Top quarks and search for New Physics

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*LIP Lisbon*

- Heavy flavor in top events
- Heavy resonances
- SUSY and 4^{th} generation
- Boosted topology
- Same sign
Contents

• Introduction (discovery, object ID)
• Top pair production at the Tevatron
• Top pair production at LHC

• Properties, mass
• Spin correlation, charge asymmetry, etc.

• Single top production
• Flavor Changing Neutral Currents (FCNC)

• $V_{tb}$, Search for top partners and 4$^{th}$ generation quarks
• Search for $t\bar{t}$bar resonances, same-sign, boosted tops
Interesting physics with Top quark

**PRODUCTION**
Cross section  
Resonances $X \rightarrow tt$  
Fourth generation $t'$  
Spin-correlations  
New physics (SUSY)  
Flavour physics (FCNC)  
...

**PROPERTIES**
Mass  
Kinematics  
Charge  
Lifetime and width  
W helicity  
Spin  
...

**DECAY**
Branching ratios  
Charged Higgs (non-SM)  
Anomalous couplings  
Rare decays  
CKM matrix elements  
Calibration sample @LHC  
...

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Top decays

top decay $t \rightarrow Wb$, but really 100%?

Indirect measurement using the CKM matrix:
- Elements $|V_{ub}|$ and $|V_{cb}|$ measured to be very small from decay of B mesons
- Unitarity and only three generations implies $|V_{tb}|$ is $0.998 \pm 0.002$ @ 90% CL

With top quark samples we can measure it directly as “$R$”:

$$R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

where $q = \{d, s, b\}$

Use the ability to identify jets with a distinguished secondary vertex: b-tagging
- The number of b-tagged jets depends strongly on $R$ and b-tagging efficiency $\varepsilon_b$

We classify the $t\bar{t}$ sample based on the number of b-tagged jets
- The relative rates of events with 0/1/2 b-tags is very sensitive to $R$
Is $\text{BR}(t \to Wb) \sim 100\%$?

- In the SM, $R = \frac{\text{BR}(t \to Wb)}{\text{BR}(t \to Wq)} \approx |V_{tb}|^2$, $0.9980 < R < 0.9984$

- measure $R$ by comparing the number of $t\bar{t}$ events with 0, 1 and 2 $b$-tags

- SM: $R=1$ constrained by CKM unitarity. $R<1$ could indicate new physics (e.g. 4th generation hep/ph-0607115)

Measure $R$ simultaneously with $t\bar{t}$ cross section:

- CDF prelim. 7.5 fb$^{-1}$ lepton+jets channel
- D0 5.4 fb$^{-1}$ l+jets & dilepton
- PRL 107, 121802 (2011)

Not yet sensitive to SM
Measure of $V_{tb}$

- Measurement with the **single top** production final state
- direct measure of $|V_{tb}|$
- sensitive to non-SM phenomena ($W'$, FCNC)

\[ \sigma \approx |V_{tb}|^2 \]
Measure $R$ in dilepton channel

- Probe heavy flavor content of ttbar events
- Use ttbar dilepton final state

Advantages:
- less background

Disadvantages:
- lower statistics
- jet assignment

Selection:
- 2 leptons+ $\geq$2 jets + MET
- no b-tagging in preselection

Clean signature

Goals:
- measure $\epsilon(b)$ and $R$

CMS TOP-11-029

Probability to observe $n$ b-tags as a function of $R$
How to model the background

Events are classified in 3 cases (weight $\alpha$):
1) 2 correctly assigned b-jet
2) 1 corr. ass. b-jet
3) 0 corr. ass. b-jet

$$M_{l,j} \approx \sqrt{m_t^2 - m_W^2} = 156 \text{ GeV}/c^2$$

Compute invariant mass of all lepton-jet pairs
Model background using:
- jets from different events
- rotate lepton direction

Background dominates at $M>M_{\text{cut}}$
Data-driven determination of background

- Reconstruct lepton-jet invariant mass
  - Correct assignment
  - Wrong assignment

- Use tail to model background in signal region
Scale shape to match spectrum observed with $M_{lj} > 180$ GeV

After background subtraction
Heavy flavor content

• Fully data-driven measurement
  – b-tagging multiplicity parametrized as function of $R \varepsilon_b, \varepsilon_q$, top contribution
  – Number of reconstructed $t \rightarrow Wq$ is estimated from lepton-jet invariant mass

• $R=0.98\pm0.04$ (stat.$\oplus$ syst.)
  – Lower boundary with confidence interval @95%CL after requiring $R \leq 1 \Rightarrow R > 0.85$
Measure R

- Variation of the likelihood used to measure $R$ from data
- Fit different categories
Summary of R results

\[ R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow Wq)} \]

- CMS preliminary (2012)
  - \[ l_l: 0.98^{+0.04}_{-0.04} \]
- DØ PRL 107, 121802 (2011)
  - \[ l_l: 0.95^{+0.07}_{-0.07} \]
  - \[ l_l: 0.86^{+0.05}_{-0.05} \]
- DØ PRL 100, 192003 (2008)
  - \[ l_l: 0.97^{+0.09}_{-0.08} \]
- DØ PLB 639, 516 (2006)
  - \[ l_l: 1.03^{+0.19}_{-0.17} \]
- CDF PRL 95, 102002 (2005)
  - \[ l_l: 1.02^{+0.31}_{-0.24} \]
  - \[ l_l: 1.41^{+0.49}_{-0.42} \]
- CDF PRL 86, 3233 (2001)
  - \[ l_l + l_l: 0.94^{+0.31}_{-0.24} \]

95% CL

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b-tagging efficiency

- Can determine b-tag efficiency and/or R
- b-tagging efficiency measured
  - (assume R=1)
- absolute b-tagging efficiency measured from data and predicted from simulation
- Ratio of data/simulation
- Total (stat.+syst.) uncertainties

Results of the fit to the b-tagging multiplicity
How else is top produced?

Standard Model LHC Single Top Production

For single top: see A. Onofre, Lecture #7 March 19, 2012

Resonance Production? 
Top Color-Assisted Technicolor 
OR 
?????
Top quark pair resonance

• No resonance expected in SM

• Why is Top so heavy?
  – new physics?
  – is third generation ‘special’?
  – couples predominantly to third generation quarks

• Top is relatively unknown experimentally

• Experimental check
  – search for a bump in the invariant mass spectrum
Search for resonances

- Semi-leptonic (muon+jets) channel
- $Z' \rightarrow t\bar{t}$ cross section normalized to SM $t\bar{t}$
- Progressive loss in reconstruction ability due to jet merging
Search for resonance $X \rightarrow \text{ttbar}$

Look at the $M_{\text{ttbar}}$ spectrum in the lepton+jets final state, to see any deviation over SM

CDF $L = 4.8 \text{ fb}^{-1}$

D0 $L = 5.3 \text{ fb}^{-1}$

A topcolor leptophobic $Z' \rightarrow \text{ttbar}$ is excluded at 95%CL with:

$M_{Z'} < 900 \text{ GeV}/c^2$

PRD 84, 072004 (2011)

$M_{Z'} < 835 \text{ GeV}/c^2$

arXiv:1111.1271 , PRD

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Search for heavy resonances

- search for narrow heavy resonances decaying to top quark pairs
- Use muon+jet final state
- Look for narrowly collimated decay products
- Reconstruct $t\bar{t}$ invariant mass
- Set limits on $Z'$ production cross section $\sigma(pp \to Z' \to t\bar{t})$
Search for heavy resonances

- search for massive neutral bosons decaying via a $t\bar{t}$ quark pair
- Use lepton+jet final state (electron and muon)
- Reconstruct $M_{t\bar{t}}$ in different categories ($e/\mu$, $n$-jets, $n$ b-tags)
- Model background
- Set limits: leptophobic topcolor $Z'$ with width much less than the detector resolution excluded for masses below 1.3 TeV
Search for ttbar+jet resonance

• Search for a heavy new particle M produced in association with a top quark:
  \[ p\bar{p} \rightarrow Mt \rightarrow \bar{t}qt \]

• Resonance in the system t+jets or ttbar+jets
• Select events in lepton+jets channel with at least 5 jets and 1 b-tag

CDF: 8.7 fb\(^{-1}\)  

![Graph showing resonance in the system t+jets or ttbar+jets](image)

CDF Run II Preliminary
SUSY and 4th generation
One theoretical group predicts lower cross section values.
Charged Higgs

This study focuses on the mass range \(100 \leq H^+ \leq 160\,\text{GeV}/c^2\), where we may observe an anomalous excess of events in the \(\tau\) dilepton channel when compared to the SM decay of \(\tilde{t}\tilde{t} \rightarrow W^+ W^- b\bar{b} \rightarrow \tau\nu_\tau l\nu_l b\bar{b}, \quad l = e, \mu\).

If top decays: \(t \rightarrow H^+ b\) (\(m_H < m_t - m_b\))

Implies a larger measured cross section (see MG, Lecture #6)

\(\Rightarrow\) probe non-standard physics (\(t \rightarrow H^\pm b, \ldots\)
Scalar top quark

- SUSY is one plausible extension of the SM
- due to the heavy top quark, mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$ can be large, such that the lighter stop $\tilde{t}_1$ can be even lighter than the top quark
- Decays dictated by mass spectrum of other SUSY particles

Light stop:

\[ m_{\tilde{t}_1} \leq m_t \]

\[ \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm \rightarrow b + \tilde{\chi}_1^0 + \nu + \ell \]

Heavy stop:

\[ \tilde{t} \rightarrow t\tilde{\chi}_1^0 \]

i.e. similar signature as in ttbar
SUSY: search for scalar top

- Status:
  - Final state: both dileptons and 1 lepton+MET +2 jets+2b jets
  - Limitations due to small xsec, large ttbar background
One example: dilepton sample

Define signal region: look for possible contributions of NP in dilepton sample

- Astrophysical evidence for dark matter suggests it may lie in high MET region
- New physics signals should have large $\sqrt{s}$
- New physics with large cross section should be produced strongly (i.e. large hadronic activity)
Stop quark: lepton+jets

- Investigate same signature in the context of a vector-like top partner, decaying to top plus dark matter candidate
  - search for new particle $T'$ decaying via $T' \rightarrow t + X$ ($X$ invisible)
  - interpret results in terms of a model where $T'$ are exotic fourth generation quarks and $X$ are dark matter particles
- Kinematics similar to SUSY stop scenario
- Study lepton+jets+MET+btag

$$m_T^W \equiv m_T(E_T^f, E_T) = \sqrt{2|E_T^f||E_T|(1 - \cos(\Delta\phi(E_T^f, E_T)))}$$

- set 95% CL limits on $T'T' \rightarrow tt+X$ production
- Exclude 4th generation exotic quarks $T'$ (95% CL) up to $m_T = 360$ GeV for $m_X \leq 100$ GeV
Stop quark: all-hadronic

- signature in the context of a vector-like top partner, decaying to top plus dark matter candidate
- Kinematics similar to SUSY $t \rightarrow t\chi^0$ scenario
- Signature: MET+jets

True MET: $ZZ \rightarrow \nu\nu q\bar{q}$
QCD: mis-measured jet
CDF
Scalar top quark

- Similar event signature as $t\bar{t}$bar dilepton final state
- Reconstruct events under stop hypothesis
- Stop mass as discriminating variable in fit to data
  - Use two categories: with b-tag and without b-tags
  - Results consistent with SM predictions
- Set 95%CL limit in dilepton BR, in 3D space of SUSY particle masses $\tilde{t}_1, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0$

CDF 1.9-2.7fb$^{-1}$

Reconstructed DIL Top Mass

Arbitrary Units

$M_{\text{Top}}^\text{Reco}$ (GeV/$c^2$)

Observed 95% CL

CDF/PUB/TOP/PUBLIC/9439

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• Assume each stop decays to tau and b (R-parity violation)

\[ \tilde{t}_1 \tilde{t}_1 \rightarrow \tau^+ \tau^- b \overline{b} \]

• Similar final state as in ttbar dilepton with taus
• Look for e/\(\mu+\geq 2\) jets + MET
• Define 6 regions in: \(m_T(l,\text{MET})\) vs \(N_{\text{jet}}\) plane
• Find 2 evts in signal region (2.2 expected)
Search for Dark Matter with taus

• search concentrates on heavy BSM particle production
  – astrophysical evidence for dark matter points to the existence of weakly-interacting massive particles (WIMPs) at EWSB scale
  – These particles escape detection ⇒ large MET

• Not constrained to a specific theory
  – general BSM search in events with jets, MET, and OS dileptons (at least one tau)
  – $e\tau_h$, $\mu\tau_h$, $\tau_\tau\tau_h$ final states
Search for 4th generation quarks

• T (or t’) and B (or b’)
• Pair production or single production
• Mechanism and cross section depend on nature of quarks (vector-like, scalar, charge)

Final state is complex
Search for heavy quarks

• Search for heavy quark (q=u,d,c,s,b):

\[ Q\bar{Q} \rightarrow W^+ q W^- \bar{q} \]

• Use dilepton channel
  – Select events with 2 leptons, MET, ≥2 jets
• Reconstruct “top” mass
• Use W collinear approximation for neutrinos
• Set limits: \( M_Q > 350 \text{ GeV} \) @95% CL

ATLAS: arXiv:1202.3389
Search for $b'$ production

- Final state with top-like signature

$$b'\bar{b}' \rightarrow tW^-\bar{t}W^+ \rightarrow bW^+W^-\bar{b}W^-W^+$$
Heavy $t'$: lepton+jets

- Search for the pair production of a 4$^{th}$ generation up-type $t'$ quark
- Study lepton+jets (at least 1 b-tag)
  - Largest background is from $t\bar{t}$
- Reconstruct $t'$ mass
  - Kinematic fit is performed by minimizing the $\chi^2$

$M_{t'} > 560$ GeV

CMS EXO-11-099
Heavy $t'$: lepton+jets

![Graphs showing $H_T$ vs. $M_{fit}$ for different processes such as $\mu+\text{jets}$, $t\bar{t}$ production, $W+\text{jets}$, and $t't' 550 \text{ GeV}$ in CMS preliminary data and simulations at $\sqrt{s} = 7 \text{ TeV}$ with 4.6 fb$^{-1}$.](image)
Heavy $t'$: dileptons

- Search for heavy $t'$ quark in **dilepton** final state
  \[ t'\bar{t}' \rightarrow bW^+\bar{b}W^- \rightarrow b\ell^+\nu \bar{b}\ell^-\bar{\nu} \]
- use variables related to the quark mass to distinguish signal from bkg
  - $M_{\text{top}} < 156$ GeV; Signal region with $M > 170$ GeV
  - use lepton-jet invariant mass
  - lepton-jet pair with minimal $\Delta R$

$M_{t,j} \approx \sqrt{m_t^2 - m_W^2} = 156$ GeV/c$^2$

⇒ observed (expected) 95% C.L. lower bounds on $t'$ mass $557$ (547) GeV

EXO-11-050+update
Boosted topology
• In many models there is high potential to discover new physics in the top sector in search for heavy resonances
  \[ pp \rightarrow X \rightarrow t\bar{t} \]
• Simple approach to merge neighboring jets

• At LHC energy, EWK scale particles produced beyond threshold
• Jets are highly collimated
• Jet-parton matching breaks down
• Decay products and FSR collected in a fat jet

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Jet/Event selection

- Locate hadronic energy deposit in detector by choosing initial jet finding algorithm
- Impose jet selection cuts on fat jet
  - Recombine jet constituents with new algorithm
  - Filtering: recombine n sub-jets min d(i,j)
  - Trimming: recombine sub-jets with min \( p_T \)
- Minimum distance between jets is \( R \)

UE, ISR, Pile-up, hard interaction
• **Highly boosted top**: three hadronic decays of the top are merged in one top jet

• **Moderately boosted top**: three hadronic decays of the top are merged in one $W$ jet plus and one $b$ jet candidates
Boosted top topology

Tested using hadronic top in semilep. tt events:

- One high-\(p_T\) isolated muon from PV.
- At least two jets \(p_T>30\) GeV with a leading jet \(p_T>200\) GeV and at least one b-tagged jet.
- Events with W tagged jets used to reconstruct W and the top mass of the hadronic side.

CMS EXO-11-006
Search for Z’: boosted topology

- Search for massive Z’ resonance
- Search in the all hadronic decay channel for top quarks
- Top quarks are boosted for high mass Z’, jets merge
- Start from jet algorithm, then find jet sub-structure
- QCD background estimated from data (mistag method)
Search for Z': boosted topology

- Massive Z' resonances
  - produce highly Lorentz-boosted top quarks
  - collimated decay products partially/fully merged into single jets
- Two categories of events
  - 1+1 channel comprises di-jet events in which each jet corresponds to a fully merged top candidate
  - 1+2 channel comprises tri-jet events, with a Type-1 top-quark candidate in one hemisphere, and at least two jets in the other, one being a jet from a b quark (no b-tag is applied) and the other a merged jet from a W
- Set upper limits on Z' production: \(~1\text{pb}\)
Boosted semi-leptonic candidate event

Hadronic top candidate

Leptonic top candidate

b tagged jet

Missing ET

ATLAS EXPERIMENT

Run Number: 180400, Event Number: 54251178
Date: 2011-04-29 03:33:58 CEST
Same sign and multi-top
Same sign dileptons

• search for anomalous production of events with two like-sign isolated leptons (e or $\mu$), b-quark jets, and missing energy
• SM sources with two isolated like-sign leptons, jets, and missing energy are rare. Anomalous production of such events would be an indication of new physics
• SUSY models predict presence of 2 to 4 b-quark jets in such events
• fraction of strongly produced SUSY events with top and bottom quarks in the final states is enhanced
Same sign top production

- FCNC in top sector could explain $A_{FB}$ at Tevatron
- t-channel exchange of $Z'$ coupling to $u$ and $t$
- Would manifest as same-sign top pair production
Same sign top production

- Measurements of forward-backward asymmetry $A_{FB}$ in $t\bar{t}$ production at the Tevatron inconsistent (?) with SM
- $A_{FB}$ increases with invariant mass of $t\bar{t}$ system
  - at high (>450 GeV) invariant mass: $A_{FB} = 0.30 \pm 0.07$
- Many attempts to explain $A_{FB}$ invoke FCNC mediated by massive $Z'$ boson
- $Z'$ exchange would create a high inv. mass asymmetry at the Tevatron

$\Rightarrow$ Search for same sign tops in data
  - Berger et al. (arXiv:1101.5625)
Same sign events

CMS EXO-11-065, SUS-11-020

- Similar event selection as in ttbar, except same-sign leptons
- Use sum of jet $p_T$ ($H_T$) and MET
- 7 events are selected in the data
- All main backgrounds data-driven
  - Background dominated by jets faking leptons
  - ttbar lepton+jets with one fake lepton
  - Mis-measured charge in dilepton (DY/ttbar)

- Set exclusion limits
- This FCNC Z’ production limit inconsistent with Tevatron FB asymmetry

- provide constraints on several models in a topology with 2 like-sign leptons, MET, b-jets
  - like-sign top quarks production in Z’ model
  - production of two sbottom quarks

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Same sign top production

• ATLAS and CMS have similar strategy
  – Search for SS di-muon pairs (ATLAS)
  – Any SS lepton pair (CMS)
• Limits set on cross section of SS top pairs
  – CMS, ee,mm,em: $\sigma (Z' \rightarrow ttX) < 17.0$ pb (35 pb$^{-1}$)
  – ATLAS,mm: $\sigma (Z' \rightarrow ttX) < 2.9$–4.0 pb (1.6 fb$^{-1}$)
• Both experiments disfavour the Z’ model as explanation to Tevatron asymmetry $A_{FB}$

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Multi-top production

- Production of 4 tops is an attractive scenario in a number of new physics models (SUSY, compositeness, resonances strongly coupled to top, etc.)
- The SM cross section is a few fb

Multi-top in SUSY? \( \tilde{g}\tilde{g} \rightarrow t\bar{t}t\bar{t}\chi_0\chi_0 \)
- Example: require one muon, at least 8 jets (one central)
- Yields in 30 fb\(^{-1}\) (gluino mass 450 GeV):
  - 330 signal events, 120 ttbar+jets, 30 W+jets

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Multi-top production

• SUSY models with four top quarks
• Consider models of gluino pair production

Type A1: \( \tilde{g} \rightarrow t\tilde{t}\chi_1^0 \)
Type A2: \( \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\chi_1^0 \) (stop on-shell)

• Final state:

\[ tttt\chi_1^0\chi_1^0 \]
Multi-top production

CMS SUS-11-020

- Study of SUSY signal with pairs of sbottom quarks

\[ \tilde{b}_1 \rightarrow t\chi^- \]

Type B1: \( pp \rightarrow \tilde{b}_1\tilde{b}_1^* \)
Type B2: \( pp \rightarrow \tilde{g}b_1, \tilde{g} \rightarrow \tilde{b}_1b \)

- Final states with up to 4 isolated leptons

\[ m(\tilde{b}_1) > 380 \text{ GeV @95\%C.L.} \]
Top quark and new physics

- Top quark production is main background in many searches for new physics
- Top quark sample may be contaminated by NP processes
- Is top quark sample compatible with top quark SM hypothesis?
- Need to compare distributions, gain good understanding of top sample

"core" $t\bar{t}$ region, e.g., $e\mu + \text{MET} + 2\ b$-tags

Event selection region