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

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Content

Motivation

- Investigation of flavor-changing neutral current (FCNC) decays is of fundamental interest.

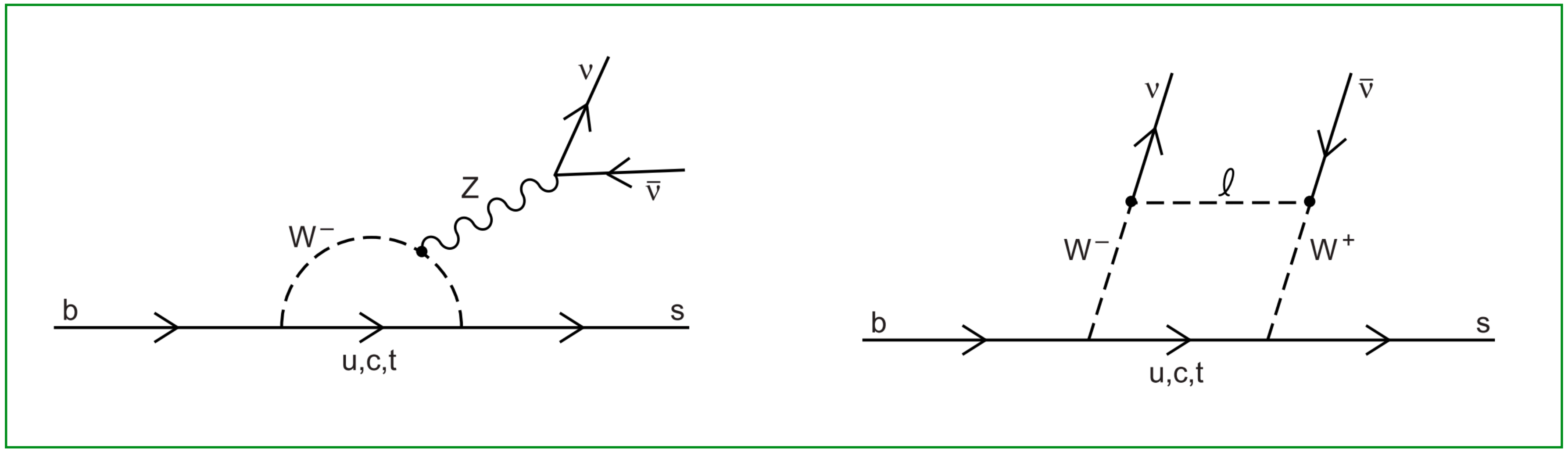
- SM prediction for the FCNC decay $b \to s\nu\bar{\nu}$ is nearly free from strong interaction effects and has very small theoretical uncertainty.

- 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 $b \to s\nu\nu$ decays may potentially lead to significant enhancements to the SM branching fraction.

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

[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

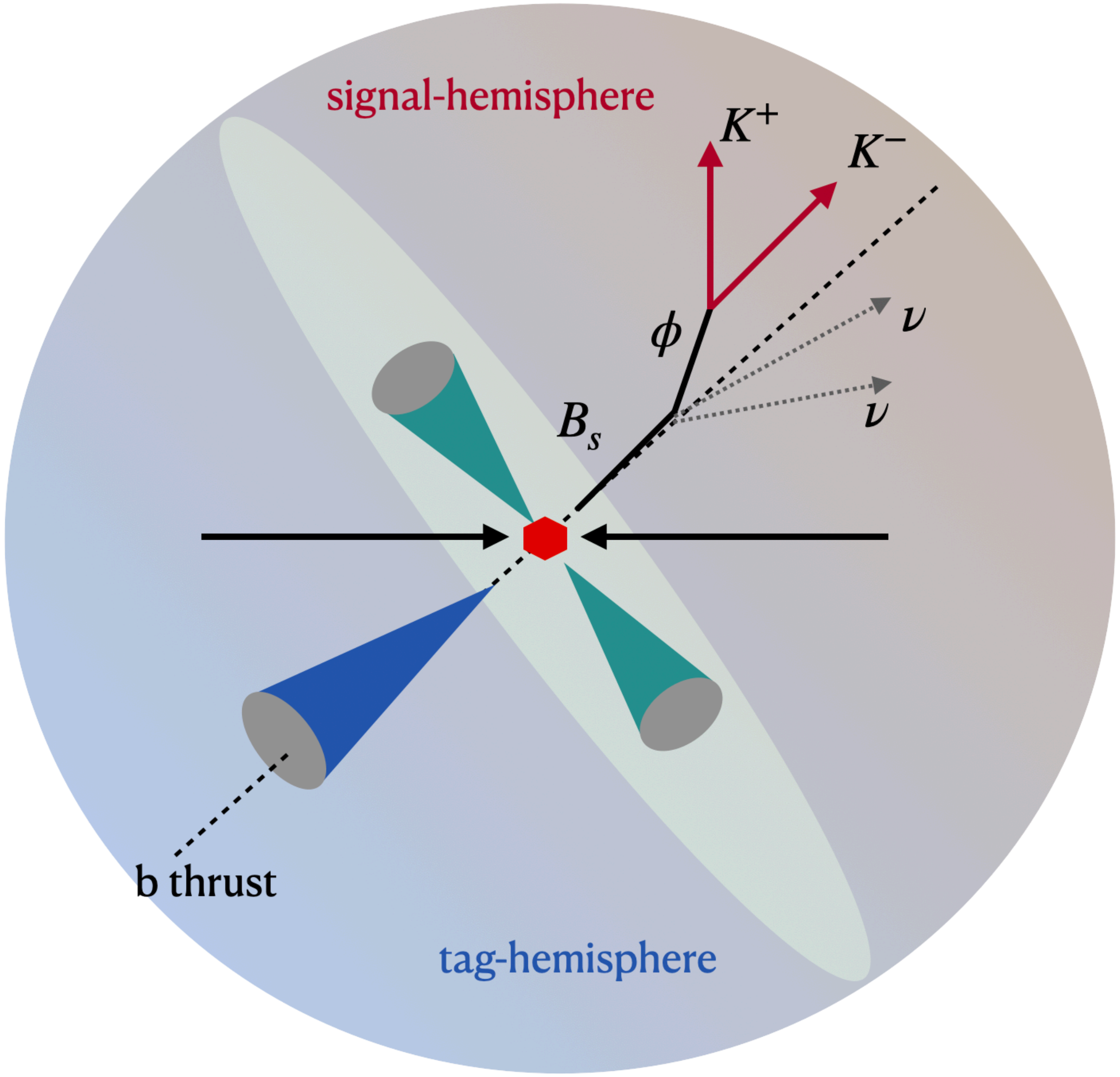
The whole space is divided into two hemisphere by the plane perpendicular to the thrust

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

Prefer signal and tag hemisphere definition:

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

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

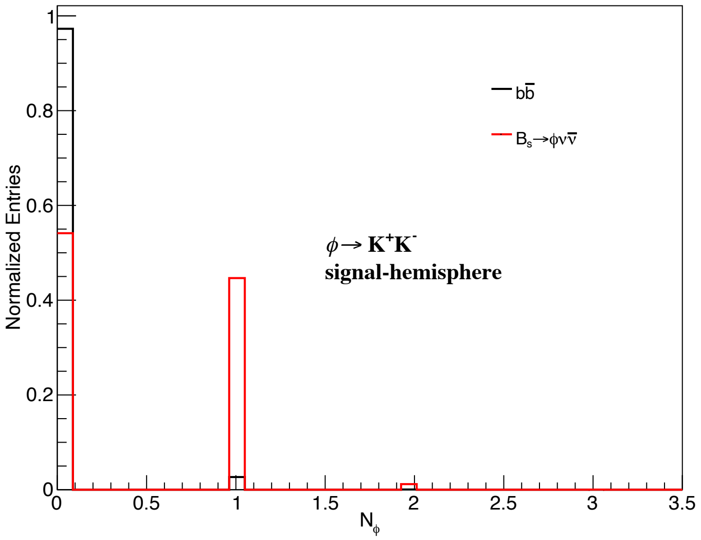


ϕ productions

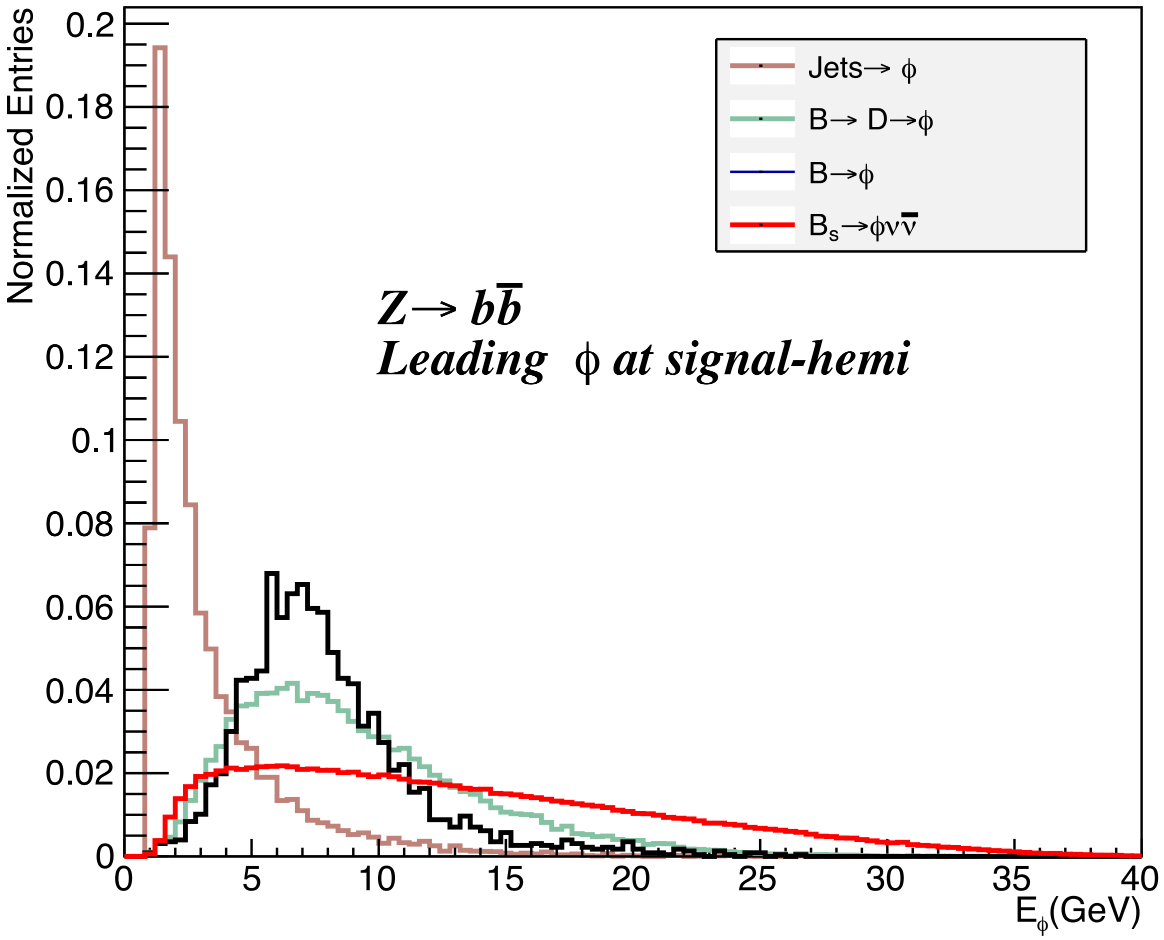
The ϕ production in $Z \to b\bar{b}$ per event.

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:

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

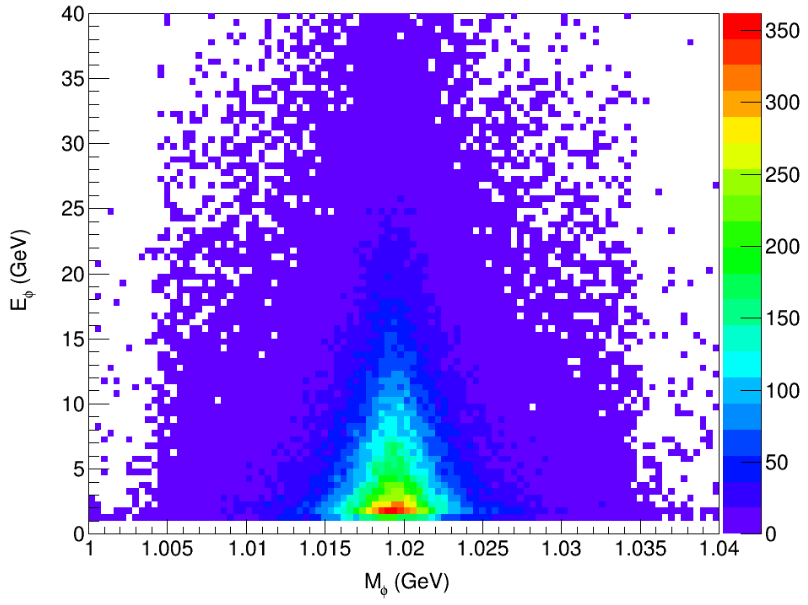
N_{Truth} : The number of truth ϕ, N_{Reco} : The number of reconstructed ϕ, N_{Recos} : The number of successfully reconstructed ϕ.

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

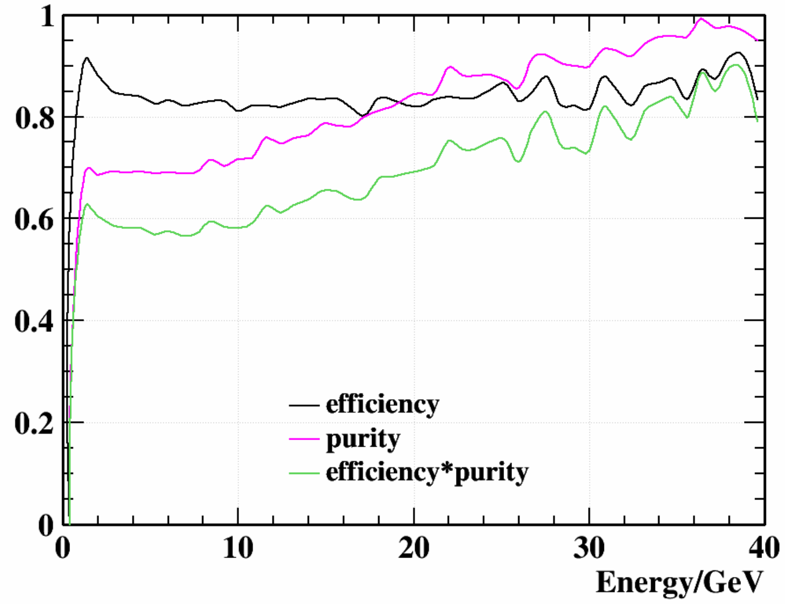
The ϕ reconstructed condition:

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

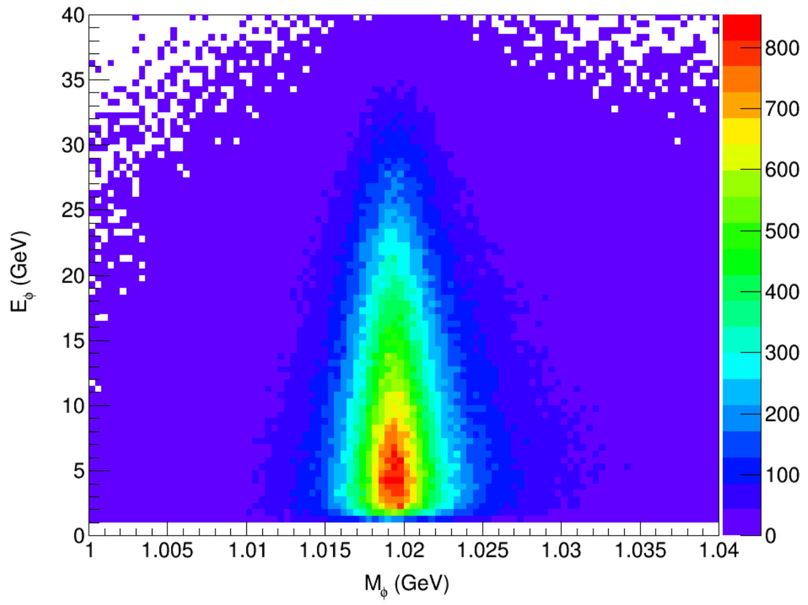
No constrain on impact parameter since small decay length of ϕ.



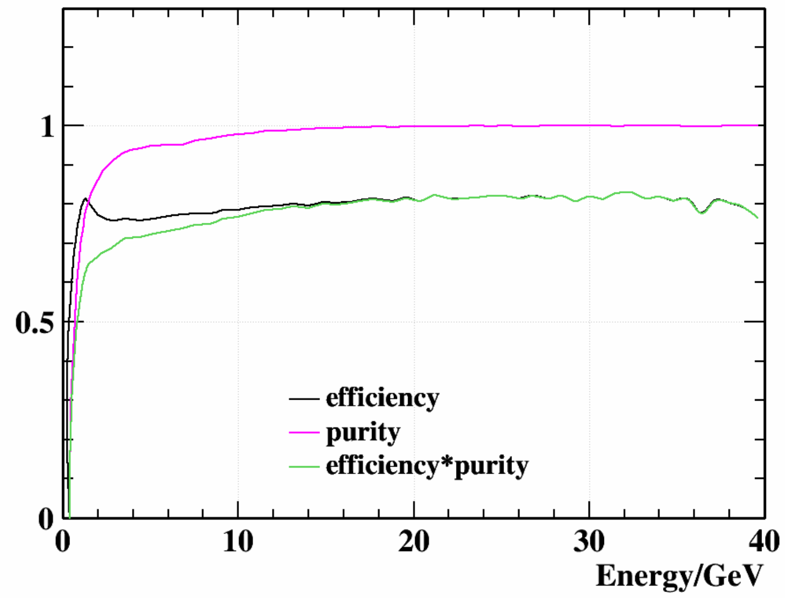
The energy and mass distribution of reconstructed ϕ by K^+K^- pair of $b\bar{b}$ samples. The total efficiency that both the two truth K^+K^- pair have the reconstructed track is 0.907.



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 $Z \rightarrow qq$ sample integrated over the momentum range of 2–20 GeV.

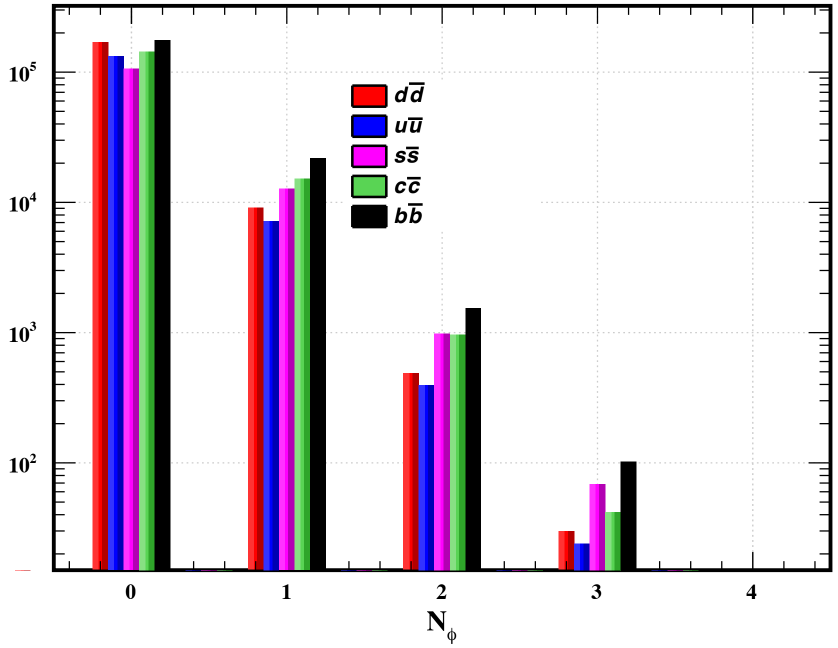


FIG. The number of samples in this figure for each channel is 1.4×10^5. Ratio of ϕ number with more than 3 is be less than 6×10^{-5}.

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

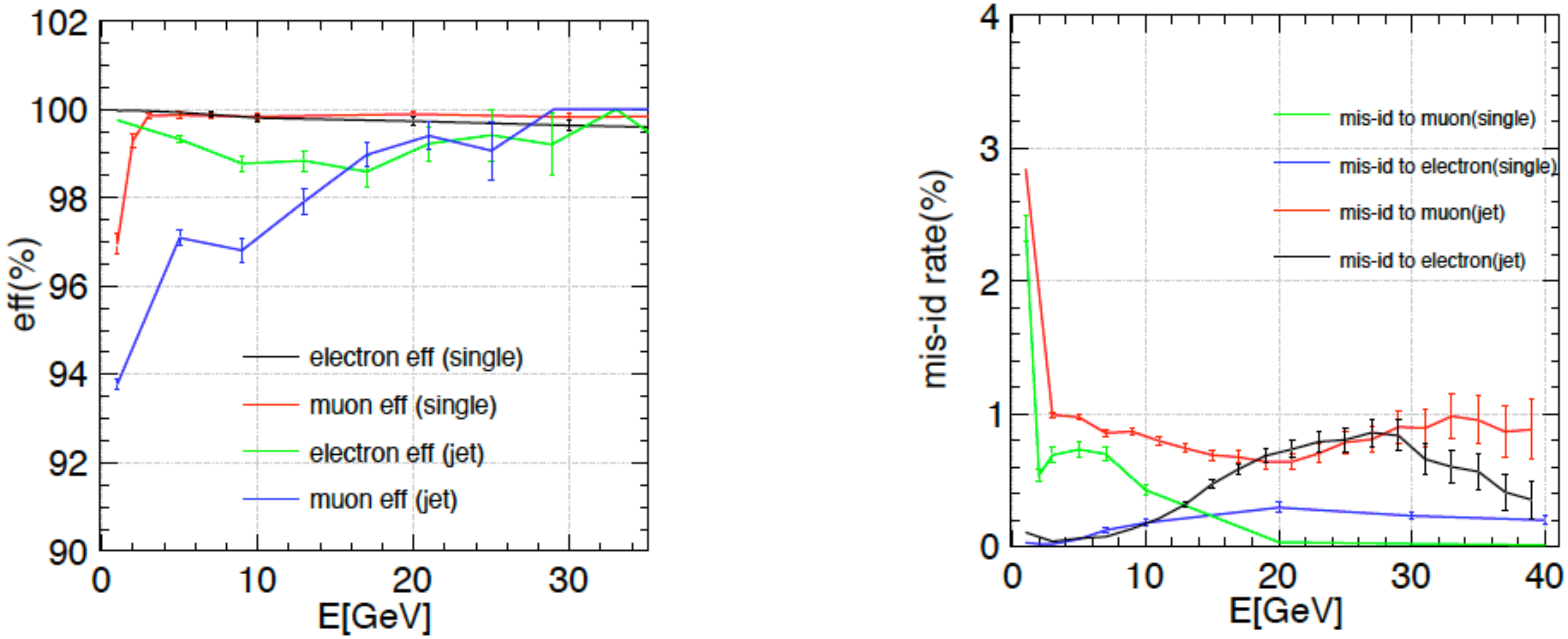
$$9.967 \times 10^5 \ Z \rightarrow bb, b \rightarrow B_s, B_s \rightarrow \phi \nu \nu$$

	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

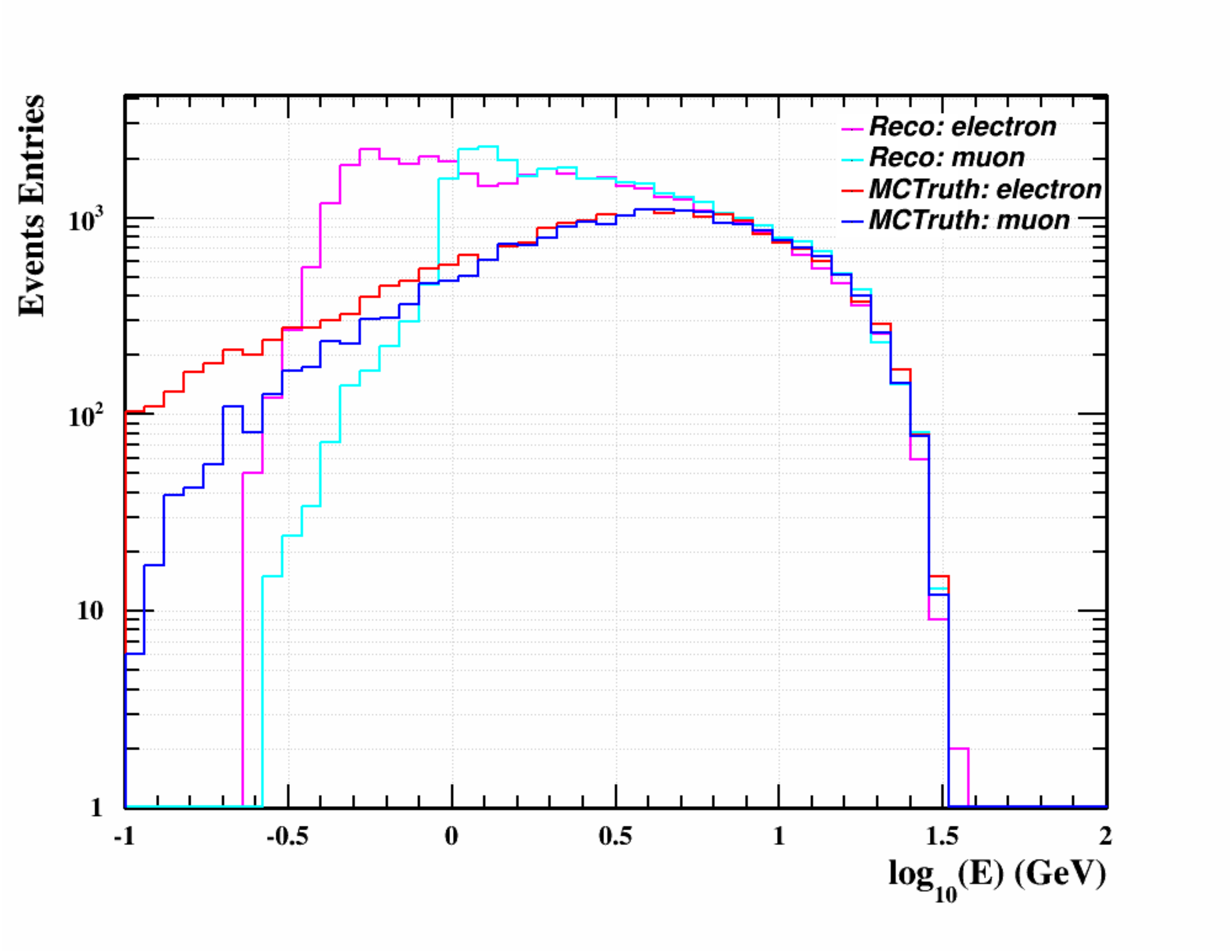
1. In the signal decay, there is no charged lepton (muon or electron) generated in the signal hemisphere.

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.

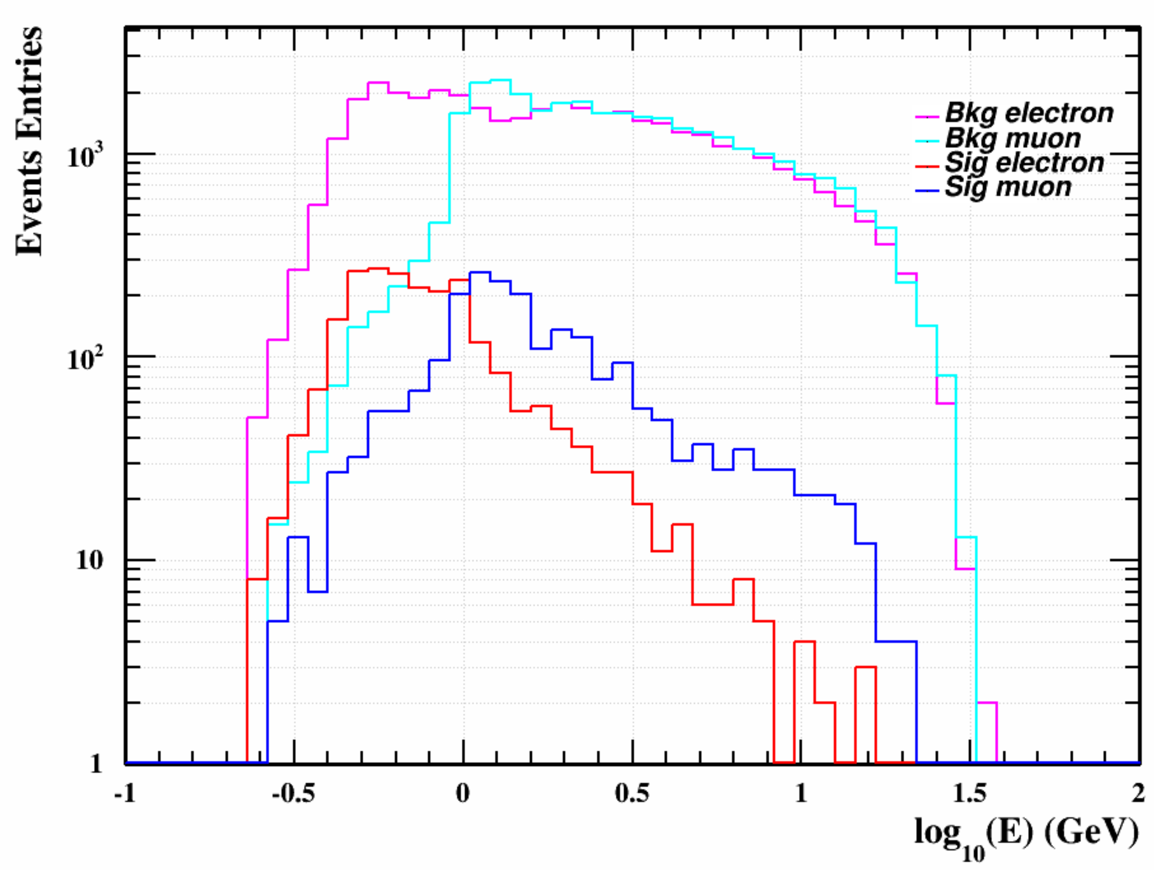


Charged lepton (muon and electron) identify by DanYu.

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

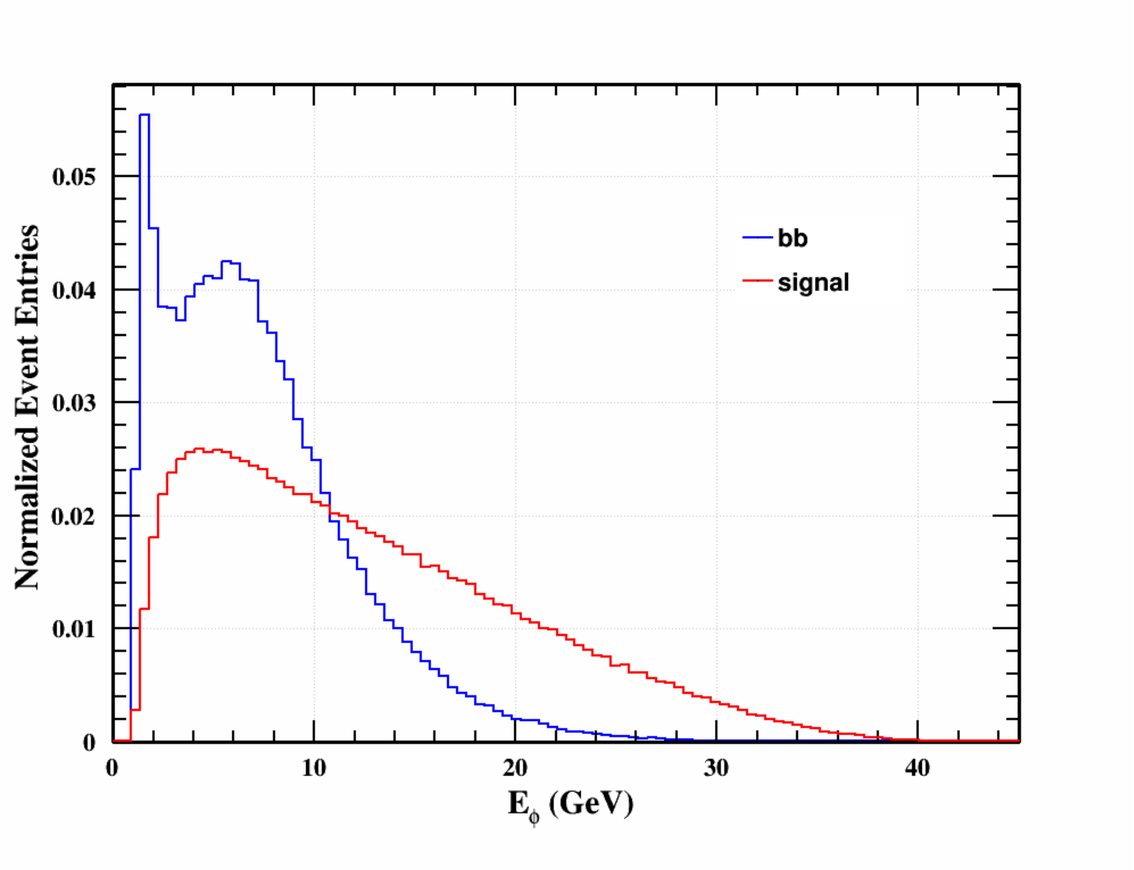


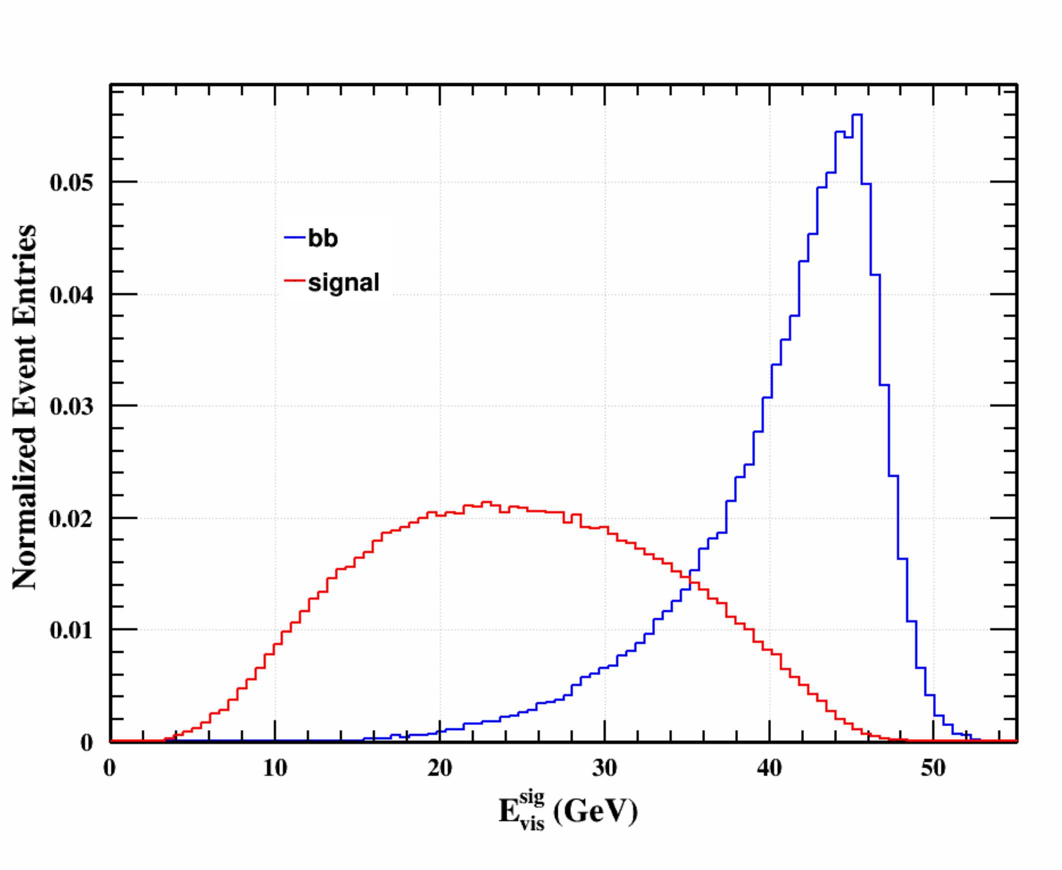
2.6×10^6 $b\bar{b}$ samples. The comparison of reconstructed and truth charged lepton identify. The mis-identify of electron and muon is large in the small energy region.



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





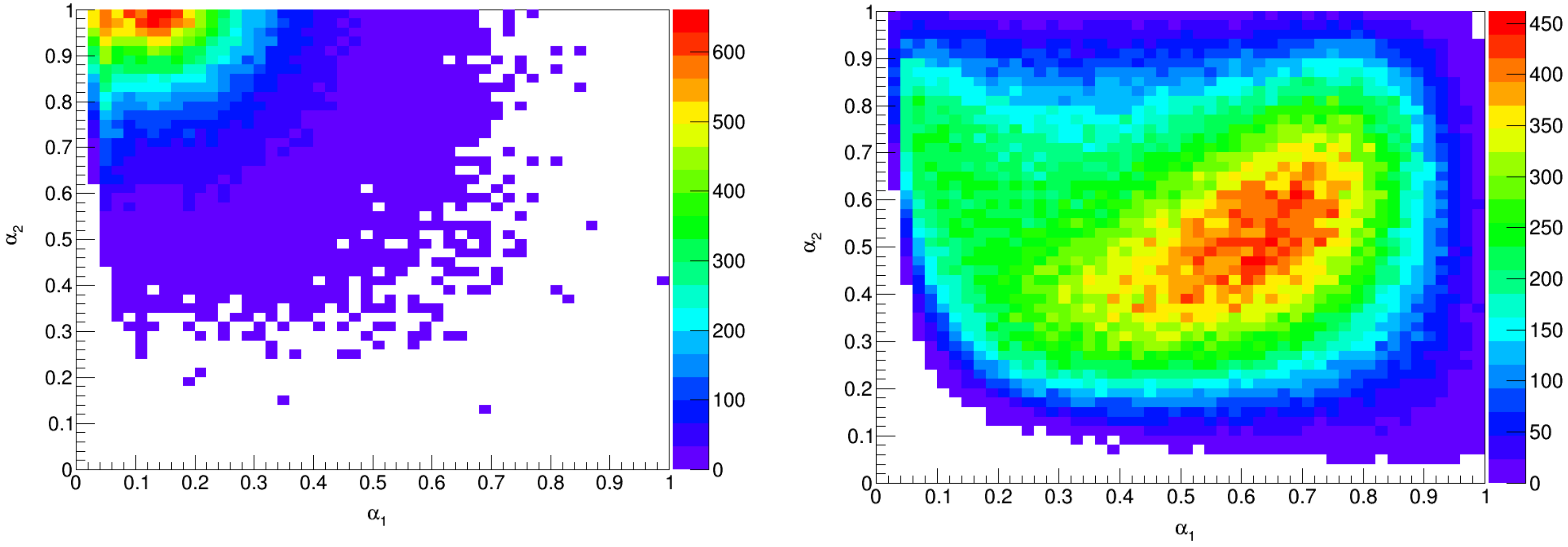
Define the ratio:

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

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

The energy of ϕ for both bb and signal peak at about $5\ \mathrm{GeV}$ 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).

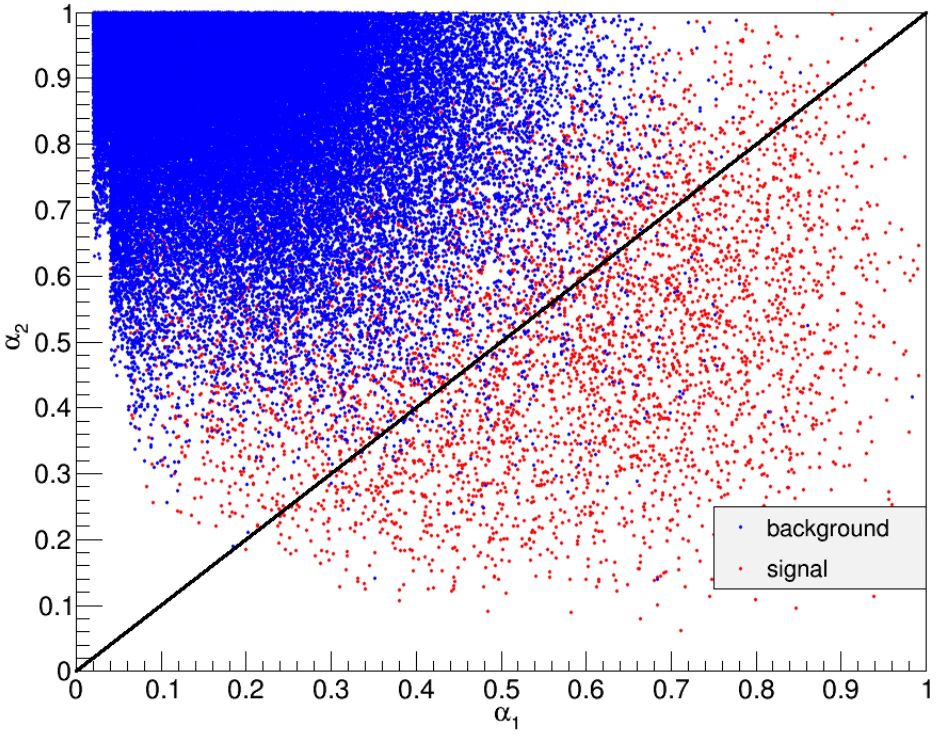


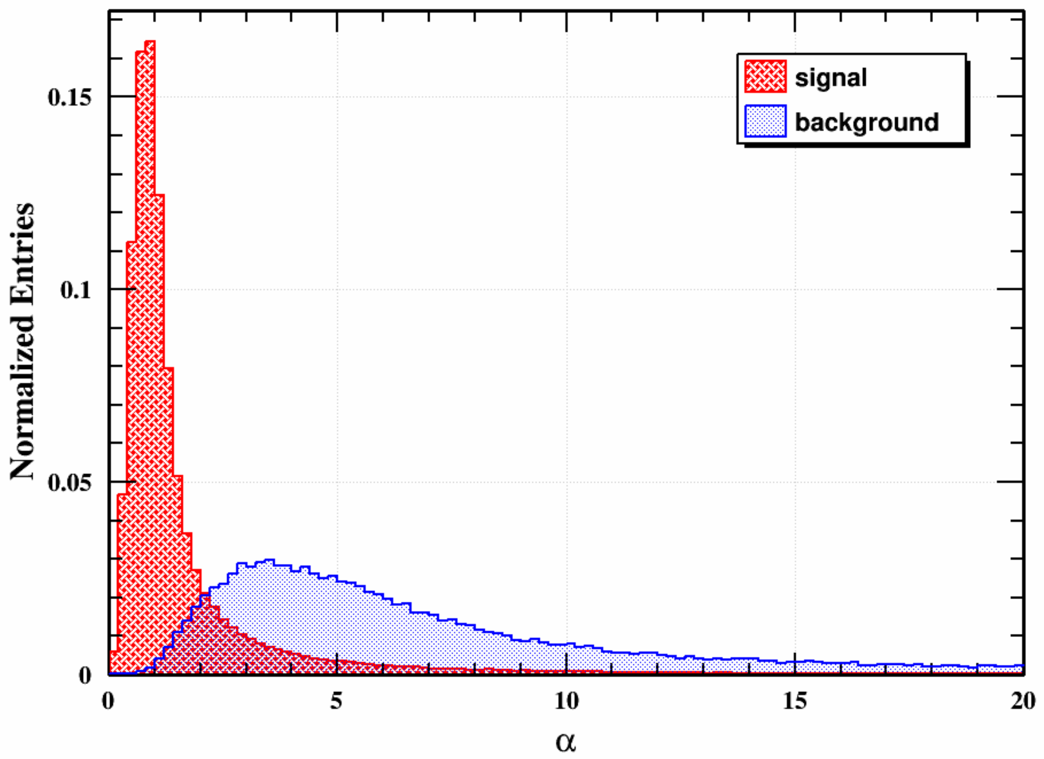
(*a*) (*b*)

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

Future optimization————————-Missing mass algorithm

Then the magnitude of momentum of B_s is obtained by the on-shell condition.

$$\begin{aligned}
&\hat{P}_{B_s} = \hat{V}_{B_s}, \\
&E_{B_s} = E_{beam} - E_{track} - E_{neutral} + E_{\phi}, \\
&|P_{B_s}| = \sqrt{E_{B_s}^2 - M_{B_s}^2}.
\end{aligned} \tag{3}$$

By the four-momentum B_s and ϕ, both the missing energy and mementum can be calculated.

$$\begin{aligned}
&E_{miss} = E_{Bs} - E_{\phi}, \\
&M_{miss} = \sqrt{(p_{Bs} - p_{\phi})^2}.
\end{aligned} \tag{4}$$

$$\begin{aligned}
E_{tag} &= \frac{s + M_{tag}^2 - M_{sig}^2}{2\sqrt{s}}, \\
E_{sig} &= \frac{s + M_{sig}^2 - M_{tag}^2}{2\sqrt{s}},
\end{aligned} \tag{5}$$

Then the missing mass of two signal neutrinos could be got by follow calculations.

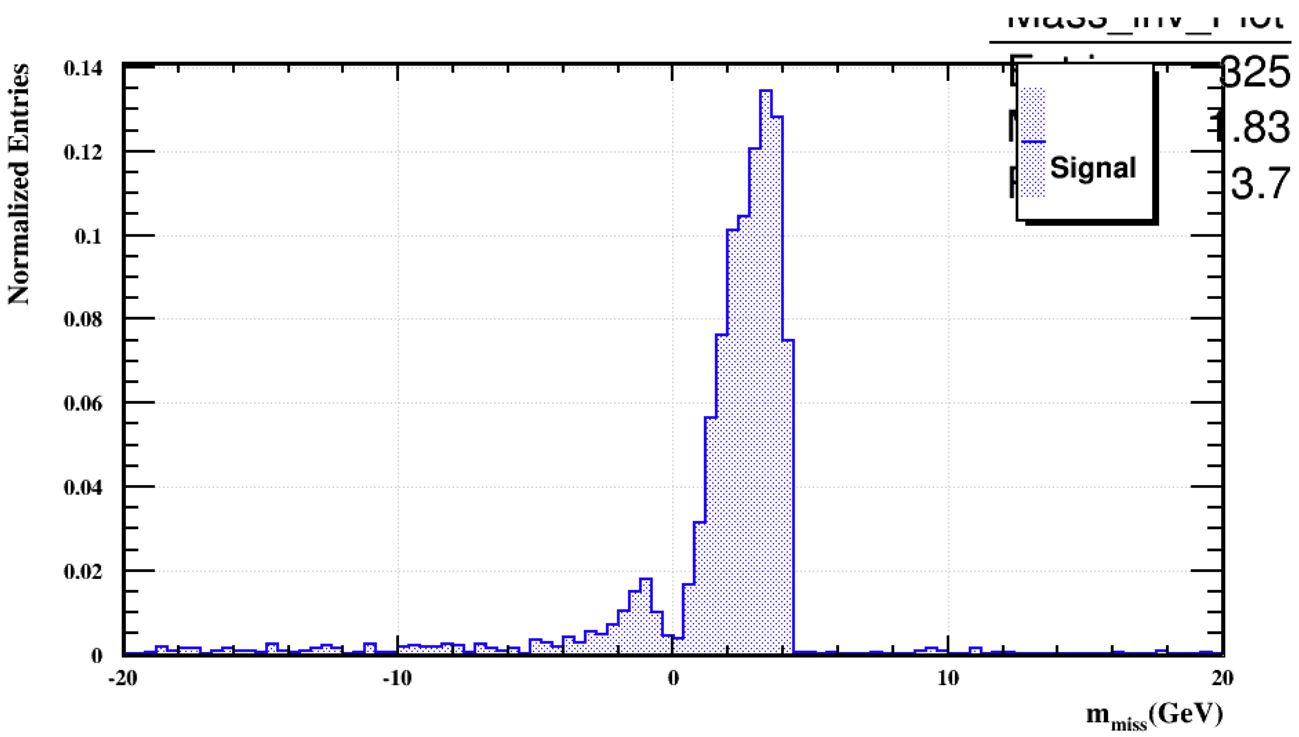
$$\begin{aligned}
M_{tag}^2 &= \left(p_{tag}^{vis}\right)^2 \\
M_{sig}^{total} &= \sqrt{s} - M_{tag} \\
E_{sig}^{total} &= \frac{s + \left(M_{sig}^{total}\right)^2 - M_{tag}^2}{2\sqrt{s}}
\end{aligned} \tag{6}$$

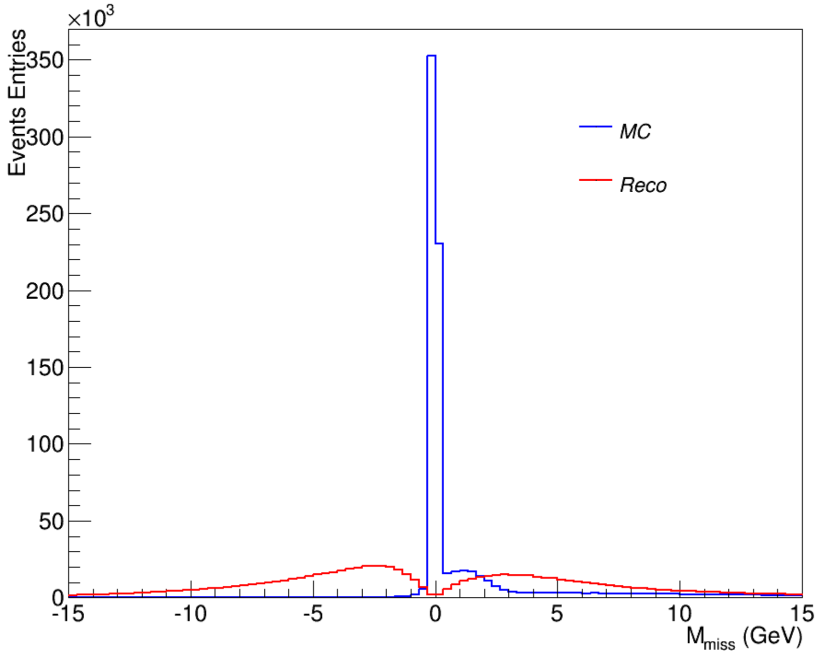
Then replace the E_{beam} in Eq. 3 by E_{sig}^{total}.

Anyway, another method can be test as follows.

$$\begin{aligned}
M_{sig}^{vis} &= \left(p_{sig}^{vis}\right)^2 \\
M_{miss} &= M_{sig}^{total} - M_{sig}^{vis}
\end{aligned} \tag{7}$$

where $\sqrt{s} = 2E_{beam}$ is the center-of-mass energy.





End

Thanks