Search for additional Higgs bosons at the FCC-ee

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Global context of the study

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- Future circular collider at CERN: FCC-ee
- Two runs considered: $\sqrt{s}$ =240 GeV with $\mathcal{L}^{tot} = 10.8\,\text{ab}^{-1}$ and $\sqrt{s}$ =365 GeV with $\mathcal{L}^{tot} = 3\,\text{ab}^{-1}$.

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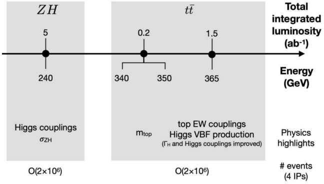

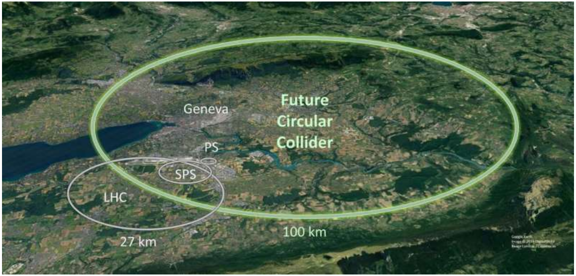

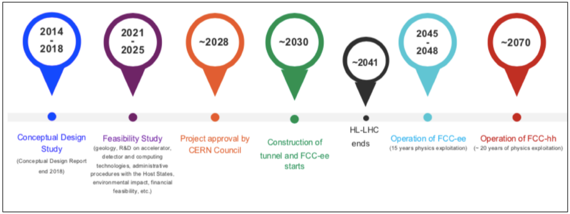

The Inert Two-Higgs-Doublet model (IDM)

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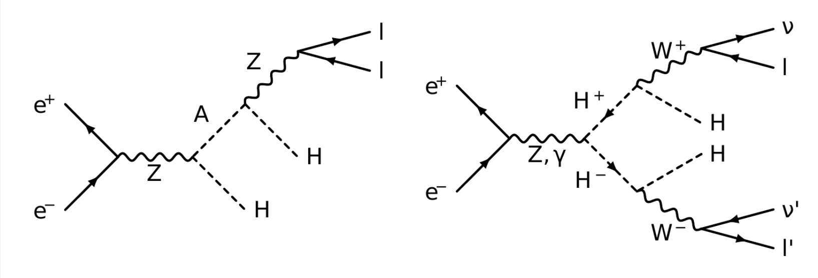
- Two Higgs-Doublet model: 5 scalars, h, H, A, H+, H-.
- h is the SM Higgs with constraints from SM measurements.
- Add Z2 symmetry:$\phi_D \rightarrow -\phi_D$,$\phi_S \rightarrow \phi_S$, SM $\rightarrow$ SM.
- New scalars do not couple to fermions and are pair-produced.
- Dark Matter candidate(s): choose H.
- Five free parameters: m_H, m_A, $m_{H^\pm}$, λ_{345}, λ_2.

Final state considered: $2\ell(=e \text{ or } \mu)$ + HH, mainly produced through AH and H^+H^-



Benchmark points

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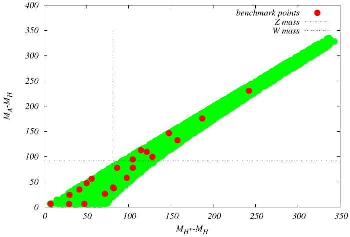
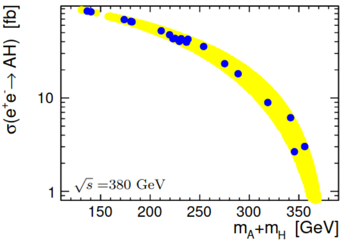
- Constraints from all experimental results: set of 20 low-mass benchmark points relevant for FCC-ee [JHEP 1812 (2018) 081]

No.	M_H	M_A	$M_{H^\pm}$	$\sigma(250)$	$\sigma(380)$	$\sigma(500)$
BP1	72.77	107.803	114.639	77.2	65.9	45.7
BP2	65	71.525	112.85	155	85.1	53.4
BP3	67.07	73.222	96.73	149	83.5	52.8
BP4	73.68	100.112	145.728	89.2	69.1	46.9
BP6	72.14	109.548	154.761	75.1	65.4	45.4
BP7	76.55	134.563	174.367	31.2	52.3	40.1
BP8	70.91	148.664	175.89	20	47.5	38.1
BP9	56.78	166.22	178.24	14.1	43	36
BP10	76.69	154.579	163.045	9.44	43	36.2
BP11	98.88	155.037	155.438	-	35.6	33.2
BP12	58.31	171.148	172.96	9.01	40.4	34.8
BP13	99.65	138.484	181.321	5.17	42.5	36.2
BP14	71.03	165.604	175.971	5.13	39.6	34.7
BP15	71.03	217.656	218.738	-	18.2	24.2
BP16	71.33	203.796	229.092	-	23.3	26.9
BP18	147	194.647	197.403	-	6.14	18.7
BP19	165.8	190.082	195.999	-	3.02	16.6
BP20	191.8	198.376	199.721	-	-	11.3
BP21	57.475	288.031	299.536	-	2.66	12.6
BP22	71.42	247.224	258.382	-	8.94	18.6
BP23	62.69	162.397	190.822	13.2	43.3	36.2





Previous studies

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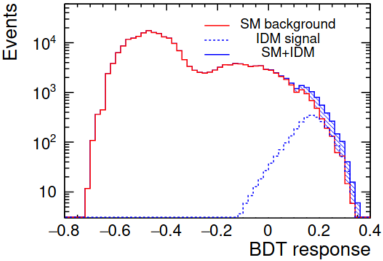
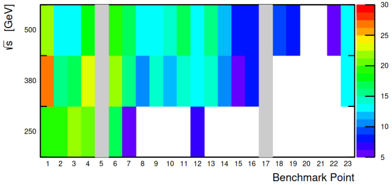
- IDM model studied with ILC/CLIC setup at different $\sqrt{s}$ scenarios, with HH$\mu\mu(+\nu\nu)$ final state, and also HHe$\mu\nu\nu$ and semi-leptonic final states.
- T. Robens et al, JHEP 07 (2019) 053 (@$\sqrt{s} = 380$ GeV)
- Snowmass report: arXiv:2002.11716 (@$\sqrt{s} = 250$ GeV up to 3 TeV)
- Main backgrounds: inclusive $ee \to \ell\ell$, WW, ZZ, ZH [and ttbar when kinematically available].
- Strategy based on BDT, extraction of maximum significance S/$\sqrt{S+B}$.
- 5-σ discovery possible up to $m_A + m_H = 220$ GeV with 1 ab^{-1} at $\sqrt{s}$ =250 GeV.





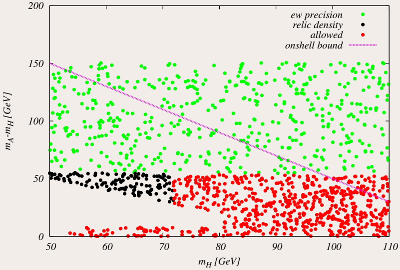
Significance for points > 5-σ threshold.

Further signal simulation and assumptions

- Signal simulated using MG5_aMC@NLO by final states: ee$\rightarrow \ell\ell$HH and ee$\rightarrow \ell\ell\nu\nu$HH.
- λ_{345} and λ_2: little impact on dominant production processes, fixed at 0 or very small values.
- Dominant sensitivity from AH production: also very little impact from $m_{H^\pm}$, "artificially" fixed at $m_A + 50$ GeV.
- Sensitivity depends mainly on m_H and mass splitting $m_A - m_H$.
- Extend benchmark points to a grid scan in $m_A - m_H$ vs m_H $\Rightarrow$ smooth exclusion/discovery limits.

Check of the validity of the simulated grid

- Apply all constraints
- Black points: excluded by relic density constraints.
- White region at low splitting: excluded by LEP SUSY recast.
- red points allowed.



Simulated parameters

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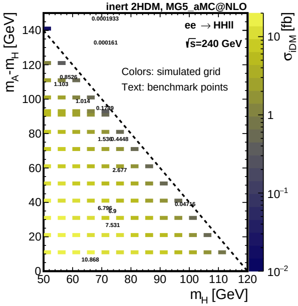
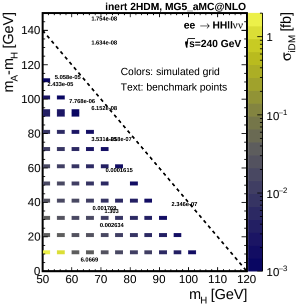
- $m_{H^\pm} = m_A + 50$ GeV constraints also $m_A - m_H < 50$ GeV
- HHll dominated by AH production: $m_{H^\pm}$ choice irrelevant, can still use sensitivity obtained for $m_A - m_H > 50$ GeV.
- HHll$\nu\nu$ depends on $m_{H^\pm}$ choice! But stays subdominant...





MC samples and selection

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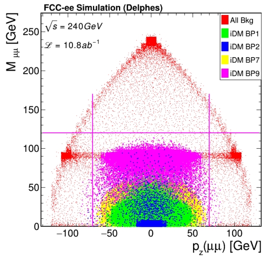
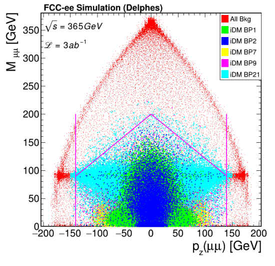
- Largely inspired from arXiv:2002.11716 with adaptation to new $\sqrt{s}$ scenarios, and addition of ee channel.
- Backgrounds: central FCC "Winter 2023" production of WW, ZZ [and ttbar] with Pythia8, inclusive ee$\rightarrow \ell\ell$ and ZH with Whizard+Pythia6.
- Using DELPHES objects from central FCC production with simplified IDEA detector.
- Final state: exactly 2e (2μ) with $p > 5$ GeV [including $\tau \rightarrow e, \mu$], no other μ (e) or γ, jets.
- Some transverse missing energy to further reject inclusive ee ($\mu\mu$) production.
- Note: for ee production, missing $M_{ee} < 30$ GeV contribution ! Combining channels only for mass splitting $m_A - m_H > 30$ GeV.

Step	Selection at $\sqrt{s}$ =240 GeV	Selection at $\sqrt{s}$ =365 GeV	target background
Preselection	$\lvert p_z(\ell\ell)\rvert < 70$ GeV	$\lvert p_z(\ell\ell)\rvert < 140$ GeV	ZZ, ee$\rightarrow ee, \mu\mu$
	$M_{\ell\ell} < 120$ GeV	$M_{\ell\ell} < (-9.0/14.0 \times \lvert p_z(\ell\ell)\rvert + 200)$	WW, ee$\rightarrow ee, \mu\mu$
	$E_T^{miss} > 5$ GeV	$E_T^{miss} > 5$ GeV	ZZ, ee$\rightarrow ee, \mu\mu$
Object veto	3rd lepton E> 5 GeV, jet, photon E> 5 GeV	3rd lepton E> 5 GeV, jet, photon E> 5 GeV	WW, ZZ, ee$\rightarrow \ell\ell$
Leptons p_T	$p_T < 80, 60$ GeV	$p_T < 140, 80$ GeV	WW, ZZ, ee$\rightarrow \tau\tau$
E/p	$p_{ll}/E_{ll} > 0.1$	$p_{ll}/E_{ll} > 0.1$	ee$\rightarrow \ell\ell$

Main variables for background rejection

Powerful 1st level rejection using 2-D cut

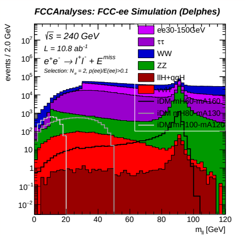




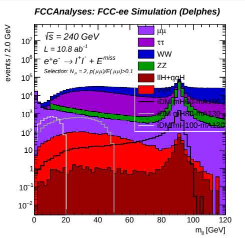
- Reproducing previous results from [arXiv:2002.11716].

- Next step: enhance signal with machine learning.

M_{ee} after ee selection



$M_{\mu\mu}$ after $\mu\mu$ selection



Input variables for ML algorithm

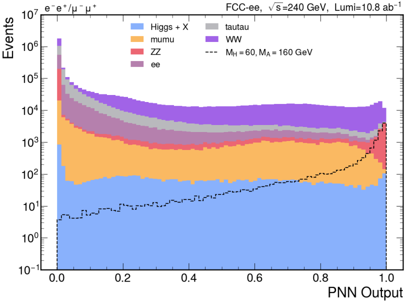
- Set of input variables with discriminating features, similar to arXiv:2002.11716.
- Problem with BDT approach: how to categorise by signal features / interpolate between signal points.

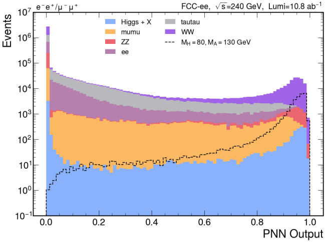
- the dilepton pair $E_{\ell\ell}$,
- the dilepton pair $p_T^{\ell\ell}$,
- the dilepton invariant mass $M_{\ell\ell}$,
- the dilepton recoil mass calculated assuming the nominal $\sqrt{s}$,
- the dilepton $p_z^{\ell\ell}$,
- the dilepton Lorentz boost $p_{\ell\ell}/E_{\ell\ell}$,
- the polar angle of the dilepton pair $\cos\theta$,
- the leptons p_T,
- the leptons $\cos(\Delta\phi)$,
- ℓ^- production angle with respect to the beam direction calculated in the dilepton centre-of-mass frame $\cos(\theta*)$,
- ℓ^- production angle with respect to the dilepton pair boost direction, calculated in the dilepton centre-of-mass frame $\cos(\theta R)$

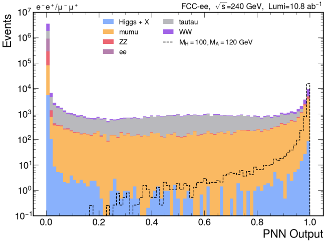
- One solution: parametric Neural Network, input signal masses as additional variables ⇒ training incorporates signal features, and can interpolate between simulated grid points.

Parametric Neural Network setup

- Implemented in PyTorch
- MC split into 3 datasets: training, validation and test with fractions 50%, 20% and 30%.
- ee and $\mu\mu$ summed together.







Extraction of the results

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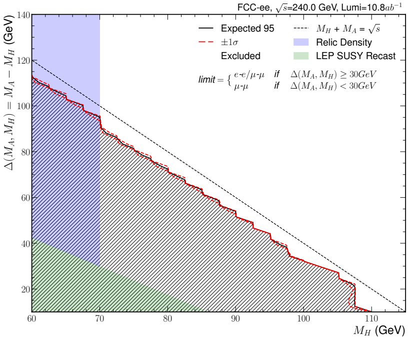
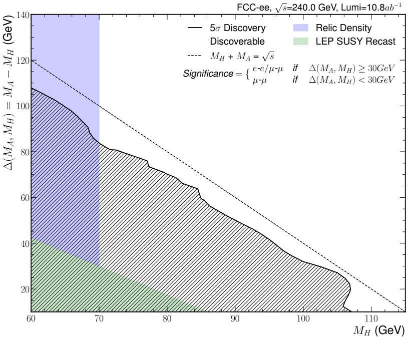
- Perform maximum likelihood fit of the pNN output above > 0.9, using for now just MC stat uncertainties as nuisance, within CMS Combine [arXiv:2404.06614].
- extract both 95% CL exclusion region, and 5-σ discovery contours, for several luminosity scenarios: nominal, half, 1/5 and 1/10.





Results at $\sqrt{s}$ =365 GeV

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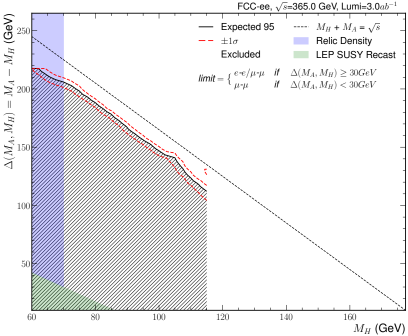

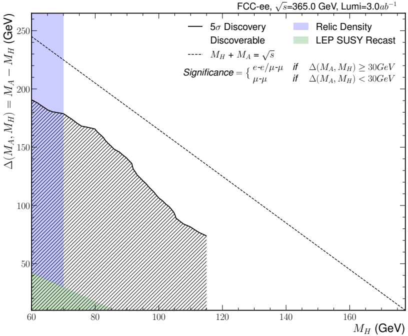

- Work-in-progress: missing simulation with higher m_H.

Conclusion

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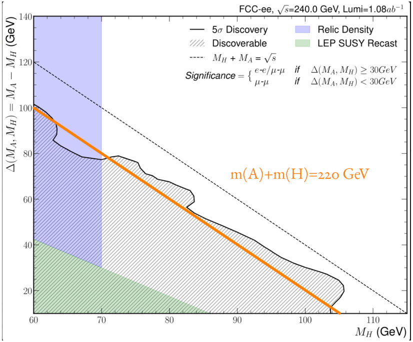
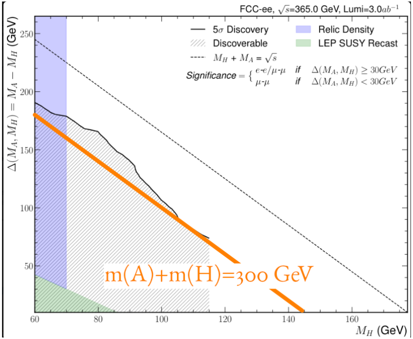
- Explored the IDM model with FCC-ee at $\sqrt{s}$ =240 (365) GeV.
- Reproduced CLIC/ILC setup results, extending a little the reach with parametric Neural Network approach with smooth limit/significance extraction.
- Will fix the model parameters to "allowed" choices but not expecting large impact on the sensitivity.
- Next: ready to incorporate realistic systematic uncertainty scenarios !





Backups

BACKUPS

Background samples

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- Using FCC officially generated samples.
- Winter 2023 production.
- ee collisions at $\sqrt{s} = 240$ GeV.
- Inclusive W, Z and Higgs decays.
- ee to ee,$\mu\mu$,$\tau\tau$ production via t- and s-channel.

Process	N Generated	xs (pb)	Eq. L (ab^{-1})
ZZ	56162093	1.359	41
WW	373375386	16.4385	23
eeH	1200000	0.00716	168
mumuH	1200000	0.00676	178
tautauH	1200000	0.00675	178
nunuH	3500000	0.0462	76
qqH	6700000	0.136	49
ee M30-150	85400000	8.305	10
mumu	53400000	5.288	10
tautau	52400000	4.668	11

FCC setup: Definition of Objects

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Electrons and photons

- Delphes electrons, p$>$ 5 GeV.
- Delphes photons, p$>$ 5 GeV.

Muons

- Delphes muons, p$>$ 5 GeV.

Jets and MET

- Reclustered jets removing selected electrons and muons.
- Durham algo, exclusive clustering N=2, E-scheme: JetClustering::clustering_ee_kt(2, 2, 1, 0)(pseudo_jets)
- MissingET collection from Delphes.

Lepton pair and recoil

- Z candidates: ReconstructedParticle::resonanceBuilder(91)(selected_leptons)
- ReconstructedParticle::recoilBuilder(240)(Zcandidates)