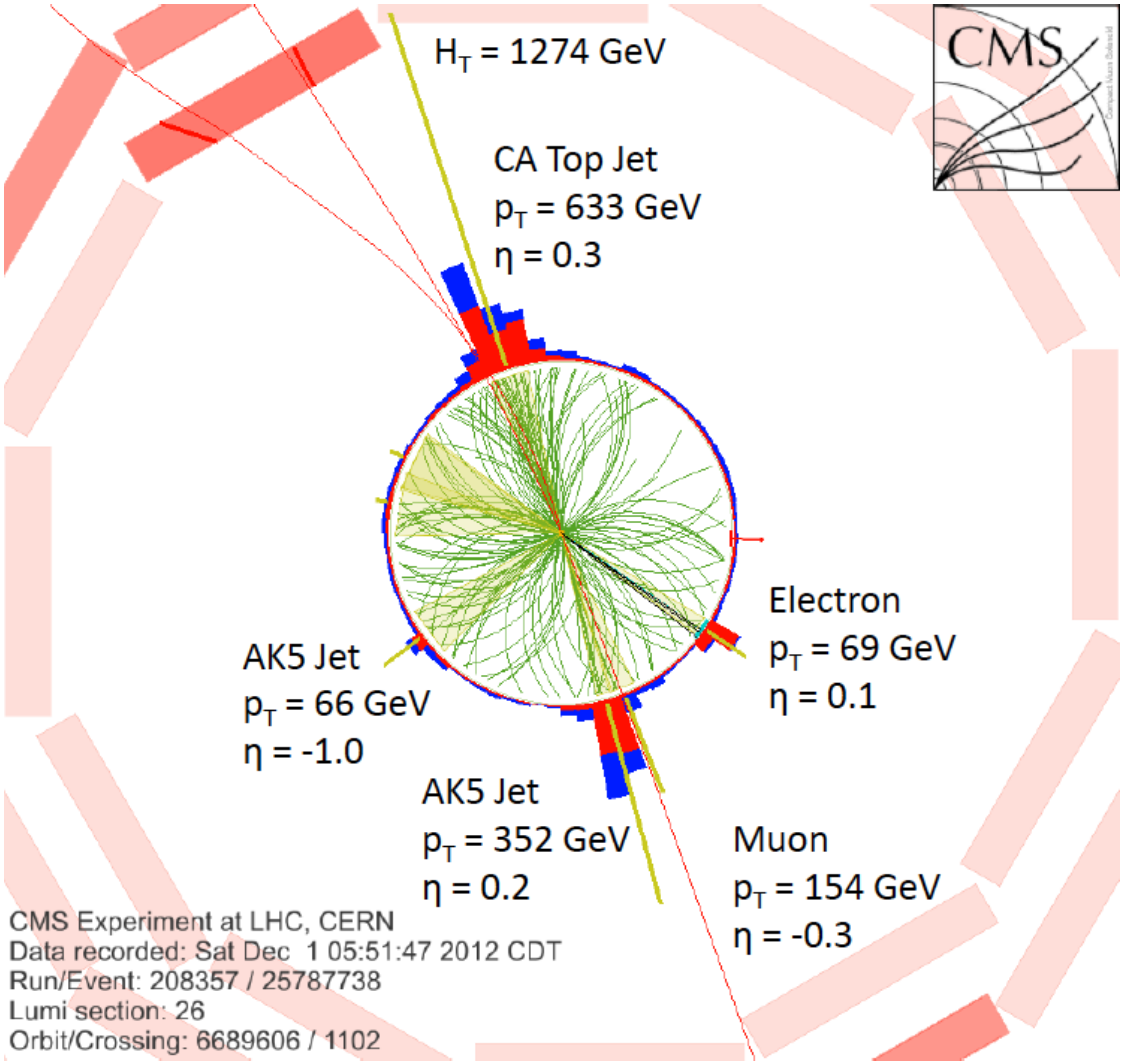


Non-SUSY Quark Partners in Boosted Topologies at CMS

Rebekka Höing
Universität Hamburg
On behalf of the CMS Collaboration

BOOST Workshop 2013
Flagstaff, Arizona
August 14th 2013

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Outline

- **Introduction to theoretical models**
- **Quark Partner Searches at 7 TeV**
- **Quark Partner Searches at 8 TeV with CMS**
  - **Technical Prerequisites:**

    b-tagging

    Jet substructure tools
  - **Analyses covered in this talk:**

    Search for a $T_{2/3}$ with leptons

    Search for a $T_{5/3}$ in the same-sign dilepton channel

Motivation

Higgs boson production cross sections measured at LHC agree well with Standard Model prediction

↓

Existence of **chiral fourth generation** of quarks **highly unlikely** in the SM framework

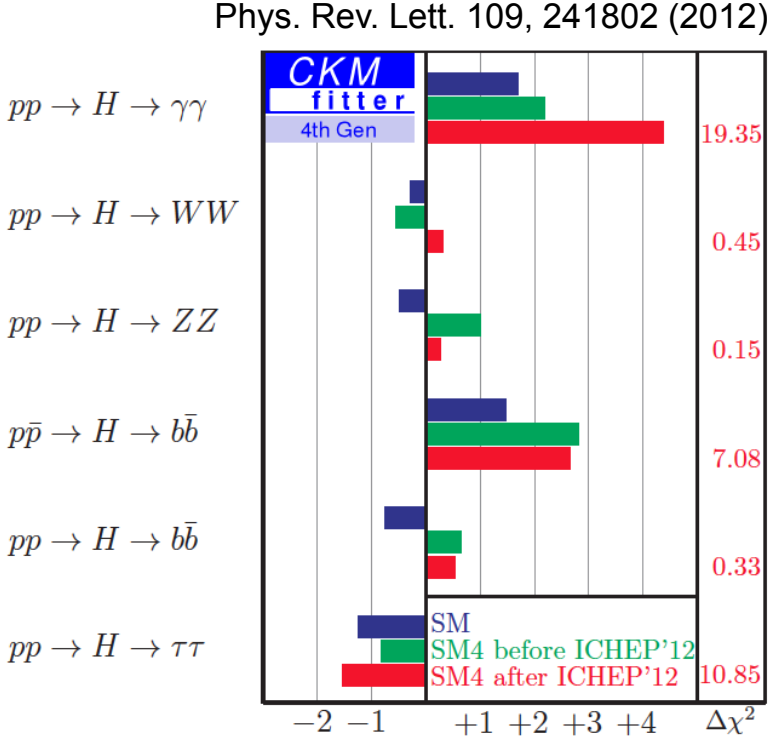
But: Loop corrections to **Higgs mass diverge** at energies well above the electroweak scale

Possible **solution**: Introduce heavy **vector-like top or bottom partners**

↓

Divergent **loop corrections cancel**

Phys. Rev. Lett. 109, 241802 (2012)



Vector-Like Quark Models

Properties of vector-like quarks:

Same transformation under
the e.w. group SU(2) x U(1)
for both chiralities

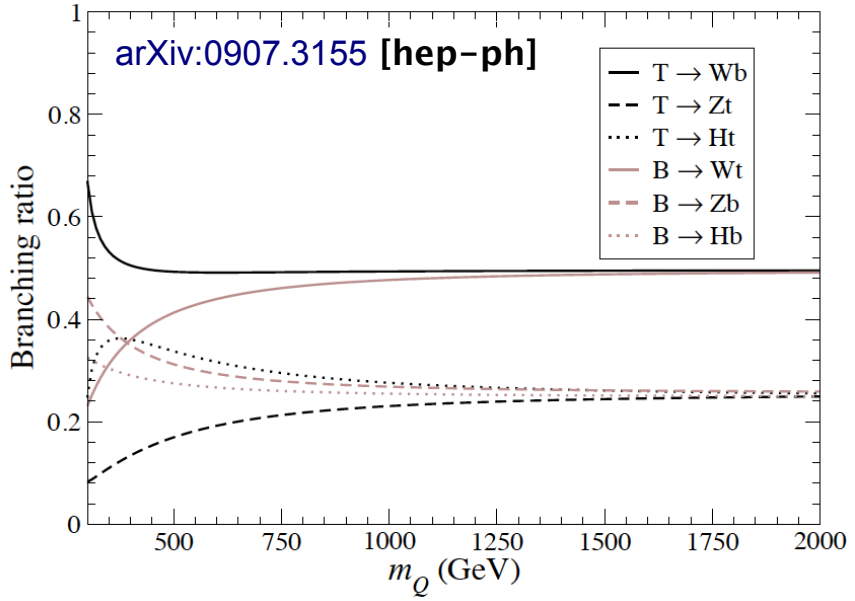
Predicted as singlets or as part of doublets

Vector-like quarks are part of several theories:

- Little Higgs Models
- Composite Higgs Models
- Extra dimensions
- ...

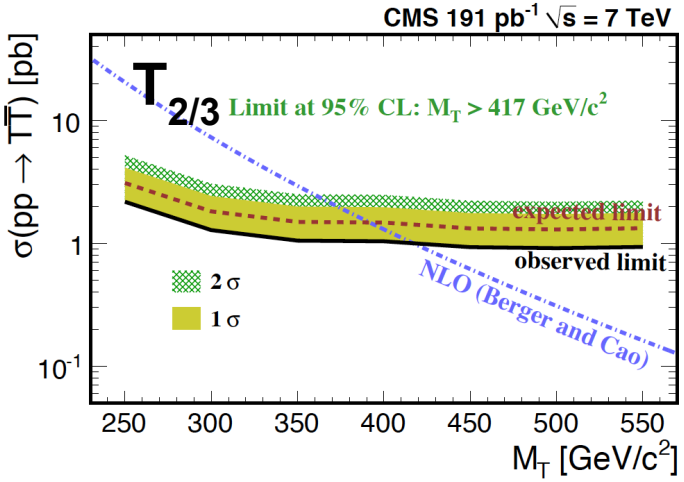
Some models allow for FCNC

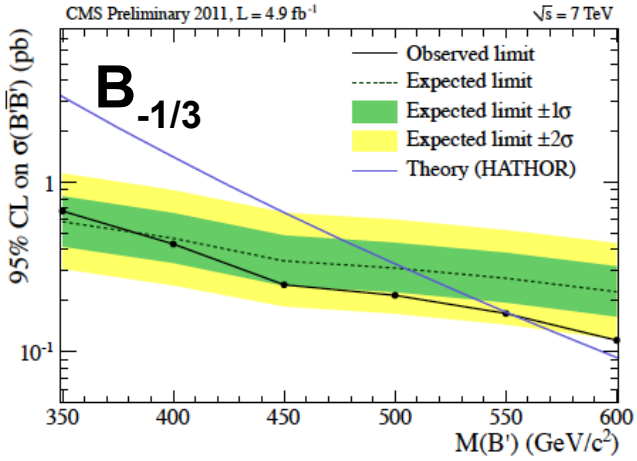
Decay modes:
$T' \rightarrow bW$, $T' \rightarrow tH$, $T' \rightarrow tZ$
$B' \rightarrow tW$, $B' \rightarrow bH$, $T' \rightarrow bZ$

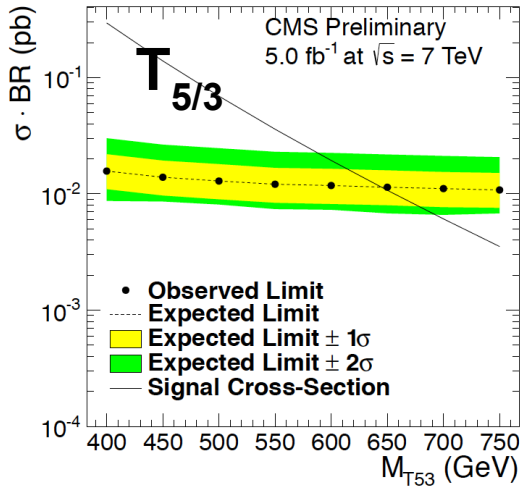


Very massive particles decaying to top or W ➡ jet substructure tools

Quark Partner Searches at 7 TeV







$T_{2/3}$ 100% T → tZ: excluded m < 417 GeV

(CMS-PAS-EXO-11-005)

$B_{-1/3}$ 100% B → bZ: excluded m < 550 GeV

(CMS-PAS-EXO-11-066)

$T_{5/3}$ 100% T → bW: excluded m < 645 GeV

(CMS-PAS-B2G-12-003)

Searches performed in single decay channel

No use of jet substructure

Handles for improvement in 8 TeV analyses

Technical Prerequisites For 8 TeV Analyses

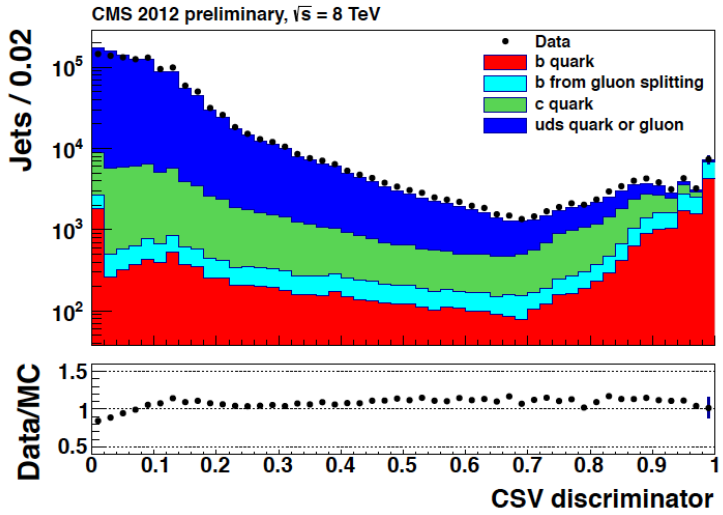
b-tagging

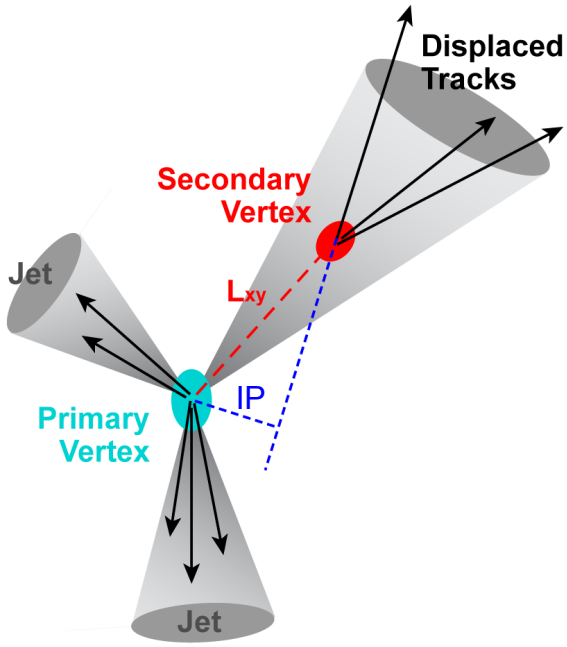
Combined Secondary Vertex (CSV) Tagger

Multivariate combination of

single track information

and secondary vertex information





New development:

B-tagging in jet substructure

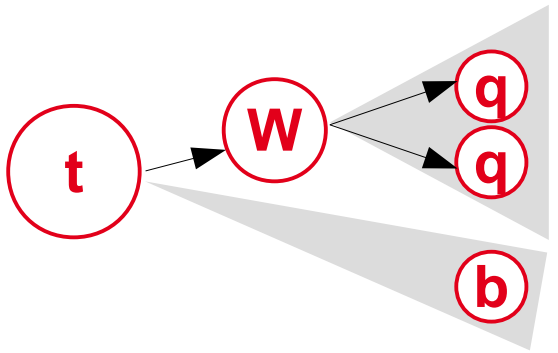
For more details see talk by Ivan Marchesini

Jet-Tagging in Boosted Decays

Identification of merged W or top decays

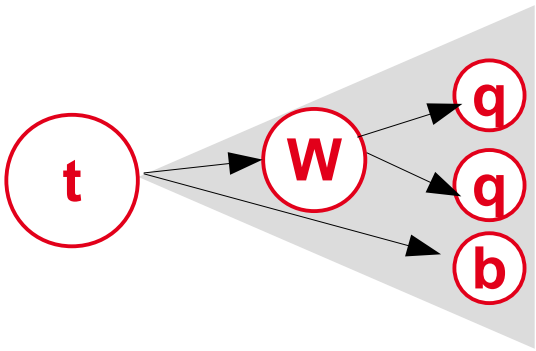
W-tagger on pruned CA8 jets:

- p_T > 200 GeV, |η| < 2.4
- ≥ 2 subjets
- 60 GeV < m_{jet} < 130 GeV



CMS top-tagger on CA8Jets:

- p_T > 200 GeV, |η| < 2.4
- 140 GeV < m(jet) < 250 GeV
- ≥ 3 subjets
- Min. pairwise mass m_{ij} > 50 GeV



For more details see talk by Emanuele Usai

$T'_{5/3} \rightarrow tW$ same-sign dilepton channel

19.6 fb-1 at $\sqrt{s}$ = 8 TeV

CMS-PAS-B2G-12-012

Analysis Setup

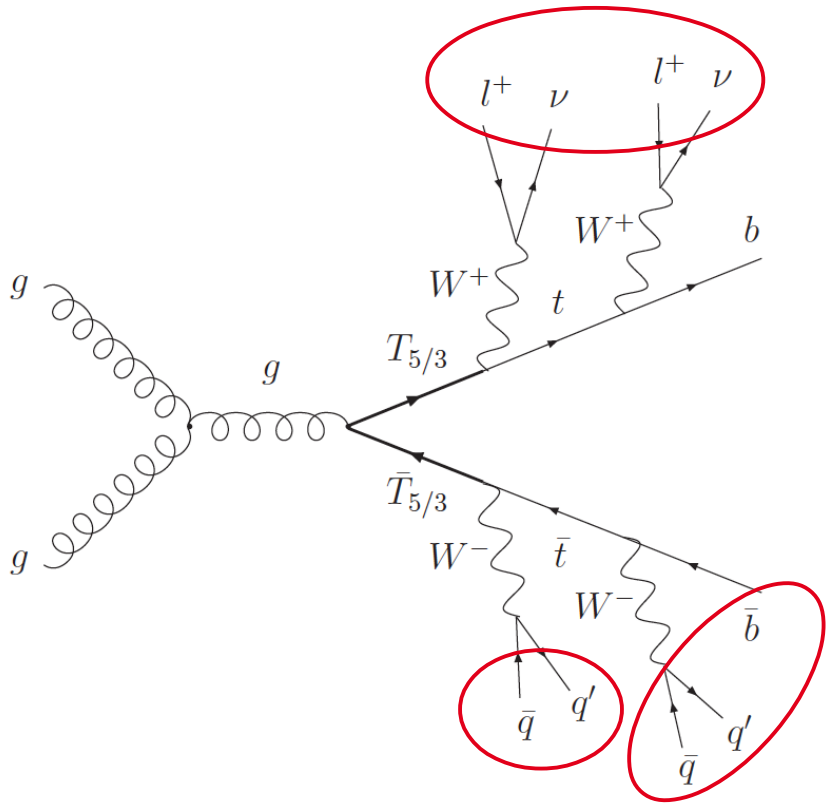
- Pair produced **T' of charge 5/3**
- Branching ratio: 100 % **T' → tW**
- 550 GeV ≤ m(T') ≤ 1000 GeV
- Assumption: m(B') > m(T')

- One leptonic T' → tW → WWb decay

  → Two **same sign leptons**

- Hadronic T' decays identification

  → **top- and W-tagging**



Event Selection

- Dilepton trigger
- 2 same-sign electrons or muons

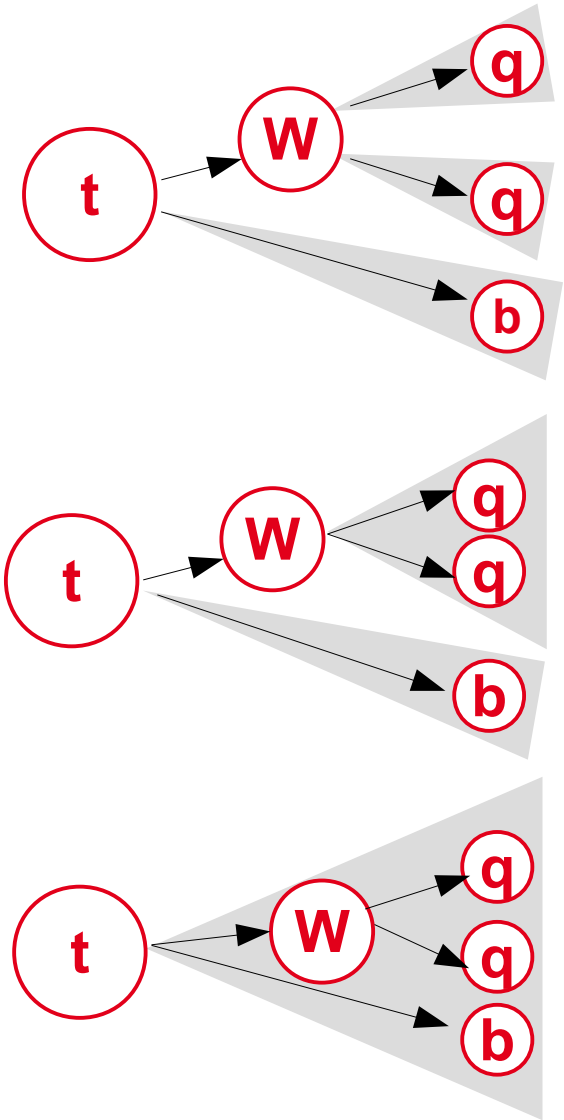
  $p_T > 30$ GeV, $|\eta| < 2.4$
- Z boson veto if 76 GeV < M(ee) < 106 GeV
- ≥ 5 constituents

Ak5 jets/ leptons	W-tagged CA08 jet	top-tagged CA08 jet
1 const.	2 const.	3 const.

- HT > 900 GeV

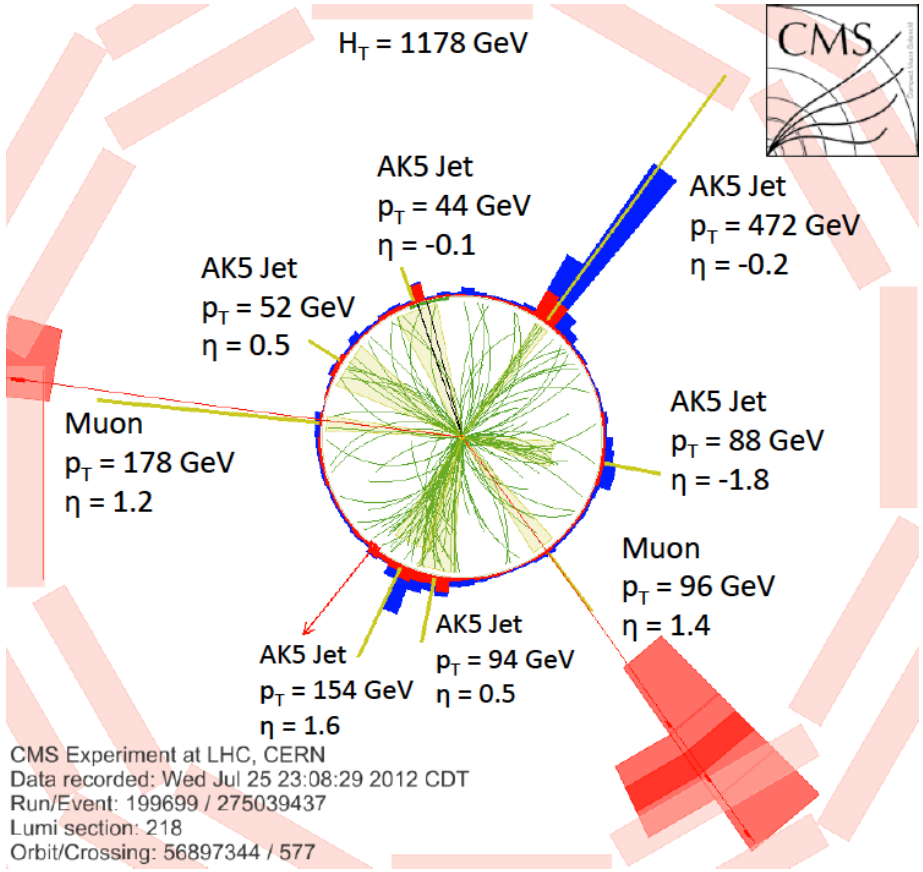
$HT = \Sigma p_T(\text{jets}) + \Sigma p_T(\text{leptons})$

All objects reconstructed using Particle Flow Algorithm

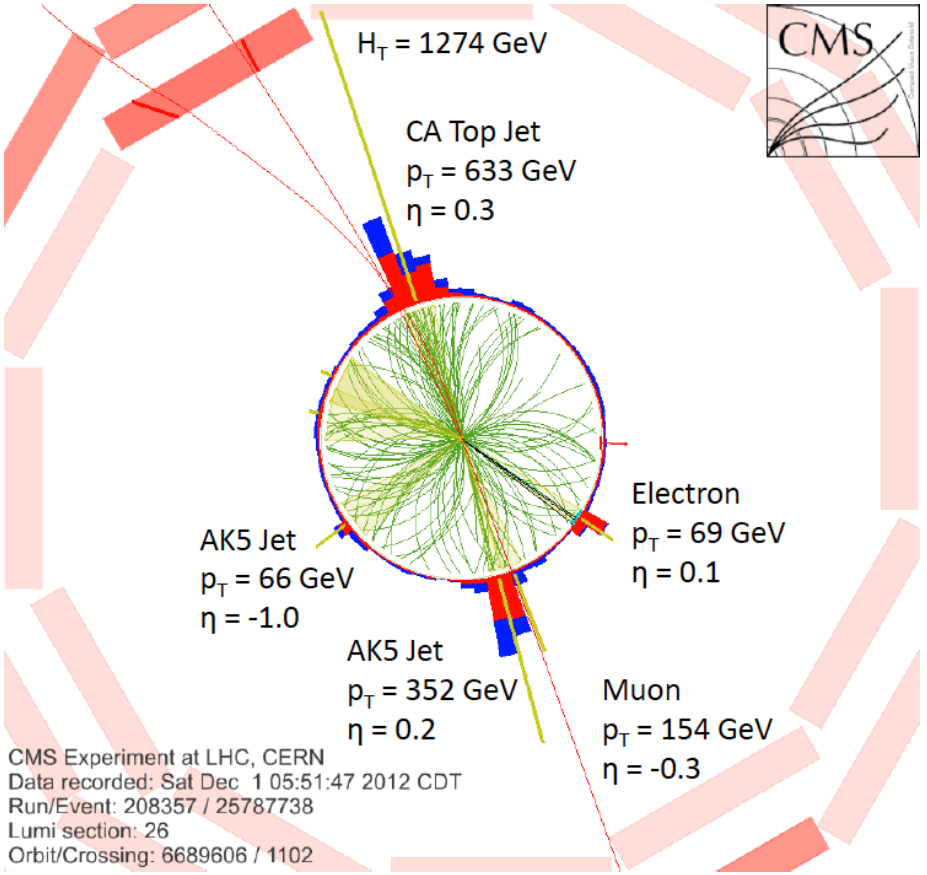


Selected events

Dimuon event with 8 constituents:
2 muons + 6 ak5 jets



Dilepton event with 7 constituents:
Electron + muon + 2 ak5 jets + top jet



Wide variety of events covered with this selection

Background Sources

- **Same sign prompt leptons** (WZ,ZZ, $t\bar{t}W$, $t\bar{t}Z$, $W^{\pm}W^{\pm}$)

  → from simulation

- **Charge misidentification** (negligible for μμ-channel):

  1. Apply full selection but require opposite lepton charges
  2. Weigh by charge misidentification probability

- **Single prompt lepton + misreconstructed lepton**

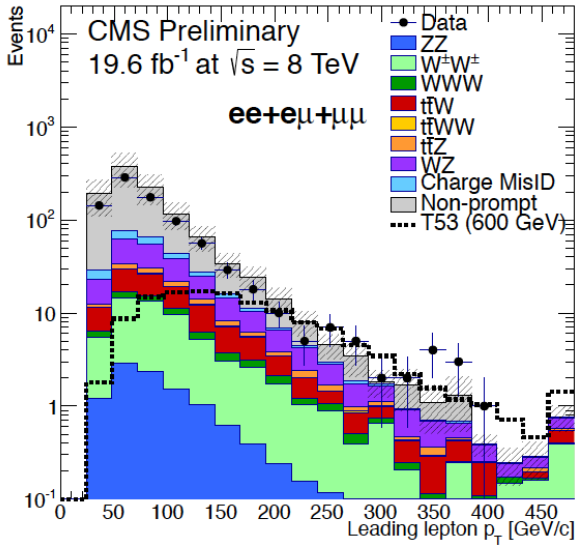
  Select events with 1 tight & 1 loose lepton

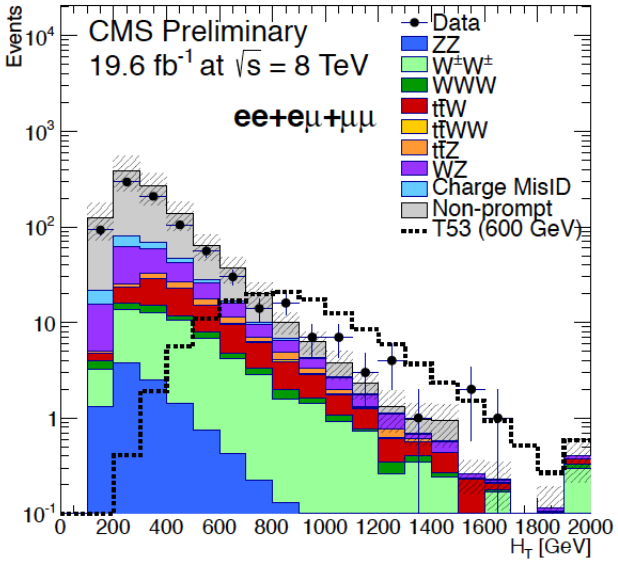
  Prompt rate: prompt leptons selected as tight → from Drell-Yan events

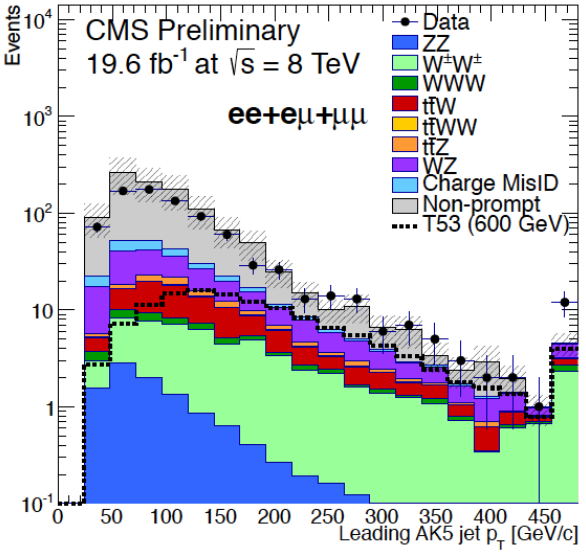
  Fake rate: loose leptons selected as tight → from data sample enriched in loose leptons

Results

Control distributions after partial selection for increased statistics
(2 same sign leptons, Z-boson veto, ≥ 2 jets)







After full selection

	Total Expected	Observed
ee	2.6 ± 1.3	0
eμ	2.5 ± 1.0	6
μμ	1.5 ± 0.7	5
all	6.6 ± 2.0	11

No significant excess seen
→ set limits

Reconstructed T Mass

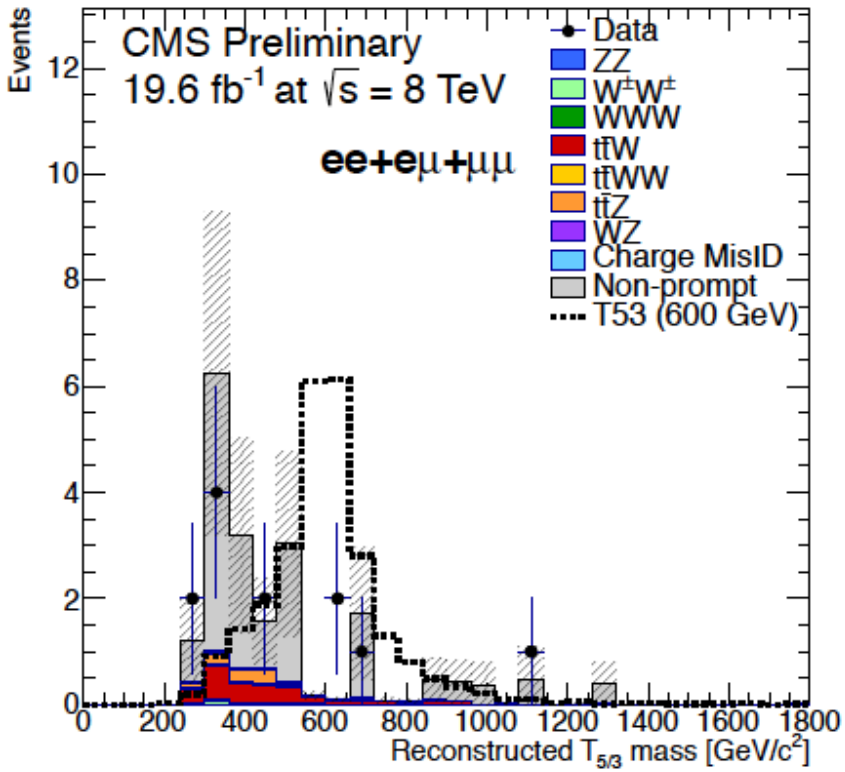
Use substructure information to reconstruct events

Slightly different selection than for limit setting:
≥ 5 constituents of T decay must all be jets in this case

Reconstructed T mass:
Invariant mass of top and W candidates

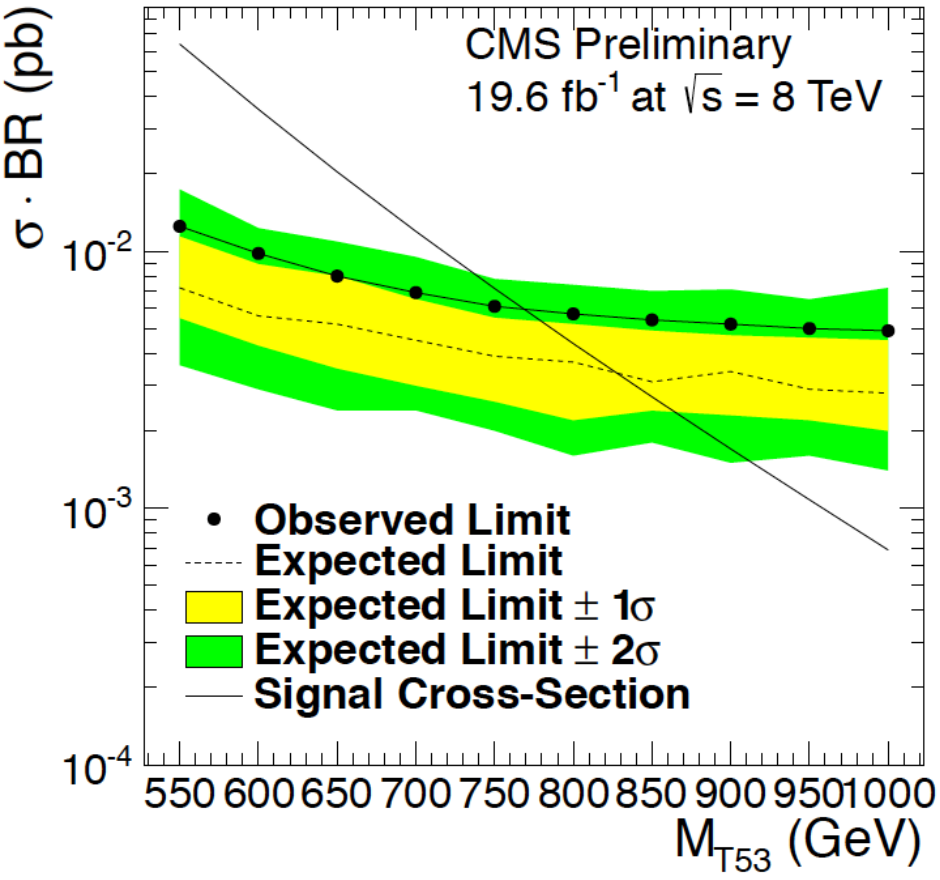
Top candidates are:
A) top-tagged CA8 jets
B) W-tagged CA8 jet + ak5 jet

W candidates are:
A) W-tagged CA8 jets
B) two ak5 jets with an invariant mass Within m_W ± 20 GeV



Future discovery → use distributions to distinguish from other exotic particles

Results



Bayesian limits computed at 95% C.L. using RooStats

Combination of event yields from all channels

Limit on T quark mass with charge 5/3:

Expected: 830 GeV
Observed: 770 GeV

$T_{2/3} \rightarrow$ tH, tZ, bW lepton channel

19.6 fb-1 at $\sqrt{s}$ = 8 TeV

CMS-PAS-B2G-12-015

Analysis Setup

- Search for vector-like **T' with charge 2/3**
- **Pair produced** T' singlets with **500 GeV ≤ m(T') ≤ 1 TeV**
- Decay modes: T' → tH, T' → tZ, T' → bW

  → Consider **all** possible **branching fractions**
- Combination of **two analysis strategies**:
  1. **Multivariate single lepton** channel analysis:
     a) In presence of a W-tagged jet
     b) Without a W-tagged jet
  2. **Multilepton** channel **counting experiment**

Single Lepton Analysis

Event Selection

- Single lepton trigger
- Exactly **1 isolated electron or muon**

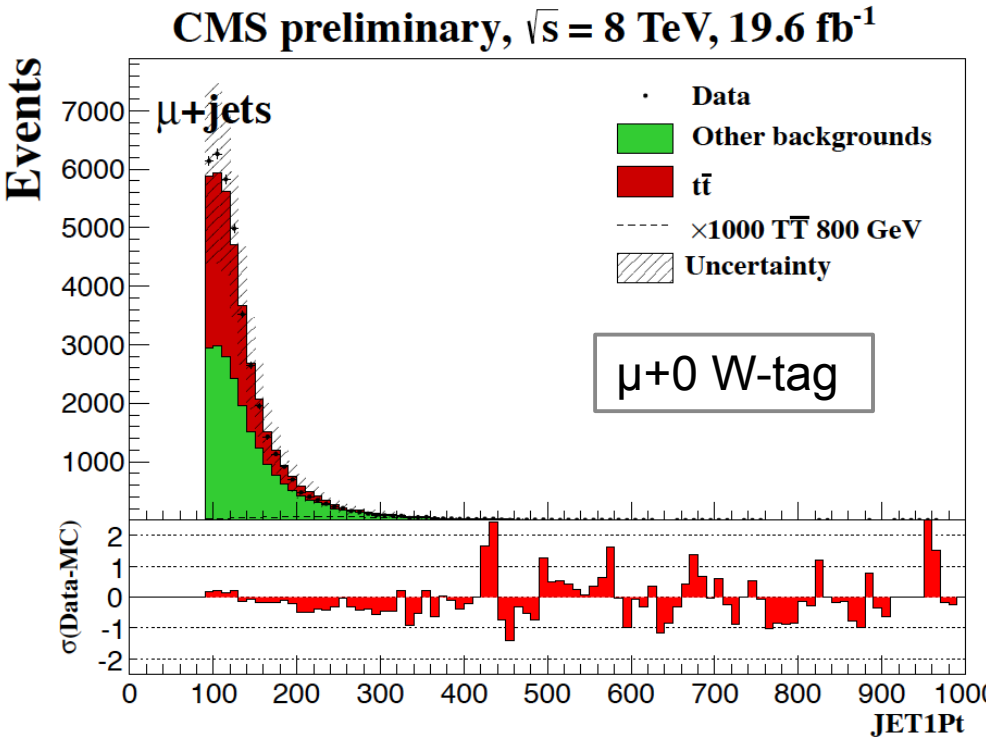
  p_T > 32 GeV

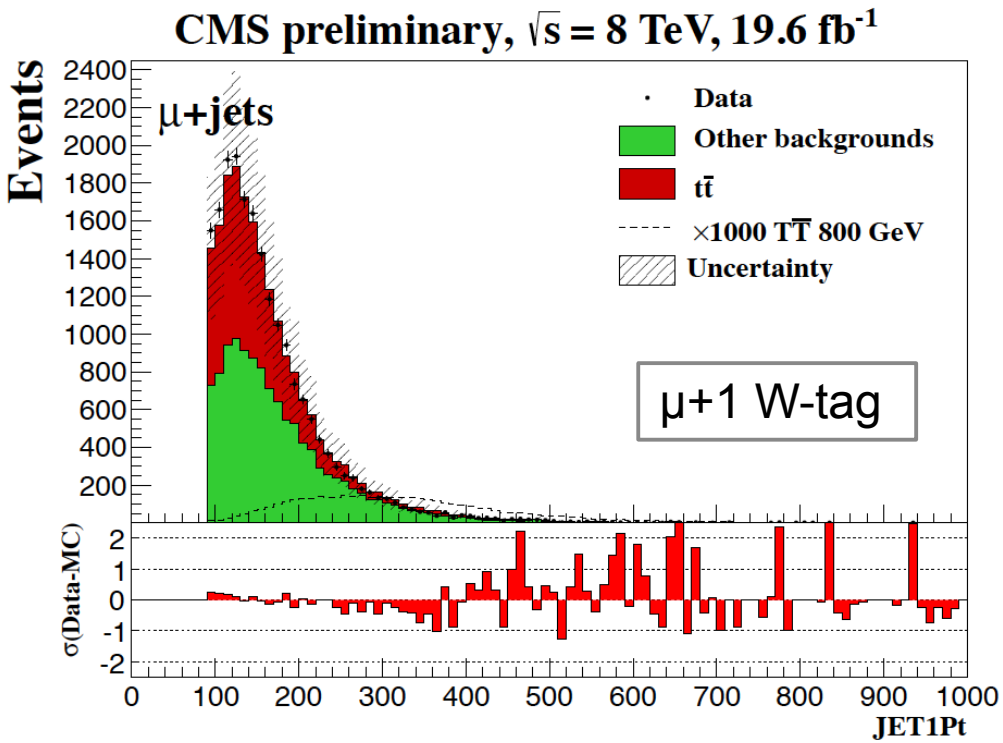
  muons: |η| < 2.1 electrons: |η| < 2.1 (excluding 1.57 < |η| < 2.5)
- $\mathbf{P_{T,\,miss}}$ > 20 GeV
- At least **3 ak5 jets** with p_T > 120, 90, 50 GeV and |η| < 2.4, where

  A) 4th ak5 jet with p_T > 35 GeV exists

  B) ≥ 1 of the 3 jets can be matched to W-tagged CA8 jet

Selection Results





Data and simulation agree well within errors in all single lepton channels

Selection Results

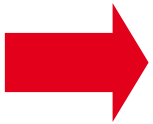
Background

- W/Z+jets, tt, single top, ttW, ttZ, ttH, diboson production
- W+jets cross section from data, all other samples scaled to NLO prediction computed with MCFM

Selected events	
μ channel	e channel
61500 ± 13700	61100 ± 13500

Selected Signal Events

T' mass	μ channel	e channel
500 GeV	850	840
700 GeV	97	98
1000 GeV	5.8	6.0
1500 GeV	0.1	0.1



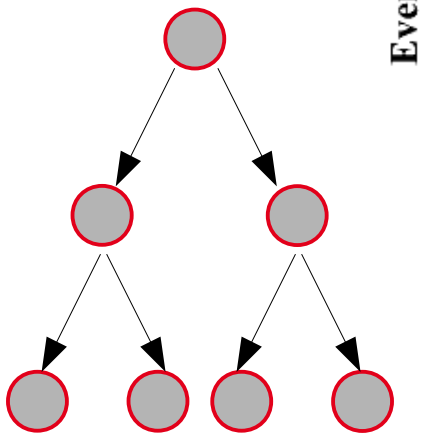
Multivariate analysis to distinguish signal from large background

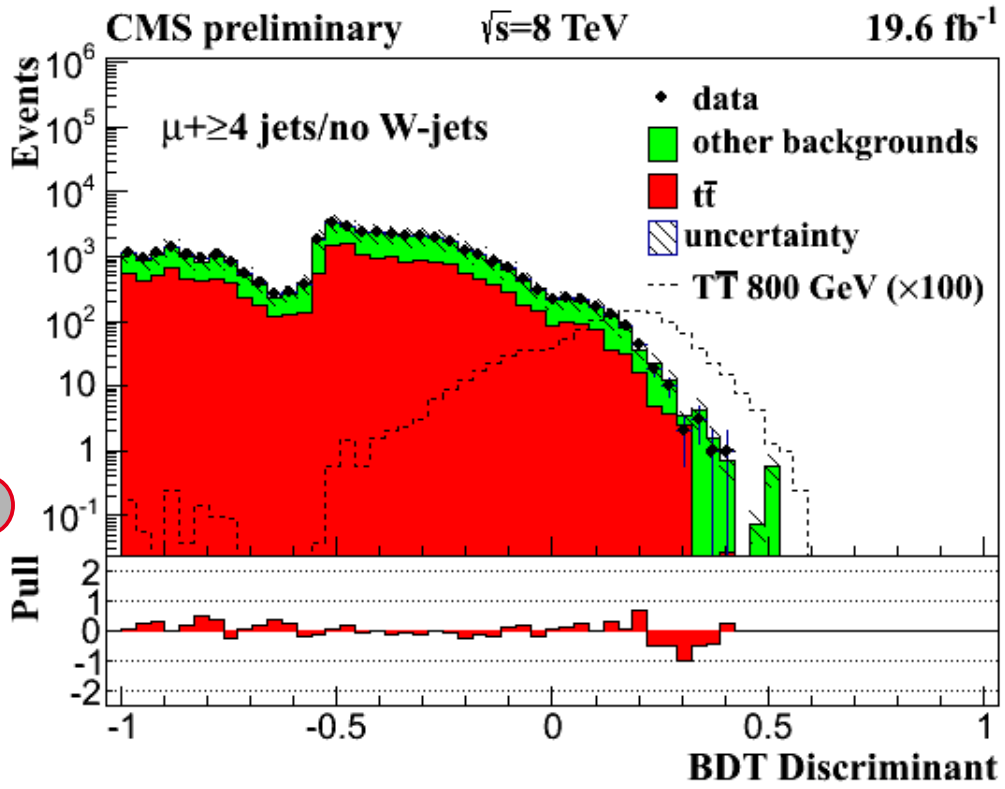
BDT in category A

Events without W-tagged jets

7 discriminating variables → Train Boosted Decision Tree → One powerful discrimination variable for statistical analysis

1. N(jets)
2. N(b-tags)
3. H_T
4. $p_{T,\ missing}$
5. p_T(lepton)
6. p_T(jet3)
7. p_T(jet4)





BDT in Category B

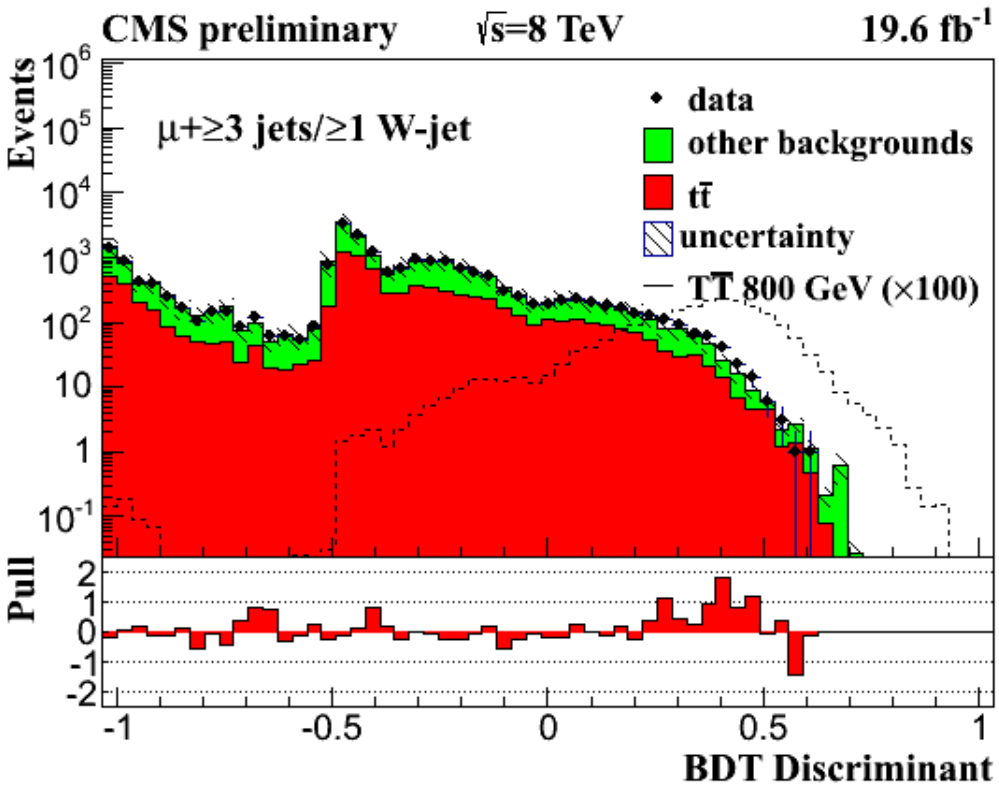
Events with ≥ 1 W-tagged jet

3 additional input variables for Boosted Decision Tree

1. N(jets)
2. N(b-tags)
3. H_T
4. p_{Tmiss}
5. p_T(lepton)
6. p_T(jet3)
7. p_T(jet4)

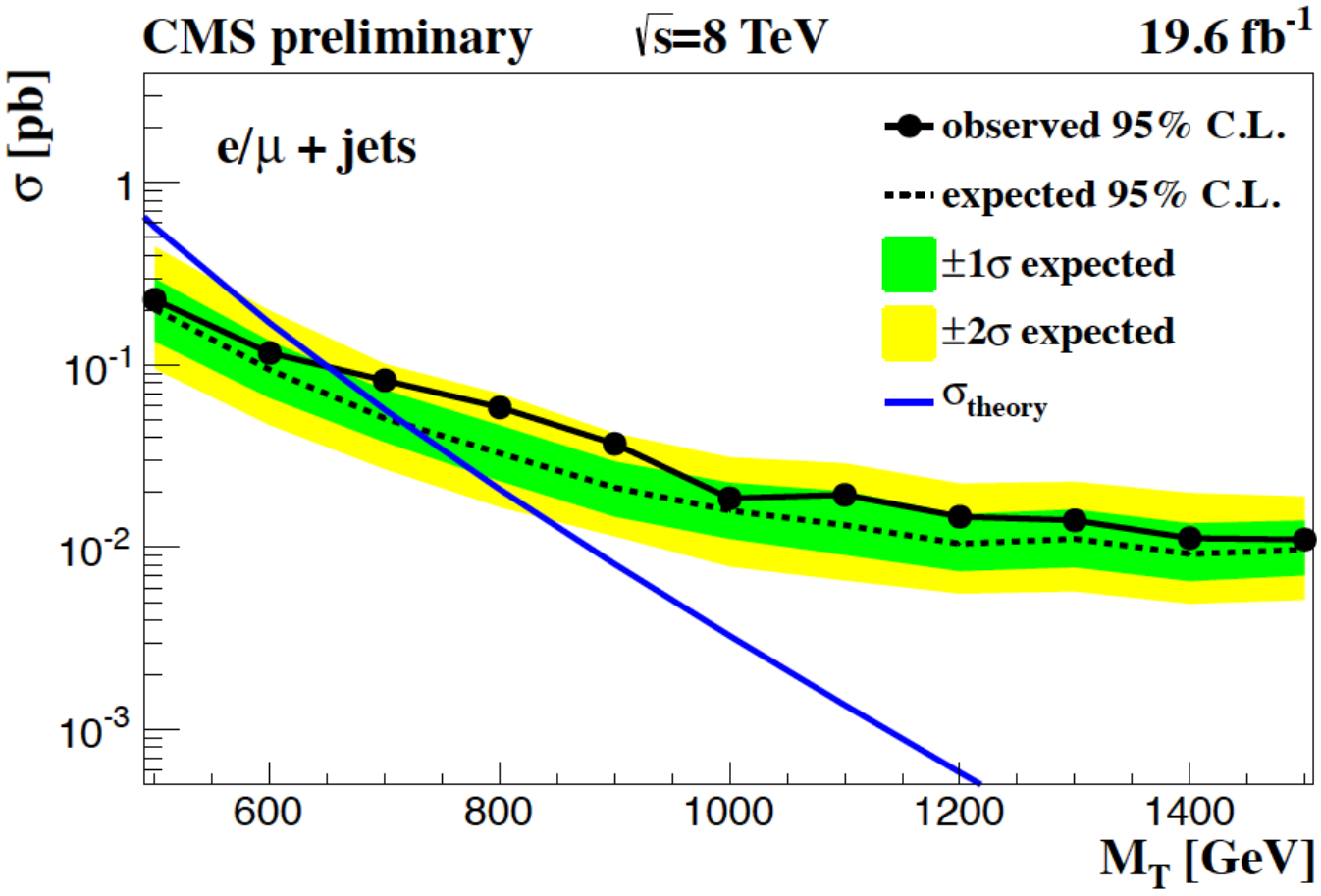
AND

8. N(top jets)
9. N(W jets)
10. p_T(W jets)



Limit Single Lepton Analysis

Compute posterior likelihood using BDT discriminant



Branching fractions

50%	T' → bW
25%	T' → tH
25%	T' → tZ

Limit on T' mass:

Expected:

733 GeV

Observed:

667 GeV

Multilepton Analysis

Dilepton trigger
≥ 2 leptons with p_T > 20 GeV and m_{ll} > 20 GeV
$p_{T,missing}$ > 30 GeV

Dilepton **opposite signs** (OS)

Z-veto: 76 GeV < m_{ll} < 106 GeV
top-veto: min. m_{lb} < 170 GeV
2 or 3 ak5 jets
H_T > 300 GeV
S_T > 900 GeV
→ most sensitive to **bWbW**

or

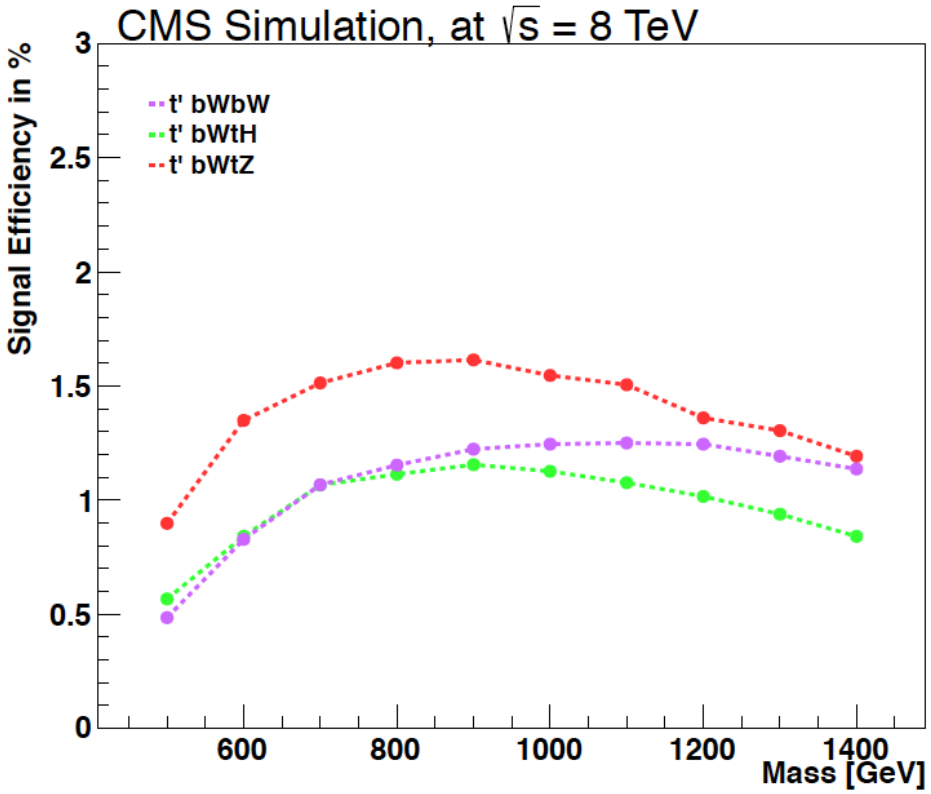
5 ak5 jets with 2 b-tags
H_T > 500 GeV
S_T > 700 GeV
→ most sensitive to **tZtZ**

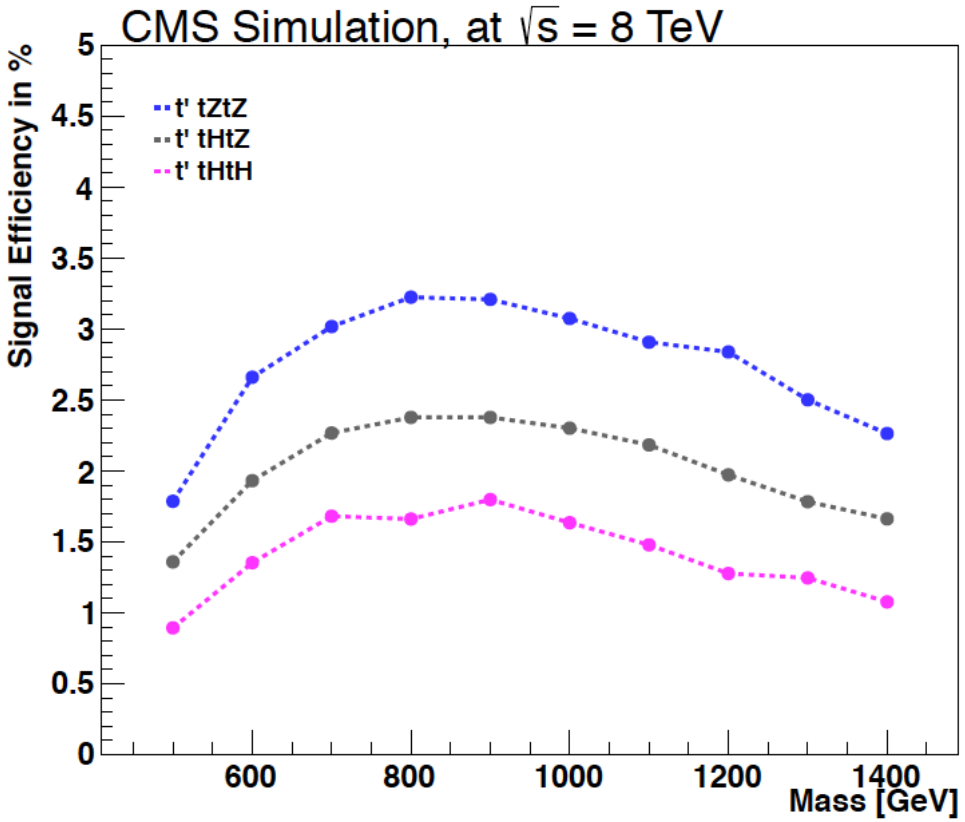
Dilepton **same sign** (SS) or **trilepton**

≥ 3 ak5 jets,
H_T > 500 GeV
S_T > 700 GeV
→ most sensitive to decays to **tZ or tH**

Signal Selection Efficiency

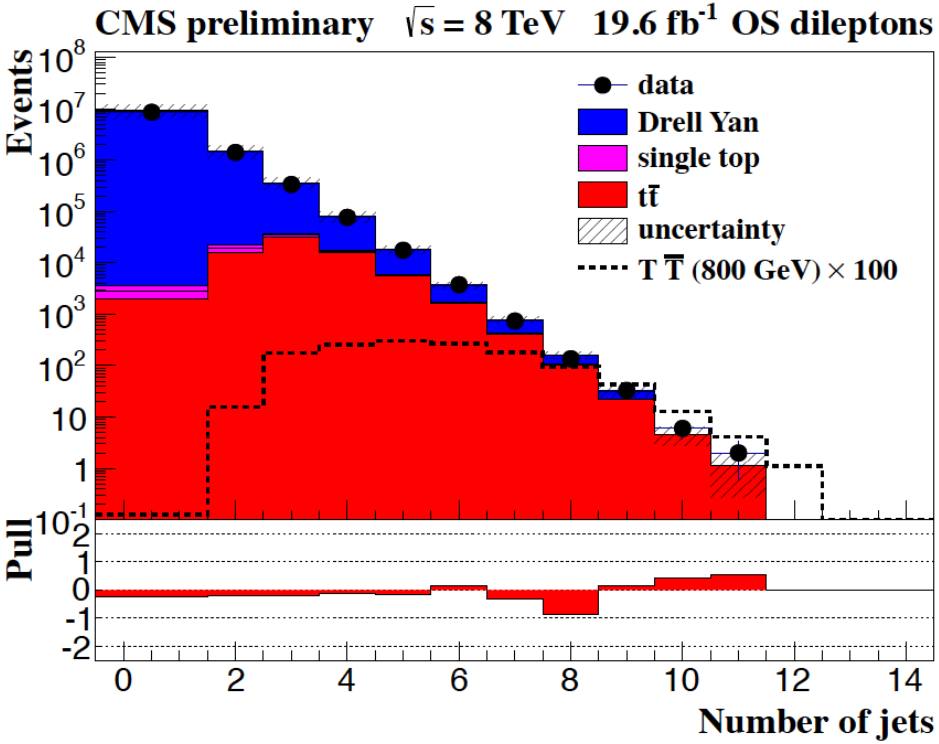
Selection efficiency in all multilepton channels combined for different decay modes

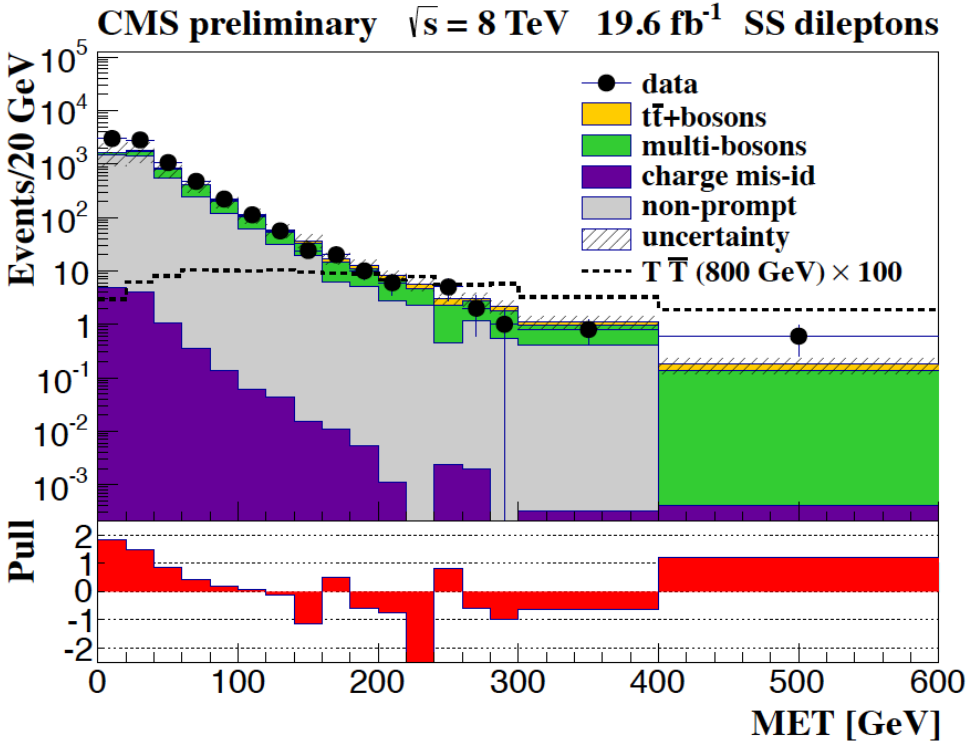




Overall best signal efficiency for **T' → tZ** decays and for T' masses around **800 GeV**

Selection Results

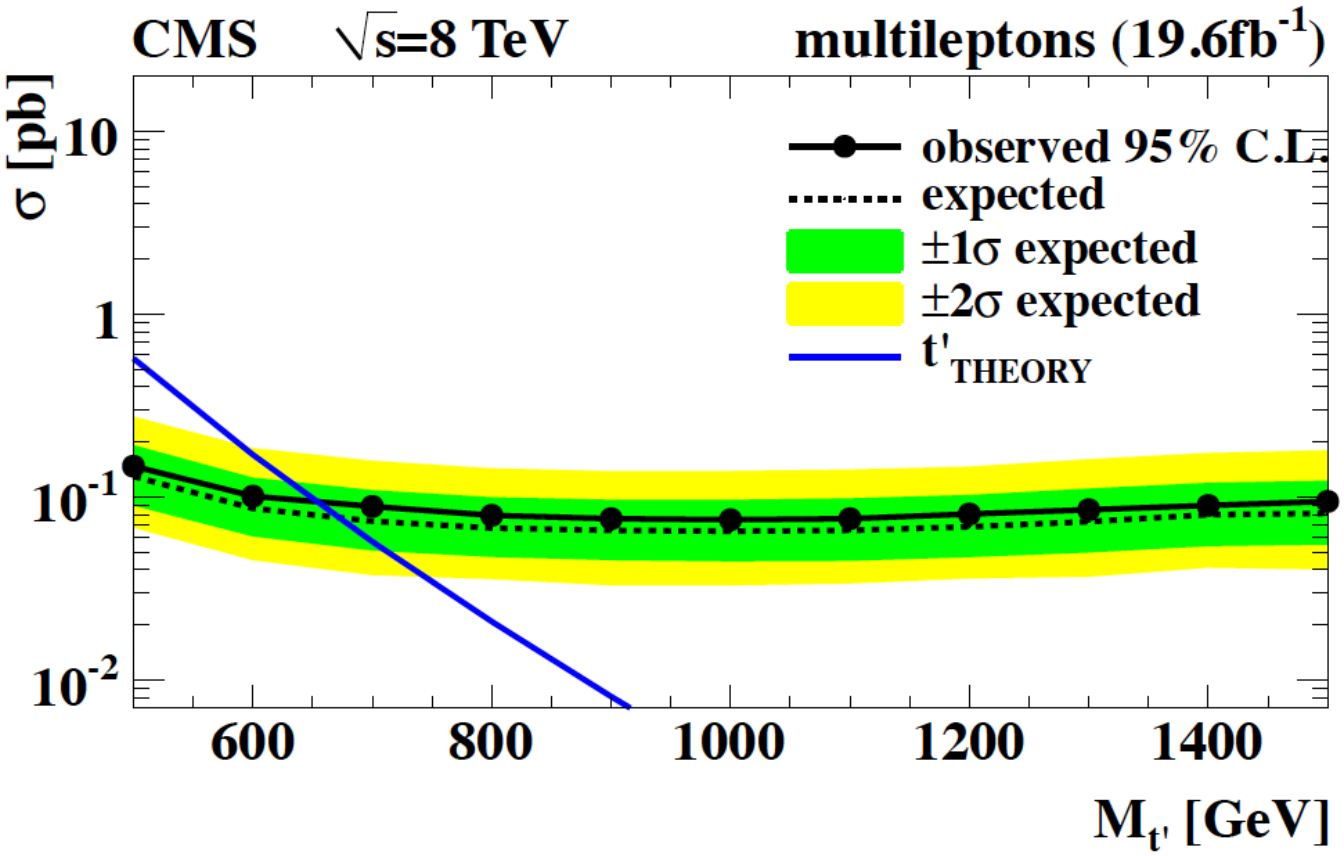




	Dilepton			trilepton
	OS 1	OS 2	SS	
Background	17.4 ± 3.7	84 ± 12	16.5 ± 4.8	3.7 ± 1.3
Data	20	86	18	2

Limits Multilepton Analysis

Compute likelihood from observed and predicted number of events in 12 subsamples



Branching fractions

50%	T' → bW
25%	T' → tH
25%	T' → tZ

Limit on T' mass:

Expected:

683 GeV

Observed:

668 GeV

Combination

Set bayesian limits at 95% C.L.

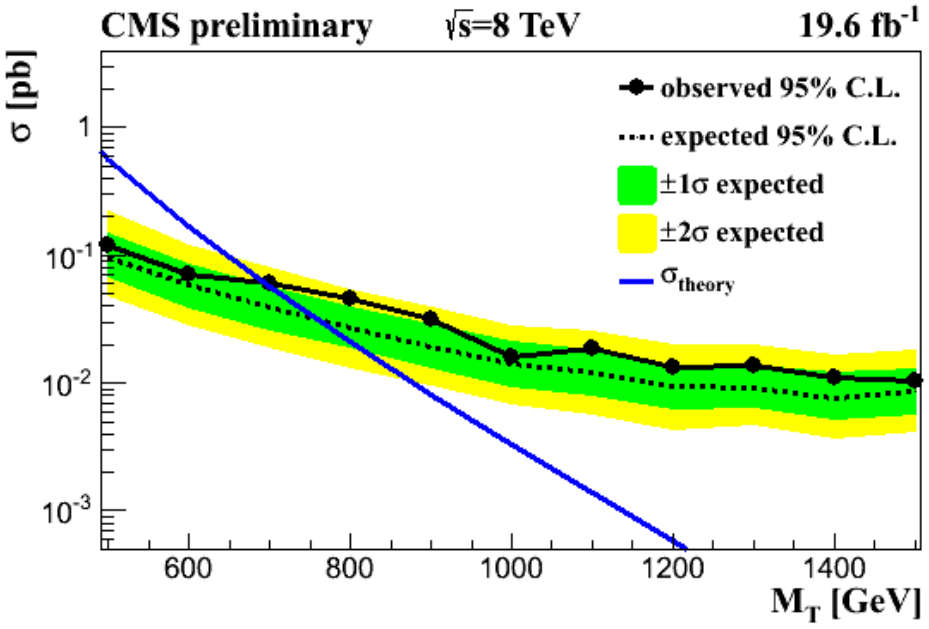
Single lepton channel:

Compute posterior likelihood using BDT discriminant

Multilepton channel:

Compute likelihood from observed and predicted number of events in 12 subsamples

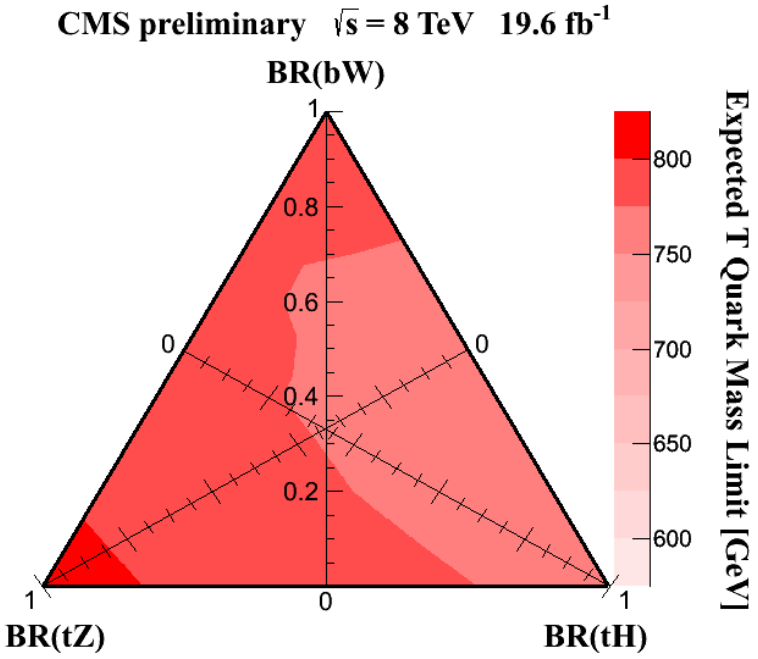
Limits on cross section for specific branching ratio scenario:
50% T' → bW
25% T' → tH
25% T' → tZ

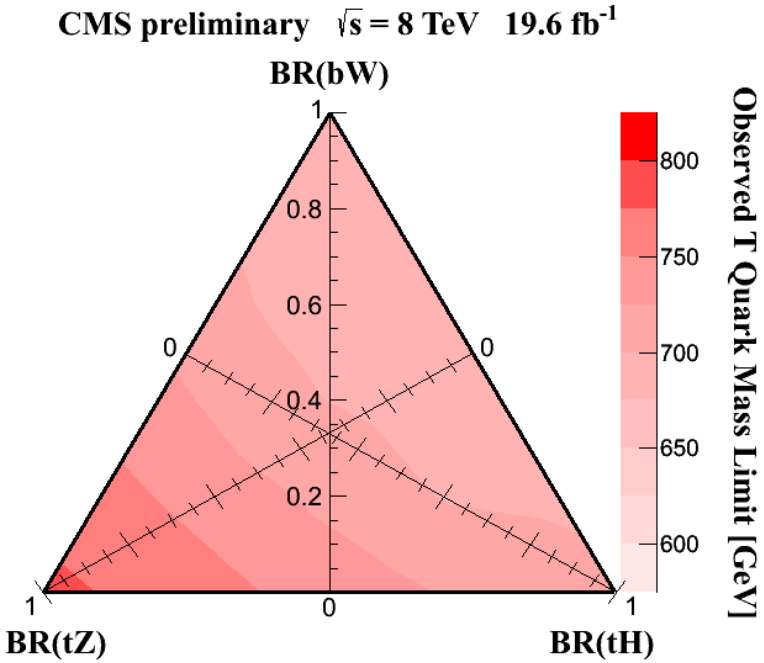


Limit on T' quark mass with charge 2/3:
Expected: 773 GeV Observed: 696 GeV

Scan of Branching Fractions

Expected and observed limits on the T' quark mass for each possible branching ratio





Greatest sensitivity for T' → tZ decays
Lower limits on m(T'): between 687 and 782 GeV

Summary and Outlook

Summary & Outlook

- **Use of substructure tools improves sensitivity of analyses**
- **Search for vector-like top partner with charge 5/3**

  For branching fraction 100% bW

  limit improved from $m(T'_{5/3}) > 645$ GeV at $\sqrt{s}$ =7 TeV

  to **$m(T'_{5/3}) > 770$ GeV** at $\sqrt{s}$ =8 TeV
- **Search for vector-like top partner with charge 2/3**

  For branching fraction 50% bW, 25% tH, 25% tZ

  limit improved from $m(T'_{2/3}) > 417$ GeV at at $\sqrt{s}$ =7 TeV

  to **$m(T'_{2/3}) > 696$ GeV** at $\sqrt{s}$ =8 TeV

  Scan of all branching fractions resulted in limits between **687 and 782 GeV**
- **More CMS searches for T' and B' getting ready before end of the year using improved substructure techniques**

BACKUP

T 5/3 Analysis Systematic Uncertainties

Sample	JES	Pileup	Normalization	Trigger	Lepton Efficiency	Luminosity
WZ	6.6%	4.5%	17%	1.0%	1.0%	4.4%
ZZ	4.8%	2.4%	5.1%	1.0%	1.0%	4.4%
$W^{\pm}W^{\pm}$	3.0%	3.8%	50%	1.0%	1.0%	4.4%
WWW	4.1%	3.8%	50%	1.0%	1.0%	4.4%
$t\bar{t}$ W	4.4%	2.7%	32%	1.0%	1.0%	4.4%
$t\bar{t}$ Z	4.4%	3.4%	50%	1.0%	1.0%	4.4%
$t\bar{t}$ WW	4.7%	2.6%	50%	1.0%	1.0%	4.4%

Table 5: Systematic uncertainties for the background contributions that are obtained from simulation.

Fake lepton background: 50%
Charge misidentification probability: 20 %

Signal JES: 2%
Signal Pileup: 3%

T 2/3 Analysis Systematic Uncertainties

Luminosity: 4.4%
Lepton ID, isolation and trigger eff.: 3%

Backgrounds
Diboson: 50%
Single Top : 50%
W/Z boson: 50%
ttbar: 8%

Multilepton analysis:
Non-prompt background from data 50%
Charge misidentification 20%

Also: JER, JES, b-tag efficiency, Q2 and matching scales

Limits on T 2/3 mass for different branching fractions in single lepton channel

Scenario	Branching Fractions T→bW	T→tH	T→tZ	expected limit	observed limit
(0) Nominal	0.5	0.25	0.25	733 GeV	667 GeV
(1) Full tZ	0.0	0.0	1.0	689 GeV	644 GeV
(2)	0.0	0.2	0.8	695 GeV	660 GeV
(3)	0.0	0.4	0.6	708 GeV	665 GeV
(4)	0.0	0.6	0.4	720 GeV	676 GeV
(5)	0.0	0.8	0.2	738 GeV	684 GeV
(6) Full tH	0.0	1.0	0.0	753 GeV	689 GeV
(7)	0.2	0.0	0.8	693 GeV	639 GeV
(8)	0.2	0.2	0.6	698 GeV	660 GeV
(9)	0.2	0.4	0.4	720 GeV	669 GeV
(10)	0.2	0.6	0.2	733 GeV	677 GeV
(11)	0.2	0.8	0.0	752 GeV	686 GeV
(12)	0.4	0.0	0.6	698 GeV	645 GeV
(13)	0.4	0.2	0.4	718 GeV	660 GeV
(14)	0.4	0.4	0.2	728 GeV	674 GeV
(15)	0.4	0.6	0.0	748 GeV	680 GeV
(16)	0.6	0.0	0.4	703 GeV	648 GeV
(17)	0.6	0.2	0.2	735 GeV	665 GeV
(18)	0.6	0.4	0.0	749 GeV	676 GeV
(19)	0.8	0.0	0.2	729 GeV	661 GeV
(20)	0.8	0.2	0.0	748 GeV	671 GeV
(21) Full bW	1.0	0.0	0.0	755 GeV	669 GeV

Limits on T 2/3 mass for different branching fractions in multilepton channel

Scenario	Branching Fractions T→bW	T→tH	T→tZ	expected limit	observed limit
(0) Nominal	0.5	0.25	0.25	683 GeV	668 GeV
(1) Full tZ	0.0	0.0	1.0	793 GeV	794 GeV
(2)	0.0	0.2	0.8	779 GeV	782 GeV
(3)	0.0	0.4	0.6	759 GeV	759 GeV
(4)	0.0	0.6	0.4	728 GeV	727 GeV
(5)	0.0	0.8	0.2	694 GeV	692 GeV
(6) Full tH	0.0	1.0	0.0	673 GeV	668 GeV
(7)	0.2	0.0	0.8	775 GeV	775 GeV
(8)	0.2	0.2	0.6	751 GeV	750 GeV
(9)	0.2	0.4	0.4	712 GeV	706 GeV
(10)	0.2	0.6	0.2	684 GeV	677 GeV
(11)	0.2	0.8	0.0	653 GeV	633 GeV
(12)	0.4	0.0	0.6	744 GeV	742 GeV
(13)	0.4	0.2	0.4	701 GeV	694 GeV
(14)	0.4	0.4	0.2	677 GeV	660 GeV
(15)	0.4	0.6	0.0	636 GeV	595 GeV
(16)	0.6	0.0	0.4	699 GeV	692 GeV
(17)	0.6	0.2	0.2	677 GeV	655 GeV
(18)	0.6	0.4	0.0	645 GeV	592 GeV
(19)	0.8	0.0	0.2	687 GeV	670 GeV
(20)	0.8	0.2	0.0	675 GeV	632 GeV
(21) Full bW	1.0	0.0	0.0	698 GeV	678 GeV