Searches in CMS for vector-like fermions (top partners) decaying to tops and bottoms

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On behalf of CMS Collaboration

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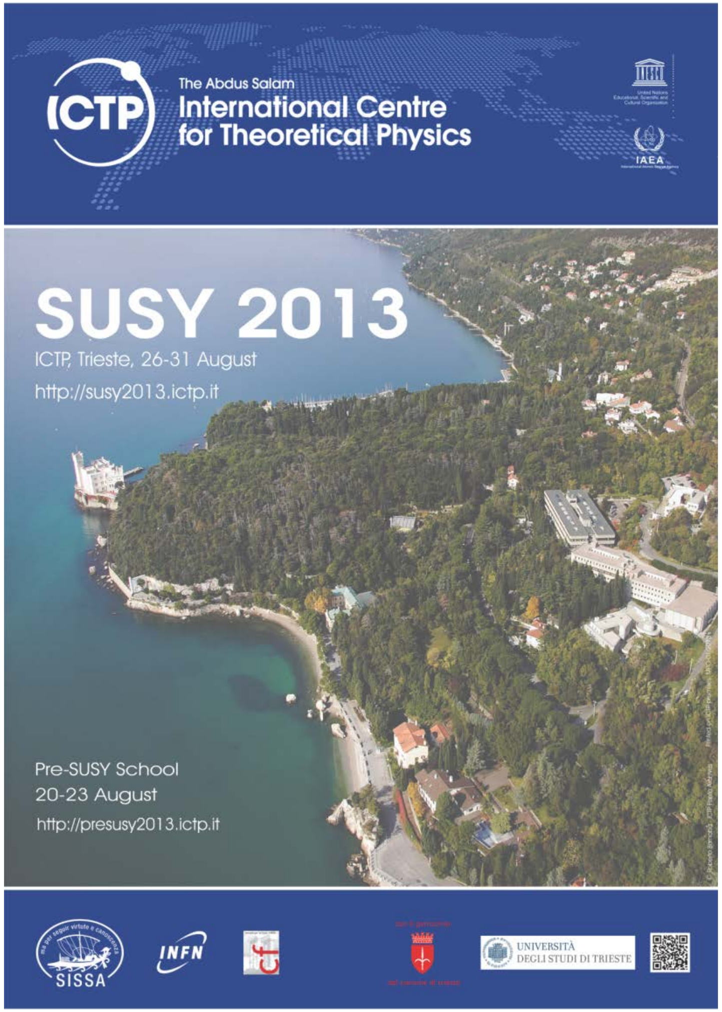


Models beyond SM

Heavy top partners arise in many extensions of the Standard Model.

Some examples are:

4th generation

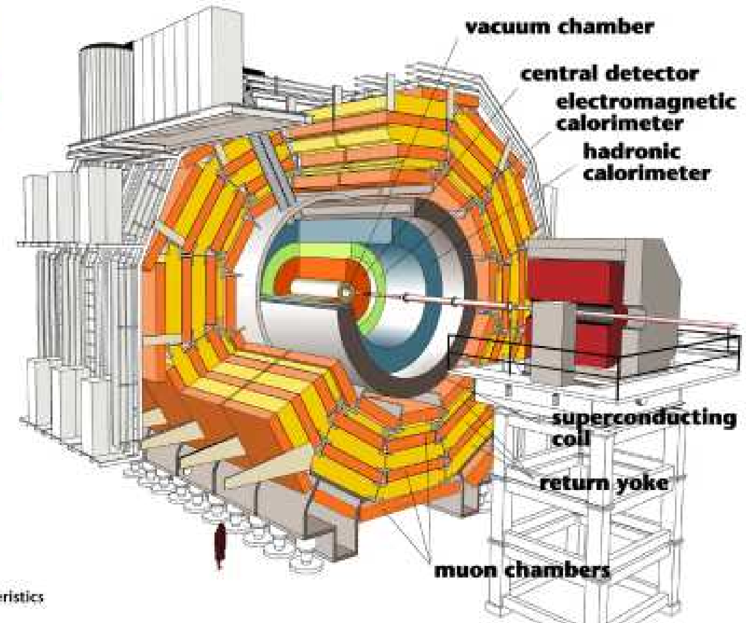
Little Higgs theories
Compositeness (composite Higgs models)
Extra dimensions
Gauged flavor group

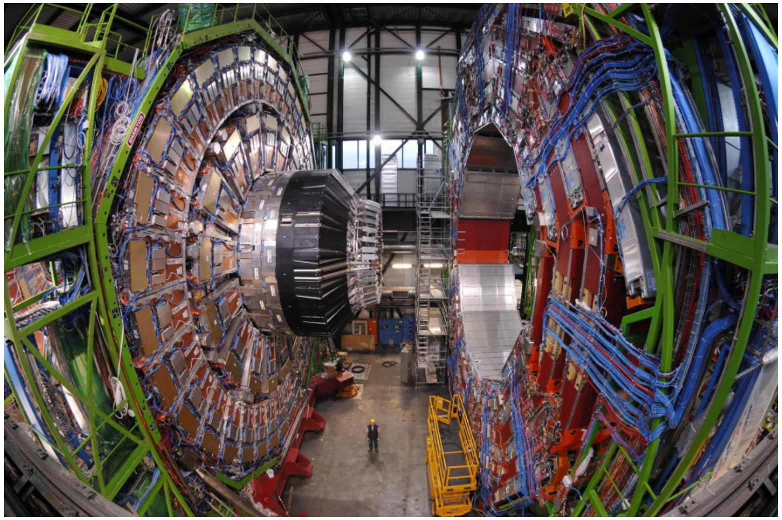
4^{th} generation: t'->Wb, b'->Wt

Vector-like: T->Wb, tZ, tH   B->Wt, bZ, bH

Quarks with exotic charges 5/3, -4/3:
X(T5/3)->Wt, Y(T-4/3)->Wb

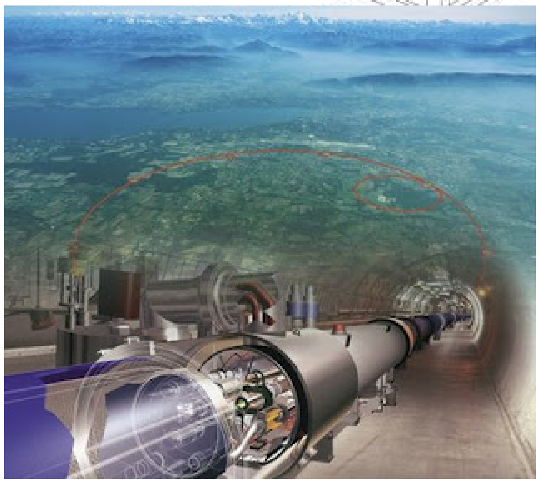
CMS detector

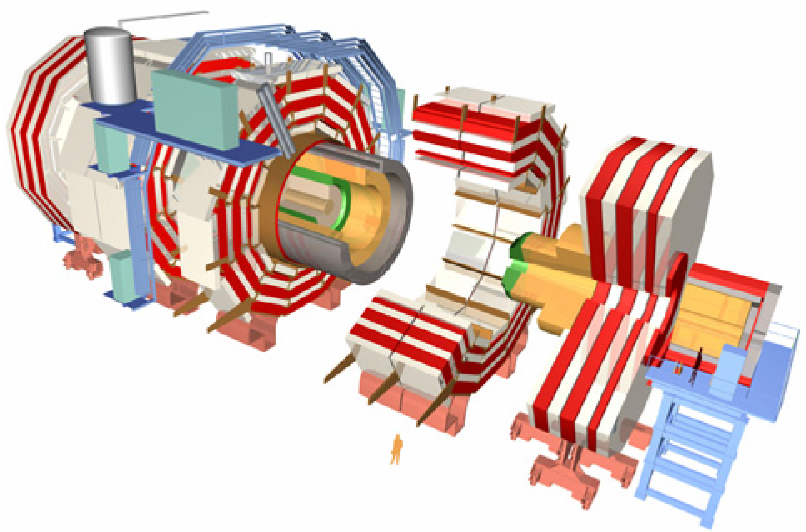




Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t





CMS searches, 7 TeV

1) CMS-PAS-EXO-10-018. Search for a heavy bottom-like quark in pp collisions at sqrt(s)=7 TeV. Phys. Lett. B 701 (2011) 204.

2) CMS-PAS-EXO-11-005. Search for a vector-like quark with charge 2/3 in t + Z events from pp collisions at sqrt(s) = 7 TeV.   Phys.Rev.Lett.107(2011)271802.

3) CMS-PAS-EXO-11-036. Search for heavy bottom-like quarks in 4.9 fb^-1 of pp collisions at sqrt(s) = 7 TeV. JHEP 05 (2012) 123.

4) CMS-PAS-EXO-11-050. Search for heavy, top-like quark pair production in the dilepton final state in pp collisions at sqrt(s) = 7 TeV. Phys.Lett. B716(2012)103.

5) CMS-PAS-EXO-11-066. Search for a vector-like quark of charge -1/3 and decaying to bZ in pp collisions at sqrt(s)=7 TeV. https://cds.cern.ch/record/1460386

6) CMS-PAS-EXO-11-098. Combined search for the quarks of a sequential fourth generation. Phys.Rev. D86(2012)112003.

7) CMS-PAS-EXO-11-099. Search for pair produced fourth-generation up-type quarks in pp collisions at sqrt(s) = 7 TeV with a lepton in the final state. Phys.Lett. B718(2012)307.

8) CMS-PAS-B2G-12-003. Search for a heavy partner of the top quark with charge 5/3. http://cds.cern.ch/record/1478430?ln=en

9) CMS-PAS-B2G-12-004. Search for heavy quarks decaying into a top quark and a W or Z boson using lepton+jets events in pp collisions at sqrt(s) = 7 TeV. JHEP 01(2013)154.

CMS searches, 8 TeV

10) CMS-PAS-B2G-12-012. Search for top partners with charge 5e/3 in the same-sign dilepton final state.
https://cds.cern.ch/record/1524087

11) CMS-PAS-B2G-12-015. Inclusive search for a vector-like T quark by CMS.
https://cds.cern.ch/record/1557571

12) CMS-PAS-B2G-12-019. Search for vector-like bottom quark partners in lepton + jets events in pp collisions at sqrt(s) = 8 TeV. NEW
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12019

13) CMS-PAS-B2G-12-021. Search for pair-produced vector-like quark of charge -1/3 and its antiparticle that decay to bZ or tW using dileptonically reconstructed Z boson+jets final state in pp collisions at sqrt(s) = 8 TeV with the CMS detector. NEW
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12021

Analysis strategies

1) Multiple leptons (or double leptons same sign).

EXO-10-018, b'b'→tWtW, trileptons and same-sign dileptons, L=34 pb-1, M(b') > 361 GeV.

EXO-11-005, TT→tZtZ→bW+bW- ZZ→(l+l-)l± +jj, L=1.14 fb-1, M(T)>475 GeV.

EXO-11-036, b'b'→tWtW→bW+bW-bW+bW- →l±l±b 3j Pt_miss, L=4.9 fb-1, M(b')>611 GeV.

B2G-12-003, T(5/3)T(5/3) -> tW tW -> W+W+b W-W-b -> l+ν l+ν b 4q b, same sign dilepton, L=5.0 fb-1, M > 645 GeV.

B2G-12-012, 8 TeV, T(5/3)T(5/3) -> tW tW -> W+W+b W-W-b -> l+ν l+ν b 4qb, same sign dileptons, boosted objects, L= 19.6 fb-1, M > 770 GeV.

2) Double leptons with opposite sign.

EXO-11-050, t't'→bW+bW- →bl+ν bl-ν, L=5 fb-1, M(t')>557 GeV.

EXO-11-066. BB-> bZ(Z->l+l-) B', L=4.9 fb-1, M>550 GeV.

B2G-12-021, 8 TeV, BB-> bZ(Z->l+l-) B, L=19.6 fb-1, M>700 GeV. NEW

Analysis strategies

3) Single lepton.

EXO-11-099, t’t’->bWbW, kinematic fit, M>570 GeV.

B2G-12-004, QQ(BB) -> tWtW, QQ(TT) -> tZtZ, L=5.0 fb-1, M(Q) > 675 (625) GeV
for Q decaying to tW (tZ).

B2G-12-019, 8 TeV, B->tW, bZ, bH, single lepton, 4 jets, E_Tmiss, boosted objects,
L= 19.8 fb-1, M > (582-732) GeV depending on BR. NEW

4) Combined searches.

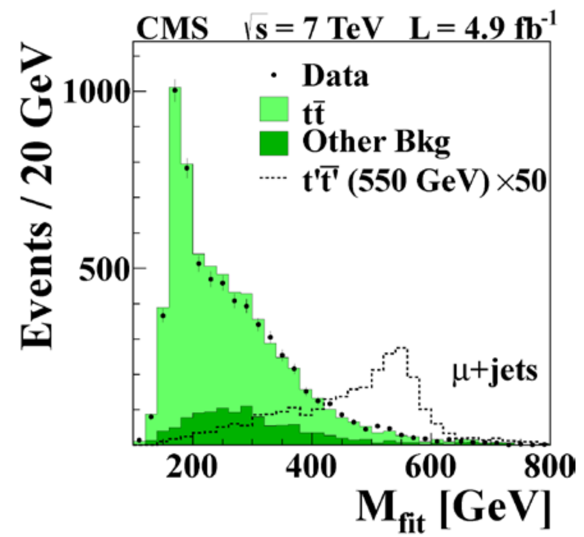
EXO-11-098, b'b', t't', b't, t'b, t'b‘, t'->bW, b'->tW, Mt’=Mb’, model dependent, 1,2,3 leptons,
L=5.0 fb-1, M > 685 GeV.

B2G-12-015, 8 TeV, T -> Wb, tZ, tH. Single, double and trilepton events, boosted objects,
BDT, L= 19.6 fb-1, M > (687-782) GeV depending on BR.

EXO-11-099, 7 TeV, t’, single lepton, kinematic fit

t’t’→WbWb→lν b qq b

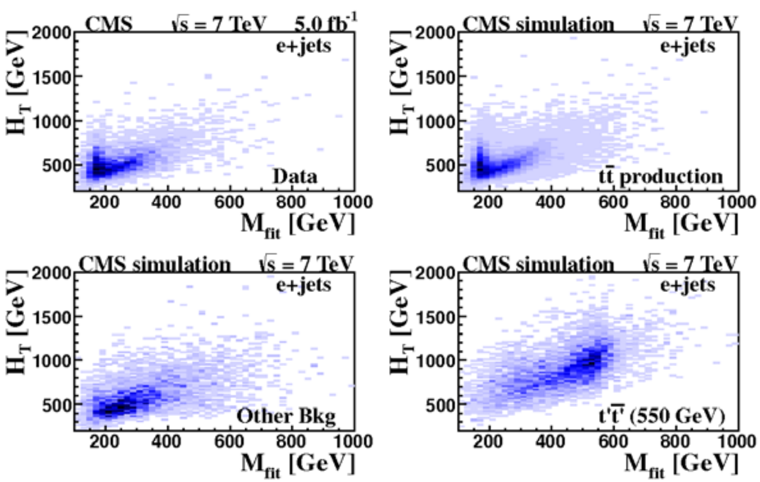
Single lepton (e, μ), at least 4 jets (Pt>120,90,50(30),35(30) GeV), at least one b-tagged jet, Pt_miss>20 GeV.



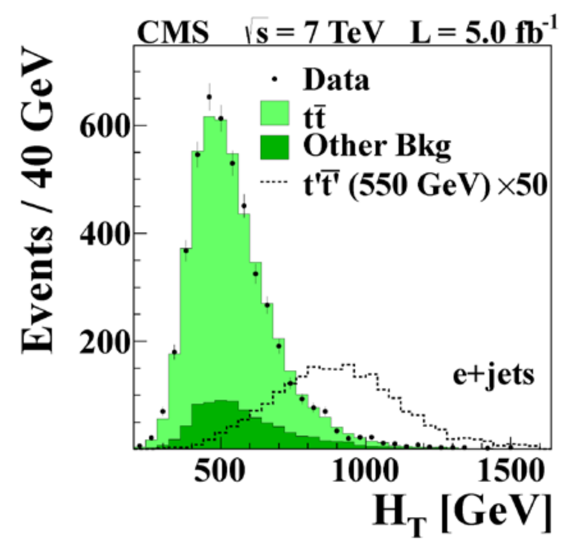
Kinematic fit:

$m(l\nu)=m(qq)=M_W$
$m(l\,\nu b)=m(qqb)=M_{fit}$

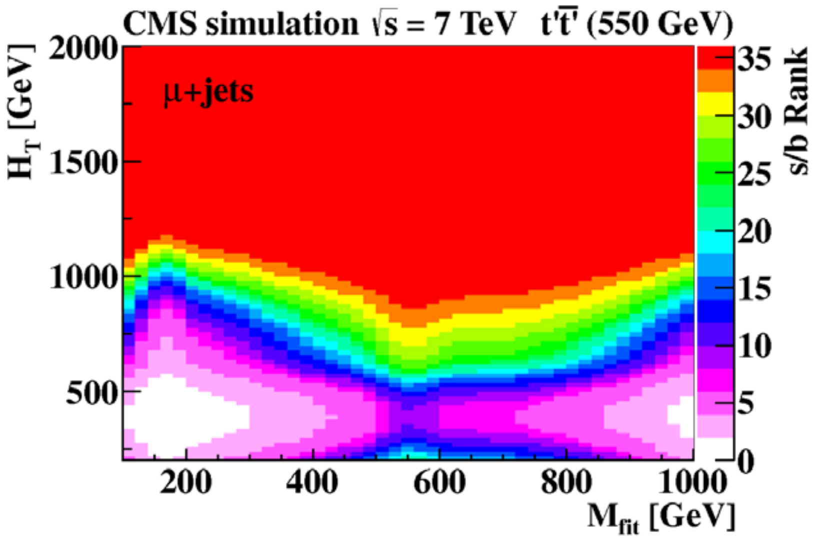
All possible jet-quark assignments, but b-tagged jet(s) assigned to b-quark(s). If 5 jets, all combinations of 4 from 5 are considered. Combination with minimal chi2 is selected.

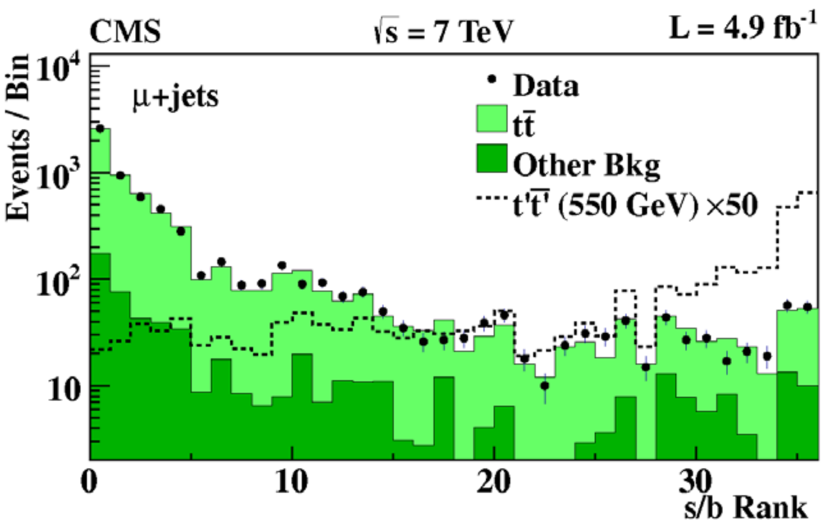


HT is scalar sum of Pt of final objects.
2-dimentional distribution of Mfit and Pt is used to extract signal.



EXO-11-099, 7 TeV, t’, single lepton, kinematic fit

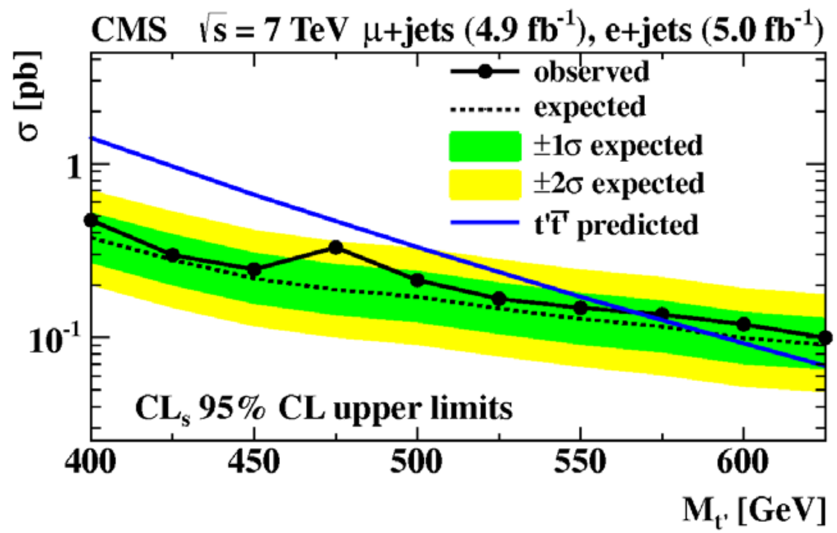




2-dimentional distribution was recast into 1-dimentional. Bins sorted in order of ascending S/B ratio.

Bins merged until the fractional statistical uncertainty in the event yield in the combined bin is below 20% for both signal and background.

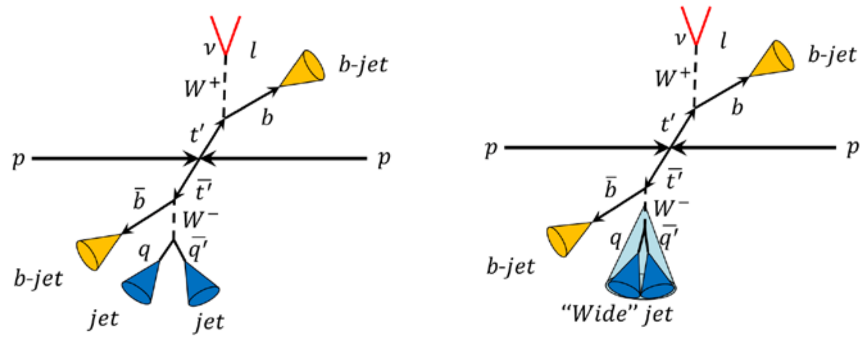
Cross section upper limit for combined e and mu channels:



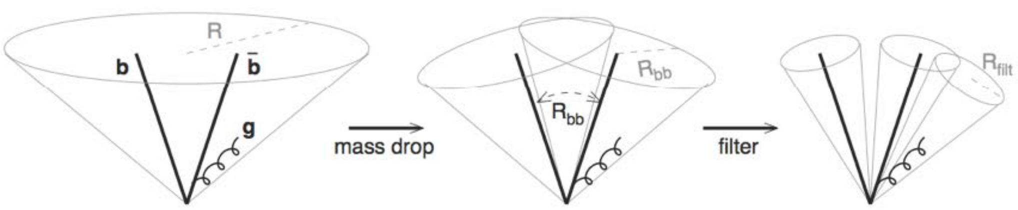
Expected mass limit: 590 GeV, observed: 570 GeV.

Boosted objects

With high mass of quark and high Pt of boson jets from decay start to merge and look like one jet. Advanced techniques of jet reconstruction are used.



"Narrow" jets – AK5 (anti-kt R=0.5), "wide" jets – CA8 (Cambridge-Aachen R=0.8).



Algorithms, producing subjets -> "split jet". With mass cuts and/or MVA methods they can be tagged as W/Z, top, H.

Boosted techniques are used in 8 TeV analyses.

B2G-12-012, 8 TeV, T(5/3), same sign leptons

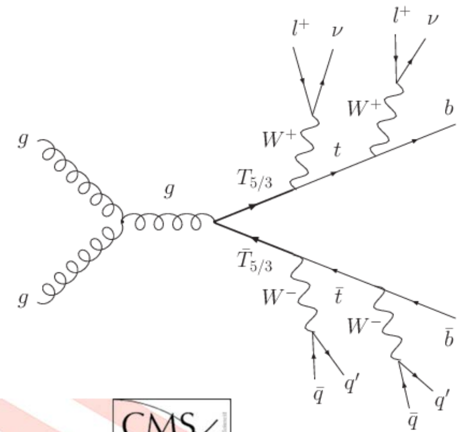
$$T_{5/3}T_{5/3} \rightarrow tWtW \rightarrow W^{+}W^{+}bW^{-}W^{-}b \rightarrow l\nu\, l\nu\; 4q\; 2b$$

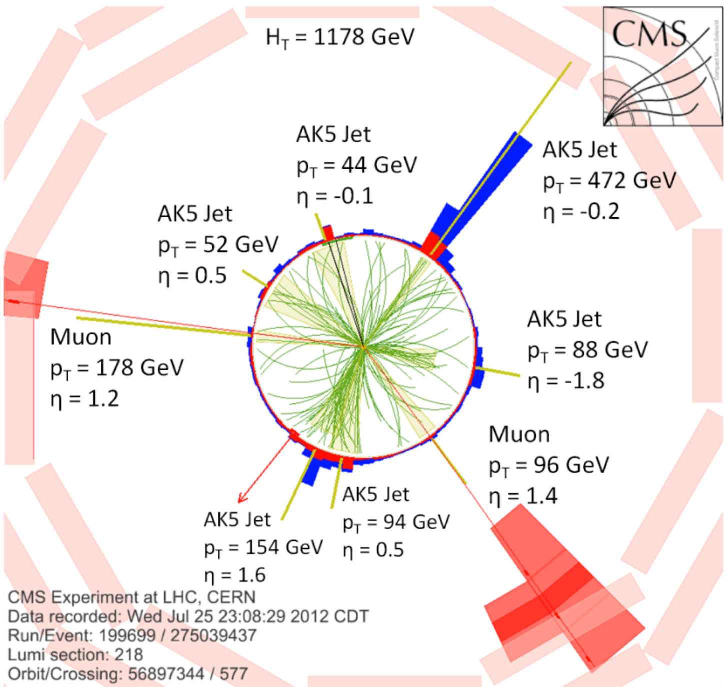
Boosted objects: Jets with Pt > 200 GeV

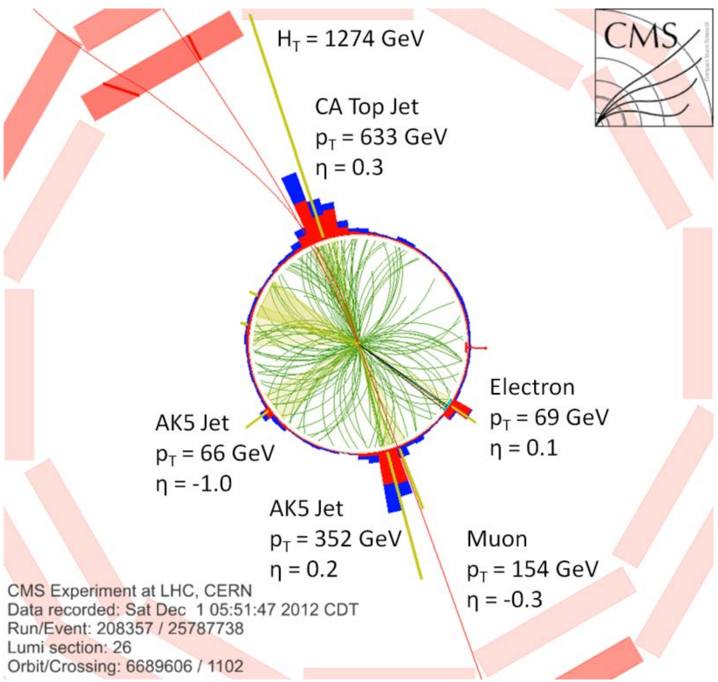
W Jet = CAJet with 60 GeV < M < 130 GeV, N subjets=2

Top Jet = CAJet with 140 GeV < M < 250 GeV, N subjets ≥ 3

Using boosted objects allows to probe cross sections of T(5/3) 13% lower than otherwise would be possible.







B2G-12-012, 8 TeV, T(5/3), same sign leptons

HT – scalar sum of Pt of all jets and leptons.

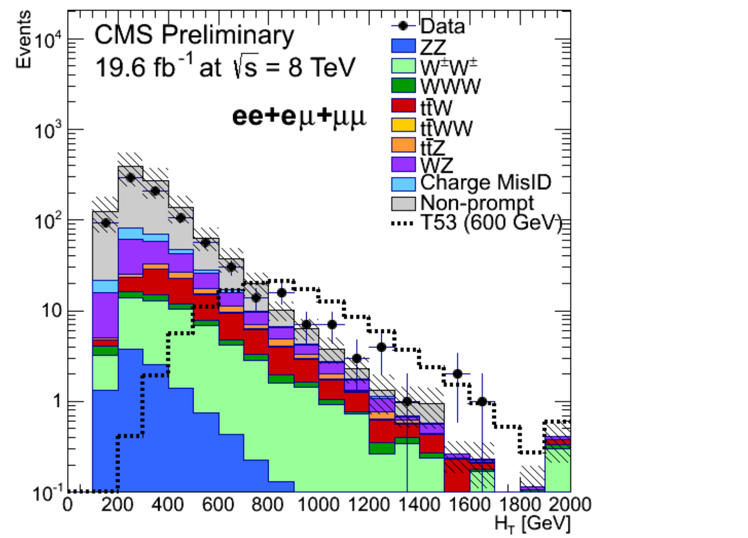
Constituent – lepton, AK5 jet; top-jet: 3 constituents, W-jet: 2 constituents.

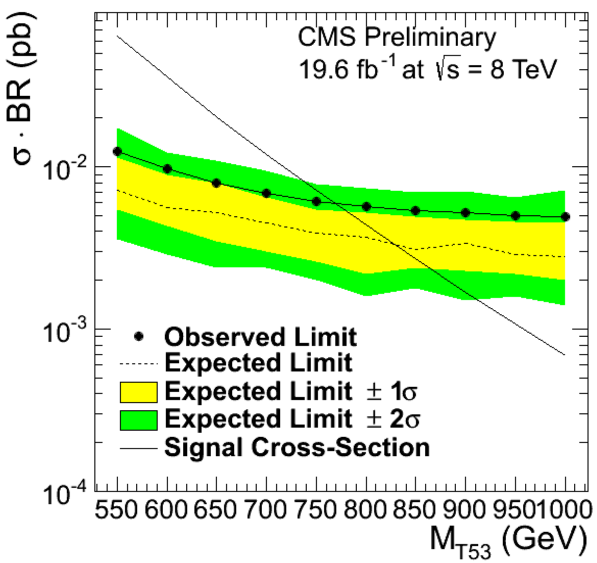
Selection: ≥5 constituents, HT>900 GeV.

Expected events: 6.6±2.0. Observed events: 11.

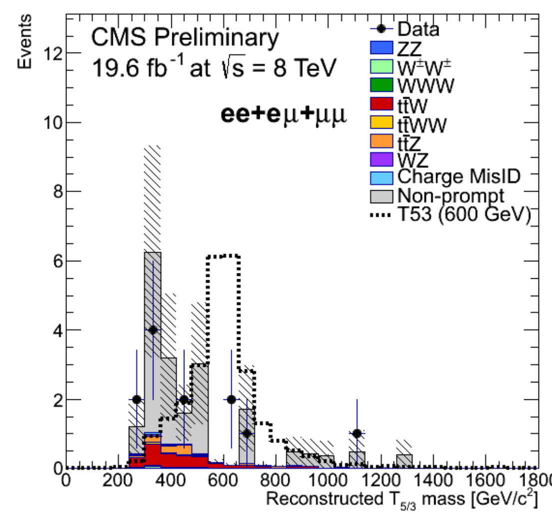
Expected mass limit: 830 Gev, observed: 770 GeV.

Relaxed selection:





Mass reconstruction: relaxed selection (no HT>900 GeV), hadronic decays of top and W (W-jets, top-jets or AK5 jets giving mass of top and W).



B2G-12-015, 8 TeV, T quark, inclusive search

Inclusive search for TT→bWbW, bWtZ, bWtH, tZtZ, tZtH, tHtH.

All possible combinations of branching fractions can be simulated by combining MC signal samples with the appropriate weights.

Boosted objects: jets with Pt > 200 GeV
W jet = CAjet with 60 GeV < M < 130 GeV, N subjets≥2
Top Jet = CAJet with 140 GeV < M < 250 GeV, N subjets ≥ 3

Boosting is mostly important for T decays to bW because the W boson tends to have large Pt.

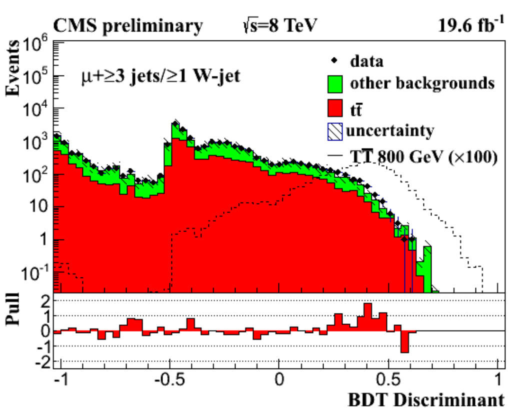
Few data samples are used:

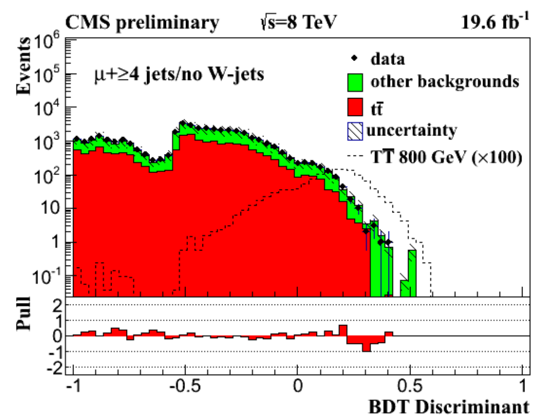
1) single lepton channel
2) multiple lepton channels:
   two opposite sign (OS) dileptons samples (OS1 is enriched by bWbW, OS2 – by Z),
   same sign (SS) dilepton sample (enriched by tZ and tH),
   trilepton sample (also enriched by tZ and tH).

Important variables are HT and ST. HT is defined as the scalar sum of all jet Pt and ST as the sum of HT, Pt_miss, and the magnitudes of all lepton Pt.

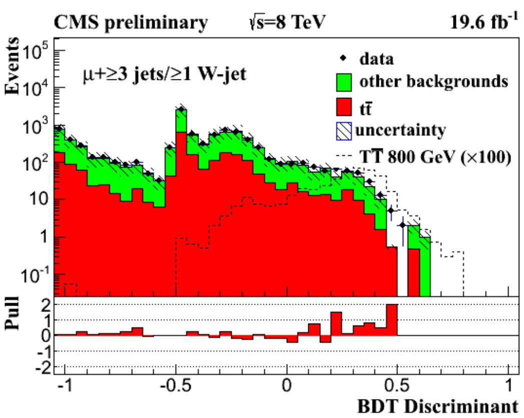
Single lepton channel

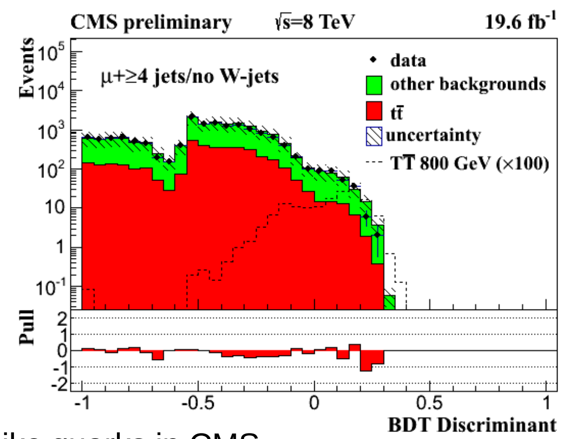
To separate TT signal from SM background Boosted Decision Trees (BDT) technique is used.
Variables used are jet multiplicity, b-tag multiplicity, HT, Pt_miss, Pt of objects.
For events with W-jet additionally – number and Pt of W-jets and number of top-jets.





Events without b-tag:

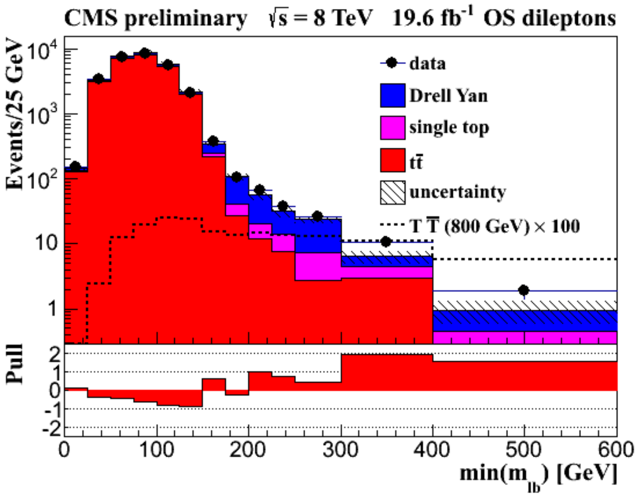


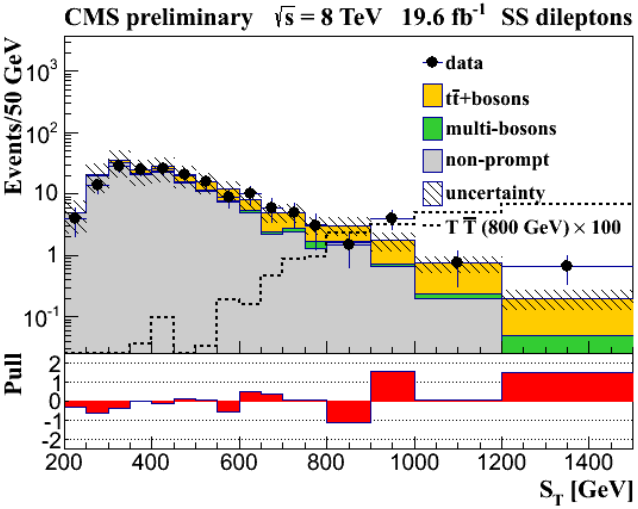


Multilepton channel

OS1,suppression of top contribution, (M(lb))min > 170 GeV (mostly WbWb state left).

SS, further filtering: at least 3 jets, HT>500 GeV, ST>700 GeV (WbWb suppressed, decays to tZ, tH left)).



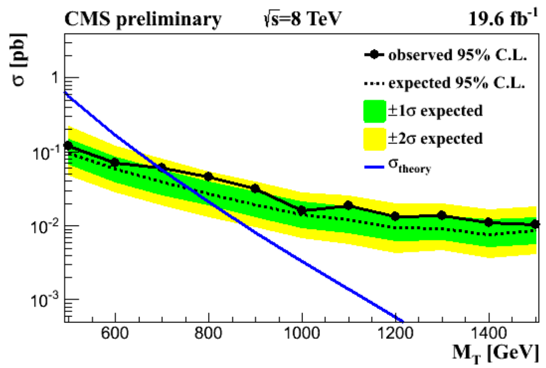


Pull: (Data – Background)/(Total bkg. error)

Events are separated into 12 categories of events based on N_leptons, lepton flavor and Z veto. Observed and predicted number of events in 12 subsamples is used to compute the likelihood.

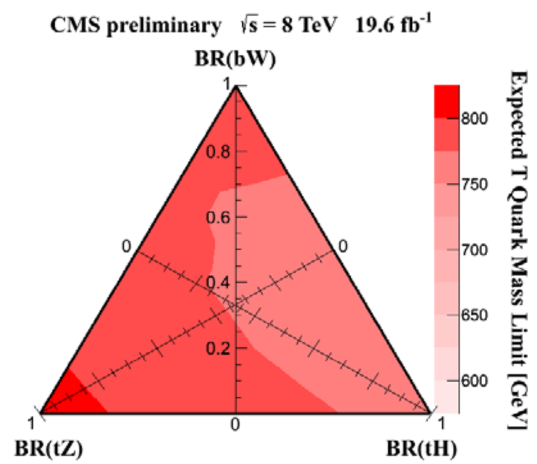
B2G-12-015, 8 TeV, T quark, inclusive search

bW(0.5)/tH(0.25)/tZ(0.25):

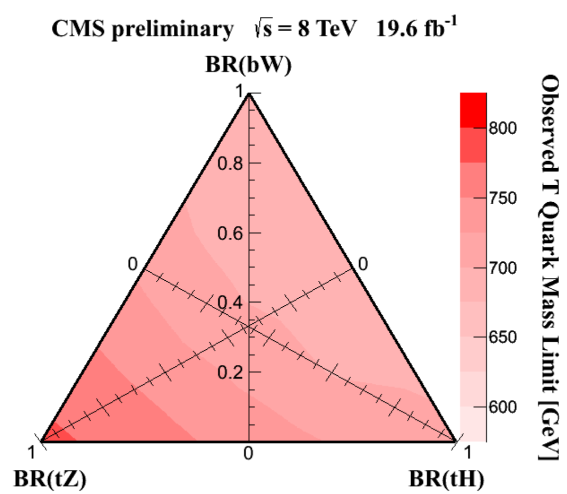


Scenario	Branching Fractions T→bW	T→tH	T→tZ	expected limit (GeV)	observed limit (GeV)
(0)	0.5	0.25	0.25	773	696
(1)	0.0	0.0	1.0	813	782
(2)	0.0	0.2	0.8	798	766
(3)	0.0	0.4	0.6	790	747
(4)	0.0	0.6	0.4	783	731
(5)	0.0	0.8	0.2	773	715
(6)	0.0	1.0	0.0	770	706
(7)	0.2	0.0	0.8	794	758
(8)	0.2	0.2	0.6	786	739
(9)	0.2	0.4	0.4	777	717
(10)	0.2	0.6	0.2	767	698
(11)	0.2	0.8	0.0	766	694
(12)	0.4	0.0	0.6	786	734
(13)	0.4	0.2	0.4	776	705
(14)	0.4	0.4	0.2	766	693
(15)	0.4	0.6	0.0	762	690
(16)	0.6	0.0	0.4	779	703
(17)	0.6	0.2	0.2	771	693
(18)	0.6	0.4	0.0	769	687
(19)	0.8	0.0	0.2	779	695
(20)	0.8	0.2	0.0	777	689
(21)	1.0	0.0	0.0	785	700

Expected limits:



Observed limits:



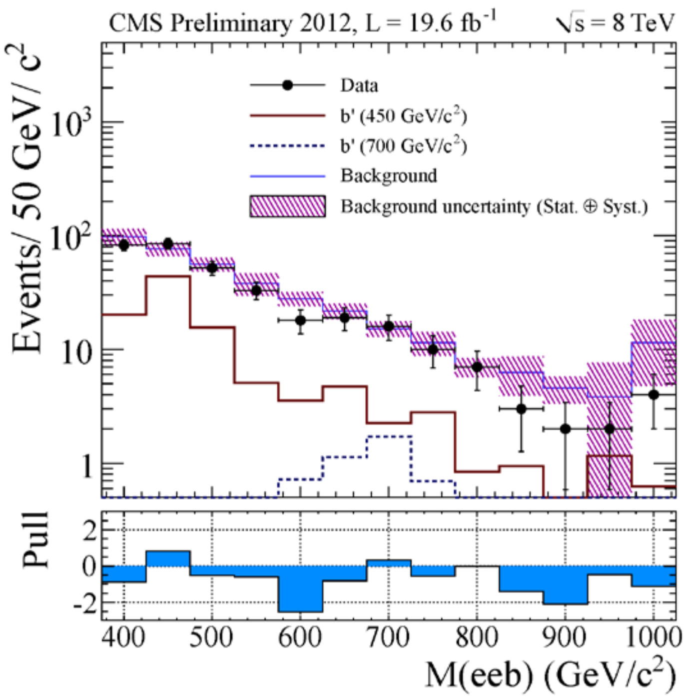
B2G-12-021, 8 TeV, B quark, double lepton with opposite sign

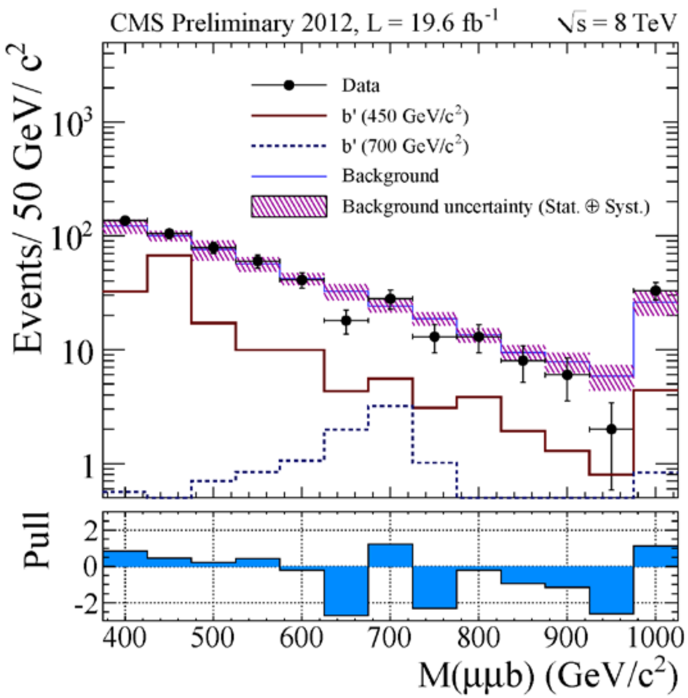
B pair production, B->bZ(Z->l+l-), tW decays are allowed.

Two opposite sign electrons or muons, 60<M(ll)<120 GeV, Pt(ll)>150 GeV;
At least one b-jet with Pt>80 GeV.

Channel	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Expected background in data	379 ± 70	534 ± 79
Observed events	334	542

Background estimated with data driven method.



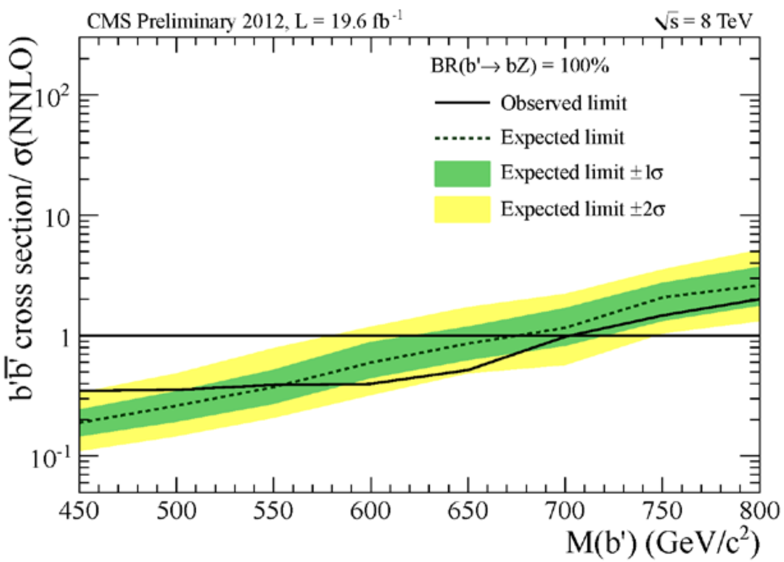


B2G-12-021, 8 TeV, B quark, double lepton with opposite sign

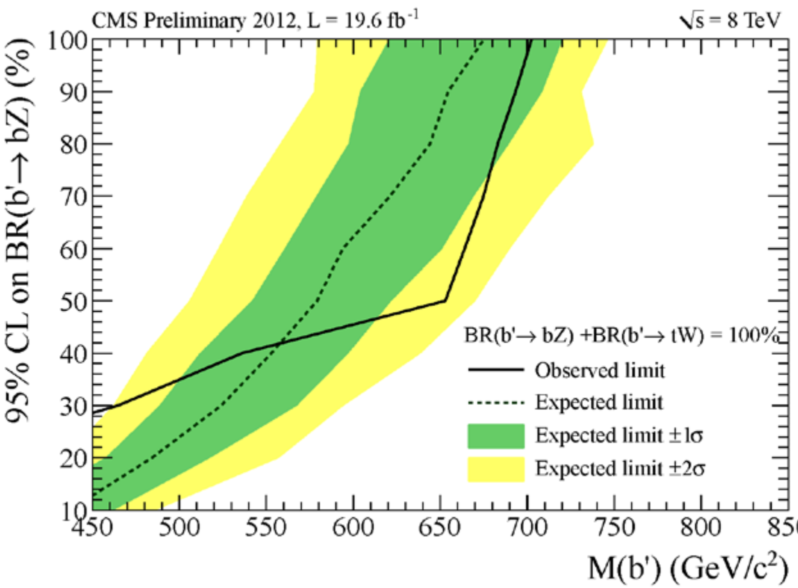
The limits are calculated using a combined fit of the signal and background shapes to the mass distribution of B candidates obtained in data.

Signal templates of M(B) mass distribution are prepared over the range 450-800 GeV with different admixtures of the B → bZ and B → tW final states, assuming
BR(B → bZ) + BR(B → tW) = 100%.

The limit from the combined
Z → e+e- and Z → μ+μ-
for the case BR(B → bZ) = 100%.
Expected: 680 GeV, observed: 700 GeV



Dependence on BR(B → bZ):



B2G-12-019, 8 TeV, B quark, all decays (single lepton)

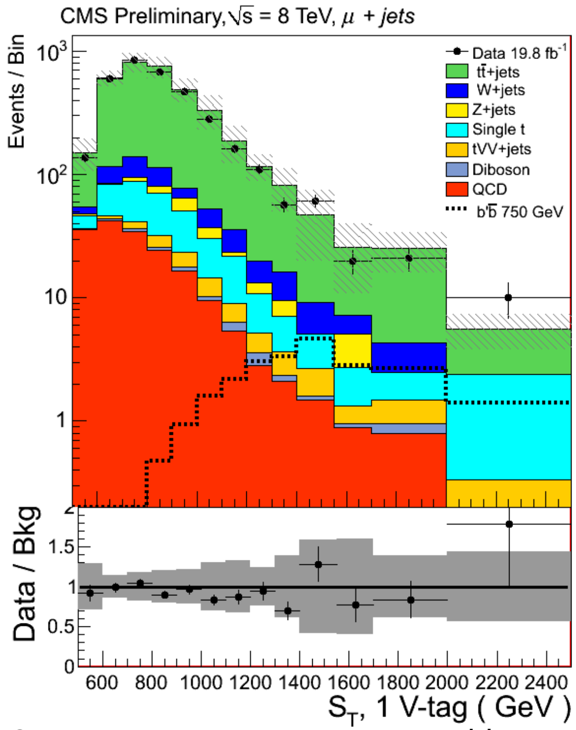
BB→tWtW, tWbZ, tWbH, bZbZ, bZbH, bHbH

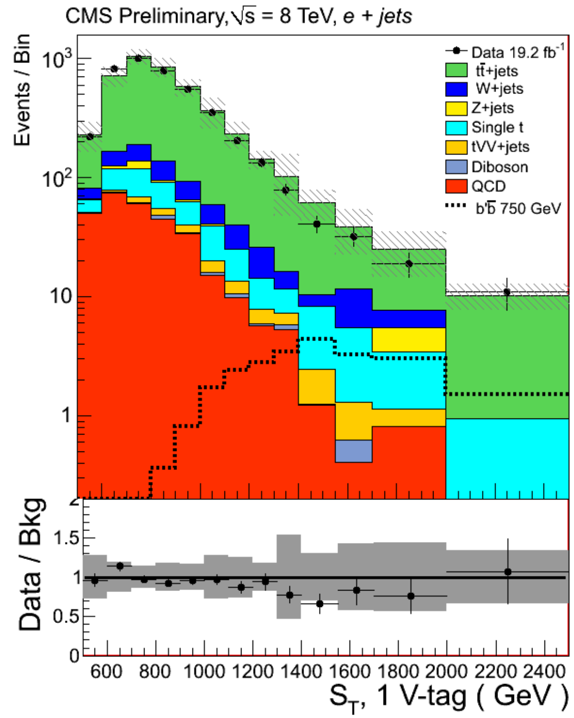
Single lepton, at least 4 AK5 jets (Pt>200,60,40,30 GeV), at least one b-tagged, Pt_miss>20 GeV.

Boosted jets, which are consistent with W, Z, H jets: Pt>200 GeV, 50 < Mjet < 150 GeV, called V-tagged jets.

Events are categorized by number of V-tagged jets (0, 1 and ≥2 V-tag categories)

ST is scalar sum of Pt of lepton,jets and Pt_miss.

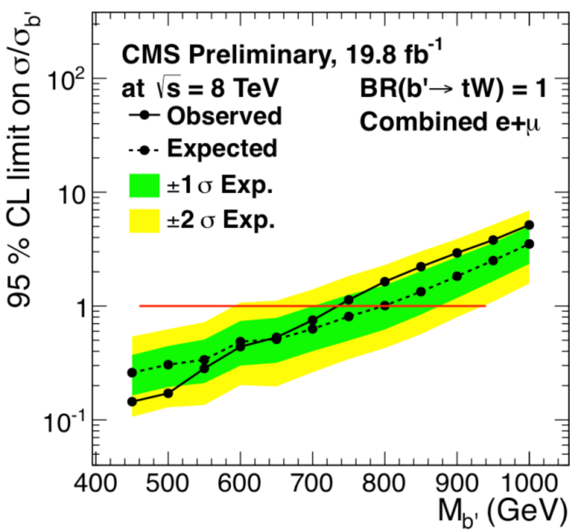




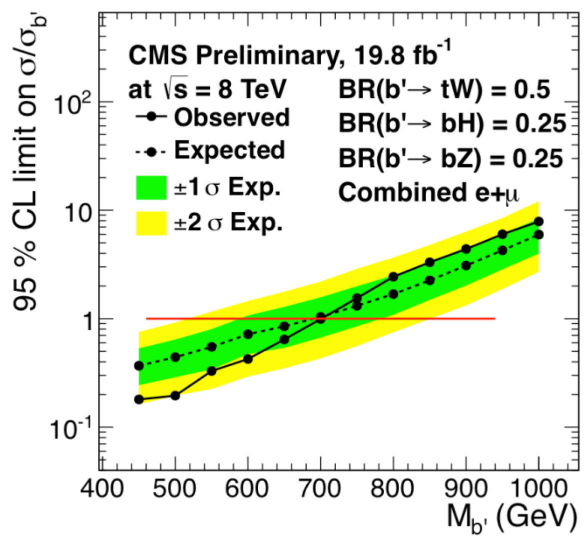
B2G-12-019, 8 TeV, B quark, all decays (single lepton)

ST distributions for 0, 1 and ≥2 V-tag categories are fit simultaneously in both e and μ channels to test for presence of signal.

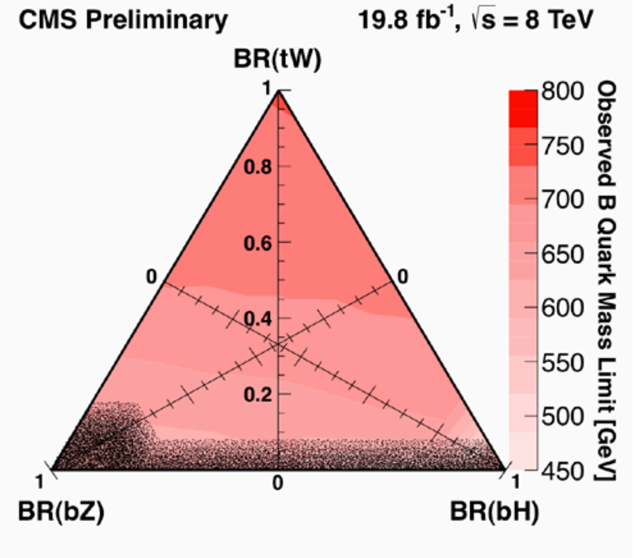
BR(tW)=1
observed limit 732 GeV:



BR(tW)=0.5, BR(bH)=0.25, BR(bZ)=0.25
observed limit 700 GeV:



A scan was done with BR to tW, bZ, bH varying with step of 0.1:



Summary of results

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EXO-11-036, b'b'→tWtW, M(b')>611 GeV.

EXO-11-050, t't'→bWbW, M(t')>557 GeV.

EXO-11-066. BB-> bZ B,M>550 GeV.

EXO-11-098, b'b', t't', b't, t'b, t'b', Mt'=Mb',
model dependent, M > 685 GeV.

EXO-11-099, t't'->bWbW, M>570 GeV.

B2G-12-003, T(5/3)T(5/3) -> tW tW, M > 645 GeV.

B2G-12-004, BB -> tWtW, TT -> tZtZ,
M(B) > 675 (625) GeV, M(T) > 625 GeV.

B2G-12-012, 8 TeV, T(5/3)T(5/3) -> tW tW, M > 770 GeV.

B2G-12-021, 8 TeV, BB-> bZ B, M>700 GeV.

B2G-12-015, 8 TeV, T -> Wb, tZ, tH.
M > (687-782) GeV depending on BR.

B2G-12-019, 8 TeV, B->tW, bZ, bH,
M > (582-732) GeV depending on BR.

Backup slides

		e+jets	μ+jets
Integrated luminosity		$4.98\,\text{fb}^{-1}$	$4.90\,\text{fb}^{-1}$
Background process	Cross section	Events	Events
$t\bar{t}$	154 pb	3950 ± 490	5460 ± 670
W+jets	31 nb	462 ± 55	750 ± 110
Single-t production	85 pb	208 ± 24	336 ± 45
Z+jets, WW, WZ, ZZ	3.1 nb	49 ± 8	69 ± 11
Multijets		78 ± 9	5 ± 5
Total background		4750 ± 560	6620 ± 800
Total observed		4734	6448

Background cross sections, number of events observed and background events predicted for the e+jets and *mu+jets samples. The predicted numbers of events are normalized to* the integrated luminosity (except for the multijet events in the e+jets channel, see text).

$M_{t'}$ (GeV)	Cross section (pb)	e+jets eff. (%)	Events	μ+jets eff. (%)	Events
400	1.41	4.3 ± 0.1	302	5.4 ± 0.1	373
425	0.96	4.4 ± 0.1	210	5.6 ± 0.1	263
450	0.66	4.7 ± 0.1	155	6.0 ± 0.1	194
475	0.46	4.7 ± 0.1	108	6.1 ± 0.1	137
500	0.33	4.8 ± 0.1	79	6.2 ± 0.1	100
525	0.24	4.7 ± 0.1	56	6.4 ± 0.1	75
550	0.17	4.9 ± 0.1	41	6.5 ± 0.1	54
575	0.13	4.7 ± 0.1	30	6.6 ± 0.1	42
600	0.092	4.7 ± 0.1	22	6.6 ± 0.1	30
625	0.069	4.8 ± 0.1	16	6.5 ± 0.1	22

Theoretical cross sections , selection efficiencies, and numbers of expected events for the t't' signal with different t' masses in the e+jets and *m+jets channels. The efficiencies* include the branching fraction of the t't' system into a single-lepton final state.

$T_{5/3}$ Mass (GeV)	2SS leptons	$M(\ell\ell)$ Veto	N(con)≥ 5	$H_T \geq 900$
550	250	235	135	62.4 ± 1.02
600	144	136	79.2	44.6 ± 0.66
650	83.1	79.1	47.1	31.1 ± 0.40
700	49.6	47.5	28.8	21.2 ± 0.26
750	30.3	29.1	18.0	14.5 ± 0.16
800	18.5	17.8	11.9	9.34 ± 0.10
850	11.5	11.1	7.03	6.12 ± 0.066
900	7.26	7.01	4.46	3.99 ± 0.042
950	4.61	4.46	2.86	2.61 ± 0.027
1000	2.91	2.82	1.82	1.69 ± 0.017

Summary table of expected signal events in all three channels.

	PSS MC	Non-Prompt	Charge Mis-ID	Total Expected	Observed
ee	0.7 ± 0.2	1.9 ± 1.2	0.06 ± 0.02	2.6 ± 1.3	0
eμ	1.9 ± 0.4	0.6 ± 0.9	0.05 ± 0.01	2.5 ± 1.0	6
$\mu\mu$	1.3 ± 0.3	0.2 ± 0.6	-	1.5 ± 0.7	5
All	3.9 ± 0.8	2.6 ± 1.8	0.1 ± 0.02	6.6 ± 2.0	11

Summary table of expected and observed events for all channels. The expected yield is composed of the prompt, same-sign ("PSS") contribution from simulation, the contribution due to fake leptons ("Non-prompt"), and that due to charge misidentification. All systematic uncertainties are included.

lepton flavor →		muon		electron	
mass (GeV)	cross section (fb)	efficiency	events	efficiency	events
500	571	7.6%	850	7.5%	840
600	170	8.3%	280	8.4%	280
700	56.9	8.7%	97	8.8%	98
800	20.8	8.9%	36	9.1%	37
900	8.09	9.0%	14.3	9.3%	14.8
1000	3.27	9.0%	5.8	9.4%	6.0
1100	1.37	9.0%	2.4	9.4%	2.5
1200	0.58	9.0%	1.0	9.4%	1.1
1300	0.25	8.9%	0.4	9.3%	0.5
1400	0.11	8.7%	0.2	9.2%	0.2
1500	0.05	8.6%	0.1	9.1%	0.1

Production cross section, efficiency, and number of events predicted for the T quark signal processes assuming branching fractions into bW, tH, tZ of 50%, 25%, 25%.

lepton flavor	muon	electron
$t\bar{t}$	36700±5500	35900±5400
single top	2190±1101	2100±1000
W	19200±9700	18200±9200
Z	2170±1100	2000±1000
multijets	0	1680±620
$t\bar{t}W$	144±72	137±68
$t\bar{t}Z$	109±54	108±54
$t\bar{t}H$	570±280	570±285
WW/WZ/ZZ	410±205	400±200
total background	61500±13700	61100±13500
data	58478	57743

Number of events predicted for background processes and observed in collision data in the signal sample. The uncertainty in the total background expectation reflects the correlation in the systematic uncertainties of the individual contributions.

channel	OS1	OS2	SS	trileptons
$t\bar{t}$	5.2±1.9	80 ±12	-	-
single top	2.5±1.3	2.0±1.0	-	-
Z	9.7±2.9	2.5±1.9	-	-
$t\bar{t}W$	-	-	5.8 ±1.9	0.25±0.11
$t\bar{t}Z$	-	-	1.83±0.93	1.84±0.94
WW	-	-	0.53±0.29	-
WZ	-	-	0.34±0.08	0.40±0.21
ZZ	-	-	0.03±0.00	0.07±0.01
WWW/WWZ/ZZZ/WZZ	-	-	0.13±0.07	0.08±0.04
$t\bar{t}WW$	-	-	-	0.05±0.03
charge mis-ID	-	-	0.01±0.00	-
non-prompt	-	-	7.9 ±4.3	0.99±0.90
total background	17.4±3.7	84 ±12	16.5 ±4.8	3.7 ±1.3
data	20	86	18	2

Number of events predicted for background processes and observed in collision data in the opposite sign dilepton samples with two or three jets (OS1) and with at least 5 jets (OS2), the same sign dilepton sample (SS), and the trilepton sample.

Background process	e+jets events	μ+jets events
$t\bar{t}$ +jets	11397 ± 85	9550 ± 79
W+jets	1247 ± 37	1137 ± 37
Multijet	1072 ± 19	505 ± 4
Single top	775 ± 17	683 ± 17
Z+jets	222 ± 22	238 ± 23
$t\bar{t}$ V+jets	92 ± 1	82 ± 1
Diboson (WW, WZ, ZZ)	43 ± 2	34 ± 2
Total background	14846 ± 99	12229 ± 91
Data	14640	11695

Number of data and expected events in the electron and muon channels after the full event selection.

$BR(b' \to bZ)$	100%		50%	
Channel	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
$M(b') = 450$ GeV/c^2	214 ± 13	336 ± 16	102 ± 4	162 ± 5
$M(b') = 500$ GeV/c^2	122 ± 7	209 ± 9	56 ± 2	94 ± 3
$M(b') = 550$ GeV/c^2	76 ± 4	114 ± 5	33 ± 1	54 ± 2
$M(b') = 600$ GeV/c^2	36 ± 2	66 ± 3	17.6 ± 0.7	30.8 ± 0.9
$M(b') = 650$ GeV/c^2	23 ± 1	41 ± 2	11.0 ± 0.4	19.5 ± 0.6
$M(b') = 700$ GeV/c^2	14.1 ± 0.7	25.9 ± 1.0	6.5 ± 0.2	12.0 ± 0.3
$M(b') = 750$ GeV/c^2	7.6 ± 0.4	15.5 ± 0.6	3.6 ± 0.1	7.4 ± 0.2
$M(b') = 800$ GeV/c^2	4.8 ± 0.3	9.9 ± 0.4	2.20 ± 0.10	4.6 ± 0.1

Event yields for signal for 19.6 fb-1, shown for b' masses M(b') from 450-800 GeV/c2 and two sets of branching ratios, BR(b'-> bZ) =100% and 50%.

Channel	$Z \to e^+e^-$	$Z \to \mu^+\mu^-$
Expected background in data	379 ± 70	534 ± 79
Observed events	334	542

Event yields for the data and background. The background is obtained using a datadriven method. The background errors include both statistical and systematic uncertainties.