Inert 2HDM scalar pair production @ FCC-ee

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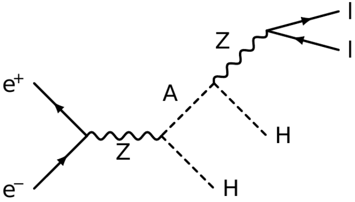
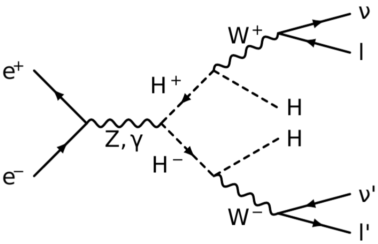
The inert Two-Higgs-Doublet model (iDM)

- 2HDM: 5 scalars, h, H, A, H+, H-.
- h: SM Higgs with constraints from SM measurements.
- Add Z2 symmetry:$\phi_D \to -\phi_D$,$\phi_S \to \phi_S$, SM $\to$ SM.
- Dark Matter candidate(s): choose H.
- Five free parameters: m_H, m_A, $m_{H\pm}$, λ_{345}, λ_2.
- Can ignore λ_{345}, λ_2 for this analysis: related to quartic iDM-H couplings and coupling to SM H, subdominant processes.
- Similarly, can set $m_{H\pm} = m_A + 50\,\text{GeV}$ as same-flavour dilepton channel less sensitive to $m_{H\pm}$ production $\Rightarrow$ Down to 2 free parameters! m_H, m_A
- Constraints from all experimental results: JHEP 1812 (2018) 081, set of 20 benchmark points relevant for FCC-ee $\Rightarrow$ helped to choose the (mH,mA) parameter space studied here.





Outline of the analysis

Final state: two same-flavour opposite-sign electrons or muons, and very little MET.

1. Define parameter space for the signal MC production - reduced to 2 free parameters, m_H and m_A.
2. Set of preselection cuts to reject main background, keeping signal for most of the parameter space under study.
3. Multivariate analysis with set of input features: parametric Neural Network.
4. Fit pNN output and extract 95% CL upper limit on signal XS using CMS Combine package.
5. Use $\mathcal{L} = 10.8$ (3) ab^{-1} of total integrated luminosity for $\sqrt{s} = 240$ (365) GeV.

Setup

Signal generation

- Generate Madgraph5_aMC@NLO cards for all benchmark points, see https://github.com/amagnan/FCC
- Generated 500k events per points, for FCC-ee @ $\sqrt{s} = 240$ and 365 GeV.
- Directly by final state: ee$\rightarrow$llHH or ll$\nu\nu$HH, with l=e, μ, τ.
- Use Pythia8 for hadronisation and τ decays.
- Finally, run through Delphes using FCC IDEA cards from official FCC-ee repository, Winter2023 production.

FCC software

- Produce events in the EDM4Hep format, root-based.
- Analyse with FCCAnalyses package, forked here: https://github.com/amagnan/FCCAnalyses
- Python-based config files to create branches with analysis variables in 2 stages,
- then python-based config files to define selection in 2 steps also: output separate histograms for each sample and selection, then plot together signal and backgrounds.

Background samples

- Using FCC officially generated samples.
- Winter 2023 production.
- ee collisions at $\sqrt{s} = 240$ and 365 GeV.
- Inclusive W, Z and Higgs decays.
- ee to ee,$\mu\mu$,$\tau\tau$ production via t- and s-channel.

Ecm	Process	N Gen	xs (pb)	Eq. L (ab^{-1})
240	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
	ee M30-150	85400000	8.305	10
	mumu	53400000	5.288	10
	tautau	52400000	4.668	11
365	ZZ	11470944	0.6428	18
	WW	11754213	10.7165	1.1
	eeH	1000000	0.00739	135
	mumuH	1200000	0.004185	287
	tautauH	1100000	0.004172	264
	nunuH	2200000	0.05394	41
	ee M30-150	3000000	1.527	2.0
	mumu	6600000	2.2858	2.9
	tautau	12800000	2.01656	6.3
	ttbar	2700000	0.8	3.4

FCC setup: Definition of Objects

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.

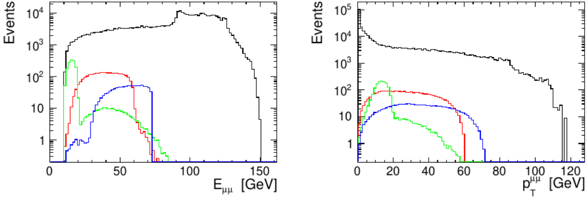
Algorithm	Objects	Selection requirements	efficiency
Tracking	e, μ, charged hadrons	p$_T$ $>$ 0.1 GeV, $\|\eta\| < 2.56$	1
Identification	γ, e, μ	E$>$ 2 GeV, $\|\eta\| < 3$	0.99

Lepton pair and recoil

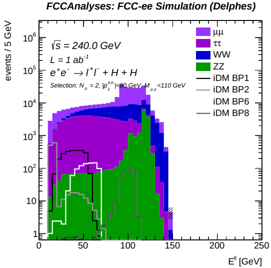
- Z candidates: ReconstructedParticle::resonanceBuilder(91)(selected_leptons)
- ReconstructedParticle::recoilBuilder(240)(Zcandidates)

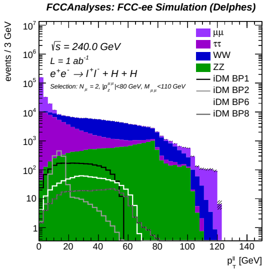
Cross-check against CLIC Setup

$\sqrt{s} = 250$ GeV



T. Robens et al, JHEP 07 (2019) 053 (@$\sqrt{s} = 380$ GeV)
Snowmass report: arXiv:2002.11716 (@$\sqrt{s} = 250$ GeV)





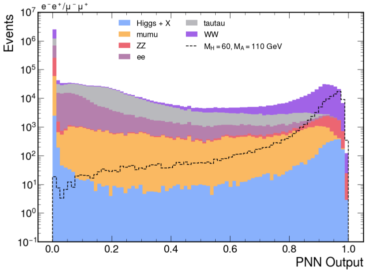
Parametric Neural Network

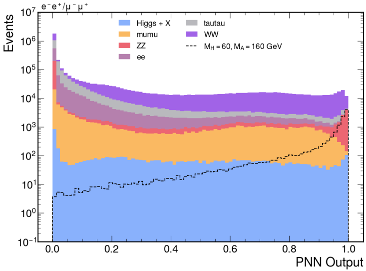
Input features

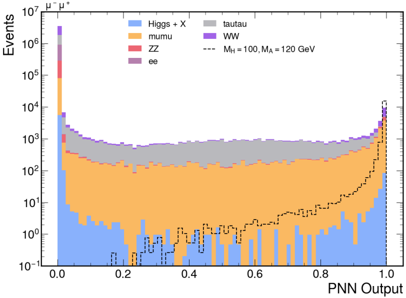
- the dilepton pair $E_{\ell\ell}$,
- the dilepton pair $p_T^{\ell\ell}$,
- the dilepton invariant mass $M_{\ell\ell}$,
- the dilepton recoil mass calculated assuming the nominal $\sqrt{s}$,
- the dilepton $p_z^{\ell\ell}$,
- the dilepton Lorentz boost $p_{\ell\ell}/E_{\ell\ell}$,
- the polar angle of 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 $\cos(\theta R)$

- Single network for all parameter space
- Interpolation between points simulated to get smooth limits everywhere.
- Implemented in PyTorch.
- Cross-checked against a simple BDT with same input features on theory benchmark point.

pNN output

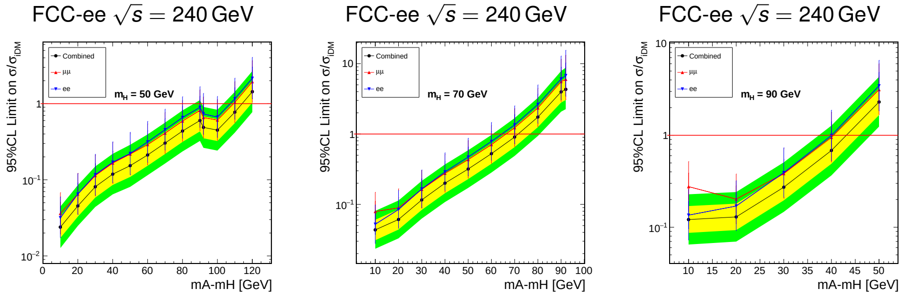

$e^-e^+/\mu^-\mu^+$
Events
Higgs + X
mumu
ZZ
ee
tautau
WW
$M_H = 60, M_A = 110$ GeV
PNN Output


$e^-e^+/\mu^-\mu^+$
Events
Higgs + X
mumu
ZZ
ee
tautau
WW
$M_H = 60, M_A = 160$ GeV
PNN Output

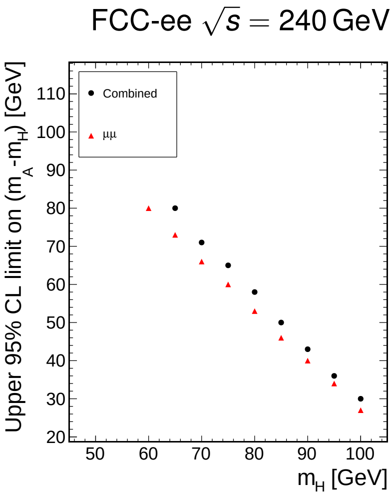

$\mu^-\mu^+$
Events
Higgs + X
mumu
ZZ
ee
tautau
WW
$M_H = 100, M_A = 120$ GeV
PNN Output

Limit results

- Maximum likelihood fit of pNN$>$ 0.9 distributions. Only one bin-by-bin uncertainty in the fit: MC stat.
- For each mH value, plot 95%CL upper limit as a function of mass splitting $m_A - m_H$, for ee and $\mu\mu$ channels separated and combination.
- Note divergence of ee vs $\mu\mu$ for low mass splitting: due to missing low mass ee$\rightarrow$ee background !



Proposed money plot - style to be improved...



- Proper interpolation between simulated grid point still running...
- Need to add 1- and 2-σ bands
- Need to blind combined results where missing ee background matters.
- + result for 365 GeV to be added.
- If possible, would like also to run with placeholder systematics.

Backups

BACKUPS

The iDM lagrangian

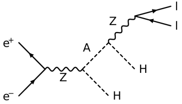
$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right]$$

Benchmark points

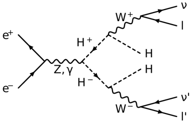
- Benchmark points: JHEP 1812 (2018) 081

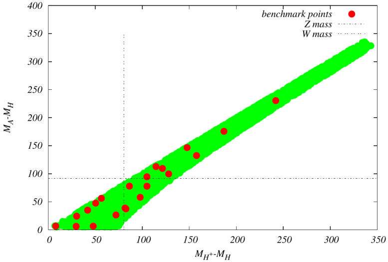
No.	M_H	M_A	$M_{H^\pm}$	$\sigma(250)$	$\sigma(380)$	$\sigma(500)$
BP1	72.77	107.803	114.639	77.2	65.9	45.7
BP2	65	71.525	112.85	155	85.1	53.4
BP3	67.07	73.222	96.73	149	83.5	52.8
BP4	73.68	100.112	145.728	89.2	69.1	46.9
BP6	72.14	109.548	154.761	75.1	65.4	45.4
BP7	76.55	134.563	174.367	31.2	52.3	40.1
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

ee→llHH



ee→ll$\nu\nu$HH





Note: my numbering goes from 1 to 20, corresponding to BP 1-4,6-10,12-16,18-23.