Setting limits on the toponium cross section

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Toponium??

According to a particle theory book from 2015:

The t-quark has, due to its large mass, only a fleeting lifetime. Thus no pronounced $t\bar{t}$ states *(toponium)* are expected.

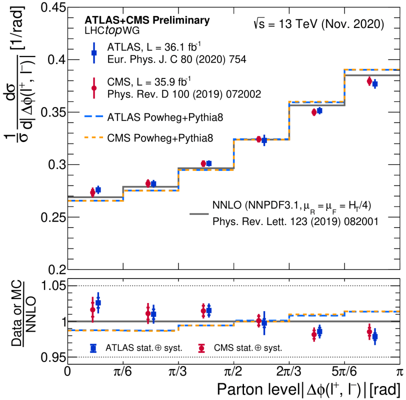
About Toponium

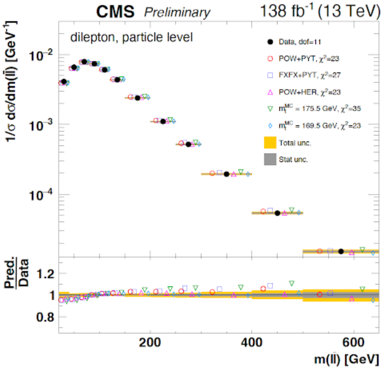
Top quarks decay into a W boson and b quark $\approx$ 100% of the time. Decays split into 3 branching ratios: dileptonic, semileptonic, full hadronic. The $t\bar{t}$ pairs are produced dileptonically as: $gg \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$

$$m_t \approx 172.44 \pm 0.13 \pm 0.47 GeV^{[arxiv:1403.4427]}$$

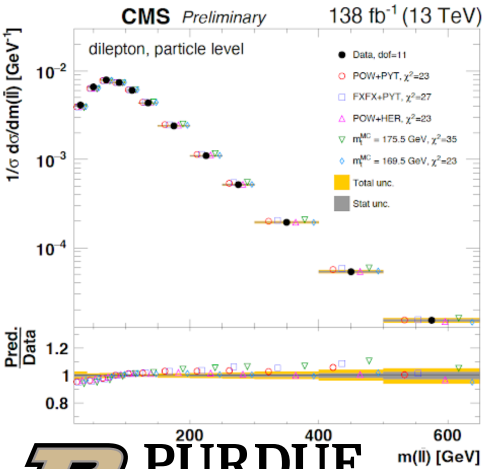
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip} \\ 10^{-21}\ \text{s}}}$$

Toponium Evidence



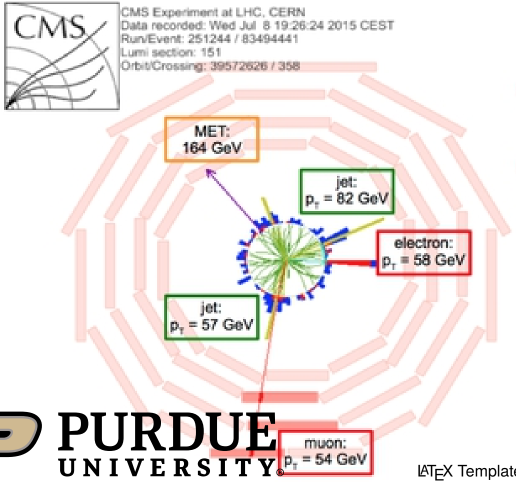


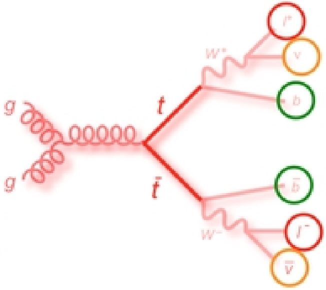
Evidence for Toponium?



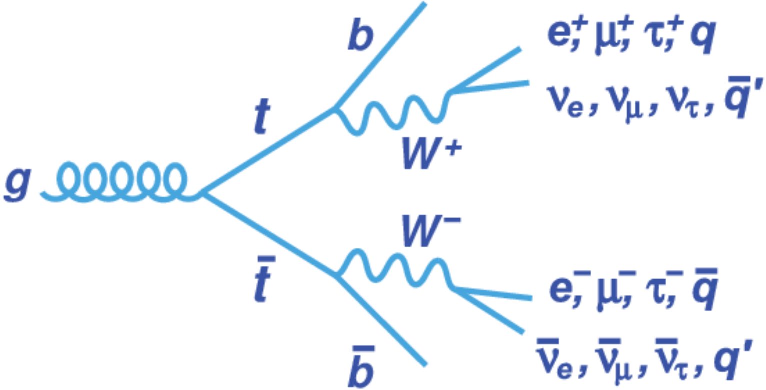
- ATLAS [arxiv:1910.08819] and CMS see an excess of low $m_{\ell\bar{\ell}}$ events (dilepton events)
- Fuks et. al. showed that this can be explained via a $t\bar{t}$ scalar resonance [arxiv:2102.11281]
- Using an event selection procedure biased for toponium production Fuks et. al. achieved a S/N ratio of 7% when considering only $t\bar{t}$ events

Top Quark Physics





Top Quark Physics



Spin Correlation Analysis

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ \mathbf{10^{-27}\ s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ \mathbf{10^{-25}\ s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization}\\ \mathbf{10^{-24}\ s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ \mathbf{10^{-21}\ s}}}$$

Basic of Spin-corr

For measurements in pp collisions, using the $\{\hat{k}, \hat{r}, \hat{n}\}$ basis vectors, the angular distribution for the two leptons (each measured in its parent top CM frame) can be stated precisely. For each of the 15 coefficients that make up $\mathbf{B_{1/2}}$ and C, a change of variables can be made to obtain a single-differential cross section dependent only on that coefficient. For example, after integrating out the azimuthal angles, $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 + B_1(i)\cos\theta_1 + B_2(i)\cos\theta_2 - C(i,i)\cos\theta_1\cos\theta_2)$, where

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1(i)\cos\theta_1^i + B_2(j)\cos\theta_2^j - C(i,j)\cos\theta_1^i\cos\theta_2^j\right),$$

Cont.

from which we can derive single-differential cross sections wrt $\cos\theta_1^i$, $\cos\theta_2^i$, and $\cos\theta_1^i \cos\theta_2^j$:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1(i)\cos\theta_1^i\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_2^i} = \frac{1}{2}\left(1 + B_2(i)\cos\theta_2^i\right)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i \cos\theta_2^j} = \frac{1}{2}\left(1 - C(i,j)\cos\theta_1^i \cos\theta_2^j\right)\log\left(\frac{1}{\left|\cos\theta_1^i \cos\theta_2^j\right|}\right).$$

15 variables at parton level:

- The 3 $\cos\theta_1^i \cos\theta_2^i$, to measure $C(i,i)$, the ”diagonal“ spin correlation coefficient for each axis i.
- The 6 sums and differences $\cos\theta_1^i \cos\theta_2^j \pm \cos\theta_1^j \cos\theta_2^i$, to measure the sums and differences of the ”cross“ spin correlation coefficients $C(i,j) \pm C(j,i)$ for each pair of axes i,j.
- The 6 $\cos\theta_1^i$ and $\cos\theta_2^i$, to measure $B_1(i)$ and $B_2(i)$, the top and anti-top polarization coefficients w.r.t each reference axis i.
- In addition, we measure 4 distributions based on modified axes $\hat{r}^*$ and $\hat{k}^*$, equal to $\pm\hat{r}$ or $\pm\hat{k}$ depending on $\mathrm{sign}(|y_t| - |y_{\bar{t}}|)$).

- The distribution $\cos\varphi_{\rm lab} = \hat{\ell}_1^{lab} \cdot \hat{\ell}_2^{lab}$, as above but using lepton directions measured in the laboratory frame (which have excellent experimental resolution).
- The distribution $|\Delta\phi_{\ell\ell}|$, the difference in azimuthal angle ϕ between the two leptons in the lab frame (whose shape is partly dependent on the above coefficients, particularly the $C(i, i)$, and has excellent experimental resolution).

Observable	Measured coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-

Table: (Partial table of) Observables and corresponding measured coefficients and production spin density matrix coefficient functions. 15 independent spin parameters and 25 direct observables/distributions and indirect observables as well.***

Statement of Classifier Problem in n = 7

From this we want to map this vector:

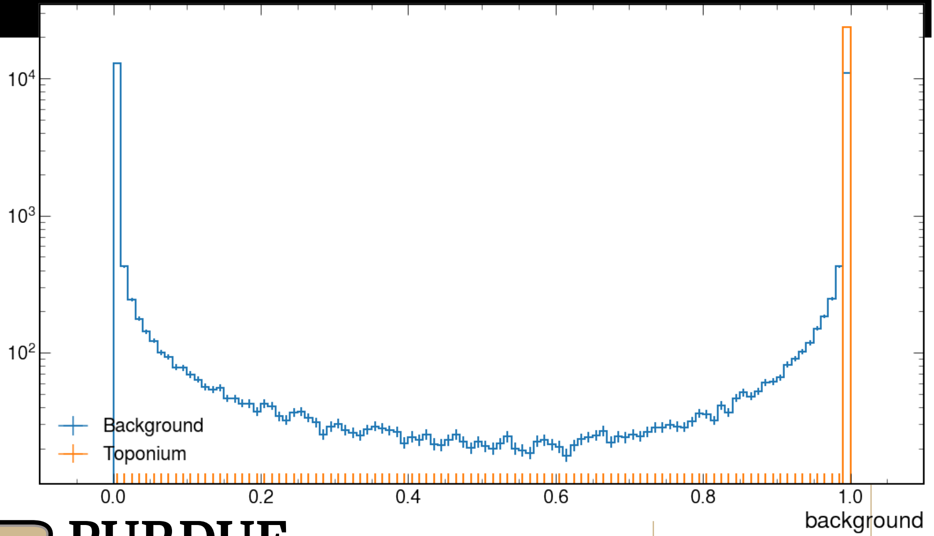
$$\mathbf{V} =< p_t, \eta_t, \phi_t, p_{\bar{t}}, \eta_{\bar{t}}, \phi_{\bar{t}}, m_{t\bar{t}} > \tag{1}$$

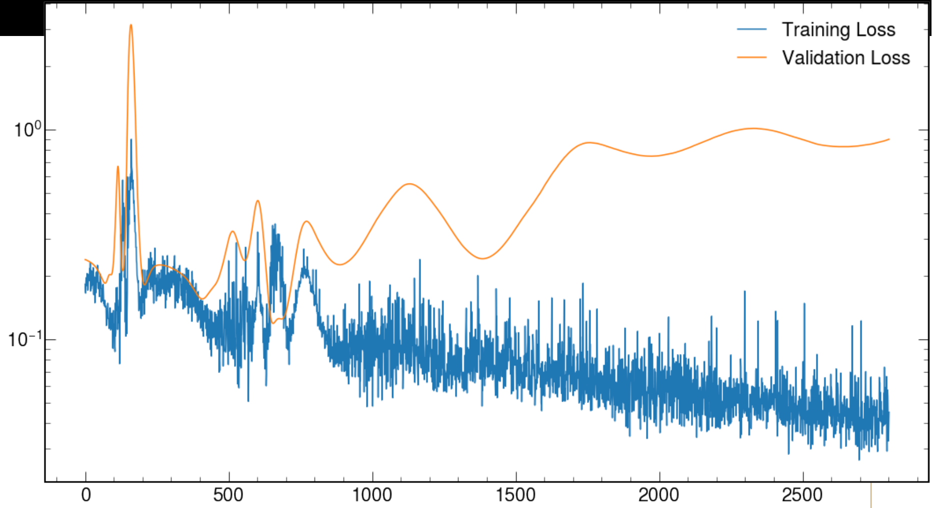
under

$$\Gamma : \mathbb{E}^7 \longrightarrow \mathbb{R}$$

where Γ is a kernel map determined by the choice of classifier architecture. The output of $\Gamma(\mathbf{V})$ is a probability that that $\mathbf{V}$ is a signal event as determined by the classifier.

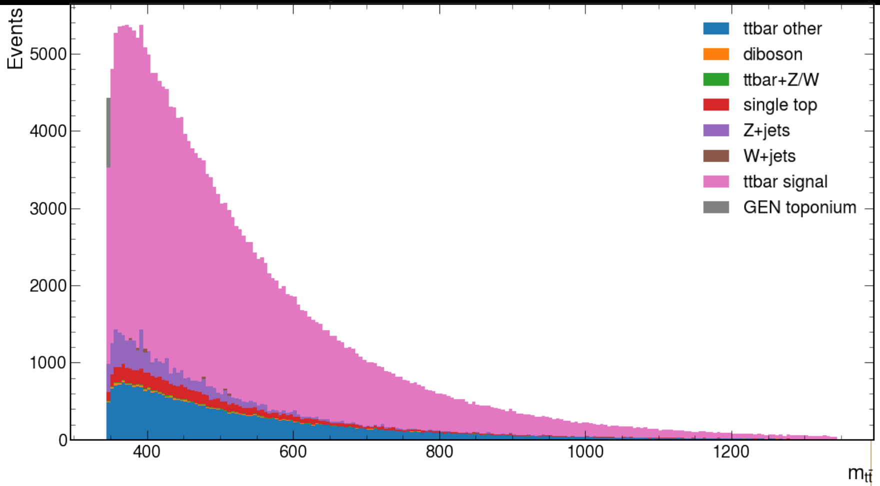
Results


10^4
10^3
10^2
Background
Toponium
0.0
0.2
0.4
0.6
0.8
1.0
background

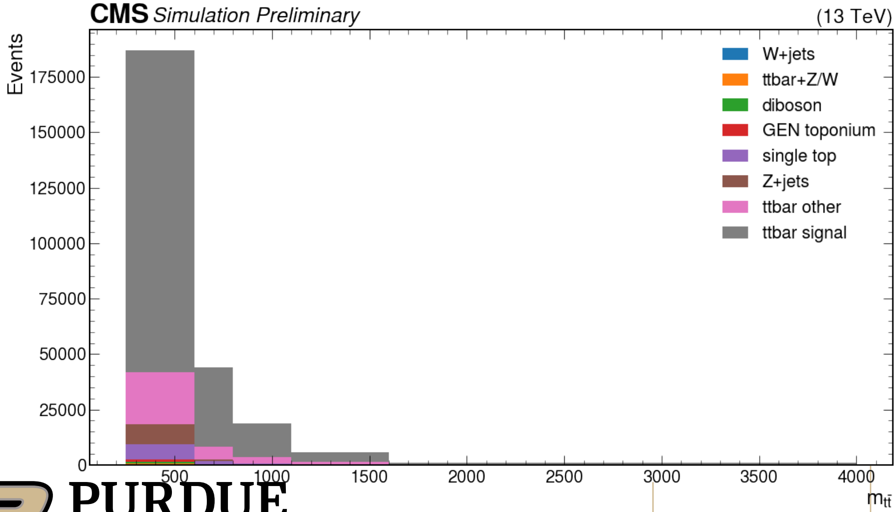


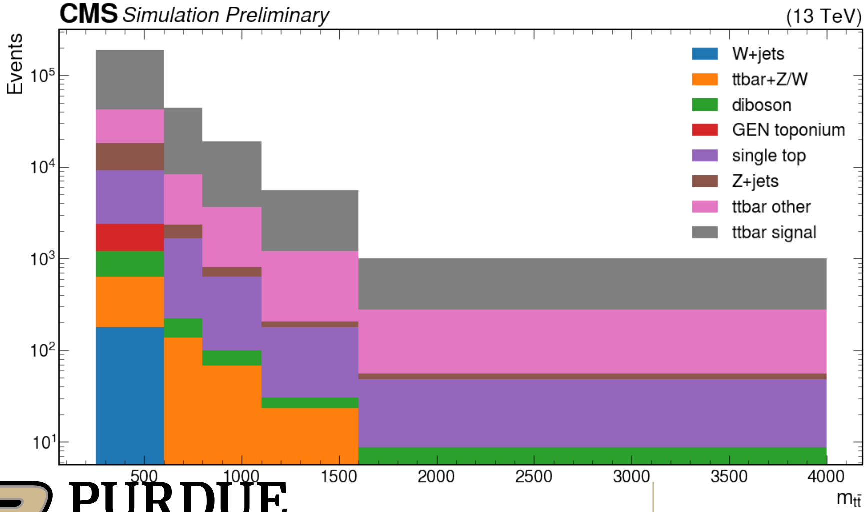
Training Loss
Validation Loss
10^0
10^{-1}
0
500
1000
1500
2000
2500

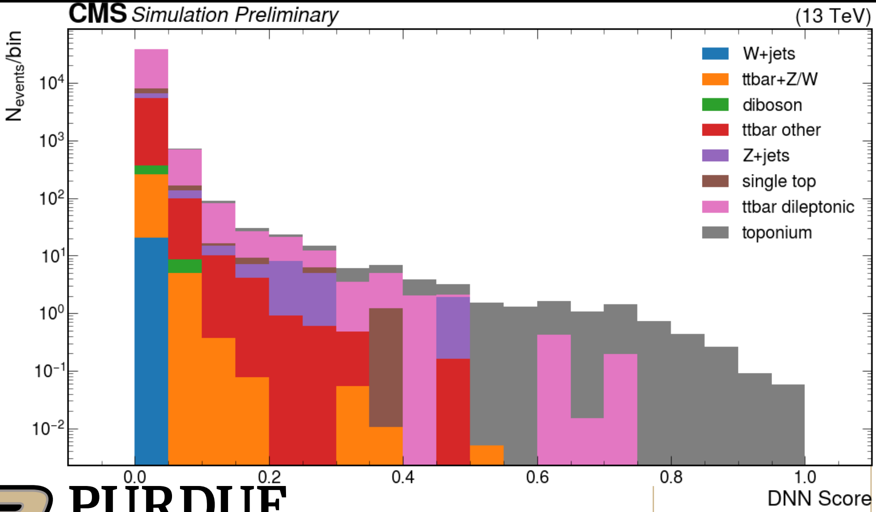
[redacted]



Events
5000
4000
3000
2000
1000
0
400
600
800
1000
1200
$m_{t\bar{t}}$
ttbar other
diboson
ttbar+Z/W
single top
Z+jets
W+jets
ttbar signal
GEN toponium


CMS Simulation Preliminary
(13 TeV)
Events
175000
150000
125000
100000
75000
50000
25000
0
500
1000
1500
2000
2500
3000
3500
4000
$m_{t\bar{t}}$
W+jets
ttbar+Z/W
diboson
GEN toponium
single top
Z+jets
ttbar other
ttbar signal


CMS Simulation Preliminary
(13 TeV)
Events
10^5
10^4
10^3
10^2
10^1
W+jets
ttbar+Z/W
diboson
GEN toponium
single top
Z+jets
ttbar other
ttbar signal
500
1000
1500
2000
2500
3000
3500
4000
$m_{t\bar{t}}$


CMS Simulation Preliminary
(13 TeV)
N_events/bin
10^4
10^3
10^2
10^1
10^0
10^−1
10^−2
0.0
0.2
0.4
0.6
0.8
1.0
DNN Score
W+jets
ttbar+Z/W
diboson
ttbar other
Z+jets
single top
ttbar dileptonic
toponium

Questions and Feedback

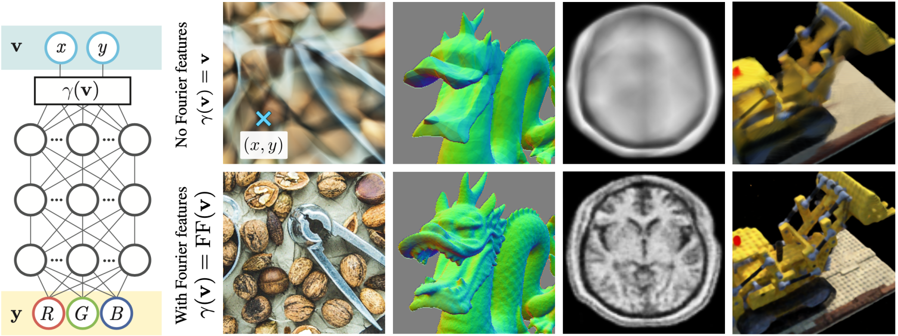
Thank you for your time.
Thank you for allowing me to take part in this internship.
Special thanks to AJ and Jason T. of the Jung Group, and Dr. Jung, Dr. Pando, Dr. Geller, Dr. Dahl, Dr. Fong, Dr. York, and Dr. Swordy.

References

- "Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s}$= 13 TeV" (2019) [arXiv:1907.03729v2]
- "Measurement of the $t\bar{t}$ production cross-section and lepton differential distributions in e dilepton events from pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector" (2020) [arxiv:1910.08819]
- "Signatures of toponium formation in LHC run 2 data" (2021) [arXiv:2102.11281v2]

Mathematical Statement of Classifier Problem

For each event, there is a list of cms2016 data and delphes gen-level data for toponium.** How to overcome class imbalance when training the classifier? SMOTE? No. Upsampling? Yes.



(a) Coordinate-based MLP

(b) Image regression $(x,y) \to$ RGB

(c) 3D shape regression $(x,y,z) \to$ occupancy

(d) MRI reconstruction $(x,y,z) \to$ density

(e) Inverse rendering $(x,y,z) \to$ RGB, density

$width = 400$
$dropout_probability = 0.05$
$best_model = nn.Sequential(nn.Dropout(dropout_probability),$
$nn.Linear(7, width), nn.BatchNorm1d(width),$
$nn.LeakyReLU(0.01), nn.Linear(width, width),$
$nn.BatchNorm1d(width), nn.LeakyReLU(0.01),$
$nn.Dropout(dropout_probability),$
$nn.Linear(width, width),$
$nn.BatchNorm1d(width), nn.LeakyReLU(0.01), nn.Dropout(dropout_probability$
$nn.Linear(width, width),$
$nn.BatchNorm1d(width), nn.LeakyReLU(0.01), nn.Dropout(dropout_probability$
$nn.Linear(width, 1), nn.Sigmoid()passoutputthroughsigmoidtogetpredictionsin$

Goal of Toponium analysis

A lot of work done so far:

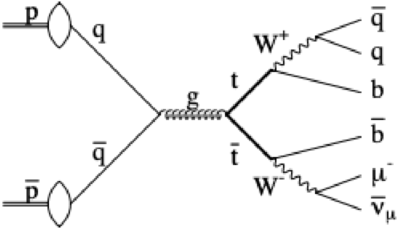
- MadGraph
- PYTHIA
- delphes
- BiLSTMs
- transformers??

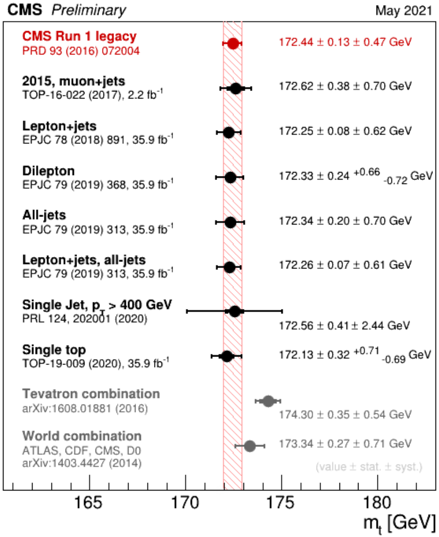
Goal: Put a limit on the cross section for Toponium using Higgs PAG - combine and machine learning tools.

Backup 0

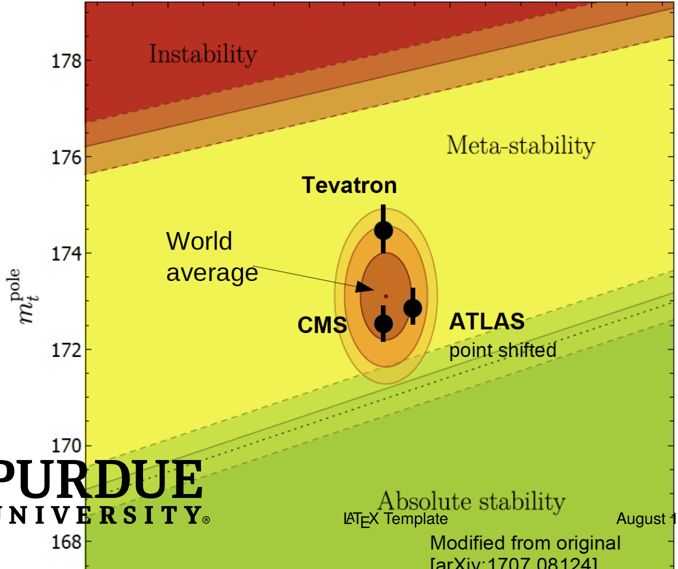
Top quark discovery (Tevatron, 1995)

$p\bar{p} \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (bq\bar{q})(\bar{b}\,\mu^-\bar{\nu}_\mu) \rightarrow 4jets+\mu^-\ \bar{\nu}_\mu$




CMS Preliminary
May 2021
CMS Run 1 legacy
PRD 93 (2016) 072004
172.44 ± 0.13 ± 0.47 GeV
2015, muon+jets
TOP-16-022 (2017), 2.2 fb^{-1}
172.62 ± 0.38 ± 0.70 GeV
Lepton+jets
EPJC 78 (2018) 891, 35.9 fb^{-1}
172.25 ± 0.08 ± 0.62 GeV
Dilepton
EPJC 79 (2019) 368, 35.9 fb^{-1}
172.33 ± 0.24 $^{+0.66}_{-0.72}$ GeV
All-jets
EPJC 79 (2019) 313, 35.9 fb^{-1}
172.34 ± 0.20 ± 0.70 GeV
Lepton+jets, all-jets
EPJC 79 (2019) 313, 35.9 fb^{-1}
172.26 ± 0.07 ± 0.61 GeV
Single Jet, p_T > 400 GeV
PRL 124, 202001 (2020)
172.56 ± 0.41 ± 2.44 GeV
Single top
TOP-19-009 (2020), 35.9 fb^{-1}
172.13 ± 0.32 $^{+0.71}_{-0.69}$ GeV
Tevatron combination
arXiv:1608.01881 (2016)
174.30 ± 0.35 ± 0.54 GeV
World combination
ATLAS, CDF, CMS, D0
arXiv:1403.4427 (2014)
173.34 ± 0.27 ± 0.71 GeV
(value ± stat. ± syst.)
165
170
175
180
m_t [GeV]

Backup 1



Modified from original [arXiv:1707.08124]

Backup 2

$t\bar{t}$ Kinematic Reconstruction

- The four momenta of the neutrinos in the decay are needed to fully reconstruct the top quark four momenta
- Analytical solutions are obtained by applying six kinematic constraints:

$$E_x^{miss} = p_{x,\nu} + p_{x,\bar{\nu}}$$

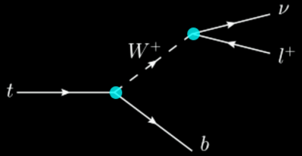
$$E_y^{miss} = p_{y,\nu} + p_{y,\bar{\nu}}$$

$$m_{W^+}^2 = (E_{l^+} + E_\nu)^2 - (p_{x,l^+} + p_{x,\nu})^2 - (p_{y,l^+} + p_{y,\nu})^2 - (p_{z,l^+} + p_{z,\nu})^2$$

$$m_{W^-}^2 = (E_{l^-} + E_{\bar{\nu}})^2 - (p_{x,l^-} + p_{x,\bar{\nu}})^2 - (p_{y,l^-} + p_{y,\bar{\nu}})^2 - (p_{z,l^-} + p_{z,\bar{\nu}})^2$$

$$m_t^2 = (E_{l^+} + E_\nu + E_b)^2 - (p_{x,l^+} + p_{x,\nu} + p_{x,b})^2 - (p_{y,l^+} + p_{y,\nu} + p_{y,b})^2 - (p_{z,l^+} + p_{z,\nu} + p_{z,b})^2$$

$$m_{\bar{t}}^2 = (E_{l^-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (p_{x,l^-} + p_{x,\bar{\nu}} + p_{x,\bar{b}})^2 - (p_{y,l^-} + p_{y,\bar{\nu}} + p_{y,\bar{b}})^2 - (p_{z,l^-} + p_{z,\bar{\nu}} + p_{z,\bar{b}})^2$$



- Choose the solution that gives lowest $t\bar{t}$ invariant mass
- Reconstruct each event 100 times smearing W mass, jet and lepton directions and energies by their resolutions
- The solution to the top quark three momenta is the weighted average of the solutions corresponding to all lepton-jet pairs (preferring the ones with most b-tags);

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Backup slide 3

"Owing to its large mass, the lifetime of the top quark is very short. Consequently, the top pairs produced in the process $q\bar{q} \rightarrow t\bar{t}$ do not have time to form bound states, such as those observed in the resonant production of charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) states"..."Hence the top quark lifetime is of order t = 1/t 5 × 1025 s. This is sufficiently short that the top quarks produced at the Tevatron decay in a distance of order 1016 m. This is small compared to the typical length scale for the hadronisation process, and therefore the tt pairs produced at the Tevatron not only decay before forming a bound state, but also decay before hadronising." (Thomson)