CMS prospects for boosted objects

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Overview

• Introduction

• CMS boosted object activities

• Boosted top quarks
  - Lepton+jets analyses
    (CMS PAS TOP-09-009, EXO-09-008)
  - All-hadronic analysis
    (CMS PAS EXO-09-002, JME-09-001)

• Summary
Motivation for boosted objects

Many BSM models predict new heavy particles, e.g.:
- SUSY particles: decay cascades → Z, W, H, t
- Heavy dark matter (DM) particles decaying to light DM particles
- Composite fermions: q* → Z q
- KK → WZ ; W' → tb ; X → tt (e.g. X: KK, G, Z')

→ decay products are highly boosted (high $\beta$, $\gamma$) and their decay products (leptons, jets) are collimated

Boosted regime can help to suppress backgrounds:
- VH, H → b$\bar{b}$

Distinguish between hadronic and leptonic final state:
- Leptonic: collimated multi leptons
  (eg. Z → ee, WZ → eeev, DM-decay)
- Hadronic: subjets in fat jets
  (eg. H → b$\bar{b}$, t → bW → bqq')
Boosted object activities at CMS

Leptonic final state
- Excited quark, $q^* \rightarrow Zq \rightarrow eeq$
  - Ongoing analysis
    See talk by James Jackson

Semileptonic final state
- Semileptonic top decay: $t \rightarrow bll\nu$
  - PAS TOP-09-009, EXO-09-008

Hadronic final state
- Boosted Higgs VH, $H \rightarrow b\bar{b}$
  - Ongoing analysis

Semileptonic top decay: $t \rightarrow bqq'$
  - PAS JME-09-001, EXO-09-002

Hadronic top decay: $t \rightarrow bqq'$
  - PAS JME-09-001, EXO-09-002

Dark matter photon ($\gamma^*$) decay
- Ongoing analysis
  See talk by Eva Halkiadakis (at LHC)
Boosted object activities at CMS

I. Leptonic final state

- Excited quark, $q^* \rightarrow Zq \rightarrow eeq$
  - Ongoing analysis
  
  *See talk by James Jackson*

- Dark matter photon ($\gamma^*$) decay
  - Ongoing analysis
  
  *See talk by Eva Halkiadakis (at LHC)*

II. Hadronic final state

- Boosted Higgs VH, $H \rightarrow b\bar{b}$
  - Ongoing analysis

- Hadronic top decay: $t \rightarrow bqq'$
  - PAS JME-09-001, EXO-09-002

III. Semileptonic final state

- Semileptonic top decay: $t \rightarrow bl\nu$
  - PAS TOP-09-009, EXO-09-008
Boosted object activities at CMS

Leptonic final state

- Excited quark, $q^* \rightarrow Zq \rightarrow eeq$
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- Dark matter photon ($\gamma^*$) decay
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  See talk by Eva Halkiadakis (at LHC)

Semileptonic final state

- Semileptonic top decay: $t \rightarrow b\ell \nu$
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Hadronic final state

- Boosted Higgs VH, $H \rightarrow b\bar{b}$
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I. Semi-leptonic final state
- Semi-leptonic top decay: $t \rightarrow bl\nu$
  - PAS TOP-09-009, EXO-09-008

See talk by Eva Halkiadakis (at LHC)

Main topic of this talk
Leptonic final state

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General issues:

- Reconstruction of close leptons ($\Delta R_l \leq 0.1$)
  e.g. less efficient standard e reconstruction

- Leptons might be low energetic ($\sim 5$ GeV)
  e.g. leptons from dark matter decay cascades
Boosted Higgs, $H \rightarrow b\bar{b}$

**Issue:** For $\Delta R_{bb} \lesssim 1$ conventional jet reconstruction will lump together $b$-quark jets $\rightarrow$ poor efficiency and mass resolution

$$R_{bb} \simeq \frac{1}{\sqrt{z(1-z)}} \frac{m_H}{p_T}, \quad (p_T \gg m_H)$$

**Proposed solution - subjet/filter algorithm**  
(J. Butterworth et al., PRL 100, 242001 (2008))

- Adapts to $p_T(H)$-dependence of $R_{bb}$
- Minimizes underlying event and pile up effects for optimal mass resolution

**Atlas:** Confirmation that this idea works with a full detector simulation

**CMS:** ??? (Work in progress)
Boosted top pairs - Motivation

Standard Model:
Top pair production with $p_T > 500 \text{ GeV} \approx 0.5\%$

New physics:
Many heavy particles decaying to top quark pairs are predicted
(spin 0, 1, 2; color singlet and octet; different couplings to SM particles)

Examples:
- Heavy Higgs (spin 0, color singlet)
- Model independent $Z'$ (spin 1, color singlet)
- KK-gluon, coloron, axigluon (spin 1, color octet)
- KK-gravitons (RS/ADD) (spin 2, color singlet)

The heavier these new particles the more boosted are the top quarks
Decay of top quark pairs

Top quark decay

\[ t \rightarrow b \ W \approx 100 \% \]

W boson decay

- 'Leptonic':
  \[ W \rightarrow l \ \nu \approx \frac{2}{9} \quad \text{with } l=e,\mu \]
- Tauonic:
  \[ W \rightarrow \tau \ \nu \approx \frac{1}{9} \quad \text{Difficult to identify} \]
- Hadronic:
  \[ W \rightarrow q \bar{q}' \approx \frac{6}{9} \quad q,\bar{q}' \text{ hadronize to jets} \]

Decay channels of top quark pairs

- Dilepton \( \approx 5\% \)
- Lepton+jets \( \approx 30\% \)
- All hadronic \( \approx 44\% \)
Boosted top pairs - challenge

The larger the invariant top pair mass $M_{tt}$, the more boosted the top quarks and the smaller the angles between the decay products.

**Leptonic side:**
Lepton close to $b$-jet or in $b$-jet
(*lepton not isolated*)

**Hadronic side:**
Jets overlap $\rightarrow$ reconstruction of 1 or 2 jets instead of 3
(*jet with substructure*)

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$M_{tt}$ [GeV/c$^2$]

500 1000 2000
Muon+jets analyses - selection

Standard selection:

- \( N_{\text{jets}} \geq 4 \) \((p_T > 35 \text{ GeV/c, } |\eta|<2.4)\)
- Isolated muon \((p_T > 25 \text{ GeV/c, } |\eta|<2.1)\)

Changes:

- **Low and high \( M_{tt} \) (account not well isolated lepton):**
  - 2D-cut instead of relative isolation cut
    (Rel. isolation relates scalar sum of \( p_T \) ET of tracks (calorimeter deposits) in a cone of \( R=0.3 \) around the muon to the muon momentum)

- **High \( M_{tt} \) (account for jet merging):**
  - \( N_{\text{jets}} \geq 2 \) \((p_T > 50 \text{ GeV/c, } p_{T,\text{jet}} > 260 \text{ GeV/c, } |\eta|<2.4)\)
  - \( H_{\text{lep}} = p_T(\mu) + E_T^{\text{miss}} > 200 \text{ GeV} \)
Muon+jets analyses - reconstruction

Low $M_{tt}$:

- Select 4 jets which minimize $\chi^2$
  
  \( \text{(had. masses } (W,\text{top}), \Delta R(l,b), m_T(l,b,\text{MET}) \text{ and } \Sigma p_T(\text{jets}) \) 

- Perform kinematic fit using selected 4 jets \((E,\eta,\Phi) \text{ of jets, } p_{xyz}(\nu), E(\mu)\)

High $M_{tt}$:

\[ \Delta R_{\text{sum}} = \Delta R(t_\ell, \mu) + \Delta R(t_\ell, \nu) + \Delta R(t_\ell, b_\ell) \]

small separation of decay products

\[ -f_1 \Delta R(t_\ell, t_h) - f_2 M_{t_\ell t_h} \]

large separation of top quarks

reduces tails at low mass edge

with $f_1=0.5$, $f_2=(0,1,5)/\text{TeV}/c^2$ for (2,3,4) jets

![CMS Simulation](image)

**CMS Simulation**

$M_x =$ 1 TeV/$c^2$

- Reconstructed
- Reco. + Kin Fit

![CMS preliminary](image)

**CMS preliminary**

- $f_2 = 5/\text{TeV}/c^2$
- $f_2 = 0$
Muon+jets analyses – top pair mass

Low $M_{tt}$ analysis

- Low background even at small $M_{tt}$
- $M_{tt}$ resolution optimal for low $M_{tt}$

High $M_{tt}$ analysis

- Background relative large at small $M_{tt}$
- $M_{tt}$ resolution optimal for high $M_{tt}$

$\sqrt{s}=10$ TeV
Muon+jets analyses – QCD background

**Low M\(_{tt}\):**
- Determination of \(N_{QCD}\) for \(H_T<350\text{GeV}\) by fitting transverse mass of W boson
- QCD sample selected by inverting 2D-cut \((p_T^{rel}(\mu,\text{jet})<35\,\text{GeV/c}, 0.1<\Delta R_{\text{min}}(\mu,\text{jet})<0.4)\)
- Extrapolate to \(H_T>350\text{GeV}\) by using the ratio of \(N_{QCD}\) of high to low \(H_T\) events

**High M\(_{tt}\):**
- QCD sample selected by inverting 2D-cut
- Contribution of heavy resonances not negligible below \(H_T^{lep}<200\text{GeV}\)
- Simultaneous fit to signal region (A, \(M_{tt}\)) and background region (B, \(H_T^{lep}\))

\[\sqrt{s} = 10\text{TeV}\]
Muon+jets analyses – exp. sensitivity

Low $M_{tt}$ analysis

Good exp. sensitivity at low $M_{tt}$

High $M_{tt}$ analysis

Improved exp. sensitivity at high $M_{tt}$

$\sqrt{s} = 10$ TeV
Hadronic decay of tops – Top Tagging

Top Tagging algorithm, modified CMS version:

- **Cluster input particles** *(calorimeter clusters)* with **$k_T$-like** algorithms with large distance parameter *(R=0.8)* to contain all top decay products into hard jet

\[ d_{ij} = \min(k_{T,i}^n, k_{T,j}^n) \frac{\Delta R_{ij}^2}{R^2} \]

beam distance: \[ d_{iB} = k_{T,i}^n \]

\textbf{C-A:} Capable of discerning components closest to the hard jet → well suited to discriminate softer subjets within harder jets

- **Decompose hard jets** *(p$_T$>250 GeV/c, |y|<2.5)* by undoing clustering steps of cluster sequence
  - Consider only clusters with p$_T$ > 0.05 p$_T^{hard}$
    → throw out soft clusters
  - If two hard parent clusters are found, a further decomposition is performed
    → get 3-4 subjets

Algorithms: $k_T \to n=2$ ;
anti-$k_T \to n=-2$ ;
Cambridge-Aachen (C-A) \( \to n=0 \)
Top Tagger – kinematic cuts

- Mass of original hard jet:
  \[ 100 \text{ GeV/c}^2 < m_{\text{Jet}} < 250 \text{ GeV/c}^2 \]
  *(loose, not optimized)*

- Min. mass of subjet pairs:
  \[ m_{\text{min}} > 50 \text{ GeV/c}^2 \]
  *(chosen to optimize S/\sqrt{B})*

Best discrimination obtained with C-A algorithm
\[ S/\sqrt{B} = 2.4 \text{ (C-A)} , 1.6 \text{ (k}_T \text{)} , 1.3 \text{ (anti-k}_T \text{)} *
Performance of C-A Top Tagger

Efficiency for hadronic top-jets (from MC)
- Top jets with $p_T > 600$ GeV/c: $\varepsilon \approx 46\%$
- Determined from MC, since stat. of top pair events in lepton+jets too low for these $p_T$
  - Largest theory uncertainty (ren. Scale): 3%
  - Jet resolution ($p_T, y, \text{angular}$): $\approx 3\%$ each

Fake rate (data driven method)
- Non top jets with $p_T = 600$ GeV/c: $\varepsilon \approx 1.5\%$
- Use of “anti-tag and probe” method:
  - Select events, where one jet is anti-tagged ($\leq 2$ subjets, $> 2$ subjets but failed kin. cuts)
  - Contamination from continuum top pair production is subtracted (simulation)
  - The other jet (probe-jet) is used to determine the tag-rates
All-hadronic analysis

Selection and backgrounds:

- 2 C-A jets with $p_T > 250$ GeV/c - $|\eta| < 2.5$
- Each jet is tagged by C-A top tagger:
  3 or 4 subjets, $m_{\text{min}} > 50$ GeV/c$^2$, $100$ GeV/c$^2 < m_{\text{jet}} < 250$ GeV/c$^2$
- QCD dijet events dominate
  Small contribution from top pair continuum, $W/Z$+jets and single top negligible

Analysis method:

- Count events in a selected mass window

Sensitivity excellent at high $M_{tt}$

\( \sqrt{s} = 10 \text{ TeV} \)
Overview of CMS activities on boosted objects:

- Boosted top pairs:
  - Modified selection and rec. for lepton+jets due to altered topology
  - Application of C-A top tagger to all-hadronic channel looks promising

Outlook:

- Apply top tagger to lepton+jets analysis
- Handle transition region between non boosted and boosted top

Commissioning of top tagger started (first public results hopefully soon)