Study of hyperon-nucleon interactions at BESIII

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MENU 2023 - The 16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

Outline

- Motivation
- BEPCII and BESIII
- Study of $\Xi^0 n \to \Xi^- p$
  Phys. Rev. Lett. 130, 251902 (2023)
- Study of $\Lambda N \to \Sigma^+ X$
  arXiv: 2310.00720
- Summary

Scattering experiments of particle beams bombarding target materials

1911

Ernest Rutherford

$\alpha + \mathrm{Au}$

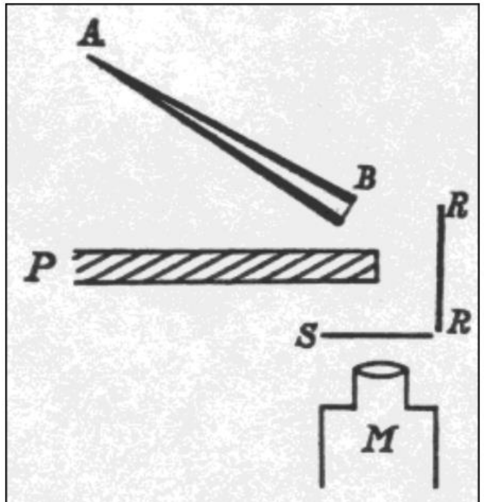


Fig. 1.

→ Nuclear structure model of atom

1919 $\alpha + \mathrm{N}$ → Observation of proton

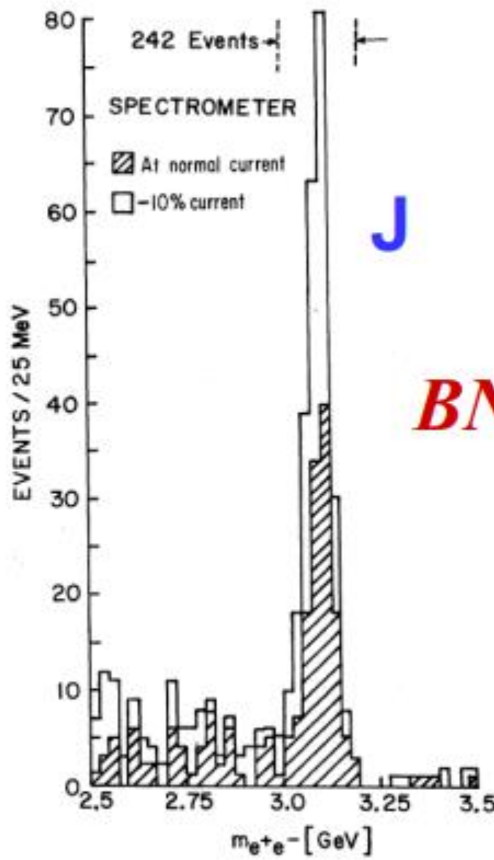
1932 $\alpha + \mathrm{Be}$ → Observation of neutron

James Chadwick

Scattering experiments of particle beams bombarding target materials

1974

$p + \mathrm{Be} \rightarrow e^+e^-X$



J.J. Aubert et al., PRL 33, 1404 (1974)

J

BNL

Discovery of the fourth type of quark:
Charm quark

"November Revolution in Physics"

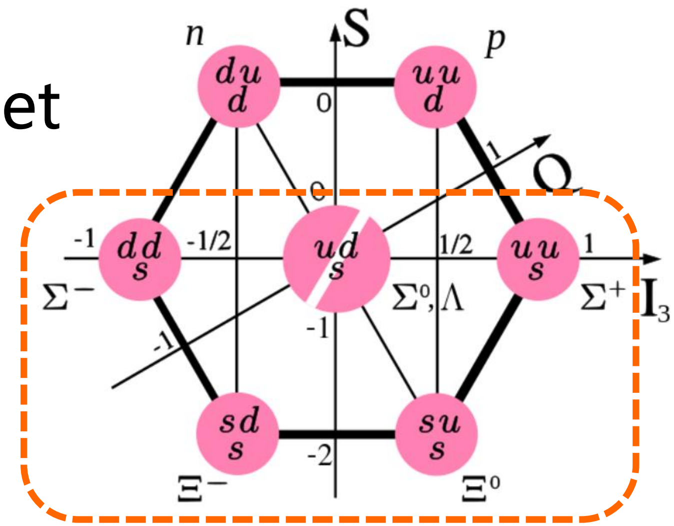
Nobel Prize 1976

Scattering experiment must have **particle source**, target material, and detector.

Hyperon source

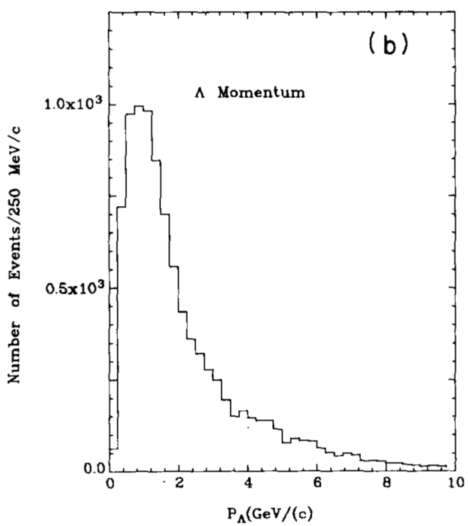
Baryon octet

One of main goals of nuclear physics is to understand baryon-baryon interaction in a unified perspective

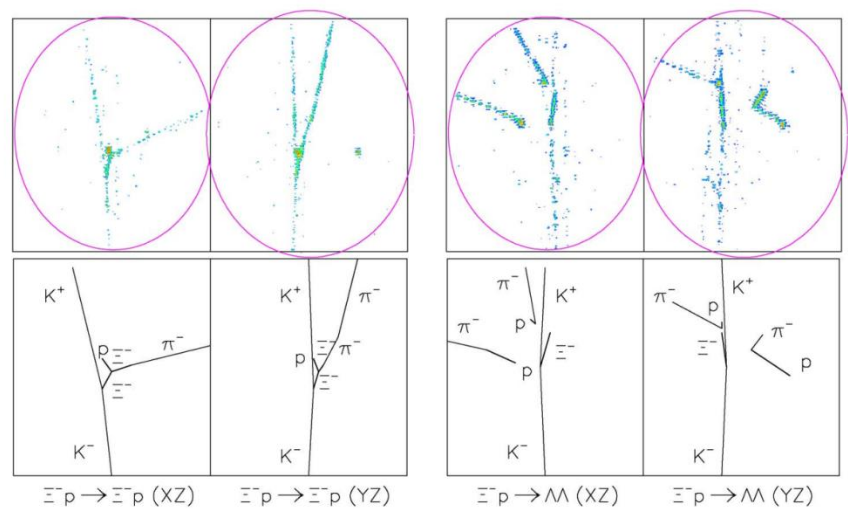


Limited by availability and short-lifetime of hyperon beams

- Hyperons are obtained by bombarding hydrogen bubble chamber or scintillating fiber target with K^-.



Nucl. Phys. B 125, 29 (1977)



Phys. Lett. B 633, 214 (2006)

Hyperon source

- Hyperons are obtained by bombarding hydrogen bubble chamber or scintillating fiber target with K^-.
- Intensity of hyperon beams is low, experimental measurements are scarce and have large uncertainty.
- No anti-hyperon source.

Reaction	Number of events	
$\Lambda p \to \Lambda p$ (elastic)	584	(1)
$\Lambda p \to \Sigma^- p \pi^+$	132	(2)
$\Lambda p \to \Sigma^+ p \pi^-$	60	(3)
$\Lambda p \to \Lambda p \pi^+ \pi^-$	181	(4)
$\Lambda p \to \Sigma^0 p$	35	(5)
various $\Xi^0 p$ interactions	25	

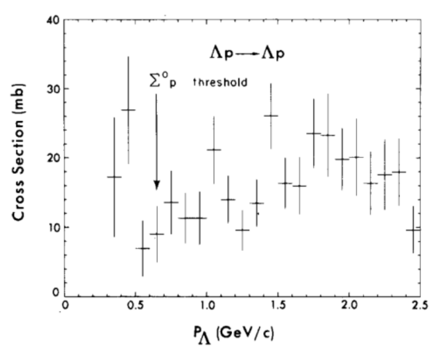
Phys. Lett. B 38, 123 (1972)

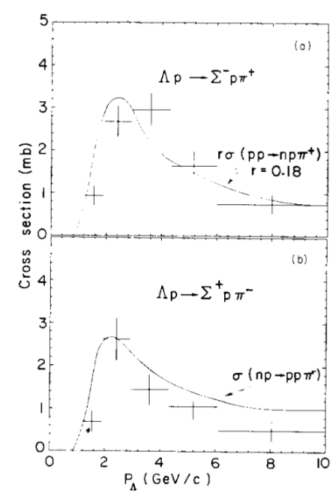
reaction	events *	signature	cross-section events **	cross-section (mb)
$\Xi^0 + p \to \Xi^0 + p$	2	K, Λ	1	8
$\Xi^0 + p \to \Lambda + \Sigma^+$	6	Λ	4	24
$\Xi^0 + p \to \Sigma^0 + \Sigma^+$	1	Λ	1	6
$\Xi^0 + p \to \pi^+ + \Lambda + \Lambda$	1	K, Λ	1	6
$\Xi^0 + p \to \pi^0 + \Lambda + \Sigma^+$	1	Λ	1	6
$\Xi^0 + p \to \pi^+ + \Xi^- + p$	1	K or Λ	1	5
$\Xi^0 + p \to \pi^+ + \pi^+ + \Xi^- + n$	1	K, Λ	1	6
$\Xi^0 + p \to \Xi^- + p$	2	Λ	2	8
$\Xi^0 + p \to \Sigma^- + \Sigma^+$	1	K	1	4
$\Xi^0 + p \to \Sigma^- + K^0 + p$	1	K	1	4

Phys. Lett. B 32, 720 (1970)

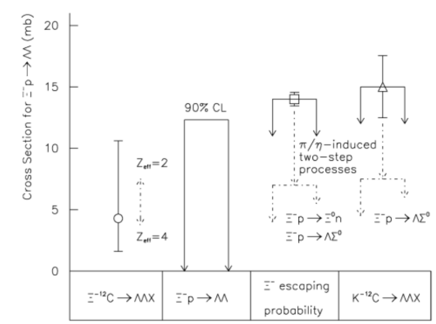
Reaction	Momentum interval (GeV/c)	Number of events	σ (mb)
$\Lambda p \to$ all	0.5 → 1.0		25.8 ± 6.2
	1.0 → 1.5		31.3 ± 6.5
	1.5 → 2.0		42.8 ± 7.1
	2.0 → 2.5		37.5 ± 7.2
	2.5 → 3.0		34.1 ± 8.3
	3.0 → 4.0		41.8 ± 10.0
$\Lambda p \to \Lambda p$	0.5 → 1.0	20	22.2 ± 5.0
	1.0 → 1.5	21	12.9 ± 2.8
	1.5 → 2.0	37	22.0 ± 3.6
	2.0 → 2.5	28	16.1 ± 3.1
	2.5 → 3.0	12	11.0 ± 3.2
	3.0 → 4.0	13	12.5 ± 3.4
$\Lambda p \to \Sigma^0$	0.66 → 4.0	11	1.5 ± 0.5
$\Lambda p \to \Lambda p \pi^0$	0.88 → 4.0	29	4.1 ± 0.8
$\Lambda p \to \Lambda p \pi^+ \pi^-$	1.36 → 4.0	12	1.9 ± 0.6
$\Sigma^+ p \to \Sigma^+ p$	0.5 → 1.5	10	31.2 ± 10.1
	1.5 → 2.5	8	18.7 ± 6.6
	2.5 → 4.0	4	15.3 ± 7.8
$\Sigma^- p \to \Sigma^- p$	0.5 → 1.5	6	13.2 ± 4.7
	1.5 → 2.5	11	13.9 ± 4.1
	2.5 → 4.0	4	7.5 ± 3.8
$\Xi^- p \to \Xi^- p$	1.0 → 4.0	6	13 ± 6
$\Xi^0 p \to \Xi^0 p$	1.0 → 4.0	4	19 ± 10

Nucl. Phys. B 125, 29 (1977)



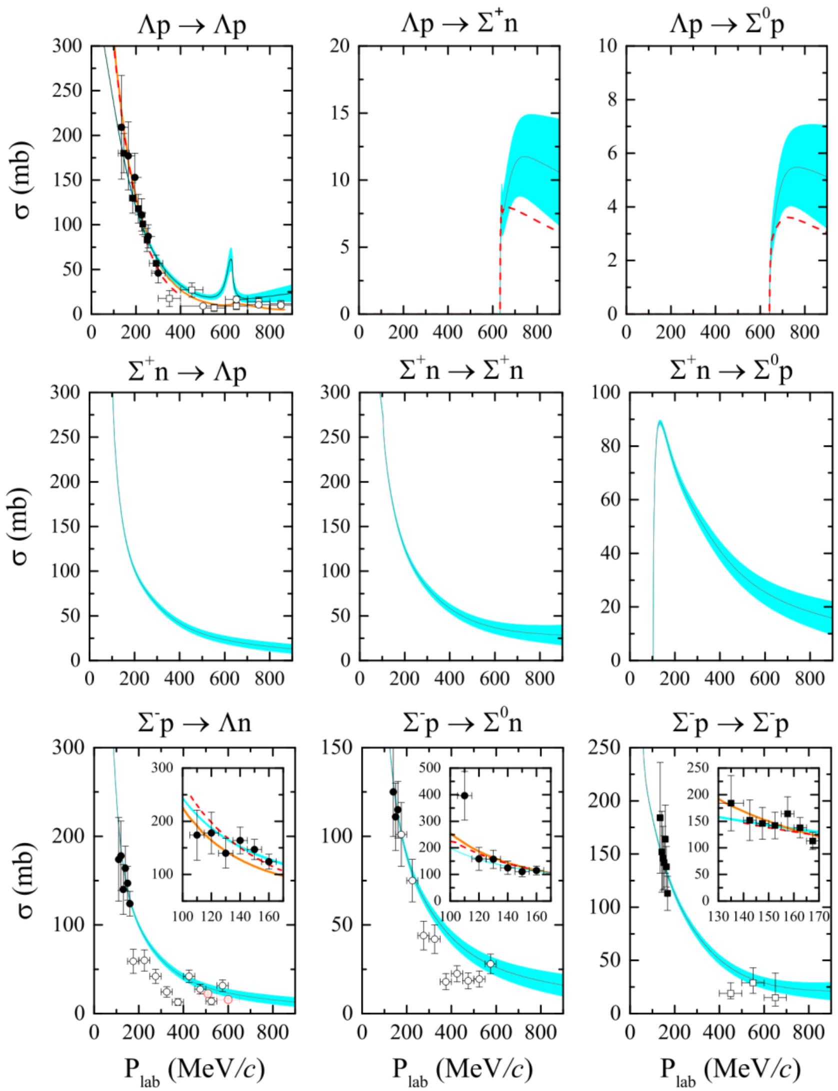


Phys. Lett. B 633, 214 (2006)



Theory of hyperon-nucleon (YN) interaction has large uncertainty due to lack of relevant measurements

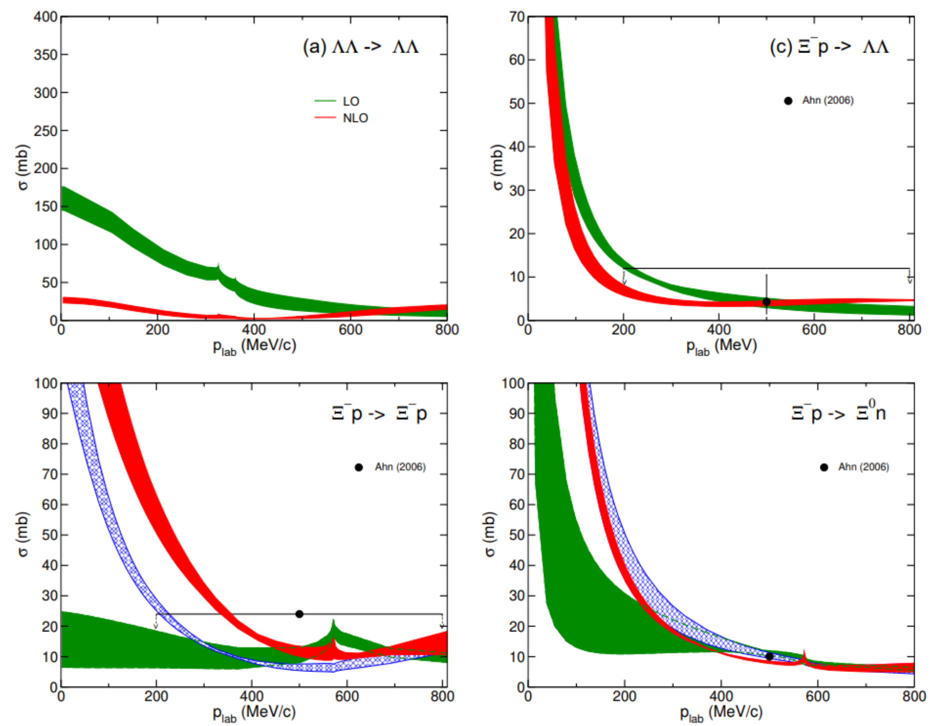
Phys. Rev. C 105, 035203 (2022)



LO : H. Polinder, J.H., U.-G. Meißner, PLB 653 (2007) 29

NLO16: J.H., U.-G. Meißner, S. Petschauer, NPA 954 (2016) 273

NLO19: J.H., U.-G. Meißner, EPJA 55 (2019) 23

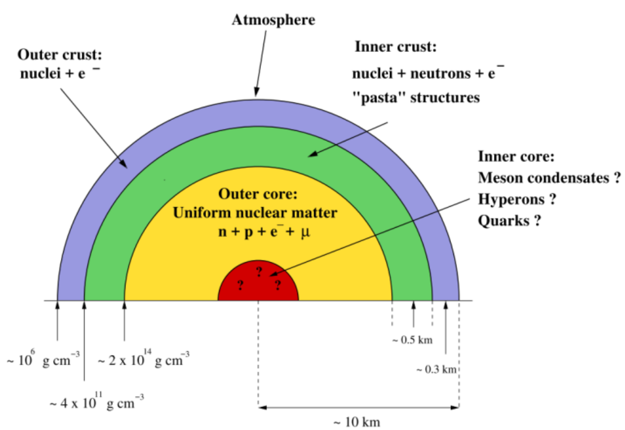


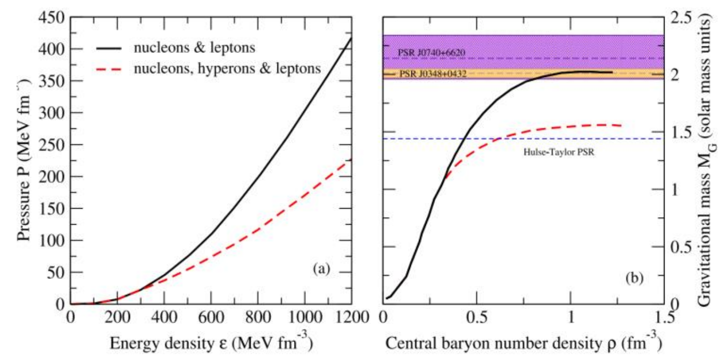
"Hyperon puzzle" of neutron stars

- Hyperons are believed to be appeared in inner core of neutron stars.

$$B_1 \to B_2 + l + \bar{\nu}_l,\ B_2 + l \to B_1 + \nu_l$$
$$n \to p + e^- + \bar{\nu}_e, p + e^- \to n + \nu_e$$
$$\Lambda \to p + e^- + \bar{\nu}_e, p + e^- \to \Lambda + \nu_e$$

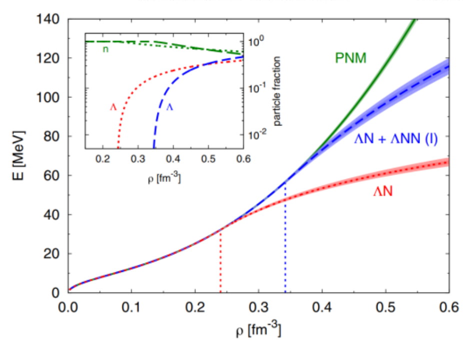
- Appearance of hyperons softens equation of state, lead to maximum mass that neutron stars can sustain is less than mass of already-observed neutron stars.
- A repulsive force is introduced to stiffen equation of state in theory, such as a combination of ΛN and ΛNN interactions. Study of hyperon-nucleon interaction is crucial to solve "hyperon puzzle" of neutron stars.

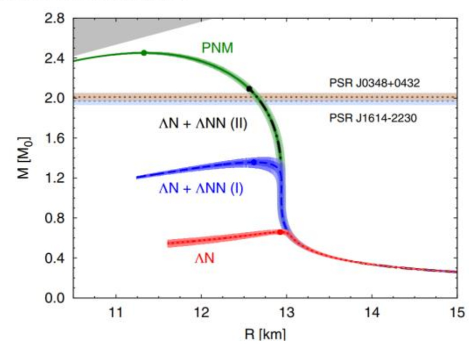




Prog. Part. Nucl. Phys. 112, 103770 (2020)

Phys. Rev. Lett. 114, 092301 (2015)



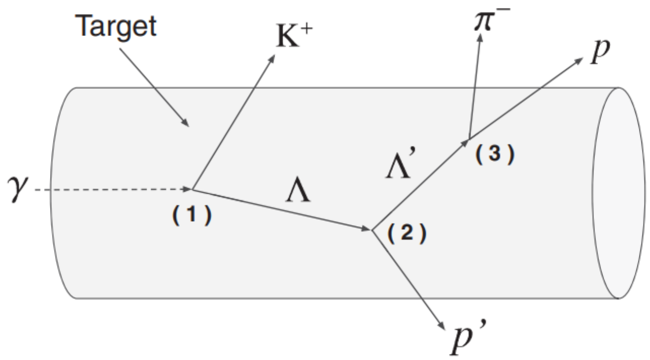


Some recent experimental results of hyperon-nucleon scattering

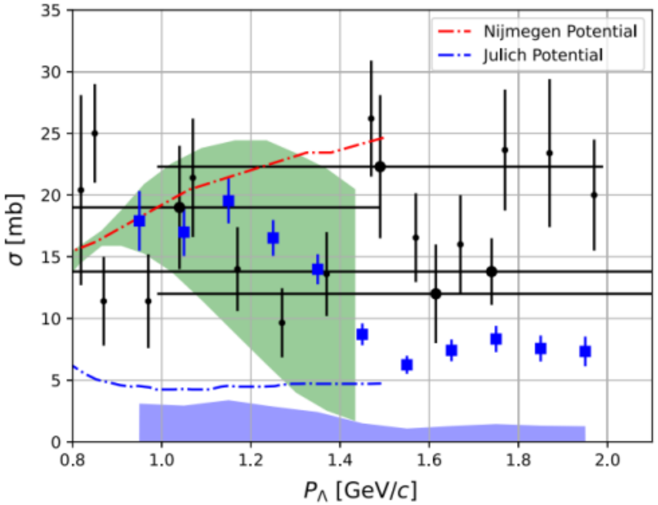
PHYSICAL REVIEW LETTERS **127,** 272303 (2021)

(CLAS Collaboration)

Improved Λp Elastic Scattering Cross Sections between 0.9 and 2.0 GeV/*c* as a Main Ingredient of the Neutron Star Equation of State

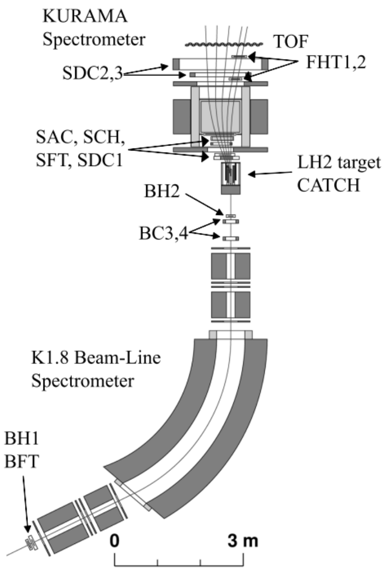


$\Lambda p \rightarrow \Lambda p$



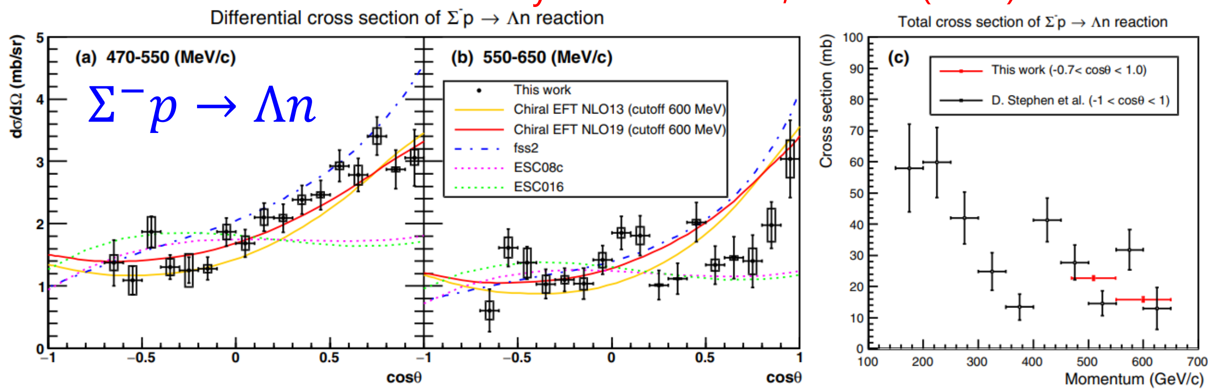
This is the first data on this reaction since the 1970s.

Some recent experimental results of hyperon-nucleon scattering

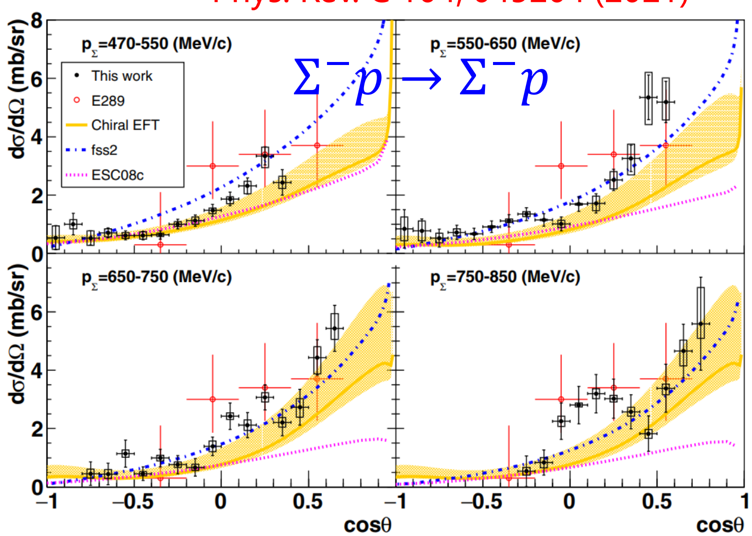


J-PARC E40 Collaboration

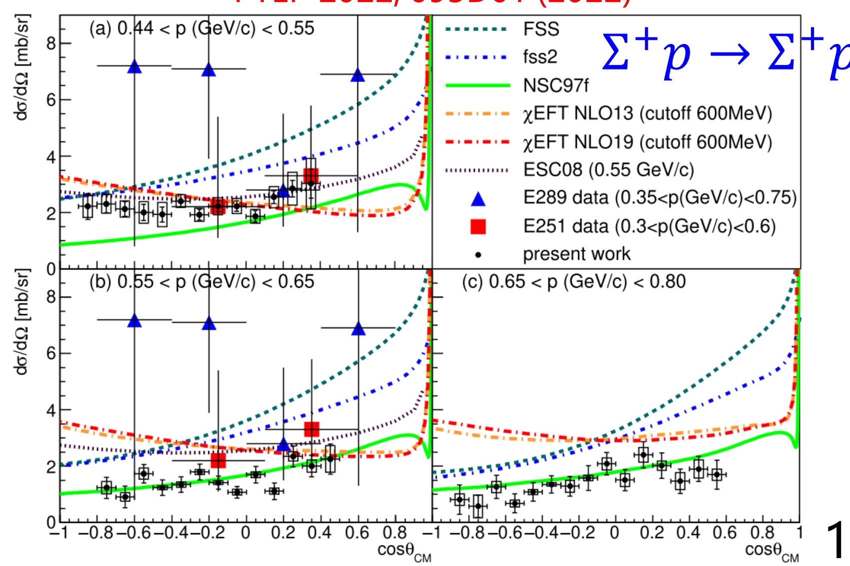
Phys. Rev. Lett. 128, 072501 (2022)



Phys. Rev. C 104, 045204 (2021)

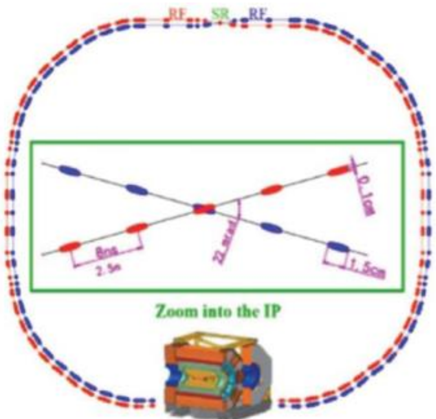


PTEP 2022, 093D01 (2022)



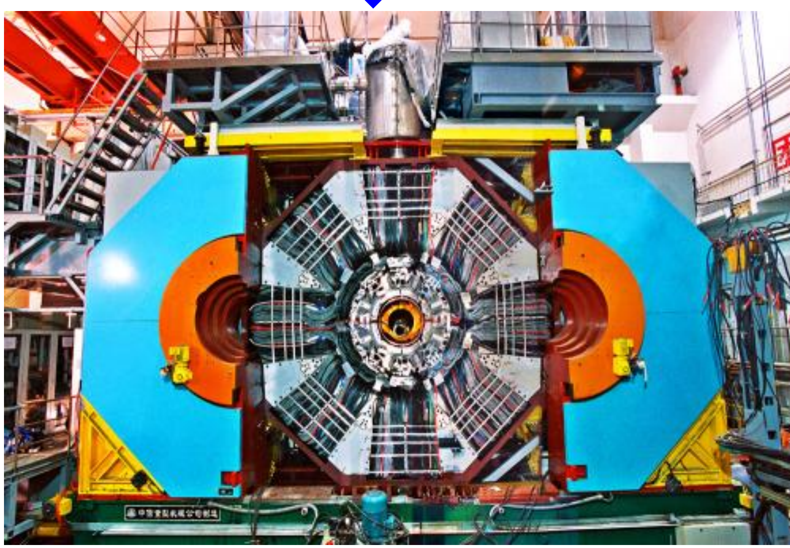
Beijing Electron Positron Collider II (BEPCII) and Beijing Spectrometer III (BESIII)

tau-charm energy region



Storage ring

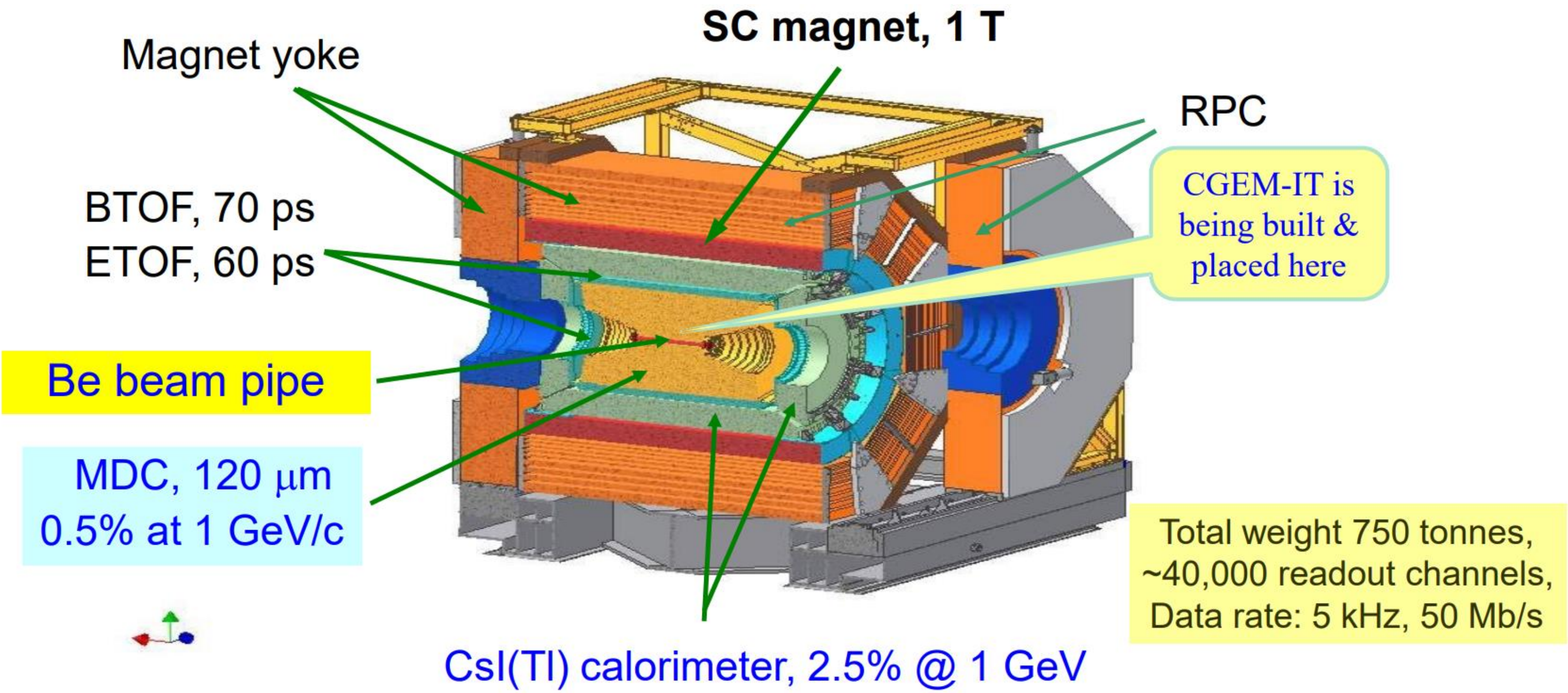
Linear accelerator



BESIII detector

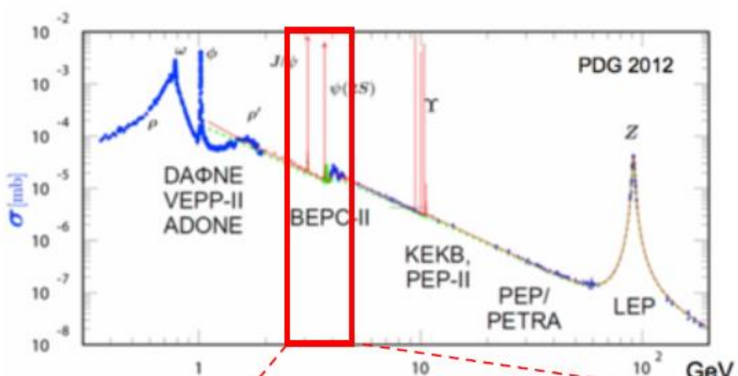
BEPCII

BESIII detector



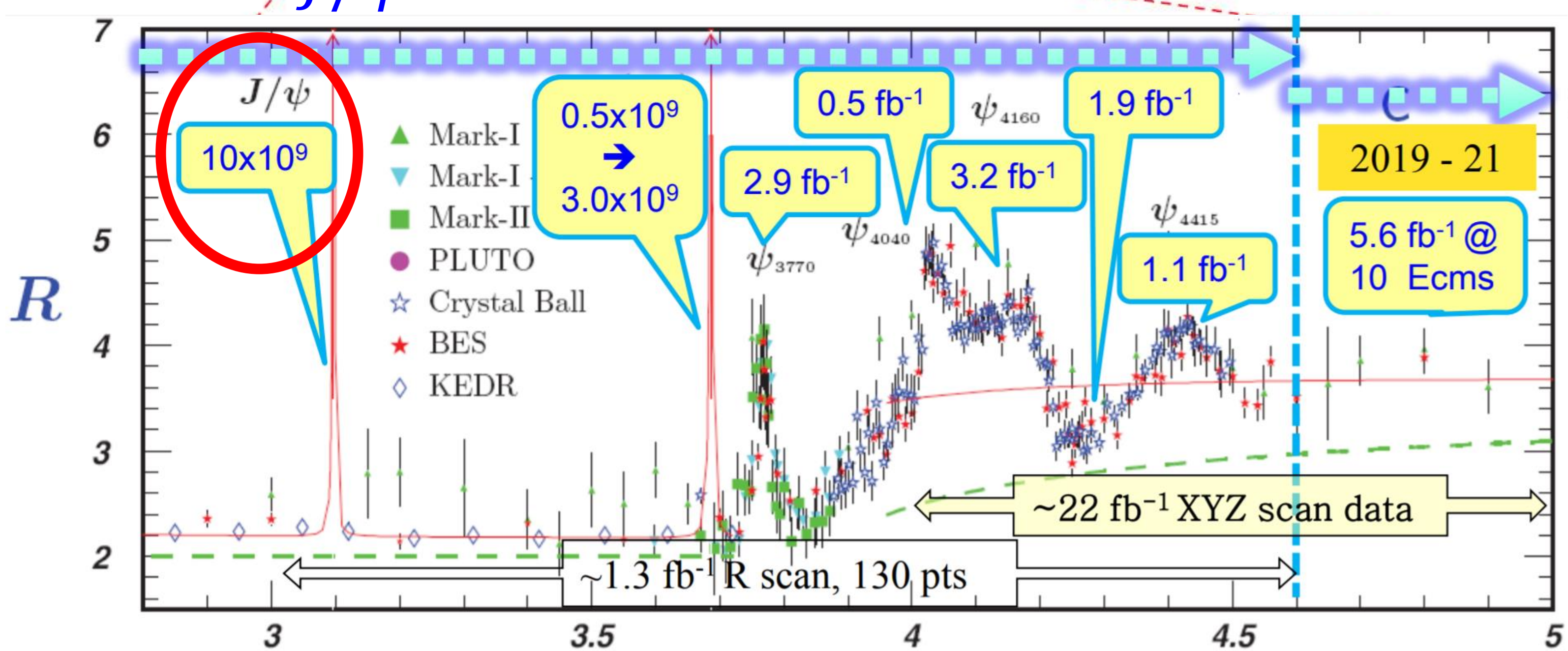
Has been in full operation since 2008,
all subdetectors are in very good status!

BESIII data samples

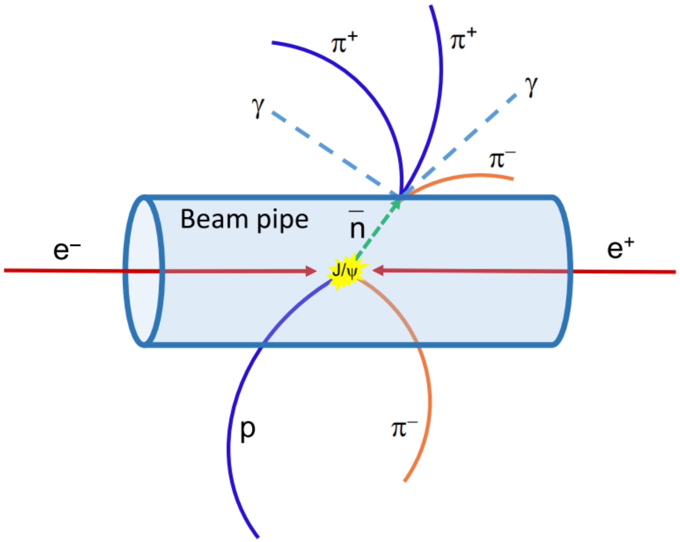


BESIII has collected the largest data samples of the J/ψ and $\psi(3686)$ in the world, and $> 20\ \mathrm{fb}^{-1}$ above $4.0\ \mathrm{GeV}$ in total.

10 billion J/ψ events

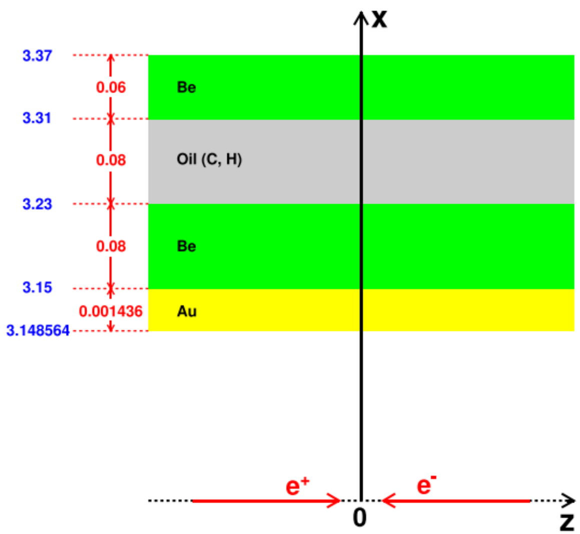


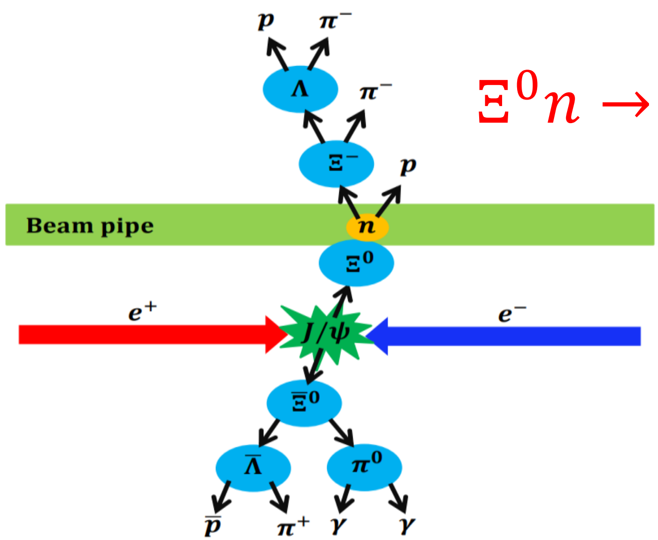
Experimental study on particle targeting at BESIII



Phys. Rev. Lett. 127, 012003 (2021)
arXiv: 2209.12601

$\bar{n}p \to \pi^+\pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$





$\Xi^0 n \to \Xi^- p$

particle source: hyperon from J/ψ decays
target material: beam pipe
detector: BESIII detector

New results on hyperon-nucleon interactions at BESIII

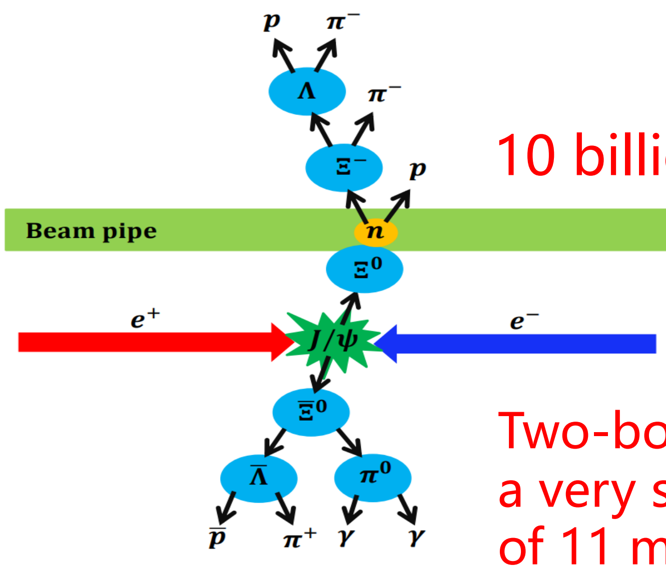
- **First Study of Reaction $\Xi^0 n \to \Xi^- p$ Using Ξ^0-Nucleus Scattering at an Electron-Positron Collider**
  Phys. Rev. Lett. 130, 251902 (2023)

- **First measurement of ΛN inelastic scattering with Λ from $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$**
  arXiv: 2310.00720

Study of $\Xi^0 n \to \Xi^- p$

Reaction chain :

$J/\psi \to \Xi^0\bar{\Xi}^0$, $\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\pi^0 \to \gamma\gamma$,
$\Xi^0 n \to \Xi^- p$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$.



10 billion J/ψ data

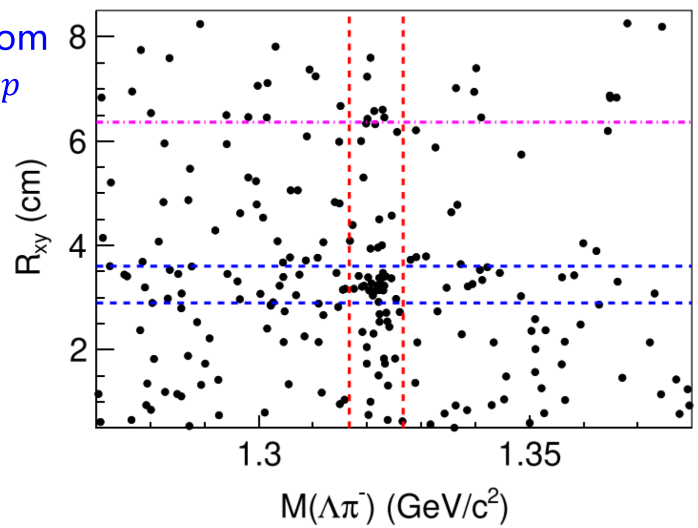
Two-body decay, $P_{\Xi^0} \approx 0.818\ \mathrm{GeV}/c$, a very small horizontal crossing angle of 11 mrad for e^+ and e^- beams.

Analysis method :

Using $\bar{\Xi}^0$ to tag the event and requiring the recoiling mass in Ξ^0 region. Then reconstructing Ξ^- and p in the signal side.

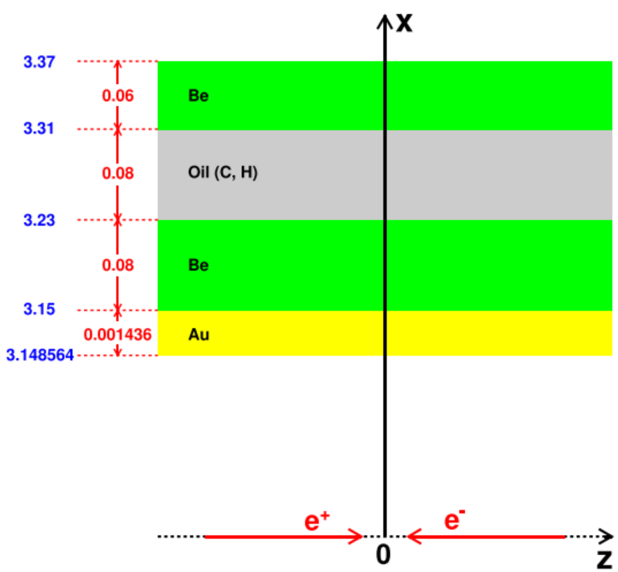
Study of $\Xi^0 n \to \Xi^- p$

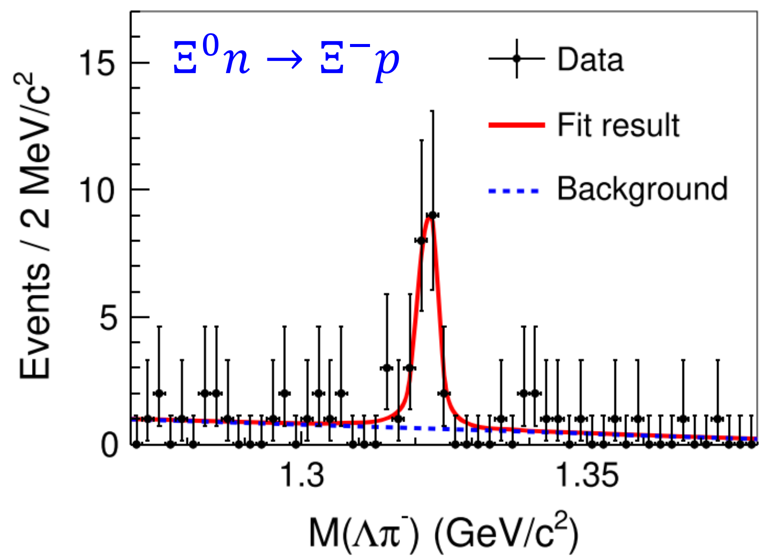
R_{xy} is distance from reconstructed $\Xi^- p$ vertex to z axis



Inner wall of MDC

Beam pipe





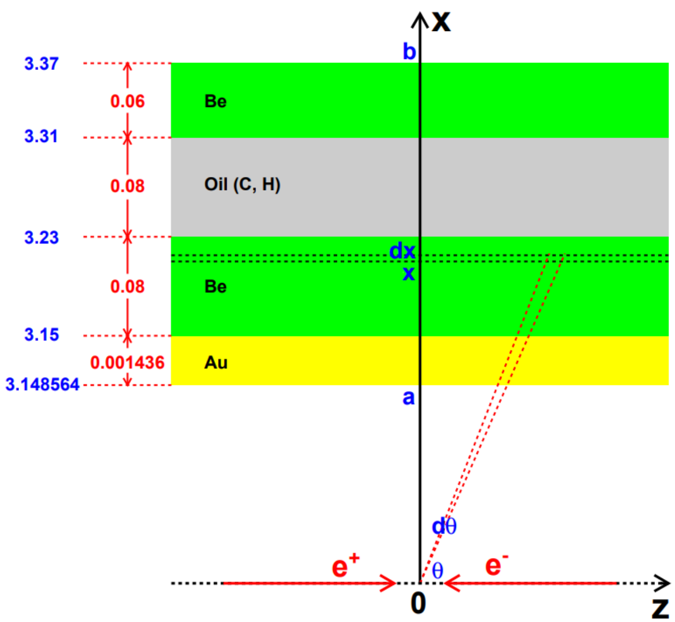
$N = 22.9 \pm 5.5$

$S = 7.1\sigma$

Cross section of $\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}$

$$\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = \frac{N^{\mathrm{sig}}}{\epsilon \mathcal{B} \mathcal{L}_{\mathrm{eff}}}$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{N_{J/\psi}\mathcal{B}_{J/\psi}}{2+\frac{2}{3}\alpha}\int_a^b\int_0^\pi (1+\alpha\cos^2\theta)e^{-\frac{x}{\sin\theta\beta\gamma L}}N(x)C(x)\,d\theta\,dx$$



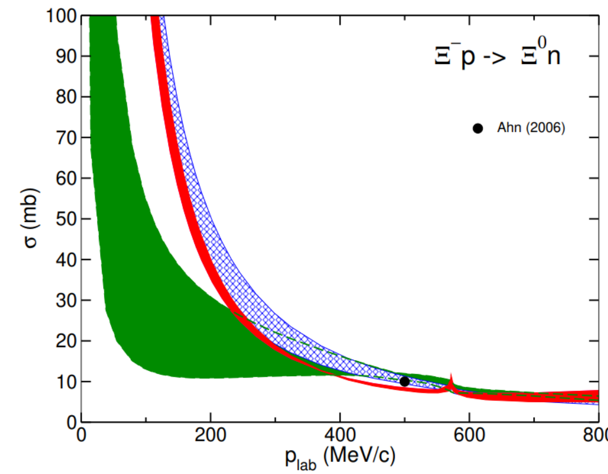
Parameter	Result
N^{sig}	22.9 ± 5.5
ϵ	1.873%
$\mathcal{B}$	$(40.114 \pm 0.444)\%$ [53]
$N_{J/\psi}$	$(1.0087 \pm 0.0044) \times 10^{10}$ [46]
$\mathcal{B}_{J/\psi}$	$(0.117 \pm 0.004)\%$ [53]
α	0.514 ± 0.016 [56]
L	(8.69 ± 0.27) cm [53]
E_{beam}	1.5485 GeV
m_{Ξ^0}	(1.31486 ± 0.00020) GeV$/c^2$ [53]
a	3.148564 cm [45]
b	3.37 cm [45]
$N(x)$	$\begin{cases} 5.91\times10^{22}\ \mathrm{cm}^{-3}, & 3.148564 \le x \le 3.15\ \mathrm{cm} \\ 1.24\times10^{23}\ \mathrm{cm}^{-3}, & 3.15 < x \le 3.23\ \mathrm{cm} \\ 3.45\times10^{22}\ \mathrm{cm}^{-3}, & 3.23 < x \le 3.31\ \mathrm{cm} \\ 1.24\times10^{23}\ \mathrm{cm}^{-3}, & 3.31 < x \le 3.37\ \mathrm{cm} \end{cases}$
$C(x)$	$\begin{cases} 8.437(23.6), & 3.148564 \le x \le 3.15\ \mathrm{cm} \\ 1.000(1.00), & 3.15 < x \le 3.23\ \mathrm{cm} \\ 1.090(1.20), & 3.23 < x \le 3.31\ \mathrm{cm} \\ 1.000(1.00), & 3.31 < x \le 3.37\ \mathrm{cm} \end{cases}$

pure surface process assumption
(proportional to number of neutrons)

Study of $\Xi^0 n \to \Xi^- p$

The measured cross section of the reaction process $\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}$ is $\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})$ mb at $P_{\Xi^0} \approx 0.818$ GeV/c.

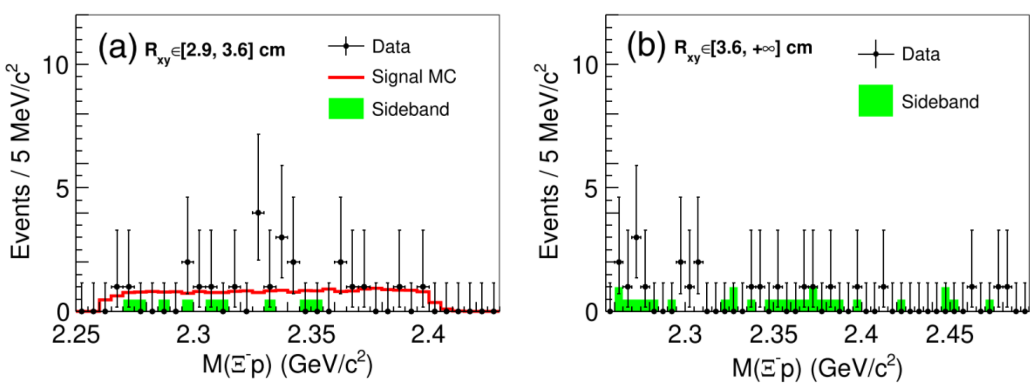
If we take the effective number of reaction neutrons in ${}^9\mathrm{Be}$ nucleus as 3, the cross section of $\Xi^0 n \to \Xi^- p$ for single neutron is determined to be $\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8_{\mathrm{stat}} \pm 1.5_{\mathrm{sys}})$ mb, consistent with theoretical predictions.



LO : H. Polinder, J.H., U.-G. Meißner, PLB 653 (2007) 29

NLO16: J.H., U.-G. Meißner, S. Petschauer, NPA 954 (2016) 273

NLO19: J.H., U.-G. Meißner, EPJA 55 (2019) 23



No significant H-dibaryon signals are seen

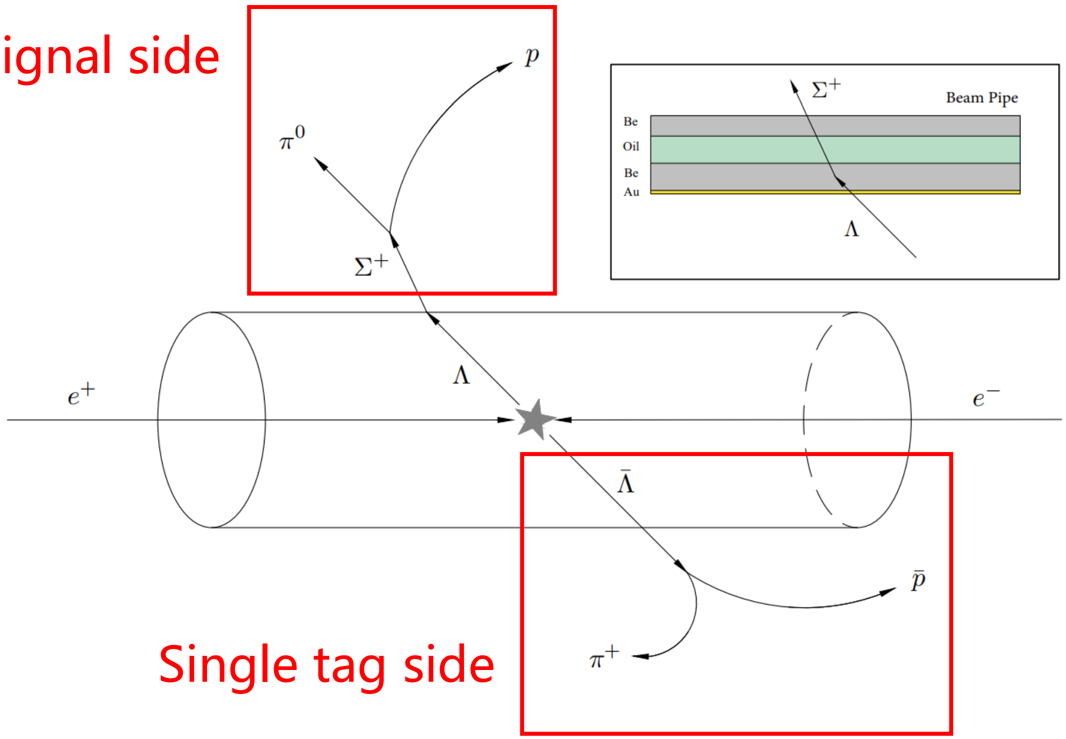
This work is the first study of hyperon-nucleon interaction in electron-positron collisions, and opens up a new direction for such research.

Study of $\Lambda N \to \Sigma^+ X$

Reaction chain :

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

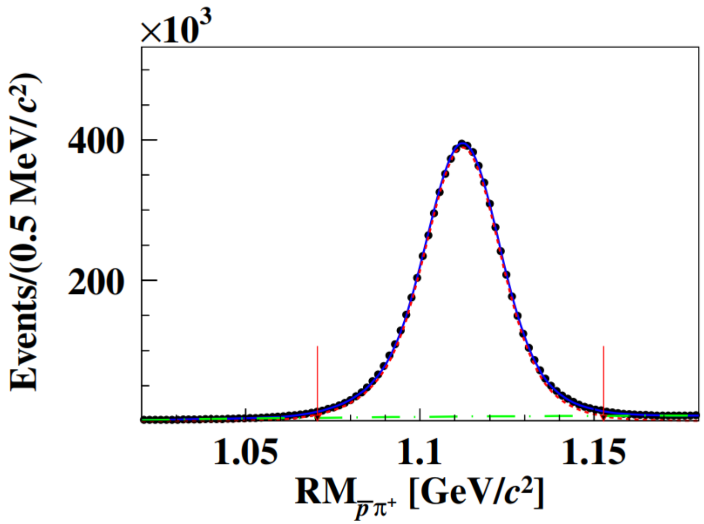
Signal side



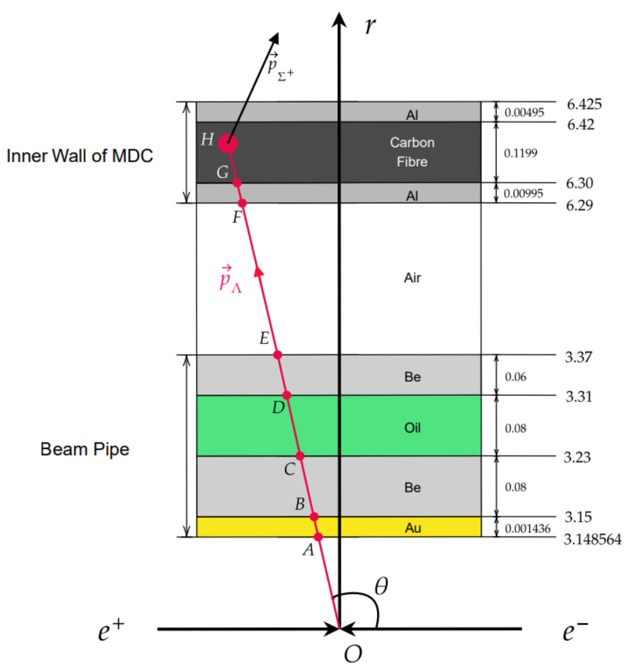
Single tag side

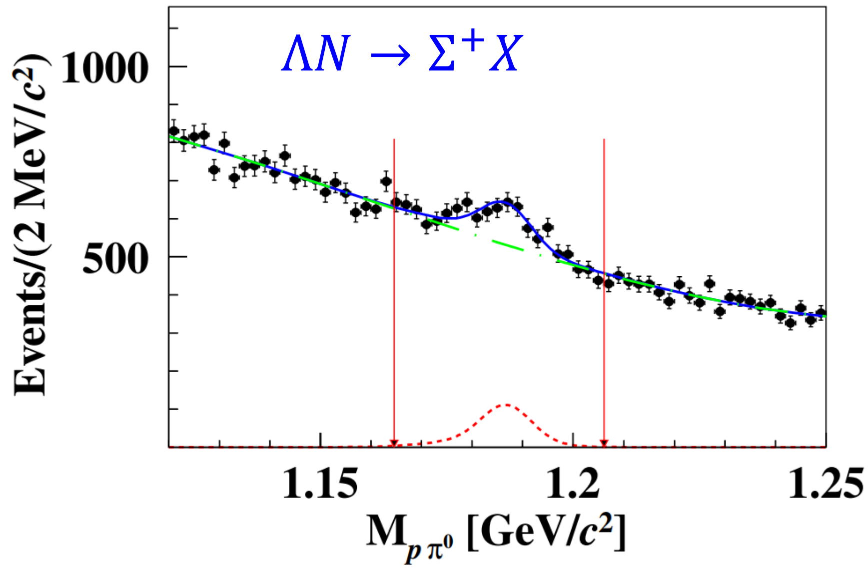
Two-body decay,
$P_\Lambda \approx 1.074\ \text{GeV}/c$,
a very small horizontal crossing angle of 11 mrad for e^+ and e^- beams, resulting in a small range of $0.017\ \text{GeV}/c$ above and below $1.074\ \text{GeV}/c$ for P_Λ.

Study of $\Lambda N \to \Sigma^+ X$



$N_{\text{ST}} = 7207565 \pm 3741$





$N_{\text{DT}} = 795 \pm 101$

The reaction position can not be determined. These signal events mainly come from the reaction with beam pipe and inner wall of MDC.

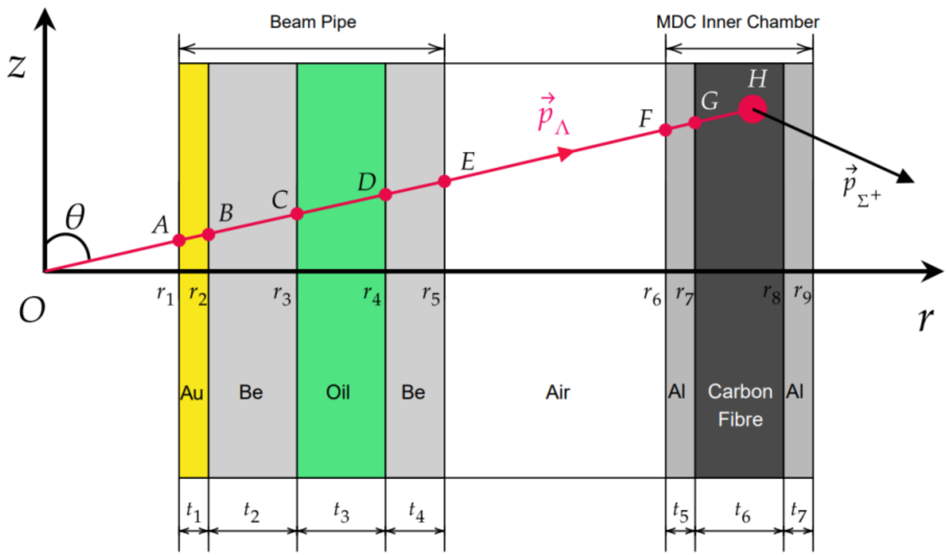
Cross section of $\Lambda + {}^9\text{Be} \to \Sigma^+ + X$

$$\sigma(\Lambda + {}^9\text{Be} \to \Sigma^+ + X) = \frac{N_{\text{DT}}}{\epsilon_{\text{sig}} \cdot \mathcal{L}_\Lambda} \cdot \frac{1}{\mathcal{B}(\Sigma^+ \to p\pi^0)}$$

$$\mathcal{L}_\Lambda = N_{\text{ST}} \cdot \frac{N_A}{N_{\text{ST}}^{\text{MC}}} \cdot \sum_j^7 \sum_i^{N_{\text{ST}}^{\text{MC}}} \frac{\rho_T^j \cdot l^{ij}}{M^j} \cdot \mathcal{R}_\sigma^j$$

path length of incident Λ of i_{th} event inside j_{th} layer

pure surface process assumption (proportional to number of protons)



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

Study of $\Lambda N \to \Sigma^+ X$

The measured cross section of the reaction process $\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X$ is $\sigma(\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X) = (37.3 \pm 4.7_{\mathrm{stat}} \pm 3.5_{\mathrm{sys}})$ mb at $P_\Lambda \approx 1.074$ 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 ${}^9\mathrm{Be}$ nucleus as 1.93, the cross section of $\Lambda p \to \Sigma^+ X$ for single proton is determined to be $\sigma(\Lambda p \to \Sigma^+ X) = (19.3 \pm 2.4_{\mathrm{stat}} \pm 1.8_{\mathrm{sys}})$ mb.

$\sigma(\Lambda p \to \Sigma^+ n)$ is twice of $\sigma(\Lambda p \to \Sigma^0 p)$

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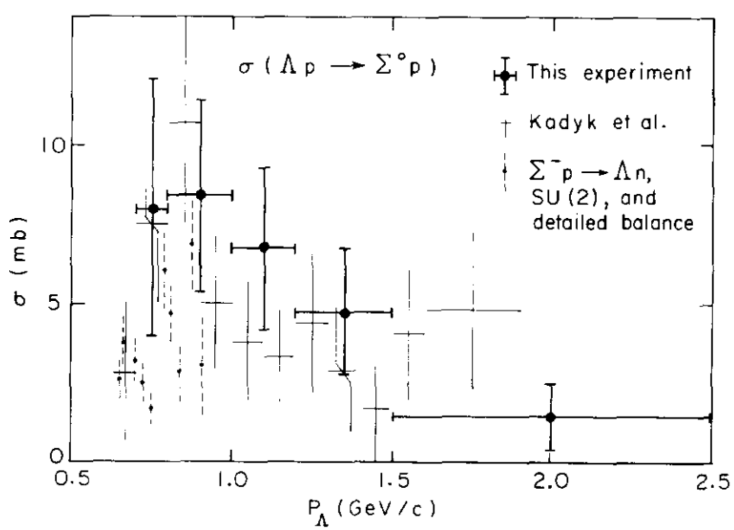

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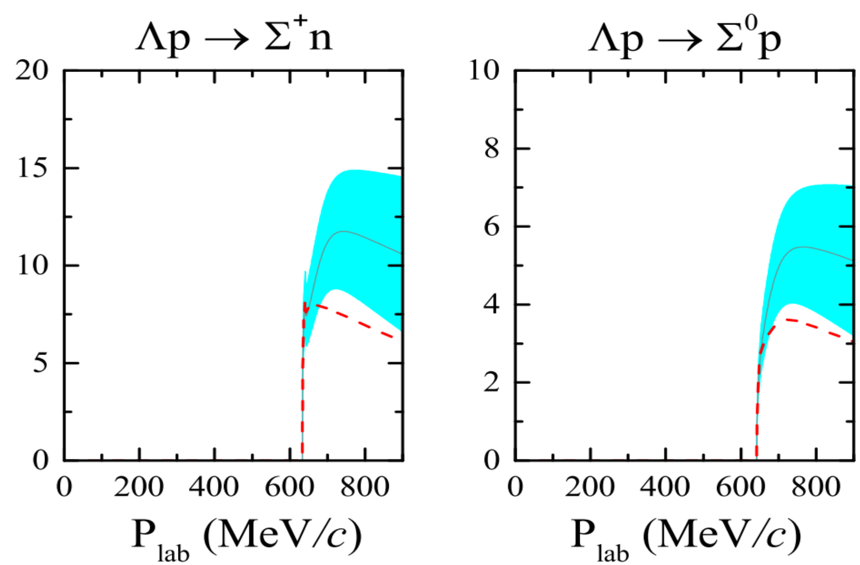
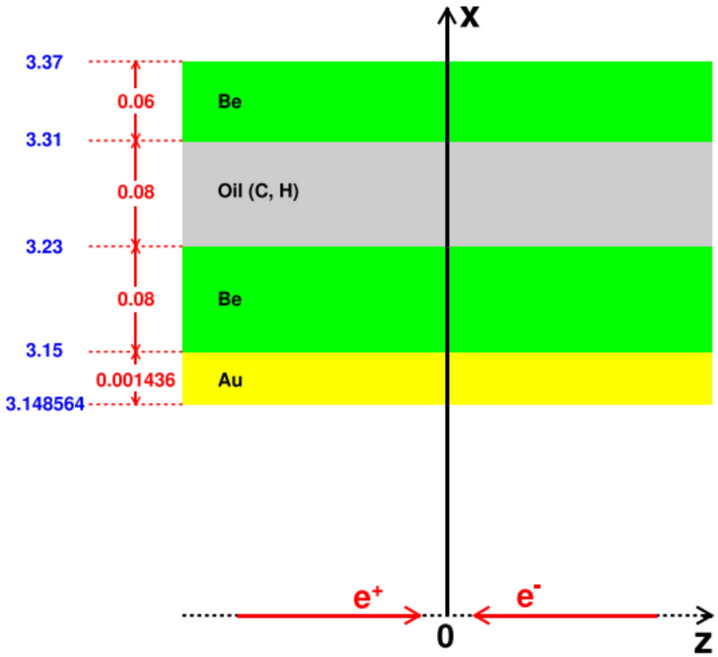


Some ongoing researches on hyperon-nucleon scattering at BESIII

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

……



More results will come out soon !!!

Summary

1. The hyperon-nucleon reaction $\Xi^0 n \to \Xi^- p$ is observed and measured with Ξ^0 beam from the decay $J/\psi \to \Xi^0\bar{\Xi}^0$ based on 10 billion J/ψ data at BESIII.The measured cross section of the reaction process $\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}$ is $\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})$ mb. This is the first study of hyperon-nucleon interaction in electron-positron collisions, and opens up a new direction for such research.

2. The inelastic scattering $\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X$ is studied with Λ from $J/\psi \to \Lambda\bar{\Lambda}$, and the cross section is measured to be $\sigma(\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X) = (37.3 \pm 4.7_{\mathrm{stat}} \pm 3.5_{\mathrm{sys}})$ mb. This study represents the first attempt to investigate Λ-nucleus interaction at an e^+e^- collider.

3. With more statistics in future super tau-charm facilities, we can also study the momentum-dependent cross section or differential cross section distributions based on the hyperons from multibody decays of J/ψ or other charmonia.

Thanks for your attention!