Setting limits on the Toponium cross section

A short survey

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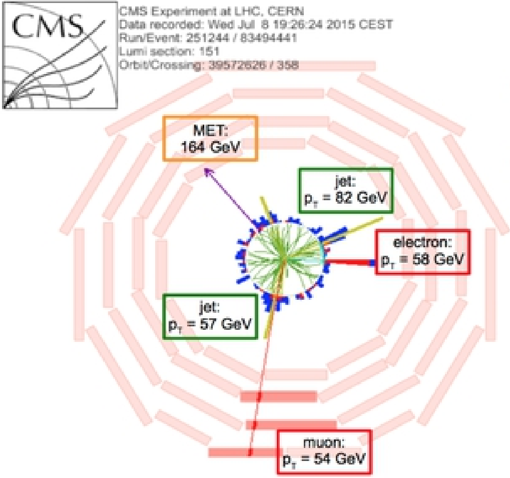
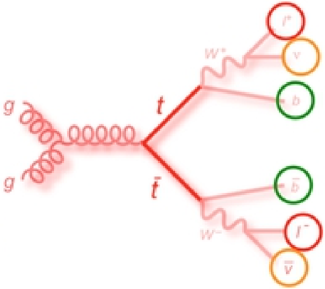
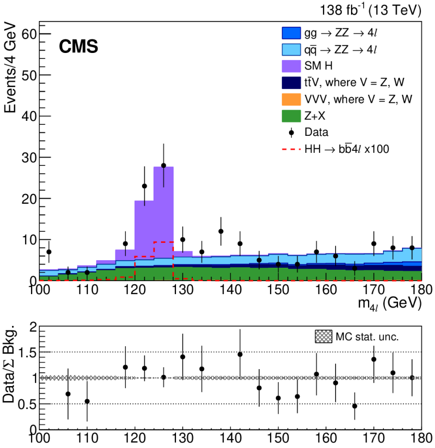
CMS Internship, June 2022

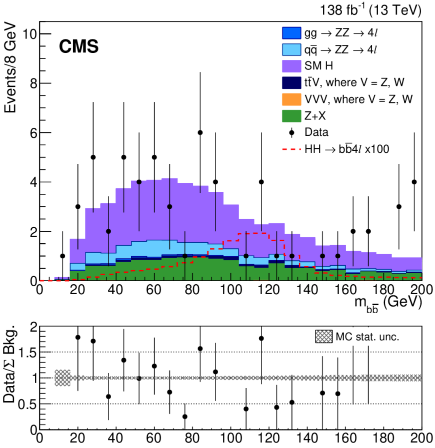

CMS
CMS Experiment at LHC, CERN
Data recorded: Wed Jul 8 19:26:24 2015 CEST
Run/Event: 251244 / 83494441
Lumi section: 151
Orbit/Crossing: 39572626 / 358
MET:
164 GeV
jet:
p_T = 82 GeV
electron:
p_T = 58 GeV
jet:
p_T = 57 GeV
muon:
p_T = 54 GeV


g
g
t
t̄

Kismet



138 fb^{-1} (13 TeV)
CMS
Events/4 GeV
$gg \to ZZ \to 4l$
$q\bar{q} \to ZZ \to 4l$
SM H
$t\bar{t}V$, where V = Z, W
VVV, where V = Z, W
Z+X
Data
$HH \to b\bar{b}4l$ x100
m_{4l} (GeV)
Data/Σ Bkg.
MC stat. unc.



138 fb^{-1} (13 TeV)
CMS
Events/8 GeV
$gg \to ZZ \to 4l$
$q\bar{q} \to ZZ \to 4l$
SM H
$t\bar{t}V$, where V = Z, W
VVV, where V = Z, W
Z+X
Data
$HH \to b\bar{b}4l$ x100
$m_{b\bar{b}}$ (GeV)
Data/Σ Bkg.
MC stat. unc.

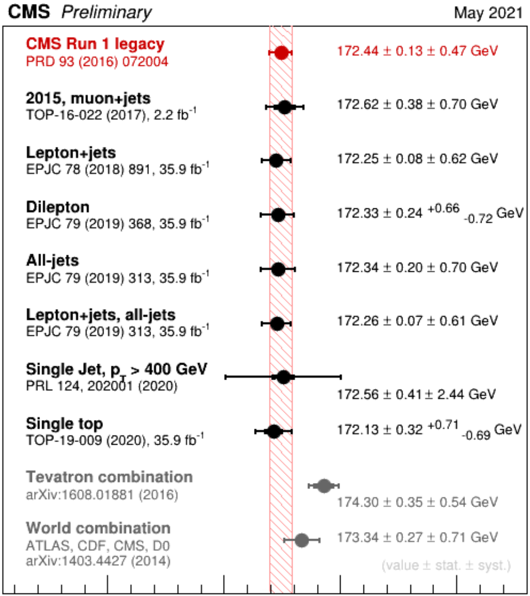
In short

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.

This may be wrong.

Top Quark Mass



About Toponium

Toponium is a hypothesized bound state between the top quark and its antiquark that was believed could not exist because the mismatch between the decay time and hadronization time of the top quark. Recent mismatches between Monte Carlo models and the observed data at the 3 sigma level suggests that toponium may exist. If it exists, it likely only forms for less than 0.5% of $t\bar{t}$ pairs produced. 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: $gg \rightarrow t\bar{t} \rightarrow (bW^+)(\bar{b}W^-) \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell)$

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

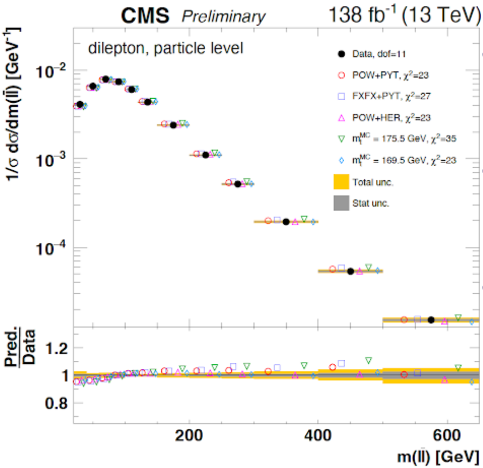
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}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

2008 theory starts to build

With its respectively short lifetime of order 0.5×10^{-24} s, the top quark is expected to decay before top-flavored hadrons or $t\bar{t}$ -quarkonium bound states can form although as far back as in [1987] possibilities for formation of toponium at $m_t \approx 170$ GeV were discussed.[arXiv:0806.4747][hep−ph]

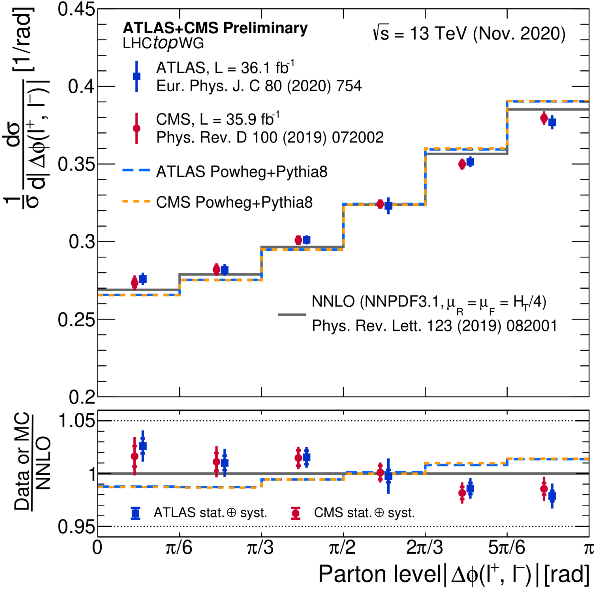
$$\mathcal{L} = \bar{\psi}_q(i\gamma^\mu)(D_\mu)\psi_q - m_q\bar{\psi}_q\psi_q - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}$$

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

More evidence?



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.

Analysis cont.

The theoretical mass of toponium is expected to be 343 GeV. In particle detectors one does not typically observe the particle mass but rather some observable that is sensitive to mass. Since toponium is a resonance, a cut on invariant mass would make sense, but the current resolution for the Jung Group is at most 50 GeV near threshold. (We need a resolution of roughly 3 GeV.) Therefore, any useful invariant mass cut is out of the question. We want some parameter that highly distinguishes between background and toponium. This requires machine learning and a careful shape-based statistical analysis.

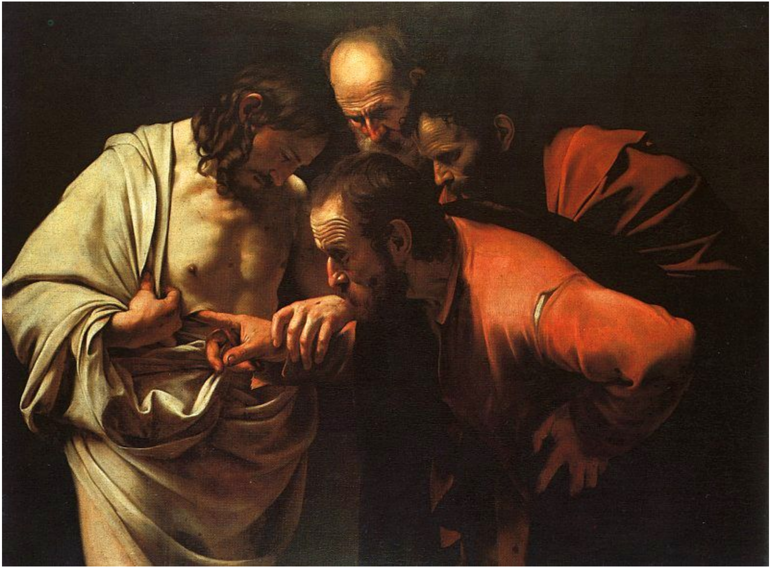
Method

- Techniques used to identify final state particles and their evaluation: neural network methods are used.
- Event Selection Criteria: TBD. Maybe use the same as Fuks et al?
- Background determination: Comes from NN classifier.
- Uncertainties: 20 known of in analysis thus far.
- Expected Results: Make a plug-and-play limit setting procedure that can be used with any Monte Carlo data and hopefully with real data in the near future

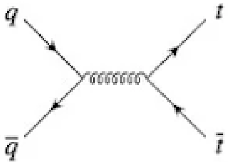
Citations

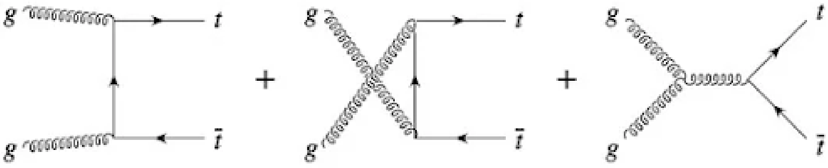
- "Estimates for parameters and characteristics of the confining SU(3)-gluonic field in the ground state of toponium: Relativistic and nonrelativistic approaches" (2008) [arXiv:0806.4747]
- "Top-Quark Decay at Next-to-Next-to-Leading Order in QCD" (2013) [arXiv:1210.2808v3]
- "First combination of Tevatron and LHC measurements of the top-quark mass" (2014) [arxiv:1403.4427]
- "Measurement of the top quark polarization and tt¯ spin correlations using dilepton final states in proton-proton collisions at s= 13 TeV" (2019) [arXiv:1907.03729v2]
- "Measurement of the tt¯ production cross-section and lepton differential distributions in e dilepton events from pp collisions at s=13 TeV with the ATLAS detector" (2020) [arxiv:1910.08819]
- "Signatures of toponium formation in LHC run 2 data" (2021) [arXiv:2102.11281v2]

Questions?



Top Quark Physics



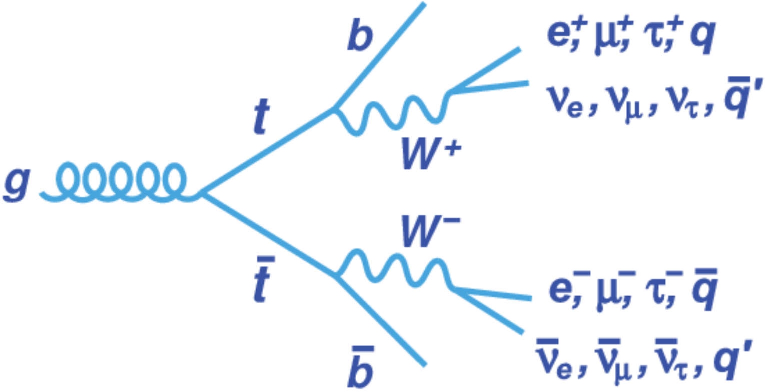


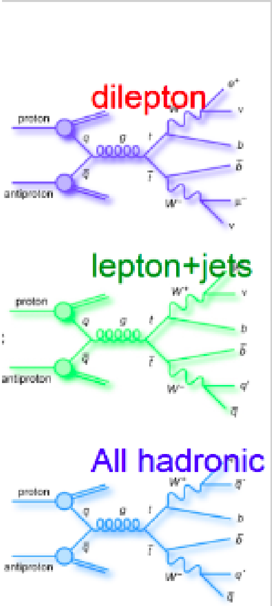
Shape-based analysis

Compared to counting experiments, the effect of uncertainties that change the shape of the distribution must also be considered in a shape-based analysis. The systematic uncertainties are based on the differences in the shapes of histograms.

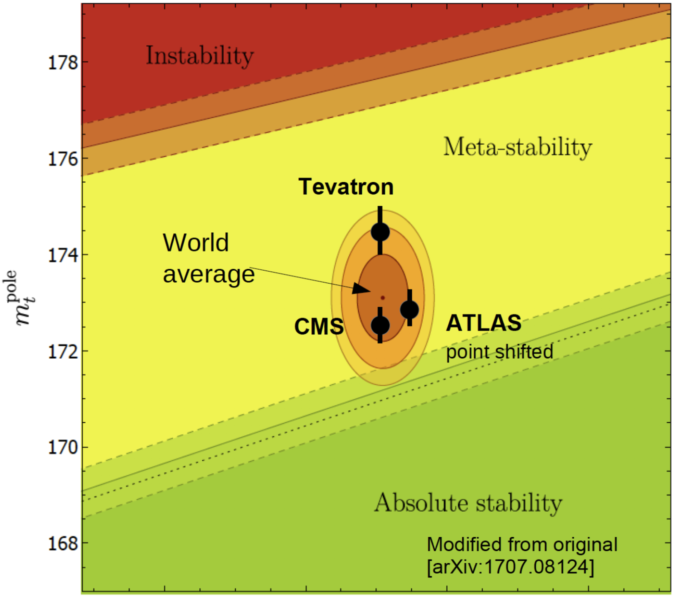
> *So you'll be inputting histograms for combine and from the differences in these shapes of the histograms it will fit for an expected limit and uncertainty from the systematic variation histograms. Sometimes we don't have shape based uncertainties but scale factor based uncertainties. Where a flat scale factor is applied per bin with an uncertainty associated with that scale factor. Same factor for all bins. (AJ)*

Top Quark Physics




dilepton
proton
antiproton
lepton+jets
proton
antiproton
All hadronic
proton
antiproton

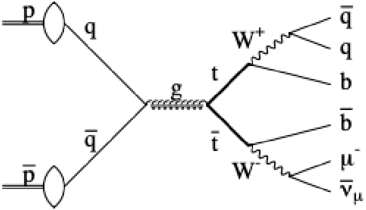
Backup slide 1



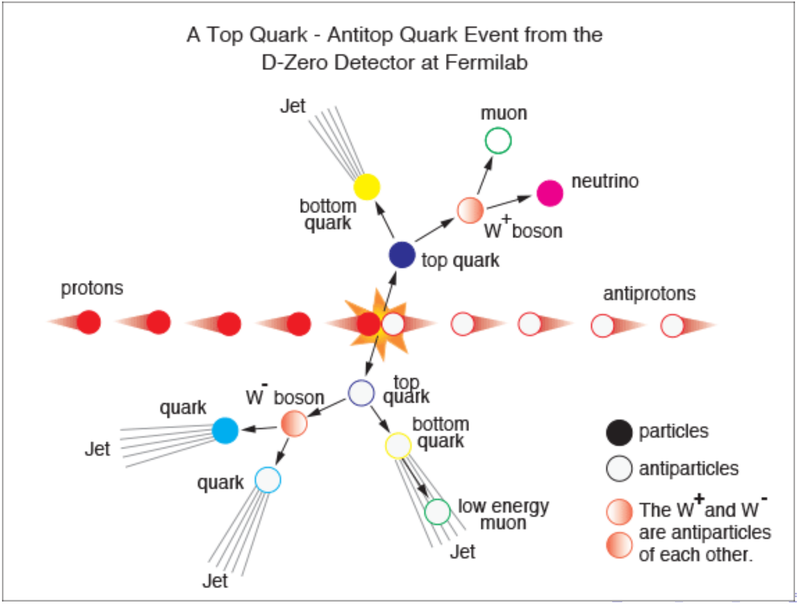
Backup slide 2

Top quark discovery (Tevatron, 1995)

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



Top Quark Physics



Backup slide 3

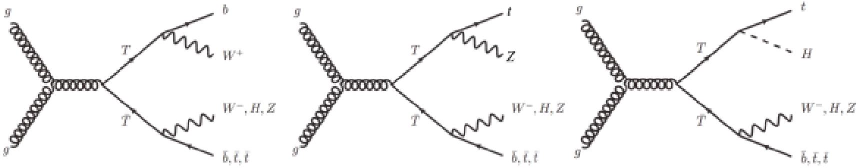


Figure 1: Feynman diagrams showing pair production of $T\bar{T}$ with T decaying to (left) bW, (middle) tZ, and (right) tH.