What LHC is telling us about the paradigms of Physics beyond the Standard Model?

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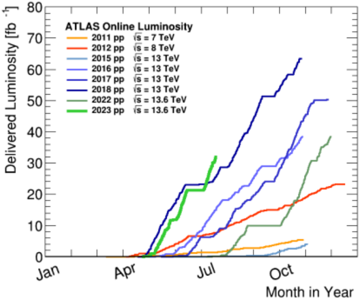
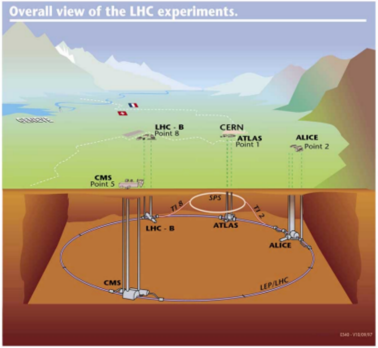
Outline

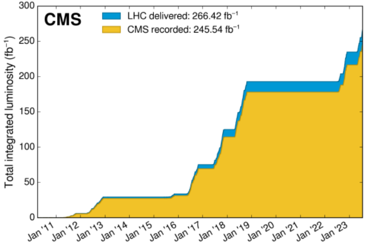
The Large Hadron Collider (LHC)

The LHC is a proton-proton collider. The twin primary goals of the LHC are to search for

1. The Higgs boson
2. New TeV scale dynamics



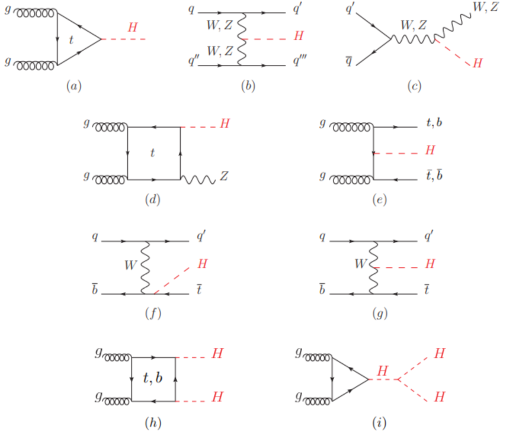


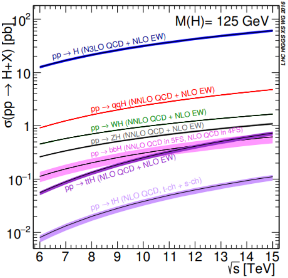


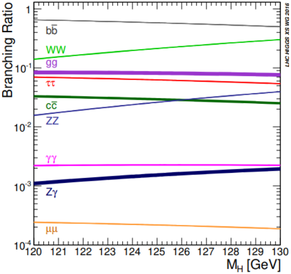
The Higgs Boson Searches

$$\mathcal{L} = -g_{Hf\bar{f}}\bar{f}fH + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu \left(g_{HVV}H + \frac{g_{HHVV}}{2}H^2\right)$$

$$g_{Hf\bar{f}} = \frac{m_f}{v},\ g_{HVV} = \frac{2m_V^2}{v},\ g_{HHVV} = \frac{2m_V^2}{v^2},\ g_{HHH} = \frac{3m_H^2}{v},\ g_{HHHH} = \frac{3m_H^2}{v^2}$$

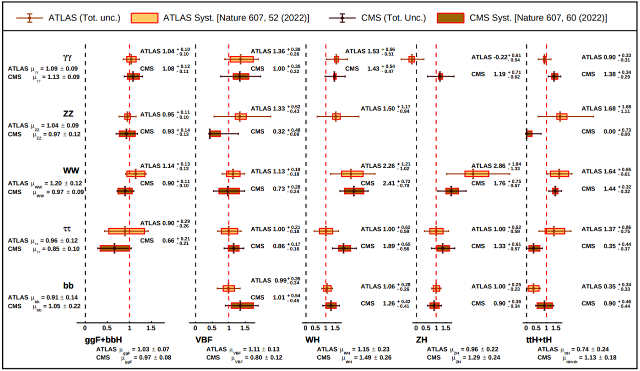






The precise theoretical predictions for the Higgs cross-section and branching ratios are key to the discovery of the Higgs.

The Higgs $\sigma \times$BR, normalised to the SM predictions



Higgs Mass

$$m_H = 125.08 \pm 0.12 \text{ GeV}$$

(The most precise single channel result obtained by CMS in the 4l channel with the full Run 2 dataset.)

For details, see Prof. Vivek Sharma's presentation

Other LHC searches

(For details, see Prof. Prolay Mal's presentation.)

1. The workhorse for theoretical predictions at the LHC are the event generators.
   1. The event generators are now automated at least to NLO@QCD essentially for all relevant signal and background processes.
2. These generators provide a pipeline for realizing theory ideas into experiments.

Beyond the SM (BSM) scenarios: Why ??

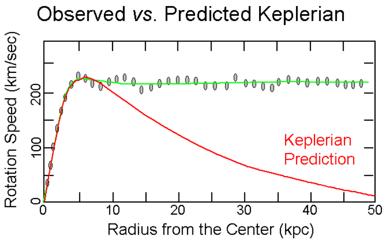
Theory Issues

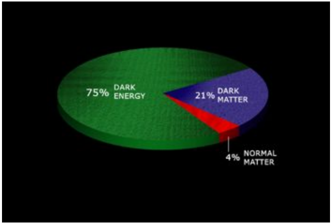
- Gravity
- Unification
- Radiative Correction to the Higgs boson mass: $m_H^2 = m_{H_0}^2 - \frac{kg^2\Lambda^2}{16\pi^2}$

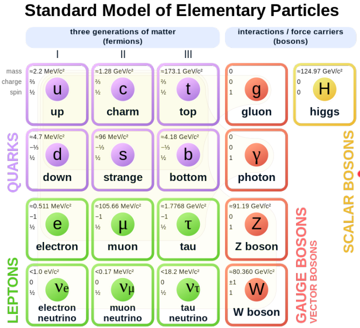
Observational Issues

- Matter anti-matter asymmetry
  - particle and anti-particle is related by Charge Parity (CP) transformation.
  - The SM predicts inadequate amount of CP violation.
- Neutrino mass
- Anomalous Muon $g-2$

Dark matter







Options to go beyond the Standard Model

4D Lorentz Symmetry

$\times$

Gauge Symmetry

$SU(3)_C \times SU(2)_W \times U(1)_Y$

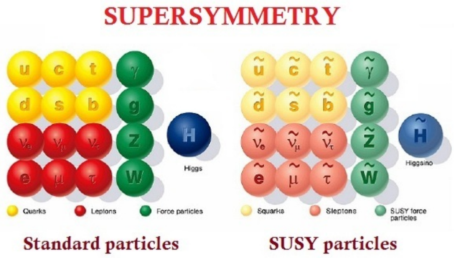
$\Downarrow$

Spontaneous breaking of electroweak symmetry

$SU(3)_C \times U(1)_{EM}$

- Extend the field content:
  Examples: *SSM, leptoquark, seesaw, etc.*
- Extend 4D Lorentz Symmetry:
  1. Supersymmetry:
  2. Extra-dimension(s):
- Extend the Gauge Symmetry:
  Examples: *Left-right Symmetry, Grand Unified Theory, etc.*
- Mechanism of SSB:

Supersymmetry: Fermion ⟷ Boson symmetry



Why is SUSY so popular?

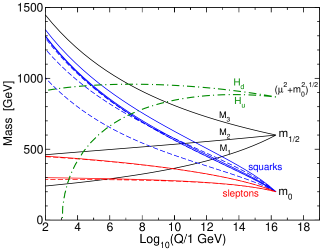
- Provides solution to hierarchy problem
  - The fermion/boson contributions to the Higgs mass exactly cancel.
- Allows unification of gauge couplings
- Offers a dark matter (DM) candidate

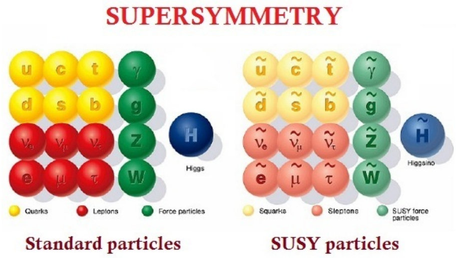
1. R-parity: $R_p = (-1)^{2S+3B+L}$
   1. Particles: $R_p = +1$
   2. Sparticles: $R_p = -1$
2. Exact SUSY: Very predictive
   1. $M_{Particle} = M_{Sparticle}$
3. SUSY has to be broken.
   - SUSY breaking introduces new parameters in the theory.

Supersymmetry: Fermion $\longleftrightarrow$ Boson symmetry

Constrained Minimal Supersymmetric SM (cMSSM)

- High scale universality of SUSY breaking terms
  - m_0: scalar mass parameters
  - $m_{1/2}$: gaugino mass parameter
  - A_0: trilinear coupling
  - $tan\beta$: ratio of Higgs VEVs
  - $sign(\mu)$: sign of SUSY Higgs parameter
- Predict phenomenology at the EW scale





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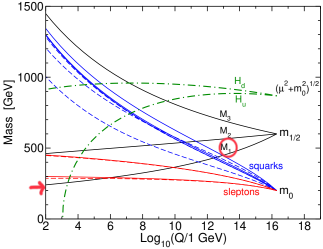

Relic density (RD)

- In the cMSSM, $\tilde{\chi}_1^0$ is mostly binolike
  - Therefore, $\tilde{\chi}_1^0$ annihilation gives rise to RD which is too large.
- The mixing term of the left and right squark states: $M_{LR}^2 = m_q(A_q - \mu\cot\beta)$
- The off-diagonal trilinear term is proportional to the mass of the SM quark
- Large A_0 can generate large mixing and hence, large mass splitting in the stop sector
- The degenerate $\tilde{t}_1 - \tilde{\chi}_1^0$ scenario
  - For $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \leq 35$ GeV, the $\tilde{t}_1$-NLSP coannihilate with the binolike $\tilde{\chi}_1^0$-LSP.

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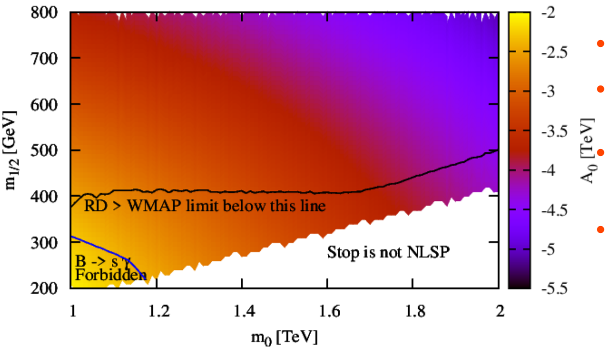

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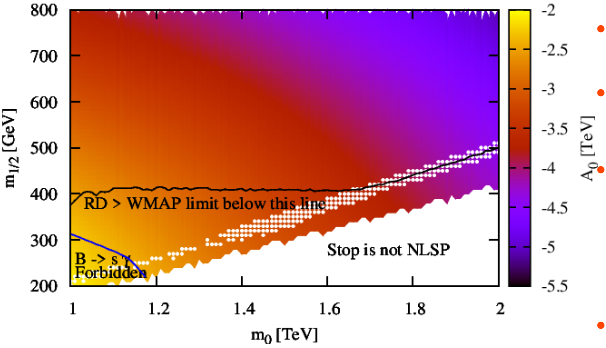

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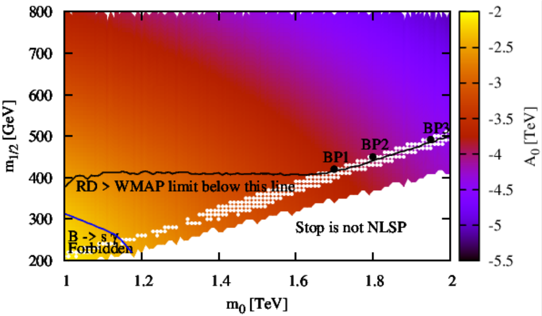
125 GeV Higgs Mass

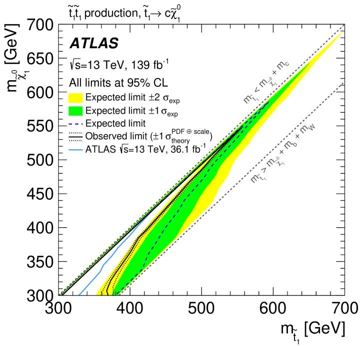
- Large stop mixing in cMSSM with $\tilde{t}_1$-NLSP may give rise to Higgs mass around 125 GeV.

BP1			BP2			BP3		
m_0	$m_{1/2}$	A_0	m_0	$m_{1/2}$	A_0	m_0	$m_{1/2}$	A_0
1700	420	-3763	1800	450	-4001	1950	491	-4349

	$\tilde{g}$	$\tilde{u}_L$	$\tilde{t}_2$	$\tilde{t}_1$	$\tilde{b}_2$	$\tilde{b}_1$	$\tilde{\chi}_1^{\pm}$	$\tilde{\chi}_1^0$	h
BP1	1064	1880	1334	217	1776	1287	352	181	124.0
BP2	1133	1994	1411	229	1883	1365	378	194	124.1
BP3	1227	2161	1523	250	2040	1478	414	213	125.3

[KG, Huitu, Laamanen, Leinonen PRL (2013)]





1. Phenomenological Minimal Supersymmetric Standard Model (pMSSM)
2. Next-to-Minimal Supersymmetric Standard Model (NMSSM)
3. $U(1)$ extended Supersymmetric Standard Model (USSM)
4. Exceptional Supersymmetric Standard Model (E_6SSM)
5. .....

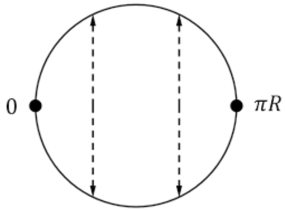
Universal Extra Dimension (UED)

UED scenarios are characterized by a single flat universal (accessible to all the SM particles) extra dimension (y), compactified on a S_1/Z_2 orbifold with radius R.

$$\mathcal{S}_{UED} = \mathcal{S}_{\text{gauge}} + \mathcal{S}_{\text{fermions}} + \mathcal{S}_{\text{scalar}}$$

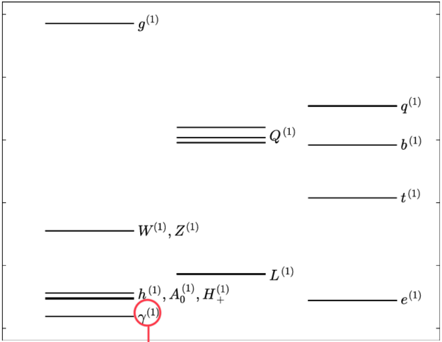
$$\mathcal{S}_{\text{gauge}} = \int d^4x \int_0^{\pi R} dy \Big\{ -\frac{1}{4} G^a_{MN} G^{aMN} + \left(\delta(y) + \delta(y - \pi R)\right)\left[-\frac{r_G}{4} G^a_{\mu\nu} G^{a\mu\nu}\right]\Big\}$$

1. Usual bulk kinetic terms
2. Kinetic terms for all the 5D fields at the boundaries of the bulk and the brane, known as boundary localized terms (BLTs).
3. In the *minimal* version of *UED* (mUED), all BLTs are assumed to vanish at the cut-off scale (Λ).
4. The phenomenology of *mUED* is determined by only two additional parameters: the radius of compactification, R and the cut-off scale, Λ.

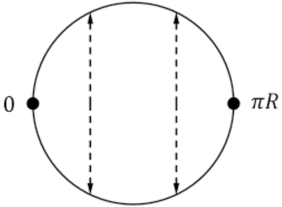


1. The particle spectrum contains infinite towers of Kaluza-Klein (KK) modes (identified by an integer n, called the KK-number).
2. The conservation of the momentum along the fifth direction implies the conservation of the KK-number.
3. The additional Z_2 symmetry ($y \leftrightarrow -y$) breaks the translational invariance along the 5^{th} dimension.
4. KK-number conservation breaks down at loop-level, leaving behind only a conserved KK-parity, defined as $(-1)^n$.

minimal Universal Extra Dimension (mUED)



1. A dark matter candidate: the lightest level-1 Kaluza-Klein (KK) particle (LKP)
2. Multijet/Multilepton plus Missing Energy final state at the LHC



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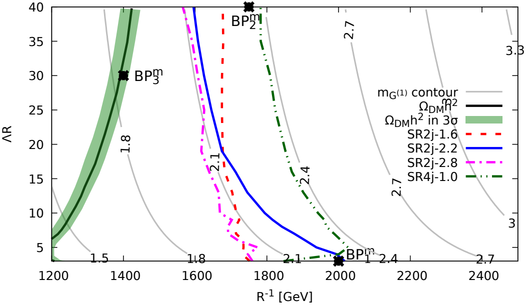
minimal Universal Extra Dimension (mUED)

95% CL exclusion plot on R^{-1}-ΛR plane from ATLAS search (ATLAS-CONF-2019-040) for multijets $+\not{E}_T$ with 139 fb^{-1} integrated luminosity.

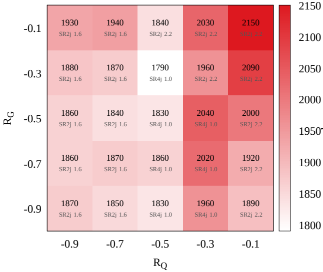


minimal UED is Ruled Out !!

[Avnish, Ghosh, Jha, Niyogi PRD 2021; PDG 2023]

Possibilities beyond mUED

1. Non-minimal UED (nmUED): Non-vanishing BLTs



2. 'Fat-brane' realization of mUED: Gravity-mediated decays

Neutrino Mass Models

The neutrino oscillation experiments provided evidences for neutrino flavour oscillations, and hence nonzero neutrino masses and mixings.

The usual Higgs mechanism: N_R (1,1,0)

$$-\mathcal{L}_Y = Y_N^{i\alpha} \bar{L}_i \widetilde{H} N_{R\alpha} + \mathrm{H.c.}$$

Dirac neutrino mass: $M_D \sim \frac{Y_N v}{\sqrt{2}}$

1. $m_\nu \sim 0.1\text{eV}$, $Y_N \sim 10^{-12}$: philosophically displeasing
2. Conservation of Lepton Number

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$$-\mathcal{L}_Y = Y_N^{i\alpha} \bar{L}_i \widetilde{H} N_{R\alpha} + \frac{1}{2} M_N^{\alpha\beta} \bar{N}_{R\alpha}^C N_{R\beta} + \text{H.c.}$$

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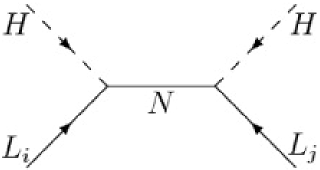
"Of the supposedly exact conservation laws of physics, two are especially questionable: the conservation of baryon number and lepton number."
Weinberg, 1979



Type-I Seesaw

$$\mathcal{M}_\nu = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^T & M_N \end{pmatrix}$$

$$M_\nu \simeq -M_D M_N^{-1} M_D^T$$

$$V_{\ell N_\alpha} \sim M_D M_N^{-1}$$

$$\mathcal{L}_{d=5} = \frac{1}{\Lambda} LLHH$$

Majorana mass

$$m_\nu \propto \frac{v^2}{\Lambda}$$

The seesaw mechanism

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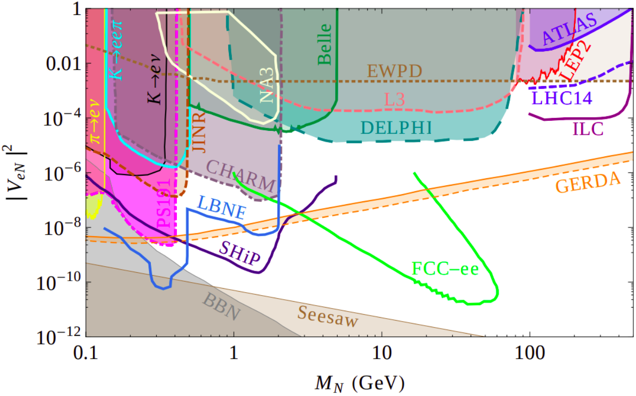
Deppisch, Bhupal Dev, Pilaftsis



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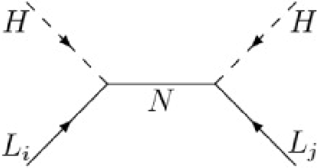

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$$m_\nu \propto \frac{v^2}{\Lambda}$$

The seesaw mechanism

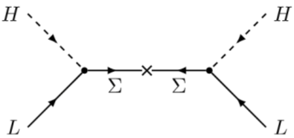
Type-III Seesaw

$SU(2)_L$ Triplet fermion

$$\begin{pmatrix} \Sigma_R^0/\sqrt{2} & \Sigma_R^+ \\ \Sigma_R^- & -\Sigma_R^0/\sqrt{2} \end{pmatrix}$$

Lagrangian generating ν-masses

$$M_\Sigma \overline{\tilde{\Sigma}_R} \Sigma_R + \sqrt{2} Y_\Sigma \tilde{H}^\dagger \overline{\Sigma_R} L + \text{h.c.}$$



Seesaw formula

$$m_\nu \approx -\frac{v^2}{2} Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$$

$$U^T m_\nu U = D_{m_\nu} = \text{diag}(m_1, m_2, m_3)$$

Most general texture of Y_Σ

$$Y_\Sigma = i\frac{\sqrt{2}}{v}\sqrt{M_\Sigma} R \sqrt{D_{m_\nu}} U^\dagger$$

Production:

- Drell-Yan processes: $q\,\overline{q'} \to \gamma/Z \to \Sigma^+\Sigma^-$, $q\,\overline{q'} \to W^\pm \to \Sigma^\pm\Sigma^0$

Decays:

- Heavy state transitions: $\Sigma^\pm \to \Sigma^0\pi^\pm$, $\Sigma^\pm \to \Sigma^0\ell^\pm\nu_\ell$
- SM 2-body decays:
  - $\Sigma^0 \to \nu h$, $\Sigma^0 \to \nu Z$, $\Sigma^0 \to \ell^\mp W^\pm$.
  - $\Sigma^\pm \to \ell^\pm h$, $\Sigma^\pm \to \ell^\pm Z$, $\Sigma^\pm \to \nu W^\pm$.

Multilepton Final States Search:

- A recent CMS multilepton search (137.1 fb^{-1}) excluded triplet fermions below 880 GeV at 95% CL in flavour democratic scenario. JHEP 03 (2020) 051
- **This CMS limit is not straightforwardly applicable for a realistic type-III seesaw model.**

Bounds on realistic Type-III Seesaw: Implications of R-matrix

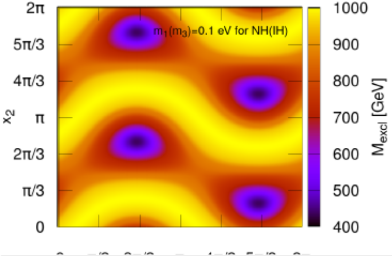
3RHN: $\theta_{12} = x_3 + iy_3$, $\theta_{23} = x_1 + iy_1$ and $\theta_{13} = x_2 + iy_2$ with $x_{1,2,3}, y_{1,2,3} \in \mathbb{R}$:

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

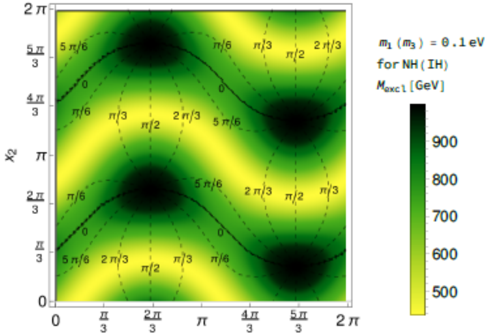
2RHN

$$R = \begin{cases} \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} & \text{for NH} \\[2ex] \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \end{pmatrix} & \text{for IH} \end{cases}$$

Only Σ_1 is produced



Only Σ_2 is produced



LHC limits are derived for a simplified type-III ssesaw model, not applicable for a realistic model accounting for the neutrino oscillation data.

Proposal: Look for τ-rich final states

A. Tumasyan *et al.* [CMS], Phys. Rev. D **105** (2022)

Type-II Seesaw

$SU(2)_L$ Triplet Scalar

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

Triplet VEV after the EWSB

$$\langle\Delta\rangle = \begin{pmatrix} 0 & 0 \\ v_t/\sqrt{2} & 0 \end{pmatrix},$$

$$v_t \approx \frac{\mu v_d^2}{\sqrt{2} m_\Delta^2}$$

Phenomenology: $m_{H^{\pm\pm}}$, v_t and

$$\Delta m = m_{H^{\pm\pm}} - m_{H^\pm}$$

Constraint on v_t and Δm

1. Oblique parameters: $|\Delta m| \lesssim 40$ GeV
2. ρ parameter:
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2}$$
3. LFV decays:
$l_\alpha \to l_\beta \gamma$@1-loop and
$l_\alpha \to l_\beta l_\gamma l_\delta$@tree-level.

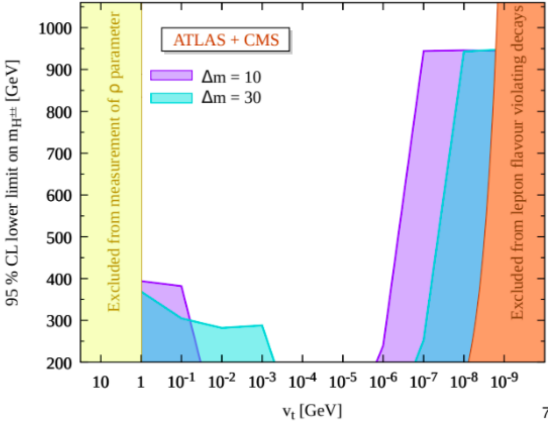
Scalar potential

$$-m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu(\Phi^T i\sigma^2 \Delta^\dagger \Phi) + \mathrm{h.c.}\right] +$$
$$\lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\left[\mathrm{Tr}(\Delta^\dagger\Delta)^2\right] + \lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi$$

Triplet Yukawa

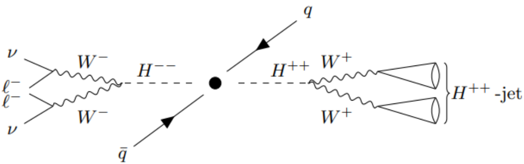
$$-\mathcal{L}_\nu = Y_{ij}^\nu L_i^T C i\sigma^2 \Delta L_j + \mathrm{h.c.} \xrightarrow{EWSB} m_\nu = \sqrt{2} Y^\nu v_t$$

Ashanujjaman, KG, JHEP 03 (2022) 195

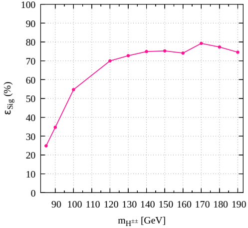


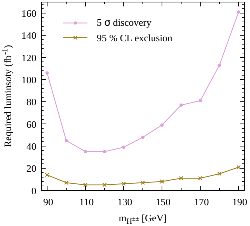
7

Search for light (within 84–200 GeV) $H^{\pm\pm} \to W^{\pm}W^{\pm(*)}$



BDT classifier for tagging boosted hadronically decaying $H^{\pm\pm}$

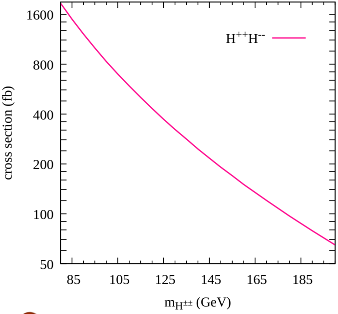




[Ashanujjaman, Ghosh, Sahu, PRD 2023]

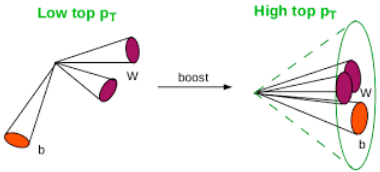
Motivation

Such a low-mass triplet $H^{\pm\pm}$, slightly heavier singly-charged and neutral components can explain the CDF measurement of the W-bosoon mass. [Kanemura and Yagyu; Heeck; Bahl, Chiu, Gao, Wang, and Zhong; Cheng, He, Huang, Sun, and Xing]



1. Large Prod. Cross section
2. Soft leptons and jets in the final state

Boosted Object Tagging

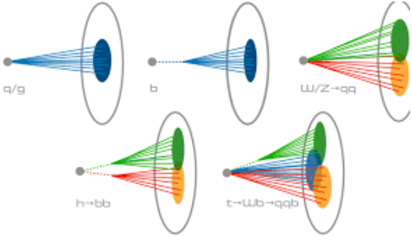


Motivation

- Absence of BSM@LHC
- QCD Background
- Visible Final States

Cut-based classifiers

Based on jet shape observables like jet mass, N-subjettiness, etc. HEPTopTagger, Johns Hopkins Tagger, YSplitter etc.



ML-based Top Tagging

High-level features (HLF)

- The Jet Mass
- The N-subjettiness
- *b*-tag
- # of tracks inside a jet.
- $w_{trk} = \frac{\sum_{trk \in J} p_{T,trk} \Delta R_{trk,J}}{\sum_{trk \in J} p_{T,trk}}$
- $w_{calo} = \frac{\sum_{i \in J} p_{T,i} \Delta R_{i,J}}{\sum_{i \in J} p_{T,i}}$
- .....
- .....

Boosted Decision Tree (BDT): Trained using the TMVA 4.3 toolkit in ROOT 6.24

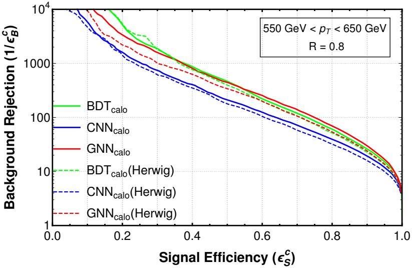
Low-level features (LLF)

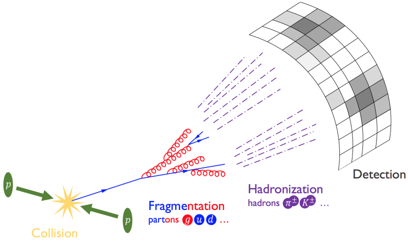
Pure or Transformed four-momentum of the jet constituents

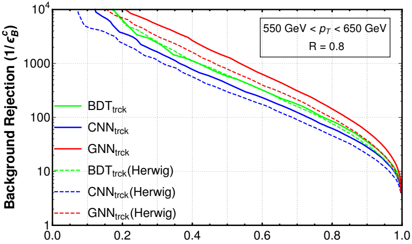
Examples

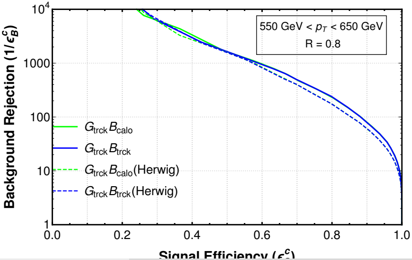
- Convolutional Neural Networks (CNNs)
  - Grid-shaped data or images
- Graph Neural Networks (GNNs)
  - The four-momentum of constituents

Track and tower Based Classifiers: Advantages of tracking data









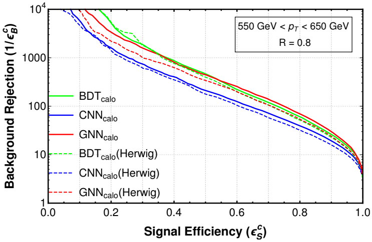
Summary

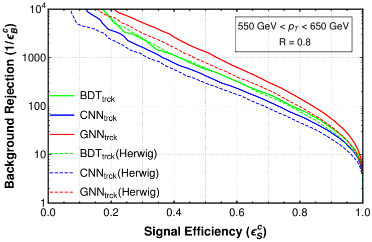
1. All predictions of the Standard Model of particle physics have been experimentally verified. Notable observations like dark matter, dark energy, neutrino masses, mixing, etc., challenge the SM as the ultimate description of the universe.
2. The Large Hadron Collider (LHC) has been running for over a decade, culminating in the discovery of the Higgs boson.
3. The Higgs discovery in its various production and decay channels, along with other final state searches, align with SM predictions and significantly constrain Beyond the Standard Model (BSM) parameter space.
4. Economic BSM scenarios with high predictability, such as the constrained MSSM and minimal UED, face significant pressure from LHC data.
5. Non-minimal models with enlarged parameter spaces and less predictability remain viable alternatives beyond the SM.
6. Cut-based search strategies at the LHC may not effectively probe certain regions of the BSM scenarios with projected luminosities.
7. To address limitations, novel object reconstruction, and event selection strategies are required. Machine learning-based approaches might be a potential solution to enhance search capabilities.

Thank You

Backpu Slides

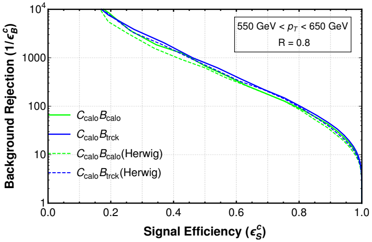
Classifiers Performance (Simple Classifiers)

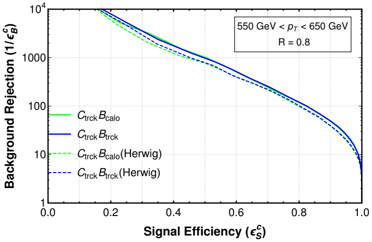




Classifier	$1/\epsilon_B^c(\epsilon_S^c = 0.7)$	$1/\epsilon_B^c(\epsilon_S^c = 0.5)$
BDT_{calo}	119(105)	467(398)
CNN_{calo}	70(57)	211(178)
GNN_{calo}	139(106)	444(341)
BDT_{trck}	175(159)	579(610)
CNN_{trck}	124(90)	423(299)
GNN_{trck}	311(214)	1322(789)
$C_{calo}B_{calo}$	176(175)	682(619)
$C_{calo}B_{trck}$	208(204)	811(737)
$C_{trck}B_{calo}$	249(218)	1023(768)
$C_{trck}B_{trck}$	257(221)	995(799)
$G_{calo}B_{calo}$	260(241)	969(842)
$G_{calo}B_{trck}$	278(256)	1141(894)
$G_{trck}B_{calo}$	489(397)	1641(1604)
$G_{trck}B_{trck}$	493(399)	1736(1666)

Classifiers Performance (Composite Classifiers CNN-based)





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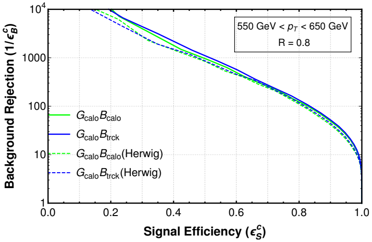
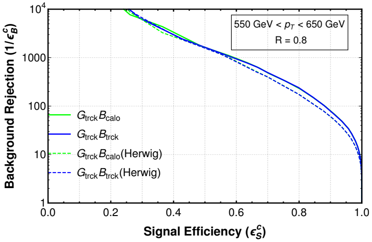
$G_{trck}B_{trck}$	493(399)	1736(1666)

Classifiers Performance (Composite Classifiers GNN-based)





Classifier	$1/\epsilon_B^c(\epsilon_S^c = 0.7)$	$1/\epsilon_B^c(\epsilon_S^c = 0.5)$
BDT_{calo}	119(105)	467(398)
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$G_{trck}B_{trck}$	493(399)	1736(1666)

Systematic Uncertainty

$C_{trck} B_{calo}$: Ranking Of Variables

Variable	Ranking
M	0.3625
score	0.309
$\tau_{2,1}$	0.099
τ_{32}	0.09
b-tag	0.0714
τ_{43}	0.0676

$G_{trck} B_{calo}$: Ranking Of Variables

Variable	Ranking
score	0.3517
M	0.3142
$\tau_{2,1}$	0.0968
τ_{32}	0.093
b-tag	0.075
τ_{43}	0.069

Classifier	$1/\epsilon_B^c(\epsilon_S^c = 0.7)$	$1/\epsilon_B^c(\epsilon_S^c = 0.5)$
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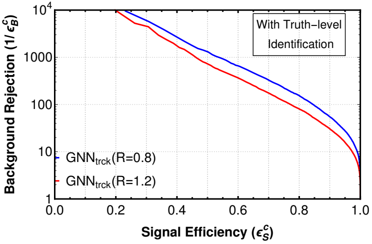
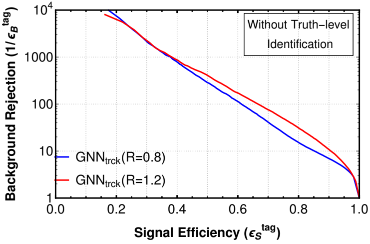
Truth-Level Tagging





Variable	$1/\epsilon_B^c$ ($\epsilon_s^c = 50\%$)	$1/\epsilon_B^{tag}$ ($\epsilon_s^{tag} = 50\%$)
$R = 0.8$	1298	274
$R = 1.2$	711	424

p_T - Dependance

With TLT : $1/\epsilon_B^c$ ($\epsilon_S^c = 50\%$)

p_T [GeV]	BDT_{calo}	BDT_{trck}	CNN_{trck}	GNN_{trck}	$C_{trck}B_{calo}$	$G_{trck}B_{calo}$
300-500	388	456	159	587	762	1413
500-700	136	276	184	765	455	1178
700-900	168	345	278	845	538	1409
900-1100	79	247	256	971	466	1175
1100-1300	56	167	214	882	318	872
1300-1500	39	127	217	877	273	850

Without TLT : $1/\epsilon_B^{tag}$ ($\epsilon_S^{tag} = 50\%$)

p_T [GeV]	BDT_{calo}	BDT_{trck}	CNN_{trck}	GNN_{trck}	$C_{trck}B_{calo}$	$G_{trck}B_{calo}$
300-500	95	119	54	121	157	250
500-700	83	152	110	303	243	581
700-900	84	166	147	421	258	582
900-1100	57	148	168	534	279	789
1100-1300	45	124	157	540	234	651
1300-1500	34	101	167	609	217	662