Proposal of data taking plan for research of charmed baryon

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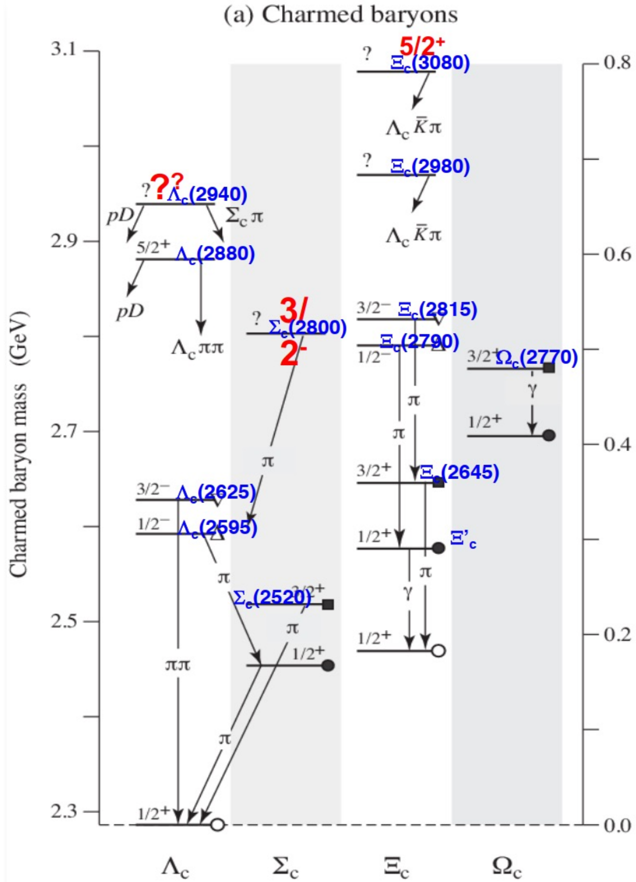
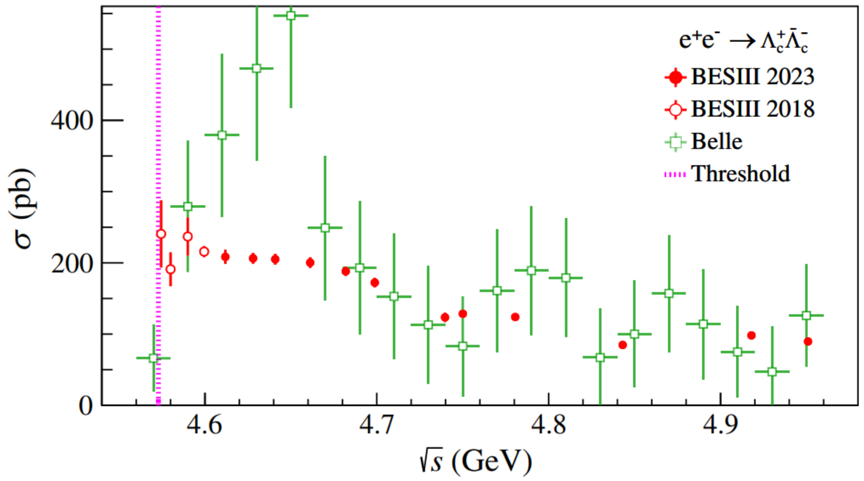
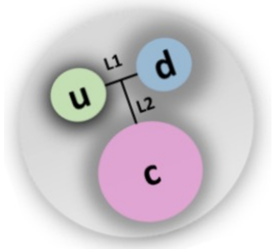
Outline

- Review of research on charmed baryons
- Part I Large data taking at certain E_{cm}
- Part II Data taking at $\Lambda_c^+\bar{\Lambda}_c^-$ threshold
- Summary

Λ_c^+ is the ground state charmed baryon, which provide important information to understand strong and weak interactions.







Energy (GeV)	Luminosity (pb^{-1})
4.575	48.9
4.580	8.5
4.590	8.2
4.600	586.9

In 2014, BESIII collected the first data of $\Lambda_c^+\bar{\Lambda}_c^-$ pair at threshold (35 days), leading to a series of important physics results of Λ_c^+.

First round physics results on Λ_c^+

7 PRL + 10 PRD / PLB / EPJC / CPC produced !

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+ + 11\ hadronic\ decay\ modes$ — PRL 116, 052001 (2016)

$\Lambda_c^+ \to pK^+K^-, p\pi^+\pi^-$ — PRL 117, 232002 (2016)

$\Lambda_c^+ \to nK_S^0\pi^+$ — PRL 118, 12001 (2017)

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$ — PRL 115, 221805 (2015)

Inclusive decay

$\Lambda_c^+ \to \Lambda X$ — PRL 121, 062003 (2018)

$\Lambda_c^+ \to Xe^+\nu_e$ — PRL 121, 251801 (2018)

Production

$\Lambda_c^+\bar{\Lambda}_c^-$ cross section — PRL 120, 132001 (2018)

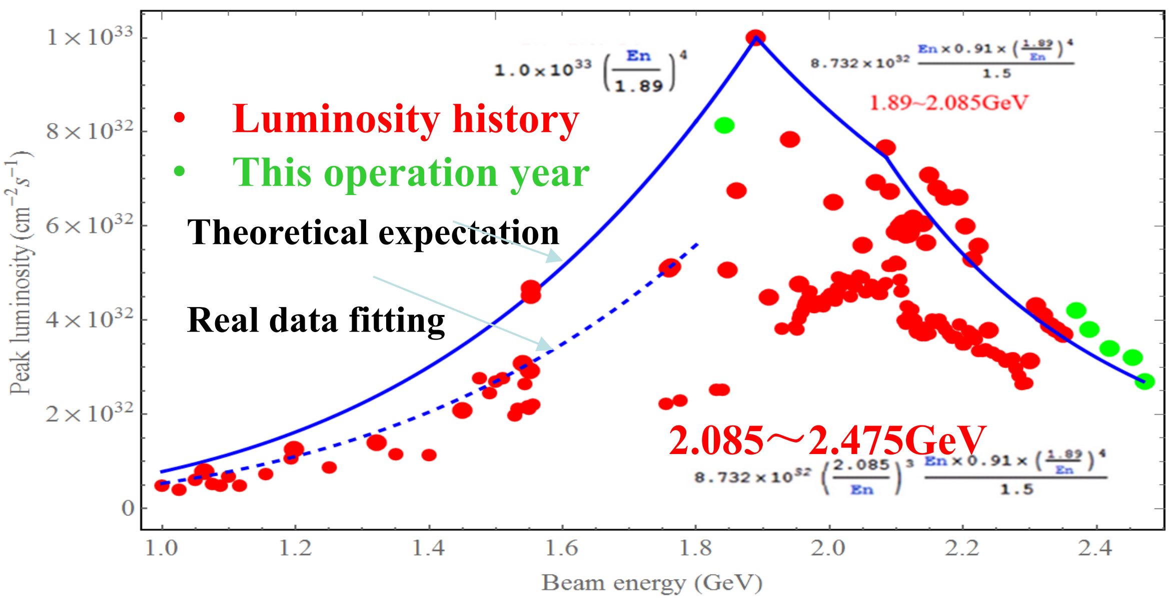
Decay Asymmetry

Λ_c^+ weak decay asymmetry — PRD 100, 072004 (2019)

Spin

Λ_c^+ spin — PRD 103 L 091101 (2021)

During December 2019 to June 2021, BESIII collected ~5.85fb^{-1} of data at $\sqrt{s}$ between 4.61 and 4.95 GeV.



E_{cms}/MeV	$\mathscr{L}_{Bhabha}$/pb^{-1}
4611.86±0.12±0.30	103.65±0.05±0.55
4628.00±0.06±0.32	521.53±0.11±2.76
4640.91±0.06±0.38	551.65±0.12±2.92
4661.24±0.06±0.29	529.43±0.12±2.81
4681.92±0.08±0.29	1667.39±0.21±8.84
4698.82±0.10±0.36	535.54±0.12±2.84
4739.70±0.20±0.30	163.87±0.07±0.87
4750.05±0.12±0.29	366.55±0.10±1.94
4780.54±0.12±0.30	511.47±0.12±2.71
4843.07±0.20±0.31	525.16±0.12±2.78
4918.02±0.34±0.34	207.82±0.08±1.10
4950.93±0.36±0.38	159.28±0.07±0.84

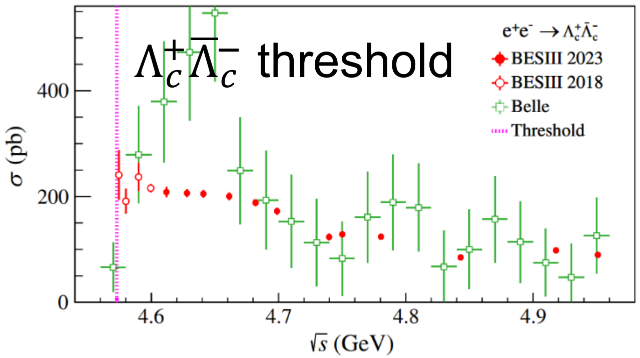
This spark another wave of research about Λ_c^+ and contribute to a serious of new important result !

Second round physics results on Λ_c^+

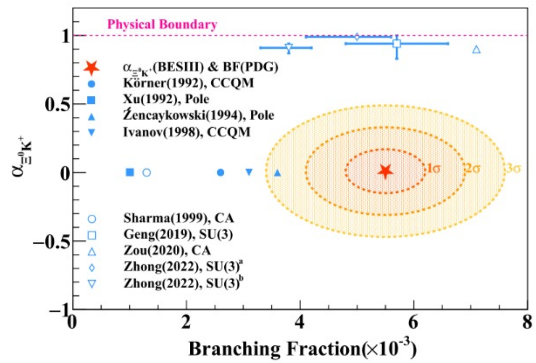
4 PRL + 3 JHEP + 15 PRDL / PRD / PLB / CPC produced !

Highlights:

$\Lambda_c^+ \to \Xi^0 K^+$ decay asymmetry



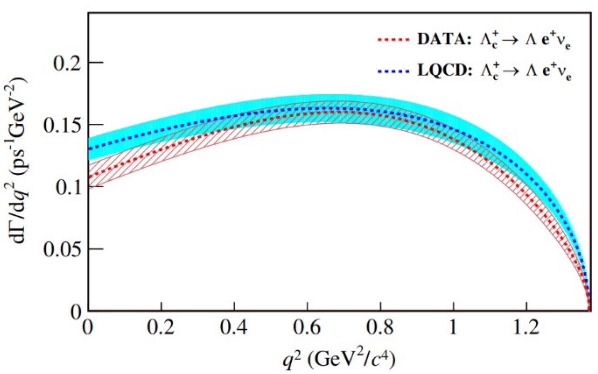
PRL 131, 191901 (2023)



PRL 132, 031801 (2024)

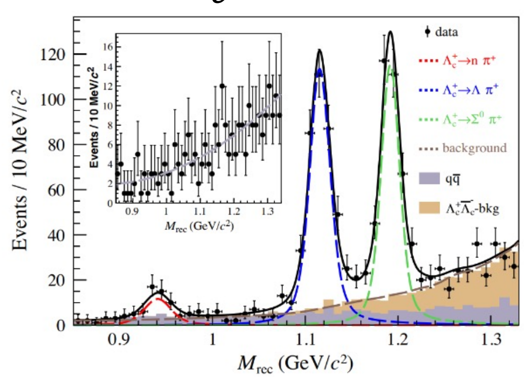
In summary, BESIII has achieved great success on Λ_c^+ study!

$\Lambda_c^+ \to \Lambda e^+ \nu_e$



PRL 131, 191901 (2023)

$\Lambda_c^+ \to n\pi^+$



PRL 131, 191901 (2023)

What's next for Λ_c^+ ?

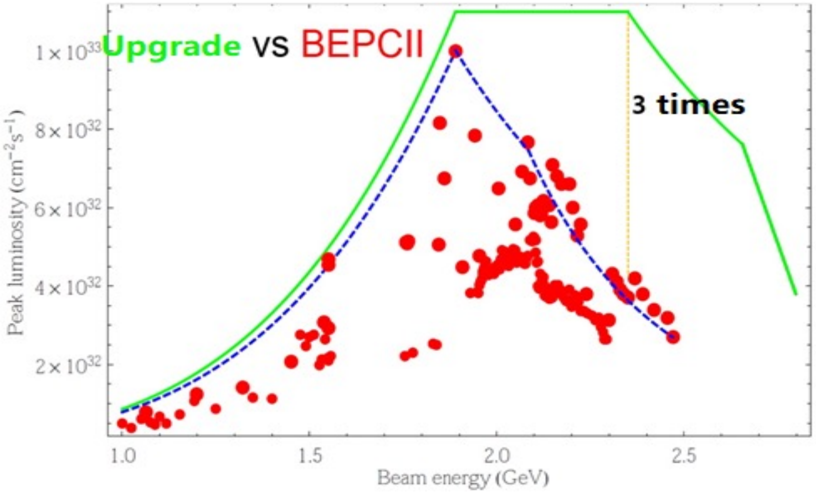
1. The precisions of measurements for Λ_c^+ decays are still less than the charm meson sector. => (need more data to improve)

2. Unique physics goals on BESIII:
   a) Polarization study;
   b) Final states containing neutral particles; (n or K_L^0)
   c) Semi-leptonic decays;
   d) Inclusive decays;
   e) Quantum correlation;
   f) Cross section close to threshold.

Part I Large data taking at certain E_{cm}

BEPCII Upgrade:

	BEPCI I @ 2.35GeV	BEPCII-U @ 2.35GeV	BEPCII-U @ 2.8GeV
L $[10^{32}cm^{-2}s^{-1}]$	**3.5**	**11**	**3.7**
β_y^* [cm]	**1.5**	**1.35**	**3.0**
Beam current [mA]	400	900	450
SR Power [kW]	**110**	**250**	**250**
$\xi_{y,\mathrm{lum}}$	0.029	0.033	0.043
Emittance [nmrad]	**147**	**152**	**200**
Couping [%]	**0.53**	**0.35**	**0.5**
Bucket Height	0.0069	0.011	0.009
$\sigma_{z,0}$ [cm]	1.54	1.07	1.4
σ_z [cm]	**1.69**	**1.22**	**1.6**
RF Voltage [MV]	1.6	3.3	3.3

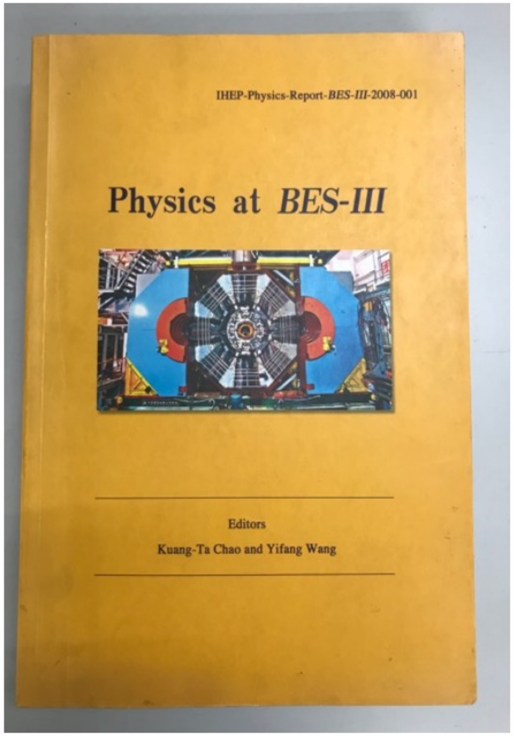


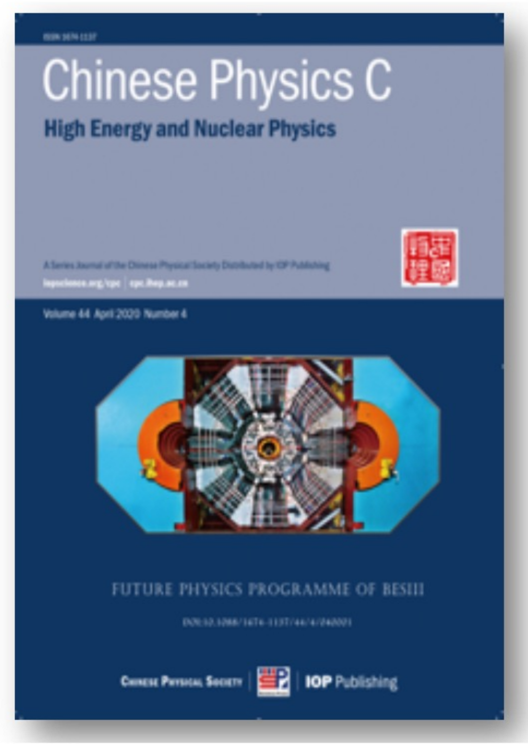
Double beam power &

Optics upgrade &

Higher gradient of magnets

BESIII Physics Report





Int. J. Mod. Phys. A 24, S1-794 (2009) [arXiv:0809.1869 [hep-ex]].

Chin. Phys. C 44, 040001 (2020) doi:10.1088/1674-1137/44/4/040001 [arXiv:1912.05983 [hep-ex]].

Planned future data set

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current (T_C) or upgraded (T_U) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	T_C / T_U
1.8 - 2.0 GeV	R values Nucleon cross-sections	N/A	0.1 fb^{-1} (fine scan)	60/50 days
2.0 - 3.1 GeV	R values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ J/ψ peak	Light hadron & Glueball J/ψ decays	3.2 fb^{-1} (10 billion)	3.2 fb^{-1} (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	0.67 fb^{-1} (0.45 billion)	4.5 fb^{-1} (3.0 billion)	150/90 days
$\psi(3770)$ peak	$D^0/D^{\pm}$ decays	2.9 fb^{-1}	20.0 fb^{-1}	610/360 days
3.8 - 4.6 GeV	R values XYZ/Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	D_s decay XYZ/Open charm	3.2 fb^{-1}	6 fb^{-1}	140/50 days
4.0 - 4.6 GeV	XYZ/Open charm Higher charmonia cross-sections	16.0 fb^{-1} at different $\sqrt{s}$	30 fb^{-1} at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/XYZ cross-sections	0.56 fb^{-1} at 4.6 GeV	15 fb^{-1} at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+\bar{\Lambda}_c^-$ cross-section	N/A	1.0 fb^{-1}	100/40 days
4.91 GeV	$\Sigma_c\bar{\Sigma}_c$ cross-section	N/A	1.0 fb^{-1}	120/50 days
4.95 GeV	Ξ_c decays	N/A	1.0 fb^{-1}	130/50 days

Completed

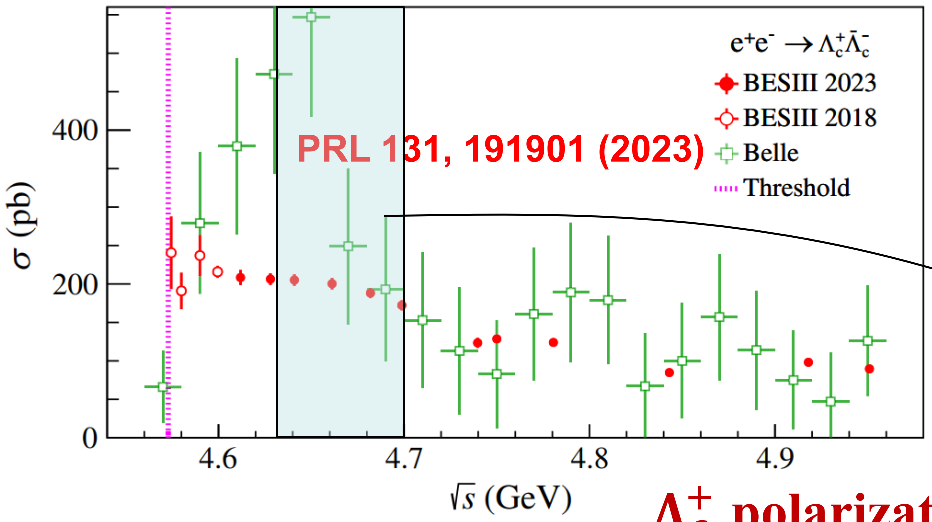
18 fb^{-1} Λ_c^+ data

in 2020-2021, 5.8 fb^{-1} is taken

Chin. Phys. C 46, 113003 (2022)

Where to take data ?

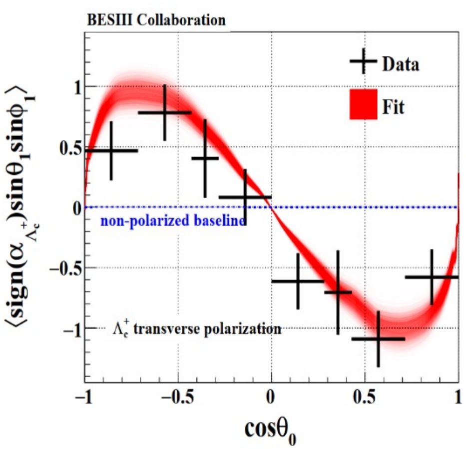
$\Lambda_c^+\bar{\Lambda}_c^-$ cross section:

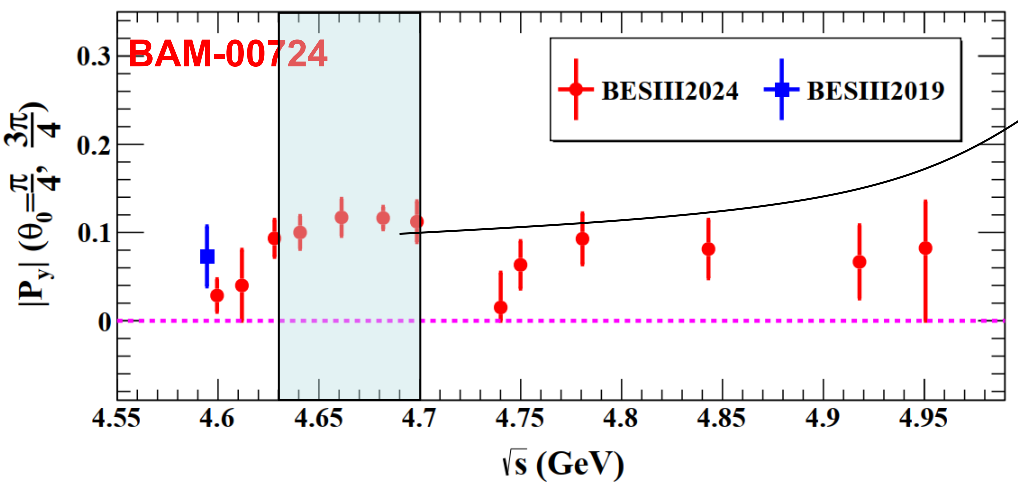


Already taken:

Sample	E_{cms}/MeV	$\mathscr{L}_{Bhabha}$/pb^{-1}	$\mathscr{L}_{di-photon}$/pb^{-1}
4610	4611.86±0.12±0.30	103.65±0.05±0.55	103.37±0.13
4620	4628.00±0.06±0.32	521.53±0.11±2.76	520.17±0.28
4640	4640.91±0.06±0.38	551.65±0.12±2.92	550.67±0.29
4660	4661.24±0.06±0.29	529.43±0.12±2.81	527.53±0.29
4680	4681.92±0.08±0.29	1667.39±0.21±8.84	1665.88±0.51
4700	4698.82±0.10±0.36	535.54±0.12±2.84	533.66±0.29
4740	4739.70±0.20±0.30	163.87±0.07±0.87	165.08±0.16
4750	4750.05±0.12±0.29	366.55±0.10±1.94	367.57±0.24
4780	4780.54±0.12±0.30	511.47±0.12±2.71	512.03±0.29
4840	4843.07±0.20±0.31	525.16±0.12±2.78	526.01±0.30
4920	4918.02±0.34±0.34	207.82±0.08±1.10	208.09±0.19
4950	4950.93±0.36±0.38	159.28±0.07±0.84	159.85±0.17

Λ_c^+ polarization:

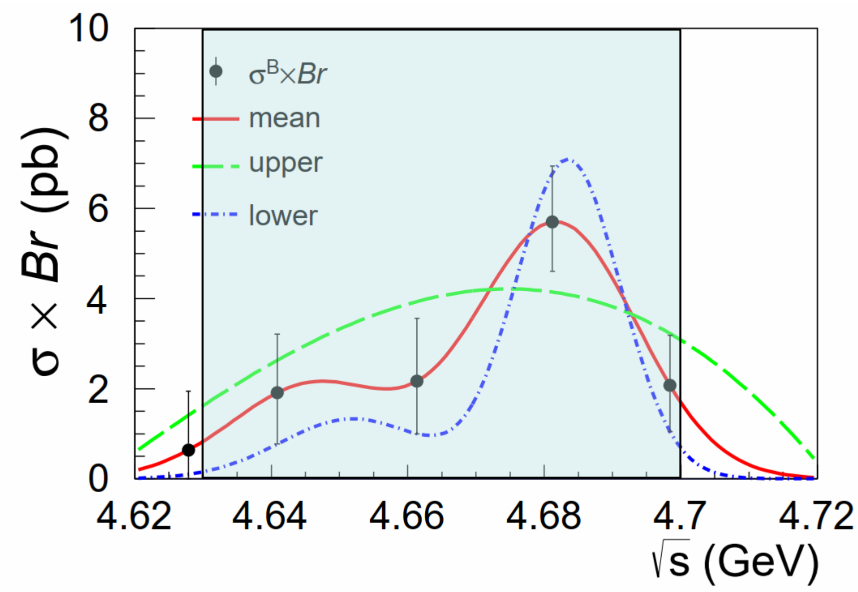




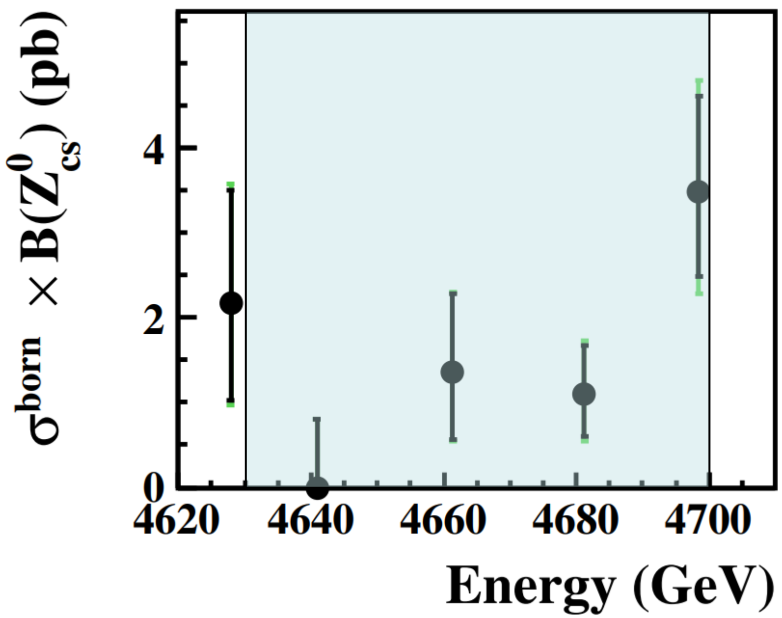
Proposed range: 4630~4700 MeV

Large cross section & large polarization

Further study of $Z_{cs}(3985)$. The cross section line shapes are:



$Z_{cs}(3985)^-$



$Z_{cs}(3990)^0$

The proposed range (4670 ~ 4690 MeV) is good for $Z_{cs}(3985)^-$.

Improve the precision of Λ_c^+ decays to the level of charmed mesons!

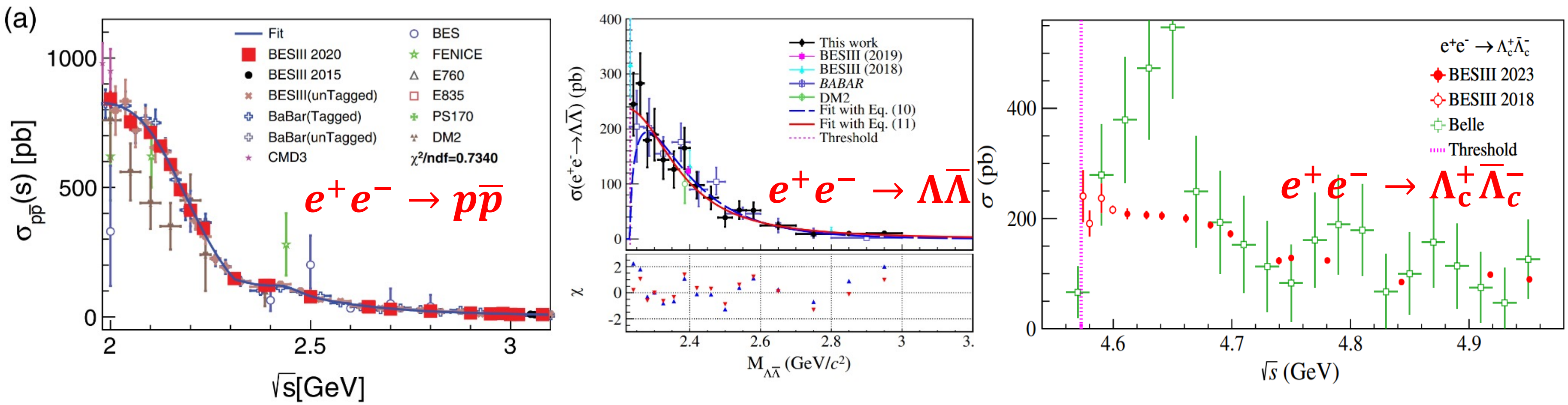
	$N_{h\bar{h}}^{tot}$	N_h^{tag}	SCS	Semi-leptonic
D^0	7.2×10^7	7.9×10^6	K^+K^-: $(4.01\pm0.07)\times10^{-3}$ (**2%**) $\pi^+\pi^-$: $(1.454\pm0.024)\times10^{-3}$ (**1.7%**)	$\pi^-e^+\nu_e$: $(2.91\pm0.04)\times10^{-3}$ (**1.4%**) $\pi^-\pi^0e^+\nu_e$: $(1.45\pm0.07)\times10^{-3}$ (**5%**)
D^+	5.7×10^7	4.1×10^6	$K_S^0K^+$: $(2.95\pm0.15)\times10^{-3}$ (**5%**) $\pi^+\pi^0$: $(1.247\pm0.033)\times10^{-3}$ (**2.6%**)	$\pi^0e^+\nu_e$: $(3.72\pm0.17)\times10^{-3}$ (**5%**) $\pi^+\pi^-e^+\nu_e$: $(2.49\pm0.11)\times10^{-3}$ (**4%**)
D_s^+	6.2×10^6	5.0×10^5	$K^+\eta$: $(1.73\pm0.08)\times10^{-3}$ (**5%**) $K_S^0\pi^+$: $(1.05\pm0.05)\times10^{-3}$ (**5%**)	$K^0e^+\nu_e$: $(3.4\pm0.4)\times10^{-3}$ (**12%**) $\phi e^+\nu_e$: $(2.39\pm0.16)\times10^{-3}$ (**7%**)
Λ_c^+	7.6×10^5	1.2×10^5	ΛK^+: $(6.21\pm0.44)\times10^{-4}$ (**7%**) $n\pi^+$: $(6.6\pm1.2)\times10^{-4}$ (**18%**)	$pK^-e^+\nu_e$: $(8.8\pm1.8)\times10^{-4}$ (**20%**) $ne^+\nu_e$: $(3.57\pm0.34)\times10^{-3}$ (**10%**)

Baseline: at least about 15 fb^{-1} $\Lambda_c^+\bar{\Lambda}_c^-$ is needed to improve the precision to 5%. (about 150 day)

Welcome your suggestion!

Part II Data Taking near $\Lambda_c^+\bar{\Lambda}_c^-$ threshold

Numerous experiments support non-zero cross sections near baryon threshold [1~6]:



To explain the non vanishment of cross section of $e^+e^- \to B\bar{B}$ (B is a spin -1/2 baryon) near threshold[1~6], Sommerfeld[7] & Sakharov[8] put forward the parameterization form based on one-photon exchange(OPEX) assumption:

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2]$$

where the interaction between the outgoing baryons is considered in the Coulomb factor $C = \varepsilon \cdot R$, which plays a very important role in description of nonzero cross section near threshold due to the enhancement factor $\varepsilon = \pi\alpha/\beta$.

Model for $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$:

$$\sigma = \frac{4\pi\alpha^2\beta C}{3\,s}\left(|G_{\mathrm{M}}(q^2)|^2 + \frac{2M^2_{\Lambda_c^+}}{s}|G_{\mathrm{E}}(q^2)|^2\right)$$

$s = q^2$ is the invariant mass squared of the e^+e^- system

$\alpha = e^2/(4\pi)$ is the electromagnetic fine structure constant

$\beta = \sqrt{1 - 4M^2_{\Lambda_c^+}/s}$ is the velocity of baryon Λ_c^+ $\quad \tau = q^2/(4M^2_{\Lambda_c^+})$

C is the s-wave Sommerfeld–Gamow factor corresponding to the final state Coulomb interaction, which is $C(y) = \frac{y}{1-e^{-y}}$ with $y = \frac{\alpha\pi}{\beta}\frac{2M_{\Lambda_c^+}}{\sqrt{s}}$

G_{E} and G_{M} can be obtained by combining the Pauli and Dirac form factors

vector meson dominance (VMD) model

$$G_{\mathrm{E}}(q^2) = F_1(q^2) + \tau F_2(q^2),$$
$$G_{\mathrm{M}}(q^2) = F_1(q^2) + F_2(q^2),$$

$$F_1 = g(s)\left(f_1 + \sum_{i=1}^{4}\beta_i B_{R_i}\right),$$
$$F_2 = g(s)\left(f_2 B_{R_1} + \sum_{i=2}^{4}\alpha_i B_{R_i}\right),$$

$$B_{R_i} = \frac{M^2_{R_i}}{M^2_{R_i} - s - iM_{R_i}\Gamma_{R_i}},$$
$$g(s) = \frac{1}{(1-\gamma s)^2}$$

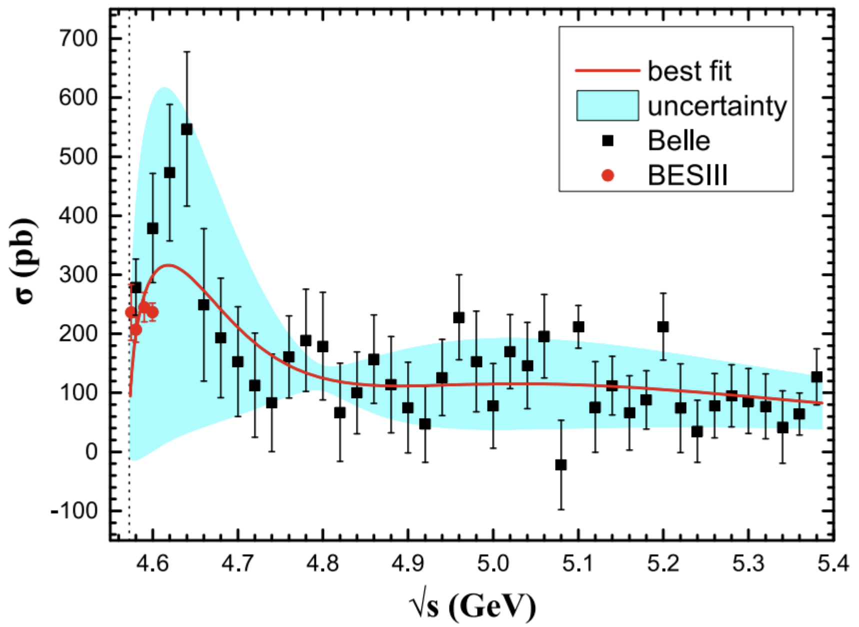
$R_1 \equiv \psi(4500)$, $R_2 \equiv \psi(4660)$, $R_3 \equiv \psi(4790)$, and $R_4 \equiv \psi(4900)$

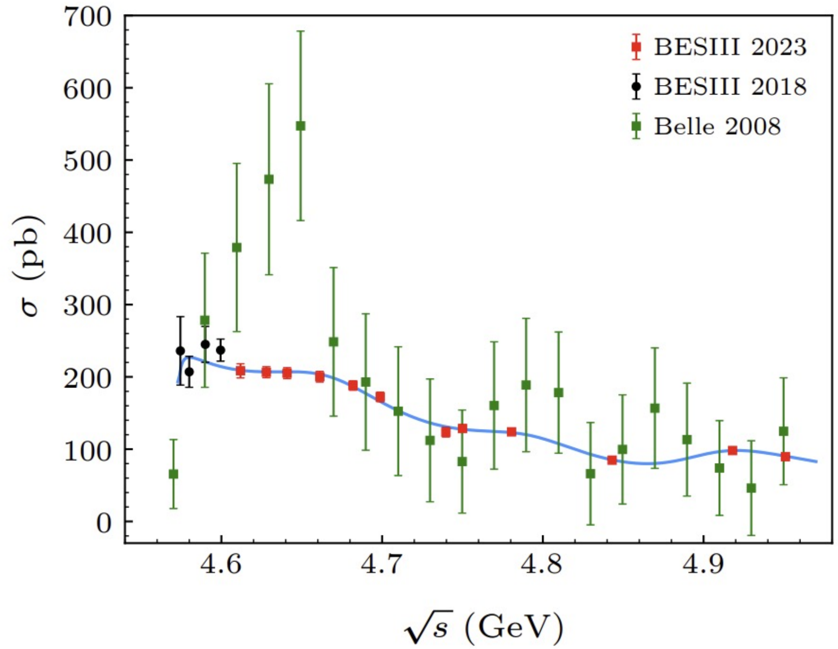
$$f_1 = 1 - \beta_1 - \beta_2 - \beta_3 - \beta_4,$$
$$f_2 = \mu_{\Lambda_c^+} - 1 - \alpha_2 - \alpha_3 - \alpha_4$$

Parameter	Value	Parameter	Value
g_{Λ_c}	1.173 ± 0.259	β_4	-0.141 ± 0.097
β_1	1.883 ± 0.484	α_2	1.089 ± 0.297
β_2	-1.101 ± 0.302	α_3	0.438 ± 0.192
β_3	-0.439 ± 0.194	α_4	0.133 ± 0.096

State	Mass M_R (MeV)	Width Γ_R (MeV)
$\psi(4500)$	4500	125
$\psi(4660)$	4670	115
$\psi(4790)$	4790	100
$\psi(4900)$	4900	100

By employing the vector meson dominance[9-11] (VMD) model, the electromagnetic form factors (EMFFs) in the formula of cross section can be described well by many theorists group[12,13]:





The electromagnetic form factors of Λ_c hyperon in the vector meson dominance model

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$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ Cross Sections and the Λ_c^+ Electromagnetic Form Factors within the Extended Vector Meson Dominance Model

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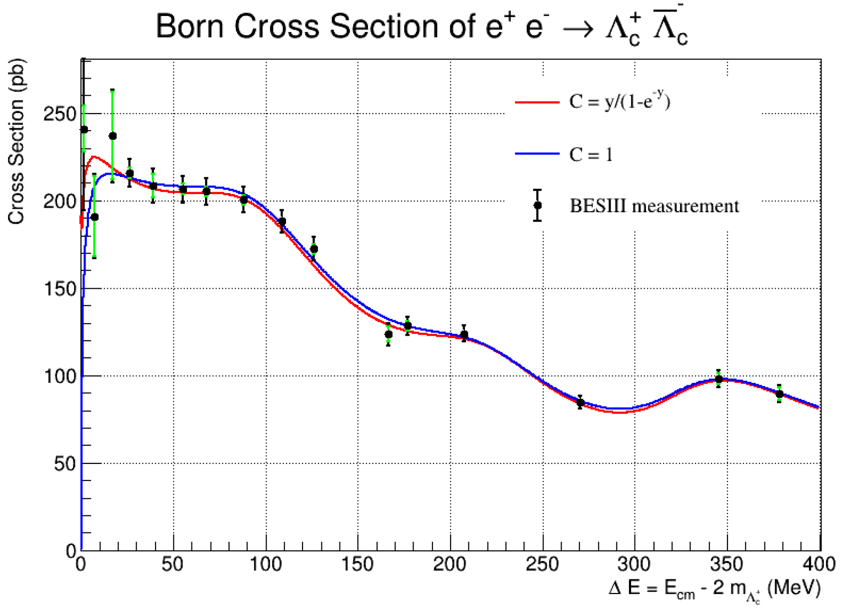
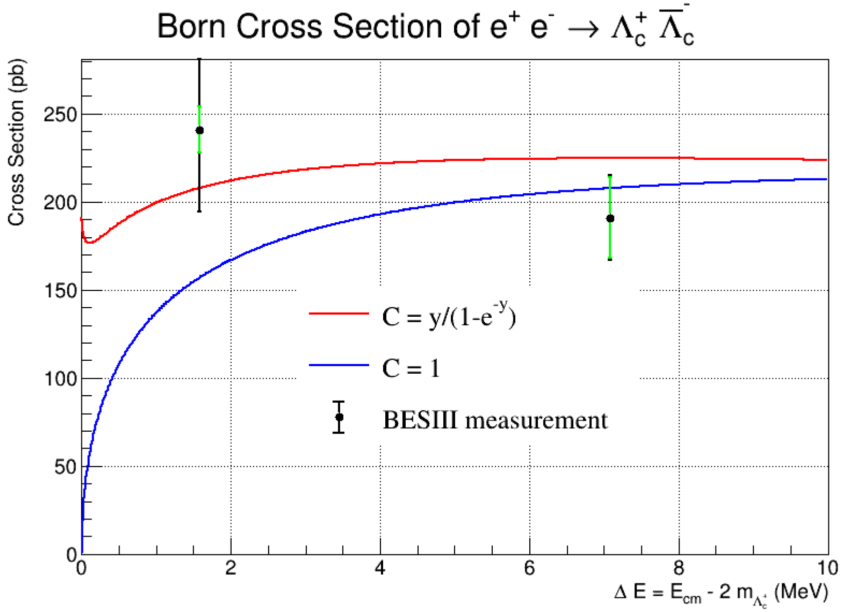
However, the existence of Coulomb factor C 's effect hasn't been really confirmed, since the current model for baryon cross section can fit to experiment data whether including the Coulomb factor or not:





The two line shapes begin to diverge only at the points extremely close to the baryon threshold !

Currently only a few measurements for baryon cross sections touch the region within 2 MeV of the baryon threshold.

$e^+e^- \to B\bar{B}$	Threshold (MeV)	First $\sqrt{s}$ point (MeV)	ΔM (MeV)	P_{child}^{max} (MeV)
$p\bar{p}$	1876.54	1876 ~ 1880 (ISR)	1.46	0
$n\bar{n}$	1879.13	2000.0	120.87	0
$\Lambda\bar{\Lambda}$	2231.34	2231 ~ 2250 (ISR)	9.16	$(p\pi^-)$ 101
$\Sigma^+\bar{\Sigma}^-$	2378.74	2379 ~ 2440 (ISR)	30.76	$(p\pi^0)$ 189
$\Sigma^0\bar{\Sigma}^0$	2385.28	2386.4	1.12	$(\Lambda\gamma)$ 74
$\Xi^-\bar{\Xi}^+$	2643.42	2644.4	0.98	$(\Lambda\pi^-)$ 140
$\Omega^-\bar{\Omega}^+$	3344.9	3490.0	145.1	(ΛK^-) 211
$\Lambda_c^+\bar{\Lambda}_c^-$	4572.92	4574.5	1.58	$(pK^-\pi^+)$ 823

Among these baryons, the measurements for cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ has great advantages, since the final state particles of Λ_c^+ still have large momenta to be detected, while other channels are not.

To confirm the non-vanishment of the baryon cross section near threshold, **$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ collision data extremely close to the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold is important !**

The observed cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ can be derived from of born cross section:

$$\sigma(E_{c.m.}, m_{\Lambda_c^+}, \delta_w^{BEMS}) = \frac{1}{\sqrt{2\pi}\delta_w^{BEMS}} \int_{2m_{\Lambda_c^+}}^{\infty} \mathrm{d}E'_{c.m.} e^{\frac{-(E_{c.m.}-E'_{c.m.})^2}{2(\delta_w^{BEMS})^2}} \int_0^{1-\frac{4m^2}{E'^2_{c.m.}}} \mathrm{d}x F(x, E'_{c.m.}) \frac{\sigma_1(E'_{c.m.}\sqrt{1-x}, m_{\Lambda_c^+})}{|1-\prod(E_{c.m.})|^2}$$

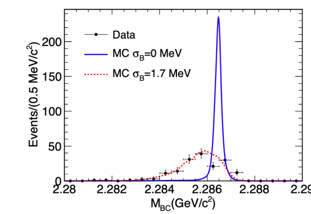
which is determined by the cernter-of-mass energy $E_{\text{c.m.}}$, baryon mass $m_{\Lambda_c^+}$ and beam energy spread δ_w^{BEMS}.

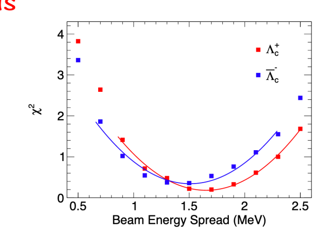
$F(x, E'_{c.m.})$ is the radiative correction factor

$|1-\Pi(E_{c.m.})|^2$ is the vacuum polarization factor.

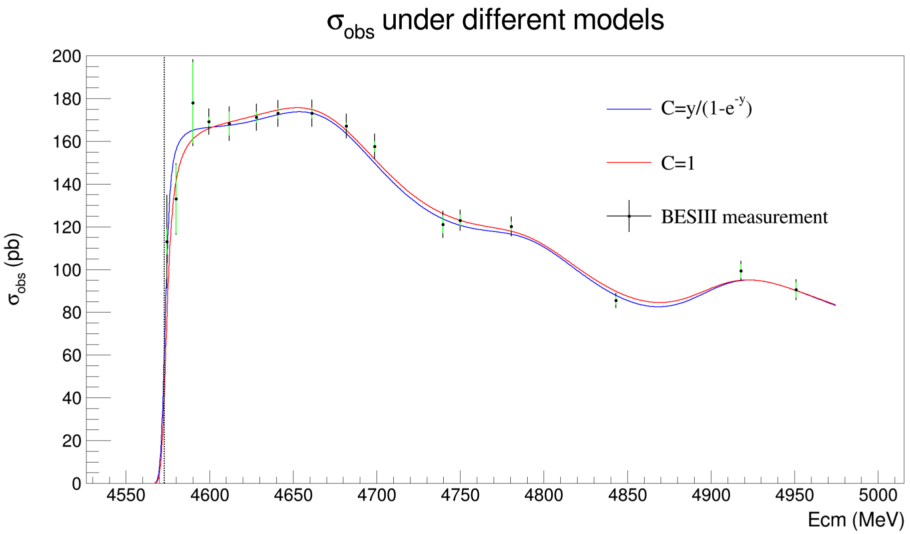
Application

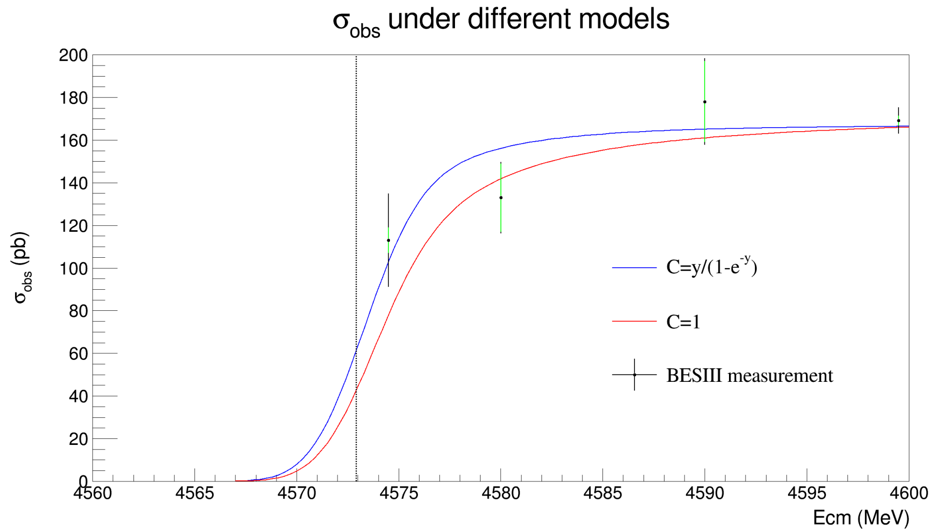
- @4600 MeV
- Smallest χ^2
  - ☐ $p_1^+ = 1.63 \pm 0.24$ MeV
  - ☐ $p_1^- = 1.50 \pm 0.24$ MeV
  - ☐ $\sigma_E = 2.22 \pm 0.24$ MeV
- Consistent with the performance of BEPCII, as well as the previous method



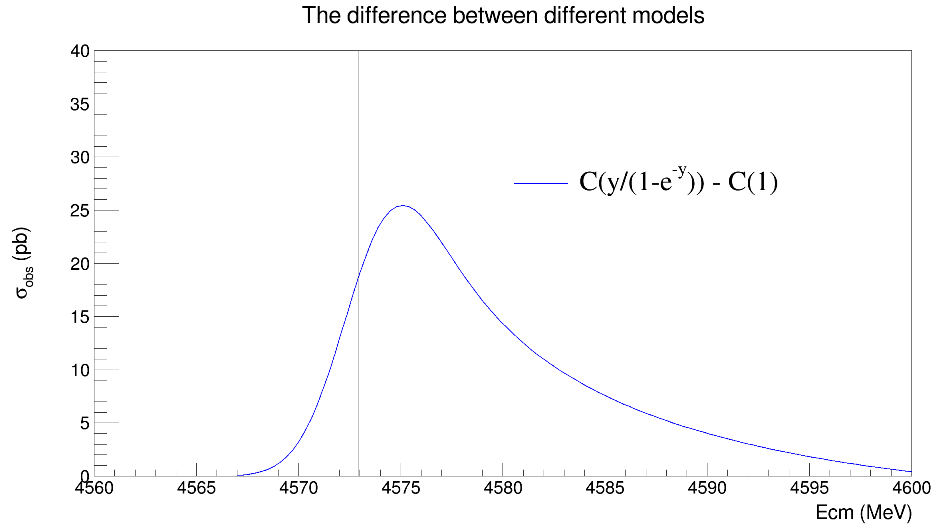


Derived observed cross section:

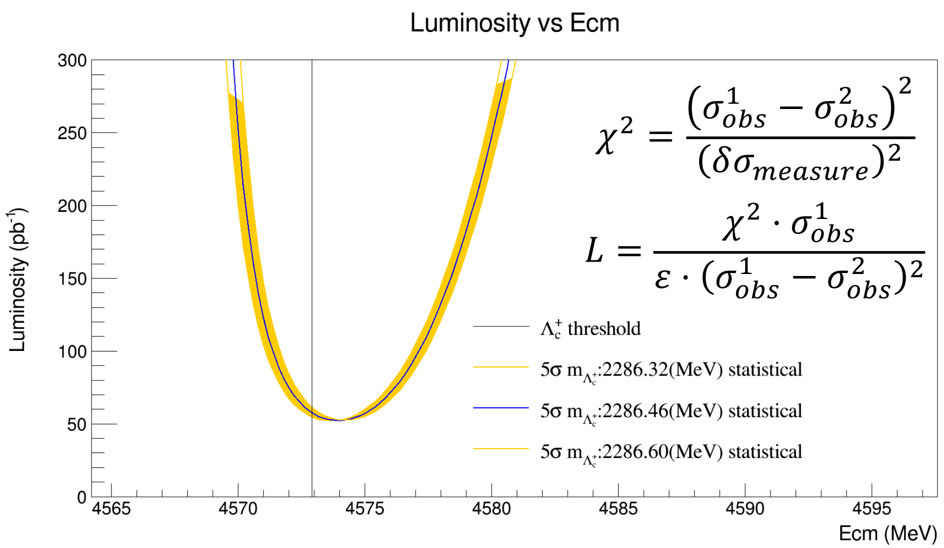


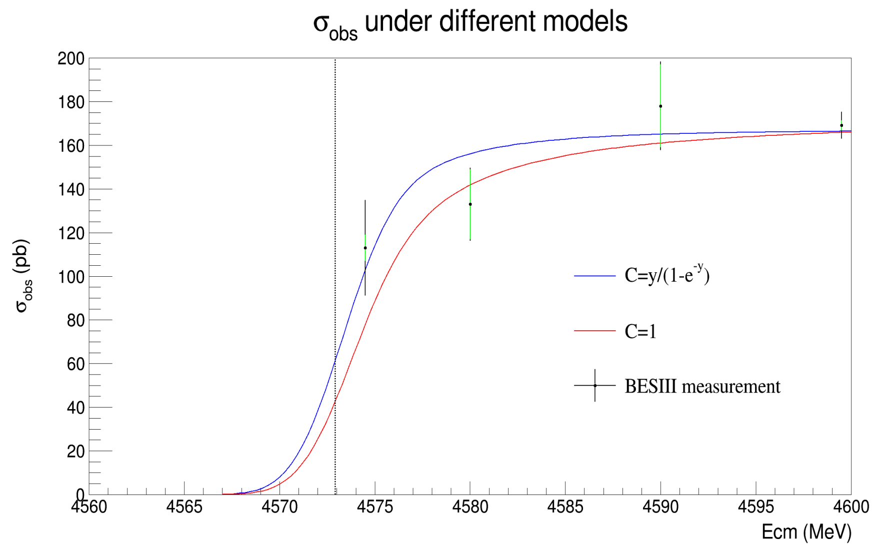


The difference of observed cross section between two possible models:



Base on statistical method of hypothesis testing, the minimum luminosity needed to distinguish two models with a significance of 5σ is estimated:





Data taken at **4573.6 MeV** (**about 0.7 MeV above the threshold**) can test the Coulomb factor best in this VMD model. [CPL 41, 021302 (2024)]

Proposed data taking points: (about 6 day)

E_{cm} (MeV)	4572	4573	4574	4575	4576	4577	All
Luminosity (pb^{-1})	100	76	70	77	95	128	546

Summary

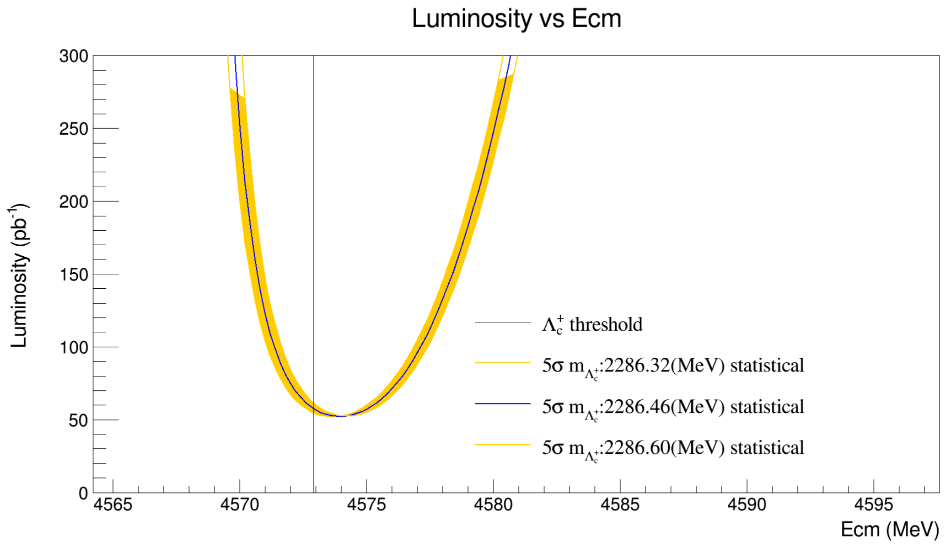
A proposal of data taking is raised up to further study the Λ_c^+ baryon.

1. Large data set taken at about 4630 ~ 4700 MeV , about 15 fb^{-1} (150 days) is needed, which has relatively large cross section and polarization;

2. Data taken at the $\sqrt{s}$ region close to $\Lambda_c^+\bar{\Lambda}_c^-$ threshold, from 4572 ~ 4577 MeV, about 550 pb^{-1} (6 days) is needed.

Backup

Base on statistical method of hypothesis testing, the minimum luminosity needed to distinguish two models with a significance of 5σ is estimated:



$$\chi^2 = \left(\frac{\sigma_1 - \sigma_2}{err}\right)^2,$$

$$err = \frac{\sigma_1 * BkgCorrection}{\sqrt{\sigma_1 * L * Alleff}} = \frac{\sqrt{\sigma_1} * BkgCorrection}{\sqrt{L * Alleff}},$$

$$L = \frac{\chi^2 * \sigma_1 * BkgCorrection^2}{Alleff * (\sigma_1 - \sigma_2)^2}$$

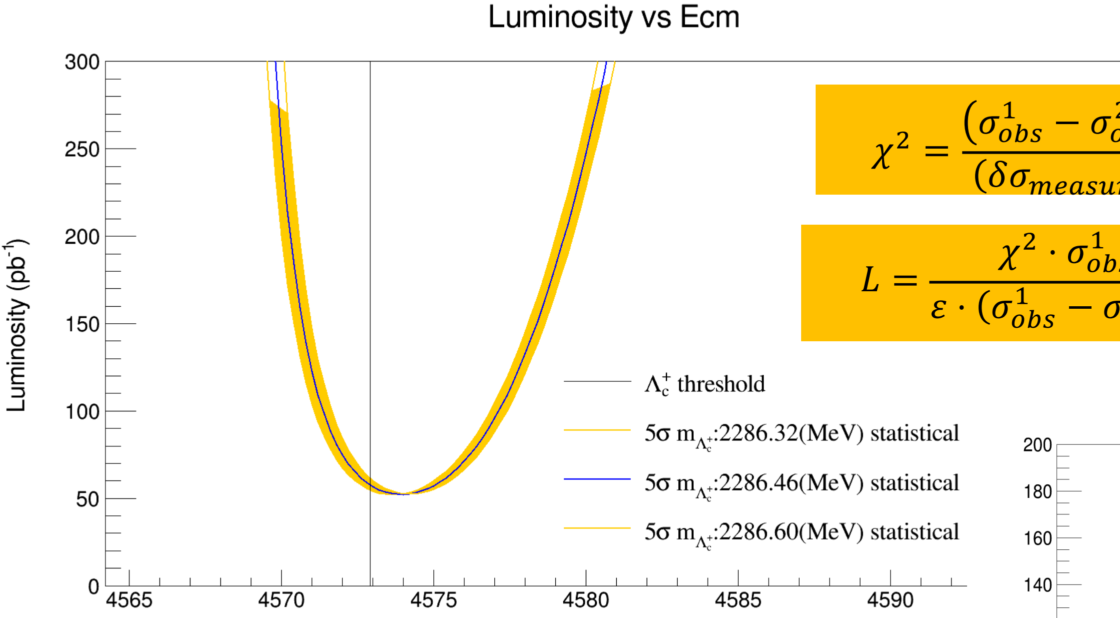
Suggestions from accelerator experts:

Thanks Prof. Cheng-hui Yu !

2.3 GeV束流能量下（质心能量4.6GeV附近），束流能量最小步长0.12MeV能确定做到精确。

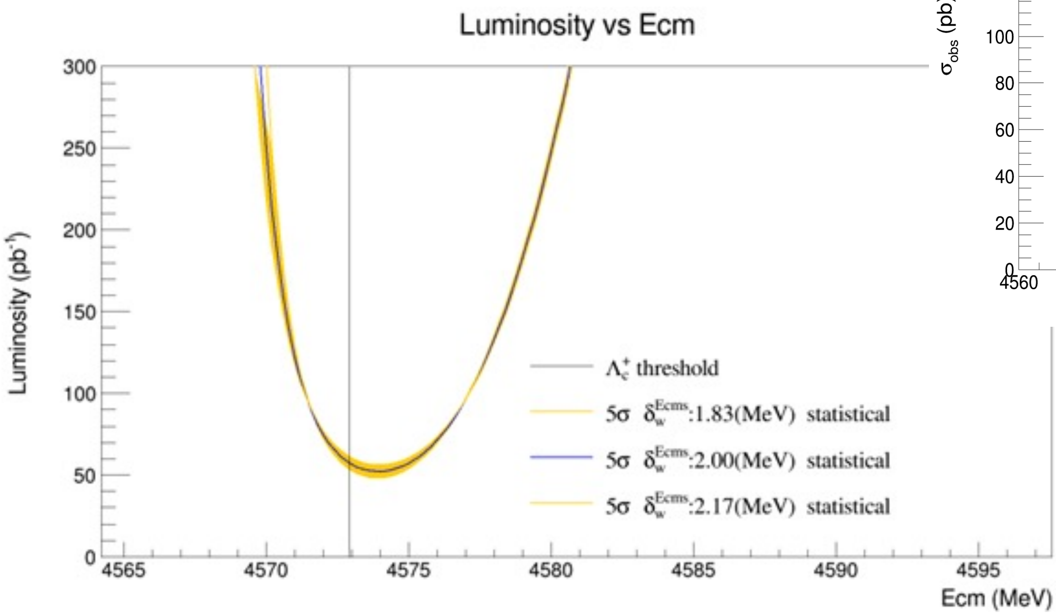
BEPCII二极磁铁电源精度按十万分之五的技术指标要求进行设计制造，实际精度肯定会更好些

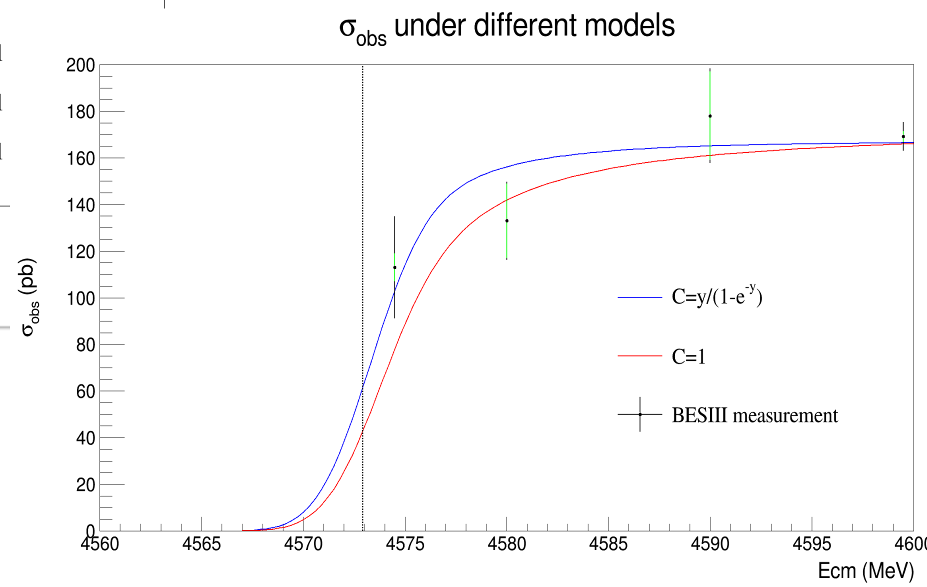
正负电子环的二极铁电流是独立的吧？那总对撞能量扫描最小精度应该是sqrt(0.12**2+0.12**2)=0.17MeV



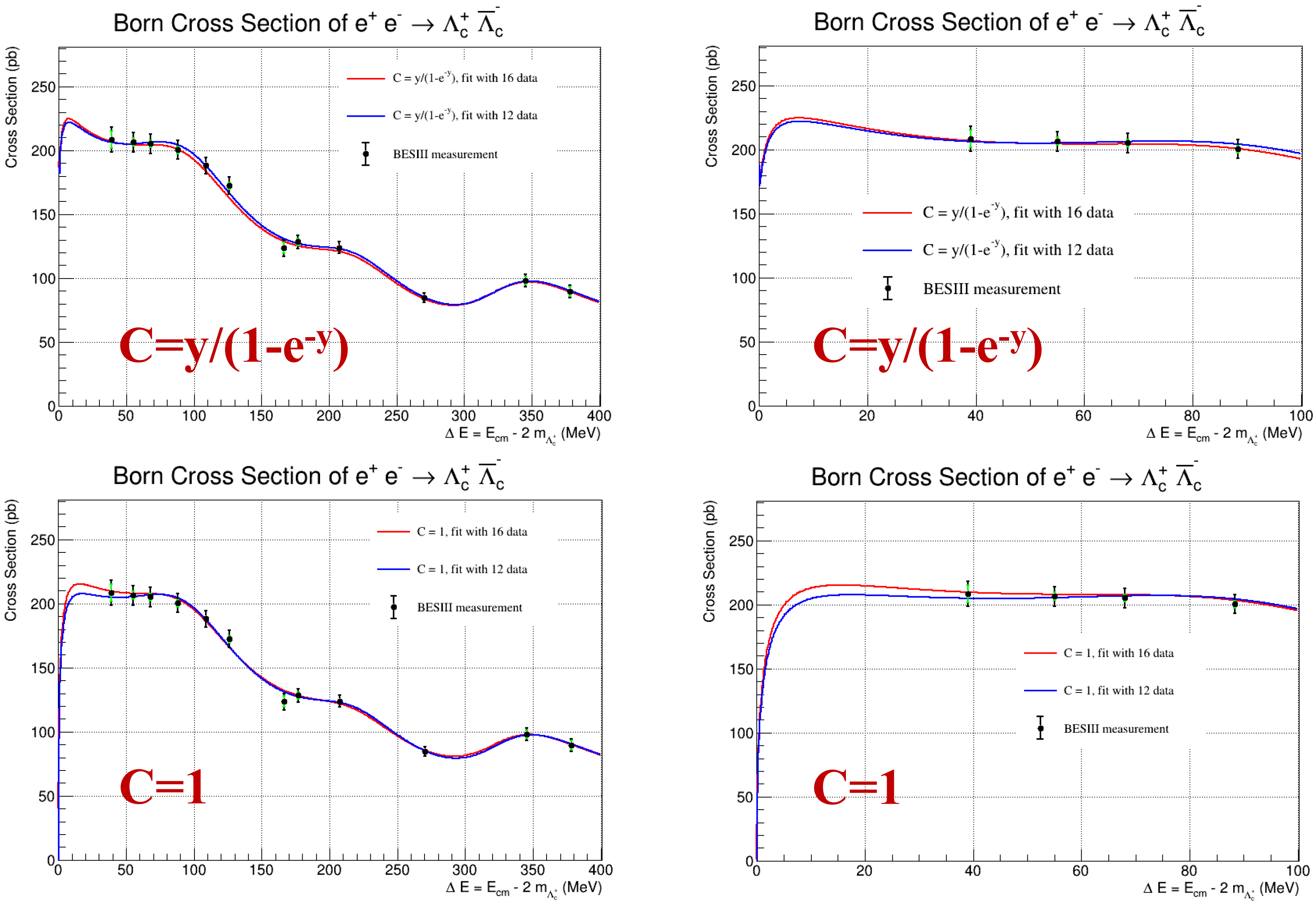
$$\chi^2 = \frac{\left(\sigma_{obs}^1 - \sigma_{obs}^2\right)^2}{(\delta\sigma_{measure})^2}$$

$$L = \frac{\chi^2 \cdot \sigma_{obs}^1}{\varepsilon \cdot (\sigma_{obs}^1 - \sigma_{obs}^2)^2}$$





Fitting the born cross section with high E_{cm} data:



χ^2 test for current data near threshold to distinguish different models:

E_{cm}(MeV)	σ_{obs}	χ^2 with σ_C is not constant	χ^2 with σ_C is constant
4574.5	$113.0 \pm 5 \pm 20$	2.7640	33.9233
4580.0	133.0 ± 16	2.1006	0.3068
4590.0	178.0 ± 19	0.4600	0.7920
4599.5	169.1 ± 2.3	1.3381	1.9107
Total	\	6.6627	36.9328