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Hyperon-Nuclei/Nucleon Scattering at BESIII

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2024. 1. 16

arxiv: 2209.12601 [hep-ex], Phys.Rev.Lett. 130 (2023) 25, 251902, arXiv: 2310.00720 [nucl-ex]

CONTENT

1 **Why to measure**

2 **How to measure**

3 **What have been measured**

4 **What will be studied**

Why to measure

From Hyperon to Neutron Stars

Hyperons in neutron stars

Phys.Lett.B 747 (2015) 43-47

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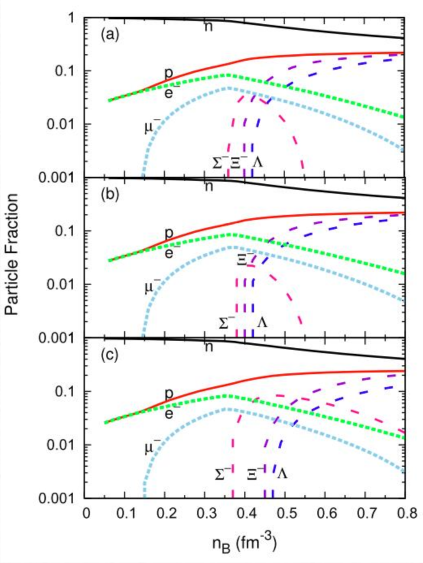
The Hyperon Puzzle in Neutron Stars

Ignazio Bombaci[1,2,3]

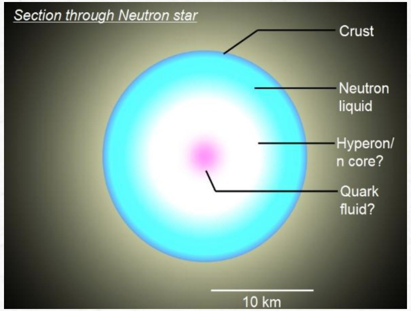
Nucl.Phys.News 31 (2021) 3, 17-21



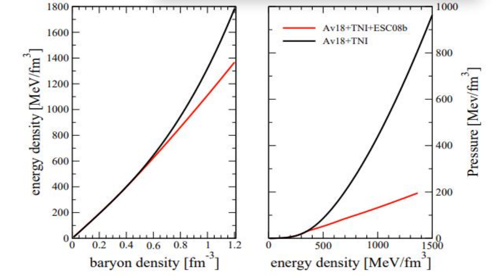
Neutron stars need hyperon! (Pauli exclusion principle)

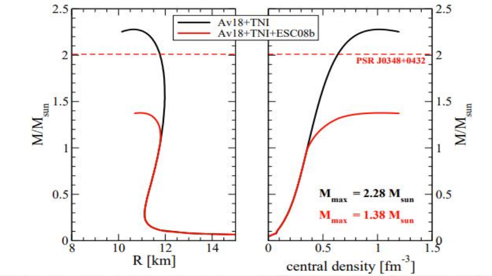
contradiction

The existence of hyperons will reduce the neutron star density. Inconsistent with observation!



Hyperon Puzzle





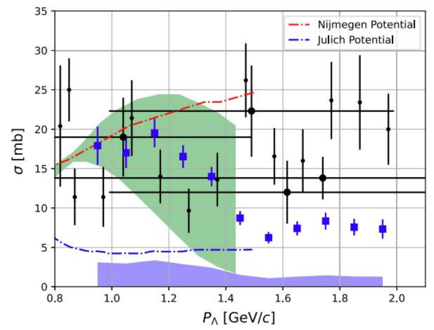
Hyperon-nucleon Interaction

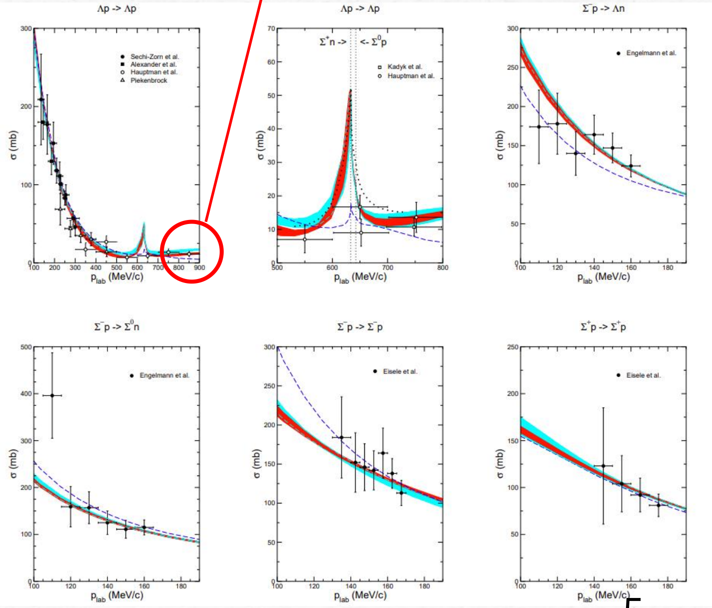
The Hyperon Puzzle in Neutron Stars

Ignazio Bombaci[1,2,3]

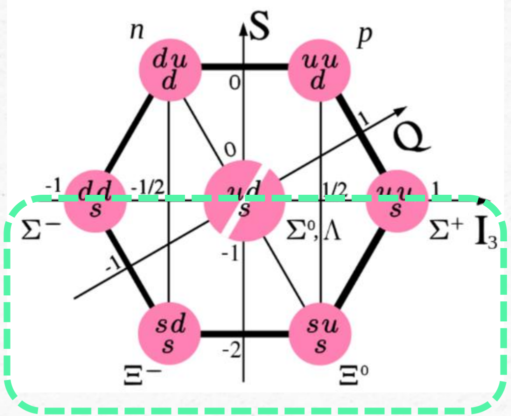
Nucl.Phys.News 31 (2021) 3, 17-21

Clearly, one should try to trace back the origin of this problem to the underlying YN and YY two-body interactions or to conceivable hyperonic three-body interactions (YTBIs) of the type YNN, YYN and YYY. Unfortunately, these two- and three-body strangeness $S \neq 0$ baryonic interactions are rather uncertain and poorly known. Basically this is due to the scarce amount of experimental data and to the considerable difficulties in their theoretical analysis. This situation is in sharp contrast to the case of the NN interaction, which is satisfactorily well known mostly due to the large number of NN scattering data and to the huge amount of measured properties of stable and unstable nuclei. The study





The vast majority of experiments came from fixed-target experiments before the 1980s.

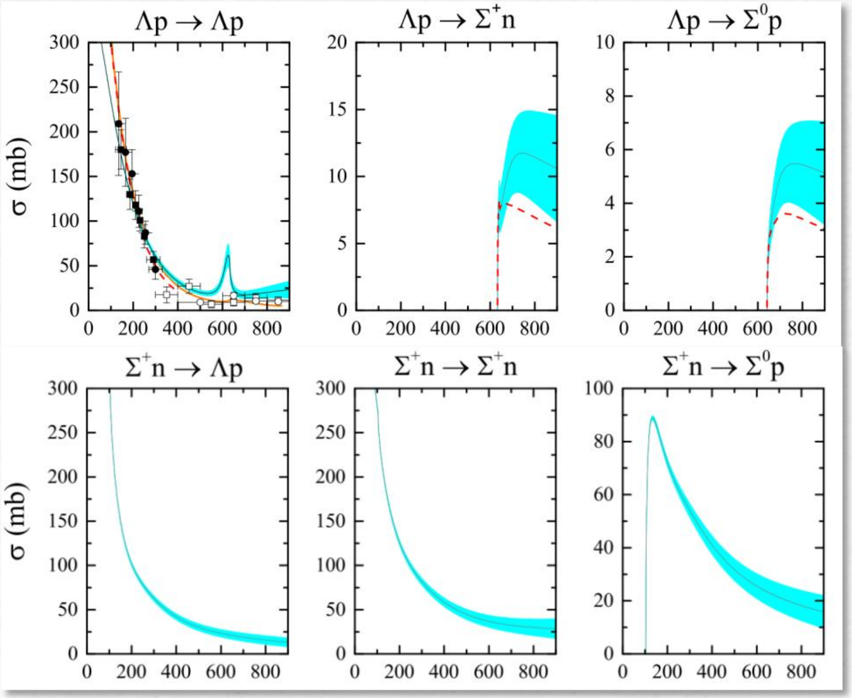


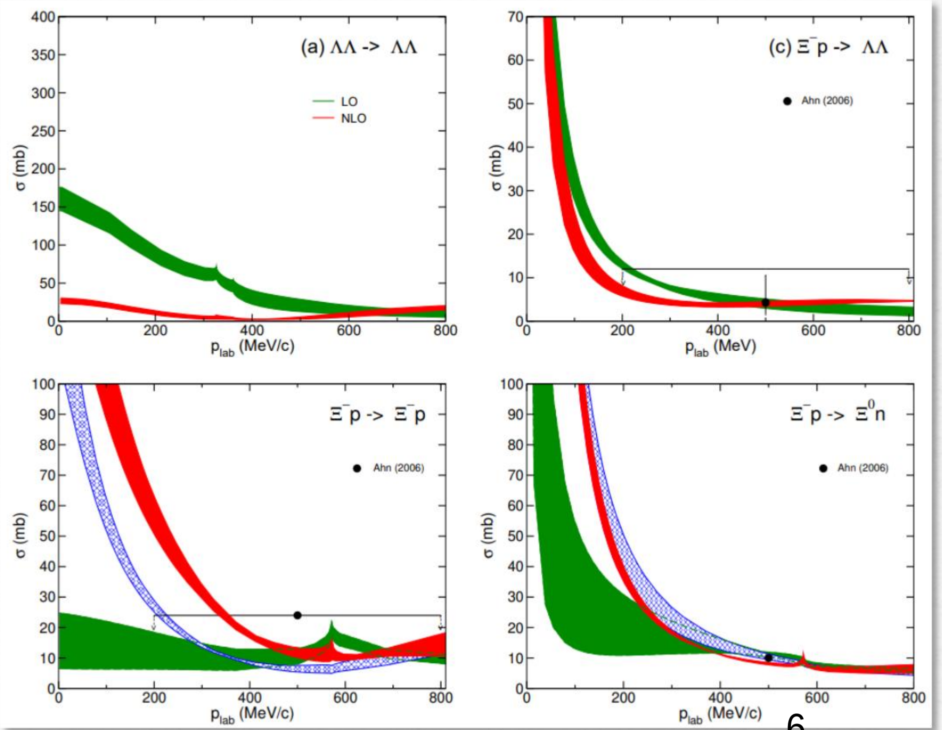
More studies of hyperon-hyperon (Y-Y) and hyperon-nucleon (Y-N) interactions are needed.

Theoretical Work

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

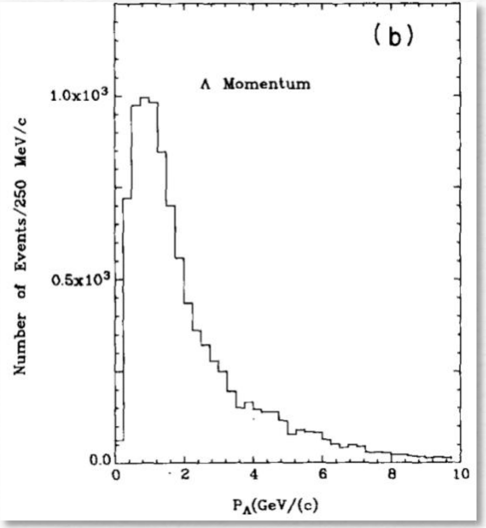
Phys. Rev. C 105, 035203 (2022)



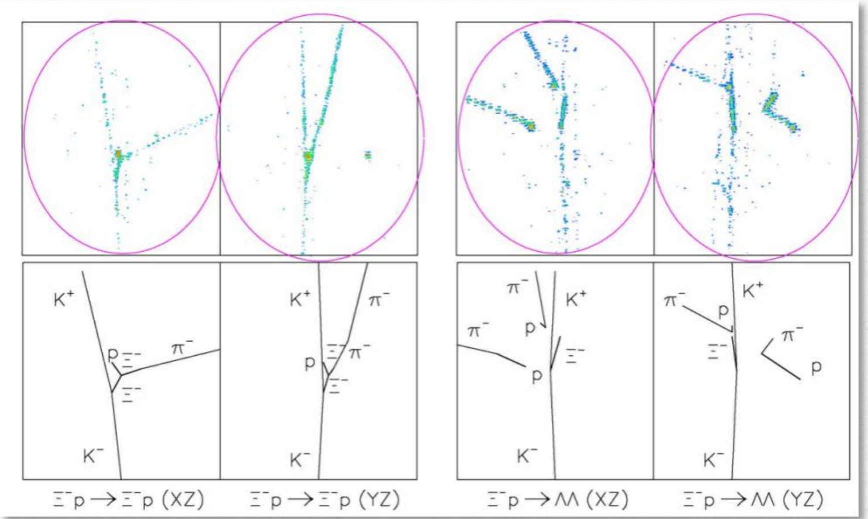


Early Measurement

- Hyperons are obtained by bombarding hydrogen bubble chamber or scintillating fiber target with K^-
- Low statistics and high background



Nucl. Phys. B 125, 29 (1977)



Phys. Lett. B 633, 214 (2006)

Early Measurements

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	

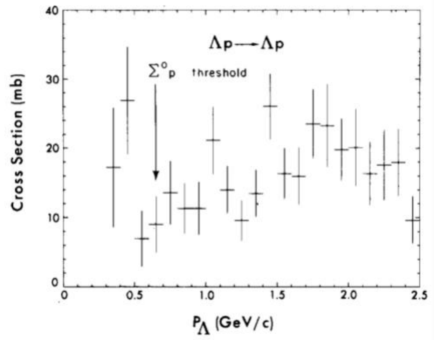
Phys. Lett. B 32, 720 (1970)

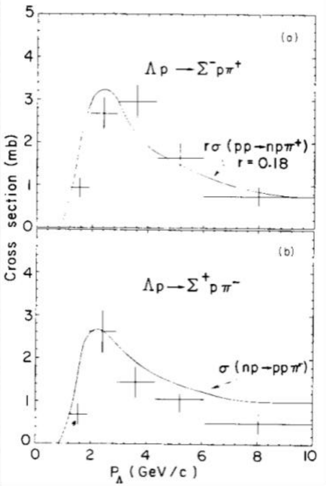
Phys. Lett. B 38, 123 (1972)

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

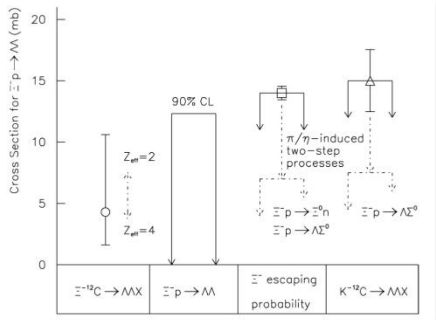
Reaction	Momentum interval (GeV/c)	Number of events	σ (mb)
$\Lambda p \to$ all	0.5 → 1.0		25.8 ± 6.2
	1.0 → 1.5		31.3 ± 6.5
	1.5 → 2.0		42.8 ± 7.1
	2.0 → 2.5		37.5 ± 7.2
	2.5 → 3.0		34.1 ± 8.3
	3.0 → 4.0		41.8 ± 10.0
$\Lambda p \to \Lambda p$	0.5 → 1.0	20	22.2 ± 5.0
	1.0 → 1.5	21	12.9 ± 2.8
	1.5 → 2.0	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)



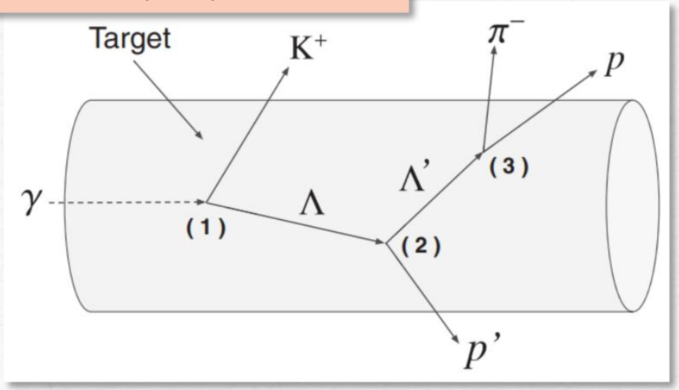
Recent Measurement

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

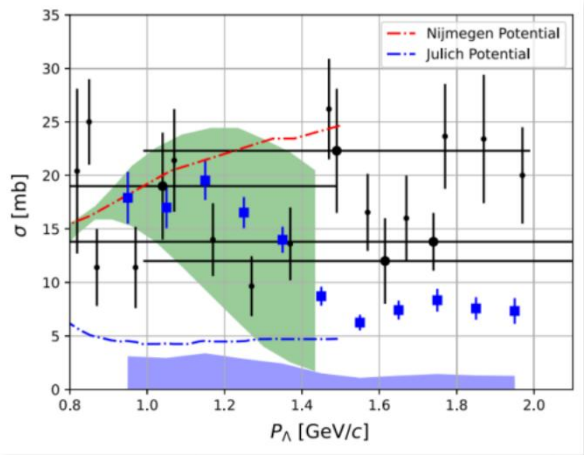
(CLAS Collaboration)

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

Phys.Rev.Lett. 127 (2021) 27, 272303



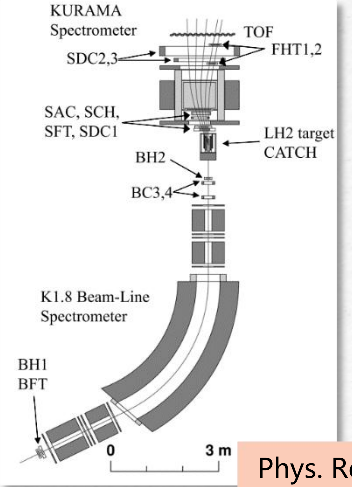
$\Lambda p \rightarrow \Lambda p$



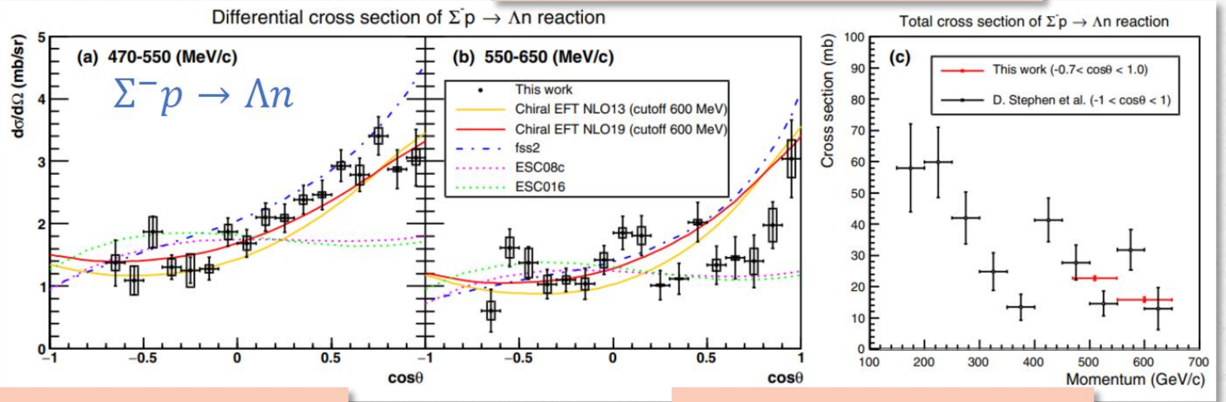
This is the first data on this reaction since the 1970s.

Recent Measurement

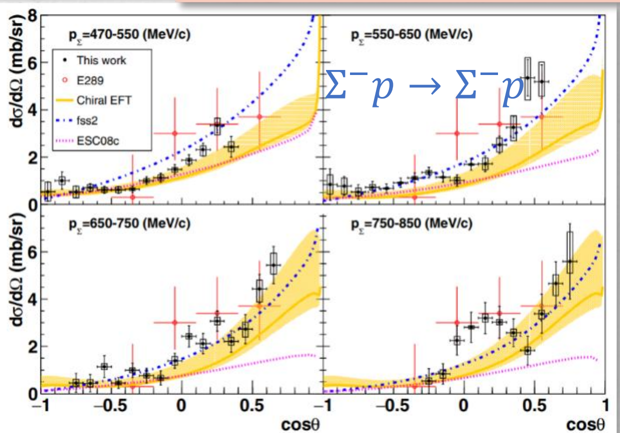
J-PARC E40 Collaboration



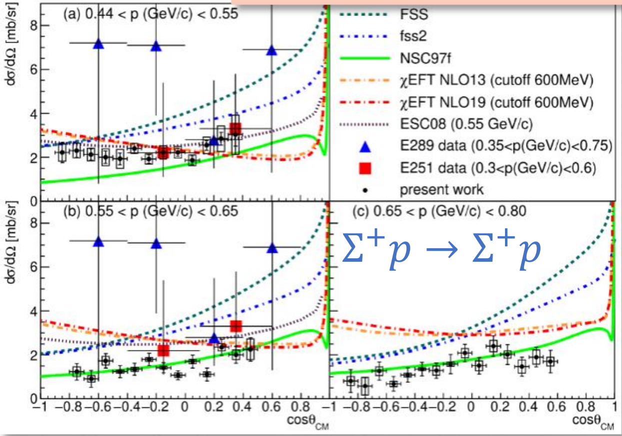
Phys. Rev. Lett. 128, 072501 (2022)



Phys. Rev. C 104, 045204 (2021)



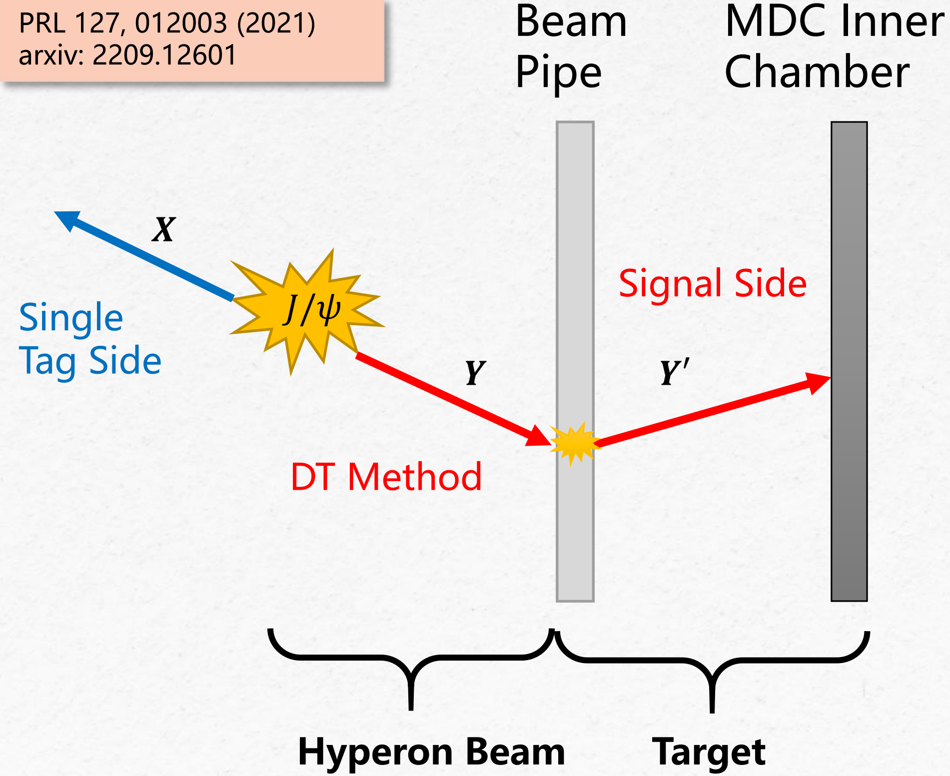
PTEP 2022, 093D01 (2022)

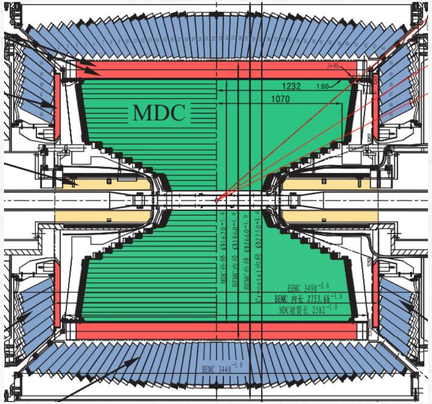


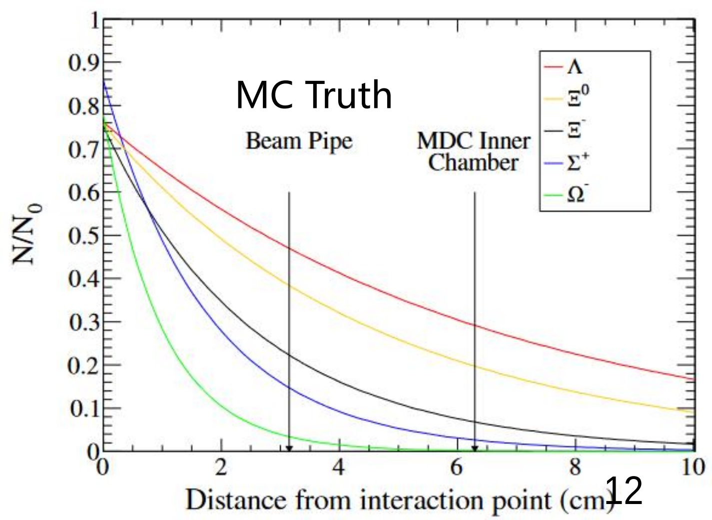
How to measure

General Thought

PRL 127, 012003 (2021)
arxiv: 2209.12601







Potential Channels

Hyperon Beam

J/ψ, $\psi(2S)$ →

- $pK^-\bar{\Lambda}$
- $\Lambda\bar{\Lambda}$
- $\Sigma^+\bar{\Sigma}^-$
- $\Xi^-\bar{\Xi}^+$
- $\Omega^-\bar{\Omega}^+$

Scattering Process

$\Lambda + p$ → $\Sigma^+ n$ (**Our Study**), $K^+\Lambda\Lambda$, $K^+\Xi^- p$

$\Lambda + n \rightarrow \Sigma^- p$

$\Sigma^- + p \rightarrow \Sigma^0 n,\ \Lambda n$

$\Sigma^+ + n \rightarrow \Sigma^0 p,\ \Lambda p$

$\Xi^- + p \rightarrow \Xi^0 n,\ \Lambda\Lambda$

$\Xi^0 + n \rightarrow \Xi^- p,\ \Lambda\Lambda$

Double-Tag Method

Double Tag Events:

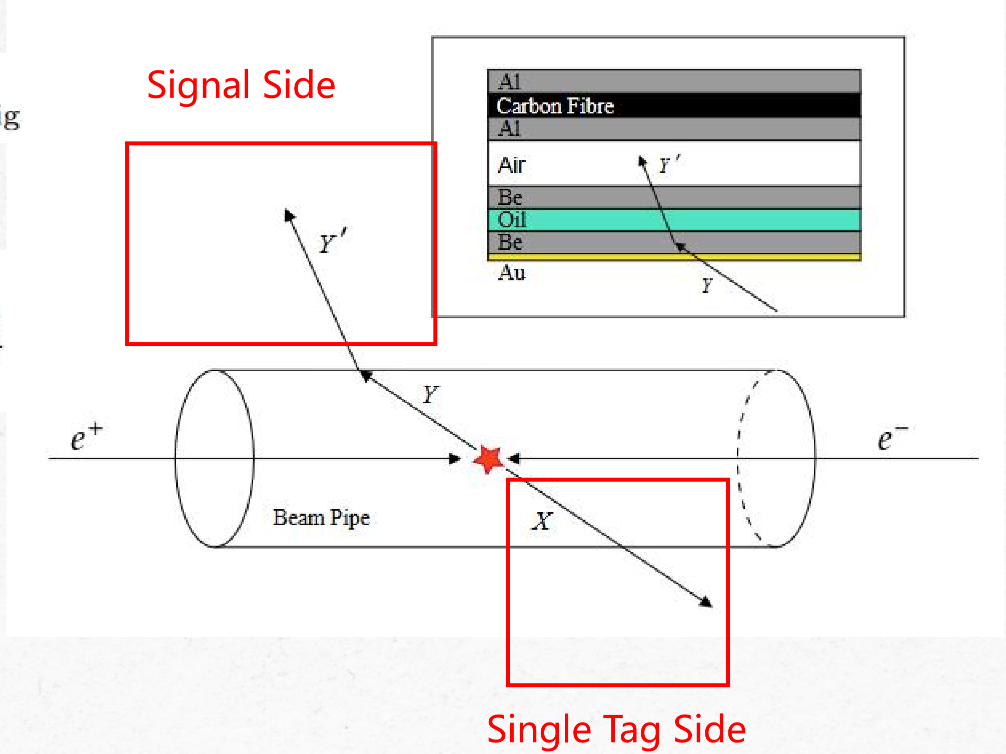
$$N_{\mathrm{DT}} = \mathcal{L}_Y \cdot \sigma(YA \to Y'A') \cdot \mathcal{B}(Y') \cdot \epsilon_{\mathrm{sig}}$$

Effective Luminosity of Λ beam:

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

Cross section:

$$\sigma(YA \to Y'A') = \frac{N_{\mathrm{DT}}}{\epsilon_{\mathrm{sig}} \cdot \mathcal{L}_Y} \cdot \frac{1}{\mathcal{B}(Y')}$$



Effective Luminosity

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

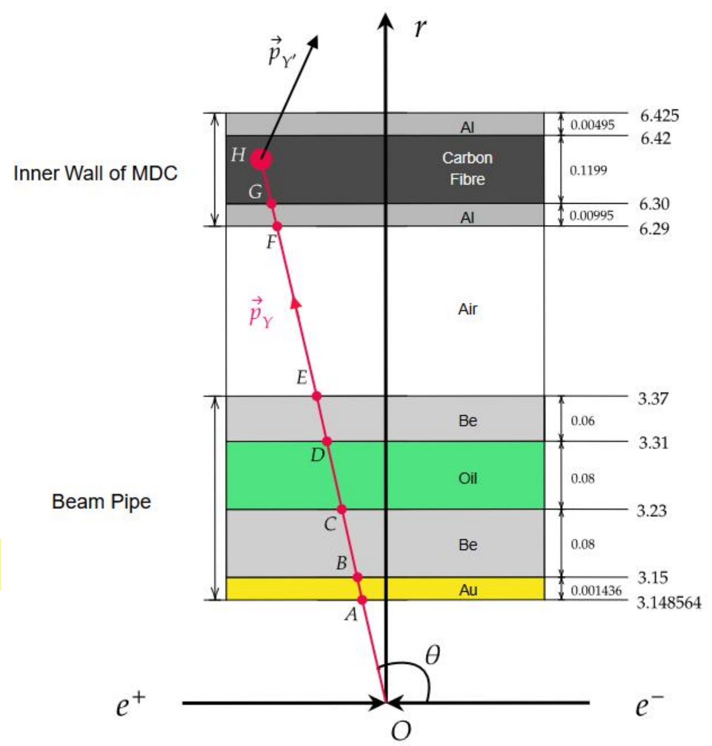
ρ_T^j - density of the j_{th} layer

M^j - molar mass of the j_{th} layer

l^{ij} - path length of the i_{th} event in the j_{th} layer (will be 0 if the incident hyperon does not reach the j_{th} layer)

R_σ^j - the ratio of the cross sections between layers

- proportional to the number of nucleons in the nuclei surface
- proportional to the number of nucleons in the nuclei
- Eikonal Approximation

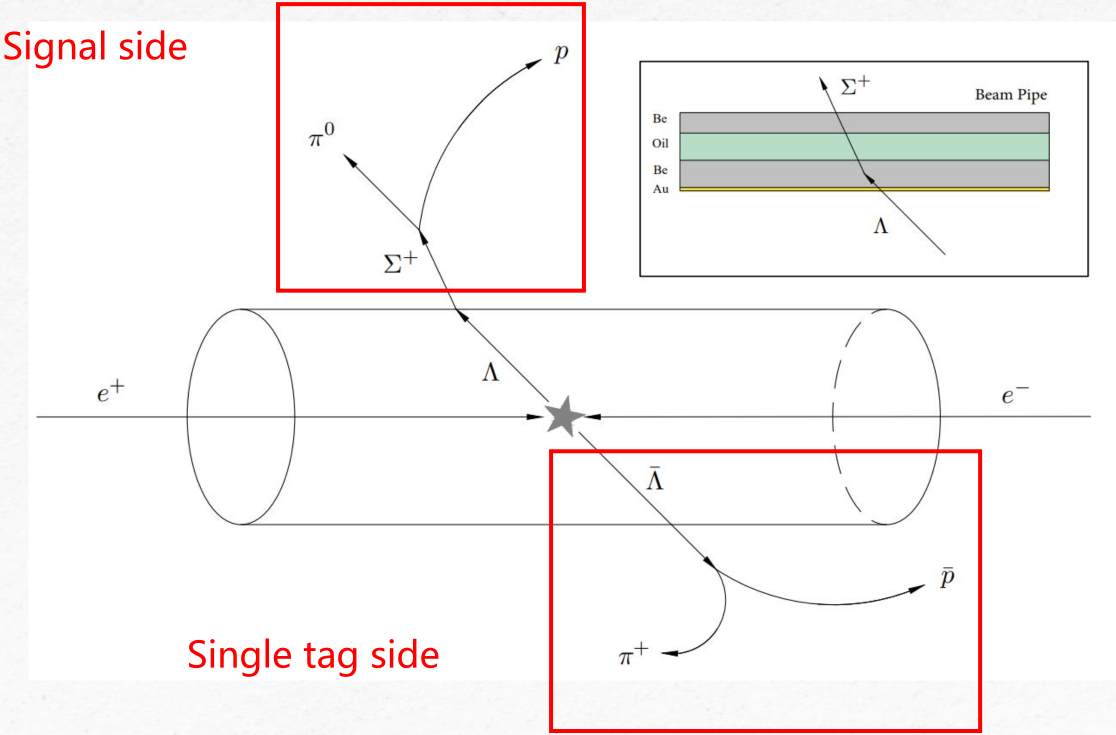


$$N_{\mathrm{eff}}\left(Z_{\mathrm{eff}}\right) = \frac{N(Z)}{A} \int \rho(\mathbf{r}) \exp\left\{-\bar{\sigma}_i \int_{-\infty}^{z} \rho\left(x, y, z'\right) dz' - \bar{\sigma}_f \int_z^{\infty} \rho\left(x, y, z'\right) dz'\right\} d^3\mathbf{r}$$

What have been measured

Reaction chain :

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

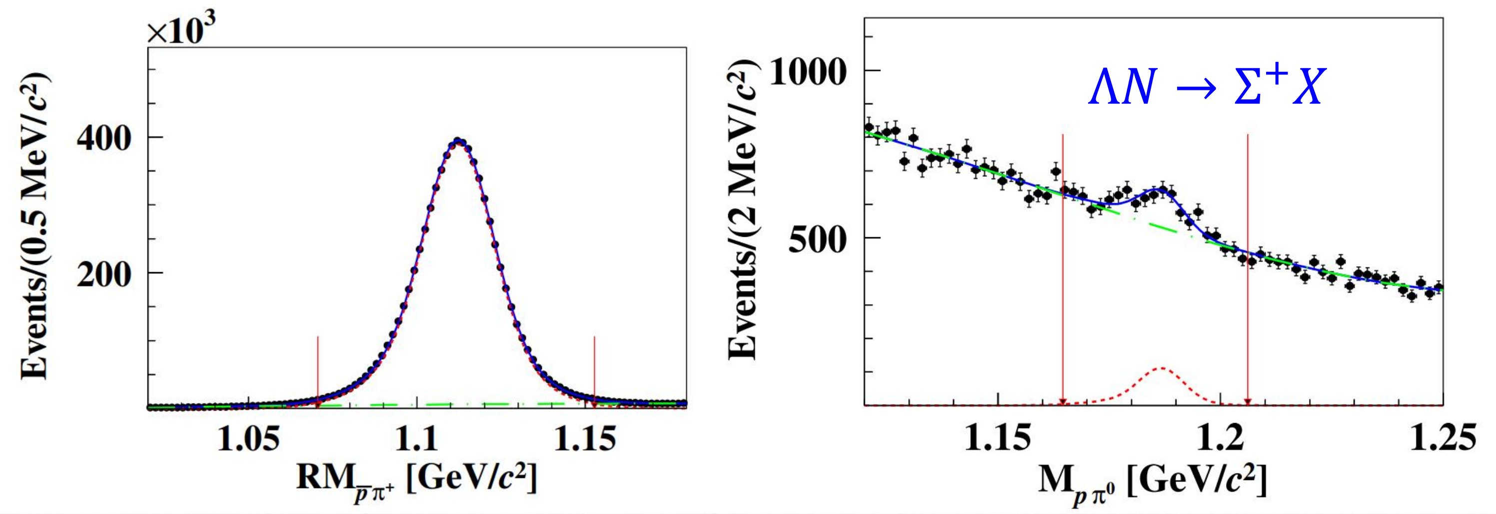


Two-body decay, $P_\Lambda \approx 1.074\ \mathrm{GeV}/c$,

Very small horizontal crossing angle of 11 mrad for e^+ and e^- beams

Very small range of $0.017\ \mathrm{GeV}/c$ above and below $1.074\ \mathrm{GeV}/c$ for P_Λ.

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



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

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

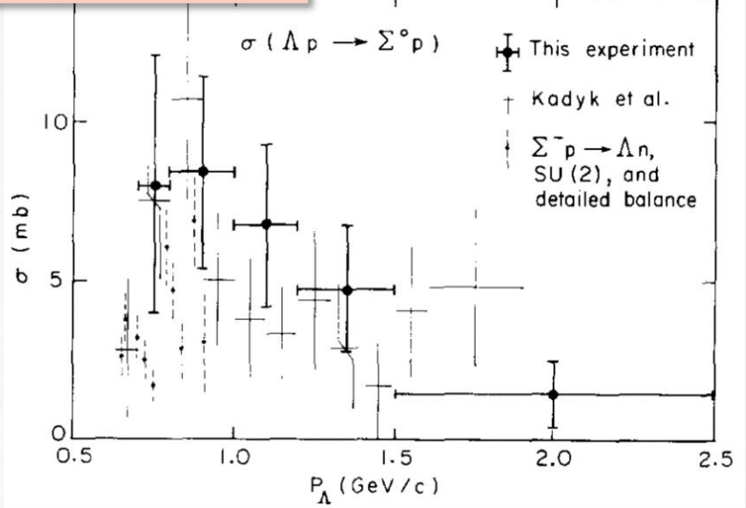
Parameter	Value
N_{DT}	795 ± 101
ϵ_{sig}	24.32%
$\mathcal{L}_{\Lambda}$	$(17.00 \pm 0.01) \times 10^{28}$ cm^{-2}
$\mathcal{B}(\Sigma^+ \to p\pi^0)$	$(51.57 \pm 0.30)\%$

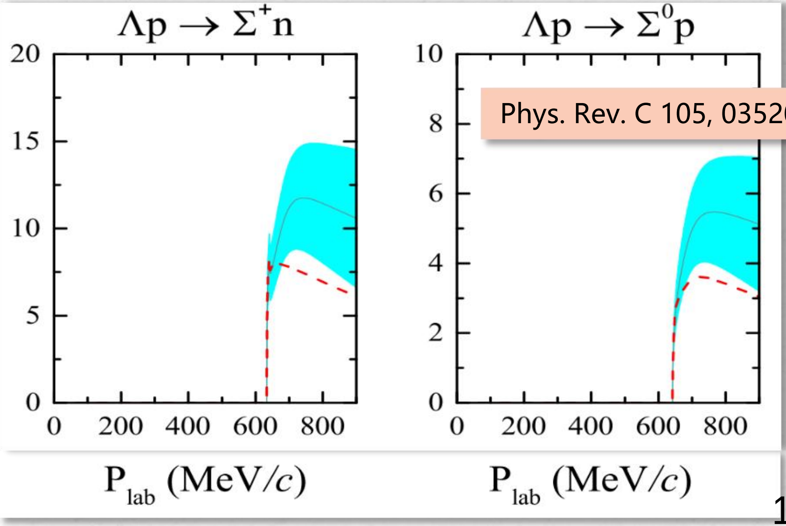
$\Lambda N \to \Sigma^+ X$

- $\sigma(\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X) = (37.3 \pm 4.7_{\mathrm{stat}} \pm 3.5_{\mathrm{sys}})$ mb at $P_\Lambda \approx 1.074$ GeV/c. The first attempt to investigate Λ-nucleus interaction at an e^+e^- collider.
- 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 $\sigma(\Lambda p \to \Sigma^+ X) = (19.3 \pm 2.4_{\mathrm{stat}} \pm 1.8_{\mathrm{sys}})$ mb.

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

Nucl. Phys. B 125, 29 (1977)



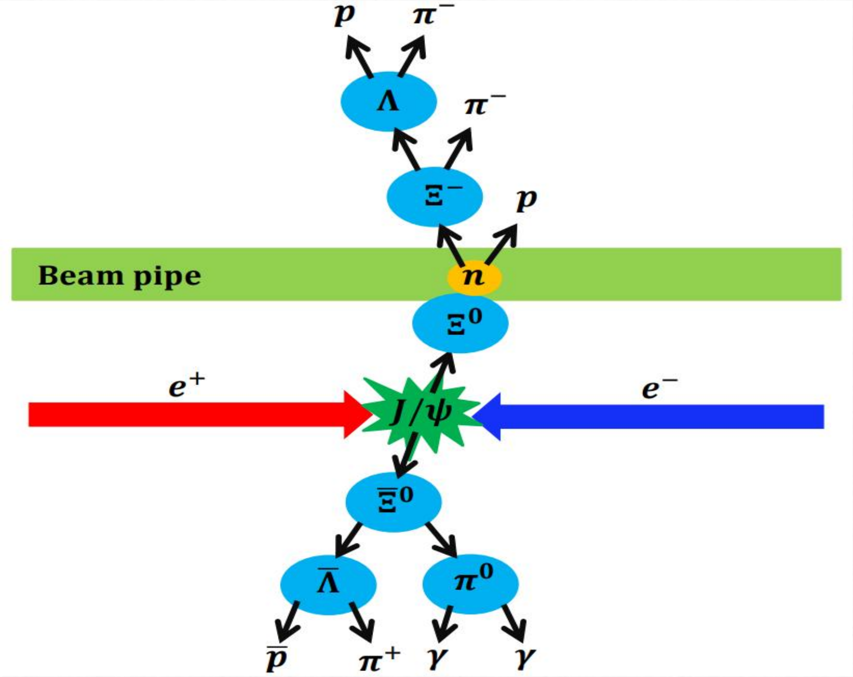


Phys. Rev. C 105, 035203 (2022)

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

Reaction chain :

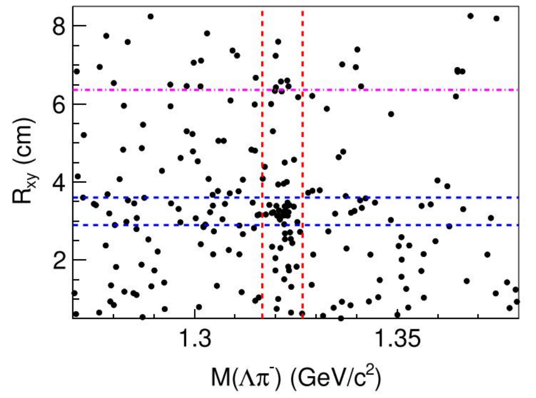
$J/\psi \to \Xi^0\bar{\Xi}^0$, $\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$, $\bar{\Lambda} \to \bar{p}\pi^+$, $\pi^0 \to \gamma\gamma$, $\Xi^0 n \to \Xi^- p$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$.



10 billion J/ψ data

Two-body decay, $P_{\Xi^0} \approx 0.818\ \mathrm{GeV}/c$

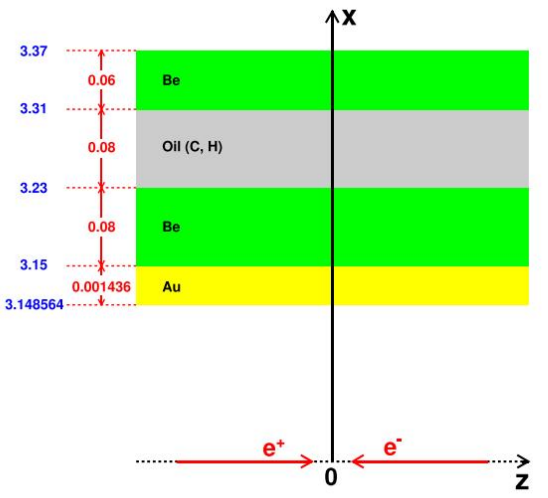
$\Xi^0 n \to \Xi^- p$

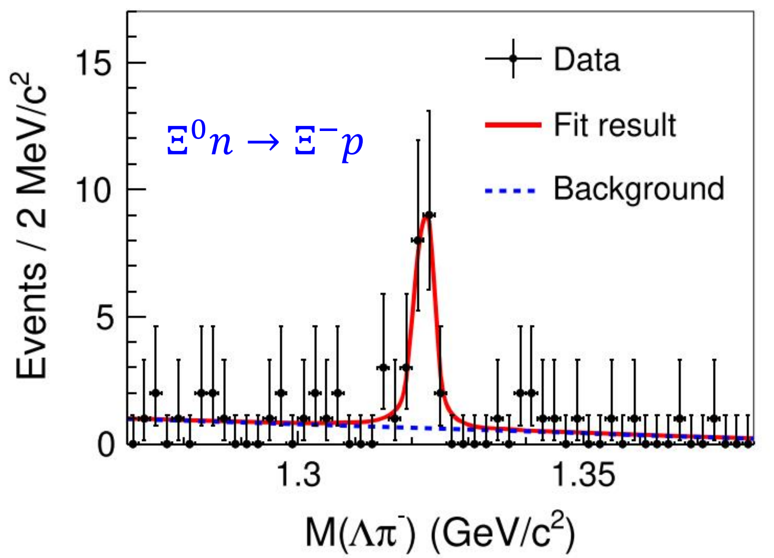


Inner wall of MDC

Beam pipe

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



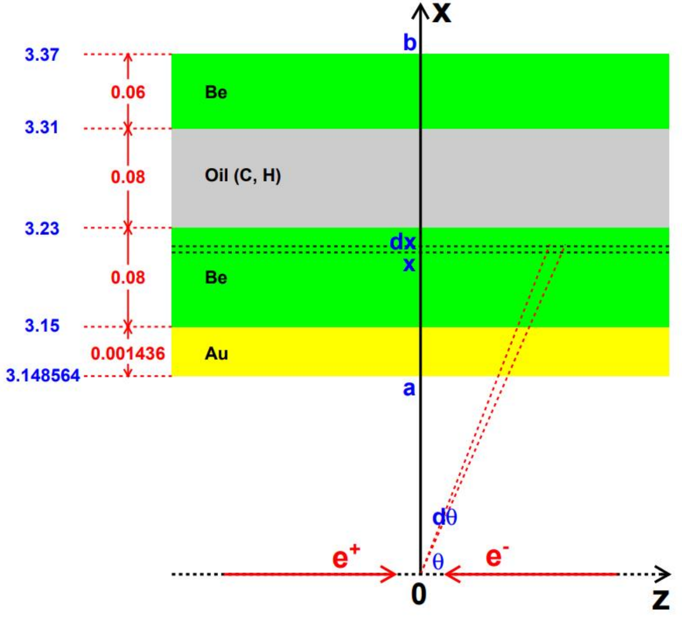


$$N = 22.9 \pm 5.5$$
$$S = 7.1\sigma$$

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

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

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

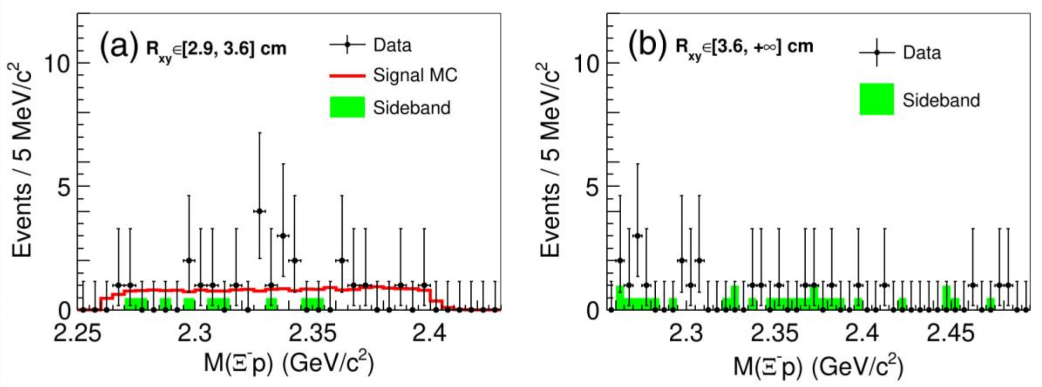


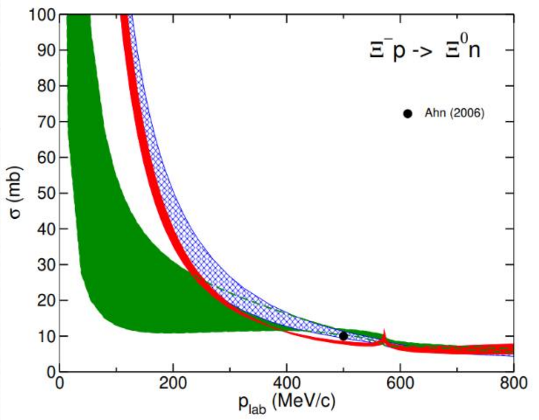
Parameter	Result
N^{sig}	22.9 ± 5.5
ϵ	1.873%
$\mathcal{B}$	$(40.114 \pm 0.444)\%$ [53]
$N_{J/\psi}$	$(1.0087 \pm 0.0044) \times 10^{10}$ [46]
$\mathcal{B}_{J/\psi}$	$(0.117 \pm 0.004)\%$ [53]
α	0.514 ± 0.016 [56]
L	(8.69 ± 0.27) cm [53]
E_{beam}	1.5485 GeV
m_{Ξ^0}	$(1.31486 \pm 0.00020)\ \mathrm{GeV}/c^2$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

pure surface process assumption (proportional to number of neutrons)

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

- $\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})$ mb at $P_{\Xi^0} \approx 0.818$ GeV/c.
- Taking the effective number of reaction neutrons in ${}^9\mathrm{Be}$ nucleus as 3, $\sigma(\Xi^0 n \to \Xi^- p) = (7.4 \pm 1.8_{\mathrm{stat}} \pm 1.5_{\mathrm{sys}})$ 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

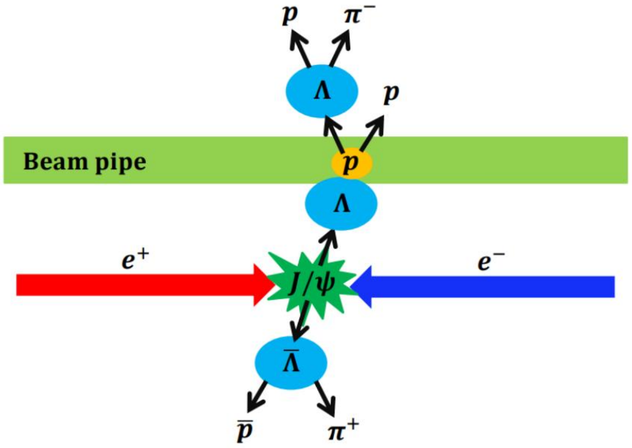
This work is the first study of hyperon-nucleon interaction in electron-positron collisions, and opens up a new direction for such research.

No significant H-dibaryon signals are seen

$\Lambda(\bar{\Lambda})p \rightarrow \Lambda(\bar{\Lambda})p$

Reaction chain :

$J/\psi \rightarrow \Lambda\bar{\Lambda}$, $\Lambda p \rightarrow \Lambda p$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$.

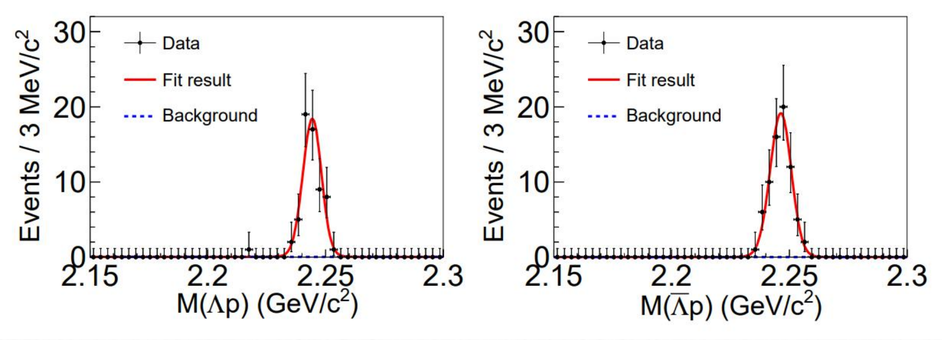


Two-body decay, $P_\Lambda \approx 1.074\ \mathrm{GeV}/c$,

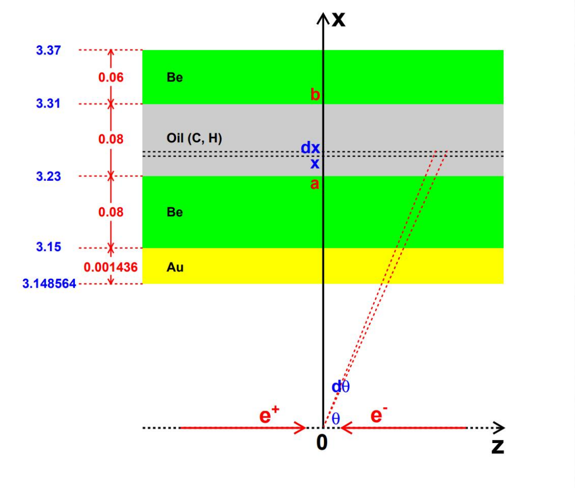
Very small horizontal crossing angle of 11 mrad for e^+ and e^- beams

Very small range of $0.017\ \mathrm{GeV}/c$ above and below $1.074\ \mathrm{GeV}/c$ for P_Λ.

$\Lambda(\bar{\Lambda})p \rightarrow \Lambda(\bar{\Lambda})p$



$$N(\Lambda p \rightarrow \Lambda p) = 60.9 \pm 7.8$$
$$N(\bar{\Lambda} p \rightarrow \bar{\Lambda} p) = 72.0 \pm 8.5$$



The center-of-mass energies for the incident $\Lambda/\bar{\Lambda}$ and a static p are all 2.243 GeV/c^2 within a range of ±0.005 GeV/c^2

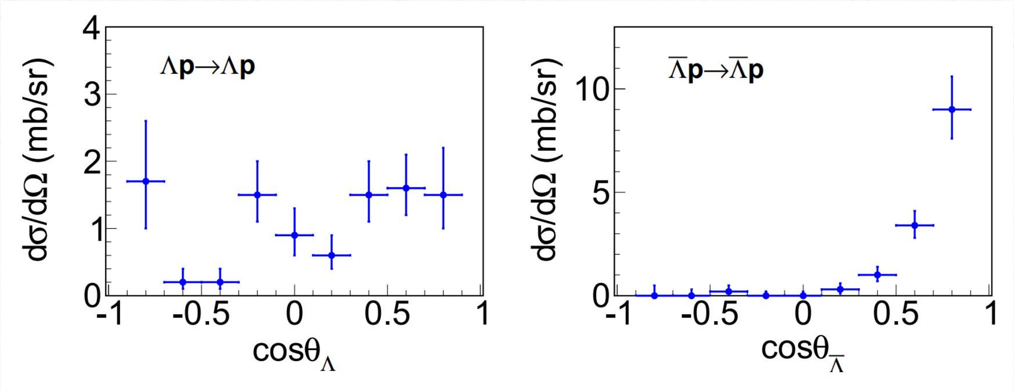
Clear enhancements are seen around $2.243\ \mathrm{GeV}/c^2$, corresponding to the reactions $\Lambda(\bar{\Lambda})p \rightarrow \Lambda(\bar{\Lambda})p$, respectively

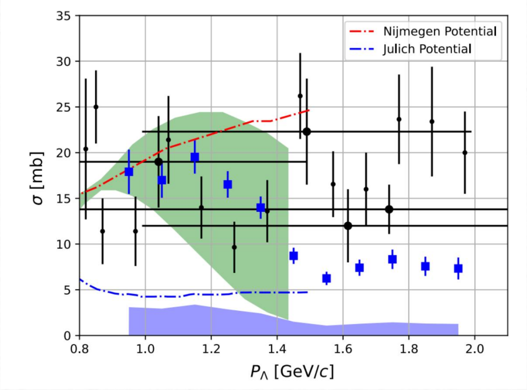
$\Lambda(\bar{\Lambda})p \rightarrow \Lambda(\bar{\Lambda})p$

First measurement of antihyperon-nucleon scattering!

- $\sigma(\Lambda + p \rightarrow \Lambda + p) = (12.2 \pm 1.6_{stat} \pm 1.1_{sys})$ mb and $\sigma(\bar{\Lambda} + p \rightarrow \bar{\Lambda} + p) = (17.5 \pm 2.1_{stat} \pm 1.6_{sys})$ mb at $P_\Lambda \approx 1.074$ GeV/c within $-0.9 < cos\theta_\Lambda < 0.9$.
- The differential cross sections of the two reactions are measured within $-0.9 < cos\theta_\Lambda < 0.9$, while there is a slight tendency of forward scattering for $\Lambda p \rightarrow \Lambda p$, and a strong forward peak for $\bar{\Lambda}p \rightarrow \bar{\Lambda}p$

Consistent results from CLAS experiment





What will be studied

BESIII Analyses

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

……

More results will come out soon !!!

Prospects at STCF

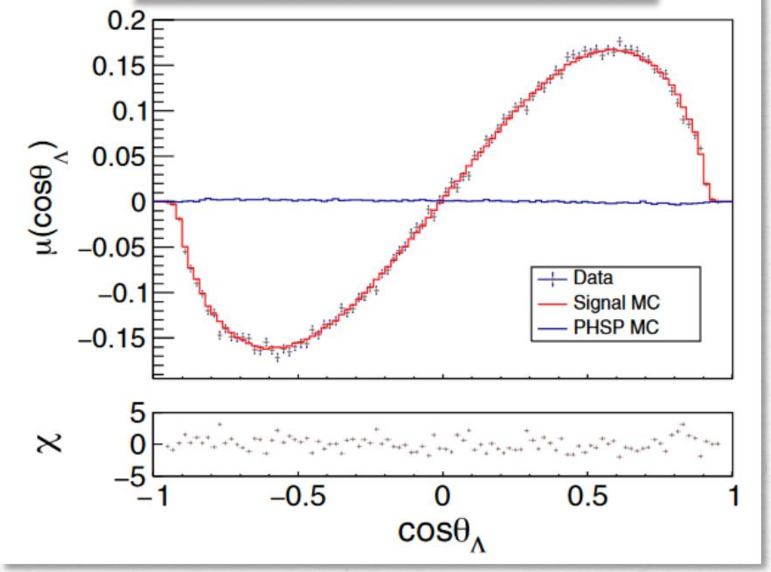
- Far more precise measurements thanks to the gaint statistics
- First measurement of the interaction between Ω^- and nuclei/nucleon (three strange quarks, spin-3/2)
- Measurements of the differential cross sections and momentum-dependent cross section
- Search for potential hypernucleus

Hyperon	$c\tau$ (cm)	decay mode	$\mathcal{B}_{decay}$ [65] ($\times 10^{-3}$)	$p_{\max}$ (MeV/c)	n^{Y}_{BP} ($\times 10^5$ for BESIII or $\times 10^8$ for STCF)	$\mathcal{B}_{tag}$ (%)	$\mathcal{L}_Y/N_{\mathrm{ST}}$ ($10^{21}\cdot$ 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

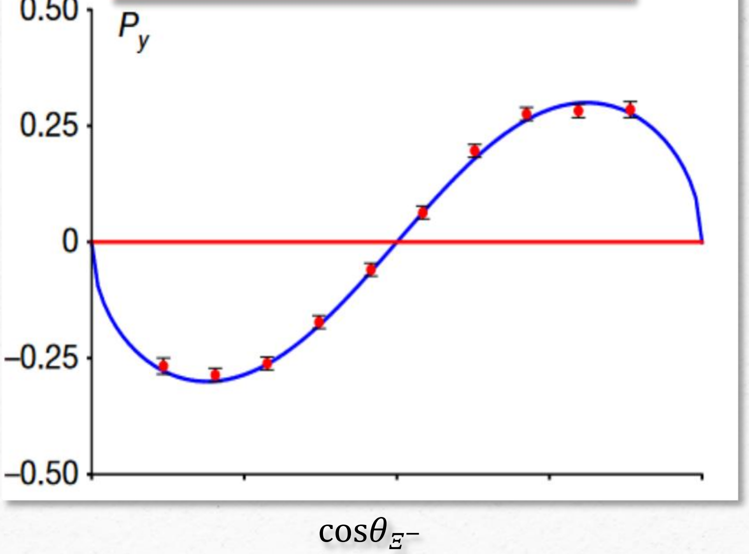
Prospects at STCF

- Potential measurement of the differential cross sections with respect to the polarization of the incident hyperons

Phys.Rev.Lett. 129 (2022) 13, 131801



Nature 606 (2022) 7912, 64-69



Summary

Summary

- The cross section of $\Xi^0 n \to \Xi^- p$ is firstly 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 to be $\sigma(\Xi^0 + {}^9\mathrm{Be} \to \Xi^- + p + {}^8\mathrm{Be}) = (22.1 \pm 5.3_{\mathrm{stat}} \pm 4.5_{\mathrm{sys}})$ mb. The first study of hyperon-nucleon interaction in electron-positron collisions, opening a new direction for such research.
- The cross section of $\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X$ is studied with Λ from $J/\psi \to \Lambda\bar{\Lambda}$ to be $\sigma(\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + X) = (37.3 \pm 4.7_{\mathrm{stat}} \pm 3.5_{\mathrm{sys}})$ mb. The first attempt to investigate Λ-nucleus interaction at an e^+e^- collider.
- With more statistics in future STCF, the momentum-dependent cross section and differential cross sections can also be studied.

Thank you ！

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2024. 1. 16