Search for Exotic Top Partners

Saptaparna Bhattacharya, for the CMS collaboration
DPF 2013, UC Santa Cruz
August 13-17, 2013

Introduction

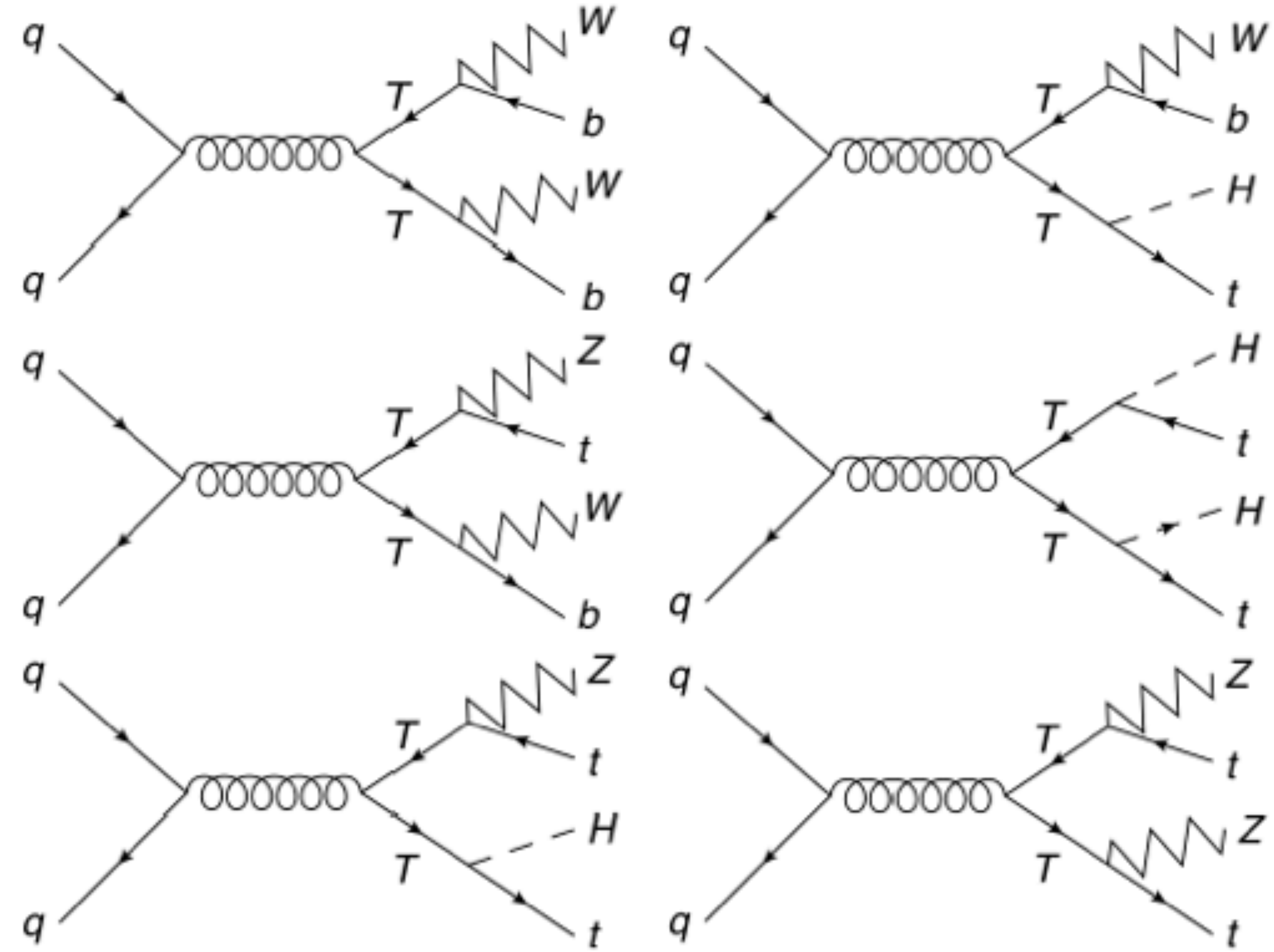
- Many extensions of physics beyond the standard model propose the existence of fermionic partners (top-partners) of the top quark.
- These quarks could be vector-like (T) or could originate in composite-Higgs models ($T_{5/3}$).
- Vector like T quark search includes T decaying to bW, tZ and tH. The newly discovered Higgs boson is used as a probe for new physics.
- $T_{5/3}$ pair production does not contribute significantly to the Higgs cross section, hence these quarks are consistent with the existence of a Higgs boson with a mass of 125 GeV.
- Just like top-partners, bottom-partners, b', could exist, decaying to tW and bZ.
- CMS SUSY searches have been interpreted to set exclusion limits on the existence of b'.

Search for vector-like top partners, CMS-B2G-12-015

- Vector-like quarks appear in many extensions of physics beyond the standard model, in models such as the Little Higgs, Extra Dimensions and MSSM.

- A vector-like quark, T is pair produced and decays to bW, tH and Zt.

- Leads to busy final states with multiple bosons and b-tagged jets.



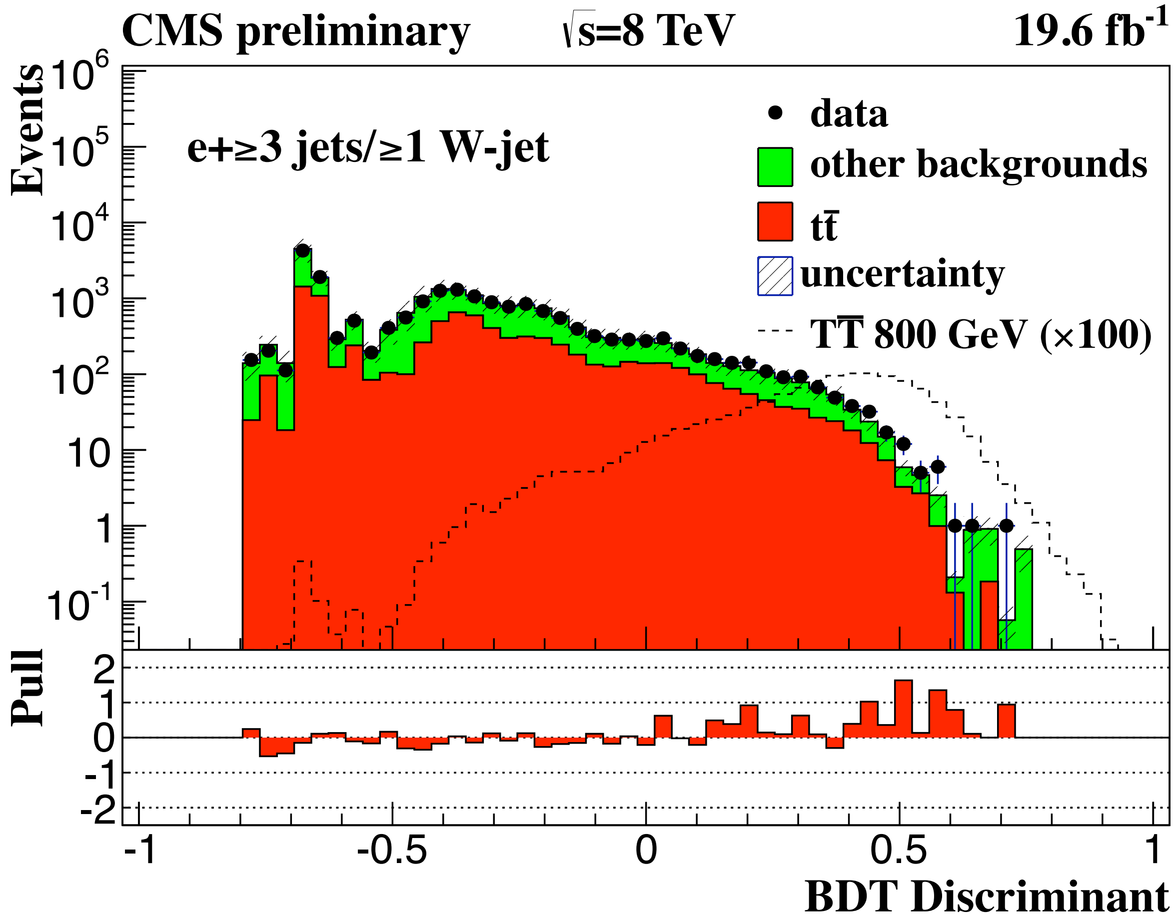
TT is pair produced through qq annihilation and gluon fusion.

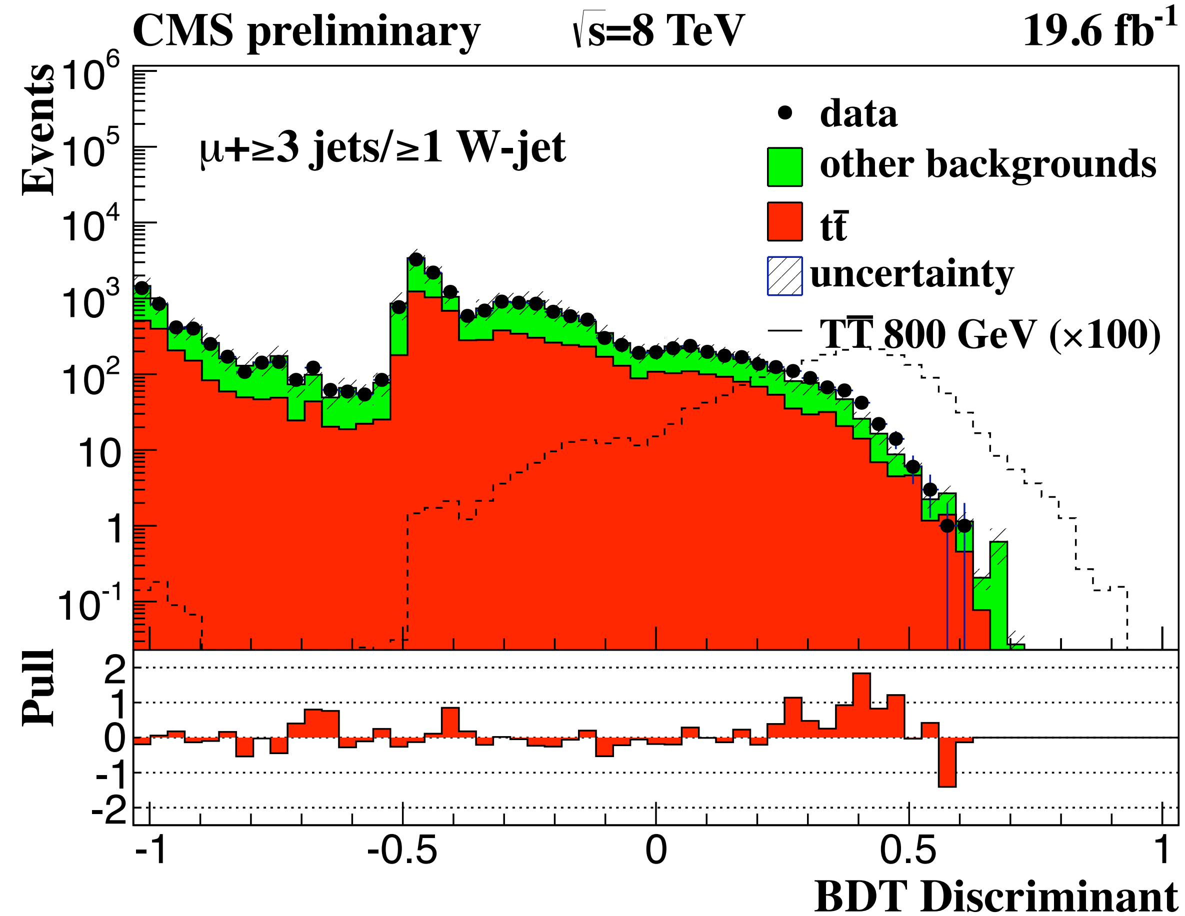
Single lepton channel

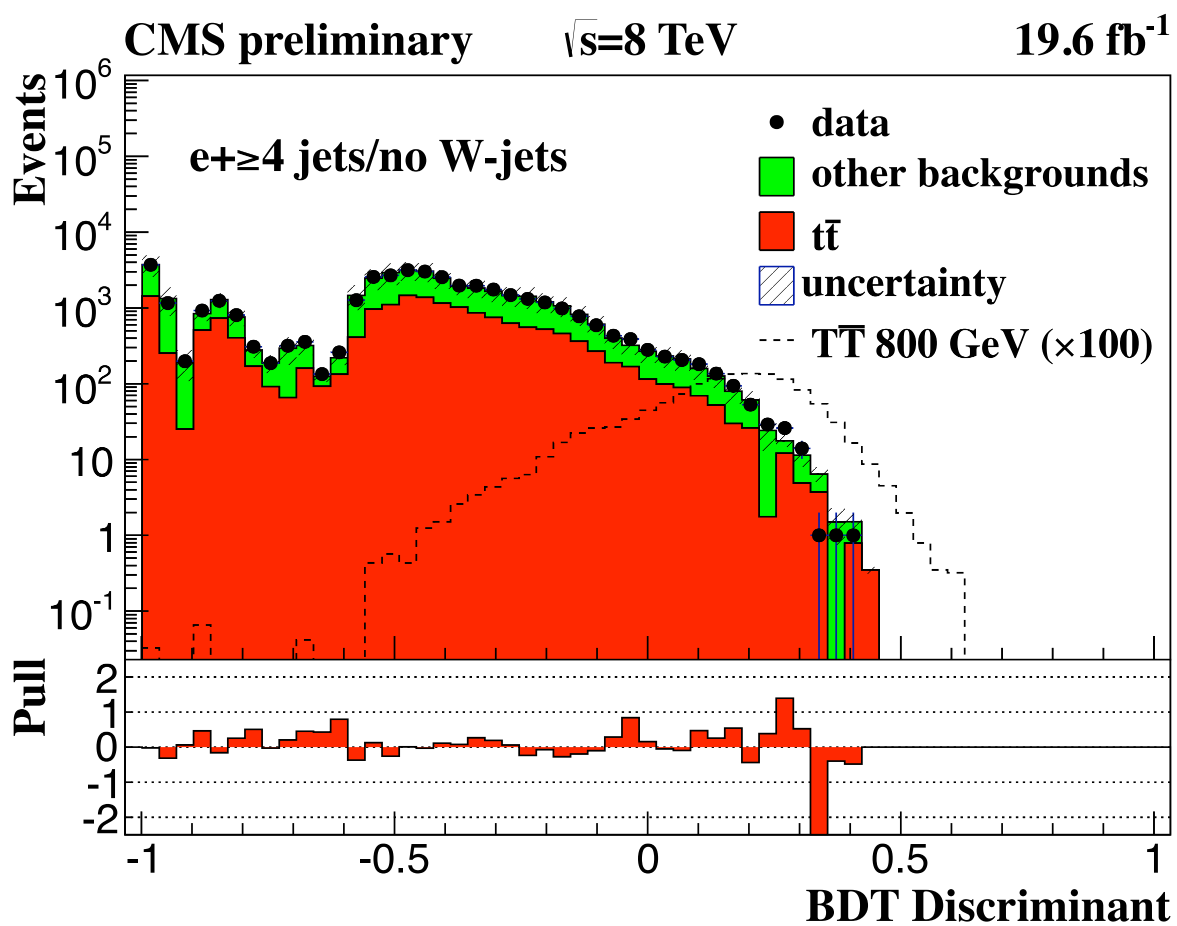
- Tools used:
    - Jet substructure variables are utilized to tag "top" and "W" jets.
    - W tagging uses a jet-pruning algorithm which takes Cambridge-Aachen (CA) jets of distance parameter, R, of 0.8 as inputs.
    - Jets from highly boosted top quarks are merged into one jet using a top-tagging algorithm.
- Analysis strategy:
    - A boosted decision tree (BDT) is used to separate signal from SM background (96% of which originates from ttbar, W and Z boson production processes).
    - Two separate event categories constructed based on the presence of a W tagged jet.
    - The input variables to the BDT are: jet multiplicity, b-tag multiplicity, sum of the transverse momenta of the selected jets (H_T), missing E_T, lepton p_T, p_T of the 3rd and the 4th jet.
    - W tagged events also utilize the p_T of the W-jets and the number of top tagged jets.

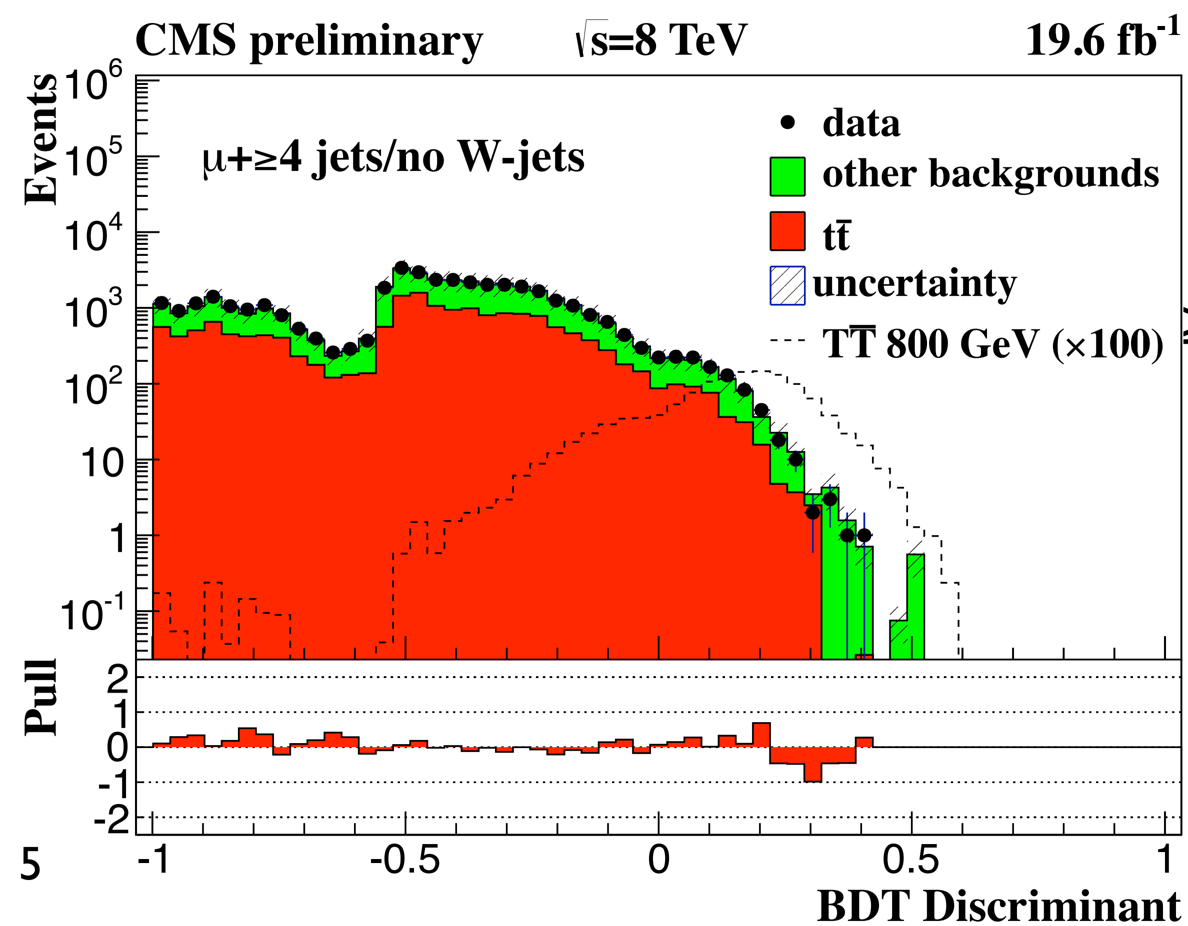
BDT distributions

with W-jet, ≥3 jets









no W-jet, ≥4 jets

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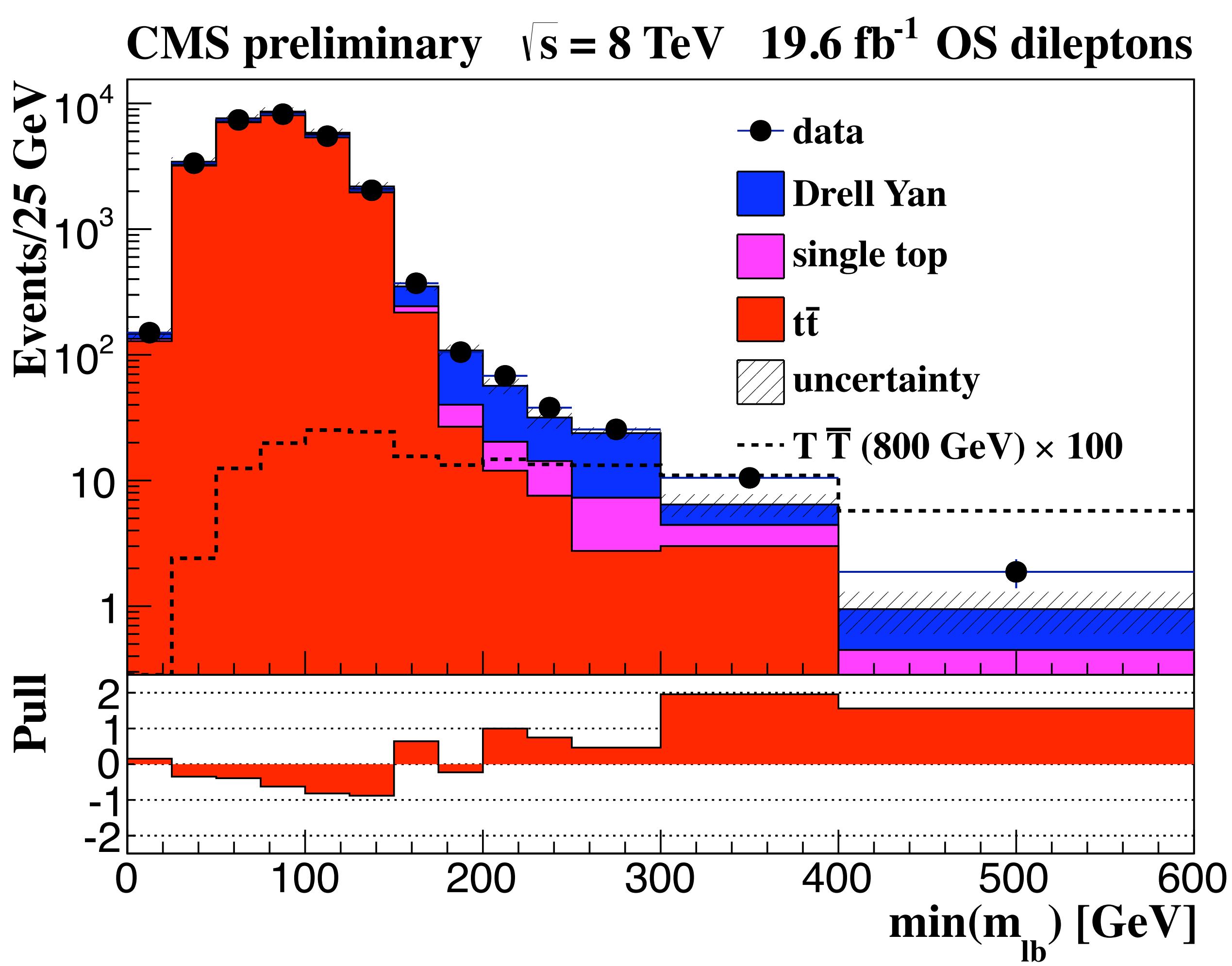
Multi-lepton channel (≥ 2 leptons)

Construct various categories:

- Opposite sign lepton final state: main backgrounds are ttbar and ZJets.
  - OS1: Constructed to be sensitive to the bWbW mode.
    - Require 2 or 3 jets, a Z-veto, 1 b-tagged jet, missing E_T > 30 GeV, H_T (sum of the p_Ts of all the selected jets) > 300 GeV, S_T (sum of the p_Ts of all the selected jets, sum of the p_Ts of all the selected leptons and MET) > 900 GeV and min(M_{lb}) > 170 GeV.
  - OS2: Sensitive to modes with tH and tZ.
    - Require at least 5 jets, 2 b-tagged jets, missing E_T > 30 GeV, H_T > 300 GeV and S_T > 900 GeV.



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- min(M_{lb}) = smallest mass of lepton-b-jet pairs. Sensitive to mass of the T.
- min(M_{lb}) > 170 GeV.

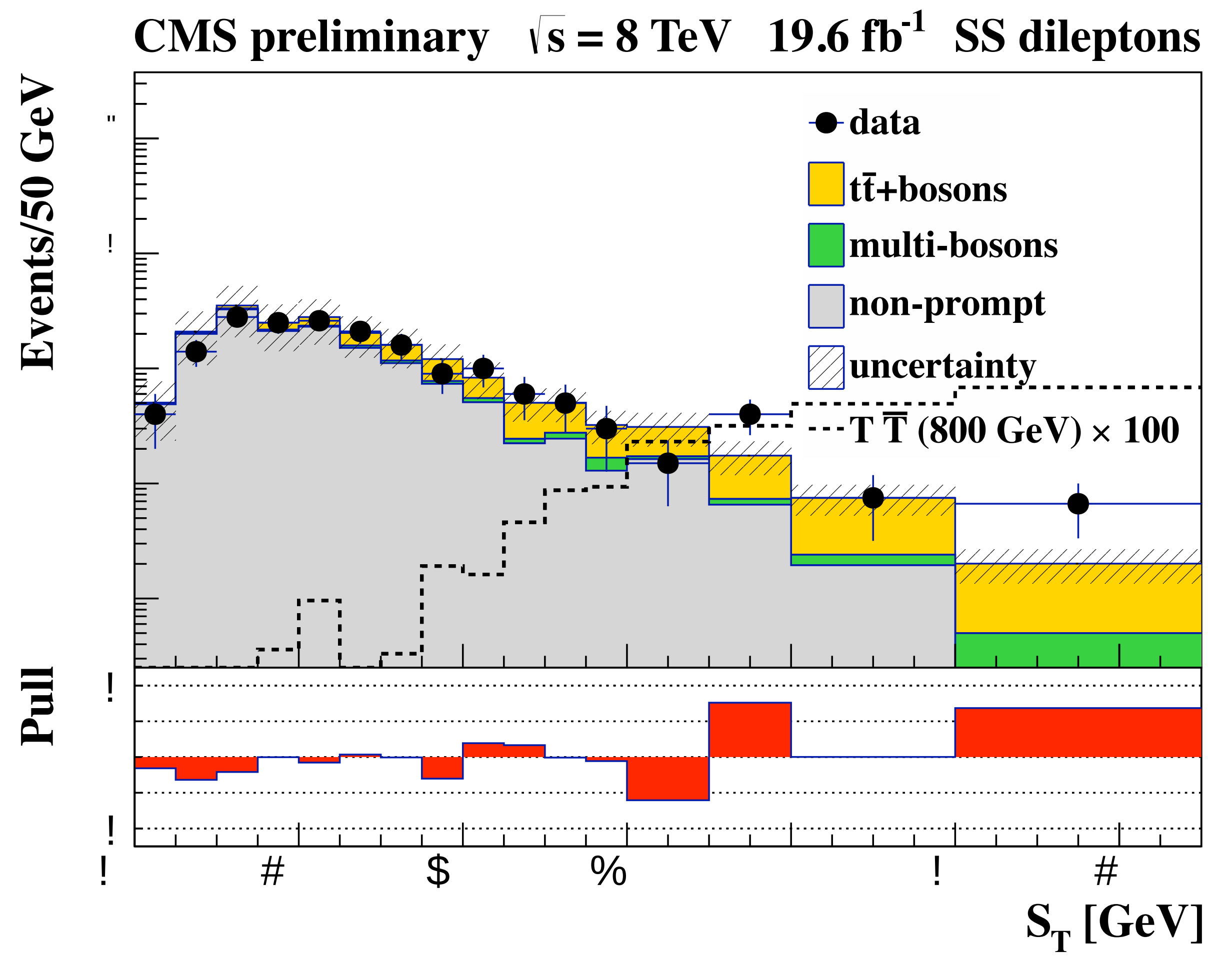
Multi-lepton channel (≥ 2 leptons)

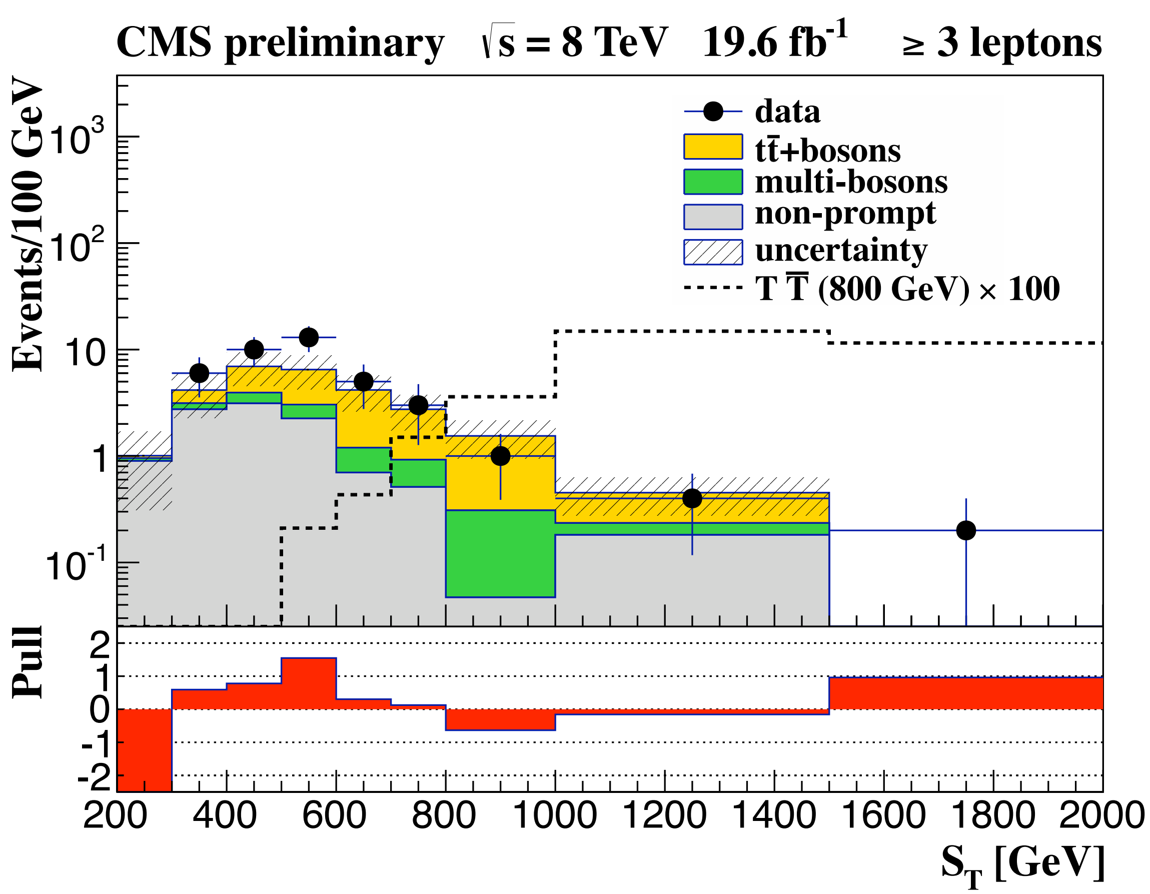
•Same sign leptonic final state (SS): Backgrounds are from SM processes with diboson and triboson decays and instrumental backgrounds from jets faking as leptons.

- •Require ≥ 3 jets, 1 b-tagged jet, missing E_T > 30 GeV, H_T > 500 GeV and S_T > 700 GeV.

•Multi-lepton/trilepton final state (≥ 3 leptons): Background processes include diboson and triboson decays and instrumental backgrounds from fake leptons.

- •Require ≥ 3 jets, 1 b-tagged jet, missing E_T > 30 GeV, H_T > 500 GeV and S_T > 700 GeV.





- H_T = sum of the p_Ts of all the selected jets.
- S_T = sum of the p_Ts of all the selected jets, sum of the p_Ts of all the selected leptons and MET.
- S_T > 700 GeV, H_T > 500 GeV
- Instrumental backgrounds or the non-prompt contribution determined directly from data.

Yields for single lepton and multi-lepton channels

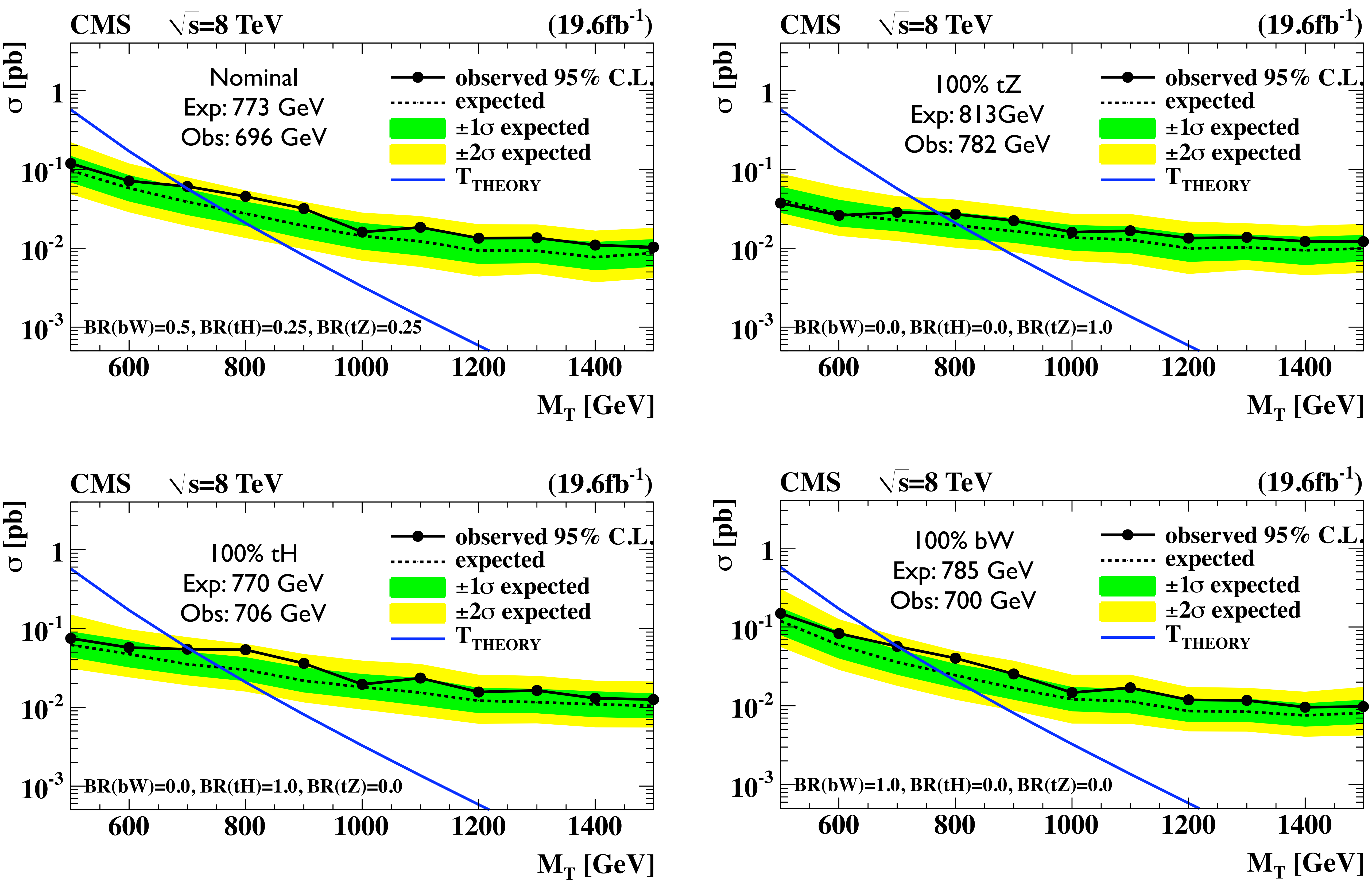
lepton flavor	muon	electron
$t\bar{t}$	36700±5500	35900±5400
single top	2190±1101	2100±1000
W	19200±9700	18200±9200
Z	2170±1100	2000±1000
multijets	0	1680±620
$t\bar{t}$ W	144±72	137±68
$t\bar{t}$ Z	109±54	108±54
$t\bar{t}$ H	570±280	570±285
WW/WZ/ZZ	410±205	400±200
total background	61500±13700	61100±13500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

Single lepton channel: likelihood computed using BDT distributions.

Multi-lepton channel: use predicted and expected number of events in 12 bins to compute likelihood.

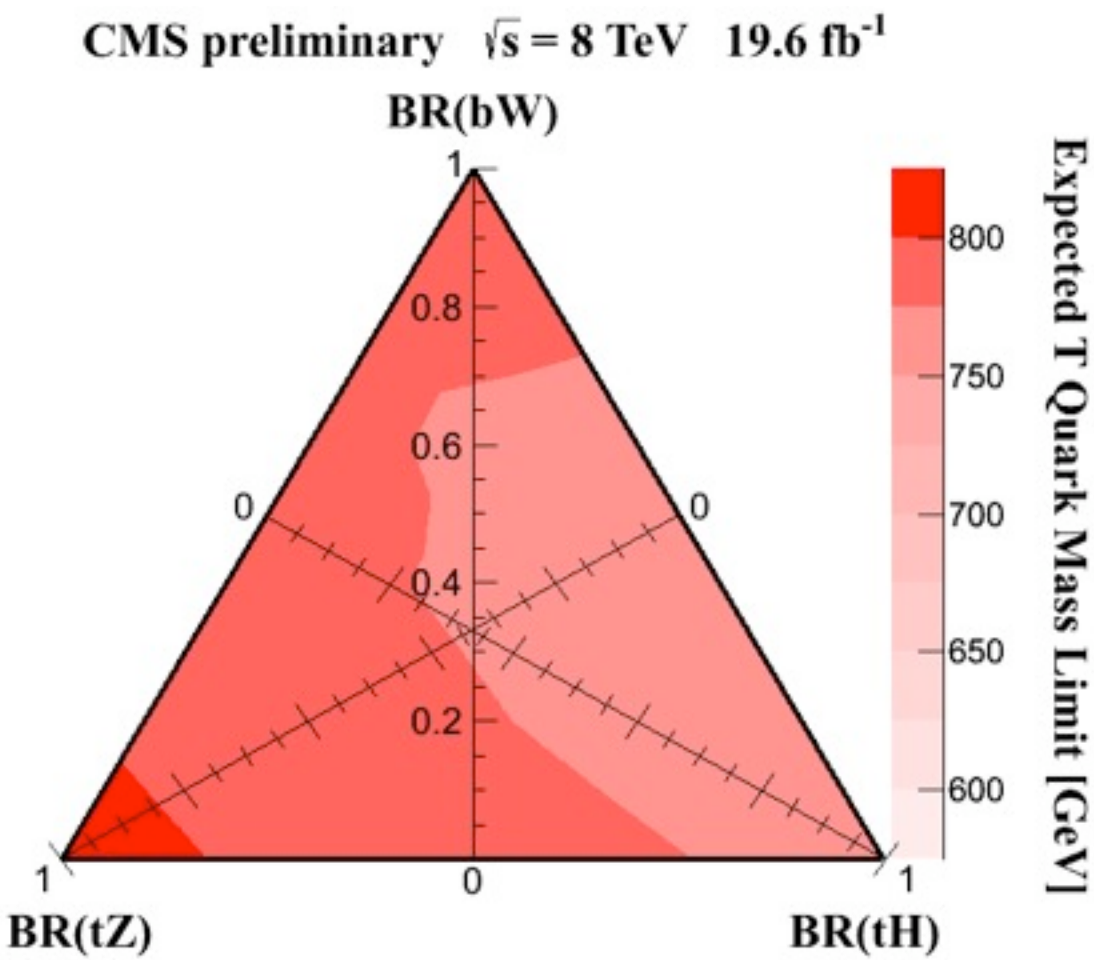
channel	OS1	OS2	SS	trileptons
$t\bar{t}$	5.2±1.9	80 ±12	-	-
single top	2.5±1.3	2.0±1.0	-	-
Z	9.7±2.9	2.5±1.9	-	-
$t\bar{t}$W	-	-	5.8 ±1.9	0.25±0.11
$t\bar{t}$Z	-	-	1.83±0.93	1.84±0.94
WW	-	-	0.53±0.29	-
WZ	-	-	0.34±0.08	0.40±0.21
ZZ	-	-	0.03±0.00	0.07±0.01
WWW/WWZ/ZZZ/WZZ	-	-	0.13±0.07	0.08±0.04
$t\bar{t}$WW	-	-	-	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

Combined limit

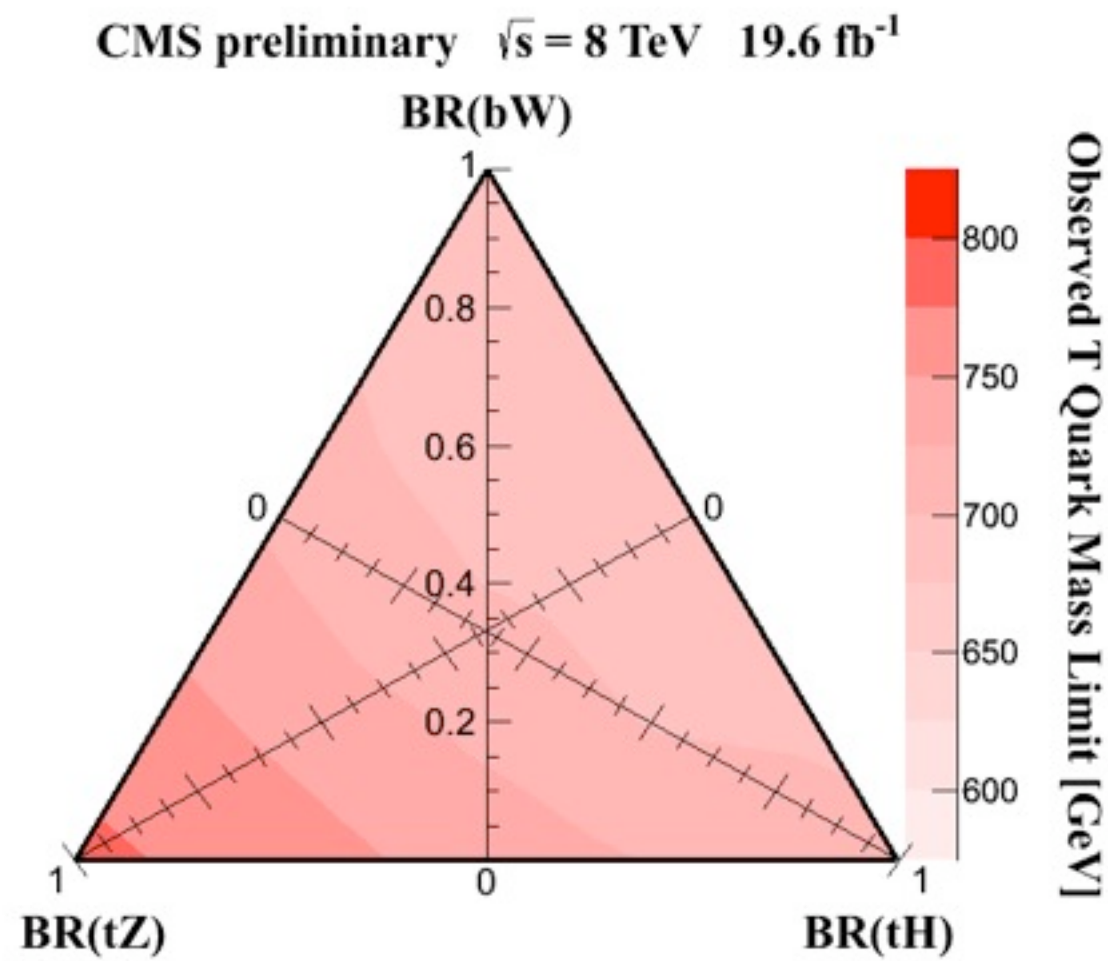


Combined limit

Scanning 22 branching fraction scenarios

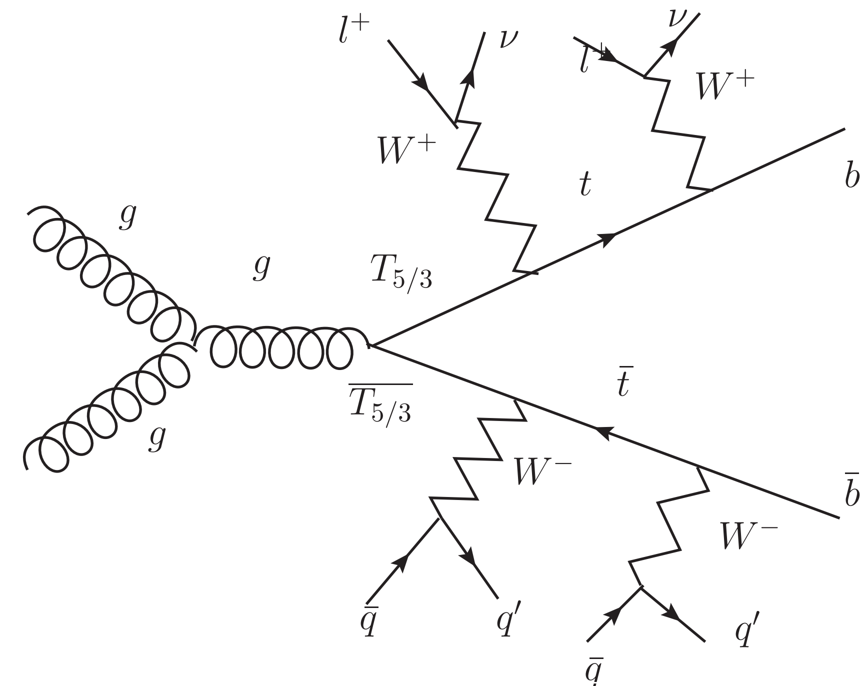


Expected Limit



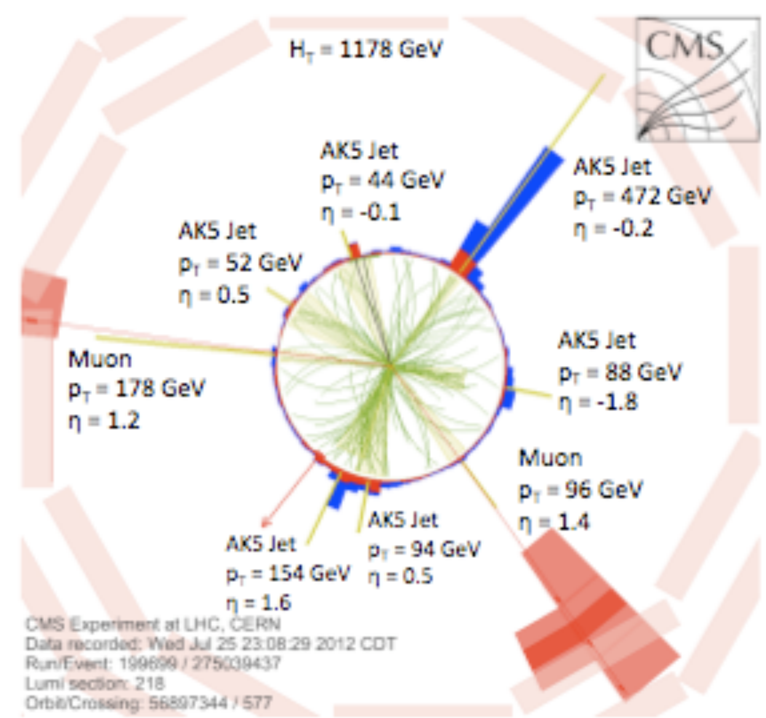
Observed Limit

Search for top partners with charge 5/3 in the same sign dileptonic final state, CMS-B2G-12-012



- <u>Signal:</u>
  - $T_{5/3}$ decaying to tW is assumed to have 100% branching fraction.
  - Same signed dileptons arise from W decays.

- <u>Background processes</u>:
  - Same signed prompt leptons: from rare SM processes. Contribution is obtained from simulated events.
  - Opposite sign prompt leptons: from charge misidentification. Estimated from data.
  - Instrumental backgrounds: from jets misidentified as leptons arising from multi-jet or ttbar processes. Estimated from data.



Candidate signal event

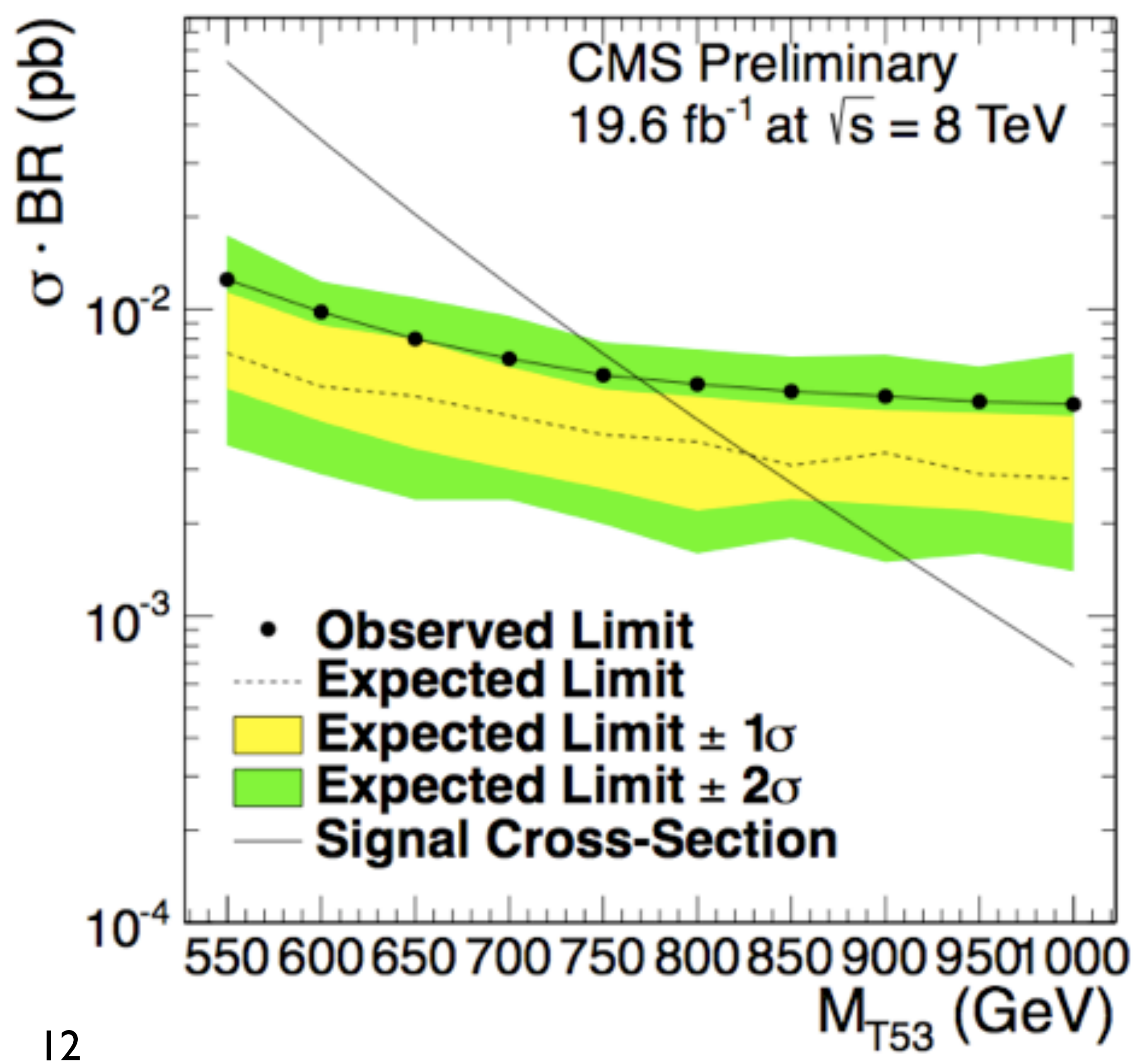
Yields and exclusion limits

PSS: prompt same sign

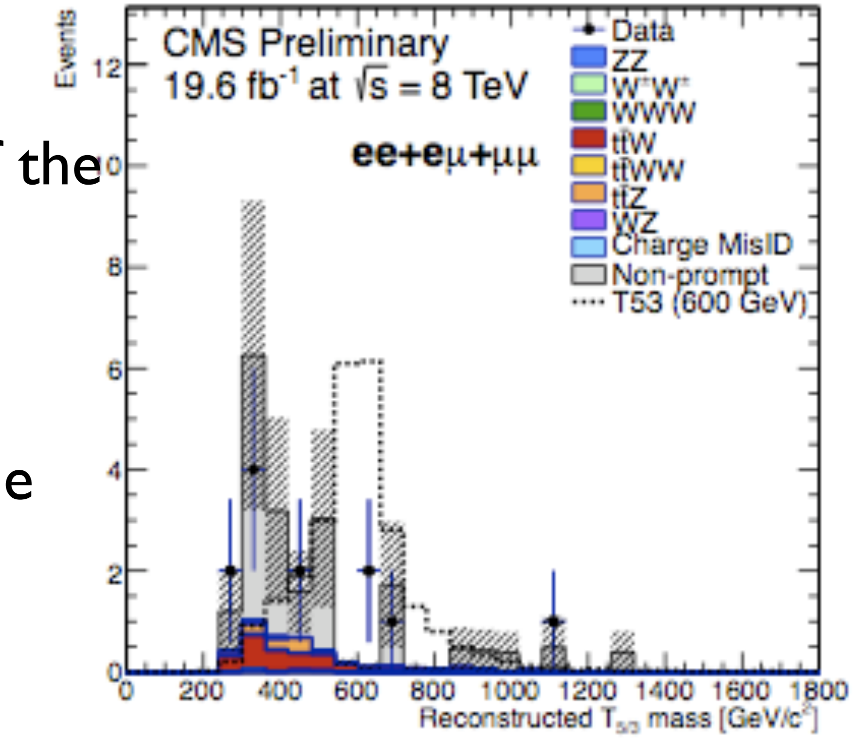
	PSS MC	Non-Prompt	Charge Mis-ID	Total Expected	Observed
ee	0.7 ± 0.2	1.9 ± 1.2	0.06 ± 0.02	2.6 ± 1.3	0
eμ	1.9 ± 0.4	0.6 ± 0.9	0.05 ± 0.01	2.5 ± 1.0	6
$\mu\mu$	1.3 ± 0.3	0.2 ± 0.6	-	1.5 ± 0.7	5
All	3.9 ± 0.8	2.6 ± 1.8	0.1 ± 0.02	6.6 ± 2.0	11

Yields computed by requiring:

- 2 SS leptons
- Z-veto
- Number of jet constituents (based on the presence of a "W" or "top" jet) ≥ 5
- H_T (sum of the p_Ts of all the selected jets and leptons) > 900 GeV



Mass reconstruction

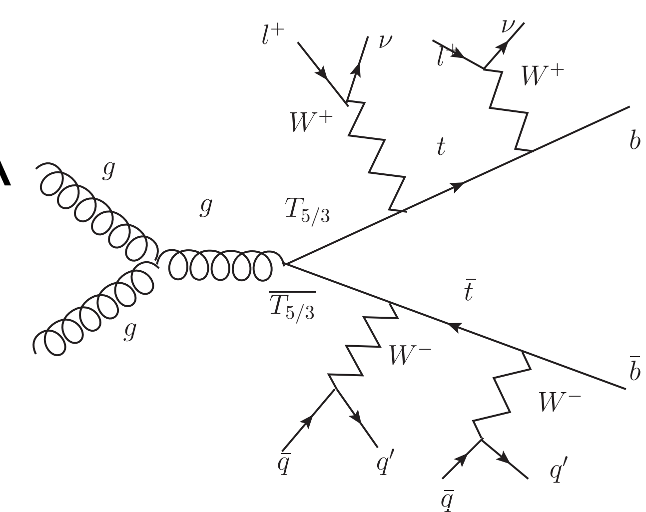


- Mass reconstruction allows one to ascertain the precise nature of the heavy top-partner.

- In the the case of the top-partner, $T_{5/3}$, $m_{T5/3}$ is reconstructed in the following way:

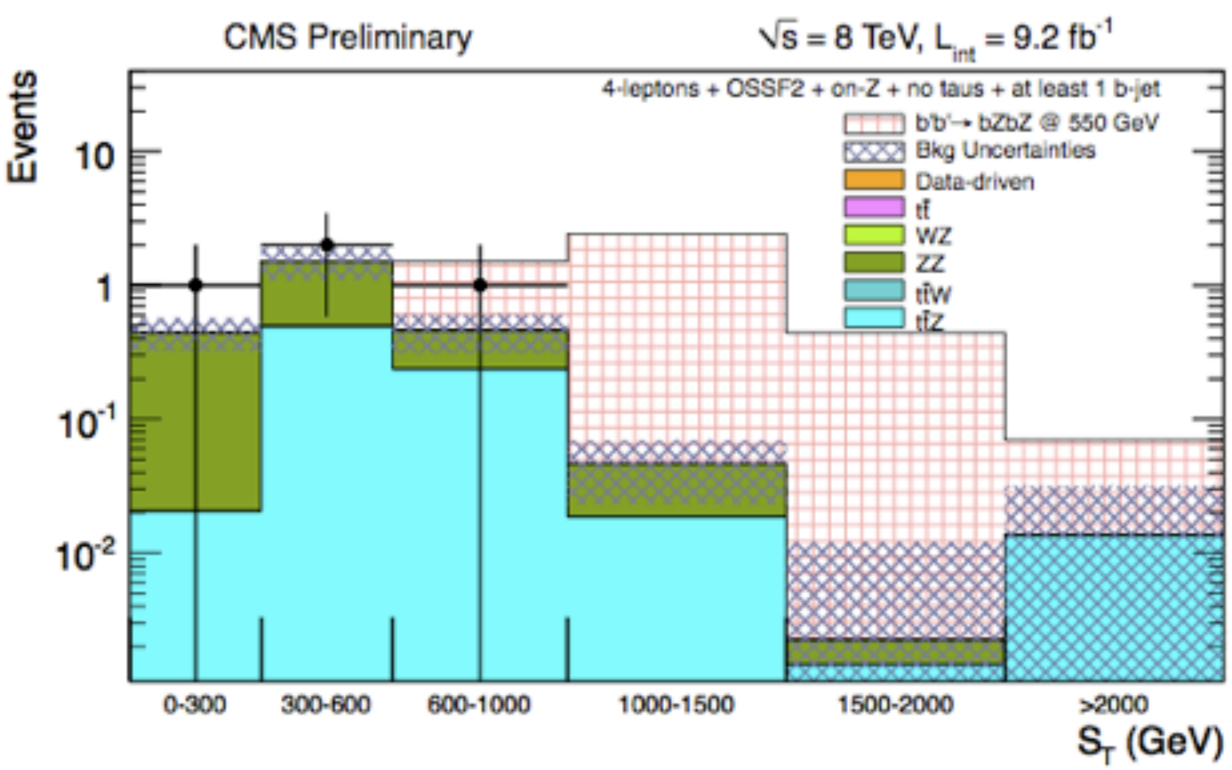
  - If there exists a CA "top" jet (in 22% signal events), then is it combined with the hadronically decaying "W" jet or 2 AK5 jets with an invariant mass within 20 GeV of m_W.

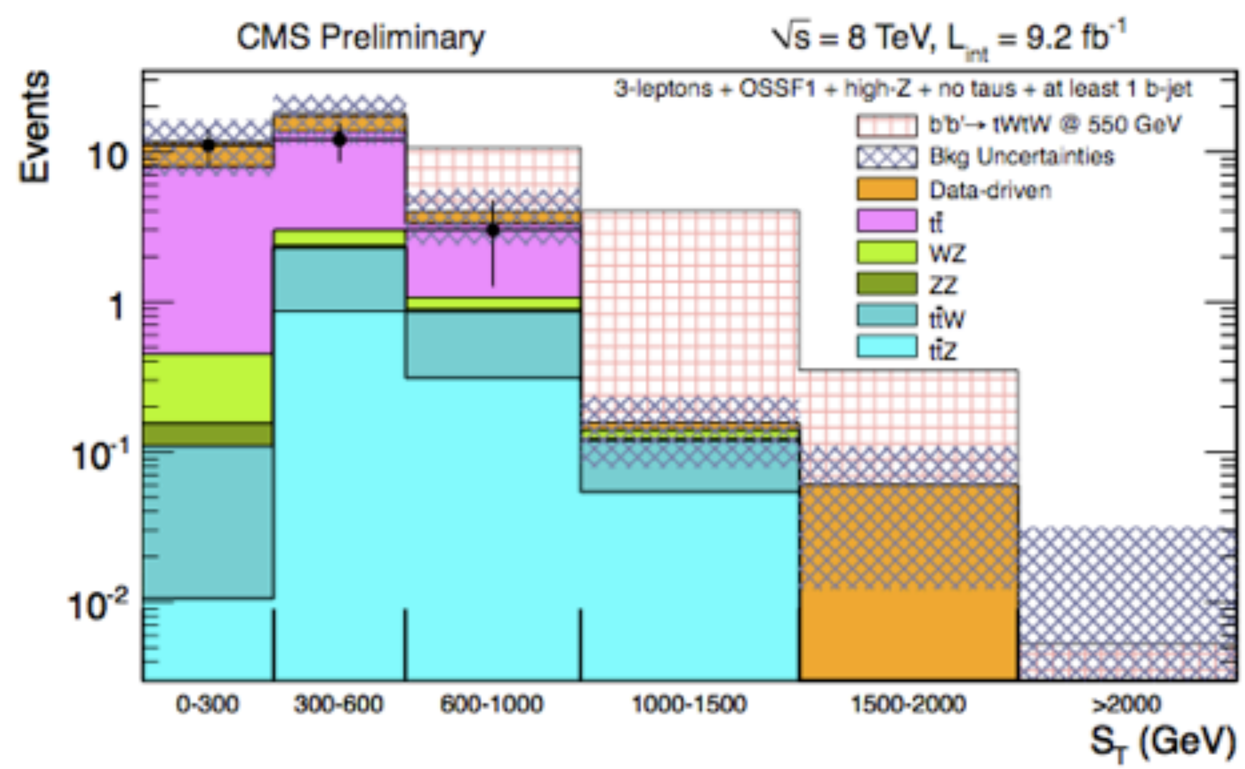
  - In the absence of CA "top" jets, two Ws are reconstructed (from CA "W" jets in 80% signal events or AK5 jets with an invariant mass within 20 GeV of m_W) and combined with a jet. The invariant mass of the "top" jet is required to be within 30 GeV of the top-quark mass.



Reinterpretations from RPV SUSY search (SUS-12-027) for b' searches

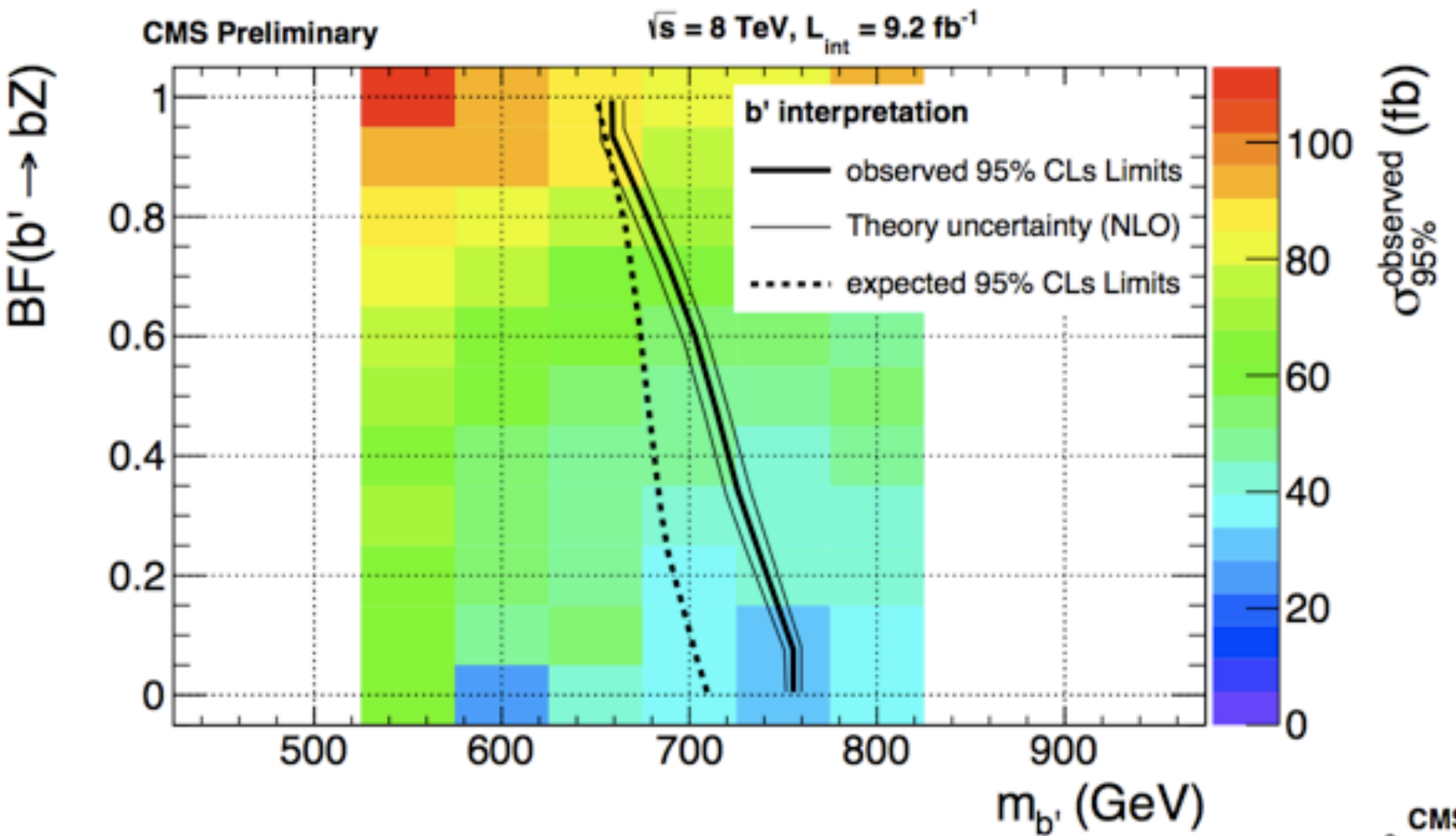
- Dedicated b' search being carried out in CMS.
- However, RPV SUSY searches can be interpreted as b'->tW and b'->bZ searches.
- Events classified into 3 and 4 lepton categories.



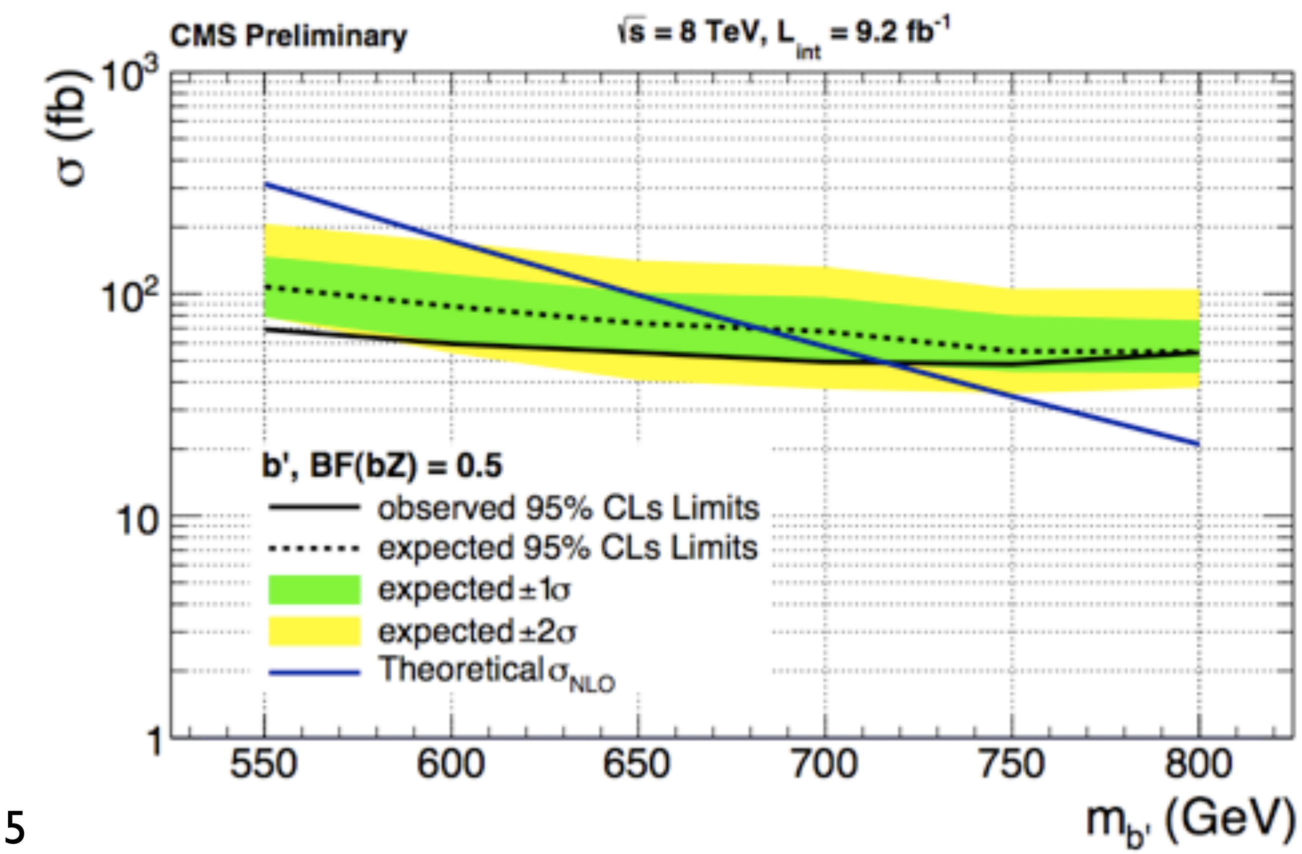


S_T distributions for 4 leptons and 3 leptons categories with requirements on opposite sign same flavor (OSSF) leptons.

Exclusion limits



Points to the left of the curve are excluded at 95% confidence level.



Exclusion limit for 50% branching ratio of b'->tW and b'->bZ.

Conclusion

Model considered	Branching fraction scenario	Exclusion limit
Vector-like T quark	50% bW, 25% tH, 25% tZ	696 GeV
$T^{5/3}$	100% tW	770 GeV
b'	50% tW, 50% bZ	715 GeV

- Several interesting searches for exotic top-parters have been carried out at CMS.
- These searches are relevant for a plethora of non-SUSY extensions of the Standard Model.
- More 8TeV results are in the pipeline.

Back-up Slides

Search for vector-like top partners, CMS-B2G-12-015

Table 17: Sets of branching fraction values and 95% confidence level lower limits for the T quark mass.

Scenario	Branching Fractions $T \to bW$	$T \to tH$	$T \to tZ$	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

Search for vector-like top partners, CMS-B2G-12-015

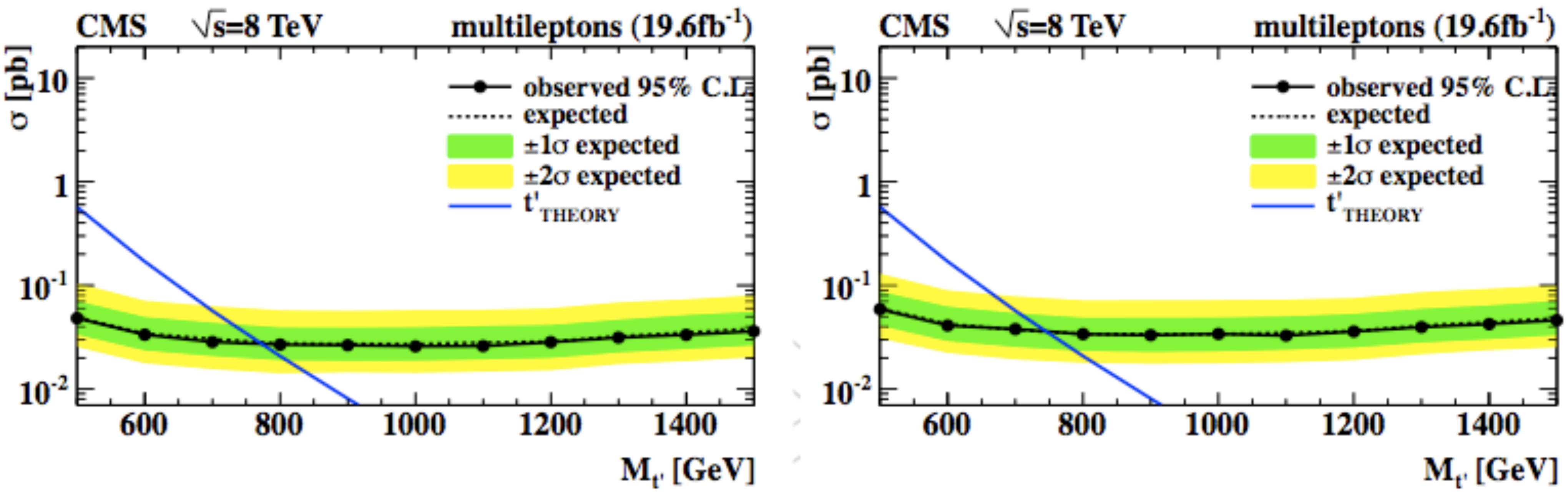


Figure 35: Limits (left to right): (2) 20% tH and 80% tZ, (3) 40% tH and 60% tZ.

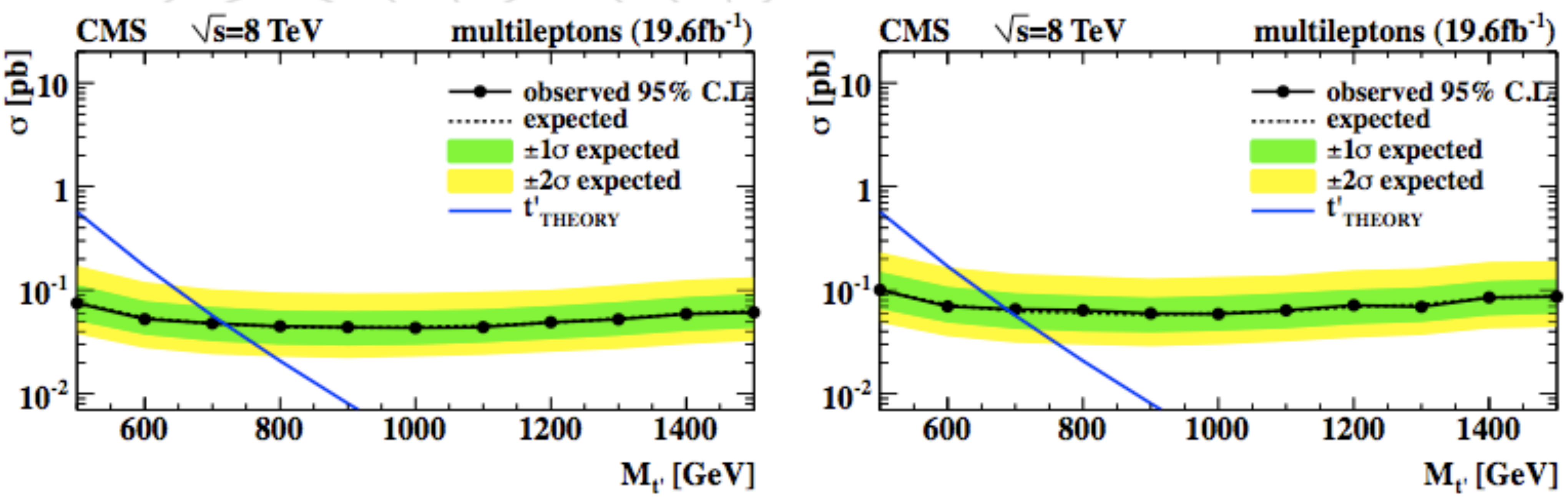


Figure 36: Limits (left to right): (4) 60% tH and 40% tZ, (5) 80% tH and 20% tZ.

Search for vector-like top partners, CMS-B2G-12-015

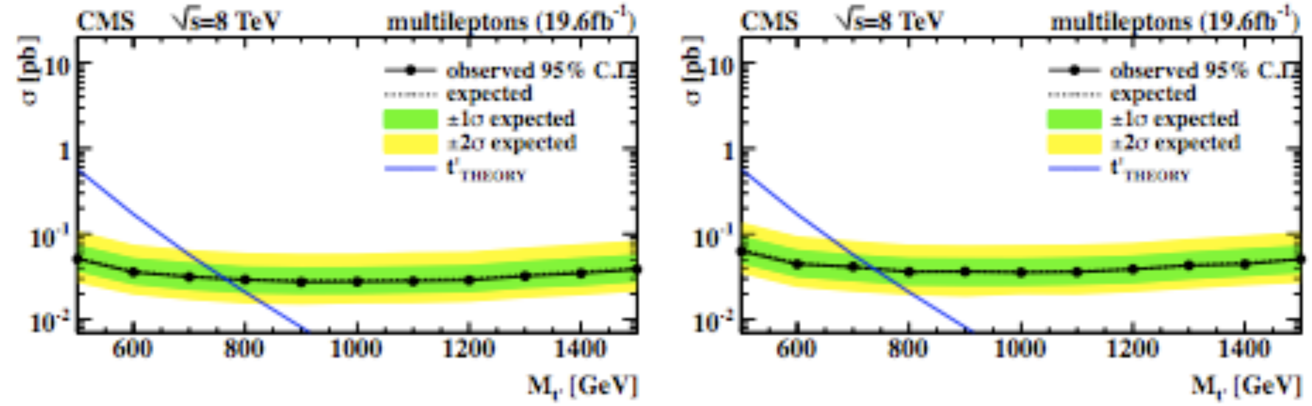


Figure 37: Limits (left to right): (7) 20% bW and 80% tZ, (8) 20% bW, 20% tH and 60% tZ.

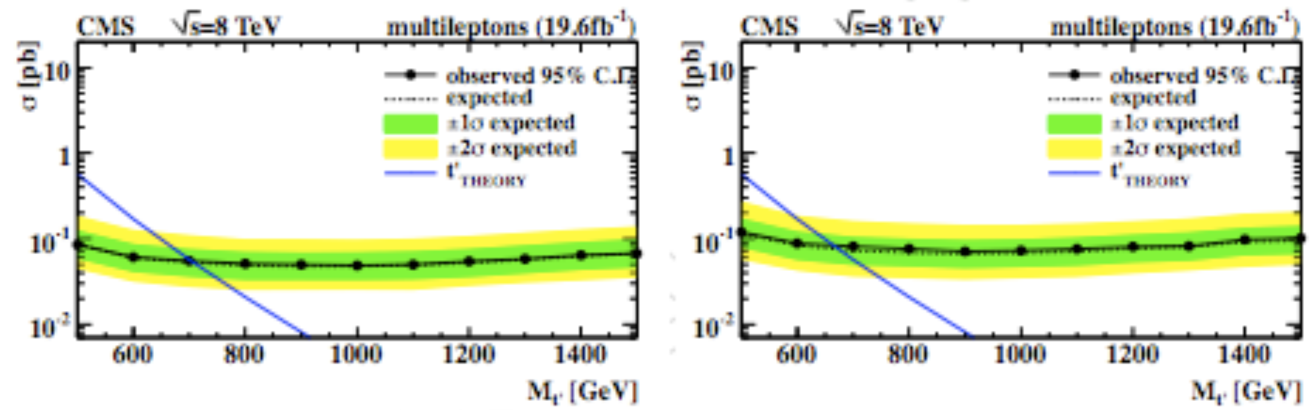


Figure 38: Limits (left to right): (9) 20% bW, 40% tH and 40% tZ, (10) 20% bW, 60% tH and 20% tZ.

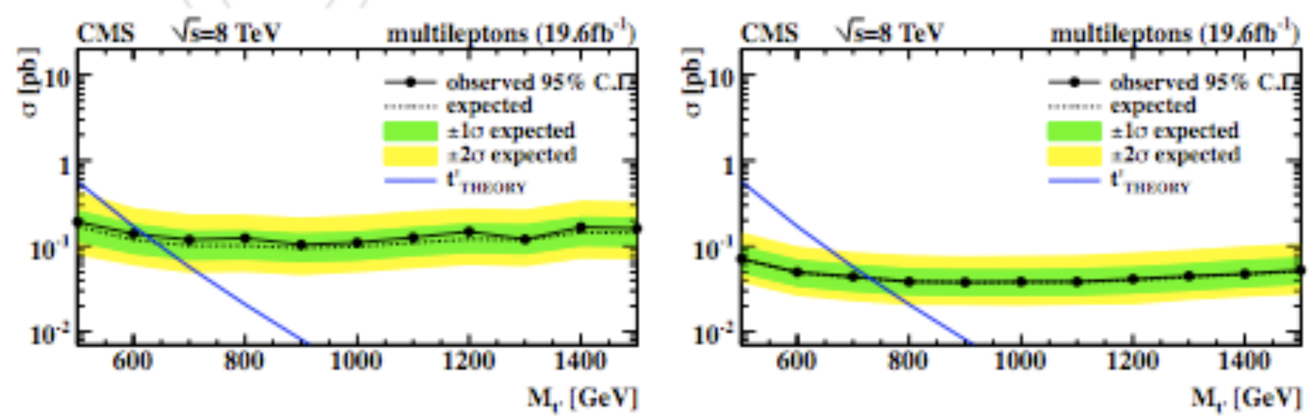


Figure 39: Limits (left to right): (11) 20% bW and 80% tH, (12) 40% bW and 60% tZ.

Search for vector-like top partners, CMS-B2G-12-015

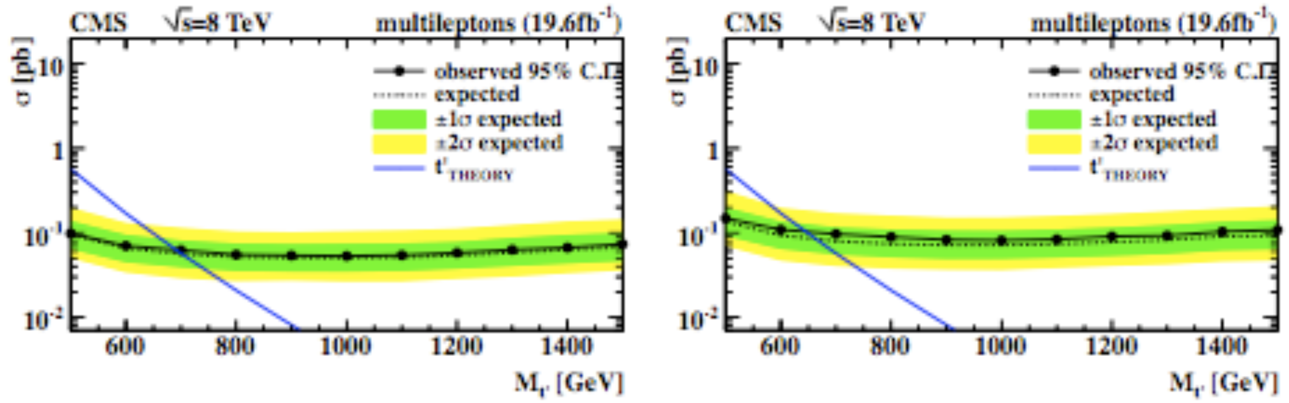


Figure 40: Limits (left to right): (13) 40% bW, 20% tH and 40% tZ, (14) 40% bW, 40% tH and 20% tZ.

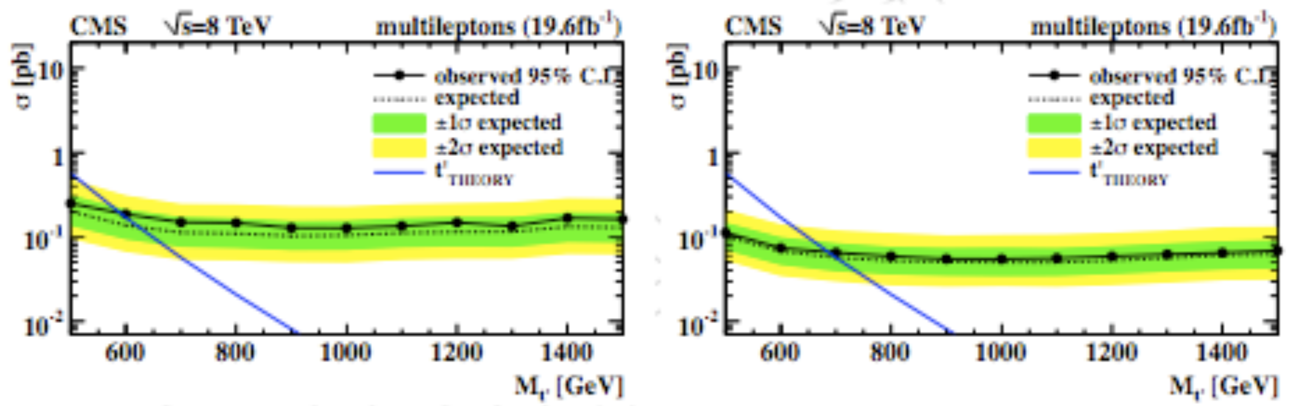


Figure 41: Limits (left to right): (15) 40% bW and 60% tH, (16) 60% bW and 40% tZ.

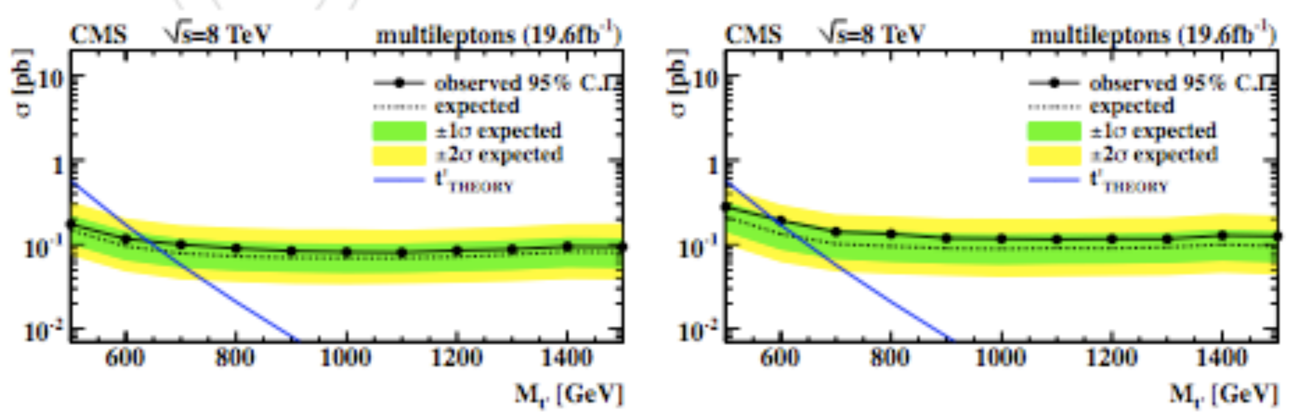


Figure 42: Limits (left to right): (17) 60% bW, 20% tH and 20% tZ, (18) 60% bW and 40% tH.

Search for vector-like top partners, CMS-B2G-12-015

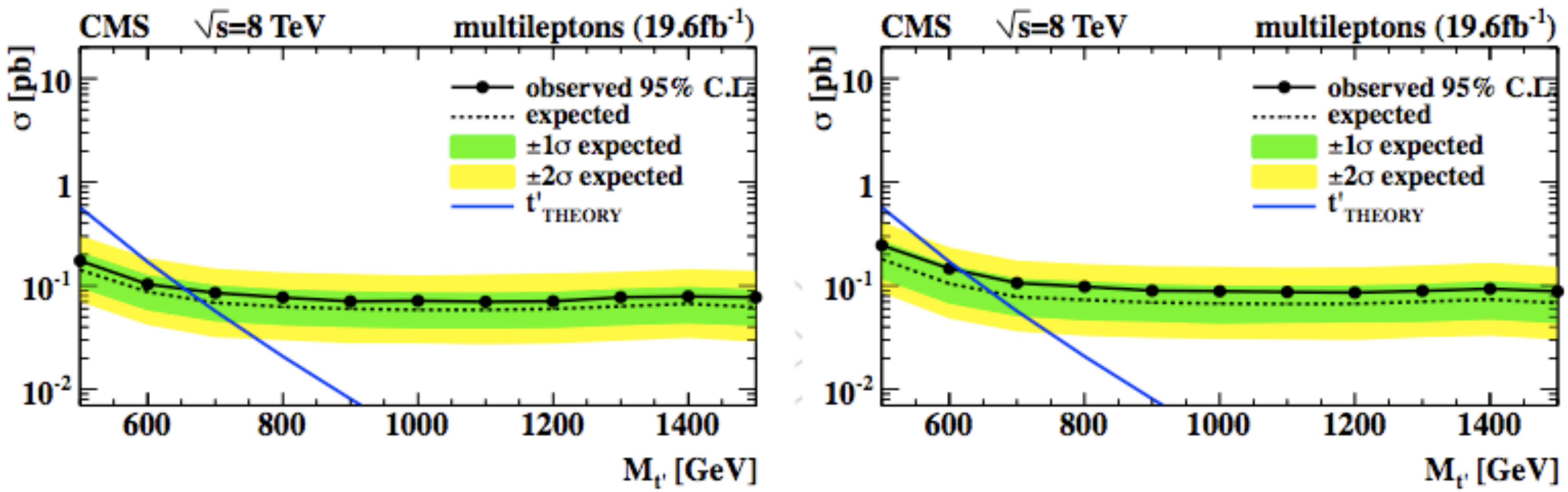
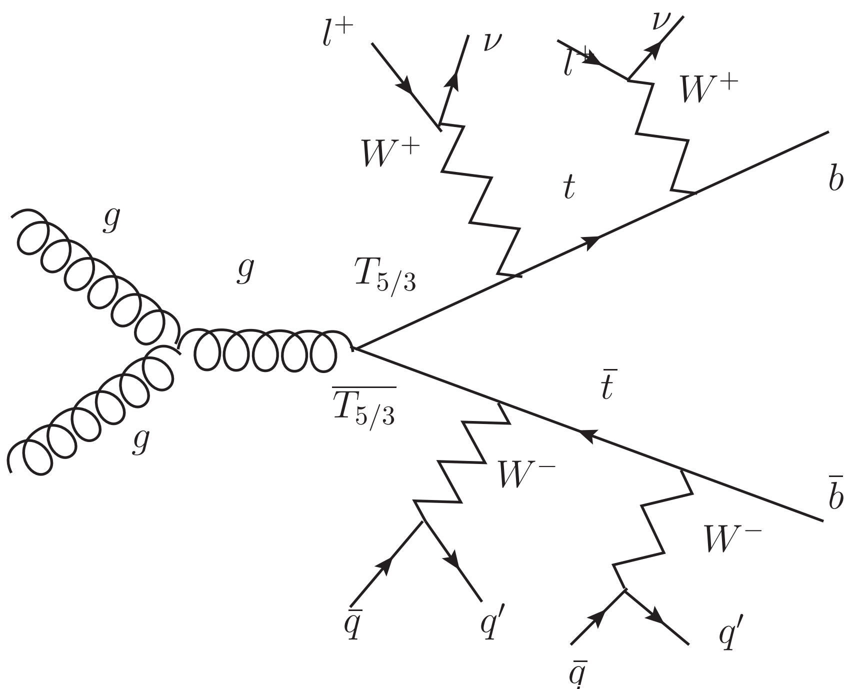


Figure 43: Limits (left to right): (19) 80% bW and 20% tZ, (20) 80% bW and 20% tH.

Search for top partners with charge 5/3 in the same sign dileptonic final state, CMS-B2G-12-012



Sample	2SS leptons	$M(\ell\ell)$ Veto	N(con)≥ 5	$H_T \geq 900$
WZ	1510	616	1.78	0.464 ± 0.0694
ZZ	359	70.5	0.272	0.0426 ± 0.00567
W^-W^-	18.7	18.1	0.127	0.0205 ± 0.0205
W^+W^+	55.4	53.7	1.62	0.688 ± 0.191
WWW	18.5	17.3	0.574	0.246 ± 0.0431
$t\bar{t}$ W	61.3	57.4	8.86	1.72 ± 0.197
$t\bar{t}$ Z	39.5	16.9	4.18	0.607 ± 0.108
$t\bar{t}$ WW	1.66	1.52	0.695	0.144 ± 0.00518

Channel	2SS leptons	$M(\ell\ell)$ Veto	N(con)≥ 5	$H_T \geq 900$
ee	1882	513.1	7.748	1.859 ± 0.8333
$\mu\mu$	1720	1696	13.02	0.1876 ± 0.5658
eμ	1058	975.5	21.5	0.5589 ± 0.8478
All	4659	3184	42.26	2.605 ± 1.317

Non-prompt contribution computed using data driven techniques.

Reinterpretations from RPV SUSY search (SUS-12-027) for b' searches

N_{OSSF}	onZ	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 ± 0.009	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

Yields for 4 lepton events

Reinterpretations from RPV SUSY search (SUS-12-027) for b' searches

			$0\text{-}\tau, 0\text{-}b$		$1\text{-}\tau, 0\text{-}b$		$0\text{-}\tau, 1+b$		$1\text{-}\tau, 1+b$	
N_{OSSF}	OSSF Mass	S_T(GeV)	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

Yields for 3 lepton events

Combined search for the quarks of a sequential fourth generation (EXO-11-098).

$$V_{\rm CKM}^{4\times4} = \begin{pmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} & V_{\rm ub'} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} & V_{\rm cb'} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} & V_{\rm tb'} \\ V_{\rm t'd} & V_{\rm t's} & V_{\rm t'b} & V_{\rm t'b'} \end{pmatrix}$$

$$= \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(0) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(1) & \mathcal{O}(0) & 0 \\ \mathcal{O}(0) & \mathcal{O}(0) & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- $t'b \to bWb$
- $t'\bar{t}' \to bWbW$
- $b't \to tWbW \to bWWbW$
- $b't' \to tWbW \to bWWbW$
- $b'\bar{b}' \to tWtW \to bWWbWW$

Combined search for the quarks of a sequential fourth generation (EXO-11-098).

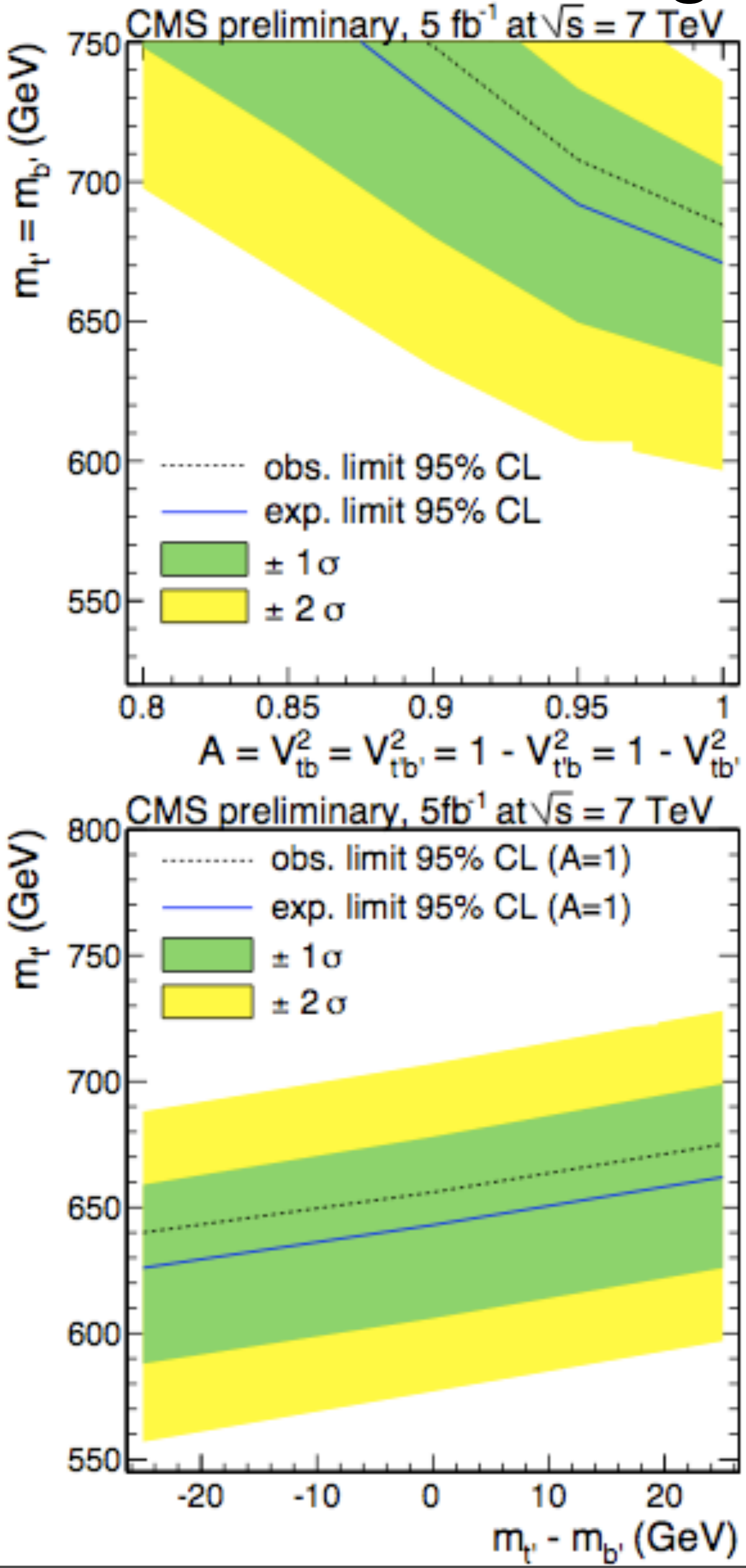


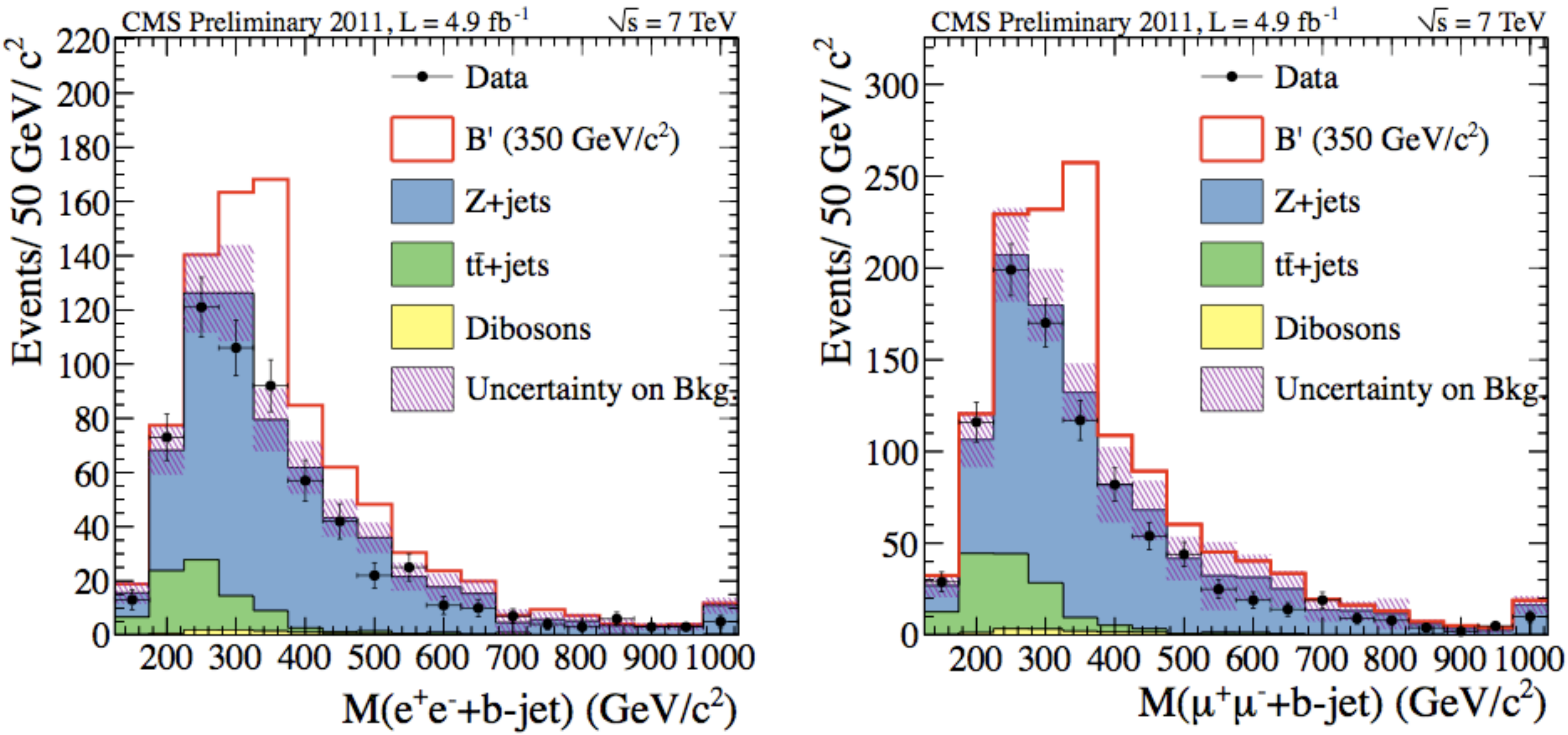
Figure 2: Top: Exclusion limit on $m_{t'} = m_{b'}$ as a function of the $V^{4\times4}_{CKM}$ parameter A. The parameter values below the line are excluded at 95% confidence level (CL). The slope indicates the sensitivity of the analysis to the $t'b$ and tb' processes. Bottom: For a $V^{4\times4}_{CKM}$ parameter value $A = 1$, the exclusion limit on $m_{t'}$ versus $m_{t'} - m_{b'}$ is shown. The exclusion limit is calculated for mass differences up to 25 GeV. The existence of up-type fourth-generation quarks with mass values below the observed limit are excluded at the 95% confidence level.

Search for a vector-like quark of charge −1/3 and decaying to bZ (EXO-11-066)

b' -> bZ with 100% branching fraction

Process	Cross section (pb)	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
Z +jets	2 939	557 ±15	847 ± 25
$t\bar{t}$ +jets	168	80±4	137 ± 7
W^+W^-	43	0.10±0.10	0.17 ± 0.11
$W^\pm$ Z	18	3.6±0.3	6.1 ± 0.5
Z Z	5.9	5.9±0.2	9.2 ± 0.3
Total		648±15	999 ± 26
Data		604 ±24	928 ± 30

Search for a vector-like quark of charge −1/3 and decaying to bZ (EXO-11-066)



Search for a vector-like quark of charge −1/3 and decaying to bZ (EXO-11-066)

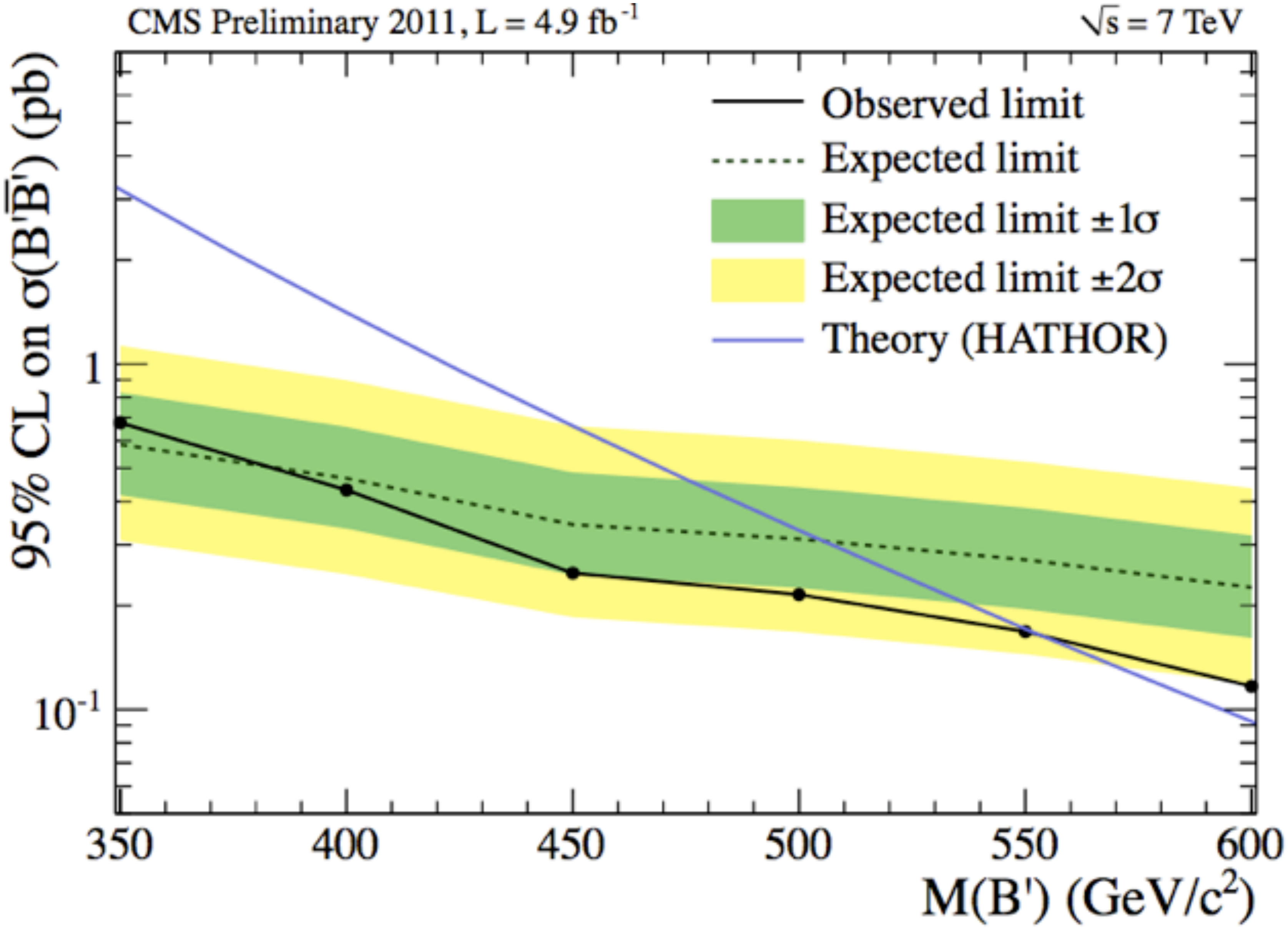


Figure 2: The 95% CL cross section exclusion limits as a function of the B′ quark mass calculated using the combined $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ channels. The expected and observed limits are 510 GeV/c^2 and 550 GeV/c^2, respectively.