- Koonin-Pratt-Lednicky-Lyuboshits-Lyuboshits (KPLLL) formula

$$\boxed{C(\mathbf{q}) = \int d^3\mathbf{r}\ S(\mathbf{r})\,|\underline{\psi^{(-)}(q;r)}|^2 + \sum_{j\neq i} \underline{\omega_j \int d^3\mathbf{r}\ S_j(\mathbf{r})\,|\psi_j^{(-)}(q;r)|^2}}$$

S.E. Koonin, PLB 70 (1977)
S. Pratt et. al. PRC 42 (1990)
R. Lednicky, et.al. Phys. At. Nucl. 61(1998)

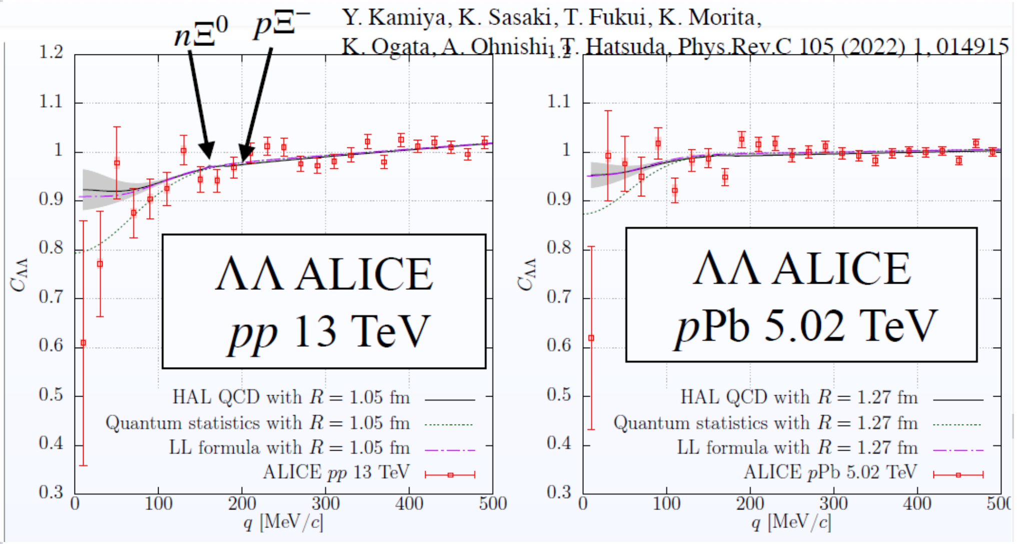
Contribution from Coupled-channel Source

$\omega_i = 1$



Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL 124 (2020) 13, 132501

Y. Kamiya, K. Sasaki, T. Fukui, K. Morita, K. Ogata, A. Ohnishi, T. Hatsuda, Phys.Rev.C 105 (2022) 1, 014915

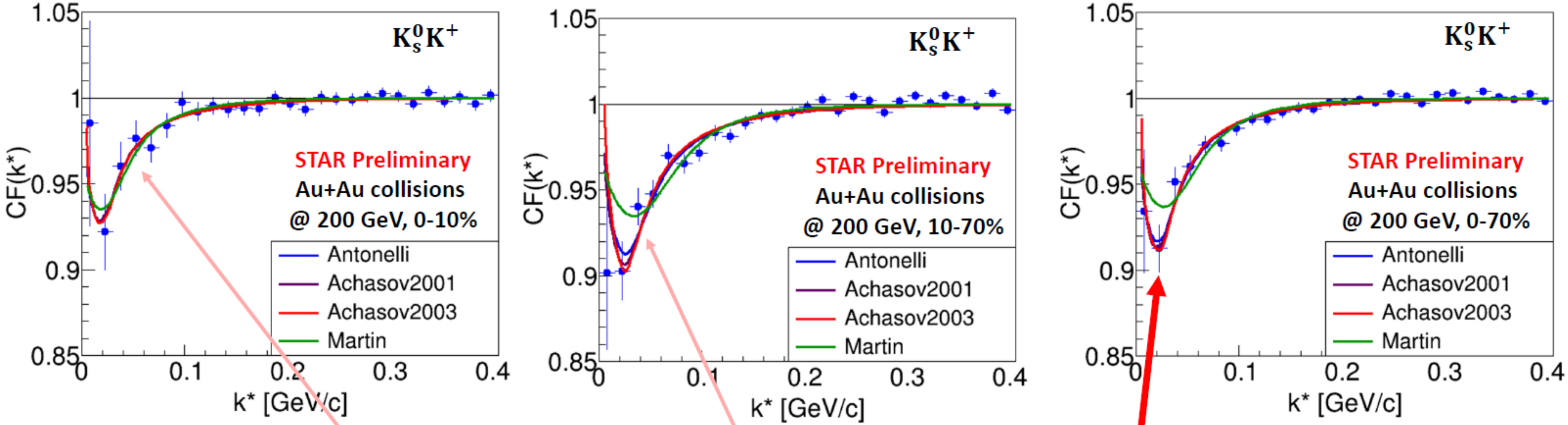


Pawlowska

Effect of FSI

Lednicky & Lyuboshitz model includes **strong FSI:** [Sov.J.Nucl.Phys. 35, 770 (1982)]

$$CF(q_{inv}) = 1 + \lambda\left(\underbrace{\boxed{e^{[-R_{inv}^2 q_{inv}^2]}}}_{\text{QS effect}} + \underbrace{\boxed{\frac{1}{2}\left[\left|\frac{f(k^*)}{R_{inv}}\right|^2 + \frac{4\Re f(k^*)}{\sqrt{\pi}R_{inv}}F_1(q_{inv}R_{inv}) - \frac{2\Im f(k^*)}{\sqrt{\pi}R_{inv}}F_2(q_{inv}R_{inv})\right]}}_{\text{strong FSI through the } f_0(980) \text{ and } a_0(980) \text{ resonances}}\right)$$

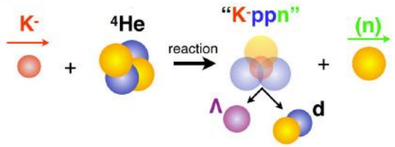


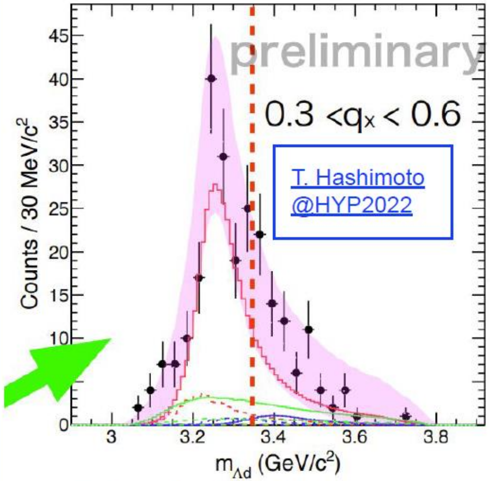
The a_0 FSI parametrization gives an excellent representation of the signal region of the data

$K^{bar}N$ systems

Data is coming

Perfect review by Oton Vazquez Doce



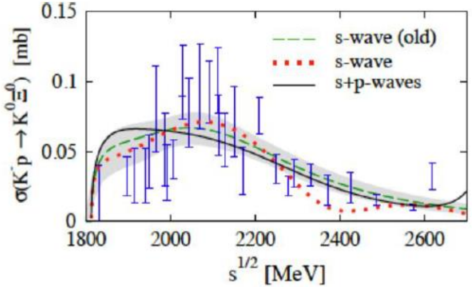


T. Hashimoto @HYP2022

- Extended J-PARC program for kaonic nuclei studies

T. Yamaga@ HYP2022

Calculations in p-wave with fitting higher mass channels



A. Feijoo @ HYP2022

⇒ J-Lab proposal for the secondary K_L beam

GLUEX:

Λ(1405) photoproduction

$$\gamma p \to K^+ \Lambda^*$$

N. Wickramaarachchi @ HYP2022

New approaches proposed:

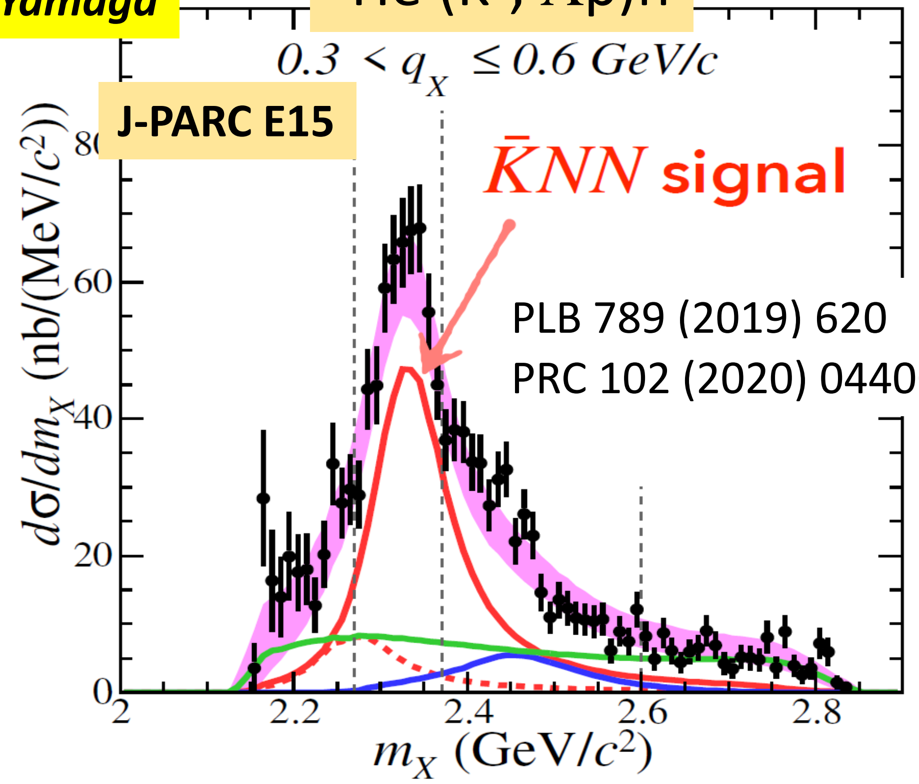
fusion reaction $K^- d \to p\Sigma^-$

⇒ can deliver information on the lower pole of Λ(1405)

E. Oset @ HYP2022

Yamaga ^{3}He (K-, Λp)n

J-PARC E15

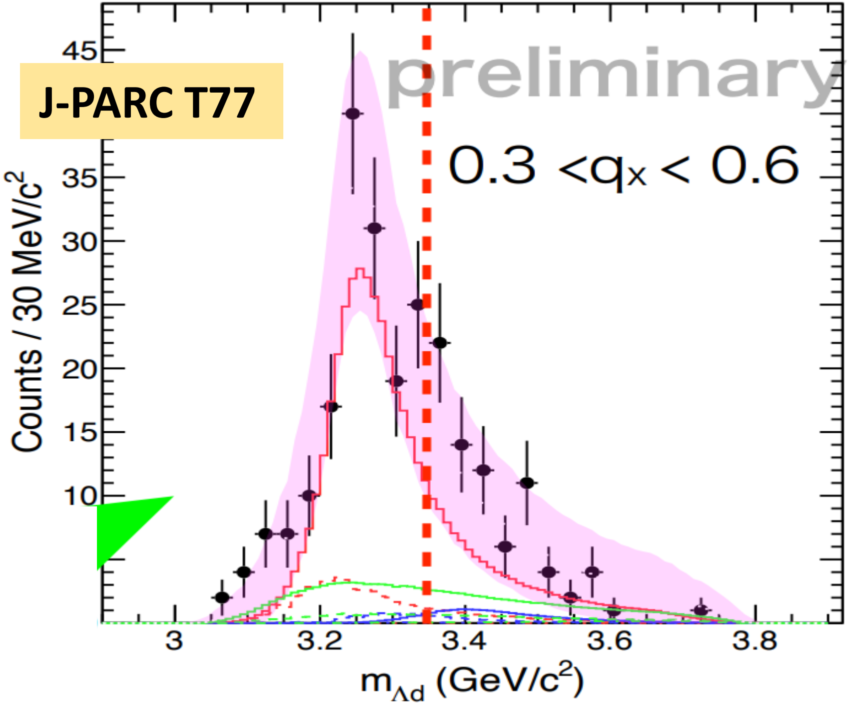


We interpreted that it is signal of $\bar{K}NN \to \Lambda p$.

$$\Rightarrow \quad BE = 42 \pm 3 \text{ (stat.) } ^{+3}_{-4} \text{ (syst.) MeV}$$
$$\Gamma = 100 \pm 7 \text{ (stat.) } ^{+19}_{-9} \text{ (syst.) MeV}$$

Hashimoto ^{4}He (K-, Λd)n

J-PARC T77



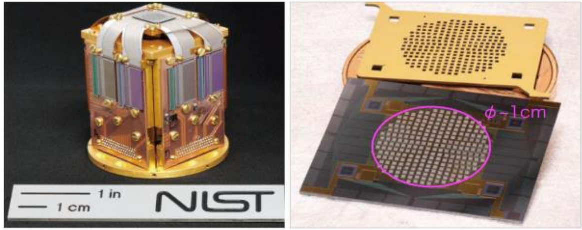
$$B_{\bar{K}NNN} = xx \pm 11(\text{stat}) \text{ MeV}$$
$$\Gamma_{\bar{K}NNN} \sim 100 \text{ MeV}$$
$$\sigma_{\bar{K}NNN \to \Lambda d} \sim 4\ \mu\text{b}$$

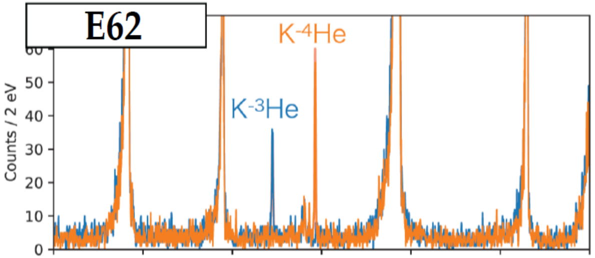
Assign spin-partity; Go to heavier systems

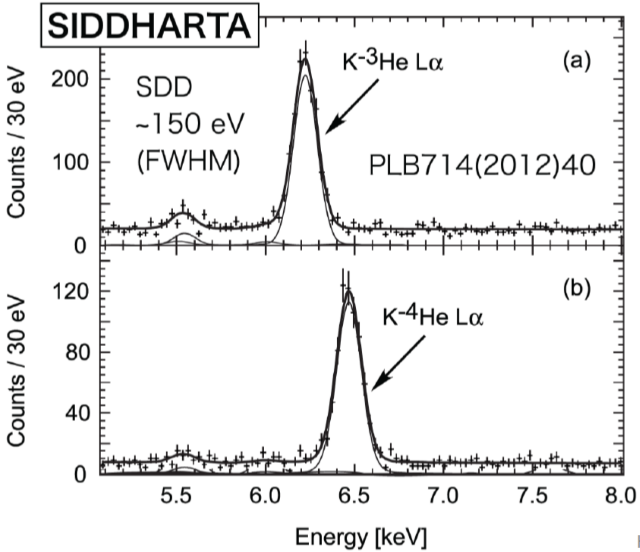
K- atomic X-rays

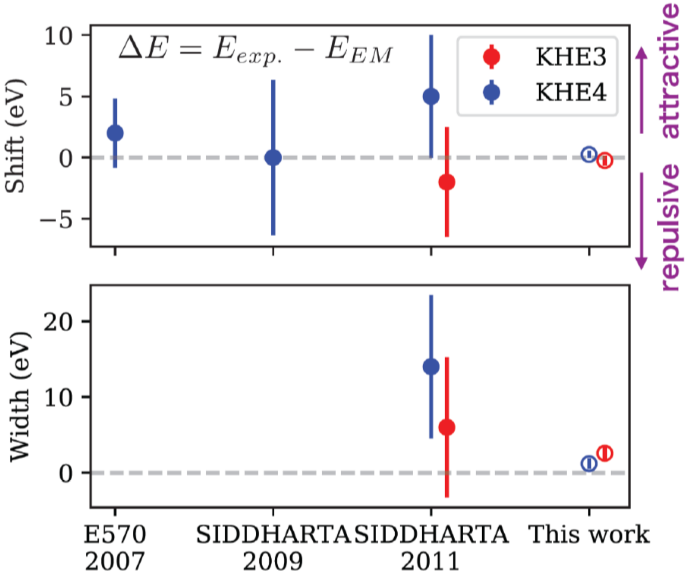
NIST(US) TES spectrometer for E62

Review of Scientific Instruments **88**, 053108 (2017)









SIDDHARTA-2 with SSD
=> challenge to K-d

Transition Edge Sensor (TES)
=> 10 times better resolution

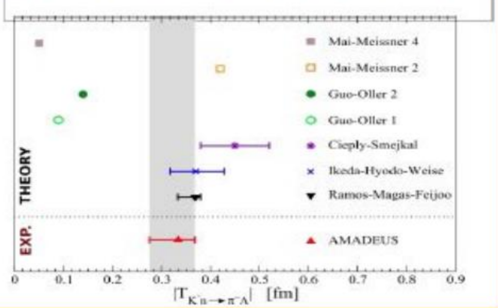
Error bar
quadratic sum of stat. & sys.

Piscicchia

Low-energy K- nucleus interaction (AMADEUS)

K- “n” → $\Lambda\pi^-$ => K-p amplitude below the threshold.

K^-n amplitude below threshold



Λ p channel: 2NA, 3NA and 4NA BRs and σ

Process	Branching Ratio (%)	σ (mb)	@	p_K (MeV/c)
2NA-QF Λp	$0.25 \pm 0.02\,(\text{stat.})\,^{+0.01}_{-0.02}(\text{syst.})$	$2.8 \pm 0.3\,(\text{stat.})\,^{+0.1}_{-0.2}\,(\text{syst.})$	@	128 ± 29
2NA-FSI Λp	$6.2 \pm 1.4(\text{stat.})\,^{+0.5}_{-0.6}(\text{syst.})$	$69 \pm 15\,(\text{stat.}) \pm 6\,(\text{syst.})$	@	128 ± 29
2NA-QF Σ^0p	$0.35 \pm 0.09(\text{stat.})\,^{+0.13}_{-0.06}(\text{syst.})$	$3.9 \pm 1.0\,(\text{stat.})\,^{+1.4}_{-0.7}\,(\text{syst.})$	@	128 ± 29
2NA-FSI Σ^0p	$7.2 \pm 2.2(\text{stat.})\,^{+4.2}_{-5.4}(\text{syst.})$	$80 \pm 25\,(\text{stat.})\,^{+46}_{-60}\,(\text{syst.})$	@	128 ± 29
2NA-CONV Σ/Λ	$2.1 \pm 1.2(\text{stat.})\,^{+0.9}_{-0.5}(\text{syst.})$	-		
3NA Λpn	$1.4 \pm 0.2(\text{stat.})\,^{+0.1}_{-0.2}(\text{syst.})$	$15 \pm 2\,(\text{stat.}) \pm 2\,(\text{syst.})$	@	117 ± 23
3NA Σ^0pn	$3.7 \pm 0.4(\text{stat.})\,^{+0.2}_{-0.4}(\text{syst.})$	$41 \pm 4\,(\text{stat.})\,^{+2}_{-5}\,(\text{syst.})$	@	117 ± 23
4NA Λpnn	$0.13 \pm 0.09(\text{stat.})\,^{+0.08}_{-0.07}(\text{syst.})$	-		
Global $\Lambda(\Sigma^0)$p	$21 \pm 3(\text{stat.})\,^{+5}_{-6}(\text{syst.})$	-		

The ratio between the branching ratios of the 2NA-QF in the Λp channel and in the Σ^0p is measured to be:

$$\mathcal{R} = \frac{BR(K^-pp \to \Lambda p)}{BR(K^-pp \to \Sigma^0 p)} = 0.7 \pm 0.2(stat.)^{+0.2}_{-0.3}(syst.)$$

$$\mathrm{BR}(K^-2\mathrm{NA} \to \mathrm{YN}) = (21.6 \pm 2.9(\mathrm{stat.})^{+4.4}_{-5.6}(\mathrm{syst.}))\%$$

Preliminary K- p -> $(\Sigma^0/\Lambda)\,\pi^0$

cross section at p_{K^-} = 98 ± 10 MeV/c :

- $\sigma_{K^-p\to\Sigma^0\pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)$ mb
- $\sigma_{K^-p\to\Lambda\pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)$ mb ,

Λ t channel: 4NA BRs and σ

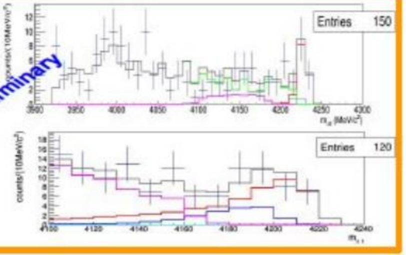
BR(K^{-4}He(4NA) → Λt) < 2.0 × 10^{-4} /K_{stop} (95% c. l.)

σ(100 ± 19 MeV/c) (K^{-4}He(4NA) → Λt) =
= (0.81 ± 0.21 (stat) $^{+0.03}_{-0.04}$ (syst)) mb

BR(K^{-12}C(4NA) → Λt ^{8}Be) = 1.5 ± 0.5 × 10^{-4} (stat) /K_{stop}

σ(K^{-12}C (4NA) → Λt ^{8}Be) = 0.58 ± 0.11 (stat) mb

σ(K^{-12}C (4NA) → Σ^0t ^{8}Be) = 1.88 ± 0.35 (stat) mb



$K^{bar}N$ interaction and $\Lambda(1405)$

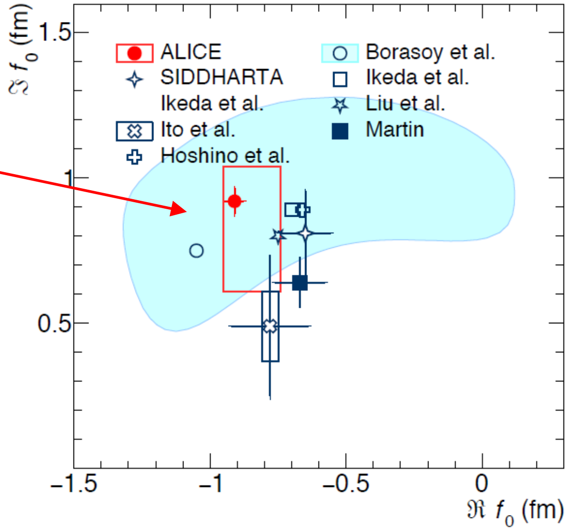
Lea *Vazquez Doce*
Wickramaarachchi
Feijoo, Oset, Cieply, Shevchenko, Ren, Hyodo, Kamiya, Obertova

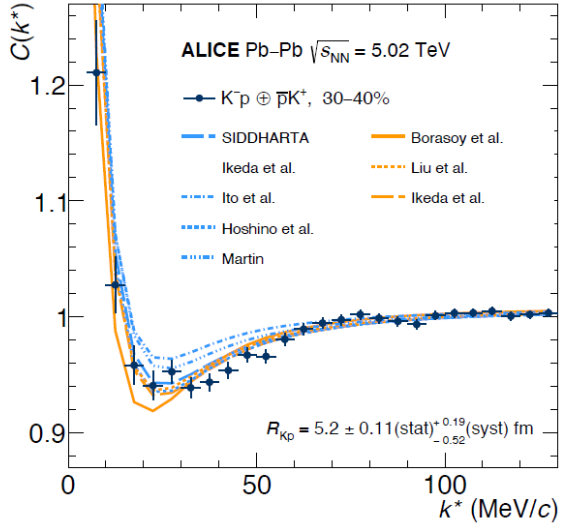
The two pole structure was accepted in PDG.

Experimental data constrain pole structure of the $\Lambda(1405)$ region : "$\Lambda(1405)$" —> $\Lambda(1405)$ + $\Lambda(1380)$

$\Lambda(1380)$	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****

K^-p femtoscopy data plays an important role.





$K^{bar}N$ interaction has been updated.

Future directions and Facilities

Tang,... *Zachariou*

JLab Hall-A, CLAS, Glue-X *Wickramaarachchi, Pauli*

GSI *Spies, Saito,..*

hypernuclear production via HI collisions *Botvina*

DAFNE *Piscicchia, Zmeskal,...*

J-PARC *Sakuma, Ozawa,...*

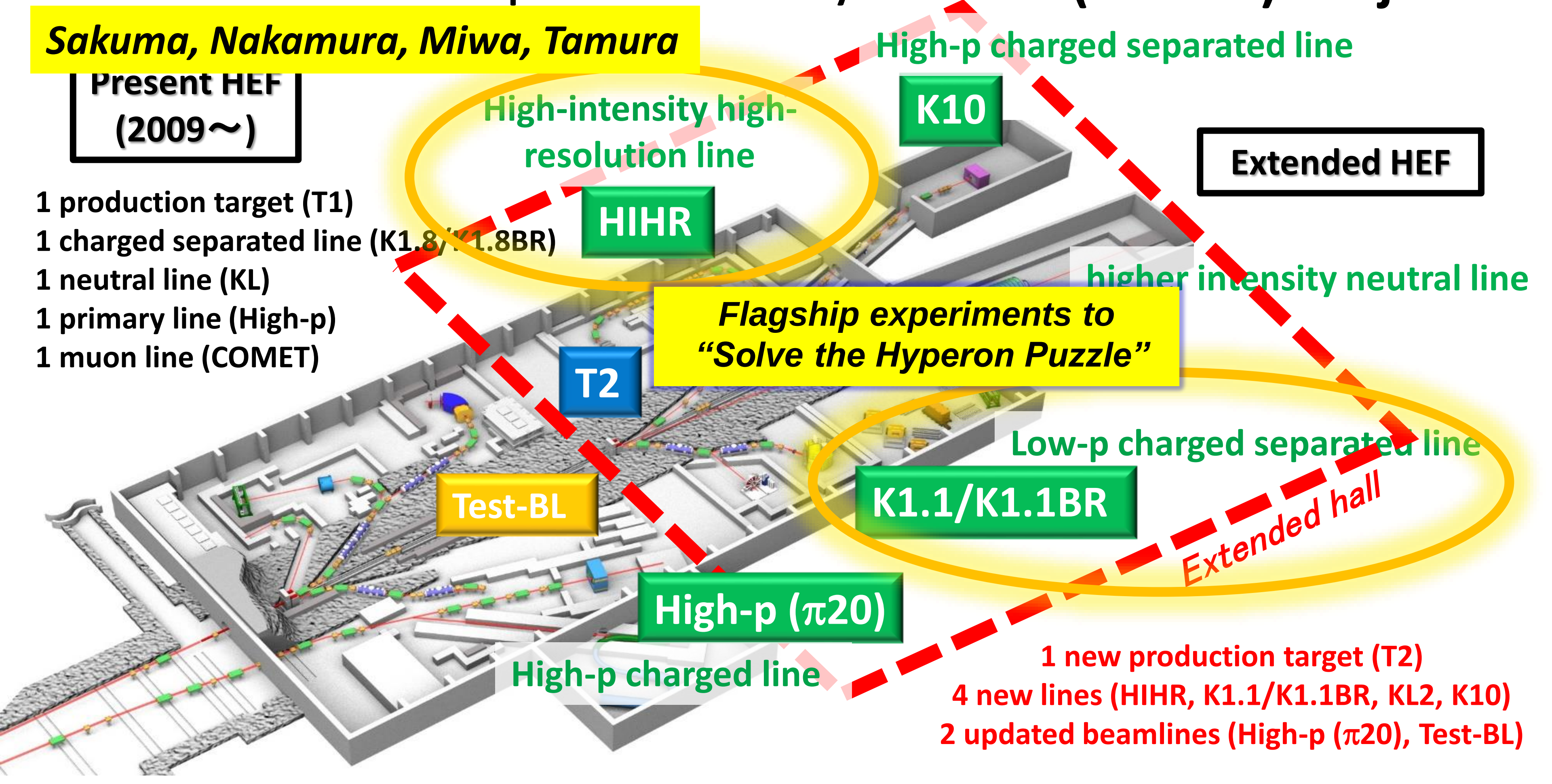
ALICE, STAR ϕ/Υ spin alignment/polarization *Chen, Niida*

Belle/Belle2, BESIII, LHC-b heavy flavor/exotic hadrons

Tanida *Guo*

J-PARC Hadron Experimental Facility extension (HEF-ex) Project

Sakuma, Nakamura, Miwa, Tamura



Vidana, Tolos, Ohnishi

Tamura

Hyperon puzzle / Topical session for ΛNN

Epelbaum
Haidenbauer
Doi, Illa
Bazak

BB interaction

Nuclear structure

Le, Barnea,
Hiyama, Gal, ..

CONCLUSIONS and OUTLOOK

Understanding strangeness in **dense matter and neutron stars** requires detailed evaluation of the **quantitative balance** between **hyperon-nuclear two- and three-body forces**.

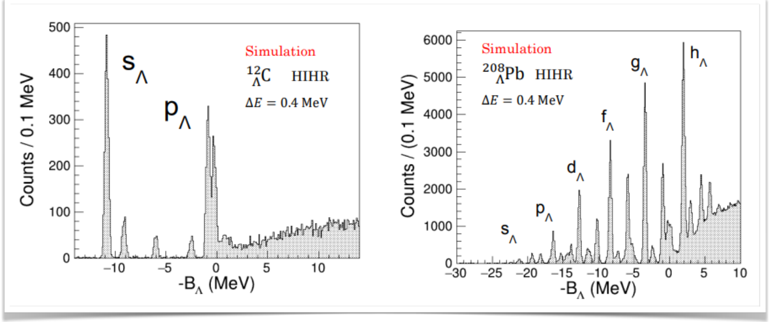
Weise

- **Improved and expanded high-statistics YN two-body data base :**
  YN scattering and reactions (e.g. J-PARC E40); **YN correlation functions** (e.g. Femtoscopy)

- **Improved systematics** of **high-resolution hypernuclear spectroscopy :**
  (π^+, K^+) at J-PARC, $(e, e'K^+)$ at JLab, MAMI, with **mass resolution better than 0.5 MeV**

Example:
simulation taken from
J-PARC HIHR beamline proposal
S. N. Nakamura et al. (2021)

expected **mass resolution :**
~ 0.33 MeV



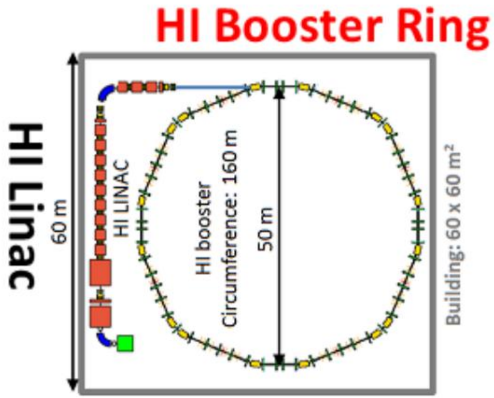
- **Increasing amounts of astrophysical data** (focus on **speed of sound** in **neutron stars**)

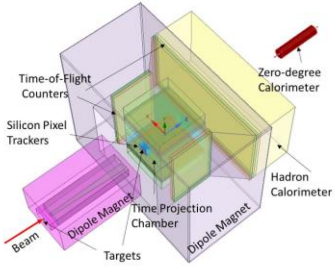
Ozawa

J-PARC HI project

- *Directly create high density matter*
- *Directed flow of Λ => U_Λ at high density*

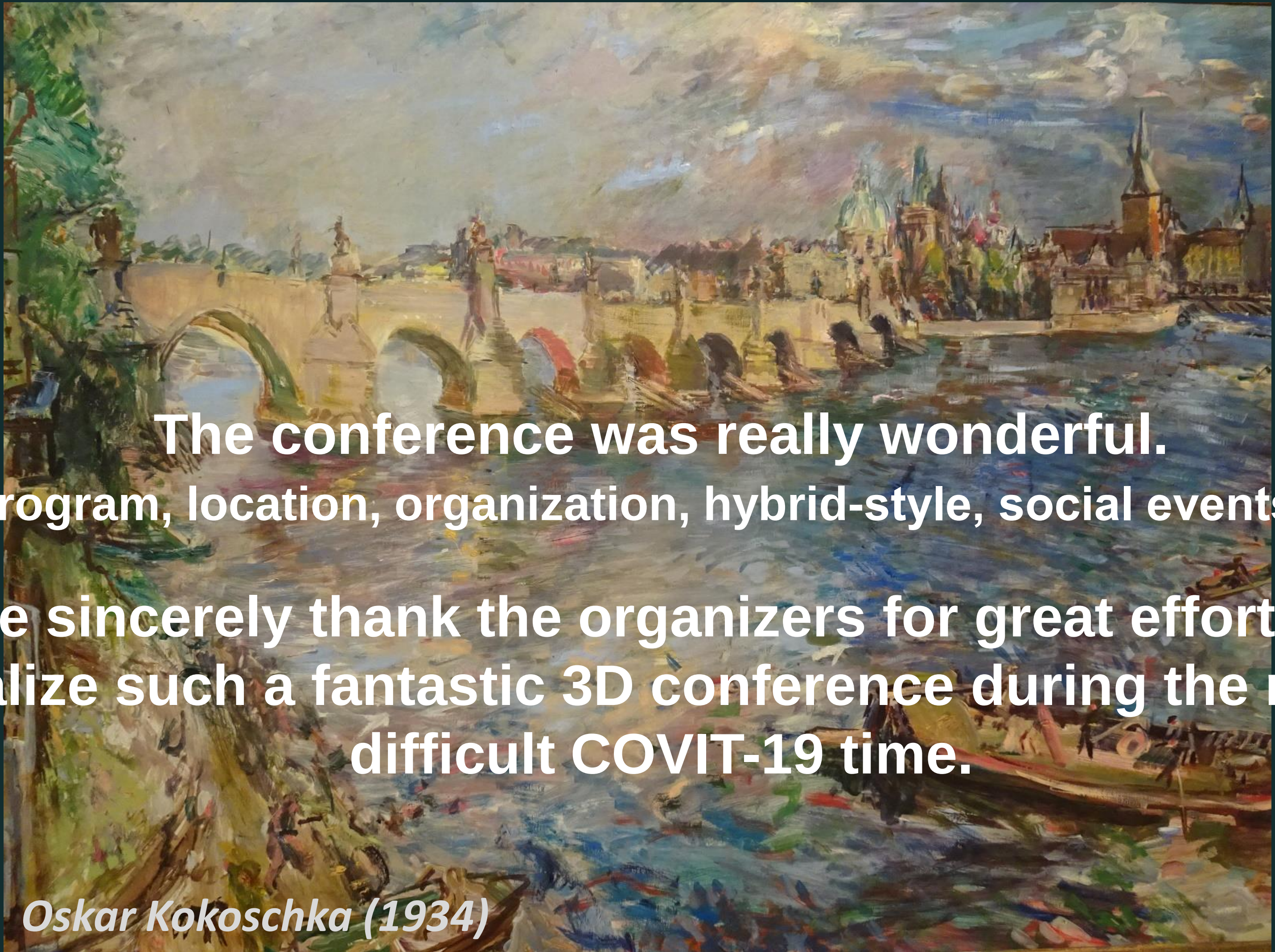
Ohnishi





Schematic view of Hyper-nuclei spe...eter

Close collaboration between theorists and experimentalists is more important



Oskar Kokoschka (1934)

The conference was really wonderful.

Program, location, organization, hybrid-style, social events,…

We sincerely thank the organizers for great efforts to realize such a fantastic 3D conference during the most difficult COVIT-19 time.