SM+Singlet Scalar Simulation

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1 Problem Statement

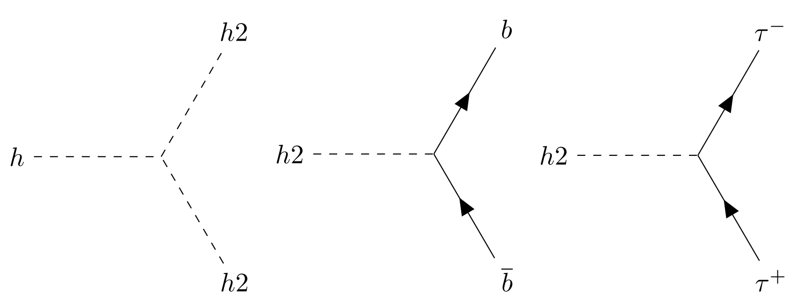
A Real Singlet Scalar(X) of mass 50 GeV is added to the Standard Model. The Standard Model Higgs Boson is observed to decay to two Singlet Scalars which are further forced to decay to $b - \bar{b}$ or $\tau^- - \tau^+$ pairs. The Higgs Boson and Singlet Scalar are reconstructed in PYTHIA8[1]+FastJet3[2] [3] via Invariant Mass plot and their transverse momenta are observed as well.
Note: The Real Singlet Scalar X may be referred to as h_2 in the text.

2 Theory

The following properties define the Real Singlet Scalar **X** -

- Real Scalar - Like the Higgs Boson, X is also a Scalar. It has a spin of 0. The field's complex conjugate remains the same due to its real nature.
- Singlet - While the Higgs Boson has two components, being a doublet, X is defined as having just one scalar component.

The decays concerned in this simulation are those of the Higgs and Singlet Scalar (X).



3 Steps

The following steps are performed to create, simulate, and observe the new particle.

1. The SSM model in SARAH[5] is used to generate the appropriate CalcHEP[6] model files.
2. The CalcHEP files are imported to CalcHEP in order to generate required LHE files and decay information.
3. PYTHIA8 is used to read the LHE files and simulate the required collision process.
4. FastJet3 is used to observe the jets formed through decay of the new particle, X, and reconstruct it.

Certain modifications had to be made to the model, LHE, decay files in order to obtain cleaner results, and thus the end-result may not be completely physically true.

4 SARAH - Model Description

The particle is defined in the SSM.m file of SARAH's SSM model folder as below. The modified lagrangian is shown below.

```
(*generations, {isospin names}, hypercharge,transformation under SU(2)L × SU(3)C*)
ScalarFields[[1]] = {H, 1, {Hp, H0},      1/2, 2, 1};
ScalarFields[[2]] = {s, 1, Sing,     0, 1, 1};

RealScalars = {s};
```

Figure 1: SARAH Particle Description

```
DEFINITION[GaugeES][Additional]= {
    {LagHC, { AddHC->True}},
    {LagNoHC,{ AddHC->False}}
};

LagNoHC = -(mu2 conj[H].H +  1/2 MS s.s + K1 conj[H].H.s + 1/2 K2 conj[H].H.s.s + κ/3 s.s.s + LambdaS/2 s.s.s.s + 1/2 λ conj[H].H.conj[H].H);

LagHC = - ( Yd conj[H].d.q + Ye conj[H].e.l - Yu H.u.q);
```

Figure 2: Modified Lagrangian

The CalcHEP files are generated using the following commands in a Mathematica Notebook with the following commands.

```
<< "<PATH TO SARAH>/SARAH-4.14.4/SARAH.m"
Start["SSM"]
MakeCHep[SLHAinput -> False, CalculateMasses -> True,
    CPViolation -> False, ModelNr -> True, CompHep -> False,
    RunSPhenoViaCalcHep -> False, UseRunningCoupling ->
    False, WriteMOfile -> True,
    IncludeEffectiveHiggsVertices -> True, FeynmanGauge -> True]
```

Errors Faced In SSM Files

1. Certain constants are missing from the files generated via MakeCHep. Those need to be calculated seperately.
2. The gluon-Higgs vertex is vacant in the model, and therefore the Higgs Boson can not be produced via that channel. For this, the HGG1 variable in the CHep vars file is set to an appropriate value to enable Higgs production.
3. If using Windows to generate your model files you will have to replace the newline character using the command *tr -d '\r' < input > output*[4]

5 CalcHEP - LHE File Creation and Modification

For the SSM model, the following files are generated by SARAH.

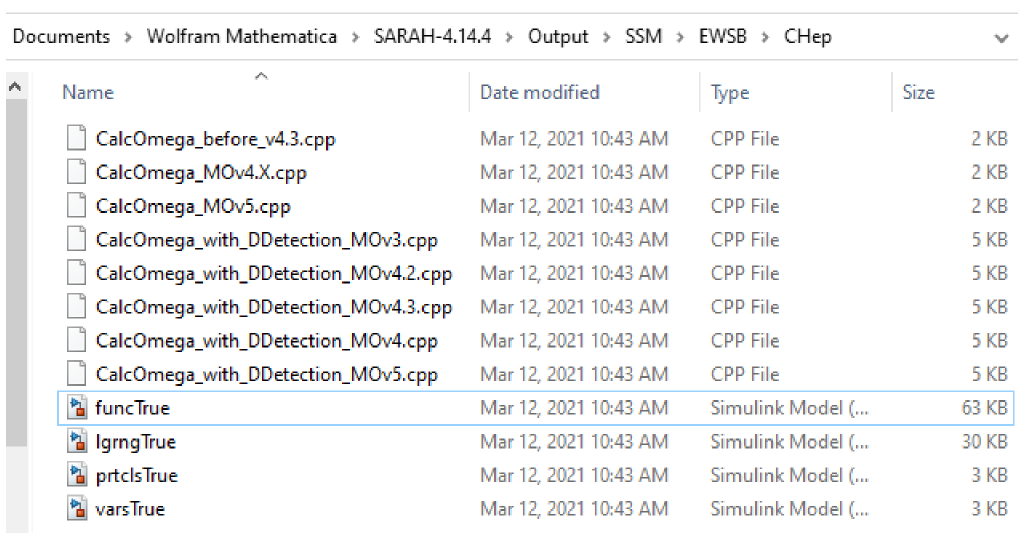


Figure 3: SARAH CHep Files

These have to be copied over to the CalcWork or Work directory in CalcHEP and renamed appropriately with the same last digit. Inside the CalcHEP menu, the new model can now be imported. Now, one can set the Real Singlet Scalar's mass to 50 GeV as defined in the problem statement.

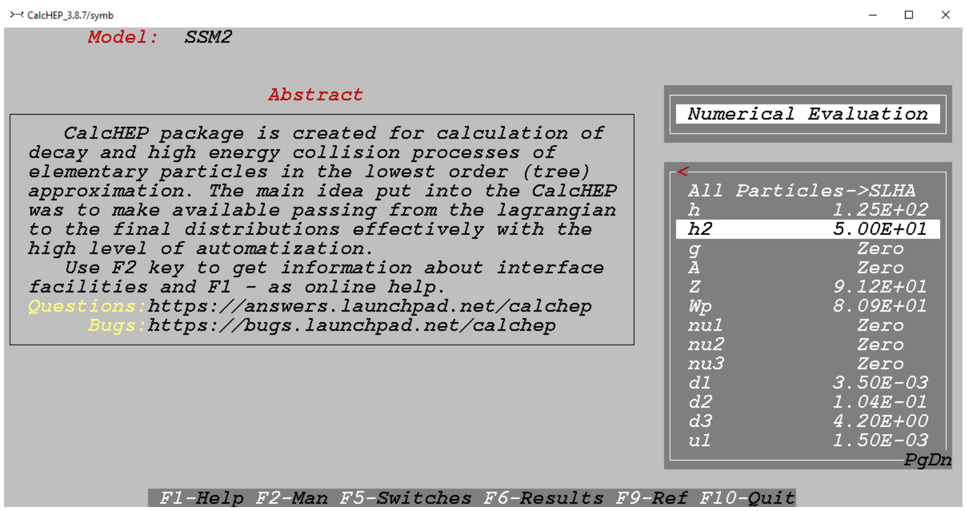


Figure 4: Setting Scalar's Mass 50 GeV

Here the $p + p \to t + \bar{t}$ process is initialised, defining the composite particle p as u, U, d , D , g.

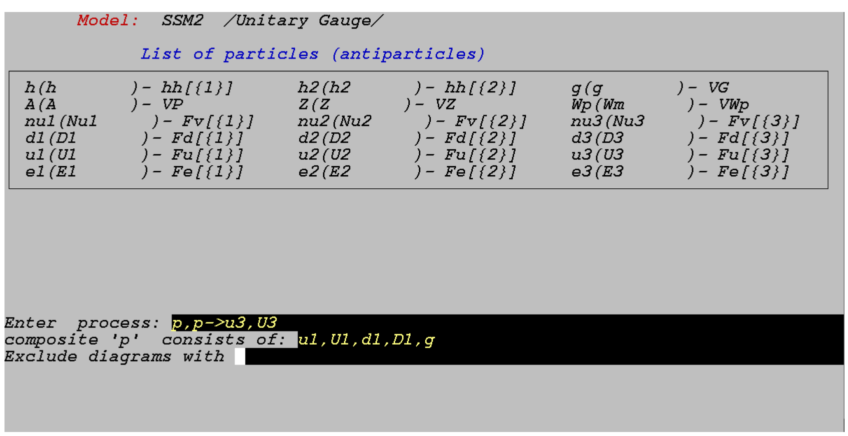


Figure 5: Setting the Process

The subproc_cycle can now be initiated for 1 Lakh events, generating the required LHE file for the SM model.

```
dhruvg@DhruvG:~/calchep_3.8.7/cpp/results$ ../bin/subproc_cycle 100000 10000
100000 events are requested
Number of enents limited by flux 10000 [1/fb]
#Subprocess 1 ( u1, U1 -> u3, U3 ) Cross section = 9.3704E+00 pb (3.38E-02%) , 100000 events
#Subprocess 2 ( U1, u1 -> u3, U3 ) Cross section = 9.3719E+00 pb (3.23E-02%) , 100000 events
#Subprocess 3 ( d1, D1 -> u3, U3 ) Cross section = 5.7893E+00 pb (3.88E-02%) , 100000 events
#Subprocess 4 ( D1, d1 -> u3, U3 ) Cross section = 5.7881E+00 pb (4.85E-02%) , 100000 events
#Subprocess 5 ( g, g -> u3, U3 ) Cross section = 1.2537E+02 pb (4.32E-02%) , 100000 events
1.557E+02  -total cross section[pb]
124183    -maximum number of events
 100000 events are generated
Events in LHE format: events_18_22.lhe
Total Cross Section 1.557E+02 [pb] (3.497E-02%)
See details in directory 18_22
```

Figure 6: Running Subprocess Cycle

Here, the decay table under the SLHA header is of importance, where the decay of the Higgs and X is stored. The decay table to Higgs can be modified to decay majorly to X, and X can in turn only decay to $b\bar{b}$ or $\tau^-\tau^+$. Shown in Figure 7.

```
<slha>
BLOCK QNUMBERS 35 # h2
 1 0
 2 1
 3 1
 4 0

BLOCK MASS
 25    1.250000E+02 #
 35    5.000000E+01 #
 21    0.000000E+00 #
 22    0.000000E+00 #
 23    9.118760E+01 #
 24    8.093901E+01 #
 12    0.000000E+00 #
 14    0.000000E+00 #
 16    0.000000E+00 #
 1    3.500000E-03 #
 3    1.040000E-01 #
 5    4.200000E+00 #
 2    1.500000E-03 #
 4    1.270000E+00 #
 6    1.712000E+02 #
 11    5.110000E-04 #
 13    1.050000E-01 #
 15    1.776000E+00 #

DECAY 25  7.310503E-01 # h
   0.99  2  35  35  # h2,h2
   !5.898107E-03  2  5  -5  # d3,D3
   !1.063807E-03  2  24  -24  # Wp,Wm
   0.01  2  21  21  # g,g
   !5.426264E-04  2  4  -4  # u2,U2
   !3.535093E-04  2  15  -15  # e3,E3
   !1.420117E-04  2  23  23  # Z,Z
   !3.641056E-06  2  3  -3  # d2,D2
   !1.237138E-06  2  13  -13  # e2,E2
   !4.123809E-09  2  1  -1  # d1,D1
   !7.574343E-10  2  2  -2  # u1,U1
   !2.930103E-11  2  11  -11  # e1,E1
DECAY 35  1.799072E-07 # h2
   0.5  2  5  -5  # d3,D3
   !8.212710E-02  2  4  -4  # u2,U2
   0.5  2  15  -15  # e3,E3
   !5.528634E-04  2  3  -3  # d2,D2
   !1.878488E-04  2  13  -13  # e2,E2
   !6.261788E-07  2  1  -1  # d1,D1
   !1.150125E-07  2  2  -2  # u1,U1
   !4.449211E-09  2  11  -11  # e1,E1
</slha>
```

Figure 7: SLHA Decay Table

6 PYTHIA8+FastJet3 - Simulating Collision and Jet Construction

The LHE file is read and the process is initiated as follows.

```
pythia.readString("Beams:frameType = 4");
pythia.readString("Beams:LHEF = /home/dhruvg/calchep_3.8.7/cpp/results
/events_ssm14tev.lhe");
```

The rest of the Pythia Initialisation -

```
Pythia pythia;
Event& event = pythia.event;
pythia.readString("HiggsSM:gg2H = on");
pythia.readString("HadronLevel:Hadronize = on");
pythia.readString("HadronLevel:Decay = on");
pythia.readString("PartonLevel:FSR = off");
pythia.readString("PartonLevel:ISR = off");
pythia.readString("PartonLevel:MPI = off");
```

The hard process list is as shown below

```
--------  PYTHIA Event Listing  (hard process)  -----------------------------------------------------------------------------

   no        id  name            status     mothers   daughters     colours      p_x        p_y        p_z         e          m
    0        90  (system)           -11     0     0     0     0     0     0     0.000      0.000      0.000  14000.000  14000.000
    1      2212  (p+)               -12     0     0     3     0     0     0     0.000      0.000   7000.000   7000.000      0.938
    2      2212  (p+)               -12     0     0     4     0     0     0     0.000      0.000  -7000.000   7000.000      0.938
    3        21  (g)                -21     1     0     5     0   101   102     0.000      0.000    274.428    274.428      0.000
    4        21  (g)                -21     2     0     5     0   102   101     0.000      0.000    -14.222     14.222      0.000
    5        25  (h0)               -22     3     4     6     7     0     0     0.000      0.000    260.206    288.649    124.944
    6        35  (h2)               -22     5     0     8     9     0     0     6.884     26.186    189.888    198.218     50.000
    7        35  (h2)               -22     5     0    10    11     0     0    -6.884    -26.186     70.318     90.431     50.000
    8         5  b                   23     6     0     0     0   103     0    -4.370     -0.782      0.531      6.560      4.800
    9        -5  bbar                23     6     0     0     0     0   103    11.254     26.968    189.357    191.658      4.800
   10        15  tau-                23     7     0     0     0     0     0     2.623     11.437      2.281     12.085      1.777
   11       -15  tau+                23     7     0     0     0     0     0    -9.506    -37.623     68.037     78.346      1.777
                                 Charge sum:  0.000           Momentum sum:      0.000      0.000    260.206    288.649    124.944

--------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------
```

Figure 8: Hard Process List

The event listing -

-------- PYTHIA Event Listing (complete event) ---

no	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
0	90	(system)	-11	0	0	0	0	0	0	0.000	0.000	0.000	14000.000	14000.000
1	2212	(p+)	-12	0	0	6	0	0	0	0.000	0.000	7000.000	7000.000	0.938
2	2212	(p+)	-12	0	0	7	0	0	0	0.000	0.000	-7000.000	7000.000	0.938
3	21	(g)	-21	6	6	5	0	101	102	0.000	0.000	274.428	274.428	0.000
4	21	(g)	-21	7	7	5	0	102	101	0.000	0.000	-14.222	14.222	0.000
5	25	(h0)	-22	3	4	8	8	0	0	0.000	0.000	260.206	288.649	124.944
6	21	(g)	-61	1	0	3	3	101	102	0.402	-0.972	274.430	274.432	0.000
7	21	(g)	-61	2	0	4	4	102	101	-0.087	0.301	-14.219	14.222	0.000
8	25	(h0)	-62	5	5	13	14	0	0	0.315	-0.671	260.211	288.654	124.944
9	2101	(ud_0)	-63	1	0	28	28	0	101	-0.539	0.781	3691.112	3691.112	0.579
10	2	(u)	-63	1	0	44	65	102	0	0.137	0.192	3034.453	3034.453	0.330
11	2103	(ud_1)	-63	2	0	44	65	0	102	0.235	-0.417	-6969.030	6969.030	0.771
12	2	(u)	-63	2	0	27	27	101	0	-0.148	0.115	-16.746	16.750	0.330
13	35	(h2)	-22	8	0	15	16	0	0	7.100	25.725	189.891	198.168	50.000
14	35	(h2)	-22	8	0	17	18	0	0	-6.785	-26.396	70.320	90.486	50.000
15	5	(b)	-23	13	0	19	26	103	0	-4.363	-0.798	0.531	6.557	4.800
16	-5	(bbar)	-23	13	0	19	26	0	103	11.463	26.523	189.360	191.612	4.800
17	15	(tau-)	-23	14	0	100	104	0	0	2.636	11.409	2.281	12.061	1.777
18	-15	(tau+)	-23	14	0	97	99	0	0	-9.421	-37.805	68.038	78.424	1.777
19	-523	(B*-)	-83	15	16	105	106	0	0	-3.896	-0.665	1.319	6.761	5.325
20	211	pi+	83	15	16	0	0	0	0	-0.088	-0.029	0.071	0.182	0.140
21	223	(omega)	-83	15	16	107	109	0	0	-0.180	-0.008	0.658	1.043	0.789
22	111	(pi0)	-84	15	16	110	111	0	0	0.326	0.700	3.386	3.475	0.135
23	313	(K*0)	-84	15	16	66	67	0	0	0.605	1.758	13.078	13.239	0.879
24	-311	(Kbar0)	-84	15	16	68	68	0	0	0.718	1.565	12.209	12.340	0.498
25	111	(pi0)	-84	15	16	112	113	0	0	-0.041	0.147	1.253	1.270	0.135
26	513	(B*0)	-84	15	16	114	115	0	0	9.657	22.256	157.916	159.858	5.325
27	2	(u)	-71	12	12	29	43	101	0	-0.148	0.115	-16.746	16.750	0.330
28	2101	(ud_0)	-71	9	9	29	43	0	101	-0.539	0.781	3691.112	3691.112	0.579
29	213	(rho+)	-83	27	28	69	70	0	0	0.035	0.116	-14.161	14.225	1.342
30	113	(rho0)	-83	27	28	71	72	0	0	0.220	-0.164	-0.858	1.264	0.887
31	111	(pi0)	-83	27	28	116	117	0	0	-0.229	0.159	-0.495	0.584	0.135
32	-213	(rho-)	-83	27	28	73	74	0	0	-0.458	0.033	-0.198	0.982	0.845
33	211	pi+	83	27	28	0	0	0	0	0.279	-0.241	0.350	0.527	0.140
34	-213	(rho-)	-83	27	28	75	76	0	0	-0.122	-0.022	1.388	1.608	0.802
35	211	pi+	83	27	28	0	0	0	0	0.033	0.009	-0.088	0.168	0.140
36	111	(pi0)	-83	27	28	118	119	0	0	0.353	-0.033	8.194	8.203	0.135

Figure 9: Event Listing

The FastJet3 Initialisation.

```
double R       = 0.6;    // JetSize
double pTMin   = 20.0;    // Min jet pT.
double etaMax  = 2.5;    // Pseudorapidity range of detector.
fastjet::JetDefinition jetDef(fastjet::cambridge_algorithm, R);
```

7 Results

The following results are obtained for the specified jet-cone radii, using Cambridge/Aachen algorithm on 1 Lakh events in Pythia8 and FastJet3.

7.1 Jet Multiplicity

The ideal, expected jet multiplicity would be 4 as the two singlet scalar would have two decay products each. However, due to the boost/high-momenta of the particles, it is difficult for the algorithm to make more precise jets.

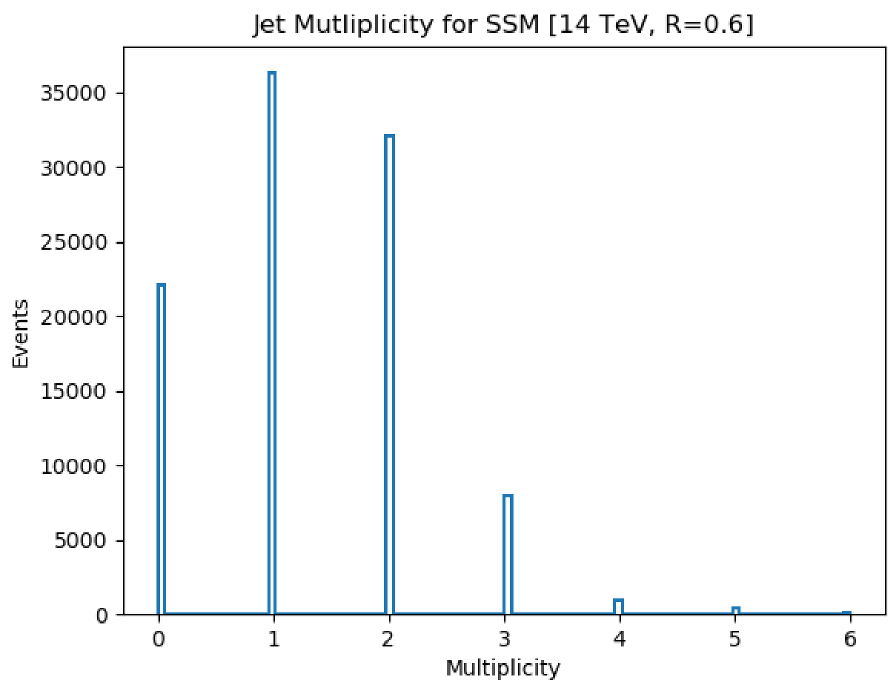


Figure 10: Jet Multiplicity

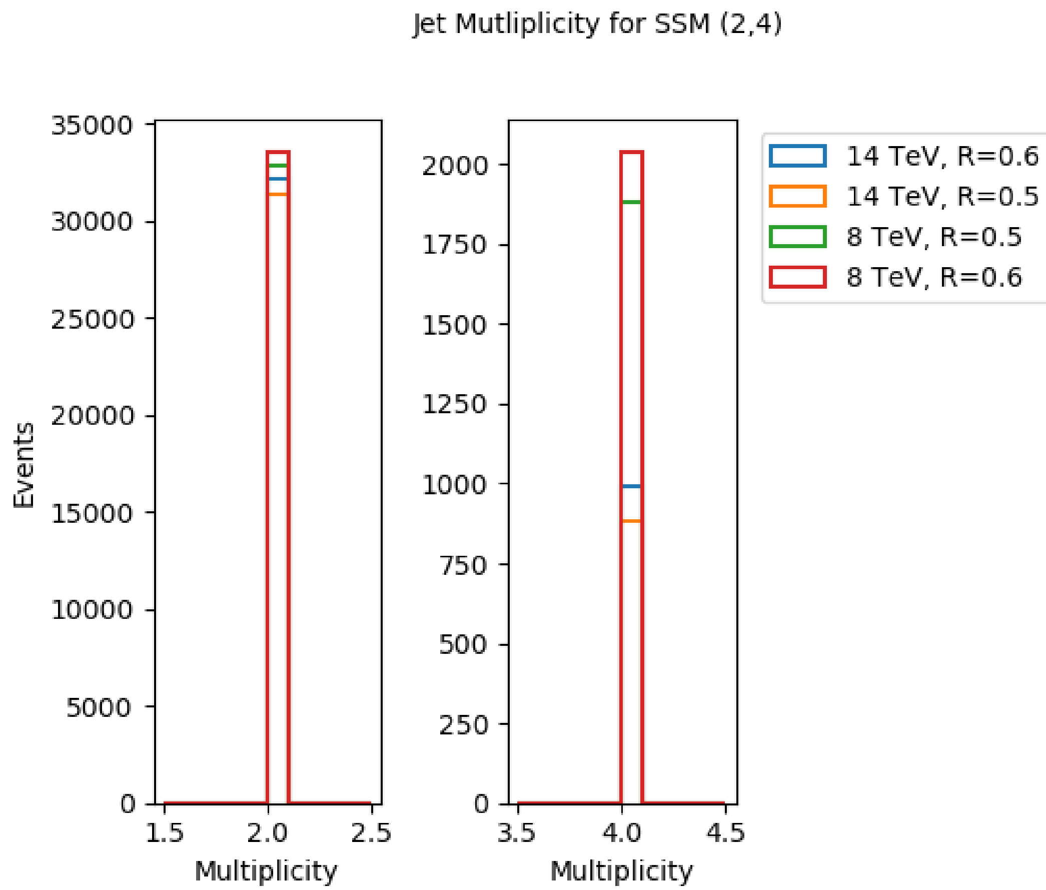


Figure 11: 2,4 Jet Multiplicities

7.2 Transverse Momenta p_T

A minimum transverse momenta cut was set for 20 GeV for this analysis.

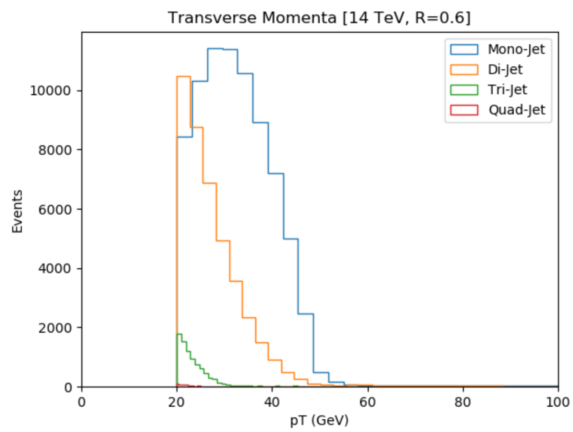


Figure 12: Transverse Momenta, 14 TeV

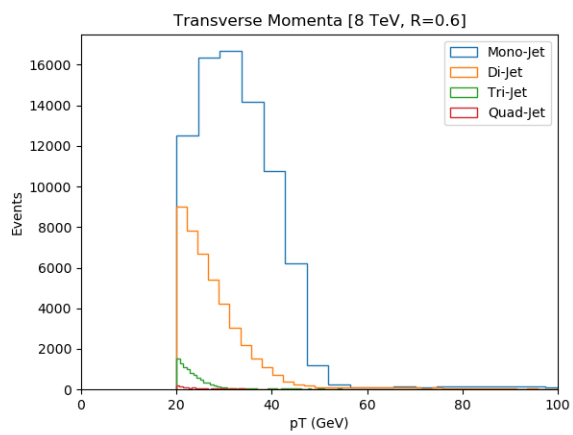


Figure 13: Transverse Momenta, 8 TeV

7.3 Invariant Mass

Here one can see that both, the Higgs Boson, and X, the singlet scalar, have been reconstructed.

1. <u>Di-Jet Invariant Mass</u> - Here, it is clear that there is a peak around 50 GeV amongst the background noise. This peak comes from the invariant

mass of the decay jets of either singlet scalar. Further analysis on decay length can be done to verify if the jet was B-hadronic or τ.

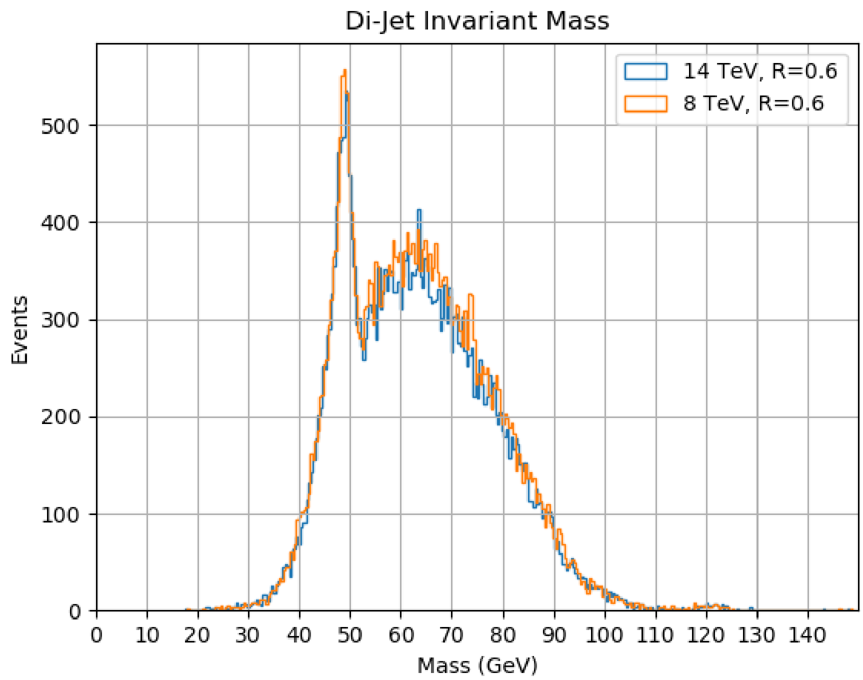


Figure 14: Di-Jet Invariant Mass

2. Quad-Jet Invariant Mass - The Higgs Boson's signature can be seen here. The jets formed in this case are through the four decay products of the two Singlet Scalars. These events are few in number owing to the imprecise resolution of the FastJet algorithm and the high centre-of-mass energy. One can see that the signature is higher in the case of 8 TeV collision.

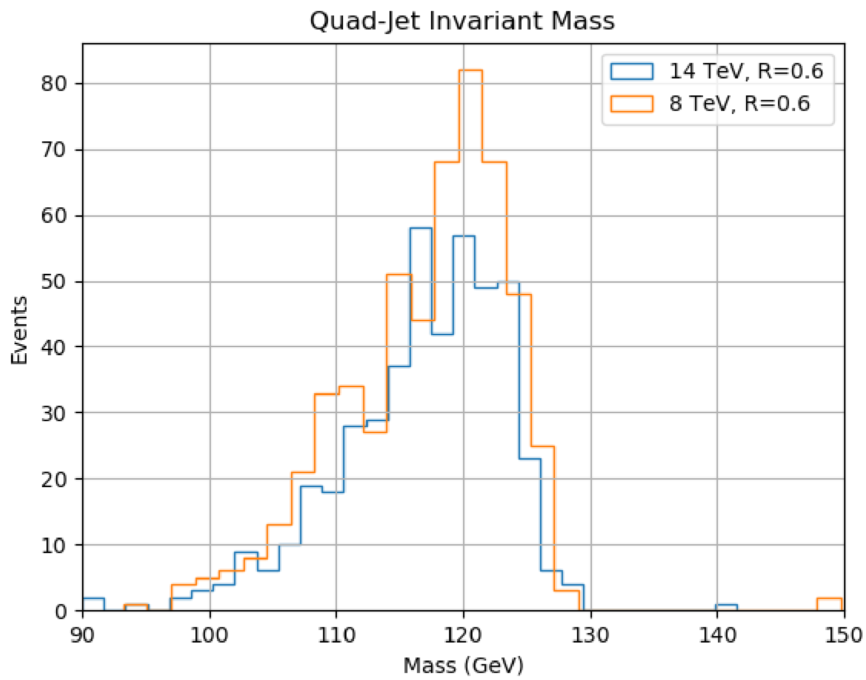


Figure 15: Quad-Jet Invariant Mass

8 Conclusion

The Real Singlet Scalar is thus reconstructed through its products. All the code, figures, relevant files are uploaded on my GitHub

References

[1] T. Sjöstrand, S. Mrenna and P. Skands, JHEP05 (2006) 026, Comput. Phys. Comm. 178 (2008) 852

[2] M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C **72** (2012) 1896 [arXiv:1111.6097 [hep-ph]].

[3] M. Cacciari and G. P. Salam, Phys. Lett. B **641** (2006) 57 [hep-ph/0512210].

[4] https://answers.launchpad.net/calchep/+question/227450

[5] SARAH, F. Staub, arXiv:0806.0538 [hep-ph] (2012)

[6] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. **184**, 1729-1769 (2013) doi:10.1016/j.cpc.2013.01.014 [arXiv:1207.6082 [hep-ph]].