Triple Top Model (ML)

David Lai

One Higgs Doublet Model (SM)

- 4 parameters: 4 degrees of freedom in the Higgs field
- Higgs field gives [massless W1, W2, Z] mass, performing W+, W-, Z bosons. Each mass giving loses one degree of freedom to Higgs field. Higgs field is left with 1 degree of freedom.

Higgs field before Spontaneous Symmetry Breaking:

$$\phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ \phi_1^0 + i\phi_2^0 \end{pmatrix},$$

with $\phi^+, \phi^0 \in \mathbb{C}$ and $\phi_1^+, \phi_2^+, \phi_1^0, \phi_2^0 \in \mathbb{R}$.

Two-Higgs Doublet Model (2HDM)

- motivation: in search for extra Higgs bosons (A, H)
- Without the Z2 symmetries (each type of charged fermions couples to a single Higgs doublet) offers extra Yukawa couplings that induce flavor-changing neutral Higgs (FCNH) interactions.
- there are five physical scalar states, the CP even neutral Higgs bosons h and H (where H is heavier than h by convention), the CP odd pseudoscalar A and two charged Higgs bosons $H\pm$.
- neutral charge (h, H, A) and +- charged ($H \pm$)

Two-Higgs Doublet Model (2HDM)

- similar to below notation, two Higgs Doublet Model has another Psi', which gives additional 4 degree of freedom.
- Combining with one Higgs model, it has 5 degrees of freedom.

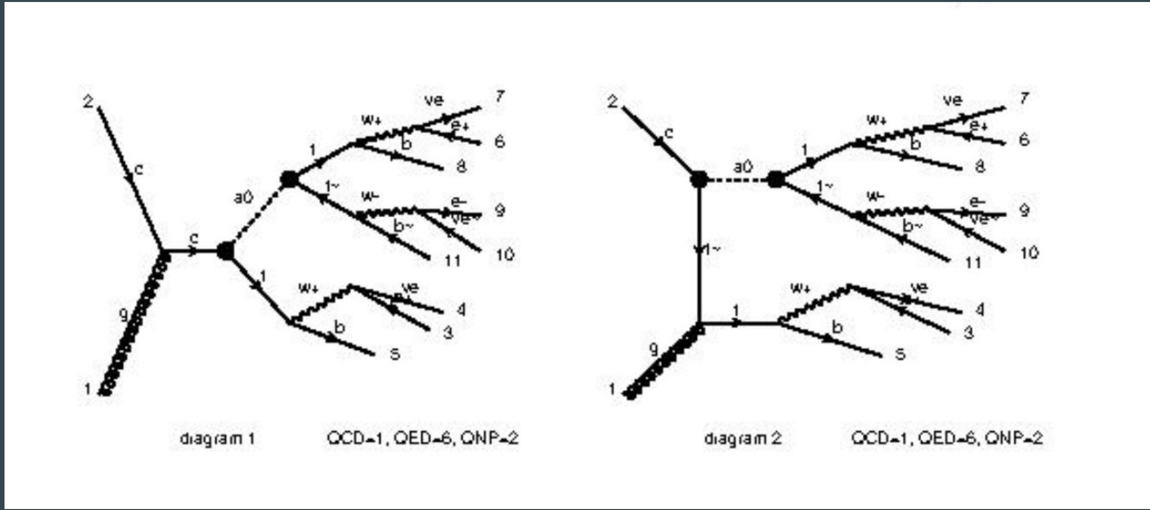
Before Spontaneous Symmetry Breaking:

$$\phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1^+ + i\phi_2^+ \\ \phi_1^0 + i\phi_2^0 \end{pmatrix},$$

with $\phi^+, \phi^0 \in \mathbb{C}$ and $\phi_1^+, \phi_2^+, \phi_1^0, \phi_2^0 \in \mathbb{R}$.

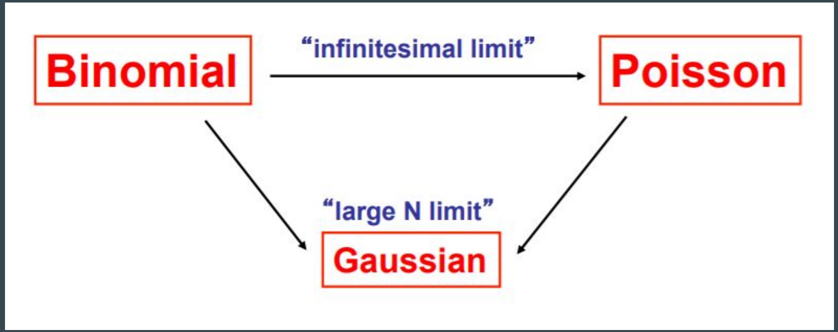
Triple Top

- Triple-top signature: denoted as 3b3l, defined as at least three leptons and at least three jets, of which at least three are b-jets, and E_T_miss.
- Dominant SM backgrounds are ttZ + jets and 4t
- ug, cg -> tS (S = H, A) -> tt t-bar
- SM: cg -> c -> s + W+



Binomial, Poisson, Gaussian Distribution

- Binomial Distribution
  - random process with 2 outcomes with probability p and (1-p)
  - repeat process a **fixed number of times** -> distribution of outcomes
- Poisson distribution
  - **discrete** random process with **fixed mean**
- Gaussian distribution
  - **continuous** high statistics limit



Binomial Distribution

- applies for **a fixed number of trials** when there are **two possible outcomes**
  - i.e. tossing a coin ten times
- sample mean = (number of trials) * (probability)
- variance = np*(1-p)
- Efficiency uncertainty
  - best estimate of efficiency = ε = k/n
  - σ^2 = ε*(1- ε)/n
    - i.e. 90/100 events pass trigger requirements
    - ε = 0.90 ± 0.03

$$\Pr(k;n,p) = \Pr(X=k) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

Derive mean & variance for Binomial Distribution

$$P(x) = \binom{n}{x} p^x q^{n-x} \quad , \quad \text{expected value} : E(x) = \sum_{x=0}^{n} x \binom{n}{x} p^x q^{n-x}$$

$$E(x) = \sum_{x=0}^{n} x \frac{n!}{(n-x)!\, x!} p^x q^{n-x}$$

$$= \sum_{x=1}^{n} \frac{n!}{(x-1)!\,(n-x)!} p^x q^{n-x}$$

$$= \sum_{x=1}^{n} \frac{n(n-1)!}{(x-1)!\,(n-x)!} (p)\, p^{x-1} q^{n-x}$$

$$= np \sum_{x=1}^{n} \frac{(n-1)!}{(x-1)!\,[(n-1)-(x-1)]!} p^{x-1} q^{n-x}$$

$$= np \sum_{x=1}^{n} \binom{n-1}{x-1} p^{x-1} q^{n-x}$$

$$= np \left[{}^{n-1}C_0\, q^{n-1} + {}^{n-1}C_1\, p q^{n-2} + {}^{n-1}C_2\, p^2 q^{n-3} + \cdots + {}^{n-1}C_{n-1}\, p^{n-1} \right]$$

$$= np[p+q]^{n-1} \quad (\text{Binomial Expansion of } (p+q)^{n-1})$$

$$= np. \quad (\text{mean})$$

$$Var(x) = E(x^2) - [E(x)]^2$$

$$E(x^2) = \sum_{x=0}^{n} x^2 \binom{n}{x} p^x q^{n-x}$$

$$\Downarrow$$

$$[x(x-1)+x]$$

$$= \sum_{x=0}^{n} [x(x-1)] \binom{n}{x} p^x q^{n-x} + \underbrace{\sum_{x=0}^{n} x \binom{n}{x} p^x q^{n-x}}$$

$$= \sum_{x=2}^{n} \frac{x(x-1)n(n-1)(n-2)!}{(n-x)!\, x(x-1)(x-2)!} p^x q^{n-x} + np.$$

$$= n(n-1)p^2 \sum_{x=2}^{n} \frac{(n-2)!}{(x-2)!\,(n-x)!} p^{x-2} q^{n-x} + np.$$

$$= n(n-1)p^2 \sum_{x=2}^{n} \binom{n-2}{x-2} p^{x-2} q^{n-x} + np.$$

$$= n(n-1)p^2 [p+q]^{n-2} + np.$$

$$E(x^2) = n(n-1)p^2 + np$$

$$Var(x) = n^2p^2 - np^2 + np - n^2p^2$$

$$= np(1-p)$$

$$= npq$$

Poisson Distribution

$$\Pr(X=k) = \frac{\lambda^k e^{-\lambda}}{k!},$$

$$\lambda = \mathrm{E}(X) = \mathrm{Var}(X).$$

- **discrete** random process with **fixed mean (λ)**
- From binomial distribution,

$$p(n;\mu) = \lim_{N\to\infty} \delta p^n (1-\delta p)^{N-n} \frac{N!}{n!(N-n)!}$$

$$\delta p = \mu \frac{\delta t}{t} = \frac{\mu}{N}$$

- For N events, the estimated uncertainty on the mean of the underlying Poisson distribution is $\sigma/\sqrt{N}$

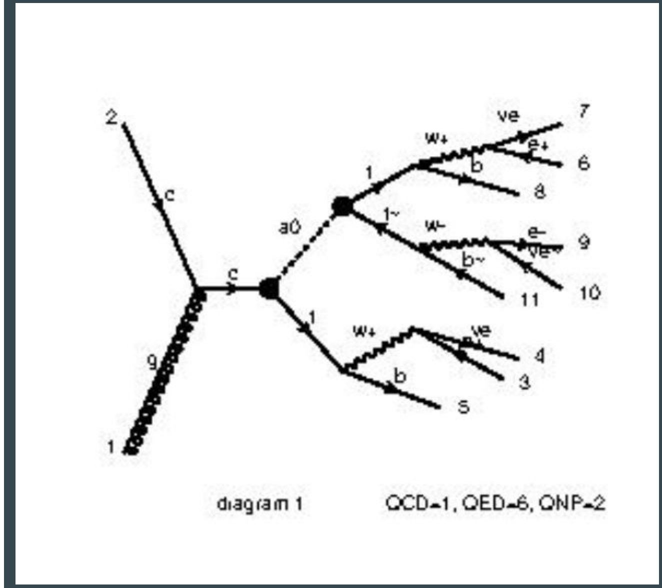
Gaussian Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

- parameters: mean (μ) & standard deviation (σ)
- property:
  - The mean, mode and median are all equal.
  - The curve is symmetric at the center (mean)
  - The total area under the curve is 1.
- Empirical Rule
  - 1σ: 68%, 2σ: 95%, 3σ: 99%

Particle Information Print Out

	mass	PID	Particle	mother1	mother2	e	px	py	pz	status
0	0.000000	21.0	g	0.0	0.0	1018.060894	0.000000	0.000000	1018.060894	-1.0
1	0.000000	4.0	c	0.0	0.0	183.401074	-0.000000	-0.000000	-183.401074	-1.0
2	171.421532	6.0	t	1.0	2.0	345.742140	-172.122123	-73.367527	234.826460	2.0
3	81.170992	24.0	W+	3.0	3.0	325.724657	-171.837734	-72.954573	254.277892	2.0
4	400.718307	5000001.0	A0	1.0	2.0	537.569126	203.257324	82.517533	283.342055	2.0
5	170.645900	6.0	t	5.0	5.0	216.841820	122.618484	-23.747535	47.969922	2.0
6	78.950911	24.0	W+	6.0	6.0	140.894814	101.527050	-54.664804	-17.947690	2.0
7	172.252943	-6.0	t~	5.0	5.0	320.727306	80.638840	106.265069	235.372133	2.0
8	79.106743	-24.0	W-	8.0	8.0	125.778071	-18.329159	61.904986	73.444271	2.0
9	0.000000	-11.0	e+	4.0	4.0	265.151122	-135.413661	-34.116438	225.398151	1.0
10	0.000000	12.0	ve	4.0	4.0	60.573536	-36.424072	-38.838135	28.879741	1.0
11	4.700000	5.0	b	3.0	3.0	20.017482	-0.284389	-0.412954	-19.451432	1.0
12	0.000000	-13.0	mu+	7.0	7.0	75.896123	71.829300	2.797157	-24.350546	1.0
13	0.000000	14.0	vu	7.0	7.0	64.998691	29.697750	-57.461961	6.402856	1.0
14	4.700000	5.0	b	6.0	6.0	75.947006	21.091434	30.917268	65.917612	1.0
15	0.000000	11.0	e-	9.0	9.0	81.863410	22.012870	52.348036	58.963842	1.0
16	0.000000	-12.0	ve	9.0	9.0	43.914660	-40.342029	9.556950	14.480429	1.0
17	4.700000	-5.0	b~	8.0	8.0	194.949235	98.967999	44.360083	161.927863	1.0
18	0.000000	21.0	g	1.0	2.0	318.150702	-31.135201	-9.150006	316.491304	1.0



Cross Section Uncertainty

- Cross section uncertainty is an estimation of the statistic error.
- For small number of events (~100 events) generation, one would expect ~8% for the statistical uncertainty
- The statistical error decreases when one increases the number of events.

Collider	Banner	Cross section (pb)	Events
p p 7000.0 x 7000.0 GeV	tag_1	0.03485 ± 7.7e-05 ± systematics	10000
p p 7000.0 x 7000.0 GeV	tag_1	0.02053 ± 4.3e-05 ± systematics	10000
p p 7000.0 x 7000.0 GeV	tag_1	0.01266 ± 2.5e-05 ± systematics	10000
p p 7000.0 x 7000.0 GeV	tag_1	0.007965 ± 1.6e-05 ± systematics	10000

```
MS0 400 σ: 0.22095%
MS0 500 σ: 0.20945%
MS0 600 σ: 0.19747%
MS0 700 σ: 0.20088%
```

Figure: p p -> t t~ S0, with rho_tt = 1 & MS0 = [400, 500, 600, 700]

Cross Section vs Mass

Previous : QCD=99; Use pdf set 274000

Current: Turn off QCD=99; Use default pdf set 230000

Paper:

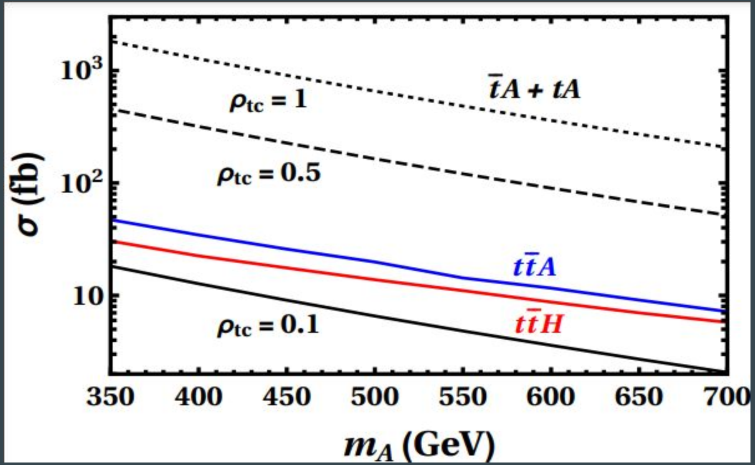
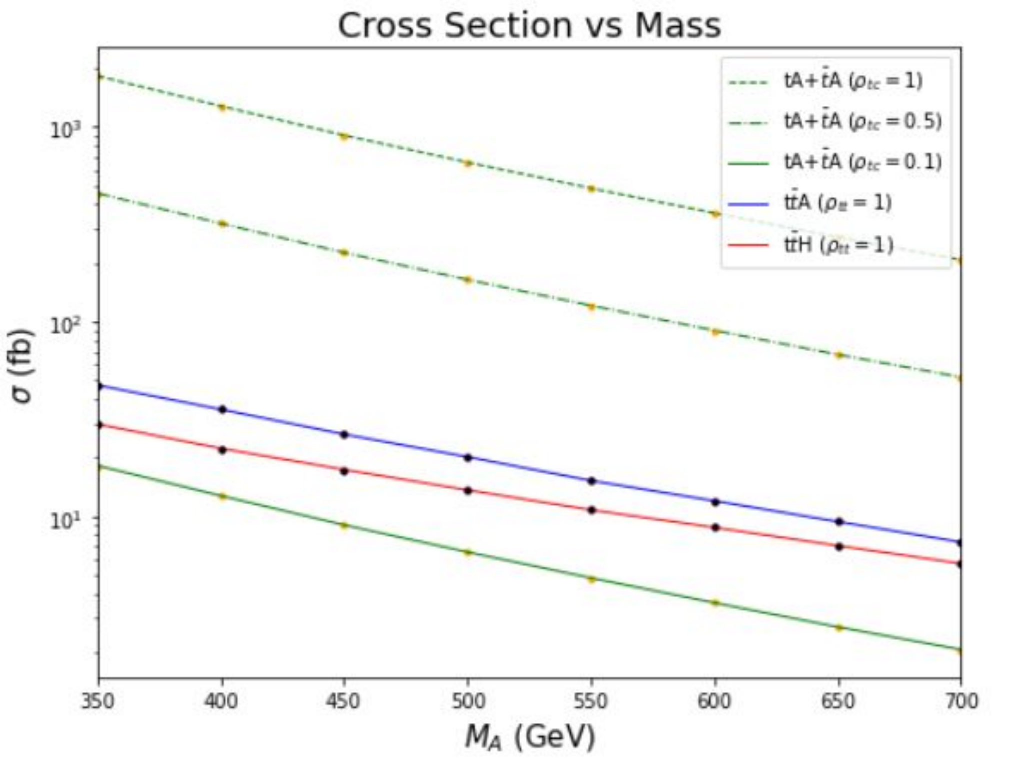
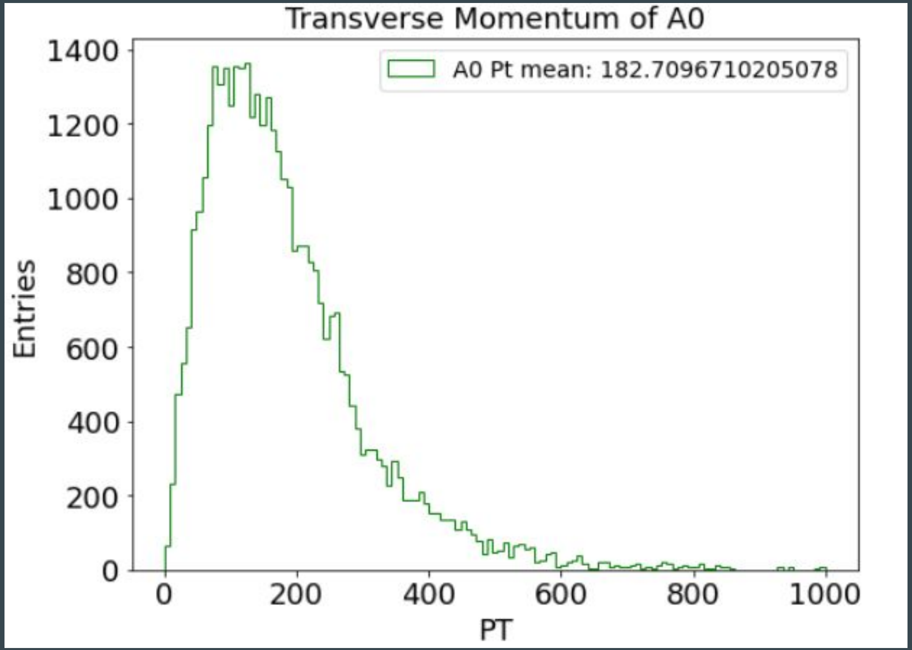


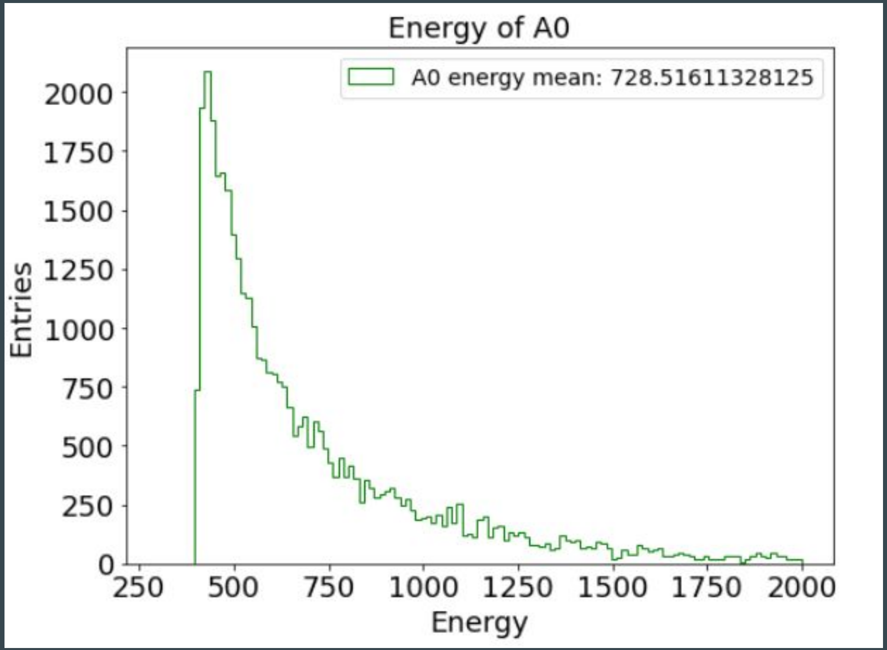
FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \to tS^0$, $\bar{t}S^0$ where $S^0 = H^0$, A^0, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \to t\bar{t}H^0$, $t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

My Result:

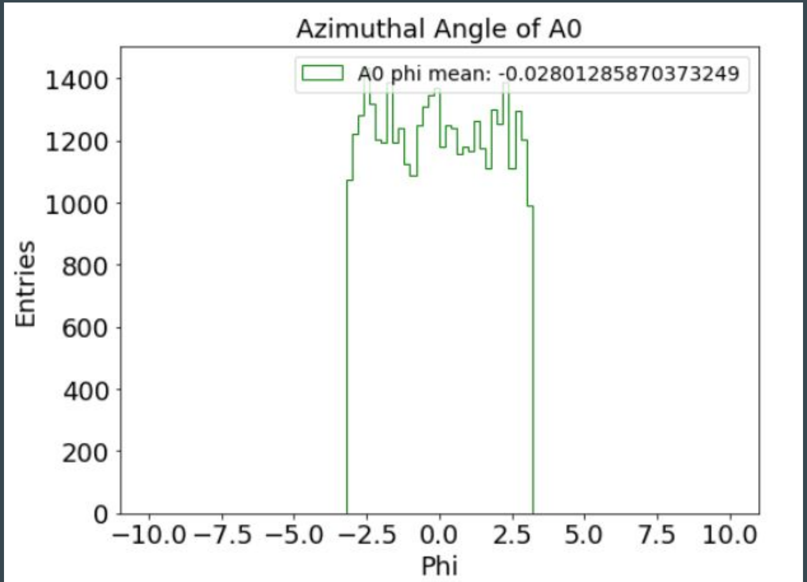


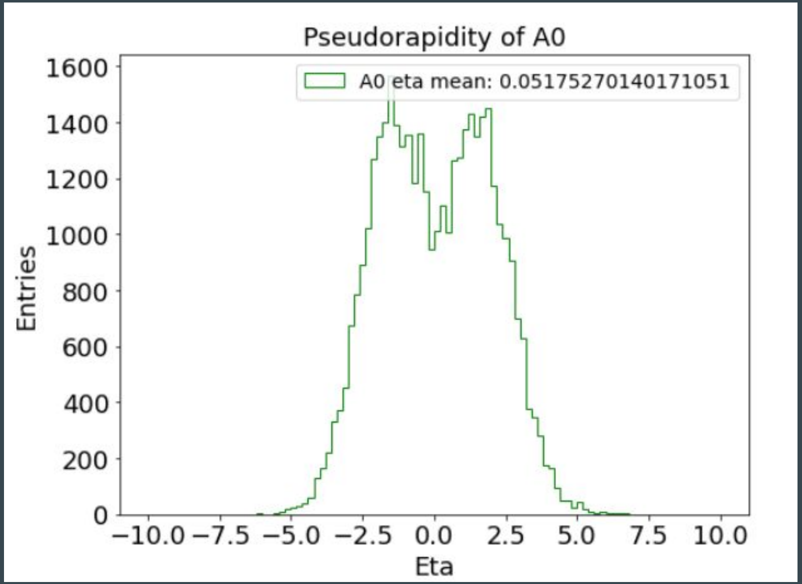
Kinematic Plots (A0 400GeV)



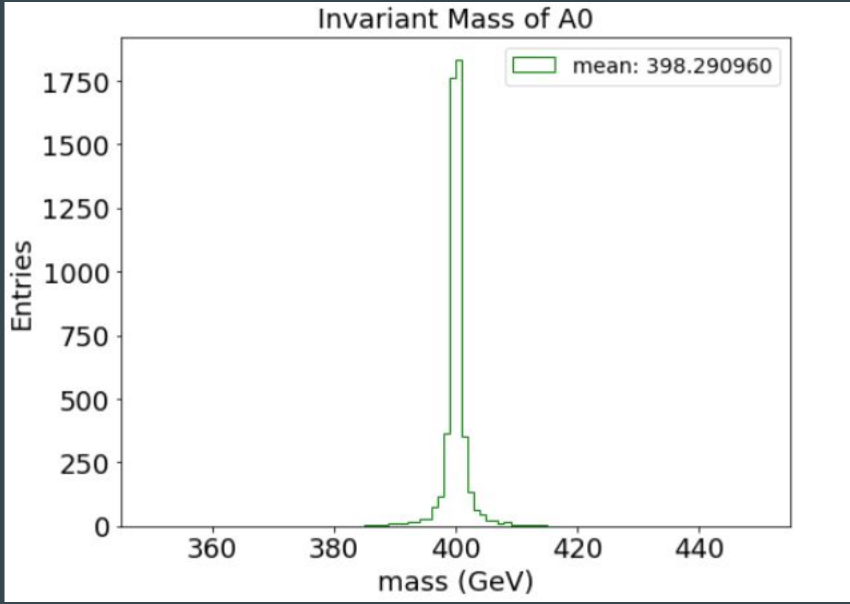


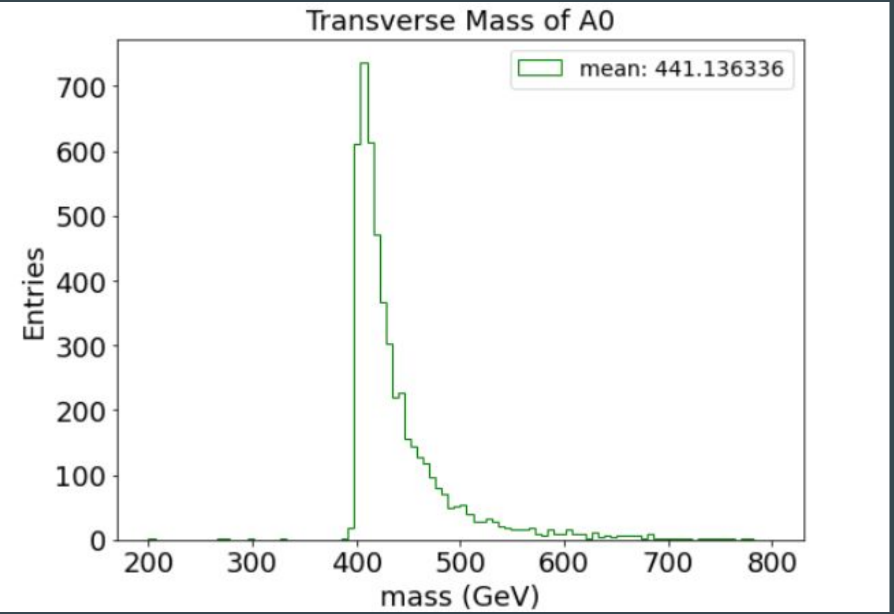
Kinematic Plots (A0 400GeV)





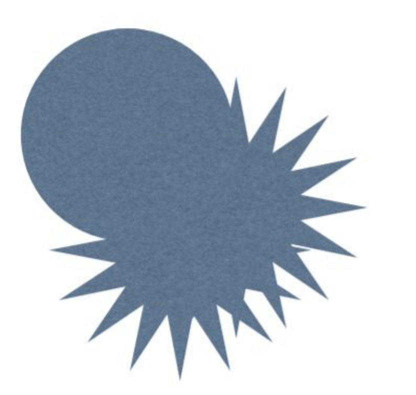
Kinematic Plots (A0 400GeV)

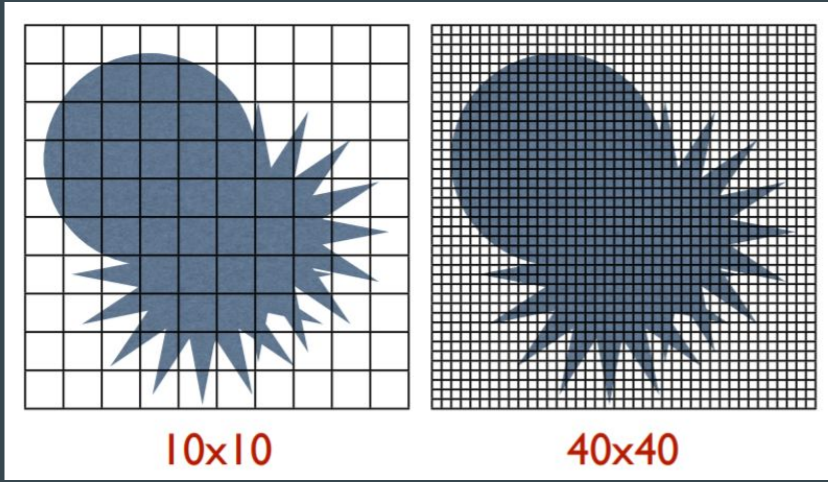




Monte Carlo

- analysis: random sampling -> simulate real world
- variable is random (AKA stochastic)
- PDF of a single stochastic variable
    - defined on an interval [a, b]
    - nonnegative on that interval
    - normalized (integral of f(x) from a to b = 1)

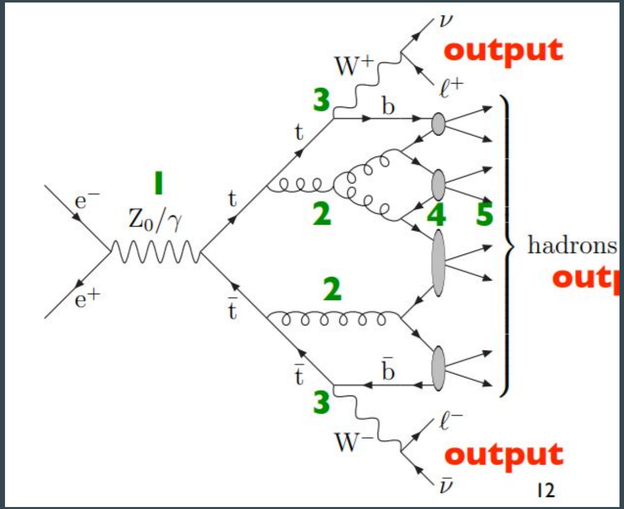




Area = (Number of hits)/(Total squares) * (Total Area)
https://upload.wikimedia.org/wikipedia/commons/8/84/

Monte Carlo

- Central Limit Theorem (CLT) obtains an estimate of an expected value & an estimate of the uncertainty in the estimate.
- MC event generator process: Hard process -> Parton-shower phase -> Hard particles decay before hadronizing -> Hadronization -> Unstable hadrons decay



Decay Width Calculation (new)

Total width for *A* (under the aforementioned assumptions) is sum of A→ t cbar +tbar c + t tbar partial decay widths. If $m_A > m_H + m_Z$ the partial decay width of A→ Z H also needs to added. The following function automatically takes care of these decays once H and A masses are chosen.

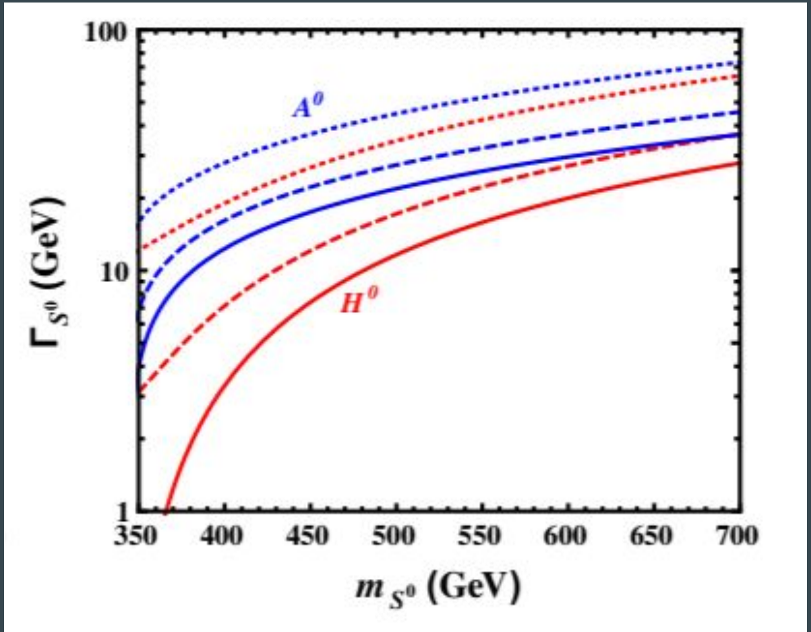
```
In[413]:= ΓtotA[rtt_, rtu_, rtc_, KAZH_, KAZh_, MA_, MH_] := If[MA > mt + mc, 2 ΓAtc[rtc, MA, 3], 0] + If[MA > mt + mu, 2 ΓAtu[rtu, MA, 3], 0] +
    If[MA > 2 mt, ΓAffbar[rtt, MA, mt, 3], 0] + If[MH > 0, If[MA > MH + mZ, ΓAZH[KAZH, MA, MH], 0], 0] + If[MH > 0, If[MA > mh + mZ, ΓAZh[KAZh, MA, MH], 0], 0];

In[452]:= ΓtotA[1, 0, 0.1, 0.37037, 0.37037, 700, 0]

Out[452]= 36.7542
```

Total decay width for *H*

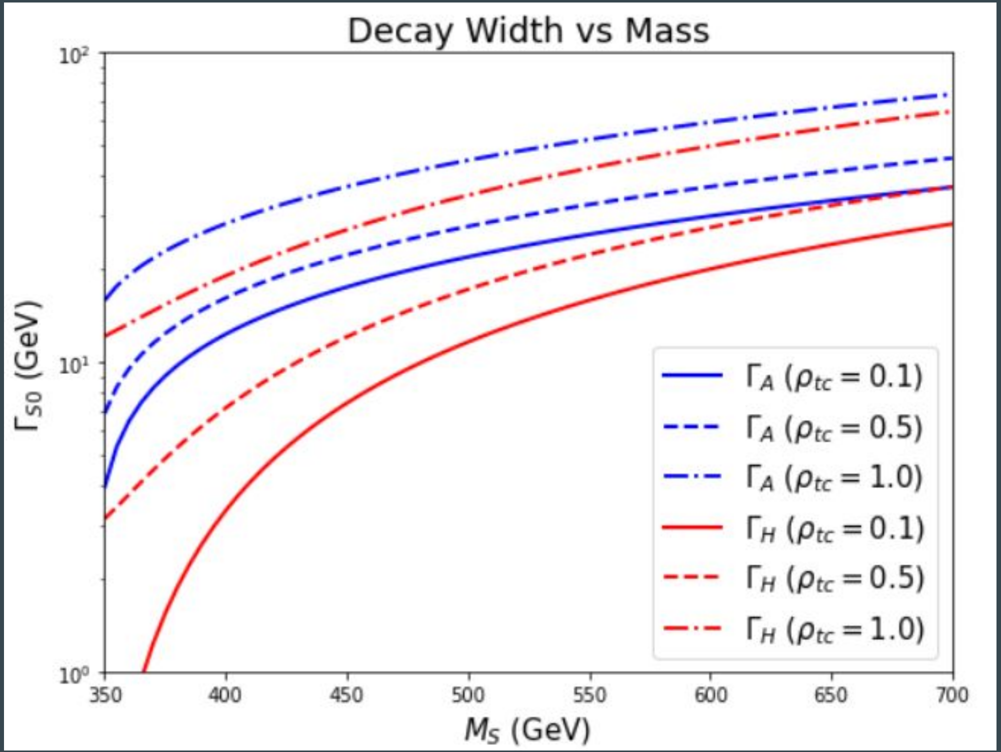
```
In[467]:= ΓtotH[rtt_, rtu_, rtc_, KHAZ_, lHhh_, MA_, MH_] := If[MH > mt + mc, 2 ΓHtc[rtc, MH, 3], 0] + If[MH > mt + mu, 2 ΓHtu[rtu, MH, 3], 0] +
    If[MH > 2 mt, ΓHffbar[rtt, MH, mt, 3], 0] + If[MH > 0, If[MH > MA + mZ, ΓHZA[KHAZ, MH, MA], 0], 0] + If[MH > 2 mh, ΓHhh[lHhh, MH], 0];

In[500]:= ΓtotH[1, 0, 0.1, 0.370372, 1, 700, 700]

Out[500]= 27.9671
```

Decay Width

Paper:



My Result:



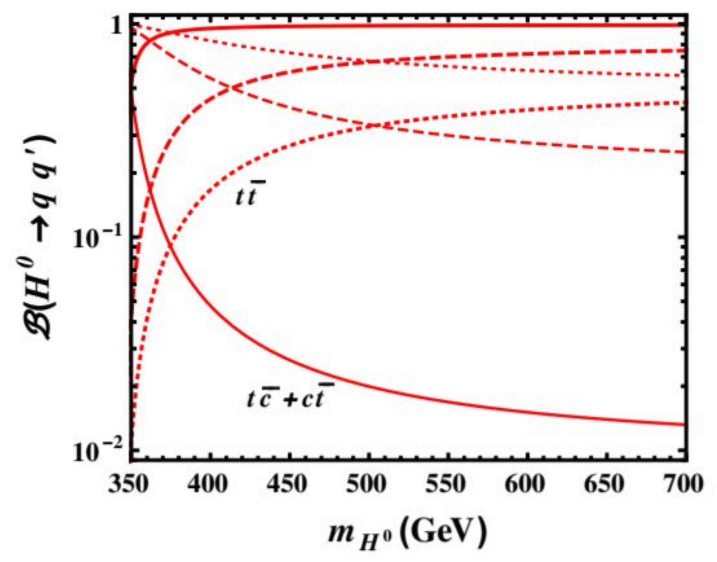
Branching Ratio

4.3. **Branching Ratio.** An unstable particle decays in general in several different decay chains, involving different final states. For each decay chain a **branching ratio** is defined as the probability that the particle decays in that chain. If Γ is the **total width** of the particle and Γ_i is the **partial width** in the decay chain i, we have:

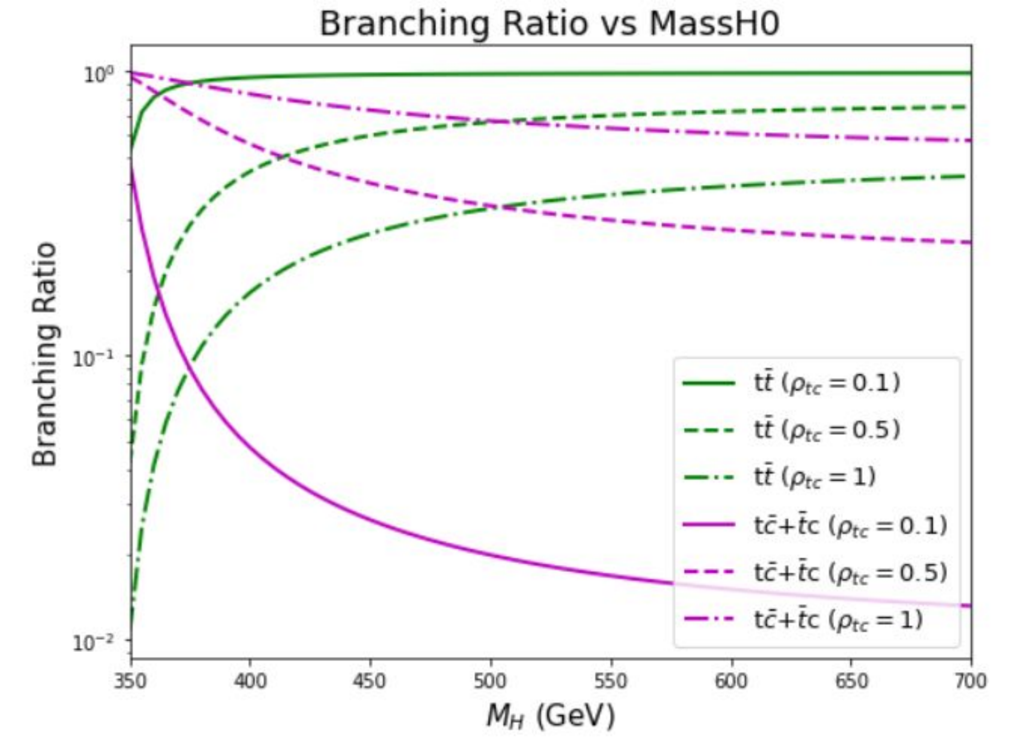
$$BR(i) = \frac{\Gamma_i}{\Gamma} \tag{82}$$

Branching Ratio (H0)

Paper:

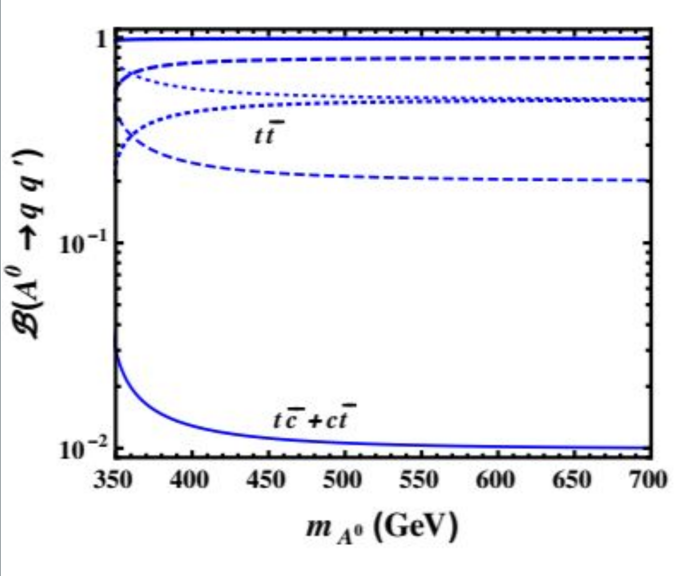


My Result:

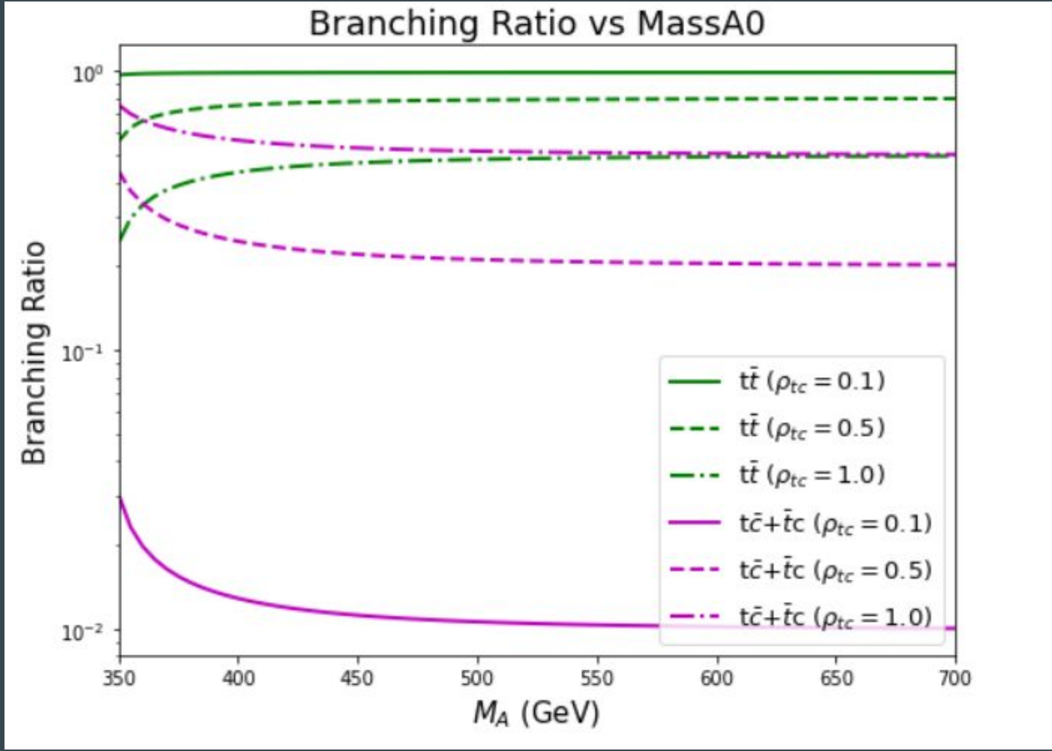


Branching Ratio (A0)

Paper:



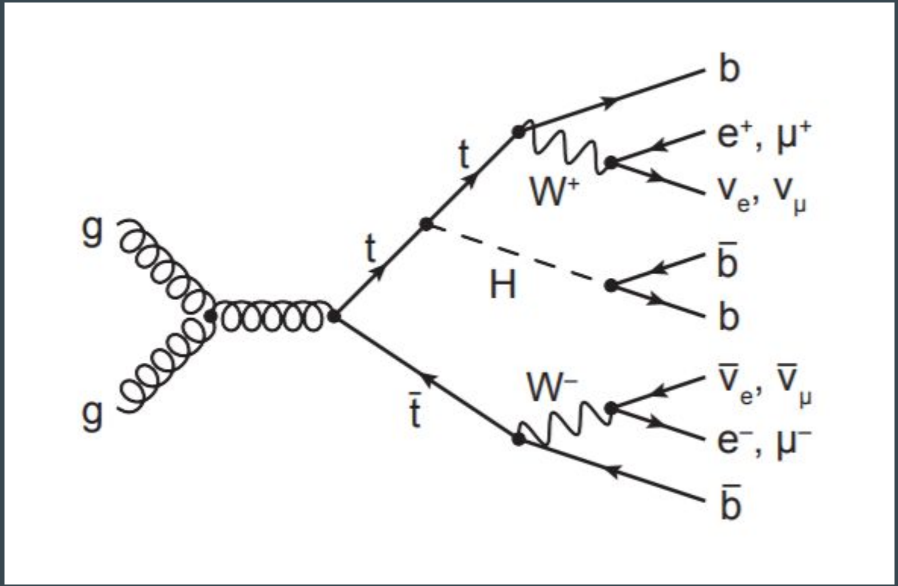
My Result:



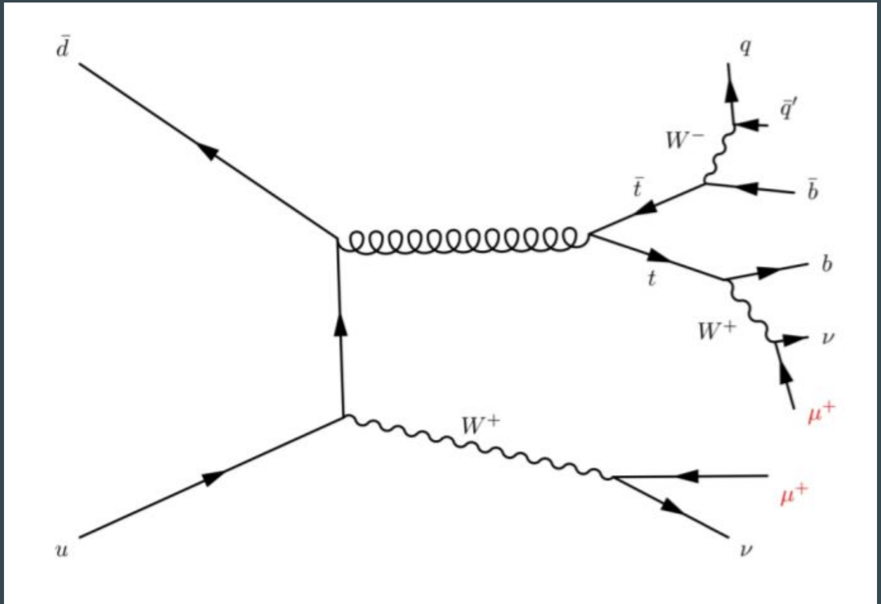
Same Sign Dilepton

Backgrounds	Cross section (fb)
$t\bar{t}Z$	0.04
$t\bar{t}W$	0.72
tZ+jets	0.001
$3t+j$	0.0002
$3t+W$	0.0004
$t\bar{t}h$	0.024
$4t$	0.04
Q-flip	0.04

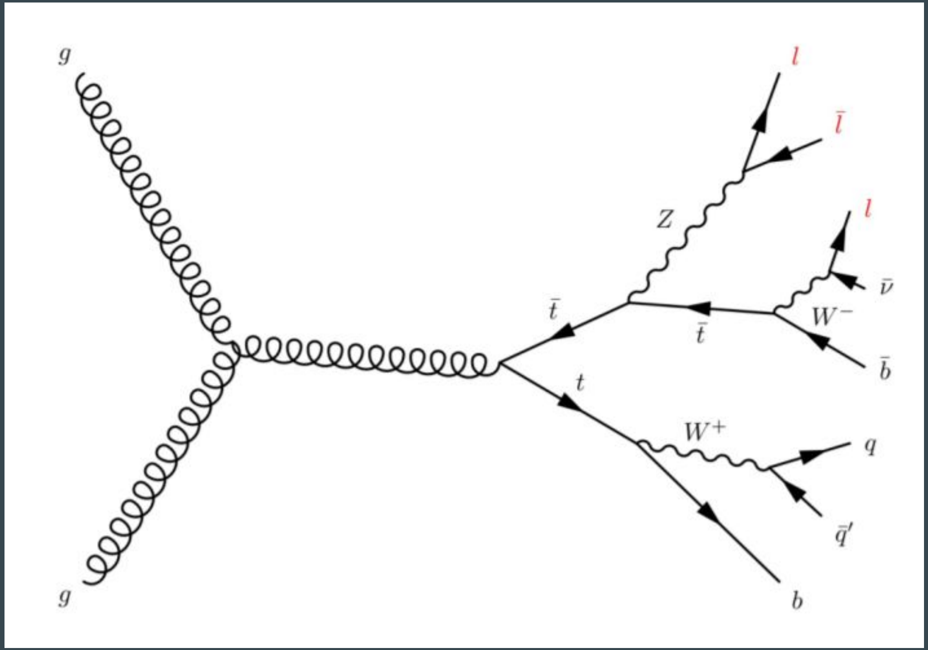
Paper (2 leptons):



Background:

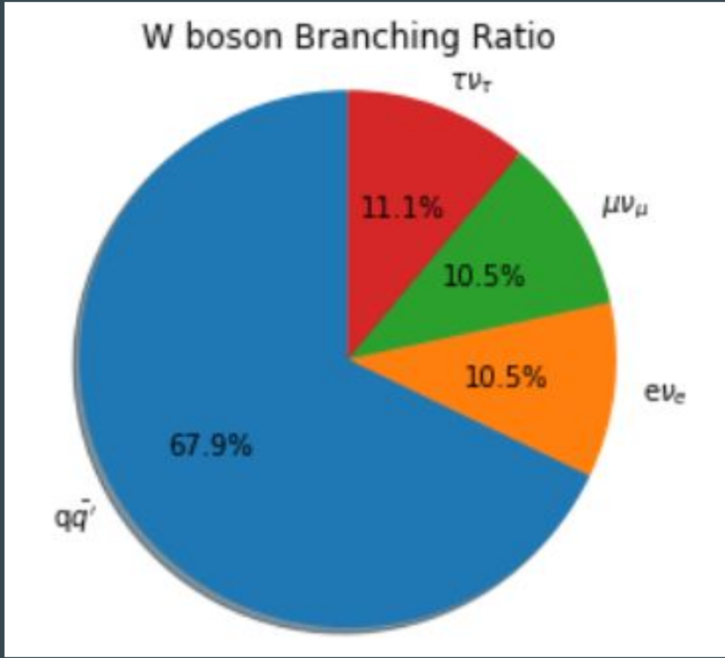


Trilepton



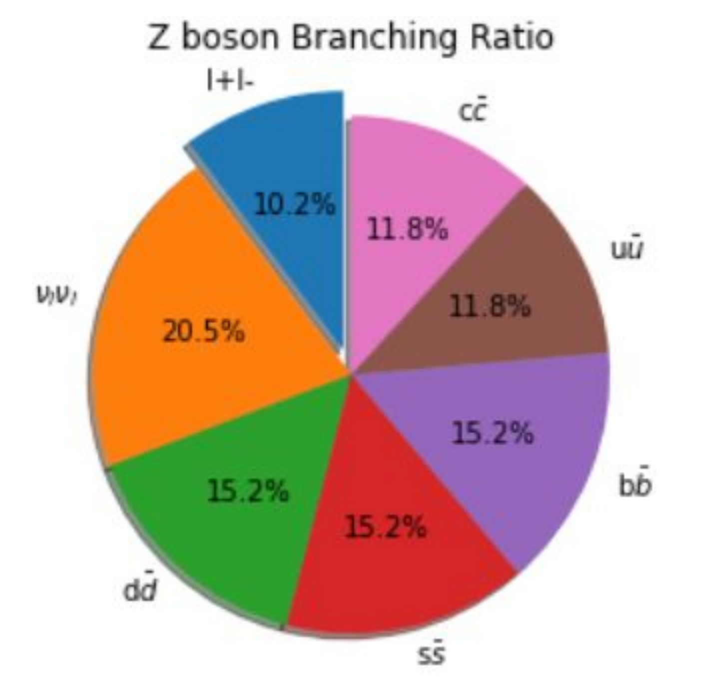
Pie charts: Branching Ratio for W boson

Leptons		Quarks					
$e^+ \nu_e$	1	$u\bar{d}$	$3\,\lvert V_{ud}\rvert^2$	$u\bar{s}$	$3\,\lvert V_{us}\rvert^2$	$u\bar{b}$	$3\,\lvert V_{ub}\rvert^2$
$\mu^+ \nu_\mu$	1	$c\bar{d}$	$3\,\lvert V_{cd}\rvert^2$	$c\bar{s}$	$3\,\lvert V_{cs}\rvert^2$	$c\bar{b}$	$3\,\lvert V_{cb}\rvert^2$
$\tau^+ \nu_\tau$	1	Decay to t is not allowed by energy conservation					



Pie charts: Branching Ratio for Z boson

$$\Gamma(Z \to e^+e^-) = \Gamma(Z \to \mu^+\mu^-) = \Gamma(Z \to \tau^+\tau^-) = 84 \text{ MeV}$$
$$\Gamma(Z \to \nu_e\bar{\nu}_e) = \Gamma(Z \to \nu_\mu\bar{\nu}_\mu) = \Gamma(Z \to \nu_\tau\bar{\nu}_\tau) = 166 \text{ MeV}$$
$$\Gamma(Z \to \mathrm{d\bar{d}}) = \Gamma(Z \to \mathrm{s\bar{s}}) = \Gamma(Z \to \mathrm{b\bar{b}}) = 354 \text{ MeV}$$
$$\Gamma(Z \to \mathrm{u\bar{u}}) = \Gamma(Z \to \mathrm{c\bar{c}}) = 276 \text{ MeV}$$



Analysis Flow Chart

Generate Sample Data

study signal and background | pre-selection cut | debug

↓

Study high level features and low level features

↓

Develop a ML Classifier (tA, ttZ, ttW, tZ+j)

↓

Interpret Model (setting upper limit)

Signal: ug -> tA0 -> ttt~

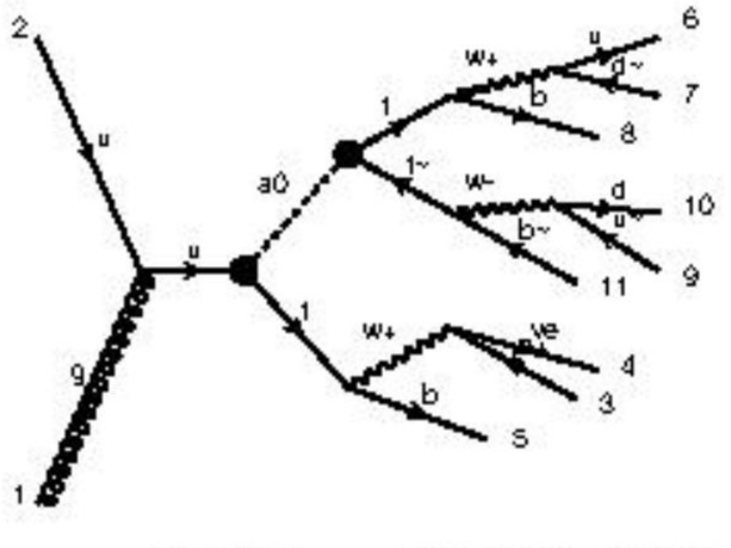
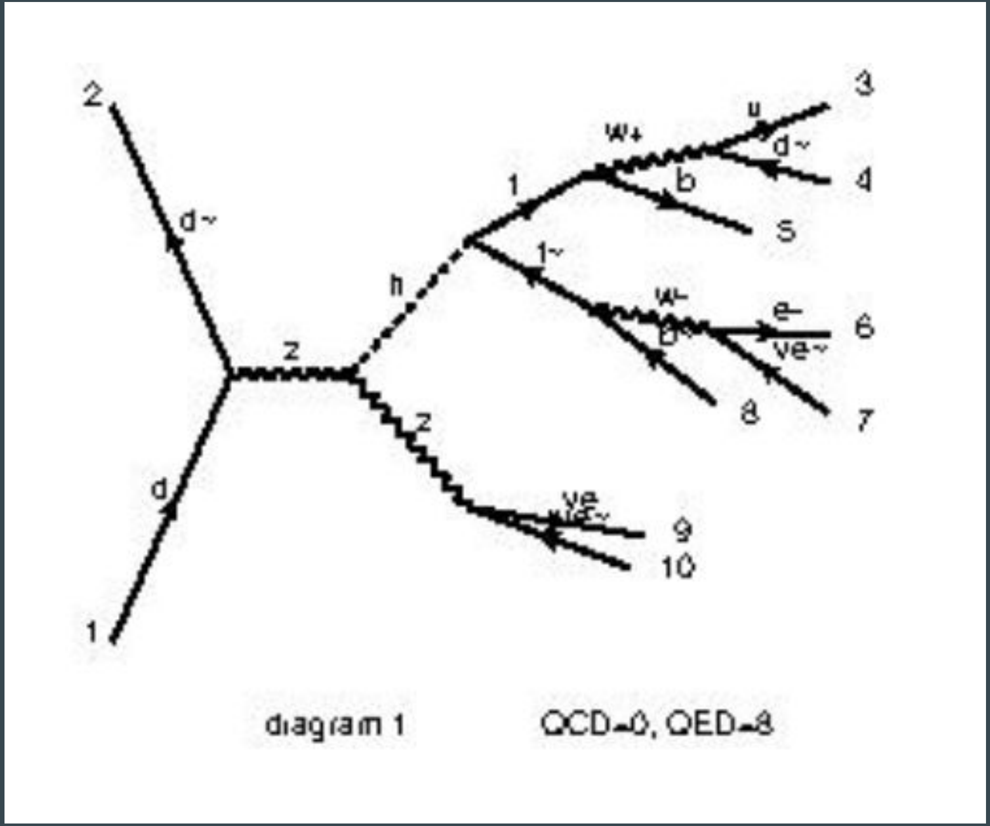
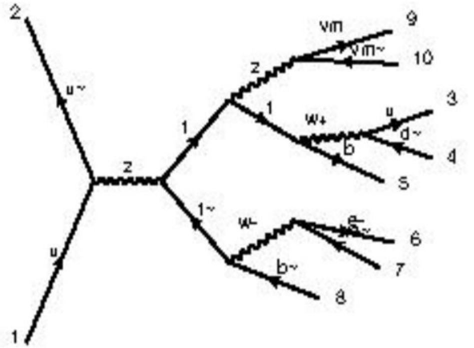


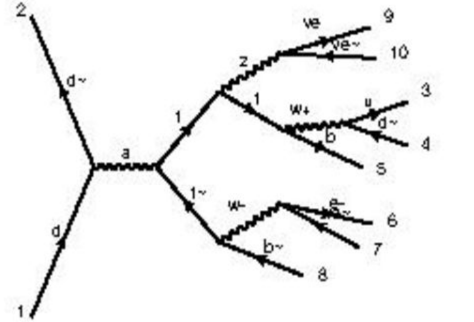
diagram 1 QCD=1, QED=6, QNP=2

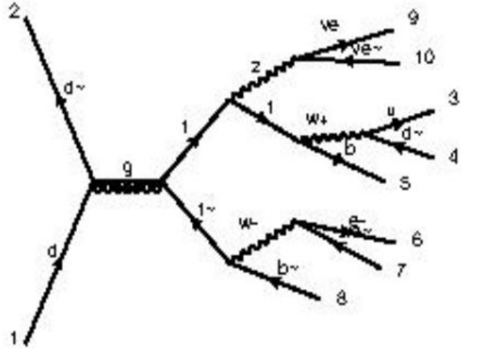
	mass	PID	Particle	mother1	mother2	e	px	py	pz	status
0	0.000000	21.0	g	0.0	0.0	409.493776	0.000000	0.000000	409.493776	-1.0
1	0.000000	4.0	q	0.0	0.0	348.673361	-0.000000	-0.000000	-348.673361	-1.0
2	172.601919	6.0	t	1.0	2.0	314.258861	17.056130	33.950287	259.853181	2.0
3	83.387344	24.0	W+	3.0	3.0	213.339537	42.379114	-33.010757	188.877234	2.0
4	394.964533	5000001.0	A0	1.0	2.0	443.908276	-17.056130	-33.950287	-199.032766	2.0
5	183.156791	6.0	t	5.0	5.0	263.951714	32.155043	-42.307372	-182.483525	2.0
6	81.276178	24.0	W+	6.0	6.0	146.065377	-10.469528	-88.189263	-82.718318	2.0
7	172.101442	-6.0	t~	5.0	5.0	179.956562	-49.211173	8.357086	-16.549241	2.0
8	73.757832	-24.0	W-	8.0	8.0	121.053095	-93.997281	-9.740954	16.830302	2.0
9	0.000000	-11.0	e+	4.0	4.0	87.833333	11.574664	26.702609	82.871540	1.0
10	0.000000	12.0	ve	4.0	4.0	125.506204	30.804450	-59.713366	106.005694	1.0
11	4.700000	5.0	b	3.0	3.0	100.919324	-25.322983	66.961044	70.975947	1.0
12	0.000000	2.0	u	7.0	7.0	91.069074	19.159427	-42.051379	-78.474035	1.0
13	0.000000	-1.0	d	7.0	7.0	54.996303	-29.628955	-46.137885	-4.244283	1.0
14	4.700000	5.0	b	6.0	6.0	117.886337	42.624571	45.881891	-99.765207	1.0
15	0.000000	-4.0	c	9.0	9.0	60.996753	-54.243768	25.630317	-11.013829	1.0
16	0.000000	3.0	s	9.0	9.0	60.056342	-39.753513	-35.371270	27.844131	1.0
17	4.700000	-5.0	b~	8.0	8.0	58.903466	44.786108	18.098040	-33.379543	1.0

SM Background: tt~Z









SM Background: tt~W

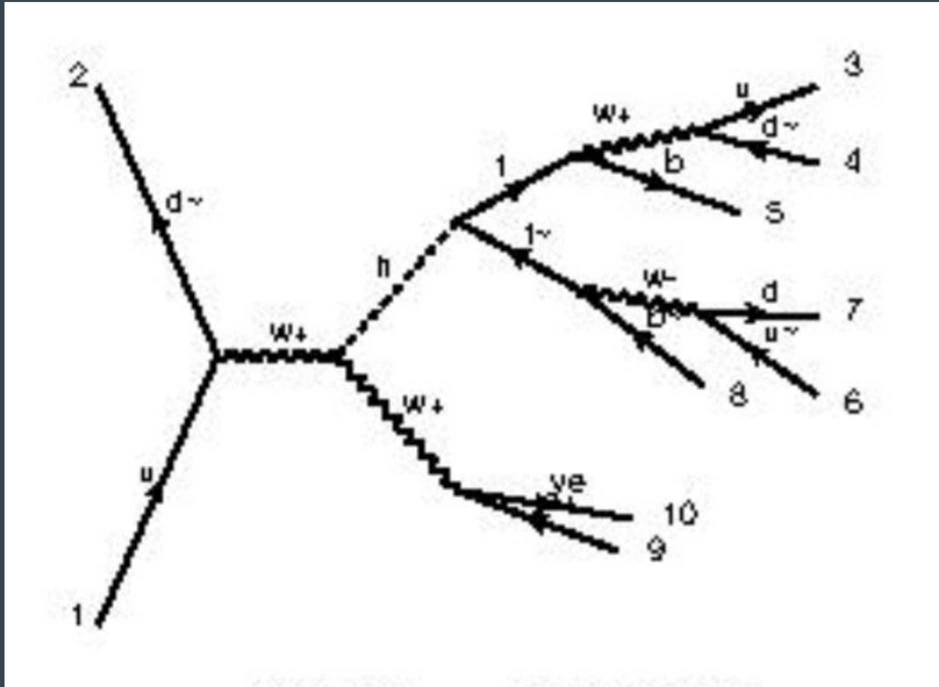
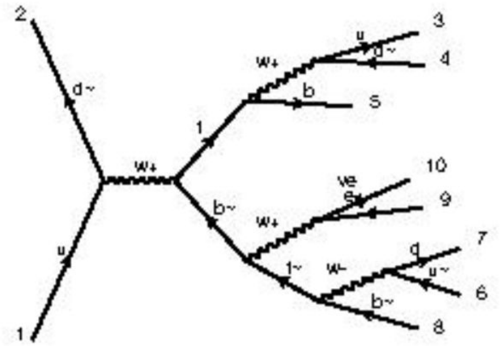
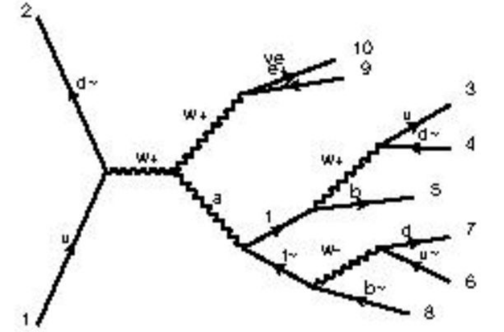
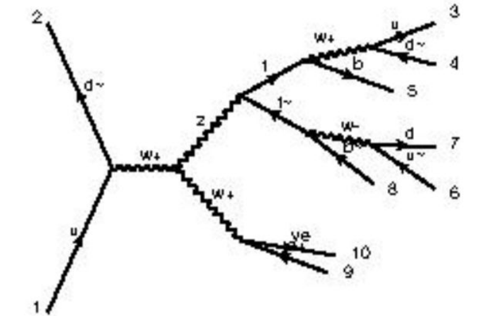


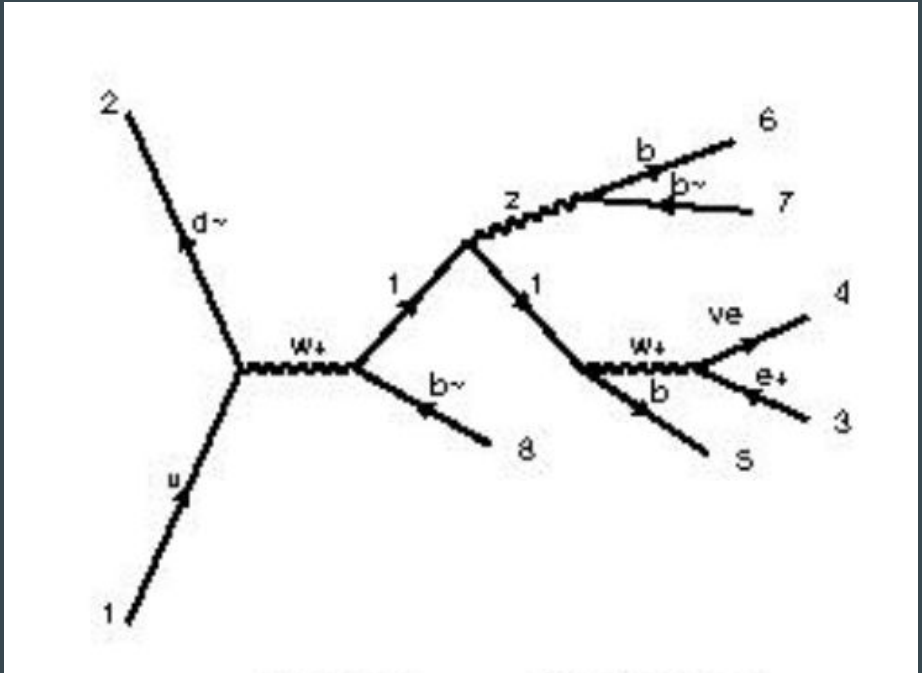
diagram 2 QCD=0, QED=8







SM Background: tZ + j



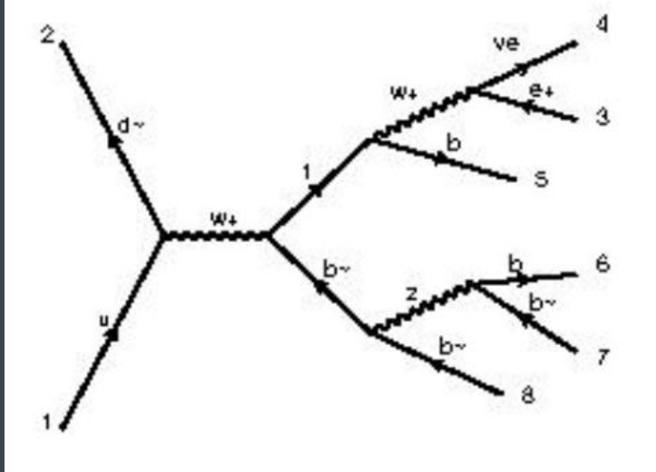


diagram 3 QCD=0, QED=6

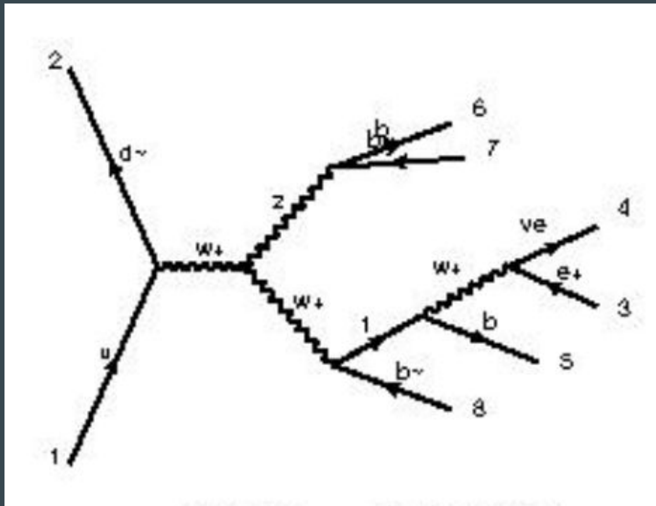
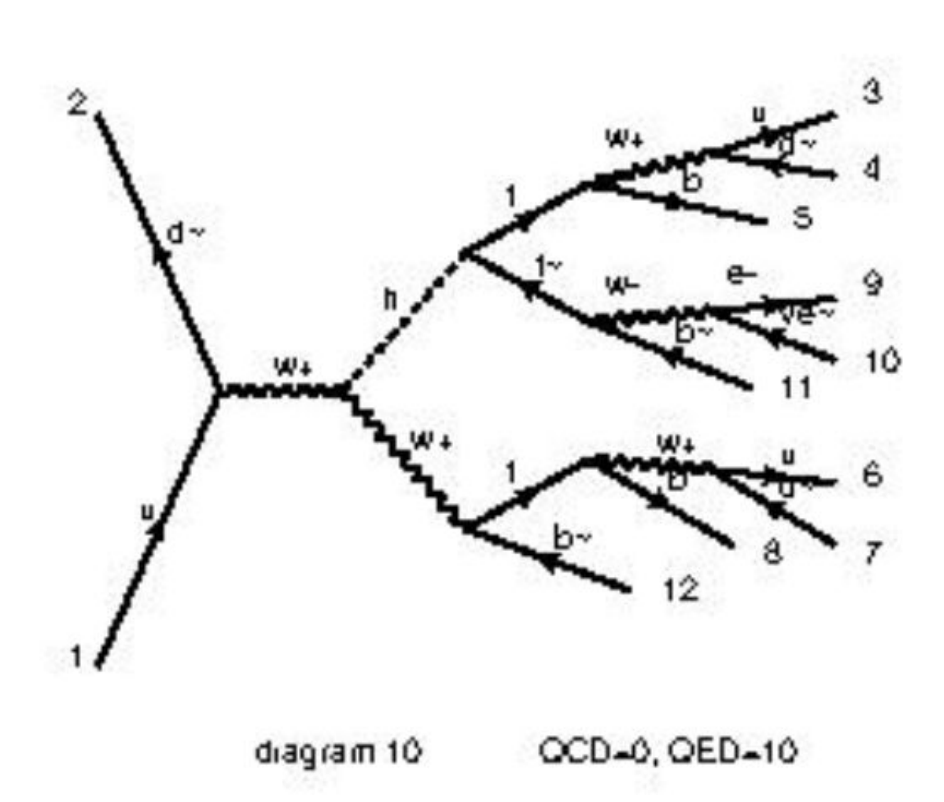
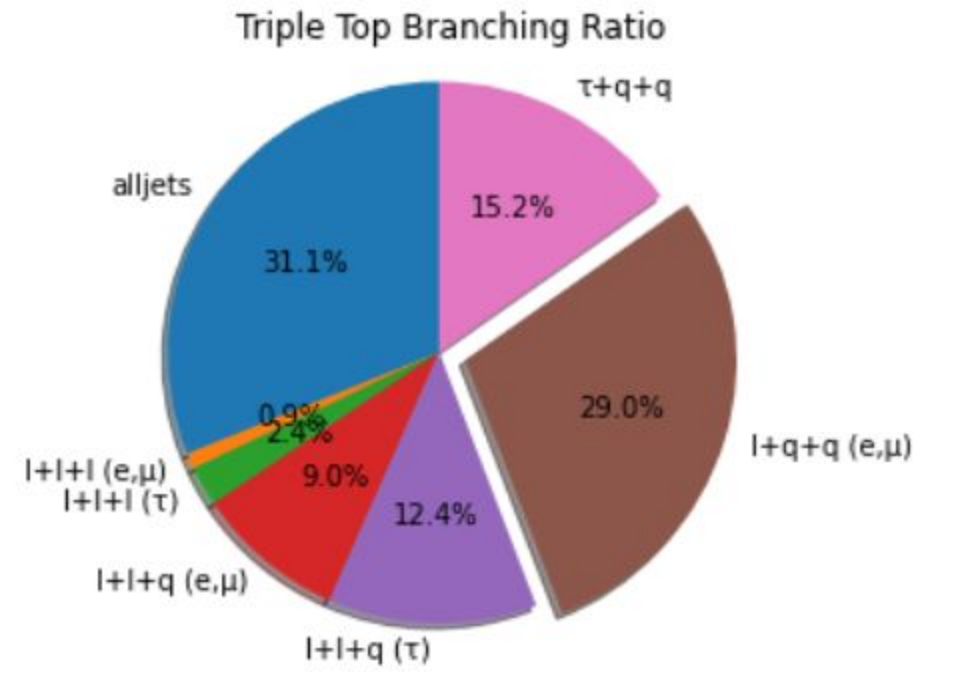


diagram 2 QCD=0, QED=6

SM Background: 3t + j

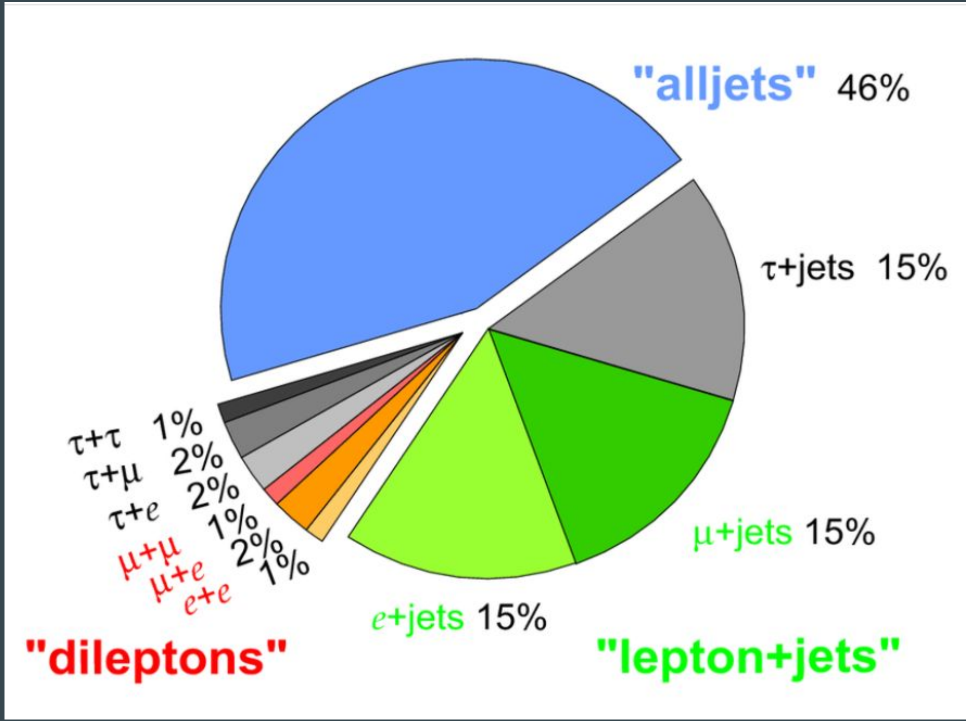


Pie charts: Branching Ratio for Triple Top

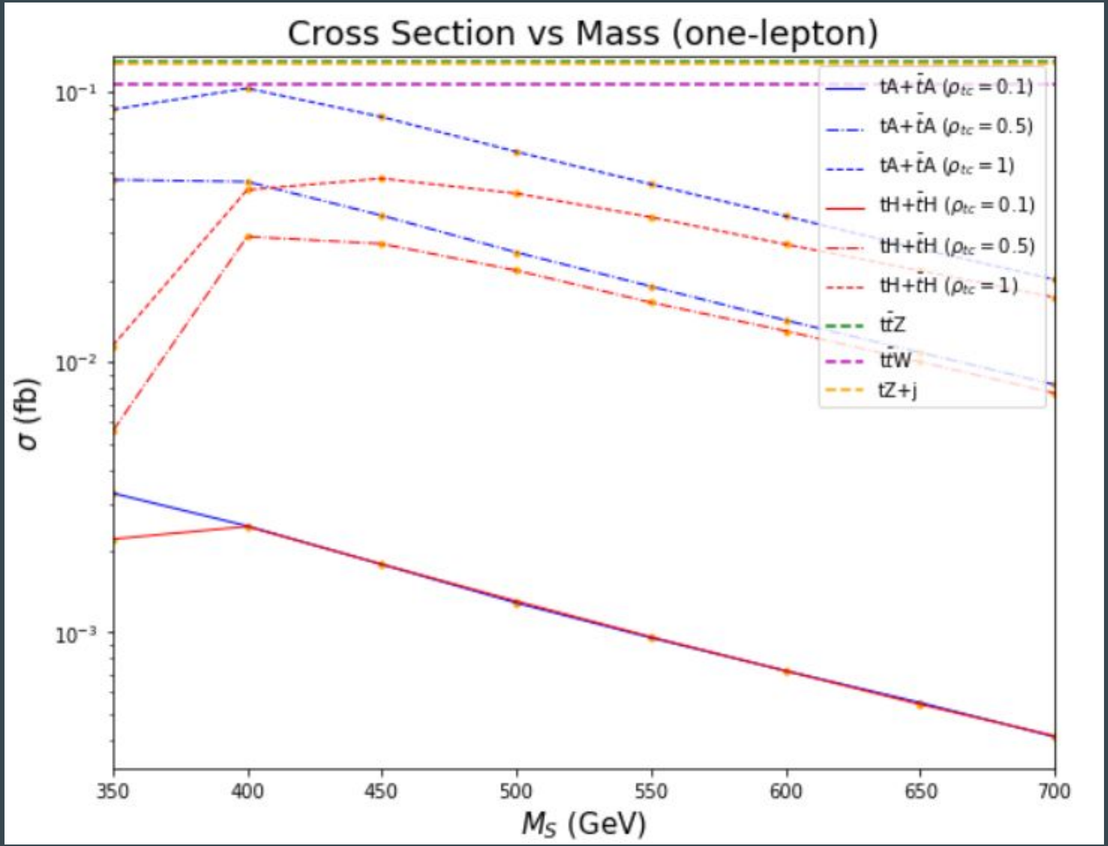


	Combinations	Probability
0	$q+q+\bar{q}$	0.313324
1	e+e+e	0.001171
2	μ+μ+μ	0.001171
3	e+μ+μ	0.003513
4	e+e+μ	0.003513
5	τ+τ+τ	0.001364
6	τ+e+μ	0.007392
7	τ+e+e	0.003696
8	τ+μ+μ	0.003696
9	τ+τ+e	0.003889
10	τ+τ+μ	0.003889
11	e+e+q	0.022636
12	μ+μ+q	0.022636
13	e+μ+q	0.045272
14	τ+τ+q	0.025060
15	τ+e+q	0.050120
16	τ+μ+q	0.050120
17	e+q+q	0.145867
18	μ+q+q	0.145867
19	τ+q+q	0.153479

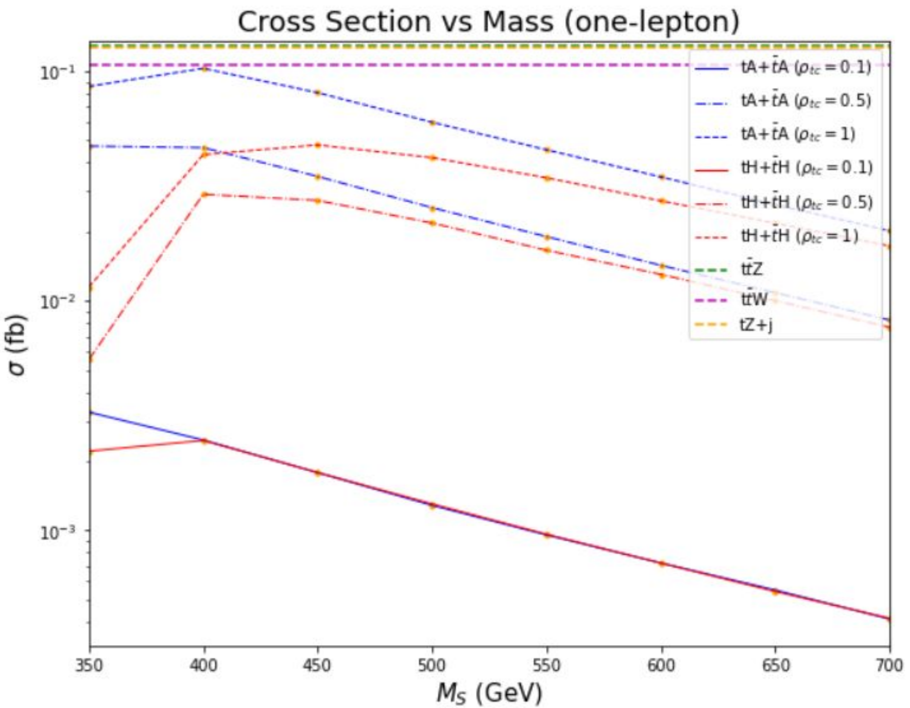
Top pair branching ratio pie chart



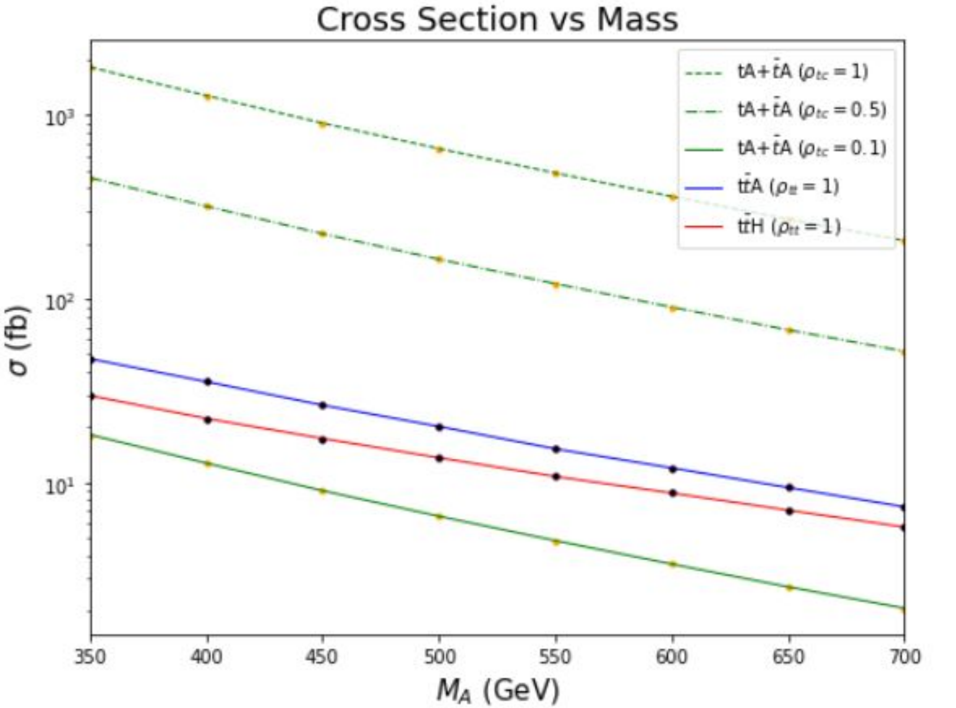
Cross Section vs Mass



Set the masses of A and H fixed to some values say both at 400 GeV. Take rho_tc = 0.5 (or rho_tu =0.2) and rho_tt = 0.5 for example. These are somewhat close to the upper limits for these couplings given current constraints. All couplings are assumed to be real

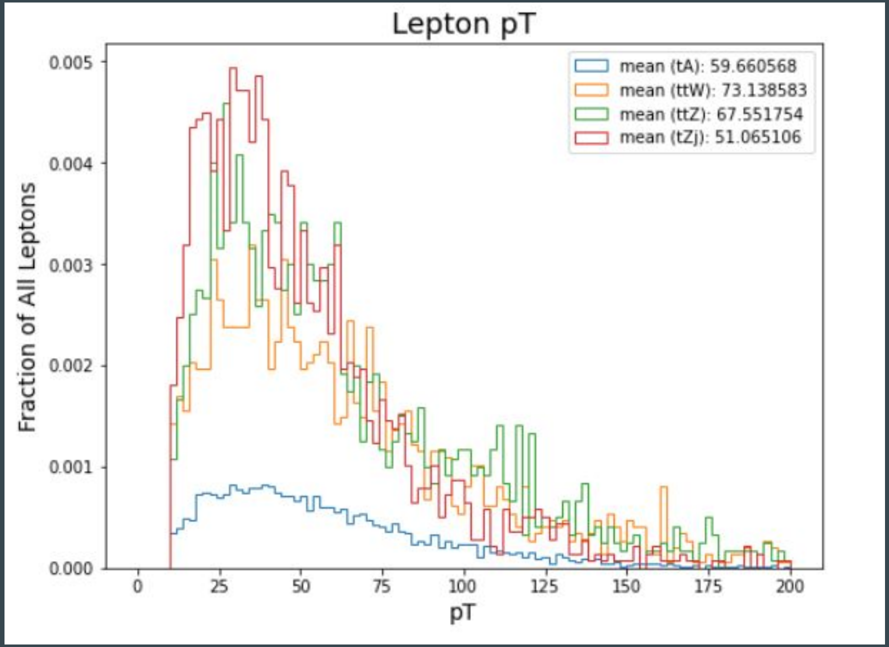


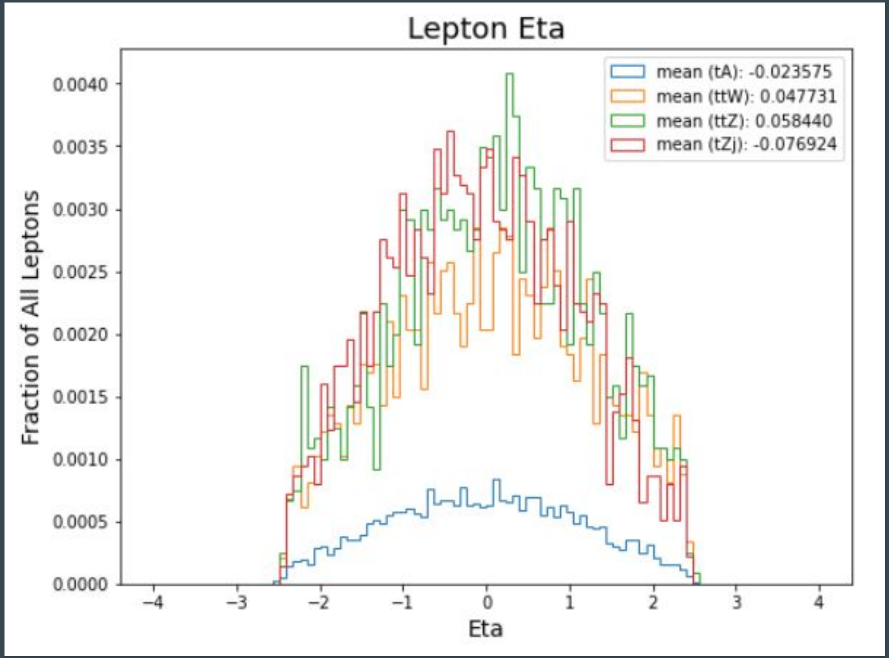
Cross Section vs Mass (one-lepton)
σ (fb)
M_S (GeV)
10^{-1}
10^{-2}
10^{-3}
350
400
450
500
550
600
650
700
tA+$\bar{t}$A ($\rho_{tc}=0.1$)
tA+$\bar{t}$A ($\rho_{tc}=0.5$)
tA+$\bar{t}$A ($\rho_{tc}=1$)
tH+$\bar{t}$H ($\rho_{tc}=0.1$)
tH+$\bar{t}$H ($\rho_{tc}=0.5$)
tH+$\bar{t}$H ($\rho_{tc}=1$)
t$\bar{t}$Z
t$\bar{t}$W
tZ+j



Cross Section vs Mass
σ (fb)
M_A (GeV)
10^{3}
10^{2}
10^{1}
350
400
450
500
550
600
650
700
tA+$\bar{t}$A ($\rho_{tc}=1$)
tA+$\bar{t}$A ($\rho_{tc}=0.5$)
tA+$\bar{t}$A ($\rho_{tc}=0.1$)
t$\bar{t}$A ($\rho_{tt}=1$)
t$\bar{t}$H ($\rho_{tt}=1$)

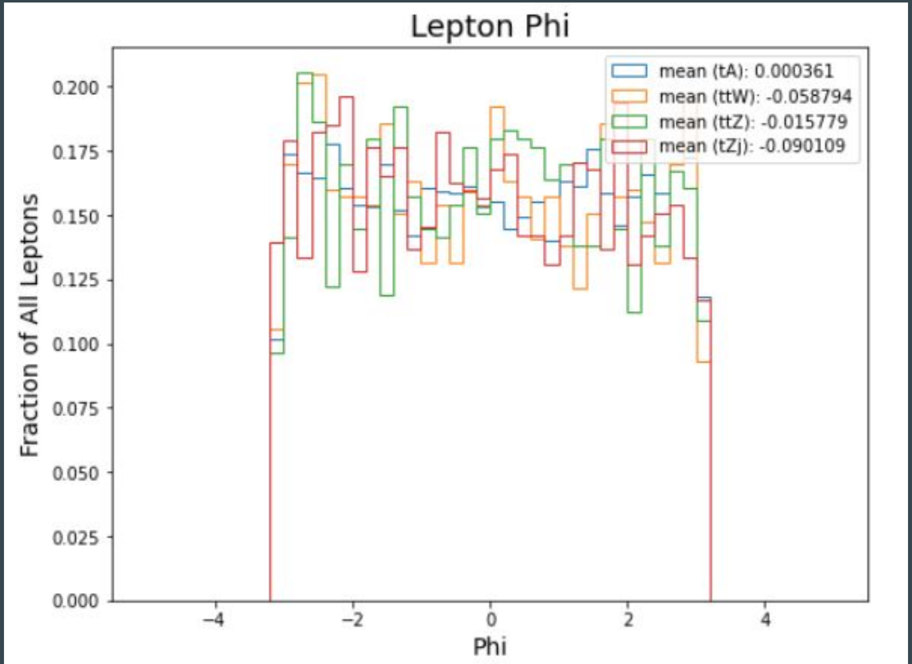
Kinematic Plot Comparison (lepton)



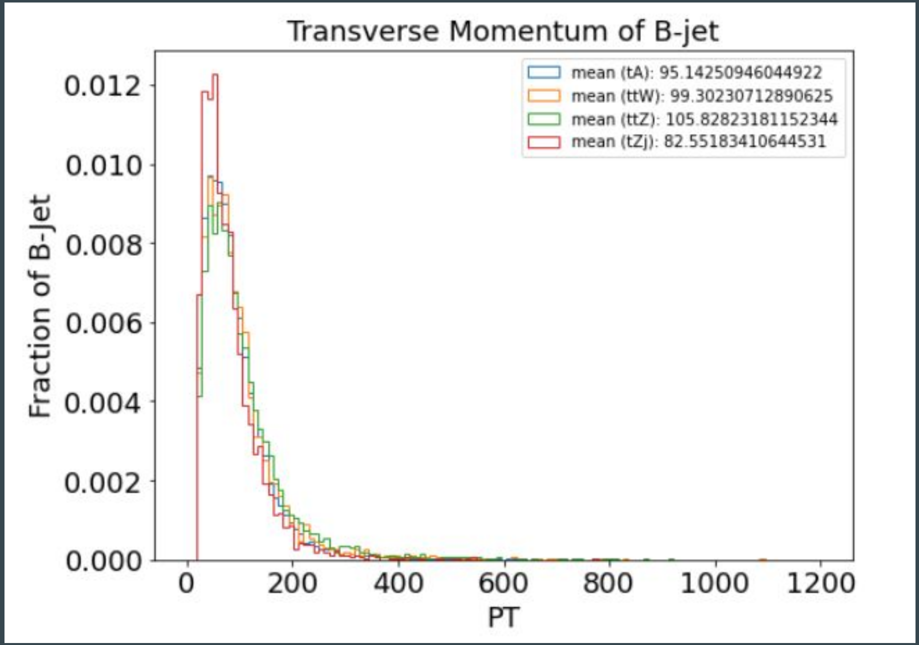


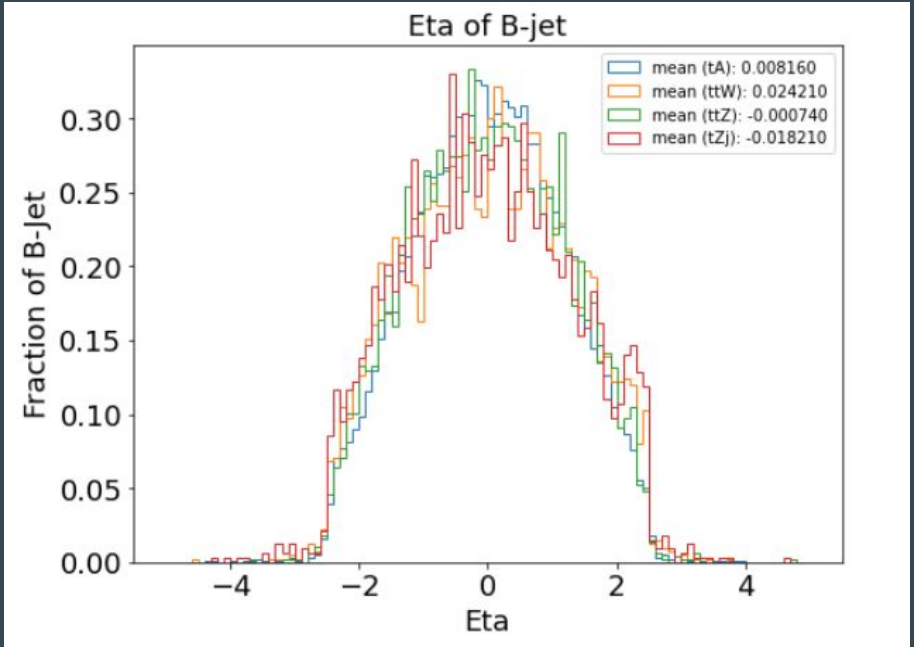
Normalize cross section

Kinematic Plot Comparison (lepton)

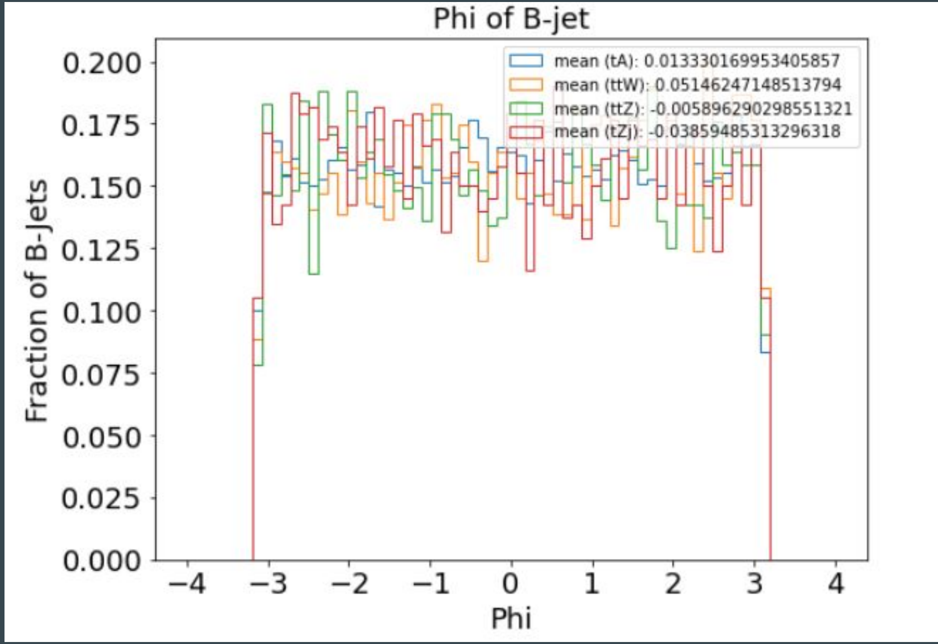


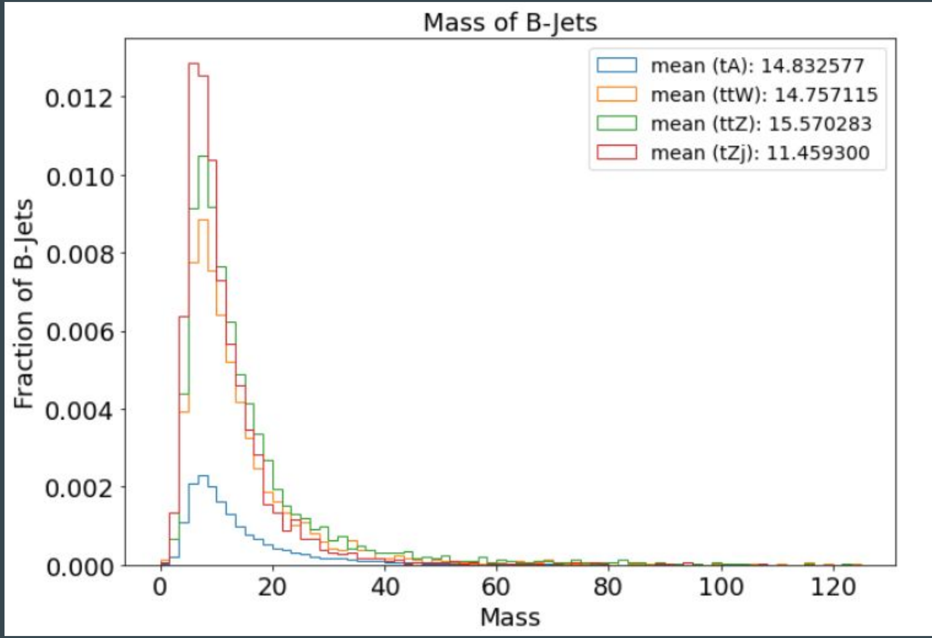
Kinematic Plot Comparison (b-jet)



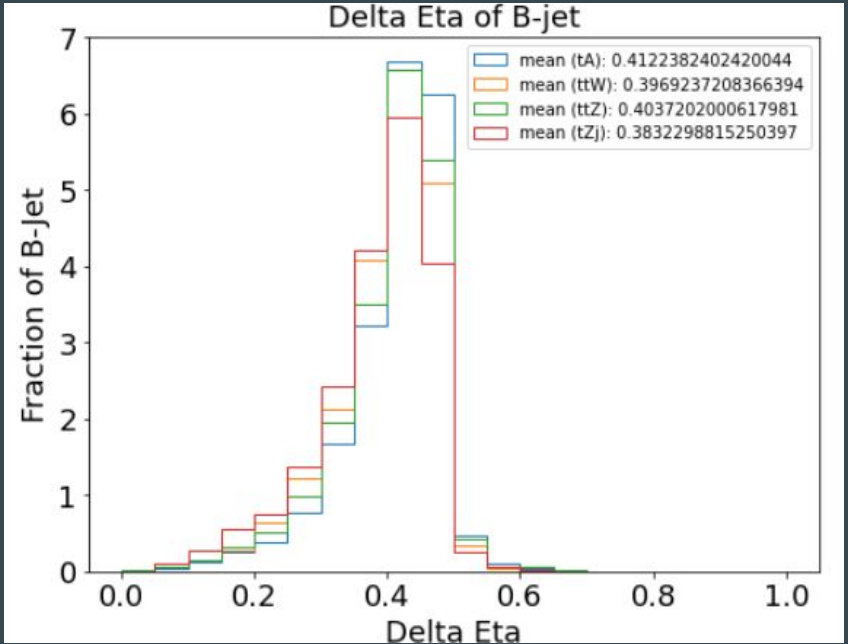


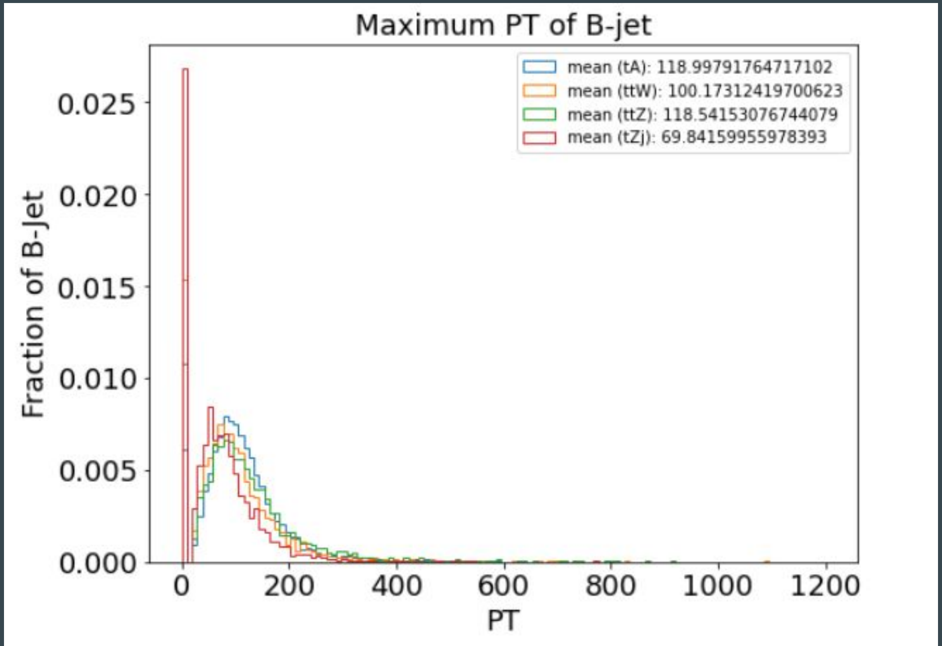
Kinematic Plot Comparison (b-jet)



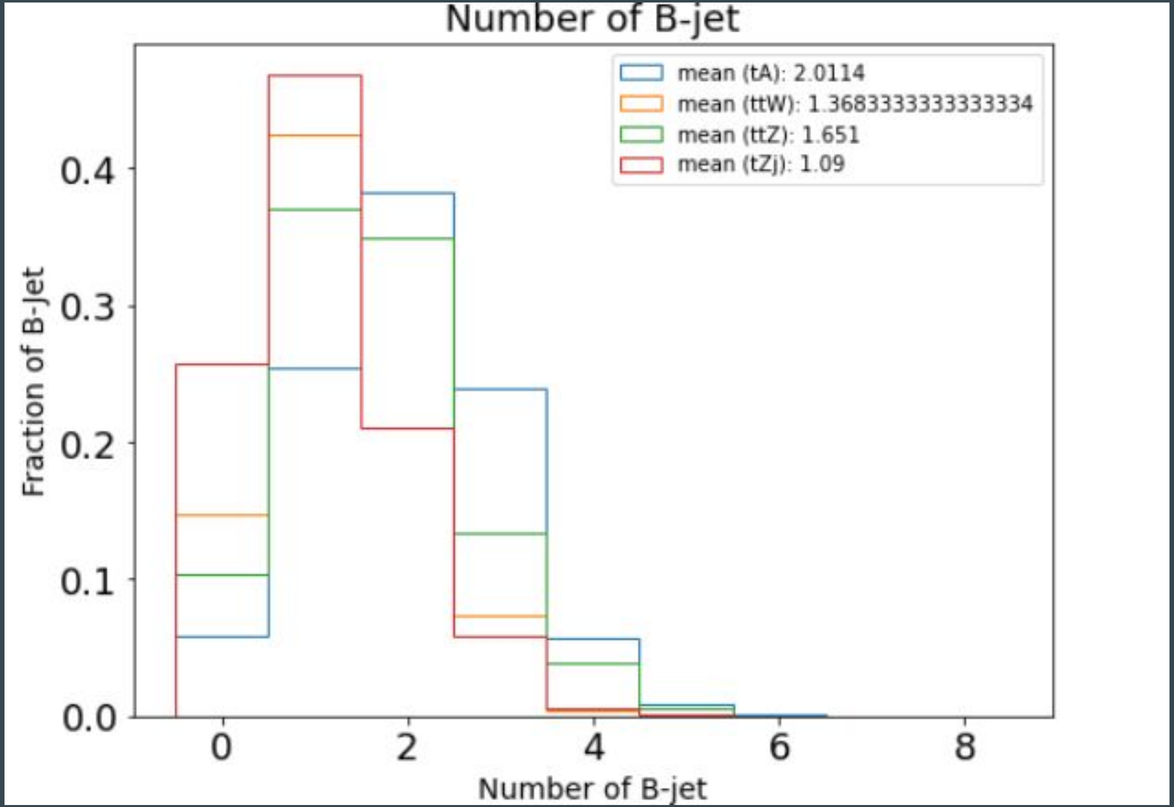


Kinematic Plot Comparison (b-jet)

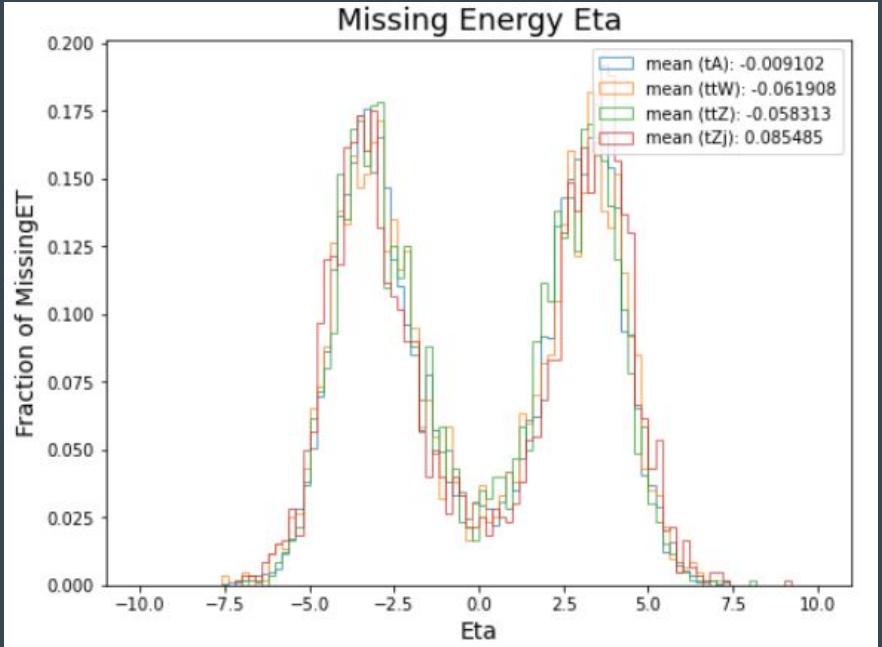


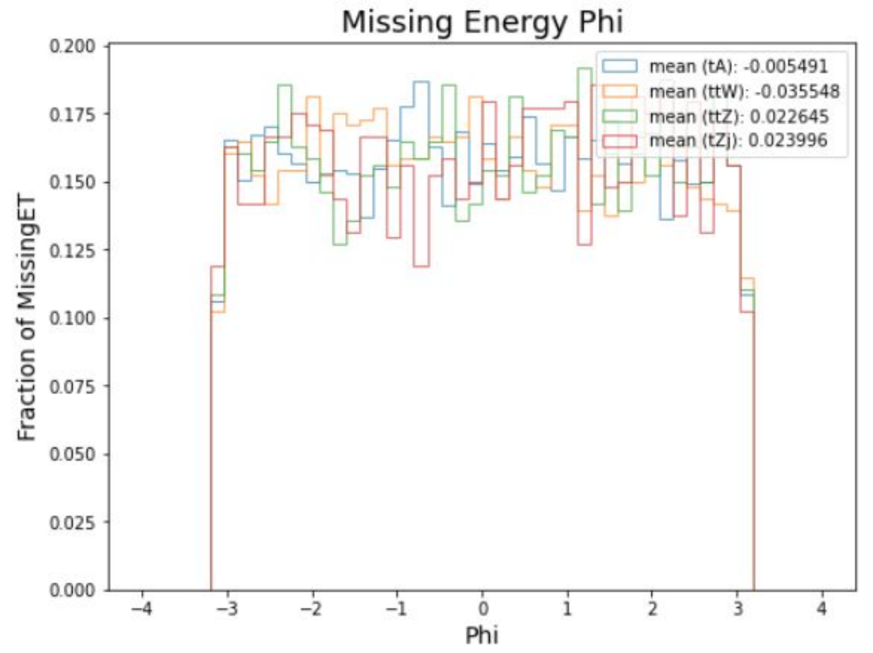


Kinematic Plot Comparison (b-jet)



Kinematic Plot Comparison (Missing Transverse Energy)





Overview

- Plots relating cross section, branching ratio, selection efficiency
- Discussion regards to the author's (Tanmoy) message and changes
- Problem encountered

Total Cross section

Paper:

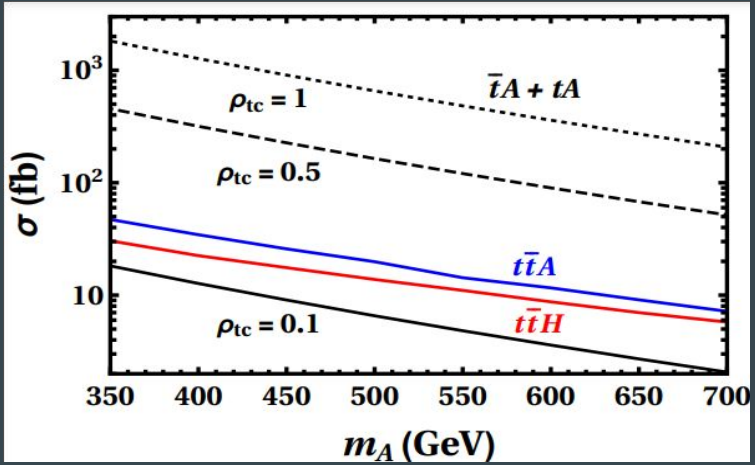
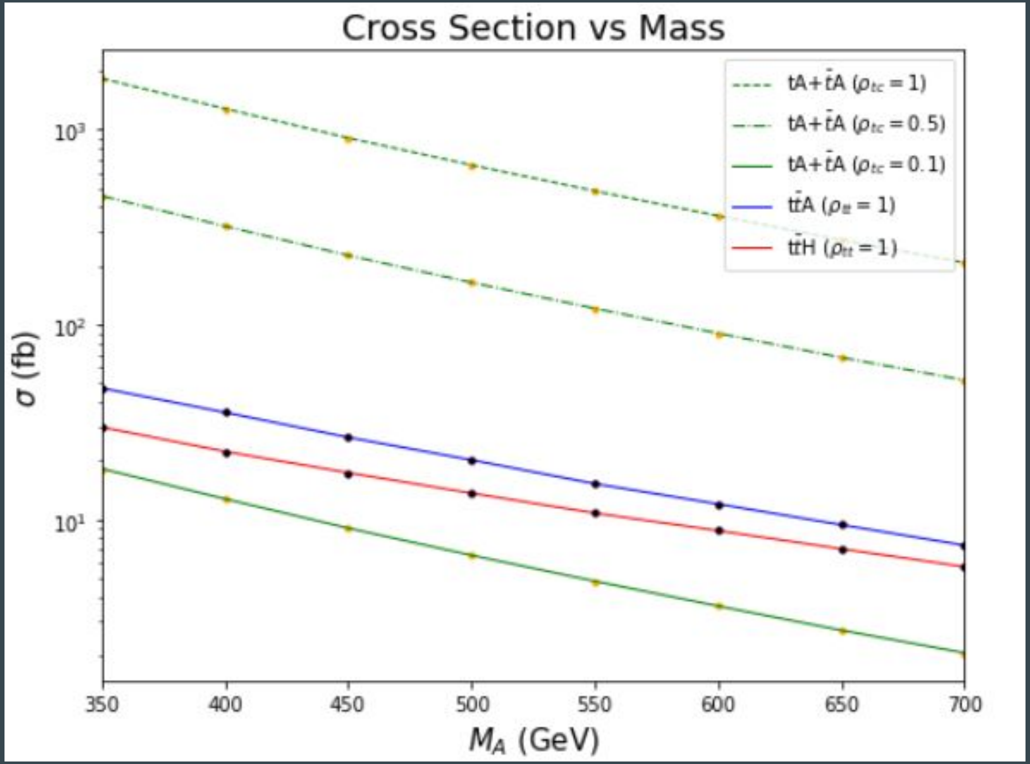
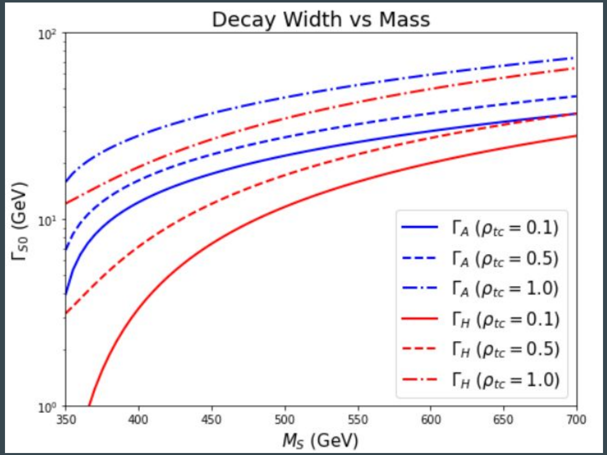


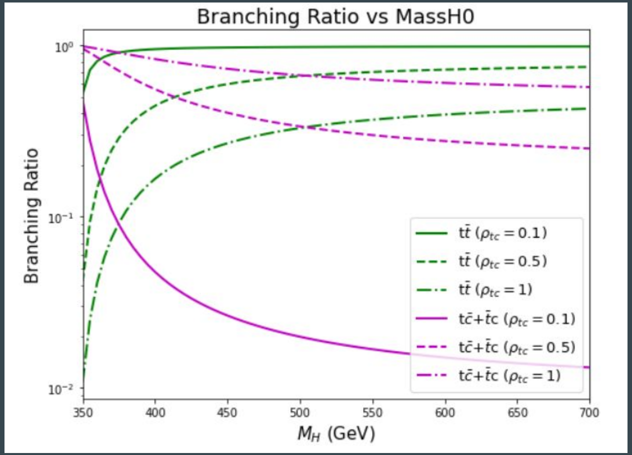
FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \to tS^0$, $\bar{t}S^0$ where $S^0 = H^0$, A^0, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \to t\bar{t}H^0$, $t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

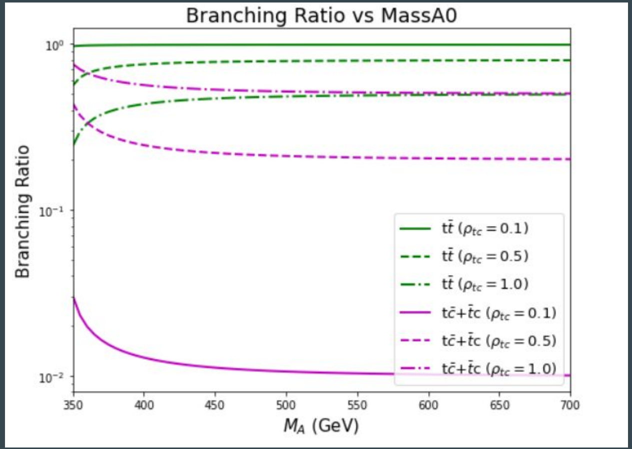
My Result:

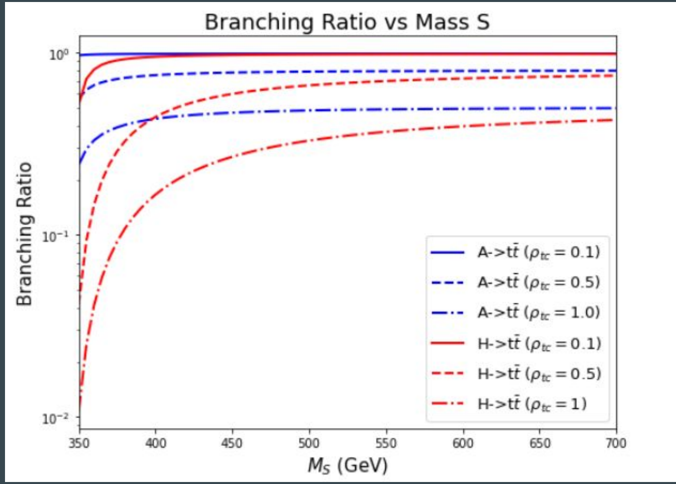


Decay Branching Ratio

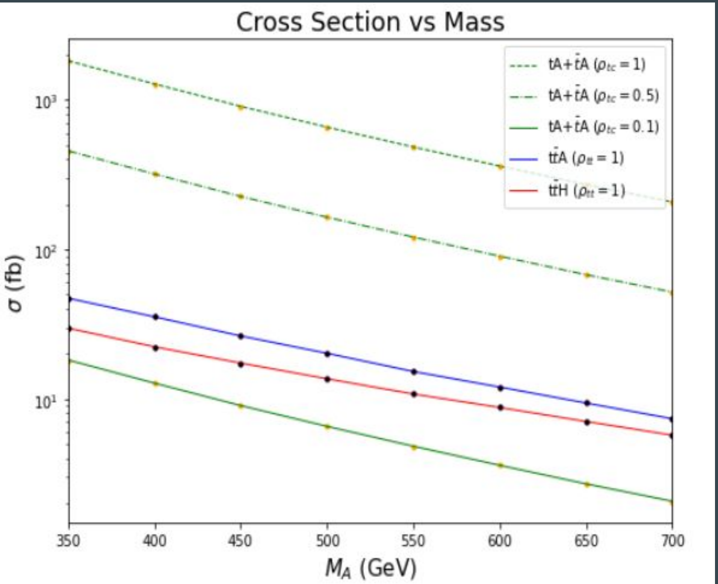


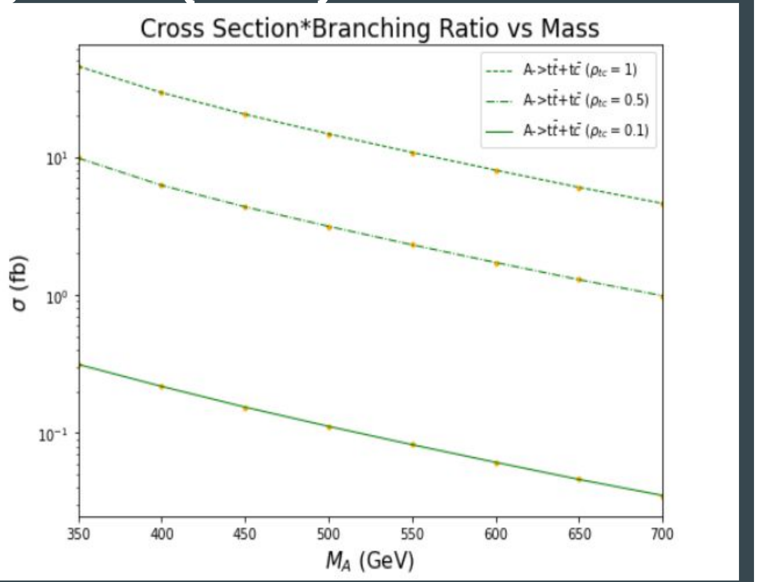


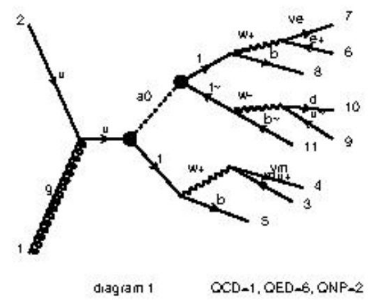


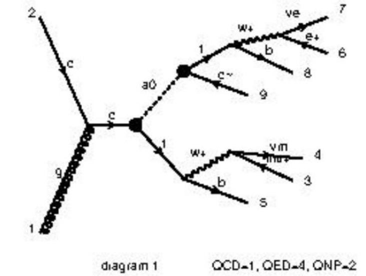


Cross section * branching ratio (SS2l)









Process: p p -> tA -> ttc~ -> SS2l & p p -> tA -> ttt~ -> SS2l

Ɓ(ttt~ -> SS2l) = (Ɓ(A0->tt~) * Ɓ(t->W b)^3 * Ɓ(W-> l vl)^2 * Ɓ(W-> q q'~)) * 3

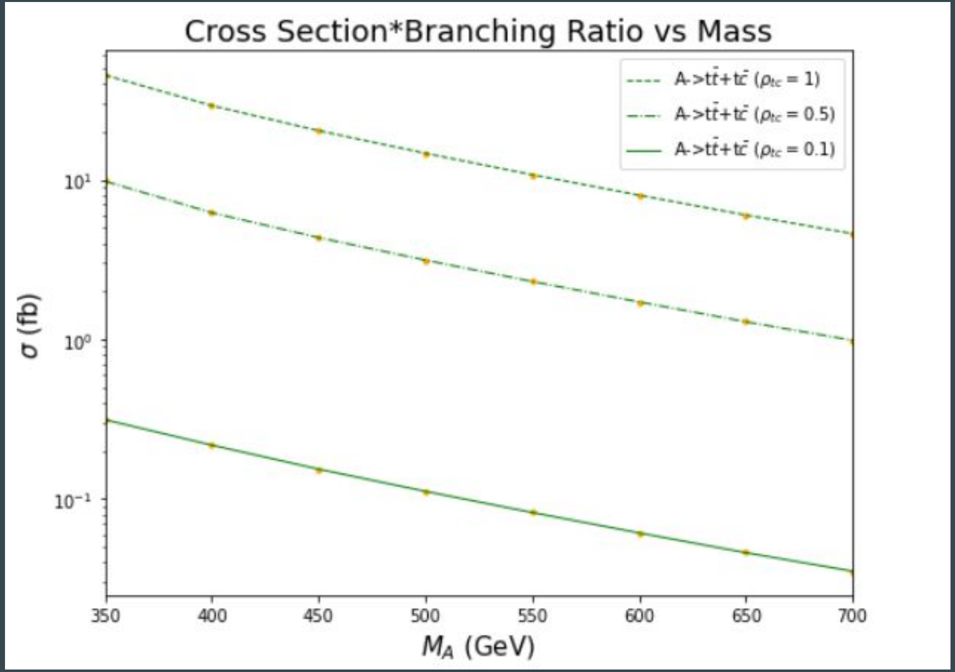
Ɓ(ttc~ -> SS2l) = (Ɓ(A0->tc~+t~c) * Ɓ(t->W b)^3 * Ɓ(W-> l vl)^2 * Ɓ(W-> q q'~)) * 3

Ɓ(t->W b) = 0.91 ± 0.04

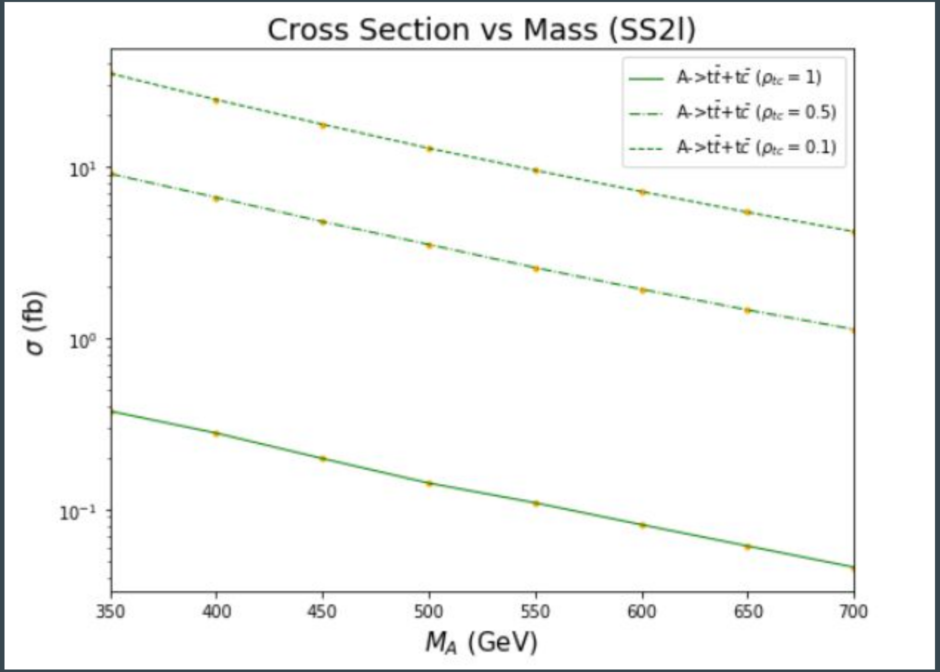
Ɓ(W-> l vl) = 0.105, where l = e, u.

Ɓ(W-> q q'~) = 0.105

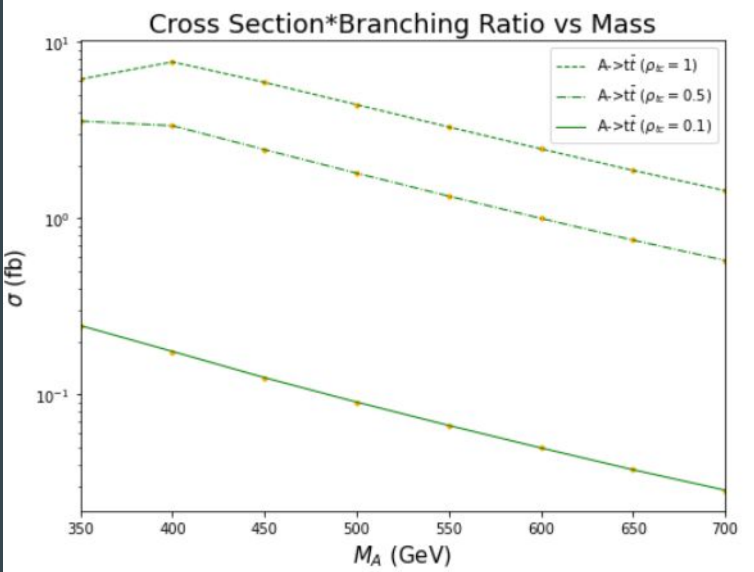
Calculation:



MadGraph Generation:



Cross Section * Branching Ratio (3b3l)



Process: p p -> tA -> ttt~ -> 3b3l

Ɓ(ttt~ -> 3b3l) = (Ɓ(A0->tt~) * Ɓ(t->W b)^3 * Ɓ(W-> l vl)^3) * 8

rho_tt = 1, rho_tc = 0.1, MA = 350 GeV, MH = 30,000 GeV

```
[0.12303583792996839,
 0.08776750824523852,
 0.06225878100054702,
 0.04524065687176229,
 0.03334588834976703,
 0.024868073925635753,
 0.018694140566302548,
 0.014308091005021247]
```

Run	Collider	Banner	Cross section (pb)	Events	Data	Output
run_01	p p 7000.0 x 7000.0 GeV	tag_1	0.0001251 ± 9.3e-07	2000	parton madevent	LHE MA5_report_analysis1
					pythia8	LOG HEPMC
					delphes	LOG rootfile
					hadron MA5	analysis2_BasicReco

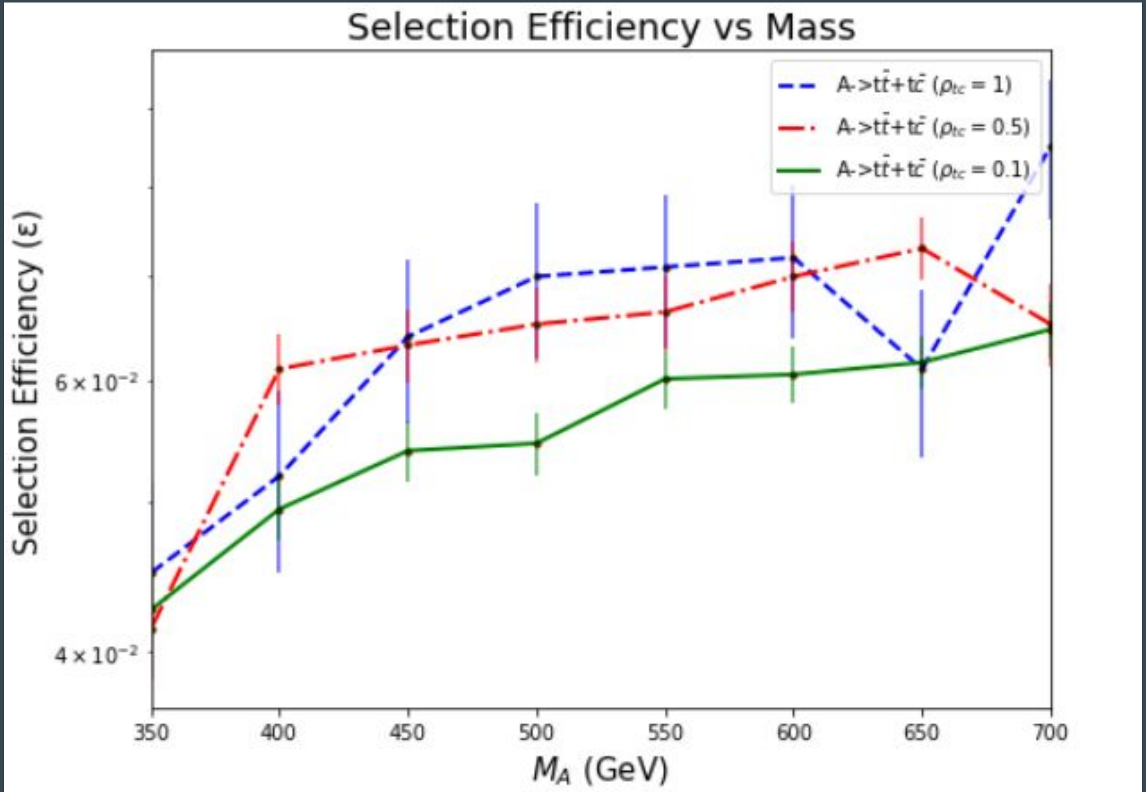
SS2l selection cut

The SS2ℓ signature is defined as two leptons with same charge plus at least three jets, with at least two jets identified as b-jets, and missing transverse energy E_T^{miss}. The SM background processes are $t\bar{t}Z$, $t\bar{t}W$, $tZ+$

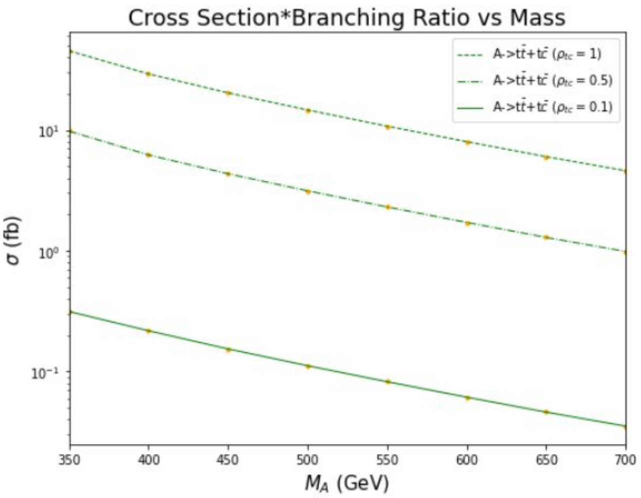
(p_T) of leading and subleading leptons > 25 GeV and 20 GeV, and > 30 GeV and 20 GeV, respectively for the two leading b-jets, while $E_T^{\mathrm{miss}} > 30$ GeV. The pseudo-rapidity of the same-sign leptons and the two leading b-jets should satisfy $|\eta^\ell| < 2.5$ and $|\eta^b| < 2.5$, respectively. Separation between a b-jet and a lepton ($\Delta R_{b\ell}$), any two b-jets (ΔR_{bb}), and any two leptons ($\Delta R_{\ell\ell}$) are required to be > 0.4. We reconstruct jets by anti-k_T algorithm with radius parameter $R = 0.6$ and take rejection factors 5 and 137 for c-jets and light-jets, respectively [27]. Finally, we require the scalar sum of transverse momenta, H_T, of two leading leptons and three leading jets to be > 300 GeV.

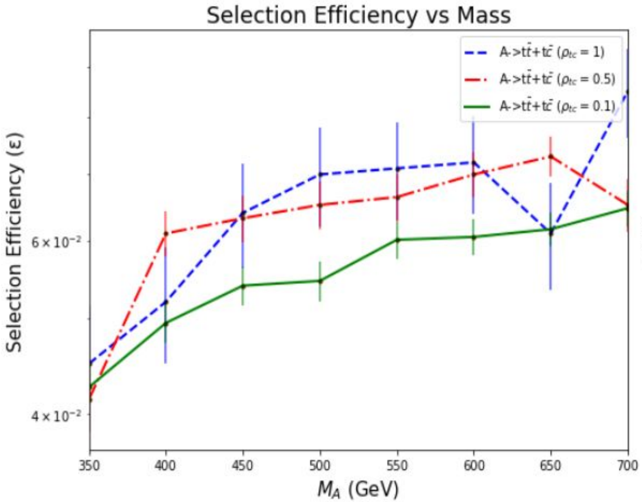
- SS2l signature: ≥ 2 same-charge leptons & ≥ 3 jets with ≥ 2 b-jets
- leading and subleading leptons > 25 GeV and 20 GeV & $|\eta^l| < 2.5$
- leading and subleading b-jets > 30 GeV and 20 GeV & $|\eta^b| < 2.5$
- Separation between a b-jet and a lepton (ΔR_{bl}) > 0.4
- Separation between any two b-jets (ΔR_{bb}) > 0.4
- Separation between any two leptons (ΔR_{ll}) > 0.4
- H_T, of 2 leading leptons and 3 leading jets, > 300 GeV

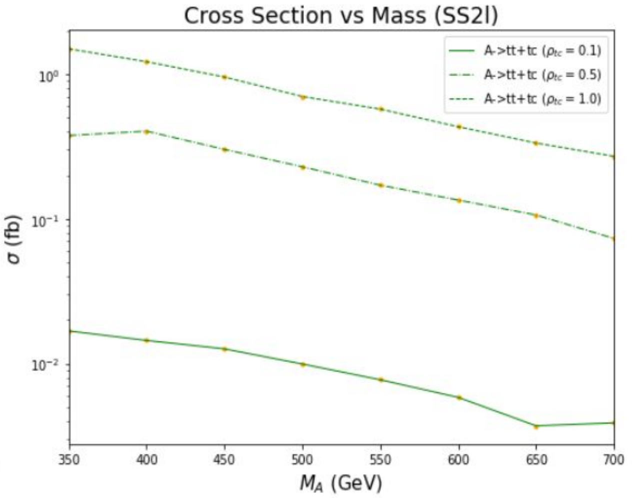
selection efficiency plots



Cross section * branching ratio * efficiency







Only Allow ee, mumu for SS2l:

```python
# find the location where it has at least 2 electrons or 2 muons
two_electron = ak.where(ak.num(Att_electron['Electron.Eta'])>=2)
two_muon = ak.where(ak.num(Att_muon['Muon.Eta'])>=2)
# combine the location results
two_lepton=ak.concatenate([two_electron, two_muon], axis=-1)

# Two leptons with same charge + at least 3 jets with 2 of them identified as b-jets
event_signal = []
for i in tqdm(two_lepton[0]): #Awkward Array has a length of 1
    num_jet, b_pt, lep_charge = jet_num[i], bjet_pt[i], lepton_charge[i]
    num_bjet = len(b_pt[ak.where(b_pt)])
    if lep_charge.count(-1) >= 2 or lep_charge.count(1) >=2:
        if num_jet >= 3 and num_bjet >=2:
            event_signal.append(i)
```

```
import model gen2HDM_UFO
define q = u c u~ c~
define q~ = d~ b~ s~ d b s
define p = p b b~
define j = p

generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
# add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ A0 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( A0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
# add process p p > t~ A0 j QCD=99, (t~ > w- b~ , w- > l- vl~) ,( A0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
# add process p p > t S0 QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))
# add process p p > t S0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))
# add process p p > t~ S0 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( S0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
# add process p p > t~ S0 j QCD=99, (t~ > w- b~ , w- > l- vl~) ,( S0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
```

Jet Inclusive

Add H0 process

```


output SS2l2+Sj
launch SS2l2+Sj

# set shower, detector
shower=Pythia8
detector=Delphes
done
###################################
# set param and run card settings #
###################################
set use_syst False
set rtc 0.1
set rtt 0
```

set rho_tt = 0

```
set rtu 0
set nevents 2000
set ebeam1 7000.0
set ebeam2 7000.0
set MS0 0
set ws0 0
# set MS0 30000
# set ws0 1790.139988
```

set Mass of H0 very very heavy

```
set MA0 scan1:[350,400,450,500,550,600,650,700]
set wa0 scan1:[6.008661958307974, 7.9302993987129, 9.791391917280869, 11.598189127055344, 13.35935405039862, 15.082906020156978, 16.77555149183397, 18.442710857402037]
done
```

Testing

1. Jet exclusive vs. Jet inclusive
2. Include H0 process & set H0 very heavy vs. Mass of H0 = 0
3. Expectation from paper vs. My result after cut

Before Selection Cut:

	Normal	Jet Inclusive	Add H0 Process
0	7.000180e-06	6.537000e-06	6.145e-06
1	4.913190e-06	4.719000e-06	4.52e-06
2	3.484695e-06	3.422000e-06	3.351e-06
3	2.509257e-06	2.411000e-06	2.406e-06
4	1.846209e-06	1.818000e-06	n/a
5	1.393447e-06	1.381000e-06	n/a
6	1.046315e-06	1.064000e-06	n/a
7	7.960760e-07	8.235000e-07	n/a

Table 1. The signal cross sections of the same-sign top SS2t after selection cuts for different m_H (in parentheses) with $m_A = m_H + 50\,\text{GeV}$ for $\rho_{tc} = 1$ at 14 TeV LHC. Various backgrounds cross sections after selection cuts are presented in the third column, where numbers in brackets in second column are LO to NLO K factors.

Signal cross section in fb (m_H in GeV)	Backgrounds	Cross section (fb)
3.83 (200)	$t\bar{t}W$ [1.35 (1.27)]	1.31
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2.35 (400)	$4t$ [2.04]	0.092
1.14 (500)	$t\bar{t}h$ [1.27]	0.058
0.75 (600)	Q-flip [1.84/1.27]	0.024
	tZ+jets [1.44]	0.007

18.807017543859647

26.4000000000

Task for this week

- compare the two papers (side by side list)
- Poisson Error for Selection Efficiency
- ckkw vs mlm matching
- add 1 jet/ 2 jets meaning
  - difference between them
  - how to combine them
- discuss with author about on-shell/ off-shell for low MA.

Comparison between two paper

Old Paper:

- Same-sign dilepton and Triple Top covered the whole paper (a more detailed explanation)
- Problem with Cross Section Plots (i.e. did NOT include **emu**, only ee and mumu)
- Include a CMS exclusion plot (<2σ) (don't know if it is correct)

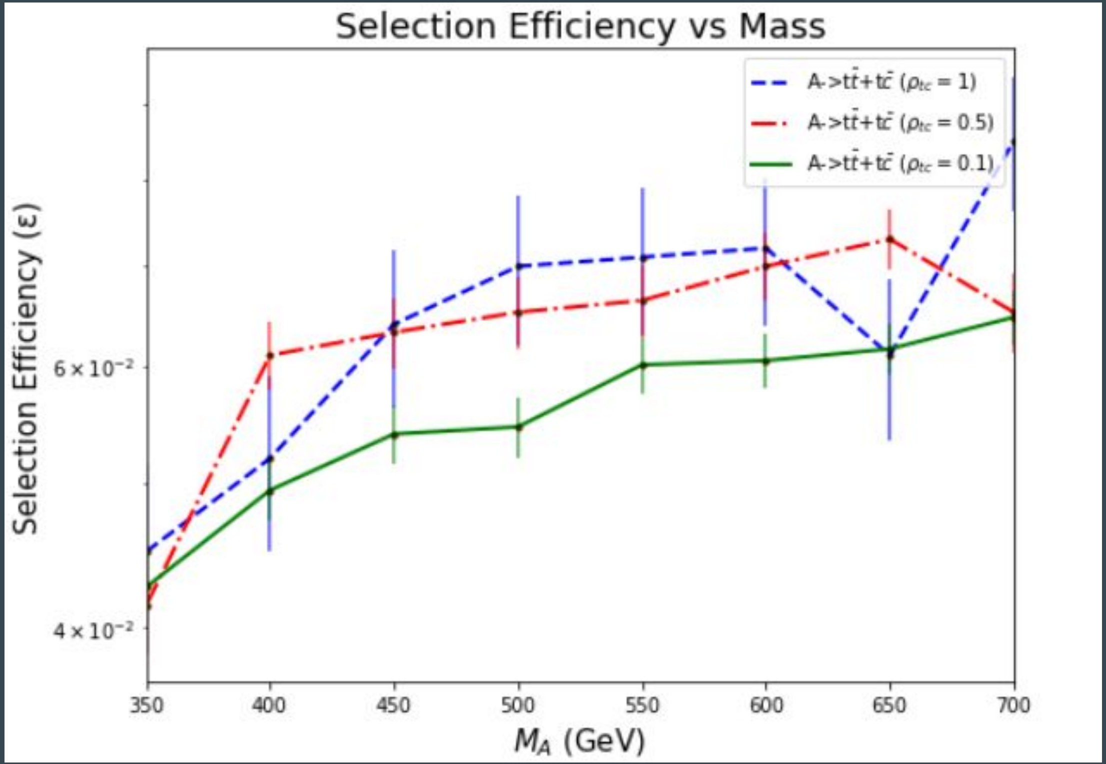
New Paper:

- ONLY 4.1.2 and 4.1.3 discuss SS2l and 3l3b (a more accurate content)
- Include a table for cross section with defined mA and mH with which I can compare easier
- Same content for 3b3l

Poisson Error

Selection Efficiency: ε = m/n, where m out of n events pass the selection cut

Uncertainty: $$\sigma^2 = \frac{\varepsilon(1-\varepsilon)}{n}$$



Merging at LO: CKKM and MLM

- MLM matching with kt jets or cone jets (where there are two options for Pythia treatment, the normal MLM procedure or the "Shower kT" scheme)
  - If xqcut=0, cone jets are used, while if xqcut > 0, kt jet matching is assumed.
- For most processes, the generation speed can be improved by setting ptj and mjj to xqcut, which is done automatically if the flag auto_ptj_mjj is set to T.
- Reject unmatched events after shower

- CKKW matching with Pythia P_T shower Sudakov form factors
- Analytic NLL Sudakovs + vetoed shower

Jet Matching

- Many (all) interesting New Physics signals at hadron colliders include hadronic jets (from decay or recoil)
- All Standard Model backgrounds to multi-jet processes (except top) have the jets coming from QCD radiation (parton shower)
- avoid double counting (madgraph -> generation, pythia8 -> decay)

Jet Matching

- MLM matching

  + Works for any shower with minimal modifications

  – Low efficiency, theoretically not (perfectly) well-controlled

- CKKW matching

  + No loss of events, theoretically well-controlled

  – Complicated shower treatment, matching unclear

- CKKW-Lönnblad matching

  + Perfect matching to shower, theoretically well-controlled

  – Low efficiency, complicated shower treatment

MLM and CKKW

1). Generate ME event with phase space cut QME
2). Reweight α s using scales for emissions in “shower history” corresponding to event (e.g., using kT -clustering)
3). Shower event with starting scale = μF = MT
4). Cluster shower emissions (before hadronization, using “hook” in shower MC) to jets using Qjet > QME. Keep event if each jet matches to one parton in the ME event – If highest parton multiplicity, allow extra jets < softest ME parton

CKKW: Vetoed showers

If matrix element cut is not aligned with shower evolution variable

1)Shower events, starting from central scale ~ μF

2)If an emission is generated, check if it has Q < Qmatch

3)If it does, keep it. Otherwise, ignore the emission and continue shower

Pythia setting:

Merging:nJetMax 2	Max number of additional jets in the matrix element.
Merging:Dparameter 0.4	Need to be defined by longitudinally invariant kT separation.
Merging:Process pp>xdxd~	The string specifying the hard core process.
Merging:nQuarksMerge 5	Control which the quarks will be merged.
Merging:TMS 100.0	The merging scale.
Merging:doKTMerging on	Decide the merging scale that is defined by LHE files kT cut.

MadGraph setting:

set ickkw 0	Decide which jet matching/merging algorithm (0 = CKKW).
set xqcut 0.0	Define the minimal kT between the partons at ME level.
set maxjetflavor 5	Consistent with Merging:nQuarksMerge.
set ktdurham 100.0	Consistent with Merging:TMS.
set dparameter 0.4	Consistent with Merging:Dparameter.

Card Settings

- ickkw (0 = no matching; 1 = MLM; 2 = CKKW)
- xqcut: minimum jet measure (pT/kT) for QCD partons, if xqcut=0 use cone jet matching, if xqcut> 0 use kt jet matching.
- ptj, ptb, drjj, drbb, drbj: for kt jet matching, ptj and ptb should be set to xqcut while drjj, drbj and drbb should be set to 0.
- maxjetflavor: (default 4) Defines which partons are considered as "j" and which are considered as "b". If matching is including b quarks, set to "5", while if b-quarks are not considered as partons in the proton, set to "4".
- QCUT. For matching using the kt scheme, this is the jet measure cutoff used by Pythia. If not given, it will be set to max(xqcut+5,xqcut*1.2)

Notes:

- For W or Z boson production, suggested xqcut scale is 10 !GeV with QCUT=15 !GeV for virtuality-ordered Pythia showers, or 30 !GeV for P_T-ordered showers with the Shower-K_T scheme.
- For t t~ production, suggested xqcut scale is 20 !GeV with QCUT=30 !GeV for virtuality-ordered Pythia showers, or 80 !GeV for P_T-ordered showers with the Shower-K_T scheme.
- For 600 !GeV SUSY particle pair production, suggested xqcut scale is 30 !GeV with QCUT=40 !GeV for virtuality-ordered Pythia showers, or 100 !GeV for P_T-ordered showers with the Shower-K_T scheme.

```
import model gen2HDM_UFO
define q = u c u~ c~
define q~ = d~ b~ s~ d b s
define p = p b b~
define j = p

generate p p > t A0 @0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ A0 @0 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( A0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j @1 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ A0 j @1 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( A0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j j @2 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ A0 j j @2 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( A0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )


add process p p > t S0 @0 QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ S0 @0 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( S0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
add process p p > t S0 j @1 QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ S0 j @1 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( S0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )
add process p p > t S0 j j @2 QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t~ S0 j j @2 QCD=99, (t~ > w- b~ , w- > l- vl~) ,( S0 > c t~ ,(t~ > w- b~ , w- > l- vl~) )

output SS214
launch SS214
```

```
#*********************************************************************
# Matching parameter (MLM only)
#*********************************************************************
 1 = ickkw ! 0 no matching, 1 MLM
 1.0 = alpsfact ! scale factor for QCD emission vx
 False = chcluster ! cluster only according to channel diag
 5 = asrwgtflavor ! highest quark flavor for a_s reweight
 True = auto_ptj_mjj ! Automatic setting of ptj and mjj if xqcut >0
                                  ! (turn off for VBF and single top processes)
 30.0 = xqcut ! minimum kt jet measure between partons

#***********************************************************************
# Turn on either the ktdurham or ptlund cut to activate                *
# CKKW(L) merging with Pythia8 [arXiv:1410.3012, arXiv:1109.4829]      *
#***********************************************************************
 -1.0 = ktdurham
 0.4 = dparameter
 -1.0 = ptlund
 1, 2, 3, 4, 5, 6, 21 = pdgs_for_merging_cut ! PDGs for two cuts above

#*********************************************************************
#
#*********************************************************************
```

```
! ----------------------------------------------------------------------
! Parameters relevant only when performing MLM merging, which can be
! turned on by setting ickkw to '1' in the run_card and chosing a
! positive value for the parameter xqcut.
! For details, see section 'Jet Matching' on the left-hand menu of
!    http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html
! ----------------------------------------------------------------------
! If equal to -1.0, MadGraph5_aMC@NLO will set it automatically based
! on the parameter 'xqcut' of the run_card.dat
JetMatching:qCut          = -1.0
! Use default kt-MLM to match parton level jets to those produced by the
! shower. But the other Shower-kt scheme is available too with this option.
JetMatching:doShowerKt    = off
! A value of -1 means that it is automatically guessed by MadGraph.
! It is however always safer to explicitly set it.
JetMatching:nJetMax       = -1
!
! ----------------------------------------------------------------------
! Parameters relevant only when performing CKKW-L merging, which can
! be turned on by setting the parameter 'ptlund' *or* 'ktdurham' to
! a positive value.
! For details, see section 'CKKW-L Merging' on the left-hand menu of
!    http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html
! ----------------------------------------------------------------------
! Central merging scale values you want to be used.
! If equal to -1.0, then MadGraph5_aMC@NLO will set this automatically
! based on the parameter 'ktdurham' of the run_card.dat
Merging:TMS               = -1.0
! This must be set manually, according to Pythia8 directives.
! An example of possible value is 'pp>LEPTONS,NEUTRINOS'
! Alternatively, from Pythia v8.223 onwards, the value 'guess' can be
! used to instruct Pythia to guess the hard process. The guess would mean
! that all particles apart from light partons will be considered as a part
! of the hard process. This guess is prone to errors if the desired hard
! process is complicated (i.e. contains light partons). The user should
! then be wary of suspicious error messages in the Pythia log file.
Merging:Process           = <set_by_user>
! A value of -1 means that it is automatically guessed by MadGraph.
! It is however always safer to explicitly set it.
Merging:nJetMax           = -1
!
! For all merging schemes, decide whehter you want the merging scale
! variation computed for only the central weights or all other
! PDF and scale variation weights as well
```

On-shell & Off-shell

- **virtual particles** are termed **off shell** because they do not satisfy the energy–momentum relation
- real exchange particles do satisfy this relation and are termed **on shell** (mass shell).

Overview

- update on generation
- update on Large-R jets

Tanmoy’s Message (SS2l) (Updated)

- Do NOT include A0/H0 > t t~, (only allow A0/H0 > t c~, t~ c)
  - $\rho_{tt} = 0$, $\rho_{tc} = 0.1, 0.5, 1$
- Figure in “old” paper ONLY has ee or mumu SS2l, NOT include emu.
- Include H0 process when doing Only A0 graph, but put H0 very very heavy to avoid any SS2l contribution
- There are contributions from p p > tA0/H0 and p p > tA0/H0 + j
  - jet inclusive process
- Contributions from pp > t t (t channel A0 and H0 exchange) and pp > t A0 j/t H0 j followed by A0/H0 > t cbar decays
- merge and match pp > tt, pp > ttj , pp > ttjj (with charge conjugate processes implied) together

“There are contributions from pp > t t (t channel A0 and H0 exchange) and pp > t A0 j/t H0 j followed by A0/H0 > t cbar decays; all of them would contribute to the SS-2l final state in the inclusive signature. Essentially you have to merge and match pp > tt, pp > ttj , pp > ttjj (with charge conjugate processes implied) together and consider SS-2l decays of the same-sign top quarks.”

The $pp \to tH/tA \to tt\bar{c}$ process with both top quarks decaying semileptonically (nonresonant $cg \to tt\bar{c}$, t-channel H/A exchange $cc \to tt$ and $gg \to t\bar{c}A/H$ processes are included) contributes to CRW of the CMS $4t$ search. Setting all other $\rho_{ij} = 0$,

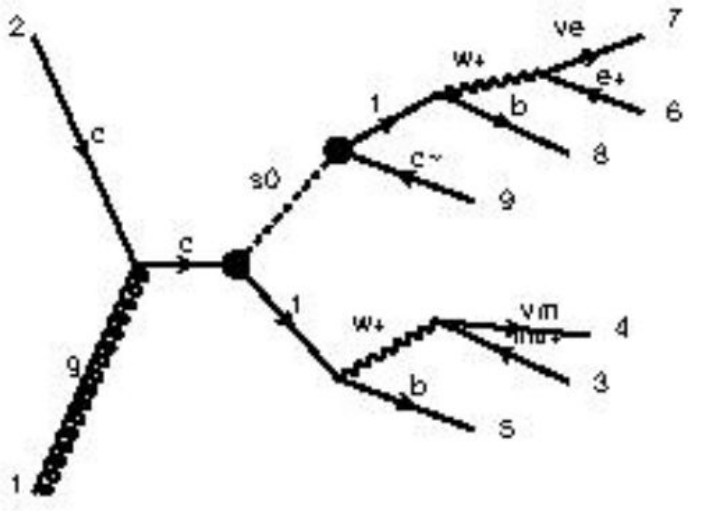
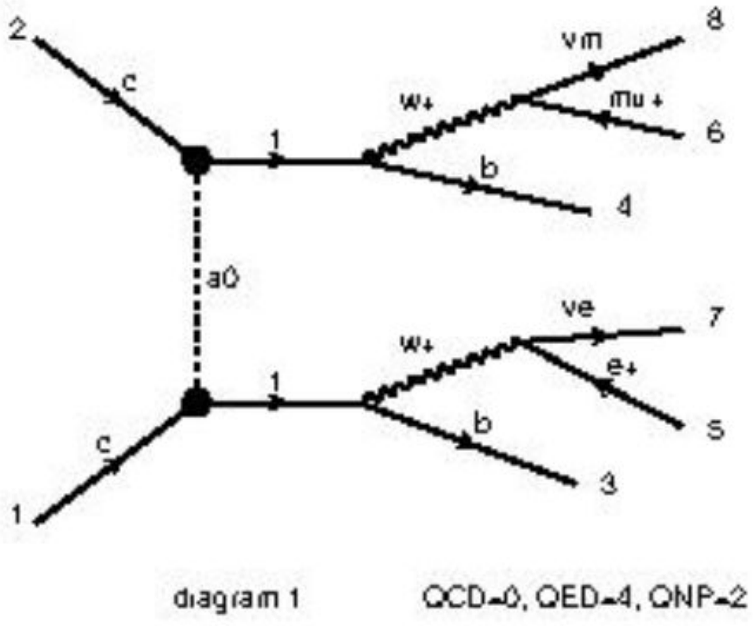
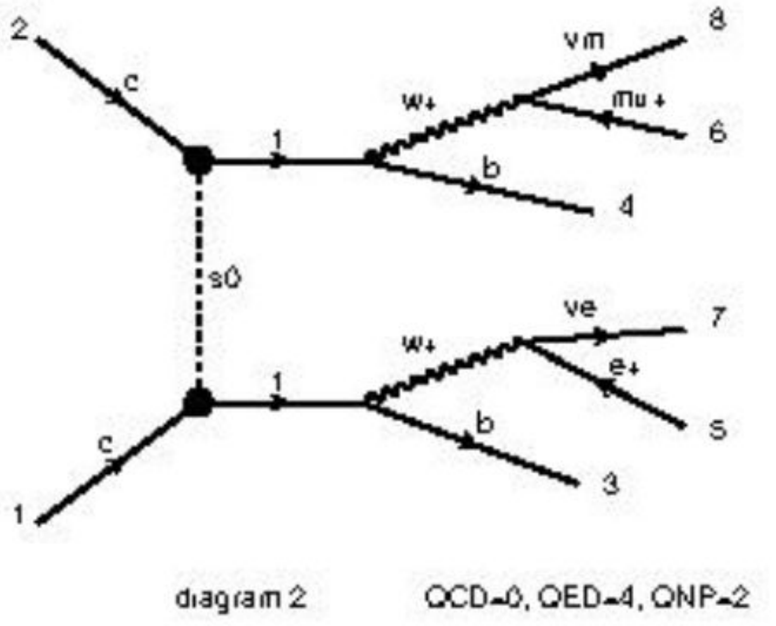


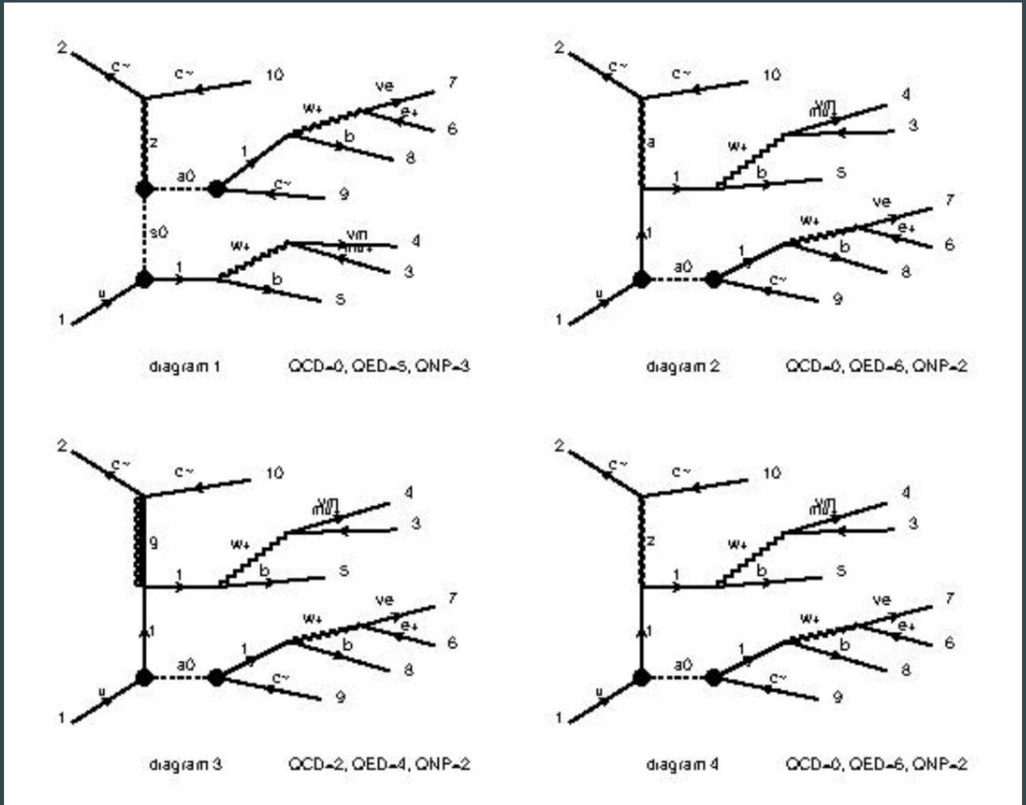
diagram 1 QCD=1, QED=4, QNP=2

p p > t t > b b l+ l+ vl vl (t-channel A0/H0 exchange)



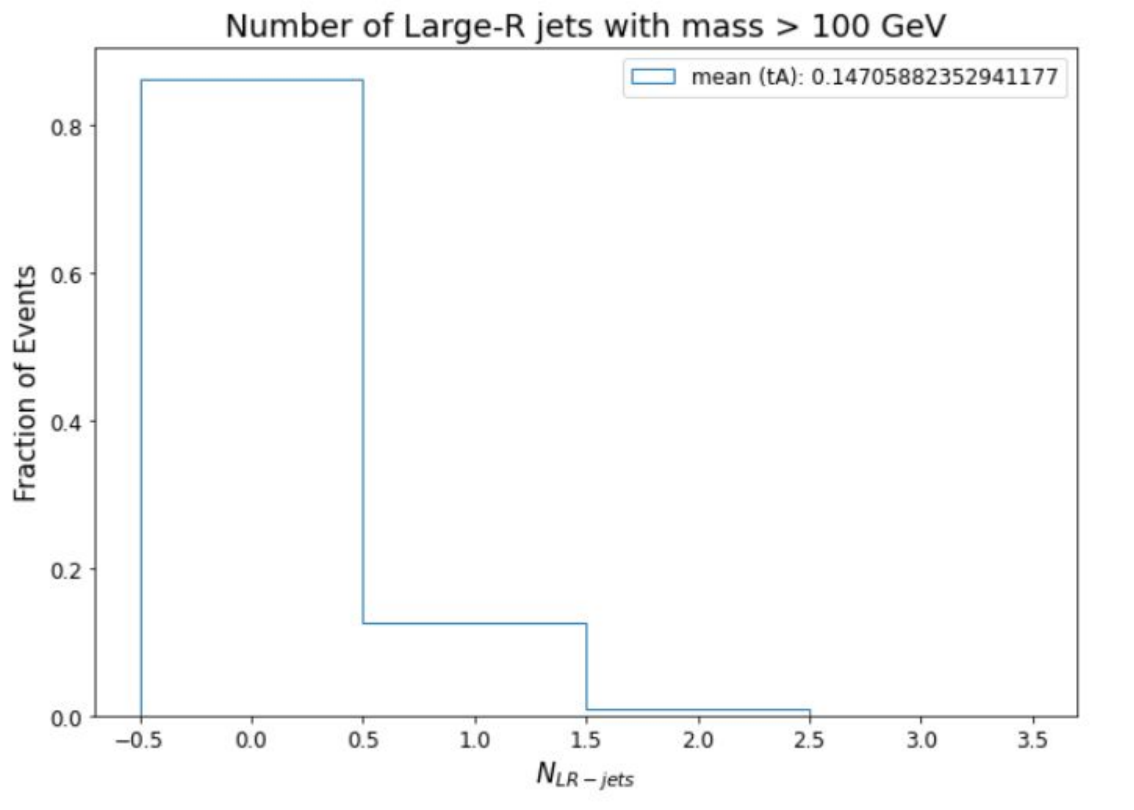


p p > t c~ A0, (A0 > t c~ , (t > w+ b , w+ > l+ vl))



Large-R Jets

1. use default FatJetFinder
2. change the name of the output in Delphes
   a. have an output
3. re-clustering coding
   a. https://cp3.irmp.ucl.ac.be/projects/delphes/wiki/WorkBook/ExternalFastJet



Number of Large-R jets with mass > 100 GeV
mean (tA): 0.14705882352941177
Fraction of Events
0.0
0.2
0.4
0.6
0.8
−0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$N_{LR-jets}$

FastJetFinder - Small-R jets

Jets are reconstructed from topological clusters [28] of energy deposits in the calorimeters using the anti-k_t algorithm [29, 30] with a radius parameter of $R = 0.4$ and calibrated as described in Ref. [31]. They are referred to as 'small-R jets'. These jets are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. To suppress the

FatJetFinder - Large-R jets

The selected and calibrated small-R jets are used as inputs for jet reclustering [35] using the anti-k_t algorithm with a radius parameter of $R = 1.0$. These reclustered jets are referred to as 'large-R jets'. The

FastJetFinder - Small-R jets

```
############
# Jet finder
############

module FastJetFinder FastJetFinder {
#  set InputArray Calorimeter/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt, 5 Cambridge/Aachen, 6 antikt
  set JetAlgorithm 6
  set ParameterR 0.4

  set JetPTMin 25.0
}
```

FatJetFinder - Large-R jets

```
##################
# Fat Jet finder
##################

module FastJetFinder FatJetFinder {
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone, 4 kt, 5 Cambridge/Aachen, 6 antikt
  set JetAlgorithm 6
  set ParameterR 1.0

  set ComputeNsubjettiness 1
  set Beta 1.0
  set AxisMode 4

  set ComputeTrimming 1
  set RTrim 0.2
  set PtFracTrim 0.05

  set ComputePruning 1
  set ZcutPrun 0.1
  set RcutPrun 0.5
  set RPrun 0.8

  set ComputeSoftDrop 1
  set BetaSoftDrop 0.0
  set SymmetryCutSoftDrop 0.1
  set R0SoftDrop 0.8

  set JetPTMin 200.0
}
```

What we have for generation

Table 1. The signal cross sections of the same-sign top SS2t after selection cuts for different m_H (in parentheses) with $m_A = m_H + 50\,\text{GeV}$ for $\rho_{tc} = 1$ at 14 TeV LHC. Various backgrounds cross sections after selection cuts are presented in the third column, where numbers in brackets in second column are LO to NLO K factors.

Signal cross section in fb (m_H in GeV)	Backgrounds	Cross section (fb)
3.83 (200)	$t\bar{t}W$ [1.35 (1.27)]	1.31
4.12 (300)	$t\bar{t}Z$ [1.56]	1.97
2.35 (400)	$4t$ [2.04]	0.092
1.14 (500)	$t\bar{t}h$ [1.27]	0.058
0.75 (600)	Q-flip [1.84/1.27]	0.024
	tZ+jets [1.44]	0.007

Generation Clues

Process:

- $pp \to tH/tA + X \to tt\bar{c} + X$
- pp > t t (t channel A0 and H0 exchange) and pp > t A0 j/t H0 j followed by A0/H0 > t cbar decays
- merge and match pp > tt, pp > ttj , pp > ttjj (with charge conjugate processes implied) together

Parameter:

- mA = mH + 50 GeV
- $\rho_{tc} = 1$
- $\mathcal{B}(A/H \to t\bar{c} + \bar{t}c) = 100\%$
- default Delphes Atlas Card
- MLM algorithm

```
import model gen2HDM_UFO
define p = p b b~
define j = p

generate p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t c~ , (t > w+ b , w+ > l+ vl))
add process p p > t S0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( S0 > t c~ , (t > w+ b , w+ > l+ vl))

add process c c > t t QCD=99, (t > w+ b , w+ > l+ vl)
add process c c > t t j QCD=99, (t > w+ b , w+ > l+ vl)
add process c c > t t j j QCD=99, (t > w+ b , w+ > l+ vl)

output test3
launch test3

# set shower, detector
analysis=MadAnalysis5
shower=Pythia8
detector=Delphes
done
###################################
# set param and run card settings #
###################################
set use_syst False
set rtc 1
set rtt 0
set rtu 0
set nevents 2000
set ebeam1 7000.0
set ebeam2 7000.0
set MS0 scan1:[200, 300, 400, 500, 600]
set ws0 scan1:[0.8084067888488623, 8.06788791041956, 15.860676327908143, 23.196447115001444, 30.16587229374456]
set MA0 scan1:[250, 350, 450, 550, 650]
set wa0 scan1:[4.761314525775488, 18.74638044683123, 39.55871096660742, 68.89074668398136, 108.79297398841524]
```

	Selection Cut (SS2t) $(M_A = M_H + 50GeV)$ $\rho_{tc} = 1$	$M_H = 200GeV$	$M_H = 300GeV$	$M_H = 400GeV$	$M_H = 500GeV$	$M_H = 600GeV$
0	Input Event Size	874.00	780.00	679.00	742.00	651.000
1	SS2l Signature	93.00	98.00	73.00	89.00	95.000
2	leading jets > 30 GeV & subleading jets > 20 G...	70.00	76.00	57.00	72.00	69.000
3	leading leptons > 25 GeV & subleading leptons ...	70.00	76.00	57.00	72.00	69.000
4	E_T^{miss} > 30GeV	56.00	63.00	48.00	68.00	66.000
5	ΔR_{bb} > 0.4	56.00	63.00	48.00	68.00	66.000
6	ΔR_{bl} > 0.4	56.00	63.00	48.00	68.00	66.000
7	ΔR_{ll} > 0.4	56.00	62.00	48.00	67.00	66.000
8	H_T (2 leading leptons & 3 leading jets) >...	40.00	49.00	40.00	67.00	66.000
9	Cross Section after Merging and Matching (fb)	69.27	35.88	14.37	7.37	3.341
10	Cross Section after Selection Cut (fb)	3.17	2.25	0.85	0.67	0.340

Signal cross section in fb (m_H in GeV)	Backgrounds	Cross section (fb)
3.83 (200)	$t\bar{t}W$ [1.35 (1.27)]	1.31
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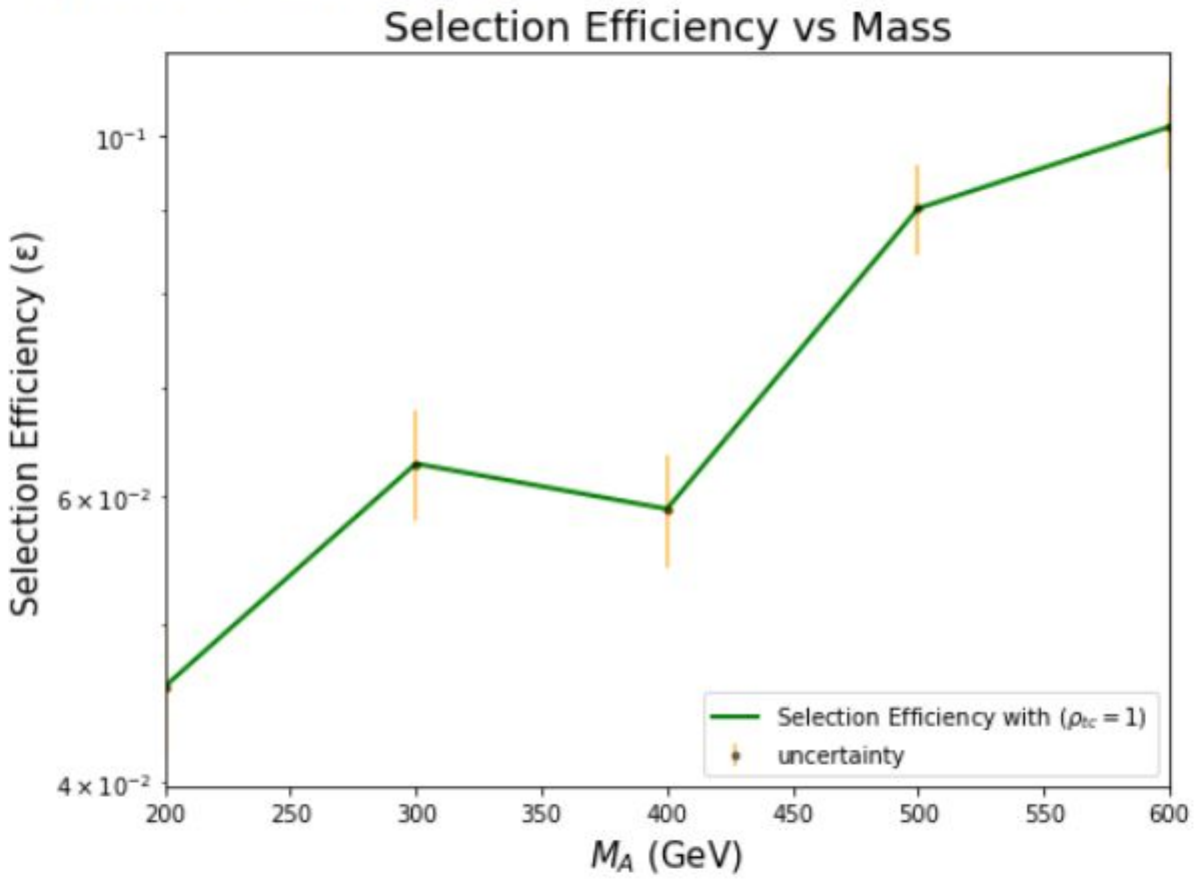
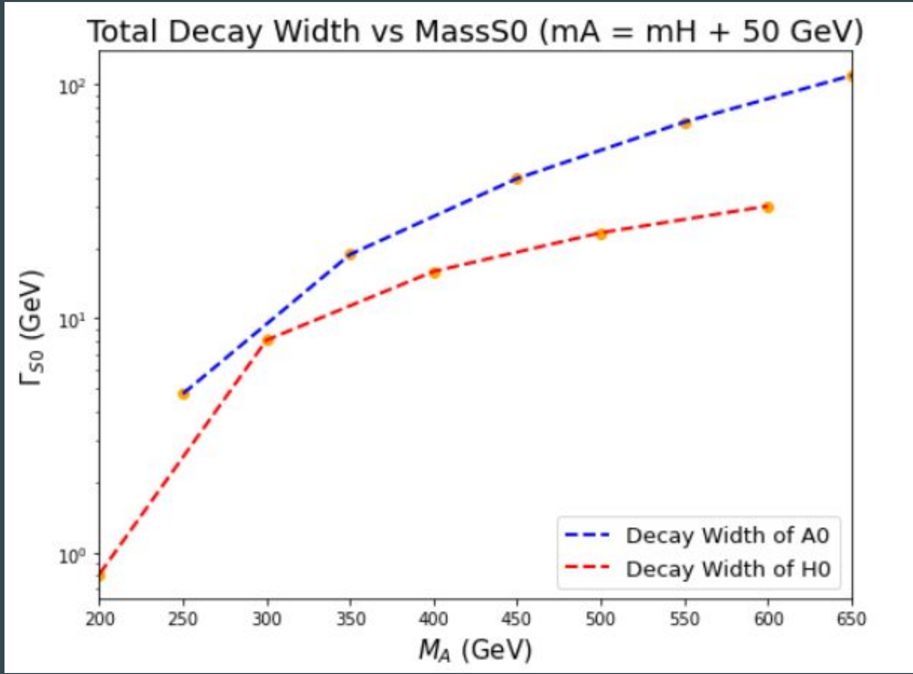
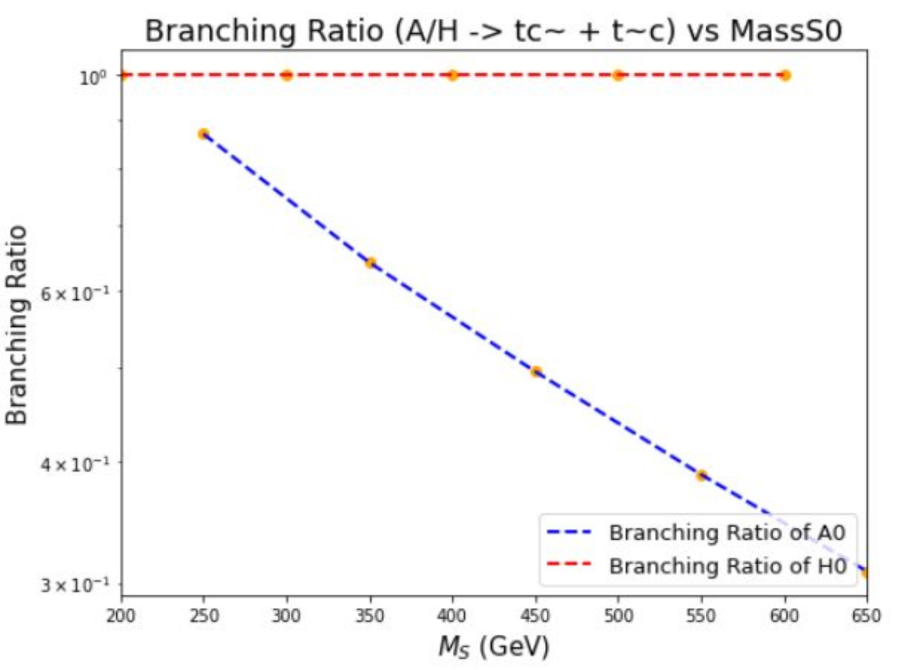
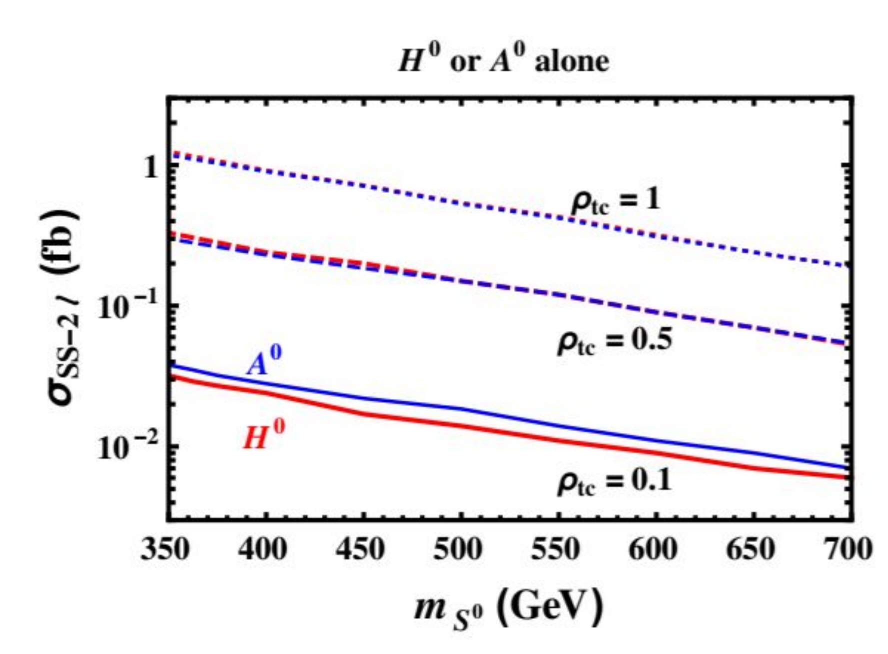
0.75 (600)	Q-flip [1.84/1.27]	0.024
	tZ+jets [1.44]	0.007

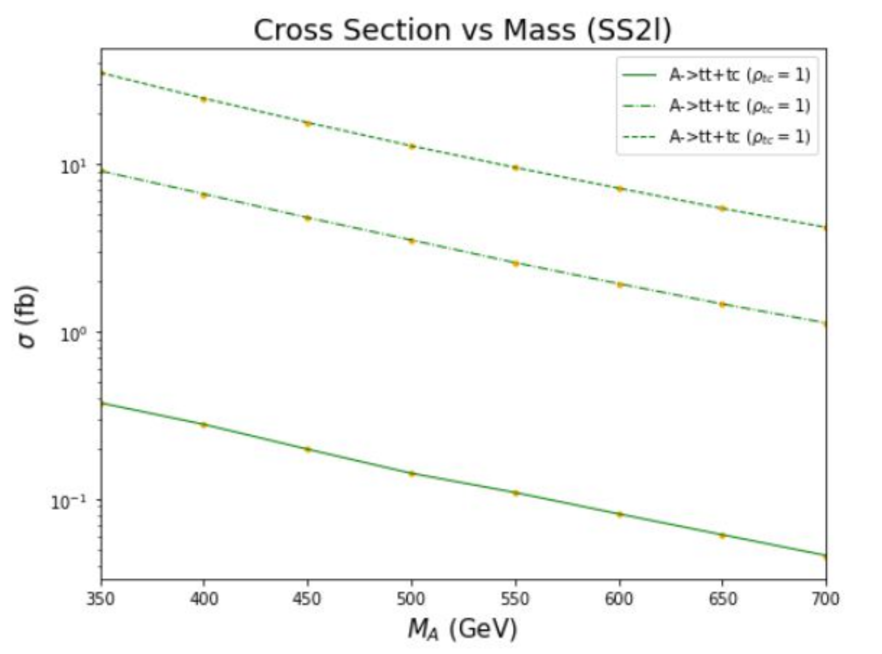

Selection Efficiency vs Mass
Selection Efficiency (ε)
M_A (GeV)
Selection Efficiency with ($\rho_{tc} = 1$)
uncertainty
10⁻¹
6 × 10⁻²
4 × 10⁻²
200
250
300
350
400
450
500
550
600


Total Decay Width vs MassS0 (mA = mH + 50 GeV)
Γ_{S0} (GeV)
M_A (GeV)
Decay Width of A0
Decay Width of H0
10^2
10^1
10^0
200
250
300
350
400
450
500
550
600
650


Branching Ratio (A/H -> tc~ + t~c) vs MassS0
Branching Ratio
M_S (GeV)
Branching Ratio of A0
Branching Ratio of H0
10^0
6×10^{-1}
4×10^{-1}
3×10^{-1}
200
250
300
350
400
450
500
550
600
650

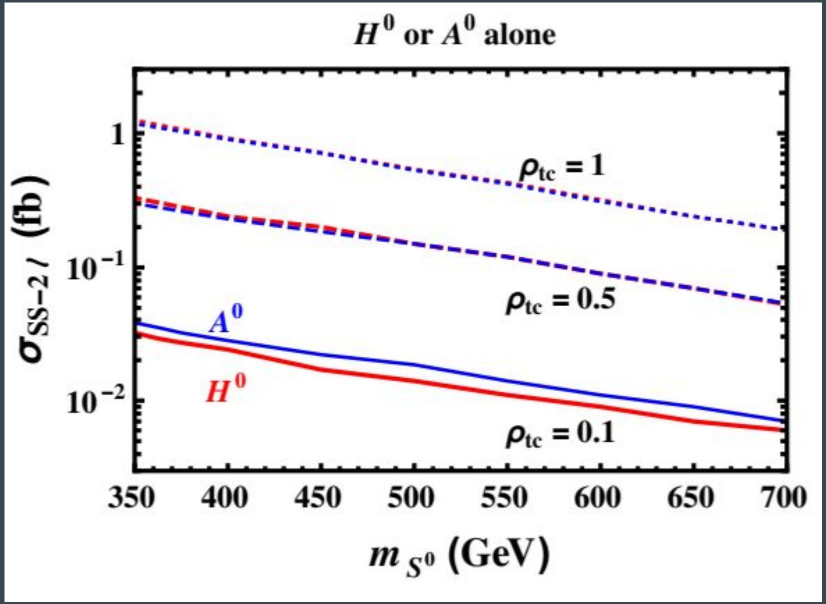
SS2l Cross Section vs Mass (before selection cut)



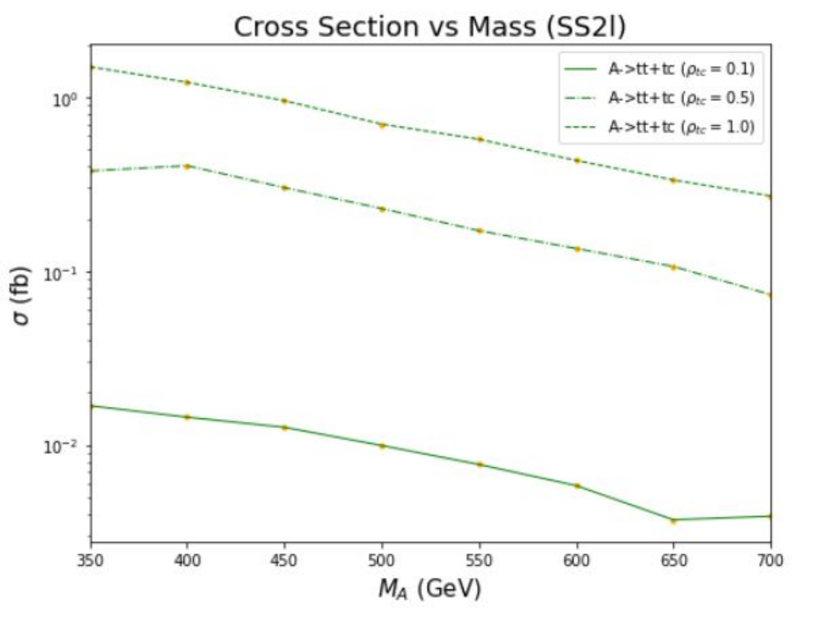


Cross Section vs Mass (after selection cut)

Paper:



My result:



1. SS2l signature: ≥ 2 same-charge leptons & ≥ 3 jets with ≥ 2 b-jets
2. leading and subleading leptons > 25 GeV and 20 GeV & $|\eta^l| < 2.5$
3. leading and subleading b-jets > 30 GeV and 20 GeV & $|\eta^b| < 2.5$
4. Emiss_T > 30 GeV
5. Separation between a b-jet and a lepton (ΔR_{bl}) > 0.4
6. Separation between any two b-jets (ΔR_{bb}) > 0.4
7. Separation between any two leptons (ΔR_{ll}) > 0.4
8. H_T, of 2 leading leptons and 3 leading jets, > 300 GeV

	Selection Cut (SS2l)$\rho_{tc} = 1.0$	$M_A = 350GeV$
0	Input Event Size	10000
1	SS2l Signature	1474
2	leading jets > 30 GeV & subleading jets > 20 G...	1169
3	leading leptons > 25 GeV & subleading leptons ...	1145
4	E_T^{miss}	994
5	ΔR_{bb} > 0.4	994
6	ΔR_{bl} > 0.4	994
7	ΔR_{ll} > 0.4	975
8	H_T (2 leading leptons & 3 leading jets) >...	876

We denote our triple-top signature as $3\ell 3b$, which is defined as: at least three leptons, at least three jets with at least three tagged as b-jets, plus $E_T^{\rm miss}$. The selection cuts are: for the three leading leptons and b-jets, $p_T^\ell > 25$ GeV and $p_T^b > 20$ GeV, respectively; η, ΔR and $E_T^{\rm miss}$ are the same as for SS2t; scalar sum, H_T, of transverse momenta of all three leading leptons and b-jets should satisfy $H_T > 320$ GeV. To reduce $t\bar{t}Z+$jets background, we veto[109] the mass range 76 GeV $< m_{\ell\ell} <$ 95 GeV for same flavor, opposite charged lepton pairs, and if more than one pair is present, the veto is applied to the pair mass closest to m_Z.

	Selection Cut (SS2l) $\rho_{tc} = 0.1$	$M_A = 350GeV$	$M_A = 400GeV$	$M_A = 450GeV$	$M_A = 500GeV$	$M_A = 550GeV$	$M_A = 600GeV$	$M_A = 650GeV$	$M_A = 700GeV$
0	Input Event Size	1000	1000	1000	1000	1000	1000	1000	1000
1	SS2l Signature	80	84	95	97	103	103	89	103
2	leading jets > 30 GeV & subleading jets > 20 G...	69	72	76	80	84	86	72	94
3	leading leptons > 25 GeV & subleading leptons ...	66	71	74	79	81	86	71	94
4	E_T^{miss} > 30GeV	58	56	68	73	73	77	63	88
5	ΔR_{bb} > 0.4	58	56	68	73	73	77	63	88
6	ΔR_{bl} > 0.4	58	56	68	73	73	77	63	88
7	ΔR_{ll} > 0.4	57	56	67	71	72	75	62	86
8	H_T (2 leading leptons & 3 leading jets) >...	45	52	64	70	71	72	61	85

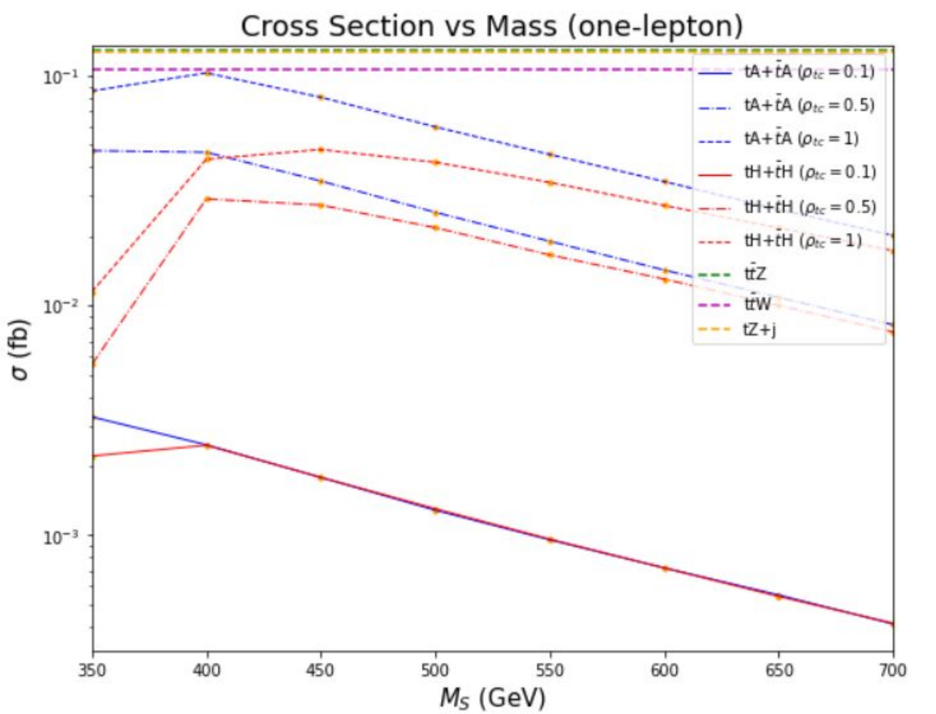
	Selection Cut (SS2l) $\rho_{tc} = 0.5$	$M_A = 350GeV$	$M_A = 400GeV$	$M_A = 450GeV$	$M_A = 500GeV$	$M_A = 550GeV$	$M_A = 600GeV$	$M_A = 650GeV$	$M_A = 700GeV$
0	Input Event Size	5000	5000	5000	5000	5000	5000	5000	5000
1	SS2l Signature	353	459	453	466	482	474	482	458
2	leading jets > 30 GeV & subleading jets > 20 G...	272	370	376	379	380	397	419	379
3	leading leptons > 25 GeV & subleading leptons ...	266	364	370	375	371	386	407	370
4	E_T^{miss} > 30 GeV	238	330	338	344	339	361	378	334
5	ΔR_{bb} > 0.4	238	330	338	344	339	361	378	334
6	ΔR_{bl} > 0.4	238	330	338	344	339	361	378	334
7	ΔR_{ll} > 0.4	235	326	336	339	336	351	372	331
8	H_T (2 leading leptons & 3 leading jets) >...	207	305	316	326	332	350	365	326

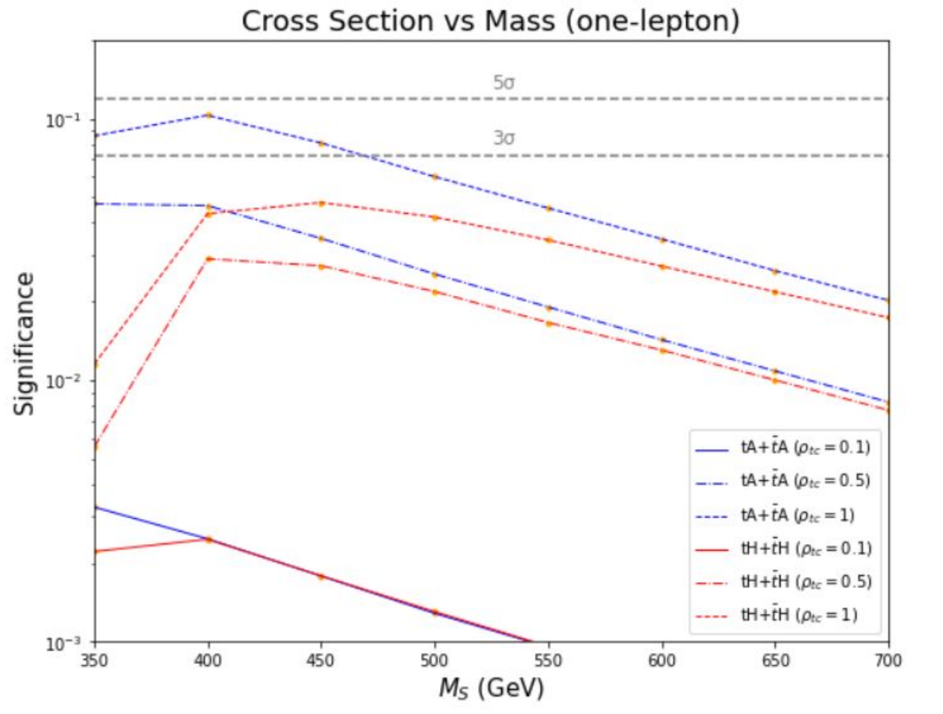
	Selection Cut (SS2l) $\rho_{tc} = 1.0$	$M_A = 350GeV$	$M_A = 400GeV$	$M_A = 450GeV$	$M_A = 500GeV$	$M_A = 550GeV$	$M_A = 600GeV$	$M_A = 650GeV$	$M_A = 700GeV$
0	Input Event Size	10000	10000	10000	10000	10000	10000	10000	10000
1	SS2l Signature	751	775	835	794	865	824	870	908
2	leading jets > 30 GeV & subleading jets > 20 G...	575	623	654	656	702	680	710	728
3	leading leptons > 25 GeV & subleading leptons ...	565	611	646	643	691	666	697	712
4	E_T^{miss} > 30 GeV	485	544	574	575	629	615	638	664
5	ΔR_{bb} > 0.4	485	544	574	575	629	615	638	664
6	ΔR_{bl} > 0.4	485	544	574	575	629	615	638	664
7	ΔR_{ll} > 0.4	476	533	562	568	615	607	627	653
8	H_T (2 leading leptons & 3 leading jets) >...	426	495	540	546	601	605	616	647

1 lepton channel selection cut

- S1l signature: ≥ 1 leptons & ≥ 3 jets with ≥ 2 b-jets
- leading > 25 GeV & $|\eta^l| < 2.5$
- leading b-jets and subleading b-jets > 30 and 20 GeV & $|\eta^b| < 2.5$
- Separation between a b-jet and a lepton (ΔR_{bl}) > 0.4
- Separation between any two b-jets (ΔR_{bb}) > 0.4
- H_T, of 2 leading leptons and 3 leading jets, > 300 GeV

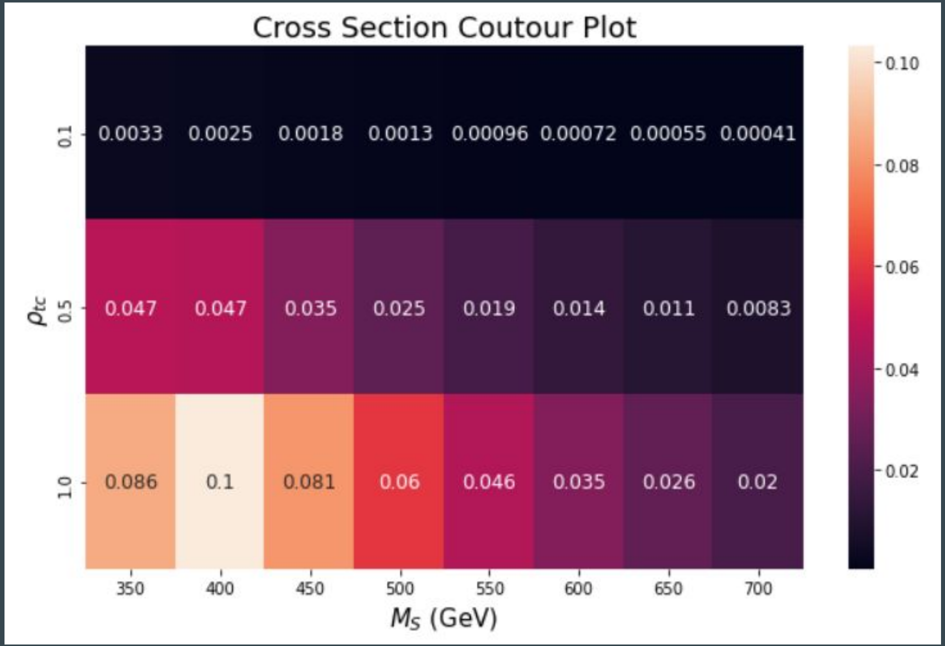
Cross Section

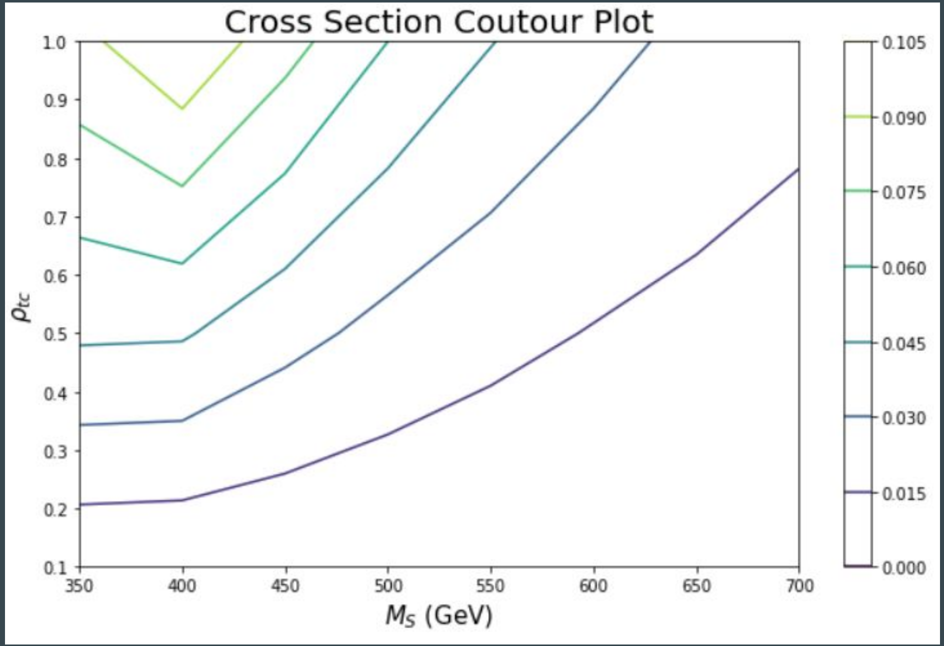




Signal Yield, Cross Section -> Number of Events

Cross Section

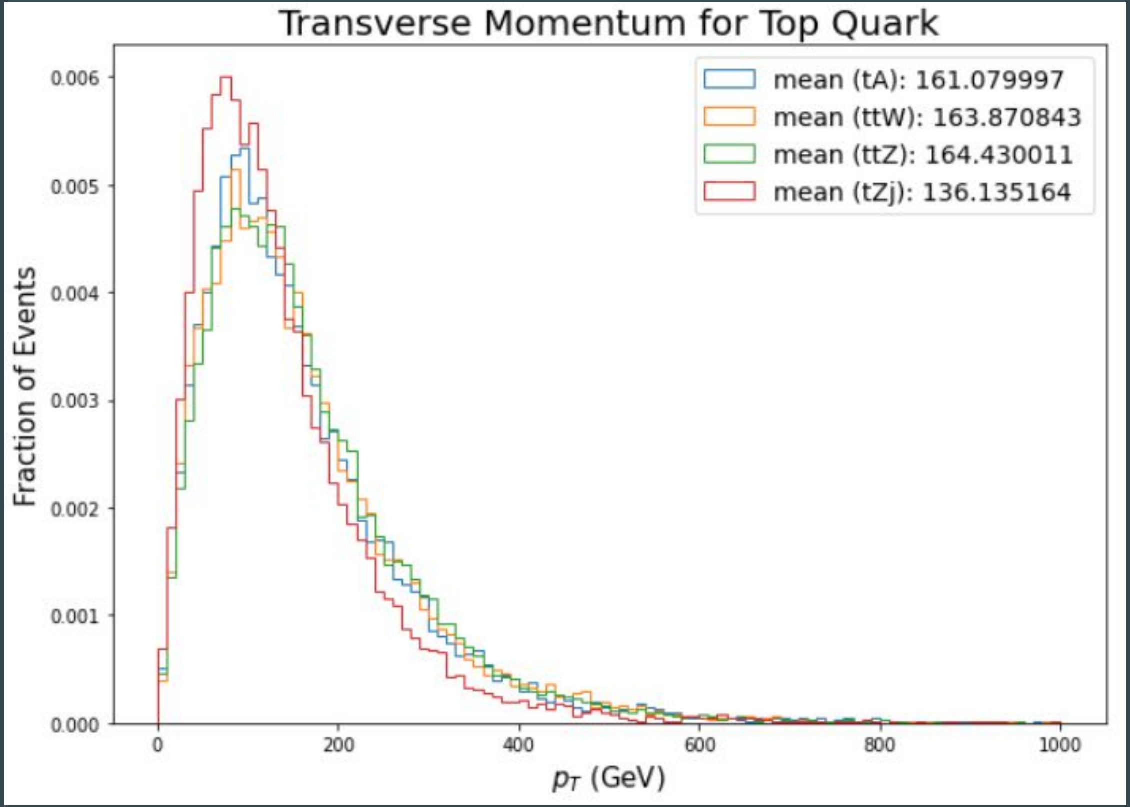




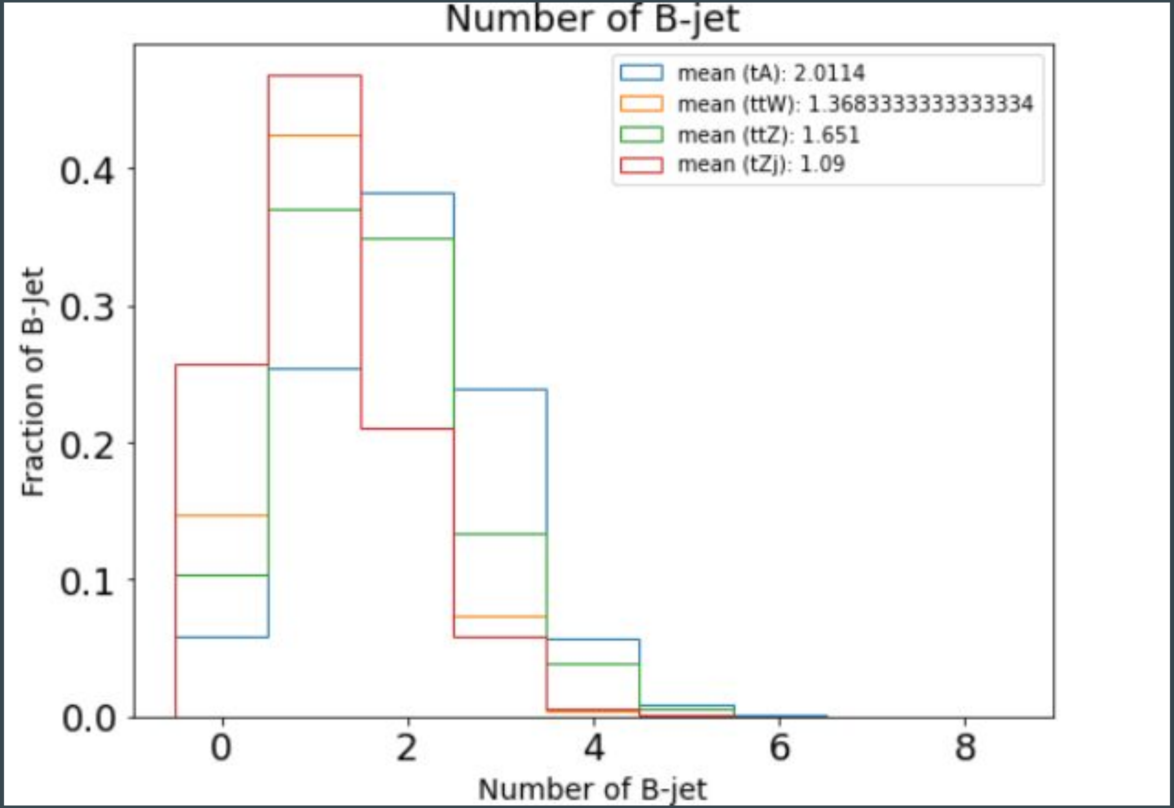
To-do

	Name	Description
0	$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
1	N_{jets}	Number of jets
1	$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
1	$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
1	C^{all}	Centrality ($\sum_i p_{\text{T}i} / \sum_i E_i$) of the leptons and jets
1	$p_{\text{T}}^{\text{lead}}$	Transverse momentum of the leading jet
1	$\Delta R_{b\ell}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets and leptons
1	$\Delta R_{jj}^{\text{avg}}$	Average ΔR between all pairs of jets
1	m_{jjj}	Invariant mass of the closest triplet of jets
1	$E_{\text{T}}^{\text{miss}}$	Missing transverse momentum
1	m_{T}^{W}	W reconstructed transverse mass $m_T(\ell, E_{\text{T}}^{\text{miss}})$ (1L)
1	$N_{\text{LR-jets}}$	Number of large-R jets with a mass above 100 GeV
0	$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} of all large-R jets
0	$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} of all large-R jets

Boosted Top Quark?



Number of b-jets



$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score

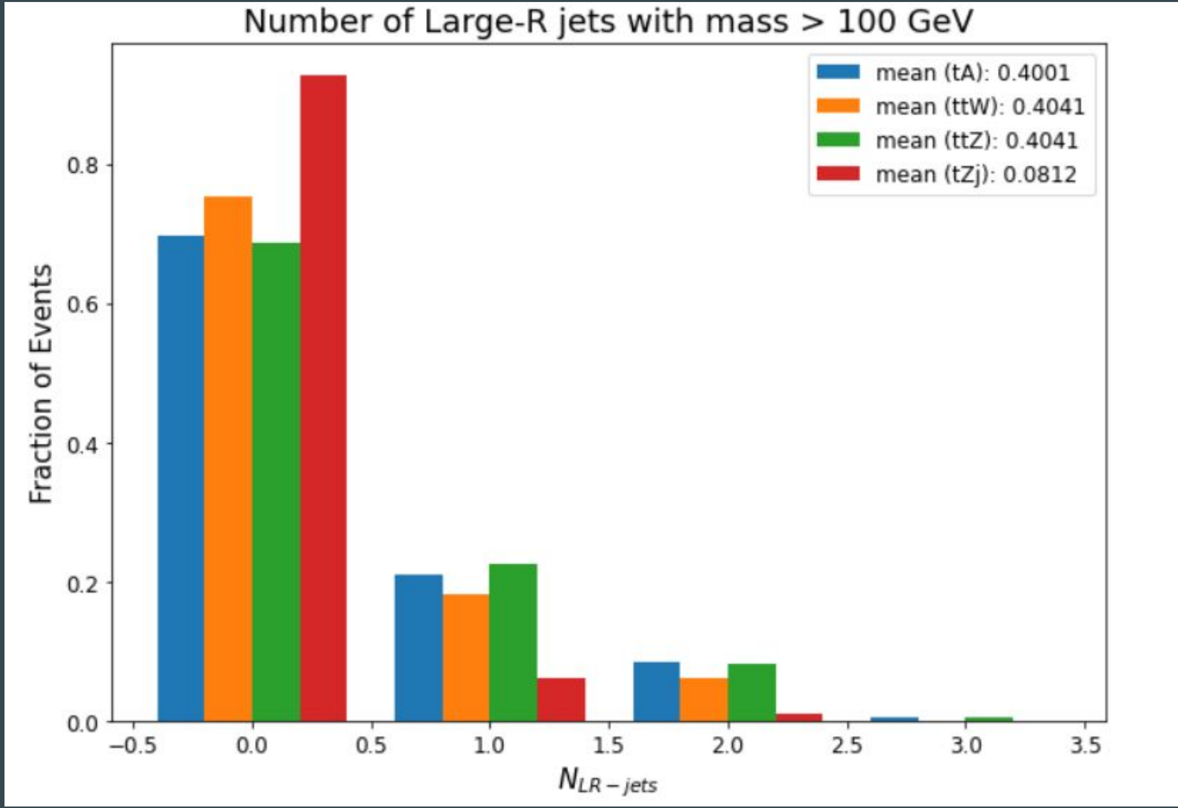
noise [33]. The MV2c10 multivariate algorithm [34] is used to identify jets containing b-hadrons. Each jet is given a score representing the likelihood of the jet to contain a b-hadron. A jet is b-tagged if the score passes a certain threshold, referred to as an operating point (OP). Four OPs are defined with average expected efficiencies for b-jets of 60%, 70%, 77% and 85%. A pseudo-continuous score is assigned to each jet passing these OPs, with an integer value ranging from five for jets that pass the 60% OP to two for jets passing only the 85% OP. A score of one is assigned if the jet does not pass any of the OPs.

$\sum b$-tag — Sum of pseudo-continuous b-tagging score over the six jets with the highest score

```
module BTagging BTagging {
  set JetInputArray JetEnergyScale/jets

  set BitNumber 0

  # add EfficiencyFormula {abs(PDG code)} {efficiency formula as a function of eta and pt}
  # PDG code = the highest PDG code of a quark or gluon inside DeltaR cone around jet axis
  # gluon's PDG code has the lowest priority

  # based on arXiv:1211.4462

  # default efficiency formula (misidentification rate)
  add EfficiencyFormula {0} {0.01+0.000038*pt}

  # efficiency formula for c-jets (misidentification rate)
  add EfficiencyFormula {4} {0.25*tanh(0.018*pt)*(1/(1+ 0.0013*pt))}

  # efficiency formula for b-jets
  add EfficiencyFormula {5} {0.85*tanh(0.0025*pt)*(25.0/(1+0.063*pt))}
```

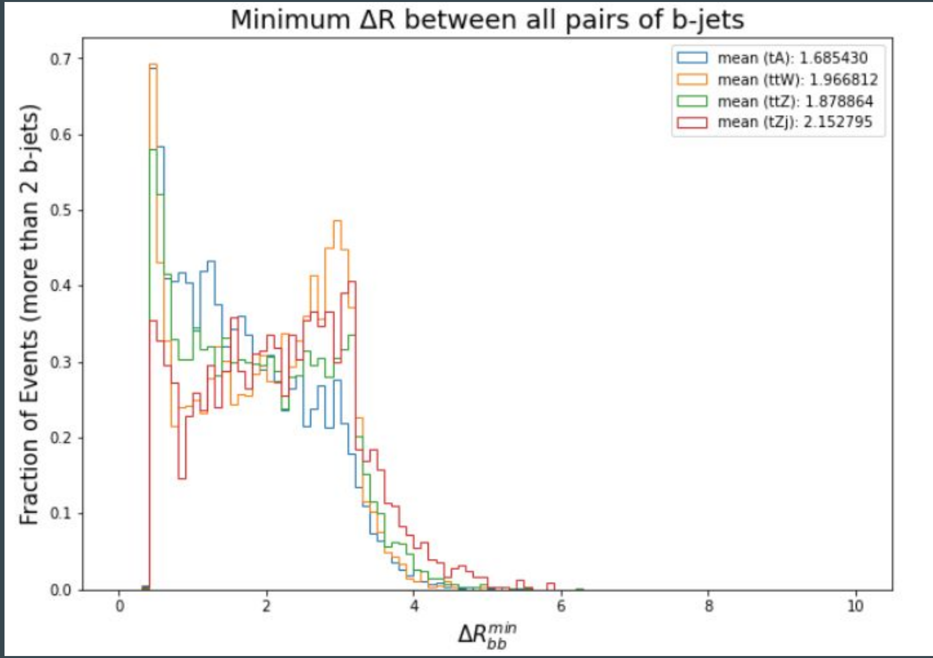
B-tagging Efficiency – The probability of b-jets being tagged.
Mistag is when an algorithm tags something else as a b-jet.

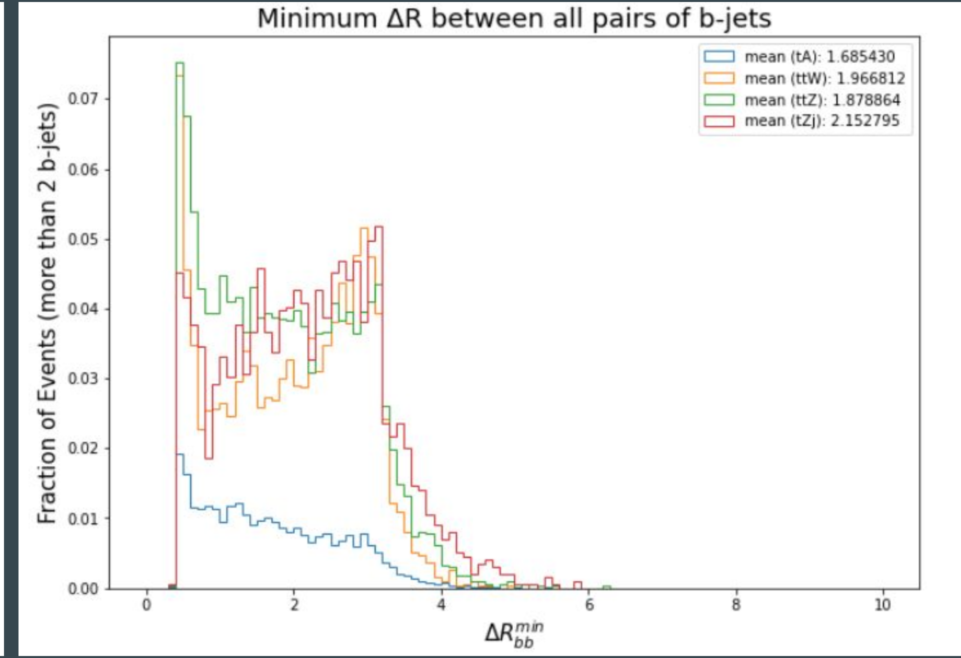
$N_{\text{LR-jets}}$ Number of large-R jets with a mass above 100 GeV



$\Delta R_{bb}^{\text{min}}$ Minimum ΔR between all pairs of b-tagged jets

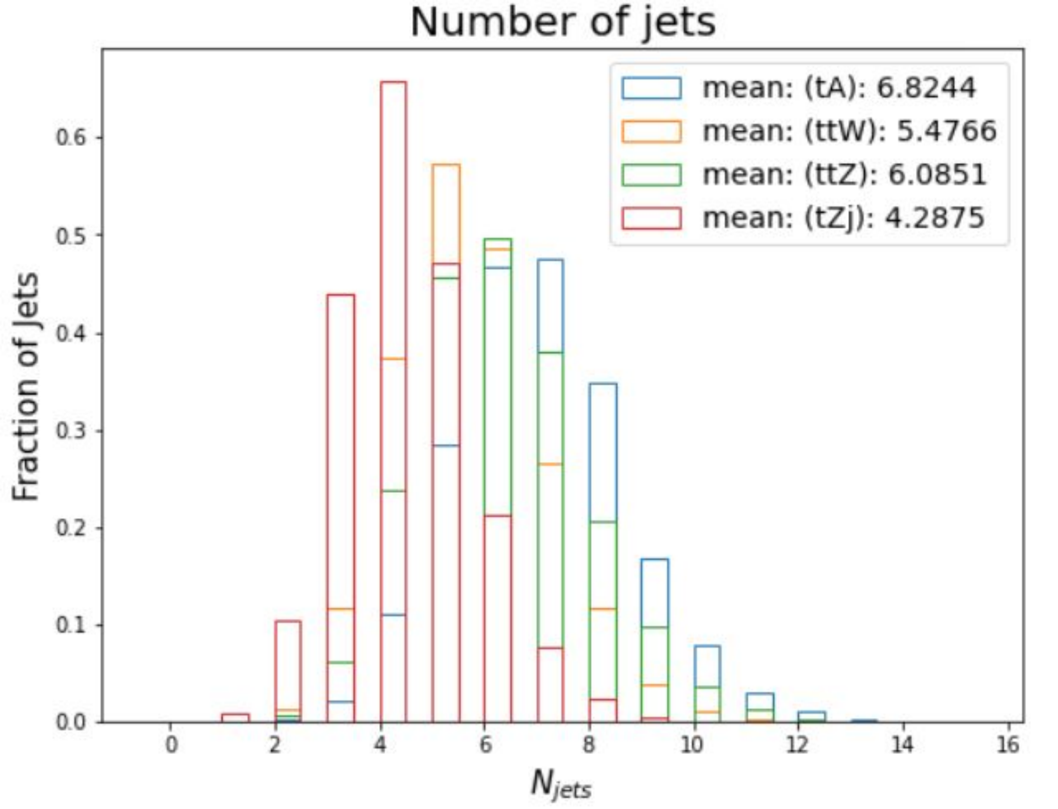
Normalized to cross section:



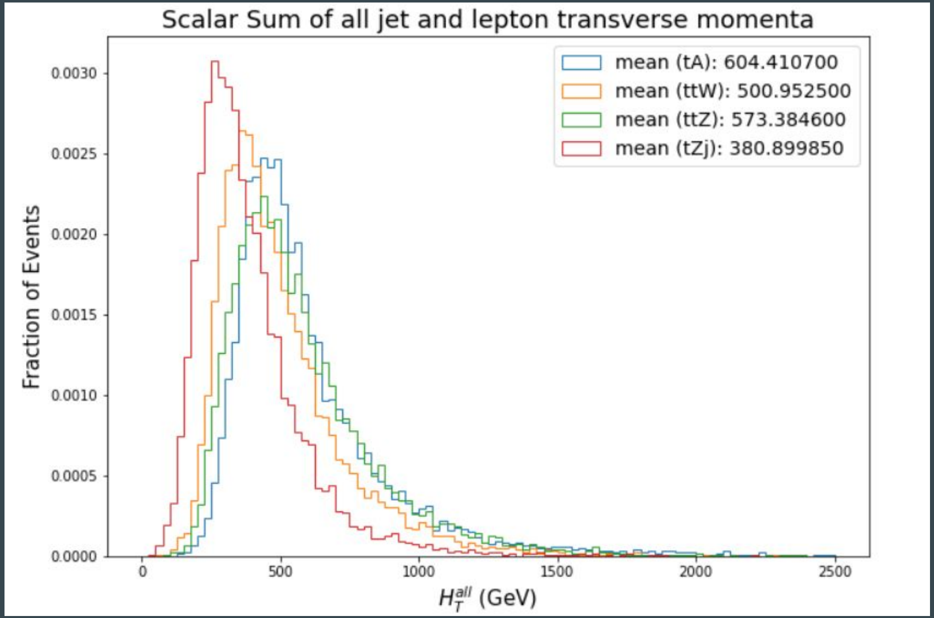


$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}.$$

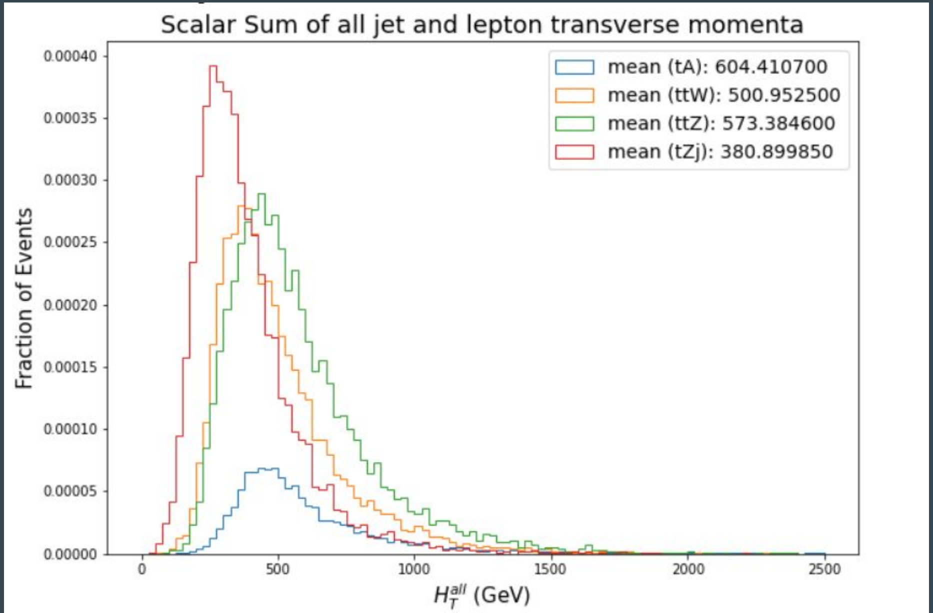
N_{jets} Number of jets



H_T^{all} Scalar sum of all jet and lepton transverse momenta

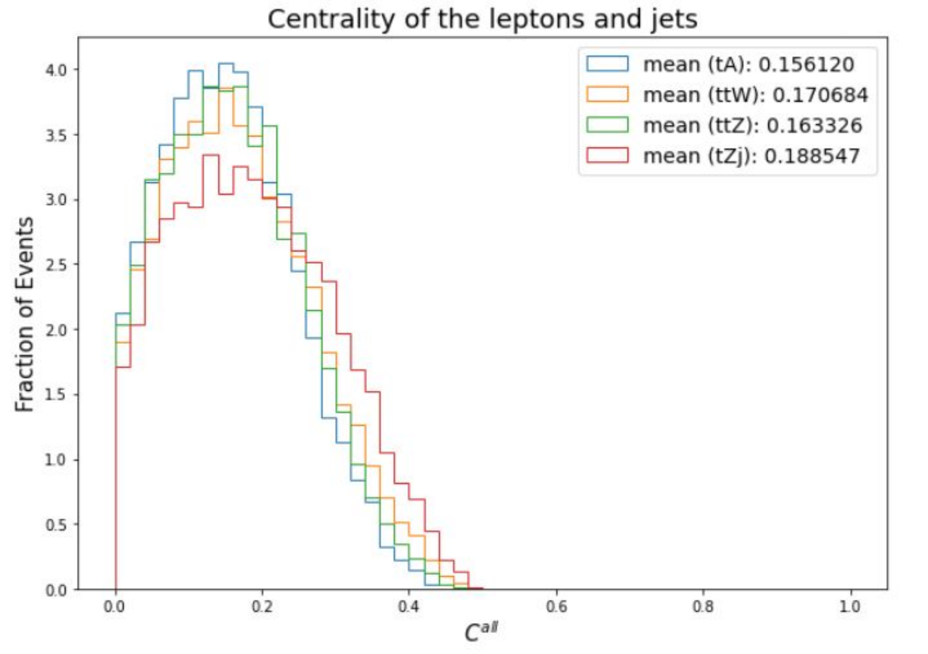


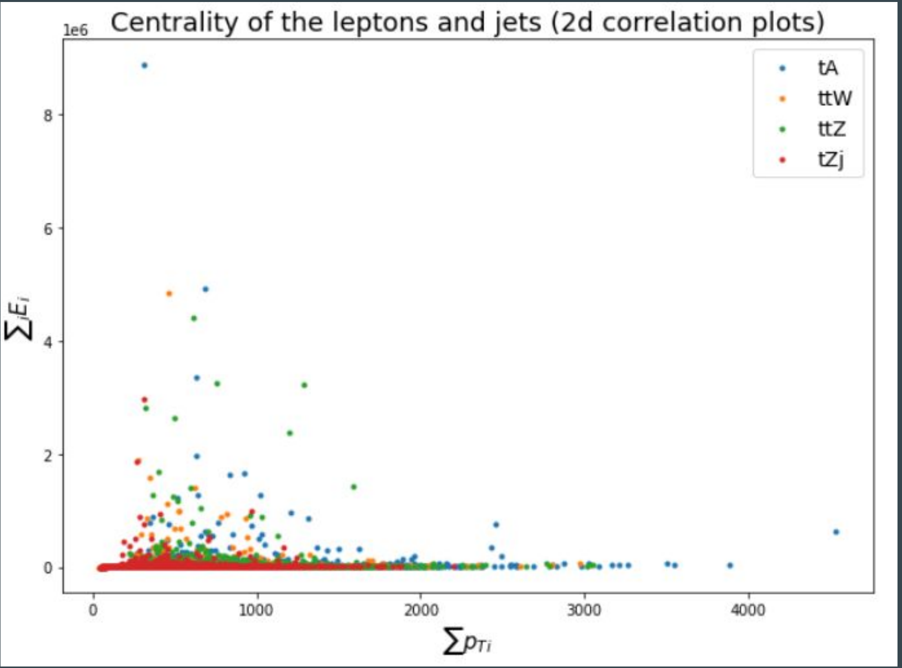
Normalized to cross section:



C^{all} Centrality ($\sum_i p_{\mathrm{T}i} / \sum_i E_i$) of the leptons and jets

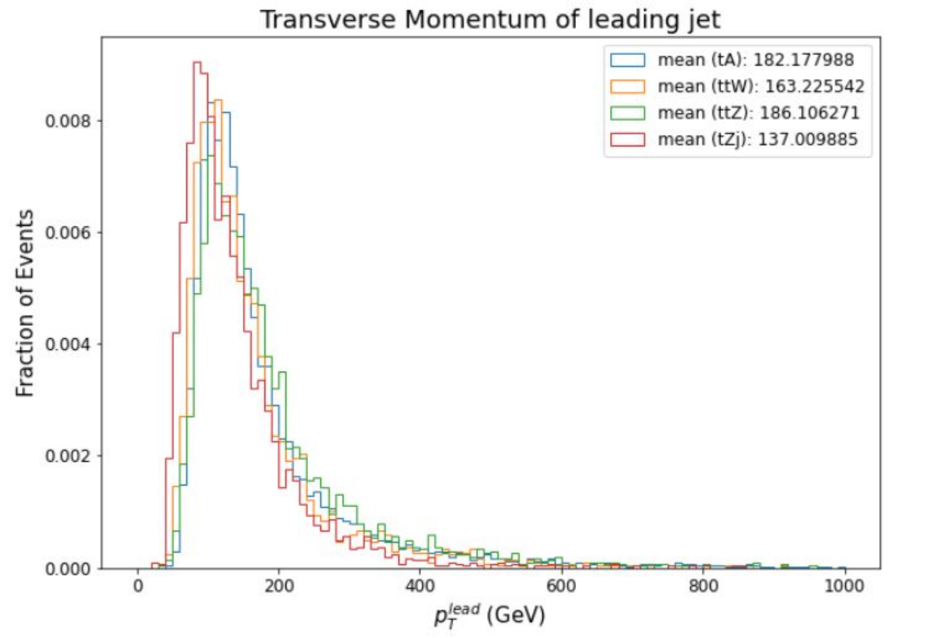
2d Scatter Plot:



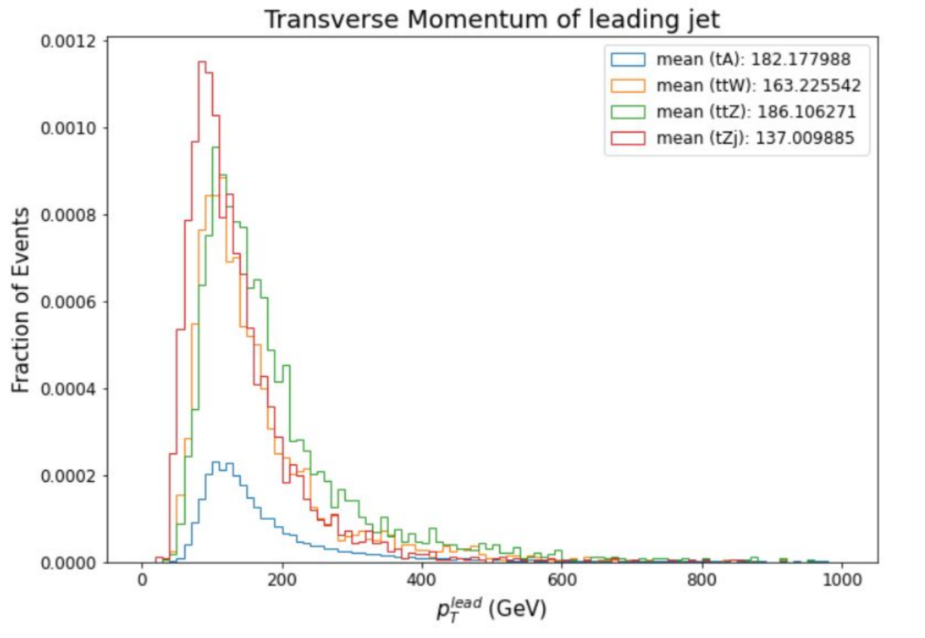


2d correlation plots

p_T^{lead} Transverse momentum of the leading jet

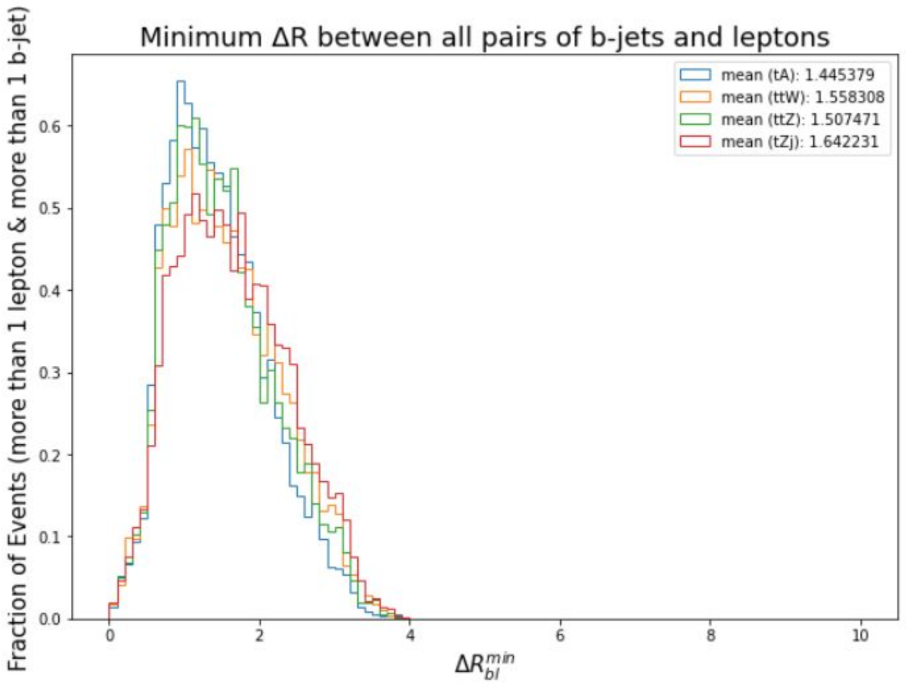


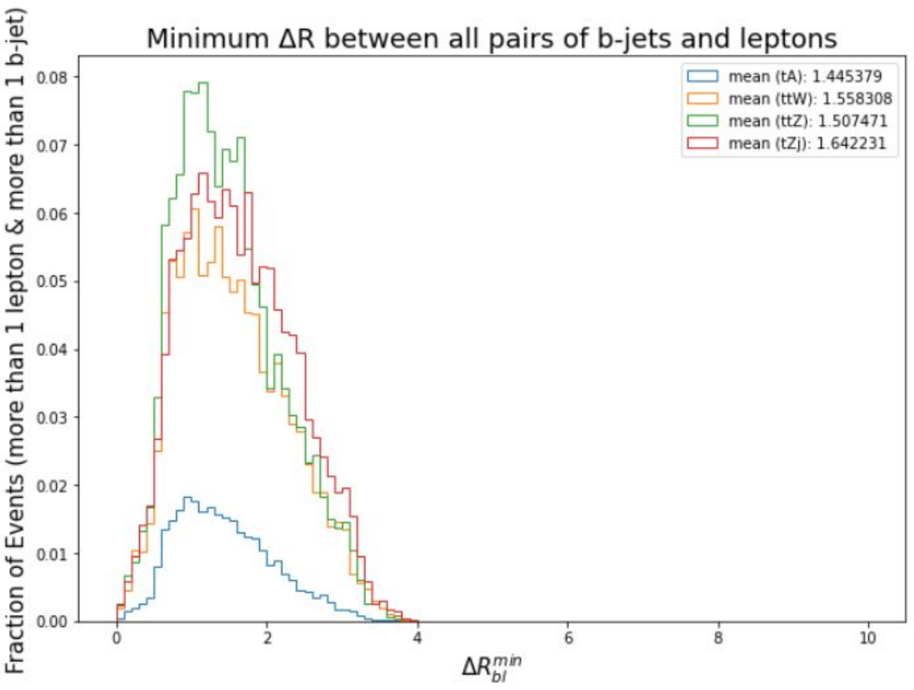
Normalized to cross section:



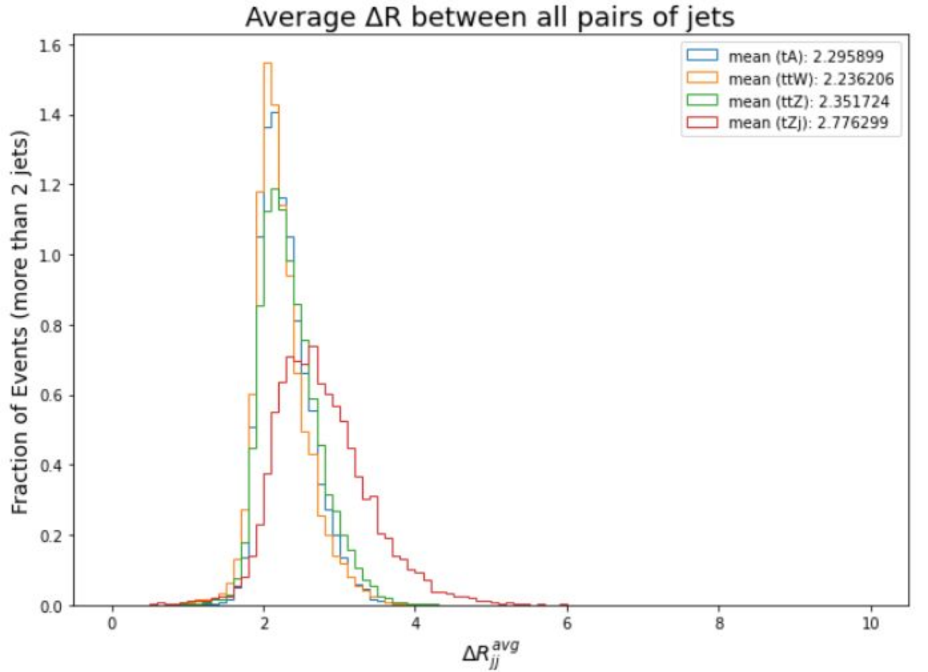
$\Delta R_{b\ell}^{\min}$ Minimum ΔR between all pairs of b-tagged jets and leptons

Normalized to cross section:

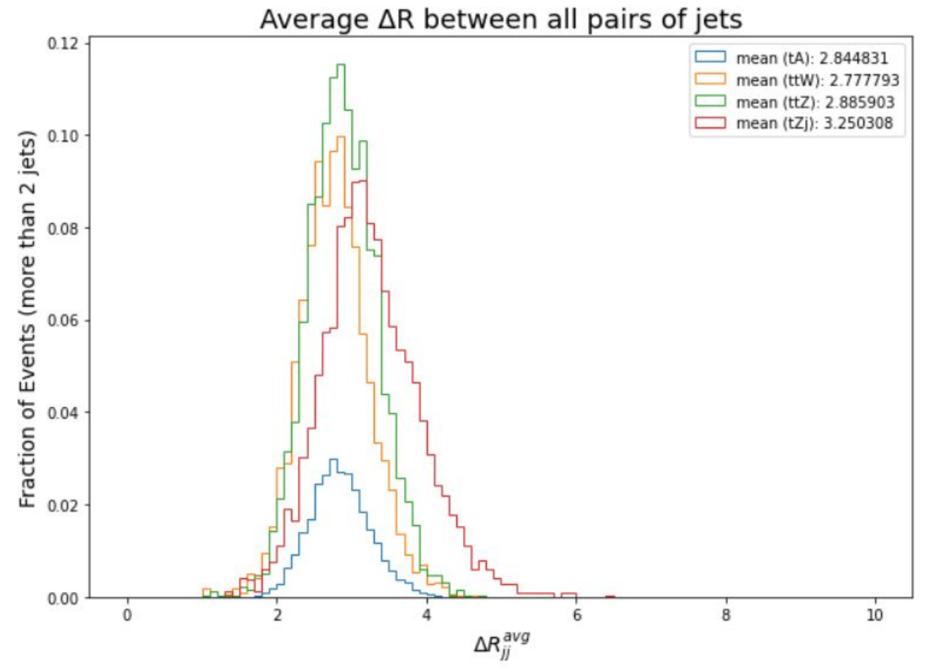




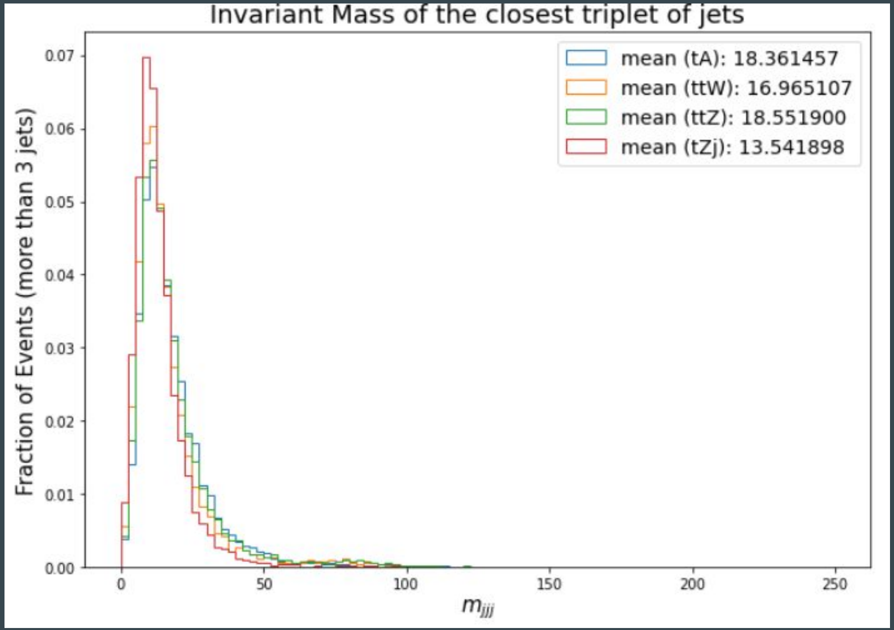
$\Delta R_{jj}^{\text{avg}}$ Average ΔR between all pairs of jets



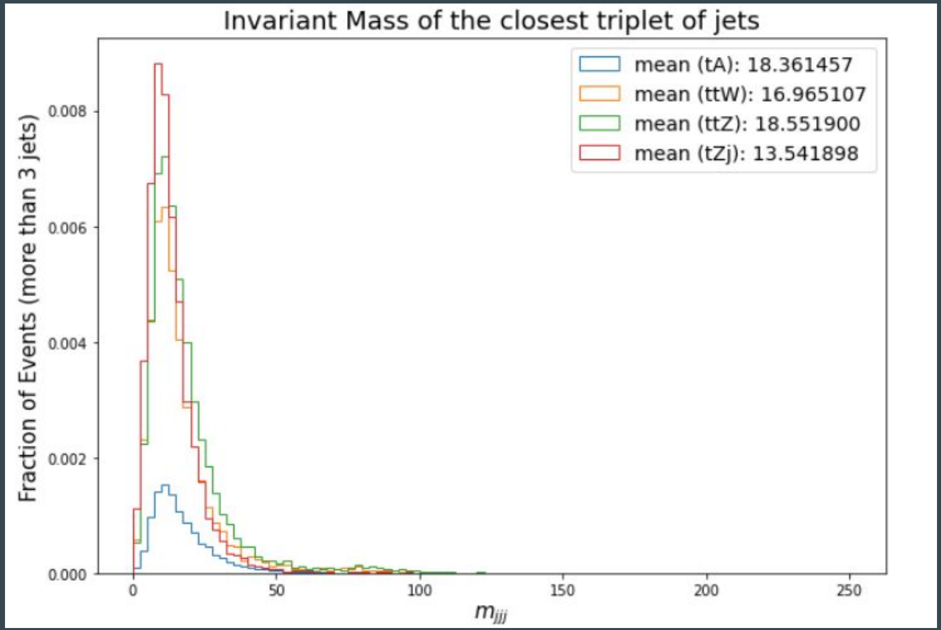
Normalized to cross section:



m_{jjj} Invariant mass of the closest triplet of jets



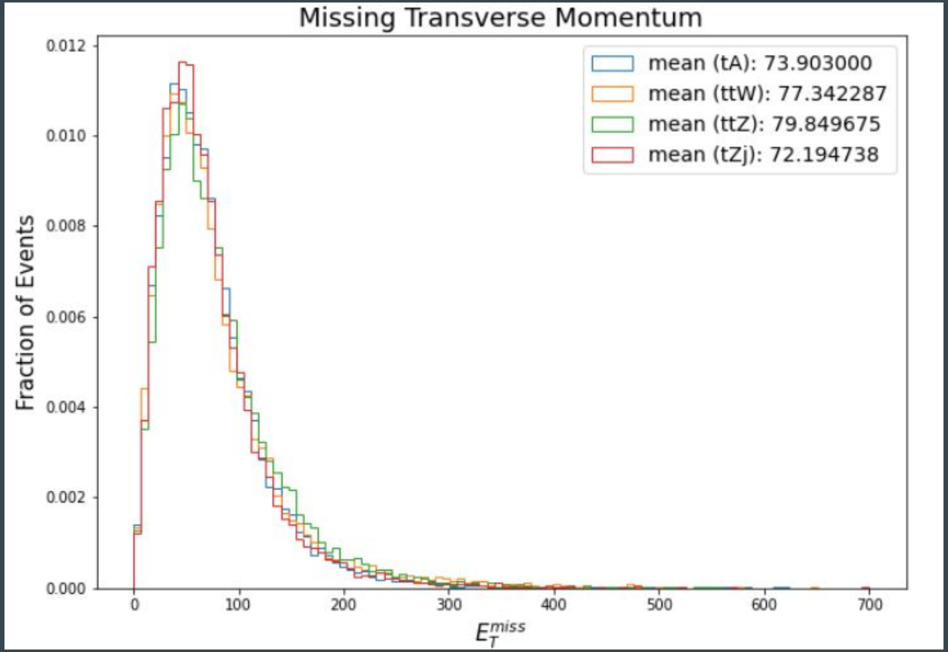
Normalized to cross section:

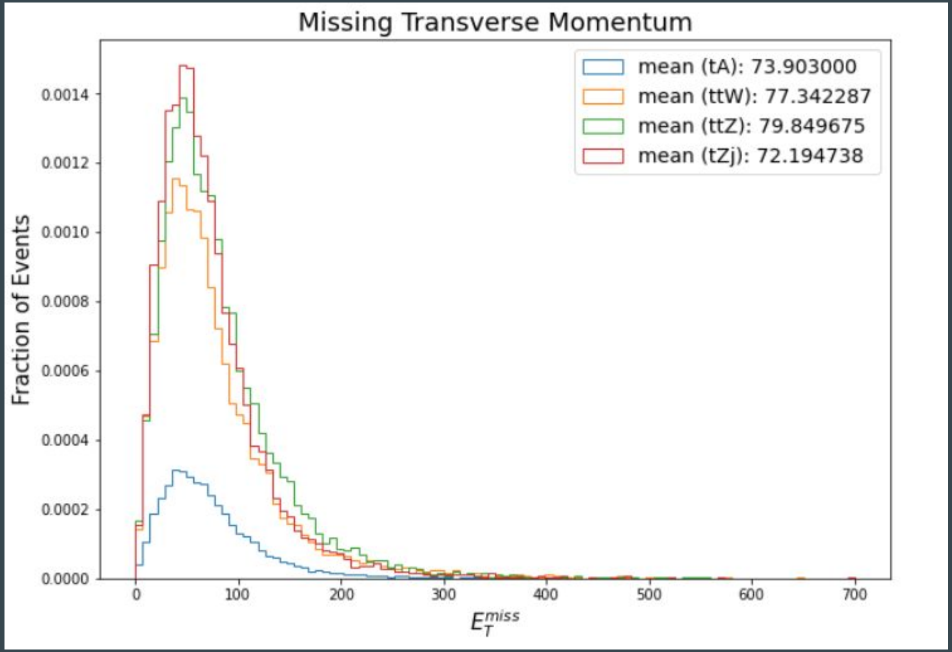


[3] The ΔR of a triplet of jets is defined as $\Delta R_{ijk} = \sqrt{\Delta R_{ij}^2 + \Delta R_{ik}^2 + \Delta R_{jk}^2}$, where i, j, k are the indices of the three jets.

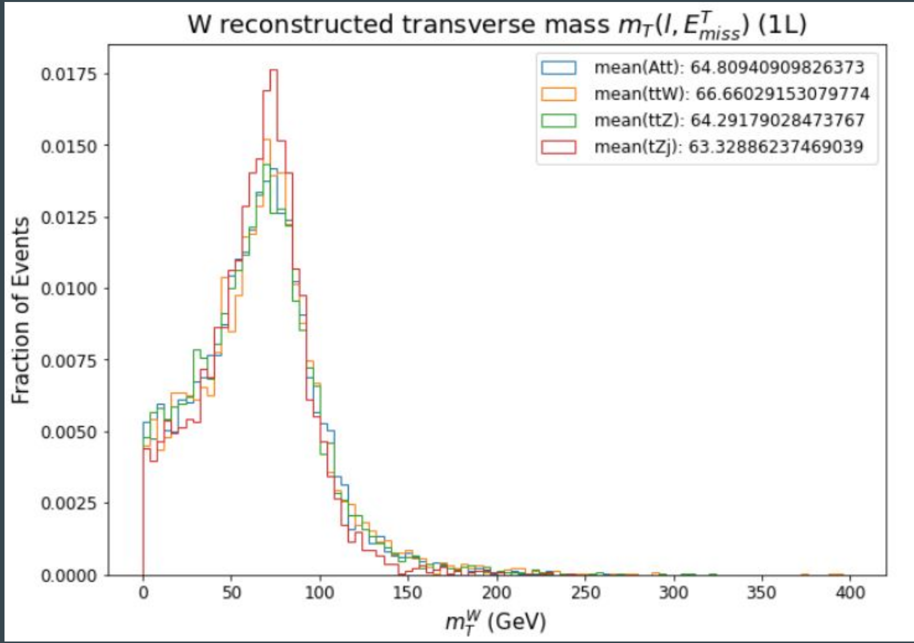
$E_{\mathrm{T}}^{\mathrm{miss}}$ Missing transverse momentum

Normalized to cross section:

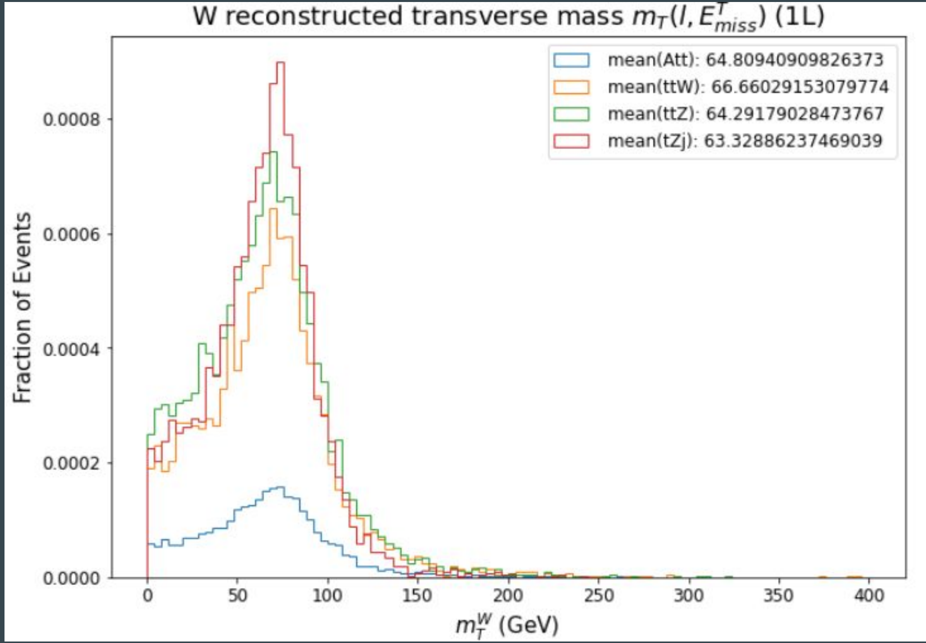




$m_{\mathrm{T}}^{\mathrm{W}}$ W reconstructed transverse mass $m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$ (1L)



Normalized to cross section:



The transverse mass is defined as $\sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$, where $\Delta\phi$ is the azimuthal angle between the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$.

$\sum d_{12}$ Sum of the first k_t splitting scale d_{12} of all large-R jets

4.3 Anti-k_t jet algorithm

This algorithm, introduced and studied in [14], is defined exactly like the standard k_t algorithm, except for the distance measures which are now given by

$$d_{ij} = \min(1/p_{ti}^2, 1/p_{tj}^2)\,\Delta R_{ij}^2/R^2\,, \tag{7a}$$

$$d_{iB} = 1/p_{ti}^2\,. \tag{7b}$$

While it is a sequential recombination algorithm like k_t and Cambridge/Aachen, the anti-k_t algorithm behaves in some sense like a 'perfect' cone algorithm, in that its hard jets are exactly circular on the y-ϕ cylinder [14]. To use this algorithm, define

```
JetDefinition jet_def(antikt_algorithm, R);
```

4.4 Generalised k_t jet algorithm

The "generalised k_t" algorithm again follows the same procedure, but depends on an additional continuous parameter p, and has the following distance measure:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p})\,\Delta R_{ij}^2/R^2\,, \tag{8a}$$

$$d_{iB} = p_{ti}^{2p}\,. \tag{8b}$$

For specific values of p, it reduces to one or other of the algorithms list above, k_t ($p = 1$), Cambridge/Aachen ($p = 0$) and anti-k_t ($p = -1$). To use this algorithm, define

```
JetDefinition jet_def(genkt_algorithm, R, p);
```

1. Use kt algorithm for FastJetFinder and FatJetFinder?
2. Input for i and j are particles from final states?

[5] The k_t splitting scale d_{ij} is defined as the recombination distance between the jet constituents from a k_t algorithm with radius parameter R: $d_{ij} = \min(p_{\mathrm{T}i}^2, p_{\mathrm{T}j}^2) \times \Delta R_{ij}^2/R^2$.

$\sum d_{23}$	Sum of the second k_t splitting scale d_{23} of all large-R jets

Information for rest of plots

The ΔR of a triplet of jets is defined as $\Delta R_{ijk} = \sqrt{\Delta R_{ij}^2 + \Delta R_{ik}^2 + \Delta R_{jk}^2}$, where i, j, k are the indices of the three jets.

The k_t splitting scale d_{ij} is defined as the recombination distance between the jet constituents from a k_t algorithm with radius parameter R: $d_{ij} = \min(p_{\mathrm{T}i}^2, p_{\mathrm{T}j}^2) \times \Delta R_{ij}^2 / R^2$.

Likelihood

- Likelihood is the compatibility of the Hypothesis with a given data set.
  - depends on the data
  - NOT the probability of the hypothesis given the data

$$P(x,a) = e^{-a}\frac{a^x}{x!} \quad .$$

Poisson Probability

$$L(a,x) = e^{-a}\frac{a^x}{x!} \quad .$$

Likelihood Function

x = counts
a = mean

$$L(H) = P(x\,|\,H)$$

$$P(x\,|\,H) \neq P(H\,|\,x)$$

Bayes Theorem

$$P(H\,|\,x) = \frac{P(x\,|\,H)\cdot P(H)}{\Sigma_H P(x\,|\,H)P(H)}$$

$$P(H\,|\,x) \approx P(x\,|\,H)\cdot P(H)$$

Parameter of the model

- import gen2HDM model (insert the information for H0, A0)
- set the process (H, A -> t, t-bar) with defined decay process
- The mass of A and H set to 400 GeV
- rho_tc = 0.5, rho_tu = 0.2, and rho_tt = 0.5 (upper limit at ATLAS)
- Enter [rho_tc, mA, mt, Nc_] into mathematica to calculate the delay width.
- enable lhapdf 247000

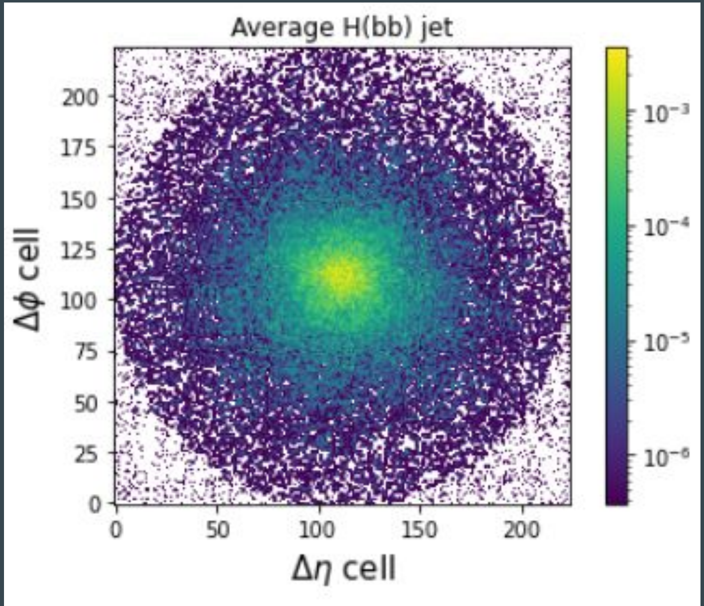
```
import model gen2HDM_UFO
define p = p b b~
define j = p
generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t~ A0 QCD=99, (t~ > w-  b~ , w- > l- vl~) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t~ A0 j QCD=99, (t~ > w-  b~ , w- > l- vl~) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )

output Att_400

launch Att_400

shower=PYTHIA8
detector=delphes

set rtc 0.5
set rtt 0.5
set rtu 0
set nevents 5000
set ebeam1 7000.0
set ebeam2 7000.0
set pdlabel lhapdf
set lhaid 247000
set MA0 400
set MS0 400
set ebeam1 7000.0
set ebeam2 7000.0
```

Prove: setting MH0 won't affect the cross section of pp -> tA + t~ A

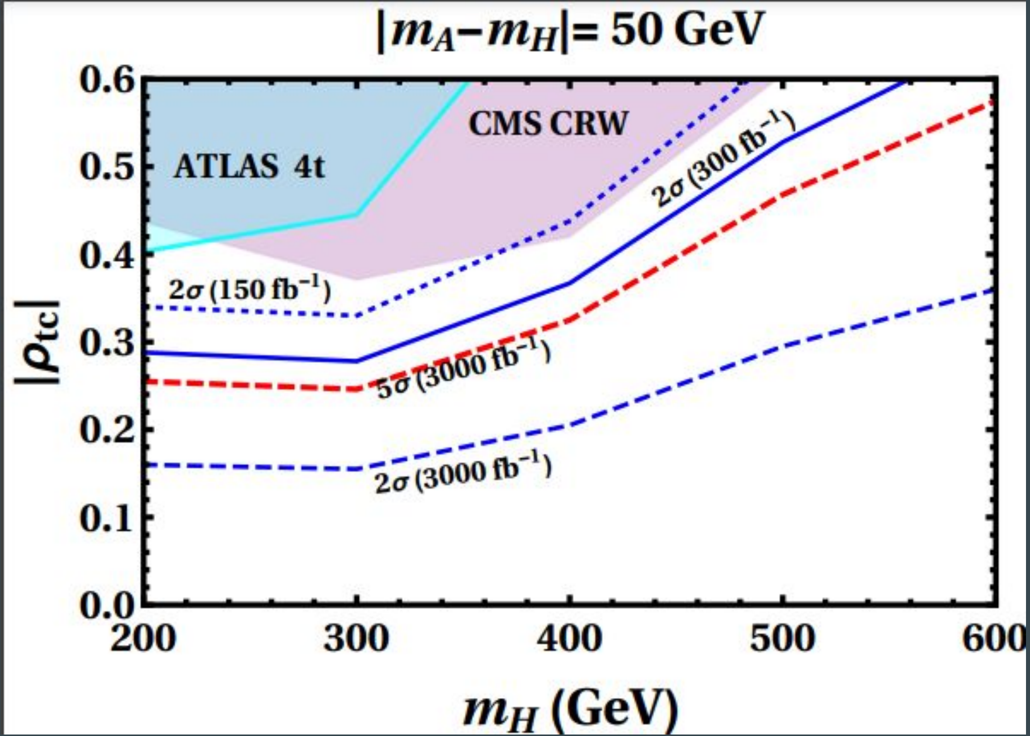
Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	1.201 ± 0.0056 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 7000.0 x 7000.0 GeV	tag_1	0.609 ± 0.0027 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_03	p p 7000.0 x 7000.0 GeV	tag_1	0.3177 ± 0.0015 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_04	p p 7000.0 x 7000.0 GeV	tag_1	0.1785 ± 0.00096 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_05	p p 7000.0 x 7000.0 GeV	tag_1	1.201 ± 0.007 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_06	p p 7000.0 x 7000.0 GeV	tag_1	0.6015 ± 0.0032 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_07	p p 7000.0 x 7000.0 GeV	tag_1	0.3219 ± 0.0019 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_08	p p 7000.0 x 7000.0 GeV	tag_1	0.1795 ± 0.0011 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_09	p p 7000.0 x 7000.0 GeV	tag_1	1.213 ± 0.0054 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_10	p p 7000.0 x 7000.0 GeV	tag_1	0.6071 ± 0.0032 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_11	p p 7000.0 x 7000.0 GeV	tag_1	0.3198 ± 0.0016 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_12	p p 7000.0 x 7000.0 GeV	tag_1	0.178 ± 0.00081 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_13	p p 7000.0 x 7000.0 GeV	tag_1	1.206 ± 0.0055 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_14	p p 7000.0 x 7000.0 GeV	tag_1	0.6063 ± 0.0028 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_15	p p 7000.0 x 7000.0 GeV	tag_1	0.3196 ± 0.0014 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_16	p p 7000.0 x 7000.0 GeV	tag_1	0.1781 ± 0.0008 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation

Machine Learning

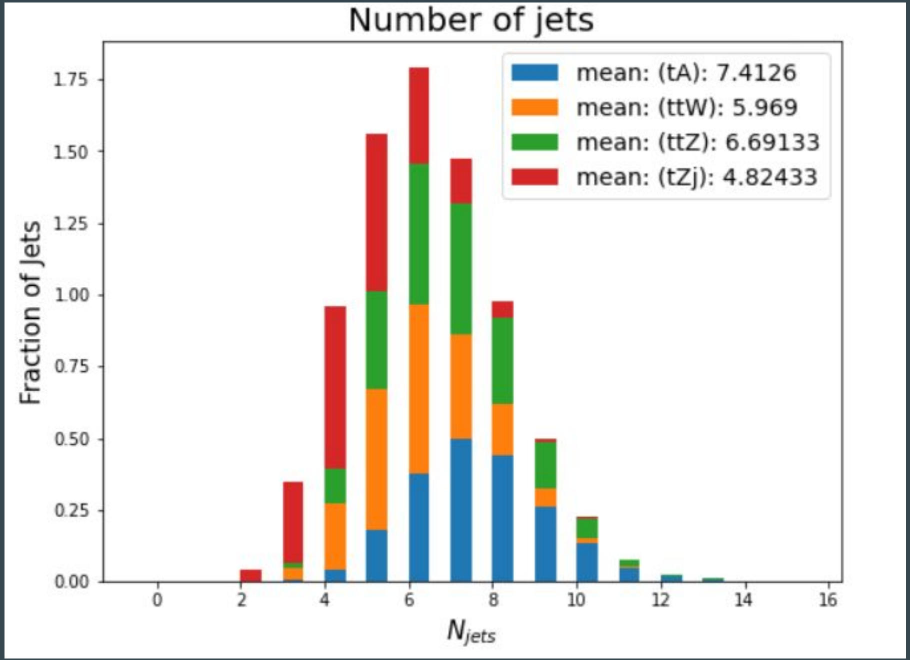
- https://jmduarte.github.io/capstone-particle-physics-domain/weeks/05-jet-images.html
- use particles’ eta and psi relate to its pt as input
- tt~Z, tt~W, tZ+j, 3t+j, 3t+W, 4t, and tt~h

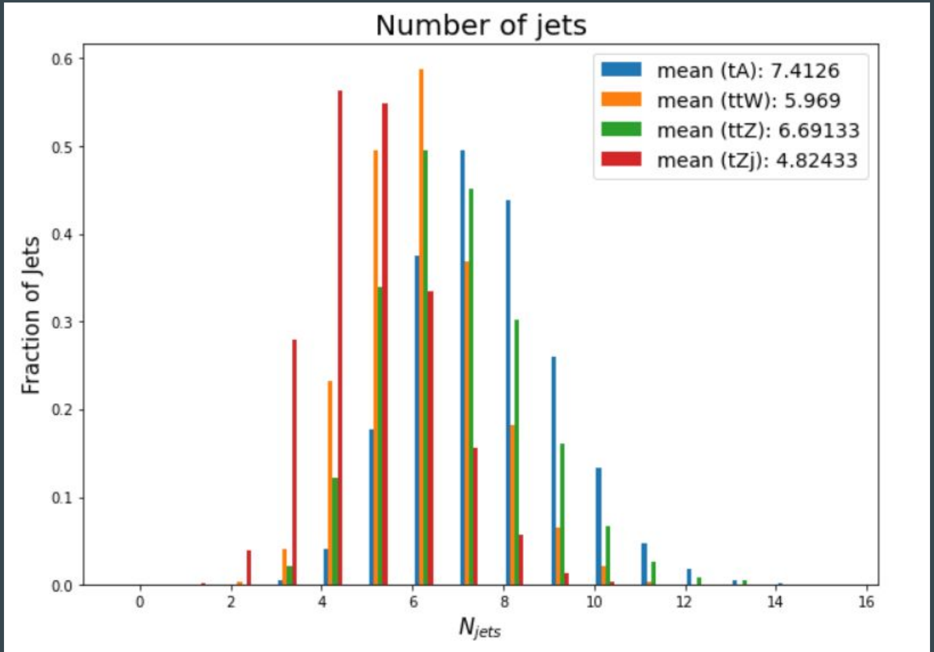


Back up slide



N_{jets} Number of jets





10/20/2021 update

- Finished reading document “Top-Assisted Di-Higgs boson Production Motivated by Baryogenesis” and some of its references BUT not understand all the material.
- Successfully ran the gen2HDM_UFO model and generate events

Code:

```
import model gen2HDM_UFO
define p = p b b~
define j = p
generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t~ A0 QCD=99, (t~ > w-  b~ , w- > l- vl~) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t~ A0 j QCD=99, (t~ > w-  b~ , w- > l- vl~) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
output sig_schannel

open index.html
launch sig_schannel

```

S-channel vs T-channel

- s-channel corresponds to the particles 1,2 joining into an intermediate particle that eventually splits into 3,4: the s-channel is the only way that resonances and new unstable particles may be discovered provided their lifetimes are long enough that they are directly detectable.
- The t-channel represents the process in which the particle 1 emits the intermediate particle and becomes the final particle 3, while the particle 2 absorbs the intermediate particle and becomes 4.

Reference

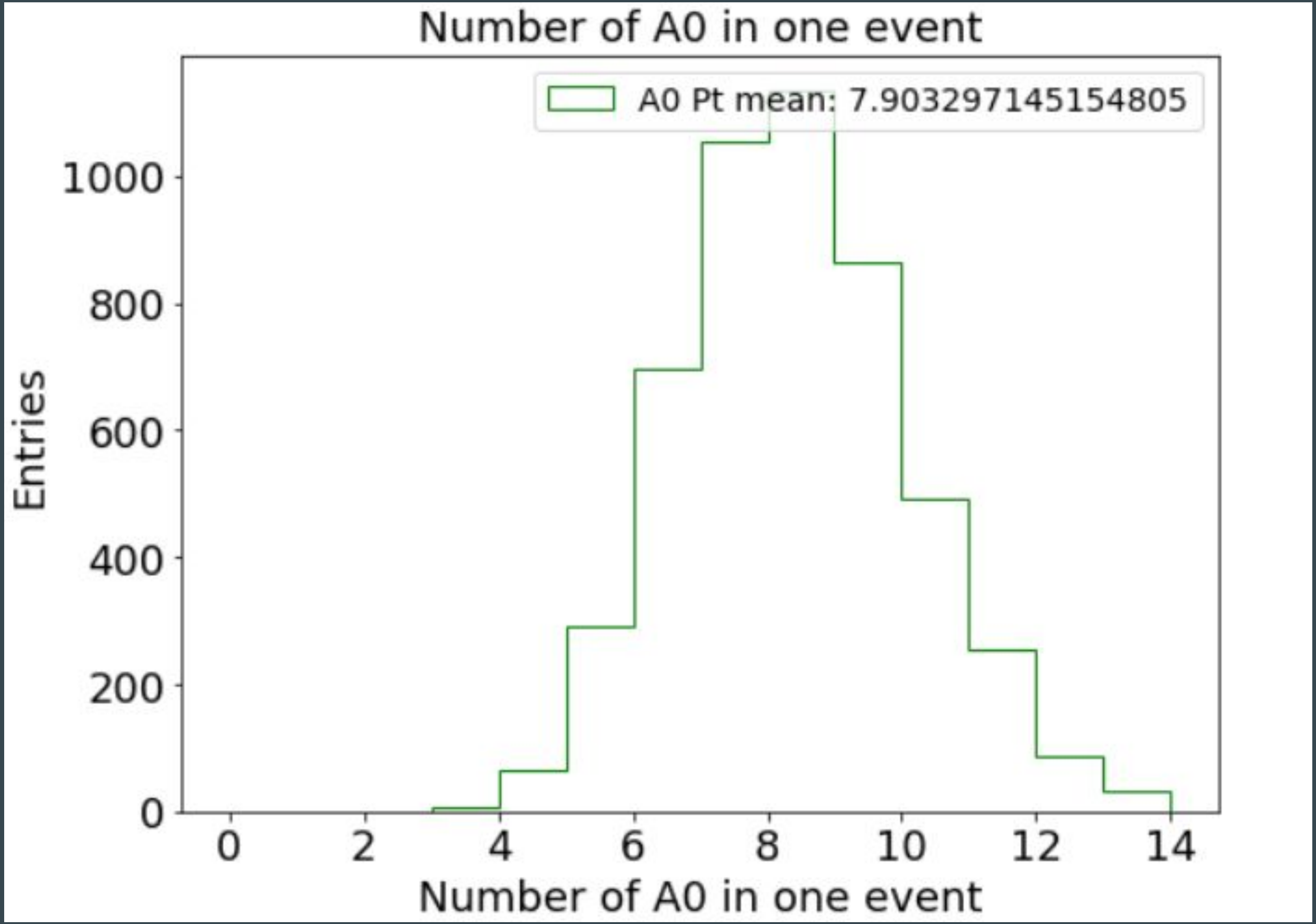
https://www.sciencedirect.com/science/article/pii/S0550321320302273 (Feynman Diagrams)

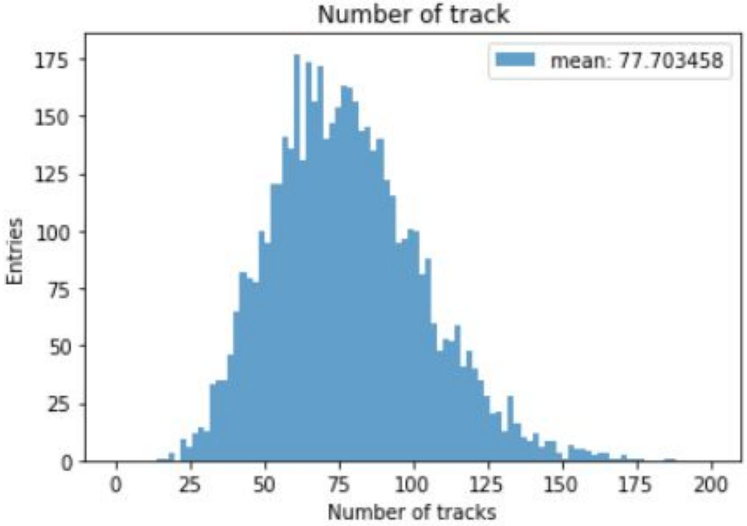
Lagrangian

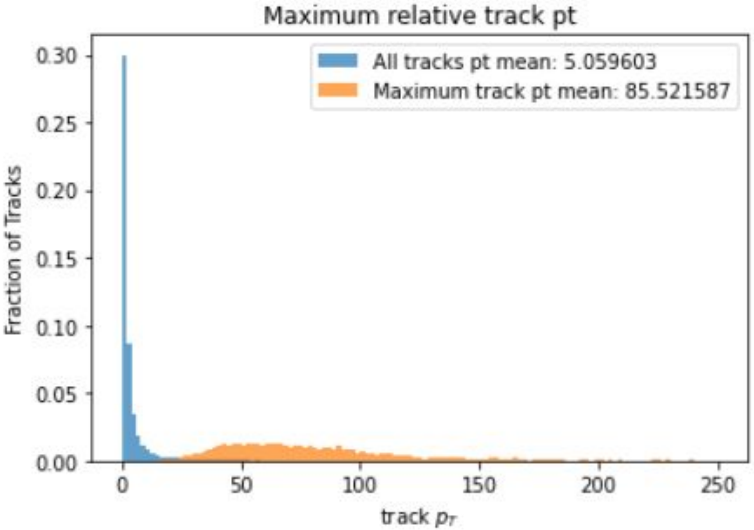
- rho_tc
- s = sin(), c = cos()

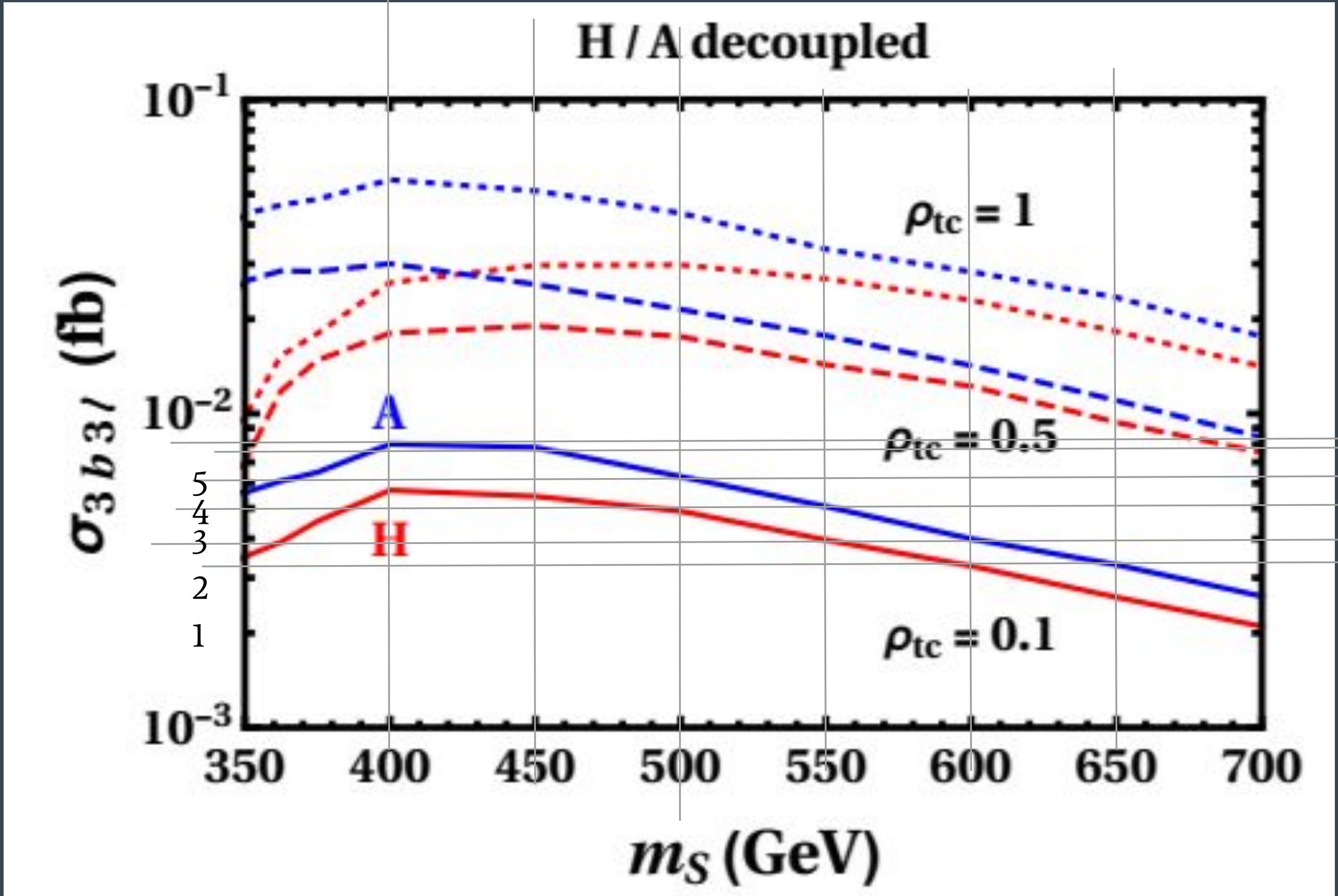
$$\mathscr{L} = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda^f_{ij} s_\gamma + \rho^f_{ij} c_\gamma) h$$

$$+ (\lambda^f_{ij} c_\gamma + \rho^f_{ij} s_\gamma) H - i\, \mathrm{sgn}(Q_f) \rho^f_{ij} A] R f_j + \mathrm{H.c.}\,,$$

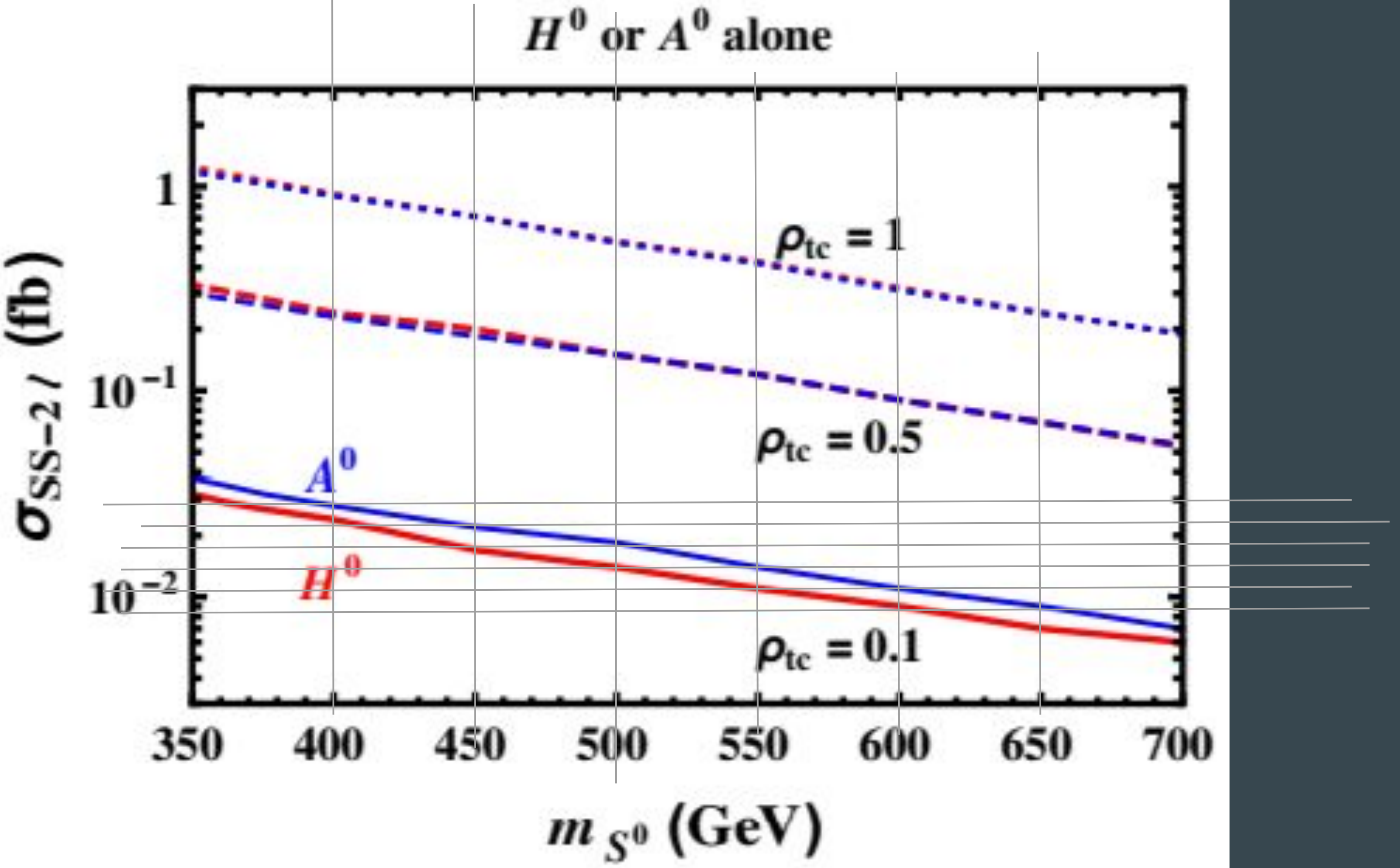

Number of A0 in one event
A0 Pt mean: 7.903297145154805
Entries
0
200
400
600
800
1000
0
2
4
6
8
10
12
14
Number of A0 in one event


Number of track
mean: 77.703458
Entries
Number of tracks


Maximum relative track pt
All tracks pt mean: 5.059603
Maximum track pt mean: 85.521587
Fraction of Tracks
track p_T



H / A decoupled
10^{-1}
10^{-2}
10^{-3}
σ_{3b3l} (fb)
5
4
3
2
1
A
H
$\rho_{tc} = 1$
$\rho_{tc} = 0.5$
$\rho_{tc} = 0.1$
350
400
450
500
550
600
650
700
m_S (GeV)



H^0 or A^0 alone
$\rho_{tc} = 1$
$\rho_{tc} = 0.5$
$\rho_{tc} = 0.1$
A^0
H^0
1
10^{-1}
10^{-2}
350
400
450
500
550
600
650
700
$\sigma_{SS\text{-}2\ell}$ (fb)
m_{S^0} (GeV)

Distribution/pdf	Example use in HEP
Binomial	Branching ratio
Multinomial	Histogram with fixed *N*
Poisson	Number of events found
Uniform	Monte Carlo method
Exponential	Decay time
Gaussian	Measurement error
Chi-square	Goodness-of-fit
Cauchy	Mass of resonance
Landau	Ionization energy loss
Beta	Prior pdf for efficiency
Gamma	Sum of exponential variables
Student's *t*	Resolution function with adjustable tails

Statistical Uncertainties:

- ★ Random fluctuations
  - e.g. shot noise, measuring small currents, how many electrons arrive in a fixed time
  - Tossing a coin N times, how many heads

Systematic Uncertianies:

- ★ Biases
  - e.g. energy calibration wrong
  - Thermal expansion of measuring device
  - Imperfect theoretical predications

Blunders, i.e. errors:

- ★ Mistakes
  - Forgot to include a particular background in analysis
  - Bugs in analysis code

Perturbative expansion

$d\hat{\sigma}_{ab\to X}(\hat{s}, \mu_F, \mu_R)$ **Parton-level cross section**

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter, schematically:

$$\hat{\sigma} = \sigma^{\mathrm{Born}}\left(1 + \frac{\alpha_s}{2\pi}\sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)} + \dots\right)$$

LO predictions

NLO corrections

NNLO corrections

N3LO or NNNLO corrections

- Including higher corrections improves predictions and reduces theoretical uncertainties