Fit the line-shapes of Λ_c^+ pair production

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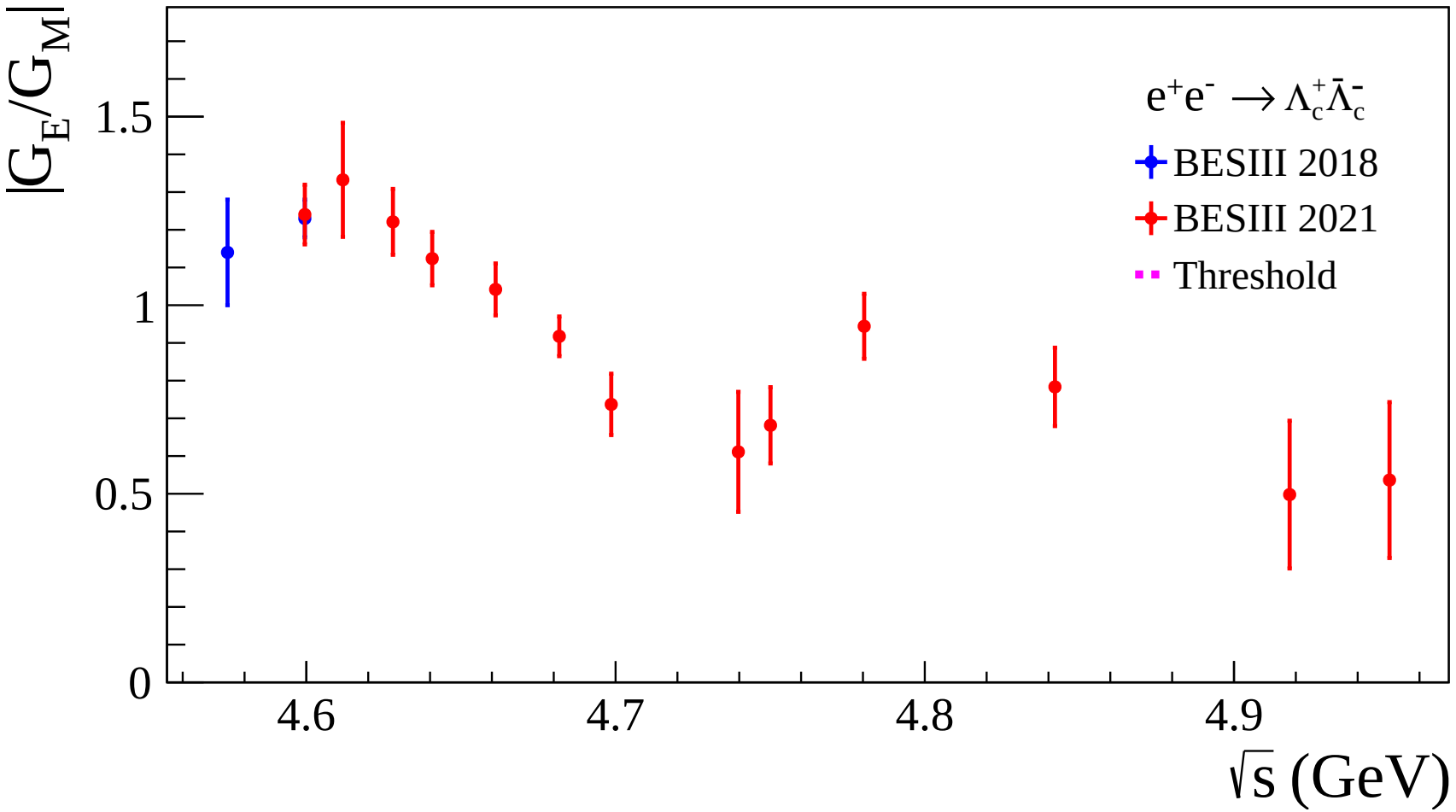
Summary on form factors

Polar angle study results:

$\sqrt{s}$ (GeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$	$\lvert G_M \rvert$ (10^{-2})
4.6115	$-0.27 \pm 0.10 \pm 0.02$	$1.32 \pm 0.14 \pm 0.03$	$43.8 \pm 3.8 \pm 0.9$
4.6277	$-0.19 \pm 0.07 \pm 0.01$	$1.22 \pm 0.09 \pm 0.02$	$42.4 \pm 2.3 \pm 0.9$
4.6405	$-0.10 \pm 0.06 \pm 0.01$	$1.12 \pm 0.07 \pm 0.02$	$41.9 \pm 1.8 \pm 0.8$
4.6609	$-0.01 \pm 0.07 \pm 0.01$	$1.03 \pm 0.07 \pm 0.01$	$40.2 \pm 1.8 \pm 0.9$
4.6816	$0.11 \pm 0.05 \pm 0.02$	$0.92 \pm 0.05 \pm 0.02$	$38.8 \pm 1.3 \pm 0.9$
4.6984	$0.31 \pm 0.10 \pm 0.02$	$0.75 \pm 0.08 \pm 0.02$	$38.1 \pm 1.9 \pm 0.7$
4.7397	$0.48 \pm 0.18 \pm 0.08$	$0.61 \pm 0.15 \pm 0.06$	$31.6 \pm 2.7 \pm 0.8$
4.7501	$0.40 \pm 0.12 \pm 0.02$	$0.68 \pm 0.10 \pm 0.02$	$31.2 \pm 1.9 \pm 0.5$
4.7804	$0.10 \pm 0.09 \pm 0.03$	$0.94 \pm 0.08 \pm 0.03$	$27.7 \pm 1.5 \pm 0.5$
4.8421	$0.29 \pm 0.12 \pm 0.02$	$0.78 \pm 0.10 \pm 0.01$	$23.1 \pm 1.5 \pm 0.5$
4.9180	$0.66 \pm 0.23 \pm 0.09$	$0.49 \pm 0.20 \pm 0.07$	$25.8 \pm 2.5 \pm 0.9$
4.9503	$0.61 \pm 0.23 \pm 0.07$	$0.54 \pm 0.20 \pm 0.06$	$24.0 \pm 2.5 \pm 0.7$

- The $|G_E/G_M|$ and $|G_M|$ results are obtained at all the used c.m. energies.
- Systematic uncertainties are addressed from two aspects.

Comparison of form factor ratios

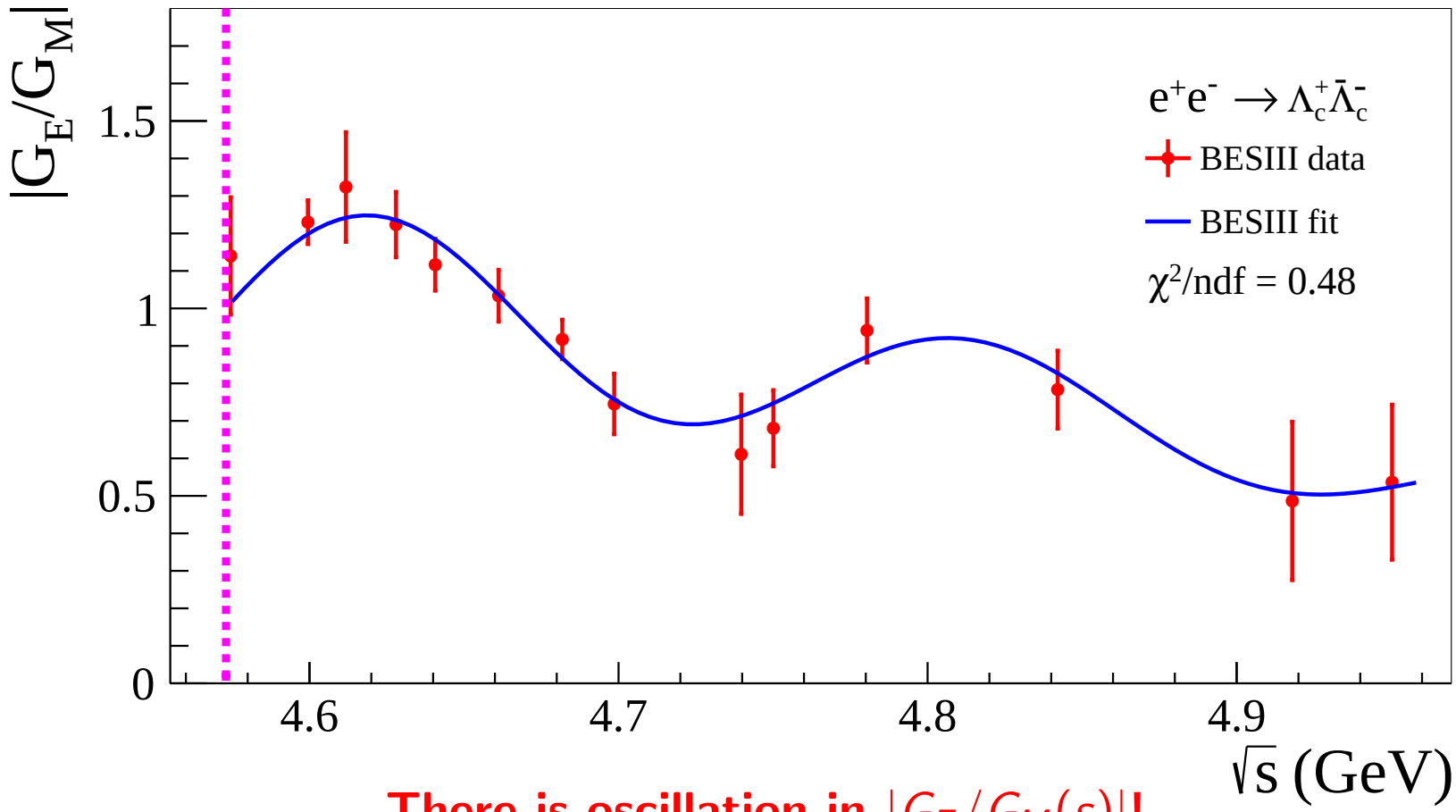


- Two measurements give consistent results of $|G_E/G_M|$.
- Oscillation along with the c.m. energy?

Fit the form factor ratios

The $|G_E/G_M|(s)$ is fitted with an oscillation function [PRC **103**, 035203 (2021)]:

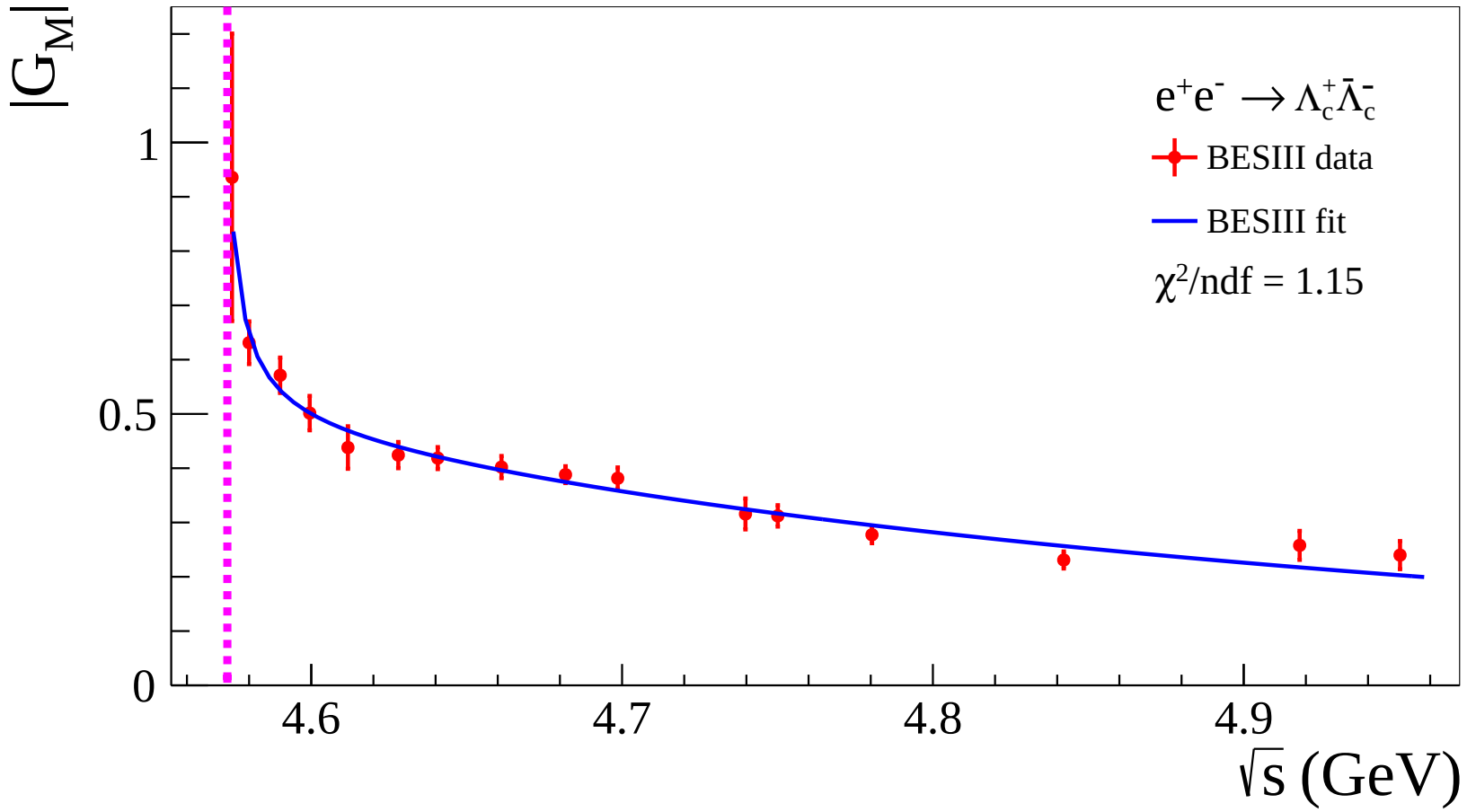
$$|G_E/G_M|(s) = \frac{1}{1+\omega^2/a^0}[1 + a_1 e^{-a_2\omega} sin(a_3\omega)], \quad \text{with} \quad \omega = \sqrt{s} - 2m_{\Lambda_c^+}$$



There is oscillation in $|G_E/G_M(s)|$!

Fit the module of magnetic form factor

The $|G_M(s)|$ is fitted with a below threshold BW function and a $1/s^n$ ($n = 2.59$) function, where the interference is not considered.



$G_E(s)$ is calculated based on the One-photon Exchange (OPE) model.

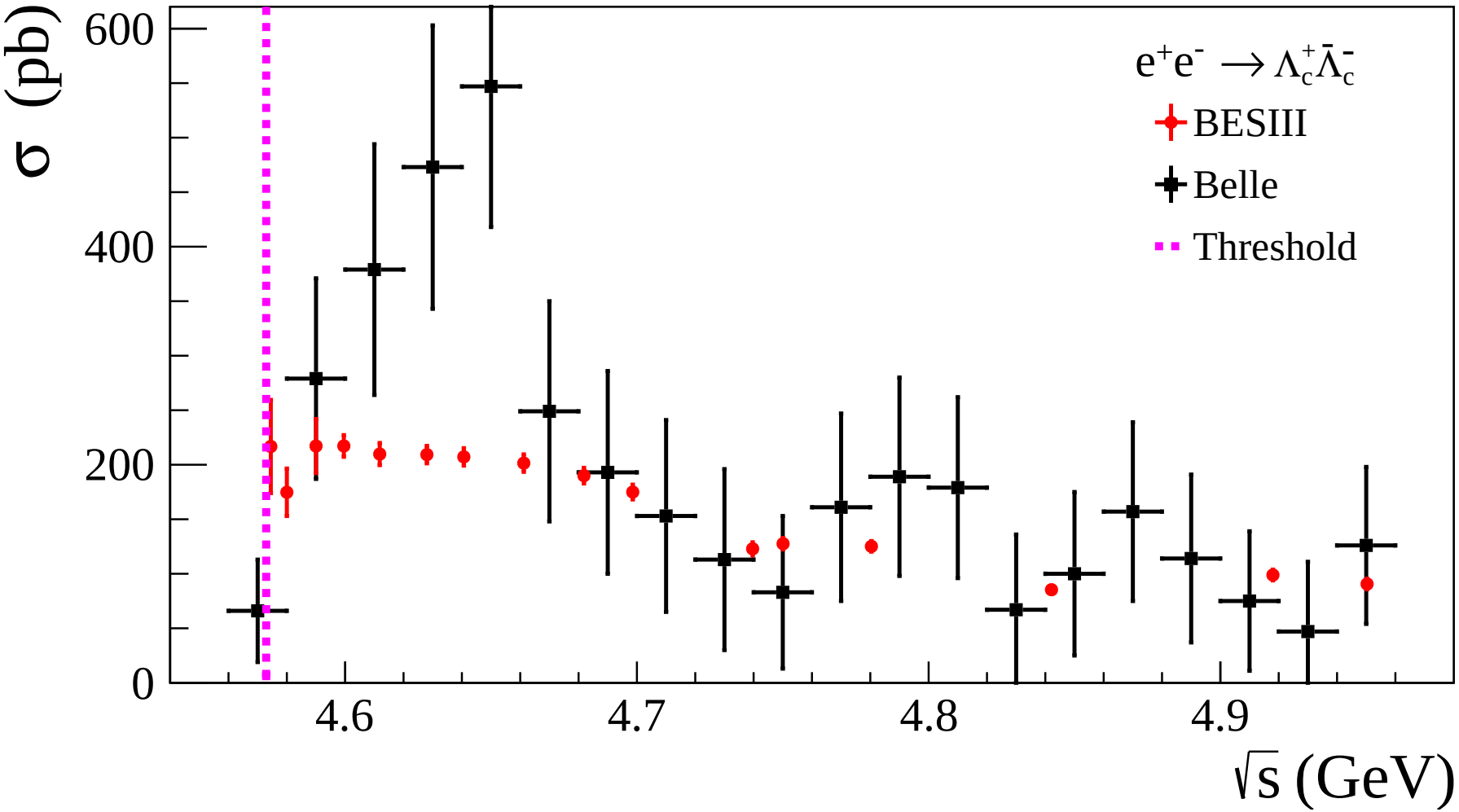
Average cross sections

Average cross sections obtained by tagging the golden mode:

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$f_{\rm ISR}$	$\sigma^{\rm Born}_{\Lambda_c^+}$ (pb)	$\sigma^{\rm Born}_{\bar{\Lambda}_c^-}$ (pb)	$\sigma^{\rm obs}$ (pb)	$\sigma^{\rm Born}$ (pb)
4.5995	587	0.743	$213 \pm 4 \pm 9$	$222 \pm 4 \pm 10$	$170 \pm 2 \pm 7$	$217 \pm 3 \pm 10$
4.6115	104	0.767	$215 \pm 10 \pm 8$	$204 \pm 10 \pm 7$	$170 \pm 6 \pm 6$	$210 \pm 7 \pm 7$
4.6277	522	0.790	$209 \pm 4 \pm 8$	$208 \pm 4 \pm 7$	$174 \pm 3 \pm 6$	$209 \pm 3 \pm 7$
4.6405	552	0.806	$208 \pm 4 \pm 8$	$203 \pm 4 \pm 7$	$176 \pm 3 \pm 6$	$207 \pm 3 \pm 7$
4.6609	530	0.828	$207 \pm 4 \pm 8$	$195 \pm 4 \pm 7$	$176 \pm 3 \pm 6$	$201 \pm 3 \pm 7$
4.6816	1669	0.849	$188 \pm 2 \pm 7$	$191 \pm 2 \pm 7$	$170 \pm 1 \pm 6$	$190 \pm 2 \pm 7$
4.6984	536	0.865	$171 \pm 4 \pm 6$	$178 \pm 4 \pm 6$	$160 \pm 2 \pm 6$	$175 \pm 3 \pm 6$
4.7397	164	0.901	$121 \pm 6 \pm 4$	$126 \pm 6 \pm 5$	$117 \pm 4 \pm 4$	$123 \pm 4 \pm 4$
4.7501	367	0.909	$133 \pm 4 \pm 5$	$123 \pm 4 \pm 4$	$122 \pm 3 \pm 4$	$128 \pm 3 \pm 5$
4.7804	513	0.930	$125 \pm 2 \pm 5$	$124 \pm 3 \pm 5$	$123 \pm 2 \pm 4$	$125 \pm 2 \pm 4$
4.8421	527	0.953	$86 \pm 3 \pm 3$	$86 \pm 3 \pm 3$	$86 \pm 2 \pm 3$	$85 \pm 2 \pm 3$
4.9180	208	0.955	$98 \pm 5 \pm 4$	$100 \pm 5 \pm 4$	$100 \pm 3 \pm 4$	$99 \pm 3 \pm 4$
4.9503	160	0.953	$88 \pm 5 \pm 3$	$92 \pm 5 \pm 3$	$91 \pm 4 \pm 3$	$91 \pm 4 \pm 3$

- Systematical uncertainties from tracking and PID are cancelled.
- Dominant systematical uncertainty is from statistical error of $\mathcal{BR}$, which reads 3.2%.
- Other systematic uncertainties are temporally quoted from previous study.

Summary of the cross sections

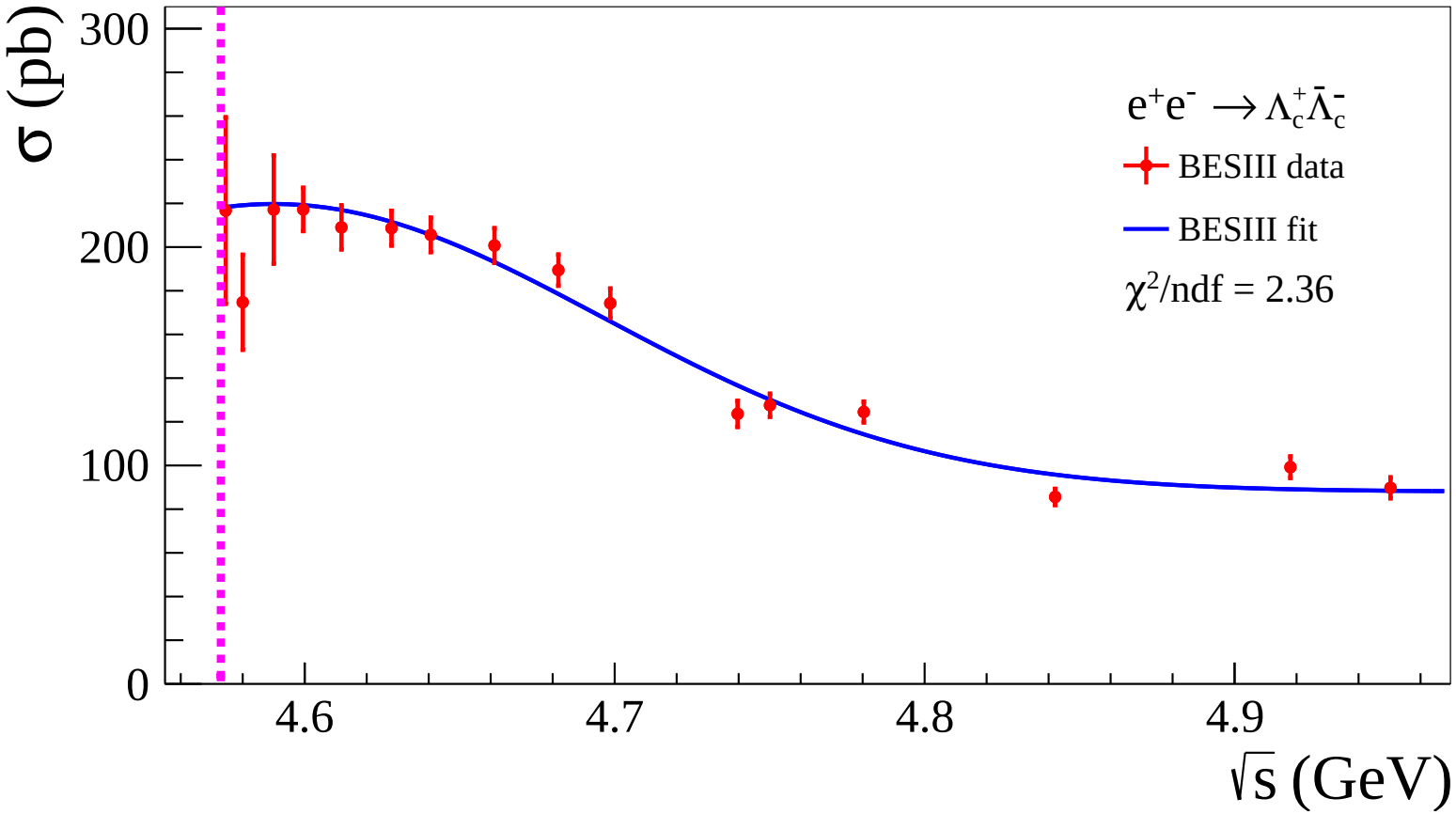


The cross sections published at 2018 are updated with new $\mathcal{BR}_{\pm}$.

Fit the cross section line-shape: Gaussian function

The cross section line-shape is fitted with a exponential decay function:

$$\sigma(s) = a_0 + a_1 \mathrm{Exp}(-\frac{(\sqrt{s} - a_2)^2}{a_3^2})$$

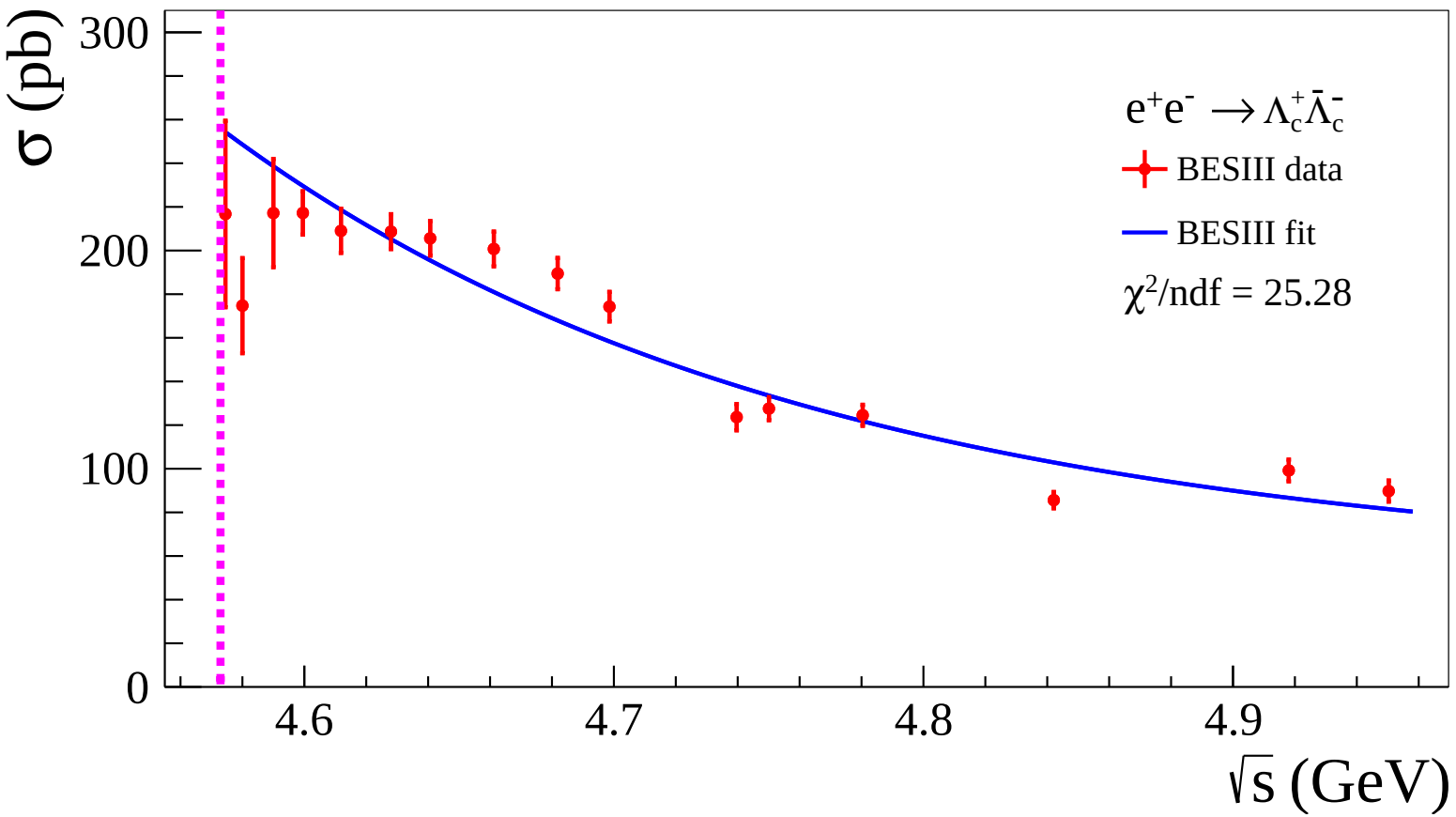


Fit quality is not good.

Fit the cross section line-shape: Exponential decay

The cross section line-shape is fitted with a exponential decay function:

$$\sigma(s) = a_0 + a_1 e^{-a_2(\sqrt{s}-2m_{\Lambda_c^+})}$$



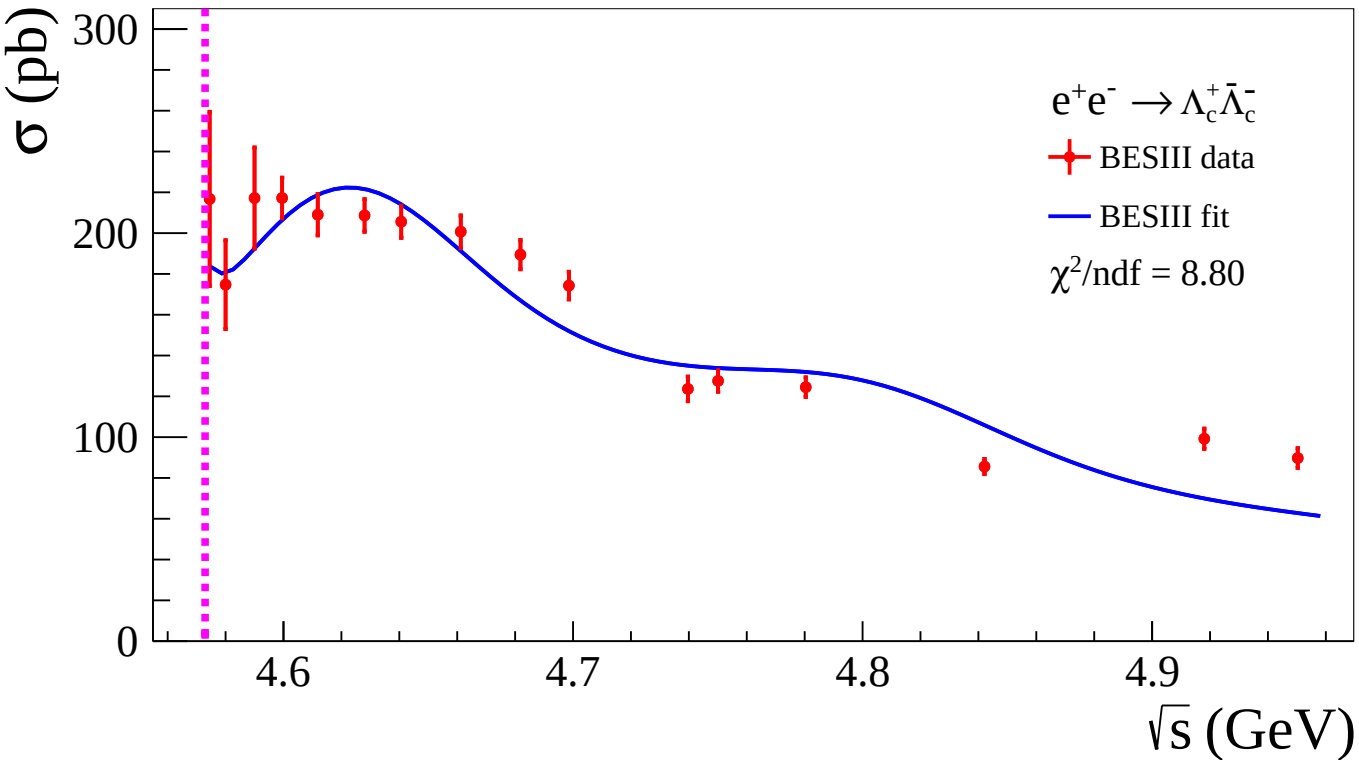
Fit quality is not acceptable!

Fit the cross section line-shape: Coulomb factor

The cross section line-shape is fitted with the previously used function:

$$\sigma(s) = a_0^2 \frac{4\pi^2\alpha^2\beta C}{3s}|G_M(s)|\left[1 + |G_E/G_M(s)|^2 \frac{2m^2_{\Lambda_c^+}}{s}\right]$$

where $|G_M(s)|$ and $|G_E/G_M(s)|$ are obtained from the previous fits.



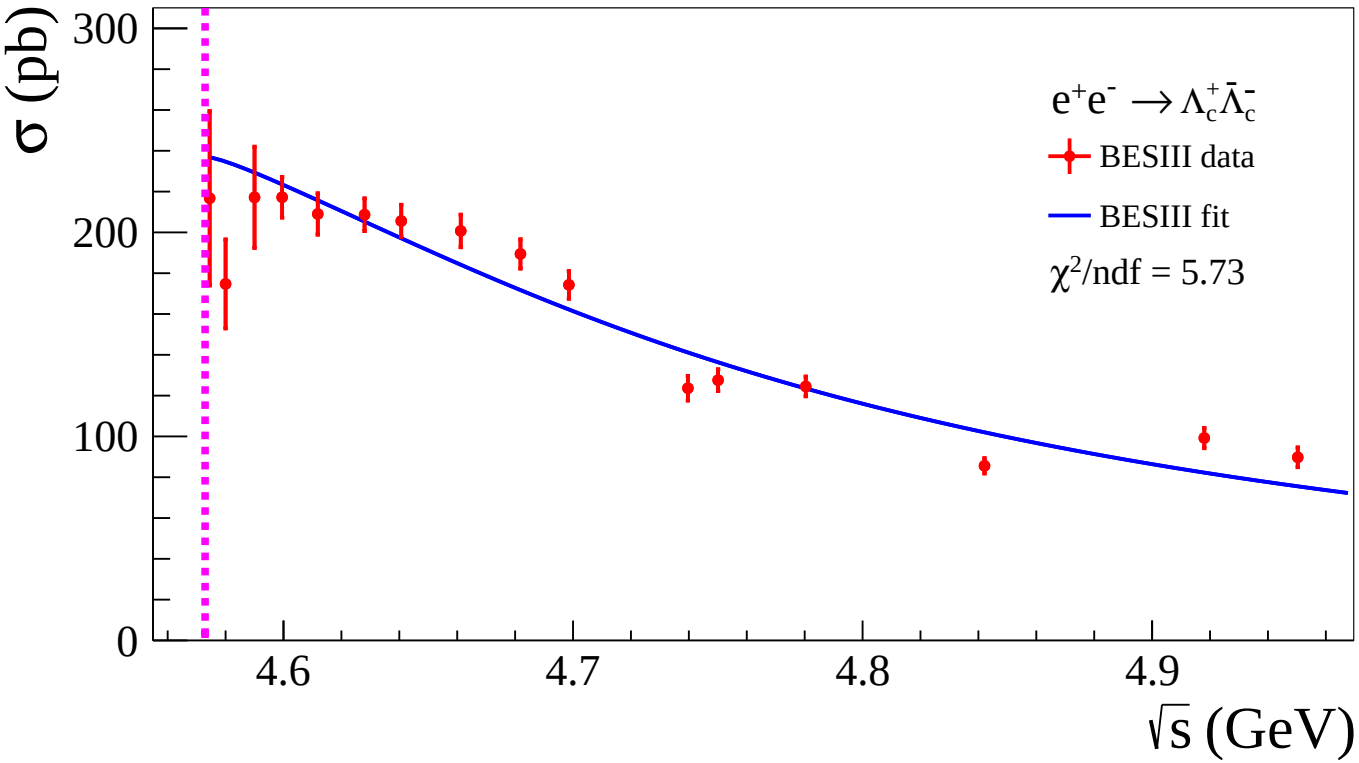
Difficult to fit cross section data by using the OPE model.

Fit the cross section line-shape: ppbar function

The cross section line-shape is fitted with a function used in $e^+e^- \to p\bar{p}$ case:

$$\sigma(s) = \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]}$$

where $\alpha_s(s)$ is the coupling constant of strong interaction.

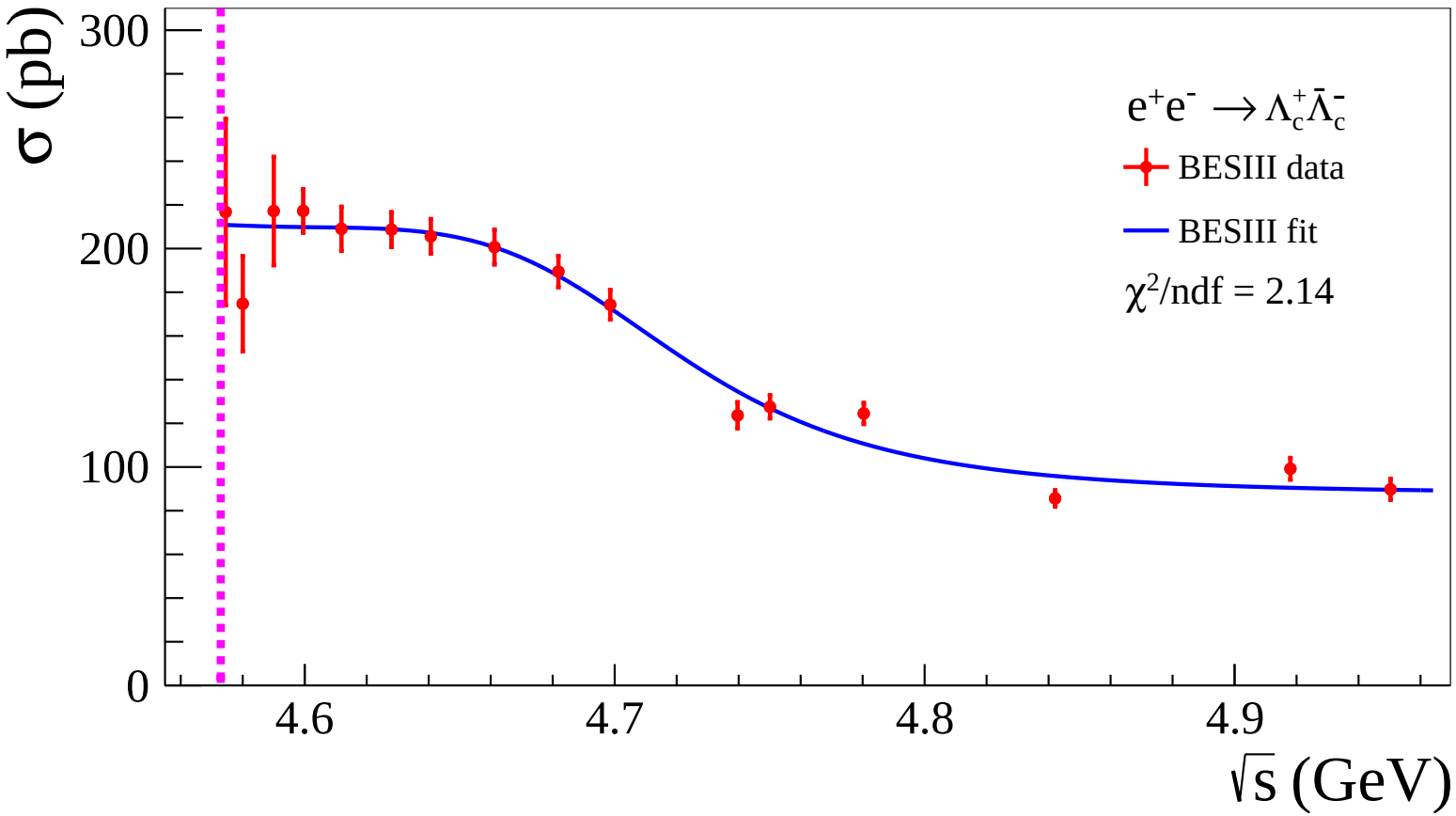


Fit quality is not acceptable!

Fit the cross section line-shape: ppbar function

The cross section line-shape is fitted with a function used in $e^+e^- \to p\bar{p}$ case but with an additional constant parameter:

$$\sigma(s) = a_3 + \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]}$$

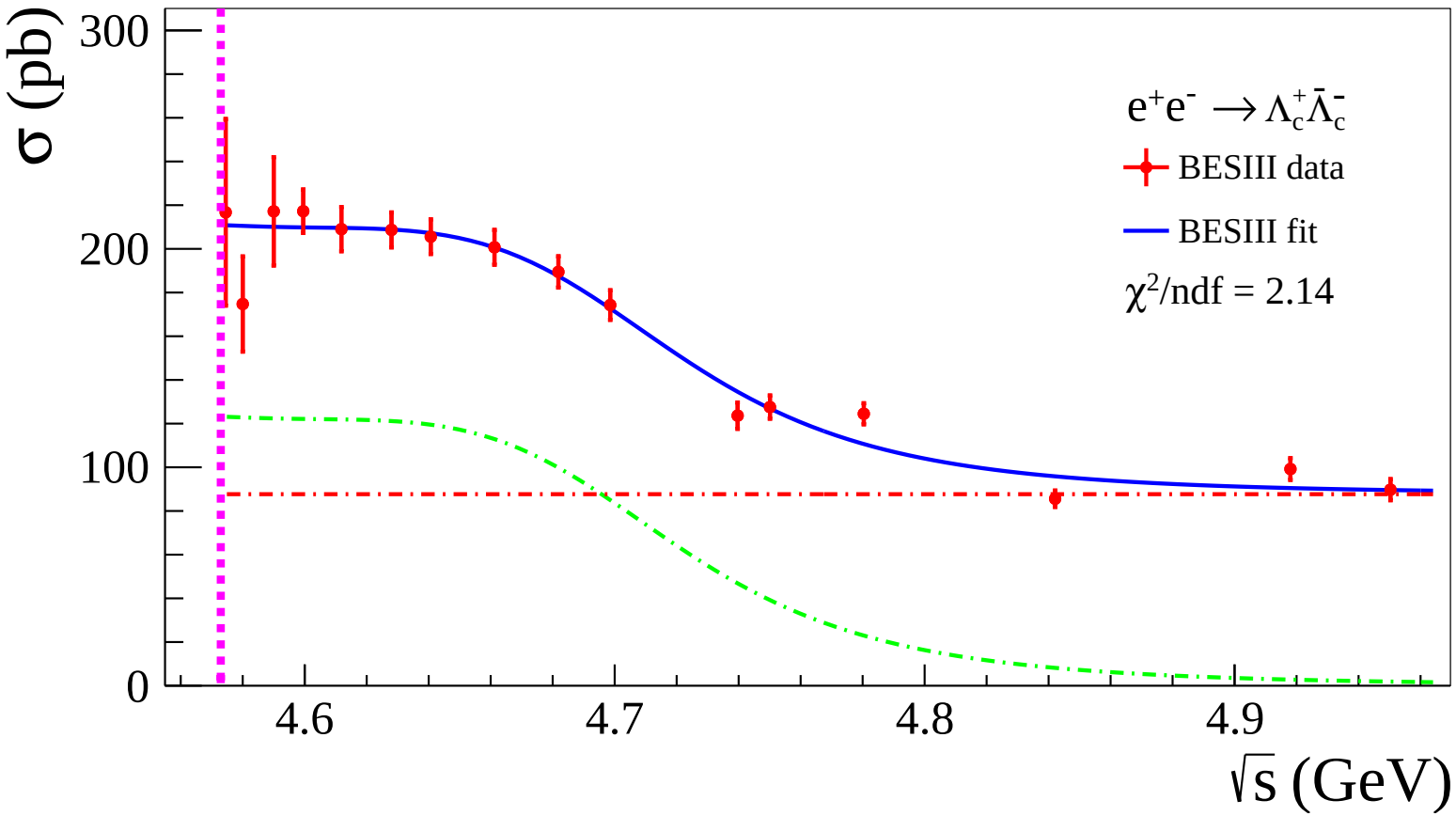


Much better, but can be further improved.

Fit the cross section line-shape: ppbar function

The cross section line-shape is fitted with a function used in $e^+e^- \to p\bar{p}$ case but with an additional constant parameter:

$$\sigma(s) = \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]} + a_3$$

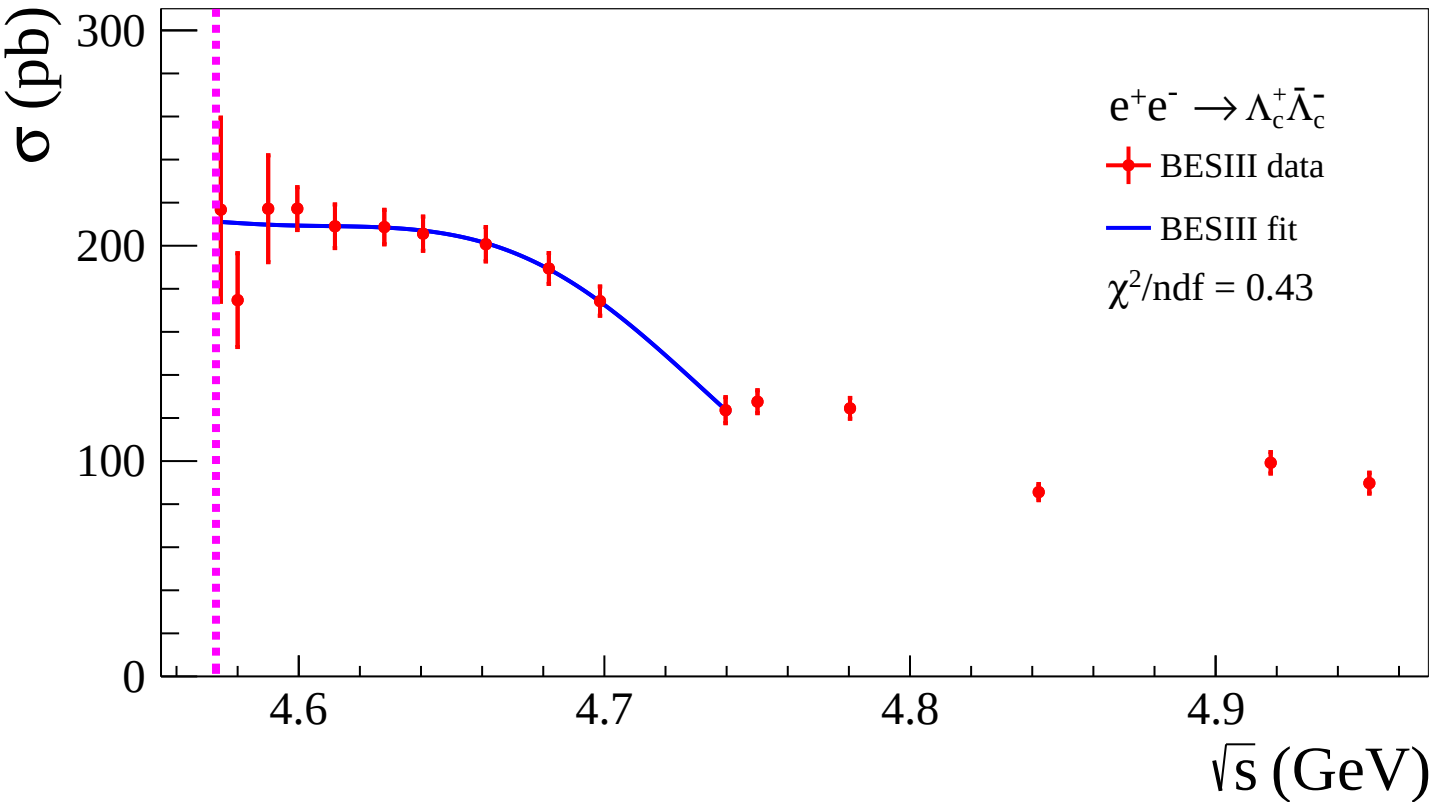


Fit the cross section line-shape: below 4.74 GeV

The cross section line-shape below 4.74 GeV is fitted with a function used in $e^+e^- \to p\bar{p}$ case:

$$\sigma(s) = \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]}$$

where $\alpha_s(s)$ is the coupling constant of strong interaction.

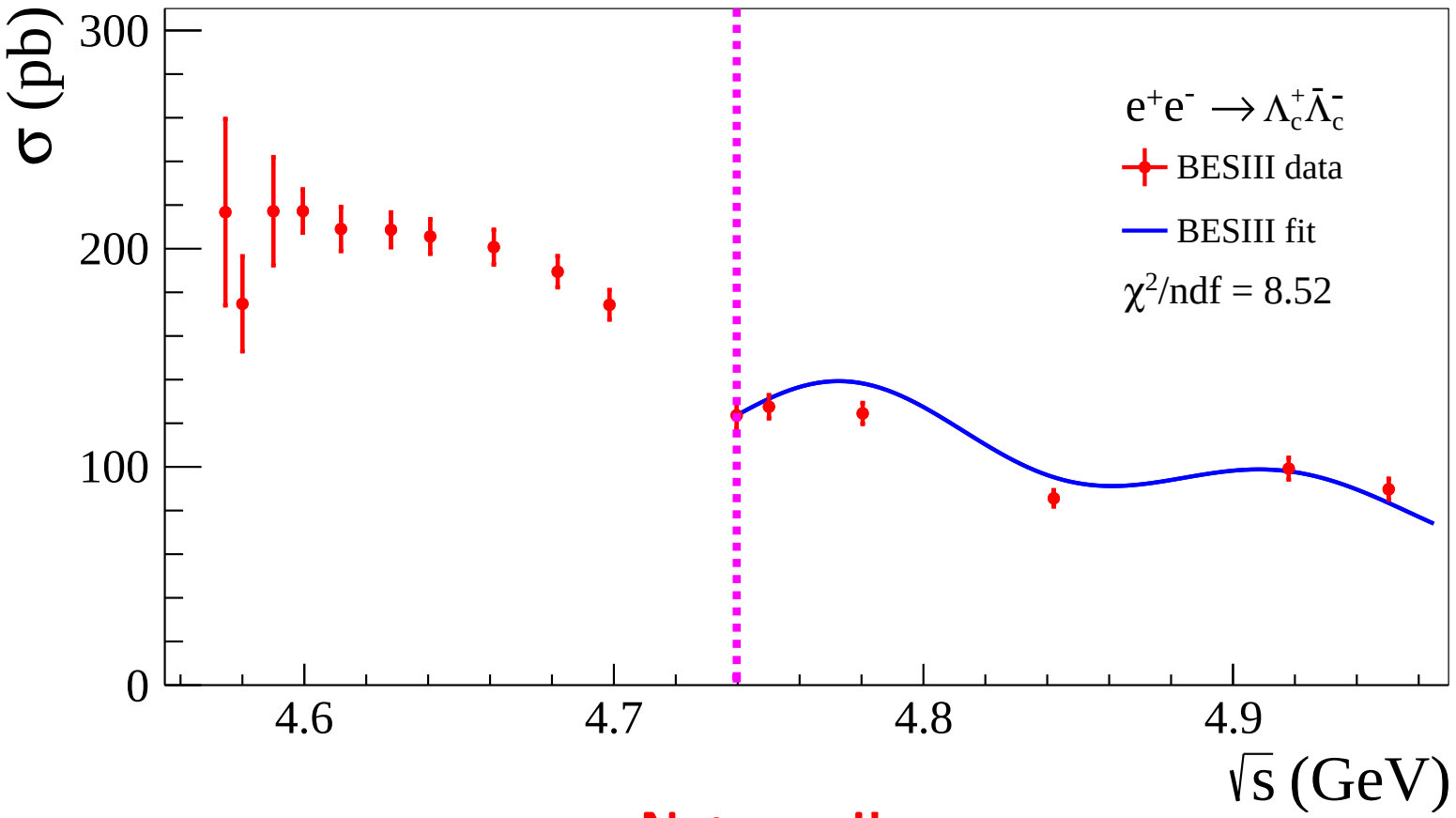


The fit quality is quite good below 4.74 GeV!

Fit the cross section line-shape: above 4.74 GeV

The cross section line-shape above 4.74 GeV is fitted with an oscillation function:

$$\sigma(s) = \frac{1}{1+\omega^2/a^0}[\sigma(\sqrt{s}=4.74) + a_1 e^{\omega} sin(a_2\omega)], \quad \text{with} \quad \omega = \sqrt{s} - 2m_{\Lambda_c^+}$$

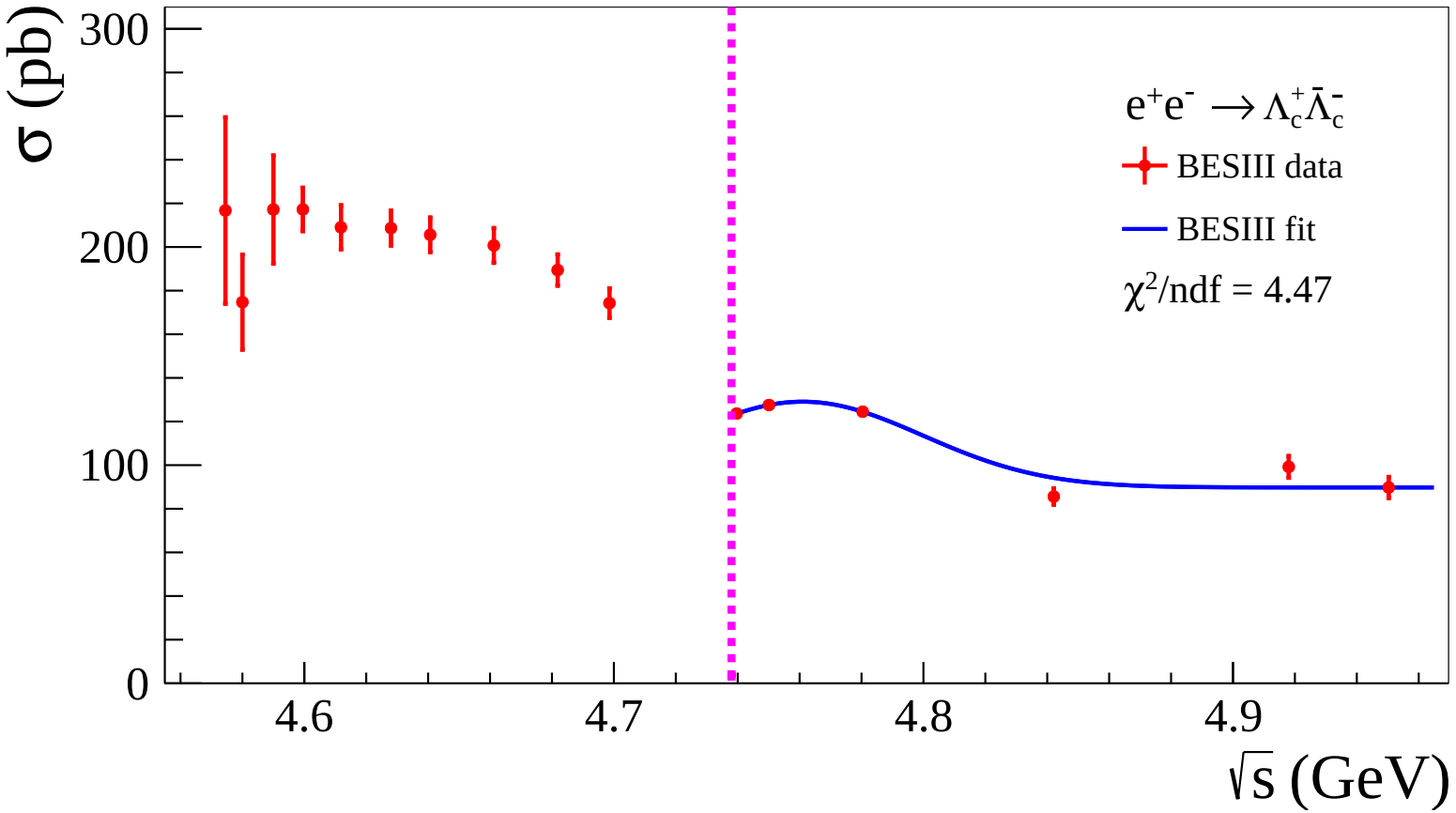


Not good!

Fit the cross section line-shape: above 4.74 GeV

The cross section line-shape above 4.74 GeV is fitted with a Gaussian function:

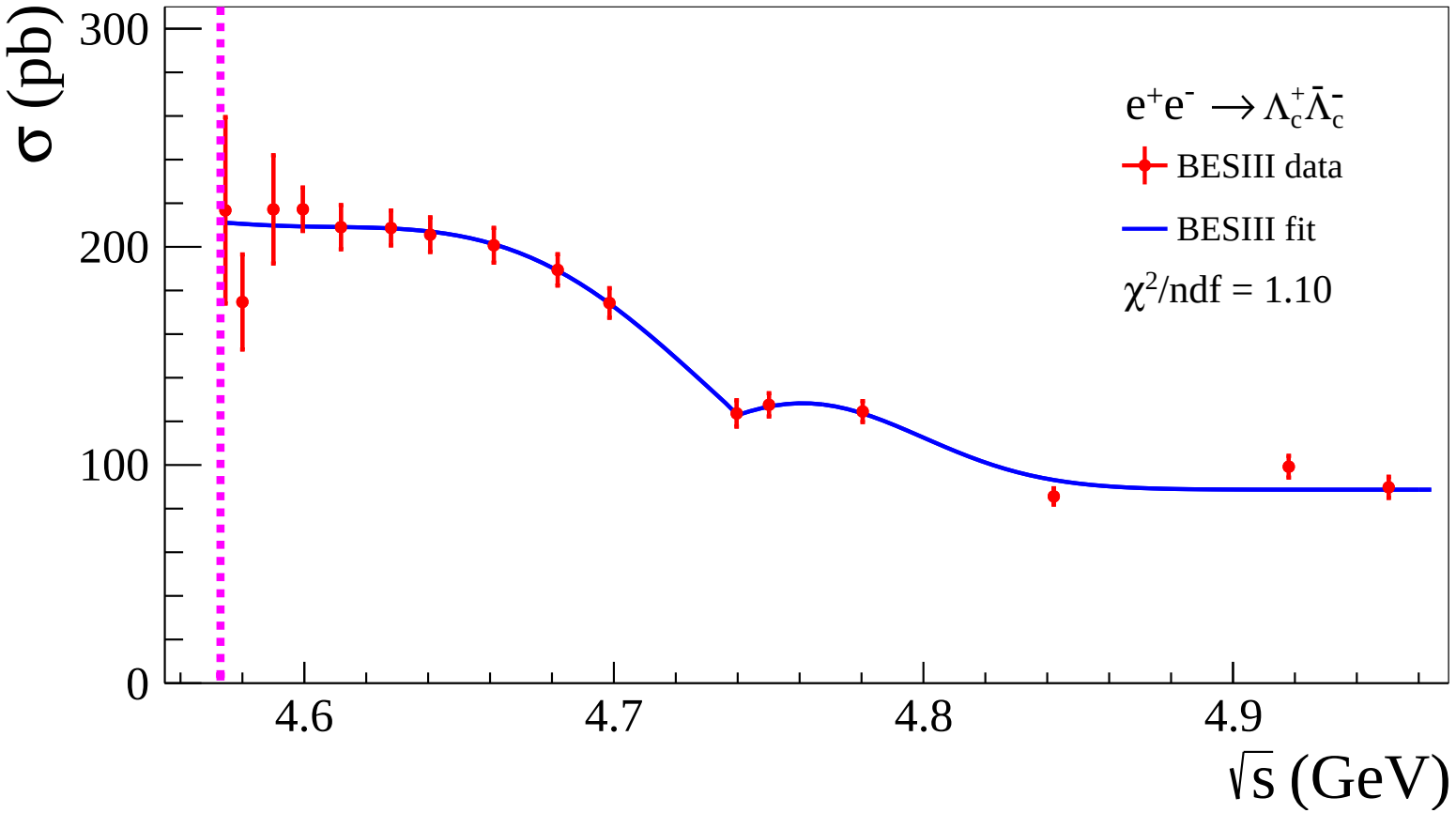
$$\sigma(s) = a_0 + a_1 \mathrm{Exp}(-\frac{(\sqrt{s} - a_2)^2}{a_3^2})$$



With vanishing uncertainties in first three points, the fit quality is good!

Fit the cross section line-shape: Piecewise function

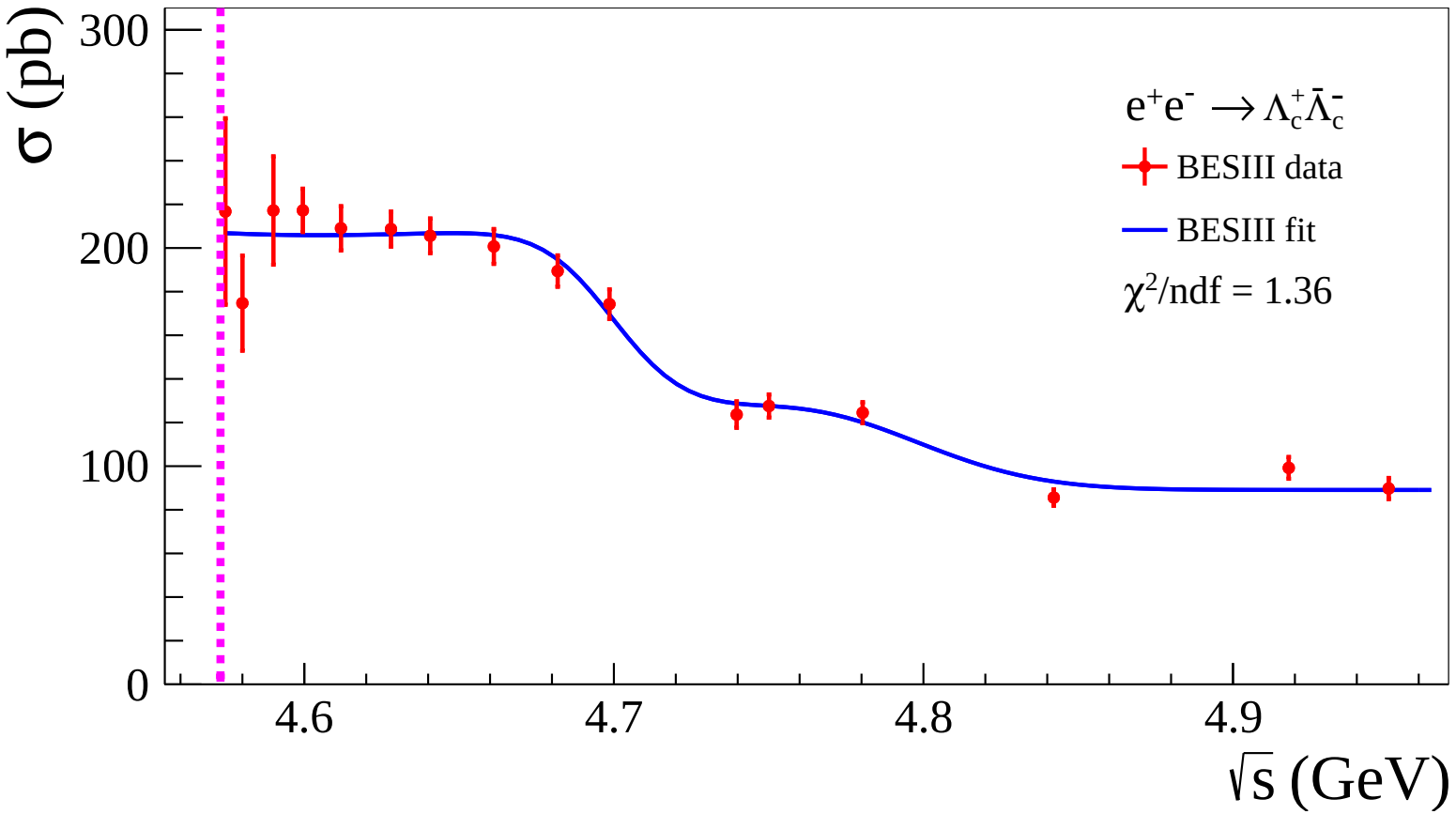
The cross section line-shape is fitted with a ppbar like function below 4.74 and Gaussian function (with the mean and resolution fixed) above 4.74 GeV:



The fit quality is good!

Fit the cross section line-shape: Combined function

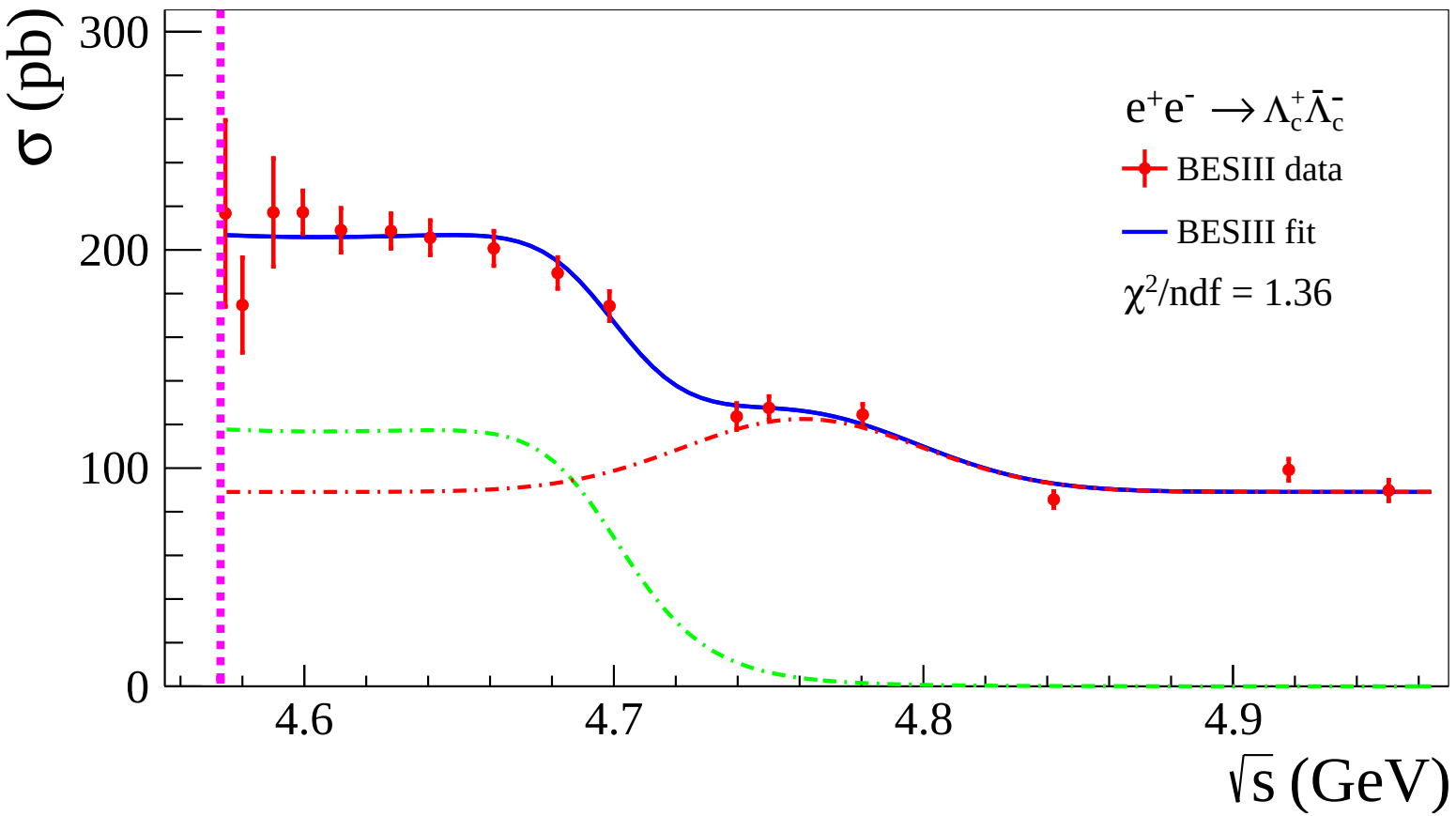
The cross section line-shape is fitted with a ppbar like function and a Gaussian function (with the mean and resolution fixed by the first three points above 4.73 GeV):



The fit quality is OK, but not good enough!

Fit the cross section line-shape: Combined function

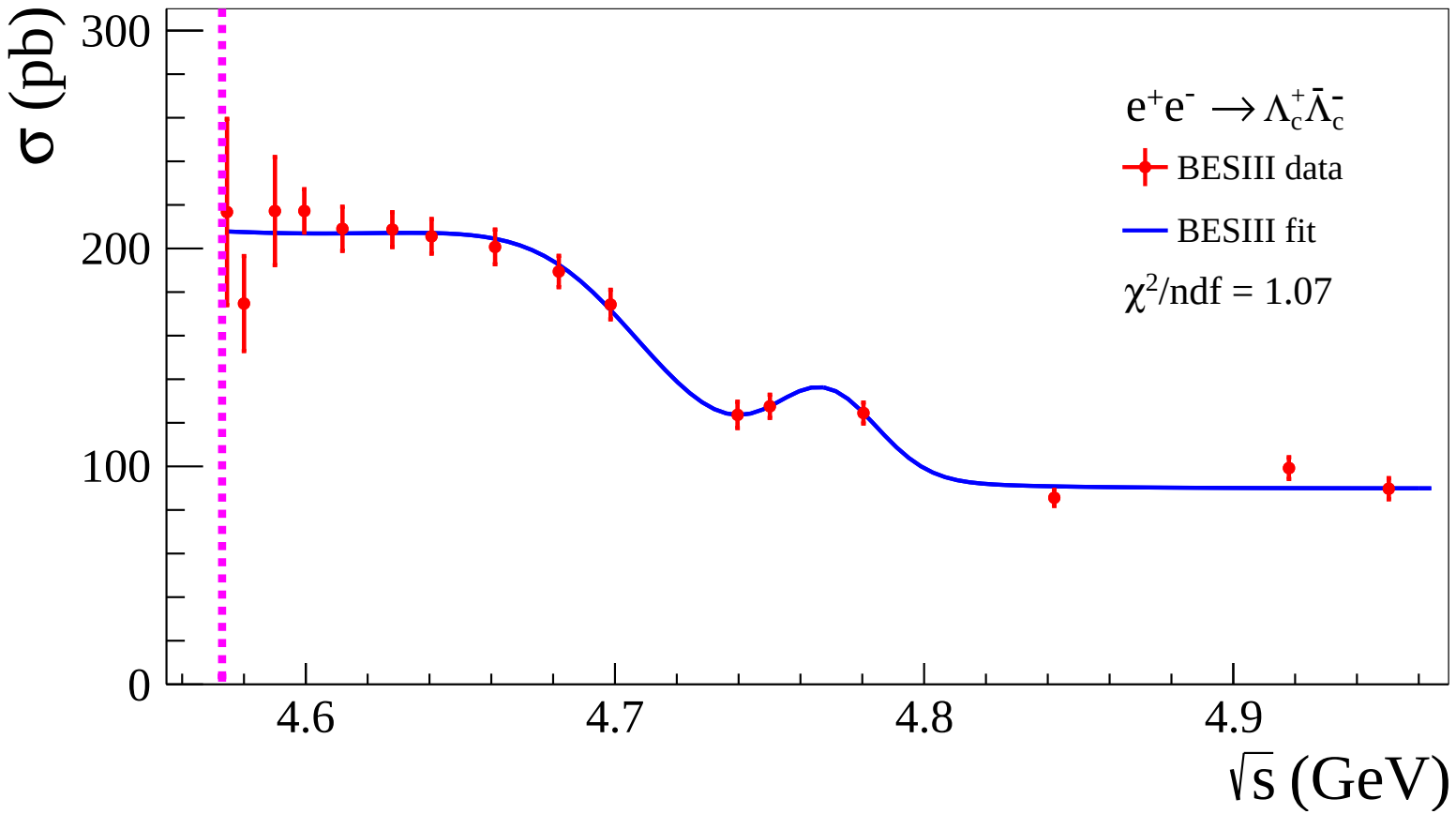
The cross section line-shape is fitted with a ppbar like function and a Gaussian function (with the mean and resolution fixed by the first three points above 4.73 GeV):



The fit quality is OK, but not good enough!

Fit the cross section line-shape: Combined function

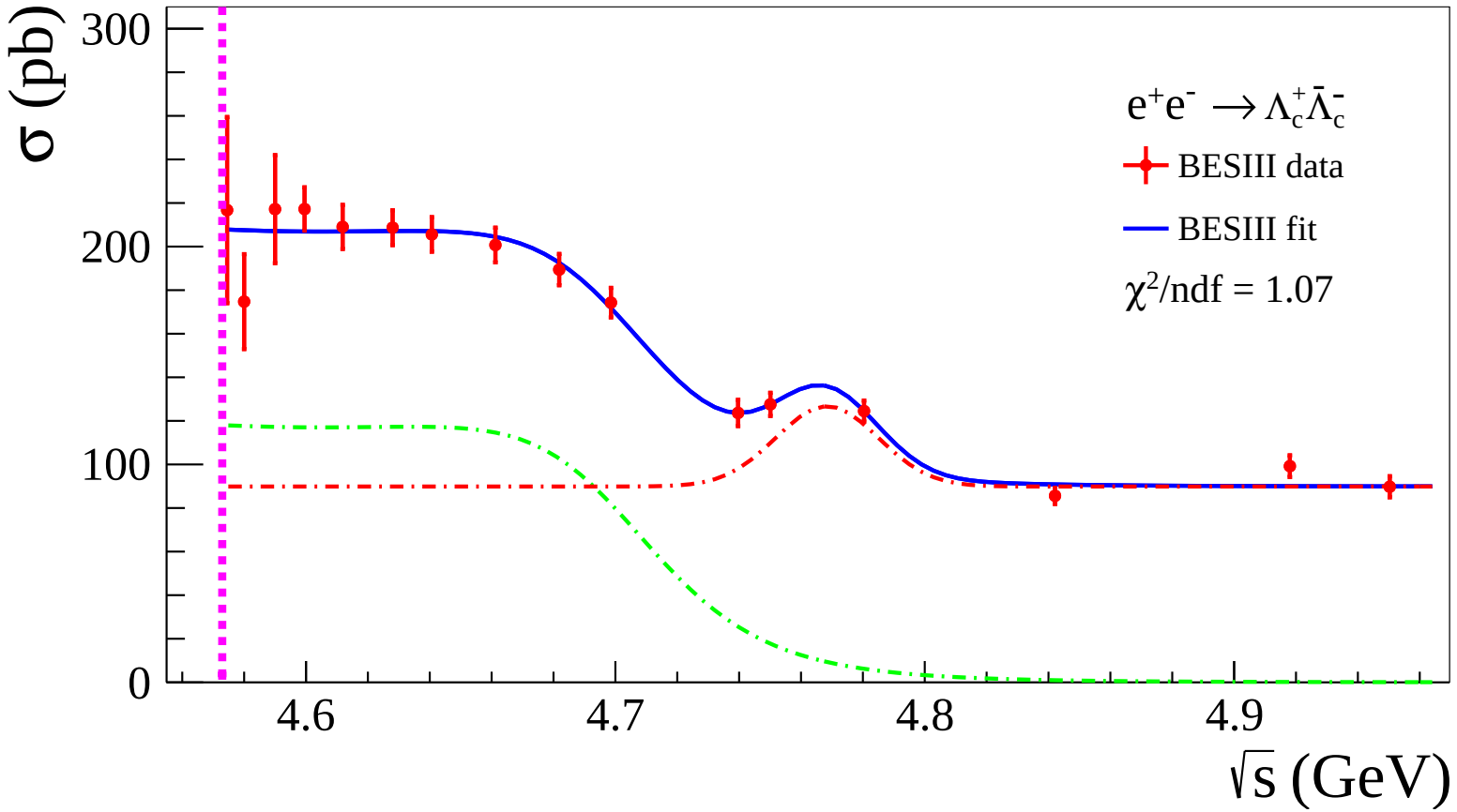
The cross section line-shape is fitted with a ppbar like function and a float Gaussian function:



A little bit overfit?

Fit the cross section line-shape: Combined function

The cross section line-shape is fitted with a ppbar-like function and a float Gaussian function:



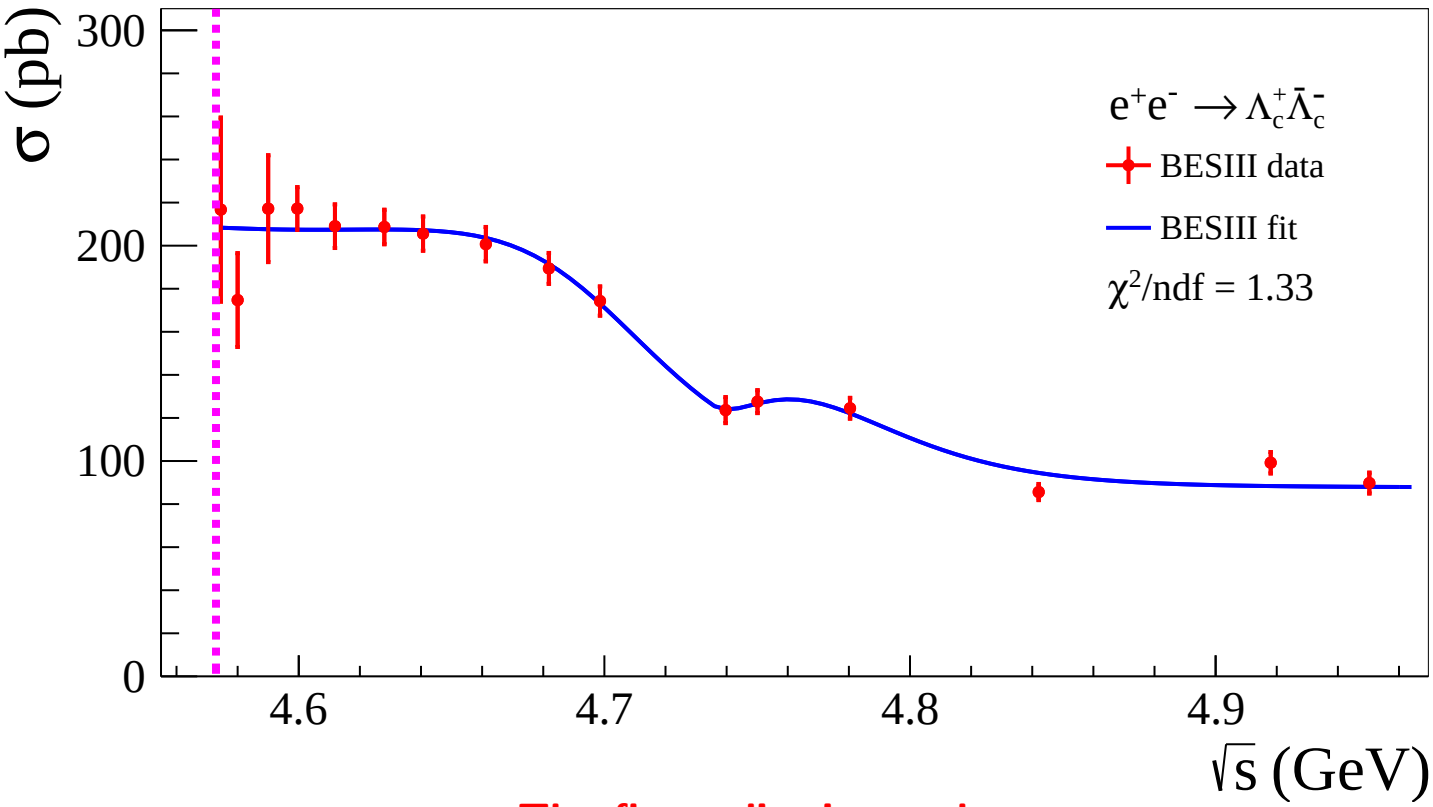
A little bit overfit?

Fit the cross section line-shape: Combined function

The cross section line-shape is fitted with a ppbar like function and a fixed Gamma function:

$$\sigma(s) = \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]} + a_4(a_3 t)^2 e^{-a_3 t/2} + a_5$$

where $t = \sqrt{s} - E_0$ and $E_0 = 4.7352\ \mathrm{GeV}$ is a properly determined truncation point from which the Gamma function starts to work, and a_3 is fixed by the first three points above 4.73 GeV.



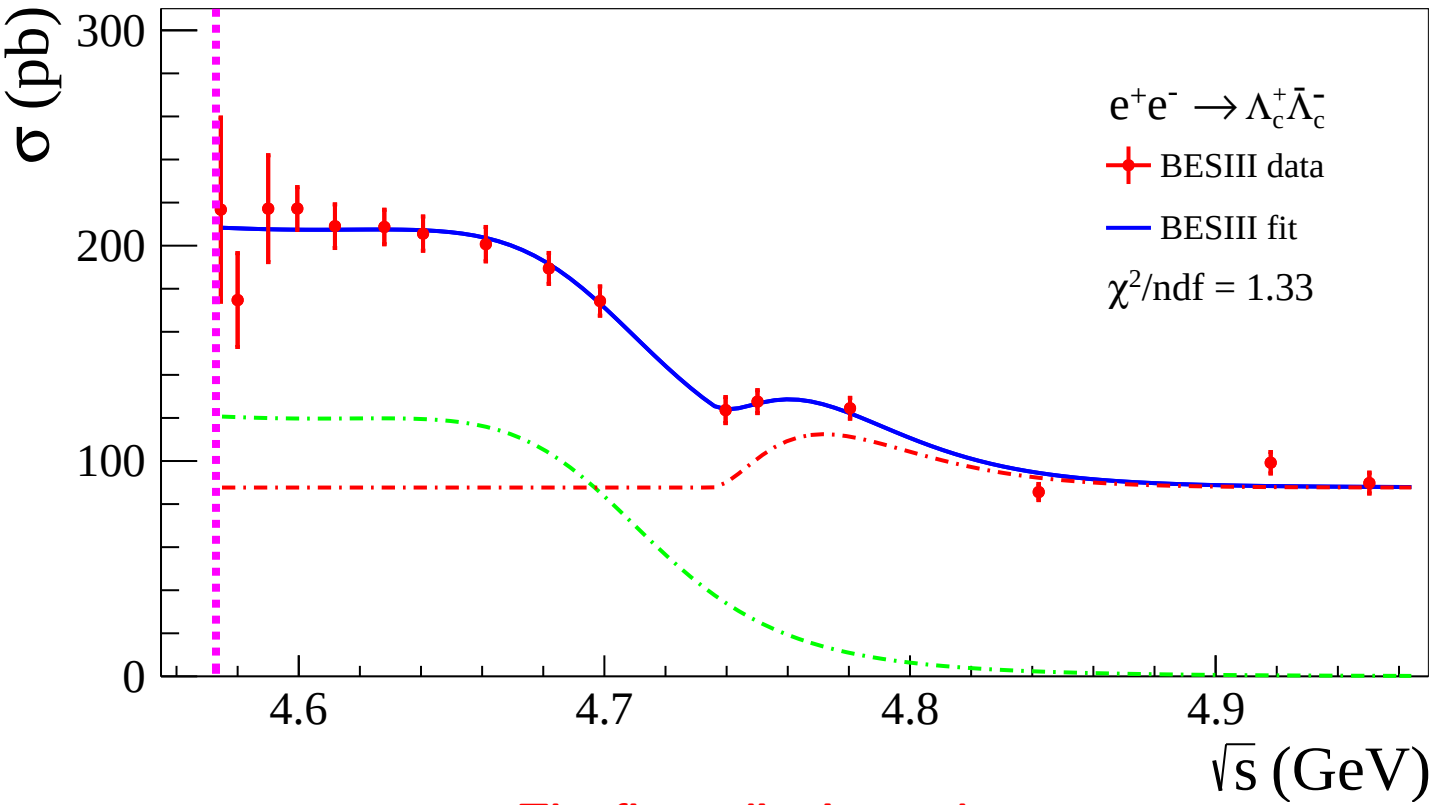
The fit quality is good.

Fit the cross section line-shape: Combined function

The cross section line-shape is fitted with a ppbar like function and a fixed Gamma function:

$$\sigma(s) = \frac{a_0}{s\left[1 - e^{-\pi\alpha_s(s)/\beta(s)}\right]\left[1 + \left(\frac{\sqrt{s}-2m_{\Lambda_c}}{a_1}\right)^{a_2}\right]} + a_4(a_3 t)^2 e^{-a_3 t/2} + a_5$$

where $t = \sqrt{s} - E_0$ and $E_0 = 4.7352\ \mathrm{GeV}$ is a properly determined truncation point from which the Gamma function starts to work, and a_3 is fixed by the first three points above 4.73 GeV.

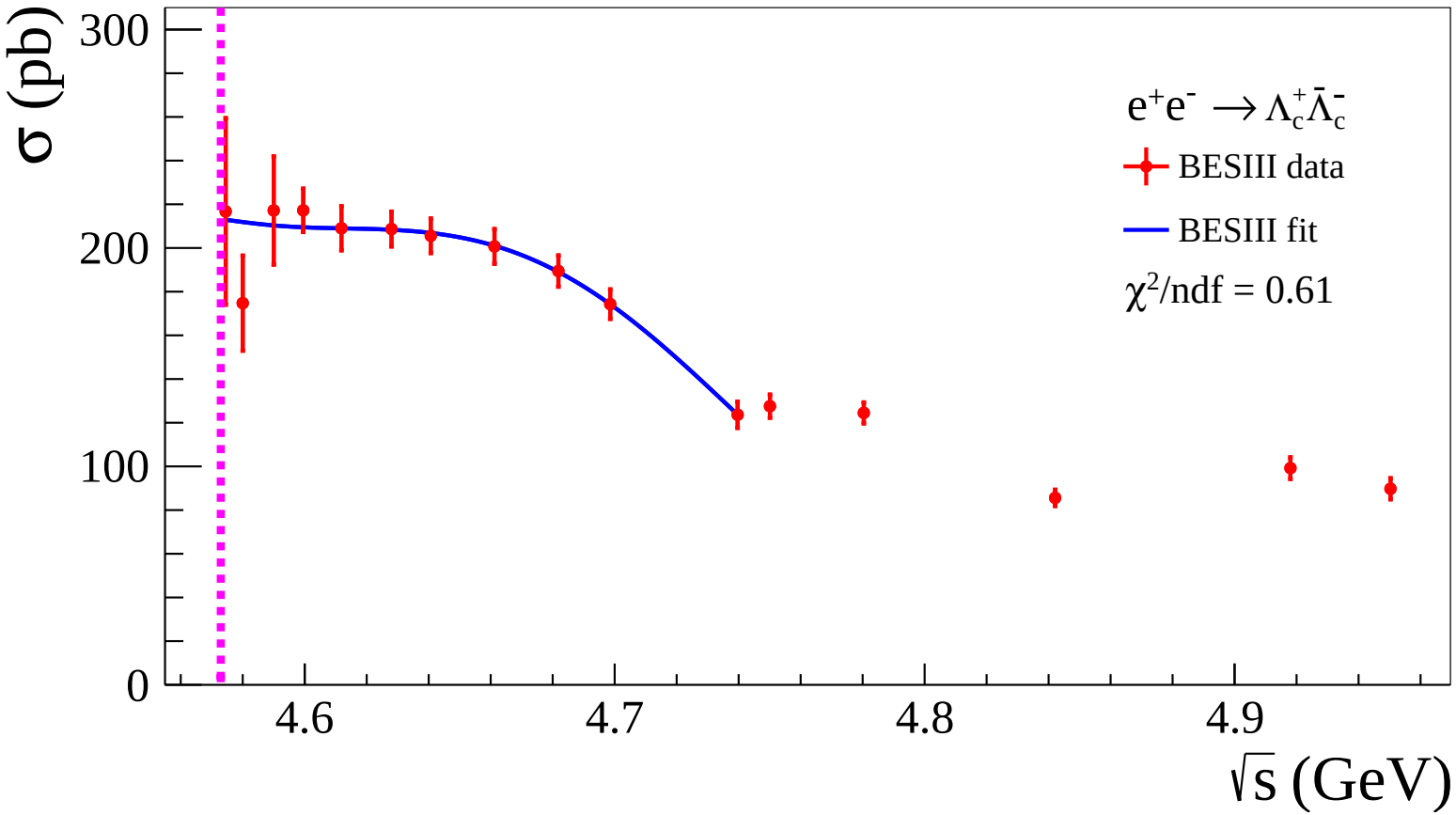


The fit quality is good.

Fit the cross section line-shape: below 4.74 GeV

The cross section line-shape below 4.74 GeV is fitted with a function used in $e^+e^- \to p\bar{p}$ case and a BW to describe possible contribution from Y(4660):

$$\sigma(s) = |a_0\sqrt{\sigma_0} + a_1 e^{i\Phi}\mathcal{A}_{\rm BW}|^2$$



In the fit, the a_1 is vanishing! No observed contribution from Y(4660)!

$f_{\rm ISR}$ resulted by the cross section line-shapes

Deviations in $f_{\rm ISR}$ resulted by the different cross section input line-shape, comparing with the $p\bar{p}$+Gamma function model. The G. stands for the Gaussian function.

$\sqrt{s}$	Nominal	Picewise		$p\bar{p}$+const.		$p\bar{p}$+fixed G.		$p\bar{p}$+free G.	
(GeV)	$f_{\rm ISR}$	$f_{\rm ISR}$	Δ (%)	$f_{\rm ISR}$	Δ (%)	$f_{\rm ISR}$	Δ (%)	$f_{\rm ISR}$	Δ (%)
4.5995	0.7434	0.7436	-0.02	0.7434	-0.00	0.7434	0.00	0.7434	0.00
4.6118	0.7657	0.7659	-0.03	0.7658	-0.02	0.7657	0.00	0.7657	0.00
4.6280	0.7864	0.7870	-0.07	0.7870	-0.07	0.7862	0.02	0.7863	0.01
4.6407	0.7988	0.7999	-0.15	0.8001	-0.17	0.7981	0.08	0.7985	0.03
4.6612	0.8170	0.8192	-0.28	0.8199	-0.36	0.8146	0.29	0.8162	0.10
4.6818	0.8387	0.8401	-0.17	0.8414	-0.32	0.8367	0.25	0.8381	0.08
4.6986	0.8624	0.8600	0.28	0.8607	0.20	0.8688	-0.74	0.8647	-0.27
4.7397	0.9240	0.9352	-1.21	0.9079	1.75	0.9093	1.60	0.9201	0.42
4.7501	0.9079	0.9100	-0.23	0.9176	-1.07	0.9069	0.11	0.9039	0.44
4.7804	0.9145	0.9123	0.24	0.9371	-2.47	0.9167	-0.23	0.9149	-0.03
4.8421	0.9589	0.9646	-0.59	0.9497	0.95	0.9611	-0.23	0.9597	-0.09
4.9180	0.9542	0.9532	0.11	0.9495	0.49	0.9506	0.39	0.9469	0.77
4.9503	0.9517	0.9502	0.16	0.9491	0.27	0.9480	0.38	0.9454	0.66

Deviations resulted by cross section line-shapes

Deviations resulted by the new nominal cross section input line-shape, comparing with the previous single Gaussian model:

$\sqrt{s}$ (GeV)	$\Delta N^{+}_{\rm ST}$ (%)	$\Delta \varepsilon^{+}_{\rm ST}$ (%)	Δ (%)	$\Delta(\frac{N^{+}_{\rm ST}}{\varepsilon^{+}_{\rm ST} f_{\rm ISR}})$ (%)
4.5995	-0.01	-0.29	0.02	0.26
4.6115	-0.06	0.38	-0.14	-0.30
4.6277	-0.45	-0.01	-0.44	-0.00
4.6405	-0.61	0.13	-0.79	0.05
4.6609	-0.84	-0.51	-1.16	0.82
4.6816	-0.43	0.47	-0.95	0.04
4.6984	0.06	0.70	-0.00	-0.65
4.7397	2.18	-1.32	2.86	0.62
4.7501	0.56	-1.04	0.20	1.38
4.7804	-0.42	0.47	-1.32	0.42
4.8421	0.51	-0.42	1.03	-0.10
4.9180	-0.75	-0.78	0.35	-0.32
4.9503	-0.03	-0.25	0.24	-0.02

All the deviations are within the statistical uncertainties.

Deviations resulted by cross section line-shapes

Deviations resulted by the new nominal cross section input line-shape, comparing with the previous single Gaussian model:

$\sqrt{s}$ (GeV)	ΔN_{ST}^{-} (%)	$\Delta \varepsilon_{ST}^{-}$ (%)	Δ (%)	$\Delta(\frac{N_{ST}^{-}}{\varepsilon_{ST}^{-} f_{ISR}})$ (%)
4.5995	-0.17	0.11	0.02	-0.30
4.6115	-0.05	0.03	-0.14	0.06
4.6277	-0.17	0.48	-0.44	-0.21
4.6405	-0.28	0.16	-0.79	0.35
4.6609	-0.70	0.26	-1.16	0.19
4.6816	-0.40	0.50	-0.95	0.05
4.6984	0.01	0.46	-0.00	-0.45
4.7397	1.25	-1.38	2.86	-0.27
4.7501	0.76	-0.77	0.20	1.32
4.7804	-0.91	-0.25	-1.32	0.65
4.8421	0.51	0.02	1.03	-0.55
4.9180	-0.22	-0.91	0.35	0.33
4.9503	-0.26	0.06	0.24	-0.56

All the deviations are within the statistical uncertainties.