Associate production of light scalars at the LHC

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Jul 30, 2024

Overview

Introduction

- We are studying the production of "light" scalars in association with W or Z vector gauge bosons.
- All studies presented in this talk are within the Two Real Singlet Model (TRSM) [1].
- In this work - "Light" scalar $\Rightarrow M_\phi < 125$ GeV.
- Available parameter space is found using `ScannerS` software.
- Light scalar decays to b-jet are considered.

DISCLAIMER

All results in this presentation are preliminary.

All error that remain are mine.

Two Real Singlet Model (TRSM) 1908.08554

- Extends the Standard Model by introducing two real singlets (CP even).
- The number of model parameters are reduced by introducing two discrete $\mathbb{Z}_2$ symmetries.
- The additional singlets do not have interactions with SM fermions/gauge bosons - it is the mixing of additionals singlets with SM Higgs that leads to three physical scalar states that have interactions with SM particles.
- The model has nine parameters - $M_{h_1}, M_{h_2}, M_{h_3}, \theta_{hS}, \theta_{SX}, \theta_{hX}, v_S, v_X, v_h$ - where M represents mass, θ is the mixing angle and v is the vacuum expectation value.
- In the above, $M_h = 125$ GeV and $v_h = 246$ GeV are SM Higgs parameters - and thus we have seven free input parameters.

Phenomenology with TRSM

- Consider the reaction:

$$pp \to h_i \to h_j h_k$$

- This reaction above is:
  - Asymmetric if $i, j, k \in [1, 2, 3]$ and $i \neq j \neq k$
  - Symmetric: if $j = k$.
- Cascade Decays: if kinematics allows, one can also have a process such as $h_3 \to h_1 h_2$ with $h_2 \to h_1 h_1$.
- In all cases, one can have SM final states.
- If either v_S (v_X) is set to zero, then this can be a Dark Matter Candidate - as then - particle whose vacuum expectation is set to zero does not interact with SM particles - as there is no mixing between $\phi_{h,X}(\phi_{h,S})$.

Benchmark Points

- Six benchmark scenarios are considered (as motivation)
- The following table lists a possible signature that can be probed in each benchmark scenario:

benchmark scenario	h_{125} candidate	target signature	possible successive decays
BP1	h_3	$h_{125} \to h_1 h_2$	$h_2 \to h_1 h_1$ if $M_2 > 2M_1$
BP2	h_2	$h_3 \to h_1 h_{125}$	-
BP3	h_1	$h_3 \to h_{125} h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\mathrm{GeV}$
BP4	h_3	$h_2 \to h_1 h_1$	-
BP5	h_2	$h_3 \to h_1 h_1$	-
BP6	h_1	$h_3 \to h_2 h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\mathrm{GeV}$

Benchmark Points

The table here gives parameter scans that are performed for each Benchmark point using the ScannerS software

Parameter	Benchmark scenario					
	BP1	**BP2**	**BP3**	**BP4**	**BP5**	**BP6**
M_1 [GeV]	$[1, 62]$	$[1, 124]$	125.09	$[1, 62]$	$[1, 124]$	125.09
M_2 [GeV]	$[1, 124]$	125.09	$[126, 500]$	$[1, 124]$	125.09	$[126, 500]$
M_3 [GeV]	125.09	$[126, 500]$	$[255, 650]$	125.09	$[126, 500]$	$[255, 1000]$
θ_{hs}	1.435	1.352	-0.129	-1.284	-1.498	0.207
θ_{hx}	-0.908	1.175	0.226	1.309	0.251	0.146
θ_{sx}	-1.456	-0.407	-0.899	-1.519	0.271	0.782
v_s [GeV]	630	120	140	990	50	220
v_x [GeV]	700	890	100	310	720	150
κ_1	0.083	0.084	0.966	0.073	0.070	0.968
κ_2	0.007	0.976	0.094	0.223	-0.966	0.045
κ_3	-0.997	-0.203	0.239	0.972	-0.250	0.246

here the κ values are coupling scale factors.

Collider Phenomenology Toolbox

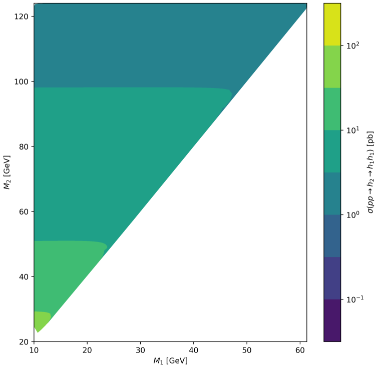
In our study we have used the following software tools:

- `ScannerS` [2] - To carry out parameter scan and determine available parameters.
- `twosinglet` [3] - To prepare `MadGraph` parameter card.
- `MadGraph5_aMC@NLO` [4] - For cross-section calculation and event sample generation.
- `LHAPDF` [5] - For accessing parton distribution functions.
- `Pythia8` [6] - parton shower.
- `FastJet` [7] - Anti-k_T jet clustering algorithm with $R = 0.4$.
- `MadAnalysis` [8] - for analysis.
- Python packages such as Numpy, Pandas, and Matplotlib were used for analysis.

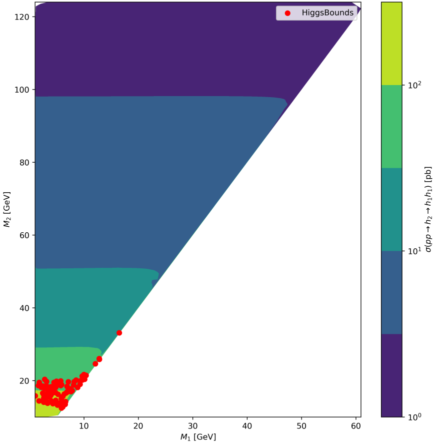
ScannerS results for Benchmark Point 4 in ggF channel

- We consider the production of h_2 in gluon-gluon fusion channel:

$$\sigma(pp \to h_2 \to h_1 h_1) = \kappa_2^2 \sigma(gg \to h_{SM})|_{M_{h2}}.BR(h_2 \to h_1 h_1)$$



ScannerS results for BP 4 with HiggsBounds Exclusion in ggF channel



ScannerS results for Benchmark Point 4 in ggF channel

- For this BP 4, the maximum cross-section for this process is 49.19 pb for parameters not excluded by ScannerS.
- Masses at the maximum cross-section:

Scalar	Mass (GeV)
M_{h_1}	10.7
M_{h_2}	22.7
M_{h_3}	125.09

- $M_{h_1}, M_{h_2} < 10$ GeV is excluded

Some shortcomings of the ggF channel

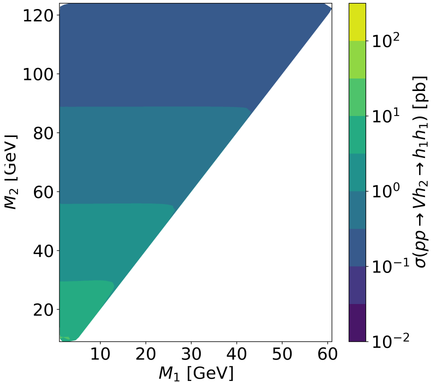
- We are interested in low p_T b-jets.
- The above channel provides four b-jets and the hard process has compartively large cross-section.
- However, while the signal is large (≈ 49 pb), the multijet background at LHC is even larger.
- So instead of looking at this production channel, one could use the associate production for probing lighter scalars as typically done for $h_{125} \to aa$ where a is a light scalar.

ScannerS results for Benchmark Point 4 in VH channel

- We consider the production of a vector gauge boson (W or Z) boson in association with h_2

$$\sigma(pp \to Vh_2 \to h_1 h_1) = \kappa_2^2 \sigma(pp \to Vh_{SM})|_{M_{h2}}.BR(h_2 \to h_1 h_1)$$

- Here $V = Z/W^{\pm}$, and the cross-section values are summed over the three gauge boson contribution.



ScannerS results for Benchmark Point 4 in VH channel

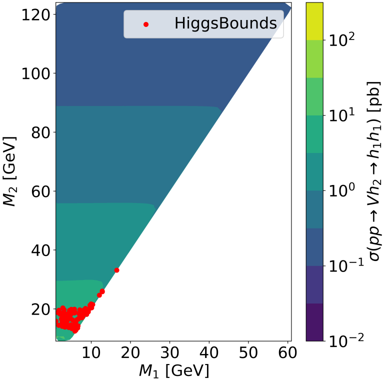
- For this BP 4, the maximum cross-section for this process is 3.99 pb for parameters not excluded by ScannerS. This value is summed over Z and $W^\pm$ bosons. Individually,

Process	Cross-Section (pb)
$pp \to Zh_2, h_2 \to h_1 h_1$	1.276
$pp \to W^\pm h_2, h_2 \to h_1 h_1$	2.719

- Masses at the maximum cross-section:

Scalar	Mass (GeV)
M_{h_1}	10.4
M_{h_2}	23.9
M_{h_3}	125.09

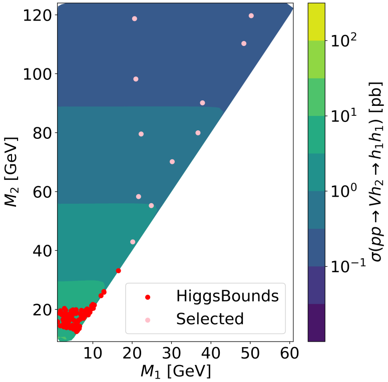
ScannerS results for BP 4 with HiggsBounds Exclusion in VH channel



- LEP results in the $e^+e^- \to Zh_2 \to (b\bar{b})Z$ are used for obtaining HiggsBounds Exclusion.
- See for example, table 14b hep-ex/0602042

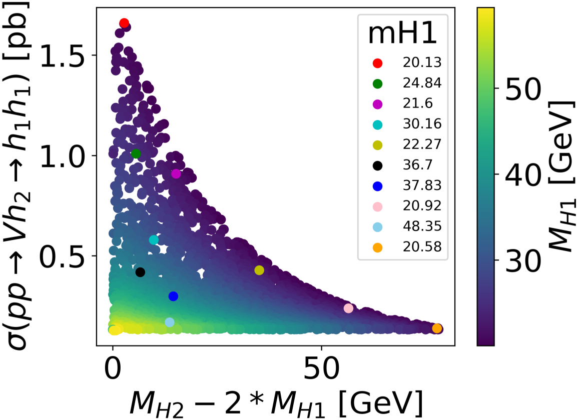
Studying Associate Vector Production using BP 4

- We study the associate vector production using BP 4.
- We have selected points on the following basis:
  - $20 < m_{H1} < 120$
  - $20 < m_{H2} < 120$
  - $10 < m_{H2} - m_{H1} < 100$
- To allow for different kinematics, points are selected such that:
  - $m_{H2} \simeq 2m_{H1}$
  - $m_{H2} > 2m_{H1}$
  - $m_{H2} \simeq 3m_{H1}$
  - $m_{H2} > 4m_{H1}$



Studying Associate Vector Production using BP 4

- The phase choice is such that we get low p_T b-jets.
- To achieve that we have required that $M_{h_2} - 2M_{h_1}$ is lower (but we also explore some other scenarios)
- We plot the cross-section as a function of $M_{h_2} - 2M_{h_1}$:



Studying Associate Vector Production using BP 4

- All the cross-section for the above processes, computed using ScannerS are presented here:

M_{h_1}	M_{h_2}	$M_{h_2} - 2M_{h_1}$	$\sigma(Vh_2)$	$\sigma(Zh_2)$	$\sigma(Wh_2)$	$Br(h_2)$	$\Gamma_{h_1} x10^{-6}$ (GeV)	$\Gamma_{h_2} x10^{-3}$ (GeV)
20.13	42.96	2.7	1.66	0.63	1.27	0.87	3.31	0.46
24.84	55.25	5.56	1.01	0.37	0.71	0.93	4.04	1.1
21.6	58.31	15.12	0.91	0.33	0.63	0.95	3.53	1.6
30.16	70.16	9.83	0.58	0.21	0.39	0.96	4.77	2.42
22.27	79.57	35.03	0.43	0.16	0.28	0.98	3.64	4.03
36.7	79.95	6.54	0.42	0.15	0.28	0.97	5.63	2.98
37.83	90.12	14.46	0.3	0.11	0.2	0.98	5.78	5.23
20.92	98.23	56.38	0.24	0.09	0.15	0.98	3.43	7.31
48.35	110.27	13.57	0.17	0.06	0.11	0.98	7.04	8.84
20.58	118.72	77.57	0.14	0.05	0.09	0.99	3.38	12.59
50.21	119.73	19.31	0.13	0.05	0.08	0.99	7.26	12.2

- All cross-section are in picobarn
- All masses are in GeV
- $\sigma(Vh_2)$ represents the cross-section for the process $pp \to Vh_2$,
- V represents $Z/W^{\pm}$
- $Br(h_2)$ represents $Br(h_2 \to h_1 h_1)$

Simulation

- We have used MadGraph5_aMC@NLO for simulating $pp \to Vh_2$ process.
- The following decay modes are considered:
  - $h_2 \to h_1 h_1$
  - $h_1 \to b\bar{b}$
  - $W^+ \to \ell^+ \nu_\ell$
  - $W^- \to \ell^- \bar{\nu}_\ell$
  - $Z \to \ell^+ \ell^-$
- Beam Energy is set to 6500 GeV (13 TeV LHC Collider settings).
- LHAPDF : Parton Distribution function NNPDF23_nlo_as_0119 is used.
- All studies are carried out at Leading Order.
- Pythia8 is used for Parton Shower.
- FastJet is used for jet clustering.
- MadAnalysis is used to analyze the events and for preparing plots.

Results

All the cross-section results in the following are presented as follows:

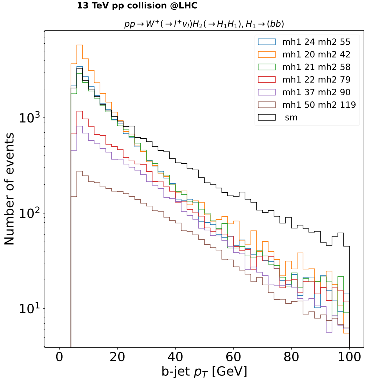
$$\text{cross section}^{\text{scale up uncertainty}}_{\text{scale down uncertainty}} \pm \text{PDF uncertainty}$$

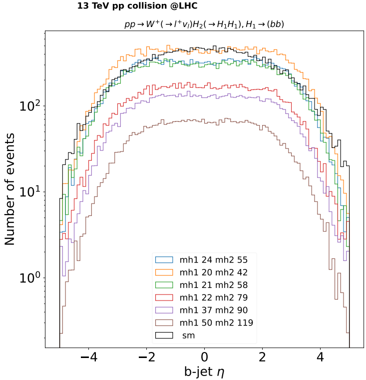
Results for W^+h_2

- We have considered the following process for studying W^+h_2: $pp \to W^+h_2(\to h_1h_1) \to \ell^+ v_\ell b\bar{b}b\bar{b}$.
- Decay widths are computed by `MadWidth`
- Decays are generated when declaring process in `MadGraph`

M_{h_1} (GeV)	M_{h_2} (GeV)	σ_{LO} (pb)	Stat. Unc. (pb)	Γ_{H1} (GeV)	Γ_{H2} (GeV)	Γ_{H3} (GeV)
20.13	42.96	$0.09533^{+6.5\%}_{-7.49\%} \pm 1.27\%$	0.00021	3.458492e-06	4.942668e-04	6.203459e-03
24.84	55.25	$0.06013^{+5.76\%}_{-6.73\%} \pm 1.26\%$	0.00015	4.860789e-06	1.144740e-03	6.203994e-03
21.6	58.31	$0.05402^{+5.47\%}_{-6.42\%} \pm 1.25\%$	0.00012	3.905856e-06	1.650158e-03	6.203090e-03
30.16	70.16	$0.03494^{+4.85\%}_{-5.78\%} \pm 1.25\%$	7.8e-05	6.360984e-06	2.484487e-03	6.203420e-03
22.27	79.57	$0.02507^{+4.34\%}_{-5.24\%} \pm 1.25\%$	4.6e-05	4.106503e-06	4.109132e-03	6.201924e-03
36.7	79.95	$0.02483^{+4.36\%}_{-5.26\%} \pm 1.25\%$	4.6e-05	8.131270e-06	3.059512e-03	6.204291e-03
37.83	90.12	$0.01825^{+3.89\%}_{-4.76\%} \pm 1.25\%$	3.9e-05	8.431475e-06	5.321814e-03	6.203298e-03
20.92	98.23	$0.01396^{+3.54\%}_{-4.38\%} \pm 1.27\%$	3.5e-05	3.700180e-06	7.402584e-03	6.201635e-03
48.35	110.27	$0.01019^{+3.08\%}_{-3.89\%} \pm 1.26\%$	1.9e-05	1.117483e-05	8.944139e-03	6.201403e-03
20.58	118.72	$0.00798^{+2.75\%}_{-3.54\%} \pm 1.24\%$	2e-05	3.596532e-06	1.268511e-02	6.200514e-03
50.21	119.73	$0.00798^{+2.71\%}_{-3.49\%} \pm 1.26\%$	1.9e-05	1.165192e-05	1.229243e-02	6.200219e-03

Results for W^+h_2



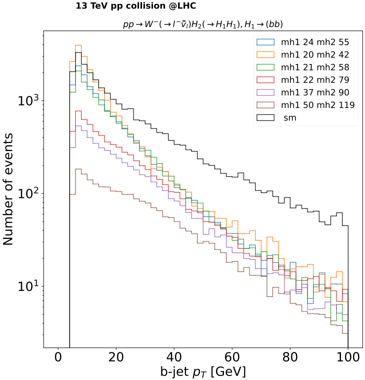


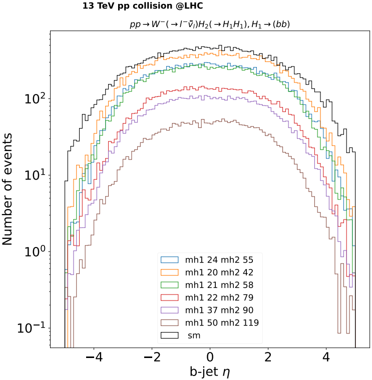
Results for $W^- h_2$

- We have considered the following process for studying $W^- h_2$: $pp \to W^- h_2(\to h_1 h_1) \to \ell^- \bar{\nu}_\ell b\bar{b}b\bar{b}$.
- Decay widths are computed by `MadWidth`
- Decays are generated when declaring process in `MadGraph`

M_{h_1} (GeV)	M_{h_2} (GeV)	σ_{LO} (pb)	Stat. Unc. (pb)	Γ_{H1} (GeV)	Γ_{H2} (GeV)	Γ_{H3} (GeV)
20.13	42.96	$0.0664^{+6.86\%}_{-7.92\%} \pm 1.17\%$	0.00015	3.458492e-06	4.942668e-04	6.203459e-03
24.84	55.25	$0.04125^{+5.96\%}_{-6.99\%} \pm 1.18\%$	9e-05	4.860789e-06	1.144740e-03	6.203994e-03
21.6	58.31	$0.037^{+5.74\%}_{-6.76\%} \pm 1.18\%$	7.5e-05	3.905856e-06	1.650158e-03	6.203090e-03
30.16	70.16	$0.02359^{+5.03\%}_{-6.02\%} \pm 1.19\%$	5.3e-05	6.360984e-06	2.484487e-03	6.203420e-03
22.27	79.57	$0.01682^{+4.63\%}_{-5.59\%} \pm 1.33\%$	4.1e-05	4.106503e-06	4.109132e-03	6.201924e-03
36.7	79.95	$0.0166^{+4.62\%}_{-5.58\%} \pm 1.16\%$	3.9e-05	8.131270e-06	3.059512e-03	6.204291e-03
37.83	90.12	$0.01204^{+4.1\%}_{-5.03\%} \pm 1.19\%$	3.1e-05	8.431475e-06	5.321814e-03	6.203298e-03
20.92	98.23	$0.0092^{+3.71\%}_{-4.62\%} \pm 1.17\%$	2.5e-05	3.700180e-06	7.402584e-03	6.201635e-03
48.35	110.27	$0.0066^{+3.24\%}_{-4.11\%} \pm 1.2\%$	1.9e-05	1.117483e-05	8.944139e-03	6.201403e-03
20.58	118.72	$0.00512^{+2.95\%}_{-3.81\%} \pm 1.2\%$	1.2e-05	3.596532e-06	1.268511e-02	6.200514e-03
50.21	119.73	$0.00511^{+2.91\%}_{-3.76\%} \pm 1.16\%$	1.2e-05	1.165192e-05	1.229243e-02	6.200219e-03

Results for $W^- h_2$



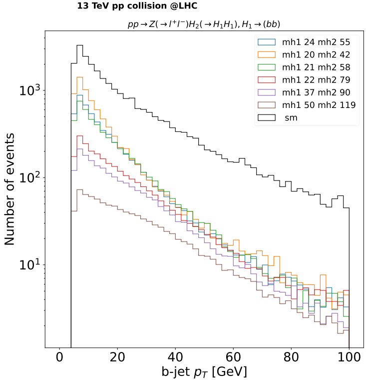


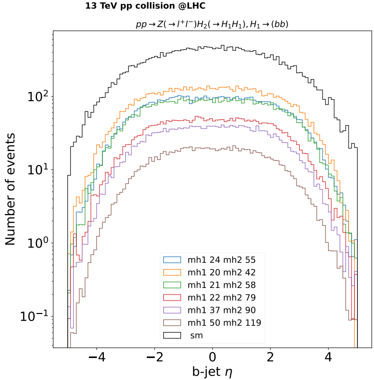
Results for Zh_2

- We have considered the following process for studying Zh_2: $pp \to Zh_2(\to h_1 h_1) \to \ell^+\ell^- b\bar{b}b\bar{b}$.
- Decay widths are computed by `MadWidth`
- Decays are generated when declaring process in `MadGraph`

M_{h_1} (GeV)	M_{h_2} (GeV)	σ_{LO} (pb)	Stat. Unc. (pb)	Γ_{H1} (GeV)	Γ_{H2} (GeV)	Γ_{H3} (GeV)
20.13	42.96	$0.02415^{+6.14\%}_{-7.14\%} \pm 1.11\%$	5.6e-05	3.458492e-06	4.942668e-04	6.203459e-03
24.84	55.25	$0.01541^{+5.33\%}_{-6.3\%} \pm 1.1\%$	2.8e-05	4.860789e-06	1.144740e-03	6.203994e-03
21.6	58.31	$0.01388^{+5.13\%}_{-6.1\%} \pm 1.11\%$	2.6e-05	3.905856e-06	1.650158e-03	6.203090e-03
30.16	70.16	$0.00909^{+4.56\%}_{-5.49\%} \pm 1.09\%$	1.7e-05	6.360984e-06	2.484487e-03	6.203420e-03
22.27	79.57	$0.00662^{+4.08\%}_{-4.98\%} \pm 1.09\%$	1.3e-05	4.106503e-06	4.109132e-03	6.201924e-03
36.7	79.95	$0.00654^{+4.07\%}_{-4.98\%} \pm 1.1\%$	1.3e-05	8.131270e-06	3.059512e-03	6.204291e-03
37.83	90.12	$0.00482^{+3.6\%}_{-4.47\%} \pm 1.09\%$	8.9e-06	8.431475e-06	5.321814e-03	6.203298e-03
20.92	98.23	$0.00373^{+3.33\%}_{-4.18\%} \pm 1.13\%$	6.9e-06	3.700180e-06	7.402584e-03	6.201635e-03
48.35	110.27	$0.00273^{+2.88\%}_{-3.7\%} \pm 1.09\%$	5.5e-06	1.117483e-05	8.944139e-03	6.201403e-03
20.58	118.72	$0.00213^{+2.54\%}_{-3.33\%} \pm 1.1\%$	3.9e-06	3.596532e-06	1.268511e-02	6.200514e-03
50.21	119.73	$0.00214^{+2.55\%}_{-3.34\%} \pm 1.09\%$	4.1e-06	1.165192e-05	1.229243e-02	6.200219e-03

Results for Zh_2





Flavour Tagging

- Flavour Tagging plays a crucial role in identifying jets that orignate due to hadronization of a *b*-quark.
- LHC experiments use Machine Learning for jet tagging.
- The following diagram summarizes the various features used for jet tagging:

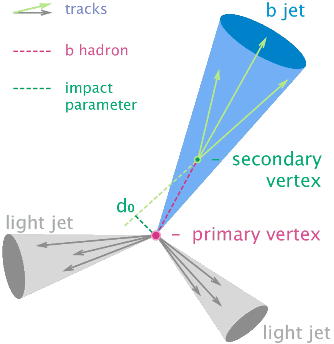
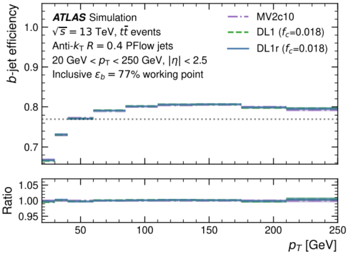


Figure Source

Performance of Flavour Tagging at LHC Experiments

- The performance of Deep Learning framework (also available are Graph Neural Network) used by ATLAS experiment as a function of jet p_T.
- This depends on jet p_T and as we see at low p_T the performance degrades.
- This is one of the challenges when probing low p_T jets at experiments.



Plot from [9]

Summary

- In this work we explored the associate production of light scalars with a Z or $W^{\pm}$.
- Prof. Kristin has some ideas regarding low p_T b-jets, and we are interested in probing this phase space with low p_T b-jets.
- Some initial analysis carried out using `ScannerS` and `MadGraph` based simulation is presented.

Further Work

The future work includes:

- Analyzing the final state particles with cuts and reconstructing events.
- Exploring the actual available phase space after applying cuts on jet p_T.
- Investigating other options to extend phase space (low pt btagging).
- Carry out some form of Recast to get the available phase space.

References I

[1] Tania Robens et al. "Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios". In: *Eur. Phys. J. C* 80.2 (2020), p. 151. DOI: 10.1140/epjc/s10052-020-7655-x.

[2] Margarete Mühlleitner et al. "ScannerS: parameter scans in extended scalar sectors". In: *Eur. Phys. J. C* 82.3 (2022), p. 198. DOI: 10.1140/epjc/s10052-022-10139-w.

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