Photon energy calibration at low energies using a π^0-calibration technique

Oleksandr Skorenok, Taras Shevchenko National University of Kyiv, Ukraine

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Abstract

The calibration of the electromagnetic calorimeter is important as compensating for various background-related effects, and correcting deposited photon energies to the true energy of photon. In this work, a π^0-calibration method is used to rectify the energy of photons that are detected by the electromagnetic calorimeter of the Belle II experiment. As a result, parameters of the energy calibration function were obtained.

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1 Introduction

SuperKEKB (Figure 1) is a lepton collider at KEK (Tsukuba, Japan). It collides electrons of the energy of 7 GeV with positrons of the energy of 4 GeV. This results in the center-of-mass energy close to mass of $\Upsilon(4S)$ resonance. The collisions are being performed at the rate which corresponds to the integrated luminosity of $2.11 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The $\Upsilon(4S)$ decays to the B-mesons, that makes SuperKEKB a second - generation B-factory for the Belle II experiment. A B-factory can be used for high-precision measurements of rare decays, CP-violation and the exploration of New Physics beyond the Standard Model. The Belle II detector measures the products of e^{+}-e^{-} collisions produced by the accelerator. The Standard B decays in the Belle II experiment produce a lot of photons, 50% of which have energy less than 200 MeV. For precision measurements of photon energy it is important to have proper calibration of the calorimeter. One of the methods is the calibration by π^0's. Formerly, this method was used at the BaBar experiment at the SLAC National Accelerator Laboratory (California, USA)[1]. In this analysis data collected with the Belle II detector in 2019 that correspond to the integrated luminosity of 1982.3 pb^{-1} were used.

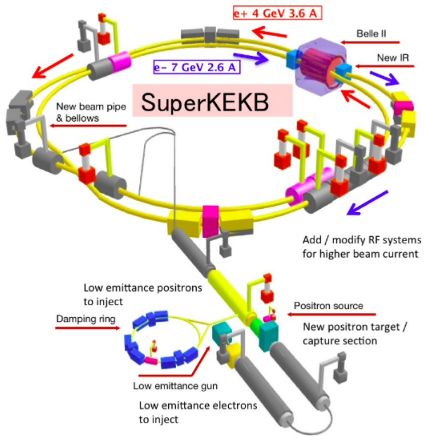


Figure 1: SuperKEKB accelerator scheme

2 Electromagnetic calorimeter

The Belle II detector consist of different major parts such as: Electromagnetic calorimeter (ECL), $\mathrm{K_L}$ and muon detector (KLM), Vertex detectors(VXD), Central drift chamber (CDC), Particle Identification (PID) and Magnets. The calorimeter is the part of detector that measures the energy of incoming particles. The electromagnetic calorimeter, measures the photons energy.
At the Belle II detector CsI(Tl) crystal scintillator with silicon photomultipliers are the key parts of the ECL. When the photon enters the ECL it interacts with the calorimeter and starts showering, than the shower particles go through the scintilators, emitting light which the SiPM registers. Than the light would be converted into the electrical signal, which is transmitted to electronics. If we investigate the amplitude distribution of the SiPM output we can reconstruct the energy of the photon.

3 Methodology of the π^0 calibration

The main idea of the π^0 ECL calibrating is simple: reconstruct the pion from the dominant decay mode $\pi^0 \to \gamma\gamma$ (Figure 2), and calibrate the detected photon energy. The calibration may be performed using the known π^0 mass, following relation (1):

$$m_{\pi^0} = m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\theta)} \tag{1}$$

,where $m_{\gamma\gamma}$ - known pion mass, E_1 - energy of the first photon, E_2 - energy of the second photon, θ - the opening angle between two photons.

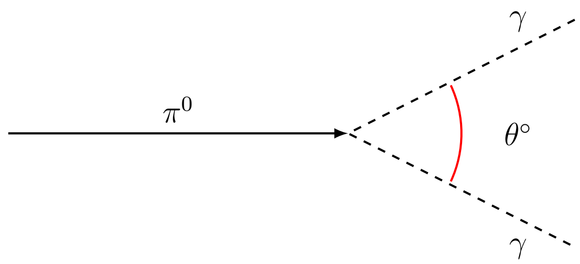


Figure 2: dominant π^0 decay

The calibration function $f(E, \theta)$ depends on the photon energy E, and the polar angle of the photon momentum [2] and is defined as:

$$f(E, \theta) = exp\Big(\sum_{i=0}^{3} a_i ln^i E + \sum_{i=1}^{2} b_i cos^i\theta\Big) \tag{2}$$

, where the coefficients a_i and b_i can be received by investigating the reconstructed π^0 mass in bins of E_γ and cosθ. To correct the photon energy the formula (3) can be used:

$$E' = E \cdot f(E, \theta) = E \cdot exp(a_0 + a_1 lnE + a_2 ln^2 E + a_3 ln^3 E + a_4 cos\theta + a_5 cos^2\theta) \tag{3}$$

In the Figure 3 signal mass distribution from Monte Carlo (MC) simulation is shown. The signal region can't be successfully described by Gaussian function only, due to the presence of an asymmetric tail. It appears if some of the photon from π^0 decay starts showering in material in front of ECL, therefore the deposited energy becomes smaller, and reconstructed π^0 mass moves to lower region.
For this reason, to describe signal, the "Novosibirsk" function (4), was chosen.

$$f_{nov}(M) = A \times exp\Big(\frac{-ln^2(1 + t\frac{sinh(t\sqrt{(ln4)})}{t\sqrt{ln4}}\frac{m - m_0}{\sigma})}{2t^2} - \frac{t^2}{2}\Big) \tag{4}$$

where A, σ, m_0 is the height, width and mean value of Gauss distribution, and t is a tail parameter.

Alternatively, the "Crystal Ball" function can be used to describe the signal (5):

$$f_{cb}(M;\alpha,n,M_0,\sigma) = N \cdot \begin{cases} \exp\left(-\frac{(M-M_0)^2}{2\sigma^2}\right), & \text{for } \frac{M-M_0}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{M-M_0}{\sigma}\right)^{-n}, & \text{for } \frac{M-M_0}{\sigma} \leqslant -\alpha \end{cases} \tag{5}$$

where coefficients are given as:

$$\begin{aligned} A &= \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right), B = \frac{n}{|\alpha|} - |\alpha|, N = \frac{1}{\sigma(C+D)} \\ C &= \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right), D = \sqrt{\frac{\pi}{2}}\left(1 + \mathrm{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right) \end{aligned} \tag{6}$$

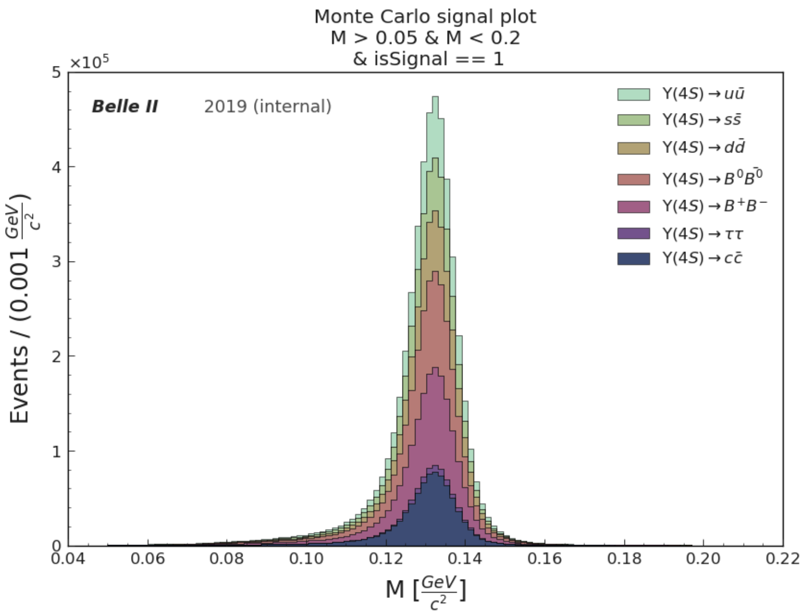


Figure 3: Signal pion mass distribution from MC simulation.

4 Measurement

4.1 The calibration procedure

1. Select photon candidates and measure their energies.

2. Build all possible $\gamma\gamma$ combinations and reconstruct $m_{\gamma\gamma}$ in bins of E_γ, and cosθ, fora data and MC.

3. Fit signal using the "Novosibirsk" (or other similar) function and the background by using the Chebychev polynoms, in every bin.
4. Extract the mean values and their errors from the signal functions.
5. Build the scatter plot of $\ln(\frac{m_{data}}{m_{mc}})$ versus $\ln(E_\gamma)$ and $\ln(\frac{m_{data}}{m_{mc}})$ versus $\ln(\cos\theta)$.
6. Fit results from the previous step by polynomial functions, get the fit parameters and put it into calibration function (2).
7. Return to step 1 applying the calibrated photon energy (3) and continue until the coefficients remain the same.

4.2 Photons & pions pre-selection

Without any selection the reconstructed pion mass distribution has a lot of background, especially at low energies. For that reason, signal selection requirements are addlied, that aims to separate photons from pion decays and that from the background events. In this analysis the following selection is used:

Preselection:

- High level trigger of hadron events > 0
- number of tracks > 3

Photon selection:

- $17° < \theta < 150°$ (Central Drift Chamber acceptance)
- cluster energy > 50 MeV
- sum of weights of all crystals in an ECL cluster > 1.5
- cluster zernike MVA > 0.6
- 50 MeV $< m_{\gamma\gamma} <$ 200 MeV

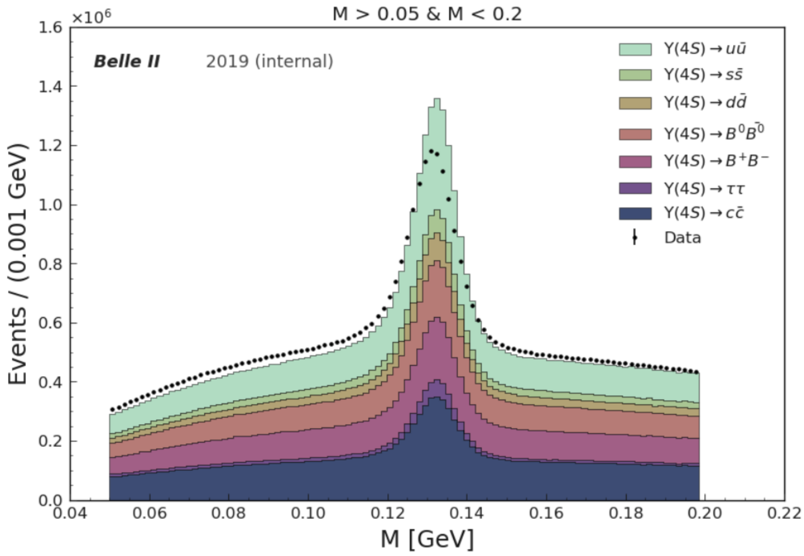


Figure 4: Reconstructed pion mass in data and MC after all selection criteria. MC is normalized to data luminosity.

4.3 $\mathrm{M}_{\gamma\gamma}$ in bins of E_γ

This work aims to perform the γ energy calibration at low energies. Therefore, an event is selected in this study if the energy of each photon from the π^0 decay is in the range from 80 MeV to 280 MeV (Table 1). The photons need to enter in the same bin of E_γ. For each bin of the E_γ pion mass spectrum was reconstructed for Data and MC as it is shown in Figure 6.

Each of the mass spectrum in bins of the E_γ is approximated by four functions: "Novosibirsk", "Crystal Ball", "Novosibirsk + Gauss" and "Crystal Ball" in the range close to the mass peak width, as a cross check.

Table 1: Bins of E_γ

Number of bin	Lower bound	Upper bound
1	80 MeV	100 MeV
2	100 MeV	120 MeV
3	120 MeV	150 MeV
4	150 MeV	190 MeV
5	190 MeV	280 MeV

4.4 $\mathrm{M}_{\gamma\gamma}$ in bins of $\cos\theta$

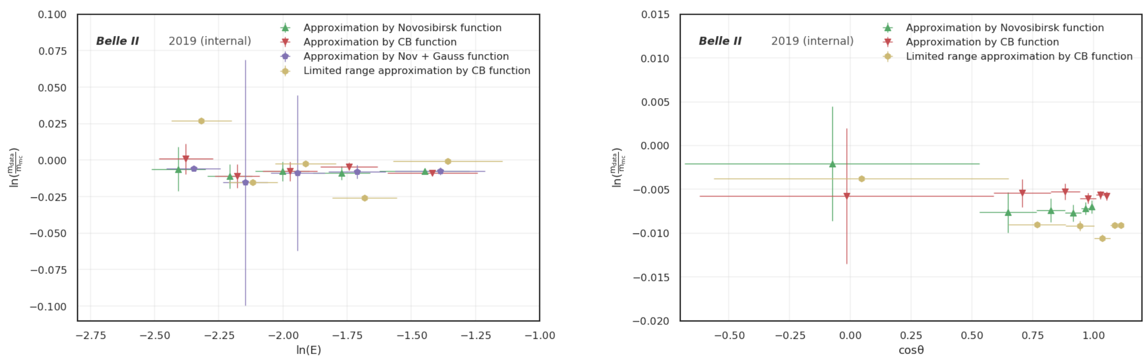
The $\cos\theta$ distribution was subdivided into 6 bins. The Table 2 lists the chosen ranges for these bins. For each bin the π^0 mass spectrum was reconstructed for Data and MC as shown in Figure 7. Each of the mass spectrum in bins of the $\cos\theta$ is approximated by three functions, "Novosibirsk", "Crystal Ball" and "Crystal Ball" in range close to peak, as a cross check.

Table 2: Bins of $cos\theta$ ranges

Number of bin	lhs ($cos\theta$)	lhs ($\theta°$)	rhs ($cos\theta$)	rhs ($\theta°$)
1	-0.681	132	0.53	58
2	0.53	69	0.765	40
3	0.765	40	0.884	27.8
4	0.884	27.8	0.950	18.2
5	0.95	18.2	0.987	9.2
6	0.987	9.2	1	0

5 Results

As the result of two previous sections the mass spectrum in each of the bins of E_γ was approximated by 4 functions and $cos\theta$ was approximated by 3 functions.
The mean values from each fit function in data and MC were used to construct $\ln(\frac{m_{data}}{m_{MC}})$ distribution as a function of $\ln E$ and $\cos\theta$ as shown in Figure 5.



a) b)

Figure 5: All of the fits for bins of: a) E_γ, b) $cos\theta$

The next step consists in fitting the graphs at Figure 5, extract fit parameters, insert them to the calibration function (2) and repeat the algorithm iteratively, as described above.. In the Figure 8 all functions fits were approximated by third order polynomial function and in the Figure 9 all functions for bins of $\cos\theta$ were approximated by second order polynomial function. Fit parameters from the Figure 8(e) and Figure 9(c) are given in Table 3. The calibration function including obtained fit parameters is given below:

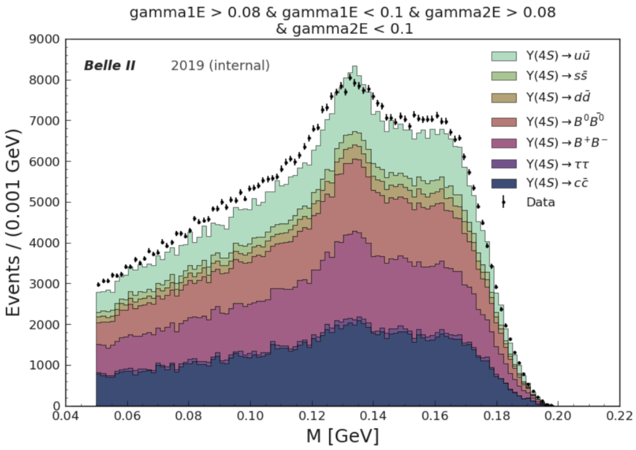
$$f(E,\theta) = exp\Big(0.323 + 0.38lnE + 0.108ln^2E + \\ + 0.00137ln^3E - 0.0131545cos\theta - 0.00908672cos^2\theta\Big) \quad (7)$$

Table 3: Calibration coefficients

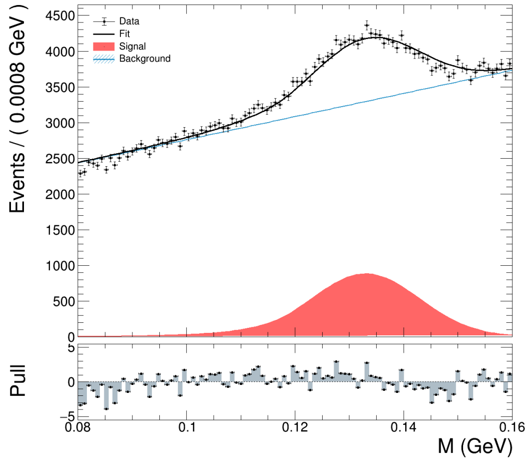
Coeff.	Value	Error
a_0	0.323	$\pm$ 0.034
a_1	0.38	$\pm$ 0.051
a_2	0.108	$\pm$ 0.027
a_3	0.00137	$\pm$ 0.0047
a_4	-0.0131545	$\pm$ 0.00018
a_5	-0.00908672	$\pm$ 0.000113

6 Conclusion

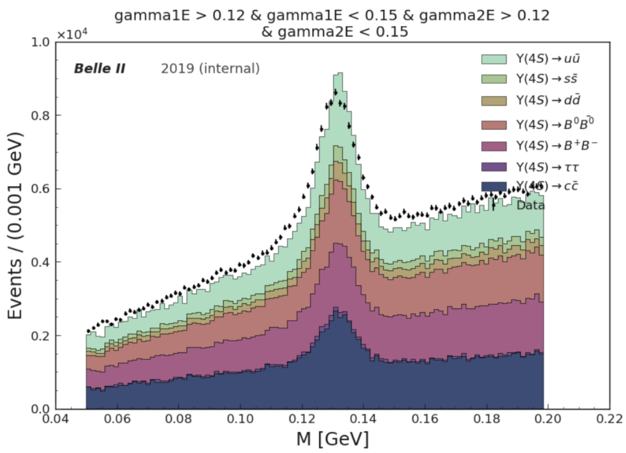
Neutral pion decay mode, $\pi^0 \to \gamma\gamma$, can be used to calibrate the energy of photons that are recorded by the electromagnetic calorimeter of the Belle II detector. in this report the selection criteria for the π^0 selection are presented. Photons with energy greater than 80 MeV are analyzed. The "Crystal Ball", "Novosibirsk" and "Novosibirsk + Gauss" functions were used to fit the pion mass. The Chebyshev polynomials can be used to describe pion mass spectrum background, in bins of E_γ, but for the background in bins of cosθ it does not work. The m_{data}/m_{mc} distribution obtained from the "Crystal Ball" function in range close to peak width agrees with results for full range fit in bins of cosθ, but not for full range fit in bins of E_γ.
The calibration coefficients were extracted from polynomial fits of m_{data}/m_{mc} and used in E_γ calibration function.
To improve the study shown in this report one could investigate a new function that can describe pion mass spectrum better e.g. "Crystal Ball" + "Crystal Ball".



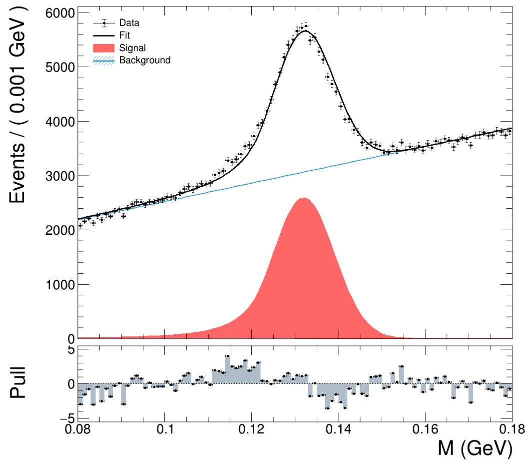
$M_{\gamma\gamma}$ in bin 1



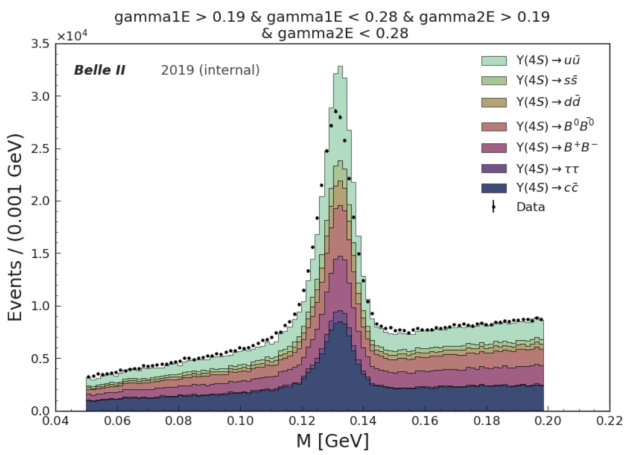
$M_{\gamma\gamma}$ fit in bin 1



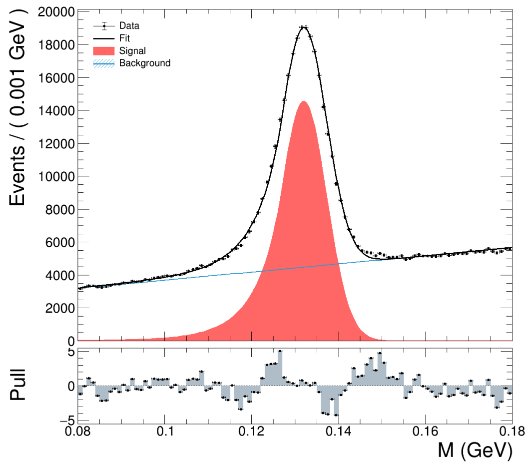
$M_{\gamma\gamma}$ in bin 3



$M_{\gamma\gamma}$ fit in bin 3

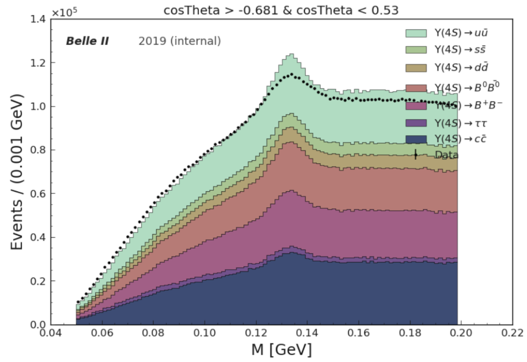


$M_{\gamma\gamma}$ in bin 5

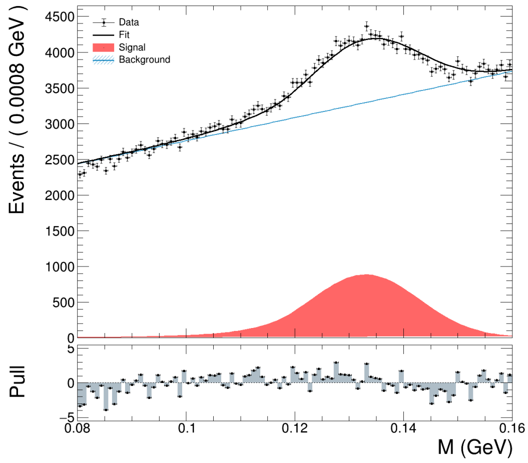


$M_{\gamma\gamma}$ fit in bin 5

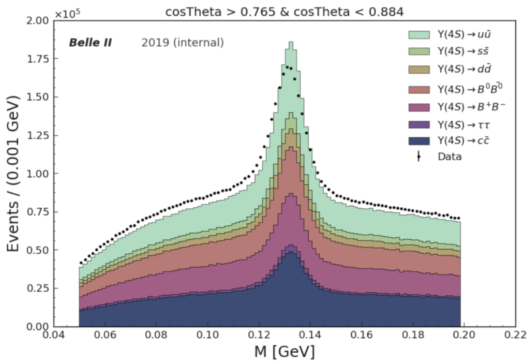
Figure 6: $M_{\gamma\gamma}$ distributions in bins of E_γ and fit data distributions by "Crystal ball"



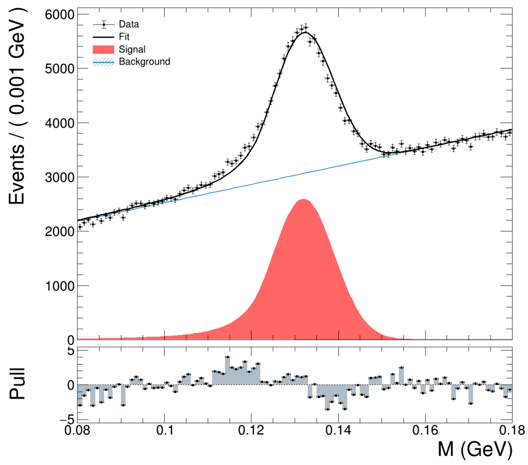
$M_{\gamma\gamma}$ in bin 1



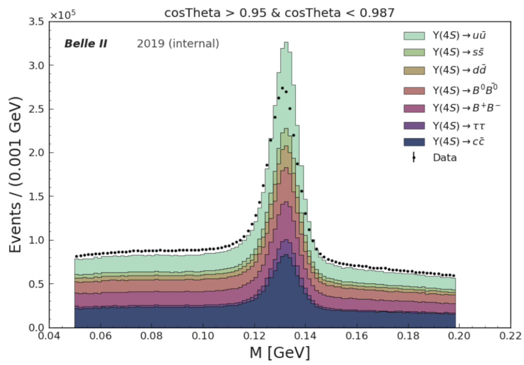
$M_{\gamma\gamma}$ fit in bin 1



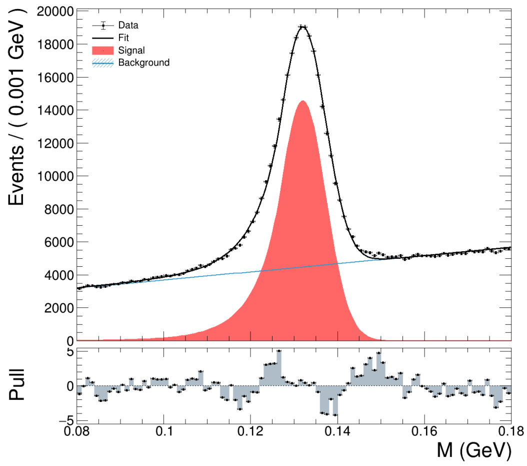
$M_{\gamma\gamma}$ in bin 3



$M_{\gamma\gamma}$ fit in bin 3



$M_{\gamma\gamma}$ in bin 5



$M_{\gamma\gamma}$ fit in bin 5

Figure 7: $M_{\gamma\gamma}$ distributions in bins of cosθ and fit data distributions by "Crystal ball".

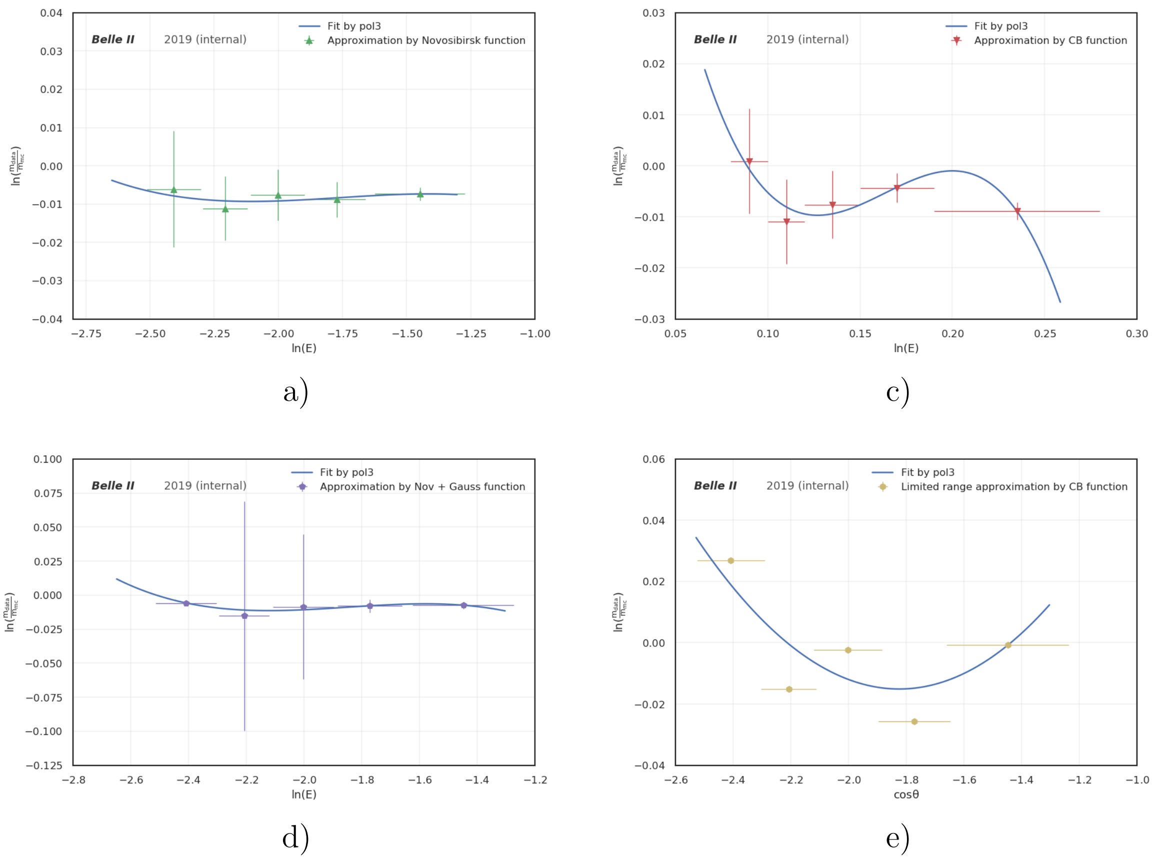
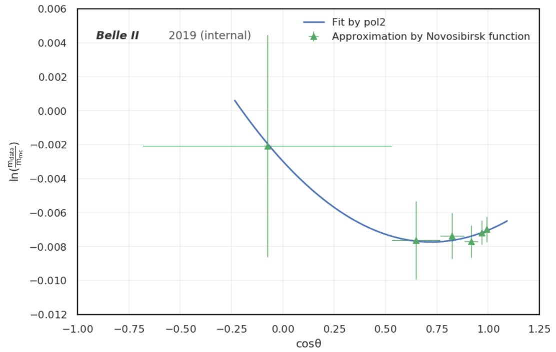
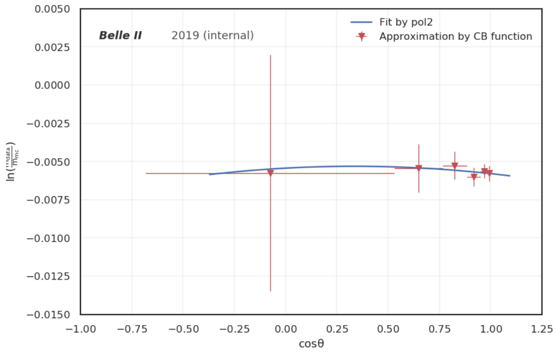


Figure 8: Fit by third order polynomial function (bins of E_γ) for: a) "Novosibirsk" function, b) "Novosibirsk + Gauss" function, c) "Crystal Ball" function, e) "Crystal Ball function" in range close to peak width



a)



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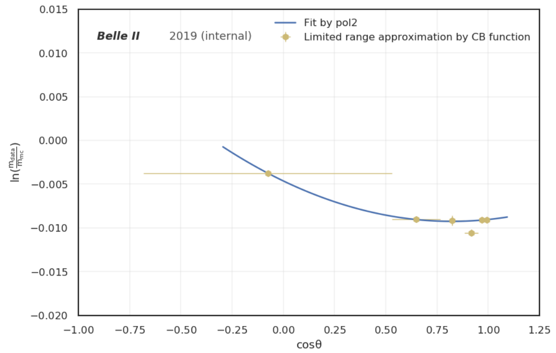

c)

Figure 9: Fit by second order polynomial function (bins of $cos\theta$) for: a) "Novosibirsk" function, b) "Crystal Ball" function, c) "Crystal Ball function" in range close to peak width

References

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