Improving sensitivity of trilinear R-parity violating SUSY searches using machine learning at the LHC

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Indian Institute of Technology Patna

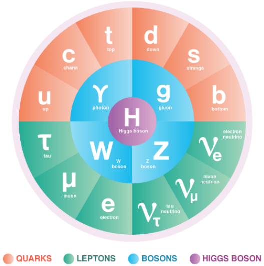
October 18, 2024

In collaboration with A. Choudhury, A. Mondal and S. Mondal
[Based on Phys.Rev.D 109 (2024) 3, 035001]

INTERNATIONAL SYMPOSIUM ON HIGH ENERGY PHYSICS

Current understanding of our universe:

THE STANDARD MODEL



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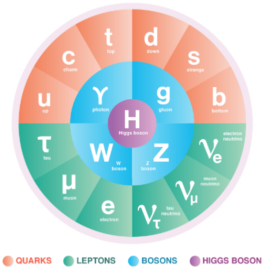

SHORTCOMINGS:

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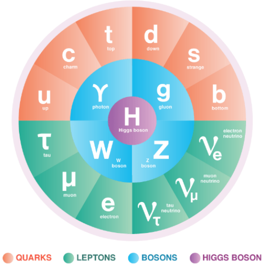

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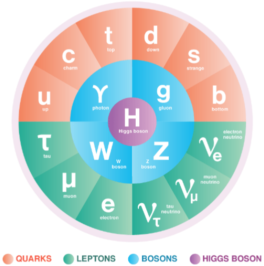

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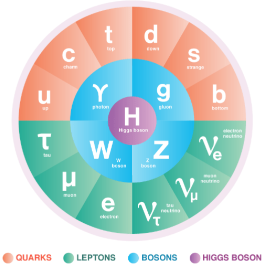

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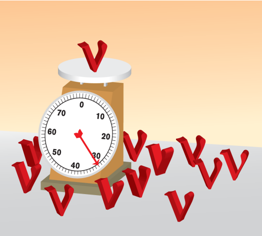

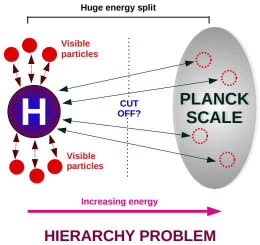

Motivation for Supersymmetry

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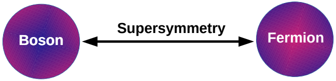

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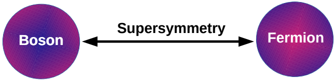

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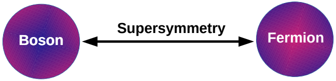

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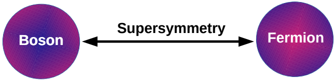

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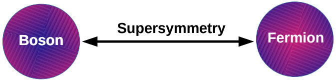

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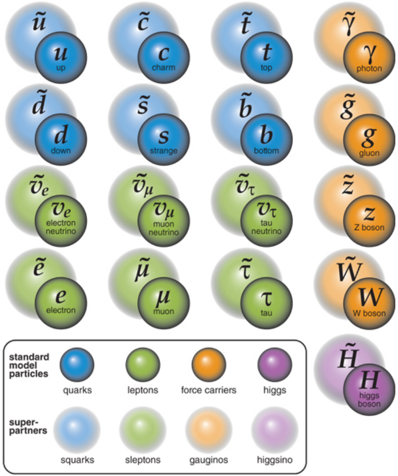

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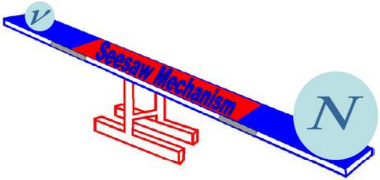

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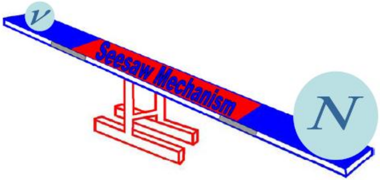

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NO SUSY PARTICLE IS FOUND SO FAR!

Resulting lower mass bounds on these particles at the LHC

- Stringent mass bound exist for squark and gluinos. [ATLAS Collaboration:https://cds.cern.ch/record/2686254]
- Mass bounds on Electroweakinos are less stringent.
- Light EW sector contributes to Muon g-2 [arXiv:1511.08874]
- Correct DM relic abundance can be predicted through gravitino LSP [hep-ph/0005214]

R-parity violation

$$\mathbf{W}^{\mathbf{RPV}}_{\mathbf{MSSM}} = \mathbf{W}_{\mathbf{MSSM}} + \frac{1}{2}\lambda_{\mathbf{ijk}}\mathbf{L_i}.\mathbf{L_j}\mathbf{e^c_k} + \lambda'_{\mathbf{ijk}}\mathbf{L_i}.\mathbf{Q_j}\mathbf{d^c_k} + \frac{1}{2}\lambda''_{\mathbf{ijk}}\epsilon_{\alpha\beta\gamma}\mathbf{u^{c\alpha}_i}\mathbf{d^{c\beta}_j}\mathbf{d^{c\gamma}_k} + \mu_{\mathbf{i}}\mathbf{H_u}.\mathbf{L_i}$$

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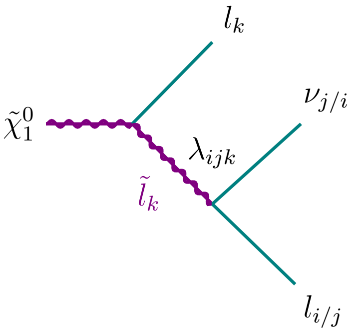

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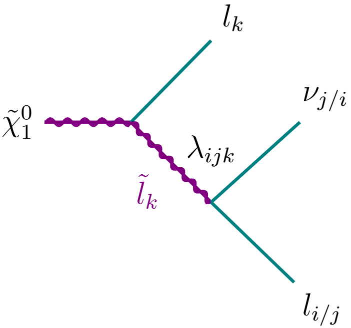

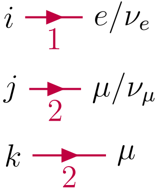

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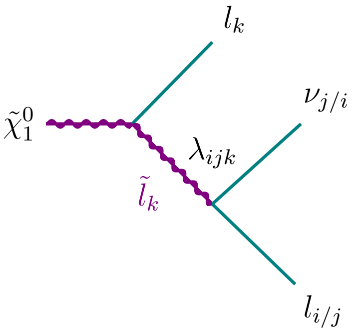
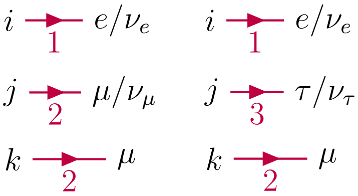
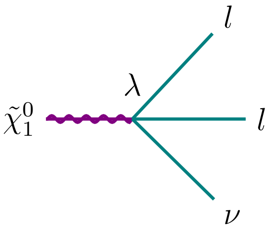




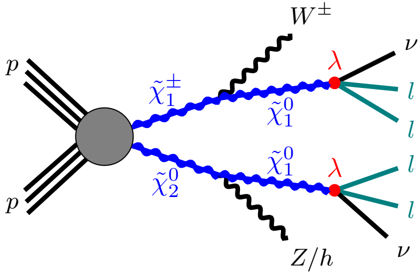


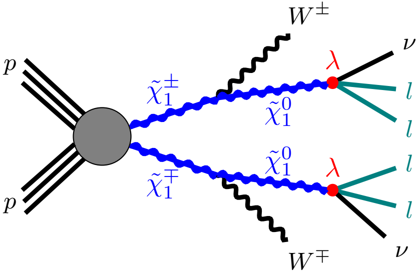
	$ij = 12$	$ij = 13$	$ij = 23$
$k = 1$	$ee\nu_\mu$ (50%), $e\mu\nu_e$ (50%)	$ee\nu_\tau$ (50%), $e\tau\nu_e$ (50%)	$e\mu\nu_\tau$ (50%), $e\tau\nu_\mu$ (50%)
$k = 2$	$\mu e\nu_\mu$ (50%), $\mu\mu\nu_e$ (50%)	$\mu e\nu_\tau$ (50%), $\mu\tau\nu_e$ (50%)	$\mu\mu\nu_\tau$ (50%), $\mu\tau\nu_\mu$ (50%)
$k = 3$	$\tau e\nu_\mu$ (50%), $\tau\mu\nu_e$ (50%)	$\tau e\nu_\tau$ (50%), $\tau\tau\nu_e$ (50%)	$\tau\mu\nu_\tau$ (50%), $\tau\tau\nu_\mu$ (50%)

Final States for different RPV Couplings

Non-zero couplings	Charged lepton configuration (Branching Ratios)			Remarks ($l = e, \mu$ only)
λ_{121} λ_{122}	$4e(25\%)$ $4\mu(25\%)$	$3e1\mu(50\%)$ $3\mu1e(50\%)$	$2e2\mu(25\%)$ $2e2\mu(25\%)$	$4l$ (100%) **Scenario-I**
λ_{131} λ_{232} λ_{132} λ_{231}	$4e(25\%)$ $4\mu(25\%)$ $2\mu2e(25\%)$ $2e2\mu(25\%)$	$3e1\tau(50\%)$ $3\mu1\tau(50\%)$ $1e2\mu1\tau(50\%)$ $2e1\mu1\tau(50\%)$	$2e2\tau(25\%)$ $2\mu2\tau(25\%)$ $2\mu2\tau(25\%)$ $2e2\tau(25\%)$	$4l(25\%)$ $3l1\tau(50\%)$ $2l2\tau(25\%)$ **Scenario-II**
λ_{123}	$2e2\tau(25\%)$	$1e1\mu2\tau(50\%)$	$2\mu2\tau(25\%)$	$2l2\tau(100\%)$ **Scenario-III**
λ_{133} λ_{233}	$2e2\tau(25\%)$ $2\mu2\tau(25\%)$	$1e3\tau(50\%)$ $1\mu3\tau(50\%)$	$4\tau(25\%)$ $4\tau(25\%)$	$2l2\tau(25\%)$ $1l3\tau(50\%)$ $4\tau(25\%)$ **Scenario-IV**

Electroweakino Production





- For $N_{lep} \geq 4$ final state, the dominant SM backgrounds are ZZ, $t\bar{t}Z$ and WWZ
- Other SM backgrounds are from $W^\pm ZZ$, ZZZ and Higgs (via GGF, associated production with jets, W and Z)

Distribution of Kinematic variables @HL-LHC

3 Benchmark Points are choosen:

1. **BP1** ($m_{\tilde{\chi}_1^\pm} = 1600$ GeV,$\mathrm{m}_{\tilde{\chi}_1^0} = 250$ GeV)
2. **BP2** ($m_{\tilde{\chi}_1^\pm} = 1800$ GeV,$\mathrm{m}_{\tilde{\chi}_1^0} = 800$ GeV)
3. **BP3** ($m_{\tilde{\chi}_1^\pm} = 1950$ GeV,$\mathrm{m}_{\tilde{\chi}_1^0} = 1850$ GeV)

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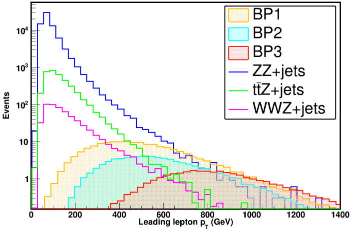
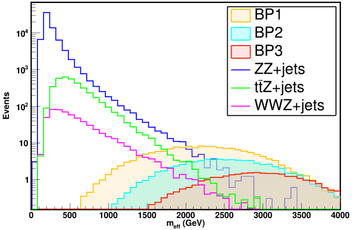


- $p_T^{l_1} \geq 100$ GeV cut is given at generation level for SM backgrounds
- $$\mathrm{m_{eff}} = \sum_i \mathrm{p_T^{l_i}} + \sum_i \mathrm{p_T^{j_i}} + \not{E}_T$$
- 2 signal regions are defined:

  SR-A: $N_l \geq 4$ + Z veto + b veto + $\mathrm{m_{eff}} > 900$ GeV

  SR-B: $N_l \geq 4$ + Z veto + b veto + $\mathrm{m_{eff}} > 1500$ GeV



Cut-flow and Significance for Scenario-I

Cut variables	$N_l \geq 4$ $(l = e, \mu)$ + $p_T^{l_1} > 100$ GeV	Z veto	b veto	Signal Region SR-A $(m_{eff} > 900)$	Signal Region SR-B $(m_{eff} > 1500)$
BP1	172.35	145.98	96.22	94.74	81.35
BP2	74.68	70.61	46.34	46.25	43.76
BP3	32.42	30.83	19.56	19.55	19.29
ZZ + jets	17350	126.56	115.63	5.79	1.12
$t\bar{t}Z$ + jets	2320	183.21	43.25	5.25	0.73
WWZ + jets	378.77	29	25.67	6.32	1.33
Others	2.075×10^3	44.05	37.37	2.83	0.318
Total background				20.19	3.498
Signal Significance σ_{ss} (σ^{ϵ}_{ss}, Sys. Unc.=5%)		BP1(1600,250)		**8.84 (7.79)**	8.83 (8.02)
		BP2(1800,800)		5.67 (5.25)	**6.36 (6.02)**
		BP3(1950,1850)		3.10 (2.96)	**4.04 (3.93)**

Projected exclusion for different scenarios

Projected exclusion @HL-LHC for $m_{\tilde{\chi}_1^0} = 800$ GeV			
Scenarios	Br. ratios from LSP pair	Projected exclusion in GeV	Projected exclusion with 20% sys. unc
Scenario-I	$4l$ (100%)	2180	2120
Scenario-II	$4l$ (25%) $3l1\tau$ (50%) $2l2\tau$ (25%)	2080	2020
Scenario-III	$2l2\tau$ (100%)	1900	1840
Scenario-IV	$2l2\tau$ (25%) $1l3\tau$ (50%) 4τ (25%)	1740	1680

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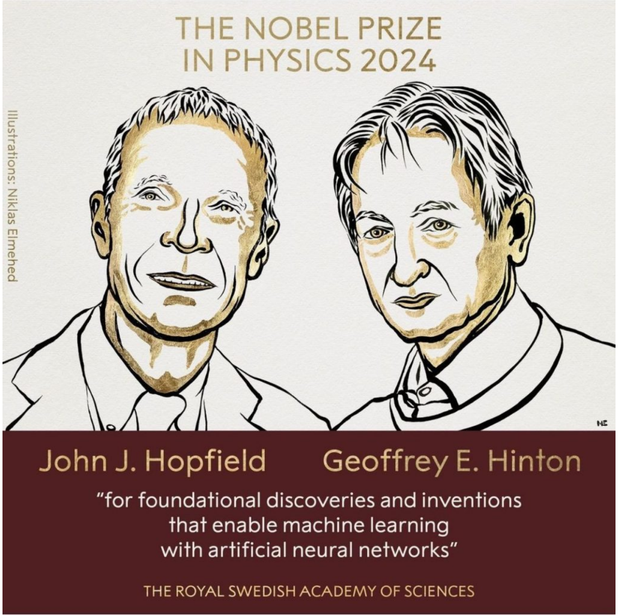
IS THERE ANY CHANCE OF IMPROVEMENT IF I USE MACHINE LEARNING?

Machine Learning: Need of the hour



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Basics of ML

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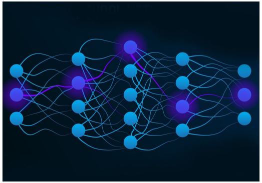

Neural Network

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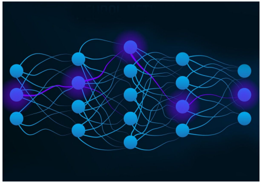

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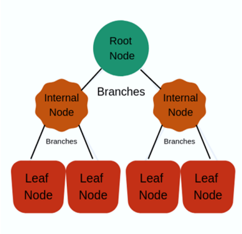
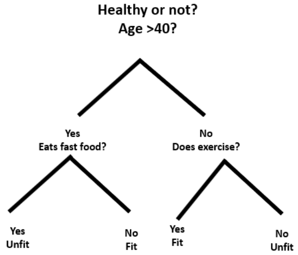


Decision Tree

Basics of BDT algorithms



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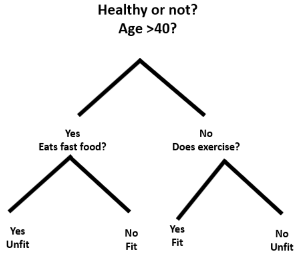

- While it is hard to make good learner, it is easy to build weak learners
- At each step, the events which are misclassified (signal as background, or vice versa), are given a larger weight, or **boosted**, and the a new tree is built on the new weights

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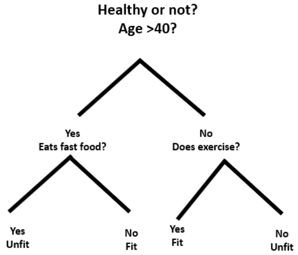

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- Scalable to almost all scenarios
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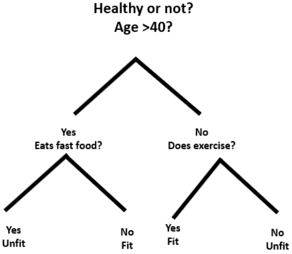

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Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-024-01308-x

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Regular Article

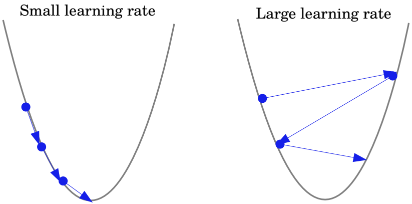
Searches for the BSM scenarios at the LHC using decision tree-based machine learning algorithms: a comparative study and review of random forest, AdaBoost, XGBoost and LightGBM frameworks

Arghya Choudhury[a], Arpita Mondal[b], and Subhadeep Sarkar[c]

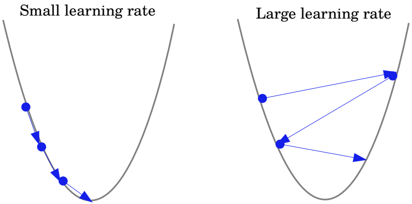
Department of Physics, Indian Institute of Technology Patna, Patna, Bihar 801106, India

Received 6 May 2024 / Accepted 23 August 2024

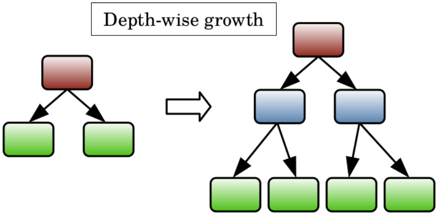
Learning rate



Learning rate



Depth of a tree



ML-Baesd Analysis @HL-LHC

- We implement multiclass classification
- 18 input features: $p_T^{l_1}$, $p_T^{l_2}$, $\Delta R_{l_\mathcal{A} l_\mathcal{B}}$ $(\mathcal{A}, \mathcal{B} \in [1,4], \mathcal{A} \neq \mathcal{B})$, $\Delta\phi_{\not{E}_\mathrm{T} l_\mathcal{A}}$, N_b, N_j, N_{SFOS}, N_Z, $\not{E}_\mathrm{T}$, $\mathrm{m_{eff}}$
- Tuned hyperparameters: `learning rate`=0.03, `number of trees`=500, `maximum depth`=10

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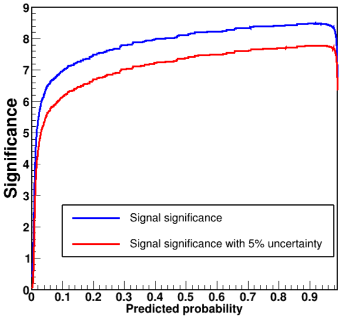

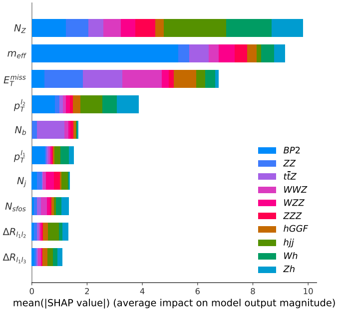

Signal Significance and Projected reach using ML @HL-LHC

Benchmark Points	Sinal Significance at cut-based	Signal Significance ML-based	Gain
BP1 (1600,250)	8.84	12.61	43%
BP2 (1800, 800)	6.36	8.48	33%
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Projected exclusion @HL-LHC for $m_{\tilde{\chi}_1^0} = 800$ GeV			
Scenarios	Br. ratios from LSP pair	Projected exclusion in GeV	Projected exclusion with 20% sys. unc
Scenario-I	$4l$ (100%)	2340	2275
Scenario-II	$4l$ (25%) $3l1\tau$ (50%) $2l2\tau$ (25%)	2240	2175
Scenario-III	$2l2\tau$ (100%)	2050	1985
Scenario-IV	$2l2\tau$ (25%) $1l3\tau$ (50%) 4τ (25%)	1935	1870

Findings @HL-LHC

Let's put everything in a figure:

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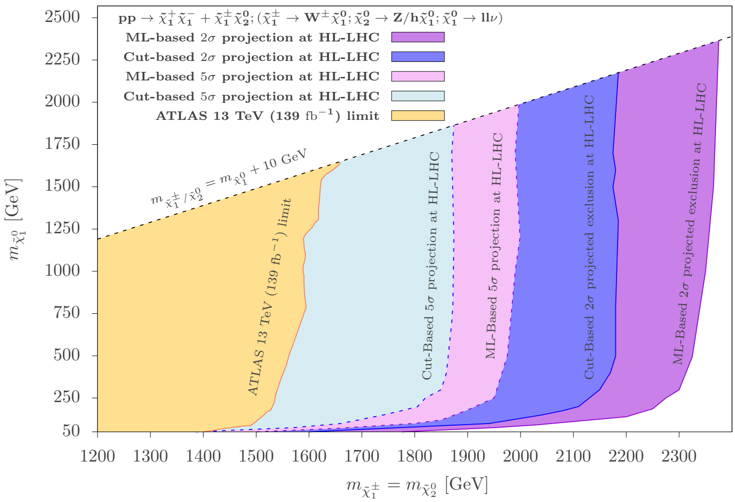

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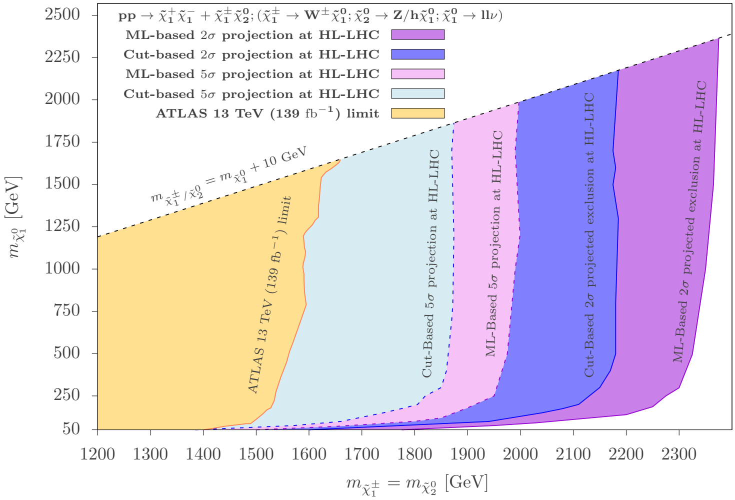


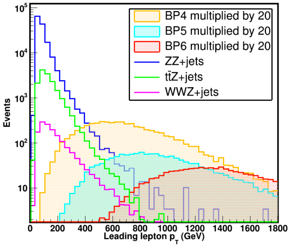
Improvement!

HIGH
ENERGY
LHC

Kinematic variables distribution @HE-LHC

3 Benchmark Points are choosen:

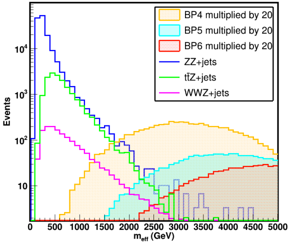
1. **BP4** ($m_{\tilde{\chi}_1^\pm} = 2300$ GeV,$m_{\tilde{\chi}_1^0} = 250$ GeV)
2. **BP5** ($m_{\tilde{\chi}_1^\pm} = 2900$ GeV,$m_{\tilde{\chi}_1^0} = 1200$ GeV)
3. **BP6** ($m_{\tilde{\chi}_1^\pm} = 3100$ GeV,$m_{\tilde{\chi}_1^0} = 3000$ GeV)



- $p_T^{l_1} \geq 150$ GeV cut is given at generation level for SM backgrounds
- 2 signal regions are defined:

  SR-C: $N_l \geq 4$+Z veto + b veto + $m_{eff} > 1500$ GeV

  SR-D: $N_l \geq 4$+Z veto + b veto + $m_{eff} > 2200$ GeV



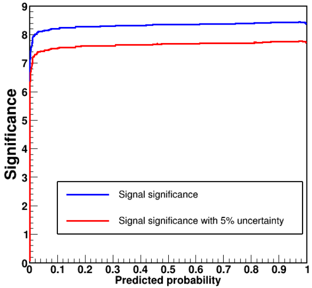
Cut-flow for Scenario-I @HE-LHC

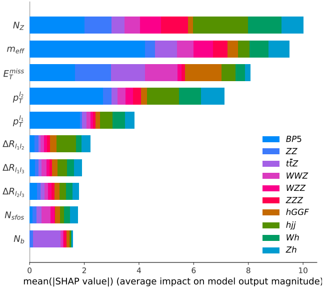
Cut variables	$N_l \geq 4$ $(l = e, \mu)$ + $p_T^{l_1} > 150$ GeV	Z veto	b veto	Signal Region SR-C ($m_{eff} > 1500$)	Signal Region SR-D ($m_{eff} > 2200$)
BP4	307.61	266.84	179.46	173.43	147.48
BP5	71.72	69.89	47.51	47.31	45.54
BP6	41.19	39.57	25.06	24.97	24.77
ZZ + jets	15980	125.38	108.31	6.01	1.2
$t\bar{t}Z$ + jets	5814	467.27	103.94	6.77	1.73
WWZ + jets	742.03	57.42	47.49	8.21	2.30
WZZ + jets	414.87	7.93	6.02	1.09	0.27
ZZZ + jets	142.17	1.47	1.06	0.08	0.02
h via GGF	3490	34.51	29.30	1.47	0.33
hjj	40.59	9.92	7.86	0.07	0
Wh + jets	9.81	3.04	2.53	0.04	0.003
Zh + jets	7.08	1.42	1.06	0.02	0.003
Total background				23.76	5.86
Signal Significance σ_{ss} (σ^{ϵ}_{ss}, Syst. Unc. = 5 %)		BP4(2300,350)		**12.35 (10.10)**	**11.90 (10.12)**
		BP5(2900,1200)		**5.61 (5.17)**	**6.35 (5.98)**
		BP6(3100,3000)		**3.58 (3.37)**	**4.47 (4.31)**

Projected exclusion for different sccenarios @HE-LHC

Projected exclusion @HL-LHC for $m_{\tilde{\chi}_1^0} = 1200$ GeV			
Scenarios	Br. ratios	Projected exclusion in GeV	Projected exclusion with 20% sys. unc
Scenario-I	$4l$ (100%)	3620	3480
Scenario-II	$4l$ (25%) $3l1\tau$ (50%) $2l2\tau$ (25%)	3400	3260
Scenario-III	$2l2\tau$ (100%)	3080	2940
Scenario-IV	$2l2\tau$ (25%) $1l3\tau$ (50%) 4τ (25%)	2780	2640

ML-Baesd Analysis @HE-LHC



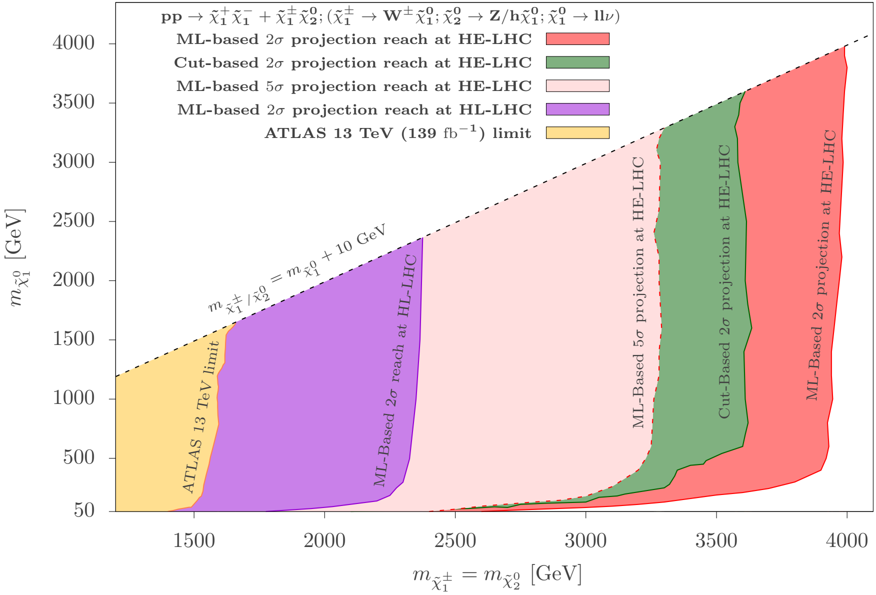


Benchmark Points	Sinal Significance at cut-based	Signal Significance ML-based	Gain
BP4 (2300,250)	12.35	18.69	51%
BP5 (2900, 1200)	6.35	8.42	33%
BP6 (3100, 3000)	4.47	6.41	43%

Projected exclusion for different sccenarios @HE-LHC

Projected exclusion @HL-LHC for $m_{\tilde{\chi}_1^0} = 1200$ GeV			
Scenarios	Br. ratios from LSP pair	Projected exclusion in GeV	Projected exclusion with 20% sys. unc
Scenario-I	$4l$ (100%)	3940	3850
Scenario-II	$4l$ (25%) $3l1\tau$ (50%) $2l2\tau$ (25%)	3790	3700
Scenario-III	$2l2\tau$ (100%)	3450	3360
Scenario-IV	$2l2\tau$ (25%) $1l3\tau$ (50%) 4τ (25%)	3200	3115

Findings @HE-LHC



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- Using ML algorithms, we obtain 2σ exclusion reach for HL-LHC (HE-LHC) is ~ 2.37 (4) TeV from electroweakino production
- Our proposed signal region is also effective for τ-enriched states, but fives weaker limit as compared to $\lambda_{121}/\lambda_{122}$


Thank you!