

# Triple Top Model (ML)

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# 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 Z<sub>2</sub> 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<sub>±</sub>.
- neutral charge (h, H, A) and +- charged (H ±)

# 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.

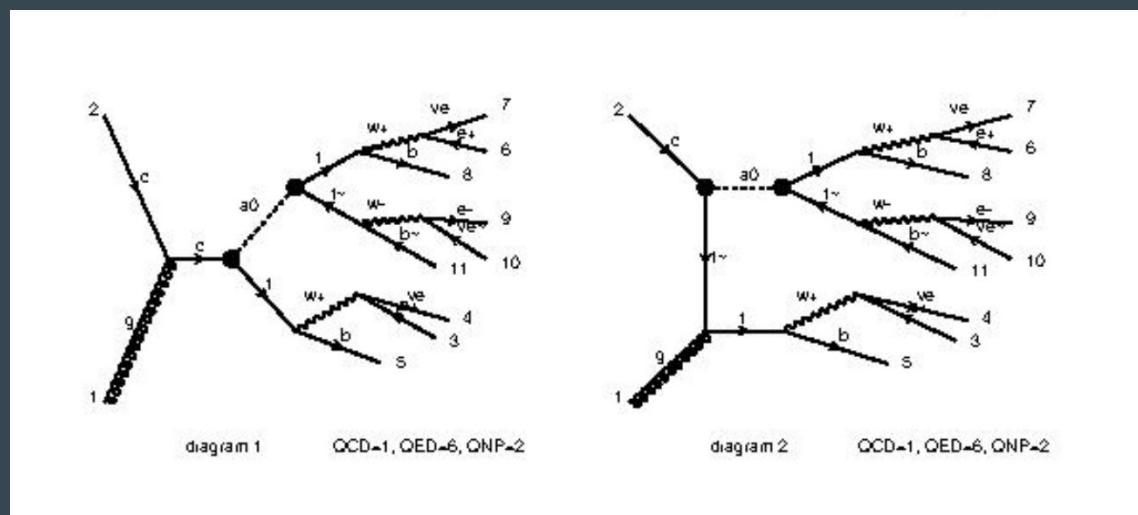
Before Spontaneous Symmetry Breaking:

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

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

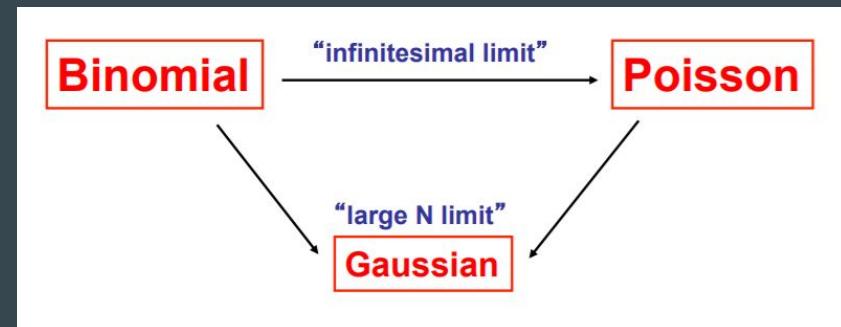
# Triple Top

- 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  $\rightarrow$  tS (S = H, A)  $\rightarrow$  tt t-bar
- SM: cg  $\rightarrow$  c  $\rightarrow$  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 =  $\varepsilon = k/n$
  - $\sigma^2 = \varepsilon^*(1-\varepsilon)/n$ 
    - i.e. 90/100 events pass trigger requirements
    - $\varepsilon = 0.90 \pm 0.03$

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

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

# Derive mean & variance for Binomial Distribution

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

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

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

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

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

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

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

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

$$\text{Var}(X) = E(X^2) - [E(X)]^2$$

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

↓  
[ $x(x-1) + x$ ]

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

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

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

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

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

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

$$\text{Var}(X) = n^2 p^2 - np^2 + np - n^2 p^2$$

$$= np(1-p)$$

$$= npq$$

# Poisson Distribution

$$\Pr(X=k) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad \lambda = \mathbb{E}(X) = \text{Var}(X).$$

- discrete random process with **fixed mean** ( $\lambda$ )
- From binomial distribution,

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

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

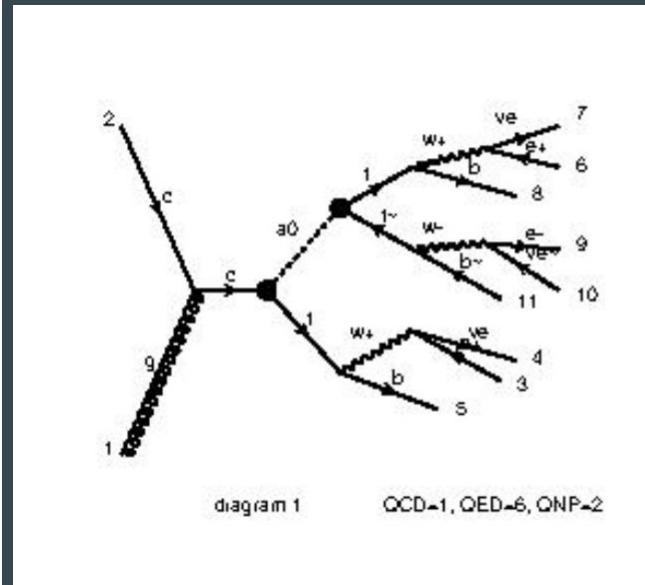
# Gaussian Distribution

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

- parameters: mean ( $\mu$ ) & standard deviation ( $\sigma$ )
- 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
  - $1\sigma$ : 68%,  $2\sigma$ : 95%,  $3\sigma$ : 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 ( $\sim 100$  events) generation, one would expect  $\sim 8\%$  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	$0.03485 \pm 7.7e-05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.02053 \pm 4.3e-05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.01266 \pm 2.5e-05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.007965 \pm 1.6e-05 \pm \text{systematics}$	10000

MS0 400	$\sigma:$	0.22095%
MS0 500	$\sigma:$	0.20945%
MS0 600	$\sigma:$	0.19747%
MS0 700	$\sigma:$	0.20088%

Figure:  $p p \rightarrow t t^{\sim} S0$ , with  $\rho_{tt} = 1$  &  $MS0 = [400, 500, 600, 700]$

# Cross Section vs Mass

Paper:

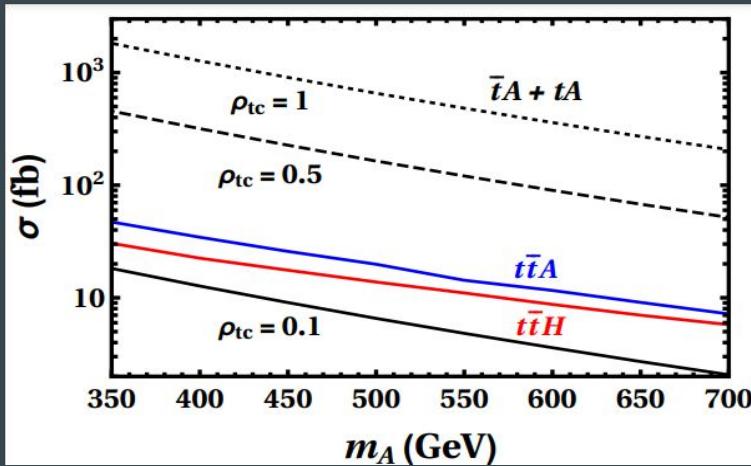
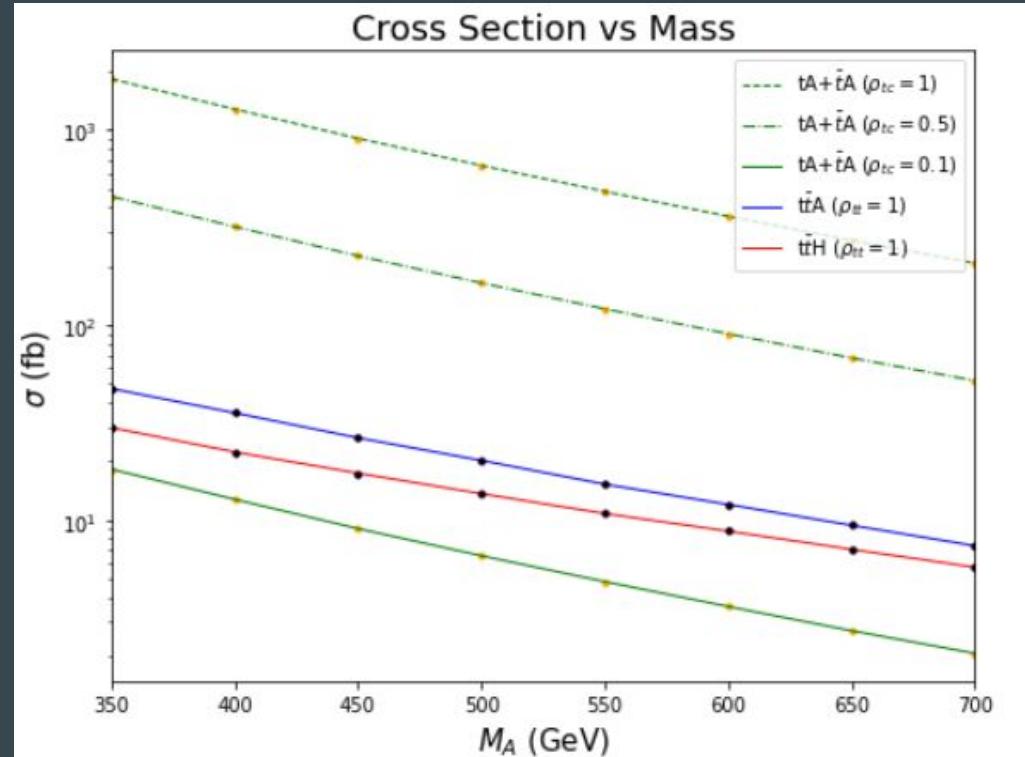


FIG. 1. Cross sections at  $\sqrt{s} = 14$  TeV for  $pp \rightarrow tS^0, \bar{t}S^0$  where  $S^0 = H^0, A^0$ , for  $\rho_{tc} = 0.1$  (solid), 0.5 (dashed) and 1 (dots), and  $pp \rightarrow t\bar{t}H^0, t\bar{t}A^0$  (for  $\rho_{tt} = 1$ ) as marked.

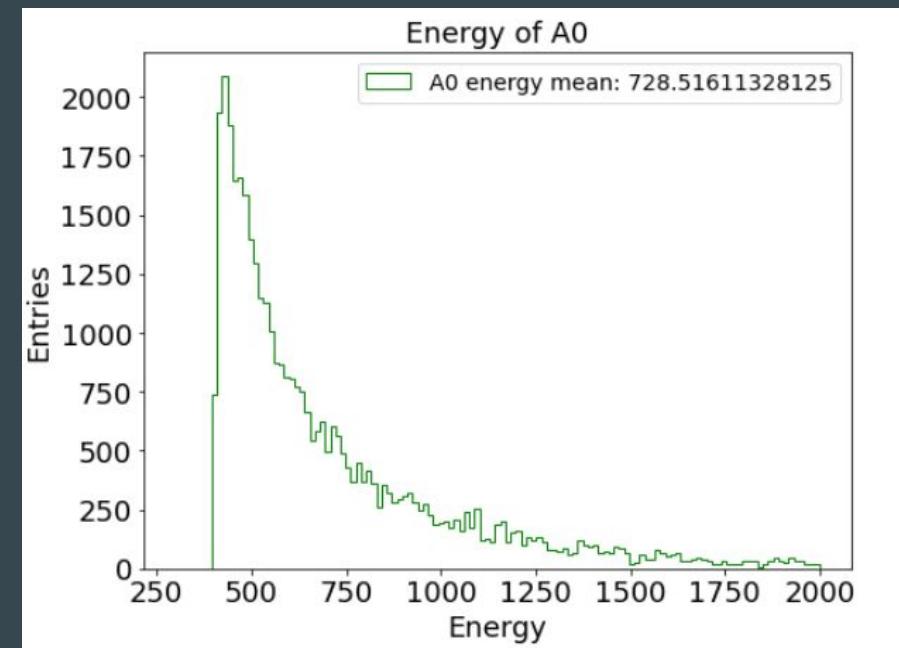
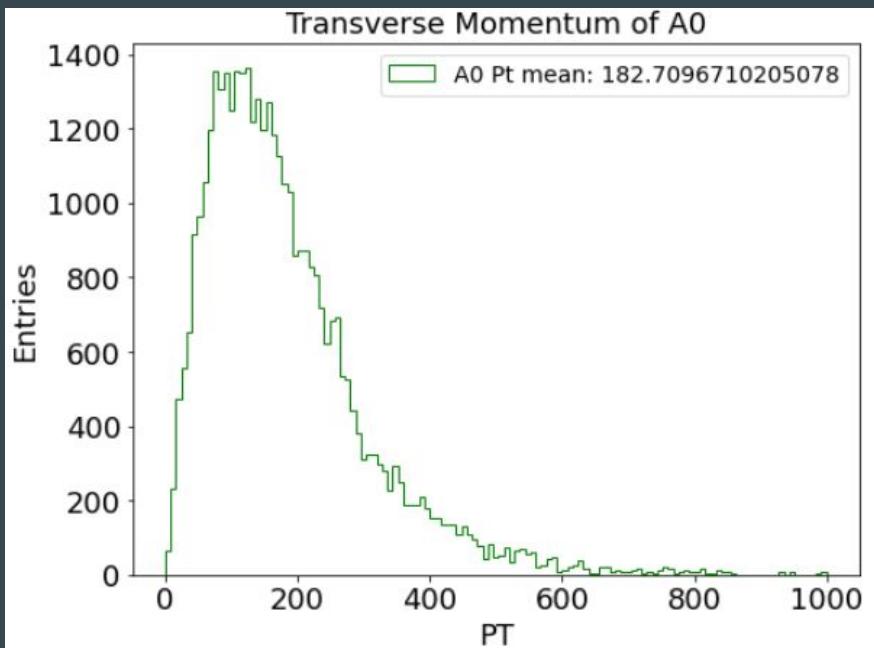
Previous : QCD=99; Use pdf set 274000

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

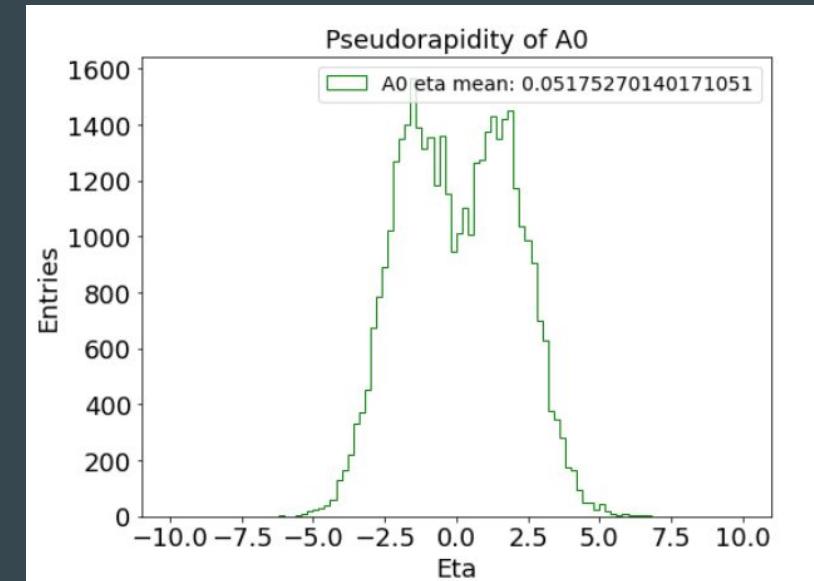
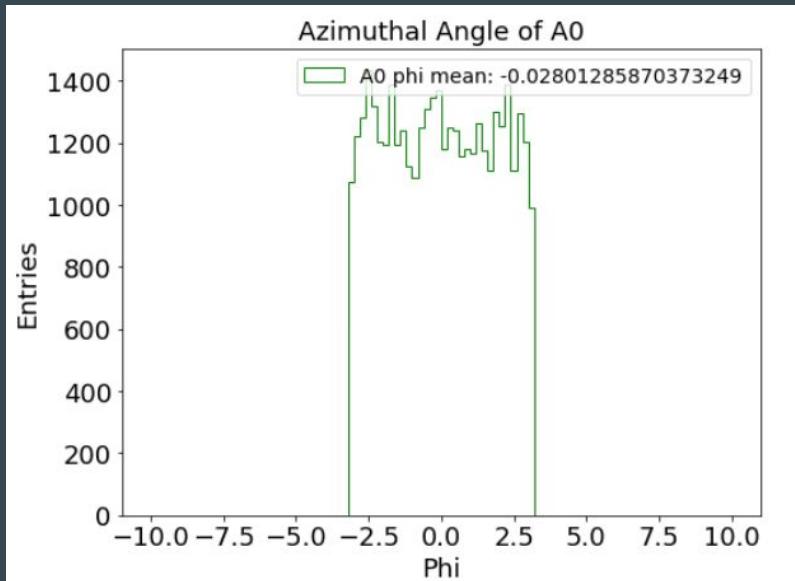
My Result:



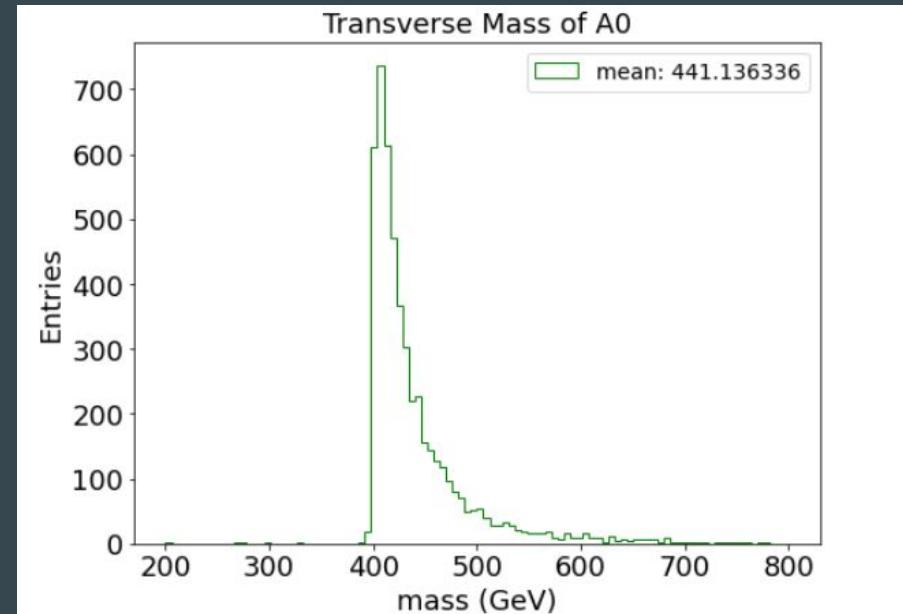
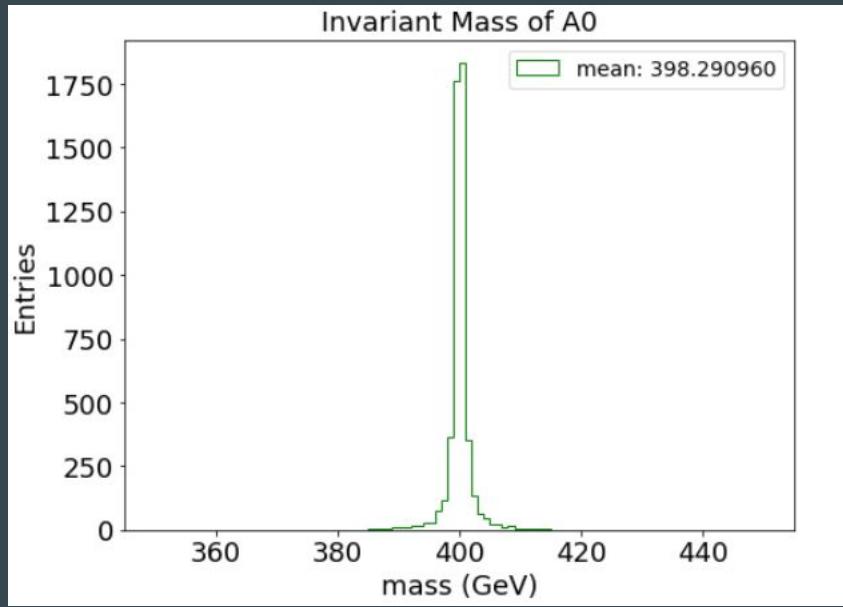
# Kinematic Plots (A0 400GeV)



# Kinematic Plots (A0 400GeV)

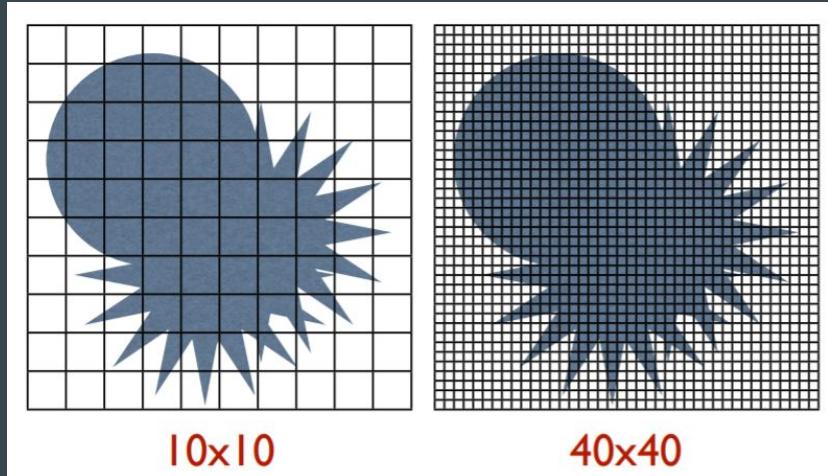
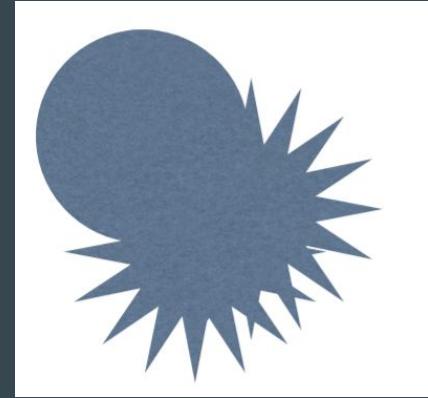


# Kinematic Plots (A0 400GeV)



# Monte Carlo

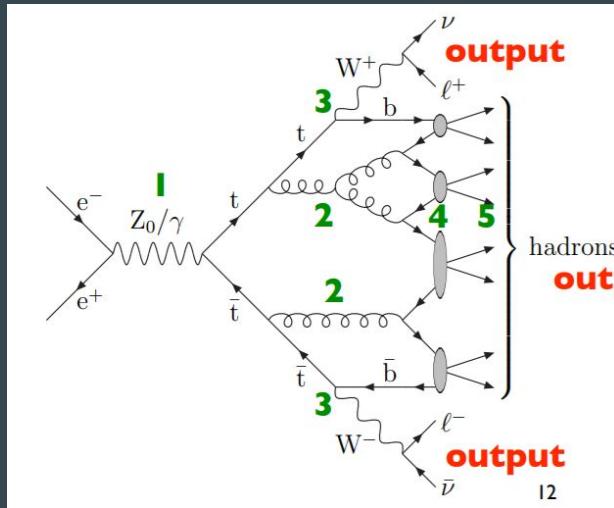
- analysis: random sampling -> simulate real world
- variable is random (AKA stochastic)
- PDF of a single stochastic variable
  - defined on an interval  $[a, b]$
  - nonnegative on that interval
  - normalized (integral of  $f(x)$  from  $a$  to  $b = 1$ )



Area = (Number of hits)/(Total squares) \* (Total Area)  
[https://upload.wikimedia.org/wikipedia/commons/8/84/Bi\\_30K.tif](https://upload.wikimedia.org/wikipedia/commons/8/84/Bi_30K.tif)

# 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  $\rightarrow$  Parton-shower phase  $\rightarrow$  Hard particles decay before hadronizing  $\rightarrow$  Hadronization  $\rightarrow$  Unstable hadrons decay



# Decay Width Calculation (new)

Total width for  $A$  (under the aforementioned assumptions) is sum of  $A \rightarrow t\bar{t} c\bar{c}$  +  $t\bar{t} b\bar{b}$  partial decay widths. If  $m_A > m_H + m_Z$  the partial decay width of  $A \rightarrow ZH$  also needs to be added. The following function automatically takes care of these decays once  $H$  and  $A$  masses are chosen.

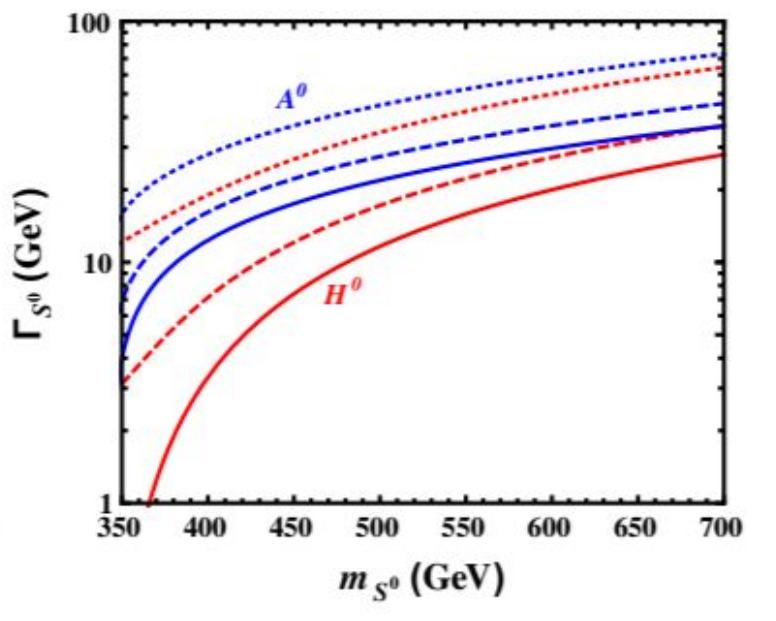
```
In[413]:= rtotA[rtt_, rtu_, rtc_, KAZH_, KAZh_, MA_, MH_] := If[MA > mt + mc, 2 rAtc[rtc, MA, 3], 0] + If[MA > mt + mu, 2 rAtu[rtu, MA, 3], 0] +
  If[MA > 2 mt, rAffbar[rtt, MA, mt, 3], 0] + If[MH > 0, If[MA > MH + mZ, rAZH[KAZH, MA, MH], 0], 0] + If[MH > 0, If[MA > mh + mZ, rAZh[KAZh, MA, MH], 0], 0];
In[452]:= rtotA[1, 0, 0.1, 0.37037, 0.37037, 700, 0]
Out[452]= 36.7542
```

Total decay width for  $H$

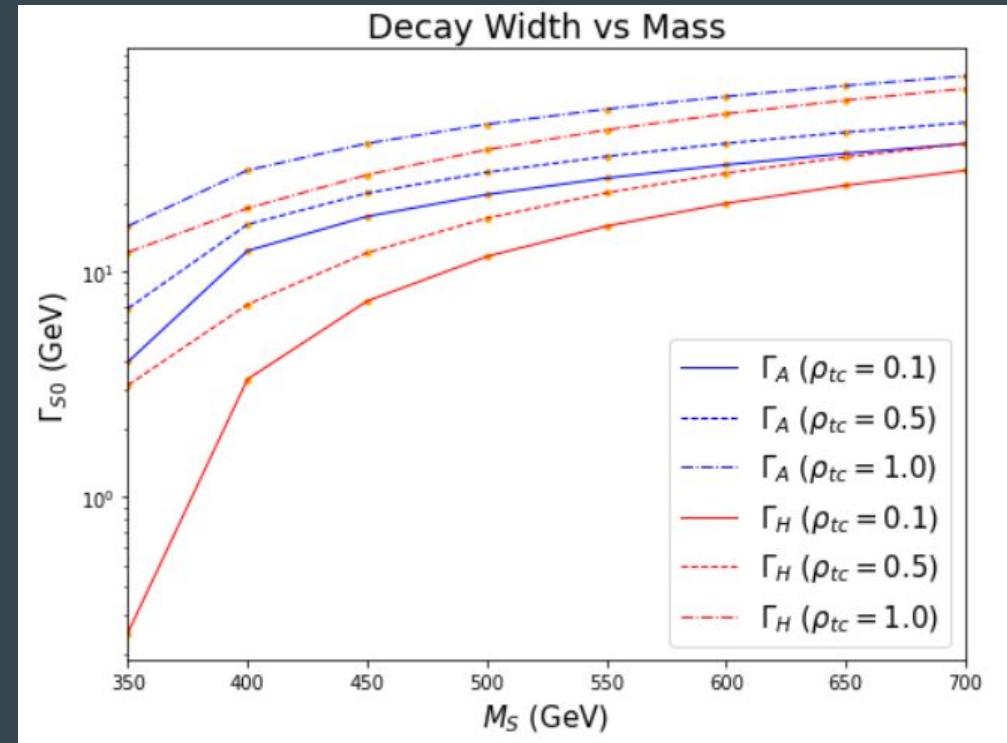
```
In[467]:= rtotH[rtt_, rtu_, rtc_, KHAZ_, LHHh_, MA_, MH_] := If[MH > mt + mc, 2 rHtc[rtc, MH, 3], 0] + If[MH > mt + mu, 2 rHtu[rtu, MH, 3], 0] +
  If[MH > 2 mt, rHffbar[rtt, MH, mt, 3], 0] + If[MH > 0, If[MH > MA + mZ, rHZA[KHAZ, MH, MA], 0], 0] + If[MH > 2 mh, rHhh[LHHh, MH], 0];
In[500]:= rtotH[1, 0, 0.1, 0.370372, 1, 700, 700]
Out[500]= 27.9671
```

# Decay Width (unscaled)

Paper:

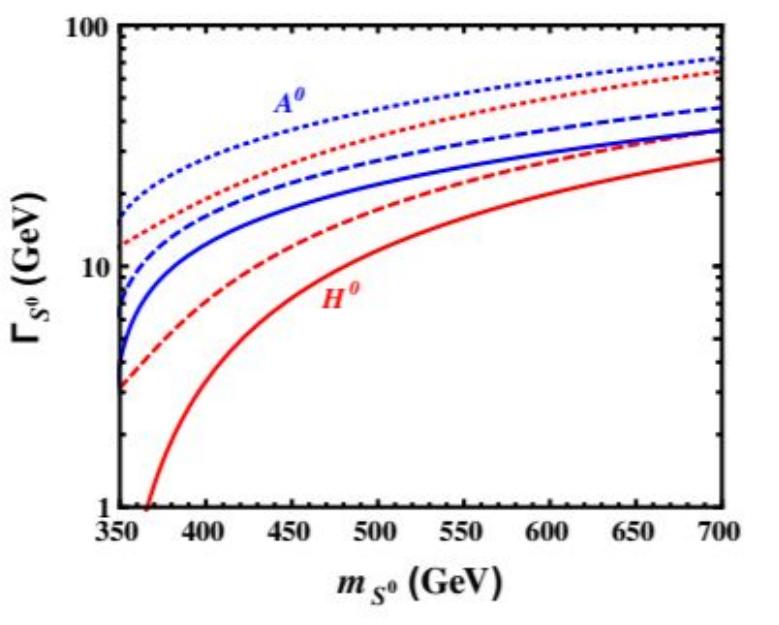


My Result:

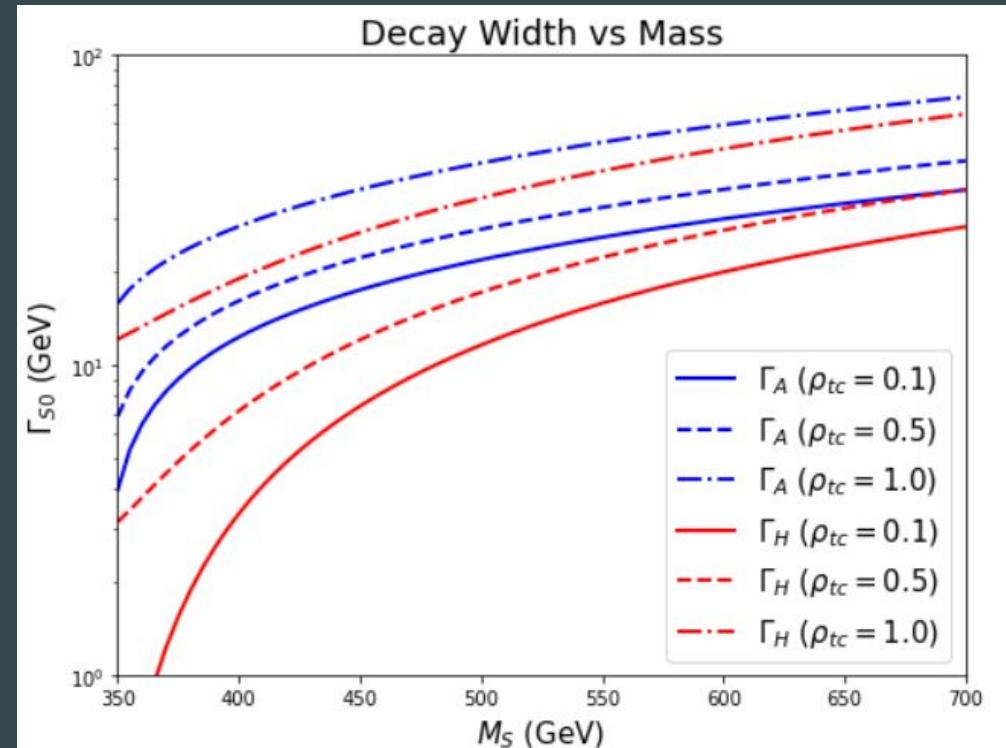


# Decay Width

Paper:



My Result:



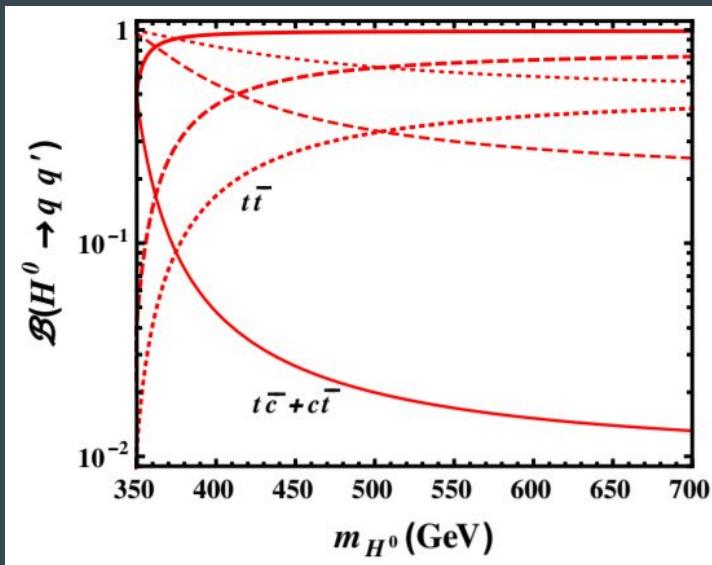
# Branching Ratio

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  $\Gamma$  is the **total width** of the particle and  $\Gamma_i$  is the **partial width** in the decay chain  $i$ , we have:

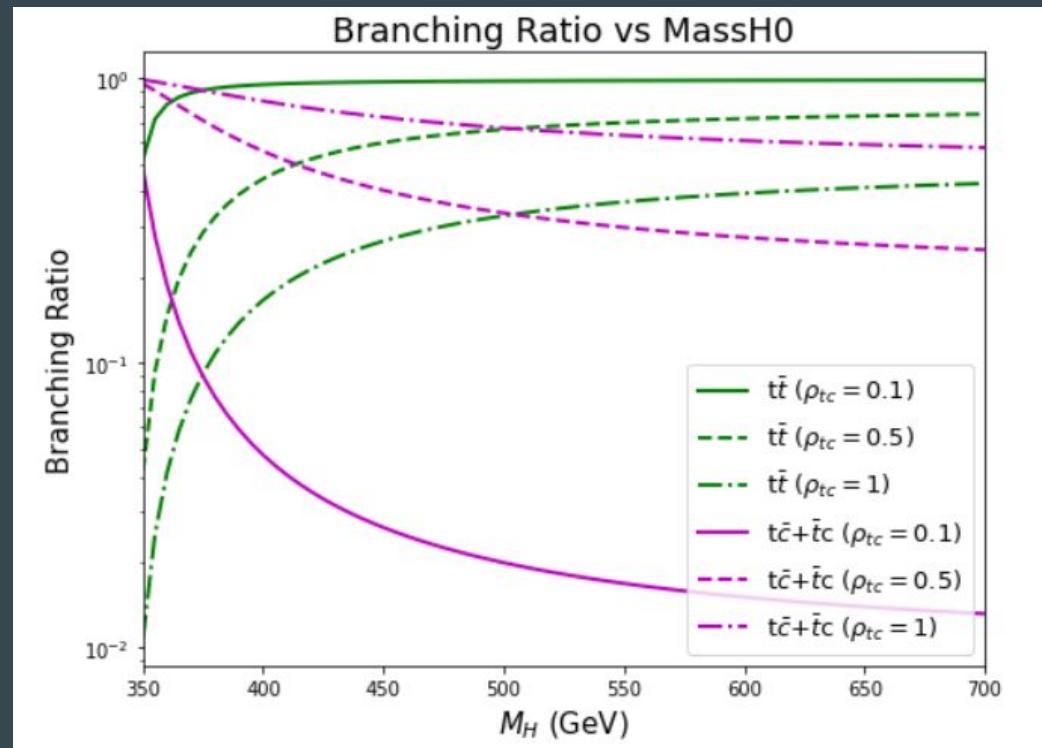
$$(82) \quad BR(i) = \frac{\Gamma_i}{\Gamma}$$

# Branching Ratio (H0)

Paper:

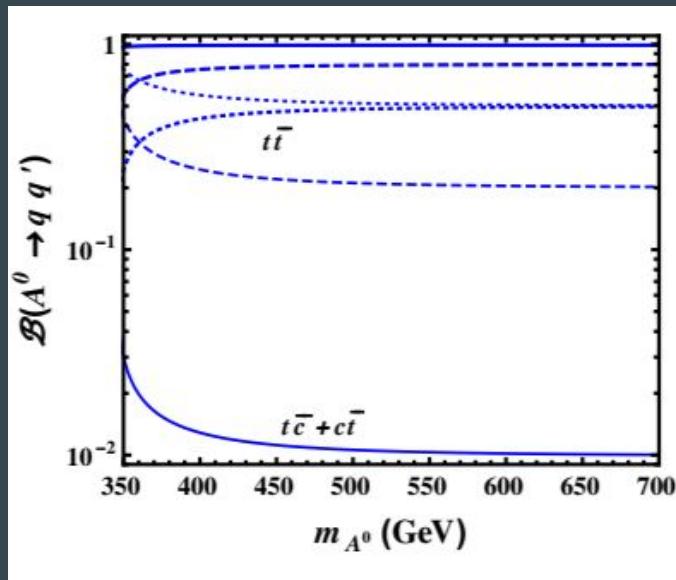


My Result:

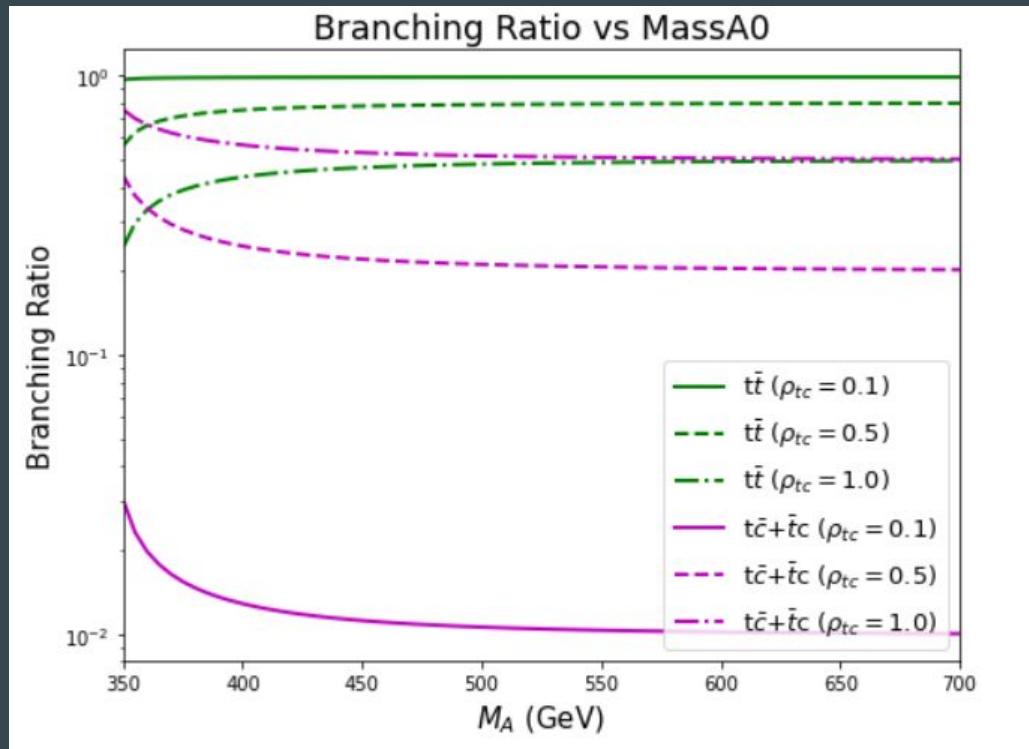


# Branching Ratio (AO)

Paper:

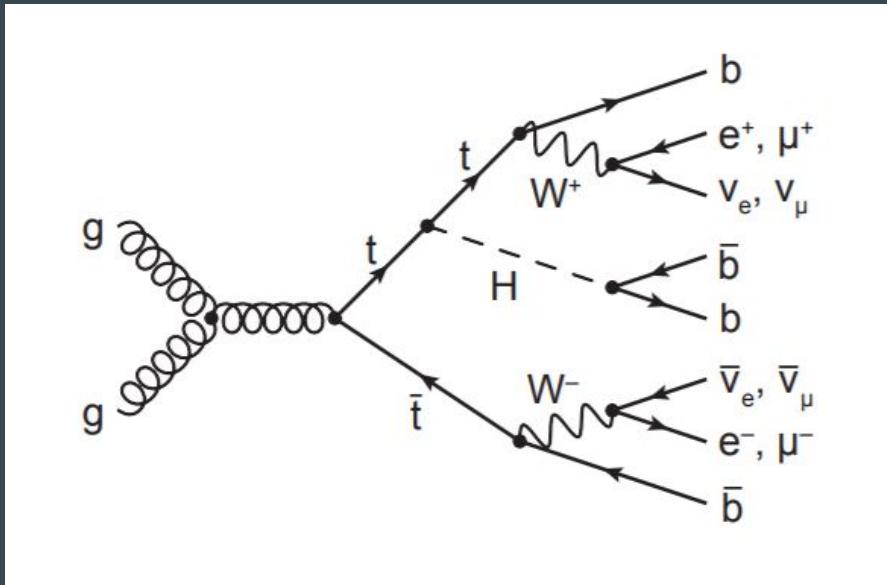


My Result:

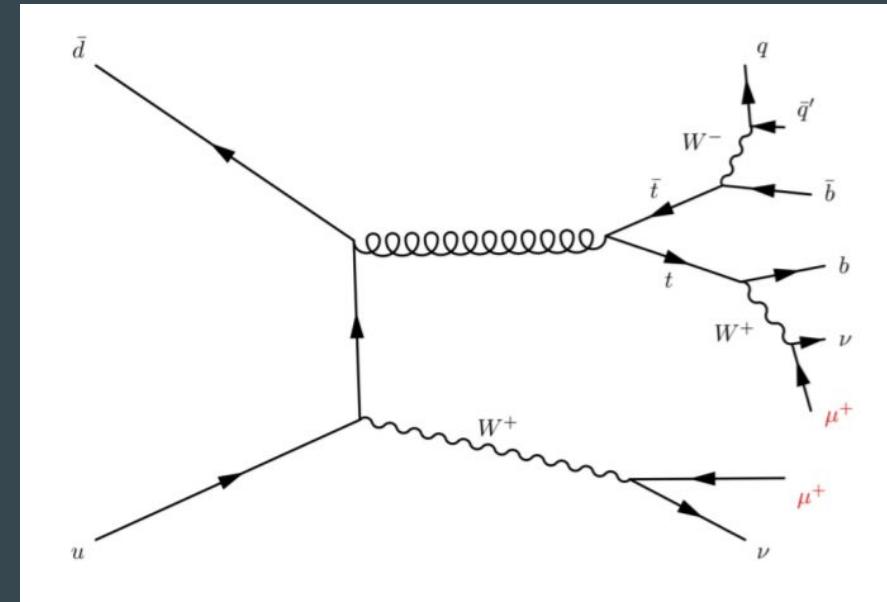


# Same Sign Dilepton

Paper (2 leptons):

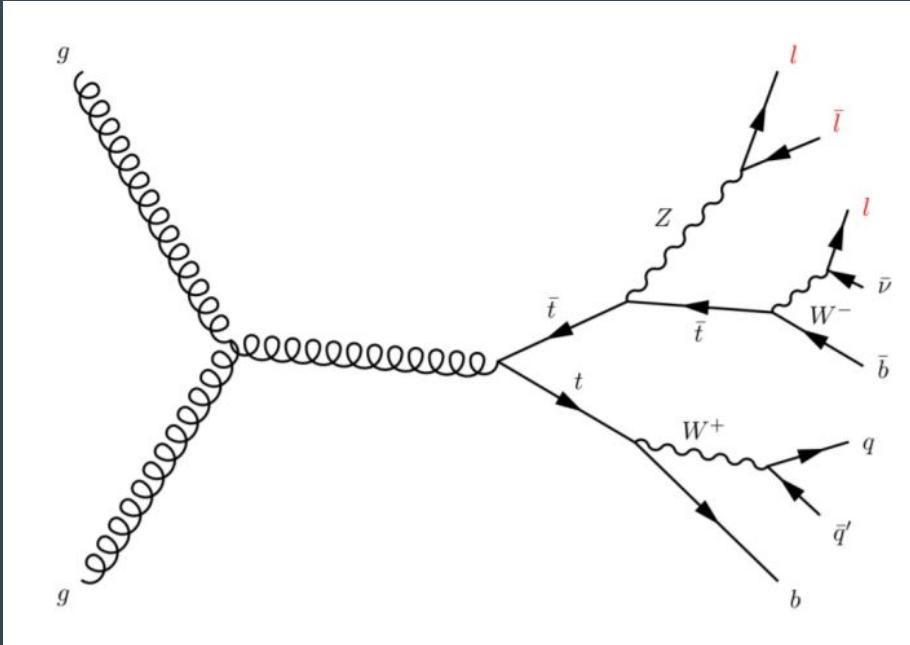


Background:



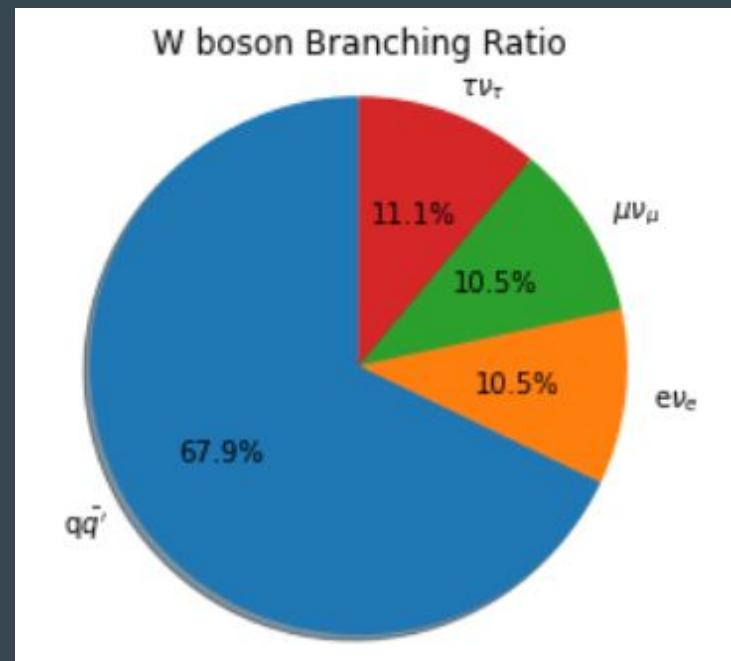
Backgrounds	Cross section (fb)
$t\bar{t}Z$	0.04
$t\bar{t}W$	0.72
$tZ + \text{jets}$	0.001
$3t + j$	0.0002
$3t + W$	0.0004
$t\bar{t}h$	0.024
$4t$	0.04
$Q\text{-flip}$	0.04

# Trilepton



# Pie charts: Branching Ratio for W boson

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



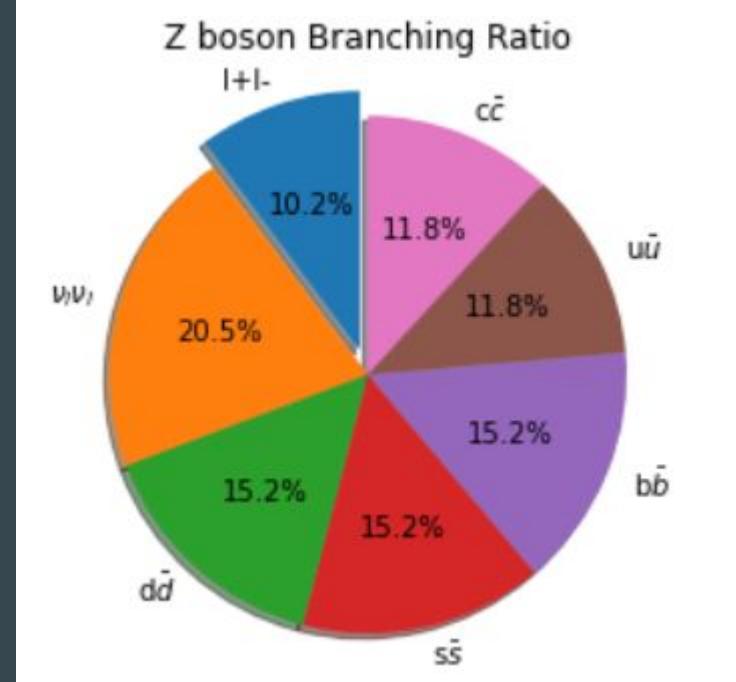
# Pie charts: Branching Ratio for Z boson

$$\Gamma(Z \rightarrow e^+e^-) = \Gamma(Z \rightarrow \mu^+\mu^-) = \Gamma(Z \rightarrow \tau^+\tau^-) = 84 \text{ MeV}$$

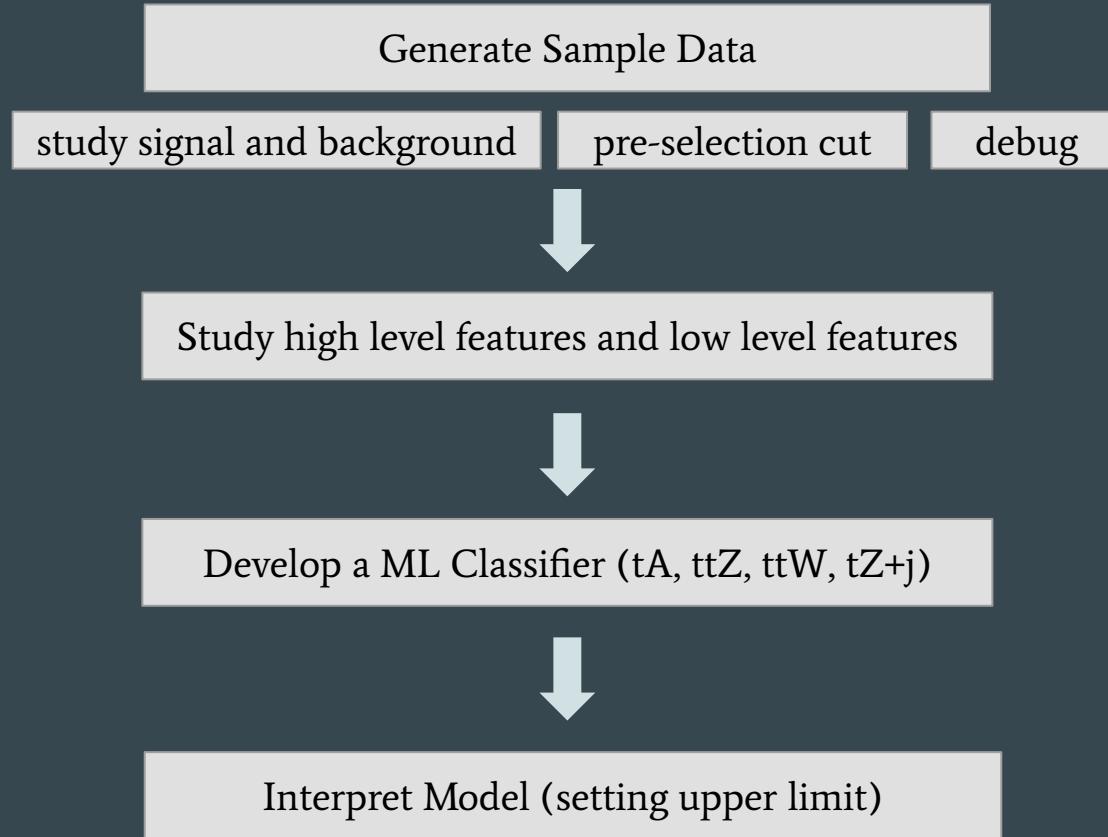
$$\Gamma(Z \rightarrow \nu_e \bar{\nu}_e) = \Gamma(Z \rightarrow \nu_\mu \bar{\nu}_\mu) = \Gamma(Z \rightarrow \nu_\tau \bar{\nu}_\tau) = 166 \text{ MeV}$$

$$\Gamma(Z \rightarrow d\bar{d}) = \Gamma(Z \rightarrow s\bar{s}) = \Gamma(Z \rightarrow b\bar{b}) = 354 \text{ MeV}$$

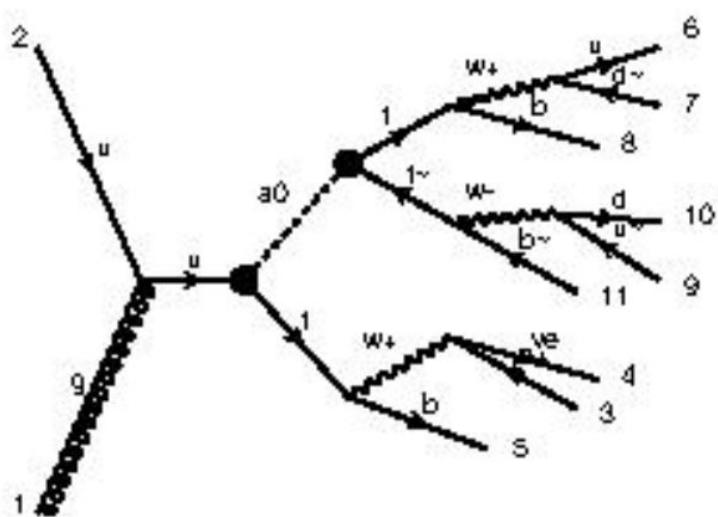
$$\Gamma(Z \rightarrow u\bar{u}) = \Gamma(Z \rightarrow c\bar{c}) = 276 \text{ MeV}$$



# Analysis Flow Chart

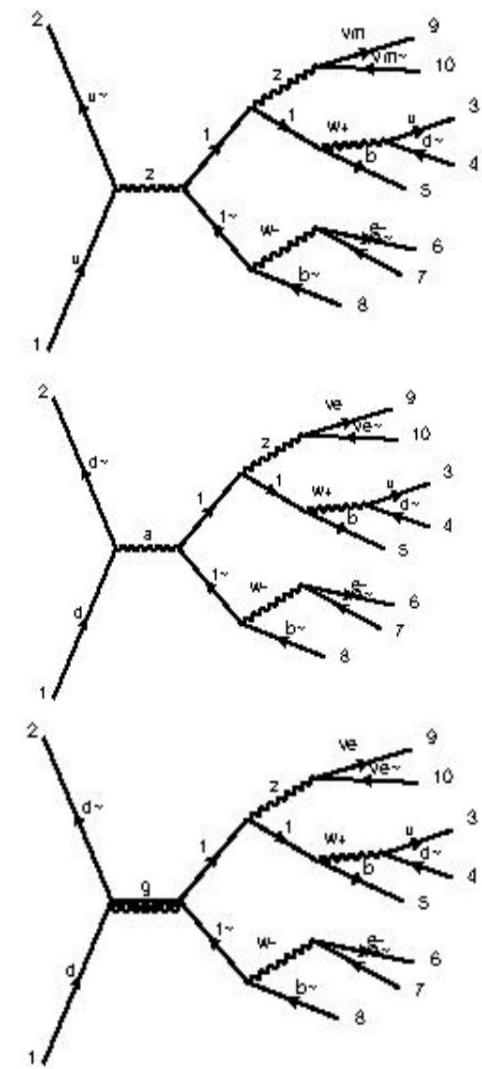
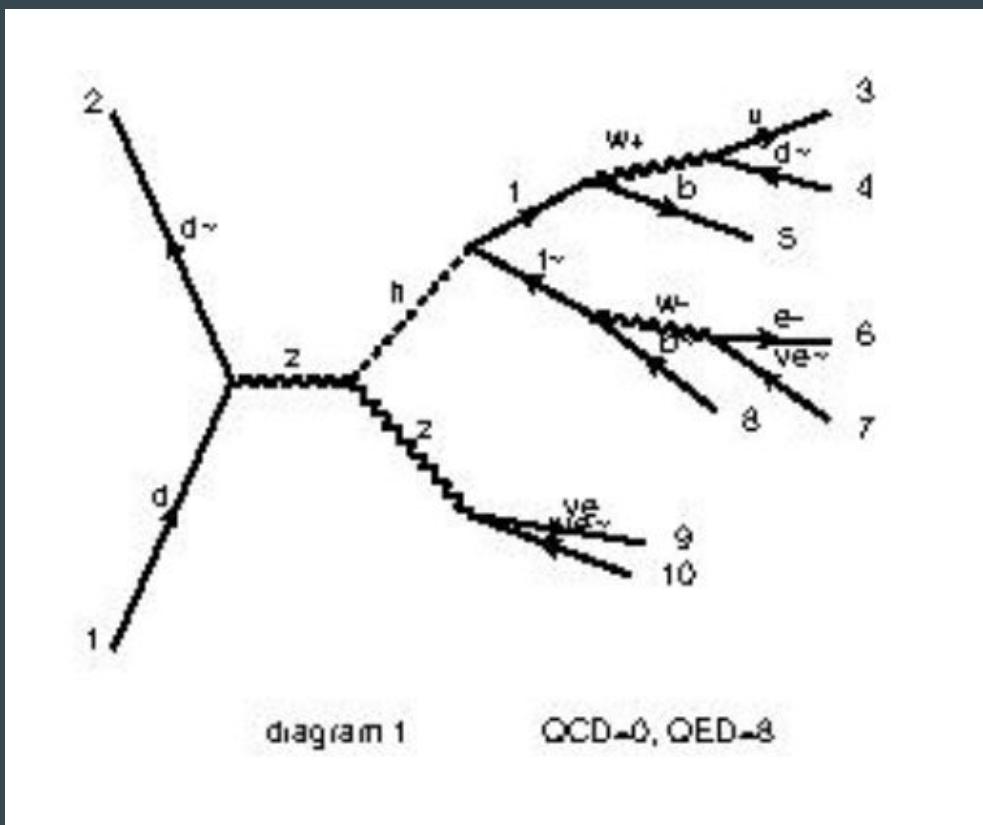


# Signal: ug → tA0 → ttt~

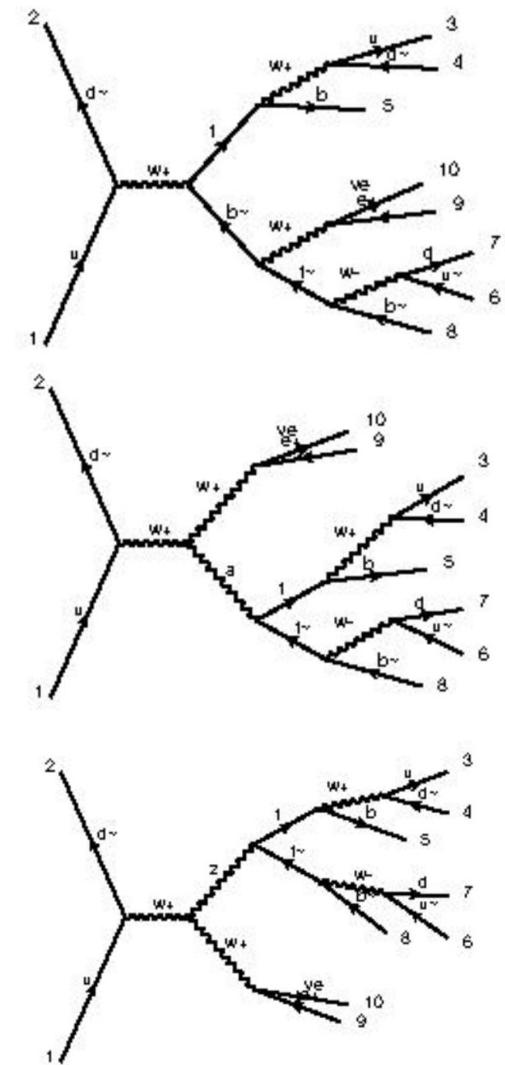
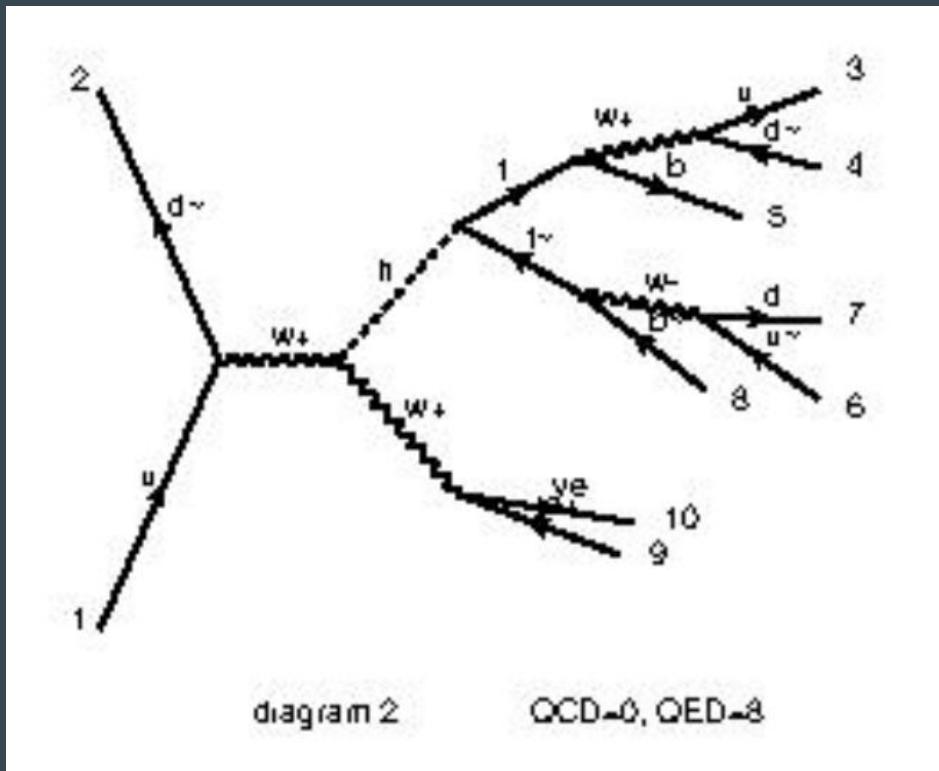


	mass	PID	Particle	mother1	mother2	e	px	py	pz	status
0	0.000000	21.0	g	0.0	0.0	409.493776	0.000000	0.000000	409.493776	-1.0
1	0.000000	4.0	q	0.0	0.0	348.673361	-0.000000	-0.000000	-348.673361	-1.0
2	172.601919	6.0	t	1.0	2.0	314.258861	17.056130	33.950287	259.853181	2.0
3	83.387344	24.0	W+	3.0	3.0	213.339537	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

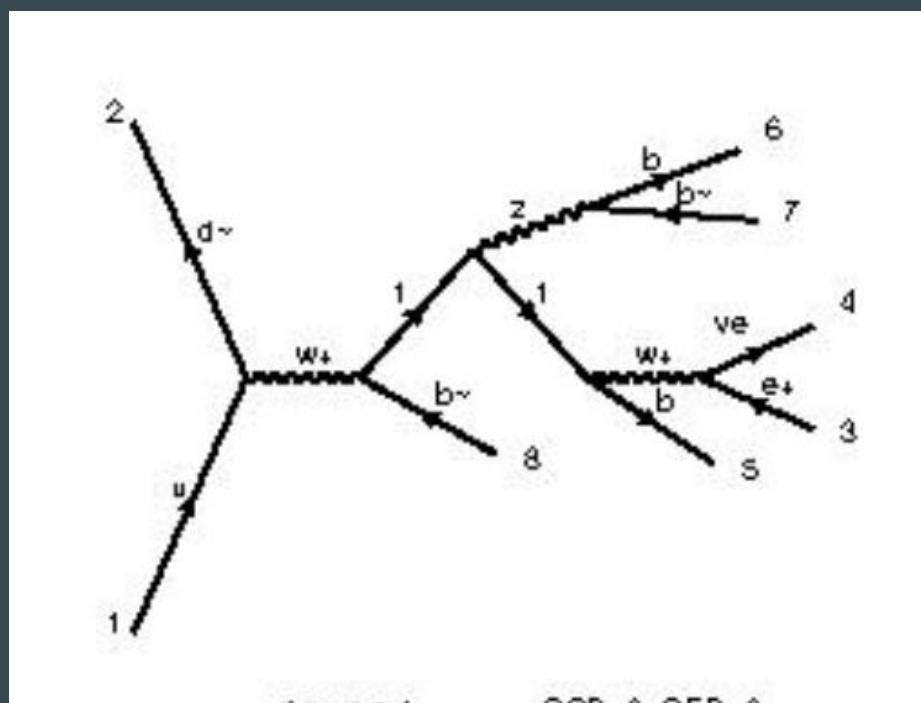
# SM Background: tt~Z



# SM Background: tt~W



# SM Background: tZ + j



OCD=0, QED=4

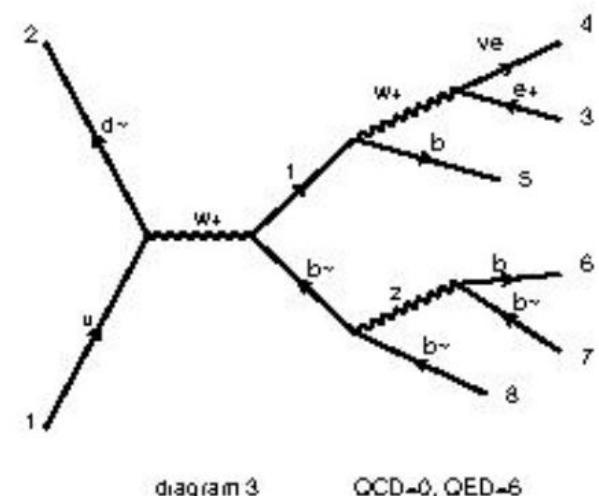


diagram 3

OCD=0, QED=6

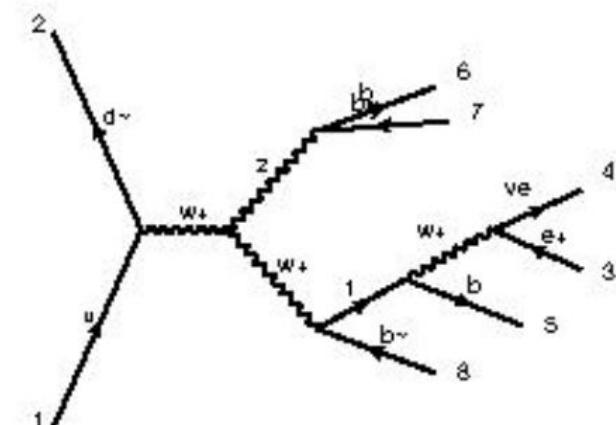


diagram 2

OCD=0, QED=6

# SM Background: 3t + j

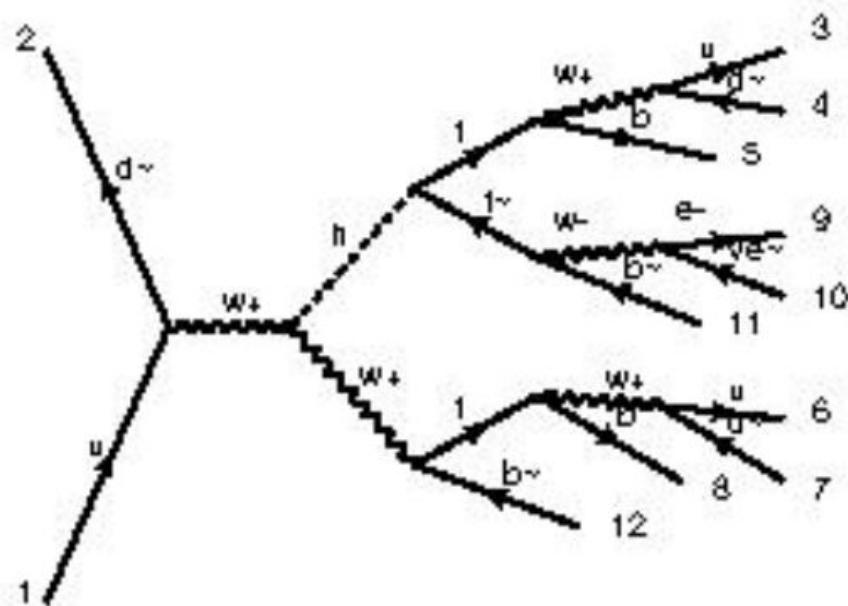
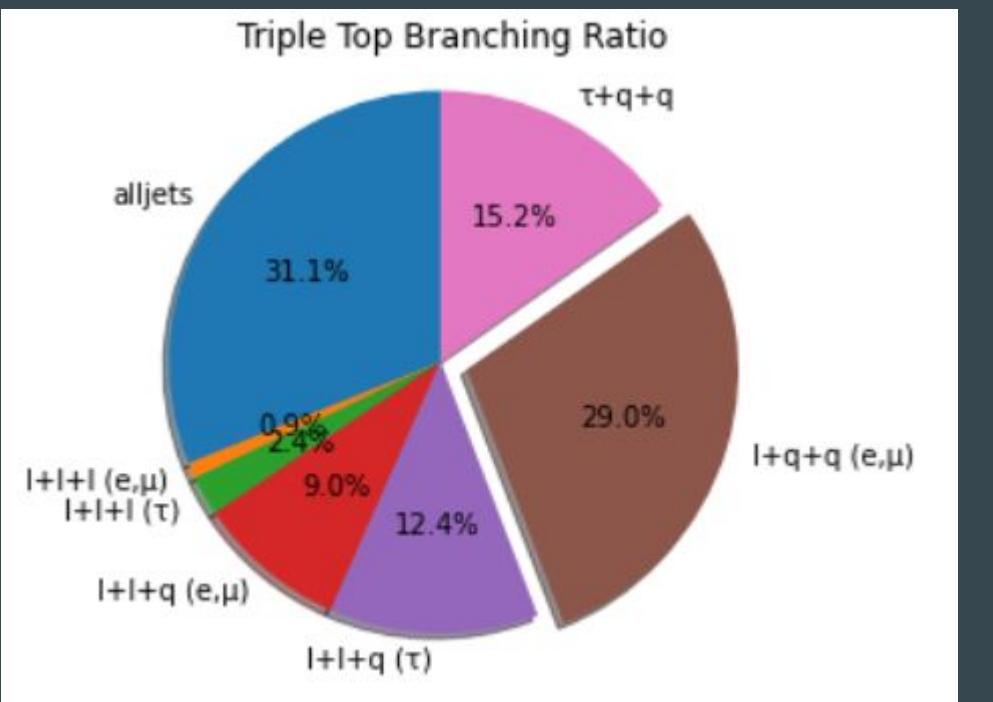


diagram 10

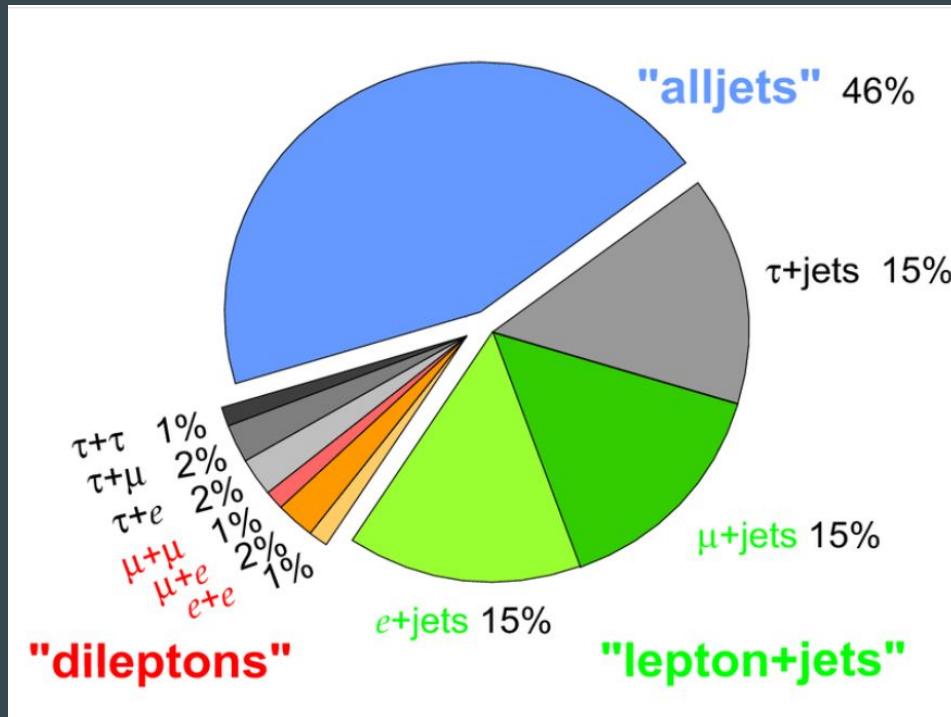
OCD=0, QED=10

# Pie charts: Branching Ratio for Triple Top



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

# Top pair branching ratio pie chart



# Attempt to replicate SS2I cross section plot (after selection cut)

```
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

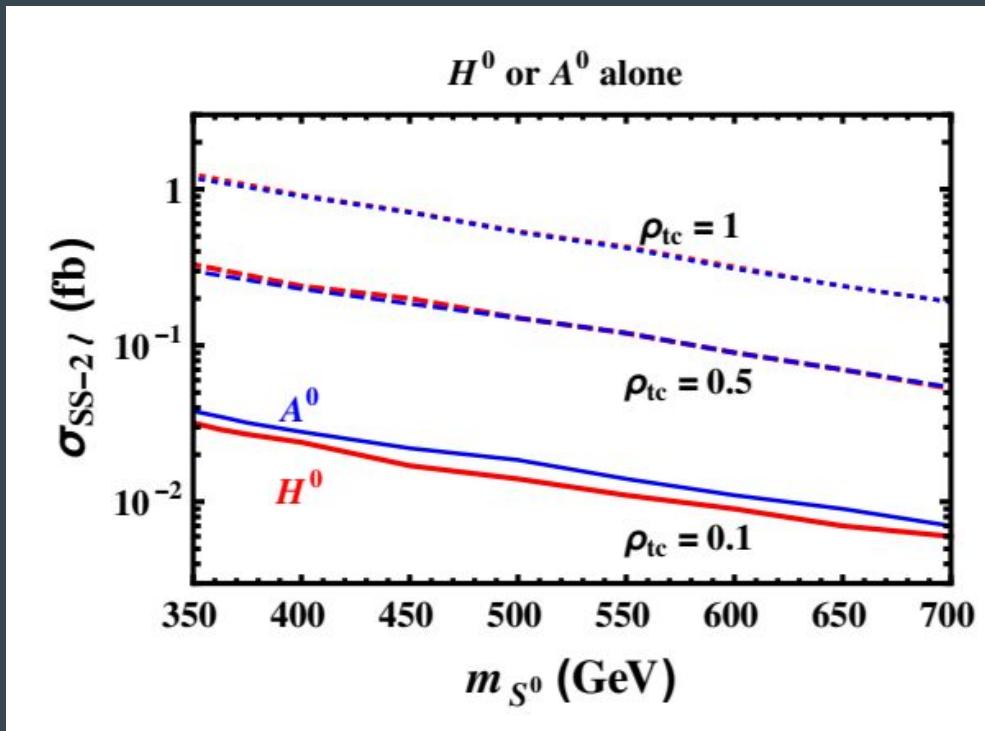
generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ v1),( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > q q~) )
add process p p > t~ A0 QCD=99, (t~ > w- b~, w- > l- v1~),( A0 > t t~, (t > w+ b , w+ > q q~),(t~ > w- b~, w- > l- v1~) )

output test

launch test
set use_syst False
set rtc 0.1
set rtt 1
set rtu 0
set nevents 500
set ebeam1 7000.0
set ebeam2 7000.0
set ptl 20
set ptb 20
set misset 30
set etal 2.5
set etab 2.5
set drbb 0.4
set drbl 0.4
set ht3min 300
set MA0 350
set MS0 0
set wa0 3.971468008
set ws0 0
```

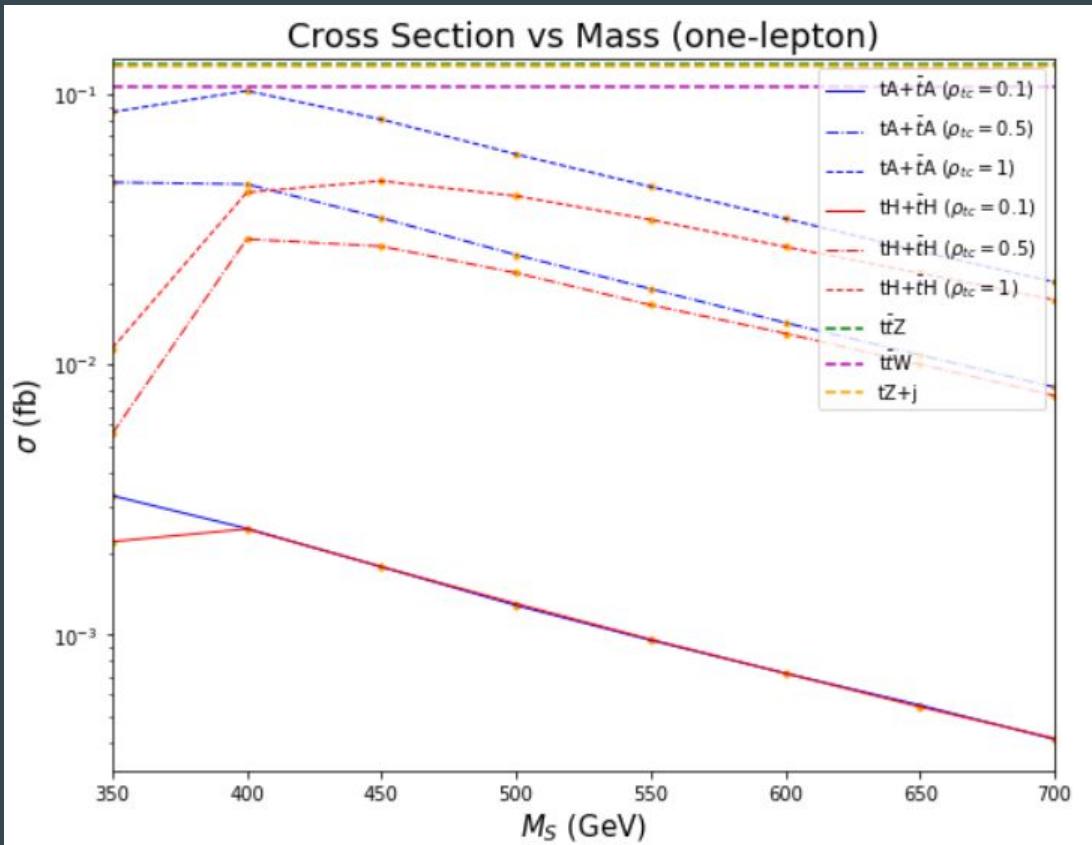
( $p_T$ ) of leading and subleading leptons  $> 25$  GeV and  $20$  GeV, and  $> 30$  GeV and  $20$  GeV, respectively for the two leading  $b$ -jets, while  $E_T^{\text{miss}} > 30$  GeV. The pseudo-rapidity of the same-sign leptons and the two leading  $b$ -jets should satisfy  $|\eta^\ell| < 2.5$  and  $|\eta^b| < 2.5$ , respectively. Separation between a  $b$ -jet and a lepton ( $\Delta R_{b\ell}$ ), any two  $b$ -jets ( $\Delta R_{bb}$ ), 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.

# Attempt to replicate SS2I cross section plot (after selection cut)

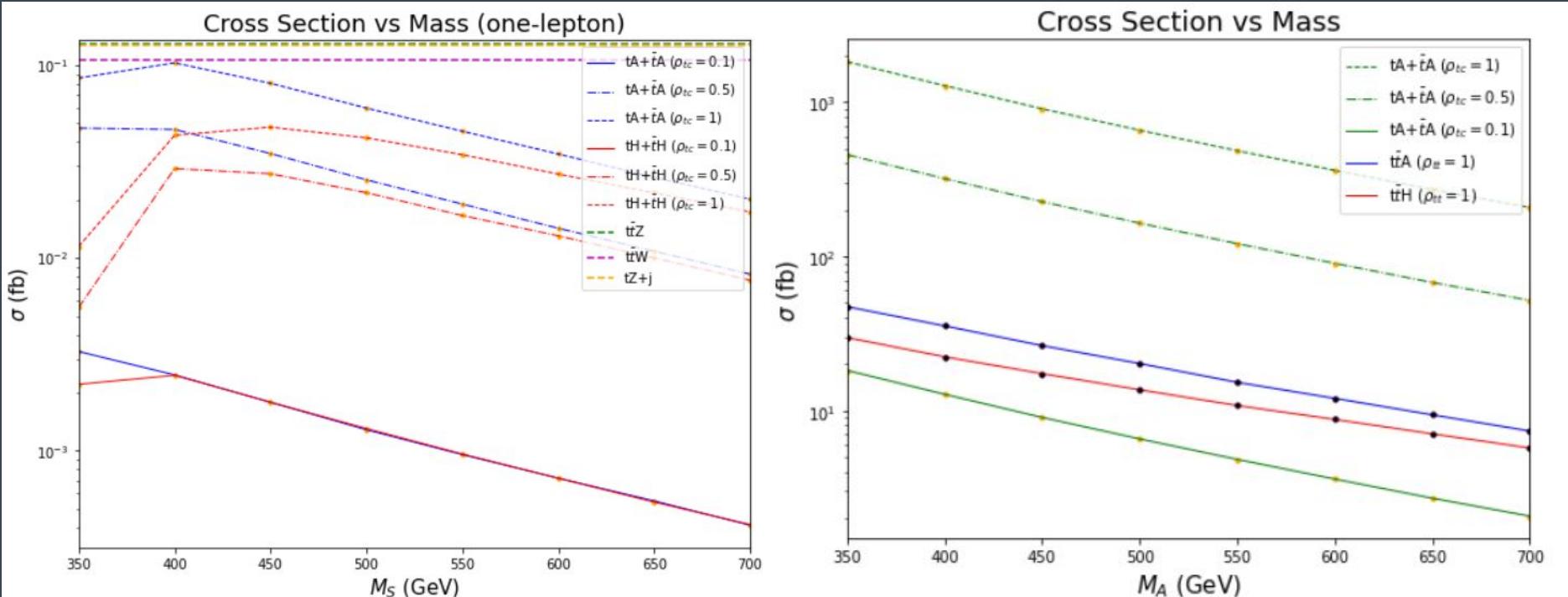


Mass A0 (GeV)	Cross Section (fb)	
0	350	0.36060
1	400	0.27330
2	450	0.20110
3	500	0.13970
4	550	0.10890
5	600	0.08045
6	650	0.05885
7	700	0.04688

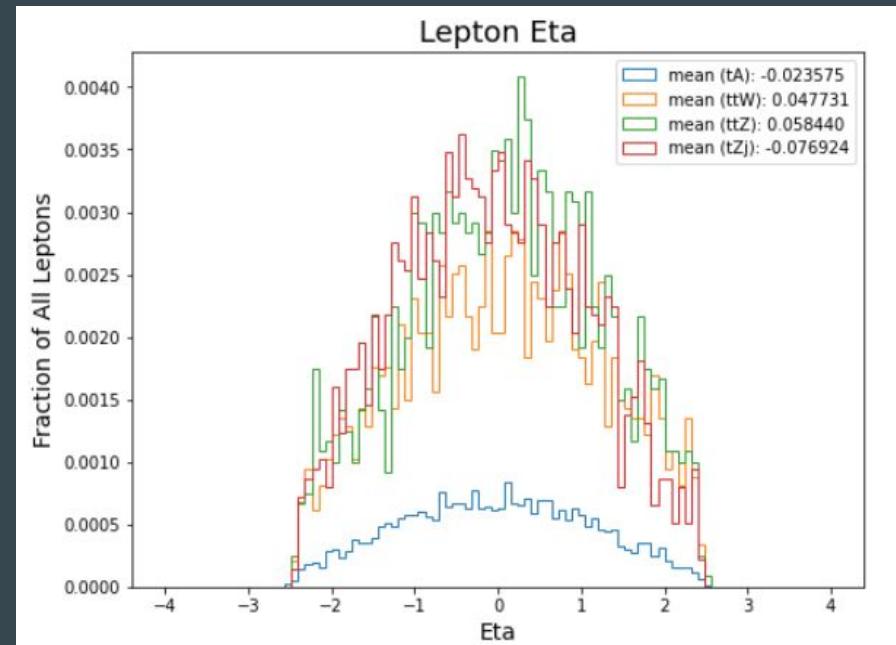
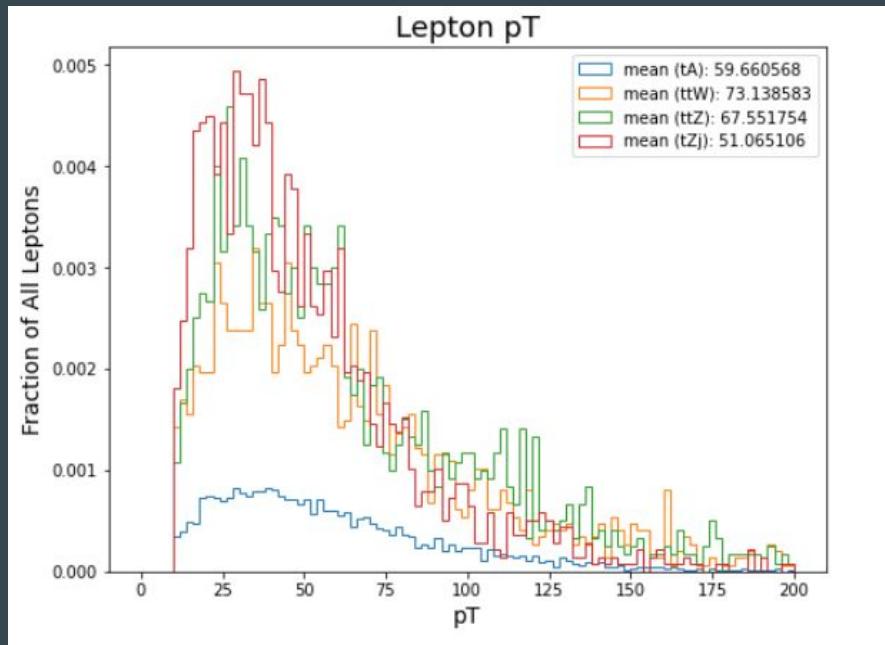
# Cross Section vs Mass



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

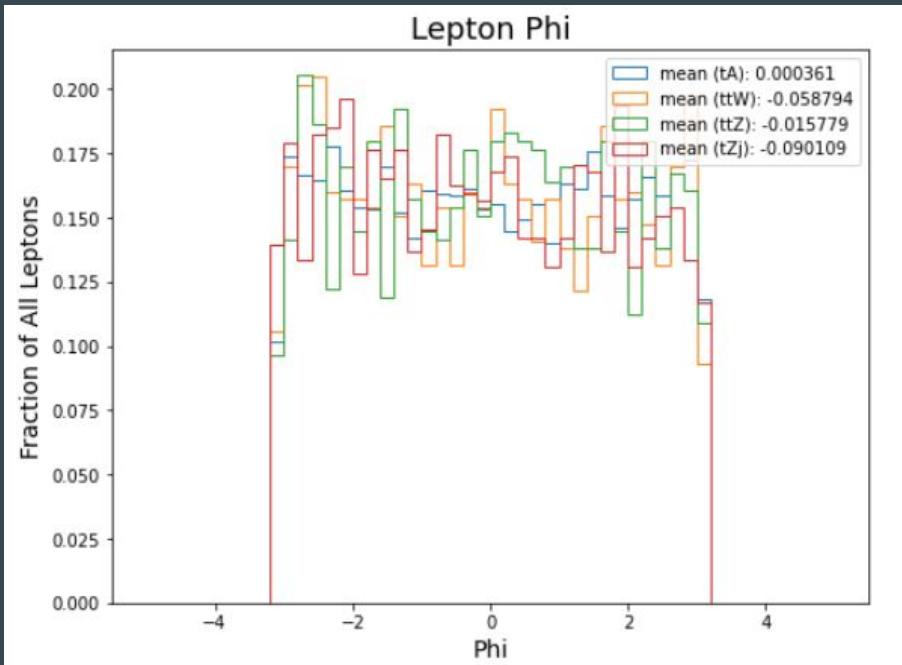


# Kinematic Plot Comparison (lepton)

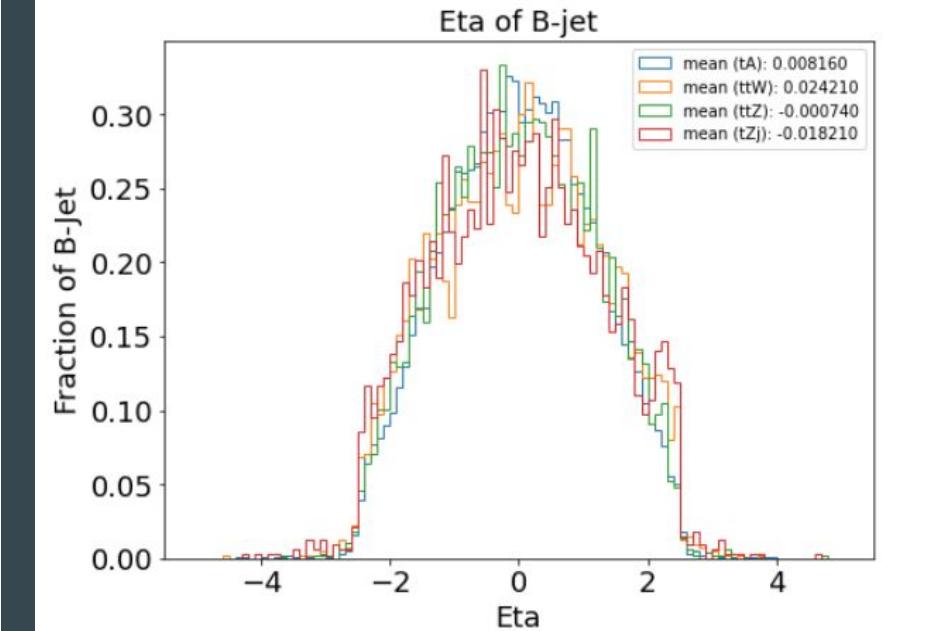
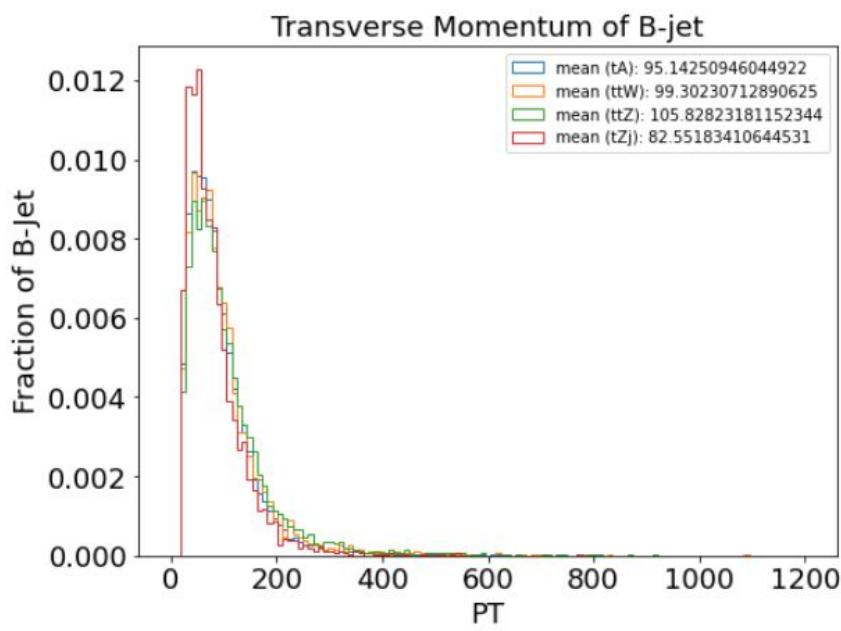


Normalize cross section

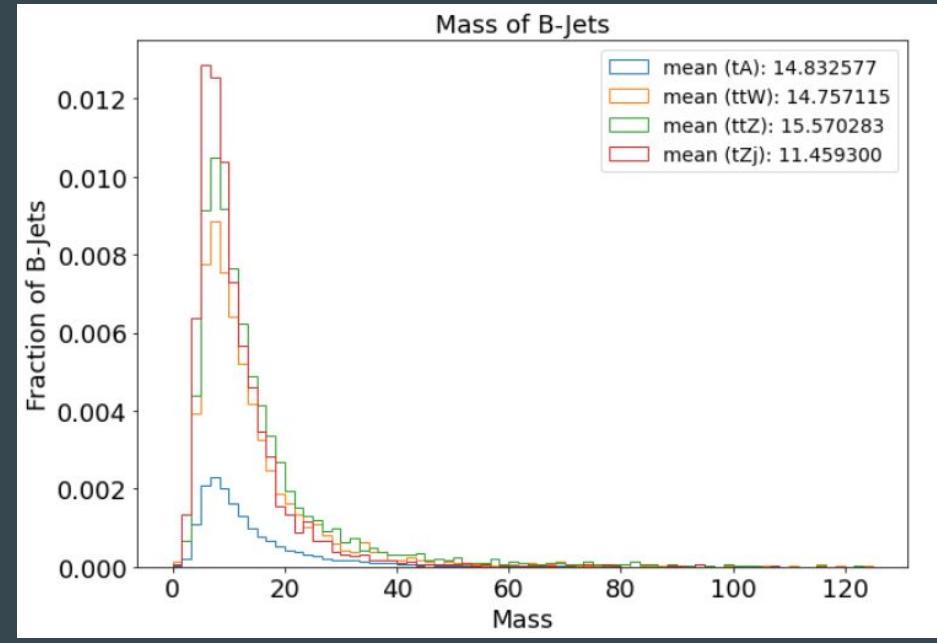
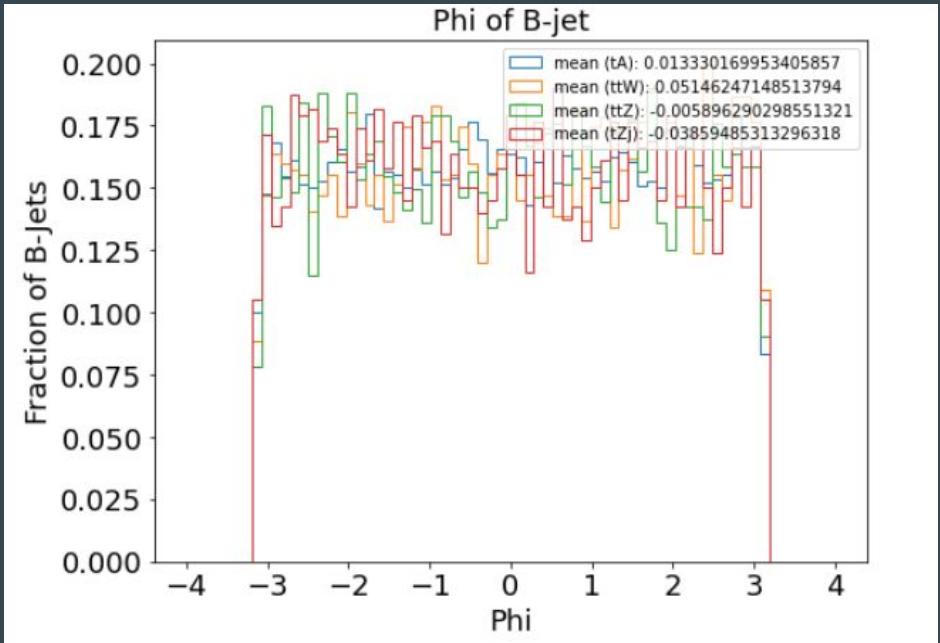
# Kinematic Plot Comparison (lepton)



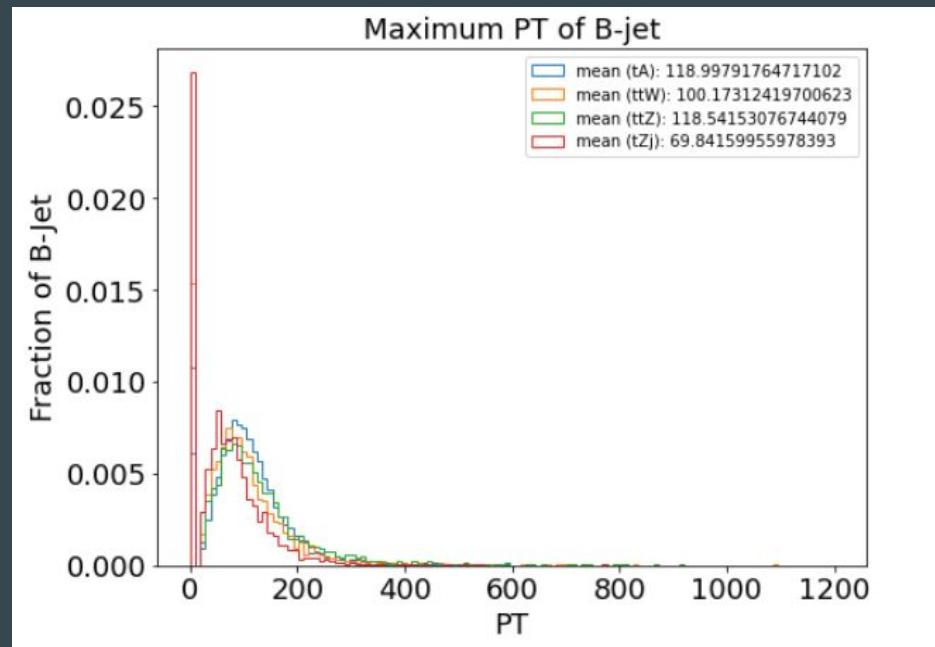
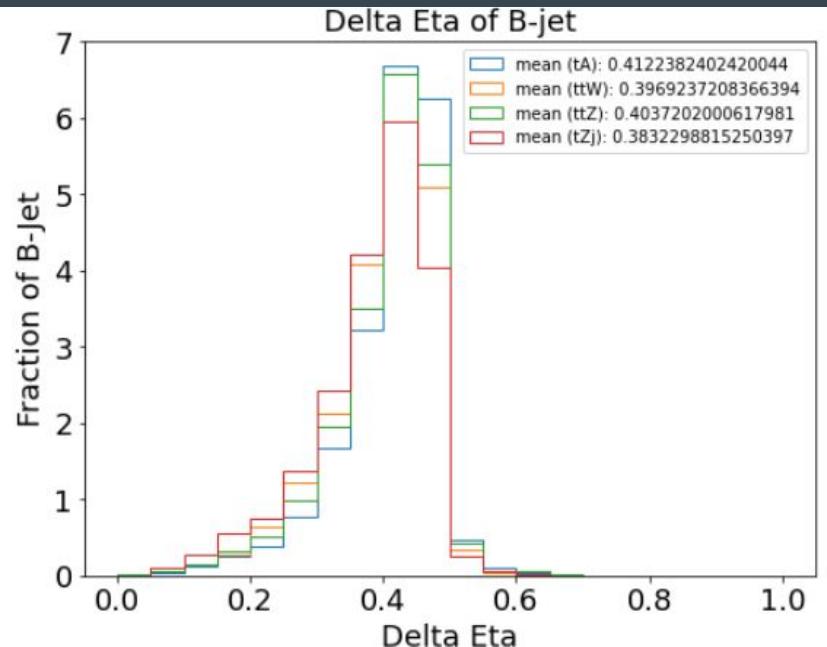
# Kinematic Plot Comparison (b-jet)



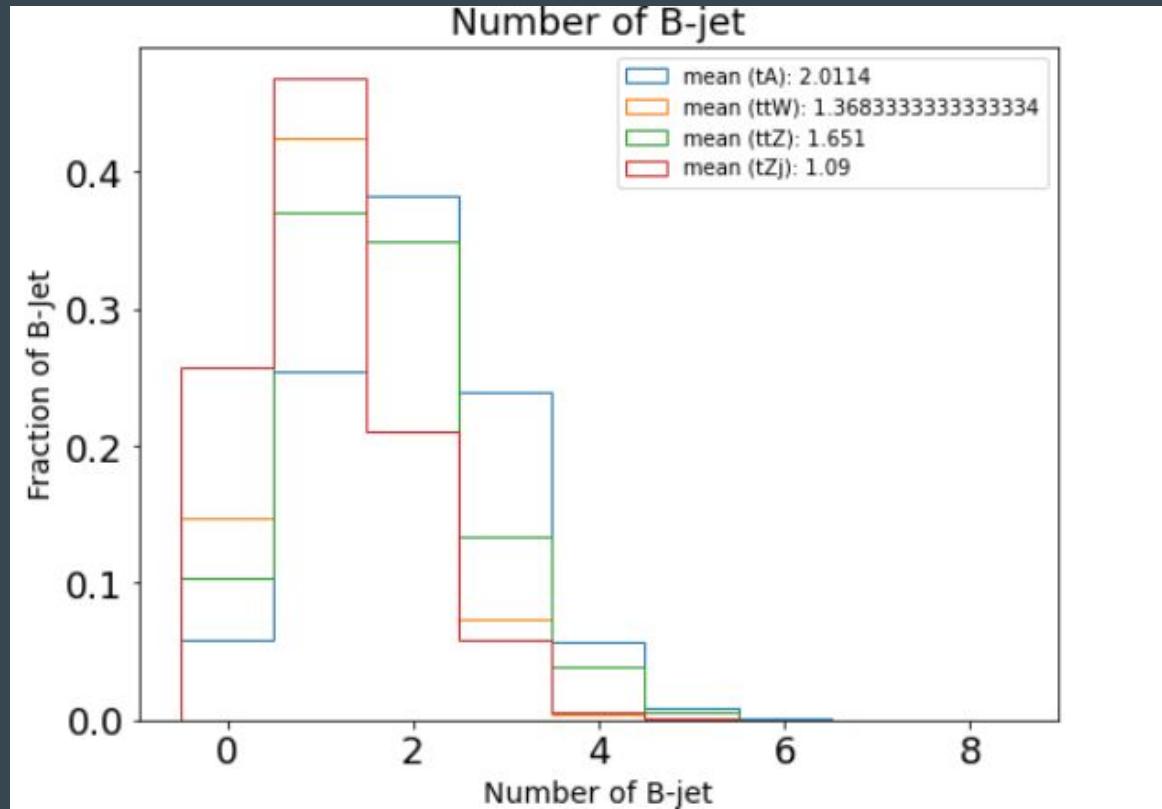
# Kinematic Plot Comparison (b-jet)



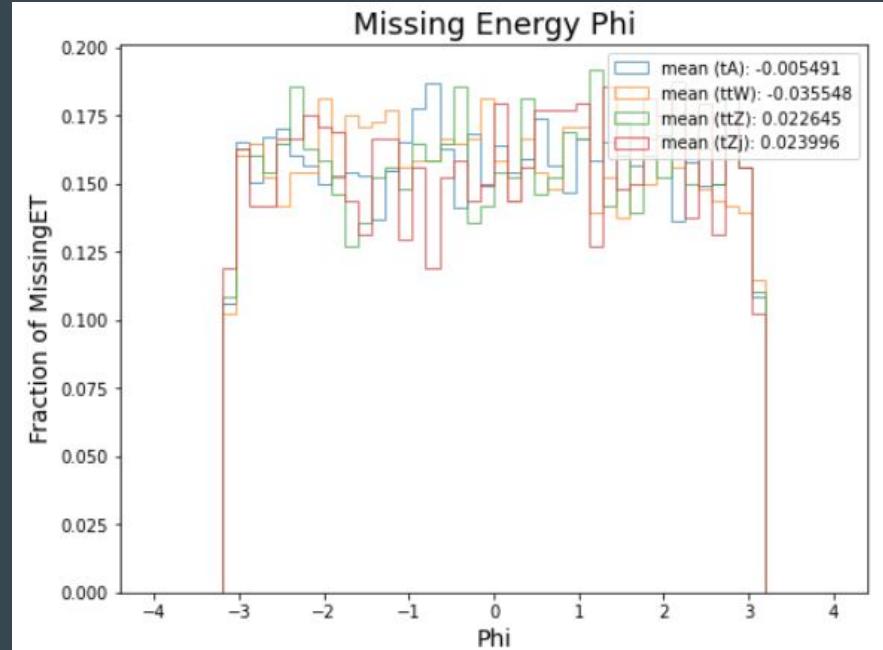
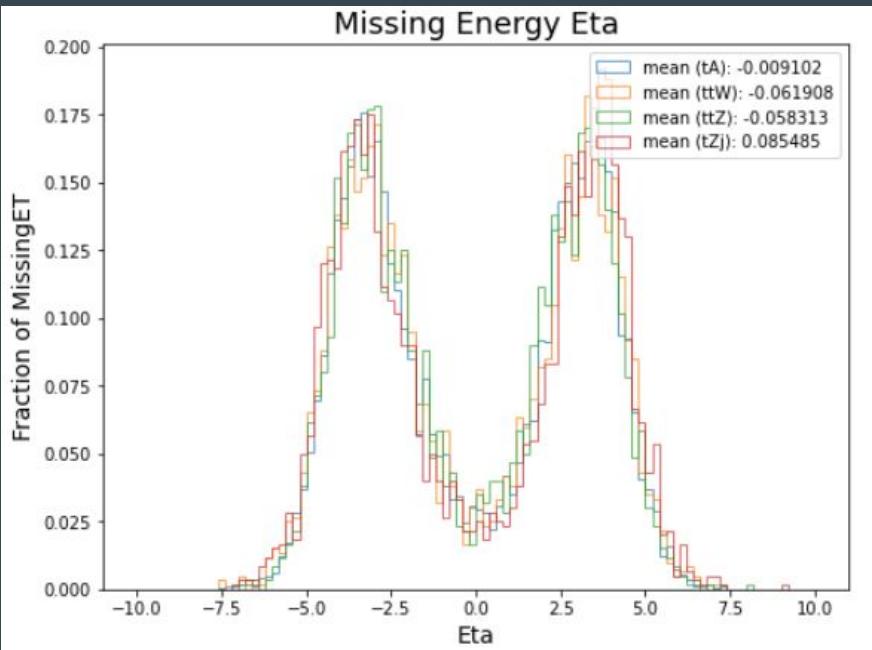
# Kinematic Plot Comparison (b-jet)



# Kinematic Plot Comparison (b-jet)



# Kinematic Plot Comparison (Missing Transverse Energy)

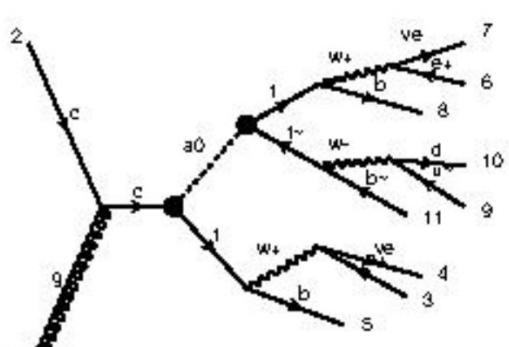


# Overview

- Cross Section vs Mass
- High Level Feature Kinematic Plots

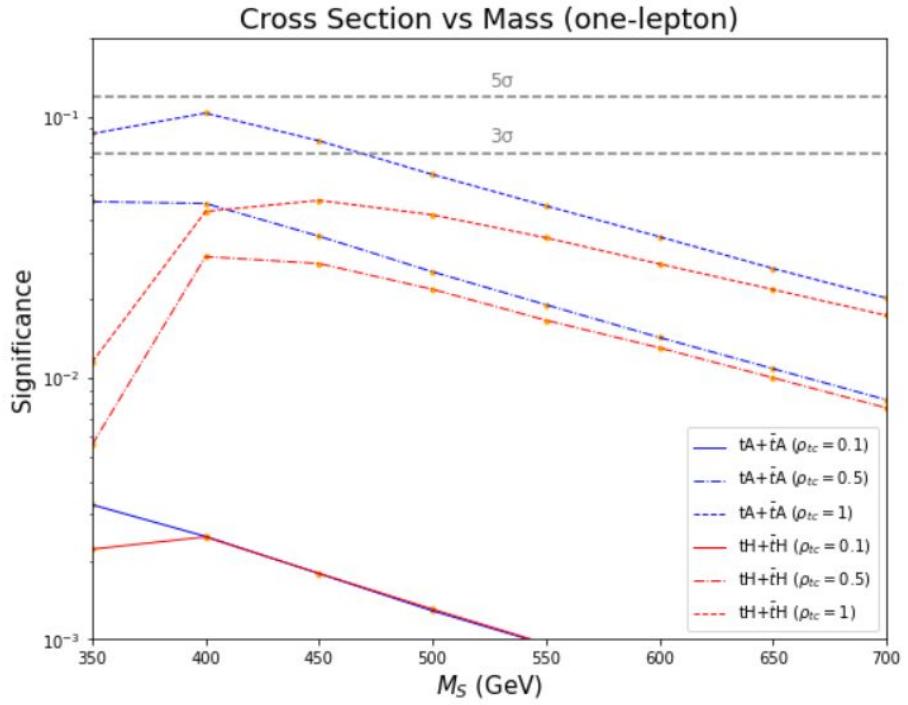
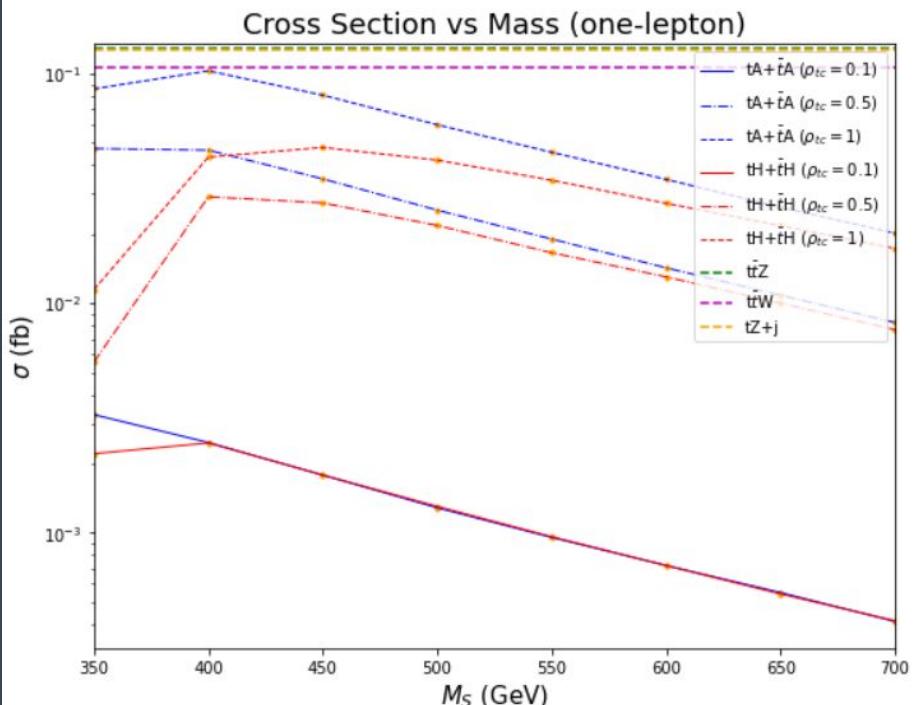
# SS2I Generation (after cut)

```
1 import model gen2HDM_UFO
2 define q = u c u~ c~
3 define q~ = d~ b~ s~ d b s
4 define p = p b b~
5 define j = p
6
7 generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > q q~) )
8 add process p p > t~ A0 QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > t t~, (t > w+ b , w+ > q q~),(t~ > w- b~, w- > l- v1~) )
9 add process p p > t A0 QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t c~, (t > w+ b , w+ > l+ v1))
10 add process p p > t~ A0 QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > c t~, (t~ > w- b~, w- > l- v1~) )
11
12 output SS2I
13 launch SS2I
```



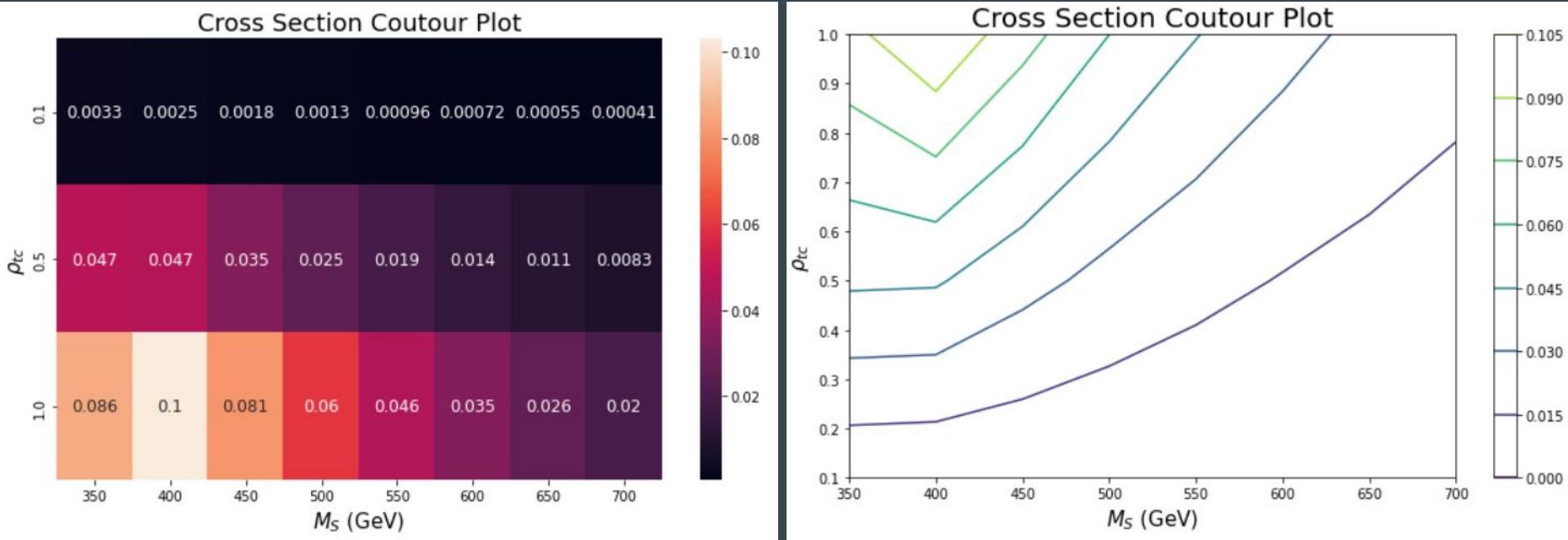
```
15 # set shower, detector
16 shower=OFF
17 detector=OFF
18 done
19 #####
20 # set param and run card settings #
21 #####
22 set use_syst False
23 set rtc 0.1
24 set rtt 1
25 set rtu 0
26 set nevents 500
27 # energy for each proton beam (in GeV)
28 set ebeam1 7000.0
29 set ebeam2 7000.0
30 # minimum pt for leading and subleading jets
31 set ptj1min 30
32 set ptj2min 20
33 # minimum pt for leading and subleading leptons
34 set ptl1min 25
35 set ptl2min 20
36 # minimum missing Et
37 set misset 30
38 # maximum rap for leptons and b-jets
39 set etal 2.5
40 set etab 2.5
41 # minimum distance between bl, bb, bl
42 set drbb 0.4
43 set drbl 0.4
44 set drll 0.4
45 # minimum Ht for two and three leading jets
46 set ht3min 300
47 set ht2min 300
48 # mass of A0 and H0
49 set MA0 350
50 set MS0 0
51 # decay width of A0 and H0
52 set wa0 3.9714680083
53 set ws0 0
54 done
```

# Cross Section



Signal Yield, Cross Section -> Number of Events

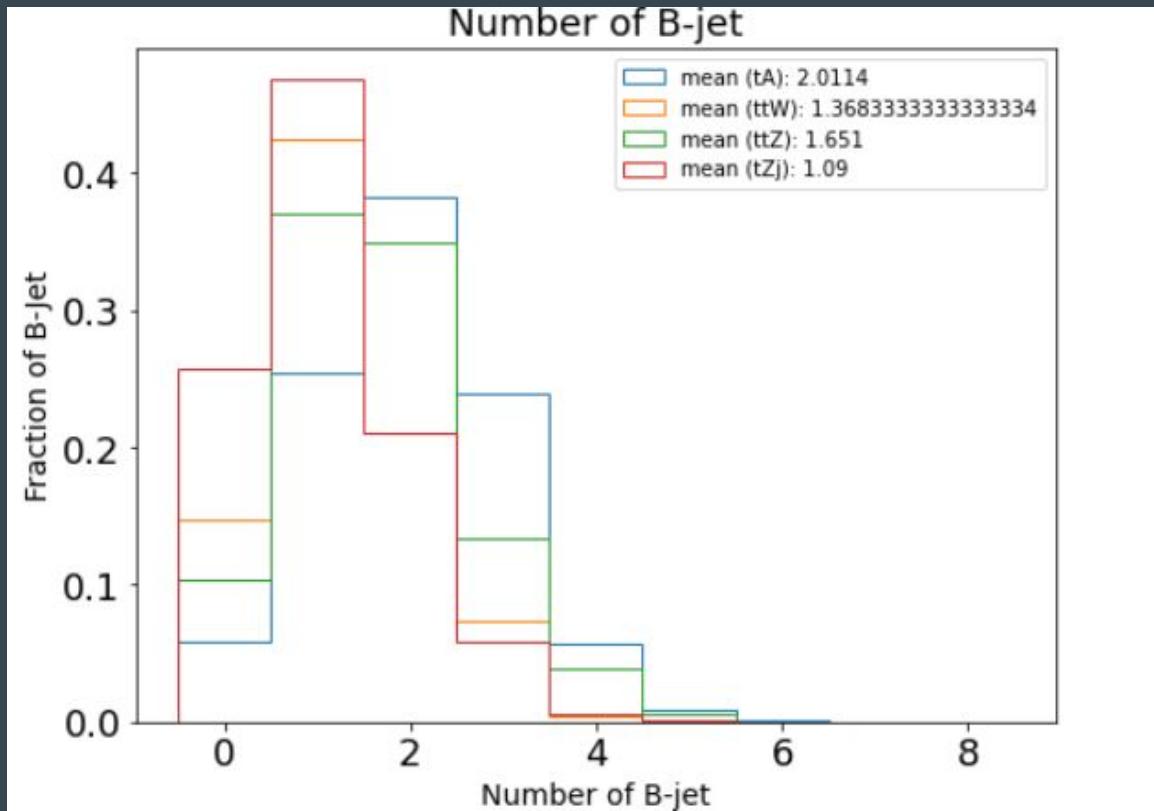
# Cross Section



# To-do

	Name	Description
0	$\sum b\text{-tag}$	Sum of pseudo-continuous $b$ -tagging score over the six jets with the highest score
1	$N_{\text{jets}}$	Number of jets
1	$\Delta R_{bb}^{\min}$	Minimum $\Delta R$ between all pairs of $b$ -tagged jets
1	$H_T^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
1	$C^{\text{all}}$	Centrality ( $\sum_i p_{Ti} / \sum_i E_i$ ) of the leptons and jets
1	$p_T^{\text{lead}}$	Transverse momentum of the leading jet
1	$\Delta R_{b\ell}^{\min}$	Minimum $\Delta R$ between all pairs of $b$ -tagged jets and leptons
1	$\Delta R_{jj}^{\text{avg}}$	Average $\Delta R$ between all pairs of jets
1	$m_{\text{jjj}}$	Invariant mass of the closest triplet of jets
1	$E_T^{\text{miss}}$	Missing transverse momentum
1	$m_T^W$	$W$ reconstructed transverse mass $m_T(\ell, E_T^{\text{miss}})$ (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

# Number of b-jets



$\sum b\text{-tag}$  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.

$\sum b\text{-tag}$  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}

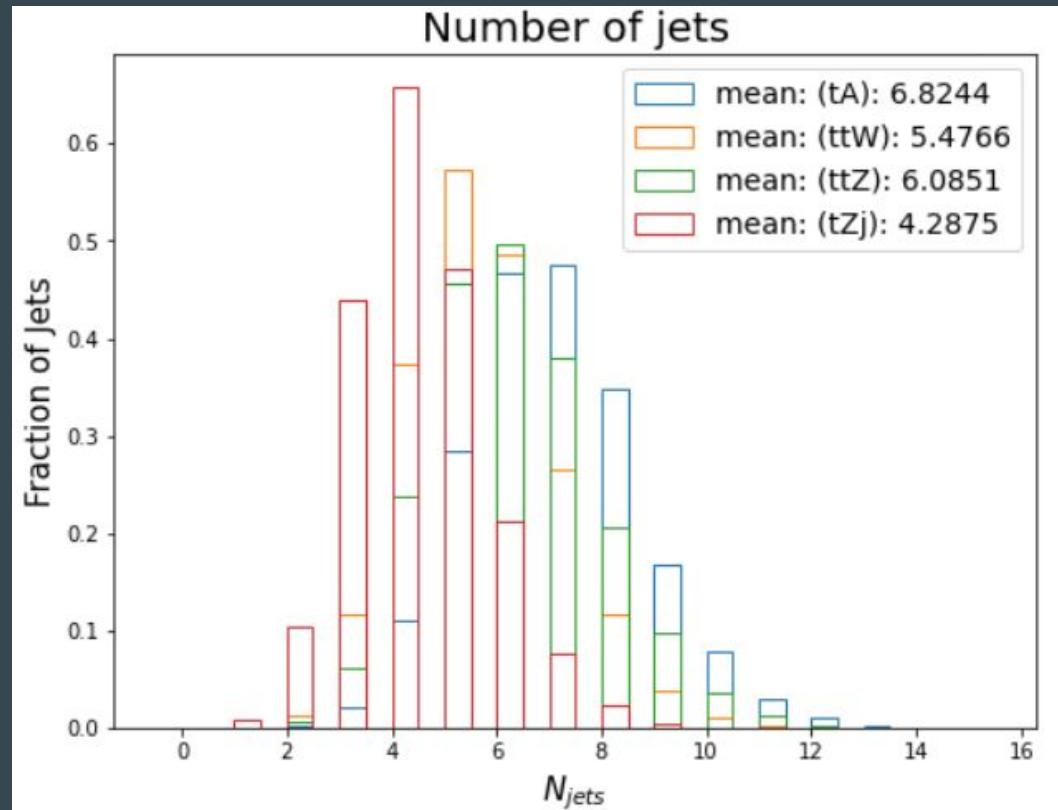
    # efficiency formula for c-jets (misidentification rate)
    add EfficiencyFormula {4} {0.25*tanh(0.018*pt)*(1/(1+ 0.0013*pt))}

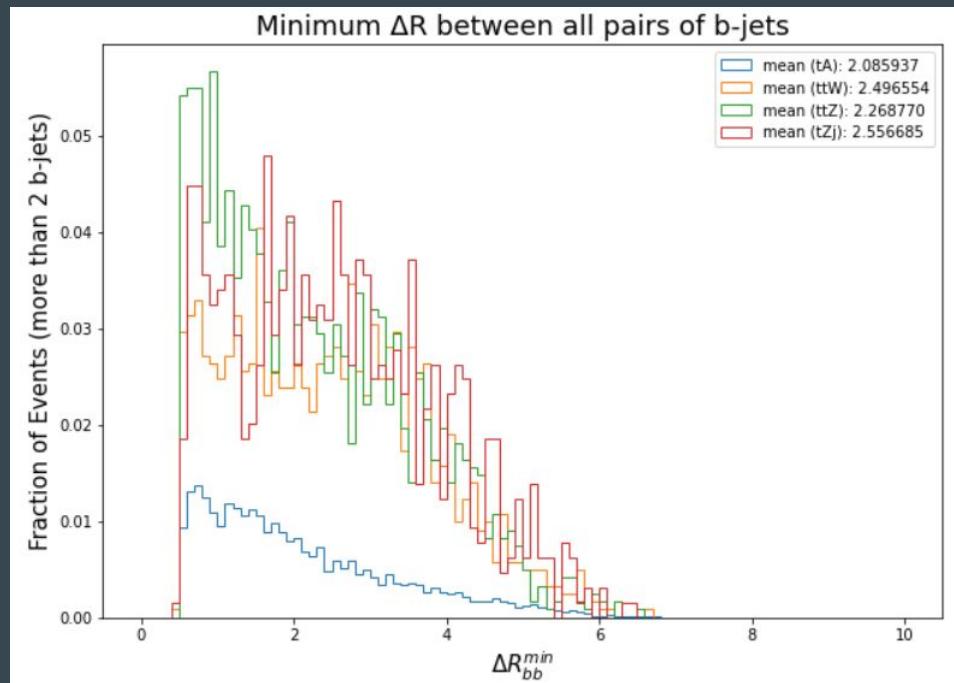
    # efficiency formula for b-jets
    add EfficiencyFormula {5} {0.85*tanh(0.0025*pt)*(25.0/(1+0.063*pt))} ←
```

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

$N_{\text{jets}}$ 

Number of jets



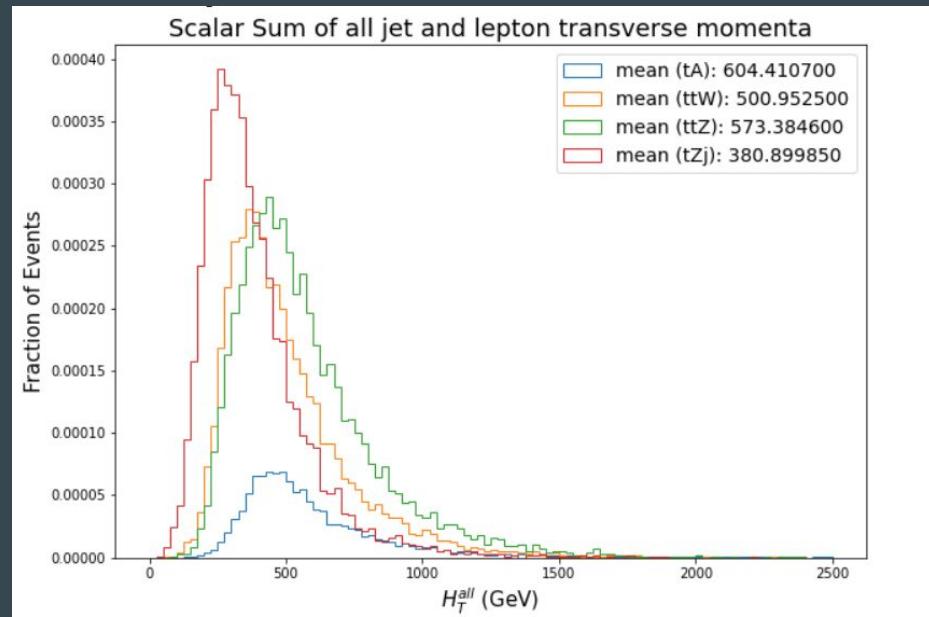
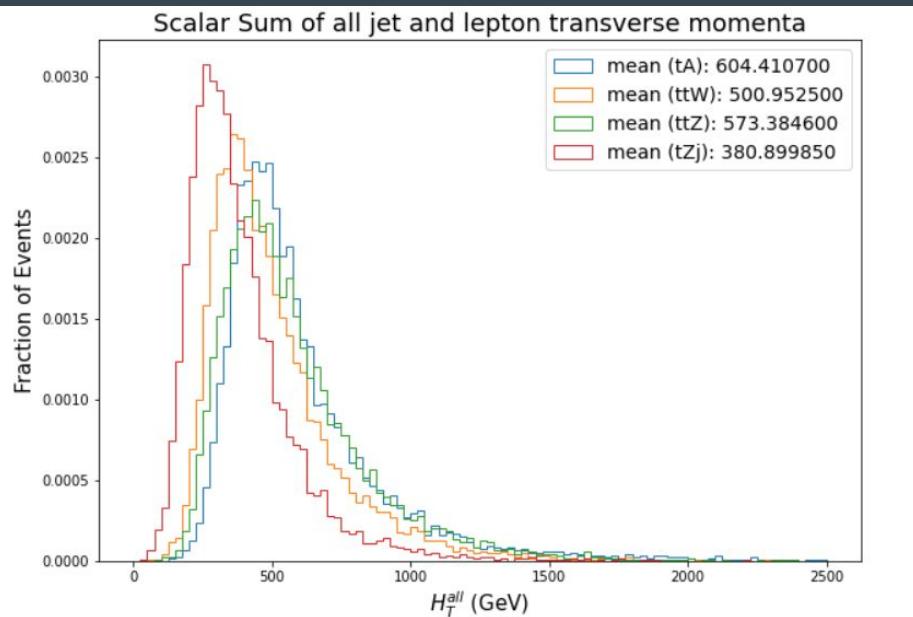
$\Delta R_{bb}^{\min}$ Minimum  $\Delta R$  between all pairs of  $b$ -tagged jets

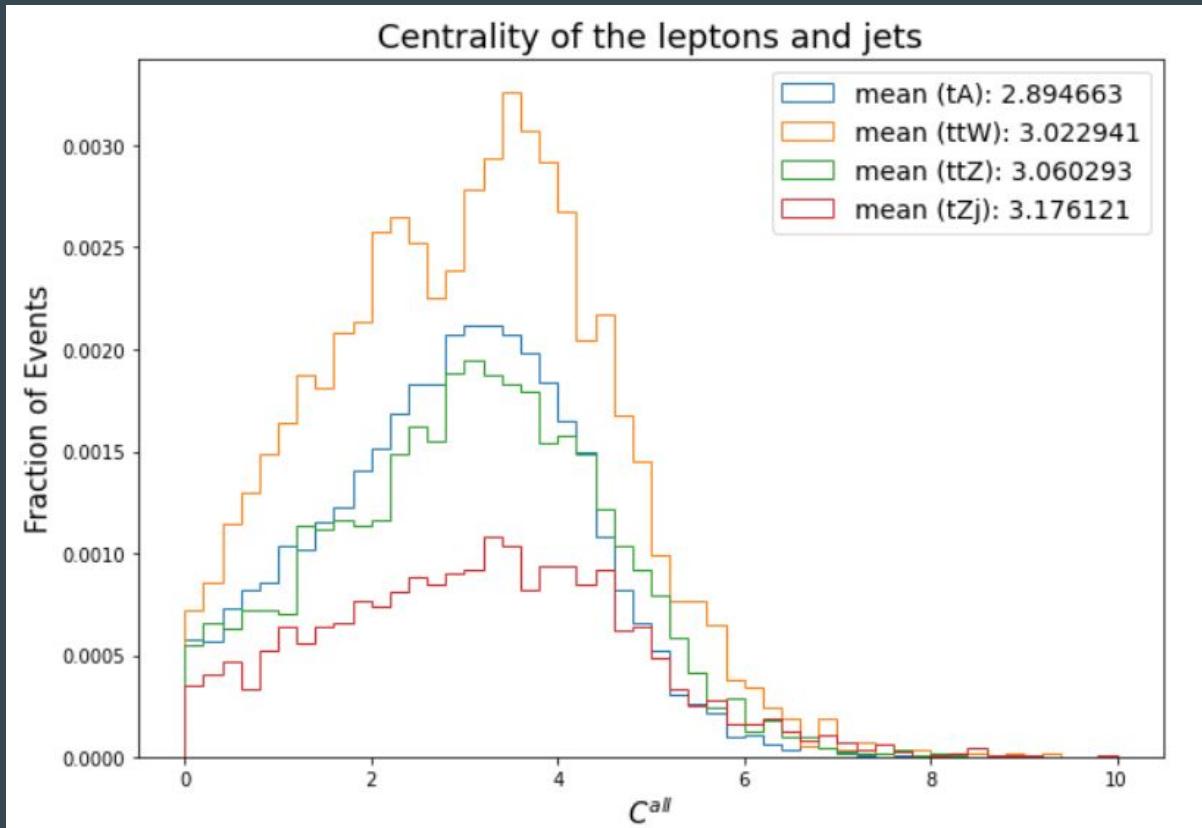
$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}.$$

$H_T^{\text{all}}$ 

# Scalar sum of all jet and lepton transverse momenta

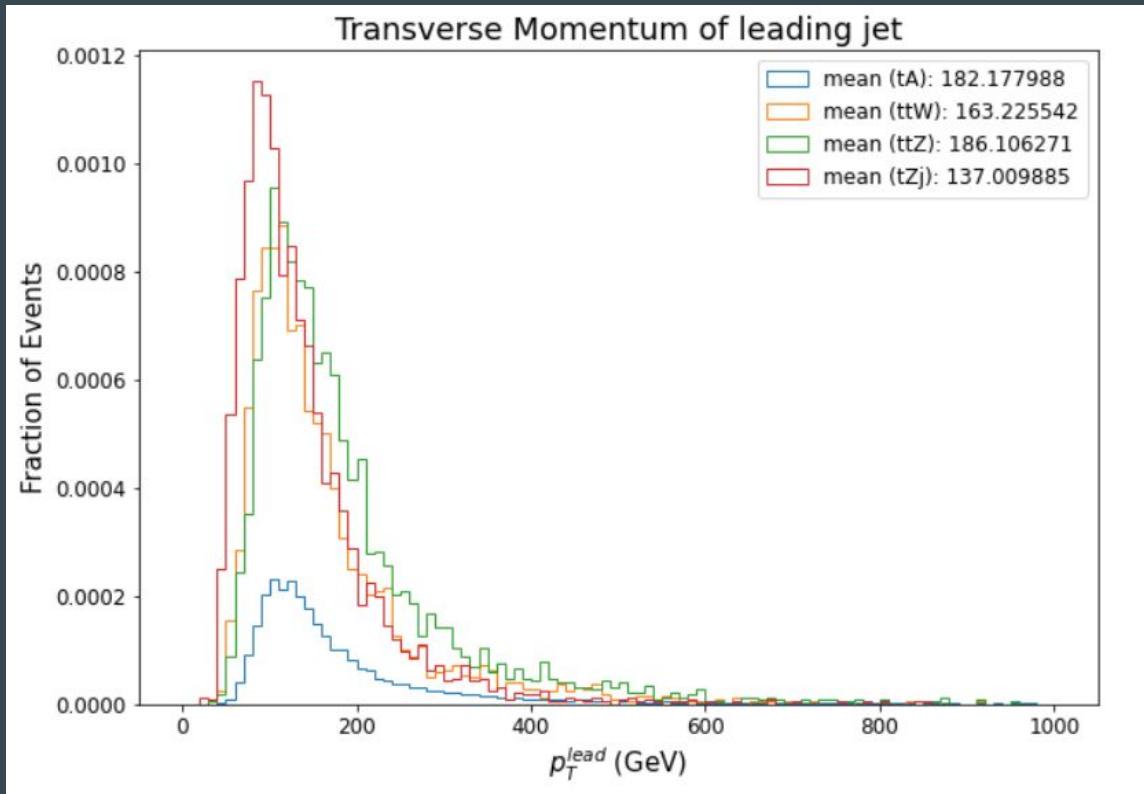
Normalize regards to cross section:

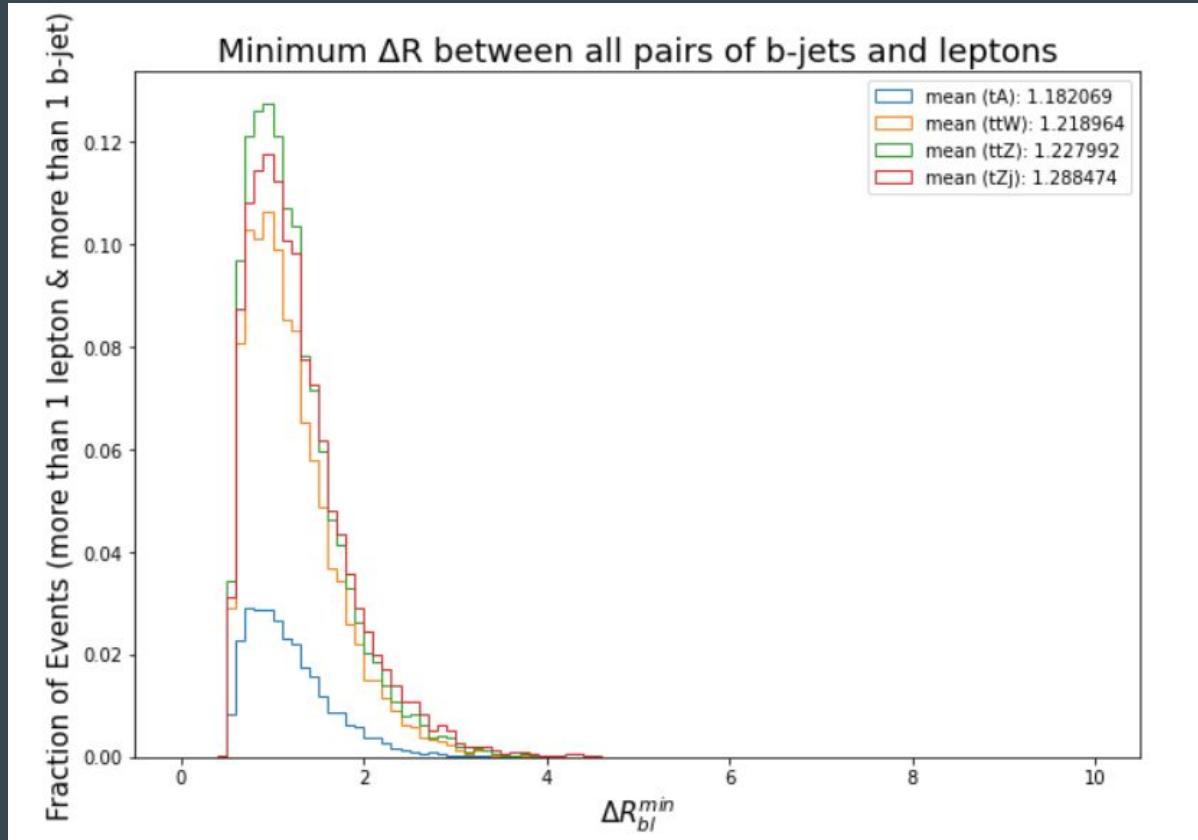


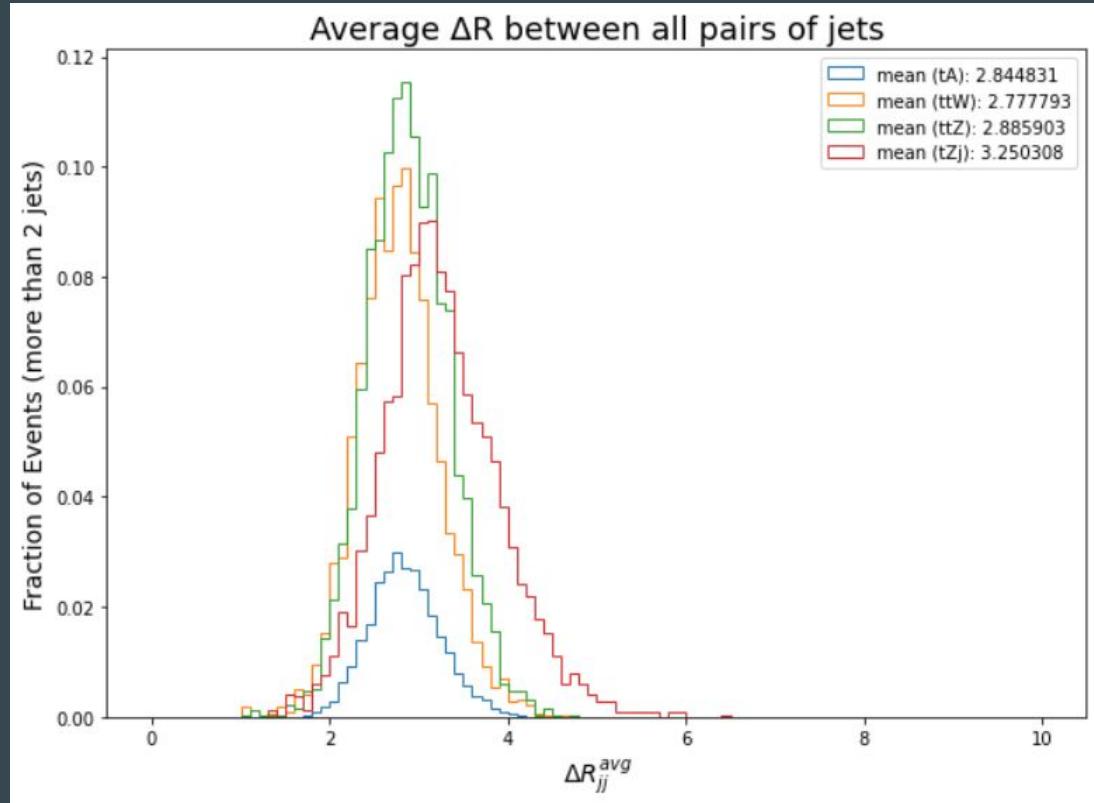
$C^{\text{all}}$ Centrality ( $\sum_i p_{\text{T}i} / \sum_i E_i$ ) of the leptons and jets

$p_T^{\text{lead}}$ 

## Transverse momentum of the leading jet

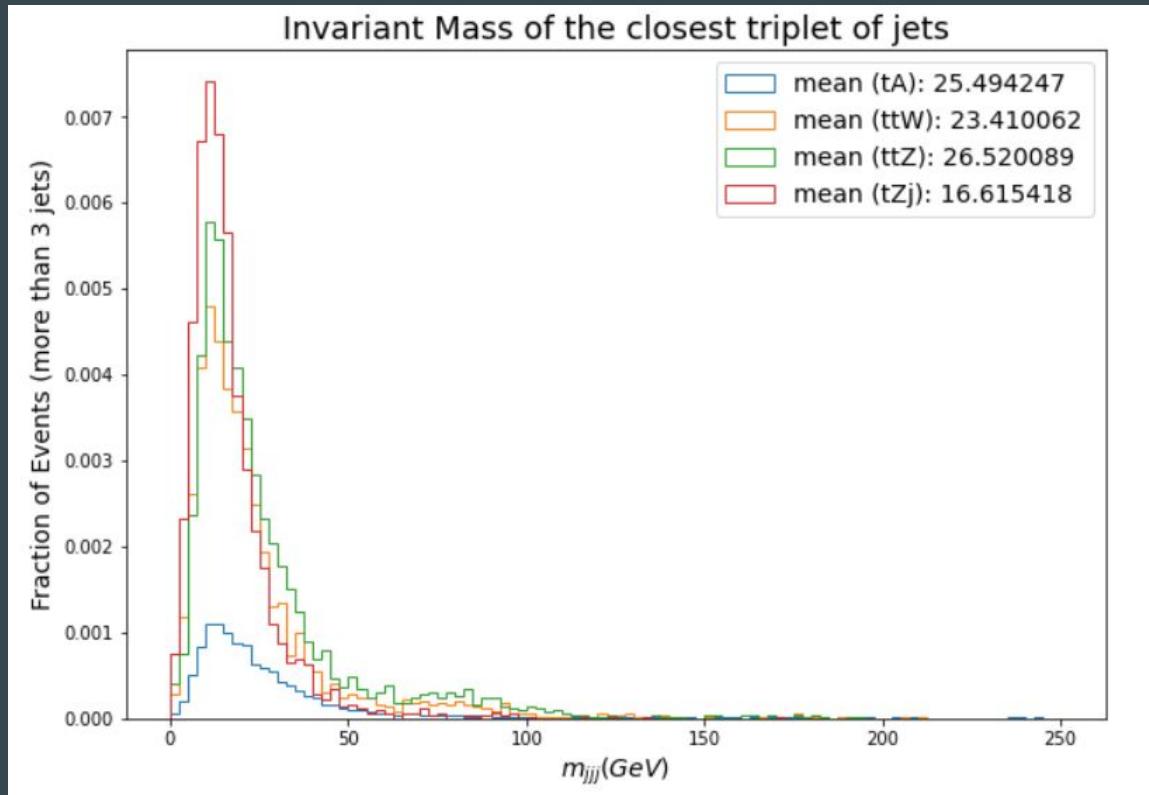


$\Delta R_{b\ell}^{\min}$ Minimum  $\Delta R$  between all pairs of  $b$ -tagged jets and leptons

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

$m_{jjj}$

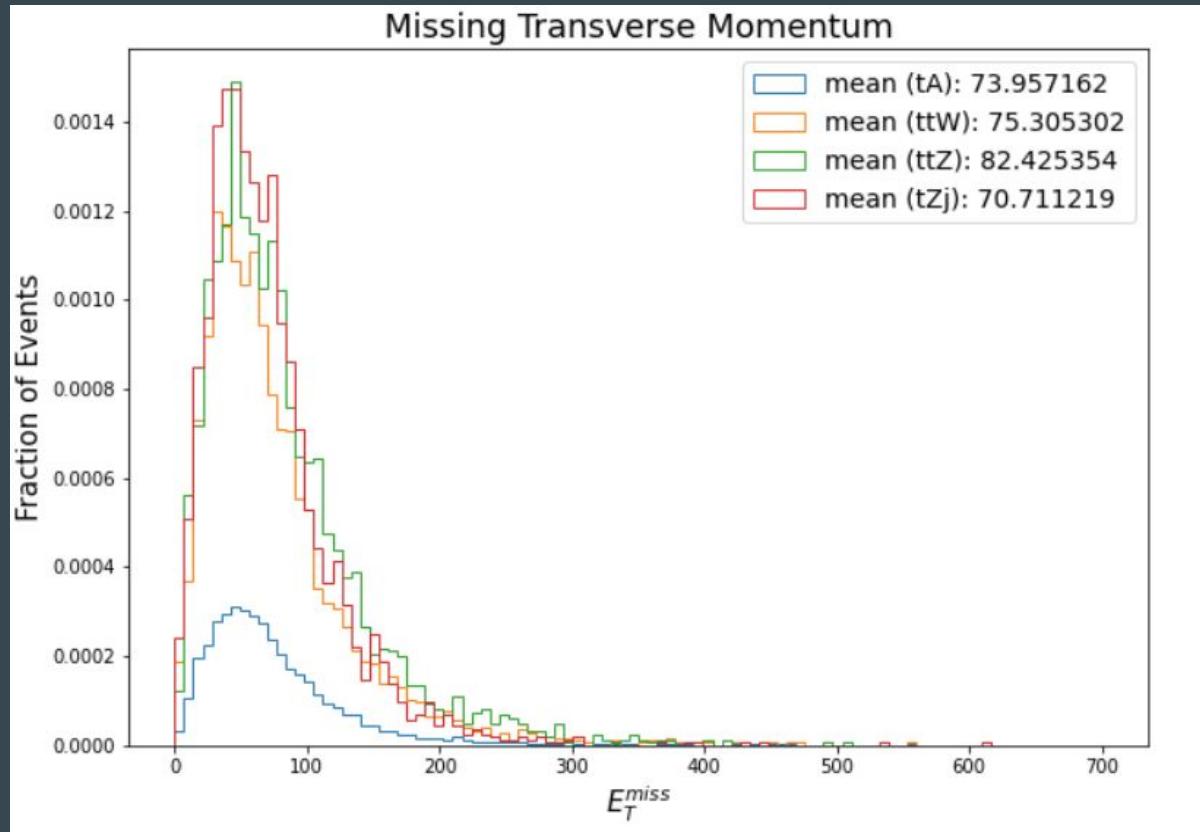
# Invariant mass of the closest triplet of jets



<sup>3</sup> The  $\Delta R$  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.

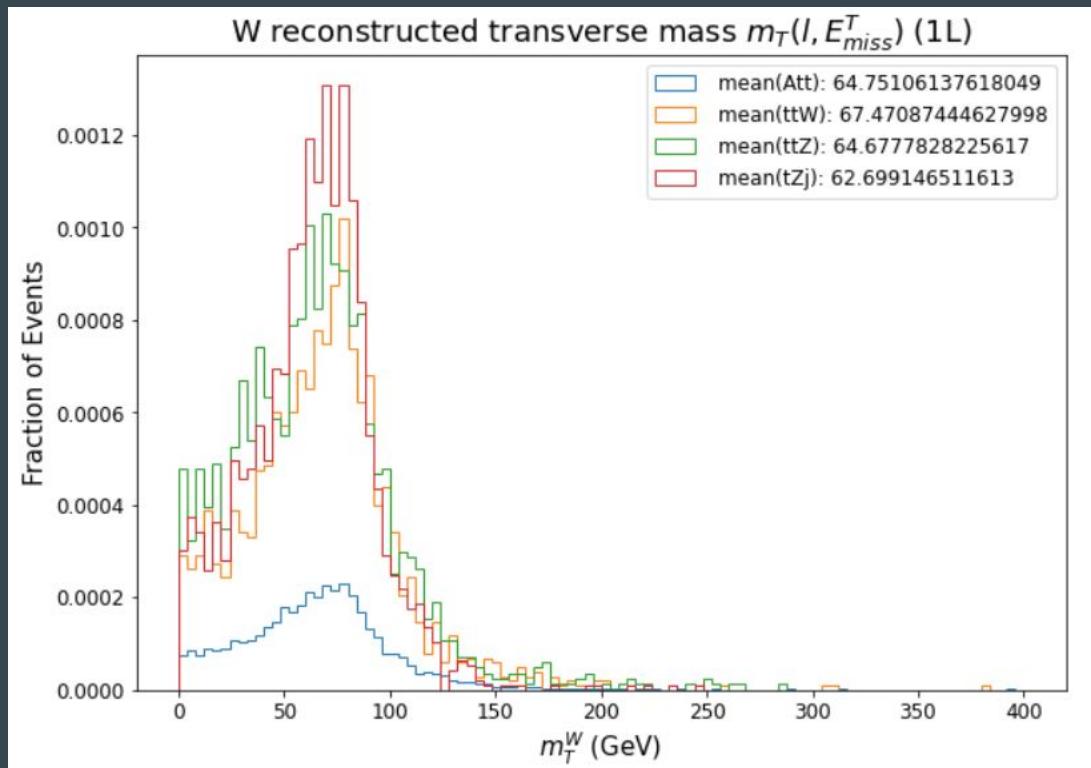
$E_T^{\text{miss}}$ 

# Missing transverse momentum



$m_T^W$ 

# $W$ reconstructed transverse mass $m_T(\ell, E_T^{\text{miss}})$ (1L)



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

## 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  $p_T > 25 \text{ GeV}$  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

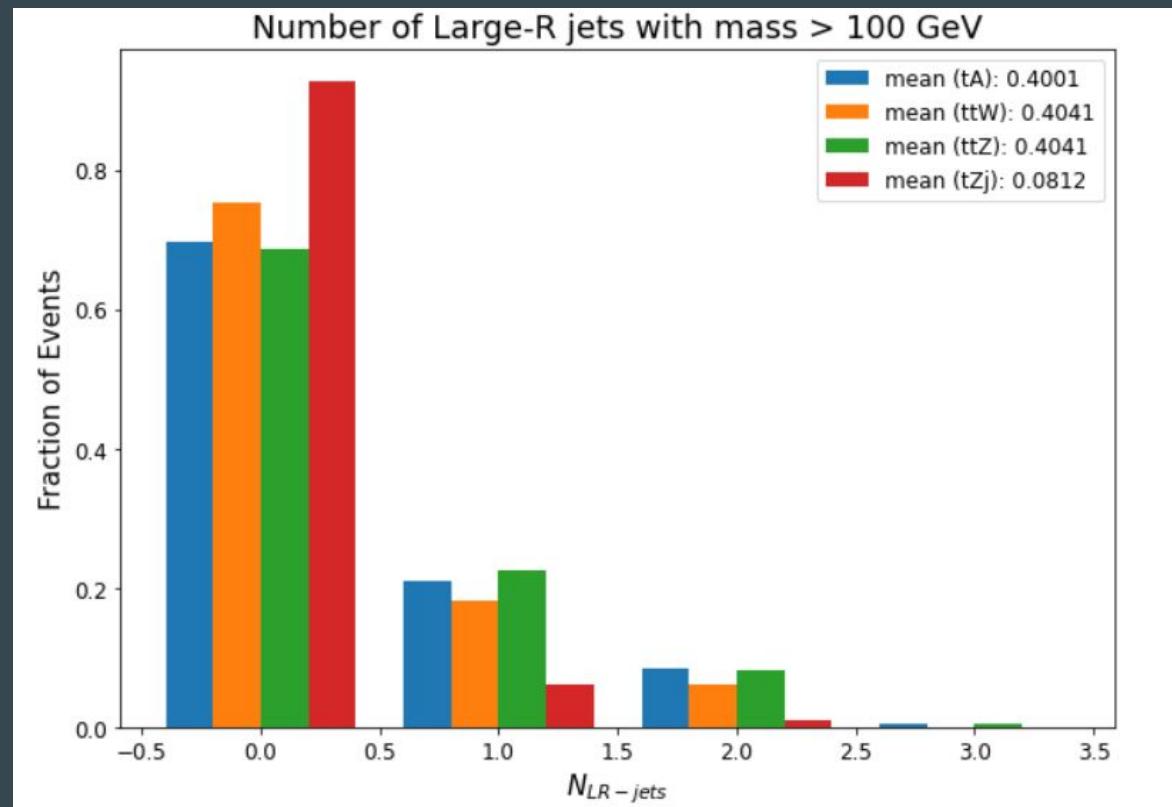
set ComputeTrimming 1
set RTrim 0.2
set PtFracTrim 0.05

set ComputePruning 1
set ZcutPrun 0.1
set RcutfPrun 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      ←

}
```

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

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

<sup>5</sup> 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  $R$ :  $d_{ij} = \min(p_{\text{T}i}^2, p_{\text{T}j}^2) \times \Delta R_{ij}^2 / R^2$ .

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

# Information for rest of plots

The  $\Delta R$  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  $R$ :  $d_{ij} = \min(p_{Ti}^2, p_{Tj}^2) \times \Delta R_{ij}^2 / R^2$ .

# 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

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

Poisson Probability

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

Likelihood Function

x = counts

a = mean

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

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

Bayes Theorem

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

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

# Parameter of the model

- import gen2HDM model (insert the information for H0, A0)
- set the process ( $H, A \rightarrow t, \bar{t}$ ) 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

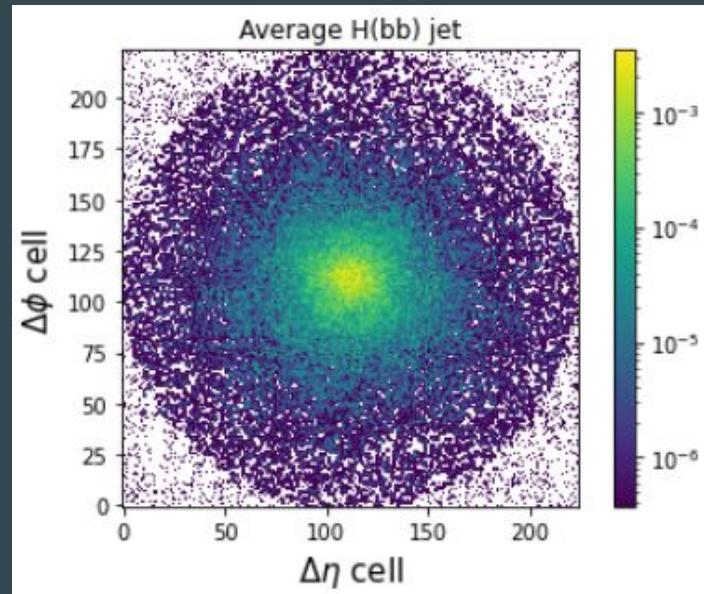
```
1 import model gen2HDM_UFO
2 define p = p b b~ 
3 define j = p
4 generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
5 add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
6 add process p p > t~ A0 QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
7 add process p p > t~ A0 j QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
8
9 output Att_400
10
11 launch Att_400
12
13 shower=PYTHIA8
14 detector=delphes
15
16 set rtc 0.5
17 set rtt 0.5
18 set rtu 0
19 set nevents 5000
20 set ebeam1 7000.0
21 set ebeam2 7000.0
22 set pdlabel lhapdf
23 set lhaid 247000
24 set MA0 400
25 set MS0 400
26 set ebeam1 7000.0
27 set ebeam2 7000.0
28
```

Prove: setting MH0 won't affect the cross section of  $pp \rightarrow tA + t\bar{A}$

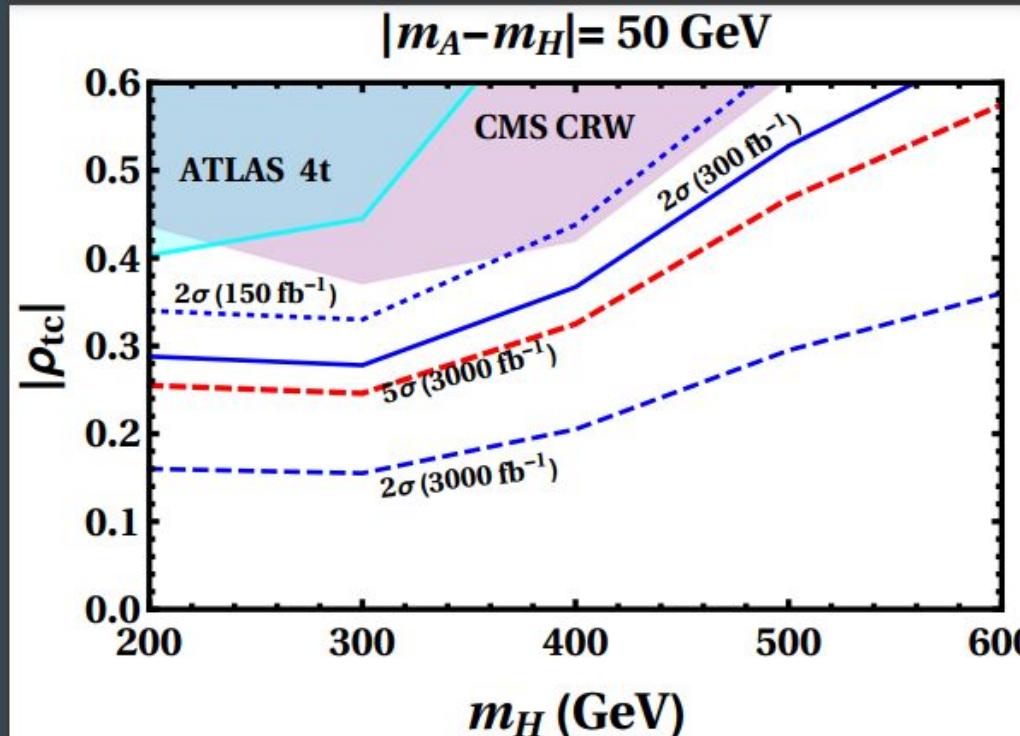
Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	$1.201 \pm 0.0056 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_02	p p 7000.0 x 7000.0 GeV	tag_1	$0.609 \pm 0.0027 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_03	p p 7000.0 x 7000.0 GeV	tag_1	$0.3177 \pm 0.0015 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_04	p p 7000.0 x 7000.0 GeV	tag_1	$0.1785 \pm 0.00096 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_05	p p 7000.0 x 7000.0 GeV	tag_1	$1.201 \pm 0.007 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_06	p p 7000.0 x 7000.0 GeV	tag_1	$0.6015 \pm 0.0032 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_07	p p 7000.0 x 7000.0 GeV	tag_1	$0.3219 \pm 0.0019 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_08	p p 7000.0 x 7000.0 GeV	tag_1	$0.1795 \pm 0.0011 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_09	p p 7000.0 x 7000.0 GeV	tag_1	$1.213 \pm 0.0054 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_10	p p 7000.0 x 7000.0 GeV	tag_1	$0.6071 \pm 0.0032 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_11	p p 7000.0 x 7000.0 GeV	tag_1	$0.3198 \pm 0.0016 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_12	p p 7000.0 x 7000.0 GeV	tag_1	$0.178 \pm 0.00081 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_13	p p 7000.0 x 7000.0 GeV	tag_1	$1.206 \pm 0.0055 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_14	p p 7000.0 x 7000.0 GeV	tag_1	$0.6063 \pm 0.0028 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_15	p p 7000.0 x 7000.0 GeV	tag_1	$0.3196 \pm 0.0014 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	remove run   launch detector simulation
run_16	p p 7000.0 x 7000.0 GeV	tag_1	$0.1781 \pm 0.0008 \pm \text{systematics}$	500	parton madevent	<a href="#">LHE MA5 report analysis</a>	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

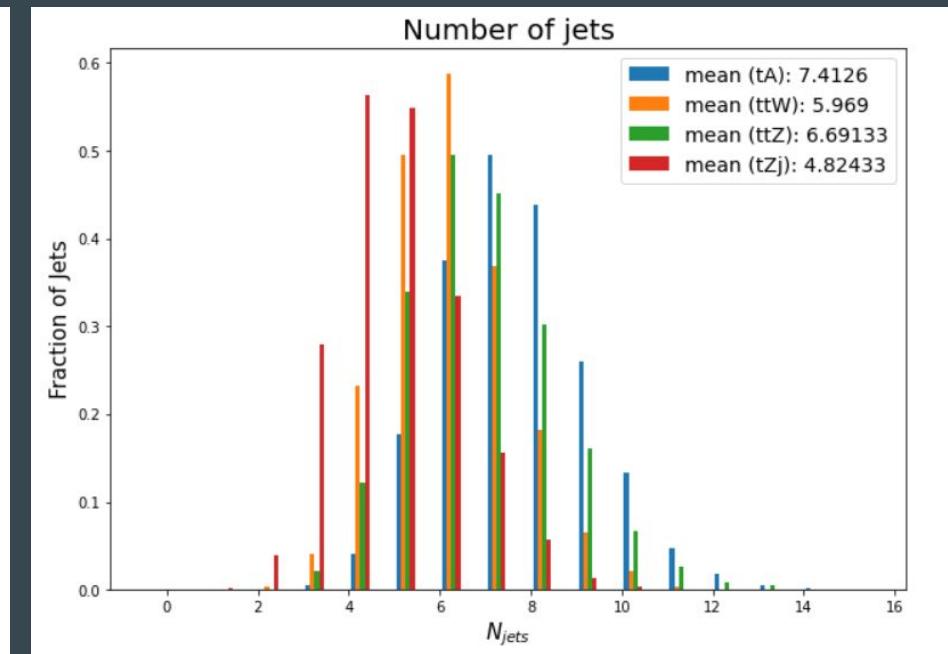
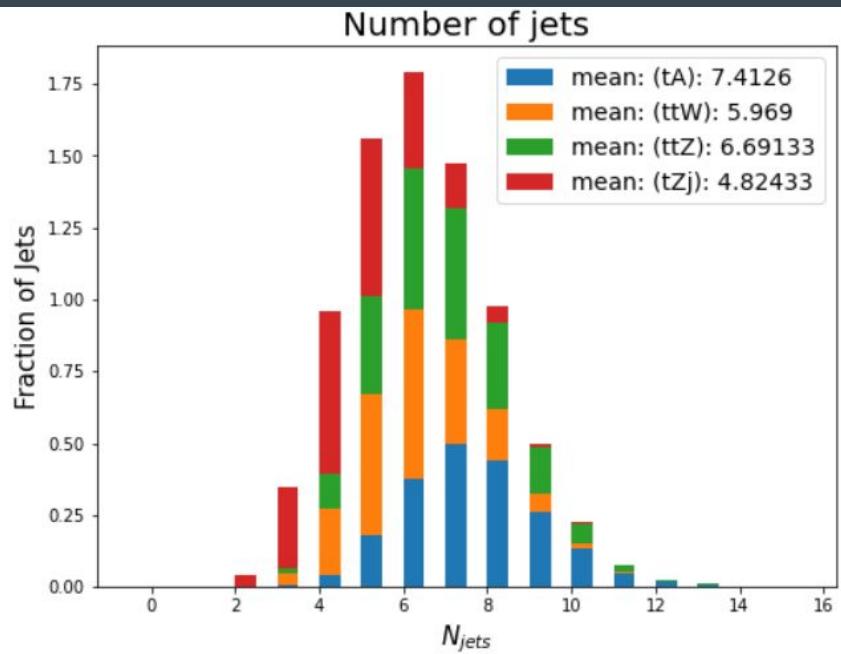


# Back up slide



$N_{\text{jets}}$ 

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:

```
1 import model gen2HDM_UFO
2 define p = p b b~ 
3 define j = p
4 generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
5 add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ v1) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
6 add process p p > t~ A0 QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
7 add process p p > t~ A0 j QCD=99, (t~ > w- b~, w- > l- v1~) ,( A0 > t t~, (t > w+ b , w+ > l+ v1),(t~ > w- b~, w- > l- v1~) )
8 output sig_schannel
9
10 open index.html
11 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

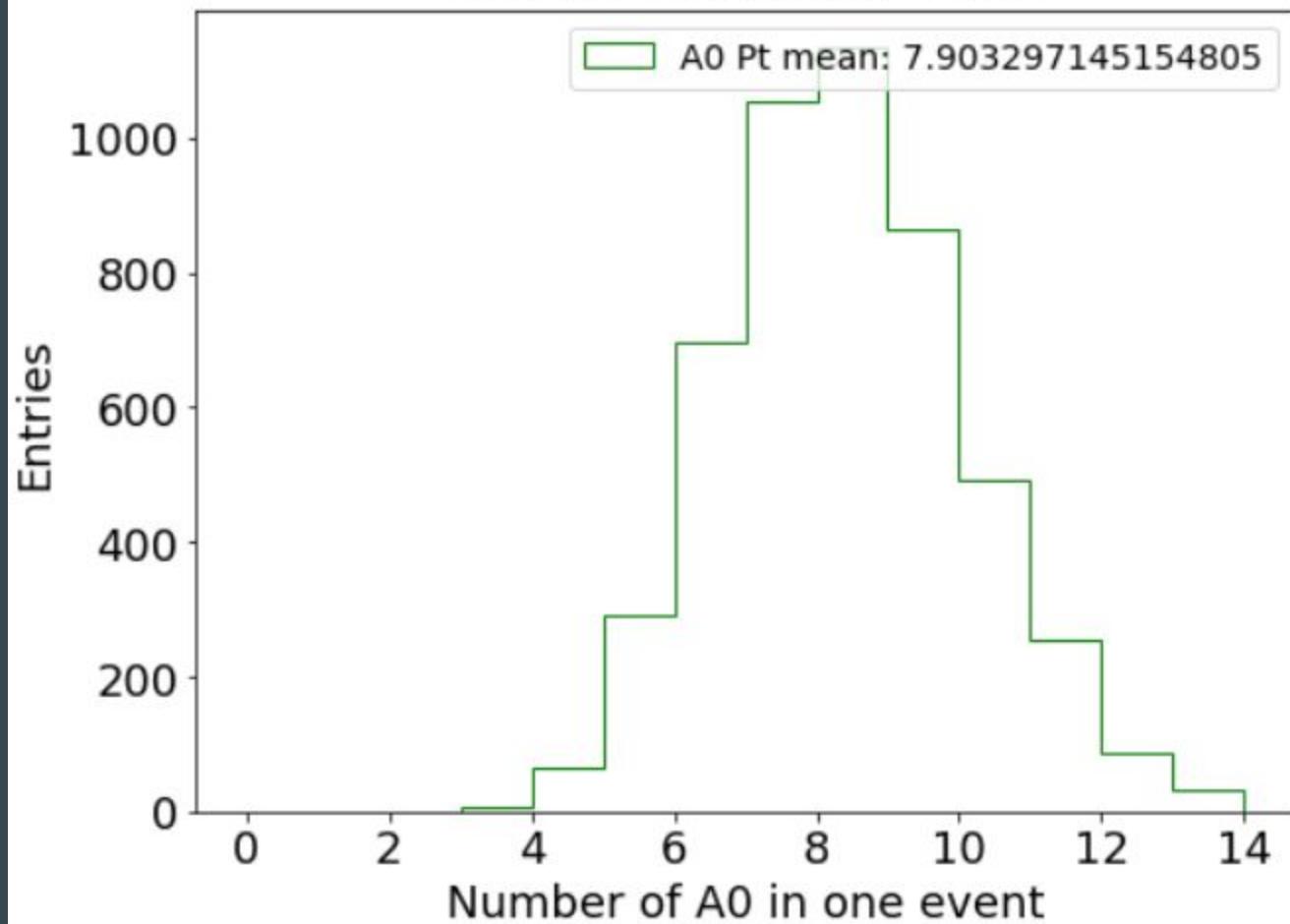
<https://www.sciencedirect.com/science/article/pii/S0550321320302273> (Feynman Diagrams)

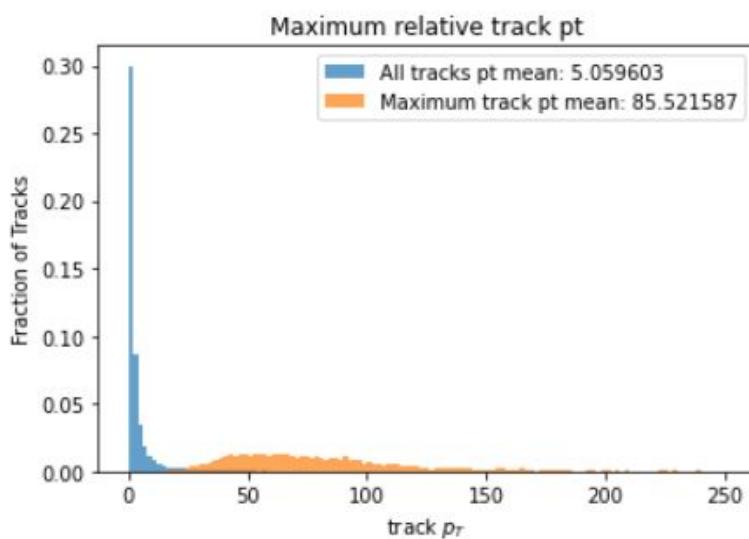
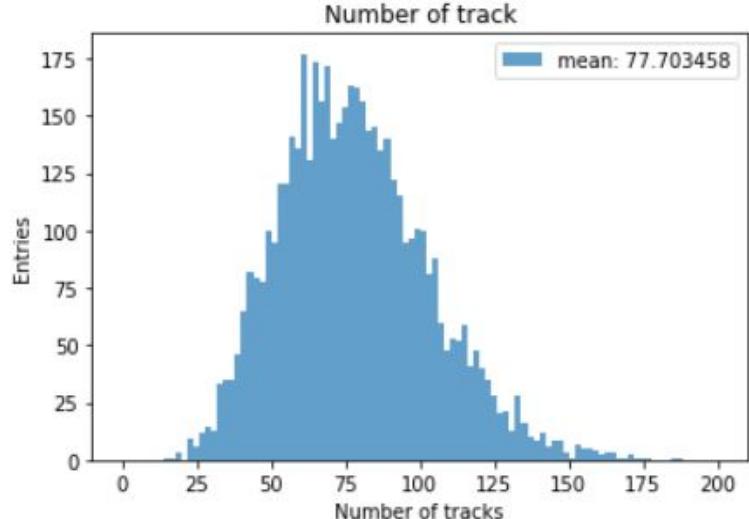
# Lagrangian

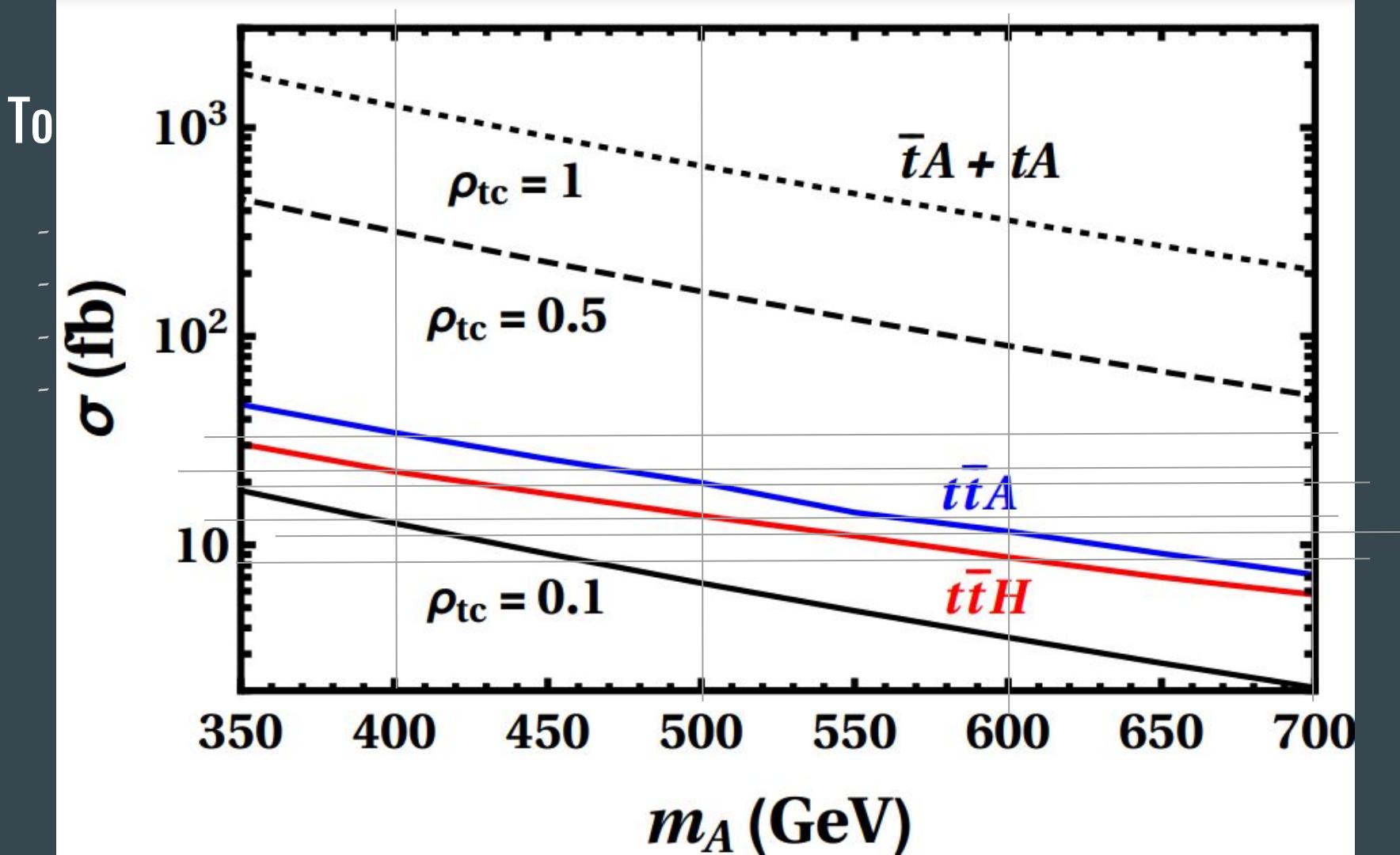
- rho\_tc
- s = sin(), c = cos()

$$\begin{aligned}\mathcal{L} = & -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda_{ij}^f s_\gamma + \rho_{ij}^f c_\gamma) h \\ & + (\lambda_{ij}^f c_\gamma + \rho_{ij}^f s_\gamma) H - i \operatorname{sgn}(Q_f) \rho_{ij}^f A] R f_j + \text{H. c.},\end{aligned}$$

### Number of A0 in one event







<u>Distribution/pdf</u>	<u>Example use in HEP</u>
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 Uncertainties:

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

### Blunders, i.e. errors:

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

# Problem:

1.