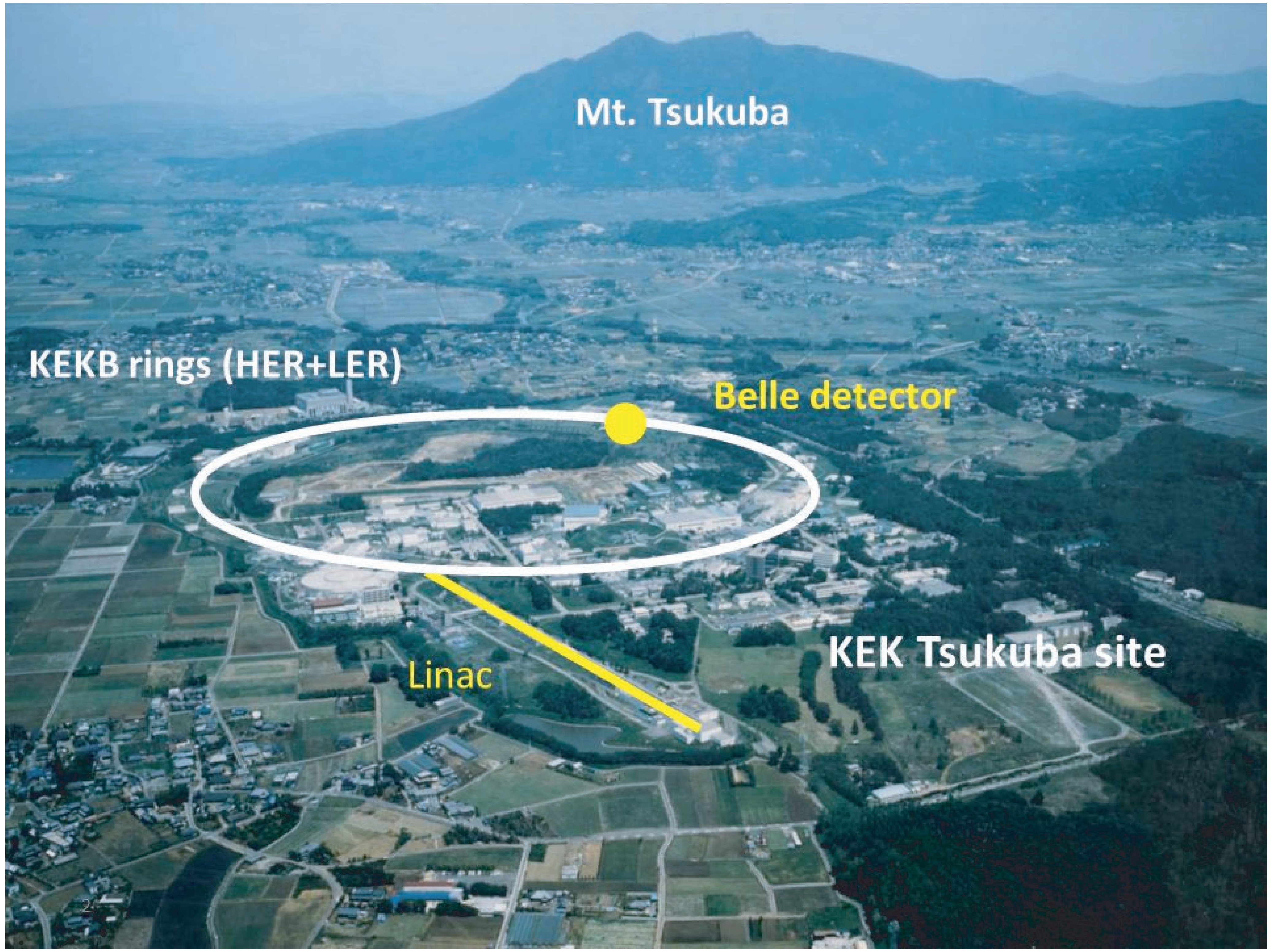
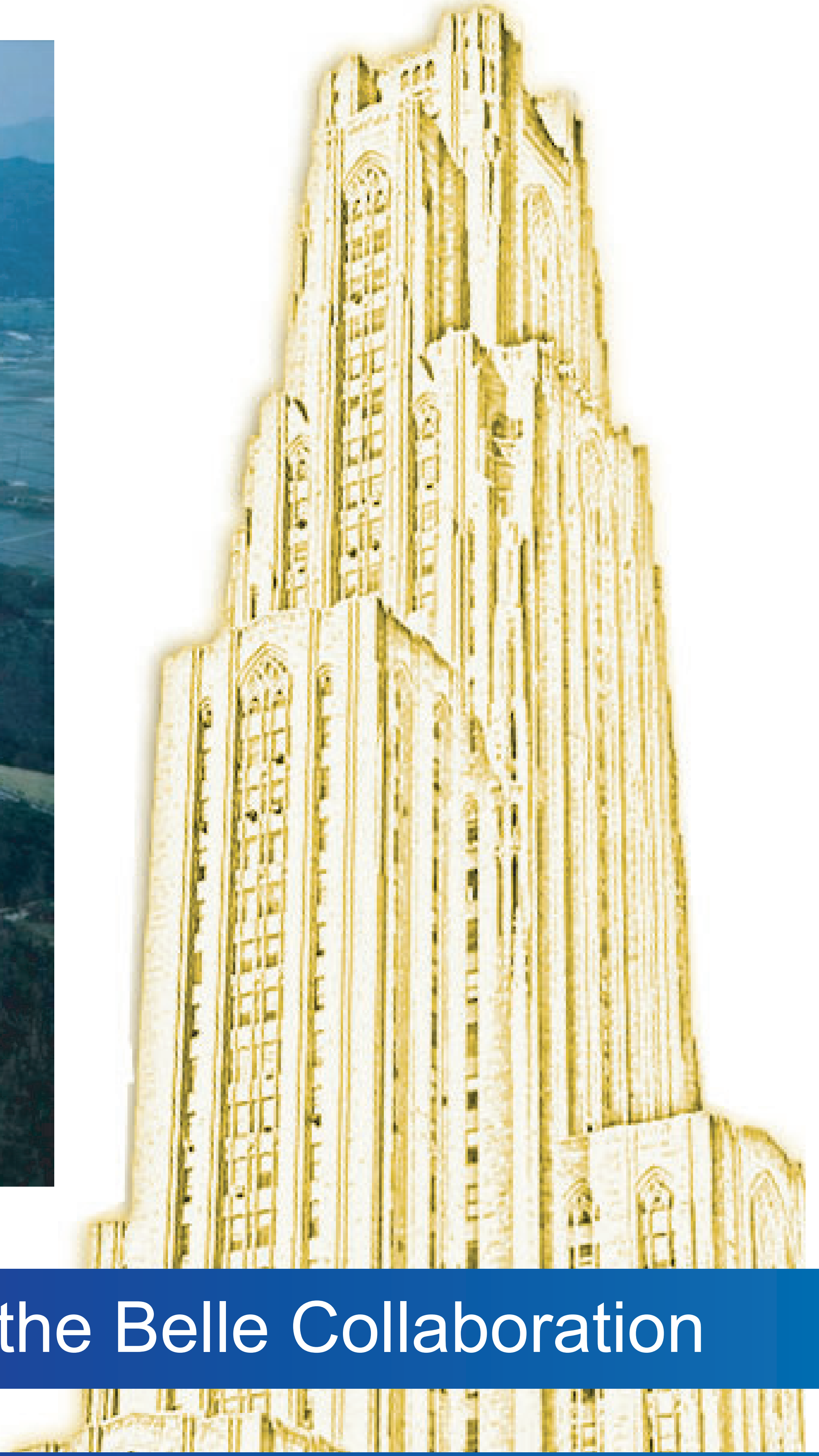
Search for Decays of B Mesons to Charmed Baryons





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* and departure from equilibrium is satisfied by expansion of the universe, so all that remains is baryon number violation.

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

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

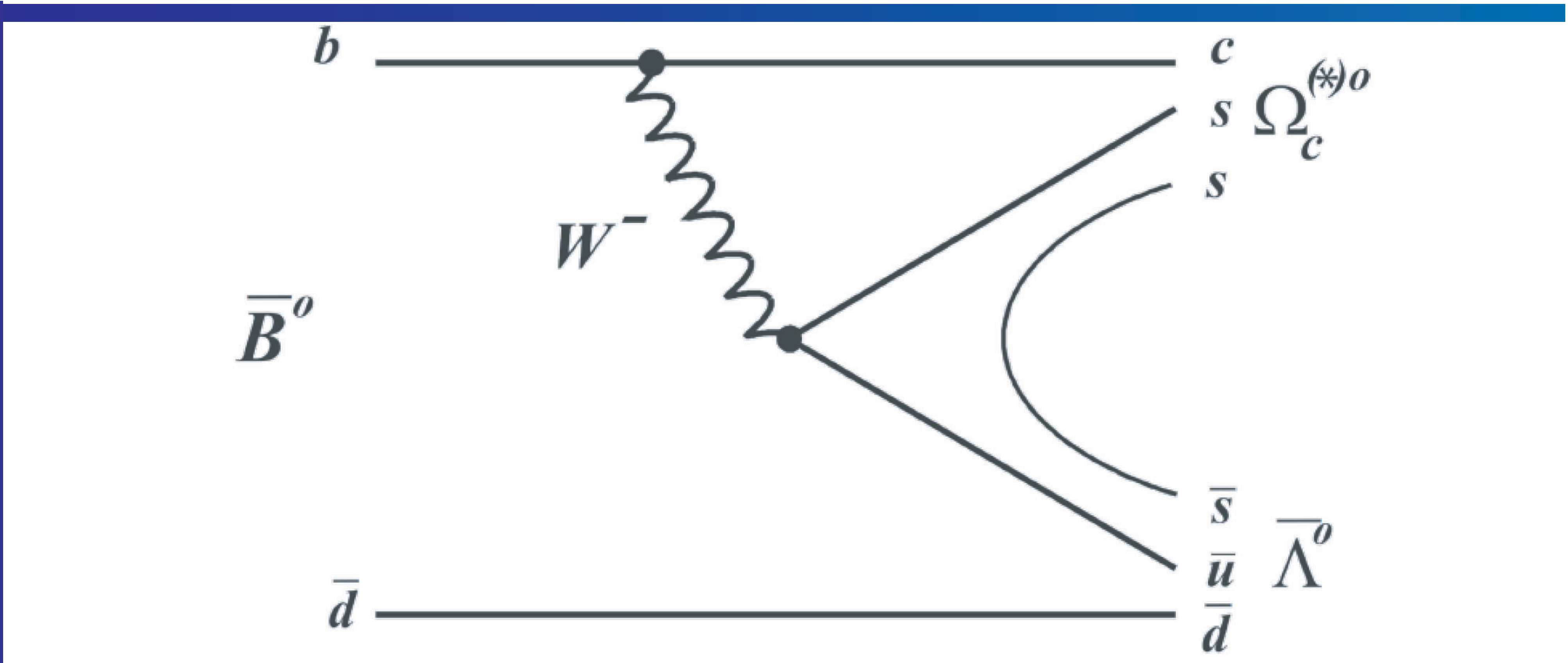
-Hence searching for not yet observed decays $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^0$ and $\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{*0}$ in data collected at Belle experiment

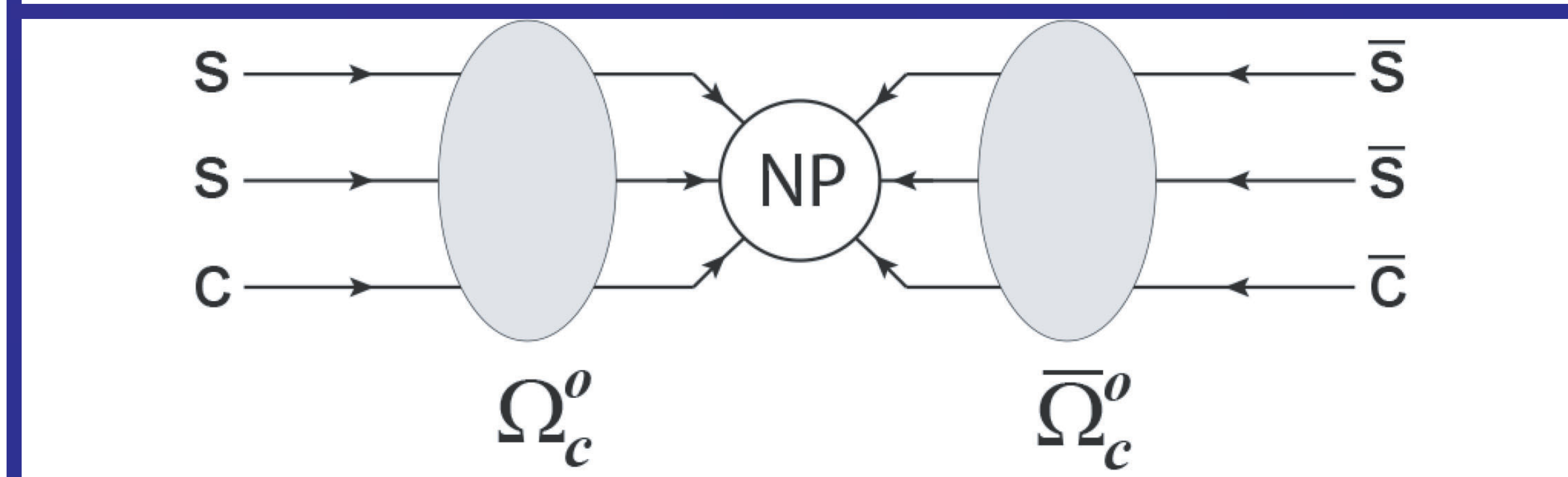
-First search of this type performed at LHCb (Ξ_b^0 oscillations)**

Decay Channels

- $\overline{B}^0 \to \overline{\Lambda}^0 \, \Omega_c^0$
  - $\overline{\Lambda}^0 \to \overline{p} \, \pi^+$
  - $\Omega_c^0 \to \pi^+ \, \Omega^-$
    - $\Omega^- \to \Lambda^0 \, K^-$
      - $\Lambda^0 \to p \, \pi^-$

- $\overline{B}^0 \to \overline{\Lambda}^0 \, \Omega_c^{*0}$
  - $\overline{\Lambda}^0 \to \overline{p} \, \pi^+$
  - $\Omega_c^{*0} \to \gamma \, \Omega_c^0$
    - $\Omega_c^0 \to \pi^+ \, \Omega^-$
      - $\Omega^- \to \Lambda^0 \, K^-$
        - $\Lambda^0 \to p \, \pi^-$





*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

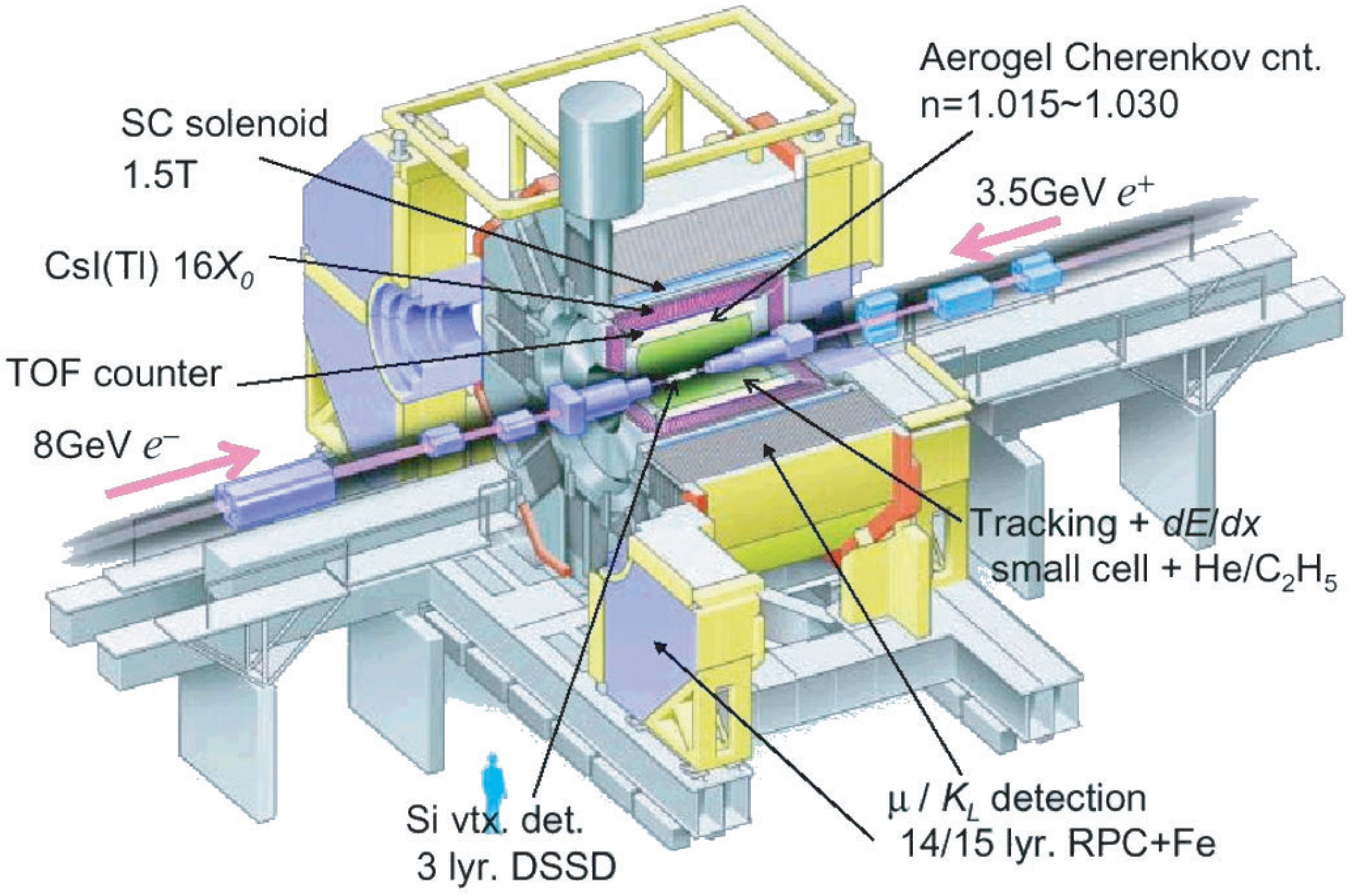
-data could be used to investigate baryon number violation

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

Approach

-develop data analysis algorithms to increase sensitivity to possible future discovery of decays

- use Monte Carlo (MC) data to optimize analysis algorithms.
  example of MC generation on right (using EvtGen)

-signal MC data mirrors searched for decays, generic MC data approximate backgrounds that reduce sensitivity

-optimization completed via application of selection criteria

-will apply analysis to real data when algorithms are finalized

EvtGen Control File

```
# B0bar -> Omega_c0 anti-Lambda0;  Omega_c0 -> Omega- pi+; Omega- -> Lambda0 K-; Lambda0 -> p pi-

Alias My-B0      B0
Alias My-anti-B0 anti-B0
ChargeConj My-B0 My-anti-B0

Alias My-Omega_c0       Omega_c0
Alias My-anti-Omega_c0          anti-Omega_c0
ChargeConj My-Omega_c0 My-anti-Omega_c0

Alias My-Omega-         Omega-
Alias My-anti-Omega+            anti-Omega+
ChargeConj My-Omega- My-anti-Omega+

#Alias My-Lambda0       Lambda0
#Alias My-anti-Lambda0  anti-Lambda0
#ChargeConj My-Lambda0 My-anti-Lambda0

Decay Upsilon(4S)
0.5 My-B0     anti-B0                          VSS;
0.5    B0  My-anti-B0                          VSS;
Enddecay

Decay My-B0
1.000       My-anti-Omega_c0 Lambda0       PHSP;
Enddecay
#
#Decay My-anti-B0
#1.000       My-Omega_c0 anti-Lambda0       PHSP;
#Enddecay
#
CDecay My-anti-B0

Decay My-Omega_c0
#1.00000        PYTHIA 84;
1.00000     My-Omega- pi+       PHOTOS PHSP;
Enddecay
CDecay  My-anti-Omega_c0

# Omega decays in GEANT  2002/04/12 H.Kakuno
#Decay  Omega-
#0.6780    Lambda0   K-                        PHOTOS PHSP;
#0.2360    Xi0   pi-                         PHOTOS PHSP;
#0.0860    Xi-   pi0                         PHOTOS PHSP;
#Enddecay
#CDecay anti-Omega+

# Lambda0 decays in GEANT 2002/04/11 H.Kakuno
#Decay  Lambda0
#0.6390    p+  pi-                            PHOTOS PHSP;
#0.3580    n0  pi0                            PHOTOS PHSP;
#0.0018    n0  gamma                           PHOTOS PHSP;
#0.0005    p+  pi-  gamma                      PHOTOS PHSP;
#0.0006    p+  e-   anti-nu_e               PHOTOS PHOTOS PHSP;
#0.0001    p+  mu-  anti-nu_mu              PHOTOS PHOTOS PHSP;
#Enddecay
#CDecay anti-Lambda0

End
```

Reconstruction Criteria

final state contains 6 charged particles:

- no cuts to pt, dz, and dr (still being investigated)
  (pions, kaons and protons that originate from primary and secondary vertices have different distributions of dr and dz.)

- charged pions PID selection: likelihood ratio (kaon/pion separation) < 0.4 (not applied to pion candidates from Λ^0 / $\overline{\Lambda}^0$ decays)

- proton PID selection: likelihood ratio (kaon/proton separation) < 0.9

- charged kaons PID selection: likelihood ratio (kaon/pion separation) > 0.4

- Λ^0 / $\overline{\Lambda}^0$ candidates are from vee2 bank (within 8 MeV of nominal mass after vertex fit)

- Ω^- candidates must have invariant mass (before vertex fit) within 60 MeV of nominal mass and (after vertex fit) within 6 MeV

- Ω_c^0 candidates must have invariant mass (before vertex fit) within 100 MeV of nominal mass and (after vertex fit) within 34 MeV

- Mbc > 5.2 (GeV/c^2) and -0.4 GeV < ΔE < 0.3 GeV

- No cuts to decay lengths and flight distances*
  (decay length is distance from particle birth to decay, flight distance is distance from origin to particle decay)

Reconstruction efficiency of $\overline{B}^0$ channel: 16.1% ($\pm$0.1%)
Reconstruction efficiency of B^0 channel: 16.5% ($\pm$0.1%)

$(\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^0)$

Reconstruction efficiency of $\overline{B}^0$ channel: 15.8% ($\pm$0.1%)
Reconstruction efficiency of B^0 channel: 15.6% ($\pm$0.1%)

$(\overline{B}^0 \to \overline{\Lambda}^0 \Omega_c^{*0})$

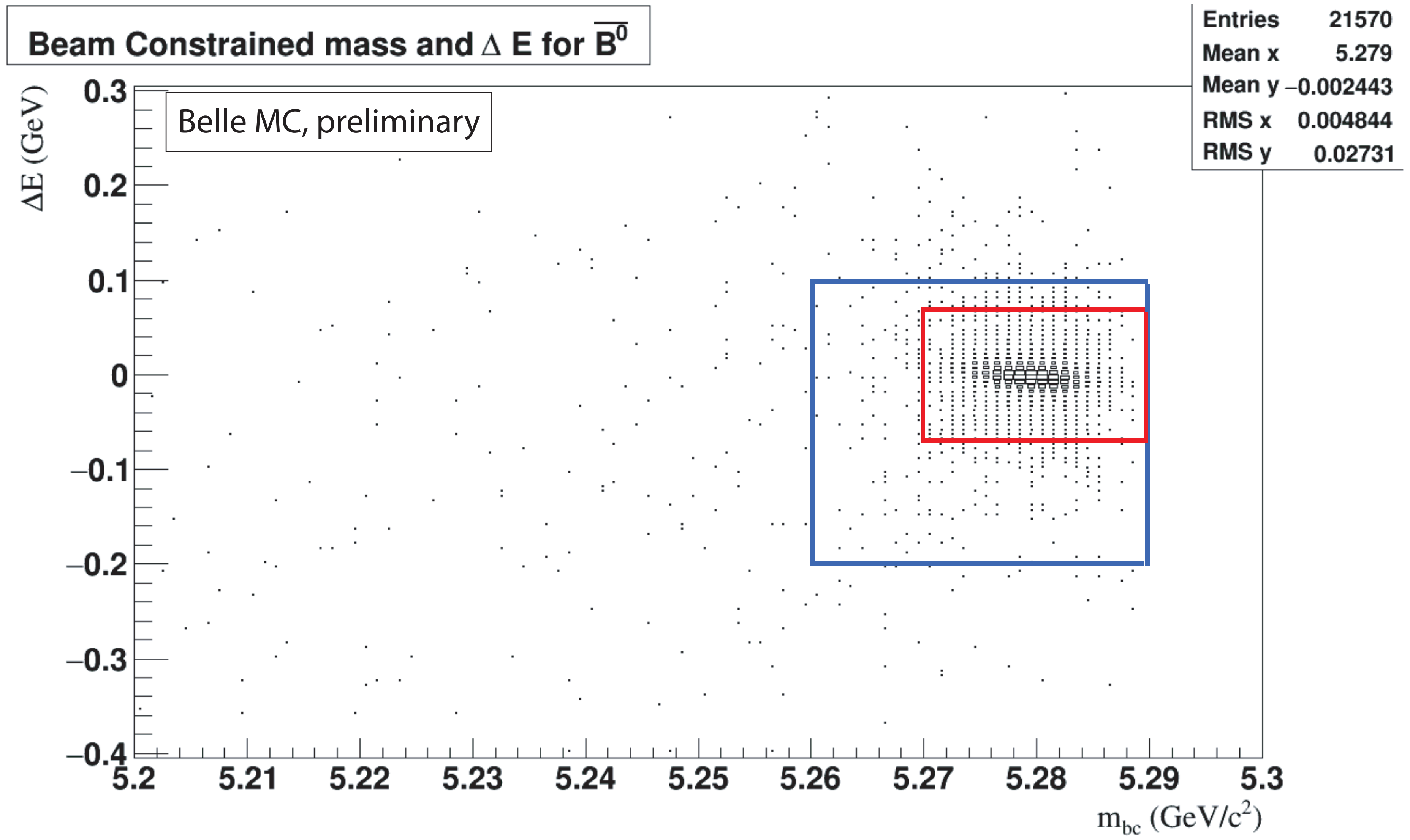
ΔE and Mbc for Signal MC ($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^0$)

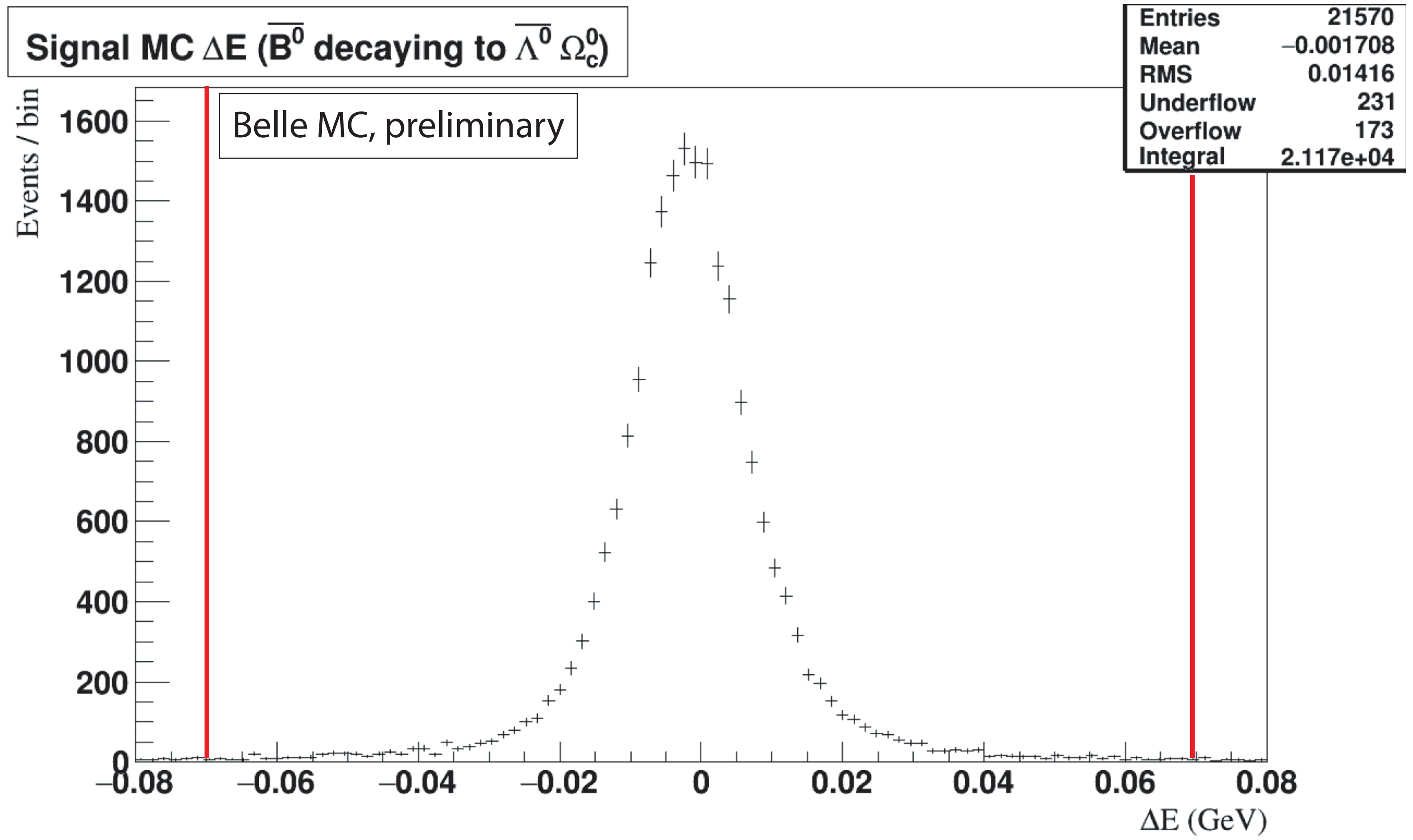
Signal Region (Red)

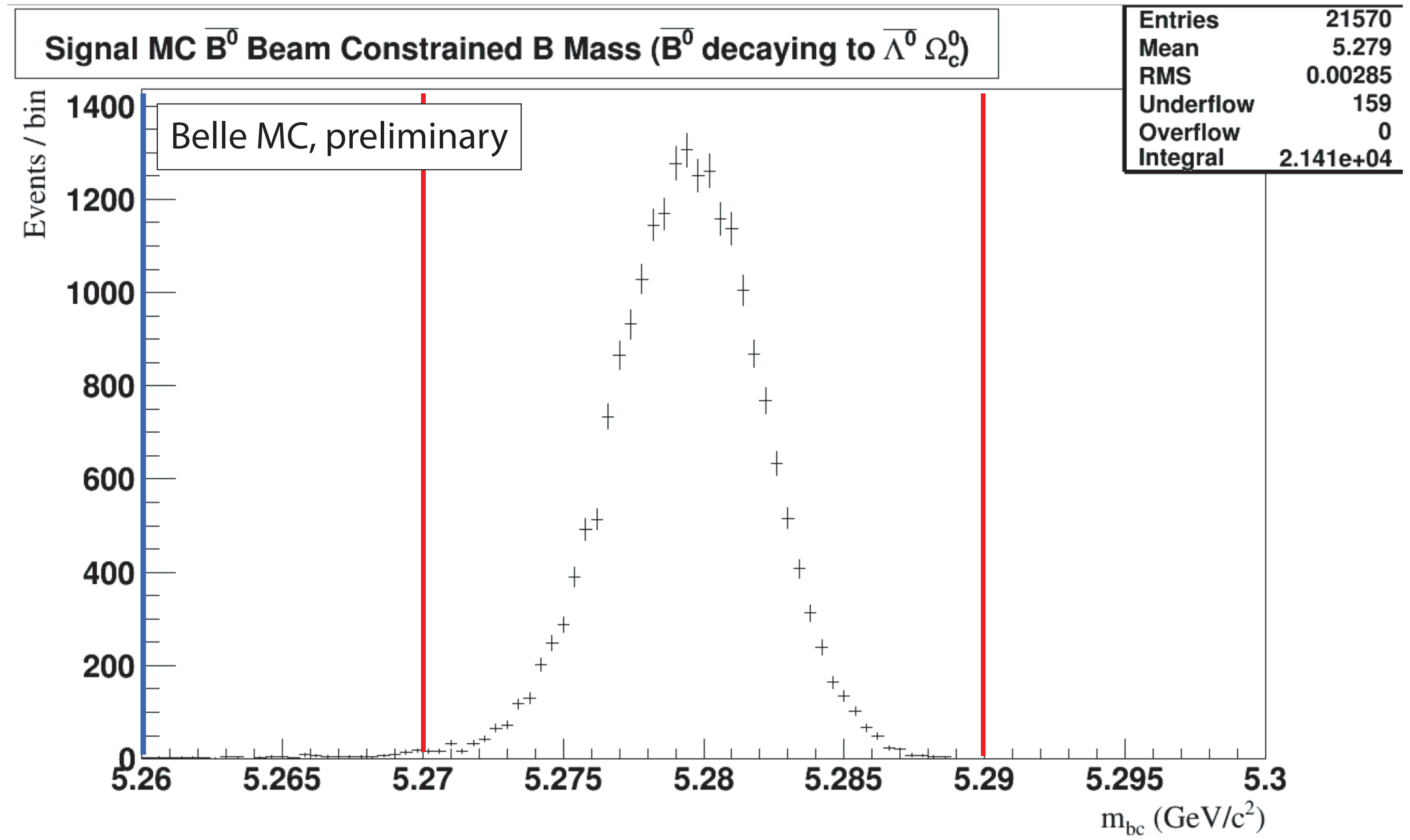
- Defined by region used to extract signal PDF's using MC for this channel ($M_{bc} > 5.27$ GeV/c^2 and (-0.07) GeV $< \Delta E < 0.07$ GeV)
- 97.3% of all signal MC events lie in this region

Region Blinded in Data (Blue)

- $M_{bc} > 5.26$ GeV/c^2 and (-0.2) GeV $< \Delta E < 0.1$ GeV
- 98.7% of all signal MC events lie in this region





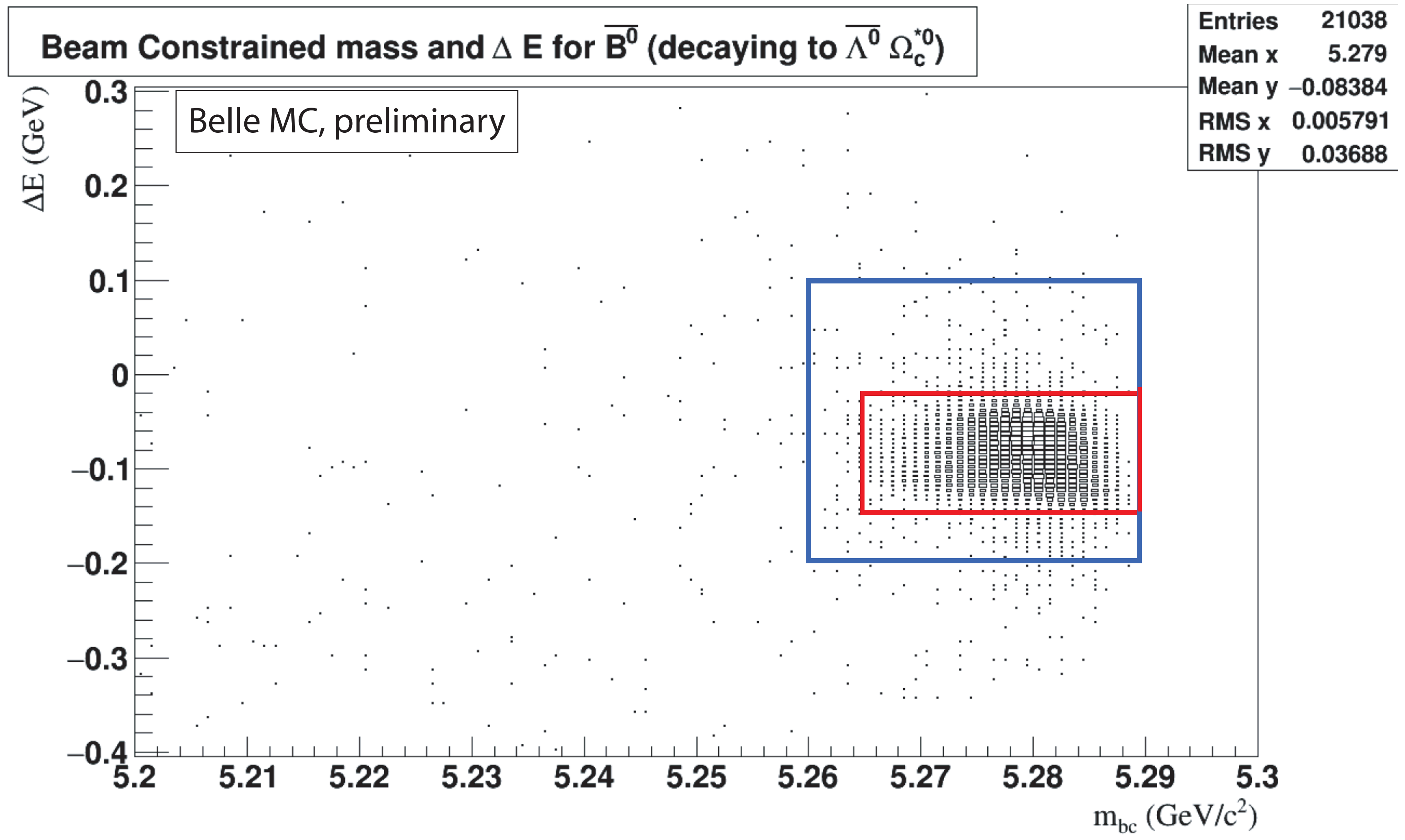


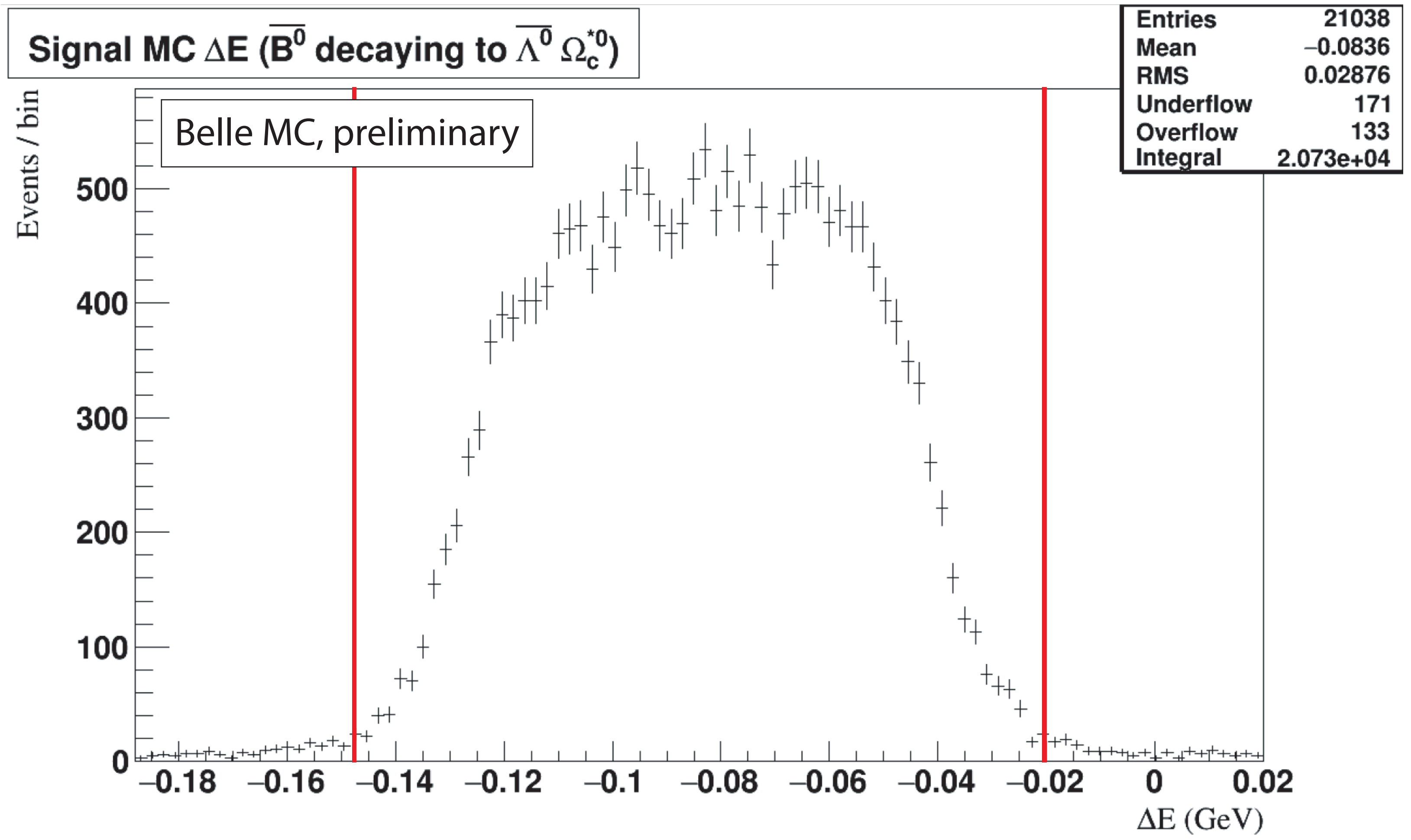
Signal Region (Red)

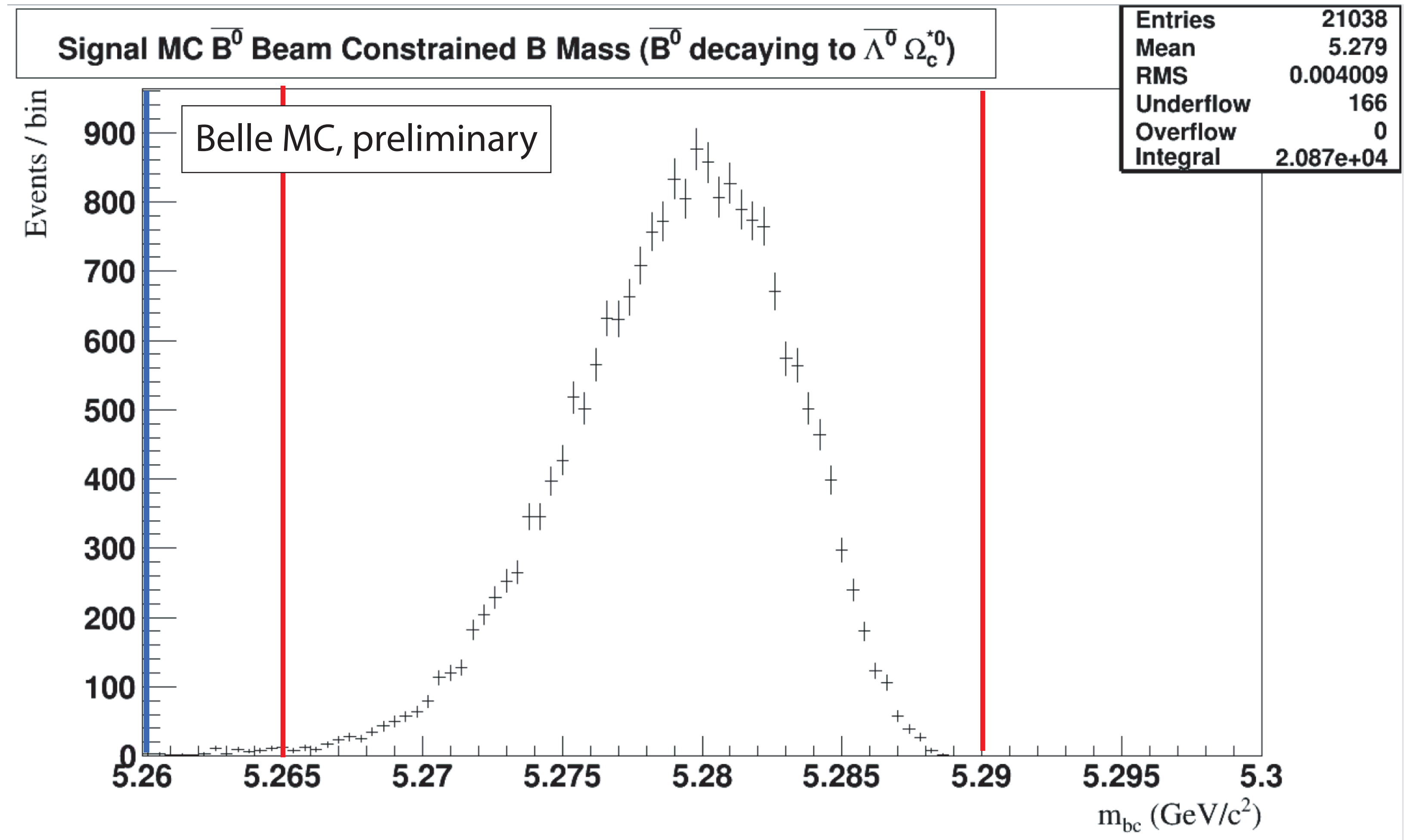
- Defined by region used to extract signal PDF's using MC for this channel (Mbc > 5.265 GeV/c^2 and (-0.145) GeV < ΔE < (-0.020) GeV)
- 96.4% of all signal MC events lie in this region

Region Blinded in Belle Data (Blue)

- Mbc > 5.26 GeV/c^2 and (-0.2) GeV < ΔE < 0.1 GeV
- 98.7% of all signal MC events lie in this region



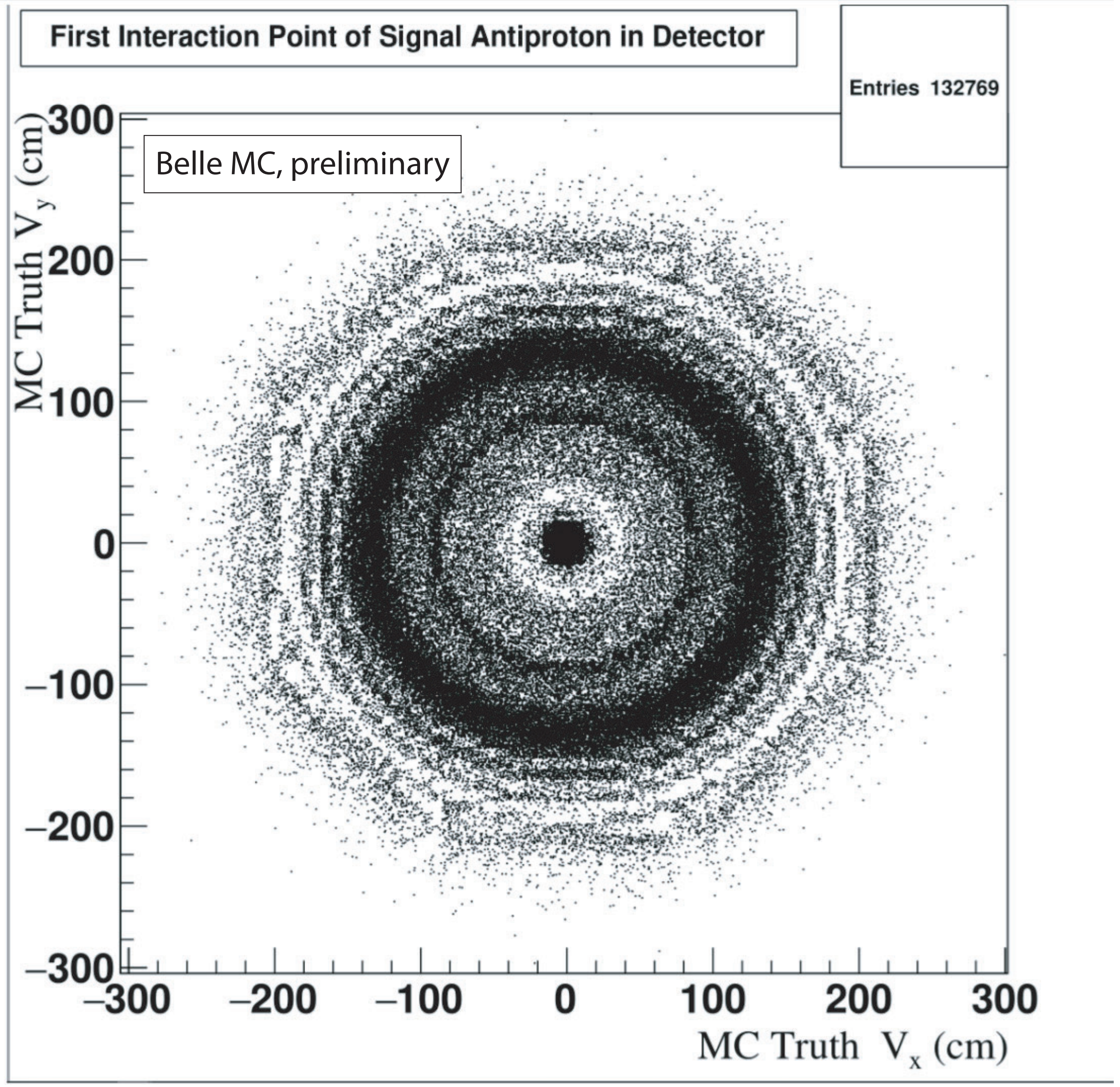




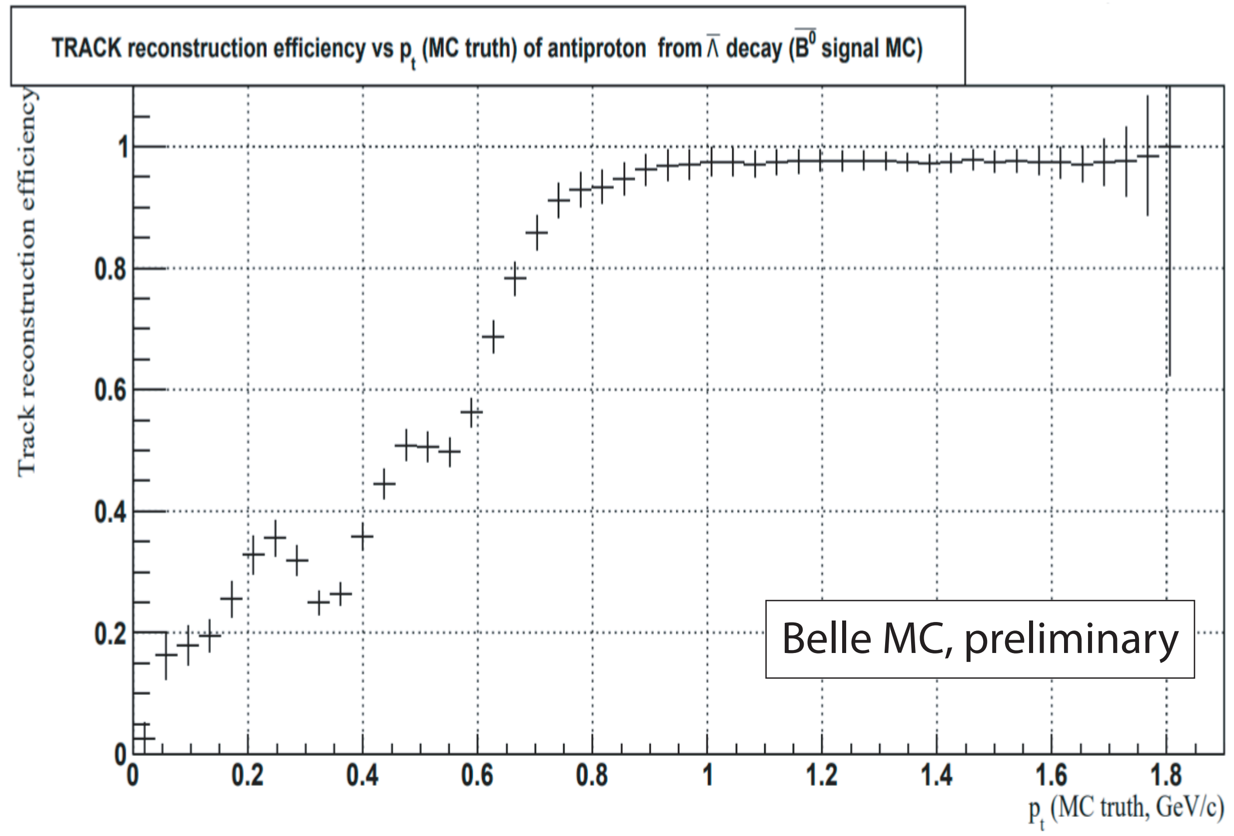
Example Investigation: Antiprotons

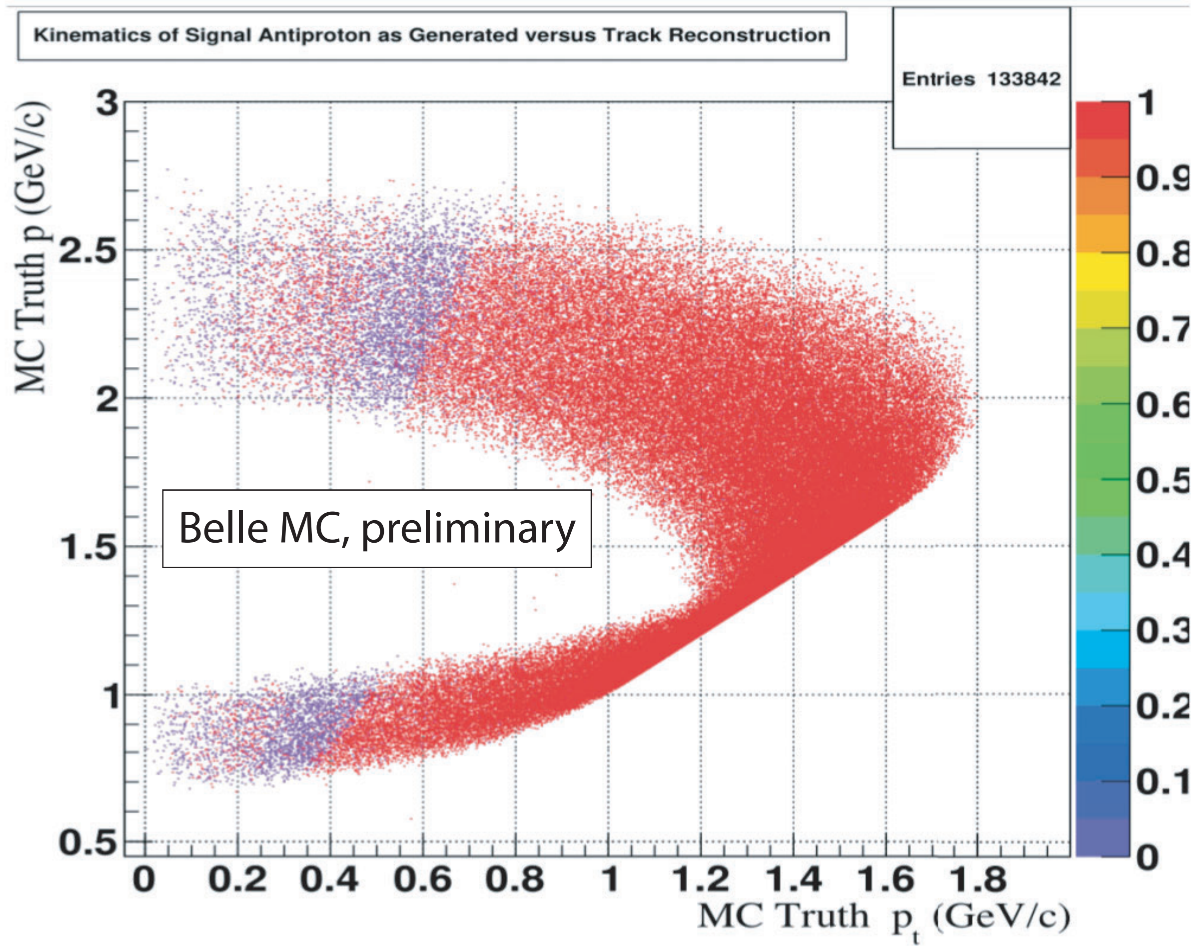
odd enhancement in track reconstruction efficiency with respect to transverse momentum of antiproton candidate in generated signal MC

investigation resulted in conclusion antiproton candidates of certain energy/ transverse momentum interacted with parts of the detector, making reconstruction efficiency higher at certain low pt values

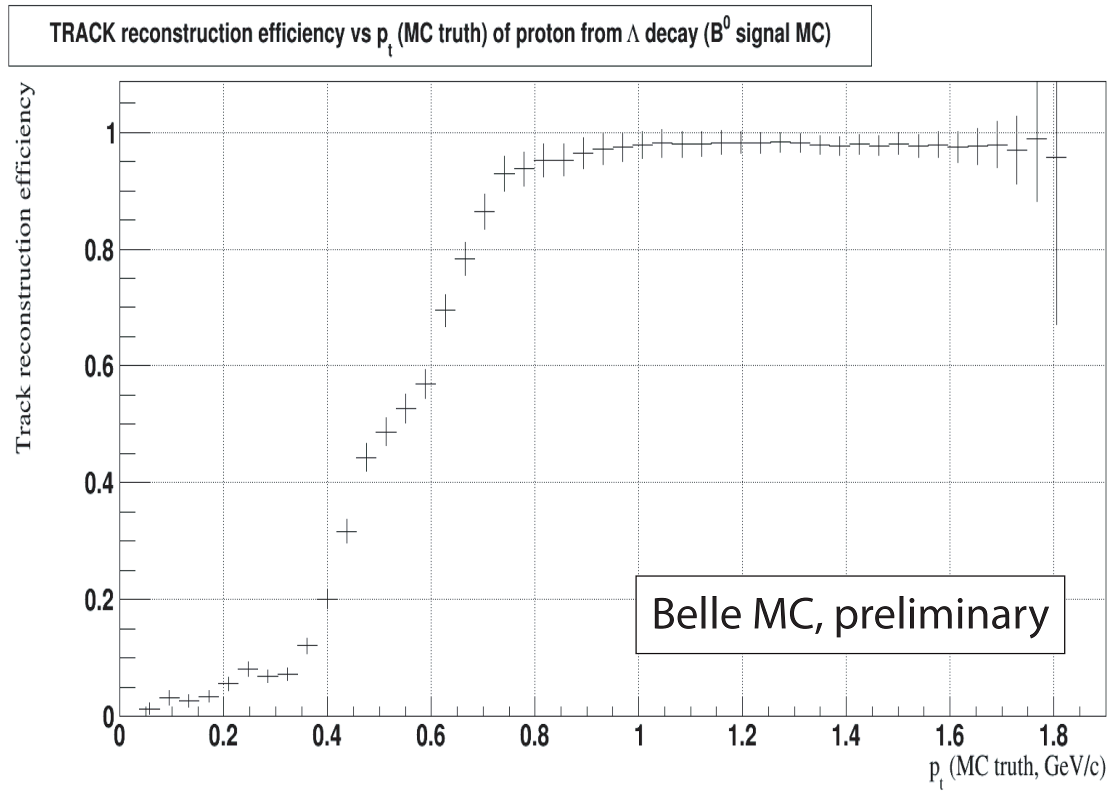


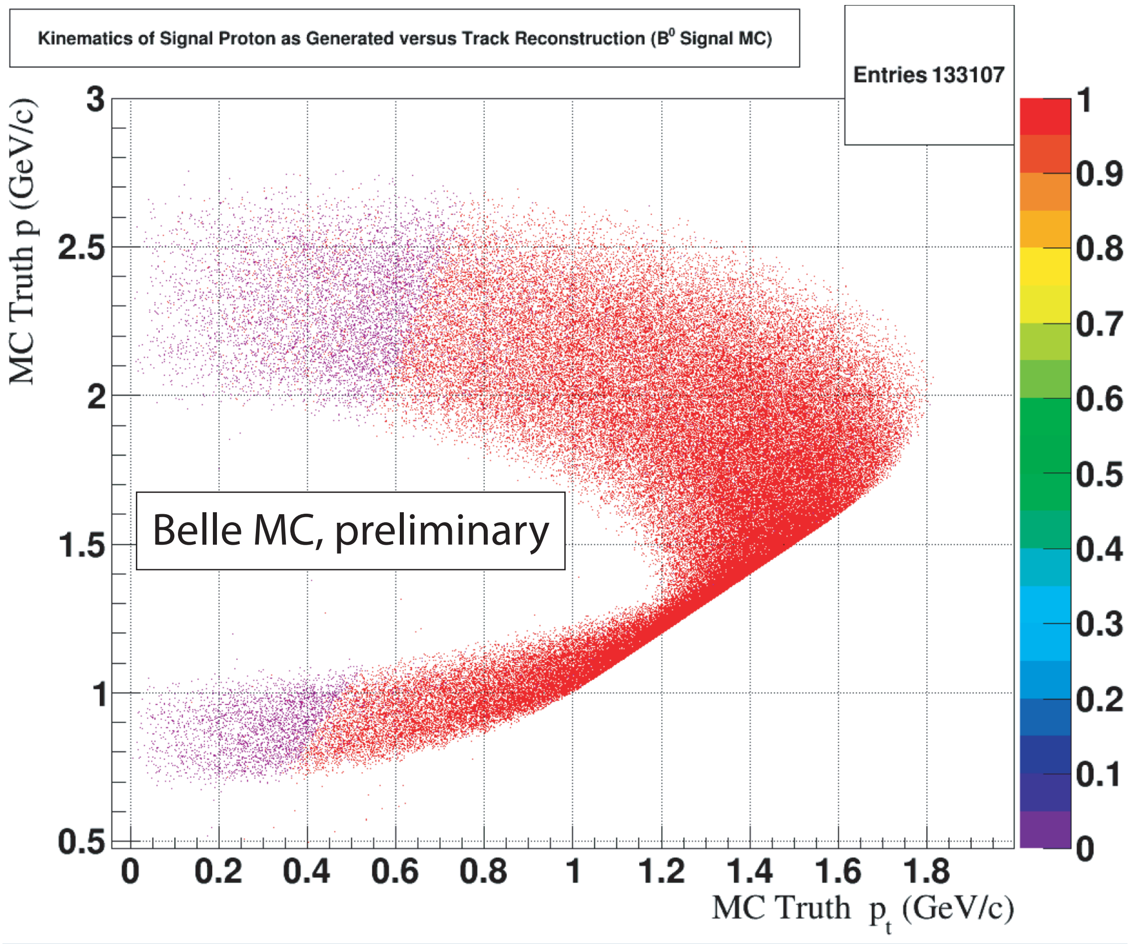
Antiproton ($\overline{B}^0$ events)





Proton (B^0 events)





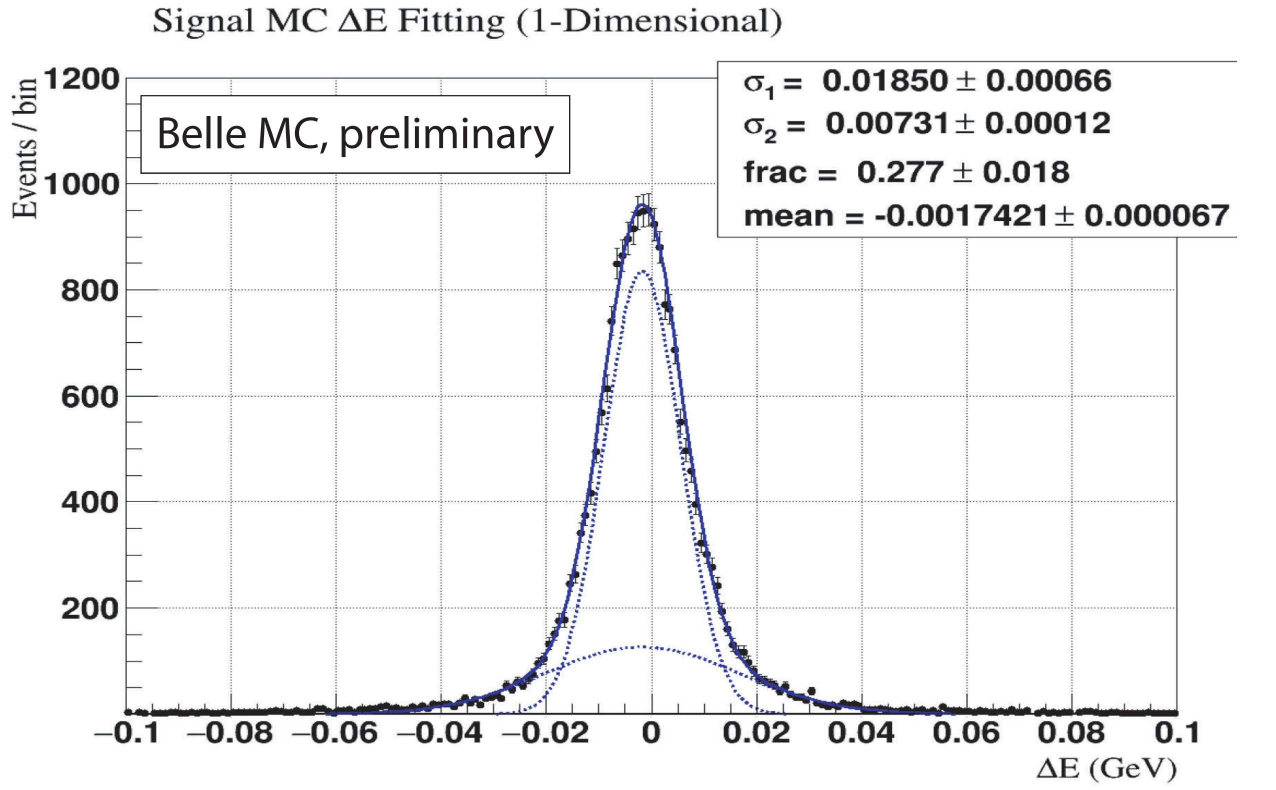
Fit Example ($\bar{B}^0 \to \bar{\Lambda}^0 \Omega_c^0$)

ΔE

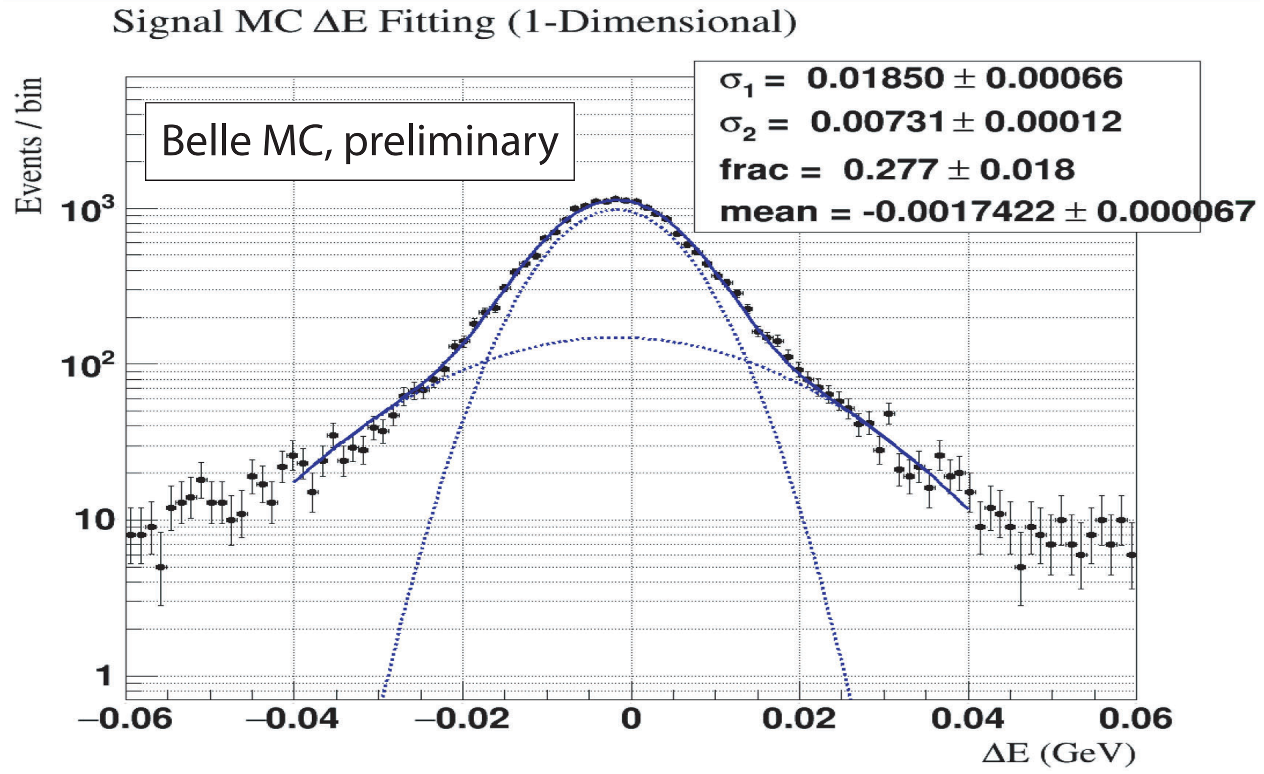
-double Gaussian

-fitting performed for region -0.04 GeV < ΔE <0.04 GeV

- selection criteria: Mbc > 5.27 GeV/c^2



Log-scale

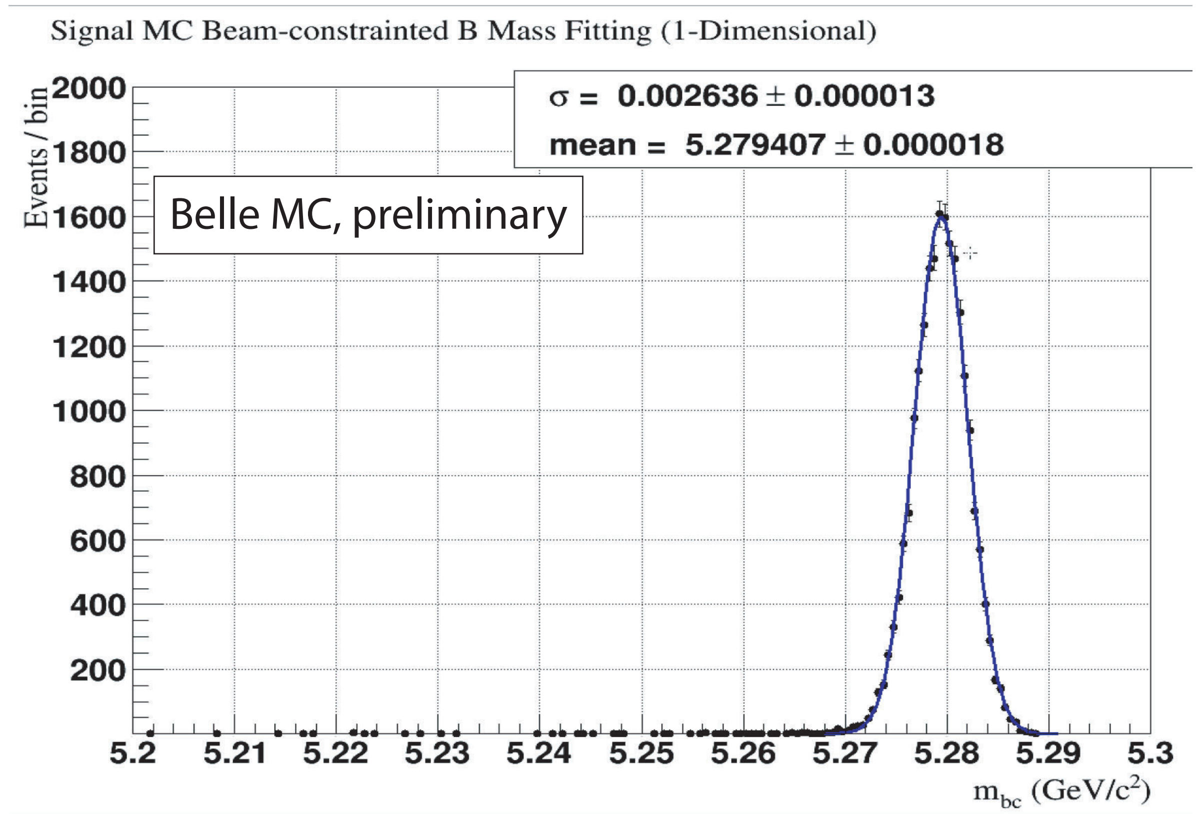


Mbc

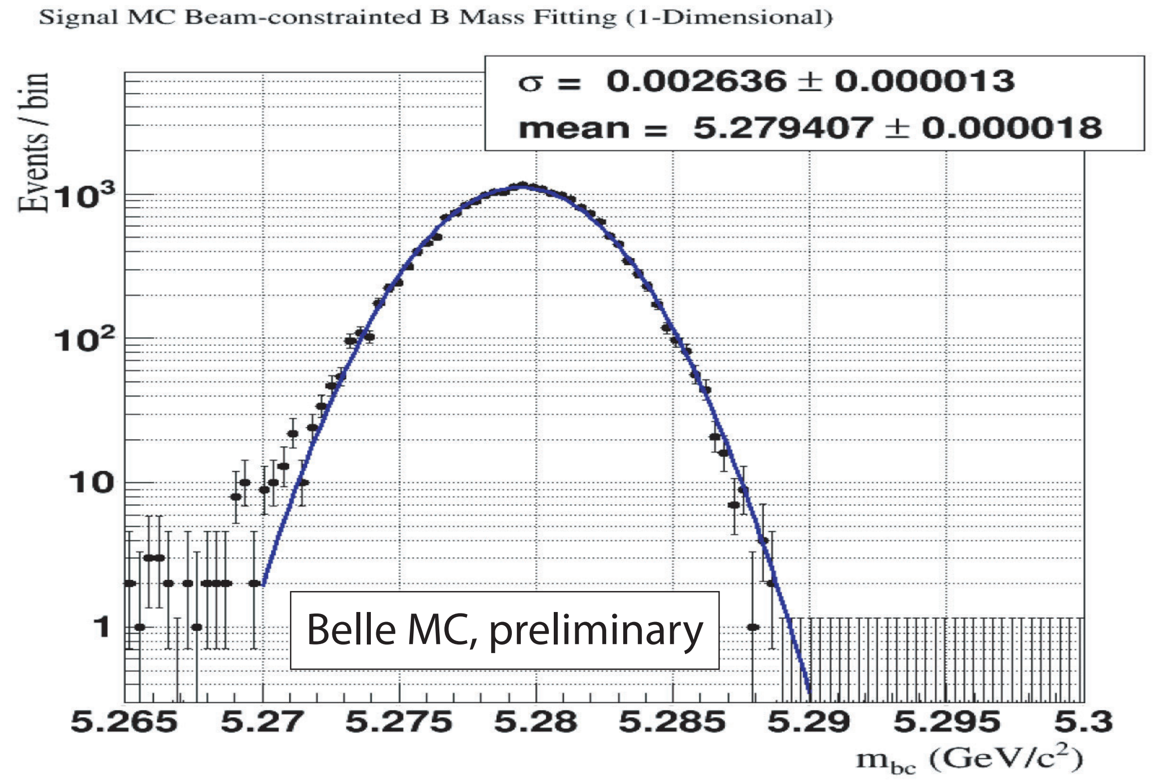
-Gaussian

-fitting performed for region 5.27 GeV/c^2< Mbc <5.29 GeV/c^2

-selection criteria: -0.07 GeV<ΔE<0.07 GeV



Log-scale



Ensemble Tests

- originally, studies were performed individually for the two channels

- currently working on fitting both signals simultaneously

- fitting variables ΔE and Mbc
  (1-D fits are with respect to Mbc)

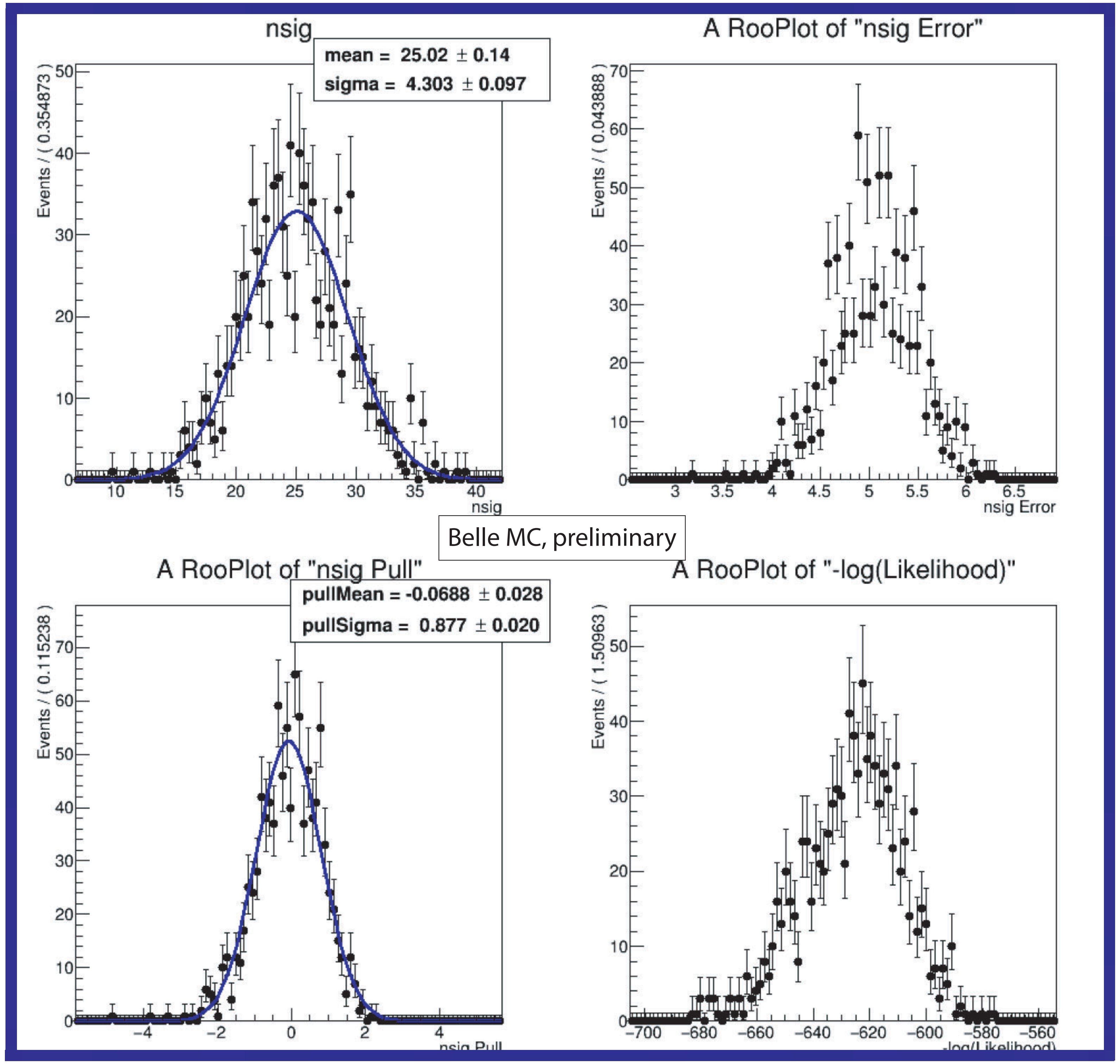
- toy MC experiments performed 1000 times for each signal hypothesis

- generate total number of background + signal events selected from combined PDF describing signal and background in each toy MC experiment

-1-D fits performed to establish upper limit if no signal is present from 2-D fit

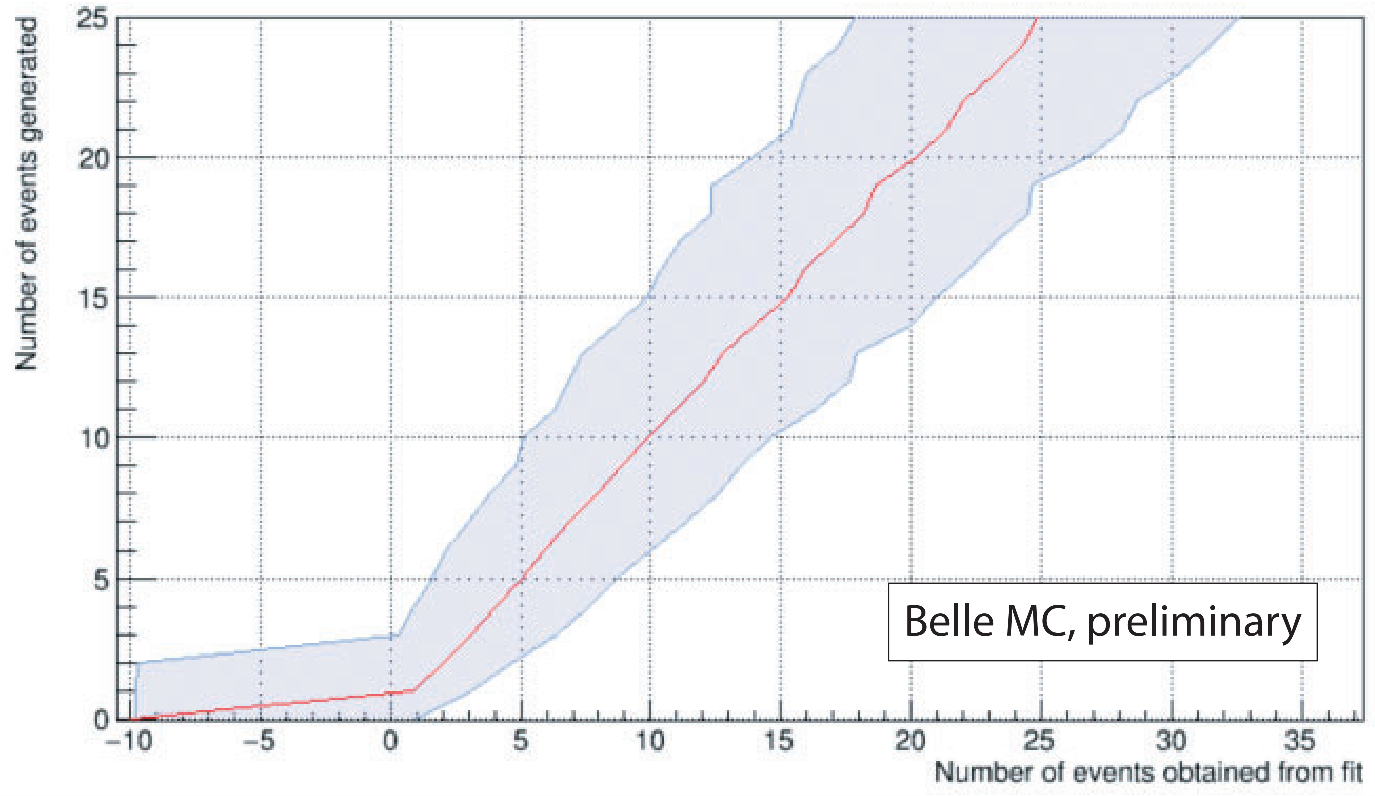
- can generate confidence belts from ensemble tests via interpolation

25 signal events hypothesis (2-D fit)

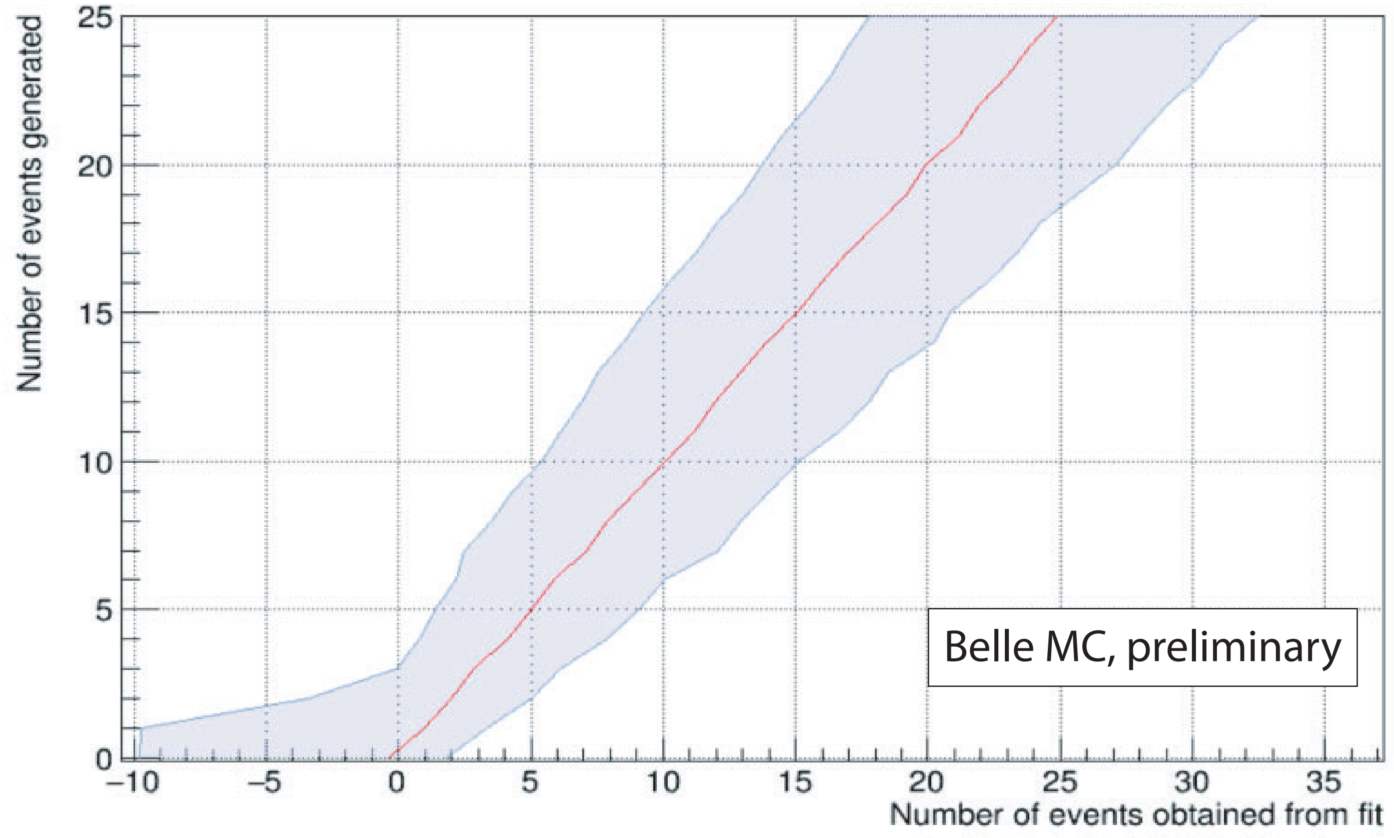


90% Confidence Belts

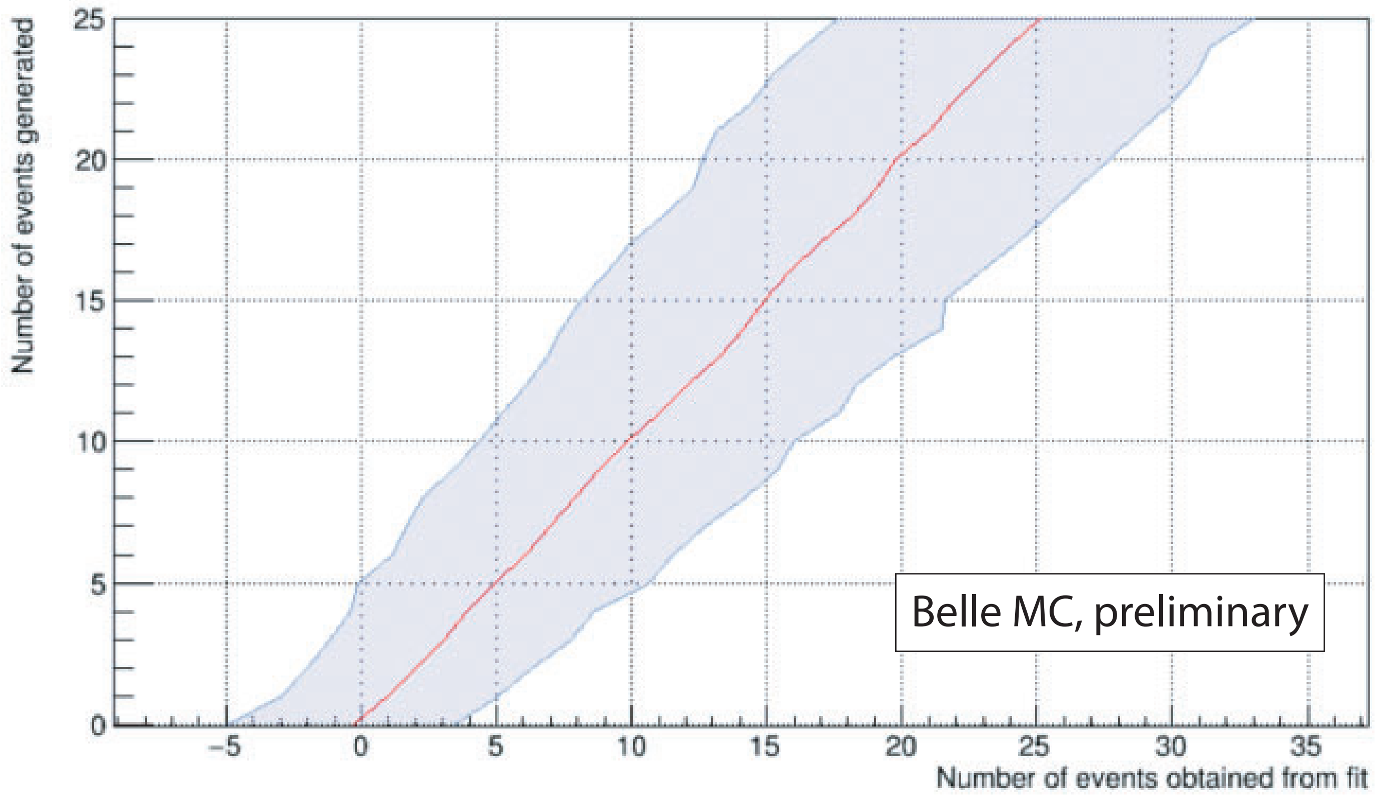
$\overline{B}^0$->$\overline{\Lambda}^0 \Omega_c^0$ (2-D)



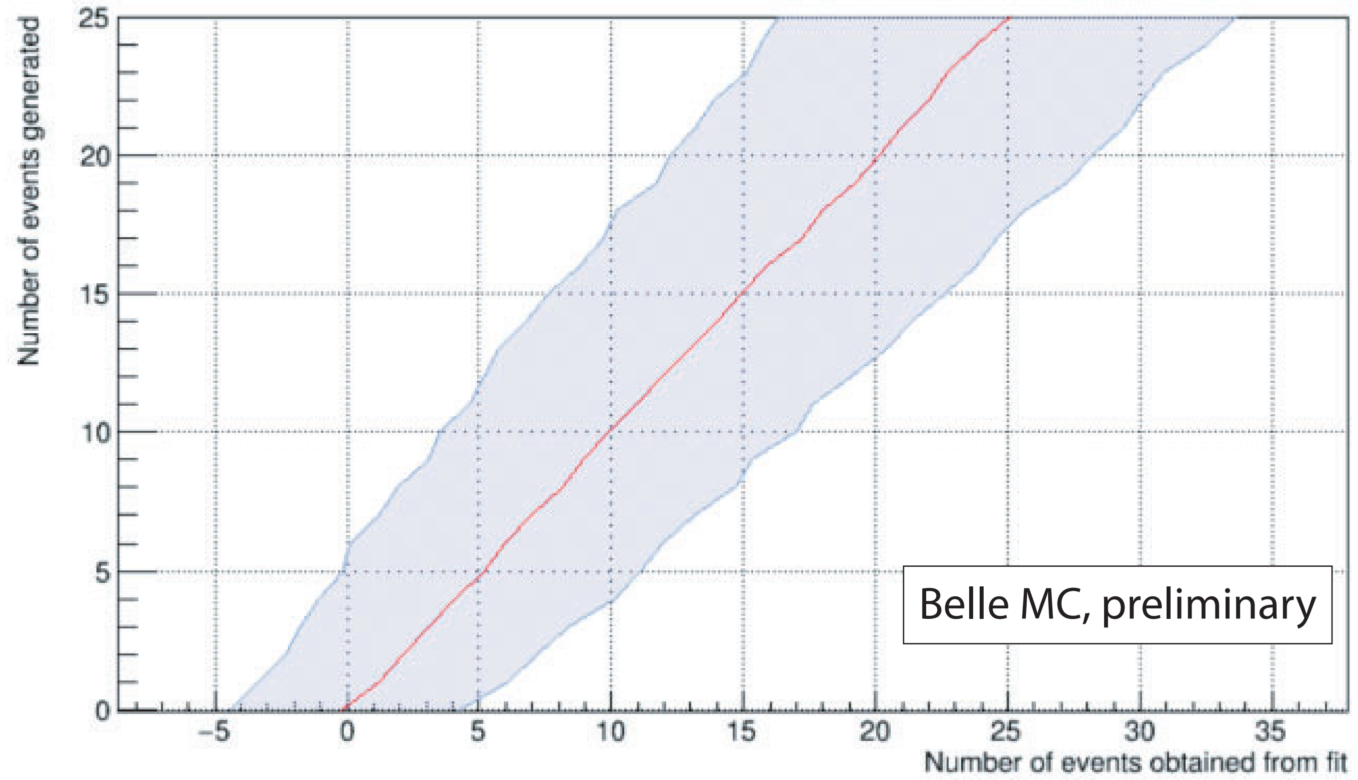
$\overline{B}^0$->$\overline{\Lambda}^0 \Omega_c^{*0}$ (2-D)



$\overline{B}^0$->$\overline{\Lambda}^0 \Omega_c^0$ (1-D)

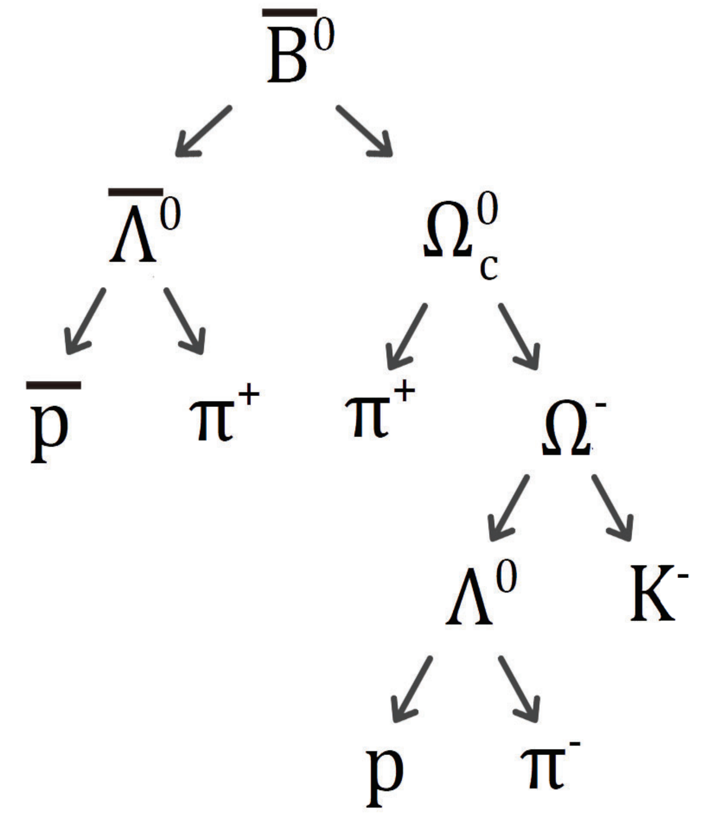


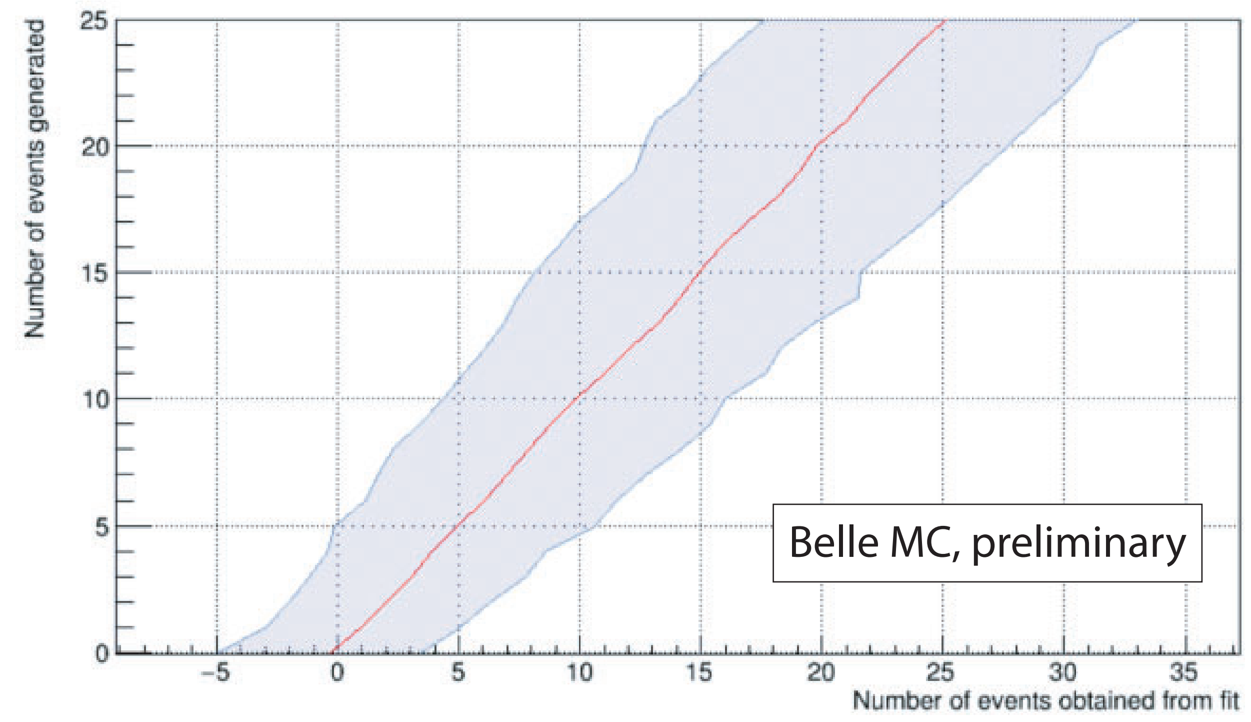
$\overline{B}^0$->$\overline{\Lambda}^0 \Omega_c^{*0}$ (1-D)



Upper Limit Calculation Example (Preliminary Estimate)

Parameter	Factor
$B\bar{B}$ pairs	772×10^6
Reconstruction Efficiency	0.161
$\Omega^- \to \Lambda^0 K^-$	0.678
$\Lambda^0 \to p\pi^-$	0.639
Estimation of $\Omega_c^0 \to \Omega^-\pi^+$	0.014*
Estimation of $\bar{B}^0 \to \bar{\Lambda}^0\Omega_c^0$	1.1×10^{-3}
Cabibbo-suppression	0.05





Λ_c^+

Γ_{28}	$\Lambda\pi^+$	$(1.30 \pm 0.07)\%$

Ξ_c^0

Γ_8	$\Xi^-\pi^+$	$(1.43 \pm 0.32)\%$

Assume 5 events observed in data -> upper limit is 10 events from confidence belt

*No absolute branching fractions have been measured for this decay, so fraction is determined based on other charmed baryon decays ($\Xi_c^0 \to \Xi^-\pi^+$ & $\Lambda_c^0 \to \Lambda\,\pi^+$)

$$\text{Upper limit on branching fraction} = \frac{10}{(772 \times 10^6) \times (0.161) \times (0.678) \times (0.639)^2 \times (0.014) \times (0.05)} = 4.15 \times 10^{-4}$$

Current Status

-Internal document detailing work has been prepared

-In discussions with analysis review committee to finalize analysis

-Need to investigate systematic uncertainties

-Will run on actual data and report findings very soon