Belle II

AUSTRALIAN INSTITUTE OF PHYSICS (AIP) CONGRESS
co-locating with the 7th International Workshop on Specialty Optical Fibers and Their Applications (WSOF) and the Australian New Zealand Conference on Optics and Photonics (ANZCOP)

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Adelaide Convention Centre

PHYSICS: Launching our future

THE UNIVERSITY OF MELBOURNE

AIP Adelaide 2022: Measurement of $B^0 \rightarrow \pi^0\pi^0$ branching fraction and A_{CP} at Belle II

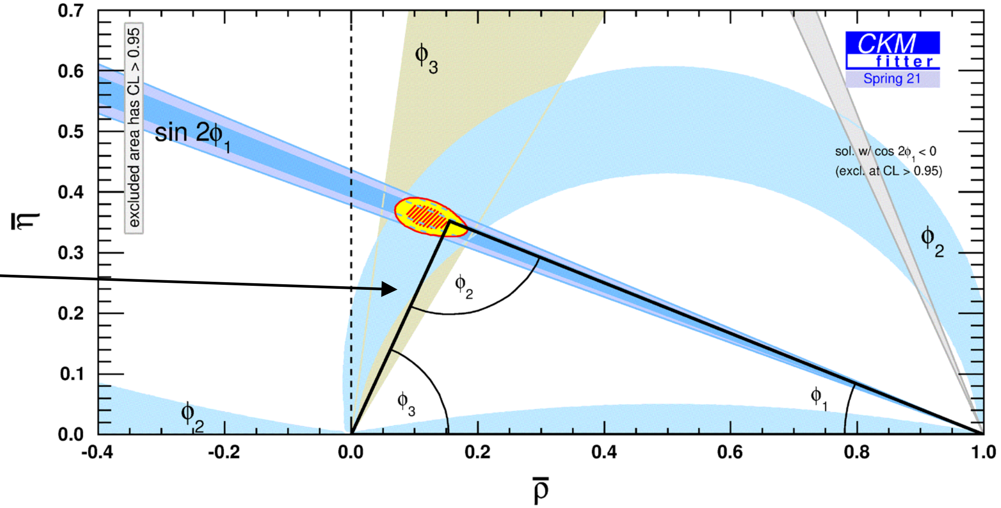
Francis Pham and Martin Sevior

University of Melbourne

Motivation: CP violation

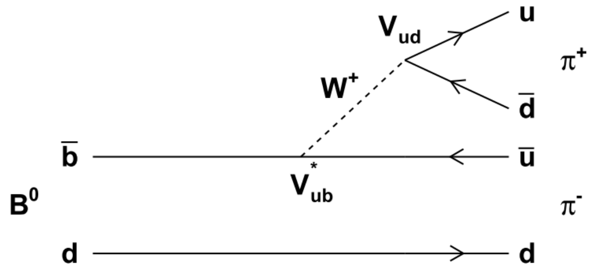
- Charge (*C*) and Parity (*P)* distinguishes matter from antimatter
- *CP*-violation can be represented by ‘the Unitarity Triangle’ (UT)
- UT observables point to a single apex with a precision of O(10)%
  - ➢Over-constraining the UT probes for New Physics
  - ➢CKM angles ϕ_2 is significantly less well measured than CKM angles ϕ_2 and ϕ_3.

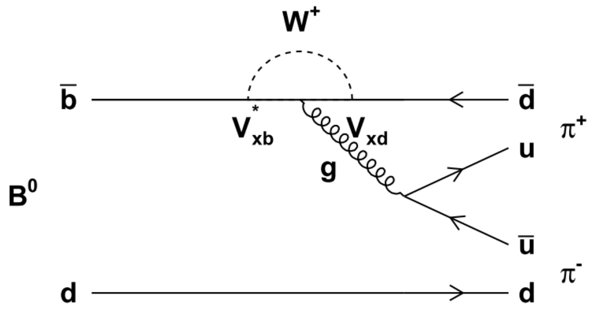
ϕ_2 can only be measured in B decays not involving charm quarks (charmless)!

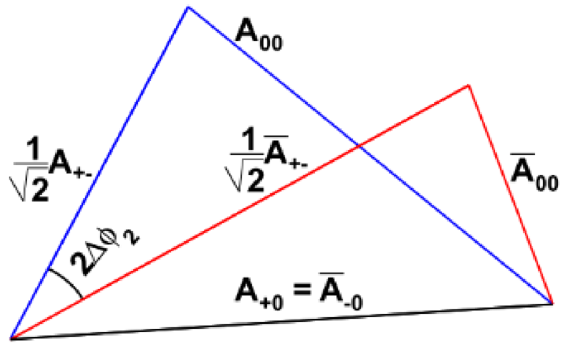


Motivation: ϕ_2

- If $B^0 \to \pi^+\pi^-$ had only 'tree-level' contributions ϕ_2 could be directly measured but the measurement is shifted by $\Delta\phi_2$ due to 'penguin' contributions.
- Contributions can be disentangled using $B \to \pi\pi$ isospin relations which require their branching fraction (BF) and *CP*-asymmetry parameters
- Current uncertainties on the $B^0 \to \pi^0\pi^0$ BF and direct *CP*-asymmetry, $A_{CP} = \frac{N(B\to\bar{f})-N(B\to f)}{N(B\to\bar{f})+N(B\to f)}$, are 3-4 times larger than $\pi^+\pi^-$ and currently poses the greatest limitation to fully exploiting the isospin relations.







Motivation: Branching fraction

- Predictions of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ from perturbative QCD and QCD factorization are significantly lower than the measured value

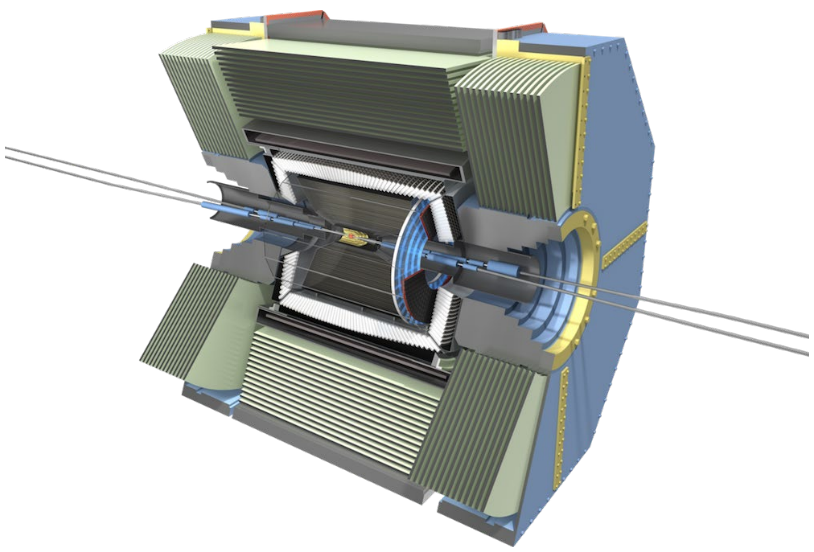
Channel	Leading Order (LO)	Next to LO	Next to LO	QCDF	Measured
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	0.12×10^{-6}	0.29×10^{-6}	0.23×10^{-6}	0.3×10^{-6}	$1.59 \pm 0.26 \times 10^{-6}$

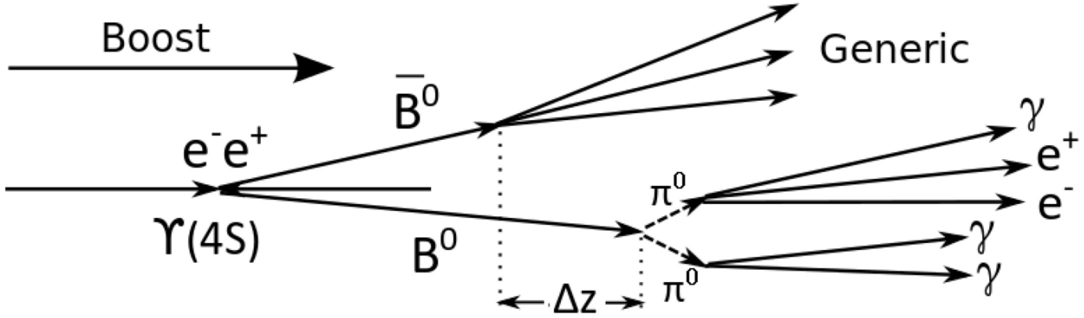
- Various approaches, which predict a wide range of values for $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $A_{CP}(B^0 \to \pi^0\pi^0)$ have been proposed as possible solutions to this disagreement
- Most approaches can explain the BF measured by Belle but not BaBar
- Only Belle II can study the $\mathcal{B}(B^0 \to \pi^0\pi^0)$

	Belle	BaBar	PDG value
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	$1.31 \pm 0.19 \pm 0.19$	$1.83 \pm 0.21 \pm 0.13$	1.59 ± 0.26
$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$	$0.14 \pm 0.36 \pm 0.10$	$0.43 \pm 0.26 \pm 0.05$	0.33 ± 0.22

Belle II

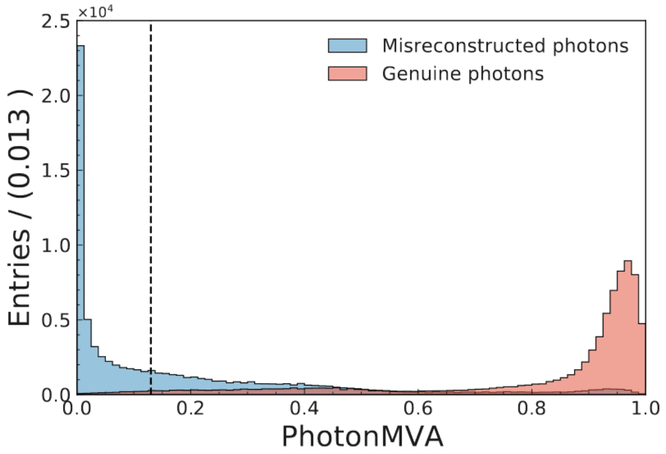
- Belle II is the successor to the Belle experiment that ran from 1999 to 2010 and is located in Tsubuka, Japan
- **Belle II Detector:** general purpose detector situated at the interaction point of SuperKEKB
- **SuperKEKB:** asymmetric e^+e^- collider operating at $\Upsilon(4S)$ resonance to produce $B\bar{B}$ pairs

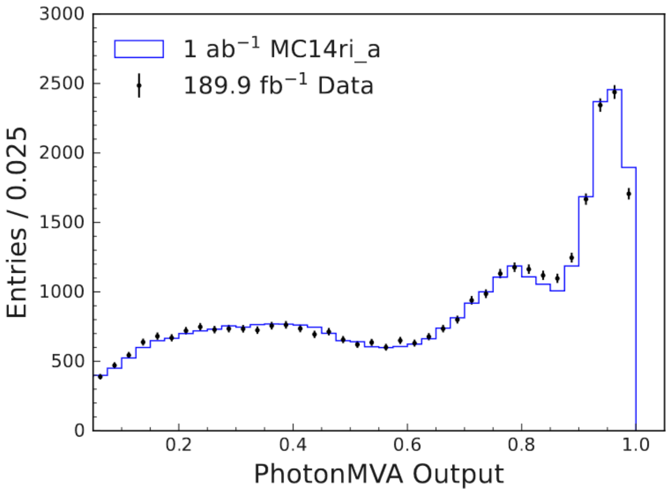




Suppressing misreconstructed photons

- **Challenge**: The π^0 decays ≈99% of the time into two photons
  - ➢Final state consist of only four photon
  - ➢Must exclude misreconstructed photons such as from residual energy in the electromagnetic calorimeter (ECL)
  - ➢Beam background scales with luminosity
- **Solution**: Train a boosted decision tree (PhotonMVA) to distinguish between genuine and misreconstructed photons
  - ➢Signal purity increases from 98.0% to 98.6% with a 5.5% decrease in yield
  - ➢Reduces the number of background by approximately 15%





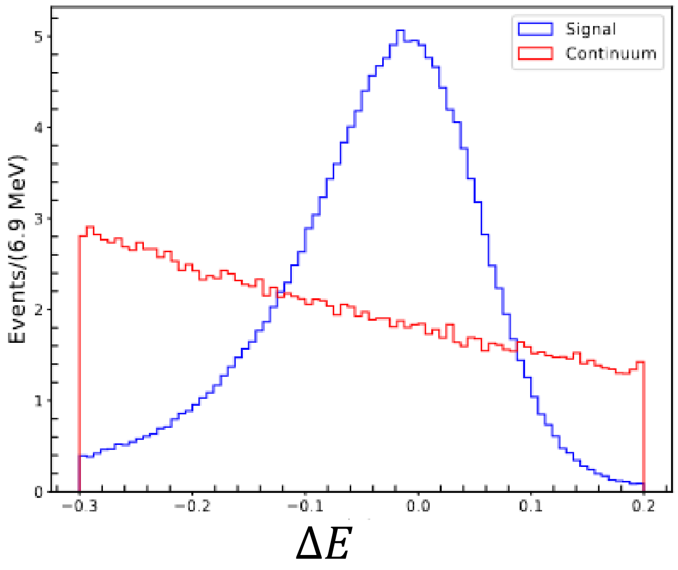
$D^{*+} \to D^0(\to K_s(\to \pi^+\pi^-)\pi^0)\pi^+$

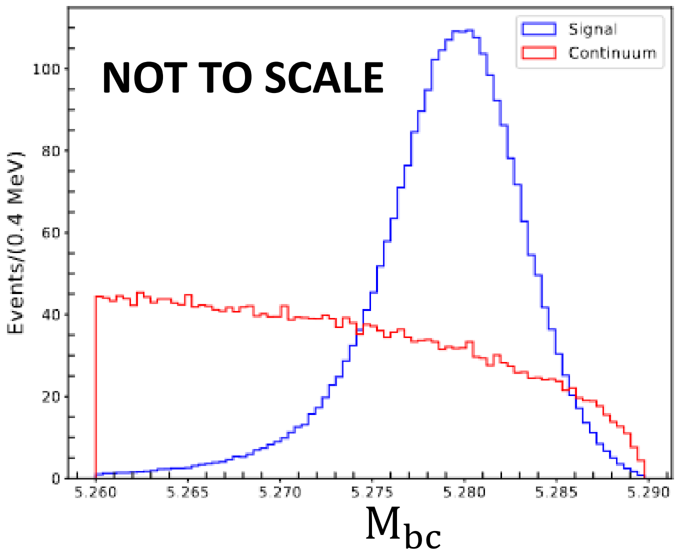
Signal selection

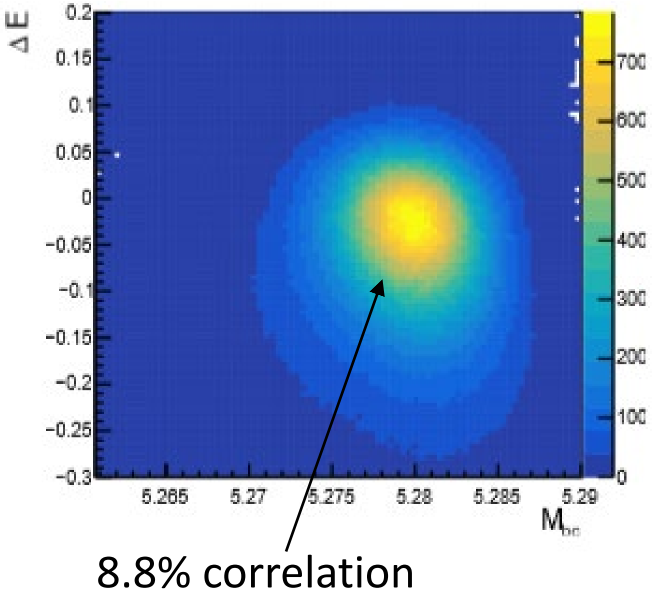
Reconstruct the signal and define two variables

$$\Delta E = E_B - E_{beam} \quad \textbf{and} \quad M_{\mathrm{bc}} = \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$$

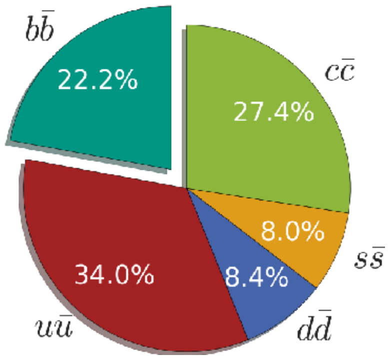
where E_{beam} is the beam energy and $(E_B, \vec{p}_B)$ is the reconstructed four momentum of the B candidate in frame of the Υ(4S) resonance





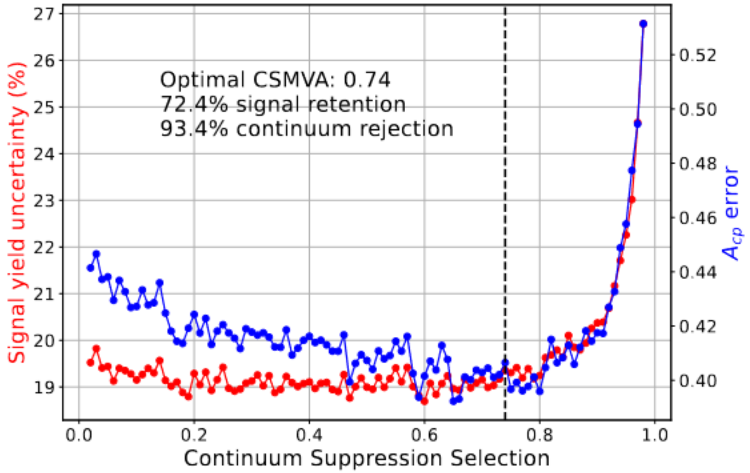


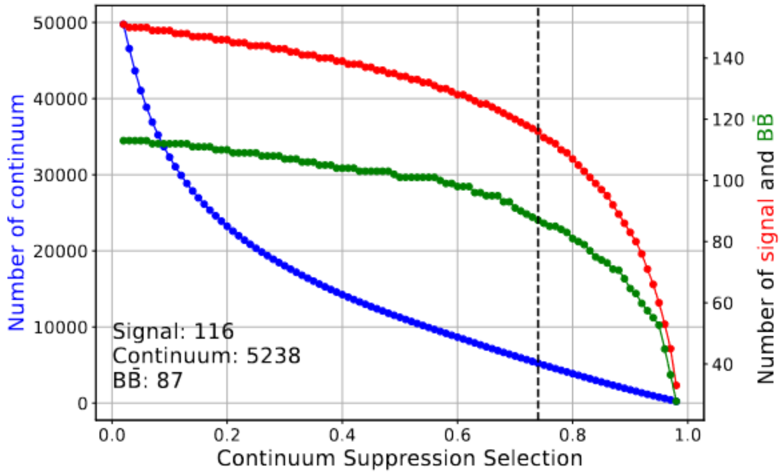
Continuum suppression



Continuum background

- **Problem:** $B^0 \to \pi^0\pi^0$ mode dominated by continuum
  - ➢ Approximately 50,000 continuum and 150 signal
  - ➢ Continuum must be well modelled
- **Solution:** Train a boosted decision tree and use experimental data that contains only continuum ($0.1 < \Delta E < 0.5$ GeV, $5.22 < M_{bc} < 5.27$ GeV/c^2) i.e., sideband





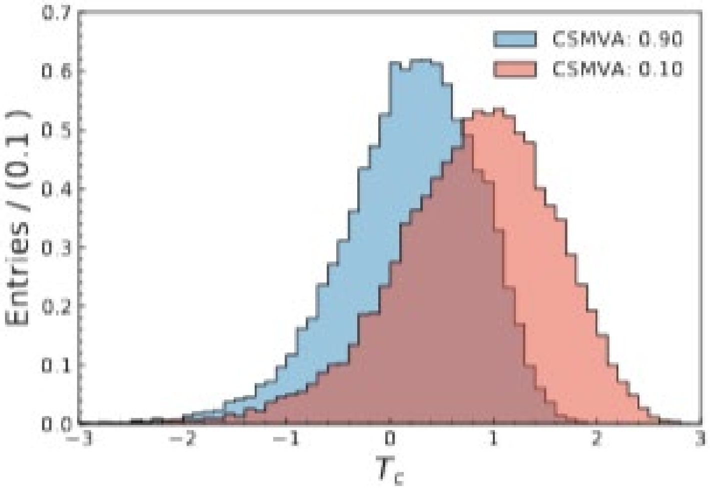
- Reject 89.4% of continuum and retains 80.7% of signal
- Signal efficiency of 35.5% and purity of 98.6%

Log transform of continuum suppresion

- Create Gaussian-like variable from continuum suppression output

$$T_c = \log(\frac{x - x_{cut}}{x_{max} - x})$$

where x is the continuum suppression variable, x_{cut} is the continuum suppression selection and x_{max} is the maximum value of the continuum suppression output



Signal and BB Fits

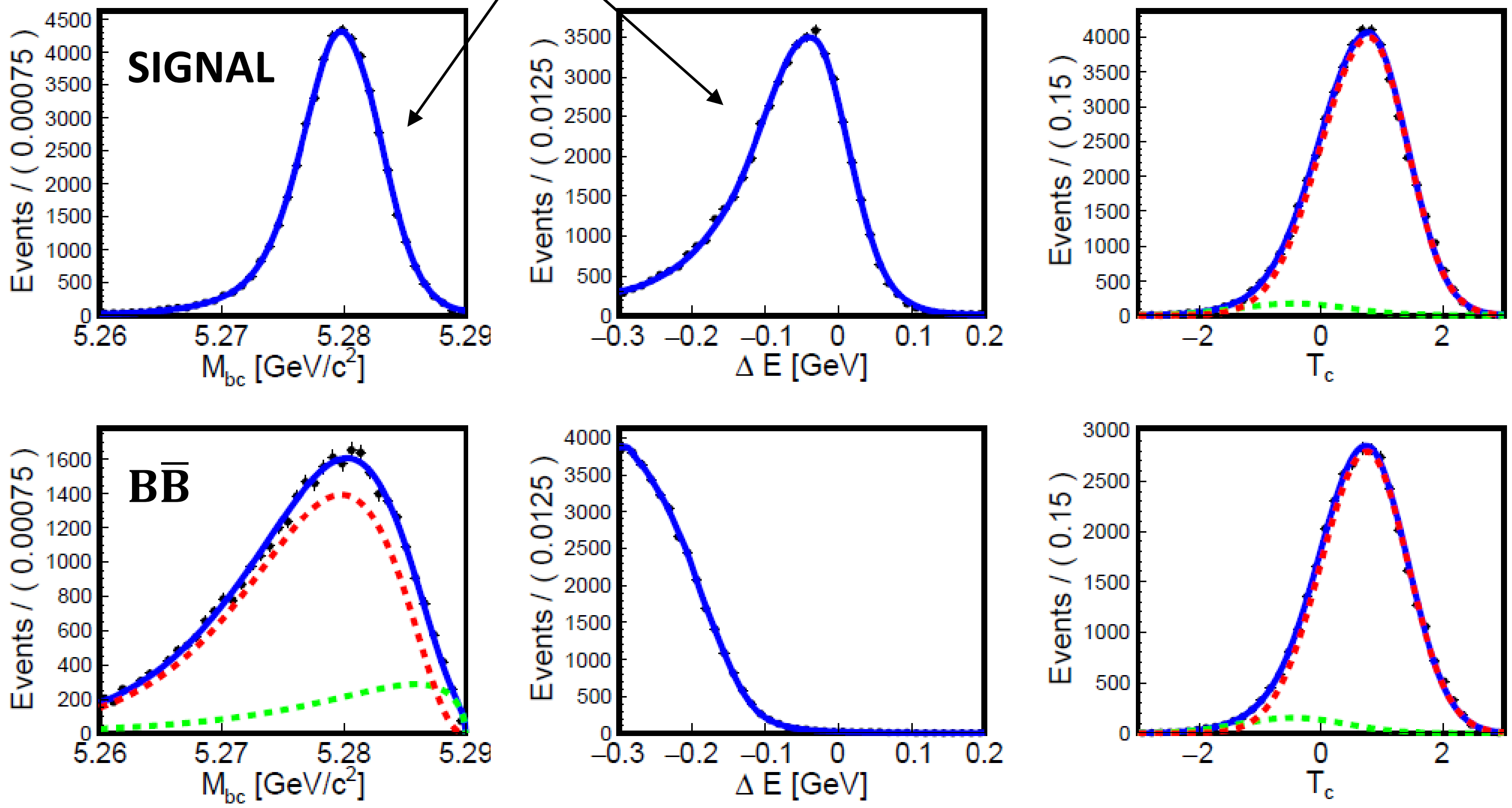
Whether the tag-side B-meson is a B^0 or $\overline{B}^0$ is determined by a FlavorTagger algorithm. It assigns a q.r value where q is the b-flavor charge (q = ±1) and r is the confidence (0 < r < 1).

- Events with q.r closer to ±1 are less likely to be continuum

- **Problem:** Incorporate q.r information to improve precision

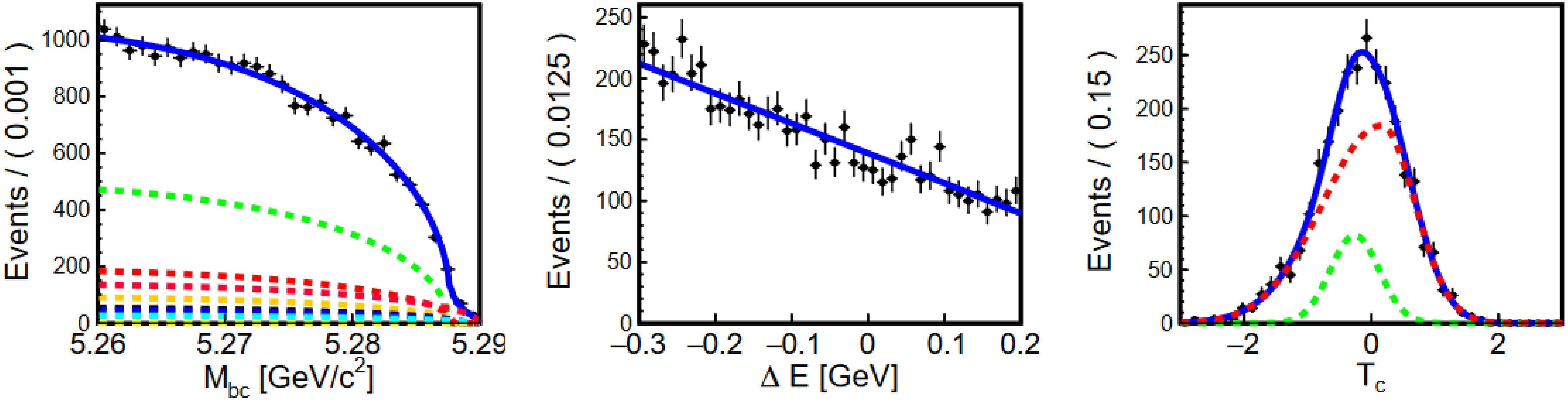
- **Solution:** Break data into 7 bins of q.r and fit simultaneously

M_{bc}-ΔE correlation accounted for using 2D kernel density function



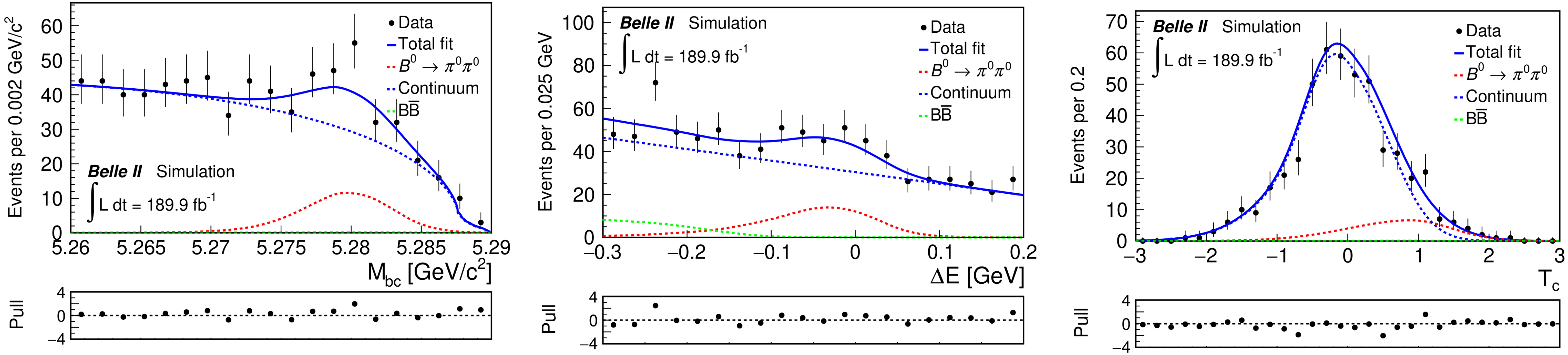
Continuum Fits

- Continuum PDF fitted to sideband data
- Distribution in the sideband and signal region are expected to be identical

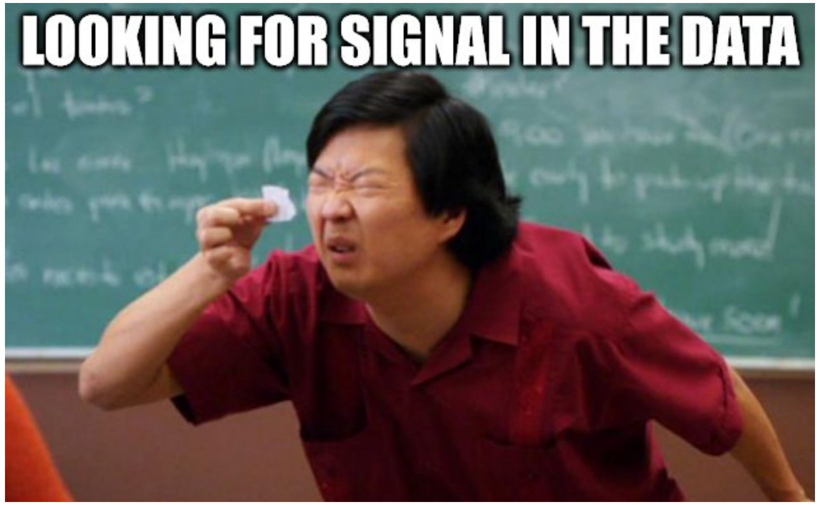


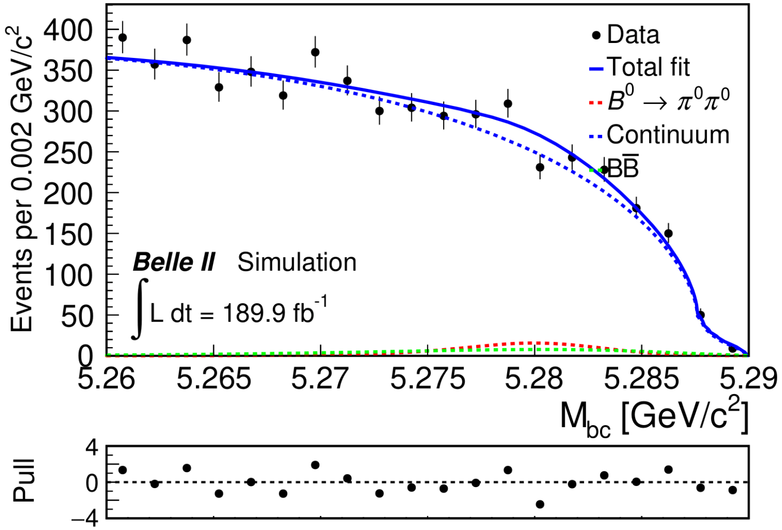
Fitting on simulated data

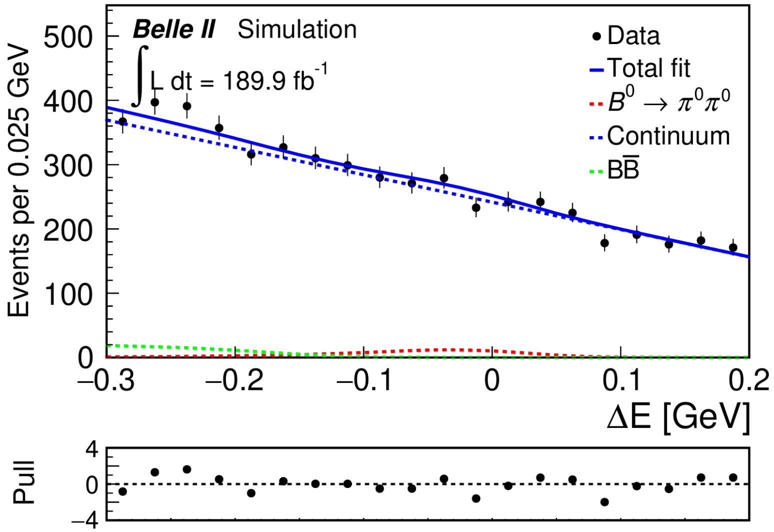
- The branching fraction and A_{CP} for the $B^0 \to \pi^0\pi^0$ decay are determined with a three-dimensional (M_{bc}, ΔE, T_c) simultaneous maximum likelihood fit in 7 bins of q.r
- Expect 116 ± 19 signal, 5238 continuum and 87 $B\bar{B}$
- Plots are signal enhanced **($2.75 < M_{bc} < 2.85$ GeV/c^2, $-0.1 < \Delta E < 0.05$ GeV, $T_c > 0$)** and corresponds to 189.9 fb^{-1}

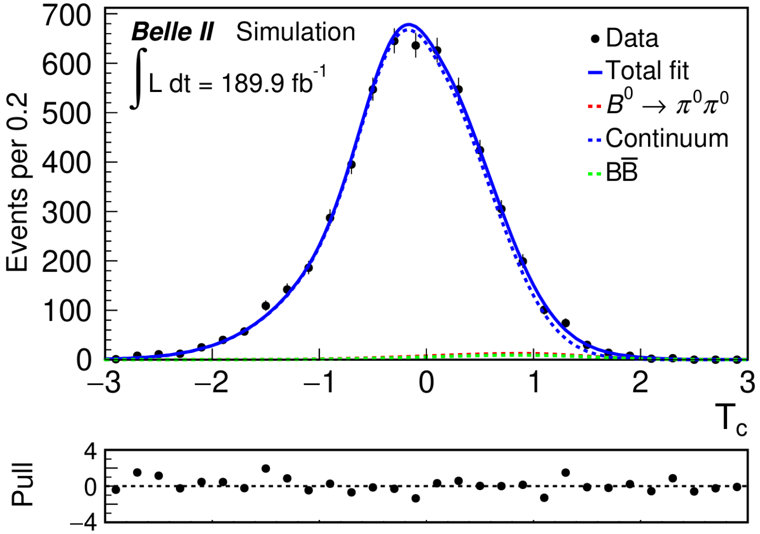


Plotting without signal-enhancement









$B^0 \to D^0(K^-\pi^+\pi^0)\pi^0$ Control mode

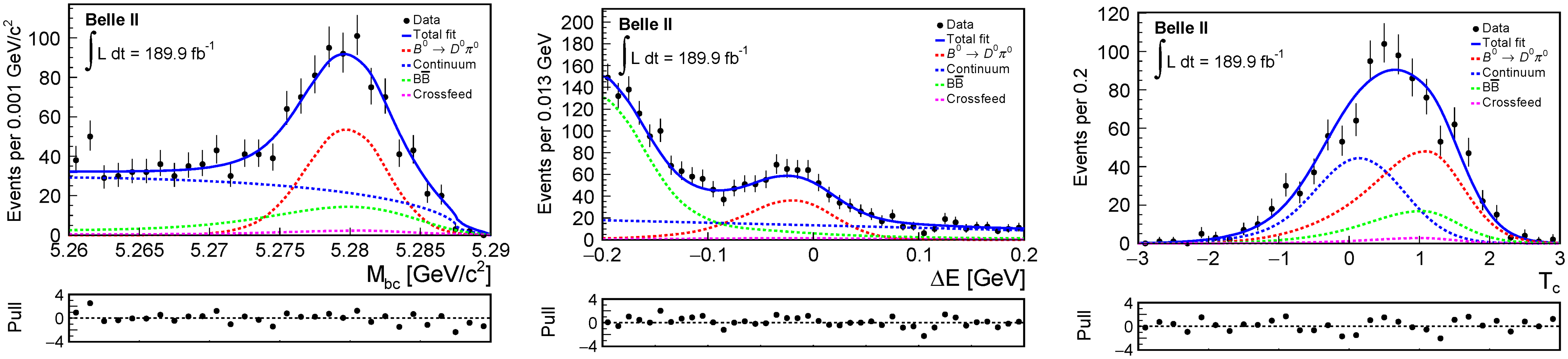
- Validate reconstruction and fitting procedure with control mode
  - BF and A_{CP} agree within uncertainty

Expected BF = $3.73 \pm 0.24 \times 10^{-5}$

Extracted BF = $4.01 \pm 0.27 \times 10^{-5}$

Expected $A_{CP} = 0$

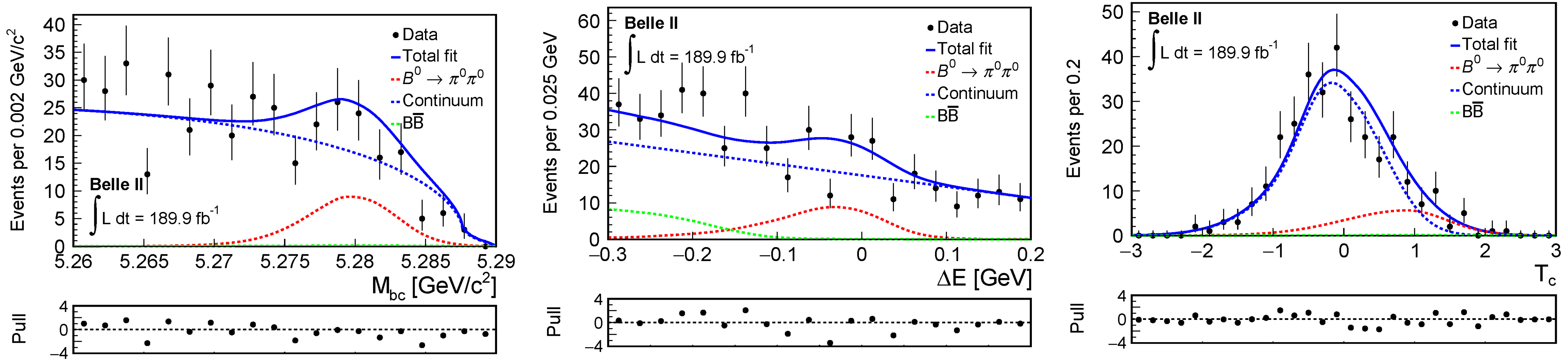
Extracted $A_{CP} = 0.14 \pm 0.16$



Results

Fitting on data

Signal Yield: 93 ± 18

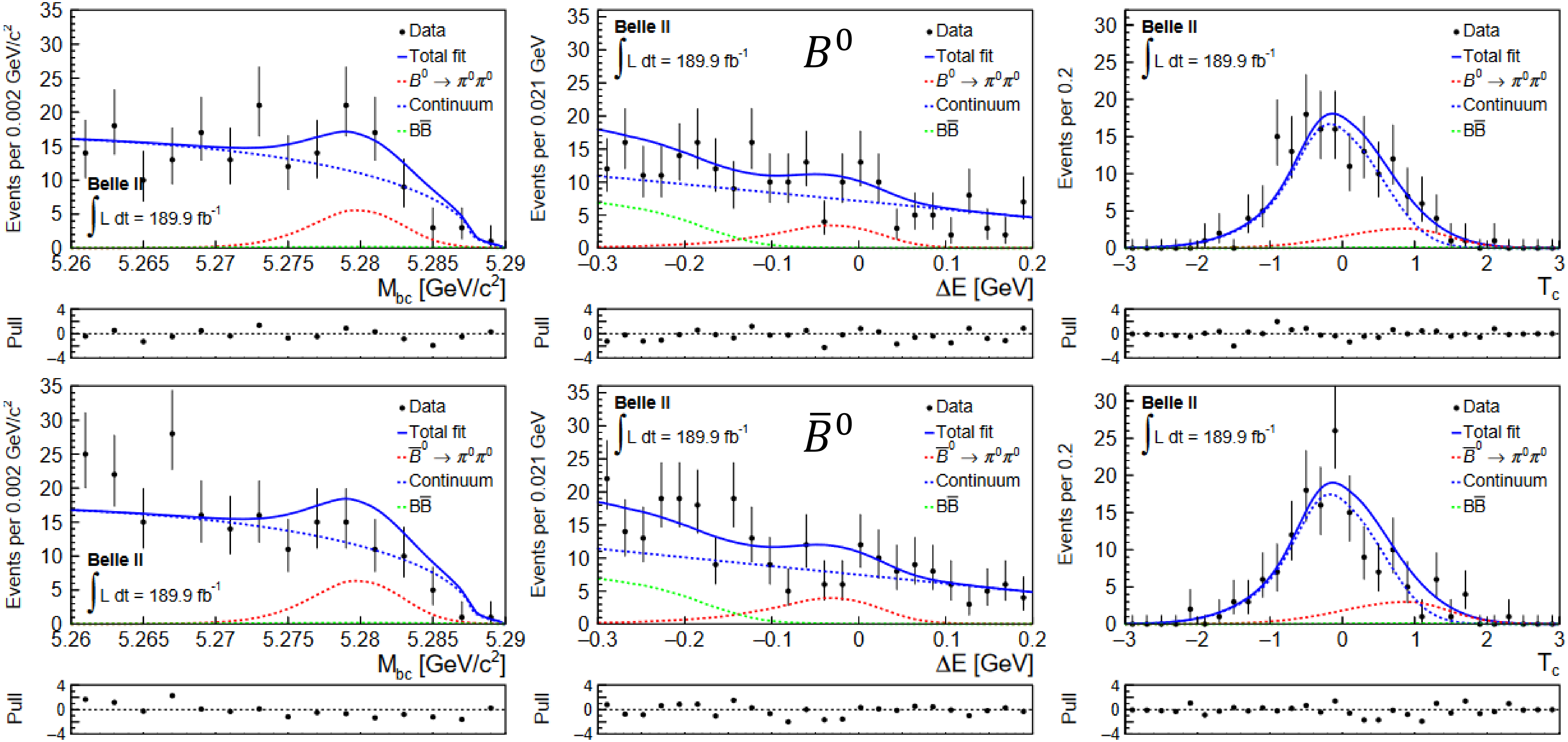


	Belle	BaBar	PDG value	Our value
$\mathcal{B}(B^0 \to \pi^0\pi^0)$	$1.31 \pm 0.19 \pm 0.19$	$1.83 \pm 0.21 \pm 0.13$	1.59 ± 0.26	$1.38 \pm 0.27 \pm 0.19$
$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$	$0.14 \pm 0.36 \pm 0.10$	$0.43 \pm 0.26 \pm 0.05$	0.33 ± 0.22	$0.14 \pm 0.46 \pm 0.07$

Units of $\times 10^{-6}$

Our results agreement with world-averaged results within uncertainty but favour the Belle result

B-flavour specific plots



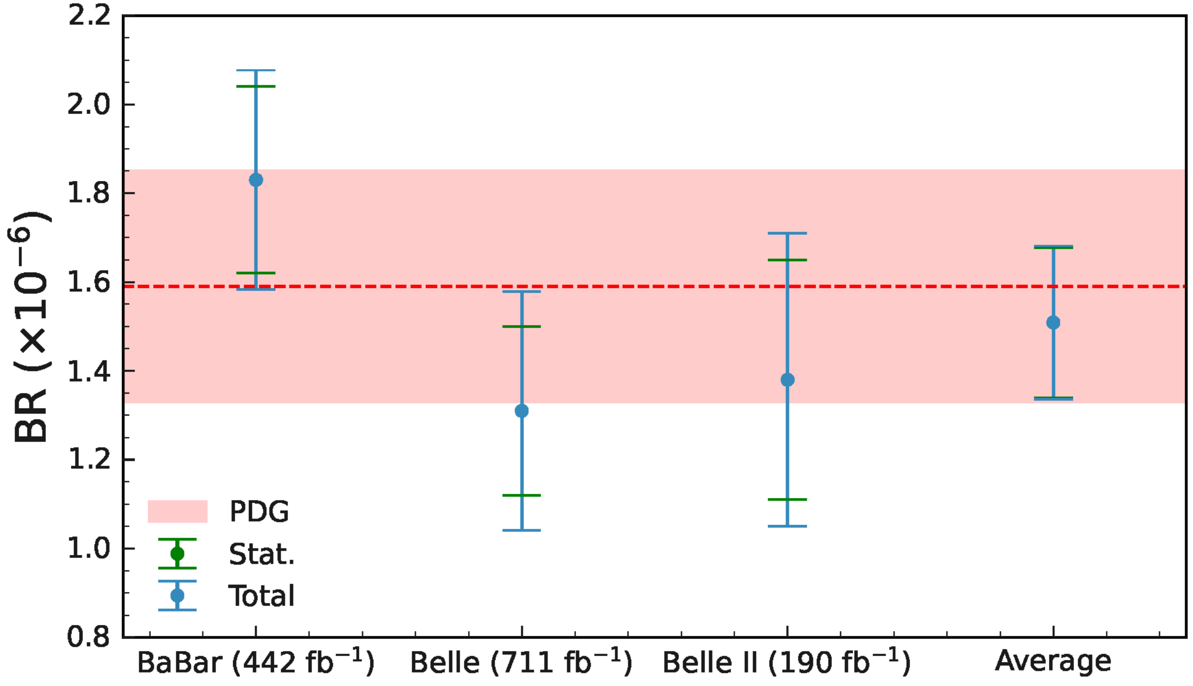
Comparison with Belle and BaBar

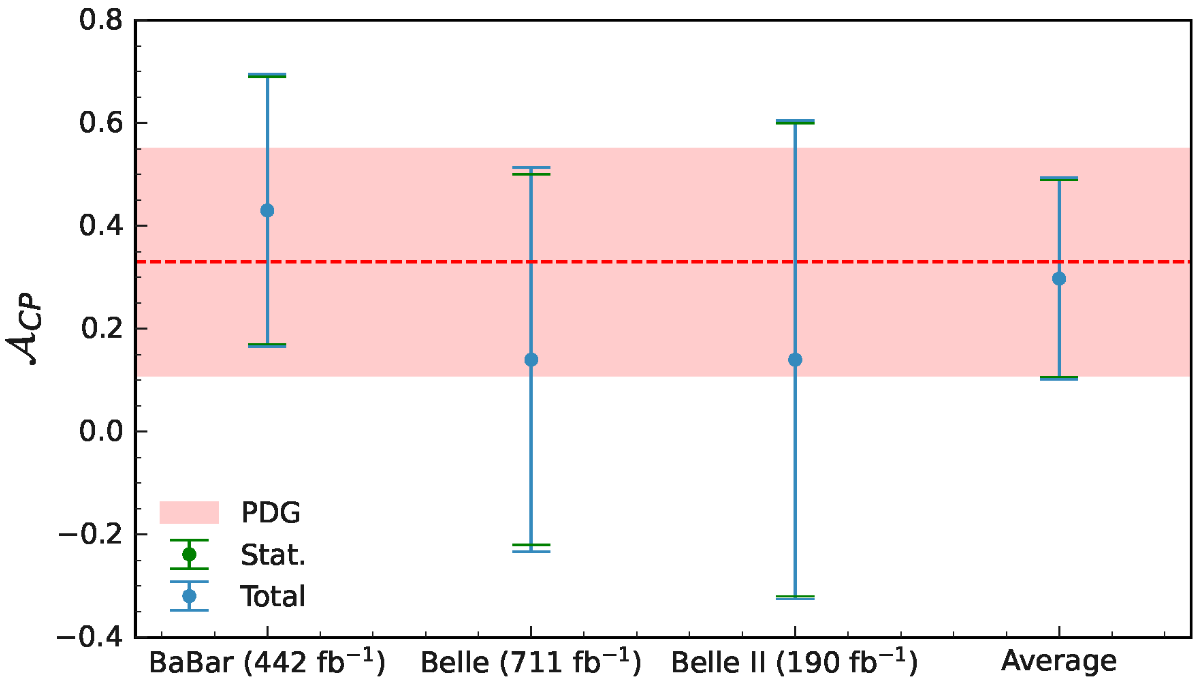
Current: $\mathcal{B}(B^0 \to \pi^0\pi^0)$ = 1.59 ± 0.26 × 10^{-6}

With our result: $\mathcal{B}(B^0 \to \pi^0\pi^0)$ = 1.54 ± 0.17 × 10^{-6}

Current: $A_{CP}(B^0 \to \pi^0\pi^0)$ = 0.33 ± 0.22

With out result: $A_{CP}(B^0 \to \pi^0\pi^0)$ = 0.30 ± 0.20





Determination of ϕ_2

Determination of ϕ_2 has a four-fold ambiguity

- Current constraints:

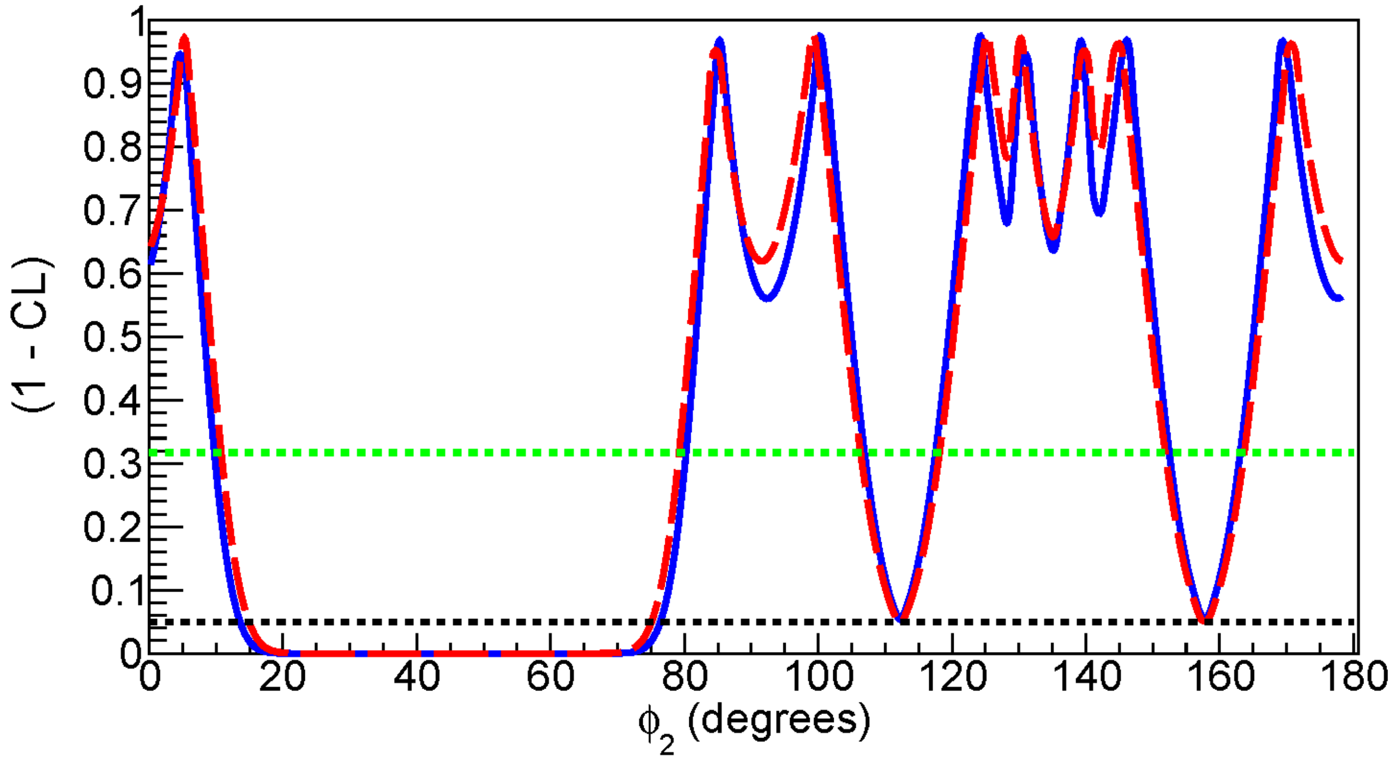
Exclude at 1σ: 11 < ϕ_2 < 79.5

Exclude at 2σ : 15.5 < ϕ_2 < 75

- Including our results:

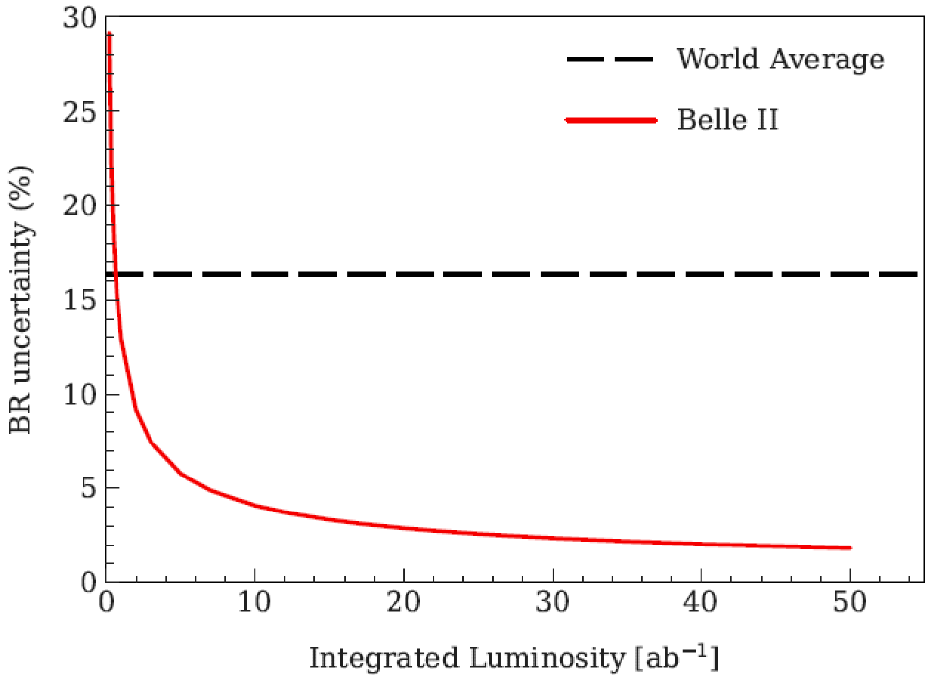
Exclude at 1σ : 10 < ϕ_2 < 80.5

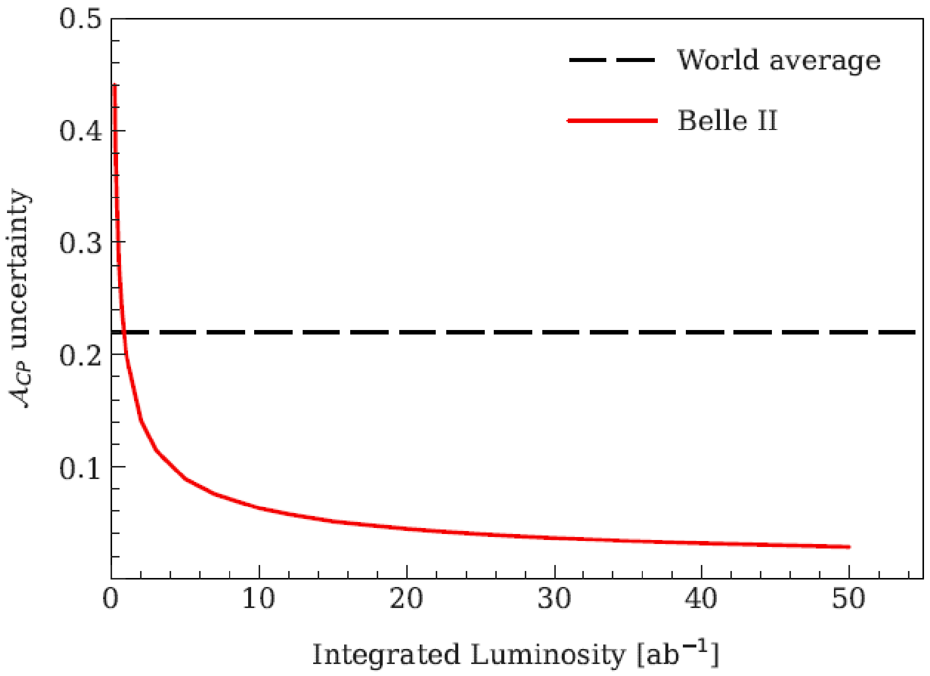
Exclude at 2σ : 14 < ϕ_2 < 76.5



Future prospects

- Expect to surpass Belle at 240/fb and the world-averaged results for branching fraction and A_{CP} at 300/fb and 500/fb respectively





Summary

- Updated measurement of the branching fraction and A_{CP} of $B^0 \rightarrow \pi^0\pi^0$
  - **Branching Fraction**: $1.38 \pm 0.27 \pm 0.19 \times 10^{-6}$
  - **A_{CP}**: $0.14 \pm 0.46 \pm 0.07$
- Results in agreement with world averages but favor Belle results
- The BF statistical uncertainty (19.7%) is comparable to Belle (14.5%) and BaBar (11.4%)

	Belle	BaBar	PDG value	Our value
$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0)$	$1.31 \pm 0.19 \pm 0.19$	$1.83 \pm 0.21 \pm 0.13$	1.59 ± 0.26	$1.38 \pm 0.27 \pm 0.19$
$\mathcal{A}_{CP}(B^0 \rightarrow \pi^0\pi^0)$	$0.14 \pm 0.36 \pm 0.10$	$0.43 \pm 0.26 \pm 0.05$	0.33 ± 0.22	$0.14 \pm 0.46 \pm 0.07$

- These results demonstrate the improved precision of Belle II and the potential for strong constraints on ϕ_2 through the full exploitation of the $B \rightarrow \pi\pi$ isospin relations.

QUESTIONS?

Systematic uncertainty

Source	$\mathcal{B}(\%)$	$\mathcal{A}_{CP}$
π^0 reconstruction efficiency	7.6	
Continuum parametrization	7.4	0.02
Continuum discriminator efficiency	6.5	
f^{+-}/f^{00}	4.9	
Fixed $B\overline{B}$ background yield	2.3	0.01
Signal $q \cdot r$ bin fractions	2.2	0.01
Knowledge of the photon-energy scale	2.0	
Assumption of independence of ΔE from $q \cdot r$	1.8	
Number of $B\overline{B}$ meson pairs	1.5	
Choice of signal model	1.3	0.02
Signal $q \cdot r$ bin fractions	1.0	0.01
Branching fraction fit bias	1.0	
Best candidate selection	0.2	
Mistagging parameter		0.05
Potential $B\overline{B}$ $q \cdot r$ asymmetry		0.03
$\mathcal{A}_{CP}$ fit bias		0.02
Continuum $q \cdot r$ asymmetry		0.01
Total	14.2	0.07

Also includes photonMVA systematic → π^0 reconstruction efficiency

Continuum parameters extracted from sideband → Continuum parametrization

BB background dominated by two modes → Fixed $B\overline{B}$ background yield

Possible bias in our modellings → Branching fraction fit bias; $\mathcal{A}_{CP}$ fit bias

Data-MC discrepancy for CS output → Continuum discriminator efficiency

Ratio between neutral and charged B-mesons → f^{+-}/f^{00}

Choice of using a KDE vs analytical function → Choice of signal model

Possible A_{CP} in continuum and BB → Potential $B\overline{B}$ $q \cdot r$ asymmetry; Continuum $q \cdot r$ asymmetry

BACKUP

Skimming

- No HLT_hadron skim since $B^0 \to \pi^0\pi^0$ contains no signal-side charged tracks ε_{total}: 44.8% → 58.4%

Particle	Selection	Skim efficiency (%)
γ	$E > 0.020$ GeV in barrel/backwards, $E > 0.0225$ GeV in forwards	99.4
π^0	$0.105 < M < 0.150$ GeV/c^2	99.9
	massKFit $\chi^2 > 0$	99.2
B^0	$\lvert\Delta E\rvert < 0.5$	99.9
	$M_{bc} > 5.20$ GeV/c^2	99.0

Skim	Channel	ε_{total} [%]
$B^0 \to \pi^+\pi^-$	$B^0 \to$ 2 tracks	85
$B^0 \to K^+\pi^-$	$B^0 \to$ 2 tracks	85
$B^+ \to \pi^+\pi^-\pi^+$	$B^+ \to$ 3 tracks	73
$B^+ \to K^+\pi^-\pi^+$	$B^+ \to$ 3 tracks	73
$B^+ \to K^+K^-\pi^+$	$B^+ \to$ 3 tracks	72
$B^+ \to K^+K^-K^+$	$B^+ \to$ 3 tracks	72
$B^+ \to K^0_S\pi^+$	$B^+ \to$ 3 tracks	70
$B^0 \to K^0_S\pi^+\pi^-$	$B^0 \to$ 4 tracks	61
$B^0 \to \pi^0\pi^0$	$B^0 \to 2\ \pi^0$s	58
$B^+ \to K^+\pi^0$	$B^+ \to$ 1 tracks + π^0	67
$B^+ \to \pi^+\pi^0$	$B^+ \to$ 1 tracks + π^0	67

Number of events after skim

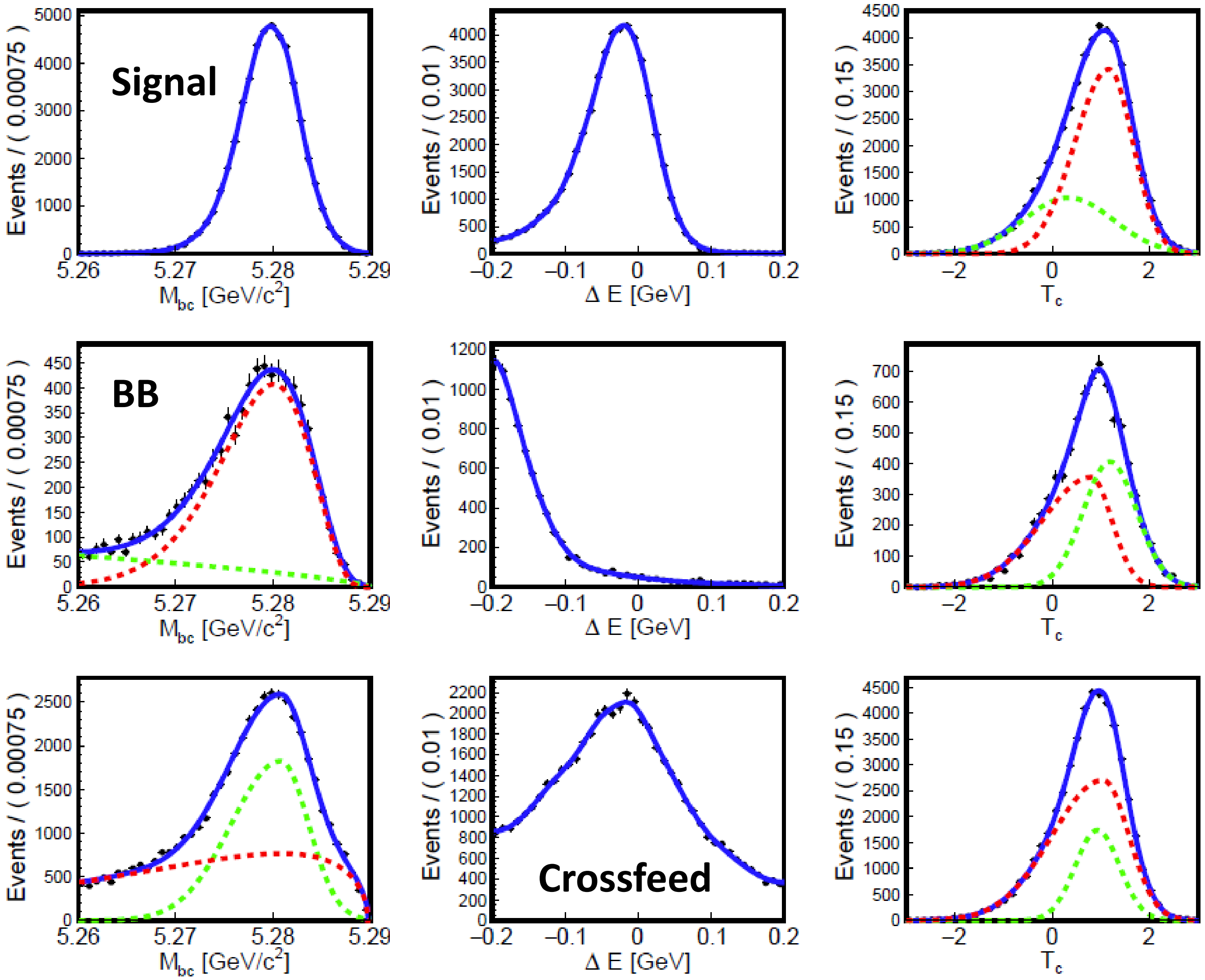
$$\varepsilon_{skim} = \frac{N_{skim}}{N_{all}} = 98.8\% \quad \text{and} \quad \varepsilon_{total} = \frac{N_{skim}}{N_{gen}} = 58.4\%$$

Number of events with no selections

Number of generated events

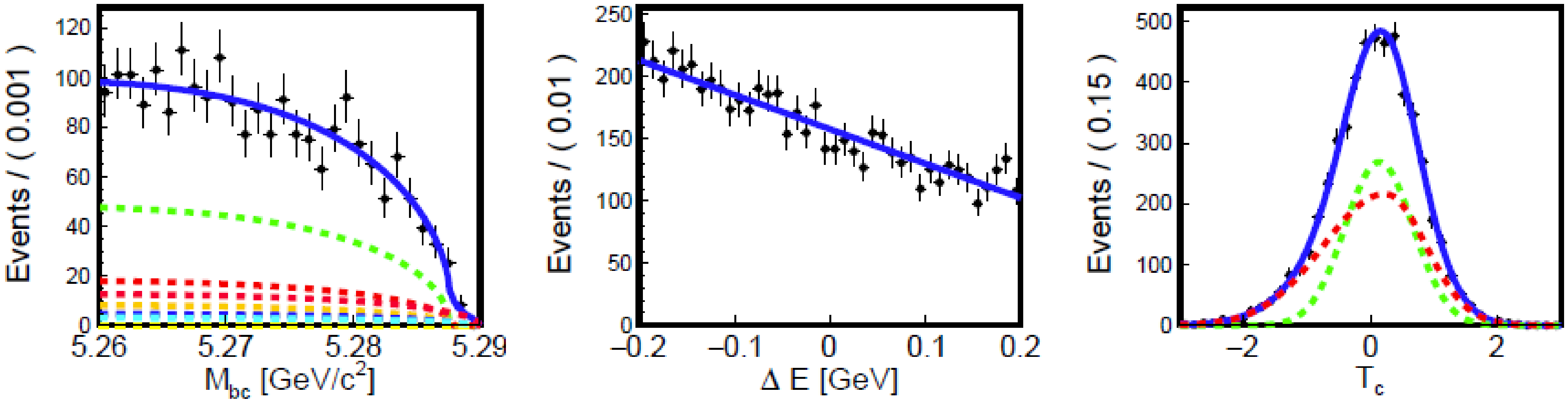
Difficult to reconstruct without tracks

Control Mode PDF Shapes



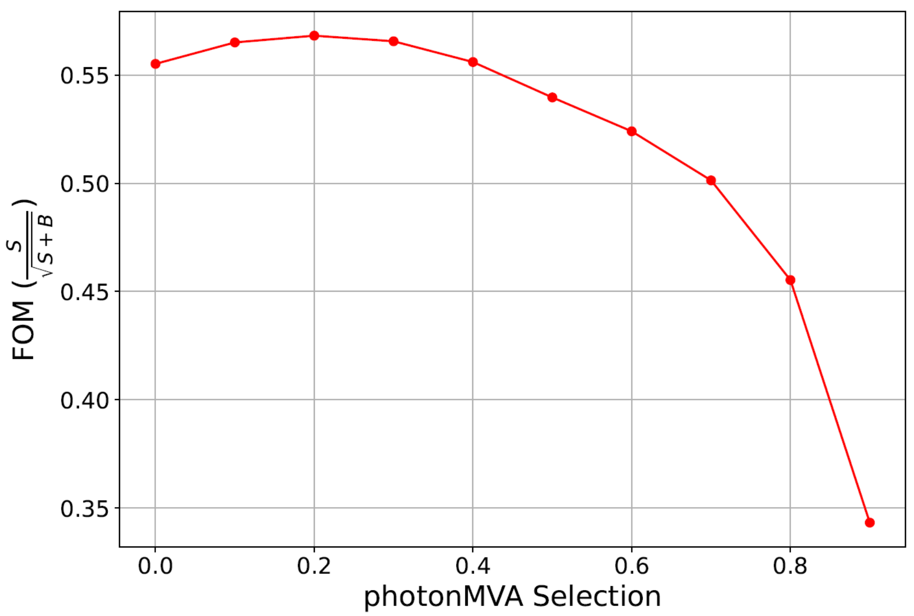
Control continuum parameterisation

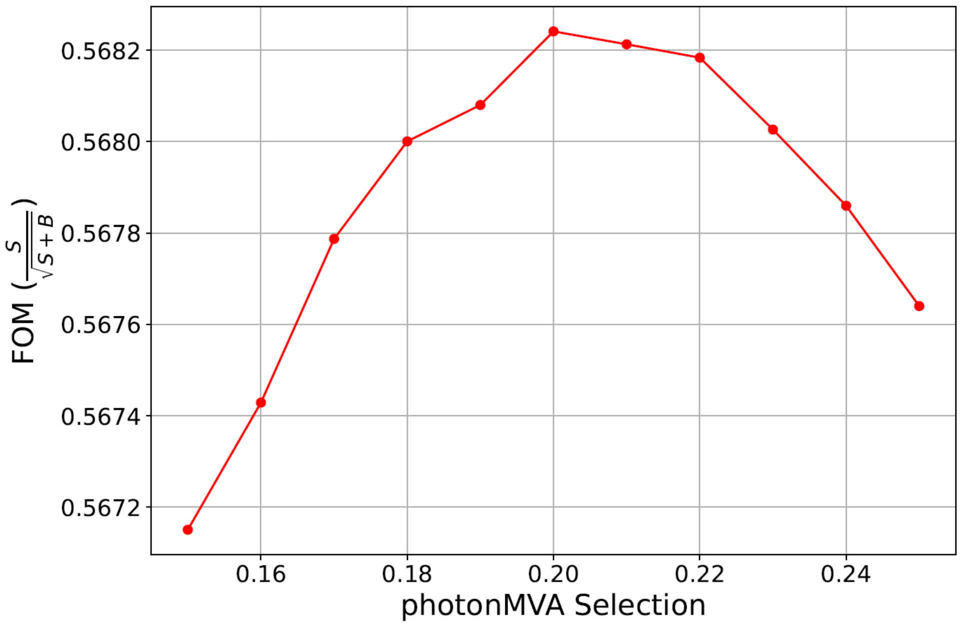
- Continuum PDF extracted from experimental sideband region
- Use 8-ARGUS PDF to model M_{bc}



photonMVA

- Optimize photonMVA selections with scan of possible parameters, maximise FOM; $\frac{s}{\sqrt{s+b}}$,
- Optimal selection is 0.2, which is used instead of 0.1



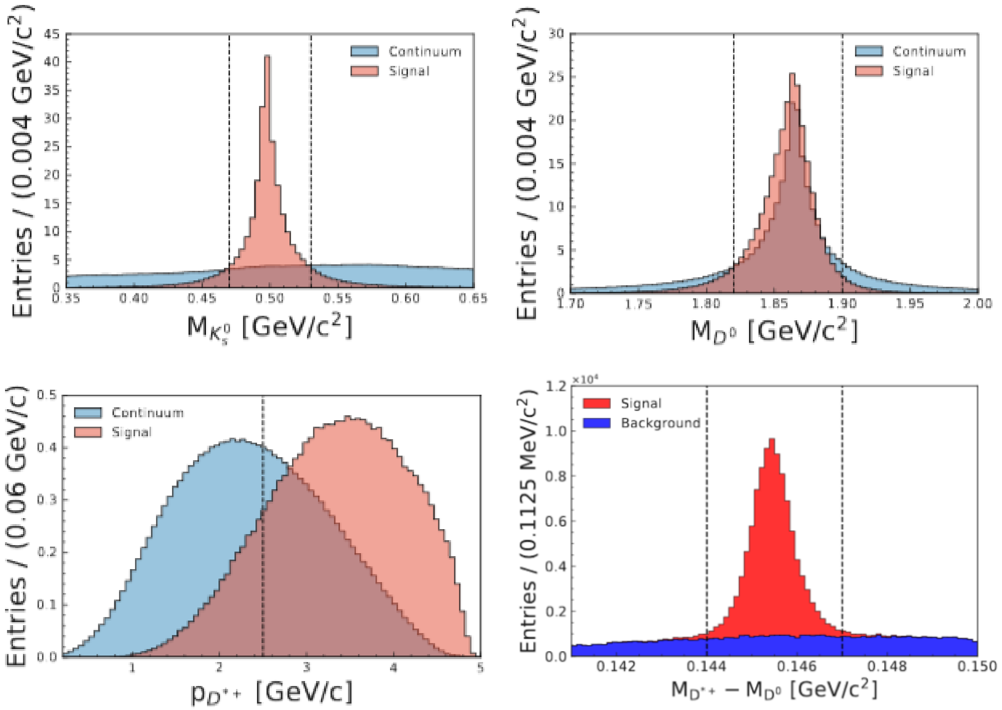


photonMVA validation

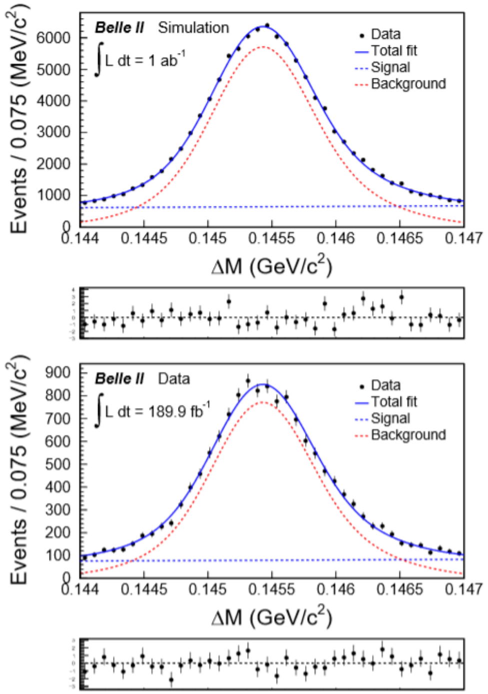
- photonMVA validated using D*+ → D$^0(K^+\pi^-\pi^0)\pi^0$ mode

Standard loose list

Particle	Selection	Particle retention (%)
$\pi^\pm$	thetaInCDCAcceptance==1	98.7
	nCDCHits > 20	82.7
	$\lvert dz \rvert < 3.0$ cm	94.2
	$\lvert dr \rvert < 0.5$ cm	86.9
	PID > 0.1	90.5
K_s^0	$0.47 < M < 0.53$ GeV/c^2	81.8
D^0	$1.82 < M < 1.90$ GeV/c^2	89.2
D^{*+}	0.144 GeV/$c^2 < \Delta M < 0.147$ GeV/c^2	89.5
	$p_{C.M} > 2.5$ GeV/c	84.4



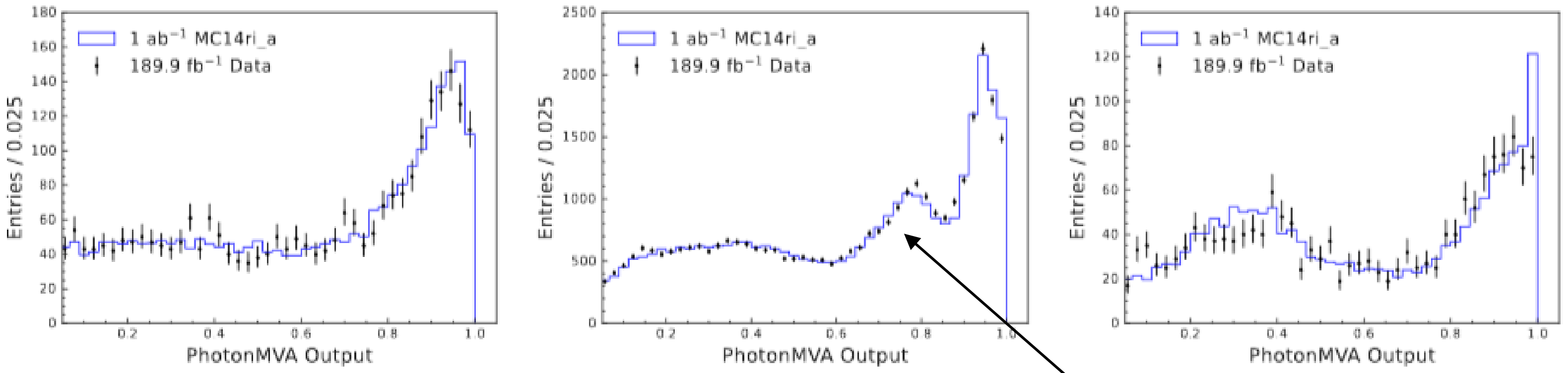
photonMVA validation

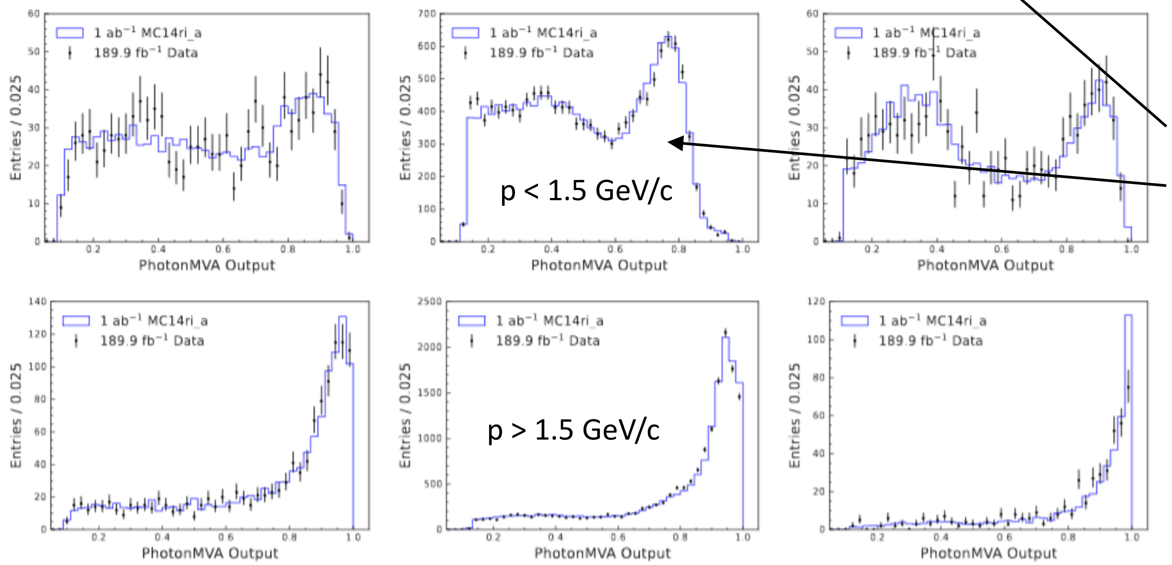


	MC	Data
Signal retention	$92.3 \pm 0.2\%$	$92.3 \pm 0.4\%$
Background rejection	$8.9 \pm 0.9\%$	$13.0 \pm 2.9\%$

Data and MC agree on signal retention and background rejection

- photonMVA validated using D*+ → D$^0(K^+\pi^-\pi^0)\pi^0$ mode

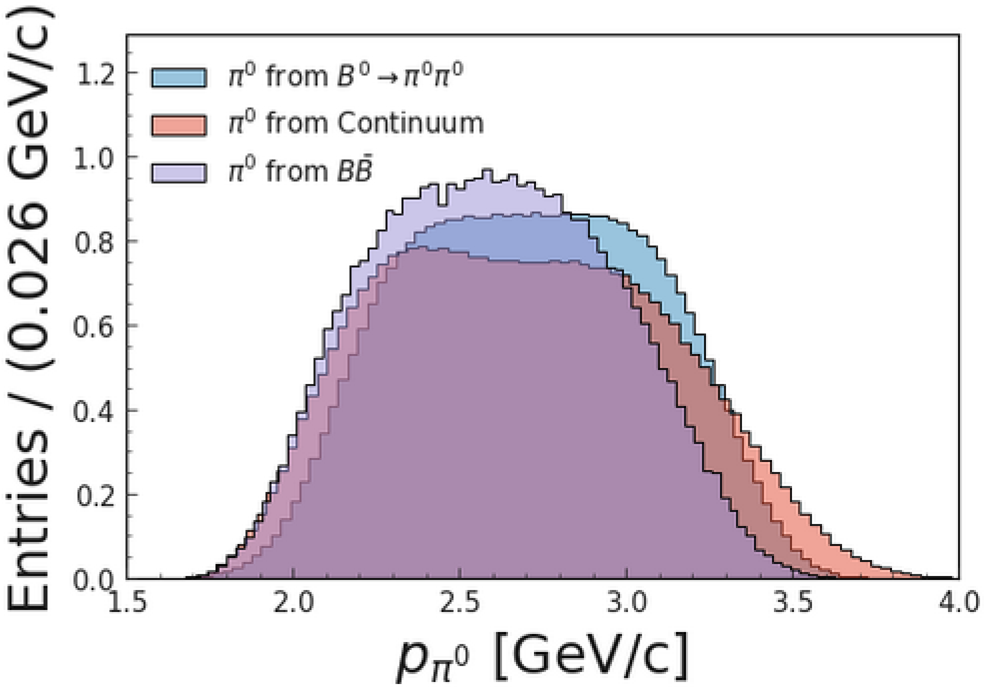


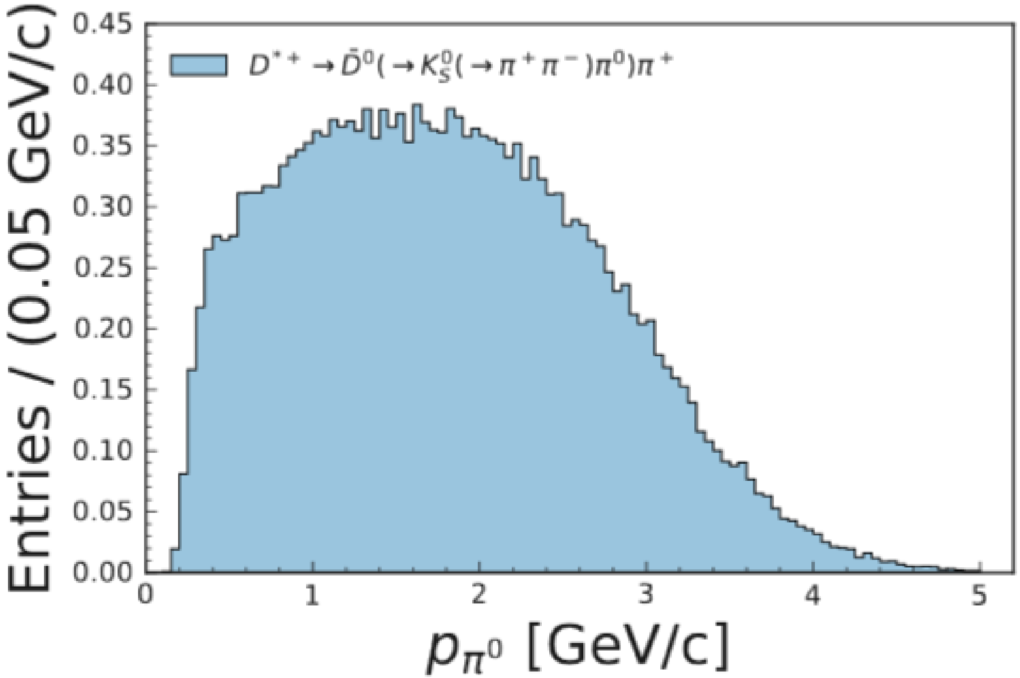


Structure due to soft π^0 which also show good agreement

PhotonMVA trained on independent sample

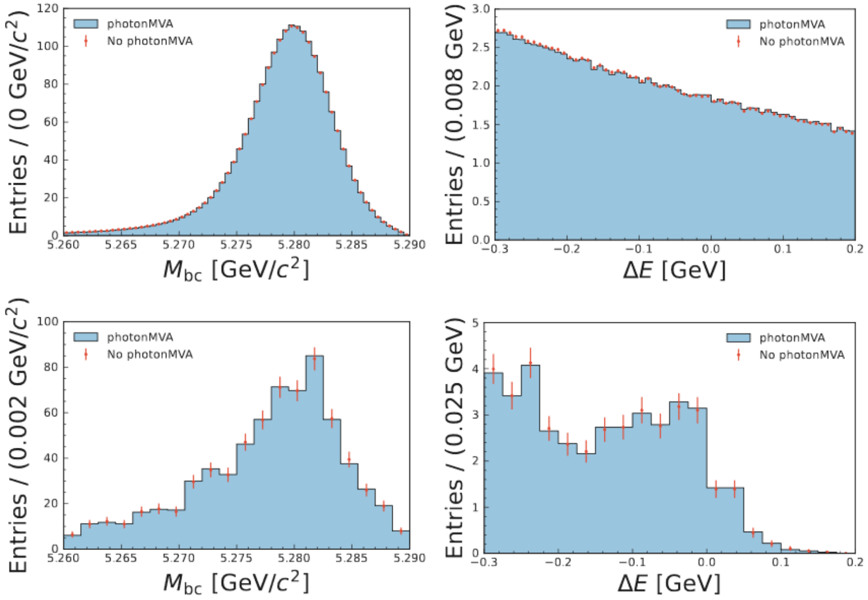
- The photonMVA is also trained using π^0 from an independent sample, D*+ $\rightarrow$ D$^0(\pi^+\pi^-\pi^0)\pi^+$ mode, restricting the momentum to p > 1.5 GeV/c





PhotonMVA applied

- We also check the effect of the photonMVA and find there is no sculpturing



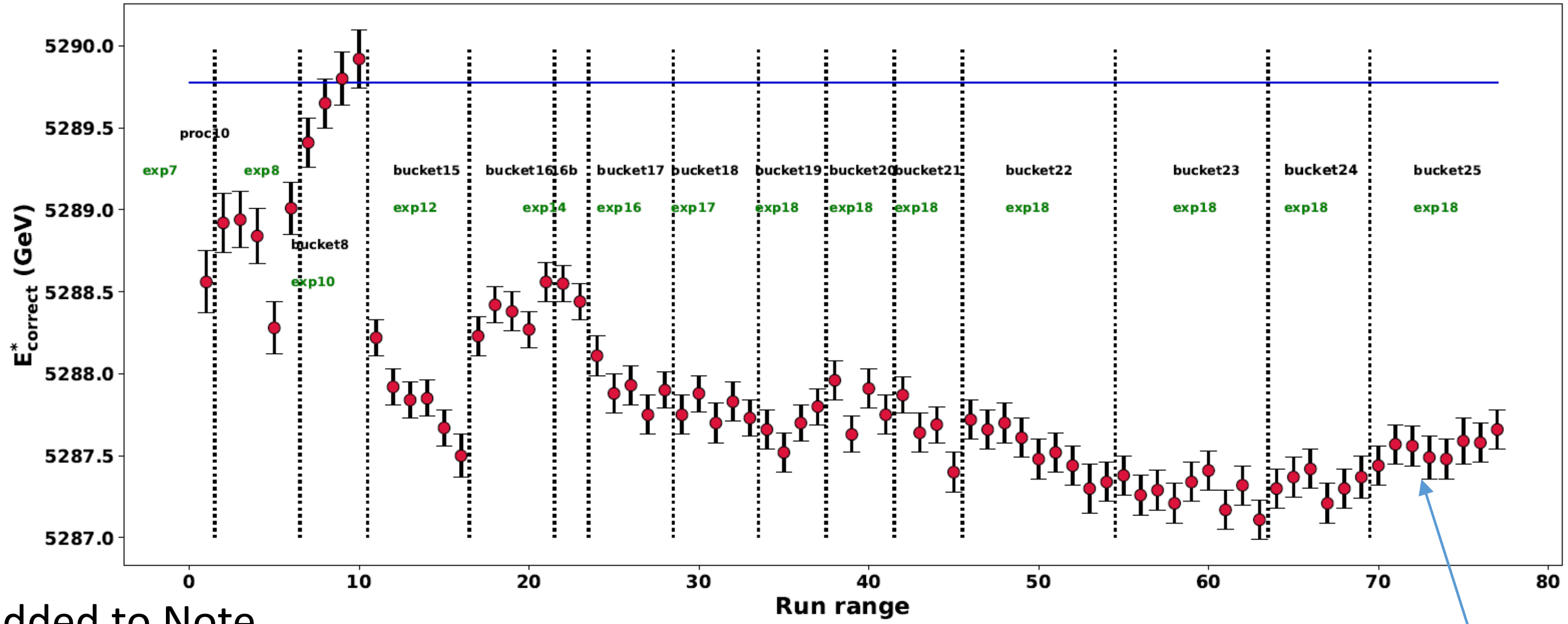
- Compared to standard charmless selections the photonMVA **reduces signal by 2.7%, continuum by 9.9% and BB by 5.9%**

	Signal (10 M)	Continuum (1 ab^{-1})	$B\overline{B}$ (1 ab^{-1})
without photonMVA	4,880,781	336,194	586
with photonMVA	4,631,398	287,317	541

M_{bc} investigation

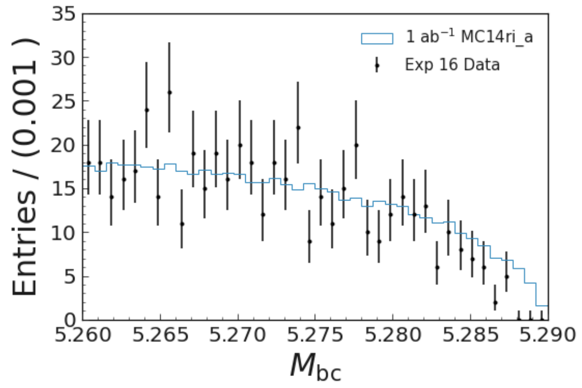
- We find that 2021 beam energy was lower than 2020, which is reflected in our data

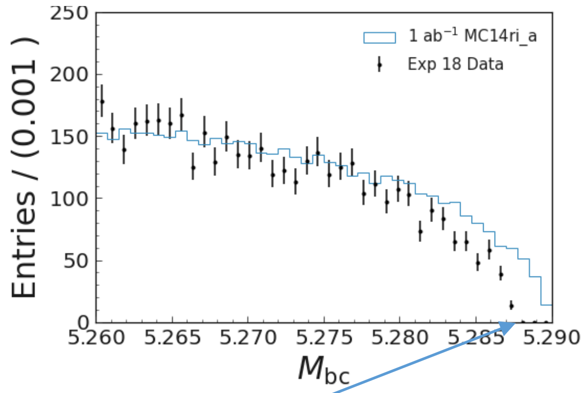
https://agira.desy.de/secure/attachment/51353/51353_BEC_buckets22to25.pdf



Added to Note

Figure: Shifted beam energy obtained in different run ranges



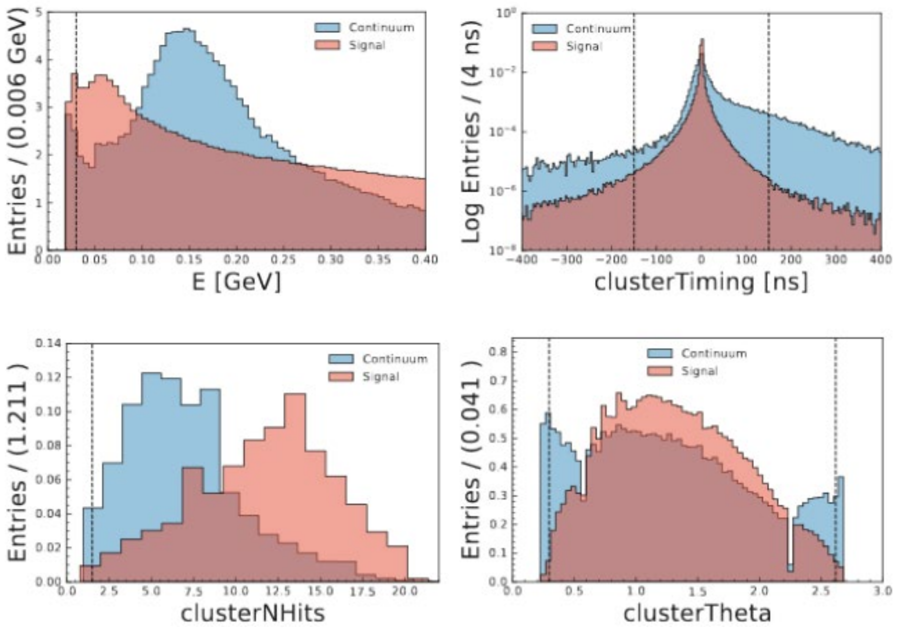


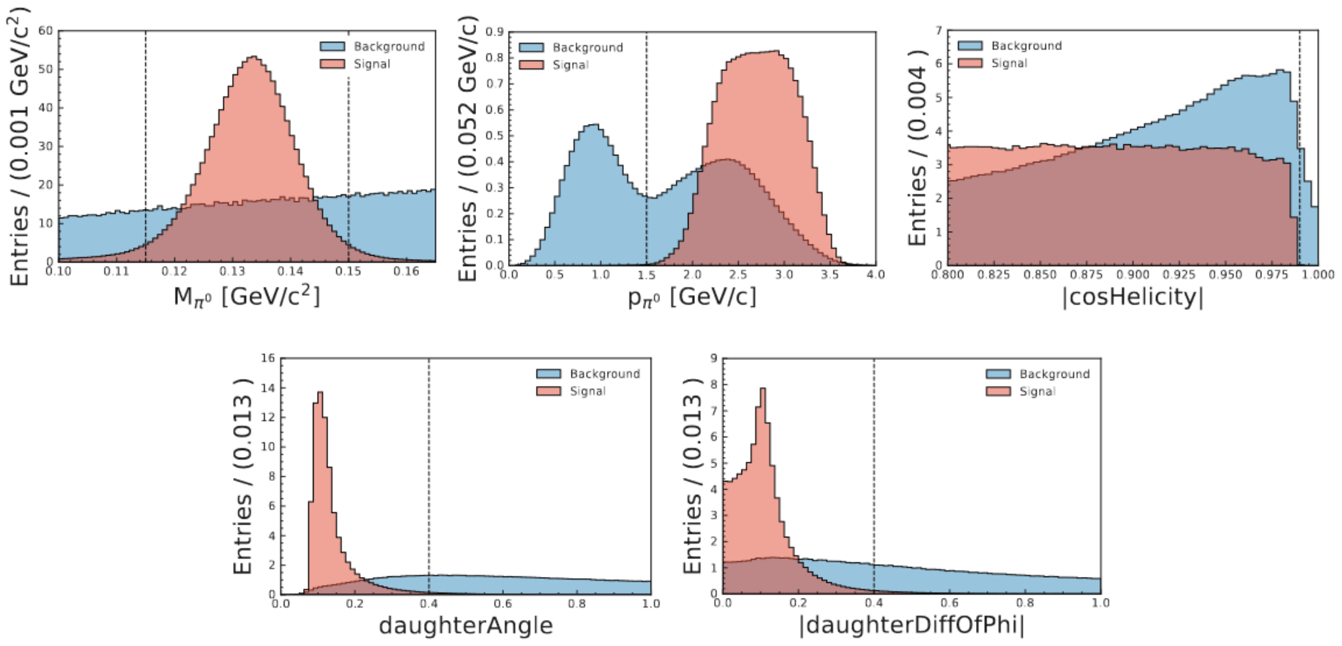
Approximately 5.2875 GeV/c^2

Signal selection

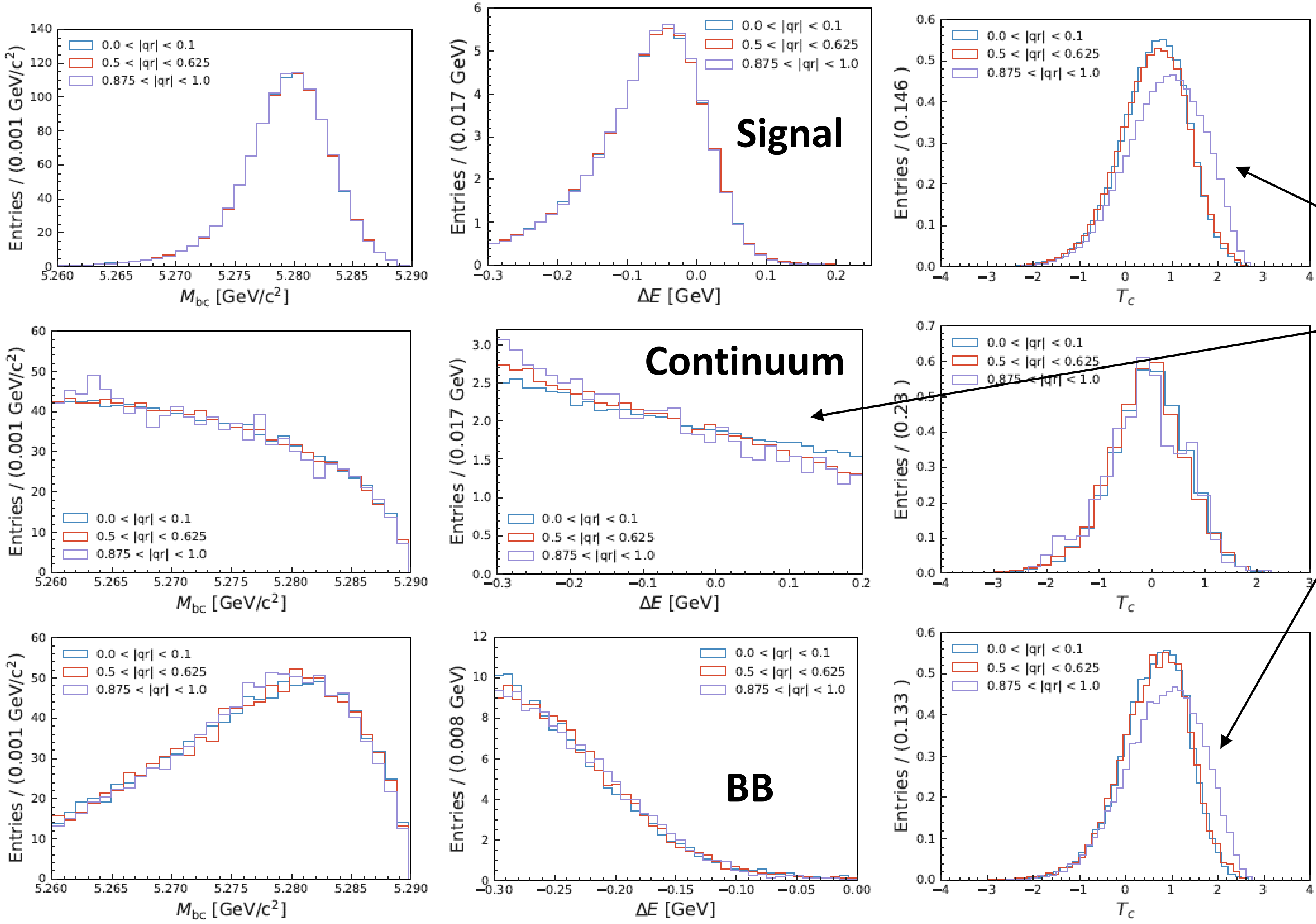
Selection	Signal γ loss (%)
`photonMVA` $>$ `0.2`	4.0
`E` $>$ `0.03`	1.17
`abs(clusterTiming)` $<$ `200`	0.0330
`clusterNHits` $>$ `1.5`	0.210
`0.2967` $<$ `clusterTheta` $<$ `2.6180`	0.608

Selection	Signal π^0 loss (%)
`daughterAngle` $<$ `0.4`	1.592
`|daughterDiffOfPhi|` $<$ `0.4`	1.547
`|cosHelicityAngleMomentum|` $<$ `0.99`	0.0004
`p` $>$ `1.5`	0.094
`0.115` $<$ `InvM` $<$ `0.150`	6.828





PDF shapes as function of q.r



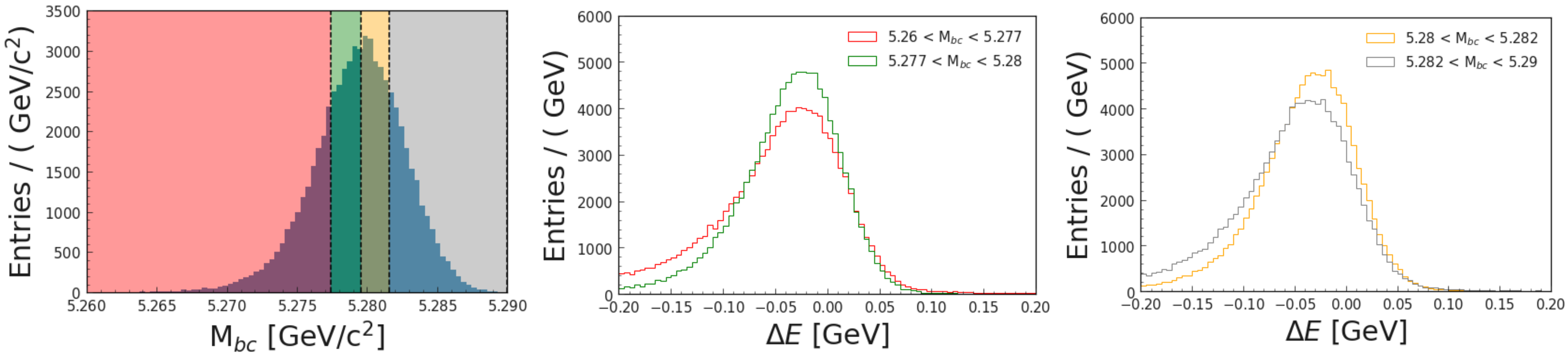
Depends on q.r

Not enough events in sideband

Component	M_{bc}	ΔE	T_c
Signal	Identical	Identical	Different
Continuum	Identical	Identical	Identical
$B\bar{B}$	Identical	Identical	Different

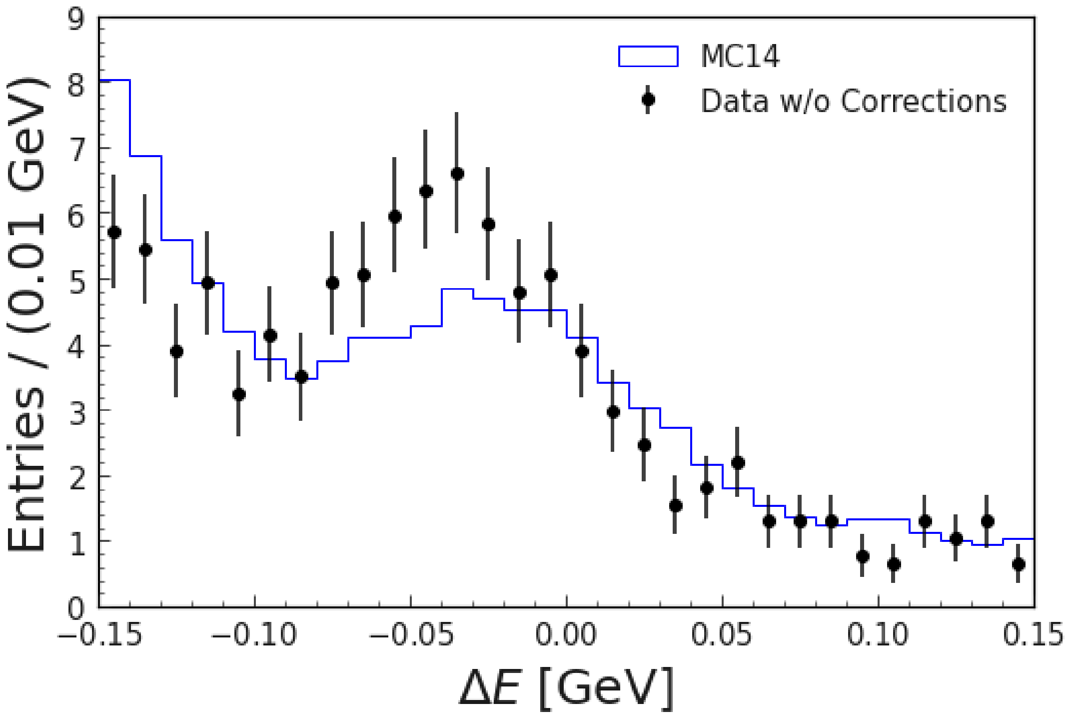
Correlation between ΔE and M_{bc}

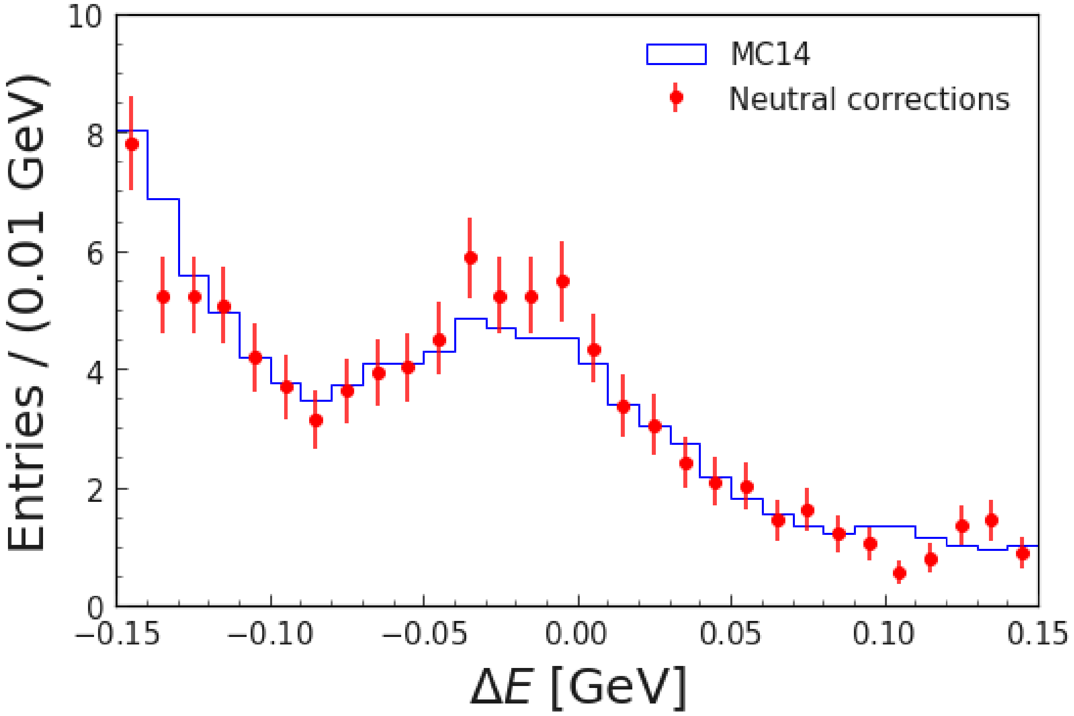
- ΔE does depend on M_{bc} in a non-linear way
  - Shape of ΔE depends on M_{bc}: the M_{bc} tail and peak region have a different ΔE distribution – Kernel Density Estimation (KDE) PDF is required
  - Peak of ΔE depends on M_{bc}: different in the tail region (red and gray) but is identical in the peak region (green and yellow)



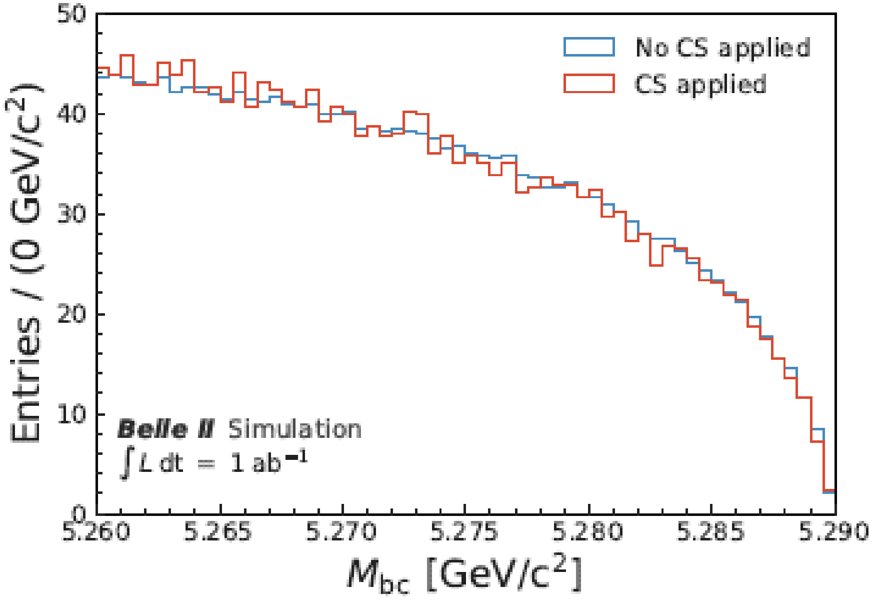
Photon Energy Bias Corrections

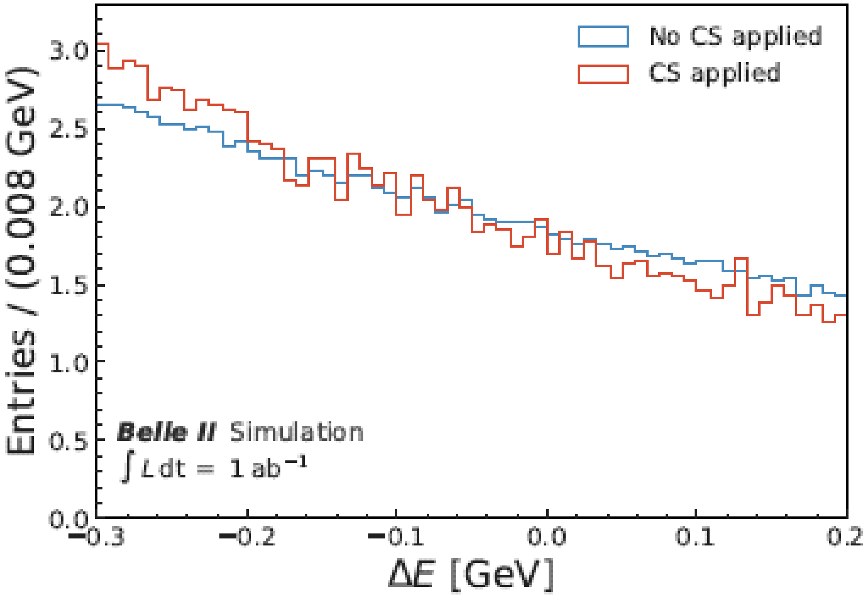
- On data ONLY we apply the “Photon Energy Bias Corrections”
- With the neutral corrections applied, the Data-MC discrepancy decreases
- Included in systematics uncertainty





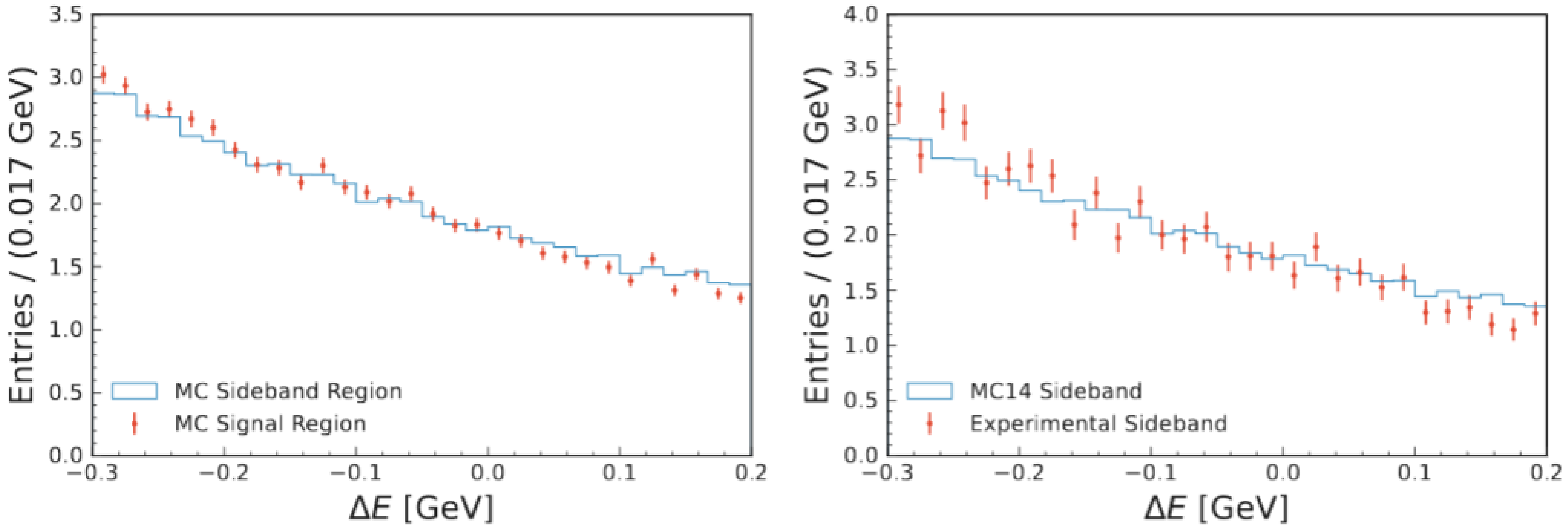
CSMVA sculpturing check





- Applying the continuum suppression changes the shape of ΔE for the continuum, true for both MC and sideband training
- Not an issue as continuum is modelled using experimental sideband

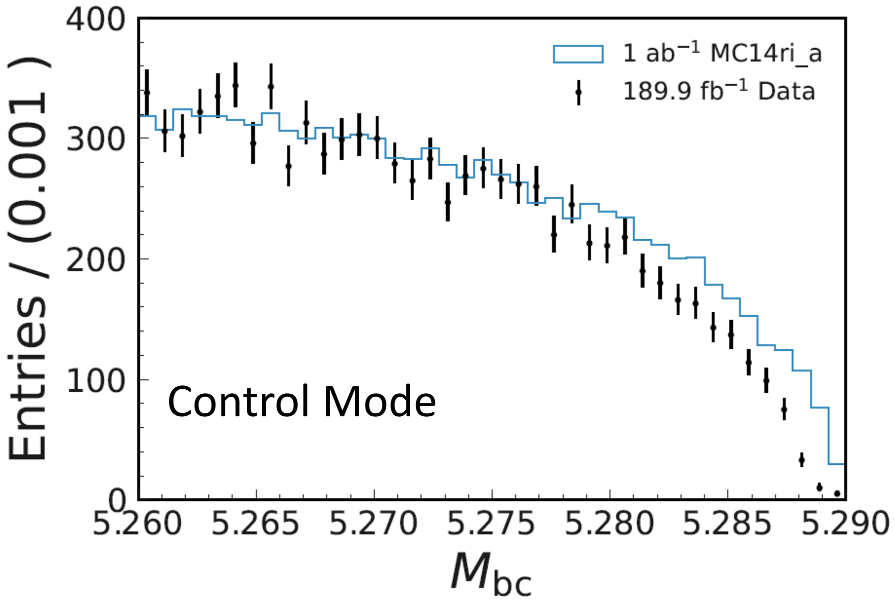
Continuum shape sideband vs MC



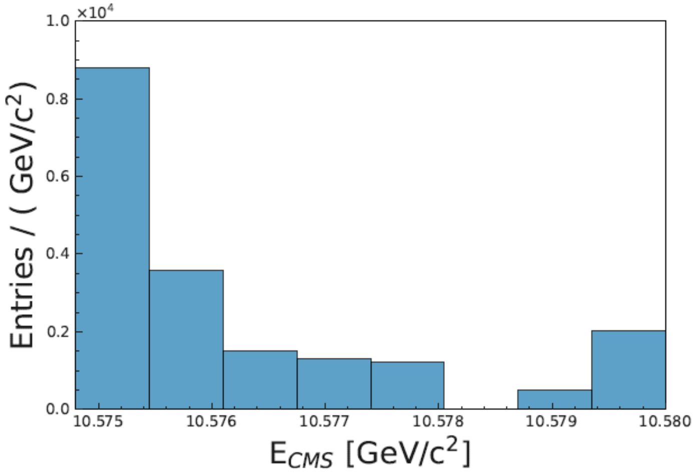
- From MC we expect ΔE in the sideband and signal region to be identical
- Experimental sideband and MC sideband agree within uncertainty

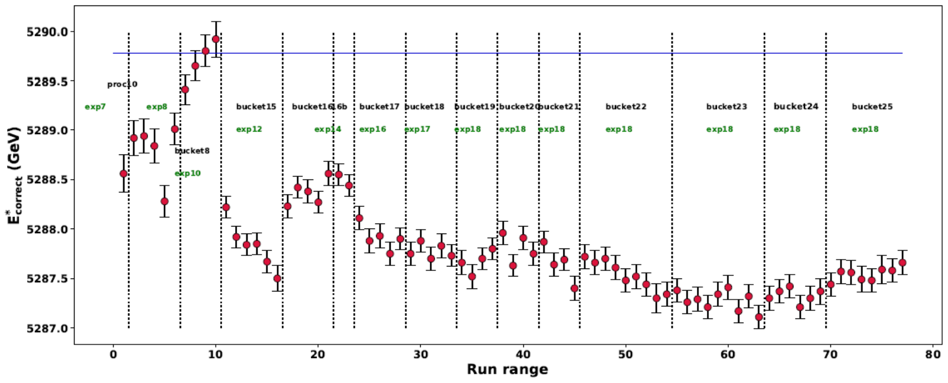
M_{bc} modelling of continuum

- Beam energy varied significantly throughout 2019-2021 data collection, shifting the M_{bc} endpoint as a result
- Instead of one ARGUS, we use 8 ARGUS functions with weight depending on the fraction of events in each E_{CMS} bin and endpoint as the upper edge of bin



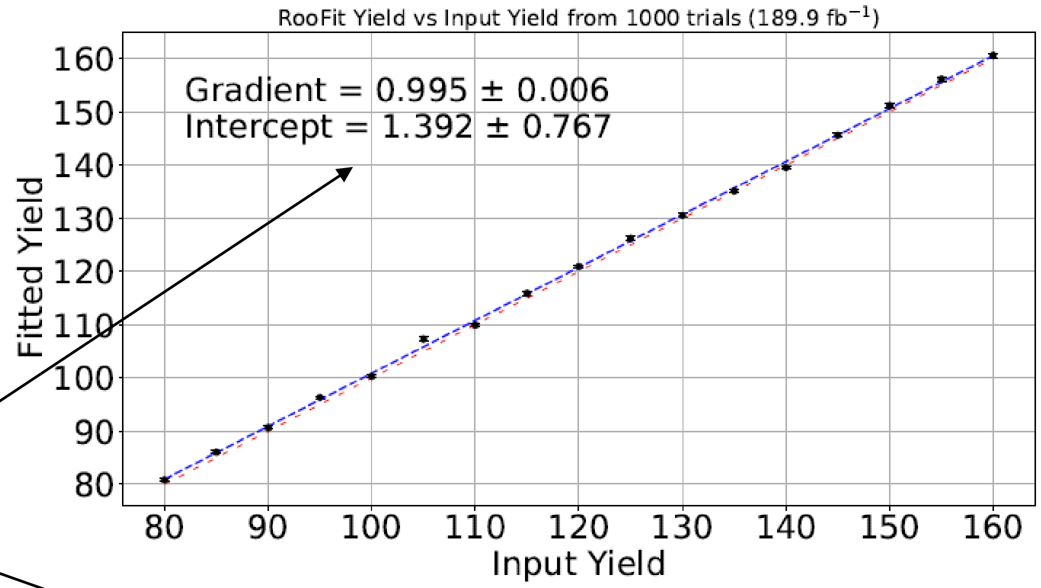
$$\mathrm{PDF}_{\mathrm{continuum}} = \sum_{i=0}^{7} h_i \cdot f(M_{bc}, \chi, E_i)$$

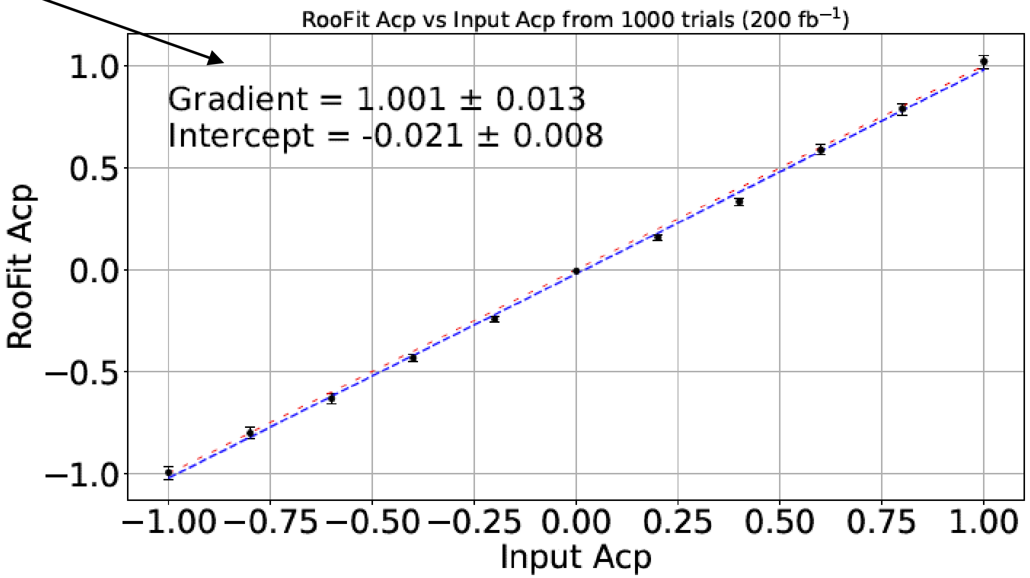




Signal Mode Linearity Test

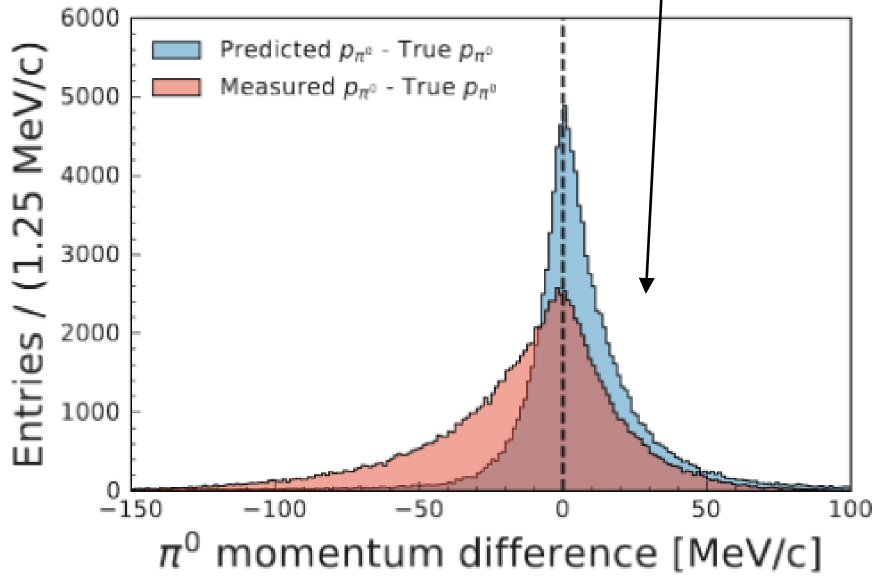
Possible bias taken into account as systematic uncertainty



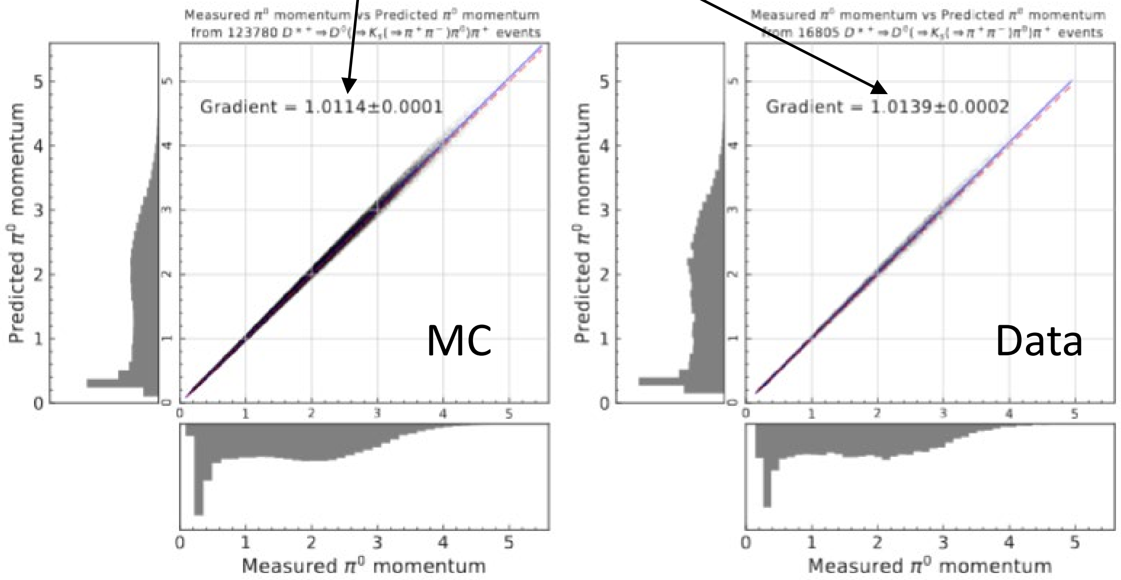


Reminder: ΔE Shift

The difference between predicted π^0 momentum and the true π^0 momentum is skewed in the positive direction

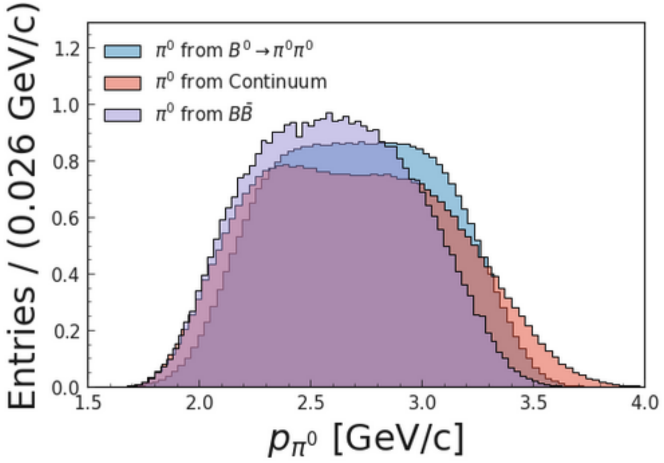


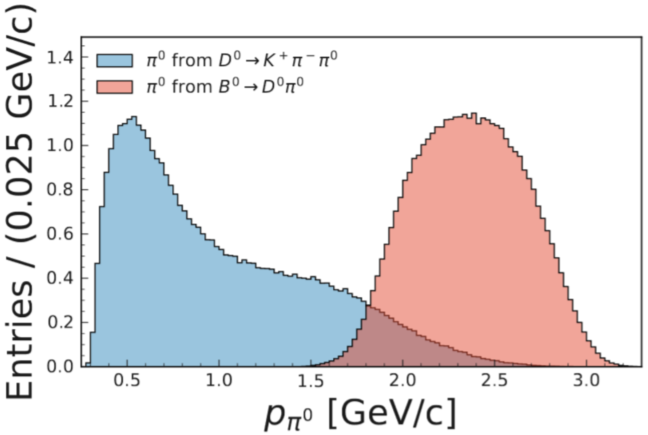
The "correction factor" between the predicted and measured π^0 momentum is estimated using best fit line in MC and data



The difference between these ``correction factor" represents the data-MC discrepancy, i.e. we want the MC gradient to equal the data gradient, 0.25%

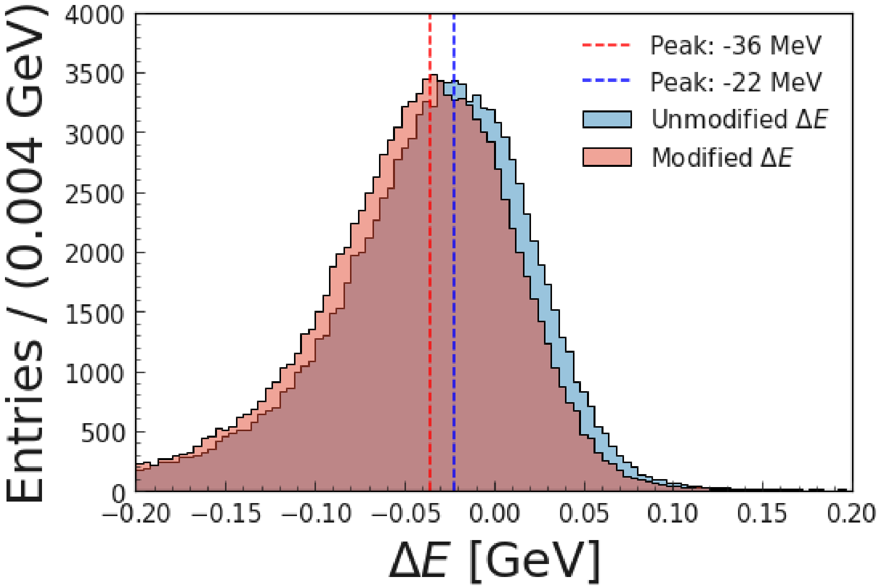
ΔE Shift





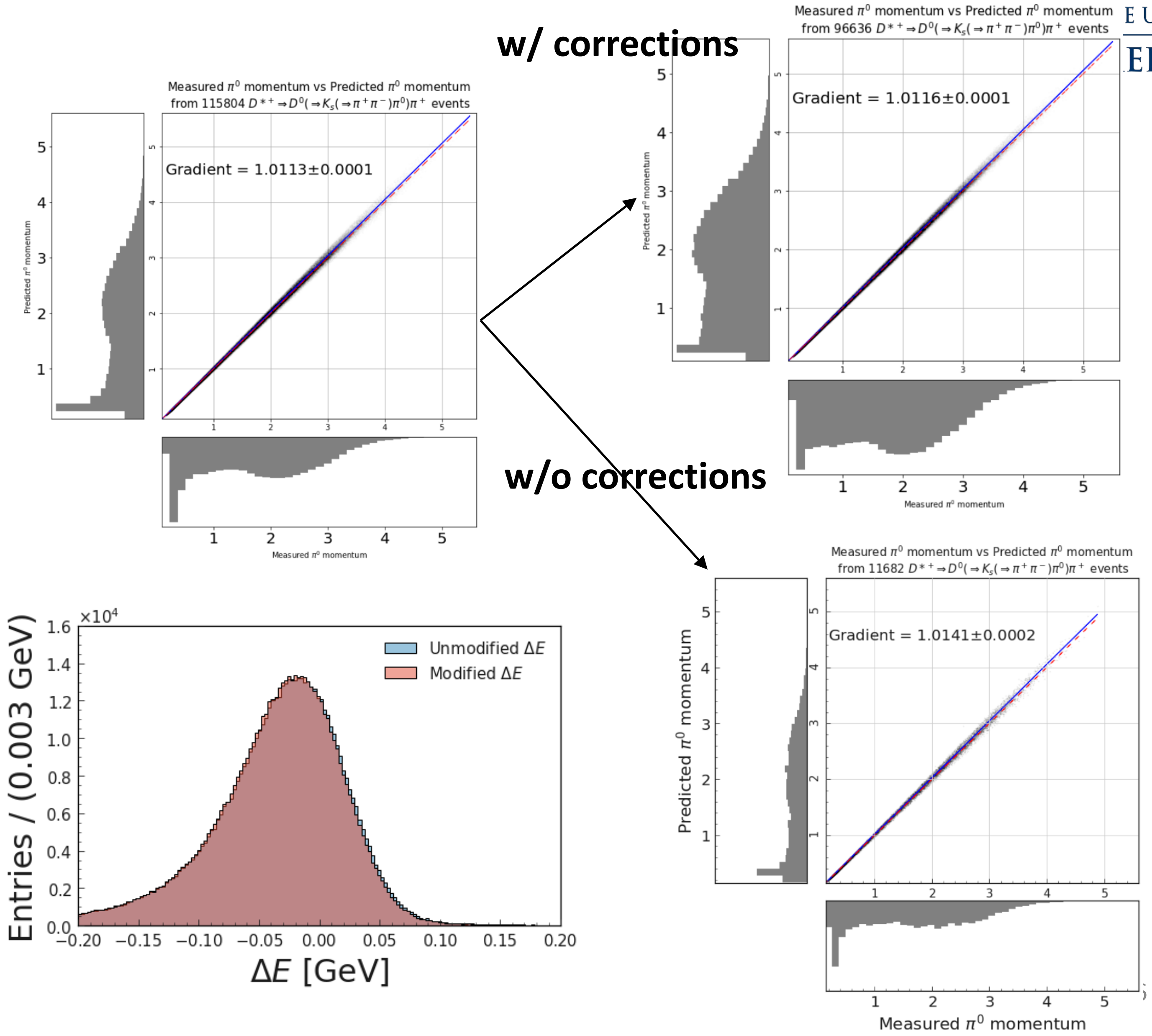
Does the ΔE shift scale with energy?

- Select only events that are similar to background, i.e. π^0 momentum is greater than 1.5 GeV/c
- The shift is now 14 MeV, similar to the shift expected in signal (15 MeV)



Is the calibration mode still useful?

- Yes, it was able to correctly determine the ΔE shift
- It can test the neutral corrections, i.e. only a 0.003 difference w/ correction vs 0.028 w/o correction in a momentum dependent way
- Shift can still be applied, but now it is much smaller, 15 MeV -> 1 MeV



Predicted π^0 momentum

Use the charged pions and energy-momentum conservation to predicted the $\boldsymbol{\pi^0}$ momentum

$$e^+e^- \to D^{*+} \to D^0(K_S^0(\to \pi^+\pi^-)\pi^0)\pi^+$$

Momentum/energy resolution of π^+ is excellent at Belle II

$$(M_{D^0})^2 = (E_{K_S^0} + E_{\pi^0})^2 - (\vec{p_{K_S^0}} + \vec{p_{\pi^0}})^2$$
$$= M_{K_S^0}^2 + M_{\pi^0}^2 + 2E_{K_S^0}E_{\pi^0} - 2p_{K_S^0}p_{\pi^0}\cos\theta$$

Solve the equation exactly for p_{π^0} using $E_{\pi^0} = \sqrt{M_{\pi^0}^2 + p_{\pi^0}^2}$:

π^+ less affected by possible ECL energy miscalibration than π^0

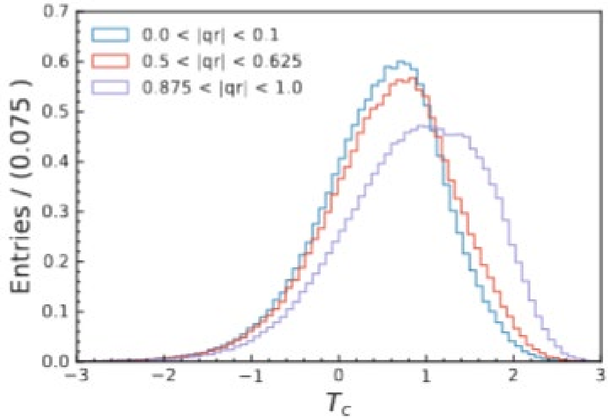
$$p_{\pi^0} = \frac{\sqrt{-4a^2B^2m^2 + 4B^4m^2 + B^2M^2} + aM}{2[a^2 - B^2]}$$

where a is $E_{K_S^0}$, B is $p_{K_S^0}\cos\theta$, M is $M_{D^0}^2 - M_{K_S^0}^2 + M_{\pi^0}^2$ and m is the mass of the π^0, taken from the PDG.

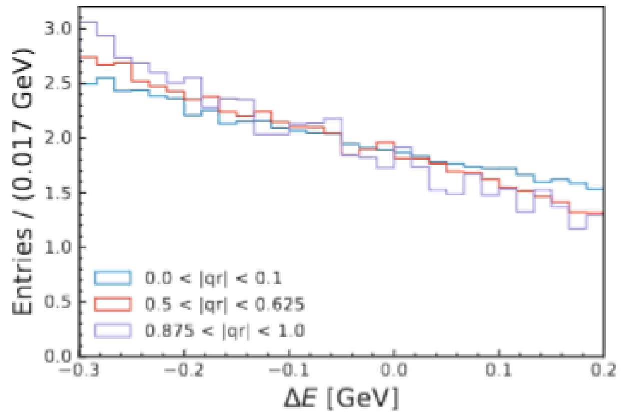
ToyMC Datasets

- ToyMC Datasets now generated with distributions different for each q.r bin for signal and BB T_C

Component	M_{bc}	ΔE	T_c
Signal	Identical	Identical	Different
Continuum	Identical	Identical	Identical
$B\bar{B}$	Identical	Identical	Different

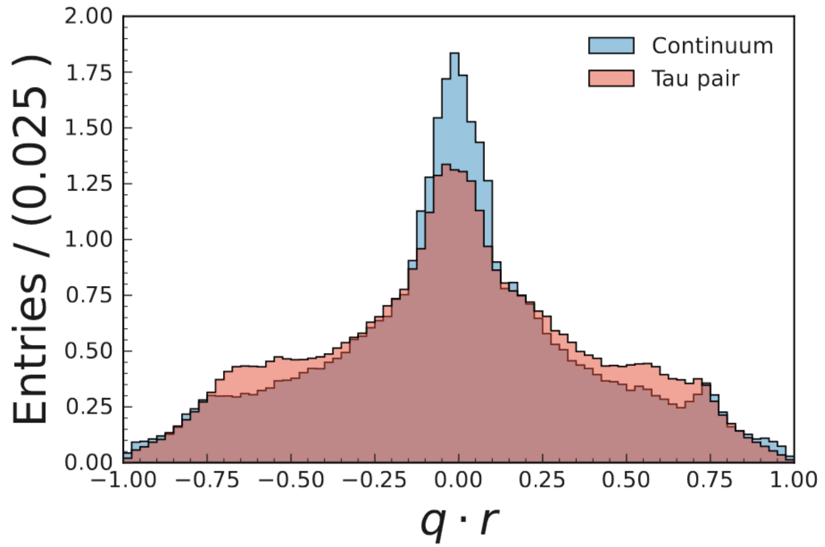


- Previously used the distribution averaged all over bins to generate identical distributions for each bin.
- Negligible effect on linearity plots, but in future continuum ΔE will depend on q.r bin



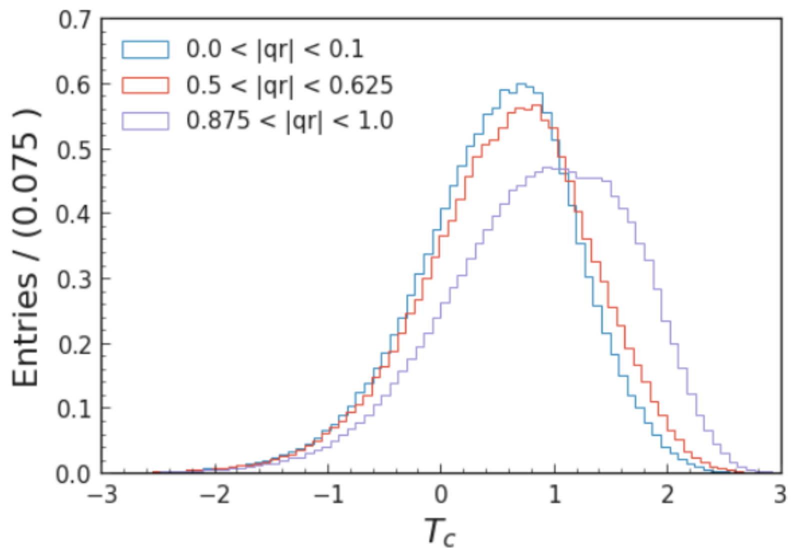
Tau pair contributions

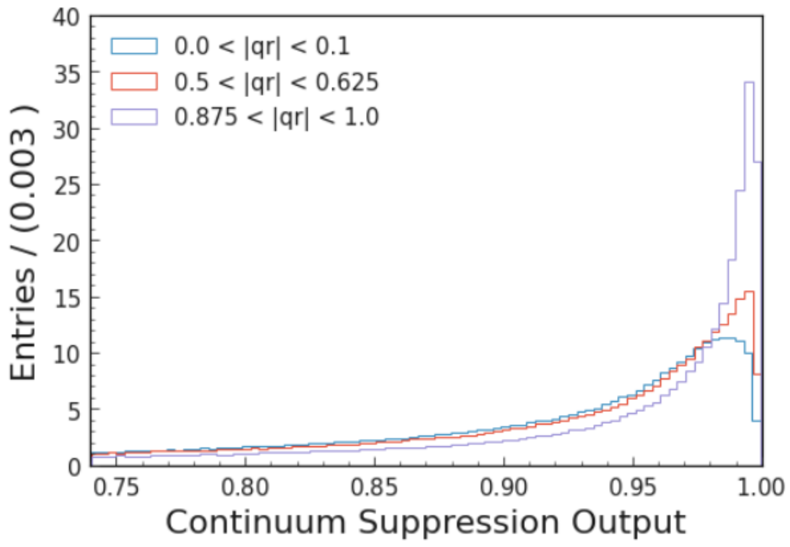
- Currently continuum bin fraction parameters are from MC, however this neglects the tau pair contribution, which have a different q.r distribution compared to continuum
- The ratio between tau pairs in the sideband and signal region is identical, 2.455% and 2.453%, respectively
- Get continuum bin fraction from experimental sideband
- Difference is small, at most 1% in each bin



Tc dependence on q.r

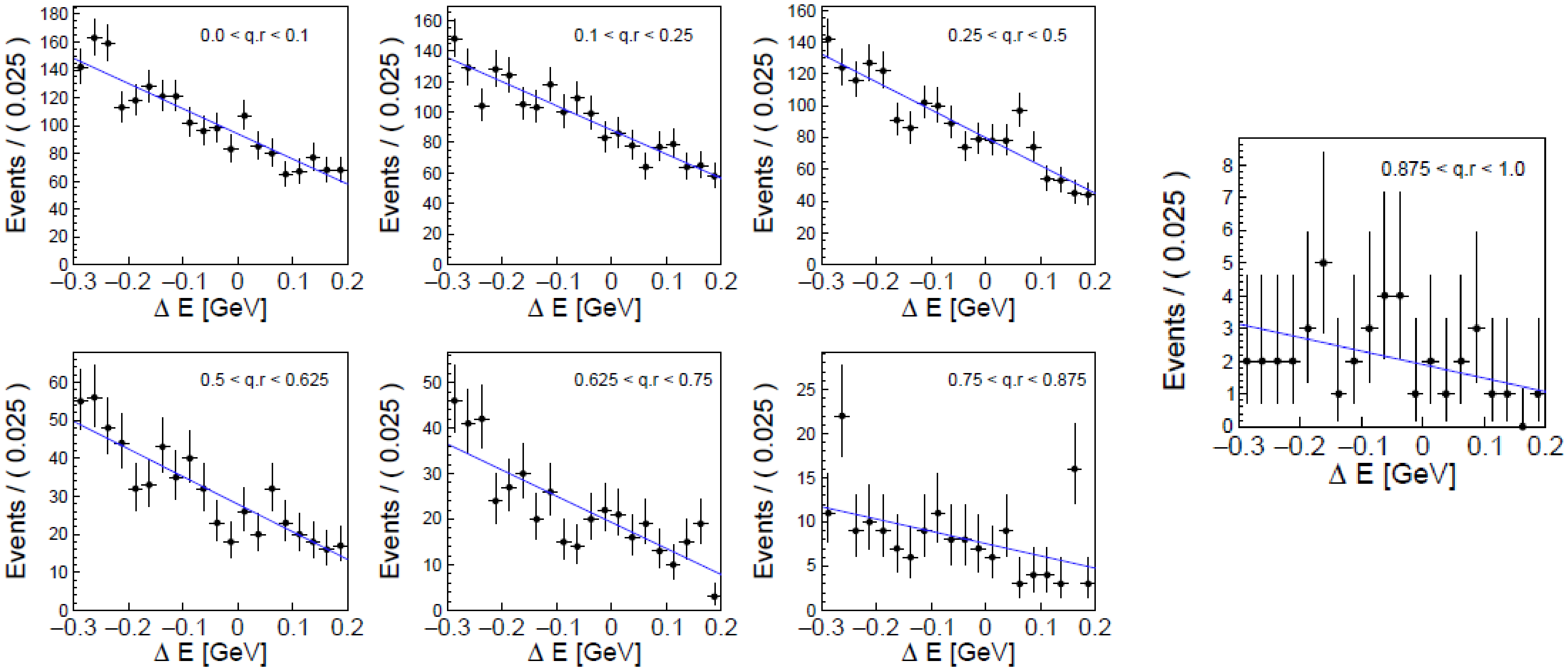
- Although we do not use q.r as a CS variable and all CS variables used have less than 5% correlation with q.r, we find the T_c distribution of the signal and BB depends on q.r
- Not surprising that the flavor tagger perform better on events with good q.r tagging
- Model the T_c distribution in each bin with a different PDF





Fitting to sideband in q.r bins

- Ideally the continuum ΔE PDFs would different as well, however we do not have enough experimental sideband data for good fits
- Taken into account in systematic uncertainty



Signal PDF

- The branching fraction and A_{CP} for the $B^0 \to \pi^0 \pi^0$ decay are determined with a three-dimensional (M_{bc}, ΔE, T_c) simultaneous maximum likelihood fit in 7 bins of q.r

$$P_i^s(M_{\rm bc}, \Delta E, T_c, q) = [1 - q \times \Delta w_i + q \cdot \mu_i \cdot (1 - 2w_i) + [q \cdot (1 - 2w_i) + \mu_i \cdot (1 - q \times \Delta w_i)](1 - 2\chi_d)\mathcal{A}_{CP}]P^s(M_{\rm bc}, \Delta E, T_c)$$

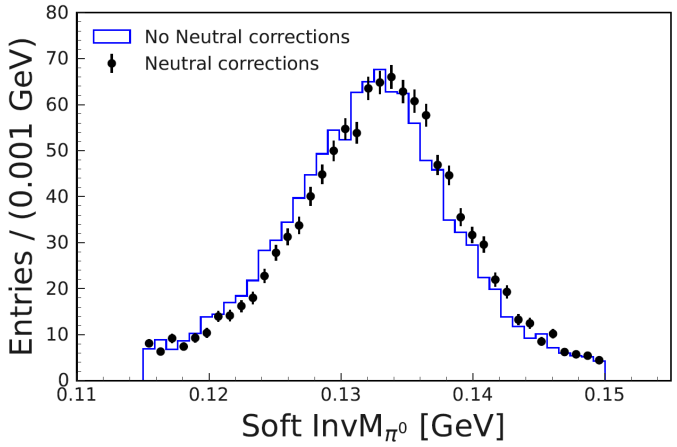
where $\chi_d = 0.1858 \pm 0.0011$ is the time-integrated $B\bar{B}$-mixing parameter, w_i is the wrong tag fraction, Δw_i is the difference in wrong tag fraction between positive and negative b-flavor tags, and μ_i is the difference in tagging efficiency between positive and negative b-flavor tags.

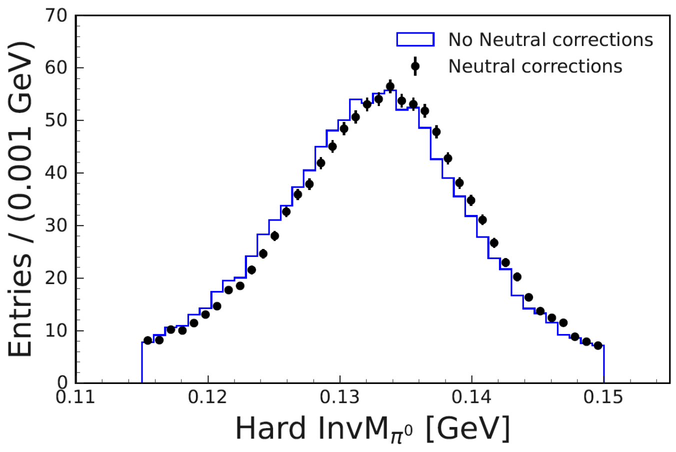
Control Mode distribution checks

- Change is small for soft $\boldsymbol{\pi^0}$ and this might explain why the ΔE difference in the control mode is so large compared to $\boldsymbol{B^+ \rightarrow D^0(K^+\pi^-\pi^0)\pi^+}$
- But more investigation is required since these corrections only depend on energy and not on the polar angle, and it could be that $\boldsymbol{\pi^0}$ from $\boldsymbol{B^0}$ are mostly located in a different region of the ECL which might affect the energy measured.
- Overall MC-DATA agreement is better

	No Corrections (MeV)	Corrections (MeV)	Difference (MeV)
Hard π^0 peak	132.39 ±0.09	133.44 ±0.06	1.05 ± 0.11
Soft π^0 peak	132.39 ±0.09	133.25 ±0.08	0.86 ± 0.12
Hard π^0 width	6.54 ±0.08	5.57 ±0.10	0.97 ± 0.13
Soft π^0 width	5.55 ±0.09	5.57 ±0.10	0.02 ± 0.13

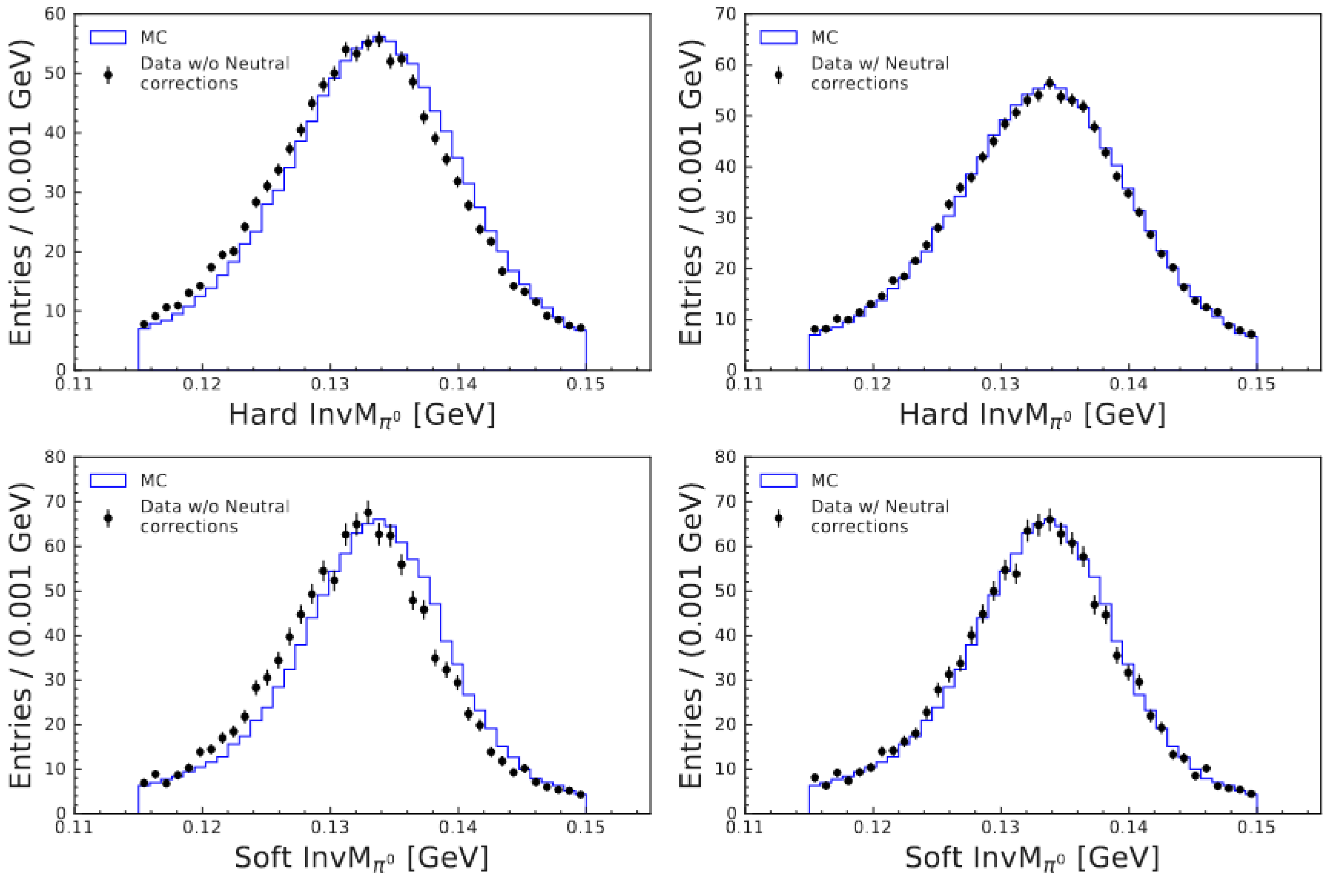
TABLE 39. Mean and width of invariant mass distribution of soft and hard π^0 before and after the 'Photon Energy Bias Correction' is applied along with the difference.





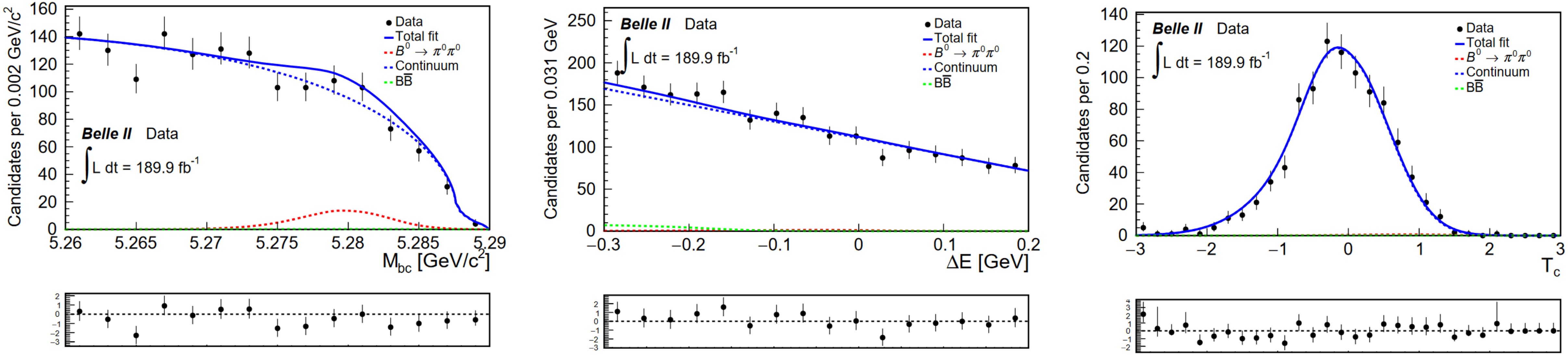
InvM of π^0 before and after neutral corrections

- Significant smaller MC-DATA discrepancy



Continuum enhanced plots

- Continuum appears mostly well modelled, particularly the M_{bc} endpoint
- Possible mismodelling on T_c
  (main contributor to continuum parameters systematic, 7.8%)



Systematics: q.r bin fractions

- For the mistagging parameters, we use the values obtained by the recent FlavorTagger paper
- Previously q.r bin fraction used MC
- Fluctuate q.r fraction by the uncertainty, and adjust all other parameters so the sum of all fractions equals one

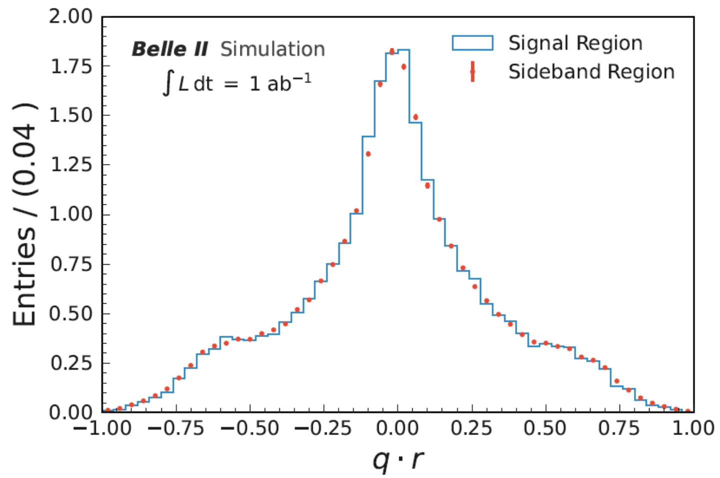
$B^0 \to D^{(*)-} h^+$

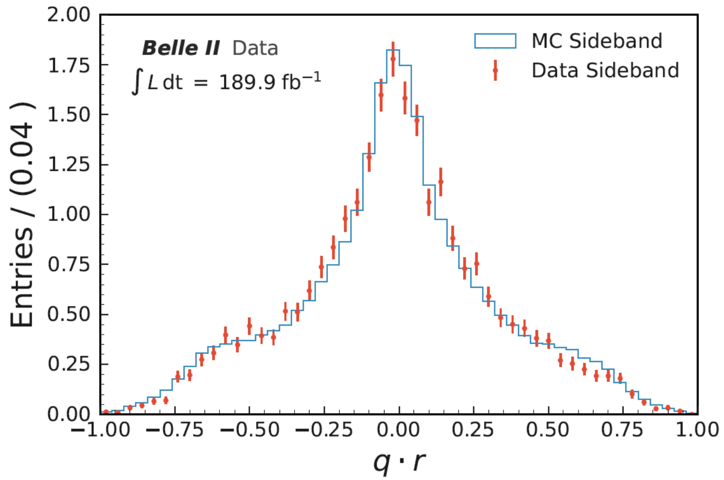
Parameter	ΔE PDF	Fit bias	Model	Total syst. uncty.	Fit results
ε_1	0.01	0.00	0.09	0.1	$19.0 \pm 0.3 \pm 0.1$
ε_2	0.01	0.00	0.09	0.1	$17.1 \pm 0.3 \pm 0.1$
ε_3	0.01	0.03	0.09	0.1	$21.3 \pm 0.3 \pm 0.1$
ε_4	0.01	0.01	0.07	0.1	$11.3 \pm 0.3 \pm 0.1$
ε_5	0.01	0.01	0.07	0.1	$10.7 \pm 0.3 \pm 0.1$
ε_6	0.00	0.01	0.06	0.1	$8.2 \pm 0.2 \pm 0.1$
ε_7	0.02	0.00	0.07	0.1	$12.4 \pm 0.2 \pm 0.1$
w_1	0.03	0.03	0.45	0.5	$47.1 \pm 1.6 \pm 0.5$
w_2	0.01	0.01	0.46	0.5	$41.3 \pm 1.7 \pm 0.5$
w_3	0.07	0.04	0.40	0.4	$30.3 \pm 1.4 \pm 0.4$
w_4	0.17	0.18	0.53	0.6	$22.9 \pm 1.8 \pm 0.6$
w_5	0.01	0.01	0.49	0.5	$12.4 \pm 1.8 \pm 0.5$
w_6	0.02	0.02	0.50	0.5	$9.4 \pm 1.9 \pm 0.5$
w_7	0.01	0.01	0.37	0.4	$2.3 \pm 1.3 \pm 0.4$
μ_1	0.01	0.03	0.91	0.9	$4.4 \pm 3.2 \pm 0.9$
μ_2	0.15	0.13	0.93	0.9	$3.9 \pm 3.3 \pm 0.9$
μ_3	0.05	0.00	0.82	0.8	$6.8 \pm 2.9 \pm 0.8$
μ_4	0.04	0.01	1.12	1.1	$3.2 \pm 4.0 \pm 1.1$
μ_5	0.16	0.23	1.06	1.1	$-0.5 \pm 4.1 \pm 1.1$
μ_6	0.02	0.04	1.14	1.1	$10.8 \pm 4.3 \pm 1.1$
μ_7	0.37	0.27	0.86	1.0	$-3.7 \pm 3.2 \pm 1.0$
Δw_1	0.16	0.12	0.57	0.6	$8.8 \pm 2.0 \pm 0.6$
Δw_2	0.12	0.15	0.59	0.6	$6.1 \pm 2.1 \pm 0.6$
Δw_3	0.12	0.11	0.54	0.6	$2.7 \pm 1.9 \pm 0.6$
Δw_4	0.05	0.01	0.77	0.8	$5.5 \pm 2.6 \pm 0.8$
Δw_5	0.05	0.03	0.74	0.7	$0.7 \pm 2.9 \pm 0.7$
Δw_6	0.08	0.07	0.84	0.9	$7.7 \pm 3.2 \pm 0.9$
Δw_7	0.19	0.17	0.66	0.7	$0.6 \pm 2.4 \pm 0.7$

Continuum qr asymmetry

- Instrumental asymmetry observed
- Signal and sideband region q.r distribution agree
- Assume this is true in experimental Data, and extract the A_{CP} from the sideband region
- Add A_{CP} term to the continuum PDF
- Repeat fit with continuum A_{CP} shifted by uncertainty, difference in A_{CP} assigned as systematic uncertainty: **0.01**

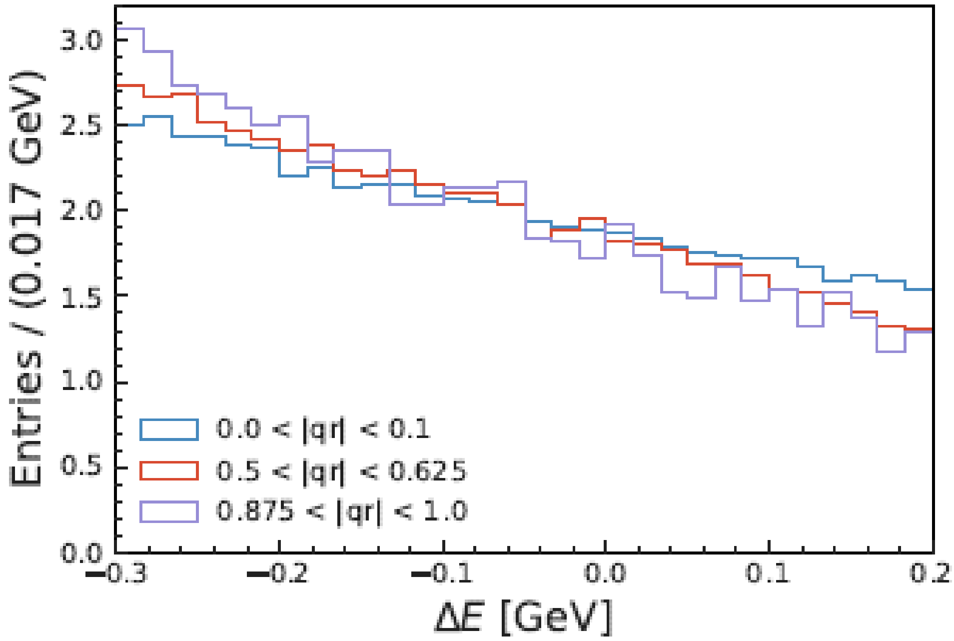
	$\mathcal{A}_{CP}$
MC Signal Region	-0.024 ± 0.006
MC Sideband Region	-0.025 ± 0.003
Data Sideband Region	-0.033 ± 0.002





Systematic: Identical PDF

- The shape of ΔE for the continuum depends on q.r, however there are not enough events in the sideband region to fit.
- The continuum parameters are identical in all bins, to account for this we estimate the ΔE parameters in each q.r bin using MC and refit

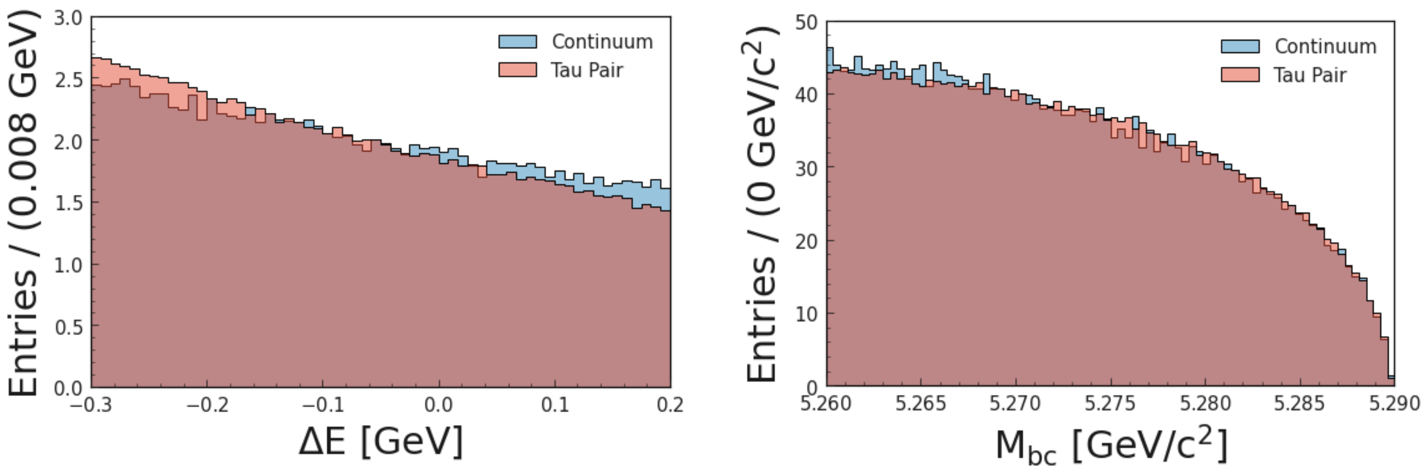


Systematics: Best candidate selection

- To account for the systematics uncertainty due to the choice of best candidate, i.e. $|dM_1| + |dM_2|$, the sum of the absolute mass deviation of the π^0 from the known value, we randomly select a candidate and refit. The difference in signal yield is taken as systematic; **0.2%**

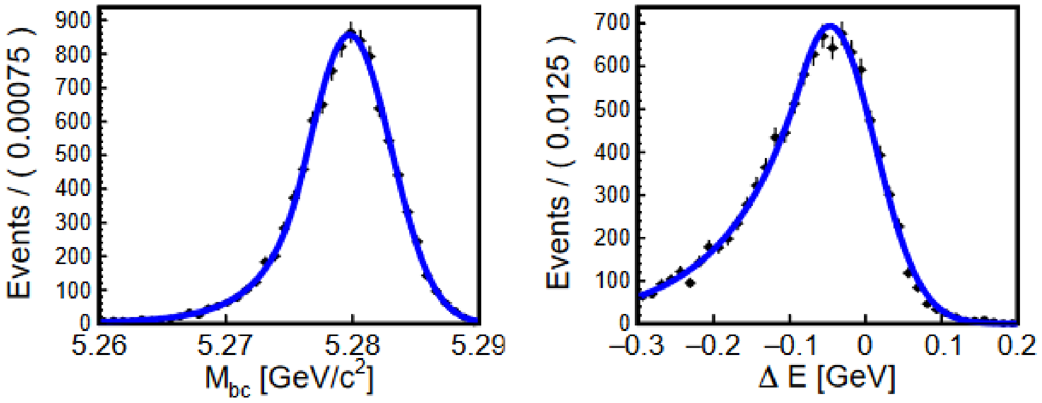
Tau pairs

- Since we get the continuum PDF parameters from the sideband region (which contains taupairs), our continuum should also include taupairs
- Expect 215 in 189.9/fb (2.4% of continuum) which is absorbed into continuum background
- Uncertainty is covered by continuum parameterisation systematic



Systematics: choice of signal PDF

- We model the signal M_{bc} and ΔE using a 2D Kernal Density Estimation (KDE) to account for the correlation
- To estimate the systematic associated with this choice, we refit using analytical functions (Crystal Ball) for M_{bc} and ΔE
- The BF and A_{CP} systematic uncertainty is **1.3% and 0.02**



Systematic: π^0 efficiency

$$\epsilon^{\pi^0} = \frac{N(K^-\pi^+\pi^0)}{N(K^-\pi^+)} \cdot \frac{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}{\mathcal{B}(\bar{D}^0 \to K^+\pi^-\pi^0) \cdot \mathcal{B}(\pi^0 \to \gamma\gamma)}$$

- π^0 selections are identical, and hence systematic associated with the photonMVA is also included
- The ratio between π^0 efficiencies in data and in simulation is found to be 1.030 ± 0.038
- 3.8% per π^0 efficiency but signal has two completely correlated π^0, so 7.6% for systematic uncertainty

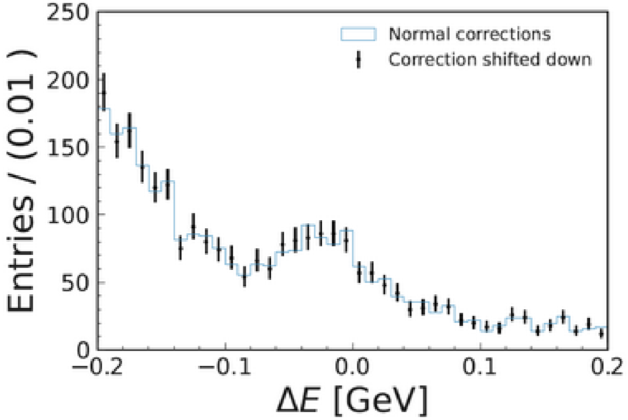
Systematic: Photon Energy Corrections

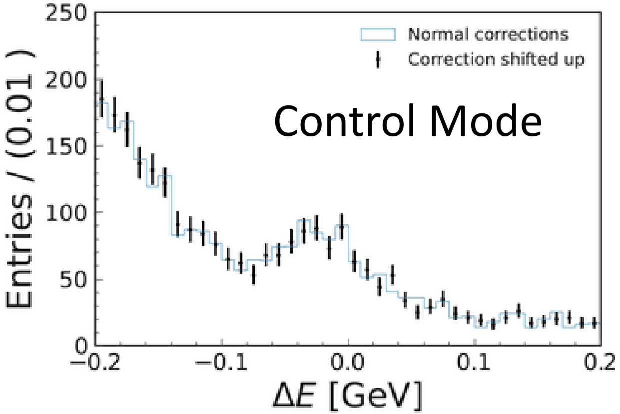
Neutral group has prepared two more payload:

- PhotonEnergyBiasCorrection_MC14a_Jan2022_lower_V3, with each point decreased by its uncertainty
- PhotonEnergyBiasCorrection_MC14a_Jan2022_upper_V3, with each point increased by its uncertainty

We then refit and take the difference in yield as the systematic uncertainty;

BF systematic uncertainty: **2.0%**.





Systematic: Fixed BB in fits

- The number of BB is fixed from MC, but has a PDG uncertainty associated

$B\bar{B}$ decay	Branching ratio	$\mathcal{A}_{CP}$	Efficiency	189.9 fb^{-1} estimation
$B^+ \to \rho^+\pi^0$	$1.09 \pm 0.14 \times 10^{-5}$	0.02 ± 0.11	4.28%	101 ± 13
$B^0 \to K_s(\to \pi^0\pi^0)\pi^0$	$3.04 \pm 0.15 \times 10^{-6}$	0.00 ± 0.13	1.54%	9.6 ± 0.5

- To estimate the uncertainty, we repeat 1000 ToyMC fit but with an additional or deficiency in BB events corresponding to 1 sigma, then we take which one creates a larger difference in yield as the systematic.
- Systematic uncertainty: **1.8%**

Systematic: Mistagging Parameters

- Fit repeated with each parameter fluctuated by its uncertainty
- The effect of all 21 parameters are added in quadrature
- Contribution of each mistagging parameter, correlations are zero or negligible
- As expected the bins with poor tagging contribute the least to A_{CP}
- **A_{CP} uncertainty is 0.05**

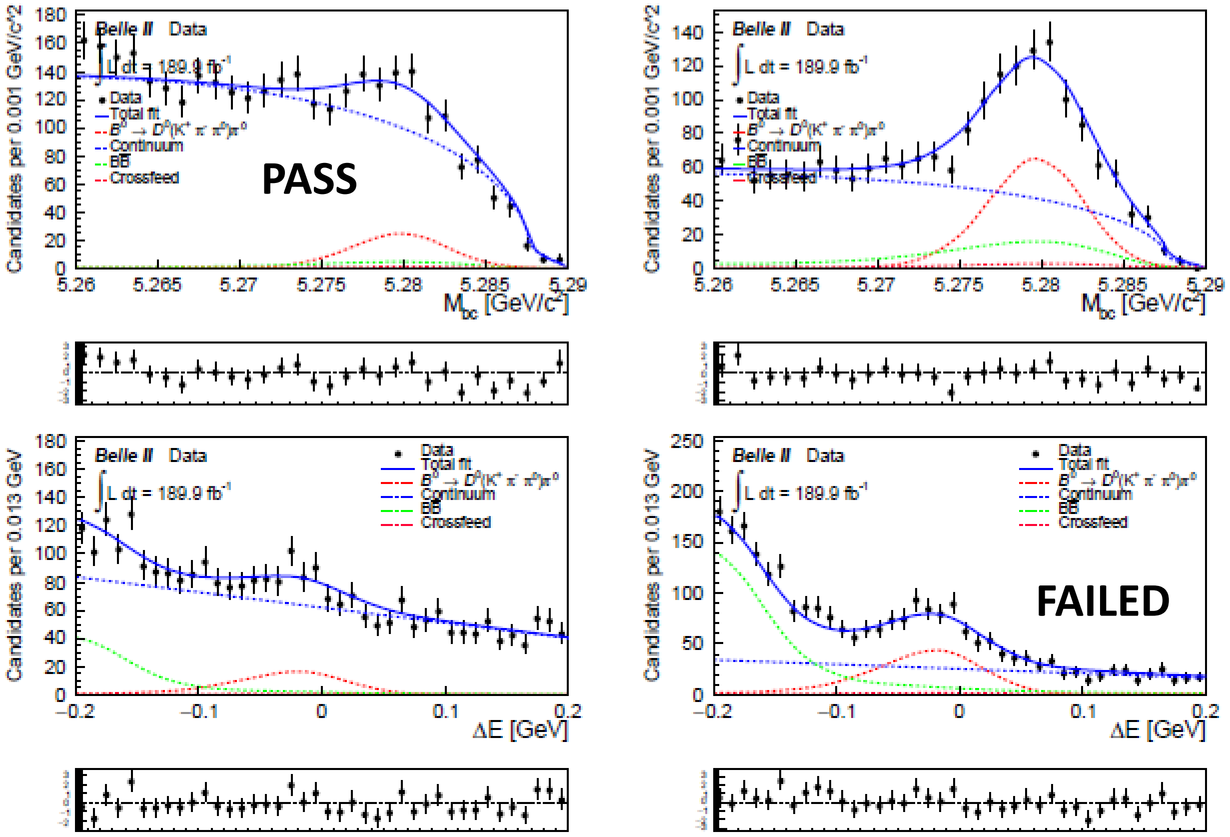
Bin	w	Δw	μ
1	0.017	0.0021	0.00071
2	0.0091	0.0024	0.0013
3	0.0071	0.0045	0.003
4	0.0086	0.0079	0.0066
5	0.012	0.023	0.019
6	0.0096	0.014	0.013
7	0.0073	0.012	0.014

Systematic: Continuum suppression

- Fit two control mode samples, pass or failed CSMVA selection and determine:

$$\epsilon = \frac{\text{Signal events that pass the selection}}{\text{Total signal events (pass and fail the selection)}}$$

$B^0 \to D^0(\to K^-\pi^+\pi^0)\pi^0$	
ϵ_{data}	0.6928 ± 0.0386
ϵ_{MC}	0.7201 ± 0.0207



- 1.040 ± 0.065, assign stat. uncertainty as syst.

Systematic: Continuum Parameterization

- Parameters and their uncertainties obtained from fits to sideband
- Fluctuate each parameter by one standard deviation, shifted all other parameters by their correlation
- Add all contributions in quadrature: **7.5% and 0.02** systematic uncertainty on BF and A_{CP} respectively

Parameter	Yield Uncertainty (%)	$\mathcal{A}_{CP}$ Uncertainty
Tc Fraction	4.38	0.013
Tc Mean Gaussian 1	5.12	0.017
Tc Width Gaussian	2.50	0.008
Tc Mean Gaussian 2	1.38	0.004
Tc Left Width Bi-Gaussian	0.90	0.002
Tc Right Width Bi-Gaussian	0.93	0.002
$M_{\rm bc}$ ARGUS shape	0.36	0.001
ΔE Chebyshev	0.31	0.001

Systematic uncertainty: BB background

$B\bar{B}$ decay	Branching ratio	$\mathcal{A}_{CP}$	Efficiency	189.9 fb^{-1} estimation
$B^+ \to \rho^+\pi^0$	$1.09 \pm 0.14 \times 10^{-5}$	0.02 ± 0.11	3.53%	83 ± 11
$B^0 \to K_s(\to \pi^0\pi^0)\pi^0$	$3.04 \pm 0.15 \times 10^{-6}$	0.00 ± 0.13	1.22%	7.6 ± 0.4

- The dominant BB background come from $\boldsymbol{B^+ \to \rho^+(\to \pi^0\pi^+)\pi^0}$ and $\boldsymbol{B^0 \to K_s(\to \pi^0\pi^0)\pi^0}$ which are expected to have A_{CP}=0.0
- Generate BB background with A_{CP} one standard deviations away from the accepted value.
- Perform 189.9/fb ToyMC with different BB background A_{CP} and use the deviation from BB background A_{CP}=0.0
- Systematic is: **0.03**

$\mathcal{A}_{CP}$ $(B^+ \to \rho^+\pi^0)$	$\mathcal{A}_{CP}$ $(B^0 \to K^0_S\pi^0)$	Average Extracted $\mathcal{A}_{CP}$
0	0	-0.339
-0.09	-0.13	-0.351
0.13	0.13	-0.318
-0.09	0.13	-0.354
0.13	-0.13	-0.327

$B^0 \to D^0(K^-\pi^+\pi^0)\pi^0$ Control mode

Selection	Control efficiency (%)
Skimming	58.0
Control selections	11.1
Continuum Suppression	8.50

- Signal mode continuum suppression is applied to the control mode to allow for continuum suppression systematic uncertainty to be estimated
- For the control mode, there is much more self-cross feed due to having two charged particles where a particle from the tag side is used in the reconstruction of the control mode
- For the fit, the cross-feed yield is constrain to be 9% of the control yield

$B^0 \to D^0(K^-\pi^+\pi^0)\pi^0$ Control mode

The control mode efficiency is 11.1%

Particle	Selection
π^+	Transverse impact parameter $\|dr\| < 0.5$ cm Longitudinal impact parameter $\|dz\| < 2$ cm Binary PID between kaons and pions, binaryPID(321,211) < 0.4 Polar angle θ within the range $17^\circ < \theta < 150^\circ$ Number of CDC hits associated to the track nCDCHits > 20
K^-	Transverse impact parameter $\|dr\| < 0.5$ cm Longitudinal impact parameter $\|dz\| < 2$ cm binaryPID(321,211) > 0.6 Polar angle θ within the range $17^\circ < \theta < 150^\circ$ Number of CDC hits associated to the track nCDCHits > 20
D^0	$1.84 < \mathrm{M} < 1.88$ massKFit $\chi^2 > 0$
B^0	$5.26 < M_{\mathrm{bc}} < 5.29$ GeV/c^2 $-0.2 < \Delta E < 0.2$ GeV