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

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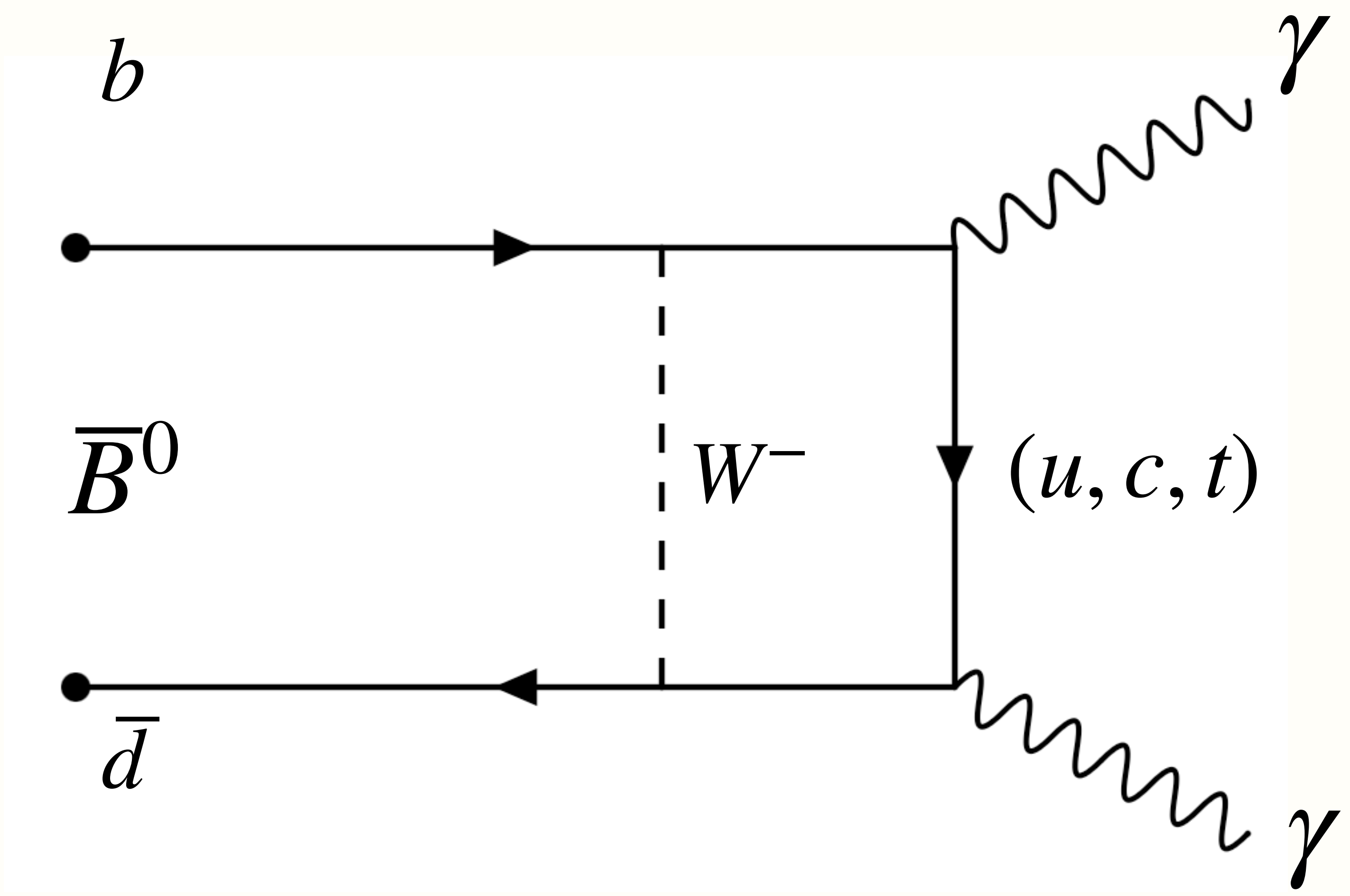
On behalf of the Belle and Belle II Collaboration

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.
- This mode is sensitive to new physics that could enhance branching fraction due to the possible contribution of non-SM heavy particles.



Previous searches	Measurement at 90 % CL	
L3 collaboration ($\int \mathcal{L}dt$=73 pb^{-1})	$< 3.9 \times 10^{-5}$	Phys. Lett. B363 137
Belle collaboration ($\int \mathcal{L}dt$=104 fb^{-1})	$< 6.2 \times 10^{-7}$	Phys. Rev. D.73.051107
BABAR collaboration ($\int \mathcal{L}dt$=426 fb^{-1})	$< 3.2 \times 10^{-7}$	Phys. Rev. D.83.032006

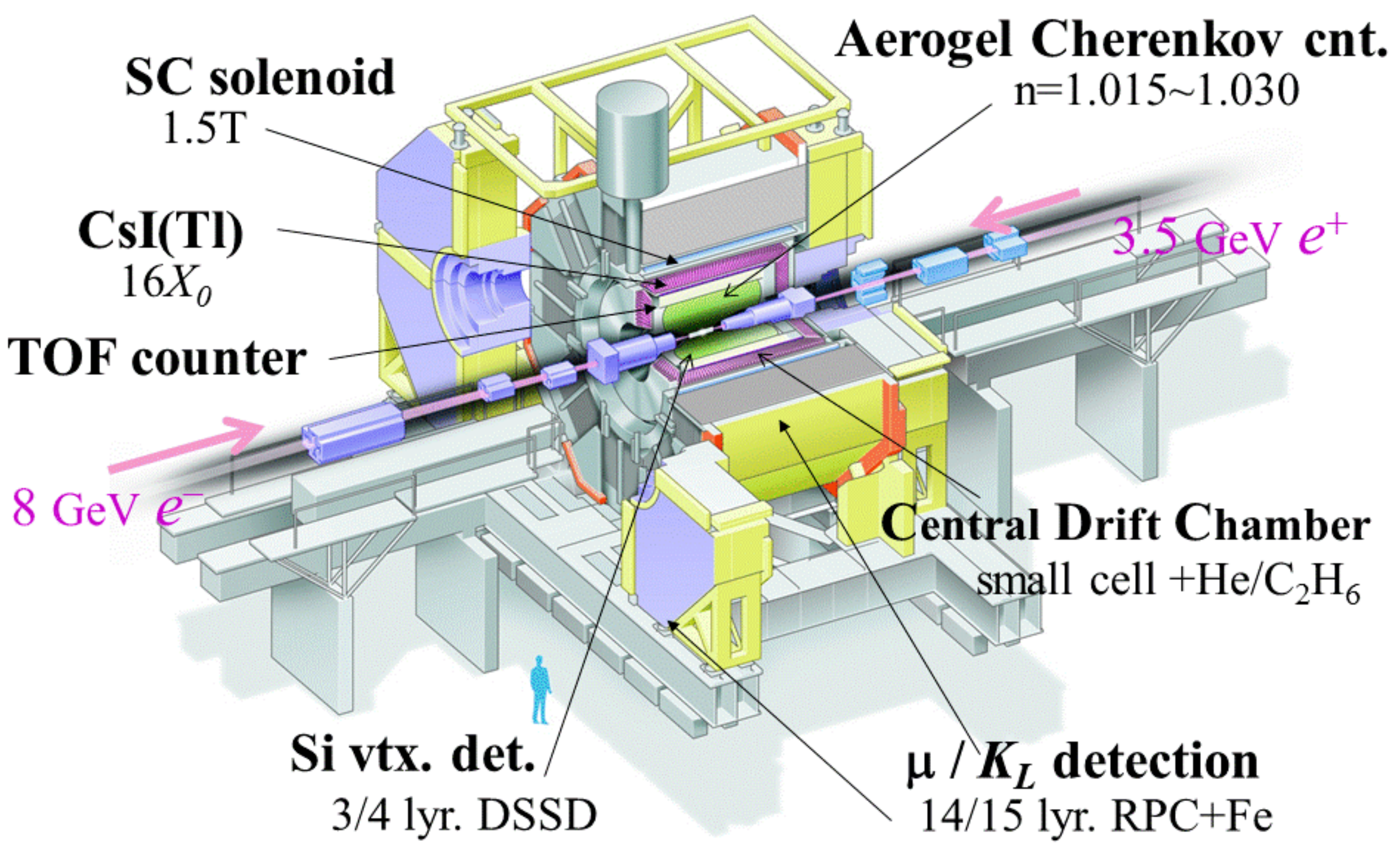
Theoretically, the BF of this decay mode is expected to be $1.4^{+1.4}_{-0.8} \times 10^{-8}$ [1].

- We perform the first Belle and Belle II measurement using a data set of 694 fb^{-1} from Belle and the dataset of Belle II ($\approx$ 362 fb^{-1}) from the Run1 period.

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

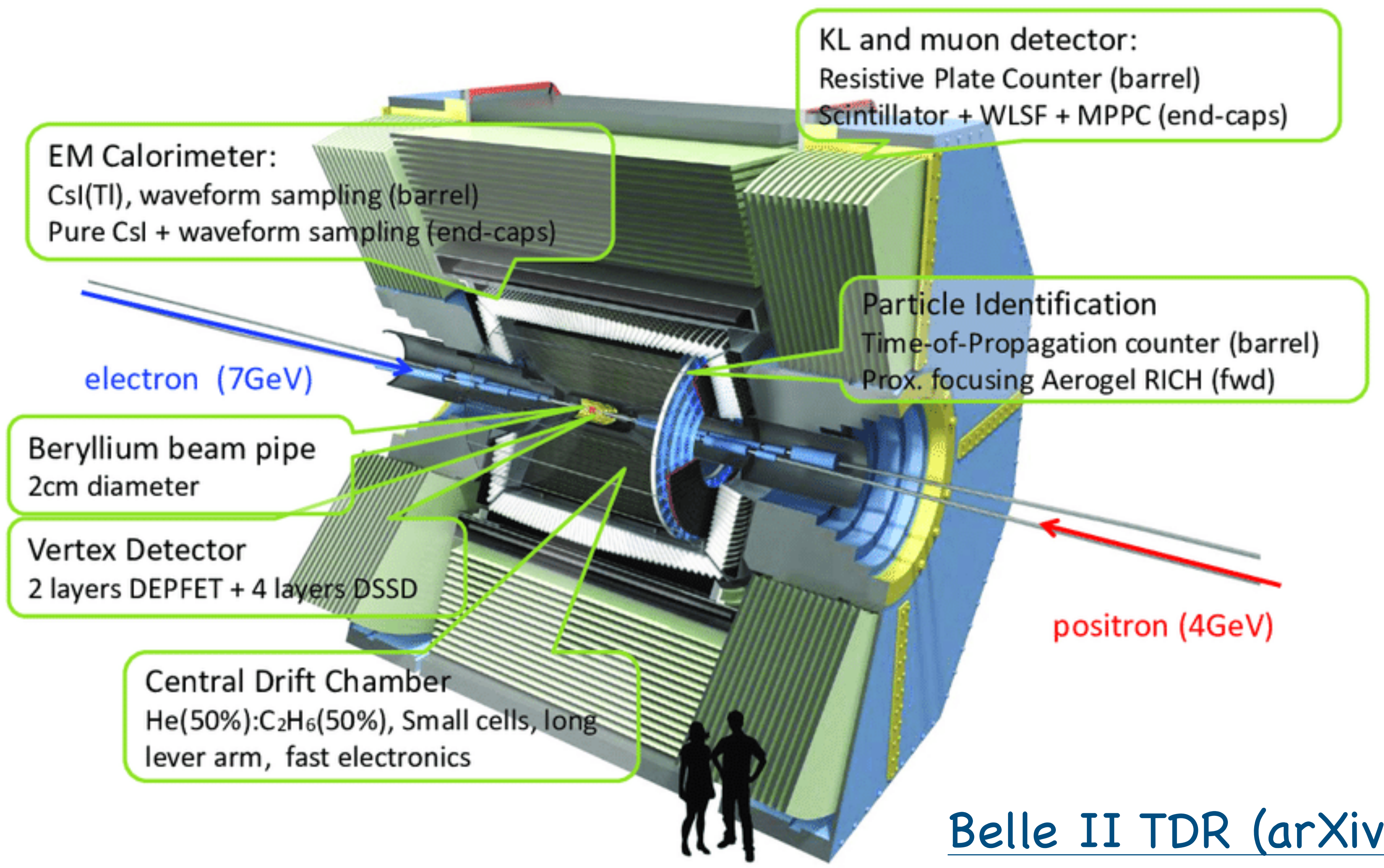
Belle vs Belle II Detector

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: 2.11×10^{34} cm^{-2} s^{-1}
- Data taken from 1999 to 2010
- Data accumulated: 1 ab^{-1} (694 fb^{-1}at $\Upsilon(4S)$)

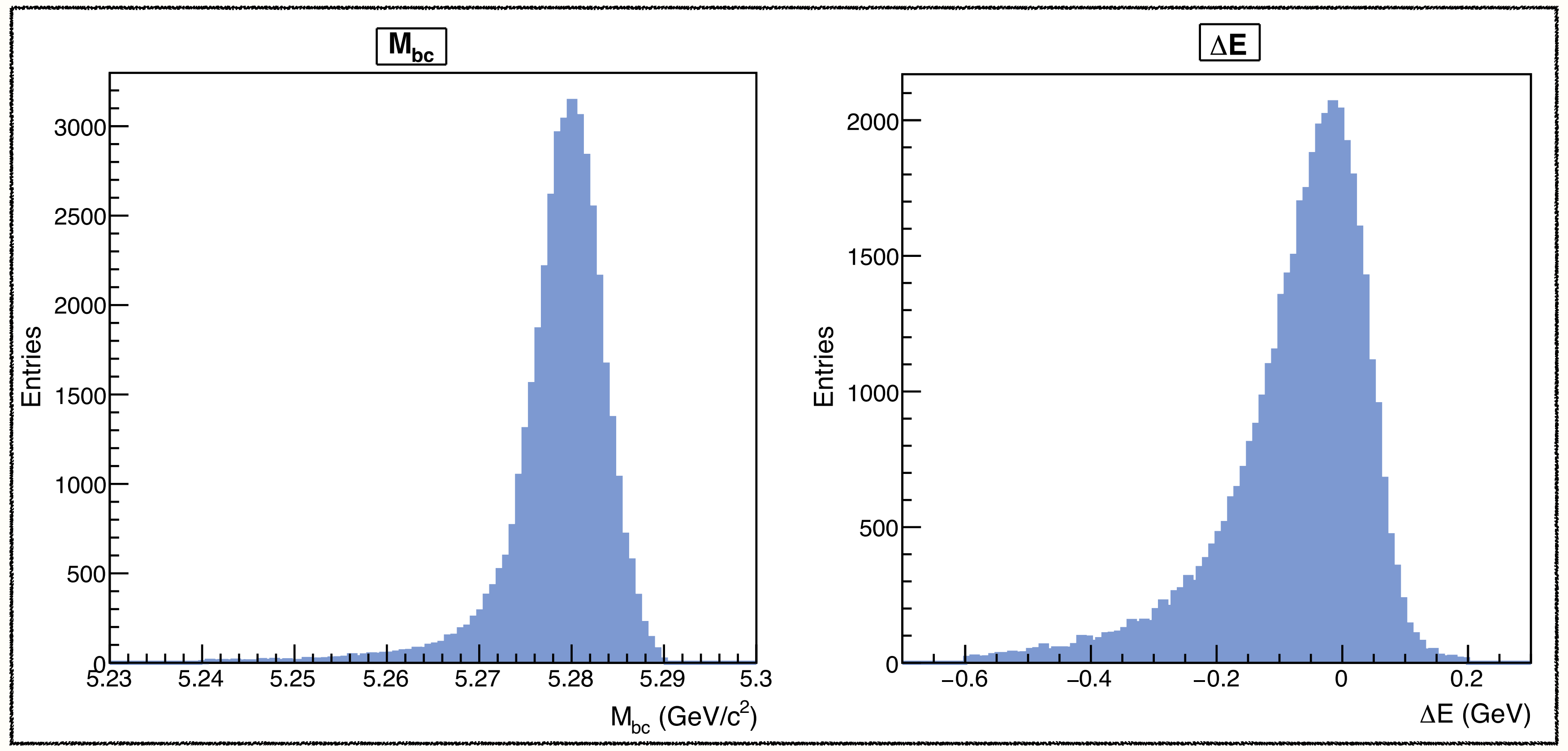
- SuperKEKB: 7 GeV e^- vs 4 GeV e^+
- Achieved world-record peak luminosity of 4.7×10^{34} cm^{-2} s^{-1}
- Data taken between 2019 - 2022 (362 fb^{-1} at $\Upsilon(4S)$)
- Planned data collection: 50 ab^{-1} by the early 2030s

Analysis in a Nutshell

Reconstruction and selection

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

- Signal events are 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.

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

- All the selection cuts are optimized.

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 only 0.63% of the expected signal events -> considered negligible.

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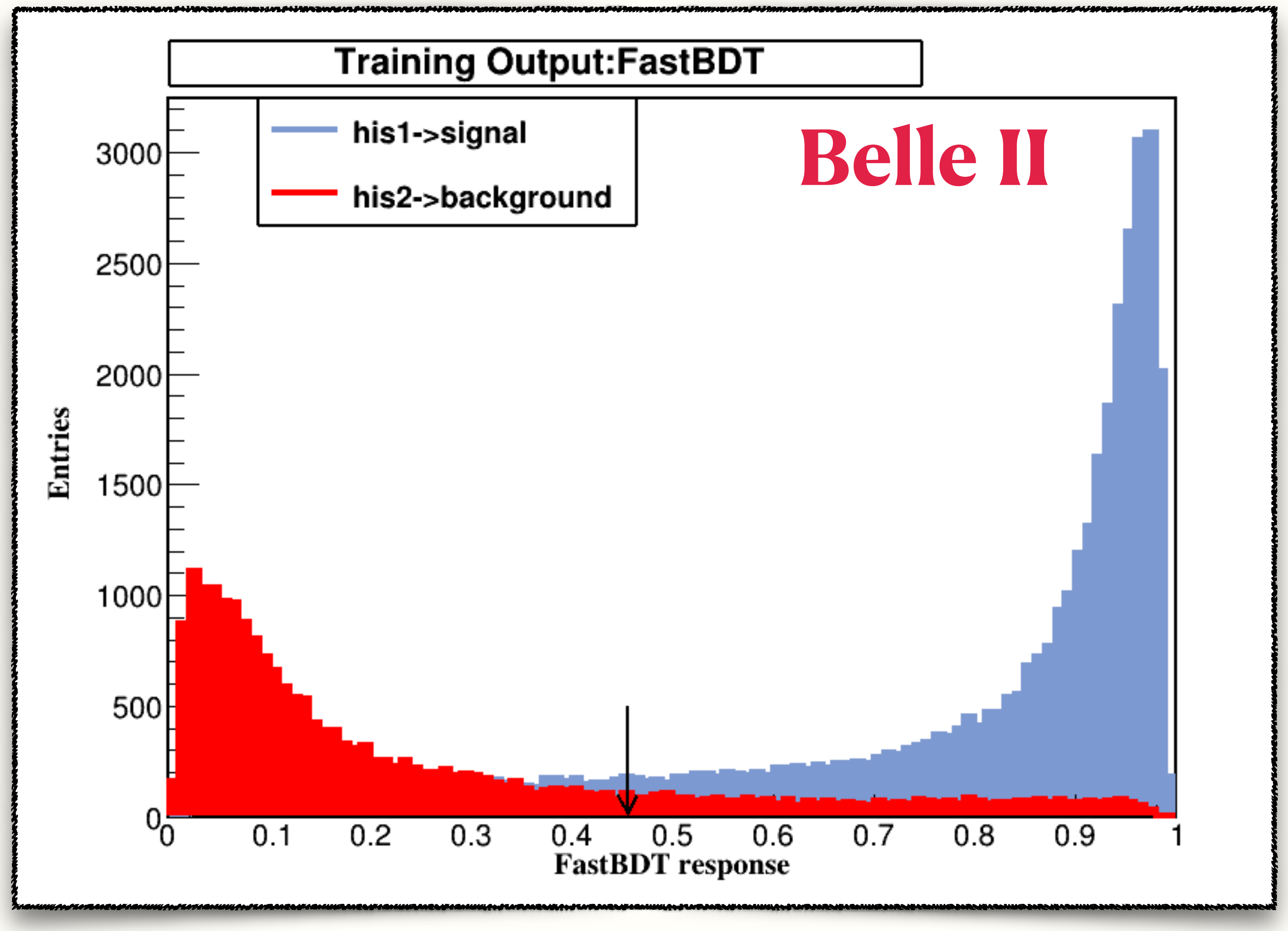
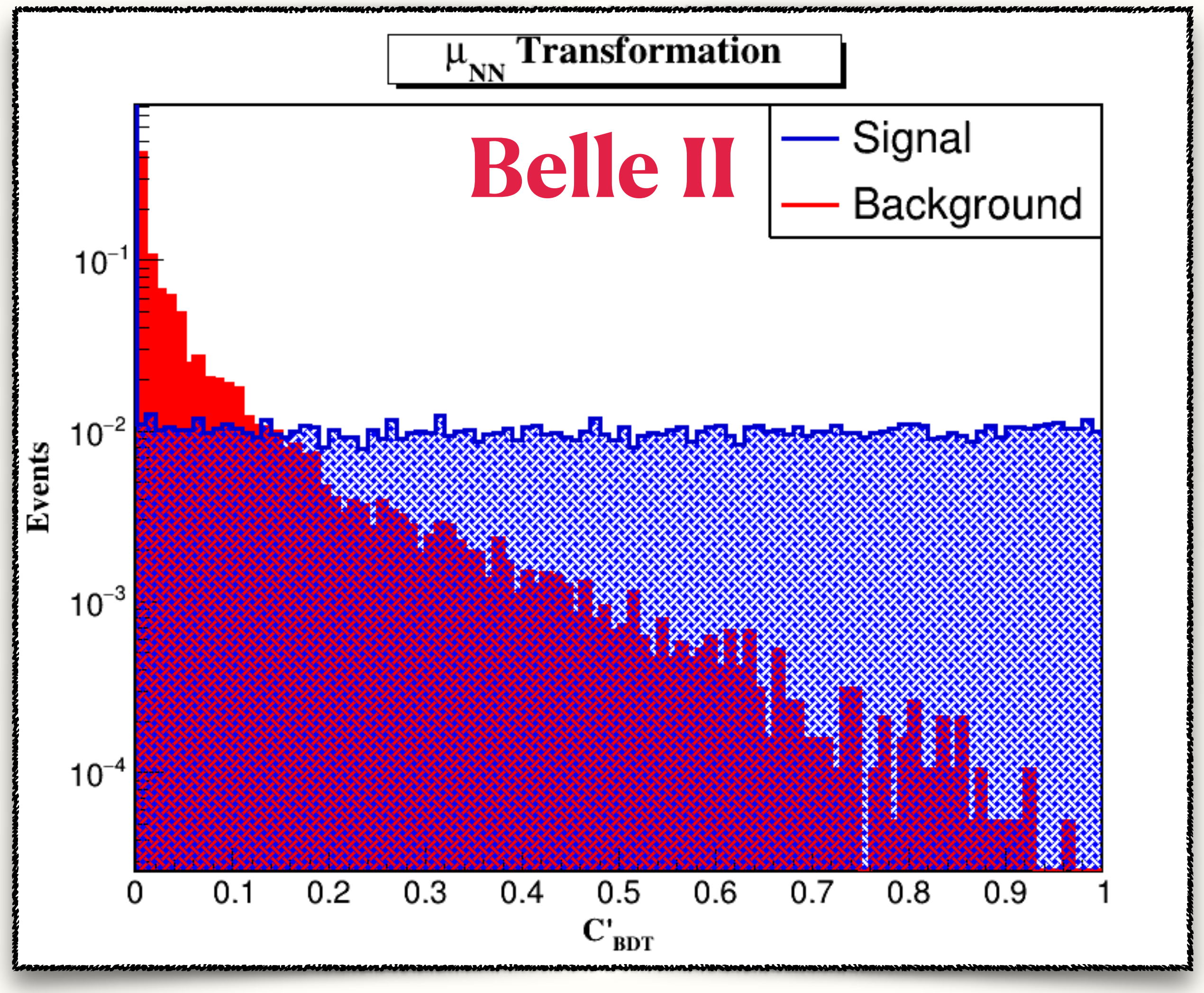
Background Suppression

- Background suppression was optimized separately for Belle and Belle II.

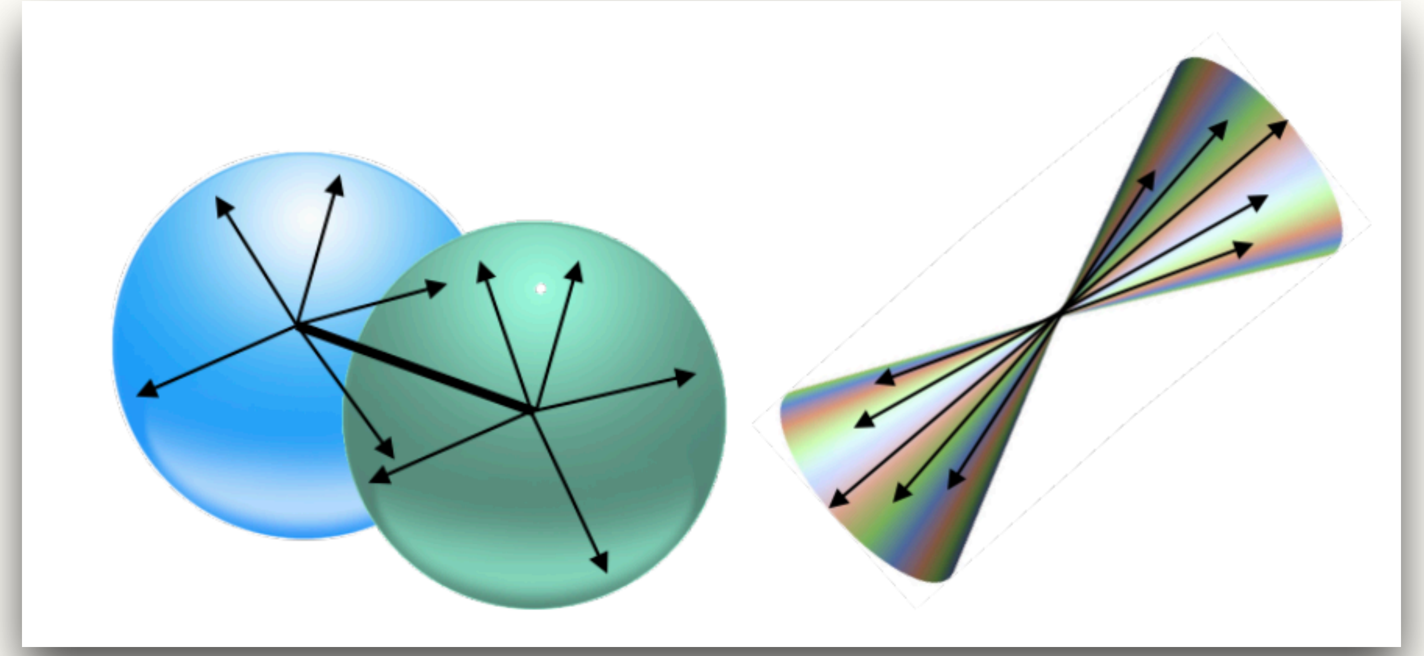
- Event shape variables are fed to the BDT classifier for discrimination.





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

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



Overall better performances in Belle II

- Improvement in the detector.
- Advanced data analysis techniques.

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

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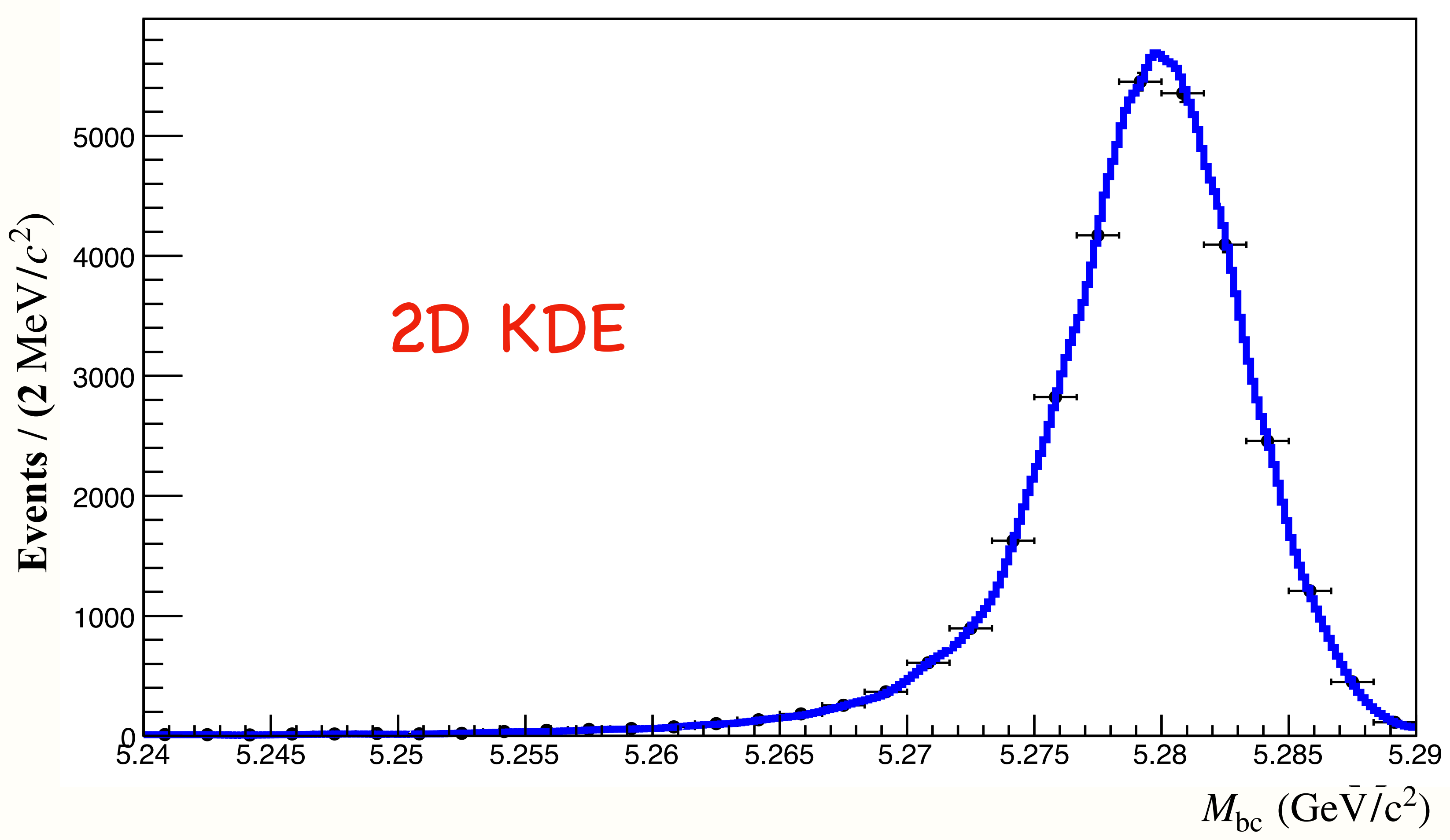
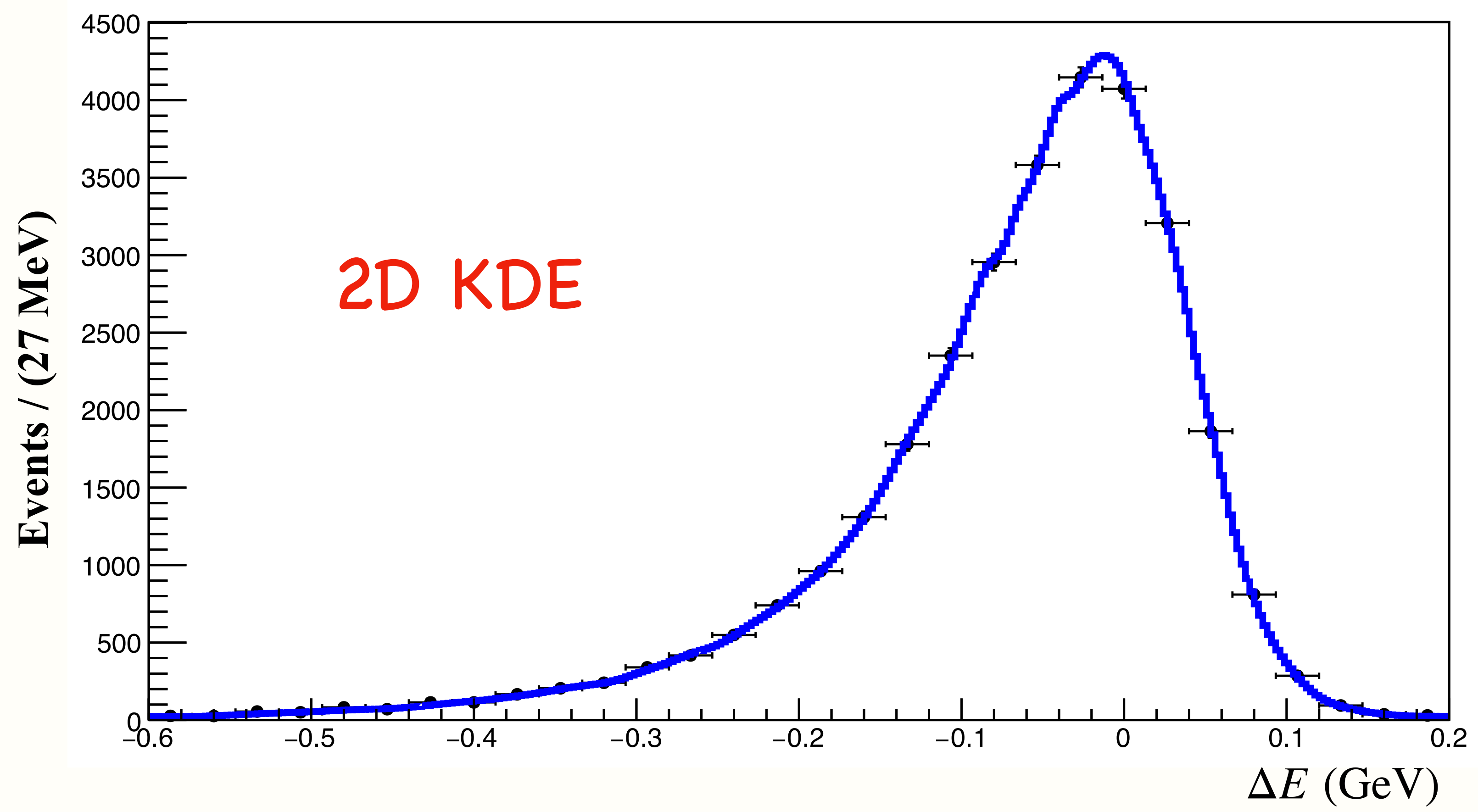
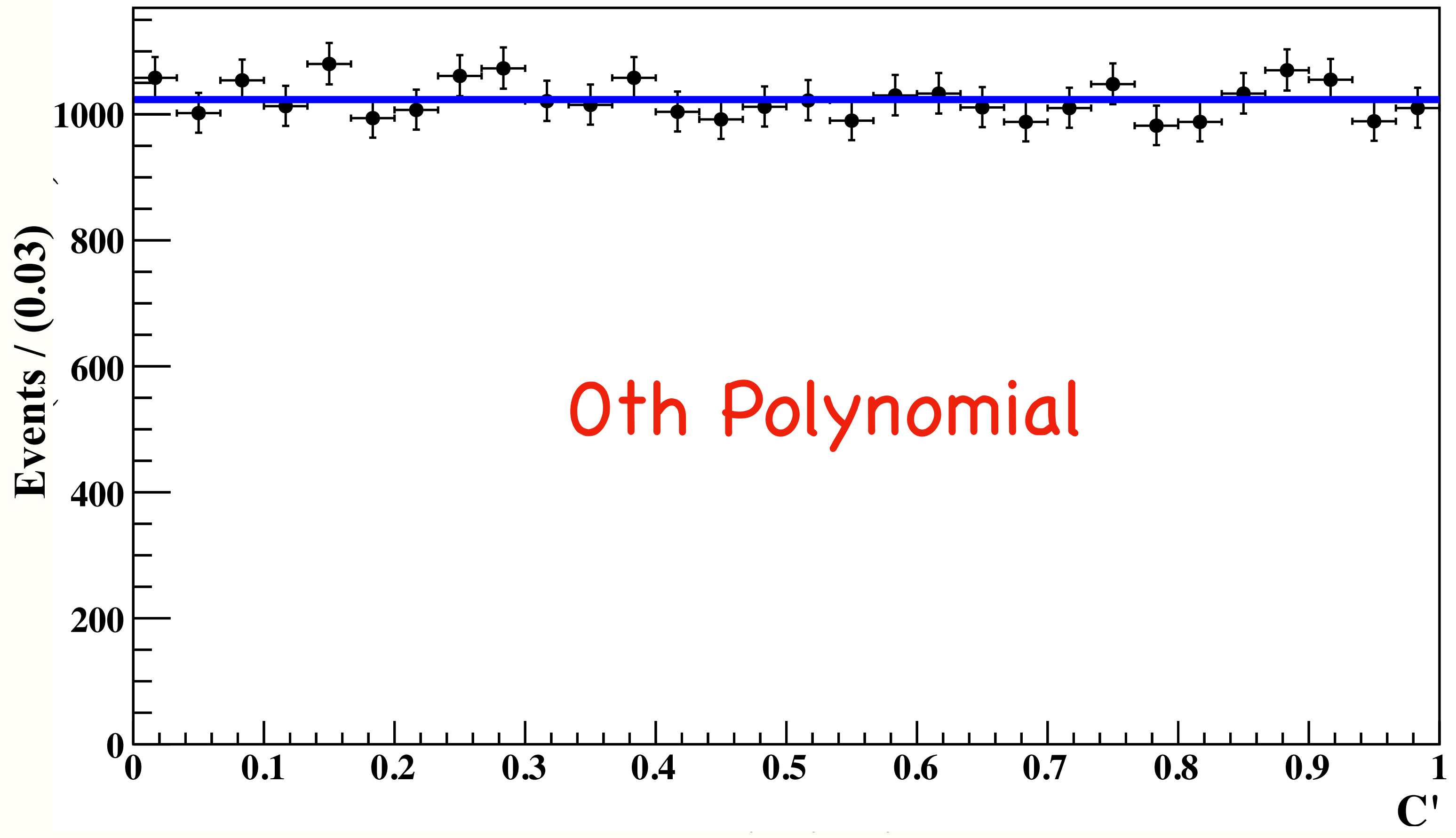
Signal Extraction

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

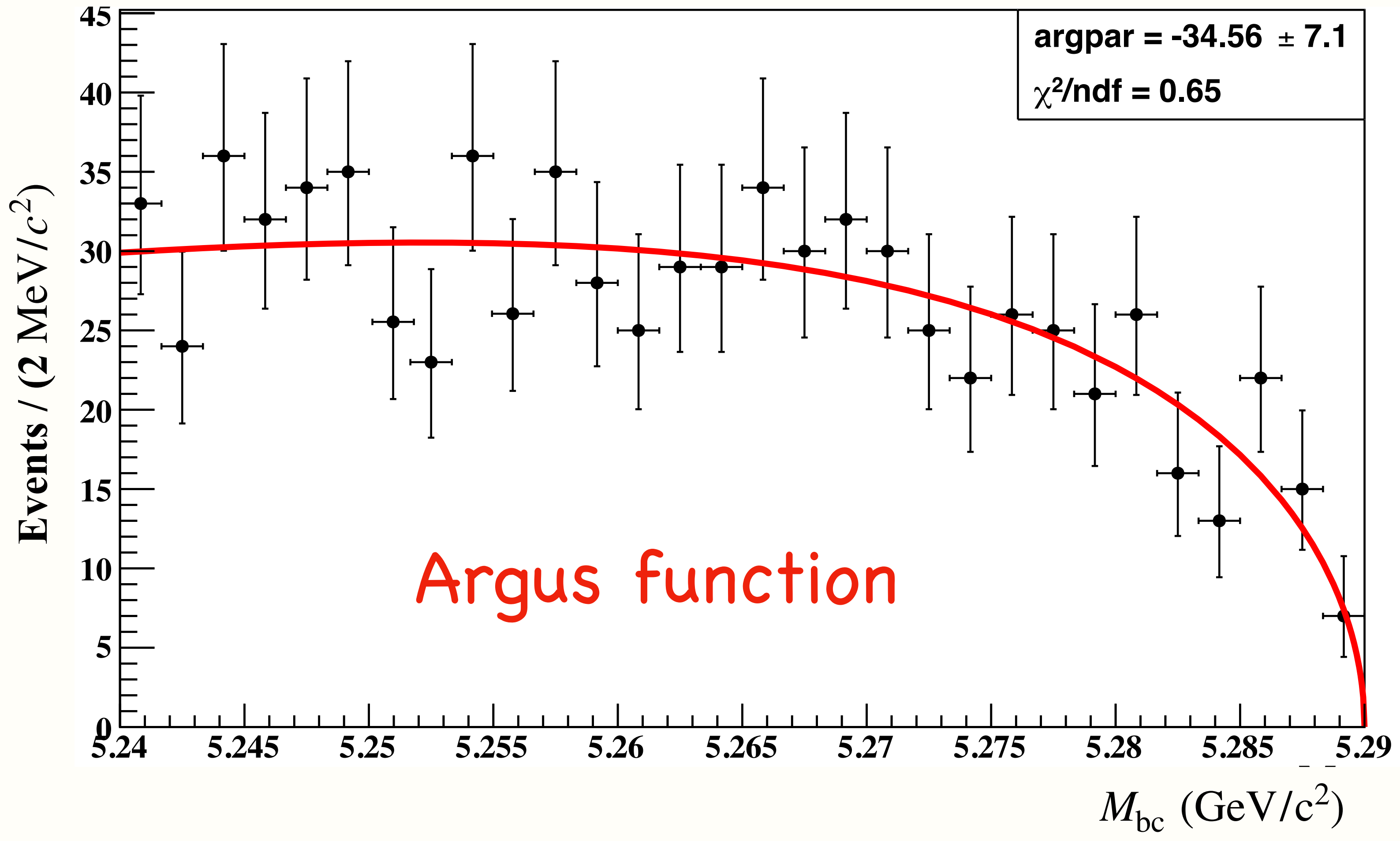
Signal PDFs

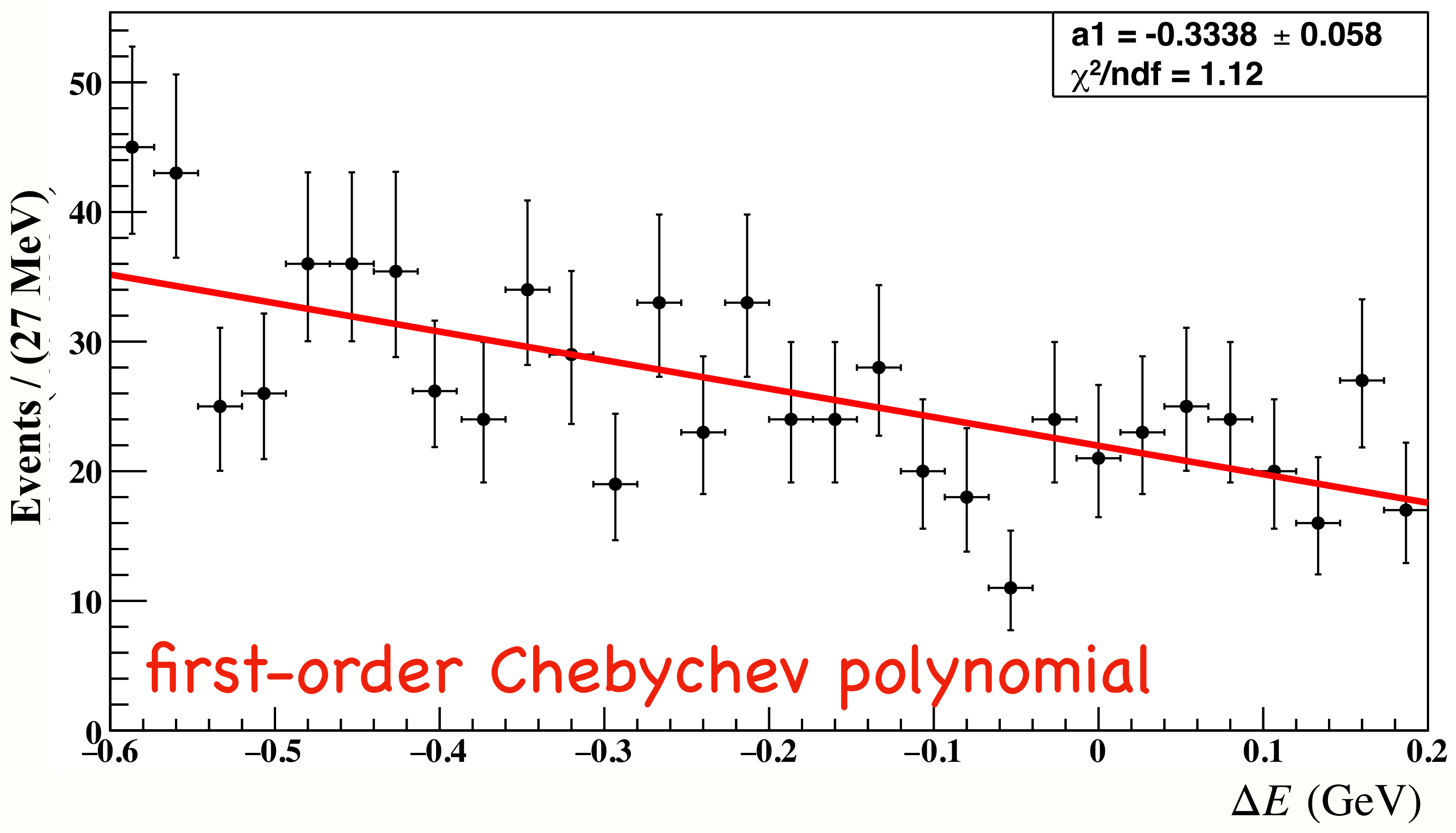


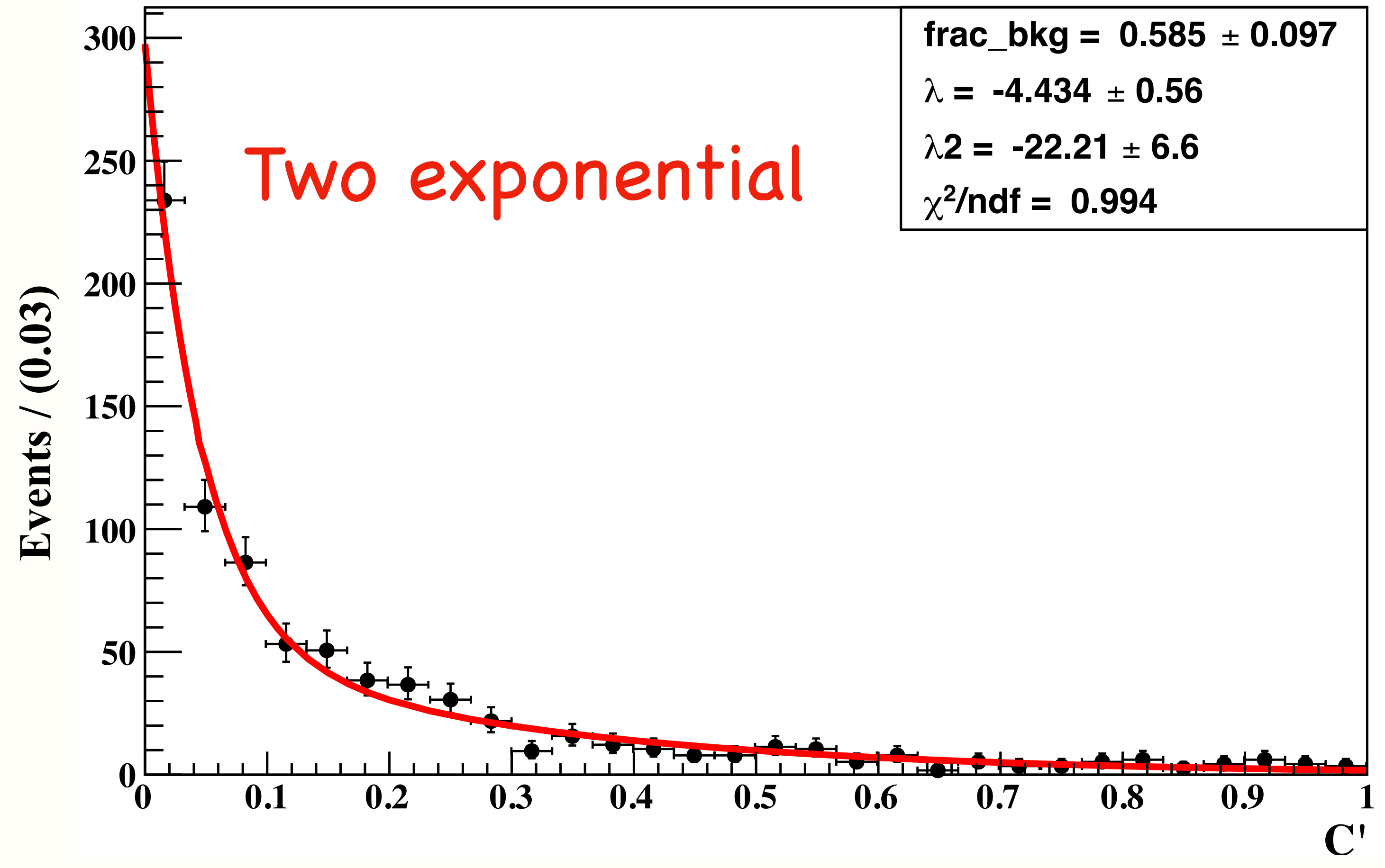




Background PDFs







Belle plots - in backup

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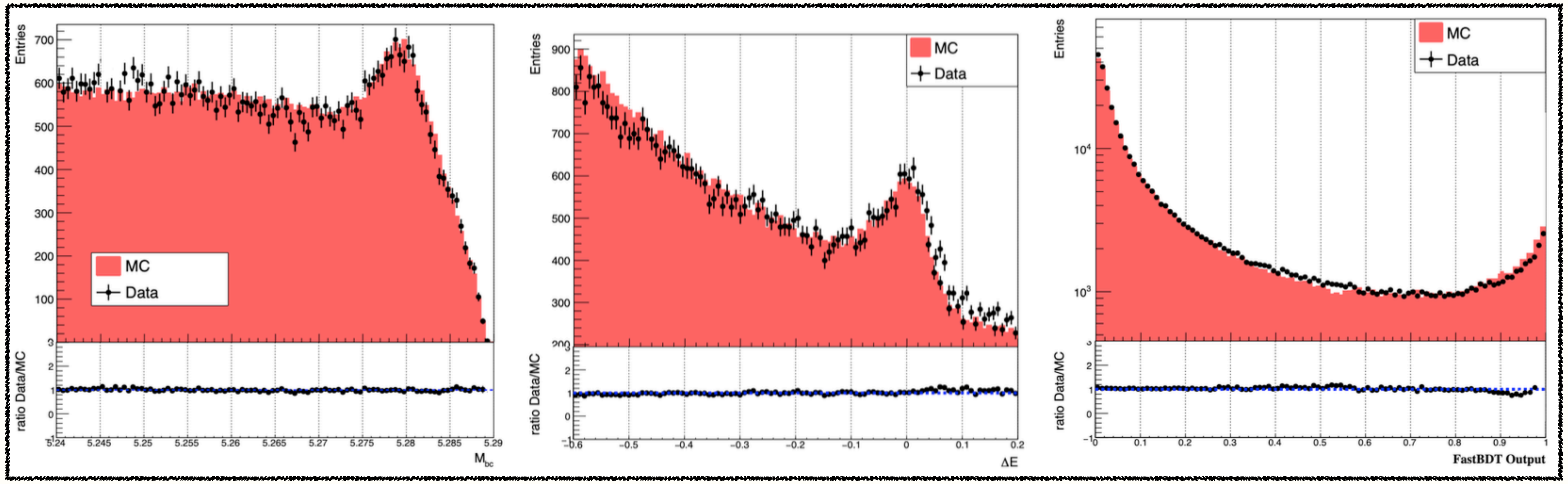
Validation

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

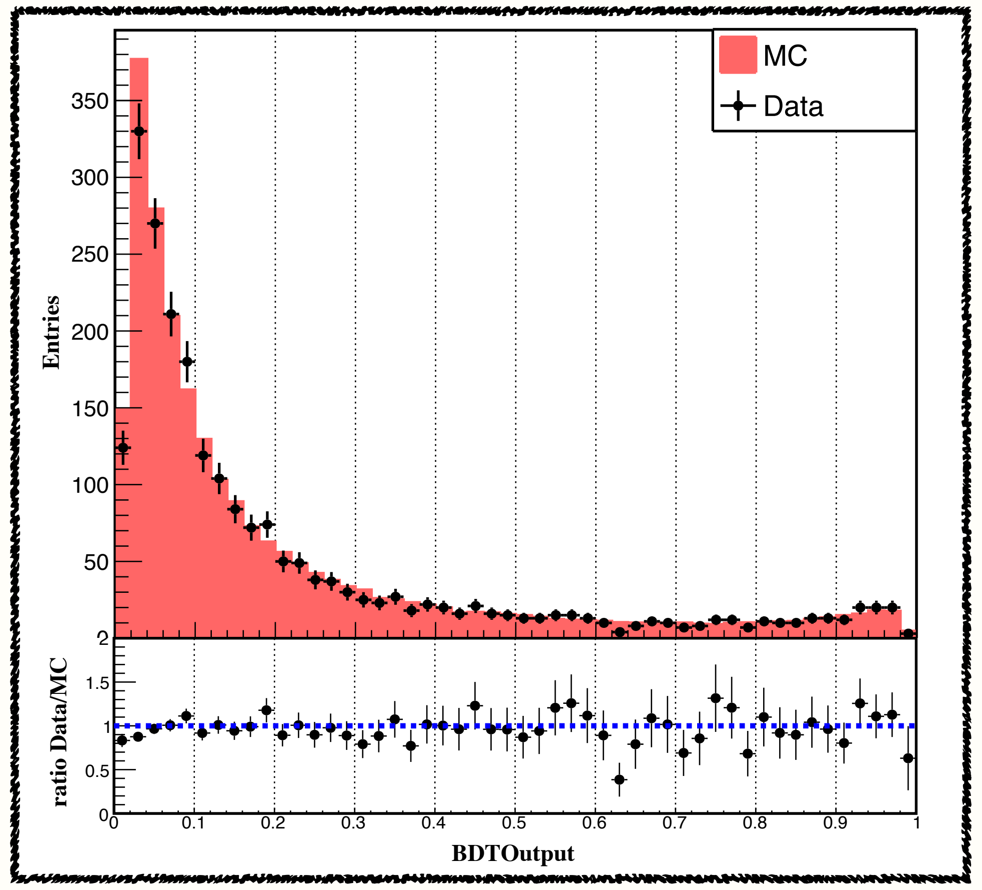


Overall, good Data-MC agreement.

- 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.



- We have performed the ensemble tests to validate the fit procedure and test the bias.
- Assigned systematic uncertainty from the fit bias.

Systematic Uncertainty

Belle II

Uncertainties on Signal Efficiency	Fractional uncertainties (%)
Number of $B\overline{B}$	2.89
Photon Efficiency	2.70
BDT selection	0.90
Reconstruction Efficiency	0.45
π^0/η Veto	0.40
Total	4.10
Uncertainties on Signal Yield	**uncertainties (events)**
PDF shape Parameter	$^{+0.28}_{-0.32}$
Fit Bias	$+0.12$
Signal Shape Modeling	$+0.04$
Total	$^{+0.30}_{-0.32}$

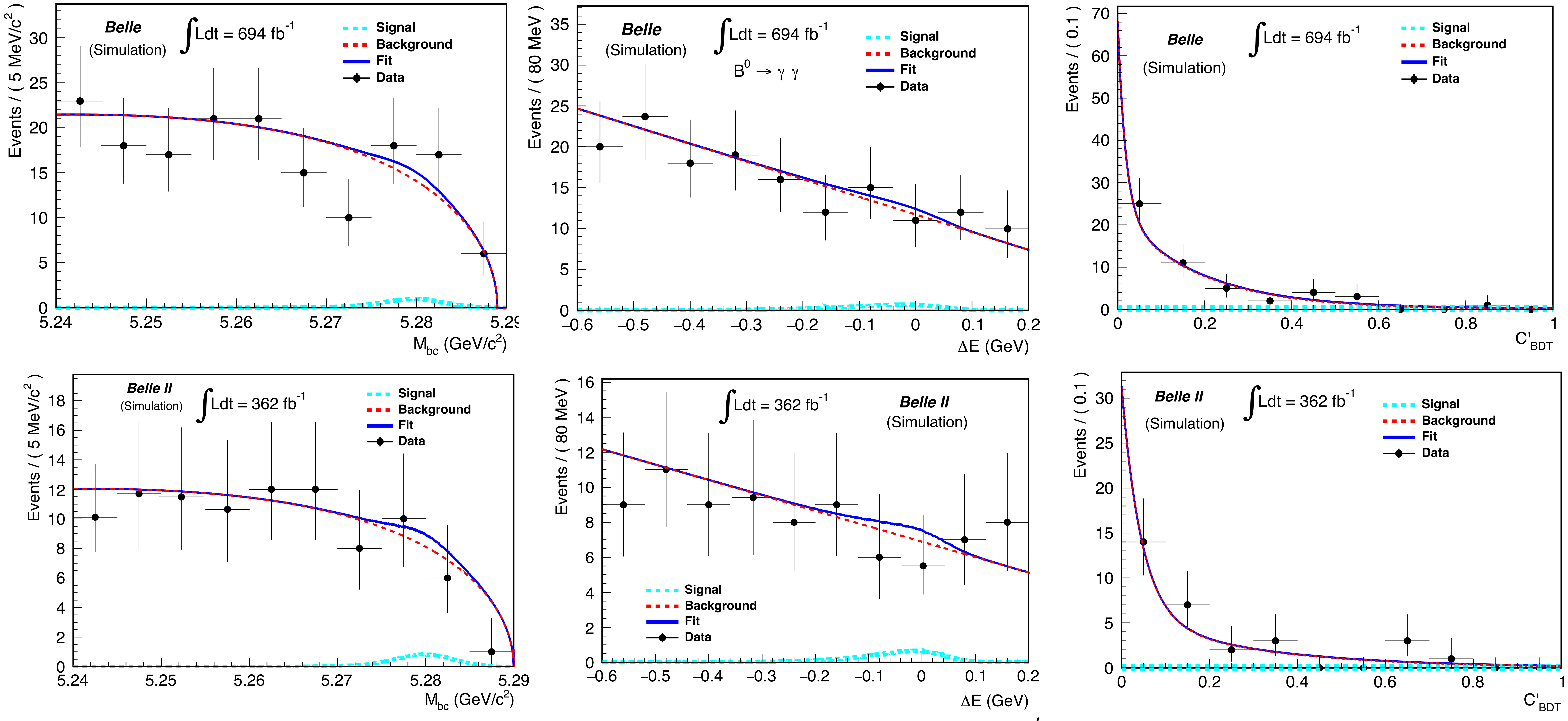
Dominant sources of systematic uncertainty

- Number of $B\overline{B}$ pairs
- Photon Efficiency
- PDF shape parameter

Negligible impact on the limit

Belle - in backup

Combined Result (Belle+Belle II)



Signal Significance

$(\sqrt{-2(\ln \mathscr{L}_0/\mathscr{L}_{max})})$

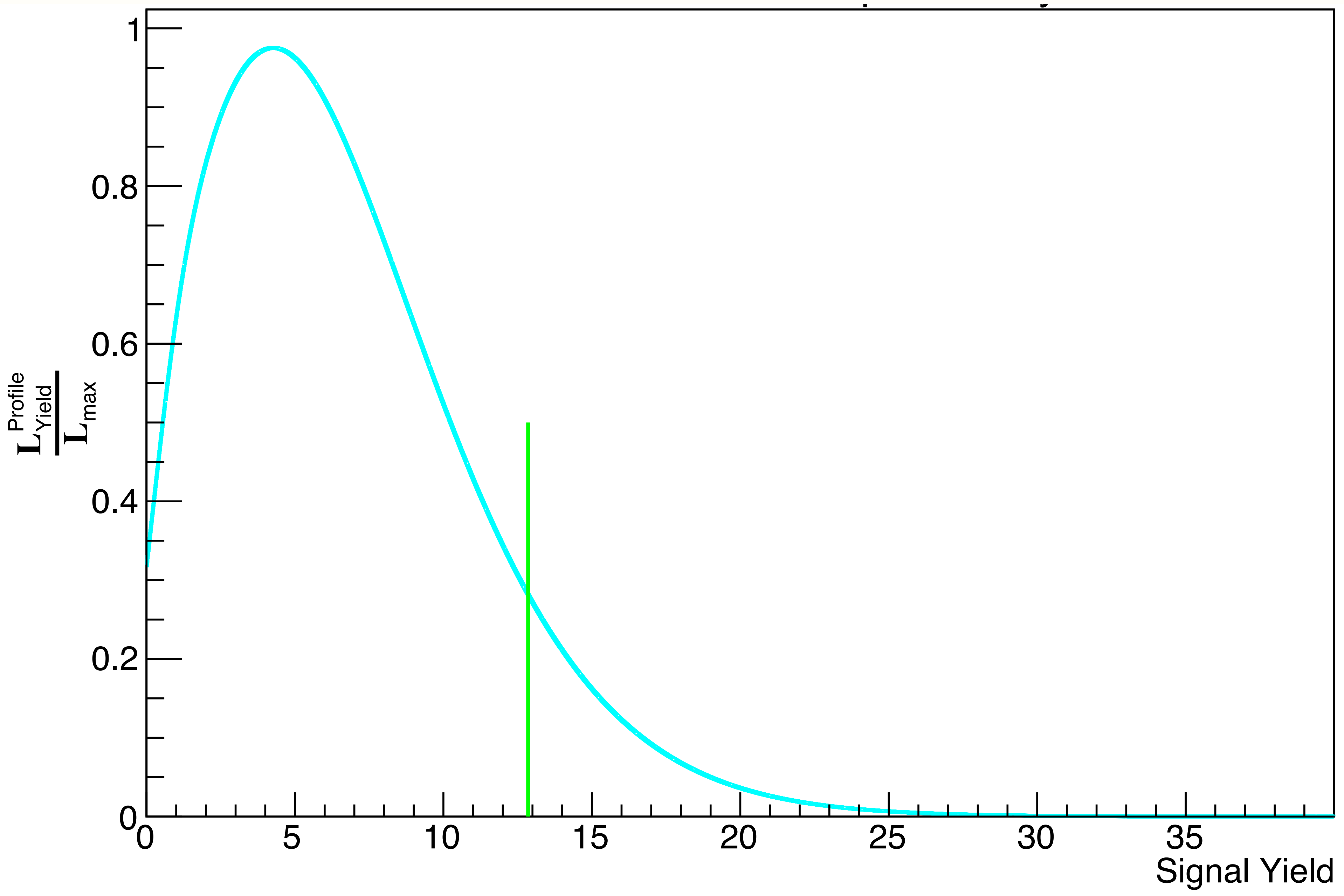
$= \ 1.2\ \sigma$

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

Signal Yield = 4.3 ± 4.2

Combined Results

- Without significant signal yield -> set UL at 90% CL.
- Improvement by a factor of seven over the previous UL set by the Babar experiment with 426 fb-1 ($< 3.2 \times 10^{-7}$ at 90% CL).



Improvements

Increased Statistics (Belle+Belle II)

Improved analysis techniques.

Better Signal Efficiency

Improved Background reduction

$$\mathscr{B}(B^0 \to \gamma\gamma) = (1.4 \pm 1.4(\text{stat}) \pm 0.27(\text{sys})) \times 10^{-8}$$

Upper limit on Branching fraction: $< 4.4 \times 10^{-8}$ **at 90% CL**

(Previous world best $< 3.2 \times 10^{-7}$) [BaBar, PRD.83.032006]

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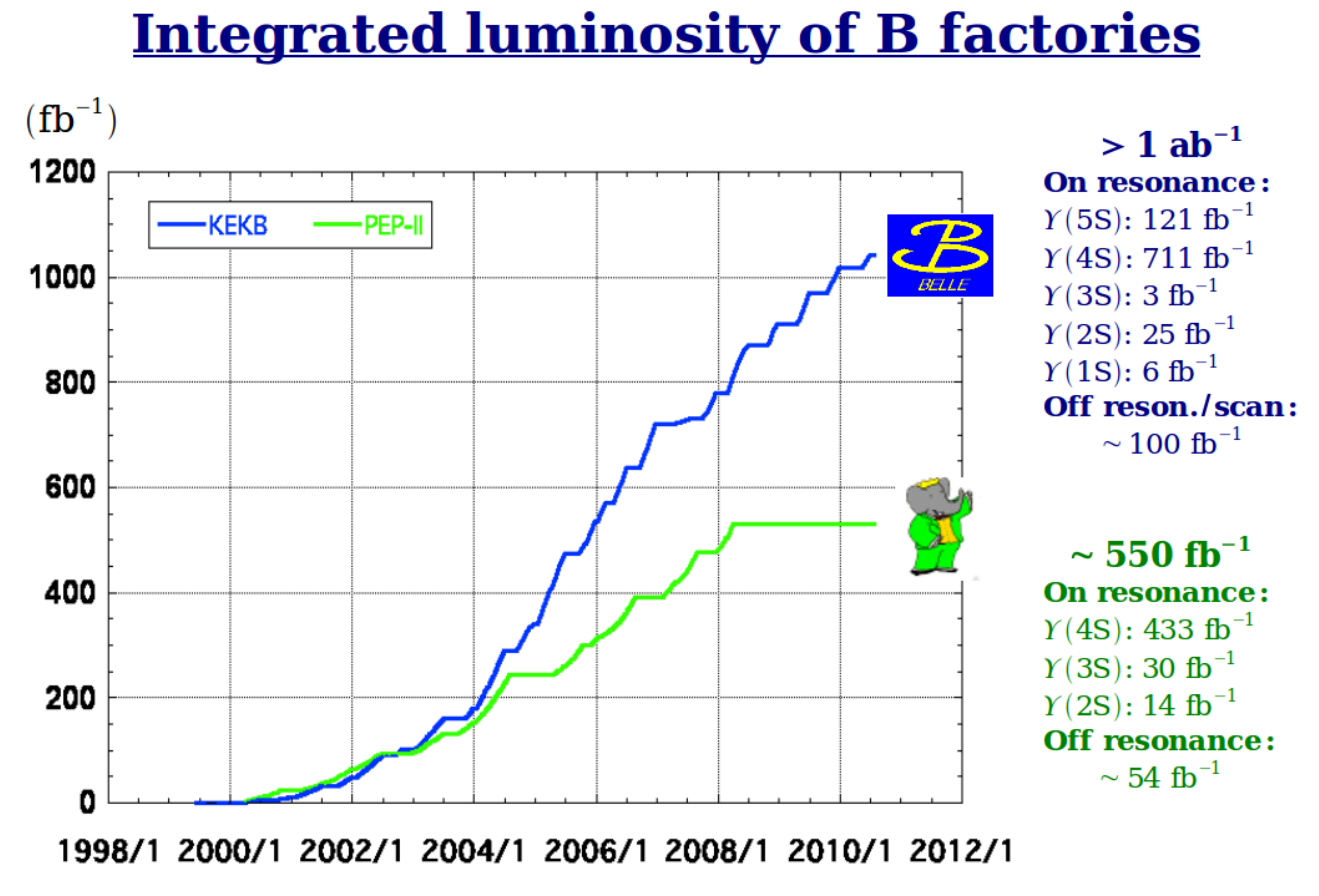
Summary

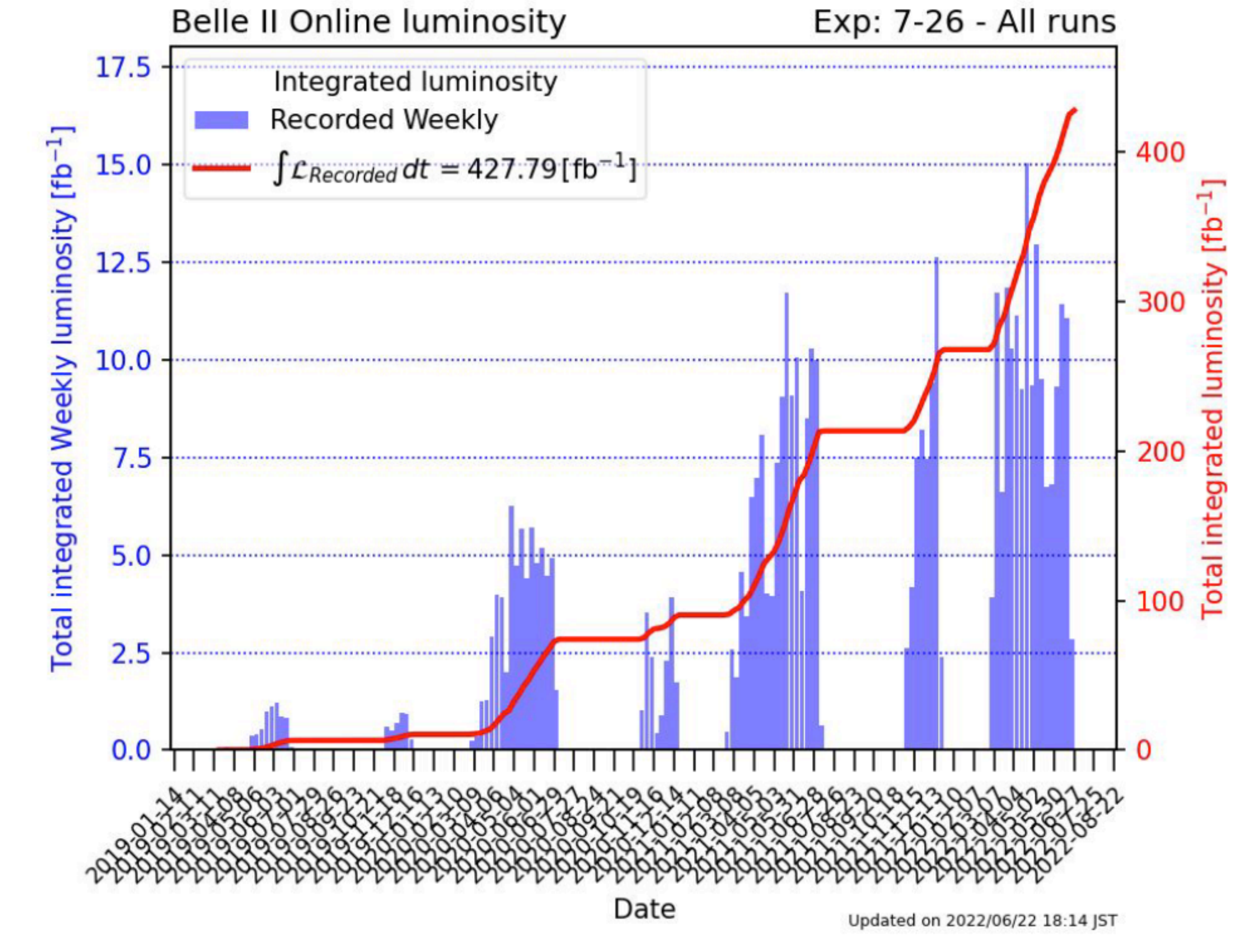
- We performed an analysis of the Belle and Belle II datasets corresponding to an integrated luminosity of 694 fb^{-1} and 362 fb^{-1} collected at $\Upsilon(4S)$ resonance, respectively.
- We observed 4.3 ± 4.2 signal events with the significance of 1.2σ and measured the combined branching fraction to be $(1.4 \pm 1.4(\mathrm{stat}) \pm 0.27(\mathrm{sys})) \times 10^{-8}$ from the MC study.
- Without any significant signal yield, we used the Bayesian approach to estimate the UL on the branching fraction.
- The estimated UL for the combined measurement $< 4.4 \times 10^{-8}$ at $90\,\%$ CL which is an improvement by a factor of seven over the previous UL $< 3.2 \times 10^{-7}$ at $90\,\%$ CL set by BaBar.
- We have unblinded the data, which is currently under collaboration-wide review.

Thank you!

Backup Slides

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. $\Upsilon(4S)$ on-resonance: 362 fb^{-1} ~ 1/2 of Belle sample

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

1D PDF Parameterization for Belle

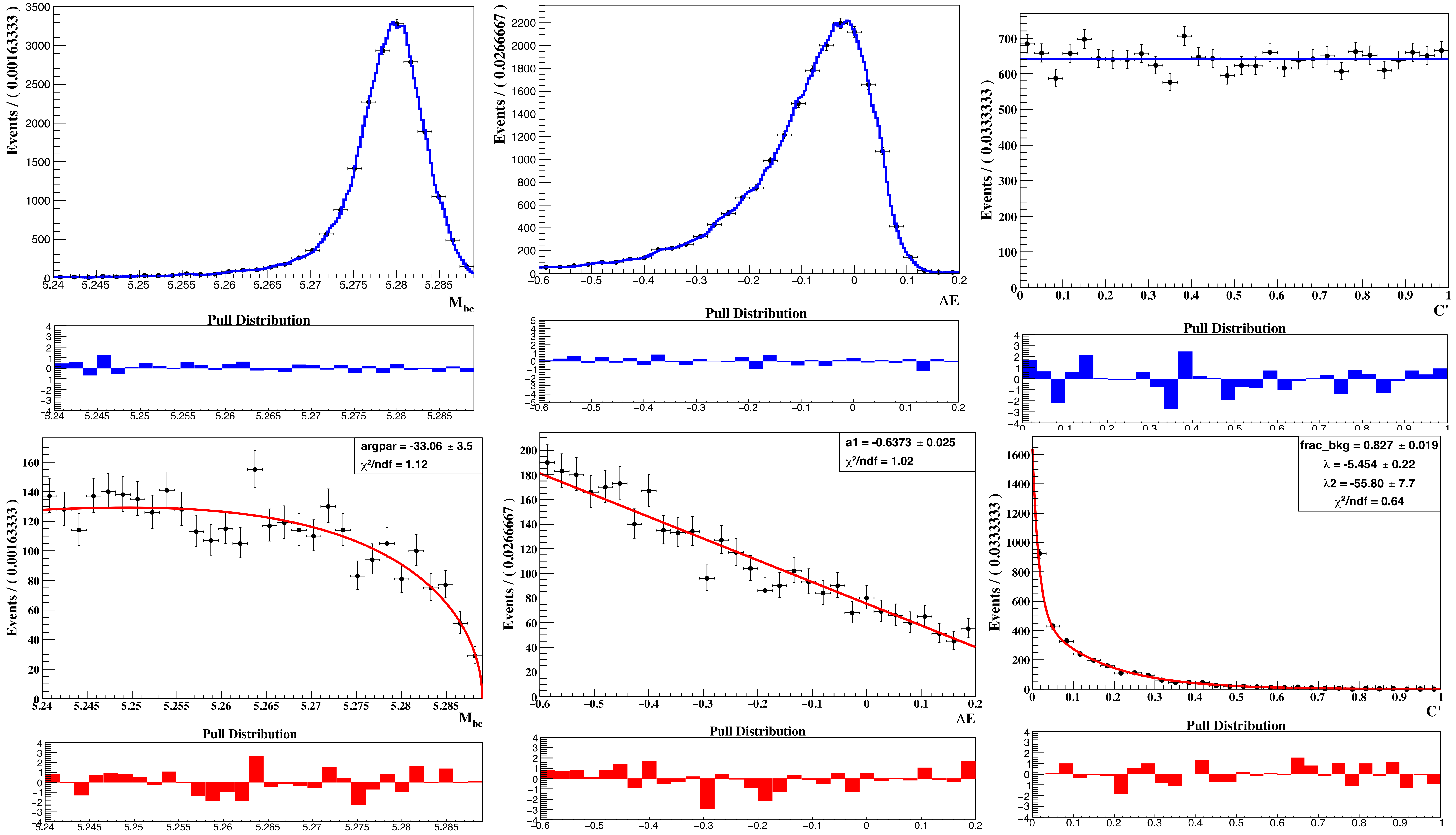


Fig: Pdf shapes of M_{bc}, ΔE, and C′ for signal and background for Belle

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Ensemble Test Results: Belle

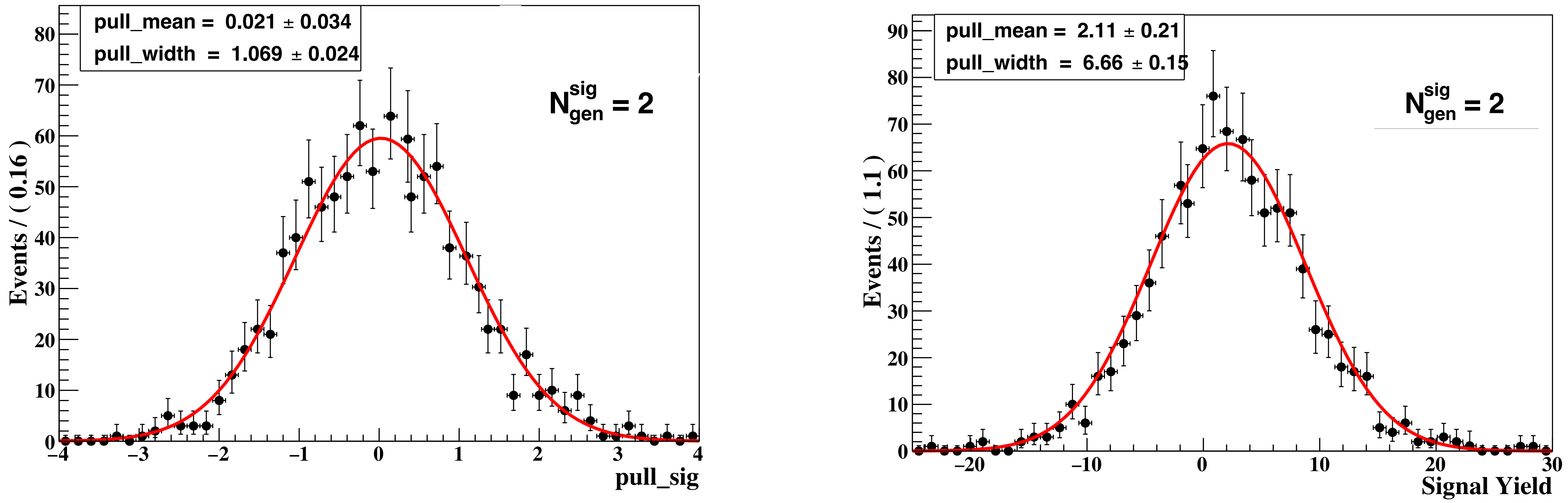

Fig: Pull (left) and signal yield (right) distribution for Belle, respectively

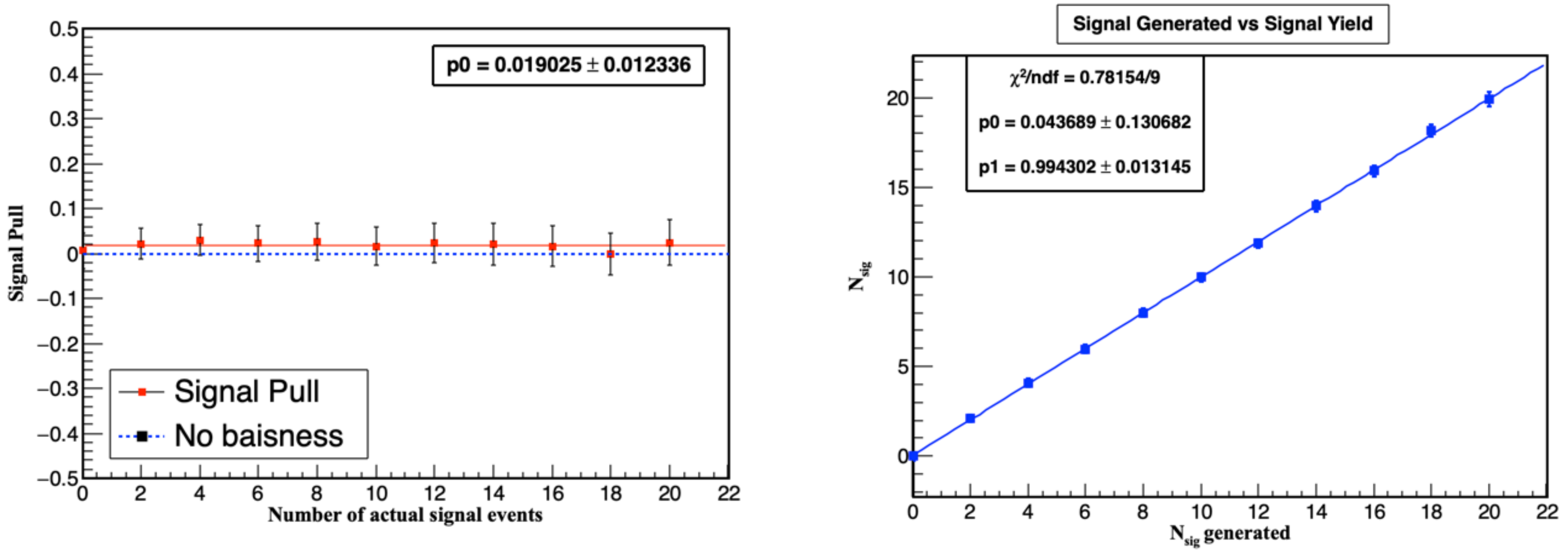

Fig: Pull vs. Nsig (left) and Linearity of the fit model (right) for Belle, respectively

- We generate 1000 such ensembles and calculate the pull for different signal yields.
- Expected signal yields in real data arbitrarily range from 0 to 20, while background events are taken from continuum MC events normalized with data luminosity.

- 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.

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.

Systematic Uncertainty

Belle

Uncertainties on Signal Efficiency	Fractional uncertainties (%)
Photon Efficiency	4.00
No. of $B\overline{B}$ pairs	2.81
Timing requirement	2.80
Reconstruction Efficiency	0.57
BDT selection	0.40
π^0/η Veto	0.30
Total	5.68
Uncertainties on Signal Yield	**uncertainties (events)**
PDF shape Parameter	$^{+0.56}_{-0.48}$
Fit Bias	$+0.16$
Signal Shape Modeling	$+0.06$
Total	$^{+0.58}_{-0.48}$

Dominant sources of systematic uncertainty

- Number of $B\overline{B}$ pairs
- Photon Efficiency
- Timing requirement
- PDF shape parameter

Negligible impact on the limit

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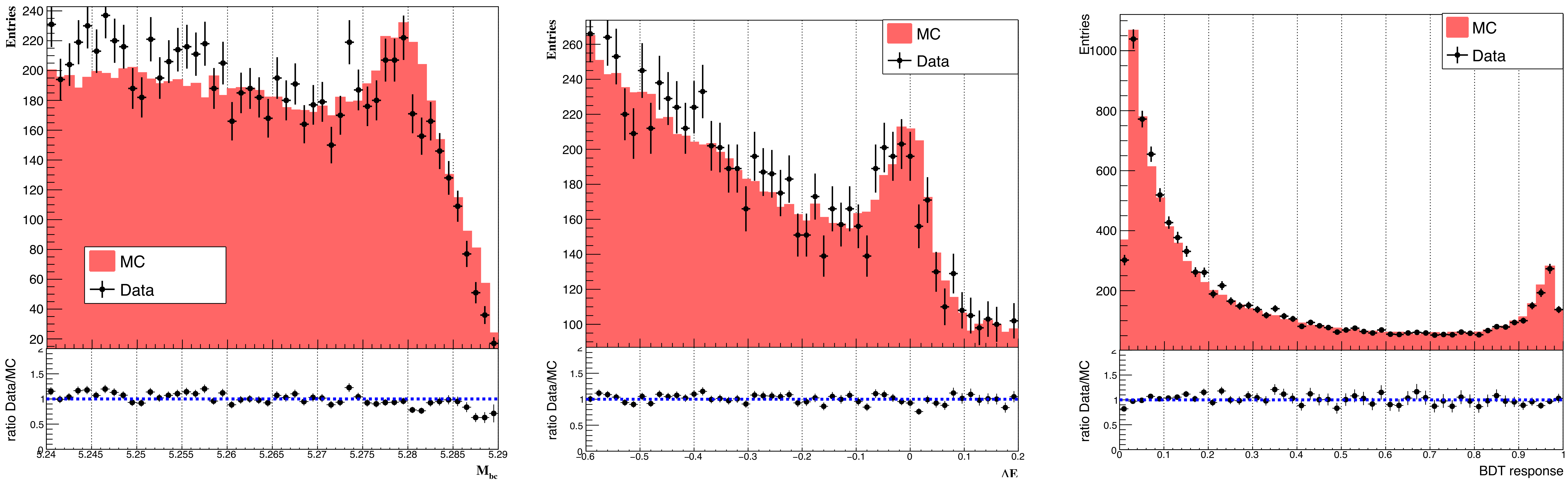
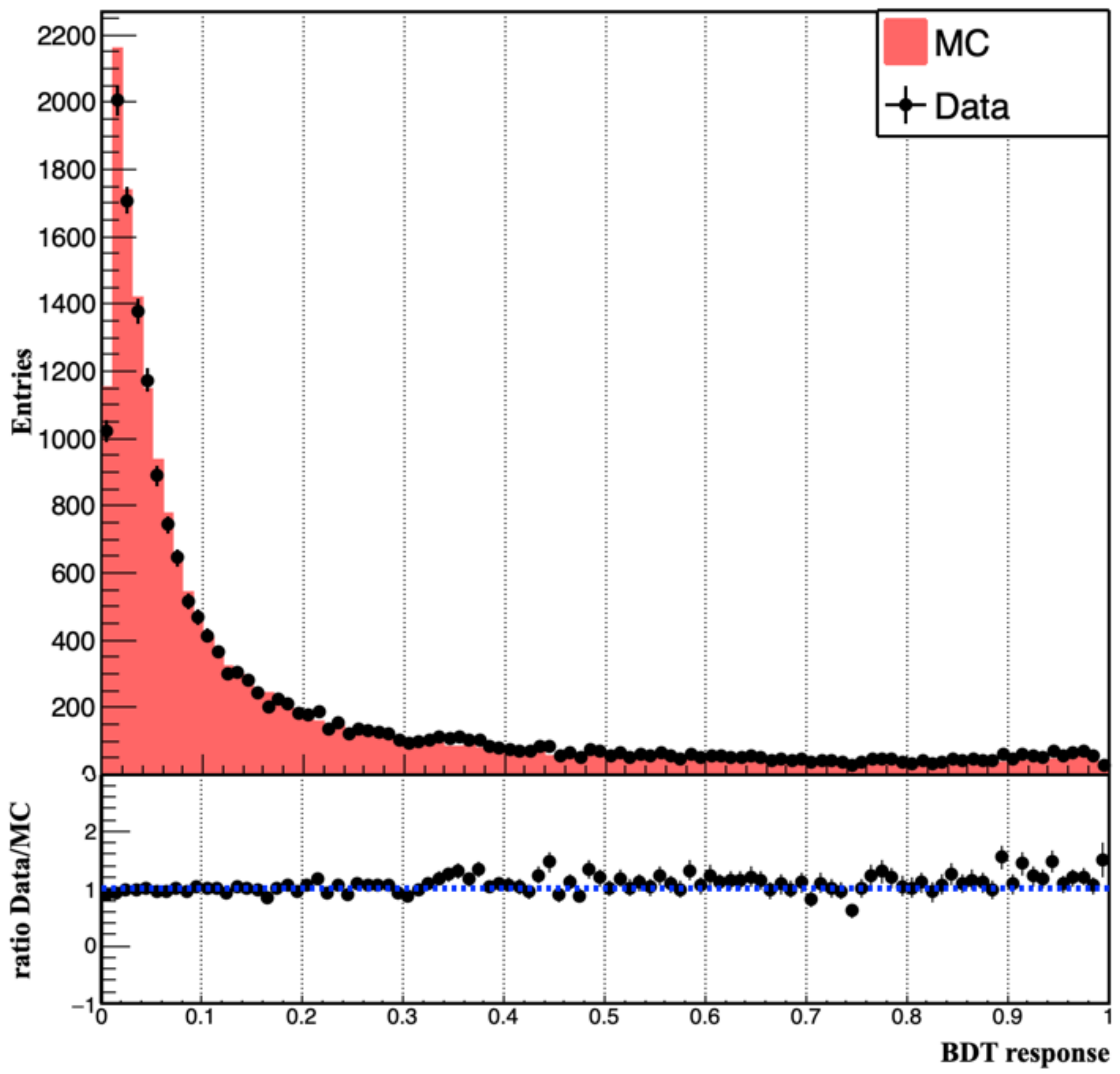
DATA-MC comparison of Belle II for $B^0 \to K^*\gamma$

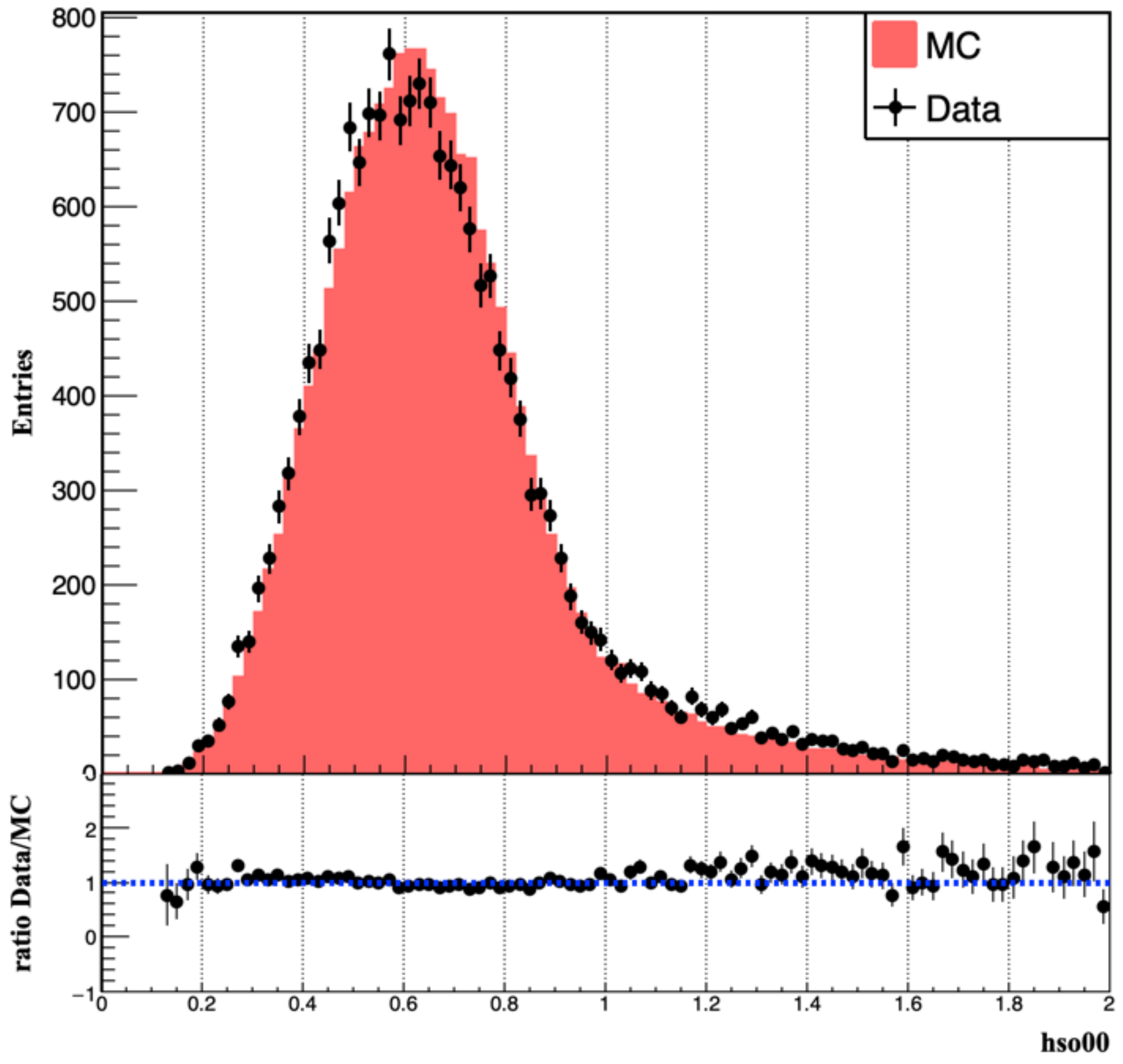


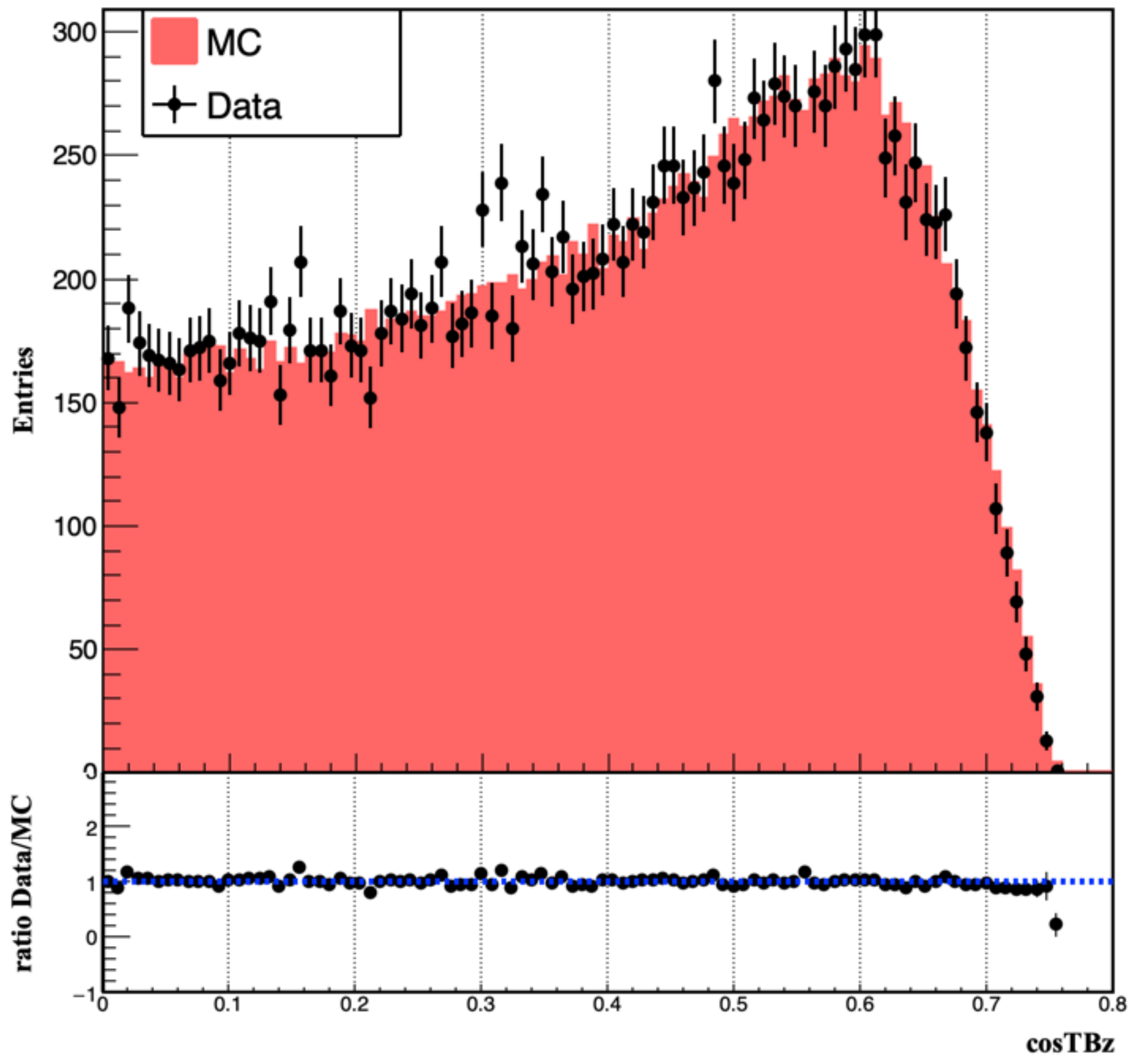
M_{bc} , ΔE and FastBDT output distributions comparing Belle II data and MC

- Overall, good Data-MC agreement.

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

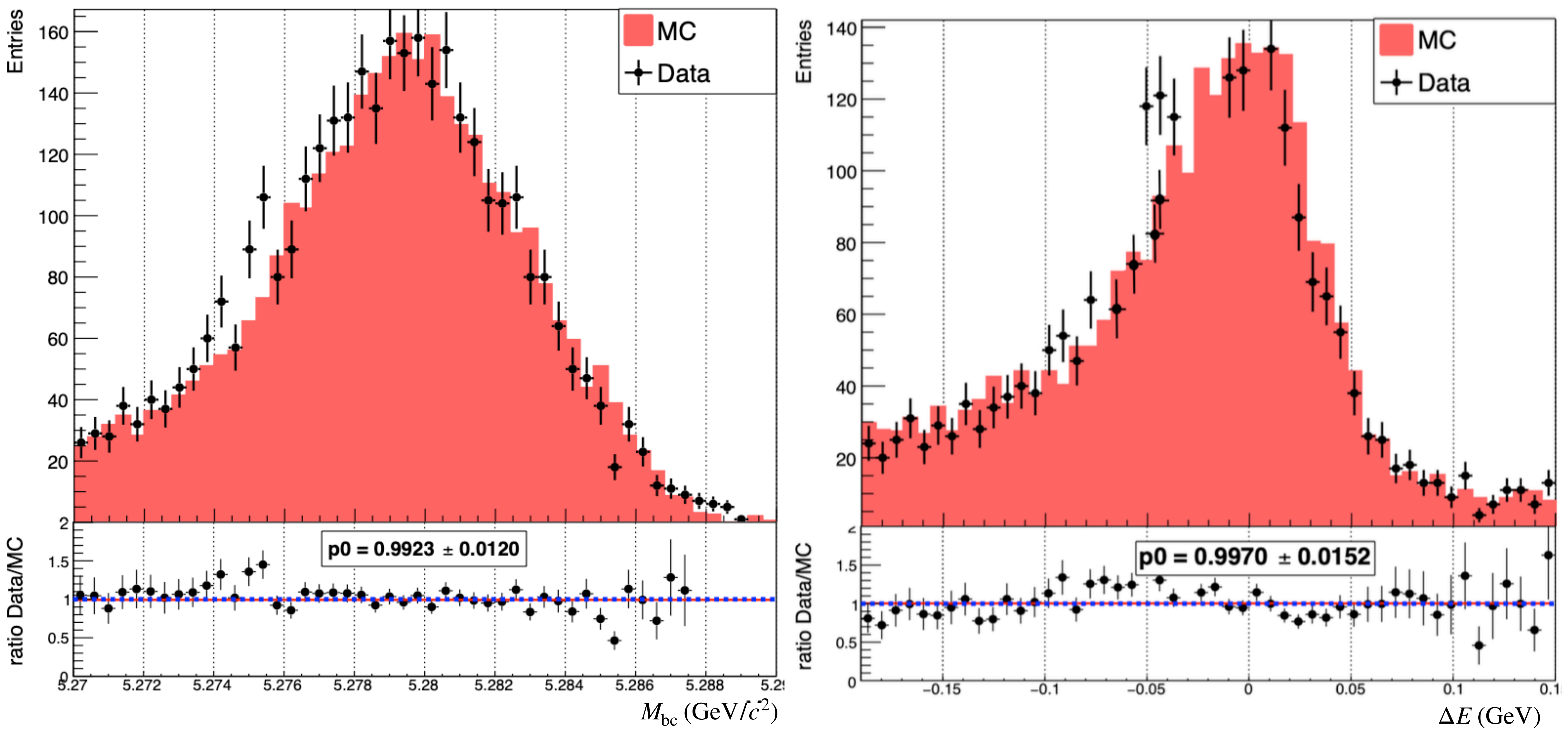




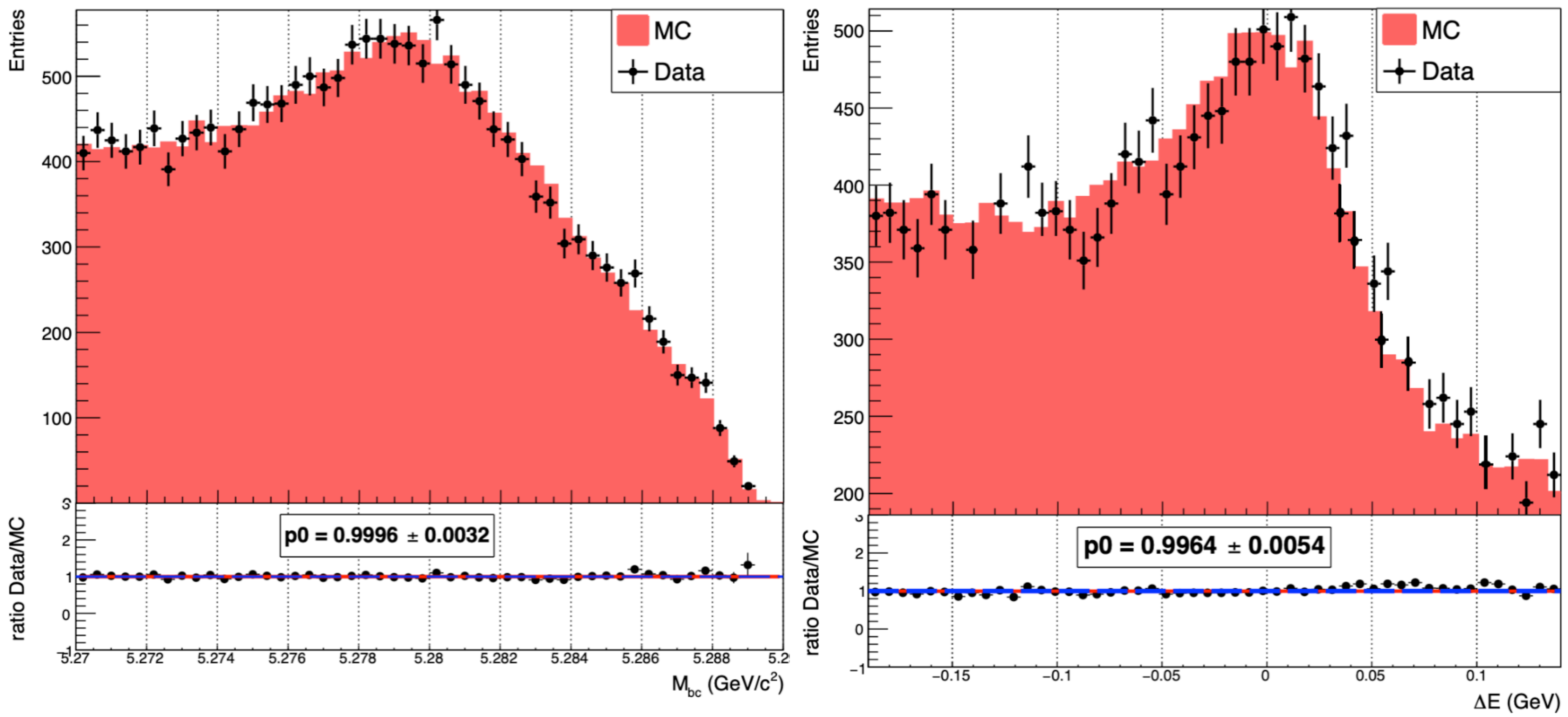


- We do not observe any serious differences in Data -MC comparison.

Uncertainty due to shape discrepancy



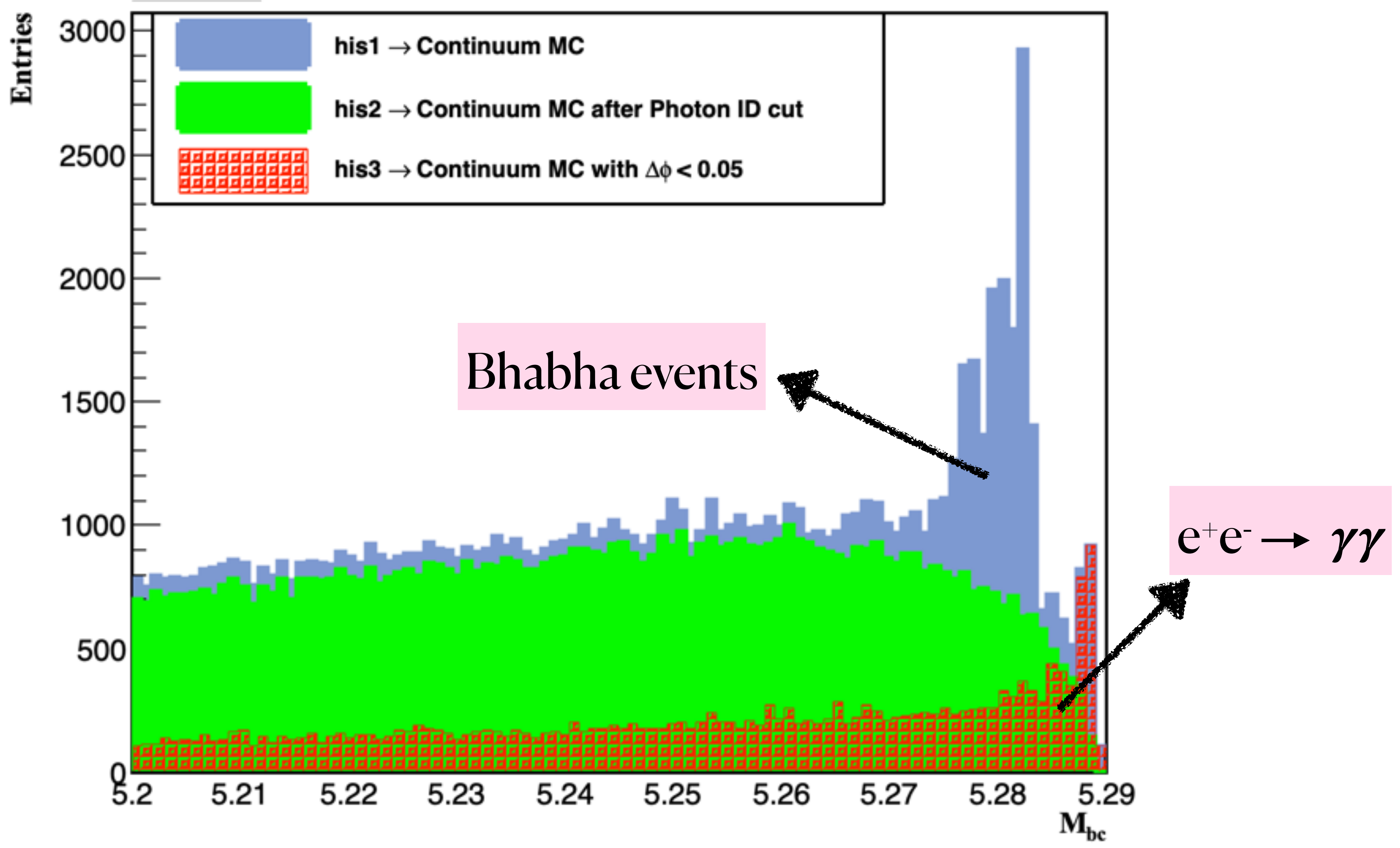
Data-MC comparison for M_{bc} and ΔE for Belle II



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).

Timing requirement : Belle Study



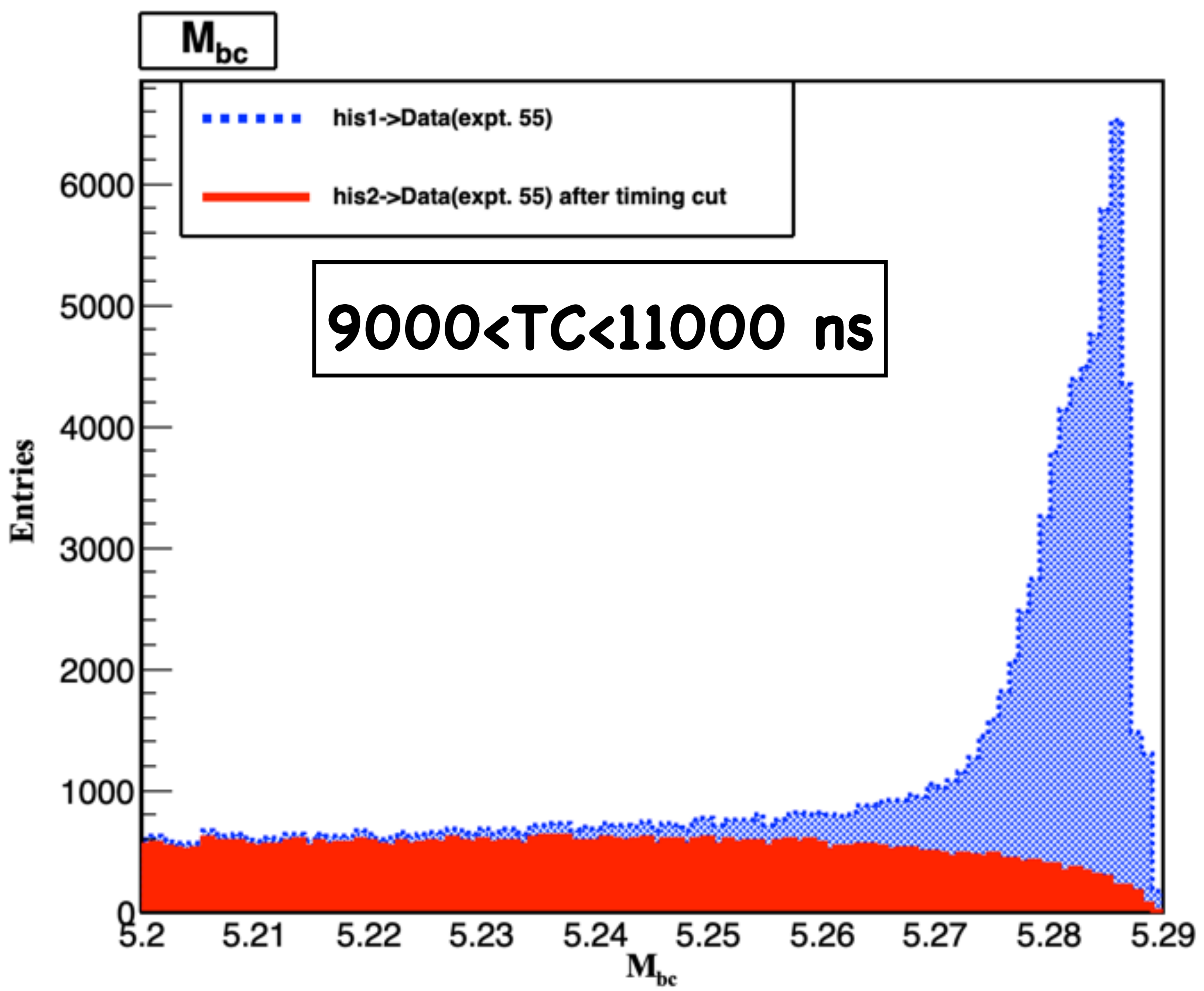


Figure 1: M_{bc} distribution for the preselected data.
The hatched histogram shows the off-time events, which correspond to $e^+e^- \rightarrow \gamma\gamma$ events.

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.