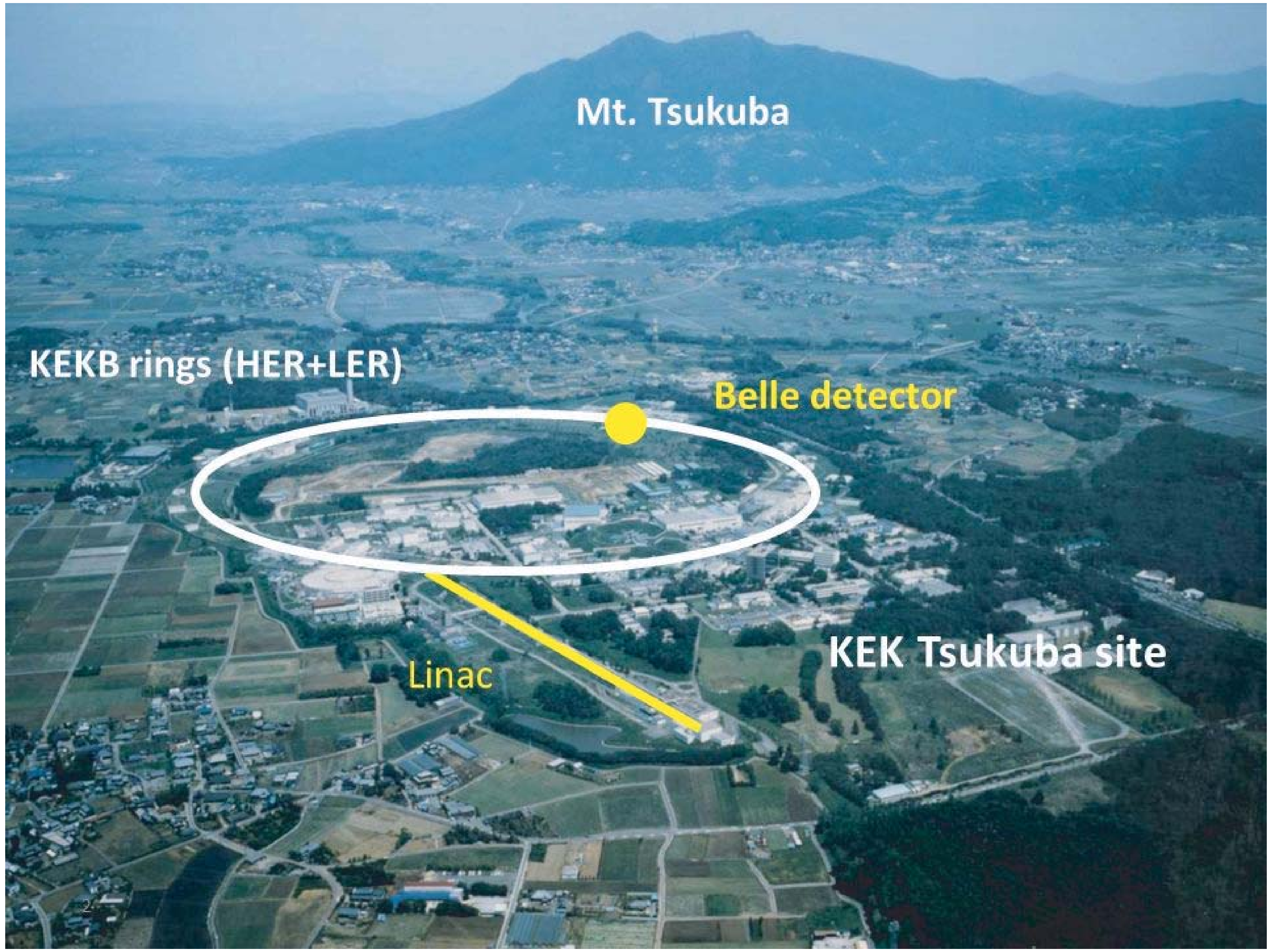
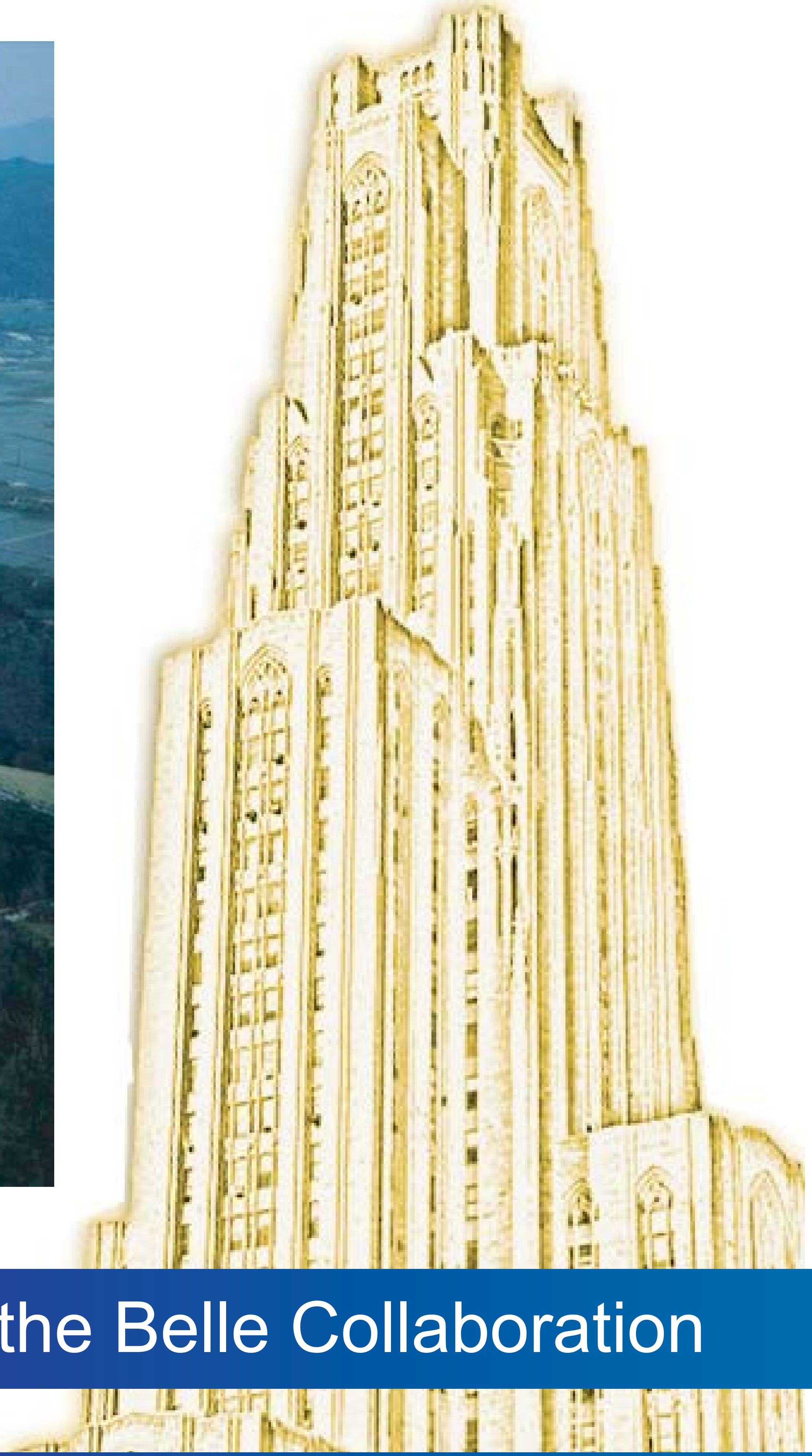
Search for New Decays of B Mesons to Charmed Baryons





Mark Farino, Vladimir Savinov (University of Pittsburgh) on behalf of the Belle Collaboration

The Beginning of Time

-Matter and antimatter should have been produced in equal amounts

-CP violation in Standard Model does not fully explain evident matter-antimatter asymmetry

-One of the greatest mysteries in physics

Baryogenesis

In 1967 Andrei Sakharov formulated three necessary conditions for baryogenesis, i.e., asymmetry between matter and anti-matter:

Sakharov's Three Conditions for Baryogenesis

- Baryon number violation
- C and CP violation
- Departure from thermal/chemical equilibrium

"According to our hypothesis, the occurrence of charge asymmetry is the consequence of violation of charge-parity (CP) invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions"

Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe -Sakharov, A.D. Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32-35, JETP Lett. 5 (1967) 24-27, Sov.Phys.Usp. 34 (1991) no.5, 392-393, Usp.Fiz.Nauk 161 (1991) no.5, 61-64

C and CP violation have been experimentally observed*

Departure from thermal equilibrium is satisfied by expansion of the universe

Numerous unsuccessful searches for baryon number violation have been performed

* CP Violation discovery: J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay (1964), Phys. Rev. Lett. 13, 138

Observation of large CP violation in the neutral B meson system: Abe K., et al. Belle Collaboration (2001), Phys. Rev. Lett. 87, 091802

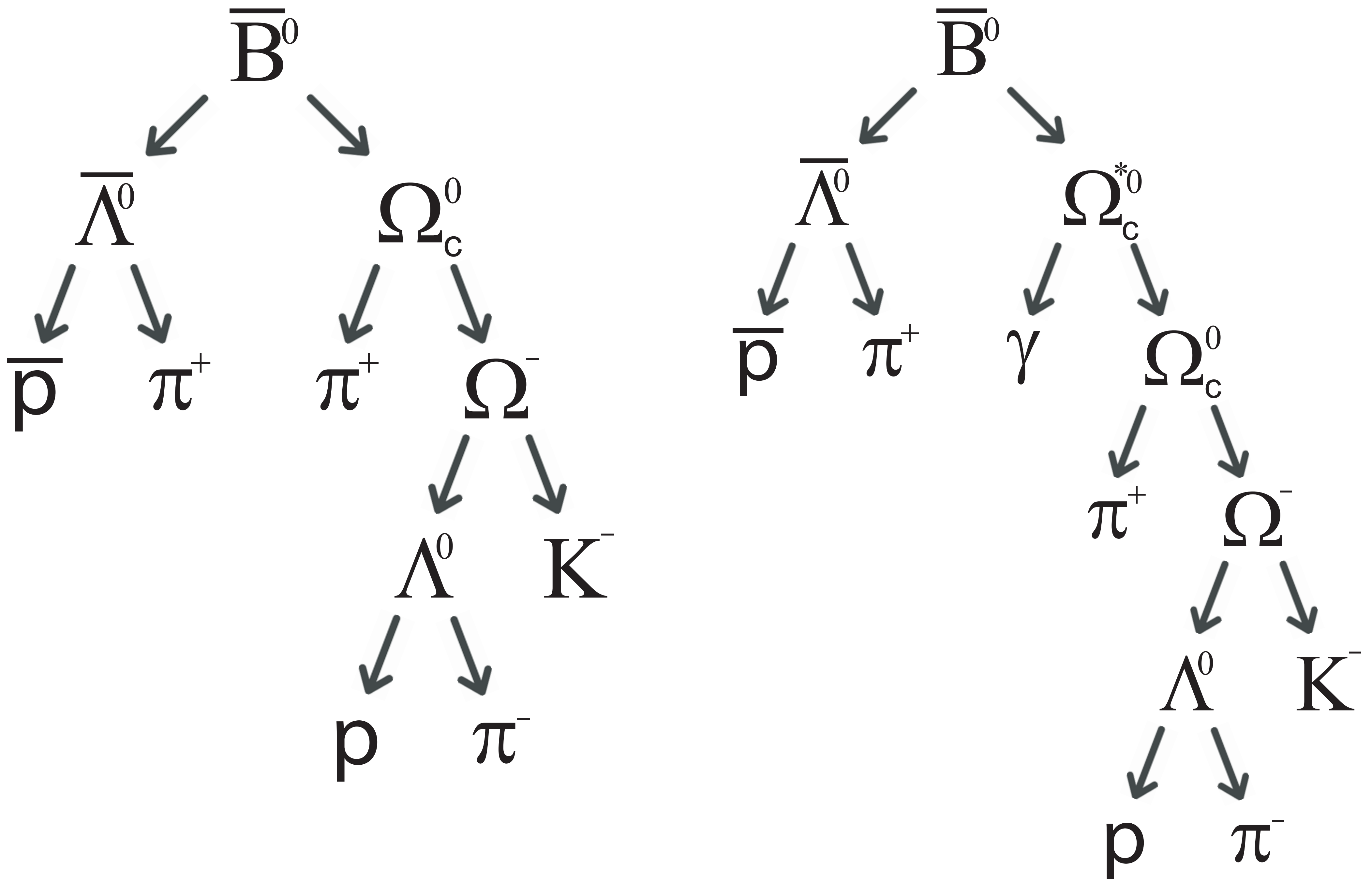
C (and P) are both maximally violated in weak interactions

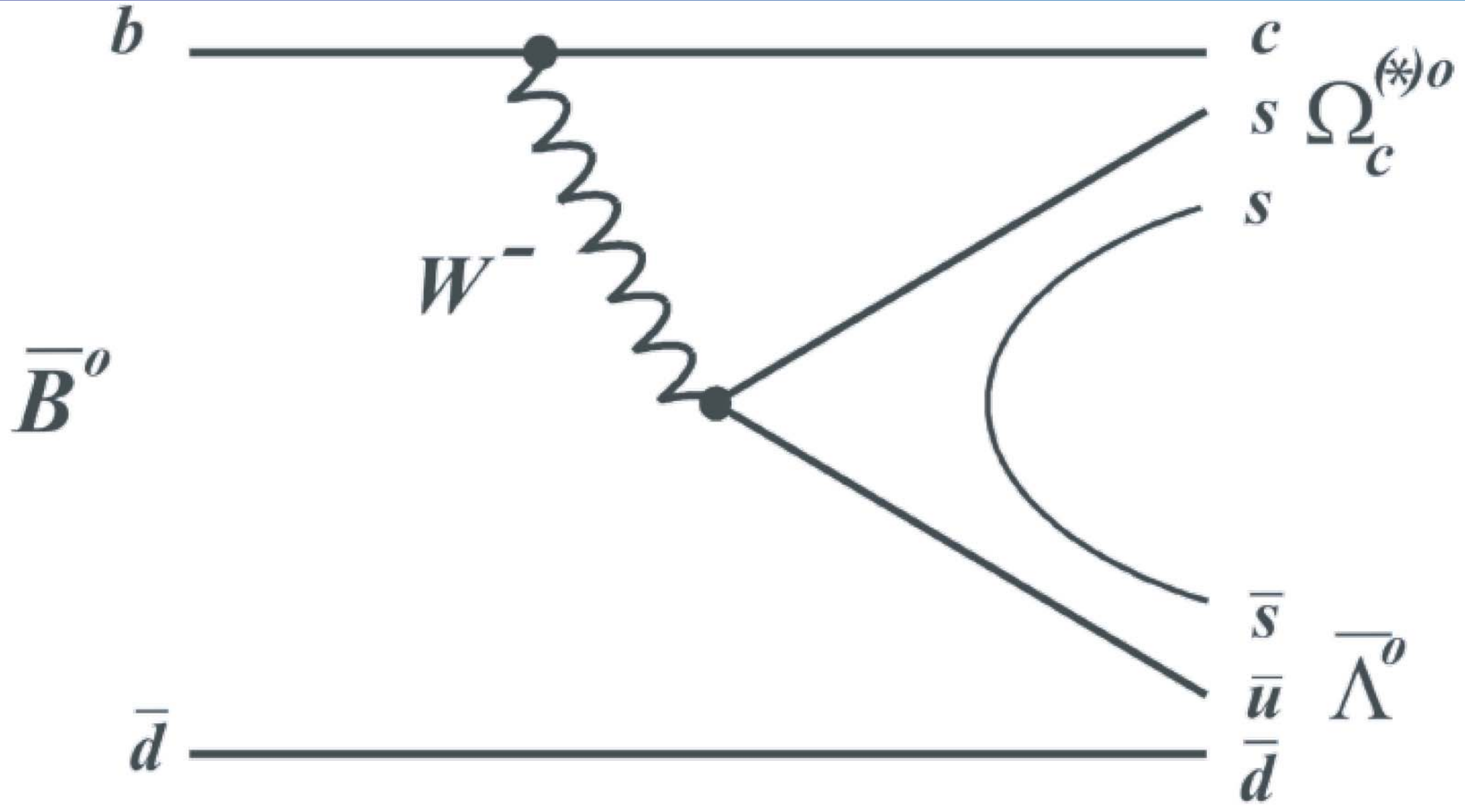
-Recent theoretical assertions suggest baryon number violation could arise from charmed baryon $\Omega_c^0 - \overline{\Omega}_c^0$ oscillations*

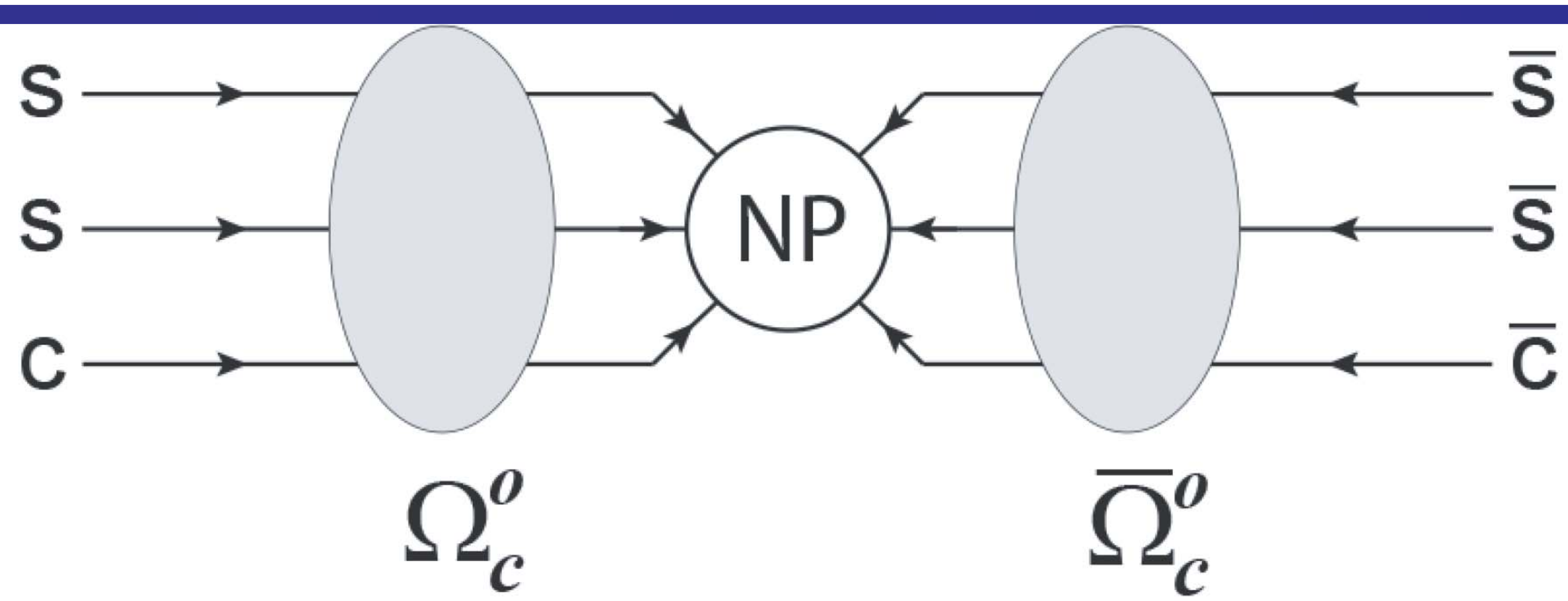
-Hence searching for not yet observed decays $\overline{B}^0 \to \overline{\Lambda}^0\,\Omega_c^0$ and $\overline{B}^0 \to \overline{\Lambda}^0\,\Omega_c^{*0}$ in data collected at Belle experiment

-First search of this type performed at LHCb (Ξ_b^0 oscillations)**

Decay Channels







*Baryogenesis from Oscillations of Charmed or Beautiful Baryons Phys.Rev. D96.7, 075009 (2017)

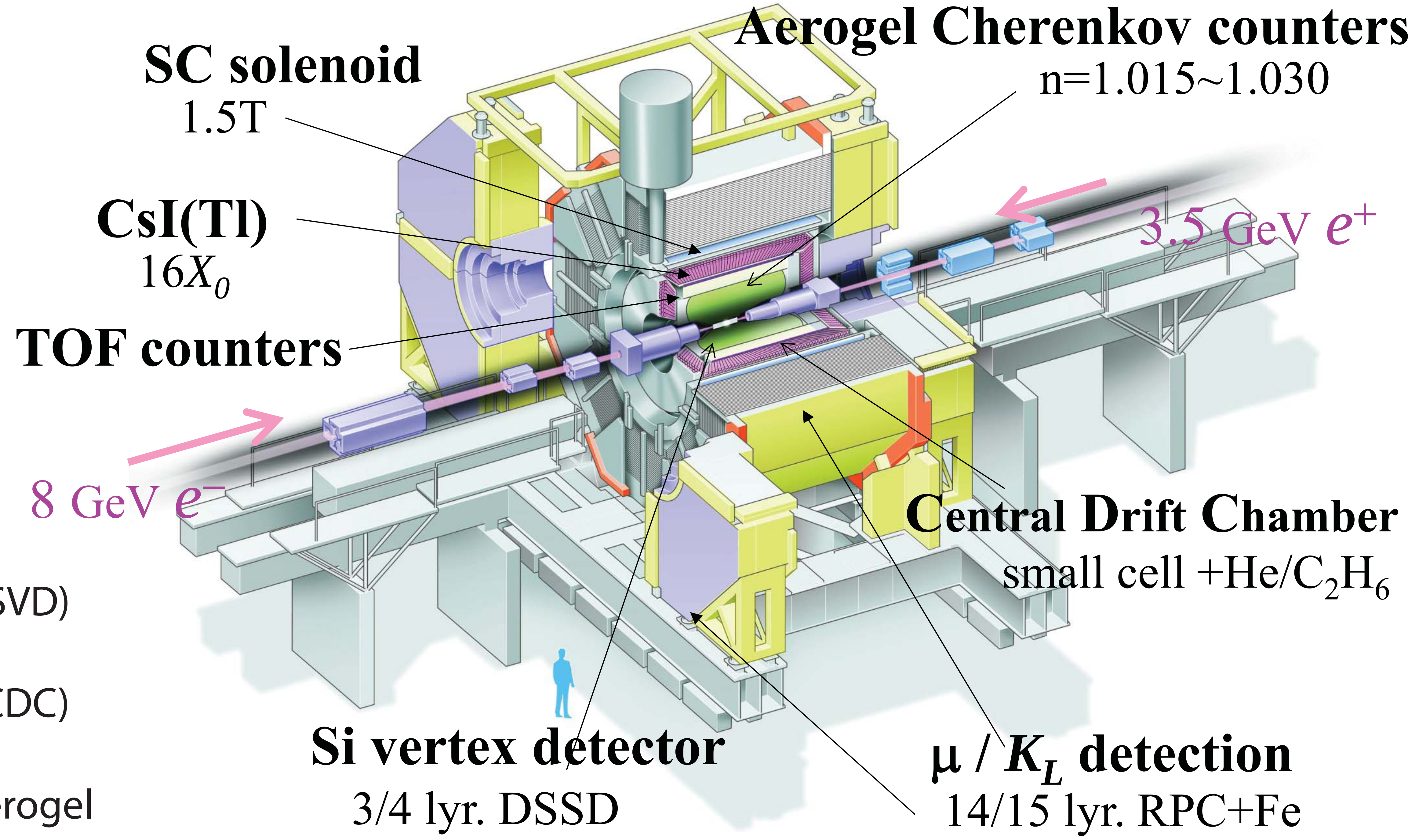
**Search for baryon-number-violating Ξ_b^0 oscillations Phys. Rev. Lett. 119, 181807 (2017)

-Collected data between 1999 and 2010 at the circular electron-positron collider KEKB in Japan

-used to obtain evidence of CP violation for particles containing heavy b quark

-data could be used to search for baryon number violation

Belle Detector



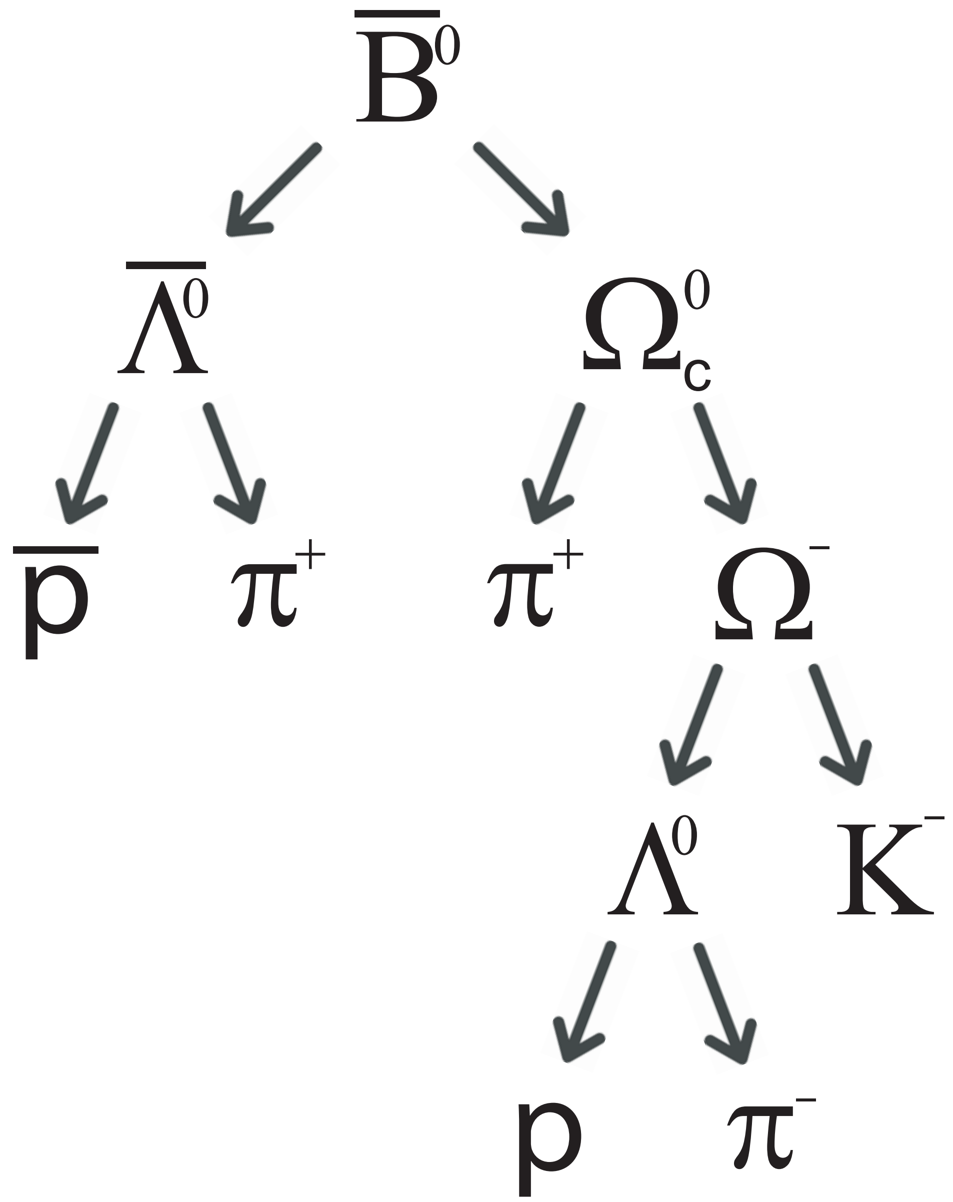
- B meson decay vertices measured by silicon vertex detector (SVD)

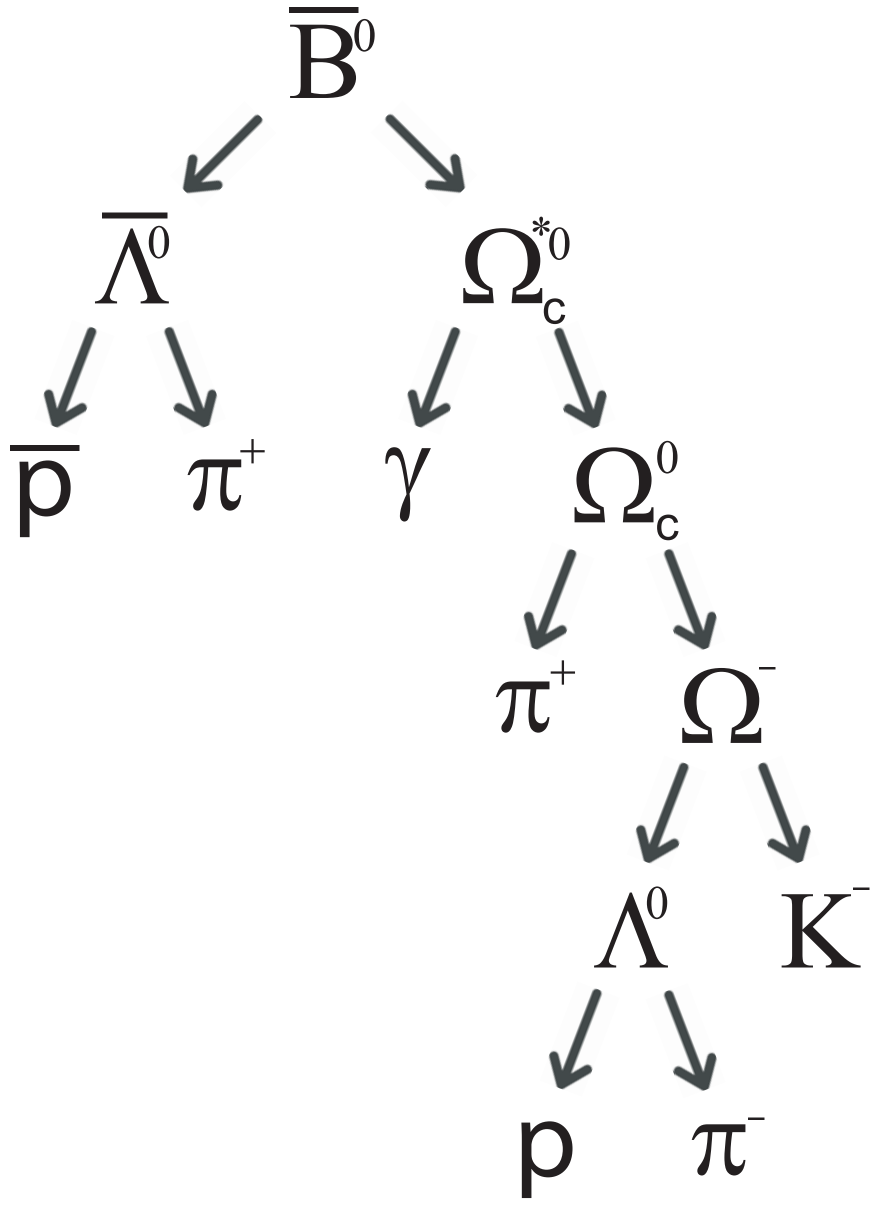
- Charged particle tracking performed by wire drift chamber (CDC)

- Particle identification performed by measurements in CDC, aerogel Cherenkov counters (ACC), and time of flight counters (TOF)

A. Abashian *et al.* [Belle], "The Belle Detector," Nucl. Instrum. Meth. A **479**, 117-232 (2002) doi:10.1016/S0168-9002(01)02013-7

- Blind analysis
- Extensive signal and generic MC samples (6 x data) are employed
- Vertex fits and mass constraints are used to reconstruct parent particles
- Discovery sensitivity is optimized using detector simulation
- Will soon unblind the signal box

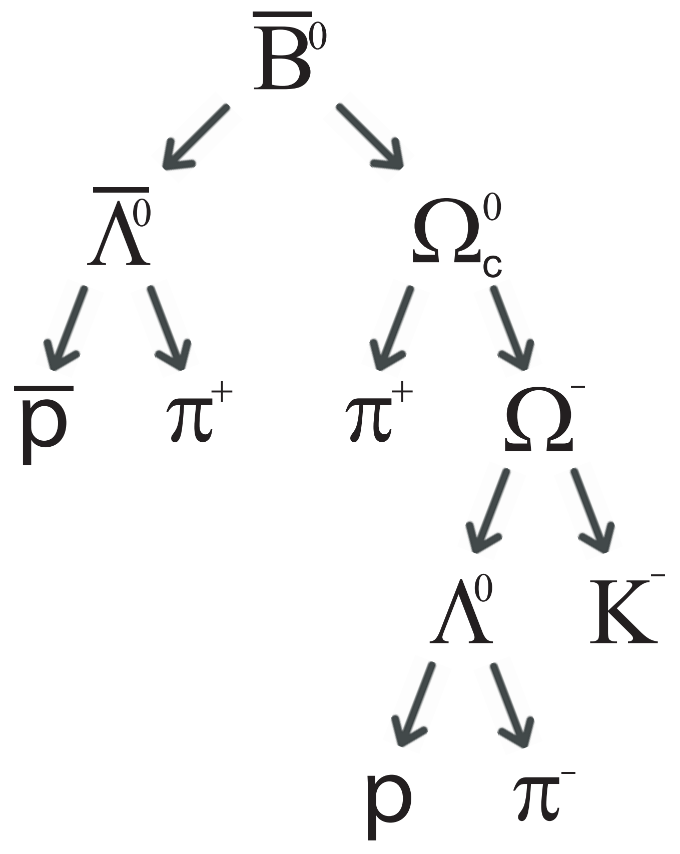


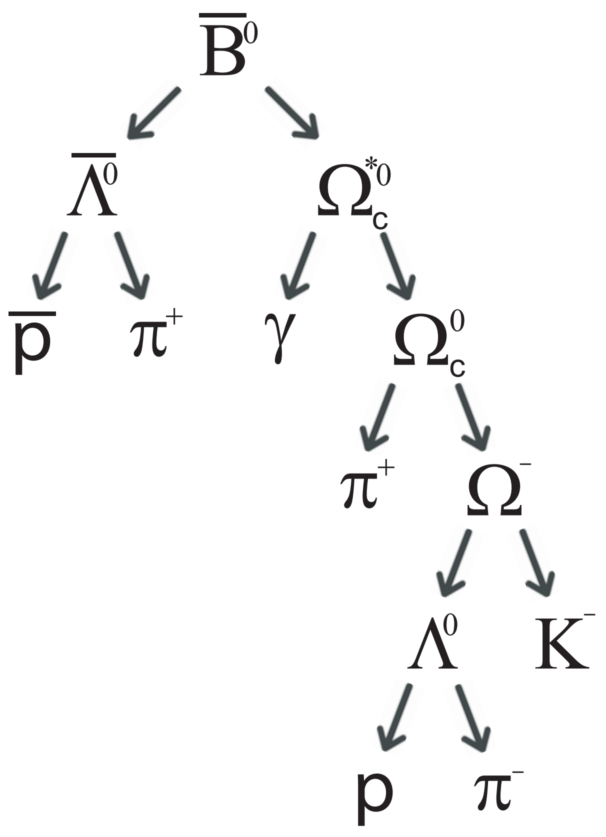


Signal Reconstruction

- Standard Belle Λ^0 candidates are used
- Ω^- candidates are then reconstructed by applying a vertex fit and mass constraint to the Λ^0 candidates, then we use the resulting four-momentum to reconstruct Ω^- candidates
- Ω_c^0 candidates are reconstructed in a similar fashion to Ω^-
- For channel $\overline{B}^0$ –> $\overline{\Lambda}^0$ Ω_c^{*0}, we do not reconstruct γ from Ω_c^{*0}
- Candidates are required to pass various selection criteria:
  1. final state particle candidates are identified using likelihood-based particle identification approach
  2. daughter particle candidates are identified using reconstructed invariant masses
  3. B^0 candidates are identified using beam-energy constrained B^0 mass $(M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_{B^0}^2})$ and energy difference $\Delta E = E_{B^0} - E_{\rm beam}$

Selection Criteria





Parameter	Requirement
π candidates (not applied to π daughters from Λ^0, $\bar{\Lambda}^0$)	$R_{\pi/K} \geq 0.6$, $R_{e/\pi} < 0.95$, $p_\perp \geq 50$ Mev$/c$
K candidates	$R_{K/\pi} \geq 0.4$, $R_{e/\pi} < 0.95$, $p_\perp \geq 50$ MeV$/c$
p candidates	$R_{p/K} \geq 0.1$ and $p_\perp \geq 50$ MeV$/c$
Ω^- candidates	Decay Length ≥ 0.50 cm
$\Lambda^0/\bar{\Lambda}^0$ candidates' reconstructed invariant masses (avf)	$\lvert$mass$_{\text{avf}}$ - Λ^0 invariant mass $\rvert \leq 8$ MeV (5.4 σ)
Ω^- candidates' reconstructed invariant masses (bvf)	$\lvert$mass$_{\text{bvf}}$ - Ω^- invariant mass $\rvert \leq 60$ MeV (15.1 σ)
Ω^- candidates' reconstructed invariant masses (avf)	$\lvert$mass$_{\text{avf}}$ - Ω^- invariant mass $\rvert \leq 7$ MeV (4.4 σ)
Ω_c^0 candidates' reconstructed invariant masses (bvf)	$\lvert$mass$_{\text{bvf}}$ - Ω_c^0 invariant mass $\rvert \leq 100$ MeV (17.5 σ)
Ω_c^0 candidates' reconstructed invariant masses (avf)	$\lvert$mass$_{\text{avf}}$ - Ω_c^0 invariant mass $\rvert \leq 19$ MeV (4.1 σ)
$\Lambda^0, \bar{\Lambda}^0, \Omega^-, \Omega_c^0$ candidates	$\frac{\chi^2 \text{from vertex or mass-constrained vertex fit}}{\text{number of deg. of freedom}} \leq 100$
ΔE	-0.4 GeV $\leq \Delta E \leq 0.3$ GeV
M_{bc}	$M_{\text{bc}} \geq 5.2$ GeV$/c^2$

$$R_{i/j} = L_i/(L_j + L_i),\ i, j \in \{\pi, K, p, e\}$$

- decay length := distance traveled between particle's production and decay

- bvf := 'before vertex fit'

- avf := 'after vertex fit'

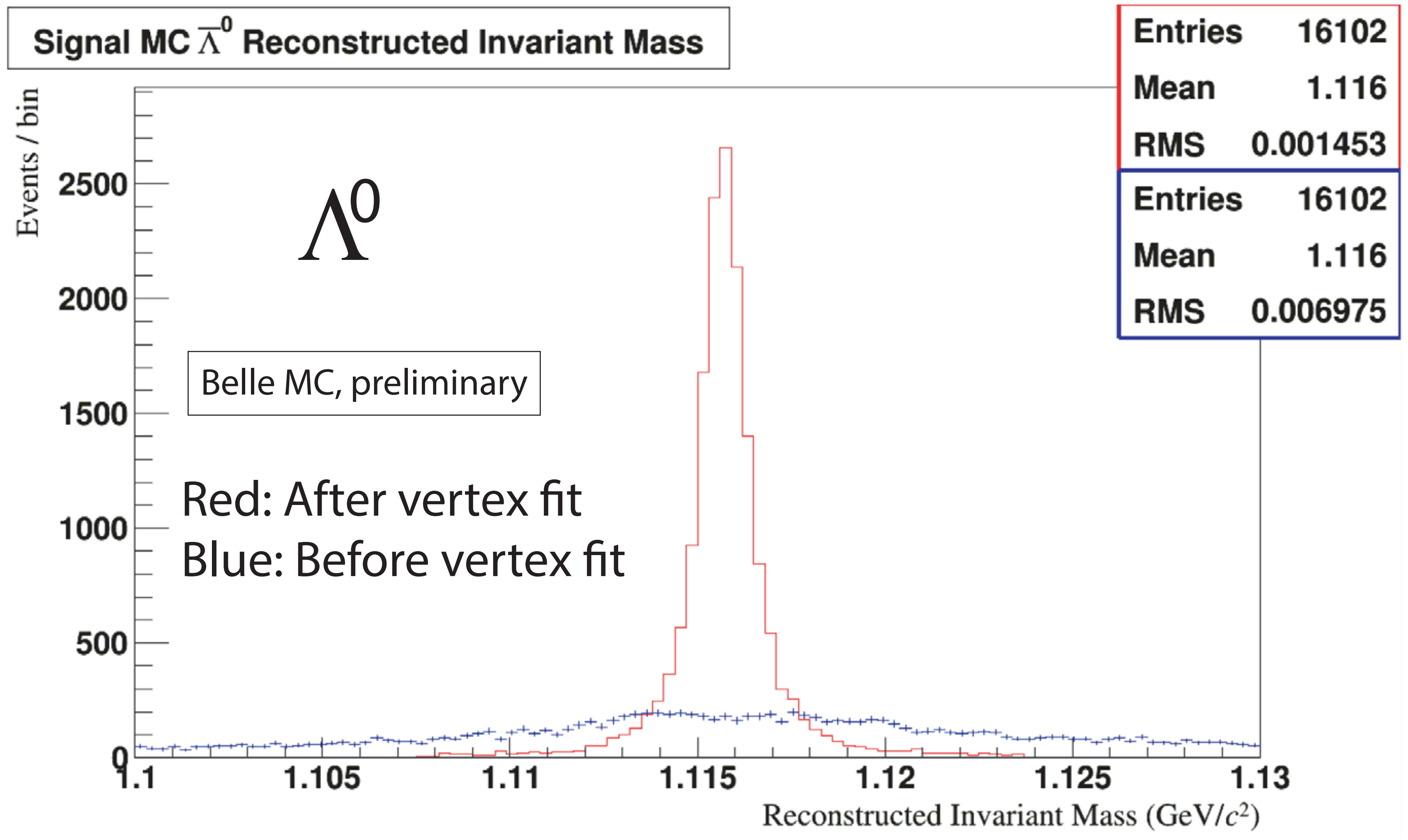
- vertex fitting procedure:
  - vertex fit and mass constraint performed simultaneously

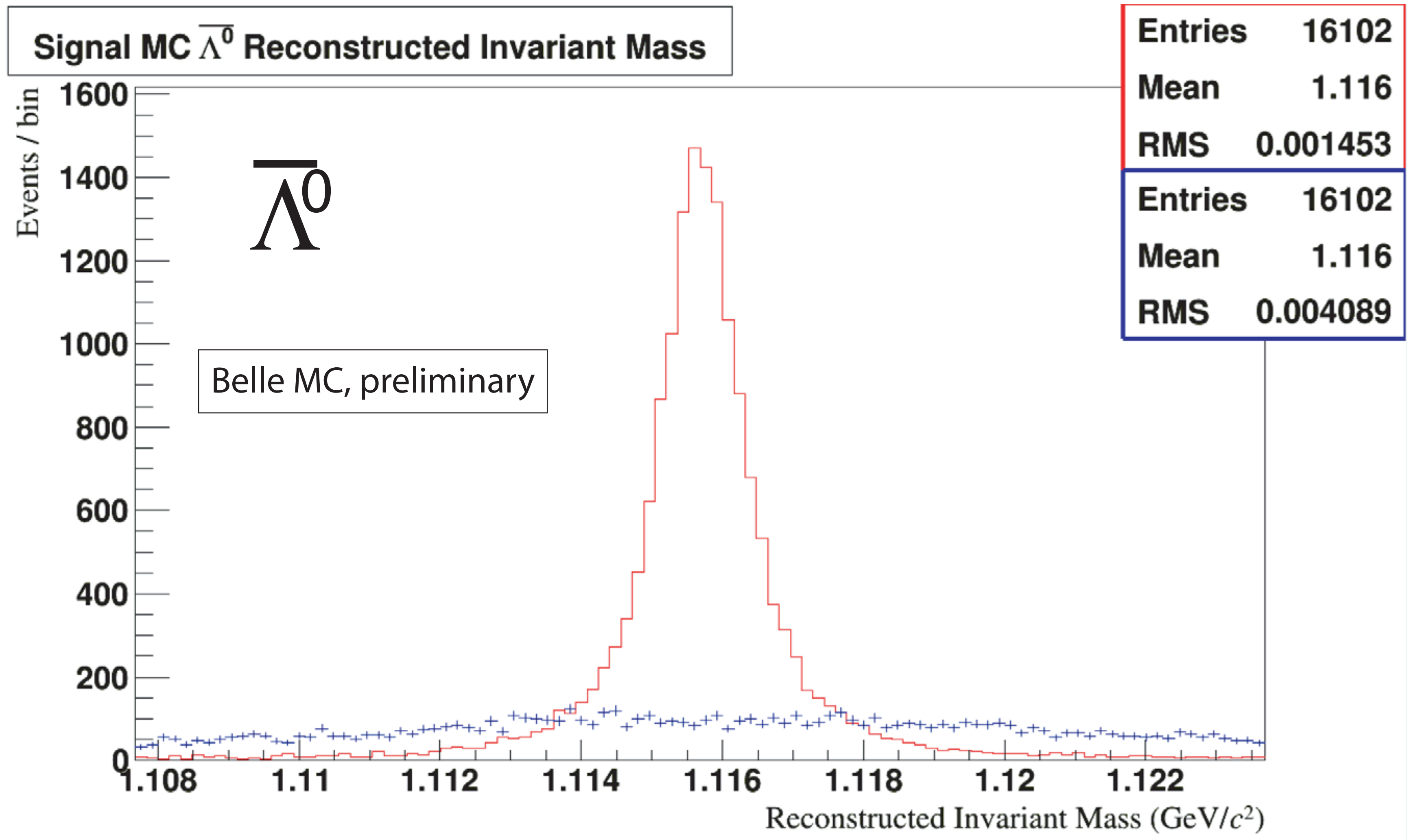
- all tracks are required to have transverse momenta above 50 MeV/c

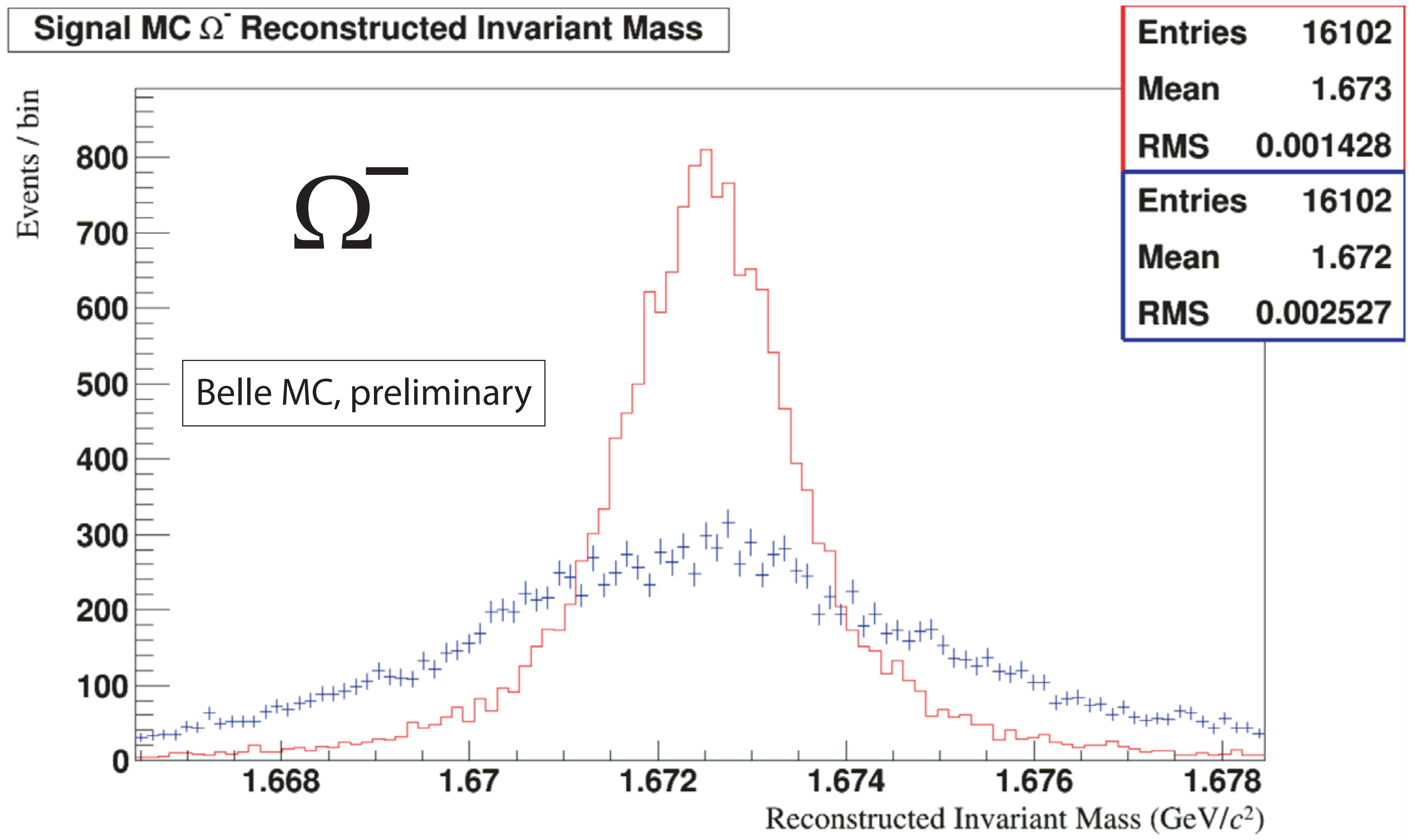
Reconstruction efficiency of $\bar{B}^0$ channel: 12.2% (± 0.1%)
Reconstruction efficiency of B^0 channel: 12.5% (± 0.1%)
($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^0$)

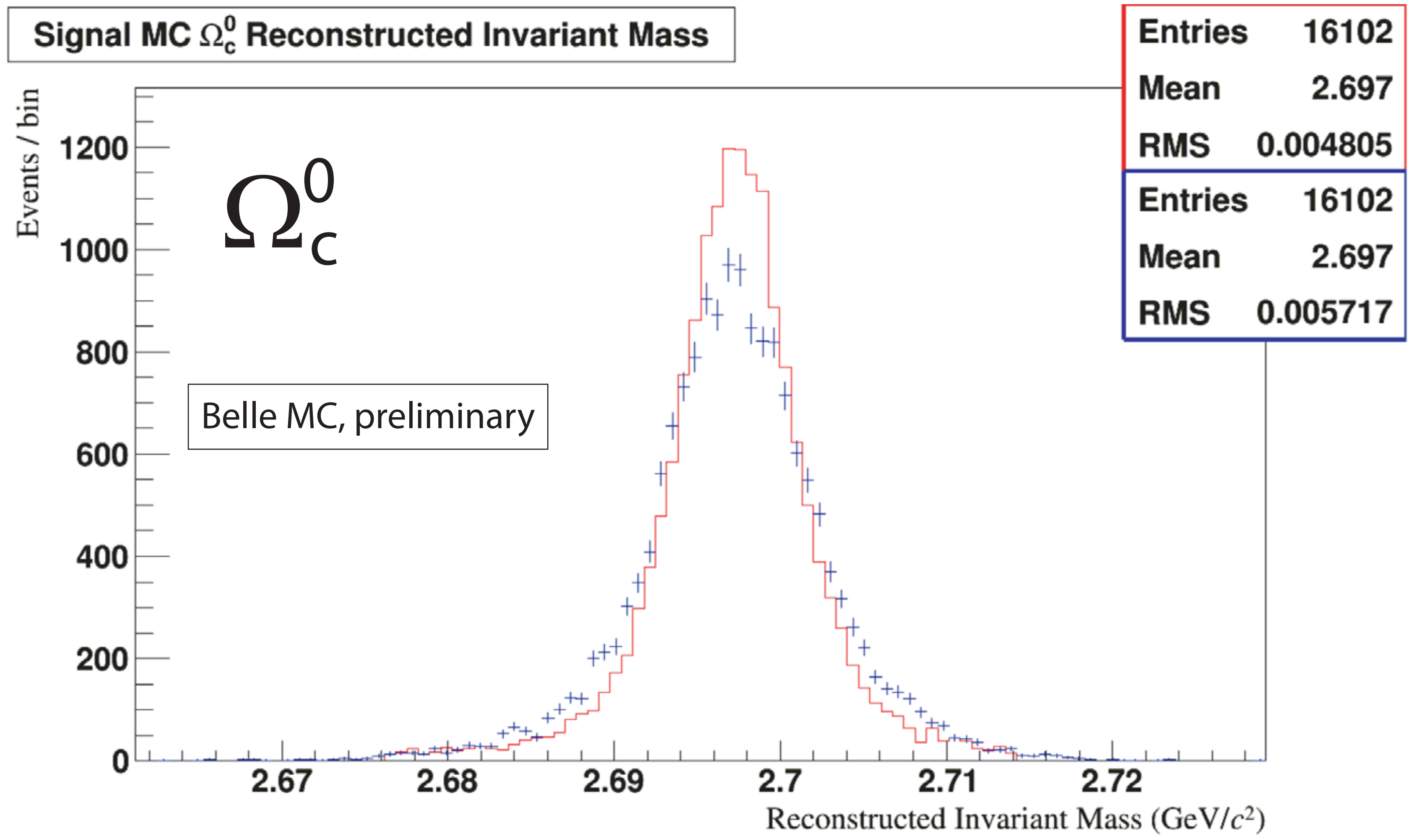
Reconstruction efficiency of $\bar{B}^0$ channel: 11.9% (± 0.1%)
Reconstruction efficiency of B^0 channel: 11.6% (± 0.1%)
($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^{*0}$)

Reconstructed Invariant Masses (Before & After Vertex Fit)









ΔE and Mbc for Signal MC ($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^0$)

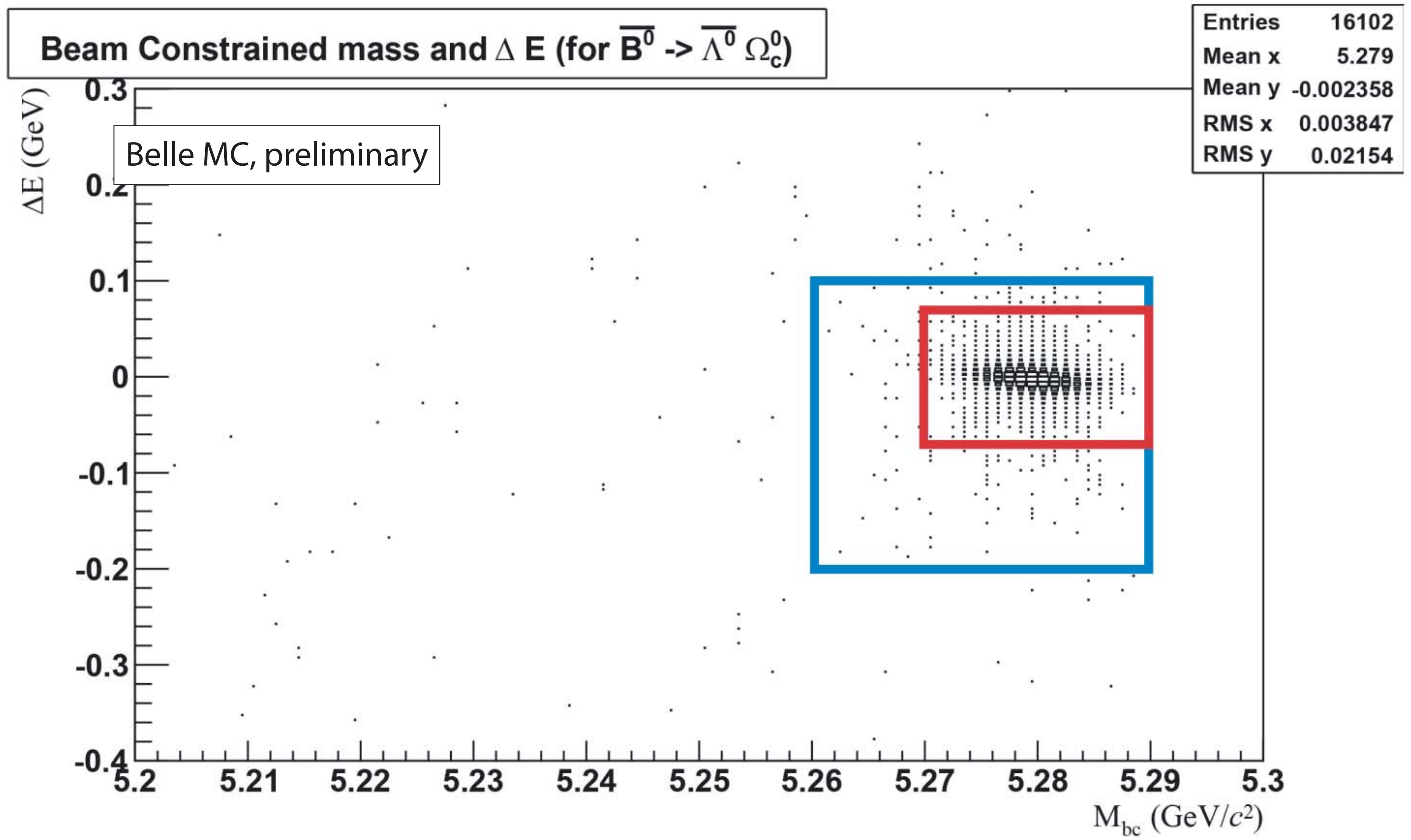
Signal Region (red box):

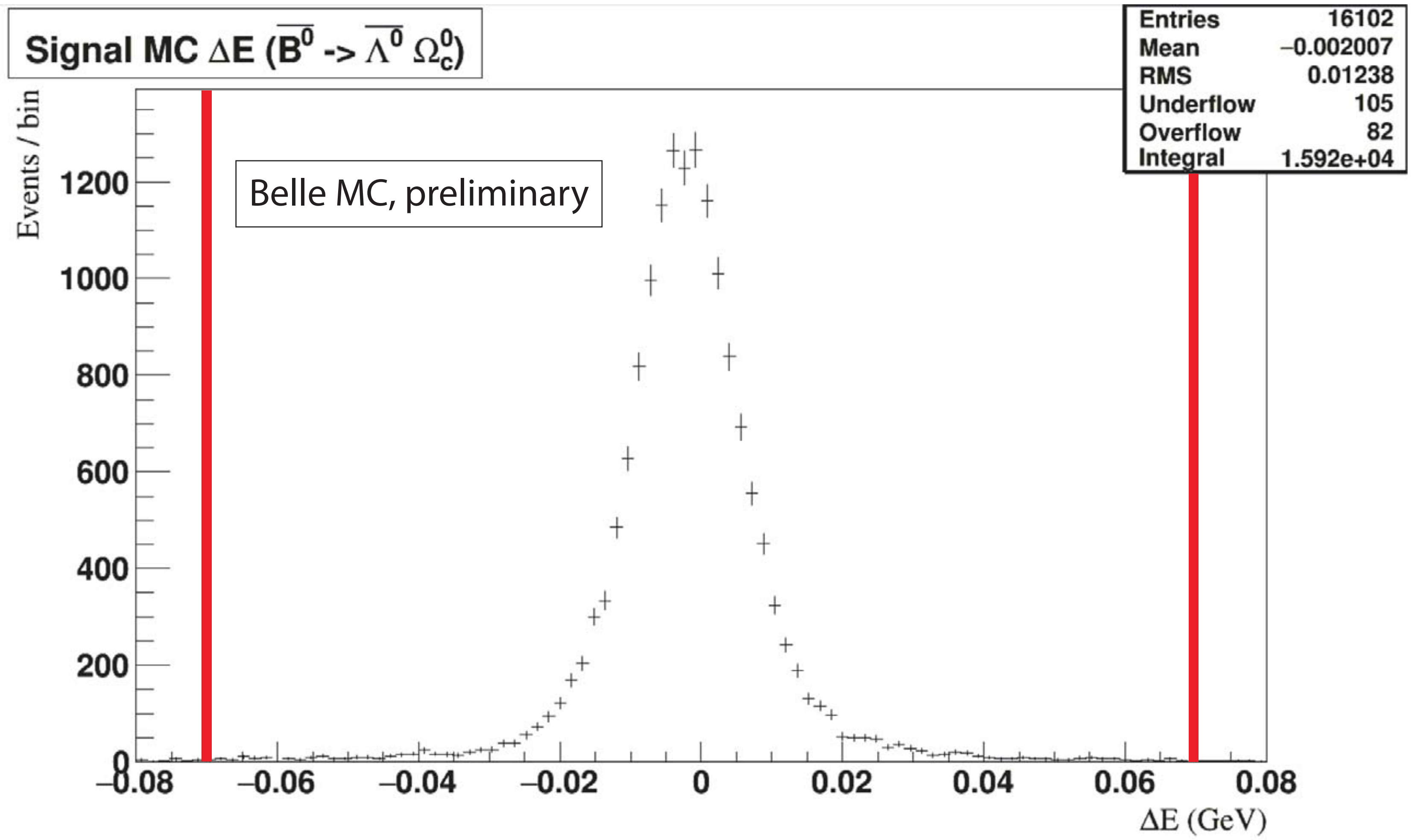
Mbc > 5.27 GeV/c^2 and -0.07 GeV < ΔE < 0.07 GeV, contains 98.4% of MC signal

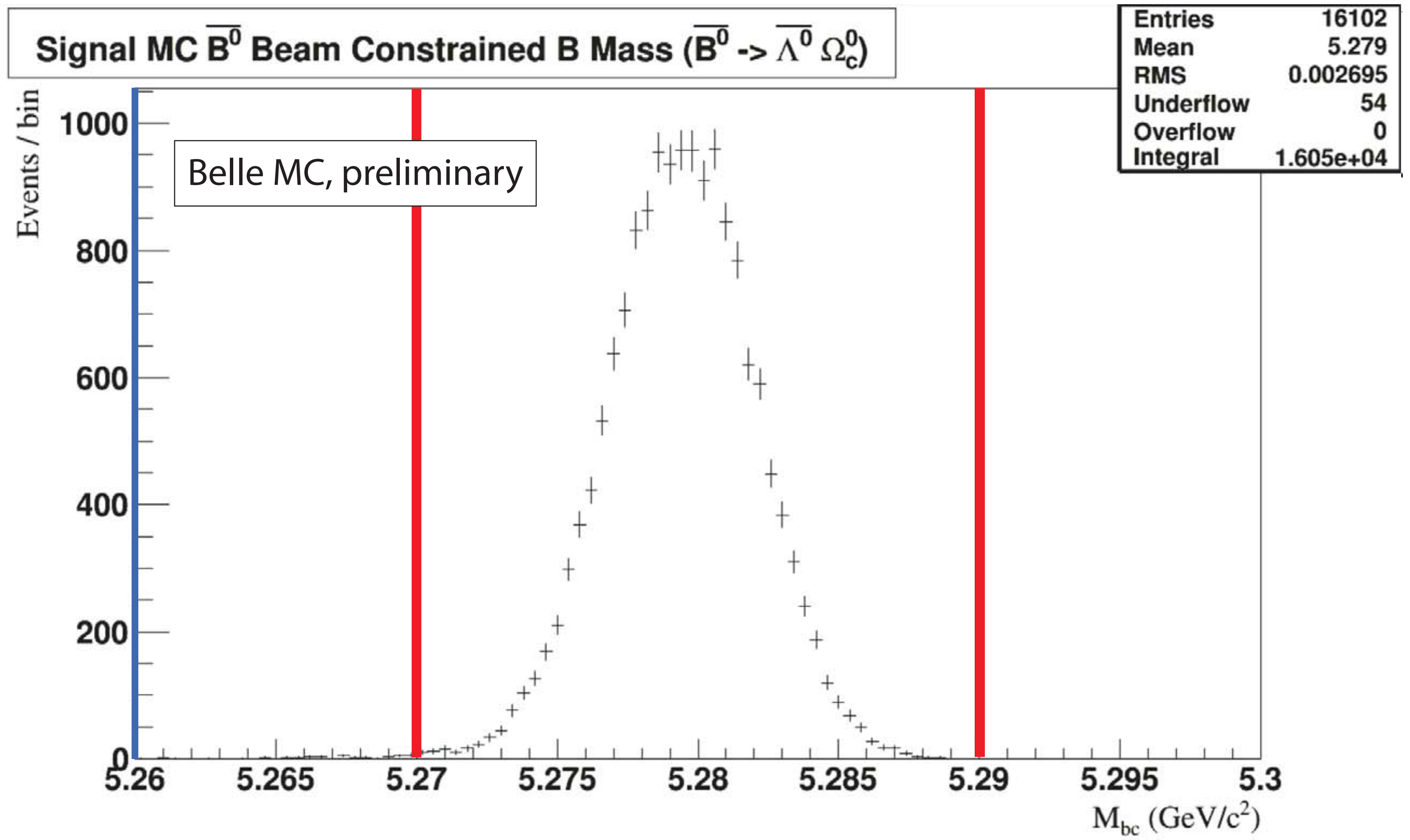
Region Blinded in Data (blue box):

Mbc > 5.26 GeV/c^2 and -0.2) GeV < ΔE < 0.1 GeV, contains 99.4% of MC signal

Strong correlation present between signal variables (global correlation coefficient in the signal region: -0.23) taken into account using 2D smoothed histograms for PDFs

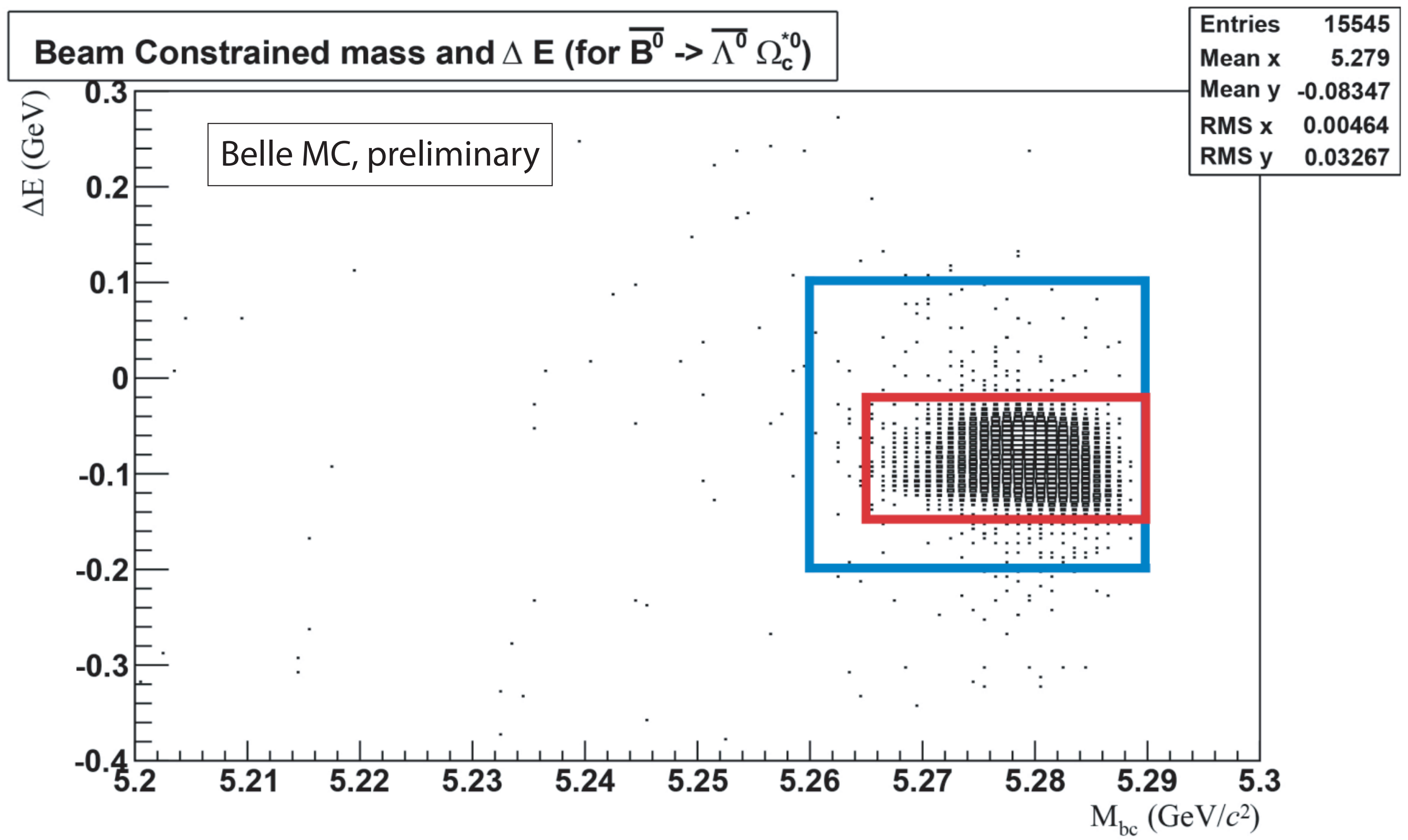






ΔE and Mbc for Signal MC ($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^{*0}$)

In the analysis of this channel we ignore radiative photon, this missing energy shifts signal ΔE distribution toward negative values but has negligible effect on beam-constrainted B mass

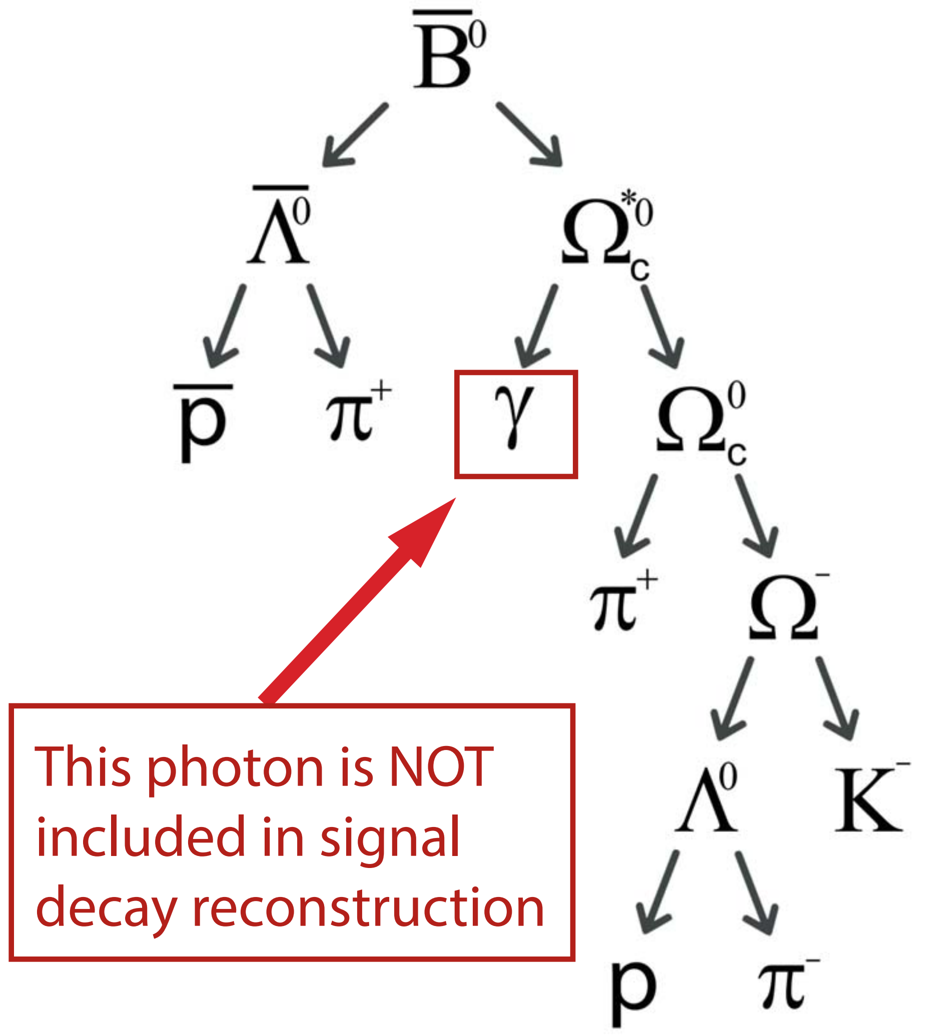


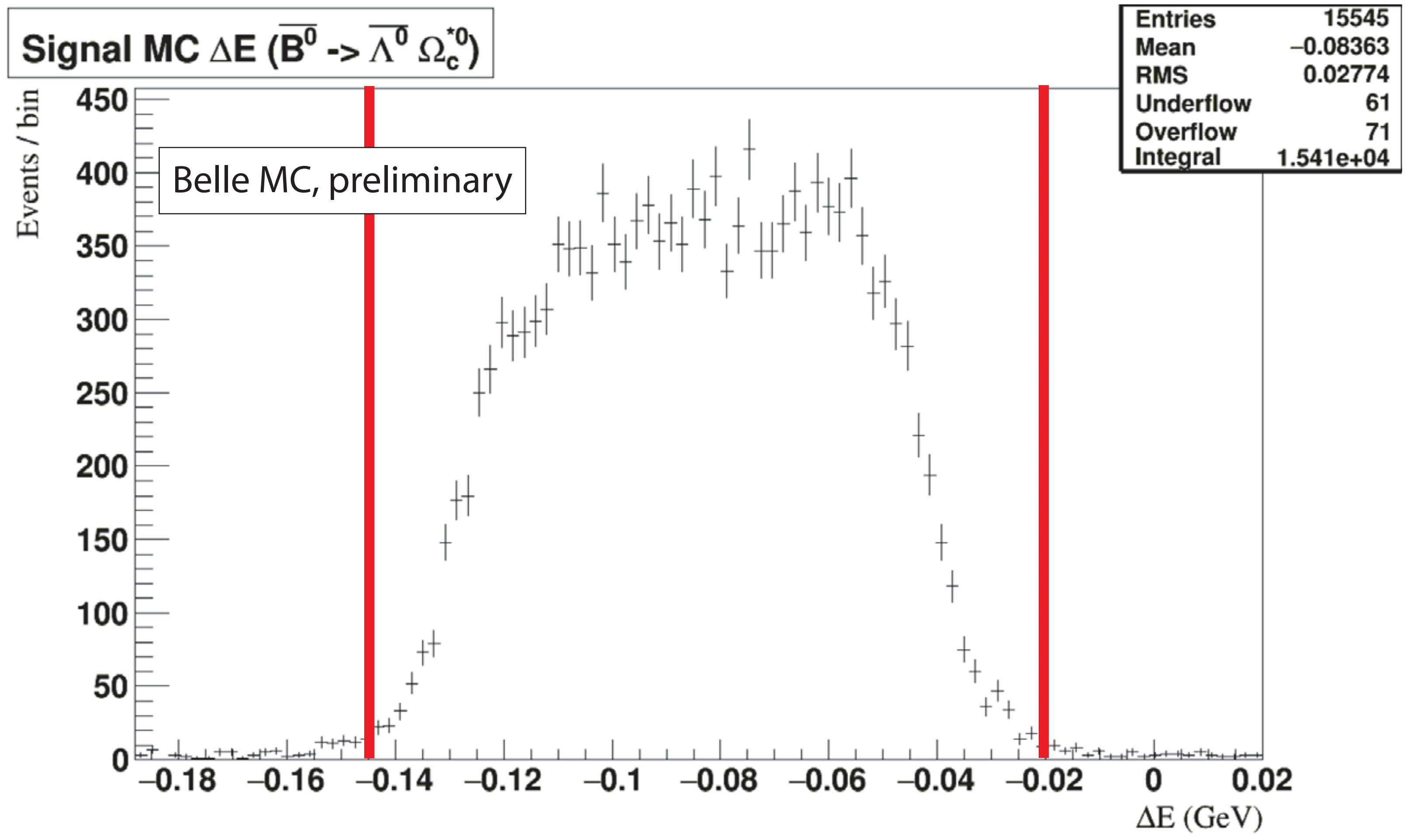
Signal region (red box):

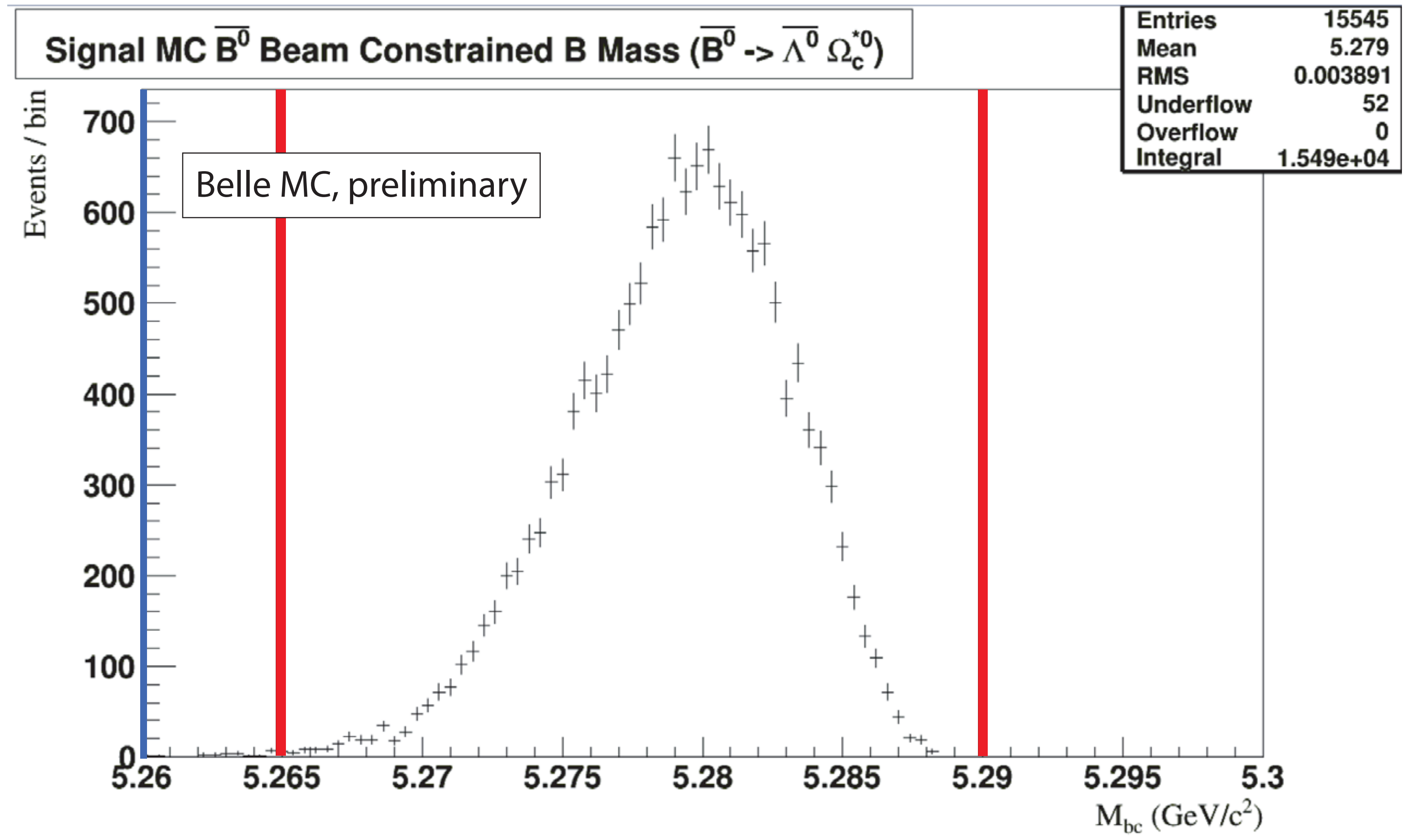
Mbc > 5.265 GeV/c^2 and -0.145 GeV < ΔE < -0.020 GeV, contains 98.2% of MC signal

Blinded region in data (blue box):

Mbc > 5.26 GeV/c^2 and -0.2 GeV < ΔE < 0.1 GeV, contains 99.3% of MC signal







Fitting Details and Background PDFs

- We perform a 2-dimensional extended unbinned maximum likelihood fit to Mbc and ΔE to statistically separate our signals from hadronic continuum background arising from e+e- annihilation into pairs of light quarks (u, d, s, and c)
- Both signals are modeled by smoothed histograms
- Background is modeled by analytic functions (below)

$$\mathcal{L} = \frac{e^{-\sum_j n_j}}{N!} \prod_{i=1}^{N} \left(\sum_j n_j \mathcal{P}_j(M_{bc}^i, \Delta E^i) \right)$$

Likelihood Function

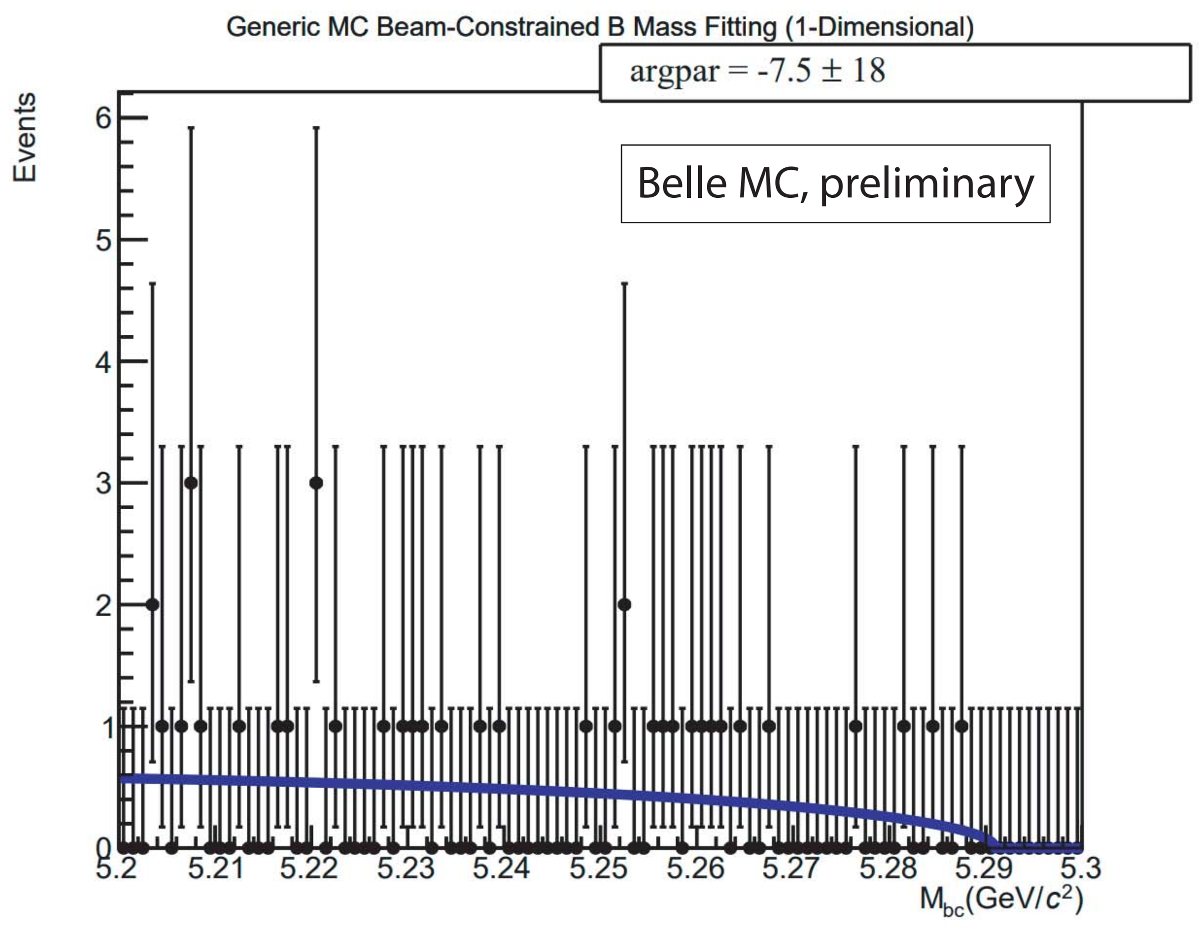
Mbc modeled with ARGUS function
ΔE modeled by first-order Chebyshev polynomial

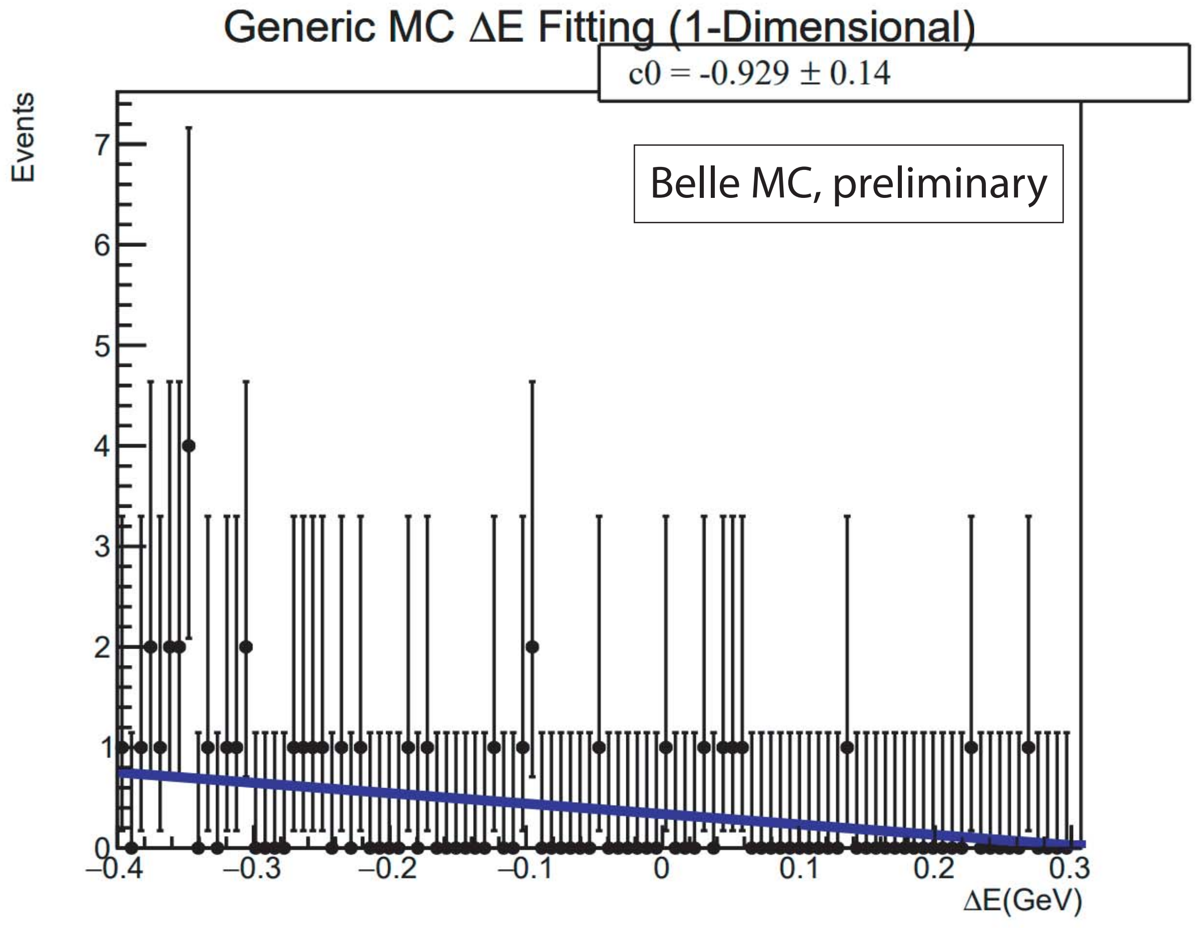
Fit Parameter	Value ± Uncertainty
ARGUS parameter	-7.5 ± 18

Fit Parameter	Value ± Uncertainty
slope coefficient	-0.929 ±0.14

Estimate for number of background events:

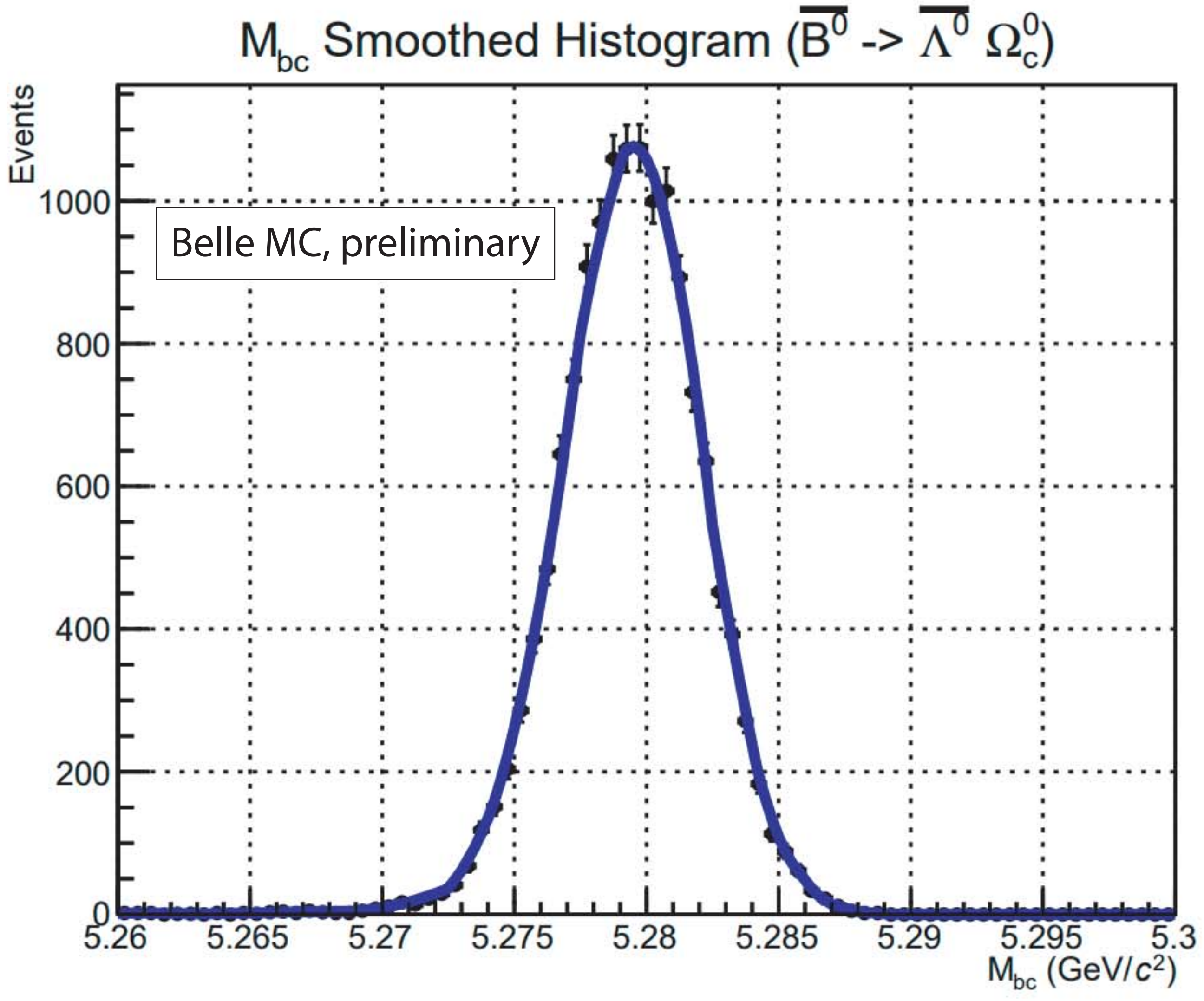
$$\#\text{ of events in blinded data} \times \frac{\text{total genMC}}{\text{genMC in blinded reg.}} = 10 \times 39/36 \approx \underline{11}$$

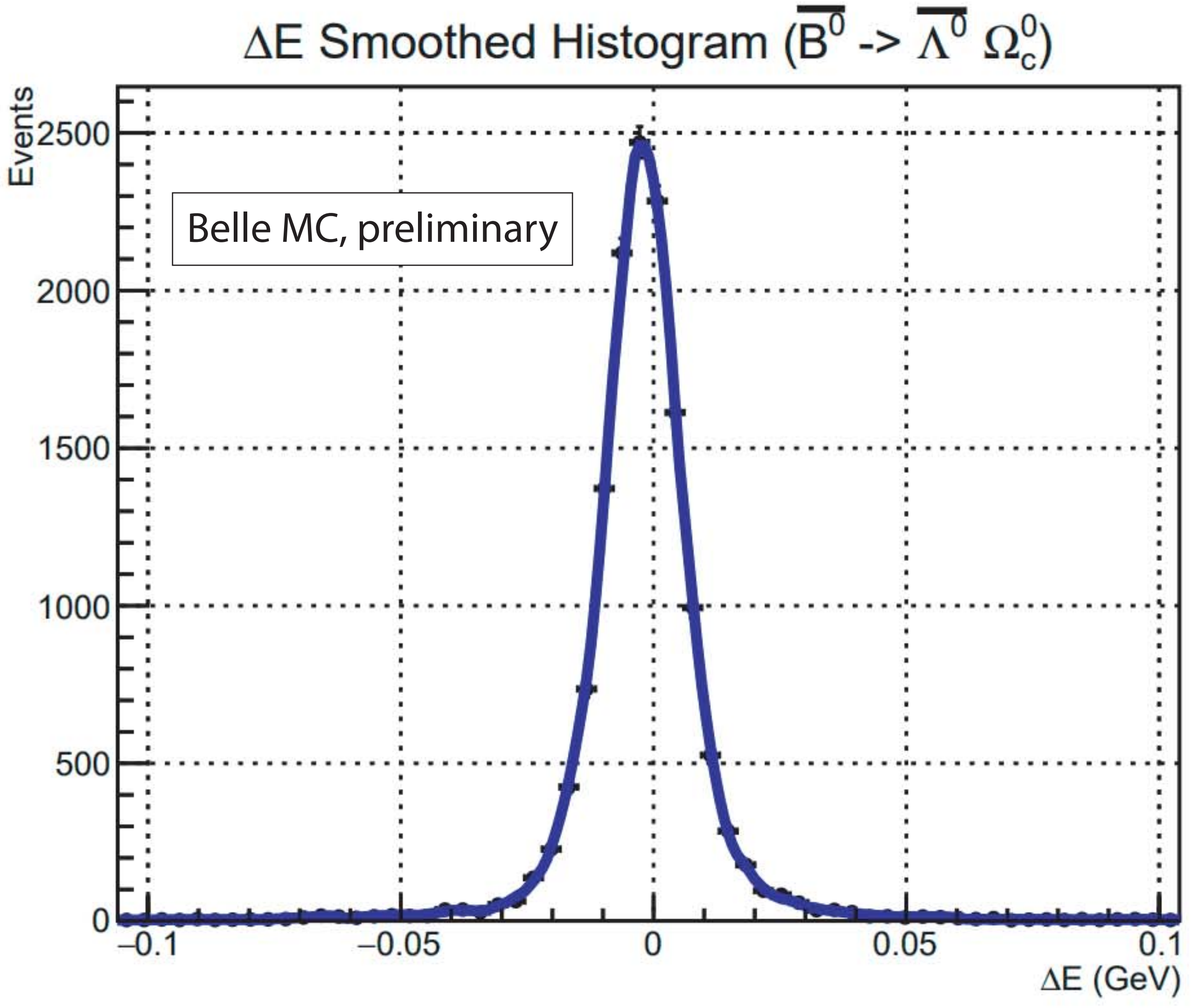




2D Smoothed Histogram for Channel $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^0$

Projections of 2D PDFs are shown after integrating over the other variable:

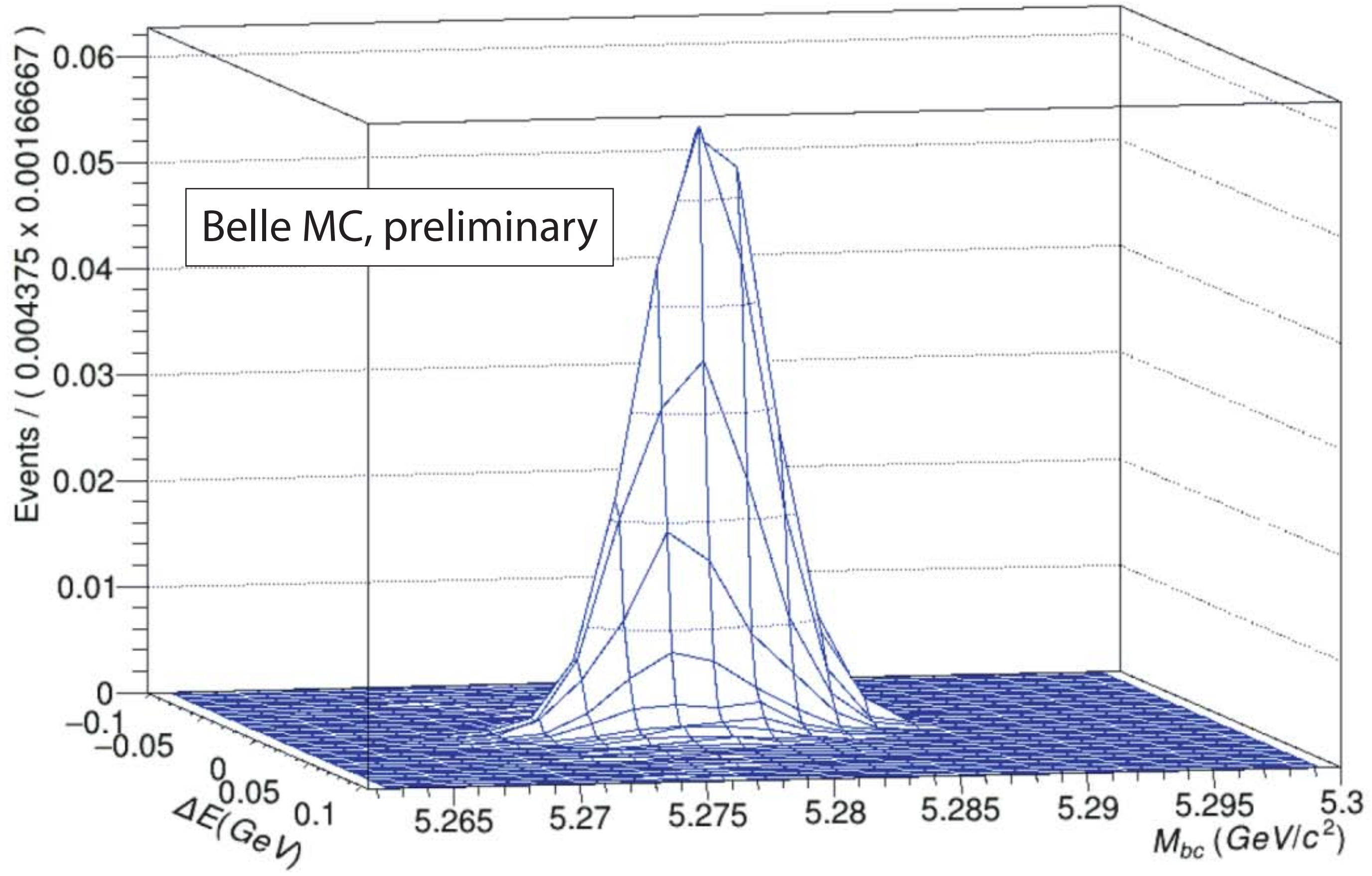


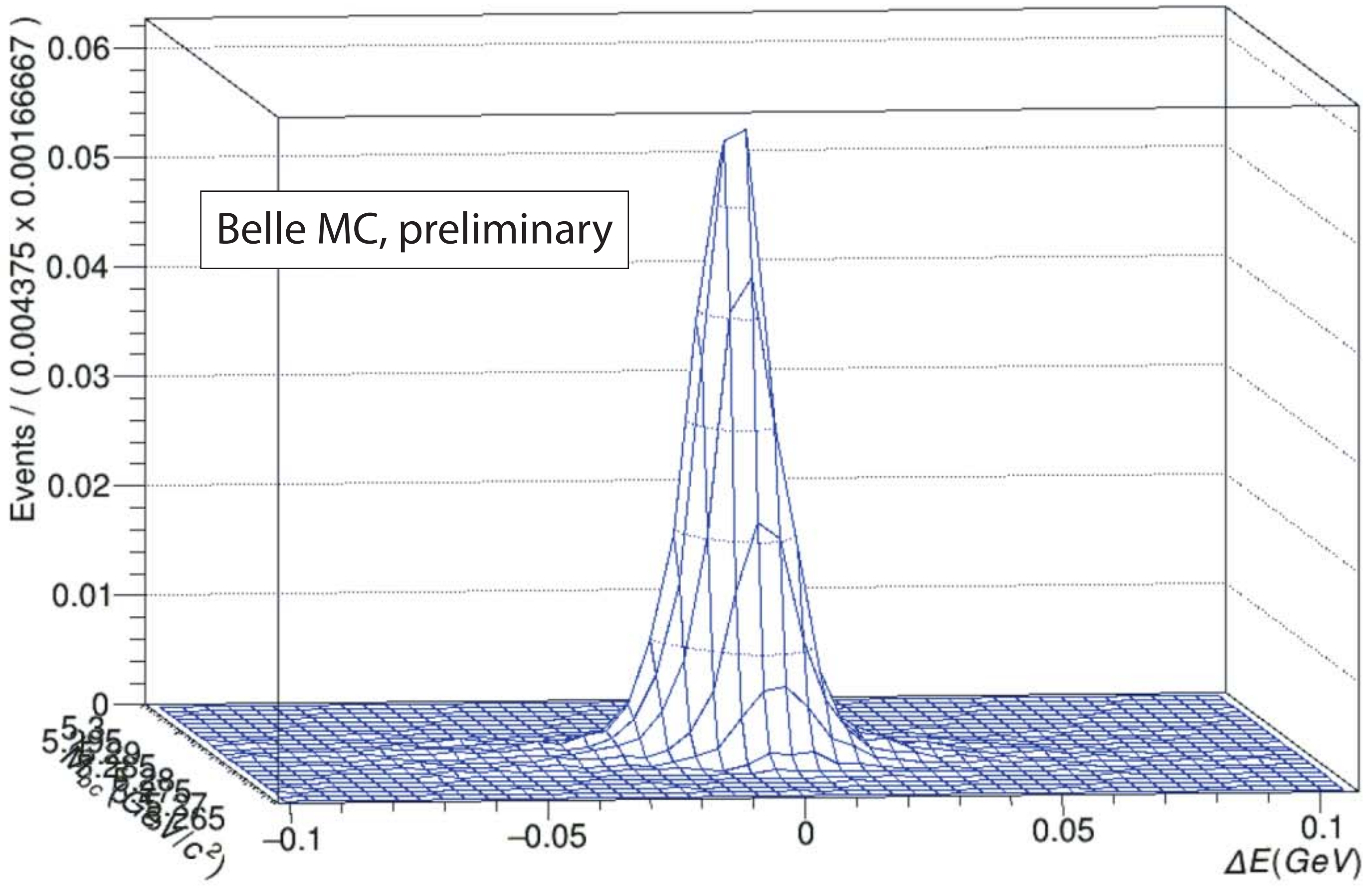


-Binning (over full ranges):

- Mbc: 60 bins
- ΔE: 160 bins

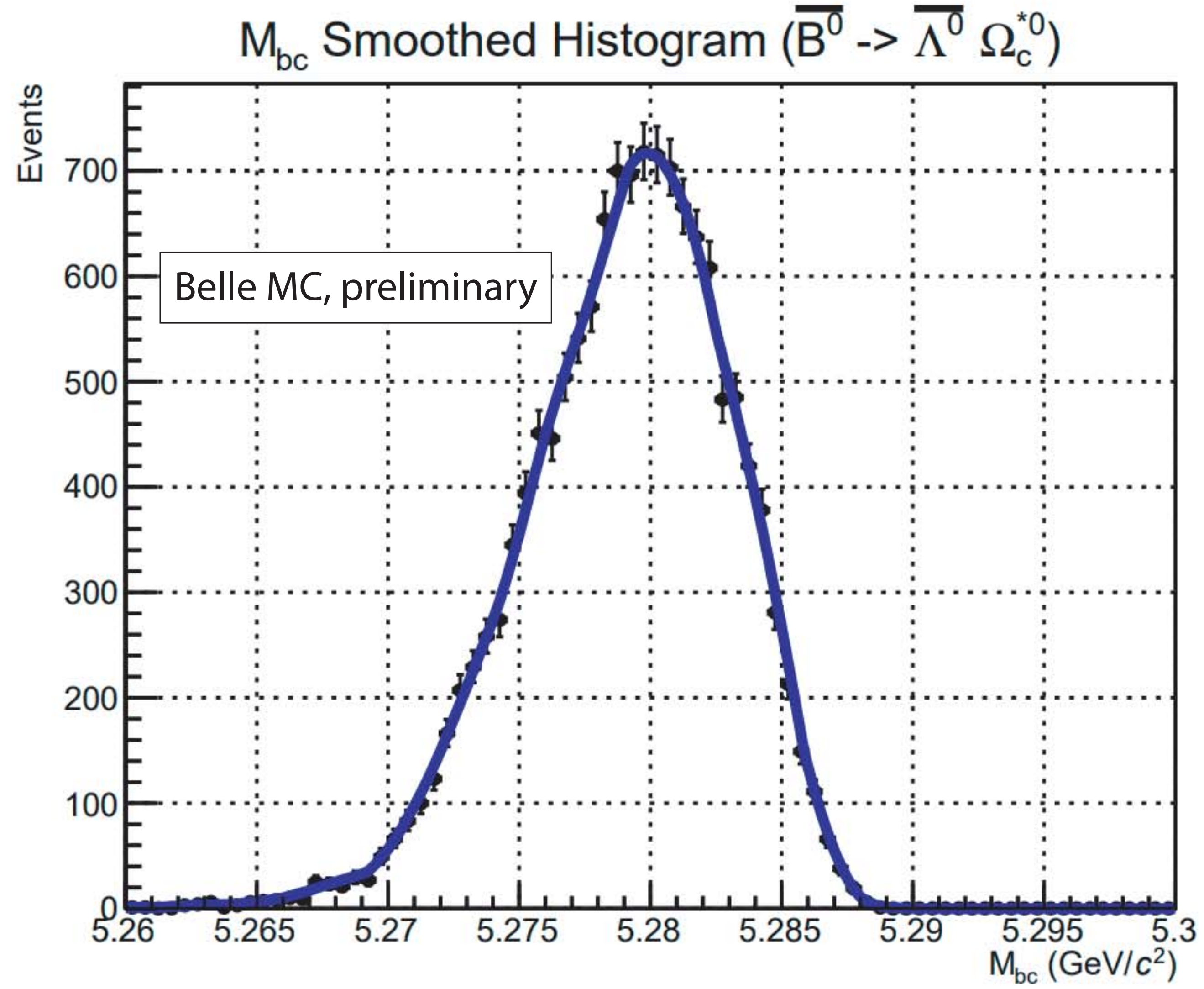
-Interpolation order 2

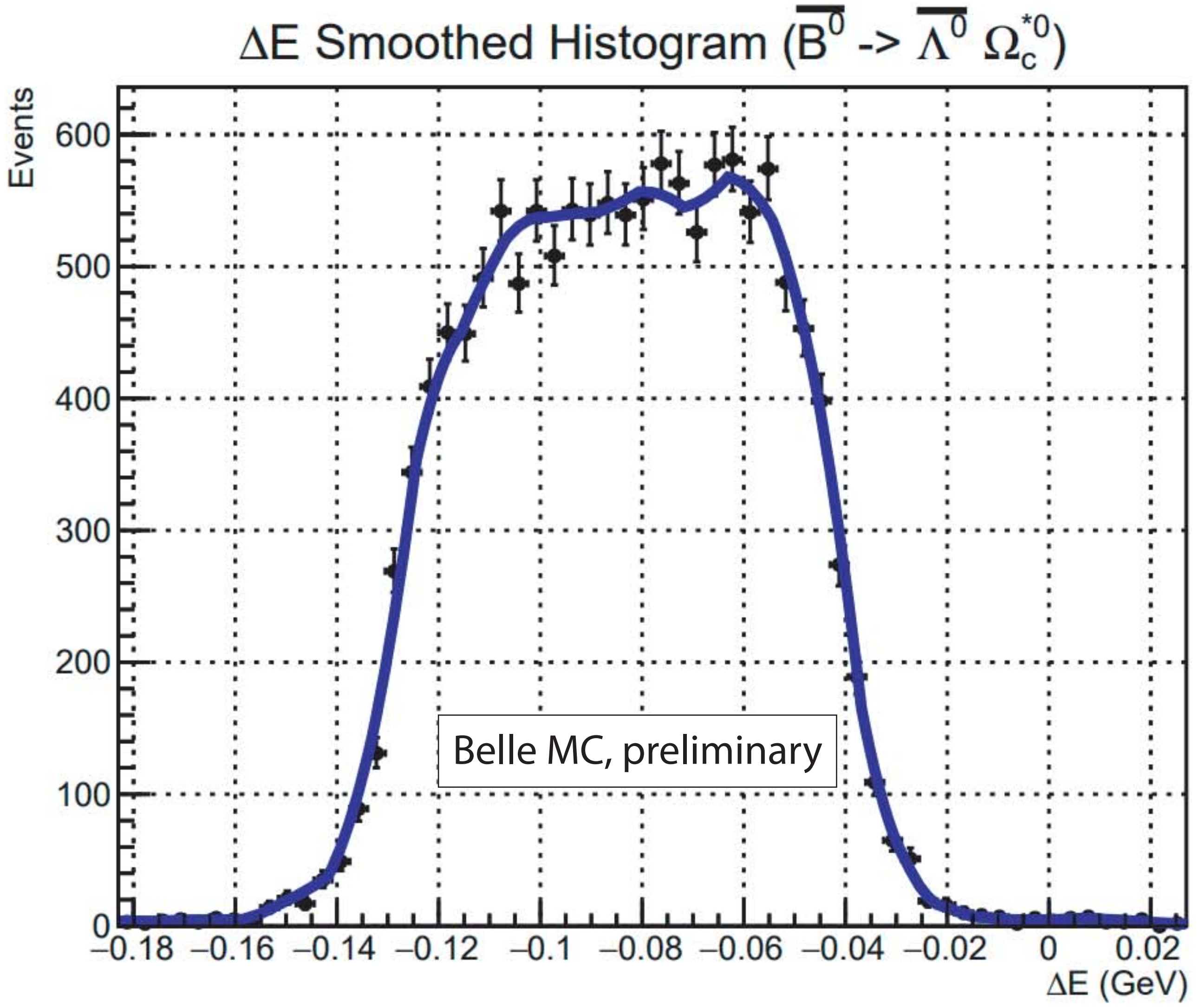




2D Smoothed Histogram for Channel $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{*0}$

Projections of 2D PDFs are shown after integrating over the other variable:

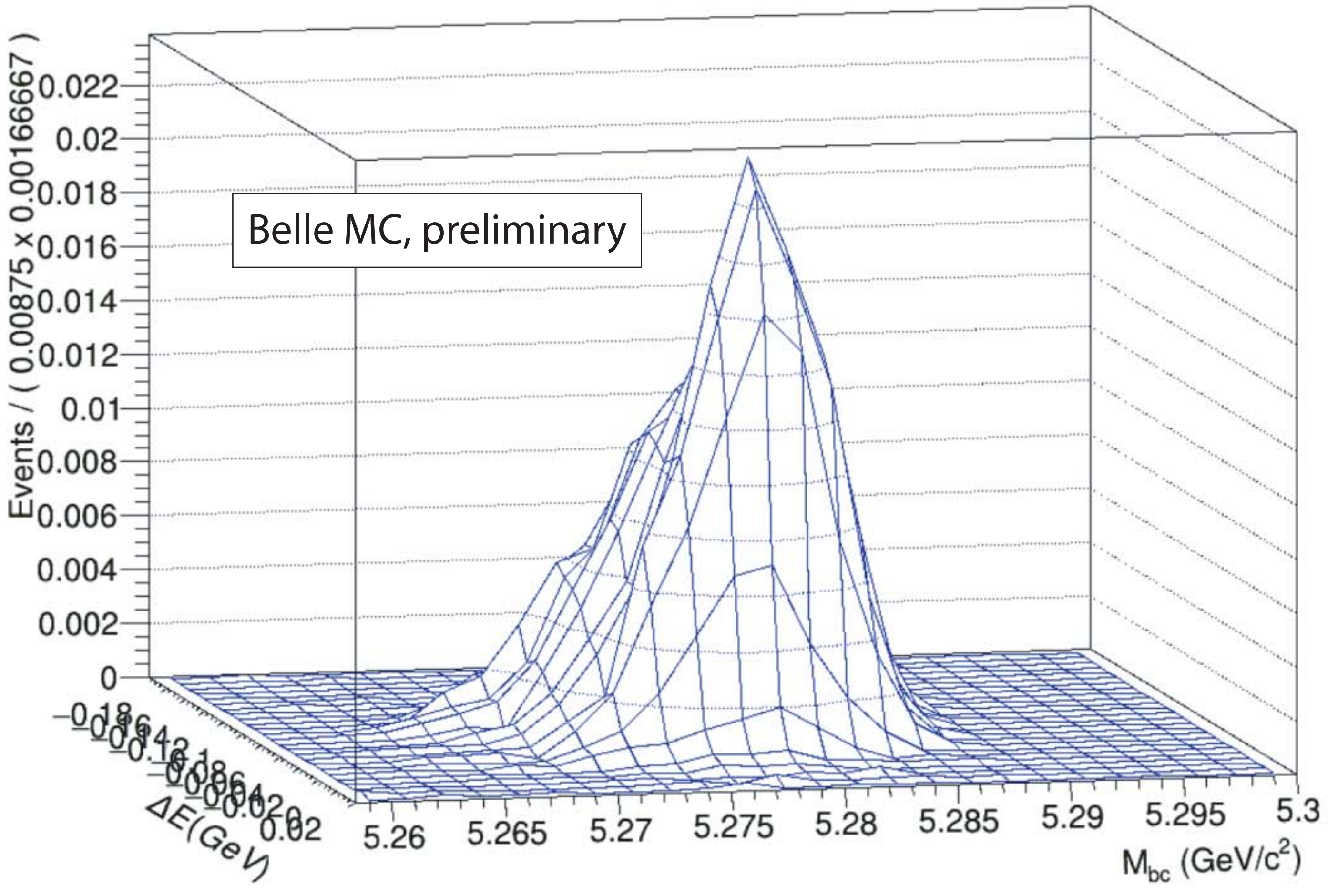


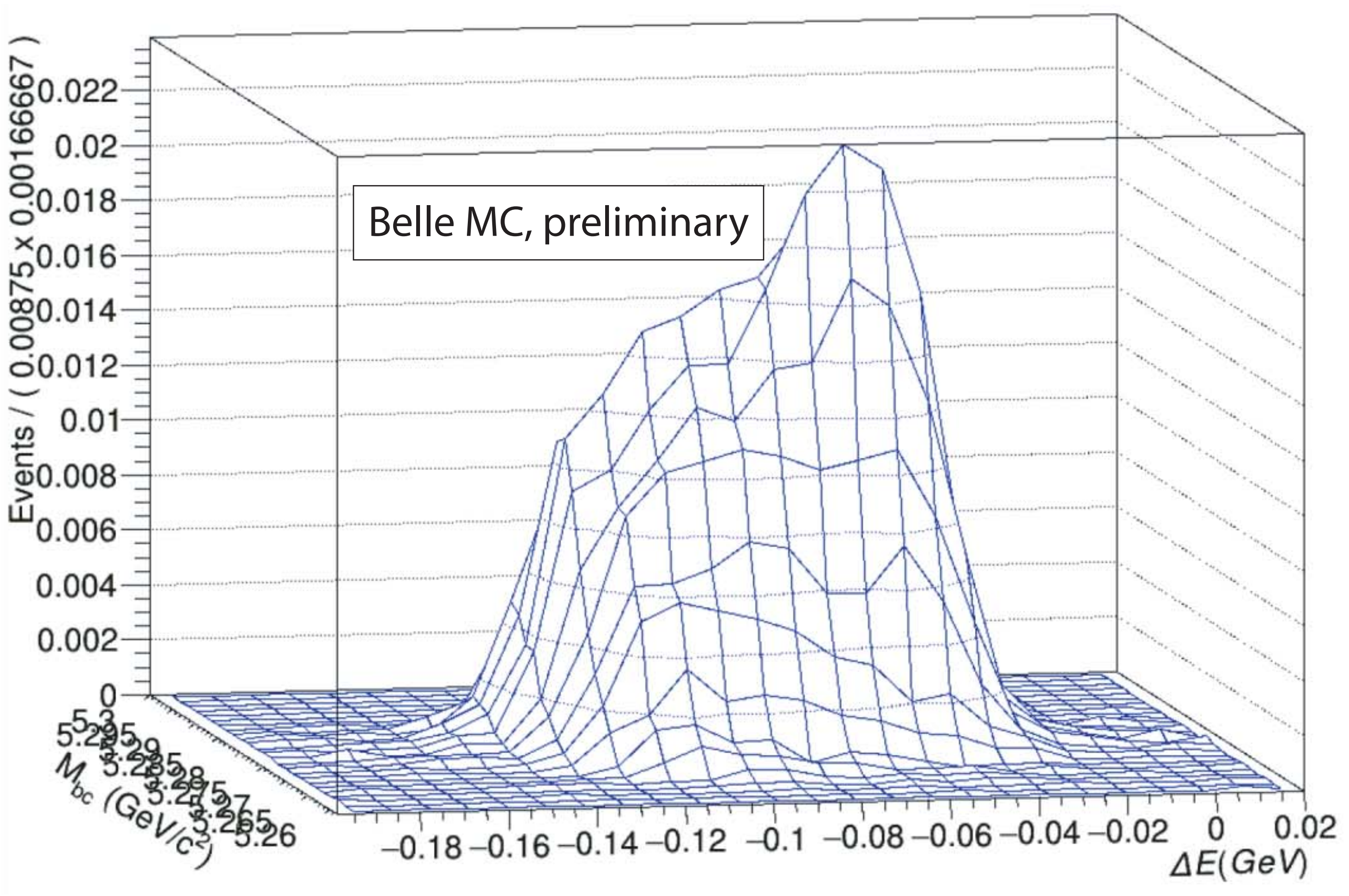


-Binning (over full ranges):

- Mbc: 60 bins
- ΔE: 80 bins

-Interpolation order 2





Overview

- studies performed fitting both signals simultaneously (ΔE allows for clear separation between the two signals)

- fitting variables ΔE and Mbc (1-D fits are for ΔE only)

- extensive toy MC experiments have been performed

- ensemble tests are used to generate confidence belts

Approach for Data

- first perform a 2D fit

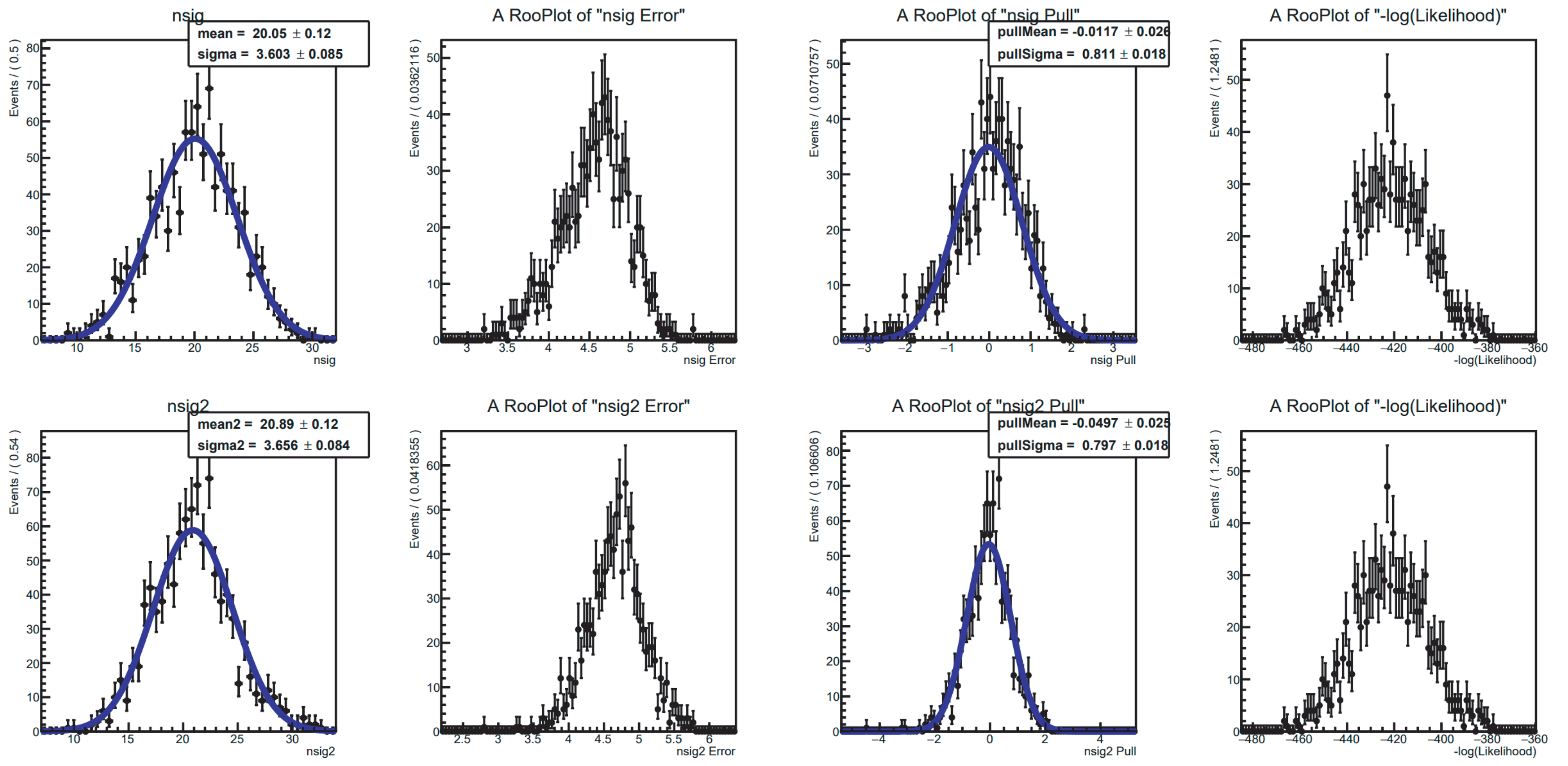
- in the absence of signal, perform a 1D fit to ΔE

- estimate upper limits for signal branching fractions

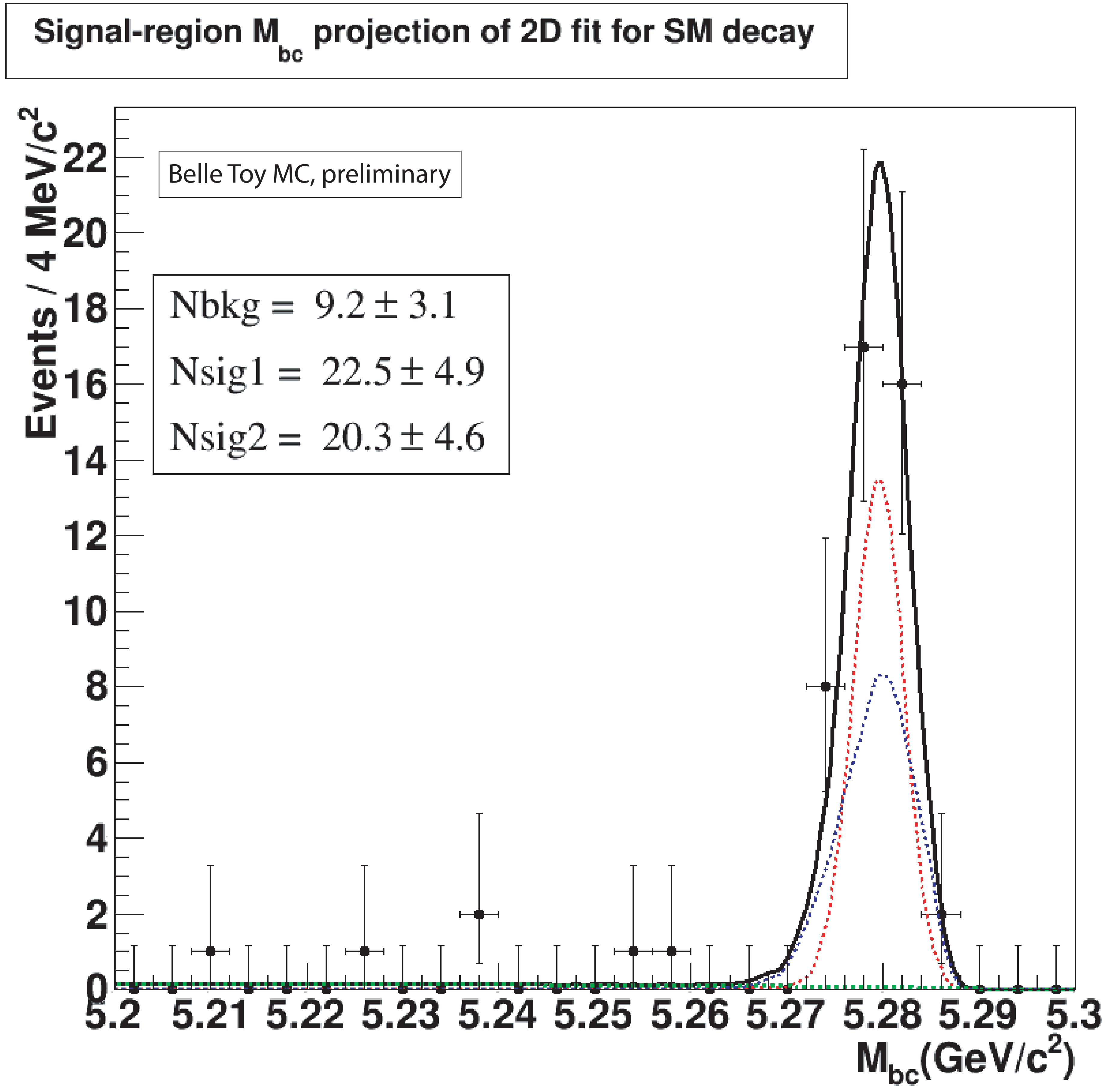
Ensemble Test Results Example

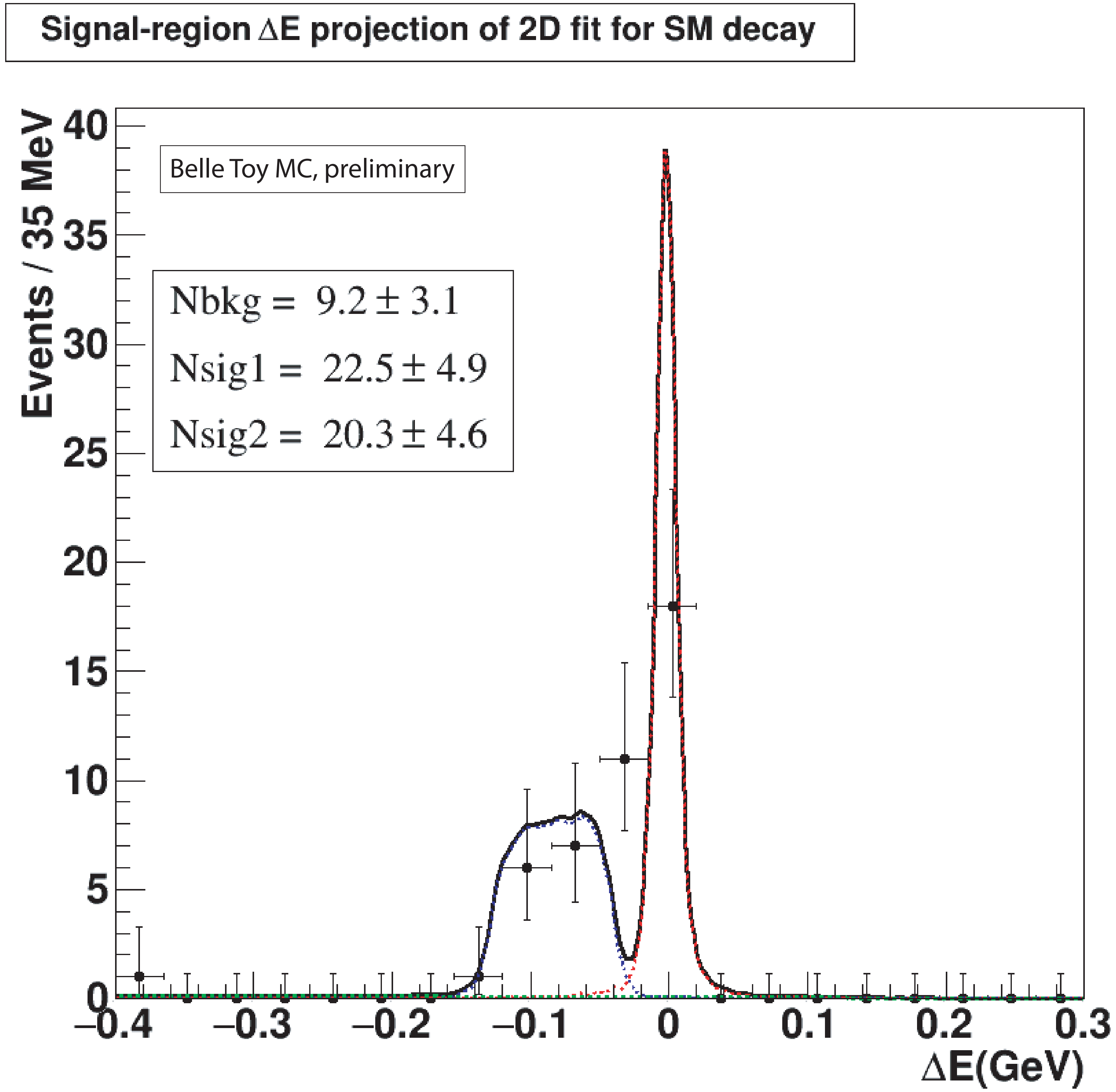
number of $\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^0$ signal events: 20
number of $\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^{*0}$ signal events: 21
number of background events: 11

Belle MC, preliminary



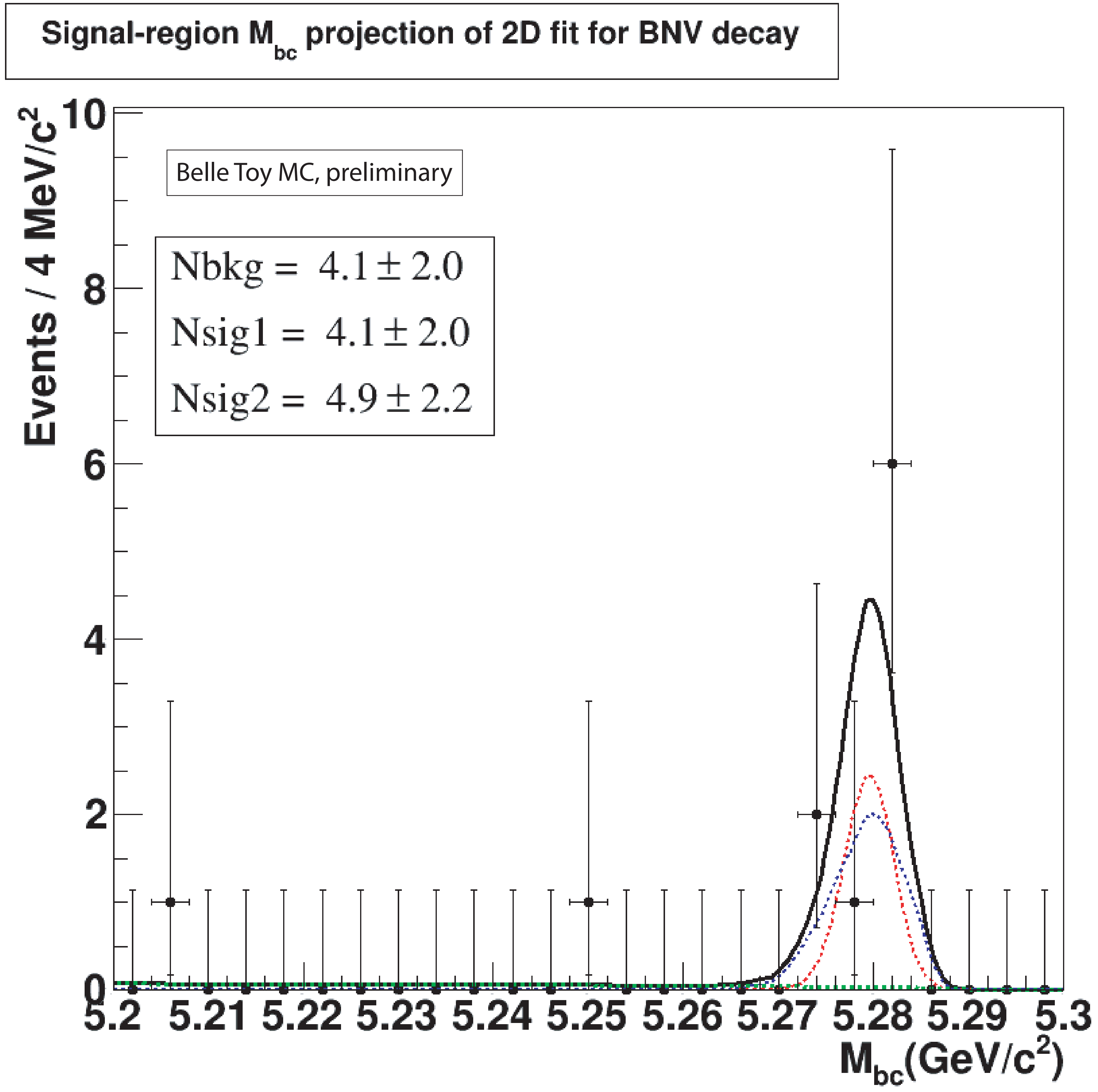
Toy MC Experiment Fit Result Example (SM Mode)

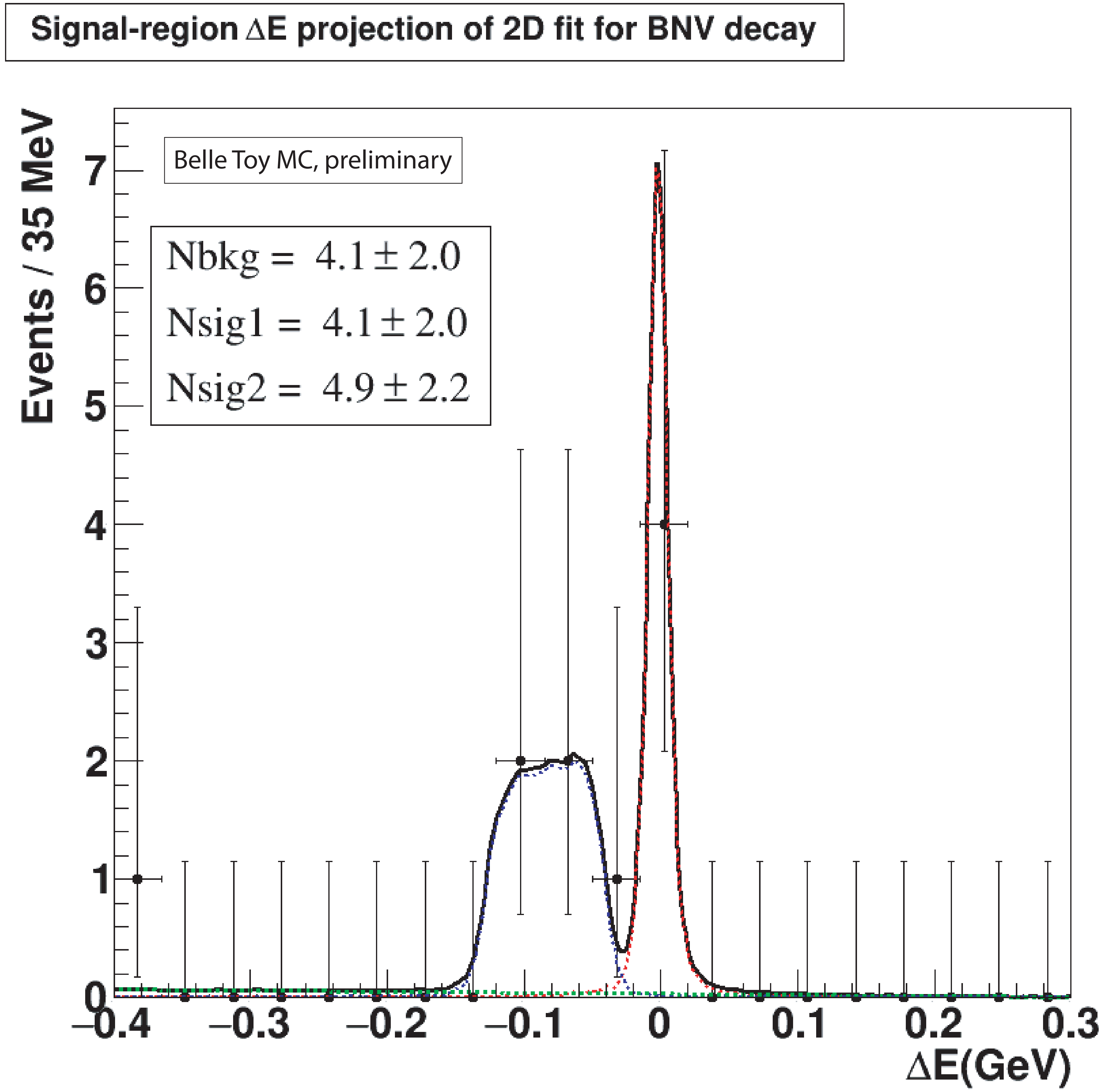




Events sampled from combined PDF: 52, signals/background weights: [20,21]/11

Toy MC Experiment Fit Result Example (BSM Mode)





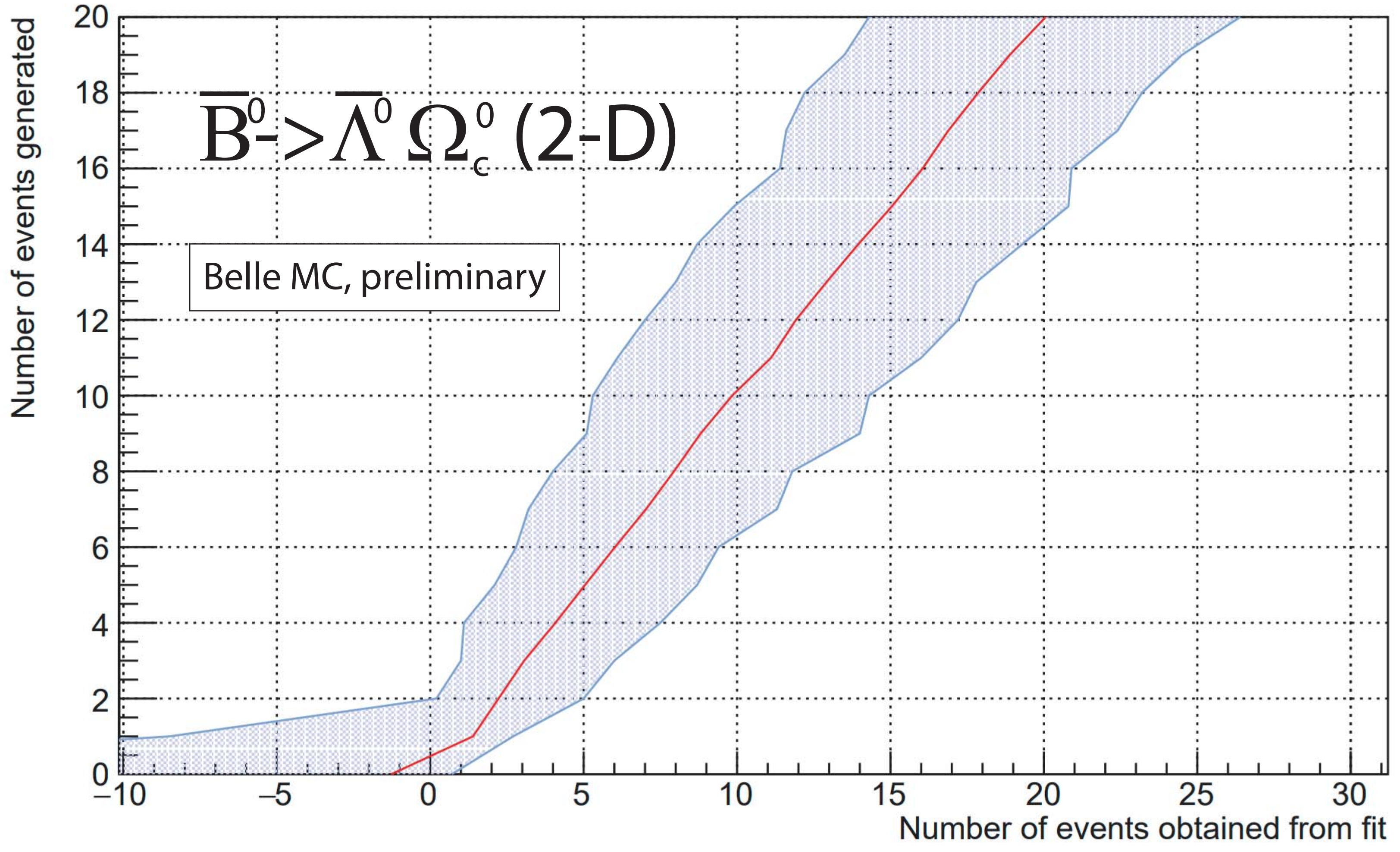
Events sampled from combined PDF: 13, signals/background weights: [5,5]/3

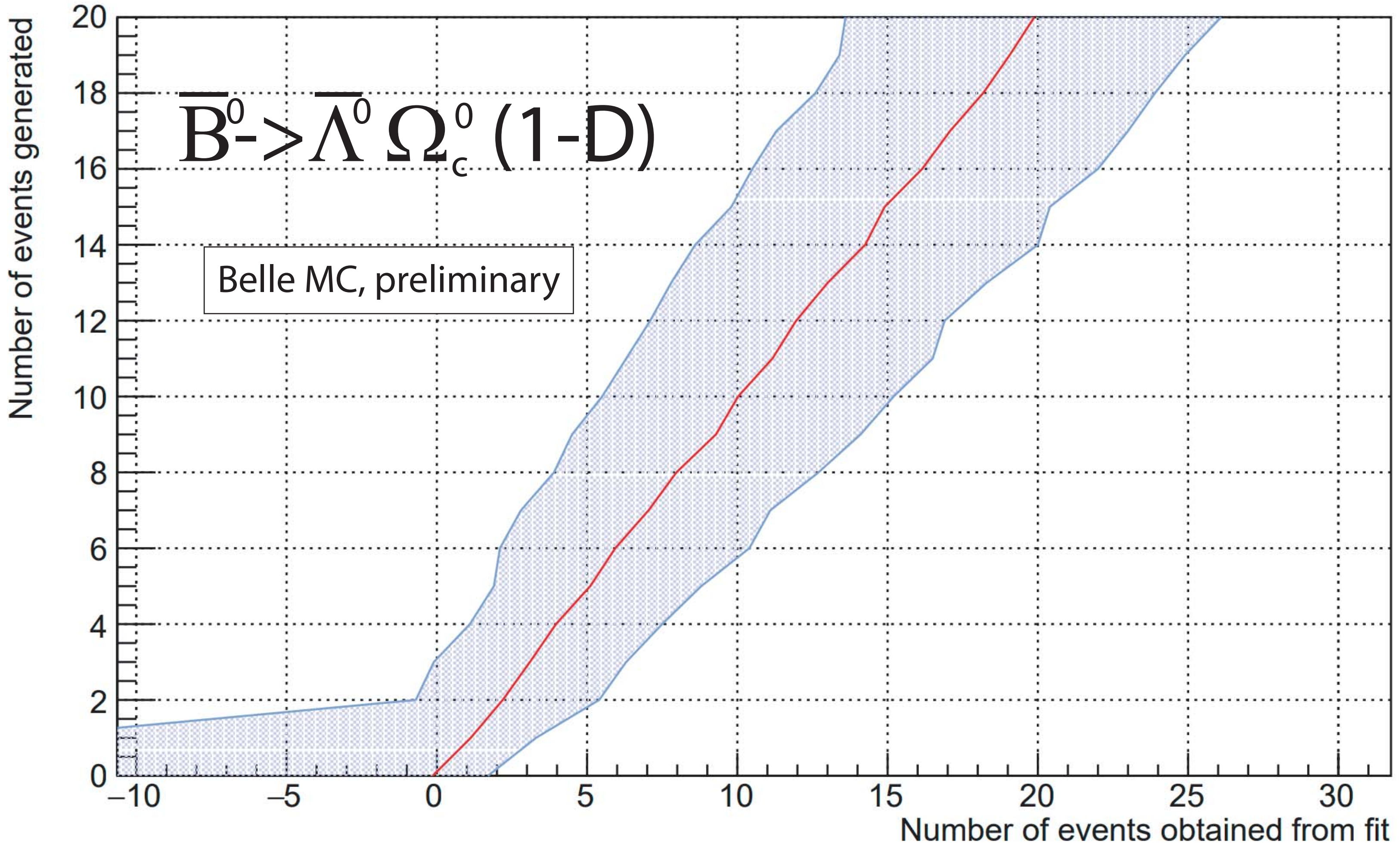
- Boundaries of confidence belts determined by ensemble tests

- 90% of MC results contained within blue region for any given hypothesis

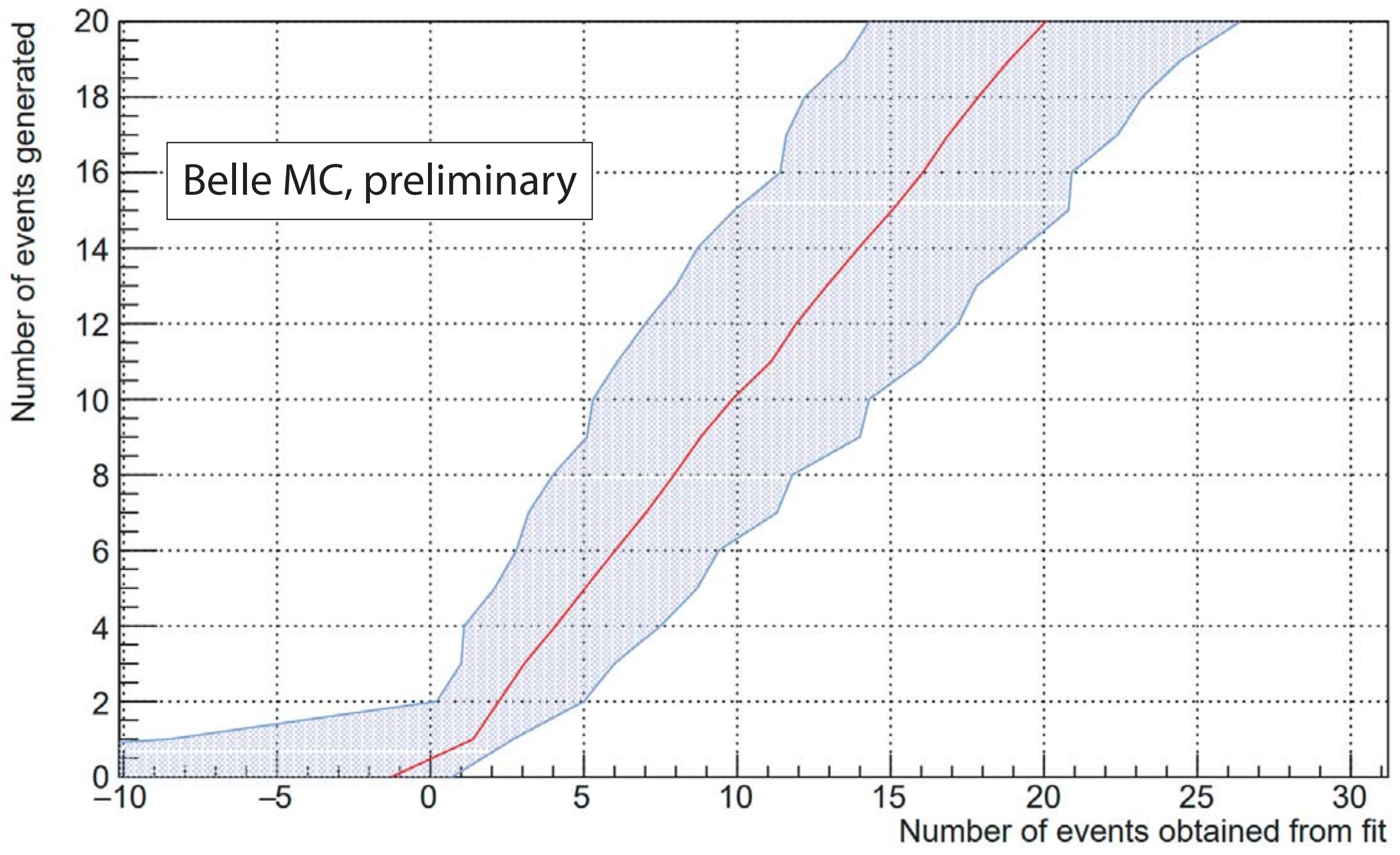
- Belts shown on right for $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^0$ (where we integrate over various hypotheses of number of $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{*0}$ events)

- Can be used to estimate sensitivity of analysis





Upper Limit Estimate Example (Preliminary)



Assume we observe 5 events in data:
=> 95% upper limit is 9 by confidence belt

$$\mathcal{B}^{95}_{\mathrm{UL}}(\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{(*)0}) = \frac{9}{N_{B\bar{B}} \times \epsilon \times \rho \times \mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) \times \mathcal{B}(\Omega^- \to \Lambda^0 K^-) \times \mathcal{B}(\Lambda^0 \to p\pi^-)^2}$$

where

- $N_{B\bar{B}}$ is the number of $B\overline{B}$ pairs,
- ϵ is our reconstruction efficiency for this channel,
- ρ is our PID correction to efficiency
- $\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$ is our estimate of the branching fraction for $\Omega_c^0 \to \Omega^- \pi^+$,
- $\mathcal{B}(\Omega^- \to \Lambda^0 K^-)$ is the branching fraction for $\Omega^- \to \Lambda^0 K^-$,
- $\mathcal{B}(\Lambda^0 \to p\pi^-)$ is the branching fraction for $\Lambda^0 \to p\pi^-$ (hence squared because the decay has two Λ^0 candidates).

$$\mathcal{B}^{95}_{\mathrm{UL}}(\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{(*)0}) = \frac{9}{(772 \times 10^6) \times 0.1222 \times 0.9840 \times 0.0143 \times 0.678 \times 0.639^2} = 2.4 \times 10^{-5}$$

Current Status

-The analysis is being checked by the internal committee

-Investigating systematic uncertainties

-Will request signal box unblinding and report findings very soon

Summary

- The reasons for matter-antimattery asymmetry remain to be understood

- A discovery of BNV would be a huge leap forward in understanding baryogenesis

- Presented first search for decays $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^0$ and $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{*0}$ in Belle data

- Expect a branching fraction sensitivity of ~2 x 10^{-5}

- Sensitivity with Belle II would improve by a factor of 3 (assuming 10 times Belle data)