The analysis of $Bs \to \phi\nu\bar{\nu}$ At CEPC

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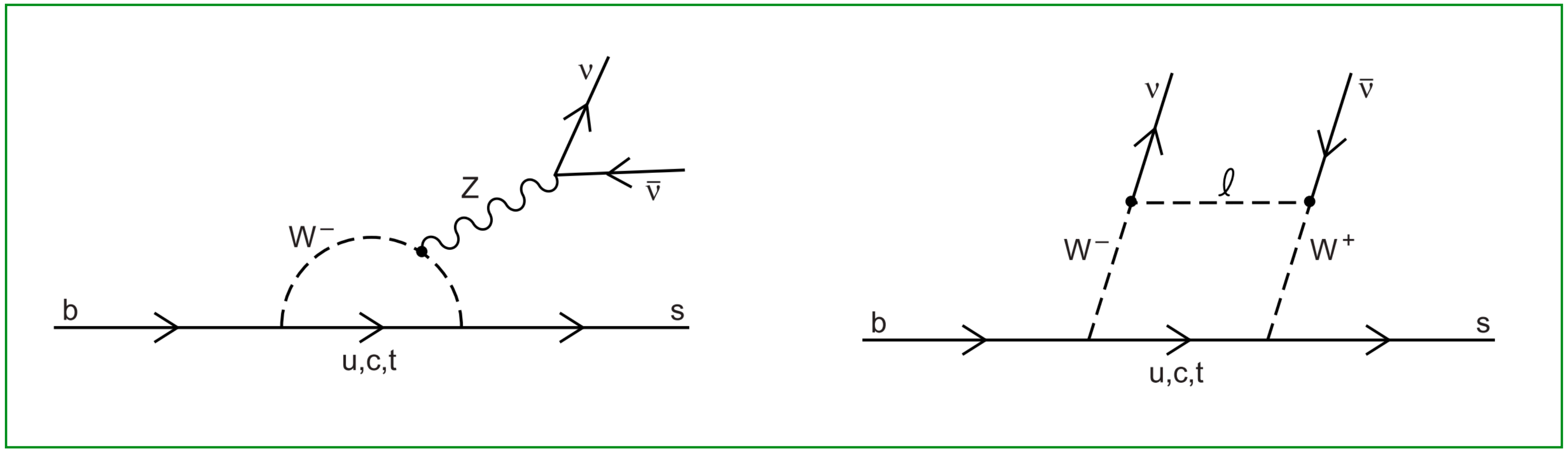
Motivation

- Investigation of flavor-changing neutral current (FCNC) decays is of fundamental interest.
- SM prediction for the FCNC decay $b \to s\nu\bar{\nu}$ is nearly free from strong interaction effects and has very small theoretical uncertainty.
- An observation of this decay at a level significantly above the SM prediction would provide unambiguous evidence for new physics.
- Performance the benchmark of simulation and reconstruction at CEPC, such as charged lepton identify, $\phi(1020) \to K^+K^-$ reconstruction, boson mass resolution (BMR) and missing energy, mass.

Rare decay $b \to s\nu\bar{\nu}$

Flavor-change-neutral-current(FCNC) process. Be highly suppressed by the loop factor and heavy weak boson mass .



One-loop level in the Standard Model (SM) via “penguin” and “box” diagrams. The decay rates of these modes ranges from $10^{-6} \sim 10^{-5}$.

Even small contributions from new physics to b → sνν decays may potentially lead to significant enhancements to the SM branching fraction.

	Experimental [2]	SM Prediction [3, 4]
$BR(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$	$(2.17 \pm 0.30) \times 10^{-6}$
$BR(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$	$(9.48 \pm 1.10) \times 10^{-6}$
$BR(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$	$(4.68 \pm 0.64) \times 10^{-6}$
$BR(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$	$(10.22 \pm 1.19) \times 10^{-6}$
$BR(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$	$(11.84 \pm 0.19) \times 10^{-6}$

[2] M. Tanabashi *et al.*, “Review of Particle Physics,” *Phys. Rev.*, vol. D98, no. 3, p. 030001, 2018.
[3] D. M. Straub, “$b \to k^{(*)}\nu\bar{\nu}$ sm predictions,” Dec 2015.
[4] C. Geng and C. Liu, “Study of $B_s \to (\eta, \eta', \phi)\ell\bar{\ell}$ decays,” *J. Phys. G*, vol. 29, pp. 1103–1118, 2003.

B_s production

At Tera-Z as planned for CEPC, the productions of $B^0/\bar{B}^0$, $B^\pm$, $B_s/\bar{B}_s$ and $\Lambda_b/\bar{\Lambda}_b$ are comparable to those at Belle II, while Bs/Bs is nearly two orders more. ILC and FCC-ee are expected to run at Z pole also, with a plan of Giga-Z and upgraded Tera-Z (namely, 10×Tera-Z), respectively.

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^8	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^8	$\sim 2 \times 10^{13}$	3.2×10^7	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 2 \times 10^{11}$	2.2×10^5	2.2×10^8	2.2×10^9
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^7	1.0×10^{10}	1.0×10^{11}

Number of B hadrons expected to be produced in Belle II, LHCb and future Z factories. We assume that Belle II will run at $\Upsilon(4S)$ mode with an integrated luminosity of 50 ab^{-1} and at $\Upsilon(5S)$ with 5 ab^{-1}, and estimate the LHCb productions. The production fractions for $B^0/\bar{B}^0$, $B^\pm$, $B_s/\bar{B}_s$ and $\Lambda_b/\bar{\Lambda}_b$ are taken as the average proposed in PDG.

Number of signal decay by SM prediction :

$$N(B_s \to \phi(K^+K^-)\nu\bar{\nu}) \sim 1.8 \times 10^5$$

Any more, the prediction of $B_0 \to \phi\nu\nu$ branch by SM is much smaller than $B_s \to \phi\nu\nu$ and thus free of the B_0 influence.

The Background at CEPC

The SM signal decay $b \to s\nu\nu$ are mainly generated via $e^+e^- \to Z^*/\gamma \to b\bar{b}$ at Z-pole at e^+e^- collider.

The SM background contains all the 2-fermion process (10^{12} Z^*):

$$\text{total } 8 \times 10^{11}\ e^+e^- \to f\bar{f}(f = e, \mu, \tau, u, d, c, s, b)$$

Mostly background except $b\bar{b}$ can be highly suppressed by the flavor tagging. The following analysis will be focus on $b\bar{b}$ background (1.5×10^{11}).

2.6×10^6 $b\bar{b}$ background samples at CEPC (generated by wizard-1.95) and 1×10^6 signal samples (generated by Pythia8 with EvtGen-1.3) are simulated and reconstructed by CEPC software chain.

The Events Analysis

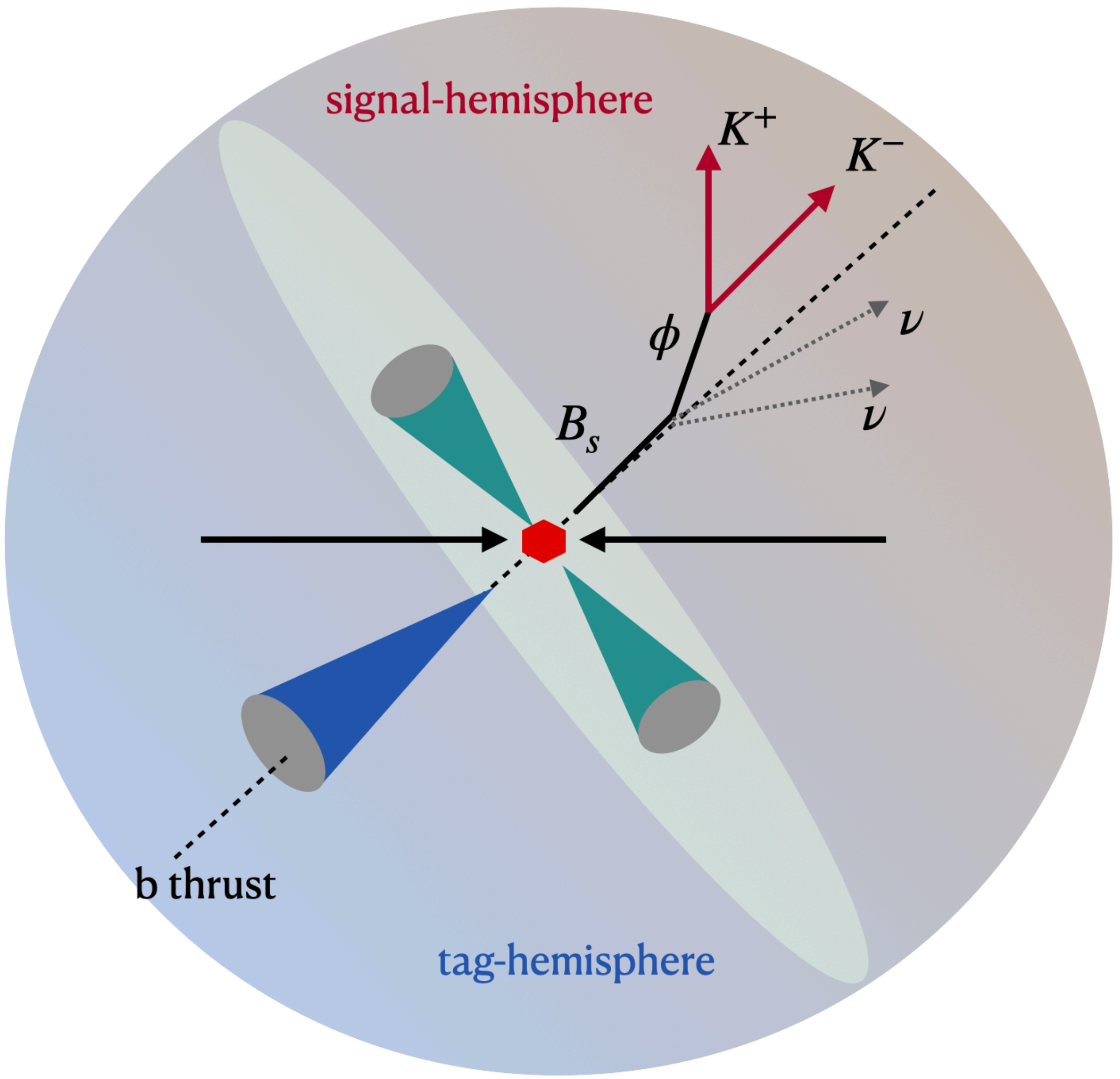
The whole space is divided into two hemisphere by the plane perpendicular to the thrust

$$T = \frac{\sum_i |\vec{p}_i \cdot \hat{n}_i|}{\sum_i |\vec{p}_i|}$$

Prefer signal and tag hemisphere definition:

The visible energy at the signal-hemi is smaller than tag-hemi.

$$E_{vis}^{sig} < E_{vis}^{tag}$$

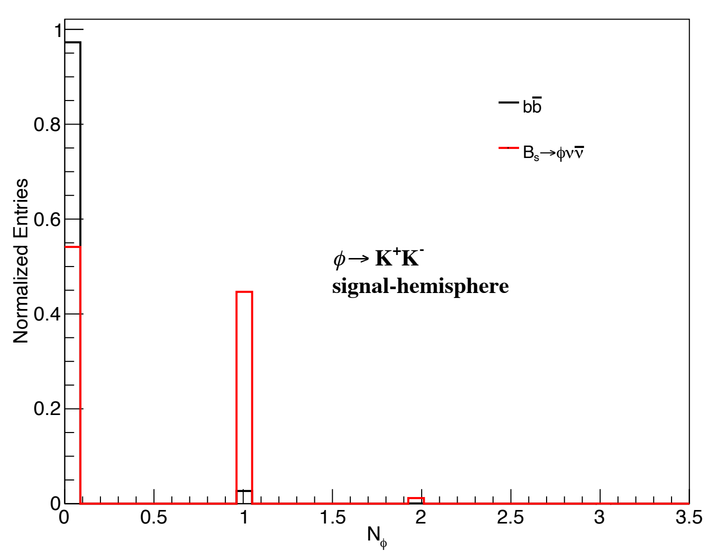


ϕ productions

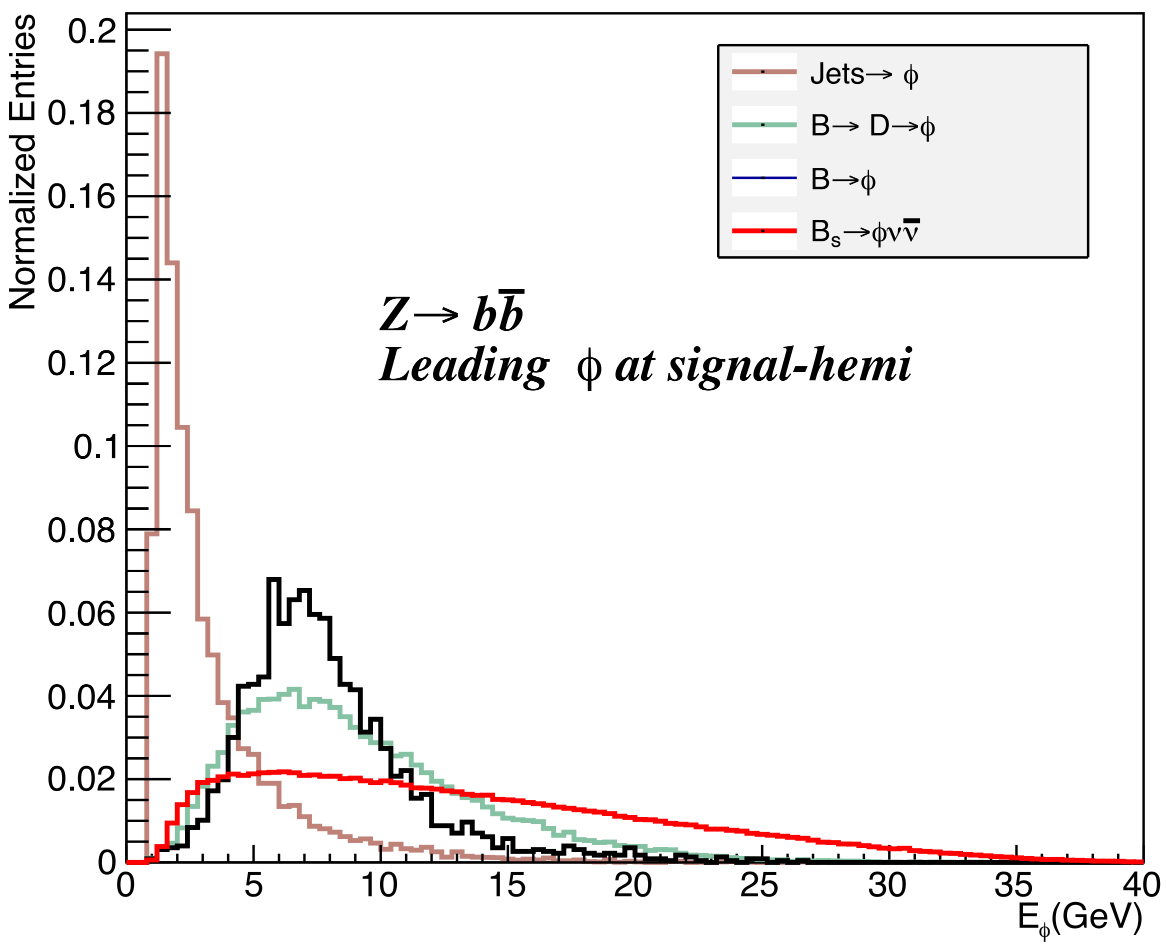
The ϕ production in $Z \to b\bar{b}$ per event.

Process	Num/Events
B decay	0.018
D decay	0.053
QCD	0.029
Others	0.001
Total	**0.1**

Number of $\phi(K^+K^-)$ distributions.



The energy distribution of ϕ from different decay process



The leading ϕ which have the largest energy will be chosen as the candidate, to exclude the ϕ by QCD process if two ϕ produced.

$\phi(K^+K^-)$ Reconstruction

The reconstruction efficiency and purity:

$$\epsilon = \frac{N_{RecoS}}{N_{Truth}} \qquad p = \frac{N_{RecoS}}{N_{Reco}}$$

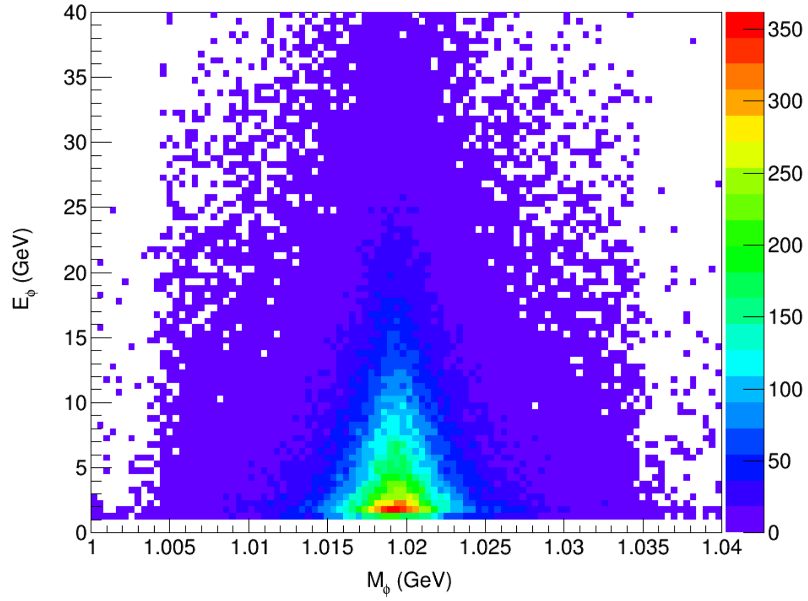
N_{Truth} : The number of truth ϕ, N_{Reco} : The number of reconstructed ϕ, N_{Recos} : The number of successfully reconstructed ϕ.

The most efficient method for reconstructing the decay $\phi(1020) \rightarrow K^+K^-$ is to take all pairs of oppositely charged tracks in the jet chamber and form their invariant mass, assuming both tracks to be kaons.

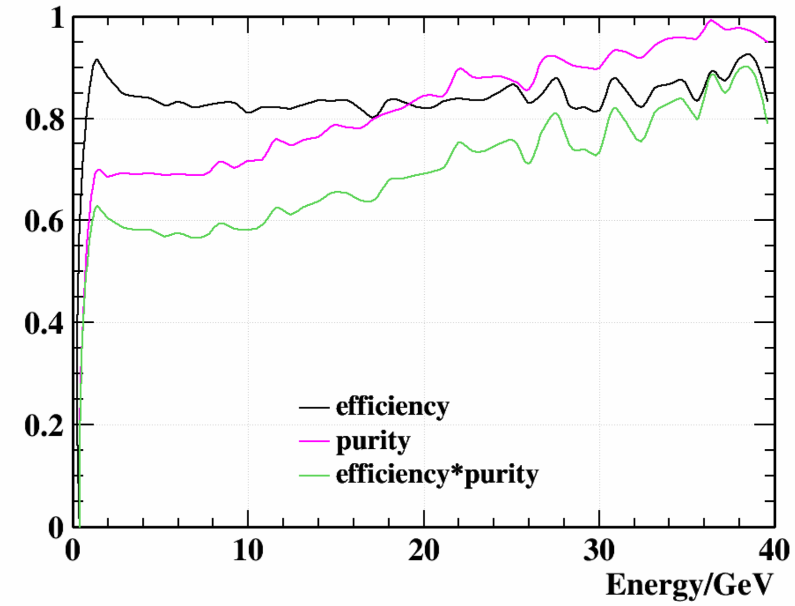
The ϕ reconstructed condition:

$$|M_{trk1,trk2} - M_\phi| < 0.01 \text{ GeV}$$

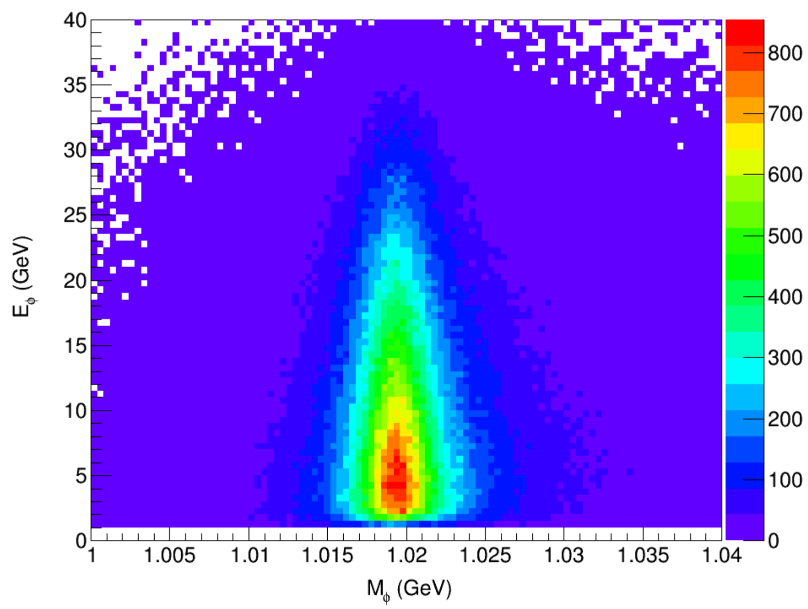
No constrain on impact parameter since small decay length of ϕ.



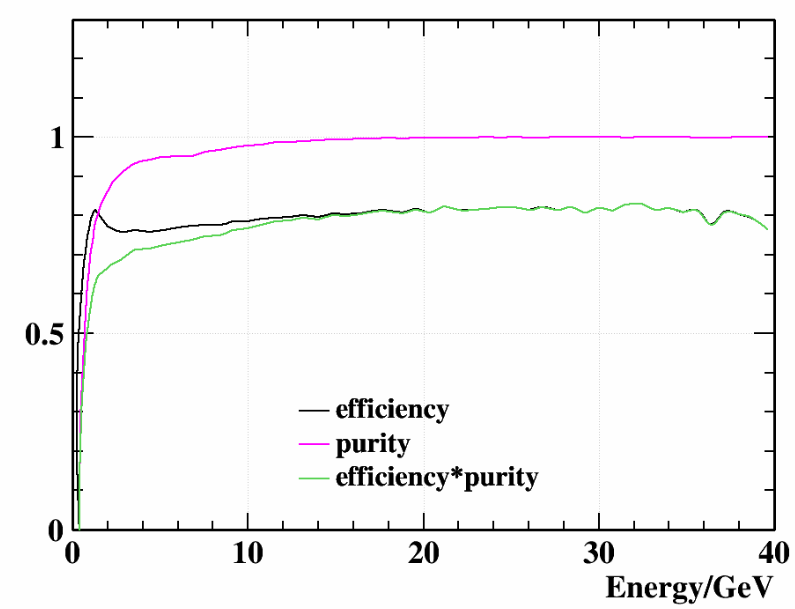
The energy and mass distribution of reconstructed ϕ by K^+K^- pair of $b\bar{b}$ samples. The total efficiency that both the two truth K^+K^- pair have the reconstructed track is 0.907.



The efficiency and purity of ϕ reconstruction by K^+K^- pair of $b\bar{b}$ samples. The integrated efficiency, purity and efficiency*purity are $0.8413, \ 0.7230, \ 0.6083$, respectively.



The energy and mass distribution of reconstructed ϕ by K^+K^- pair of signal samples. The total efficiency that both the two truth K^+K^- pair have the reconstructed track is 0.924.



The efficiency and purity of ϕ reconstruction by K^+K^- pair of signal samples. The integrated efficiency, purity and efficiency*purity are $0.7887, \ 0.9652, \ 0.7613$, respectively.

K± identification:

kaons can be separated from pions at 2 for momentum up to 20 GeV, corresponding to efficiency/purity of 95%/95% for identifying kaons in the $Z \to qq$ sample integrated over the momentum range of 2–20 GeV.

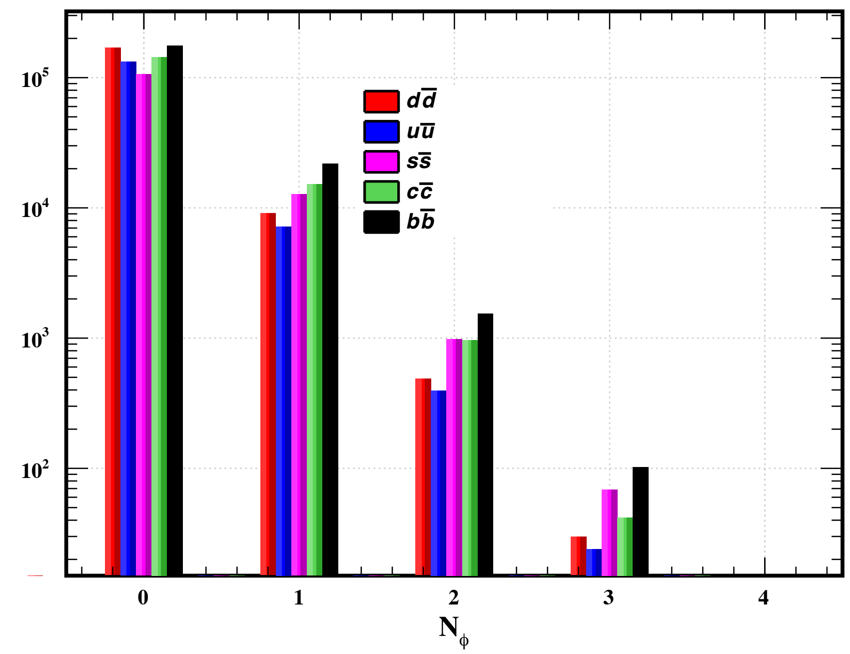


FIG. The number of samples in this figure for each channel is 1.4×10^5. Ratio of ϕ number with more than 3 is be less than 6×10^{-5}.

With reconstructed 2×10^6 $Z \to bb$ samples:

	Number $(N_{\phi(K^+K^-)}/N_{total})$	Signal-hemisphere(N_{sig}/N_{total})
$N_{Truth} > 0:$	8.932×10^4 (4.48%)	3.87×10^4 (1.94%)
$N_{Track} > 0:$	8.10×10^4 (4.07%)	3.59×10^4 (1.80) %
$N_{Reco} > 0:$	9.97×10^4 (5.00%)	4.36×10^4 (2.19%)
$N_{RecoS} > 0:$	7.43×10^4 (3.73%)	3.28×10^4 (1.64%)

The ratio that K^+K^- pair decay from ϕ all be identified thus is about $0.95 * 0.95 = 0.9025$

Reconstructed samples:

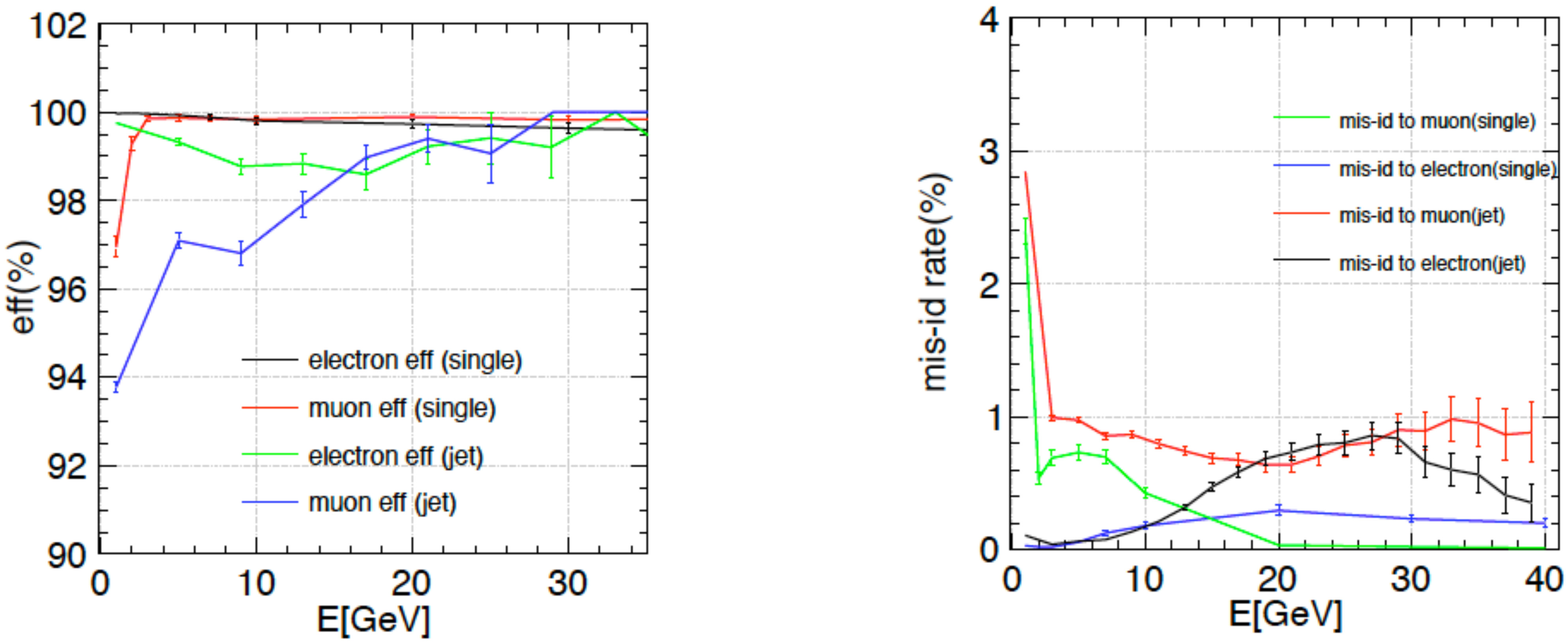
$$9.967 \times 10^5 \ Z \to bb, b \to B_s, B_s \to \phi\nu\nu$$

	Number $(N_{\phi(K^+K^-)}/N_{total})$	Signal-hemisphere$(N_{sig}/N_{\phi(K^+K^-)})$
$N_{Truth} > 0:$	5.186×10^5 (52.0%)	4.610×10^5 (46.25%)
$N_{Track} > 0:$	4.810×10^5 (48.26%)	4.222×10^5 (42.36) %
$N_{Reco} > 0:$	4.186×10^5 (42.00%)	3.601×10^5 (36.13%)
$N_{ReSucess} > 0:$	4.073×10^5 (40.86%)	3.563×10^5 (35.75%)

Charged Lepton Identify

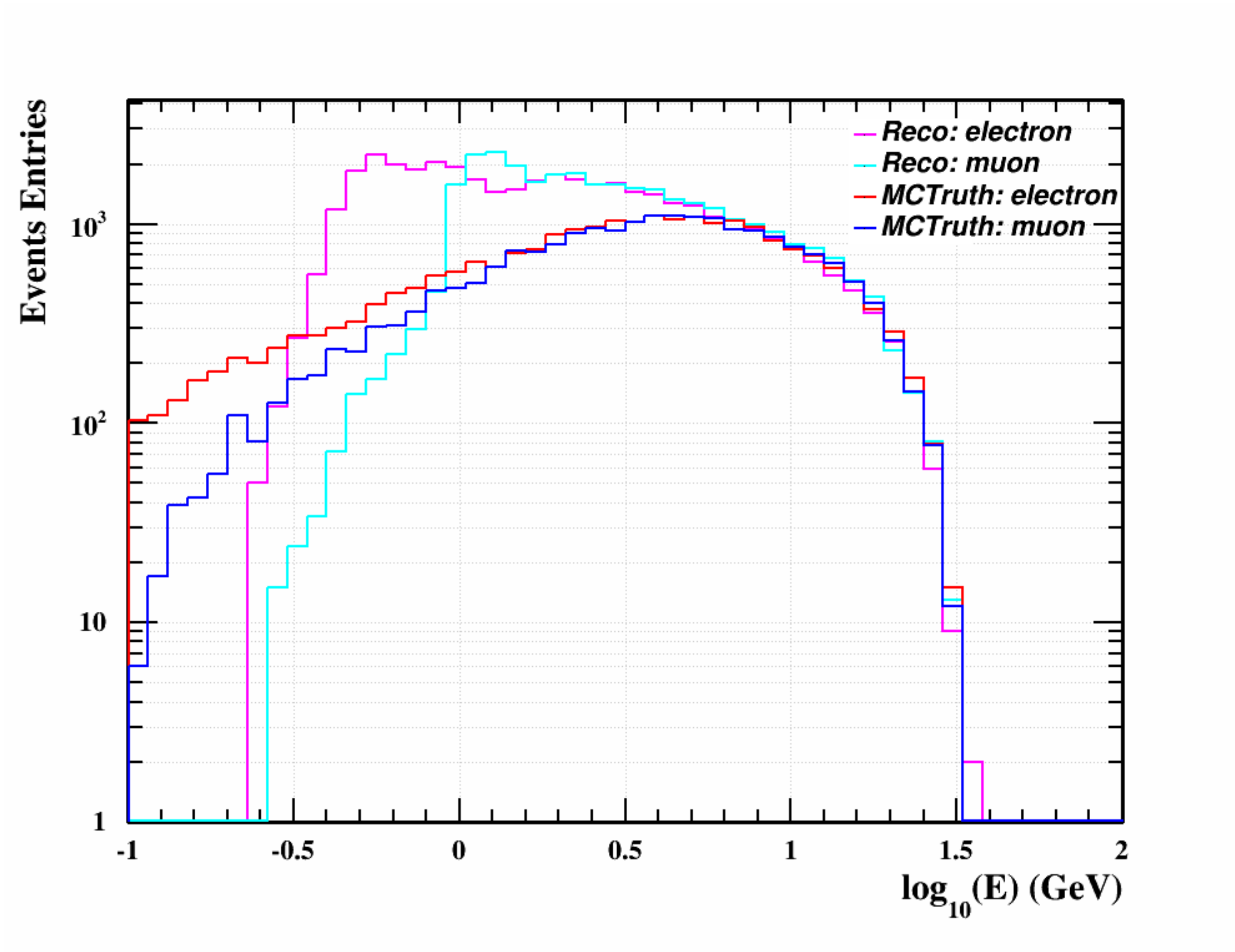
1. In the signal decay, there is no charged lepton (muon or electron) generated in the signal hemisphere.

2. The background that behavior like the signal should at least one missing neutrinos in the signal-semi and usually generated accompanied with a charged lepton.

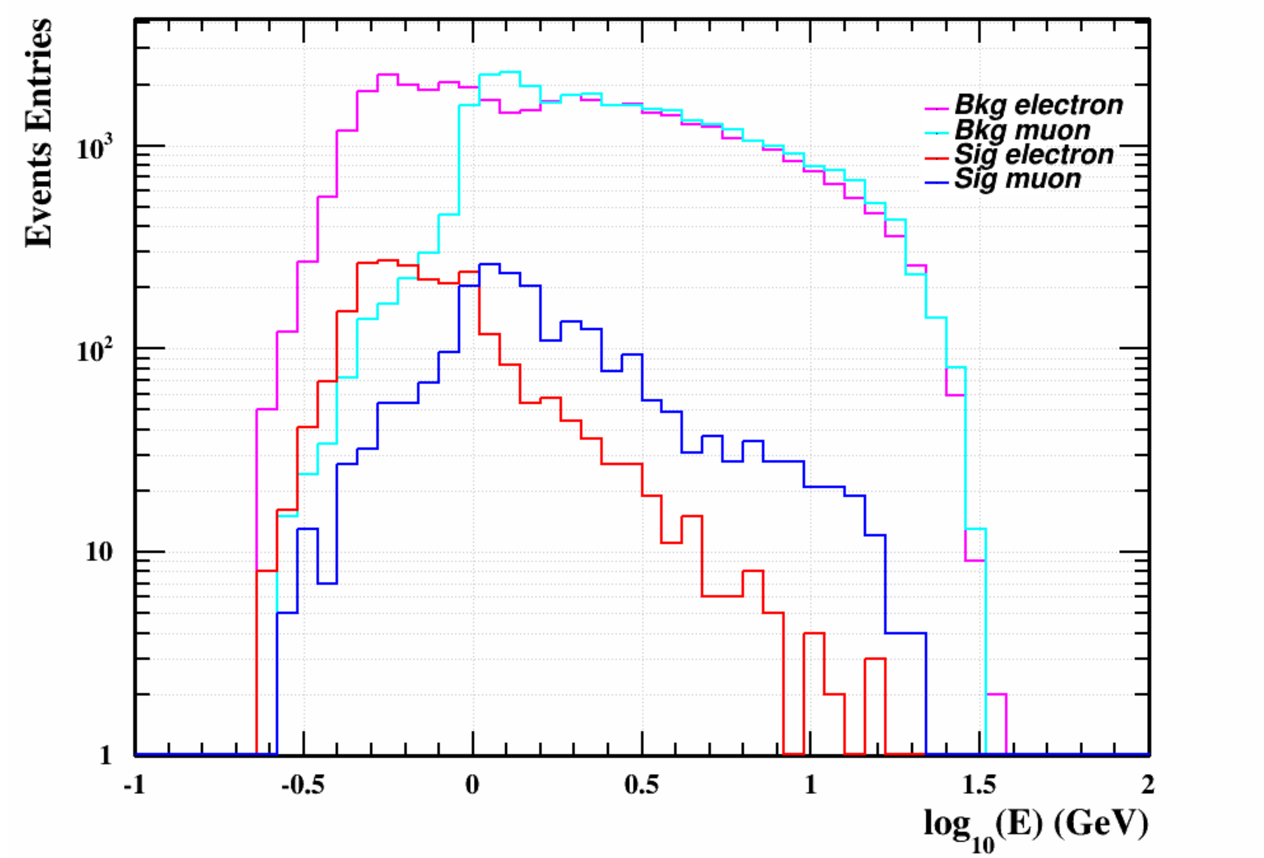


Charged lepton (muon and electron) identify by DanYu.

Leading charged lepton with $N_{\phi} > 0$:

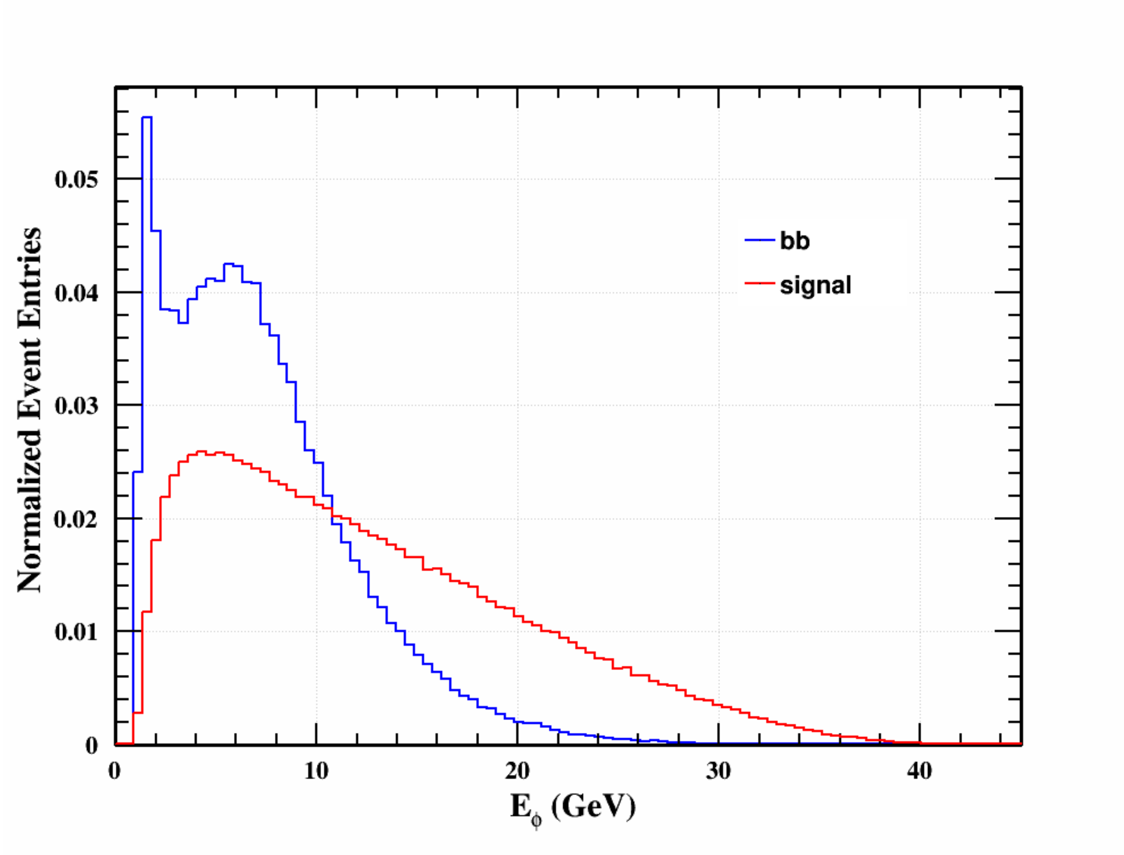


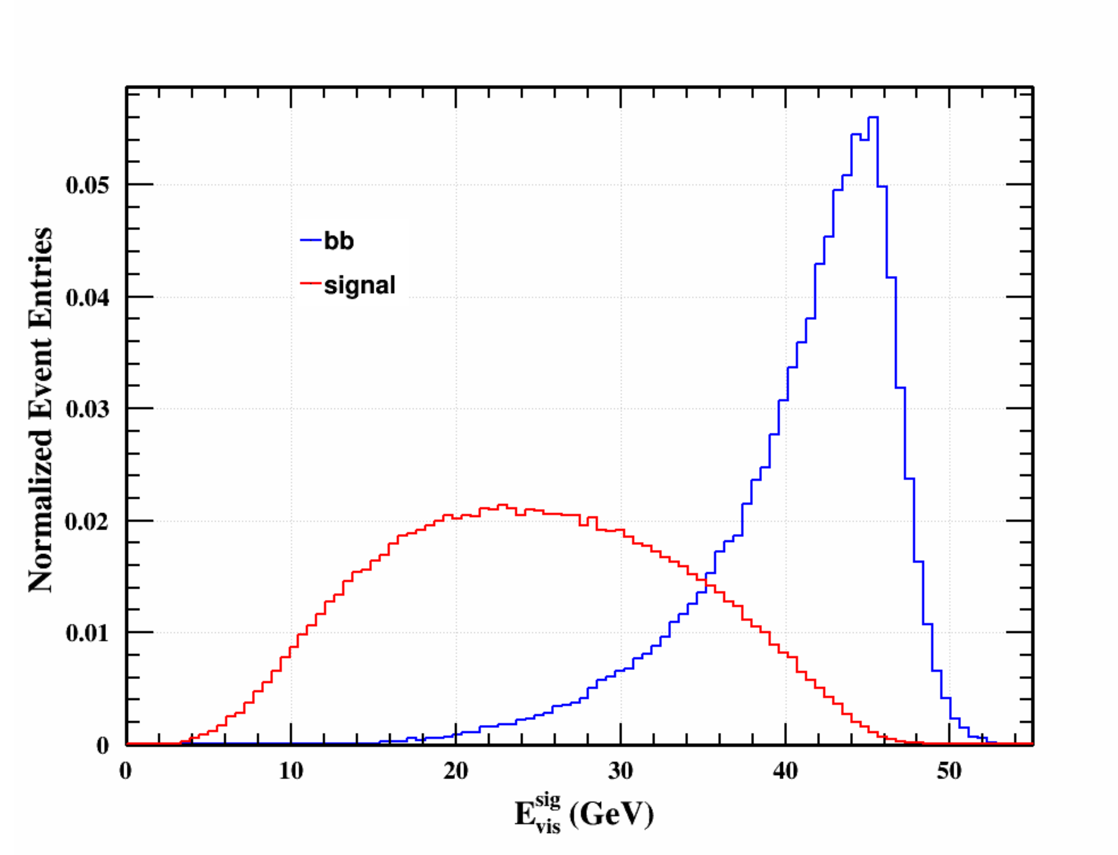
2.6×10^6 $b\bar{b}$ samples. The comparison of reconstructed and truth charged lepton identify. The mis-identify of electron and muon is large in the small energy region.



2.6×10^6 $b\bar{b}$ samples and 1×10^6 signal samples. The charged lepton identify ratio of signal is much smaller than $b\bar{b}$ events.

ϕ and visible energy





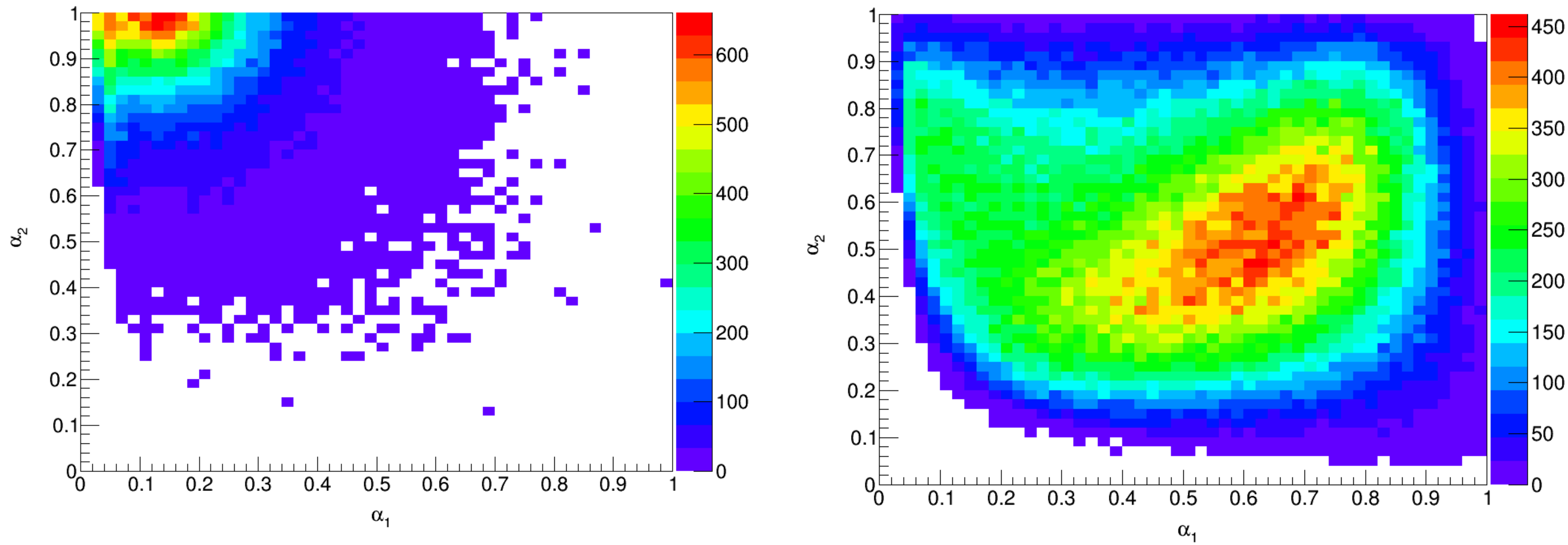
Define the ratio:

$$\alpha_1 = \frac{E_\phi}{E_{vis}^{sig}} \qquad \alpha_2 = \frac{E_{vis}^{sig}}{E_{beam}}$$

E_{vis}^{sig} is the energy of signal-hemisphere and $E_{beam} = 45.6$ GeV

The energy of ϕ for both bb and signal peak at about 5 GeV while large discrepancy for E_{vis}^{sig}.

α_1 and α_2 show the strong correction between missing energy (E_{miss}), visible energy (E_{vis}) and ϕ energy (E_ϕ).

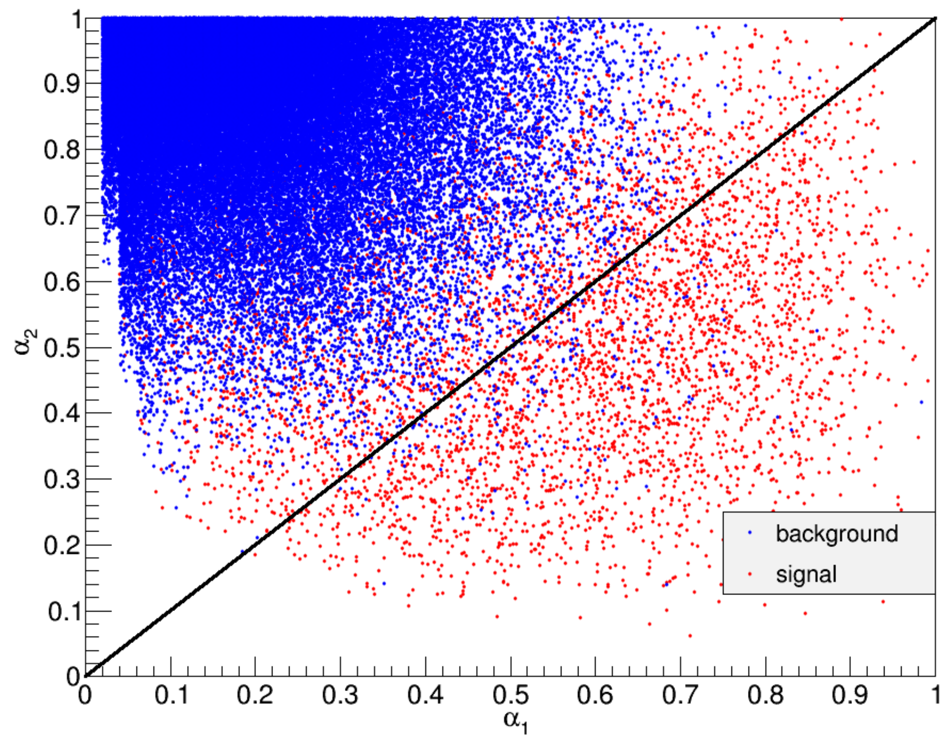


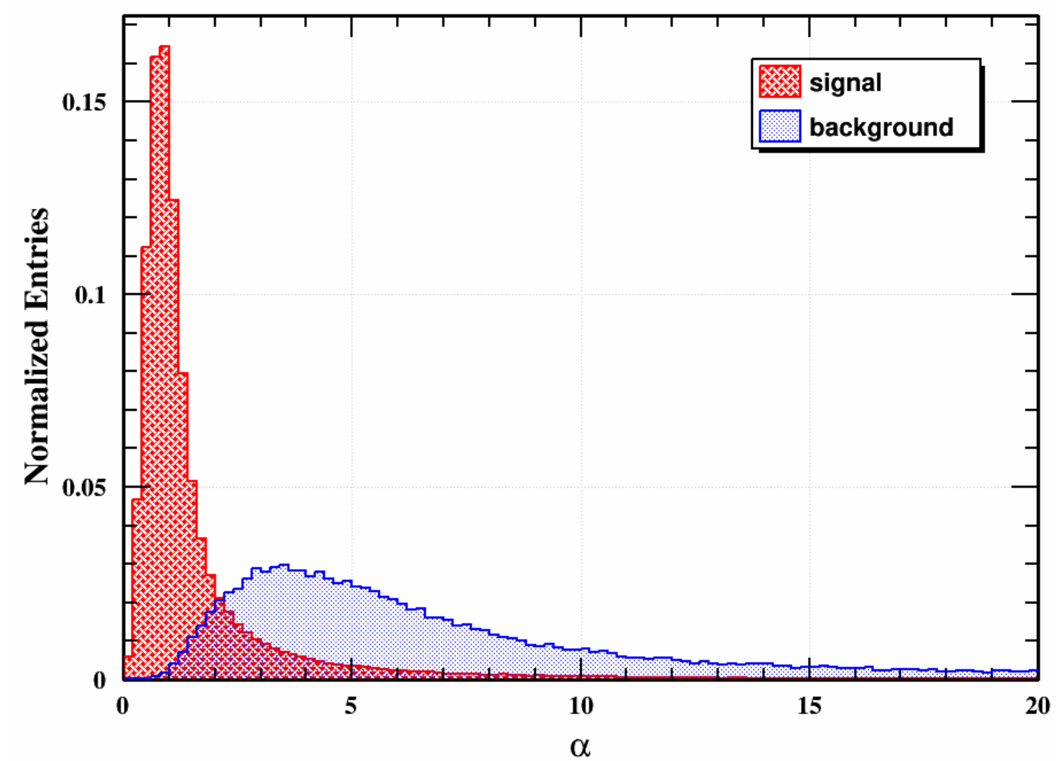
(*a*) (*b*)

The correction distribution of α_1 and α_2 for $b\bar{b}$ background (a) and signal (b). The background mostly locate at left of $\alpha_2 = \alpha_1$ mean while signal locate at right.

It is clearly that there exist a linear boundary $\alpha_2 = \alpha\alpha_1$ to separate the background and signal efficiently.

$$\alpha = \frac{\alpha_2}{\alpha_1} = \frac{(E_{vis}^{sig})^2}{E_\phi \cdot E_{beam}}$$





The measurement of α depend on the BMR and the purity of ϕ reconstruction.

The jets BMR reconstructed by CEPC software is about 4 % , by the large denominator, the influence of BMR here is soft.

The preliminary cut chain

	N_S	N_B	S/sqrt(B)	sqrt(S+B)/S
Total	180000	1.5e+11	0.46	2.15
$N_\phi > 0$	6.78e4	4.82e+09	0.98	1.02
$E_l < 1$ GeV	5.55e4	2.05e9	1.22	0.82
$E^{ISO}_{Neutral} < 2.7$ GeV	4.59e4	6.91e8	1.75	0.57
$E^{ISO}_{track} < 4$ GeV	4.25e4	4.17e8	2.08	0.48
$\alpha < 0.8$	1.71e4	5.77e+5	22.52	0.045
Efficiency	0.095	3.85e-06		

$E^{ISO}_{Neutral}$ is defined by that all the neutral energy whose momentum have a angle with ϕ smaller than 0.2 rad. This variable reflect the isolated ϕ feature in B_s signal decay.

The cut chain not included other $f\bar{f}$ background yet, for their contributions compared to $b\bar{b}$ is much smaller.

Major background remain:

$$b\bar{b}: b \to B(B^*) \to D(D^*)\ell\nu_\ell \text{ with } D(D^*) \to \phi X$$

The future optimization?

1) The missing mass or nominal mass of B_s?

The invariant mass that involved the missing momentum is vary sensitive to the BMR. Not yet a better algorithm to reconstruct the momentum of B_s.

2) The variables which have little effect not uesd.

Such as the angle between ϕ and missing momentum ($\theta_{<\vec{P}_{\phi},\vec{P}_{miss}>}$), the impact parameter of ϕ, the large impact parameter of track… The two BDT cut could be organized for the kinematic and track variables.

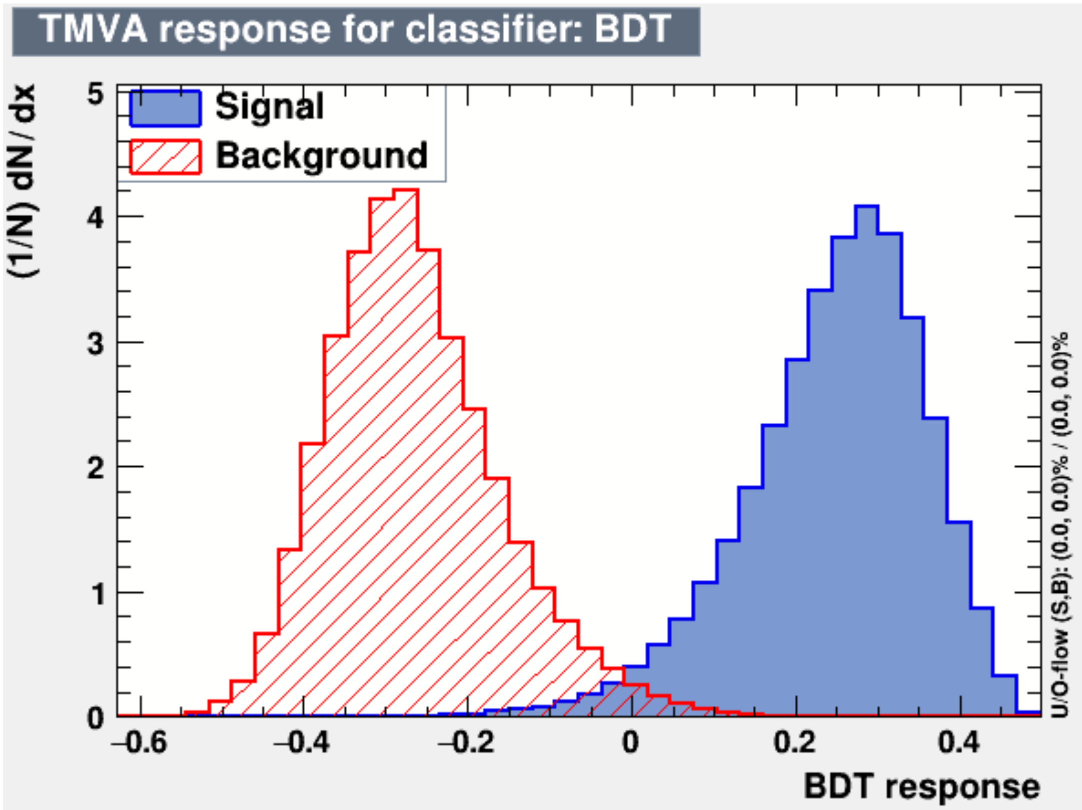
3) The optimization of ϕ reconstruction.

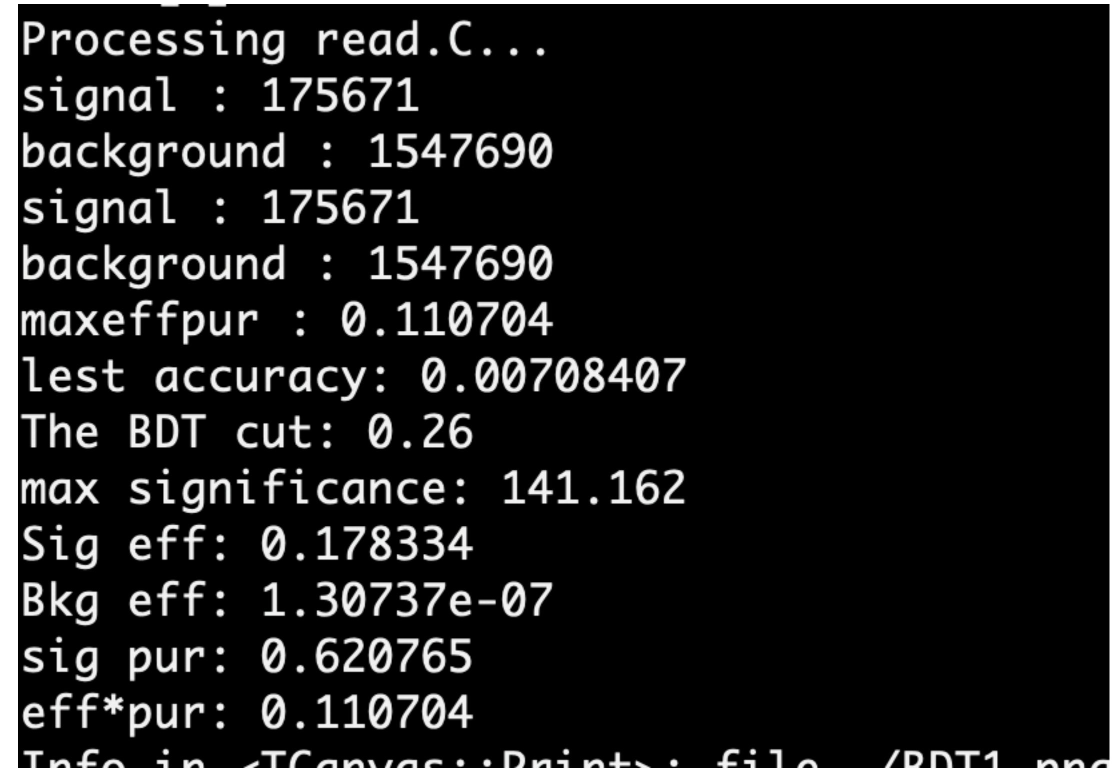
4) The charged lepton mis-identify at small energy (< 2 GeV).

5) Larger background samples:

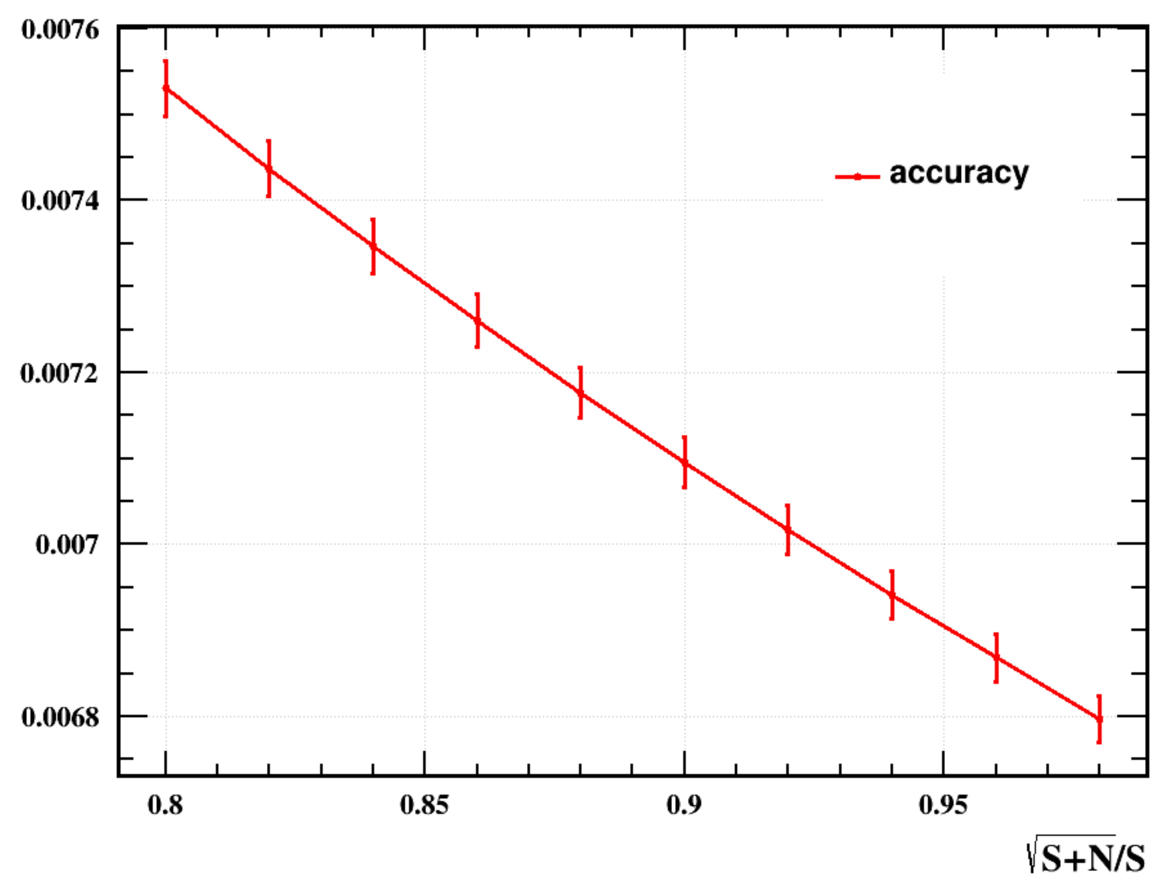
exclusive background simulation

Primary and BDT cut chain



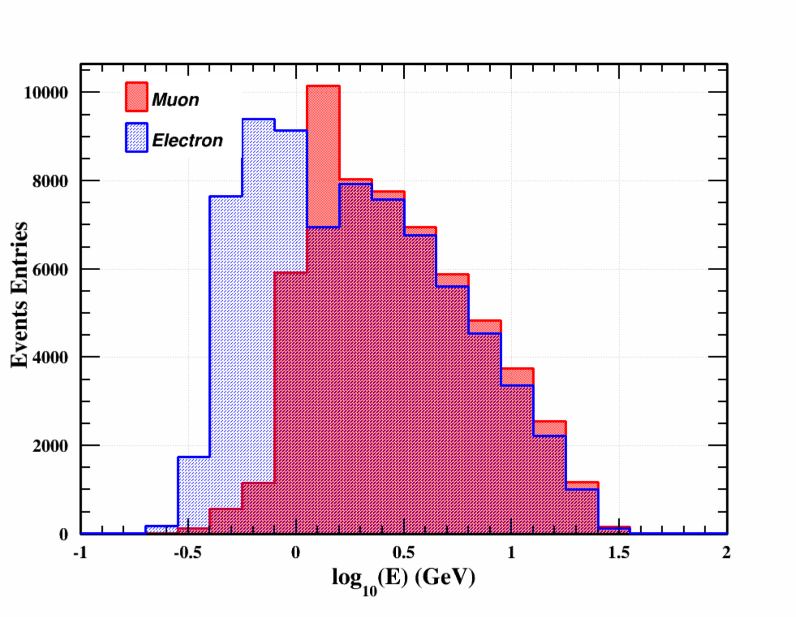

```
Processing read.C...
signal : 175671
background : 1547690
signal : 175671
background : 1547690
maxeffpur : 0.110704
lest accuracy: 0.00708407
The BDT cut: 0.26
max significance: 141.162
Sig eff: 0.178334
Bkg eff: 1.30737e-07
sig pur: 0.620765
eff*pur: 0.110704
```

conditions	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}$	dd	ss	$c\bar{c}$	bb	$\sqrt{S+B}/S$ (%)
total generated	1.221e6	2.949e10	5.494e9	5.482e9	2.9318e9	4.685e8	
b-tag > 0.6	9.77e5(80%)	2.949e8 (1%)	5.494e7(1%)	5.482e7(1%)	2.9318e8(10%)	3.7480e8(80%)	
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	449132	2997693	556410	1417245	6555440	10180889	
Energy asymmetry > 10 GeV	351343	243363	44277	100981	792949	1913810	
BDT score > 0.26	178334	0	0	0	10	39	
Efficiency	0.1460	0	0	0	3.41e-9	8.32e-8	-
Scaled number	26280	0	0	0	408	12486	0.75

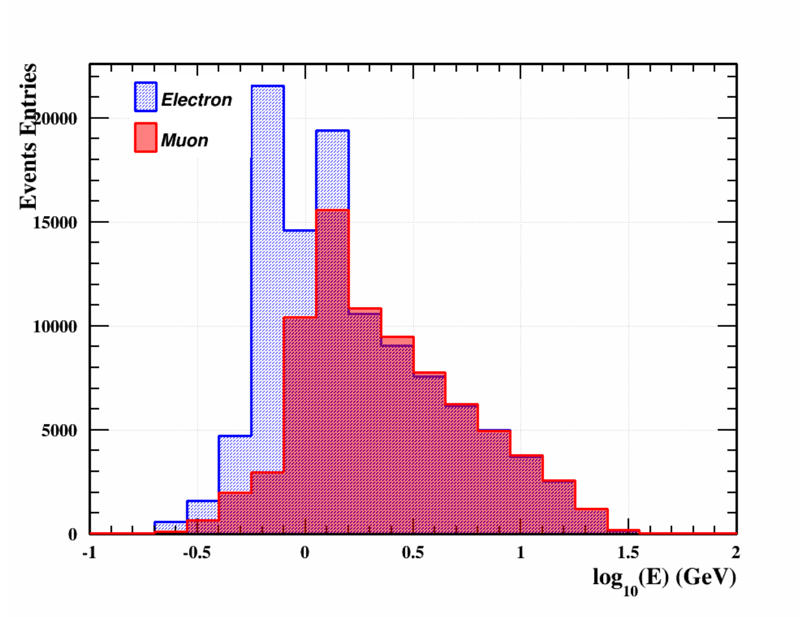


0.0076
0.0074
0.0072
0.007
0.0068
0.8
0.85
0.9
0.95
√S+N/S
accuracy

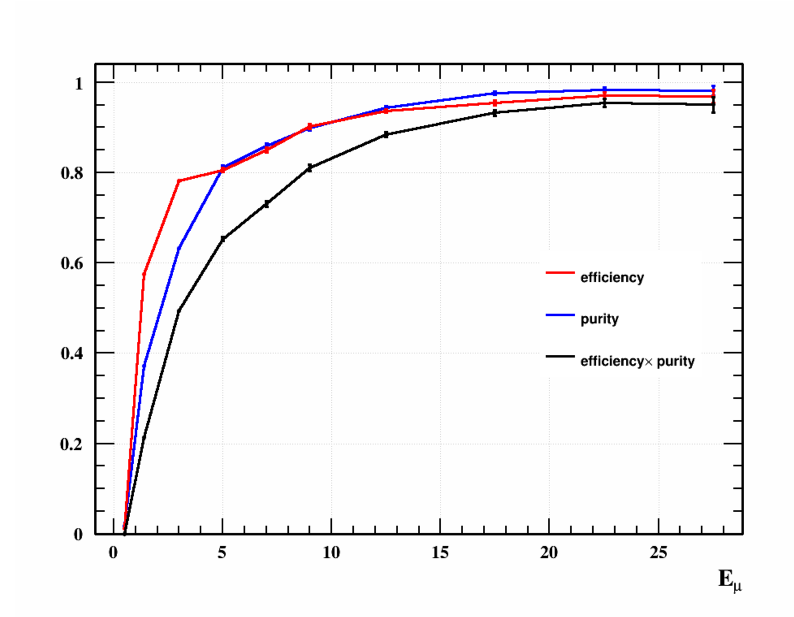
Charge Lepton Identify



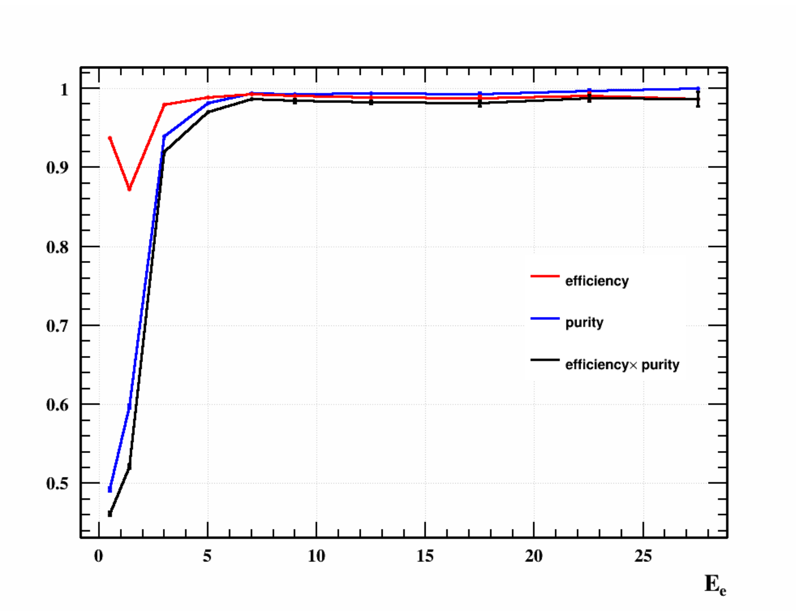
All the charged lepton in signal-hemisphere



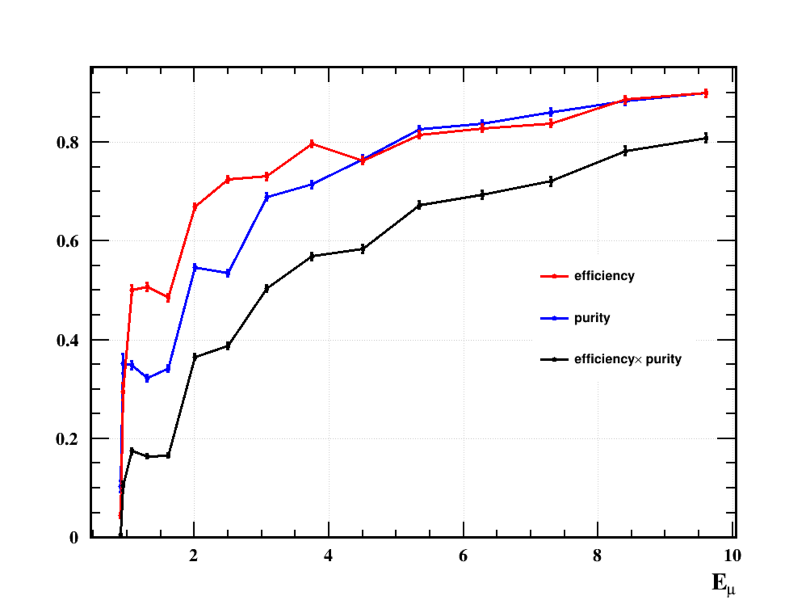
The leading charged lepton in signal-hemisphere



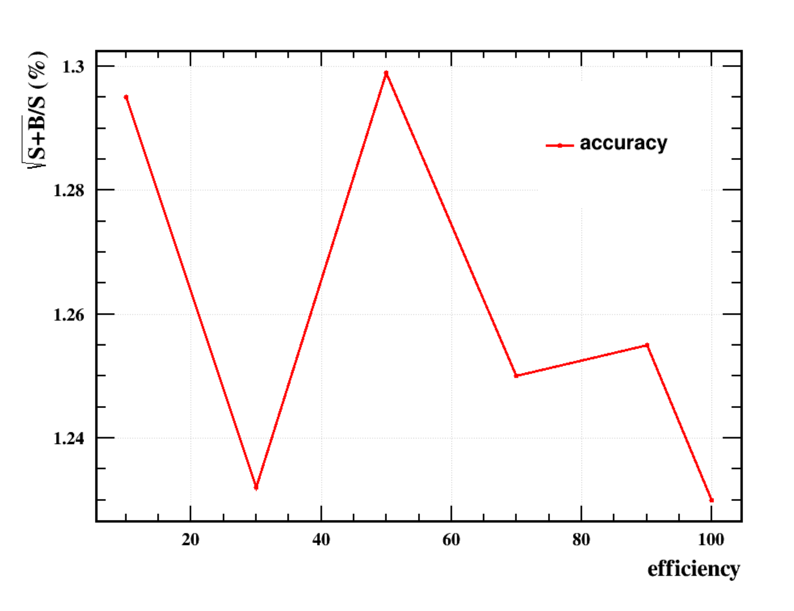
The efficiency and purity of muon.



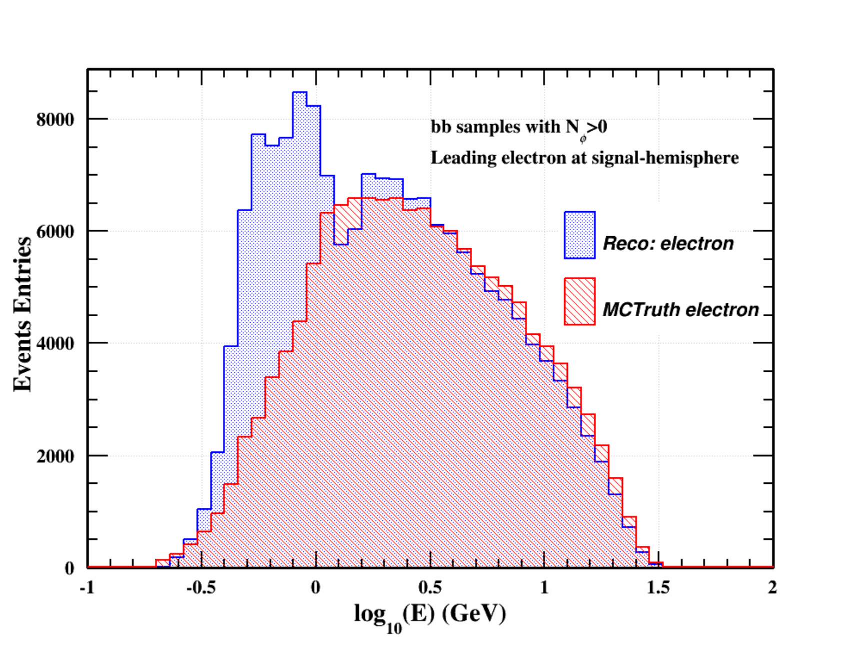
The efficiency and purity of electron.



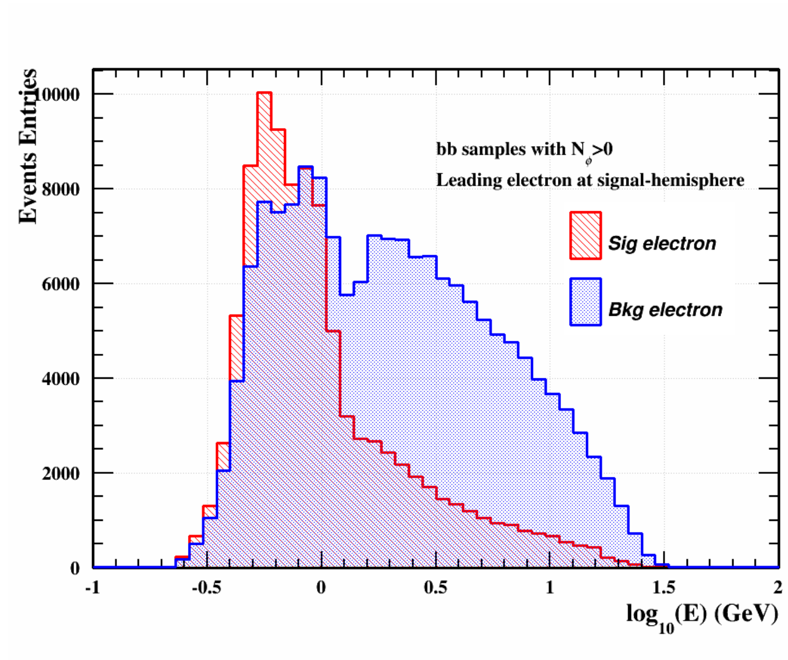
The efficiency and purity of leading muon.



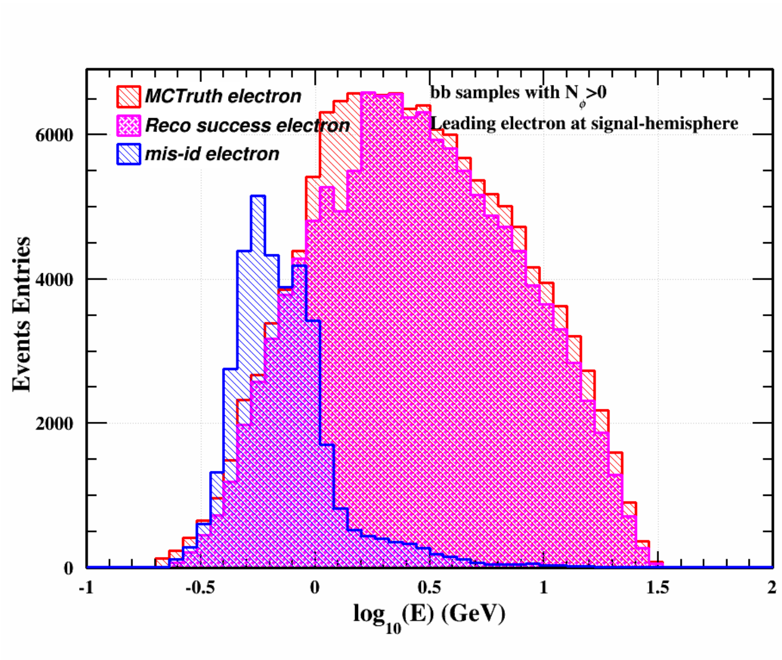
The performance of accuracy on the muon efficiency.



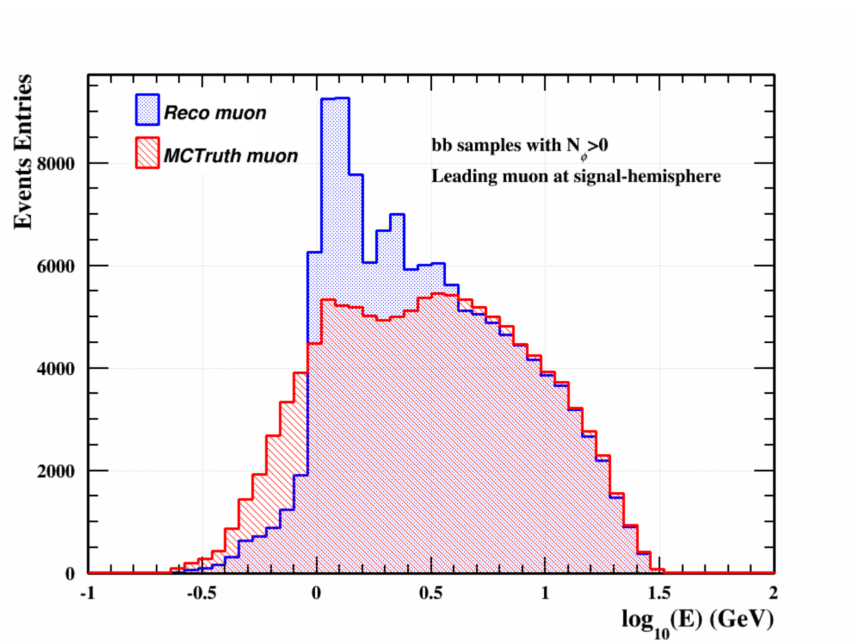
bb samples with N_ℓ >0
Leading electron at signal-hemisphere
Reco: electron
MCTruth electron
Events Entries
$\log_{10}$(E) (GeV)



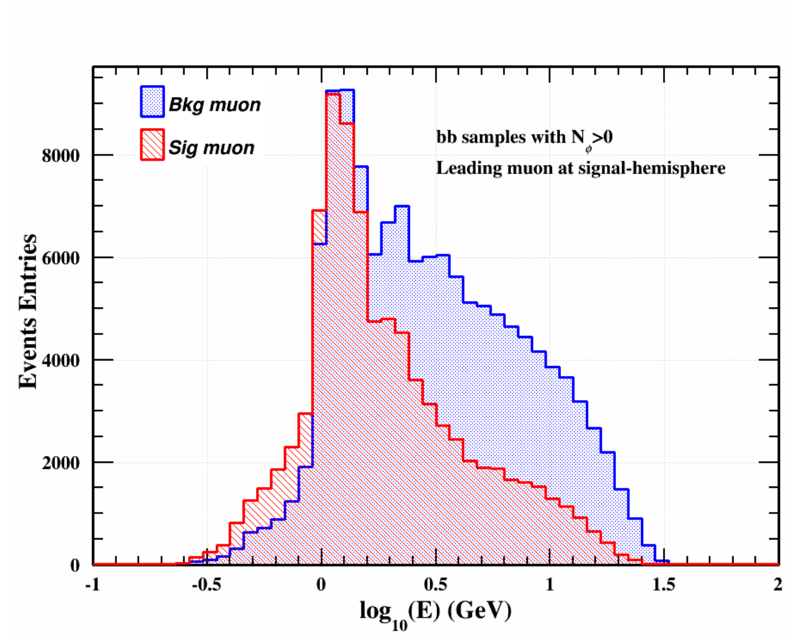
bb samples with N_ℓ >0
Leading electron at signal-hemisphere
Sig electron
Bkg electron
Events Entries
$\log_{10}$(E) (GeV)



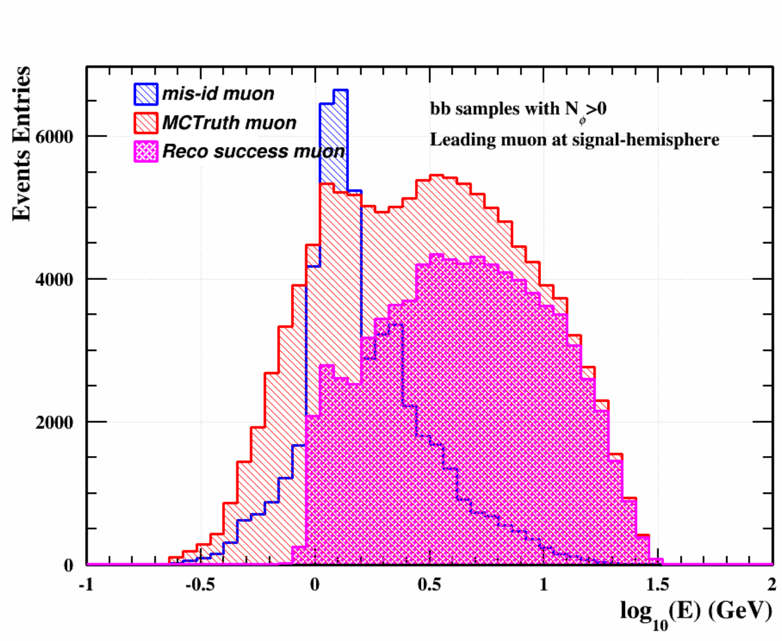
MCTruth electron
Reco success electron
mis-id electron
bb samples with N_ℓ >0
Leading electron at signal-hemisphere
Events Entries
$\log_{10}$(E) (GeV)



Reco muon
MCTruth muon
bb samples with N_ℓ >0
Leading muon at signal-hemisphere
Events Entries
$\log_{10}$(E) (GeV)

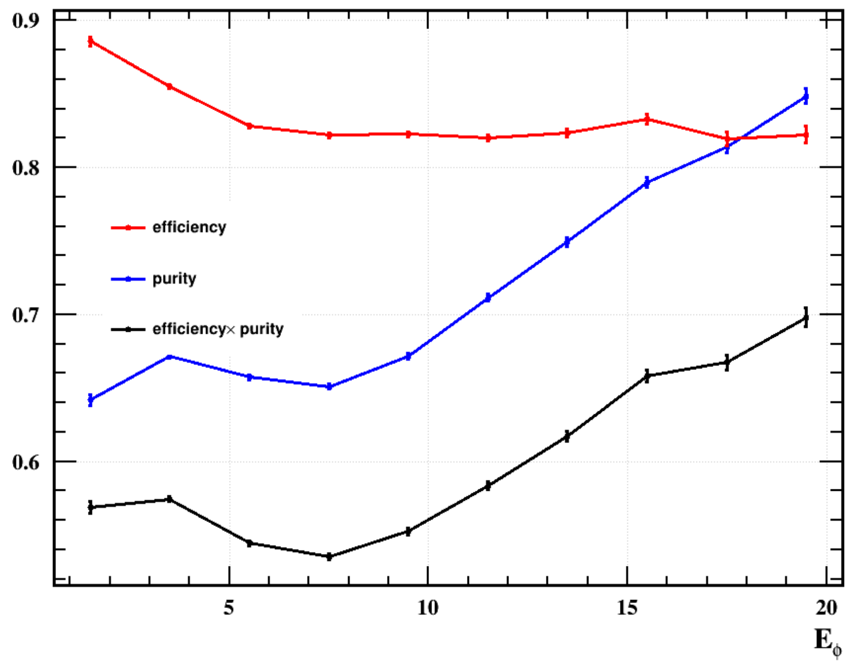


Bkg muon
Sig muon
bb samples with N_ℓ >0
Leading muon at signal-hemisphere
Events Entries
$\log_{10}$(E) (GeV)



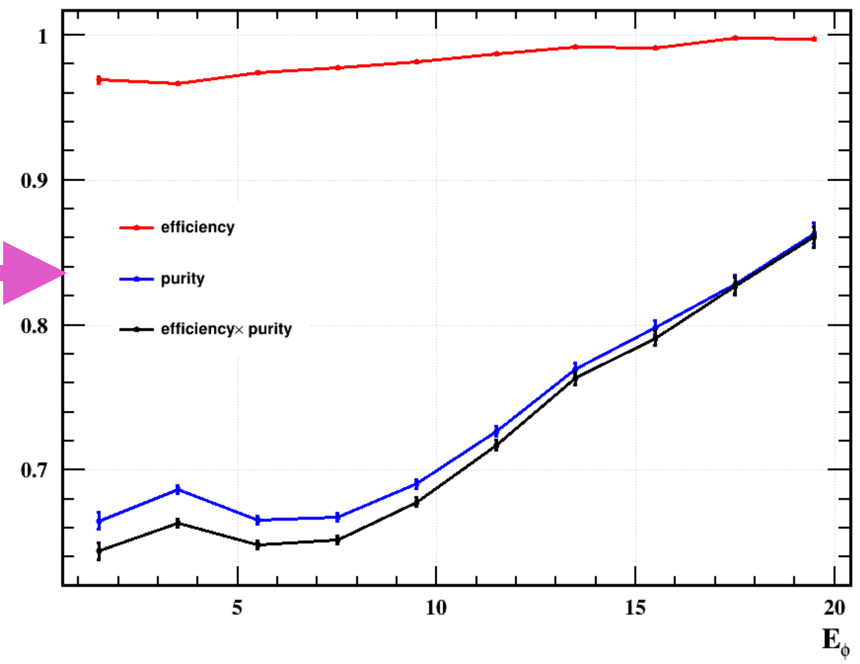
mis-id muon
MCTruth muon
Reco success muon
bb samples with N_ℓ >0
Leading muon at signal-hemisphere
Events Entries
$\log_{10}$(E) (GeV)

ϕ Reconstruction



Leading ϕ choice

Signal-hemisphere direction



The efficiency and purity of all the ϕ reconstruction in $b\bar{b}$.

The efficiency and purity of selected leading ϕ reconstruction in $B_s \to \phi\nu\bar{\nu}$ analysis.

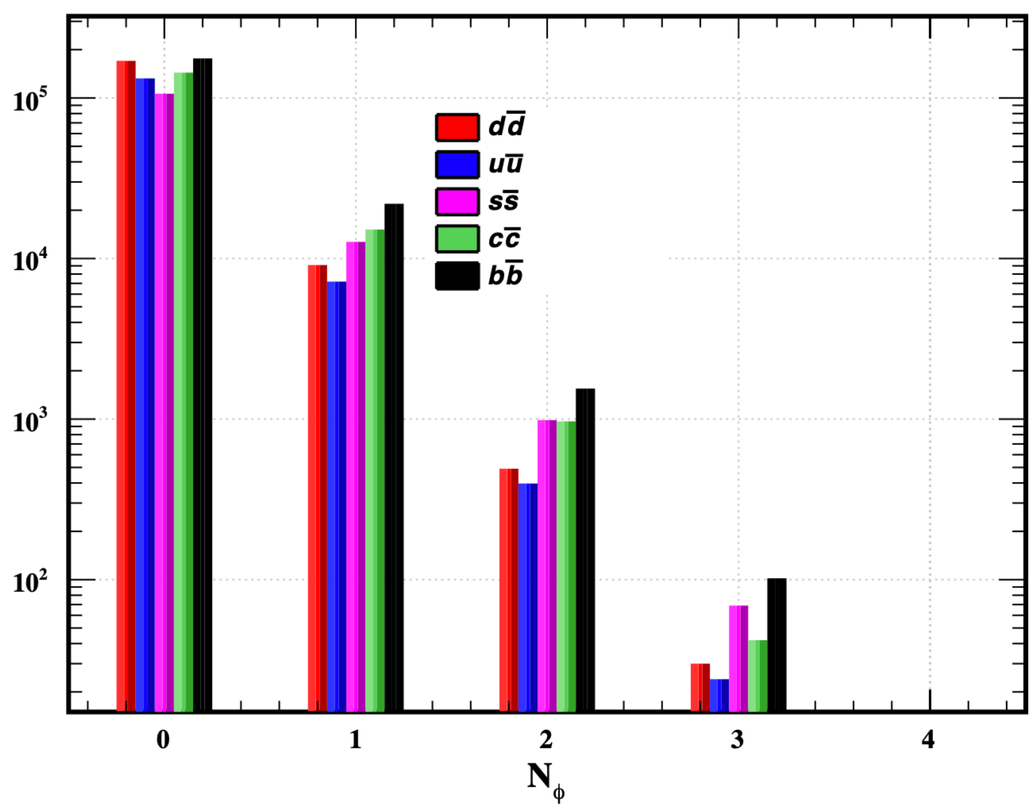


FIG. 1: The number ϕ in the different channel, for the events which have at least one ϕ account for around about 5.4%, 5.3%, 11.5%, 10.1% and 11.7% for $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$ and $b\bar{b}$, respectively. Consider the situation that in this analysis the ϕ whose direction is in the signal-hemisphere (assumption to be 50%) and decay to K^+K^- pair (49.2%), the selected ϕ ratio should be 1.3%, 1.3%, 2.8%, 2.5% and 2.9% for the background, respectively).

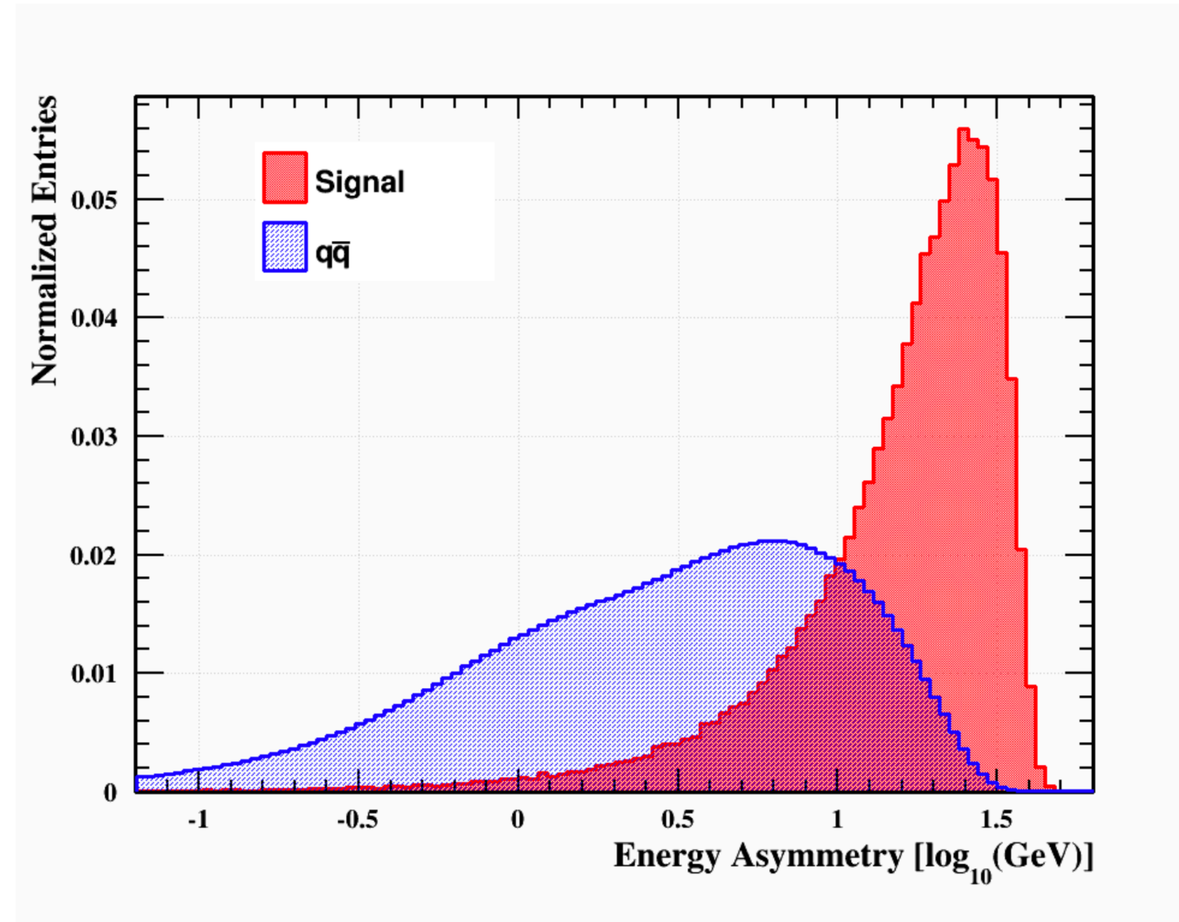


FIG. 2: The energy asymmetry which defined as the energy difference of tag-hemisphere to signal-hemisphere. The events used here satisfy the condtions that number of ϕ larger than 0 (According to the Table. IV, number of samples used here are 144000, 113000, 160000, 409000, 2683000 and 32813000 for signal, uu, dd, ss, cc and bb, respectively.

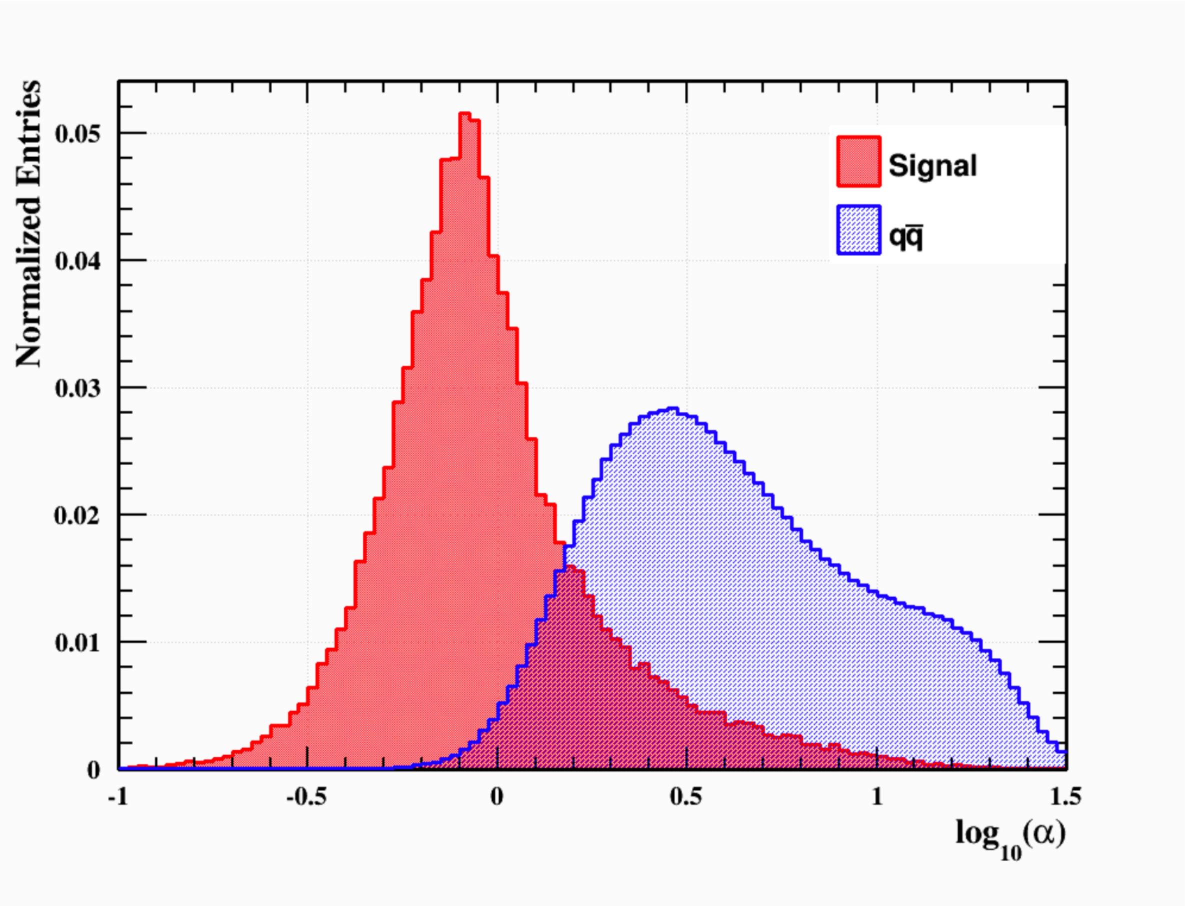


FIG. 3: The ratio α which defined as the Eq. 2 for the signal and backgourd. The events used here satisfy the condtions that number of ϕ larger than 0 and energy asymmetry shown in the Fig. 2 larger than 10 GeV. (According to the Table. IV, number of samples used here are 51800, 9200, 12700, 29200, 324500 and 6168300 for signal, uu, dd, ss, cc and bb, respectively.

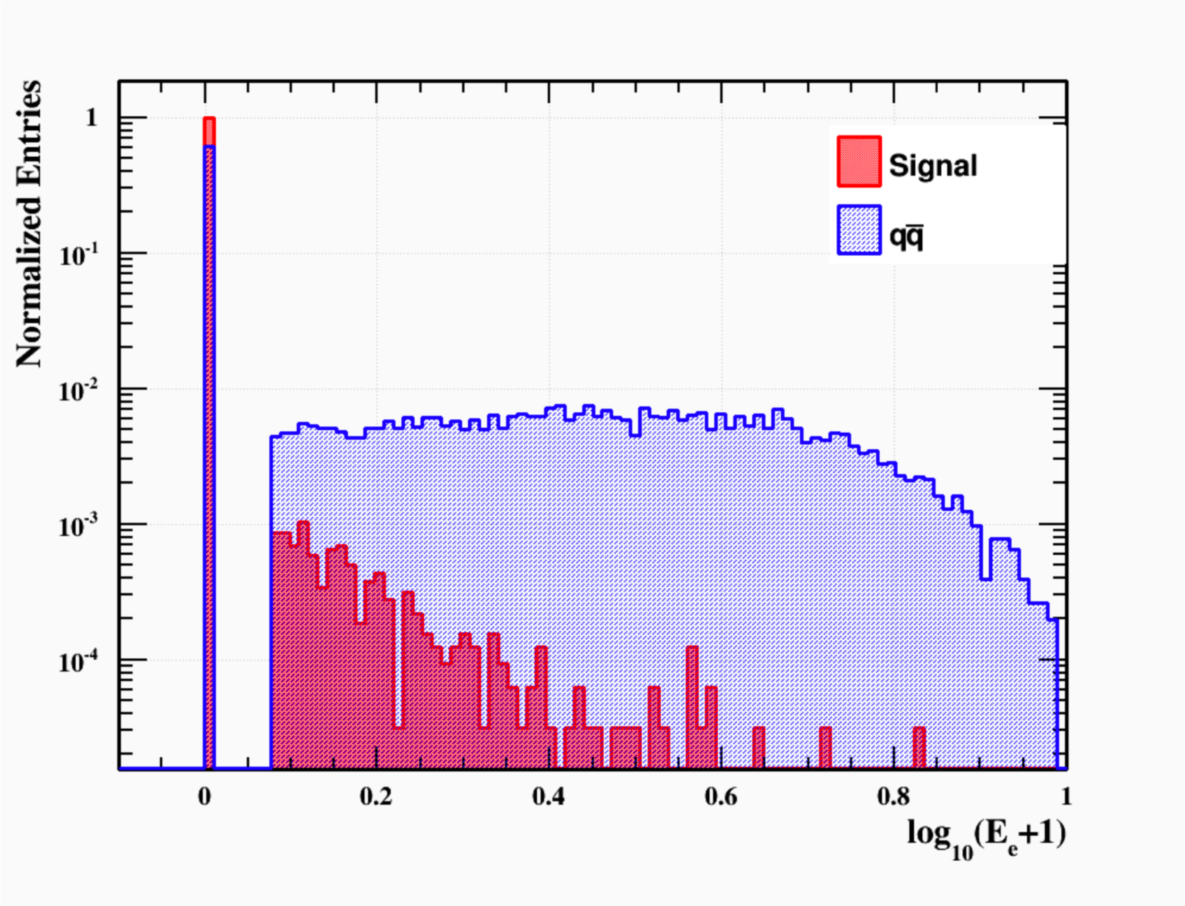


FIG. 5: The energy distribution of leading electron. The events used here satisfy the condtions that number of ϕ larger than 0 and energy asymmetry shown in the Fig. 2 larger than 10 GeV, $\alpha < 1.0$. (According to the Table. IV, number of samples used here are 32202, 1, 1, 10, 1029 and 14313 for signal, uu, dd, ss, cc and bb, respectively.

Missing energy:

1. The general missing energy in the whole events (Energy total).

2. The detail of missing energy origin.

a. In the signal hemishphere, weather the missing energy count for mostly energy except ϕ. ($\alpha_1 = E_\phi / E_{sig}$)

b. Weather the missing energy come from the signal-hemisphere. ($\alpha_2 = E_{sig} / E_{beam}$ and $E_{asymmetry}$)

c. The possibility that missing energy come from the same mother particle as ϕ.

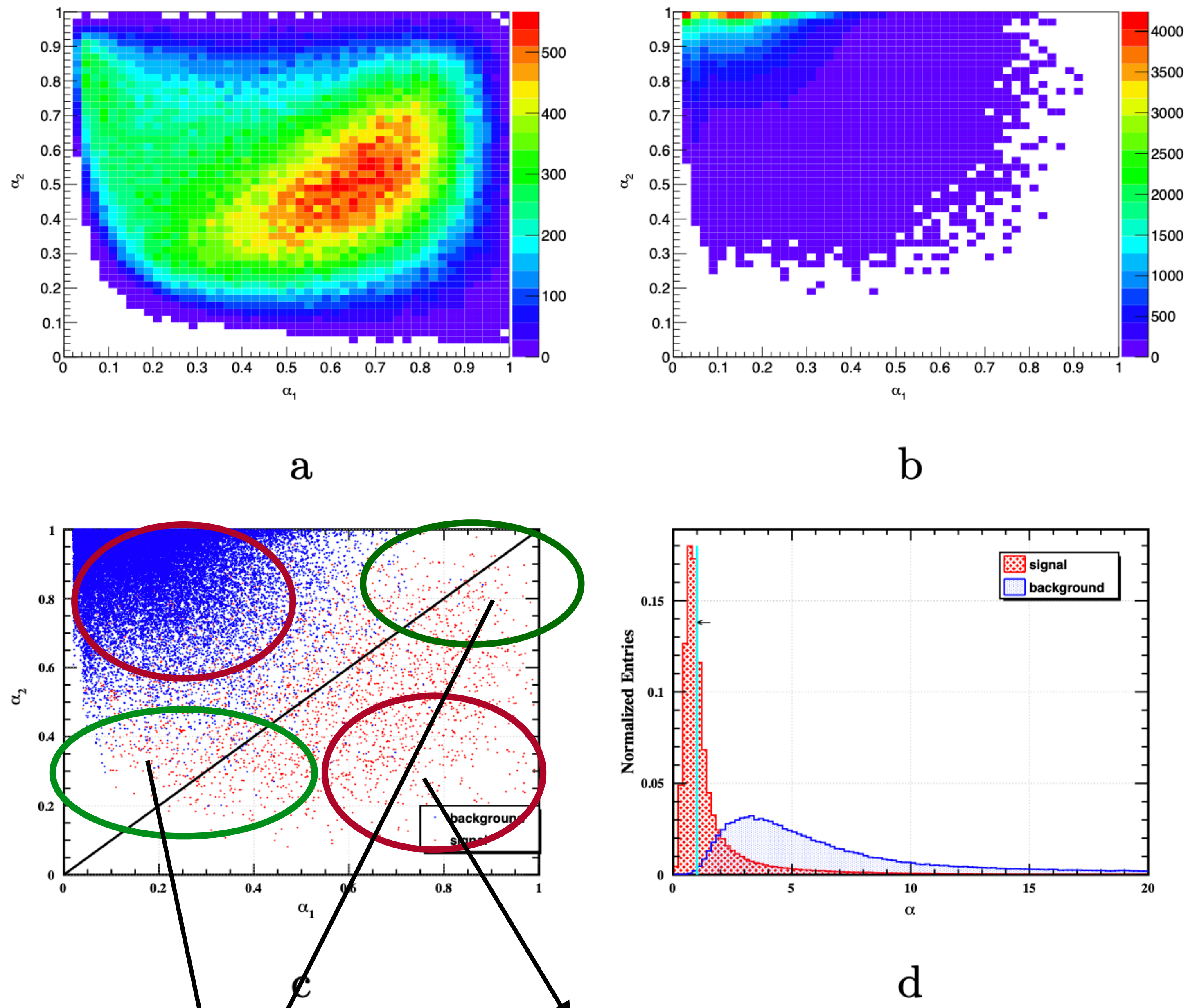
conditions	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	bb	total	$\sqrt{S+B}/S$ (%)
total generated	1.8e5	1.120e11	1.585e11	1.585e11	1.20e11	1.510e11	7.0e11	464.81
b-tag > 0.6	1.44e5	1.12e9	1.585e9	1.585e9	1.20e10	1.208e11	1.3029e11	250.66
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	66198	1.13888e7	1.60522e7	4.09765e7	2.68317e8	3.28135e9	3.61809e9	90.87
Energy asymmetry > 10 GeV	51784	924581	1277380	2919640	3.24558e7	6.16831e8	6.54408e8	49.40
Energy total< 81 GeV	50653	2678	3433	4047	1.04827e7	3.63637e8	3.7413e8	38.19
$E_{B_s} > 30$ GeV	43798	34	28	86	1.96728e6	5.04482e7	5.24156e7	16.54
$\alpha < 1.0$	31722	0	0	0	464193	8.23425e6	8.69845e6	9.31
$E_\mu < 1.2$ and $E_e < 1.2$	31663	0	0	0	279432	4.4159e6	4.69534e6	6.87
BDT score > 0.22	12644	0	0	0	368	9284	9652	1.09
Efficiency (%)	7.02	0	0	0	3.06e-7	6.15e-6	1.38e-7	-

TABLE IV: The cut chain with truth-level samples with all kinds of ideal situation. The number of signal and background samples are scaled to the integrated luminosity by 16 ab^{-1} at CEPC. The b-tagging is assumed that the score larger than 0.6 get 1% for light quark, 10% for $c\bar{c}$ and 80% for $b\bar{b}$.

There still significant condition to suppress the background in the BDT.

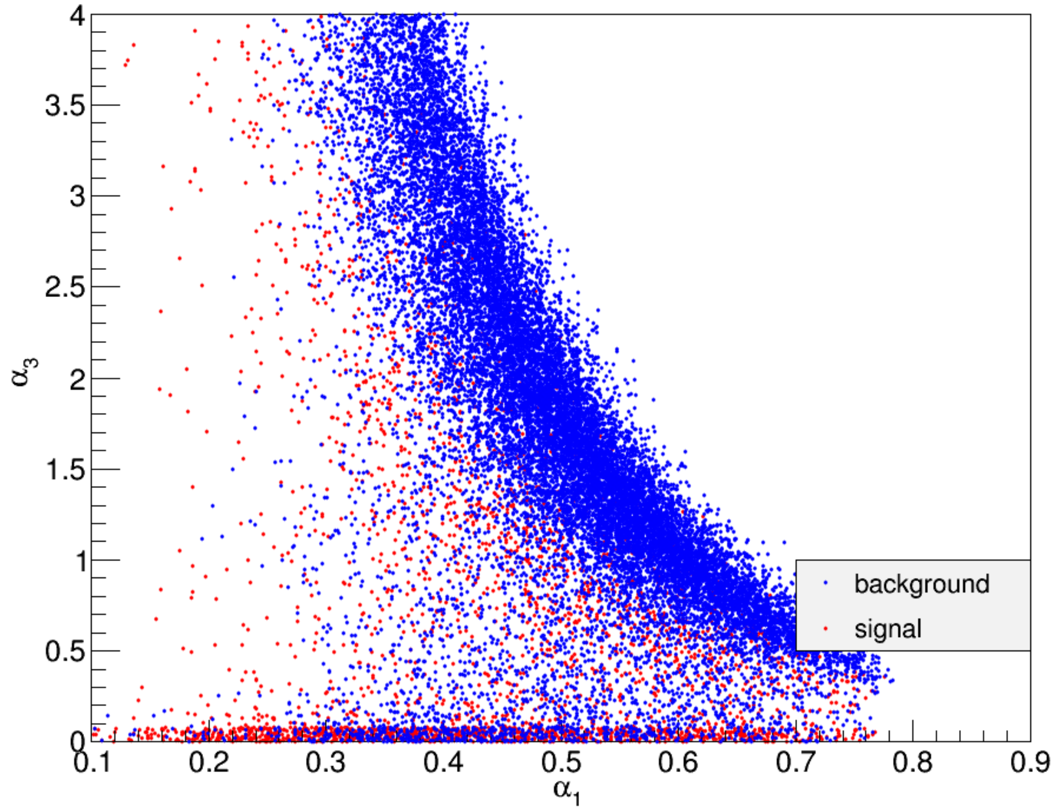
Isolated ϕ

Review the cut condition on α



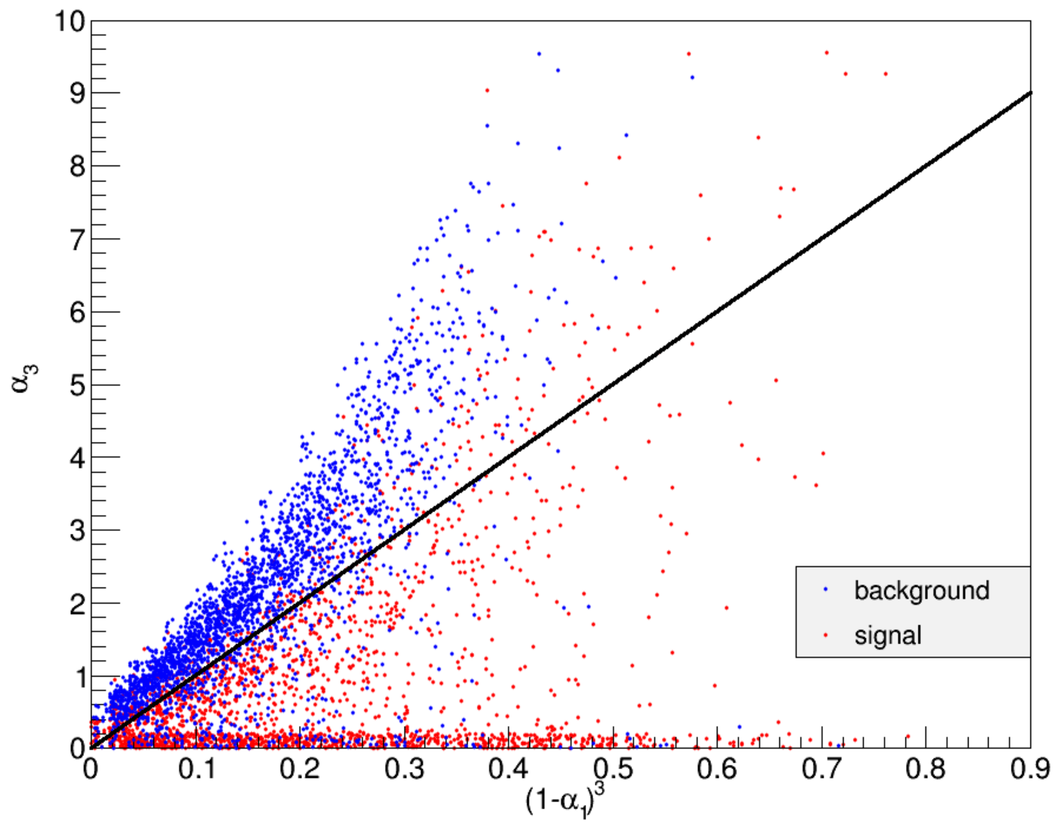
Perfect signal region

The mostly remain background region



To scale the magnitude of the isolated neutral energy, define the ratio

$$\alpha_3 = E^{Cone}_{neutral}/E_{\phi}$$



To get a linear boundary cut,

the plane is transformed to the

$\alpha_3 - (1 - \alpha_1)^3$

Truth-level

conditions	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	bb	total	$\sqrt{S+B}/S$ (%)
total generated	1.8e5	1.120e11	1.585e11	1.585e11	1.20e11	1.510e11	7.0e11	464.81
b-tag > 0.6	1.44e5	1.12e9	1.585e9	1.585e9	1.20e10	1.208e11	1.3029e11	250.66
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	66198	1.13888e7	1.60522e7	4.09765e7	2.68317e8	3.28135e9	3.61809e9	90.87
Energy asymmetry > 10 GeV	51784	924581	1277380	2919640	3.24558e7	6.16831e8	6.54408e8	49.40
Energy total< 81 GeV	50653	2678	3433	4047	1.04827e7	3.63637e8	3.7413e8	38.19
$E_{B_s} > 30$ GeV	43798	34	28	86	1.96728e6	5.04482e7	5.24156e7	16.54
$\alpha < 1.0$	31722	0	0	0	464193	8.23425e6	8.69845e6	9.31
$E_\mu < 1.0$ and $E_e < 1.0$	31644	0	0	0	262078	4.14098e6	4.40306e6	6.65
$\alpha_3/(1-\alpha_1)^3 < 9.0$	23884	0	0	0	6385	546952	553337	3.18
BDT score > 0.21	10430	0	0	0	81	6403	6584	1.25
Efficiency (%)	5.79	0	0	0	3.06e-7	6.15e-6	1.38e-7	-

TABLE IV: The cut chain with truth-level samples with all kinds of ideal situation. The number of signal and background samples are scaled to the integrated luminosity by 16 ab^{-1} at CEPC. The b-tagging is assumed that the score larger than 0.6 get 1% for light quark, 10% for $c\bar{c}$ and 80% for $b\bar{b}$.

Full Simulation

conditions	$B_s \to \phi\nu\bar{\nu}$	bb	$S/\sqrt{B}$	$\sqrt{S+B}/S$ (%)
total generated	1.8e5	1.5e11	1.2e-6	2.151
b-tag > 0.6	1.359e5	1.1852e11		
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	5.117e4	3.818e9	0.83	120.7
Energy asymmetry > 10 GeV	4.093e4	8.016e8	1.45	69.15
Energy total < 85	39790	4.53105e8	1.87	53.50
$E_{B_s} > 28$	34072	6.9252e7	4.09	24.43
$\alpha < 1.0$	23152	8.05e6	8.16	12.27
$E_\mu < 1.0$ GeV and $E_e < 1.0$ GeV at signal-hemisphere	20249	2.85861e6	11.98	8.38
BDT score > 0.31		0	-	0.98 ?
Efficiency		0	-	-

TABLE V: The number of signal and $b\bar{b}$ samples are 1×10^6 and 4.88×10^6 and norm to the integrated luminosity by 16 ab^{-1} at CEPC which shown in the table.

End

Thanks