上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

Study of Electroweak Phase Transition in Exotic Higgs Decays with CEPC simulation

Zhen Wang, Xu-Liang Zhu, Yanda Wu, Yuwen Zhang, Elham Khoda, Shih-Chieh Hsu, Shu Li, M. J. Ramsey-Musolf

Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022

2022-05-25

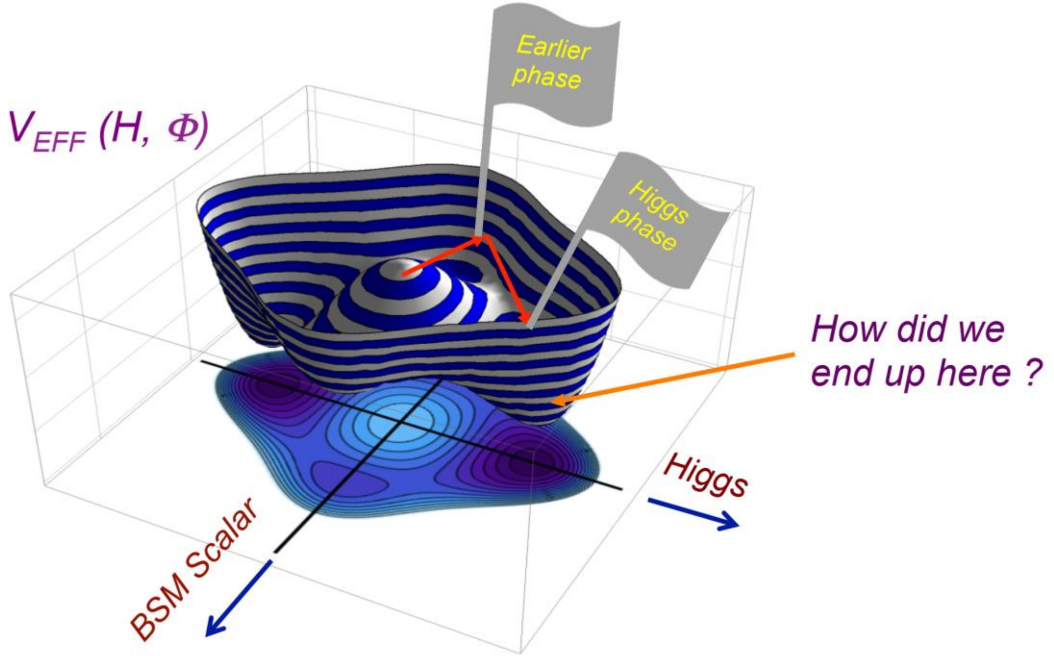
Physics Motivation

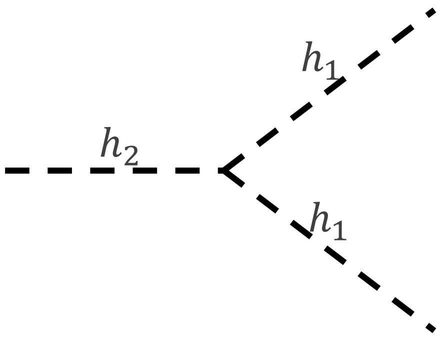
[J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).]

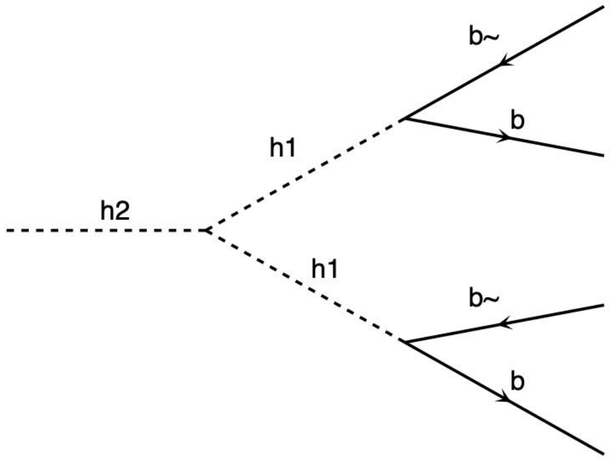
- We are interested in the strong first-order electroweak phase transition in the "SM Higgs + Light Real Singlet Scalar" model:

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

- Mass eigenstates: $h_1 = h\cos\theta + s\sin\theta$ (h_1 : singlet-like)
  $h_2 = -h\sin\theta + s\cos\theta$ (h_2 : SM-like Higgs)





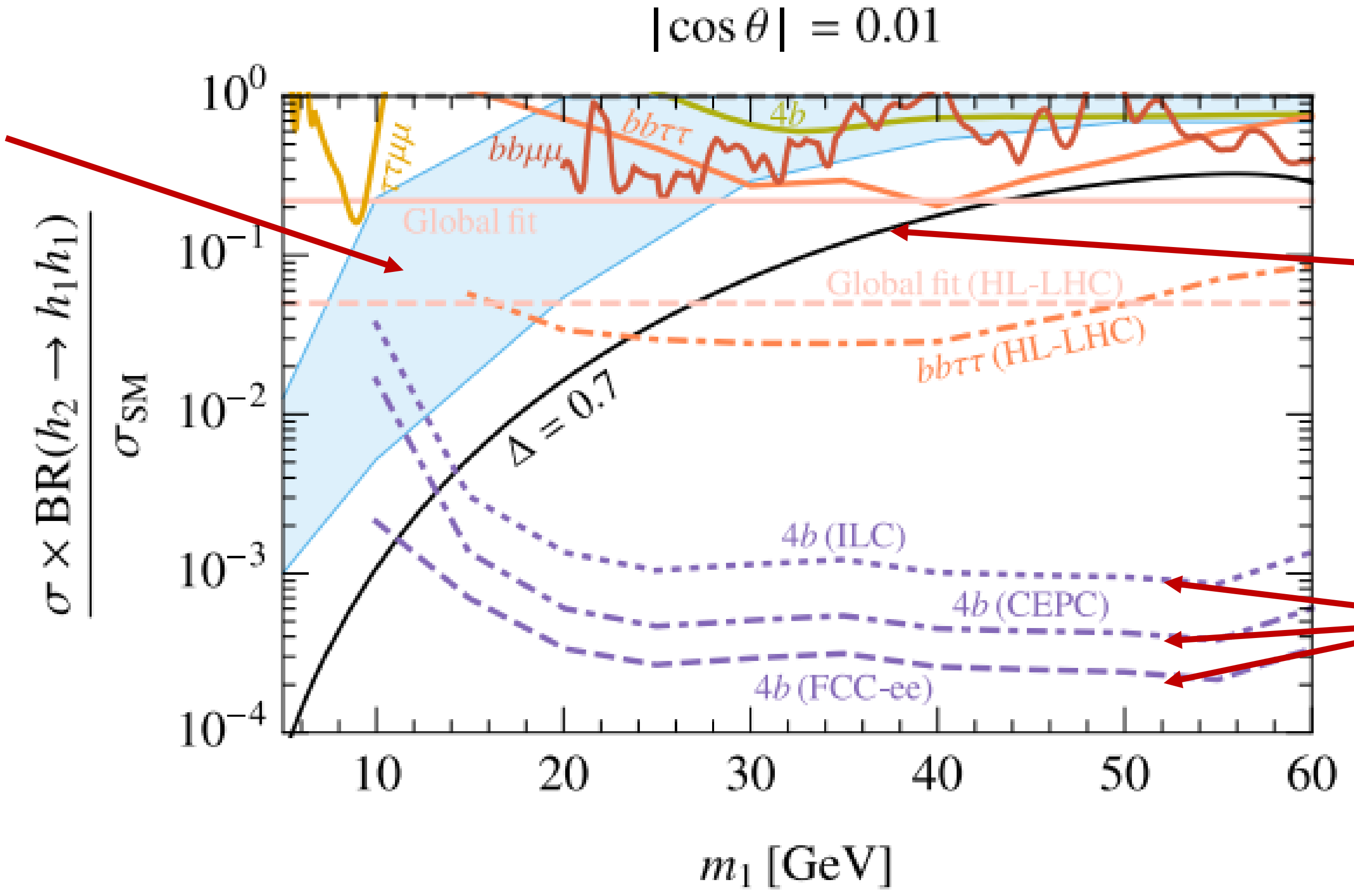


Extrema can evolve differently as T evolves
→ Rich possibilities for symmetry breaking

Theoretical Prospects

$h_2 \to h_1 h_1 \to 4b$

EWPT viable:
numerical



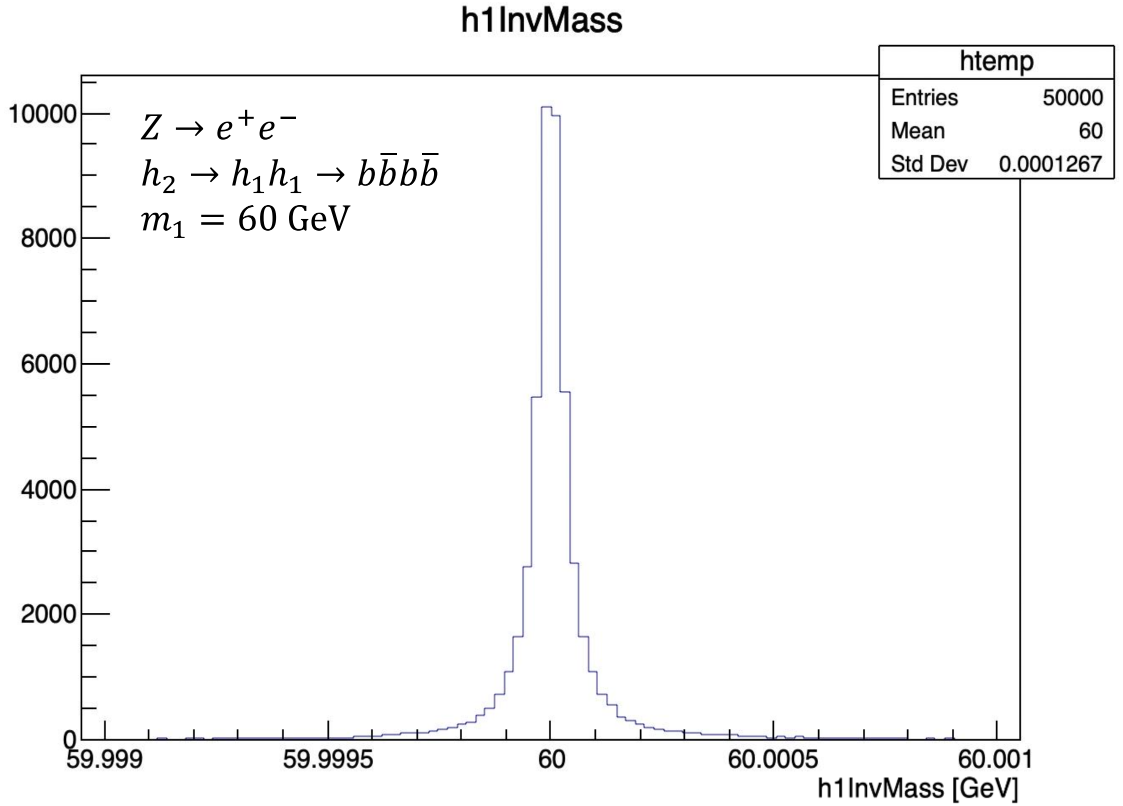
EWPT viable:
semi analytic

Future e^+e^-

[J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).]
[Z. Liu *et al., Chinese Phys. C* **41**, 063102 (2017).]

Sample Production

- **Signal:** The samples are generated at 240 GeV. 50000 events per mass point from 5 to 60 GeV for electron and muon channel separately
- **Generator:** Madgraph5 and Pythia8
- **Simulation and reconstruction:** cepcsoft 0.1.1 , CEPC_v4



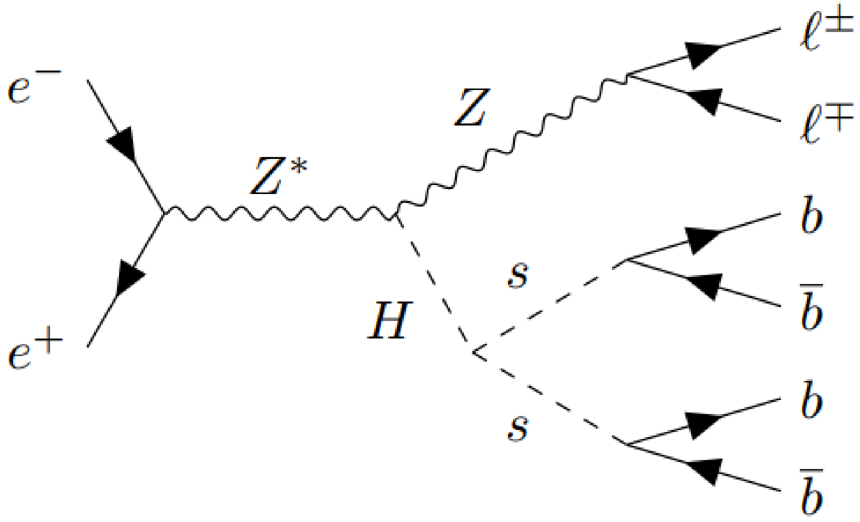


Fig. Mass distribution of h_1 when $m_1 = 60\text{GeV}$

Sample Production

- Background : 2-Fermion, 4-Fermion, Higgs involved process as our background. Expect luminosity : $5.0\ \mathrm{ab}^{-1}$.

Process	$\int L$	Final states	X-sections (fb)	Comments
Higgs signal	5 ab^{-1}	ffH	203.66	all signals
	5 ab^{-1}	e^+e^-H	7.04	including ZZ fusion
	5 ab^{-1}	$\mu^+\mu^-H$	6.77	
	5 ab^{-1}	$\tau^+\tau^-H$	6.75	
	5 ab^{-1}	$\nu\bar{\nu}H$	46.29	all neutrinos (ZH+WW fusion)
	5 ab^{-1}	$q\bar{q}H$	136.81	all quark pairs (Z→ $q\bar{q}$)

2 fermion backgounds

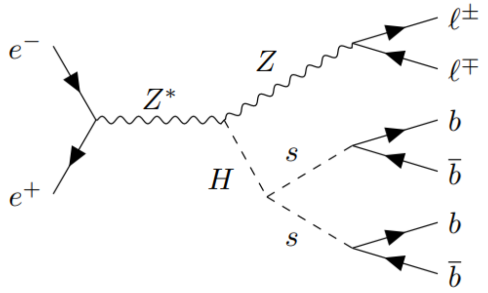
Process	$\int L$	Final states	X-sections (fb)	Comments
$e^+e^- \to e^+e^-$	5 ab^{-1}	e^+e^-	24770.90	

decay mode	branching ratio	relative uncertainty
$H \to b\bar{b}$	57.7%	+3.2%, −3.3%
$H \to c\bar{c}$	2.91%	+12%, −12%
$H \to \tau^+\tau^-$	6.32%	+5.7%, −5.7%
$H \to \mu^+\mu^-$	2.19×10^{-4}	+6.0%, −5.9%
$H \to WW^*$	21.5%	+4.3%, −4.2%
$H \to ZZ^*$	2.64%	+4.3%, −4.2%
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0%, −4.9%
$H \to Z\gamma$	1.53×10^{-3}	+9.0%, −8.8%
$H \to gg$	8.57%	+10%, −10%
Γ_H	4.07 MeV	+4.0%, −4.0%

https://iopscience.iop.org/article/10.1088/1674-1137/43/4/043002/pdf
http://cepcsoft.ihep.ac.cn/guides/Generation/docs/ExistingSamples/#240-gev
lxslc7 : /cefs/data/DstData/CEPC240/CEPC_v4_update

Cut Based Approach

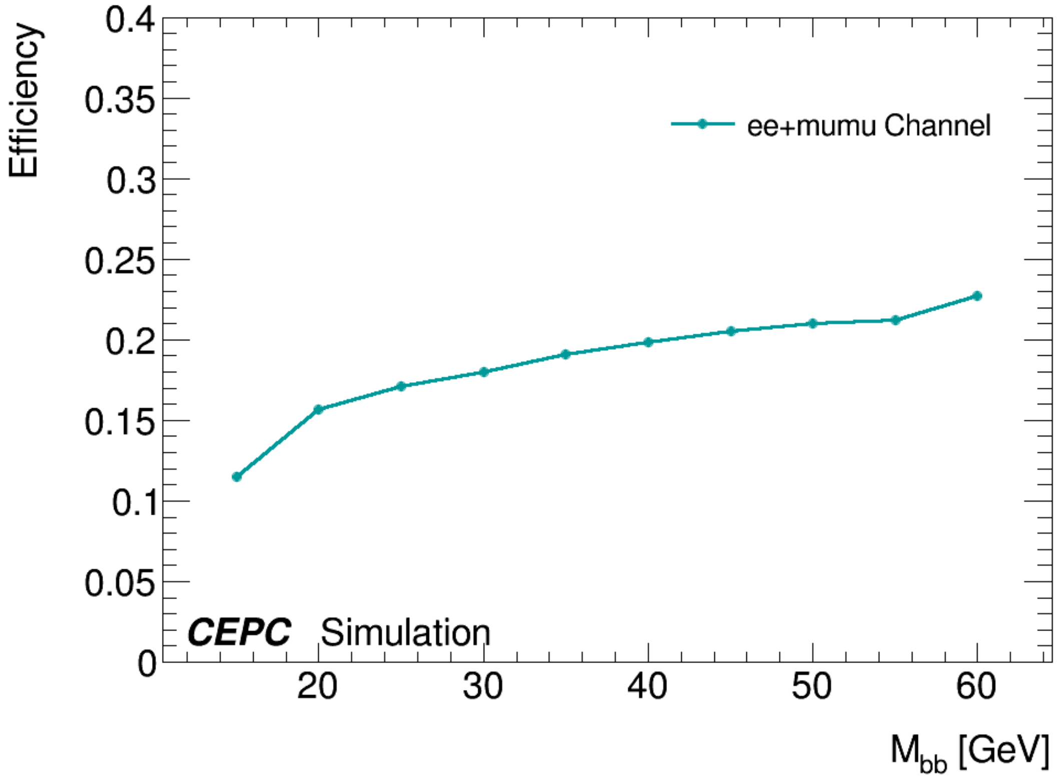
- Same flavor opposite sign lepton pair with energy larger than 20 GeV
- Invariant lepton pair mass should be within the Z mass window [77.5,104.5] GeV
- Recoiled mass of the lepton pair system should be within [124,140] GeV
- 4 jets are required to be reconstructed. Reconstructed S particle is decided by pairing them 2 by 2 and find the set with smallest mass difference.
- Number of energetic particles(energy > 0.4 GeV) in the 4jets should be larger than 40
- B-inefficiency : GBDT-based b-jet tagging algorithm. $L_{b1}, L_{b2}, L_{b3}, L_{b4}$ should satisfy
  $$Log10\left(\frac{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}}{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}+(1-L_{b1})\times(1-L_{b2})\times(1-L_{b3})\times(1-L_{b4})}\right) < -4.0$$



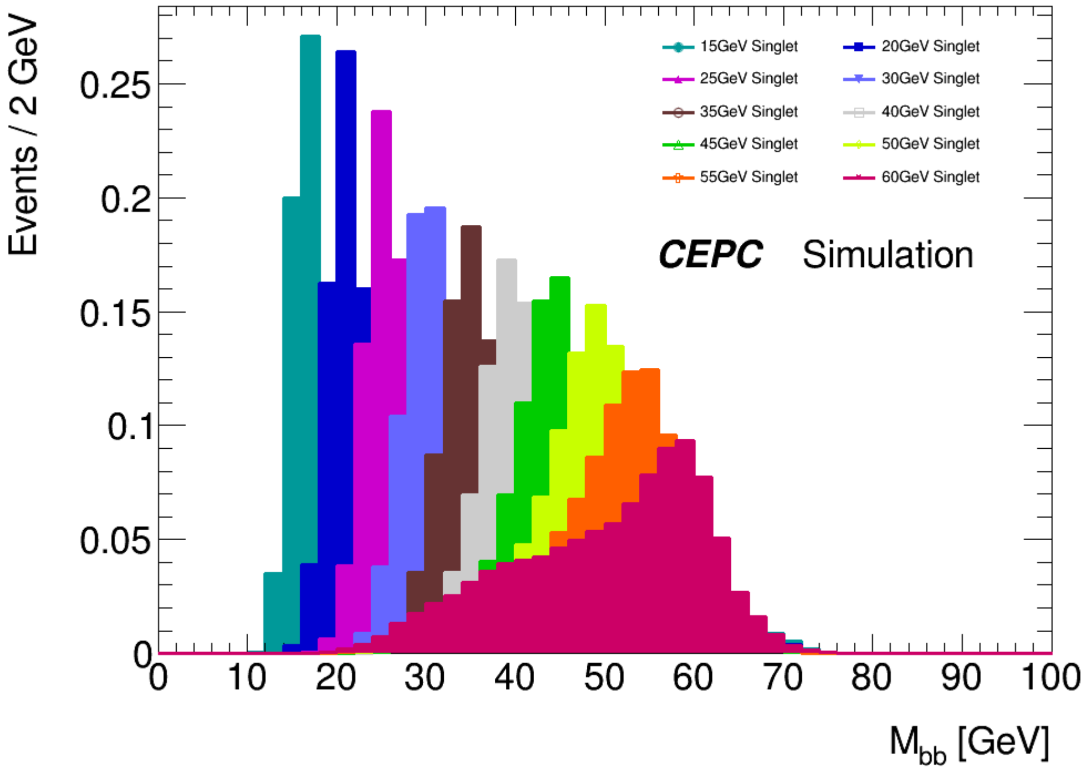
Thanks to Yu Bai.
Y. Bai *et al., Chinese Phys. C* **44**, 013001 (2020).

Cut Based Approach

- **Signal Selection Efficiencies:**



- **Signal Distribution:**

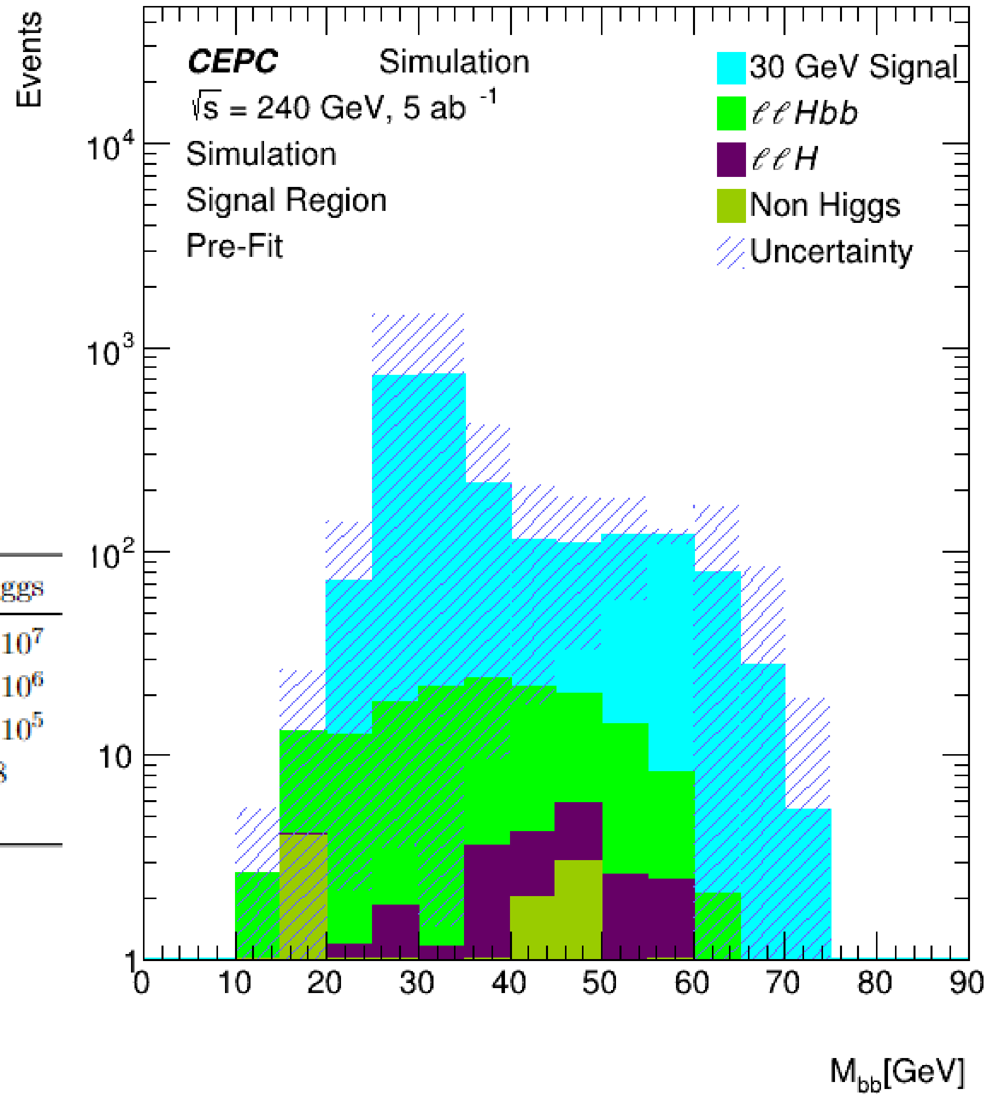


Cut Based Approach

- Signal:
  - Singlet mass at 30 GeV
- Background:
  - llH_bb (dominant)
  - Other llH process
  - Non Higgs process

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

Cutflow Table



BDT Approach

- Trained the variables after some loose selections :
- **Same flavor opposite sign lepton pair with energy larger than 20 GeV**
- **Invariant lepton pair mass should be within the Z mass window [77.5,104.5] GeV**
- **Recoiled mass of the lepton pair system should be within [124,140] GeV**

10 BDTs are trained with 10 different signal samples from 15GeV to 60 GeV

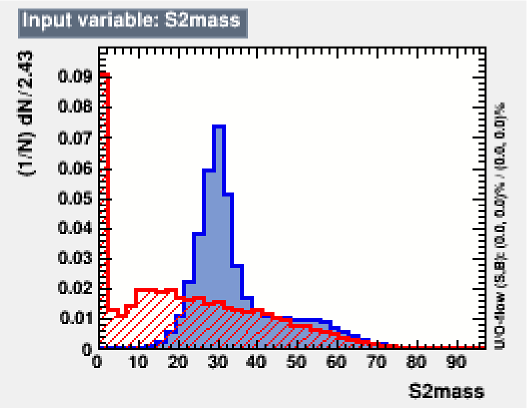
Variables used in training

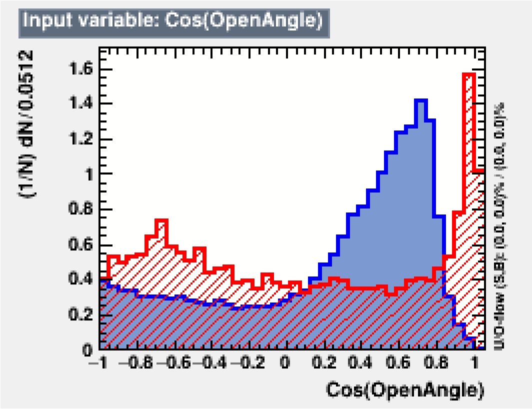
- lep_pt
- jet_energy
- jet_inv_mass
- opening_angle
- jet_recoil_mass
- S_mass
- btag_ineff
- Y12
- Y23
- Y34
- Y45
- Y56

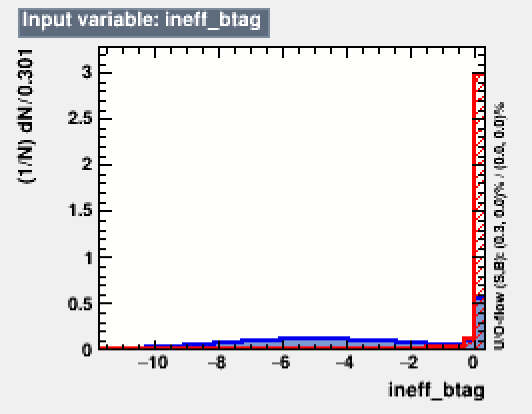
Output of BDT classifier is used as the discriminant and used in the fitting and limit setting.

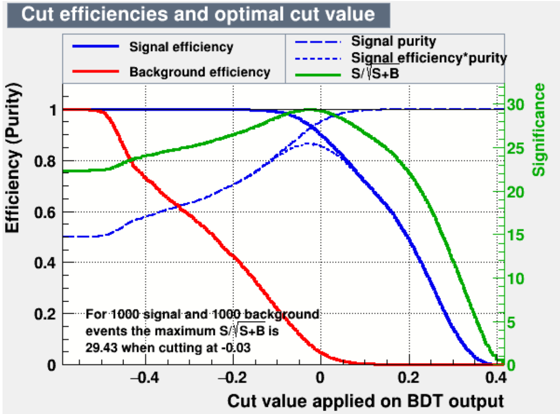
BDT Approach

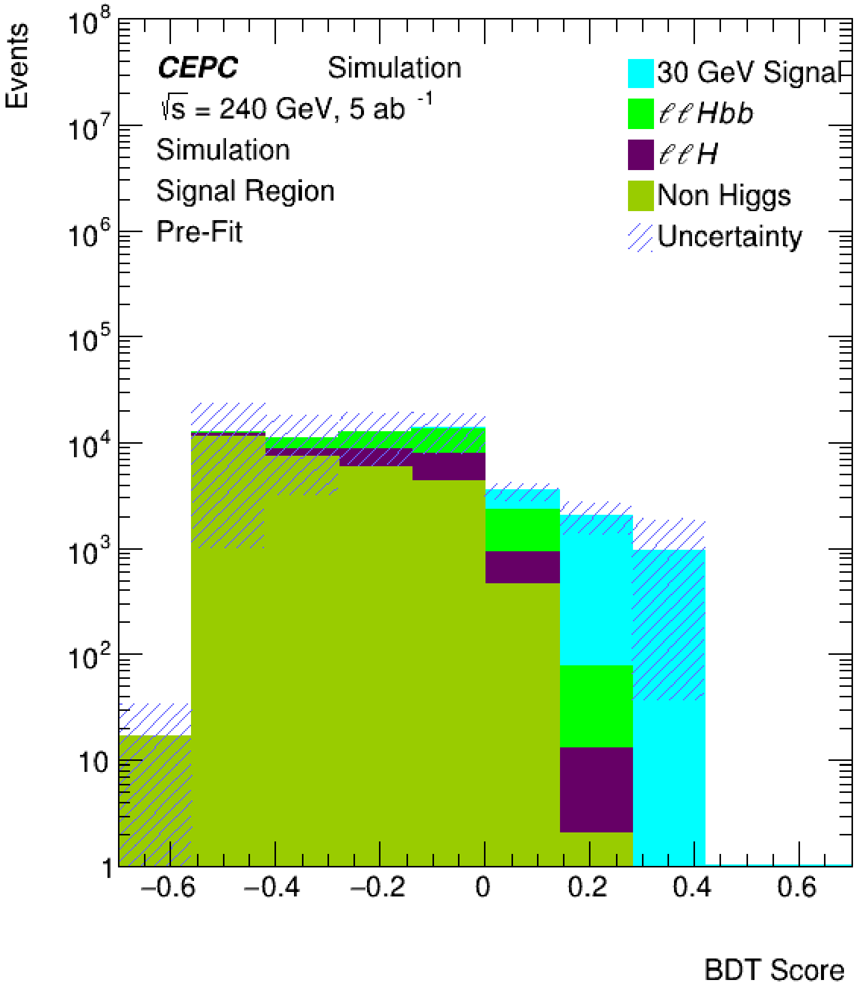
- Example of BDT inputs with 30GeV signal











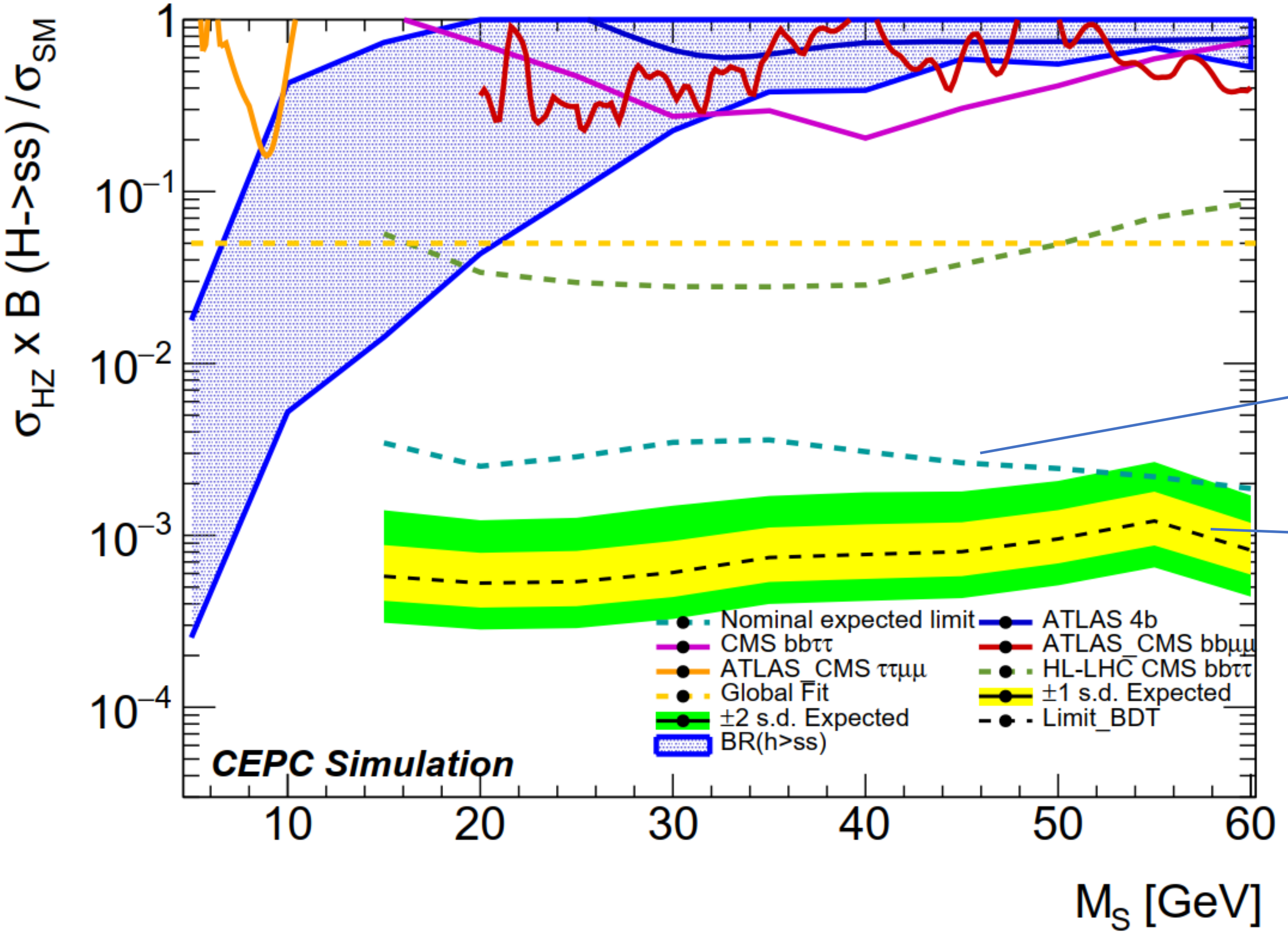
Systematic Uncertainty

- Systematic uncertainty from luminosity and lepton identification are considered to be small.
- Event yield of all kinds of backgrounds are conservatively considered by varying event yields by 5% for dominant process and 100% for other processes.
- Flavor tagging uncertainty is estimated on ZZ->qq+mumu control sample and yields 0.78% for 2jet analysis, we conservatively set this term to 1%.
- Jet energy resolution is estimated by varying energy of each jet with a Gaussian function according to CEPC calorimeter energy resolution.

P.-Z. Lai *et al* 2021 *JINST* **16** P07037

Limit Setting with TRExFitter

- Current Limits of cut-based and BDT approach.



Cut-based Limits

Limits in BDT approach

Summary

- A search for exotic decays of the Higgs boson into a pair of spin-zero singlet-like particles is done with 5 ab-1 simulation data with CEPC.
- Snowmass submission (EF02) https://arxiv.org/abs/2203.10184
- BDT based analysis gives better sensitivity than the cut-based analysis approach.
- This realistic study yields a weaker exclusion limit compared to the theoretical projections
- The study with 4b final states could conclusively test the possibility of an SFOEWPT in the extended-SM with a light singlet of mass as low as 20 GeV.

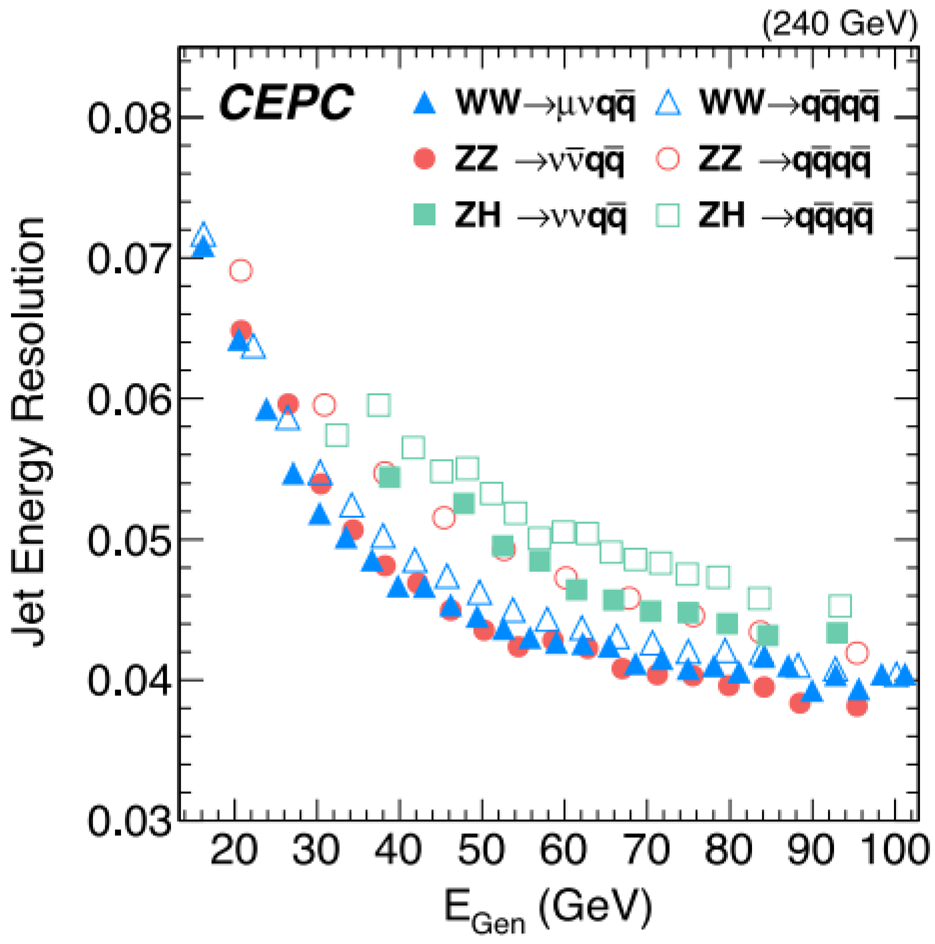
Future Plans

- Boosted and resolved topology in the S particle decay.
- Jet energy resolution uncertainty

Thanks!

Backup

- Jet energy resolution reference.



P.-Z. Lai *et al* 2021 *JINST* **16** P07037

Jet energy resolution is performed by extrapolating the curve to low energy region and apply smearing.

https://doi.org/10.1088/1748-0221/16/07/P07037

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY | 李政道研究所 Tsung-Dao Lee Institute

- Backup

$m_1[GeV]$	a_2	b_3	b_4	D_width	BR
5	0.00379269019	0.00087284094	3.16227766017e-05	7.3774e-05	0.01780479
	0.00033598183	0.00693322201	8.91250938133e-07	1.0348e-06	0.00025421
10	0.02511886432	0.01954047457	0.00125892541179	0.0030277	0.42627589
	0.00199526231	0.04908345294	1.58489319246e-05	2.1351e-05	0.00521904
15	0.05011872336	0.00389883725	0.00446683592151	0.011795	0.73632455
	0.00375837404	0.19540474574	7.94328234724e-05	5.9206e-05	0.01422012
20	0.00630957344	0.49083452948	0.00025118864315	0.0001866	0.04347394
25	0.01	0.97934363956	0.00063095734448	0.00044524	0.09859974
30	0.01678804018	1.55215506742	0.00125892541179	0.0011898	0.22613126
35	0.02511886432	2.46	0.00251188643151	0.0025006	0.38033656
40	0.02660725059	3.89883725345	0.00398107170553	0.0025799	0.38771480
45	0.04216965034	4.90834529482	0.00630957344480	0.0058611	0.58957125
50	0.04216965034	7.77920304401	0.01	0.0050107	0.55126677
55	0.06309573445	9.79343639562	0.01584893192461	0.0089054	0.68549957
60	0.05956621435	15.5215506742	0.02511886431509	0.0045989	0.53001523

Table. Parameters and related BRs that satisfy a strong 1-st order electroweak phase transition. The orange shading represent parameter when BR is at its upper bound, and blue shading represent the lower bound.

Mass	BDT Limits	Theory
20GeV	0.0005	0.0006
30GeV	0.0006	0.0005

Limits from BDT and Theory

Backup

- Backup

10 BDTs are trained with 10 different signal samples from 15GeV to 60 GeV

Number of events in one training:

```
: Number of training and testing events
: ---------------------------------------------------
: Signal     -- training events             : 30000
: Signal     -- testing events              : 7806
: Signal     -- training and testing events: 37806
: Dataset[dataset] : Signal     -- due to the preselec
: Background -- training events             : 400000
: Background -- testing events              : 166345
: Background -- training and testing events: 566345
```