Search for exotic heavy top and bottom quark partners with CMS

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On behalf of the CMS Collaboration

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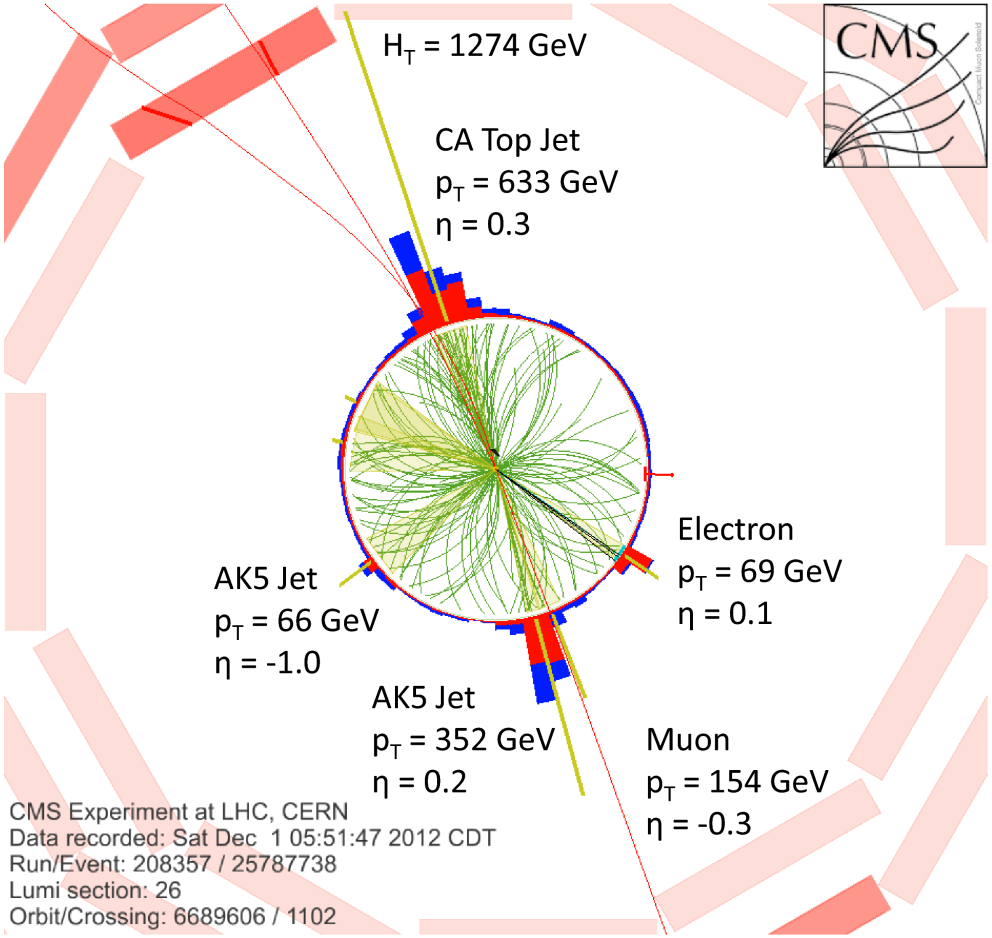


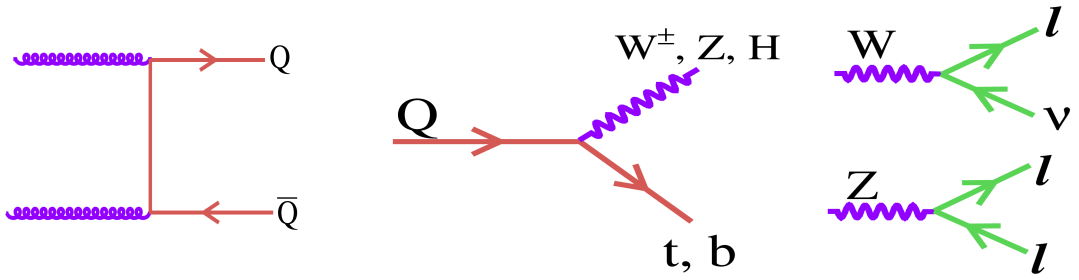
Motivation and overview

- Motivation: Understand electroweak symmetry breaking mechanism.
  - Leads to physics beyond the standard model (BSM).
  - Heavy quarks (vector-like top T or vector-like bottom b') or quarks with charge 5/3 ($T^{5/3}$) exist in many BSM scenarios.
  - Interesting and complex final states composed of vector bosons ($W^{\pm}$, Z) and Higgs (H) and 3rd generation SM quarks (top or bottom).
- Searches are model independent.

Signal	Decay modes explored	Int. Lumi.	Reference
Pair-produced vector-like top partner: pp -> TT	$bW^{\pm}$, tZ, tH	19.6	CMS PAS B2G-12-015
Pair-produced charge 5/3 quark: pp -> $T^{5/3}T^{5/3}$	tW^{+}	19.6	CMS PAS B2G-12-012
Pair-produced vector-like bottom partner: pp -> b'b'	$tW^{\pm}$, bZ	9.2	CMS PAS SUS-12-027

Analysis techniques

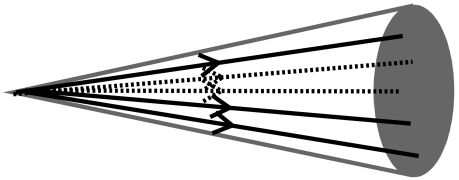
- Production and decay:



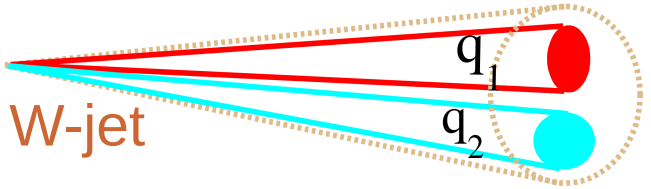
Final state with at least one W± or Z decaying leptonically:
- Clean signature
- Used for triggering

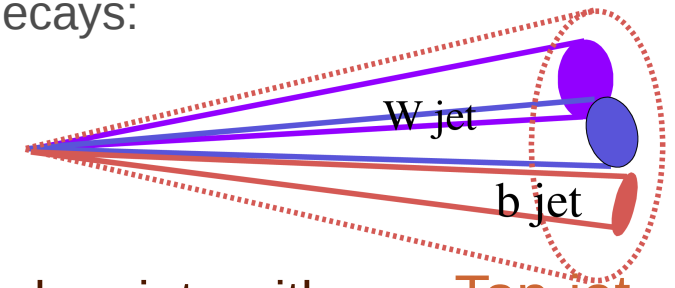
- Event classifiers: Lepton multiplicity, charge and flavour:
  - 1 lepton, 2 leptons of opposite-charge and same flavour (OSSF), opposite-charge and oppposite flavours (OSOF), same-charge (SS2L), multileptons

- Several types of jets: for single partons, hadronic W or top decays:



Anti-kT cone 0.5(AK5)





Cambridge-Aachen jets with cone 0.8 (CA8) for W- or top-tagging

Top-jet

- Other reconstructed objects:
  - Missing transverse energy (MET).
  - H_T = sum of p_T of all jets in the event.
  - S_T = sum of p_T of all selected objects (jets, leptons, MET).

Analysis techniques - 2

Backgrounds

- W, Z, ttBar+jets, single top (Madgraph+Pythia6/ Powheg)
- Dibosons (Madgraph/Pythia6)
- ttBar+V and ttBar+VV: Madgraph

Signal

- QQ (Madgraph+Pythia6).
- Cross section from HATHOR (approx. NNLO).

Background estimation

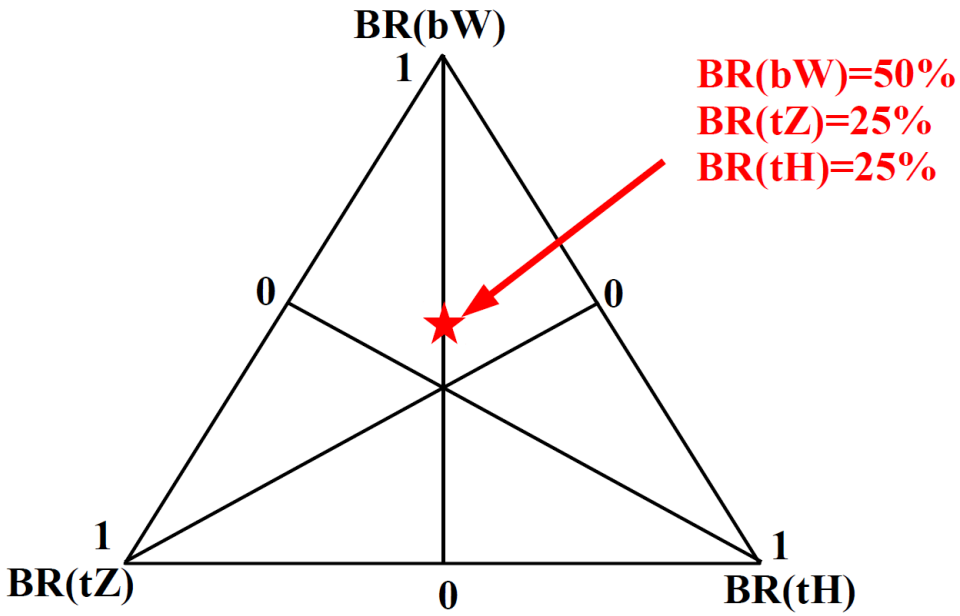
- Using data control samples wherever possible.
- Else from simulation with corrections derived from data control samples.

Systematic uncertainties

- Luminosity (4.4% for 2012).
- Object reconstruction and simulation, b-tagging, W- and top-tagging.
- Uncertainties on simulations: PDFs, factorisation, renormalisation scales.
- Jet energy scale and resolution.
- Background estimation uncertainty.

Vector-like top quark CMS PAS B2G-12-015

- All possible final states covered:
  - TT -> bWbW, bWtZ, bWtH, tZtZ, tZtH, tHtH
- Limit set over plane spanned by BR(T->bW), BR(T->bZ), BR(T->bH).
- Two analyses: Single lepton and multilepton:



Single lepton

- 1 lepton, b- W- and top-tagged jets to identify singal.
- BDT discriminatorin categories of lepton flavour and N(W-jets).
- Fit to BDT shape to obtain limits.

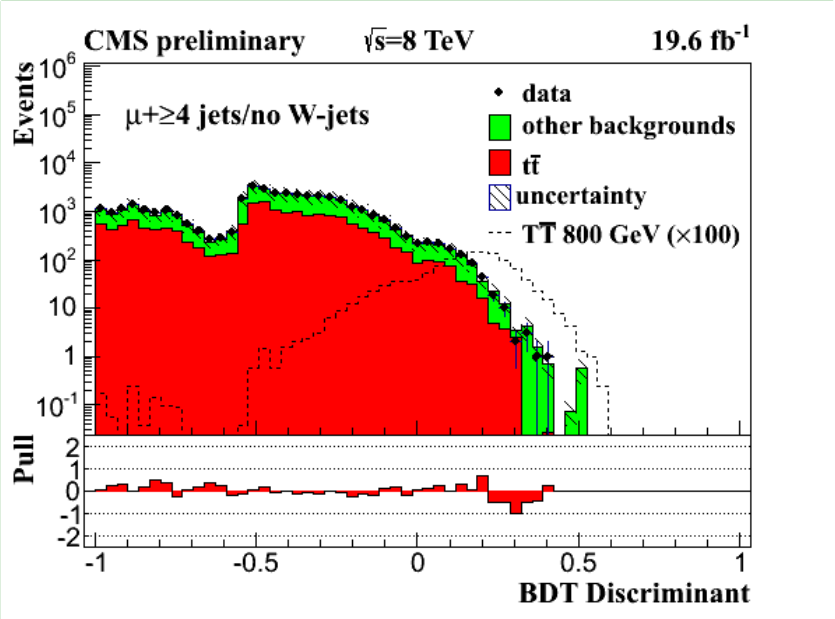
Multilepton

- 2 leptons (OSSF, OSOF, SS2L) and 3 leptons categories.
- Bkg. rejection using $N(jets)_S$, S_T, H_T, min(M(l,b-jet)) to reduces ttBar.
- Counting experiment in categories.

Vector-like top quark

Single lepton

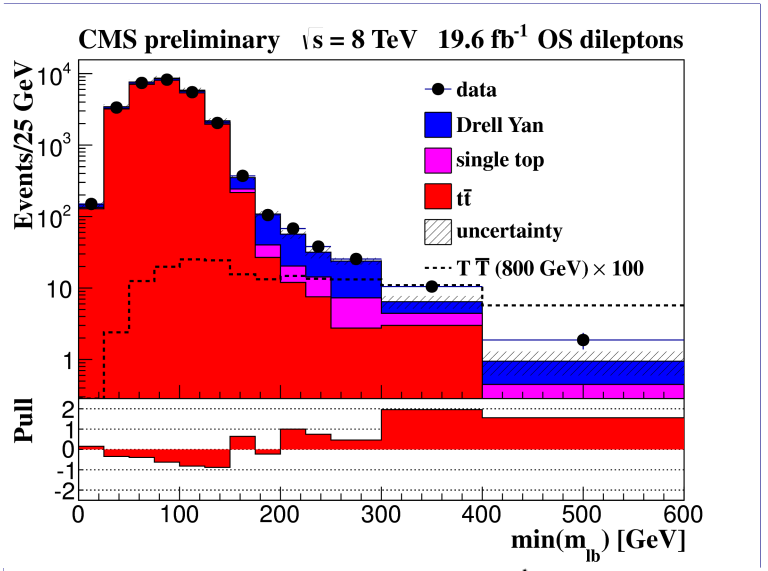
- Dominant background ttBar.
- W+jets constrained using control samples in data.
- Background modelling validated in data sample without b-tagged jets (signal highly supppressed.)



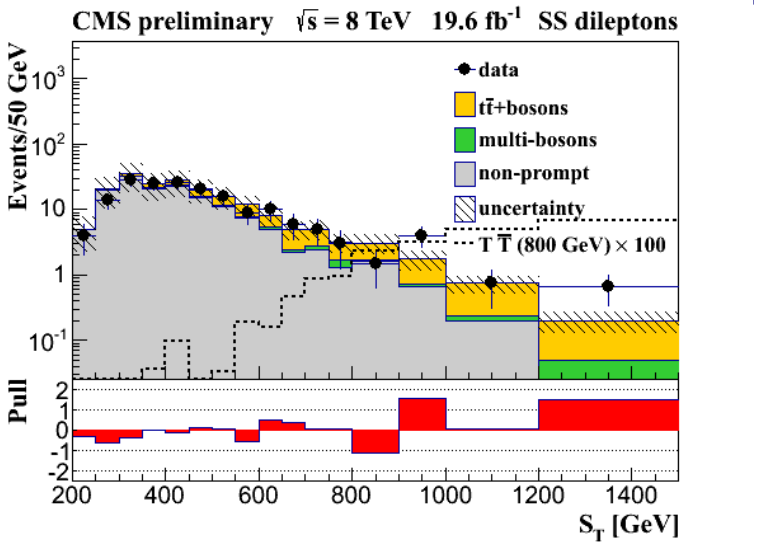
Pull: (Data – Background)/(Total bkg. error)

Multileptons

- 12 categories of events based on $N_{leptons}$, lepton flavour and Z veto.



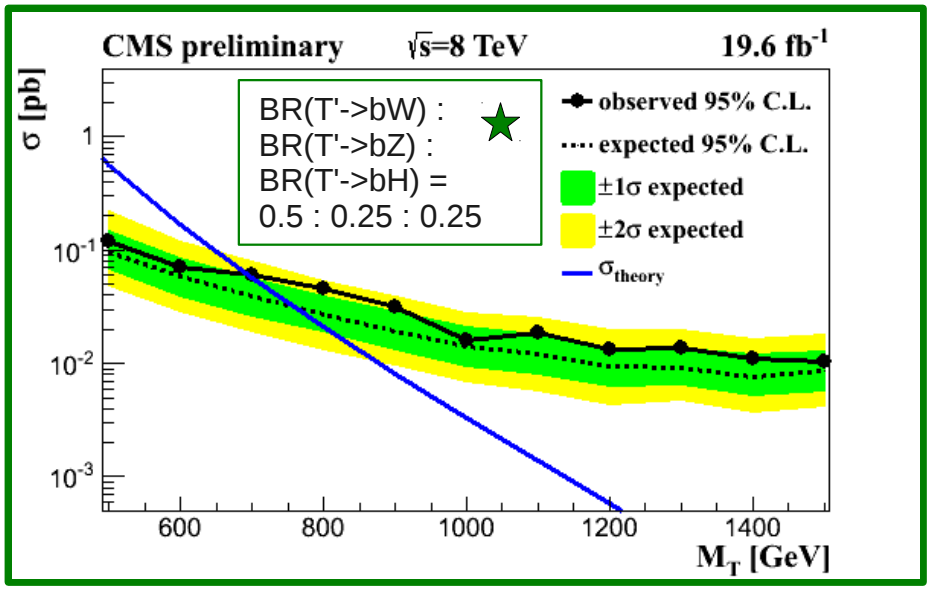
TT->bWbW

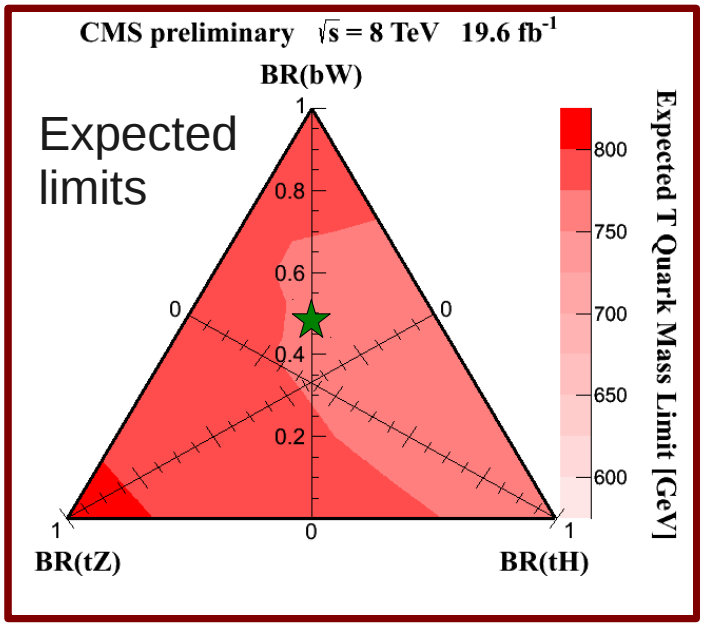


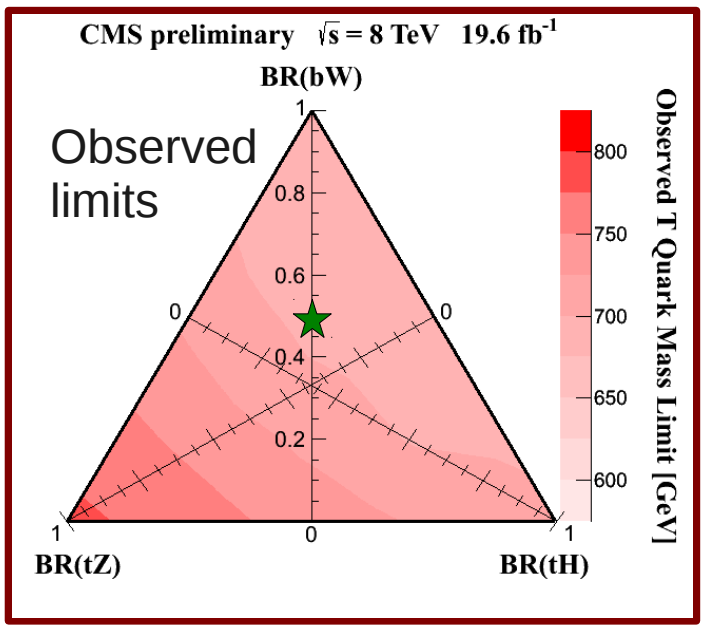
T->tZ/tH

Vector-like top quark - limits

- Single lepton limit: likelihood fit to BDT shapes for each T mass point
- Multilepton limit: Counting events in 12 different categories.
- T mass limit:
  773 GeV (expected) 696 GeV (observed)
- Limit also set for different combinations of BR(bW), BR(tZ), BR(bH)





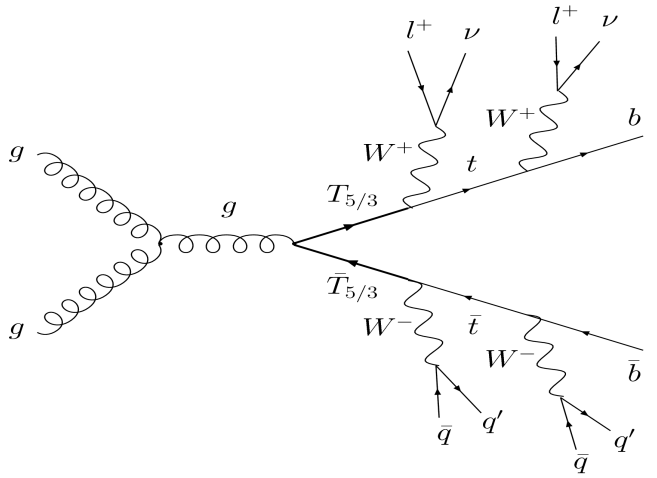


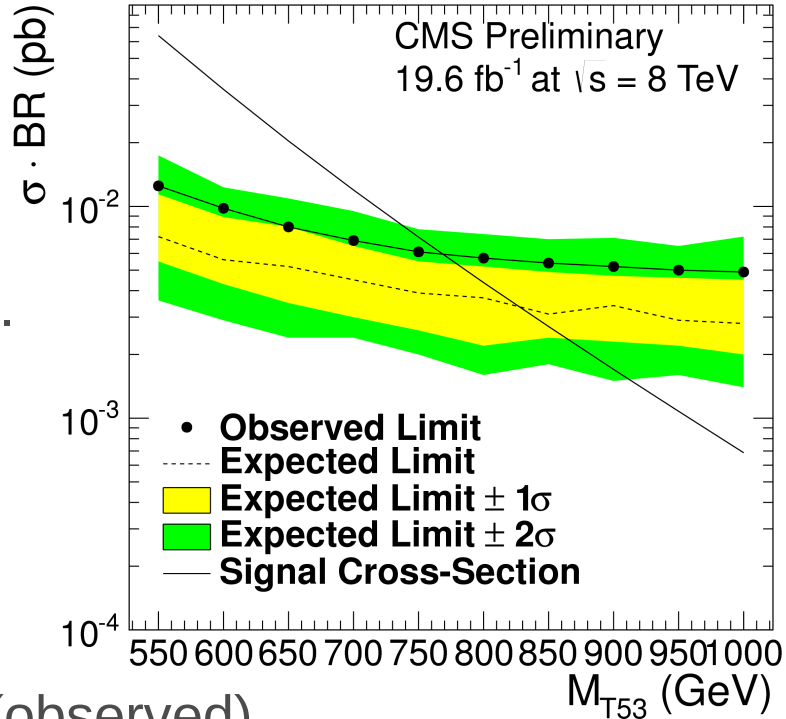
Charge 5/3 top partner CMS PAS B2G-12-012

- $T^{5/3}$ decay and final state:
  - 100% to tW with same-signed leptons (e^+e^+, $\mu^+\mu^+$, $e^\pm\mu^\pm$)
- Backgrounds:
  - ttW, ttZ, WWW and same-signed W.
  - Prompt OS2L (charge misID)
  - Fake leptons
- Event categories (using “constituents”):
  - Top-tagged jets: 3 constituents
  - W-tagged jets: 2 constituents
  - Other jets and leptons: 1 constituent each.
- Events selection:
  - >= 5 constituents
  - H_T > 900 GeV
  - Quarkonia, dilepton and trilepton Z veto.

Expected events:
6.6 ± 2.0
Observed: 11

- $T^{5/3}$ mass limit: 830 GeV (expected) 770 GeV (observed)

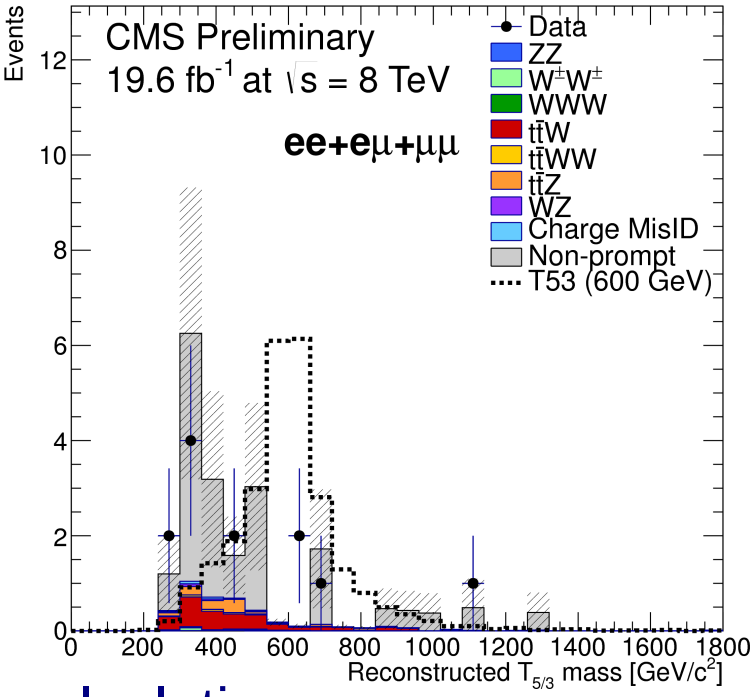




Mass reconstruction of $T^{5/3}$

- Improve discovery potential in the future.
- Mass reconstruction: From hadronically decaying top quark and W boson

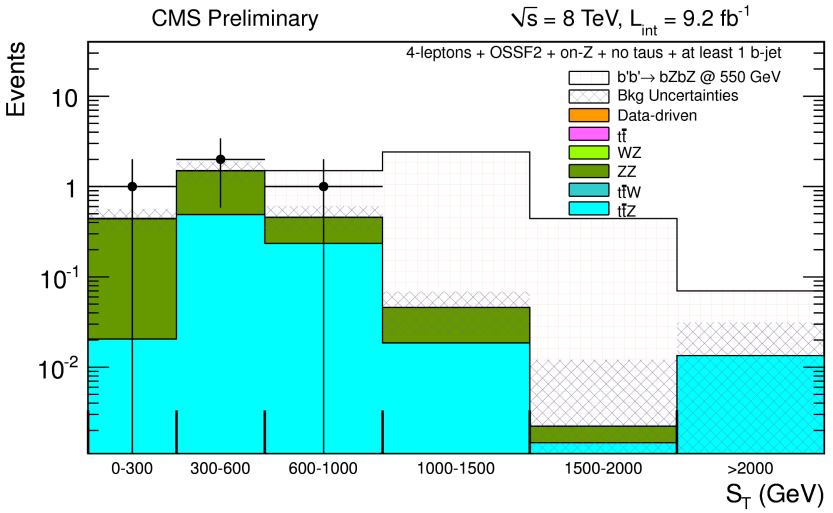
	Top-jet	W-jet	AK5 jet
Combination 1	1	1	
Combination 2	1		2 (W)
Combination 3		2	1
Combination 4		1	2(W) + 1
Combination 5			2x2 (W)+1

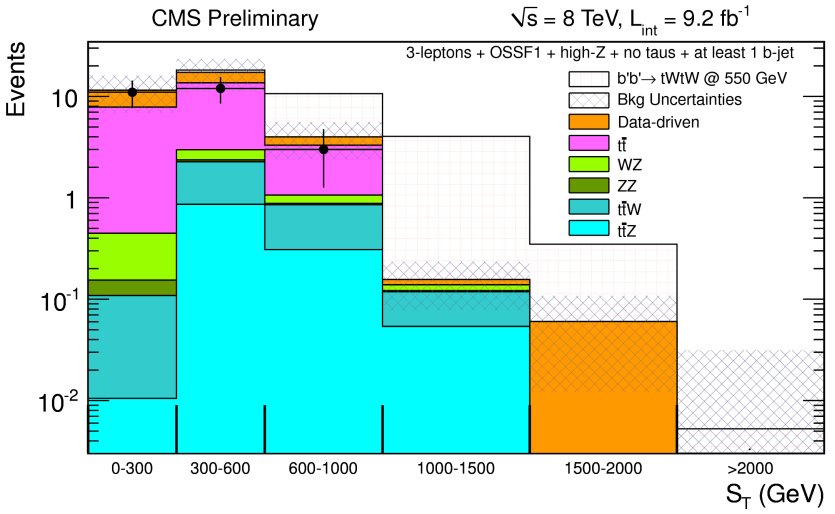


- Relaxed event selection compared to mass limit calculation.
- Five high-p_T jets trequired: reduces reconstructon efficiency by ~1/3

Vector-like bottom quark CMS PAS SUS-12-027

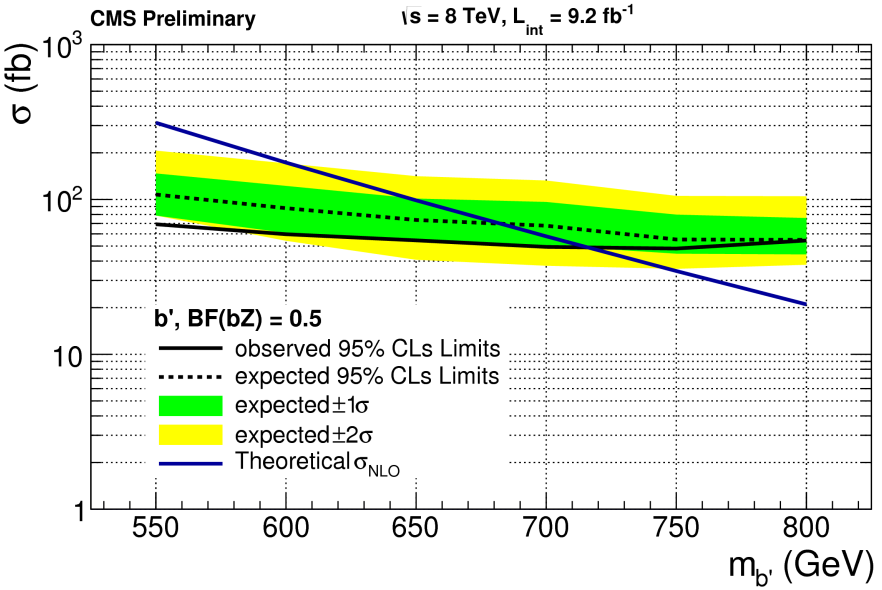
- Decay channels: b' -> tW or b' -> bZ.
- Final states: 3 or 4 leptons
- Event categories: As per lepton charge and flavour
  - μ+μ+μ-, μ+μ-e- (OSSF1) μ+μ+e- (OSSF0) μ+μ-e+e- (OSSF1)
  - Leptonic Z if 75 < M(l+l-) < 105 GeV
  - Number of b-tagged jets
- Backgrounds:
  - Misidentified, non-prompt leptons from data.
  - ttBar, dibosons from simulations – verified in data control samples.

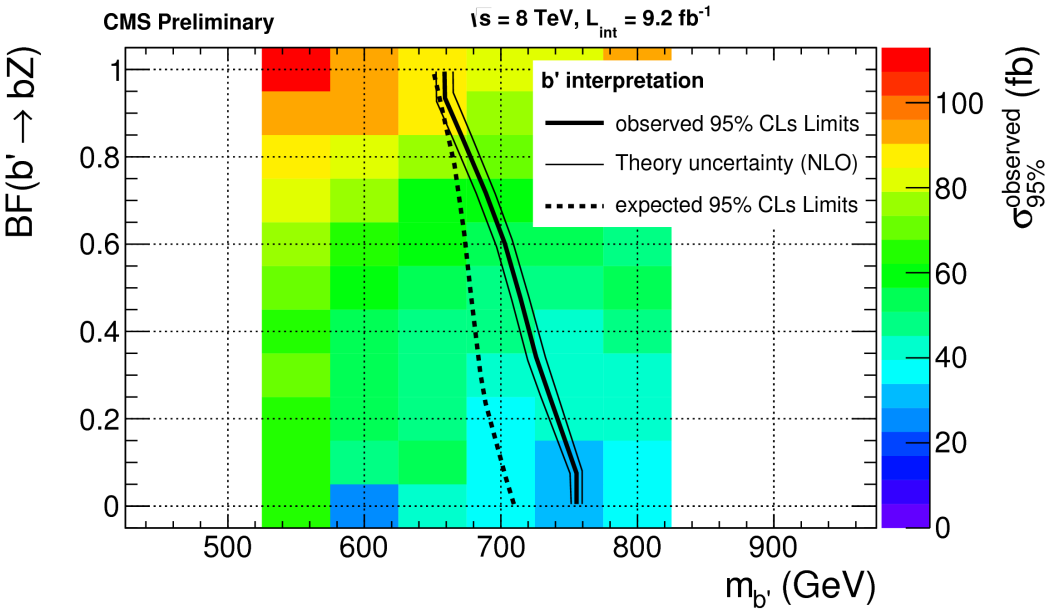




Vector-like bottom quark -- limits

- B' quark mass limit: 700 GeV for BR(b'->tW) = BR(b'-bZ)=0.5.
- Branching ratio dependent limit: 660-760 GeV





Conclusion

- Heavy quark-like states arise in many BSM physics models.
- Limits set on pair-produced heavy quarks of charge +2/3, +5/3 and -1/3:

Heavy quark	Branching ratios	Mass Limit
T (+2/3)	BR(bW):BR(tZ):BR(tH) = 0.5:0.25:0.25	696 GeV
$T^{5/3}$ (+5/3)	BR(tW) = 1	770 GeV
b' (-1/3)	BR(tW):BR(bZ) = 0.5:0.5	700 GeV

- Searches continue for new physics that may be just around the corner....

Backup

VLQ top search: single lepton

- BDT shape fits.
- Categories according to N(W-jets) = 0 or >1 to enhance sensitivity.
- Background modelling checked in events with b-tag veto.
- W-jets estimated from Monte Carlo with normalisation from data controls for W+jets (for light and heavy jet flavours.)

Single lepton

- MET > 20 GeV
- With W-tagged jet
  - CA8 jets with p_T > 200 GeV
  - Mass between 860-130 GeV
  - >= 3 AK5 jets (p_T > 120, 90 and 50 GeV)
- Without W-tagged jet
  - >= 4 AK5 jets (p_T > 120, 90, 50 and 35 GeV)
- Use BDT discriminator with above variables plus p_T(3rd jet), p_T(4th jet), $N_{b\text{-jets}}$, $N_{W\text{-jets}}$, p_T(W-jets), $N_{t\text{-jets}}$

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

BDT categories

- Electron/ muon
  - With W-jet, N(jet) >= 3
  - No W-jets , N(jets) >= 4

VLQ top search: multileptons

1. OS2L with Z veto (OS1):
   - 2 or 3 jets (1 b-tagged)
   - H_T > 300 GeV
   - S_T > 900 GeV
   - M(l, b-jet) > 170 GeV

bWbW mode

2. OS2L (OS2):
   - >= 5 jets (2 b-tagged)
   - H_T > 500 GeV
   - S_T > 1000 GeV

tHtZ mode

3. SS2L:
   - >= 3 jets (1 b-tagged)
   - H_T > 500 GeV
   - S_T > 300 GeV

4. 3 leptons
   - >= 3 jets (1 b-tagged)
   - H_T > 500 GeV
   - S_T > 700 GeV
   - MET > 30 GeV (all categories)

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

12 categories				
OS	Z veto	ee	eμ	μμ
	No Z veto	ee	eμ	μμ
SS		ee	eμ	μμ
3 leptons		eee	μμμ	eeμ/ eμμ

$T^{5/3}$ event yields

- Signal

$T_{5/3}$ 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

- Data and background

	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

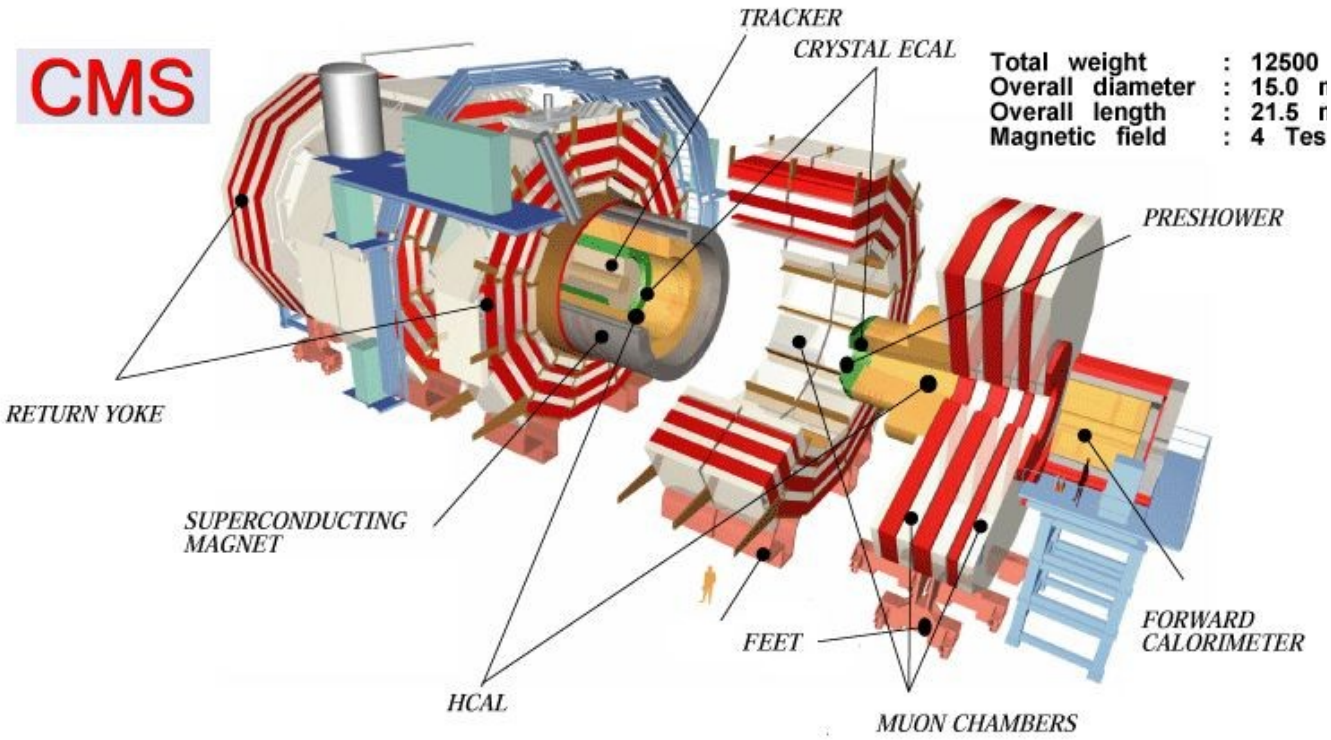
b' yields in 3 lepton channel

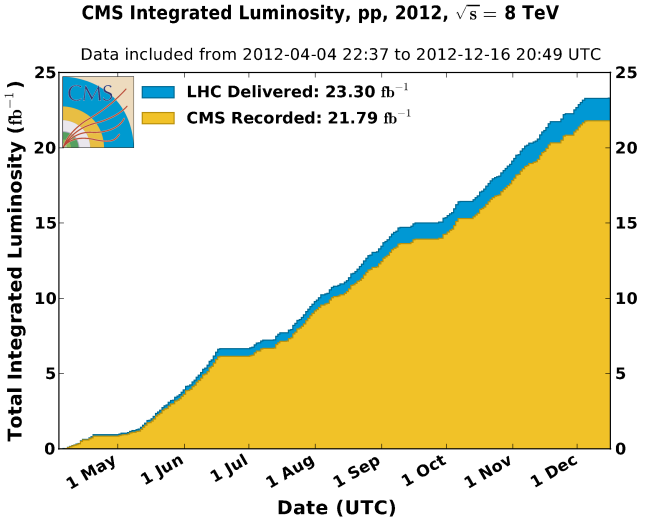
N_{OSSF}	OSSF Mass	S_T (GeV)	0-τ, 0-b		1-τ, 0-b		0-τ, 1+ b		1-τ, 1+ b	
			obs	exp	obs	exp	obs	exp	obs	exp
0	-	$S_T > 2000$ GeV	0	0 ± 0.009	0	0 ± 0.2	0	0 ± 0.01	0	0 ± 0.2
0	-	$1500 < S_T < 2000$ GeV	0	0.01 ± 0.01	0	0.003 ± 0.2	0	0 ± 0.01	0	0.5 ± 0.48
0	-	$1000 < S_T < 1500$ GeV	0	0.07 ± 0.03	0	0.4 ± 0.22	0	0.6 ± 0.5	2	1.3 ± 0.9
0	-	$600 < S_T < 1000$ GeV	2	2.1 ± 1.2	17	9 ± 3.5	1	3.3 ± 1.6	23	20 ± 10
0	-	$300 < S_T < 600$ GeV	14	13 ± 5.7	129	134 ± 53	20	16 ± 6.5	206	186 ± 98
0	-	$0 < S_T < 300$ GeV	30	37 ± 10	555	581 ± 130	22	13 ± 5.9	150	150 ± 72
1	$m_{\ell^+\ell^-} > 105$ GeV	$S_T > 2000$ GeV	0	0.0005 ± 0.01	0	0 ± 0.2	0	0 ± 0.03	0	0 ± 0.2
1	$m_{\ell^+\ell^-} < 75$ GeV	$S_T > 2000$ GeV	0	0.002 ± 0.01	0	0 ± 0.2	0	0 ± 0.03	0	0 ± 0.2
1	onZ	$S_T > 2000$ GeV	0	0.12 ± 0.04	0	0.005 ± 0.2	0	0.01 ± 0.04	0	0 ± 0.2
1	$m_{\ell^+\ell^-} > 105$ GeV	$1500 < S_T < 2000$ GeV	0	0.08 ± 0.04	0	0.2 ± 0.2	0	0.06 ± 0.04	0	0.05 ± 0.05
1	$m_{\ell^+\ell^-} < 75$ GeV	$1500 < S_T < 2000$ GeV	1	0.02 ± 0.03	0	0 ± 0.2	0	0.06 ± 0.04	0	0 ± 0.2
1	onZ	$1500 < S_T < 2000$ GeV	2	0.5 ± 0.28	0	0.12 ± 0.08	0	0.11 ± 0.07	0	0.07 ± 0.05
1	$m_{\ell^+\ell^-} > 105$ GeV	$1000 < S_T < 1500$ GeV	0	0.46 ± 0.11	0	0.6 ± 0.28	0	0.15 ± 0.07	1	0.9 ± 0.6
1	$m_{\ell^+\ell^-} < 75$ GeV	$1000 < S_T < 1500$ GeV	0	0.41 ± 0.08	0	0.2 ± 0.12	0	0.16 ± 0.08	0	0.6 ± 0.6
1	onZ	$1000 < S_T < 1500$ GeV	6	7.6 ± 1.3	3	2.4 ± 0.5	1	1.6 ± 0.43	1	0.8 ± 0.6
1	$m_{\ell^+\ell^-} > 105$ GeV	$600 < S_T < 1000$ GeV	6	5.2 ± 1.2	12	8.5 ± 2.6	3	3.9 ± 1.5	13	9.8 ± 5.4
1	$m_{\ell^+\ell^-} < 75$ GeV	$600 < S_T < 1000$ GeV	2	4.7 ± 0.9	11	6.8 ± 2.5	0	3.3 ± 1.1	5	5.1 ± 2.8
1	onZ	$600 < S_T < 1000$ GeV	42	56 ± 7.6	48	35 ± 7.2	7	10 ± 2.7	10	6.5 ± 1.9
1	$m_{\ell^+\ell^-} > 105$ GeV	$300 < S_T < 600$ GeV	34	31 ± 5.3	149	170 ± 39	12	17 ± 6.1	80	73 ± 35
1	$m_{\ell^+\ell^-} < 75$ GeV	$300 < S_T < 600$ GeV	34	38 ± 6	139	128 ± 29	26	23 ± 9	87	81 ± 35
1	onZ	$300 < S_T < 600$ GeV	314	356 ± 45	1023	1219 ± 290	63	44 ± 8.1	131	132 ± 31
1	$m_{\ell^+\ell^-} > 105$ GeV	$0 < S_T < 300$ GeV	81	97 ± 9.5	799	761 ± 182	11	11 ± 4.6	50	41 ± 17
1	$m_{\ell^+\ell^-} < 75$ GeV	$0 < S_T < 300$ GeV	308	325 ± 36	4933	4208 ± 1033	31	35 ± 13	146	129 ± 38
1	onZ	$0 < S_T < 300$ GeV	2054*	2260 ± 213	24078	22191 ± 5517	57	67 ± 9.3	391	369 ± 87
Total3	All	All	2930	3239 ± 308	31896	29460 ± 7204	254	252 ± 59	1296	1211 ± 351

b' yields in 4 lepton channel

N_{OSSF}	onZ	S_T(GeV)	0-τ, 0-b obs	0-τ, 0-b exp	1-τ, 0-b obs	1-τ, 0-b exp	0-τ, 1+ b obs	0-τ, 1+ b exp	1-τ, 1+ b obs	1-τ, 1+ b exp
0	-	$S_T > 2000$ GeV	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009
0	-	$1500 < S_T < 2000$ GeV	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009
0	-	$1000 < S_T < 1500$ GeV	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009
0	-	$600 < S_T < 1000$ GeV	0	0 ± 0.009	0	0.01 ± 0.01	0	0.01 ± 0.02	0	0 ± 0.009
0	-	$300 < S_T < 600$ GeV	0	0.009 ± 0.01	0	0.6 ± 0.5	0	0.0007 ± 0.009	0	0.11 ± 0.07
0	-	$0 < S_T < 300$ GeV	0	0.004 ± 0.009	2	0.16 ± 0.08	0	0.0002 ± 0.009	0	0.14 ± 0.09
1	offZ	$S_T > 2000$ GeV	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009
1	onZ	$S_T > 2000$ GeV	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009	0	0 ± 0.009
1	offZ	$1500 < S_T < 2000$ GeV	0	0 ± 0.009	0	0.007 ± 0.01	0	0 ± 0.009	0	0 ± 0.009
1	onZ	$1500 < S_T < 2000$ GeV	0	0 ± 0.009	0	0.01 ± 0.01	0	0.009 ± 0.01	0	0 ± 0.009
1	offZ	$1000 < S_T < 1500$ GeV	0	0.001 ± 0.009	0	0.06 ± 0.03	0	0.01 ± 0.01	0	0.001 ± 0.009
1	onZ	$1000 < S_T < 1500$ GeV	0	0.03 ± 0.02	0	0.05 ± 0.03	0	0.06 ± 0.04	0	0.02 ± 0.02
1	offZ	$600 < S_T < 1000$ GeV	0	0.02 ± 0.02	2	0.15 ± 0.05	0	0.03 ± 0.02	0	0.09 ± 0.05
1	onZ	$600 < S_T < 1000$ GeV	0	0.18 ± 0.06	0	0.7 ± 0.13	0	0.22 ± 0.13	0	0.32 ± 0.14
1	offZ	$300 < S_T < 600$ GeV	0	0.07 ± 0.02	1	0.7 ± 0.15	0	0.1 ± 0.06	0	0.47 ± 0.21
1	onZ	$300 < S_T < 600$ GeV	2	0.6 ± 0.17	5	4.7 ± 0.7	0	0.47 ± 0.25	1	0.7 ± 0.23
1	offZ	$0 < S_T < 300$ GeV	1	0.17 ± 0.05	9	4 ± 1.2	0	0.009 ± 0.01	0	0.19 ± 0.11
1	onZ	$0 < S_T < 300$ GeV	0	1.2 ± 0.38	18	18 ± 5.2	2	0.02 ± 0.02	2	0.37 ± 0.17
2	offZ	$S_T > 2000$ GeV	0	0 ± 0.009	0	0 ± 0	0	0 ± 0.009	0	0 ± 0
2	onZ	$S_T > 2000$ GeV	0	0.001 ± 0.009	0	0 ± 0	0	0.01 ± 0.01	0	0 ± 0
2	offZ	$1500 < S_T < 2000$ GeV	0	0 ± 0.009	0	0 ± 0	0	0 ± 0.009	0	0 ± 0
2	onZ	$1500 < S_T < 2000$ GeV	0	0.02 ± 0.01	0	0 ± 0	0	0.002 ± 0.009	0	0 ± 0
2	offZ	$1000 < S_T < 1500$ GeV	0	0.004 ± 0.01	0	0 ± 0	0	0 ± 0.009	0	0 ± 0
2	onZ	$1000 < S_T < 1500$ GeV	0	0.27 ± 0.06	0	0 ± 0	0	0.04 ± 0.02	0	0 ± 0
2	offZ	$600 < S_T < 1000$ GeV	0	0.04 ± 0.01	0	0 ± 0	0	0.04 ± 0.02	0	0 ± 0
2	onZ	$600 < S_T < 1000$ GeV	1	2.6 ± 0.5	0	0 ± 0	1	0.45 ± 0.14	0	0 ± 0
2	offZ	$300 < S_T < 600$ GeV	1	0.46 ± 0.1	0	0 ± 0	1	0.1 ± 0.06	0	0 ± 0
2	onZ	$300 < S_T < 600$ GeV	10	19 ± 3.8	0	0 ± 0	2	1.4 ± 0.39	0	0 ± 0
2	offZ	$0 < S_T < 300$ GeV	4	3.4 ± 0.9	0	0 ± 0	0	0.07 ± 0.03	0	0 ± 0
2	onZ	$0 < S_T < 300$ GeV	68	56 ± 13	0	0 ± 0	1	0.44 ± 0.12	0	0 ± 0
Total4	All	All	87	84 ± 19	37	29 ± 6.9	7	3.6 ± 1.1	3	2.5 ± 0.7

The CMS detector





- CMS: general purpose detector
- Approximate scale:
  - 66M pixel channels, 10M tracker channels
  - 76K ECAL crytals, 150K silicon preshower channels
  - 15K HCAL channels
  - 250 DT chambers (170K wires), 470 CSC chambers (200K wires), 900 RPCs.