Search for HH-->4b production and H-->aa-->4b exotic decays with ATLAS and CEPC

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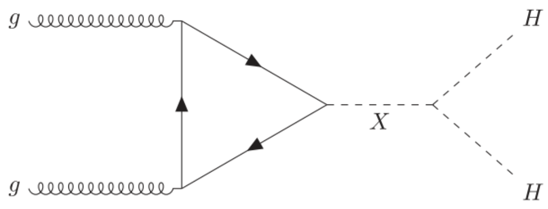
中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

ATLAS HH4b Part

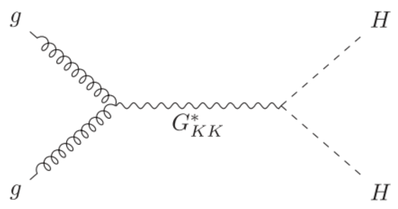
Motivation

- Discovery of 125GeV Higgs boson at the LHC has promoted the investigation of Higgs boson property.
- Resonances decays to Higgs boson pair(HH)
- Search for non-resonant Higgs boson pair

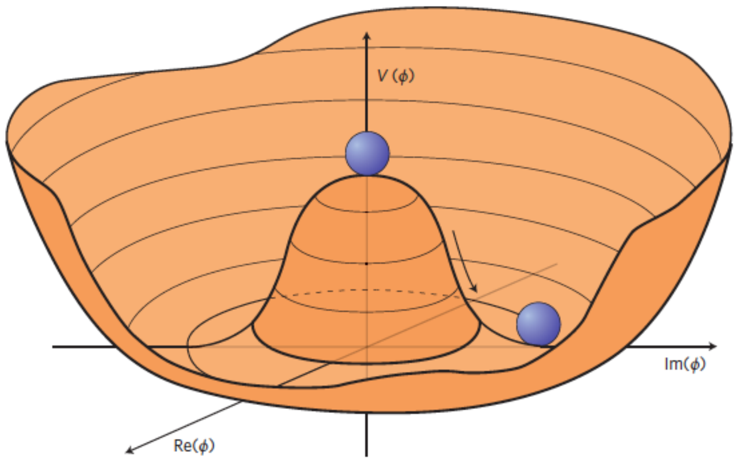
Two benchmark signal models for Resonant HH:



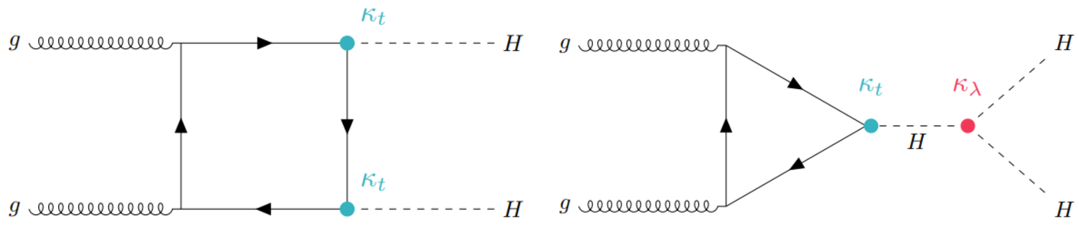
A generic spin-0 boson



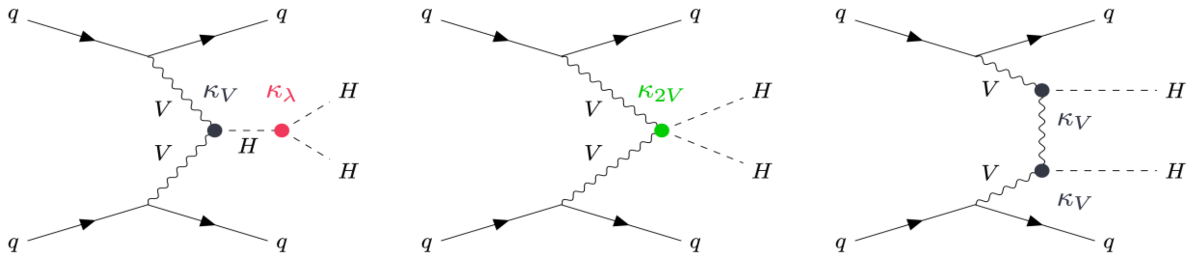
A Kaluza-Klein Graviton



Production process for non-resonant HH:



ggF



VBF

Non-resonant HH→ 4b Categorization

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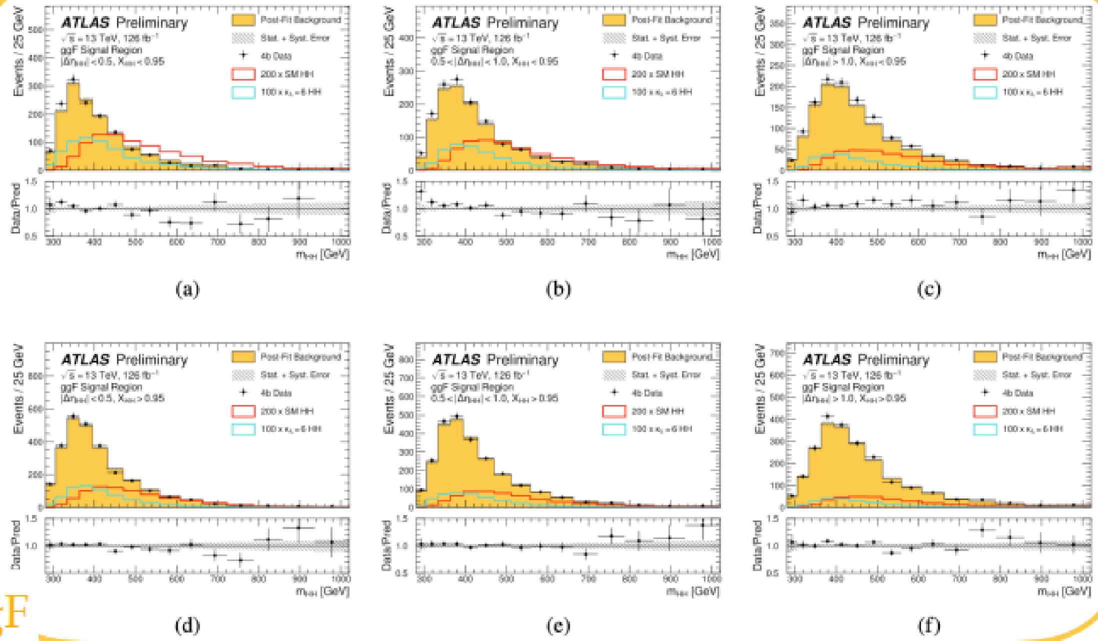
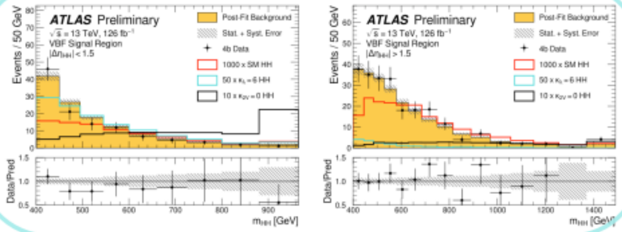
- Events are categorised in 6 categories in ggF and 2 categories in VBF   [ATLAS-CONF-2022-035]



ggF



VBF

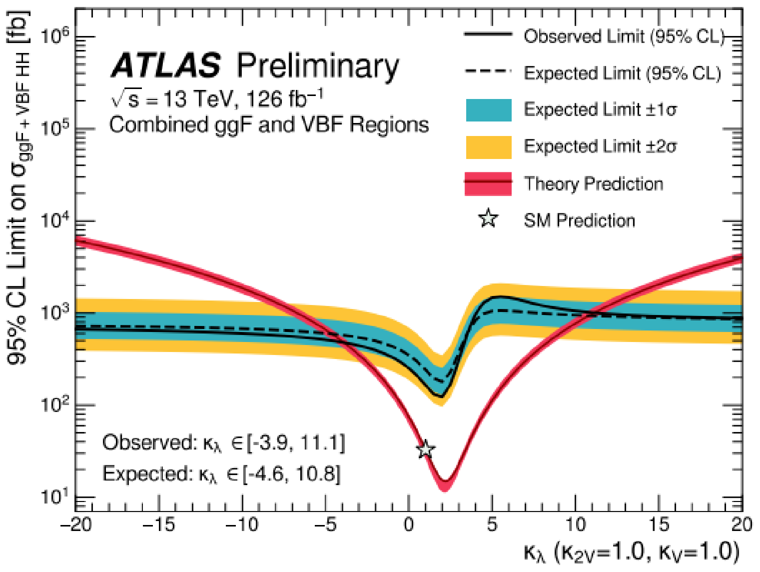
ggF signal region
$\|\Delta\eta_{HH}\| < 0.5,\ X_{HH} < 0.95$
$\|\Delta\eta_{HH}\| < 0.5,\ X_{HH} > 0.95$
$0.5 < \|\Delta\eta_{HH}\| < 1.0,\ X_{HH} < 0.95$
$0.5 < \|\Delta\eta_{HH}\| < 1.0,\ X_{HH} > 0.95$
$\|\Delta\eta_{HH}\| > 1.0,\ X_{HH} < 0.95$
$\|\Delta\eta_{HH}\| > 1.0,\ X_{HH} > 0.95$
VBF signal region
$\|\Delta\eta_{HH}\| < 1.5$
$\|\Delta\eta_{HH}\| > 1.5$

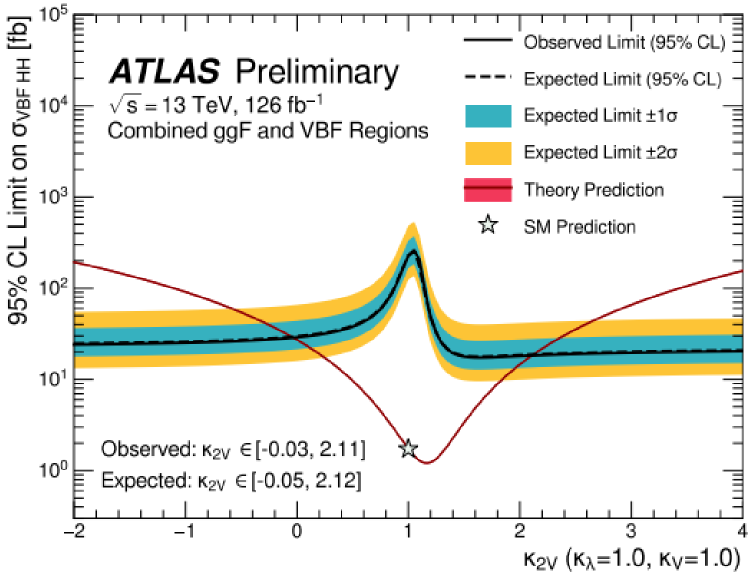
The categorization improves the S/B ratio in different categories and therefore improves the sensitivity

Non-resonant HH→ 4b Results

- Combined ggF and VBF regions for non-resonant HH: ATLAS-CONF-2022-035

	Observed Limit	-2σ	-1σ	Expected Limit	$+1\sigma$	$+2\sigma$
$\sigma_{ggF}/\sigma_{ggF}^{SM}$	5.5	4.4	5.9	8.2	12.4	19.6
$\sigma_{VBF}/\sigma_{VBF}^{SM}$	130.5	71.6	96.1	133.4	192.9	279.3
$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{SM}$	5.4	4.3	5.8	8.1	12.2	19.1





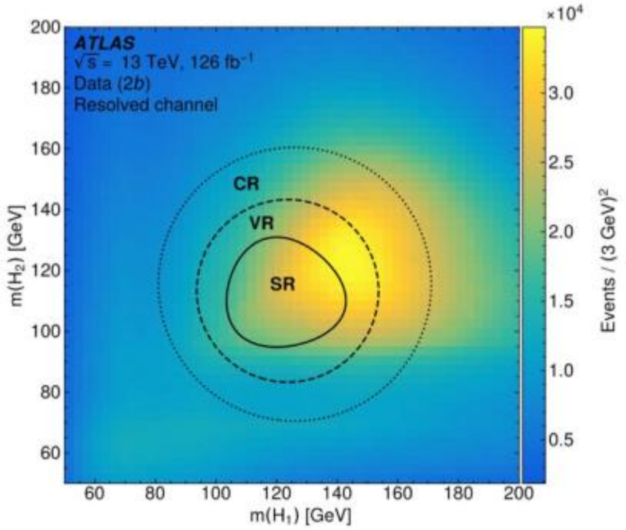
The observed (expected) upper limit on the cross section for non-resonant Higgs boson pair production is determined to be 5.4 (8.1) times the Standard Model predicted cross-section at 95% confidence level.

Resonant HH→ 4b channels

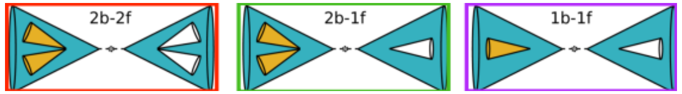
- Resolved channel:
  - Target up to 1.5 TeV resonance decay to two Higgs

  - Event selection similar to the non-resonant analysis
  - Pairing: BDT pairing parametrised to m_{HH}
  - Background estimation similar to the non-resonant

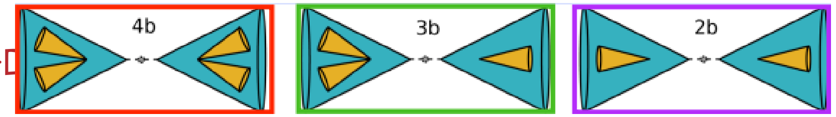
  - Final observable: corrected m_{HH}
    - m_{HH} obtained by scaling Higgs candidate to match $m_H = 125GeV$



- Boosted channel:
  - Target up to 5 TeV resonance decay to two Higgs
  - Event selection
    - ≥ 2 large-R jets pT> 250 GeV,|η|< 2
    - m(H) > 50 GeV
    - |ΔηHH | < 1.3
    - Resolved events veto
    - Categorized to 2/3/4 b-track-jet
  - Background estimation: data-driven QCD estimation, MC based tt
    - Use of low-tag regions

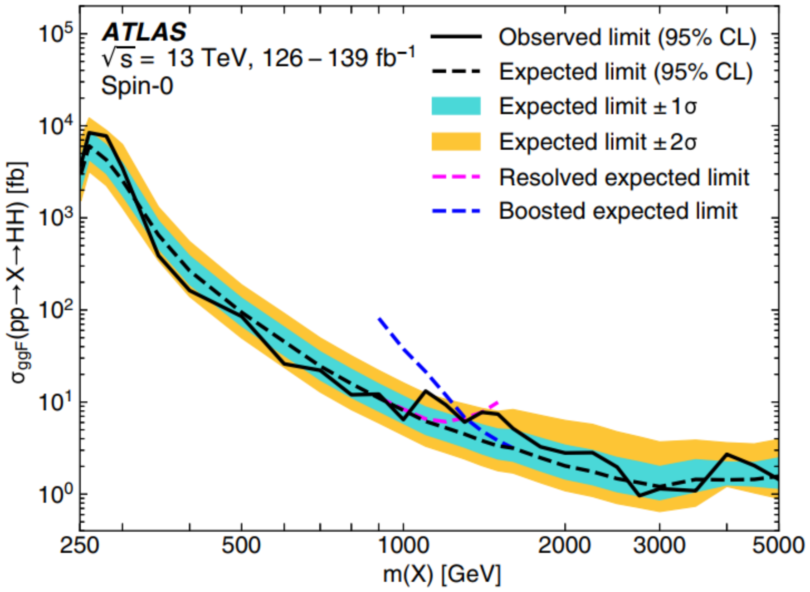


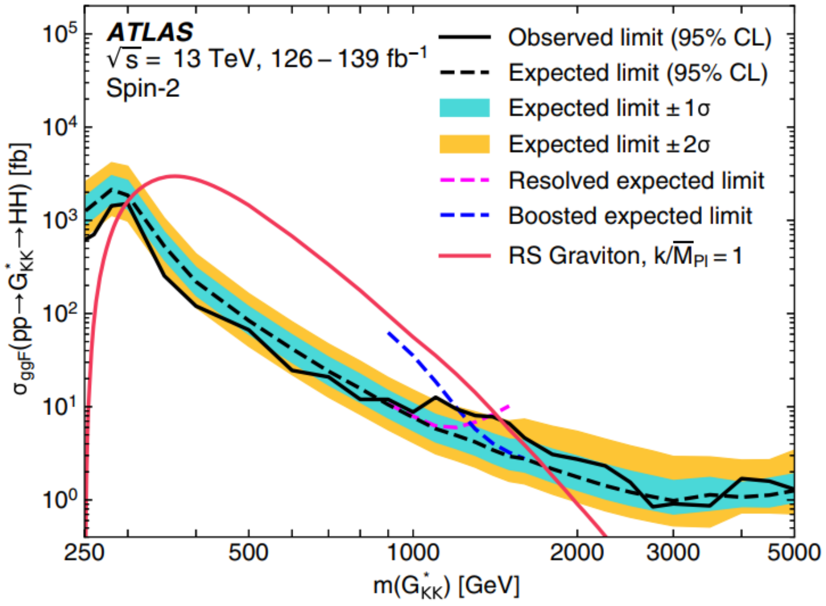
  - Final observable: m_{HH}



Resonant HH→ 4b Results

- Combined resolved and boosted results for resonant HH:





Most significant excess is found for a signal mass of 1100 GeV, local significance is 2.3σ for spin-0 model and 2.5σ for the spin-2 model.

Global significance of the excess is 0.4σ for the spin-0 signal model and 0.8σ for the spin-2 signal model.

Ongoing boosted VBF HH4b

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- Current non-resonant VBF analysis overview

Signal selection studies:

- Signals: SM, and VBF HH (DSIDs 502970, 502971 and 502972)
- Backgrounds: b-filtered dijets and ttbar_HT (not including inclusive ttbar/dijets, W/Z+jets, or single Higgs)
- Validated the improvements of Xbb Tagger and use it as a starting point
- Using simple significance calculation on histogram:

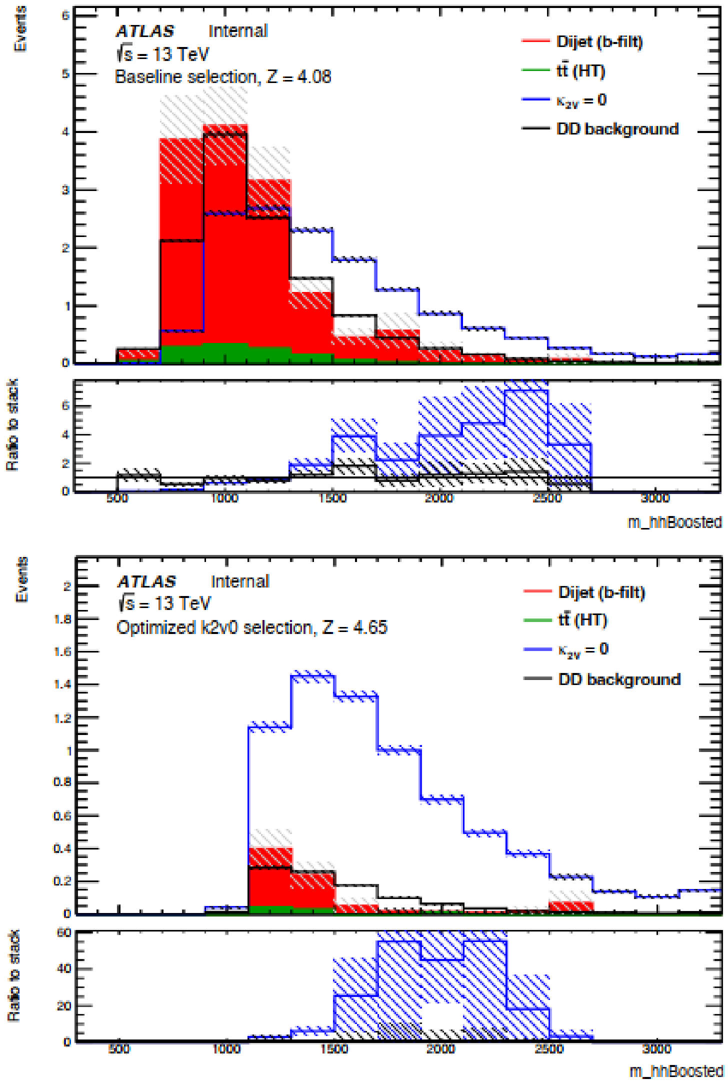
$$Z = \sqrt{\sum_i 2\left((s_i + b_i)\cdot \ln\left(1 + \frac{s_i}{b_i}\right) - s_i\right)}$$

Signal selection Optimization

- Results

Cut Value	Baseline	Optimized
m_h1Boosted	50 GeV	90 GeV
m_h2Boosted	50 GeV	90 GeV
pt_h1Boosted	450 GeV	550 GeV
pt_h2Boosted	250 GeV	480 GeV
m_VBFjjBoosted	1 TeV	1.2 TeV
deta_VBF	3	5.2
pt_vecsum_VBF	N/A	455 GeV
dphi_hhBoosted	N/A	2.8
Z	4.08	4.65

Work in Progress



CEPC Exotic Decay Part

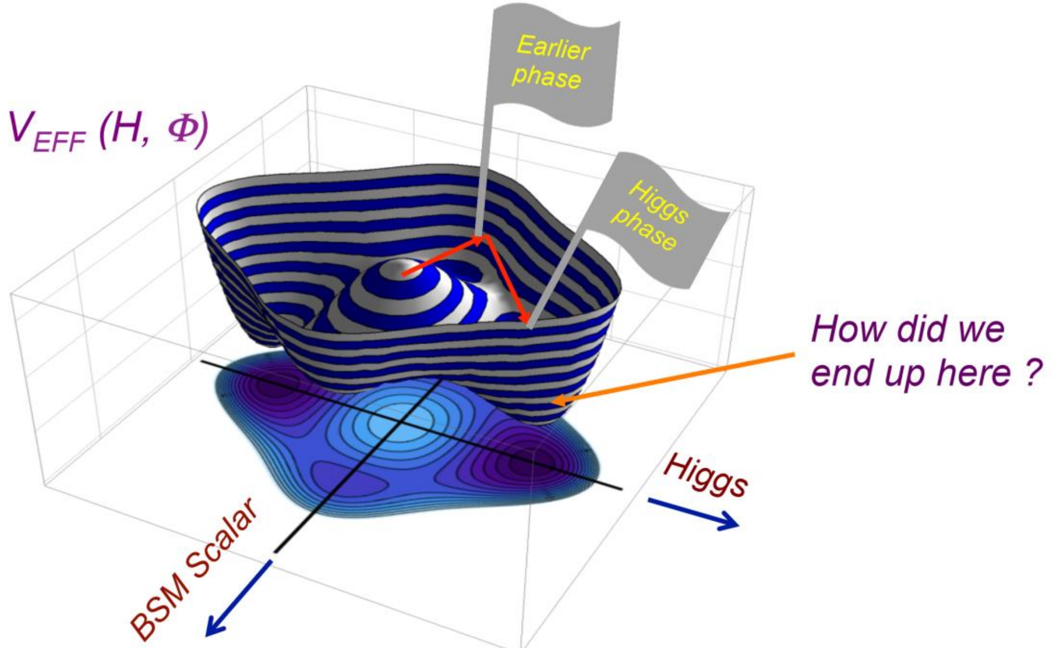
Physics Motivation

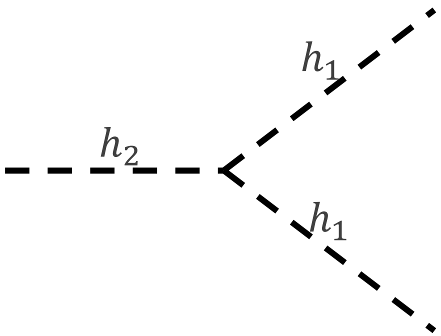
J. Kozaczuk, M. J. Ramsey-Musolf, and J. Shelton *Phys. Rev. D* **101**, 115035 (2020).

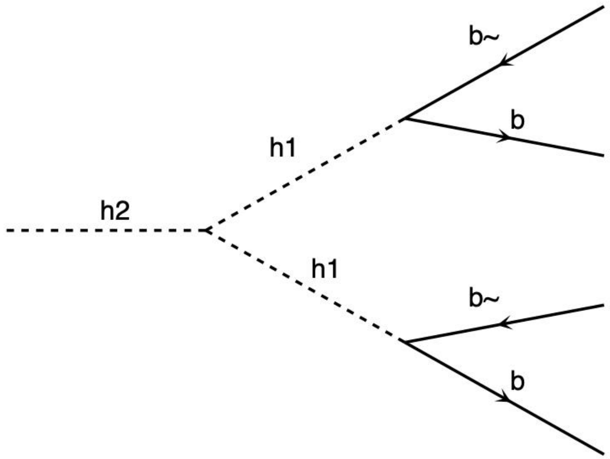
- We are interested in the strong first-order electroweak phase transition in the "SM Higgs + Light Real Singlet Scalar" model:

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

- 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)





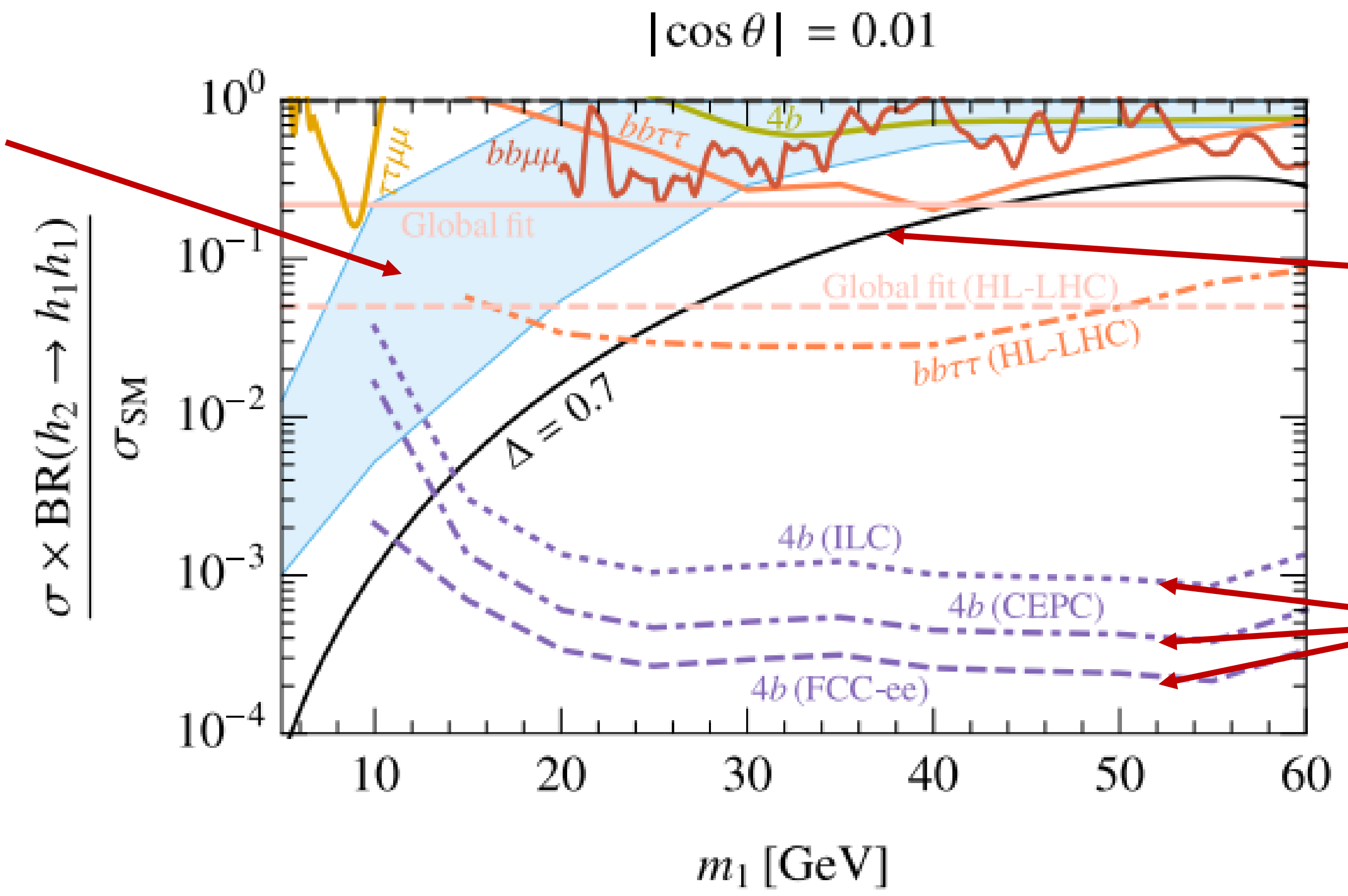


Extrema can evolve differently as T evolves
→ Rich possibilities for symmetry breaking

Theoretical Prospects

$h_2 \to h_1 h_1 \to 4b$

EWPT viable: numerical



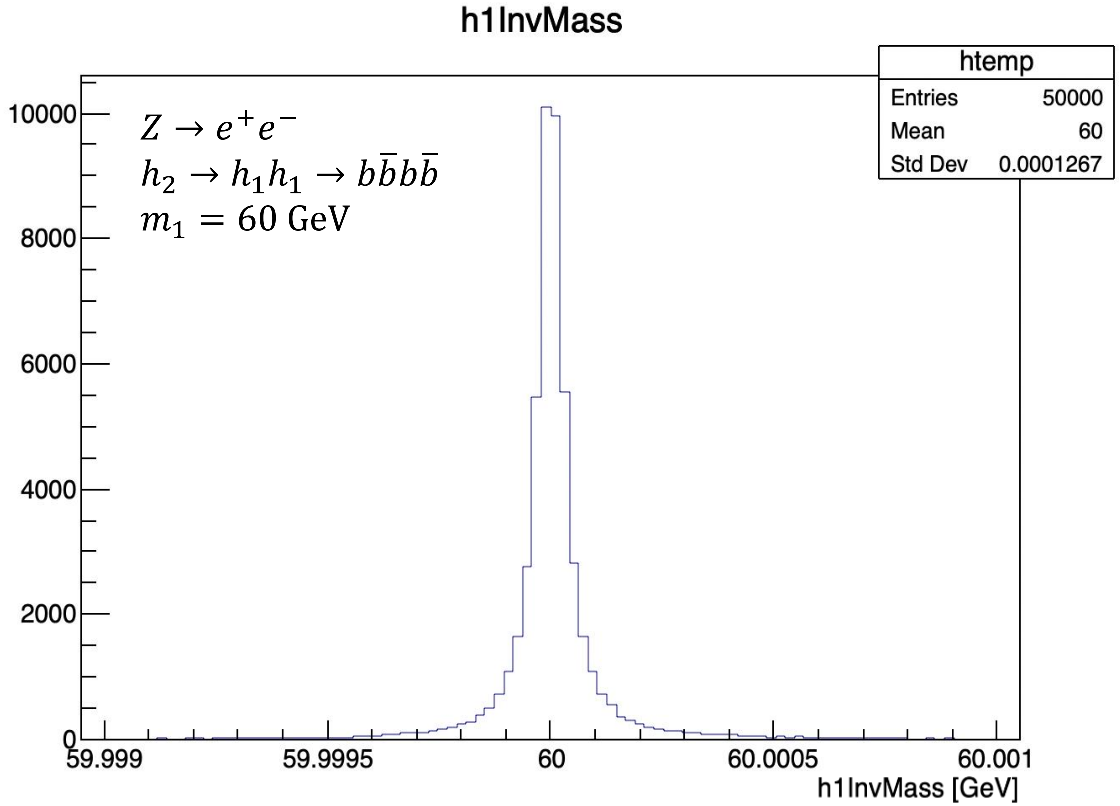
EWPT viable: semi analytic

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



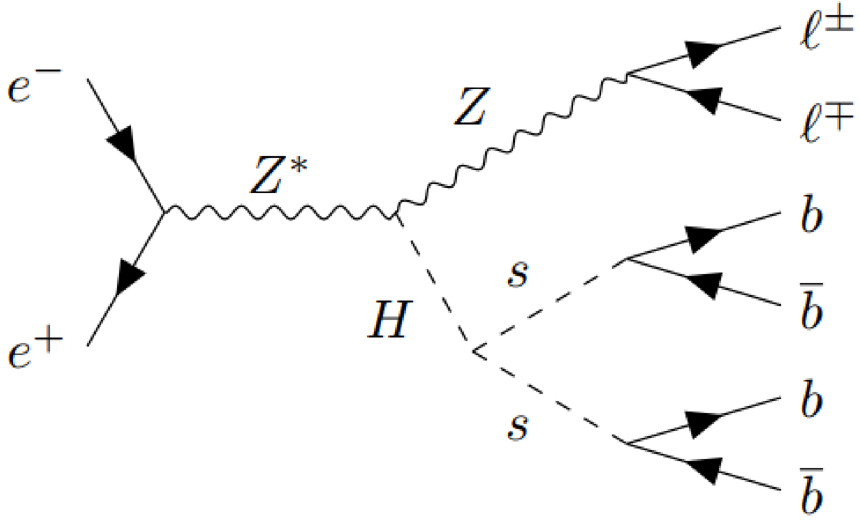


Fig. Mass distribution of h_1 when $m_1 = 60\text{GeV}$

Sample Production

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- 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%

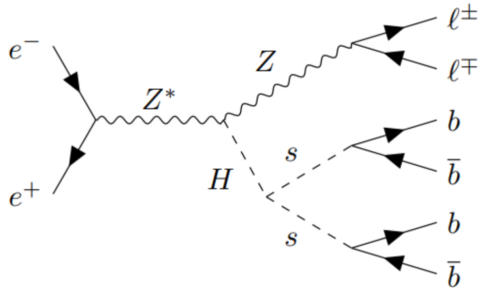
https://iopscience.iop.org/article/10.1088/1674-1137/43/4/043002/pdf
http://cepcsoft.ihep.ac.cn/guides/Generation/docs/ExistingSamples/#240-gev
lxslc7 : /cefs/data/DstData/CEPC240/CEPC_v4_update

arXiv:2203.10184

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

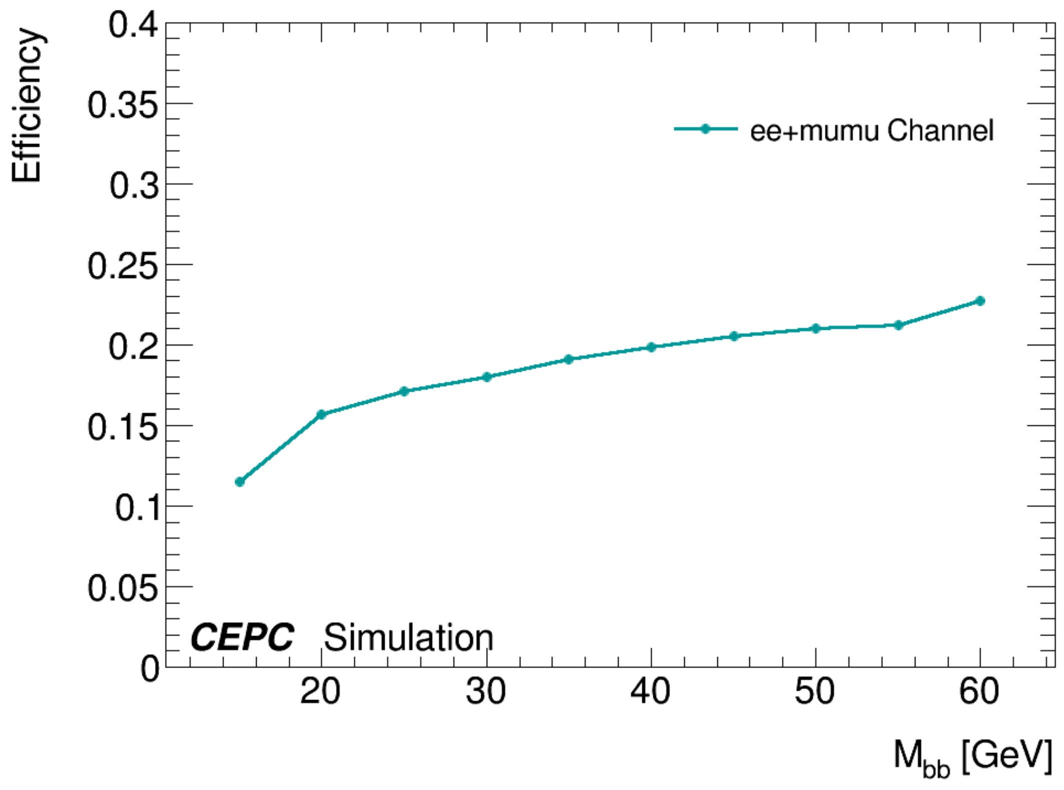
$$Log10\left(\frac{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}}{L_{b1}\times L_{b2}\times L_{b3}\times L_{b4}+(1-L_{b1})\times(1-L_{b2})\times(1-L_{b3})\times(1-L_{b4})}\right) < -4.0$$



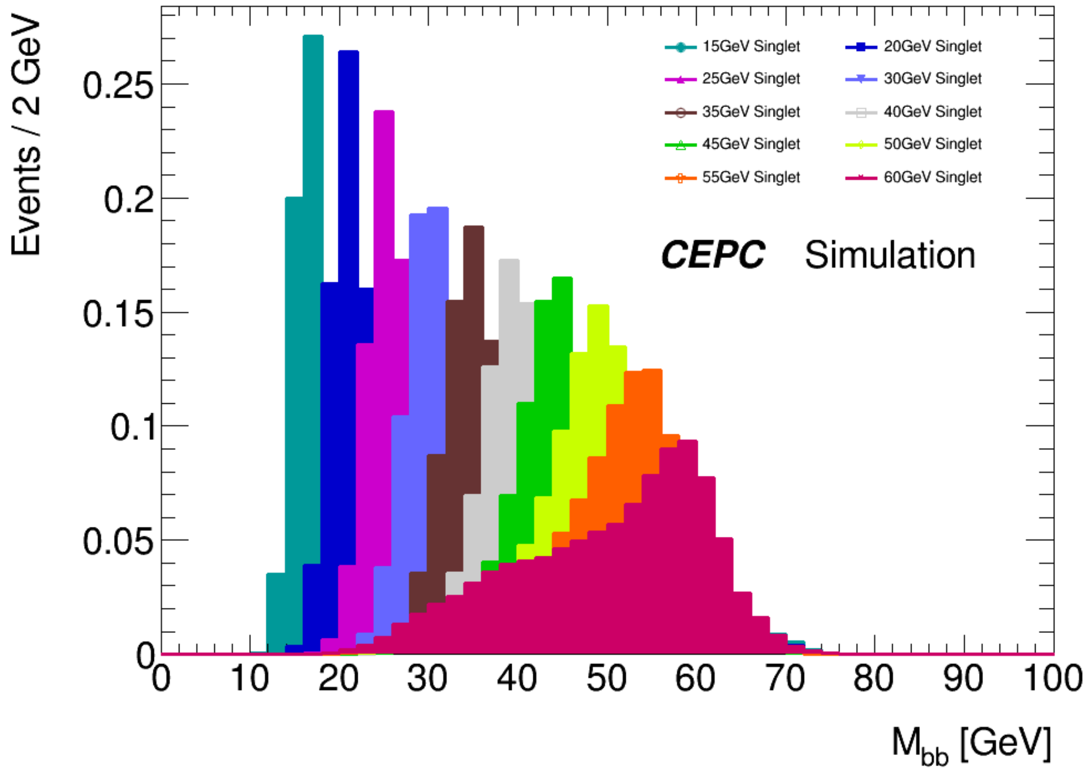
Thanks to Yu Bai.
Y. Bai *et al., Chinese Phys. C* **44**, 013001 (2020).

Cut Based Approach

- **Signal Selection Efficiencies:**



- **Signal Distribution:**



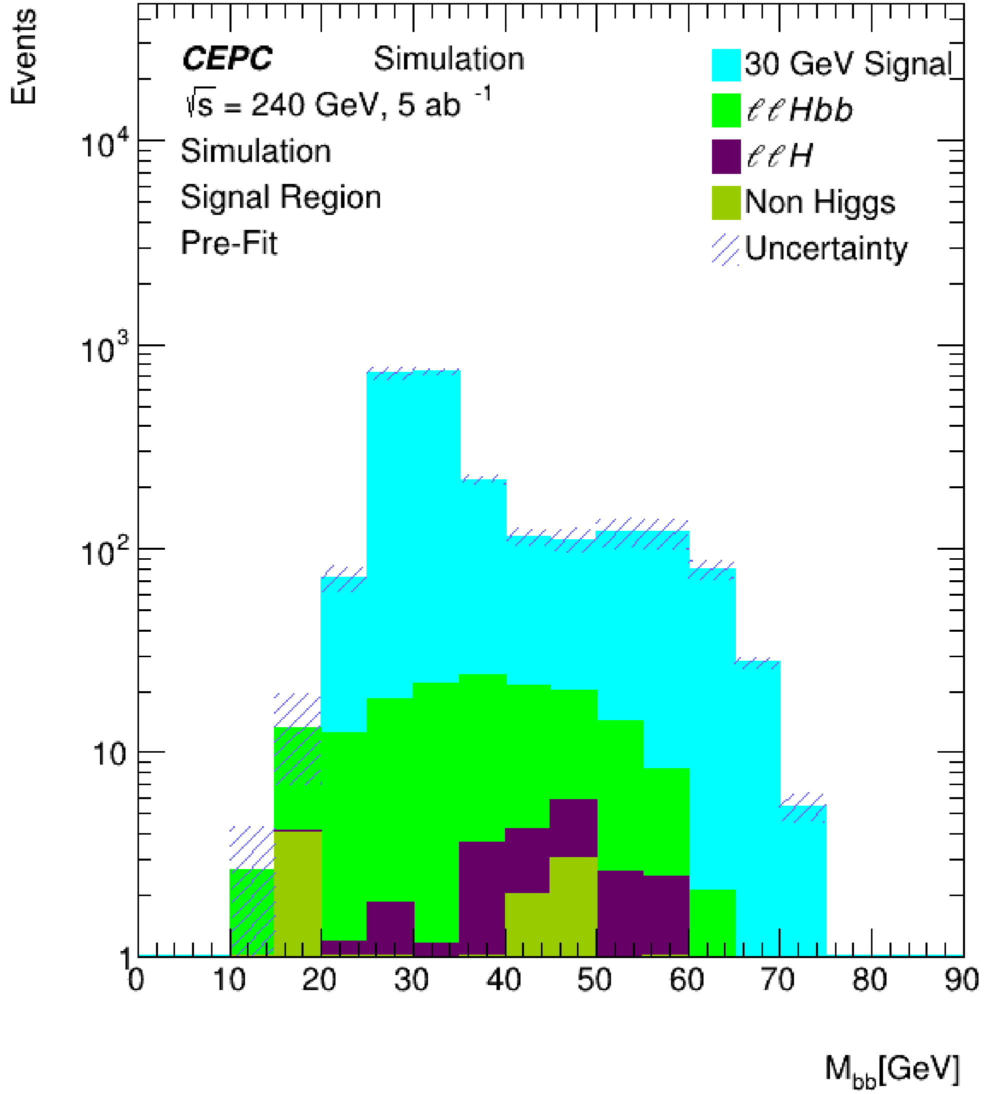
arXiv:2203.10184

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
- jetcoshel
- sscosphi

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

MARCH 21, 2012 BY UPAUDEL

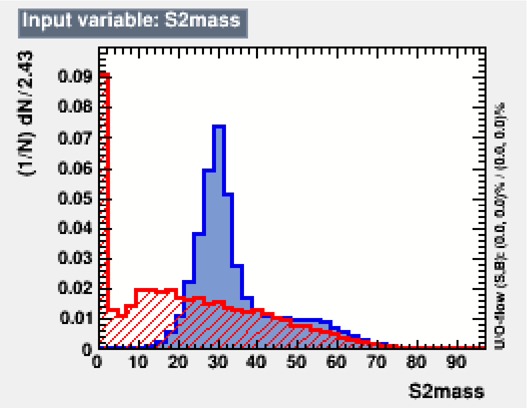
Helicity angle calculations

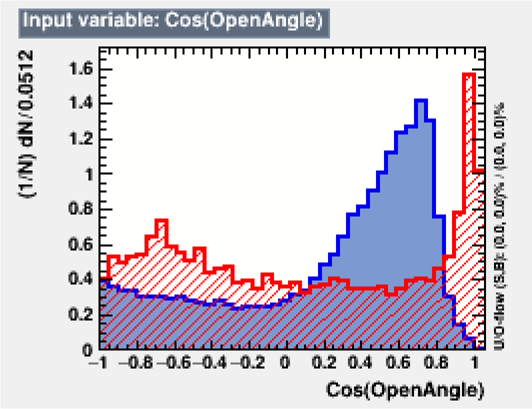
A useful quantity in many analyses is the helicity angle. In the reaction Y -> X -> a + b, the helicity angle of particle a is the angle measured in the rest frame of the decaying parent particle, X, between the direction of the decay daughter a and the direction of the grandparent particle Y.

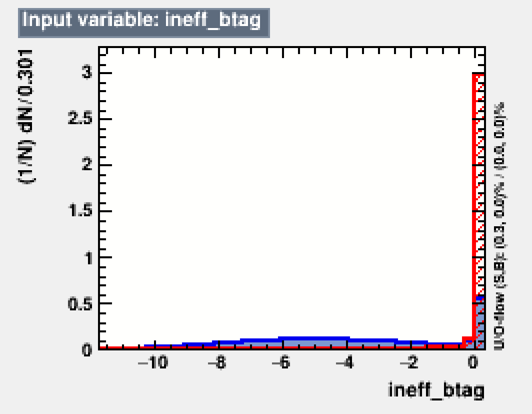
arXiv:2203.10184

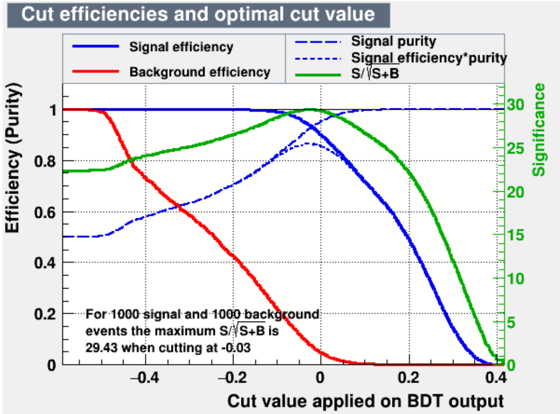
BDT Approach

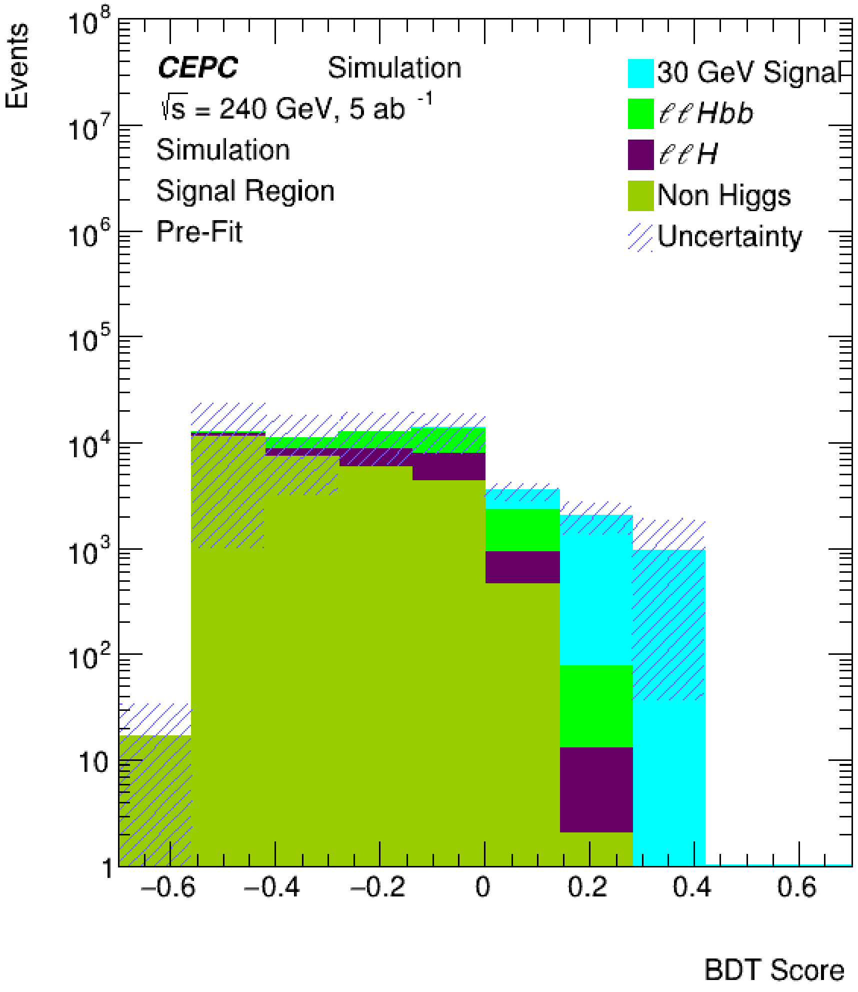
- Example of BDT inputs with 30GeV signal











arXiv:2203.10184

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.

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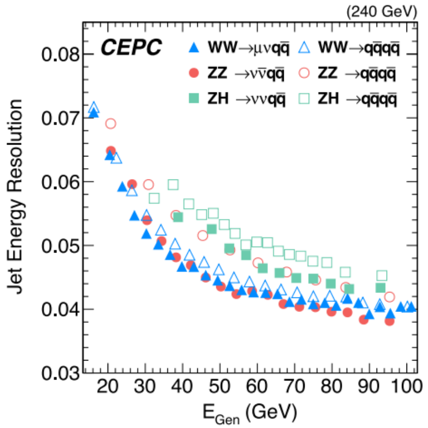
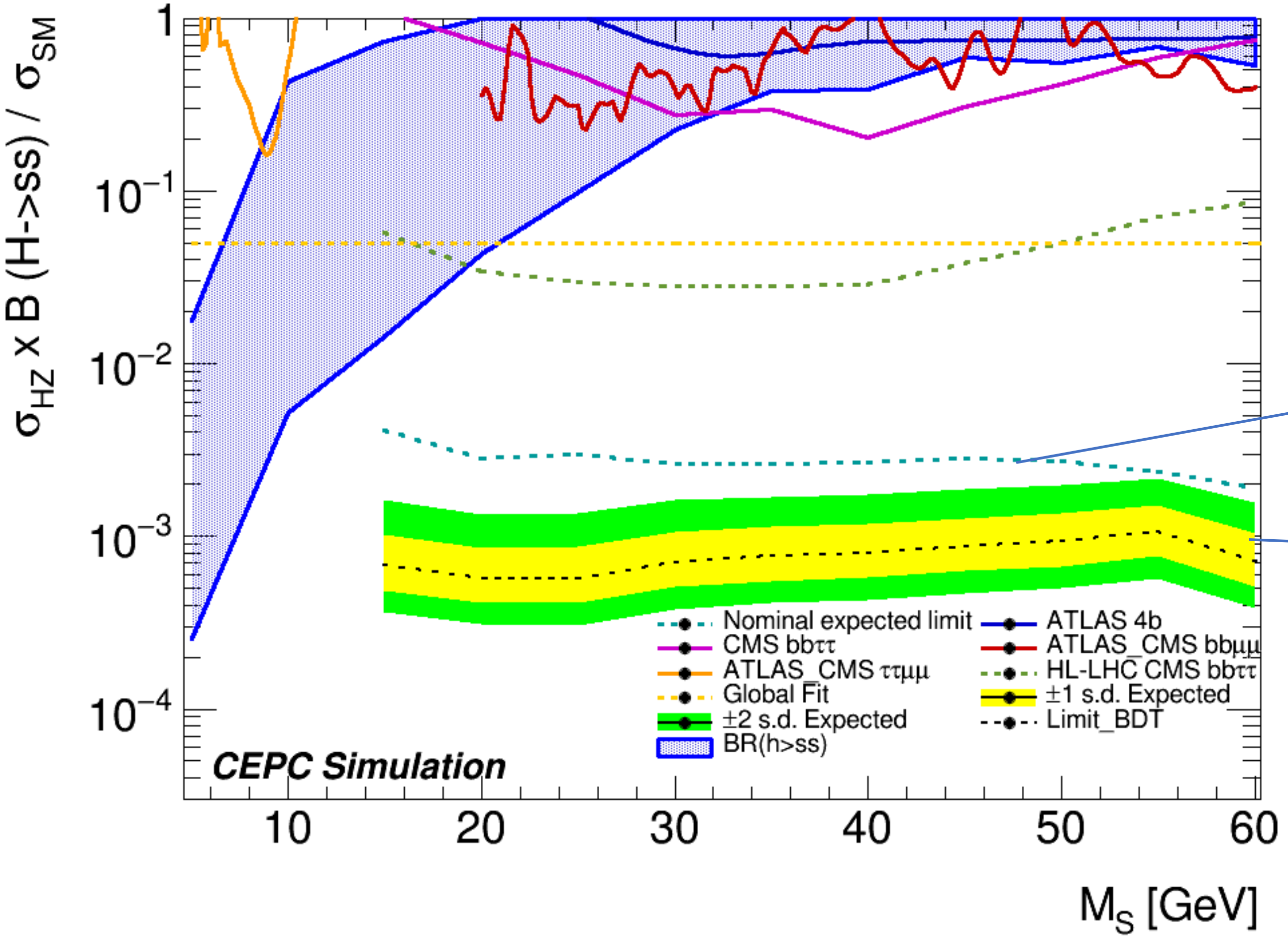


arXiv:2203.10184

Limit Setting with TRExFitter

- Current Limits of cut-based and BDT approach.



Lepton collider does have advantages in sensitivity compared with hadronic colliders

Cut-based Limits

Limits in BDT approach

arXiv:2203.10184

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 White Paper Submitted: https://arxiv.org/abs/2203.10184
- BDT based analysis gives better sensitivity than the cut-based analysis approach.
- 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

- Jet energy resolution uncertainty, aiming at a more specific and detailed study
- Journal publication plan at the end of this year hopefully
- More discriminant power selections…

Thanks!

arXiv:2203.10184

Backup

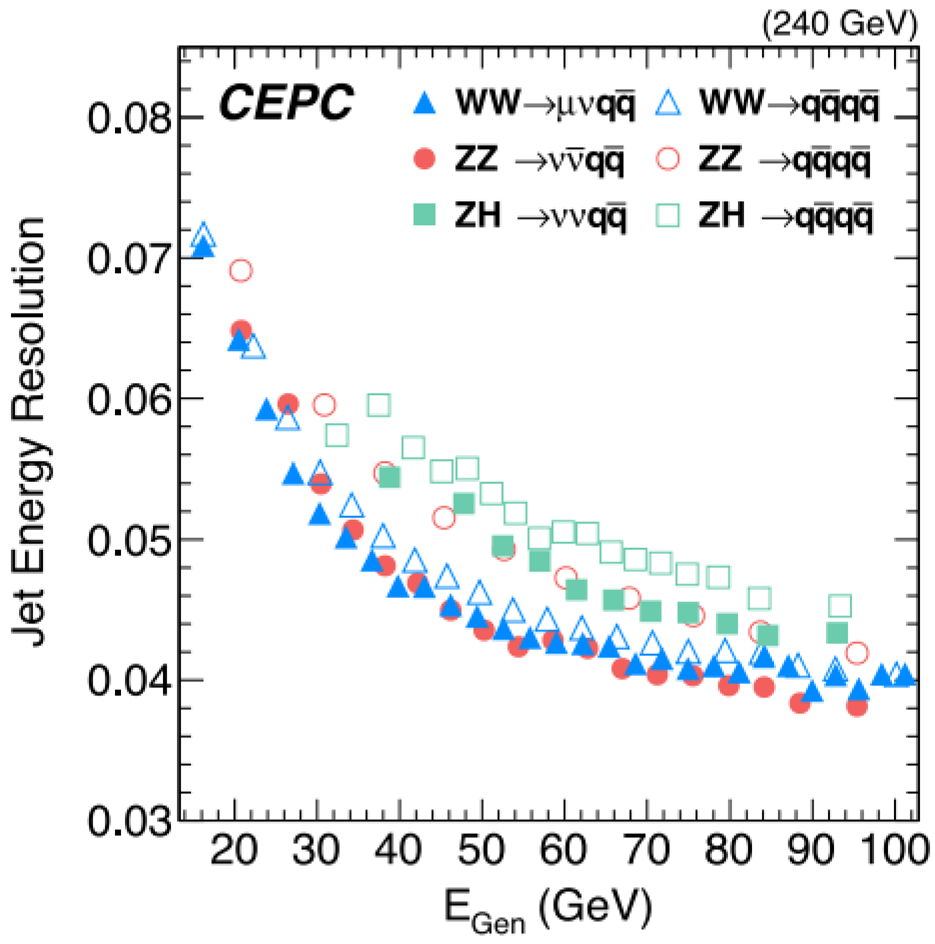
- XHH definition

$$X_{HH} = \sqrt{\left(\frac{m_{2b}^{\text{lead}} - 123.7\text{ GeV}}{11.6\text{ GeV}}\right)^2 + \left(\frac{m_{2b}^{\text{subl}} - 116.5\text{ GeV}}{18.1\text{ GeV}}\right)^2}$$

where 11.6 GeV and 18.1 GeV are the widths of the simulated leading and subleading Higgs boson candidates, respectively. These values are derived using a 600 GeV resonant signal sample and are similar for other signal samples.

Backup

- Jet energy resolution reference.



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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

Backup

- 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
```