Search for vector-like T quarks in final states with leptons at CMS

Gerrit Van Onsem (VUB)
on behalf of the CMS Collaboration

Workshop on Vector-like Quarks 2014
Hamburg, 15 September 2014

Overview

Introduction to vector-like T quarks

The CMS detector

Event reconstruction and W/top jet tagging

Search for T (charge 2/3) → bW, tZ, tH
    single-lepton and multilepton channels

Search for T (charge 5/3) → tW^+
    same-sign dilepton channel

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Introduction to vector-like quarks (VLQs)

- **Right-handed and left-handed components** of VLQ fields **interact similarly** via electroweak force
  - No *chiral* "V-A" structure in Lagrangian, but purely "V"

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- **VLQs appear in many BSM models**:
  - Little Higgs models
    - addressing naturalness problem: top-quark partner stabilizes Higgs-boson mass
  - composite Higgs models
    - e.g. top quark and VLQ condensate driving electroweak symmetry breaking
  - Grand Unified Theories
  - Extra dimensions
    - Kaluza-Klein states of SM fields in extra dimensions can have VLQ properties

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   can have VLQ properties

- VLQs can have charge 2/3, 1/3, 5/3 or 4/3 and decay to W, Z or H bosons (model-dependent)
  → **rich phenomenology**

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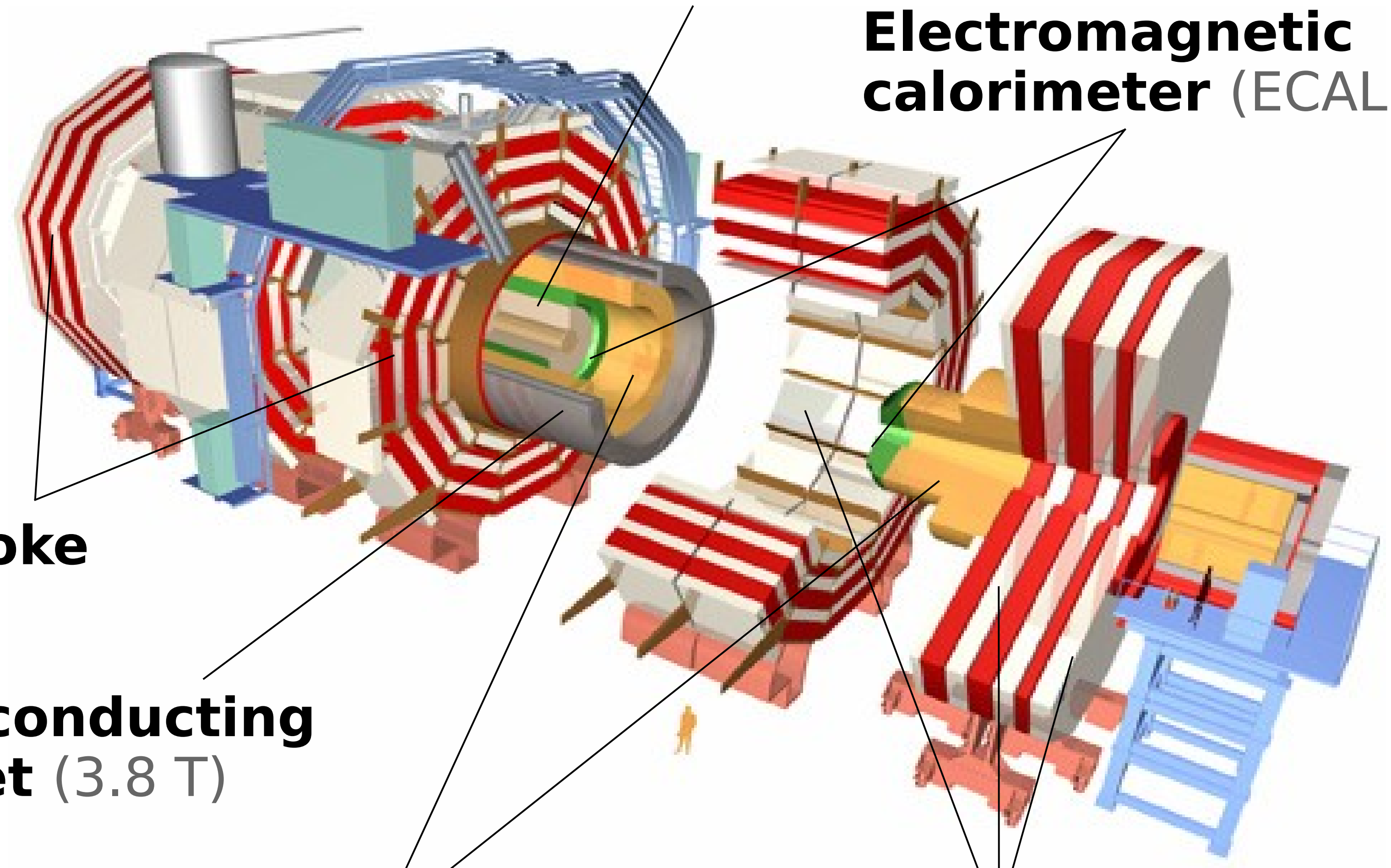
The Compact Muon Solenoid (CMS) detector



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Physics-object reconstruction

- **Particle-flow (PF) algorithm** combines information of all subdetectors to reconstruct particles traversing the detector

muons

relative isolation defined in cone of ΔR = 0.4

electrons

relative isolation defined in cone of ΔR = 0.3

Relative isolation

$$I_{rel} = \frac{\sum p_T^{\text{charged hadron}} + \sum p_T^{\text{neutral hadron}} + \sum p_T^{\text{photon}}}{p_T^{\mu}}$$

Corrected for pile-up interactions on event-by-event basis

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Corrected for pile-up interactions on event-by-event basis

electrons

relative isolation defined in cone of $\Delta R = 0.3$

missing transverse energy (MET)

jets

anti-k_T jet clustering with **distance parameter 0.5** (AK5)

energy corrections (1-10% depending on p_T and η)

resolution smearing in simulation

b-tagging using 'Combined Secondary Vertex' algo

W-boson and top-quark jet tagging

- Decay of heavy quark → **boosted decay products**

    Additional Cambridge-Aachen jet
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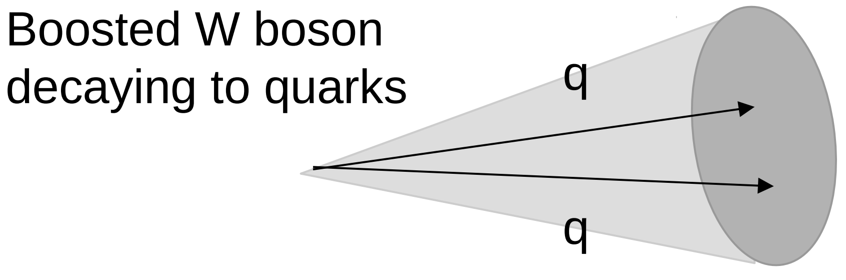

'W jet'

p_T > 200 GeV
Mass = [60,130] GeV
Exactly 2 subjets

W-boson and top-quark jet tagging

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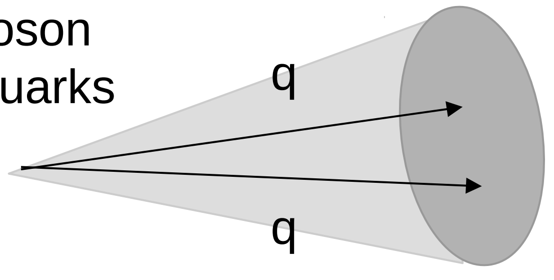
Boosted W boson decaying to quarks



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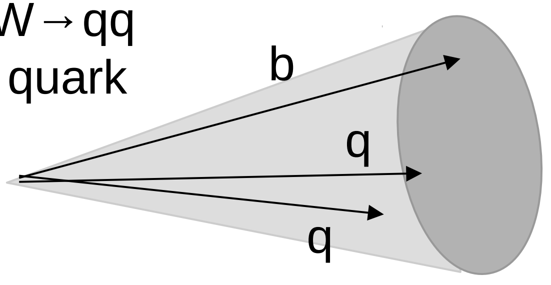
Boosted top quark decaying to W→qq boson and b quark



'top-quark jet'

p_T > 200 GeV (or 400 GeV)
Mass = [140,250] GeV
⩾ 3 subjets
Minimum pairwise mass > 50 GeV

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single-lepton and multilepton channels

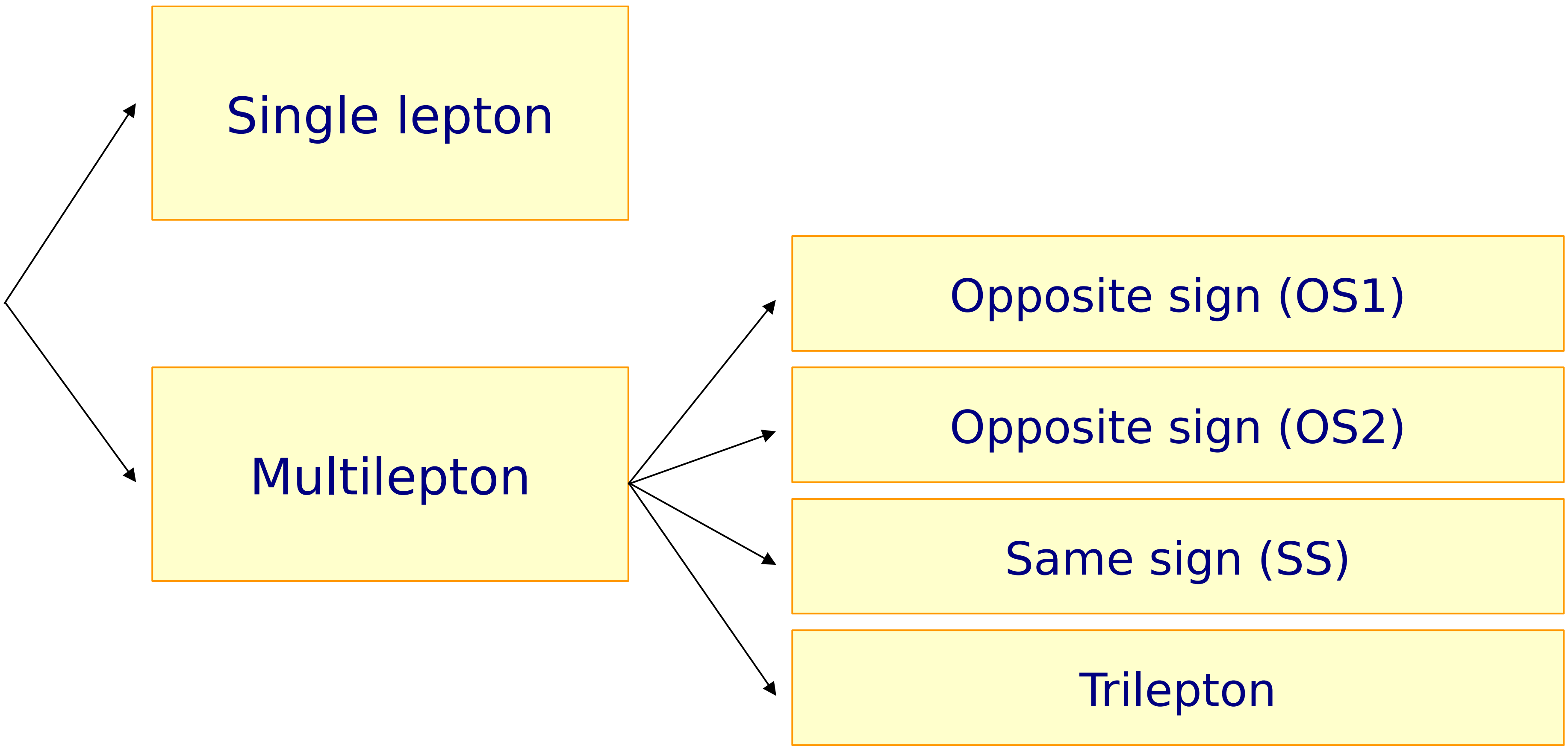
B2G-12-015
1311.7667v2

Search for T (charge 5/3) → tW^+
same-sign dilepton channel

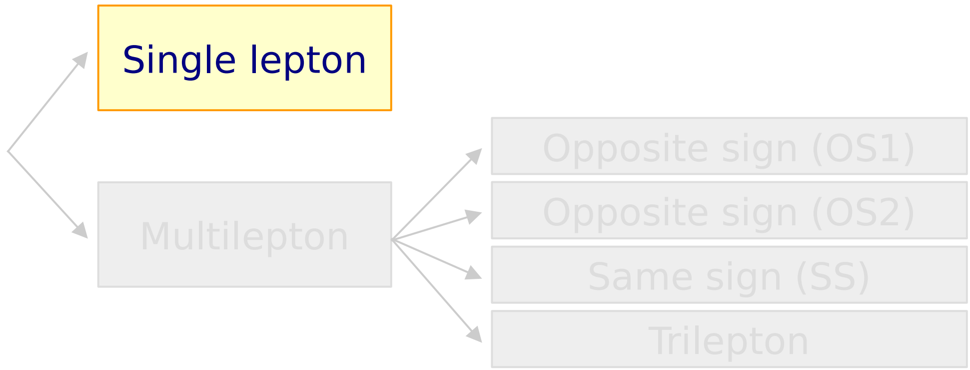
Summary

Signal selection

- Strong pair production of TT with T → bW / tZ / tH leads to signature with possibly multiple leptons
  → **different search channels according to leptons**

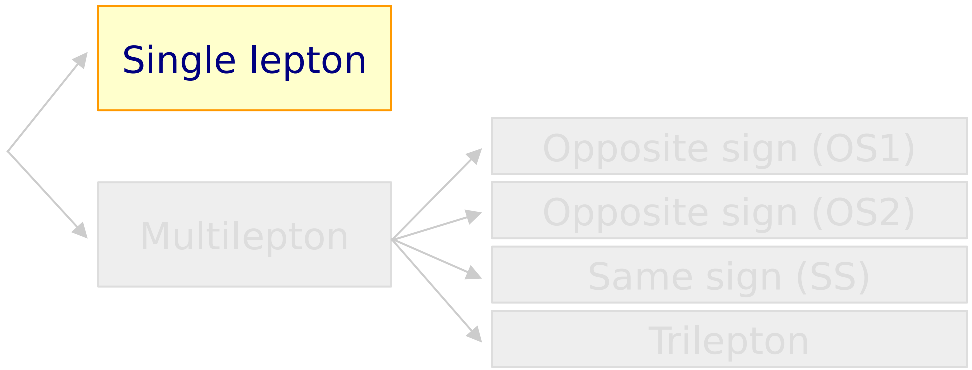


Single-lepton channel



- 1 isolated muon ($|\eta| < 2.1$, $p_T > 32$ GeV, $I_{rel} < 0.12$)
  or 1 isolated electron ($|\eta|<1.44$ or $1.57<|\eta|<2.5$, $p_T > 32$ GeV, $I_{rel} < 0.10$)
- $\geqslant$ 3 AK5 jets ($p_T > 120, 90, 50$ GeV, $|\eta| < 2.4$)
- $\geqslant$ 1 W jet, or fourth AK5 jet with $p_T > 35$ GeV
- MET > 20 GeV

Single-lepton channel



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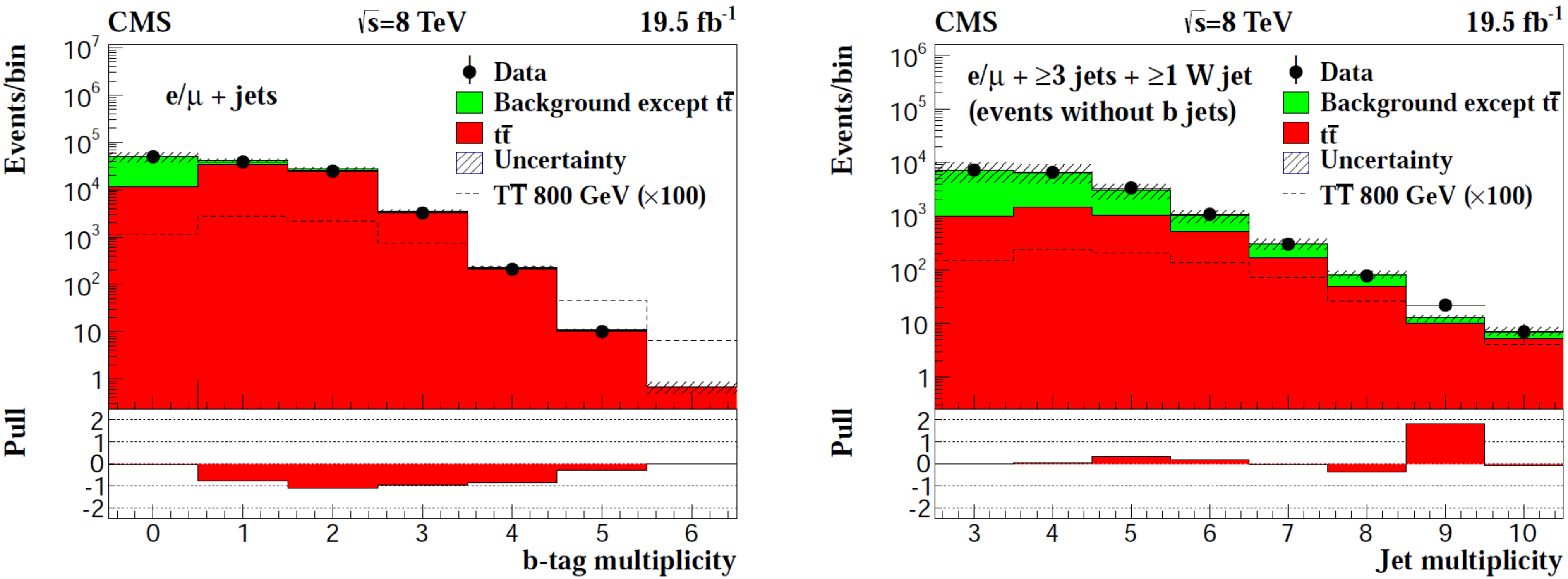
Simulated W+jets background normalized
to control data sample ($\leqslant$ 3 jets but *no* W jet)

Separate scale factors for light-flavor and heavy-flavor components of simulated W+jets

B-jet and jet multiplicities well modeled by the simulation



Pull = (observed – expected) / (Sum in quadrature of syst. and stat. uncertainties)

Uncertainties include luminosity, cross sections and correction factors

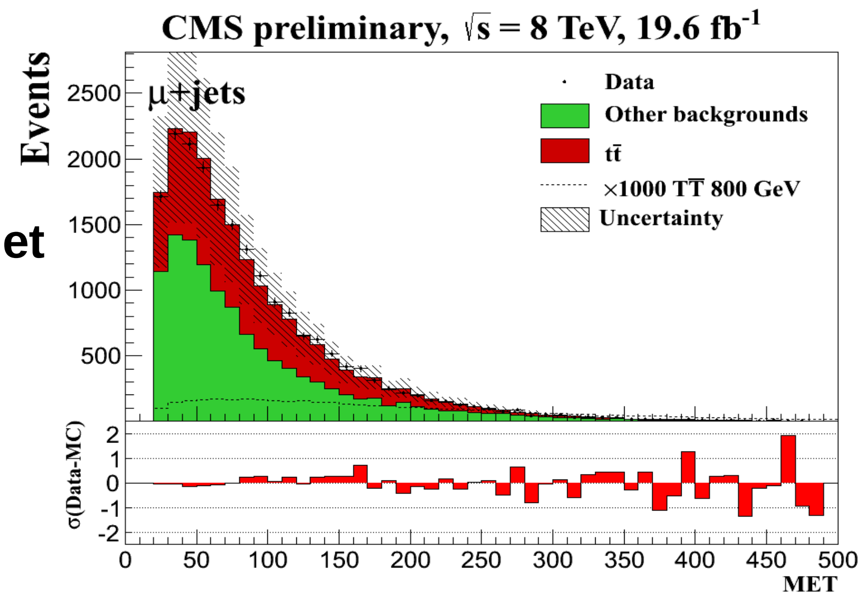
- No explicit b-jet requirement, but b-jet multiplicity enters as input variable in Boosted Decision Trees

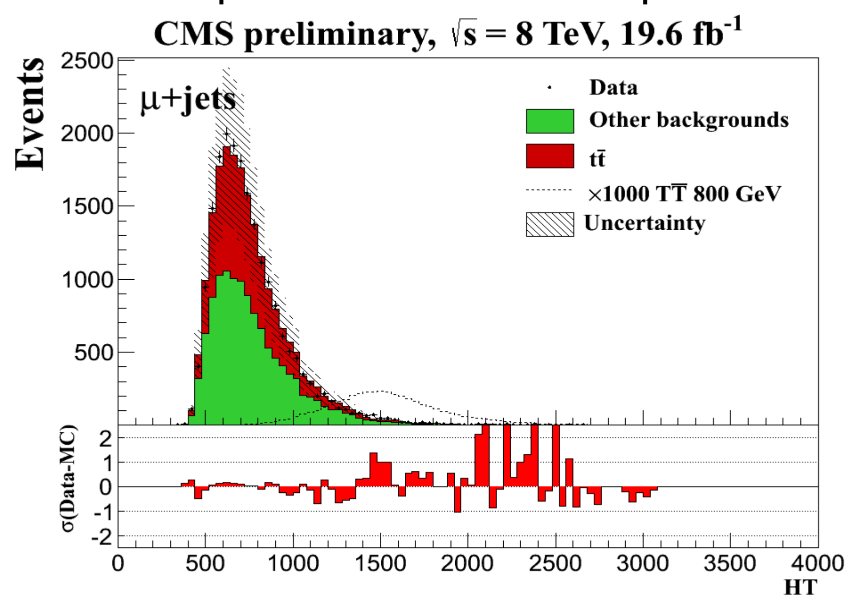
Missing transverse energy and H_T well modeled by the simulation

B2G-12-015 T (charge **2/3**)
Single-muon channel

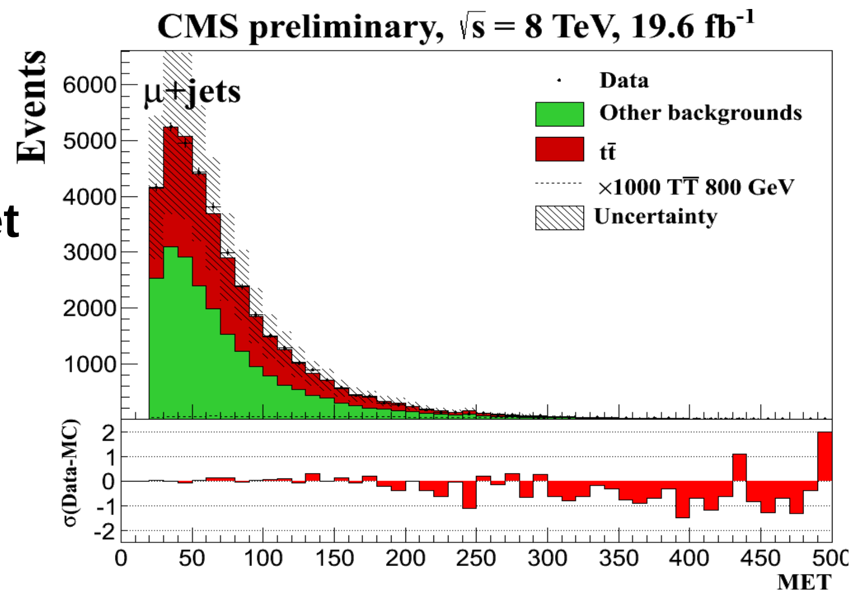
Missing transverse energy | **H_T = scalar sum of p_T of jets**

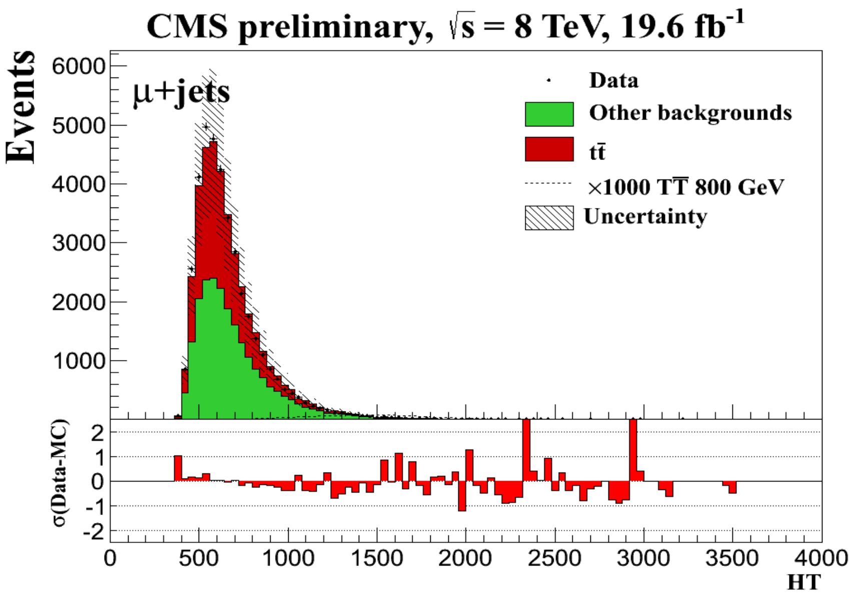
⩾ 1 W jet





no W jet





Single-lepton channel: event yields

- ttbar and W+jets largest backgrounds
- **Predicted number of events agree with observed**, within uncertainties

Lepton flavor	Muon	Electron
$t\bar{t}$	36700±5500	35900±5400
Single top quark	2200±1100	2100±1000
W	19700±9900	18600±9400
Z	2200±1100	2000±1000
Multijets	<60	1680±620
$t\bar{t}W$	144±72	137±68
$t\bar{t}Z$	109±54	108±54
$t\bar{t}H$	570±290	570±290
WW/WZ/ZZ	410±200	400±200
Total background	61900±13900	61500±13700
Data	58478	57743

Single-lepton channel: signal efficiencies

- pp → TT signal samples generated with Madgraph

- Table: assuming 'nominal' branching fractions
  BF(T → bW) = 50%, BF(T → tZ) = BF(T → tH) = 25%

Lepton flavor	Cross section	Muon		Electron	
T mass (GeV)	(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

approximate NNLO (HATHOR)

T-quark signal separated from SM background via Boosted Decision Trees (BDT)

- **Input variables**

  jet multiplicity, b-tagged jet multiplicity,
  MET, H_T (scalar sum of p_T of all jets),
  p_T lepton, p_T third jet, p_T fourth jet,
  number and p_T of W jets
  number of top jets

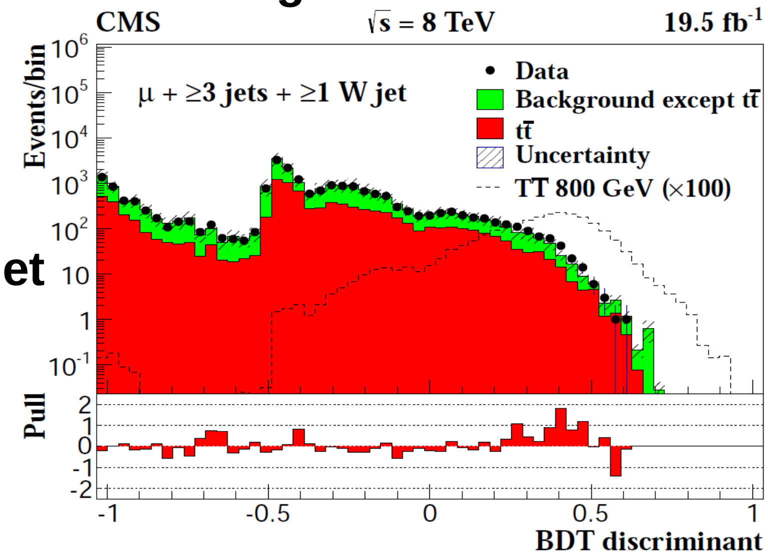
  For events with W jet

- Separate BDT trainings for events with ⩾ 1 W jet and without W jet, at every T-quark mass

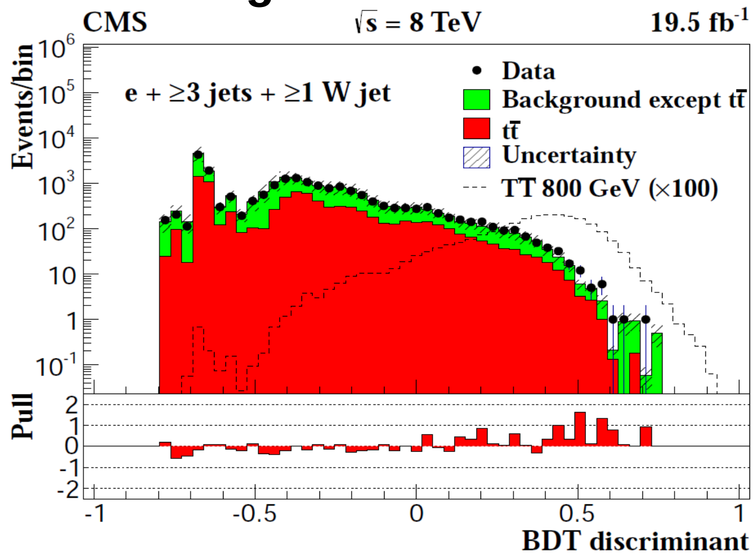
BDT discriminator distributions show good discrimination power

⩾ 1 W jet

Single-muon channel



Single-electron channel



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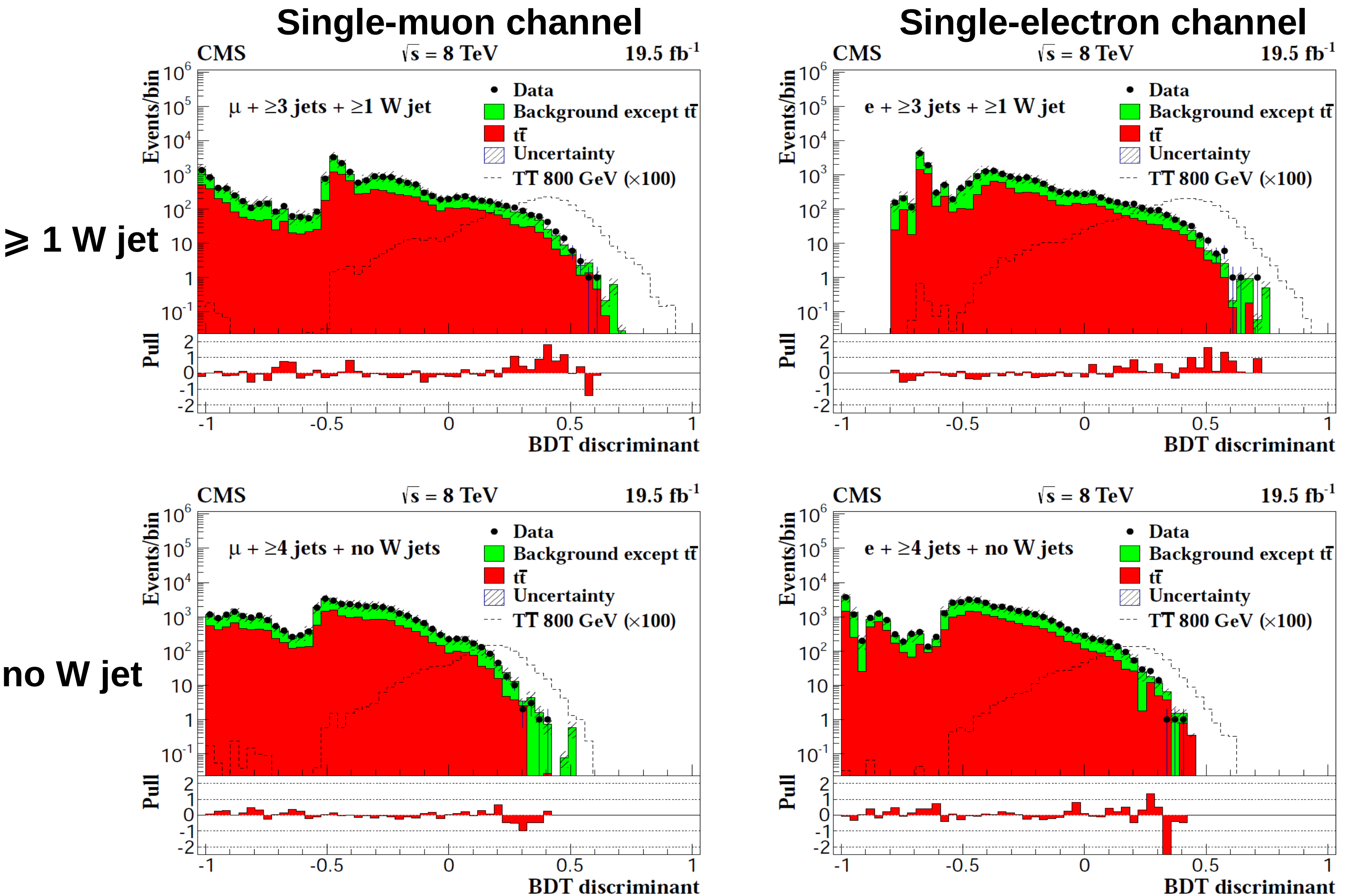
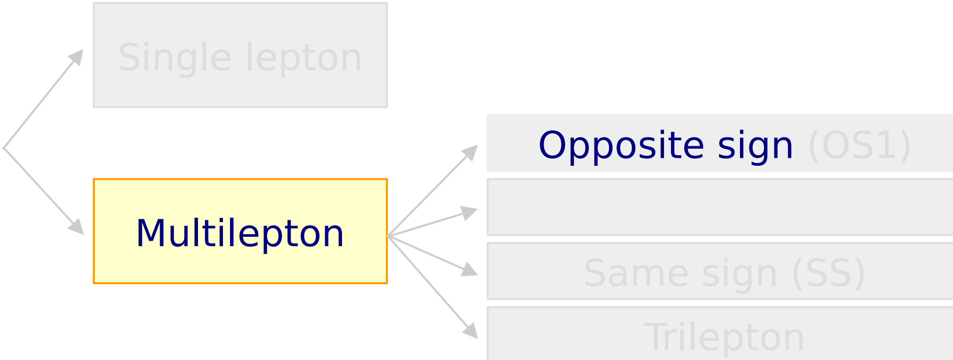
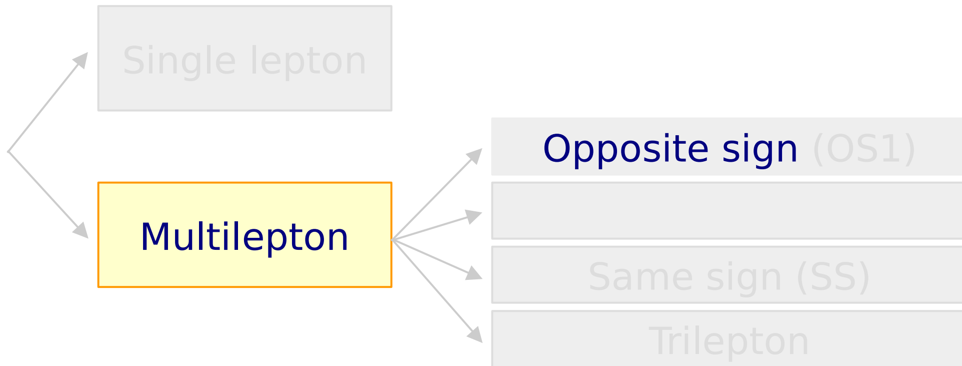


Multilepton channel: opposite-sign dileptons

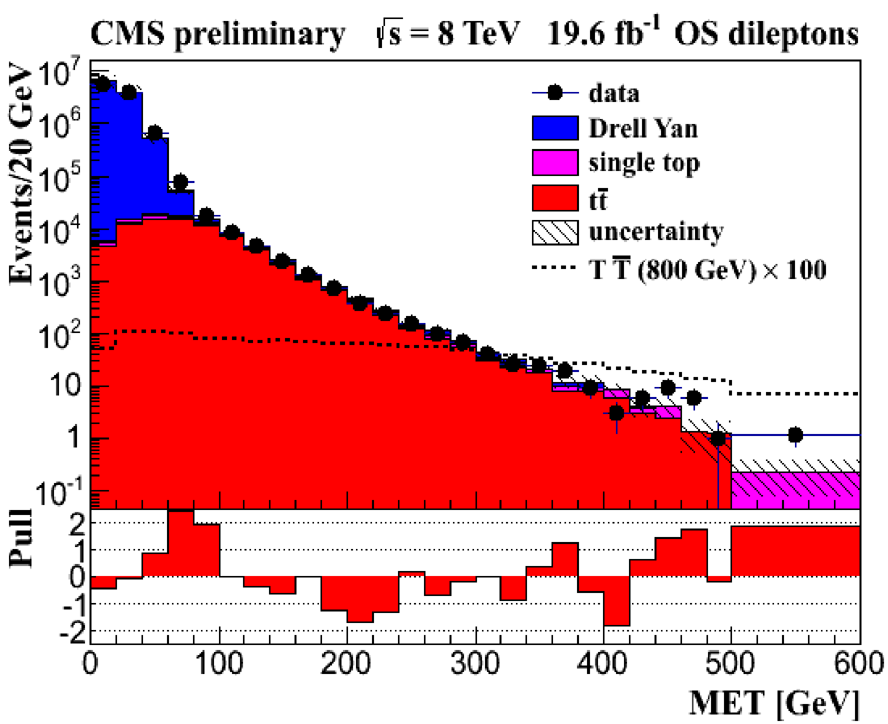


- 2 isolated opposite-charged leptons (p_T > 20 GeV)
- ⩾ 1 dilepton pair with mass > 20 GeV
- MET > 30 GeV and ⩾ 1 b jet

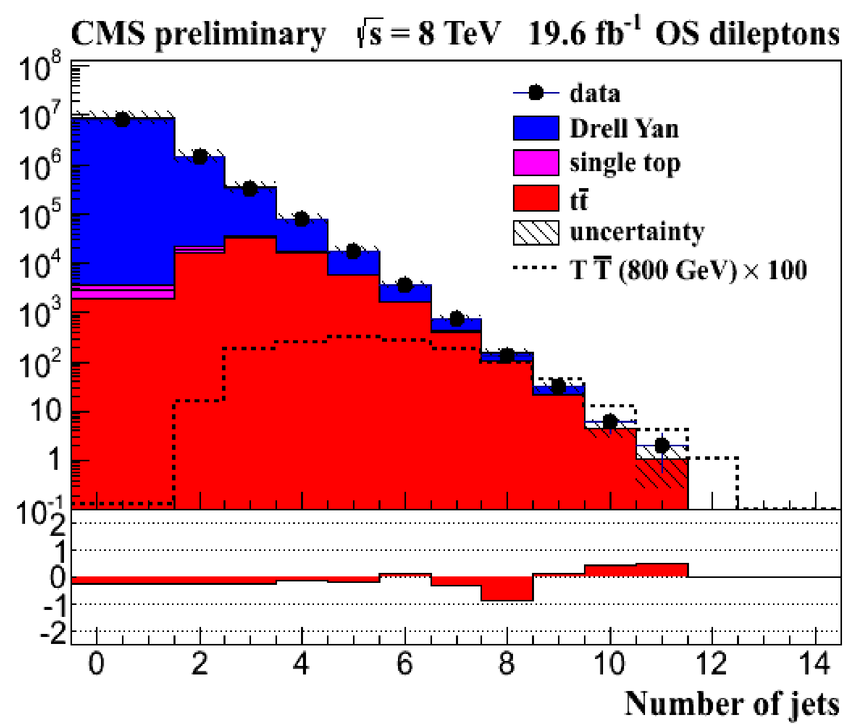
Multilepton channel: opposite-sign dileptons



Missing transverse energy



Number of jets



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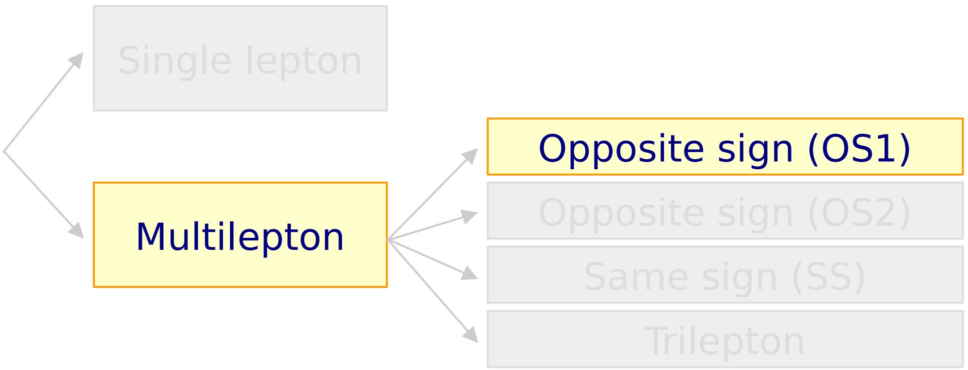


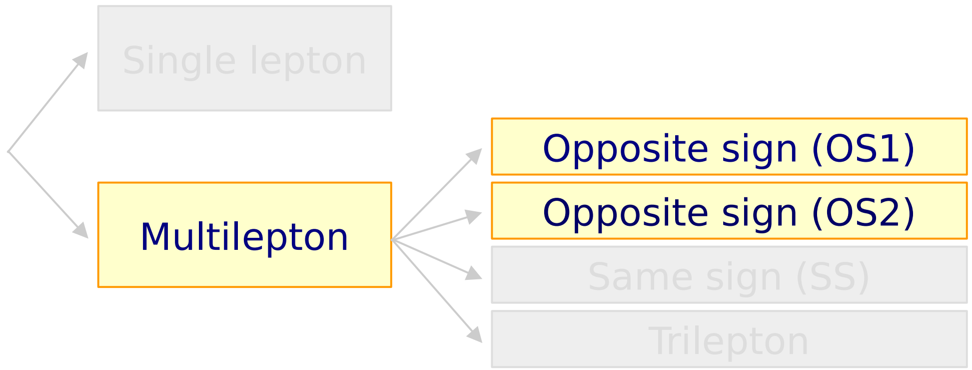
Sensitive to TT→bWbW

- 2 isolated opposite-charged leptons (p_T > 20 GeV)
- ⩾ 1 dilepton pair with mass > 20 GeV
- MET > 30 GeV and ⩾ 1 b jet

OS1

- 2 or 3 jets (p_T > 30 GeV, |η| < 2.4)
- H_T > 300 GeV, S_T > 900 GeV (sum of H_T, MET and p_T of all leptons)
- dilepton pair mass veto in 15 GeV window around Z-boson mass
  suppresses DY background
- Smallest mass of (lepton,b-jet) system M_{lb} > 170 GeV
  suppresses ttbar background

Multilepton channel: opposite-sign dileptons



Sensitive to $TT \to bWbW$

Sensitive to $T \to tZ$ decays

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- Smallest mass of (lepton,b-jet) system M_{lb} > 170 GeV

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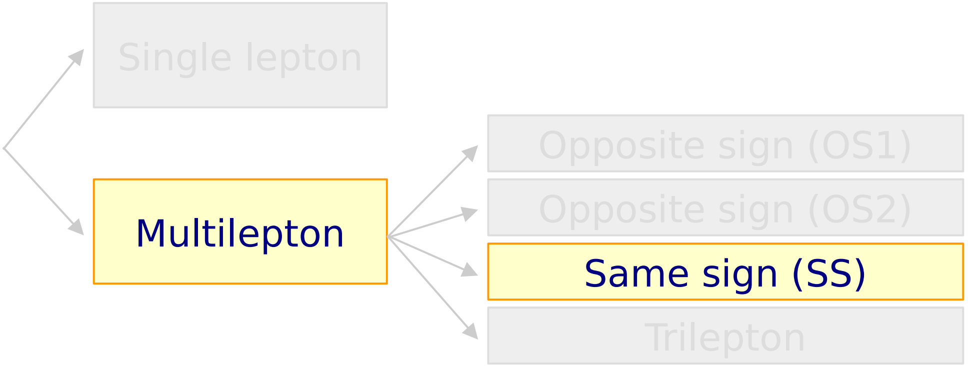
OS2

- ⩾ 5 jets of which 2 b-tagged
- H_T > 500 GeV, S_T > 1000 GeV

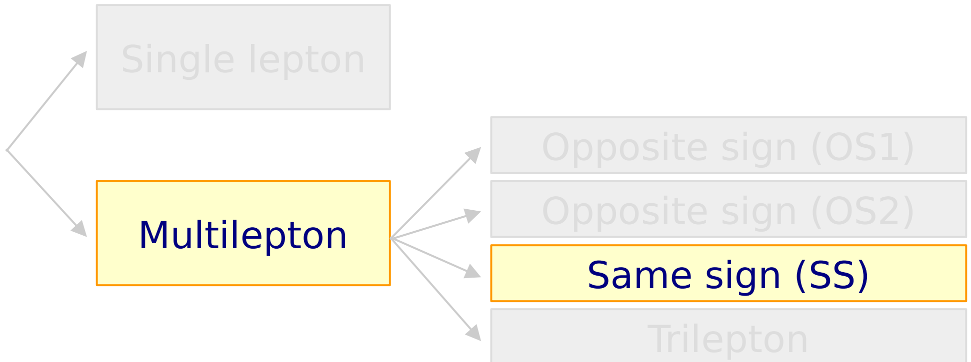
Multilepton channel: same-sign dileptons



Sensitive to $T \rightarrow tZ/tH$ decays

- 2 isolated same-charged leptons ($p_T > 20$ GeV)
- $\geqslant$ 1 dilepton pair with mass > 20 GeV
- MET > 30 GeV
- $\geqslant$ 3 jets
- $H_T > 500$ GeV, $S_T > 700$ GeV

Multilepton channel: same-sign dileptons



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Three main backgrounds

irreducible (SM processes with SS dileptons)

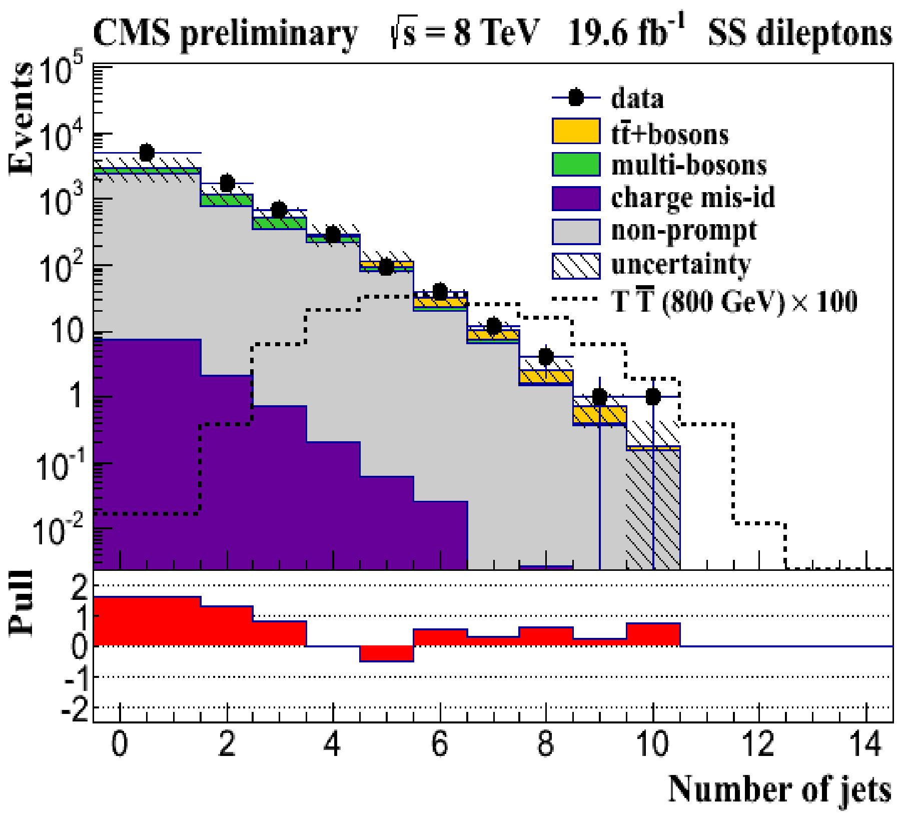
charge misidentification in OS dileptons

non-prompt leptons (lepton misidentification)

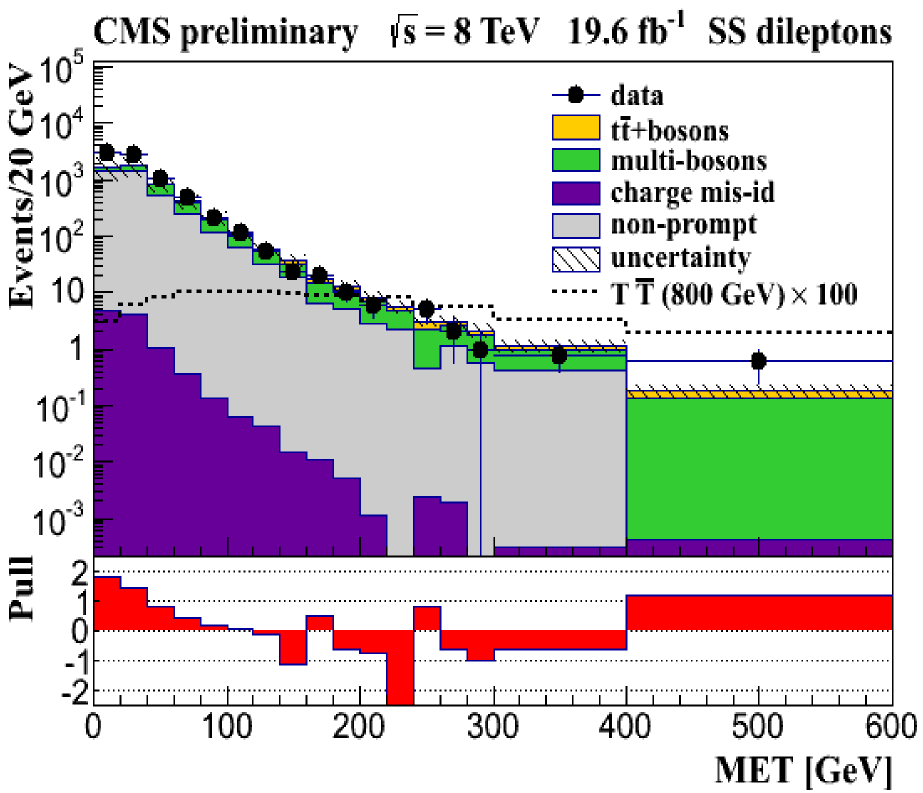
$\left.\begin{array}{l} \\ \\ \end{array}\right\}$ **Estimated from observed data**

Multilepton channel: same-sign dilepton distributions

Number of jets



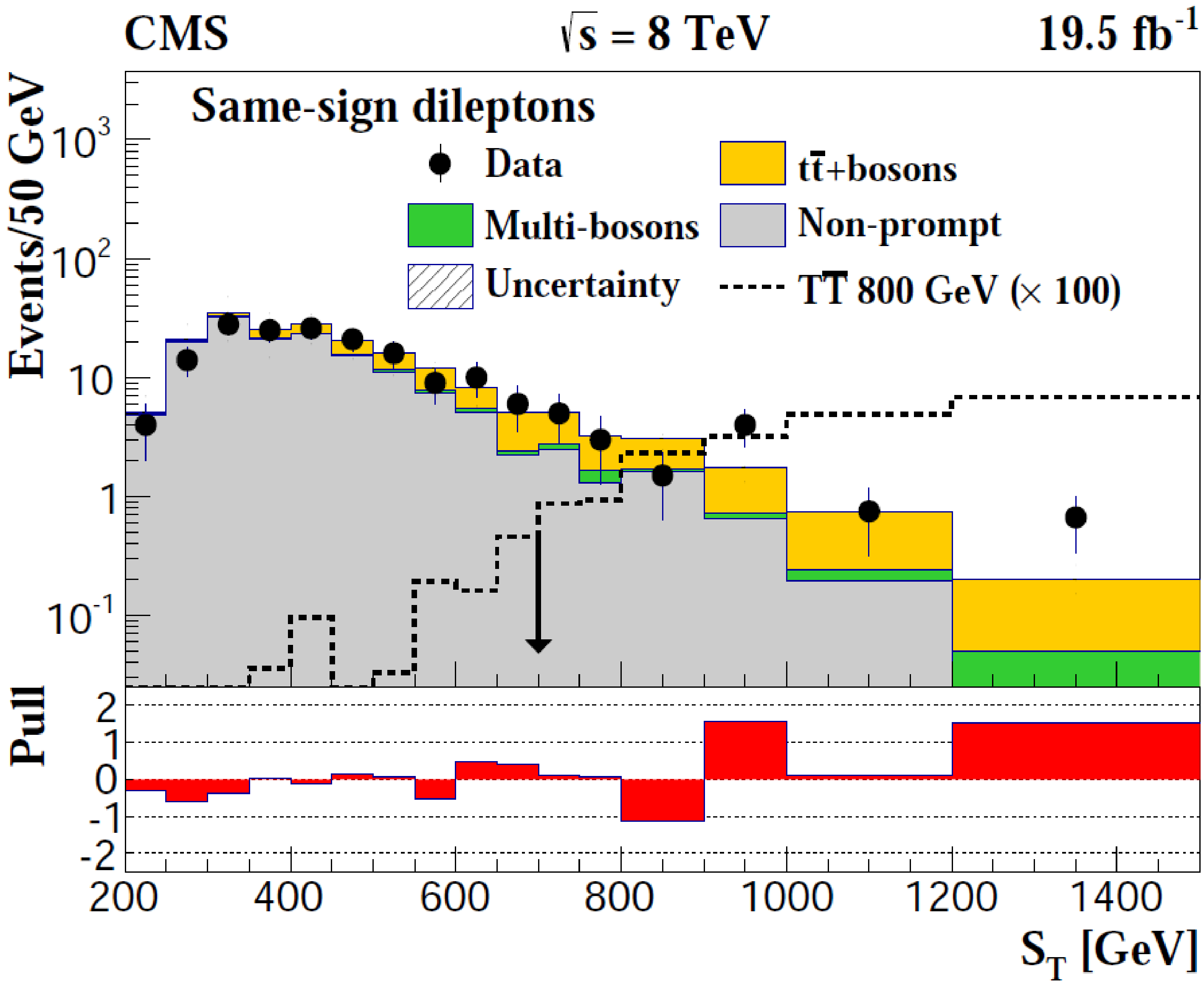
Missing transverse energy



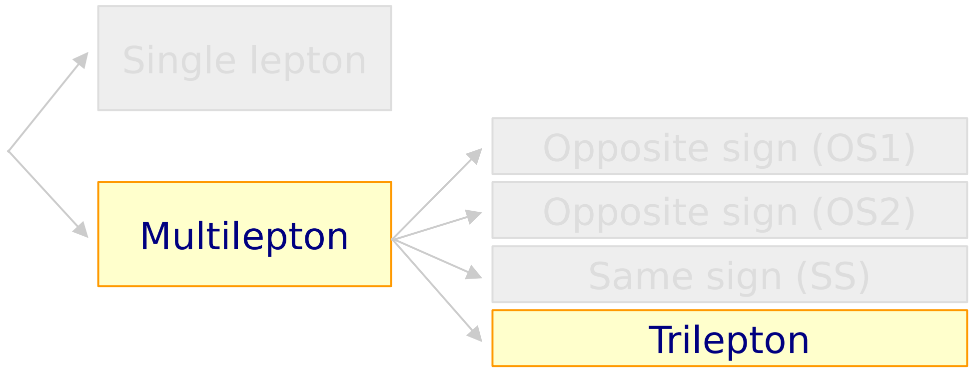
before MET cut

Multilepton channel: same-sign dilepton S_T distribution

before S_T cut



Multilepton channel: trileptons



Sensitive to $T \rightarrow tZ/tH$ decays

- $\geqslant$ 3 isolated leptons (p_T > 20 GeV)
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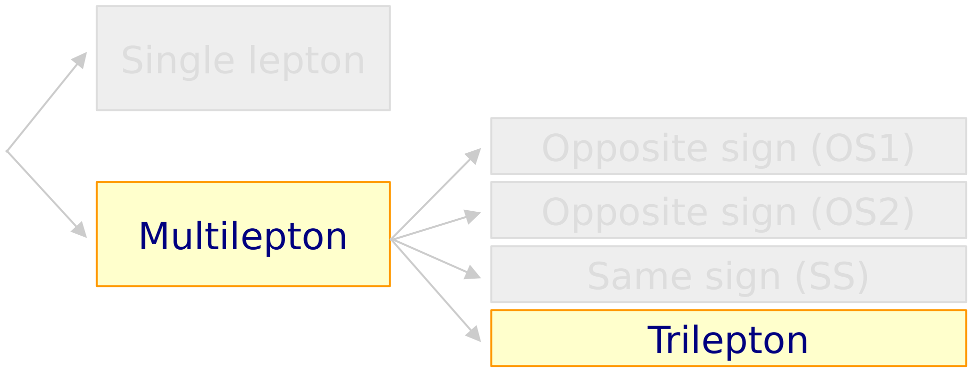

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Estimated from observed data

Multilepton channel: trilepton distributions

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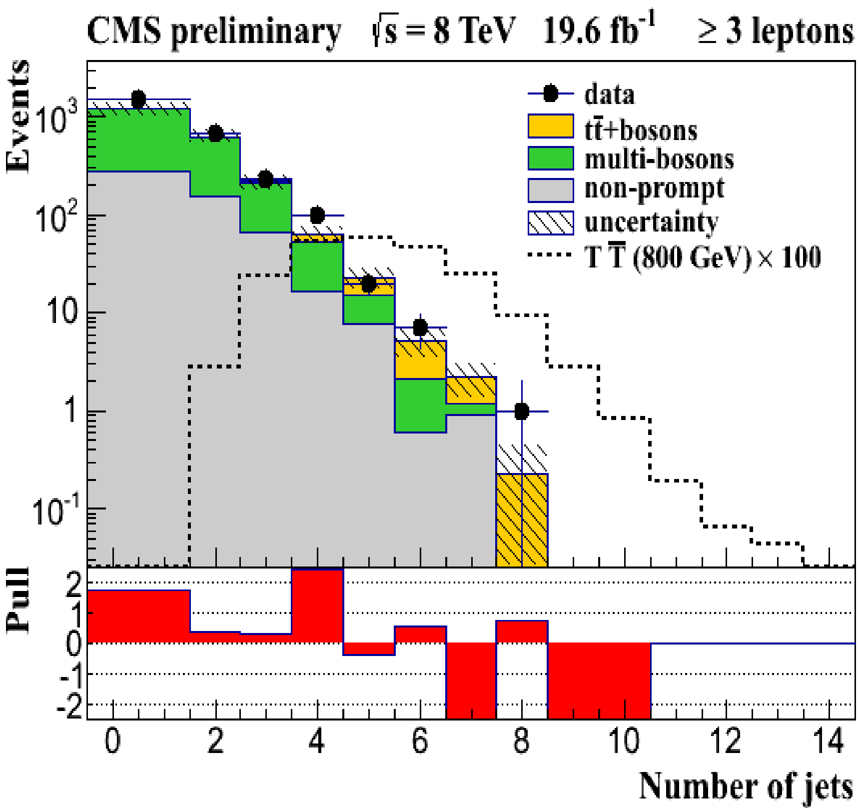
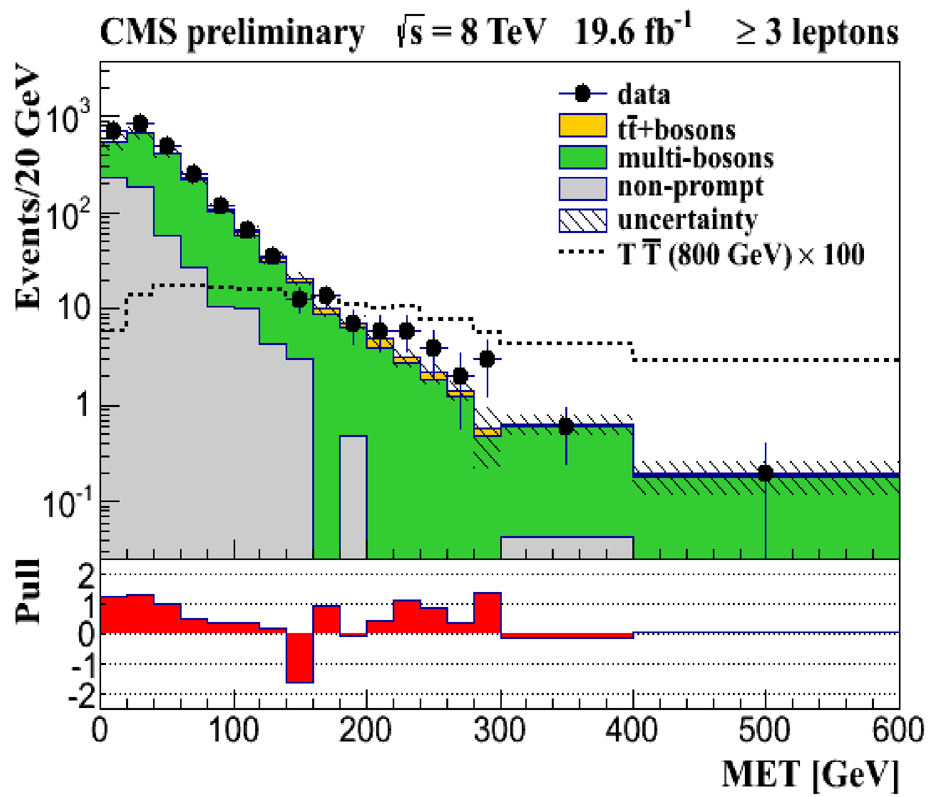


Missing transverse energy



before MET cut

Multilepton channel: event yields

- **Predicted number of events agree with observed**, within uncertainties

Channel	OS1	OS2	SS	Trileptons
$t\bar{t}$	5.2 ± 1.9	80 ± 12	–	–
Single top quark	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 misidentification	–	–	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

Multilepton channel: signal efficiencies

- Table: assuming 'nominal' branching fractions
  BF(T → bW) = 50%, BF(T → tZ) = BF(T → tH) = 25%

Channel	OS1		OS2		SS		Trileptons	
T mass (GeV)	ϵ	N	ϵ	N	ϵ	N	ϵ	N
500	0.15%	16.7	0.31%	35.1	0.19%	21.3	0.17%	19.1
600	0.27%	8.9	0.50%	16.6	0.22%	7.5	0.26%	8.5
700	0.36%	4.0	0.60%	6.6	0.25%	2.8	0.28%	3.1
800	0.39%	1.6	0.61%	2.5	0.25%	1.0	0.32%	1.3
900	0.43%	0.67	0.60%	0.96	0.25%	0.40	0.33%	0.52
1000	0.44%	0.28	0.56%	0.36	0.23%	0.15	0.33%	0.21
1100	0.44%	0.12	0.52%	0.14	0.22%	0.06	0.32%	0.09
1200	0.45%	0.05	0.46%	0.05	0.20%	0.02	0.31%	0.04

Systematic uncertainties

- Treated as **nuisance parameters** in statistical limit setting

  normalization of signal and background simulation
  - luminosity 2.6%
  - cross sections
    - diboson, single top, W/Z+jets 50%
    - ttbar 8%
  - efficiency corrections
    - lepton trigger and identification 3%

  jet energy scale and resolution

  b-tagging efficiency

  renormalization and factorization scale

  jet-parton matching threshold

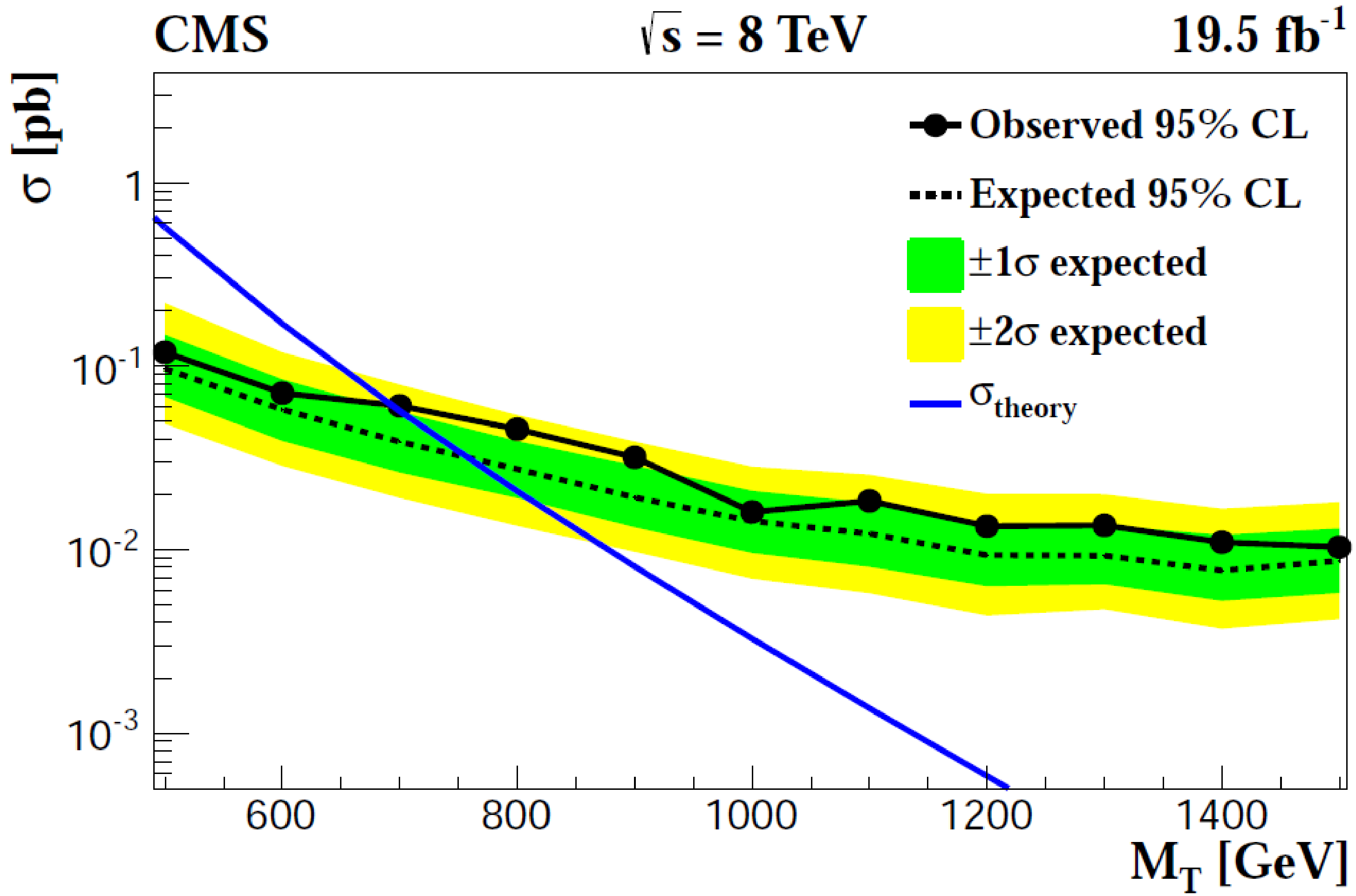
  top-quark p_T distribution

  proton PDF uncertainties negligible

Combined mass limits on vector-like T (charge 2/3) quarks

- Figure: assuming 'nominal' branching fractions

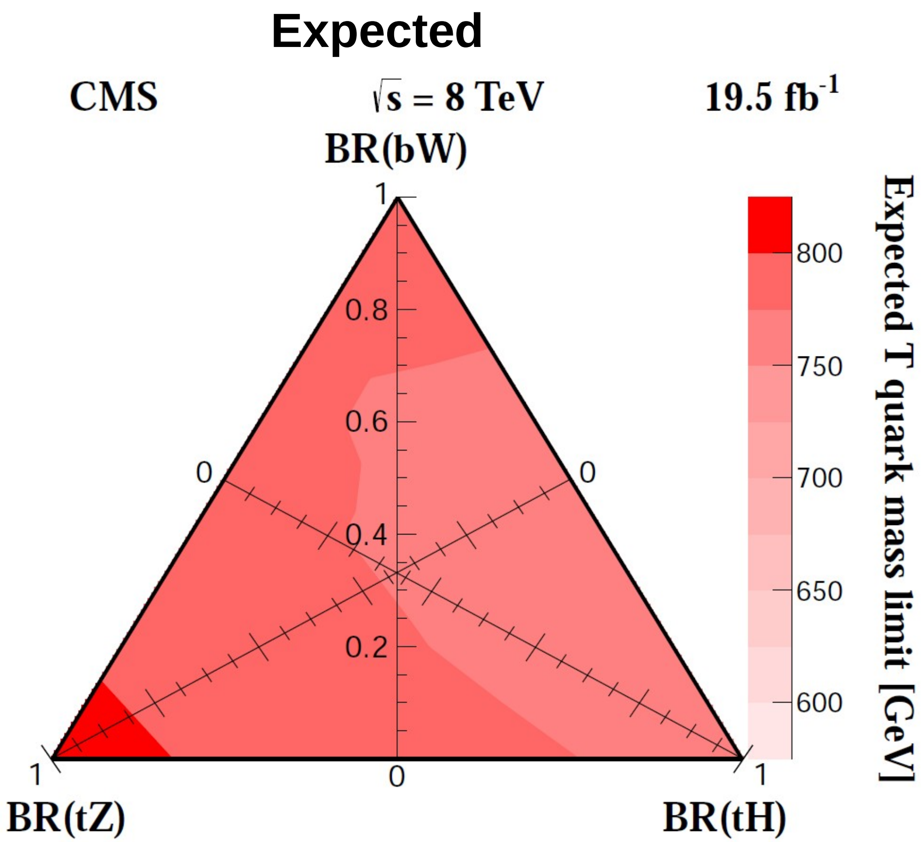
  BF(T → bW) = 50%, BF(T → tZ) = BF(T → tH) = 25%

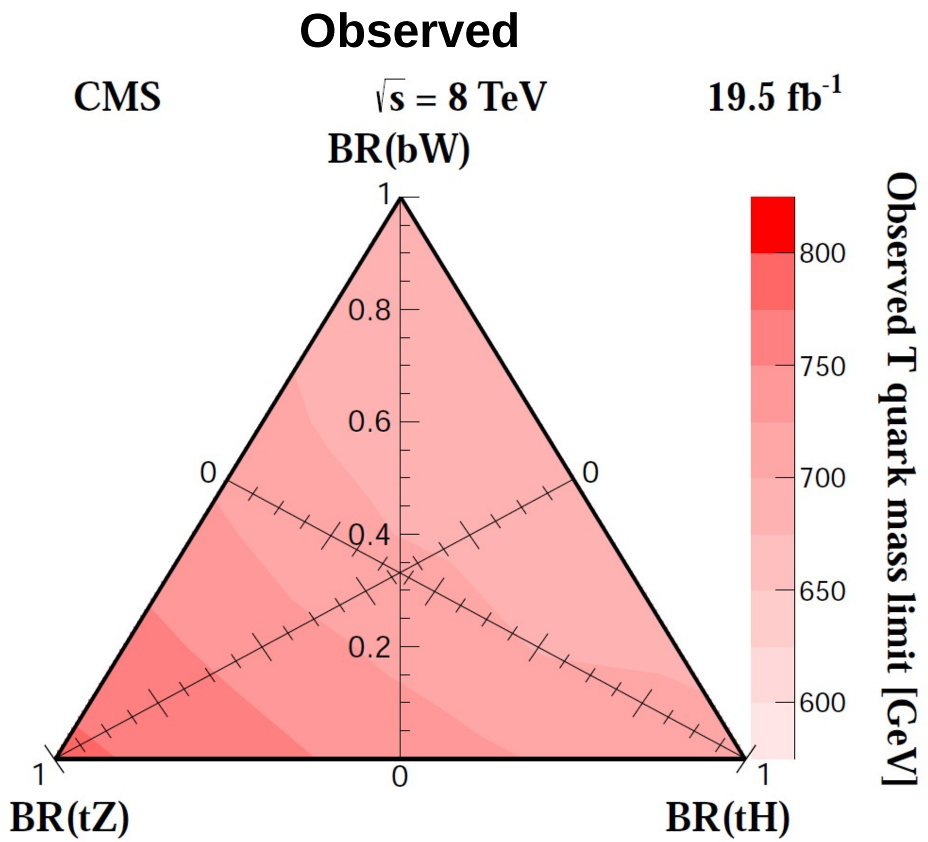


Scanning branching fractions: combined limits

Branching fractions			Expected	Observed
$T \to bW$	$T \to tH$	$T \to tZ$	limit (GeV)	limit (GeV)
0.5	0.25	0.25	773	696
0.0	0.0	1.0	813	782
0.0	0.2	0.8	798	766
0.0	0.4	0.6	790	747
0.0	0.6	0.4	783	731
0.0	0.8	0.2	773	715
0.0	1.0	0.0	770	706
0.2	0.0	0.8	794	758
0.2	0.2	0.6	786	739
0.2	0.4	0.4	777	717
0.2	0.6	0.2	767	698
0.2	0.8	0.0	766	694
0.4	0.0	0.6	786	734
0.4	0.2	0.4	776	705
0.4	0.4	0.2	766	693
0.4	0.6	0.0	762	690
0.6	0.0	0.4	779	703
0.6	0.2	0.2	771	693
0.6	0.4	0.0	769	687
0.8	0.0	0.2	779	695
0.8	0.2	0.0	777	689
1.0	0.0	0.0	785	700

Limits represented in branching-fraction triangles

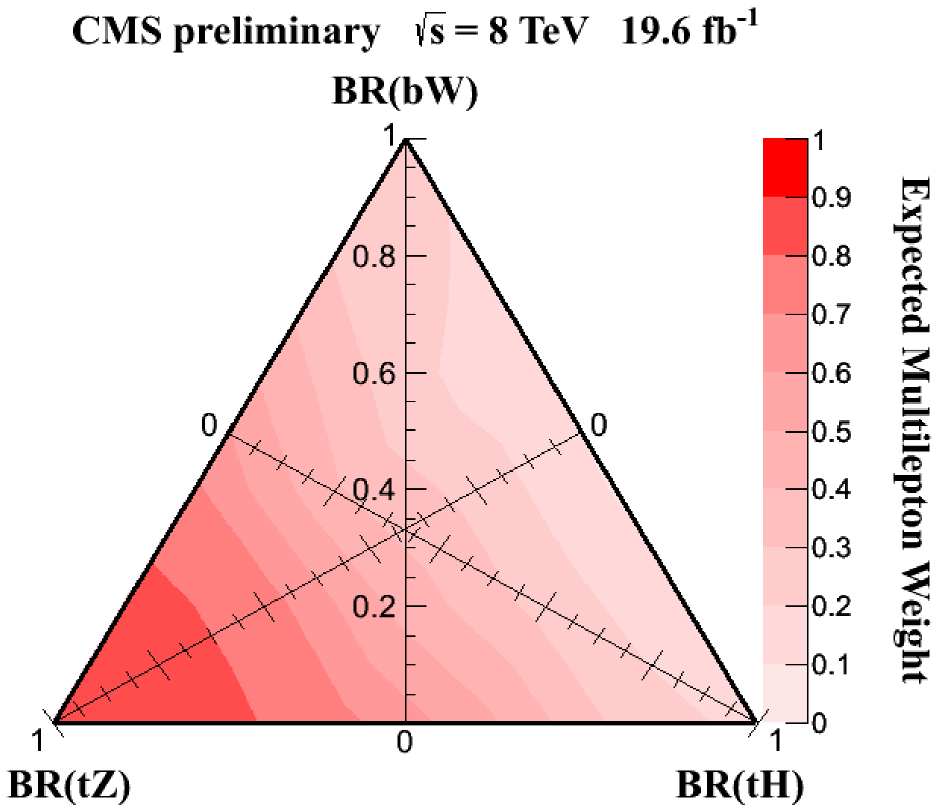




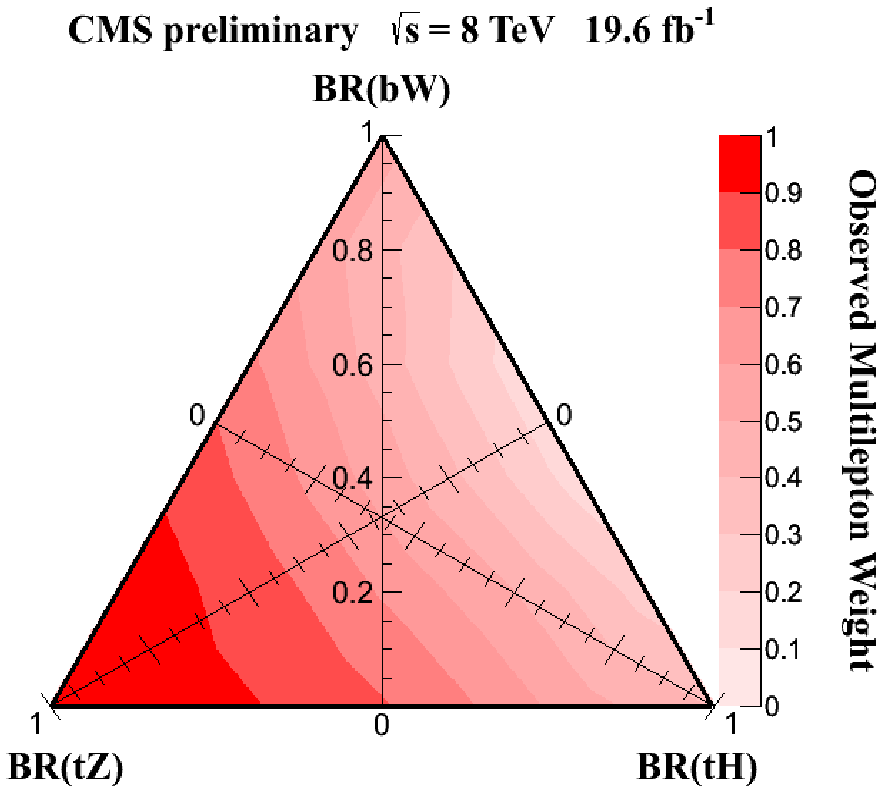
- **Lower mass limits** at 95% CL **between 687 GeV and 782 GeV** for all possible branching fractions

Weights of multilepton channel in combination of limits

Expected



Observed



Introduction to vector-like T quarks

The CMS detector

Event reconstruction and W/top jet tagging

Search for T (charge 2/3) → bW, tZ, tH
single-lepton and multilepton channels

Search for T (charge 5/3) → tW^+
same-sign dilepton channel

B2G-12-012
1312.2391v2

Summary

Signal selection

- 2 isolated same-sign leptons
  ($|\eta| < 2.4$, $p_T > 30$ GeV, muon $I_{rel} < 0.20$, electron $I_{rel} < 0.15$)
- ΔR(lepton,top-jet) > 0.8
- Dilepton Z-boson veto M(ee) < 76 GeV or M(ee) > 106 GeV
- Trilepton Z-boson veto using mass of pair of lepton and 'loose' lepton ($p_T > 15$ GeV, muon $I_{rel} < 0.40$, electron $I_{rel} < 0.60$)
- Number of constituents $N_c \geqslant 7$
  - AK5 jet, lepton = both 1 constituent
  - W boson = 2 constituents
  - top jet = 3 constituents
- $H_T > 900$ GeV (scalar sum of p_T of all jets *and leptons*)

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Signal efficiency 10-13% for strong pair production of $T_{5/3}$ quarks with masses in [750-1000] GeV

Three main background sources

Irreducible

SM processes with prompt same-sign dileptons:
diboson, ttW, ttWW, ttZ, $W^{\pm}W^{\pm}$, WWW from simulation

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Lepton charge misidentification in OS leptons (ttbar, DY)

- electron charge misid probability R (~10^{-3}, dependent on p_T and η) determined from data DY events in Z mass window
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Non-prompt leptons (lepton misidentification)

estimated from data using "*Tight-Loose method*"

a) $N_{\text{tight}} / N_{\text{loose}}$ determined from data:

- for prompt leptons from DY events in Z mass window
- for non-prompt leptons from bkg enriched sample
  MET < 25 GeV, transverse mass(lepton,MET) < 25 GeV,
  ⩾ 1 jet with p_T > 40 GeV and ΔR > 1.0 w.r.t lepton

b) events with ⩾1 loose leptons weighted with these ratios

Systematic uncertainties influencing acceptance

- luminosity 2.6%
- cross sections
  - WZ 17%, ZZ 5.1%, ttW 32%
  - other rare backgrounds 50%
- lepton trigger (1%), reconstruction and identification (1% per lepton)
- pile-up
  - signal 3%
  - background: 3-6%
- jet energy scale
  - signal: 2%
  - background: 3-6% for AK5 jets
  - constant 3% for CA8 jets
- charge misidentification background 20%
- non-prompt lepton background 50%

Same-sign dilepton event yields

- **Predicted number of events agree with observed**, within uncertainties

Channel	ee	eμ	$\mu\mu$	All
Same-sign	0.8 ± 0.2	1.9 ± 0.4	1.3 ± 0.3	4.0 ± 0.8
Chrg. misid.	0.06 ± 0.02	0.04 ± 0.01	—	0.11 ± 0.02
Non-prompt	1.9 ± 1.2	0.6 ± 0.9	0.3 ± 0.6	2.8 ± 1.9
Tot. bkgnd	2.7 ± 1.3	2.5 ± 1.0	1.6 ± 0.7	6.8 ± 2.1
Obs. events	0	6	3	9
$T_{5/3}$	2.1 ± 0.1	4.7 ± 0.3	2.8 ± 0.2	9.7 ± 0.5

$T_{5/3}$ mass 800 GeV

H_T distribution after full selection (w/o H_T cut)

- **Expected and observed spectra agree**

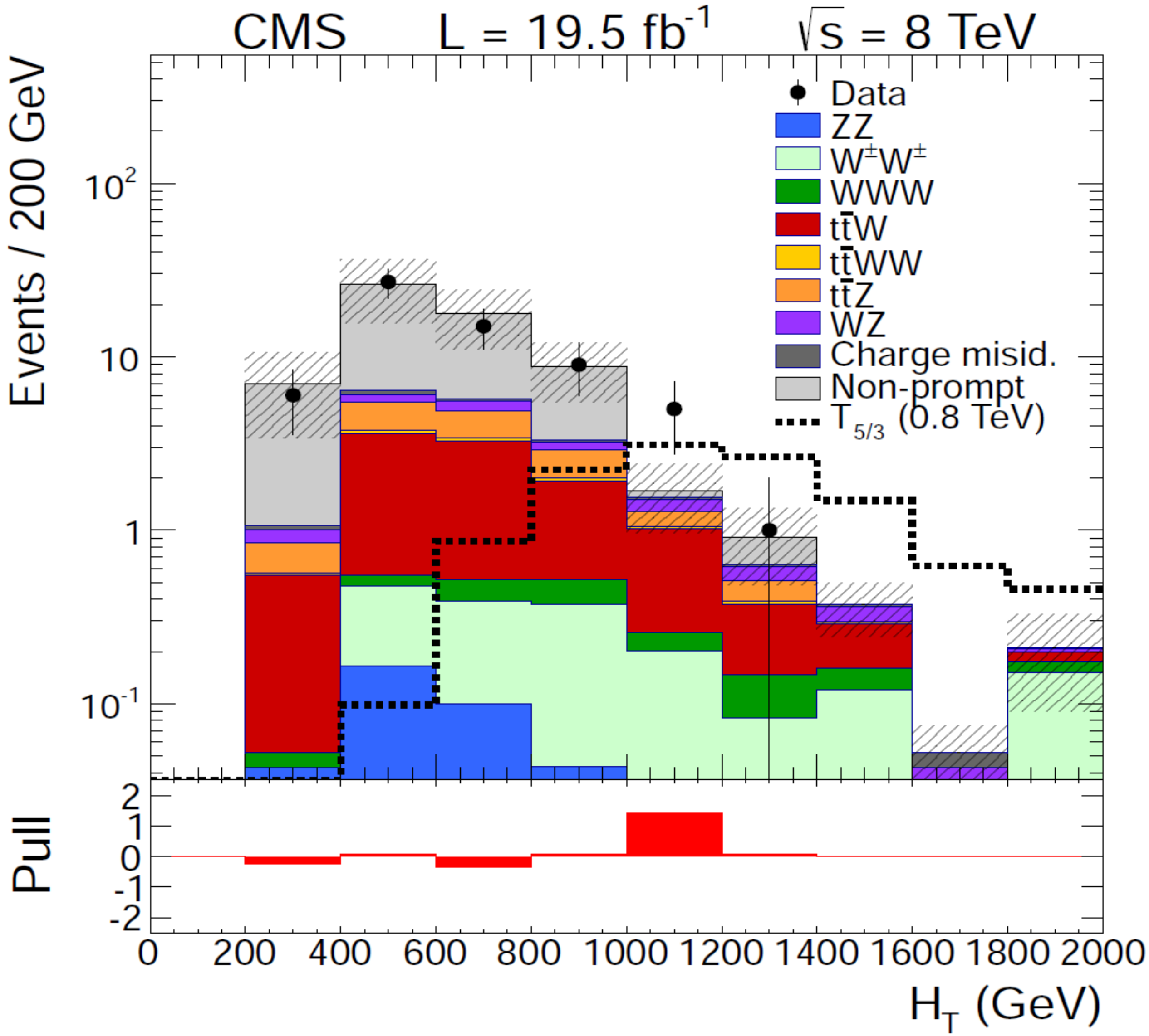
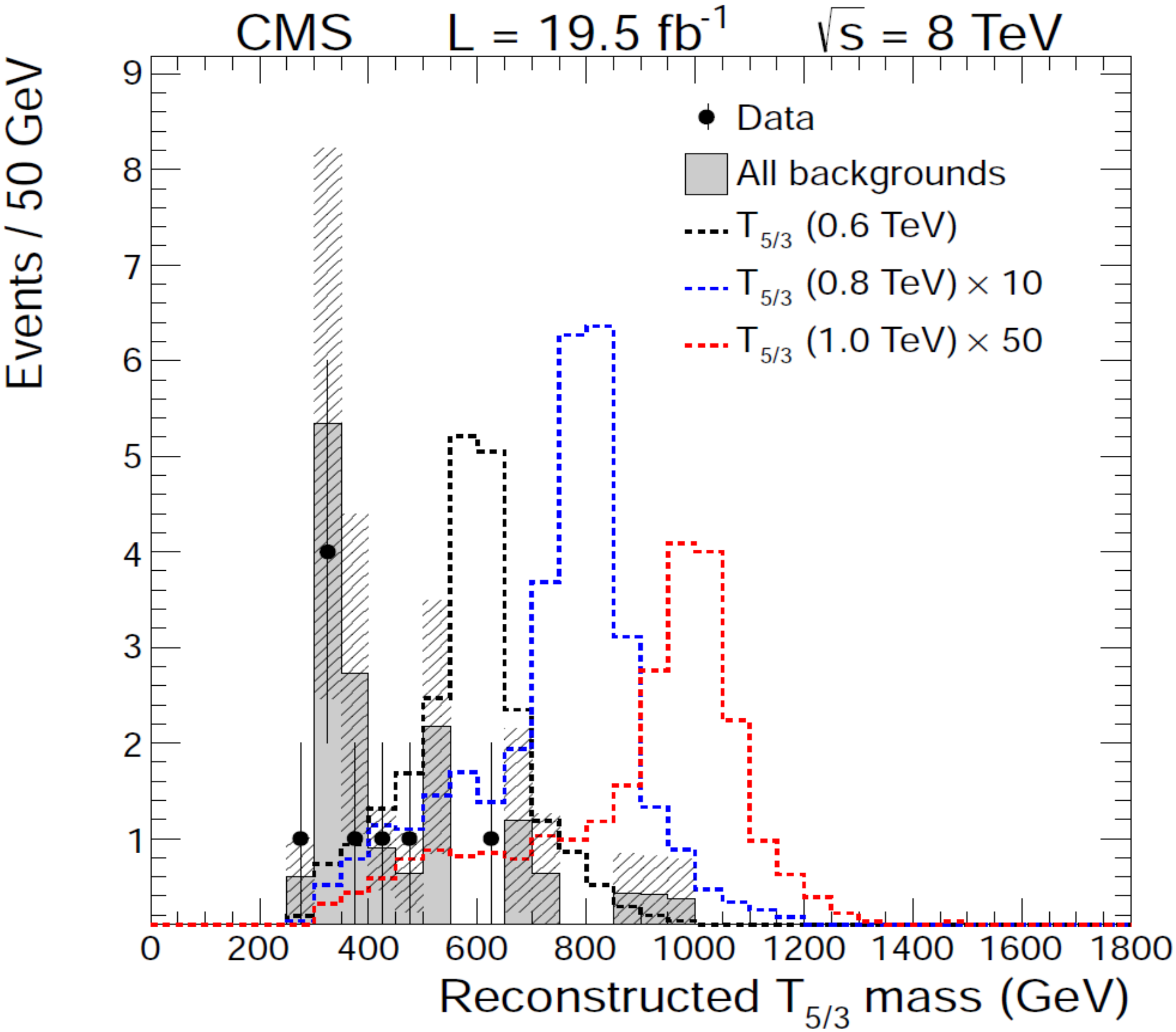


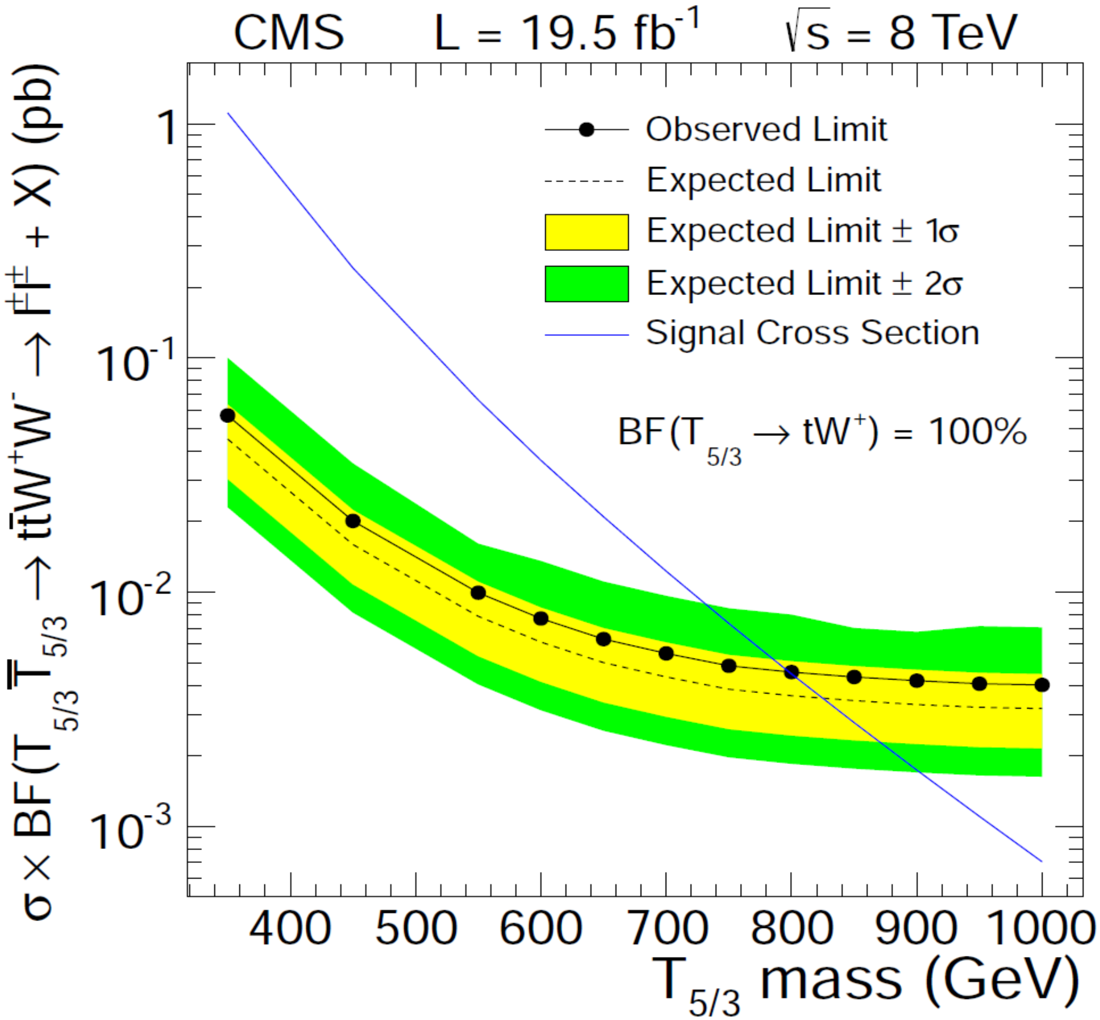
Illustration: vector-like quark mass variable

- $T_{5/3}$ quark mass can be reconstructed via combination of top jets, W jets and AK5 jets



Limits assuming BF($T_{5/3} \rightarrow tW^{+}$) = 100%

- Event yields from all lepton (ee, eμ, μμ) channels combined
- **Observed** (expected) **lower mass limit** at 95% CL:
  800 GeV (830 GeV)



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  B2G-12-015
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B2G-12-012
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  search for **T (charge 5/3) → tW^+** B2G-12-012
  same-sign dilepton 1312.2391v2

  → observed lower mass limit of **800 GeV**

- Stay tuned for **new searches in the next LHC runs!**
  T (charge 2/3) expected reach at 14 TeV with 3000/fb:
  5σ discovery: 1.48 TeV
  95% CL exclusion: 1.85 TeV

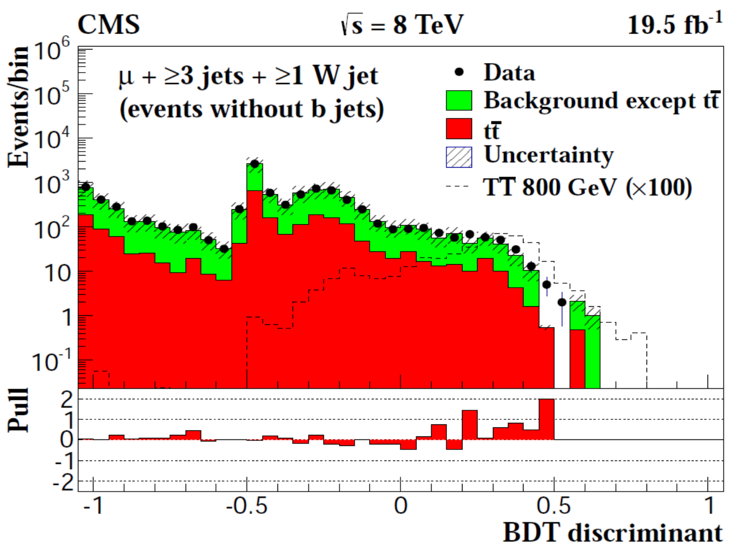
  CMS PAS FTR-13-026

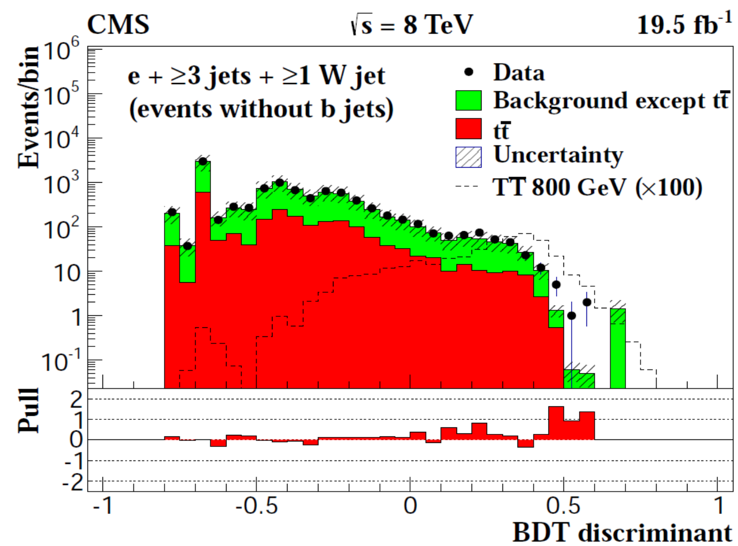
BACKUP

BDT discriminator for events without b jets

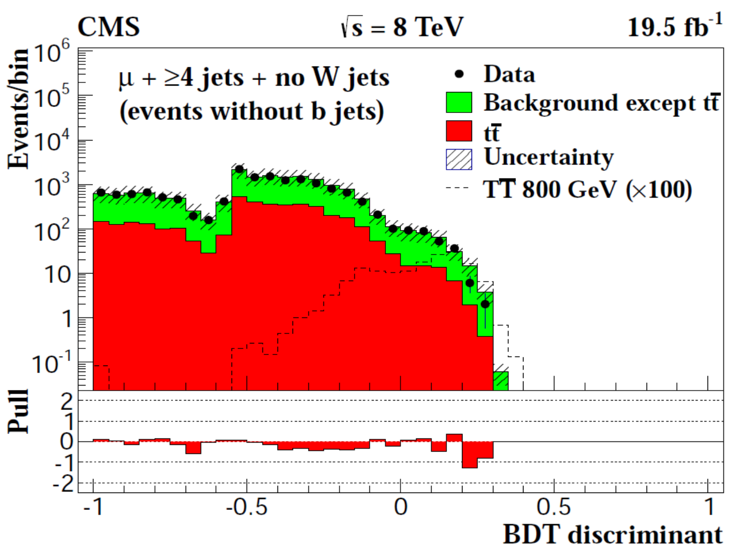
Single-muon channel | **Single-electron channel**

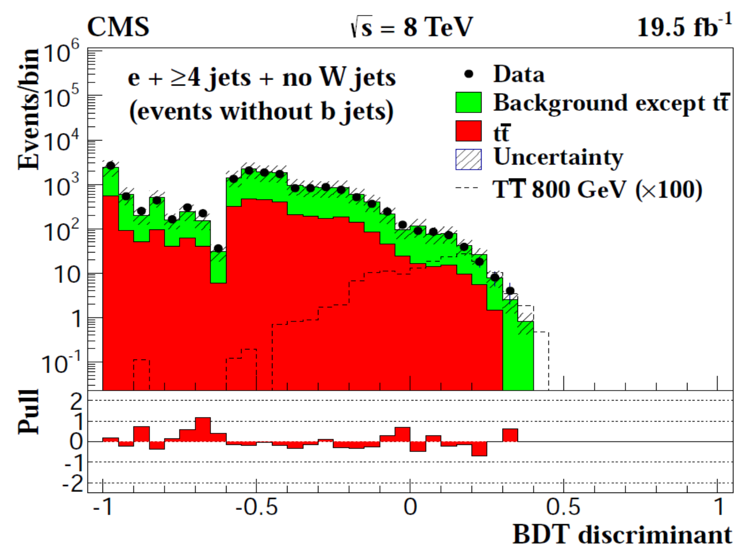
⩾ 1 W jet



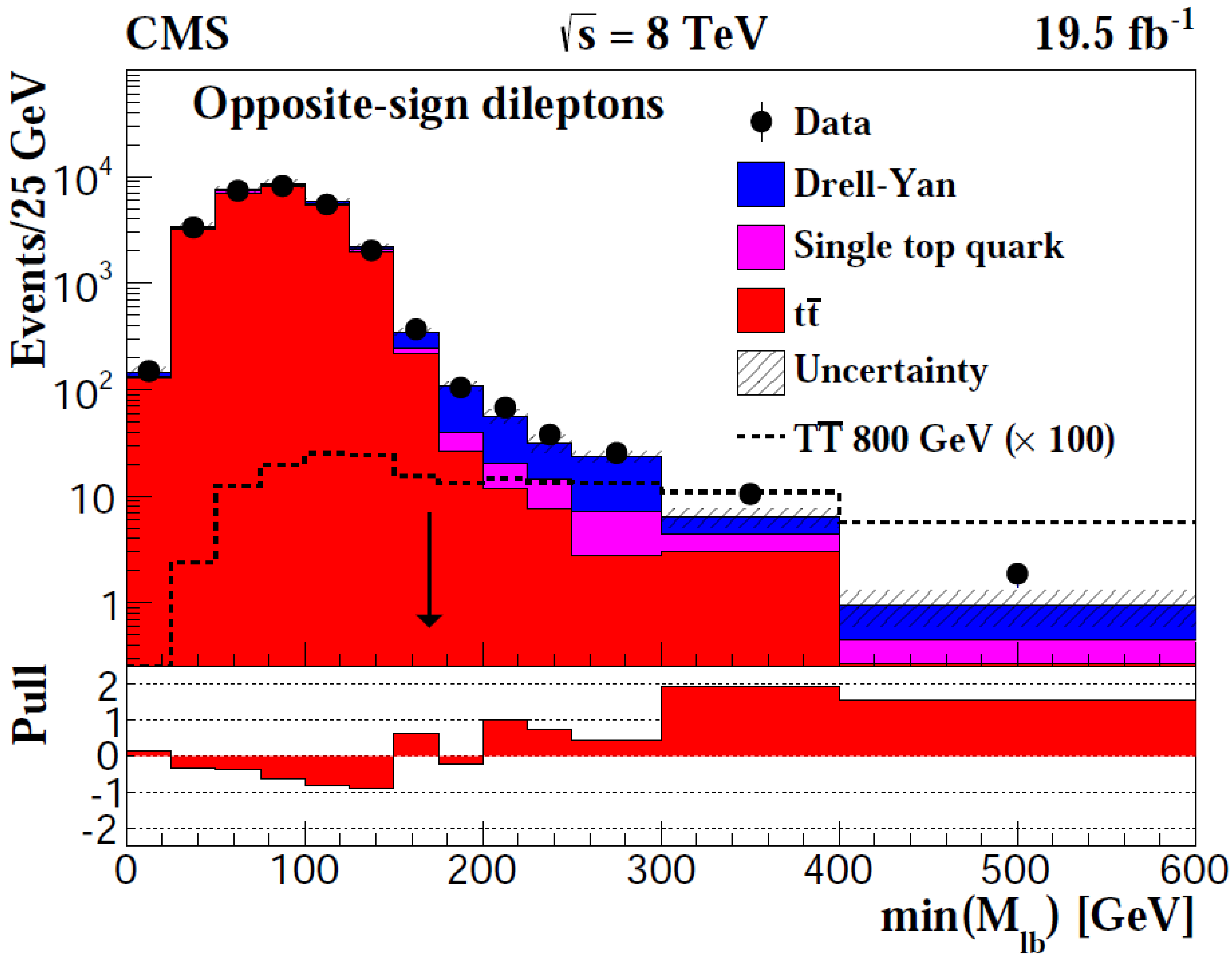


no W jet



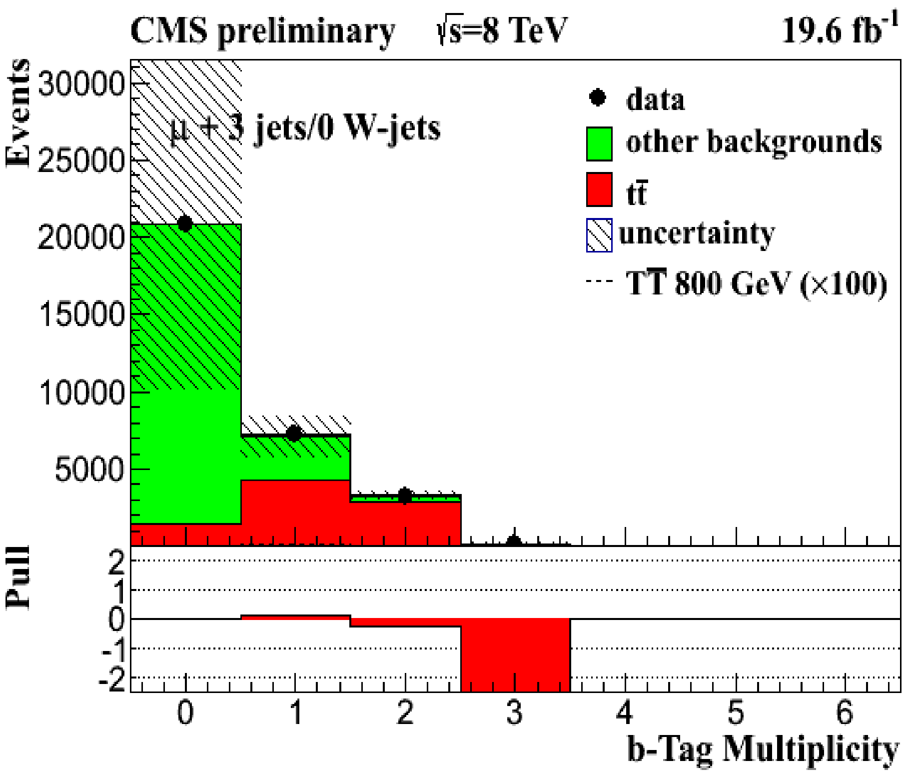


Smallest M_{lb} for opposite-sign dileptons

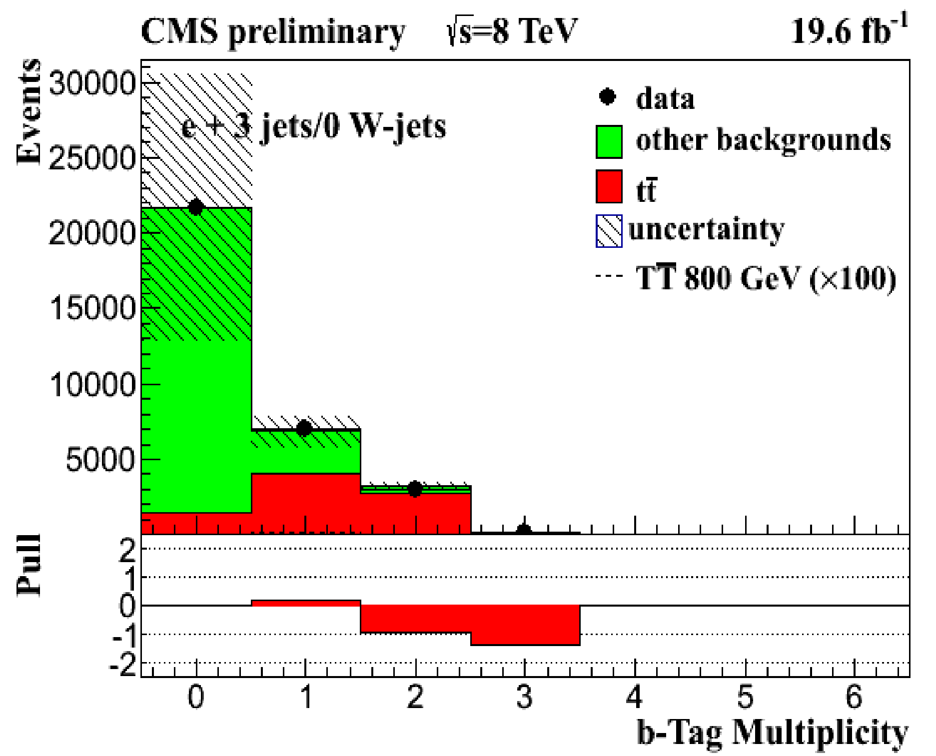


B-tagged jet multiplicity in control region

Single-muon channel



Single-electron channel



Missing transverse energy and H_T well modeled by the simulation

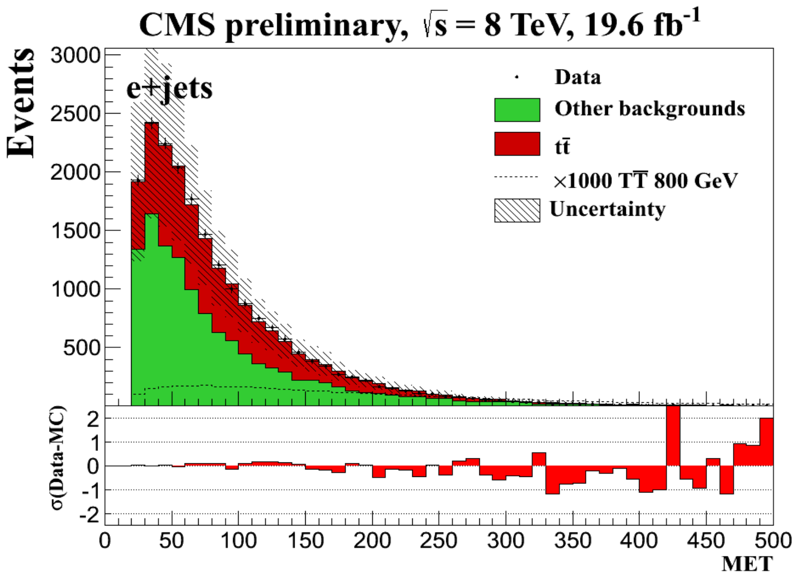
B2G-12-015 T (charge **2/3**)

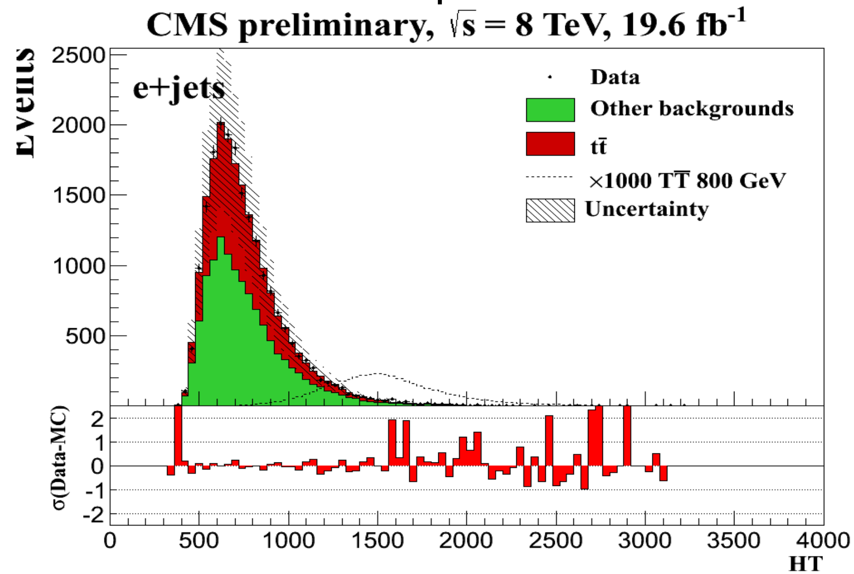
Single-electron channel

Missing transverse energy

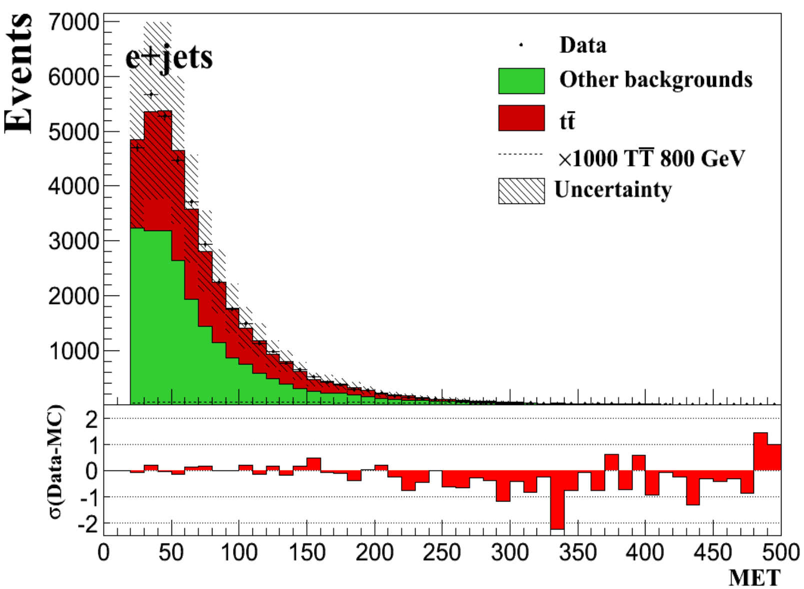
H_T

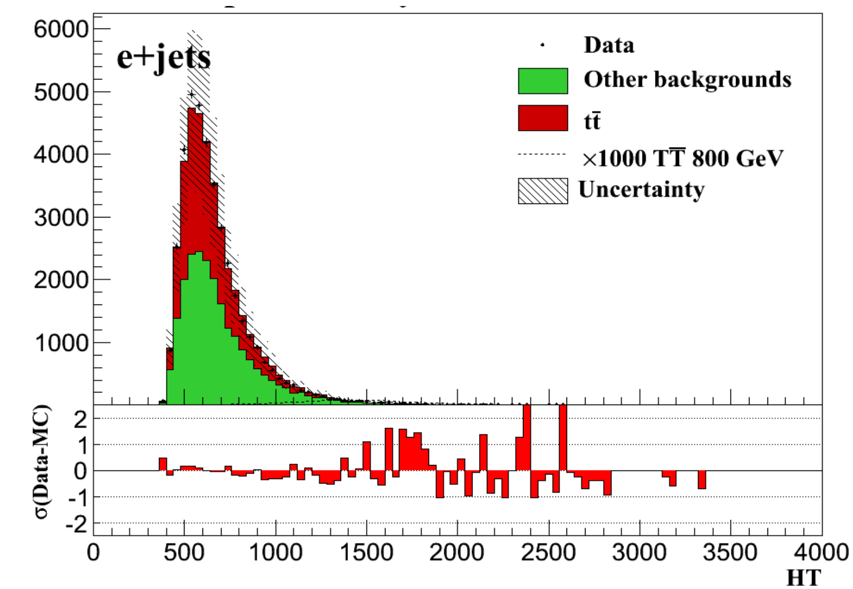
⩾ 1 W jet





no W jet





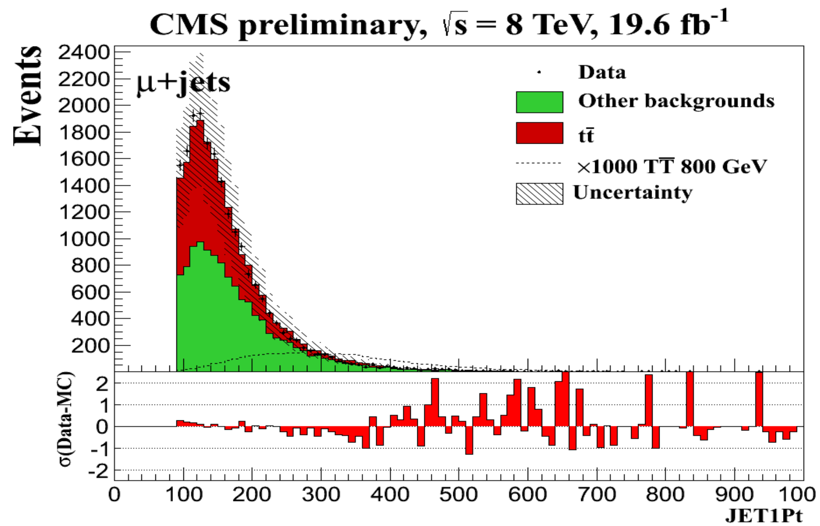
Jet p_T spectrum well modeled by the simulation

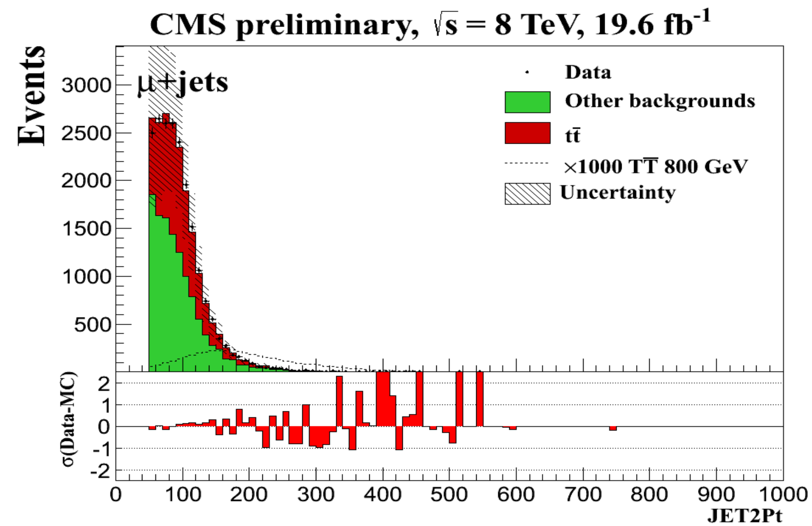
B2G-12-015 T (charge **2/3**)

Single-muon channel

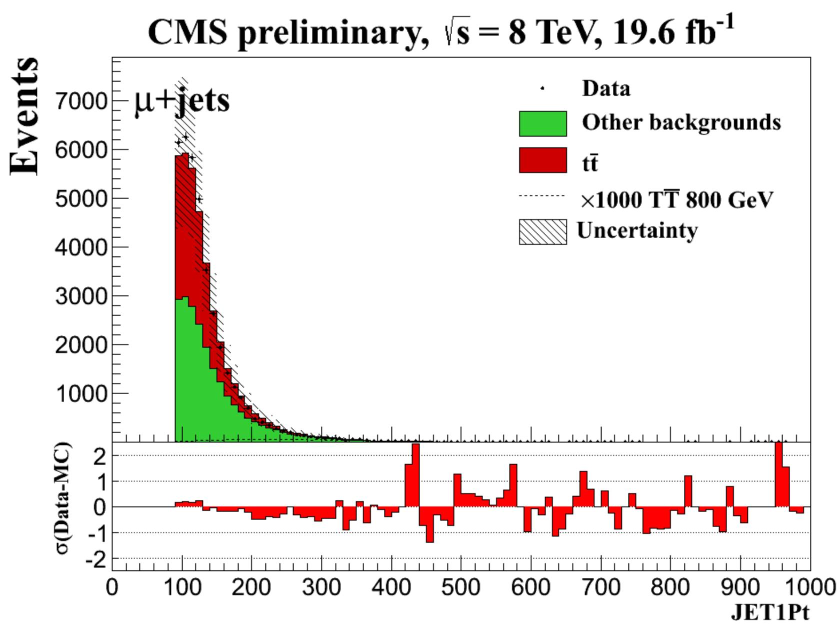
Jet 1 **Jet 2**

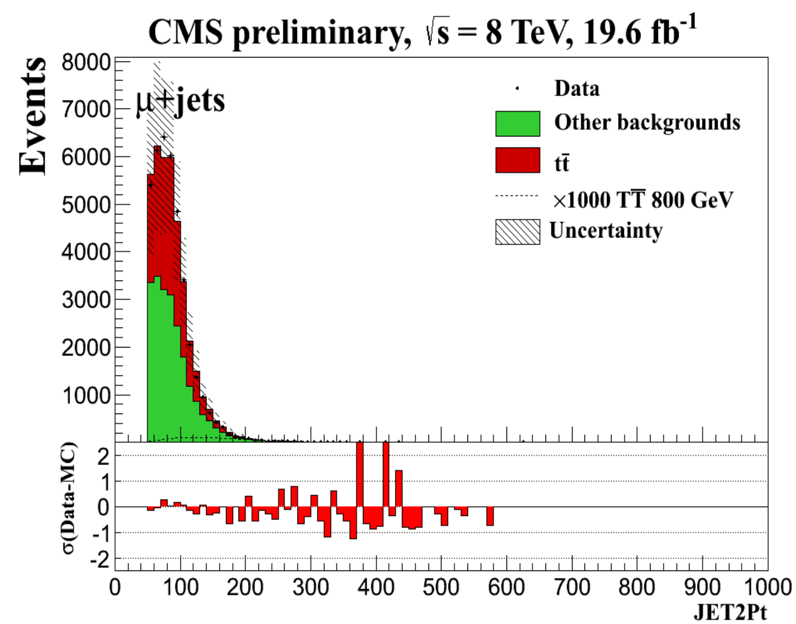
⩾ 1 W jet





no W jet





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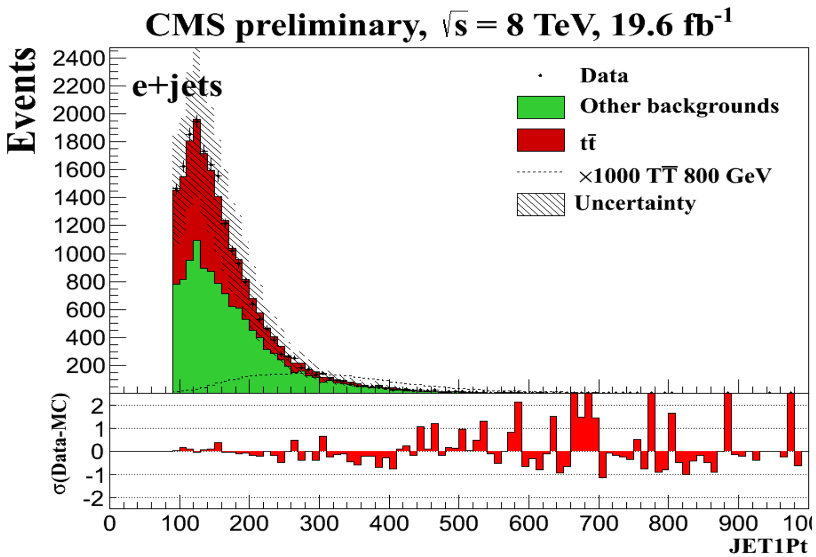
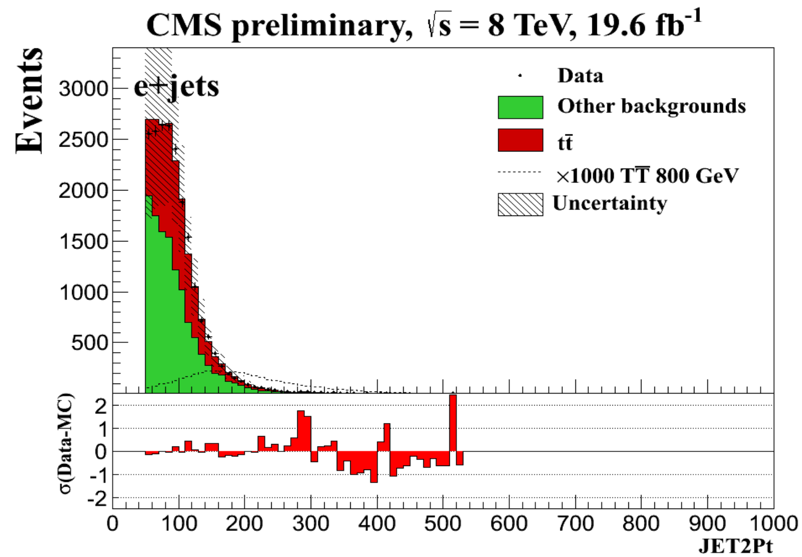
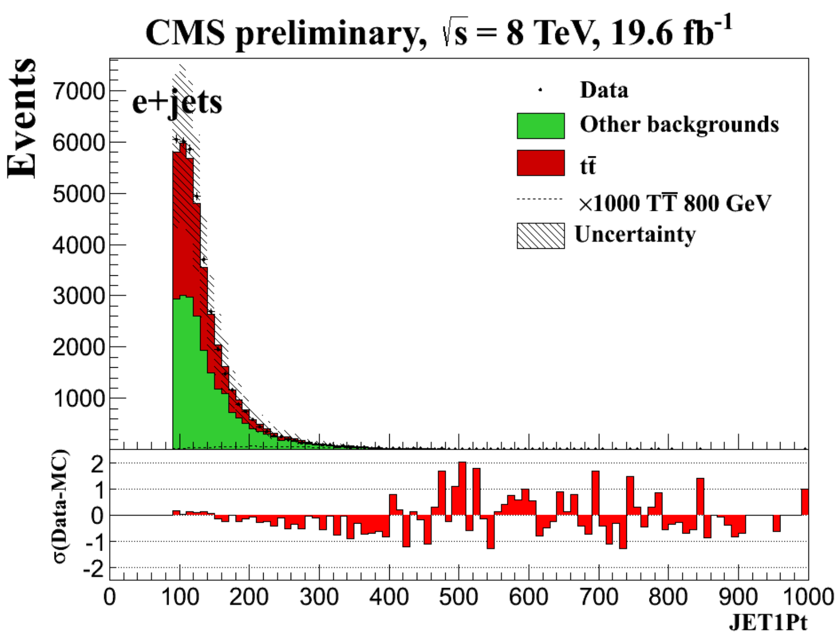
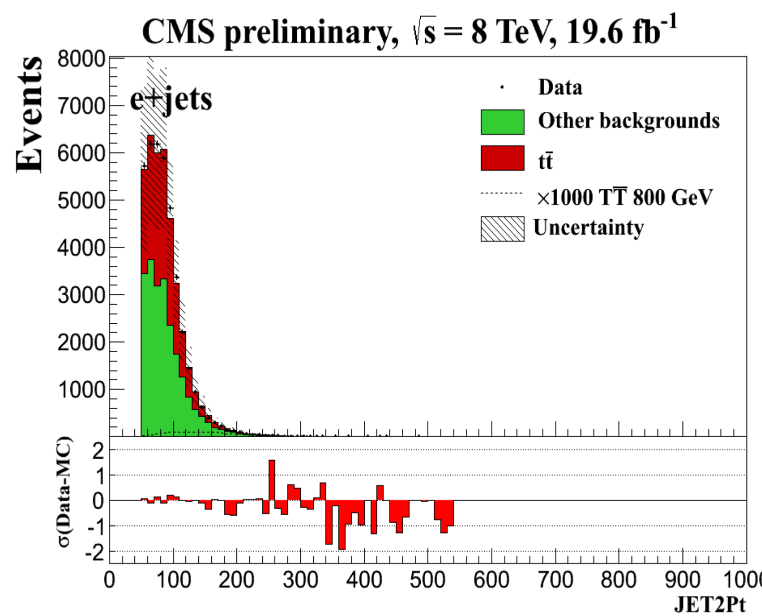


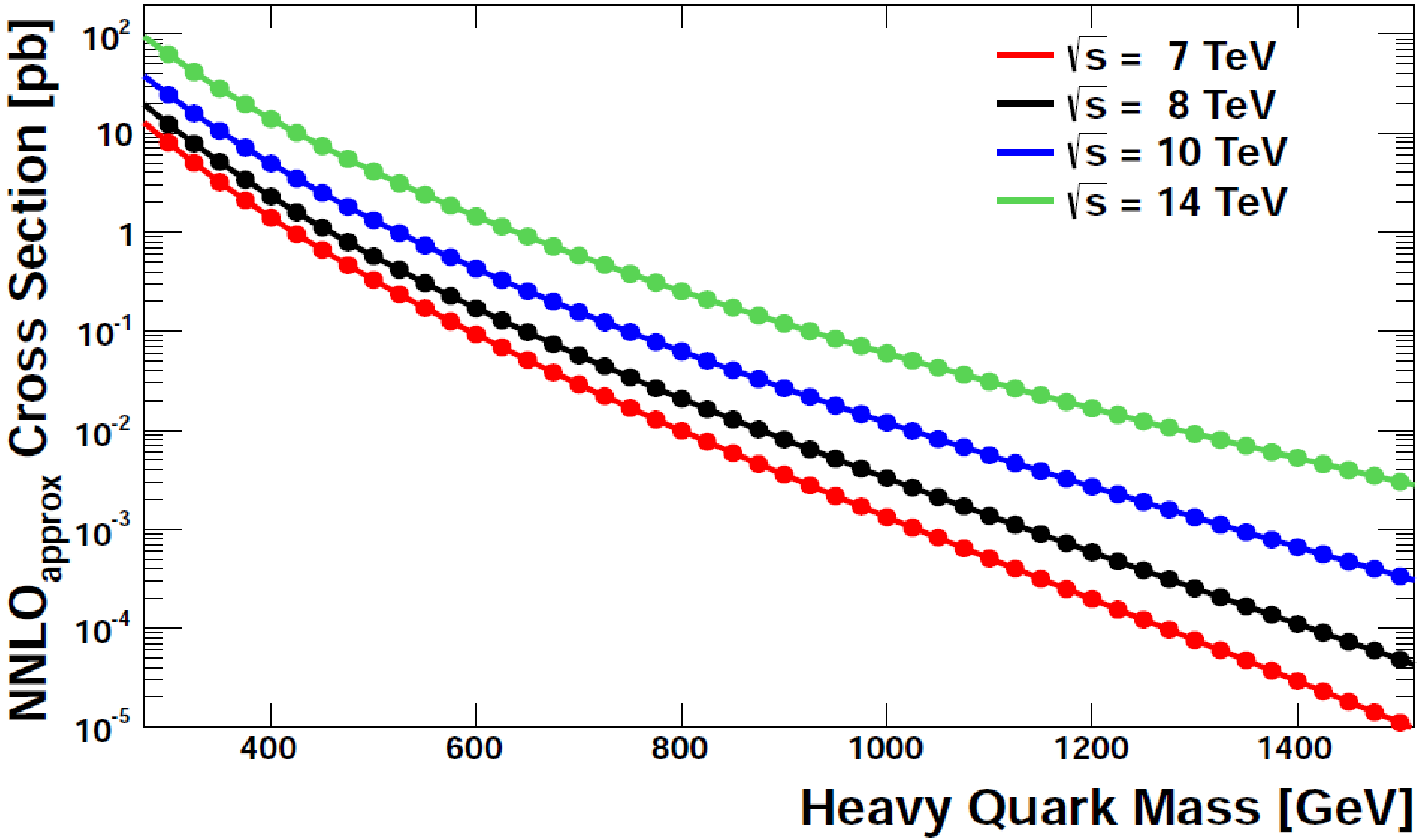


no W jet





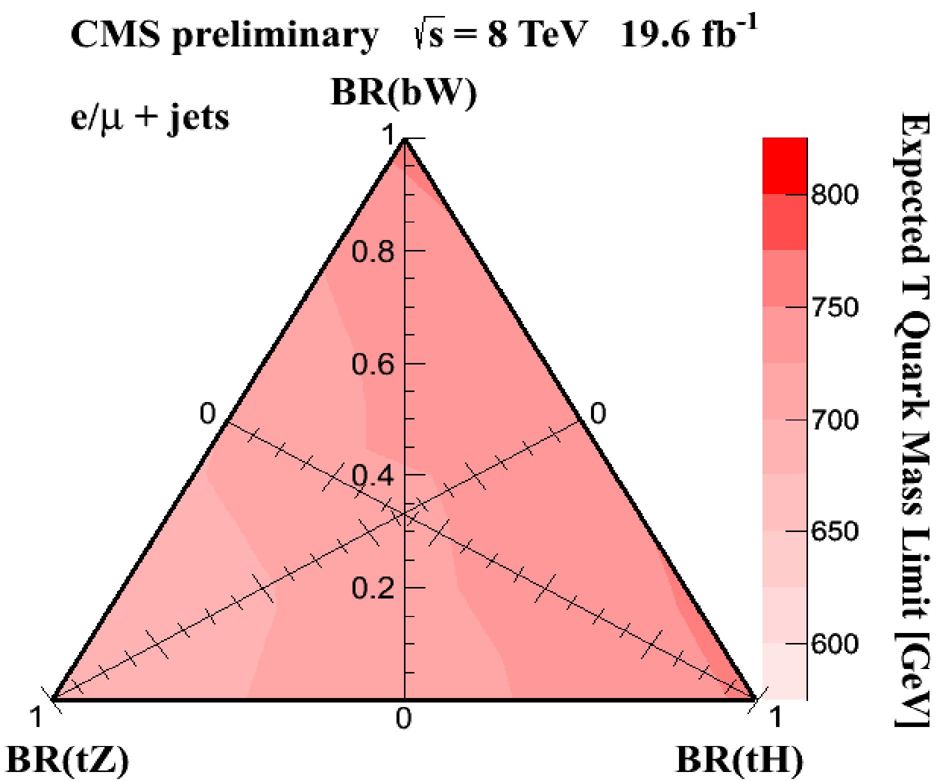
T signal approximate NNLO cross sections (HATHOR)



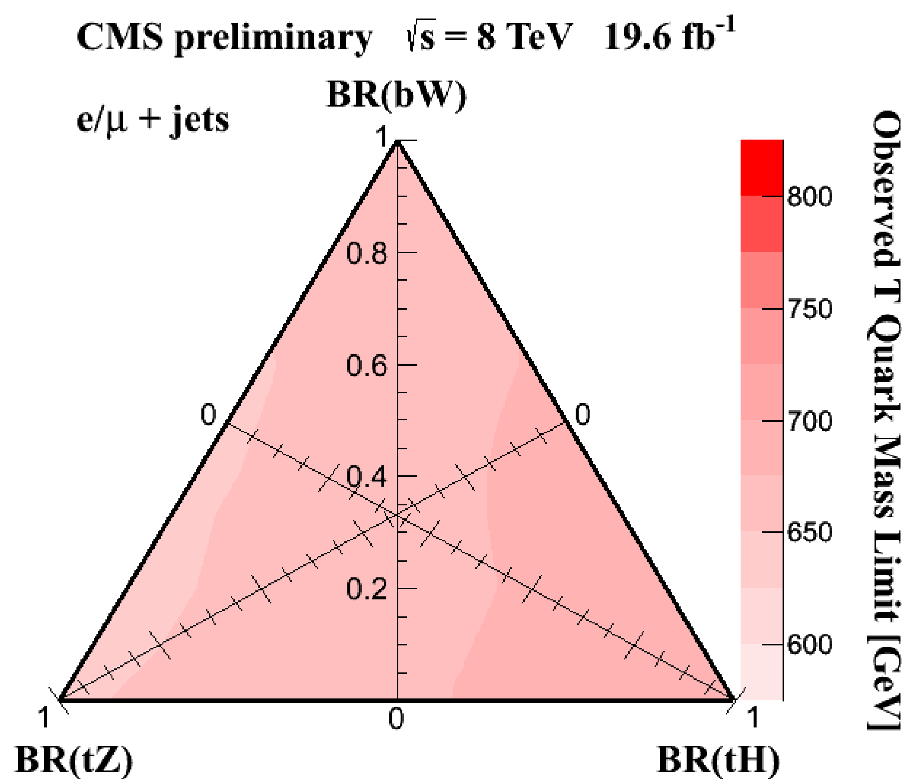
Limits represented in branching-fraction triangles

Single-lepton channel

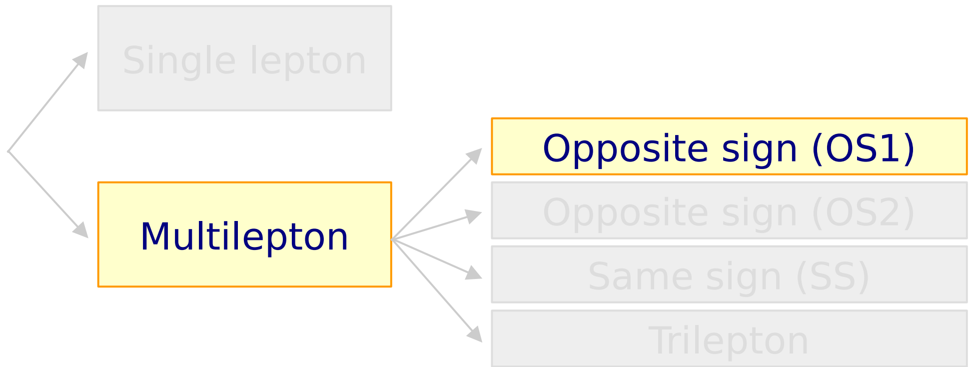
Expected



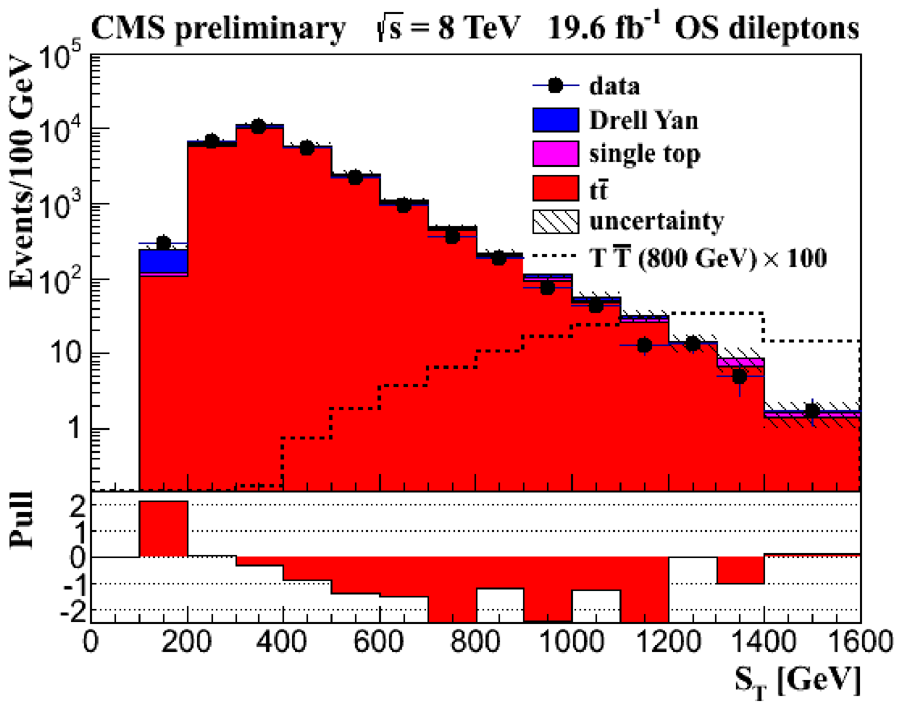
Observed



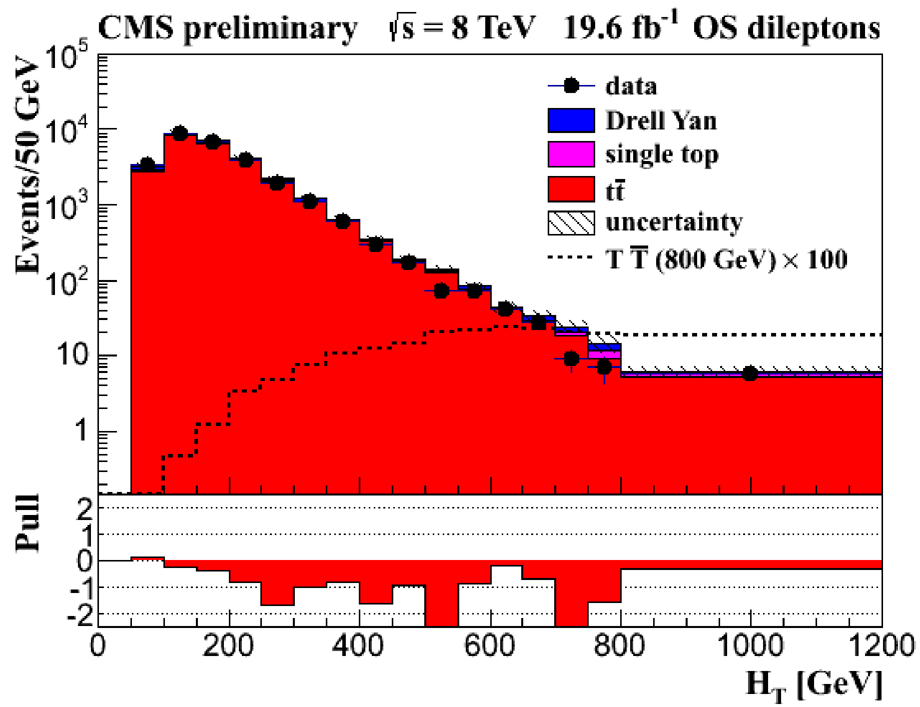
Multilepton channel: opposite-sign dileptons



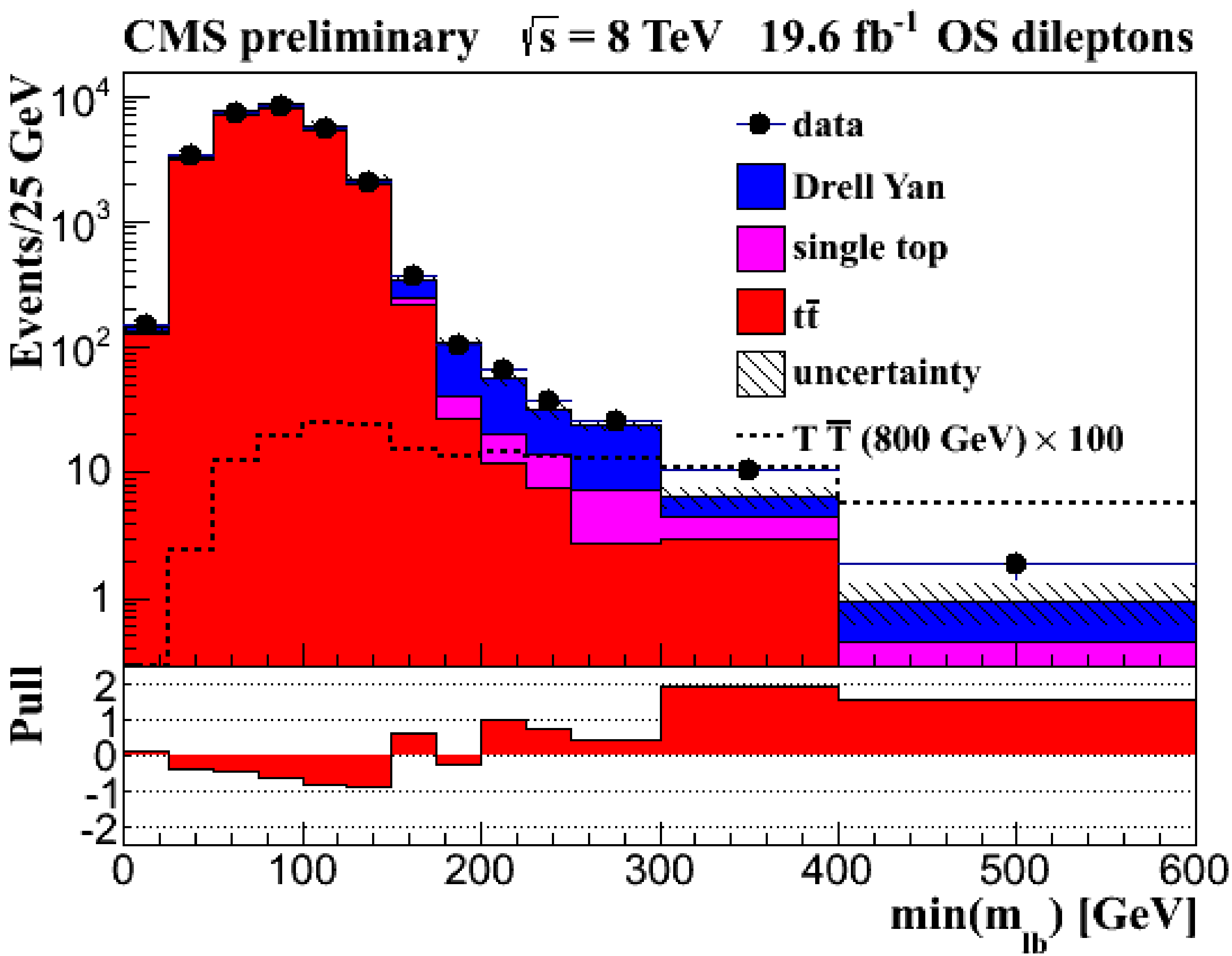
S_T



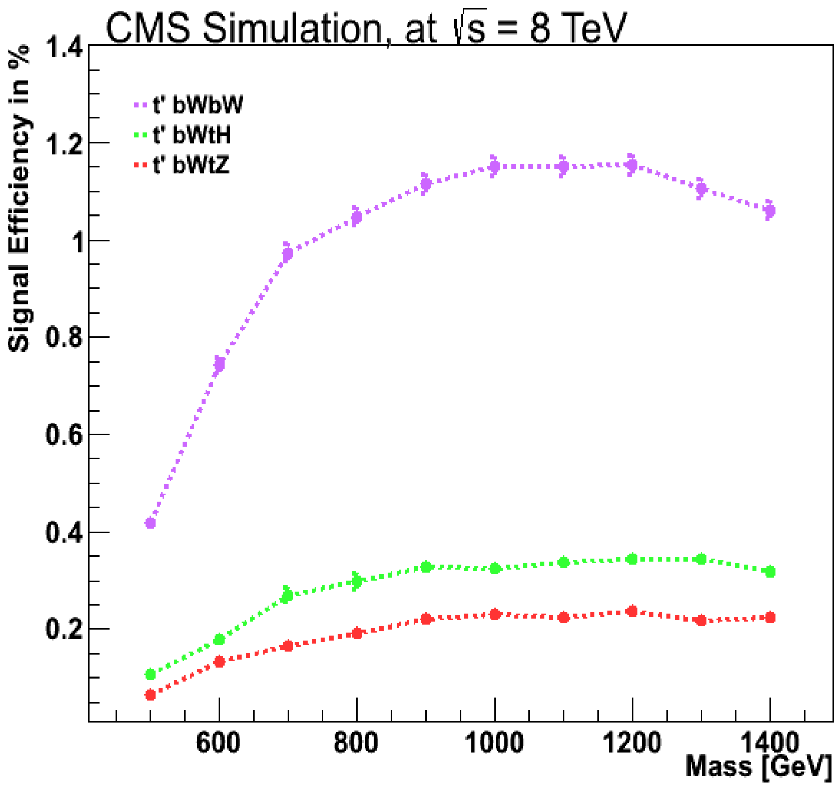
H_T

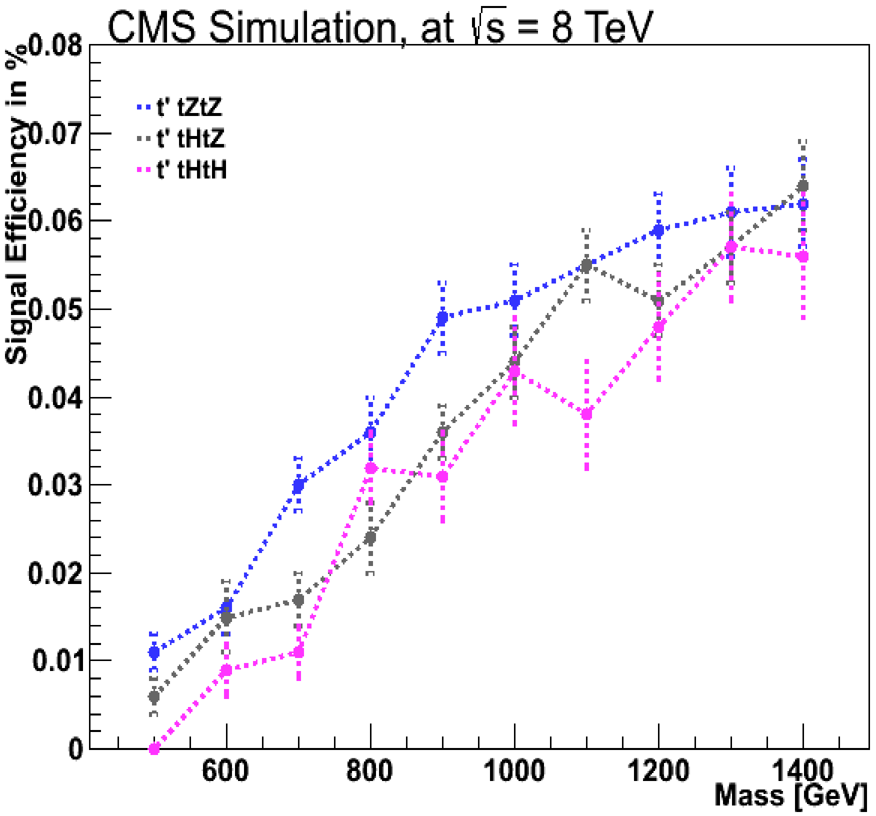


Multilepton channel: opposite-sign dileptons (OS1)

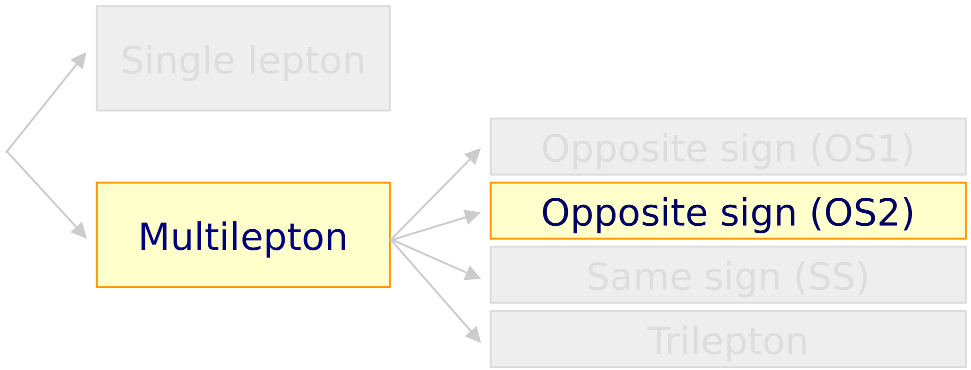


Signal efficiency vs T mass (OS1)

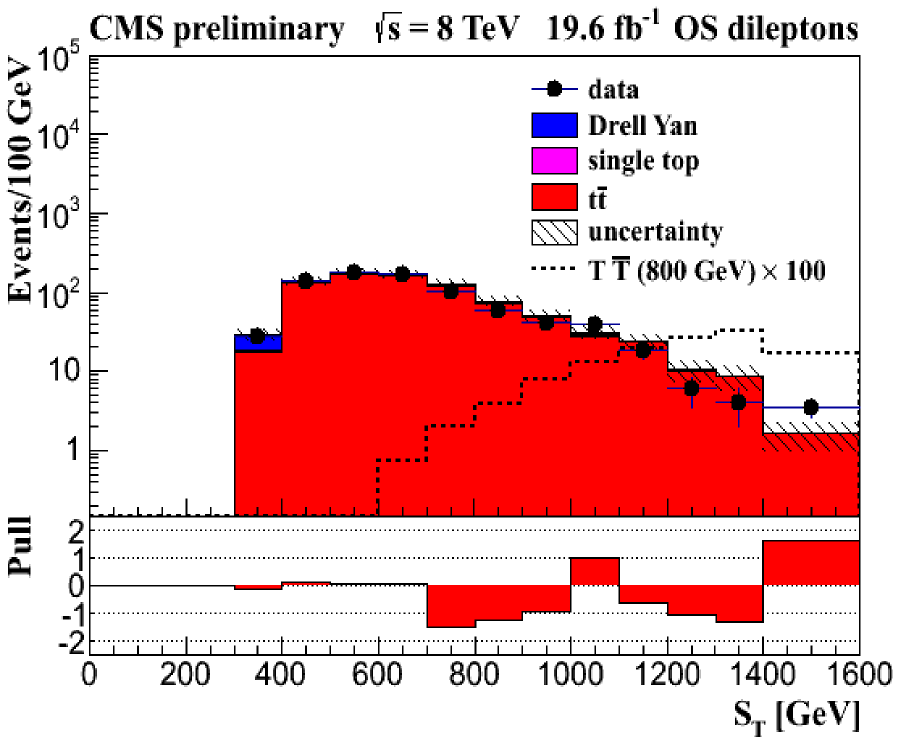




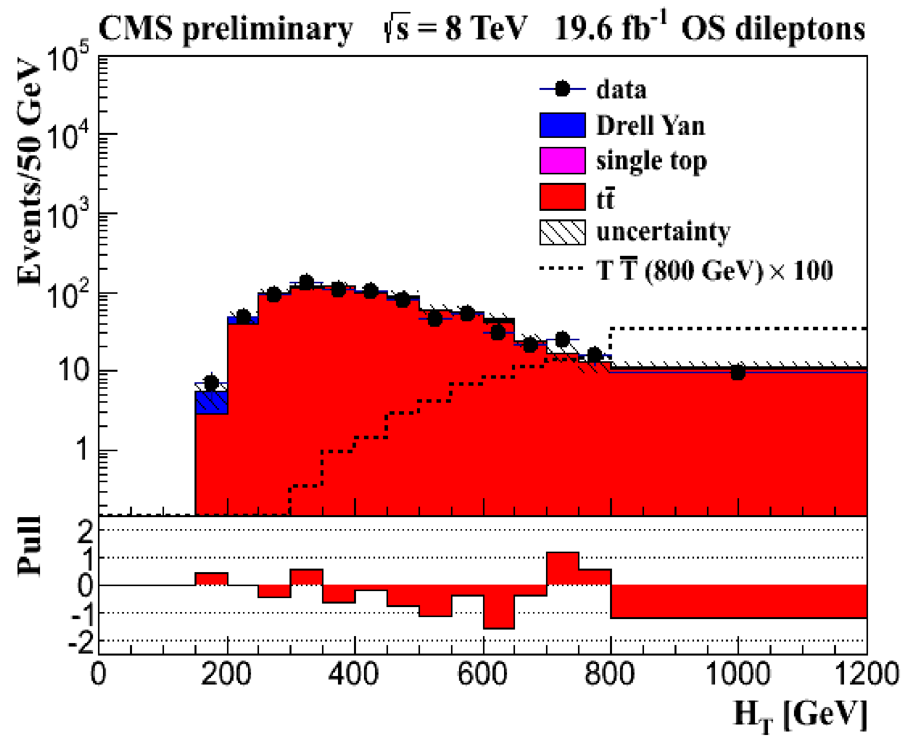
Multilepton channel: opposite-sign dileptons



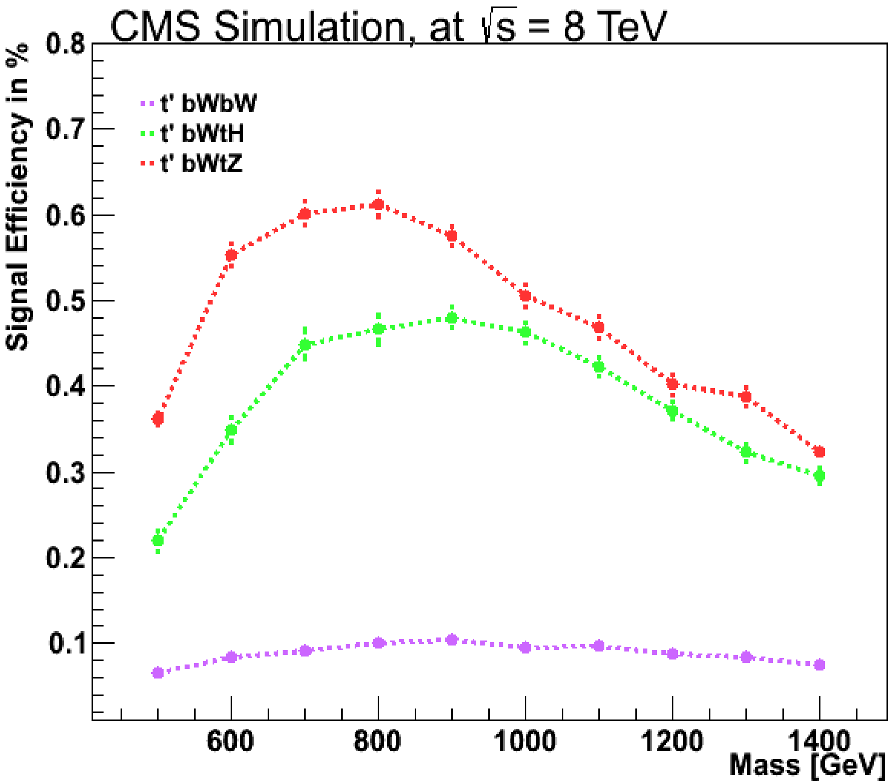
S_T

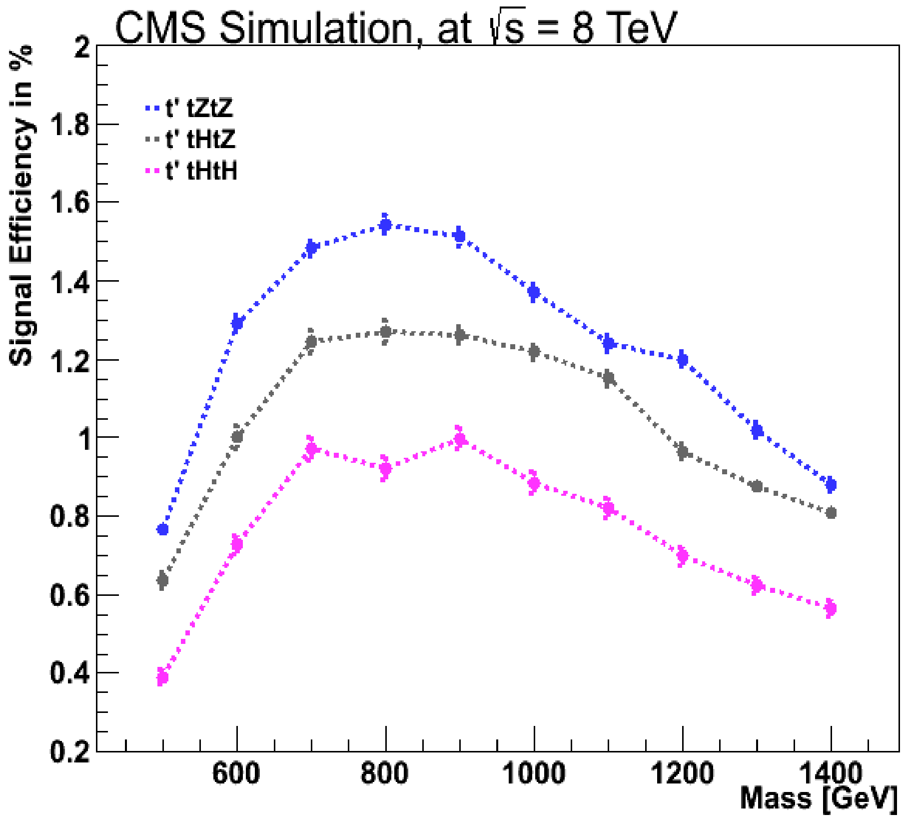


H_T

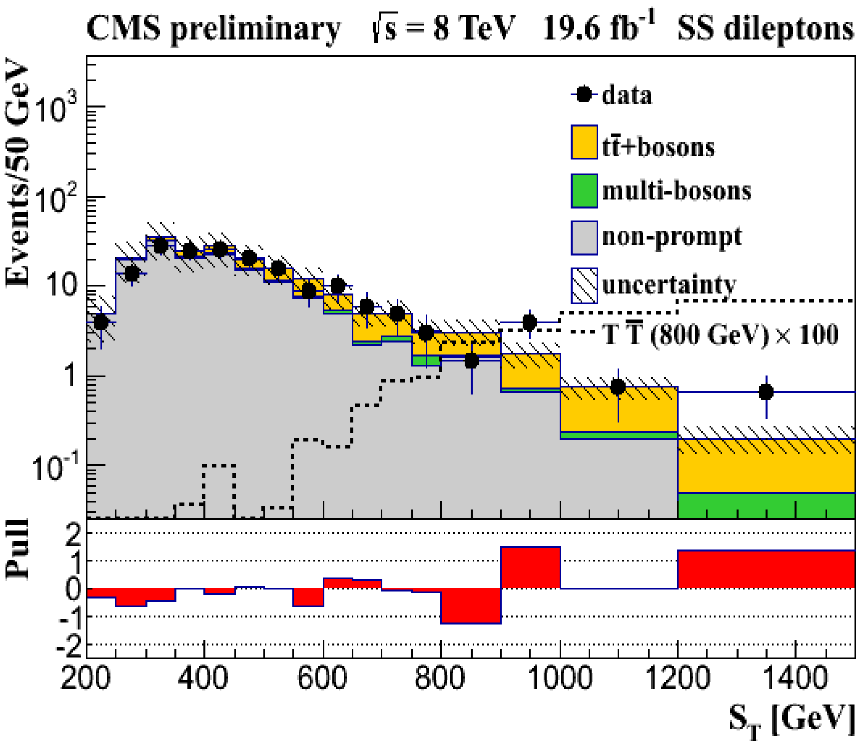


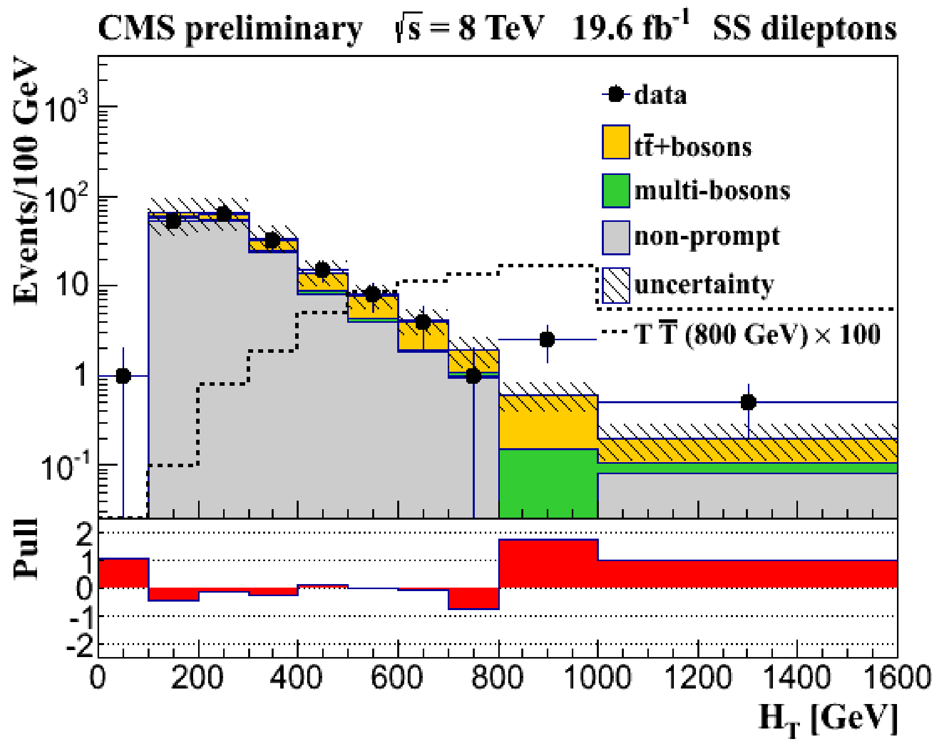
Signal efficiency vs T mass (OS2)



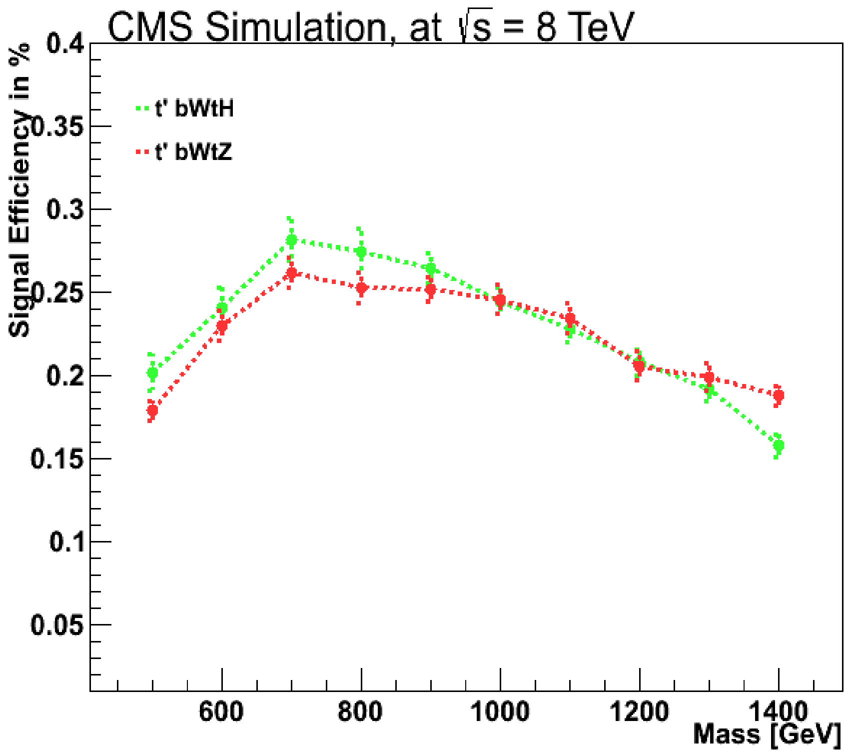


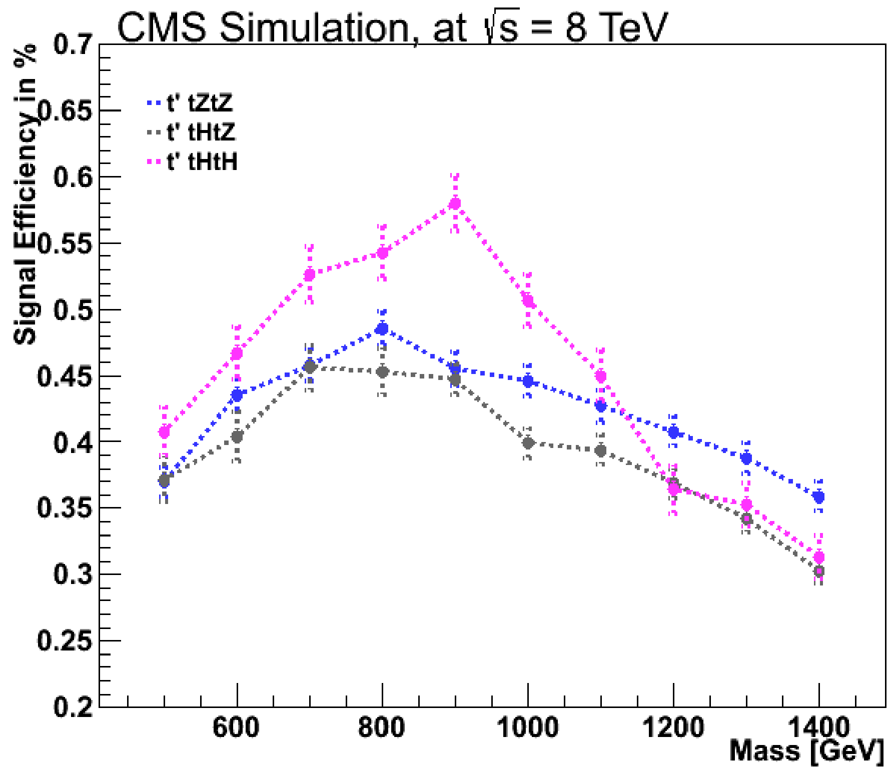
Same-sign dilepton channel



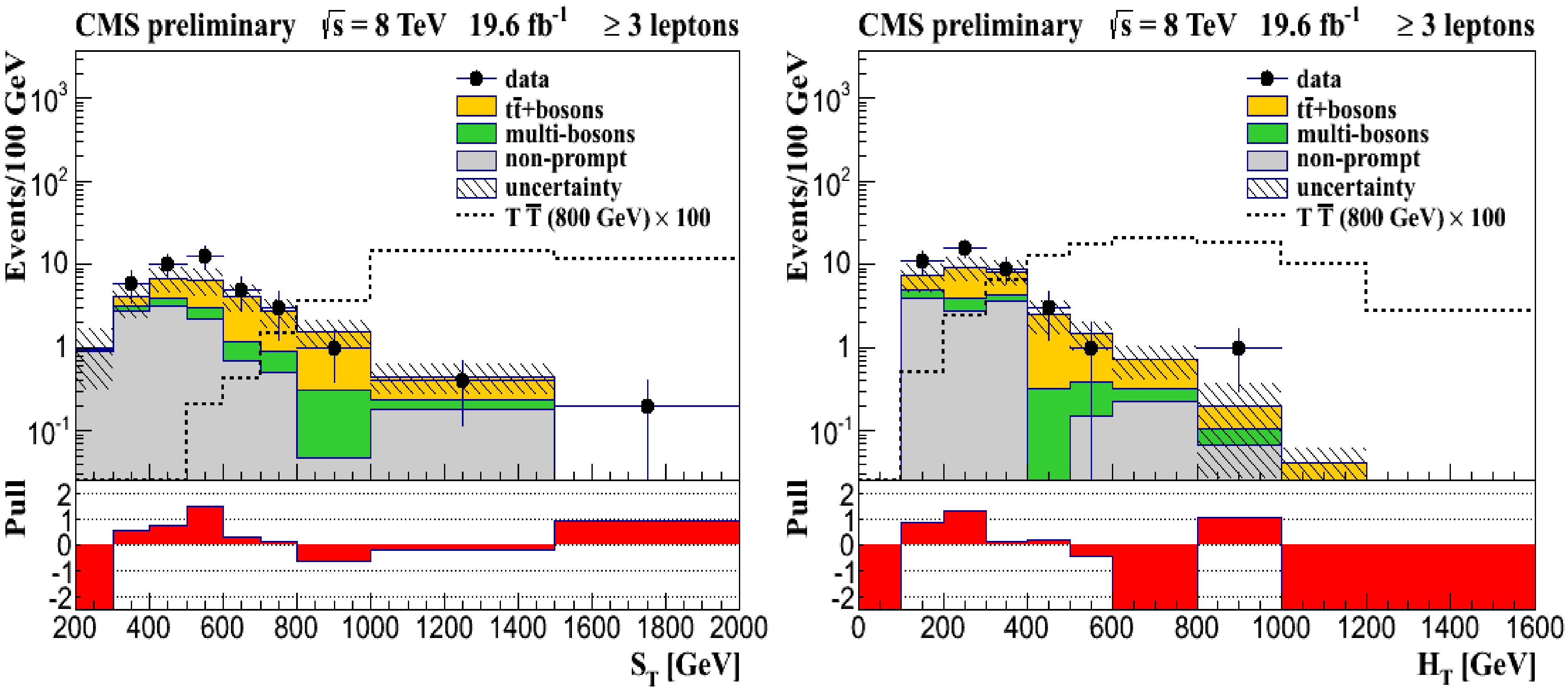


Signal efficiency vs T mass (same-sign dilepton)

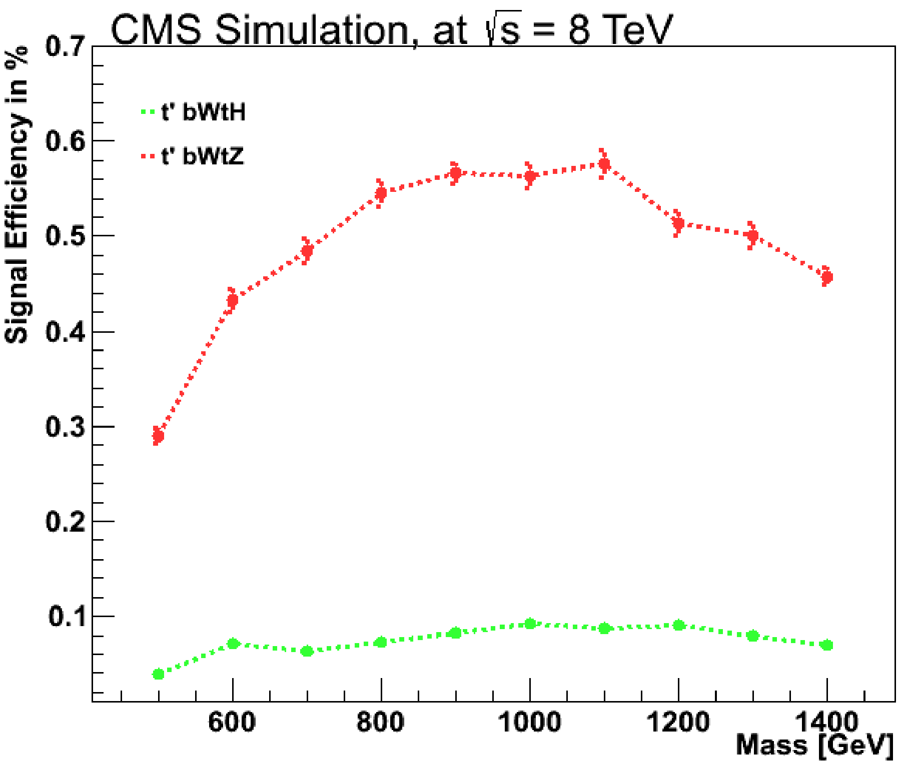


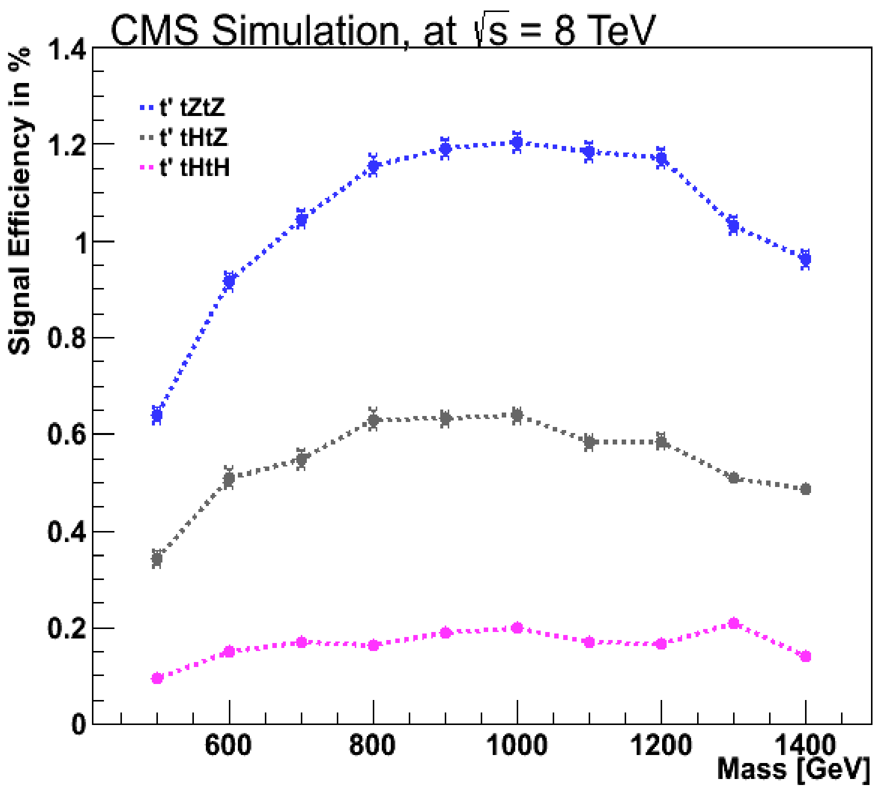


Trilepton channel

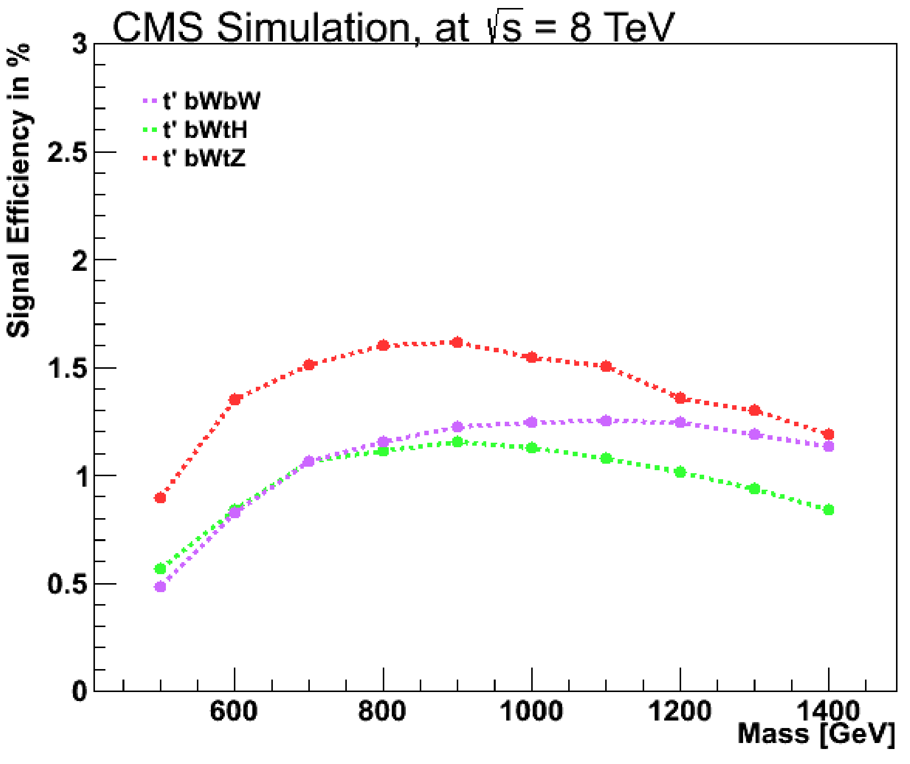


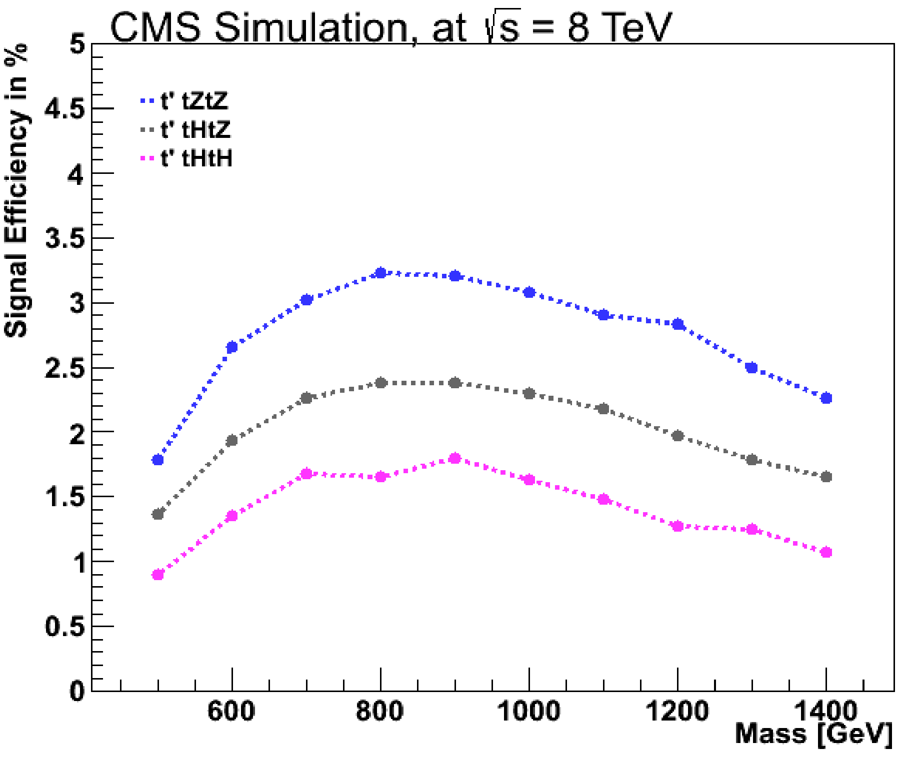
Signal efficiency vs T mass (trilepton)



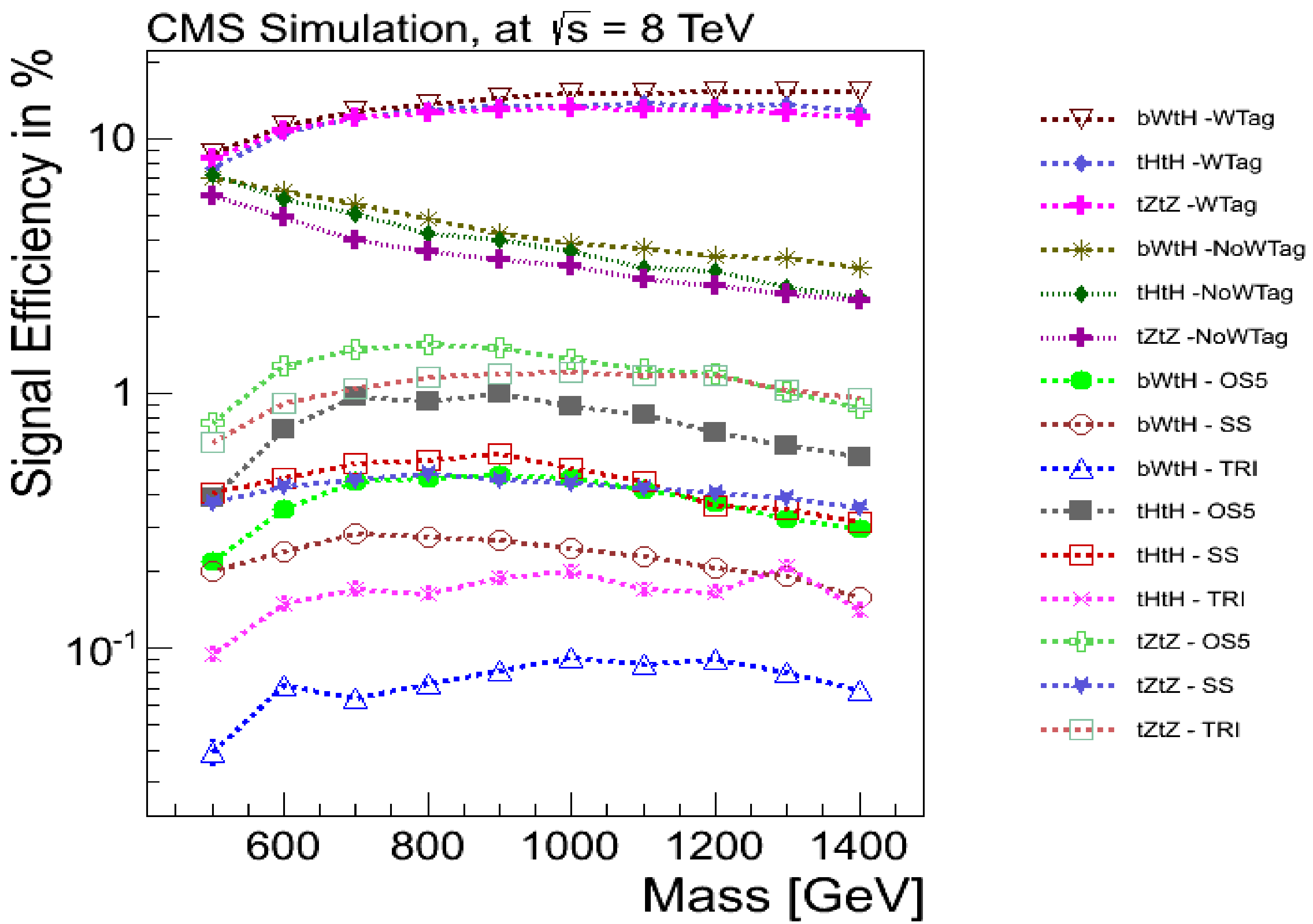


Signal efficiency vs T mass (multilepton)

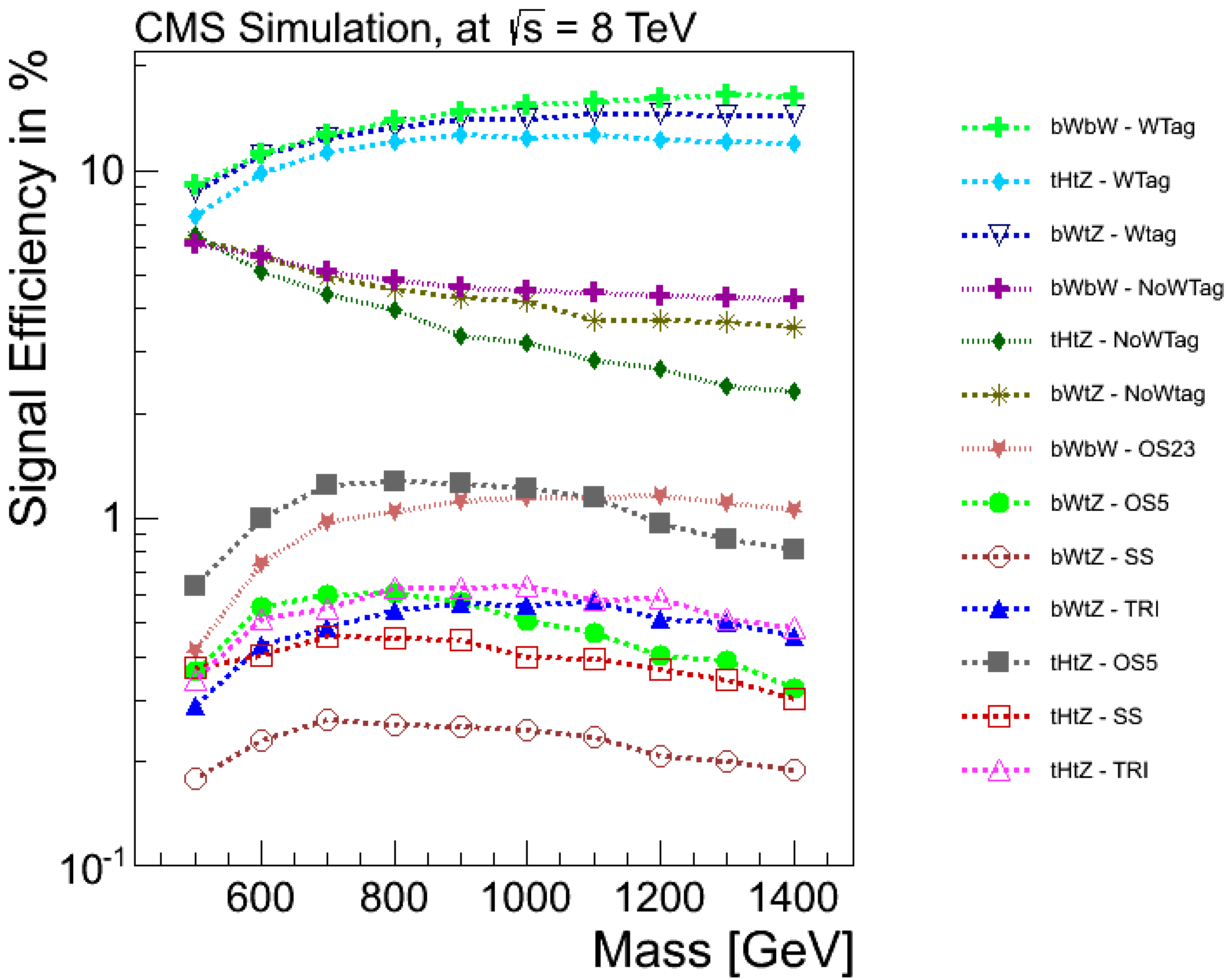




Signal efficiency vs T mass (multilepton + lepton+jets [1])

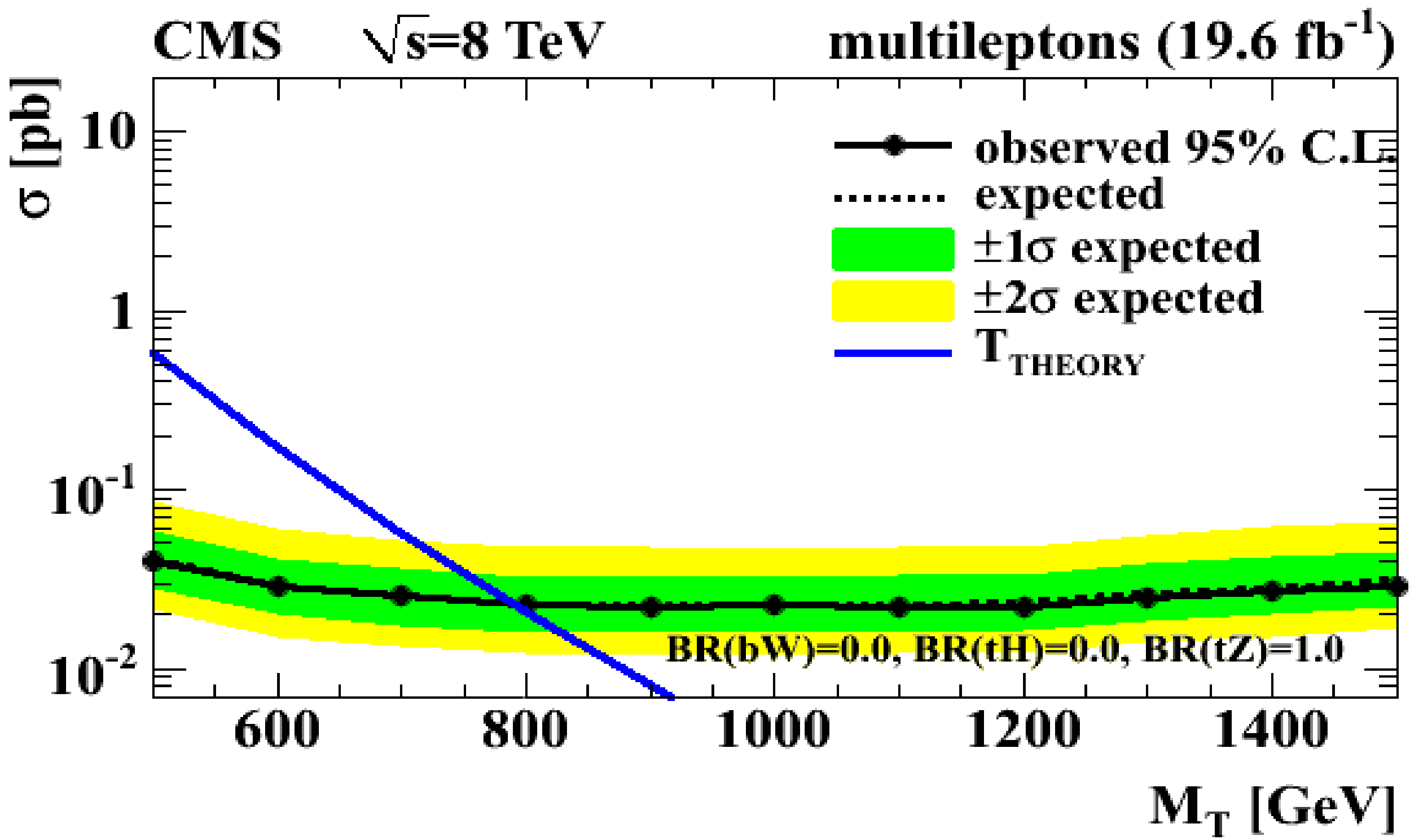


Signal efficiency vs T mass (multilepton + lepton+jets [2])



Mass limits on vector-like T (charge 2/3) quarks in multilepton channel

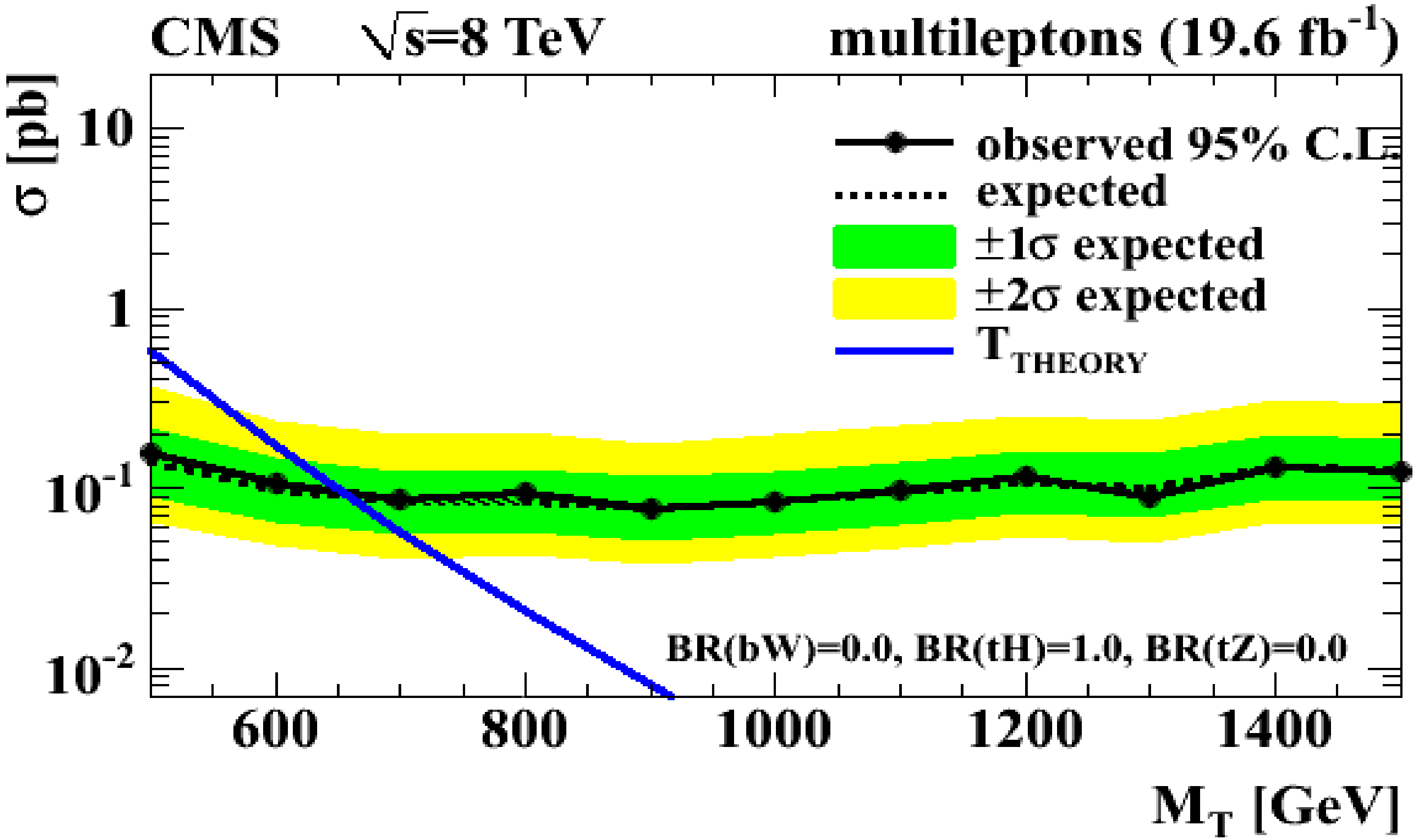
- Figure: assuming 100% branching fraction to tZ
  BF(T → tZ) = 100%, BF(T → bW) = BF(T → tH) = 0%



Mass limits on vector-like T (charge 2/3) quarks in multilepton channel

- Figure: assuming 100% branching fraction to tH

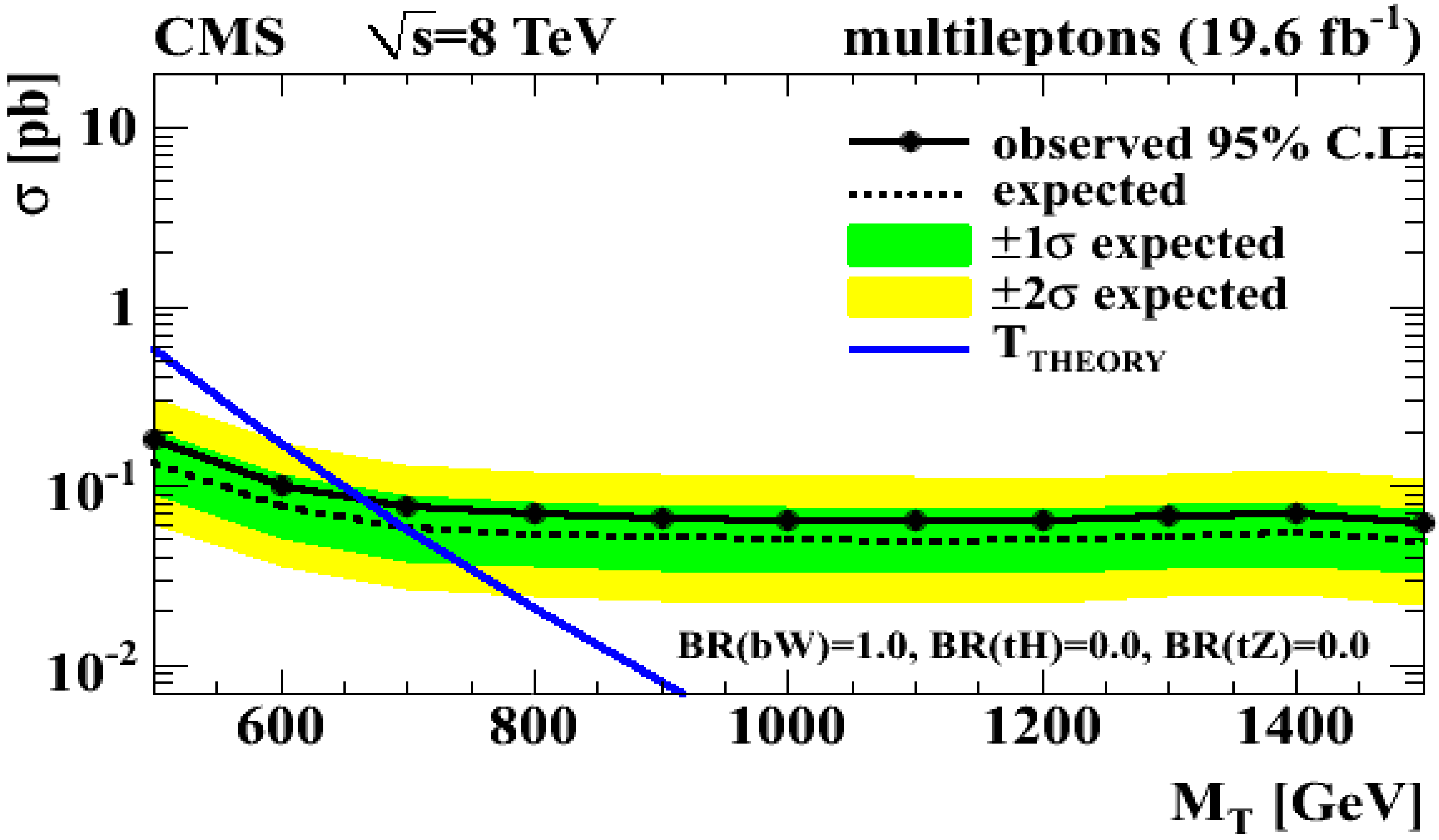
  BF(T → tH) = 100%, BF(T → bW) = BF(T → tZ) = 0%



Mass limits on vector-like T (charge 2/3) quarks in multilepton channel

- Figure: assuming 100% branching fraction to bW

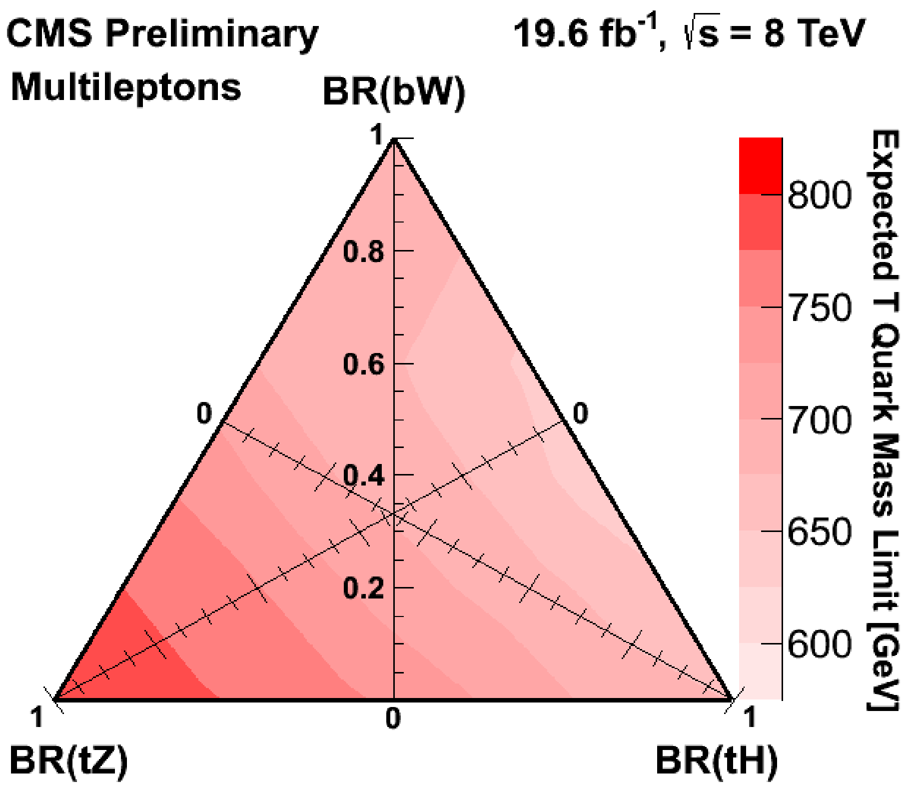
  BF(T → bW) = 100%, BF(T → tH) = BF(T → tZ) = 0%



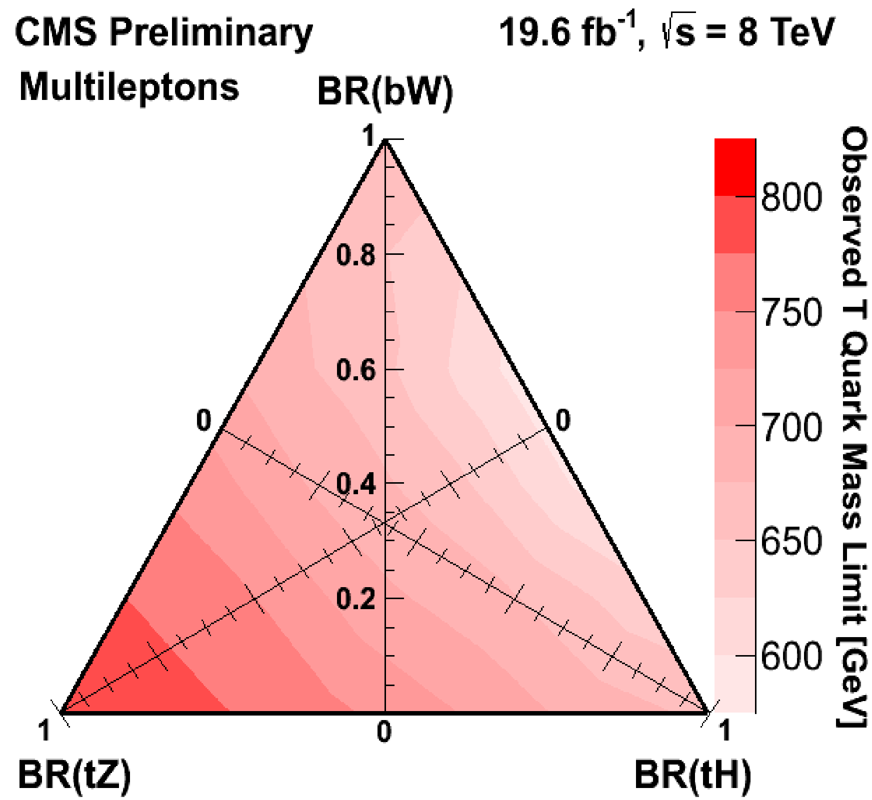
Limits represented in branching-fraction triangles

Single-lepton channel

Expected

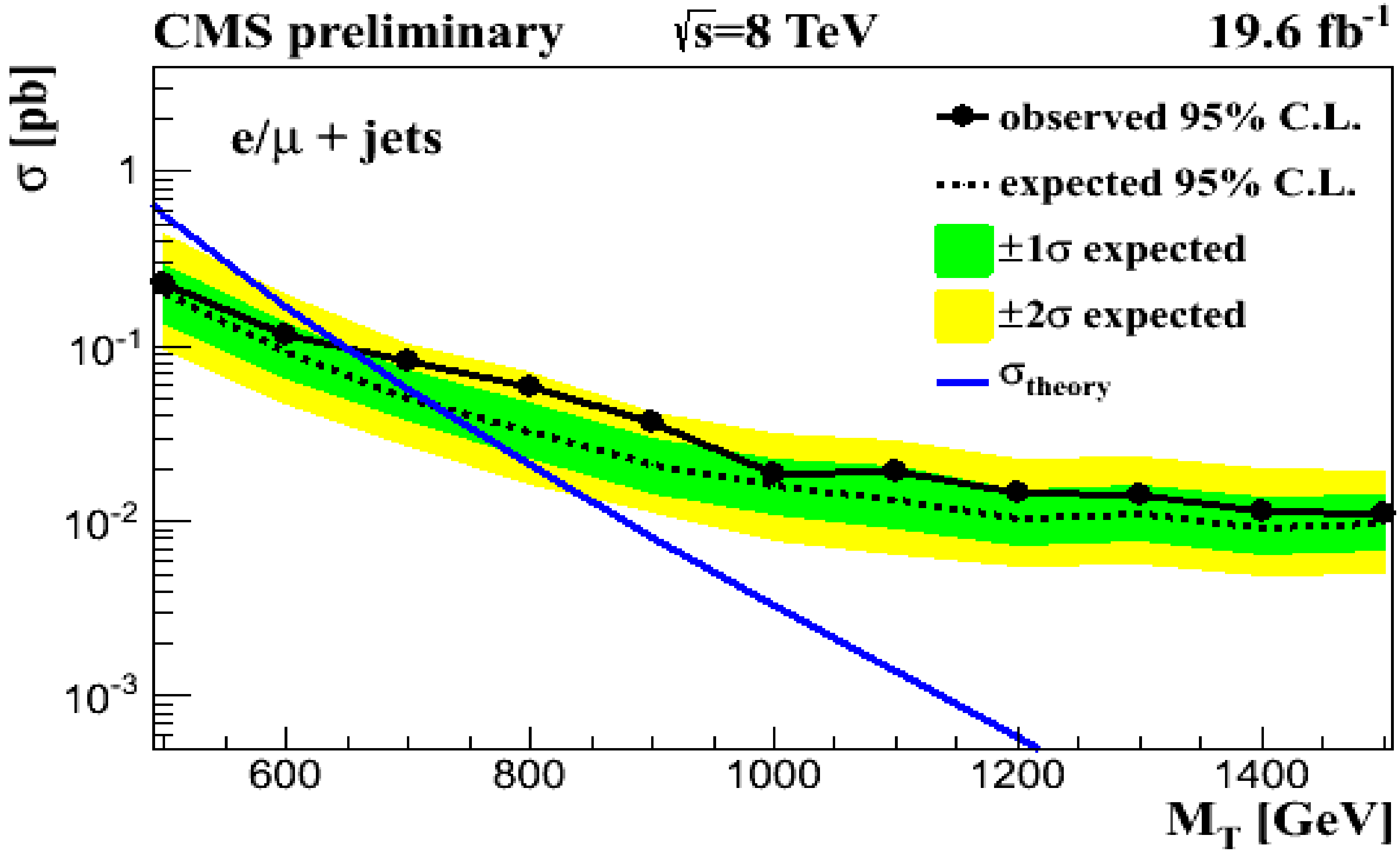


Observed



Mass limits on vector-like T (charge 2/3) quarks in lepton+jets channel

- Figure: assuming 'nominal' branching fractions
  BF(T → bW) = 50%, BF(T → tZ) = BF(T → tH) = 25%

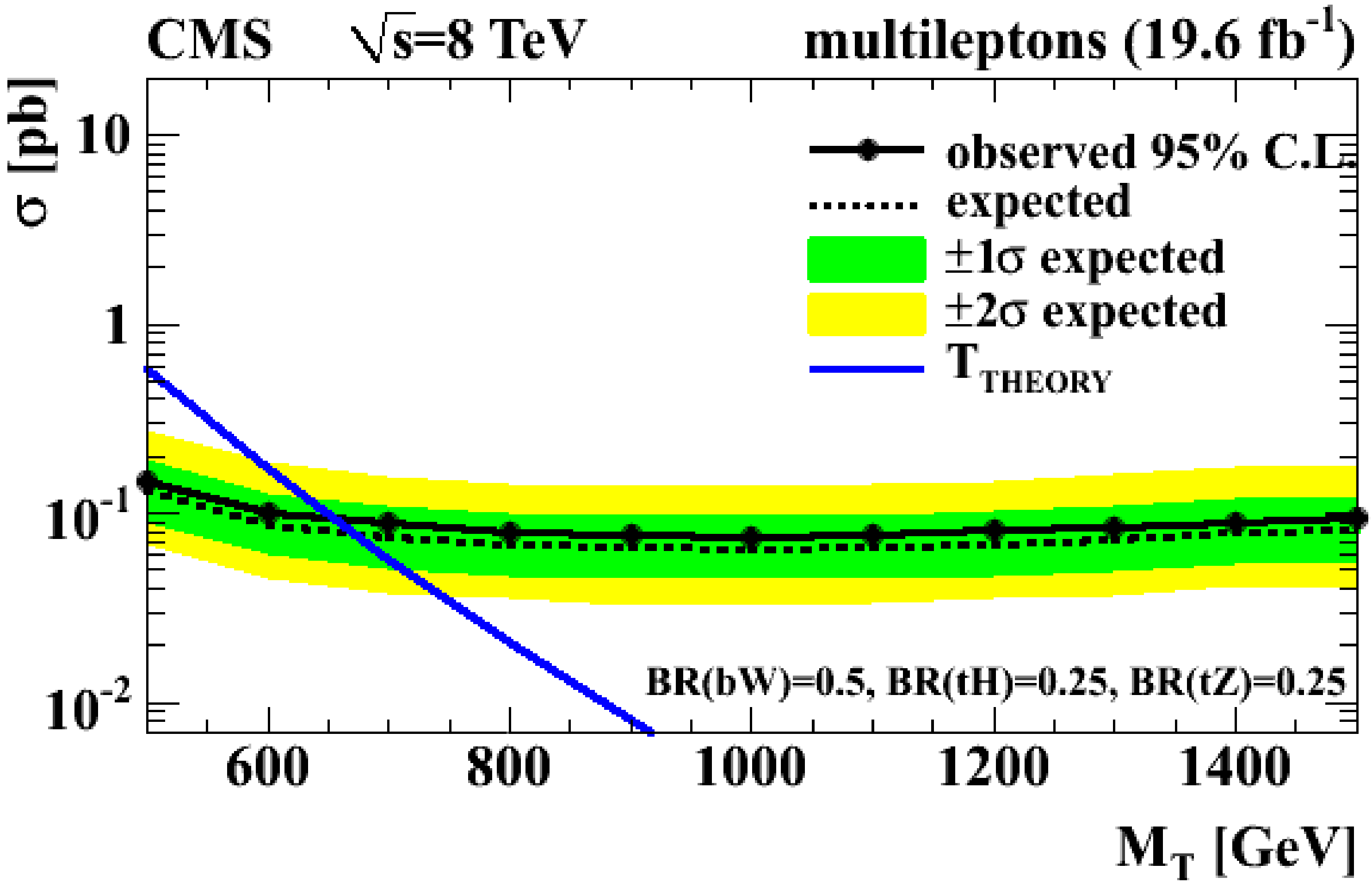


Scanning branching fractions in lepton+jets channel

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

Mass limits on vector-like T (charge 2/3) quarks in multilepton channel

- Figure: assuming 'nominal' branching fractions
  BF(T → bW) = 50%, BF(T → tZ) = BF(T → tH) = 25%

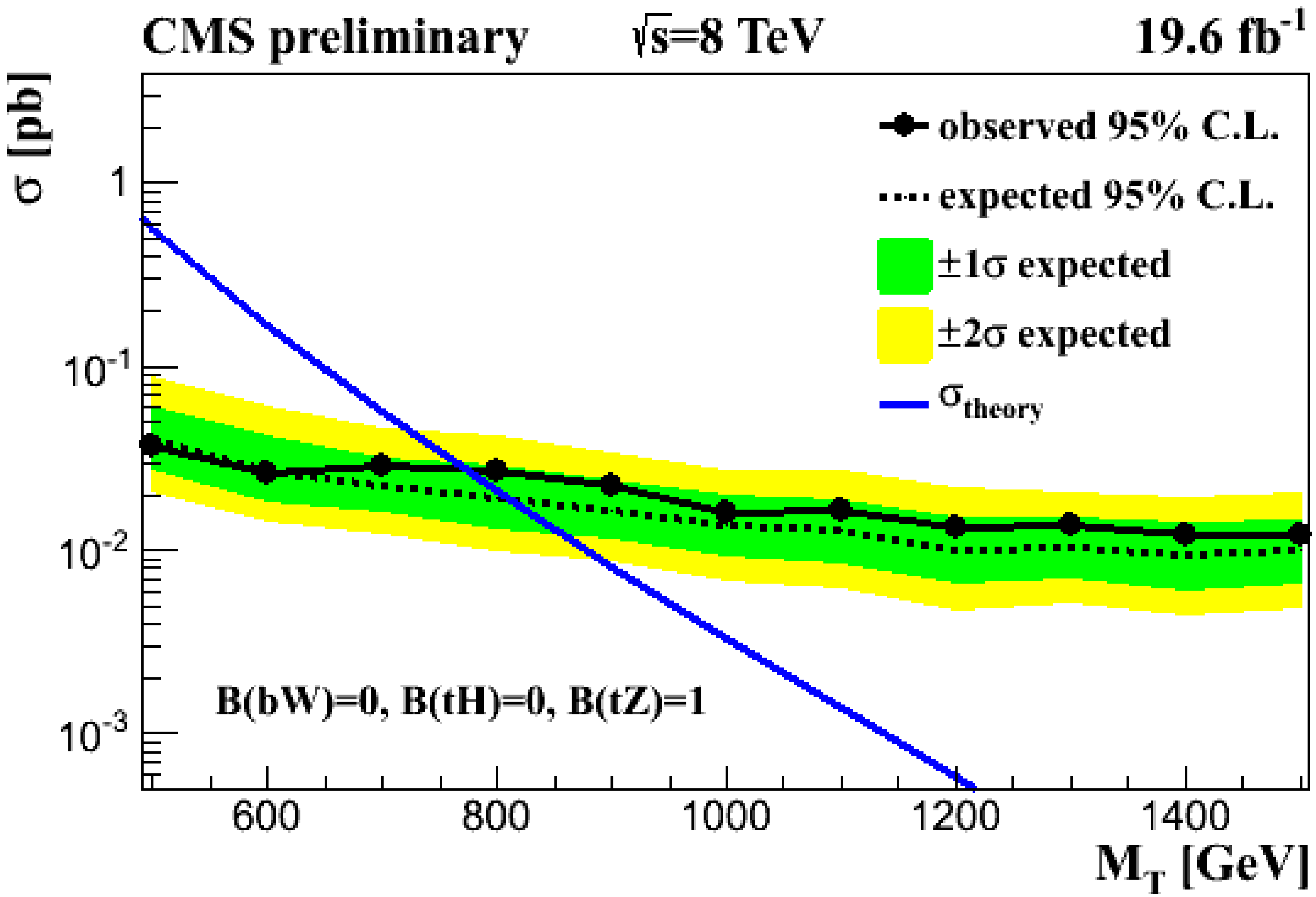


Scanning branching fractions in multilepton channel

	Branching Fractions			expected	observed
Scenario	T→bW	T→tH	T→tZ	limit	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

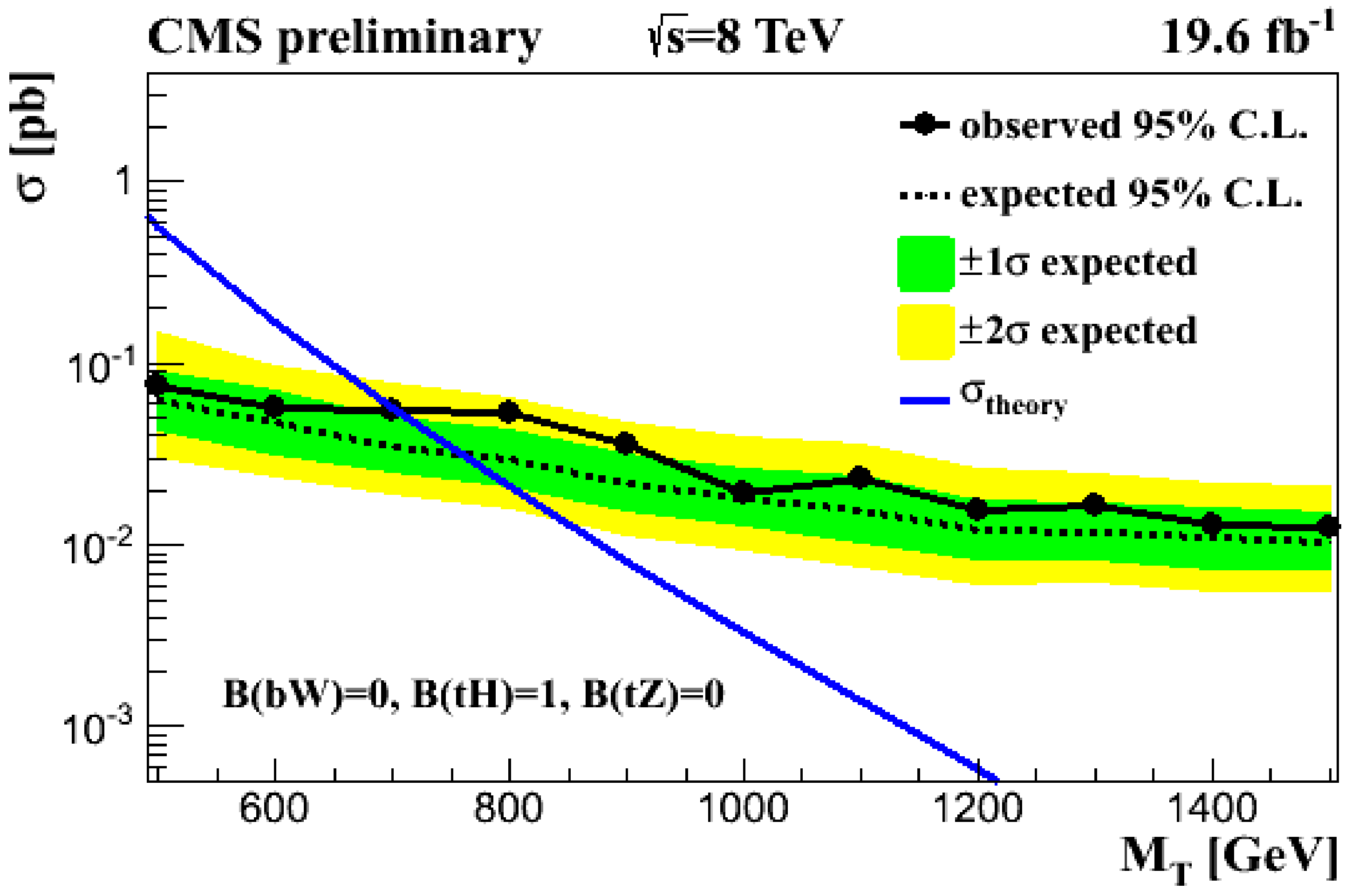
Mass limits on vector-like T (charge 2/3) quarks with all channels

- Figure: assuming 100% branching fraction to tZ
  BF(T → tZ) = 100%, BF(T → bW) = BF(T → tH) = 0%



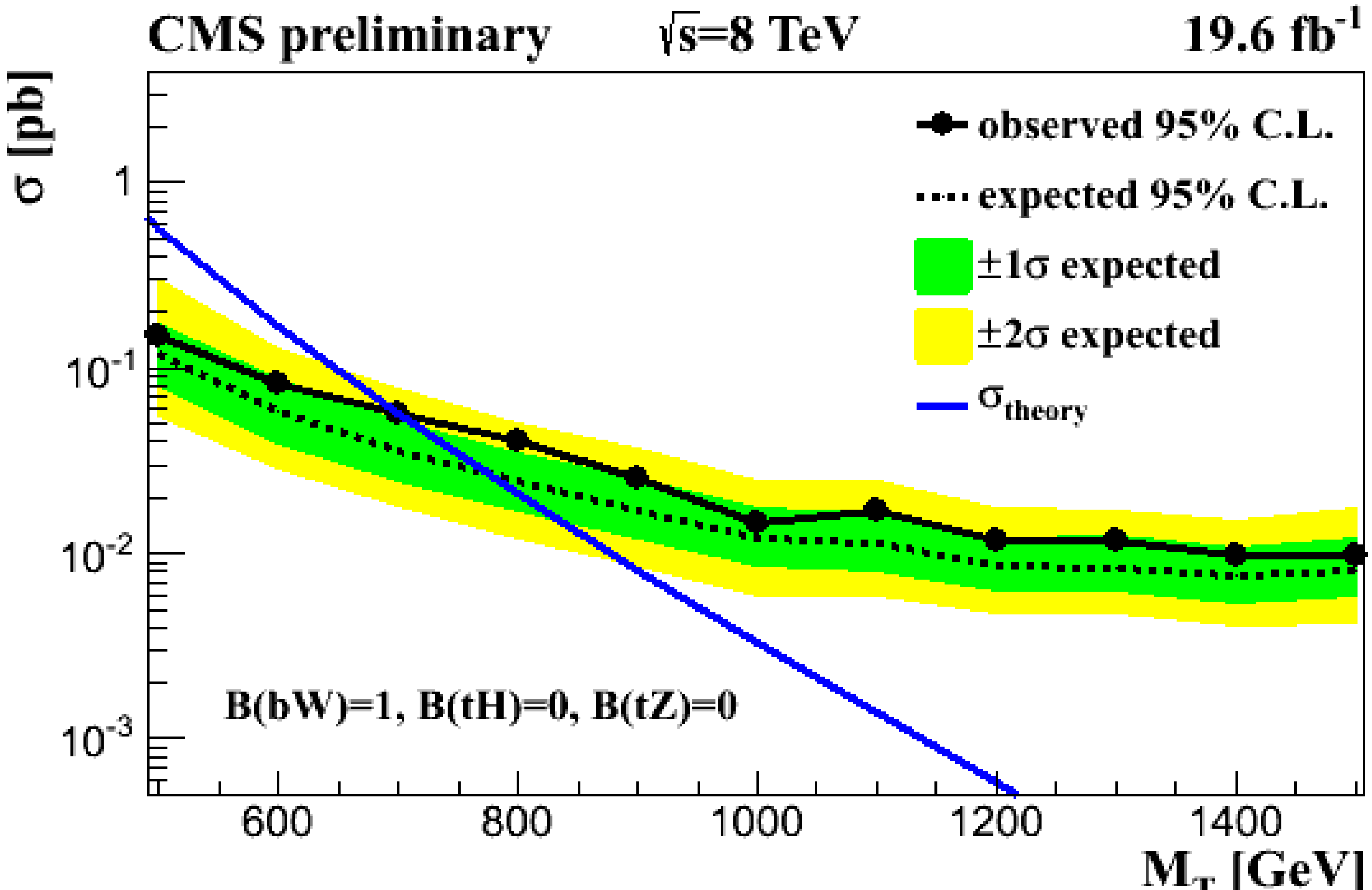
Mass limits on vector-like T (charge 2/3) quarks with all channels

- Figure: assuming 100% branching fraction to tH
  BF(T → tH) = 100%, BF(T → bW) = BF(T → tZ) = 0%



Mass limits on vector-like T (charge 2/3) quarks with all channels

- Figure: assuming 100% branching fraction to bW
  BF(T → bW) = 100%, BF(T → tH) = BF(T → tZ) = 0%



Number of selected events (OS1)

Sample	$\mu\mu$	$e\mu$	ee	Sum
Signal:				
Tprime500 BWTZ	2.52 ± 0.28	3.50 ± 0.33	1.47 ± 0.19	7.49 ± 0.59
Tprime500 TZTZ	0.44 ± 0.13	0.50 ± 0.13	0.27 ± 0.10	1.21 ± 0.22
Tprime500 THTZ	0.02 ± 0.02	0.39 ± 0.20	0.20 ± 0.14	0.62 ± 0.25
Tprime500 THTH	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Tprime500 BWTH	3.98 ± 0.61	5.38 ± 0.73	2.50 ± 0.48	11.86 ± 1.20
Tprime500 BWBW	13.66 ± 1.07	22.63 ± 1.60	10.39 ± 0.86	46.68 ± 3.06
Summed Signal (Nominal BR):				16.66
Tprime800 BWTZ	0.19 ± 0.02	0.39 ± 0.03	0.19 ± 0.02	0.78 ± 0.06
Tprime800 TZTZ	0.05 ± 0.01	0.07 ± 0.01	0.03 ± 0.01	0.15 ± 0.02
Tprime800 THTZ	0.03 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.10 ± 0.02
Tprime800 THTH	0.04 ± 0.02	0.08 ± 0.02	0.01 ± 0.01	0.13 ± 0.03
Tprime800 BWTH	0.41 ± 0.04	0.56 ± 0.05	0.25 ± 0.03	1.22 ± 0.09
Tprime800 BWBW	1.28 ± 0.08	2.11 ± 0.13	0.88 ± 0.06	4.27 ± 0.26
Summed Signal (Nominal BR):				1.60
Backgrounds:				
TTbar	0.69 ± 0.69	3.00 ± 1.39	1.50 ± 1.08	5.19 ± 1.95
SingleTop	0.99 ± 0.73	1.05 ± 0.77	0.51 ± 0.52	2.54 ± 1.25
DrellYan	6.64 ± 1.99	0.00 ± 0.00	3.03 ± 0.91	9.67 ± 2.90
Total Background	8.31 ± 2.23	4.04 ± 1.59	5.05 ± 1.50	17.40 ± 3.71
Data	7.00	6.00	7.00	20.00

Signal efficiency (OS1)

t' Mass	Decay channel					
	$bWtZ$	$tZtZ$	$tHtZ$	$tHtH$	$bWtH$	$bWbW$
500 GeV	0.067 ± 0.004	0.011 ± 0.002	0.006 ± 0.002	0.000 ± 0.000	0.106 ± 0.009	0.418 ± 0.012
600 GeV	0.132 ± 0.007	0.016 ± 0.003	0.015 ± 0.004	0.009 ± 0.003	0.179 ± 0.012	0.742 ± 0.016
700 GeV	0.165 ± 0.008	0.030 ± 0.003	0.017 ± 0.003	0.011 ± 0.003	0.271 ± 0.014	0.974 ± 0.018
800 GeV	0.191 ± 0.008	0.036 ± 0.004	0.024 ± 0.004	0.032 ± 0.004	0.299 ± 0.015	1.048 ± 0.018
900 GeV	0.221 ± 0.007	0.049 ± 0.004	0.036 ± 0.003	0.031 ± 0.005	0.328 ± 0.011	1.116 ± 0.020
1000 GeV	0.230 ± 0.009	0.051 ± 0.004	0.044 ± 0.004	0.043 ± 0.006	0.326 ± 0.011	1.150 ± 0.019
1100 GeV	0.225 ± 0.009	0.055 ± 0.004	0.055 ± 0.004	0.038 ± 0.006	0.339 ± 0.011	1.151 ± 0.019
1200 GeV	0.238 ± 0.009	0.059 ± 0.004	0.051 ± 0.004	0.048 ± 0.006	0.345 ± 0.011	1.155 ± 0.020
1300 GeV	0.217 ± 0.009	0.061 ± 0.005	0.057 ± 0.004	0.057 ± 0.006	0.343 ± 0.011	1.106 ± 0.019
1400 GeV	0.223 ± 0.006	0.062 ± 0.005	0.064 ± 0.005	0.056 ± 0.007	0.318 ± 0.011	1.065 ± 0.013
1500 GeV	0.219 ± 0.006	0.069 ± 0.005	0.068 ± 0.003	0.048 ± 0.006	0.290 ± 0.010	1.174 ± 0.019

Number of selected events (OS2)

Sample	$\mu\mu$	$e\mu$	ee	Sum
Signal:				
Tprime500 BWTZ	19.98 ± 1.35	8.70 ± 0.66	11.83 ± 0.85	40.51 ± 2.58
Tprime500 TZTZ	43.74 ± 2.89	13.94 ± 1.07	27.86 ± 1.92	85.54 ± 5.40
Tprime500 THTZ	33.44 ± 2.66	13.94 ± 1.40	23.87 ± 2.06	71.25 ± 4.98
Tprime500 THTH	15.55 ± 1.72	17.91 ± 1.86	10.29 ± 1.45	43.75 ± 3.61
Tprime500 BWTH	7.51 ± 0.98	12.18 ± 1.33	4.94 ± 0.74	24.64 ± 2.15
Tprime500 BWBW	1.94 ± 0.28	3.43 ± 0.39	2.04 ± 0.30	7.41 ± 0.67
Summed Signal (Nominal BR):				35.13
Tprime800 BWTZ	1.22 ± 0.08	0.53 ± 0.04	0.74 ± 0.05	2.49 ± 0.16
Tprime800 TZTZ	3.14 ± 0.20	1.05 ± 0.07	2.10 ± 0.14	6.30 ± 0.39
Tprime800 THTZ	2.40 ± 0.17	1.26 ± 0.10	1.51 ± 0.11	5.17 ± 0.33
Tprime800 THTH	1.15 ± 0.10	1.96 ± 0.15	0.64 ± 0.07	3.76 ± 0.26
Tprime800 BWTH	0.57 ± 0.06	0.91 ± 0.08	0.42 ± 0.05	1.90 ± 0.14
Tprime800 BWBW	0.12 ± 0.01	0.20 ± 0.02	0.09 ± 0.01	0.41 ± 0.03
Summed Signal (Nominal BR) :				2.48
Backgrounds:				
TTbar	26.63 ± 5.17	39.48 ± 6.93	13.54 ± 3.26	79.65 ± 11.89
SingleTop	0.97 ± 0.71	1.03 ± 0.63	0.00 ± 0.00	2.00 ± 0.99
DrellYan	0.00 ± 0.00	0.00 ± 0.00	2.47 ± 1.90	2.47 ± 1.90
Total Background	27.59 ± 5.22	40.51 ± 6.96	16.02 ± 3.77	84.12 ± 12.08
Data	33.00	37.00	16.00	86.00

Signal efficiency (OS2)

t' Mass	Decay channel					
	$bWtZ$	$tZtZ$	$tHtZ$	$tHtH$	$bWtH$	$bWbW$
500 GeV	0.362 ± 0.008	0.765 ± 0.016	0.637 ± 0.022	0.391 ± 0.018	0.220 ± 0.012	0.066 ± 0.005
600 GeV	0.554 ± 0.013	1.293 ± 0.021	1.002 ± 0.029	0.727 ± 0.025	0.349 ± 0.015	0.084 ± 0.005
700 GeV	0.602 ± 0.014	1.483 ± 0.020	1.246 ± 0.029	0.972 ± 0.028	0.449 ± 0.017	0.092 ± 0.006
800 GeV	0.612 ± 0.015	1.545 ± 0.023	1.269 ± 0.029	0.922 ± 0.028	0.466 ± 0.017	0.101 ± 0.005
900 GeV	0.575 ± 0.011	1.512 ± 0.023	1.262 ± 0.020	0.999 ± 0.028	0.480 ± 0.012	0.105 ± 0.006
1000 GeV	0.506 ± 0.013	1.372 ± 0.021	1.219 ± 0.019	0.885 ± 0.027	0.463 ± 0.012	0.095 ± 0.006
1100 GeV	0.469 ± 0.013	1.241 ± 0.021	1.151 ± 0.019	0.821 ± 0.026	0.422 ± 0.011	0.097 ± 0.006
1200 GeV	0.402 ± 0.012	1.200 ± 0.019	0.966 ± 0.017	0.698 ± 0.024	0.372 ± 0.010	0.088 ± 0.005
1300 GeV	0.387 ± 0.011	1.019 ± 0.019	0.874 ± 0.016	0.626 ± 0.021	0.323 ± 0.010	0.083 ± 0.005
1400 GeV	0.323 ± 0.007	0.880 ± 0.017	0.809 ± 0.016	0.566 ± 0.021	0.296 ± 0.009	0.074 ± 0.003
1500 GeV	0.301 ± 0.007	0.773 ± 0.015	0.690 ± 0.009	0.518 ± 0.021	0.269 ± 0.009	0.052 ± 0.004

Number of selected events (same-sign dilepton)

Sample	$\mu\mu$	$e\mu$	ee	Sum
Signal:				
Tprime500 BWTZ	5.85 ± 0.50	9.55 ± 0.70	4.64 ± 0.40	20.04 ± 1.35
Tprime500 TZTZ	12.06 ± 0.96	20.21 ± 1.46	9.11 ± 0.77	41.38 ± 2.74
Tprime500 THTZ	10.63 ± 1.17	22.47 ± 1.99	8.51 ± 1.00	41.62 ± 3.17
Tprime500 THTH	13.57 ± 1.59	22.31 ± 2.23	9.66 ± 1.32	45.55 ± 3.73
Tprime500 BWTH	5.89 ± 0.85	12.98 ± 1.44	3.68 ± 0.64	22.56 ± 2.06
Summed Signal (Nominal BR) :				21.31
Tprime800 BWTZ	0.28 ± 0.03	0.50 ± 0.04	0.25 ± 0.02	1.03 ± 0.07
Tprime800 TZTZ	0.53 ± 0.04	0.99 ± 0.07	0.46 ± 0.04	1.98 ± 0.13
Tprime800 THTZ	0.48 ± 0.05	0.90 ± 0.08	0.46 ± 0.05	1.85 ± 0.13
Tprime800 THTH	0.68 ± 0.07	1.01 ± 0.09	0.52 ± 0.06	2.21 ± 0.17
Tprime800 BWTH	0.35 ± 0.04	0.55 ± 0.06	0.21 ± 0.03	1.12 ± 0.09
Summed Signal (Nominal BR) :				1.03
Backgrounds:				
WW	0.08 ± 0.06	0.38 ± 0.22	0.07 ± 0.06	0.53 ± 0.29
WZ	0.09 ± 0.03	0.22 ± 0.06	0.04 ± 0.02	0.34 ± 0.08
ZZ	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.03 ± 0.00
TTW	1.97 ± 0.66	2.84 ± 0.94	0.94 ± 0.33	5.75 ± 1.87
WWW	0.03 ± 0.02	0.09 ± 0.05	0.01 ± 0.01	0.13 ± 0.07
TTZ	0.65 ± 0.35	0.91 ± 0.47	0.27 ± 0.15	1.83 ± 0.93
ChargeMisID	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.00
Total Prompt MC	2.84 ± 0.75	4.45 ± 1.08	1.33 ± 0.37	8.62 ± 2.12
Non-Prompt	1.25 ± 1.01	4.81 ± 2.68	1.85 ± 1.14	7.91 ± 4.26
Total Background	4.09 ± 1.26	9.26 ± 2.89	3.19 ± 1.20	16.53 ± 4.75
Data	8.00	8.00	2.00	18.00

Signal efficiency (same-sign dilepton)

t' Mass	Decay channel					
	$bWtZ$	$tZtZ$	$tHtZ$	$tHtH$	$bWtH$	$bWbW$
500 GeV	0.179 ± 0.006	0.370 ± 0.011	0.372 ± 0.017	0.408 ± 0.018	0.202 ± 0.011	0.001 ± 0.000
600 GeV	0.230 ± 0.009	0.435 ± 0.012	0.404 ± 0.019	0.467 ± 0.020	0.241 ± 0.012	0.002 ± 0.001
700 GeV	0.262 ± 0.009	0.458 ± 0.012	0.456 ± 0.017	0.527 ± 0.021	0.282 ± 0.013	0.001 ± 0.001
800 GeV	0.253 ± 0.009	0.486 ± 0.013	0.453 ± 0.017	0.543 ± 0.020	0.275 ± 0.013	0.004 ± 0.001
900 GeV	0.252 ± 0.007	0.455 ± 0.013	0.447 ± 0.012	0.580 ± 0.021	0.265 ± 0.009	0.001 ± 0.001
1000 GeV	0.246 ± 0.009	0.446 ± 0.012	0.399 ± 0.011	0.507 ± 0.020	0.245 ± 0.008	0.000 ± 0.000
1100 GeV	0.235 ± 0.009	0.427 ± 0.012	0.394 ± 0.011	0.450 ± 0.019	0.228 ± 0.008	0.002 ± 0.001
1200 GeV	0.206 ± 0.009	0.408 ± 0.011	0.369 ± 0.011	0.364 ± 0.018	0.208 ± 0.008	0.002 ± 0.001
1300 GeV	0.199 ± 0.008	0.388 ± 0.012	0.342 ± 0.010	0.353 ± 0.016	0.192 ± 0.007	0.003 ± 0.001
1400 GeV	0.188 ± 0.006	0.359 ± 0.011	0.303 ± 0.010	0.313 ± 0.016	0.158 ± 0.007	0.001 ± 0.000
1500 GeV	0.182 ± 0.005	0.311 ± 0.010	0.287 ± 0.006	0.299 ± 0.015	0.171 ± 0.007	0.001 ± 0.001

Number of selected events (trilepton)

Sample	$\mu\mu\mu$	$e\mu\mu$ or $ee\mu$	eee	Sum
Signal:				
Tprime500 BWTZ	11.46 ± 0.83	15.89 ± 1.10	5.08 ± 0.44	32.44 ± 2.10
Tprime500 TZTZ	23.84 ± 1.69	36.02 ± 2.42	11.71 ± 0.94	71.57 ± 4.56
Tprime500 THTZ	10.72 ± 1.15	22.95 ± 1.98	4.77 ± 0.68	38.43 ± 2.94
Tprime500 THTH	2.99 ± 0.69	6.57 ± 1.03	1.05 ± 0.43	10.61 ± 1.39
Tprime500 BWTH	1.27 ± 0.39	2.80 ± 0.55	0.31 ± 0.18	4.38 ± 0.73
Summed Signal (Nominal BR):				19.14
Tprime800 BWTZ	0.74 ± 0.05	1.11 ± 0.08	0.37 ± 0.03	2.22 ± 0.14
Tprime800 TZTZ	1.49 ± 0.10	2.43 ± 0.16	0.79 ± 0.06	4.72 ± 0.29
Tprime800 THTZ	0.72 ± 0.06	1.41 ± 0.11	0.45 ± 0.04	2.57 ± 0.18
Tprime800 THTH	0.15 ± 0.03	0.42 ± 0.05	0.10 ± 0.02	0.67 ± 0.07
Tprime800 BWTH	0.08 ± 0.02	0.19 ± 0.03	0.03 ± 0.01	0.30 ± 0.04
Summed Signal (Nominal BR):				1.29
Backgrounds:				
TTWW	0.01 ± 0.01	0.03 ± 0.02	0.00 ± 0.00	0.05 ± 0.03
TTW	0.03 ± 0.03	0.22 ± 0.10	0.00 ± 0.00	0.25 ± 0.11
TTZ	0.54 ± 0.29	0.95 ± 0.49	0.35 ± 0.19	1.84 ± 0.94
WW	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
WZ	0.12 ± 0.07	0.26 ± 0.14	0.02 ± 0.02	0.40 ± 0.21
ZZ	0.02 ± 0.00	0.03 ± 0.01	0.01 ± 0.00	0.07 ± 0.01
Tri-bosons	0.03 ± 0.02	0.04 ± 0.03	0.00 ± 0.00	0.08 ± 0.04
ZG	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Total Prompt MC	0.76 ± 0.30	1.54 ± 0.52	0.39 ± 0.19	2.69 ± 0.97
Non-Prompt	0.00 ± 0.00	0.99 ± 0.90	0.00 ± 0.00	0.99 ± 0.90
Total Background	0.76 ± 0.30	2.54 ± 1.04	0.39 ± 0.19	3.69 ± 1.32
Data	0.00	0.00	2.00	2.00

Signal efficiency (trilepton)

t' Mass	Decay channel					
	$bWtZ$	$tZtZ$	$tHtZ$	$tHtH$	$bWtH$	$bWbW$
500 GeV	0.290 ± 0.008	0.640 ± 0.015	0.344 ± 0.016	0.095 ± 0.009	0.039 ± 0.005	$0. \pm 0.$
600 GeV	0.433 ± 0.012	0.916 ± 0.018	0.510 ± 0.021	0.150 ± 0.011	0.072 ± 0.006	$0. \pm 0.$
700 GeV	0.484 ± 0.013	1.046 ± 0.017	0.548 ± 0.020	0.171 ± 0.012	0.064 ± 0.006	$0. \pm 0.$
800 GeV	0.545 ± 0.014	1.157 ± 0.020	0.631 ± 0.021	0.164 ± 0.011	0.073 ± 0.006	$0. \pm 0.$
900 GeV	0.566 ± 0.011	1.192 ± 0.020	0.632 ± 0.015	0.188 ± 0.012	0.082 ± 0.005	$0. \pm 0.$
1000 GeV	0.564 ± 0.013	1.205 ± 0.020	0.639 ± 0.014	0.200 ± 0.013	0.092 ± 0.005	$0. \pm 0.$
1100 GeV	0.576 ± 0.014	1.184 ± 0.020	0.583 ± 0.014	0.170 ± 0.012	0.087 ± 0.005	$0. \pm 0.$
1200 GeV	0.514 ± 0.013	1.171 ± 0.019	0.586 ± 0.014	0.167 ± 0.011	0.091 ± 0.005	$0. \pm 0.$
1300 GeV	0.501 ± 0.013	1.033 ± 0.019	0.510 ± 0.013	0.210 ± 0.012	0.080 ± 0.005	$0. \pm 0.$
1400 GeV	0.458 ± 0.009	0.962 ± 0.018	0.486 ± 0.013	0.142 ± 0.011	0.069 ± 0.004	$0. \pm 0.$
1500 GeV	0.420 ± 0.008	0.883 ± 0.016	0.447 ± 0.008	0.158 ± 0.011	0.057 ± 0.004	$0. \pm 0.$

H_T distribution cross-check

- Expected and observed spectra agree after requirement of same-sign dileptons, Z-boson veto and ⩾ 2 jets