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# Study of Electroweak Phase Transition in Exotic Higgs decays at the CEPC


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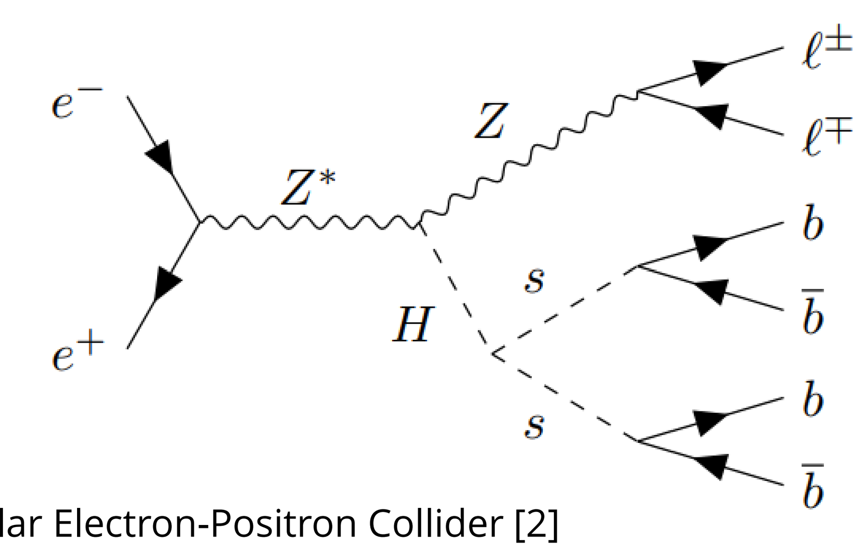
## Introduction

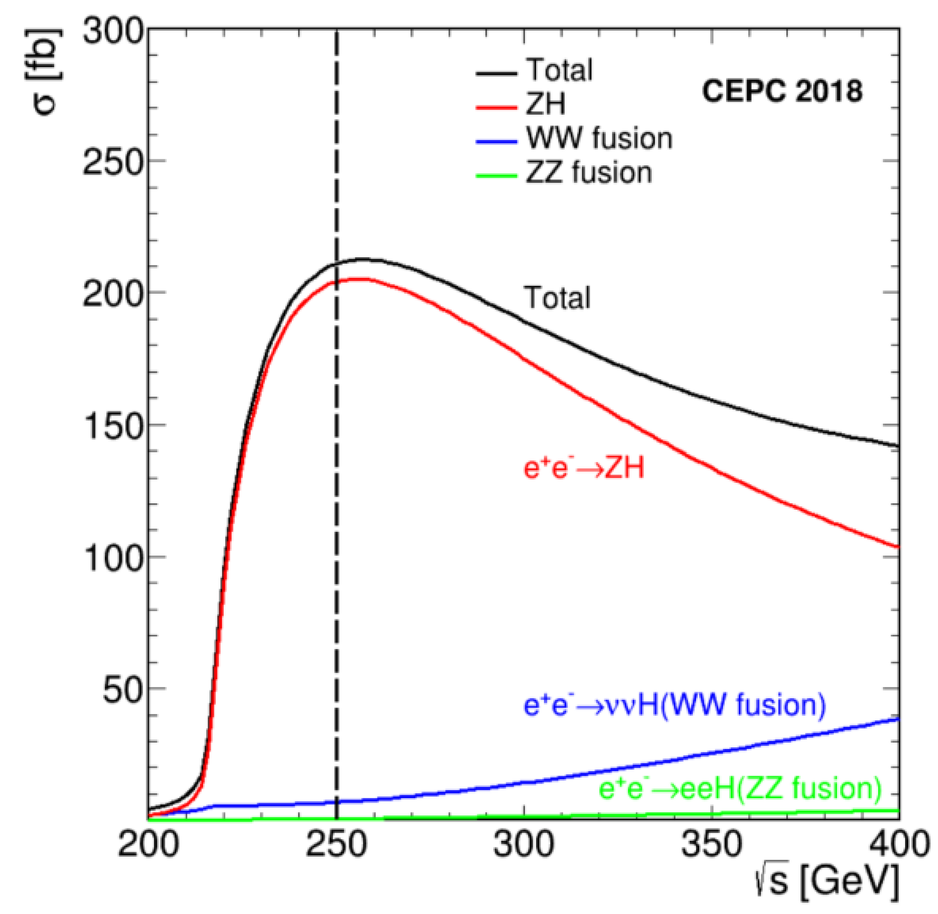
A strong first-order electroweak phase transition (EWPT) can be induced by light singlet ($S$) weakly coupled to the SM Higgs boson ($H$) [1]

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}a_1|H|^2S + \frac{1}{2}a_2|H|^2S^2 + b_1S + \frac{1}{2}b_2S^2 + \frac{1}{3}b_3S^3 + \frac{1}{4}b_4S^4$$

The two scalar fields $h$ and $s$ can mix to produce the mass eigenstates

$$h_1 = h\cos\theta + s\sin\theta$$
$$h_2 = -h\sin\theta + s\cos\theta,$$




The sensitivity is estimated at one of the proposed higgs factories, i.e. CEPC (Circular Electron-Positron Collider [2]

- Much more clean than hadron collider
- 5.6 ab-1 data at $\sqrt{s} = 240$ GeV
- ~1 million Higgs bosons ($e^+e^- \to ZH$) will be collected
- Sensitive to $s$ down to ~15 GeV
- Focus on $H \to ss \to 4b$ channel given it has the largest branching fraction

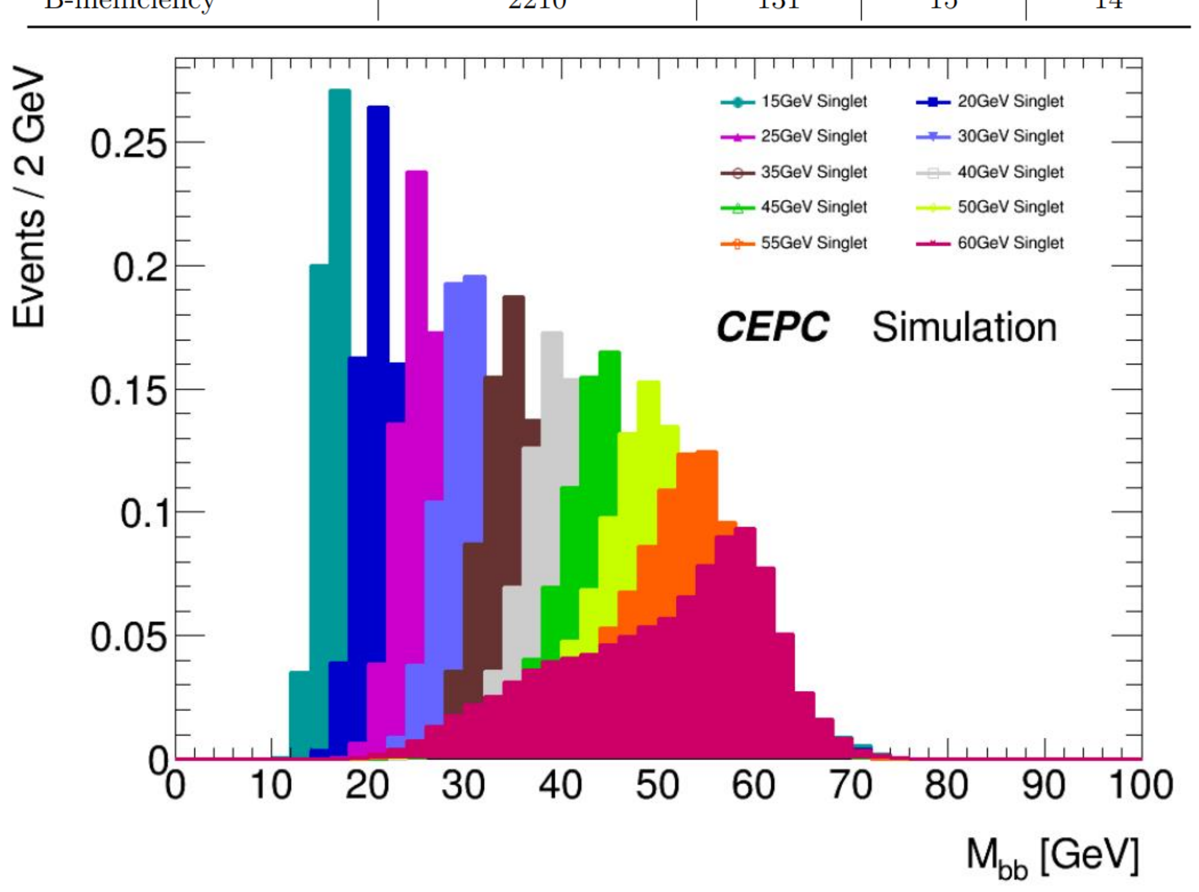
## Simulation and reconstruction

- The CEPC detector is consist of a low material tracking system, a high-granularity calorimeter system surrounded by a 3T solenoid and a muon detector
- MadGraph5_aMC@NLO and Whizard are used to generator signal and background processes.
- Parton showering and hadronization are done using Pythia
- The interactions with detector is simulated with Geant4
- The jet reconstruction and flavor tagging are done by LCFIPlus [3] including integrates vertex finding, jet reconstruction and flavor tagging.
- Jets are reconstructed by Durham algorithm[4]. Exclusive clustering is performed to reconstruct exactly four jets in the final state.

## Event selections

- Two isolated leptons with opposite charge and E>20 GeV
- Open angle for 2 leptons: $|cos\theta_{e^+e^-}|$ < 0.71 or $|cos\theta_{\mu^+\mu^-}|$ < 0.81
- Z mass window: 77.4 – 104.5 GeV
- The recoil mass of 2 lepton is required to be [124, 140 ] GeV $M^{\ell\bar{\ell}}_{\rm recoil} = \sqrt{(\sqrt{s} - E_\ell - E_{\bar{\ell}})^2 - (\vec{P}_\ell + \vec{P}_{\bar{\ell}})\cdot(\vec{P}_\ell + \vec{P}_{\bar{\ell}})}$
- Exactly 4 jets with b-tagging information
- B-tagging is performed using jet kinematic variables, track impact parameters and secondary vertices

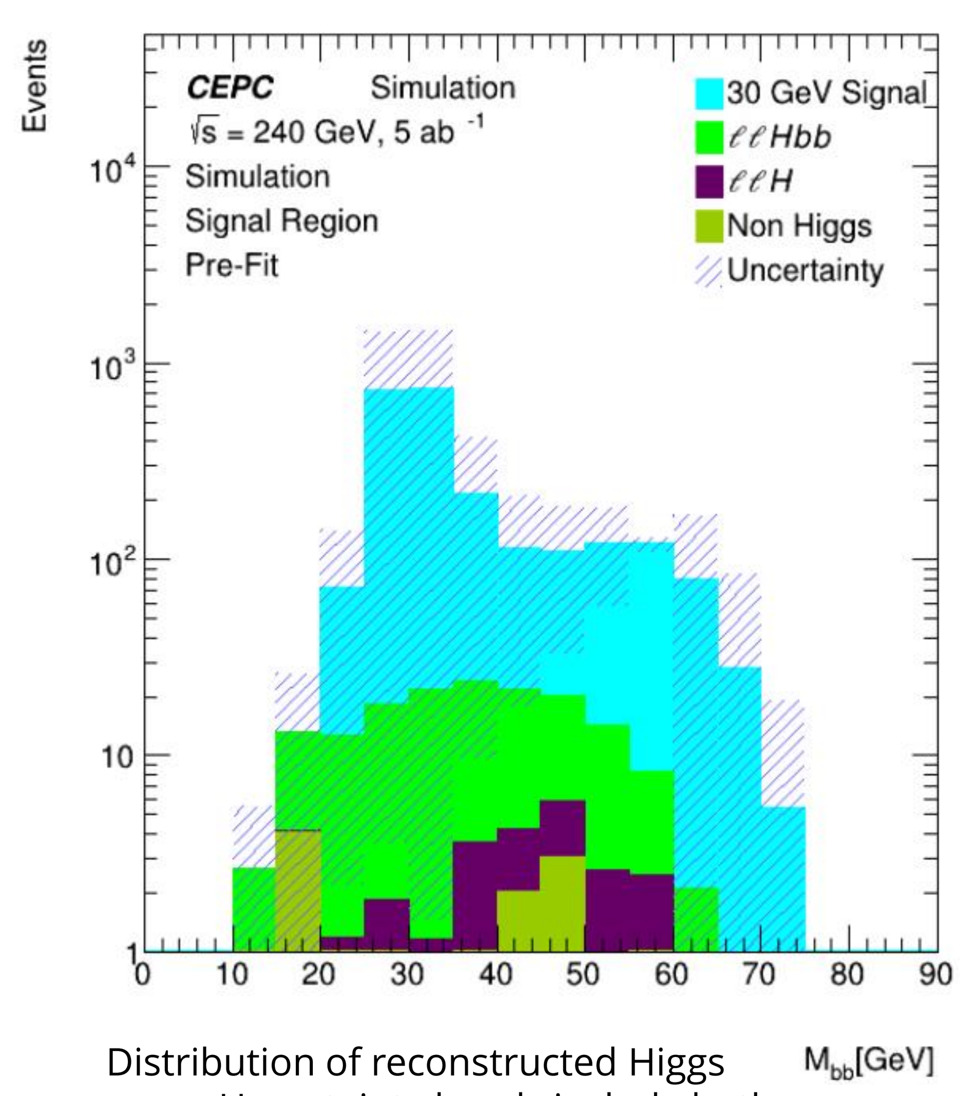
| Selection | Signal ($m_s = 30$ GeV) | $\ell\ell Hbb$ | other $\ell\ell H$ | non Higgs |
|---|---|---|---|---|
| Original | 8865 | $2.92 \times 10^4$ | $2.41 \times 10^4$ | $3.79 \times 10^7$ |
| Lepton pair selection | 6042 | $1.83 \times 10^4$ | $1.20 \times 10^4$ | $1.32 \times 10^6$ |
| Lepton pair mass | 5537 | $1.65 \times 10^4$ | $1.07 \times 10^4$ | $6.17 \times 10^5$ |
| Jet selection and pairing | 4054 | 7947 | 4661 | 3698 |
| B-inefficiency | 2210 | 131 | 15 | 14 |



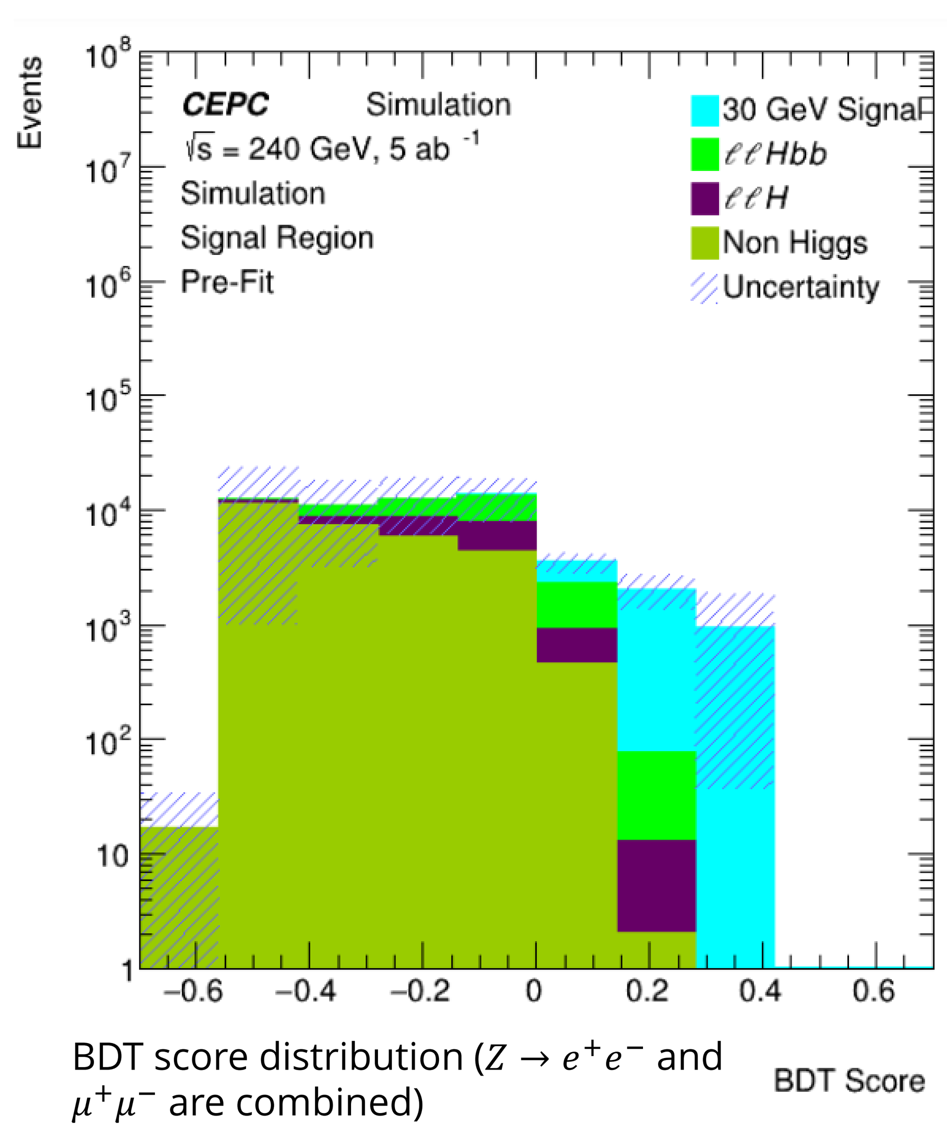

Normalized distribution for the new singlet mass ($s \to bb$)

## BDT training

- A BDT classifier is used to improve the sensitivity in the fitting and limit setting
- Input features:
  - Jet kinematic variables, opening angles, jets invariant and recoil masses, b-tagging information
- Background:
  - Higgs decay to $bb$
  - Higgs decay to others
  - Non-Higgs




Distribution of reconstructed Higgs mass. Uncertainty bands include both statistical and systematic uncertainties

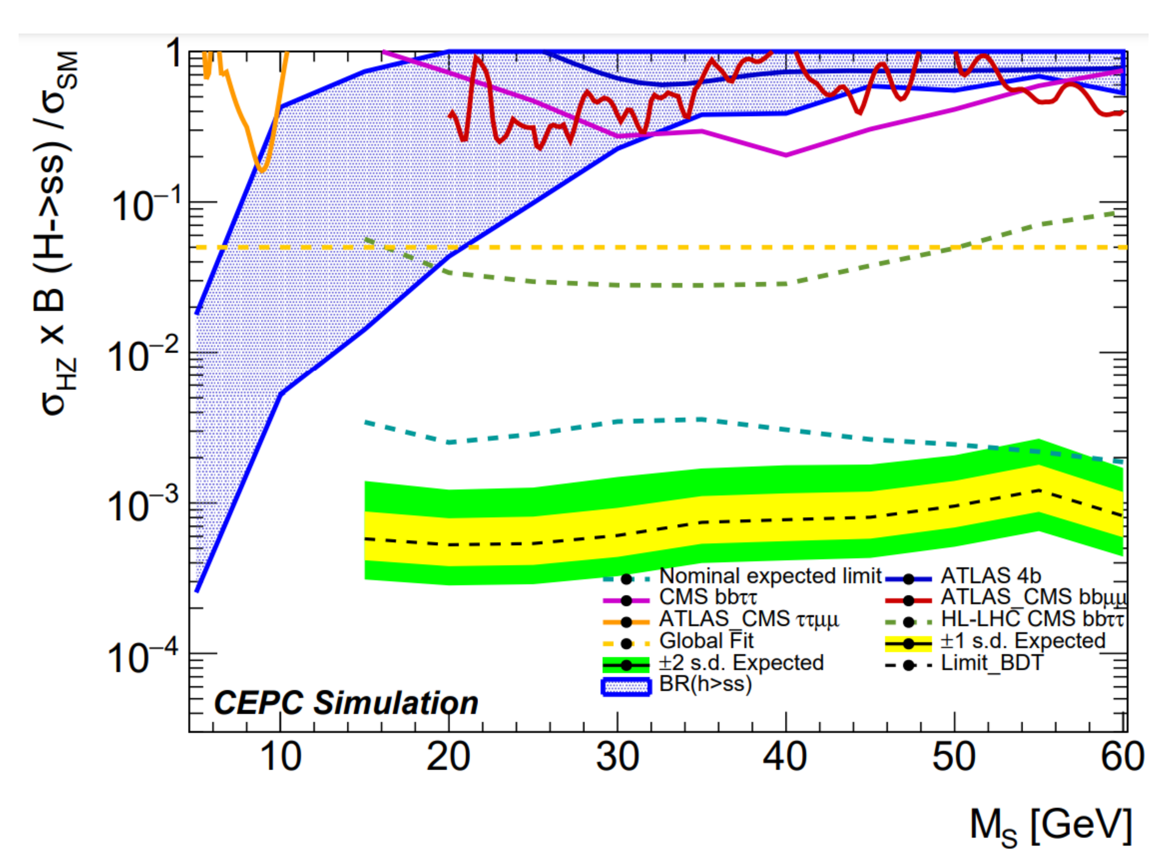



BDT score distribution ($Z \to e^+e^-$ and $\mu^+\mu^-$ are combined)

## Systematic uncertainty

- Background estimation:
  - Varies the branching fraction of $H \to bb$ by 5% and others by 100%
- B-tagging:
  - Conservatively take 1% from a control sample of $ZZ \to qq + \mu^+\mu^-$ [5]
- Jet Energy resolution:
  - Varies the jet energy by the expected calorimeter energy resolution
- Negligible uncertainty due to luminosity, tracking and lepton identification

## Summary




- Upper limit at 95% C.L. on cross section is estimated for the new singlet at mass from 15 to 60 GeV with all the systematic uncertainties
- BDT can improve the sensitivity significantly
- The expected limit from CEPC is lower than the current limit by 3 orders, and much better than HL-LHC projection

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