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

2021 – 04 – 15

The SnowMass Group:
Yudong Wang, Lingfeng Li, Manqi Ruan, Yanyun Duan, Tao Liu, Taifan Zheng

Outline

1. Introduction and Motivation
2. Signal and background
3. Reconstruction of ϕ
4. Events analysis
5. Results and conclusion

Motivation

- Investigation of flavor-changing-neutral current decays is of fundamental interest and are widely recognized as important flavor probes
- Large luminosity and advantage on the τ, B_s, B_c, $\Lambda_b \dots$ measurements the missing final state rare decay by full reconstruction
- Free from strong interaction effects and not affected by non-factorizable corrections thus theoretically cleaner compared to $b \to s\ell\ell$ transitions (exist multiple anomalies)
- Observation of this decay could test the SM prediction precisely and provide opportunity to explore new physics.
- Performance the benchmark of simulation and reconstruction at CEPC detector, such as charged lepton identify, $\phi(1020) \to K^+K^-$ reconstruction, energy resolution and missing energy, mass.

Luminosity and Statistics

CEPC scheme

operation mode	Z factory	WW threshold scan	Higgs factory
center-of-mass energy (GeV)	91.2	160	240
running time (yeas)	2	1	7
L (10^{34}cm^{-2}s^{-1})	32	10	3
intergrated luminosity (ab^{-1})	16	2.6	5.6
Higgs yield	-	-	10^6
W yield	-	10^7	10^8
Z yield	10^{12}	10^8	10^8

Provides unique opportunities for various flavor measurements

$Z \to b\bar{b}$: ~1.5×10^{11}

$Z \to c\bar{c}$: ~1.2×10^{11}

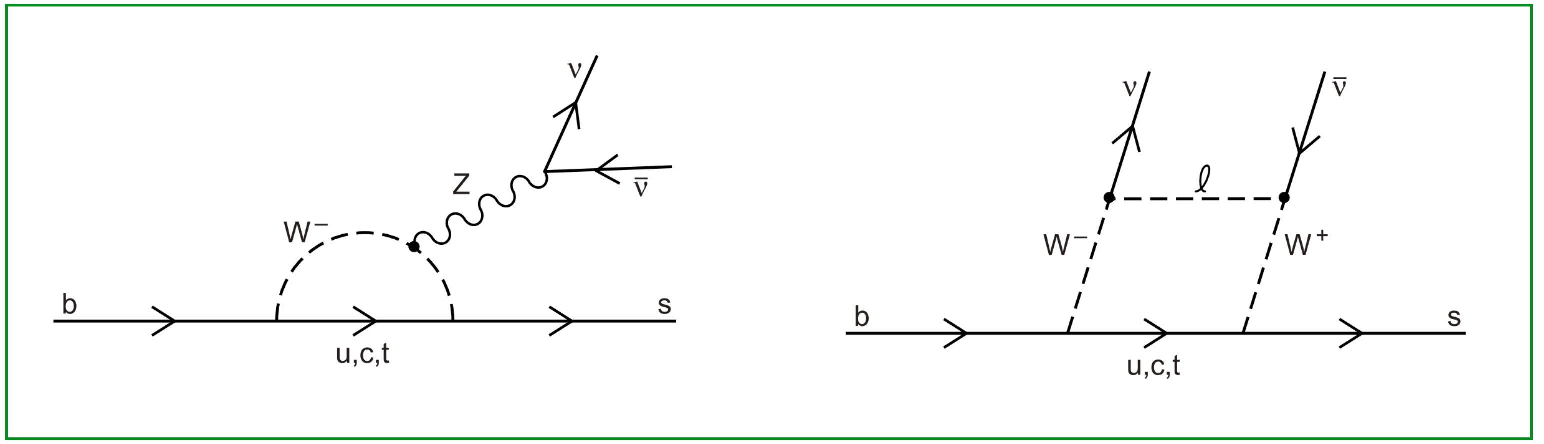
$Z \to \tau^+\tau^-$: ~3.37×10^{10}

Huge B flavor physics potential of Tera-Z, especially B_s , B_c and Λ_b $\cdots$

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}

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

The decay rates for each exclusive channel by SM ranges from $10^{-6} \sim 10^{-5}$.



- Difficulty on the experiment

  Direct measurement on $\nu\bar{\nu}$ is difficult

  Need the full reconstruction technique

  Large luminosity

  PFA algorithm at CEPC

- Main experiments attempted at B factory

  None have been found

- The precise measurement are expected in the future e^+e^- collider

$(9.94 \pm 0.75) \times 10^{-6}$ calculated by LingFeng with updated form factor

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

DELPHI : No update since 1996

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

The effective Hamiltonian for $b \to s\nu\bar{\nu}$ transitions in the SM reads

$$\mathcal{H}_{\text{eff}}^{\text{SM}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* C_L^{\text{SM}} \mathcal{O}_L \; + \; \text{h.c.}\,,$$

Beyond the SM, a second operator can appear in the effective low-energy Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left(C_L \mathcal{O}_L + C_R \mathcal{O}_R\right) \; + \; \text{h.c.}\,,$$

$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,, \qquad \mathcal{O}_R = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)\,.$$

The relation of BSM and SM for inclusive branch could be expressed as

$$\text{BR}(B \to X_s\nu\bar{\nu}) \approx \text{BR}(B \to X_s\nu\bar{\nu})_{\text{SM}} \cdot F(C_L, C_R)$$

$$\text{BR}(B \to X_s\nu\bar{\nu})_{\text{SM}} = (2.9 \pm 0.3) \times 10^{-5}\,.$$

New physics contribution will be constrained via the this relation

1.Buras, A. J., Girrbach-Noe, J., Niehoff, C. & Straub, D. M. B→K∗νν¯ decays in the Standard Model and beyond. *J High Energy Phys* **2015**, 184 (2015).

The Signal Topology

Number of signal decay by SM prediction at CEPC :

$$N(B_s \to \phi(K^+K^-)\nu\bar{\nu}) \sim 1.8 \times 10^5 \times 0.492$$

Branch of $B_0 \to \phi\nu\nu$ is much smaller than $B_s \to \phi\nu\nu$ and thus free of the B_0 influence.

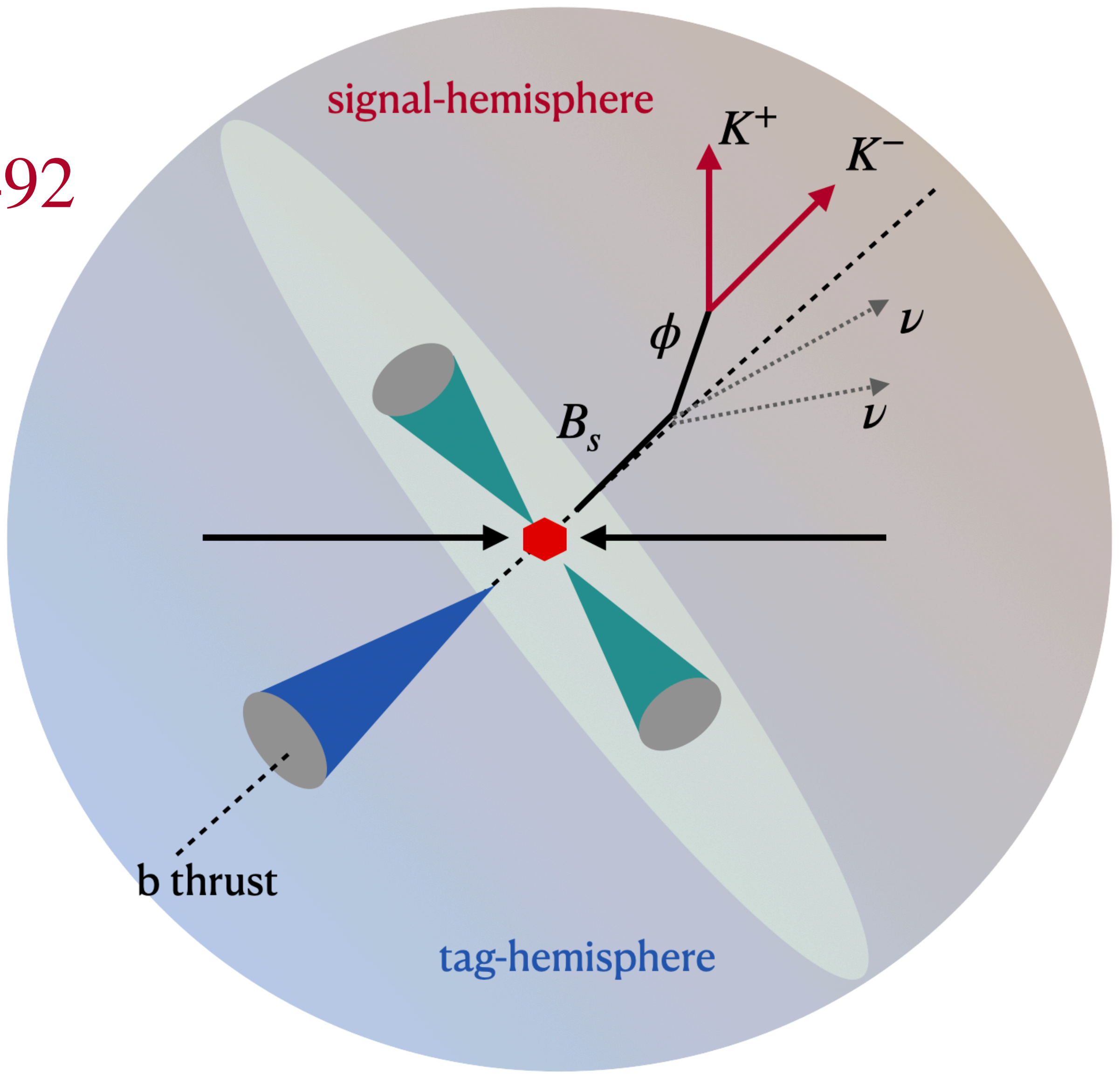
Signal ϕ reconstruction:

$\phi \to K^+K^-$ (49.2%)

Signal samples:

10^6 signal events by Pythia8 with EvtGen

$$e^+e^- \to Z \to b\bar{b}, \bar{b} \to B_sX, B_s \to \phi\nu\bar{\nu}$$

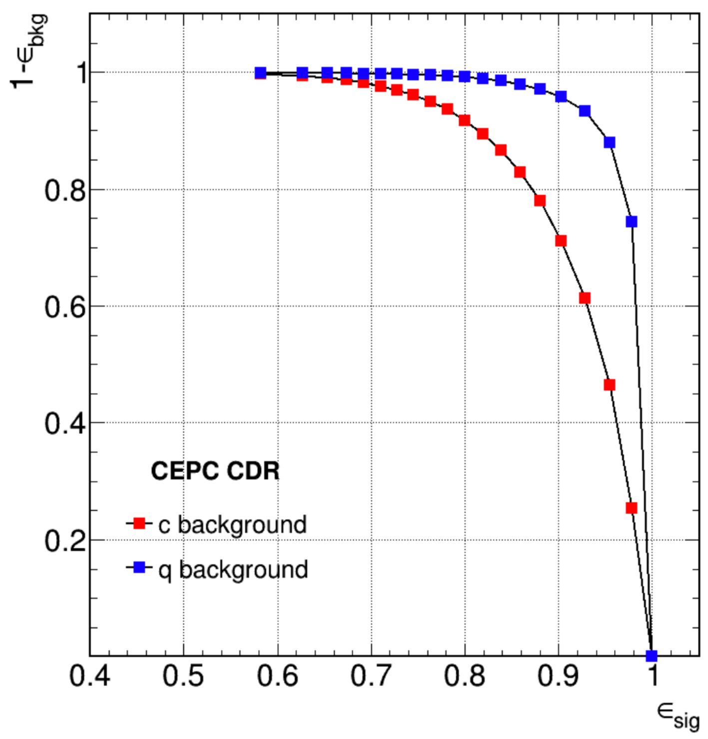


The Background

Generator : CEPC official - whizard-1.9.5

General background

- The $q\bar{q}$ events especially the heavy-flavor $b\bar{b}$ and $c\bar{c}$
- $10^6 \sim 10^7$ full simulation samples for each channel



> 99 % Light-flavor are suppressed by flavor tagging

Main background

- The semi-leptonic decay of $B^{(*)}$ or $D^{(*)}$ decay

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

- One or more ϕ produced and decay to K^+K^- pair
- Significant missing energy
- Full simulation samples generated corresponding to ~3×10^8 for each heavy-flavor channel

At CEPC, with 1.5×10^{11} $b\bar{b}$ events, the expected advance?

- More than 5 higher order magnitude of luminosity than current limit (2.844×10^6 $e^+e^- \to Z$)
- At least 2-3 order optimization for the branch limit
- Test the SM prediction precisely

ϕ reconstruction

Reconstruct the decay $\phi(1020) \to K^+K^-$

Method in reconstruct K_S and Λ by TaiFan

Zheng, T., Wang, J., Shen, Y., Cheung, Y.-K. E. & Ruan, M. Reconstructing KS0 and Λ in the CEPC baseline detector. *European Phys J Plus* **135**, 274 (2020).

- Lose ~50% signal decay inevitable
- Take pairs of oppositely charged tracks in the jet chamber
- Assuming both tracks to be Kaons (No Kaon PID yet)
- Employ the kinematic fit package for ILC to reconstruct the secondary vertex

Suehara, T. & Tanabe, T. LCFIPlus: A framework for jet analysis in linear collider studies. *Nucl Instruments Methods Phys Res Sect Accel Spectrometers Detect Assoc Equip* **808**, 109–116 (2016).

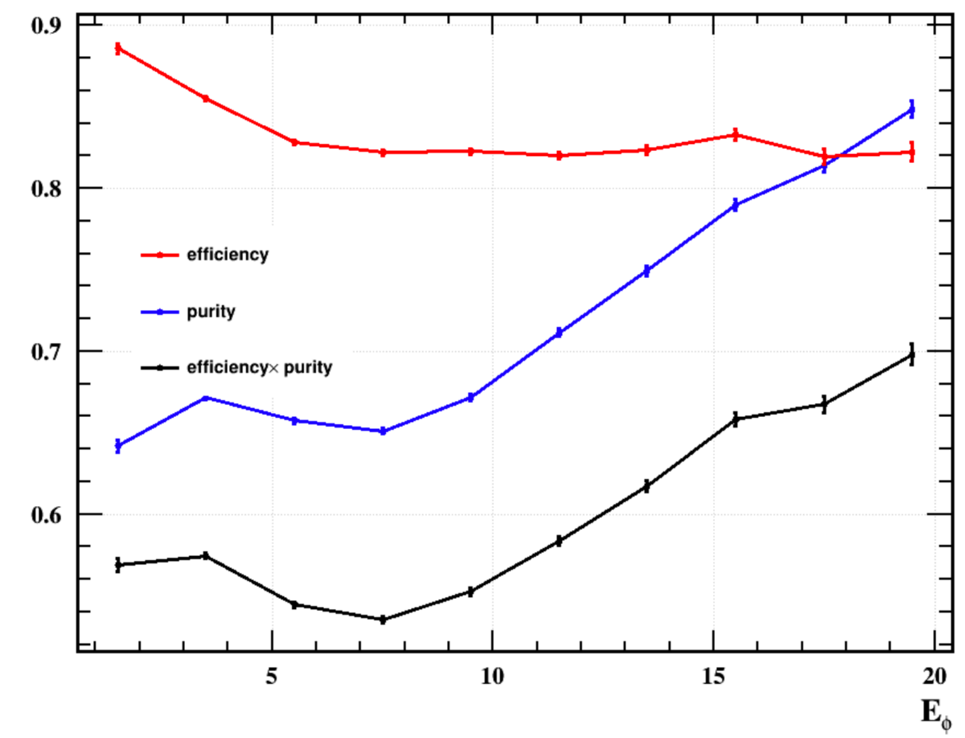
- Form their invariant mass

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

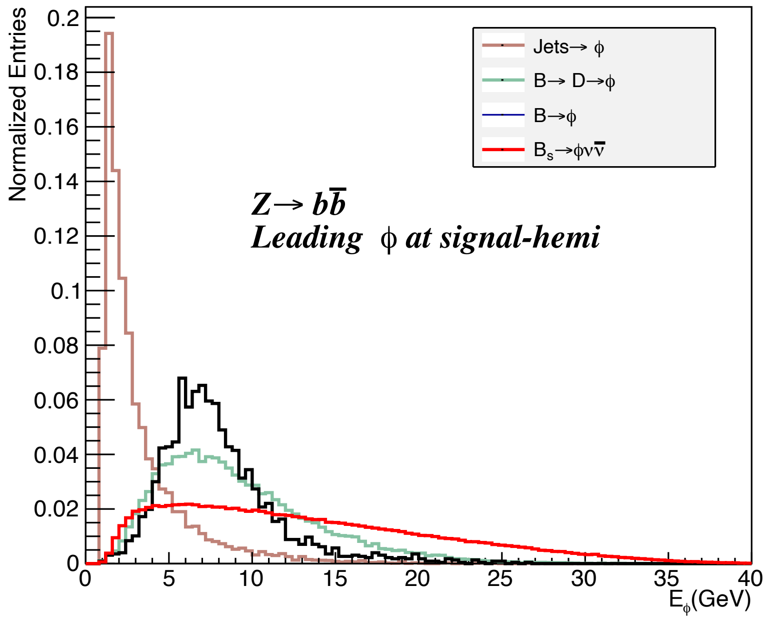
The ϕ reconstruction efficiency and purity for general background

$$\epsilon = \frac{\text{Number of correctly selected track pair candidates}}{\text{Number of } \phi \to K^+K^- \text{ events}}$$

$$p = \frac{\text{Number of correctly selected track pair candidates}}{\text{Number of selected track pair candidates}}$$

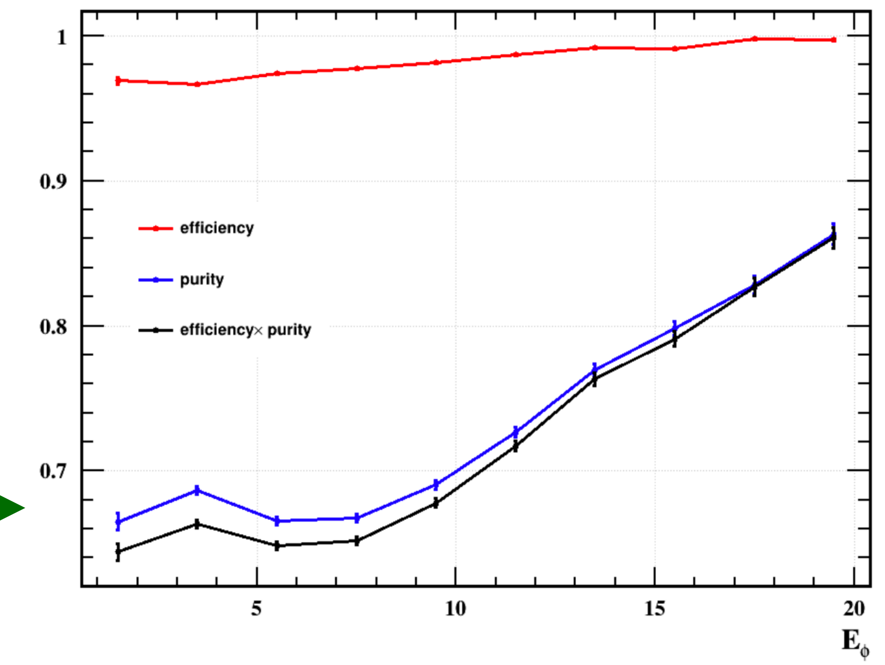


ϕ reconstruction



In the $B_s \to \phi \nu \bar{\nu}$ analysis

- ϕ in signal-hemisphere
- Leading energy one

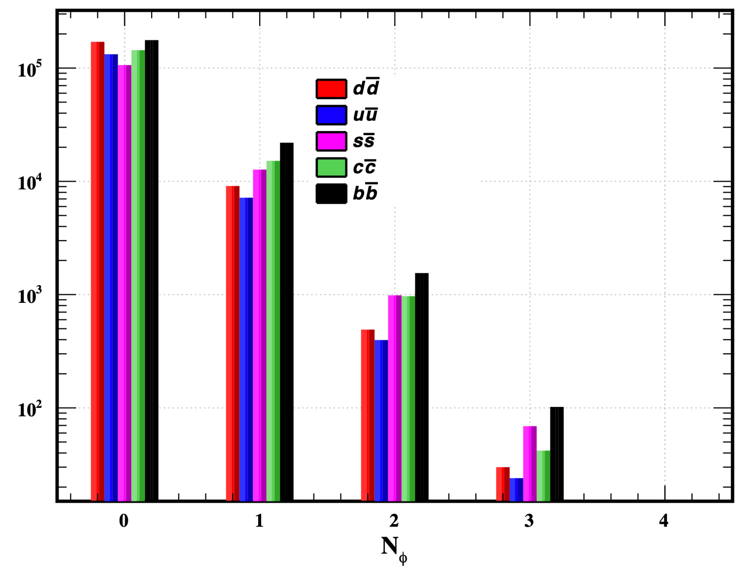


- Integrated efficiency and purity

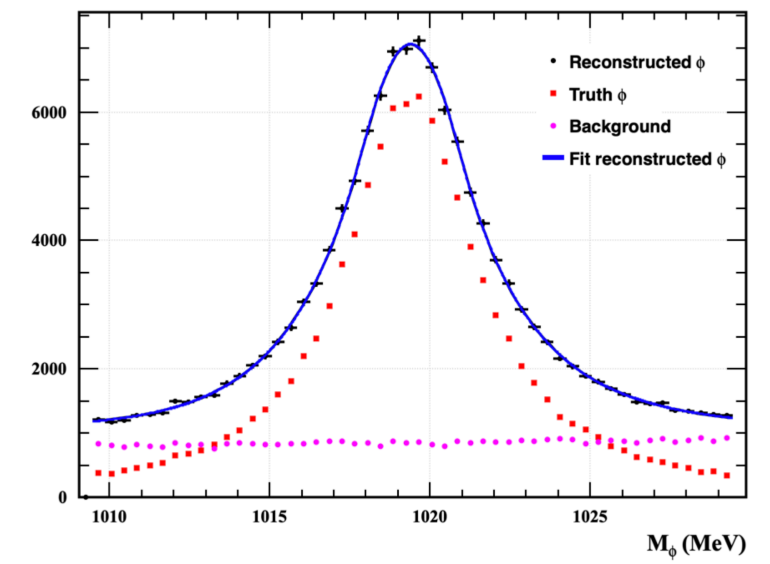
0.9790 and 0.7062

By ϕ with track pair decay in signal-sphere, background are suppressed by about 1/40

Potential optimization space for purity by Kaon PID (~15 % less background could be left in the last results)



Number of ϕ distributions for each channel



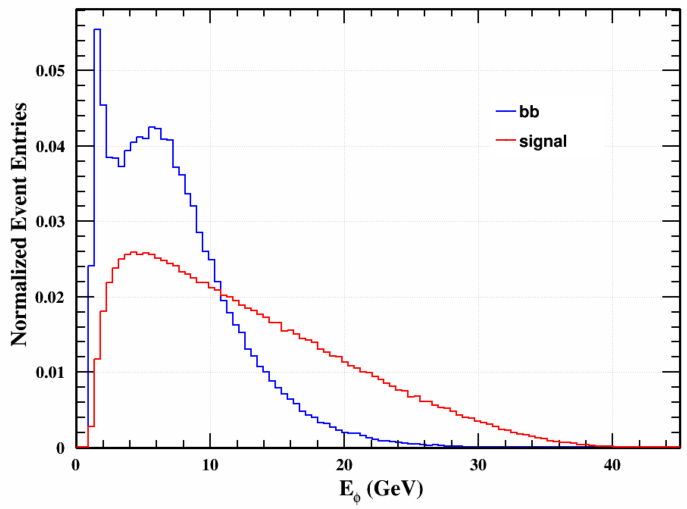
Mass distribution of reconstructed ϕ

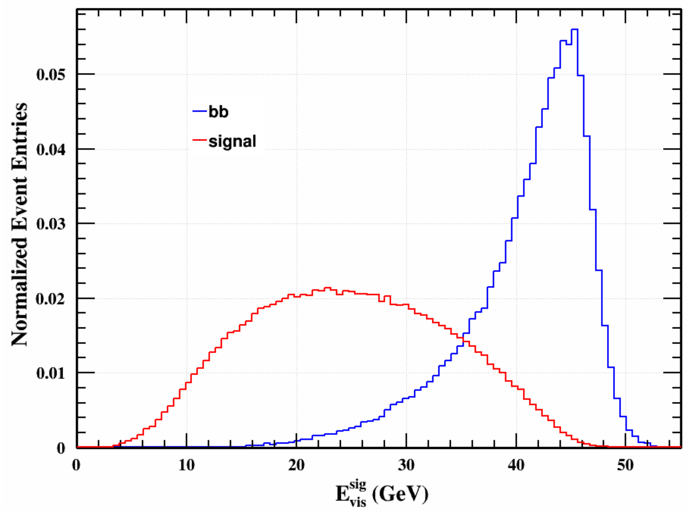
Events Analysis By ϕ

Now, we have a leading ϕ with its momentum and vertex

Define the scaleless variables $\alpha_1 = \frac{E_\phi}{E^{sig}_{vis}}$ and $\alpha_2 = \frac{E^{sig}_{vis}}{E_{beam}}$

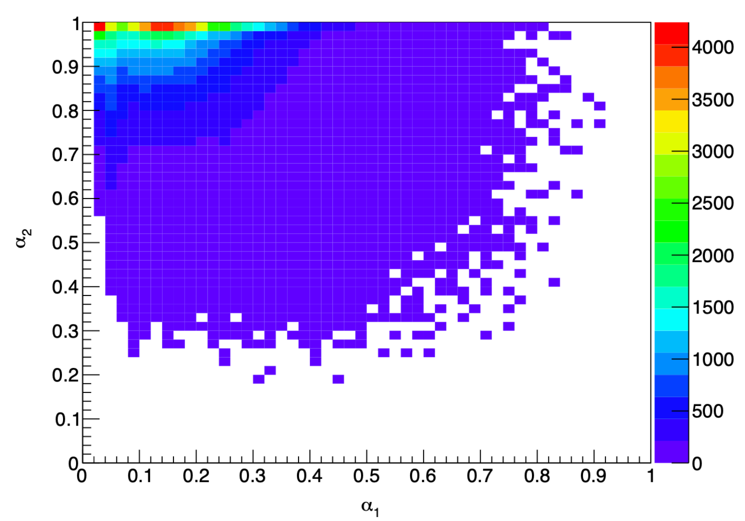
E^{sig}_{vis} is the energy of signal-hemisphere and $E_{beam} = 45.6$ GeV



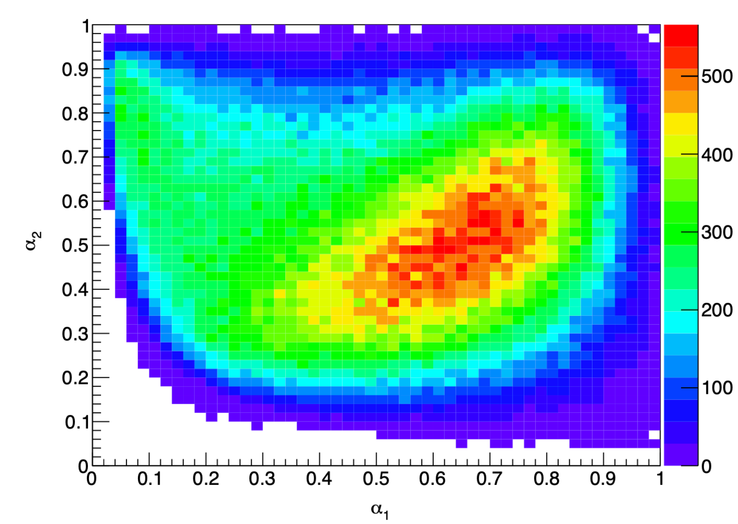


α_1 and α_2 show the strong correlation via missing energy, signal-hemi energy and ϕ energy.

Significant difference of $\alpha_2 - \alpha_1$ distribution for background and signal events.

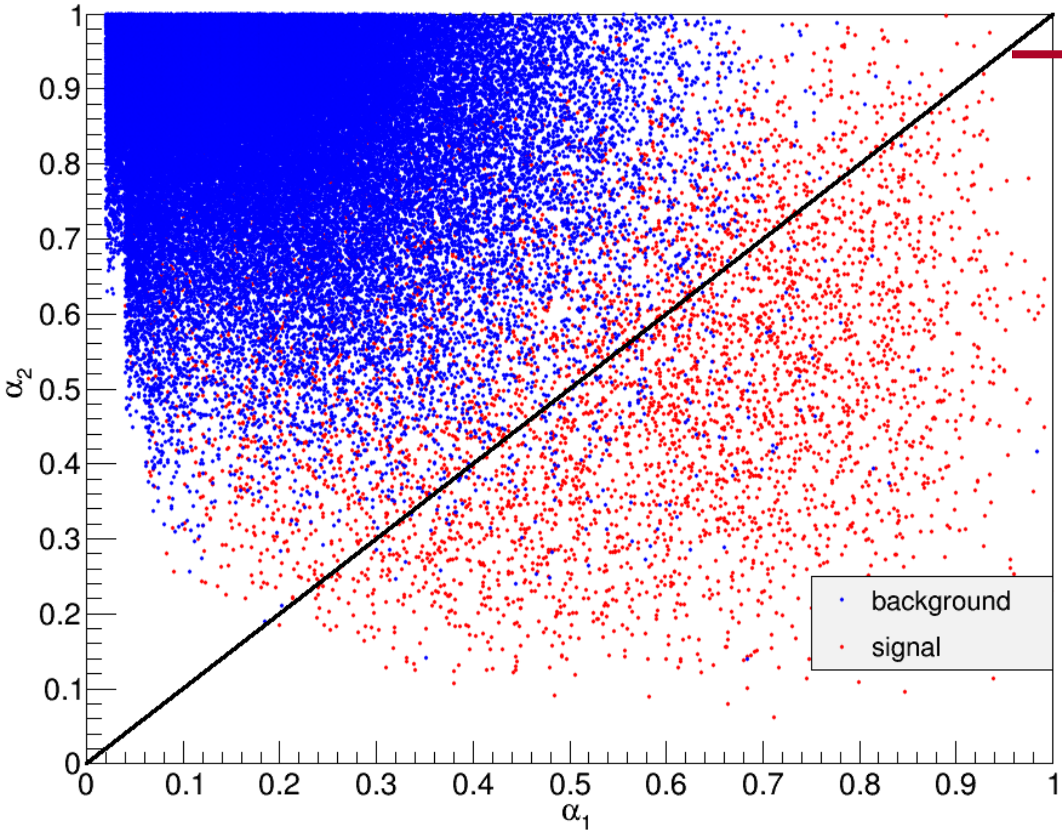


$b\bar{b}$ background



Signal events

Events Analysis By ϕ



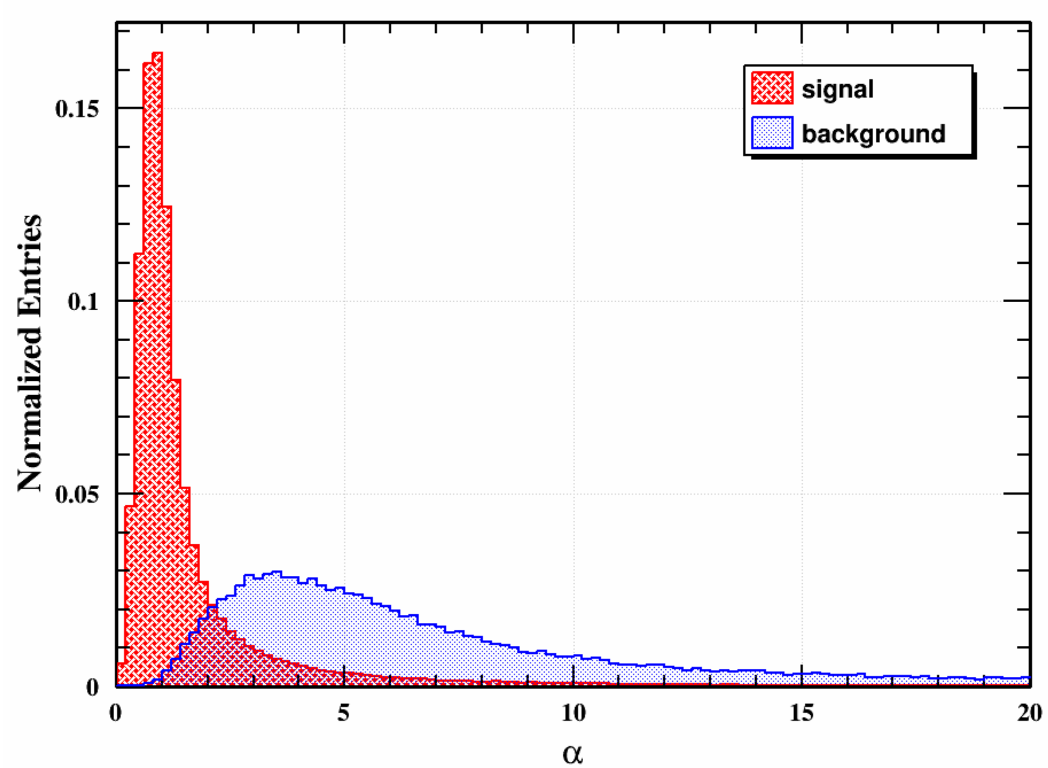
Loose boundary defined by

$$\alpha = \frac{\alpha_2}{\alpha_1} = \frac{(E_{vis}^{sig})^2}{E_\phi \cdot E_{beam}} = 1.0$$

The accuracy of α depend on the energy resolution (about 4 % in CEPC baseline full simulation)

Mostly background (more than 99 %) could be rejected

Amount of remain background still be large compared to signal



Analysis of $\nu\bar{\nu}$ System

Indirect measurement by the full reconstruction

- The general total energy (missing energy) in the whole events

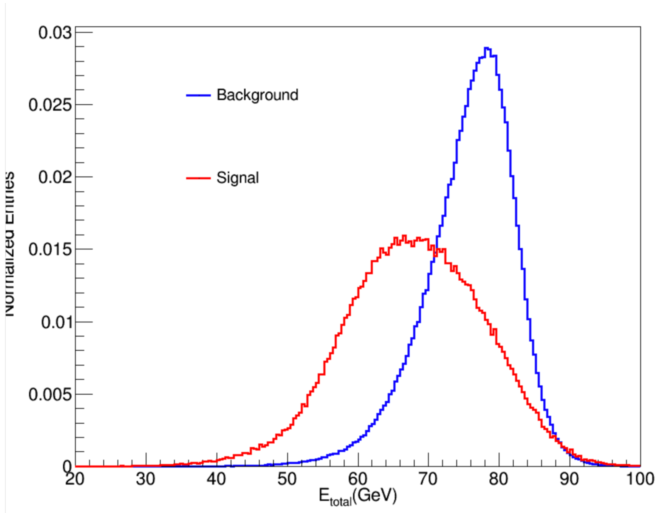
- Where missing energy come from.

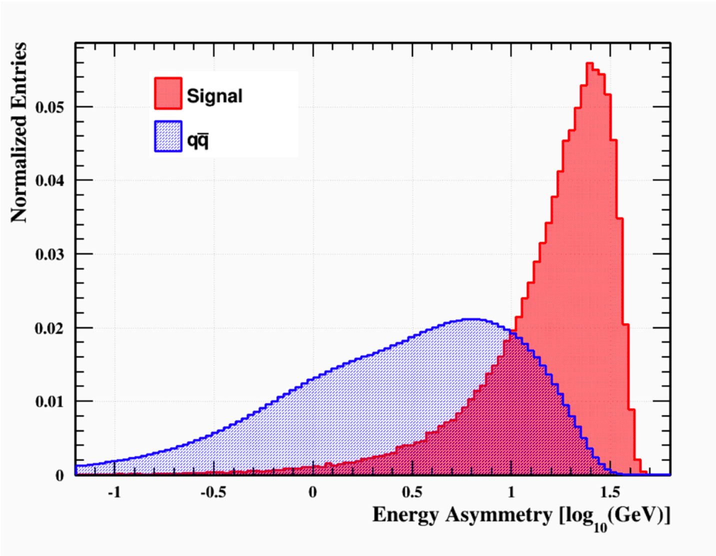
a). In the signal hemishphere, weather the missing energy count for mostly energy except ϕ. ($\alpha_1 = E_\phi / E_{sig}$)

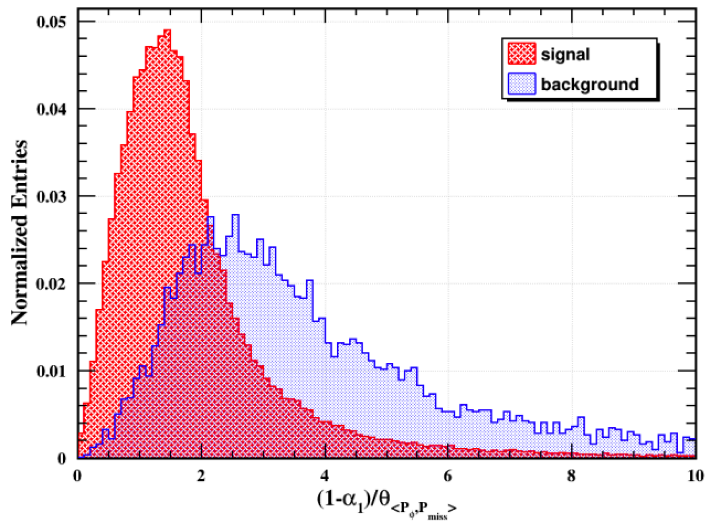
b). Weather the missing energy come from the signal-hemisphere. ($\alpha_2 = E_{sig}/E_{beam}$ and $E_{asymmetry}$)

c). The possibility that missing energy come from the same mother particle as ϕ i.e. $(1-\alpha_1)/\theta_{<P_\phi,P_{miss}>}$

d). An algorithm to get the signal energy of B_s and mass of $\nu\bar{\nu}$







Samples satisfy $N_\phi > 0$, $E_\ell < 1$ GeV and $\alpha < 1.0$

Analysis of $\nu\bar{\nu}$ System

An algorithm for correctional signal B_s energy and invariant mass of $\nu\bar{\nu}$

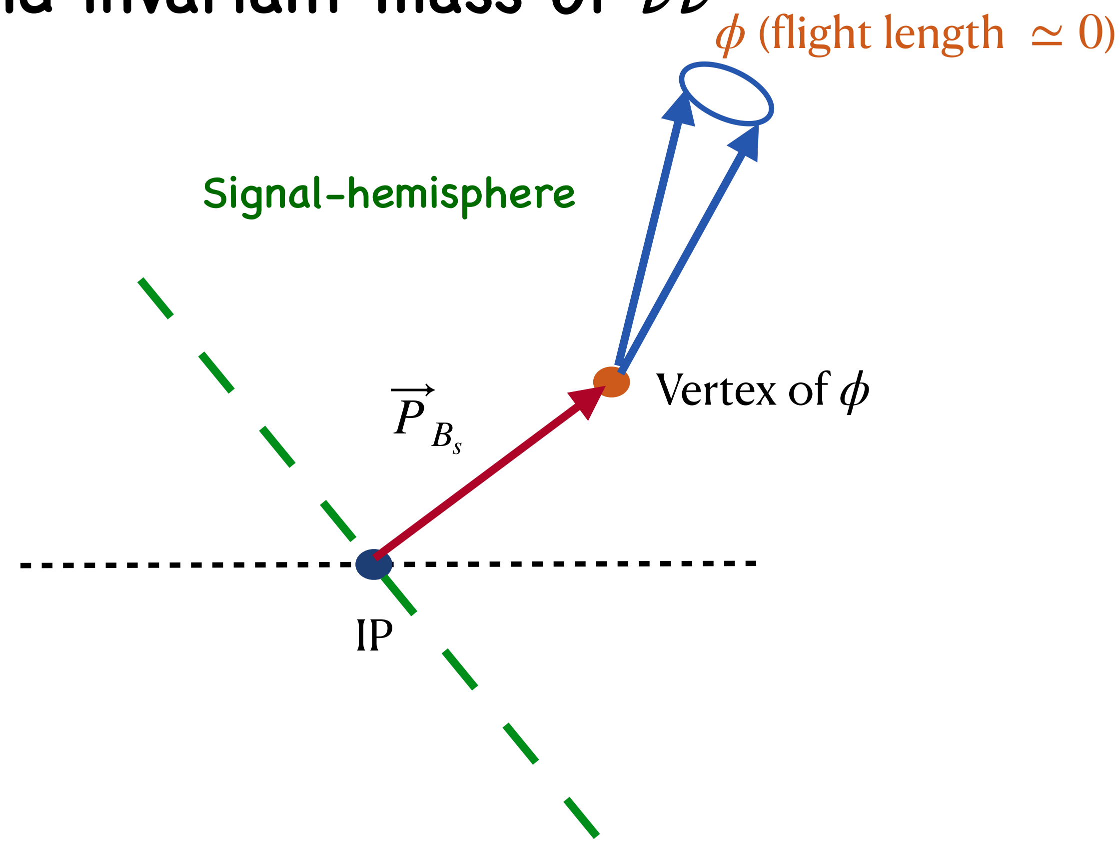
(Proposed by LingFeng based their work)

$$\hat{P}_{B_s} = \hat{V}_{B_s}(\hat{P}_{B_s} = \hat{P}_\phi \text{ if } |V_\phi| < 0.02\text{mm}),$$

$$E_{B_s} = E_{beam} - E_{track} - E_{neutral} + E_\phi,$$

$$|P_{B_s}| = \sqrt{E_{B_s}^2 - M_{B_s}^2}, \longrightarrow 5.367 \text{ GeV}$$

$$M_{\nu\nu} = \sqrt{(p_{Bs} - p_\phi)^2}(\text{or} - \sqrt{-(p_{Bs} - p_\phi)^2})$$



Best choice : Fit the signal B_s mass

- No good method to fit by the only ϕ information
- No good resolution for missing momentum v.s. $\nu\nu$ momentum

Alternative way :

- Use the truth B_s mass to deduce other variables in this algorithm

$$M_{tag} = \sqrt{\left(\sum p_{tag}^{track} + \sum p_{tag}^{neutral}\right)^2},$$

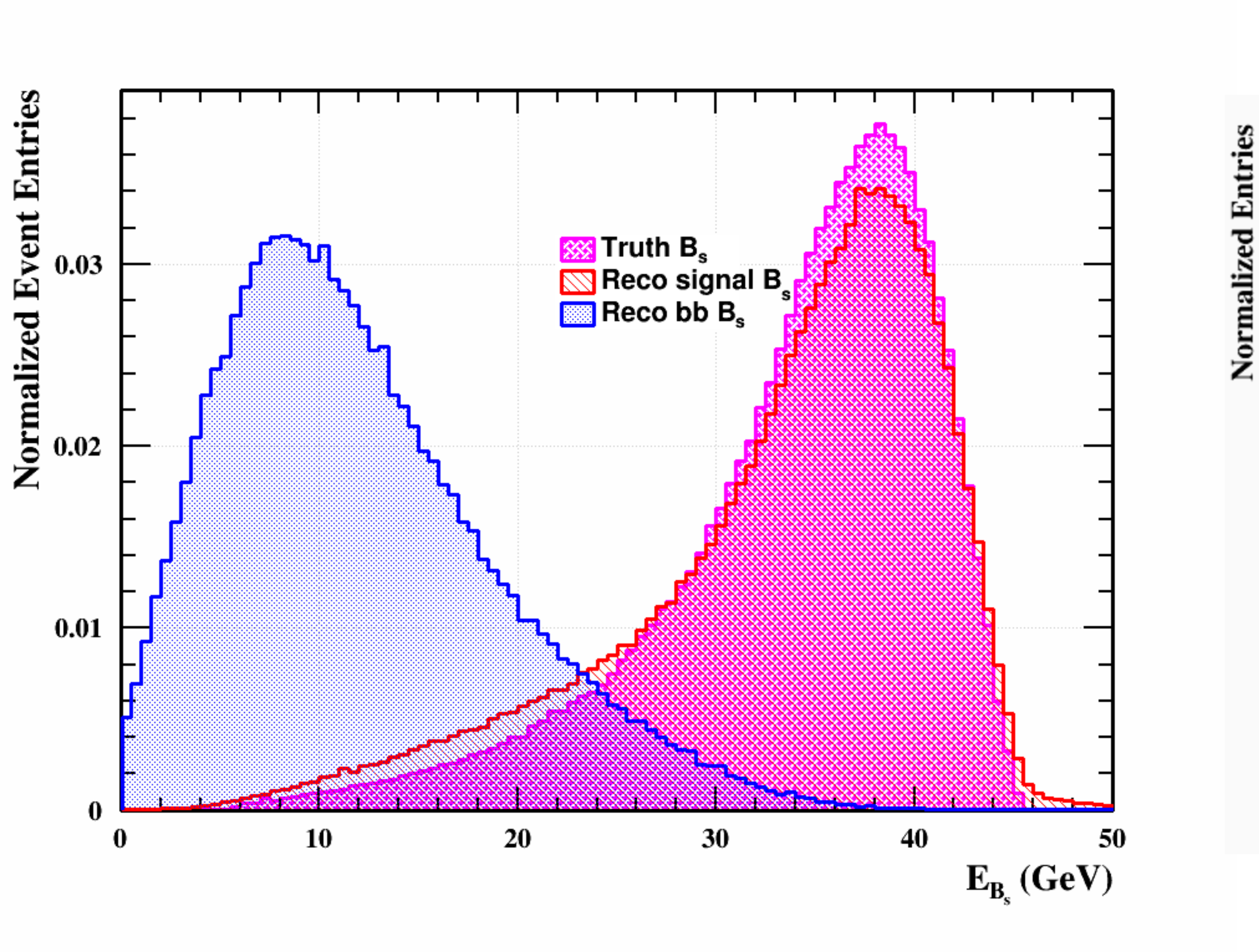
$$M_{sig} = \sqrt{\left(\sum p_{sig}^{nuetral} + \sum p_{sig}^{track} + p_{B_s} - p_\phi\right)^2},$$

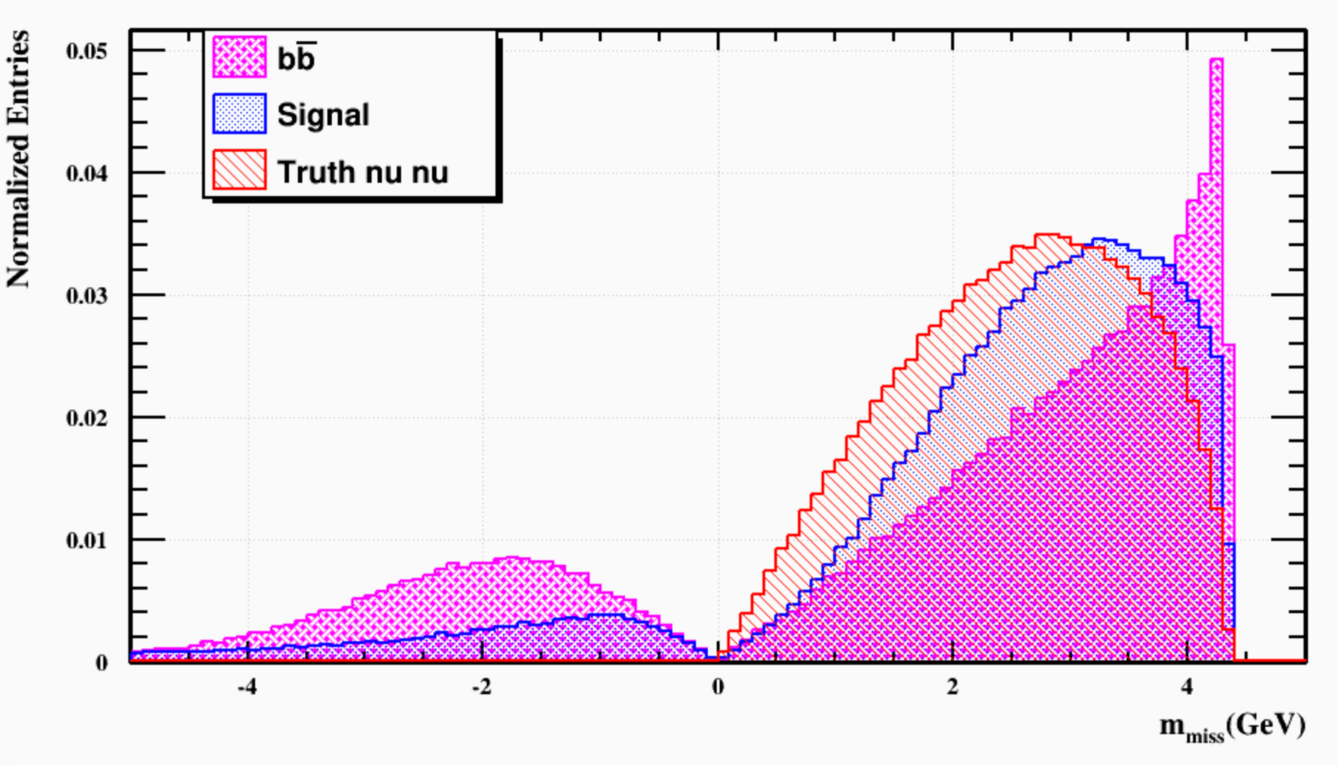
$$E_{sig} = \frac{s + M_{sig}^2 - M_{tag}^2}{2\sqrt{s}},$$

Replace E_{beam} in the above equation by E_{sig} and get a more precise E_{B_s} and $M_{\nu\nu}$

Repeat this process any times until get a good results

Analysis of $\nu\bar{\nu}$ System





Consistent distribution for the signal B_s energy

Not good enough while still apparent difference for signal and background

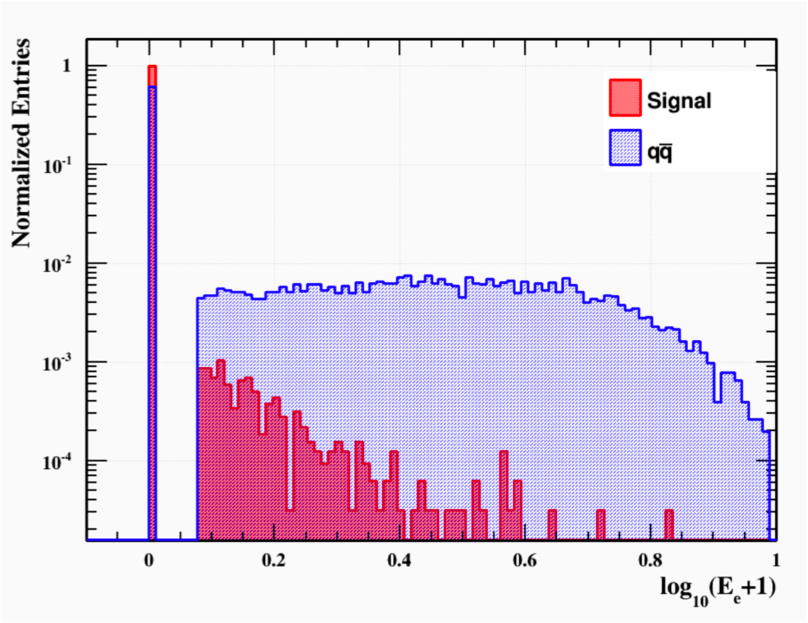
Analysis

Charged Lepton Identify

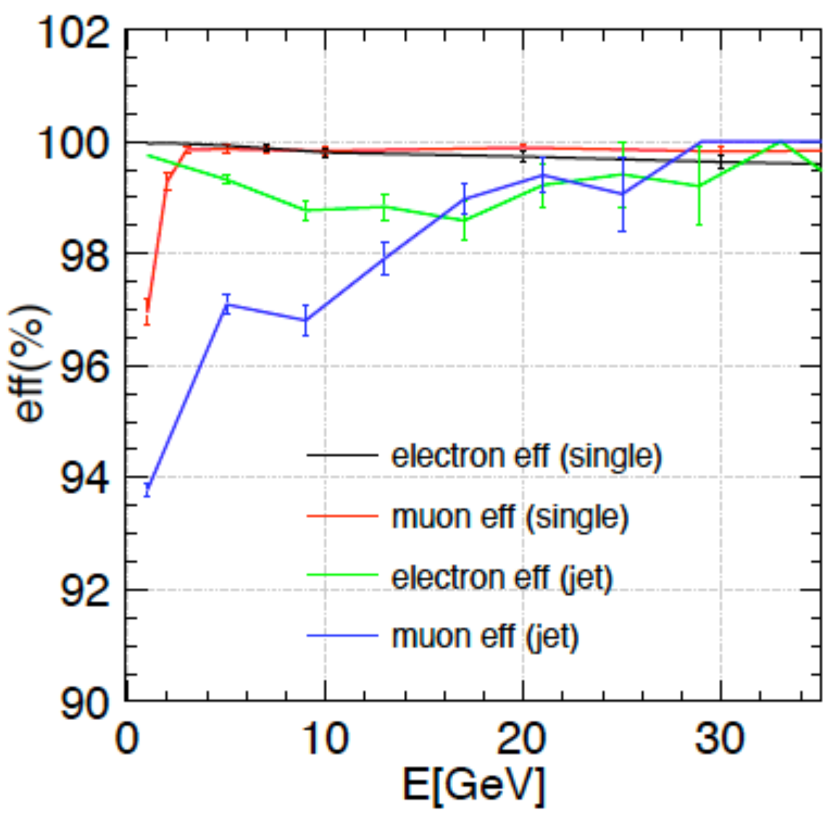
No charged lepton generated in the signal hemisphere for signal decay

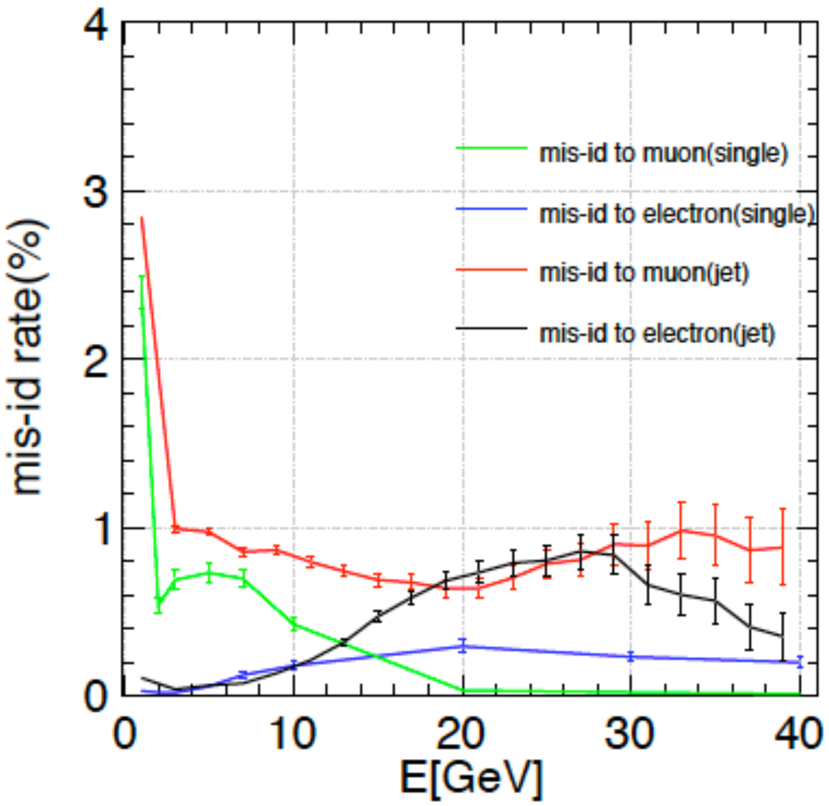
Main background usually generated accompanied with a charged lepton

Good performance for the charged lepton as the energy larger than 1 GeV



Samples satisfy $N_\phi > 0$ and $\alpha < 1.0$





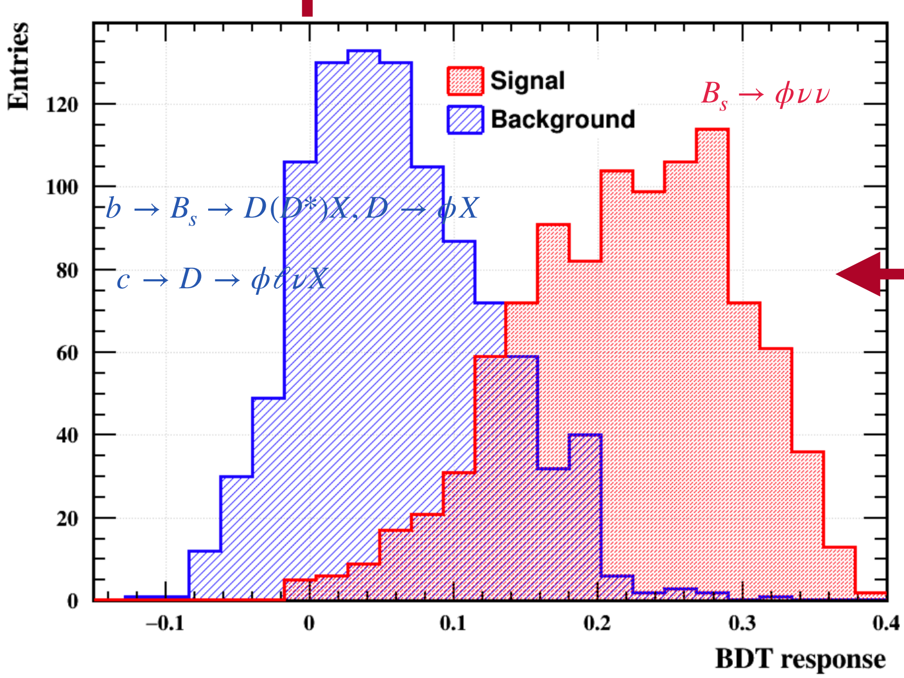
Charged lepton (muon and electron) identify by DanYu.

Cut chain and result

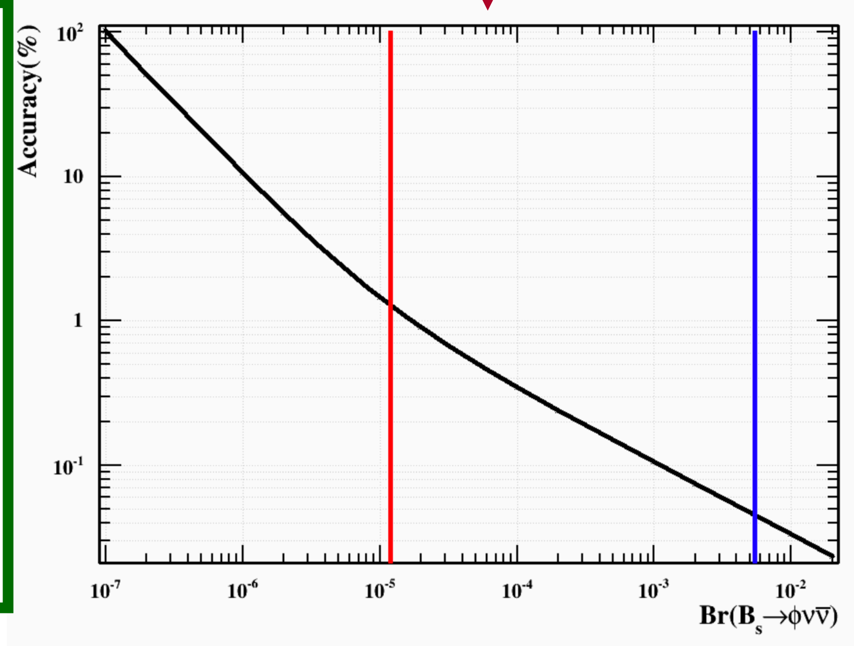
conditions	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events (16 ab^{-1})	1.8e5	1.12e11	1.585e11	1.58511	1.20e11	1.51e11	7e11	464.81
b-tag > 0.6	1.36e5	8.09e8	1.19e9	1.17e9	8.24e9	1.19e11	1.30e11	265.22
$N_{\phi(\to K^+K^-)} > 0$ at signal-hemisphere	51171	1.06e7	1.30e7	3.30e7	2.15e8	3.84e9	4.12e9	125.36
$E_\phi < 45$ GeV Kaon IP > 0.01 mm Energy asymmetry > 8 GeV	42054	3.34e6	3.07e6	6.27e6	4.86e7	1.05e9	1.11e9	79.10
Energy total < 85	40579	4.09e5	7.47e5	8.56e5	1.28e7	5.31e8	5.45e8	57.56
nominal $E_{B_s} > 30$ GeV	32033	68126	0	38929	1.18e6	4.94e7	5.07e7	22.23
$\alpha < 1.0$	22699	0	0	0	5.17e5	7.70e6	8.22e6	12.65
$E_\mu < 1.1$ GeV and $E_e < 1.0$ GeV	20091	0	0	0	1.11e5	2.18e6	2.29e6	7.57
$(1-\alpha_1)/\theta_{<miss,\phi>} < 2.0$	13543	0	0	0	29060	4.27e5	4.56e5	5.06
BDT score > 0.20	7285	0	0	0	0	5240	5240	1.54
Efficiency(%)	40.47	0	0	0	0	3.47e-6	7.49e-7	

TABLE III: The cut chain for the signal and $q\bar{q}$ with full simulation samples and scaled to the integrated luminosity by 16 ab^{-1} at CEPC which shown in the table.

Good separation from specific background performance



- The scaleless ratio α_1.
- The scaleless ratio α_2.
- The invariant mass of all visible final states.
- The invariant mass of tag hemisphere.
- The invariant mass of signal hemisphere.
- The angle between missing momentum and ϕ momentum.
- The energy of signal B_s and invariant mass of $\bar{\nu}\nu$



Summary

- By 10^{12} Z decay, CEPC will produce 1.5×10^{11} $b\bar{b}$ and 1.8×10^{5} rare decay $B_s \to \phi\nu\bar{\nu}$ under SM
- B_s Statistics : More than 5 higher order than the LEP (current up limit) and least $2-3$ higher order than Belle II
- Expected good accuracy to measure the rare decay $B_s \to \phi\nu\bar{\nu}$

  Be the level of 1.5 % under SM and about 8 % even 1 order smaller
- More optimization and detector requirement.
  - PID: Necessary if one desires to separate π/K modes at $0-45$ GeV momentum range(~15 % less background)
  - More full simulation samples to study rare decay and calorimeter
  - Missing energy and mass performance by the neutral hadron reconstruction?
  - Charged lepton identify at $1-2$ GeV (8 % ~ 10 % better for accuracy)
- More measurement of flavor rare decay processes of B_s, B_c and Λ_b at CEPC are expected

End

Thanks