A first look at Inert 2HDM scalar pair production @ FCC-ee

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The inert Two-Higgs-Doublet model (iDM)

- Two Higgs-Doublet model: 5 scalars, h, H, A, H+, H-.
- h is the SM Higgs with constraints from SM measurements.
- Add Z2 symmetry: $\phi_D \to -\phi_D$, $\phi_S \to \phi_S$, SM $\to$ SM.
- Dark Matter candidate(s): choose H.
- Five free parameters: m_H, m_A, $m_{H\pm}$, λ_{345}, λ_2.
- Constraints from all experimental results: set of 20 benchmark points relevant for FCC-ee.

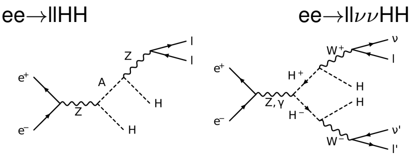
$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$

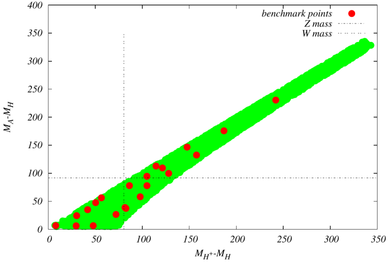
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right]$$

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





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

FCC 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 @ $\sqrt{s} = 240$ GeV.
- Directly by final state: ee→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 $\sqrt{s} = 240$ 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

Electrons and photons

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

Muons

- Delphes muons, p$>$ 5 GeV.

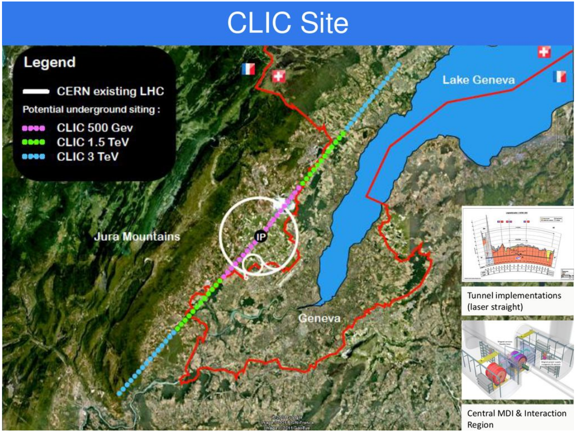
Jets and MET

- 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)

Part I - reproducing CLIC cut&count selection



CLIC Setup

CLIC analysis strategy

- ee collisions at $\sqrt{s} = 250$ and 380 GeV, $L_{int} = 1ab^{-1}$, $\mu\mu$ and $e\mu$ final state.
- MG5_aMC@NLO used to produce inclusive final states for ll+X and ll+$\nu\nu$+X.
- Generator-level selection to mimic detector acceptance.
- Preselection based on 2D distribution of m_Z vs p_Z^Z for signal vs backgrounds.
- Selection and cut-and-count strategy.
  - energy $E_{\mu\mu} < 100\,\text{GeV}$,
  - transverse momentum $p_T^{\mu\mu} > 10\,\text{GeV}$,
  - production angle (polar angle of the Z boson) $30° < \Theta_{\mu\mu} < 150°$,
  - difference of the lepton azimuthal angles $|\Delta\varphi_{\mu\mu}| < \frac{\pi}{2}$.
- Improve significance using BDT and cut-and-count strategy.

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

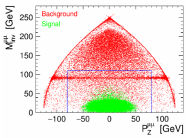
CLIC BDT variables

- total energy of the lepton pair, $E_{\ell\ell}$;
- dilepton invariant mass, $M_{\ell\ell}$;
- dilepton transverse momentum, $p_T^{\ell\ell}$;
- polar angle of the dilepton pair, $\Theta_{\ell\ell}$;
- Lorentz boost of the dilepton pair, $\beta_{\ell\ell} = p_{\ell\ell}/E_{\ell\ell}$;
- reconstructed missing (recoil) mass M_{miss} (calculated assuming nominal e^+e^- collision energy);
- ℓ^- production angle with respect to the beam direction, calculated in the dilepton center-of-mass frame, $\Theta_\ell^\star$;
- ℓ^- production angle with respect to the dilepton pair boost direction, calculated in the dilepton center-of-mass frame, $\angle^\star(\ell, \ell\ell)$,

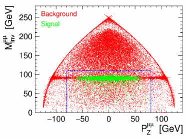
First step: reproduce CLIC paper results for cut&count

- Trying to mimic CLIC analysis generator-level selection:
  - Exactly 2 muons E$>$ 5 GeV: asking then also for 0 e with $p_T > 3$ GeV and 0 jets.
  - No photon with E$>$ 10 GeV
- Preselection from CLIC study using the 2D plot: use $|p_z(Z)| < 60$ GeV and $M_Z < 60$ GeV.

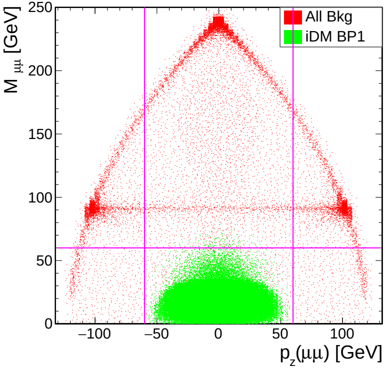
Snowmass report: arXiv:2002.11716



BP1



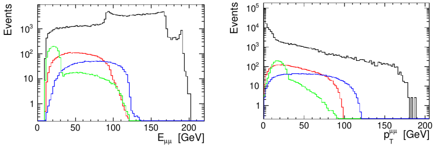
BP9



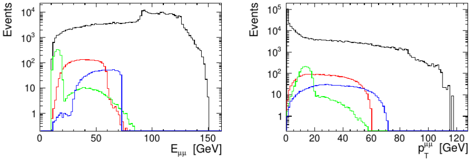
Comparisons with CLIC results for Z kinematics

SumBkg BP1 BP2 BP7

$\sqrt{s} = 380$ GeV

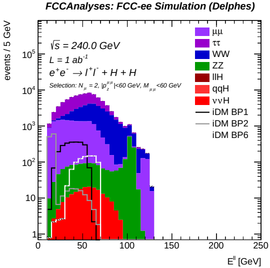


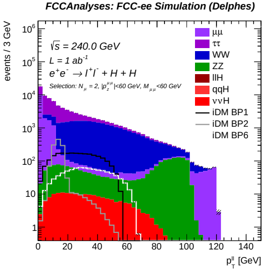
$\sqrt{s} = 250$ GeV



JHEP 07 (2019) 053, arXiv:2002.11716

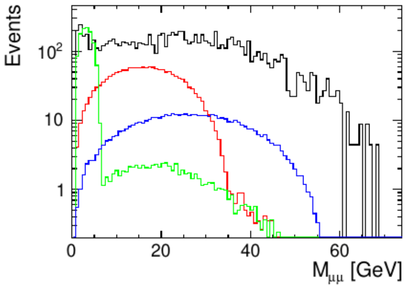
After presel

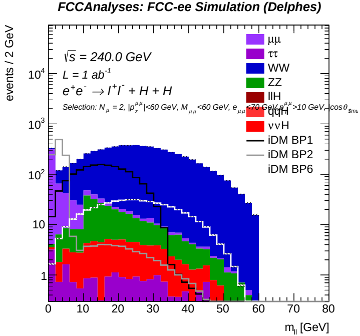




After CLIC preselection and cut-and-count selection

SumBkg BP1 BP2 BP7
$\sqrt{s} = 250$ GeV





arXiv:2002.11716

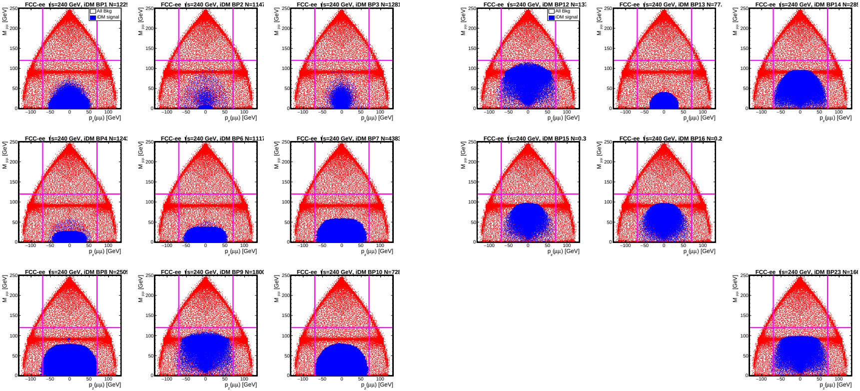
Sample	CLIC yield (380 GeV)	FCC yield
Sum bkg	5400	$\simeq$ 6800
BP1	1810	1571
BP2	1290	1023
BP7	540	480

- Obtaining about same yields...
- Background shape is completely different for $E_{\mu\mu}$...
- Signal shapes reasonably similar though.

Part II - BDT selection for FCC

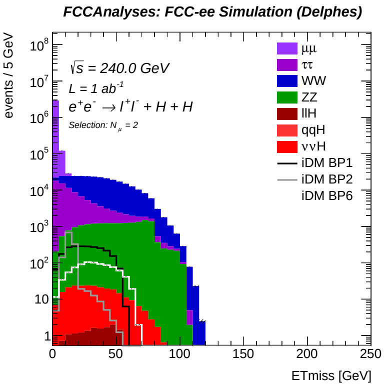
- Define preselection to skim backgrounds: optimise to select all signal BPs.
- Train BDT on ee+$\mu\mu$ together.
- Do a separate training for each BP.
- Calculate BDT score for each BP (20 variables in output tree).
- Find optimal significance using Asimov sig, separately for ee and $\mu\mu$.

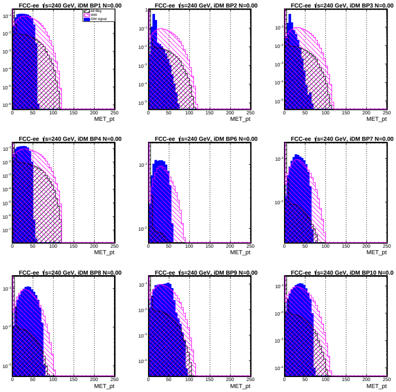
Preselection on Z kinematics



- For all signal points: choose $|p_z(Z)| < 70$ GeV and $M_Z < 130$ GeV.

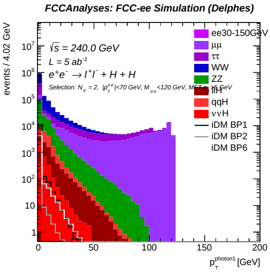
Preselection on MET p_T to reduce backgrounds

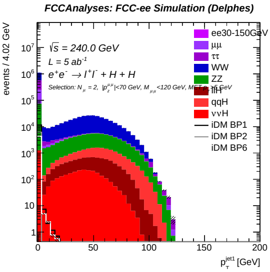




- Cut at MET $p_T > 5$ GeV helps reduce inclusive ll background by O(100).
- Loss of signal eff is minimal for all points.

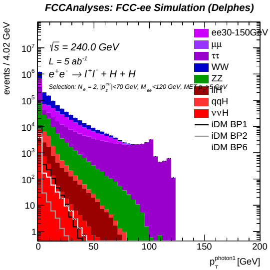
Veto on other objects

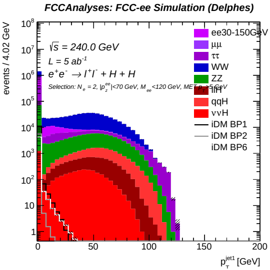




$\Leftarrow \mu\mu$ selection

- Vetoing any photon or jet or additional e or μ with $p > 5$ GeV.
- Ask also $p_T^{lep1} < 80$ GeV, $p_T^{lep2} < 60$ GeV, $p^{ll}/E^{ll} > 0.1$.

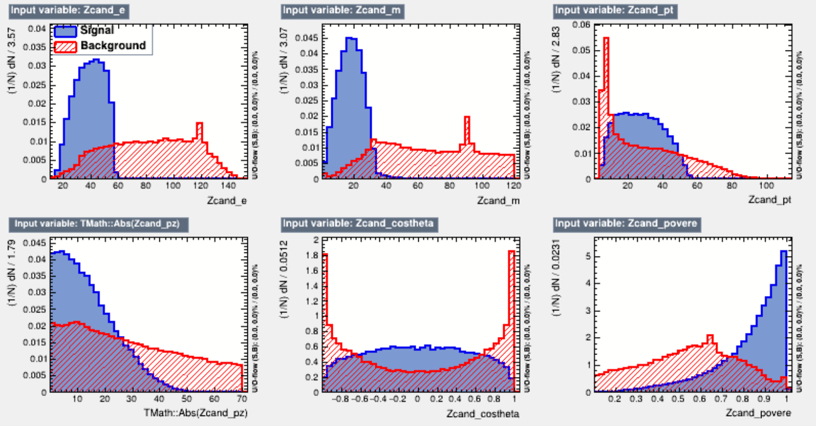




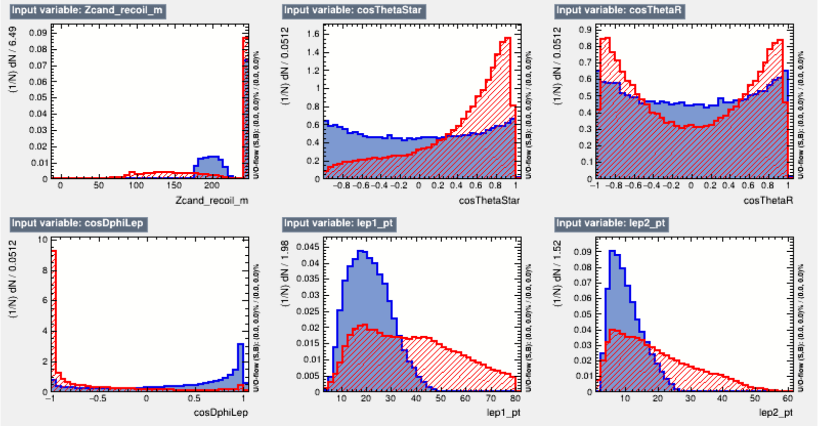
$\Leftarrow$ *ee* selection

BDT variables - ee+$\mu\mu$ - for BP1 - 1/2

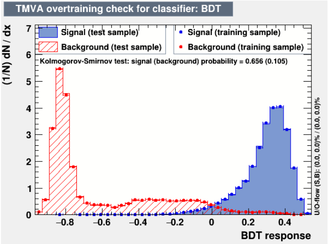
Bug in recoil variable found for ee ⇒ fixed but pb with lxplus update to EL9 to rerun in time for today...

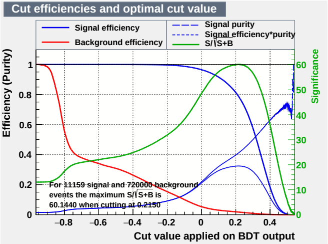


BDT variables - ee+$\mu\mu$ - for BP1 - 2/2



Overtrain check, example of significances and ranking for BP1

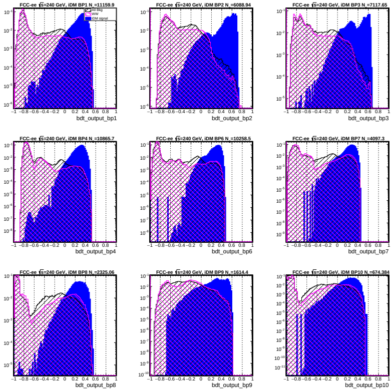


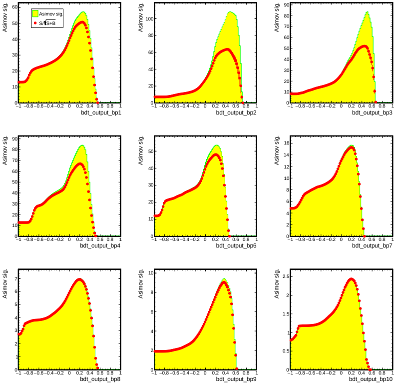


Ranking results after BDT for BP1

Rank	Variable	Importance
1	Zcand_e	3.11E-01
2	Zcand_m	1.30E-01
3	cosDphiLep	8.37E-02
4	cosThetaStar	8.18E-02
5	lep2_pt	7.90E-02
6	lep1_pt	7.01E-02
7	Abs(Zcand_pz)	6.44E-02
8	Zcand_povere	4.97E-02
9	Zcand_pt	3.60E-02
10	Zcand_recoil_m	3.47E-02
11	Zcand_costheta	3.26E-02
12	cosThetaR	2.72E-02

For each BP for $\mu\mu$: BDT shapes and Asimov significance





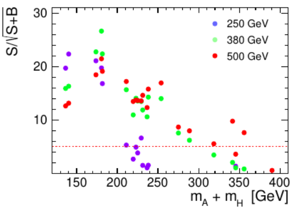
Expected yields and efficiency of BDT selection for $\mu\mu$

- Background yields before BDT selection: 723039 (just WW: 403813)
- BDT cut chosen by max Asimov significance.

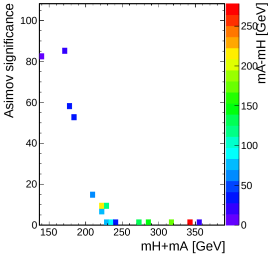
BP	Nsig before cut	max Asimov sig.	BDT cut	signal eff	bkg eff	WW eff
1	11159.9	57.232	0.26	0.711339	0.0231882	0.0311006
2	6088.94	108.197	0.48	0.695825	0.000831171	0.000326537
3	7117.65	83.7101	0.5	0.421401	0.000806775	0.000336895
4	10865.7	84.1889	0.24	0.727795	0.00904478	0.0108461
6	10258.5	53.56	0.22	0.734448	0.0241045	0.0355277
7	4097.3	15.6752	0.18	0.778986	0.0558884	0.0925529
8	2325.06	7.00913	0.2	0.64386	0.062404	0.104831
9	1614.4	9.43991	0.36	0.408398	0.00644949	0.0074155
10	674.384	2.45261	0.18	0.700887	0.0511504	0.0850992
12	1240.62	9.48808	0.36	0.448016	0.00449675	0.00499019
13	71.9903	0.921553	0.28	0.661325	0.00366938	0.00573485
14	249.234	1.64436	0.38	0.31818	0.0031803	0.00324629
15	0.262371	0.00253401	0.52	0.140541	0.000292844	0.000325447
16	0.219338	0.00176442	0.54	0.100562	0.000216127	0.000200065
21	41.2234	0.674664	0.42	0.496616	0.00126408	0.00108973
22	0.195533	0.00187675	0.5	0.131895	0.000261159	0.000294374
23	1457.96	8.54532	0.42	0.278871	0.00294902	0.00347307

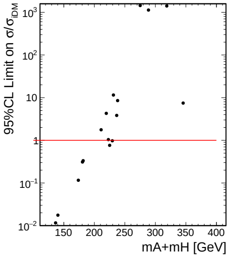
Results

- Signal eff and background rejection in same ball park as in CLIC paper.
- Comparison with CLIC theory paper:



arXiv:2002.11716





- Attempt at getting proper limits with CMS Combine program.
- Plot style, 1- and 2-σ bands to be added !
- Proper systematics to add !

Conclusion and Outlook

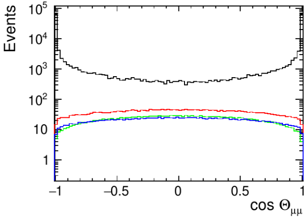
- Already existing studies for i-2HDM at CLIC, but generator-level or at higher $\sqrt{s}$ than initial FCC-ee running.
- PS: newest CLIC paper also explores 1.5 and 3 TeV scenarios with semileptonic decays at detector level, Eur.Phys.J.C 82 (2022) 8, 738 (arXiv:2201.07146).
- At FCC-ee $\sqrt{s} = 240$ GeV, using a BDT also allows pretty good significances to be obtained for several BPs, at detector level.
- Will extract proper limits at 95% CL with 1- and 2-σ bands on the signal cross section using CMS Combine.
- Do we have realistic experimental systematics as inputs ?
- FCC-ee here, but should also investigate FCC-hh.
- Interest to use this channel for detector performance studies?

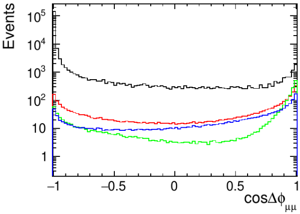
Backups

BACKUPS

Comparisons with CLIC results for angular variables

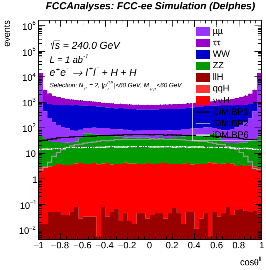
SumBkg BP1 BP2 BP7

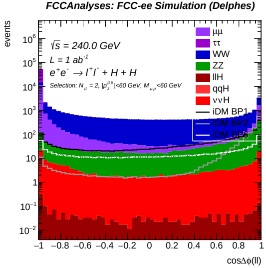




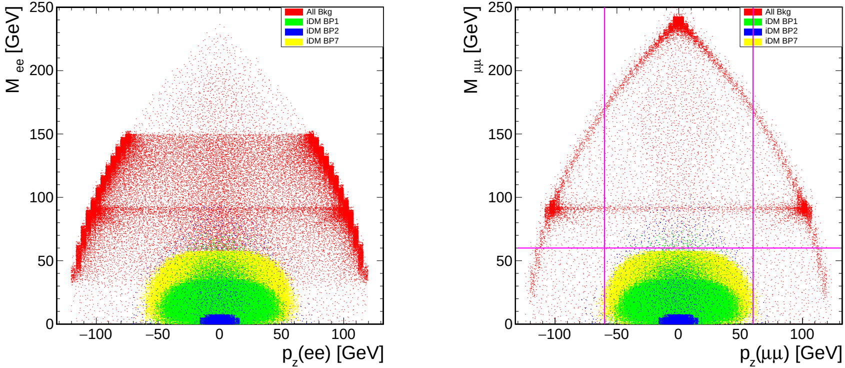
T. Robens et al, JHEP 07 (2019) 053

After presel

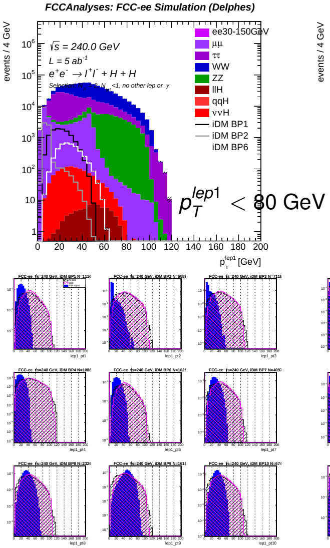


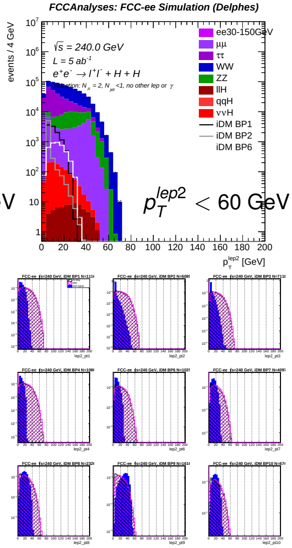


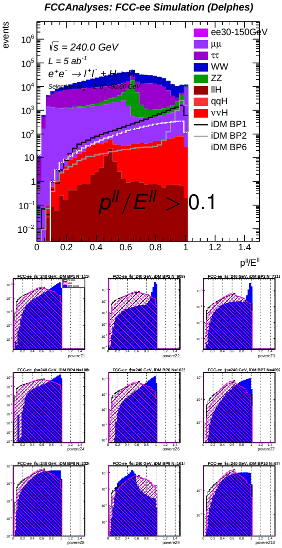
Preselection for ee and mumu separated



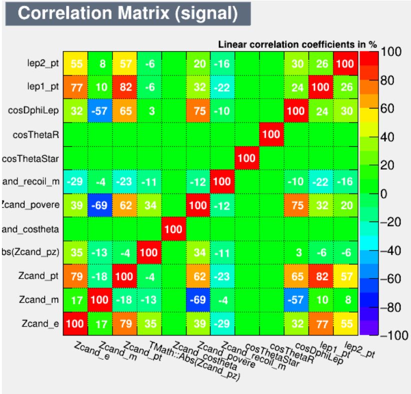
Further preselection ($\mu\mu$) to reduce WW and ll backgrounds

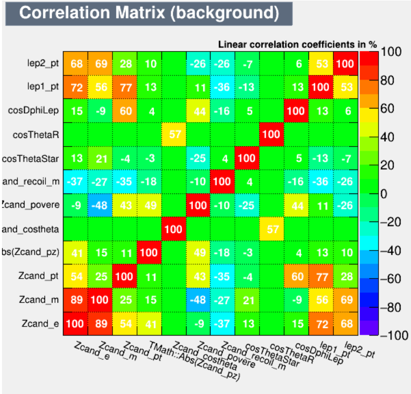




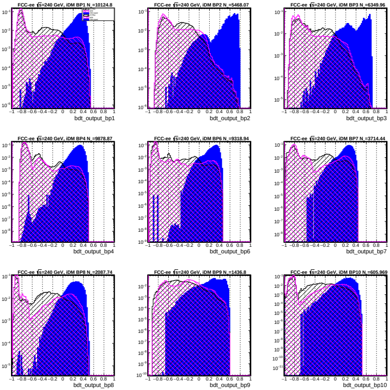


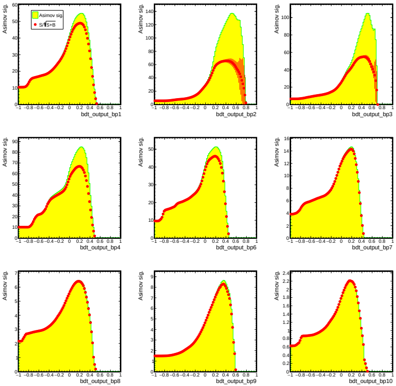
Correlations between variables - for BP1





Each BP for *ee*: BDT shapes and Asimov significance





Expected yields and efficiency of BDT selection for ee

- Background yields before BDT selection: 931005 (just WW: 371474)
- BDT cut chosen by max Asimov significance.

BP	Nsig before cut	max Asimov sig.	BDT cut	signal eff	bkg eff	WW eff
1	10124.8	54.9307	0.22	0.770255	0.0190292	0.0377832
2	5468.07	137.175	0.5	0.779888	0.00022648	0.000306964
3	6349.96	104.942	0.5	0.478244	0.000260187	0.000376297
4	9878.87	85.1288	0.22	0.799152	0.00679741	0.0135799
6	9318.94	51.3698	0.2	0.763453	0.0182058	0.0393909
7	3714.44	14.6656	0.18	0.732999	0.0360582	0.0830509
8	2087.74	6.4836	0.18	0.62109	0.0424996	0.100339
9	1436.8	8.65703	0.34	0.406248	0.00467839	0.00751469
10	605.969	2.21871	0.16	0.695847	0.0386442	0.0907866
12	1128.02	7.94791	0.3	0.483804	0.00487257	0.00781395
13	66.1278	0.812884	0.28	0.633604	0.00283865	0.00619617
14	222.001	1.45352	0.38	0.231537	0.00132497	0.00194608
15	0.267712	0.00220511	0.48	0.140532	0.000312644	0.000466372
16	0.222774	0.00157042	0.5	0.098989	0.00021179	0.00026726
21	39.0537	0.434033	0.42	0.268209	0.000621828	0.000605631
22	0.209838	0.00171976	0.48	0.121974	0.000237903	0.000344297
23	1285.71	7.71059	0.4	0.258068	0.00187364	0.00302993