

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 Z_2 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 \pm charged (H_{\pm})

Two-Higgs Doublet Model (2HDM)

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

Before Spontaneous Symmetry Breaking:

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

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

Triple Top

- Triple-top signature: denoted as 3b3l, defined as at least three leptons and at least three jets, of which at least three are b-jets, and E_{T_miss} .
- Dominant SM backgrounds are ttZ + jets and $4t$
- $ug, cg \rightarrow tS$ ($S = H, A$) $\rightarrow tt t\text{-bar}$
- SM: $cg \rightarrow c \rightarrow s + W^+$

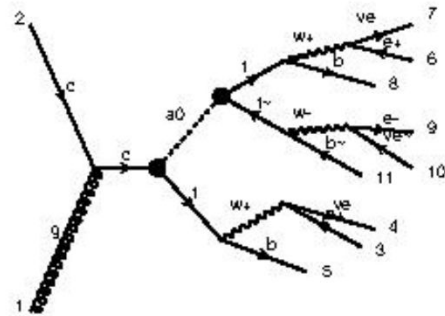


diagram 1

QCD=1, QED=6, QNP=2

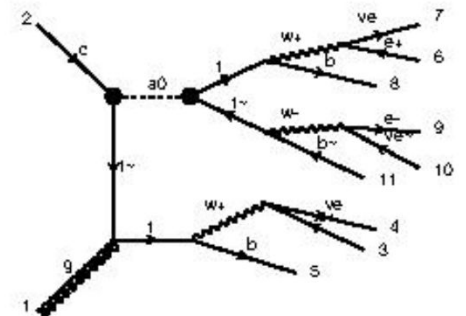


diagram 2

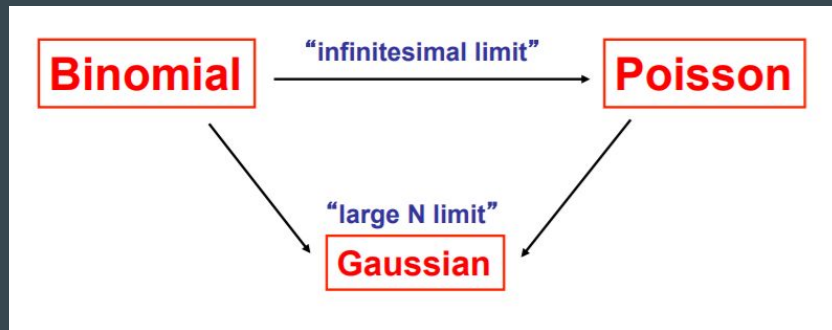
QCD=1, QED=6, QNP=2

Overview (11.19.2021)

- Binomial, Poisson, Gaussian Distribution
- Cross Section vs Mass Update
- Kinematic Plots
- Branching Ratio & Decay width
- Monte Carlo

Binomial, Poisson, Gaussian Distribution

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



Binomial Distribution

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

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

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

Poisson Distribution

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

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

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

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

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

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

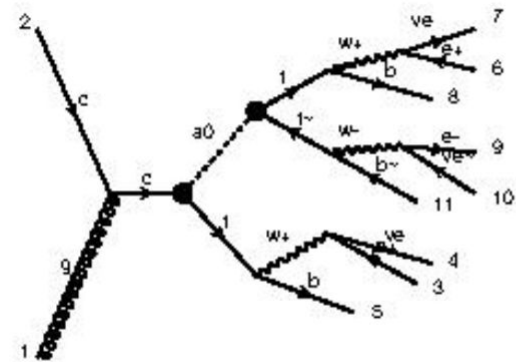
Gaussian Distribution

- 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%

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

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	nu	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	$0.03485 \pm 7.7\text{e-}05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.02053 \pm 4.3\text{e-}05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.01266 \pm 2.5\text{e-}05 \pm \text{systematics}$	10000
p p 7000.0 x 7000.0 GeV	tag_1	$0.007965 \pm 1.6\text{e-}05 \pm \text{systematics}$	10000

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

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

Cross Section vs Mass

Paper:

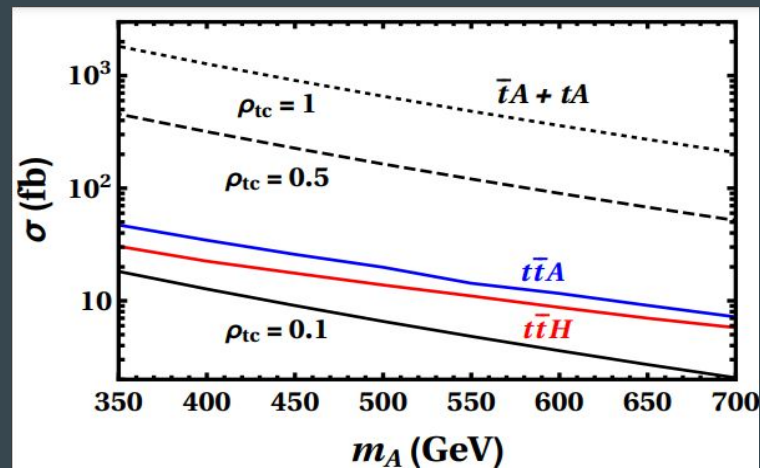
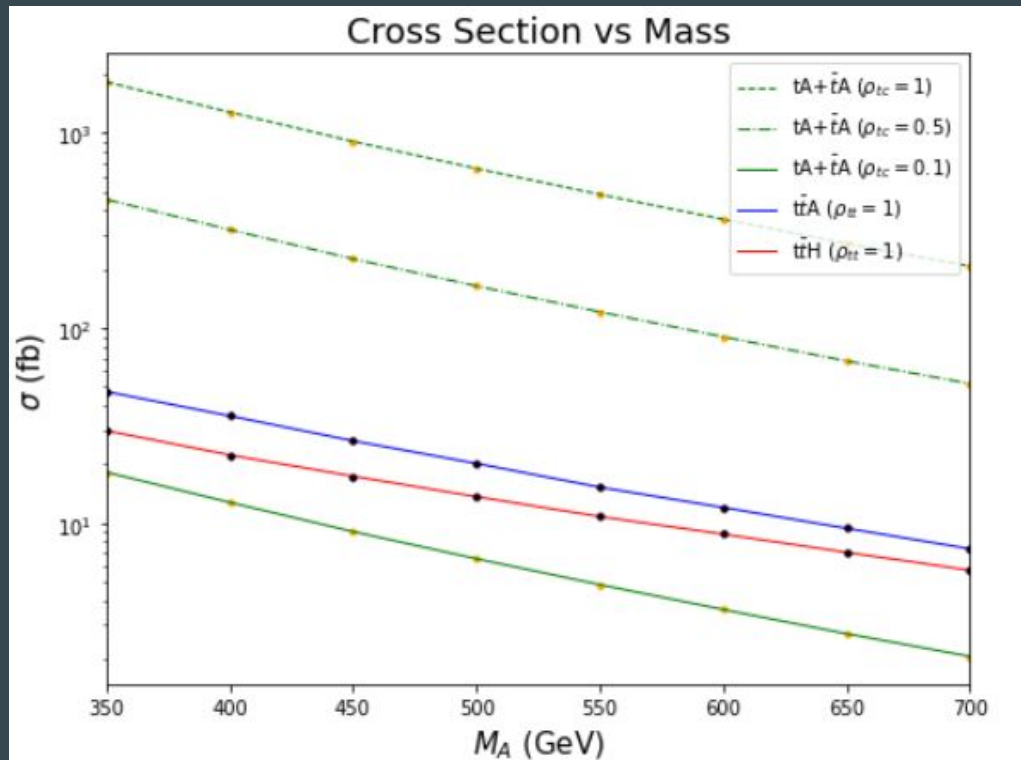


FIG. 1. Cross sections at $\sqrt{s} = 14$ TeV for $pp \rightarrow tS^0, \bar{t}S^0$ where $S^0 = H^0, A^0$, for $\rho_{tc} = 0.1$ (solid), 0.5 (dashed) and 1 (dots), and $pp \rightarrow t\bar{t}H^0, t\bar{t}A^0$ (for $\rho_{tt} = 1$) as marked.

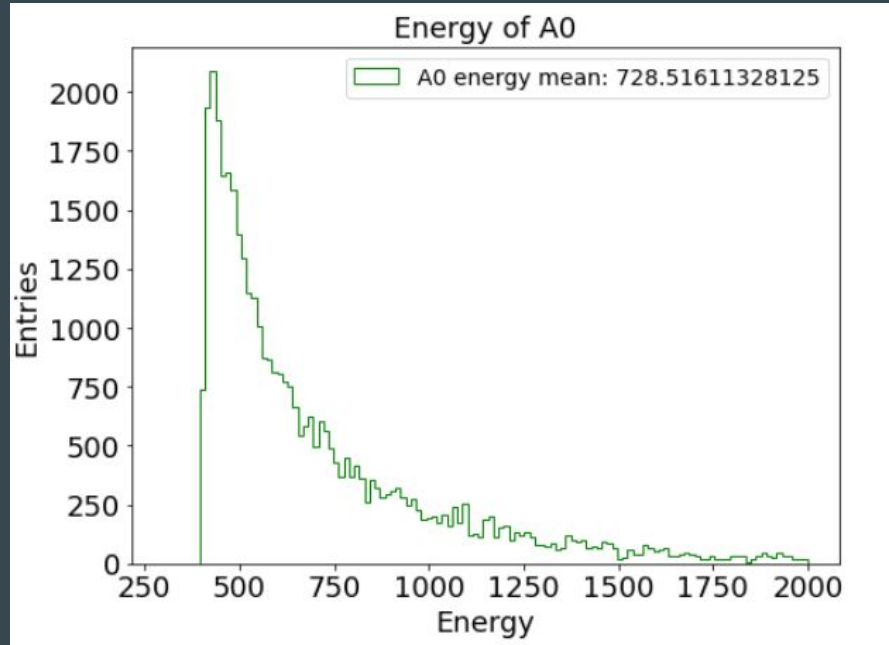
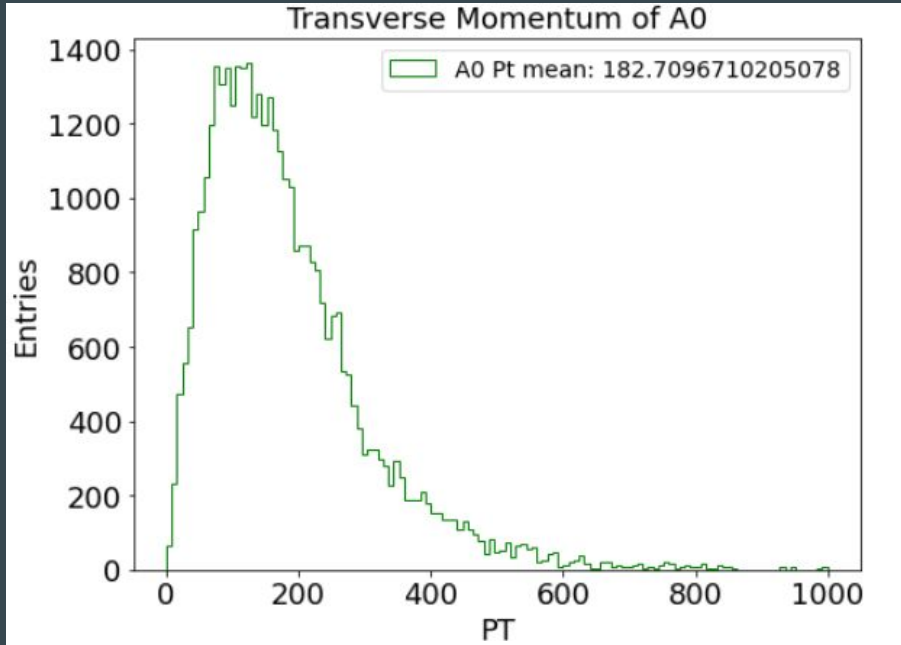
Previous : QCD=99; Use pdf set 274000

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

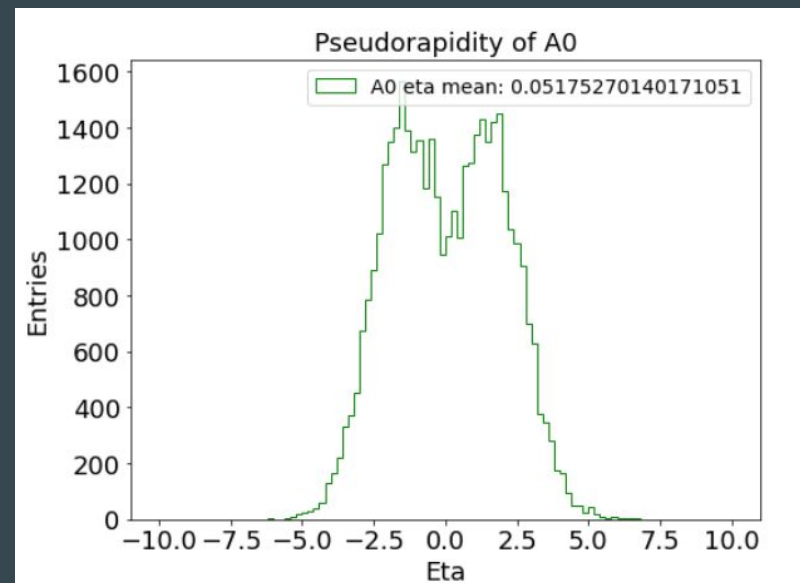
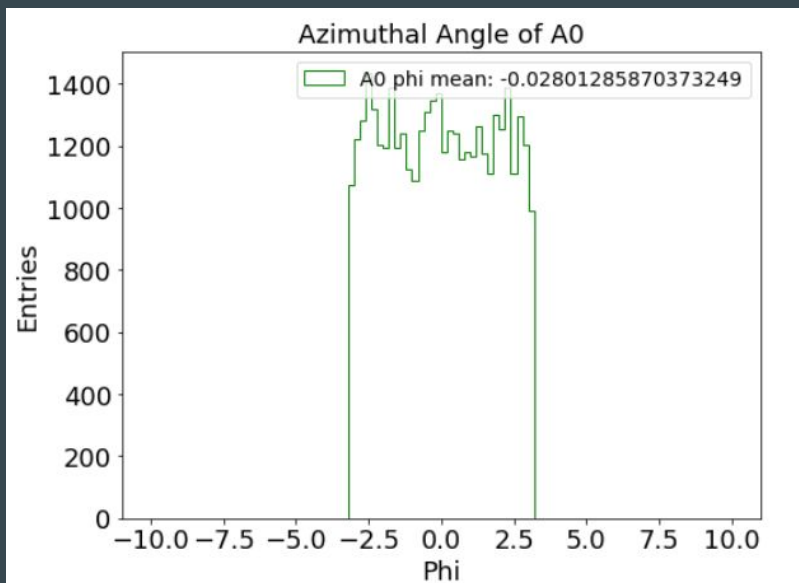
My Result:



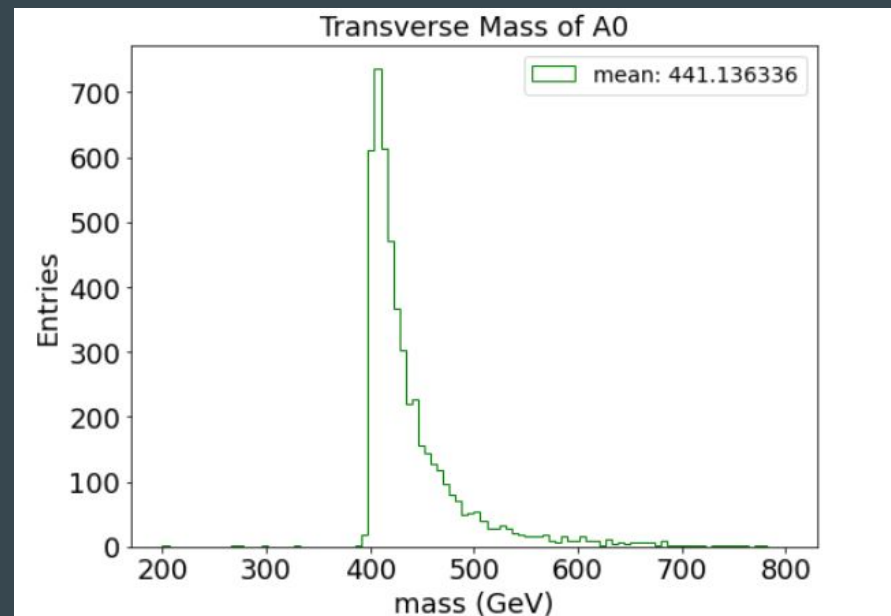
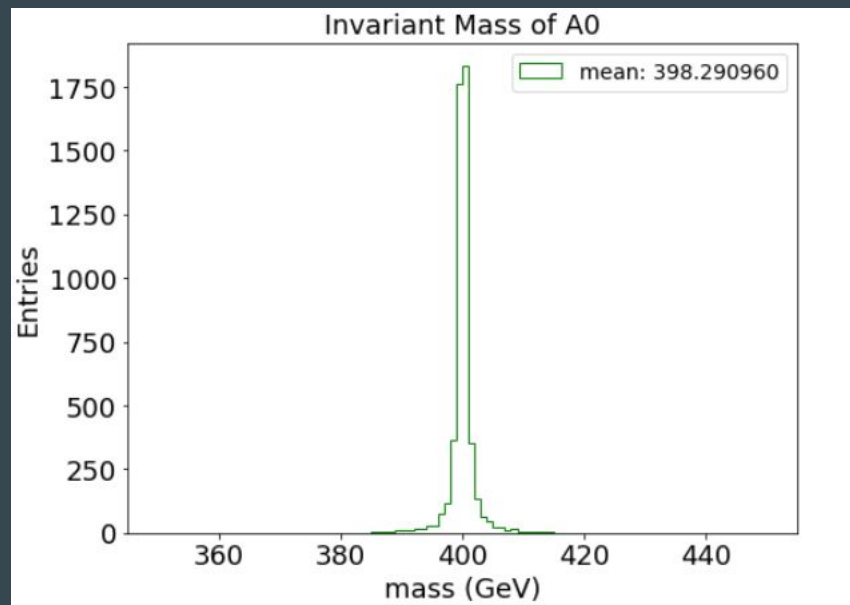
Kinematic Plots (A0 400GeV)



Kinematic Plots (A0 400GeV)



Kinematic Plots (A0 400GeV)



Decay Width

$$- \Gamma_{tt} + \Gamma_{tc \sim t \sim c}$$

A decay width

$A \rightarrow f \bar{f}$ (Will be used for $A \rightarrow t \bar{t}$ decay)

$$\text{In[92]} := \text{rAffbar}[rff_ , MA_ , mf_ , Nc_] := \frac{Nc \sqrt{\lambda[MA^2, mf^2, mf^2]}}{8 \pi MA^3} \left(\left(\text{Abs}\left[-\frac{i rff}{\sqrt{2}}\right] \right)^2 MA^2 \right);$$

$\text{In[124]} := \text{rAffbar}[1, 400, mt, 3]$

$$\text{Out[124]} = \frac{3 \sqrt{651}}{2 \pi}$$

$A \rightarrow t \bar{c} + \bar{t} c$

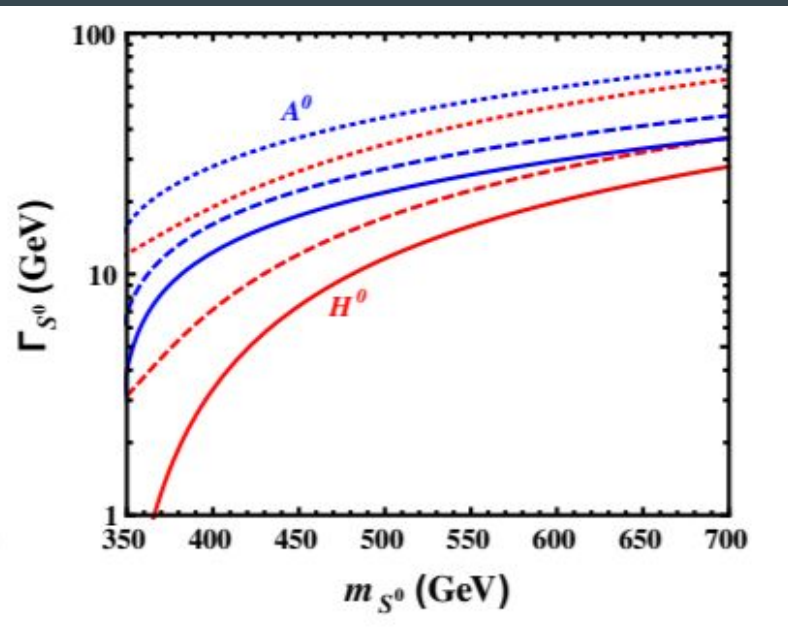
$$\text{In[94]} := \text{rAtc}[rtc_ , MA_ , Nc_] := Nc \frac{\sqrt{\lambda[MA^2, mt^2, mc^2]}}{8 \pi MA^3} \frac{1}{8} \left((rtc)^2 (MA^2 - (mt + mc)^2) + (rtc)^2 (MA^2 - (mt - mc)^2) \right)$$

$\text{In[123]} := \text{rAtc}[0.1, 400, 3]$

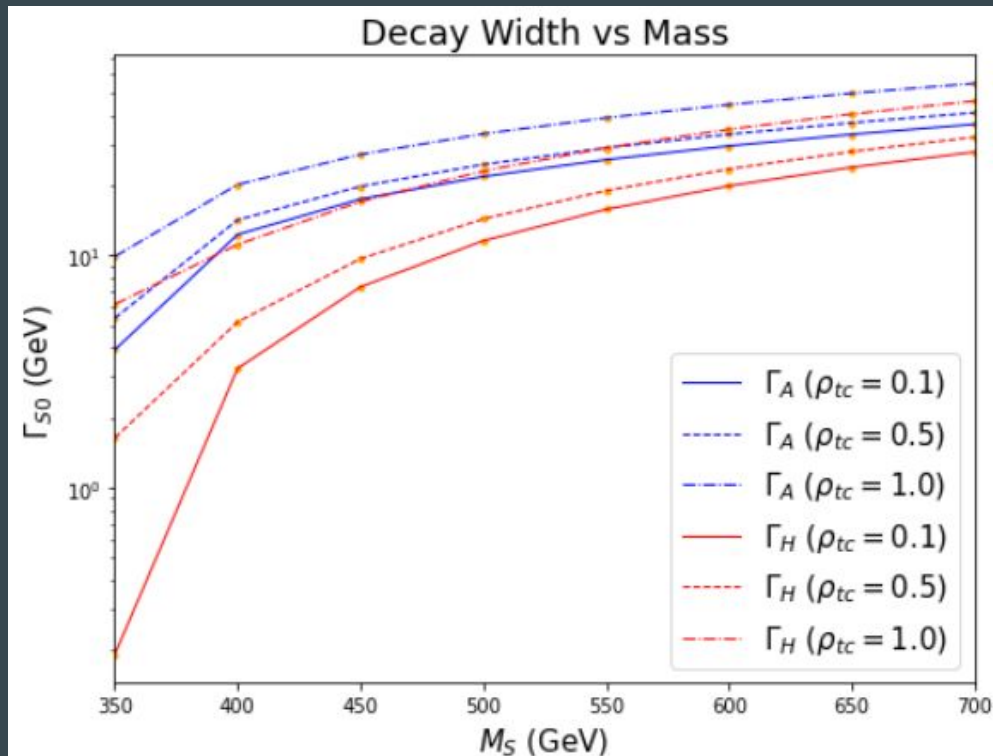
$\text{Out[123]} = 0.079303$

Decay Width vs Mass

Paper:

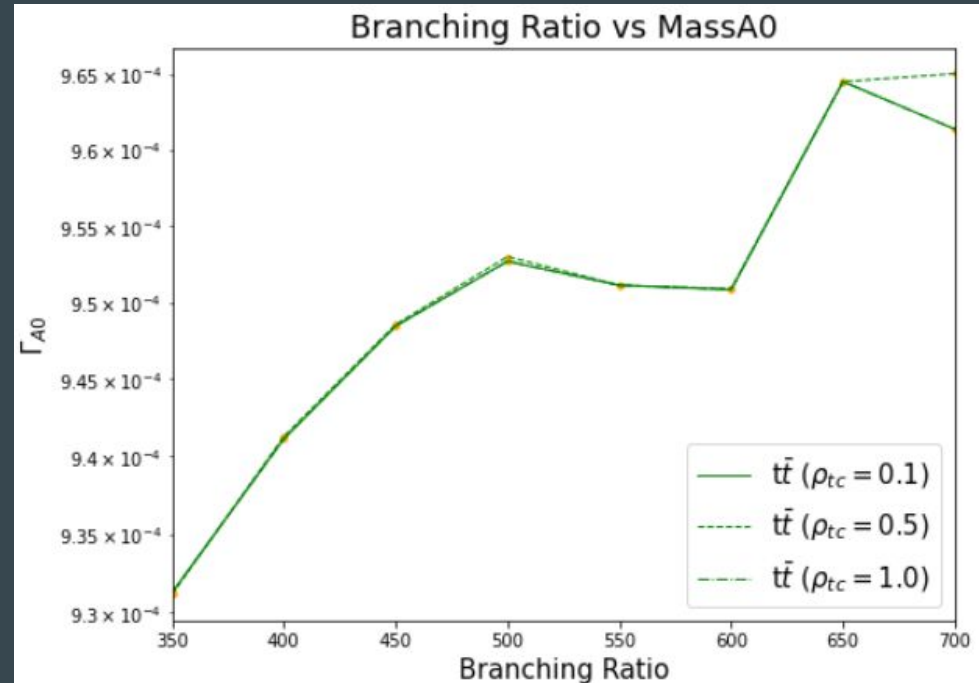
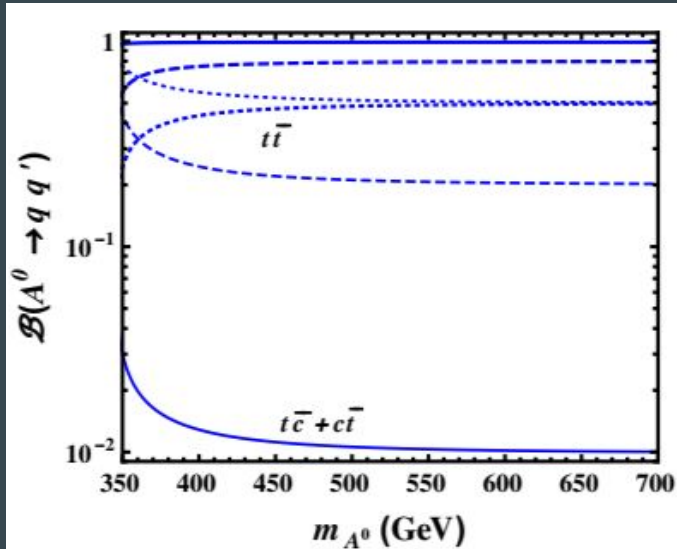


My Result:



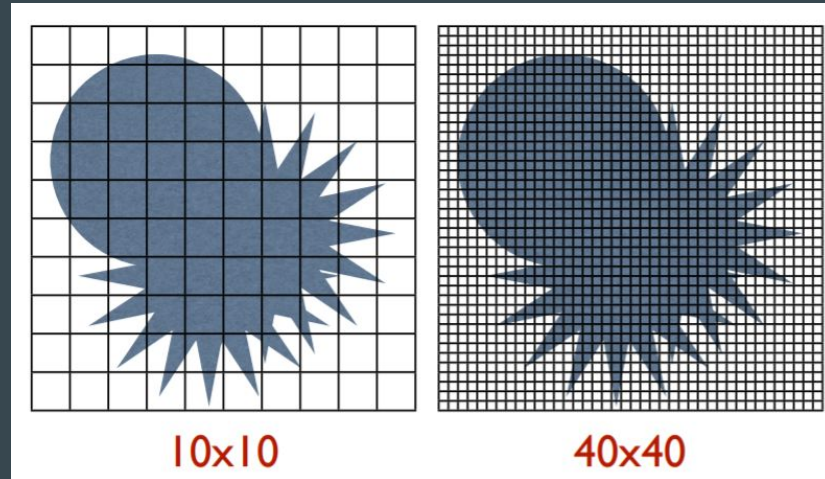
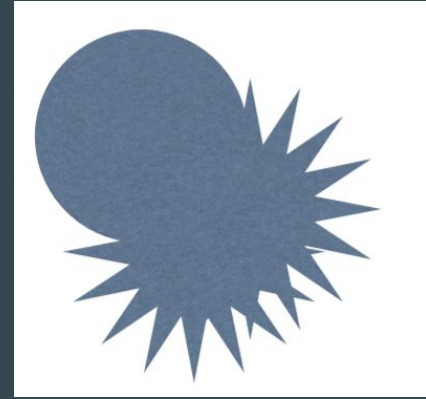
Branching Ratio

- (cross section with $t\bar{t}$ decay) / (cross section with no decay).
- Problem: inconsistent plot & Unable to generate cross section of $c\bar{t} + c\bar{t}$
- The branching ratio (branching fraction) is the fraction of events for a chosen particle measured to decay in a certain way. The sum of branching ratios for a particle is one. The branching ratio is defined as the partial decay width divided by the total width.



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 $b = 1$)

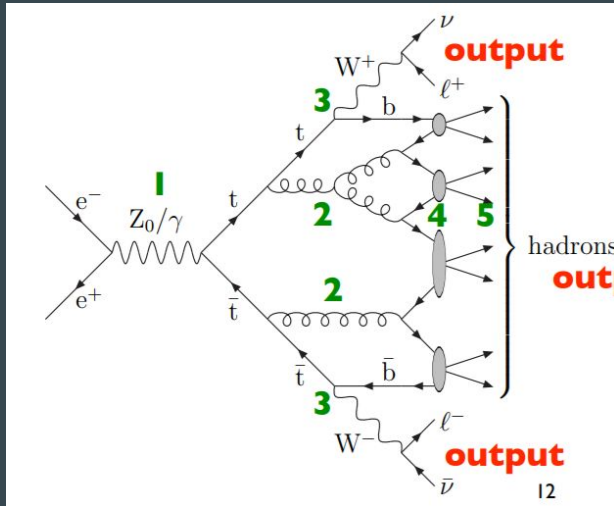


Area = (Number of hits)/(Total squares) * (Total Area)

https://upload.wikimedia.org/wikipedia/commons/8/84/Pi_20K.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 \rightarrow Parton-shower phase \rightarrow Hard particles decay before hadronizing \rightarrow Hadronization \rightarrow Unstable hadrons decay



To-do:

- Analysis flow for particle physics
- derive the mean and variance of binomial distribution
- Branching Ratio (ask Ali)
- Decay Width (ask Tanmoy)
- Decay channel for the signals
 - one, two, three lepton channels (calculate each BR)
- design an analysis for one lepton channels * (read the paper)
- feynman diagrams SM backgrounds/ different processes (focus on one lepton)

Analysis Flow

- study feynman's diagrams, generate samples, study simple values.
- distinguish signal and background (pt cut)
- set limits

Parameter of the model

- import gen2HDM model (insert the information for H_0 , A_0)
- set the process ($H, A \rightarrow t, t\text{-bar}$) 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 [ρ_{tc} , m_A , m_t , N_c] into mathematica to calculate the delay width.
- enable lhpdf 247000


```

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

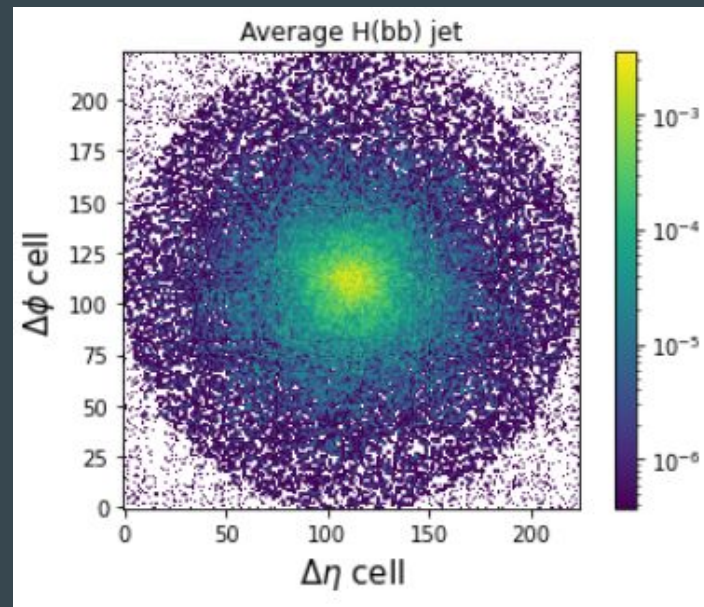
```

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

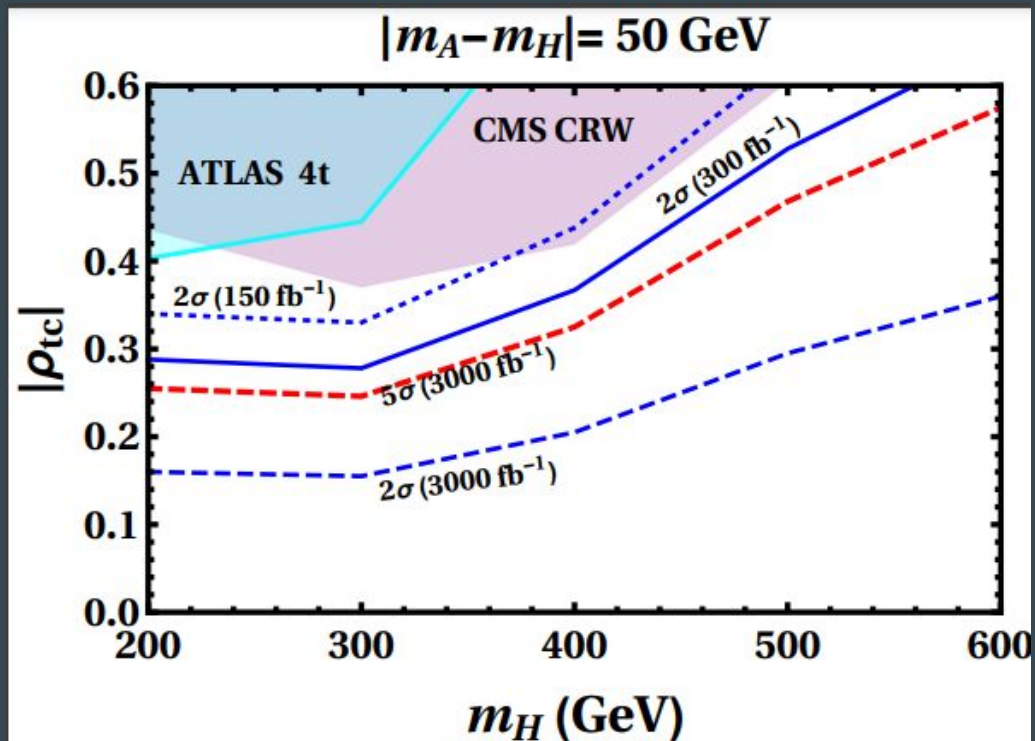
Run	Collider	Banner	Cross section (pb)	Events	Data	Output	Action
run_01	p p 7000.0 x 7000.0 GeV	tag_1	$1.201 \pm 0.0056 \pm \text{systematics}$	500	parton madevent	LHE MA5_report_analysis1	<input type="button" value="remove run"/> <input type="button" value="launch detector simulation"/>
run_02	p p 7000.0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

Machine Learning

- <https://jmduarte.github.io/capstone-particle-physics-domain/weeks/05-jet-images.html>
- use particles' eta and phi relative to its pt as input
- $t\bar{t}\rightarrow Z$, $t\bar{t}\rightarrow W$, $tZ+j$, $3t+j$, $3t+W$, $4t$, and $t\bar{t}\rightarrow h$



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:

```
1 import model gen2HDM_UFO
2 define p = p b b~
3 define j = p
4 generate p p > t A0 QCD=99, (t > w+ b , w+ > l+ vl) ,( A0 > t t~ , (t > w+ b , w+ > l+ vl),(t~ > w- b~ , w- > l- vl~) )
5 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~) )
6 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~) )
7 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~) )
8 output sig_schannel
9
10 open index.html
11 launch sig_schannel
12
```

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.

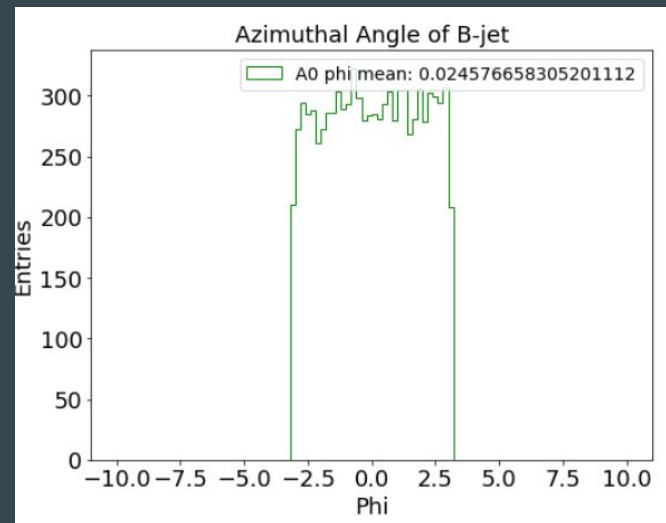
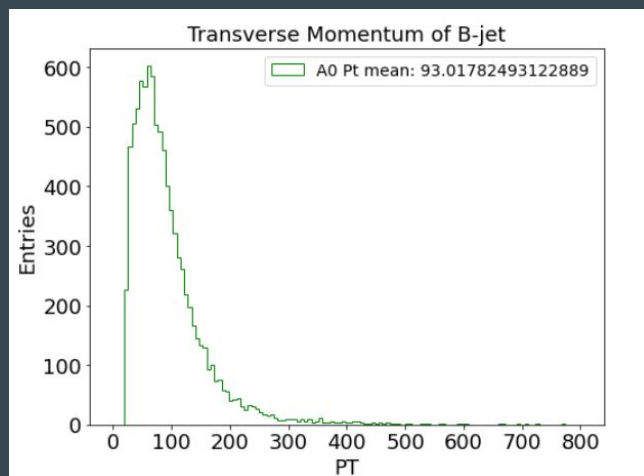
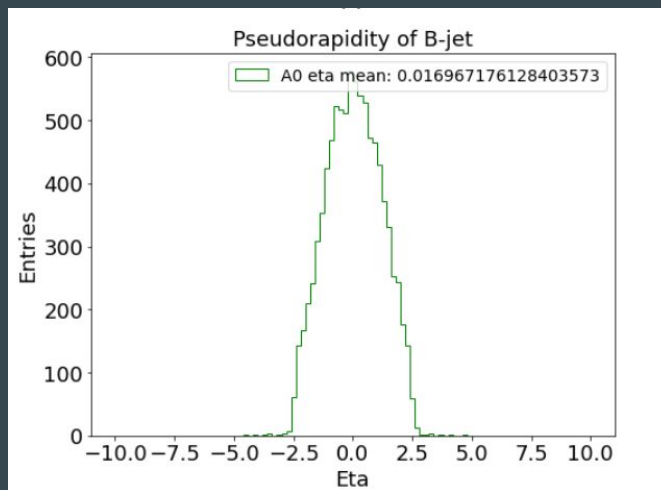
the indices in the event record where the first and last mothers are stored, if any. There are six allowed combinations of `mother1` and `mother2`:

1. `mother1 = mother2 = 0`: for lines 0 - 2, where line 0 represents the event as a whole, and 1 and 2 the two incoming beam particles;
2. `mother1 = mother2 > 0`: the particle is a "carbon copy" of its mother, but with changed momentum as a "recoil" effect, e.g. in a shower;
3. `mother1 > 0, mother2 = 0`: the "normal" mother case, where it is meaningful to speak of one single mother to several products, in a shower or decay;
4. `mother1 < mother2`, both > 0 , for `abs(status) = 81 - 86`: primary hadrons produced from the fragmentation of a string spanning the range from `mother1` to `mother2`, so that all partons in this range should be considered mothers; and analogously for `abs(status) = 101 - 106`, the formation of R-hadrons;
5. `mother1 < mother2`, both > 0 , except case 4: particles with two truly different mothers, in particular the particles emerging from a hard $2 \rightarrow n$ interaction.
6. `mother2 < mother1`, both > 0 : particles with two truly different mothers, notably for the special case that two nearby partons are joined together into a status 73 or 74 new parton, in the $g + q \rightarrow q$ case the q is made first mother to simplify flavour tracing.

Reference

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

B-jet

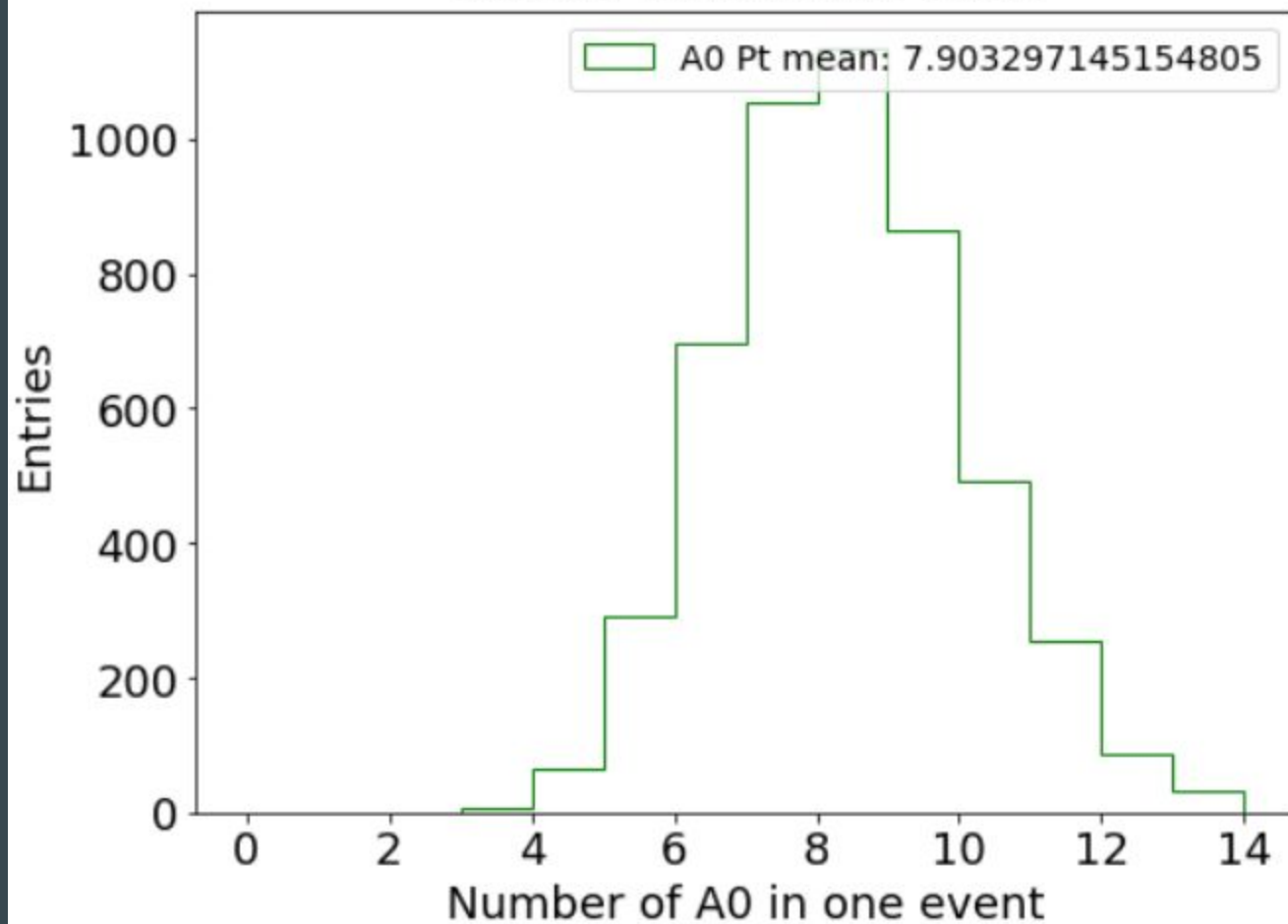


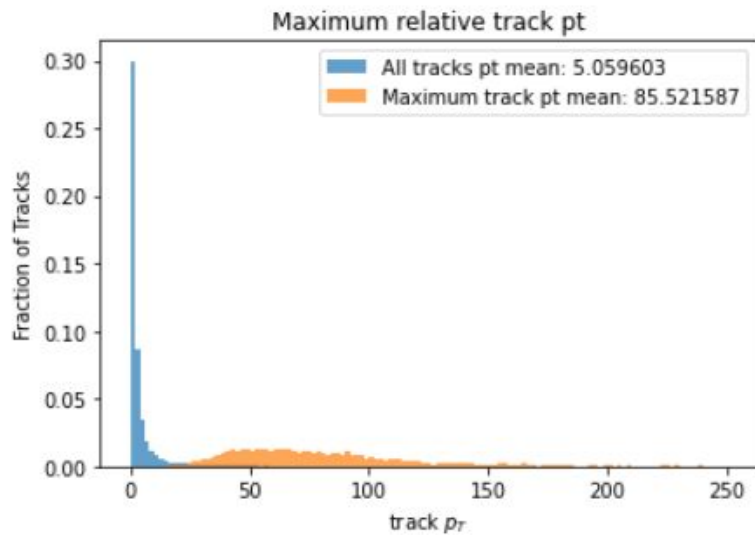
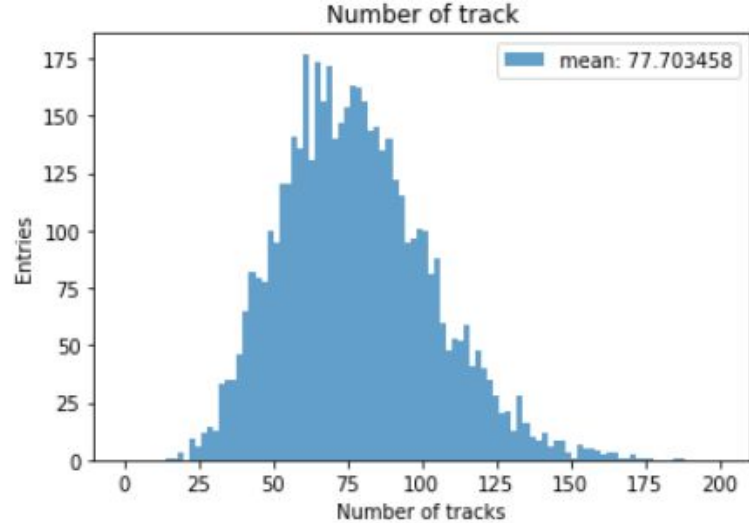
Lagrangian

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

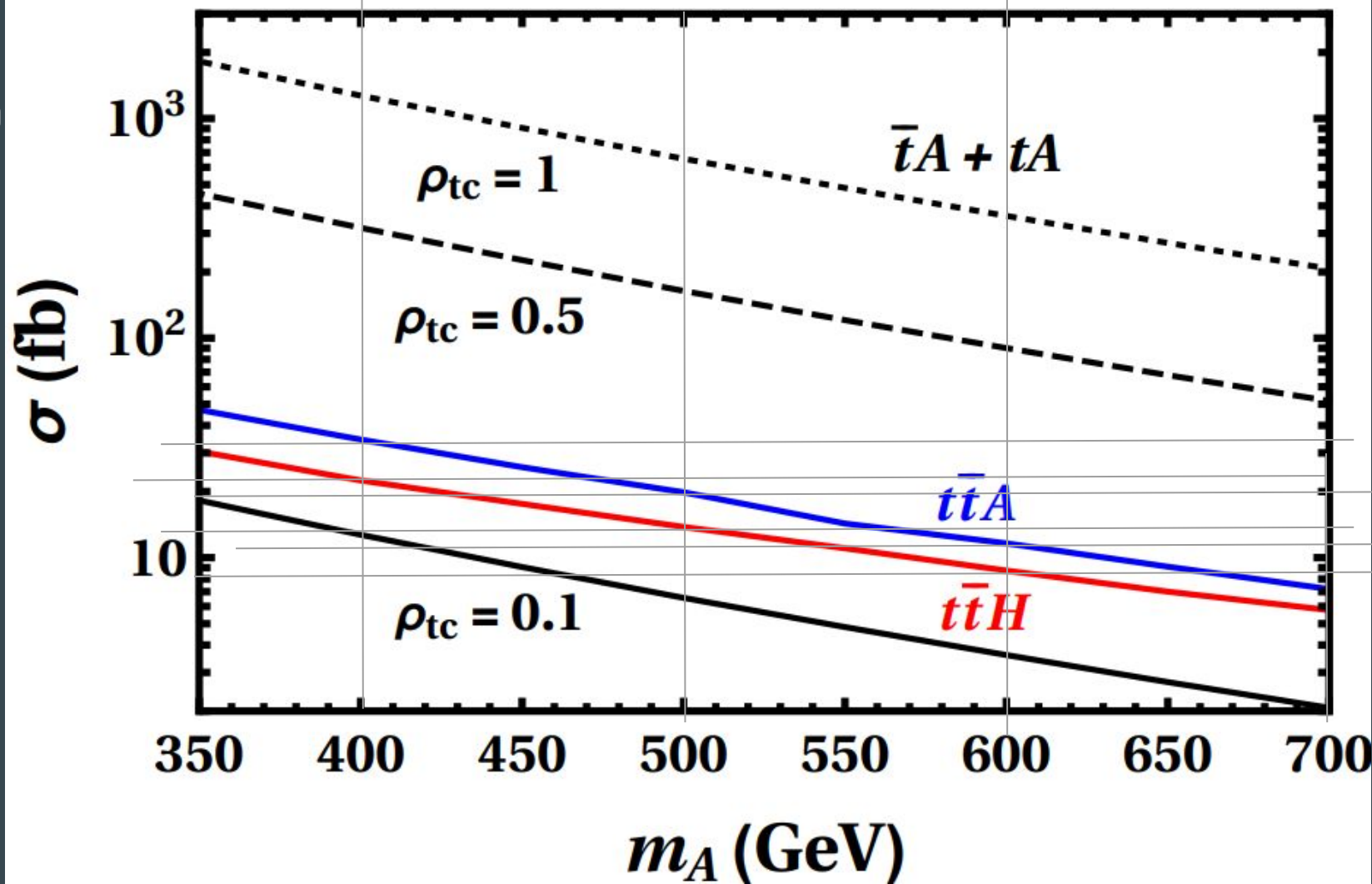
$$\begin{aligned}\mathcal{L} = & -\frac{1}{\sqrt{2}} \sum_{f=u,d,\ell} \bar{f}_i [(-\lambda_{ij}^f s_\gamma + \rho_{ij}^f c_\gamma) h \\ & + (\lambda_{ij}^f c_\gamma + \rho_{ij}^f s_\gamma) H - i \operatorname{sgn}(Q_f) \rho_{ij}^f A] R f_j + \text{H. c.},\end{aligned}$$

Number of A0 in one event





T_0



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

Statistical Uncertainties:

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

Systematic Uncertainties:

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

Blunders, i.e. **errors**:

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