

EMMI Workshop “5th Workshop on Anti-Matter, Hyper-Matter and Exotica Production”

November 10—14, 2025, Salerno, Italy

Hypertriton and kaonic nuclei at J-PARC

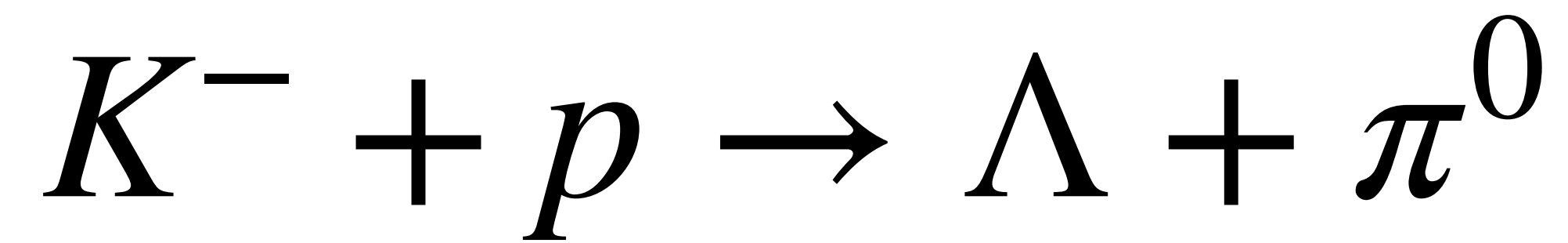
Tadashi Hashimoto (RIKEN)

for J-PARC E15/E31/E73 + E80/E89 collaboration

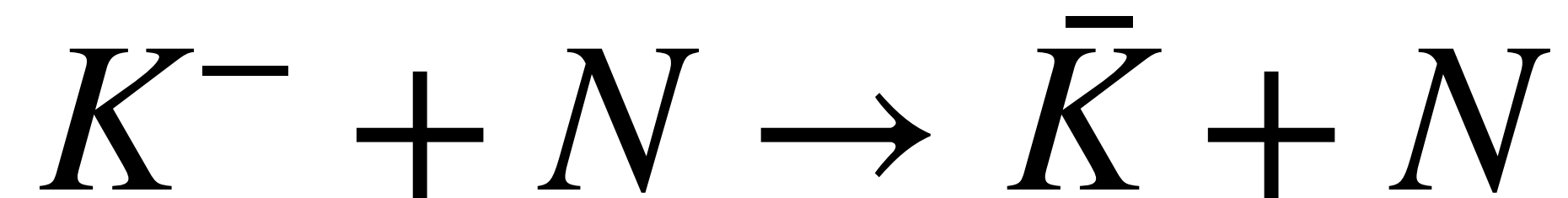
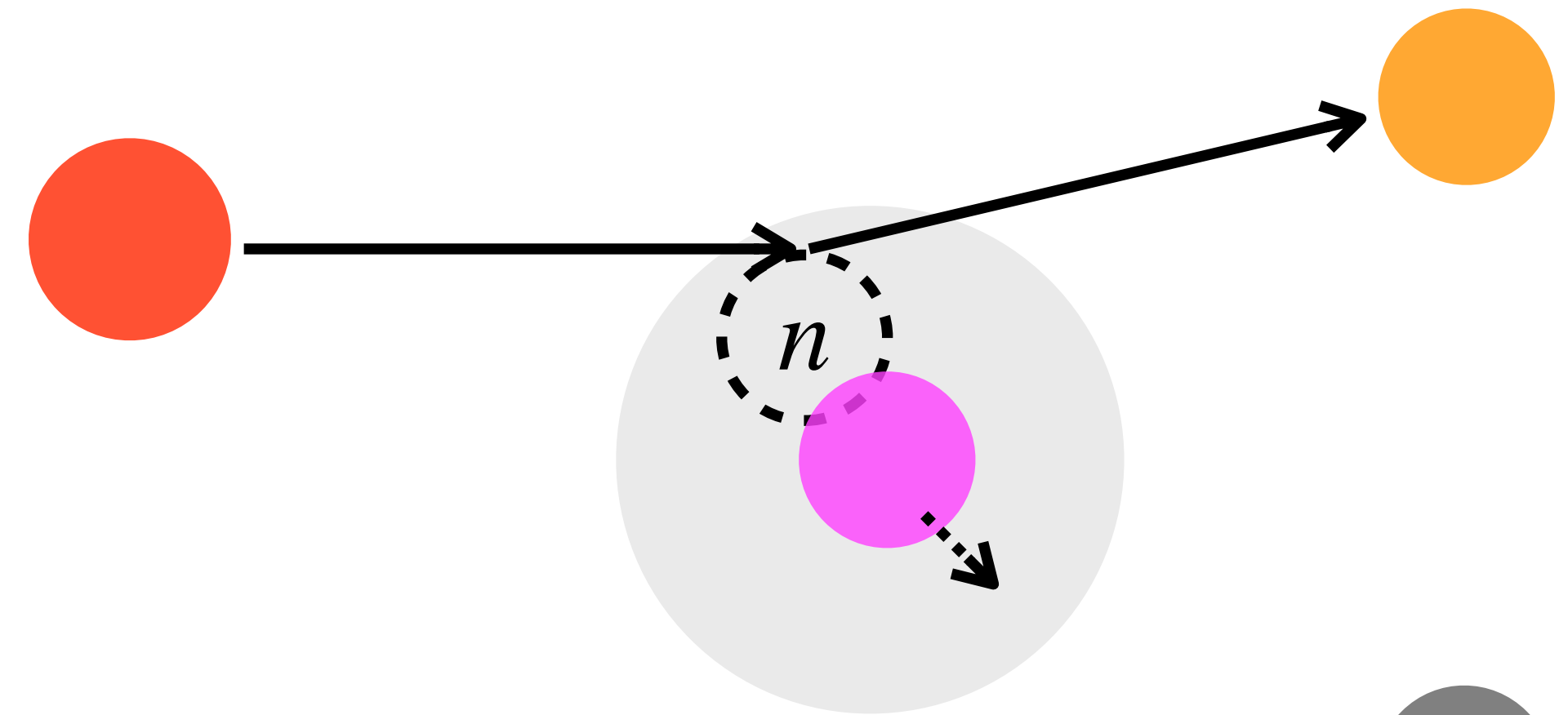
tadashi.hashimoto@riken.jp



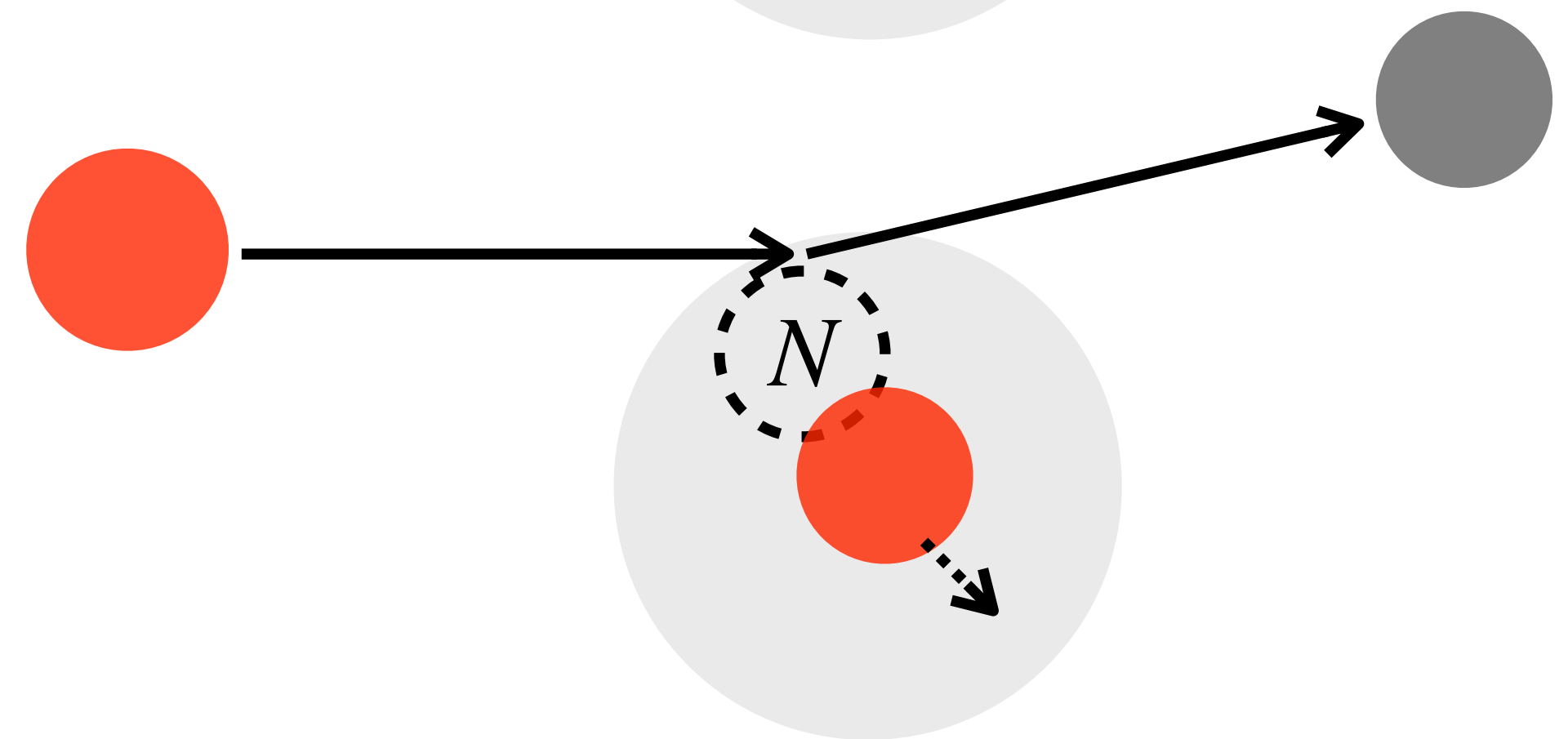
K⁻ induced reactions



→ hypernucleus



→ Kaonic nucleus



✓ large cross section for the elementary processes ~ mb/sr

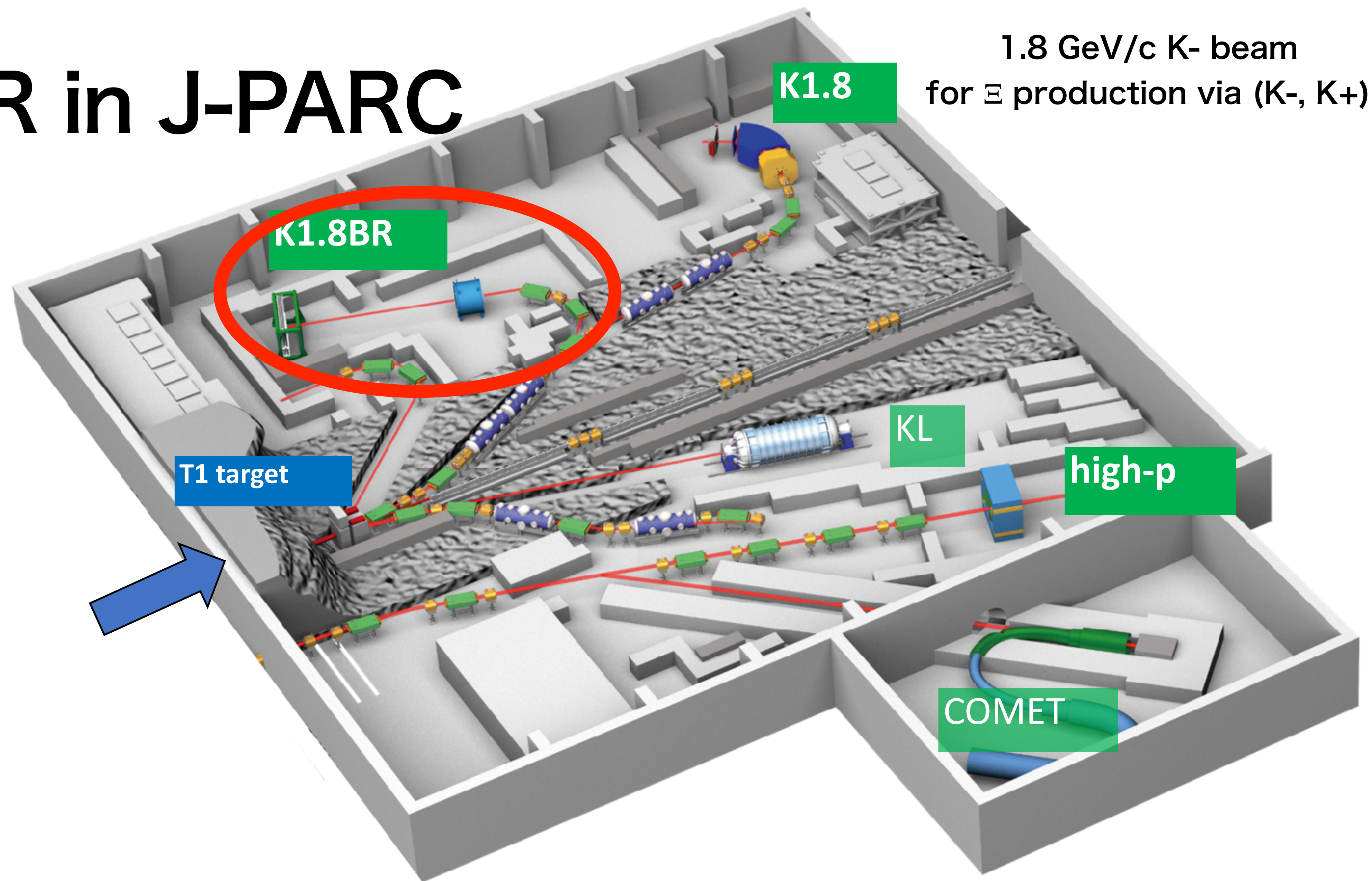
✓ Clean production + controlled kinematics

J-PARC: Japan Proton Accelerator Research Complex

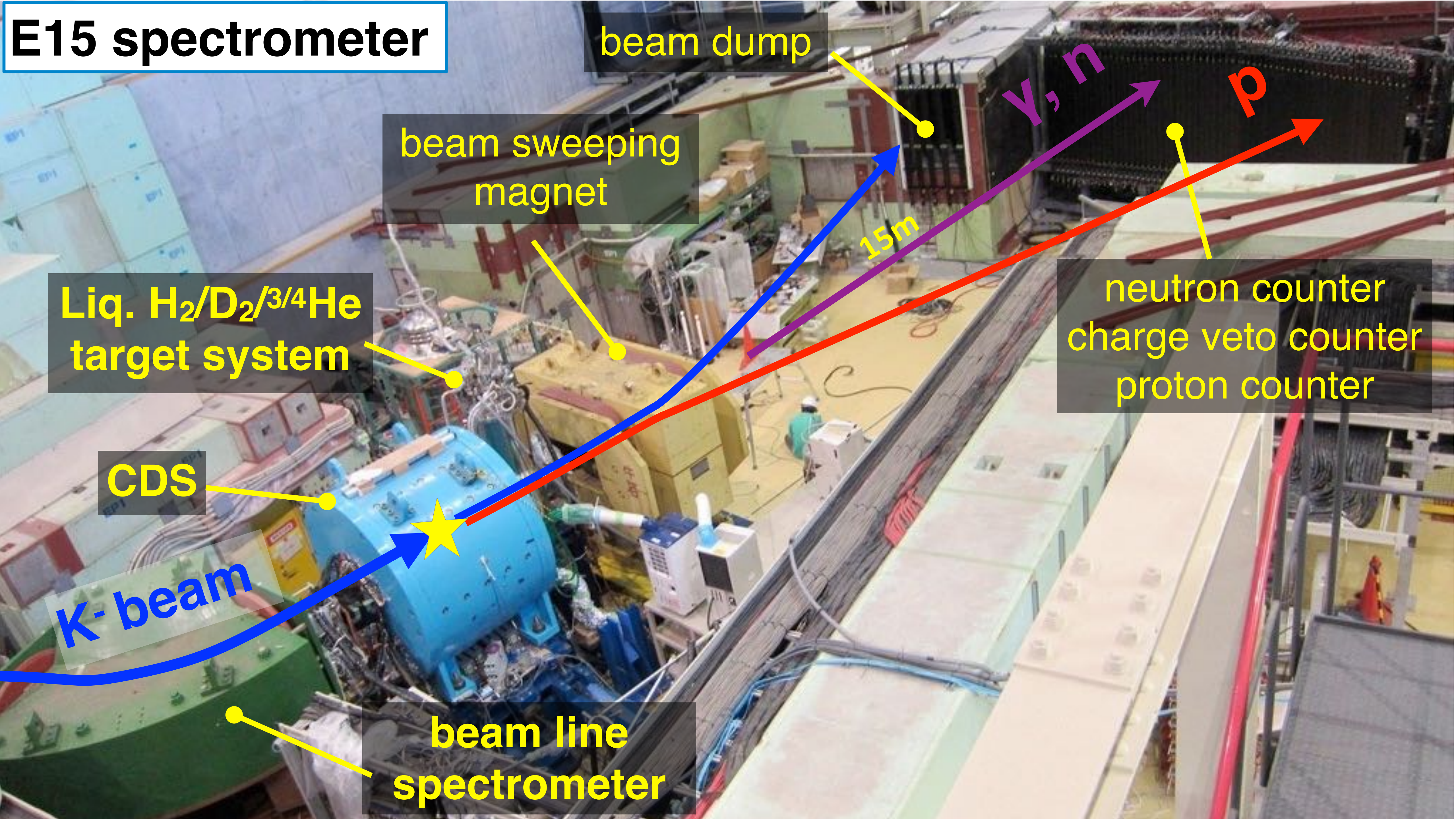


High-intensity proton driver to produce variety of secondary beams

K1.8BR in J-PARC



K1.8BR suitable for low-energy K- beam below 1 GeV/c



E15 spectrometer

beam dump

beam sweeping
magnet

Liq. $H_2/D_2/^{3/4}He$
target system

neutron counter
charge veto counter
proton counter

CDS

K- beam

beam line
spectrometer

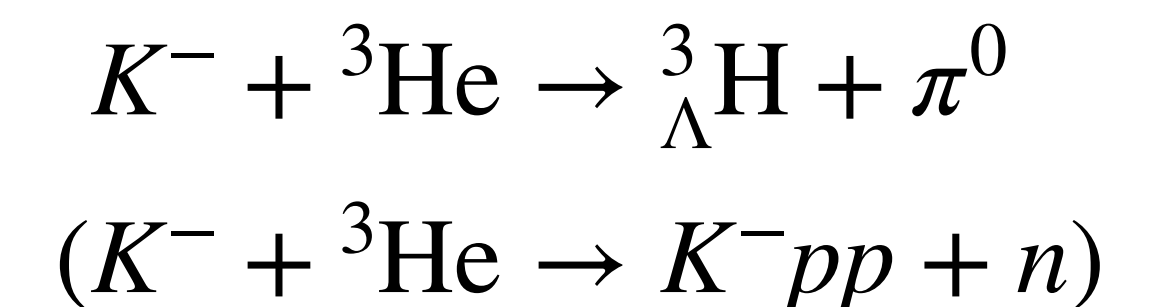
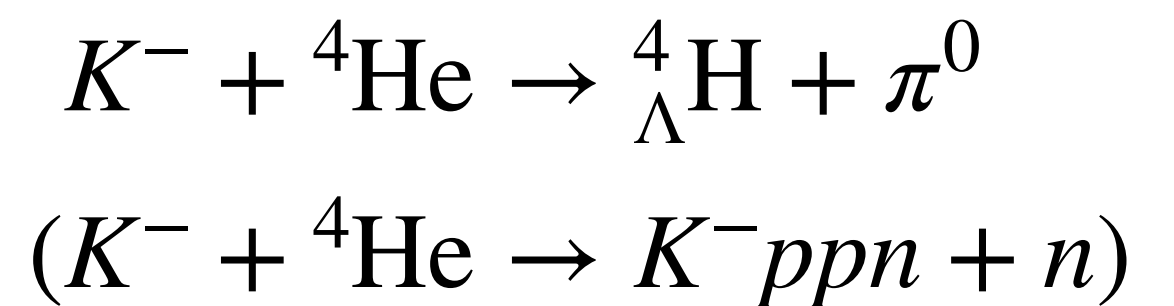
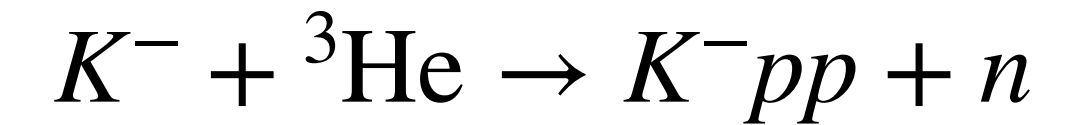
15m

γ, n

p

Experiments with E15-CDS

- 2012: Completed the construction [PTEP 02B011(2012)]
- 2013: **E15** 1st, “**K-pp**” search.
[PTEP 061D01 (2015), PTEP, 051D01 (2016)]
- 2015: **E15** 2nd, “**K-pp**” search
[PLB789, 620 (2019), PRC102, 044002 (2020), PRC10, 014002 (2024)]
- 2018: **E31**, **$\Lambda(1405)$**
[PLB837,137637(2023) + 2 in preparation]
- 2020: **T77**, ${}^4_{\Lambda}\text{H}$ lifetime, (“**K-ppn**” search)
[PLB485, 138128 (2023) + 1 in preparation]
- 2021: **E73** 1st, ${}^3_{\Lambda}\text{H}$ production cross section
[arXiv:2509.16967]
- 2024~2025: **E73** 2nd, ${}^3_{\Lambda}\text{H}$ lifetime, (“**K-pp**” study)
[>3 publications expected]

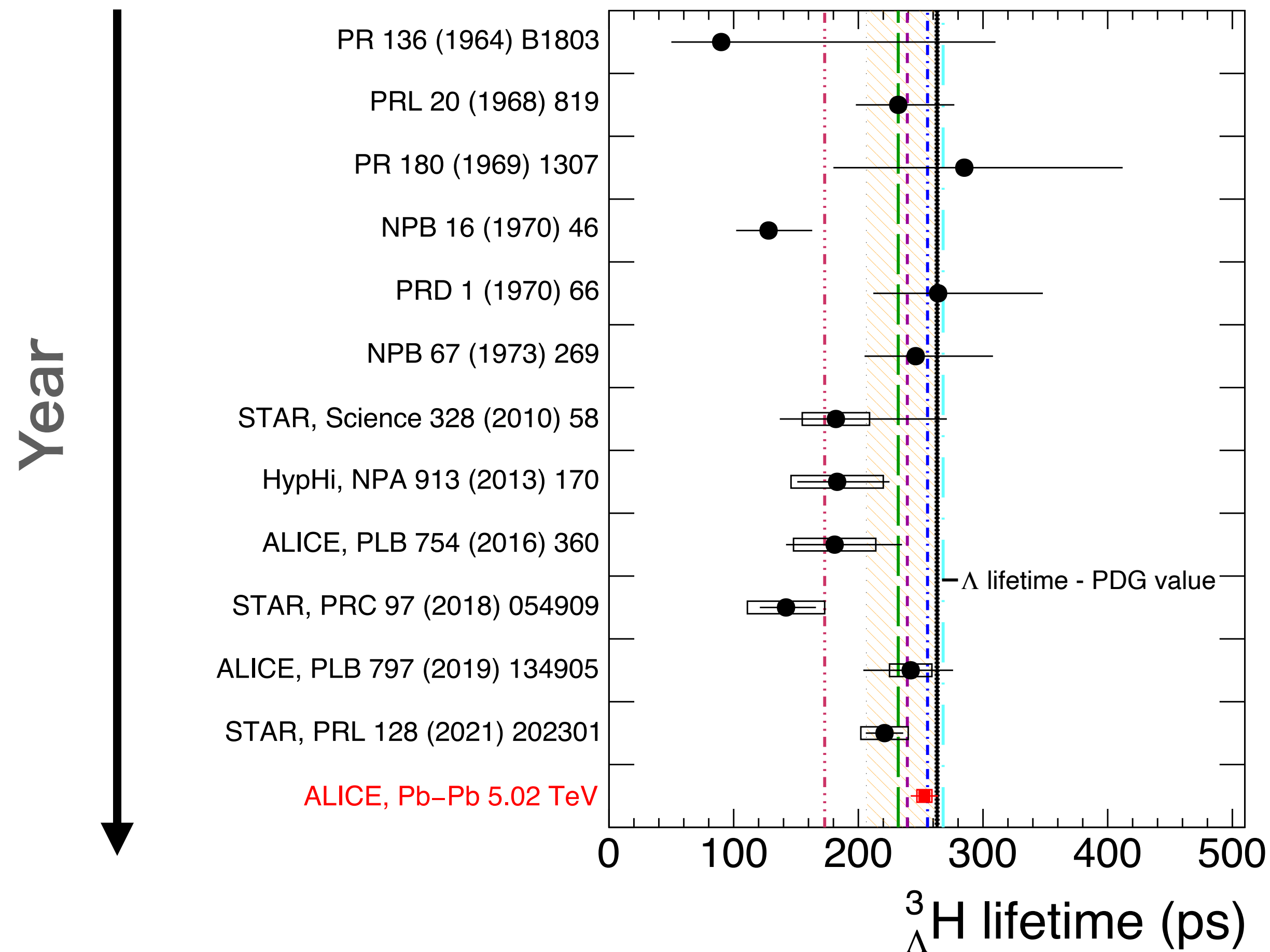


Light hypernucleus

Hypertriton puzzle

taken from

PRL 131(2023)102302



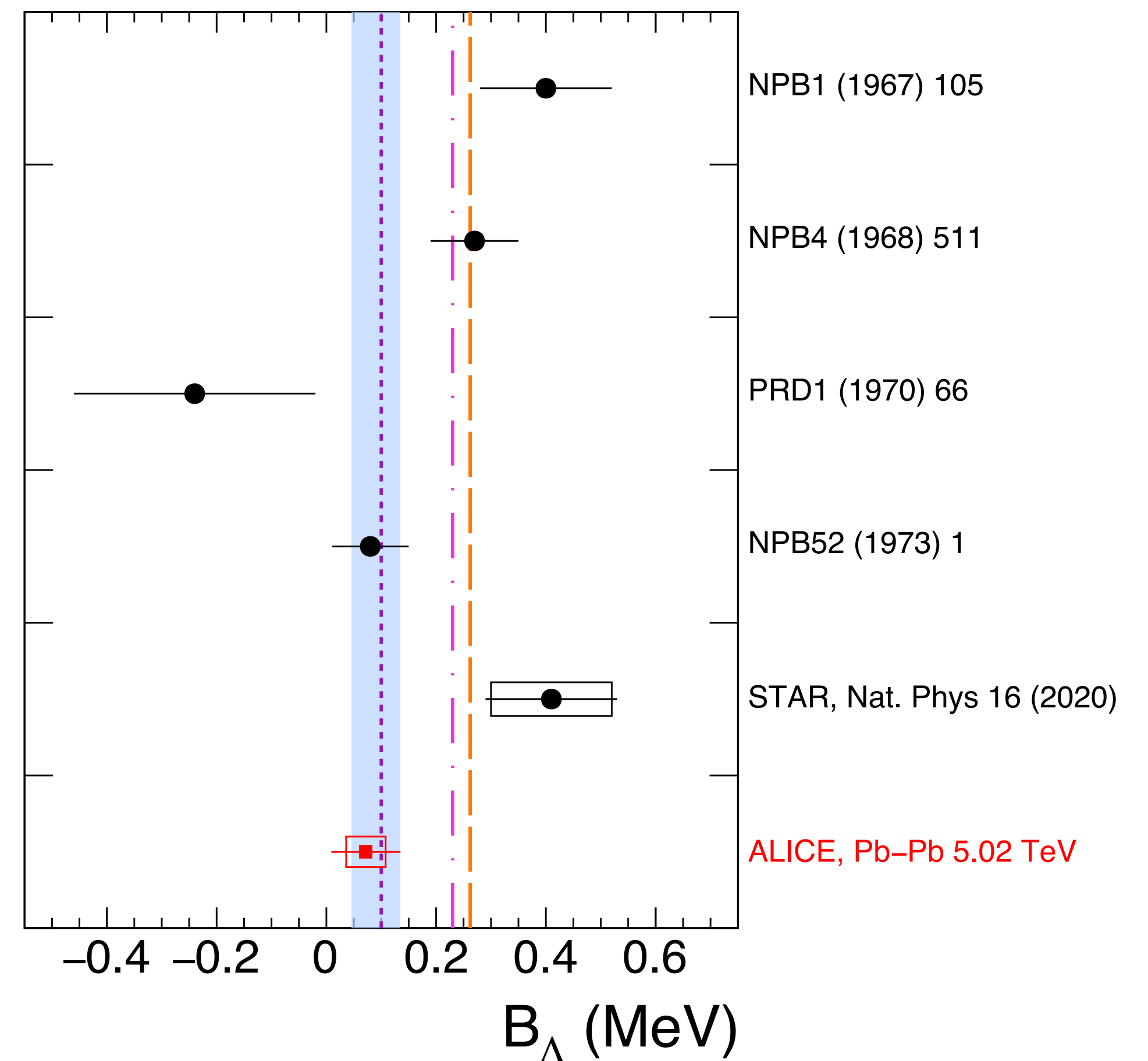
Theoretical predictions

NPB47 (1972) 109-137

arXiv:1711.07521

PRC77 (2008) 027001

EPJA(2020) 56



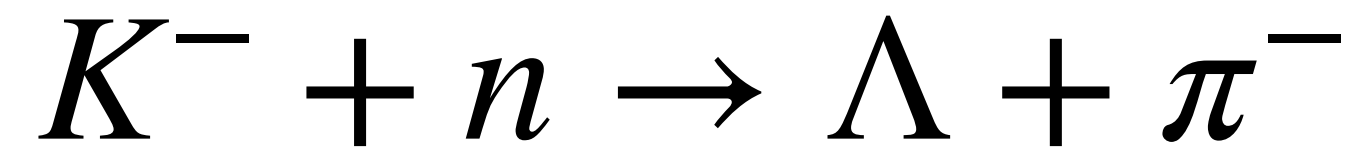
$^3_\Lambda\text{H} (1/2^+)$

deuteron

if $B_\Lambda \sim 130$ keV,
 ~ 10 fm separation

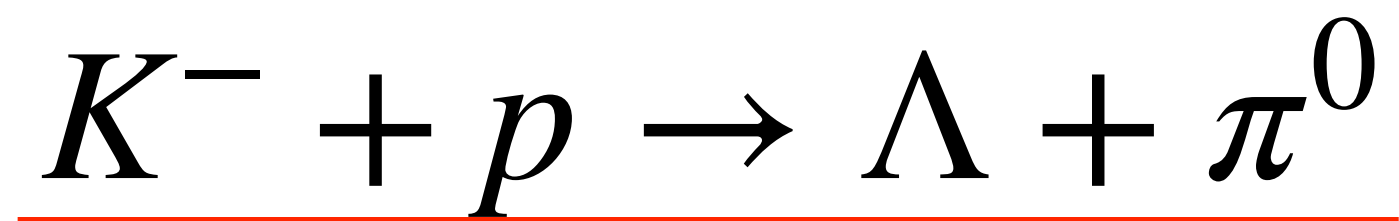
Even for the benchmark hypernucleus, we do not understand well.

(K^-, π^0) reaction: complementary to HI experiments

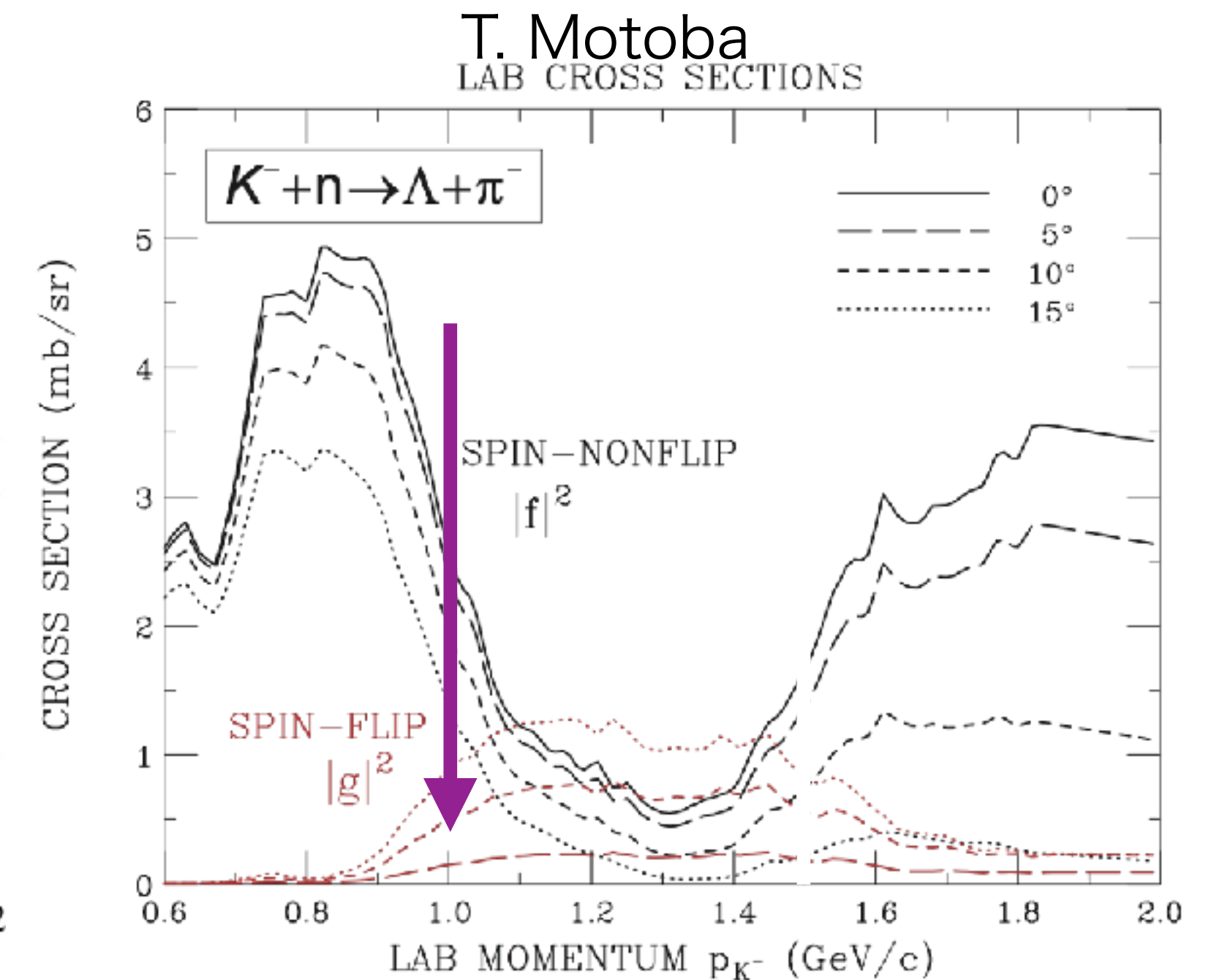
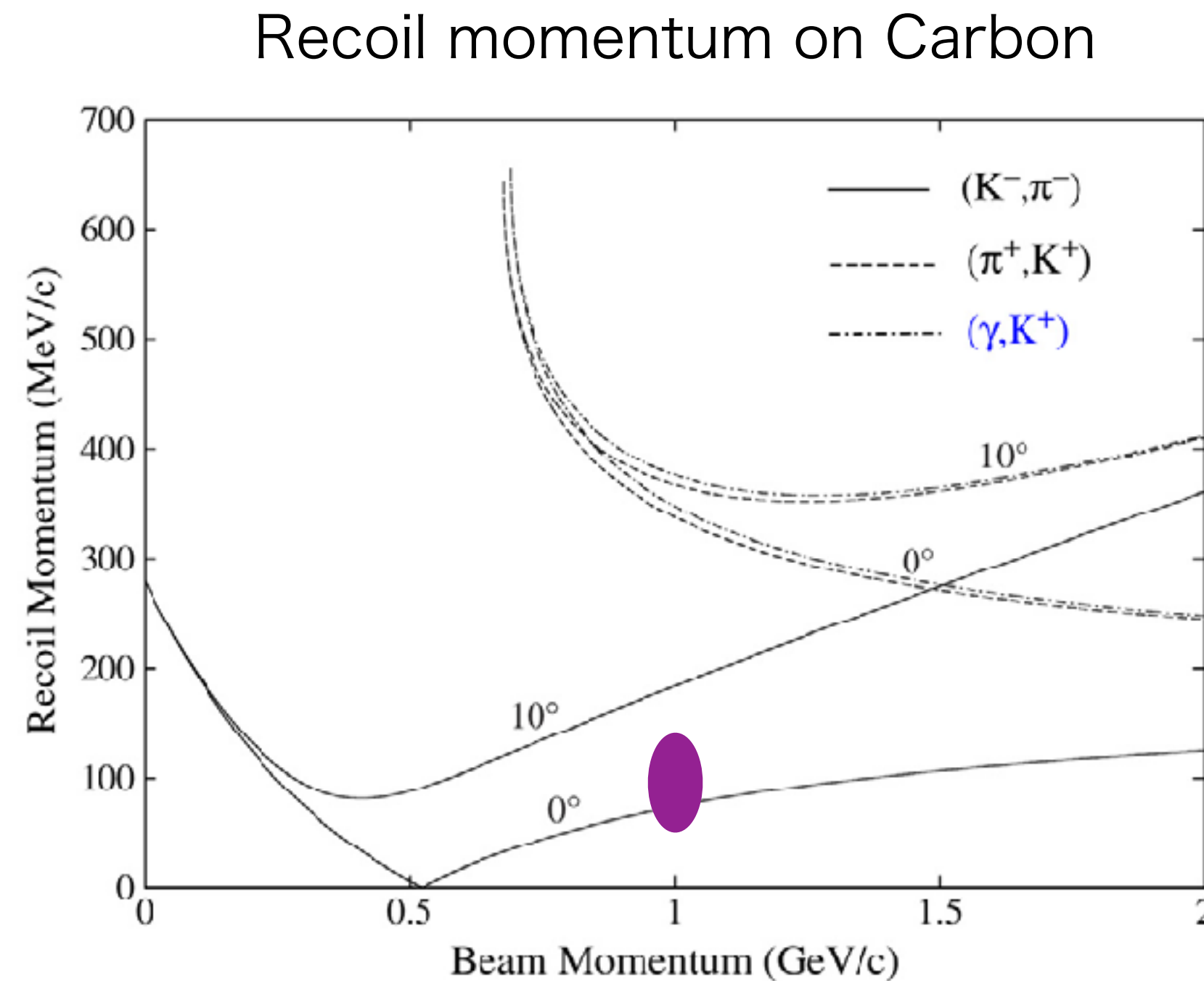


widely adopted

with magnetic spectrometers

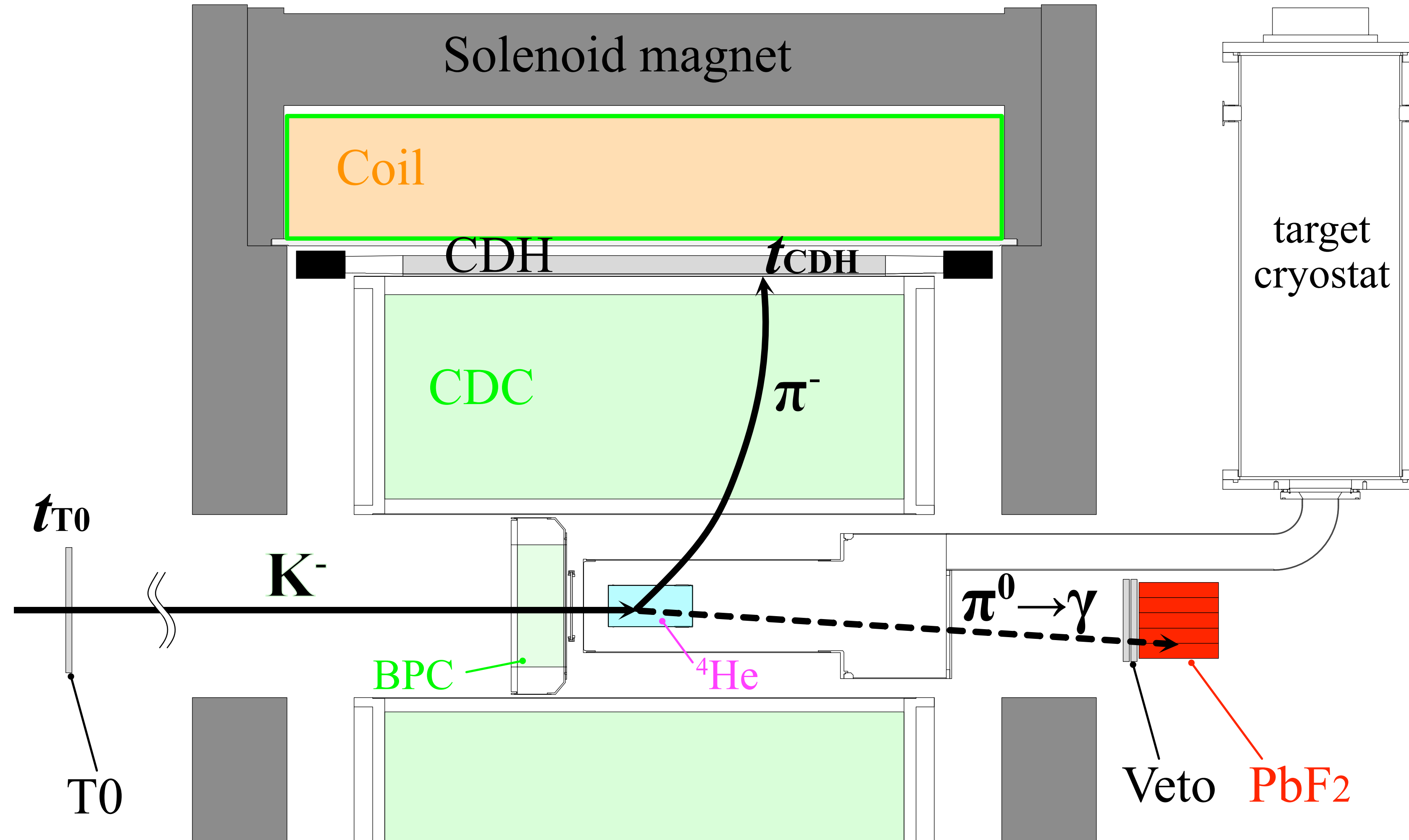


difficult to do π^0 spectroscopy



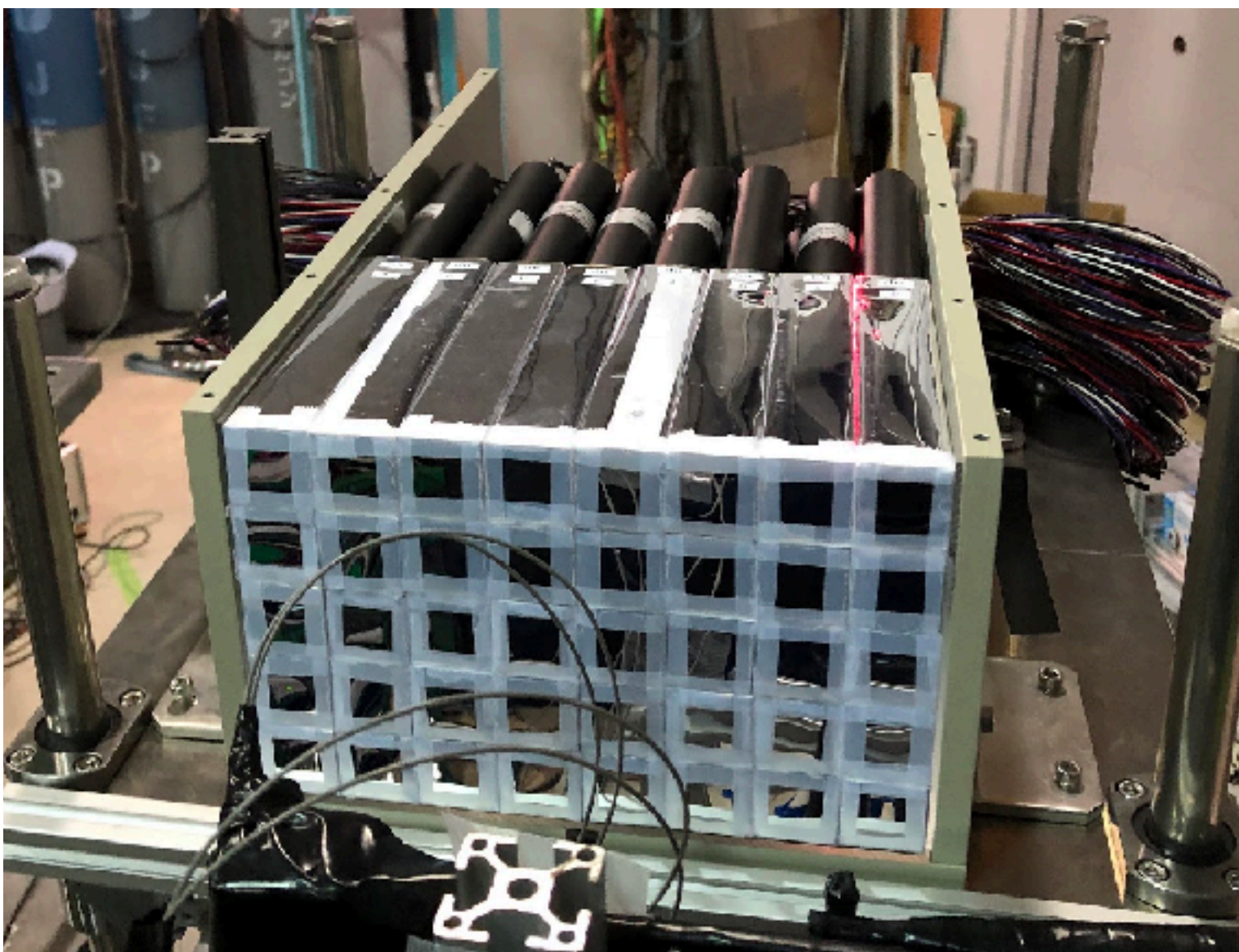
- **Low recoil momentum** → hypernucleus mostly stops before its decay
- **Spin-nonflip reaction** is dominant at 1.0 GeV/c or lower
- π^0 spectroscopy is difficult → **high-energy gamma tagging at forward angle**

Time-domain lifetime measurement

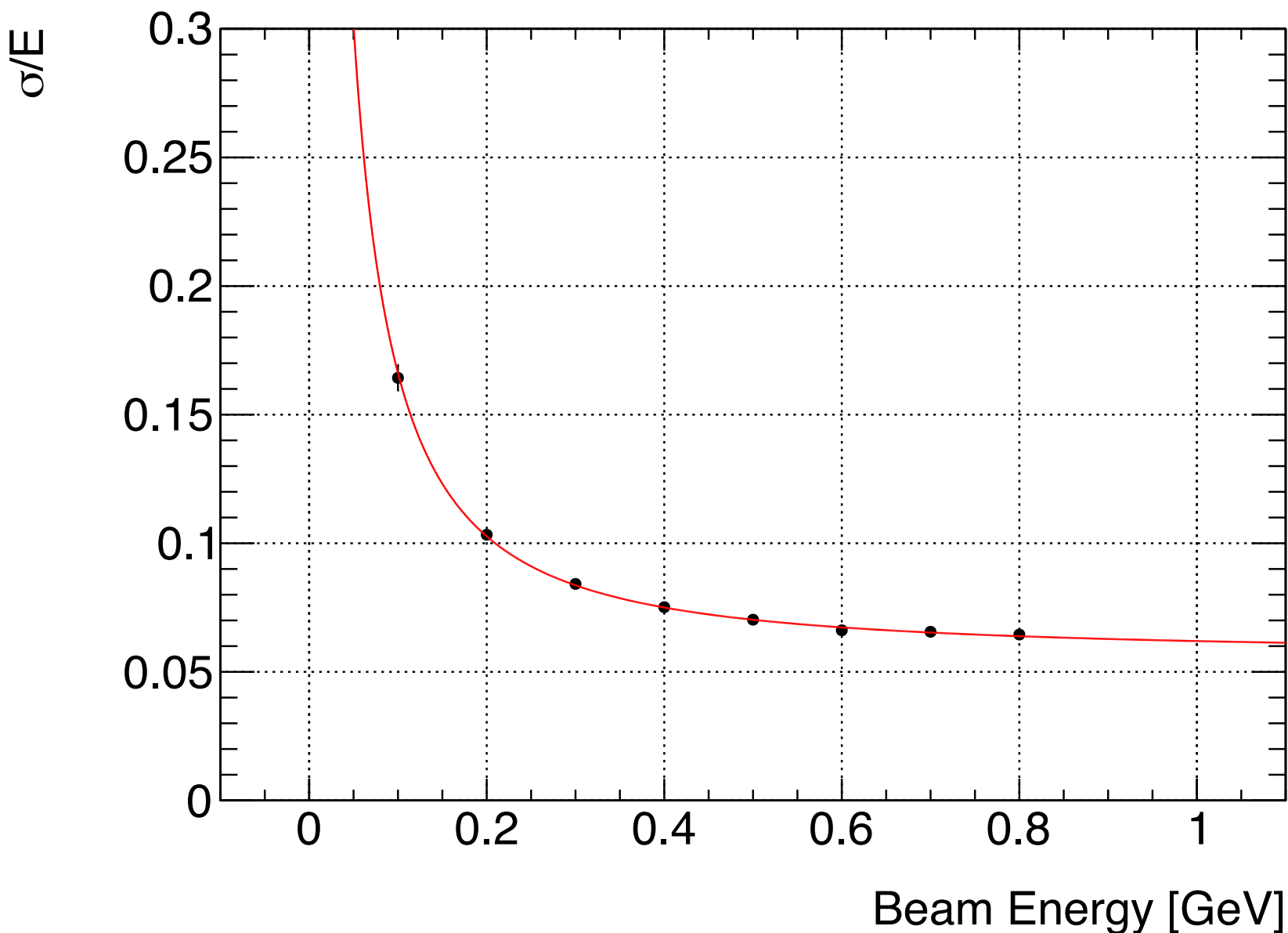


$$t_{\text{decay}} = (t_{\text{CDH}} - t_{\text{T0}}) - t_{\text{CDC}}^{\text{calc.}} - t_{\text{beam}}^{\text{calc.}}$$

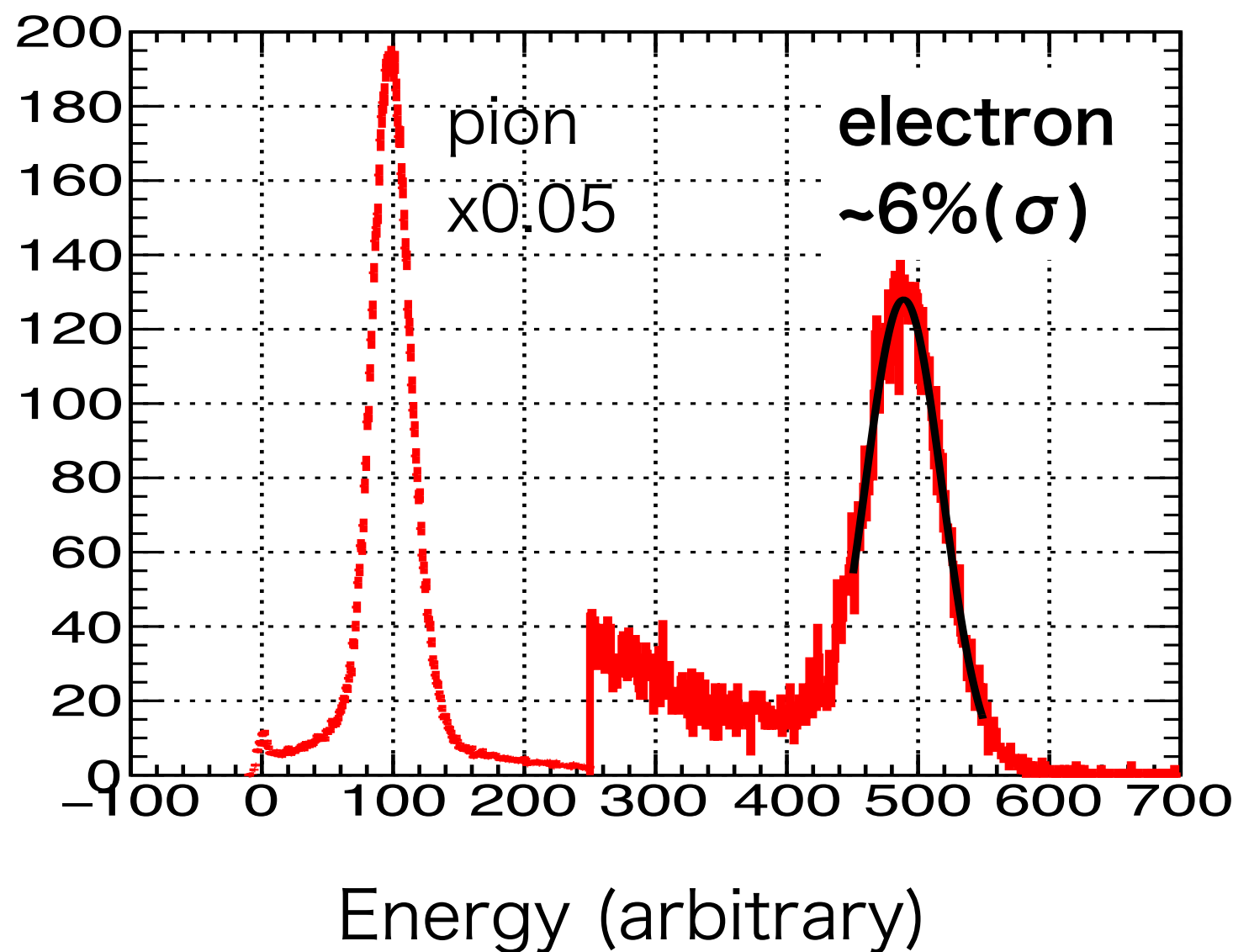
PbF₂ EM calorimeter for π^0 tag



2019.12: Test experiment @ ELPH
using 100~800 MeV e⁺ beam



Response to 1 GeV/c π^-/e^- @ J-PARC



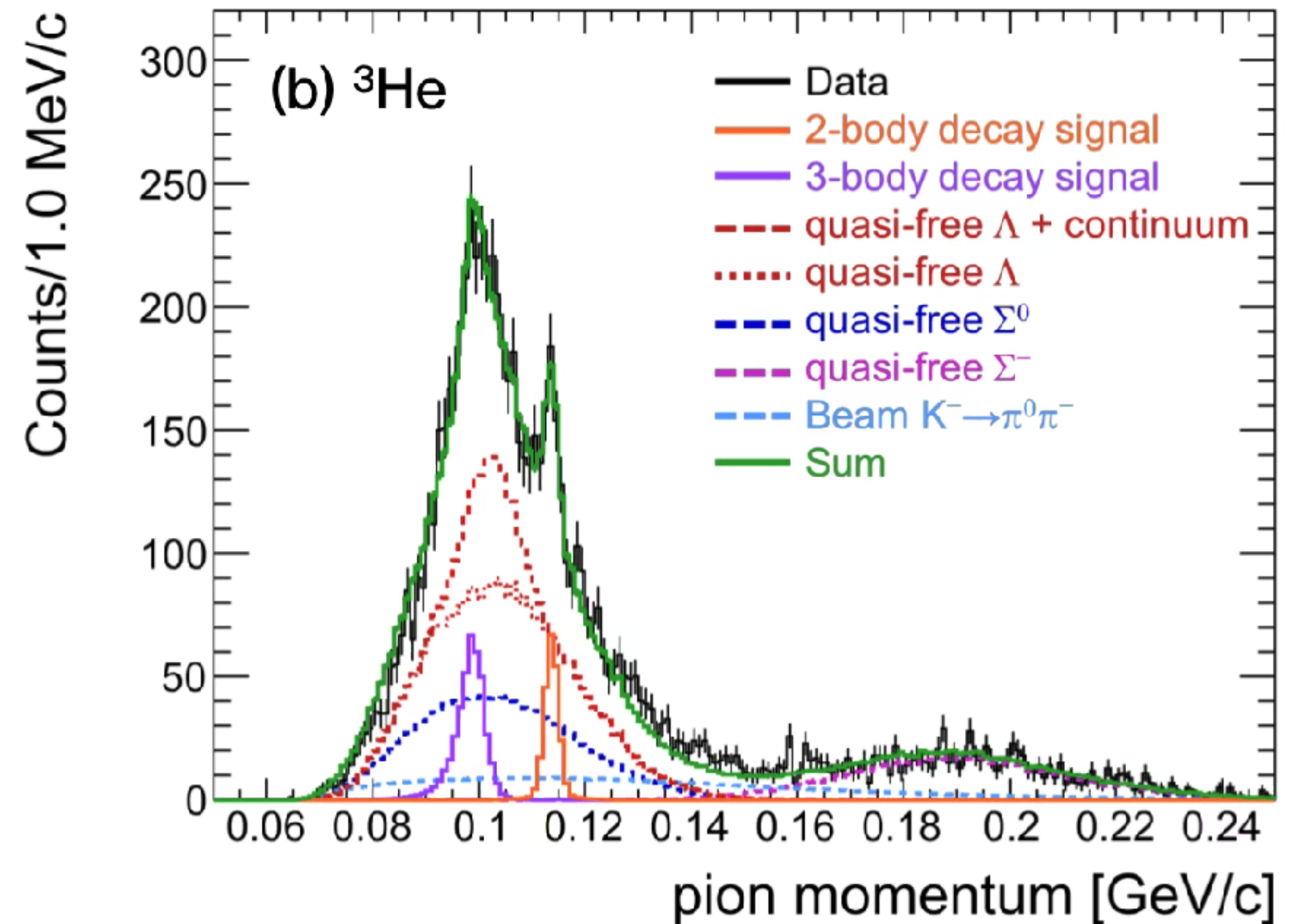
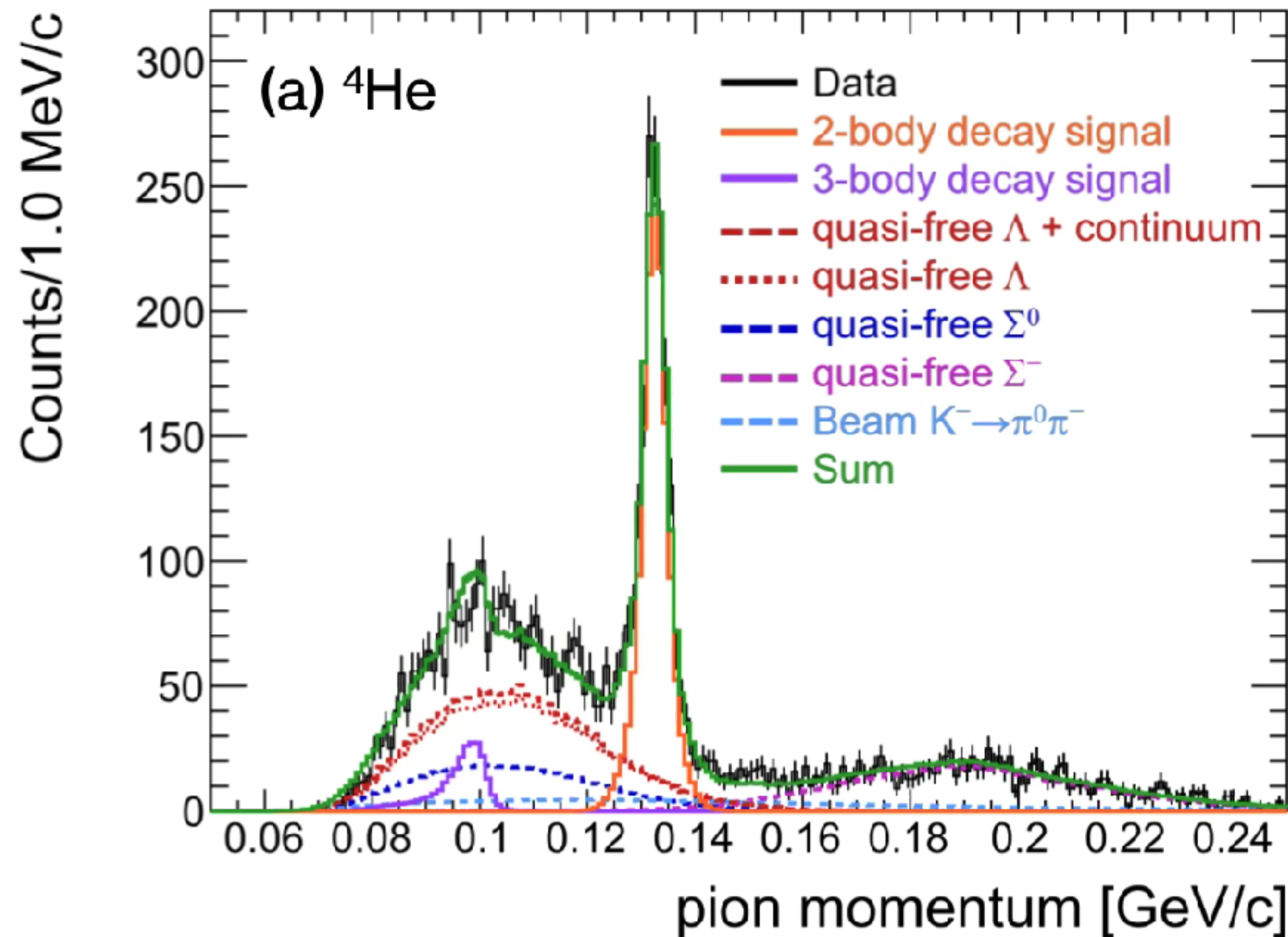
- Cherenkov-type, **Fast & Radiation hard**
- 25 x 25 x 140 mm³
- 40 segment
- 1/4" PMT with Fe magnetic shield

Crystal	Radiation length	Moliere radius	Density	Cost	Resolution	Signal length
PbF ₂	0.93 cm	2.22 cm	7.77 g/cm ³	12 USD/cc	5%	2ns

D.F. Anderson, *et al.*, Nucl. Inst. Meth. A290 (1990) 385
P. Achenbach, *et al.*, Nucl. Inst. Meth. A416 (1998) 357

Decay pion spectrum with gamma-tag

<http://arxiv.org/abs/2509.16967>



✓ Two-body decay peaks are observed.

✓ Backgrounds from quasi-free hyperons are well under control

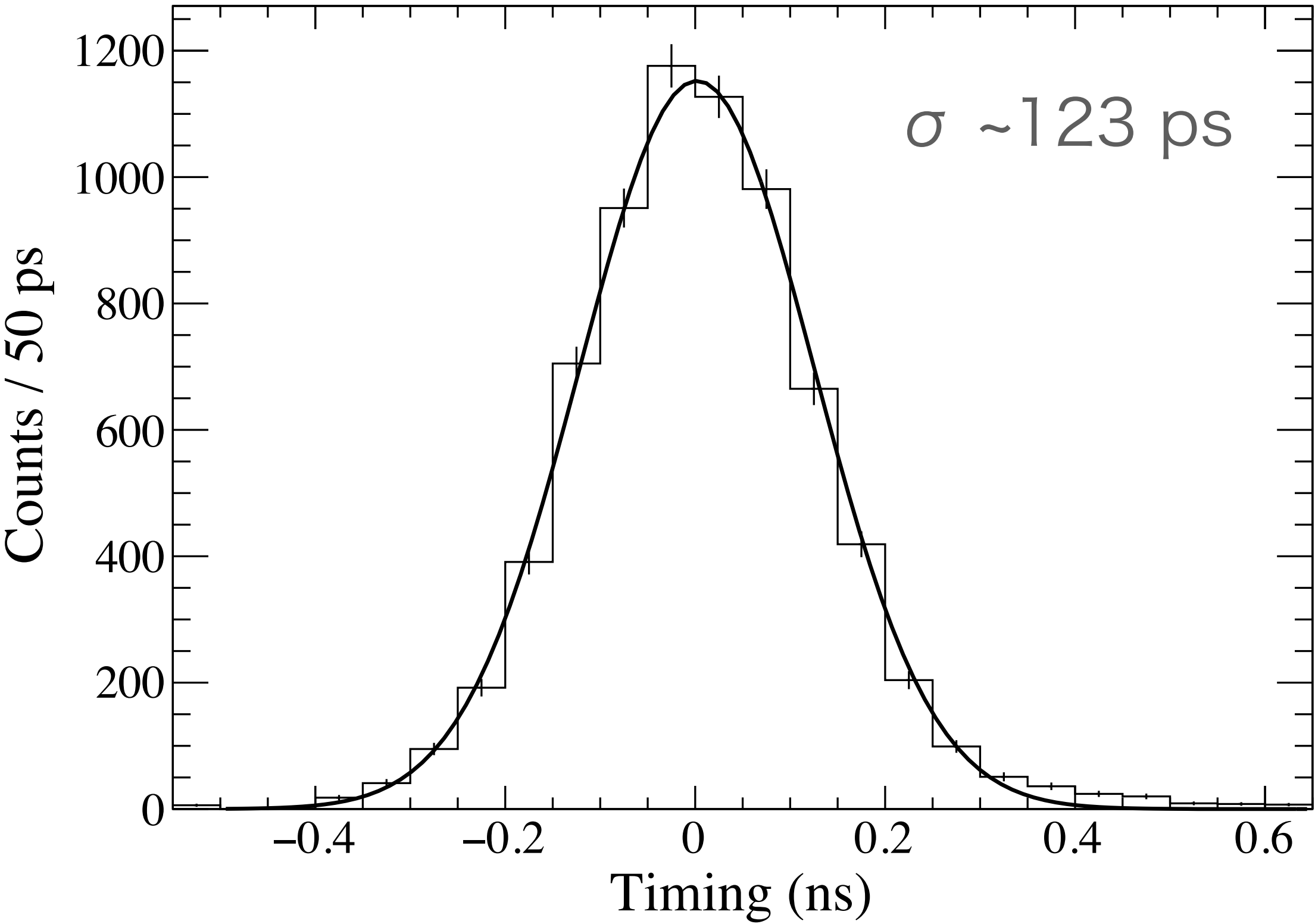
$^4\Lambda$ H lifetime

PLB845, 138128 (2023)

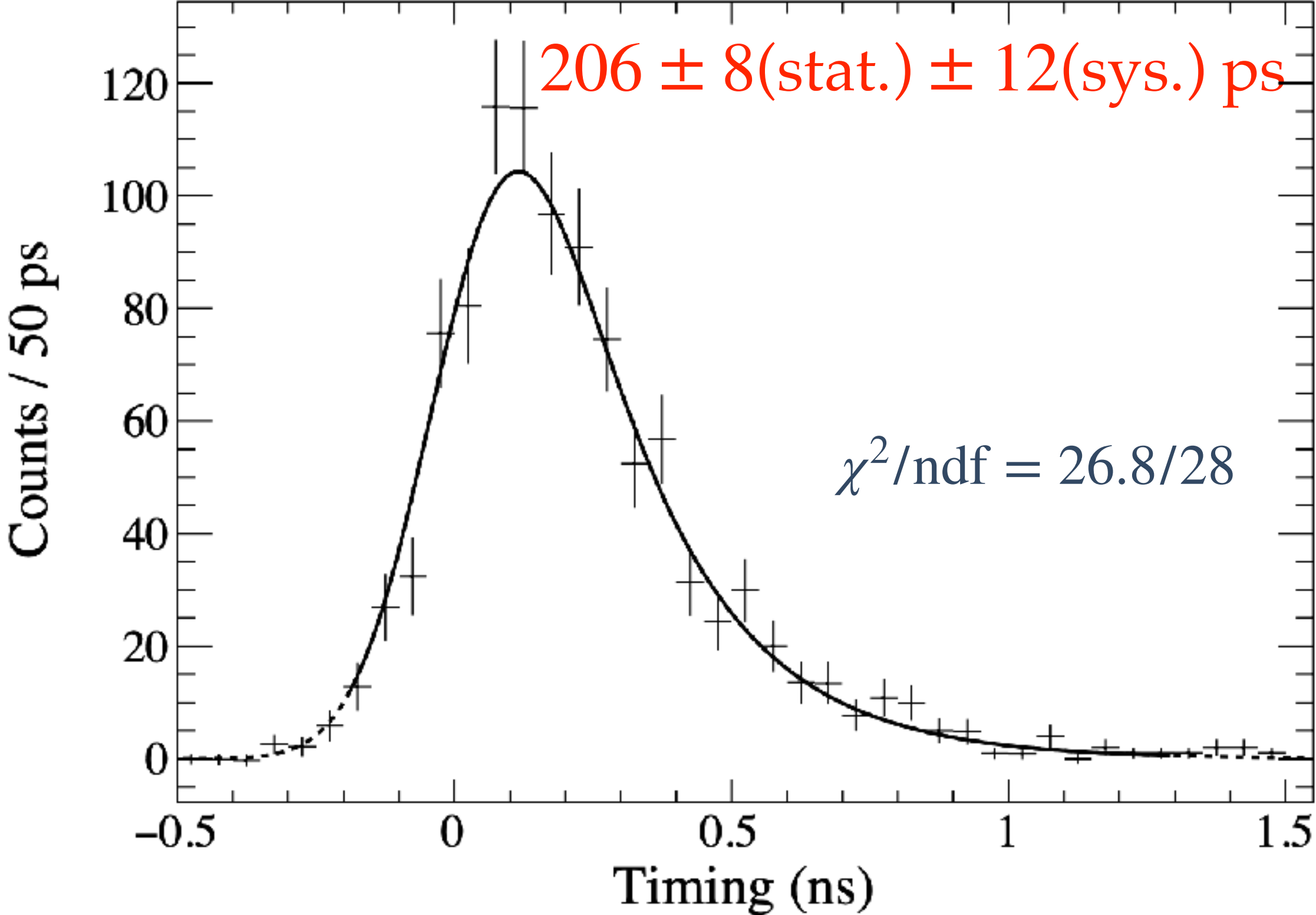
Systematic errors

Contribution	Value
Intrinsic bias of J-PARC T77 approach	± 2 ps
Uncertainty from γ selection	± 4 ps
Uncertainty of time calibration	± 7 ps
Uncertainty of background subtraction	± 5 ps
Uncertainty in fitting process	± 7 ps
Total (quadratic sum)	± 12 ps

(π^-, π^-) data for time-zero alignment



(K^-, π^-) data for H4L production



• Comparable precision with the latest STAR data $(218 \pm 6(\text{stat.}) \pm 13(\text{sys.}))$

Production cross sections & ${}^3_{\Lambda}\text{H}$ binding energy

What we directly measured

$$\sigma_{\Lambda}^{\theta_{\text{lab}}=0^\circ-20^\circ} \times Br_{2\text{-body}}({}^4_{\Lambda}\text{H}) = 25.3 \pm 1.1 \text{ (stat.) } {}^{+3.0}_{-3.2} \text{ (syst.) } \mu\text{b},$$

$$\sigma_{\Lambda}^{\theta_{\text{lab}}=0^\circ-20^\circ} \times Br_{2\text{-body}}({}^3_{\Lambda}\text{H}) = 3.5 \pm 0.6 \text{ (stat.) } {}^{+0.5}_{-0.6} \text{ (syst.) } \mu\text{b}.$$

<http://arxiv.org/abs/2509.16967>

R_3, R_4 from references

$$\sigma_{\Lambda}^{\theta_{\text{lab}}=0^\circ-20^\circ} = 49.9 \pm 2.1 \text{ (stat.) } {}^{+7.7}_{-8.0} \text{ (syst.) } \mu\text{b},$$

$$\sigma_{\Lambda}^{\theta_{\text{lab}}=0^\circ-20^\circ} = 15.0 \pm 2.6 \text{ (stat.) } {}^{+2.4}_{-2.8} \text{ (syst.) } \mu\text{b},$$

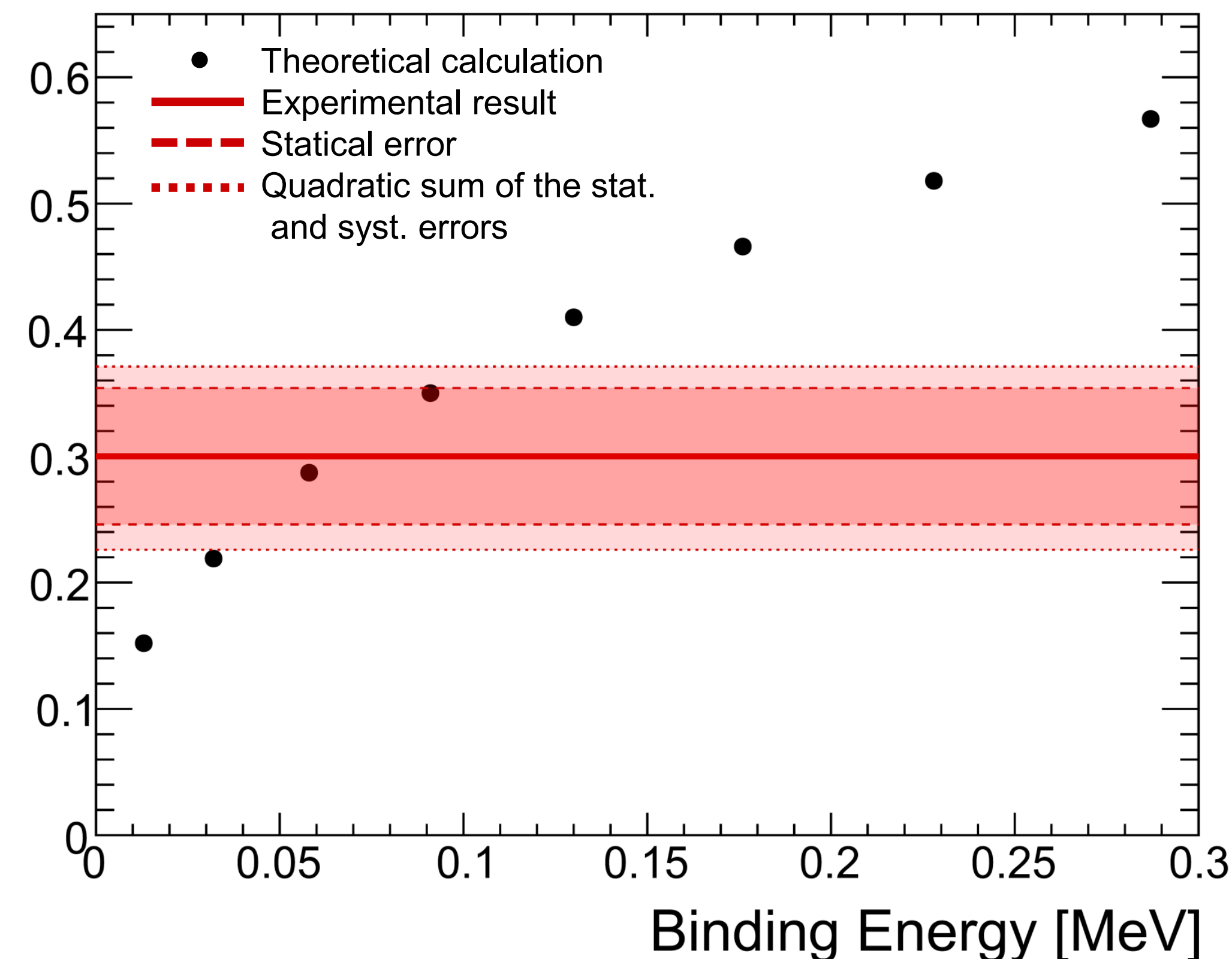
$$R_{34} = 0.300 \pm 0.054 \text{ (stat.) } {}^{+0.047}_{-0.051} \text{ (syst.)},$$

DWIA calc.

Harada, et al.,
NPA1015, 122301 (2021)

$$B_{\Lambda} = 0.063 {}^{+0.029}_{-0.023} \text{ (stat.) } {}^{+0.025}_{-0.021} \text{ (syst.) MeV},$$

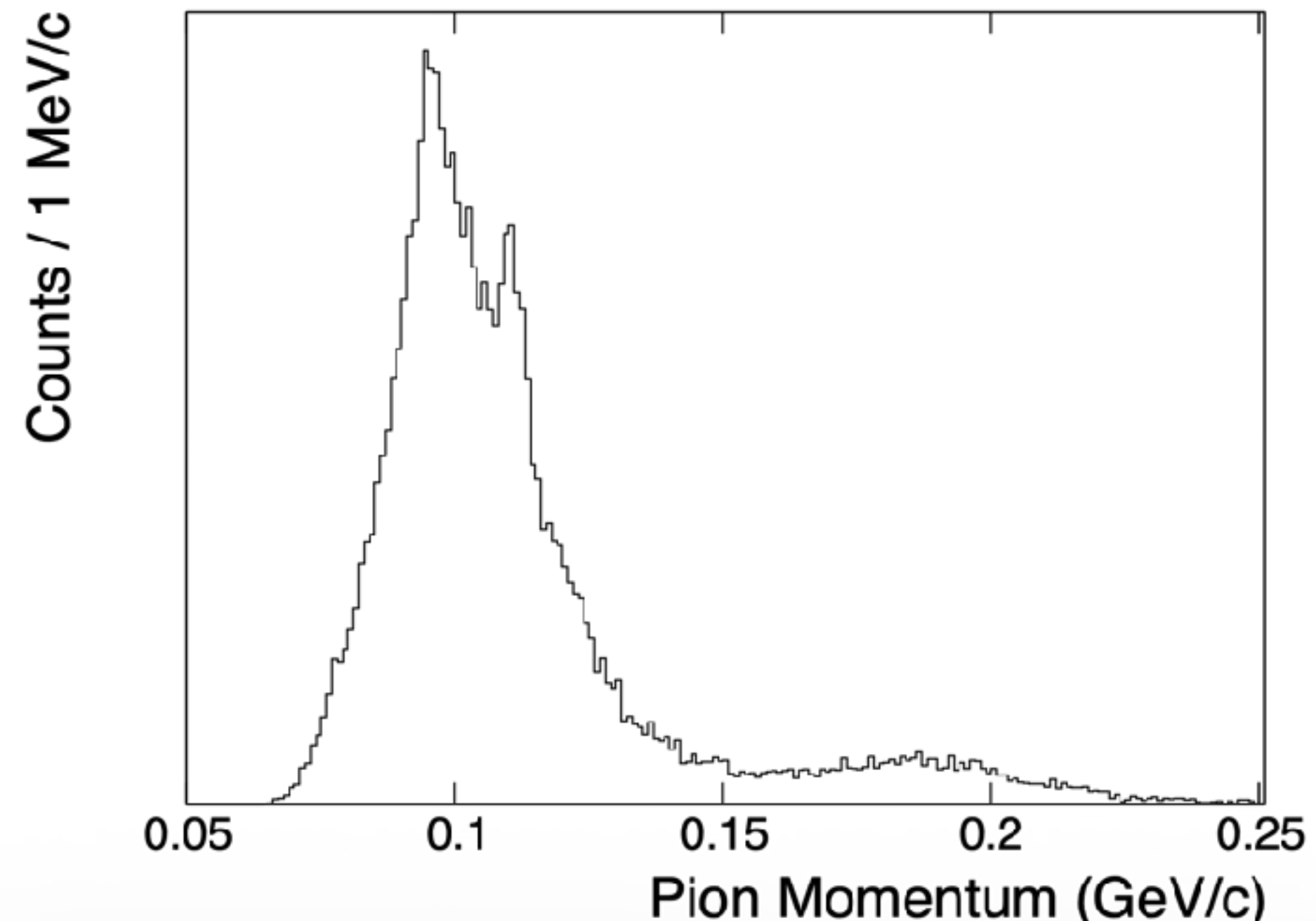
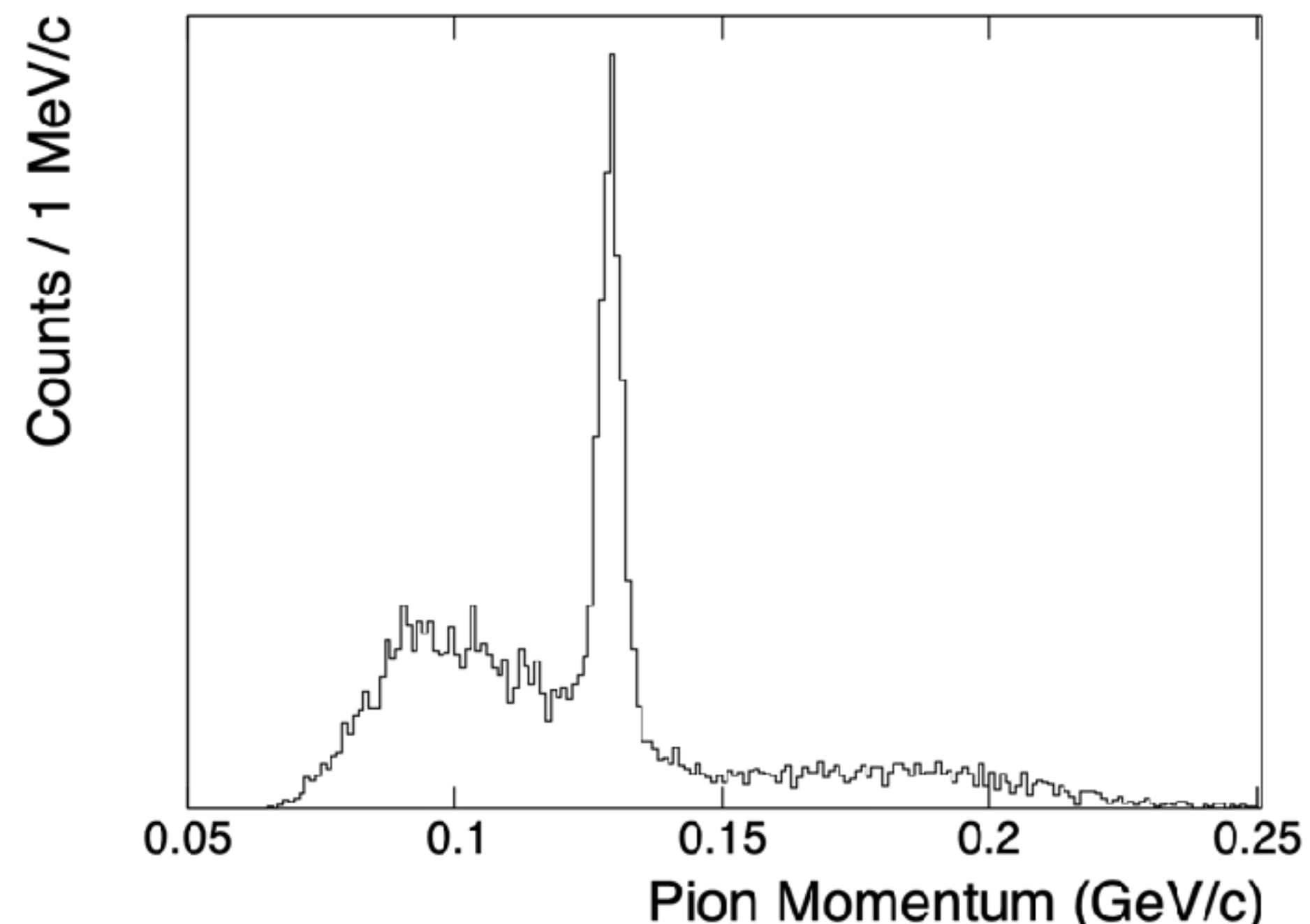
R_{34}



- Sizable production cross section for ${}^3_{\Lambda}\text{H}$ supports for $J^P = 1/2^+$
- Cross section ratio ${}^3_{\Lambda}\text{H}/{}^4_{\Lambda}\text{H}$ imply shallow bininding of ${}^3_{\Lambda}\text{H} \sim 100 \text{ keV}$

Latest dataset for hypertriton lifetime

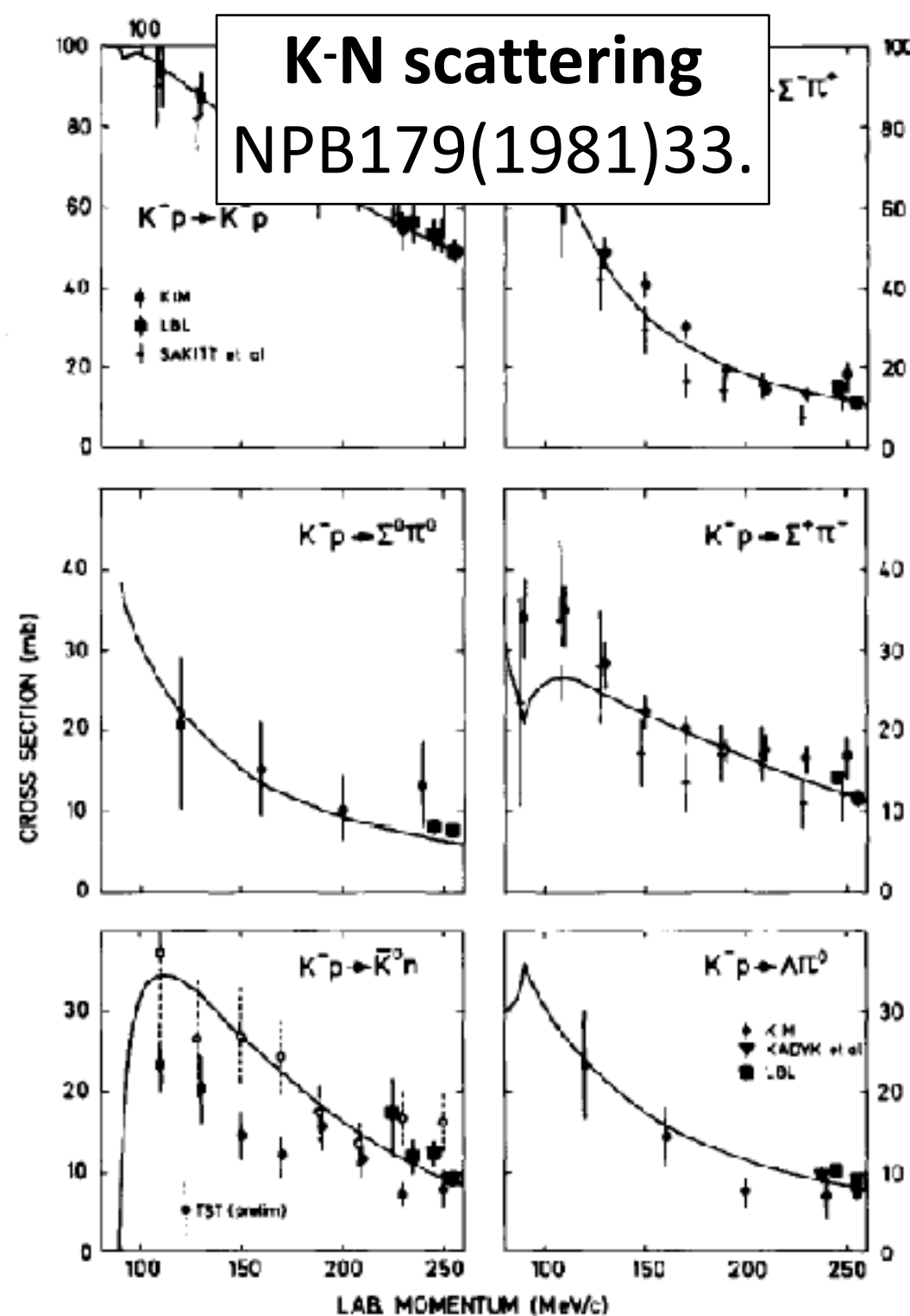
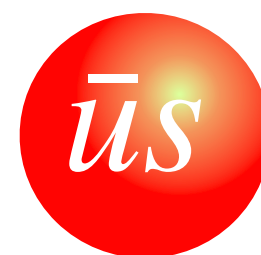
Data-taking completed in 2025



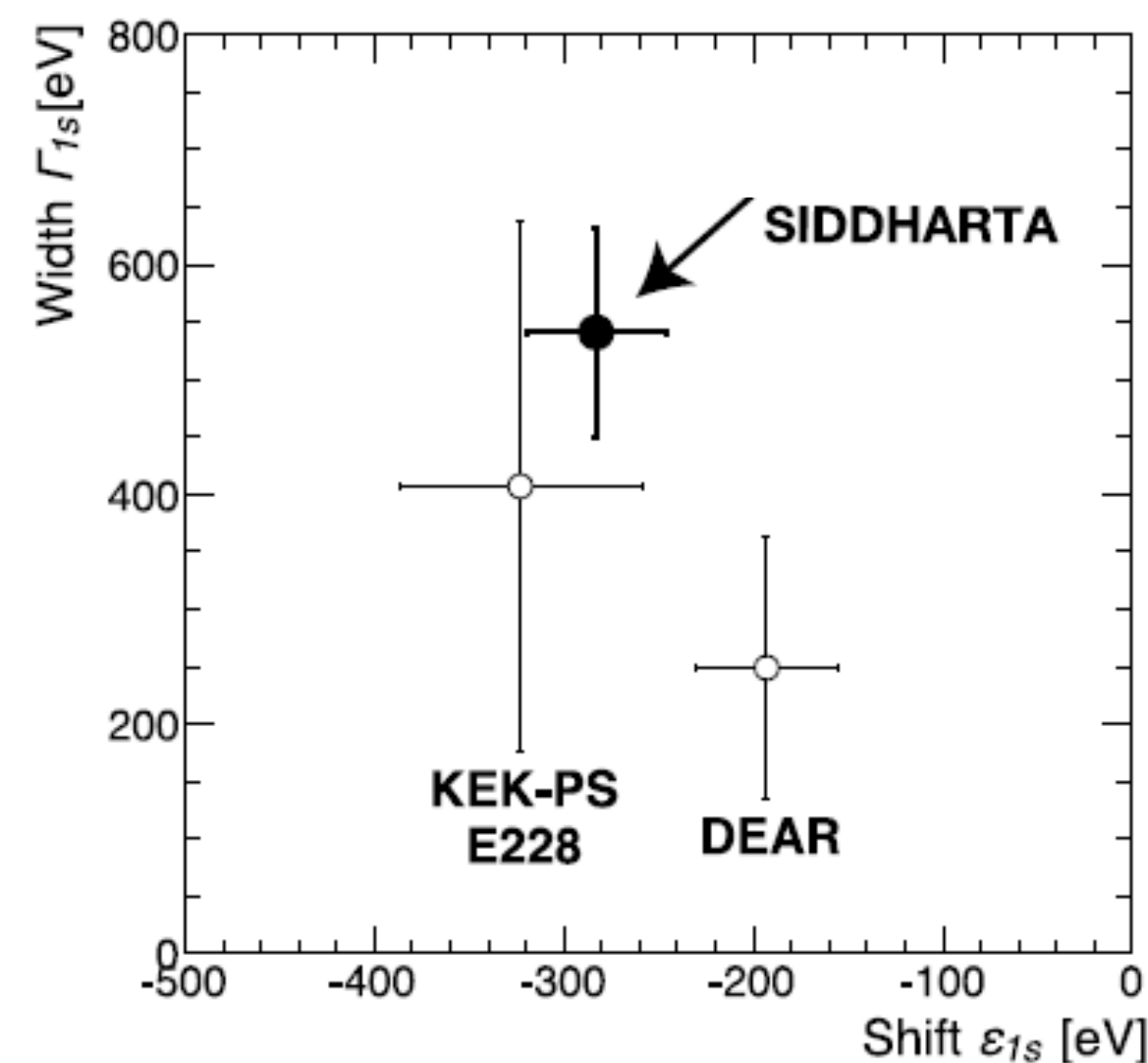
- ^4He target as calibration data demonstrates the consistency across different data taking periods
- ^3He data shows ~ 1000 two-body decay signal events as proposed. Further improvement is expected by optimizing tracking and cutting conditions.

Kaonic nuclei

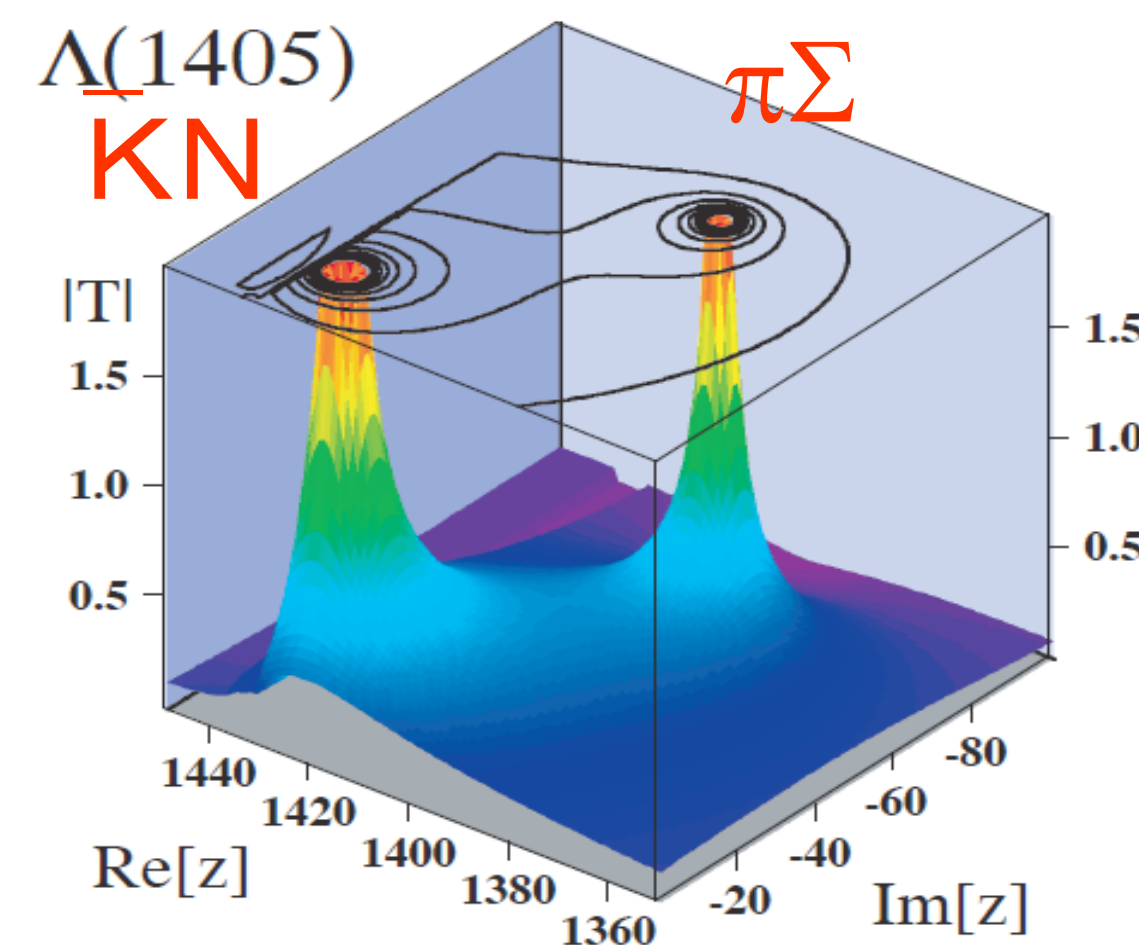
$\bar{K}N$ interaction



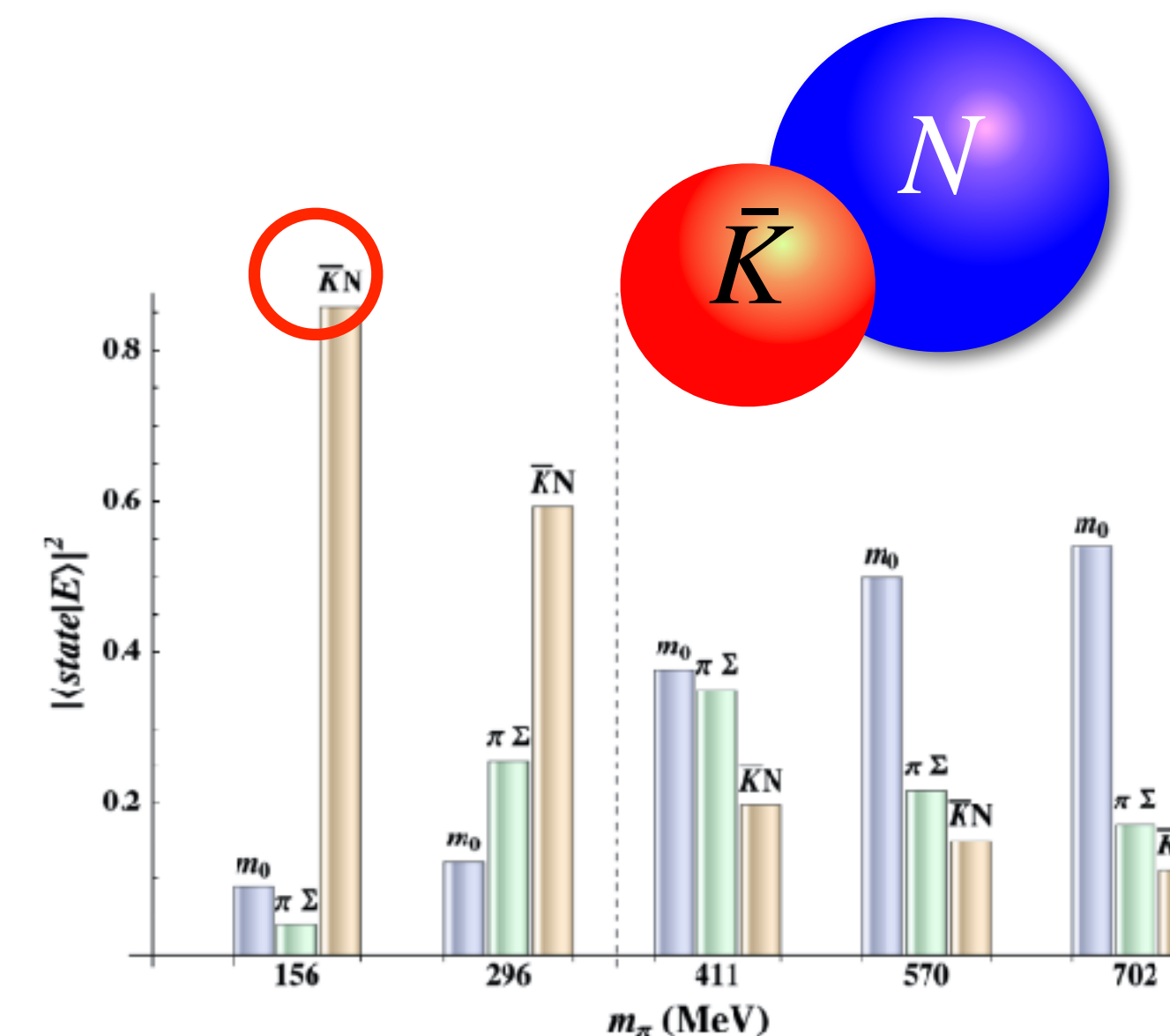
K-p atom
PLB704(2011)113.



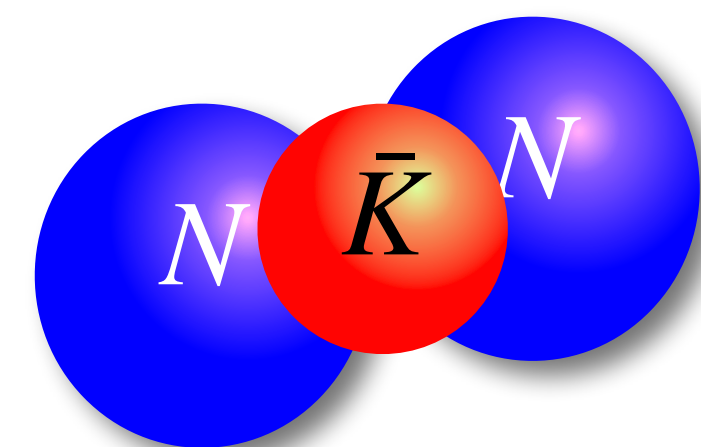
$\Lambda(1405)$ in
chiral unitary model
T. Hyodo



$\bar{K}N$ molecule from **Lattice QCD**
PRL114(2015)132002.



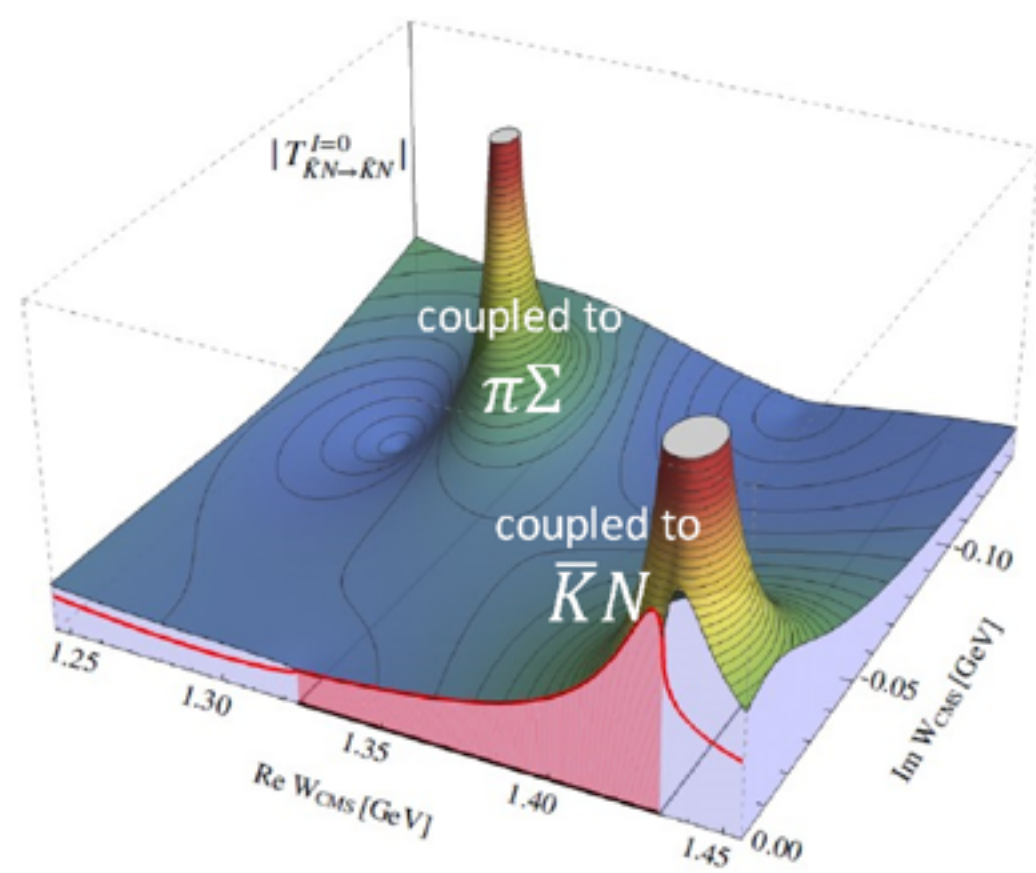
- Strong attraction in $l=0$ from scattering and X-ray experiments.
- $\Lambda(1405) = \bar{K}N$ molecule picture is now widely accepted
- Why not kaonic nucleus with additional nucleons?



Theoretical calculations of $\bar{K}NN$ $I(J^P) = \frac{1}{2}(0^-)$

Chiral unitary model
(energy dependent)

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

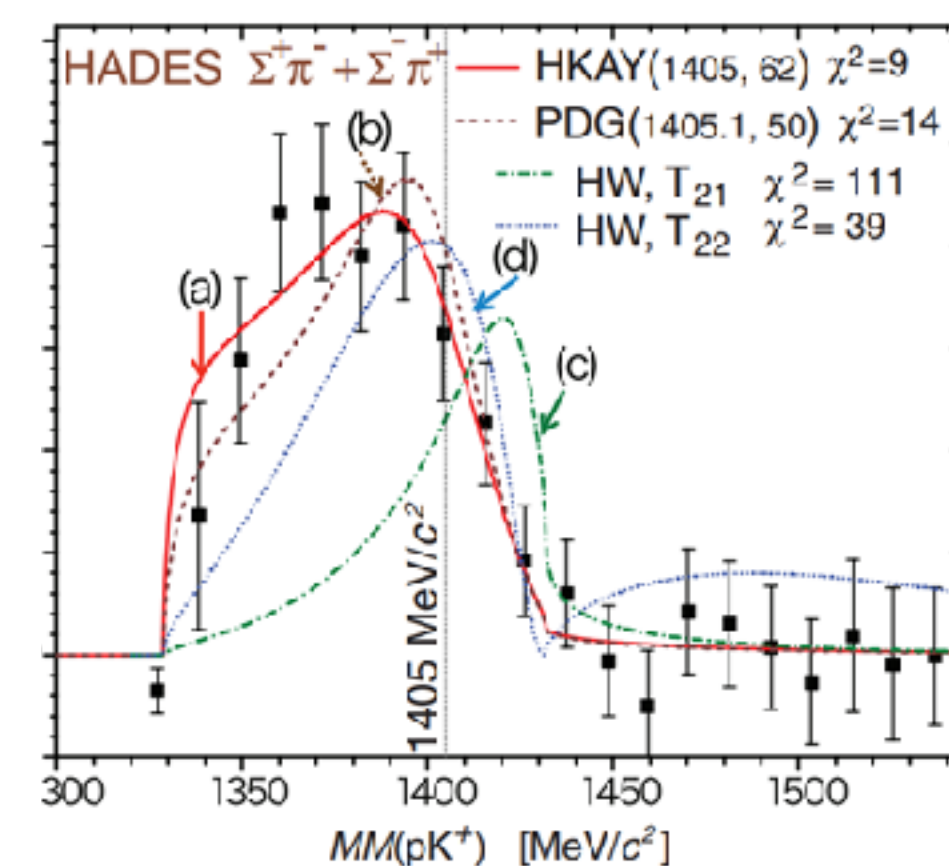


shallow $\bar{K}N$ potential

B.E. $\sim 10-30$ MeV

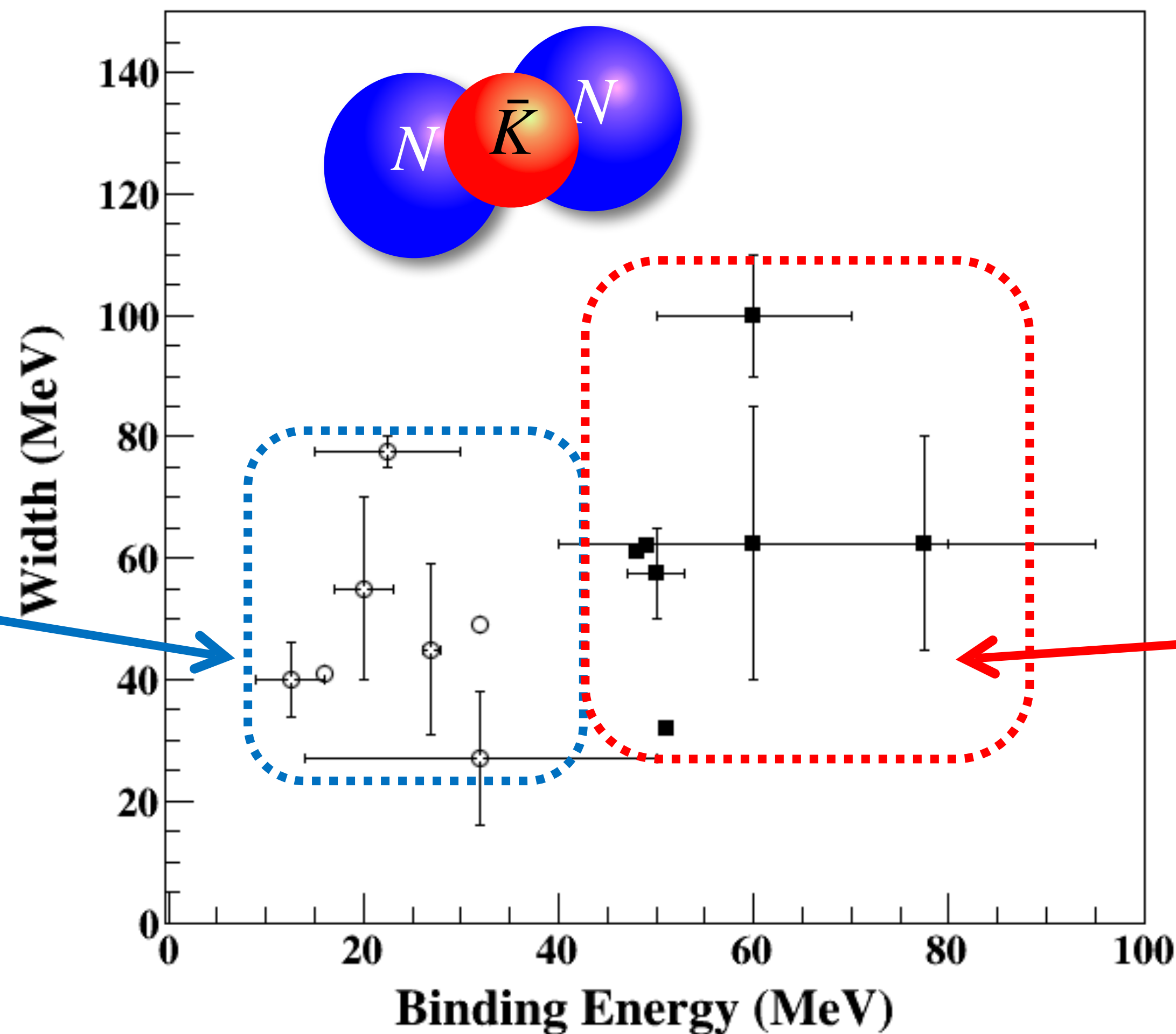
Phenomenological model
(energy independent)

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



deep $\bar{K}N$ potential

B.E. $\sim 40-70$ MeV
suggesting a more compact
and dense system

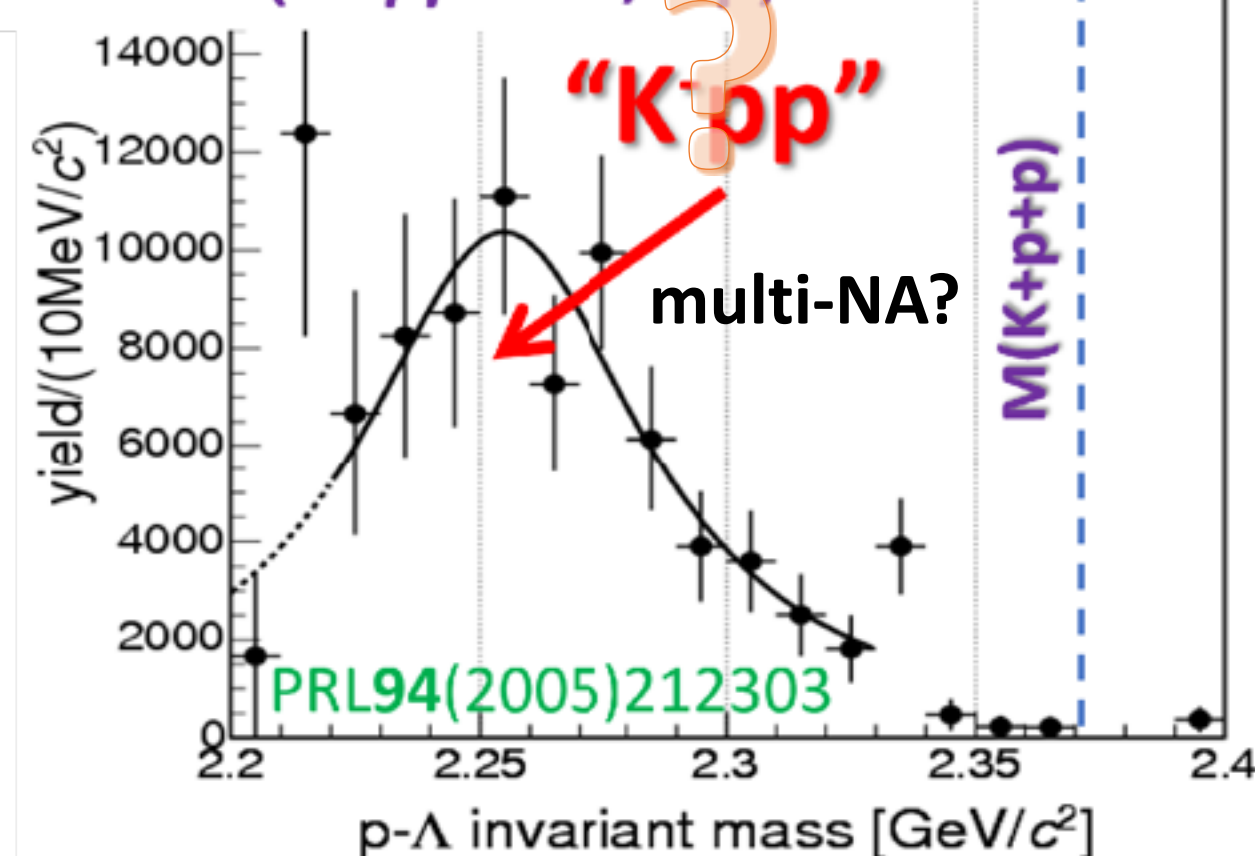


- $\bar{K}NN$ should exist. Then, how to produce and observe it?

“K-pp” searches

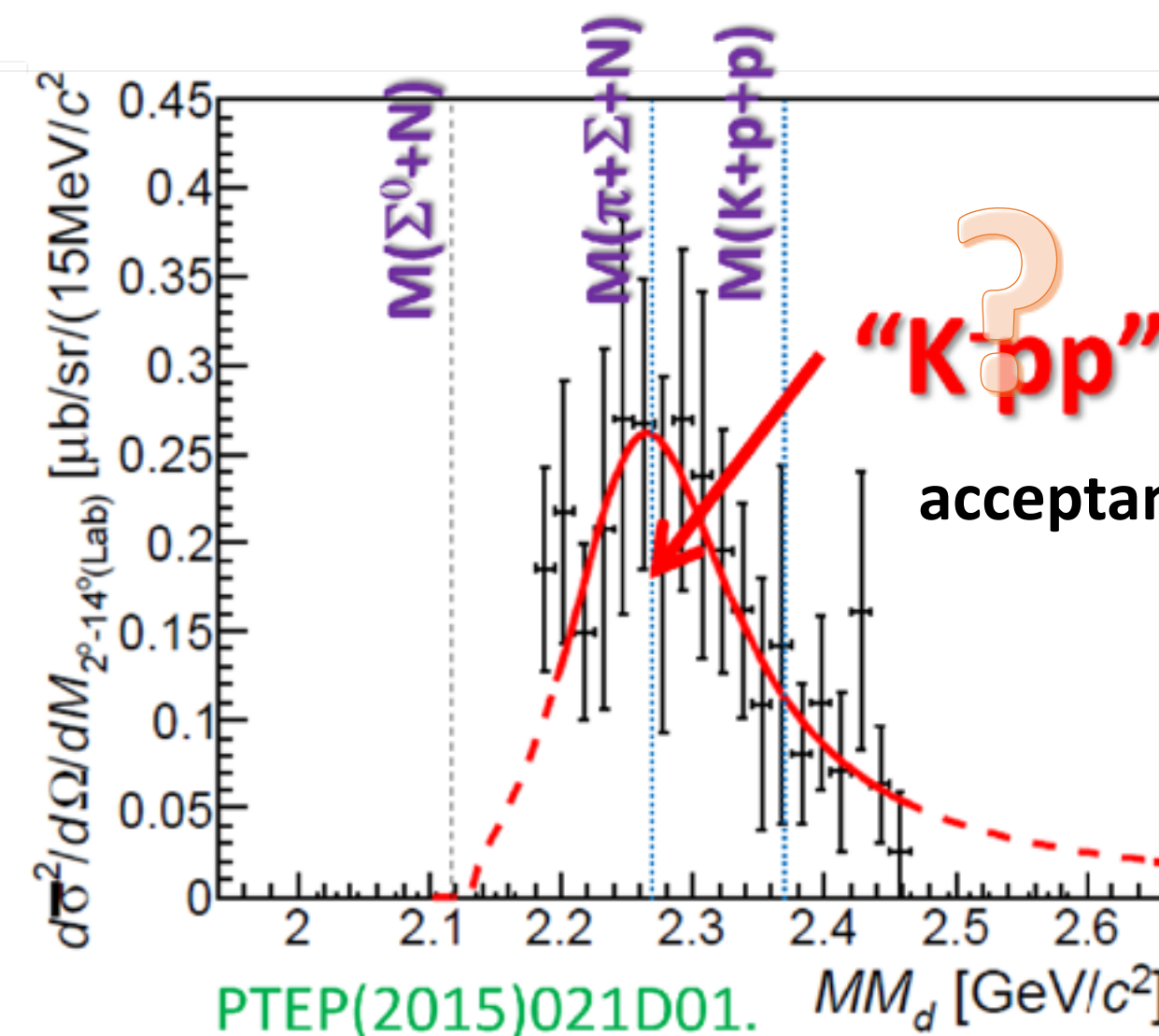
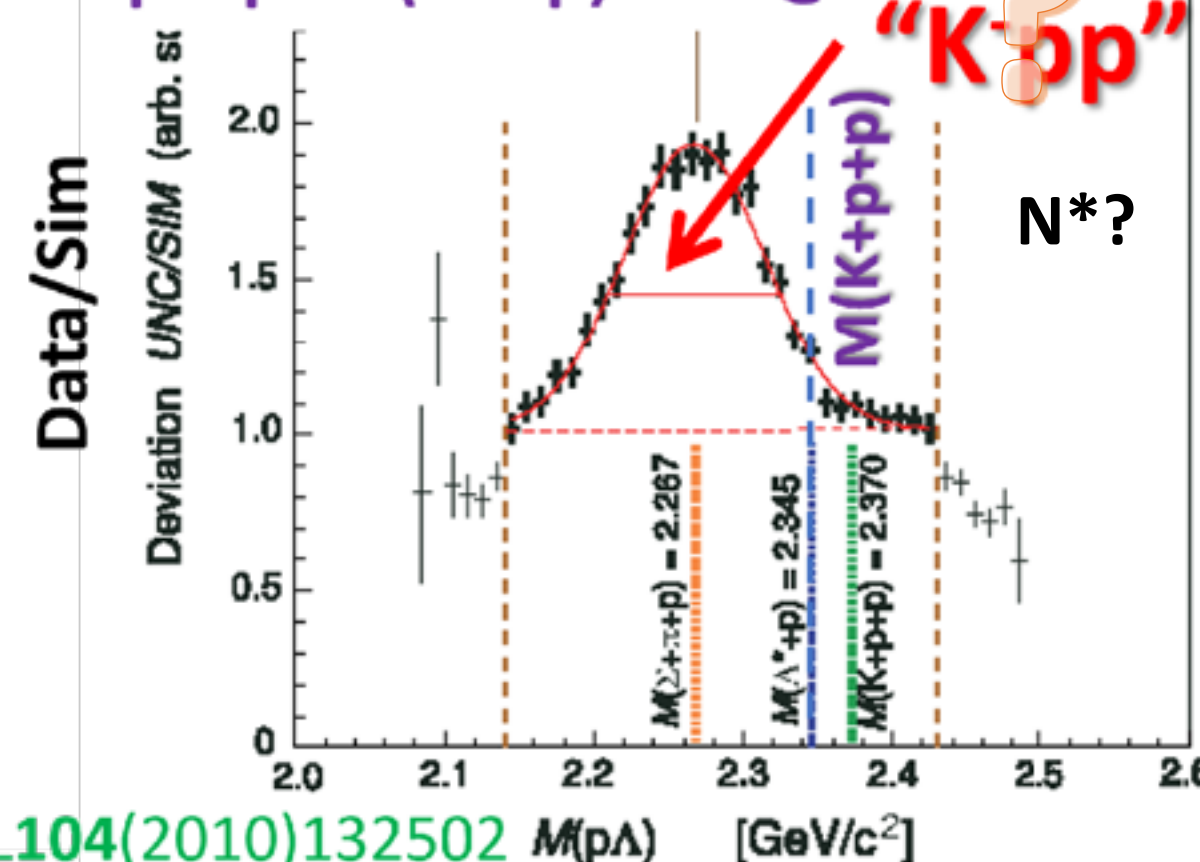
FINUDA@DAΦNE

${}^6\text{Li}+{}^7\text{Li}+{}^{12}\text{C}(\text{stopped } K^-, \Lambda p)$



DISTO@SATURNE

$p + p \rightarrow (\Lambda + p) + K^+ @ 2.85 \text{ GeV}$



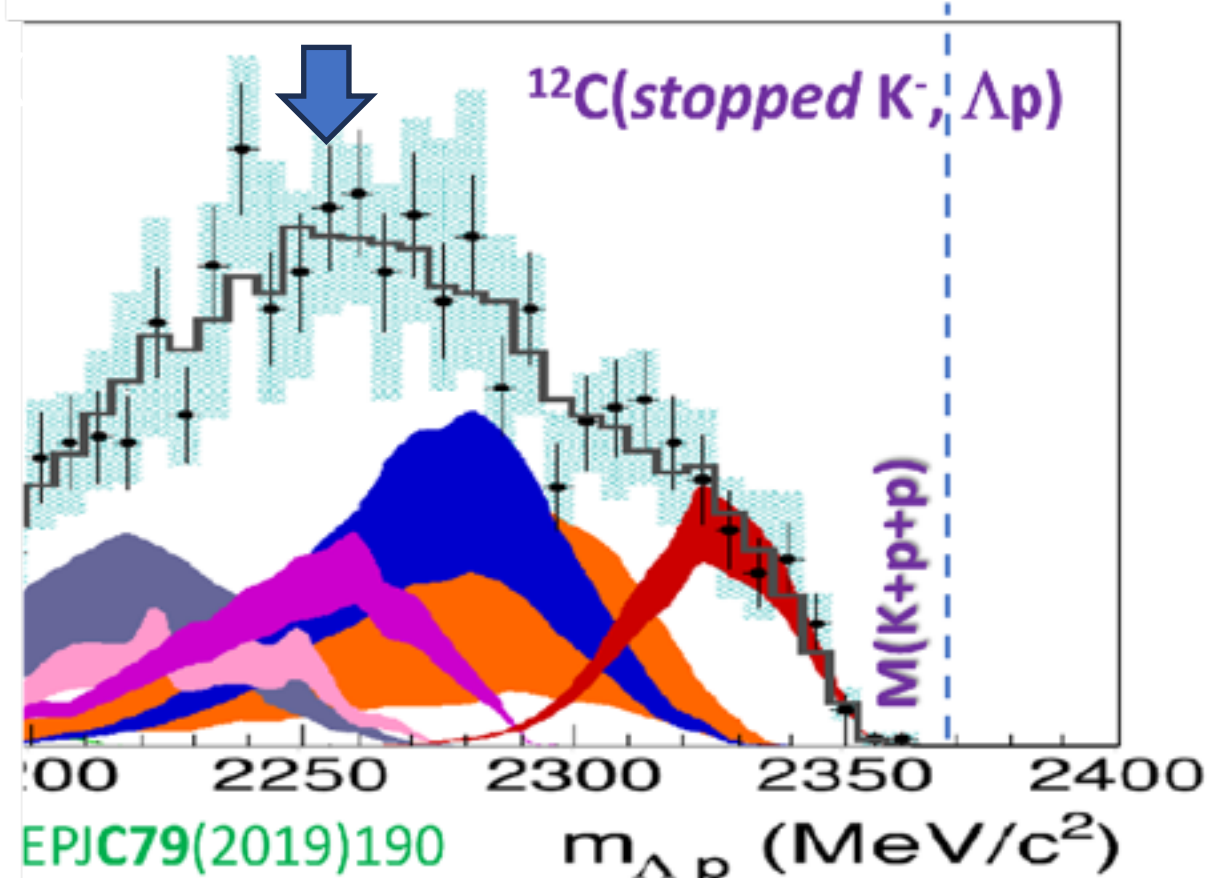
E27@J-PARC

$d(\pi^+, K^+)\Sigma^0 p @ 1.69 \text{ GeV/c}$

LEPS@SPring-8

$d(\gamma, K^+\pi^-)X @ 1.3\text{-}2.4 \text{ GeV/c}$
PLB728(2014)616.

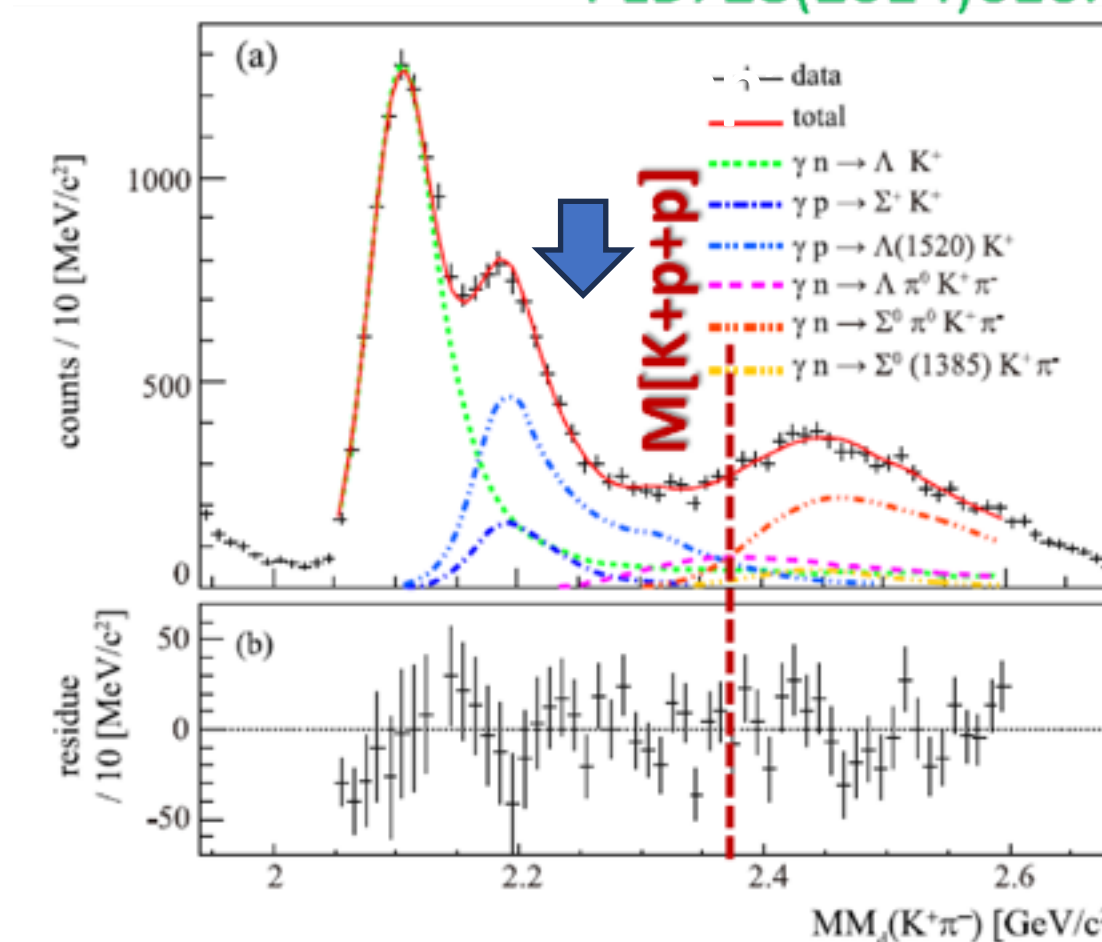
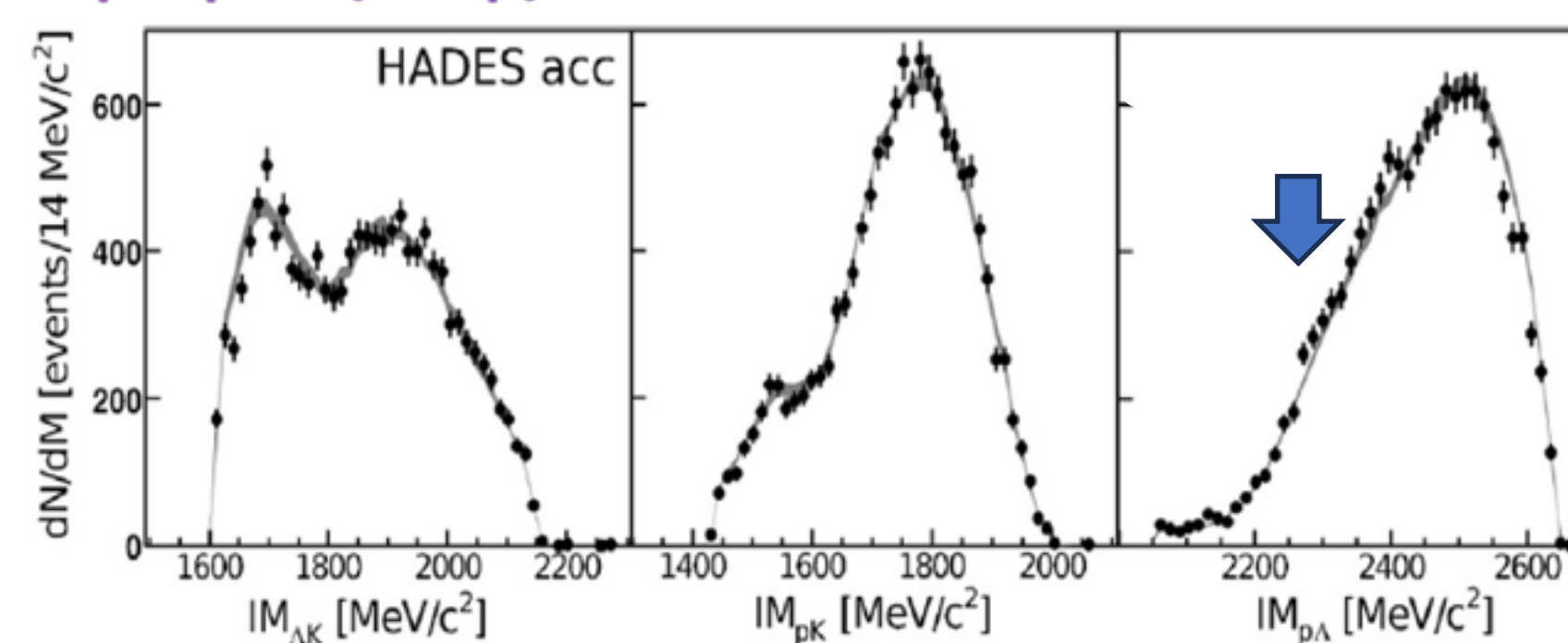
AMADEUS@DAΦNE



HADES@GSI

PLB742(2015)242

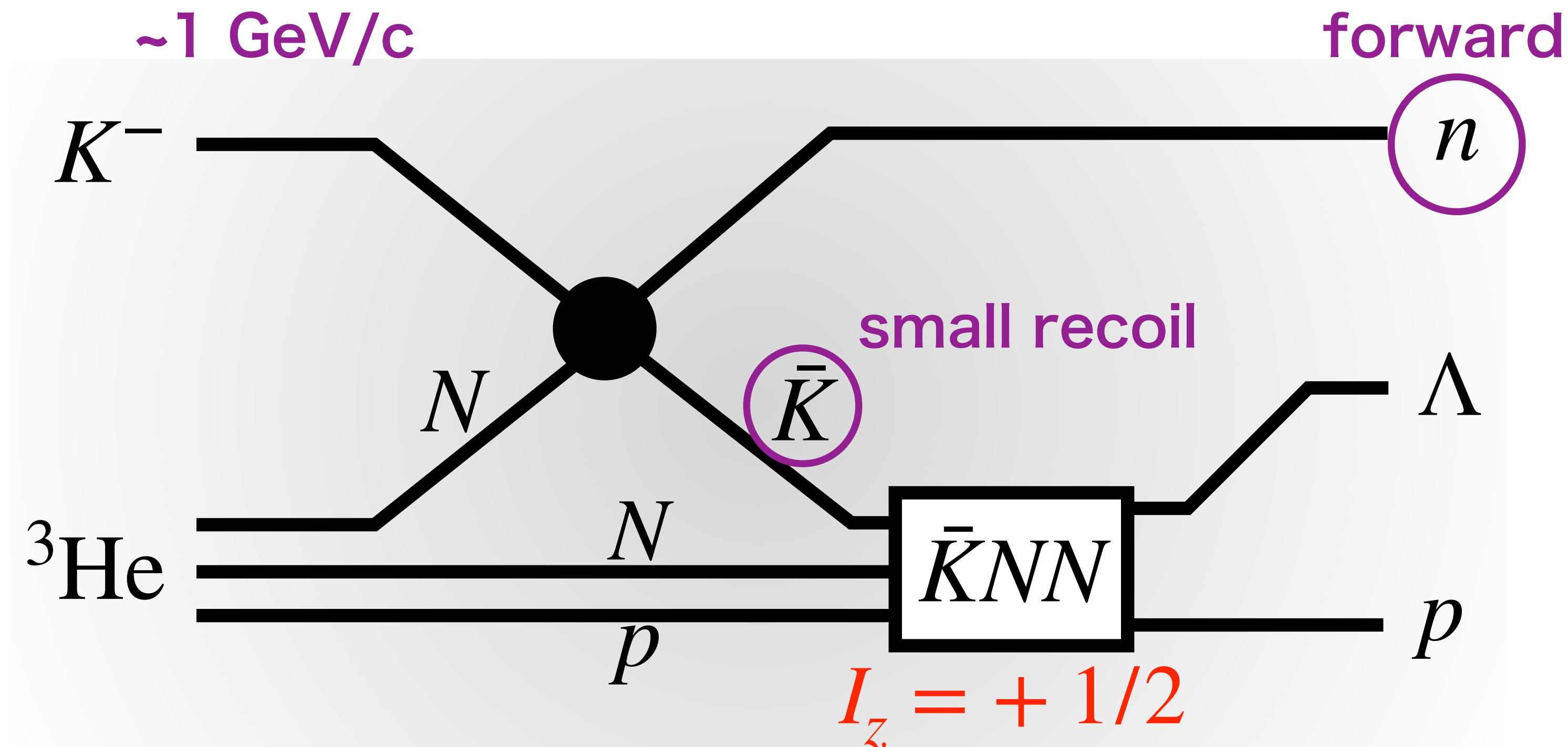
$p + p \rightarrow (\Lambda + p) + K^+ @ 3.5 \text{ GeV}$



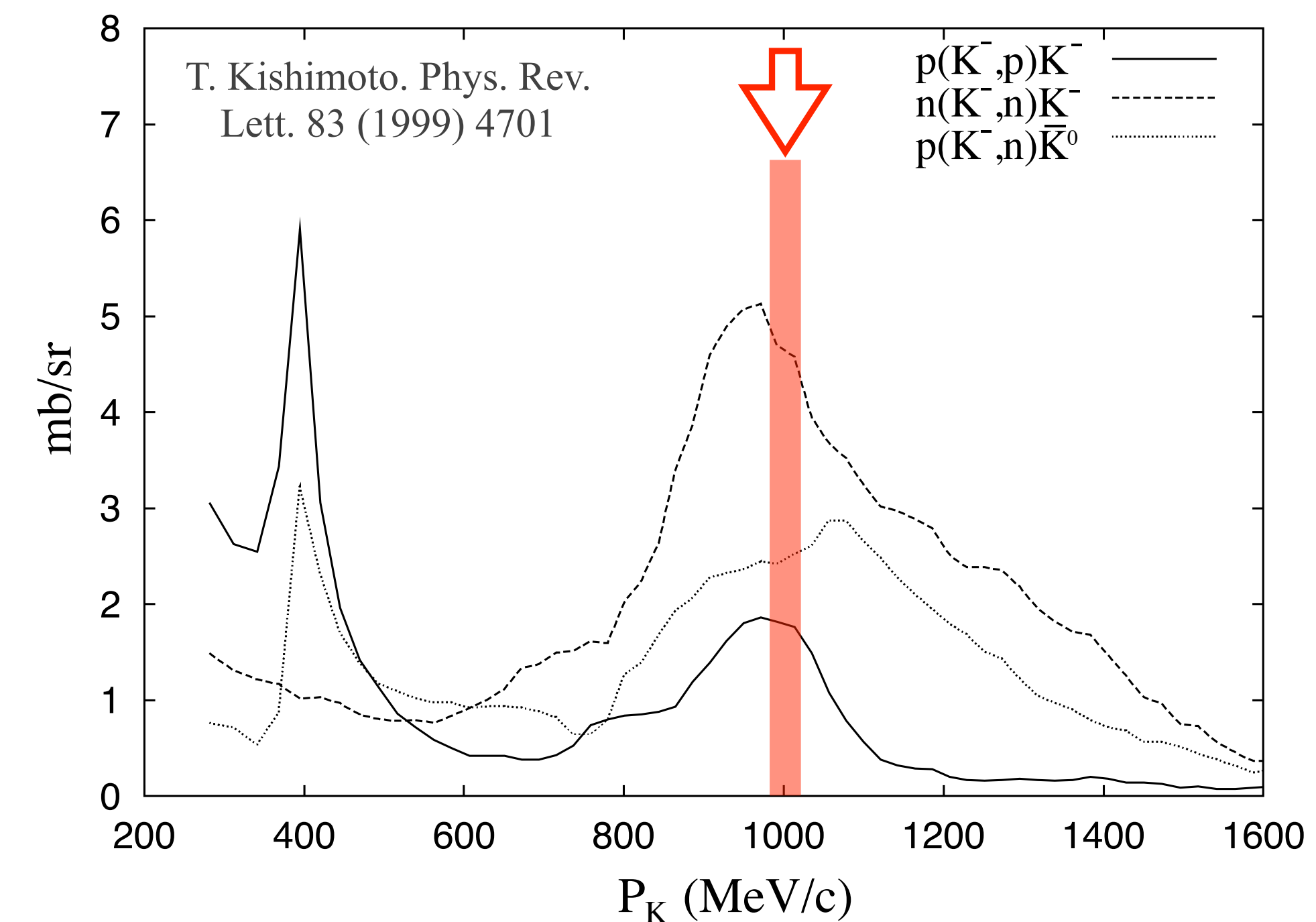
- No conclusive result because of complex reactions & background...

Our approach: in-flight (K^- , n) reaction

T. Kishimoto, Phys. Rev. Lett. **83**, 4701 (1999).

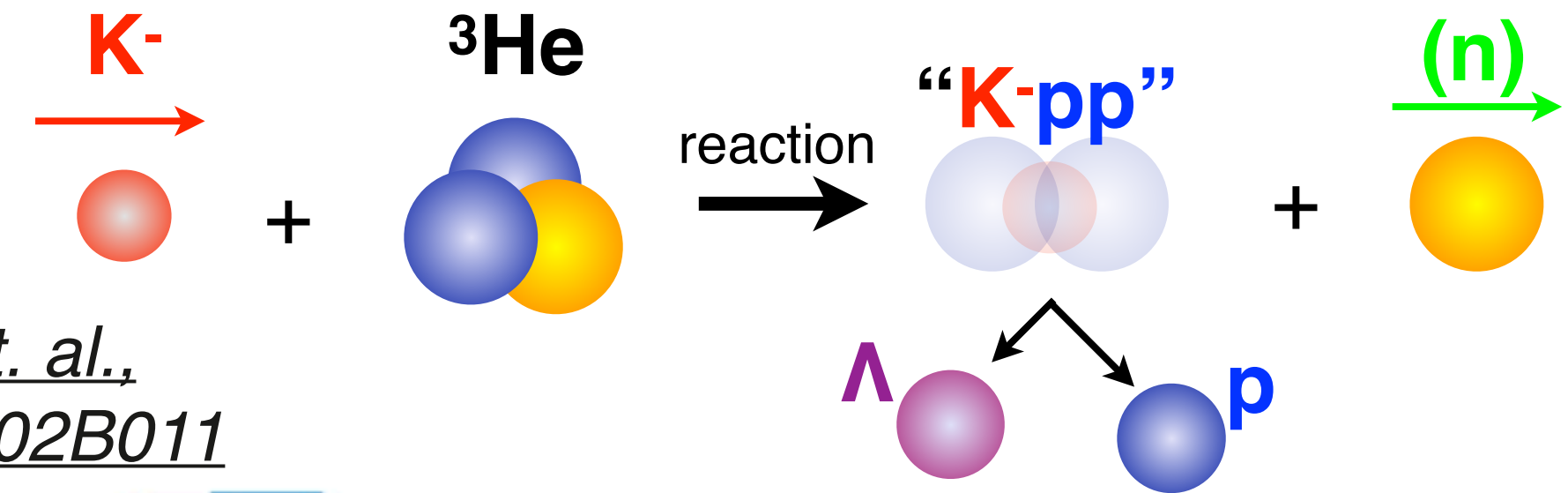


K-N elementary cross-sections

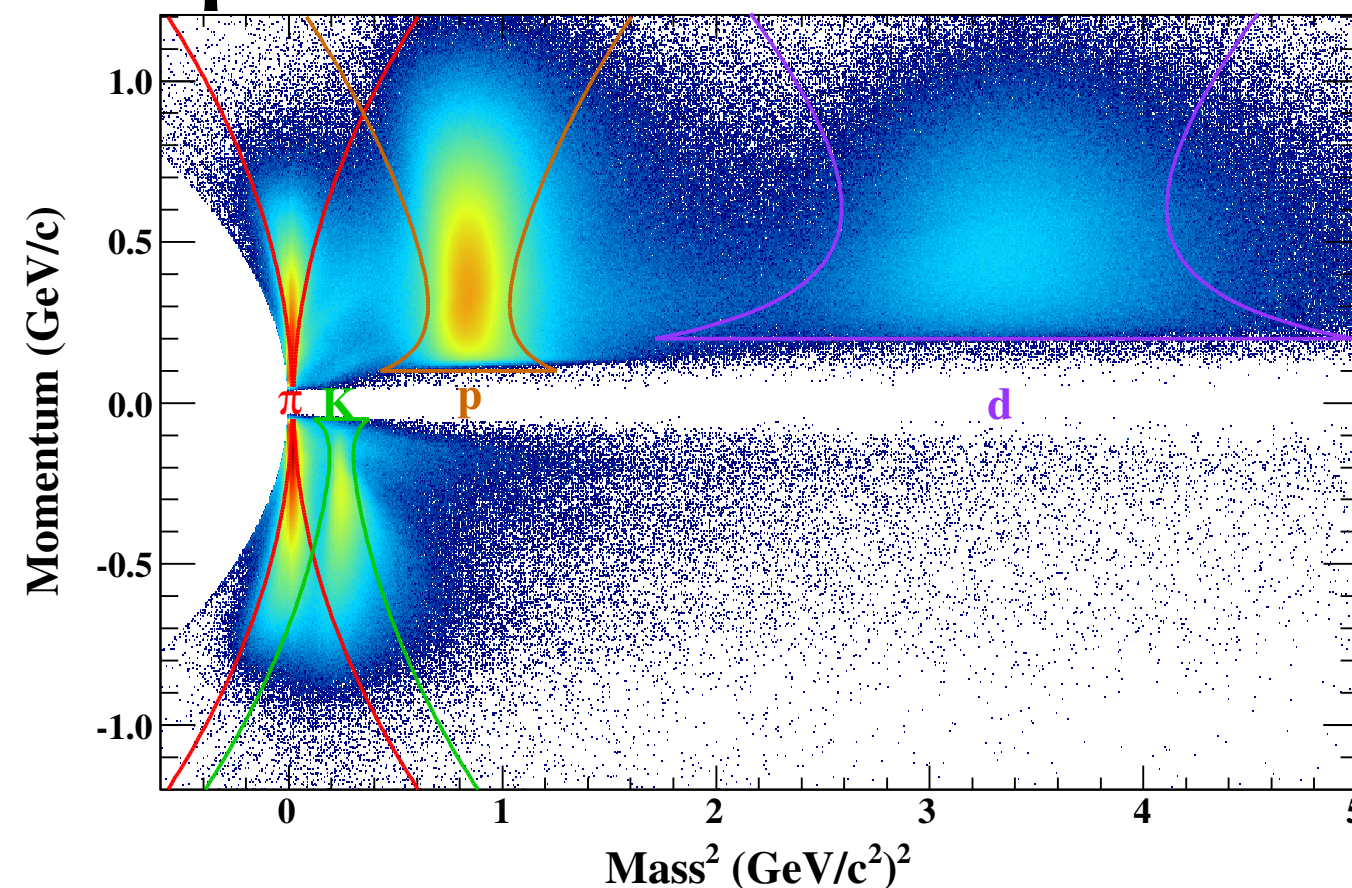


- ✓ Efficiently produce sub-threshold virtual $\bar{K}$
- ✓ Simplest target allows an exclusive analysis
- ✓ Large-acceptance detector to cover a wide range of kinematical region

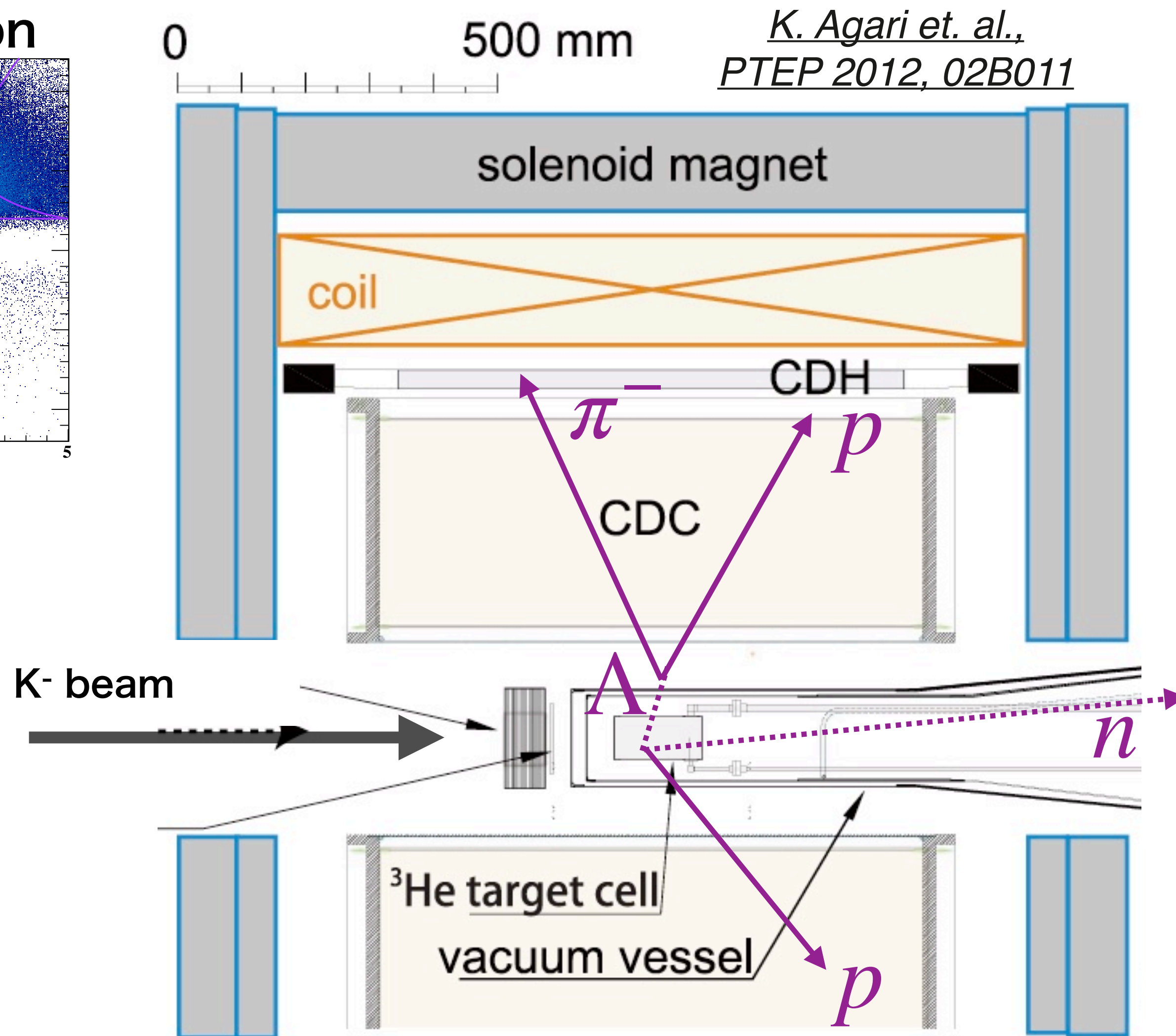
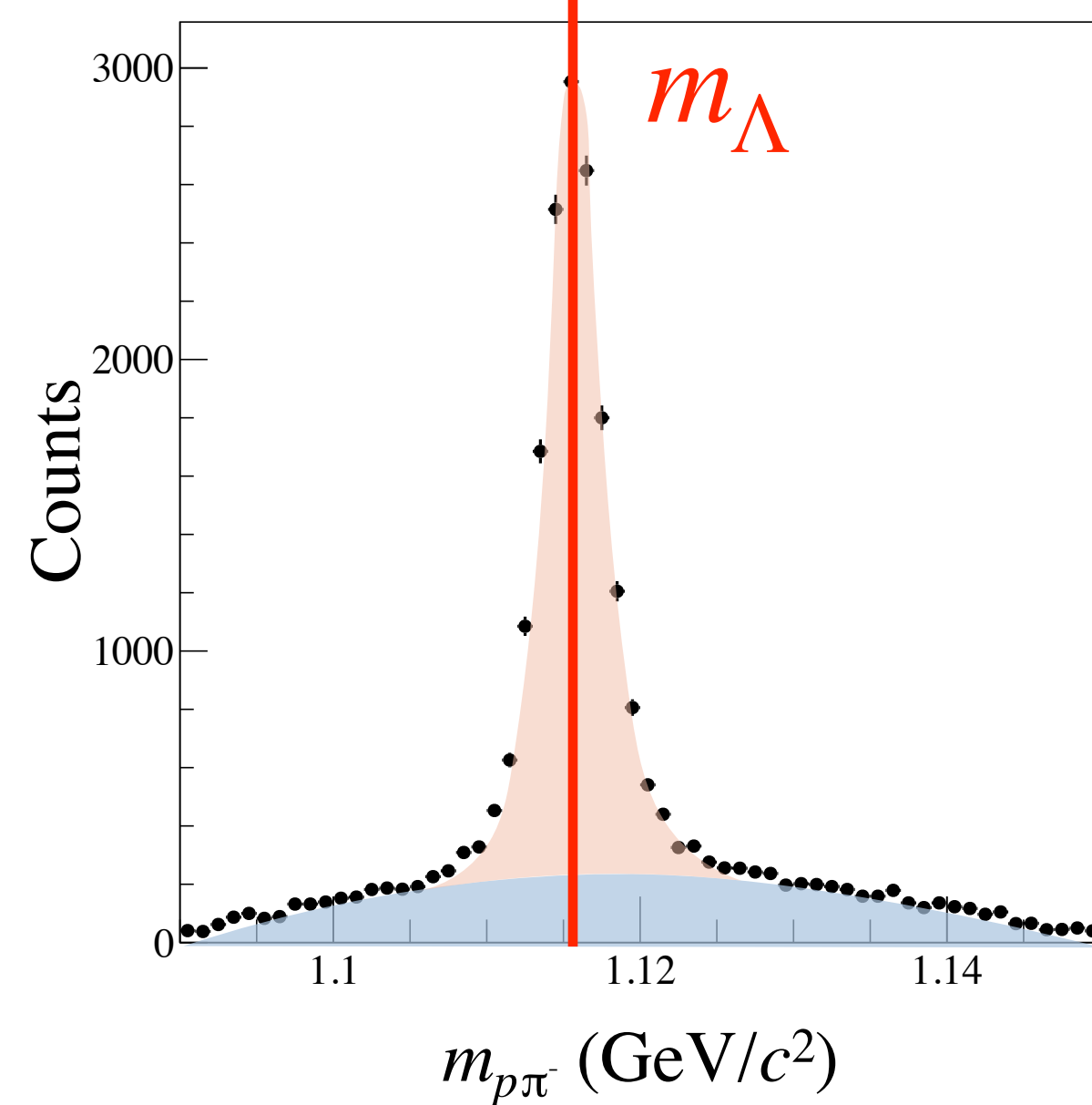
Λpn Exclusive measurement



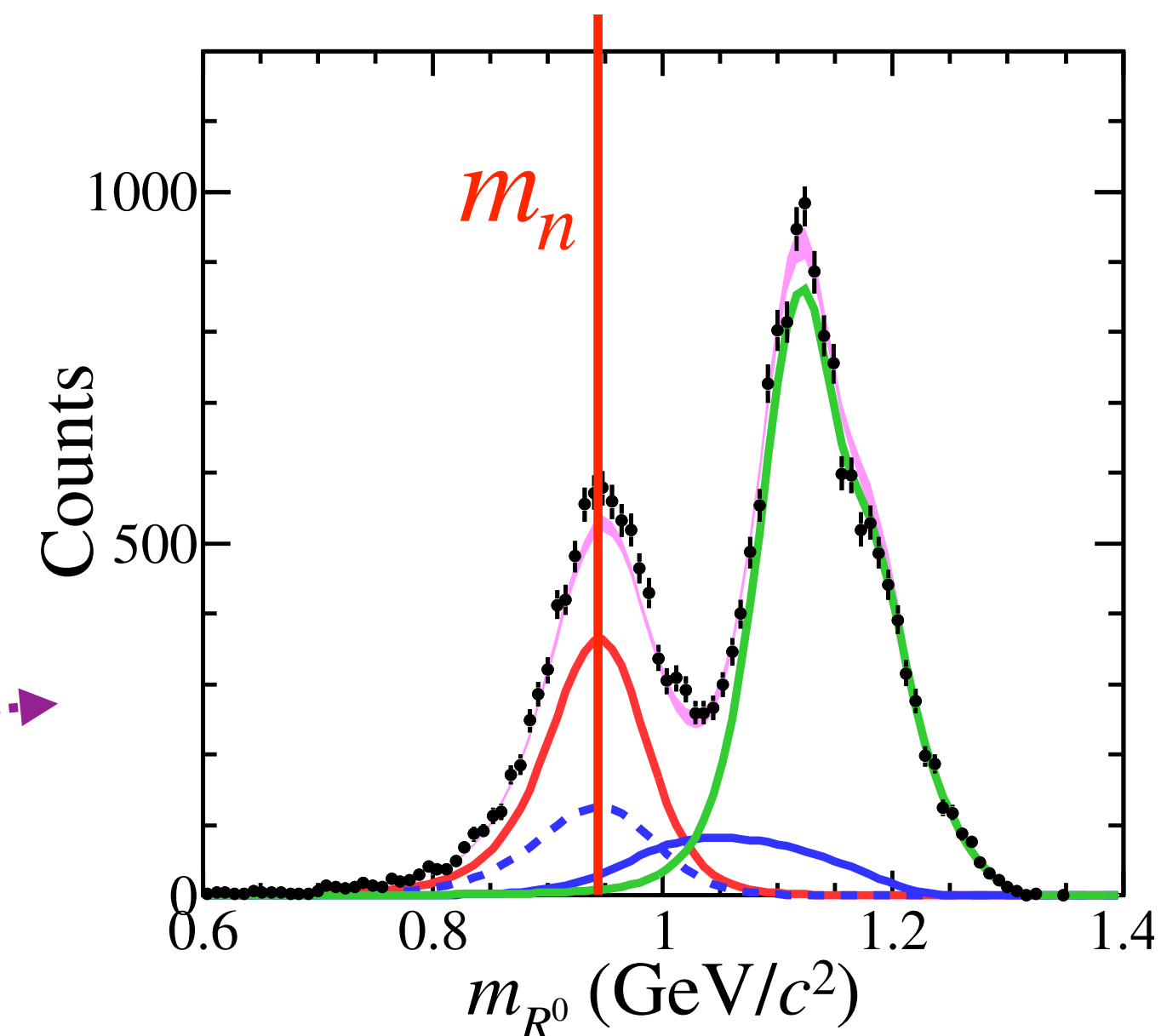
particle identification



Λ reconstruction



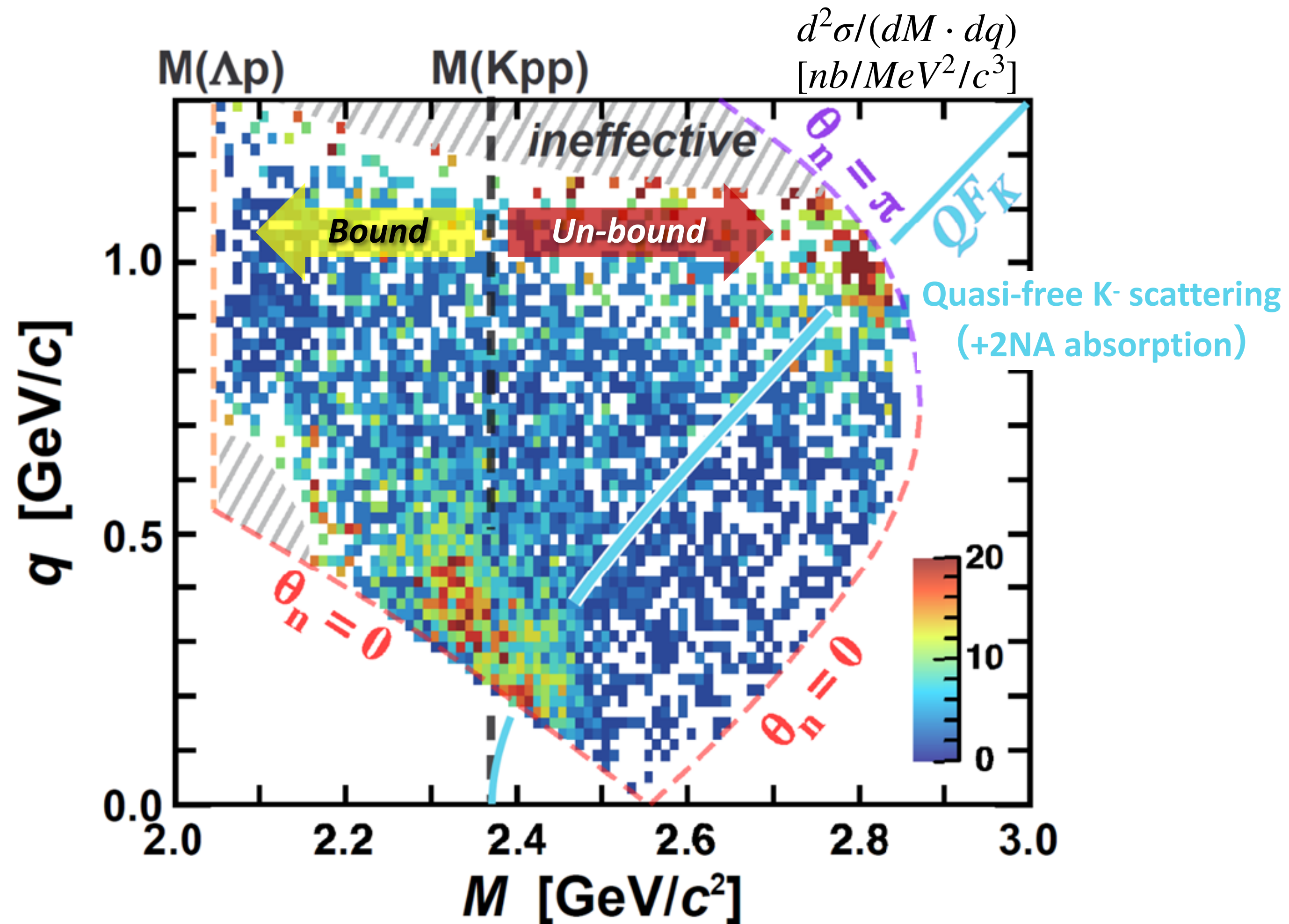
missing neutron selection



Purity of Λpn events $\sim 80\%$

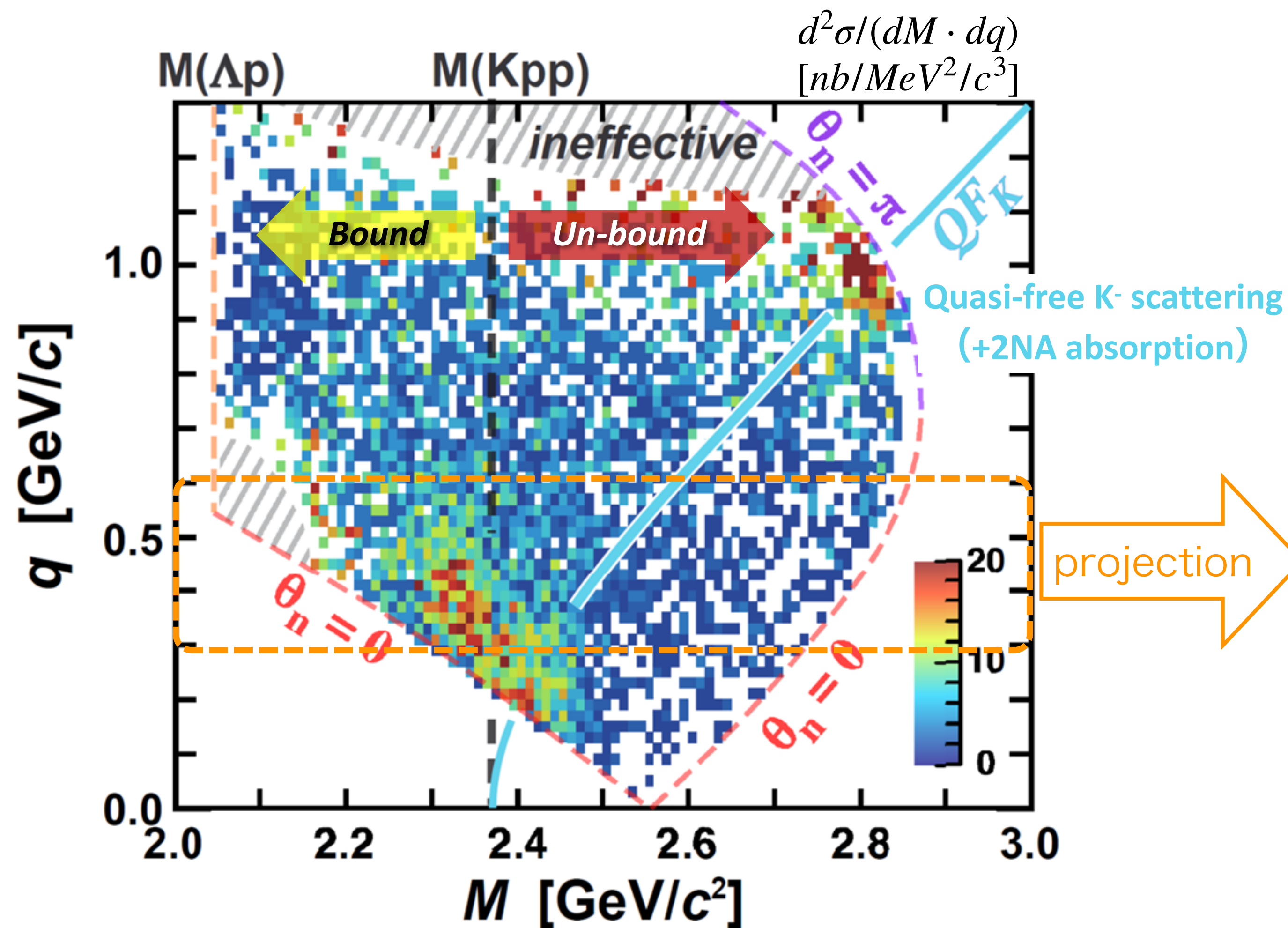
“K-pp” observation in J-PARC E15

PLB789(2019)620., PRC102(2020)044002.



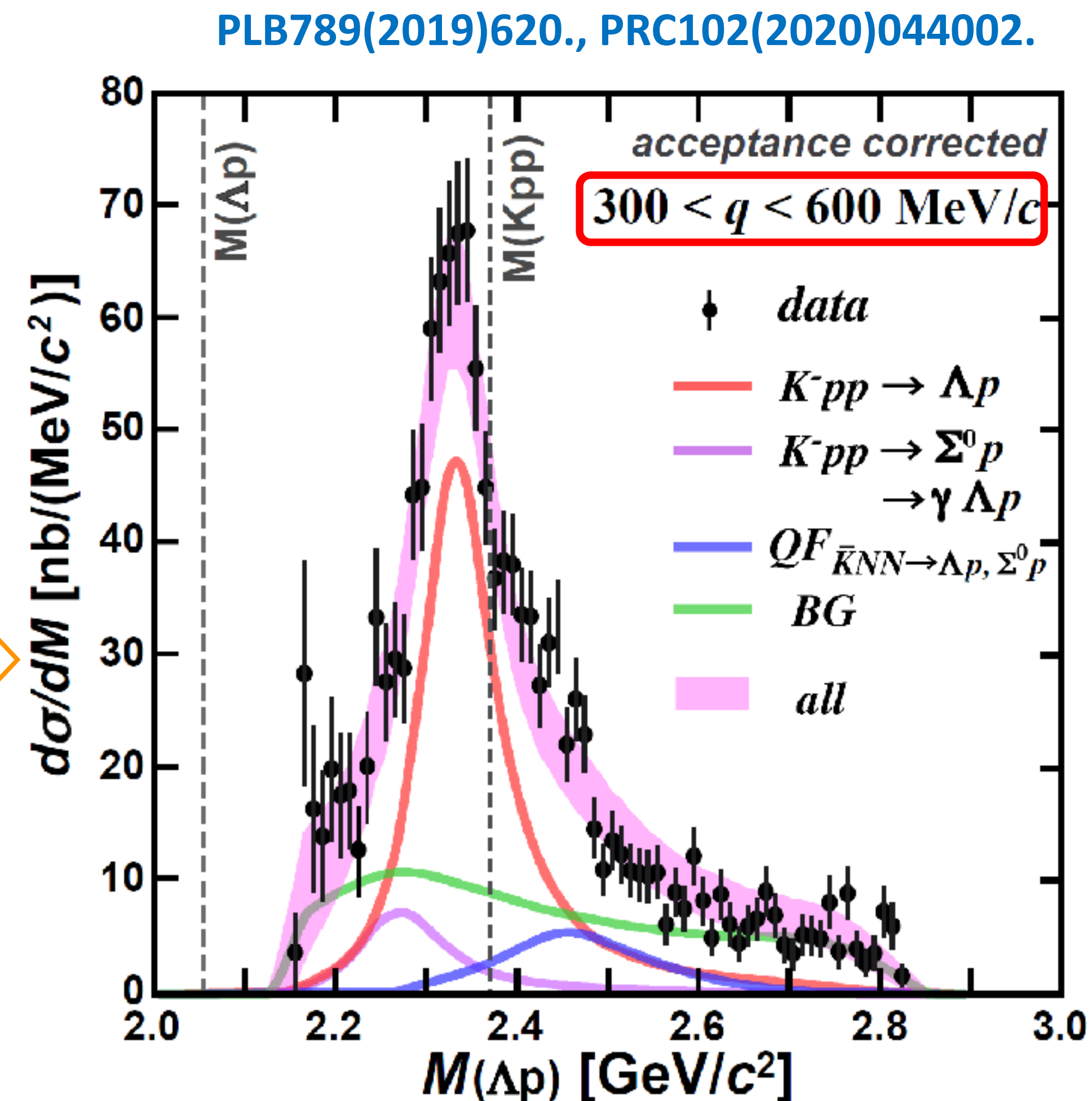
q : (K-,n) momentum transfer, M : Λp invariant mass

“K-pp” observation in J-PARC E15



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

projection

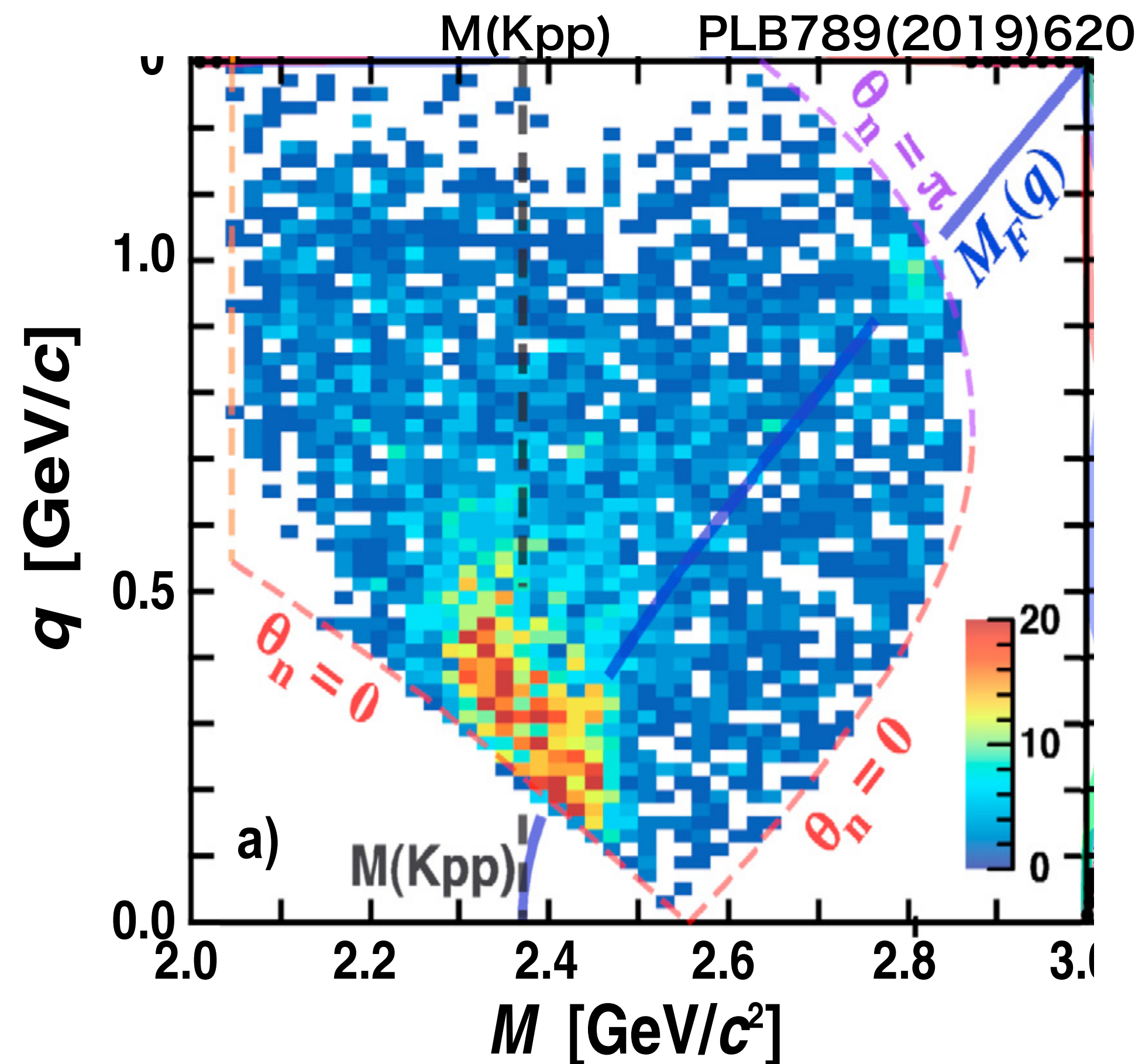


PLB789(2019)620., PRC102(2020)044002.

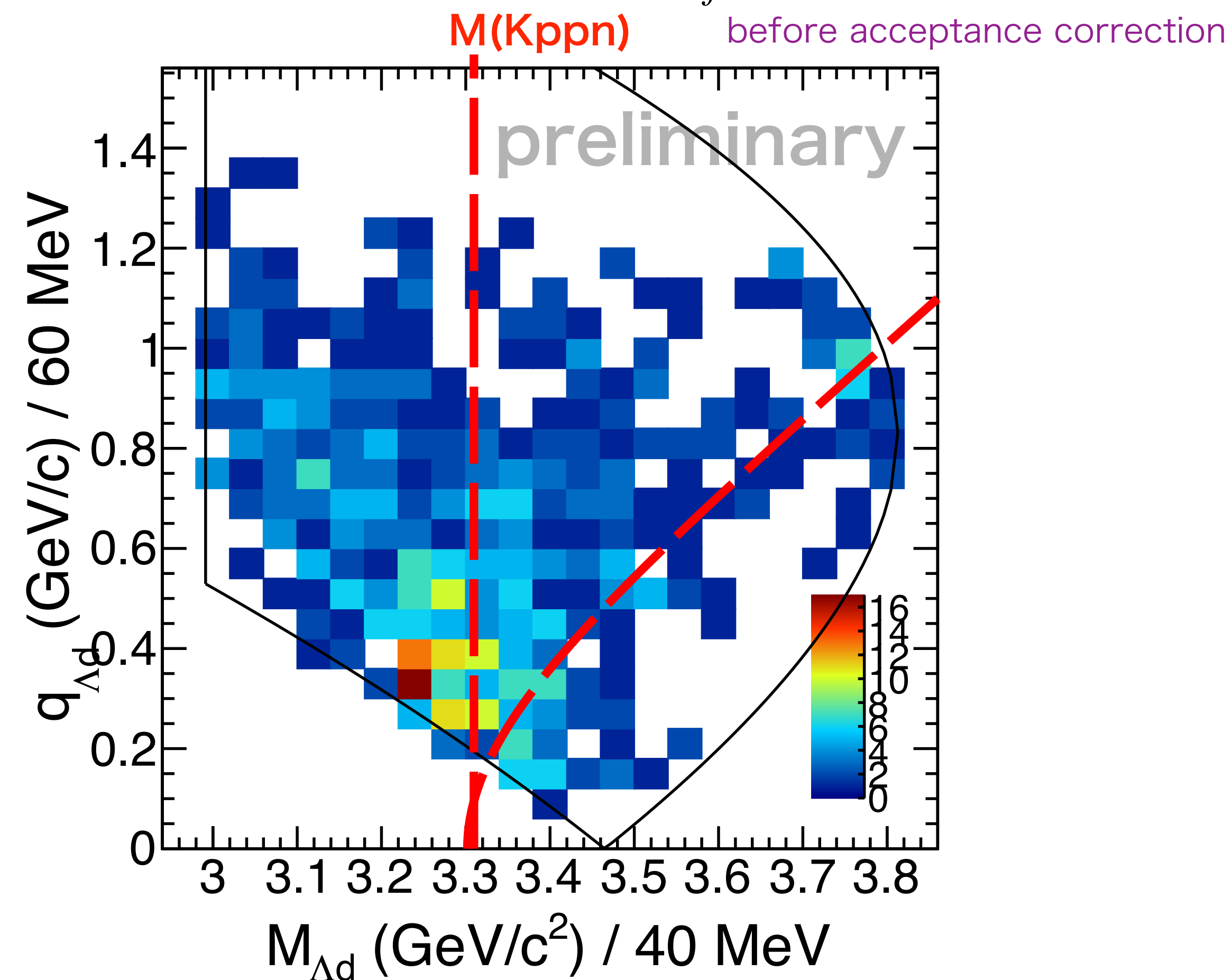
Deep binding (B.E. ~ 40 MeV), Large decay width ($\Gamma \sim 100$ MeV), Large momentum transfer

Λd analysis with the ^4He target

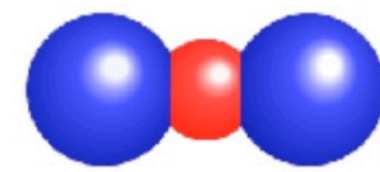
E15: $K^- + ^3\text{He} \rightarrow \Lambda p + n_f$ ($\sim 42 \times 10^9 K^-$)



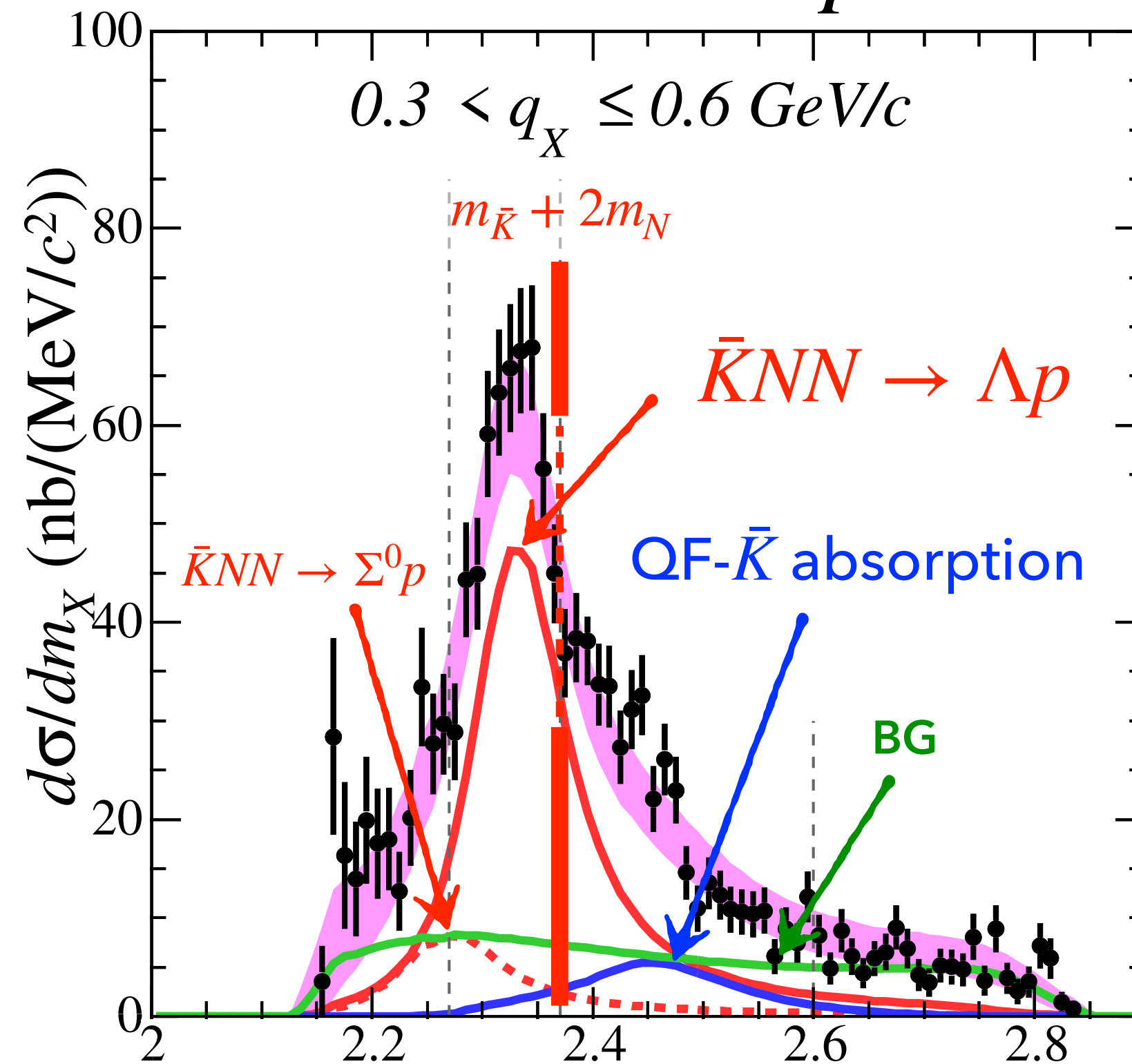
T77: $K^- + ^4\text{He} \rightarrow \Lambda d + n_f$ ($\sim 6 \times 10^9 K^-$)



- Similar distribution as ^3He data. Publication coming soon with x3 ^4He data.



K^-pp



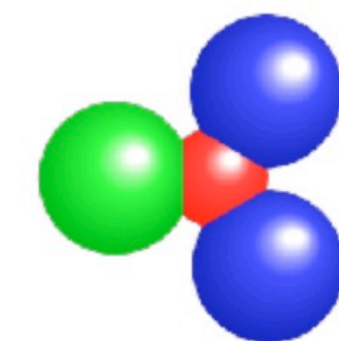
Invariant mass of Λp (GeV/c^2)

$$B_{\bar{K}NN} = 42 \pm 3 \text{ (stat.) } {}^{+3}_{-4} \text{ (syst.) MeV}$$

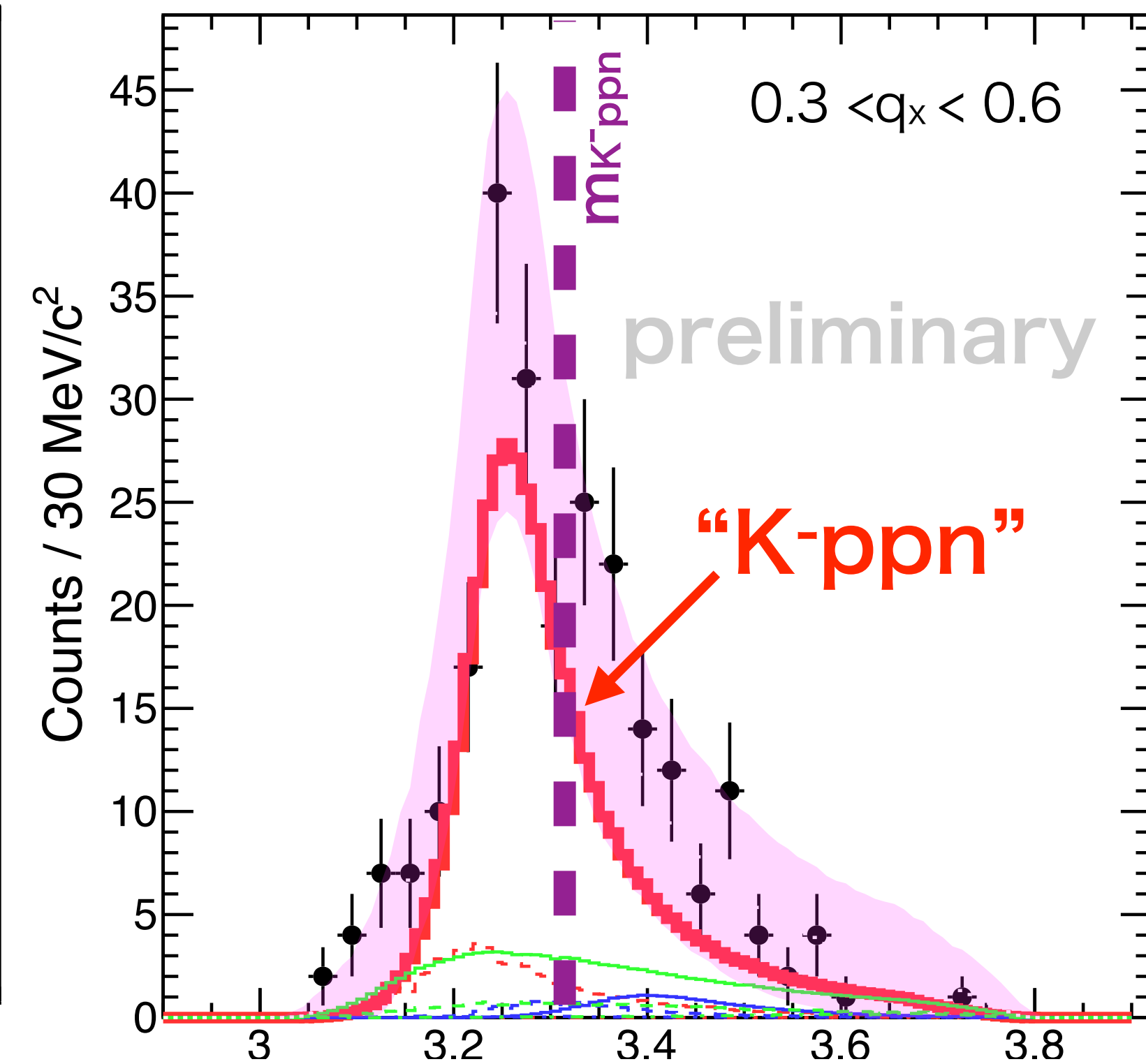
$$\Gamma_{\bar{K}NN} = 100 \pm 7 \text{ (stat.) } {}^{+19}_{-9} \text{ (syst.) MeV}$$

$$\sigma_{\bar{K}NN \rightarrow \Lambda p} = 9.3 \pm 0.8 \text{ (stat.) } {}^{+1.4}_{-1.0} \text{ (syst.) } \mu\text{b}$$

PRC102, 044002 (2020).



K^-ppn



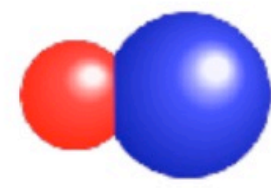
Invariant mass of Λd (GeV/c^2)

$$B_{\bar{K}NNN} \sim 60 \pm 11 \text{ (stat) MeV}$$

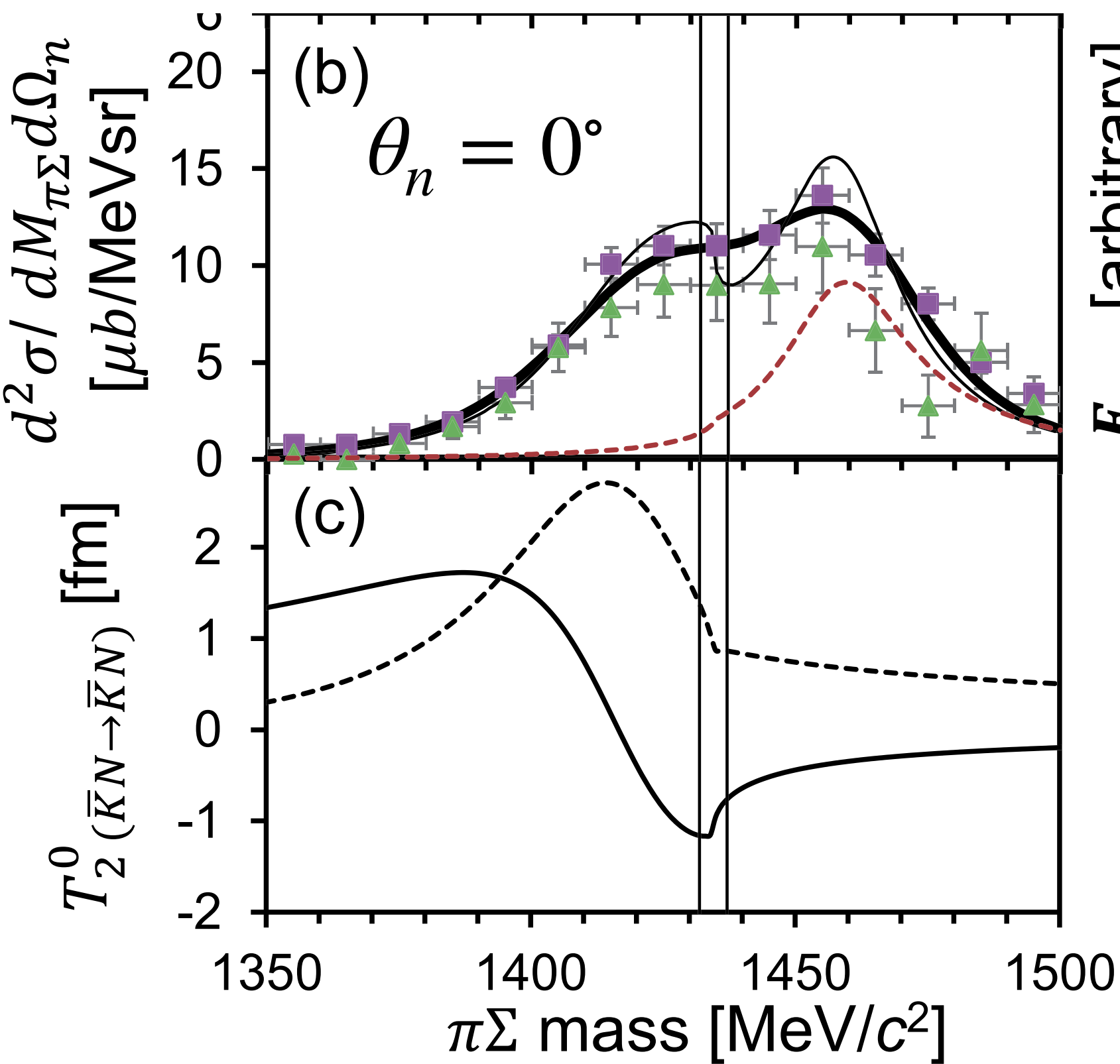
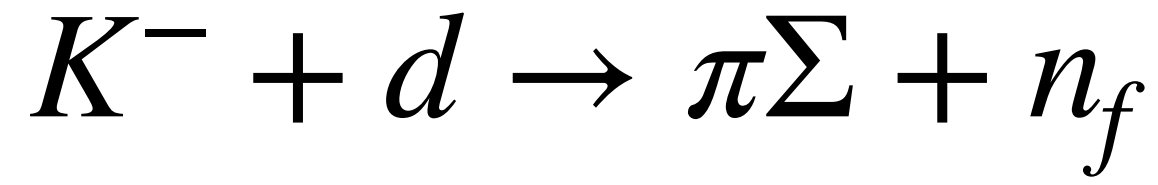
$$\Gamma_{\bar{K}NNN} \sim 100 \text{ MeV}$$

$$\sigma_{\bar{K}NNN \rightarrow \Lambda d} \sim 4 \mu\text{b}$$

$I(J^P) = 0(1/2^-)$ with high certainty

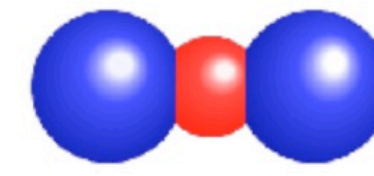


K^-p

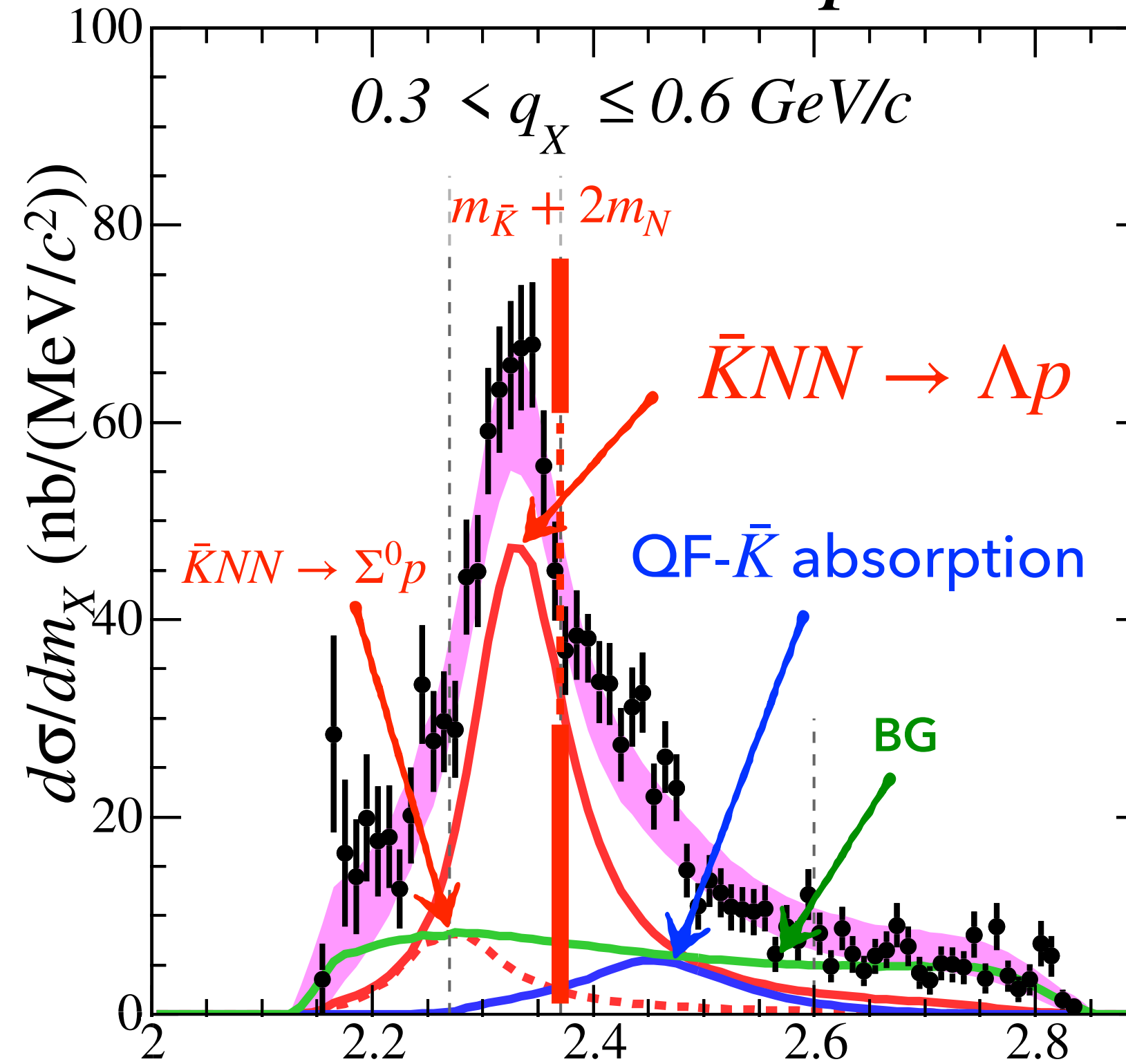
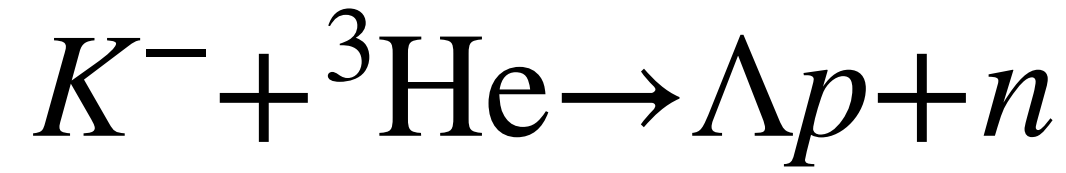


With two-step reaction processes
S-wave $\bar{K}N$ amplitude ($l=0$) was deduced
pole: $1417.7 - 26.1i$ [MeV]

PLB 736, 137637 (2023)

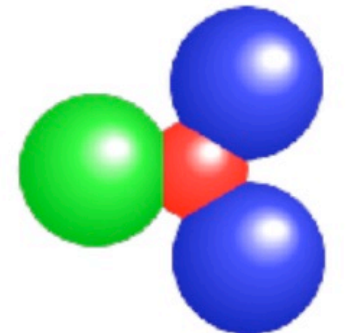


K^-pp

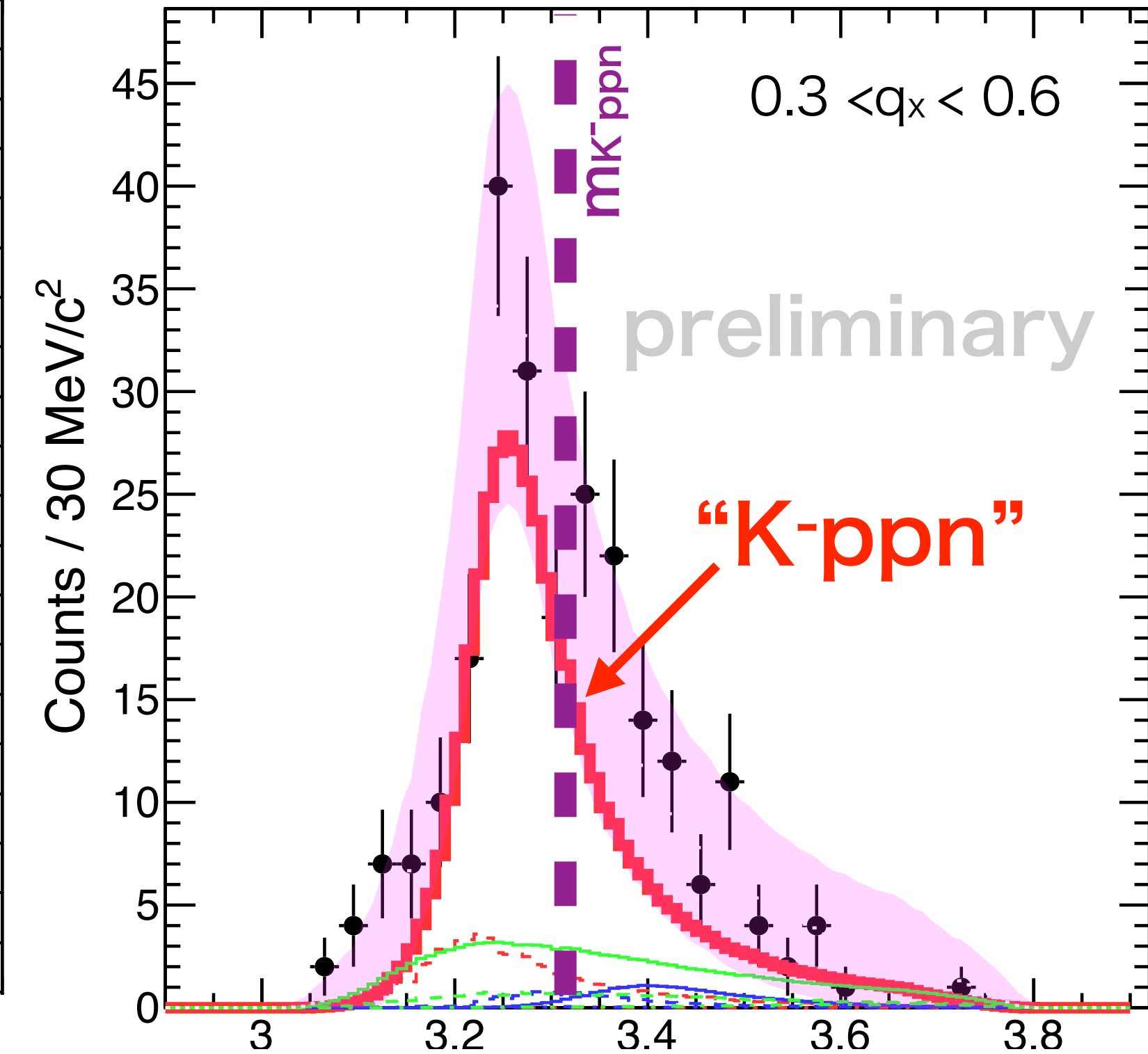
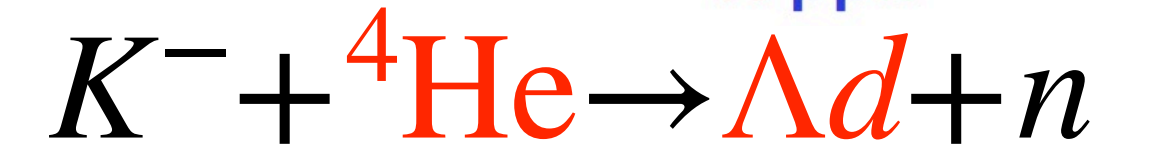


$B_{\bar{K}NN} = 42 \pm 3$ (stat.) $^{+3}_{-4}$ (syst.) MeV
 $\Gamma_{\bar{K}NN} = 100 \pm 7$ (stat.) $^{+19}_{-9}$ (syst.) MeV
 $\sigma_{\bar{K}NN \rightarrow \Lambda p} = 9.3 \pm 0.8$ (stat.) $^{+1.4}_{-1.0}$ (syst.) μb

PRC102, 044002 (2020).

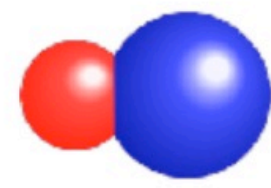


K^-ppn

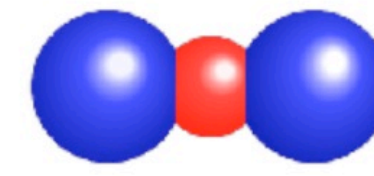
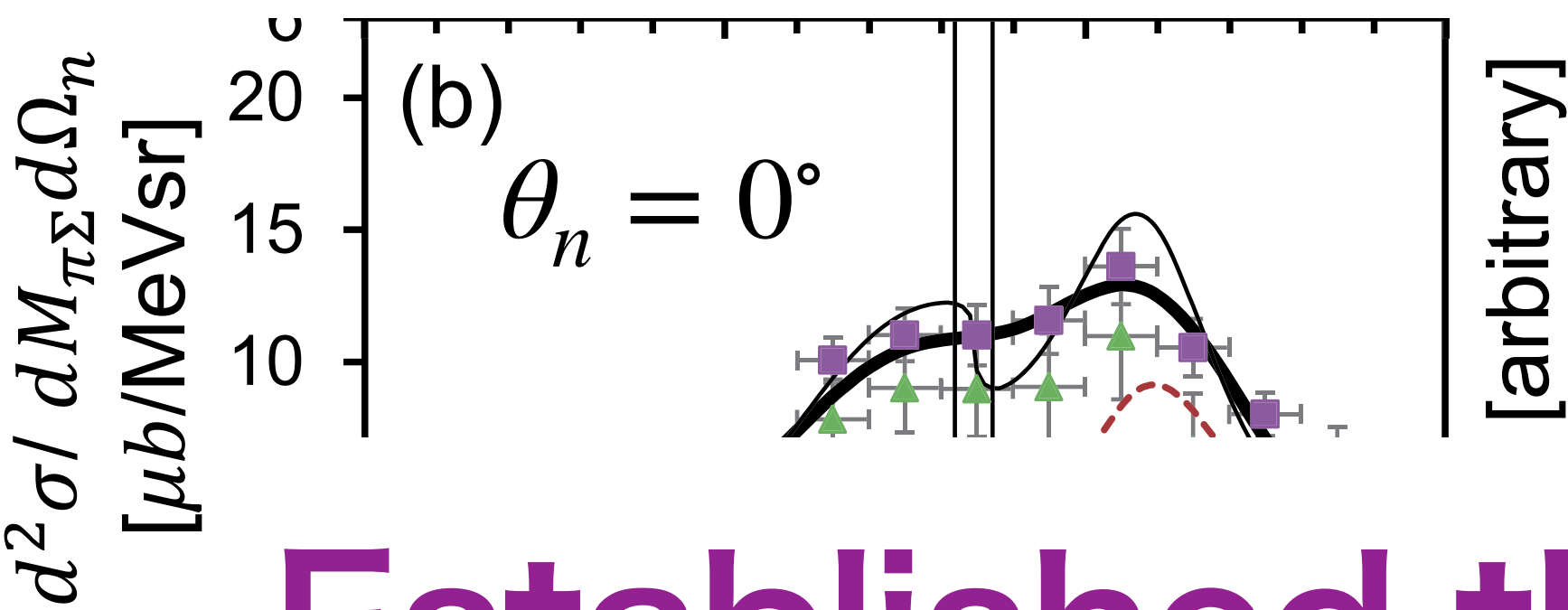
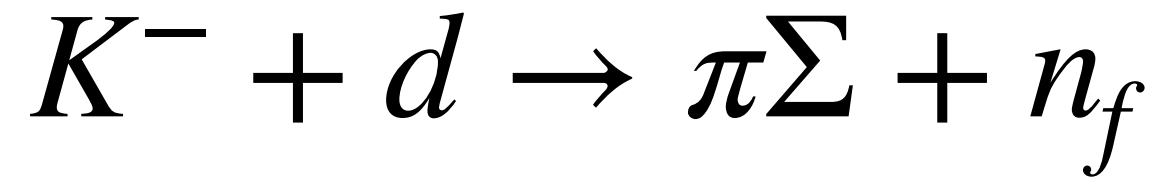


$B_{\bar{K}NNN} \sim 60 \pm 11$ (stat) MeV
 $\Gamma_{\bar{K}NNN} \sim 100$ MeV
 $\sigma_{\bar{K}NNN \rightarrow \Lambda d} \sim 4 \mu\text{b}$

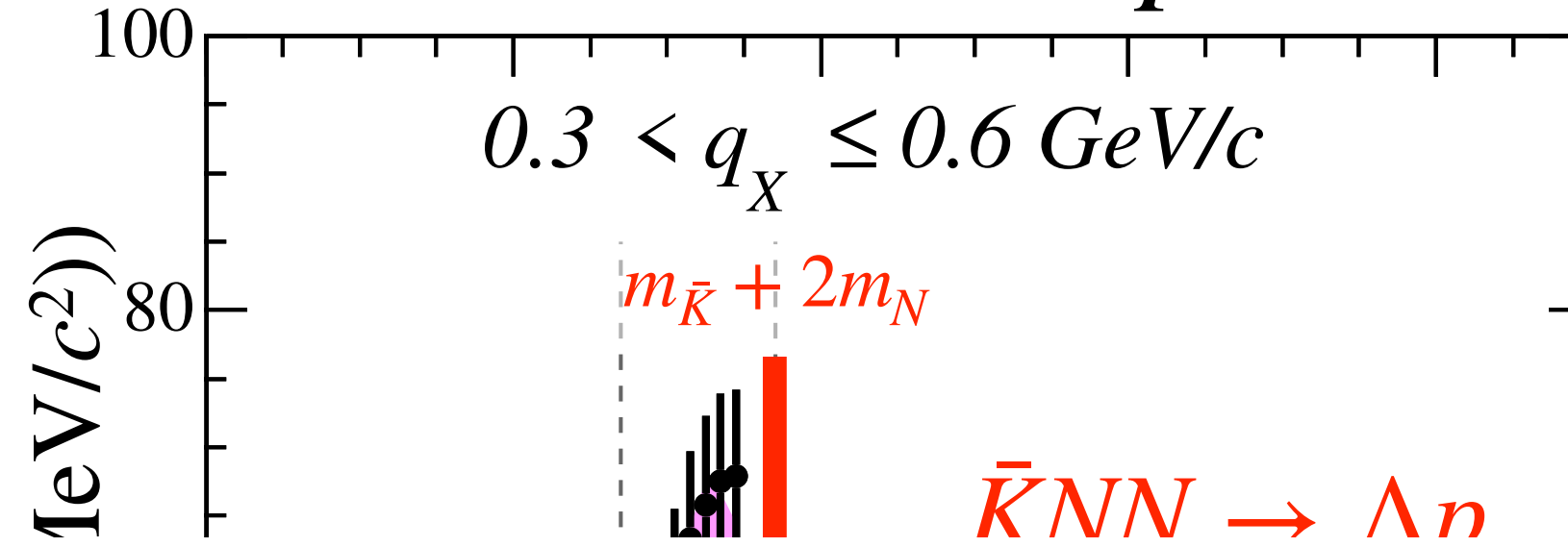
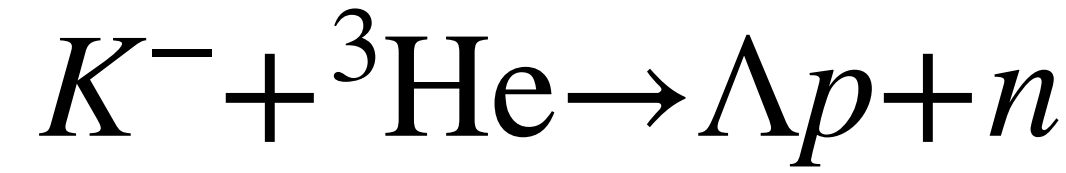
$I(J^P) = 0(1/2^-)$ with high certainty



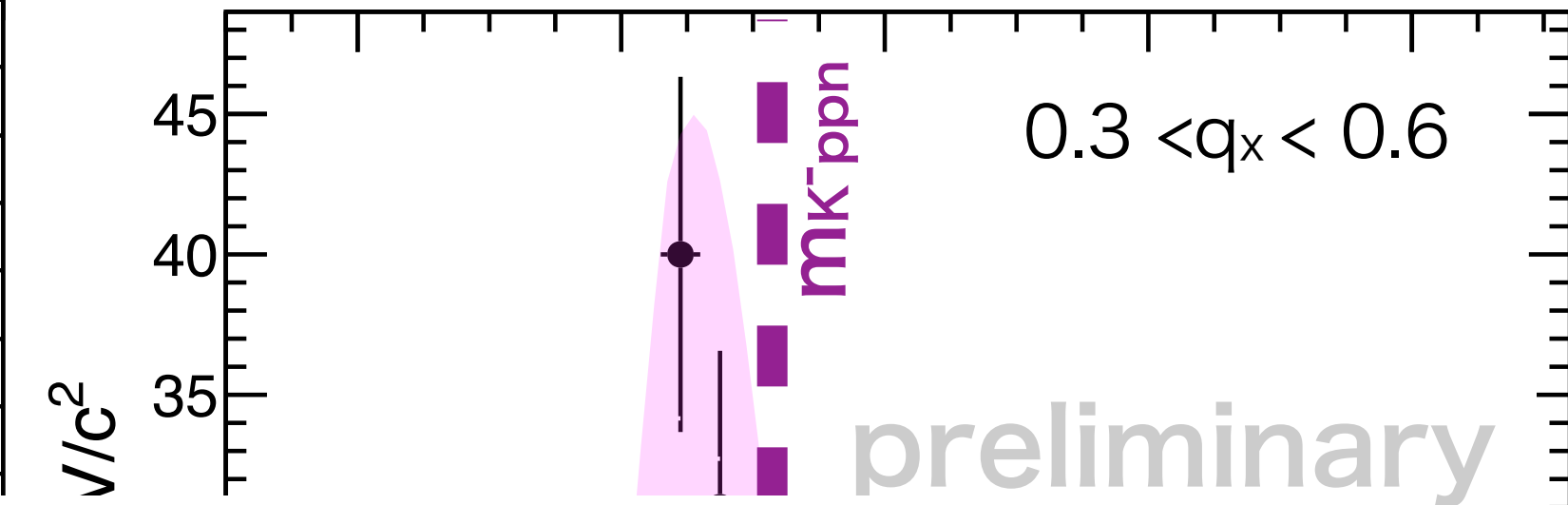
K^-p



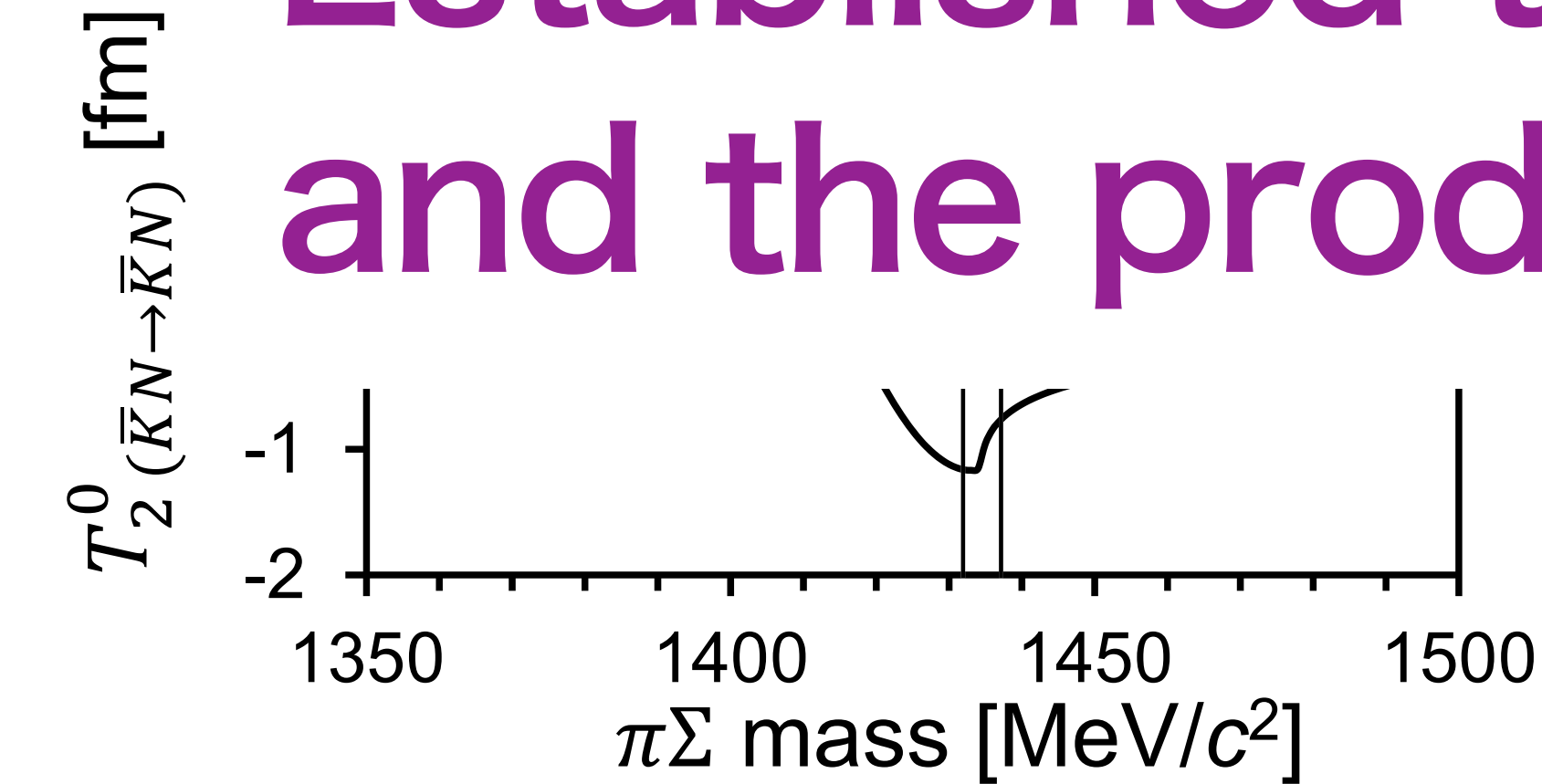
K^-pp



K^-ppn

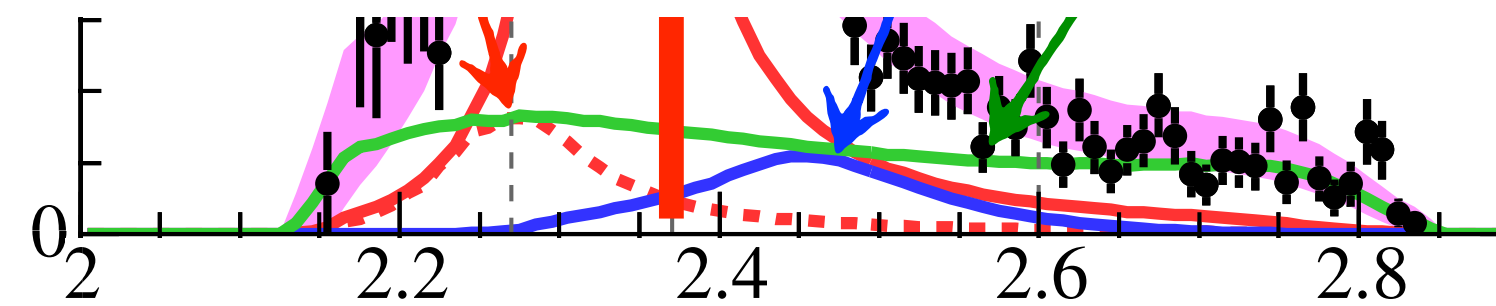


Established the existence of Kaonic nuclei
and the production method via (K^-, N)



With two-step reaction processes
S-wave $\bar{K}N$ amplitude ($l=0$) was deduced
pole: $1417.7 - 26.1i$ [MeV]

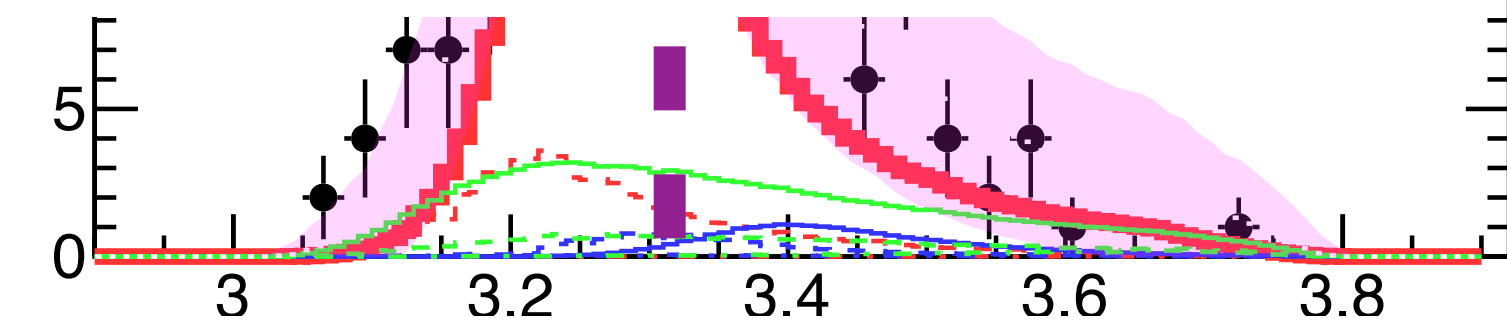
PLB 736, 137637 (2023)



Invariant mass of Λp (GeV/c^2)

$B_{\bar{K}NN} = 42 \pm 3$ (stat.) $^{+3}_{-4}$ (syst.) MeV
 $\Gamma_{\bar{K}NN} = 100 \pm 7$ (stat.) $^{+19}_{-9}$ (syst.) MeV
 $\sigma_{\bar{K}NN \rightarrow \Lambda p} = 9.3 \pm 0.8$ (stat.) $^{+1.4}_{-1.0}$ (syst.) μb

PRC102, 044002 (2020).



Invariant mass of Λd (GeV/c^2)

$B_{\bar{K}NNN} \sim 60 \pm 11$ (stat) MeV
 $\Gamma_{\bar{K}NNN} \sim 100$ MeV
 $\sigma_{\bar{K}NNN \rightarrow \Lambda d} \sim 4 \mu\text{b}$

$I(J^P) = 0(1/2^-)$ with high certainty

Future plan

Confirmation of “ K^-ppn ” $\rightarrow$ J-PARC E80

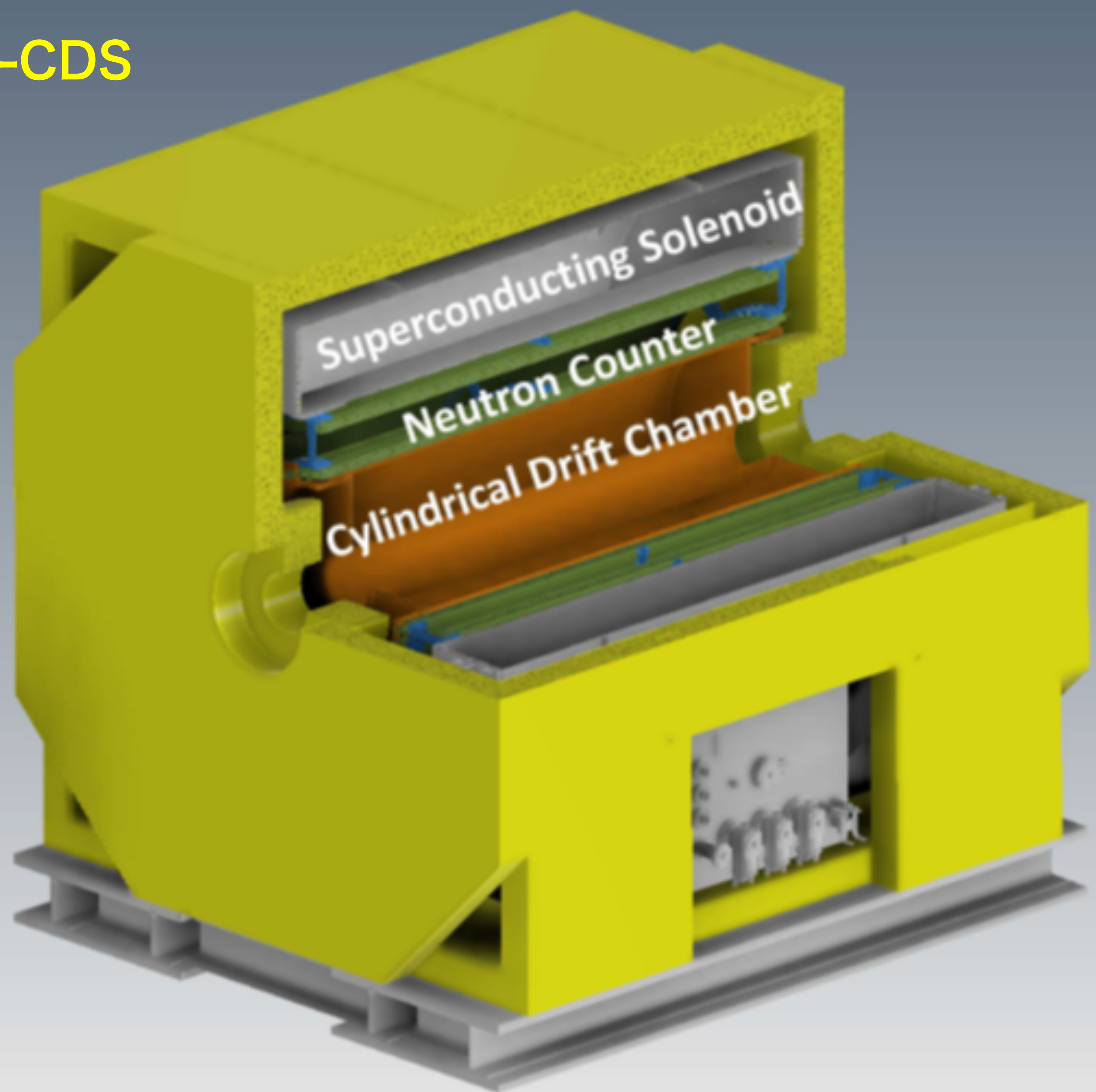
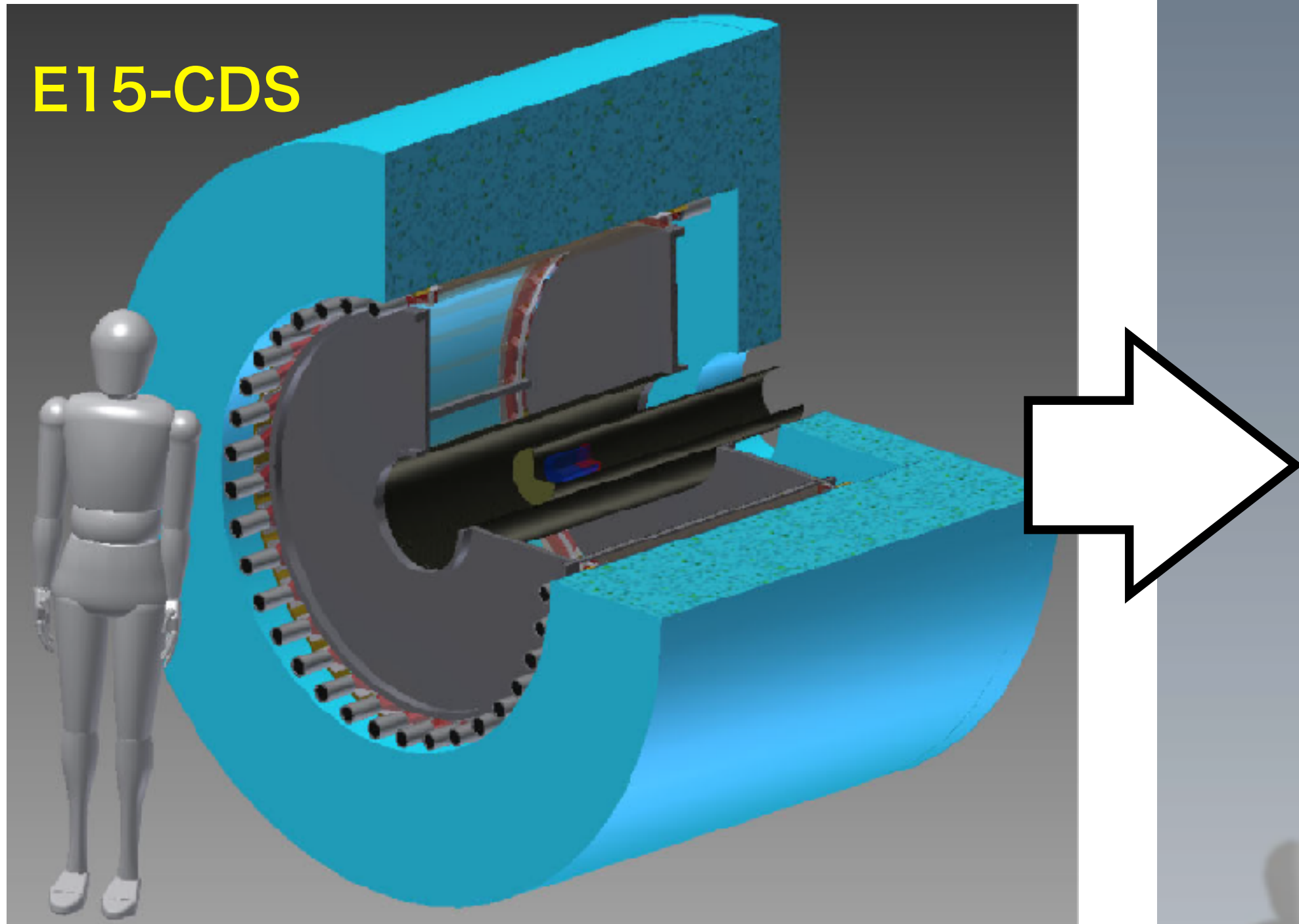
Further investigation of the $\bar{K}NN$ system $\rightarrow$ J-PARC E89

Quantum number, Spatial size, heavier system, double $\bar{K}$ nuclei...

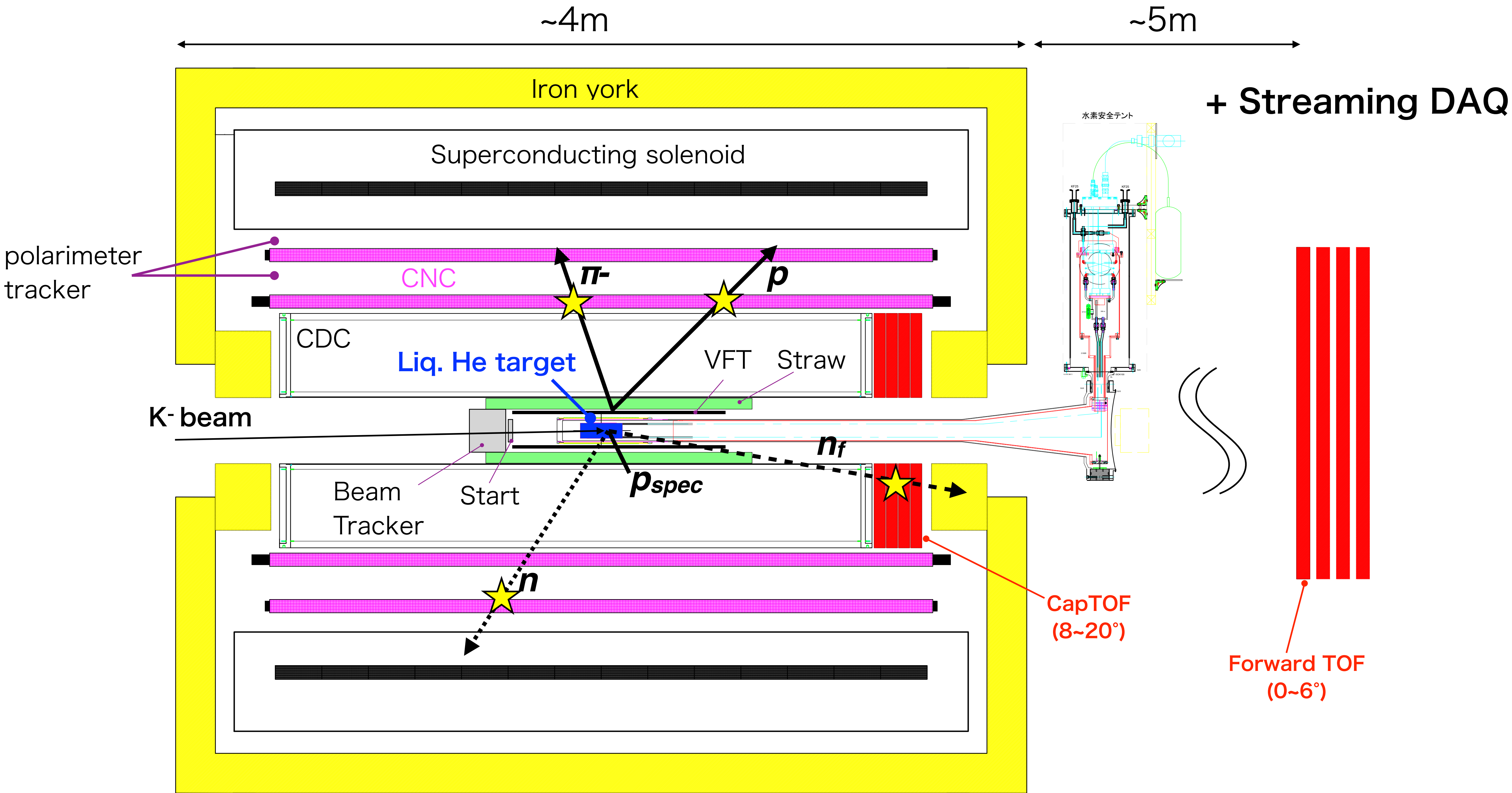
New CDS

E80-CDS

E15-CDS



- ✓ Solid angle: x1.6 (59%→93%)
- ✓ Neutron eff. x4 (3%→12%)
- ✓ forward TOF counters
- ✓ proton polarimeter in future



Is the observed state really $\bar{K}NN$?

- Isospin partner should exist

- “ $\bar{K}^0nn$ ” $\rightarrow \Lambda n, \Sigma^-p$ analysis

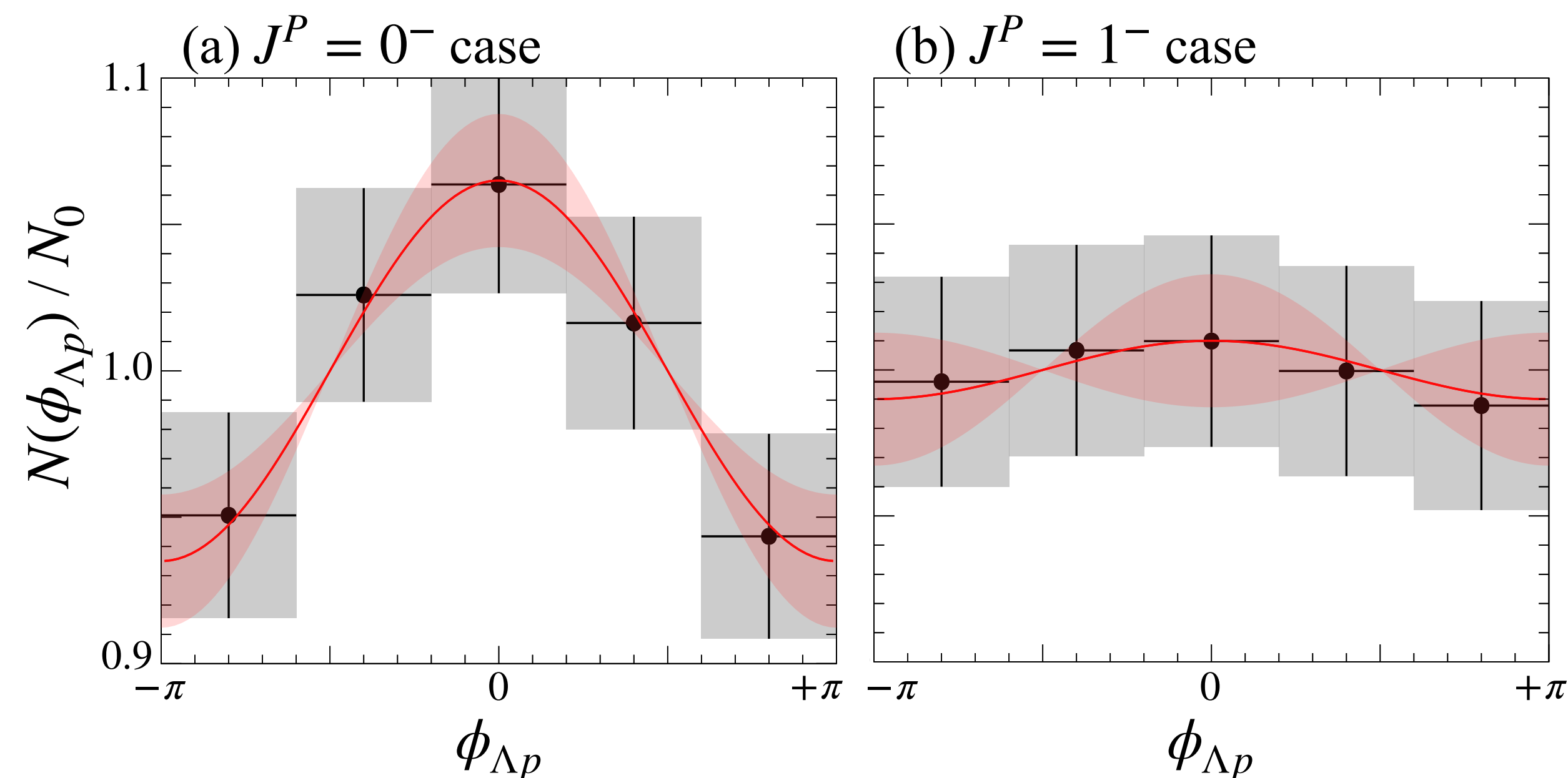
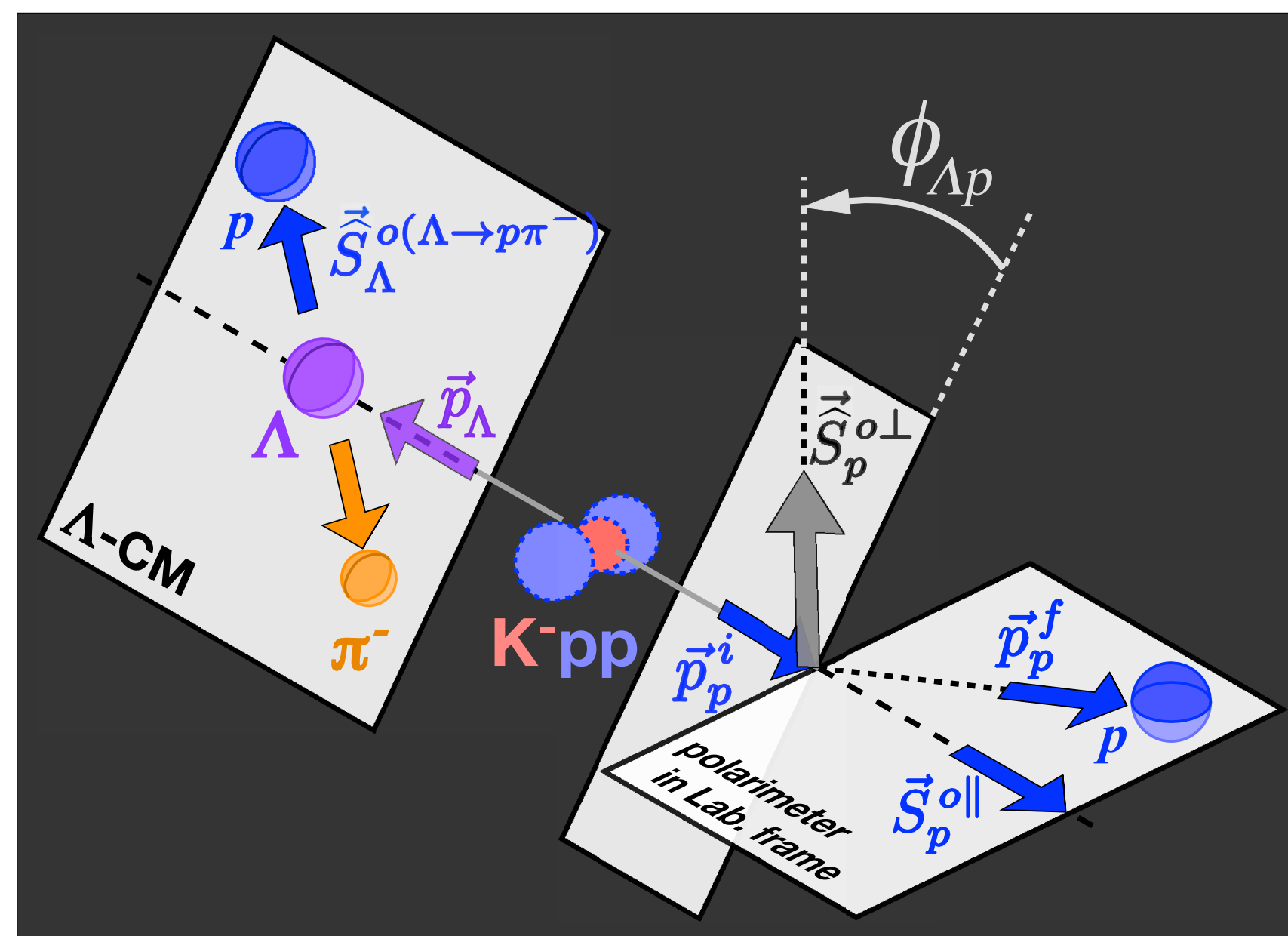
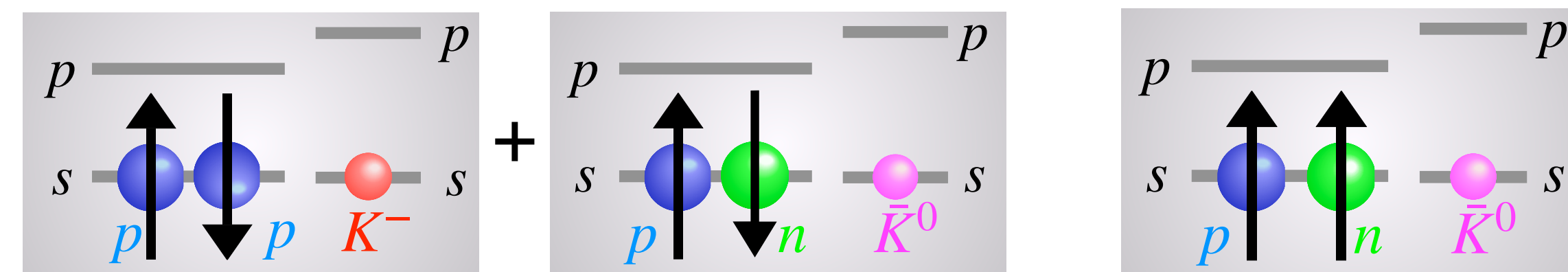
- need **neutron detection**

- Spin-parity measurement:

- spin-spin correlation between Λ and p

- need **polarimeter** for proton

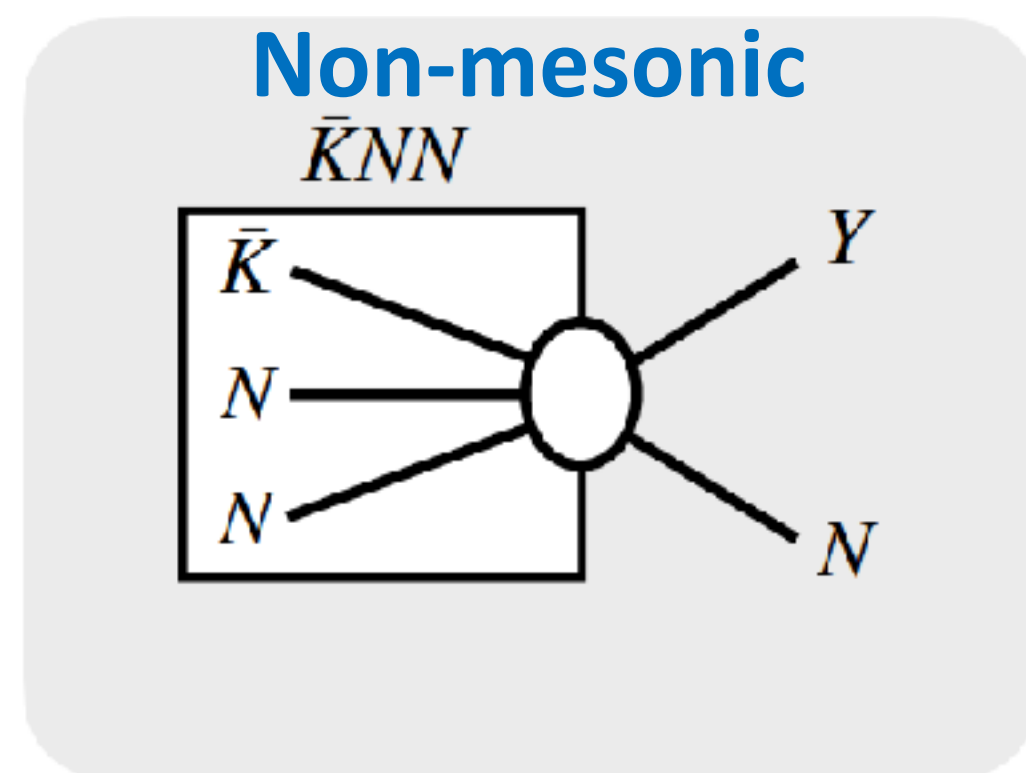
$$\bar{K}NN(I = 1/2) \begin{array}{l} \xrightarrow{I_z = +1/2} K^-pp - \bar{K}^0pn \\ \xrightarrow{I_z = -1/2} K^-pn - \bar{K}^0nn \end{array}$$



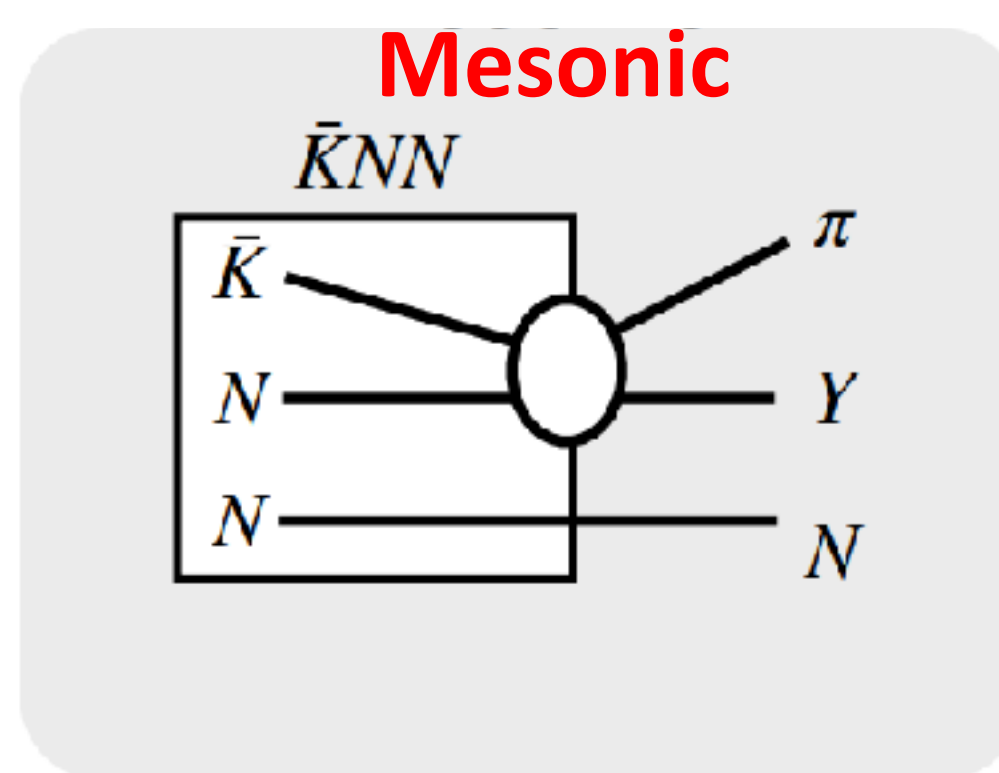
How compact is the system?

- Momentum-transfer distribution
 - large S-wave gauss. form factor $Q \sim 400 \text{ MeV}/c$
- Decay branching ratio $1N_{\bar{K}A} : 2N_{\bar{K}A} : 3N_{\bar{K}A} = \rho_N : \rho_N^2 : \rho_N^3$?

• $\bar{K}NN \rightarrow \Lambda N$ vs. $\bar{K}NN \rightarrow \pi Y N_s$, $\Sigma^\pm \rightarrow \pi^\pm$ n neutron detection



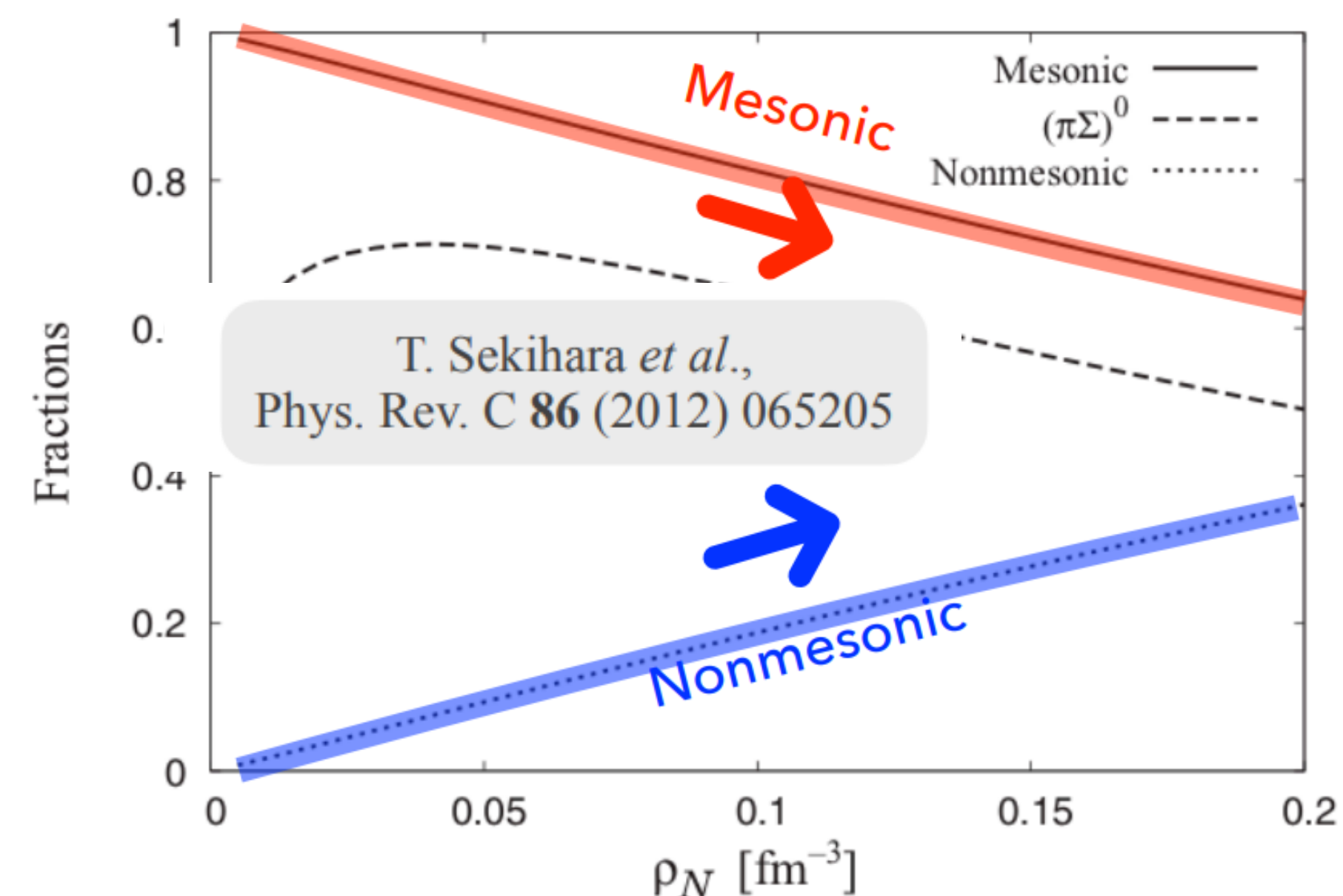
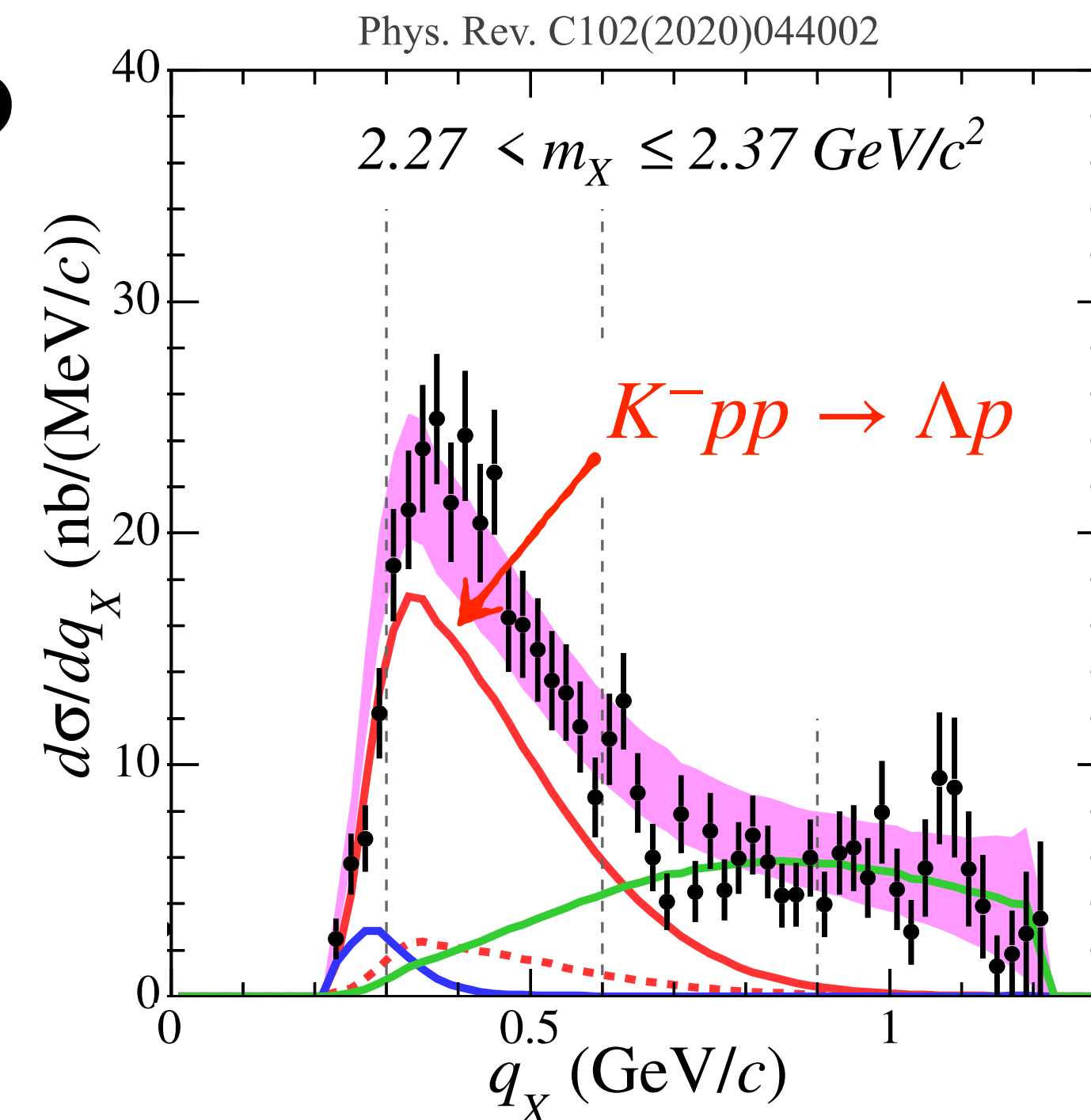
2N absorption



1N absorption

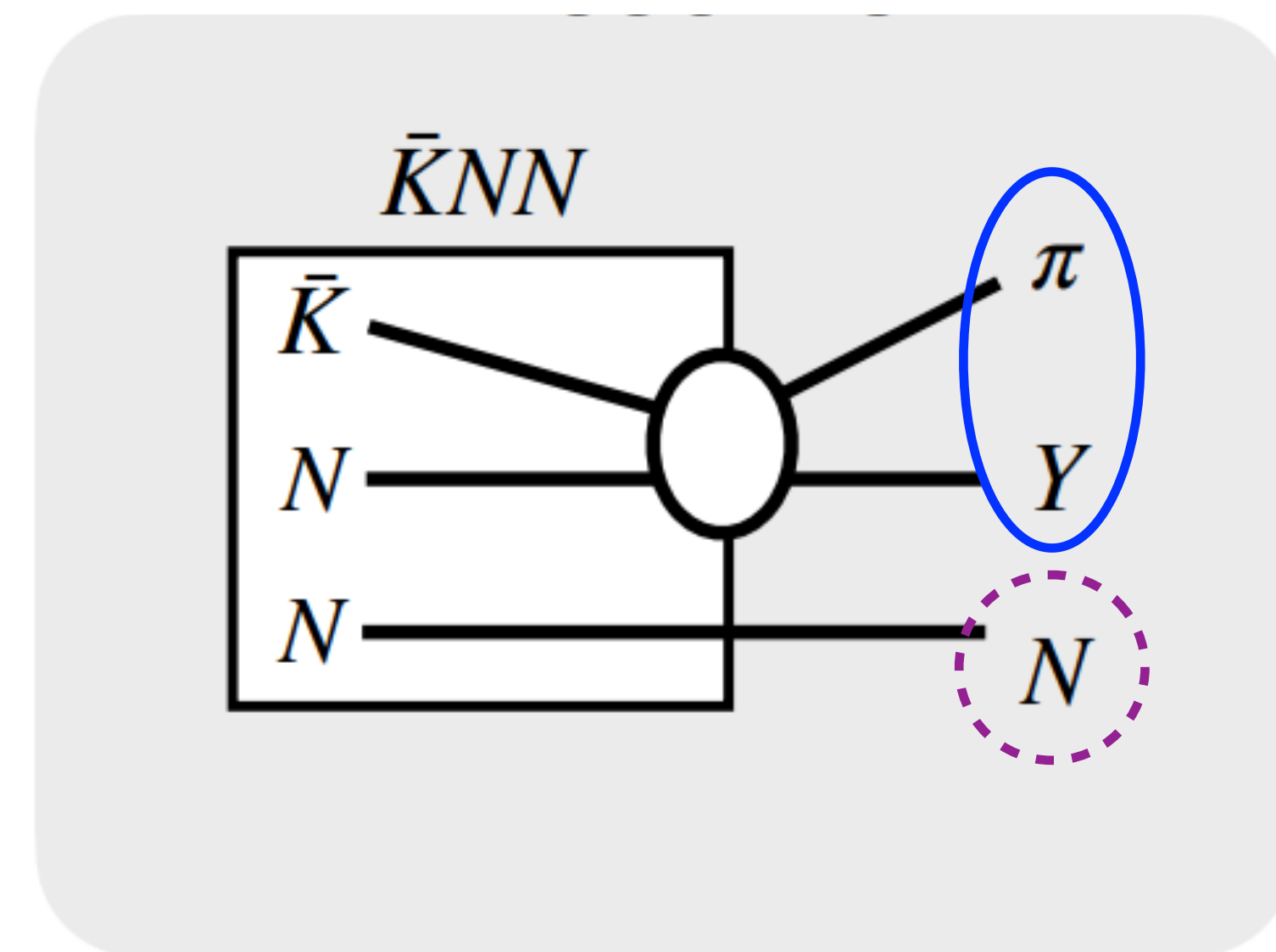
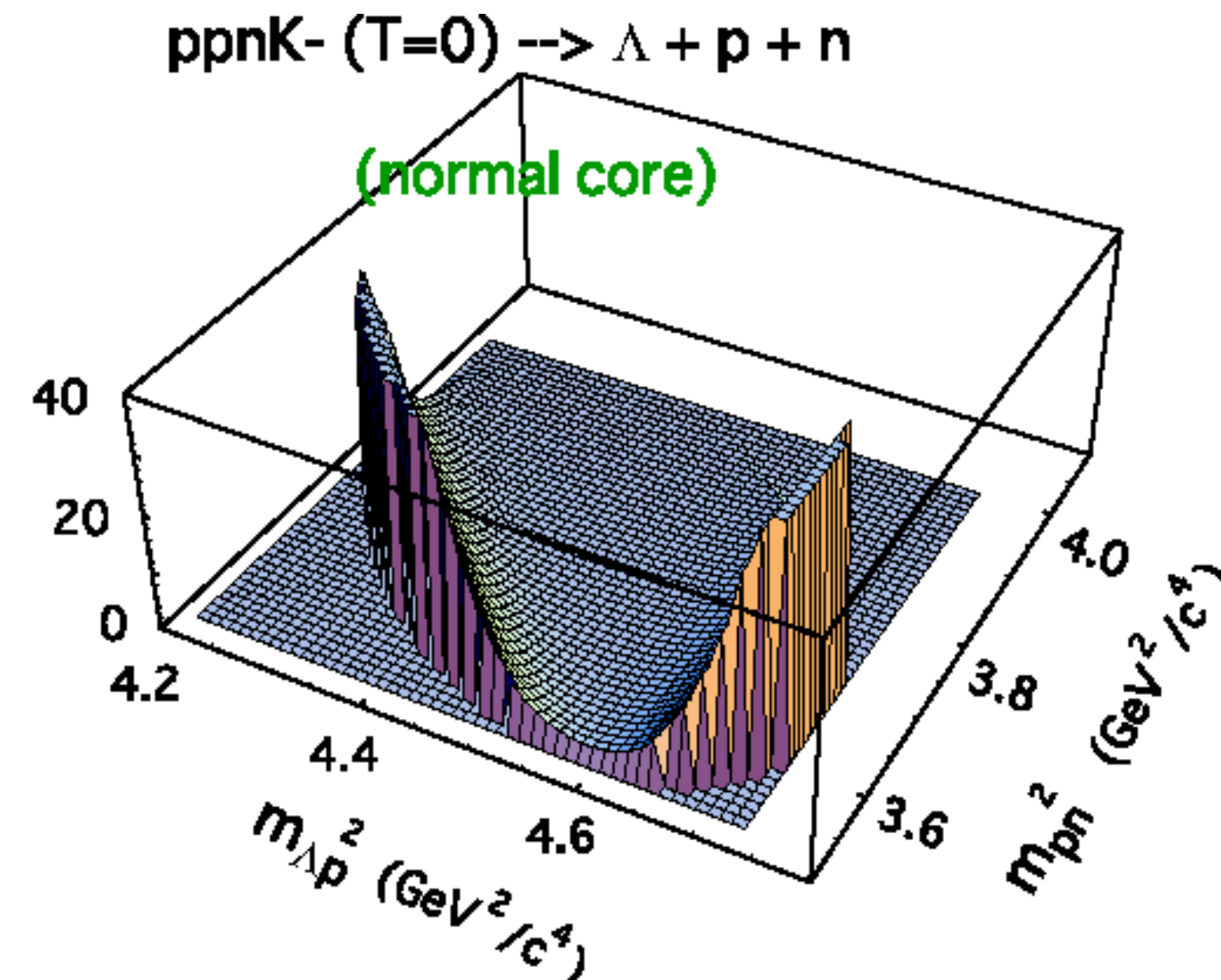
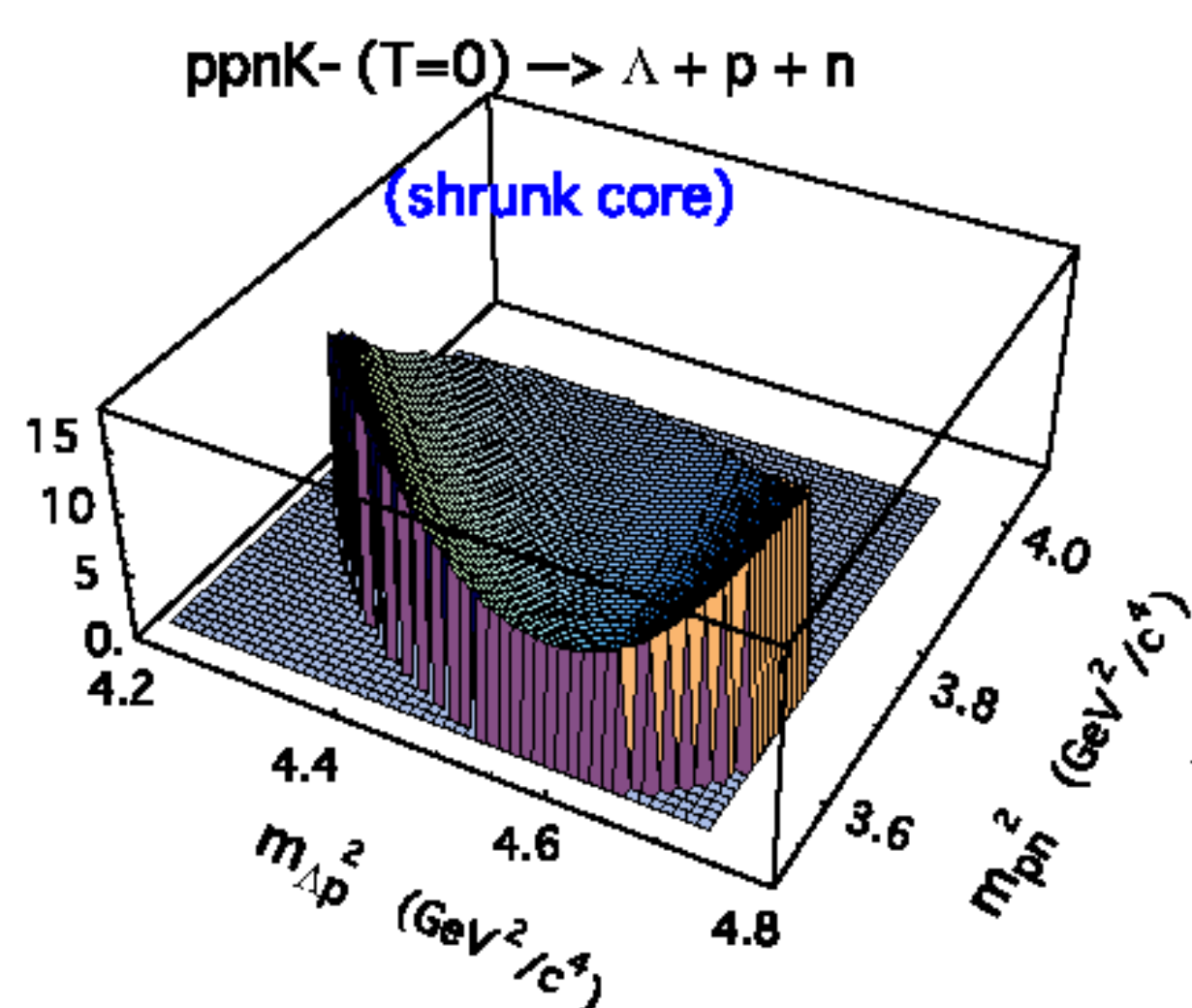
• $\bar{K}NNN \rightarrow \Lambda d$ vs. $\bar{K}NNN \rightarrow \Lambda p$ n neutron detection

3N absorption 2N absorption

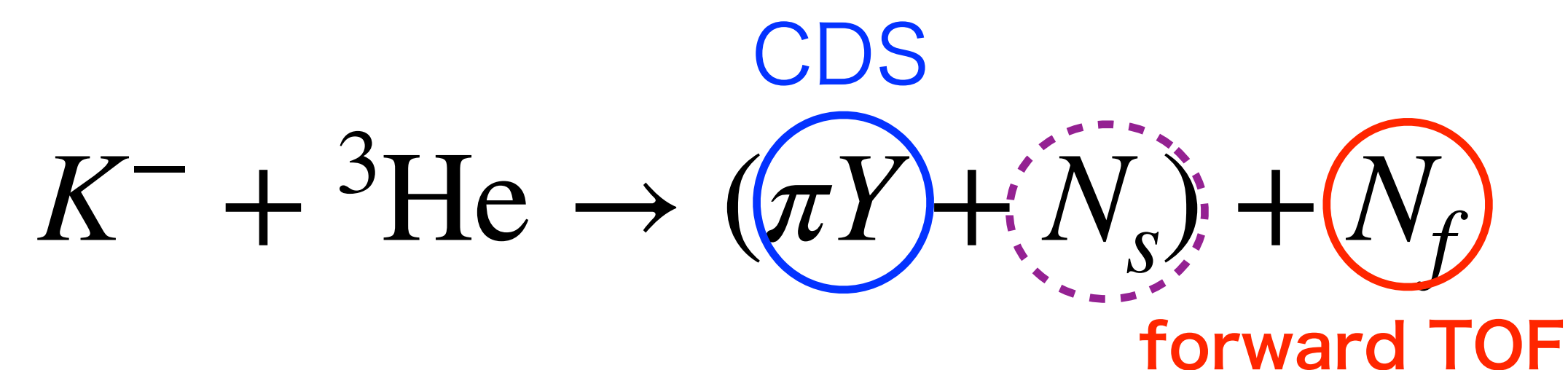
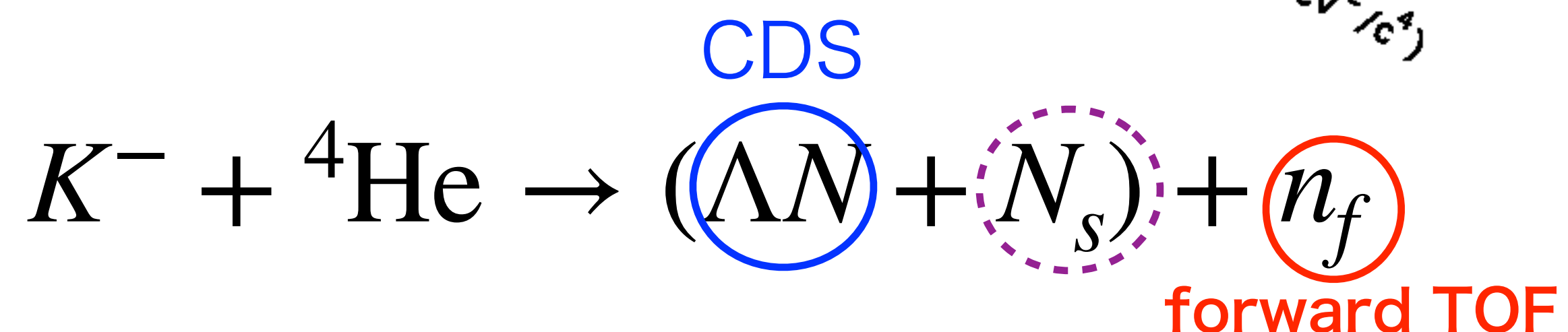


How compact is the system?

P. Kienle et al., PLB 632 (2006) 187–191



1N absorption



- Momentum of the “spectator” nucleon should reflect the system size.
- Most of the spectator nucleons have too low momentum to be detected.
 $\rightarrow$ detect the forward knocked-out nucleon in the production reaction

Construction status

Solenoid yolk



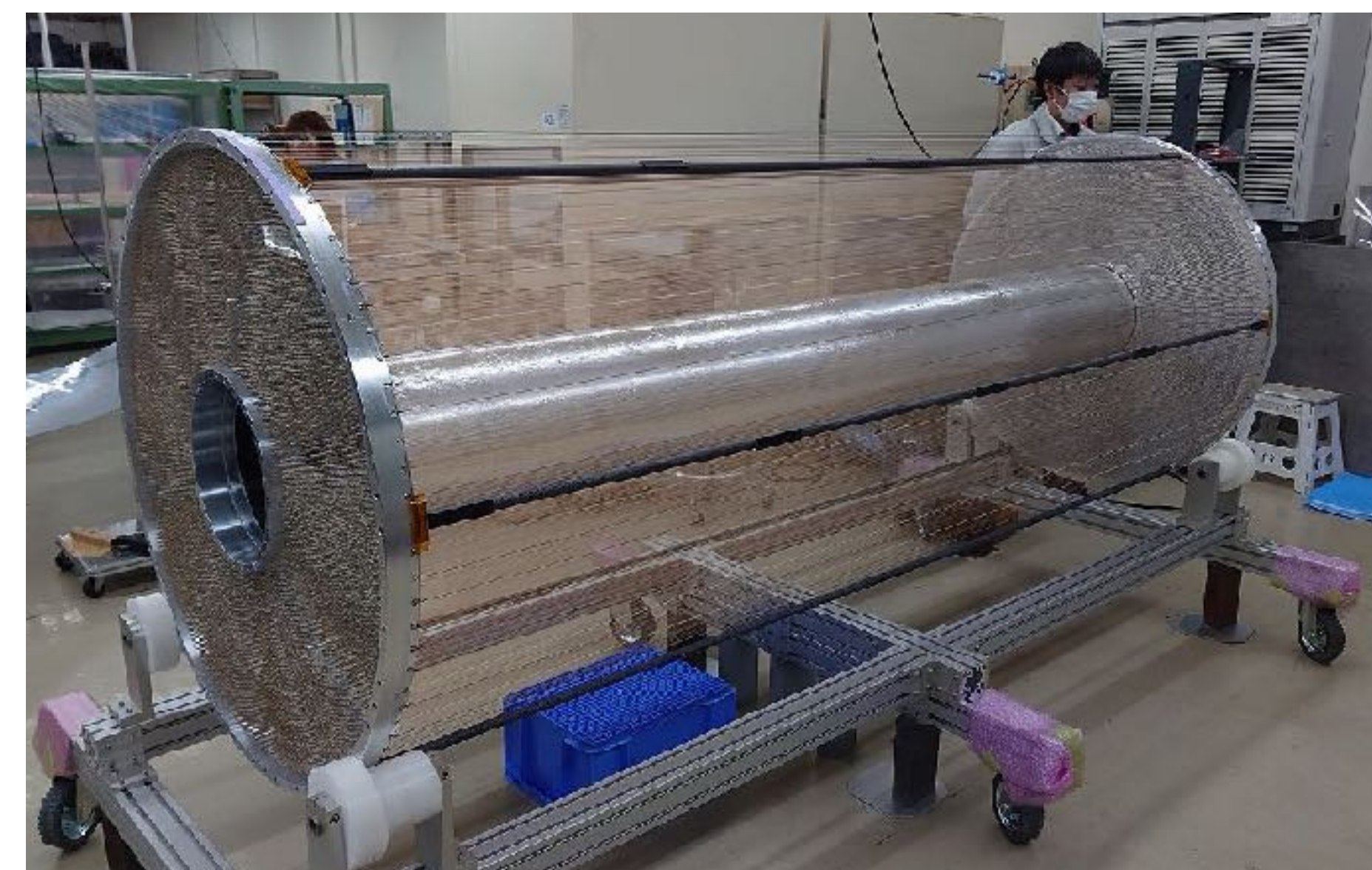
completed in JFY2022

Superconducting solenoid



completed in JFY2024

CDC: completed, in commissioning



CNC: prototype tested, in production



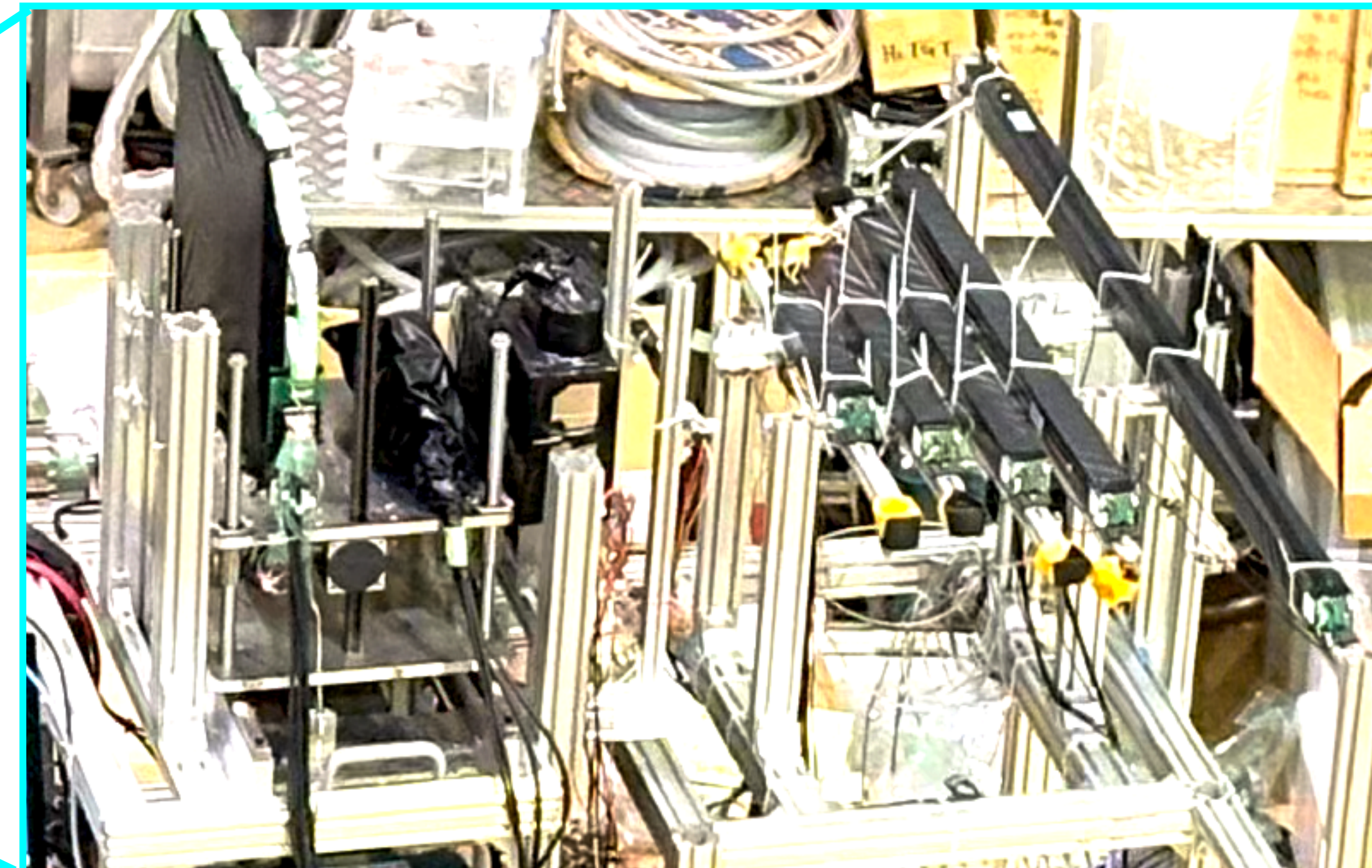
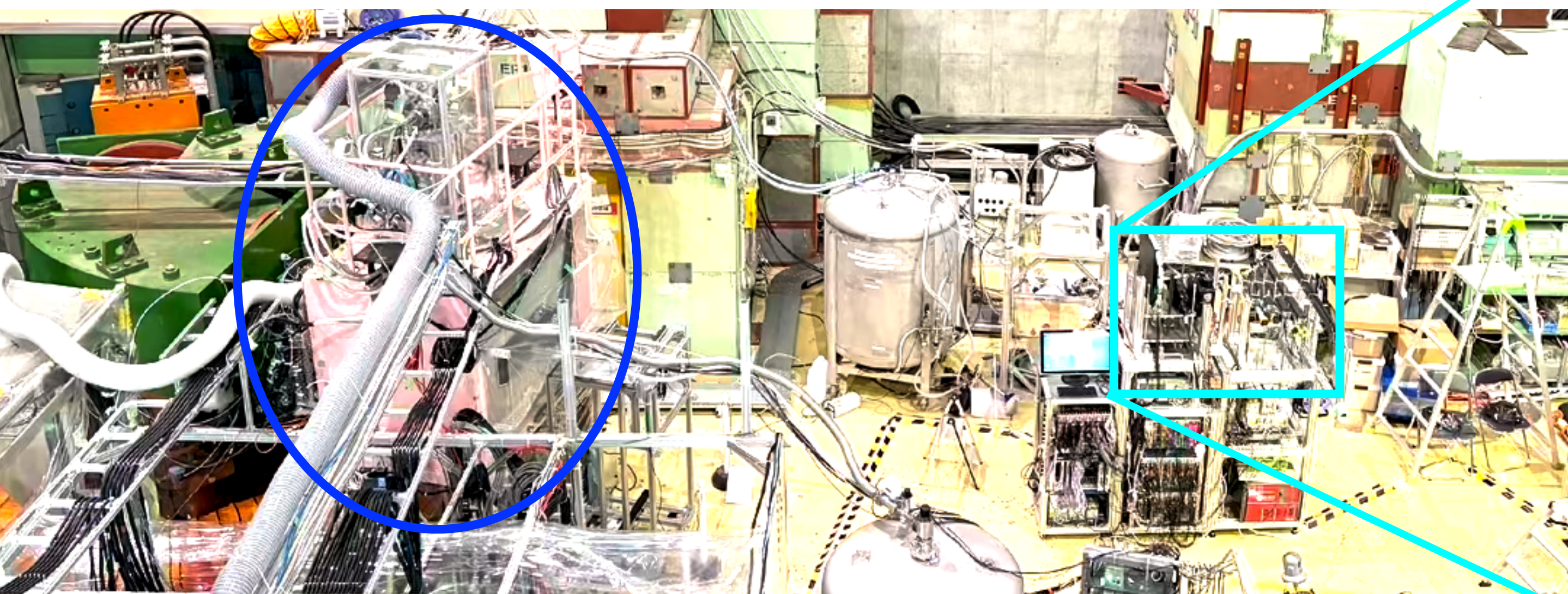
Installation from summer 2026
Beam commissioning in early 2027

J-PARC SX beamtime Nov. 5–26

Detector tests as a parasite

AC, polarimeter tracker, TOF counters, ...

Hyperon Spectrometer
(Helmholtz + TPC)



- **E72:** Λ resonance at Λ_η threshold
- E63: commissioning of ${}^4_\Lambda\text{H}(1^+ \rightarrow 0^+)$ gamma-ray spectroscopy
- E16: spectral modification of vector mesons in nuclei (ϕ/ω)

Summary

- **K⁻ beam provides unique opportunities for strange nuclear physics.**
- **Light hypernuclei**
 - lifetime measured with high precision for H4L
 - Hypertriton binding energy can be assessed with the production cross section
 - hypertriton lifetime under analysis. stay tuned!
- **Kaonic nuclei**
 - **(K⁻, N) reaction efficiently excites the sub-threshold anti-kaon amplitude.**
 - $\Lambda(1405)$, “ K^-pp ”, “ K^-ppn ”, More analysis results to come. (d, ^3He , ^4He)
 - **Next-gen. experiments start in 2027 with an upgraded solenoid detector**
 - **Key questions: quantum number, spatial size from the decay observables**
 - Many opportunities with E80-CDS: hypernuclei, p^{bar} beam, K^+ beam, ...

Collaboration

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. Marton,⁶ 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. Piscicchia,^{24,9} 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. Sirghi,^{9,5} 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. Zmeskal⁶
(J-PARC E15 Collaboration)

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(J-PARC E73 collaboration)

T. Akaishi, M. Bazzi, P. Buehler, A. Clozza, C. Curceanu, H. Fujioka, M. Fujita, T. Hashimoto, M. Iio, M. Iliescu, K. Inoue, S. Ishimoto, K. Itahashi, M. Iwasaki, S. Kawasaki, Y. Kimura, T. Kishimoto, G. Kojima, Y. Ma, Y. Makida, S. Manti, R. Murayama, T. Nagae, S. Nagao, S.N. Nakamura, T. Nanamura, H. Noumi, H. Ohhata, H. Ohnishi, S. Okada, M. Oonaka, K. Ozawa, F. Sakuma, K. Sasaki, S. Sasaki, A. Scordo, F. Sgaramella, K. Shirotori, D. Sirghi, F. Sirghi, N. Sumi, K. Suzuki, S. Suzuki, K. Tanida, K. Toho, M. Tsuruta, Y. Tsutsumi, E. Widmann, T. Yamaga, M. Yoshida
(J-PARC E80 collaboration)



Thank you for your attention !