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.

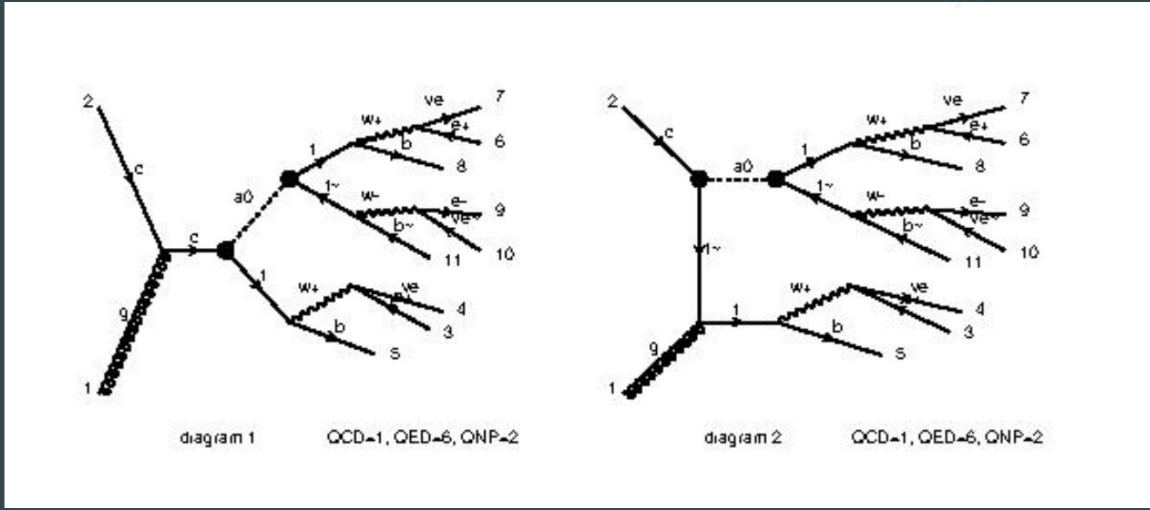
Before Spontaneous Symmetry Breaking:

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

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

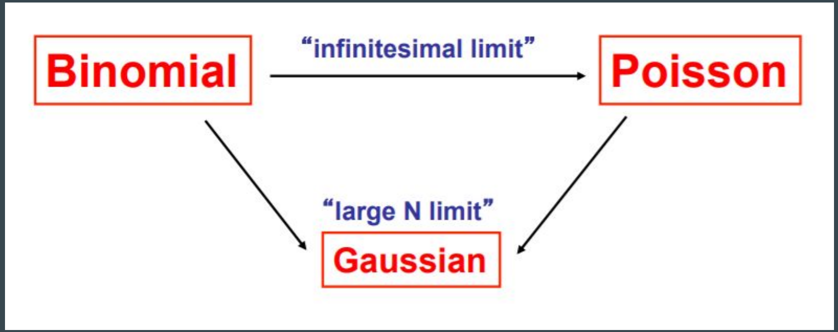
Triple Top

- 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

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

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

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

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

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

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

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

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

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

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

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

$$\Downarrow$$

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

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

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

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

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

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

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

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

$$= np(1-p)$$

$$= npq$$

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 $\sigma/\sqrt{N}$

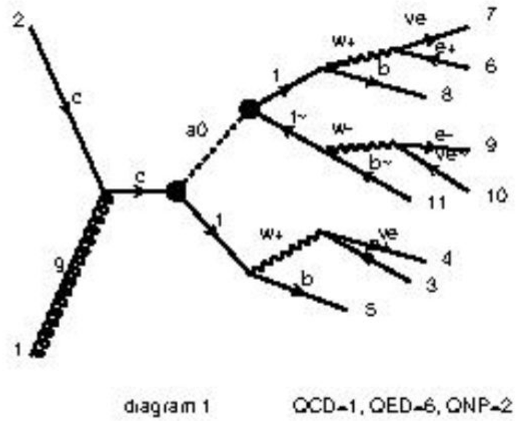
Gaussian Distribution

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

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

Particle Information Print Out

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



Cross Section Uncertainty

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

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

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

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

Cross Section vs Mass

Previous : QCD=99; Use pdf set 274000

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

Paper:

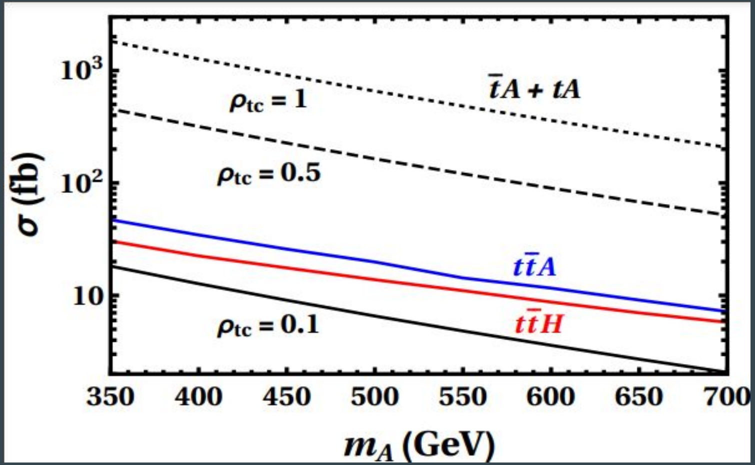
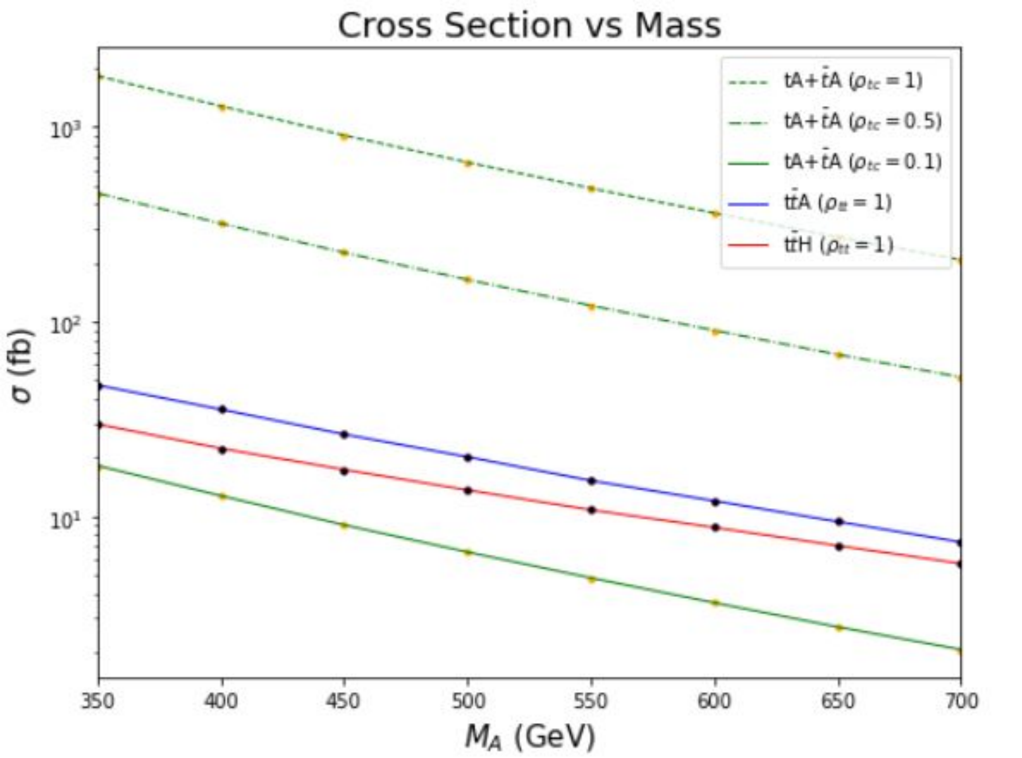
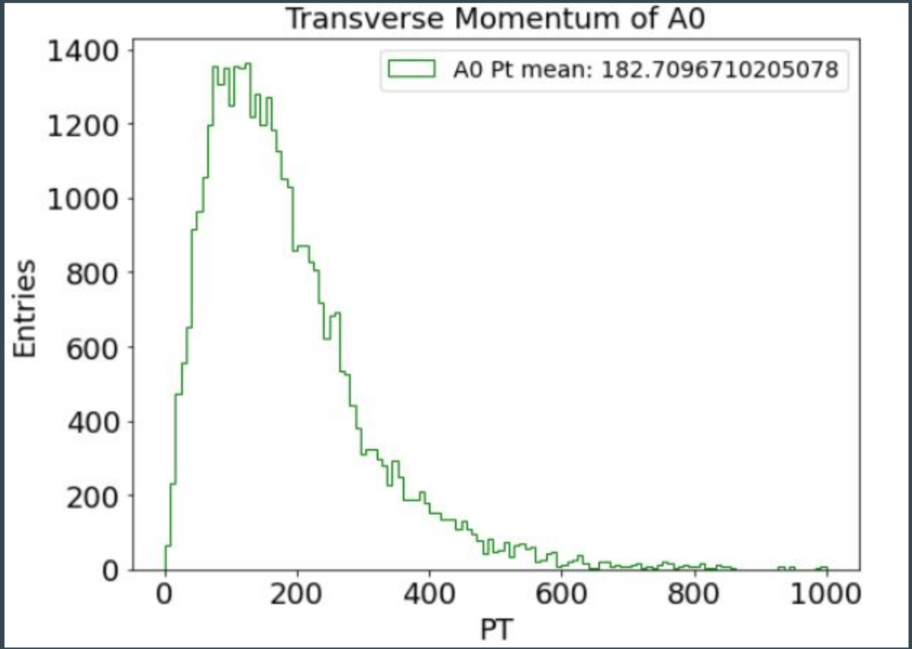


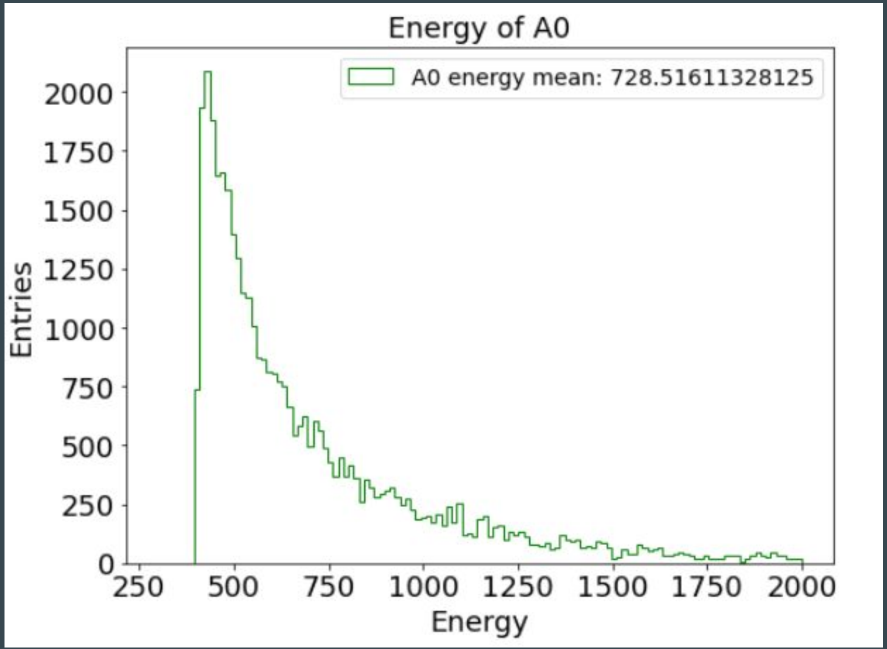
FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \to tS^0$, $\bar{t}S^0$ where $S^0 = H^0$, A^0, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \to t\bar{t}H^0$, $t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

My Result:

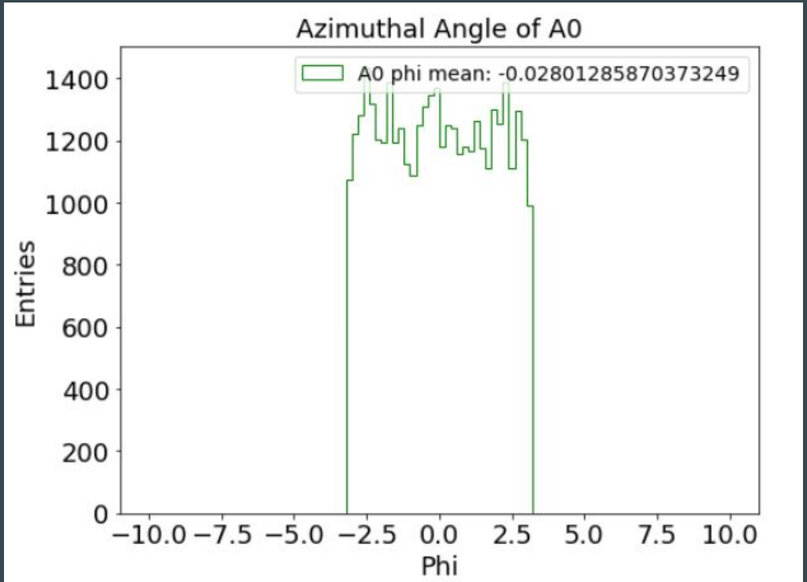


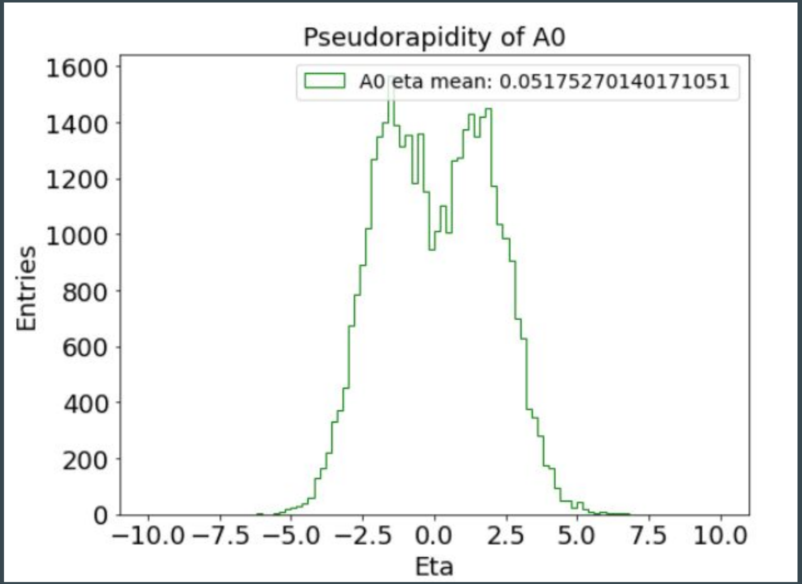
Kinematic Plots (A0 400GeV)



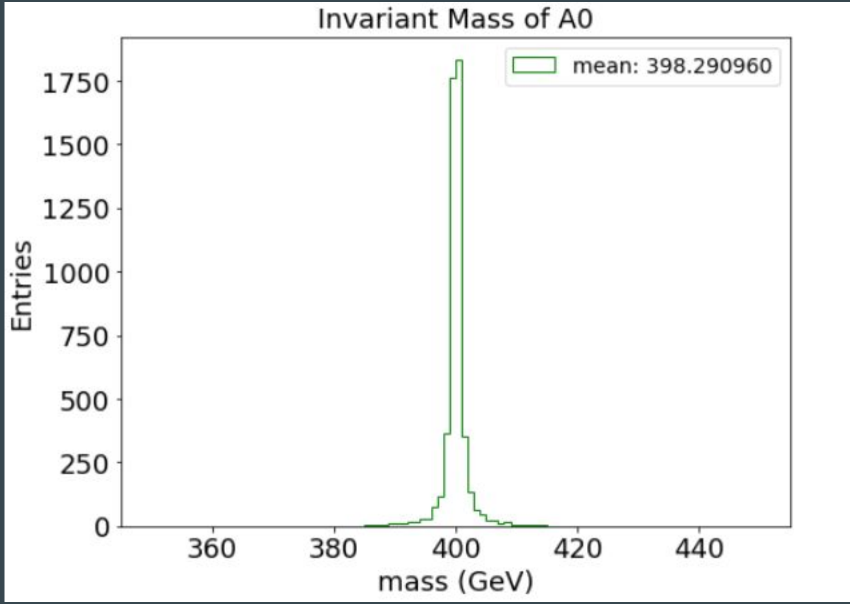


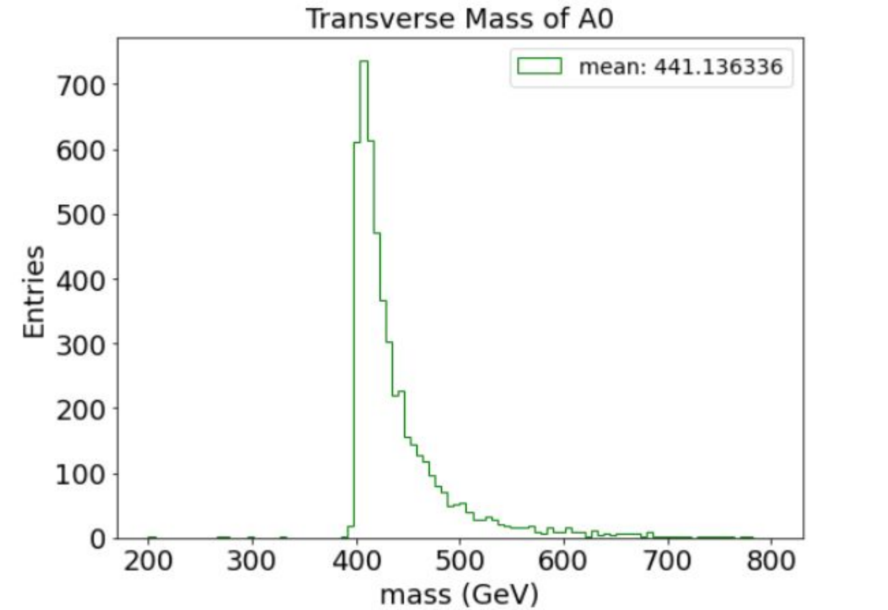
Kinematic Plots (A0 400GeV)





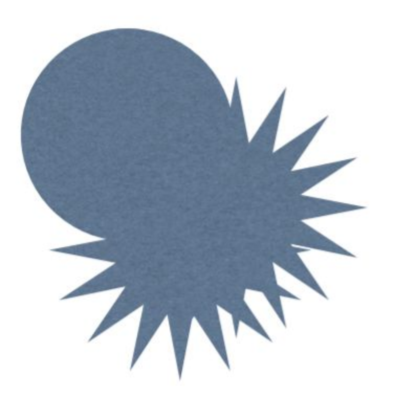
Kinematic Plots (A0 400GeV)

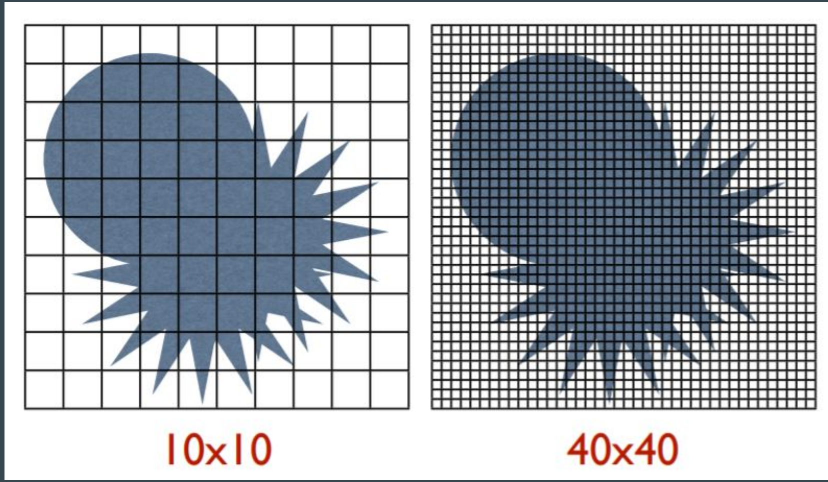




Monte Carlo

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

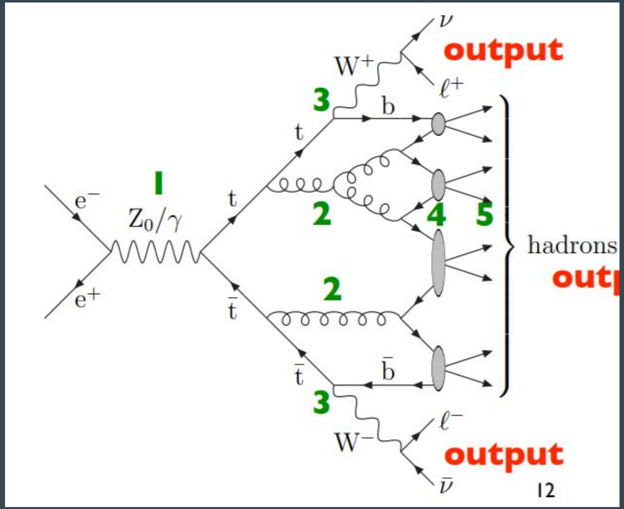




Area = (Number of hits)/(Total squares) * (Total Area)
https://upload.wikimedia.org/wikipedia/commons/8/84/Pi_30K.gif

Monte Carlo

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



Decay Width Calculation (new)

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

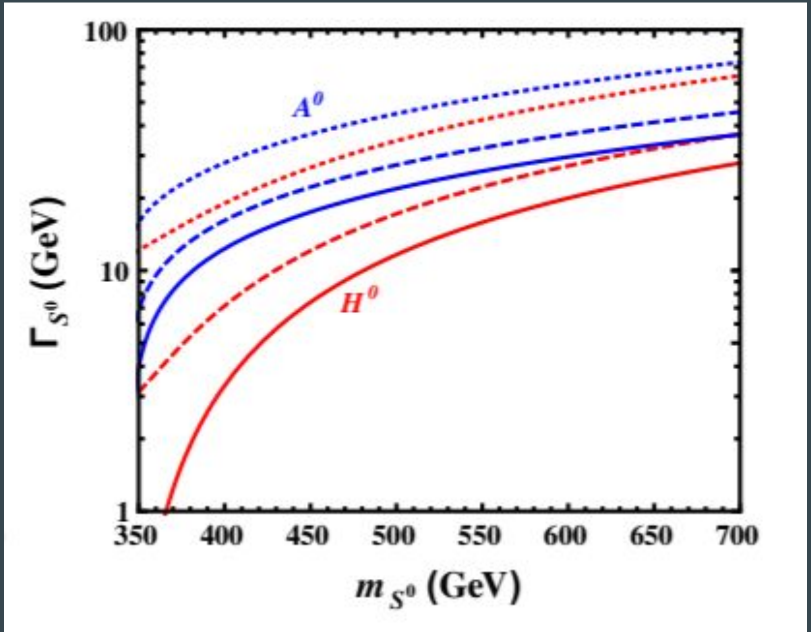
```
In[413]:= ΓtotA[rtt_, rtu_, rtc_, KAZH_, KAZh_, MA_, MH_] := If[MA > mt + mc, 2 ΓAtc[rtc, MA, 3], 0] + If[MA > mt + mu, 2 ΓAtu[rtu, MA, 3], 0] +
    If[MA > 2 mt, ΓAffbar[rtt, MA, mt, 3], 0] + If[MH > 0, If[MA > MH + mZ, ΓAZH[KAZH, MA, MH], 0], 0] + If[MH > 0, If[MA > mh + mZ, ΓAZh[KAZh, MA, MH],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

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

Out[452]= 36.7542
```

Total decay width for *H*

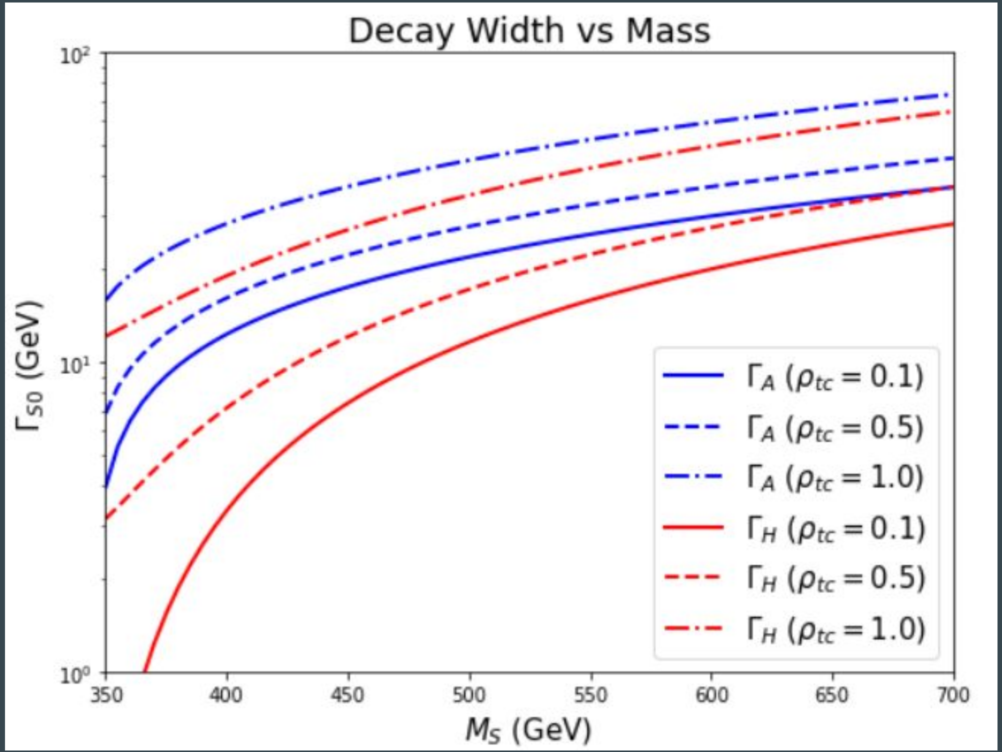
```
In[467]:= ΓtotH[rtt_, rtu_, rtc_, KHAZ_, lHhh_, MA_, MH_] := If[MH > mt + mc, 2 ΓHtc[rtc, MH, 3], 0] + If[MH > mt + mu, 2 ΓHtu[rtu, MH, 3], 0] +
    If[MH > 2 mt, ΓHffbar[rtt, MH, mt, 3], 0] + If[MH > 0, If[MH > MA + mZ, ΓHZA[KHAZ, MH, MA], 0], 0] + If[MH > 2 mh, ΓHhh[lHhh, MH], 0];

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

Out[500]= 27.9671
```

Decay Width

Paper:



My Result:



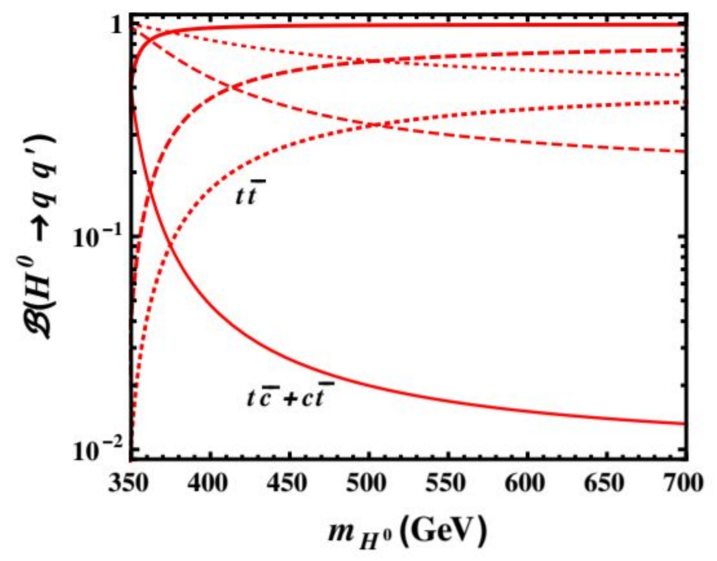
Branching Ratio

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

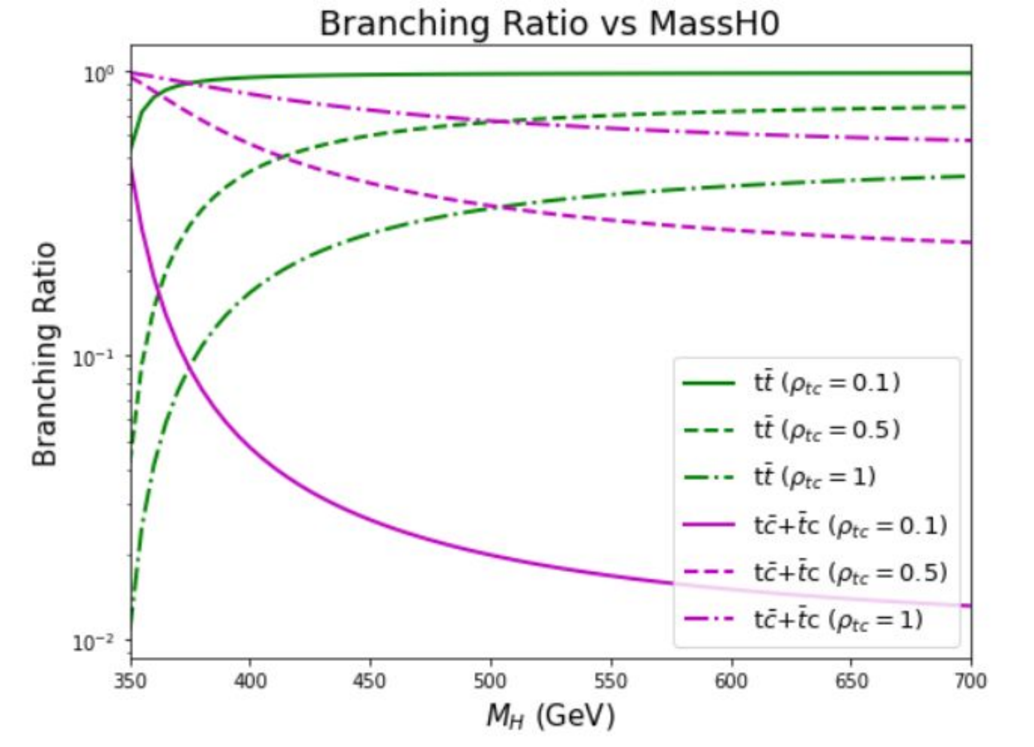
$$BR(i) = \frac{\Gamma_i}{\Gamma} \tag{82}$$

Branching Ratio (H0)

Paper:

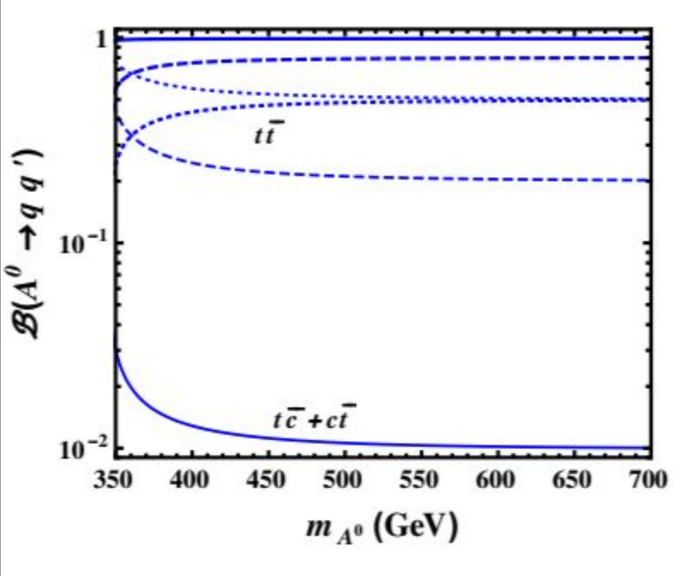


My Result:

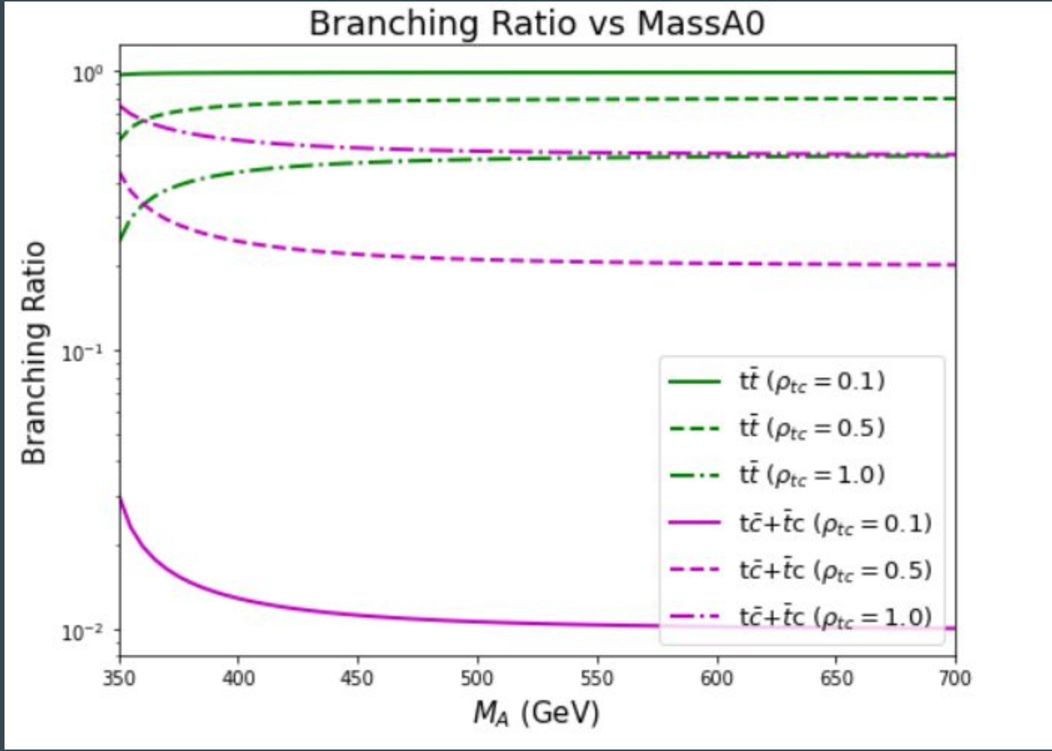


Branching Ratio (A0)

Paper:



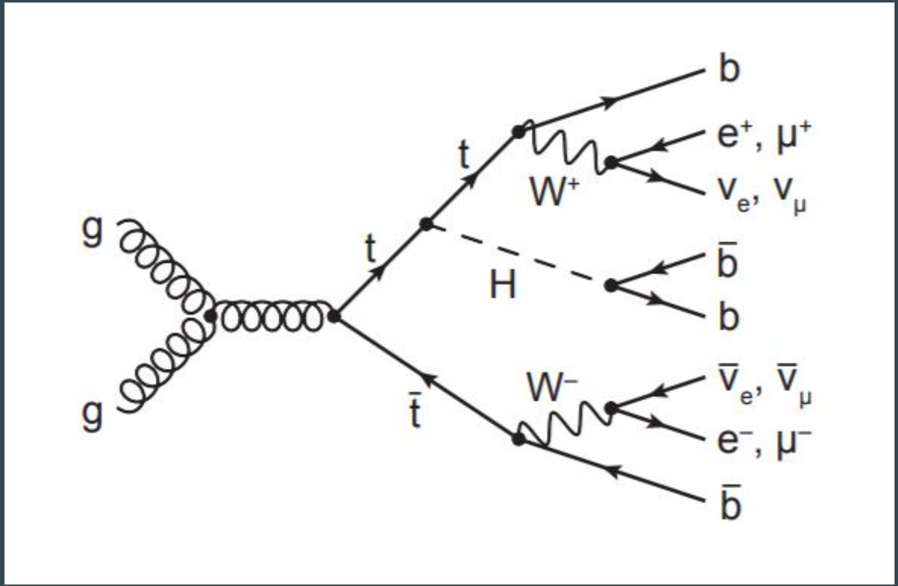
My Result:



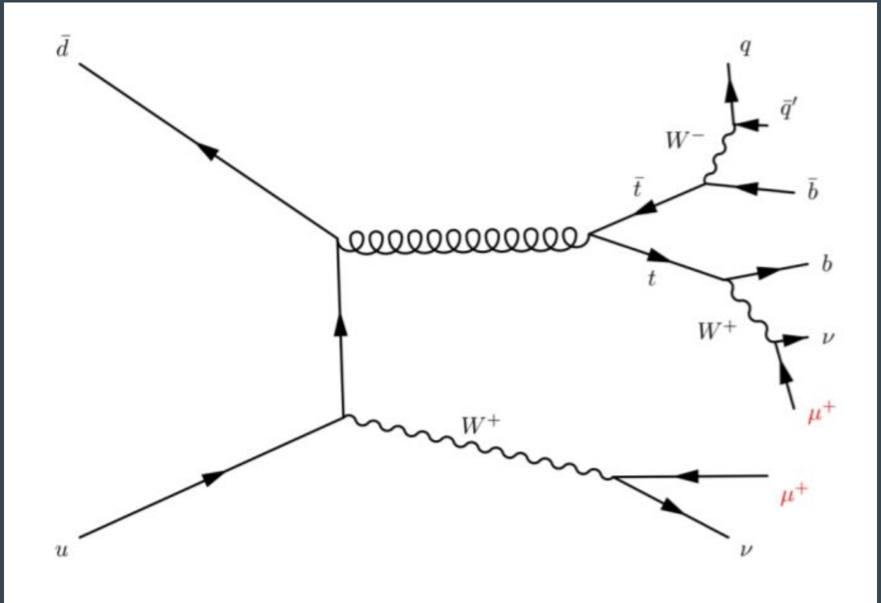
Same Sign Dilepton

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

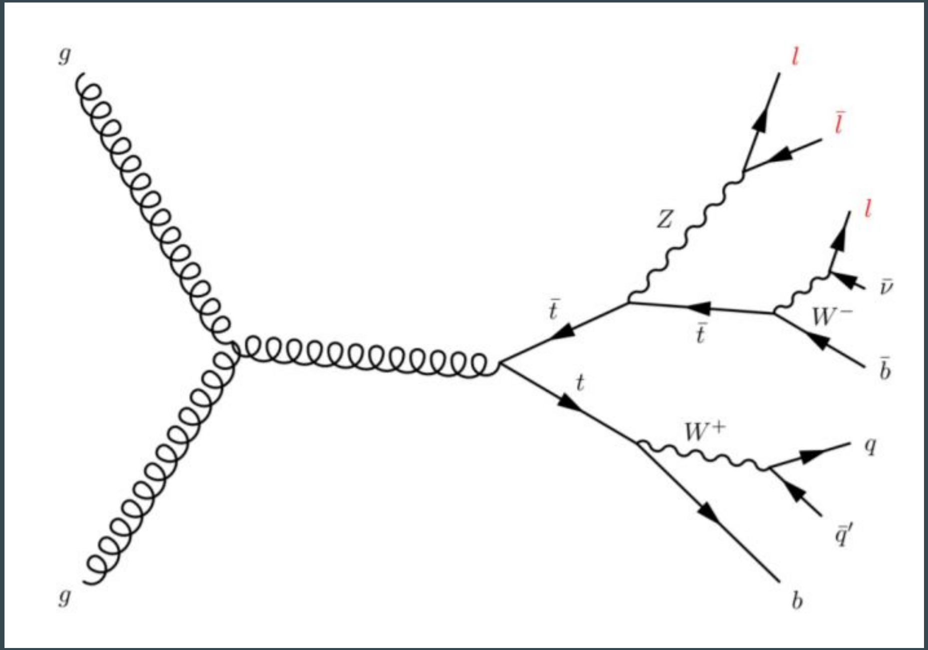
Paper (2 leptons):



Background:

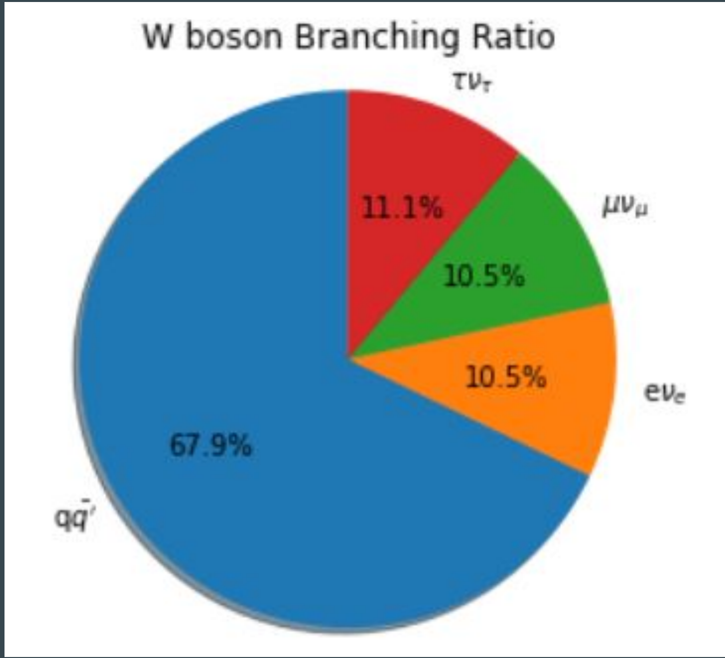


Trilepton



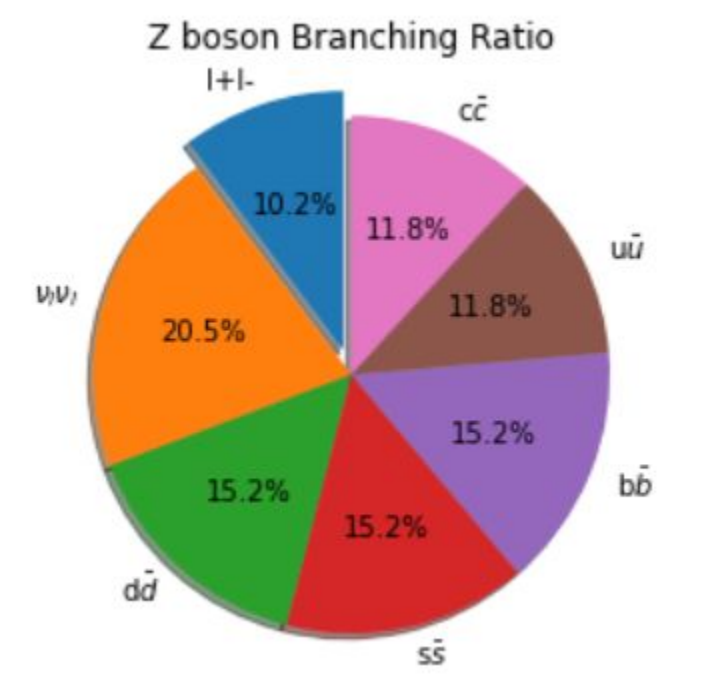
Pie charts: Branching Ratio for W boson

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



Pie charts: Branching Ratio for Z boson

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



Analysis Flow Chart

Generate Sample Data

study signal and background | pre-selection cut | debug

Study high level features and low level features

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

Interpret Model (setting upper limit)

Signal: ug -> tA0 -> ttt~

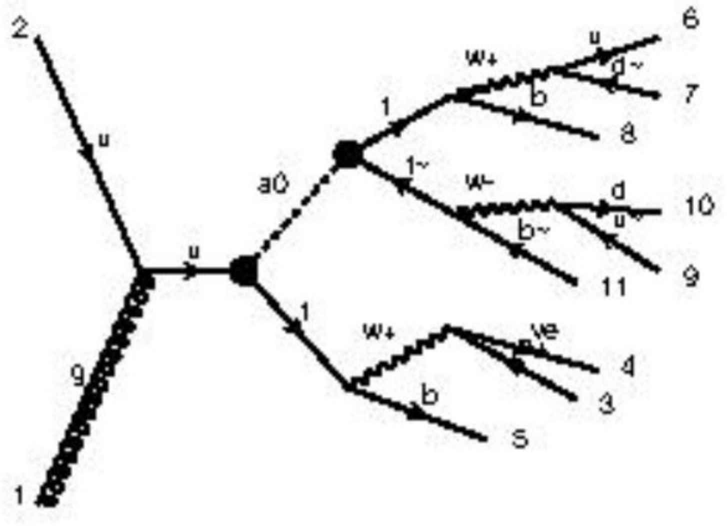


diagram 1 QCD=1, QED=6, QNP=2

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

SM Background: tt~Z

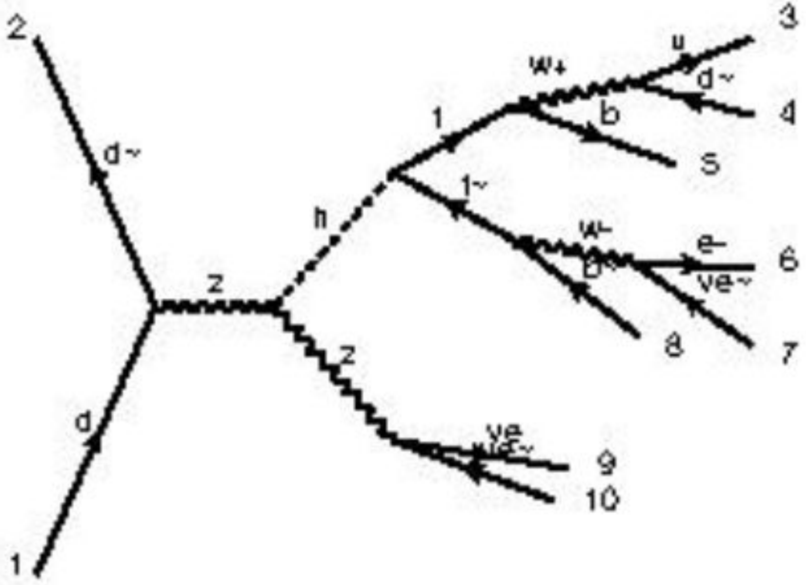
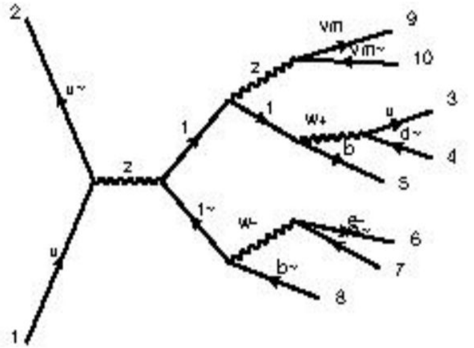
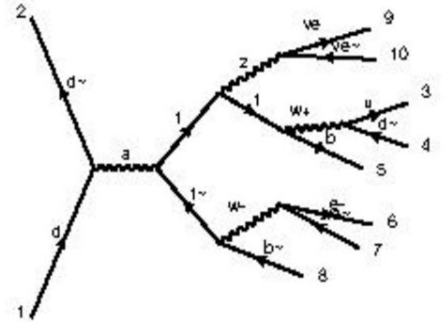
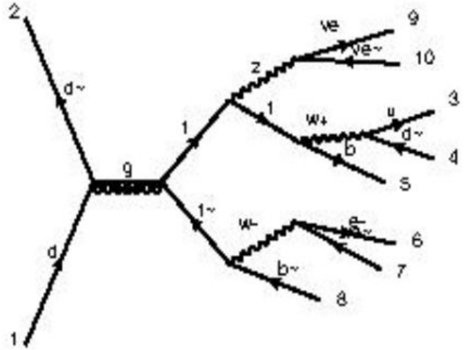


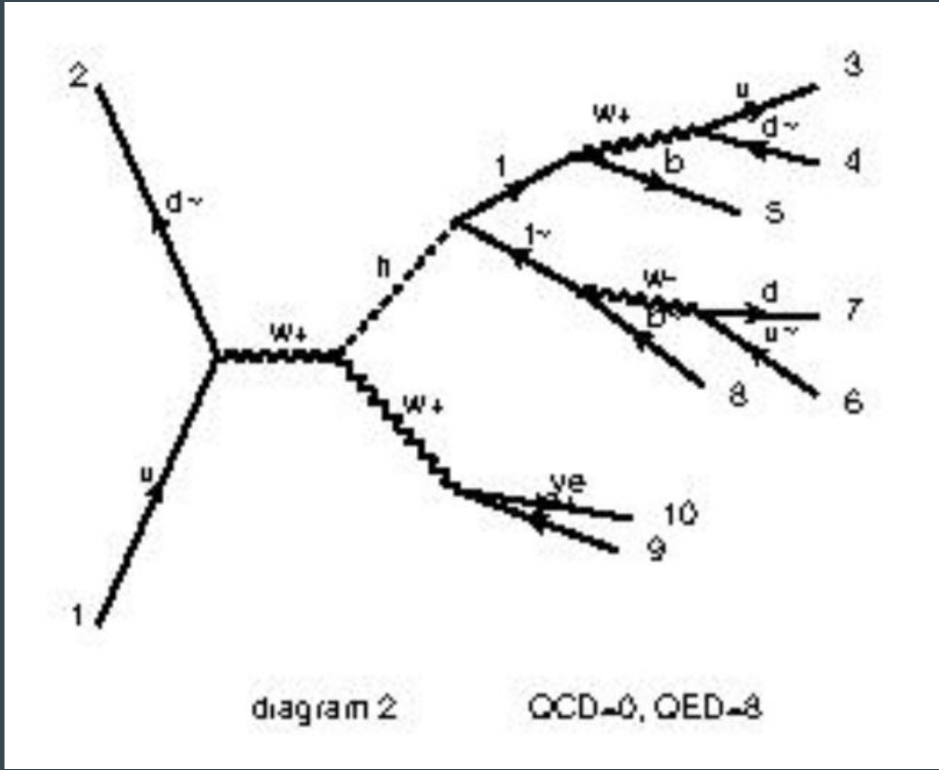
diagram 1 QCD=0, QED=8

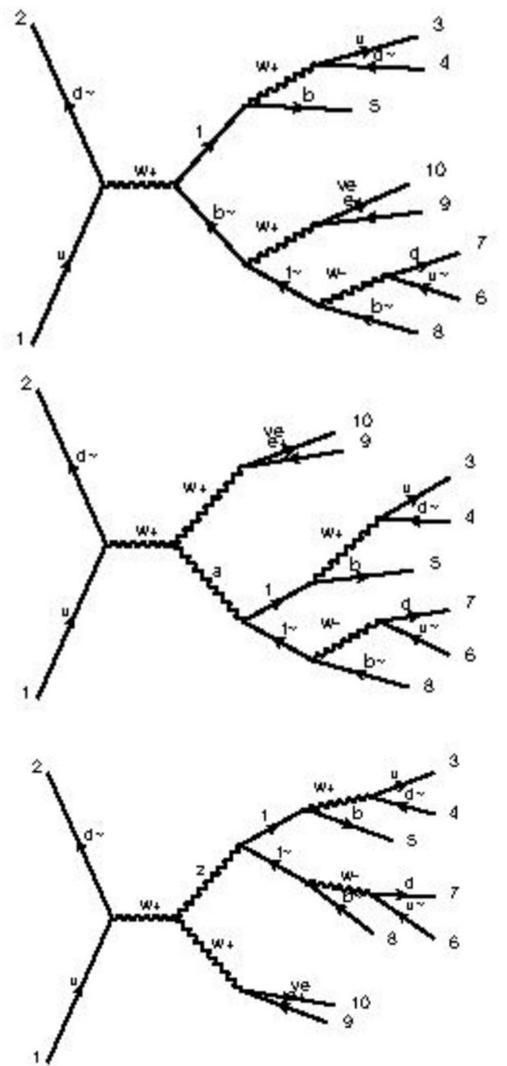




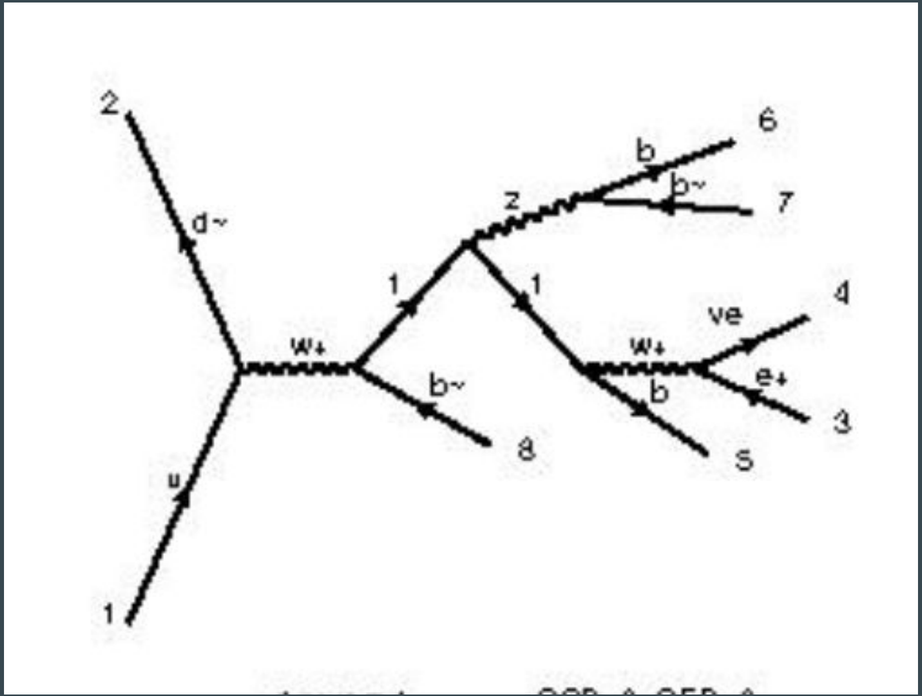


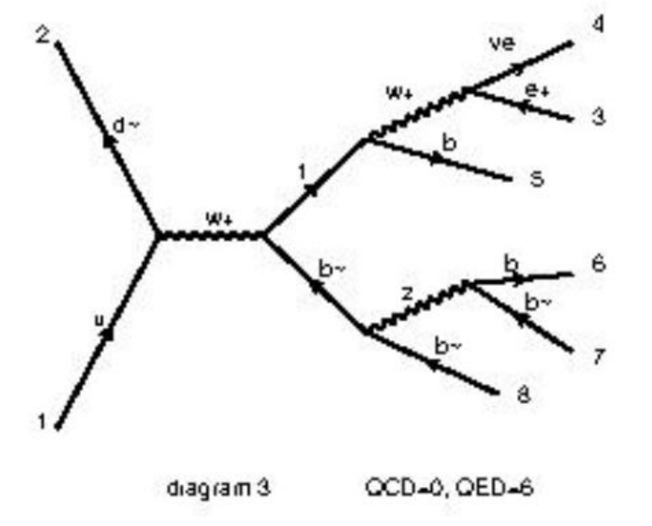
SM Background: tt~W

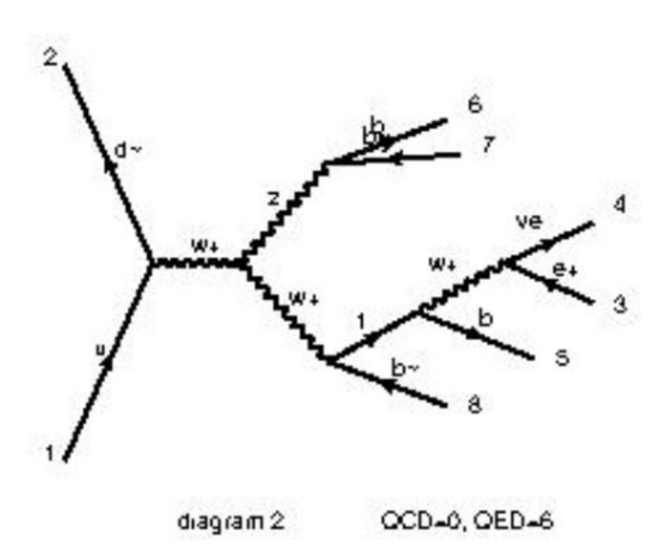




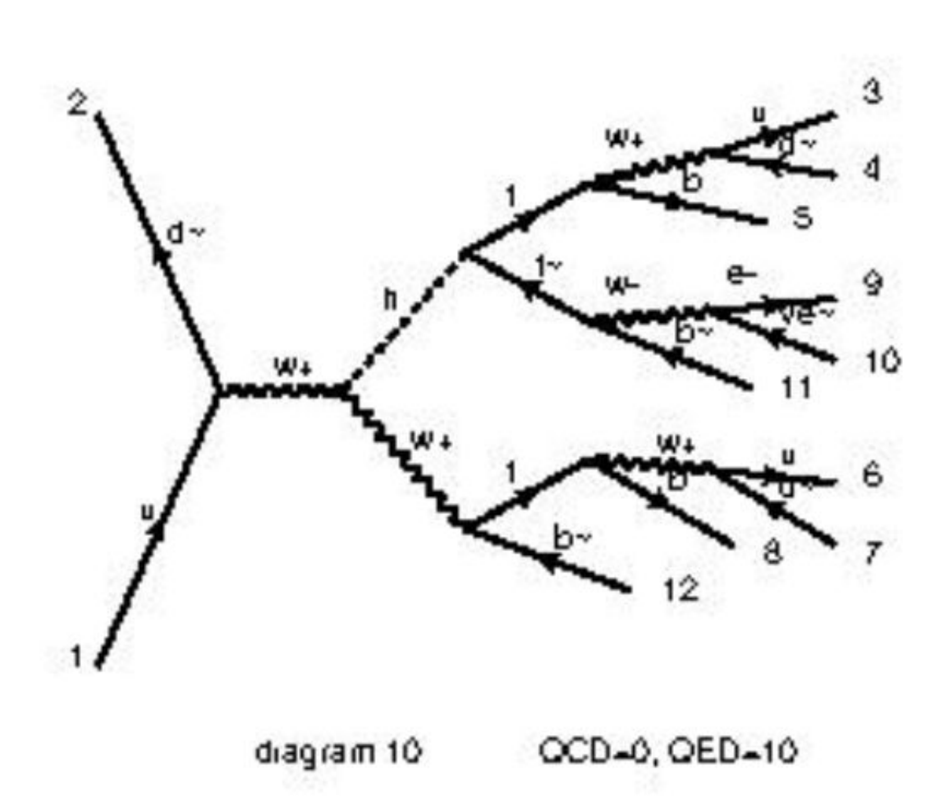
SM Background: tZ + j



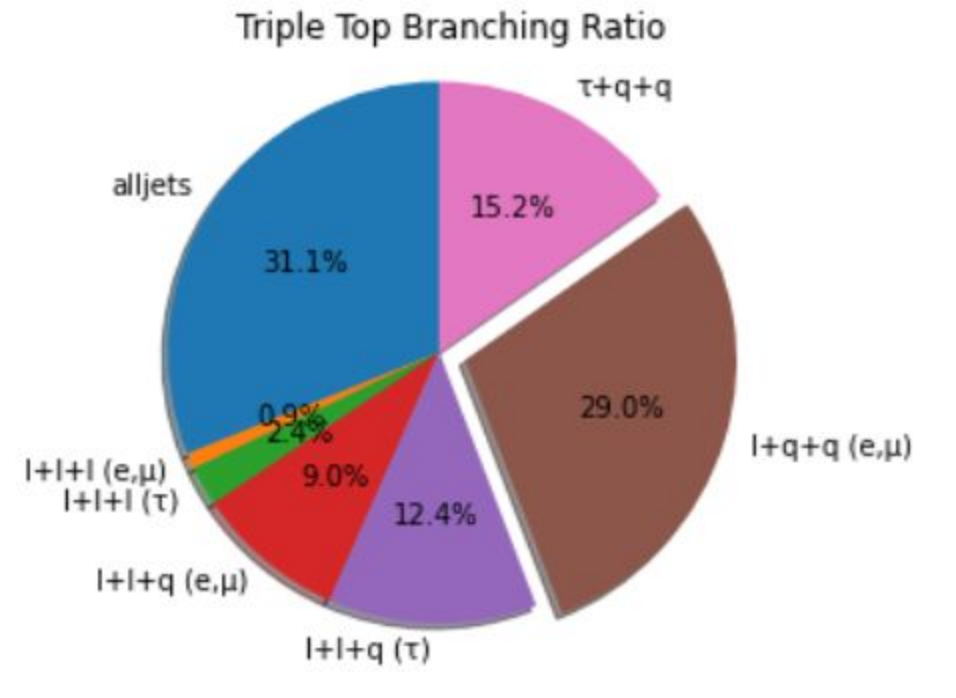




SM Background: 3t + j

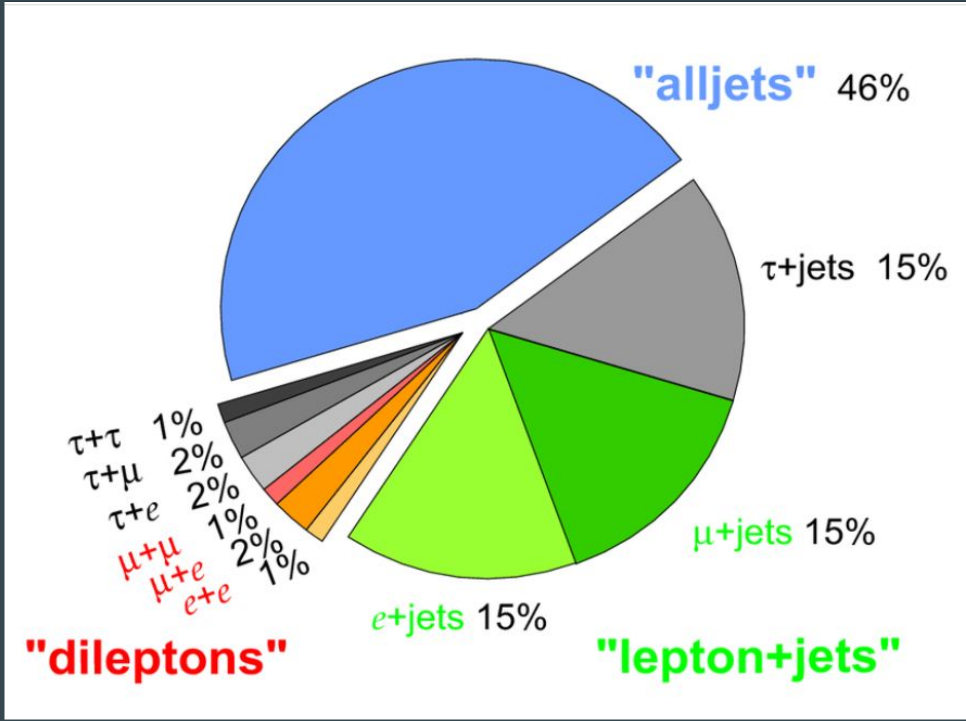


Pie charts: Branching Ratio for Triple Top

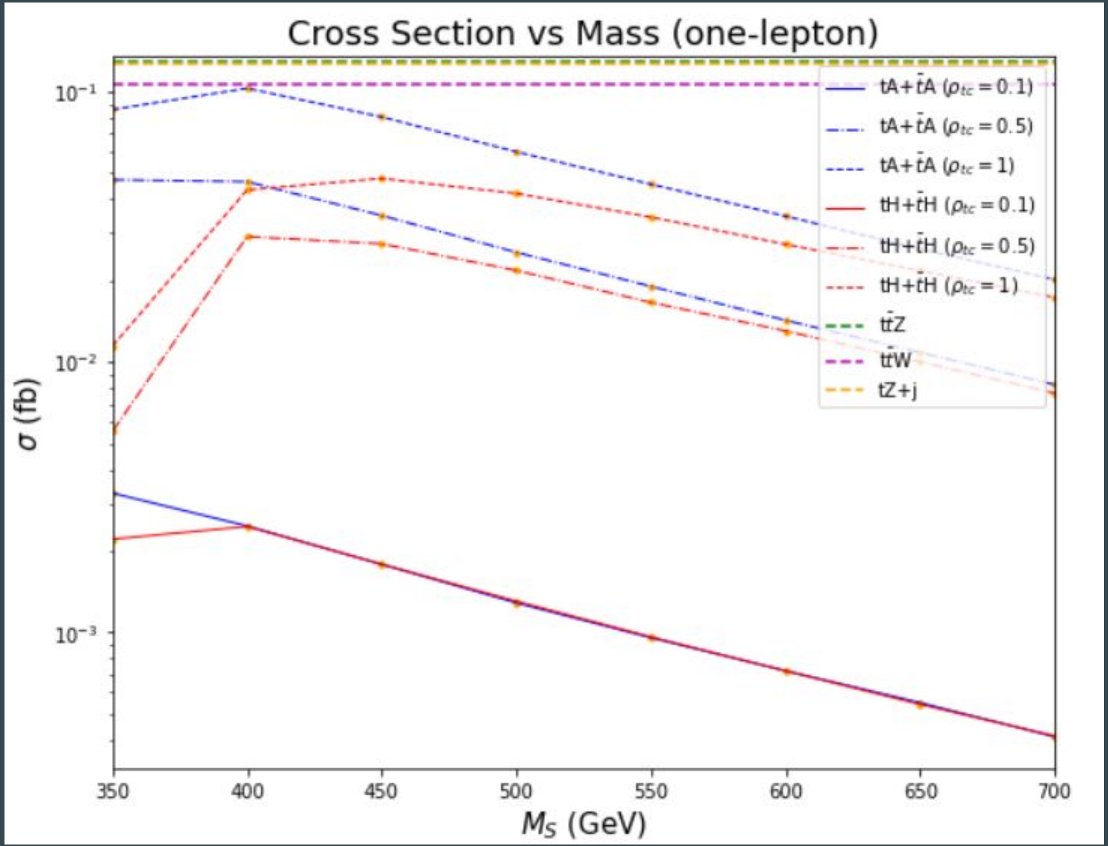


	Combinations	Probability
0	q+q+$\bar{q}$	0.313324
1	e+e+e	0.001171
2	μ+μ+μ	0.001171
3	e+μ+μ	0.003513
4	e+e+μ	0.003513
5	τ+τ+τ	0.001364
6	τ+e+μ	0.007392
7	τ+e+e	0.003696
8	τ+μ+μ	0.003696
9	τ+τ+e	0.003889
10	τ+τ+μ	0.003889
11	e+e+q	0.022636
12	μ+μ+q	0.022636
13	e+μ+q	0.045272
14	τ+τ+q	0.025060
15	τ+e+q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

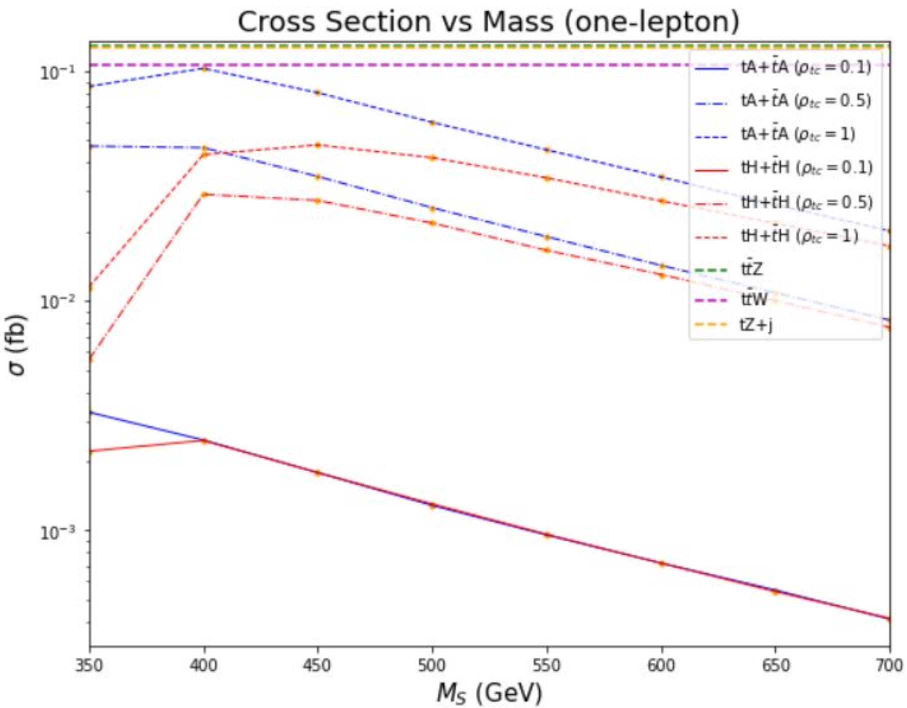
Top pair branching ratio pie chart

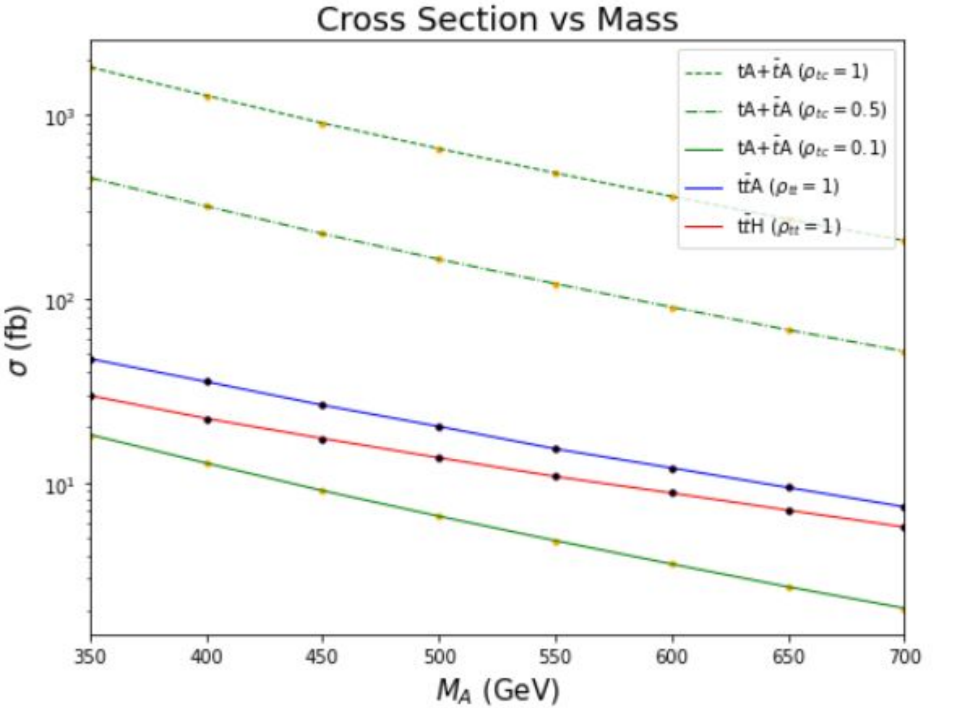


Cross Section vs Mass

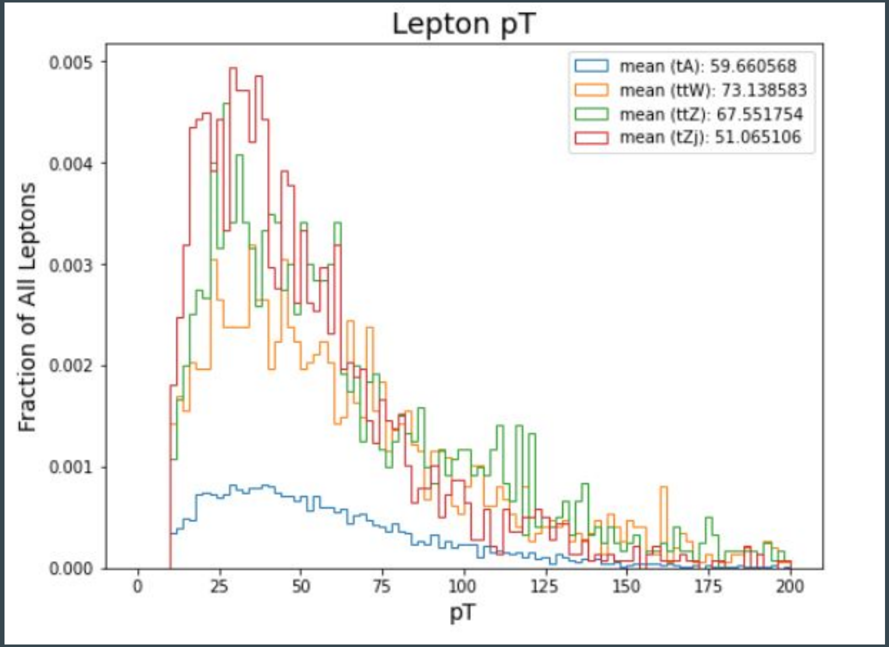


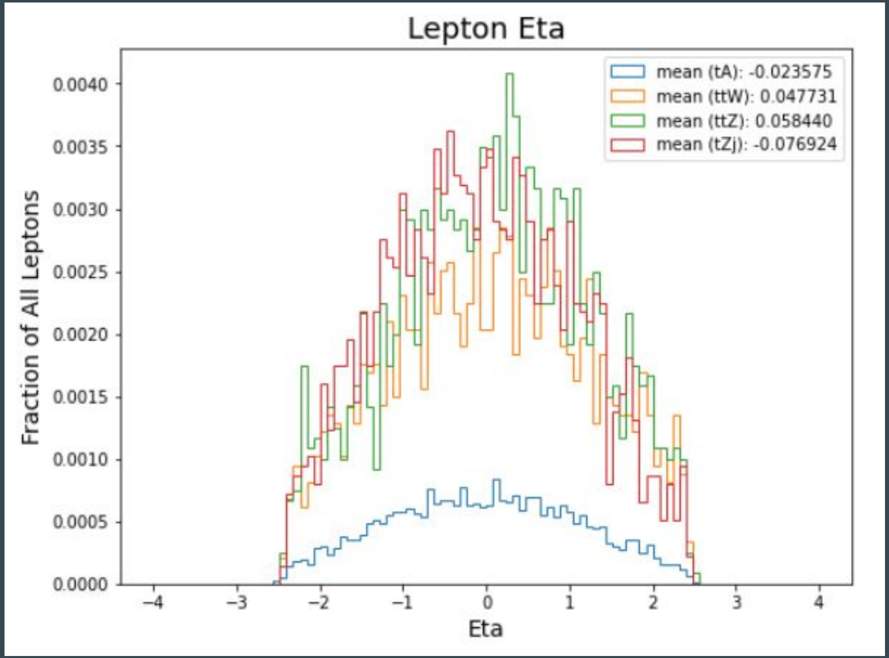
Set the masses of A and H fixed to some values say both at 400 GeV. Take rho_tc = 0.5 (or rho_tu =0.2) and rho_tt = 0.5 for example. These are somewhat close to the upper limits for these couplings given current constraints. All couplings are assumed to be real


Cross Section vs Mass (one-lepton)
σ (fb)
M_S (GeV)
tA+t̄A ($\rho_{tc}=0.1$)
tA+t̄A ($\rho_{tc}=0.5$)
tA+t̄A ($\rho_{tc}=1$)
tH+t̄H ($\rho_{tc}=0.1$)
tH+t̄H ($\rho_{tc}=0.5$)
tH+t̄H ($\rho_{tc}=1$)
tt̄Z
tt̄W
tZ+j


Cross Section vs Mass
σ (fb)
M_A (GeV)
tA+t̄A ($\rho_{tc}=1$)
tA+t̄A ($\rho_{tc}=0.5$)
tA+t̄A ($\rho_{tc}=0.1$)
tt̄A ($\rho_{tt}=1$)
tt̄H ($\rho_{tt}=1$)

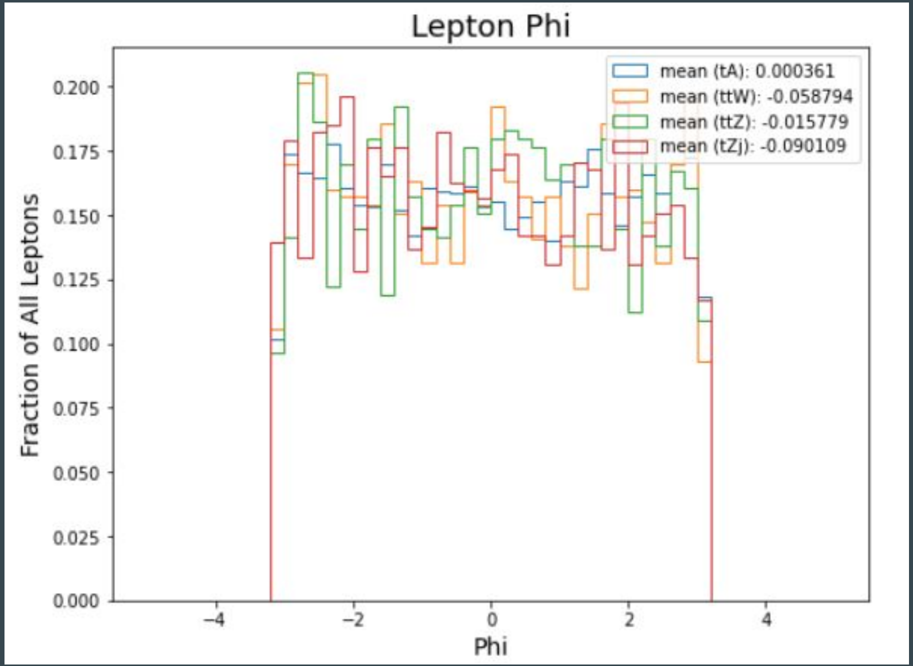
Kinematic Plot Comparison (lepton)



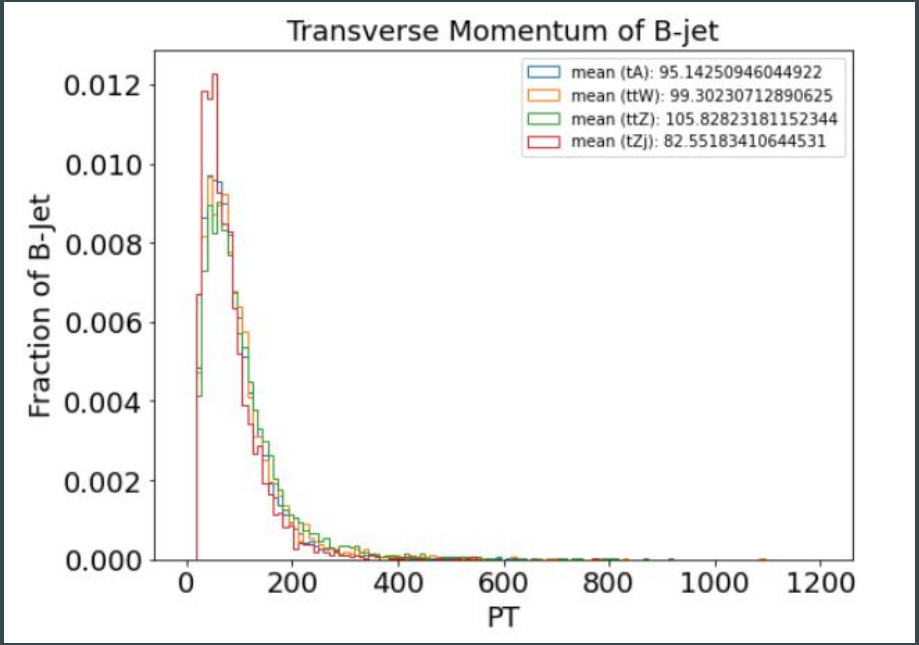


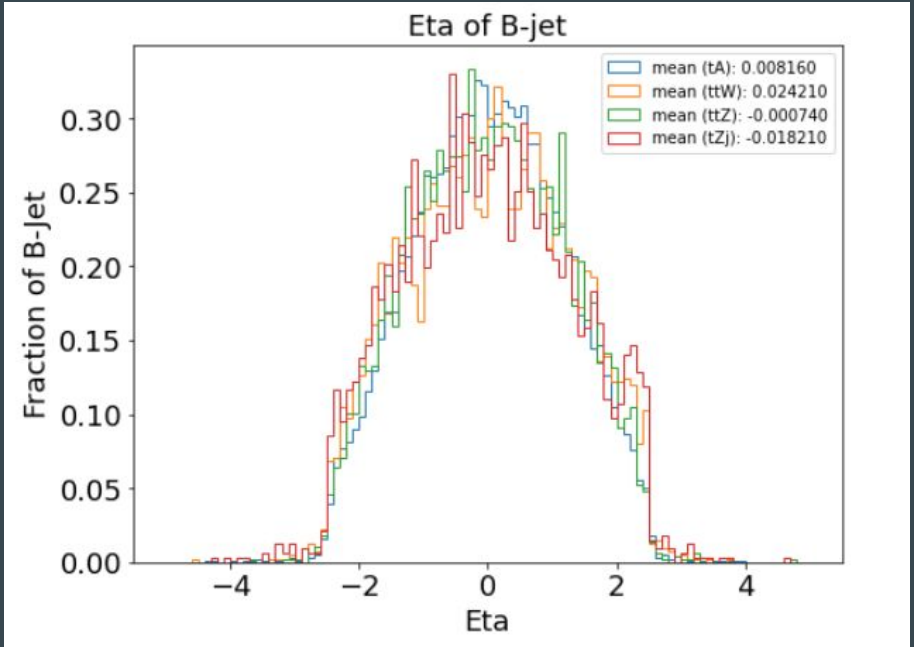
Normalize cross section

Kinematic Plot Comparison (lepton)

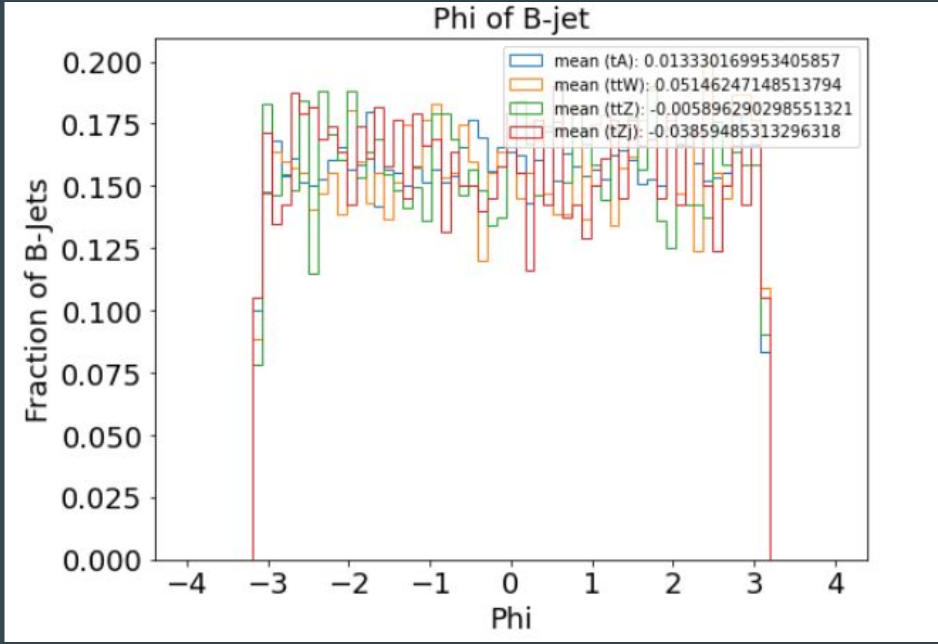


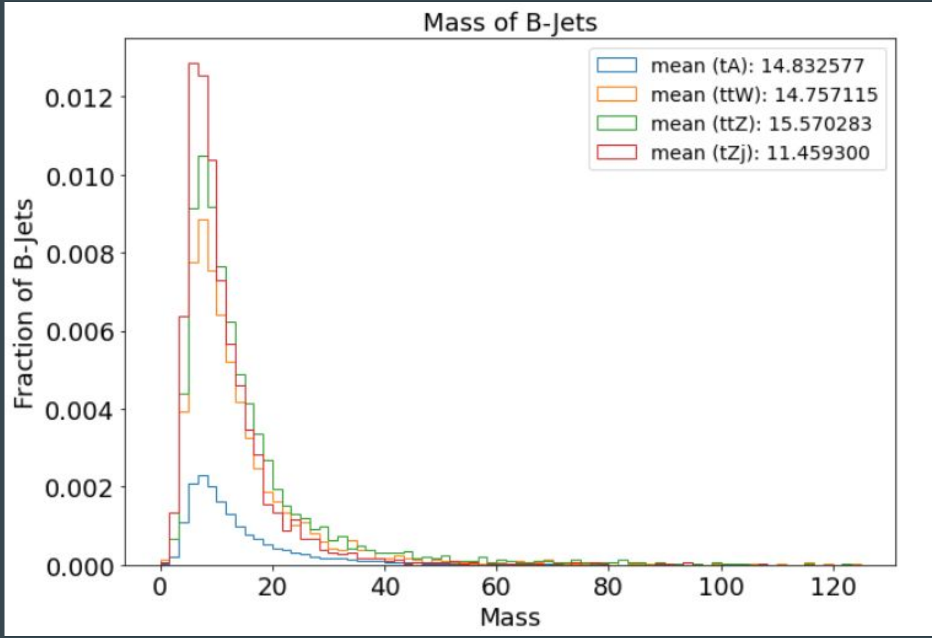
Kinematic Plot Comparison (b-jet)



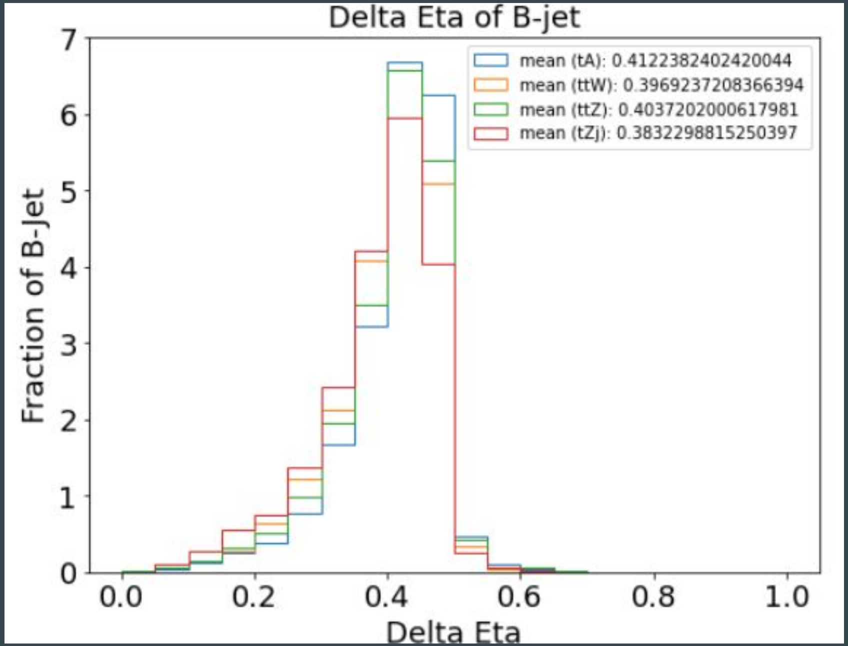


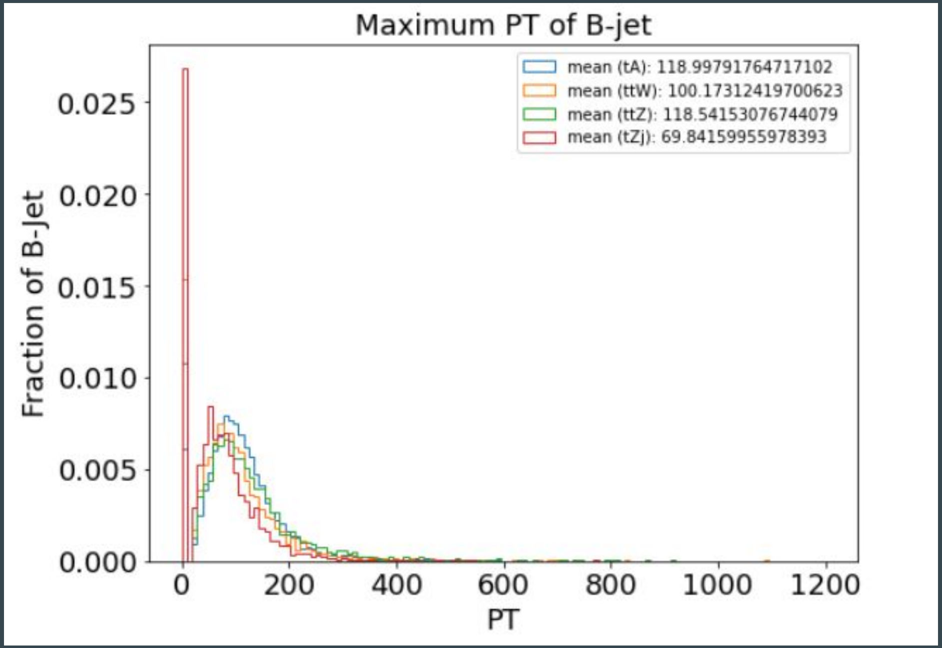
Kinematic Plot Comparison (b-jet)



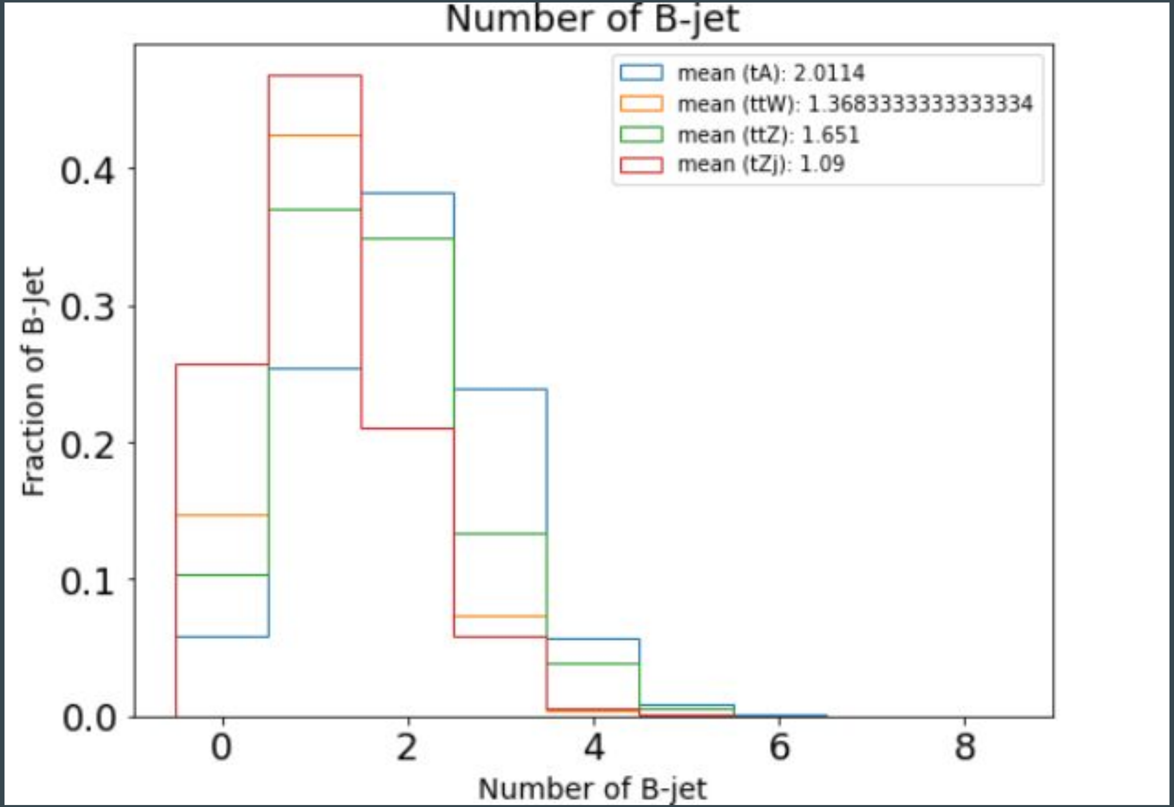


Kinematic Plot Comparison (b-jet)

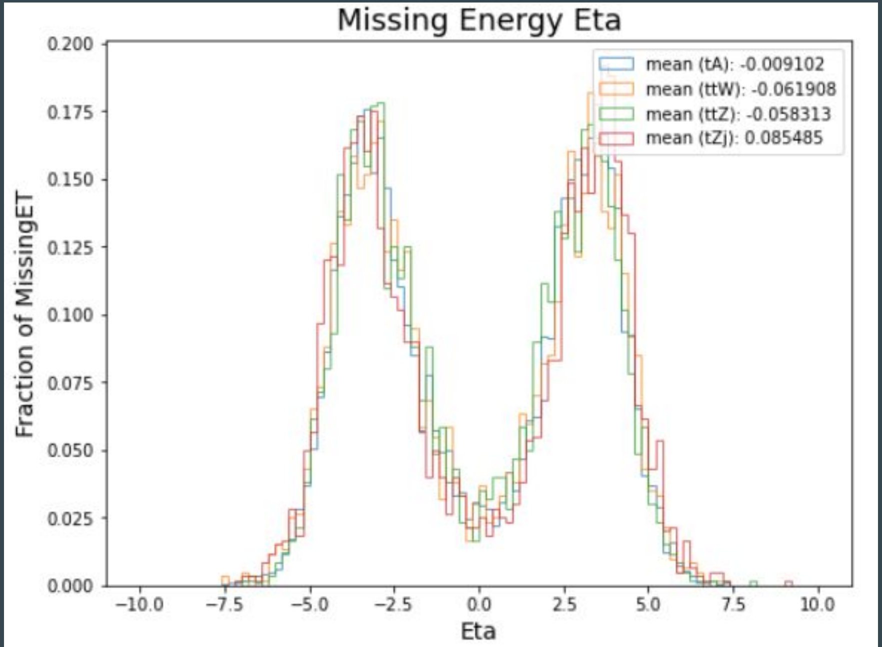


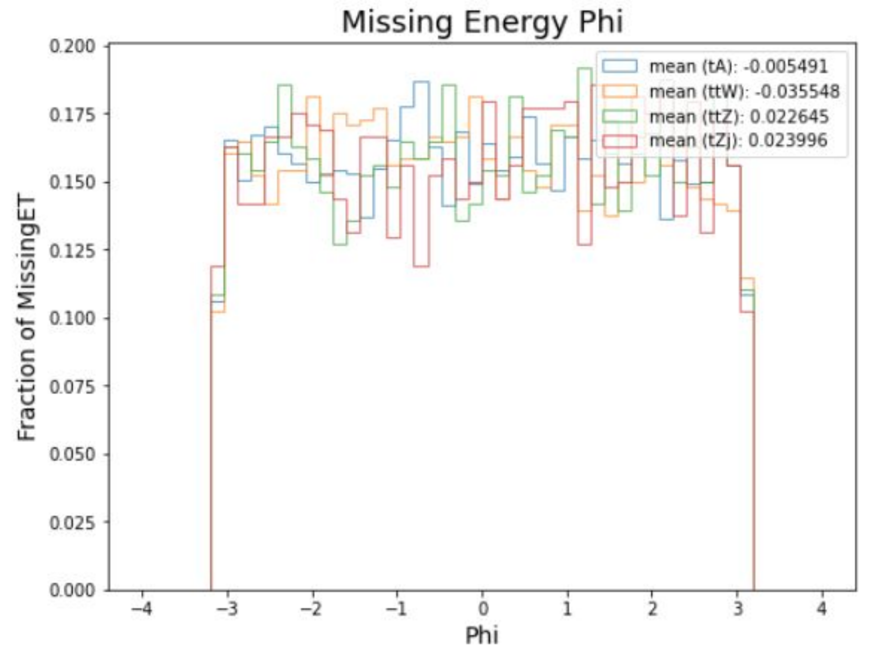


Kinematic Plot Comparison (b-jet)



Kinematic Plot Comparison (Missing Transverse Energy)





Overview

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

Total Cross section

Paper:

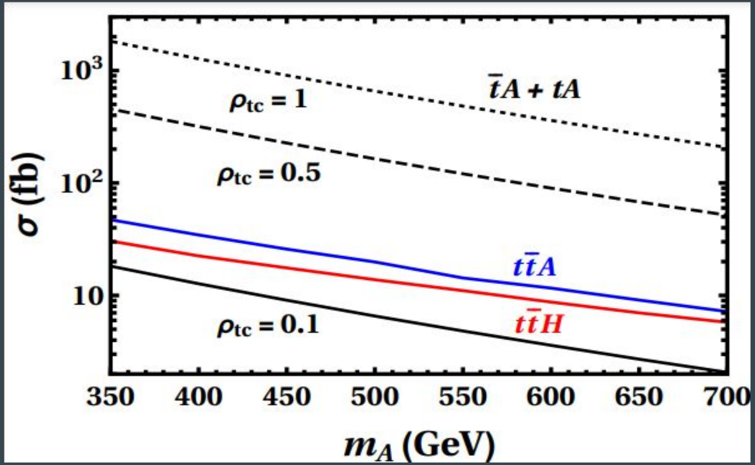
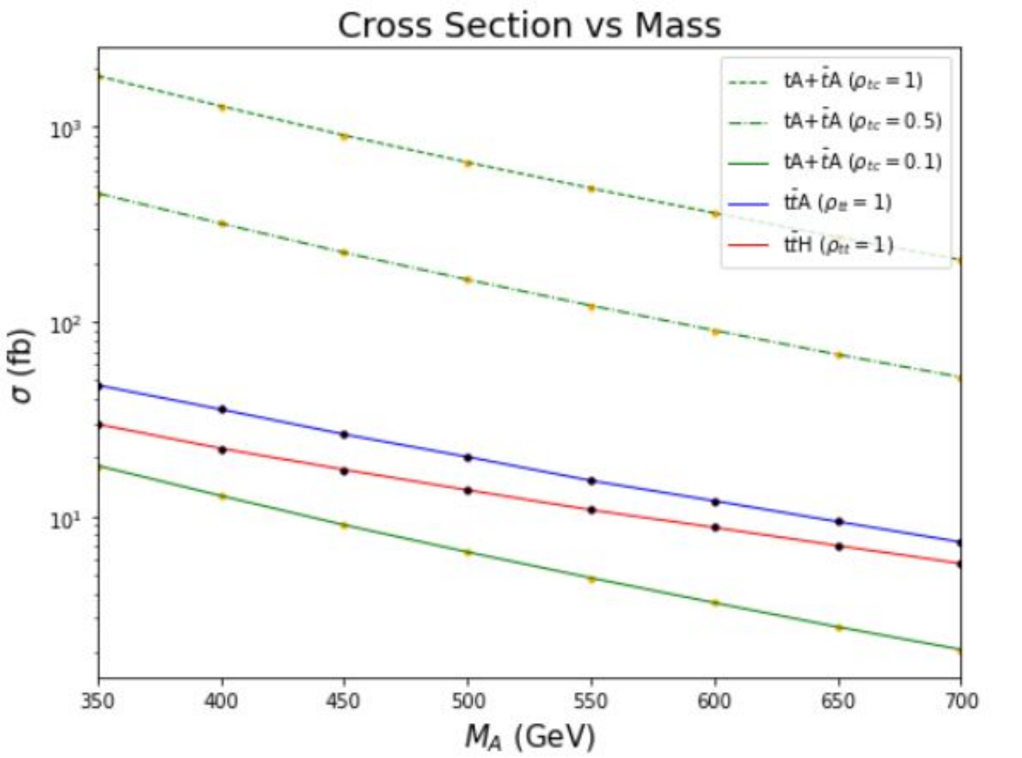
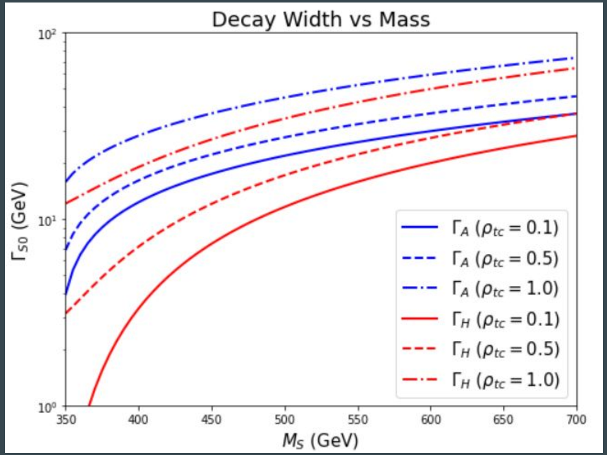


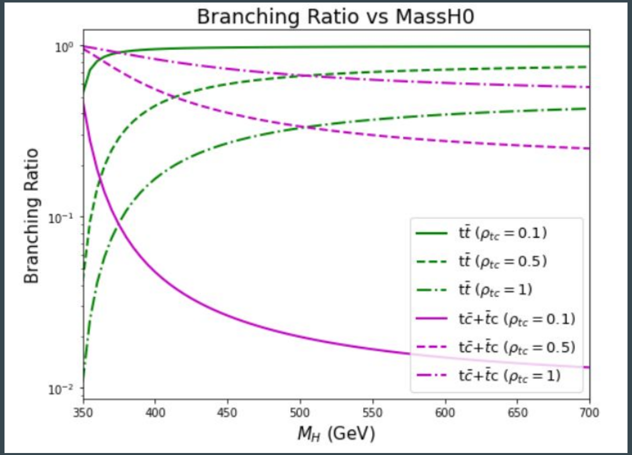
FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \to tS^0$, $\bar{t}S^0$ where $S^0 = H^0$, A^0, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \to t\bar{t}H^0$, $t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

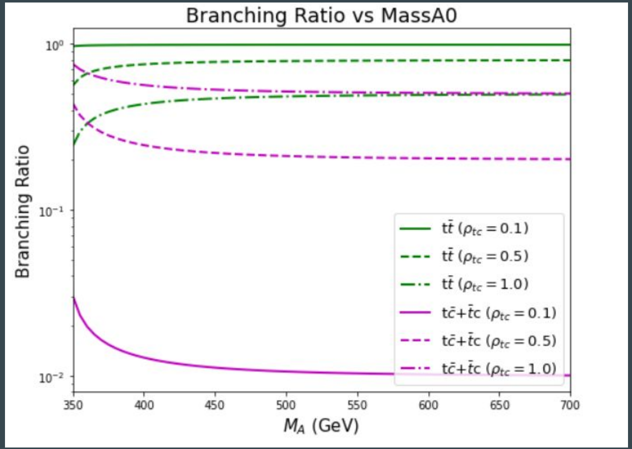
My Result:

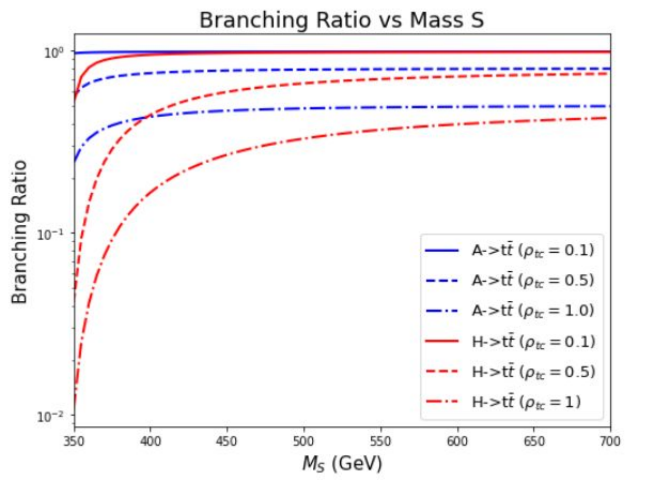


Decay Branching Ratio

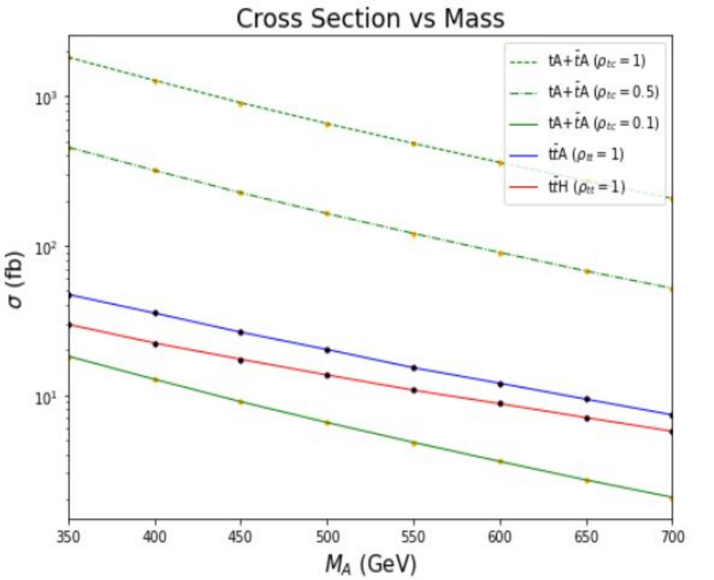


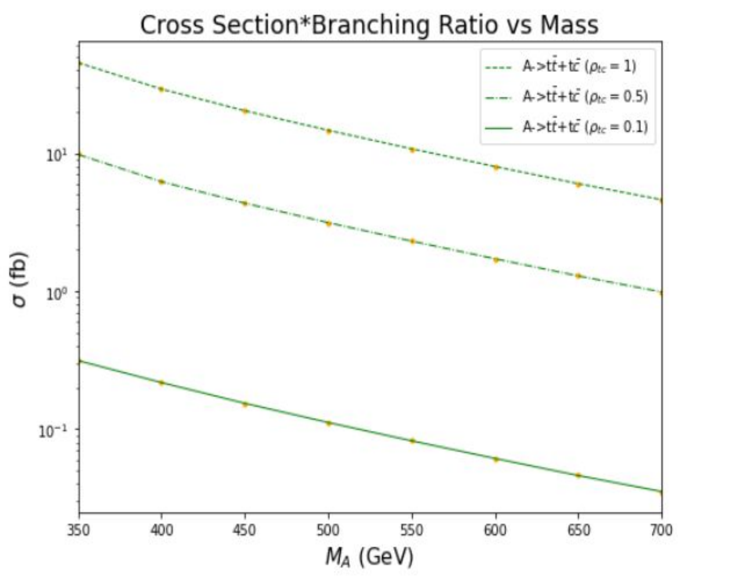


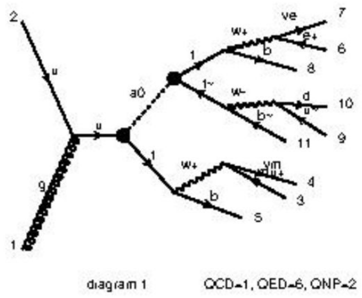


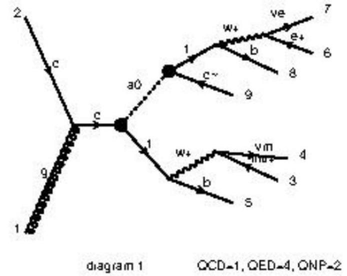


Cross section * branching ratio (SS2l)









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

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

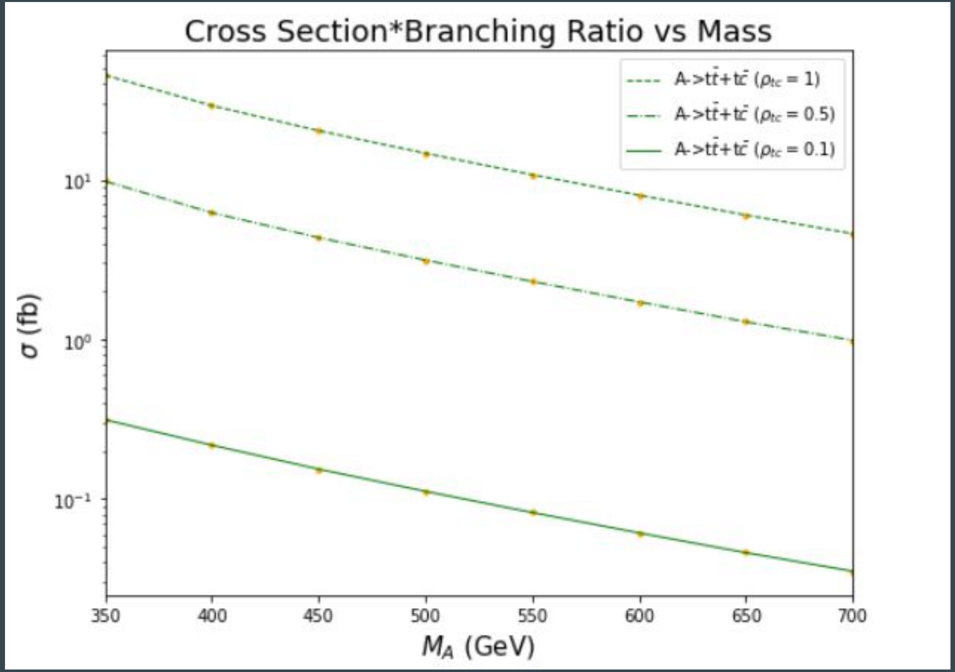
ℬ(ttc~ -> SS2l) = (ℬ(A0->tc~+t~c) * ℬ(t->W b)^3 * ℬ(W-> l vl)^2 * ℬ(W-> q q'~)) * 3

ℬ(t->W b) = 0.91 ± 0.04

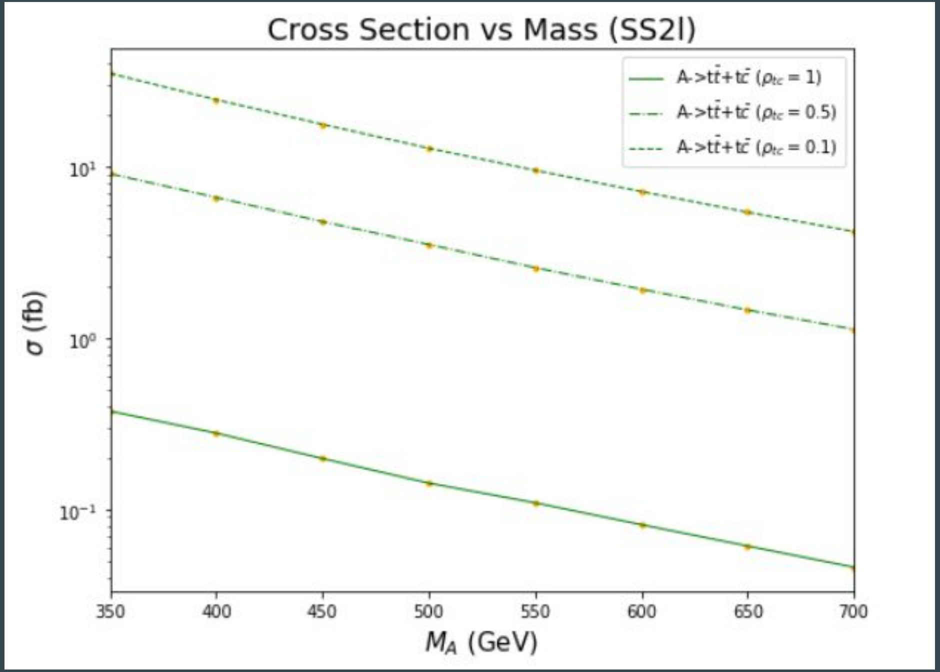
ℬ(W-> l vl) = 0.105, where l = e, u.

ℬ(W-> q q'~) = 0.105

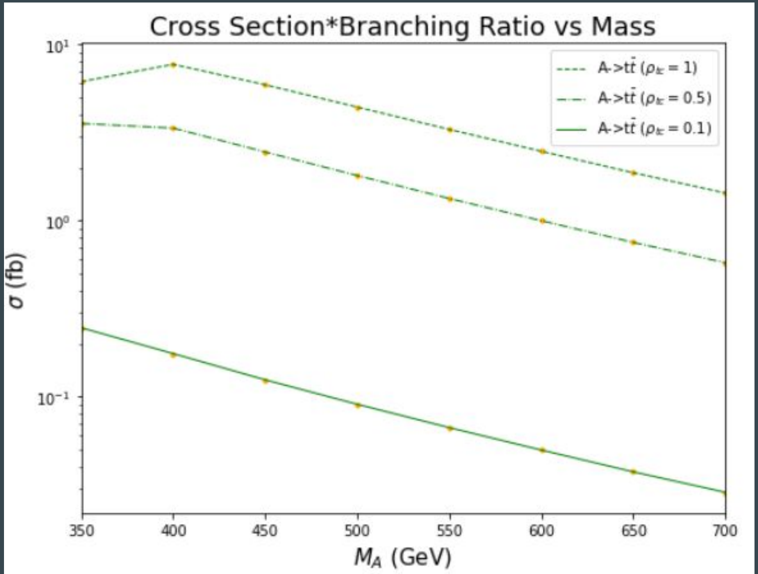
Calculation:



MadGraph Generation:



Cross Section * Branching Ratio (3b3l)



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

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

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

```
[0.12303583792996839,
 0.08776750824523852,
 0.06225878100054702,
 0.04524065687176229,
 0.03334588834976703,
 0.02486807392563575З,
 0.01869414056630254‍8,
 0.014308091005021244]
```

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

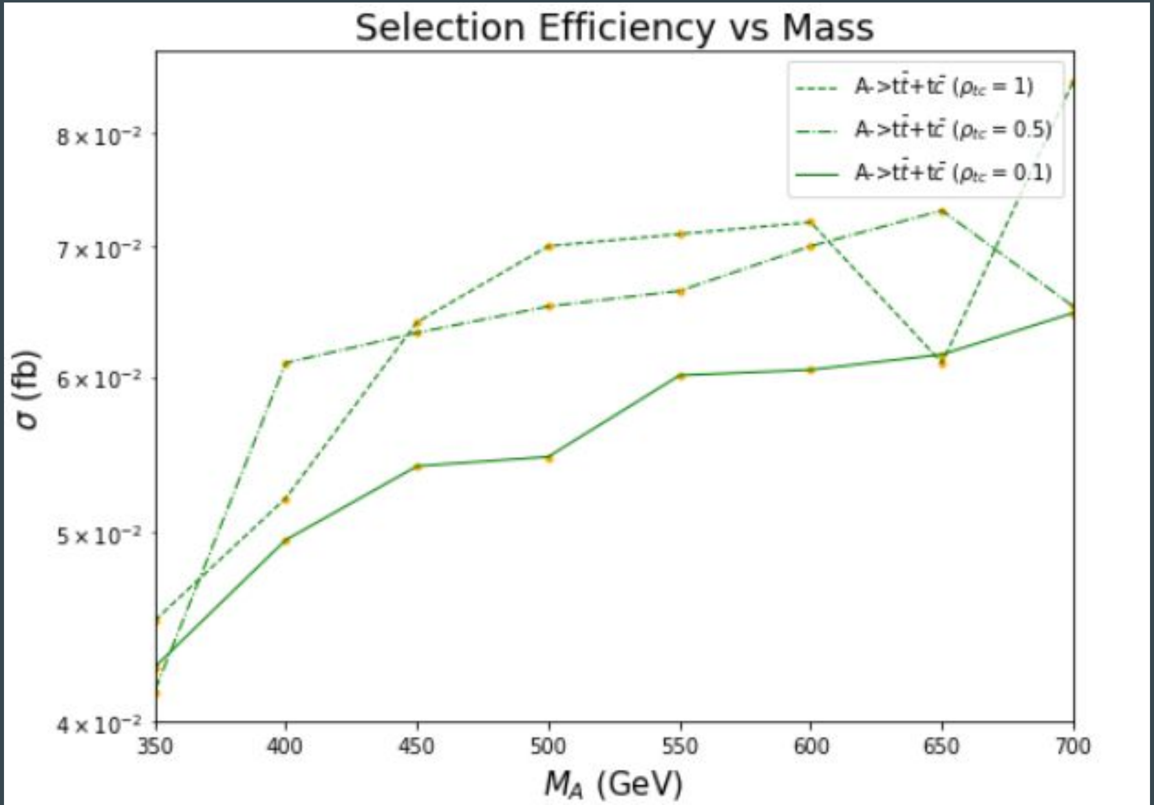
SS2l selection cut

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

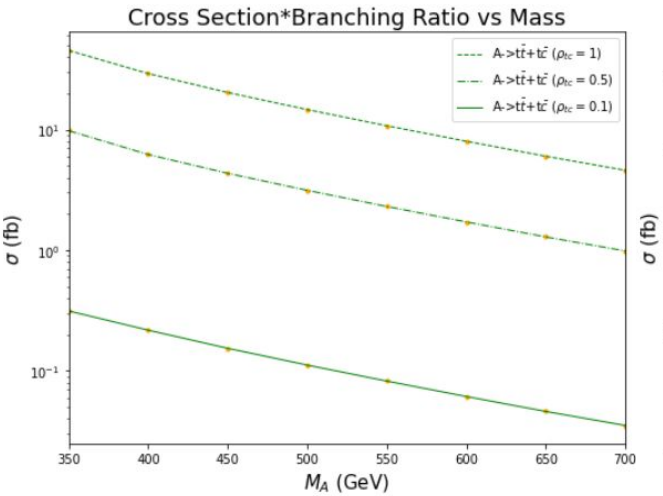
(p_T) of leading and subleading leptons > 25 GeV and 20 GeV, and > 30 GeV and 20 GeV, respectively for the two leading b-jets, while $E_T^{\text{miss}} > 30$ GeV. The pseudo-rapidity of the same-sign leptons and the two leading b-jets should satisfy $|\eta^\ell| < 2.5$ and $|\eta^b| < 2.5$, respectively.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

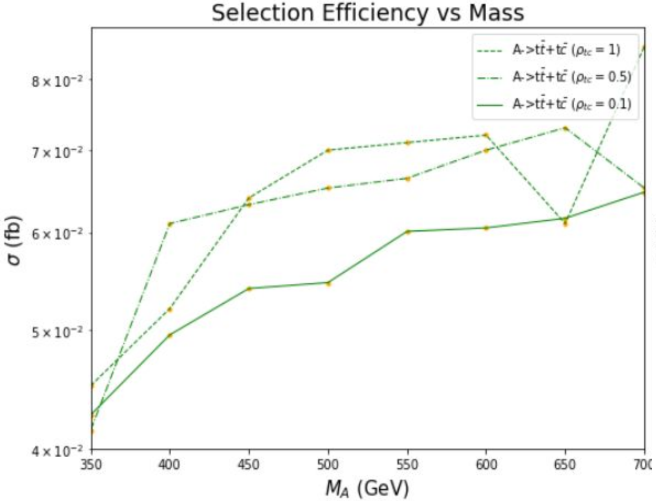
- SS2l signature: ≥ 2 same-charge leptons & ≥ 3 jets with ≥ 2 b-jets
- leading and subleading leptons > 25 GeV and 20 GeV & $|\eta^l| < 2.5$
- leading and subleading b-jets > 30 GeV and 20 GeV & $|\eta^b| < 2.5$
- Separation between a b-jet and a lepton (ΔR_{bl}) > 0.4
- Separation between any two b-jets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

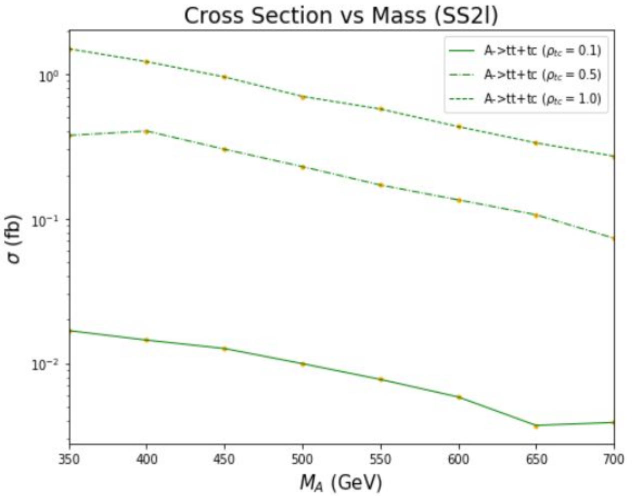
selection efficiency plots



Cross section * branching ratio * efficiency







Tanmoy's Message (SS2l)

- Do NOT include A0/H0 > t t~, (only allow A0/H0 > t c~, t~ c)
  - $\rho_{tt} = 0$, $\rho_{tc} = 0.1, 0.5, 1$
- Figure in "old" paper ONLY has ee or mumu SS2l, NOT include emu.
- Include H0 process when doing Only A0 graph, but put H0 very very heavy to avoid any SS2l contribution
- There are contributions from p p > tA0/H0 and p p > tA0/H0 + j
  - jet inclusive process

Only Allow ee, mumu for SS2l:

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

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

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

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

Jet Inclusive

Add H0 process

```
output SS2l2+Sj
launch SS2l2+Sj

# set shower, detector
shower=Pythia8
detector=Delphes
done
###################################
# set param and run card settings #
###################################
set use_syst False
set rtc 0.1
set rtt 0
set rtu 0
set nevents 2000
set ebeam1 7000.0
set ebeam2 7000.0
set MS0 0
set ws0 0
# set MS0 30000
# set ws0 1790.139988
set MA0 scan1:[350,400,450,500,550,600,650,700]
set wa0 scan1:[6.008661958307974, 7.9302993987129, 9.791391917280869, 11.598189127055344, 13.35935405039862, 15.082906020156978, 16.77555149183397, 18.442710857402037]
done
```

set rho_tt = 0

set Mass of H0 very very heavy

Testing

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

Before Selection Cut:

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

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

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

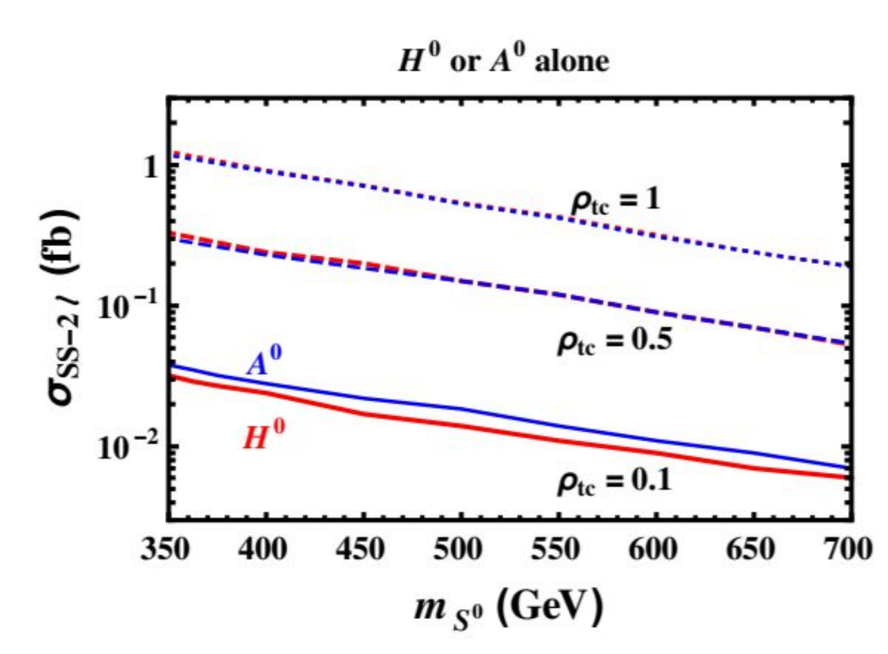
18.807017543859647

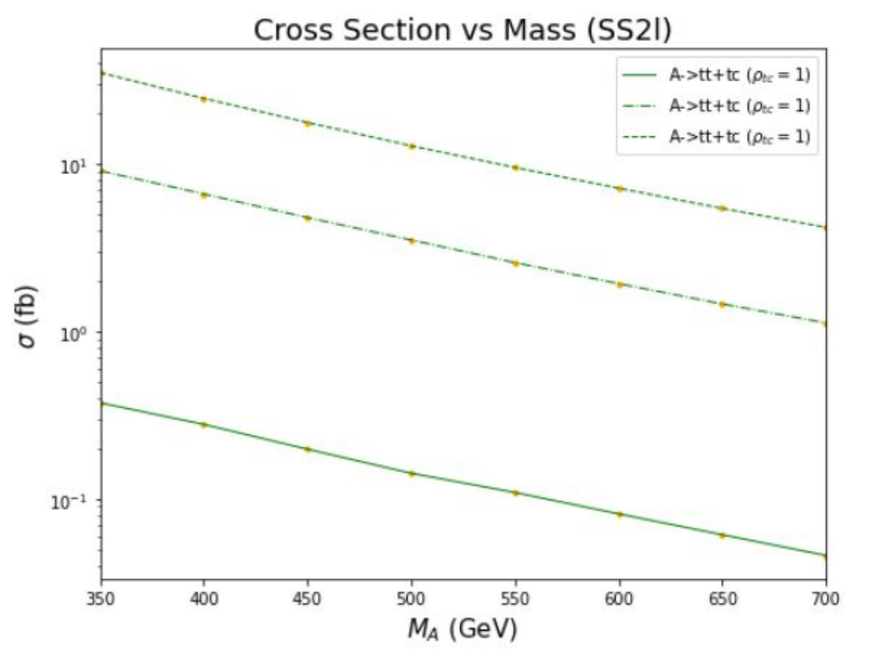
26.4000000000

Task for this week

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

SS2l Cross Section vs Mass (before selection cut)





Tanmoy Modak
to me

8:21 AM (3 hours ago)

Hi David,

First you do not include A0/H0 > t t~ decays. Of course it would contribute to SS-2l if two SS top decays semileptonically but for SS-2l we turned off rho_tt. So any A/H > ttbar decay is not possible. The figure in https://arxiv.org/pdf/1710.07260.pdf only has ee or mumu same-sign dileptons and not emu type of SS-2l contribution. This is simply what we missed in that paper and the cross sections would be larger than the quoted. But your madgraph processes are not complete. Also if you generate the SS-2l cross section only from A0 you should put H0 very very heavy to avoid any SS-2l contributions from the latter.

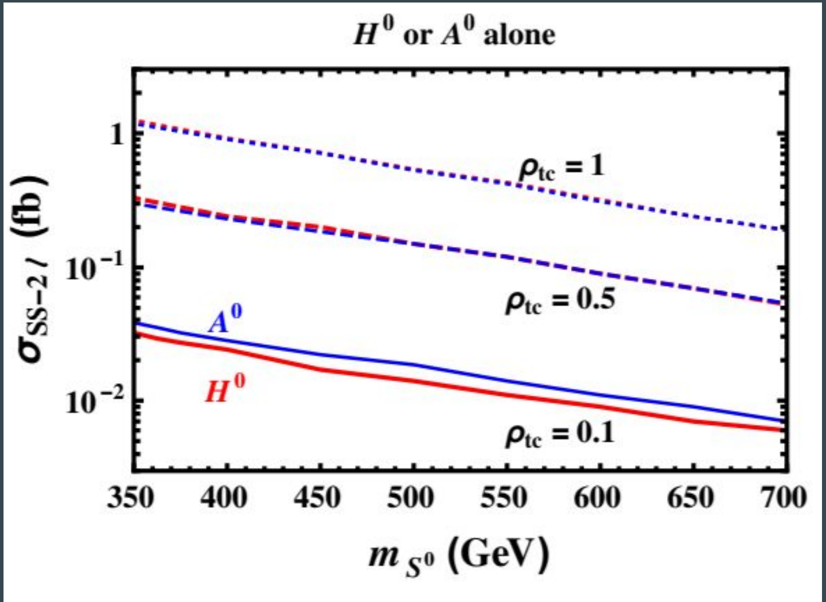
For more recent analysis details I suggest you follow 2012.05735 (sec 4.1.2) and cut based analysis therein. In fact there is a table (table 1) in 2012.05735 for signal and background cross sections with the mA = mH+50 GeV mass scheme for SS-2l. But you have to be careful here. There are contributions from pp > t t (t channel A0 and H0 exchange) and pp > t A0 j/t H0 j followed by A0/H0 > t cbar decays; all of them would contribute to the SS-2l final state in the inclusive signature. Essentially you have to merge and match pp > tt, pp > ttj , pp > ttjj (with charge conjugate processes implied) together and consider SS-2l decays of the same-sign top quarks. You can check these Feynman diagrams in madgraph. And check whether you can generate/reproduce the numbers in (table 1) in 2012.05735.

There is a twiki link for this process and if you are working on the topic please cite the main papers (1710.07260,1808.00333, 2008.02573) together.
https://twiki.org/cgi-bin/view/Sandbox/FlavorChangingNeutralHiggs

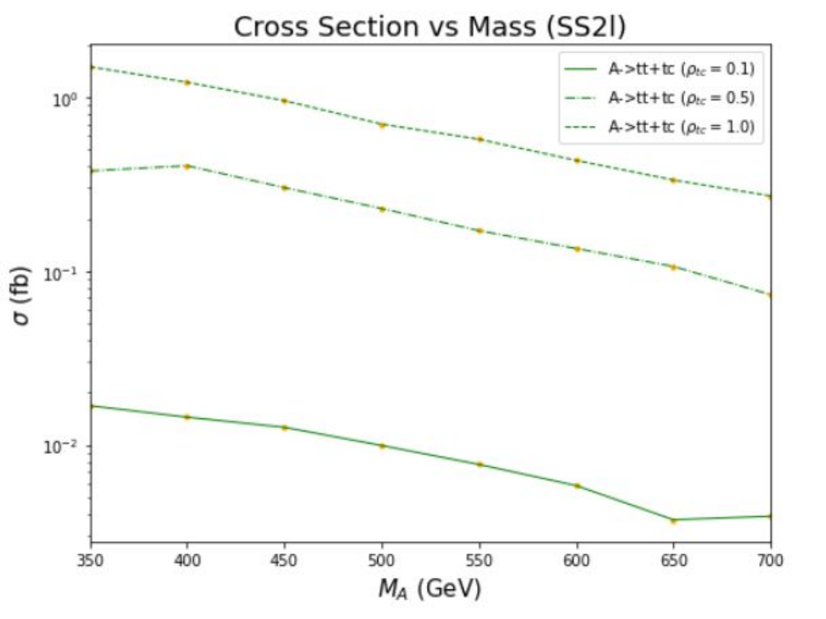
Best,
Tanmoy

Cross Section vs Mass (after selection cut)

Paper:



My result:



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

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

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

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

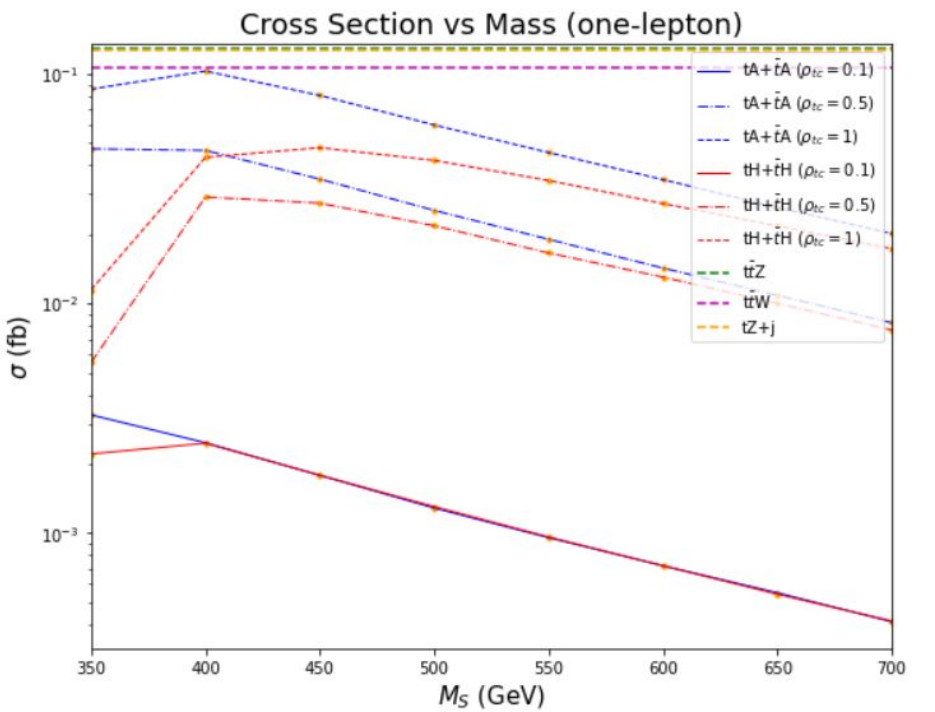
	Selection Cut (SS2l) $\rho_{tc} = 0.5$	$M_A = 350GeV$	$M_A = 400GeV$	$M_A = 450GeV$	$M_A = 500GeV$	$M_A = 550GeV$	$M_A = 600GeV$	$M_A = 650GeV$	$M_A = 700GeV$
0	Input Event Size	5000	5000	5000	5000	5000	5000	5000	5000
1	SS2l Signature	353	459	453	466	482	474	482	458
2	leading jets > 30 GeV & subleading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

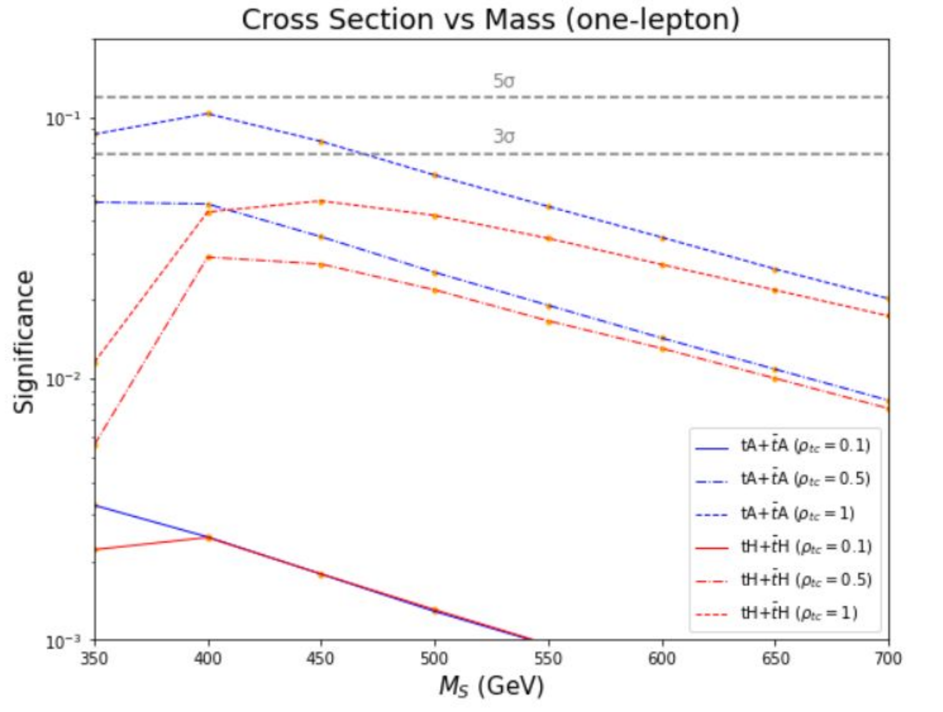
	Selection Cut (SS2l) $\rho_{tc} = 1.0$	$M_A = 350GeV$	$M_A = 400GeV$	$M_A = 450GeV$	$M_A = 500GeV$	$M_A = 550GeV$	$M_A = 600GeV$	$M_A = 650GeV$	$M_A = 700GeV$
0	Input Event Size	10000	10000	10000	10000	10000	10000	10000	10000
1	SS2l Signature	751	775	835	794	865	824	870	908
2	leading jets > 30 GeV &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

1 lepton channel selection cut

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

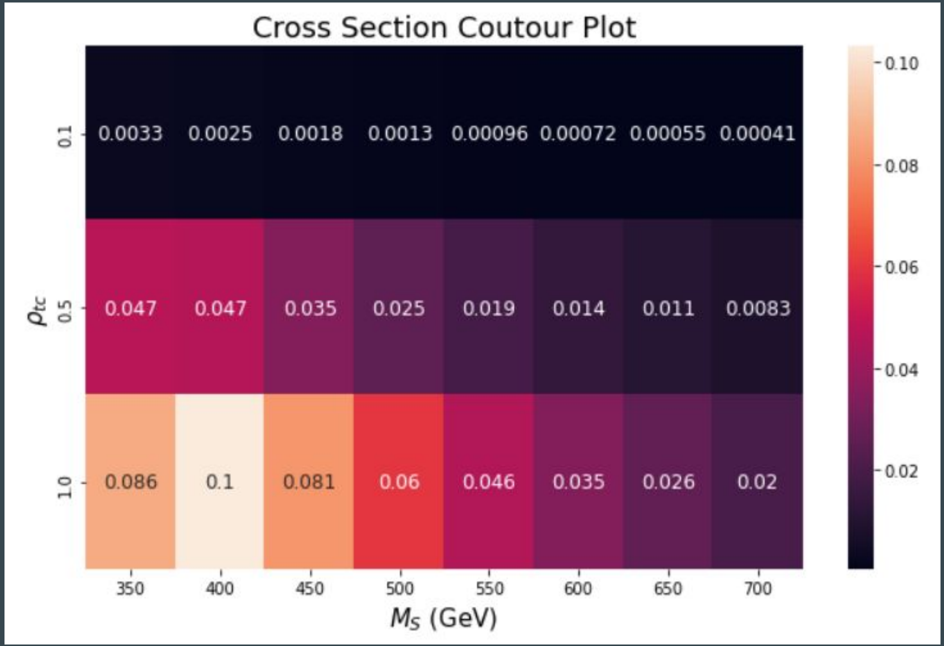
Cross Section

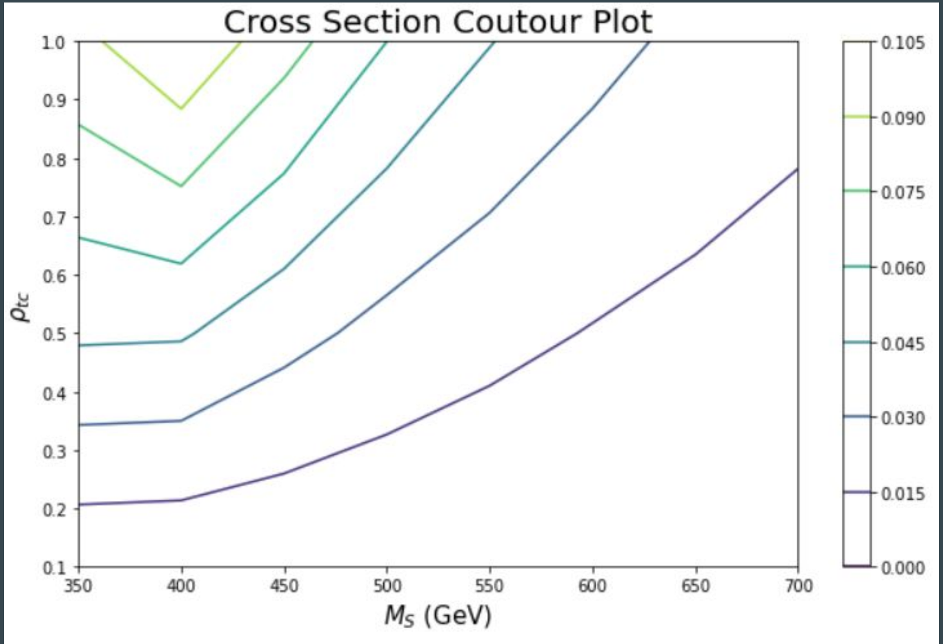




Signal Yield, Cross Section -> Number of Events

Cross Section

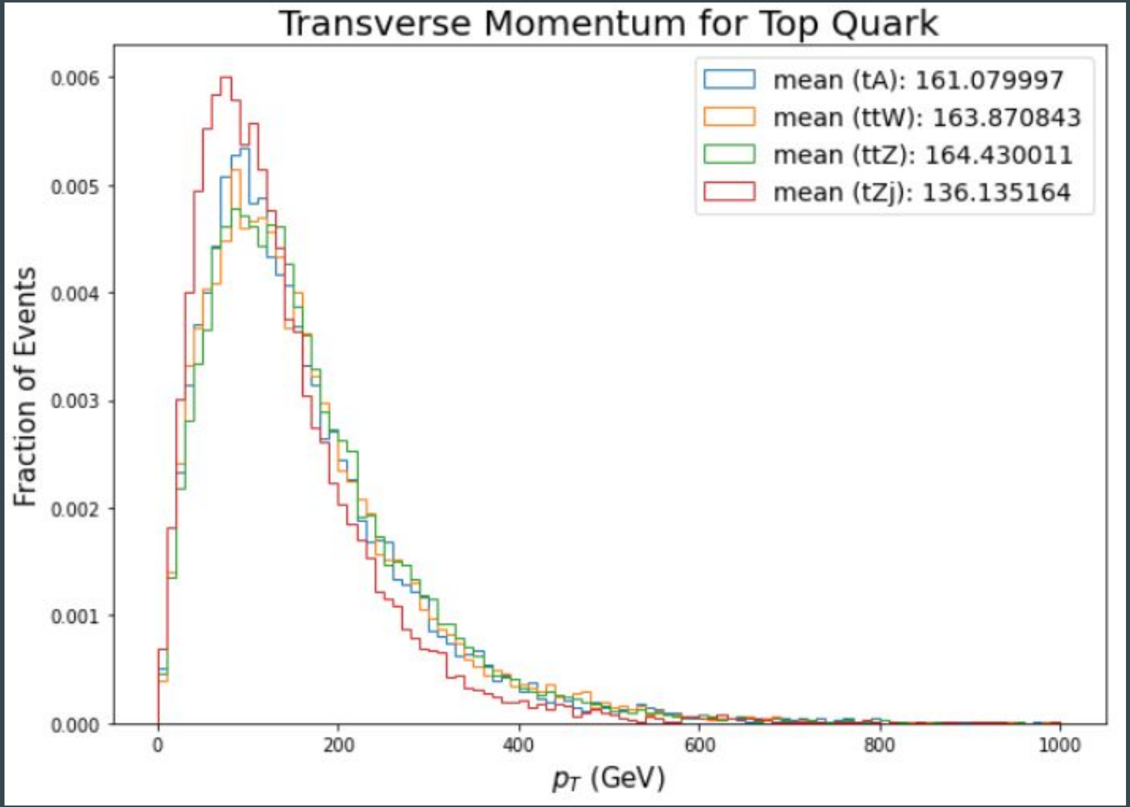




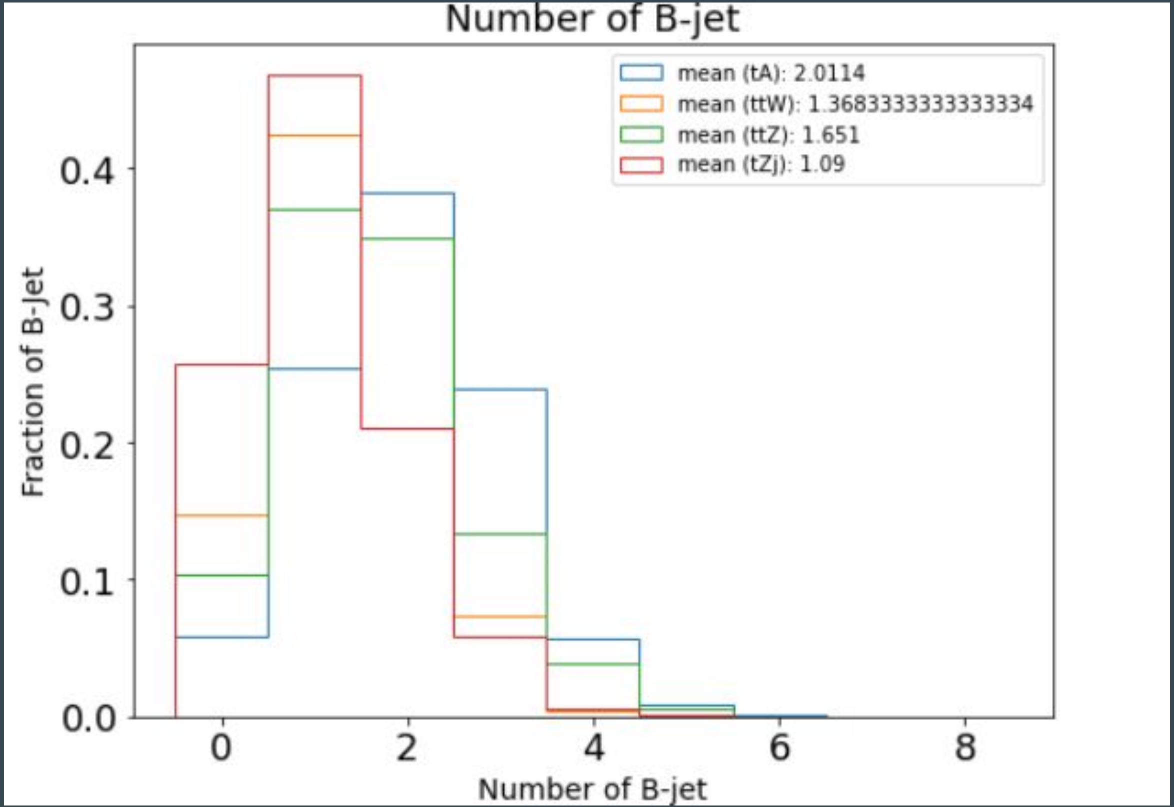
To-do

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

Boosted Top Quark?



Number of b-jets



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

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

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

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

  set BitNumber 0

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

  # based on arXiv:1211.4462

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

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

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

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

FastJetFinder - Small-R jets

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

FatJetFinder - Large-R jets

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

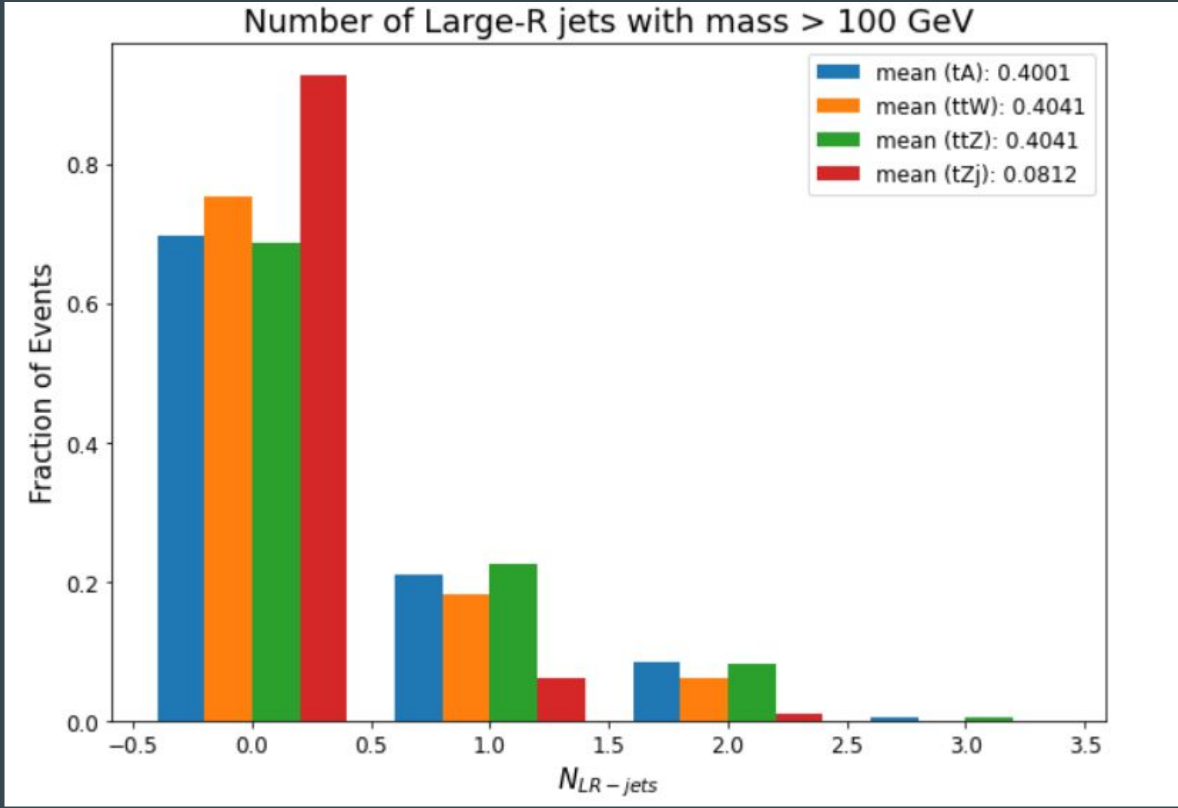
FastJetFinder - Small-R jets

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

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

  set OutputArray jets

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

  set JetPTMin 25.0
}
```

FatJetFinder - Large-R jets

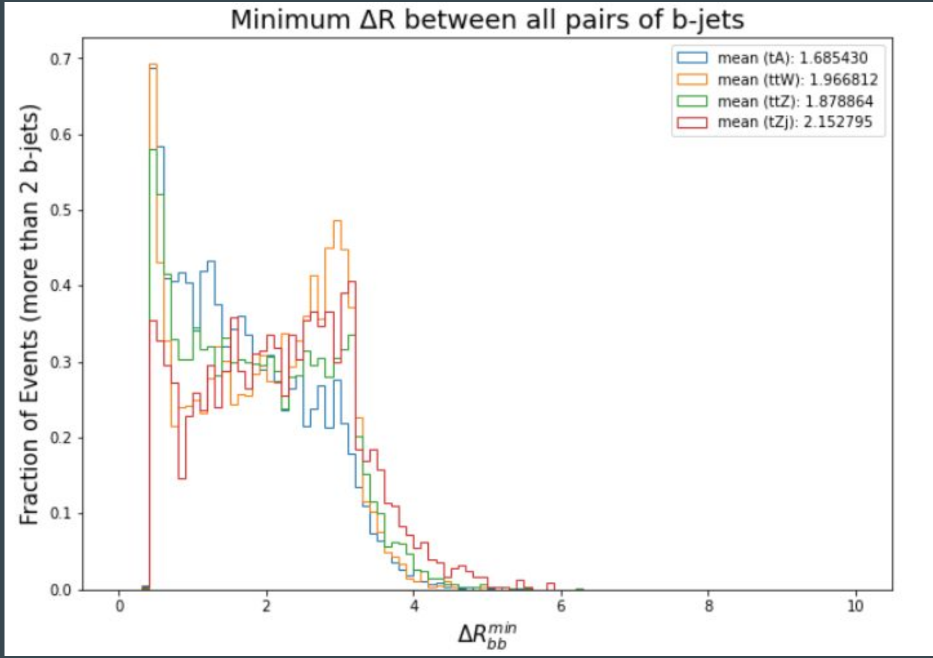
```
##################
# Fat Jet finder
##################

module FastJetFinder FatJetFinder {
  set InputArray EFlowMerger/eflow

  set OutputArray jets

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

  set ComputeNsubjettiness 1
  set Beta 1.0
  set AxisMode 4

  set ComputeTrimming 1
  set RTrim 0.2
  set PtFracTrim 0.05

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

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

  set JetPTMin 200.0
}
```

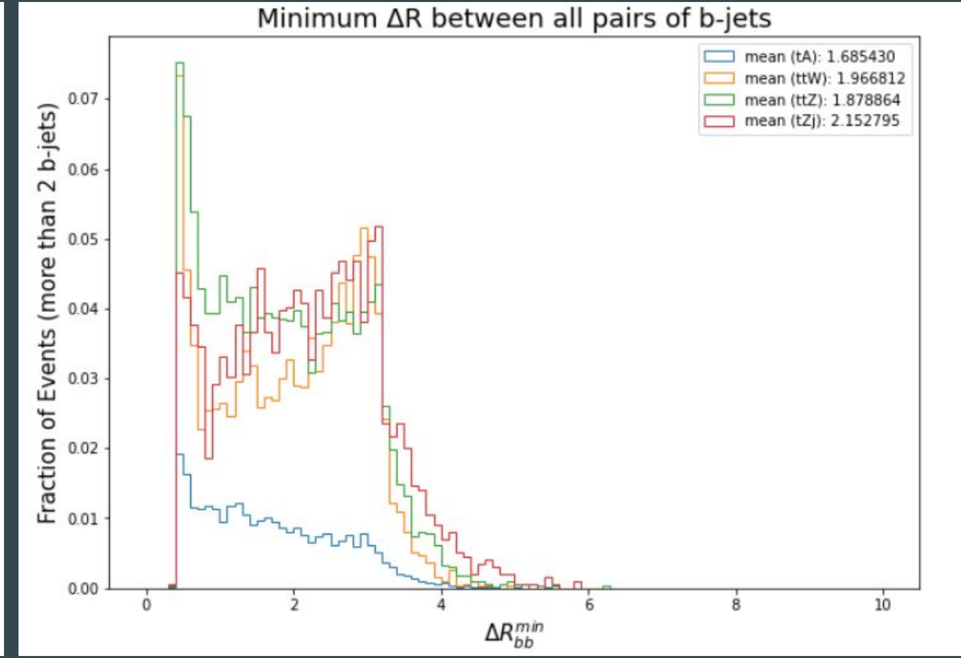
$N_{\text{LR-jets}}$ Number of large-R jets with a mass above 100 GeV



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

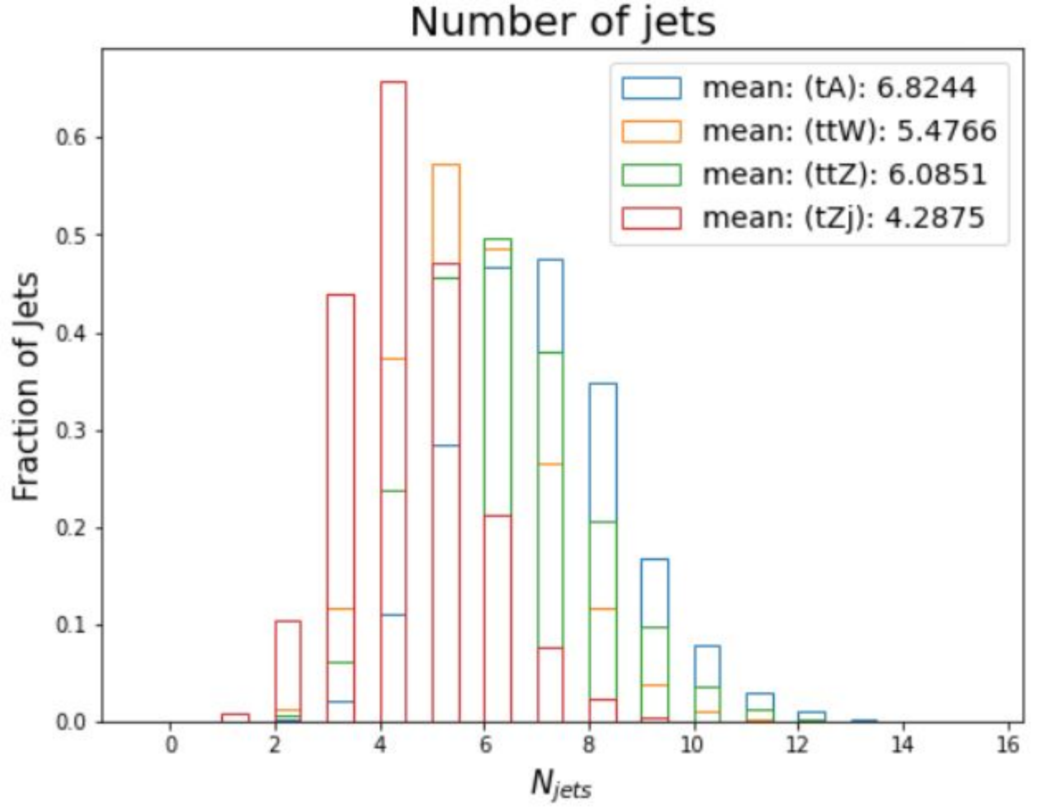
Normalized to cross section:



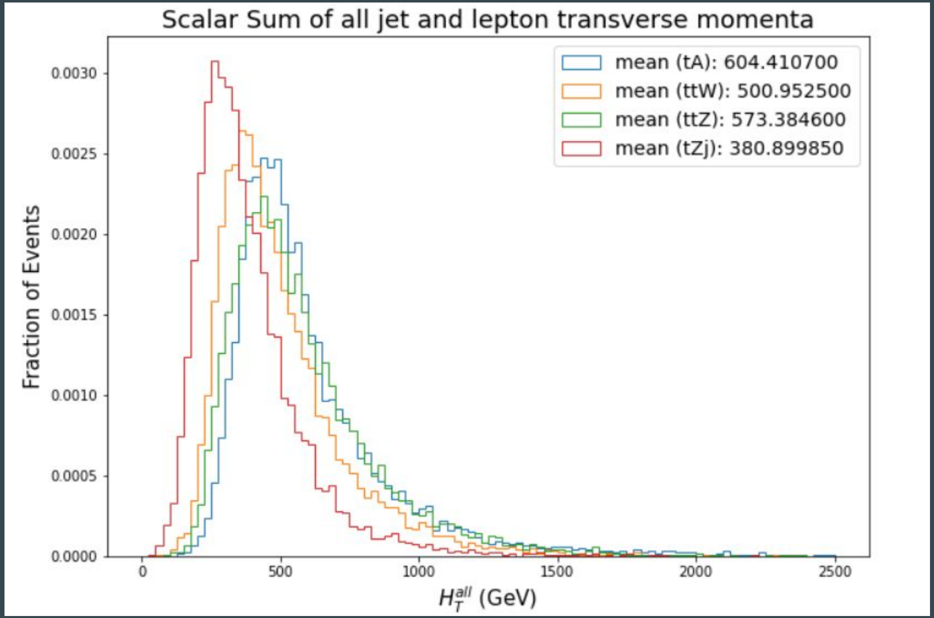


$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}.$$

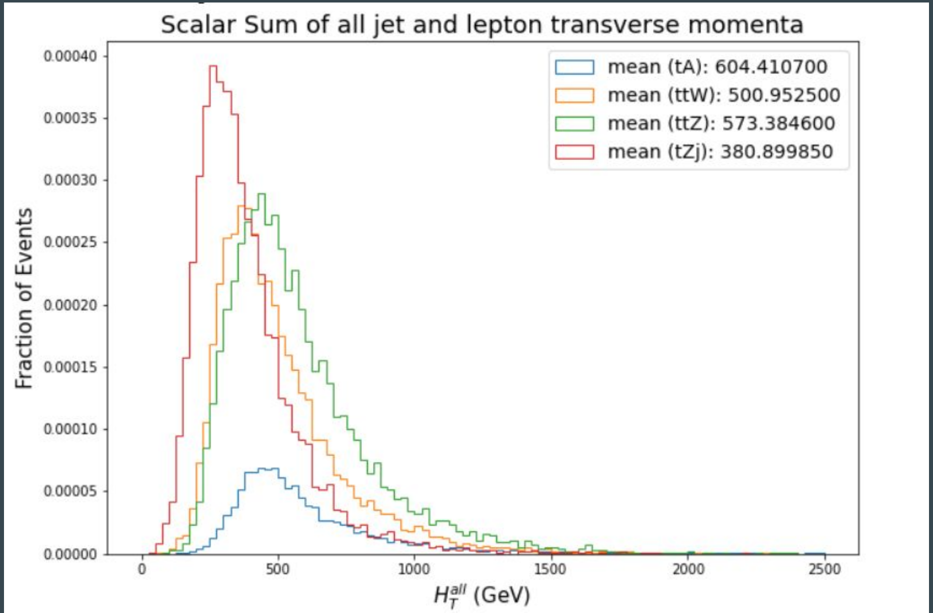
N_{jets} Number of jets



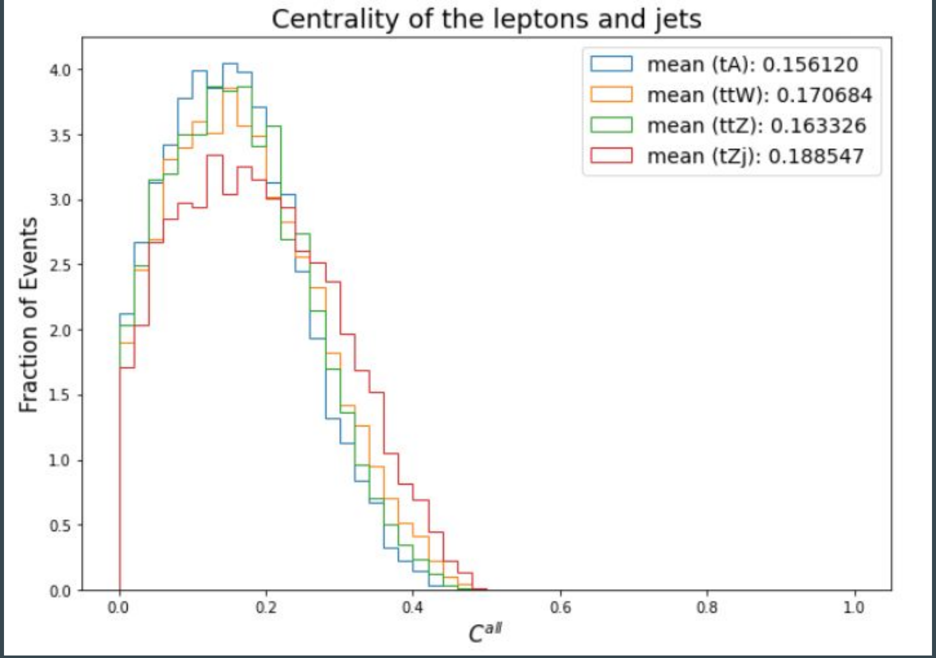
H_T^{all} Scalar sum of all jet and lepton transverse momenta



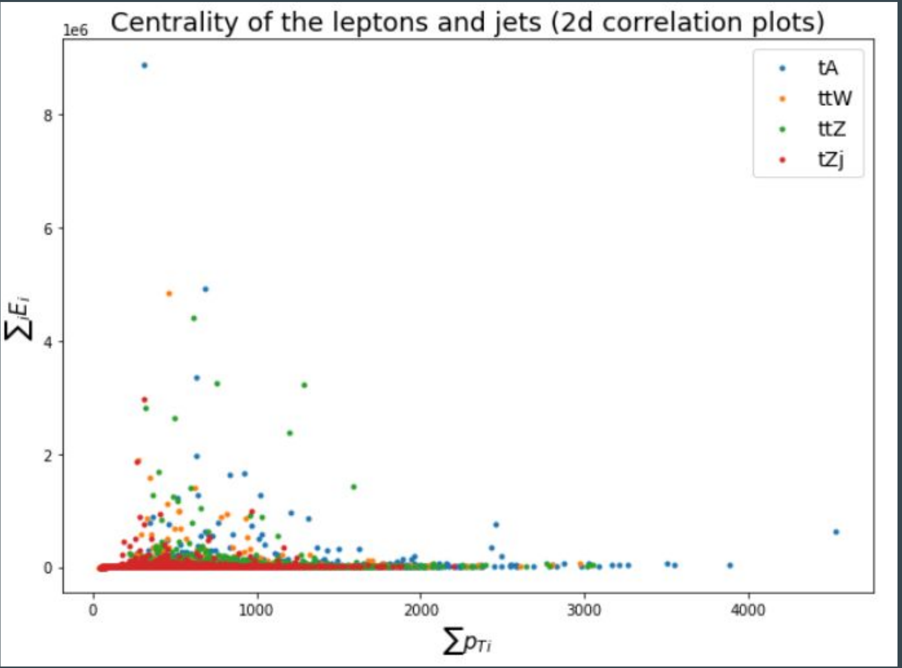
Normalized to cross section:



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



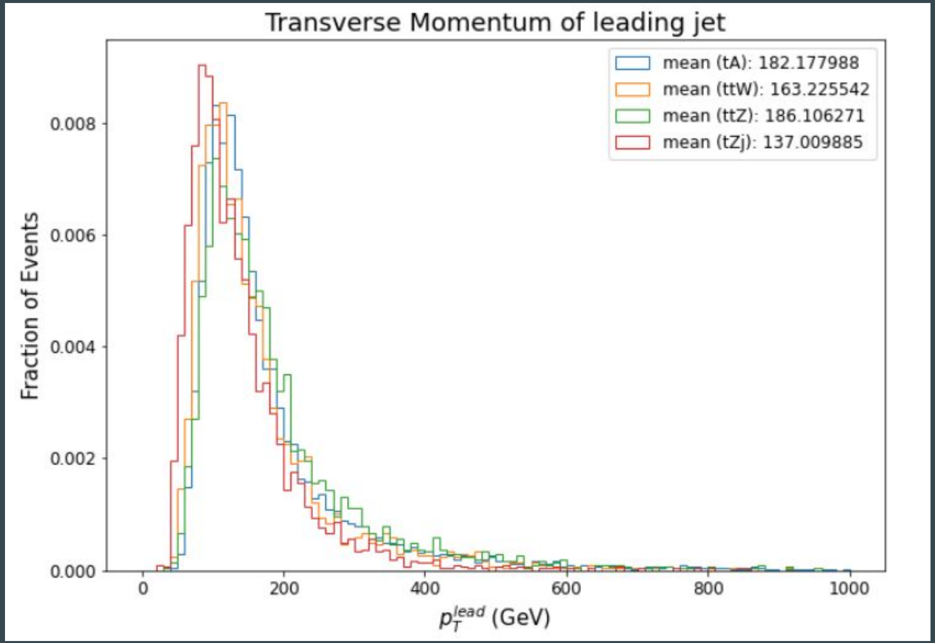
2d Scatter Plot:

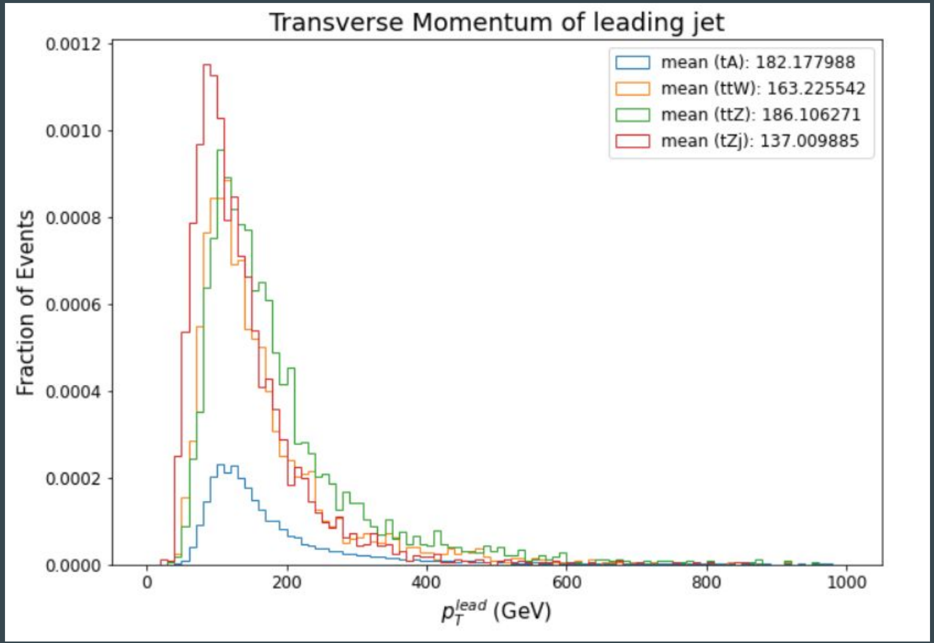


2d correlation plots

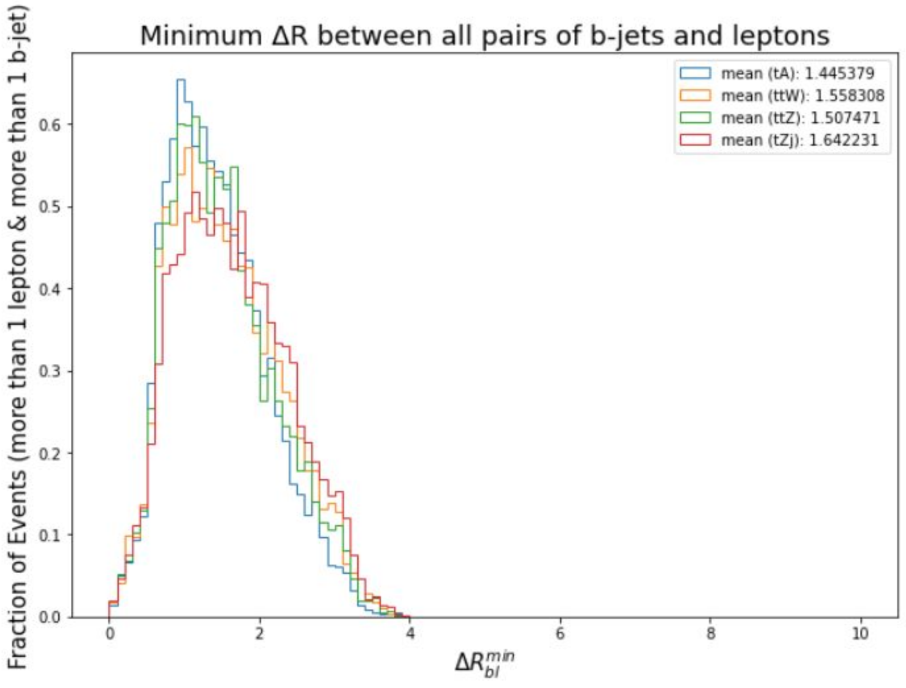
p_T^{lead} Transverse momentum of the leading jet

Normalized to cross section:

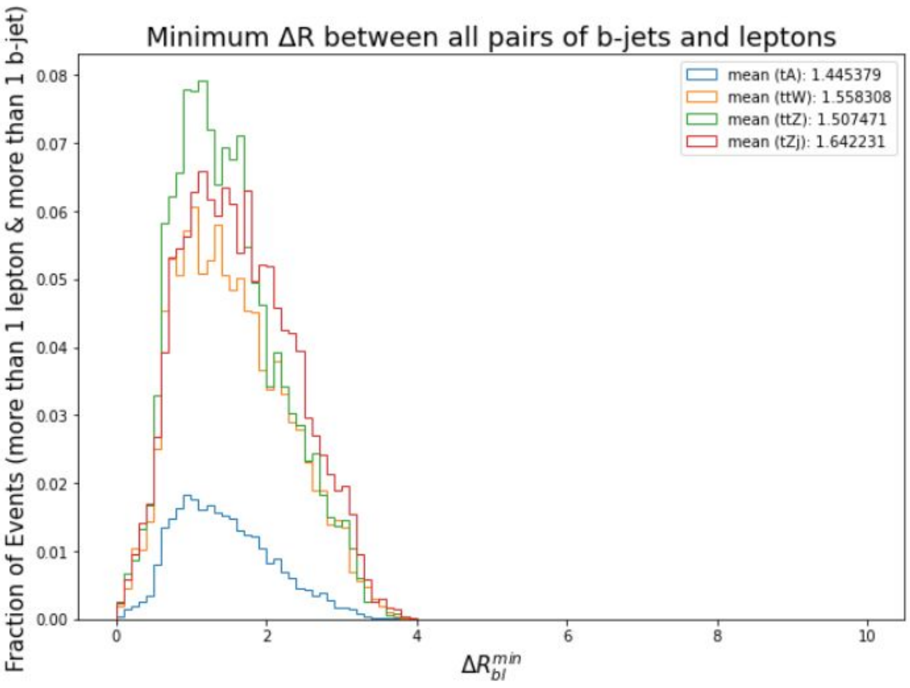




$\Delta R_{b\ell}^{\mathrm{min}}$ Minimum ΔR between all pairs of b-tagged jets and leptons

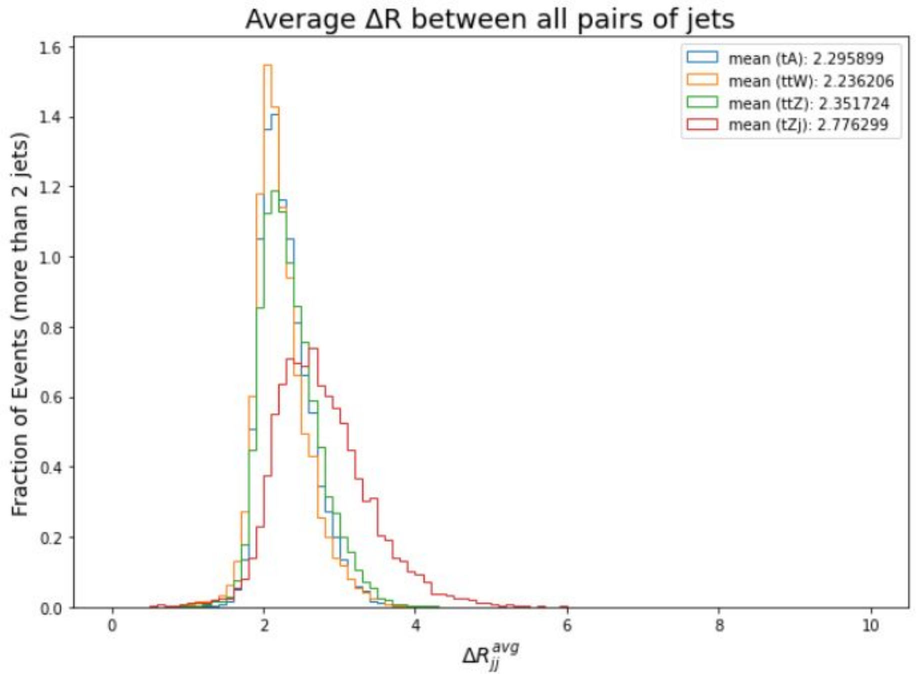


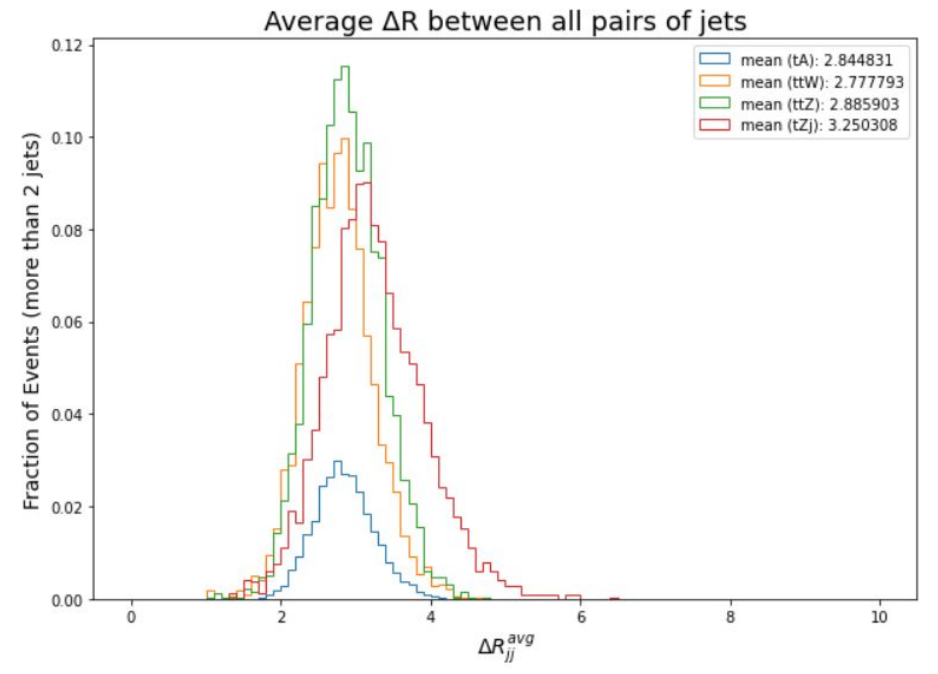
Normalized to cross section:



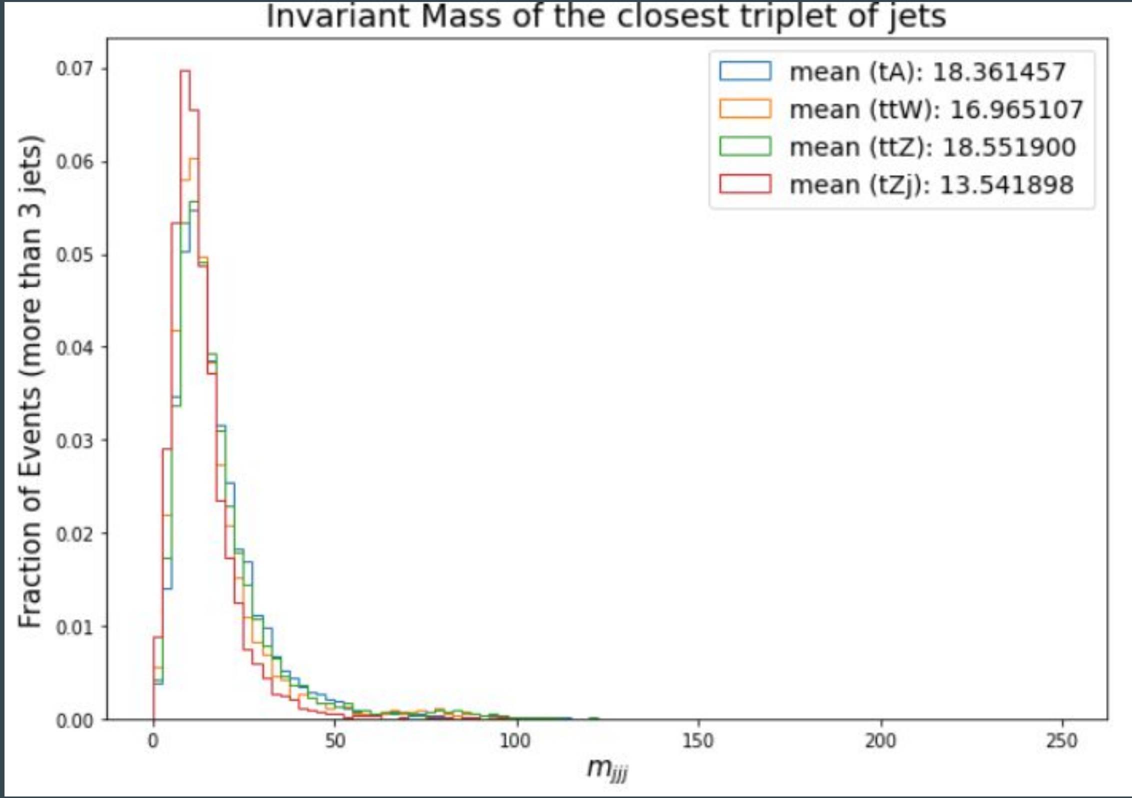
$\Delta R_{jj}^{\text{avg}}$ Average ΔR between all pairs of jets

Normalized to cross section:



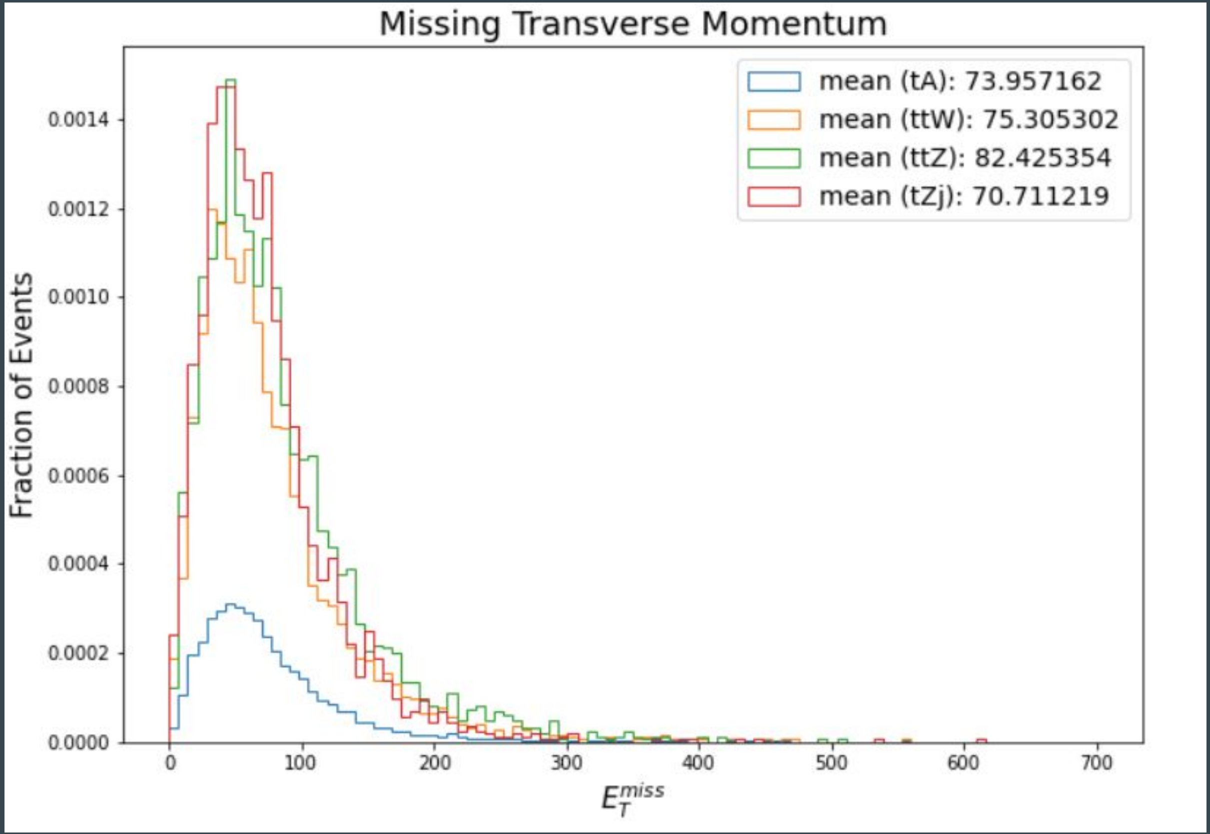


m_{jjj} Invariant mass of the closest triplet of jets

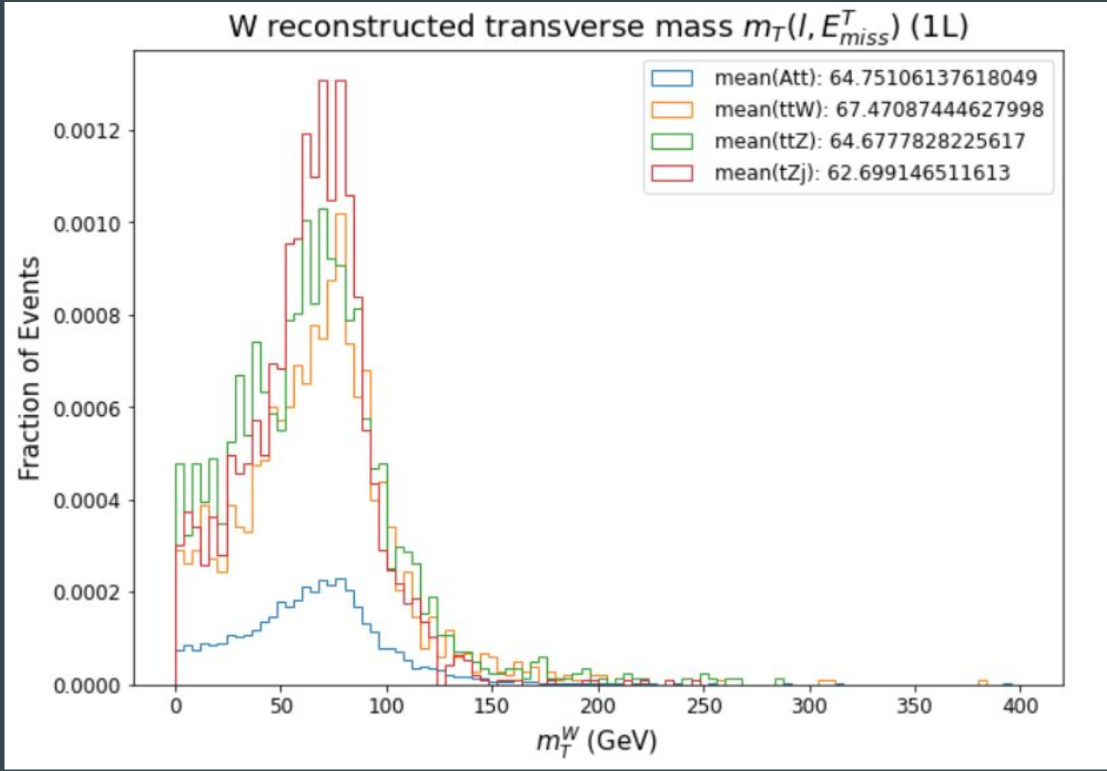


[3] The ΔR of a triplet of jets is defined as $\Delta R_{ijk} = \sqrt{\Delta R_{ij}^2 + \Delta R_{ik}^2 + \Delta R_{jk}^2}$, where i, j, k are the indices of the three jets.

E_T^{miss} Missing transverse momentum



m_T^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 $E_\mathrm{T}^\mathrm{miss}$.

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

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

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

Information for rest of plots

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

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

Likelihood

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

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

Poisson Probability

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

Likelihood Function

x = counts
a = mean

$$L(H) = P(x \mid H)$$

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

Bayes Theorem

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

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

Parameter of the model

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

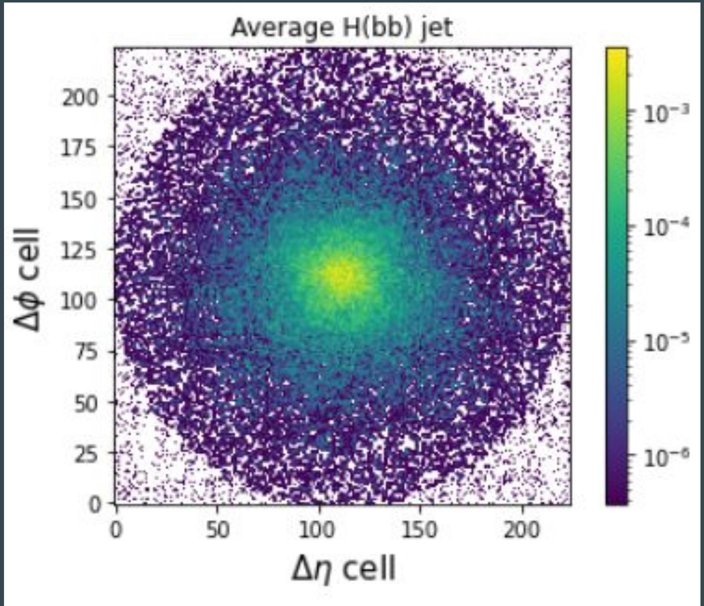
```
import model gen2HDM_UFO
define p = p b b~
define j = p
generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
add process p p > t A0 j QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~)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

output Att_400

launch Att_400

shower=PYTHIA8
detector=delphes

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

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

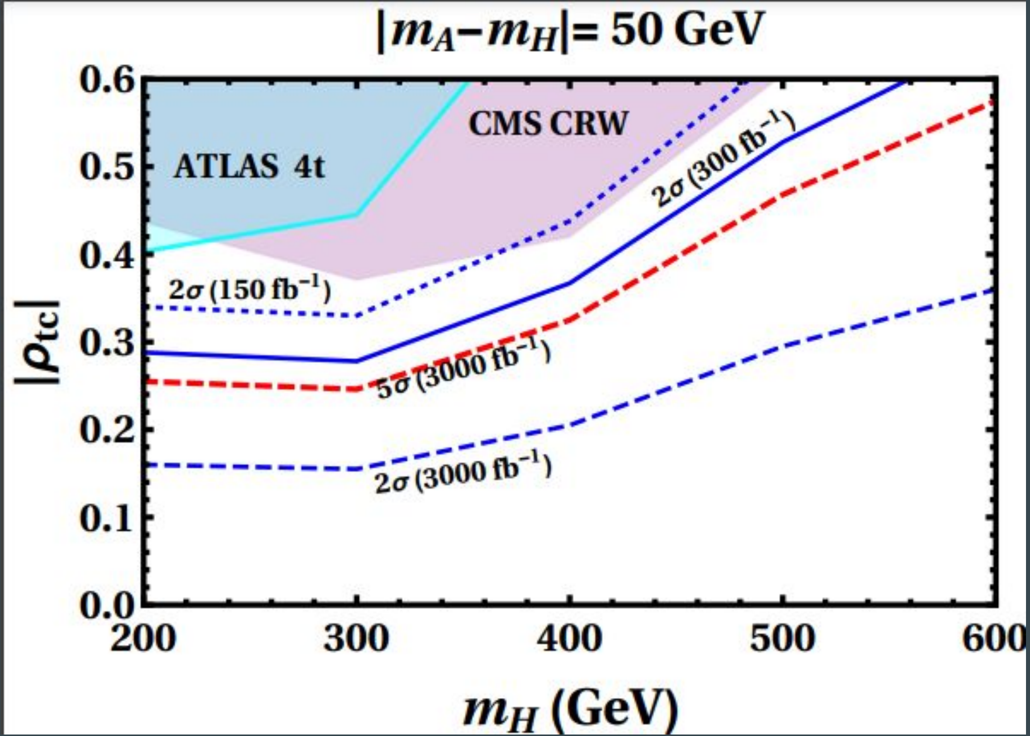
Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	1.201 ± 0.0056 ± systematics	500	parton madevent	LHE MA5_report_analysis1	remove run launch detector simulation
run_02	p p 7000.0 x 7000.0 GeV	tag_1	0.609 ± 0.0027 ± systematics	500	parton madevent	LHE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

Machine Learning

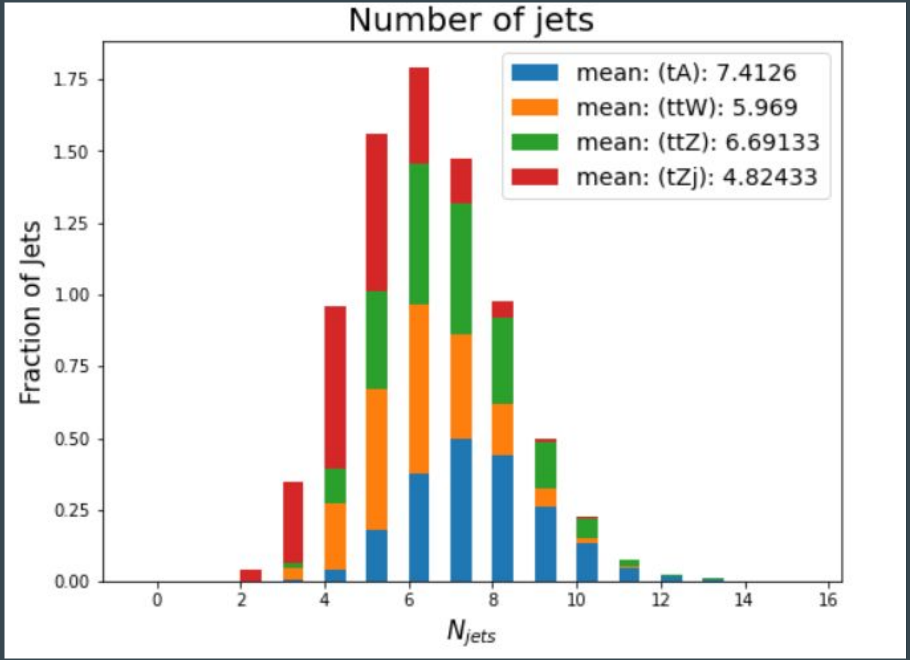
- https://jmduarte.github.io/capstone-particle-physics-domain/weeks/05-jet-images.html
- use particles' eta and psi relate to its pt as input
- tt~Z, tt~W, tZ+j, 3t+j, 3t+W, 4t, and tt~h

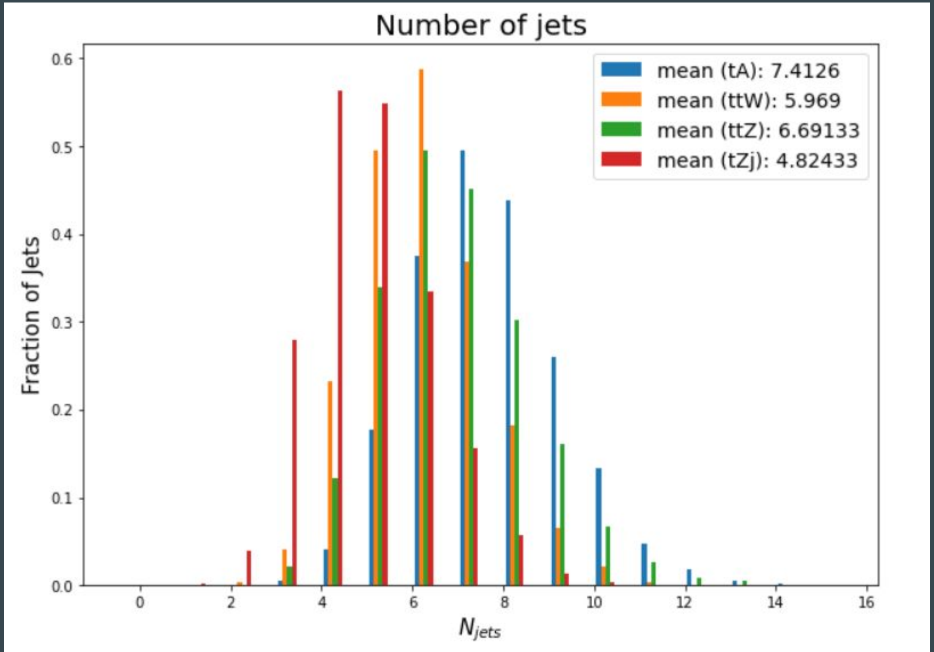


Back up slide



N_{jets} Number of jets





10/20/2021 update

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

Code:

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

open index.html
launch sig_schannel

```

S-channel vs T-channel

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

Reference

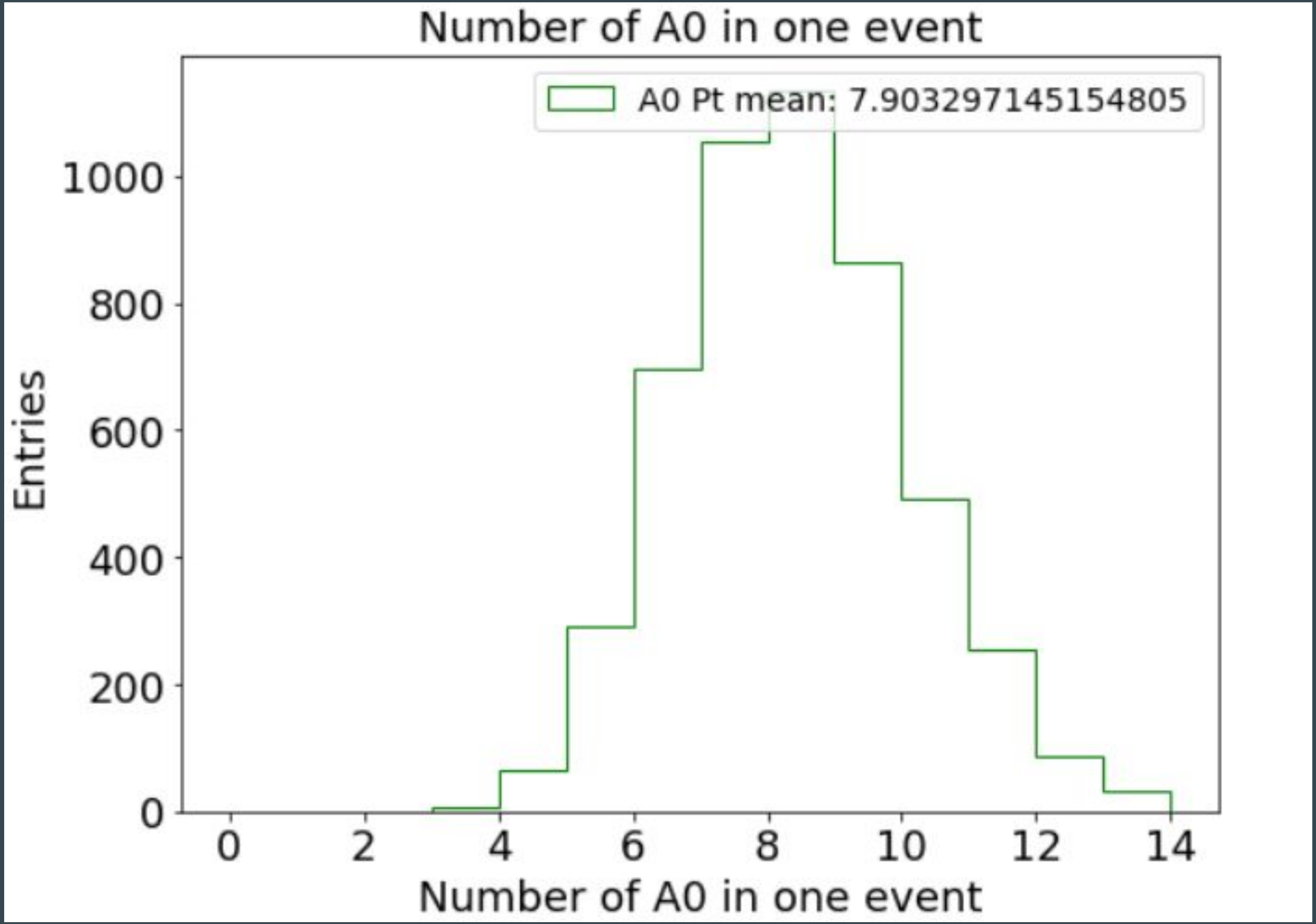
https://www.sciencedirect.com/science/article/pii/S0550321320302273 (Feynman Diagrams)

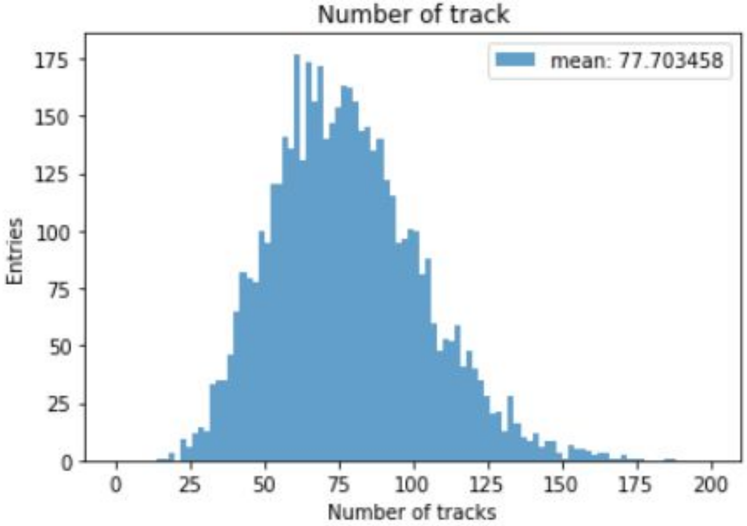
Lagrangian

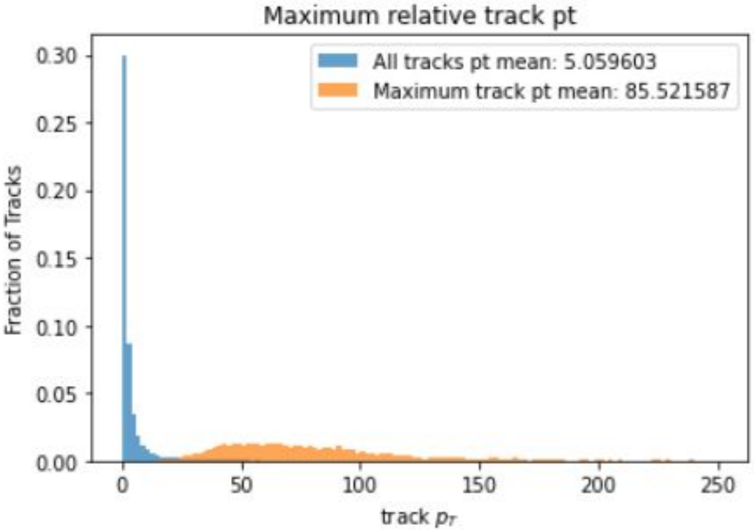
- rho_tc
- s = sin(), c = cos()

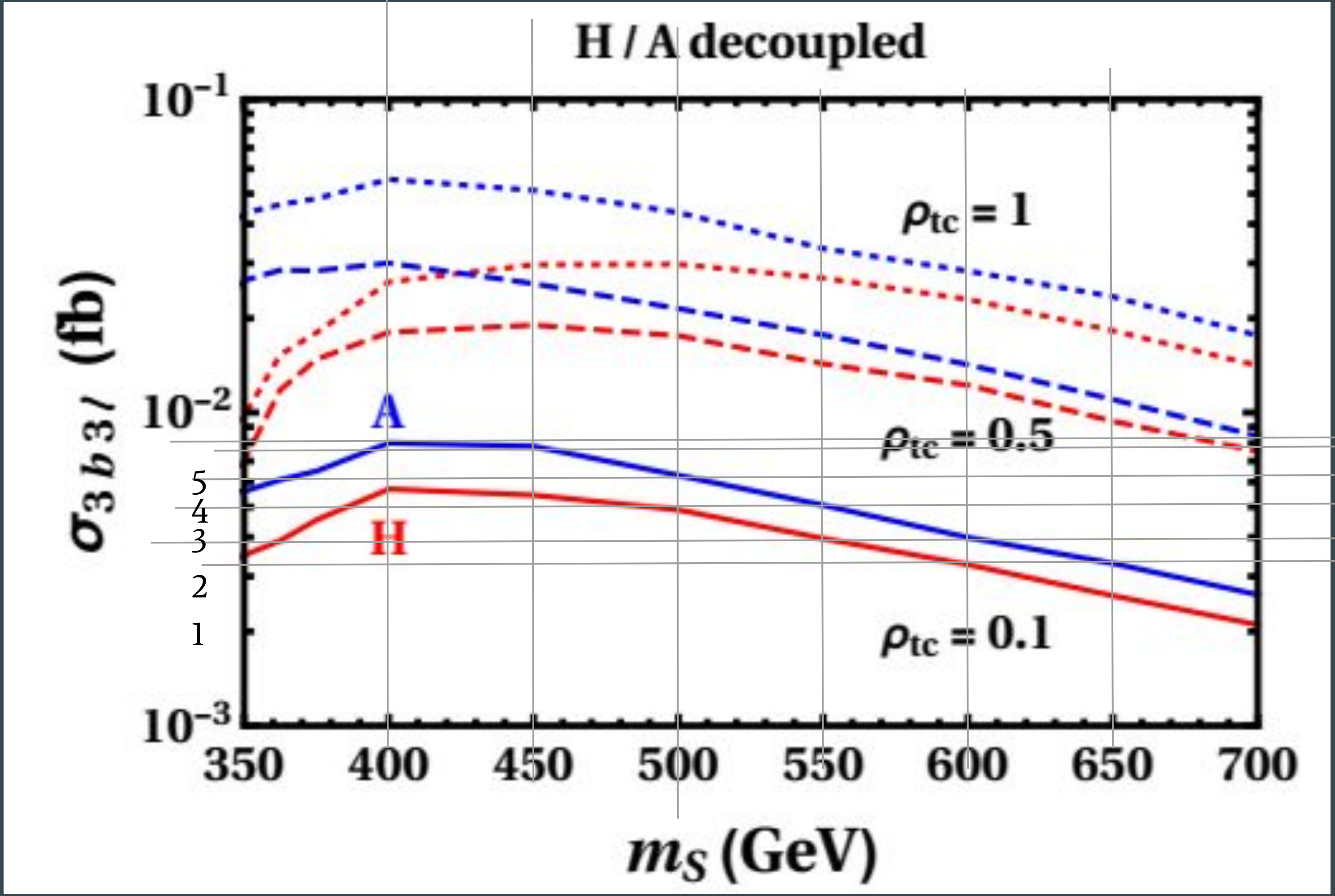
$$\mathscr{L} = -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda^f_{ij} s_\gamma + \rho^f_{ij} c_\gamma) h$$

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

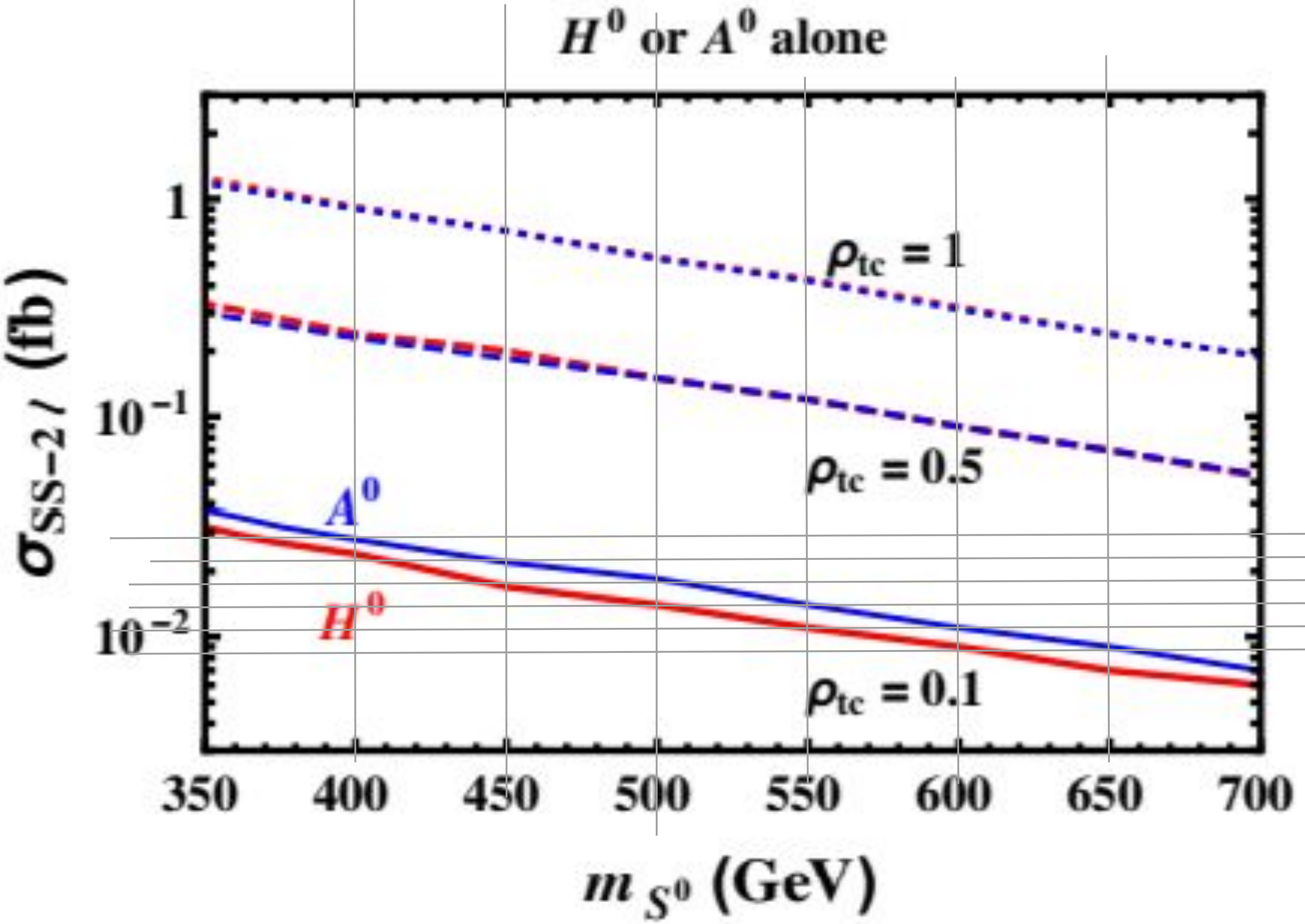

Number of A0 in one event
A0 Pt mean: 7.903297145154805
Entries
0
200
400
600
800
1000
0
2
4
6
8
10
12
14
Number of A0 in one event


Number of track
mean: 77.703458
Entries
Number of tracks
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



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



H⁰ or A⁰ alone
1
10⁻¹
10⁻²
σ_SS-2l (fb)
ρ_tc = 1
ρ_tc = 0.5
ρ_tc = 0.1
A⁰
H⁰
350
400
450
500
550
600
650
700
m_S⁰ (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

Problem:

1.