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

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Outline

1. Introduction and Motivation
2. Reconstruction of ϕ
3. Kaon PID
4. Events selection
5. Results and conclusion

Motivation

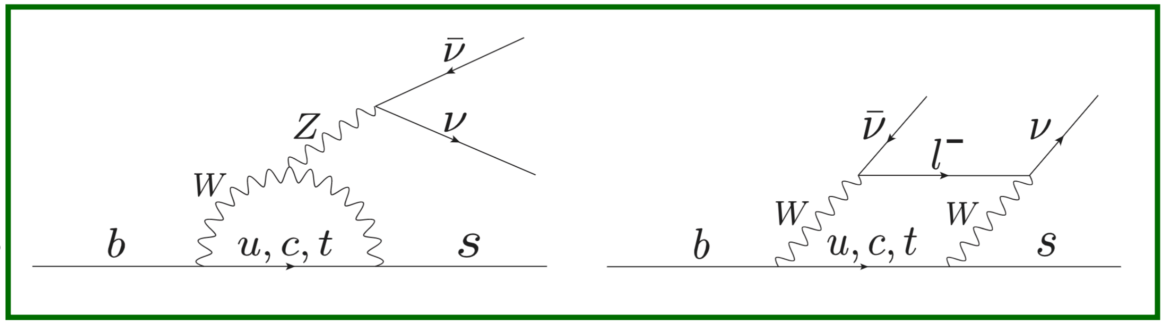
- Large statistics for the heavy hadron ($B_s, B_c, \Lambda_b \ldots$) meanwhile clean background.
- Free from strong interaction and not affected by non-factorizable corrections thus theoretically cleaner compared to $b \to s\ell\ell$ transitions (exist multiple anomalies)
- Verify the SM mechanism 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 general effective Hamiltonian for $b \to s\nu\bar{\nu}$ transitions reads

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

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



The penguin and box diagrams of $b \to s\nu\bar{\nu}$ transition at the leading order

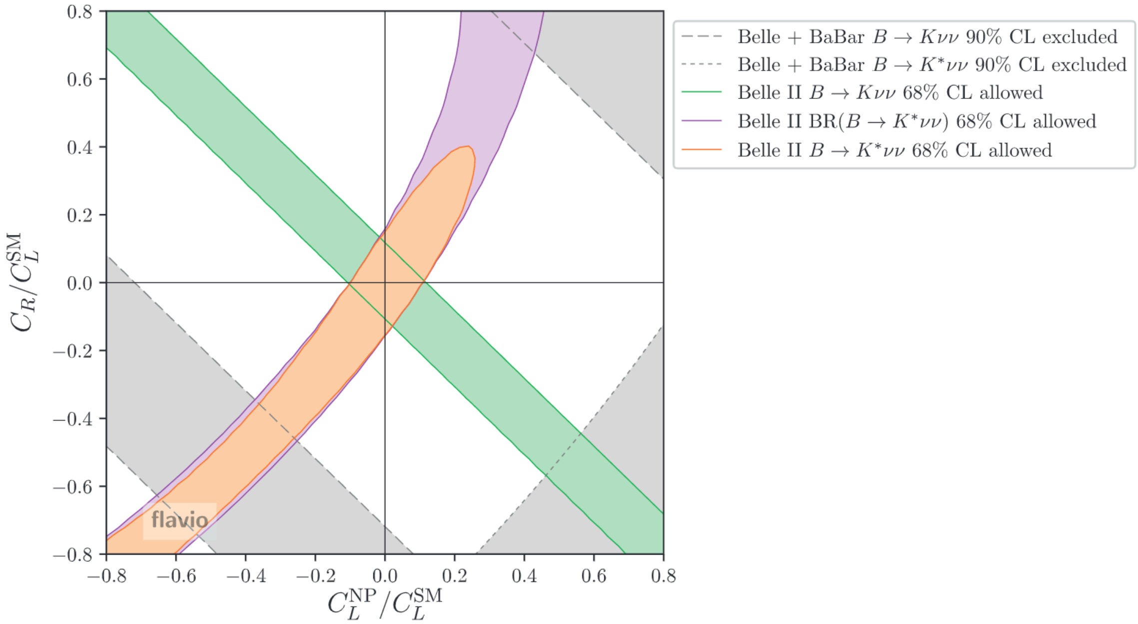
Relation between BSM and SM for inclusive branch

$$\frac{\text{BR}(B_s \to \phi\nu\bar{\nu})}{\text{BR}(B_s \to \phi\nu\bar{\nu})_{\text{SM}}} = \frac{1}{3}\sum_{\ell}(1+\kappa_\eta\eta_\ell)\epsilon_\ell^2 \;,(\ell = e, \mu, \tau)$$

$$\epsilon_\ell \equiv \frac{\sqrt{|C_L^\ell|^2 + |C_R^\ell|^2}}{|C_L^{\text{SM}}|}\,, \qquad \eta_\ell \equiv -\frac{\text{Re}(C_L^\ell C_R^{\ell\,*})}{|C_L^\ell|^2 + |C_R^\ell|^2}$$

$$F_L = F_{L,\text{SM}}\frac{\sum_\ell(1+2\eta_\ell)\epsilon_\ell^2}{\sum_\ell(1+\kappa_\eta\eta_\ell)\epsilon_\ell^2}$$

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



Constrained region in $C_L^{NP} - C_R^{NP}$ plane by Belle II.

Kou, E. *et al*. The Belle II Physics Book. *Prog Theor Exp Phys* **2019**, (2019).

The background and Signal

Number of signal decay by SM prediction at CEPC: $N(B_s \to \phi\nu\bar{\nu}) \sim 3.0 \times 10^5$

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

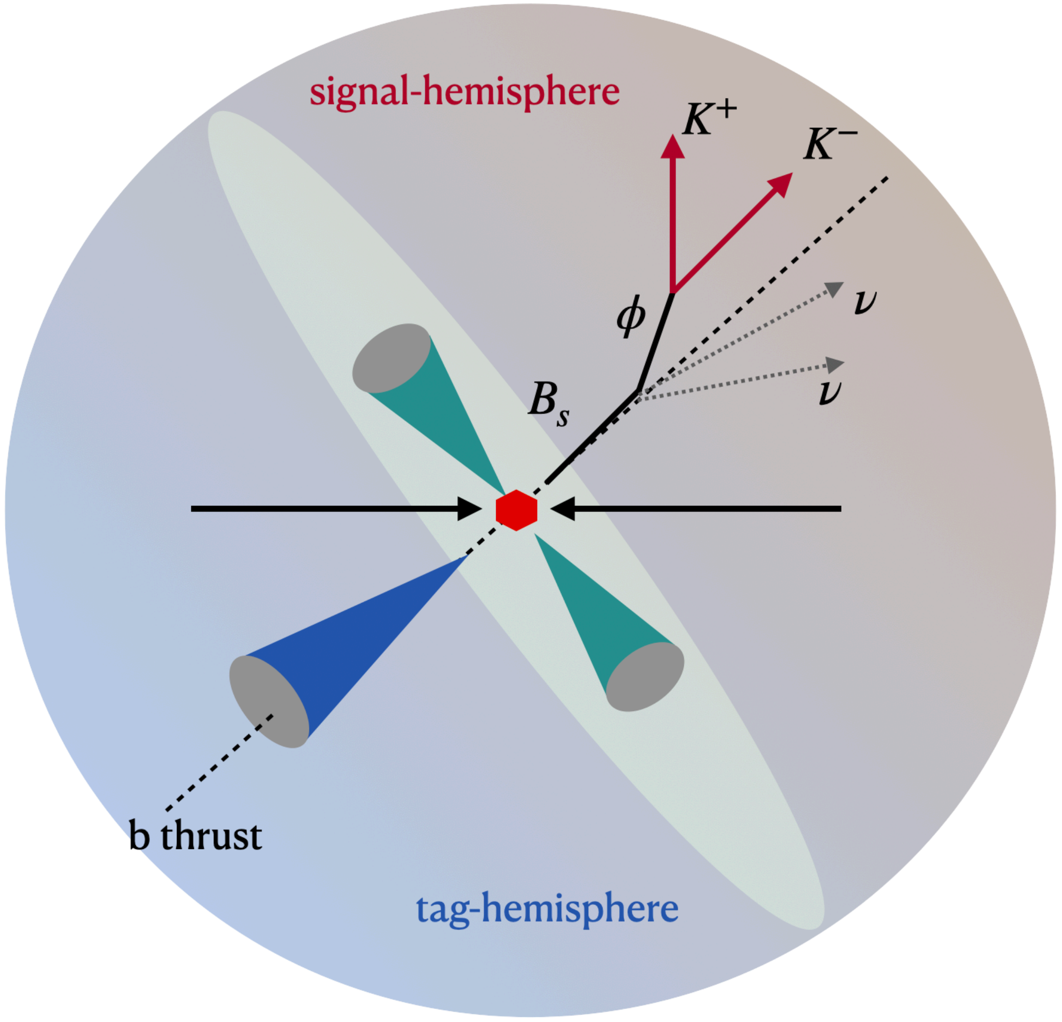
The dominant background contain all relevant 2-jets continuum events, $Z \to q\bar{q}$ $(f = u, d, c, s, b) \simeq 7 \times 10^{11}$.

The data samples

The statistics of CEPC detector fully simulated $Z \to q\bar{q}$ samples are of $\mathcal{O}(10^7)$ level, limited by the storage and computational resources.

Another set of exclusive samples from ~10^9 raw $Z \to q\bar{q}$ MC samples will be used in the final analysis stage, to compensate the statistics in the final. They satisfy the conditions at truth level:

b or c produced, at least one neutrino produced, one $\phi \to K^+K^-$decay exists.



The signal topology, i.e., the charged kaon pair generated by the ϕ decay and the neutrino-induced missing energy

Events Selection

The analysis methods.

- Reconstruct the inclusive $\phi \to K^+K^-$ in $Z \to q\bar{q}$ events.
- Select the target signal ϕ tagging (by vertex distance, kaon impact parameter, ϕ energy).
- Choose the significant missing energy and ϕ energy events.
- Suppress the light-flavor and $c\bar{c}$ channel by b-tagging.
- Specific condition to remove the difficult exclusive background, such as the semi-leptonic decay of B and D meson occurred in heavy flavor.
- Loose the cut conditions in above steps and used the BDTG method at last.

ϕ reconstruction

Reconstruction of inclusive $\phi(K^+K^-)$ in $Z \to q\bar{q}$ events

- Reconstruct all charged kaon tracks.
- Match all pairs of oppositely charged kaon tracks and use the kinematic fitting package LCFIPlus to reconstruct their vertex.
- Select kaon pairs with $\chi^2 < 8$ in the vertex fit and an invariant mass $|m_{K^+K^-} - m_\phi| < 10$ MeV.

$$\chi^2 = \sum_{i=1}^{2} \left(\frac{\left| V_i - V_{\text{fit}} \right|}{\sigma_i} \right)^2$$

where V_i, σ_i are the truth level vertex location uncertainty of the i-th track, and V_{fit} is the fitted vertex location.

The key points of ϕ reconstruction are the vertex fit and kaon PID.

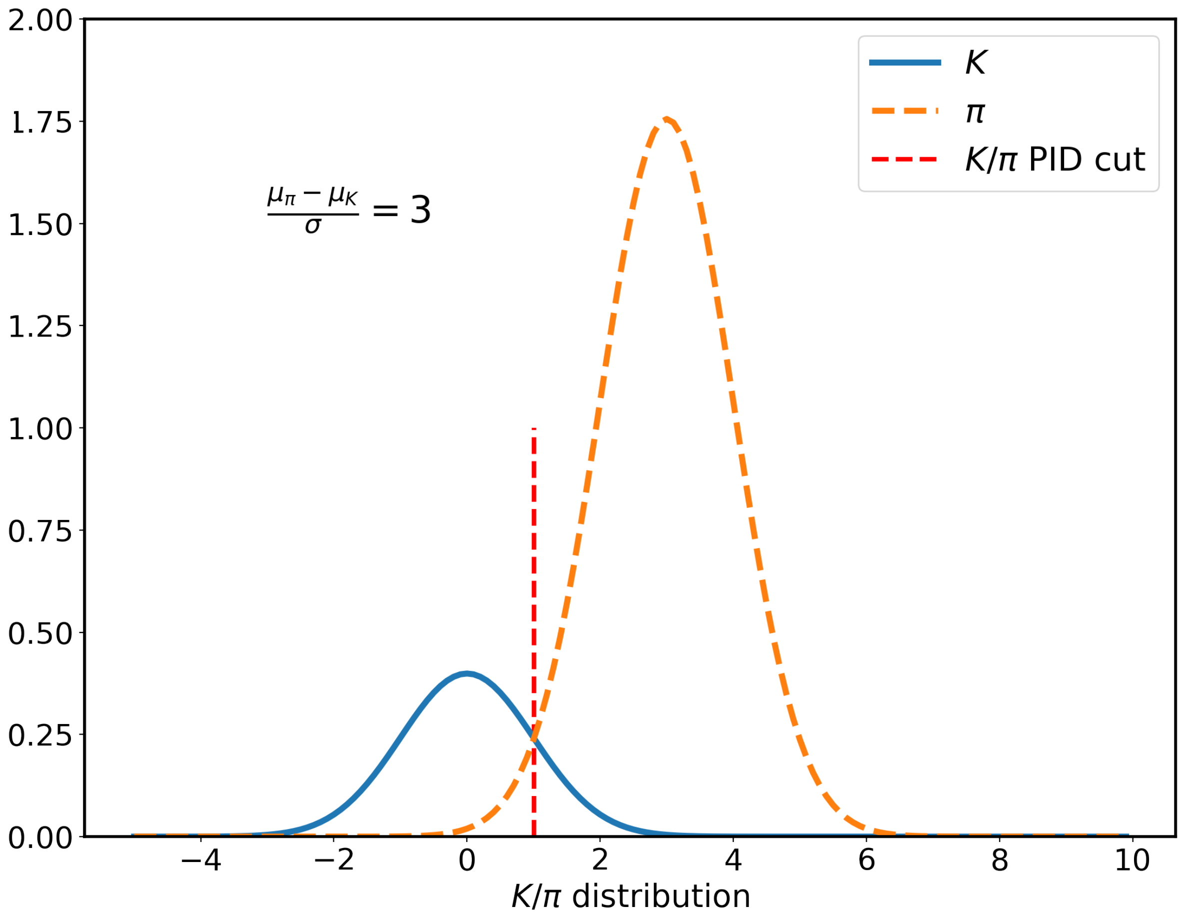
Kaon PID Performance

Kaon PID toy model

- Kaon PID resources: K/π misidentification (protons, muons are neglected since they are rarer)
- Gaussian distribution

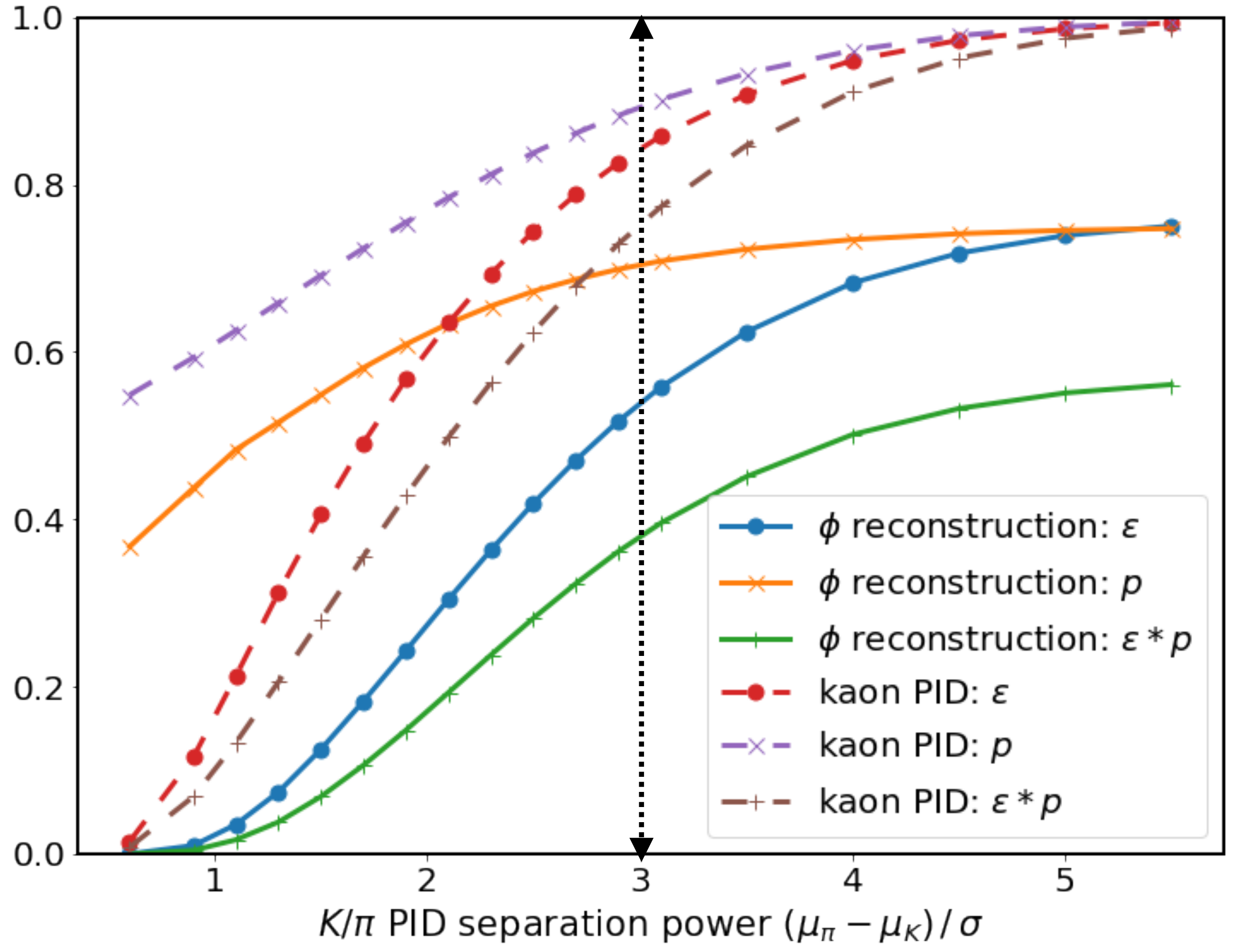
$$f(x) = \frac{N}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

- The relative track number : $N_\pi \simeq 4.4N_K$
- We use the identical σ for both K and π
- The kaon PID is evaluated by the K/π separation power, $\frac{\mu_K - \mu_\pi}{\sigma}$ (There is also the convention use $\sqrt{2}\sigma$ here).
- The cut for K/π PID is chosen by the intersections of the two gaussian.



The $\phi \to K^+K^-$ reconstruction performance dependence on the kaon PID.

The kaon PID and inclusive $\phi \to K^+K^-$ reconstruction performance with varying K/π separation power.



For a specific ϕ reconstruction, such as the $B_s \to \phi\nu\bar{\nu}$ target, constrains on the vertex distance and kaon impact parameters could optimize the ϕ reconstruction effectively.

By kaon impact parameter > 0.05 mm, ϕ vertex distance > 0.4 mm, signal-hemi identify.

$\epsilon, p = 54\,\%, 70\,\% \to 98\,\%, 75\,\%$

According to the CEPC CDR , a K/π separation power greater 3σ can be achieved for tracks harder than 1 GeV, we choose this PID value in the following analysis.

The sensitivity of branch ratio as a function of kaon PID will also be shown in later.

ϕ reconstruction by 3σ separation power Kaon PID

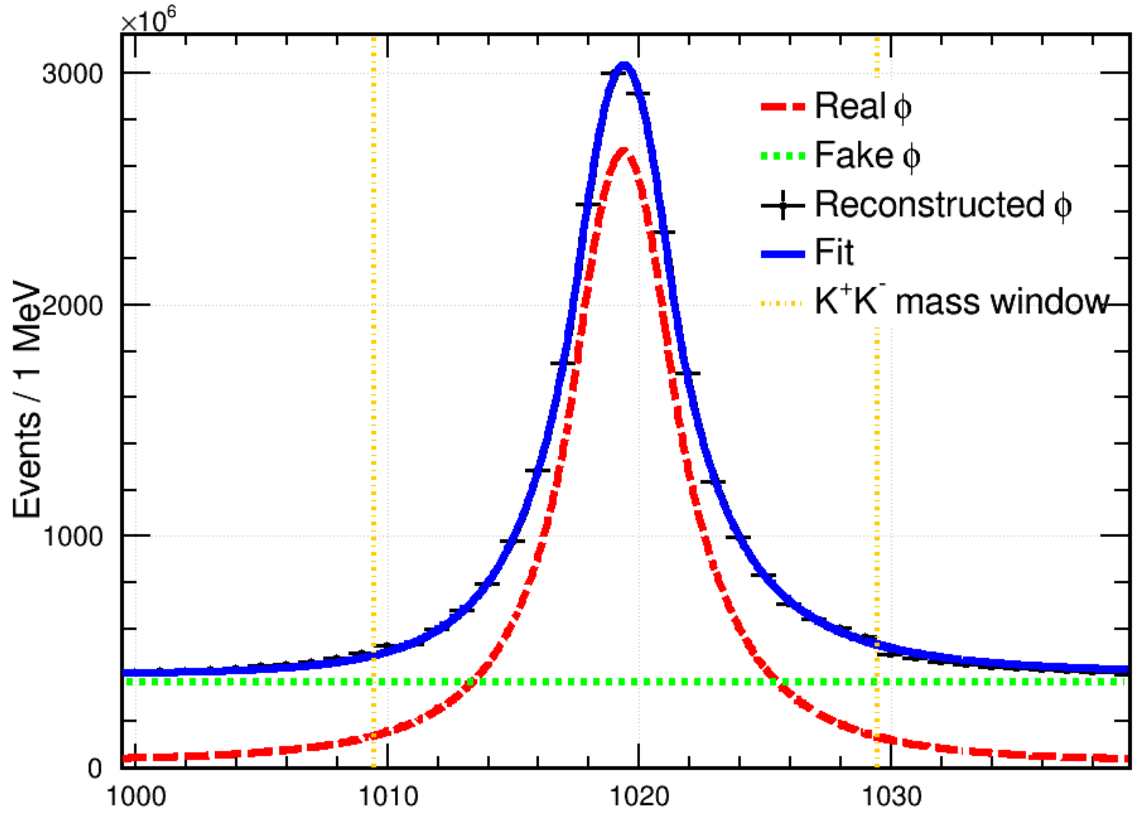
Define the efficiency and purity to evaluate the ϕ reconstruction performance

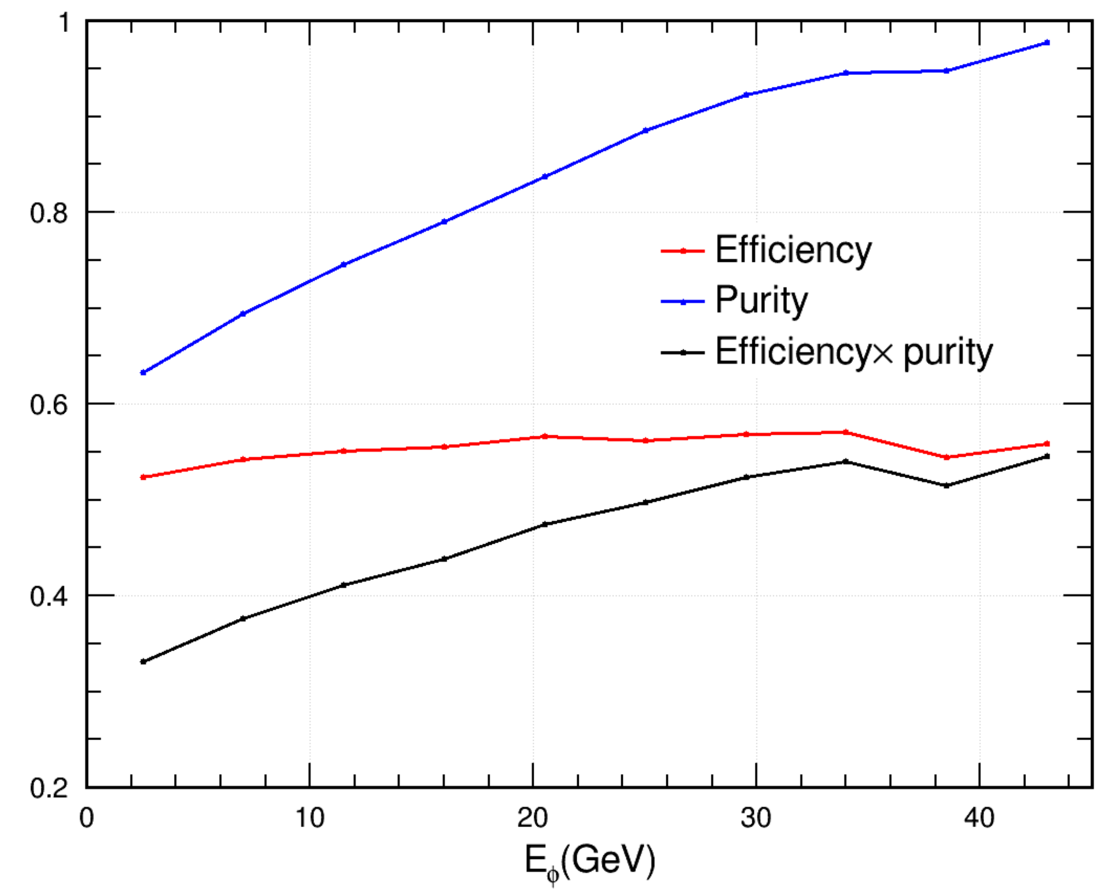
$$\epsilon = \frac{\text{Number of correctly selected track pair candidates}}{\text{Number of } \phi \to K^+K^- \text{ events}}$$

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

Integrated efficiency and purity are achieved by

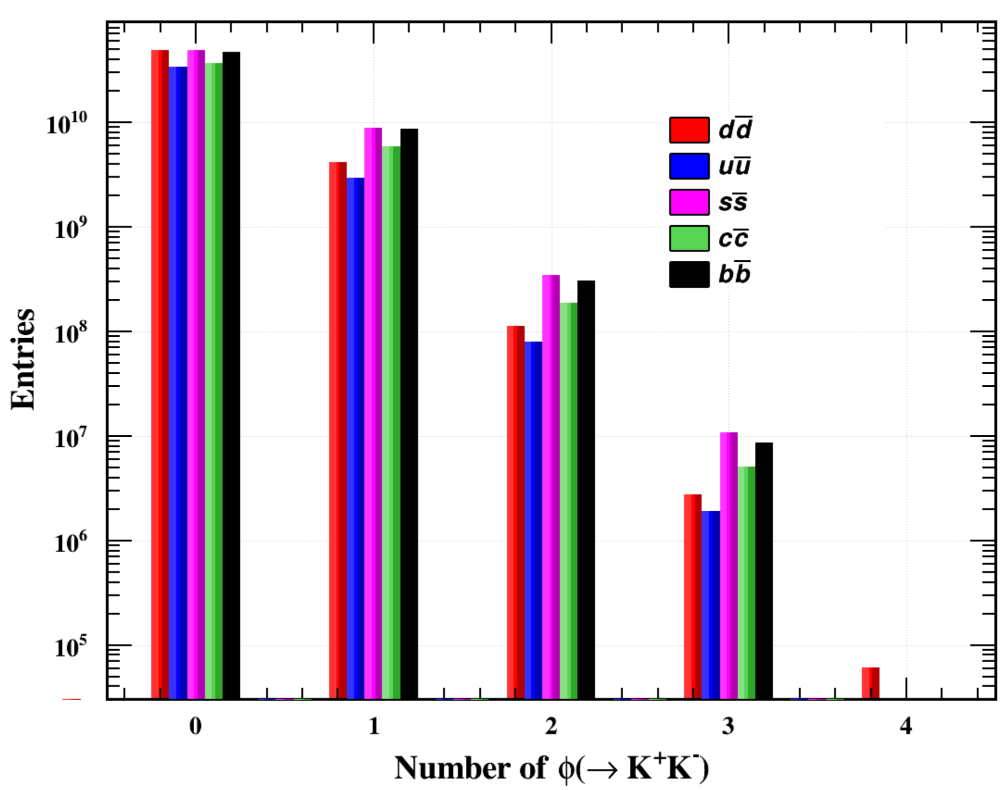
$$\epsilon, p = 54\,\%, 70\,\%$$



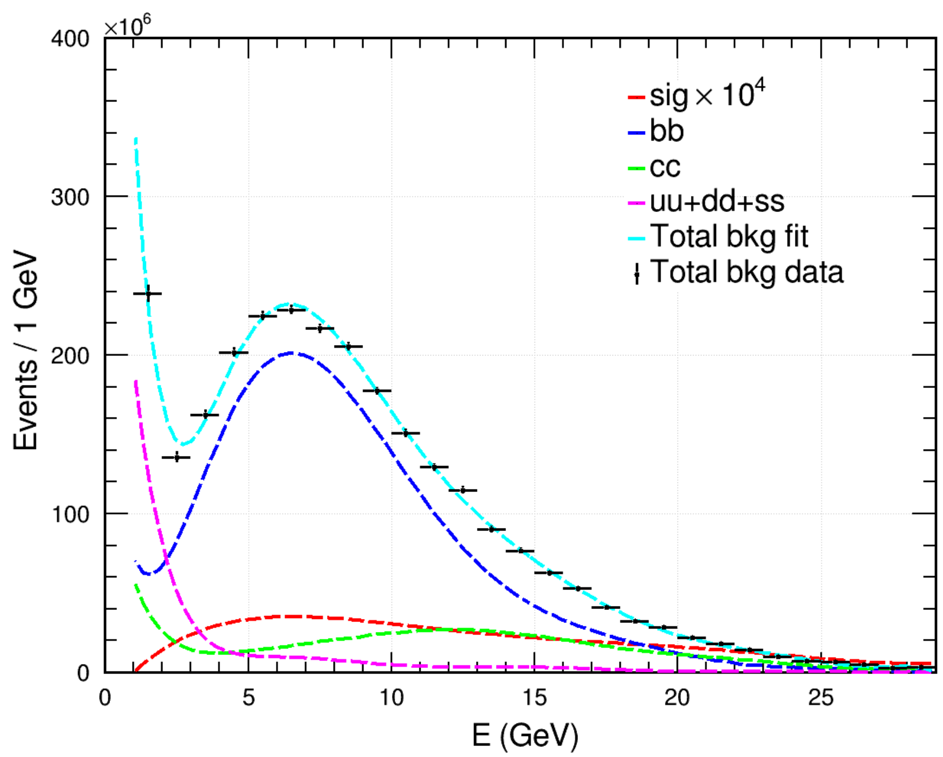


Inclusive $\phi(K^+K^-)$ production rate (%)	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$Z \to q\bar{q}$
distance$<$ 0.01 mm	2.72	2.71	5.99	2.48	1.94	3.26
distance$>$ 0.01 mm	0.04	0.04	0.04	2.73	4.22	1.40
total	2.76	2.75	6.03	5.21	6.16	4.66

TABLE I. The $\phi \to K^+K^-$ production rate for each $Z \to q\bar{q}$ channel. The distance of ϕ is defined by its decay vertex with respect to the interaction point. The light-flavor channels ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$), ϕ are mainly produced via QCD process. For the heavy-flavor channels ($c\bar{c}$ and $b\bar{b}$), both situation have a significant proportion.



The number of $\phi \to K^+K^-$ for each 2-jets channel in 10^{12} $e^+e^- \to Z$ events at Z-pole in truth-level.

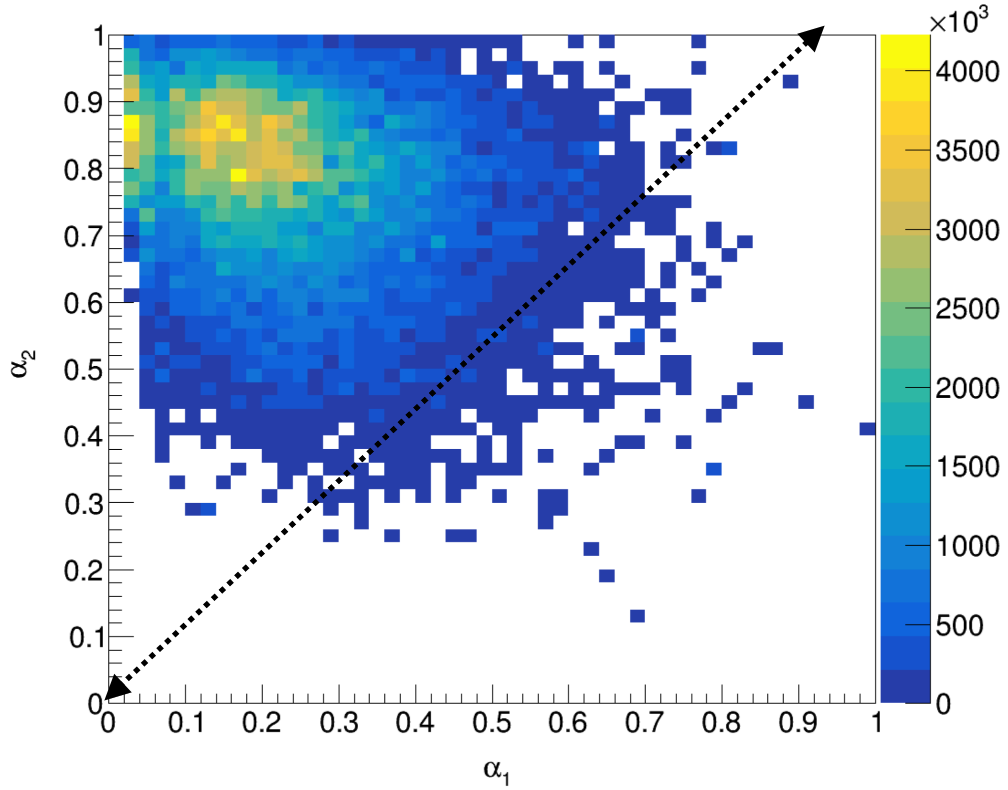


The fitted energy distributions of the leading candidate ϕ in the signal hemisphere, kaon impact parameter > 0.05 mm, ϕ vertex distance > 0.4 mm

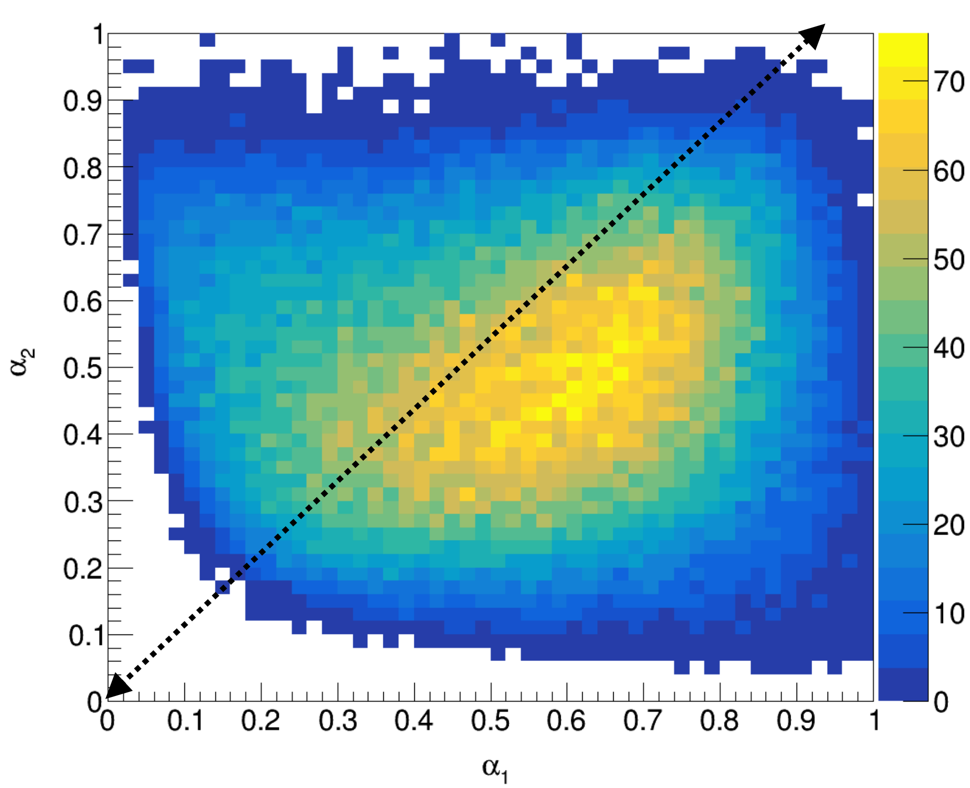
The distribution of some representative variables used in the analysis

The scaled variables α_1, α_2 and α are defined by

$$\alpha_1 \equiv \frac{E_\phi}{E_{\mathrm{sig}}}, \alpha_2 \equiv \frac{E_{\mathrm{sig}}}{E_{\mathrm{beam}}}, \alpha \equiv \frac{\alpha_2}{\alpha_1} = \frac{\left(E_{\mathrm{sig}}\right)^2}{E_{\mathrm{beam}}\,E_\phi}$$



$Z \to q\bar{q}$ background



Signal

Considering the topology of signal decay :

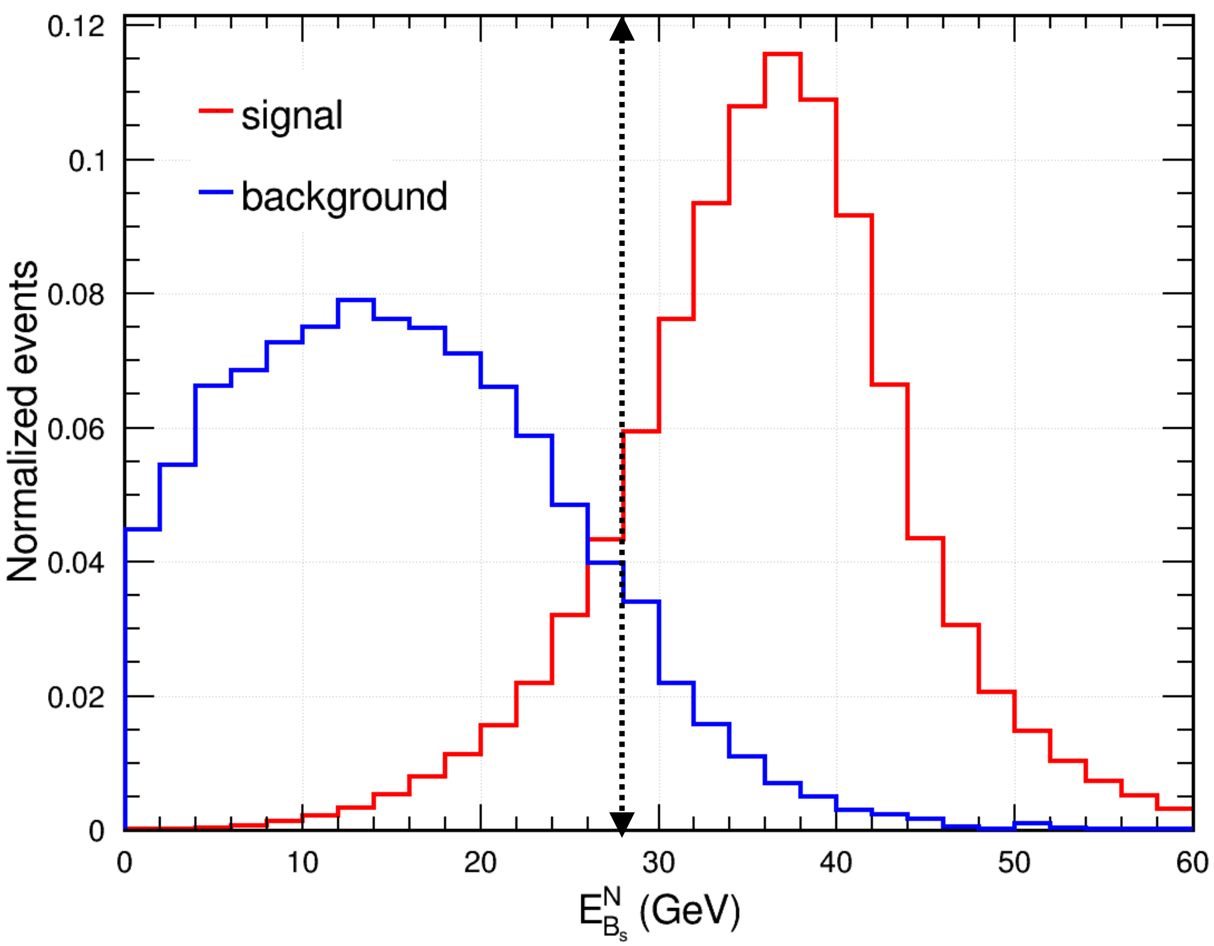
1) Most energy of the signal hemisphere should come from the ϕ → a large α_1.

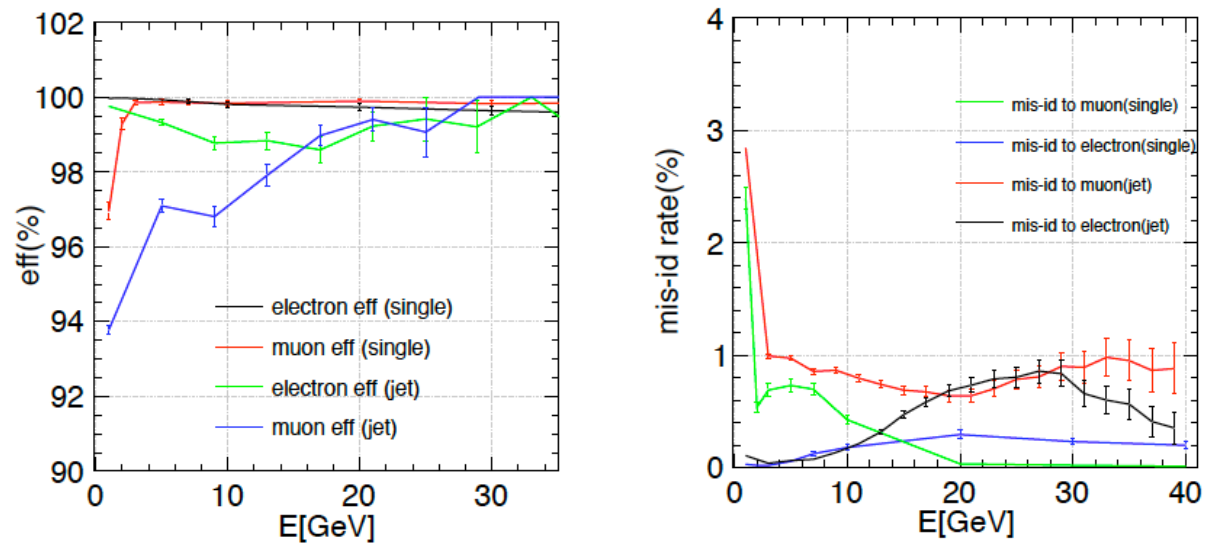
2) Missing energy from the B_s meson has the same significant effect as ϕ → a relatively small α_2.

3) Use the line that $\alpha = 1.1$ to separate background and signal.

The nominal B_s energy defined by

$$E^{N}_{\mathrm{B_s}} \equiv \sqrt{s} - E_{\mathrm{tot}} + E_{\phi}$$





Charged lepton (muon and electron) identify by DanYu.

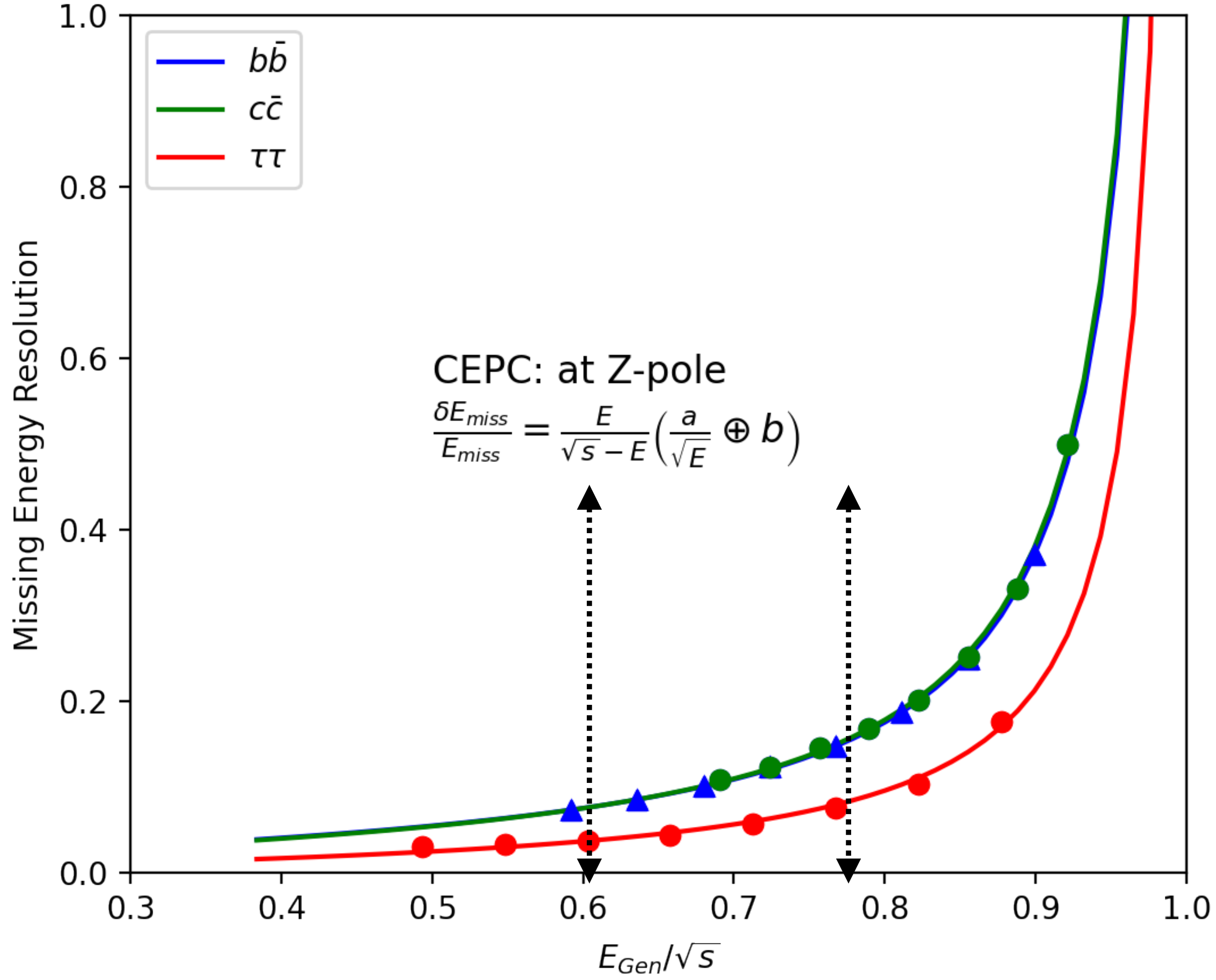
There will be no hard leptons in the signal hemisphere, thus the energy of charged lepton is constrained to be less than 1.2 GeV according to the lepton PID.

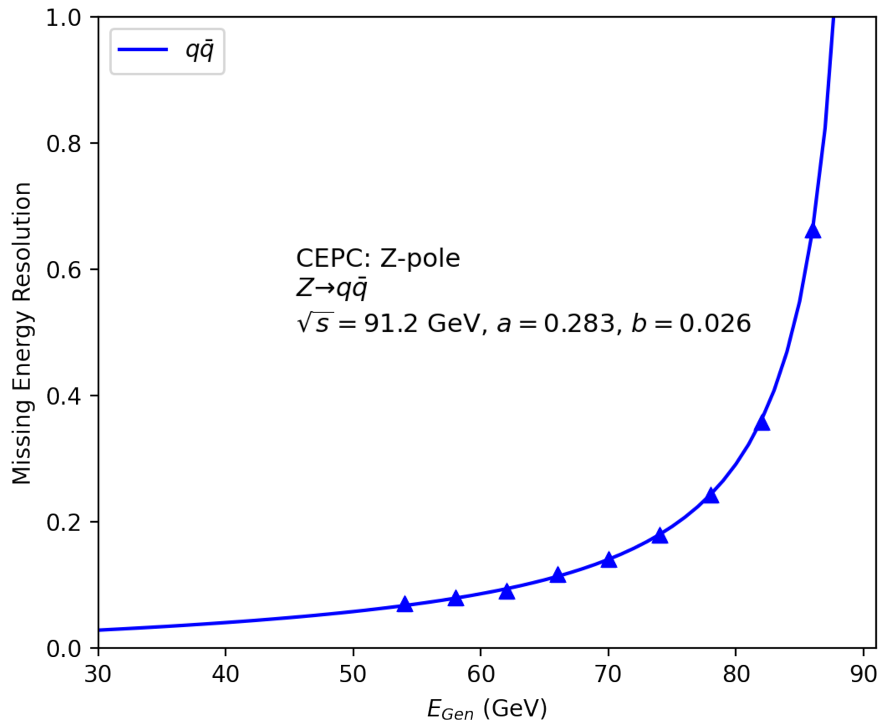
Missing Energy Resolution

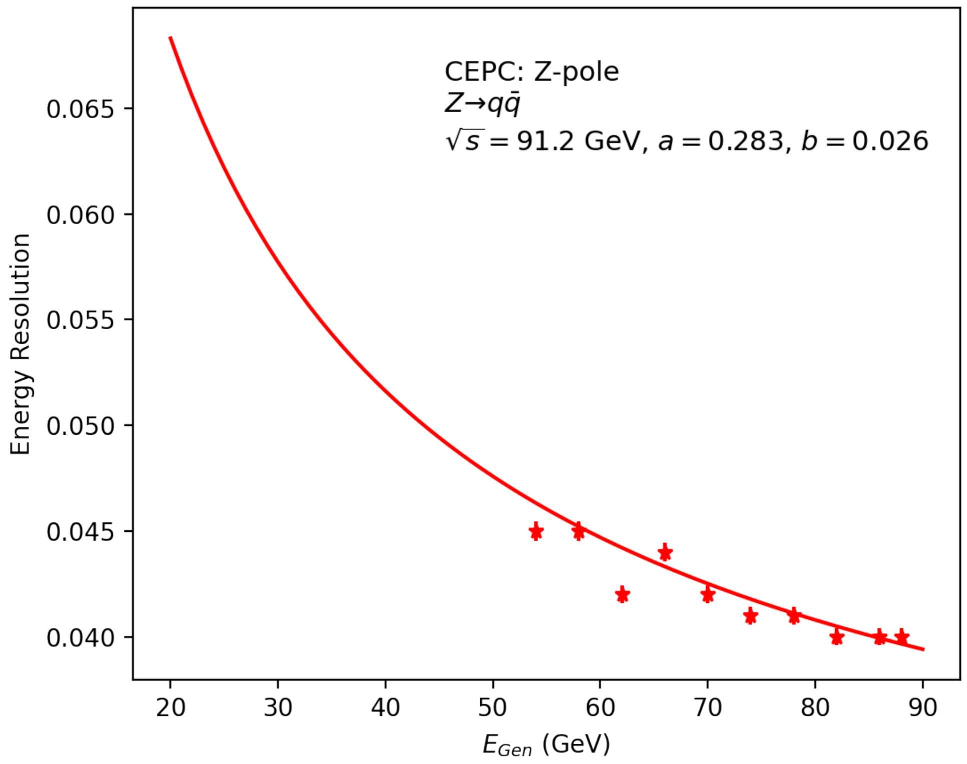
The missing energy resolution in events reconstruction play vital role for the signal decay search.

$$E_{\text{miss}} = \sqrt{s} - E_{tot}$$

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







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

A rough estimating of q^2, i.e. the invariant mass of $\nu\bar{\nu}$, and B_s energy could be used by:

$$p_{miss} = p_{total} - p_{vis}, \quad E^N_{B_s} = \sqrt{s} - E_{total} + E_\phi$$

have large error.

We proposed an optimization algorithm.

$$E^{(0)}_{B_s} = \frac{\sqrt{s}}{2} - E_{\rm sig} + E_\phi$$

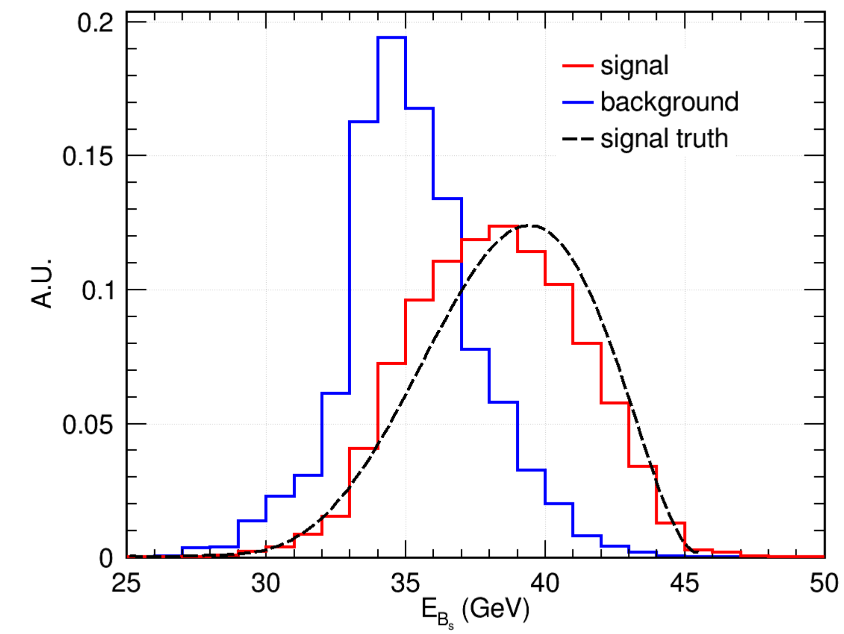
$$M_{\rm tag} = \sqrt{\left(\sum p^{\rm vis}_{\rm tag}\right)^2}$$

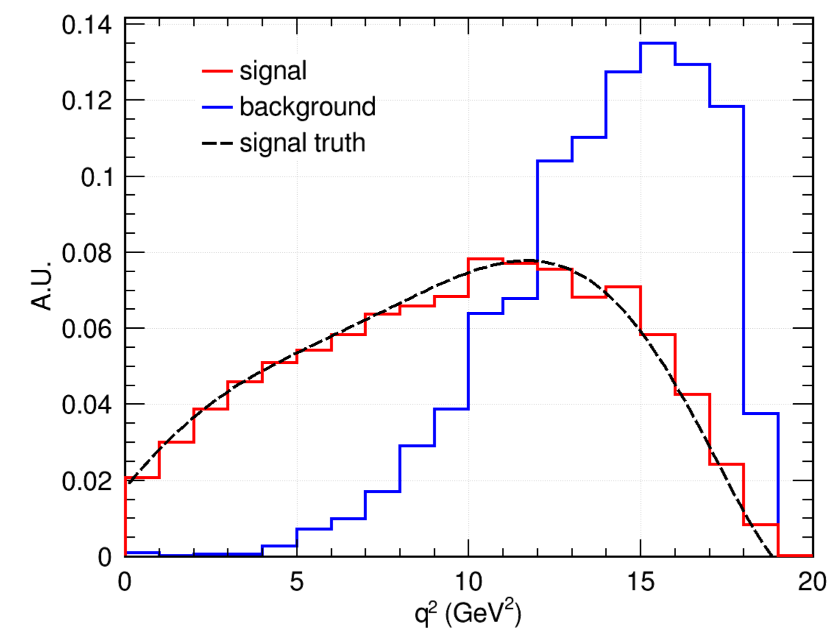
$$M^{(i)}_{\rm sig} = \sqrt{\left(\sum p^{\rm vis}_{\rm sig} + p^{(i-1)}_{B_s} - p_\phi\right)^2}$$

$$E^{(i)}_{B_s} = \frac{s + \left(M^{(i-1)}_{\rm sig}\right)^2 - M^2_{\rm tag}}{2\sqrt{s}} - E_{\rm sig} + E_\phi$$

$$\left(q^2\right)^{(i)} = \left(p^{(i-1)}_{B_s} - p_\phi\right)^2$$

we solve above equation iteratively to get a self- Bs consistent signal reconstruction. In this analysis, it turns out to converge quickly, leaving little room for improvement after the first iteration. Therefore, we choose the values of the first iteration .



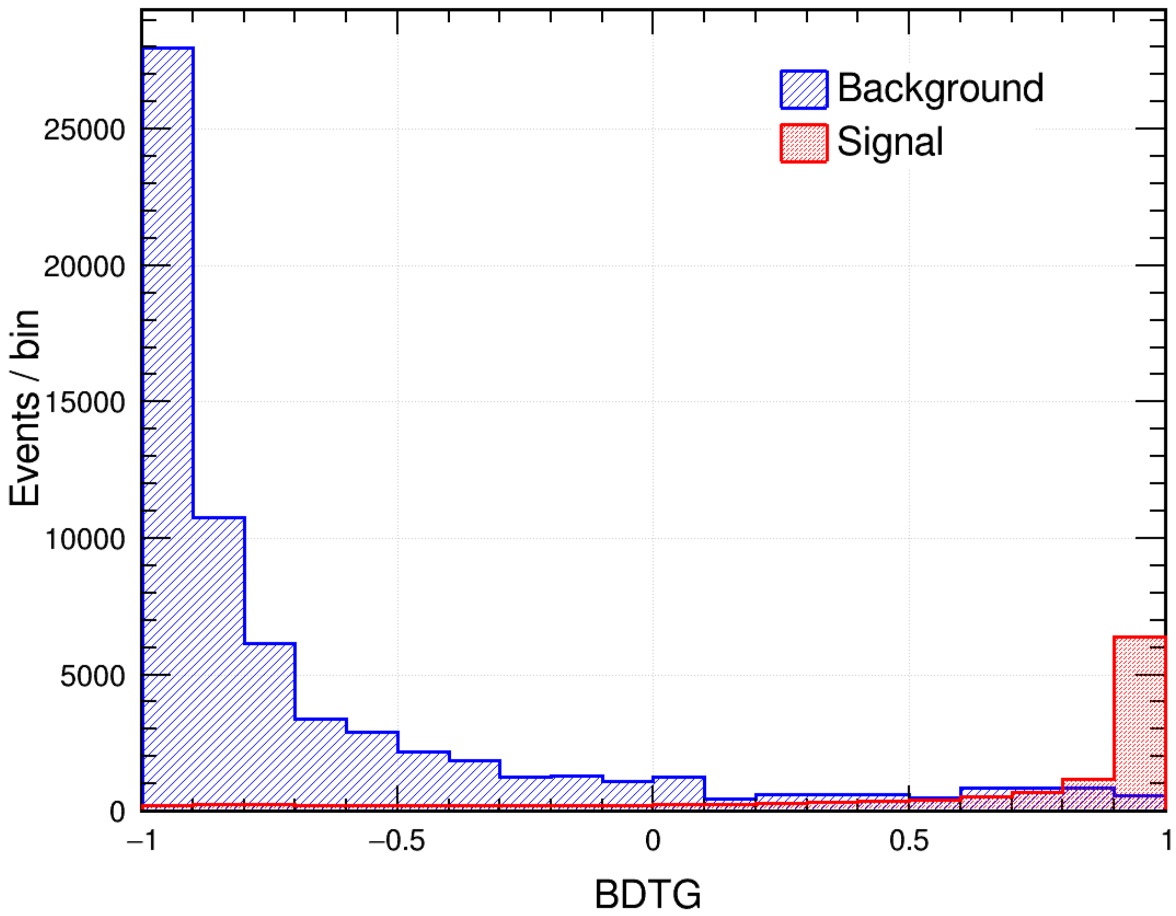


The typical reconstruction error for q^2 and E_{B_s} are 2.5 GeV^2 and 1.7 GeV, respectively.

Optimization by the BDTG method

- General event-shape variables: energy asymmetry and $E_{B_s}^N$.
- The largest impact parameter of all tracks.
- Parameters α_1 and α_2
- The angle $\theta_\phi^{\text{miss}}$.
- The invariant mass of all visible particles, so as the

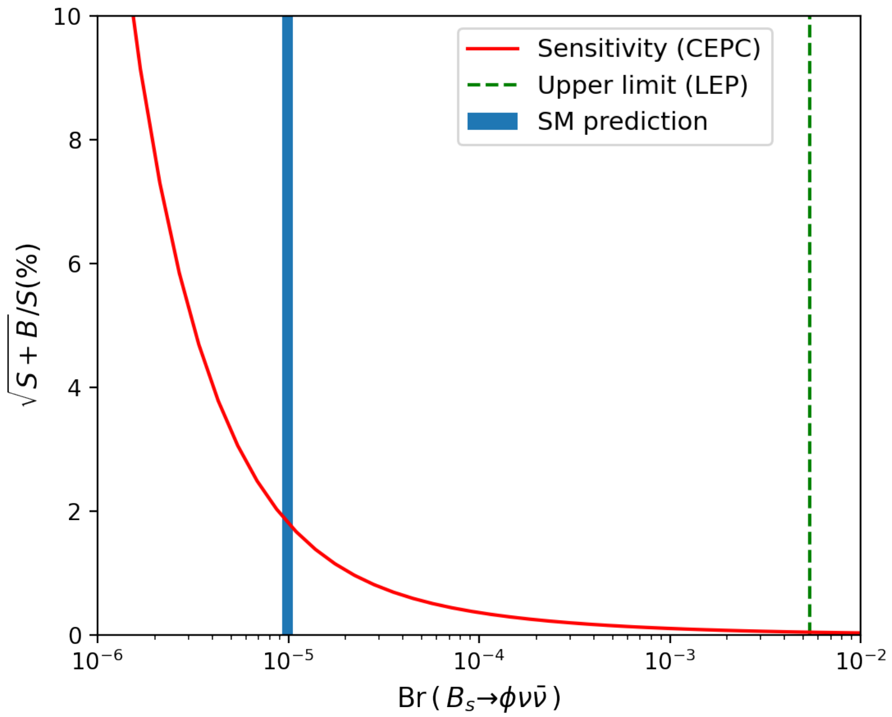
  visible particle invaraint masses in the tag/signal hemisphere.
- Reconstructed E_{B_s} and q^2.
- The leading electron and muon energies in the signal hemisphere.
- The largest track impact parameter in the signal hemisphere, excluding kaons from any reconstructed ϕ.
- Kaon tracks' impact parameters from the signal ϕ.



BDTG responses to test samples, where signal and background distributions peak at −1.0 and 1.0, respectively. With the optimized cut of BDTG response at 0.75, we reject almost 97% $b\bar{b}$ and $c\bar{c}$ backgrounds at the cost of a 38% signal loss.

Results

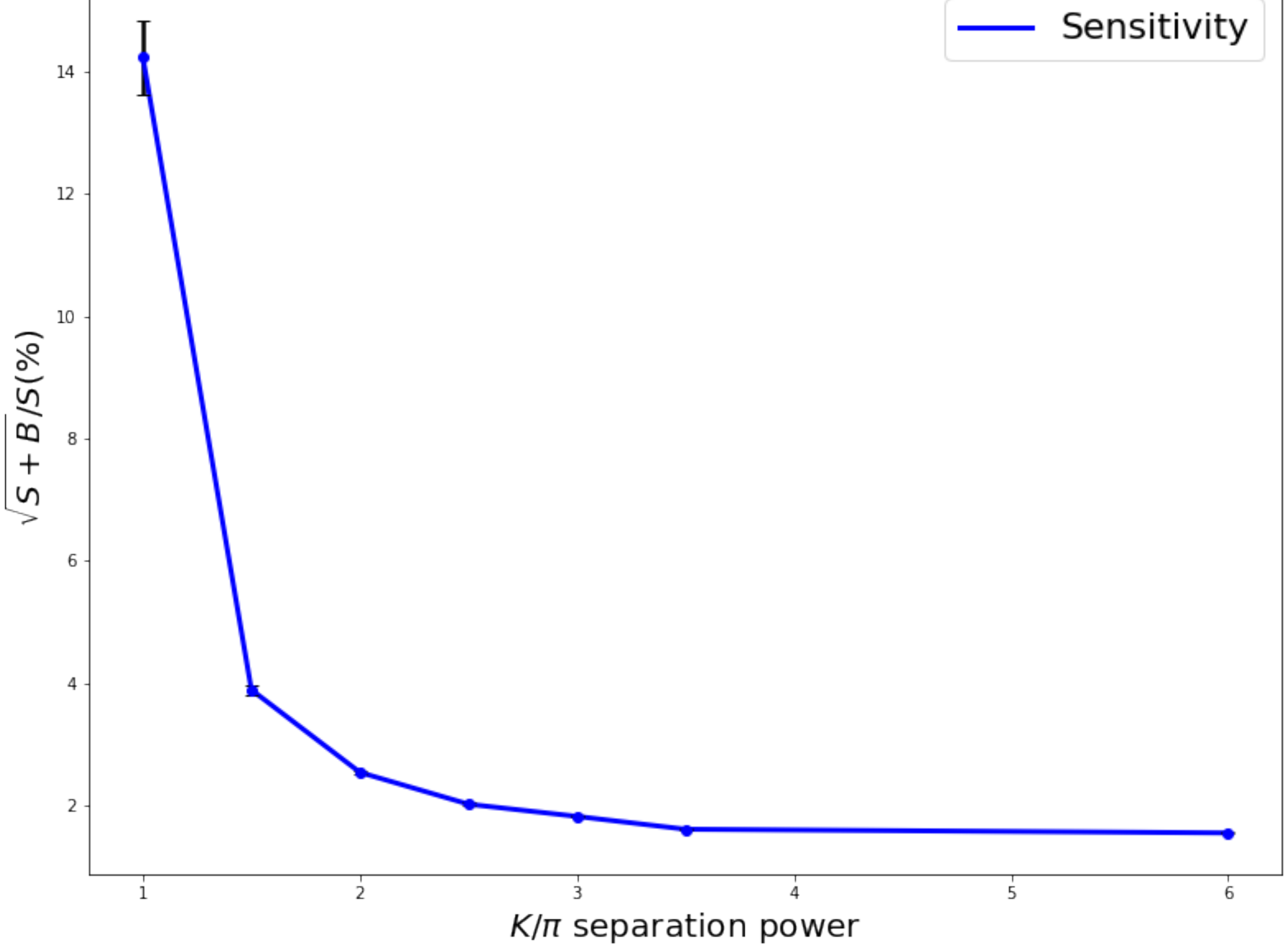
$Z \to q\bar{q}$ with full simulation samples and scaled to the integrated luminosity that 10^{12} bosons at CEPC. The kaon PID are simulated with 3σ K/π separation power in the table.

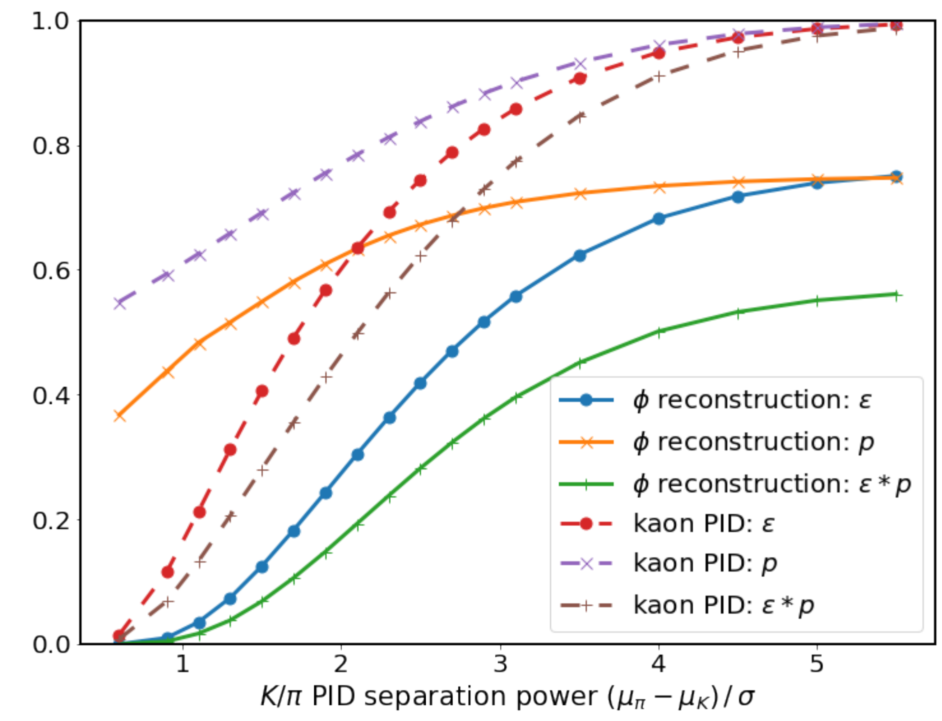


Cuts	$B_s \to \phi\nu\bar{\nu}$	$u\bar{u}+d\bar{d}+s\bar{s}$	$c\bar{c}$	$b\bar{b}$	total bkg	$\sqrt{S+B}/S$ (%)
CEPC events ($10^{12}Z$)	3.03×10^{5}	4.28×10^{11}	1.20×10^{11}	1.51×10^{11}	6.99×10^{11}	276
$N_{\phi(\to K^+K^-)} > 0$	8.86×10^{4}	1.25×10^{10}	4.62×10^{9}	6.99×10^{9}	2.41×10^{10}	175
[a] "Signal" ϕ	5.89×10^{4}	2.95×10^{8}	4.46×10^{8}	1.93×10^{9}	2.68×10^{9}	87.9
Energy asymmetry > 8 GeV	5.18×10^{4}	7.38×10^{7}	1.08×10^{8}	5.63×10^{8}	7.45×10^{8}	52.7
$E^N_{B_s} > 28$ GeV	4.43×10^{4}	5.83×10^{6}	1.08×10^{7}	5.56×10^{7}	7.22×10^{7}	19.2
$\alpha < 1.1$	3.31×10^{4}	2.53×10^{6}	3.32×10^{6}	1.02×10^{7}	1.61×10^{7}	12.4
b-tag > 0.6	2.55×10^{4}	$< 2.0\times10^{4}$	3.69×10^{5}	7.08×10^{6}	7.45×10^{6}	10.7
E_μ and $E_e < 1.2$ GeV	2.29×10^{4}	-	5.81×10^{4}	2.04×10^{6}	2.10×10^{6}	6.36
$\theta^{\mathrm{miss}}_{\phi} > 0.1$ rad	1.93×10^{4}	-	2.62×10^{4}	1.34×10^{6}	1.37×10^{6}	6.10
$q^2 < 14.0$ GeV^2	1.46×10^{4}	-	2.09×10^{4}	5.95×10^{5}	6.16×10^{5}	5.44
BDTG response> 0.75	0.91×10^{4}	-	0.21×10^{4}	1.61×10^{4}	1.82×10^{4}	1.82
Efficiency	3.00%	-	1.75×10^{-8}	1.07×10^{-7}	2.60×10^{-8}	-

[a] The candidate ϕ here satisfy the following conditions: 1) In the signal hemisphere. 2) The impact parameters of both kaon pair tracks are larger than 0.05 mm. 3) The distance of ϕ decay vertex to interact point(IP) is larger than 0.4 mm. 4). The energy less than 45 GeV.

The sensitivity of branch ratio depending on the kaon PID





Constrains on wilson coefficients

ϕ longitudinal polarization fraction F_L measurement

It could be related to the angle θ differential distribution.

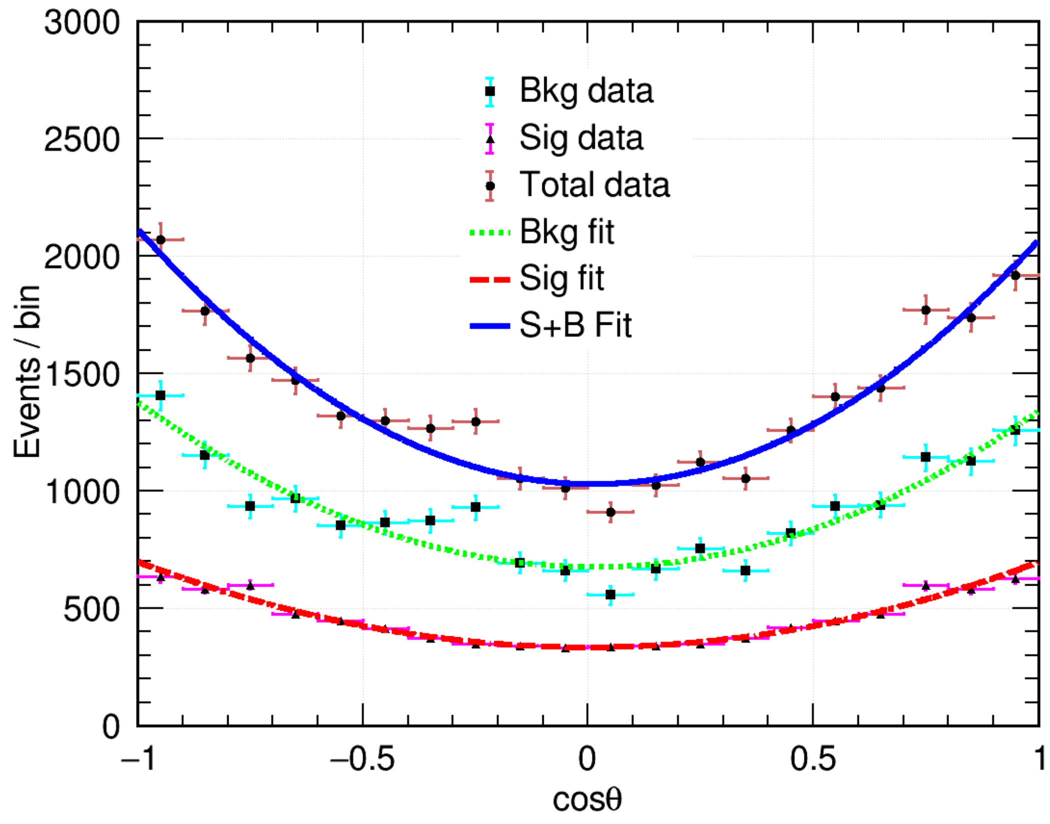
$$\frac{d\Gamma}{d\cos\theta} = \frac{3}{4}\left(1 - F_L\right)\sin^2\theta + \frac{3}{2}F_L\cos^2\theta$$

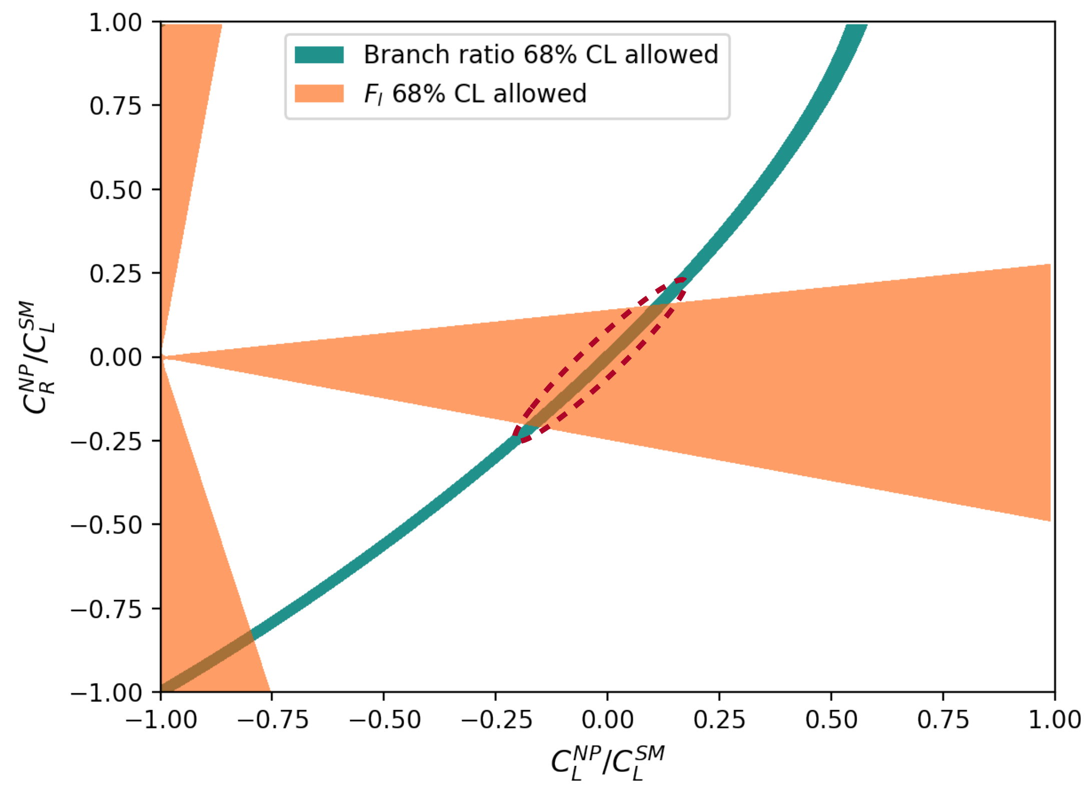
where θ is the angle between B_s and K^+(or K^-) in the ϕ rest frame.

$$\sigma_\theta = 0.047 \text{ rad}$$

$$F_L = 0.53 \pm 0.04 \pm 0.008$$

Combined the F_L and BR($B_s \to \phi\nu\bar{\nu}$) sensitivity at CEPC, a tight constrain region in $C_L^{NP} - C_R^{NP}$ plane could be obtained .





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 1.82 % 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
  - Kaon PID (sensitivity could reach 1.5 % in perfect PID).

End

Thanks