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.

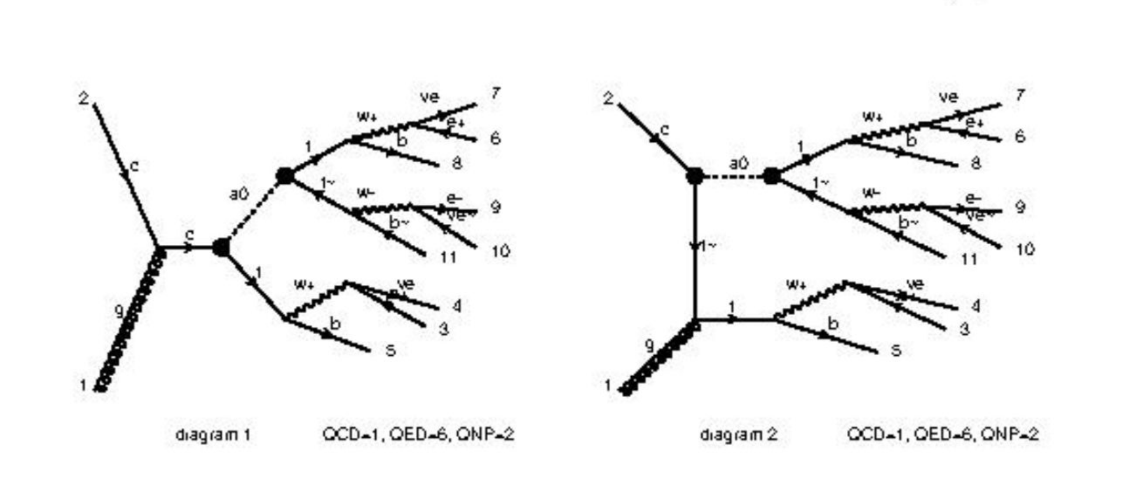
Before Spontaneous Symmetry Breaking:

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

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

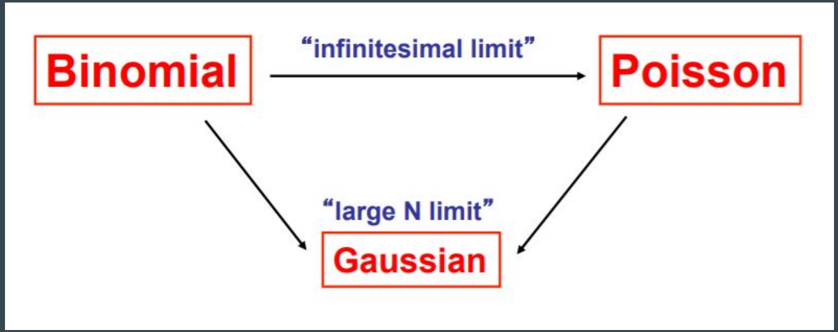
Triple Top

- 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

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

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

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

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

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

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

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

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

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

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

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

$$\Downarrow$$

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

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

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

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

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

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

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

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

$$= np(1-p)$$

$$= npq$$

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 $\sqrt{N}$

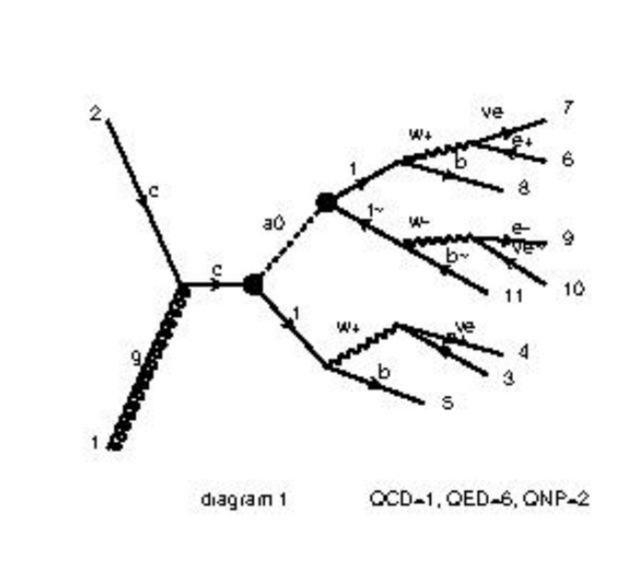
Gaussian Distribution

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

- 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:

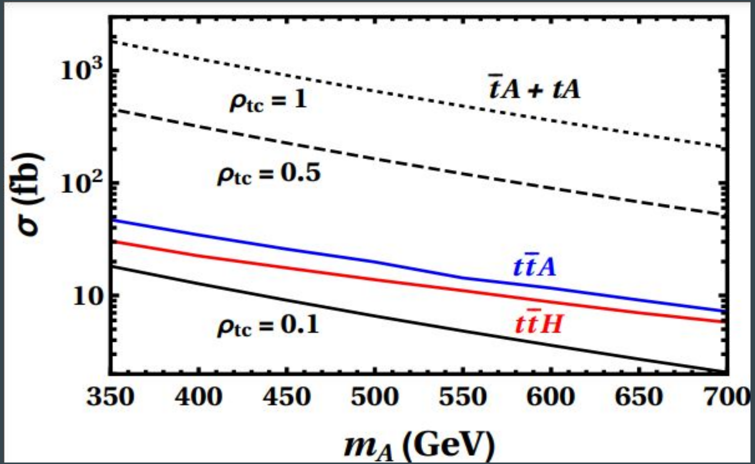
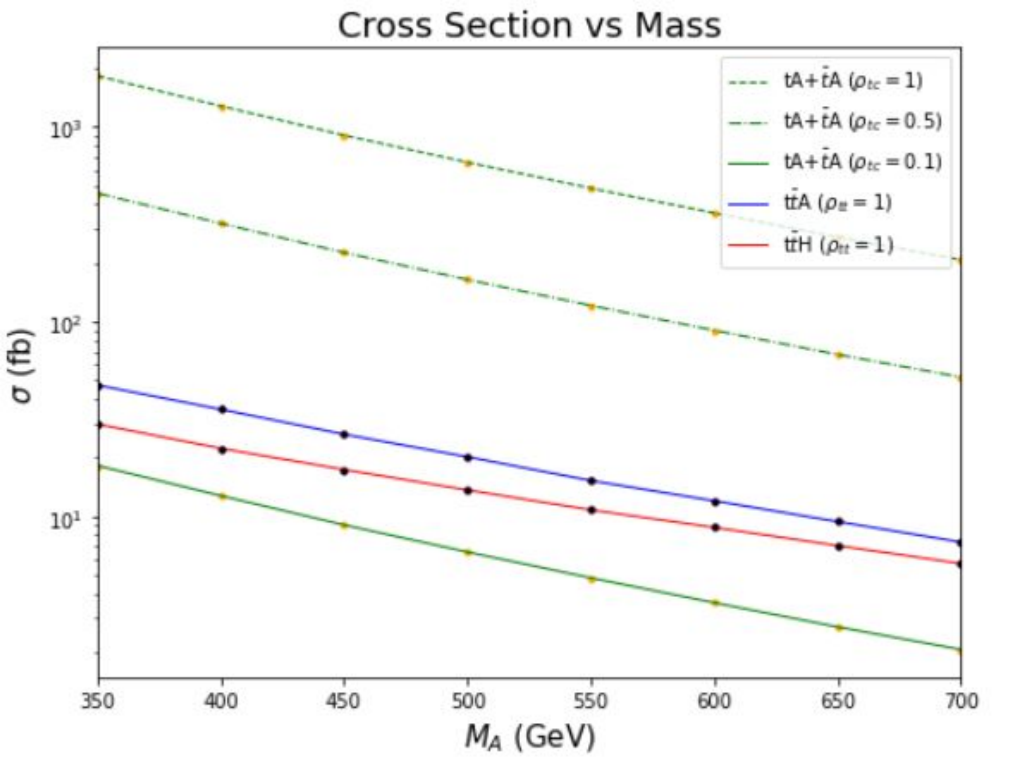
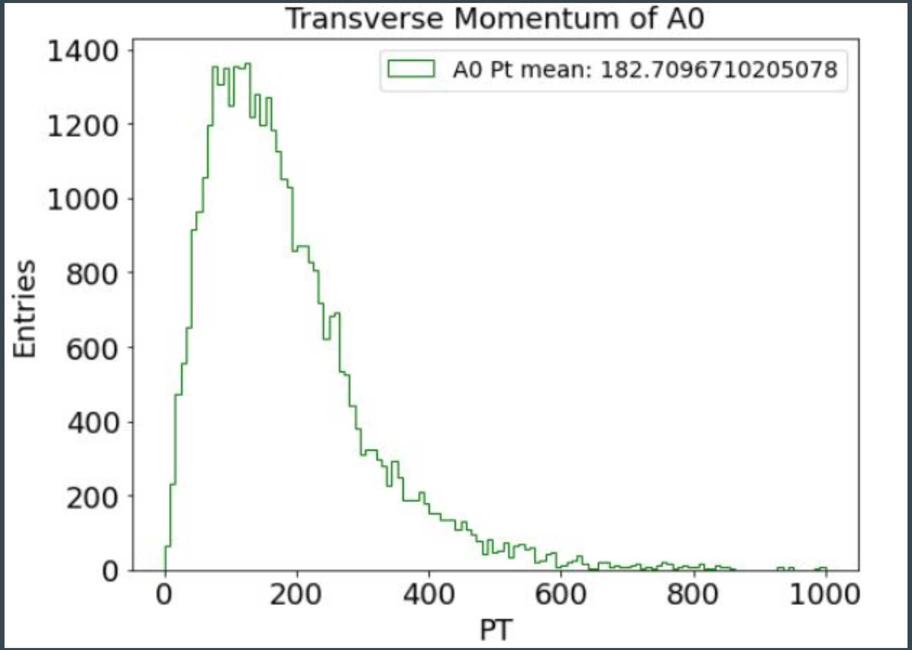


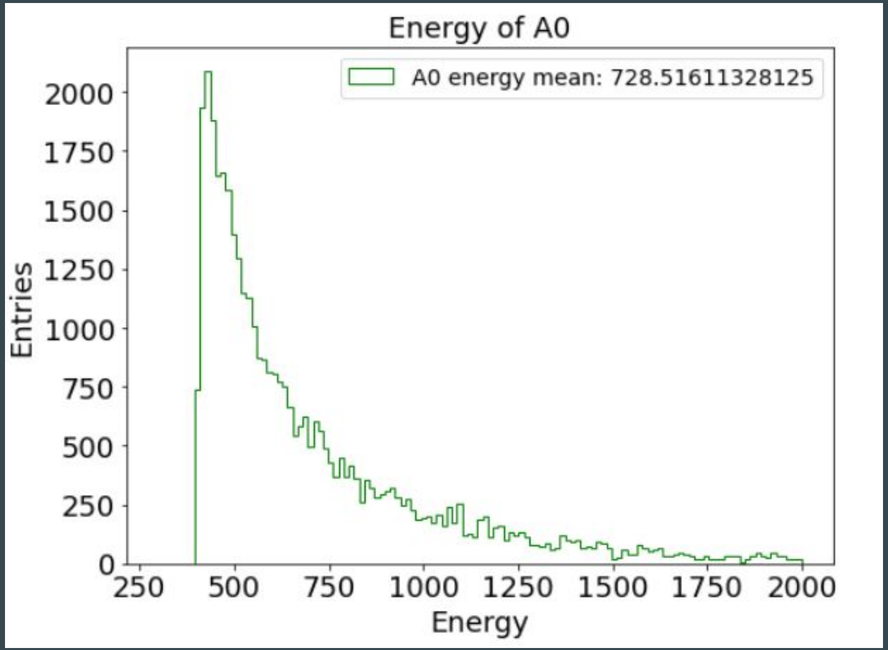
FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \to tS^0$, $\bar{t}S^0$ where $S^0 = H^0$, A^0, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \to t\bar{t}H^0$, $t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

My Result:

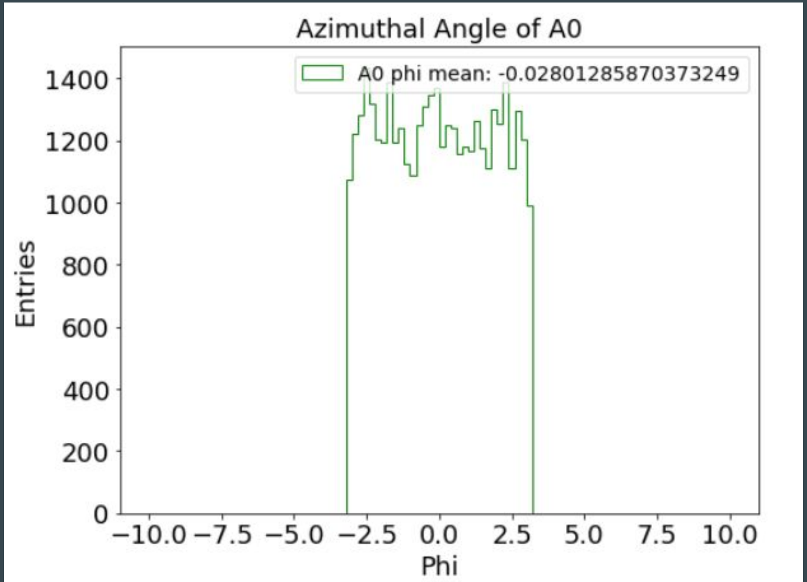


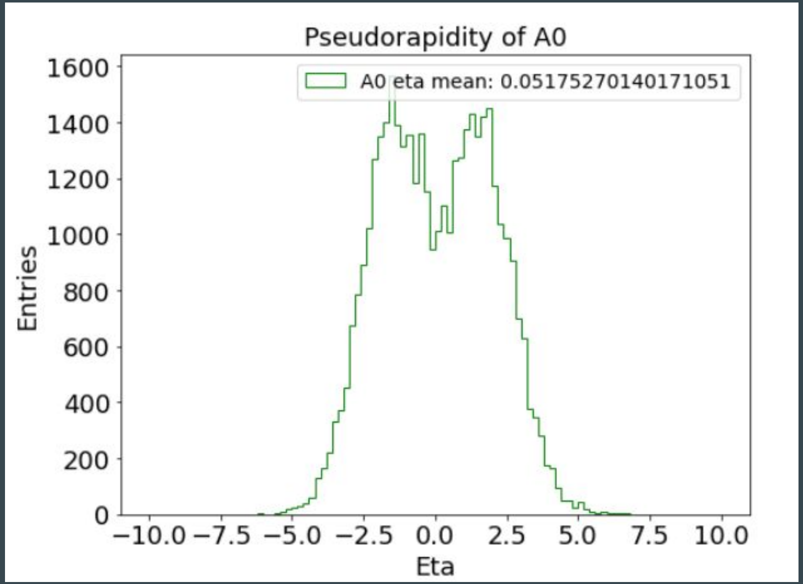
Kinematic Plots (A0 400GeV)



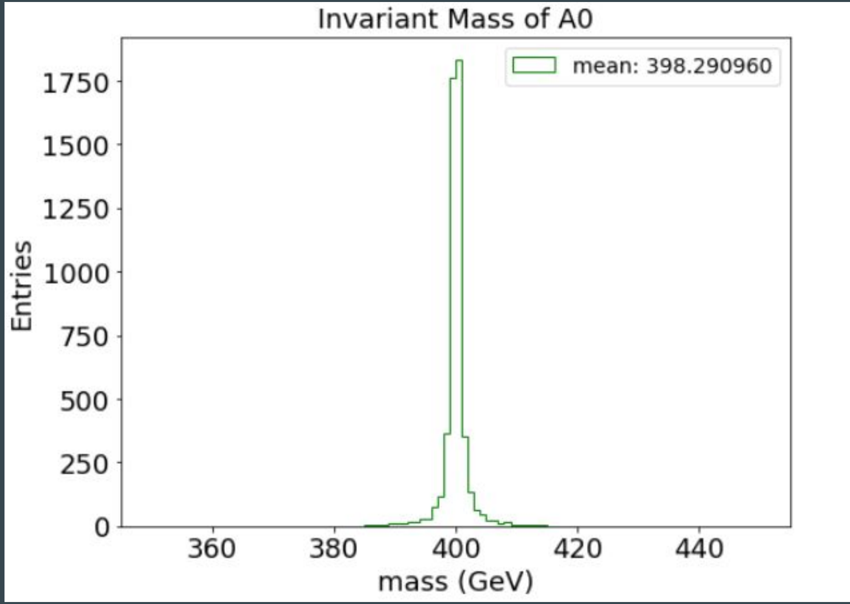


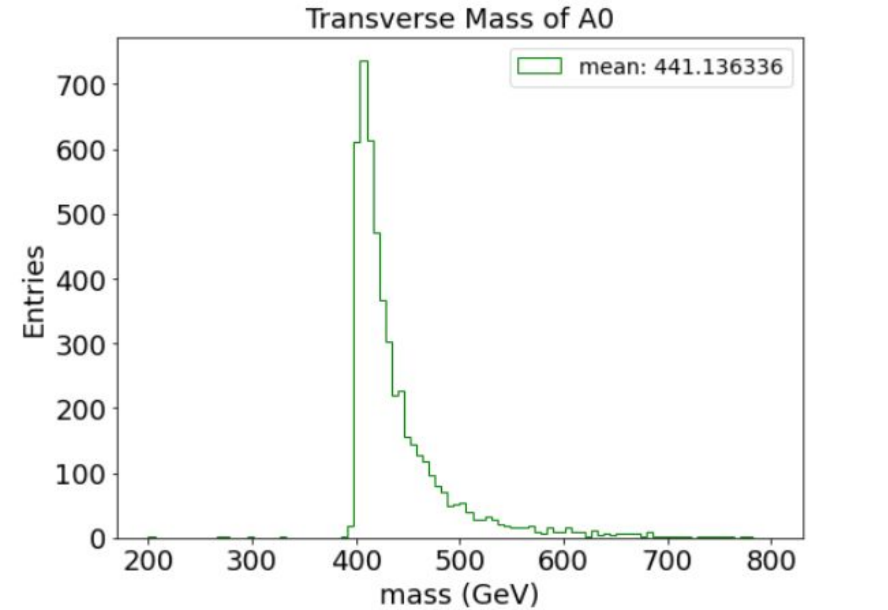
Kinematic Plots (A0 400GeV)





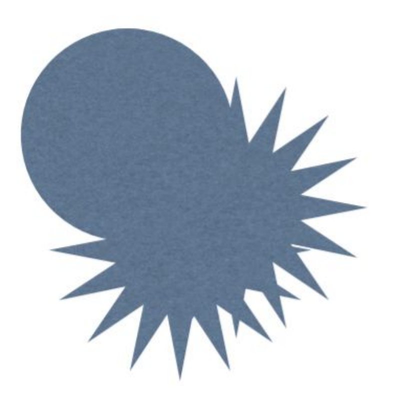
Kinematic Plots (A0 400GeV)

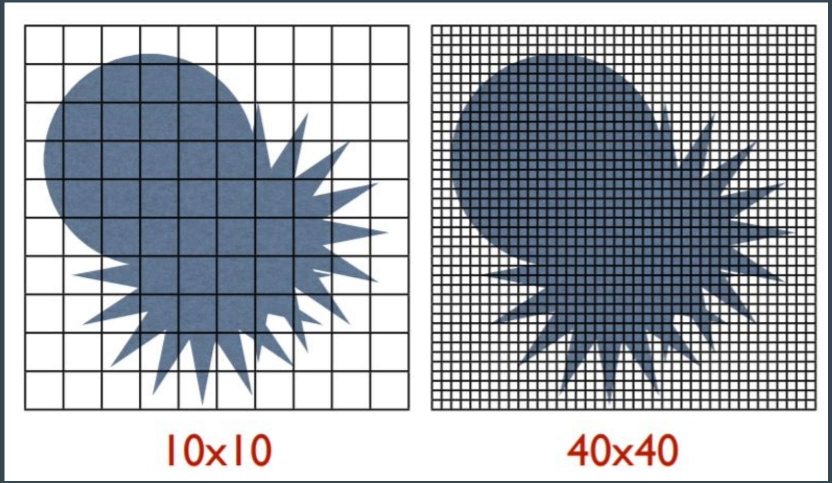




Monte Carlo

- 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)

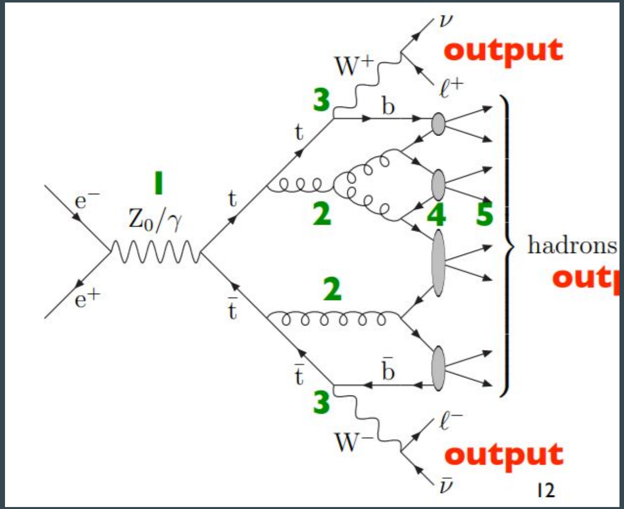




Area = (Number of hits)/(Total squares) * (Total Area)
https://upload.wikimedia.org/wikipedia/commons/8/84/

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.

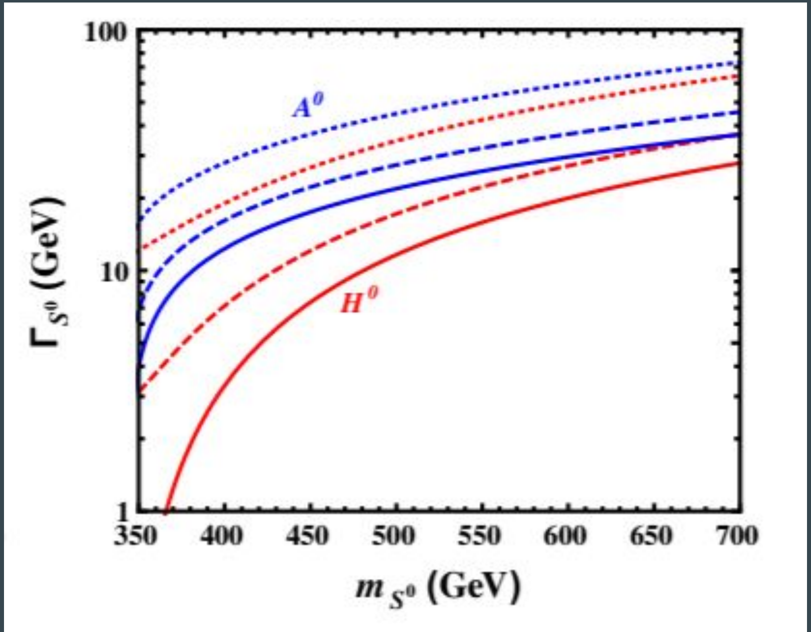
```
In[413]:= ΓtotA[rtt_, rtu_, rtc_, KAZH_, KAZh_, MA_, MH_] := If[MA > mt + mc, 2 ΓAtc[rtc, MA, 3], 0] + If[MA > mt + mu, 2 ΓAtu[rtu, MA, 3], 0] +
      If[MA > 2 mt, ΓAffbar[rtt, MA, mt, 3], 0] + If[MH > 0, If[MA > MH + mZ, ΓAZH[KAZH, MA, MH], 0], 0] + If[MH > 0, If[MA > mh + mZ, ΓAZh[KAZh, MA, MH],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

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

Out[452]= 36.7542
```

Total decay width for *H*

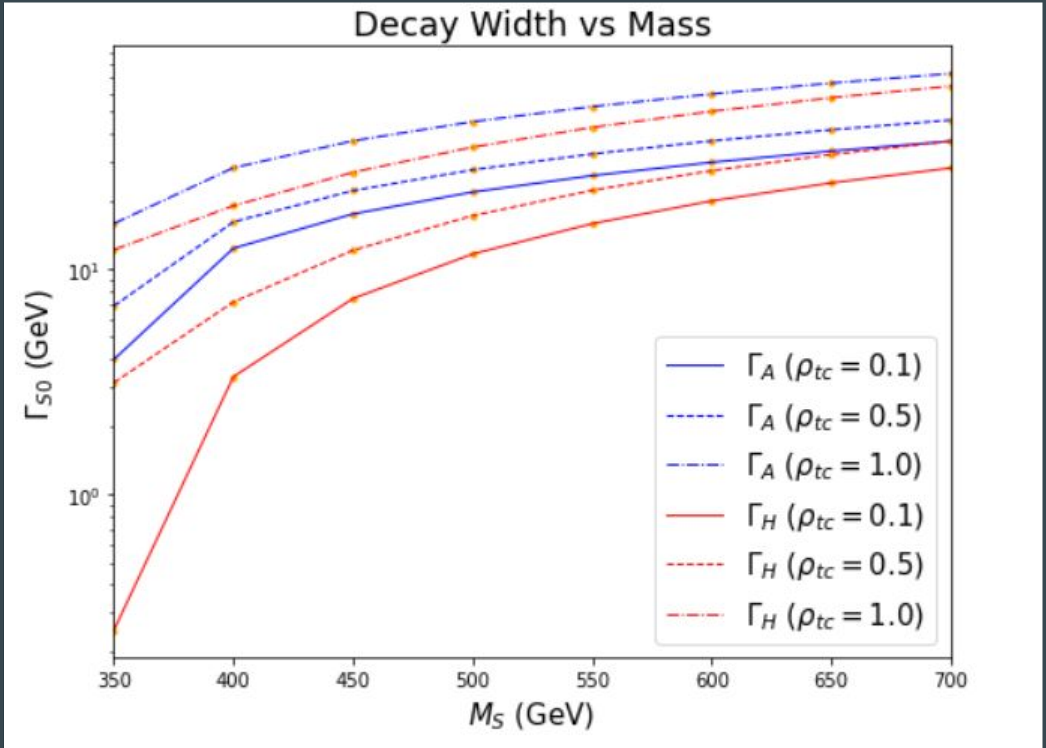
```
In[467]:= ΓtotH[rtt_, rtu_, rtc_, KHAZ_, lHhh_, MA_, MH_] := If[MH > mt + mc, 2 ΓHtc[rtc, MH, 3], 0] + If[MH > mt + mu, 2 ΓHtu[rtu, MH, 3], 0] +
      If[MH > 2 mt, ΓHffbar[rtt, MH, mt, 3], 0] + If[MH > 0, If[MH > MA + mZ, ΓHZA[KHAZ, MH, MA], 0], 0] + If[MH > 2 mh, ΓHhh[lHhh, MH], 0];

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

Out[500]= 27.9671
```

Decay Width (unscaled)

Paper:

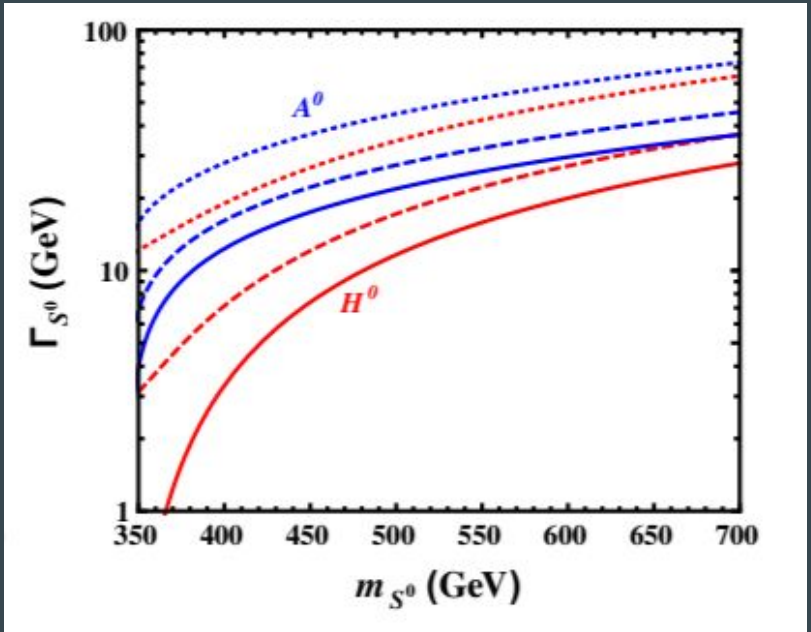


My Result:

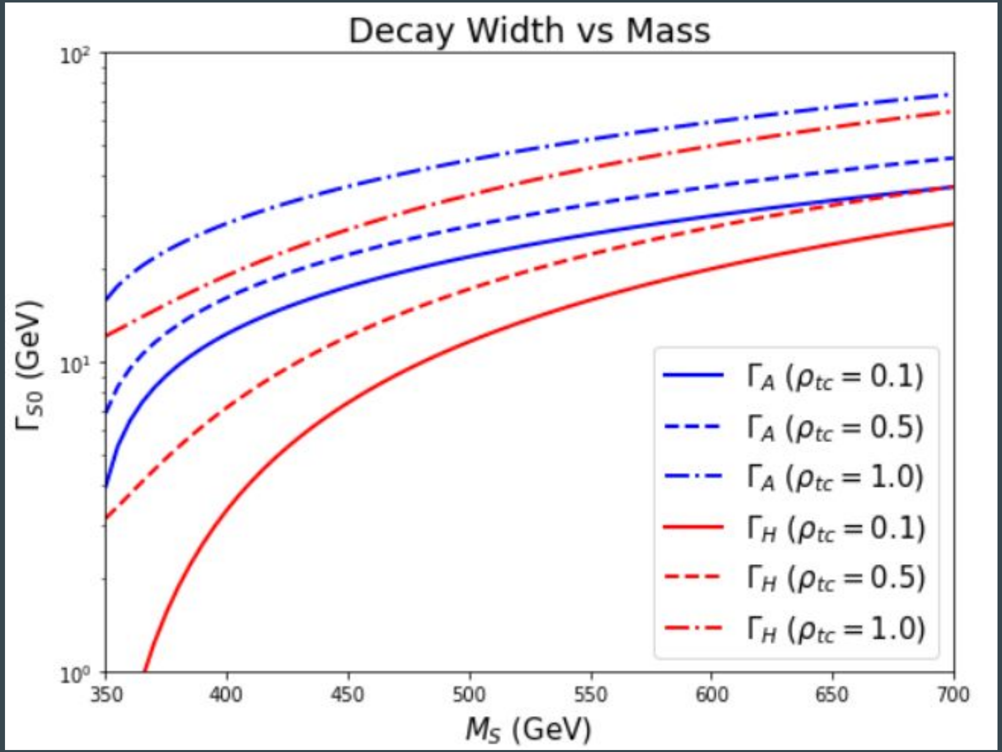


Decay Width

Paper:



My Result:



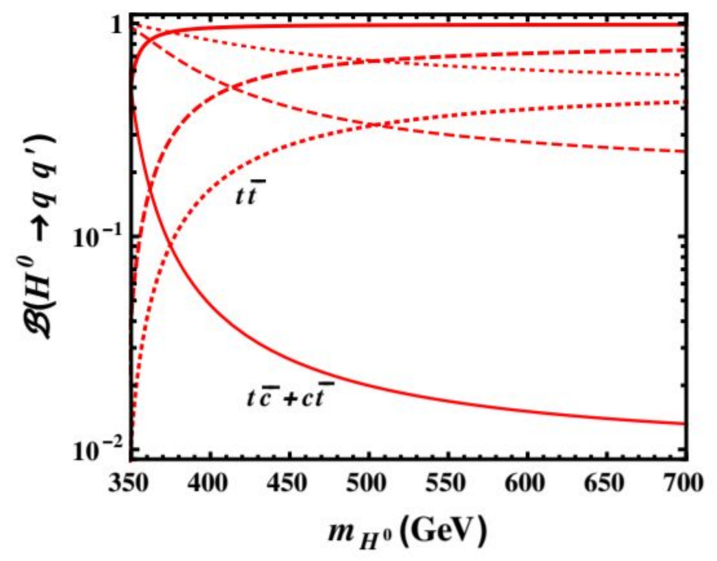
Branching Ratio

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 Γ is the **total width** of the particle and Γ_i is the **partial width** in the decay chain i, we have:

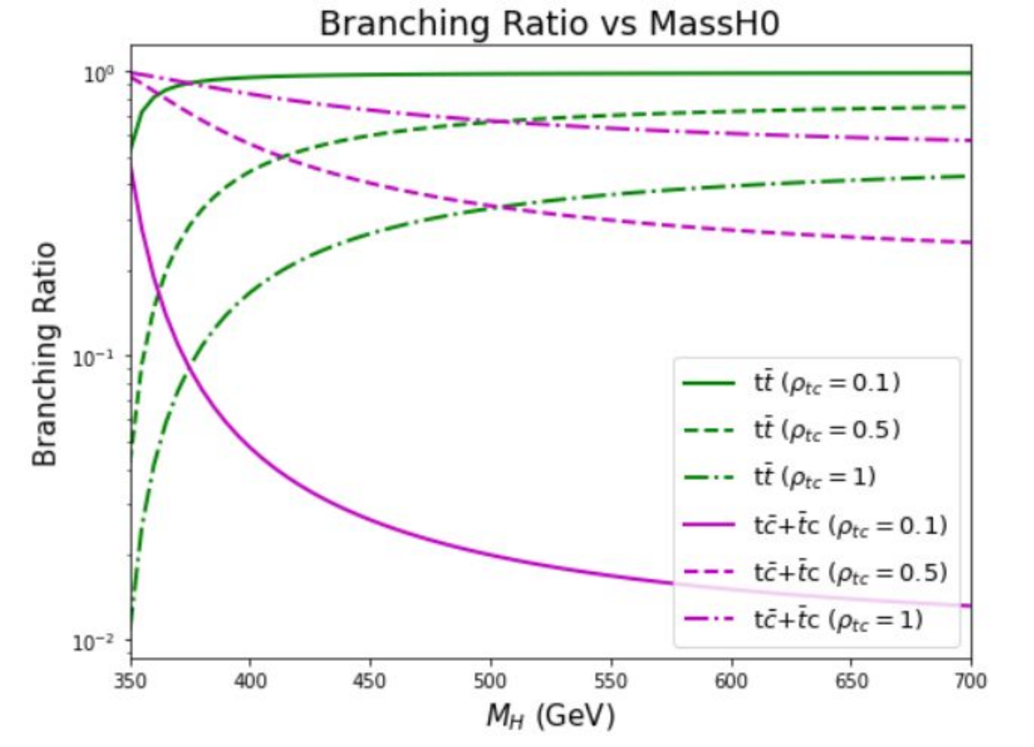
$$BR(i) = \frac{\Gamma_i}{\Gamma} \tag{82}$$

Branching Ratio (H0)

Paper:

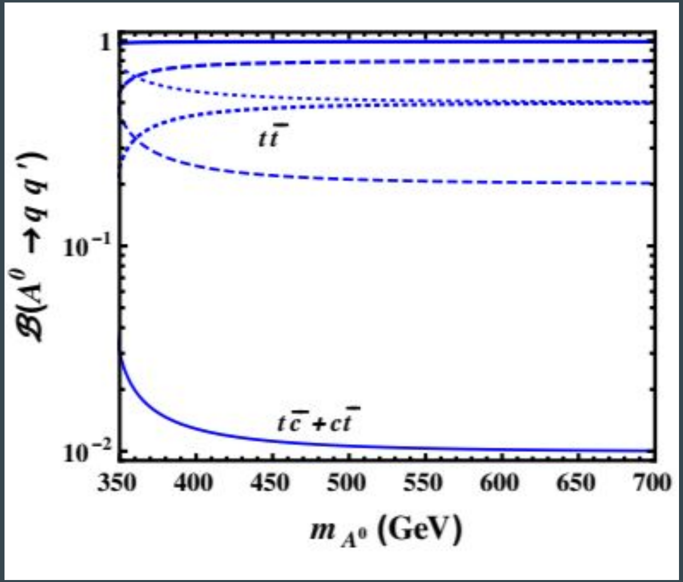


My Result:

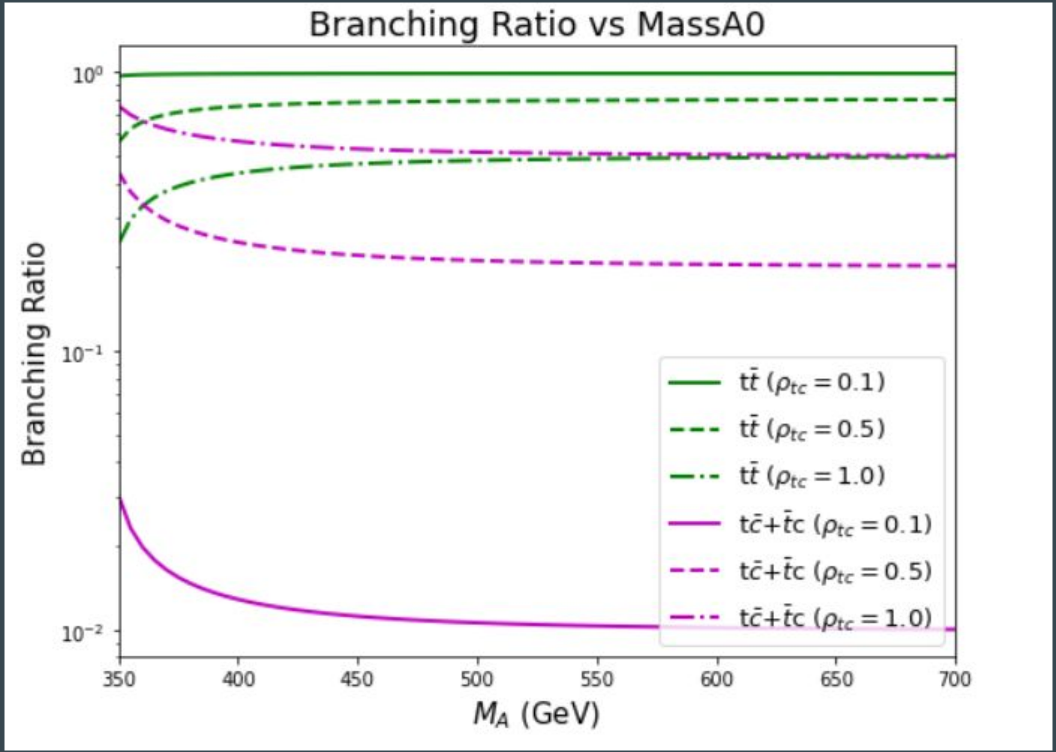


Branching Ratio (A0)

Paper:



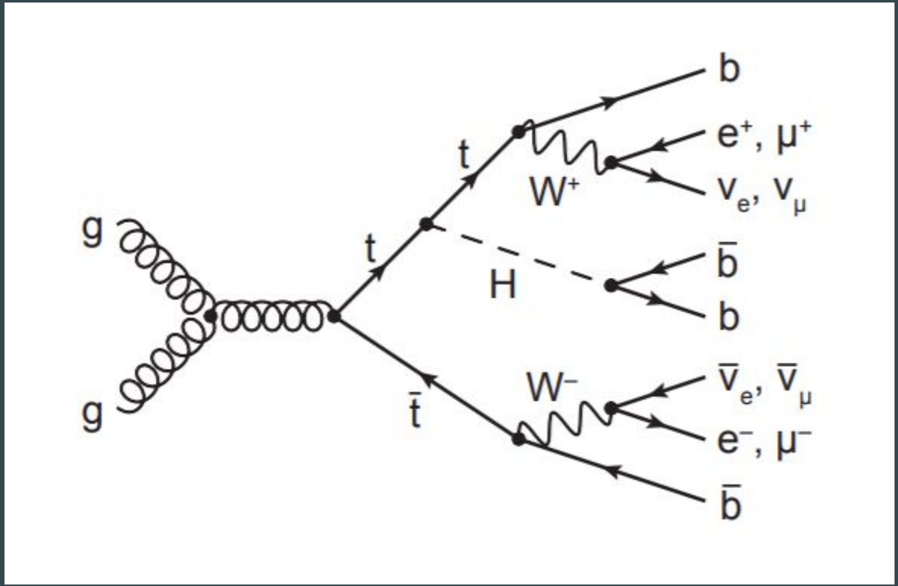
My Result:



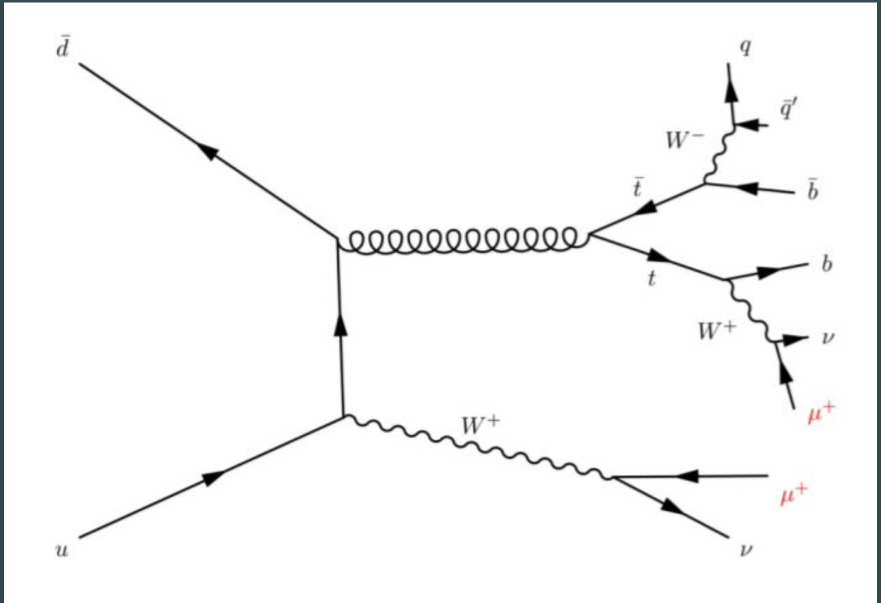
Same Sign Dilepton

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

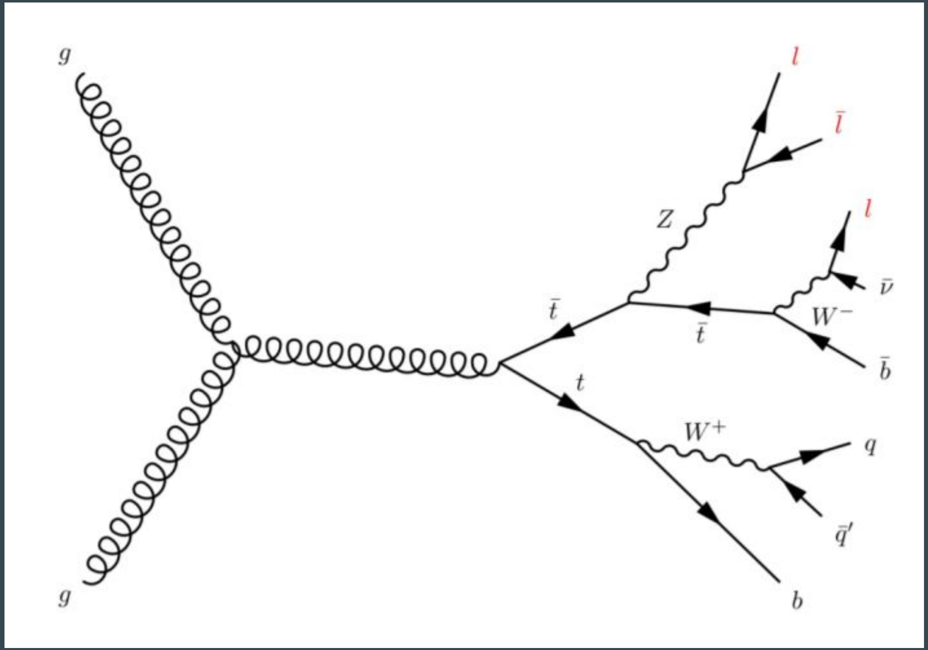
Paper (2 leptons):



Background:

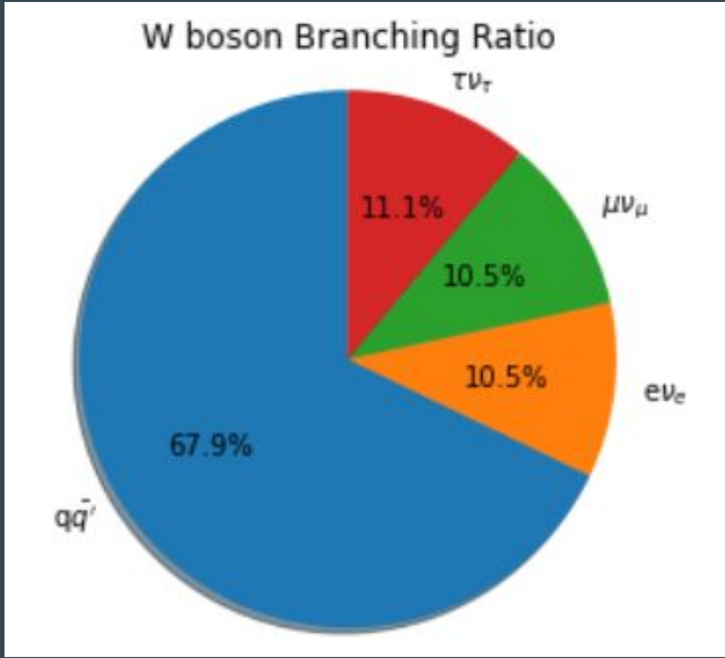


Trilepton



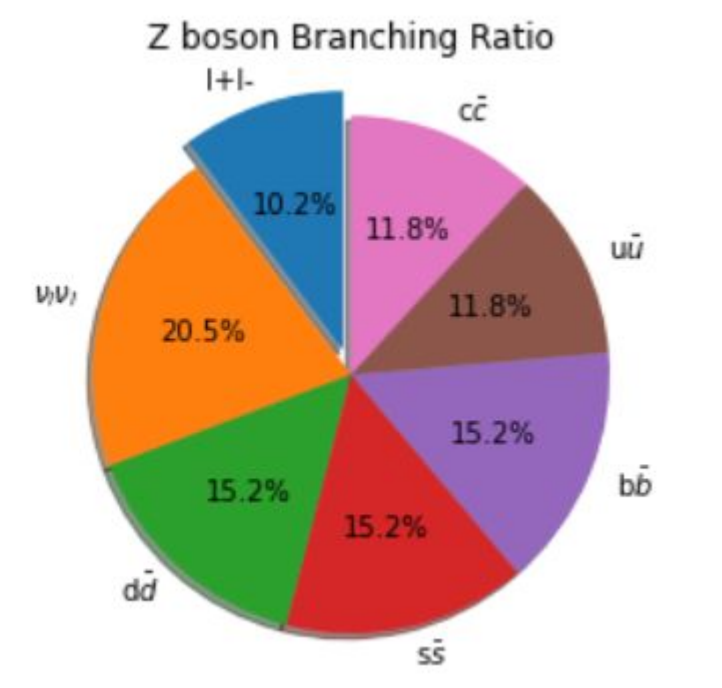
Pie charts: Branching Ratio for W boson

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

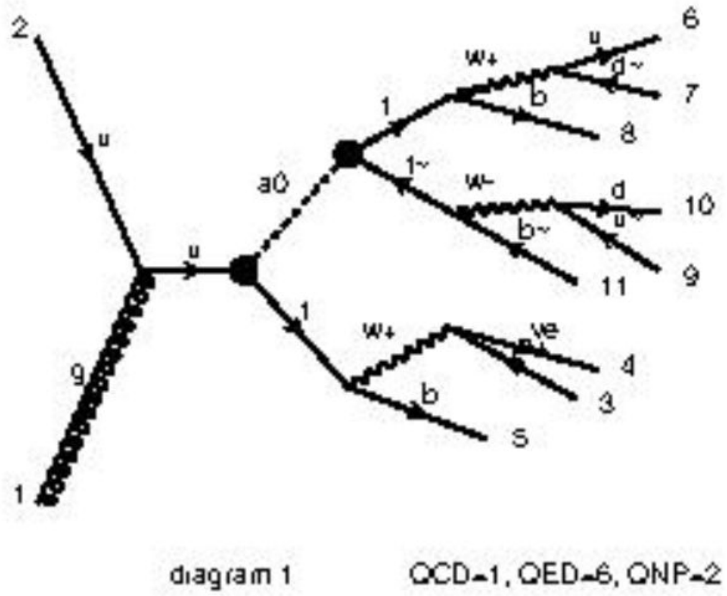
debug

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~



	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

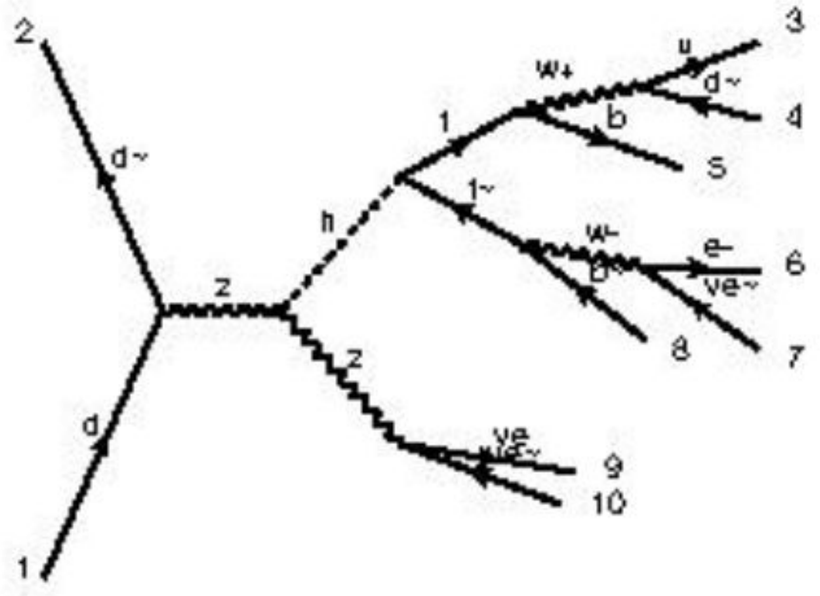
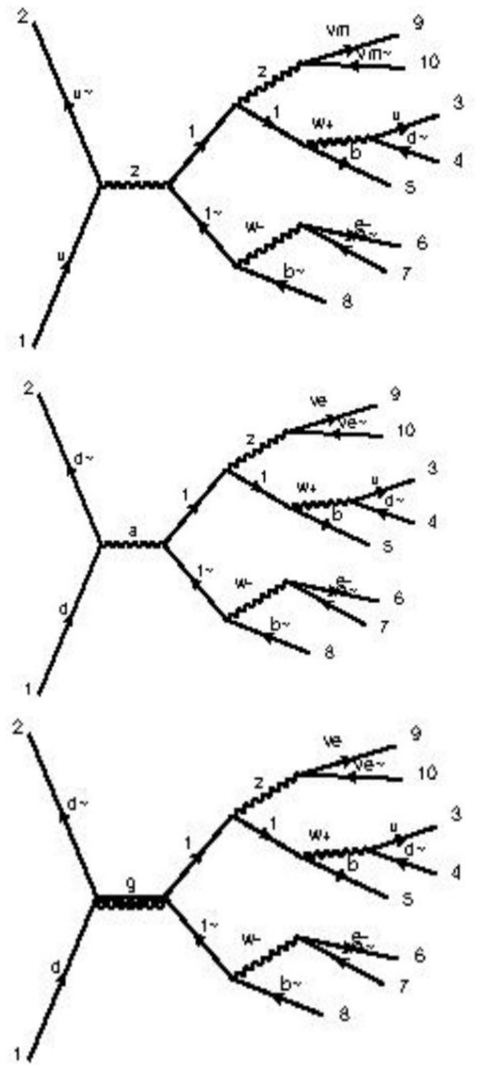
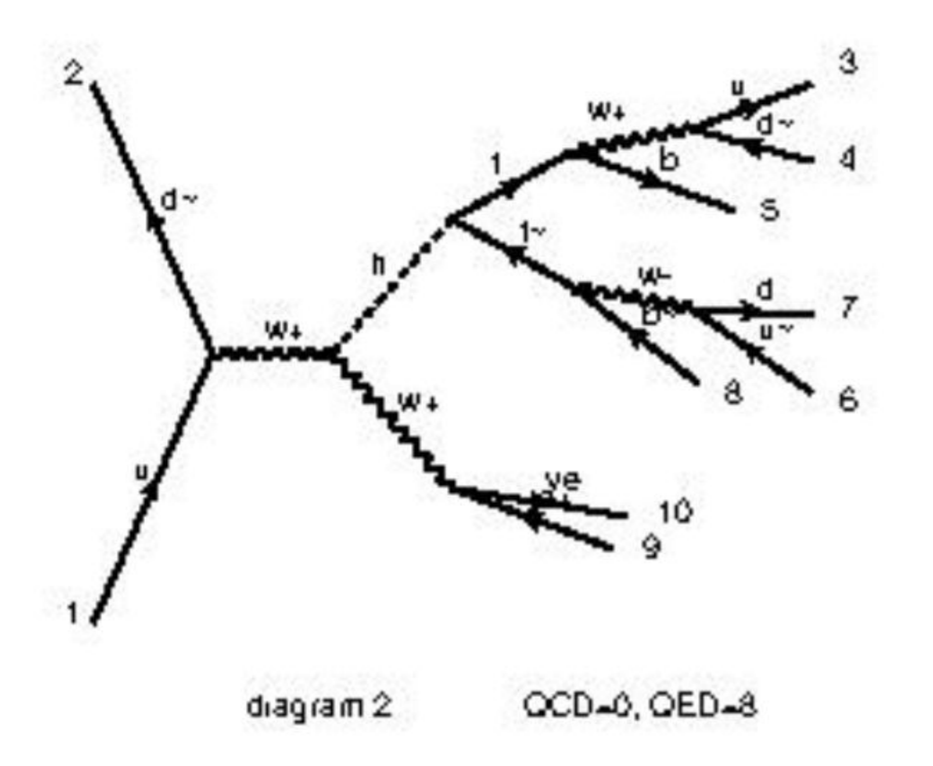
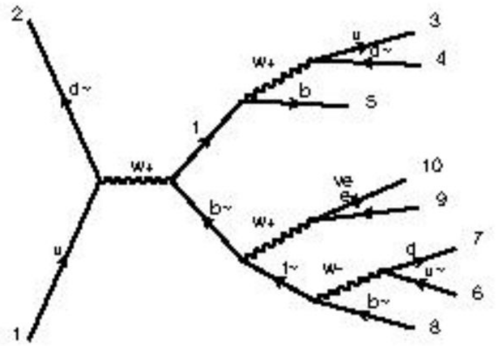


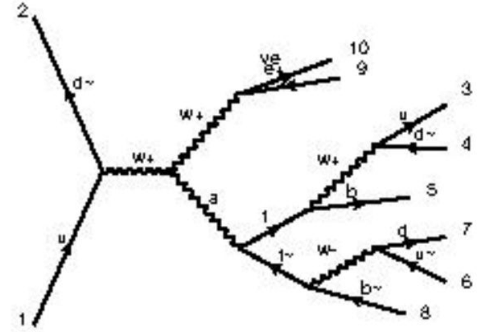
diagram 1 QCD=0, QED=8

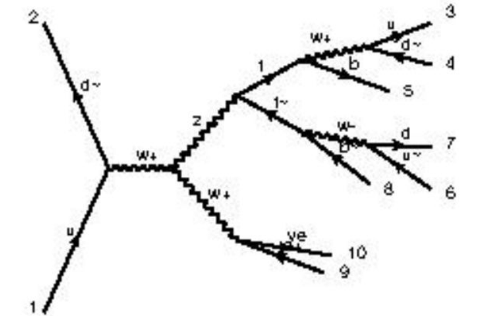


SM Background: tt~W

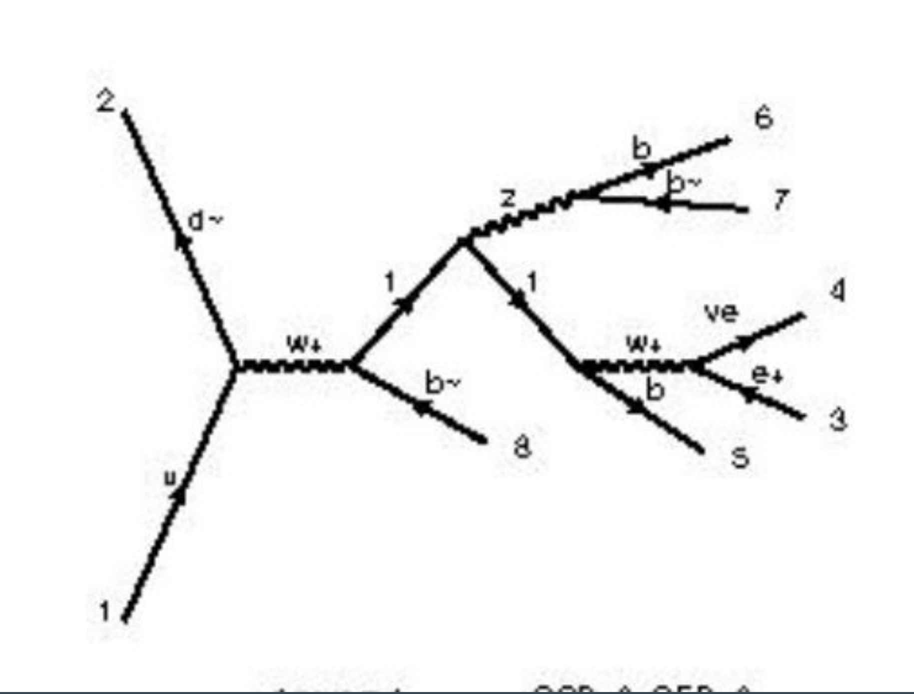


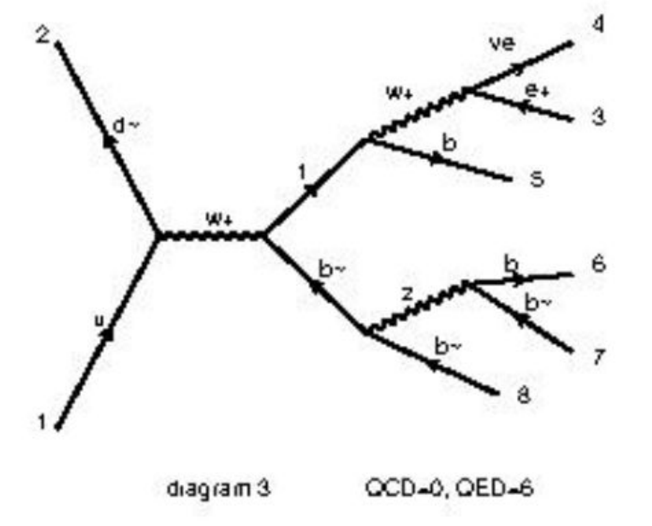


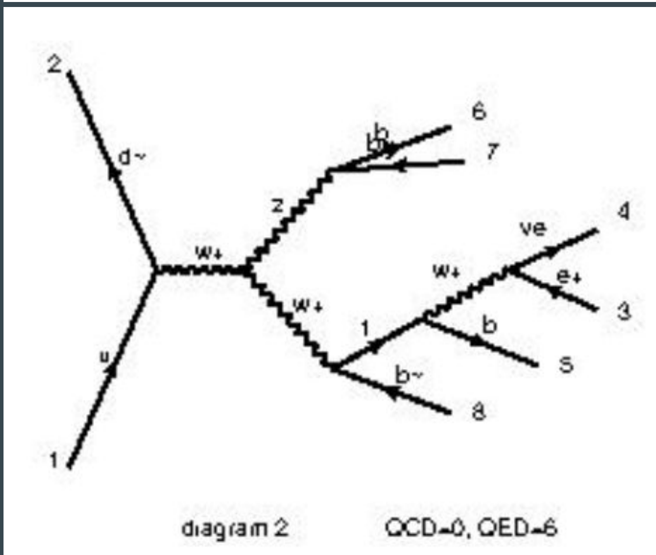




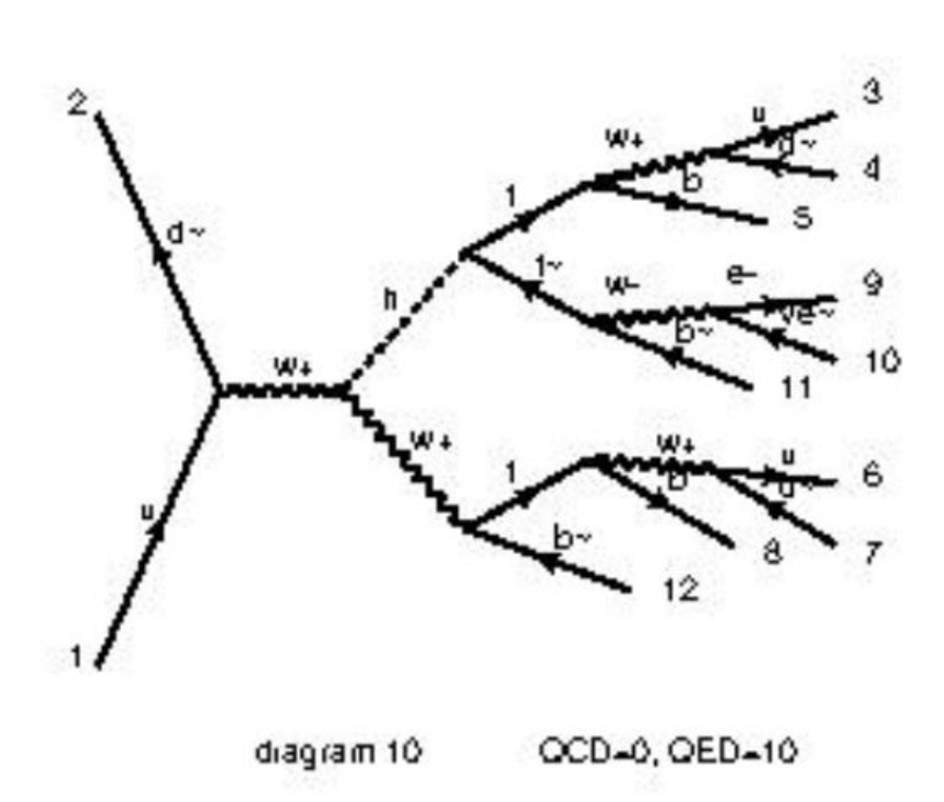
SM Background: tZ + j



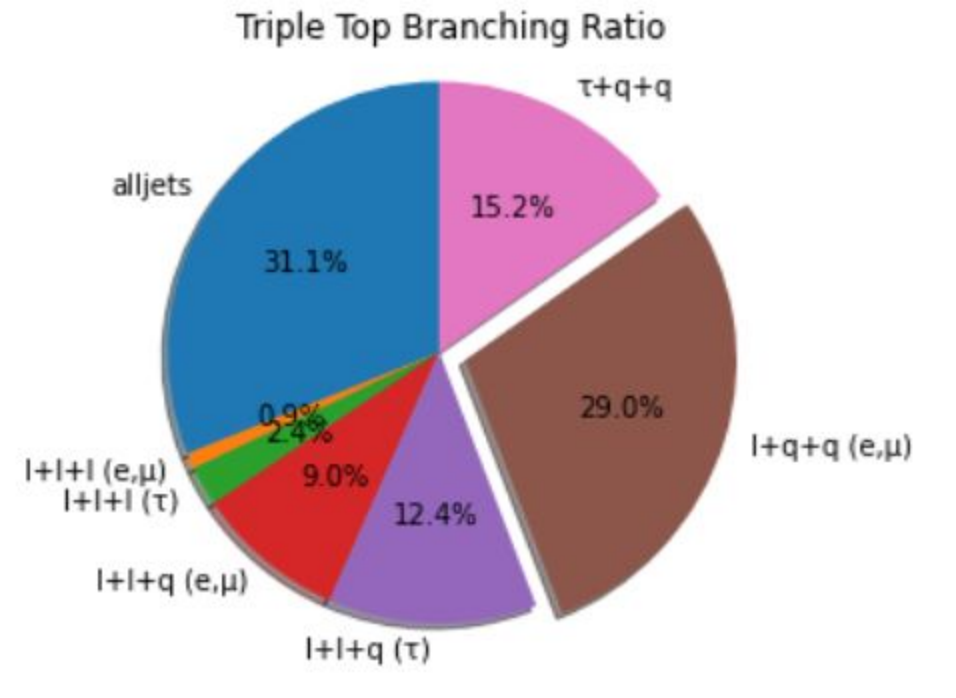




SM Background: 3t + j

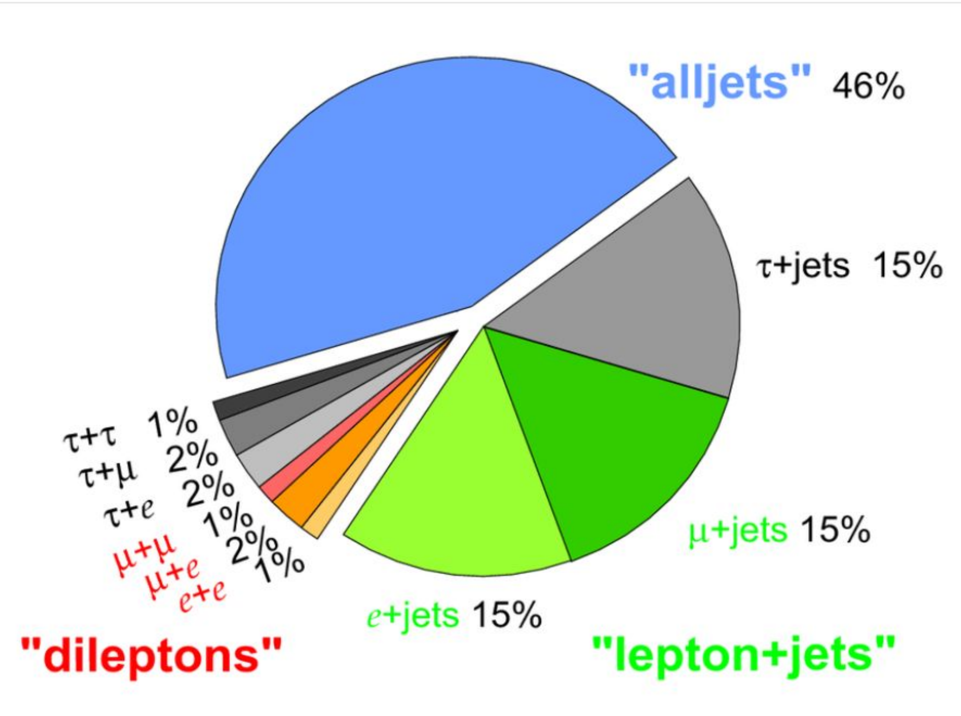


Pie charts: Branching Ratio for Triple Top



	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

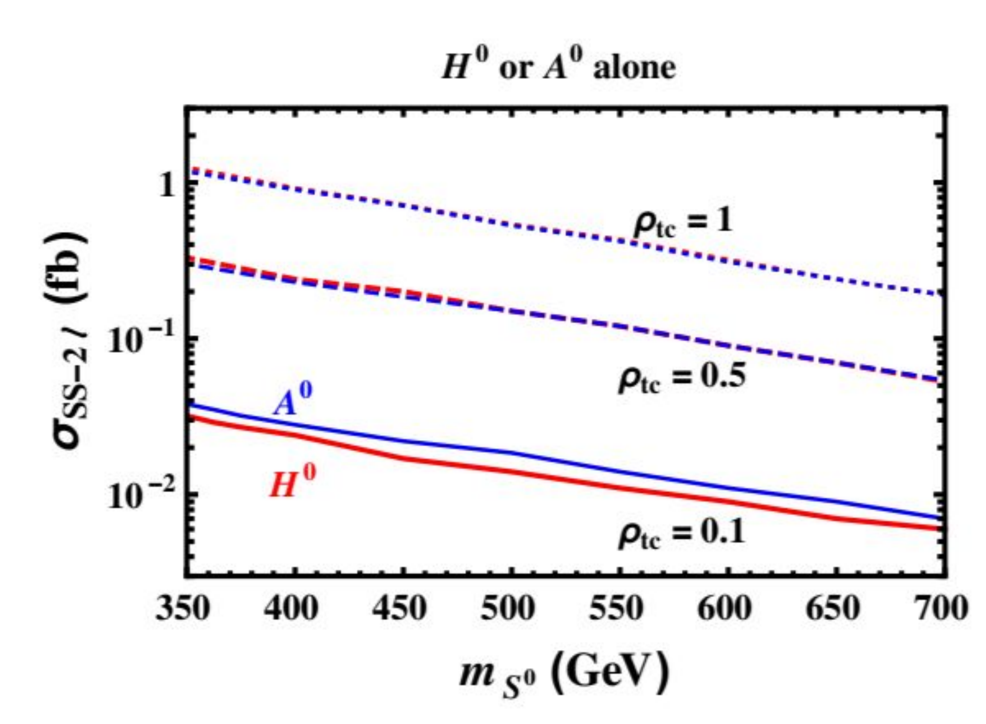


Attempt to replicate SS2l cross section plot (after selection cut)

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

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 $E_T^{\rm miss} > 30$ 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.

Attempt to replicate SS2l cross section plot (after selection cut)

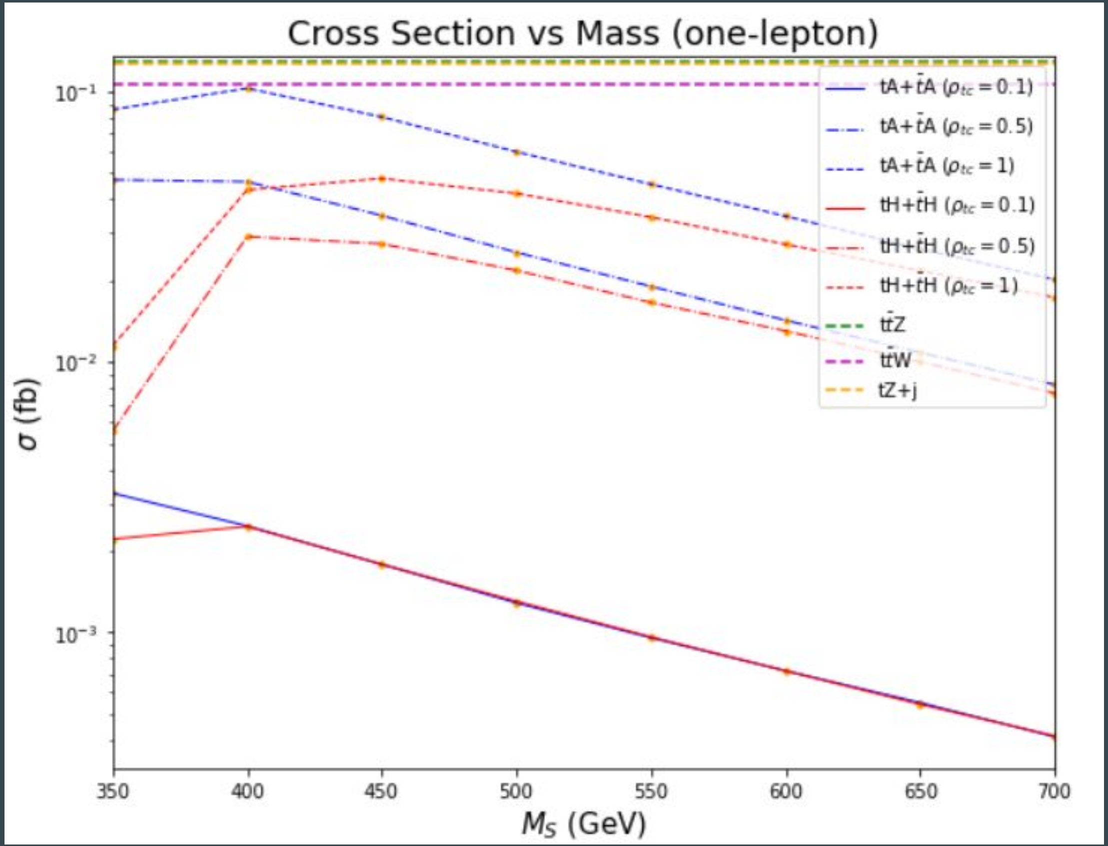


	Mass A0 (GeV)	Cross Section (fb)
0	350	0.36060
1	400	0.27330
2	450	0.20110
3	500	0.13970
4	550	0.10890
5	600	0.08045
6	650	0.05885
7	700	0.04688

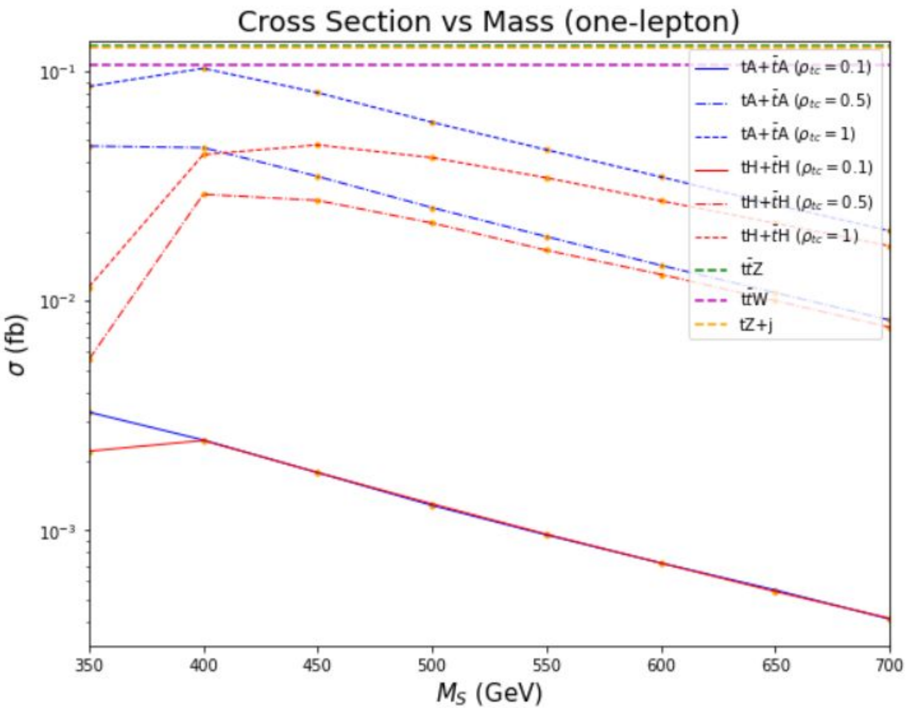
Overview

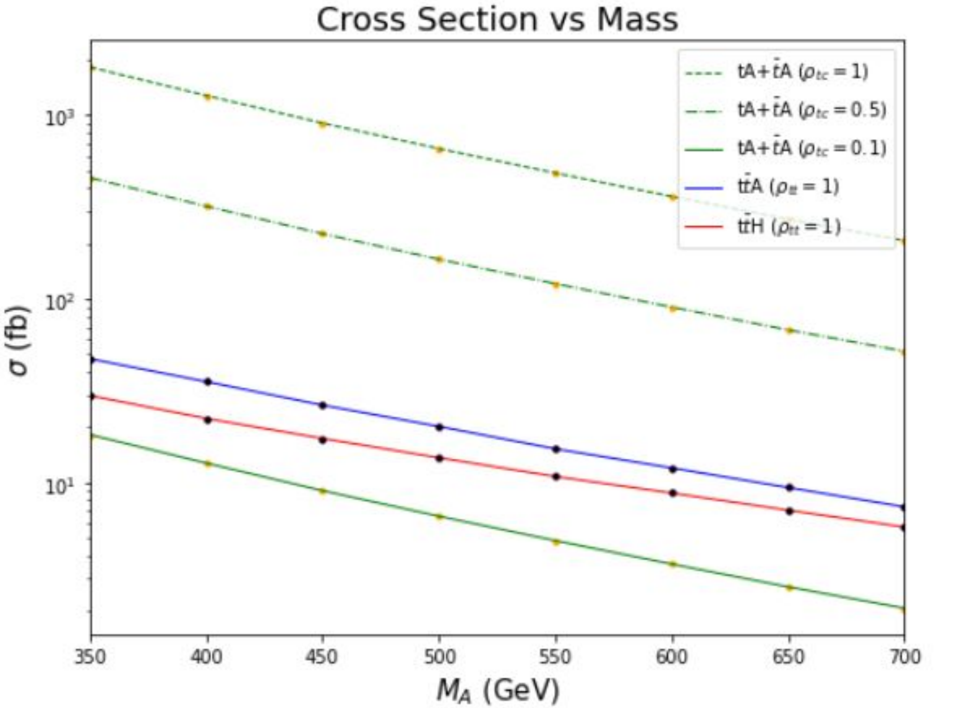
- Signal and Background
    - cross section vs mass
    - kinematic plot comparison
    - selection cut?

Cross Section vs Mass

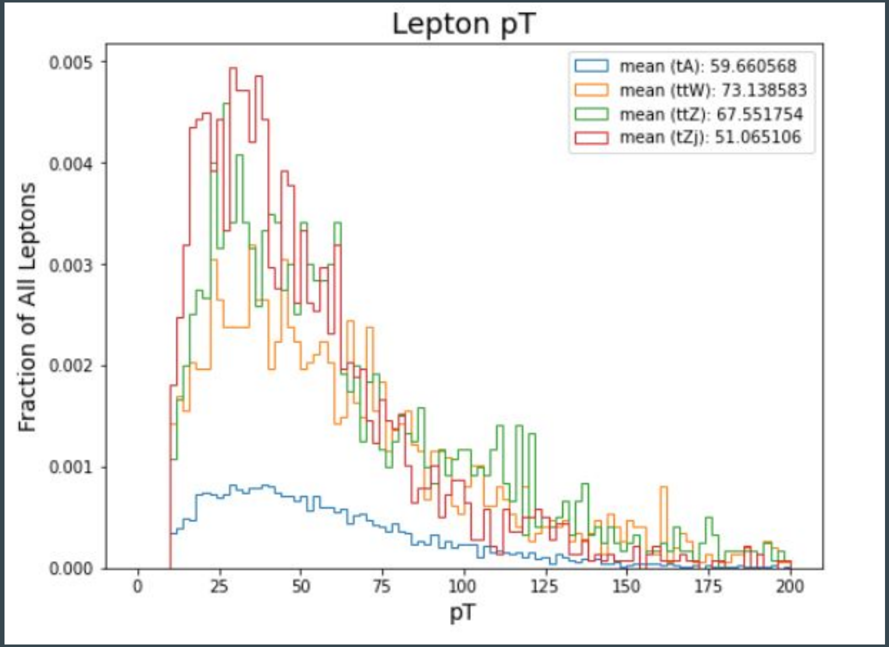


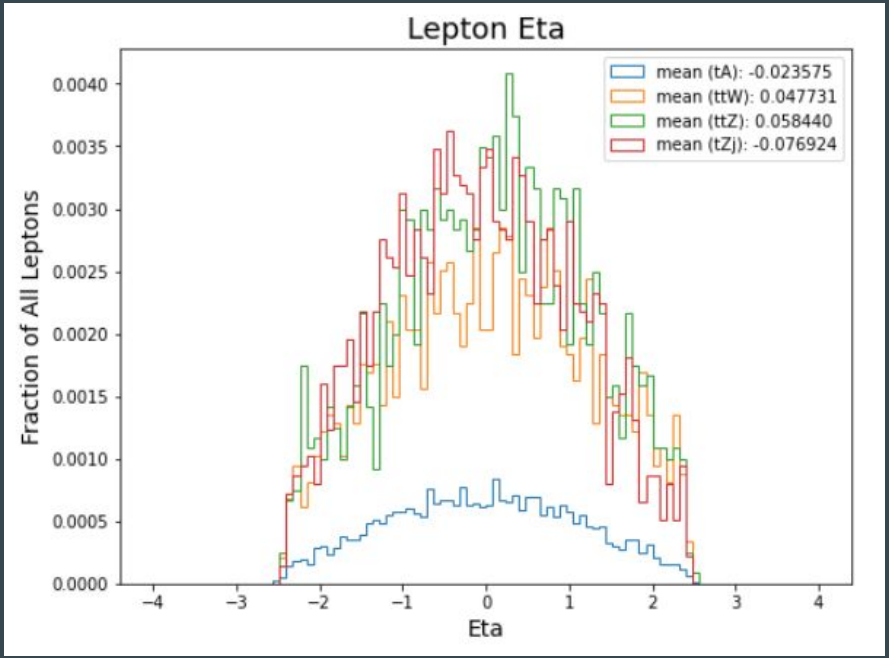
Set the masses of A and H fixed to some values say both at 400 GeV. Take rho_tc = 0.5 (or rho_tu =0.2) and rho_tt = 0.5 for example. These are somewhat close to the upper limits for these couplings given current constraints. All couplings are assumed to be real


Cross Section vs Mass (one-lepton)
σ (fb)
M_S (GeV)
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)
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 ($\rho_{tt}=1$)

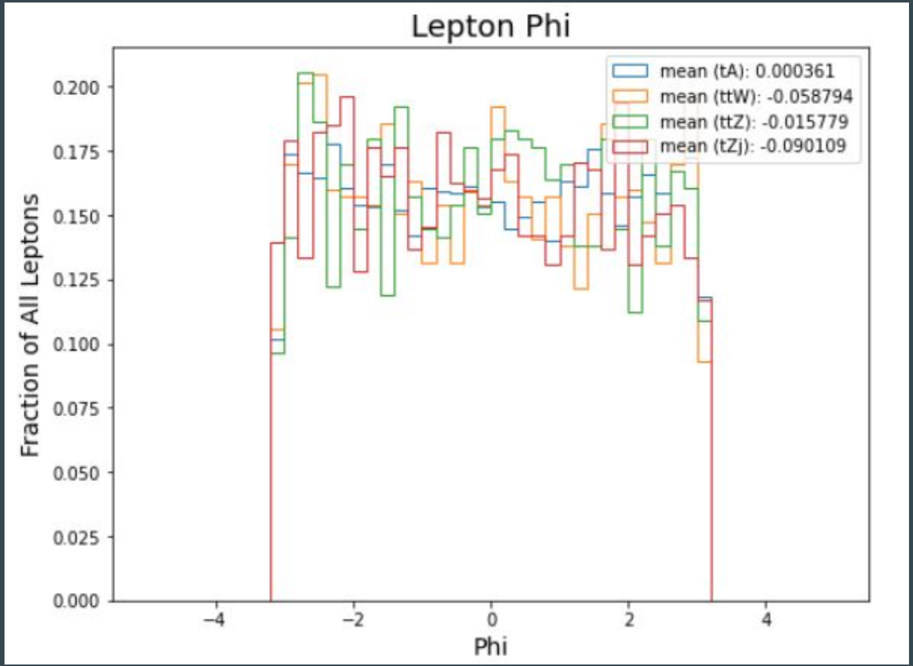
Kinematic Plot Comparison (lepton)



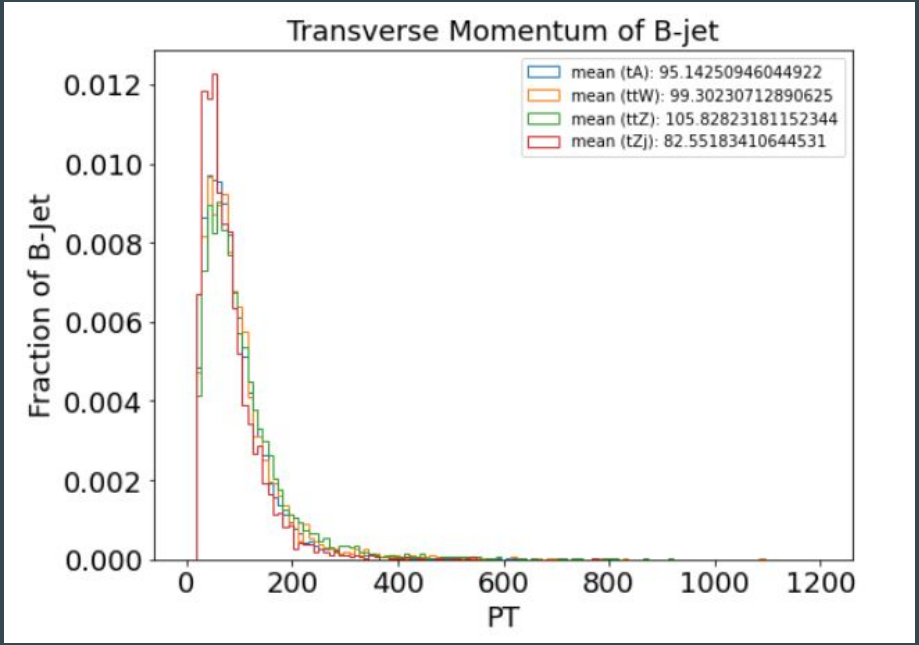


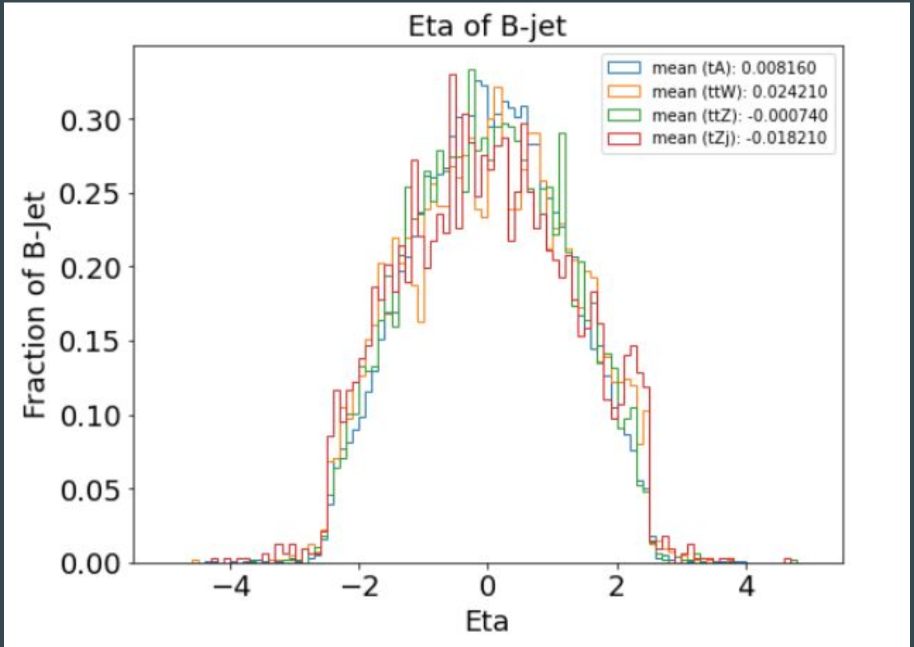
Normalize cross section

Kinematic Plot Comparison (lepton)

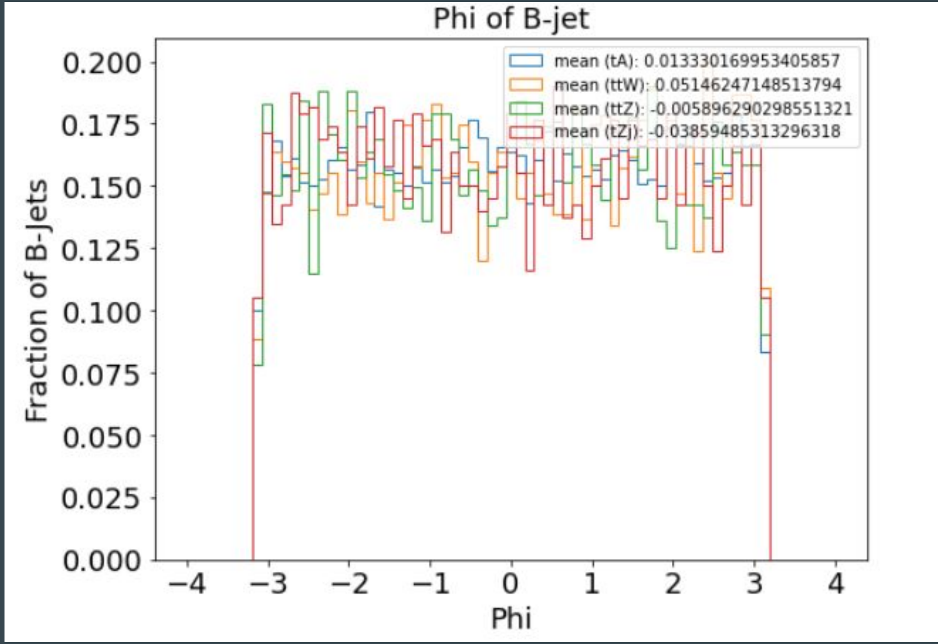


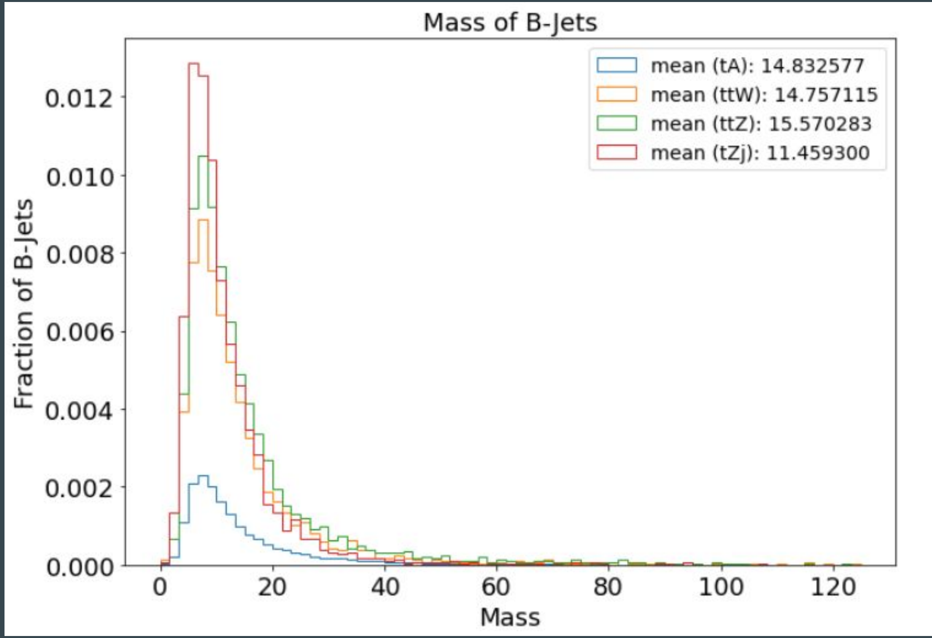
Kinematic Plot Comparison (b-jet)



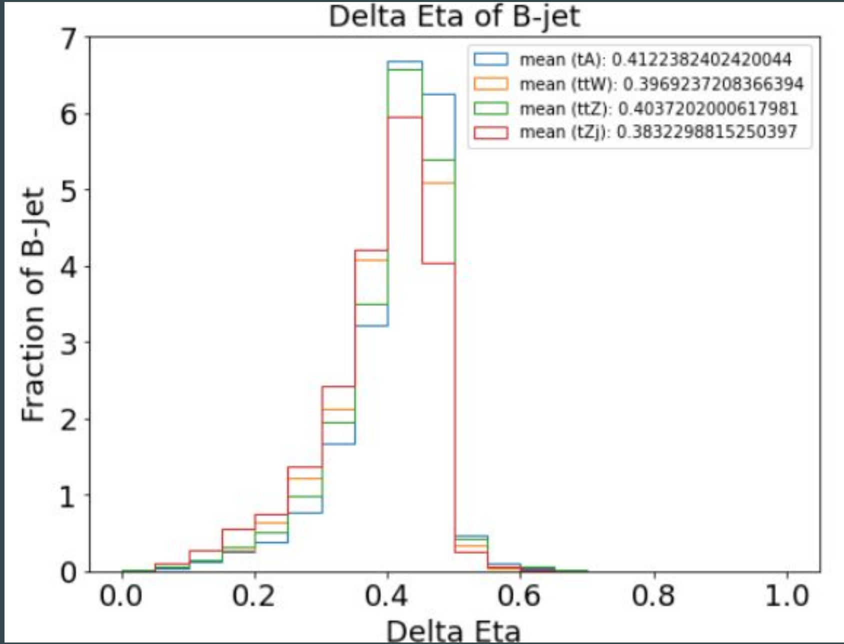


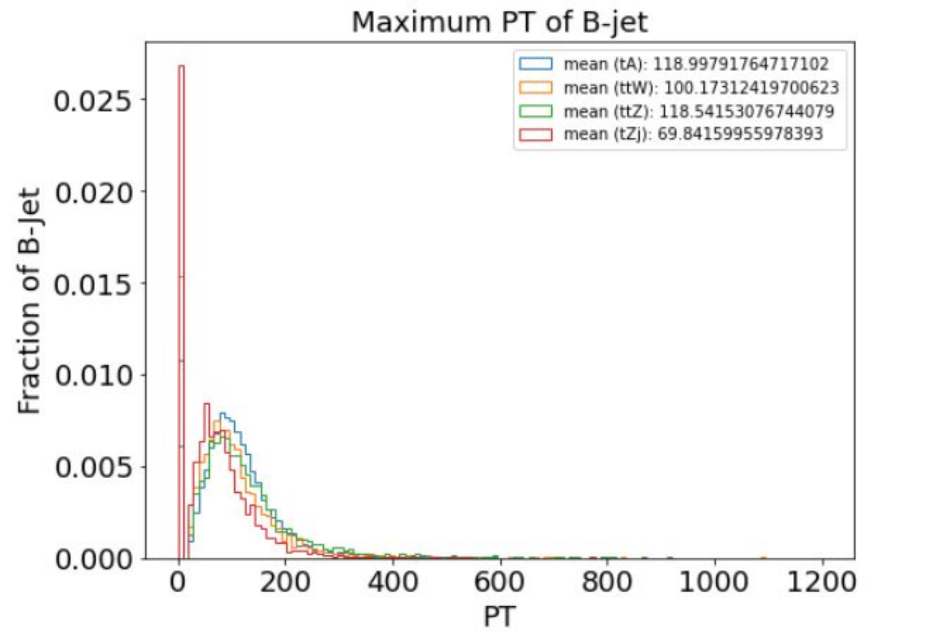
Kinematic Plot Comparison (b-jet)



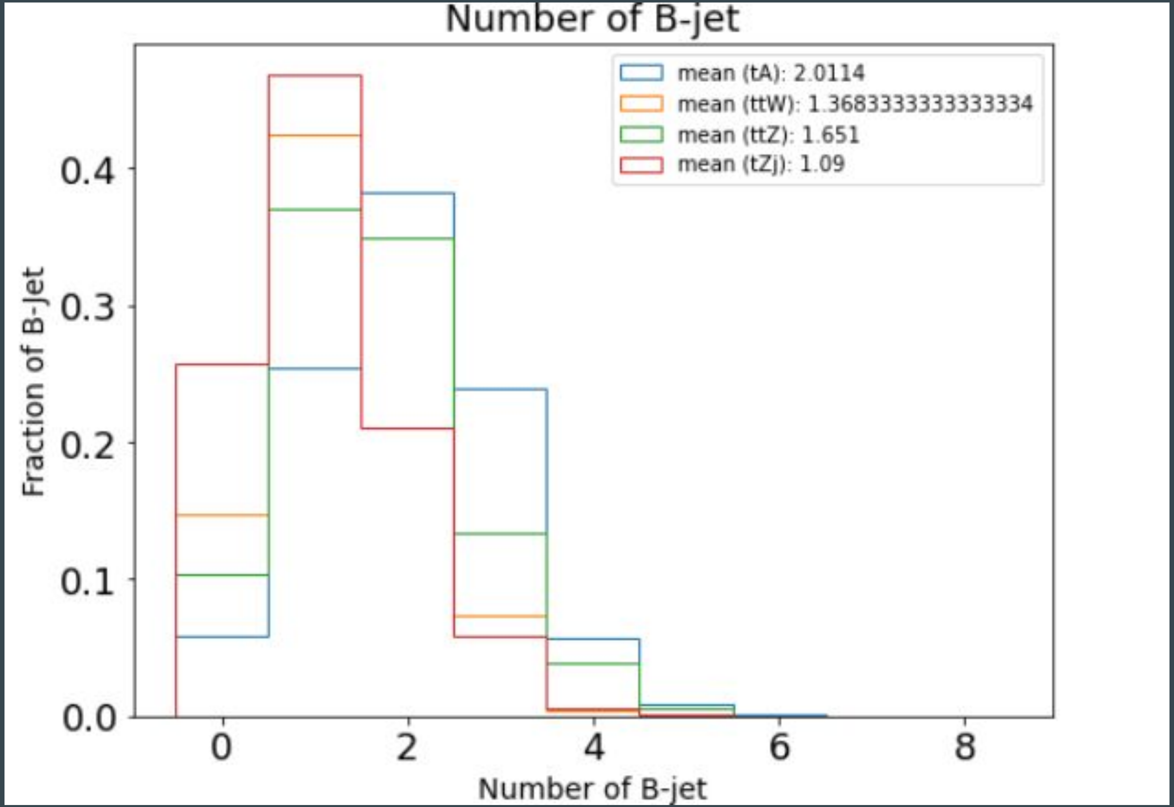


Kinematic Plot Comparison (b-jet)

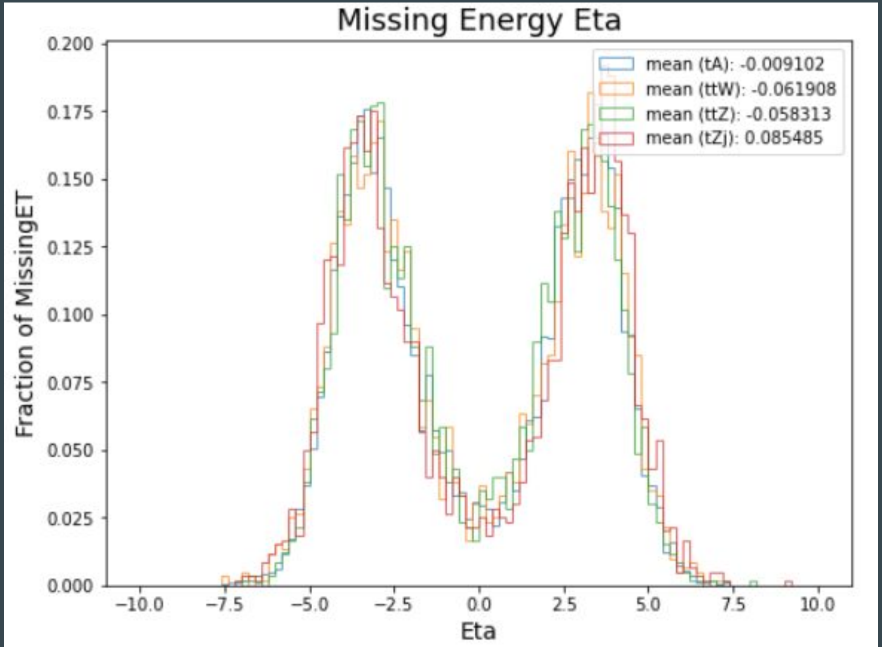


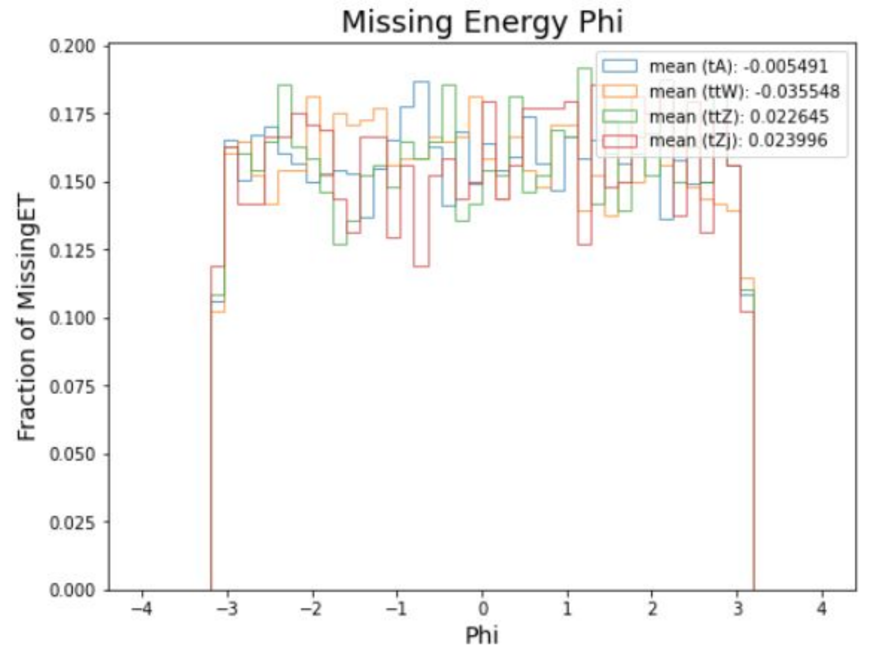


Kinematic Plot Comparison (b-jet)

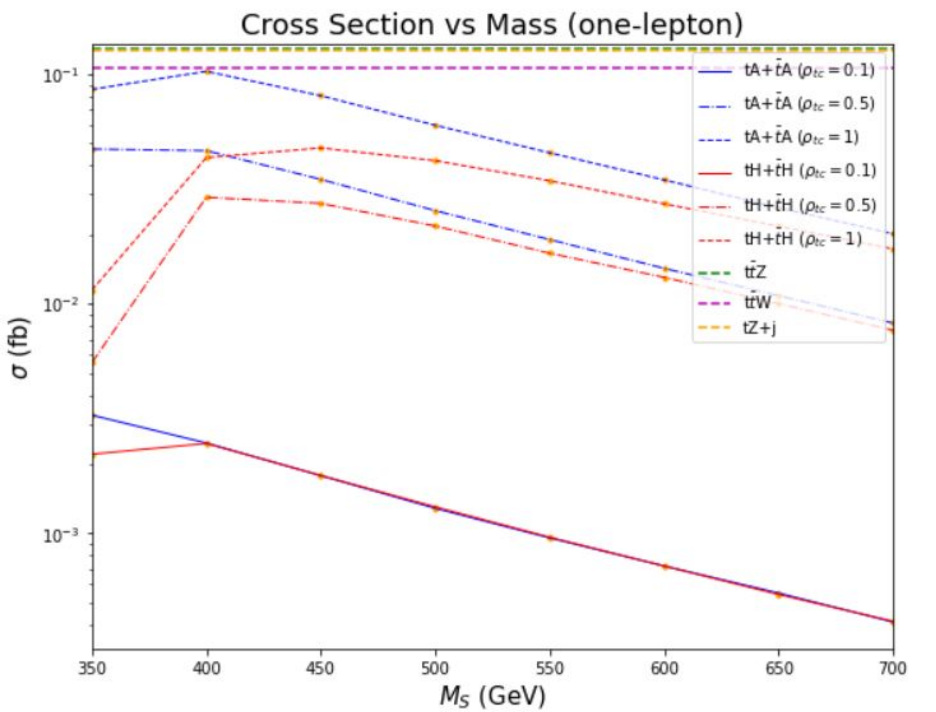


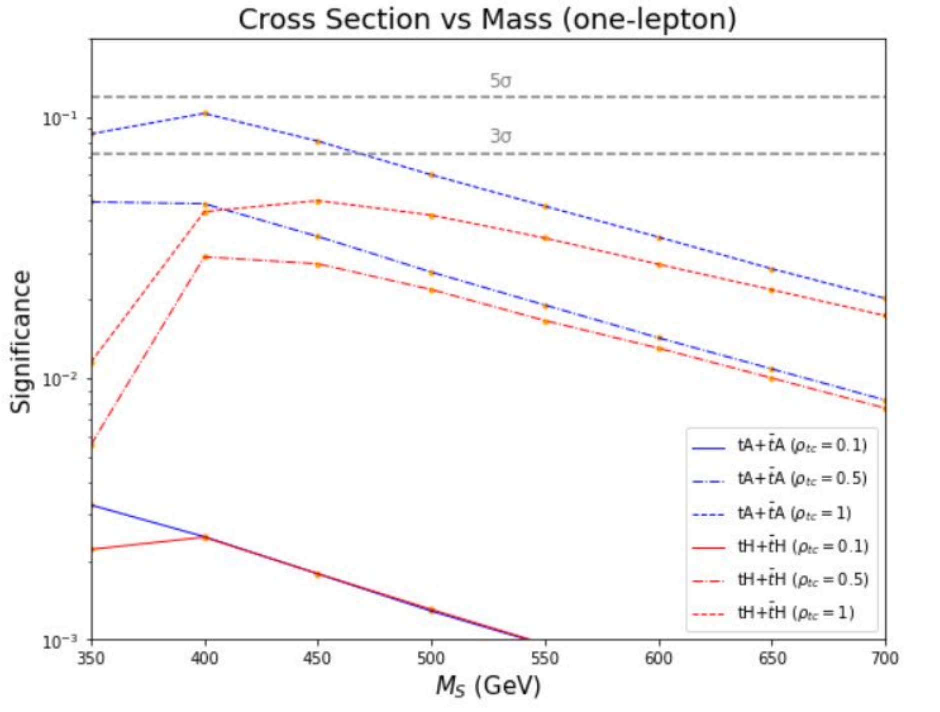
Kinematic Plot Comparison (Missing Transverse Energy)



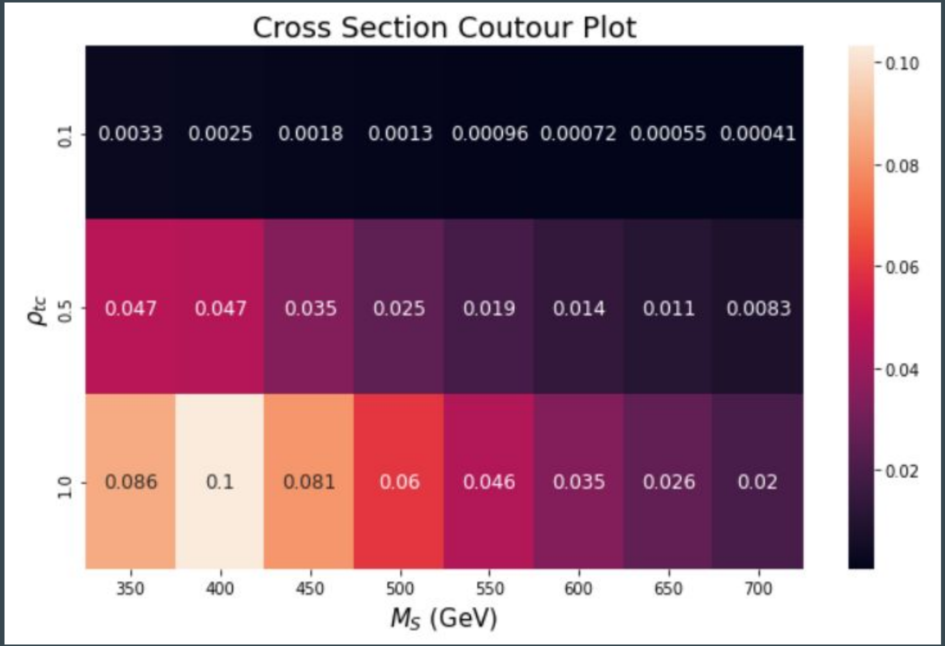


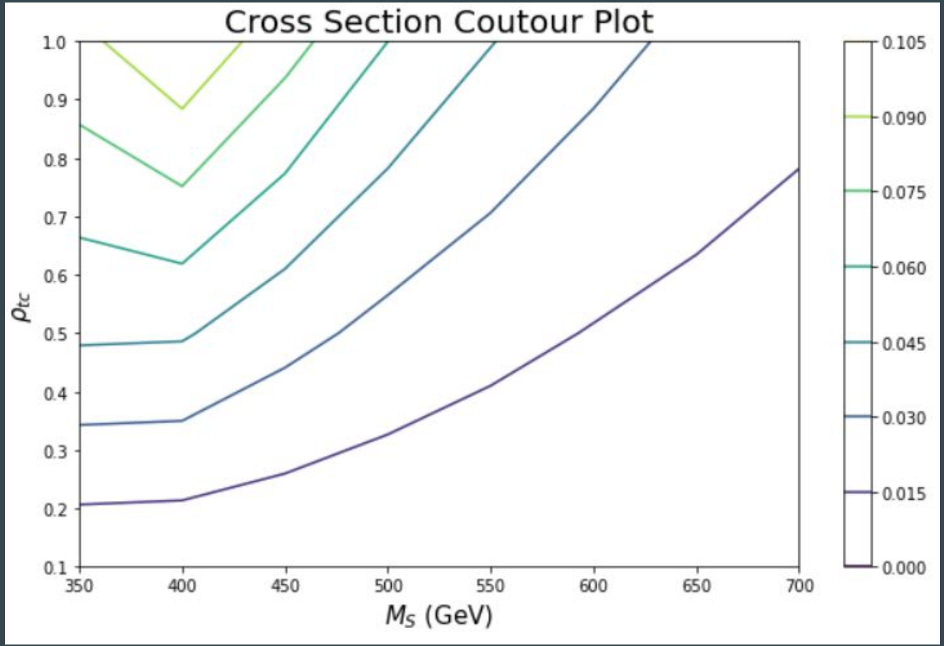
Cross Section





Cross Section

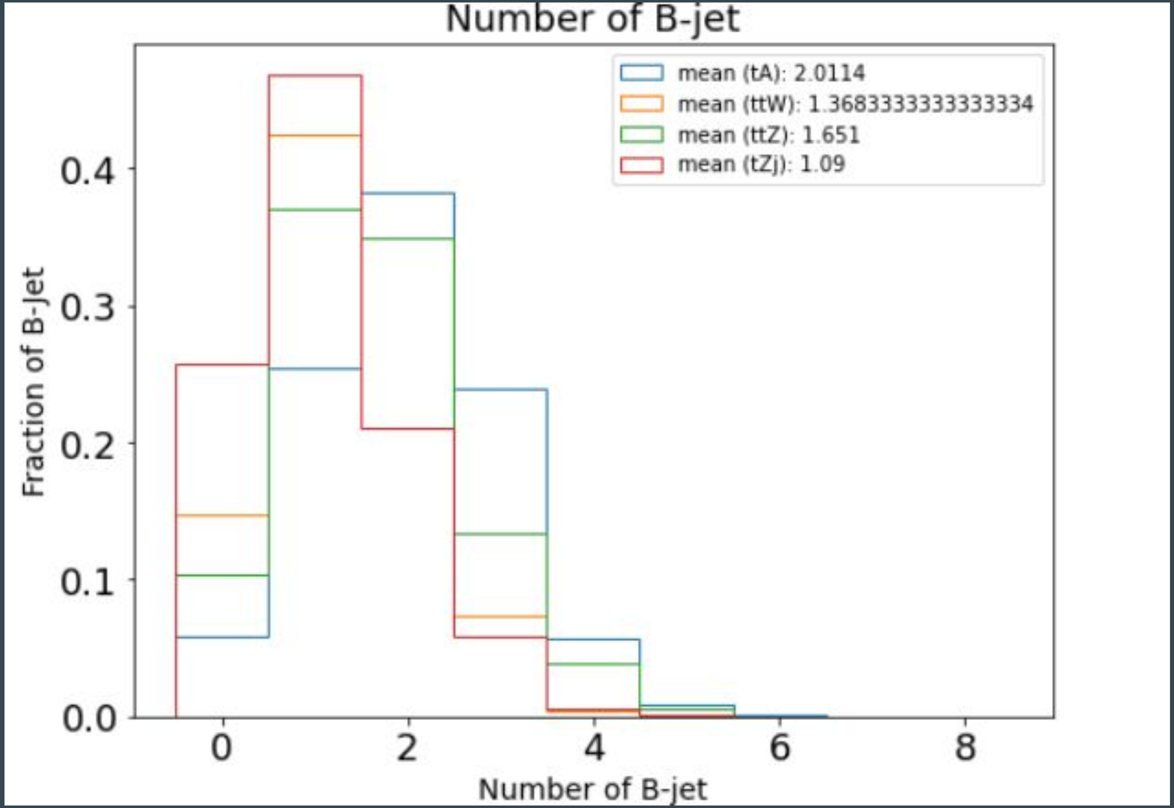




To-do

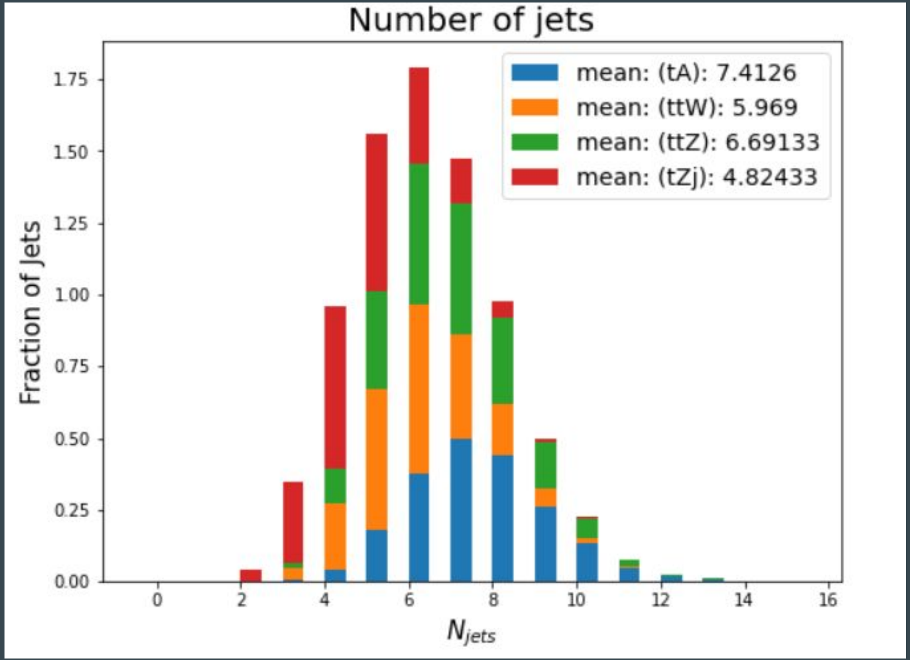
	Name	Description
0	$\sum b\text{-tag}$	Sum of pseudo-continuous b-tagging score over the six jets with the highest score
1	N_{jets}	Number of jets
1	$\Delta R_{bb}^{\text{min}}$	Minimum ΔR between all pairs of b-tagged jets
1	$H_{\text{T}}^{\text{all}}$	Scalar sum of all jet and lepton transverse momenta
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)
0	$N_{\text{LR-jets}}$	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

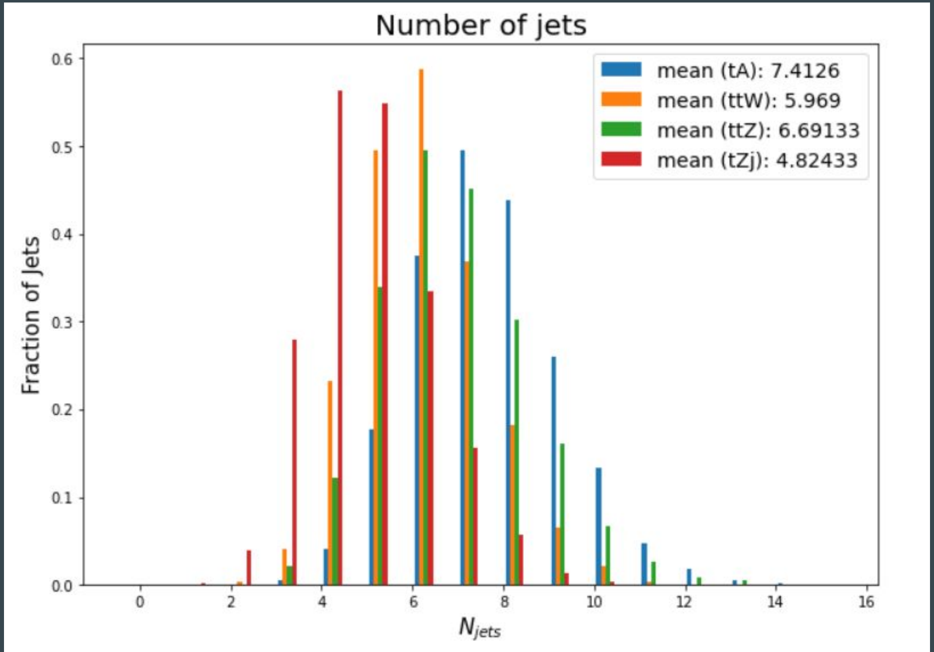
Number of b-jets



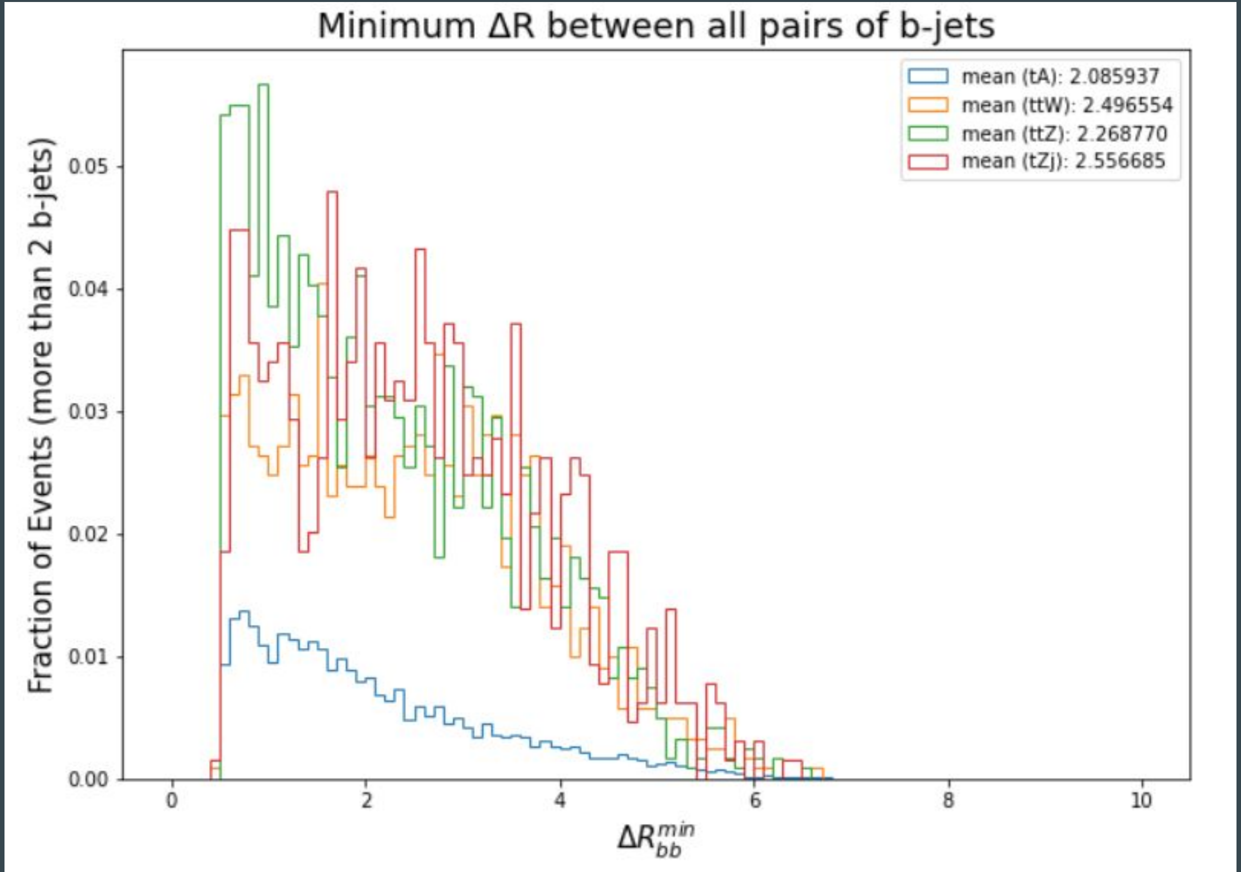
$\sum b$-tag	Sum of pseudo-continuous b-tagging score over the six jets with the highest score

N_{jets} Number of jets

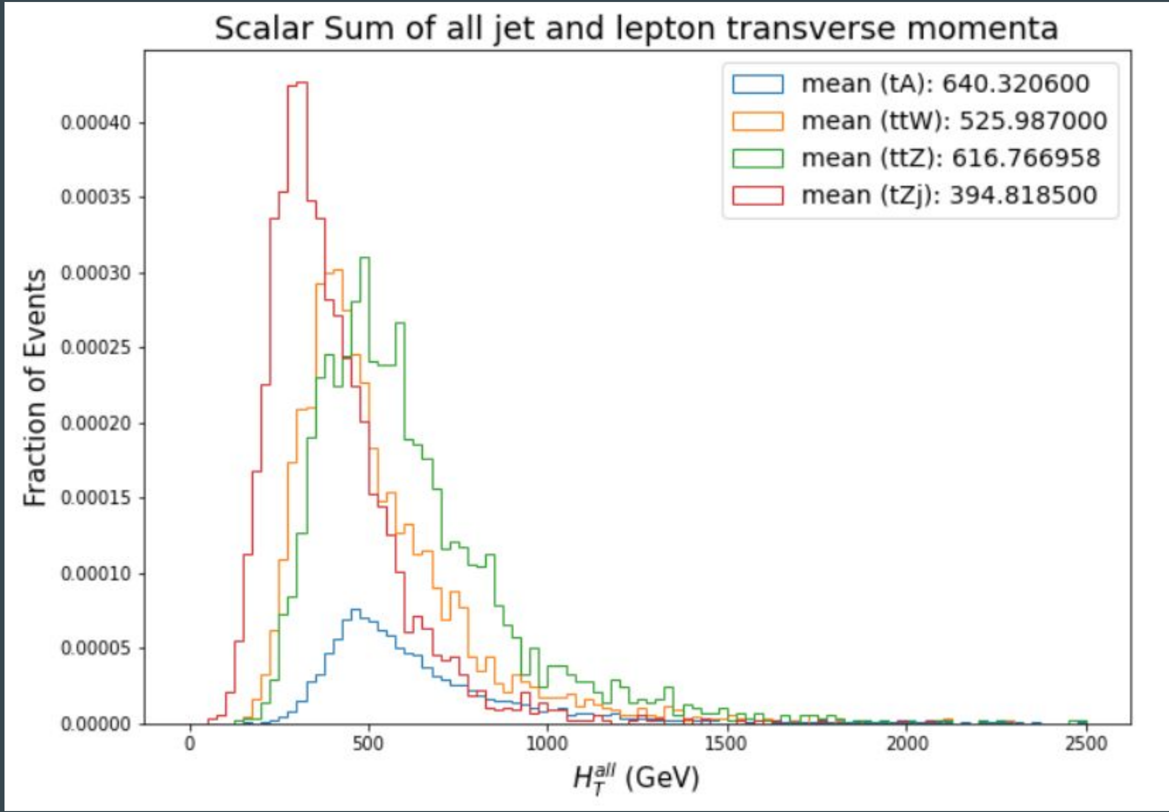




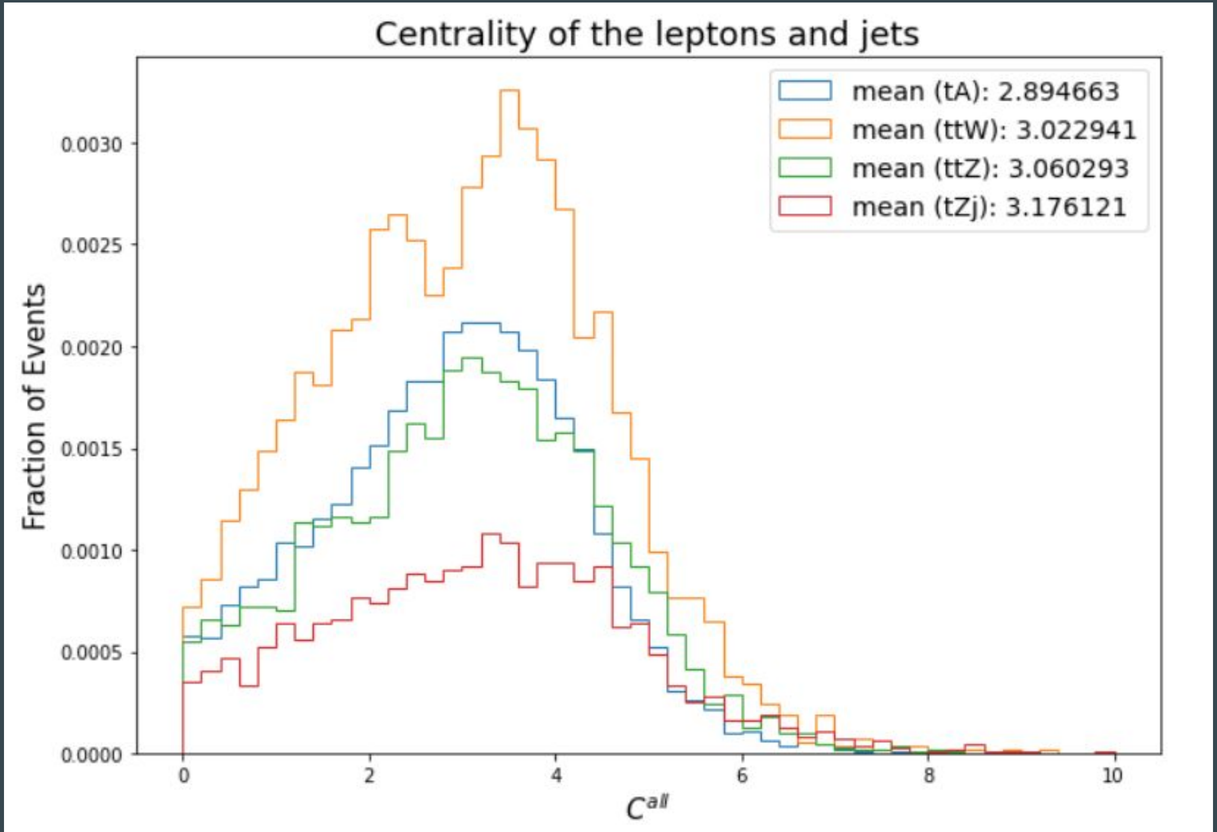
$\Delta R_{bb}^{\min}$ Minimum ΔR between all pairs of b-tagged jets



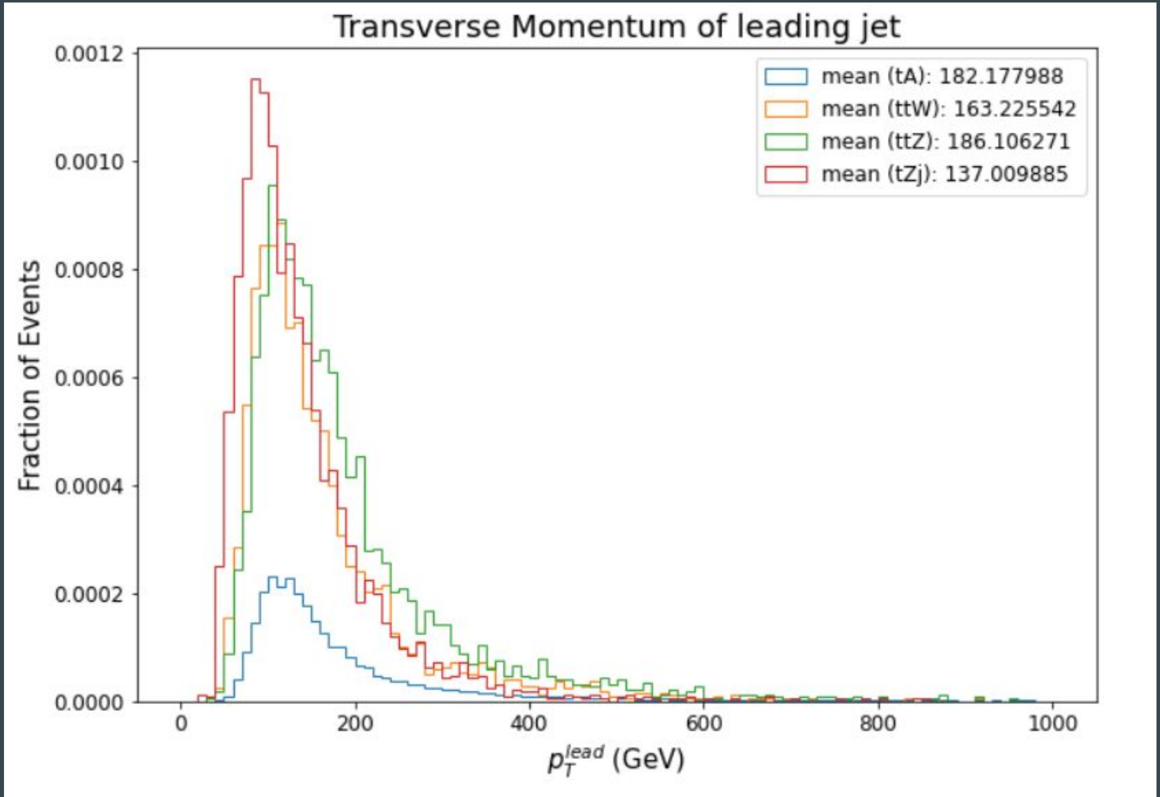
$H_{\mathrm{T}}^{\mathrm{all}}$ Scalar sum of all jet and lepton transverse momenta



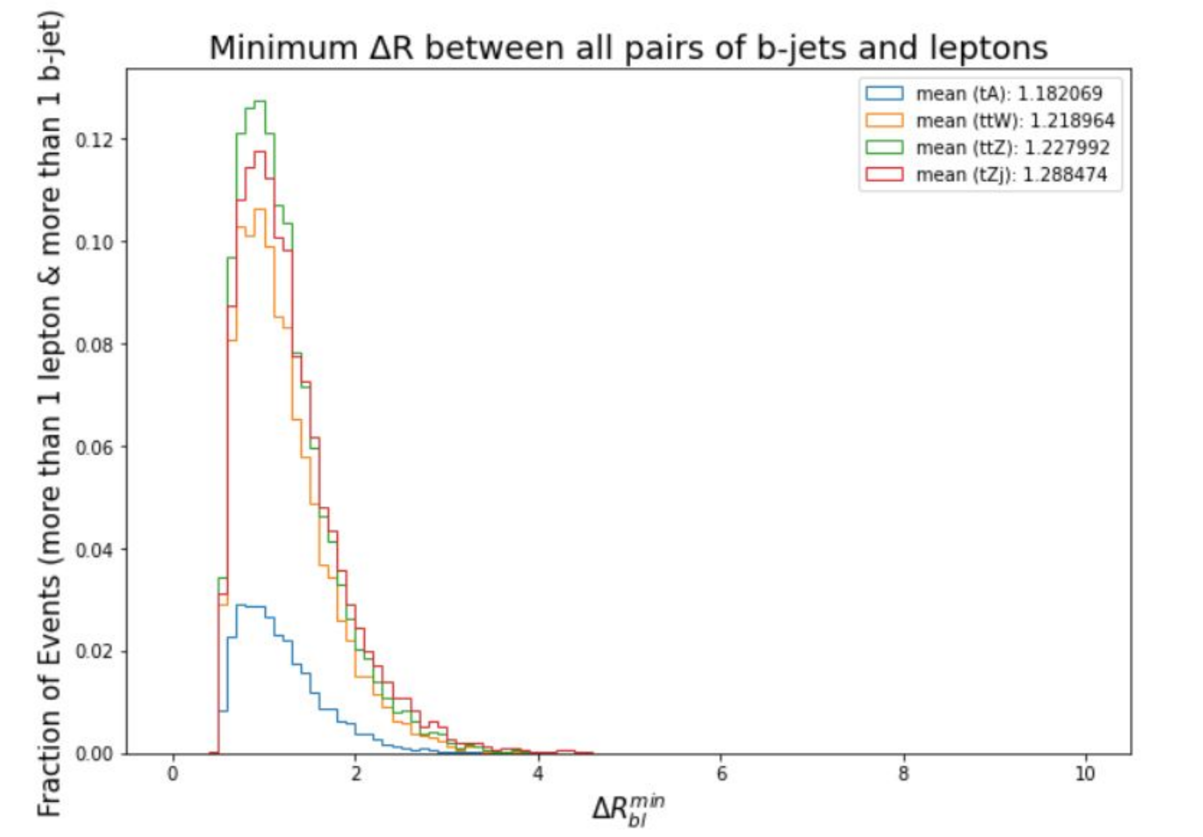
C^{all} Centrality ($\sum_i p_{\text{T}i} / \sum_i E_i$) of the leptons and jets



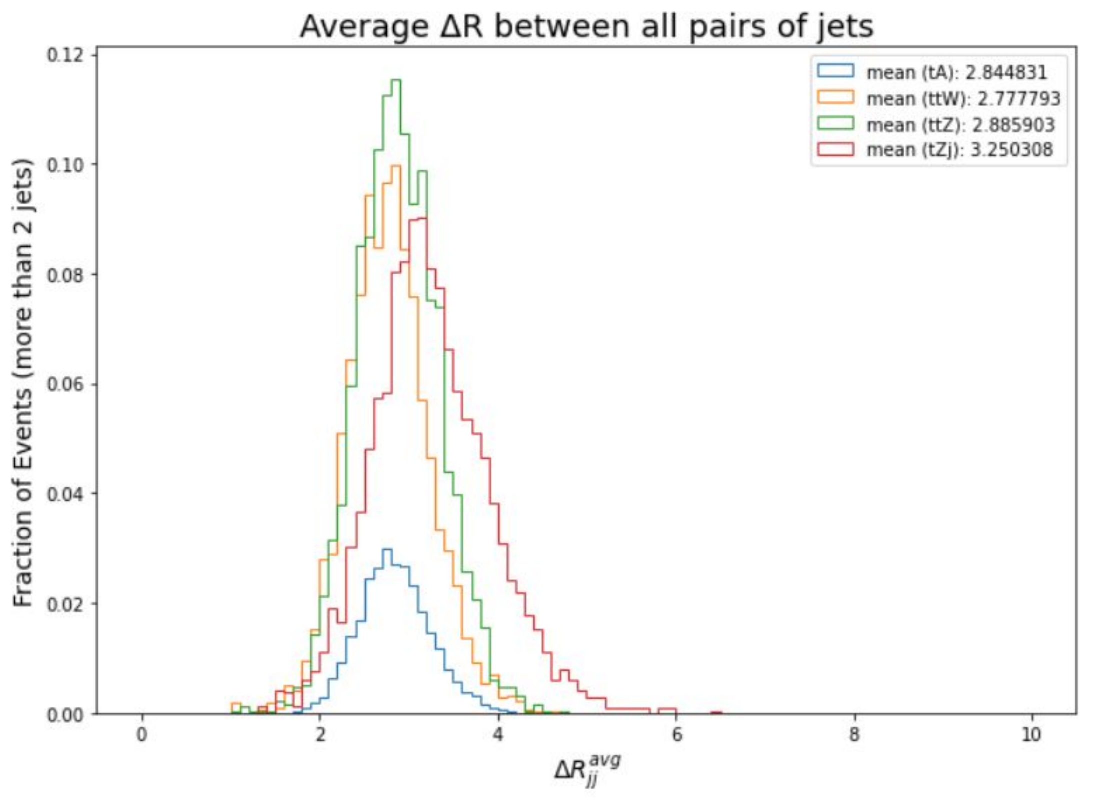
$p_{\mathrm{T}}^{\mathrm{lead}}$ Transverse momentum of the leading jet



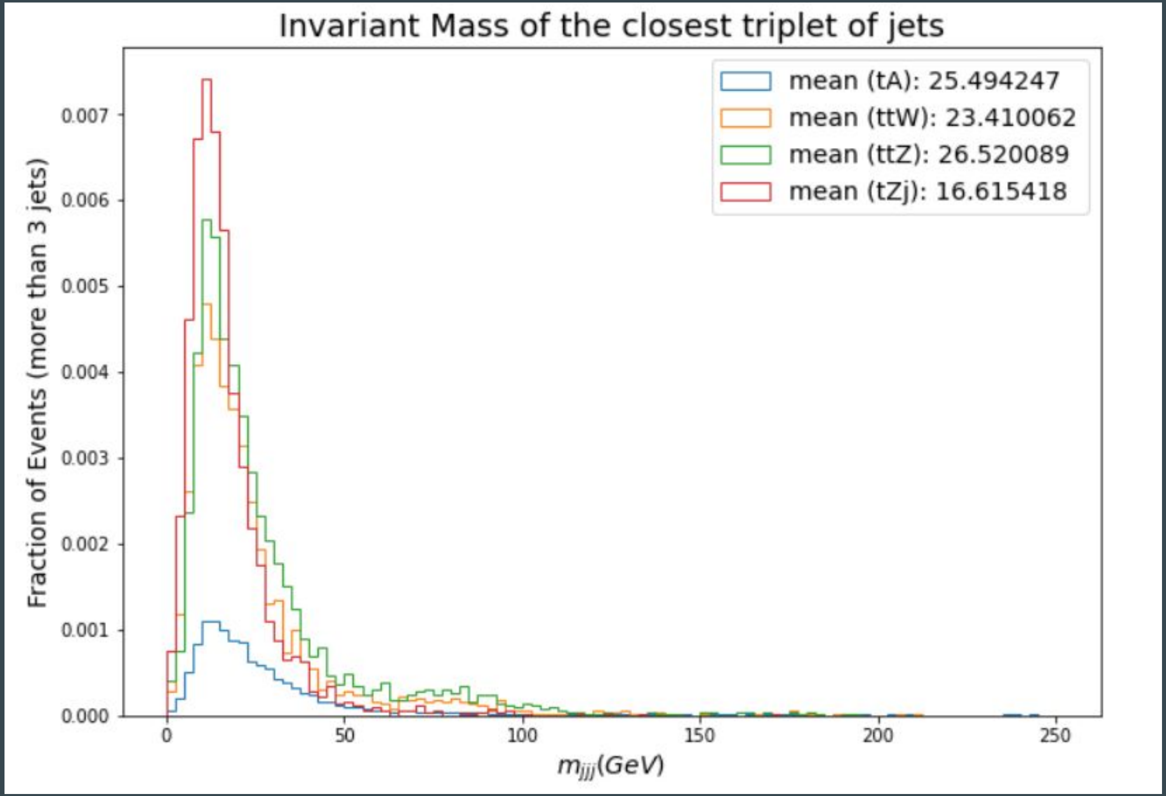
$\Delta R_{b\ell}^{\mathrm{min}}$ Minimum ΔR between all pairs of b-tagged jets and leptons



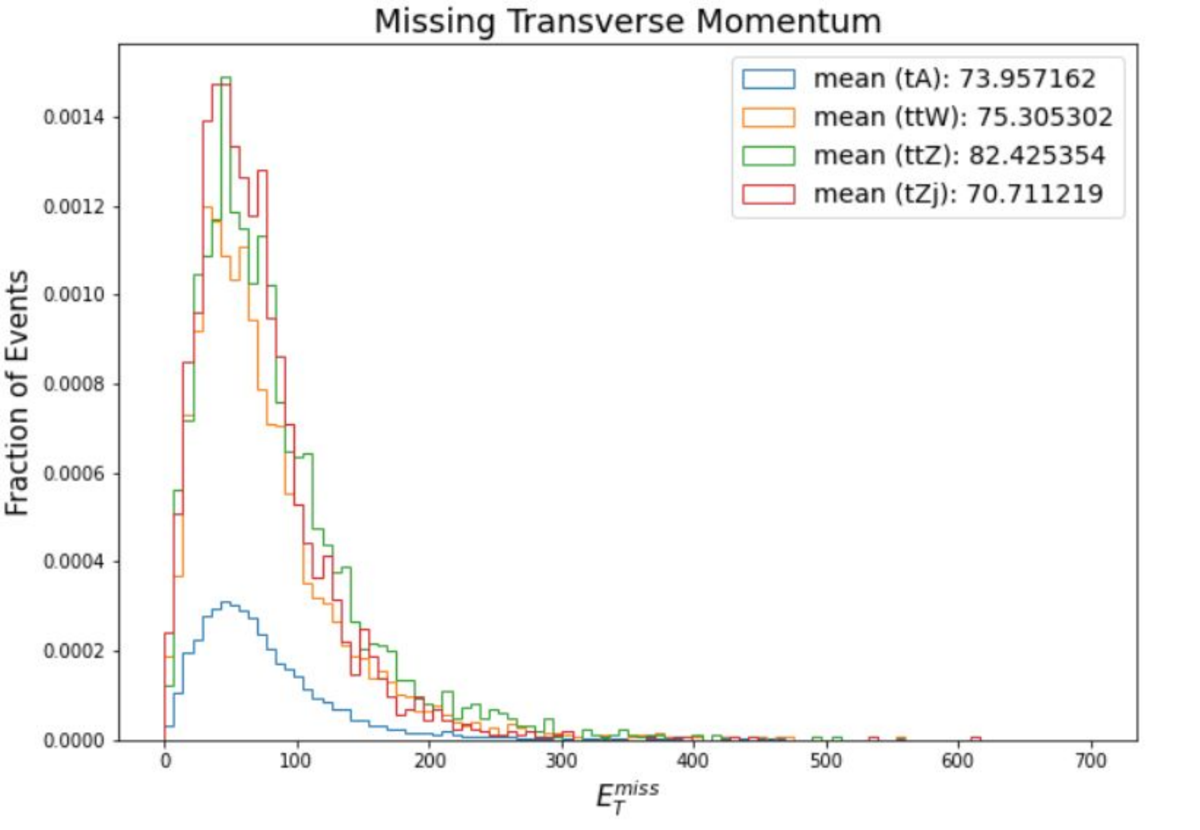
$\Delta R_{jj}^{\text{avg}}$ Average ΔR between all pairs of jets



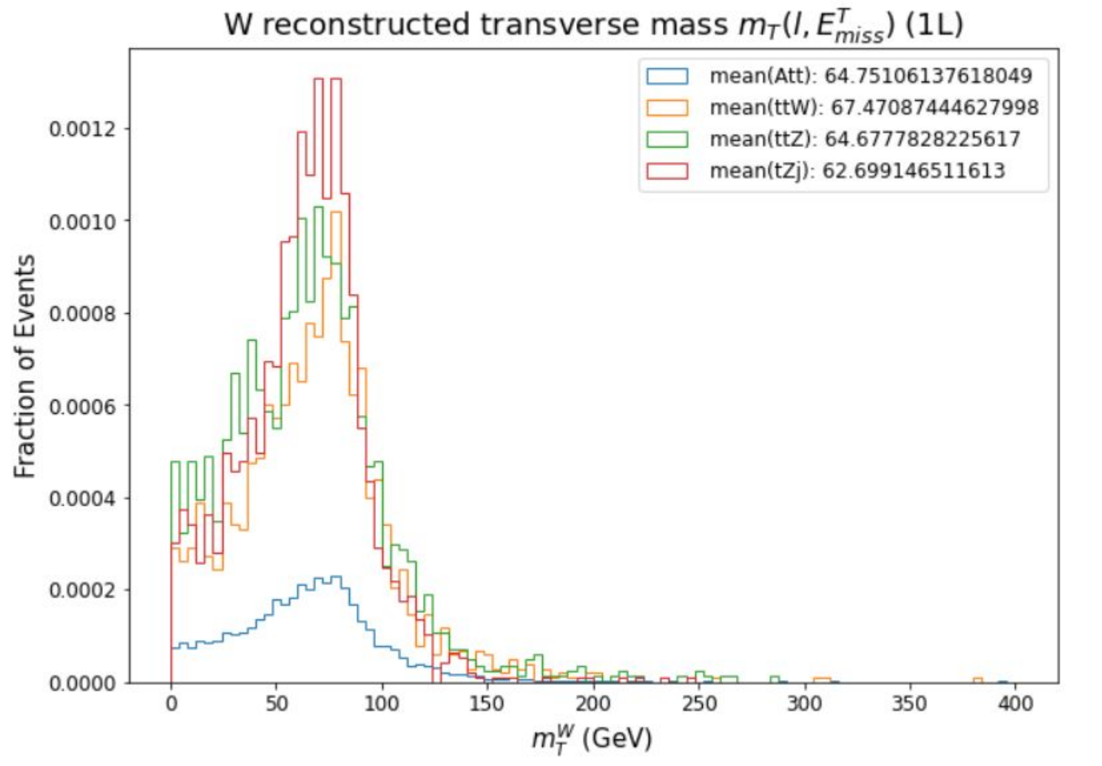
m_{jjj} Invariant mass of the closest triplet of jets



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



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



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

$N_{\text{LR-jets}}$	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

$\sum d_{23}$	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: $d_{ij} = \min(p_{\mathrm{T}i}^2, p_{\mathrm{T}j}^2) \times \Delta R_{ij}^2 / R^2$.

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

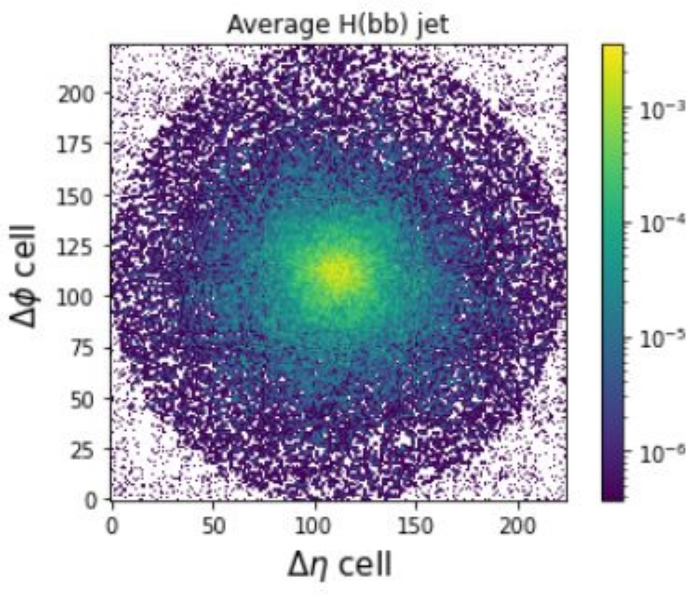
```
import model gen2HDM_UFO
define p = p b b~
define j = p
generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~)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

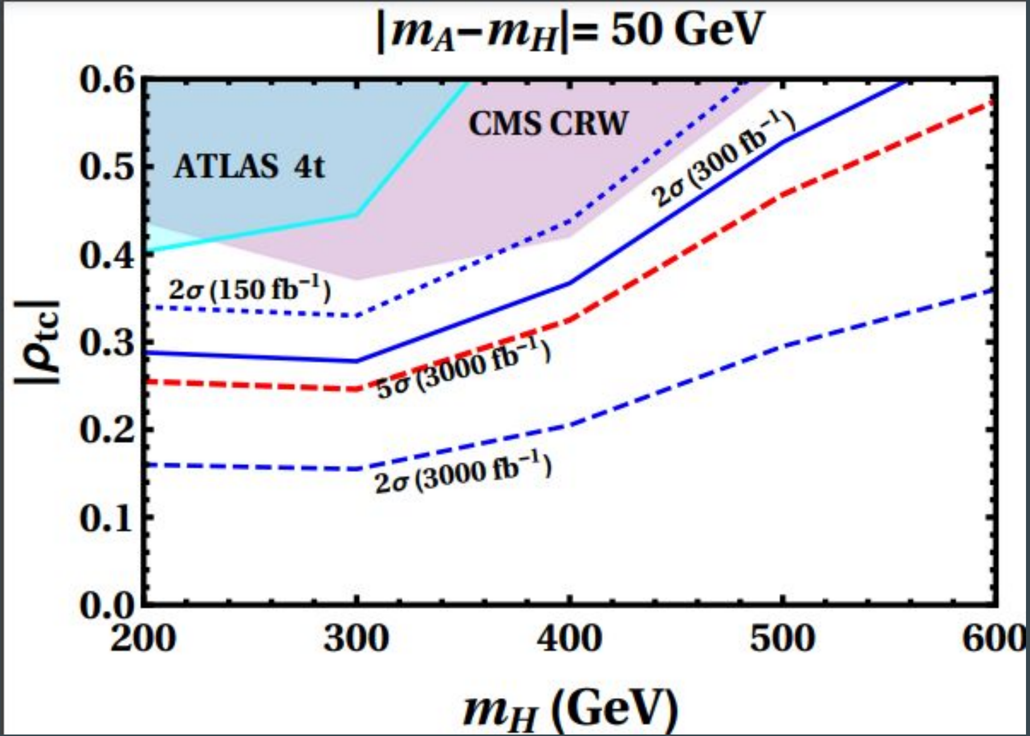
Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	1.201 ± 0.0056 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 7000.0 x 7000.0 GeV	tag_1	0.609 ± 0.0027 ± systematics	500	parton madevent	LHE 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



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

```

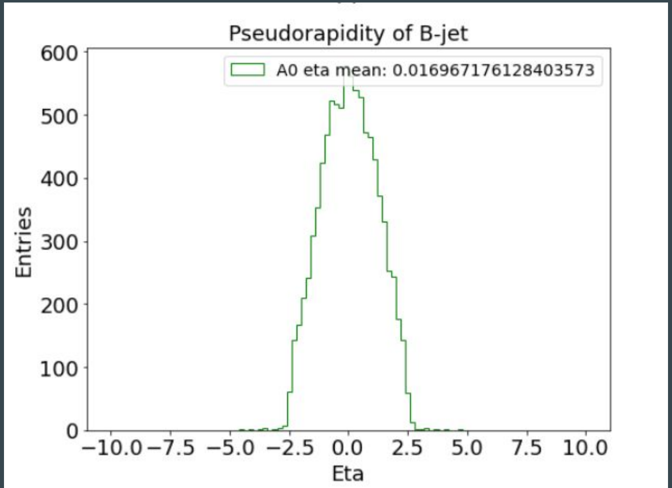
S-channel vs T-channel

- 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.

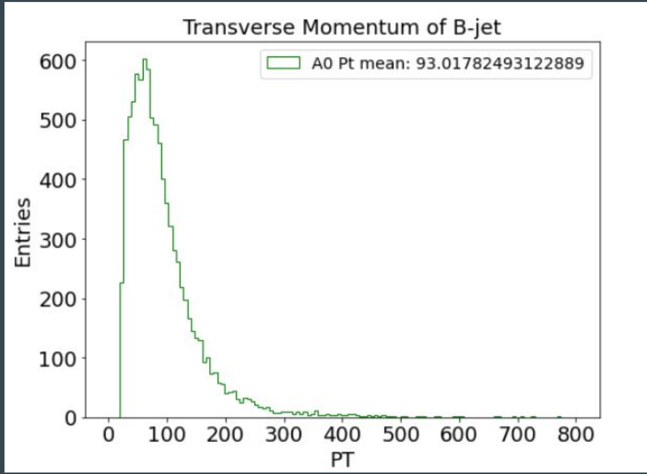
Reference

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

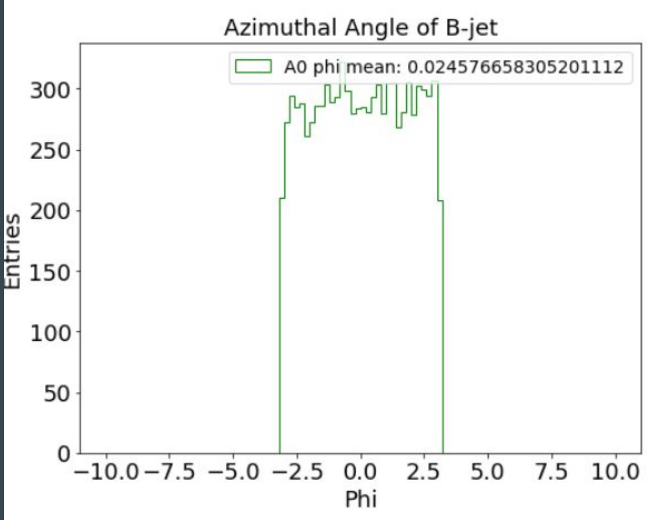
B-jet



Pseudorapidity of B-jet
A0 eta mean: 0.016967176128403573
Entries
0
100
200
300
400
500
600
−10.0 −7.5 −5.0 −2.5 0.0 2.5 5.0 7.5 10.0
Eta



Transverse Momentum of B-jet
A0 Pt mean: 93.01782493122889
Entries
0
100
200
300
400
500
600
0 100 200 300 400 500 600 700 800
PT



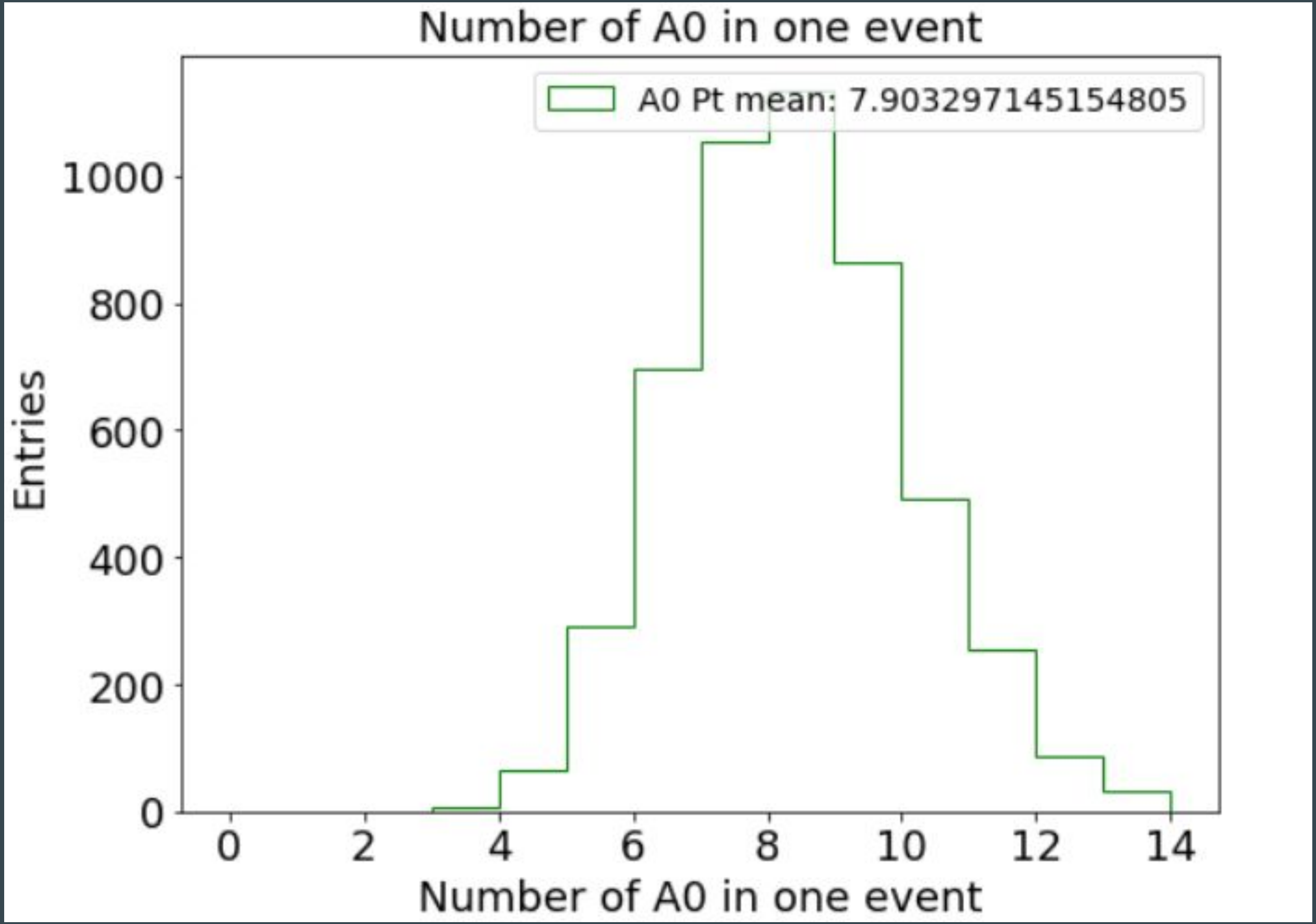
Azimuthal Angle of B-jet
A0 phi mean: 0.024576658305201112
Entries
0
50
100
150
200
250
300
−10.0 −7.5 −5.0 −2.5 0.0 2.5 5.0 7.5 10.0
Phi

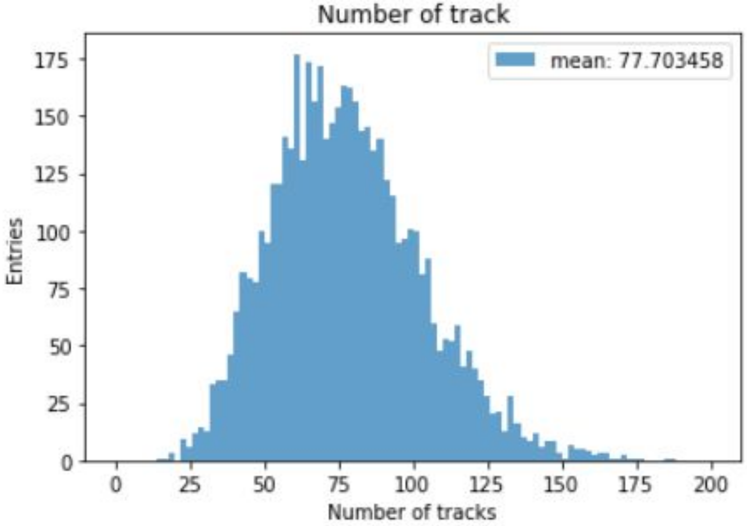
Lagrangian

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

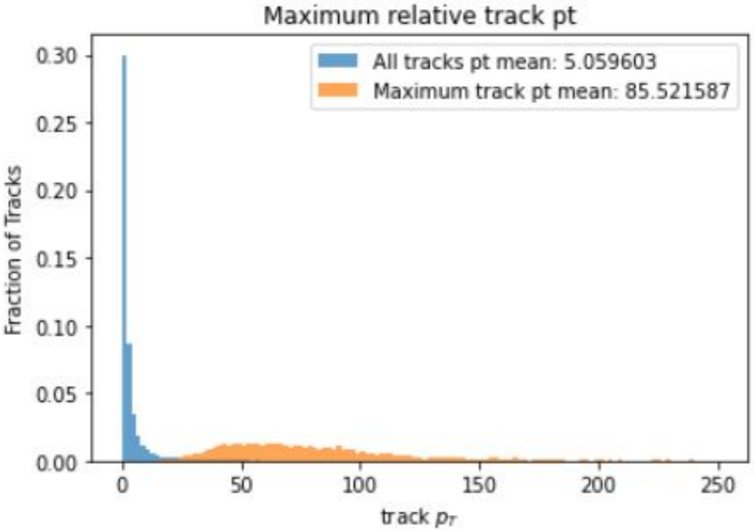
$$\mathscr{L} = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda^f_{ij} s_\gamma + \rho^f_{ij} c_\gamma) h$$

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


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

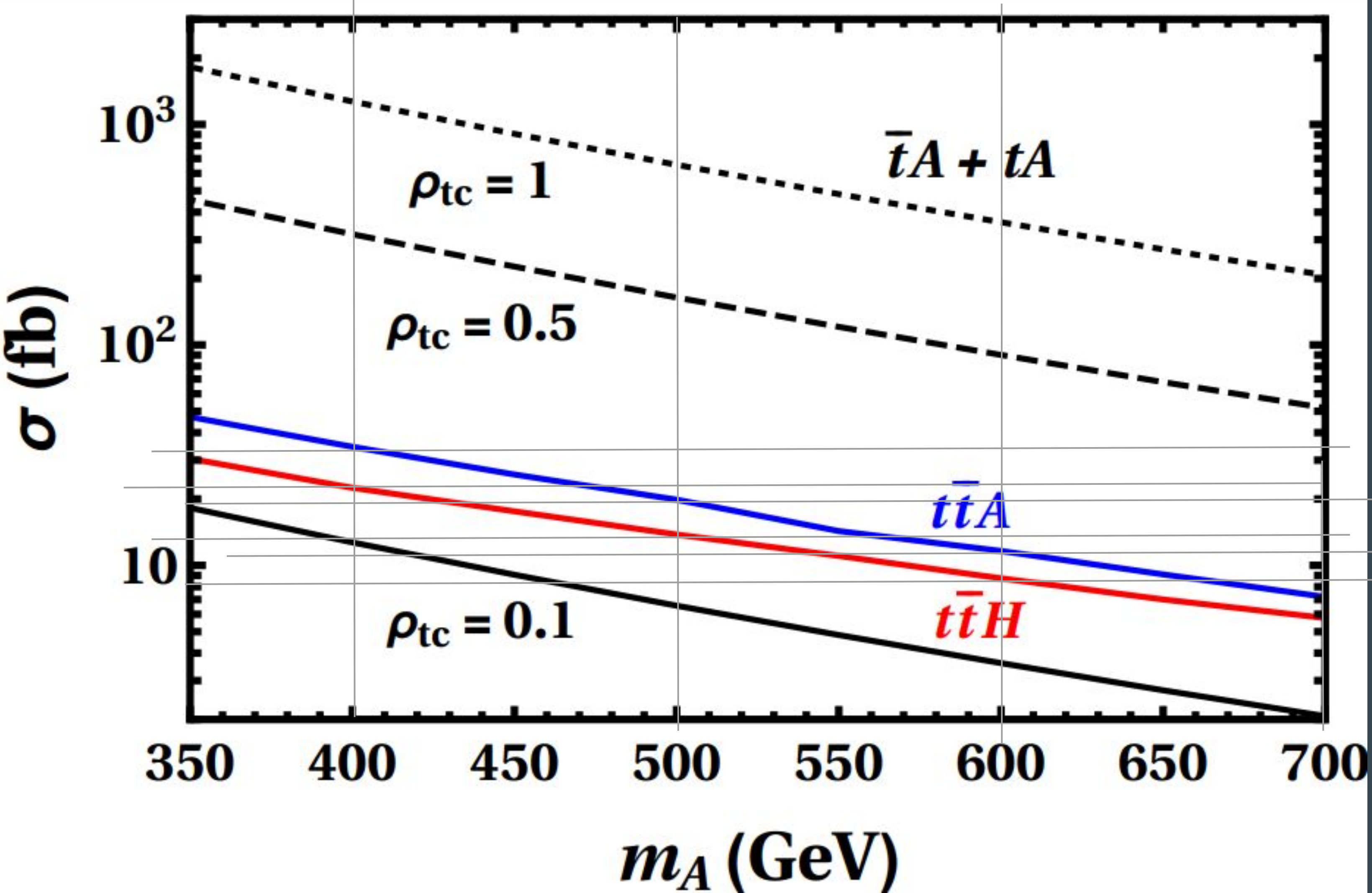


Number of track
mean: 77.703458
Entries
Number of tracks
0
25
50
75
100
125
150
175
200



Maximum relative track pt
All tracks pt mean: 5.059603
Maximum track pt mean: 85.521587
Fraction of Tracks
track p_T
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
50
100
150
200
250

To


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