Study of the $B^0 \to \gamma\gamma$ decay at Belle and Belle II

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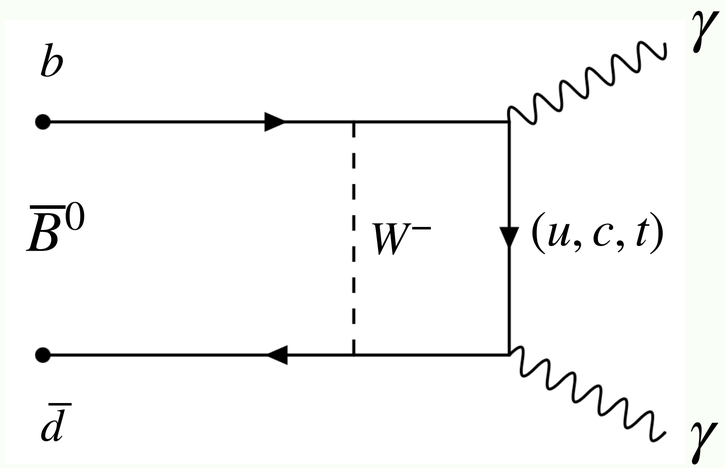
On behalf of the Belle and Belle II Collaboration

Significance of rare decay of $B^0 \longrightarrow \gamma\gamma$

- In the Standard Model (SM), this decay mode is a flavor-changing neutral current(FCNC) process involving penguin diagrams.
- The FCNC processes are forbidden in the SM at the tree level, as in the case of b $\longrightarrow$ d, there is no direct coupling between the b quark and d quark.
- The modest size of the SM prediction for the branching fraction turns its measurement into a compelling test for theories beyond the SM.



Previous searches	Measurement	
L3 collaboration ($\int \mathcal{L}dt$=73 pb^{-1})	$< 3.9 \times 10^{-5}$	Phys. Lett. B363 137
BABAR collaboration ($\int \mathcal{L}dt$=426 fb^{-1})	$< 3.2 \times 10^{-7}$	Phys. Rev. D.83.032006
Belle collaboration ($\int \mathcal{L}dt$=104 fb^{-1})	$< 6.2 \times 10^{-7}$	Phys. Rev. D.73.051107

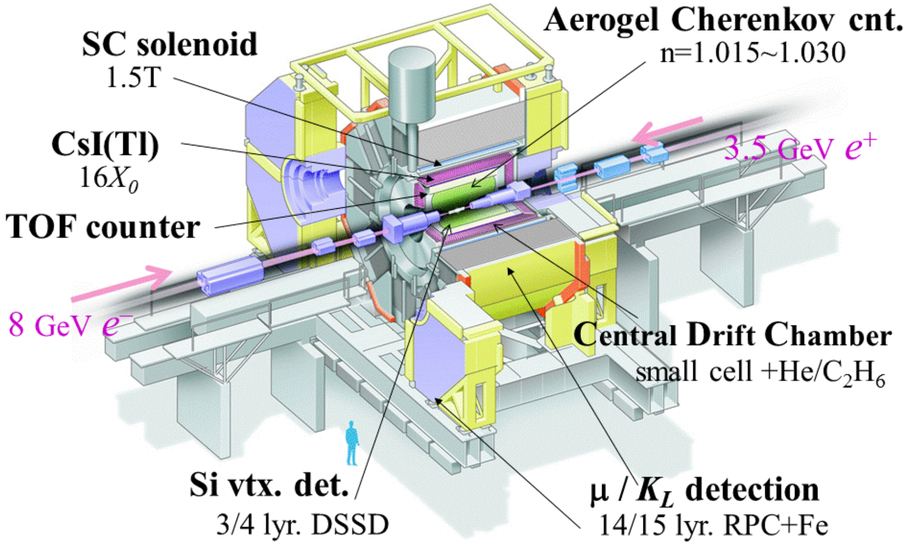
Theoretically, the BF of this decay mode is expected to be $1.434^{+1.351}_{-0.795} \times 10^{-8}$ [1].

- We perform the first Belle and Belle II measurement using a data set of 694 fb^{-1} from Belle and the entire dataset of Belle II ($\approx$ 362 fb^{-1}) from the LS1 run period.

[1] **Yue-Long Shen et al.** (2020), Journal of High Energy Physics, *169 (2020)*

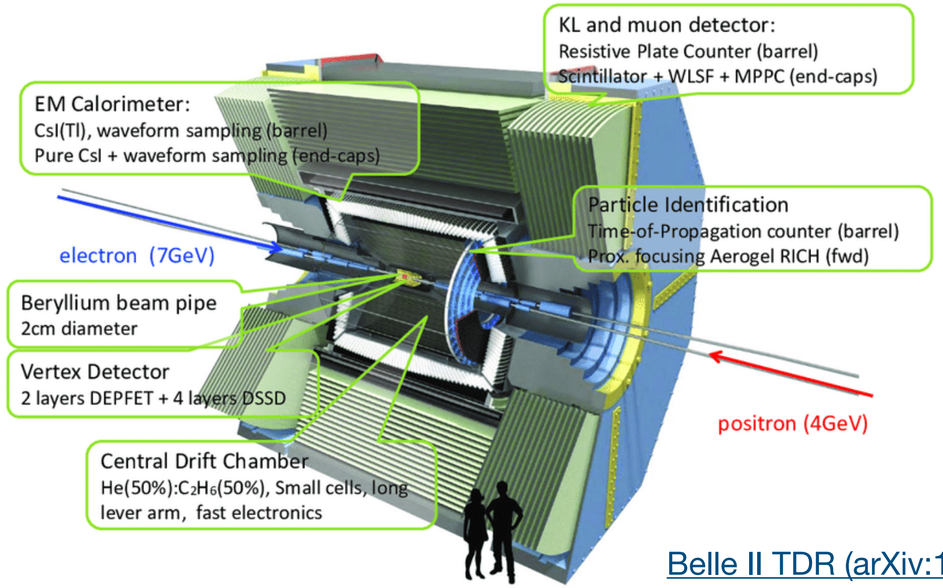
Belle vs Belle II Detector

Belle Detector



Belle TDR: Nucl. Instrum. Method A479, 112 (2002)

Belle II Detector

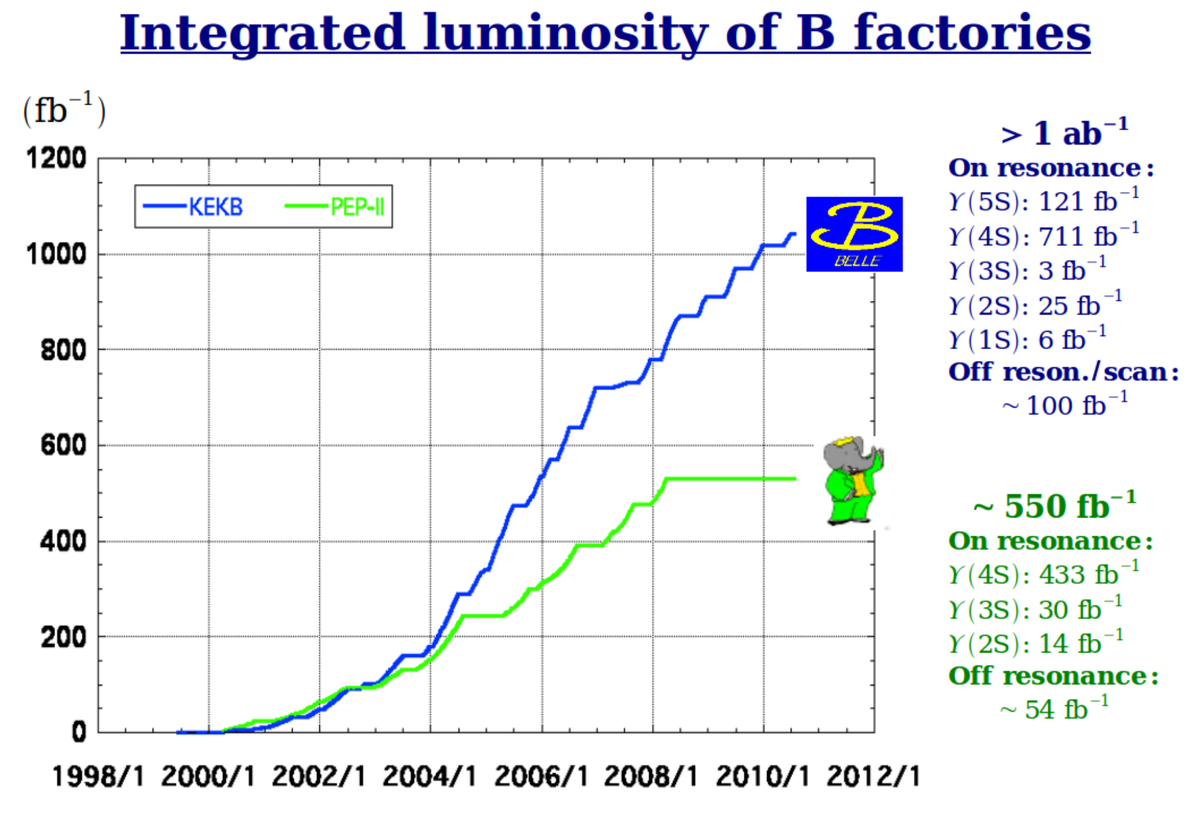


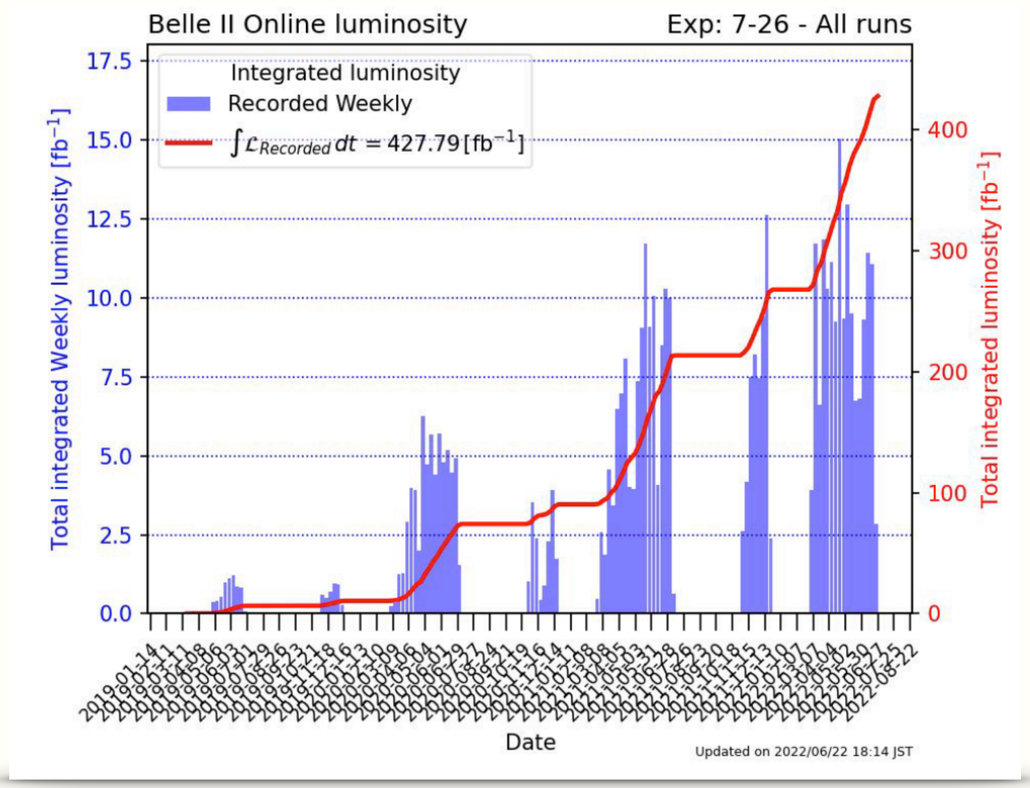
Belle II TDR (arXiv:1011.0352)

- KEKB: 8 GeV e- vs 3.5 GeV e^+
- Instantaneous Luminosity: 2.11 x 10^{34} $cm^{-2}s^{-2}$
- Data taken from 1999 to 2010
- Data accumulated: 1 ab^{-1}

- SuperKEKB: 7 GeV e- vs 4 GeV e+
- Achieved world-record peak luminosity of 4.7 x 10^{34} cm^{-2} s^{-2}
- Improved tracking and Vertexing.
- Data taken between 2019 - 2022
- Planned data collection: 50 ab^{-1} by the early 2030s

Belle/Belle II Status





Data taking has resumed from February 20, 2024 after a long shutdown period, during which the accelerator and detector have improved.

Recorded total integrated luminosity of ~ 424 fb^{-1} — equivalent to BaBar dataset. Υ(4S) on-resonance: 362 fb^{-1} ~ 1/2 of Belle sample

42 fb^{-1} data collected 60 MeV below Υ(4S) peak 19 fb^{-1} taken around 10.75 GeV for exotic hadron searches

Analysis in a Nutshell

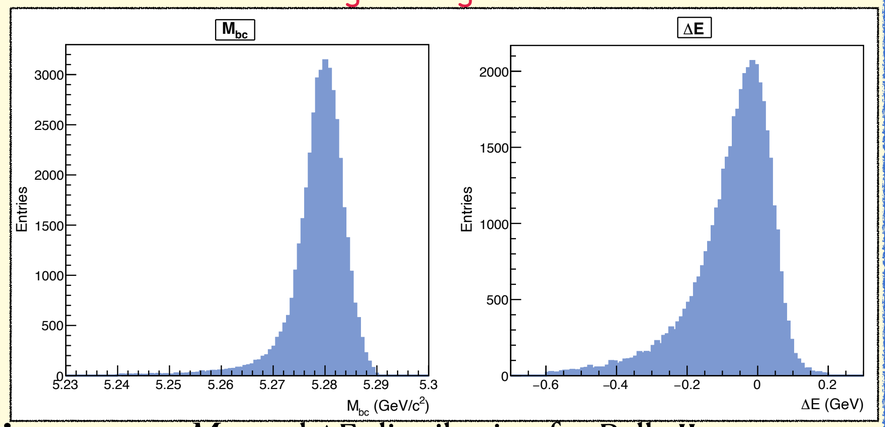
Reconstruction and selection

- Signal events reconstructed from the two highly energic photons.
- Reject the photon candidates from asymmetric π^0 and η decays.
- B^0 candidate is selected based on $M_{\rm bc}$ and ΔE.

$$M_{bc} = \sqrt{(E^{CM}_{beam})^2 - (p^{CM}_{B^0})^2}$$
$$\Delta E = E^{CM}_{B^0} - E^{CM}_{beam}$$

- All the selection cuts are optimized.

Challenging due to neutral final states, smaller signal rate
Large backgrounds



$M_{\rm bc}$ and ΔE distribution for Belle II

Background Study

$$e^+e^- \to udsc\ (uubar, ddbar, ssbar, ccbar)$$
$$e^+e^- \to B^+B^-\ (Charged)$$
$$e^+e^- \to B^0\overline{B^0}\ (Mixed)$$

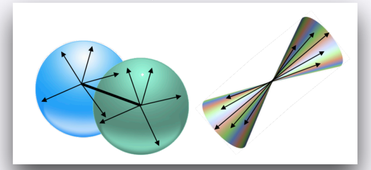
- 90% of bkg contamination from $q\bar{q}$.

$$e^+e^- \to q\bar{q}(q : u, d, s, c)$$

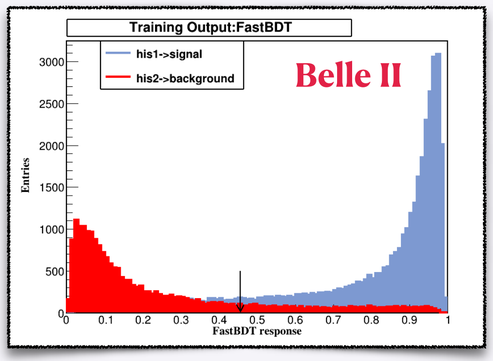
- Background from the other B^0 decays, such as $\pi^0\pi^0$ can mimic the signal if photons are merged.
- Largest contribution from $B^0 \to \pi^0\pi^0$ constitutes 0.63% of the expected signal event. Therefore, consider them negligible.

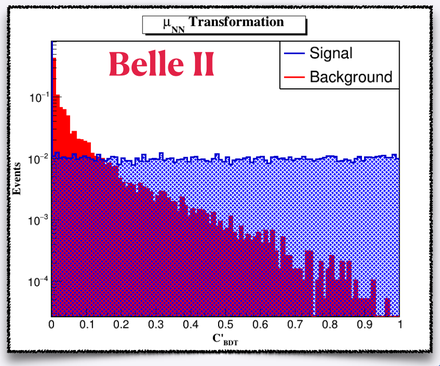
Background Suppression

- Background suppression was optimized separately for Belle and Belle II.
- Event shape variables are fed to the BDT classifier for discrimination.



Signal retains = 86%,
Bkg loss = 93% (Belle).
Signal retains = 89%,
Bkg loss = 87% (Belle II)





Overall better performances in Belle II

	Belle	Belle II
Sig efficiency	23%	31%
Exp. bkg/fb^{-1}	~ 0.8	

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1D PDF Parameterization

3D Fit model: $\mathscr{P}(M_{\rm bc}, \Delta E) \times \mathscr{P}(C'_{\rm BDT})$

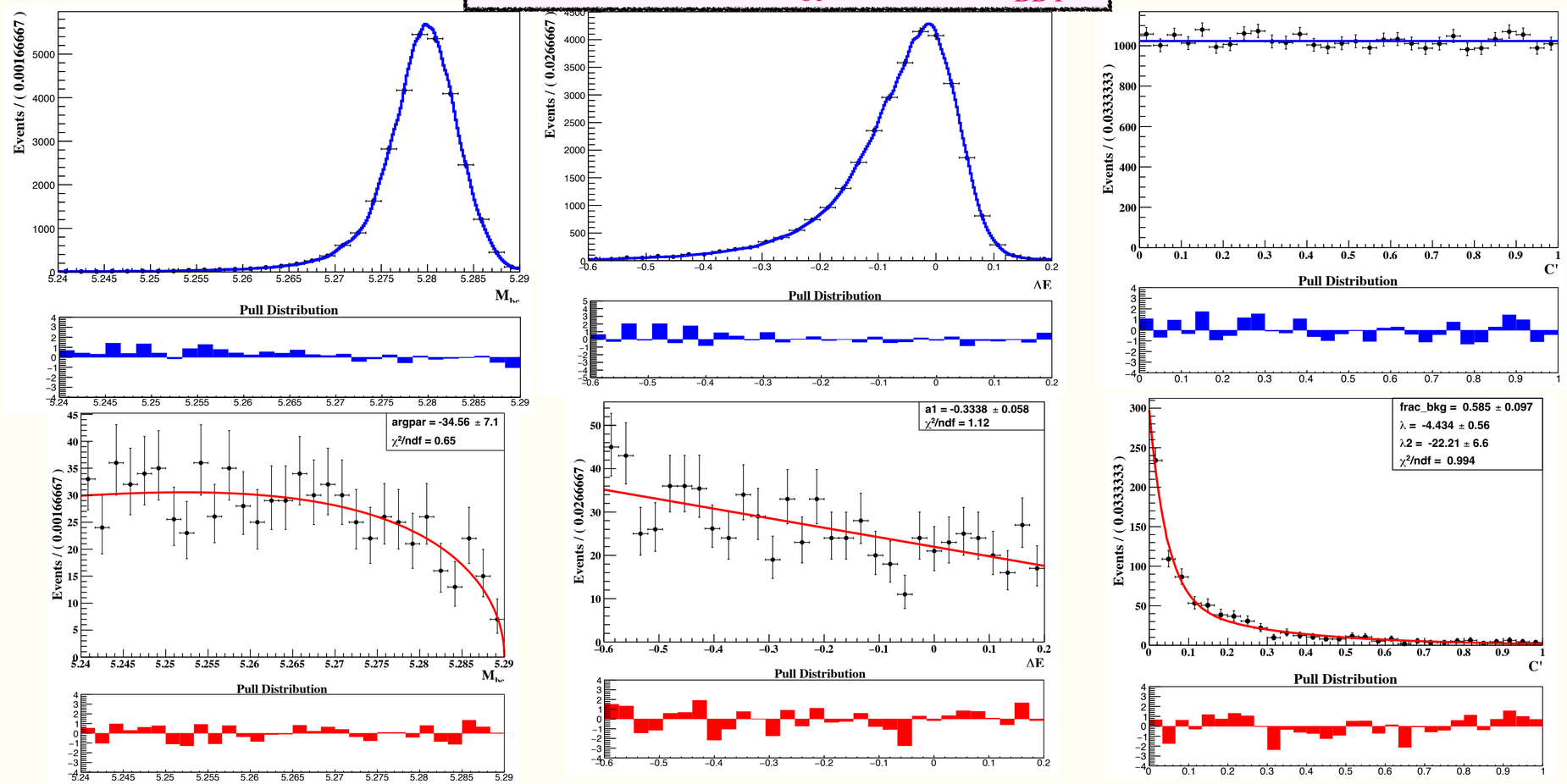


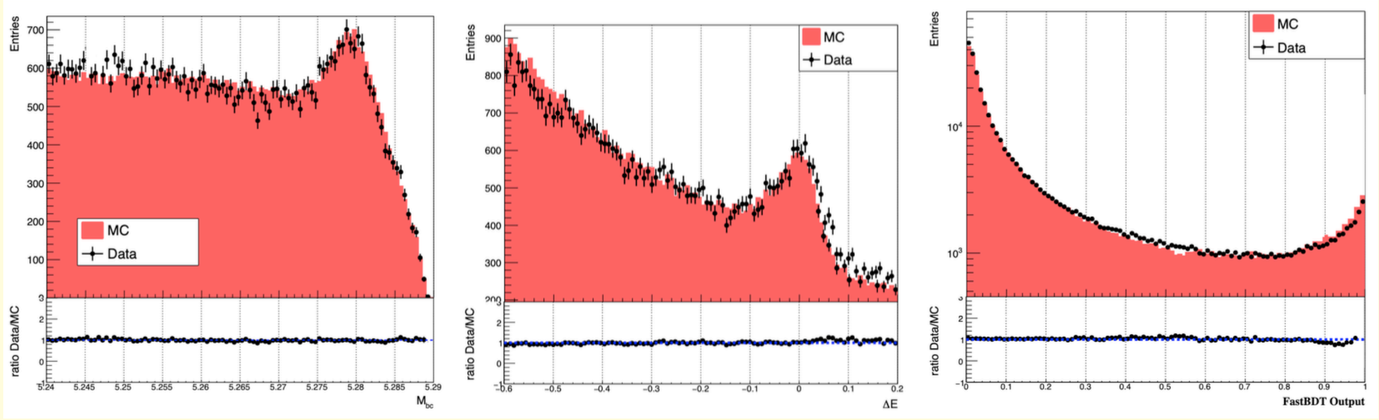
Fig: Pdf shapes of M_{bc}, ΔE, and $C'_{\rm BDT}$ for signal and background for Belle II

Fit Variables	Signal	Background
M_{bc}	2D KDE	Argus
ΔE	2D KDE	1^{st} Order Chebyshev polynomial
C'_{BDT}	0^{th} Polynomial	2 exponencial

Belle plots - in backup

Analysis Validation

- Control mode $B^0 \to K^{*0}\gamma$ is used to study the data/MC differences.



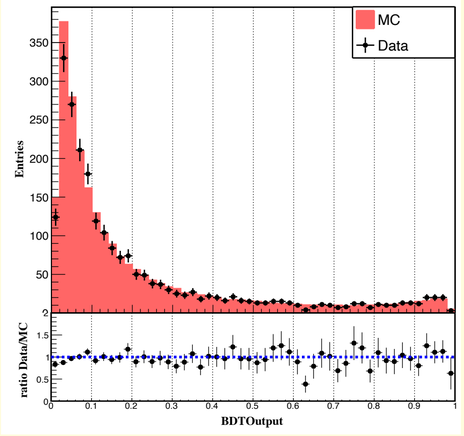
M_{bc} , ΔE and BDT output distributions comparing Belle data and MC

Overall, good Data-MC agreement.

- Calibration is performed for the BDT and π^0/η veto selection.

Calibration => Signal efficiency,
Uncertainty => Systematics

- Off-resonance data is used to validate the modeling of $q\bar{q}$ backgrounds.
- Difference in data/MC normalisation (used as systematic uncertainty)



Fit Validation

- We have performed the ensemble tests to check the stability of the fit procedure and the fit bias of the fit model.

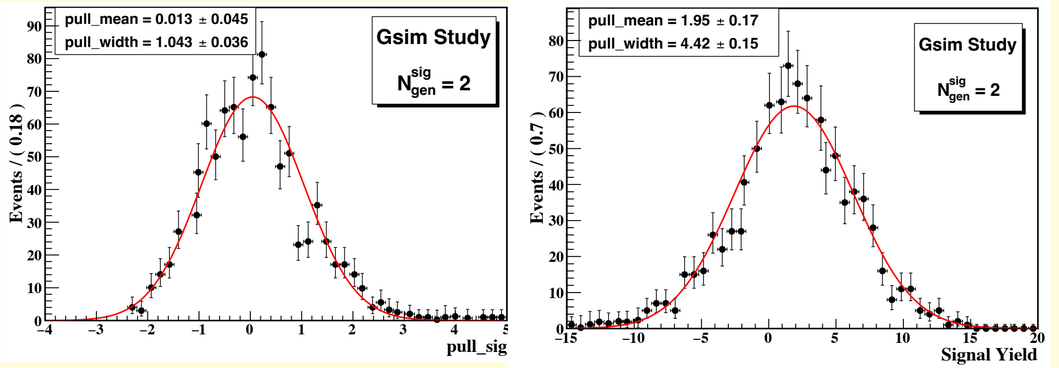


Fig: Pull (left) and signal yield (right) distribution for Belle II, respectively

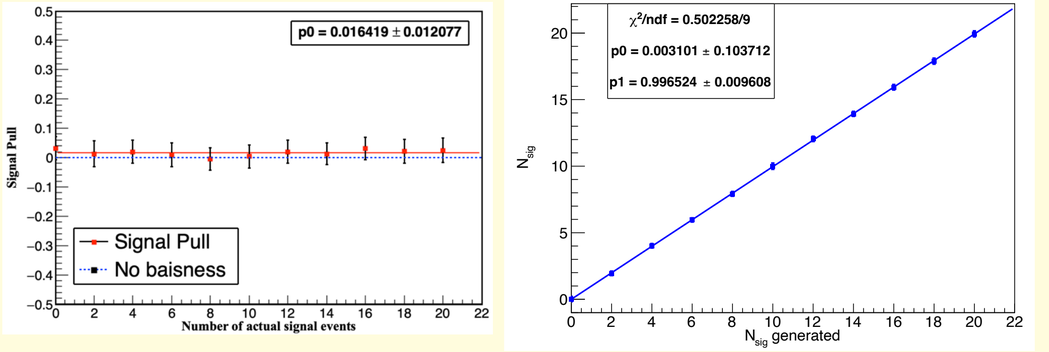


Fig: Pull vs. Nsig (left) and Linearity of the fit model (right) for Belle II

- We found our fitting strategy stable.
- Gsim study shows a bias of 1.64% for Belle II in the fitting strategy.
- We have assigned the combined systematic of +0.12 event from the fit bias and linearity test.

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Systematic Uncertainty

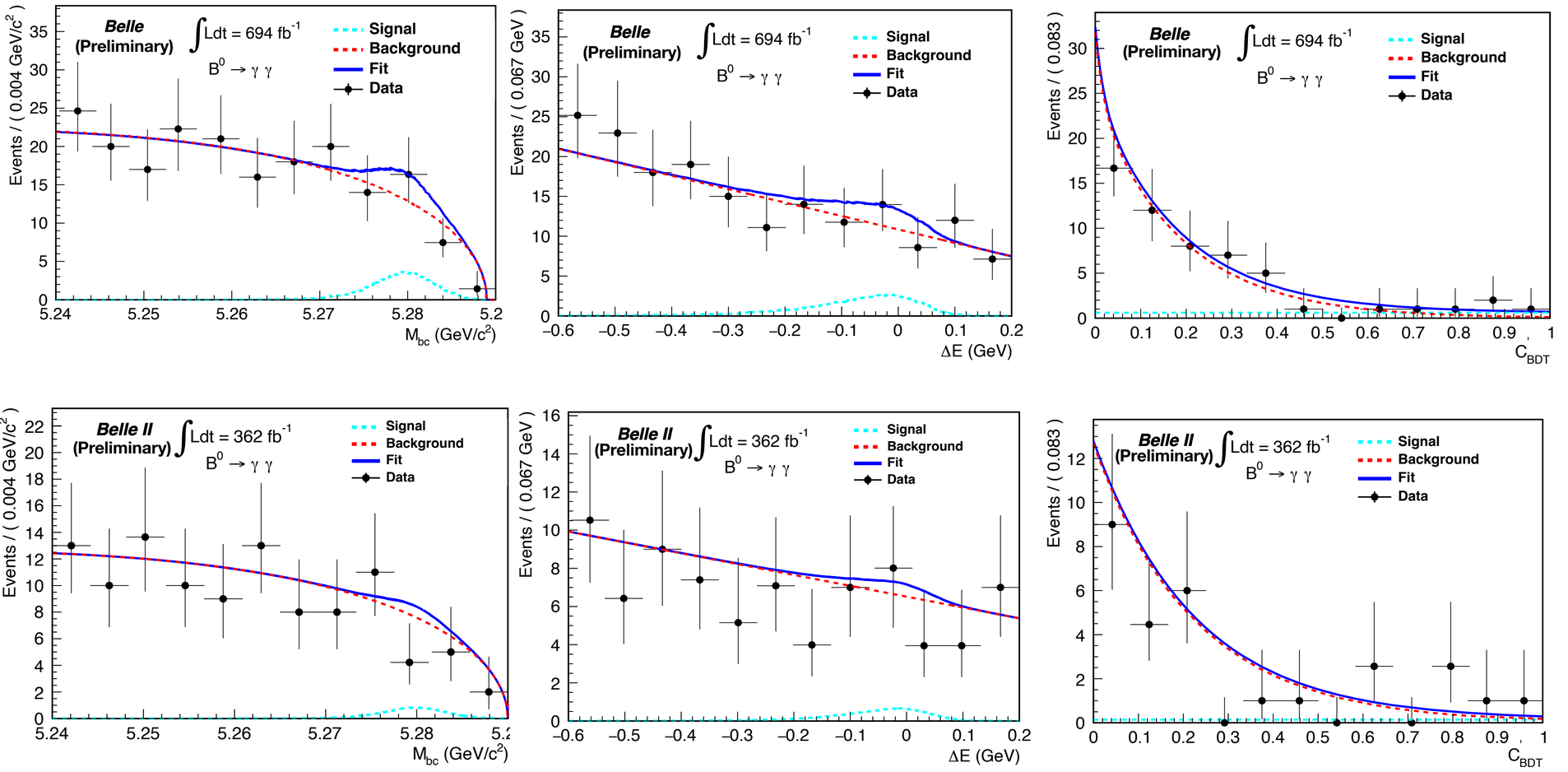
Belle II

Uncertainties on Signal Efficiency	Fractional uncertainties (%)
Photon Efficiency	± 2.70
π^0/η Veto	± 0.40
BDT selection	± 0.90
Reconstruction Efficiency	± 0.45
No. of $B\overline{B}$ pairs	± 1.45
f00	± 1.20
Normalization of $q\overline{q}$ yield	± 2.20
Shape discrepancy	± 2.00
Sum in quadrature	± 4.57
Uncertainties on Signal Yield	**uncertainties (events)**
PDF shape Parameter	$^{+0.28}_{-0.32}$
Fit Bias	+ 0.12
Sum in quadrature	$^{+0.30}_{-0.32}$

Belle

Uncertainties on Signal Efficiency	Fractional uncertainties (%)
Photon Efficiency	± 4.00
π^0/η Veto	± 0.30
BDT selection	± 0.40
Reconstruction Efficiency	± 0.57
No. of $B\overline{B}$ pairs	± 1.30
f00	± 1.20
Timing Cut	± 2.80
Normalization of $q\overline{q}$ yield	± 1.78
Shape discrepancy	± 0.72
Sum in quadrature	± 5.59
Uncertainties on Signal Yield	**uncertainties (events)**
PDF shape Parameter	$^{+0.56}_{-0.48}$
Fit Bias	+ 0.16
Sum in quadrature	$^{+0.58}_{-0.48}$

Combined Result (Belle+Belle II)



- Simultaneous 3D unbinned ML fitting on M_{bc}, ΔE and C'_{BDT} using Belle and Belle II data sets.

Signal yield = $11.0^{+6.48}_{-5.48}$.

- We calculated the branching fraction using the combined Belle and Belle II data sets.

Figure: The results of the simultaneous fit using Belle and Belle II combined data. The figures are shown in the signal enriched regions: $M_{bc} > 5.27$ GeV/c² and $-0.19 < \Delta E < 0.14$ GeV for Belle and $M_{bc} > 5.27$ GeV/c² and $-0.19 < \Delta E < 0.15$ GeV for Belle II.

Combined Results

$$\mathcal{B}(B^0 \to \gamma\gamma) = (3.69^{+2.17}_{-1.84}(\text{stat}) \pm 0.68(\text{sys})) \times 10^{-8}$$

Signal Significance

$$(\sqrt{-2(\ln \mathcal{L}_0/\mathcal{L}_{max})}) = 2.5\ \sigma$$

- In the absence of any significant signal yield, we used the Bayesian approach to estimate the upper limit on the branching fraction.
- $\mathcal{B}(B^0 \to \gamma\gamma) < 6.40 \times 10^{-8}$ @ 90% CL.
- This is an improvement by a factor of 5 over the previous upper limit set by the Babar experiment with 426 fb^{-1} (< 3.2×10^{-7} at 90% CL).

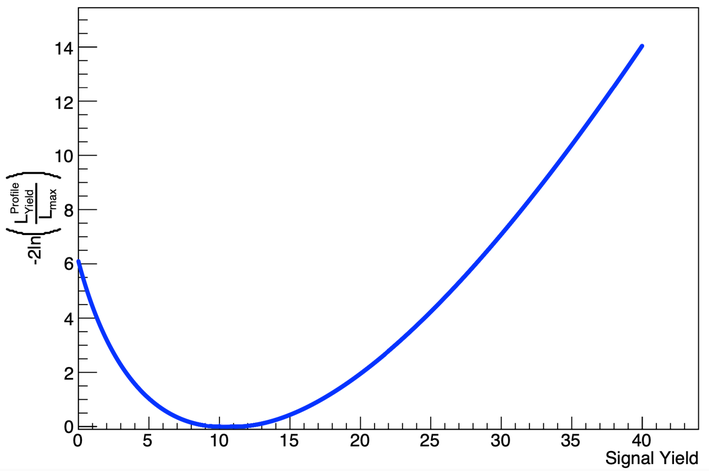


Fig 1: Profile Likelihood vs signal yield

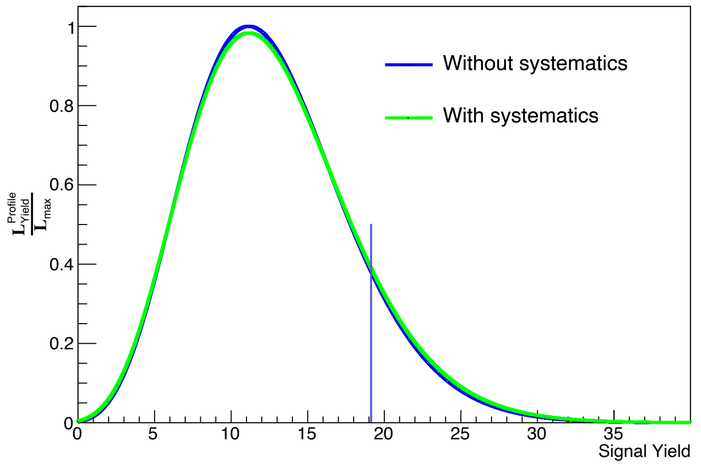


Fig 2: Comparison between unconvoluted and convoluted likelihood with and without systematics.
The violet line represents the 90% CL.

Improvements

Increased Statistics (Belle+Belle II)

Improved analysis techniques.

Better Signal Efficiency

Improved Background reduction

Upper limit Branching fraction (without systematics): $< 6.32 \times 10^{-8}$

Upper limit Branching fraction (with systematics): $< 6.40 \times 10^{-8}$

World Best UL
Approaching SM sensitivity

Summary

- We performed an analysis of the Belle and Belle II datasets corresponding to an integrated luminosity of 694 fb^{-1} and 362 fb^{-1} collected at $\Upsilon(4S)$ resonance, respectively.
- After the box opening, we observed $11.0^{+6.48}_{-5.48}$ signal events with the significance of 2.5σ and measured the combined branching fraction to be $(3.69^{+2.17}_{-1.84}(\text{stat}) \pm 0.68(\text{sys})) \times 10^{-8}$.
- In the absence of any significant signal yield, we used the Bayesian approach to estimate the upper limit on the branching fraction.
- The estimated upper limit for the combined measurement is less than 6.40×10^{-8} @ 90% CL which is an improvement by a factor of 5 over the previous upper limit $< 3.2 \times 10^{-7}$ set by BaBar.
- These results are consistent within 0.90 σ of the SM prediction.

Thank you!

Backup Slides

1D PDF Parameterization for Belle

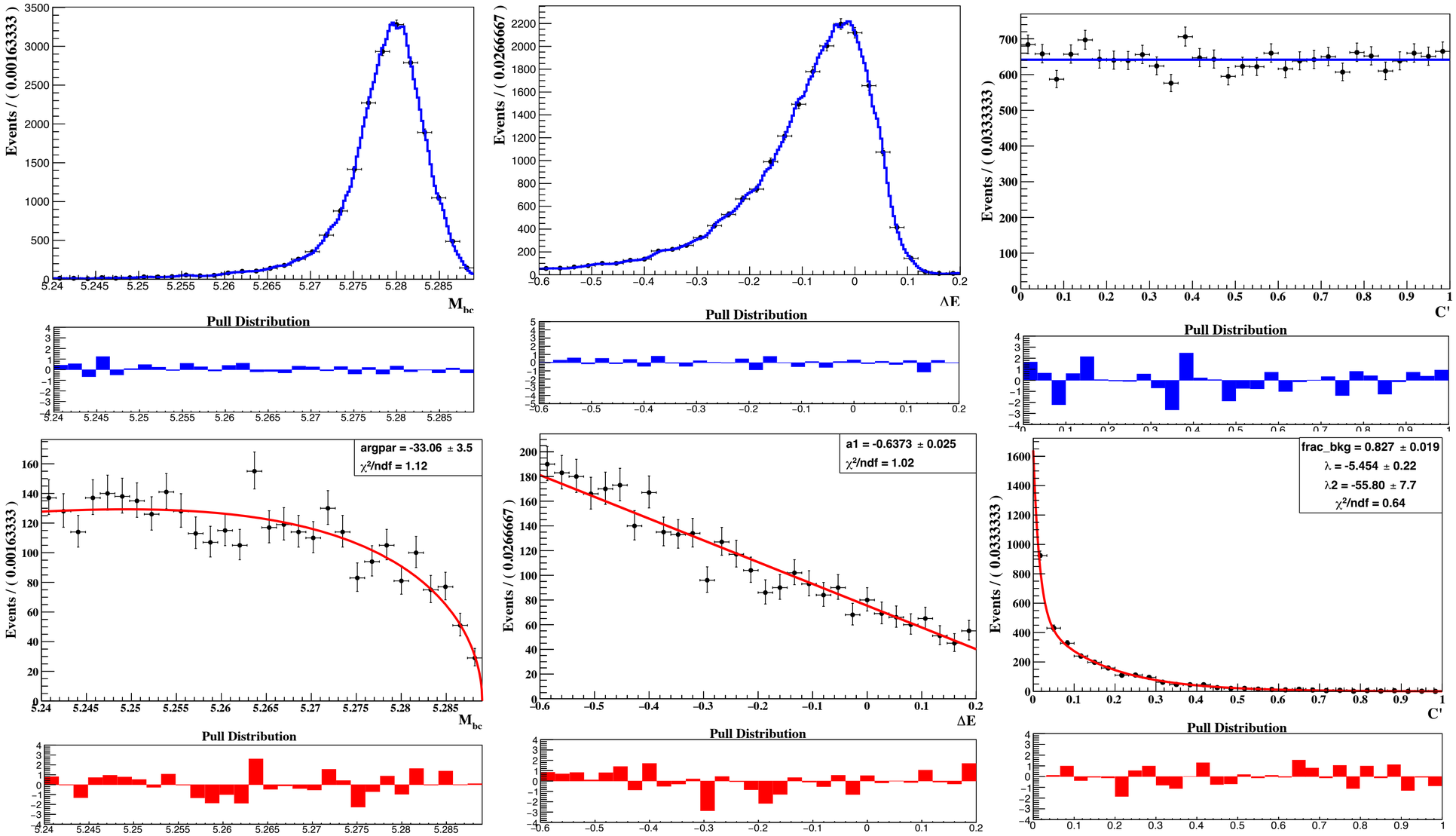


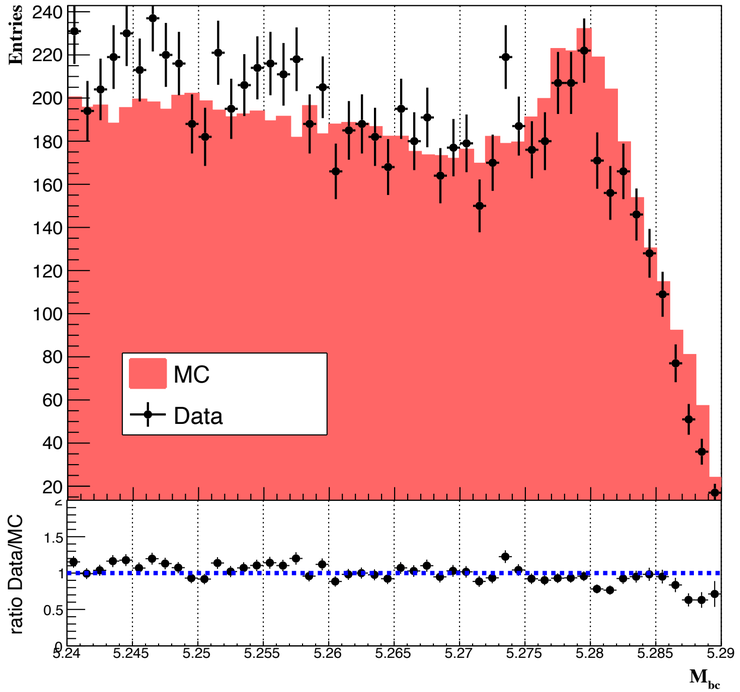
Fig: Pdf shapes of M_{bc}, ΔE, and C' for signal and background for Belle

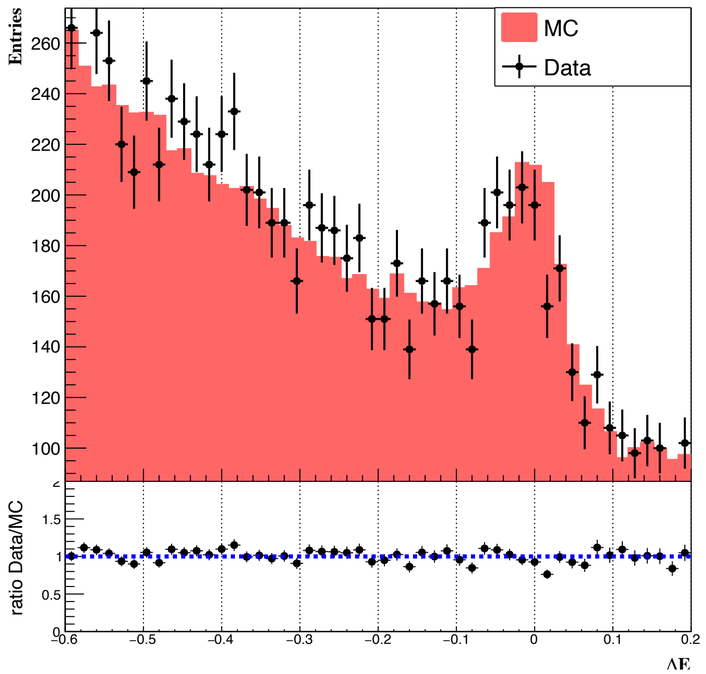
Fixed and Floated parameters for the 3D Fit model

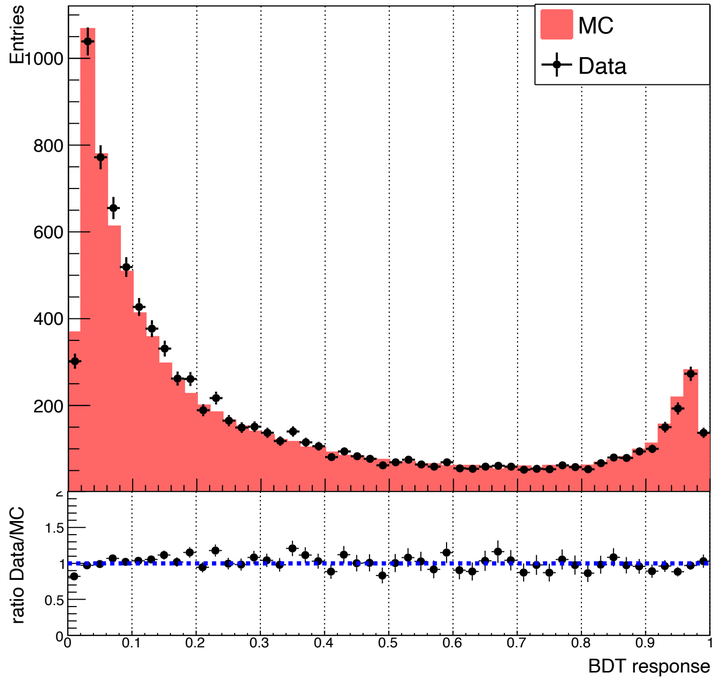
Variable		Function	Parameter	Comment
M_{bc}	Signal	2D KDE	-	No parameter
	Background	Argus	Endpoint	Fixed
			Curvature(argpar)	Floated
ΔE	Signal	2D KDE	-	No parameter
	Background	1^{st} Order Chebyshev polynomial	Coefficient(a1)	Floated
C'_{BDT}	Signal	0^{th} order Polynomial	-	No parameter
	Background	Exponential	λ_1	Fixed
			λ_2	Fixed
			frac	Floated

Table: PDF used in the Fit model of $B^0 \to \gamma\gamma$ sample and parameter information.

DATA-MC comparison of Belle II for $B^0 \rightarrow K^*\gamma$



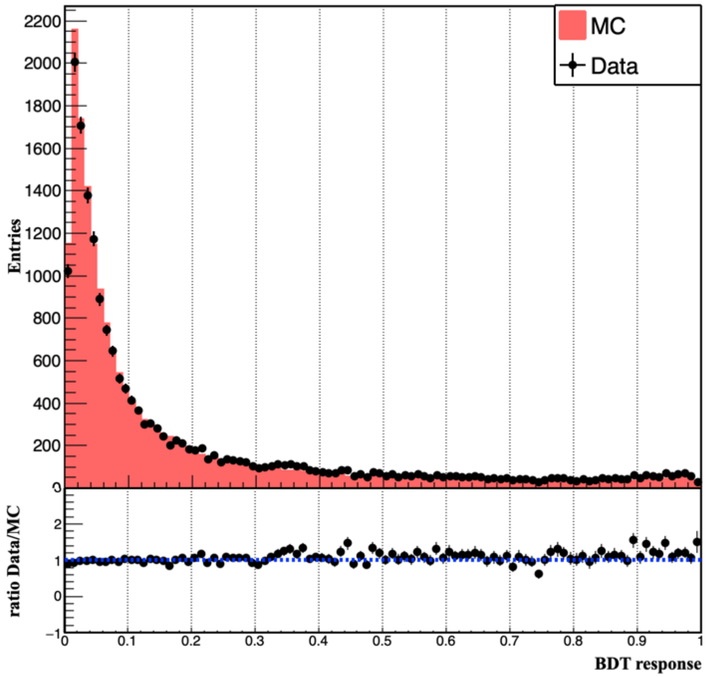


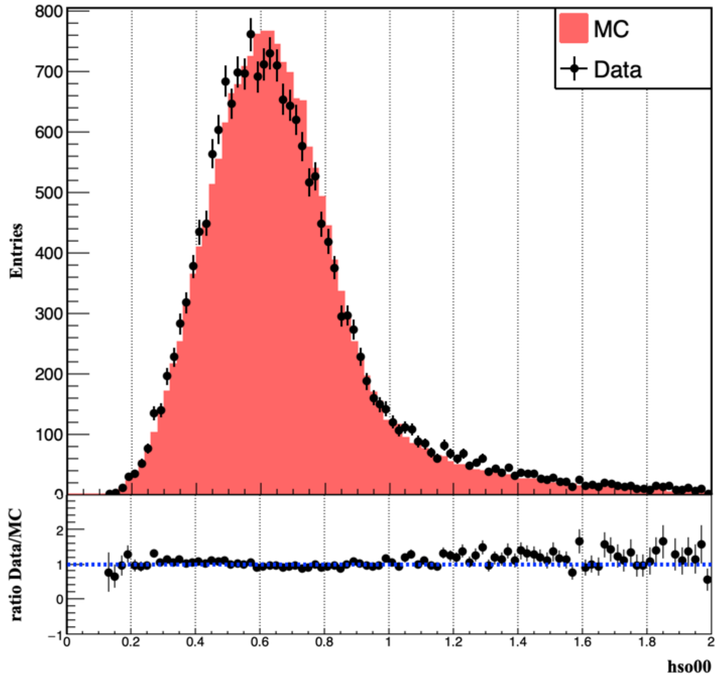


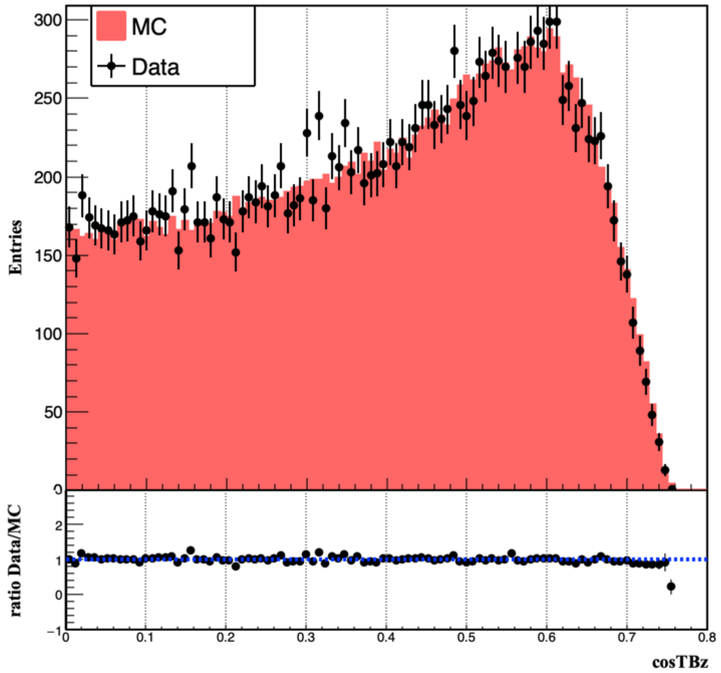
M_{bc} , ΔE and FastBDT output distributions comparing Belle II data and MC

- Overall, good Data-MC agreement.

Data-MC Comparision for FastBDT output and Eventshape Variable: Belle







- We do not observe any serious differences in Data -MC comparison.

hso02

Ensemble Test Results: Belle

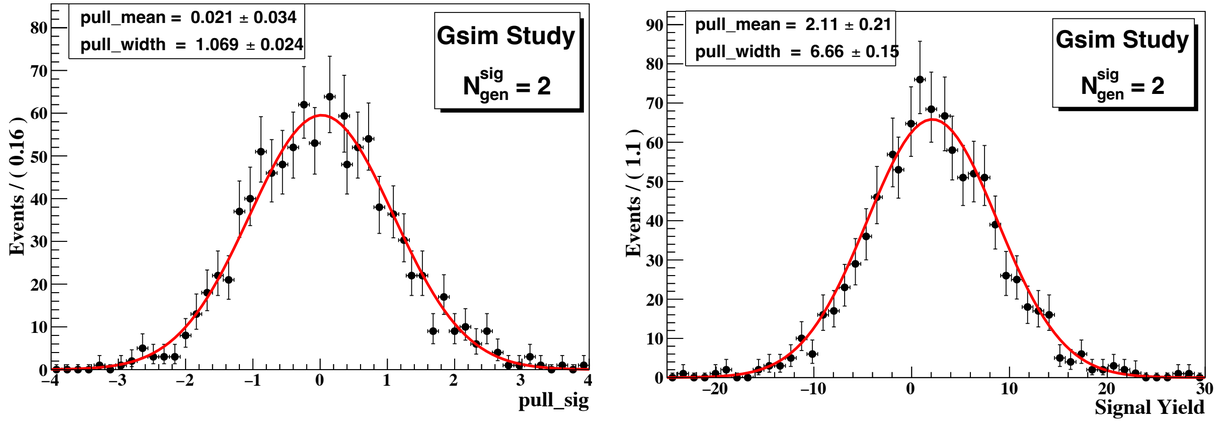


Fig: Pull (left) and signal yield (right) distribution for Belle, respectively

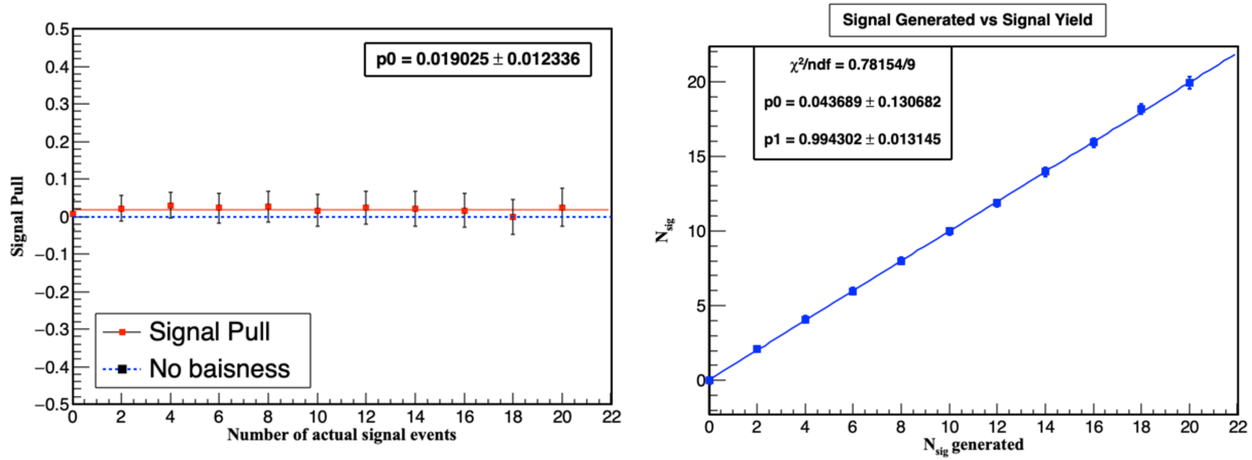
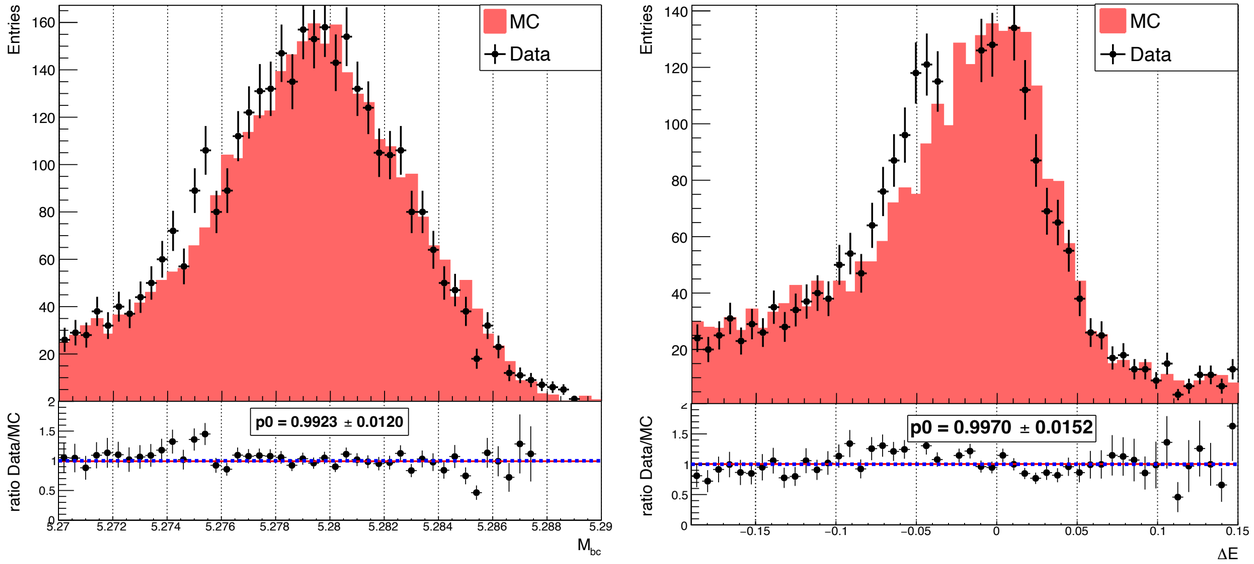


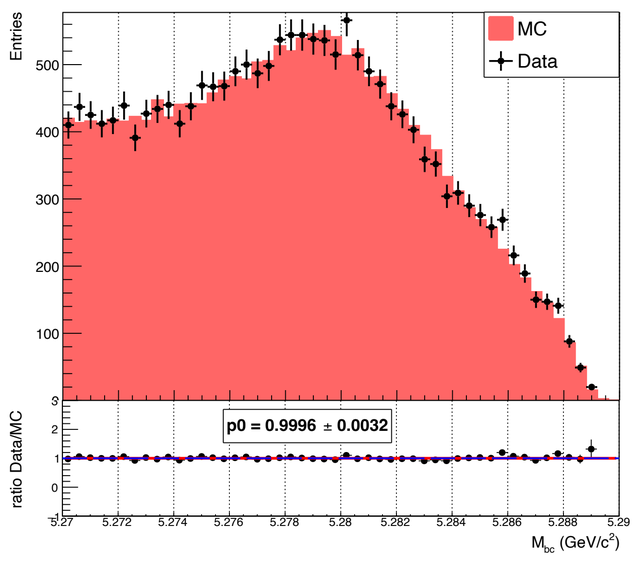
Fig: Pull vs. Nsig (left) and Linearity of the fit model (right) for Belle, respectively

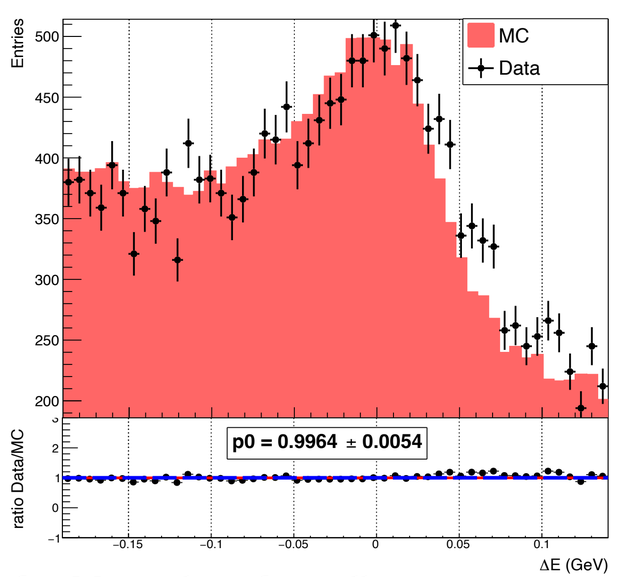
- Gsim study shows a bias of 1.90% for Belle in the fitting strategy.
- We have assigned the combined systematic of +0.16 event from the fit bias and linearity test for Belle.

Uncertainty due to shape discrepancy



Data-MC comparison for M_{bc} and ΔE for Belle II





Data-MC comparison for M_{bc} and ΔE for Belle

- Systematic due to shape discrepancy between the Data and MC is studied using a control sample $B^0 \to K^*\gamma$.
- The deviation from the unity in the DATA/MC ratio which is 0.72% (2%) will be considered a source of systematic uncertainty for Belle (Belle II).

Normalization of $q\bar{q}$ yield

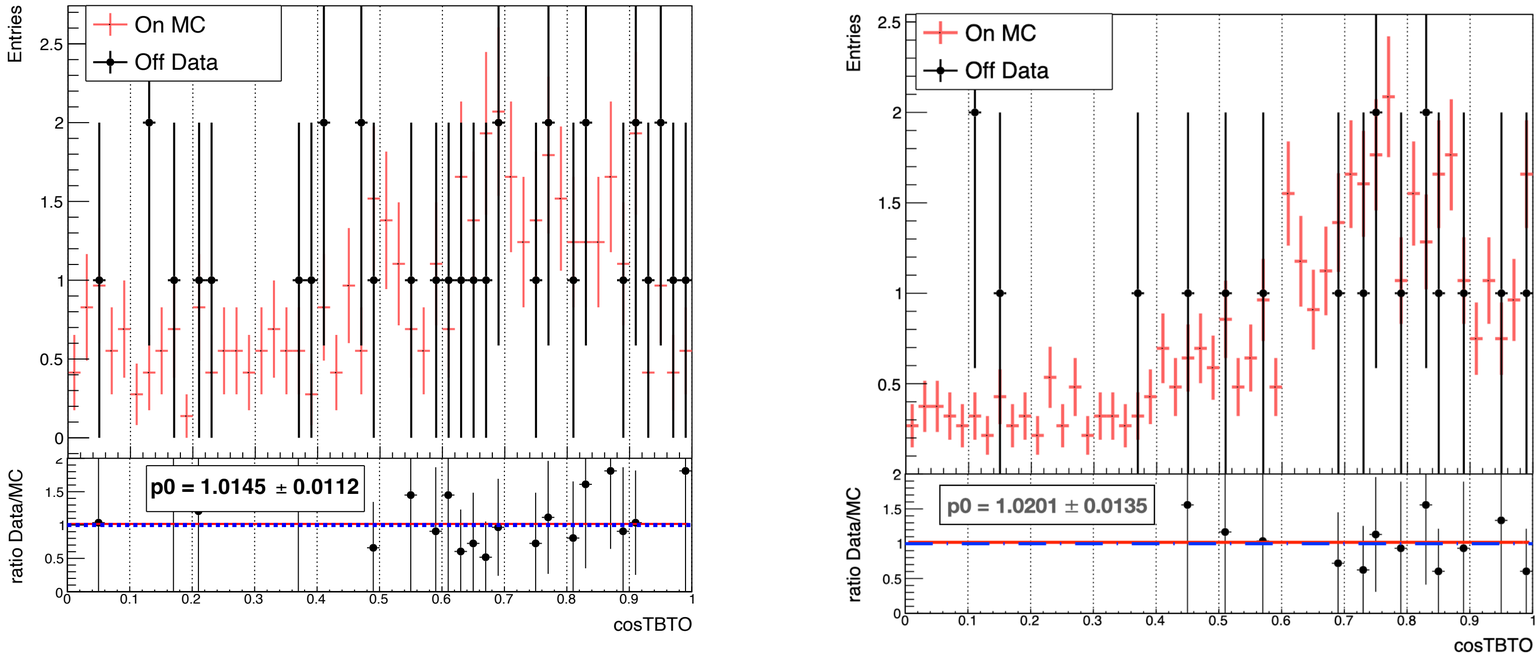


Fig: DATA-MC Comparision of cosTBTO distribution for Belle (left) and Belle II (right), respectively

- To correct the number of $q\bar{q}$ components in MC, off-resonance data are compared to the number of events in the signal region with on-resonance MC.
- The deviation from the unity in the DATA/MC ratio is calculated to be 1.78% and 2.20% for the Belle and Belle II, respectively.

Timing Cut : Belle Study

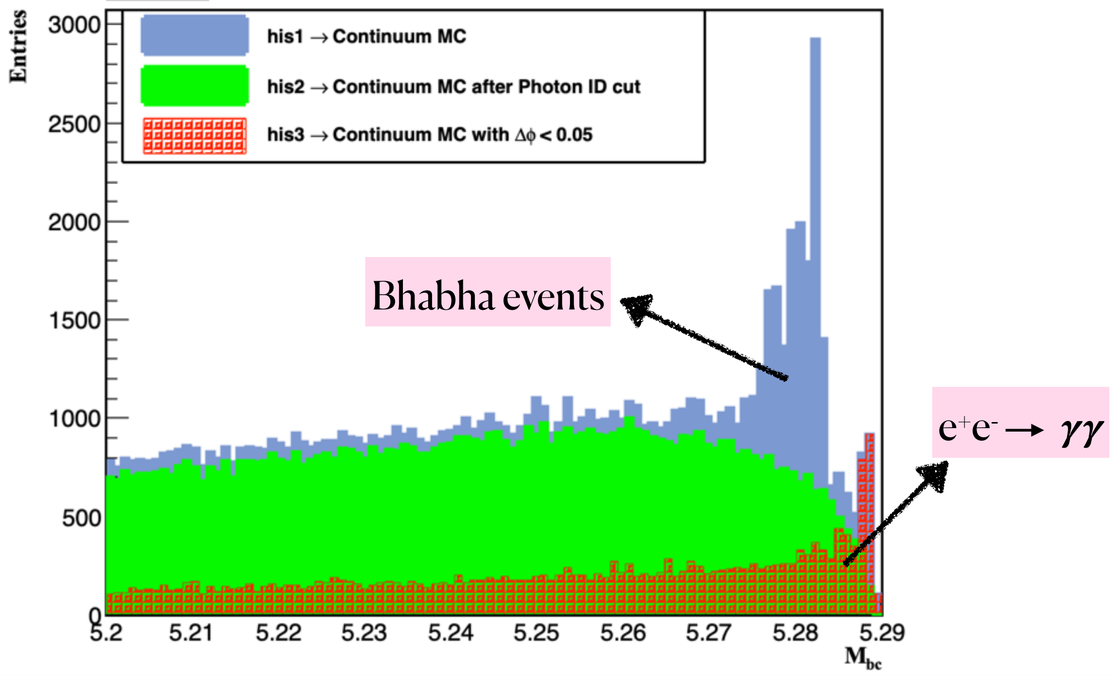


Figure 1: M_{bc} distribution for the preselected data.
The hatched histogram shows the off-time events, which correspond to $e^+e^- \rightarrow \gamma\gamma$ events.

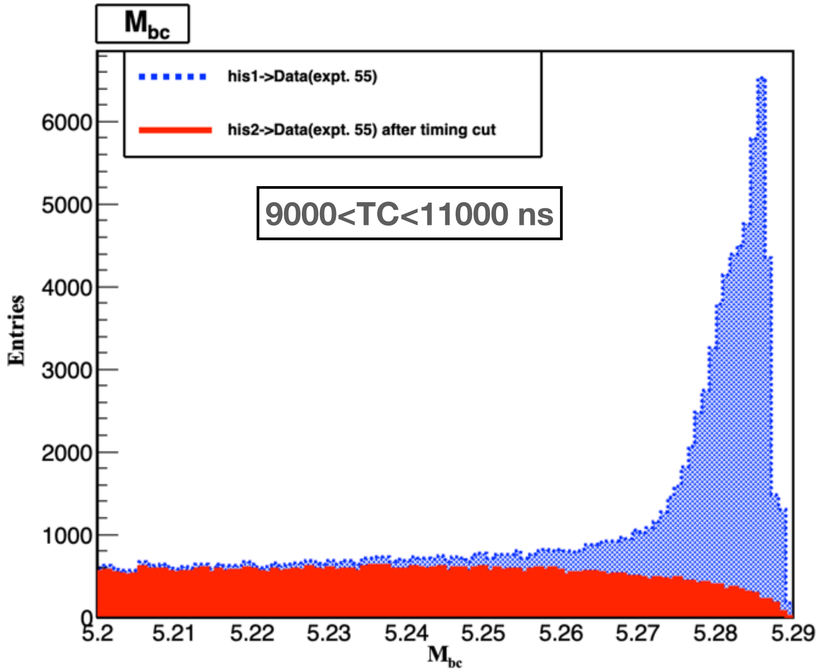


Fig 2: Peaking component rejected after applying the timing cut in real data

- Due to the overlap of a hadronic event with energy deposits in the ECL by QED processes like Bhabha events and $e^+e^- \rightarrow \gamma\gamma$ can mimic the signal events.
- The peaking effect of off-time QED backgrounds is completely removed by applying the timing criterion requiring that the photons hit the ECL clusters within 9 to 11 microseconds.