Search for heavy narrow resonances decaying to $t\bar{t}$ in the muon+jets channel at CMS

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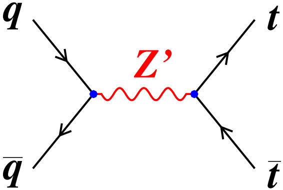
Introduction

The top quark has the largest mass among the Standard Model particles. As such, it plays some special role in some theories Beyond the Standard Model.



Some models predict resonances coupling favorably to top quarks. In this case, the $\mathrm{t\bar{t}}$ decay channel is the most prominent discovery channel.

This analysis is a model-independent search for narrow resonances $\mathrm{Z}' \rightarrow \mathrm{t\bar{t}}$ and provides limit on the cross section $\sigma(\mathrm{Z}' \rightarrow \mathrm{t\bar{t}})$ as a function of $m_{\mathrm{Z}'}$. The techniques can also be used for other studies of high $m_{\mathrm{t\bar{t}}}$ events, irrespective of their origin.

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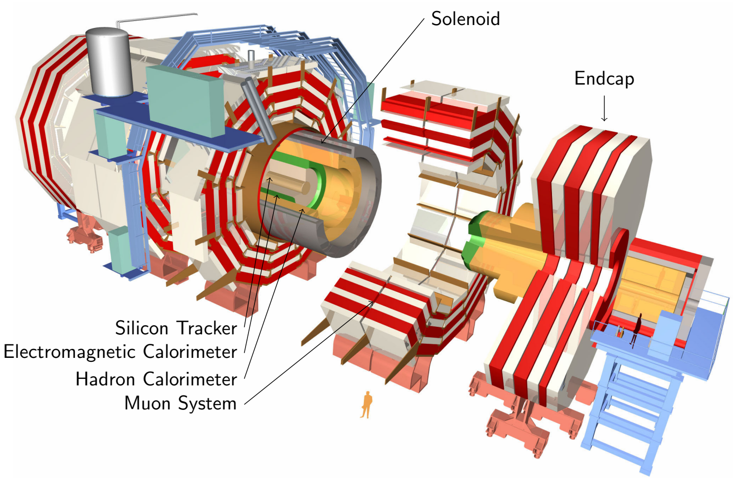
The CMS Experiment



The Solenoid provides a magnetic field of 3.8 T used to measure the momentum of charged particles in the silicon tracker.

The 10 000-foot View

1. Use Monte-Carlo event generators to generate signal and background events
2. On simulation, study differences between signal and background and develop an event selection
3. Develop event selections to select background events to check/enhance/replace the Monte-Carlo modeling
4. Apply all this on events recorded by the CMS detector

The separation of signal and background events is done on a statistical basis comparing expected and observed distributions for variables different in signal and background. Here, use the reconstructed invariant mass of the $\mathrm{t\bar{t}}$ system, $M_{\mathrm{t\bar{t}}}$.

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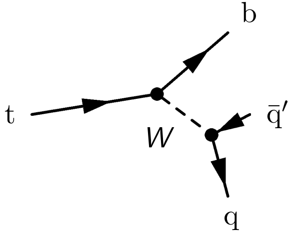
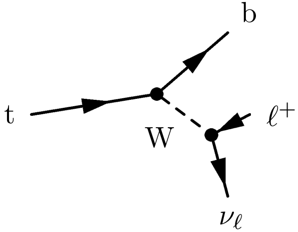
Top Quark Properties

The top mass $m_{\mathrm{t}} = 173.2 \pm 0.9\ \mathrm{GeV}/c^2$ [Tevatron Electroweak Working Group, arXiv:1107.5255], the SM top pair production cross section at the LHC is 163 ± 11 pb [NNLO from HATHOR, arXiv:1007.1327].

The Top quark decays in almost all cases to a b-quark and a W boson. The W boson in turn decays either into quarks or a lepton + neutrino:

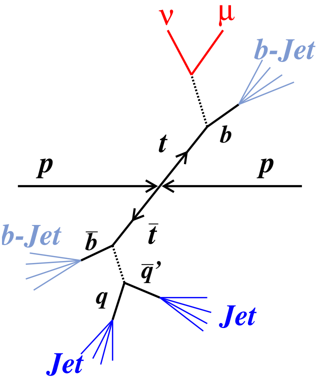


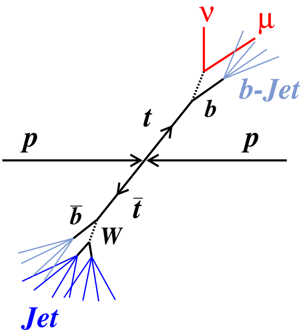


This analysis considers the "semileptonic muon channel" which is defined by one top decaying to $\mu\nu\mathrm{b}$ and the other hadronically to $\mathrm{q}\bar{\mathrm{q}}'\mathrm{b}$.

Signal Topology

Going from SM $\mathrm{t\bar{t}}$ to high-mass bsm $\mathrm{t\bar{t}}$ muon+jets topology:



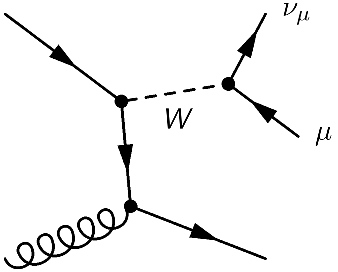


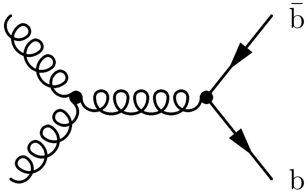
One muon, missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$), jets. But: high top quark p_T leads to small ΔR between decay products $\rightsquigarrow$ not always 4 reconstructed jets

Selection

- muon trigger, exactly 1 muon and no electron
- ≥ 2 jets with $p_T > 50$ GeV$/c$, leading jet $p_T \geq 250$GeV$/c$
- $H_{\mathrm{T,lep}} > 150$ GeV, where $H_{\mathrm{T,lep}} = E_{\mathrm{T}}^{\mathrm{miss}} + p_{T,\mu}$

Standard Model backgrounds are QCD $\mathrm{t\bar{t}}$, W+jets, QCD multijet (including μ from heavy flavor decays) and a little Z+jets, single top.

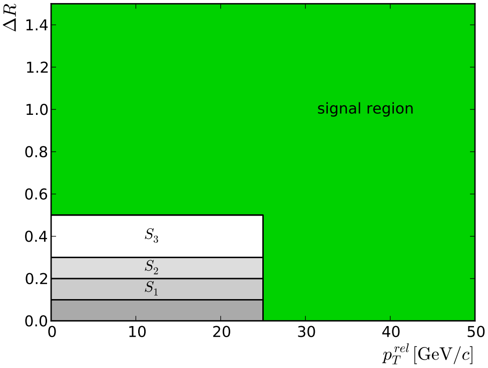




With decays $\mathrm{b} \rightarrow B \rightarrow \mu + X$

Muon 2D-cut

For each reconstructed muon, search the next jet in the $\eta - \phi$-plane. Only consider the muon as "prompt" if it has $\Delta R > 0.5$ or $p_{T,\mathrm{rel}} > 25\mathrm{GeV}/c$ w.r.t. this jet.



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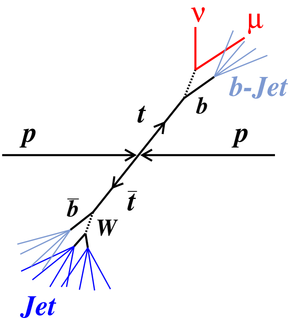
$M_{t\bar{t}}$ Reconstruction



Construct a list of hypotheses for jet assignment and neutrino solutions:

- One or two solutions for the neutrino momentum from W mass constraint, take real part in case of complex solutions.
- Assign each jet to either the leptonically or hadronically decaying top quark or to none of them.

Filter the list of hypotheses based on the leptonic top by keeping only hypotheses with smallest

$$\sum \Delta R = \Delta R(b_{lep}, t_{lep}) + \Delta R(\nu, t_{lep}) + \Delta R(\mu, t_{lep}).$$

Then choose the hypothesis with largest $\Delta R(t_{had}, t_{lep})$.

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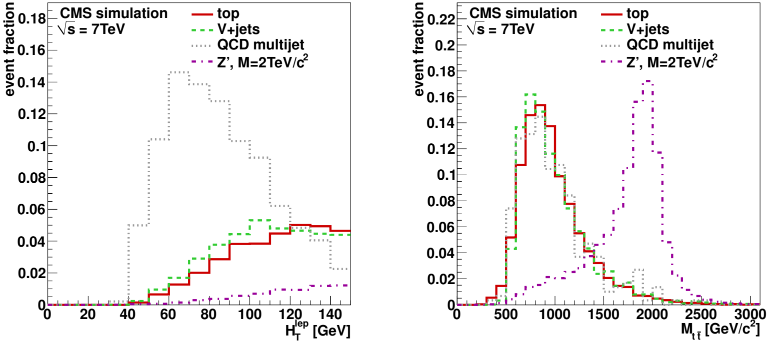
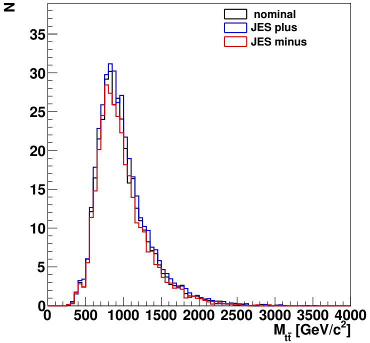
Analysis Strategy

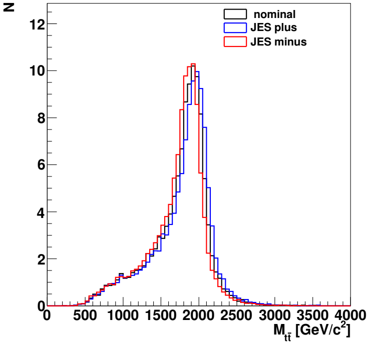
Use the $M_{t\bar{t}}$ distribution after the selection and the $H_{T,lep}$ distribution for $H_{T,lep} < 150$ GeV for the statistical evaluation:



Systematic Uncertainties

Different sources of uncertainty can affect the event selection and reconstruction. In general, each uncertainty results in "shifted templates":





List of Systematic Uncertainties

- Jet energy scale: vary jet energies within their uncertainties (2–3%)
- Jet energy resolution: vary jet energy resolution within its uncertainty (10–20%)
- Uncertainty on the integrated Luminosity ($\pm$4.5%)
- Q^2 renormalization and factorization scale: by a factor of 0.5 / 2 for $\mathrm{t\bar{t}}$, $\mathrm{W/Z}$+jets
- ME-PS matching: modify parametrs for the MLM matching algorithm used in $\mathrm{t\bar{t}}$ and $\mathrm{W/Z}$+jets simulation
- Modify Pythia shower parameters for $\mathrm{t\bar{t}}$
- Theory uncertainty on cross sections: 15% for $\mathrm{t\bar{t}}$.

QCD yield and $\mathrm{W/Z}$+jets yield are free parameters in the stat. treatment.

Limit Calculation

Evaluate Bayesian 95% C.L. upper limits, using Poisson statistics in each bin of the templates $H_{\mathrm{T,lep}}$ and $M_{\mathrm{t\bar{t}}}$. The limit is the value $\hat{\beta}_{\mathrm{Z'}}$ for which

$$\int_0^{\hat{\beta}_{\mathrm{Z'}}} \mathrm{d}\beta_{\mathrm{Z'}} \int \mathrm{d}(\beta_k, \delta_u) p(\beta_{\mathrm{Z'}}, \beta_k, \delta_u) = 0.95.$$

where β_k are the template scale factors and δ_u are nuisance parameters used to interpolate between nominal and shifted templates.
This integral has 13 dimensions and is evaluated with a Markov-Chain Monte-Carlo method implemented in theta.

Commercial Break: theta

During the analysis, I developed the theta framework which can be used for statistical inference.

Models are based on binned templates/data and can include

- rate uncertainties using gamma, log-normal, or Gaussian priors (or user-written plugins!)
- shape uncertainties using bin-by-bin interpolation

Statistical methods include Markov-Chain Monte-Carlo for Bayesian limits / posteriors, CLs limits, profile likelihood intervals, and more.

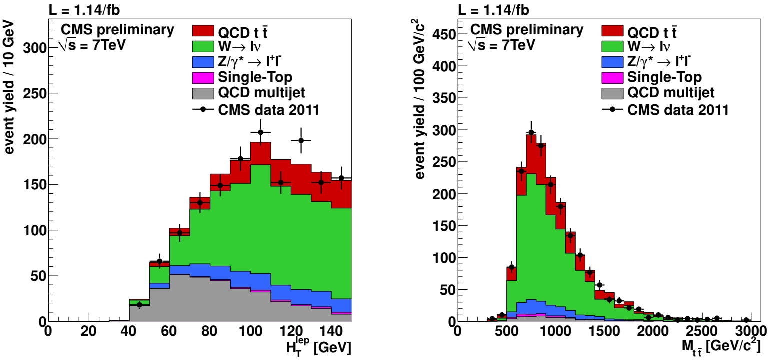
theta has very high runtime performance and contains robust implementations for many methods. It is used in a growing number of Top, Exo, and Higgs analyses at CMS.

Θtheta

http://theta-framework.org/

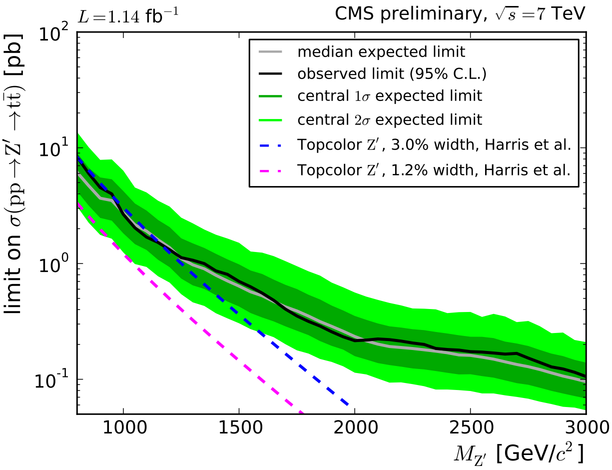
Result

Scaling the templates using the most probable parameters:



Limits

The expected and observed 95% C.L. upper limits:



Conclusion and Outlook

Developed selection and reconstruction criteria for high-$m_{\mathrm{t\bar{t}}}$ events in the muon+jets channel.

A Topcolor Z' with 3% width is excluded for $805 < m_{\mathrm{Z}'} < 935$ GeV/c^2 and $960 < m_{\mathrm{Z}'} < 1060$ GeV/c^2 and model-independent sub-picobarn limits on $\sigma(\mathrm{Z}' \to \mathrm{t\bar{t}})$ are set.

This analysis is publicly available in CMS Physics Analysis Summary EXO-11-055.

Future plans include:

- Use of top-tagging algorithms in the event selection which identify high-p_T, hadronically decaying top quarks by searching jet substructure
- Use of b-tagging in the event selection
- Statistical combination with all-hadronic and electron+jets analyses