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

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Outline

1. Introduction and Motivation
2. Signal and background
3. Reconstruction of ϕ
4. Missing energy and missing mass
5. Results and conclusion

Motivation

- Large statistics for the heavy hadron ($B_s, B_c, \Lambda_b \ldots$) meanwhile clean background.
- Free from strong interaction and not affected by non-factorizable corrections thus theoretically cleaner compared to $b \to s\ell\ell$ transitions (exist multiple anomalies)
- Verify the SM mechanism and provide opportunity to explore new physics.
- Performance some benchmark of simulation at CEPC (charged lepton identify, vertex reconstruction, energy and momentum resolution).

Physics of $b \to s\nu\bar{\nu}$

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

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

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

Relation between BSM and SM for inclusive branch

$$\frac{\text{BR}(B_s \to \phi\nu\bar{\nu})}{\text{BR}(B_s \to \phi\nu\bar{\nu})_{\text{SM}}} = \quad R(\frac{C_L}{C_R})$$

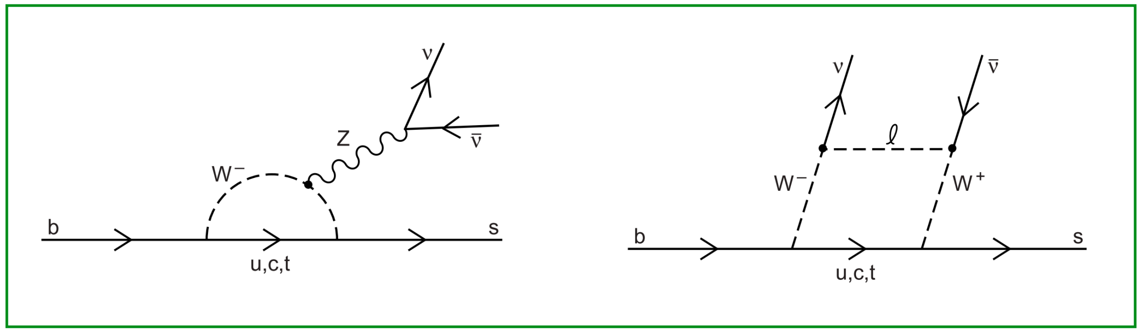
F_L determines the kinematic distribution of $\phi \to K^+K^-$ decays as

$$\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}(1 - F_L)\sin^2\theta + \frac{3}{2}F_L\cos^2\theta$$

where $\theta \in [0,\pi)$ is the angle between the K^+ and B_s flight directions in the ϕ rest frame

$$F_{L,SM} = 0.53 \pm 0.04$$

By the calculation of LingFeng, which take both theoretical uncertainties and their correction into consideration



$$\mathrm{BR}\left(B_s \to \phi\nu\bar{\nu}\right)_{\mathrm{SM}} = (9.9 \pm 0.7) \times 10^{-6}$$

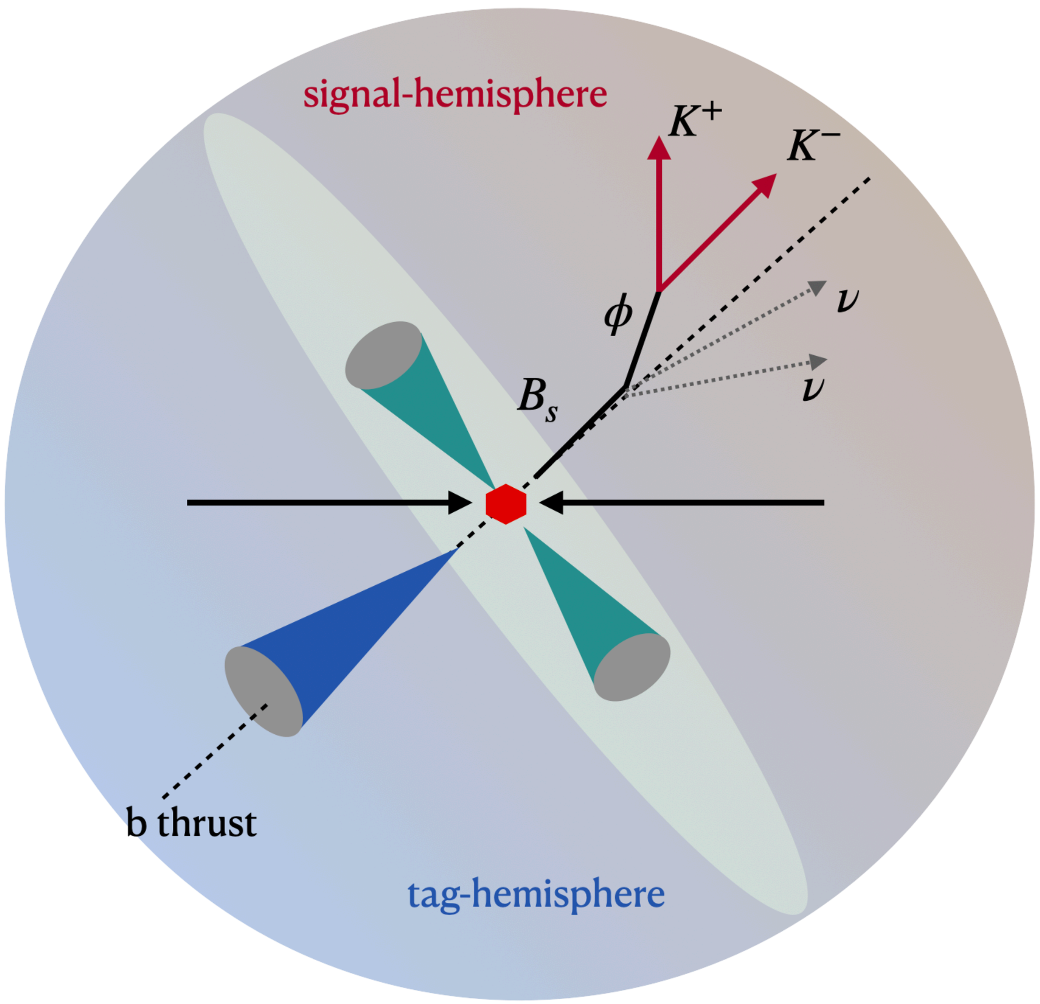
The Signal Topology

Number of signal decay by SM prediction at CEPC :

$$N(B_s \to \phi\nu\bar{\nu}) \sim 3.0 \times 10^5$$

The analysis strategy

- The signal-hemisphere choice and ϕ reconstruction
- The kinematics of ϕ and other final state (charge lepton)
- The kinematics of missing states
- BDT method of TMVA



ϕ reconstruction

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

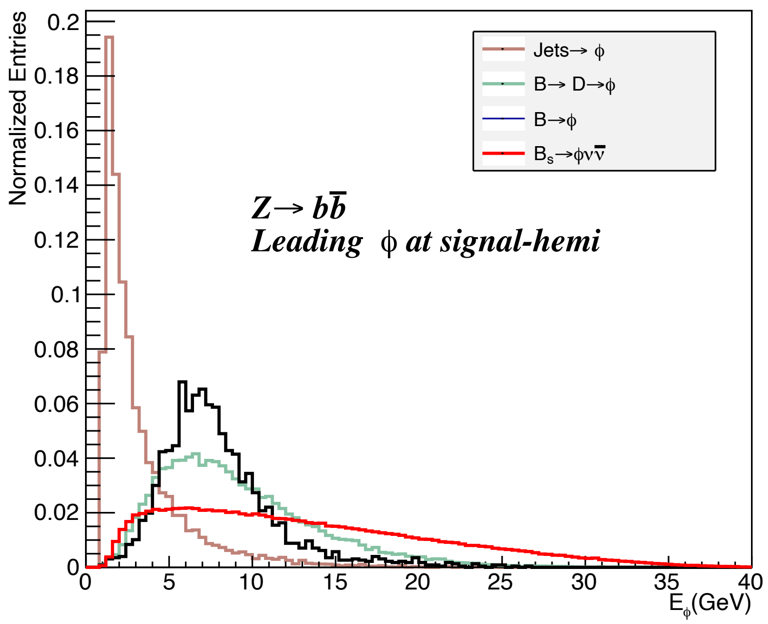
- $Br(\phi \to K^+K^-) = 49.2\,\%$
- Take oppositely charged tracks pair in the jet chamber
- Employ the kinematic fit package for ILC to reconstruct the secondary vertex
- Form their invariant mass window

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

The ϕ reconstruction efficiency and purity are defined to reflect the results

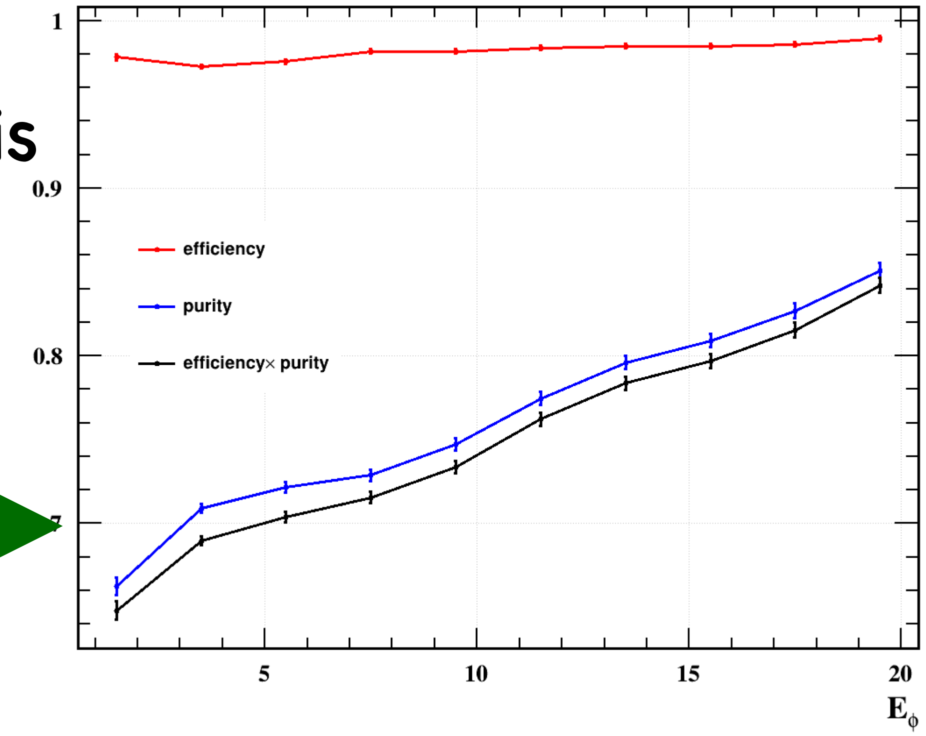
$$\epsilon = \frac{\text{Number of correctly selected track pair candidates}}{\text{Number of } \phi \to K^+K^- \text{ events}} \qquad p = \frac{\text{Number of correctly selected track pair candidates}}{\text{Number of selected track pair candidates}}$$

ϕ reconstruction



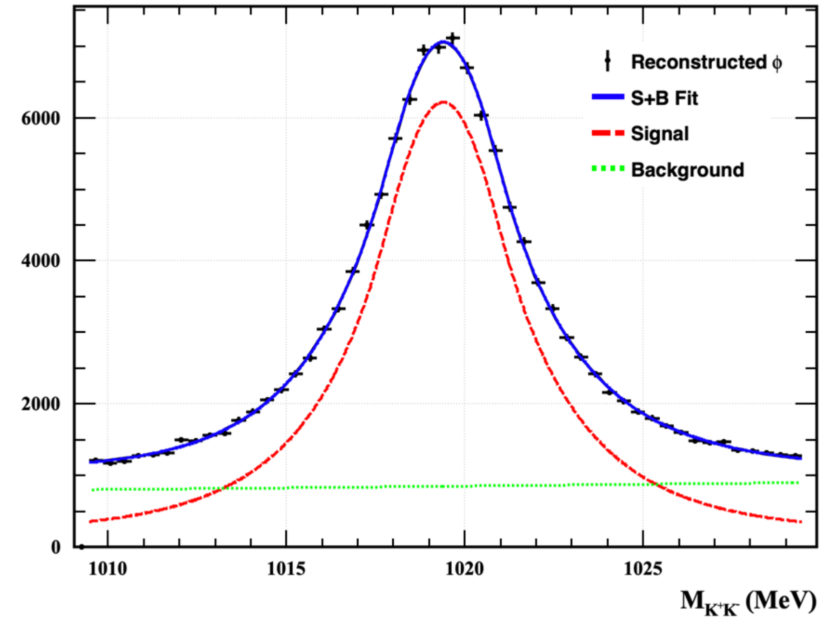
In the $B_s \to \phi\nu\bar{\nu}$ analysis

- ϕ in signal-hemisphere
- Leading energy one



Integrated efficiency and purity are 0.985, 0.756

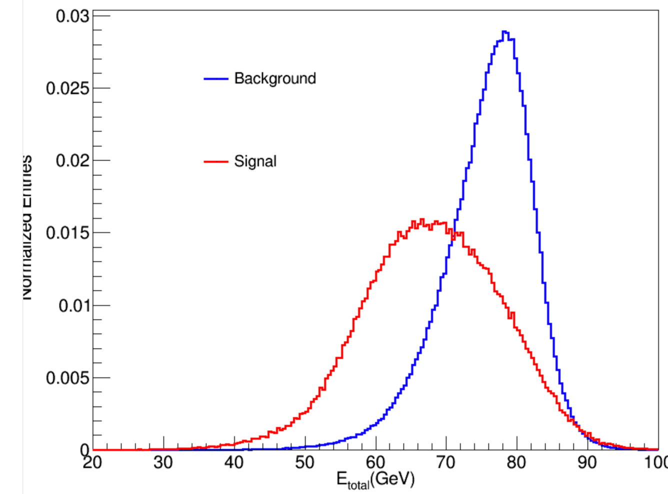
Further requirements for signal ϕ : 1) Located at the signal hemisphere. 2) The impact parameters of both Kaon pair tracks are larger than 0.01 mm. 3) The distance of ϕ decay vertex to interact point(IP) is larger than 0.4 mm.

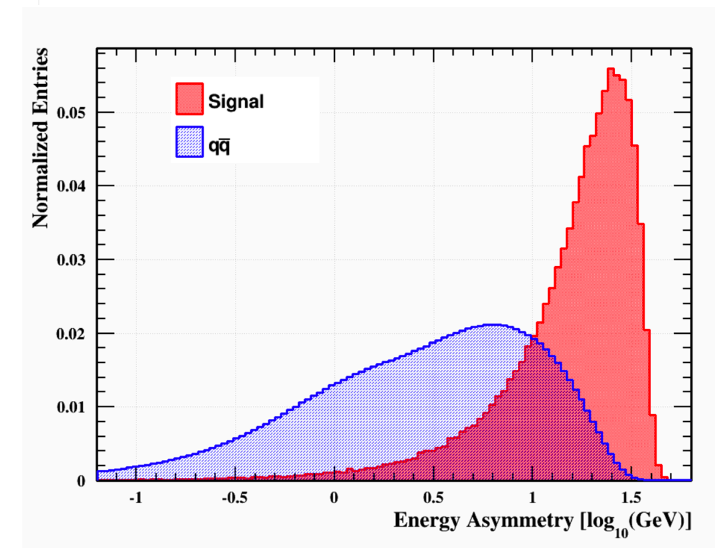


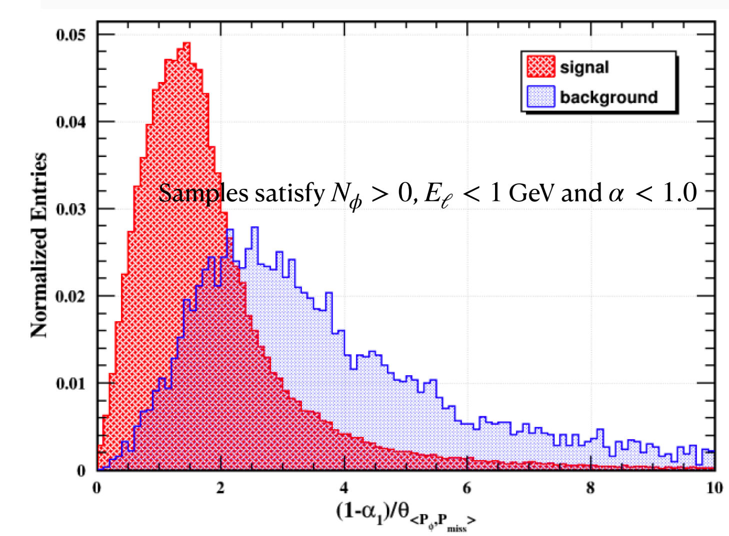
Mass distribution of reconstructed ϕ

Kinematics of $\nu\bar{\nu}$

Indirect measurement by the **full reconstruction**







- The total energy
- Missing energy

a). In the signal-hemisphere, the ϕ energy ratio. ($\alpha_1 = E_\phi/E_{sig}$)

b). The missing energy ratio in the signal-hemisphere. ($\alpha_2 = E_{sig}/E_{beam}$ and $E_{asymmetry}$)

c). The direction that missing momentum $i.e.$ $(1-\alpha_1)/\theta_{<P_\phi,P_{miss}>}$

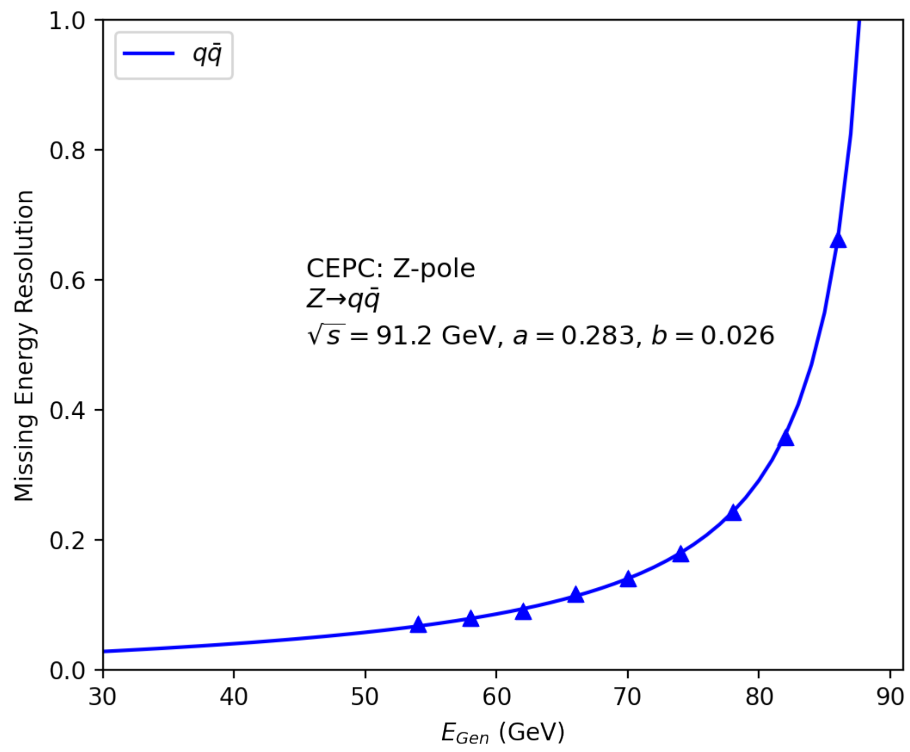
d). The correctional signal energy of B_s and mass of $\nu\bar{\nu}$

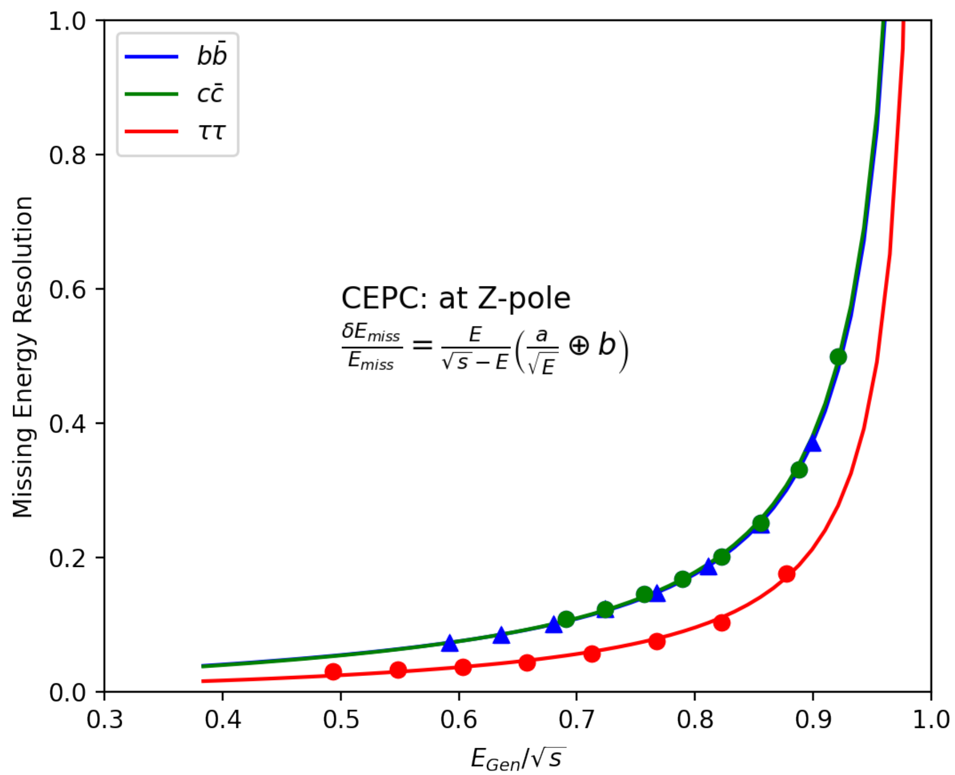
Missing Energy Resolution

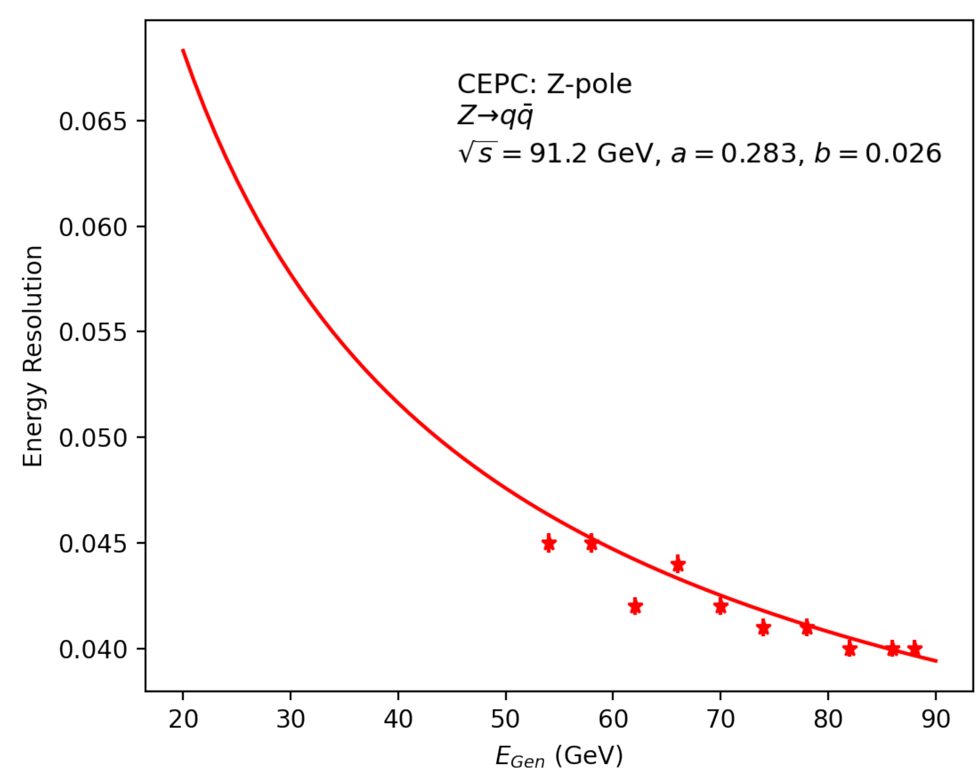
$$\frac{\delta E}{E} = \frac{a}{\sqrt{E}} \oplus b$$

$$\frac{\delta E_{miss}}{E_{miss}} = \frac{E_{miss}^{Reco} - E_{miss}^{Gen}}{E_{miss}^{Gen}} = \frac{E}{\sqrt{s} - E}\left(\frac{a}{\sqrt{E}} \oplus b\right)$$

Resolution: Fit by double-side crystal ball function







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

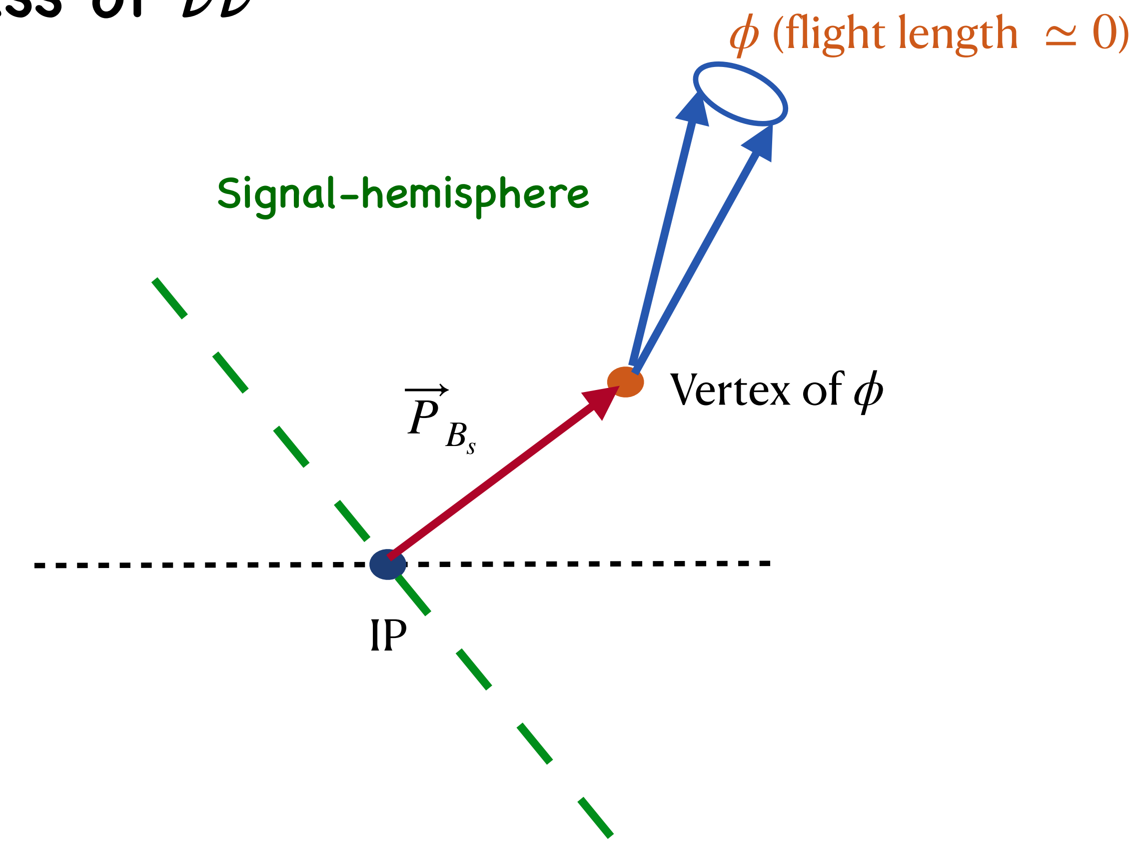
A correctional signal B_s energy and invariant mass of $\nu\bar{\nu}$

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

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

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

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



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

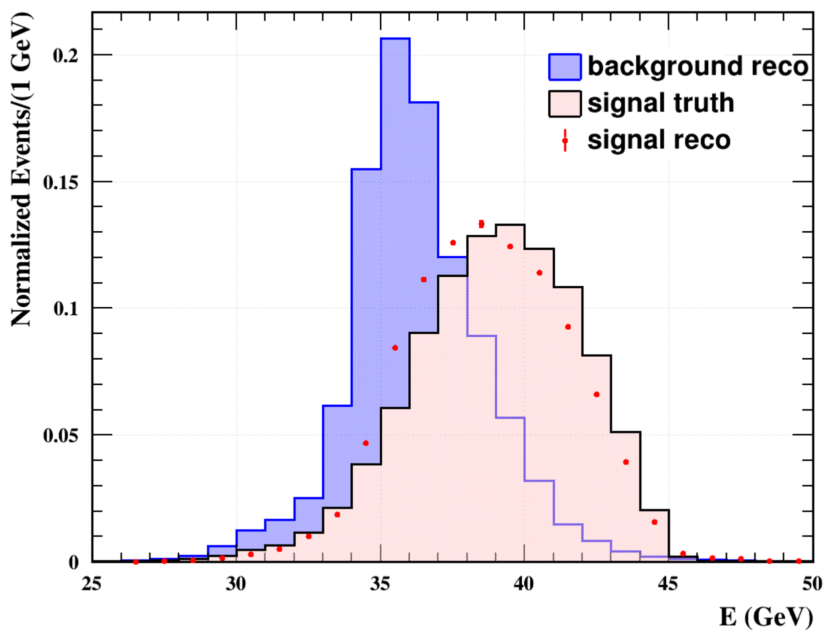
$$M_{tag} = \sqrt{\left(\sum p_{tag}^{track} + \sum p_{tag}^{neutral}\right)^2},$$

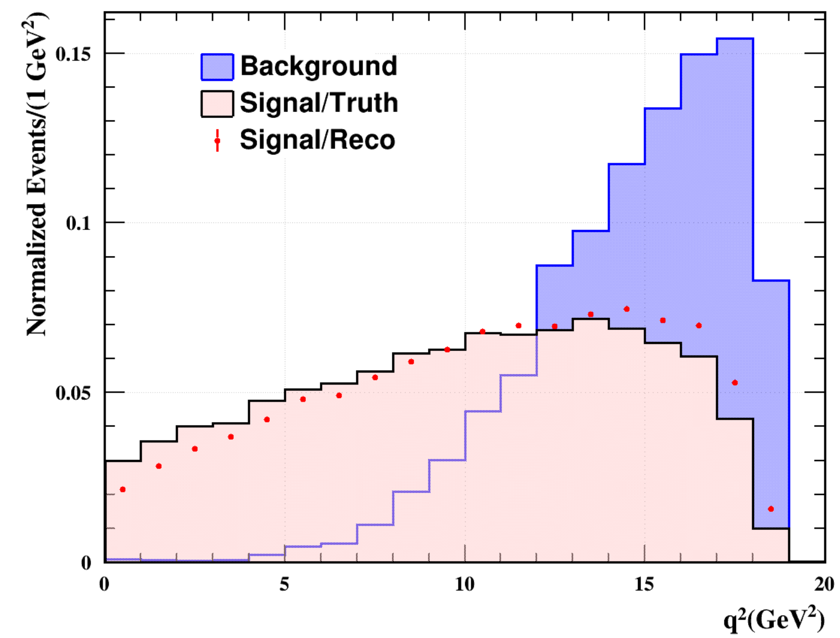
$$M_{sig} = \sqrt{\left(\sum p_{sig}^{nuetral} + \sum p_{sig}^{track} + p_{B_s} - p_\phi\right)^2},$$

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

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





The typical reconstruction error for $q^2(m^2_{\nu\nu})$ and E_{B_s} are 2.5 GeV^2 and 1.7 GeV, respectively.

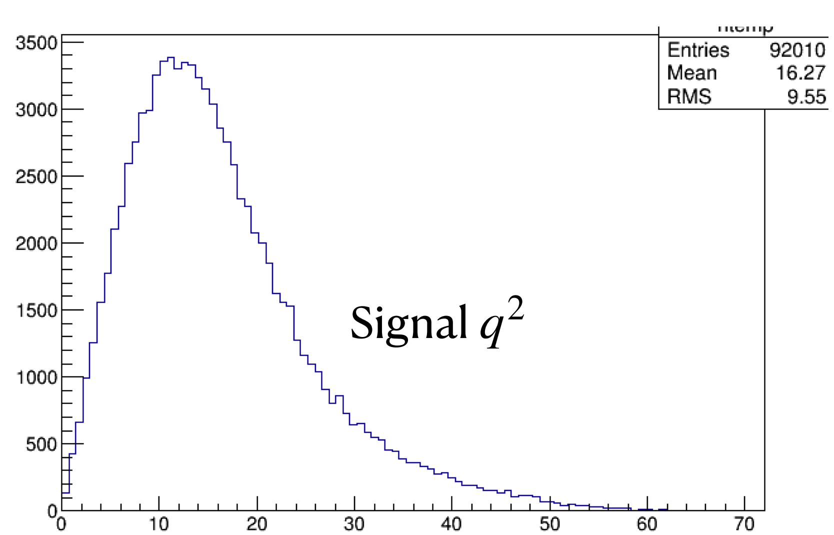
Directly $q^2 = p^2_{miss}$ by

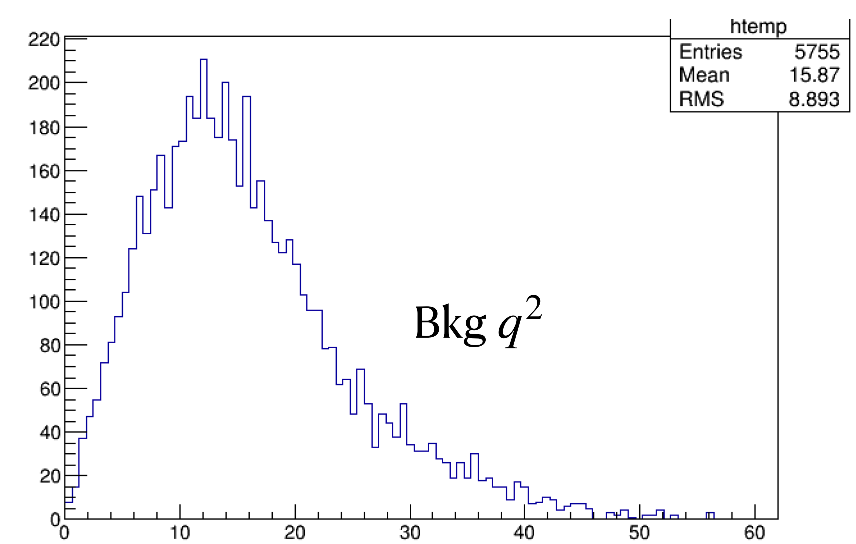
$p_{miss} = (\sqrt{s}, \vec{0}) - p_{vis}$

and

$E^N_{B_s} = \sqrt{s} - E_{total} + E_\phi$:

Error = 5.1 GeV





Any strategy to improve the missing momentum resolution ?

GeV GeV

Cut chain and result

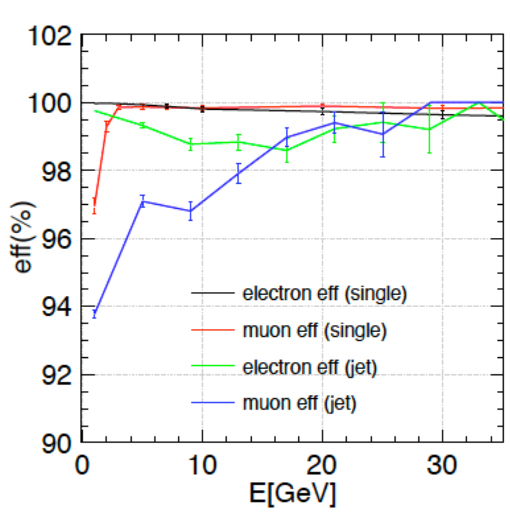
Cuts	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events ($10^{12}Z$)	3.03×10^{5}	4.28×10^{11}	1.20×10^{11}	1.51×10^{11}	6.99×10^{11}	276
$^{*}N^{\mathrm{sig}}_{\phi(\to K^+K^-)} > 0$	9.00×10^{4}	1.39×10^{9}	1.55×10^{9}	3.14×10^{9}	6.08×10^{9}	86.7
Energy asymmetry > 8 GeV	7.61×10^{4}	2.97×10^{8}	3.61×10^{8}	9.05×10^{8}	1.56×10^{9}	51.9
Energy total < 85 GeV	7.36×10^{4}	6.28×10^{7}	1.16×10^{8}	4.65×10^{8}	6.44×10^{8}	34.5
$E^{N}_{B_s} > 28$ GeV	6.40×10^{4}	1.77×10^{7}	3.03×10^{7}	8.83×10^{7}	1.36×10^{8}	18.2
$\alpha < 1.0$	4.34×10^{4}	6.22×10^{6}	6.42×10^{6}	1.00×10^{7}	2.26×10^{7}	11.0
b-tag > 0.6	3.34×10^{4}	$< 2.0\times10^{4}$	2.54×10^{5}	6.44×10^{6}	6.69×10^{6}	7.76
$E_\mu < 1.2$ GeV and $E_e < 1.2$ GeV	3.02×10^{4}	-	1.08×10^{5}	2.33×10^{6}	2.44×10^{6}	5.20
$(1-\alpha_1)/\theta^{\mathrm{miss}}_{\phi} < 2.0$	2.04×10^{4}	-	2.82×10^{4}	4.53×10^{5}	4.81×10^{5}	3.47
BDT response> 0.20	1.30×10^{4}	-	$< 1.0\times10^{3}$	1.65×10^{4}	$< 1.75\times10^{4}$	1.34
Efficiency	4.29%	-	$< 8\times10^{-9}$	1.09×10^{-7}	2.36×10^{-8}	

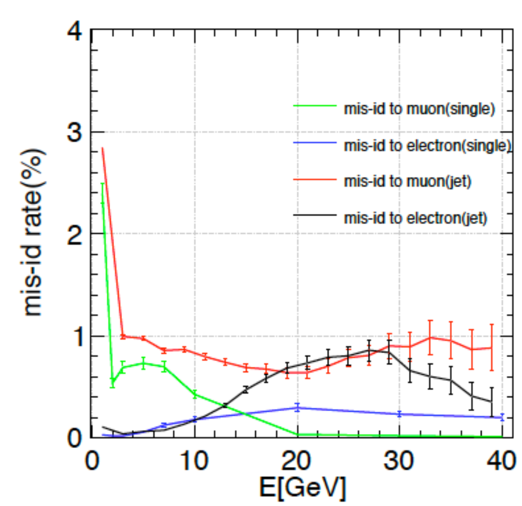
* The signal ϕ here is required to satisfy the following conditions : 1) Located at the signal hemisphere. 2) The impact parameters of both Kaon pair tracks are larger than 0.01 mm. 3) The distance of ϕ decay vertex to interact point(IP) is larger than 0.4 mm.

TABLE III: The cut chain for the signal and $q\bar{q}$ with full simulation samples and scaled to the integrated luminosity to $10^{12}Z$ bosons at CEPC.

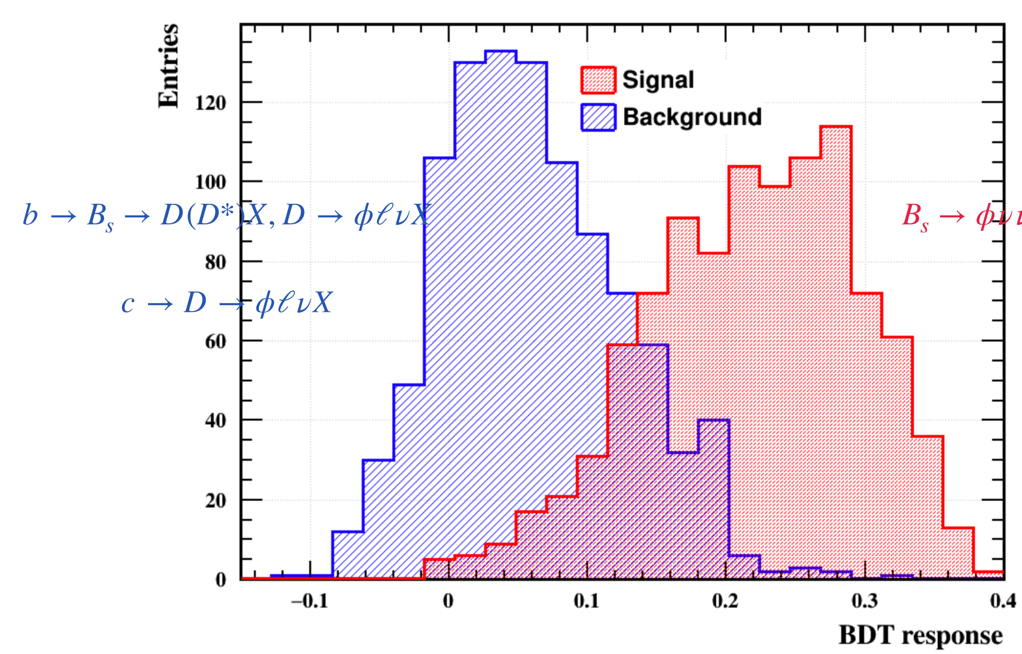
The semi-leptonic decay background performance

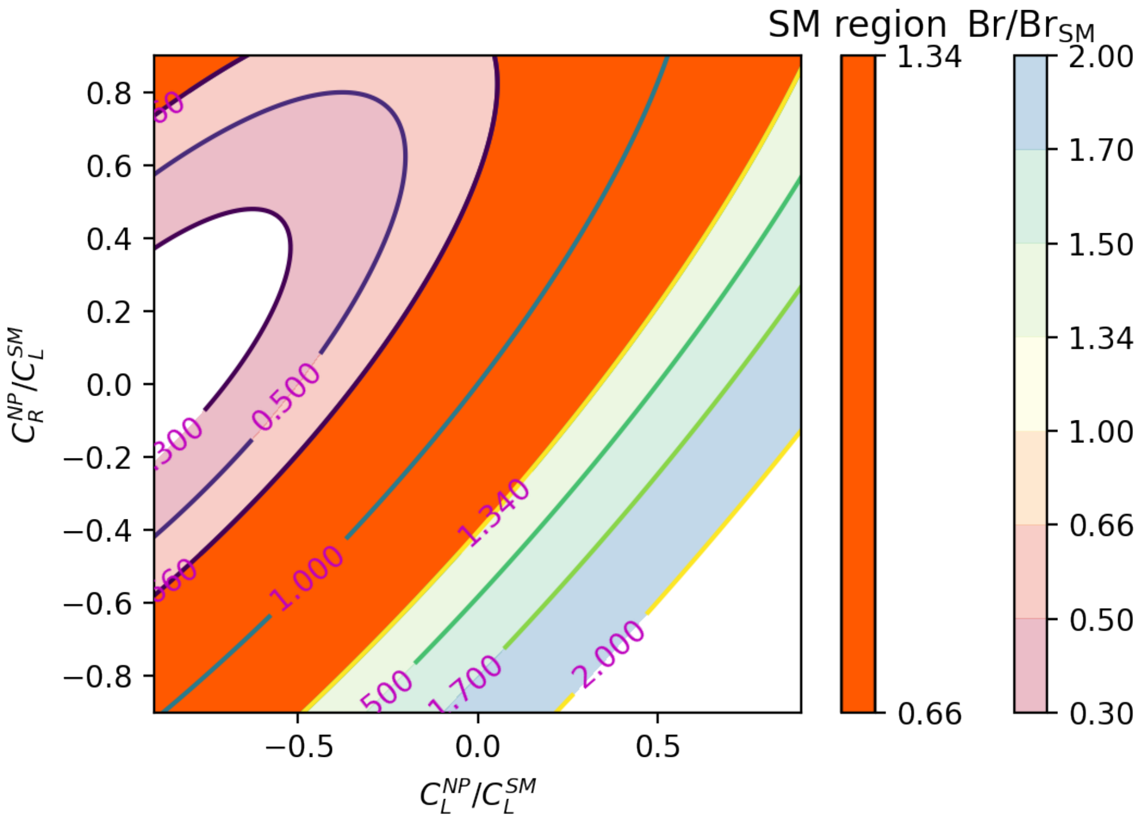
Always companied charged lepton produced in the signal-hemi, benefit from the optimism for the low energy lepton identify?

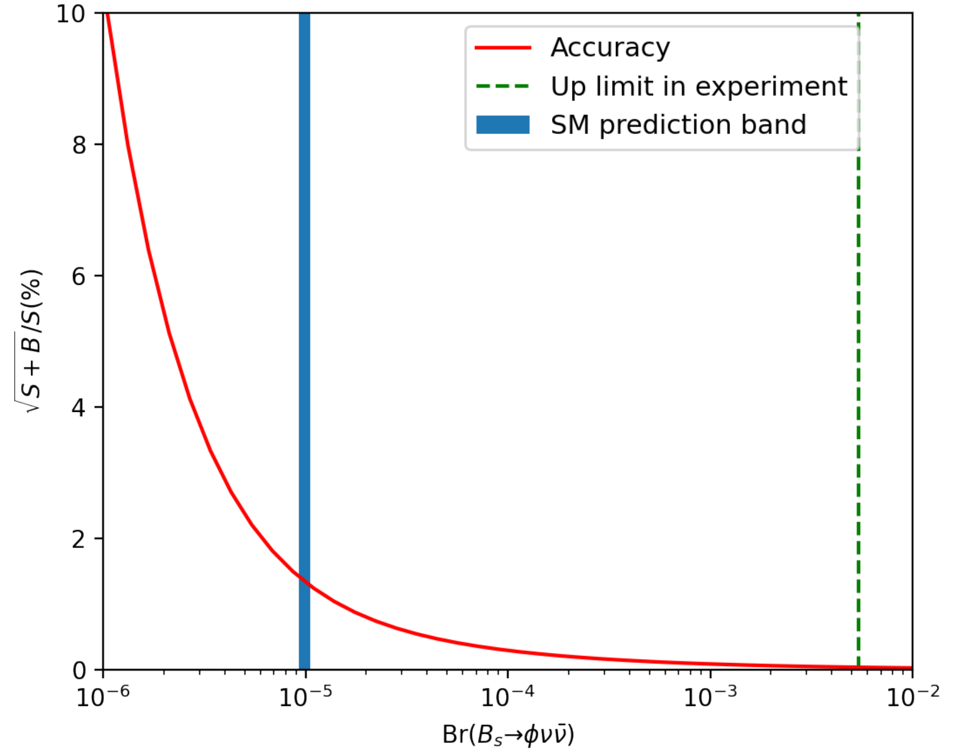


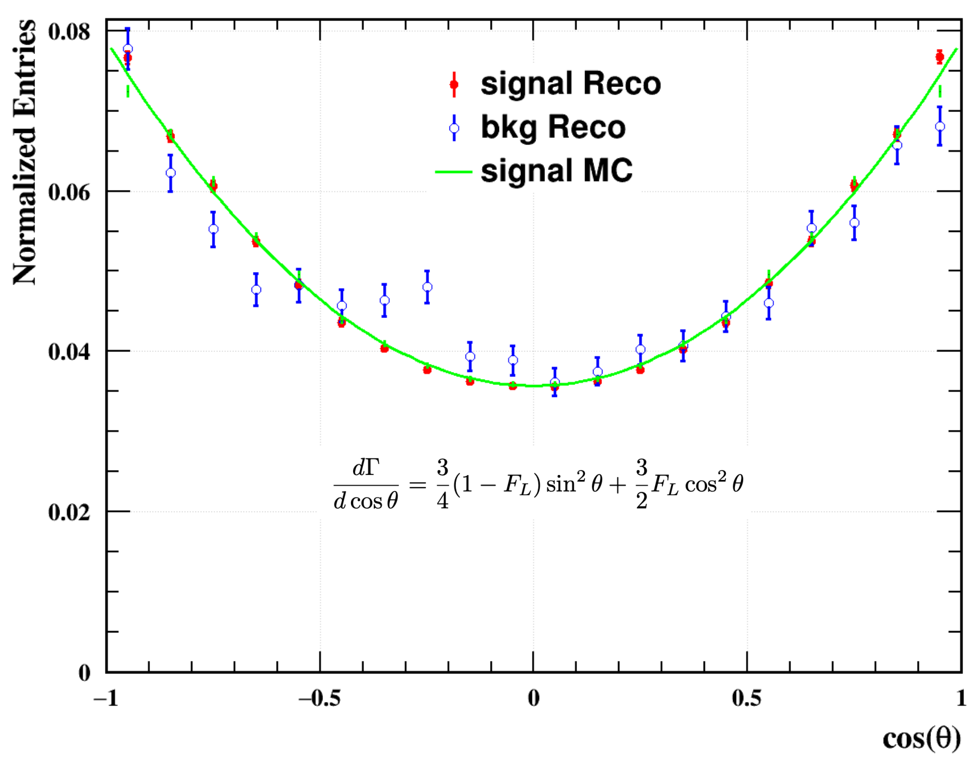


Charged lepton (muon and electron) identify by DanYu.









The ϕ longitudinal polarization fraction $F_{L,SM}$ to be

$$0.53 \pm 0.04 \text{ (SM)} \pm 0.04 \text{ (reco)}$$

Summary

- By 10^{12} Z decay, CEPC will produce 1.5×10^{11} $b\bar{b}$ and 3.0×10^5 signals ($B_s \to \phi\nu\bar{\nu}$) by SM prediction
- B_s Statistics : More than 5 higher order compared to current measurement
- Expected accuracy

About 1.34 % for the branch ratio

- ϕ longitudinal polarization fraction $F_{L,SM}$ measurements

$$F_L = 0.53 \pm 0.04\ \text{(SM)} \pm 0.04\ \text{(reco)}$$

- Potential optimization and detector requirement.
  - Charged lepton identify at low energy region ($<$ 1.2 GeV)
  - The missing energy and momentum resolution : are largely determined by the hadronic final states
  - Study of the flavor rare decay processes of B_s, B_c and Λ_b at CEPC are expected

End

Thanks

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 ($10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	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}

Events Analysis By ϕ

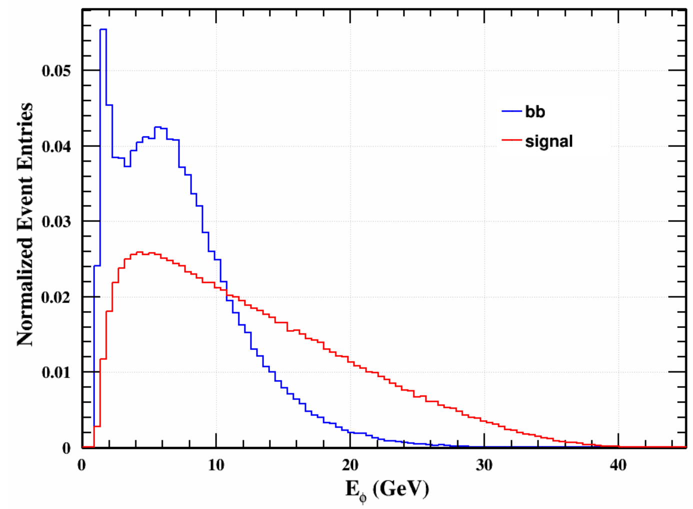
Now, we have a leading ϕ with its momentum and vertex

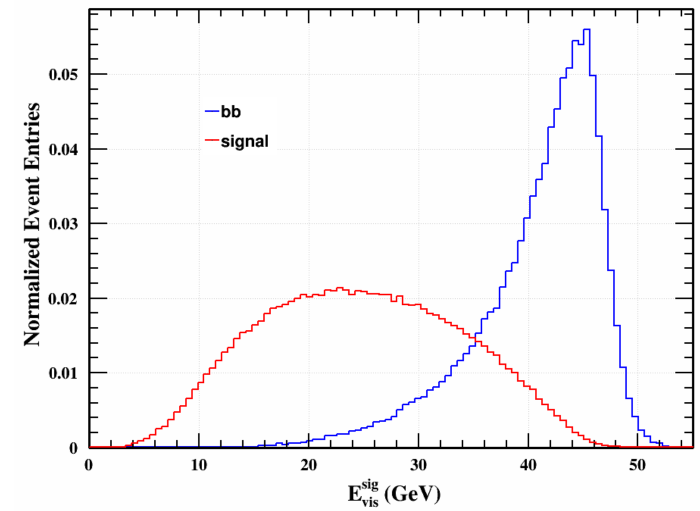
Define the scaleless variables $\alpha_1 = \dfrac{E_\phi}{E^{sig}_{vis}}$ and $\alpha_2 = \dfrac{E^{sig}_{vis}}{E_{beam}}$

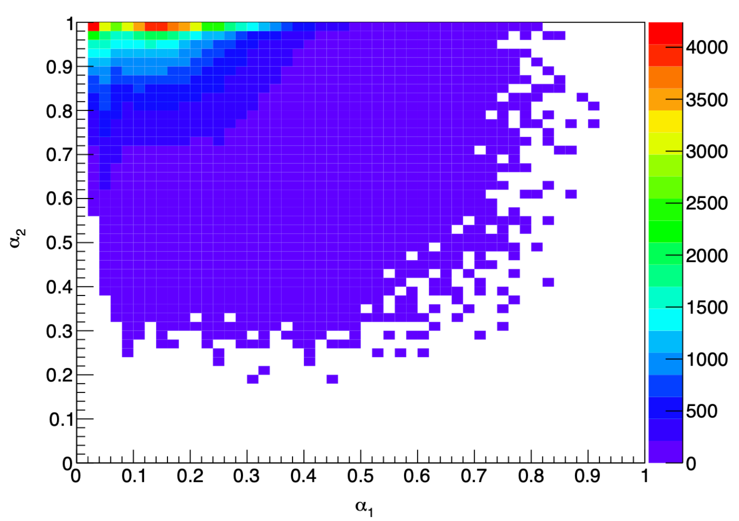
E^{sig}_{vis} is the energy of signal-hemisphere and $E_{beam} = 45.6$ GeV

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

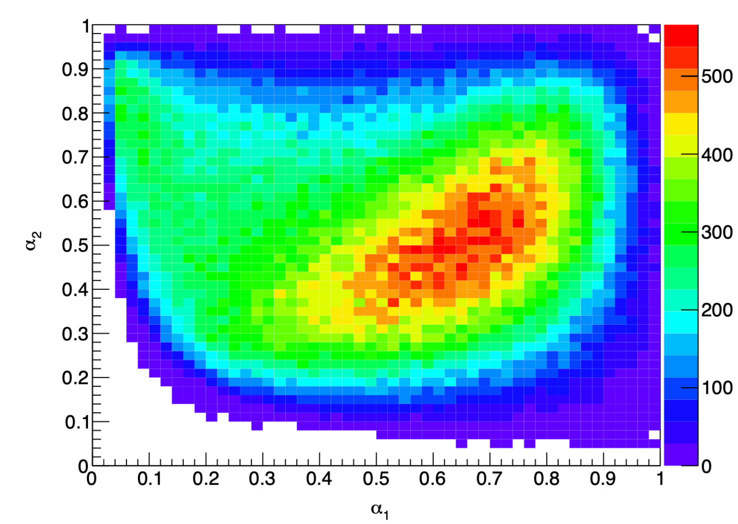
Significant difference of $\alpha_2 - \alpha_1$ distribution for background and signal events.





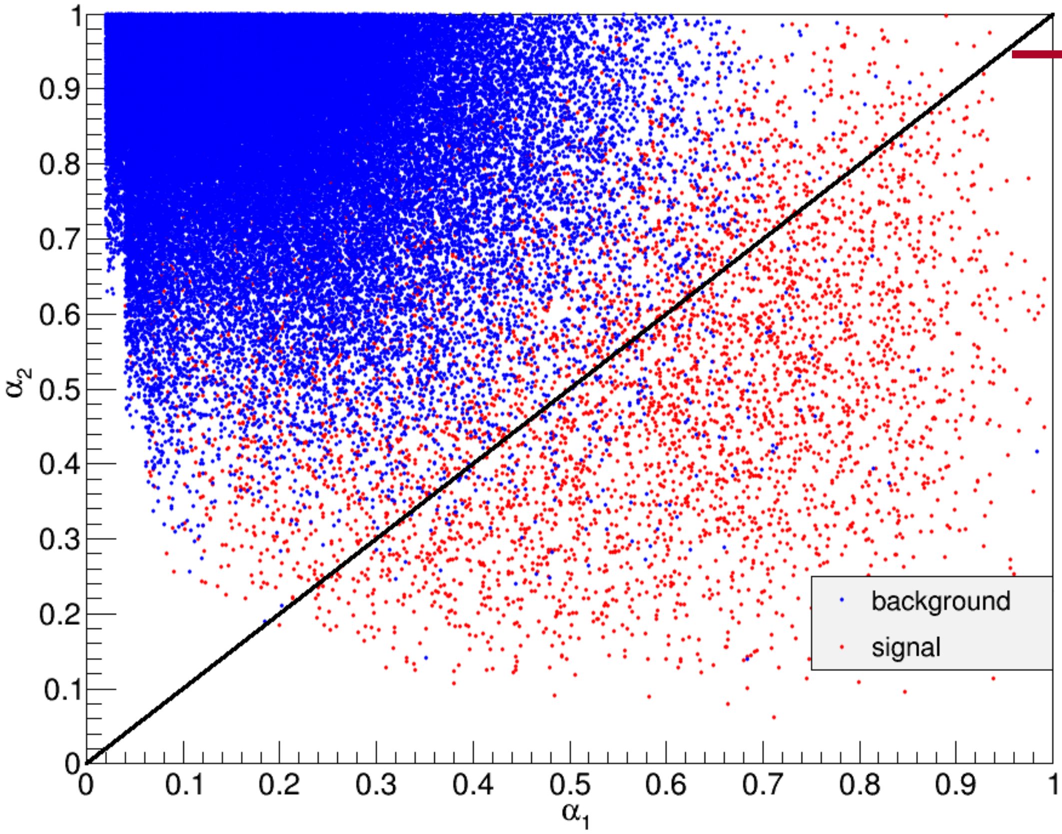


$b\bar{b}$ background



Signal events

Events Analysis By ϕ

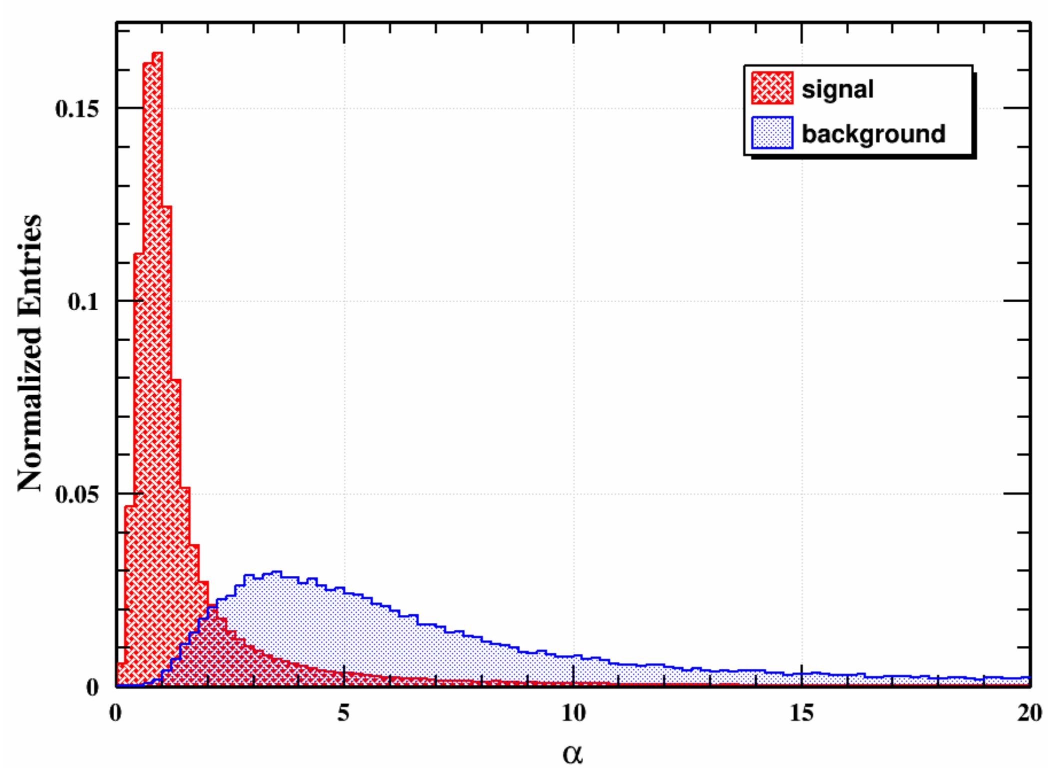


Loose boundary defined by

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

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



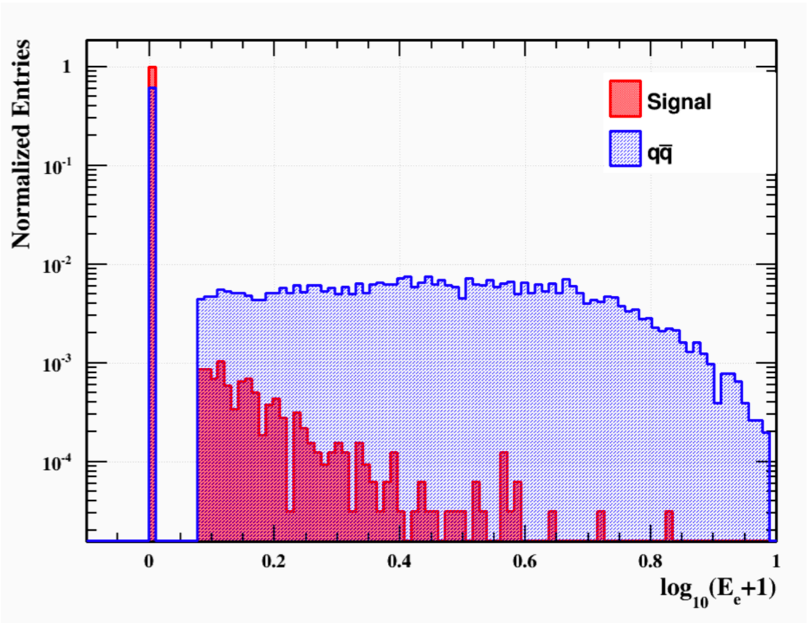
Analysis

Charged Lepton Identify

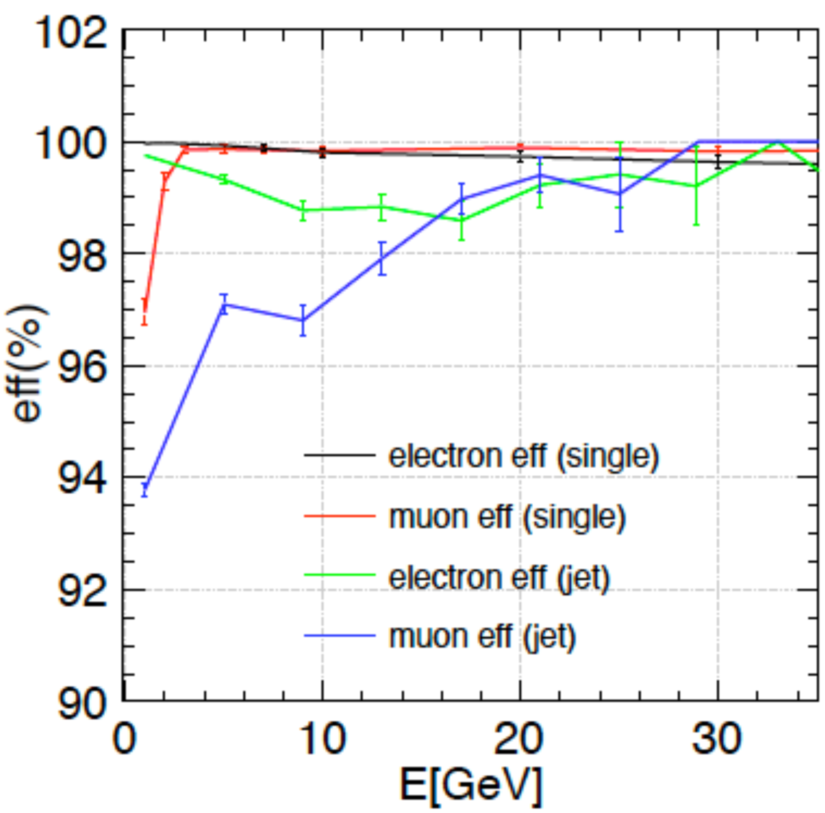
No charged lepton generated in the signal hemisphere for signal decay

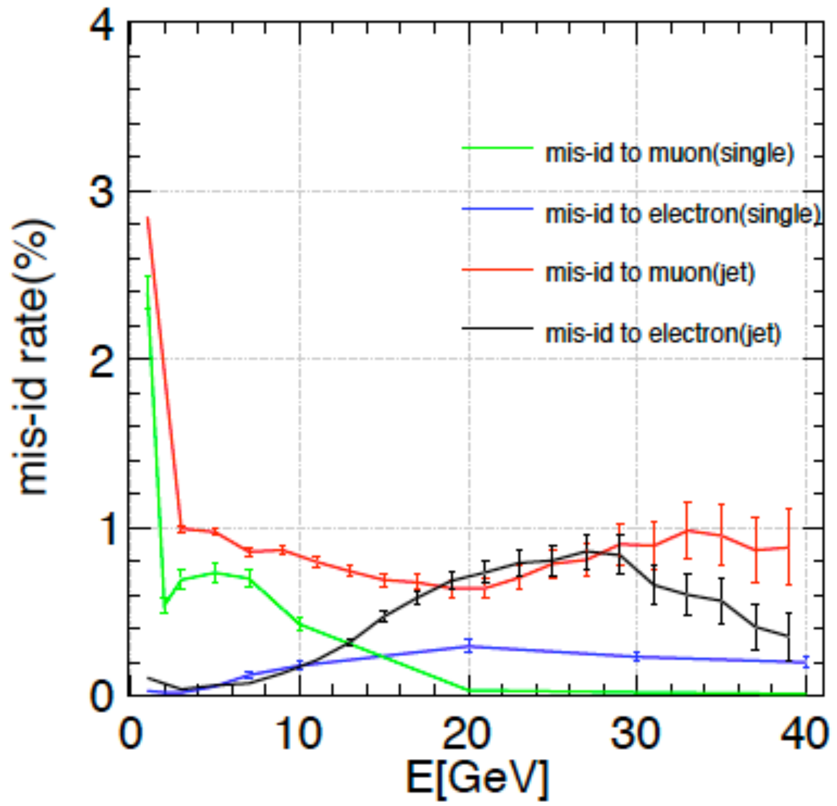
Main background usually generated accompanied with a charged lepton

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

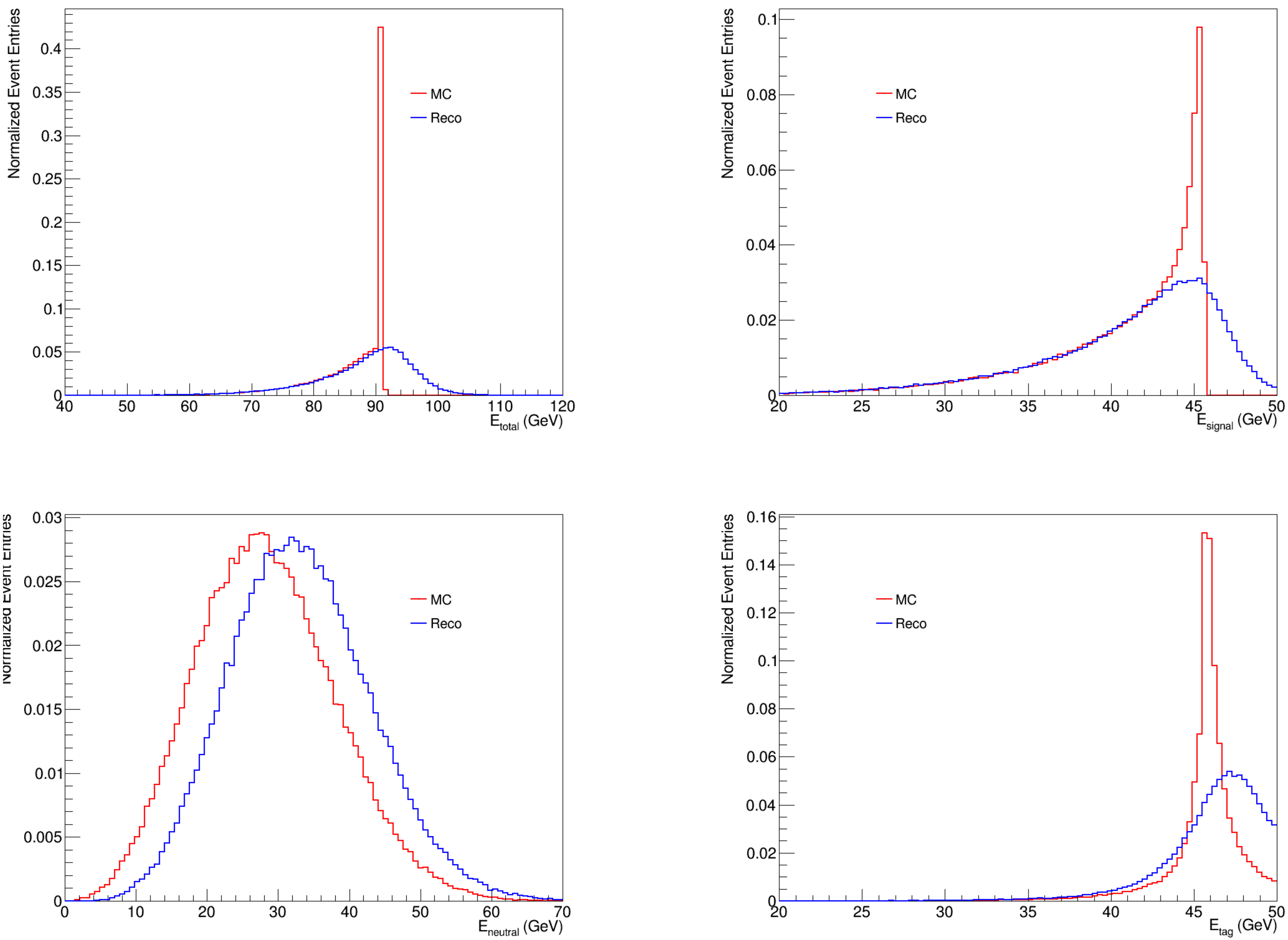


Samples satisfy $N_\phi > 0$ and $\alpha < 1.0$





Charged lepton (muon and electron) identify by DanYu.



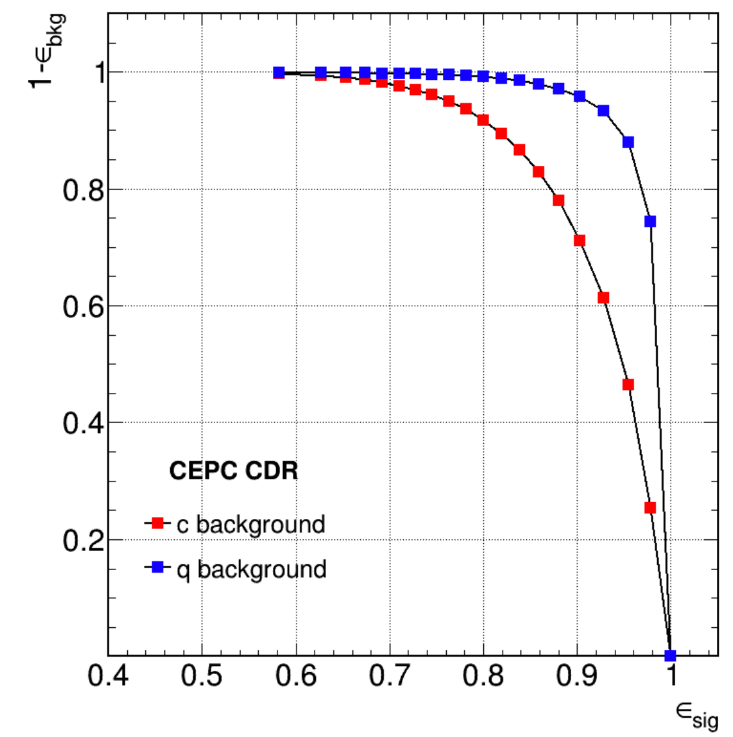
Normalized Event Entries
MC
Reco
E_total (GeV)
E_signal (GeV)
E_neutral (GeV)
E_tag (GeV)

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

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

- 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