BESIII实验上超子-核子相互作用的研究

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第10届BESIII R值与QCD强子结构研讨会
新疆，乌鲁木齐
2025.07.28

Outline

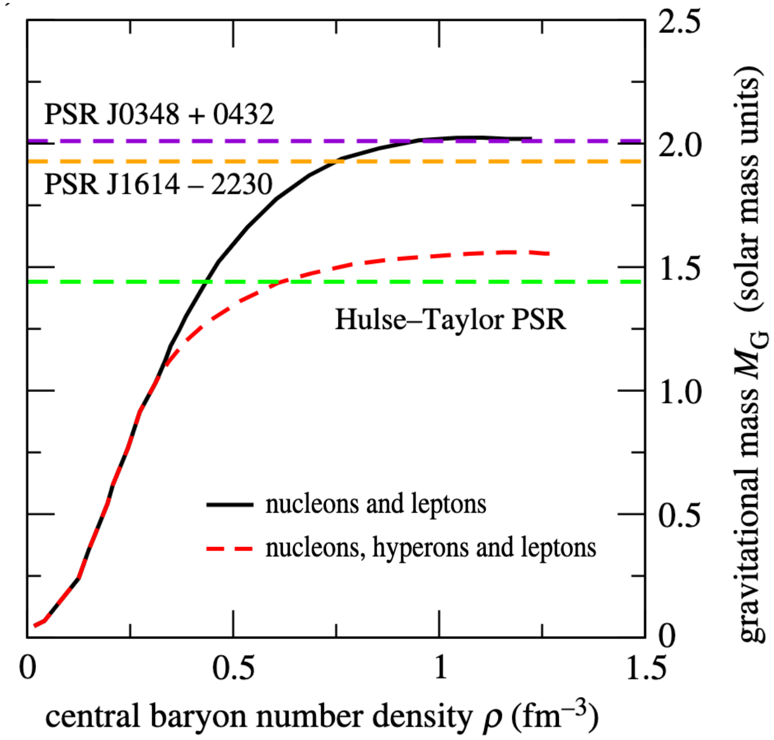
- Introduction
- Measurement Methods at BESIII
- Experimental Results and Analysis
- Discussion and Outlook
- Summary

Introduction

Hyperon Puzzle:

- Hyperons are predicted to appear in neutron star (NS) cores at baryon density $\rho \sim 2\text{–}3\rho_0$.
- Their presence softens the equation of state (EoS), leading to a reduced maximum NS mass.
- Observations of neutron stars with masses > $2M_\odot$ (e.g., PSR J0348+0432, PSR J1614−2230) contradict this prediction.
- This discrepancy is known as the 'Hyperon Puzzle' — a major challenge in nuclear and astrophysics.

I. Vidana, Proc. R. Soc. A 474, 20180145 (2018)



Nat Astron (2019), $M_G = 2.14 \pm 0.1\ M_\odot$

Possible solutions

- YY and YN force
- YNN and YYN three body forces

Experimental data are needed to place constraints on the interaction

YN interaction: Understanding strong interaction, Original of nuclear force, Probe of nuclear structure

Early attempts

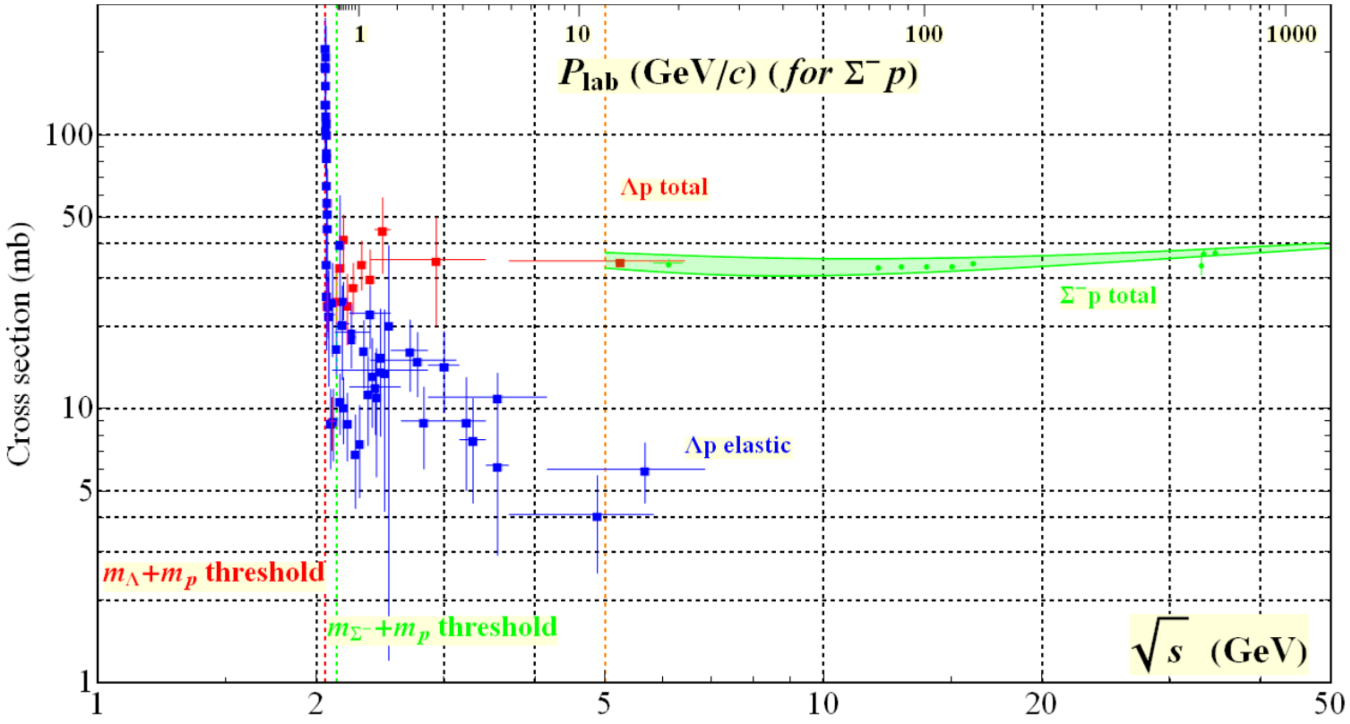


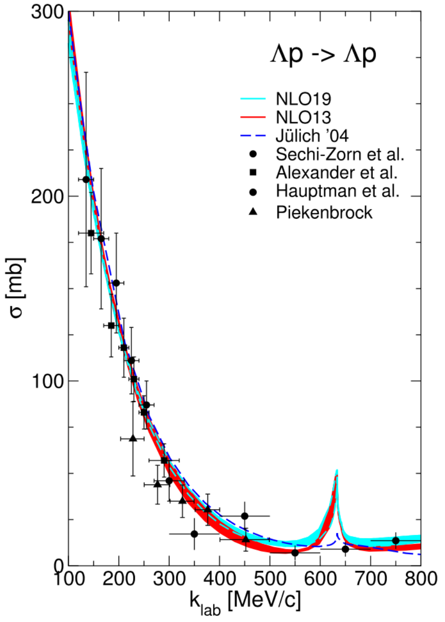
Figure adapted from Particle Data Group (2024)

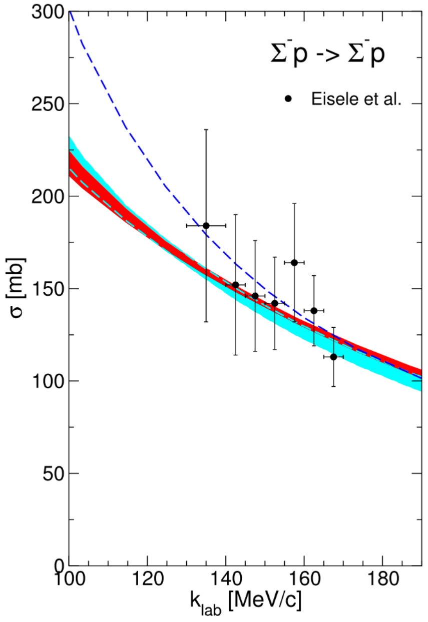
In the 1960s and 1970s focused on experiments using bubble chambers and provided the current database available for the two-body interaction between hyperons and nucleons, with only about 1300 scattering events observed

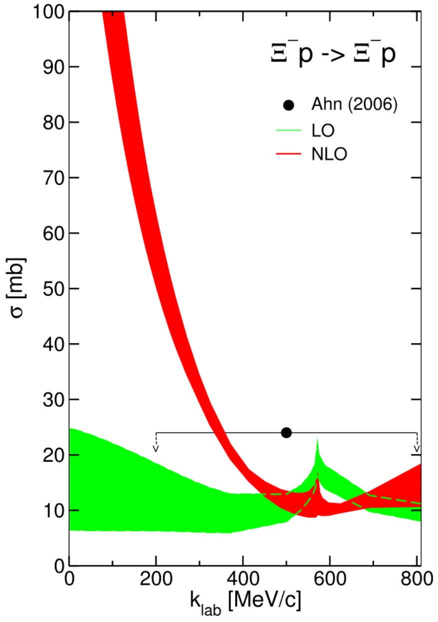
Difficulties performing high-precision scattering experiments with short-lived beams

Theoretical Studies of YN and YY interactions

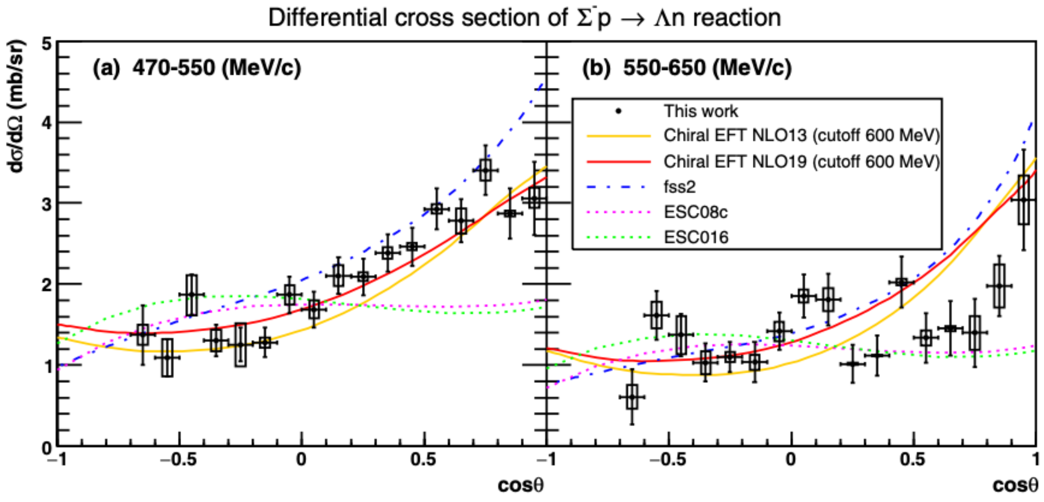
- Meson-Exchange Models : Nijmegen, Bonn-Jülich
- Quark models: Beijing-Tübingen Collaboration, Kyoto-Niigata SU(6)
- Lattice QCD: NPLQCD, HAL QCD Colloboration
- Chiral Effective Field Theory: LO, NLO, N^2LO, relativistic ChEFT

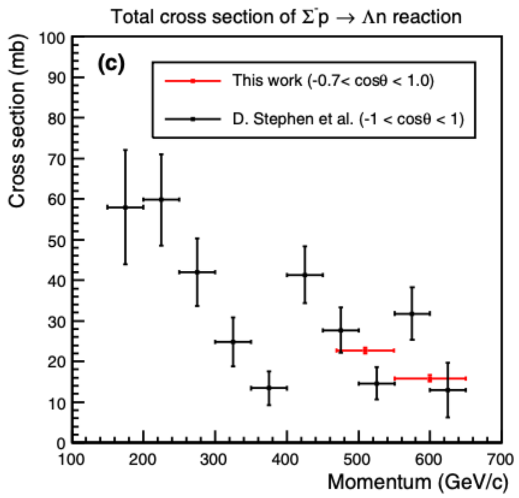


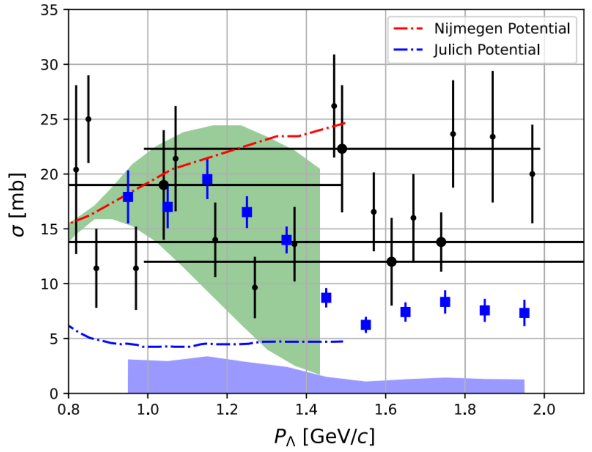




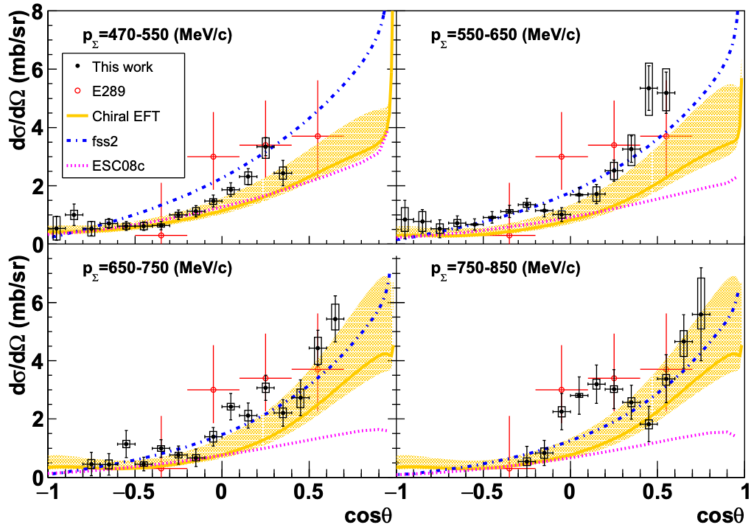
Recent experimental progress on YN interaction

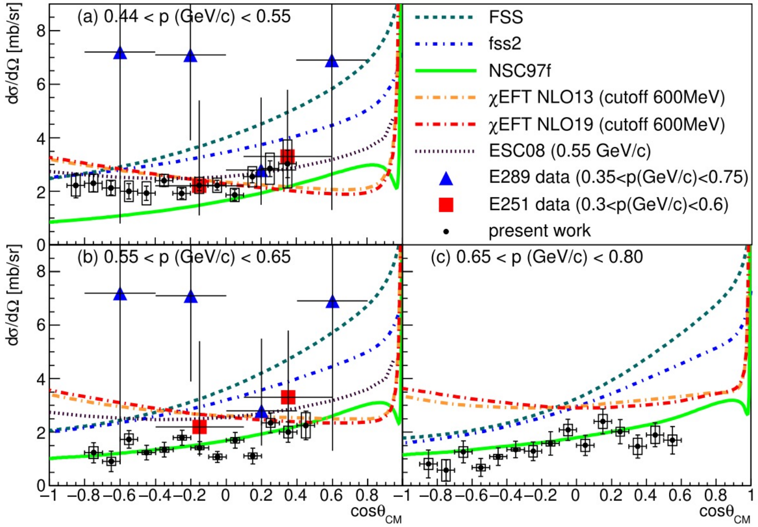






CLAS Collaboration
PHYSICAL REVIEW LETTERS 127, 272303 (2021)



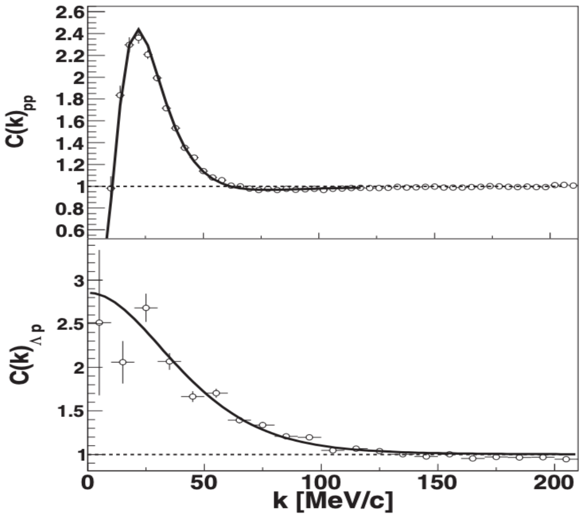


New ΛN and ΣN scattering data: Recent experiments have reported updated measurements, including the first more extensive differential cross-section data for Σ^+p and Σ^-p scattering away from threshold energies.

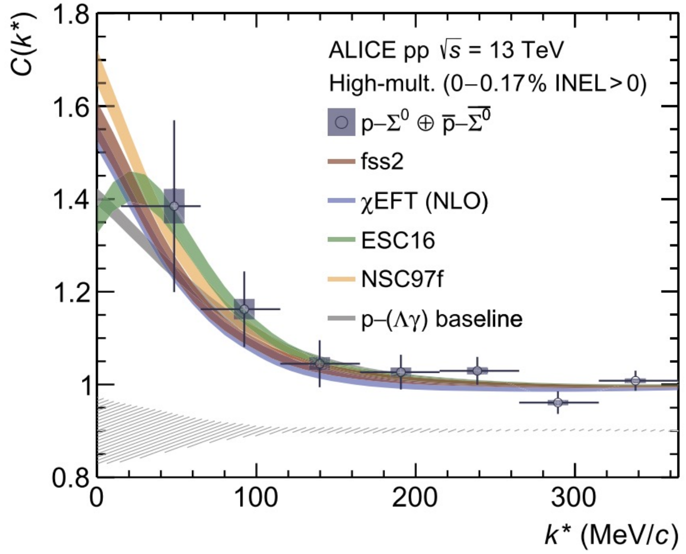
J-RARC E40 Collaboration
PHYSICAL REVIEW C 104, 045204 (2021), PHYSICAL REVIEW LETTERS 128, 072501 (2022), PTEP 2022, 093D01 (2022)

Non-scattering Experiments related to YN interaction

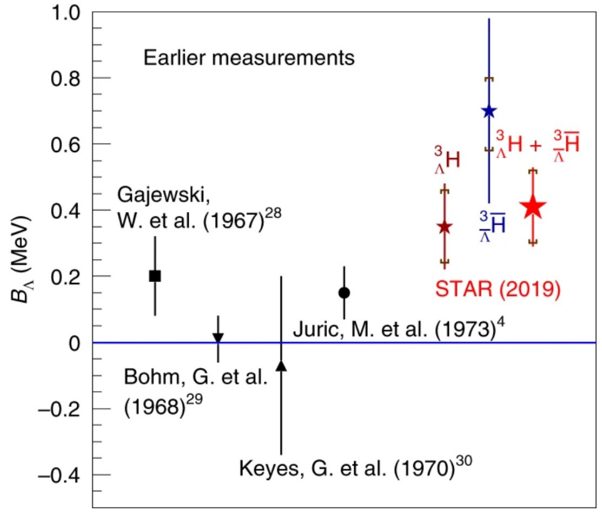
- **Momentum correlation studies**: Two-particle momentum correlation functions involving strange baryons have been measured in heavy-ion and high-energy proton-proton collisions, providing access to YN interactions at very low relative momenta. (ALICE, STAR, HADES)
- **Improved binding energy measurements**: Ongoing efforts aim to achieve more precise determinations of the binding energies of light Λ hypernuclei, offering valuable input for theoretical models. (ALICE STAR)



HADES Collaboration
PHYSICAL REVIEW C 94, 025201 (2016)

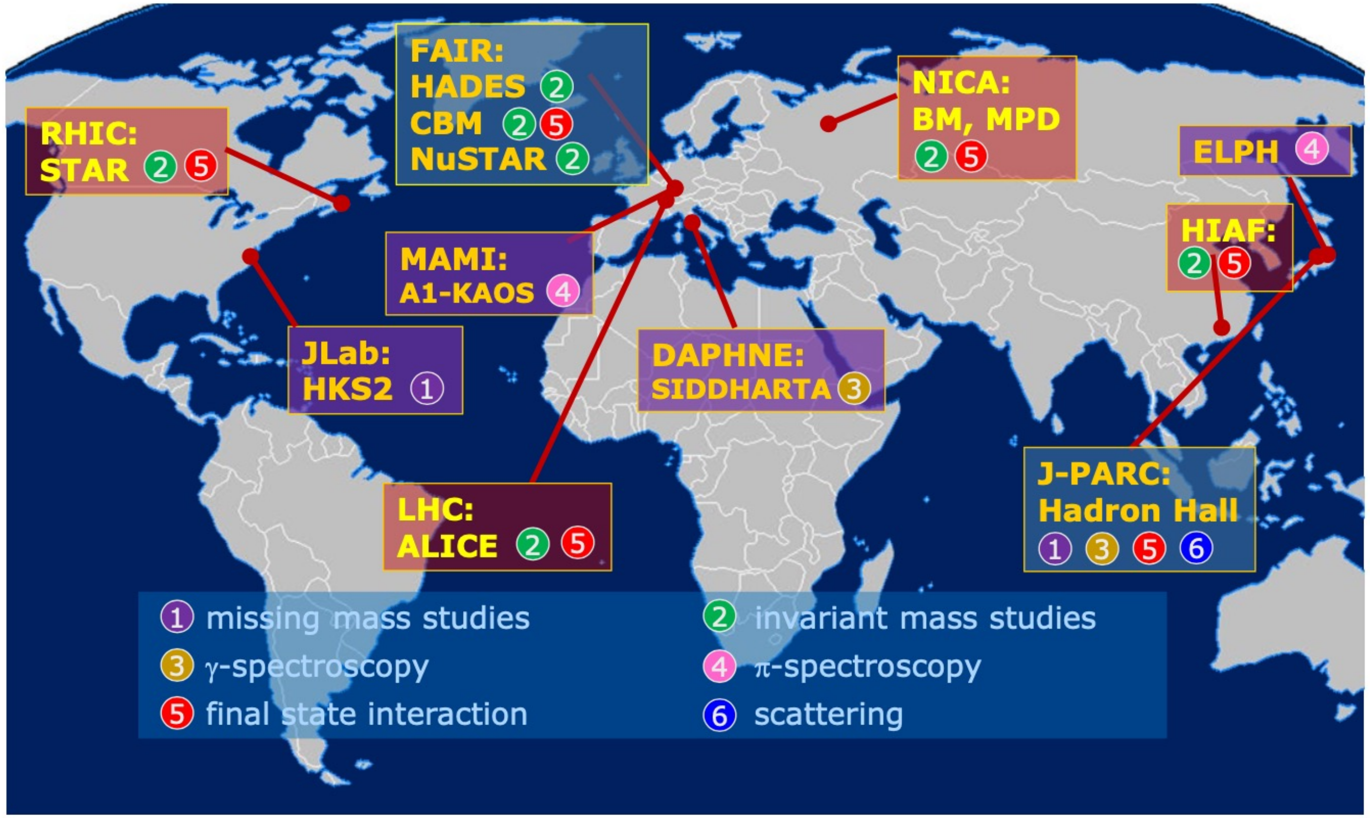


ALICE Collaboration
PHYSICS LETTERS B 805, 135419 (2020)



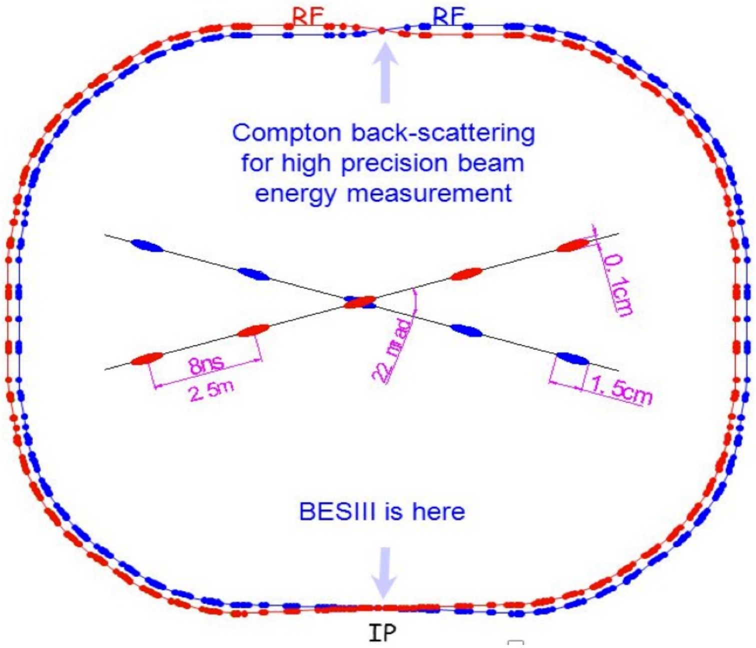
STAR Collaboration
NATURE PHYSICS 16, 409-412 (2020)

Facilities for stangeness nuclear physics



J. H. Chen, L. S. Geng, E. Hiyama, Z. W. Liu and J. Pochodzalla
arXiv:2506.00864 [nucl-th]

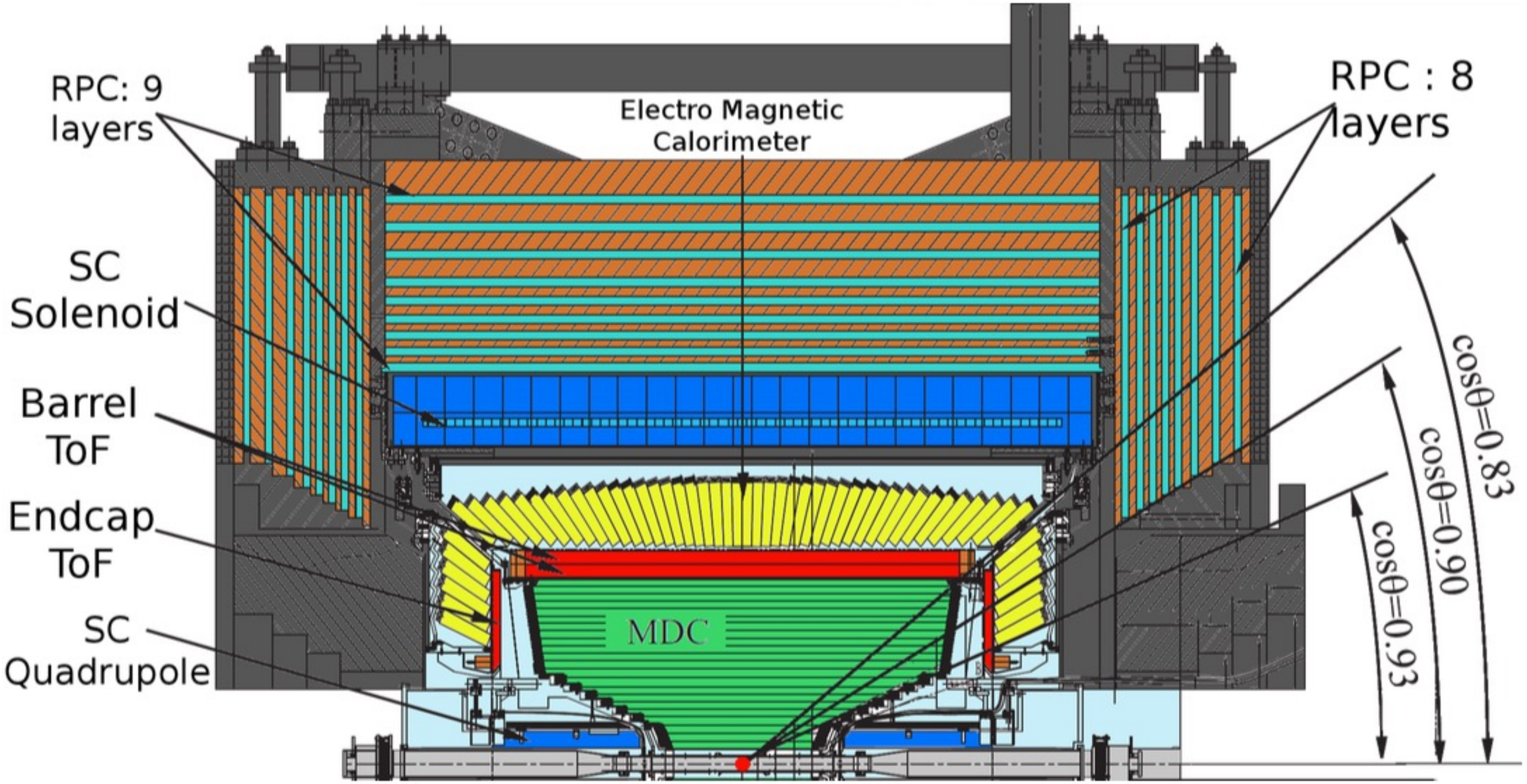
BEPCII storage rings: a τ-charm factory



Update of BEPC (started 2004, first collisions July 2008)

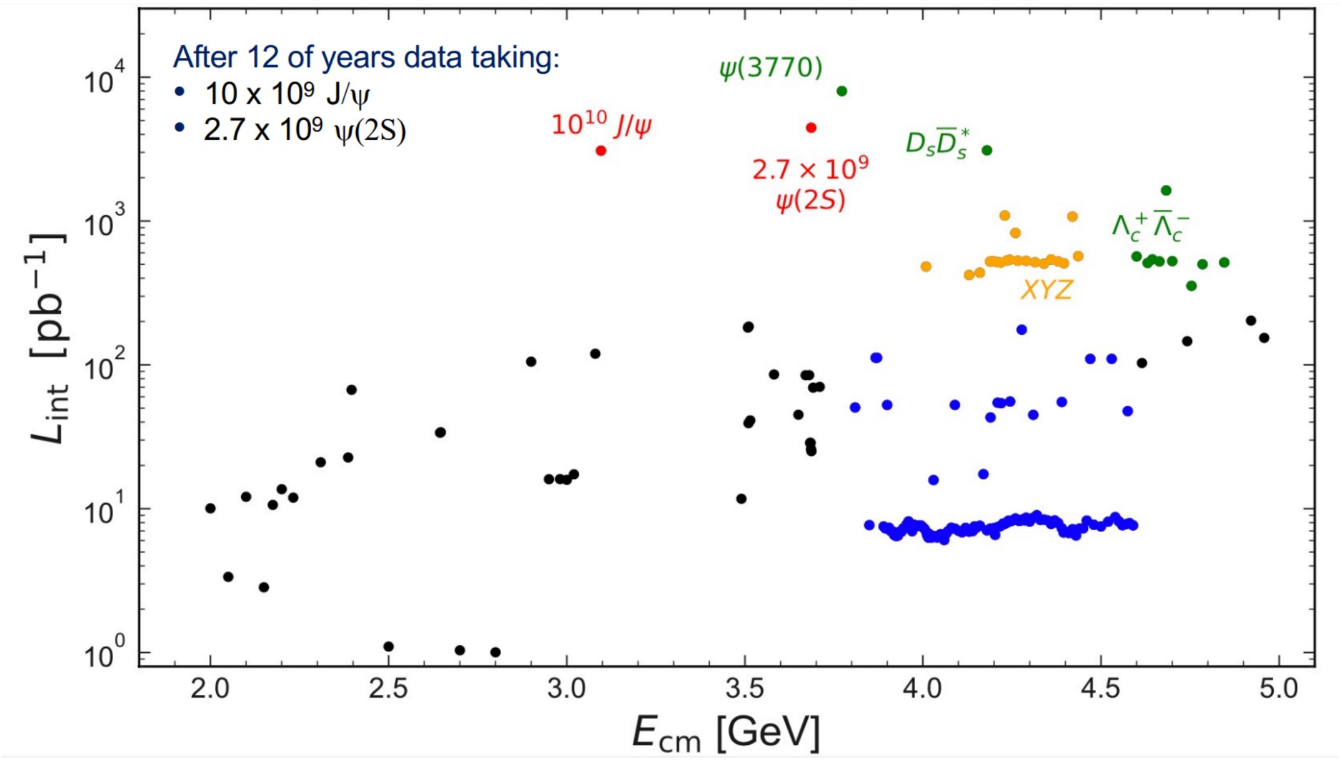
Beam energy	0.92 - 2.475 GeV
Optimum energy	1.89 GeV
Single beam current	0.91 A
Crossing angle	11mrad
Design luminosity	1×10^{33} cm^{-2} s^{-1}
Achieved	1×10^{33} cm^{-2} s^{-1}

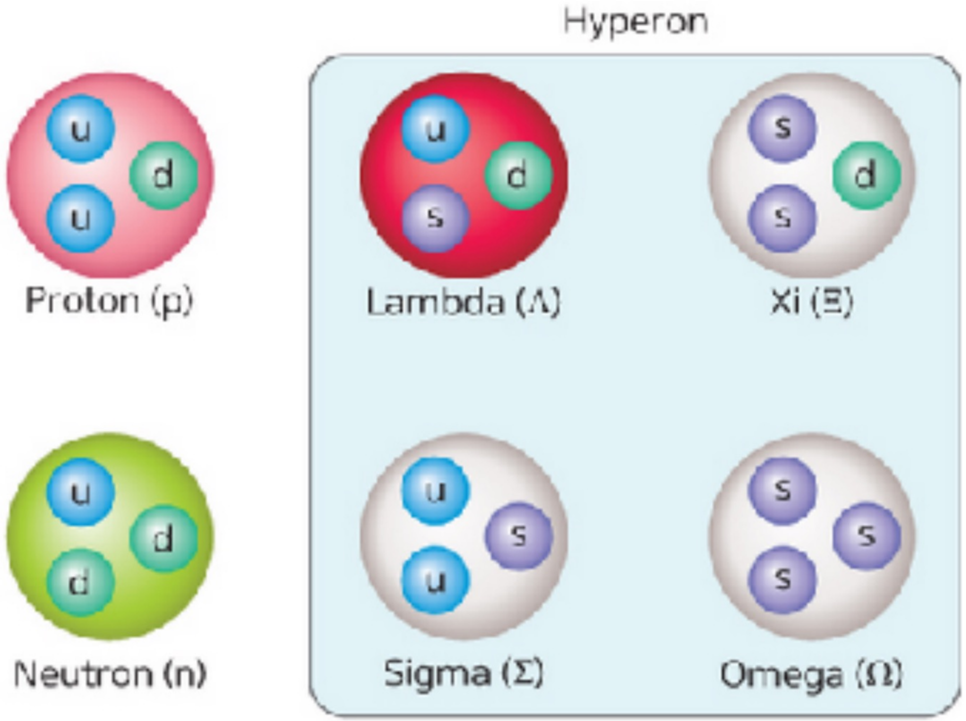
BESIII detectors



- Main Drift Chamber (MDC)
  - σ(p)/p = 0.5%
  - $\sigma_{dE/dX}$ = 5.0%
- Time-of-flight (TOF)
  - σ(t) = 68ps (barrel)
  - σ(t) = 65ps (endcap)
- Electro Magnetic Calorimeter (EMC)
  - σ(E)/E = 2.5%
  - $\sigma_{z,\phi}$(E) = 0.5 – 0.7 cm
- RPC MUON Detector
  - σ(xy) < 2 cm

Hyperon pairs at BESIII





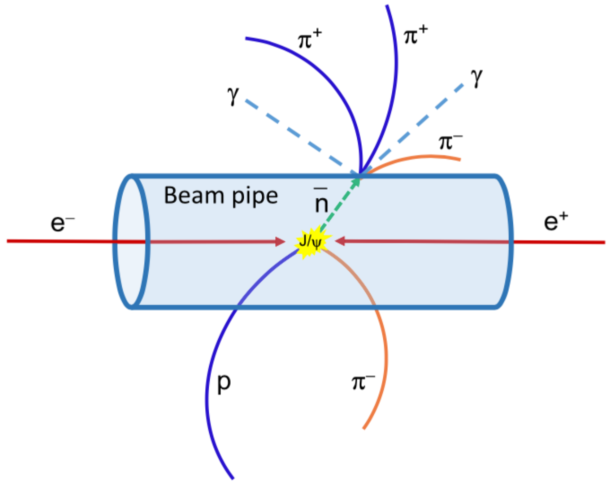
Decay	$\mathcal{B}$ (10^{-5})	Events at BESIII
$J/\psi \rightarrow \Lambda\bar{\Lambda}$	189 ± 9	18.9×10^6
$J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$	150 ± 24	15.0×10^6
$J/\psi \rightarrow \Xi\bar{\Xi}$	97 ± 8	9.7×10^6
$\psi(2S) \rightarrow \Sigma\bar{\Sigma}$	23.2 ± 1.2	116×10^3
$\psi(2S) \rightarrow \Omega\bar{\Omega}$	5.66 ± 0.30	28×10^3

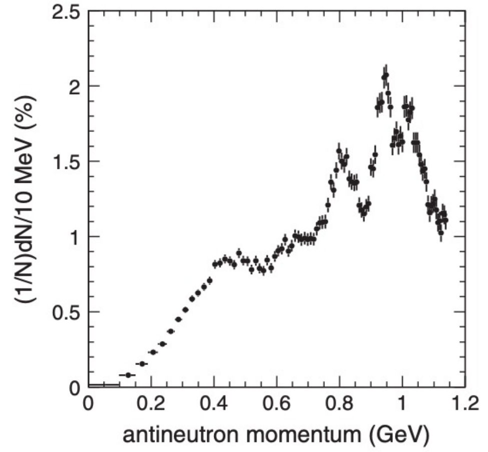
How to study hyperon-nucleon interaction at BESIII

A new fronier: Cornucopia of Antineutrons and Hyperons from a Super J/ψ Factory (by C. Z. Yuan and M. Karliner)

- Key idea : Use J/ψ decays at a high-luminosity e^+e^- collider as copious, clean sources of antineutron and hyperons (Λ Σ Ξ Ω)

- Advantages: High yield, well-known kinematics, in-situ targets, low background levels



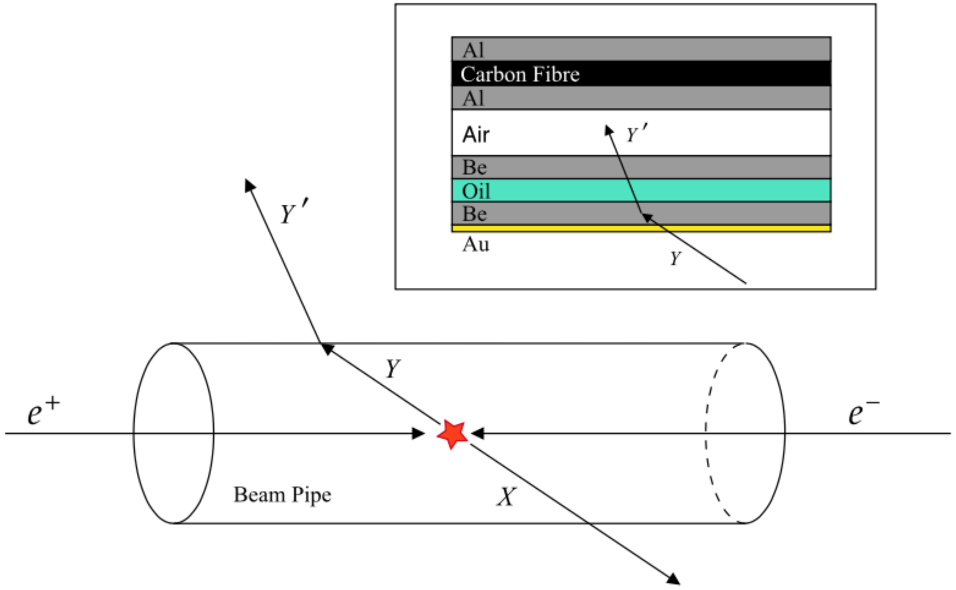


Physical Review Letters 127, 012003 (2021)

Study hyperon-nucleon interaction at BESIII

Prospects to study hyperon-nucleon interaction at BESIII (by J. P. Dai, H. B. Li, H. Miao and J. Y. Zhang)

- Investigate Y-N interactions using hyperons produced at BESIII
- The “double tag” technique to reconstruct the initial and final states



“Single-tag”: Momentum and direction of hyperon Y inferred from reconstructing associated particle X

$$RM_X = \sqrt{|p_{e^+e^-} - p_X|^2}$$

Chinese Physics C 48, 073003 (2024)

Study hyperon-nucleon interaction at BESIII

”Double tag” : Hyperon Y’ from Y-N scattering is reconstructed via its decay products.

$$N_{\mathrm{DT}} = \mathcal{L}_Y \cdot \sigma(YA \to Y'A') \cdot \mathcal{B}(Y') \cdot \epsilon_{\mathrm{sig}}$$

The “effectivie luminosity” ($\mathcal{L}_{\mathrm{Y}}$) : account for the properties of the target and the behavior of the incident hyperon beam.

$$\mathcal{L}_Y = N_{\mathrm{ST}} \cdot \frac{N_A \cdot \rho_T \cdot l}{M}$$

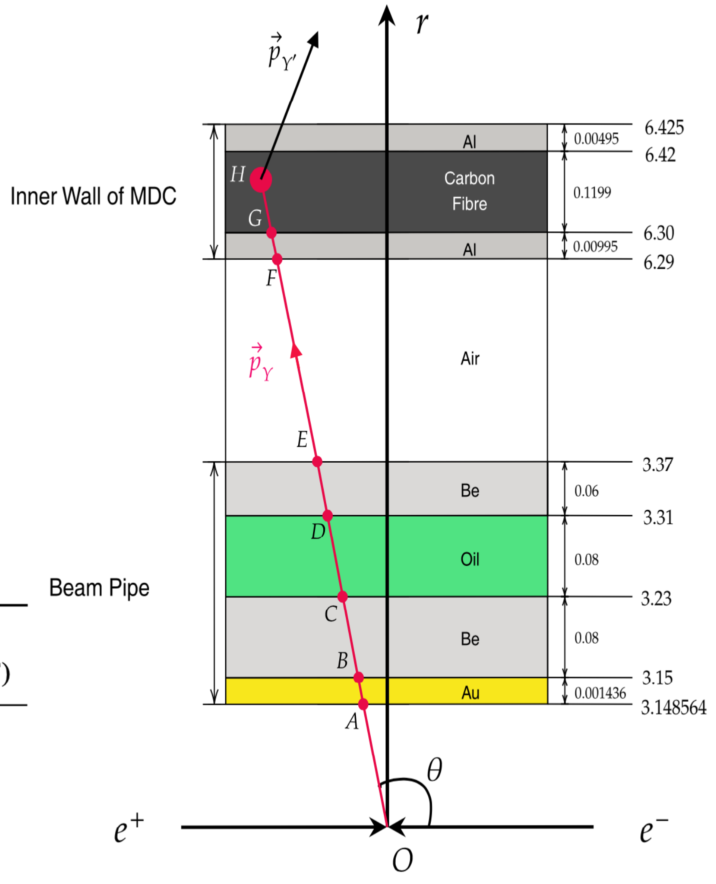
Study hyperon-nucleon interaction at BESIII

The target comprises several layers, the total value $\mathcal{L}_{\mathrm{Y}}$ of is sum of the contribution of each layer.

$$\mathcal{L}_Y = \sum_j^7 \mathcal{L}_Y^j = N_{\mathrm{ST}} \cdot N_A \cdot \sum_j^7 \frac{\rho_T^j \cdot l^j}{M^j} \cdot \mathcal{R}_\sigma^j$$

$$l^j = \frac{\sum_i^{N_{\mathrm{ST}}^{\mathrm{MC}}} l^{ij}}{N_{\mathrm{ST}}^{\mathrm{MC}}}$$

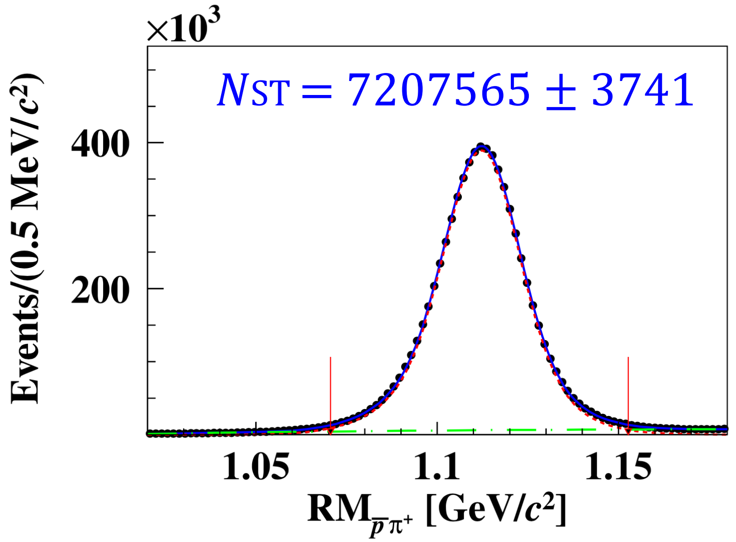
Hyperon	$c\tau$/cm	decay mode	$\mathcal{B}_{\mathrm{decay}}$ [62] ($\times 10^{-3}$)	$p_{\max}$ (MeV/c)	n_{BP}^{Y} ($\times 10^5$ for BESIII or $\times 10^8$ for STCF)	$\mathcal{B}_{\mathrm{tag}}$ (%)	$\mathcal{L}_Y/N_{\mathrm{ST}}(10^{21} \cdot \mathrm{cm}^{-2})$	Estimated signal yield ($\times 10^3$ for STCF)
Λ	7.89	$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	1074	26	64	23.59	5290
Σ^+	2.40	$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	992	4	52	4.83	537
Ξ^0	8.71	$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	818	7	64	15.81	2368
Ξ^-	4.91	$J/\psi \to \Xi^-\bar{\Xi}^+$	0.97 ± 0.08	807	3	64	7.44	924
Ω^-	2.46	$\psi(3686) \to \Omega^-\bar{\Omega}^+$	0.056 ± 0.003	774	0.05	43	2.61	3

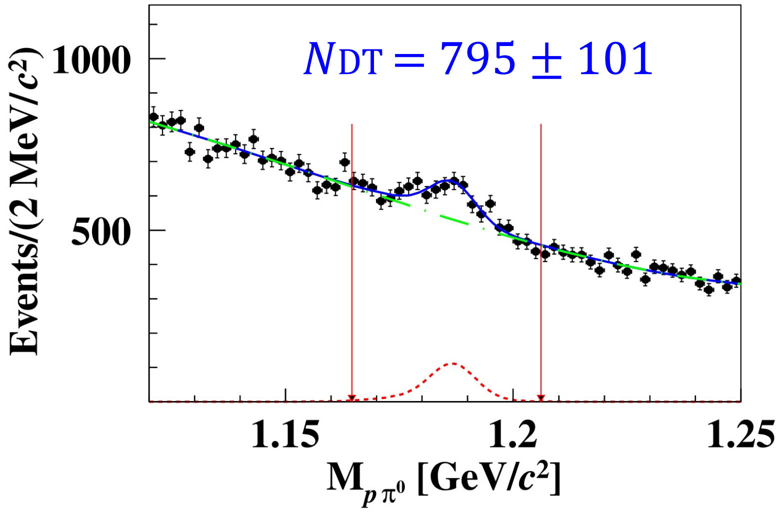


Experimental results (I) $\Lambda + {}^{9}\mathrm{Be} \to \Sigma^{+} X$

First measurement of ΛN inealatic scattering at e+e- collider

Reaction chain: $J/\psi \to \Lambda\bar{\Lambda},\ \bar{\Lambda} \to \bar{p}\pi^{+},\ \Lambda + N(\text{nucleus}) \to \Sigma^{+} + X(\text{anything}),$
$\Sigma^{+} \to p\pi^{0},\ \pi^{0} \to \gamma\gamma.$





Physical Review C 109, L052201 (2024)

Experimental results (I) $\Lambda + {}^9\mathrm{Be} \rightarrow \Sigma^+ X$

$$\sigma(\mathrm{Be}) = \frac{N_{\mathrm{DT}}}{\epsilon_{\mathrm{sig}}\mathcal{L}_{\Lambda}} \frac{1}{\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)}$$

The measured cross section of the reaction process $\Lambda + {}^9\mathrm{Be} \rightarrow \Sigma^+ X$ is

$\sigma(\Lambda + {}^9\mathrm{Be} \rightarrow \Sigma^+ X) = 37.3 \pm 4.7_{\mathrm{stat}} \pm 3.5_{\mathrm{sys}}$ mb at $P_\Lambda \approx 1.074\,\mathrm{GeV}/c$.

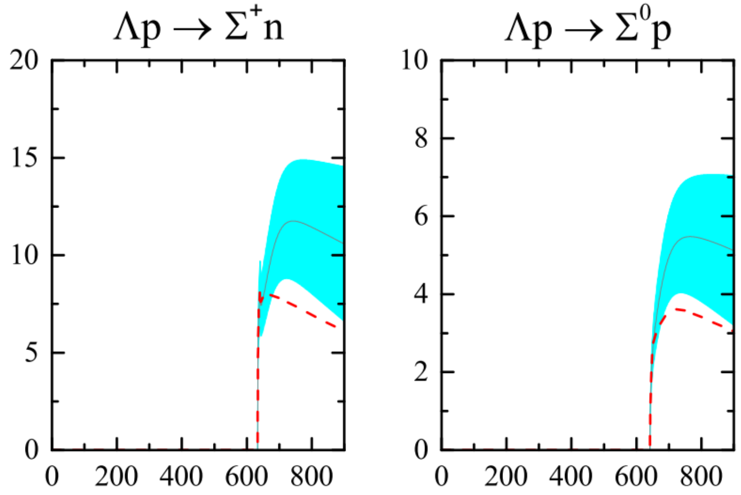
This work represents the first attempt to investigate Λ-nucleus interaction at an e+e- collider.

If taking the effective number of reaction protons in ^{9}Be nucleus as 1.93, the cross section of $\Lambda p \rightarrow \Sigma^+ X$ for single proton is determined to be $\sigma(\Lambda p \rightarrow \Sigma^+ X) = (19.3 \pm 2.4_{\mathrm{stat}} \pm 1.8_{\mathrm{sys}})$ mb.

TABLE I. Inputs used to calculate the cross section of $\Lambda + {}^9\mathrm{Be} \rightarrow \Sigma^+ + X$.

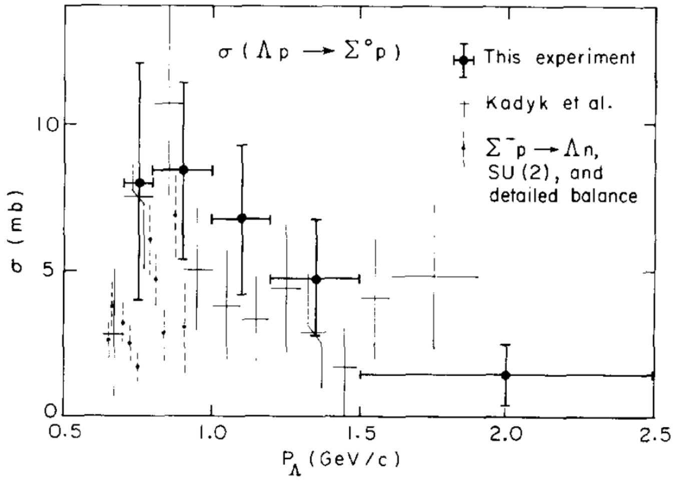
Parameter	Value
N_{DT}	795 ± 101
ϵ_{sig}	24.32%
$\mathcal{L}_{\Lambda}$	$(17.00 \pm 0.01) \times 10^{28}\ \mathrm{cm}^{-2}$
$\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)$	$(51.57 \pm 0.30)\%$

Nucl. Phys. B **27**, 13 (1971).
Nucl. Phys. B **125**, 29 (1977).



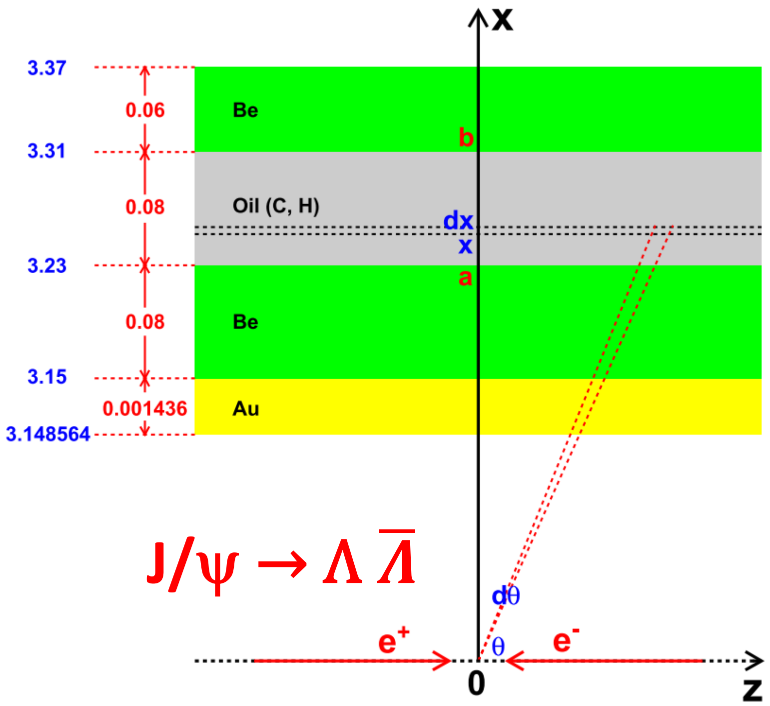
Test of the hyperon-nucleon interaction within leading order covariant chiral effective field theory: higher energies to 900 MeV/c

J. Song, Z. W. Liu, K. W, Li and L. S. Geng
PRC 105, 035203 (2022)

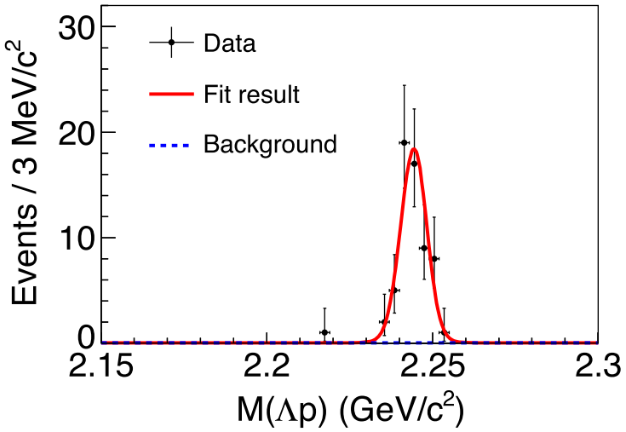


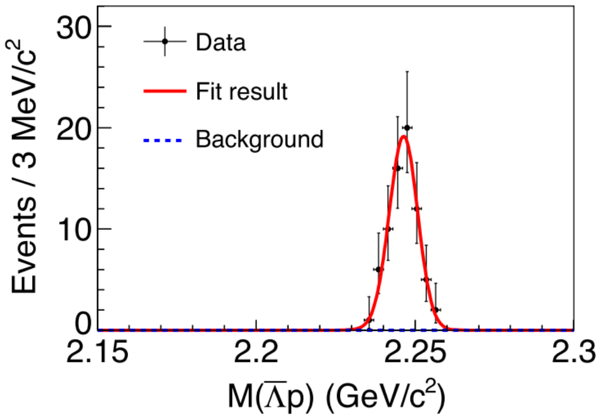
Experimental results (II) $\Lambda p \to \Lambda p$, $\bar{\Lambda} p \to \bar{\Lambda} p$

Using the similar method, the ^{1}H of the cooling oil in the beam pipe, the interaction between (anti)hyperon and proton can be directly extracted.



Two-body decay, $P_{\Lambda/\Lambda} \approx 1.074$ GeV/c

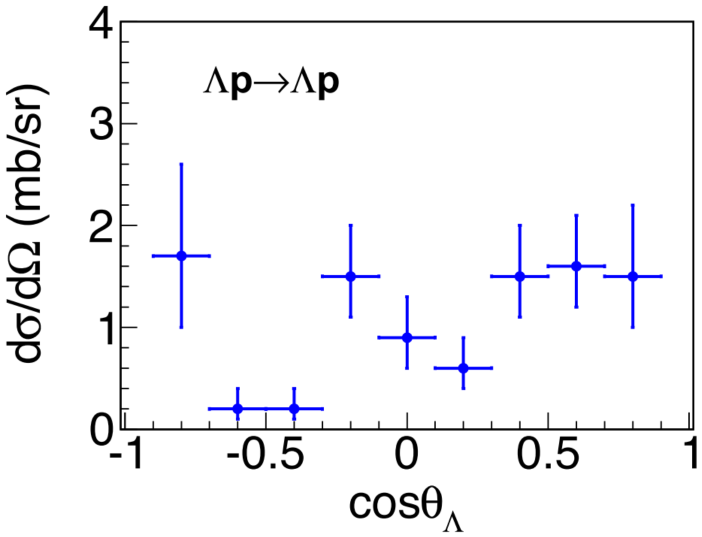


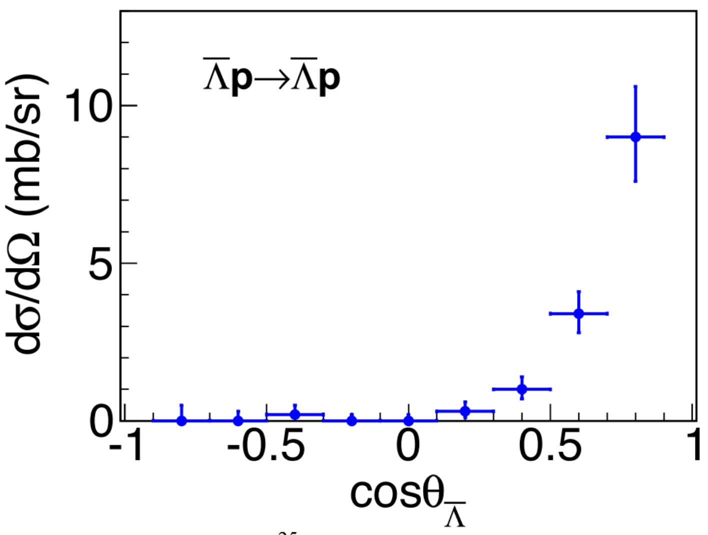


The center-of-mass energies for the incident $\Lambda/\bar{\Lambda}$ and a static p are all 2.243 GeV/c² within a range of 0.005 GeV/c².

Physical Review Letters 132, 231902 (2024)

Experimental results (II) $\Lambda p \rightarrow \Lambda p$, $\bar{\Lambda} p \rightarrow \bar{\Lambda}\, p$





The total elastic cross sections integrated over the full angular region are determined to be

$\sigma(\Lambda p \rightarrow \Lambda p) = 14.2 \pm 1.8_{stat} \pm 1.3_{sys}$ mb

$\sigma(\bar{\Lambda} p \rightarrow \bar{\Lambda}\, p) = 27.4 \pm 3.2_{stat} \pm 2.5_{sys}$ mb

X. Y. Wang, Y. Gao and X. Liu
Physics Letters B 862, 139321 (2025)

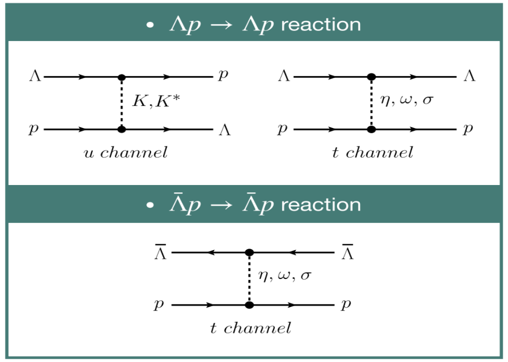
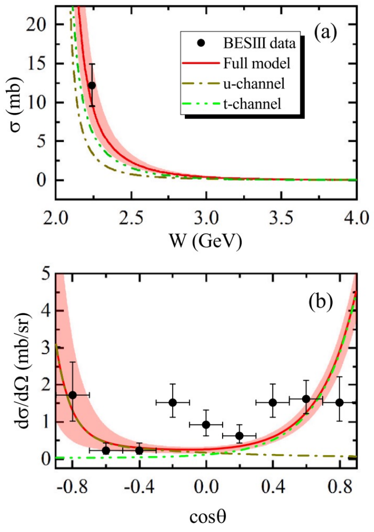
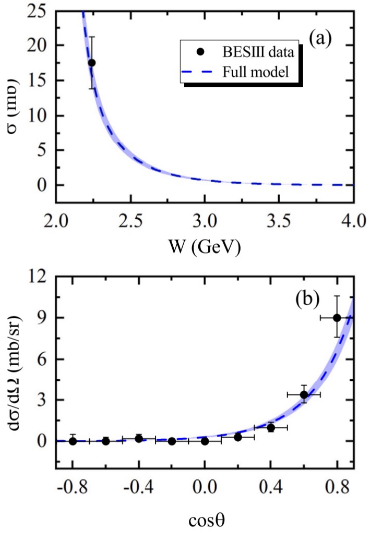
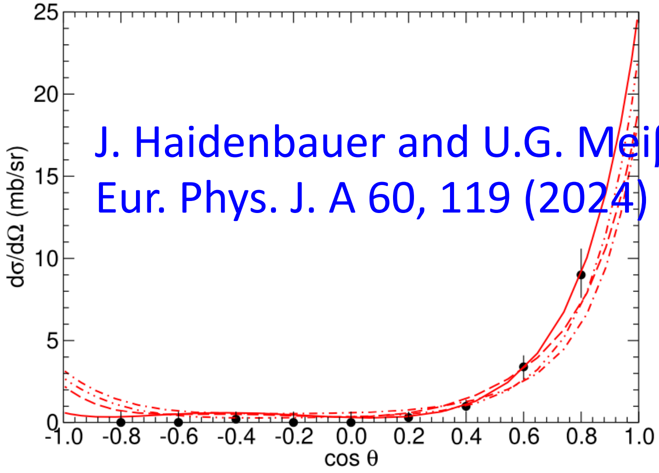


Fig. 1. Feynman diagrams for the $\Lambda p \rightarrow \Lambda p$ and $\bar{\Lambda} p \rightarrow \bar{\Lambda} p$ reactions.







J. Haidenbauer and U.G. Meiβner
Eur. Phys. J. A 60, 119 (2024)

The properties of the $p\bar{\Lambda}$ and $\Lambda\bar{\Lambda}$ interactions can be expected to be very similar

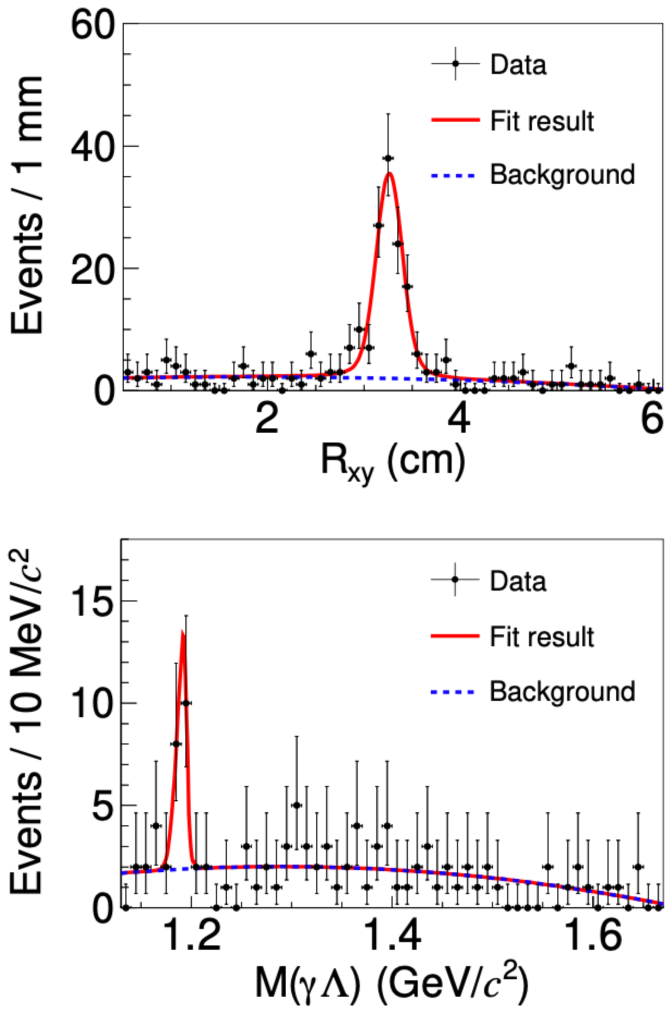
This discrepancy arises because the u-channel contribution is forbidden

Experimental results (III) $\Sigma^+ n \to \Lambda p$ $\Sigma^+ n \to \Sigma^0 p$

Σ^+ source: $J/\psi \to \Sigma^+ \bar{\Sigma}^-$, with Momentum = 0.992 GeV/c

With the vertex fit of Λ p, the total number of Λ p and Λ p γ events are N_{total} = 126.2 ± 13.4.

By fitting the invariant mass of γ Λ, we could separate two signal events.

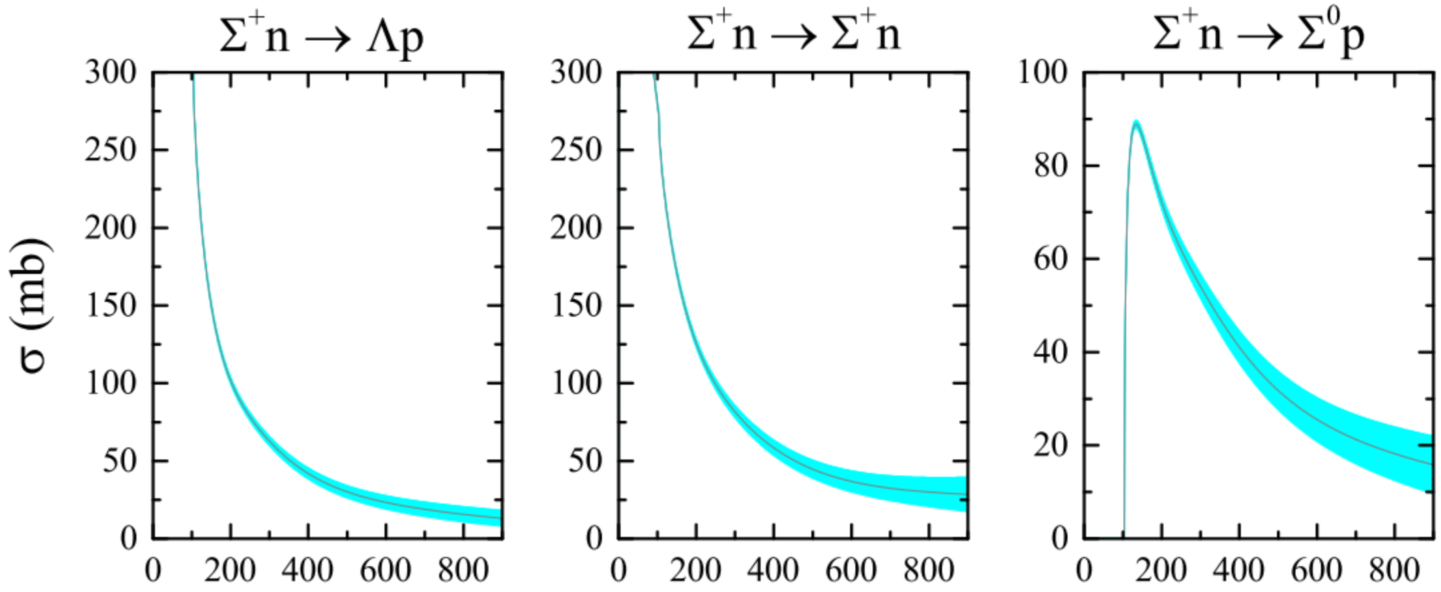


arXiv:2505.19907 [hep-ex]

Experimental results (III) $\Sigma^{+}n \rightarrow \Lambda p$ $\Sigma^{+}n \rightarrow \Sigma^{0}\,p$

The cross-sections of these two reactions are measured to be
$\sigma(\Sigma^{+}+{}^{9}Be \rightarrow \Lambda+p+{}^{8}Be)=(45.2\pm12.1_{stat}\pm7.2_{sys})$mb and $\sigma(\Sigma^{+}+{}^{9}Be \rightarrow \Sigma^{0}+p+{}^{8}Be) = (29.8\pm9.7_{stat}\pm 6.9_{sys})$ mb

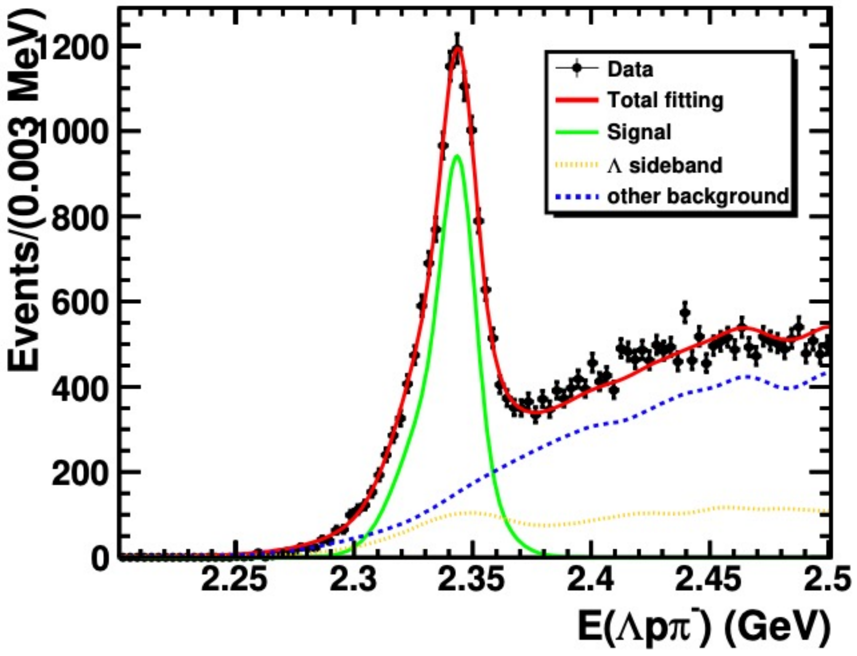
Assuming the effective number of reaction neutrons in a beryllium nucleus to be approximately 3, the cross-sections of $\Sigma^{+}n \rightarrow \Lambda p$ and $\Sigma^{+}n \rightarrow \Sigma^{0}p$ for a single neutron are determined to be
$\sigma(\Sigma^{+}n \rightarrow \Lambda p) = (15.1 \pm 4.0_{stat} \pm 2.4_{sys})$ mb and $\sigma(\Sigma^{+}n \rightarrow \Sigma^{0}p) = (9.9 \pm 3.2_{stat} \pm 2.3_{sys})$ mb

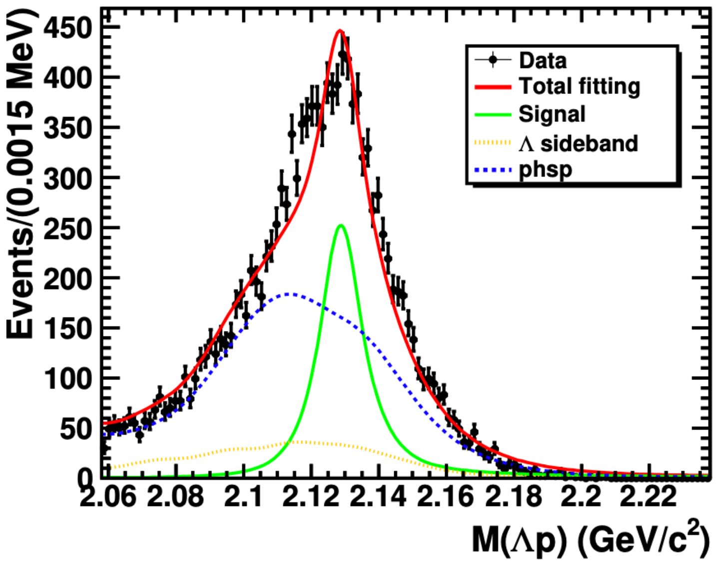


J. Song, Z. W. Liu, K. W, Li and L. S. Geng
PRC 105, 035203 (2022)

Study Λ-Proton invariant mass (in progress)

$$K^- + d \rightarrow \Lambda\, p\, \pi^-$$





N_{sig}	Mass (MeV/c^2)	Width (MeV)
3392 ± 152	2125.8 ± 0.4	8.3 ± 0.6

Blow the Σ n threshold (2128.9 MeV/c^2)
binding energy 3 MeV, Σ n bound state?

Discussion and Outlook

Ongoing reserches on YN scattering at BESIII

- ❖ $\boldsymbol{\Lambda p \to \Sigma^0 p,\ \bar{\Lambda} p \to \bar{\Sigma}^0 p}$
- ❖ $\boldsymbol{\Xi^0 n \to \Lambda\Lambda,\ \Xi^- p \to \Lambda\Lambda}$
- ❖ $\boldsymbol{\Sigma^+ p \to \Sigma^+ p,\ \bar{\Sigma}^- p \to \bar{\Sigma}^- p}$
- ❖ $\boldsymbol{\Xi^- p \to \Xi^- p,\ \bar{\Xi}^+ p \to \bar{\Xi}^+ p}$

The upcoming STCF collider, with a peak luminosity 100 times that of BEPCII and improved energy resolution (down to 20–80 keV), will enable the production of 10^{12}–10^{13} J/ψ per year—yielding 10^6–10^7 scattering events annually.

- The differential cross section with the momentum
- Relationship between cross section and the incident hyperon polarization
- The study of polarization of the produced hyperons

M. Achasov, et al., STCF conceptual design report
Front. Phys. 19(1), 14701 (2024)

Summary

- BESIII provides a unique platform to study YN interactions through clean and abundant hyperon production in e^+e^- collisions, especially leveraging the quantum-entangled hyperon pairs from **J/ψ** decays.
- Our recent studies at BESIII include the **first measurement of $\Lambda + {}^9Be \rightarrow \Sigma^+ X$**, providing the first insight into Λ-nucleus scattering at an e^+e^- collider, and new constraints on $\mathbf{\Sigma^+ n \rightarrow \Lambda p}$ and $\mathbf{\Sigma^+ n \rightarrow \Sigma^0 p}$ cross-sections.
- The future **STCF** collider, with unprecedented luminosity and precision, will dramatically enhance the event yield, enabling high-statistics studies of YN and Y-A interactions.

THANK YOU