WHEPP XVI

A Search for the $B_s^0 \to J/\psi\ \pi^0$ Decay at $\Upsilon(5S)$ Resonance

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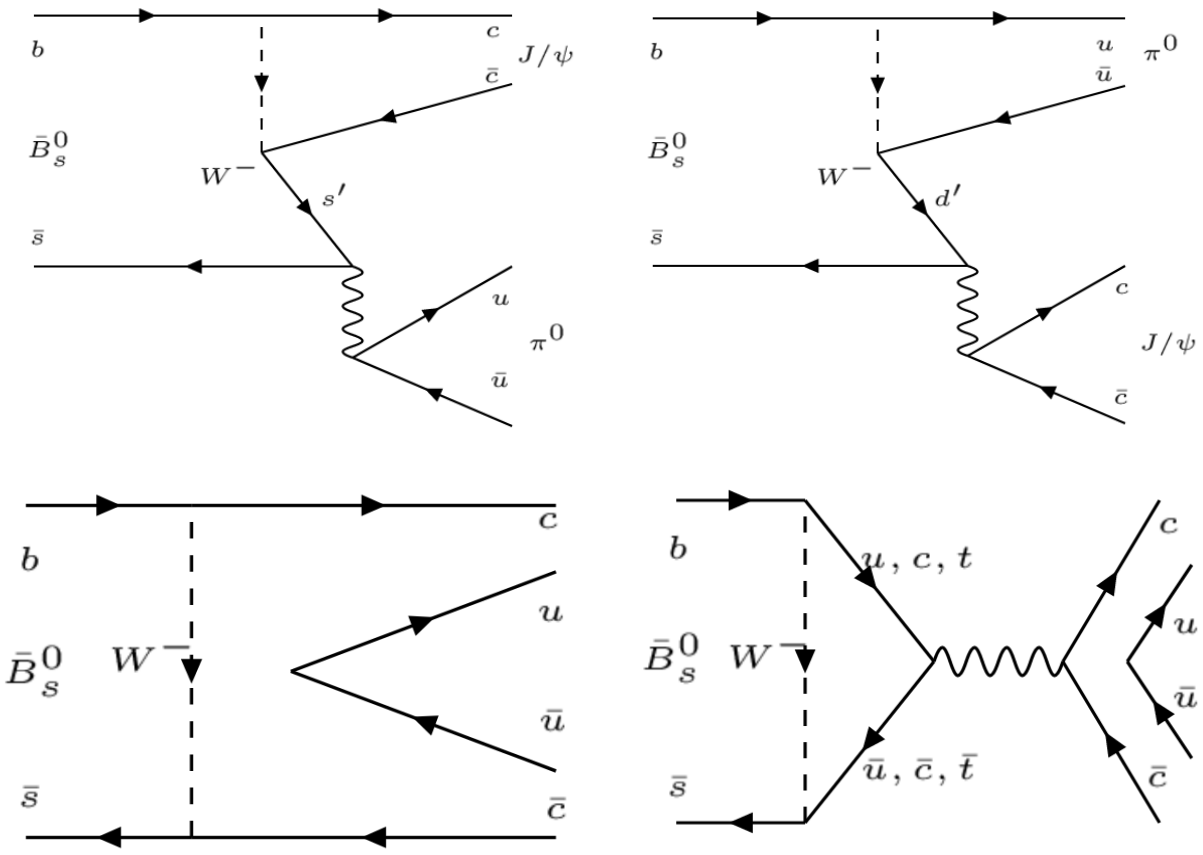
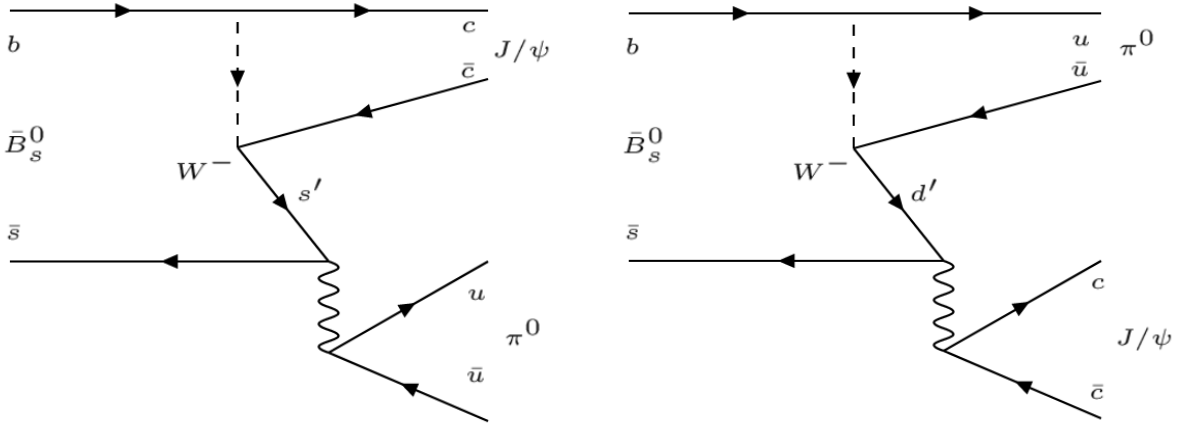
Theoretical motivation

Within the SM, the decay $B_s^0 \to J/\psi\pi^0$ can proceed through the following Feynman diagrams:

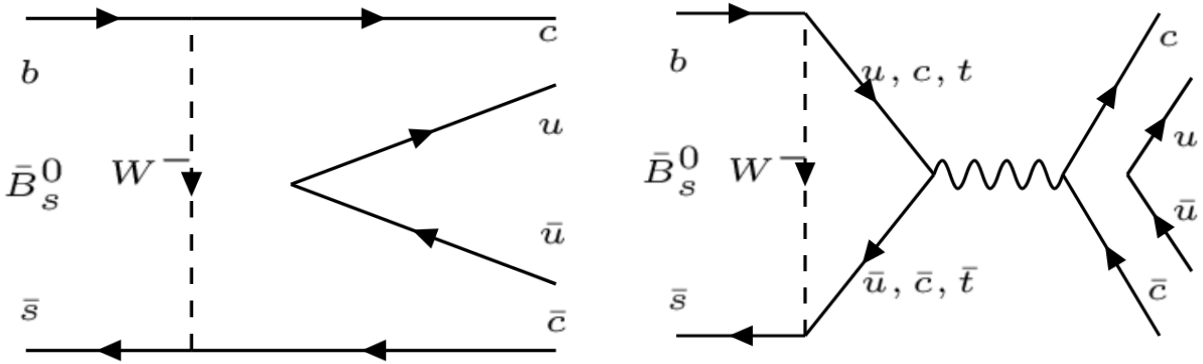


Theoretical motivation



1. Experimentally, $(|V_{ub}|/|V_{cb}|)^2 \approx 5 \times 10^{-3}$ and $(|V_{us}|/|V_{cs}|)^2 \approx 2 \times 10^{-3}$. Therefore, the diagram in the right is highly CKM-suppressed.
2. Both the diagrams are color suppressed.

Theoretical motivation



1. The diagram in the right has an addition annihilation topologies to the W-boson exchange process in left.

Theoretical motivation

- ⋆ Experimentally measured branching fraction for $B_d^0 \to J/\psi$ $\pi^0/\ \eta$ are the of the order of $O(10^{-5})$ which at the tree level are dominated by the spectator quark model.[1] [2]
- ⋆ Decay $B_s^0 \to \pi^+\pi^-$ mainly dominated by the annihilation mechanism is measured to be of the order of $O(10^{-7})$.[3] [4]
- ⋆ We expect $Br(B_s^0 \to \mathrm{J}/\psi\ \pi^0)$ to be of the order of $O(10^{-7} - 10^{-5})$ mainly contributing from the left two diagrams.

[1] JHEP01(2015)024/arXiv:1411.0943
[2] Phys. Rev. D 98
[3] Phys.Rev.Lett. 108 (2012)
[4] arxiv:1111.6264v3

Current status

	L3 experiment	Belle Experiment
$B_s^0 \bar{B}_s^0$ production	From scanning the beam energy on and around the Z-peak resonance.	From $\Upsilon(5S)$ resonance by tuning the beam CM energy at 10.865 GeV
Number of $B_s^0 \bar{B}_s^0$ pairs	$\approx$ 0.1 million	$\approx$ 7.1 million
$Br(B_d^0 \to J/\psi\ \pi^0)$	$< 3.2 \times 10^{-4}$ with 90% CL [5]	$= (1.62 \pm 0.11 \pm 0.07) \times 10^{-5}$ [2]
$Br(B_s^0 \to J/\psi\ \pi^0)$	$< 1.2 \times 10^{-3}$ with 90% CL [5]	Not measured yet.

5

[5] Phys.Lett. B391 (1997)

Event generation

- ⋆ The MC signal events are generated by the event generator 'EvtGen' which generates the events according to the provided decay file.
- ⋆ 100,000 generated events along with a background is simulated by the GEANT and stored in the mini data summary tables (MDST).

Decay Table	
Decay mode	Decay Model
$\Upsilon(5S) \to B_s^* \bar{B}_s^*$	PHSP
$B_s^* \to B_s^0 \gamma$	VSP_PWAVE
$B_s^0 \to J/\psi\ \pi^0$	SVS
$J/\psi \to \mu^+ \mu^-$	VLL
$\pi^0 \to \gamma\gamma$	PHSP

Event reconstruction and possible background

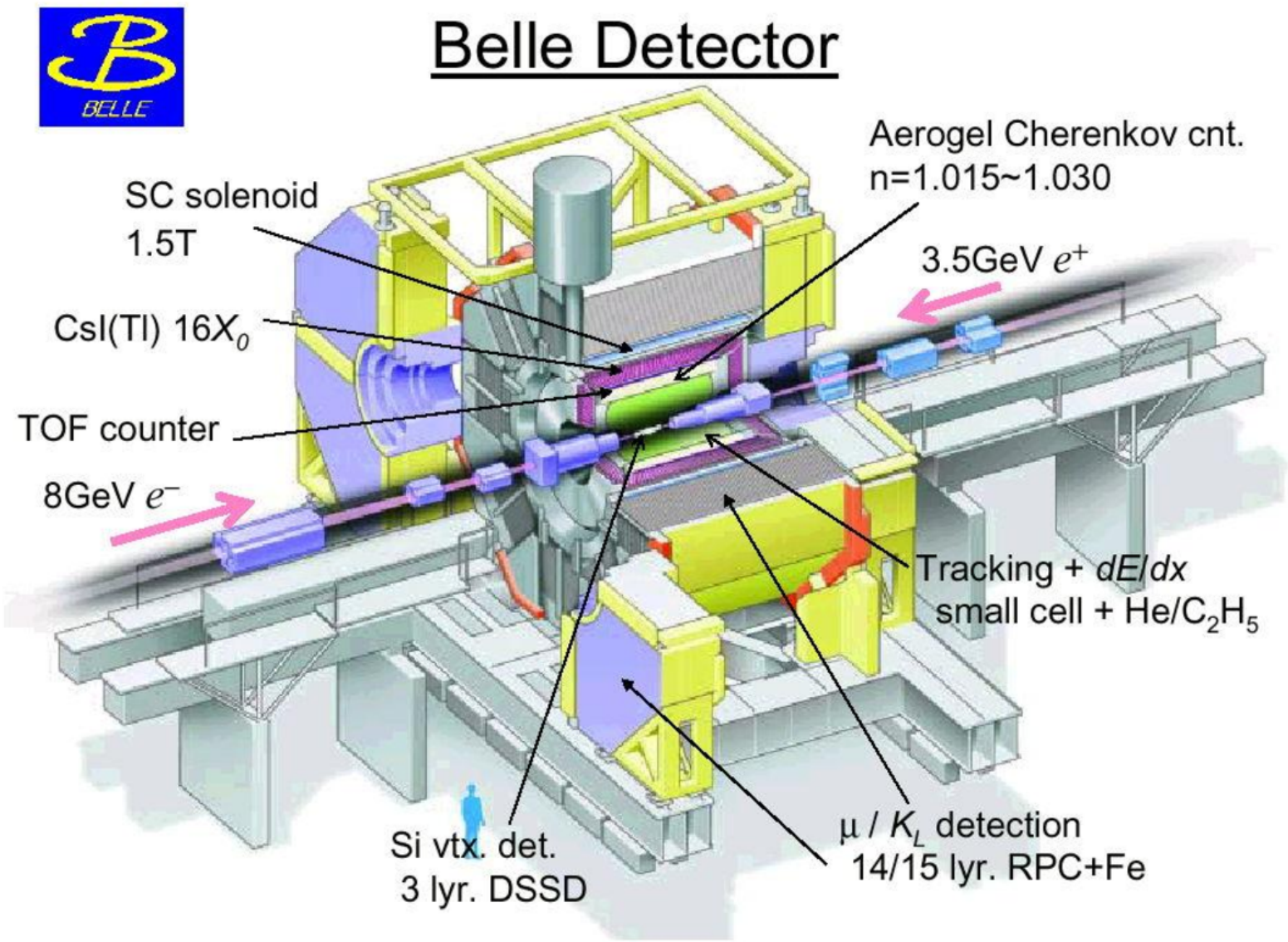
Signal reconstruction

- ⋆ $B_s^0 \bar{B}_s^0$ mesons are produced by tuning the $e^- e^+$ beam energy at $\Upsilon(5S)$ resonance state in the CM frame.
- ⋆ J/ψ and π^0 for the decay $B_s^0 \to J/\psi \pi^0$ are reconstructed from the $\mu^+ \mu^-$ and $\gamma\gamma$ final state particles respectively.

Background contribution

- ⋆ However, $\Upsilon(5S)$ state can also lead to non-B_s^0 events.
- ⋆ The production of other hadronic states from $e^- e^+ \to q\bar{q}$, where $q = u, d, s, c$ i.e., continuum background.
- ⋆ Contribution from *udsc*-continuum is expected because of the final state J/ψ and π^0 mesons.
- ⋆ The MC data generated by the dedicated Belle team are used to study the background.

Belle Detector: An Overview



μ identification

- ⋆ Muons are identified from the hits in SVD, CDC and KLM detectors.
- ⋆ Tracks with no-hit in the KLM detector are rejected.
- ⋆ The closest approach of a track to the interaction point (IP) is required within the region $r < 0.5$ cm and $z < 3.0$ cm.

μ_ID:

1. Based on the hit information in the the above detectors,
2. $\Delta R = R_{expected} - R_{measured}$ inside the KLM detector, and
3. Transverse deviation of an associated hit from the extrapolated track.

μ identification

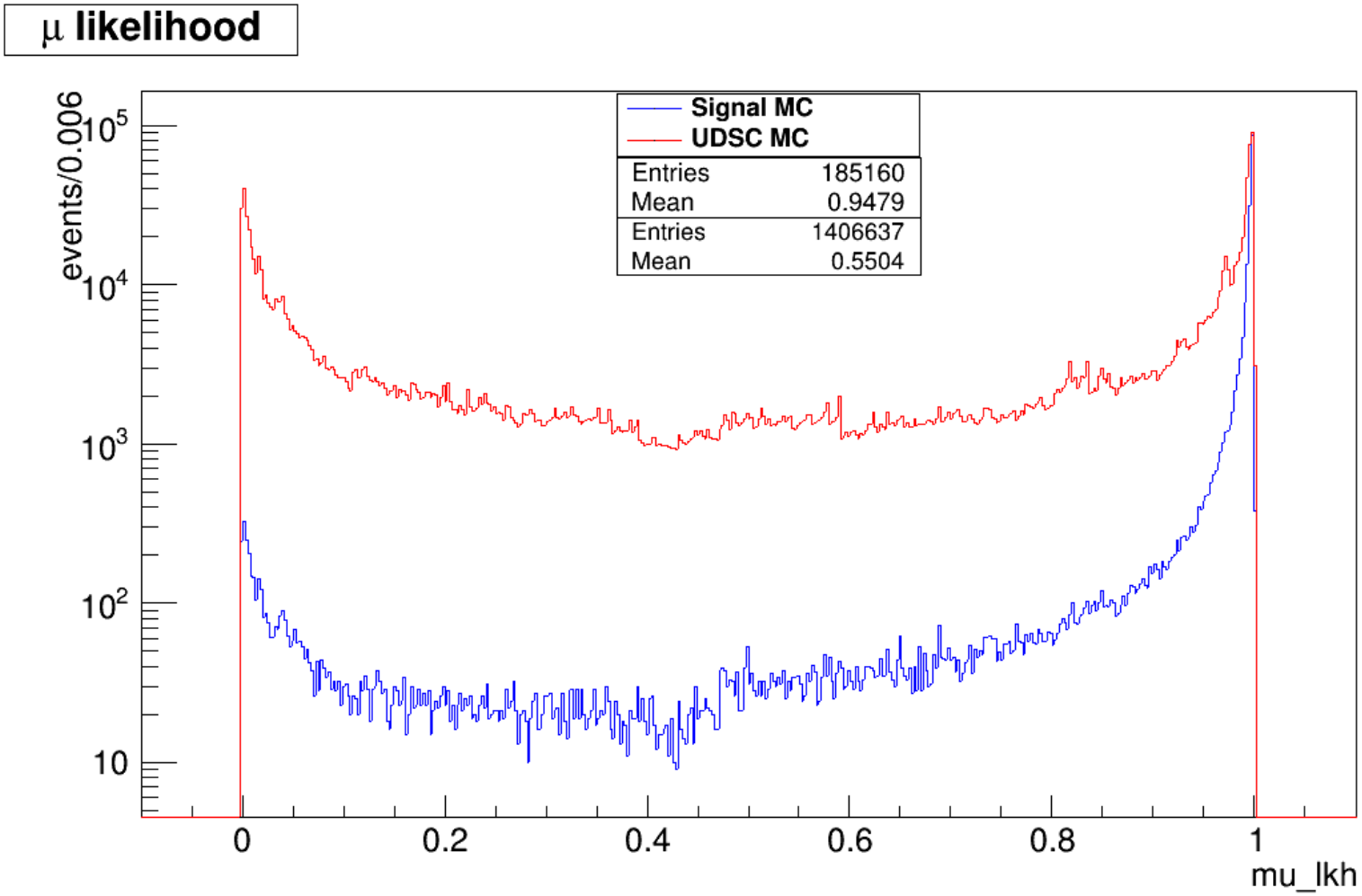


Figure: Muon-likelihood ratio for the charged tracks in the signal and *udsc*-background MC.

J/ψ reconstruction

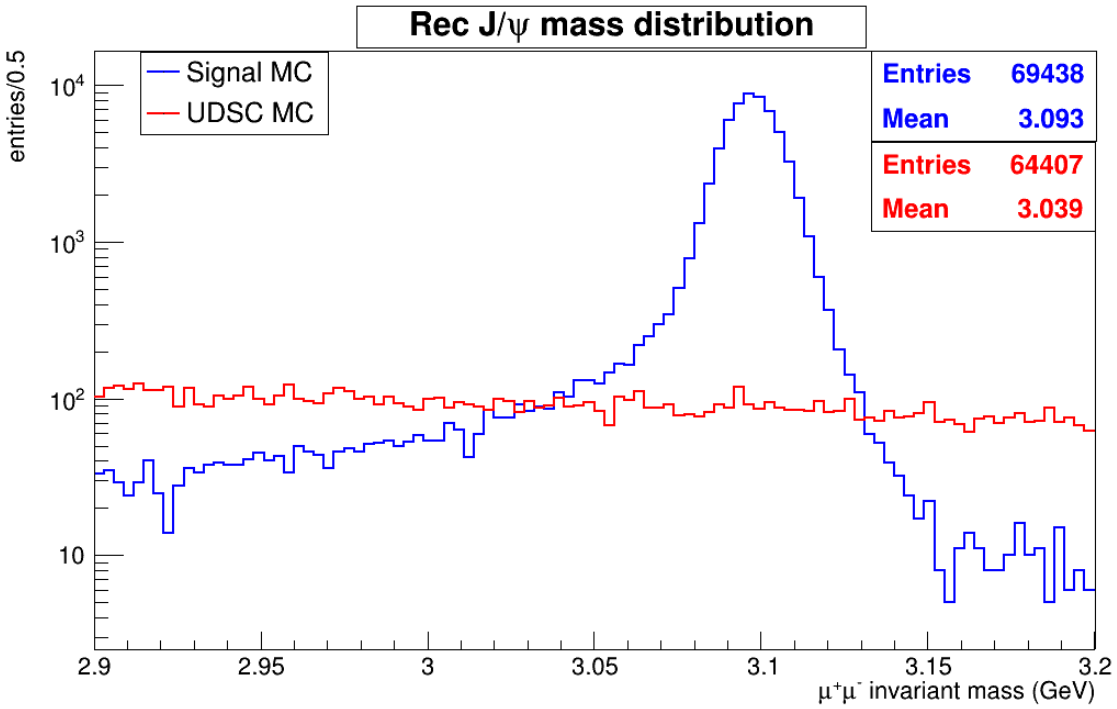
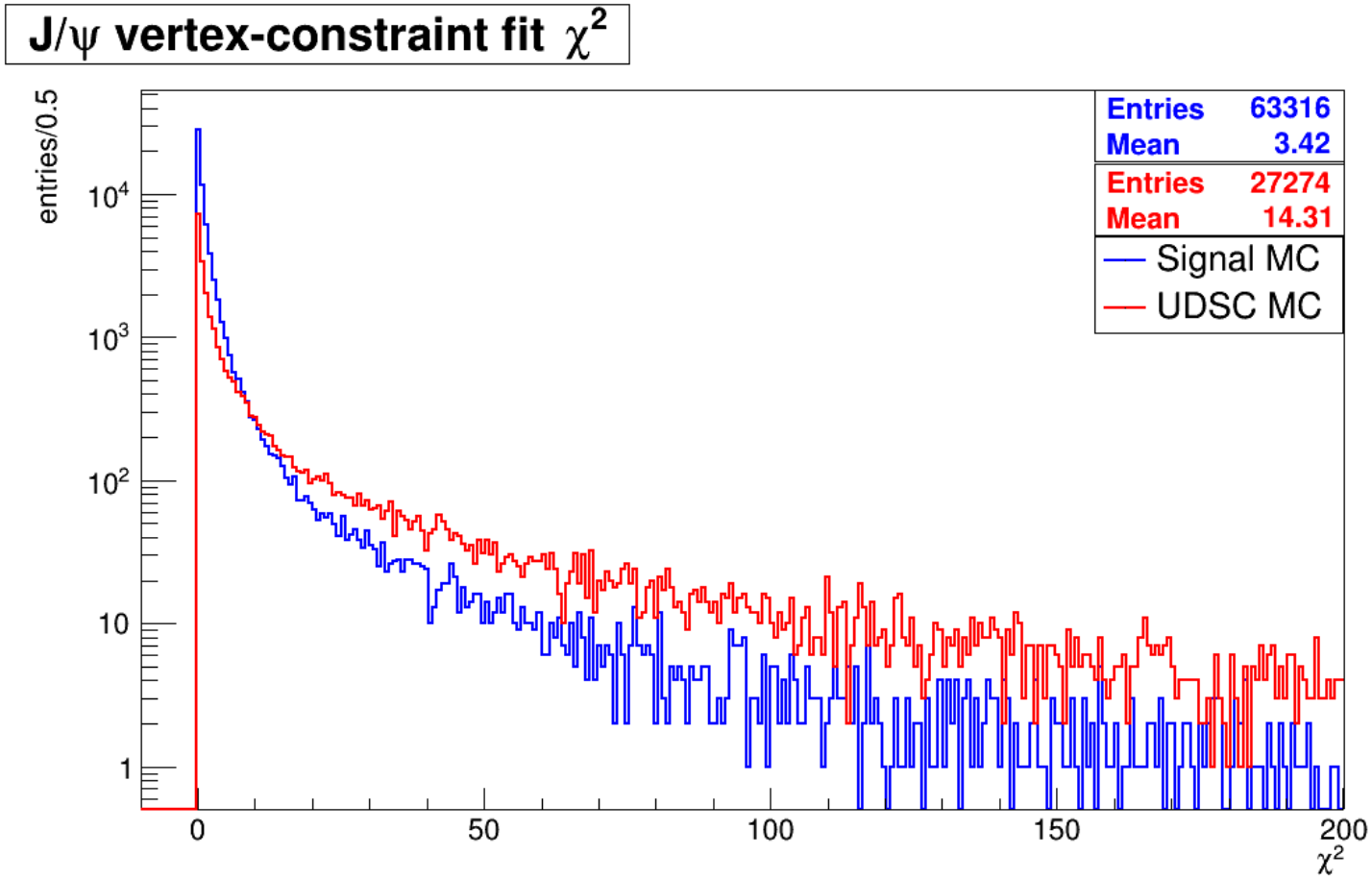


Figure: $\mu^+\mu^-$ invariant mass distribution for the MC signal (blue) and uds-charm background(red).

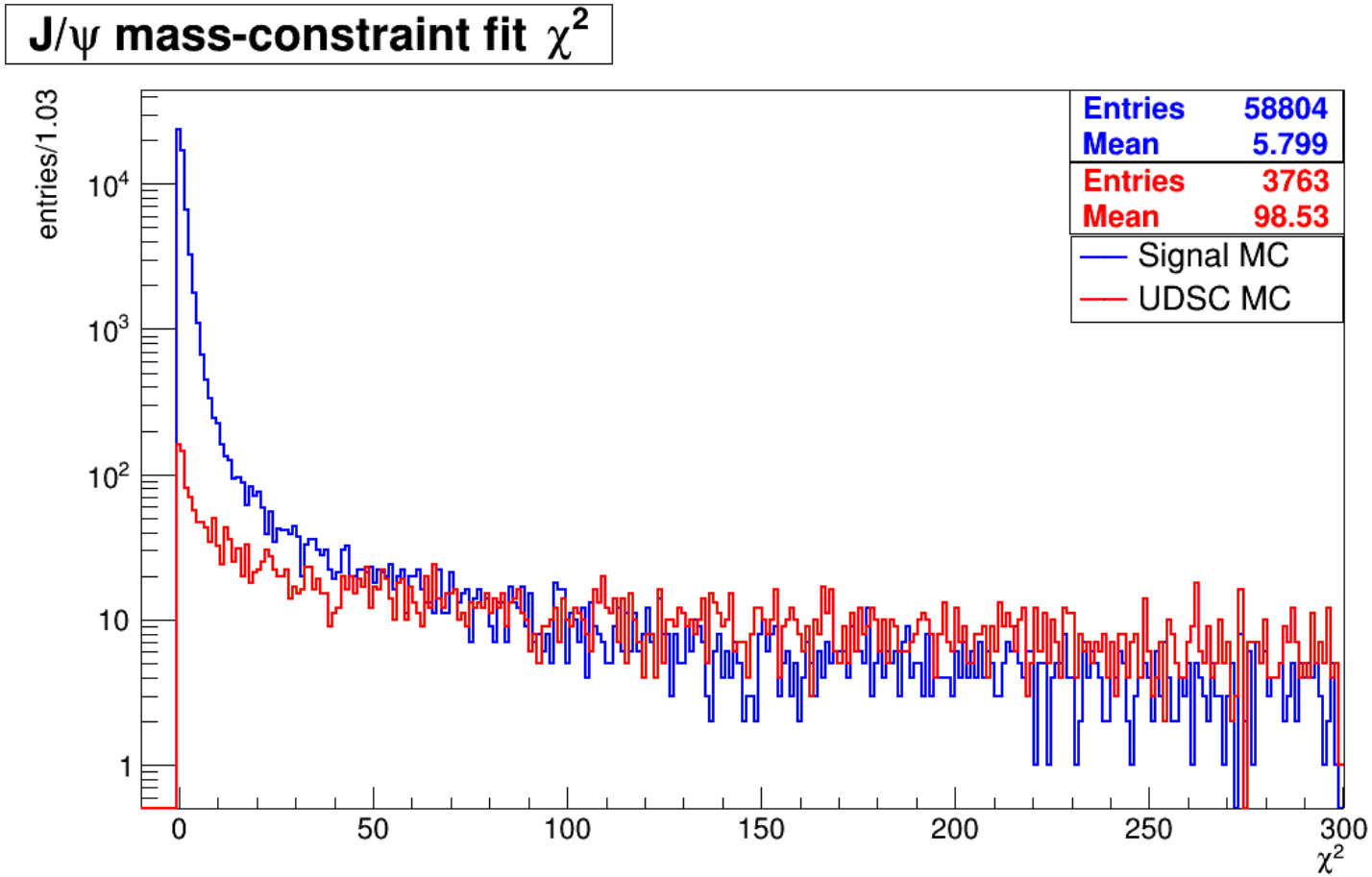
Vertex requirements and μ_likelihood > 0.4 are required in the above distribution.

J/ψ reconstruction



⋆ To avoid the udsc MC background and improve the J/ψ reconstruction, vertex-constraint fit $\chi^2 < 50$ is required.

J/ψ reconstruction



- ⋆ The random combinations of the muon candidates in the MC background sample give poor J/ψ mass-constraint fit χ^2.

γ selection

- ⋆ Photons are selected from the ECL where they deposit energy along with the electrons through electromagnetic interactions.
- ⋆ Candidates with good shower shape and no track available in CDC and SVD detectors are considered as photons.

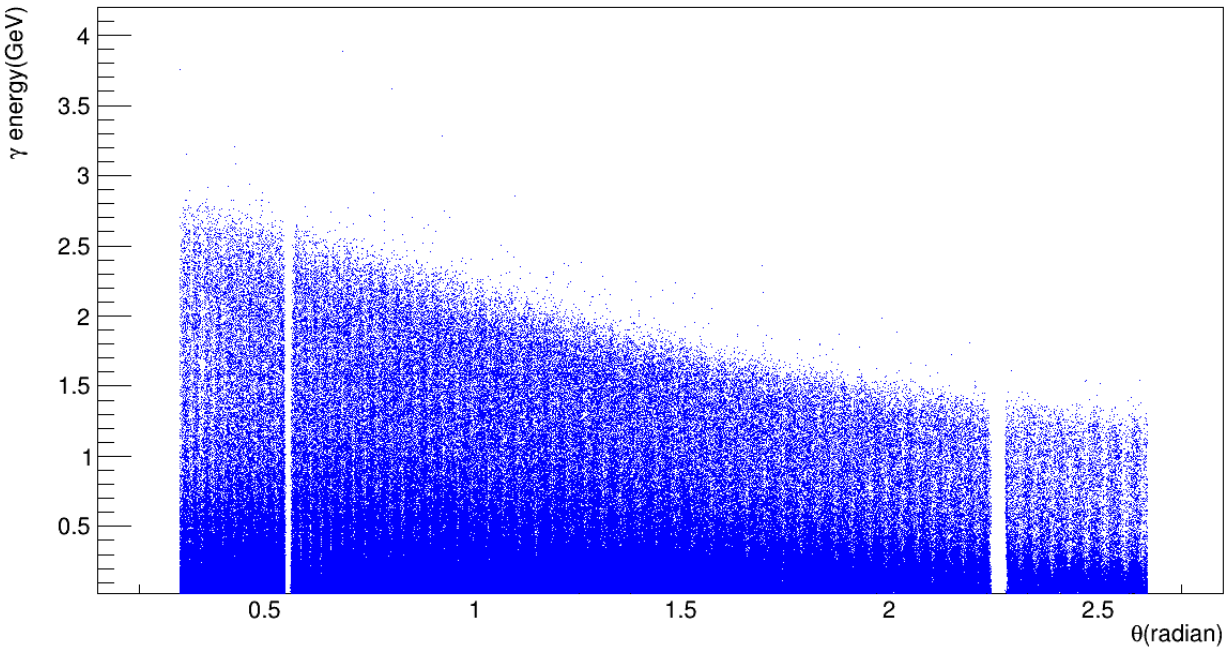
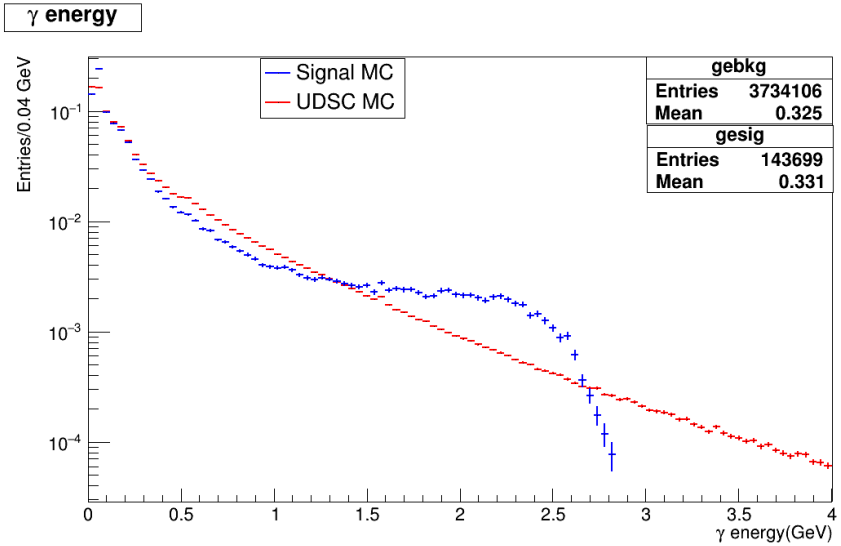


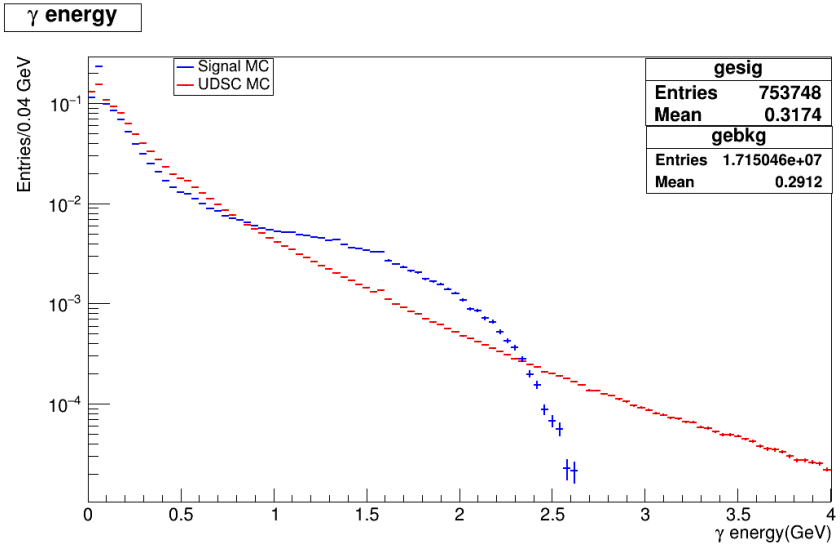
Figure: γ energy vs θ distribution.

⋆ Asymmetry in γ energy with respect to polar angle can be exploited in the π^0 reconstruction.

γ selection



(a) Forward Endcap



(b) Barrel Region

As the beam is boosted in the forward direction, we require γ energy in the barrel and both endcaps to be greater than 50 MeV and 100 MeV, respectively.

γ selection

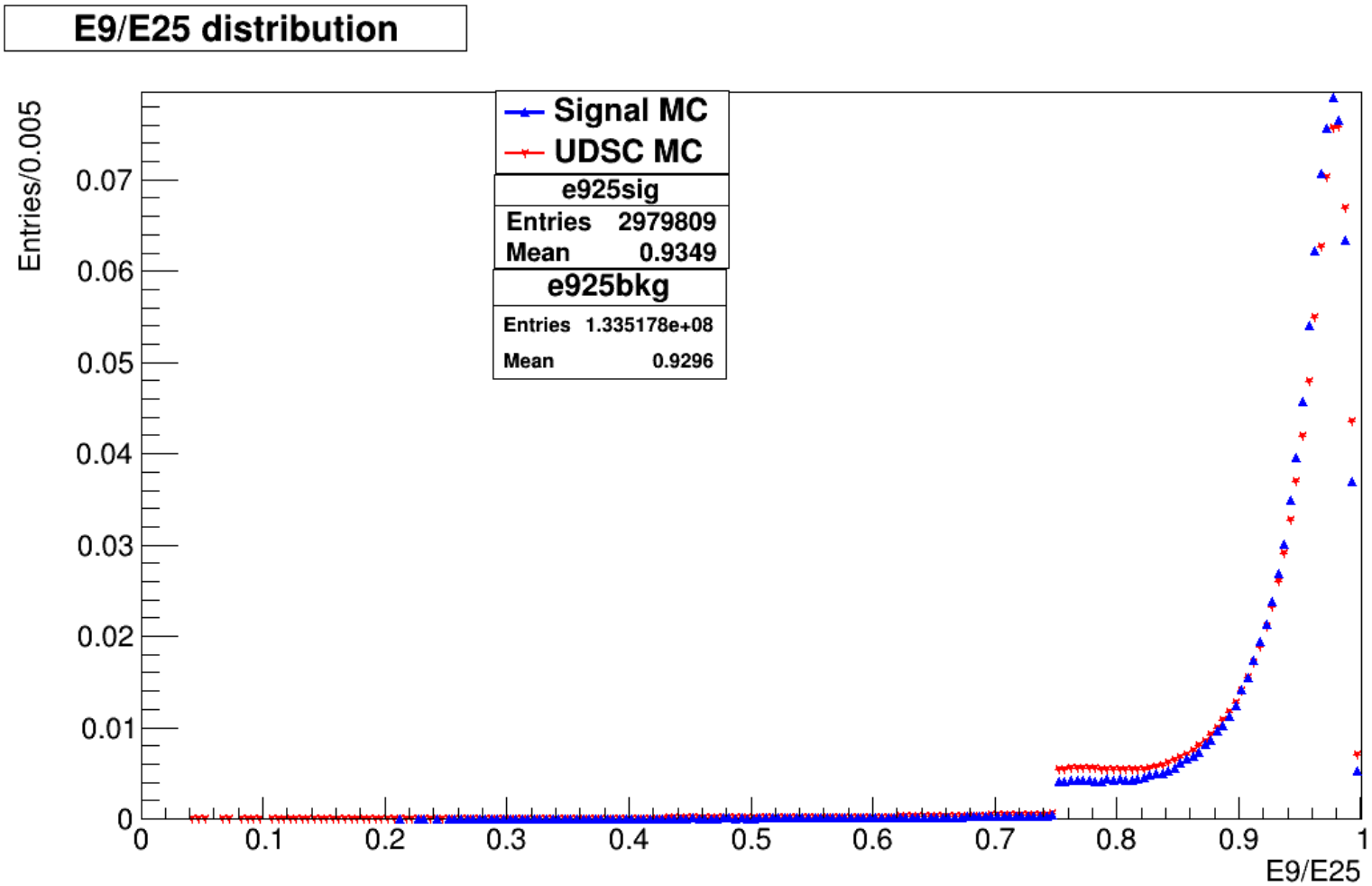
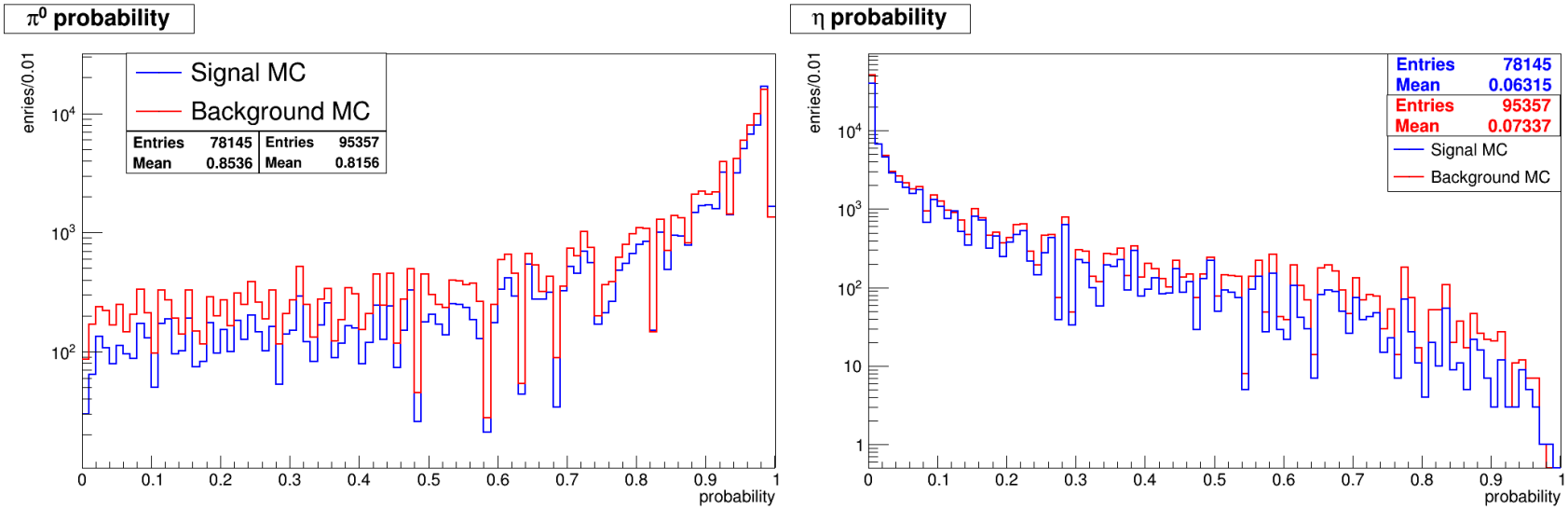


Figure: E9/E25 distribution for the photon candidates.

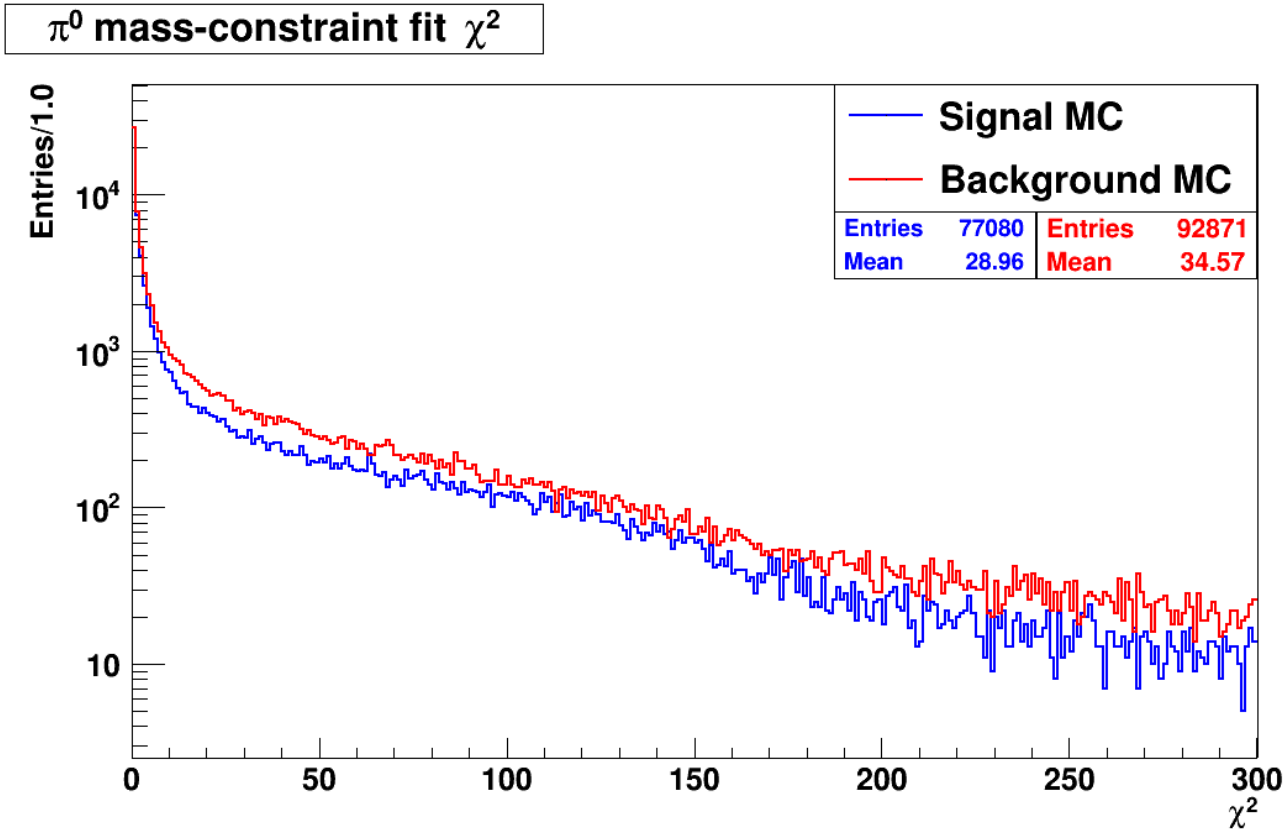
- We require E9/E25 > 0.75 to reject the contribution from neutral hadrons.

The probability of an incoming γ from π^0 and η



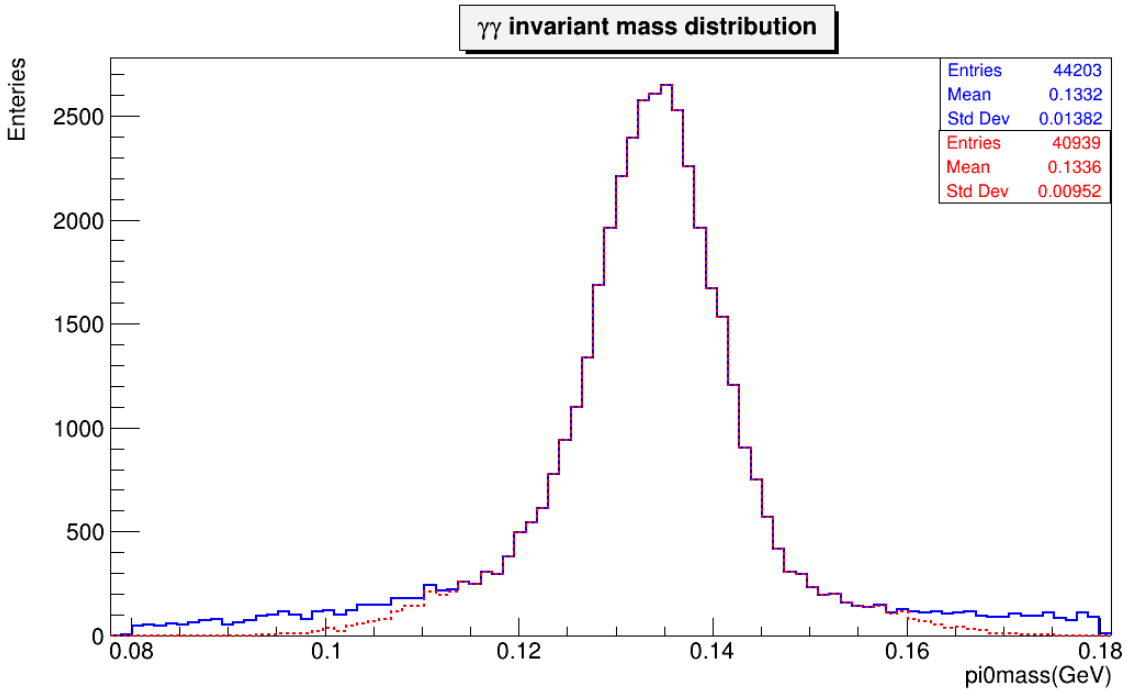
- To reject π^0 miss-reconstruction, η_probability < 0.3 and π^0_probability > 0.6 are required.

π^0 reconstruction



- χ^2 in the π^0 mass constraint fit cannot be used to distinguish the contribution from the MC signal and background but can be used to reject the miss-reconstructed π^0 candidates.

$\gamma\gamma$ invariant mass distribution



⋆ (1) γ energy, (2) E9/E25$>$ 0.75, (3) π^0_probability $>$ 0.6, (4) *eta*_probabilty$<$ 0.3, and (5) beam constraints.

B_s^0 reconstruction

- ⋆ Reconstructed π^0 and J/ψ from an event are combined kinematically to reconstruct the B_s^0 meson. Following kinematic variables are calculated for the reconstructed candidate.
- ⋆ $\Delta E = E_B$ - E_{beam}
- ⋆ $M_{bc} = \sqrt{E_{beam}^2 - P_B^2}$

  where E_B is energy of the reconstructed B_s^0 meson and E_{beam} is the beam energy, both in the centre of mass frame of the electron-positron beam collider.
- ⋆ Candidates are selected with $M_{bc} > 5.3$ GeV and $-0.8 < \Delta E < 0.3$ GeV preselection requirements.

Kinematic variables in the MC signal sample

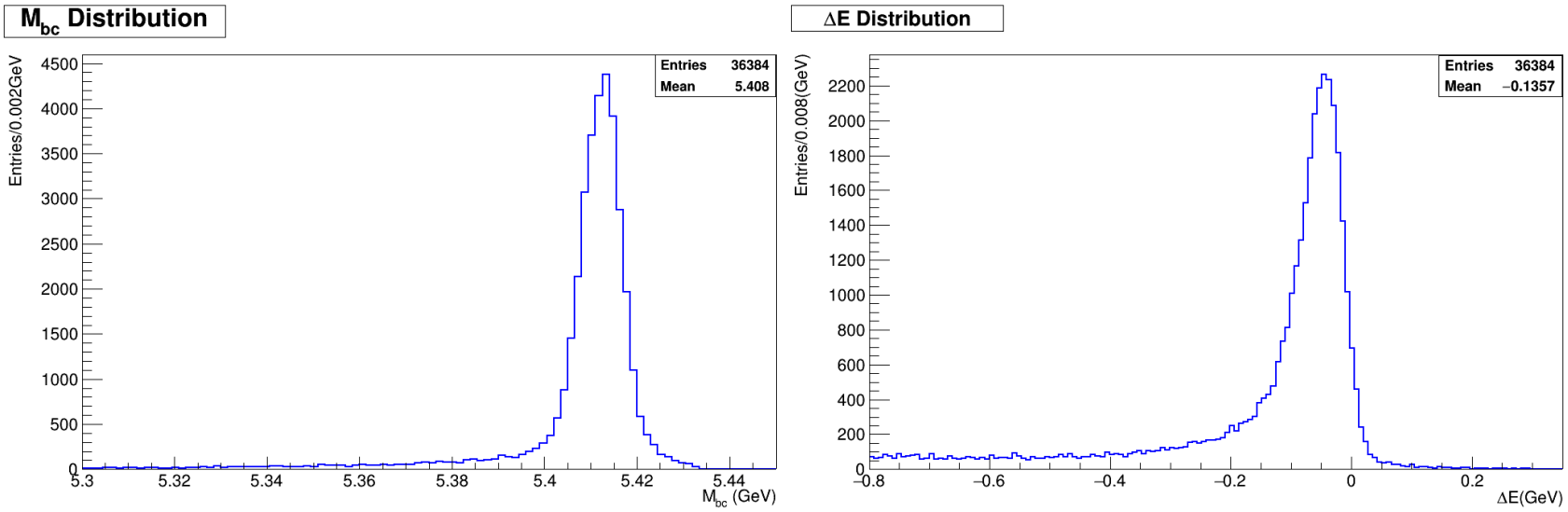
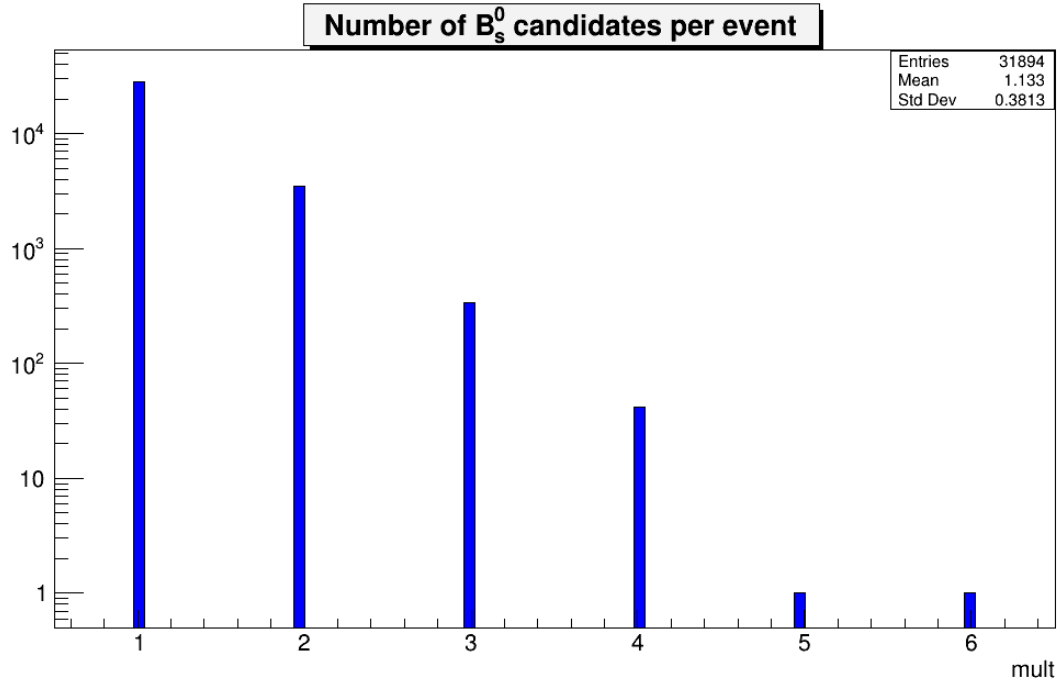


Figure: M_{bc} and ΔE distributions.

- ⋆ M_{bc} and ΔE distributions peaks around 5.41 GeV and -0.05 GeV, respectively.
- ⋆ A shift in the ΔE and the long tail are because of the leakage in shower reconstruction and the response of the calorimeter to the EM interactions.

Multiple candidates per event



- ⋆ Multiple B_s^0 candidates per event are seen because of the poor π^0-reconstruction.
- ⋆ Best candidate are choosen with least χ^2/ndf in π^0 and J/ψ reconstruction.

Best and truth-matched best B_s^0 candidates

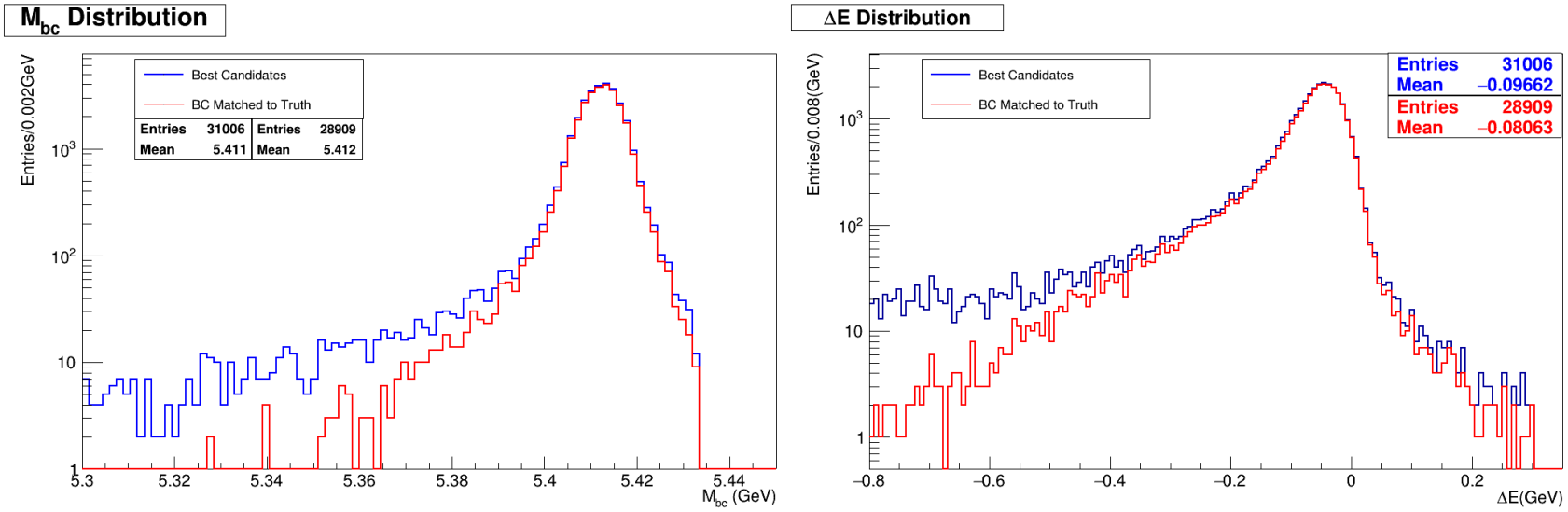
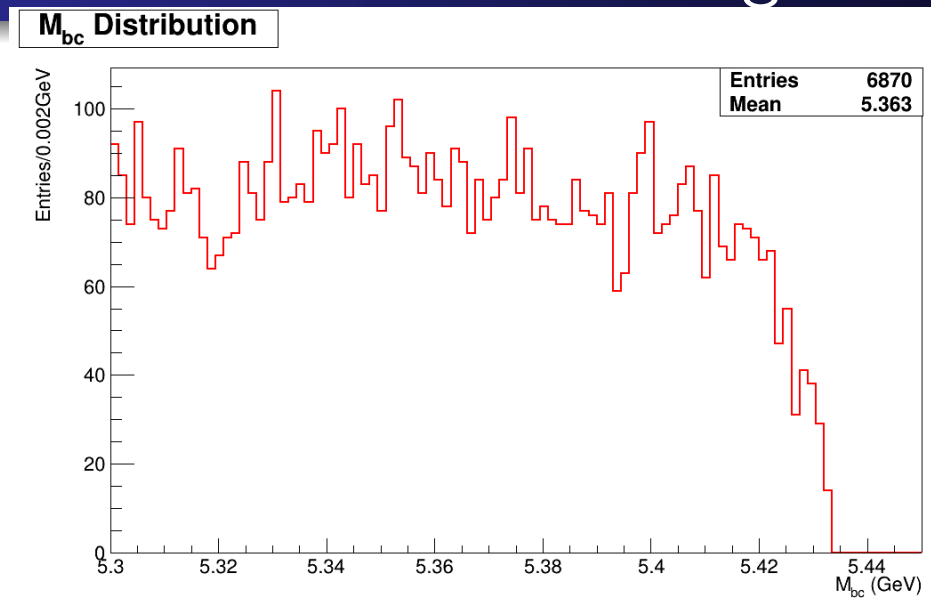


Figure: M_{bc} and ΔE distribution for the best selected (blue) and truth-matched best B_s^0 (red) candidates.

The disagreement between the best candidates and the true signal candidates is around 6.7%, which is mostly in the tail part of the M_{bc} and ΔE distributions.

Kinematic variables in the MC background sample



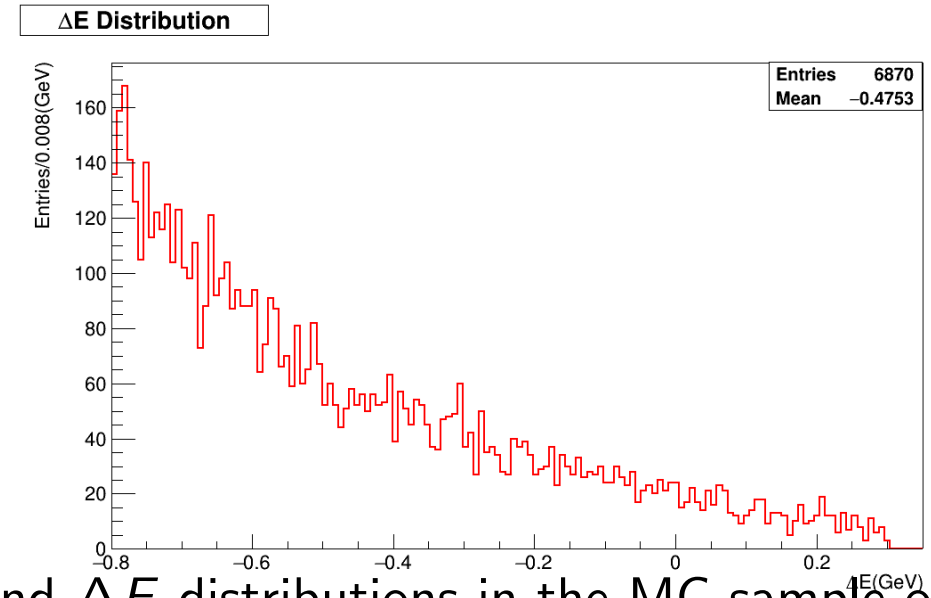


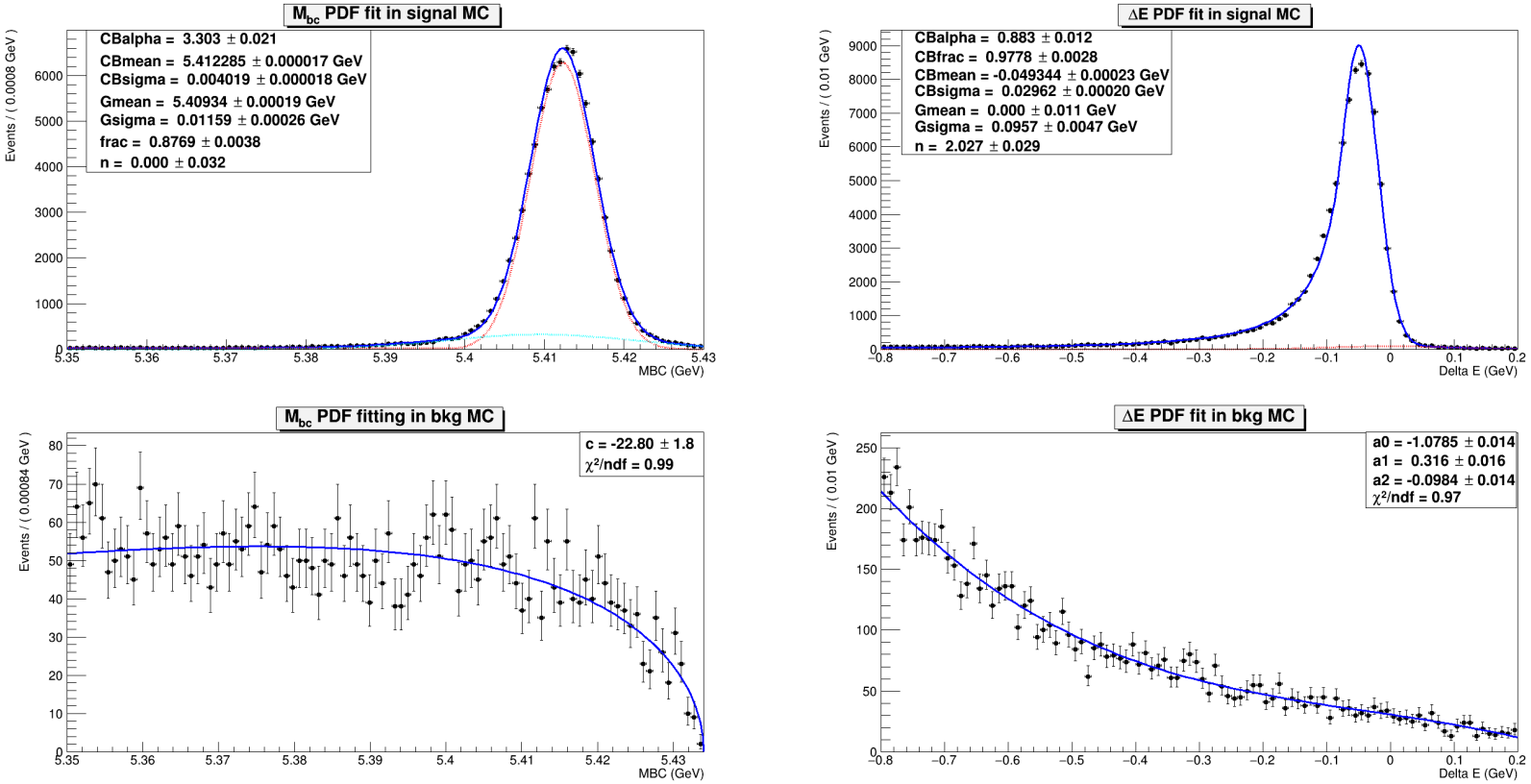
Figure: M_{bc} and ΔE distributions in the MC sample of all kind of backgrounds which corresponds to the total luminosity of $6 \times 121.4 fb^{-1}$.

Cut flow table for the MC signal and backgrounds

Variables	Requirement	Rec signal	True signal	uds	Charm	$B_s^0 B_s^0$	Non-$B_s^0 B_s^0$	All-bkg
Pre-selection cuts	$M_{bc} > 5.25$ and $-0.8 < \Delta E < 0.3$	76918	44836	56679	33855	863	3960	95357
Forward Endcap	$>$ 100 MeV	72421(94.15)	44188(98.55)	53728(94.79)	32078(94.75)	814(94.32)	3741(94.47)	90361(94.76)
Barrel Region	$>$ 50 MeV	61051(84.30)	42955(97.21)	46083(85.77)	27937(87.09)	673(82.68)	3170(84.74)	77863(86.16)
Backward Endcap	$>$ 100 MeV	59856(98.04)	42662(99.31)	44994(97.63)	27289(97.68)	641(95.24)	3098(97.73)	76022(97.64)
E9/E25	> 0.75	57503(96.06)	40867(95.79)	41797(92.89)	25633(93.93)	628(97.97)	3005(97.0)	71063(93.47)
$M^{\chi^2}_{\pi^0}$	< 50	50443(87.72)	39312(96.19)	34751(83.14)	20617(80.43)	462(73.56)	2435(81.03)	58265(81.99)
π^0_prob	> 0.6	46800(96.89)	37069(97.55)	31132(95.13)	18252(94.62)	395(93.38)	2189(95.55)	51968(94.95)
η_prob	< 0.3	40427(92.88)	31991(92.84)	25891(91.31)	15567(92.18)	313(90.72)	1881(92.72)	43652(91.68)
$\lvert dr \rvert$	< 0.5 cm	40314(99.72)	31933(99.81)	24116(93.14)	14337(92.10)	304(97.12)	1828(97.18)	40585(92.97)
$\lvert dz \rvert$	< 3.0 cm	40204(99.73)	31856(99.75)	23778(98.60)	14160(98.76)	302(99.34)	1823(99.73)	40063(98.71)
$V^{\chi^2}_{J/\psi}$	< 50	39410(98.02)	31298(98.24)	21982(92.44)	12121(85.60)	282(93.38)	1640(89.96)	36025(89.92)
$M^{\chi^2}_{J/\psi}$	< 50	36773(93.30)	30765(98.30)	1924(8.75)	977(8.06)	69(24.46)	404(24.63)	3374(9.36)
μ_ID	> 0.4	36144(98.29)	30252(98.33)	384(19.95)	323(33.06)	67(97.10)	382(94.55)	1156(34.26)
Best B_s^0	Least χ^2	30954(85.64)	28971(95.77)	329(85.68)	289(89.47)	57(85.07)	349(91.36)	1024(88.58)

Table: Table showing the effect of different selection criteria applied for the MC signal and different background samples. Survival ratios are also given in the parentheses.

Probability distribution fitting



Summary

- ⋆ A data sample composed of 100,000 signal MC are used to study the decay $B_s^0 \to J/\psi\pi^0$. J/ψ and π^0 are reconstructed from the muon and photon channels respectively.
- ⋆ For the background study, a sample composed of *uds*, charm, $B_s^0\bar{B}_s^0$ and non-$B_s^0\bar{B}_s^0$ generated by the dedicated Belle team is used. Background sample under study is equivalent to the total luminosity of 121.4 fb^{-1} in the real data sample.
- ⋆ M_{bc} and ΔE are used as the primary kinematic variables. All other variables are used to improve the signal to noise ratio.
- ⋆ We have reconstructed 36384 number of signal candidates with an efficiency of 37.2%. For the efficiency calculation 97776 number of processed events are used in the denominator.
- ⋆ We further select best candidates at the cost of 5.5% in efficiency through best candidate selection as multiple candidates per event are observed.
- ⋆ Around 93.2% of the selected best candidates were turned out to be true with an efficiency of 31.7%.

Future plans

- ⋆ Helicity of π^0 candidates can be useful in improving the π^0 resolution.
- ⋆ Further optimization of the cuts will be studied, if required.
- ⋆ A control sample will be studied to check the data-MC discrepancies in the M_{bc} and ΔE resolutions.
- ⋆ Signal and background yields will be extracted through multi-dimensional maximum likelihood fitting.
- ⋆ Statistical and systematic uncertainties will be estimated.
- ⋆ The BF will be calculated if the significant signals are observed. Otherwise, an upper limit will be computed.

Thank You

μ selection

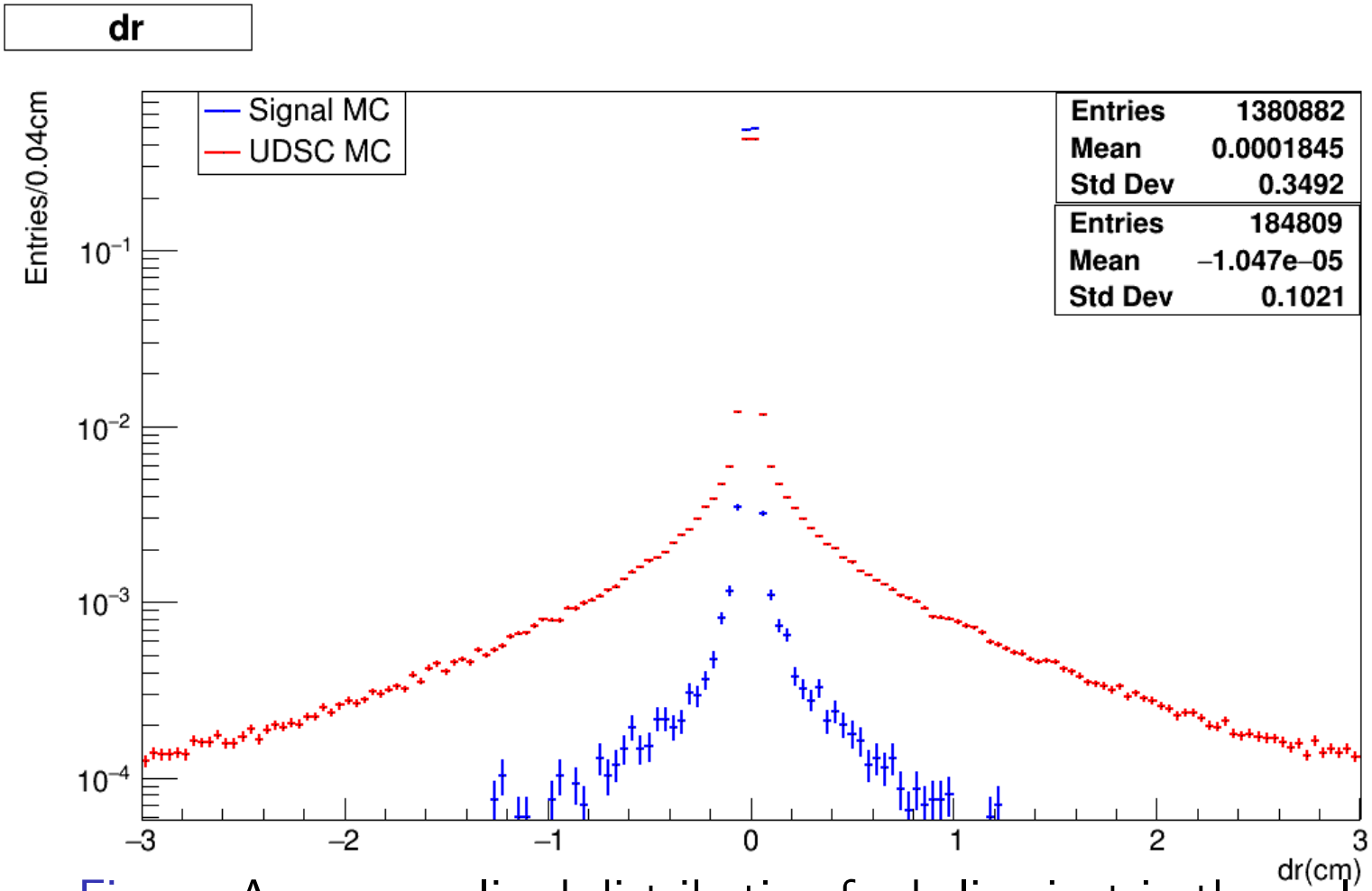


Figure: Area normalized distribution for helix pivot in the z-plane

A loose cut of $|\delta r| < 0.5$ cm can be applied.

μ selection

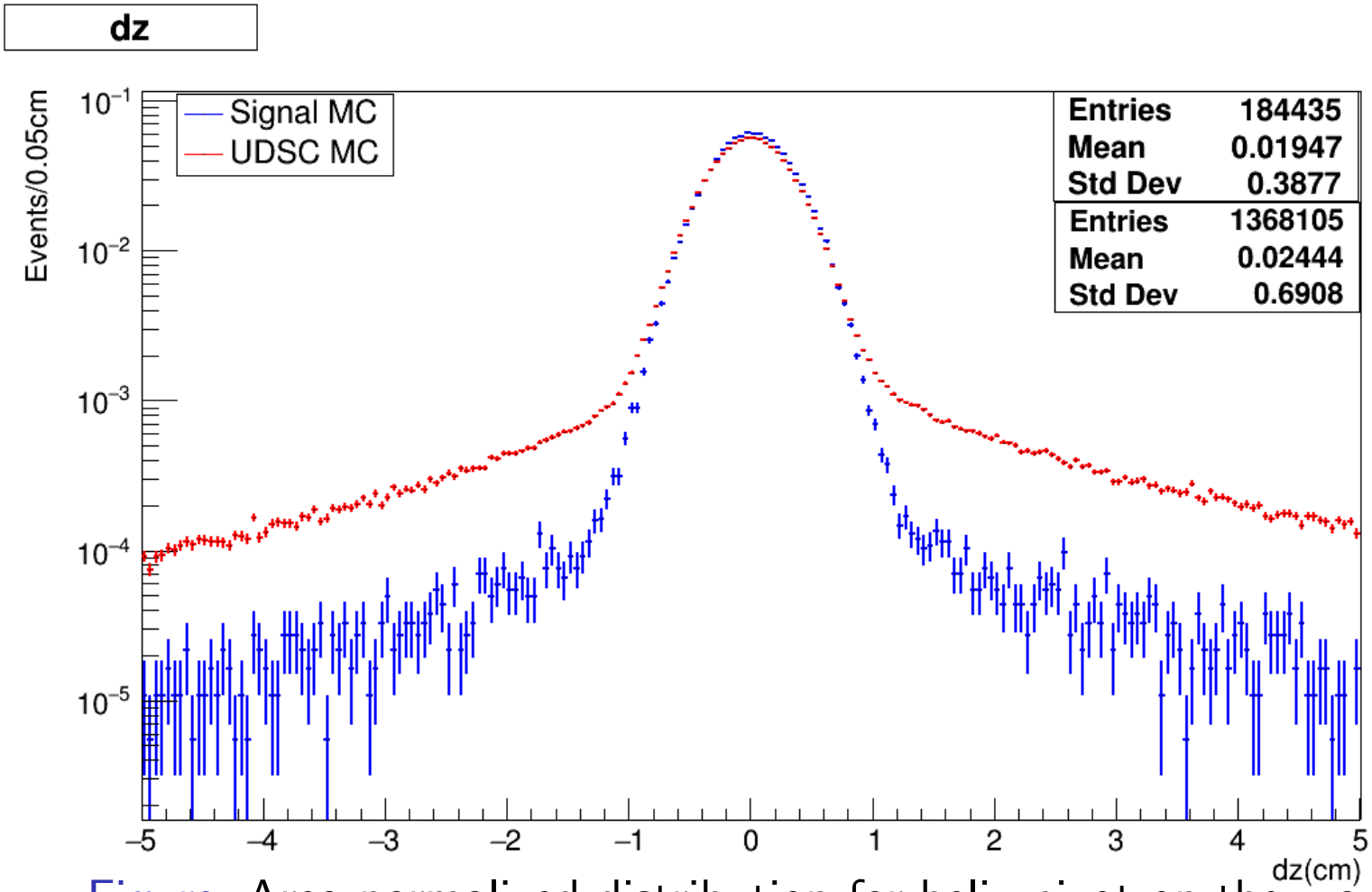


Figure: Area normalized distribution for helix pivot on the z-axis

A lower cut of $|dz| < 3.0$ cm can be applied.

Variation in M_{bc} distribution in the MC signal sample concerning to different selection criteria

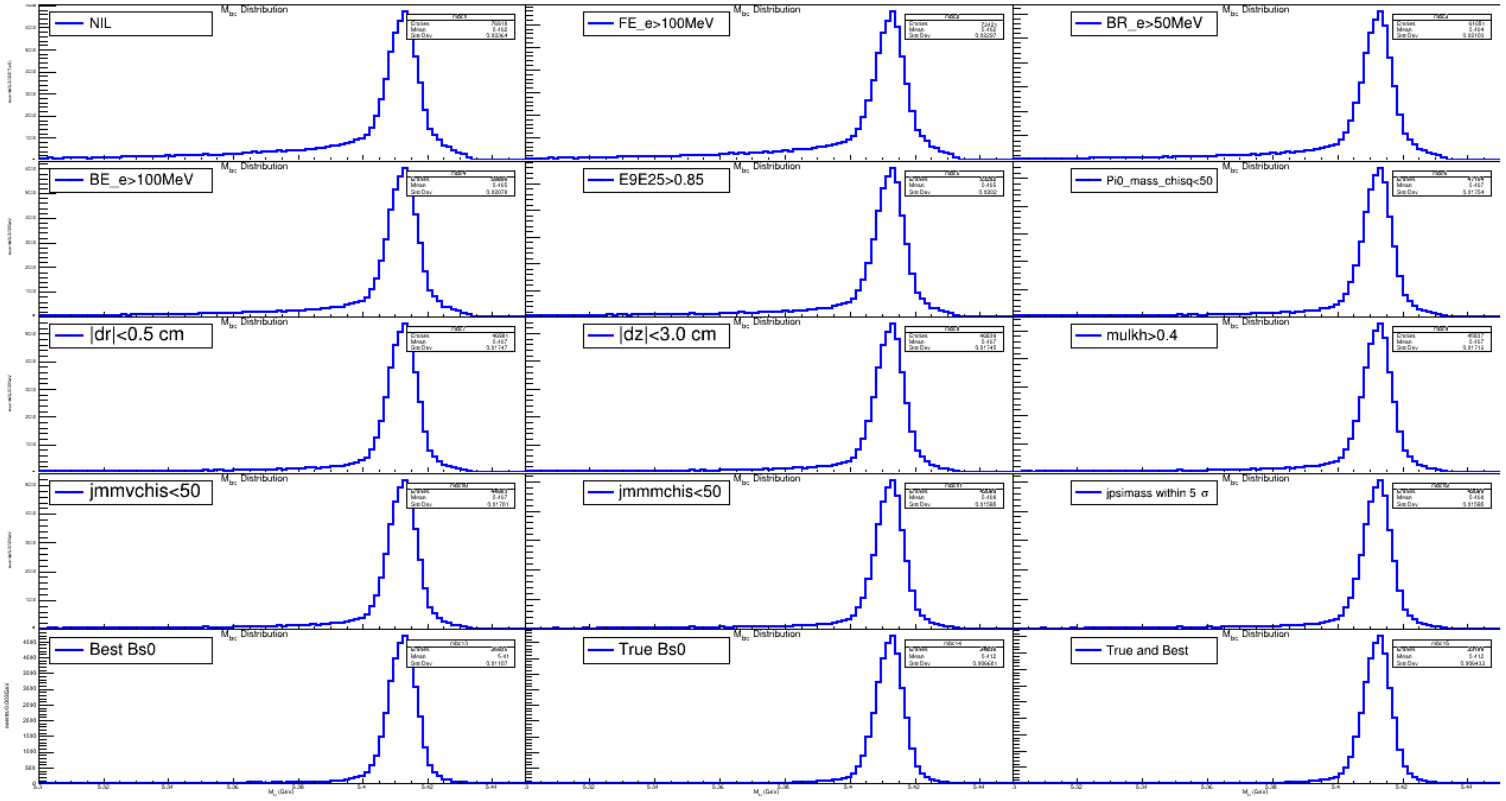


Figure: M_{bc} distribution for applied cuts on different variables calculated in the reconstruction.

Variation in ΔE distribution in the MC signal sample concerning to different selection criteria

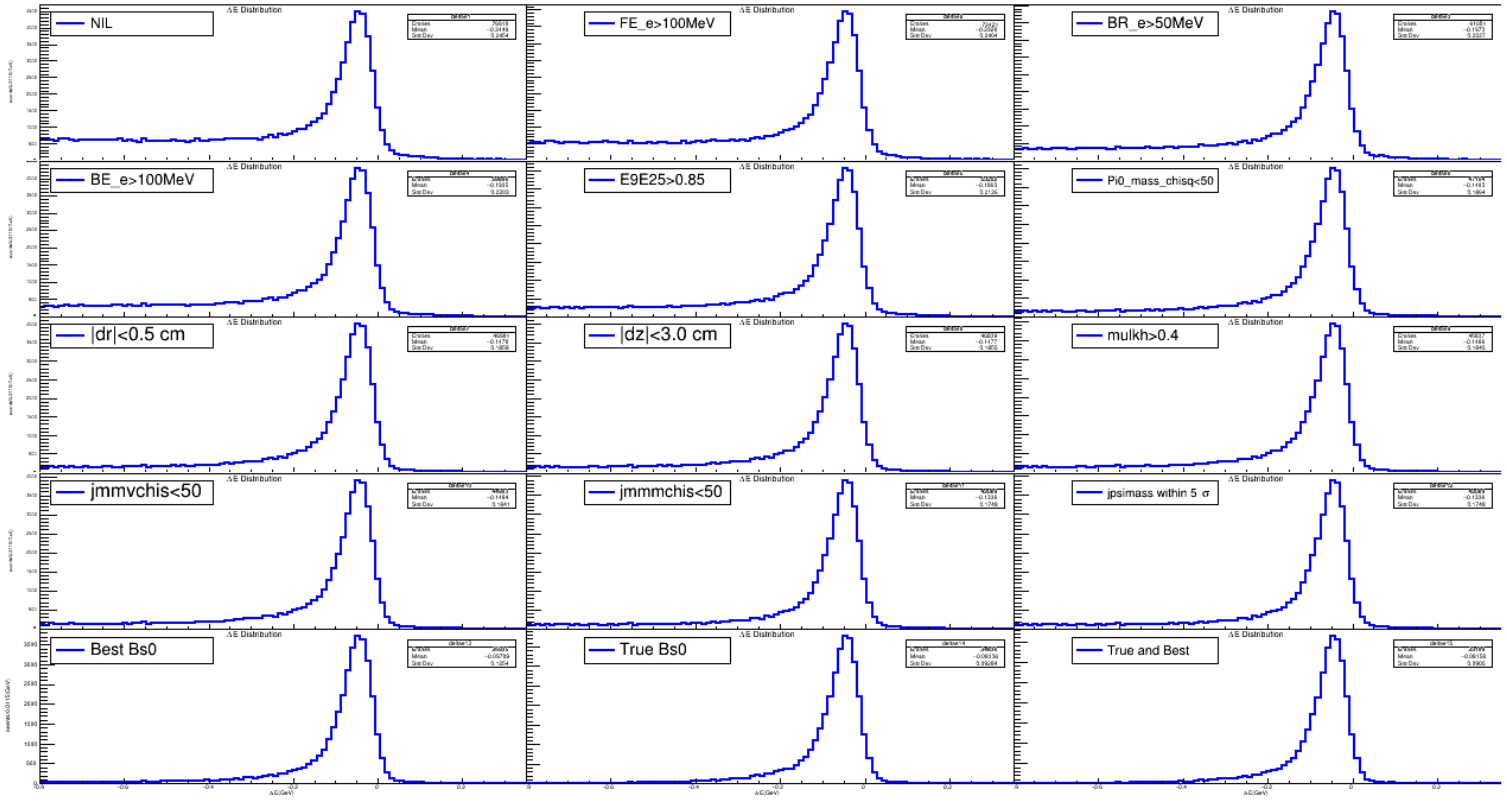


Figure: ΔE distribution for applied cuts on different variables calculated in the reconstruction.

Variation in M_{bc} distribution in the MC background sample concerning to different selection criteria

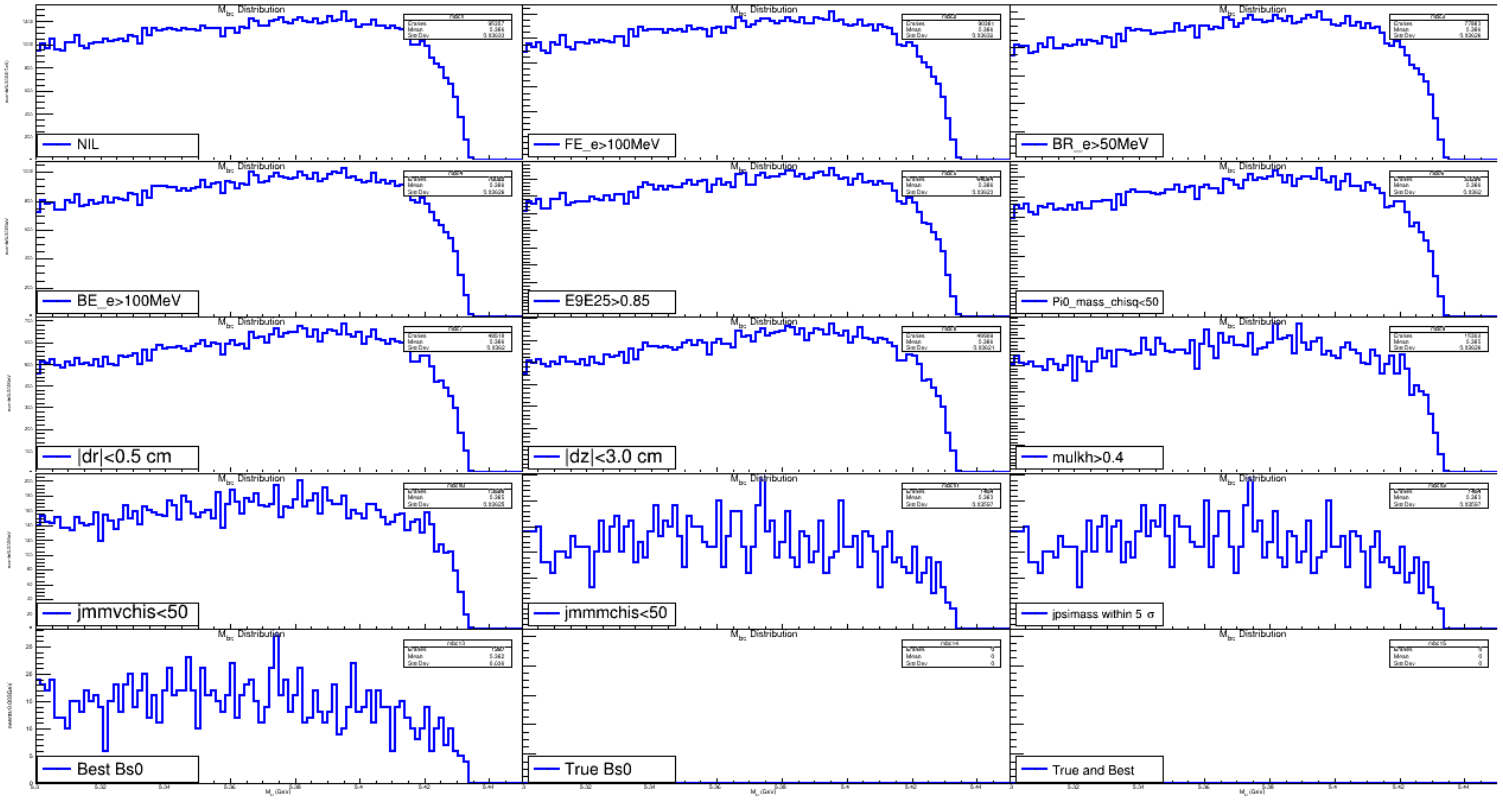


Figure: M_{bc} distribution for applied cuts on different variables calculated in the reconstruction.

Variation in ΔE distribution in the MC background sample concerning to different selection criteria

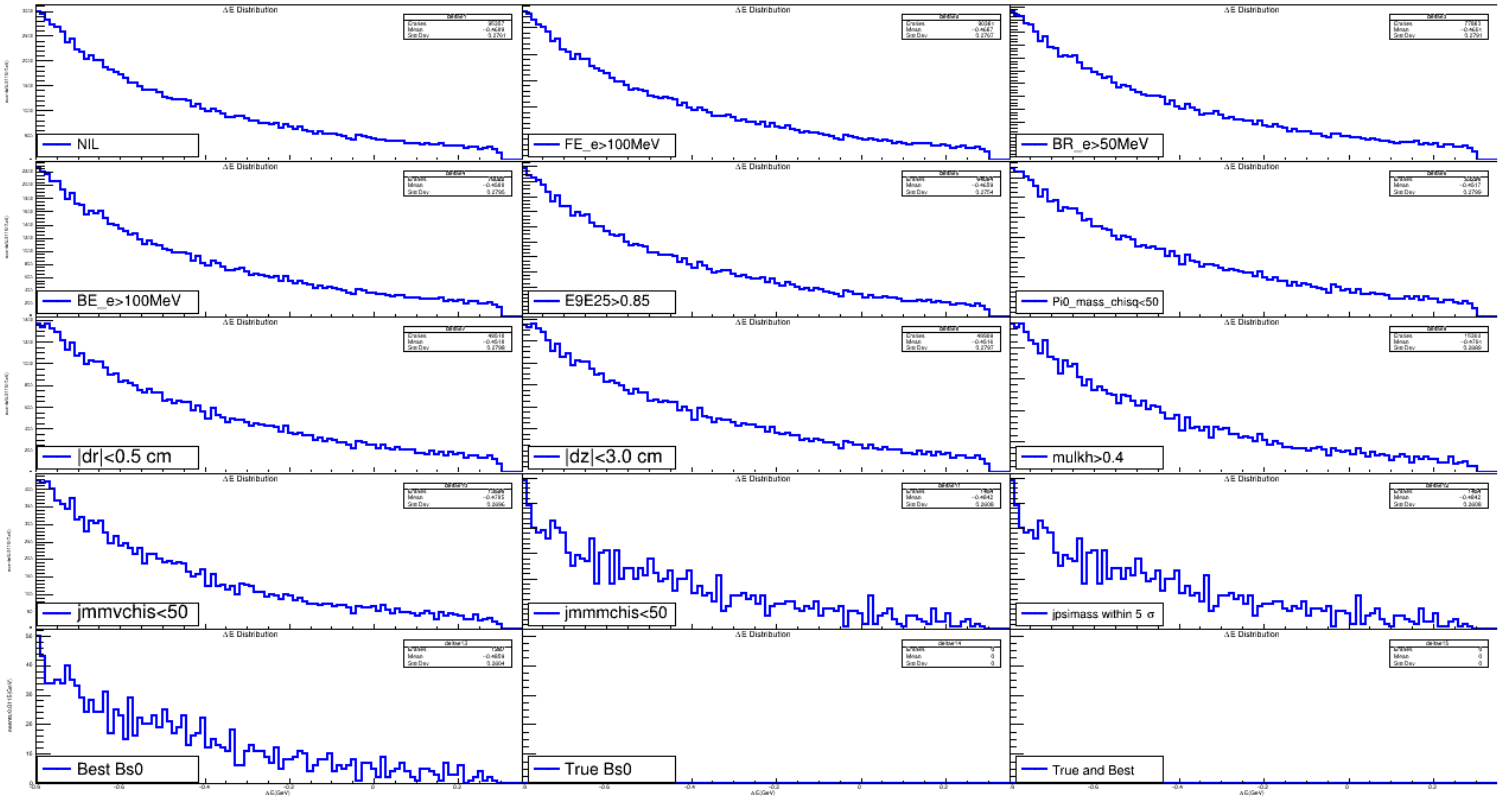
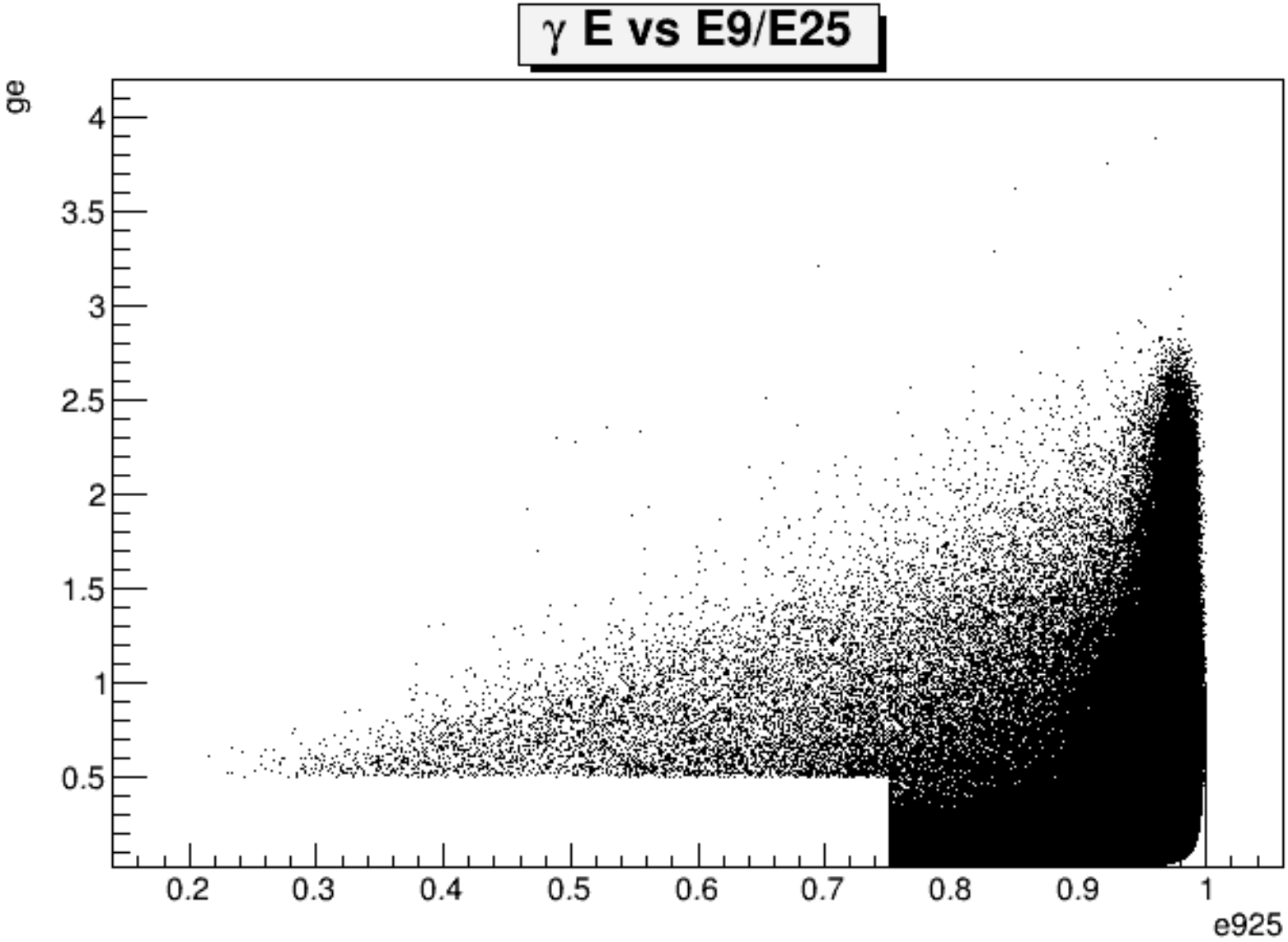


Figure: ΔE distribution for applied cuts on different variables calculated in the reconstruction.

γ energy vs E9/E25



γ energy distribution