Probing extended Higgs sector and dark matter at colliders : Improvements with machine-learning

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Higgs data and effective operators

- The newly discovered Higgs boson is an excellent laboratory to look for physics beyond SM.
- Is it really our SM Higgs?
- Although experimental data have pinned down its interactions to known SM states to almost corresponding SM predictions, there is still room to explore.
- Is there one Higgs boson or our 125 GeV Higgs is part of an extended sector just like all other SM particles?
- To answer these questions, studying the properties of the 125 GeV Higgs, as well as directly looking for additional scalar states become necessary.

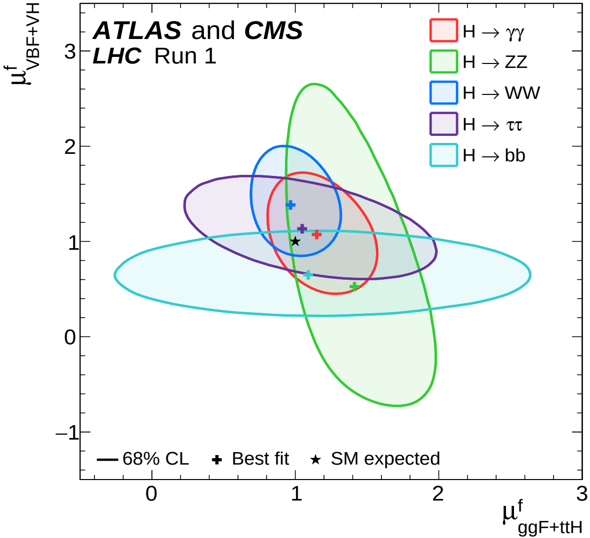
- Heavy states in some new physics models may have low direct production rate at the collider.
- These states can make their presence felt by modifying the Higgs couplings with fermions and gauge bosons multiplicatively(due to mixing between scalar doublets) or modifying the effective Higgs coupling by running in the loops(e.g charged Higgs loop in $h \to \gamma\gamma$ or $h \to Z\gamma$).
- Explored the scope of new physics in the Higgs sector with modified couplings with multiplicative scale factors κ_i as well as loop contributions parametrized by effective dimension-6 operators.
- We have imposed all existing experimental constraints and found the regions of parameter space allowed at the 1 and 2σ levels.

Lorentz structure of the couplings are unaltered.

$$
\begin{aligned}
\tilde{g}_{hVV} &= \kappa_v \times g_{hVV} \\
\tilde{g}_{ht\bar{t}} &= \kappa_t \times g_{ht\bar{t}} \\
\tilde{g}_{hb\bar{b}} &= \kappa_b \times g_{hb\bar{b}} \\
\tilde{g}_{h\tau\bar{\tau}} &= \kappa_\tau \times g_{h\tau\bar{\tau}}
\end{aligned}
$$

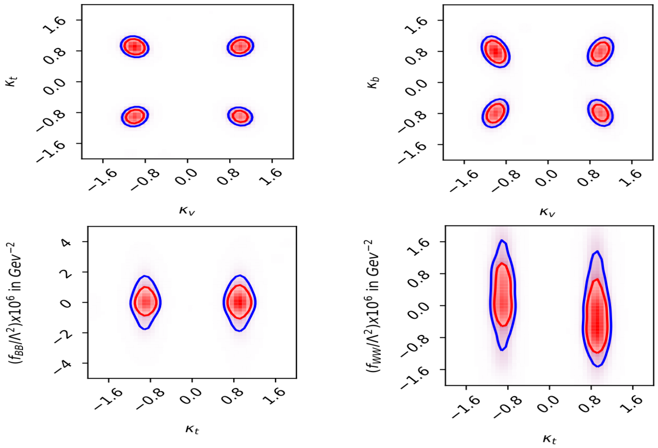
- Heavy states(TeV scale or even less) running in the loop can be parametrized in terms of higher dimensional operators.
- New physics should be SU(2)$_L\times$ U(1)$_Y$ invariant.
- Effect of such operators on tree-level couplings have been neglected and non-negligible effect on $h\gamma\gamma$ and $hZ\gamma$ vertices are considered.

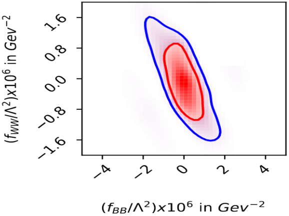
$$\begin{aligned}
\mathcal{O}_{BB} &= \frac{f_{BB}}{\Lambda^2}\Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi \\
\mathcal{O}_{WW} &= \frac{f_{WW}}{\Lambda^2}\Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \\
\mathcal{O}_{B} &= \frac{f_{B}}{\Lambda^2}D_\mu\Phi^\dagger \hat{B}^{\mu\nu}D_\nu\Phi \\
\mathcal{O}_{W} &= \frac{f_{W}}{\Lambda^2}D_\mu\Phi^\dagger \hat{W}^{\mu\nu}D_\nu\Phi
\end{aligned}$$

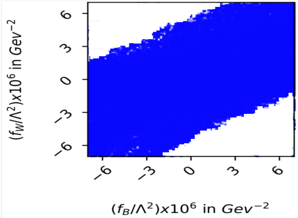


CMS and ATLAS combined result : Arxiv: 1606.02266

Allowed parameter space







- The contribution of the operators with coefficients f_{BB} and f_{WW} is to $h \to \gamma\gamma$ is in of the form $f_{BB} + f_{WW}$ and to $h \to Z\gamma$ is of the form $\tan^2\theta_W f_{BB} - f_{WW}$.
- The simultaneous restriction from the two gives rise to a closed region in the $f_{BB} - f_{WW}$ plane.
- f_B and f_W contribute to only $h \to Z\gamma$ but not to $h \to \gamma\gamma$. Therefore we do not get a closed region.

- Even when the heavy Higgs states in question are not much higher than the EWSB scale, it is possible to describe the new physics in terms of gauge-invariant effective operators.
- We were able to make a correspondence between the model-independent and model-dependent approach and translated the limit obtained on the effective operators into those on specific model parameters.

2HDM + a scalar singlet DM

- Dark matter is still a mystery of our universe. Assuming their particle nature, it is intriguing to know how they interact with SM particles.
- What will be key signature of such interactions?
- The interaction strength is most likely to be of weak coupling strength for WIMP DM candidates.
- SM Higgs can act as a DM-portal?
- Simultaneous satisfaction of direct detection bounds and relic density bounds makes it highly constrained.
- Extended Higgs sector opens up possibilities.
- Heavier scalars as possible DM-portal.

- Assuming CP-conservation in the Higgs sector, we assume the CP-even Higgs as the portal to DM sector.
- Non-negligible invisible branching ratio is possible to achieve.
- With considerable Yukawa or gauge interaction at the production level, new signals can be looked at in the High-Luminosity LHC.

The Lagrangian

$$\mathcal{L} = \mathcal{L}_{2HDM} + \mathcal{L}_{DM} + \mathcal{L}_{Int}$$

$$\begin{aligned} \mathcal{L}_{DM} + \mathcal{L}_{Int} &= \frac{1}{2}\partial^{\mu}\chi\partial_{\mu}\chi - \frac{1}{2}M_{\chi}^2\chi^2 \\ &+ \lambda_S\chi^4 + \lambda_{1s}\chi^2\Phi_1^{\dagger}\Phi_1 + \lambda_{2s}\chi^2\Phi_2^{\dagger}\Phi_2 \end{aligned} \tag{1}$$

The most general 2HDM scalar potential

$$\begin{aligned} \mathcal{V}_{2HDM} &= m_{11}^2\Phi_1^{\dagger}\Phi_1 + m_{22}^2\Phi_2^{\dagger}\Phi_2 - [m_{12}^2\Phi_1^{\dagger}\Phi_2 + \mathrm{h.c.}] + \frac{1}{2}\lambda_1(\Phi_1^{\dagger}\Phi_1)^2 \\ &+ \frac{1}{2}\lambda_2(\Phi_2^{\dagger}\Phi_2)^2 + \lambda_3(\Phi_1^{\dagger}\Phi_1)(\Phi_2^{\dagger}\Phi_2) + \lambda_4(\Phi_1^{\dagger}\Phi_2)(\Phi_2^{\dagger}\Phi_1) \\ &+ \left\{\frac{1}{2}\lambda_5(\Phi_1^{\dagger}\Phi_2)^2 + \left[\lambda_6(\Phi_1^{\dagger}\Phi_1) + \lambda_7(\Phi_2^{\dagger}\Phi_2)\right]\Phi_1^{\dagger}\Phi_2 + \mathrm{h.c.}\right\} \end{aligned} \tag{2}$$

- χ is odd under a postulated $\mathcal{Z}_2$ symmetry and $\Phi_{1,2}$ are even under it.
- λ_6, λ_7 both taken to be 0 and m_{12}^2, λ_5 are taken to be real.

Constraints on the Dark matter sector

- The thermal relic density should not exceed the Planck upper limit.
- χ-nucleon scattering cross section should be below the Xenon-1T/Lz limit.
- Annihilation cross-section of χ should be consistent with the constraints from indirect detection.
- Invisible branching ratio of 125 GeV $h < 19\%$

$$\lambda_{H\chi\chi} = \lambda_{1s} v \cos\alpha \cos\beta + \lambda_{2s} v \sin\alpha \sin\beta$$
$$\lambda_{h\chi\chi} = -\lambda_{1s} v \sin\alpha \cos\beta + \lambda_{2s} v \cos\alpha \sin\beta$$

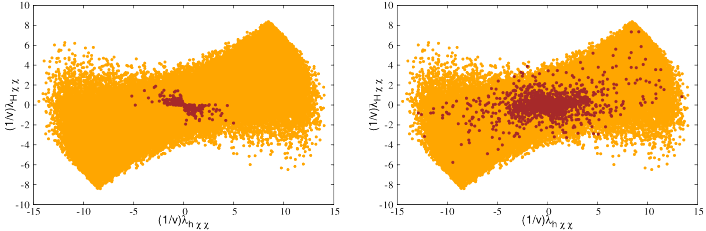
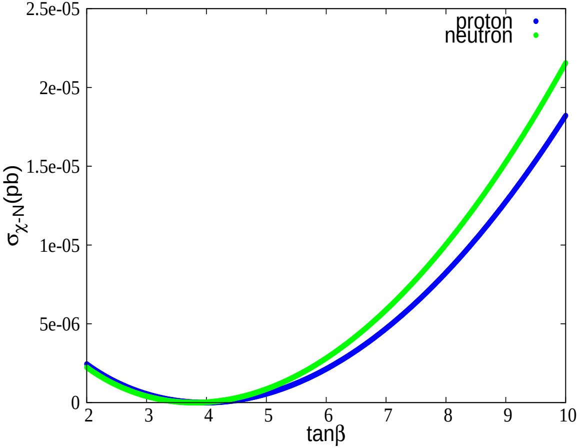


Figure: Type I (left) and Type II (right) 2HDM

- Type I case looks more restrictive.
- In Type II, a specific cancellation takes place between the t-channel digrams involving h and H for a range of $\tan\beta$.
- In Type I, this cancellation takes place at low $\tan\beta$.



proton
neutron
2.5e-05
2e-05
1.5e-05
1e-05
5e-06
0
2
3
4
5
6
7
8
9
10
$\sigma_{\chi\text{-}N}$(pb)
tanβ

Collider signature for heavy-Higgs-portal scenario

- To look for the signal involving $\not{E}_T$, one needs to have a visible final state to recoil against it.
- Major production channel for H is gluon fusion. Signal to look for monojet $+ \not{E}_T$
- Despite considerable production cross section, strong QCD background
- VBF with two forward jets provide a complimentary approach.
- It gives better background reduction despite its low signal rate.

Gluon fusion in a nut-shell

Signal

- One hard jet + $\not{E}_T$

- Hard p_T cut reduces Z + jets and W + jets background to a large extent.
- For $t\bar{t}$ a hard MET cut is essential.
- Cut on $\Delta\phi$ between jet and MET is useful to reduce the QCD background.

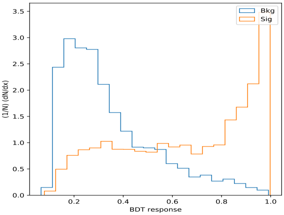
Vector Boson fusion

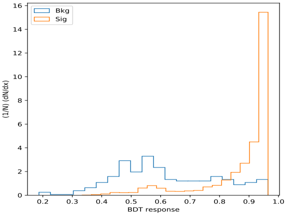
- Signal is two forward jets + $\not{E}_T$.
- VBF is a pure electro-weak process with no color flow in the central region.
- Background processes involve hadronic activity in the central region.
- Therefore it is possible to observe even small signal rate in the region of phase-space where is not populated by QCD events.
- $|\Delta\eta_{j_1 j_2}|$ peaks at a larger value for signal as compared to the backgrounds.
- Although VBF has lower cross section than gluon fusion, further $\cos(\beta-\alpha)$ suppression close to alignment limit, the VBF channel performs better than the gluon fusion channel because of better discriminating power.

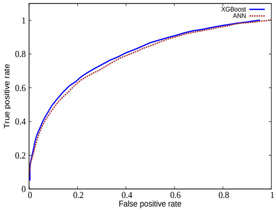
Improvement with multivariate analysis and neural network

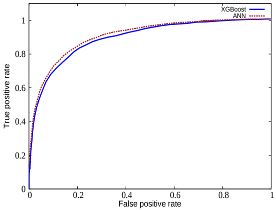
- One can go beyond the rectangular cut based analysis and apply some machine-learning and see the improvement.
- We have employed ANN and BDT techniques.
- Important input feature variables are identified from cut-based analysis.
- For both 80% of the data have been used for training and 20% for validation and testing.
- Some network parameters are adjusted in order to avoid over-training.

Distributions - ML









Comparison GGF

BP	$\mathcal{S}$ (Cuts)	$\mathcal{S}$ (Cuts + XGboost)	$\mathcal{S}$ (Cuts + ANN)
Type I BP I	5.1 σ	5.7 σ	5.6 σ
Type I BP II	1.9 σ	2.1 σ	2.0 σ
Type II BP I	2.7 σ	5.5 σ	4.3 σ
Type II BP II	2.3 σ	4.9 σ	4.8 σ

Table: Signal significance for the benchmark points at 14 TeV with $\mathcal{L} = 3000$ fb^{-1} in the gluon fusion channel with rectangular cuts and XGboost and ANN method with some initial cuts.

- MET acts as the best discriminator, p_T of the leading jet is the second and jet multiplicity is the third best discriminator.

Comparison VBF

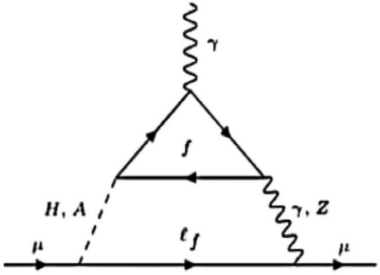
BP	$\mathcal{S}$ (Cuts)	$\mathcal{S}$ (Cuts + XGboost)	$\mathcal{S}$ (Cuts + ANN)
Type I BP I	3.8 σ (600 fb^{-1})	8.0σ(600 fb^{-1})	7.4σ(600 fb^{-1})
Type I BP II	2.3 σ (3 ab^{-1})	4.7σ (3000 fb^{-1})	4.6 σ(3000 fb^{-1})
Type II BP I	4.5 σ (3 ab^{-1})	11.0 σ(3000 fb^{-1})	12.1 σ(3000 fb^{-1})
Type II BP II	3.3 σ (3 ab^{-1})	9.9 σ(3000 fb^{-1})	10.0 σ(3000 fb^{-1})

Table: Signal significance for the benchmark points at 14 TeV in the vector fusion channel with rectangular cuts and XGboost and ANN techniques after applying some initial cuts.

- $m_{j_1 j_2}$, $|\Delta\eta_{j_1 j_2}|$, MET and p_T of the leading and sub-leading jets play the key-role in enhancing signal over background.

Type-X 2HDM + DM : a unique scenario

- Low mass non-standard scalars are very much allowed, since the additional doublet preferrably couples to leptons.
- two-loop contributions to $g_\mu - 2$



- Low pseudoscalar mass and large $\tan\beta$ is most favored to produce the desired result.

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11} \quad \text{with} \quad a_\mu = \frac{g_\mu - 2}{2} \qquad (3)$$

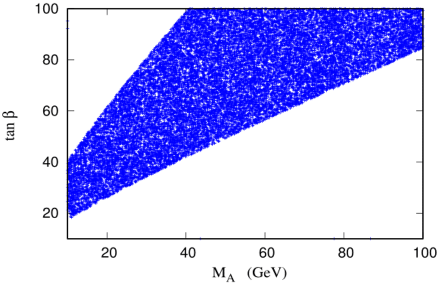


Figure: Region allowed by Fermilab(2021) and BNL(2006) data

- Low $\tan\beta$ and low non-standard scalar masses are valid till high scales from perturbative unitarity.
- A possibility for a UV-complete scenario.
- Type X + DM offers a much relaxed situation compared to Type I and II.
- λ_{2s} coupling gets constrained by direct detection bounds, whereas λ_{1s} coupling can be adjusted to produced adequate $\tau\tau$ channel for the DM.
- Probing such scenarios at LHC will be challenging because of poor production rate in GGF or VBF channel. Drell-Yan production and τ-final state has interesting prospect.
- $pp \to H(\chi\chi)H^{\pm}(\tau\nu_{\tau})$ or $pp \to H(\chi\chi)A(\tau\tau)$

Additional triplet as a portal to DM sector

- Exploring heavier scalar states of scalar triplet models (namely Type II seesaw) to be the portal for DM.
- Interesting regions of the parameter space, consistent with all the requirements from Higgs data, dark matter experiments, precision measurement as well as theoretical constraints can be identified.
- Two cases: with large and small charged lepton Yukawa couplings, consistent with neutrino mass hierarchy arising from the lepton number number violating Majorana mass term for neutrinos, same-sign dilepton final states.
- Owing to smallness of triplet vev, Drell Yan production of $H^{\pm\pm}H^{\mp}$, with $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}/W^{\pm}W^{\pm}, H^{\pm} \to HW^{*\pm}, H \to \chi\chi$ is considered.
- We have first performed a cut-based collider analysis, same-sign dilepton pair + $\not{E}_T$ +jets channel. Significant gain in the signal background separation has been achieved by employing the machine learning methods.

Mono-Higgs+MET search at HL-LHC

- We investigate the potential of the mono-Higgs+MET signal for dark matter at HL-LHC.
- We consider a Higgs-portal scenario whose phenomenological viability is ensured by the introduction of higher dimensional operators indicative of a TeV scale physics.
- These operators are also found to have non-negligible contribution to the mono-Higgs signal.
- We perform a detailed analysis of the proposed signal for $\gamma\gamma$ and $b\bar{b}$ decay mode of Higgs.
- In the $\gamma\gamma$ analysis we have taken into account the prompt as well as non-prompt photons (jet faking photons) as background and made a realistic study including systematic uncertainty.
- We have gone beyond the cut-based analysis and performed both BDT and ANN to achieve improved signal significance.

Work on lepton-flavor violation

- Considered two-Higgs doublet model in a parameter region motivated by the muon magnetic moment and lepton-flavour violation constraints (LFV).
- We look for the parameter space which can give considerable contribution to muon g-2 as well as LFV without violating low energy LFV constraints.
- All other constraints such as theoretical constraints, precision constraints, collider constraints, B-physics constraints are all taken into account.
- We have tried to look for observable signature of lepton-flavor-violating decay of Non-Standard Higgs(mainly light pseudoscalar A) at the HL-LHC.
- We have witnessed significant improvement over cut-based analysis in terms of signal significance with ANN analysis.

Signature of two-component DM at e^+e^- colliders

- Dark matter remains one of the most elusive aspects of nature and SM of particle physics fails to provide an answer.
- Two major classes of ideas, both of which can account for correct relic density : WIMP and FIMP.
- We focus on WIMP since it is likelier to be found at present/future collider experiments.
- Is there only one DM particle in nature? No a priori reason.
- Direct search experiments may probe two-component WIMP via observation of kink/distortion in the differential event rate.
- How to unequivocally establish the existence of multiple DM if they are produced simultaneously in collider experiments?
- We develop some criteria for the discrimination of two peaks in missing energy distributions at collider experiments.

Possible WIMP signatures at colliders

- The smoking gun signature for WIMP-like DM is energy/momentum imbalance in the final state, over and above SM background.
- Such imbalance can be quantified in terms of the following kinematic variables:
  - *Missing Transverse Energy or MET ($\not{E}_T$)*, defined as:

$$\not{E}_T = -\sqrt{(\sum_{\ell,j,\gamma} p_x)^2 + (\sum_{\ell,j,\gamma} p_y)^2}; \tag{4}$$

  - *Missing Energy or ME ($\not{E}$)* defined as:

$$\not{E} = \sqrt{s} - \sum_{\ell,j,\gamma} E_{\rm vis}\,; \tag{5}$$

  - *Missing Mass or MM ($\not{M}$)*, defined as:

$$\not{M}^2 = \left(\sum_i p_i - \sum_f p_f\right)^2, \tag{6}$$

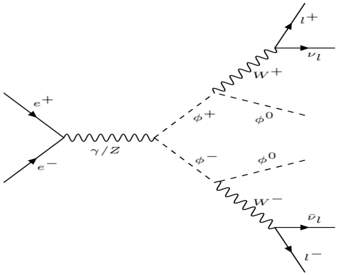
Possible final states

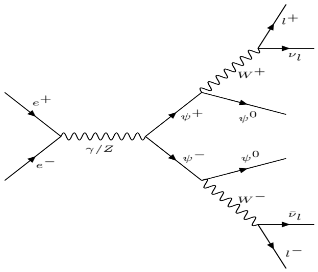
- **mono-X + $\not{E}$ ($\not{E}_T$)**, where X is a jet, a photon, a weak boson or a Higgs:
  The mono-X signature usually arises when two DM particles are produced directly via either a portal to dark sector or effective operators.
  Limited observables in the final state, with most of them being correlated.
- ***n*-leptons + *m*-jets + *p*-photons + $\not{E}$ ($\not{E}_T$)**: Occurs when a pair of heavy particles(HDSP) are produced and subsequently decays into DM and visible particles in the final state. Offers a richer topology. We choose this category for our study.

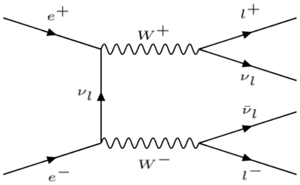
Bump-hunting: kinematics of it

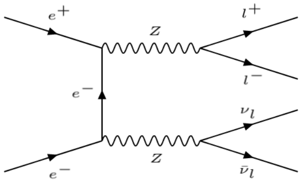
- Our major objective is to look for multiple maxima(bumps) in the spectrum of our chosen observables as a signature of multi-component DM.
- The spectrum is expected to be sensitive to both mass of the DM as well as mass of the heavier state(s) that finally decays into the DM and visible particles.
- One should choose the observable judiciously to capture the shift in kinematics as a result of shift in the masses of the dark sector particles in consideration.
- We consider here a $\ell^+\ell^- +$ missing momenta(energy) final state after one-step cascade and explore the observable spectrum in terms of m_{DM} and Δm(mass difference between the heavy state and DM).

Signal and backgrounds









Advantages of linear collider in multi-component DM search

- The availability of energy as well as full four-momentum gives a better handle over the kinematics.
- $\not{E}$ turns out to be advantageous over $\not{E}_T$, more sensitive to DM sector parameters.
- Absence of QCD backgrounds, hadronically quiet environment.
- The major backgrounds (in our case W^+W^- production) can be minimized by using the polarization combination maximally right polarized e^- beam and maximally left polarised e^+ beam.
- The mass range that is available to e^+e^- collider can be better probed there compared to LHC.

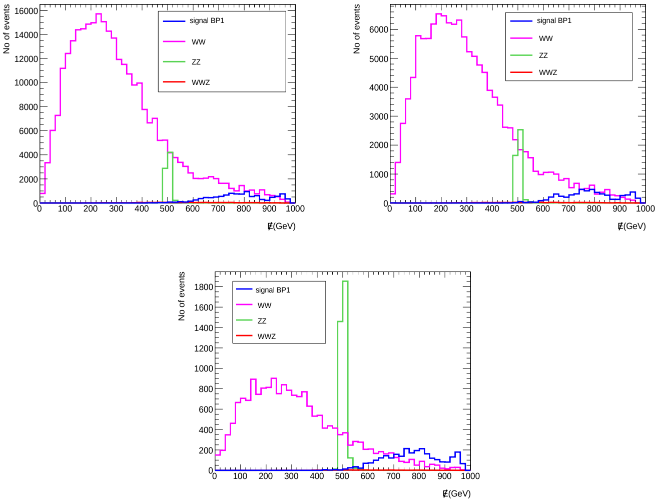


Figure: (a) $P1 \equiv \{P_{e^-} : -0.8, P_{e^+} : +0.3\}$, (b) $P2 \equiv \{P_{e^-} : 0, P_{e^+} : 0\}$ and (c) $P3 \equiv \{P_{e^-} : +0.8, P_{e^+} : -0.3\}$

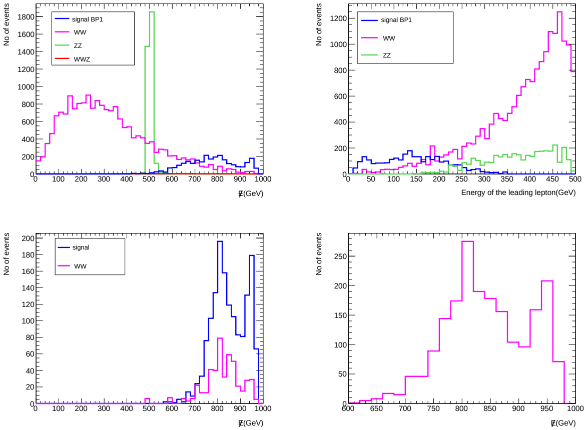


Figure: (c) $\not{E}$ after applying the cut on the energy of leading lepton $<$ 150 GeV, (d) $\not{E}$ distribution of signal(BP1) + background after applying the cut $E_{\ell_1} < 150$ GeV at ILC with $\sqrt{s} = 1$ TeV, $\{P_{e^-} : +0.8, P_{e^+} : -0.3\}$ at $\mathcal{L} =$1000 fb^{-1}.

Thank you