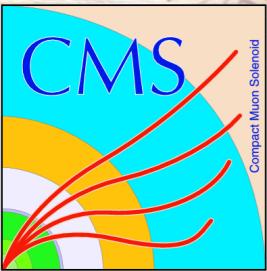


# Search for Heavy BSM Particles Coupling to Third Generation Quarks at CMS

Doug Berry  
On behalf of the CMS Collaboration  
April 18<sup>th</sup>, 2018



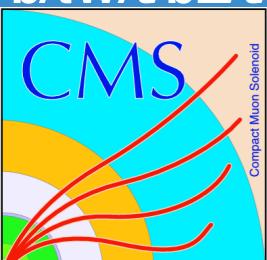
DIS2018: 26<sup>th</sup> International Workshop on Deep Inelastic  
Scattering April 16th-20th 2018, Kobe University

**UIC**  
UNIVERSITY  
OF ILLINOIS  
AT CHICAGO

# Outline

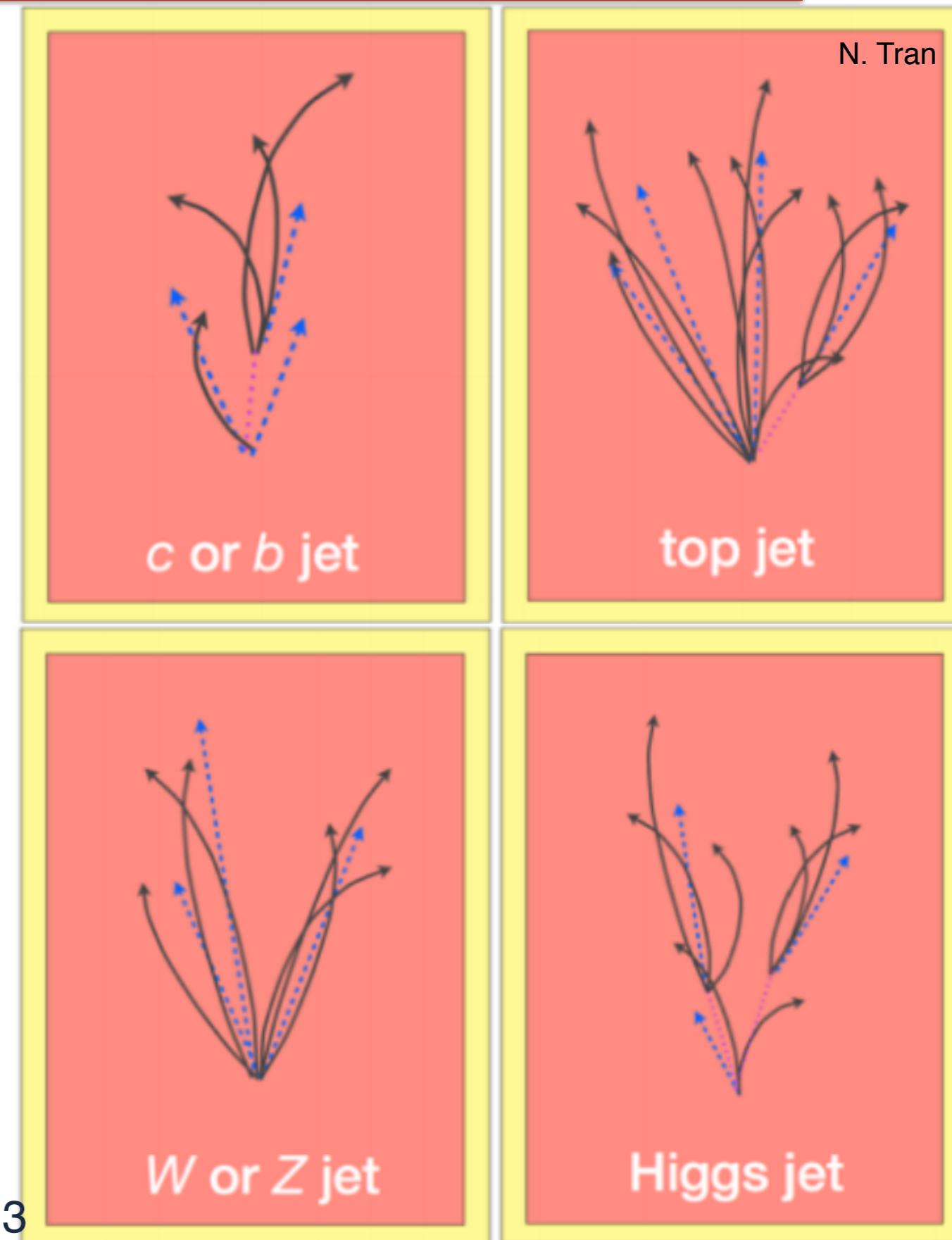
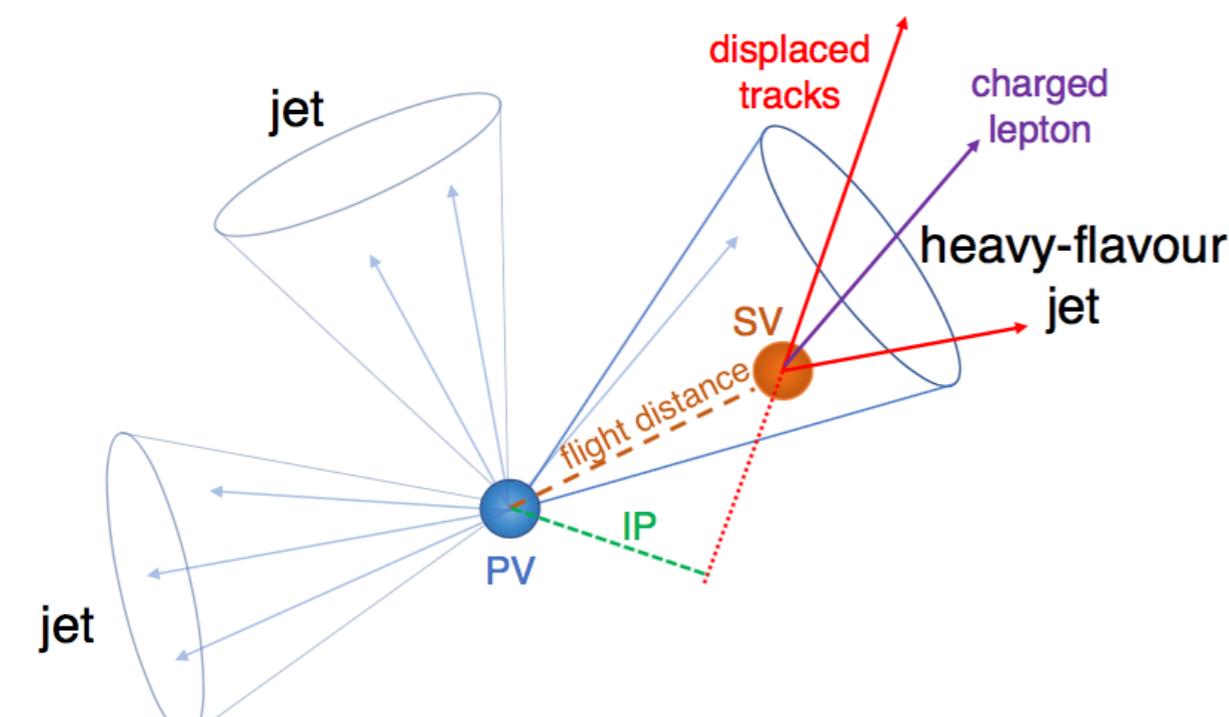
- Talk focuses on heavy objects decaying to third generation quarks
  - Overview tagging approaches
  - Present 8 heavy object searches

Process	Final State(s)	Boosted Object Tagging	Luminosity (fb <sup>-1</sup> )	CMS PAS	Publication
$W' \rightarrow tb$	$b\bar{b}\ell\nu$	No	35.9	<a href="#">B2G-17-010</a>	<a href="#">PLB 777 (2017) 39</a>
$LQ_3 LQ_3 \rightarrow (\tau\tau)(\tau\tau)$	$\tau_h \tau_h \ell + \text{jets}$ and $\tau_h \ell + \text{jets}$	No	35.9	<a href="#">B2G-16-028</a>	Submitted to EPJC
$t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$	$(qq'bg)(\ell v bg)$	No	35.9	<a href="#">B2G-16-025</a>	<a href="#">PLB 778 (2018) 349</a>
$T \rightarrow tZ$	$\ell\ell q\bar{b}b$	Yes	35.9	<a href="#">B2G-17-007</a>	Submitted to PLB
$B \rightarrow Hb$	$b\bar{b}b$	Yes	35.9	<a href="#">B2G-17-009</a>	Submitted to JHEP
$X_{5/3} X_{5/3} \rightarrow (tW)(\bar{t}W)$	$\ell + \text{jet}$ and $\ell^\pm \ell^\pm + \text{jets}$	Yes	35.9	<a href="#">B2G-17-014</a>	Preparing for JHEP
$T\bar{T} \rightarrow WbW\bar{b}$	$b\ell v \bar{b}\bar{q}'$	No	35.8	<a href="#">B2G-17-003</a>	<a href="#">PLB 779 (2018) 82</a>
$T\bar{T}/B\bar{B} \rightarrow b/tW/t/bZ/t/bH$	$\ell v + \text{jets}$ , $\ell\ell + \text{jets}$ , and $\ell\ell\ell + \text{jets}$	Yes	35.9	<a href="#">B2G-17-011</a>	Preparing for JHEP



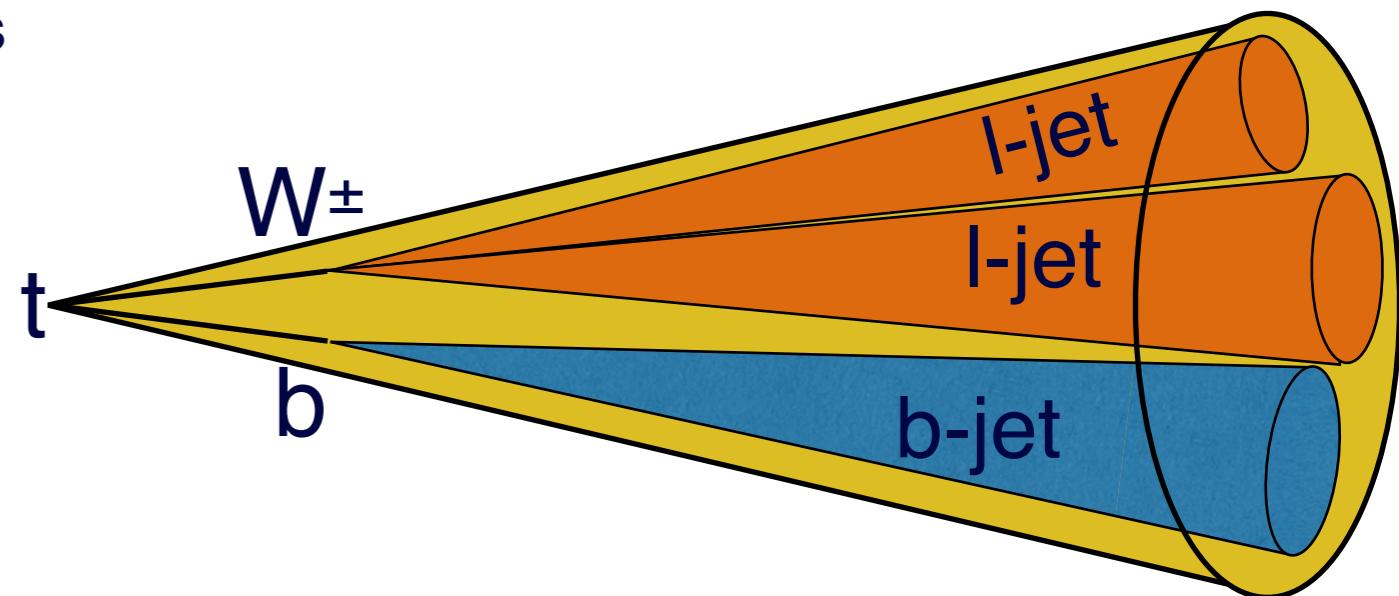
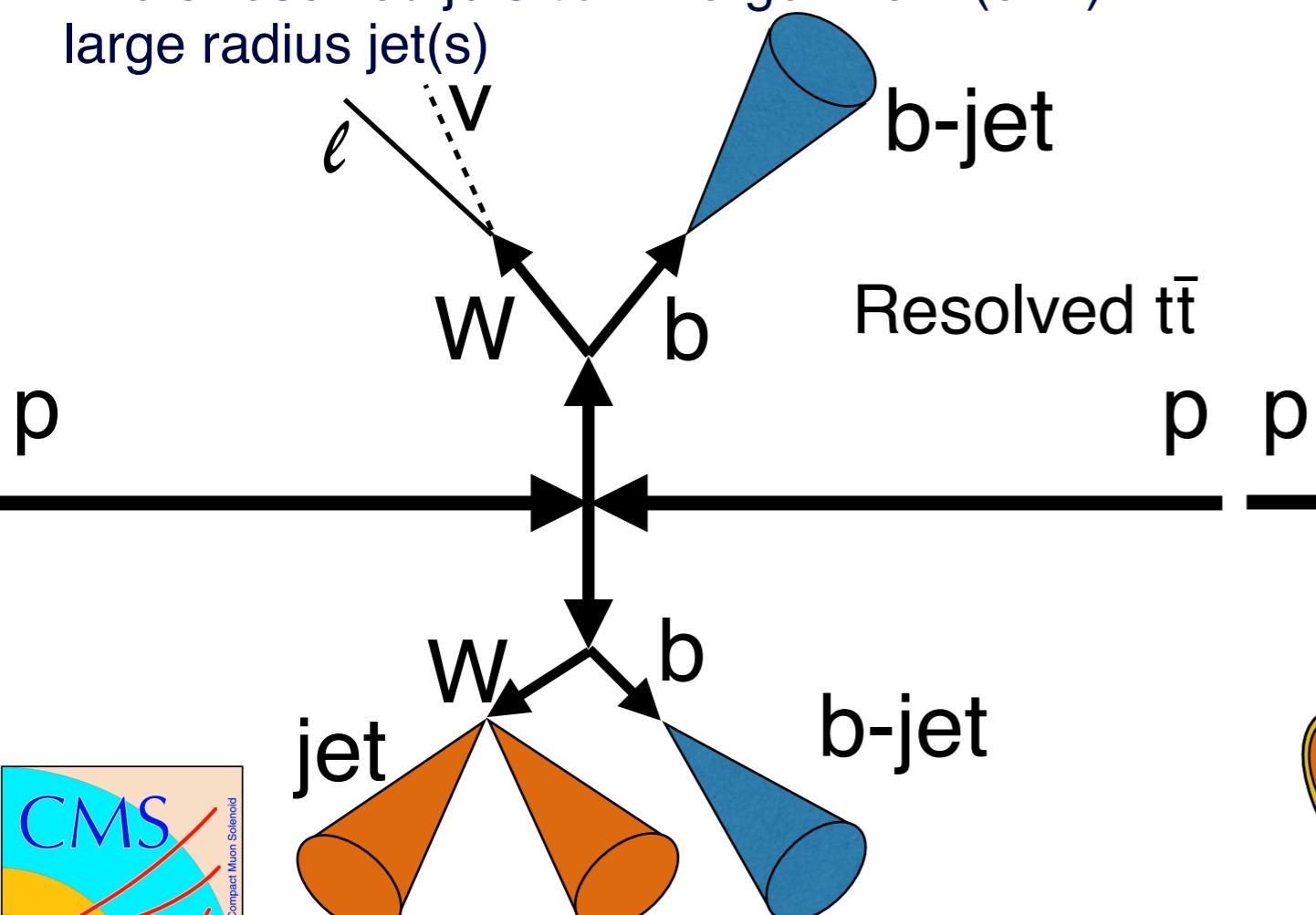
# Object Tagging

- Jet tagging techniques are used to identify bottom and top quarks and heavy gauge and Higgs bosons
- B-jet discriminate (CSVv2) used to identify jets originating from b-quarks
- Tagging methods use large footprint jets and sub-structure techniques to identify boosted objects
  - Jet mass window use to restrict mass range of large radius jets
  - N-subjettiness ( $\tau_{21}$  or  $\tau_{32}$ ) is used to evaluate the compatibility of a large radius jet of having 2 or 3 sub-jets

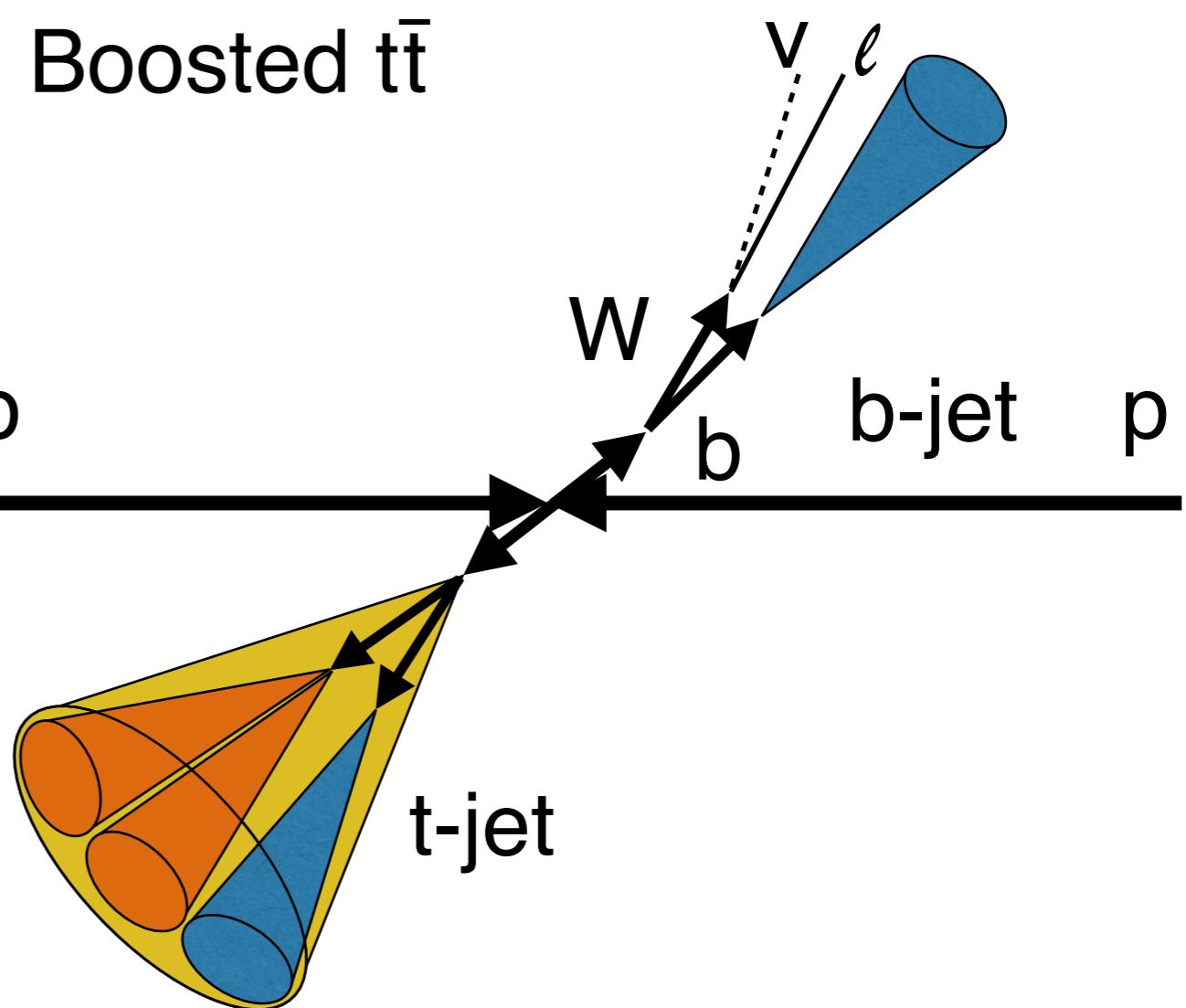


# Top Decay

- Kinematics of top decay change as it becomes boosted
  - $t \rightarrow Wb$  (99%)
  - $Wb \rightarrow (\ell\nu)b$  (32.4%)
  - $Wb \rightarrow (q\bar{q})b$  (67.6%)
- Leptons are no longer isolated
- The 3 resolved jets can merge into 1 (or 2) large radius jet(s)



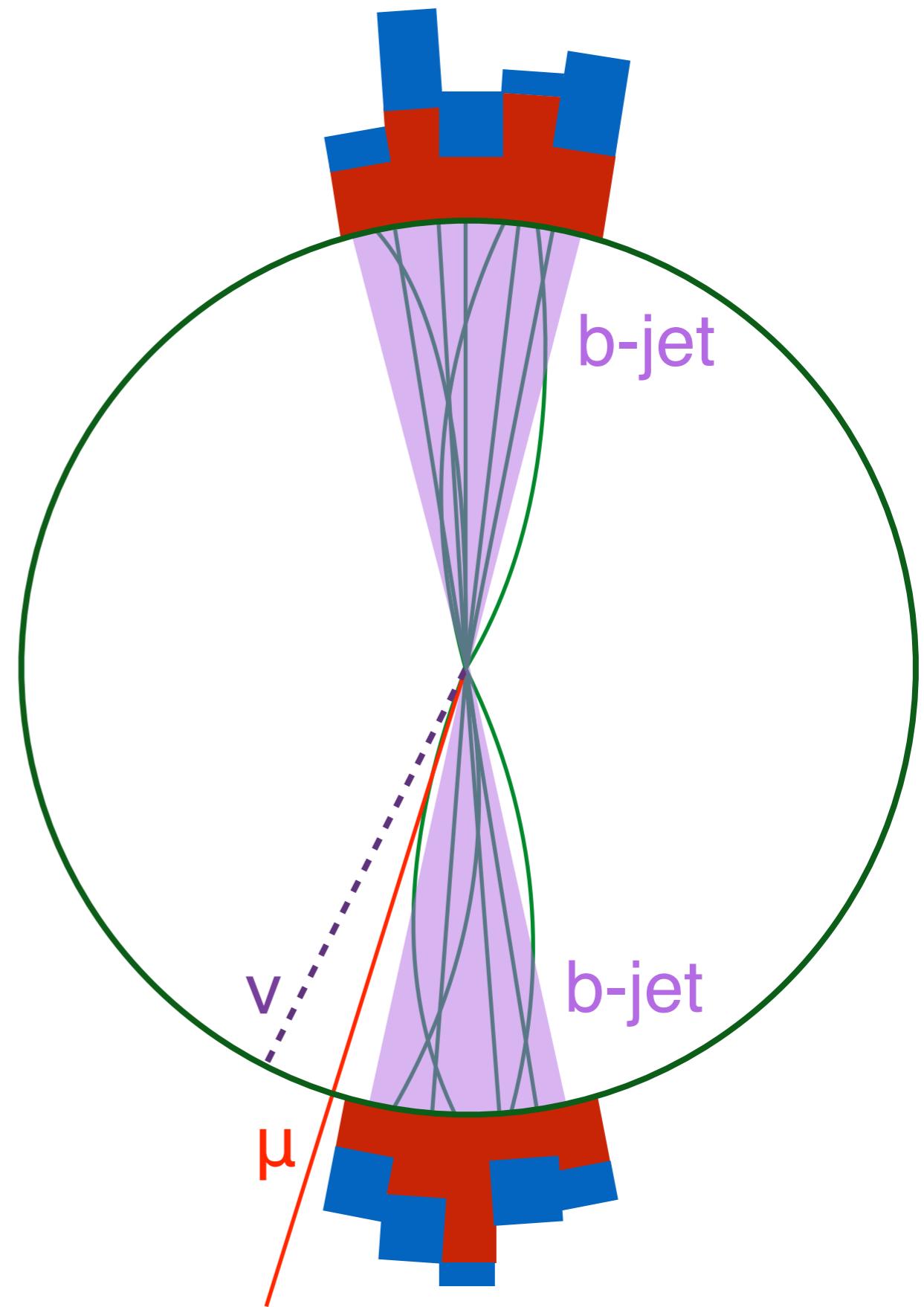
Boosted  $t\bar{t}$



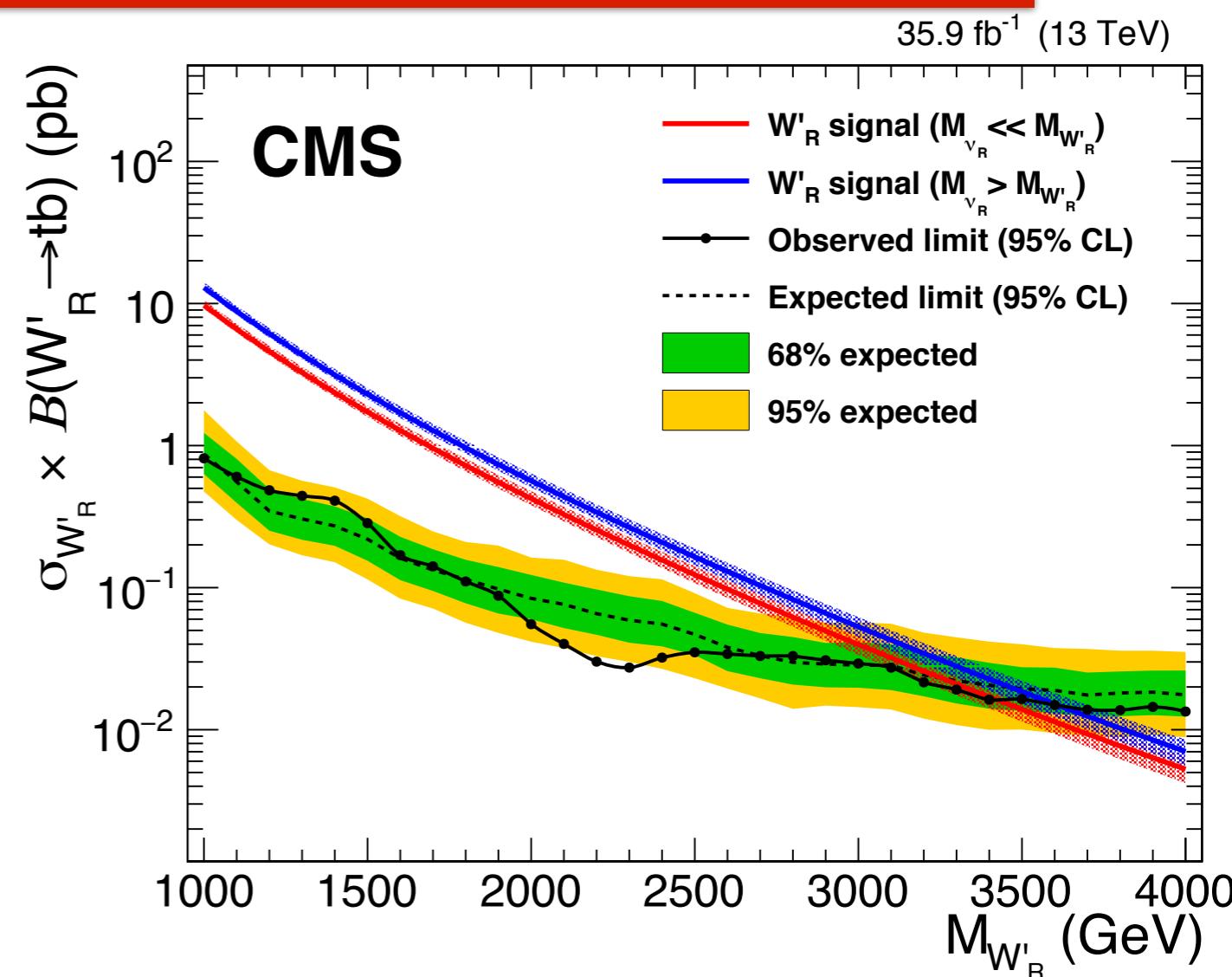
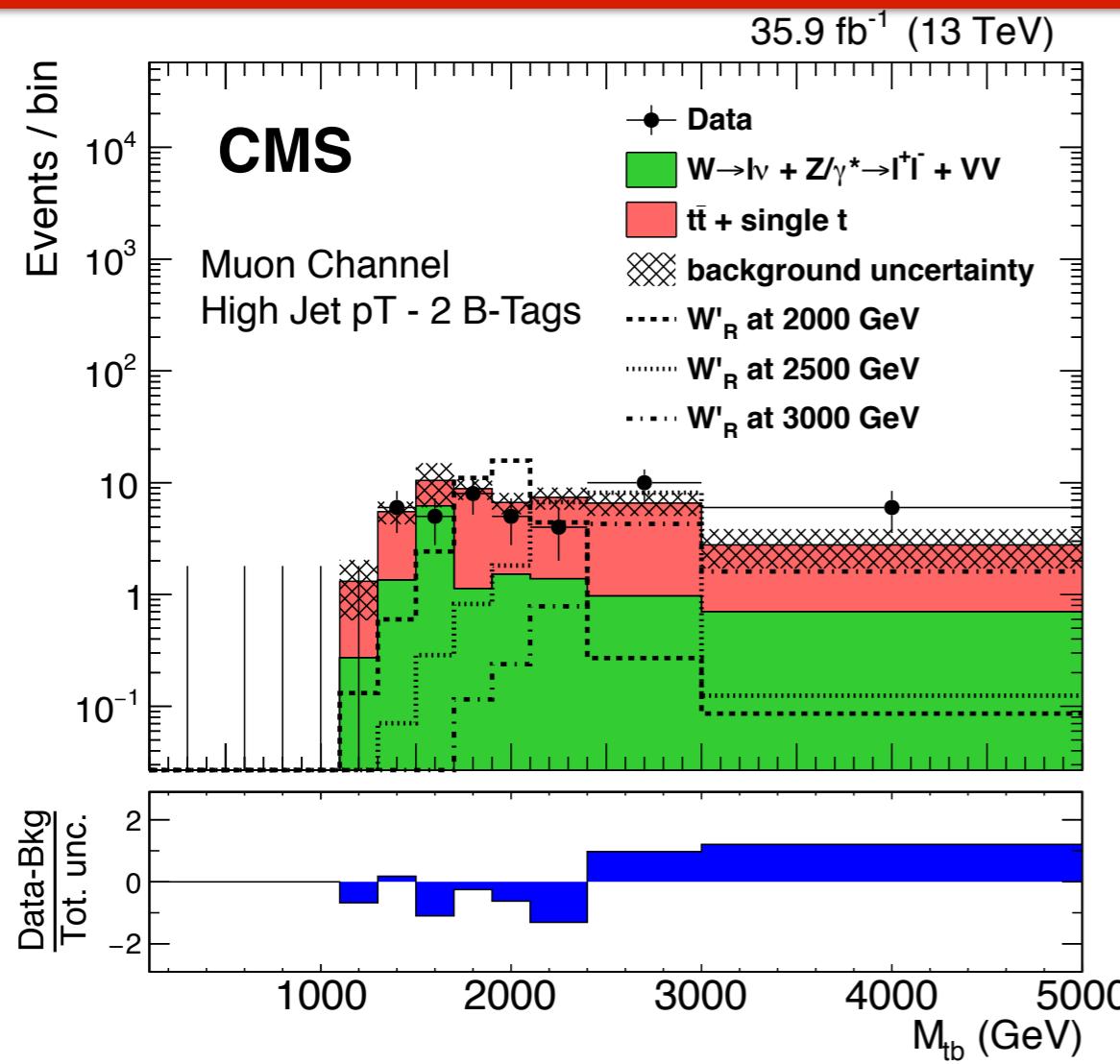
$t$ -jet

# $W' \rightarrow tb \rightarrow \ell v bb$

- $W'$  simulated with narrow width approximation ( $\Gamma_{W'}/M_{W'}=3\%$ ) and right-handed couplings
- Analysis searches for heavy resonances decaying to a top and bottom quark
- Analysis searches in the semileptonic channel
  - One high  $p_T$  lepton ( $e/\mu$ )
    - MET near lepton
  - Two high  $p_T$  jets
    - One of which is b-tagged
- Due to Lorentz boost of the top decay the lepton is not well separated from the b-jet
  - $p_{T,\text{rel}}$  cut instead of isolation requirement
- Major backgrounds are  $t\bar{t}+j$ ets and  $W+J$ ets
  - Minor backgrounds are  $t(W/Z)$ ,  $Z+j$ ets, and diboson production
  - All backgrounds are simulated using MC



# $W' \rightarrow tb \rightarrow \ell v bb$ Results

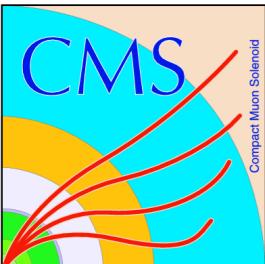
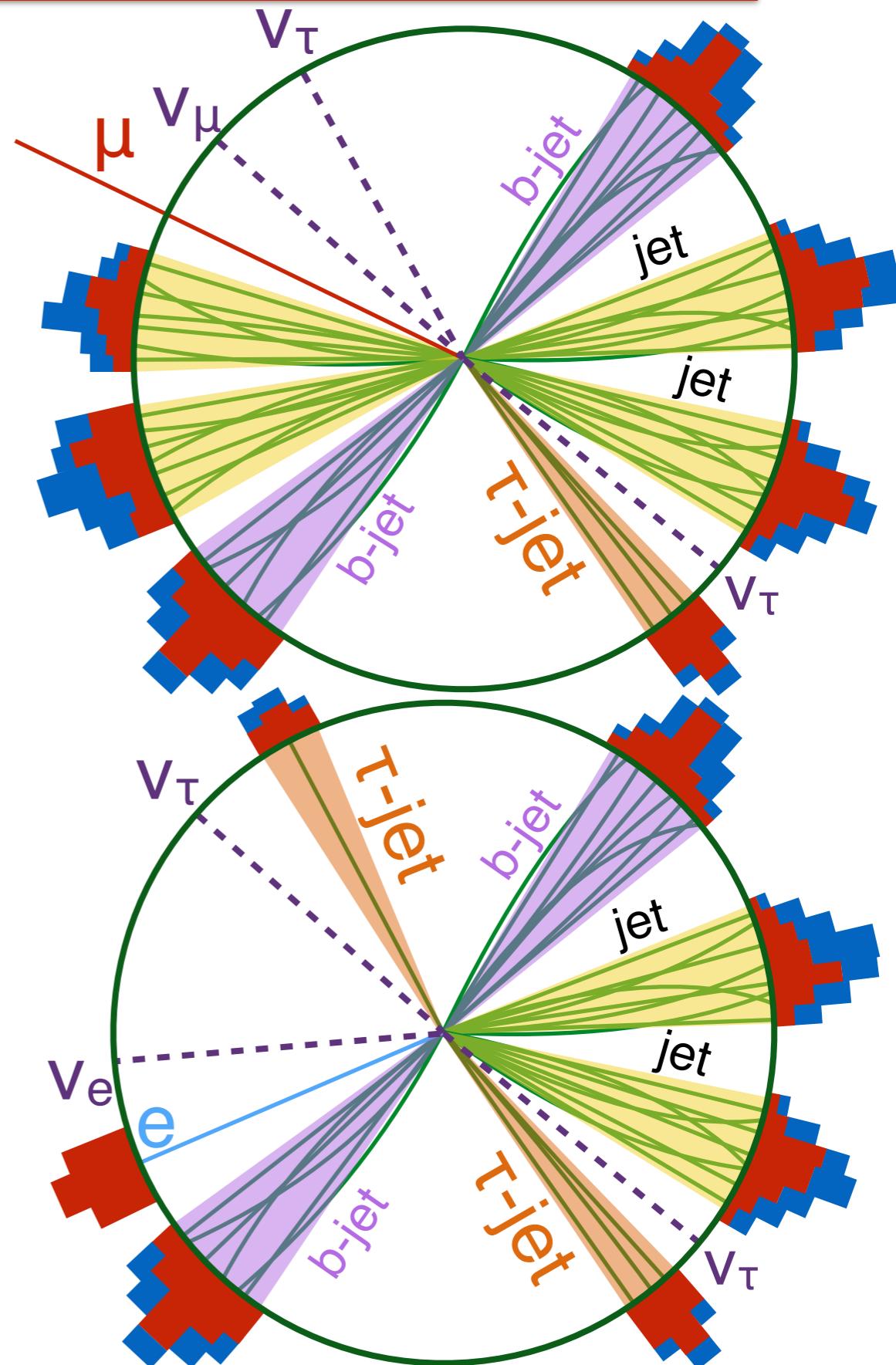


- EWK and top background shapes modeled using Monte Carlo (MC) method and their normalizations are determined using control regions (CR) in data
- Most sensitive  $W'$  search region shown on left (post-fit)
- 8 total search regions with 1 or 2 b-tags, low and high  $p_T$  top jets, and electron or muon channel
  - $W'_R$  excluded below 3.4 and 3.6 TeV for the  $M_{V_R} \ll M_{W'_R}$  and  $M_{V_R} > M_{W'_R}$ , respectively
  - Bayesian methods used to derive 95% CL upper limits
    - Dominate systematic is renormalization and factorization scales and top  $p_T$  spectrum

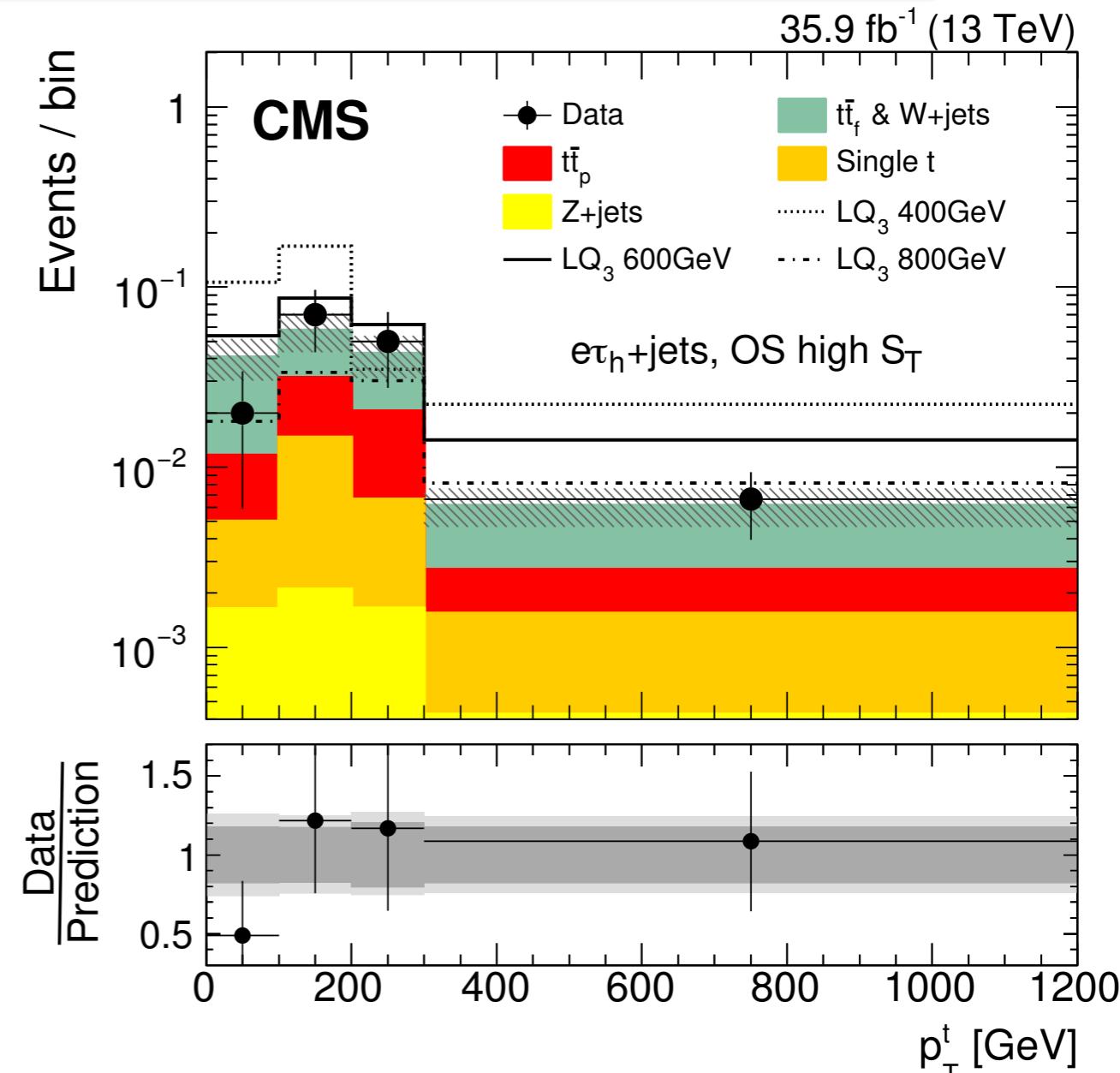
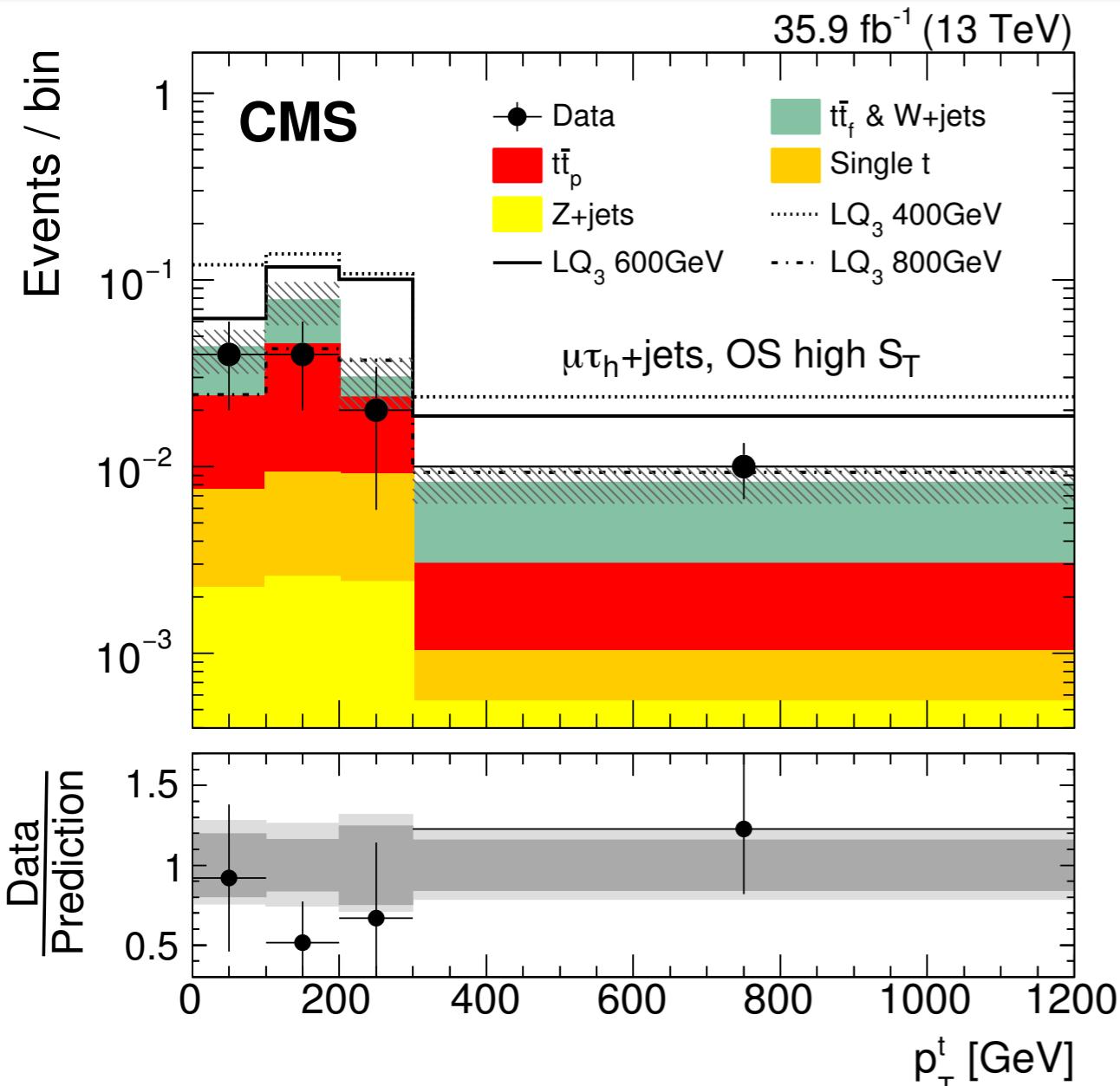


# LQ<sub>3</sub>LQ<sub>3</sub> → τ<sub>h</sub>tτ<sub>h</sub>t

- Search for third generation leptoquark
  - Can account for lepton universality violation in  $\bar{B} \rightarrow D\tau\bar{\nu}$  and  $\bar{B} \rightarrow D^*\tau\bar{\nu}$  rates
- 2 τ and a t̄t decay results in a busy multijet event topology with MET and leptons (e or μ)
- Two different event types are analyzed
  - Events with one  $\tau_h$  are categorized based on  $\ell$  flavor, the charge assignment of the  $\ell$  and  $\tau_h$ , and the ST of the event
  - Events with two  $\tau_h$  are analyzed using cut-n-count procedure
- t̄t, W+Jets, and Z+Jets backgrounds measured in control regions (CR) and simultaneously fit using the top p<sub>T</sub> spectrum
- Backgrounds normally contain fake  $\tau_h$ 
  - $\tau_h$  mis-identification rate is measured simultaneously with background fits



# LQ<sub>3</sub>LQ<sub>3</sub> → T<sub>h</sub>tT<sub>h</sub>t Results

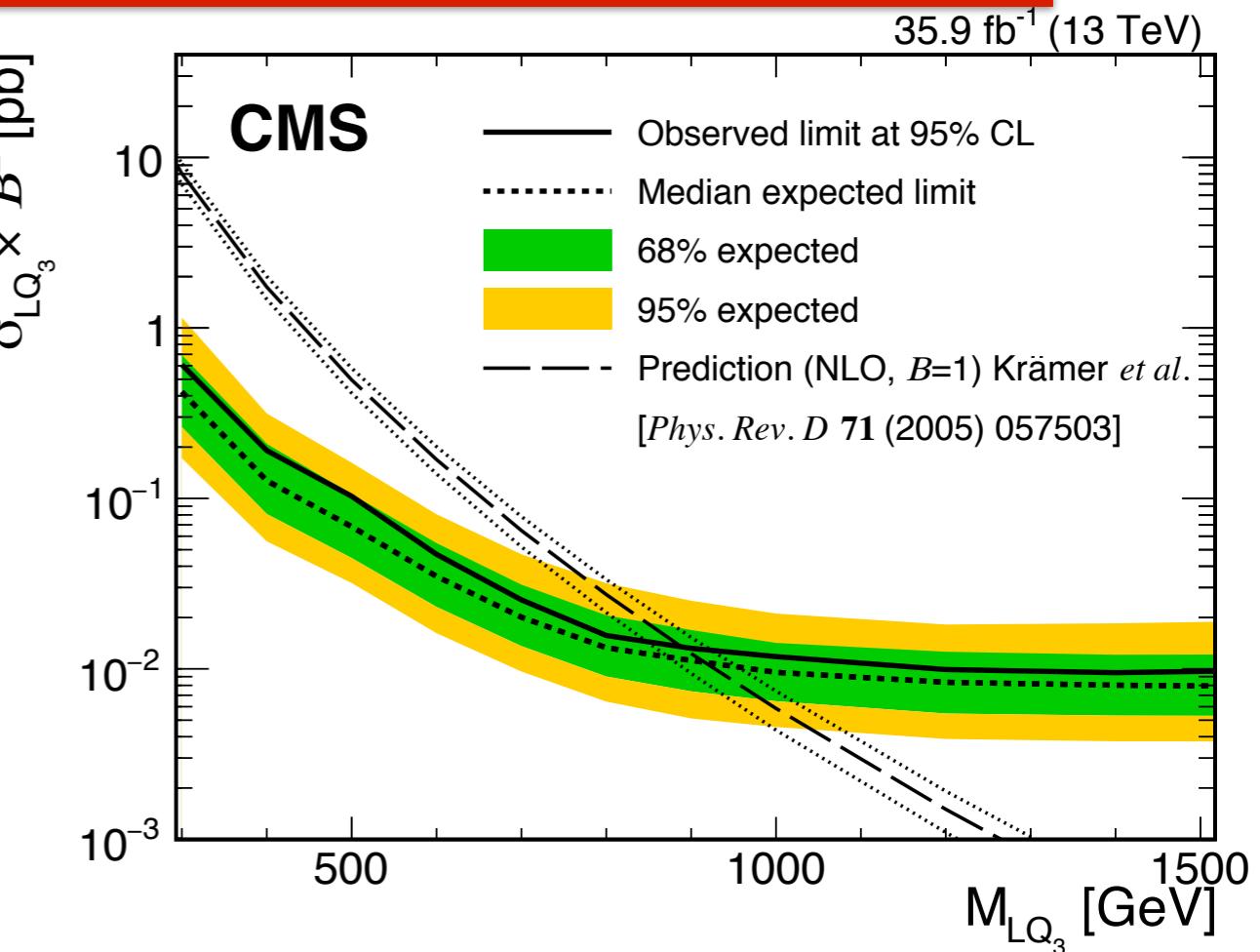


- Muon and electron opposite-charge, high-ST, single  $\tau_h$  channels are shown
- 9 different search regions are used with lepton flavor, same sign and opposite sign charge assignment of the  $\ell\tau_h$  pair, low and high ST, and two  $\tau_h$  events

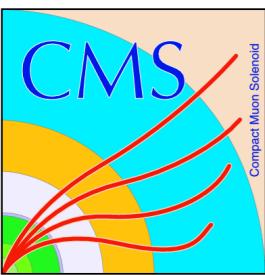


# LQ<sub>3</sub>LQ<sub>3</sub> → τ<sub>h</sub>tτ<sub>h</sub>t Limits

- Bayesian methods used to derive 95% CL upper limits
- Exclusion limit on the pair production of LQ<sub>3</sub> where  $B(LQ_3 \rightarrow \tau t) = 1$ 
  - LQ<sub>3</sub> excluded up to 900 GeV
  - Where 900 GeV is also expected
- Limits as a function of branching fraction can be found in backup slides

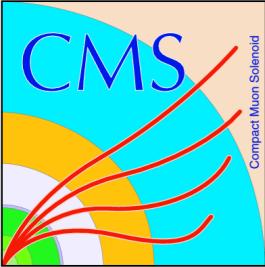
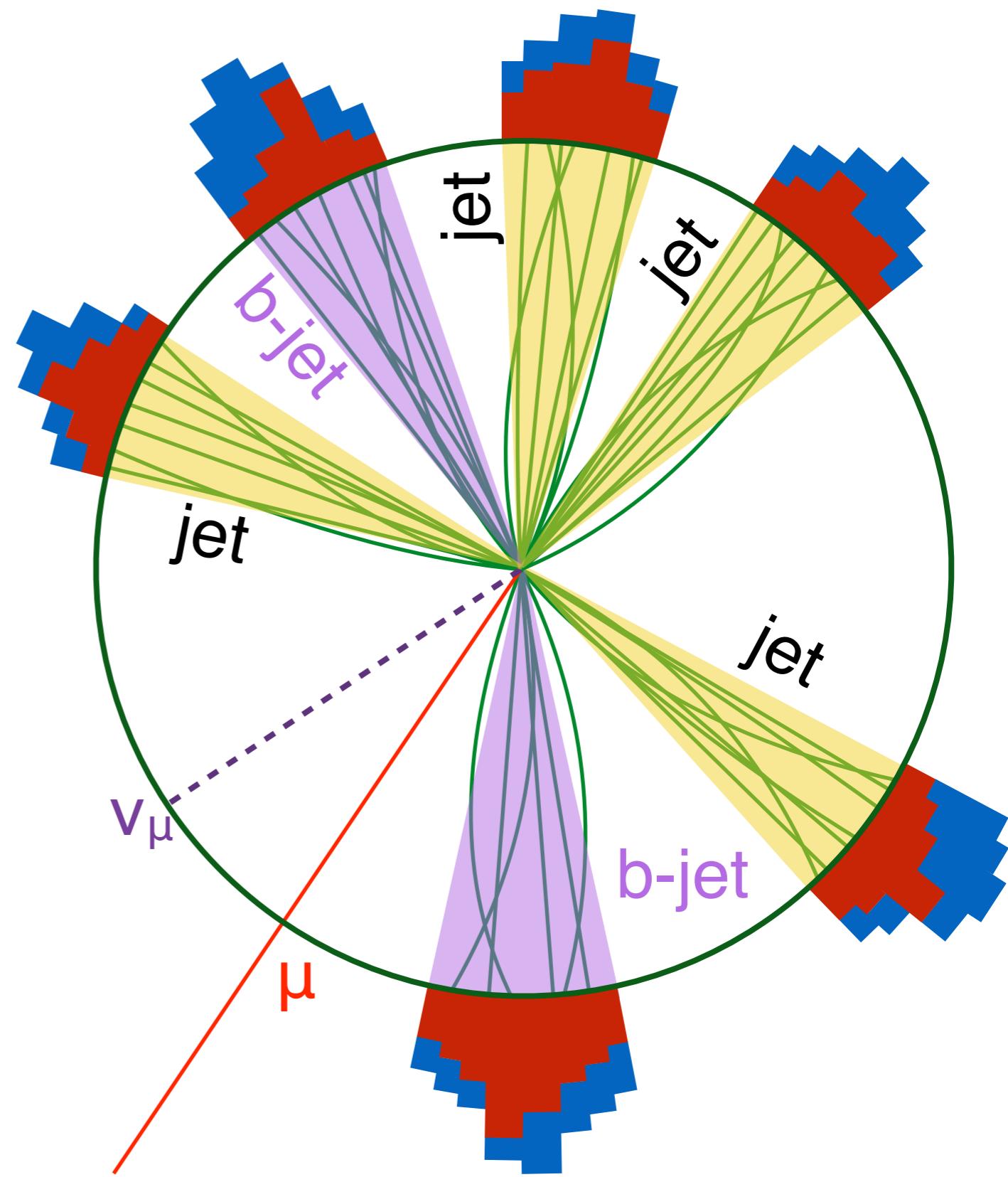


- Largest systematic uncertainties are the renormalization and factorization scales and the τ<sub>h</sub> (prompt and fake) rate from t̄t

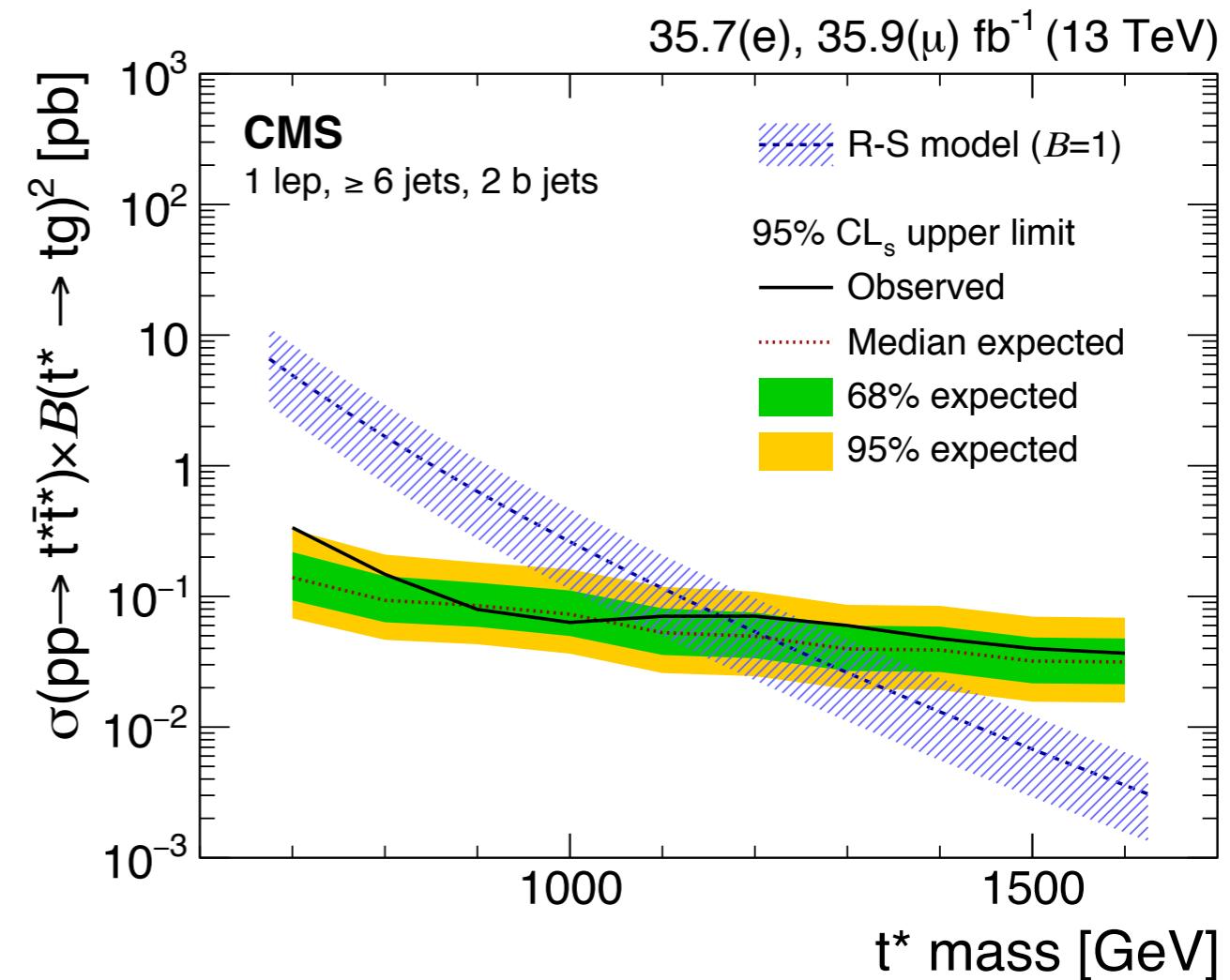
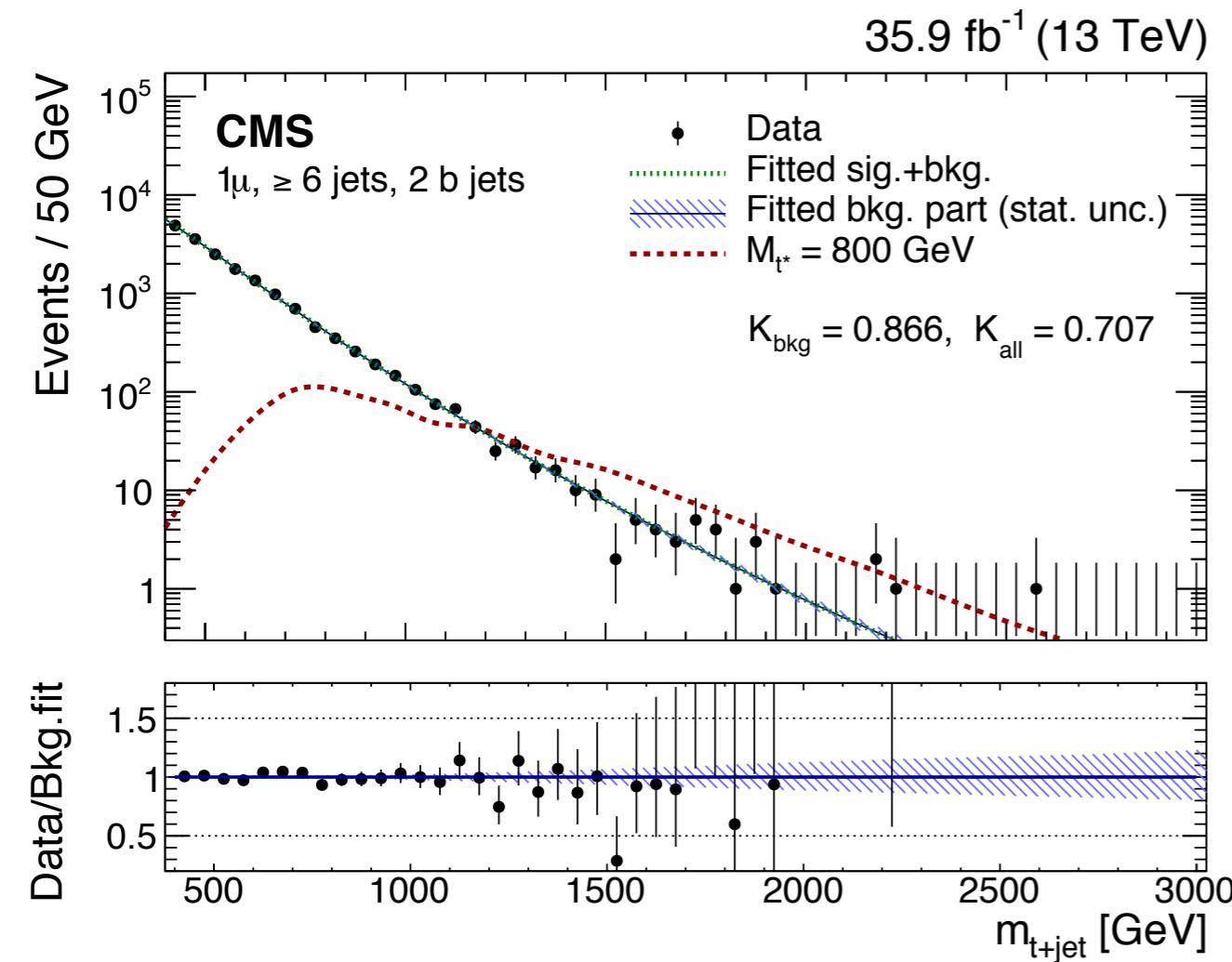


# $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$

- Analysis searches for the pair production of  $t^*$ 
  - $t^*$  is a spin 3/2 RS excitation of a top quark that decays to a top quark and gluon
- Analysis searches in the single lepton decay channel
  - $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g) \rightarrow \ell v bbbqq$
- Searches for events with exactly one isolated lepton ( $e$  or  $\mu$ ) and at least 6 jets, two of which are b-tagged
- Minimum S value used to assign jets for  $t^*$  reconstruction (see next slide)
- Background modeled using a log-normal function fit to simulation



# $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$ Results

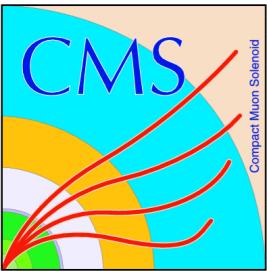


$$S = \left( \frac{m_{\text{qq}'} - m_W}{\sigma_W} \right)^2 + \left( \frac{m_{\text{qq}'b} - m_t}{\sigma_{t,\text{had}}} \right)^2 + \left( \frac{m_{\ell\nu_1b} - m_t}{\sigma_{t,\text{lep}}} \right)^2 + \left( \frac{m_{\text{qq}'bg} - m_{\ell\nu_1bg}}{\sigma_{t^*}} \right)^2$$

- Fit  $m_{t+\text{jet}}$  spectrum and data for the muon channel on the left
- 95% CL limits calculated using frequentist asymptotic CLs approach
- $t^* \bar{t}^*$  pair production excluded up to 1.2 TeV

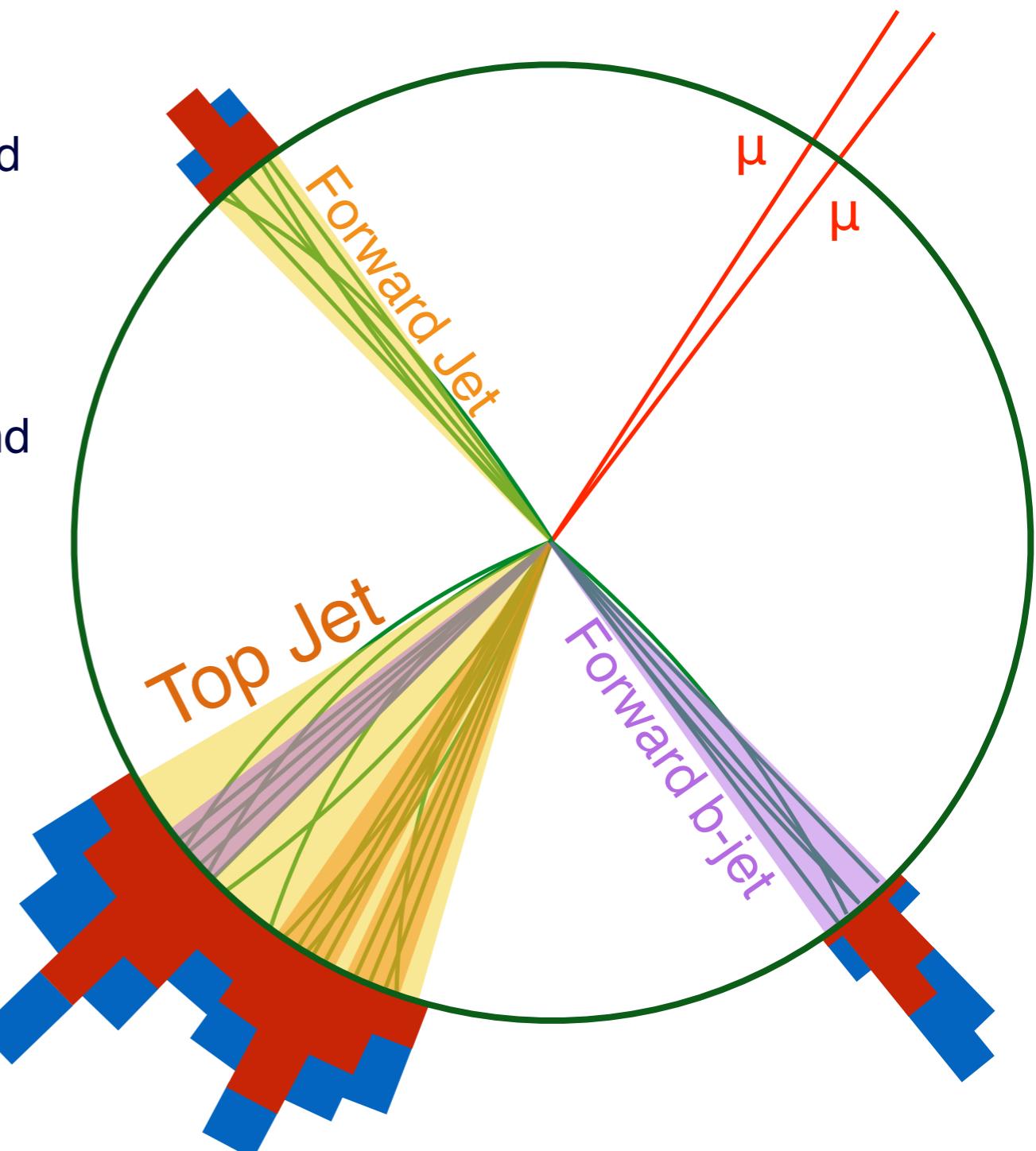
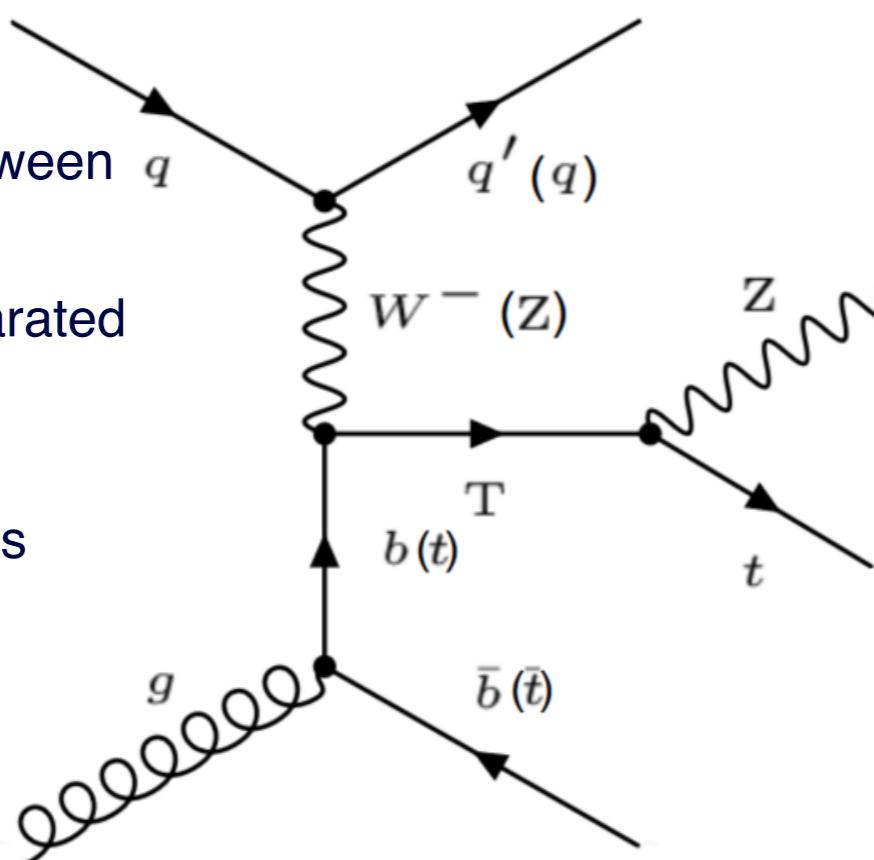


# Vector Like Quarks (VLQs)

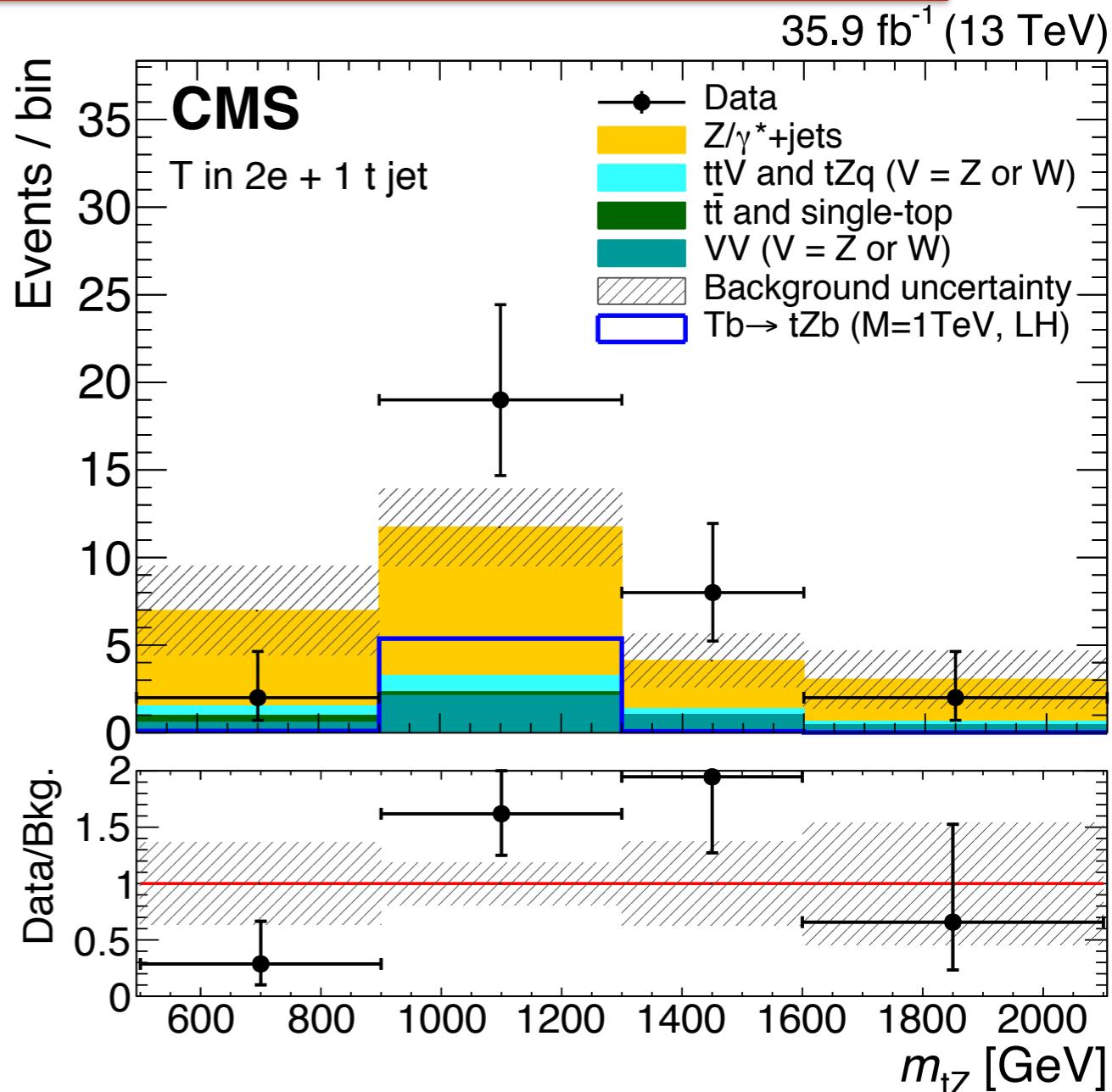
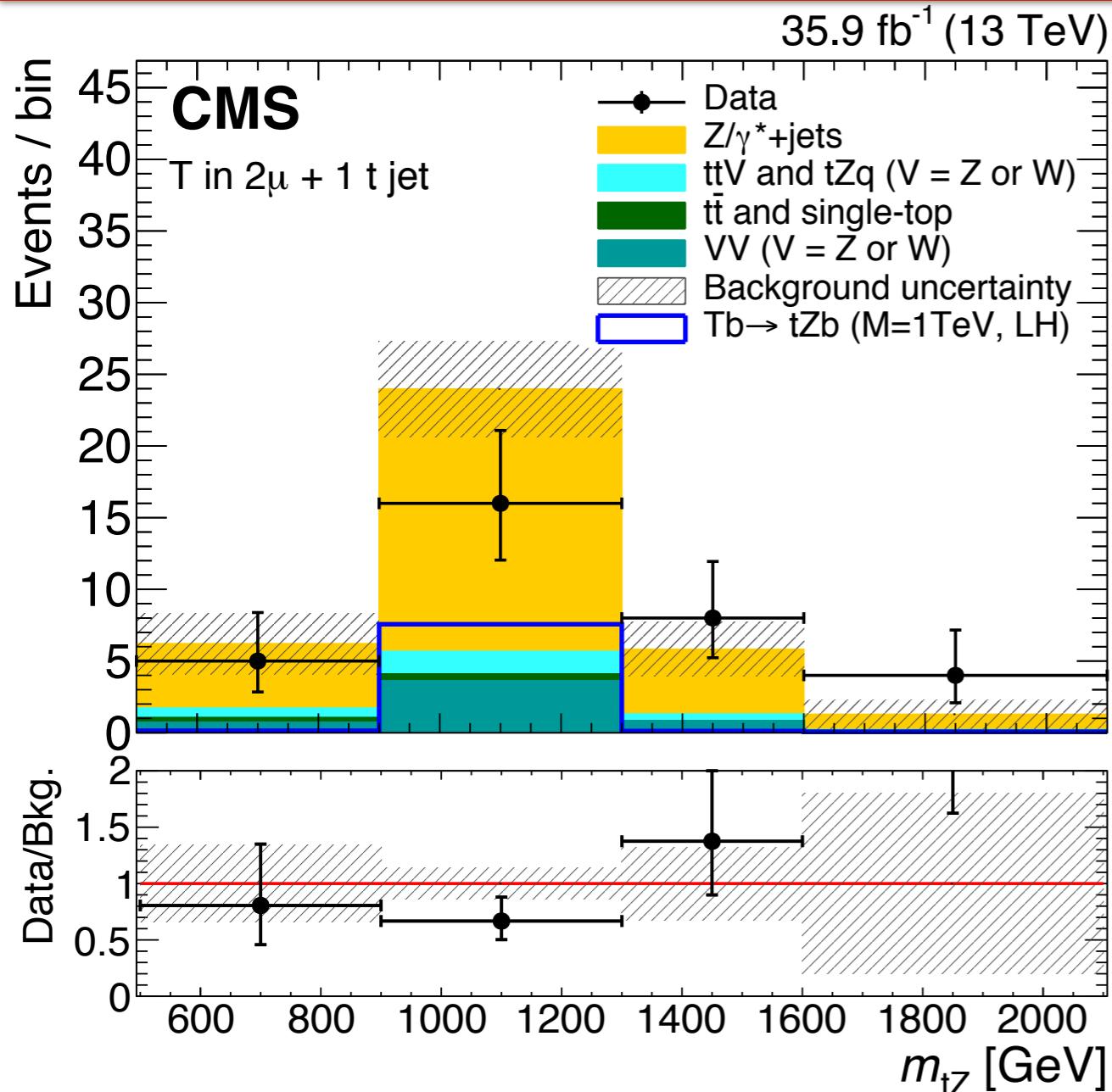


# T $\rightarrow$ tZ Analysis

- Analysis searches for vector like T quark in the single production channel
  - T VLQ produced in association with far forward jets
    - Left-Handed (Singlet):  $B(T \rightarrow bW) = 0.50$ ,  $B(T \rightarrow tZ) = 0.25$ , and  $B(T \rightarrow tH) = 0.25$
    - Right-Handed (Doublet):  $B(T \rightarrow tZ) = 0.50$  and  $B(T \rightarrow tH) = 0.50$
  - Analysis searches in  $\ell\ell b\bar{q}q$  channel
- High-p<sub>T</sub> lepton
  - Small  $\Delta R$  between leptons
- Jets are well separated from leptons
- Three different t-tagging techniques used



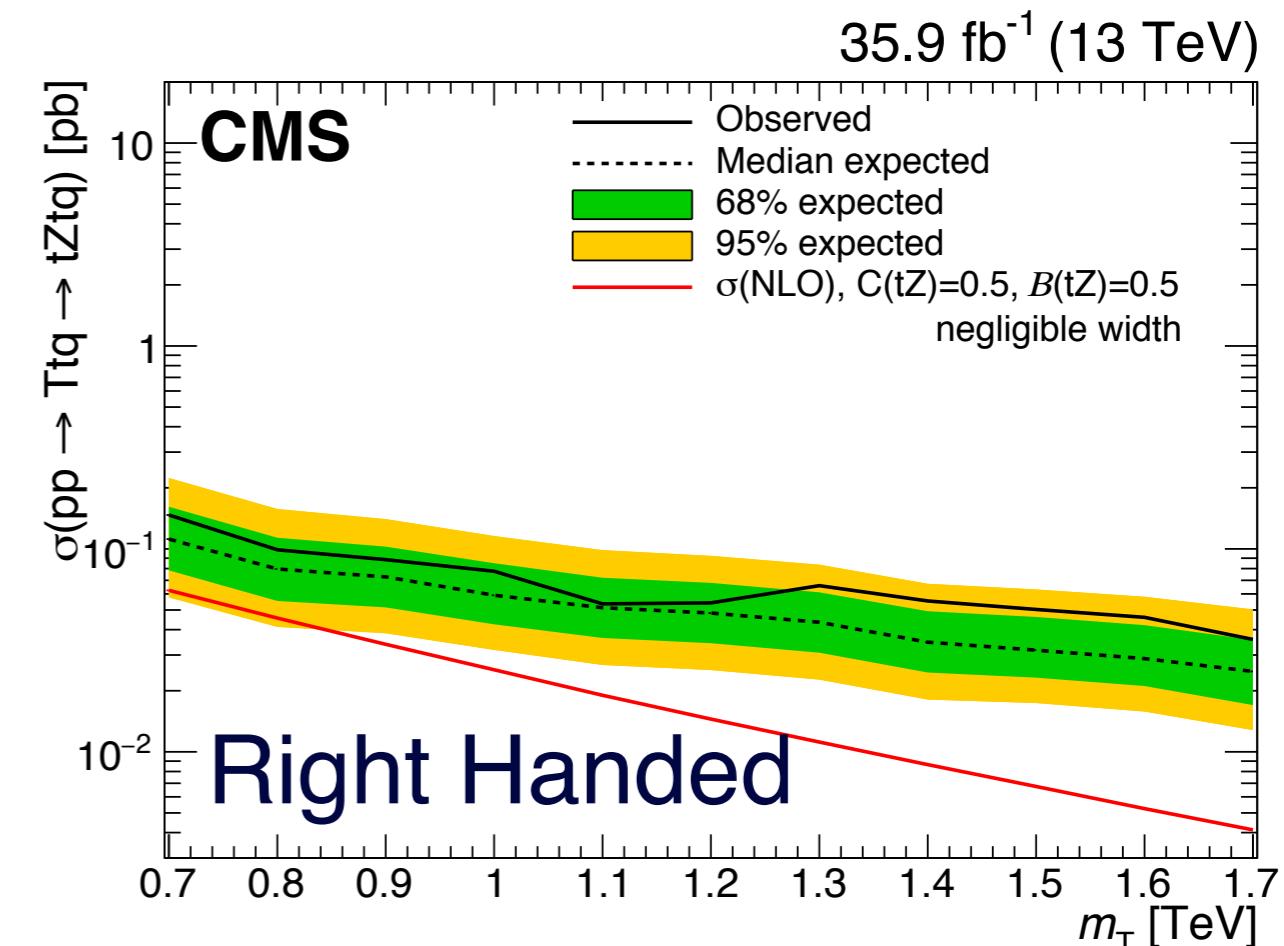
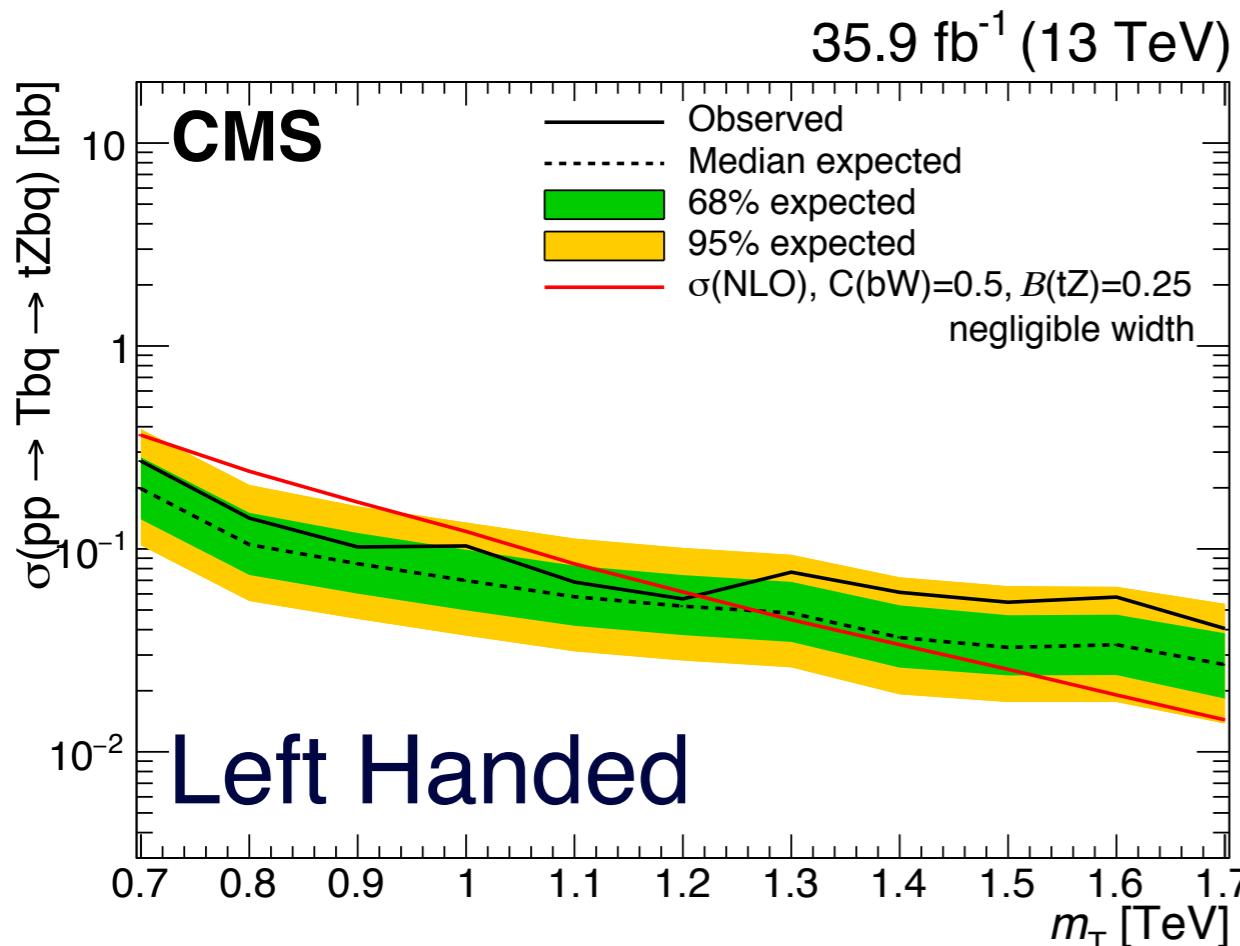
# $T \rightarrow tZ \rightarrow \ell\ell b\bar{q}q$ Results



- 10 different categories covering the different lepton flavors (e and  $\mu$ ), the amount of merging of the hadronic top decay, and the number of additional forward jets
- Z+Jets background modeled from data, and all other backgrounds from MC



# VLQ T: Narrow Width Limits

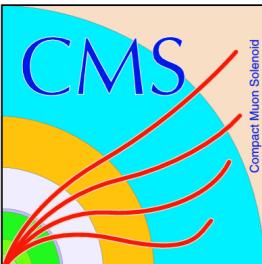
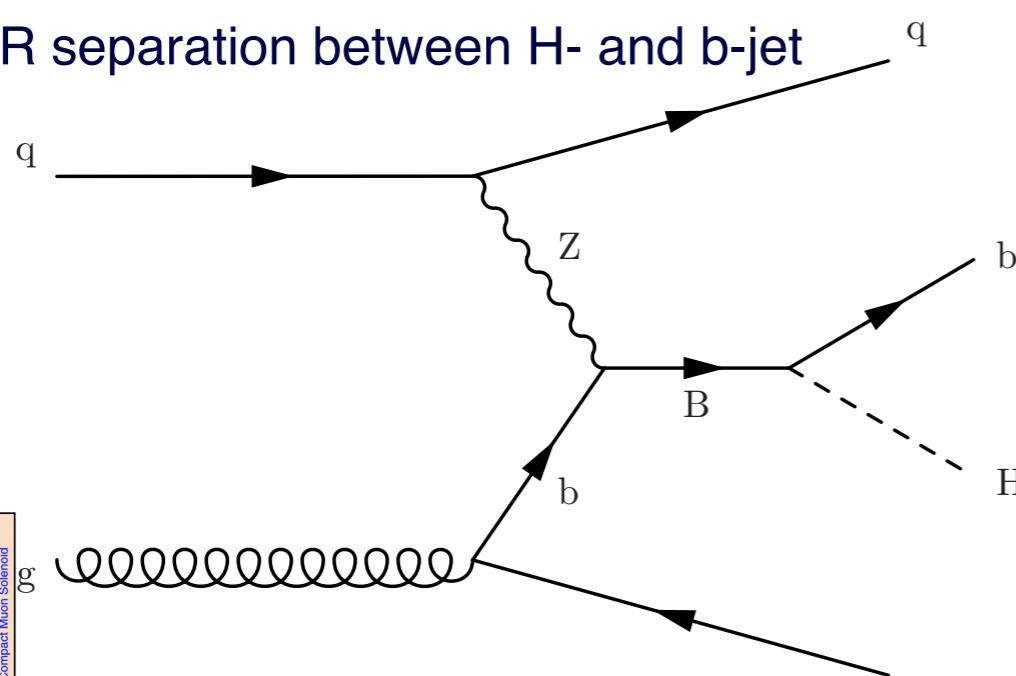
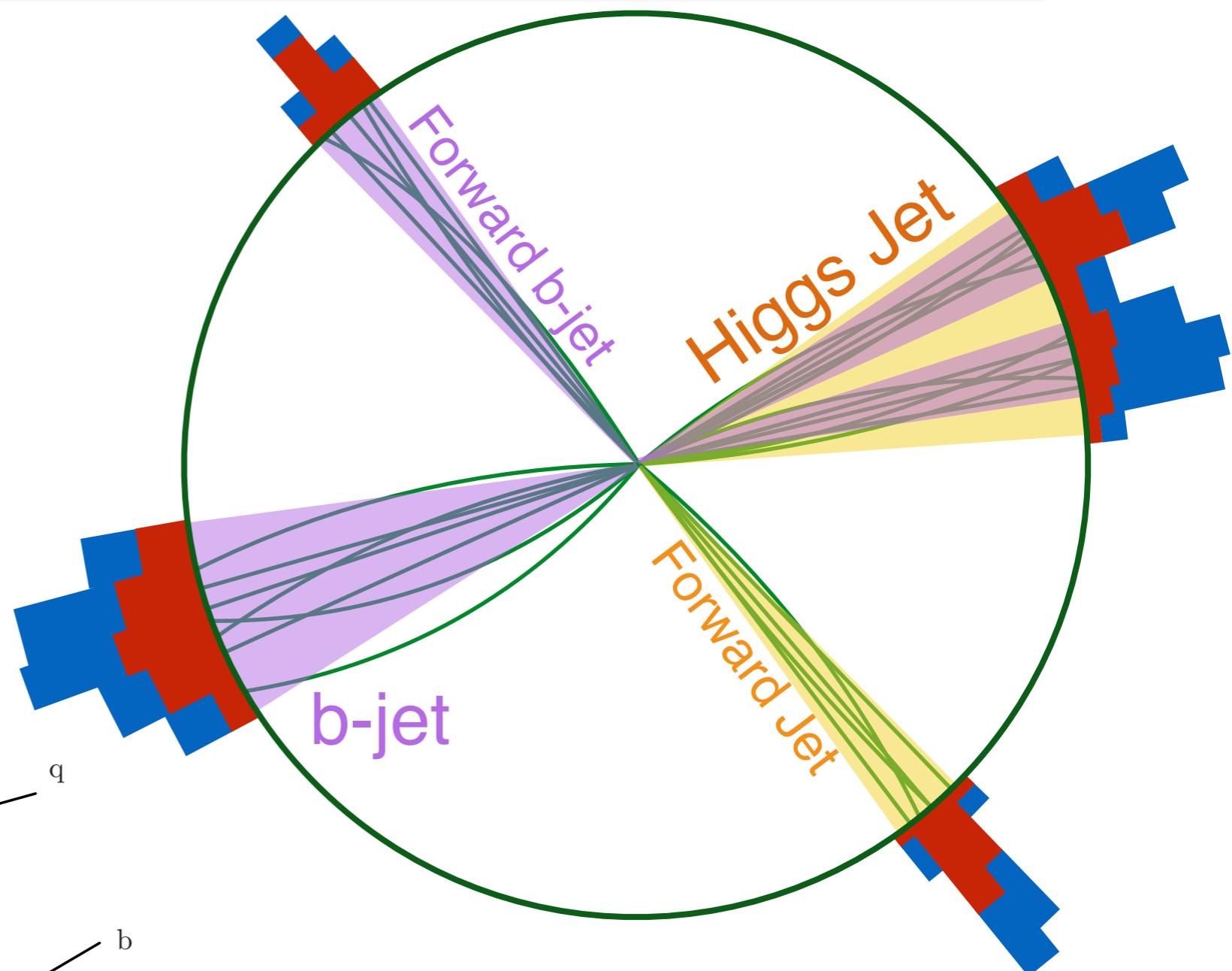


- 95% CL limits calculated using frequentist asymptotic CLs approach
- A left-handed VLT with  $C(\text{bW})=0.5$  is excluded with a mass below 1.2 TeV at 95% CL
- Right-handed VLT is not excluded due to smaller production cross section
- Exclusion limits for wider VLT can be found in backup slides
  - Largest uncertainty is the Z+Jet background model
    - Especially in categories with low statistics



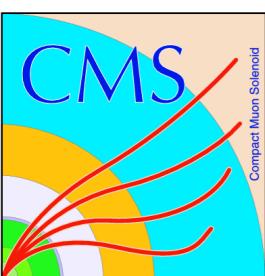
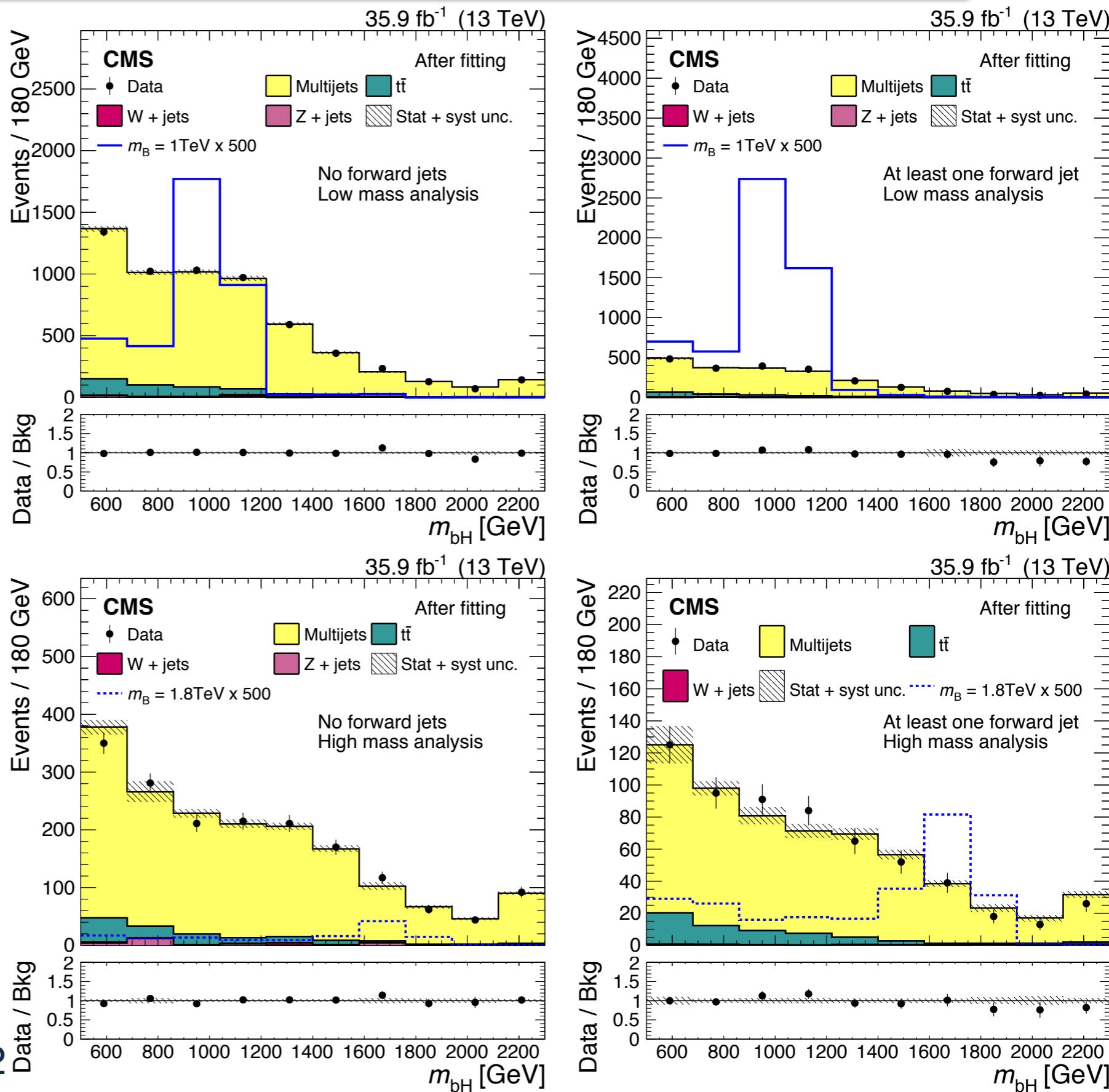
# B $\rightarrow$ Hb Analysis

- Searches for a VLB in the bbb channel
  - B is produced in association with forward jets
    - Left-Handed (Singlet):  $B(B\rightarrow tW)=0.50$ ,  $B(B\rightarrow bZ)=0.25$ , and  $B(B\rightarrow bH)=0.25$
    - Right-Handed (Doublet):  $B(B\rightarrow bZ)=0.50$  and  $B(B\rightarrow bH)=0.50$
- Large amount of  $H_T$
- At least 3 jets
  - One of which is b-tagged
  - One H-tagged jet pair
- Large  $\Delta R$  separation between H- and b-jet



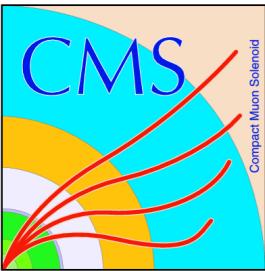
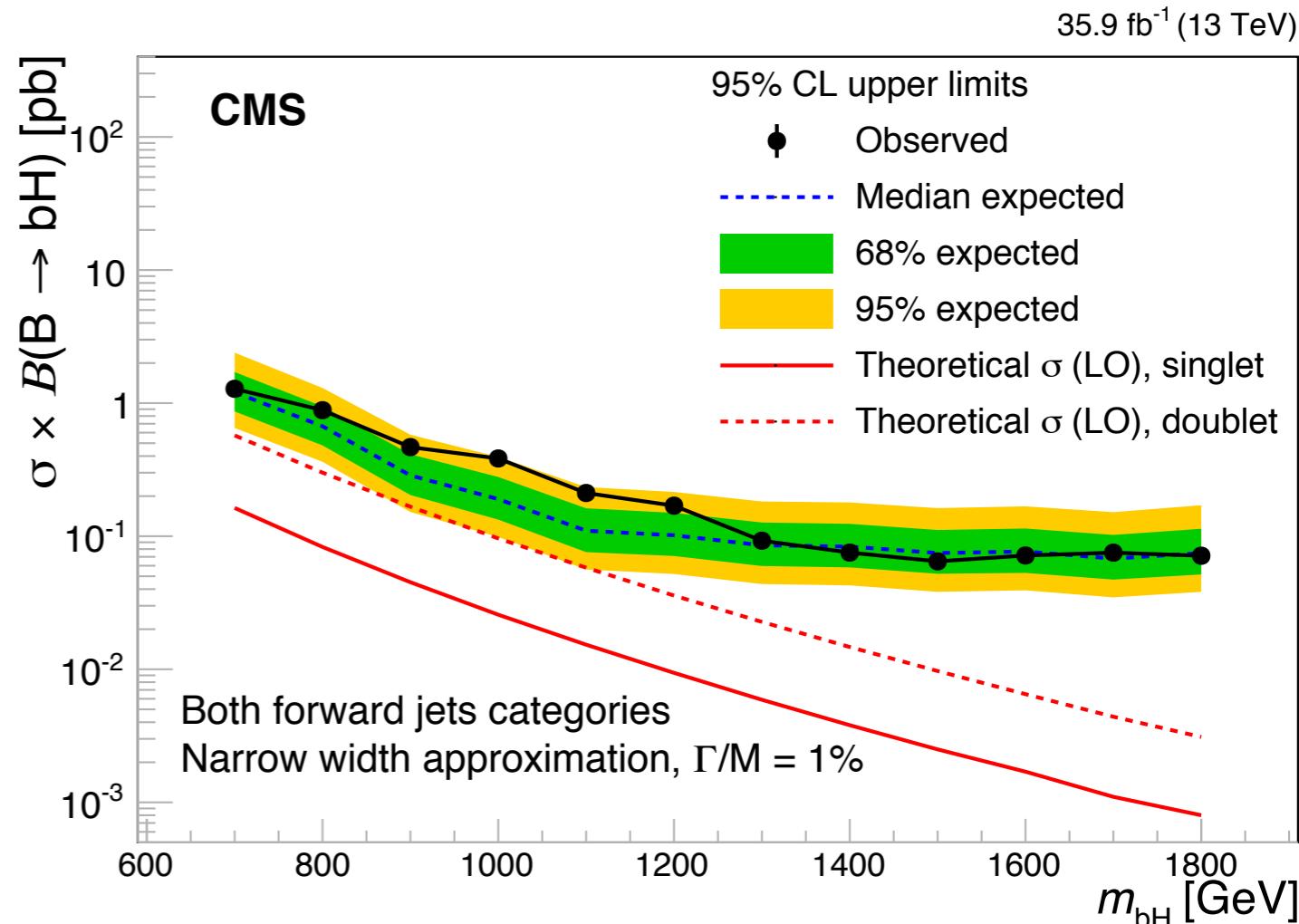
# B $\rightarrow$ Hb $\rightarrow$ bbb Results

- Number of additional forward jets and  $H_T$  used for event categorization
- Low  $H_T$  region optimized for low mass region
- High  $H_T$  region optimized for high mass search region



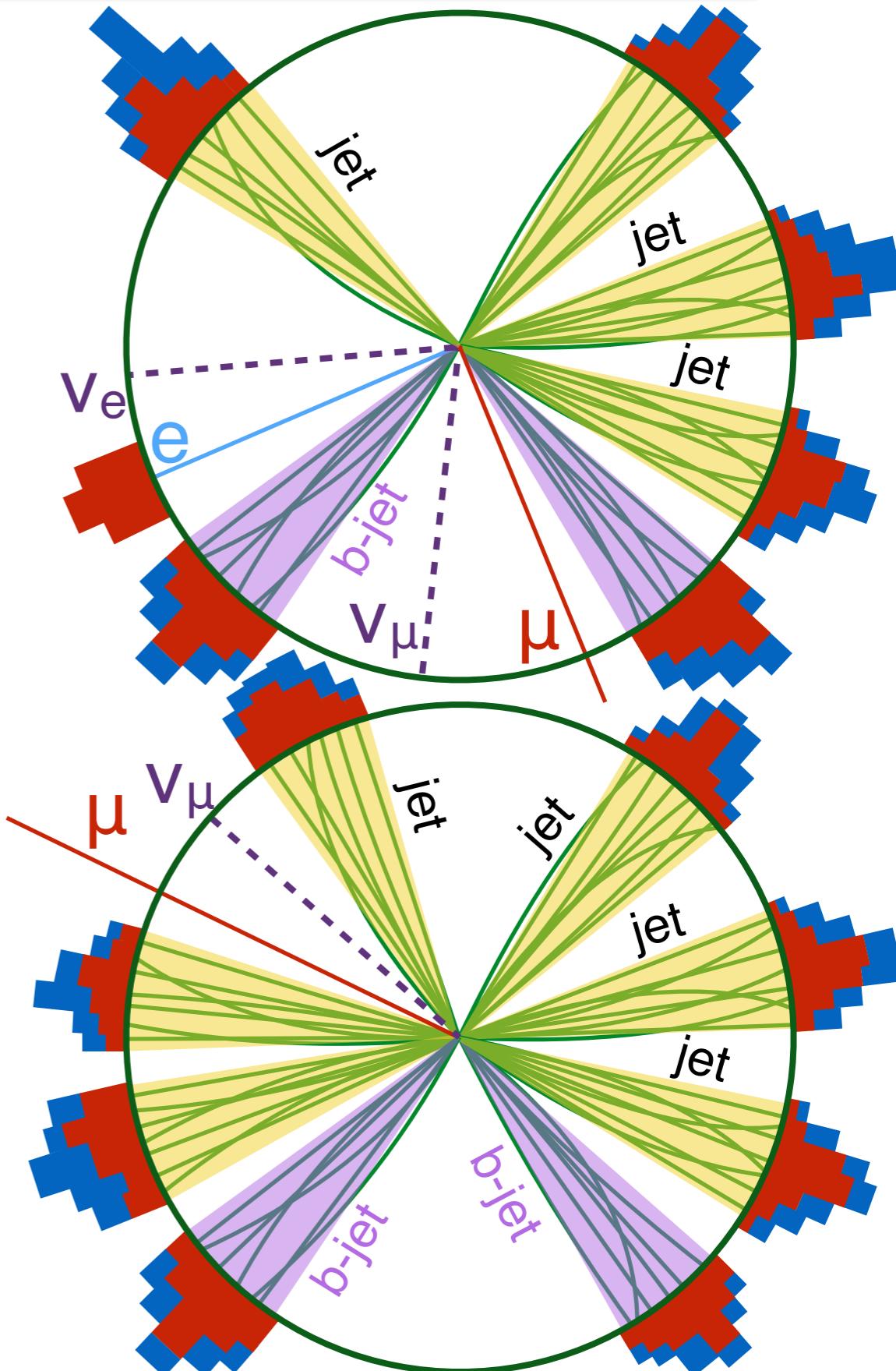
# B $\rightarrow$ Hb $\rightarrow$ bbb Limits

- Factorization and renormalization scale uncertainty is the largest systematic uncertainty
- Second largest uncertainty is on the QCD multijet background
- 95% CL limits calculated using frequentist asymptotic CLs approach
- Narrow VLB is not excluded under the narrow width hypothesis (NWA)
- Stronger exclusion limits for wider resonances
  - Limits for  $\Gamma_B = 1\%, 10\%, 20\%$ , and 30% in backup slides



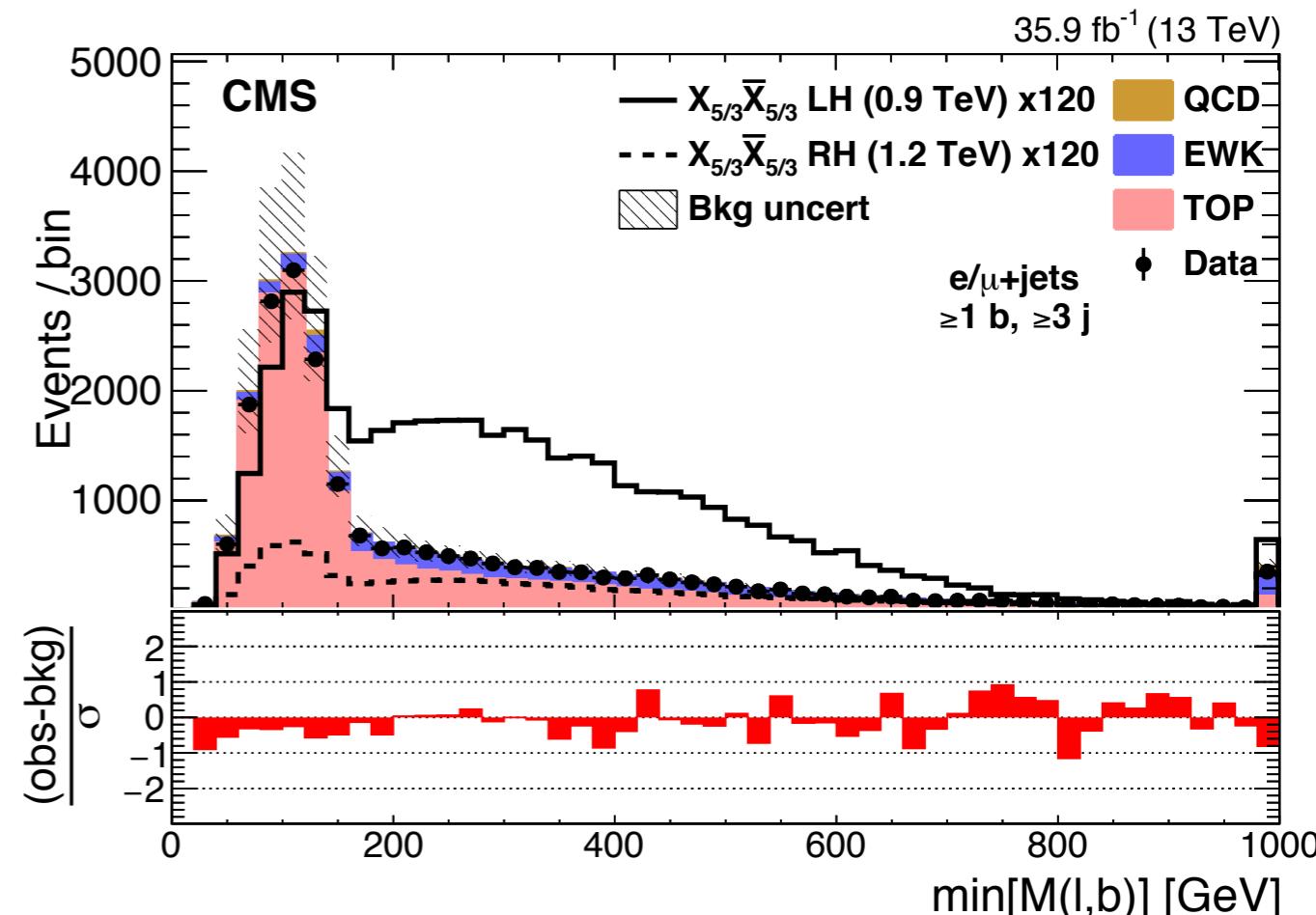
# X<sub>5/3</sub>X<sub>5/3</sub> → WtWt Analysis

- Analysis searches for the pair production of charge 5/3 VLQs decaying to a tW
- Analysis covers the single lepton and dilepton same-sign channels
- Same-sign dilepton channel
  - Two same-sign leptons
  - $M_{\ell\ell} > 20$  GeV,  $M_Z$  veto, and at least 2 jets, at least 5 additional leptons or jets, and a high  $H_{T\text{lep}}$  requirement
- Single Lepton Channel
  - Exactly one high- $p_T$  lepton
    - Lepton is either isolated or passes  $p_{T\text{rel}}$  selection
    - Large MET and at least 4 jets
      - One of which is b-tagged
    - Minimum  $\Delta R$  between the lepton and sub-leading jet
    - Minimum requirement on the invariant mass of the lepton and all b-jets

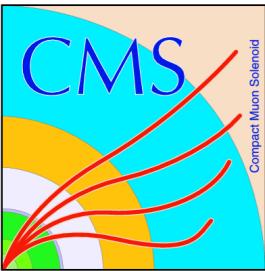


# $X_{5/3}X_{5/3} \rightarrow WtWt$ Yields

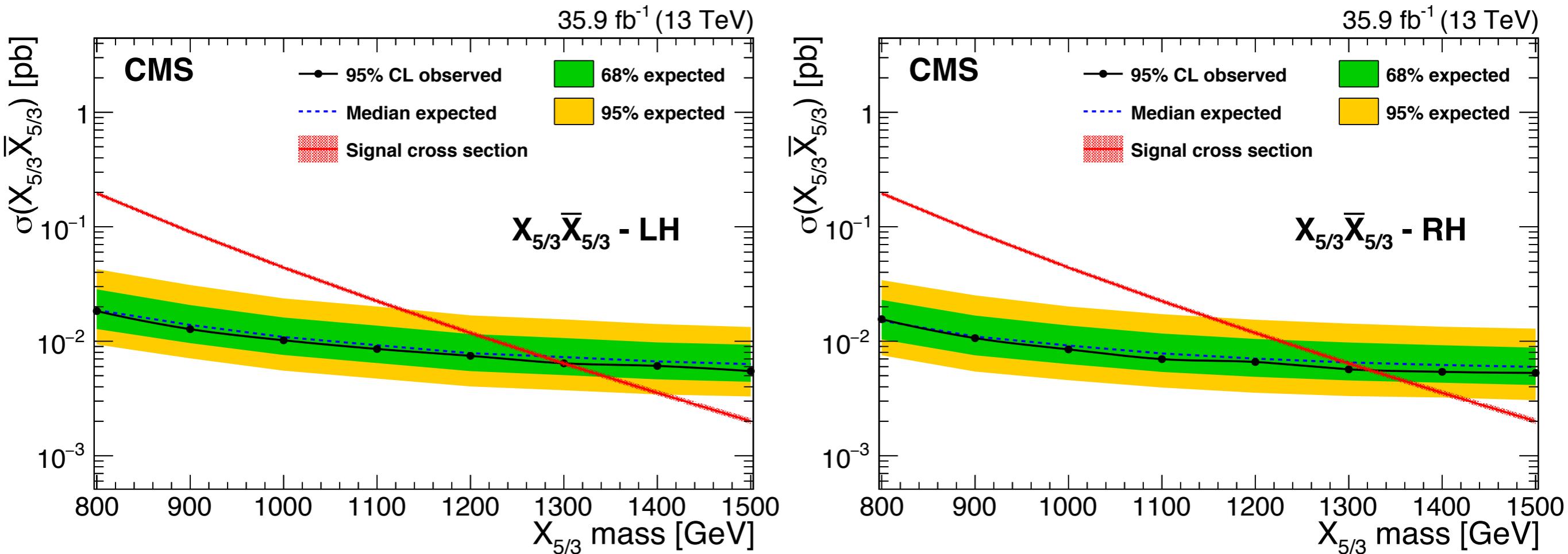
- 16 channels in the single lepton channel based on the lepton flavor, number of b-tagged jets, number of W-tagged jets, and the number of t-tagged jets
  - Single lepton backgrounds modeled using simulation
- 3 different search regions in the dilepton channel based on lepton flavor
  - Same sign dilepton background estimated from MC (prompt) and data (Non-prompt and charge Mis-ID)



- Simultaneous fit of all single lepton and dilepton categories using background only hypothesis to extract best fit cross sections
- Largest systematic uncertainties are jet energy scales and the QCD renormalization and factorization scale



# $X_{5/3}X_{5/3} \rightarrow WtWt$ Limits



## Analysis

## Observed Limit

## Expected Limit

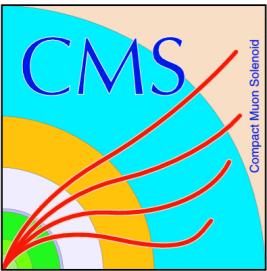
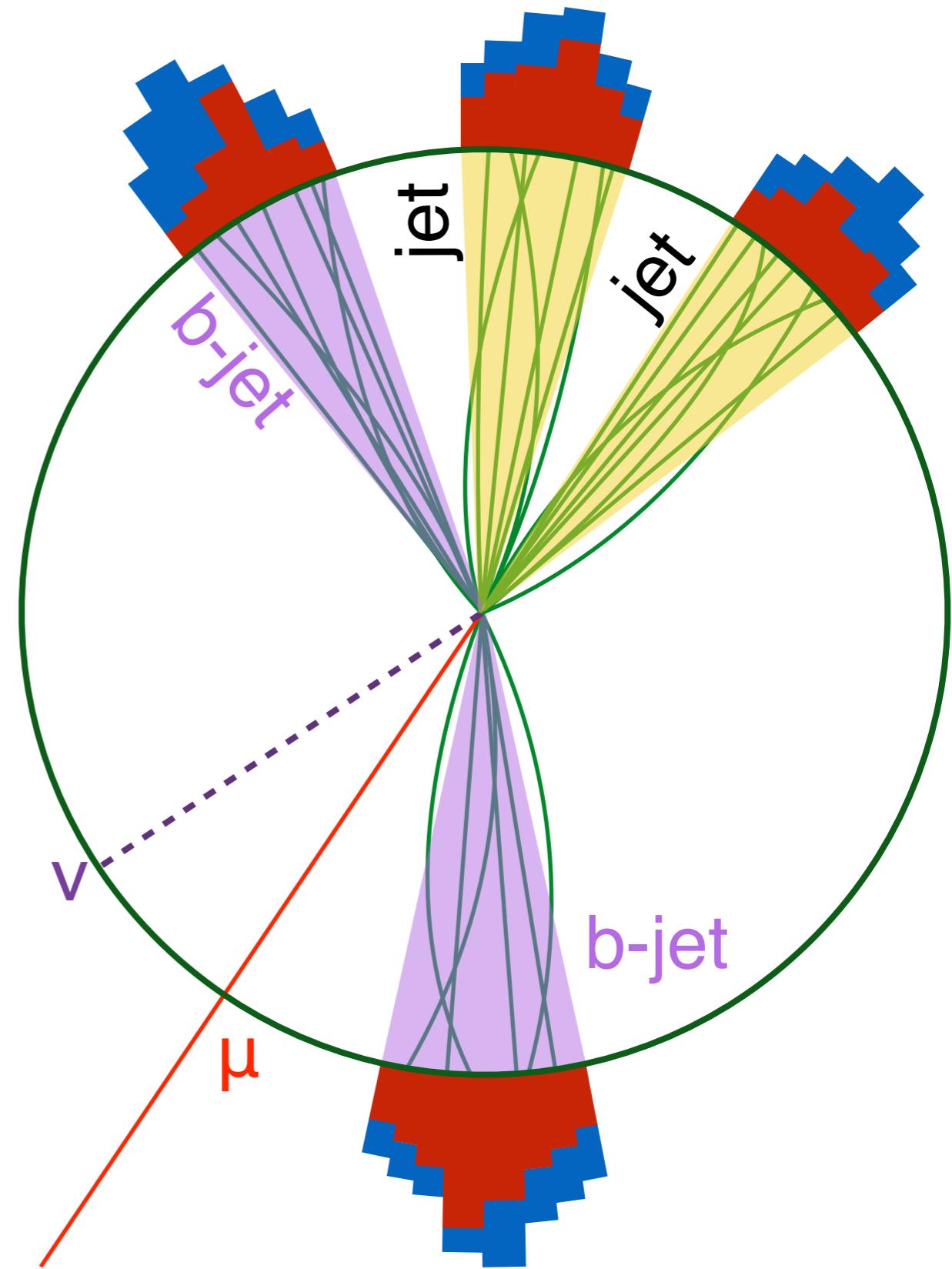
	Left-Handed	Right-Handed	Left-Handed	Right-Handed
Same Sign	1.10 TeV	1.16 TeV	1.16 TeV	1.20 TeV
Single Lepton	1.30 TeV	1.32 TeV	1.23 TeV	1.23 TeV
Combined	1.30 TeV	1.28 TeV	1.33 TeV	1.30 TeV



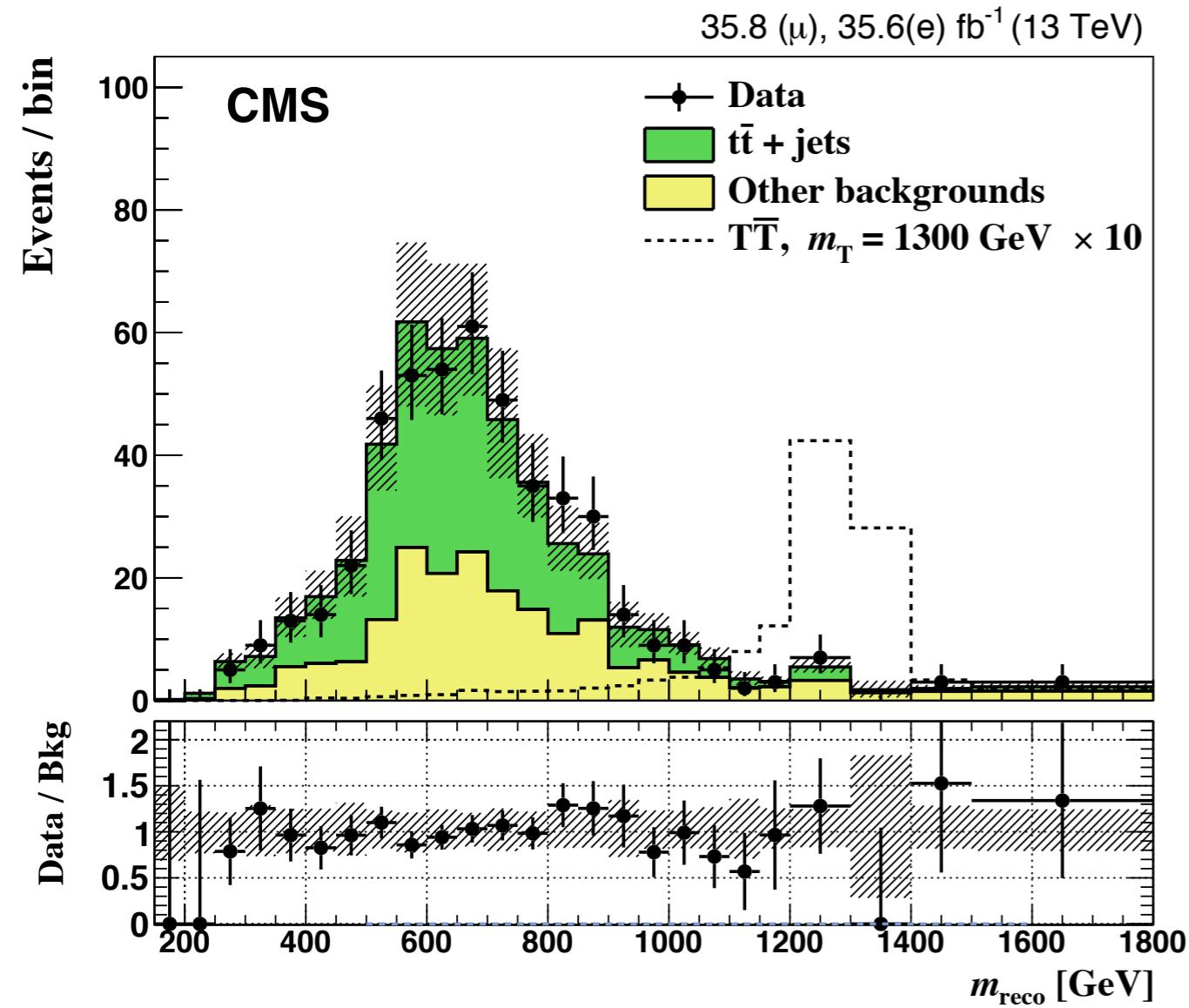
- Bayesian methods used to derive 95% CL upper limits

# $T\bar{T} \rightarrow WbW\bar{b}$ Analysis

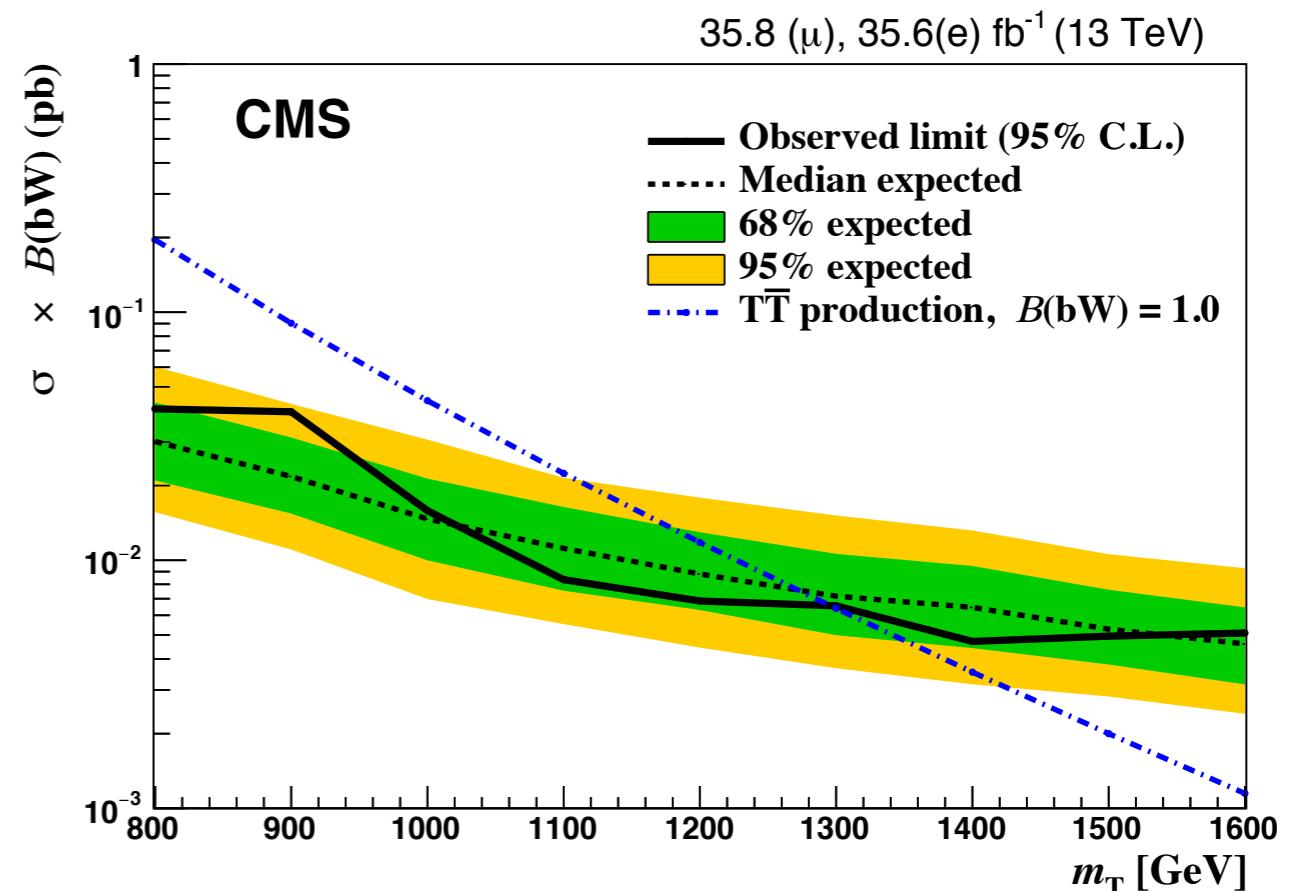
- Analysis search for pair produced VLTs
  - $B(T \rightarrow bW) = 1.0$
- Search is performed in the single lepton channel  $b\ell v bqq$
- Exactly one charged lepton ( $e$  or  $\mu$ ) is required
- At least 4 jets
- Boosted W-tagging used for categorization



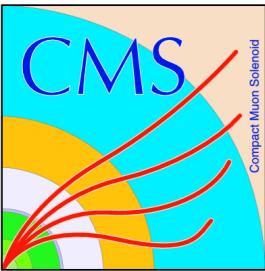
# $T\bar{T} \rightarrow WbW\bar{b}$ Results and Limits



- $m_{\text{RECO}}$  is the reconstructed  $T_{Wb}$  mass

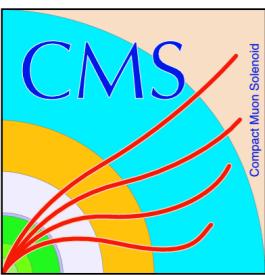
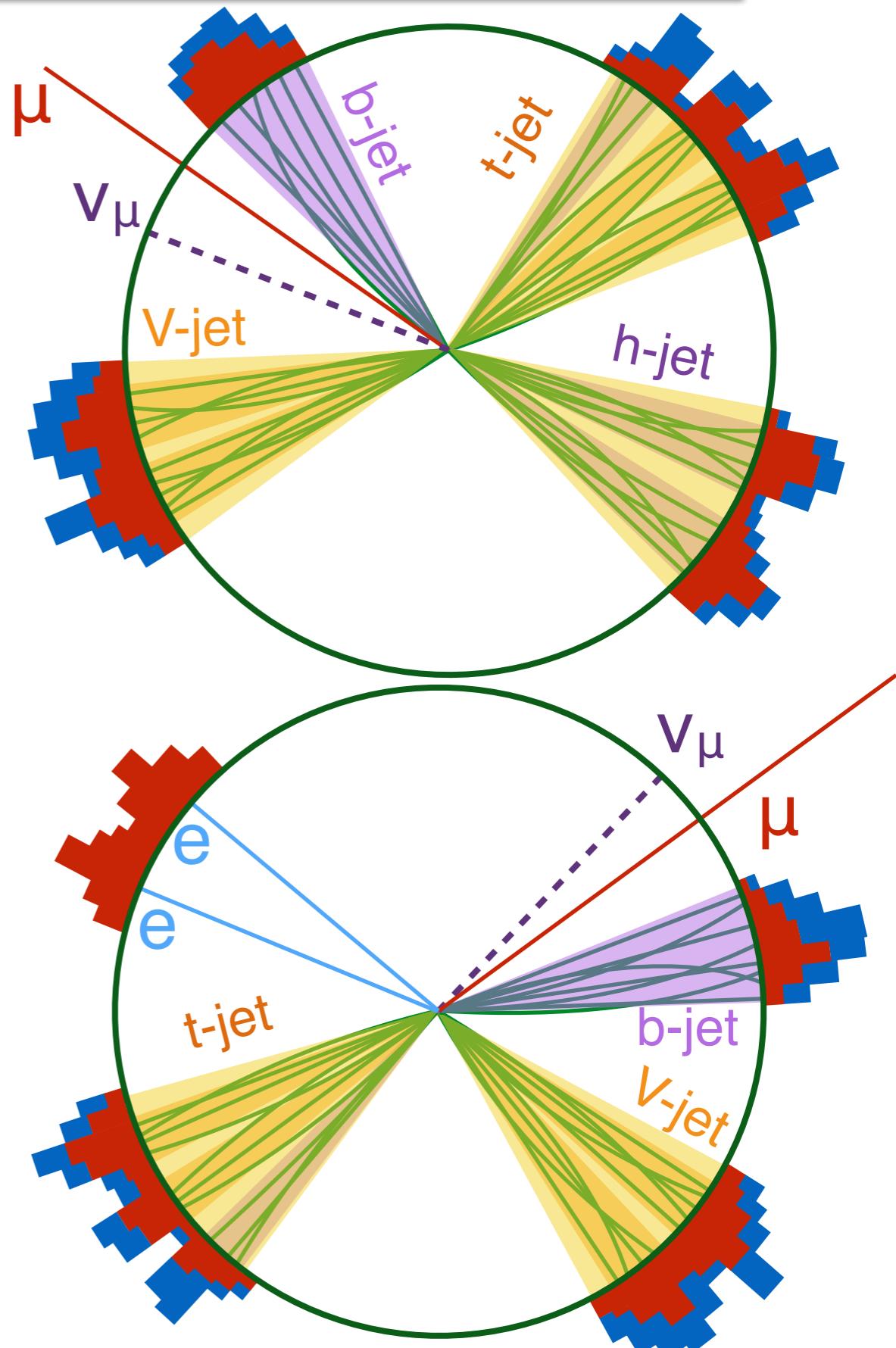


- Bayesian methods used to derive 95% CL upper limits
  - Largest systematic uncertainty is the renormalization and factorization scales and the top  $p_T$  spectrum
  - Pair production of  $T\bar{T}$  excluded up to 1.3 TeV



# T $\bar{T}$ (B $\bar{B}$ ) $\rightarrow$ bW/tZ/tH(tW/bZ/bH) Analysis

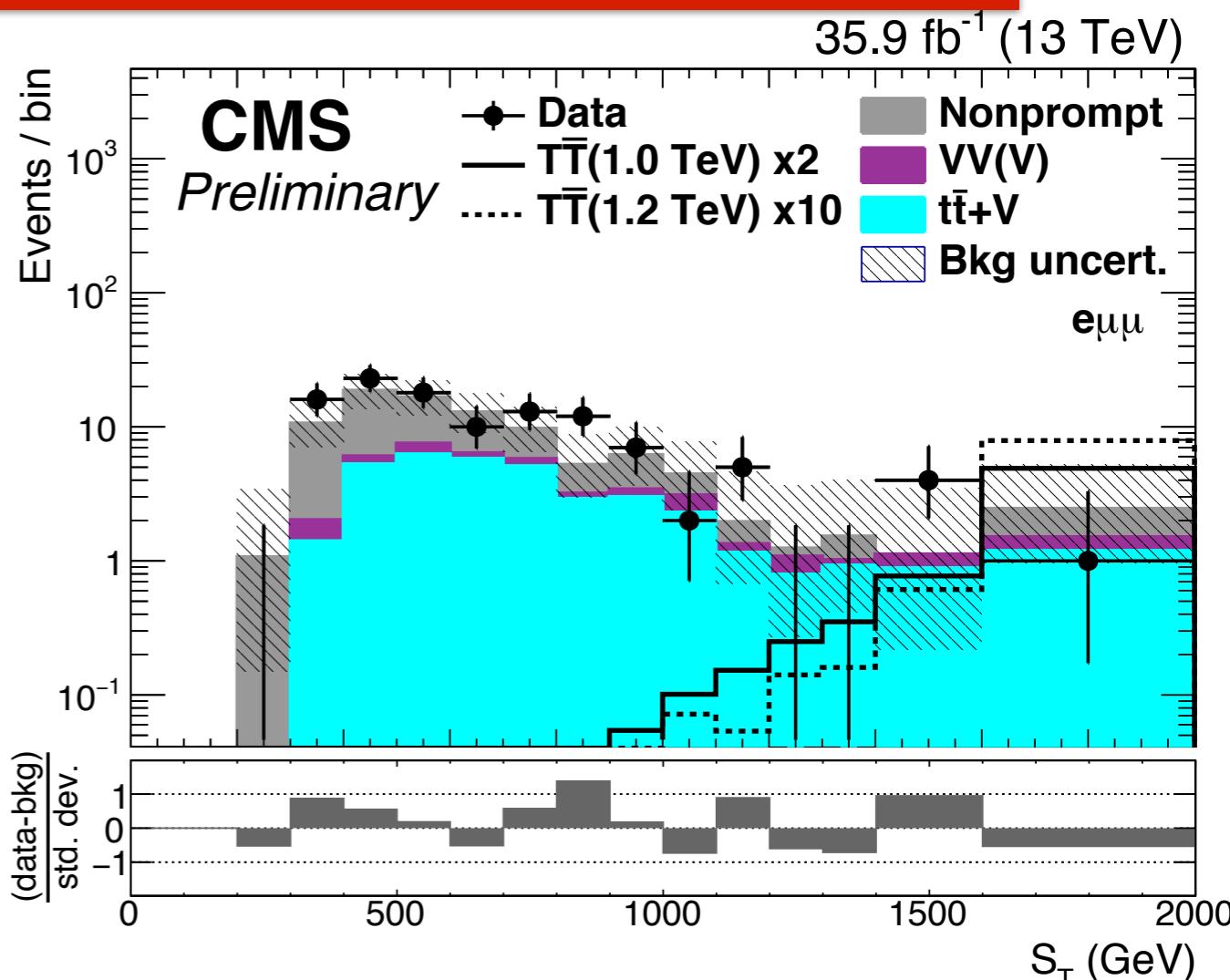
- Search for vector like T $\bar{T}$  or B $\bar{B}$  pair production
- Single Lepton Channel
  - Exactly 1 high- $p_T$  lepton (e or  $\mu$ )
  - MET requirement
  - At least 3 jets and 2 large radius jets
- Same-Sign Dilepton Channel
  - Two leptons with the same charge
  - Minimum  $M_{\ell\ell}$  and  $M_Z$  veto window
  - Requires 4 jets
  - Large  $H_{T\text{lep}}$  requirement
- Trilepton Channel
  - Three Leptons
    - Minimum pair-wise  $M_{\ell\ell}$  selection
    - At least 3 jets



# $T\bar{T}(B\bar{B}) \rightarrow bW/tZ/tH(tW/bZ/bH)$ Results

Sample	ee	e $\mu$	$\mu\mu$
$T\bar{T}$ (1.0 TeV)	$1.34 \pm 0.08$	$3.11 \pm 0.18$	$2.12 \pm 0.12$
$T\bar{T}$ (1.2 TeV)	$0.42 \pm 0.02$	$1.00 \pm 0.06$	$0.66 \pm 0.04$
Prompt SS	$4.03 \pm 0.57$	$10.2 \pm 1.4$	$5.79 \pm 0.82$
Nonprompt	$4.6 \pm 2.6$	$10.6 \pm 5.6$	$5.4 \pm 3.0$
Charge misid.	$4.1 \pm 1.3$	$2.61 \pm 0.81$	—
Total Bkg	$12.8 \pm 3.0$	$23.4 \pm 5.8$	$11.2 \pm 3.1$
Data	12	31	9
Data/Bkg	$0.94 \pm 0.35$	$1.33 \pm 0.41$	$0.80 \pm 0.35$

- 16 single lepton categories based on lepton flavor, and b-, W-, and H-tagging
- Three same-sign dilepton flavor categories
- 4 trilepton flavor categories
- Prompt backgrounds derived from MC

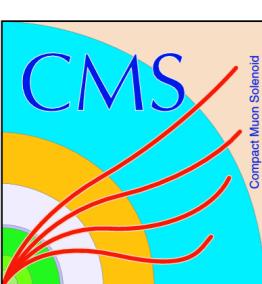
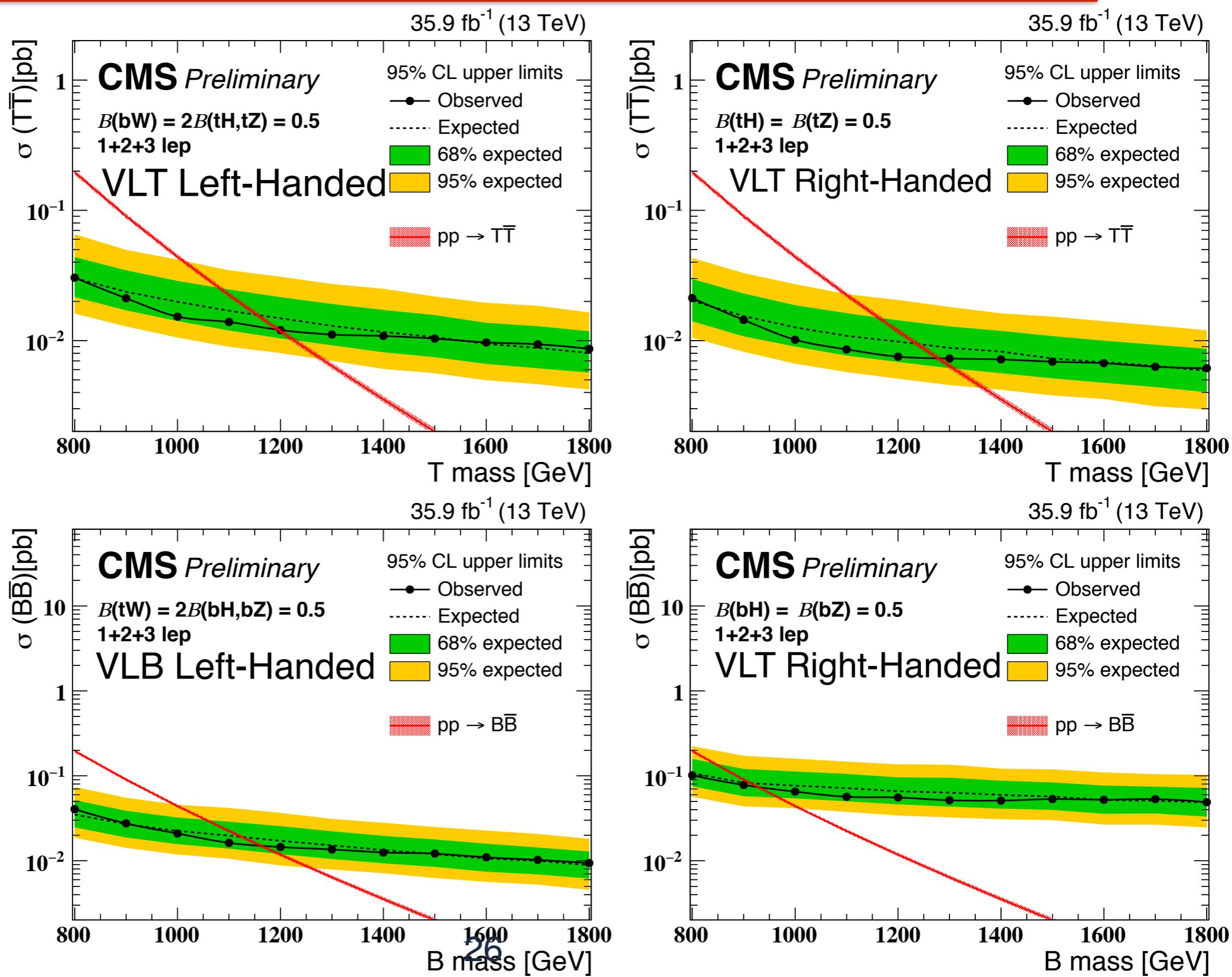


- Non-prompt and charge mis-IDed lepton background derived from data using tight-to-loose technique in dedicated control regions
- Largest systematics are due to lepton fake rate and charge mis-ID



# $T\bar{T}(B\bar{B}) \rightarrow bW/tZ/tH(tW/bZ/bH)$ Limits

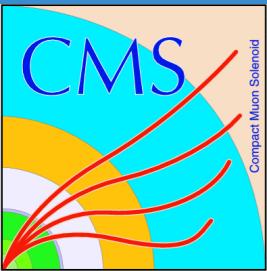
- Bayesian methods used to derive 95% CL upper limits



D. Berr

# VLQ Limit Summary

Model	Observed Exclusion		Expected Exclusion	
	Left Handed	Right Handed	Left Handed	Right Handed
$T \rightarrow tZ$	1.2 TeV	-	1.25 TeV	-
$B \rightarrow Hb$	-	-	-	-
$X_{5/3} \bar{X}_{5/3} \rightarrow tWtW$	1.30 TeV	1.28 TeV	1.33 TeV	1.30 TeV
$T\bar{T} \rightarrow Wb\bar{W}\bar{b}$	1.295 TeV		1.275 TeV	
$T\bar{T} \rightarrow bW/tZ/tH$	1.20 TeV	1.28 TeV	1.16 TeV	1.24 TeV
$B\bar{B} \rightarrow tW/bZ/bH$	1.17 TeV	0.94 TeV	1.13 TeV	0.92 TeV



# Summary

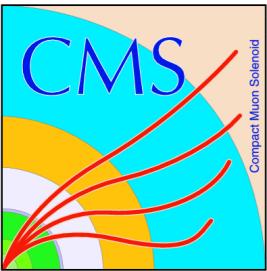
- Results were present for many Beyond the Standard Model Searches that decay to third generation quarks and leptons
- All of the analyses make use of tagging techniques: b-, W-, H-, or t-tagging
- $W'_R$  excluded to 3.4 and 3.6 TeV depending on  $M_{vR}$
- Third generation leptoquarks ( $LQ_3$ ) are excluded up to 900 GeV
- Pair production of RS excitations of the top quark ( $t^*$ ) are excluded up to 1.2 TeV
- Single VLT production excluded up to 1.2 TeV
  - No exclusion on single VLB production under the NWA
- Pair production of VLQ  $X_{5/3}$  excluded up to 1.295 TeV
- Pair production of VLT with  $B(T \rightarrow Wb) = 100\%$  is excluded up to 1.3 TeV
- Pair production of VLTs and Bs excluded to 1.20 and 1.28 and 1.17 and 0.94 TeV for the left- and right-handed cases, respectively



*Thank You*

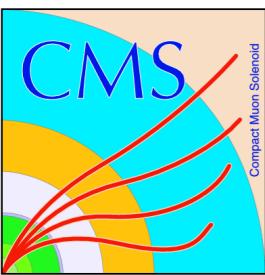


# Backup



# $W' \rightarrow tb \rightarrow \ell v bb$ : Yields

Process	Electron channel				Muon channel			
	Type A		Type B		Type A		Type B	
	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags	1 b tag	2 b tags
<b>Background</b>								
t̄t	760	249	69	22	731	263	75	30
tqb	14	6	1	0	14	6	1	0
tW	117	50	15	5	116	44	22	5
tb	2	2	0	0	3	1	0	0
W( $\rightarrow \ell\nu$ )+jets (LF)	189	17	16	2	177	16	15	1
W( $\rightarrow \ell\nu$ )+jets (HF)	581	98	52	7	631	107	51	8
Z( $\rightarrow \ell\ell$ )+jets	19	11	0	0	64	1	20	0
VV	35	9	2	0	33	1	5	4
Total background	$1717 \pm 62$	$442 \pm 34$	$155 \pm 23$	$36 \pm 7$	$1769 \pm 70$	$439 \pm 30$	$189 \pm 22$	$48 \pm 9$
Data	1750	437	133	40	1754	482	164	44
<b>Signal</b>								
$M_{W'_R} = 2000 \text{ GeV}$	53	43	41	25	79	75	57	35
$M_{W'_R} = 2600 \text{ GeV}$	8	6	16	10	14	12	24	15
$M_{W'_R} = 3200 \text{ GeV}$	2	1	4	3	3	2	8	5

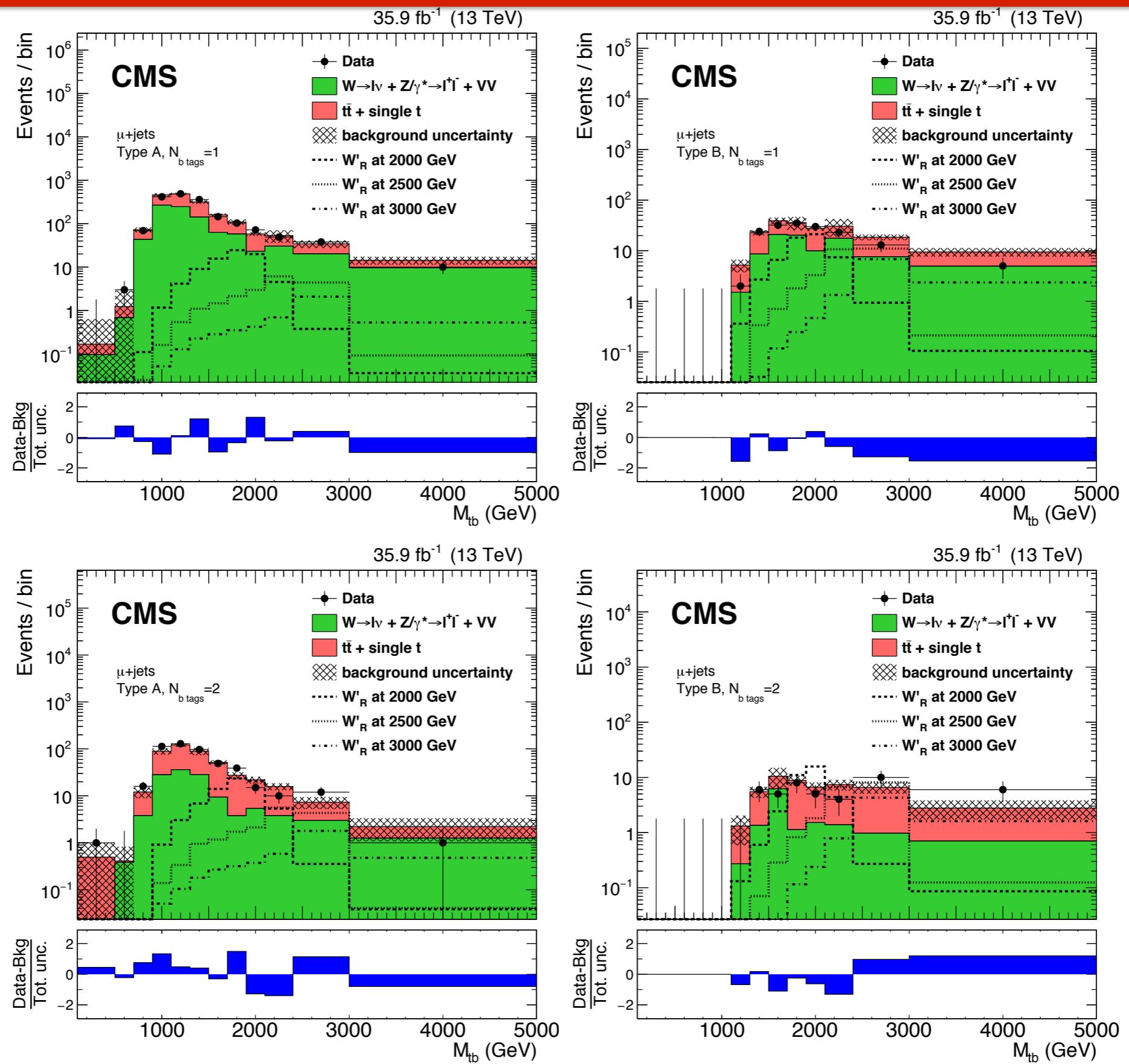


# $W' \rightarrow tb \rightarrow \ell vbb$ : Systematics

Source	Rate uncertainty	Signal
<b>Normalization</b>		
Integrated luminosity	2.5%	✓
$t\bar{t}$ cross section	8%	—
$W+jets$ cross section	10%	—
Trigger eff. ( $e/\mu$ )	2%/2%	✓
Lepton id. eff. ( $e/\mu$ )	2%/2%	✓
<b>Shape and normalization</b>		
Jet energy scale	3%	✓
Jet energy resolution	1%	✓
b/c tagging	2%	✓
Light quark mistagging	2%	✓
Pileup	1%	✓
PDF	6%	✓
Top quark $p_T$ reweighting	15%	—
$W+jets$ heavy/light flavor	1%	—
$\mu_R$ and $\mu_F$ scales	15%	—

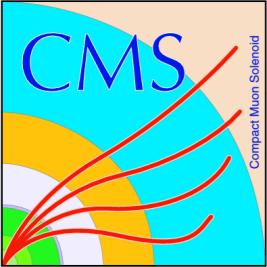
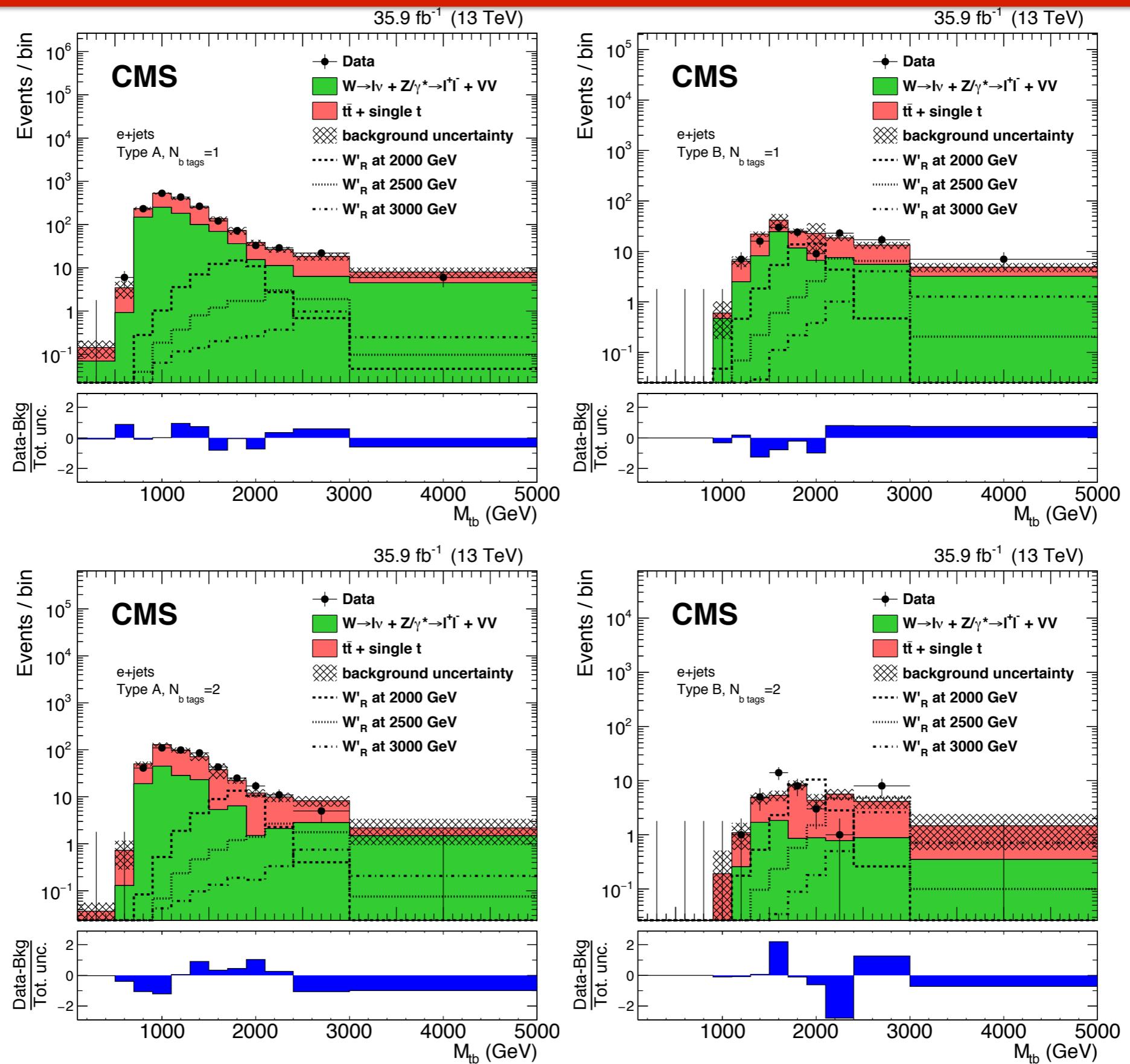


# $W' \rightarrow tb \rightarrow \ell vbb$ : Muon Channel



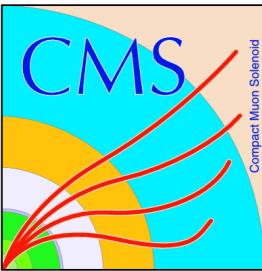
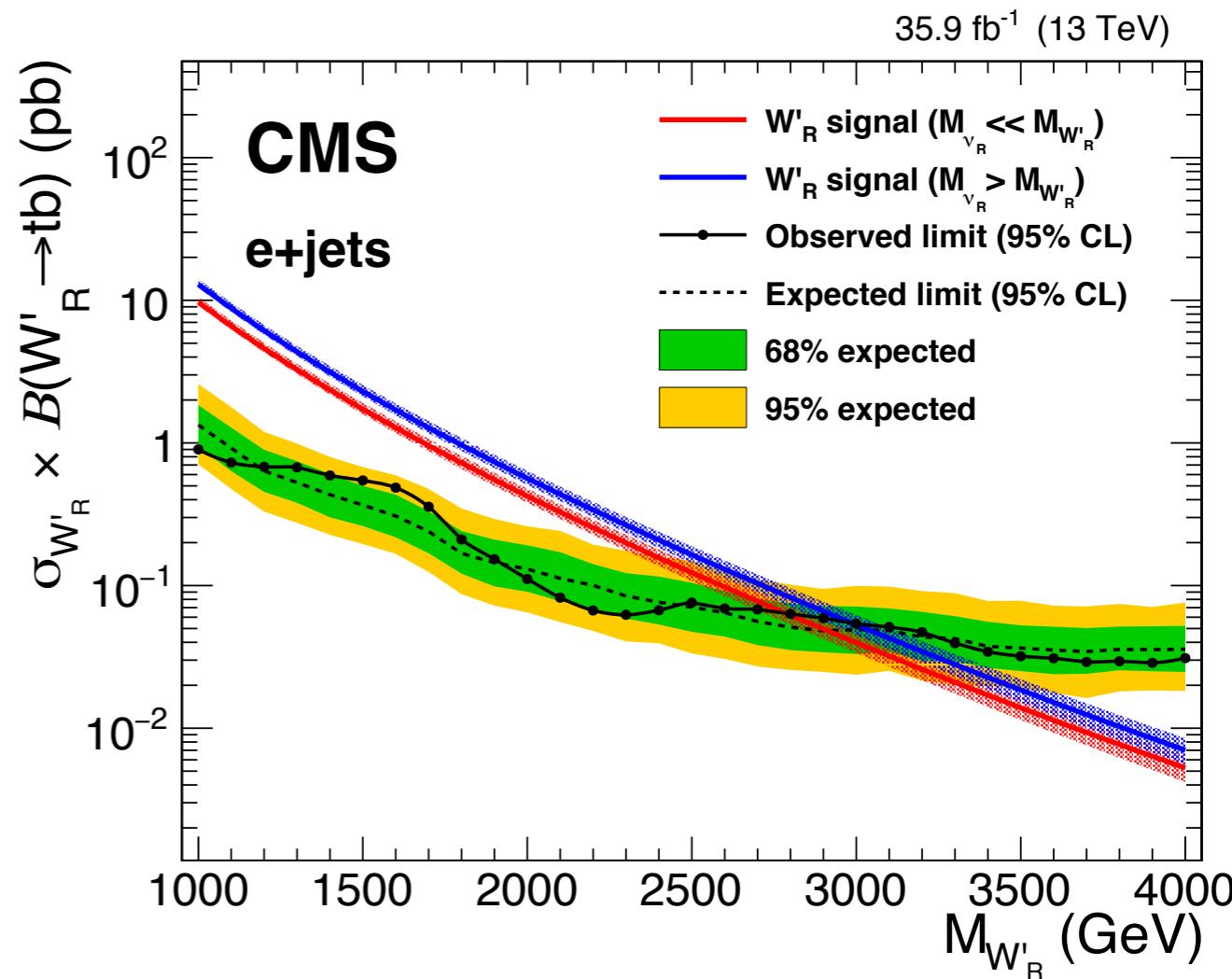
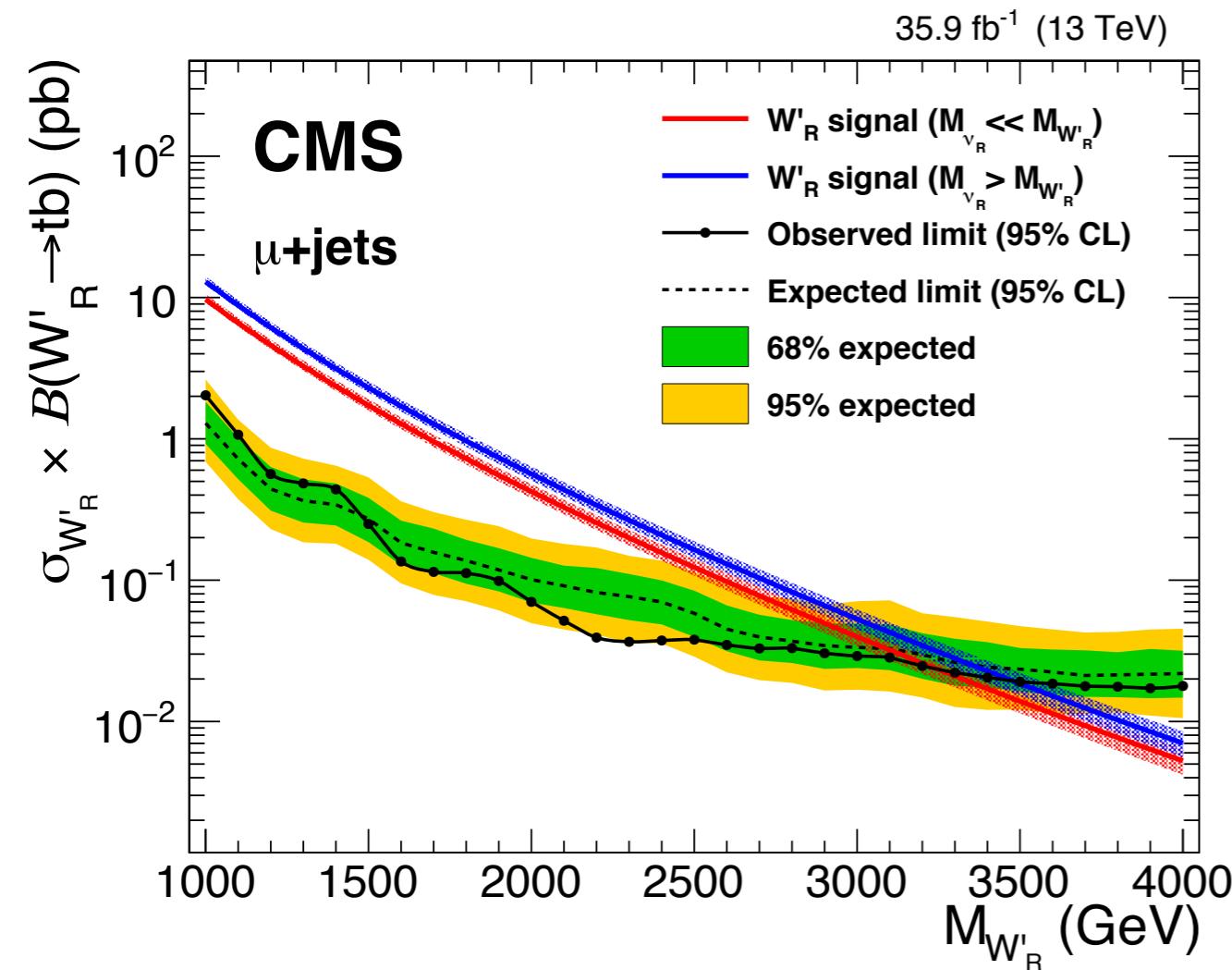
D. Be

# $W' \rightarrow tb \rightarrow \ell vbb$ : Electron Channel



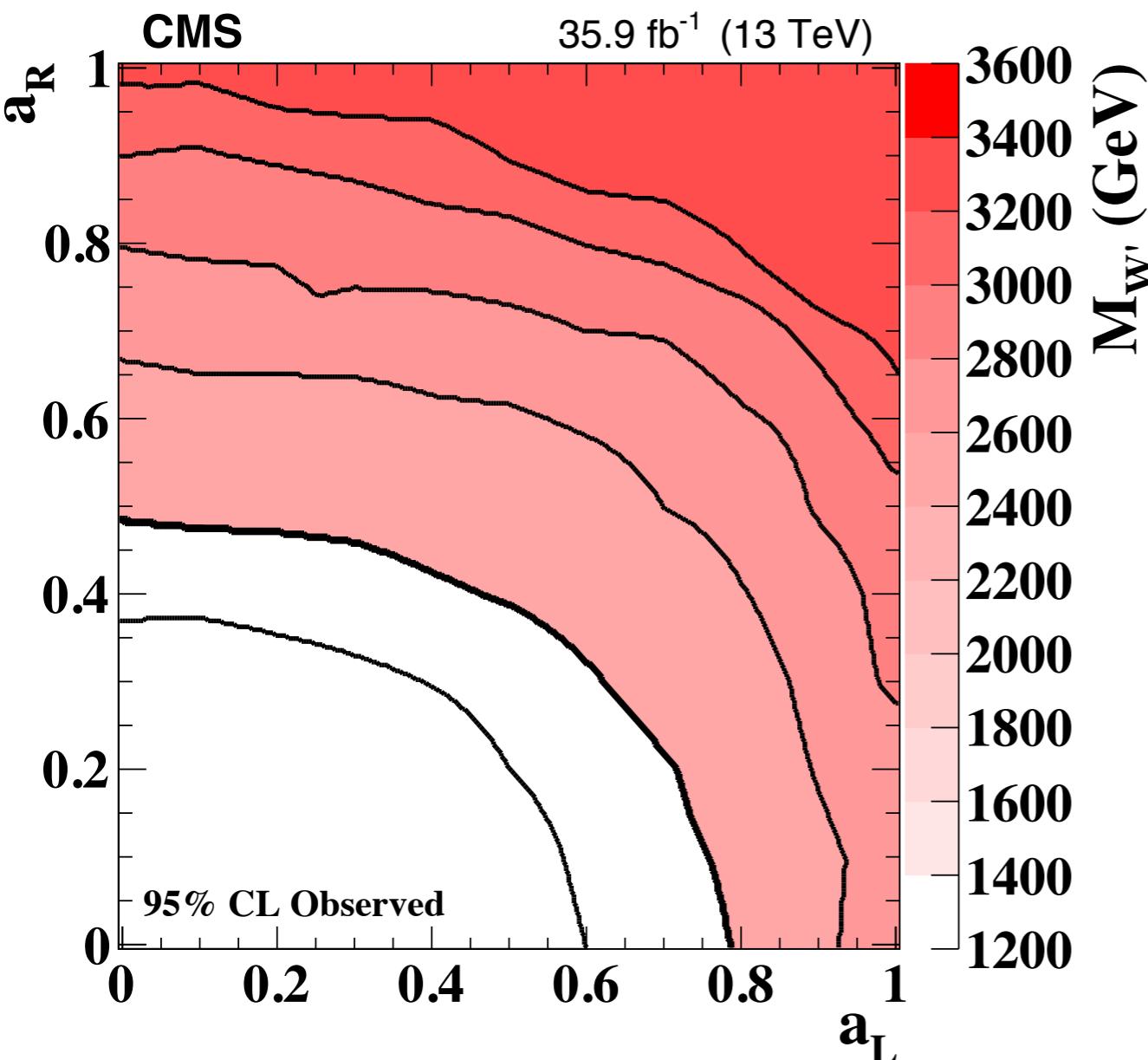
D. Be

# $W' \rightarrow tb \rightarrow \ell vbb$ : Per Channel Limits

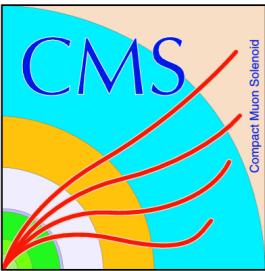
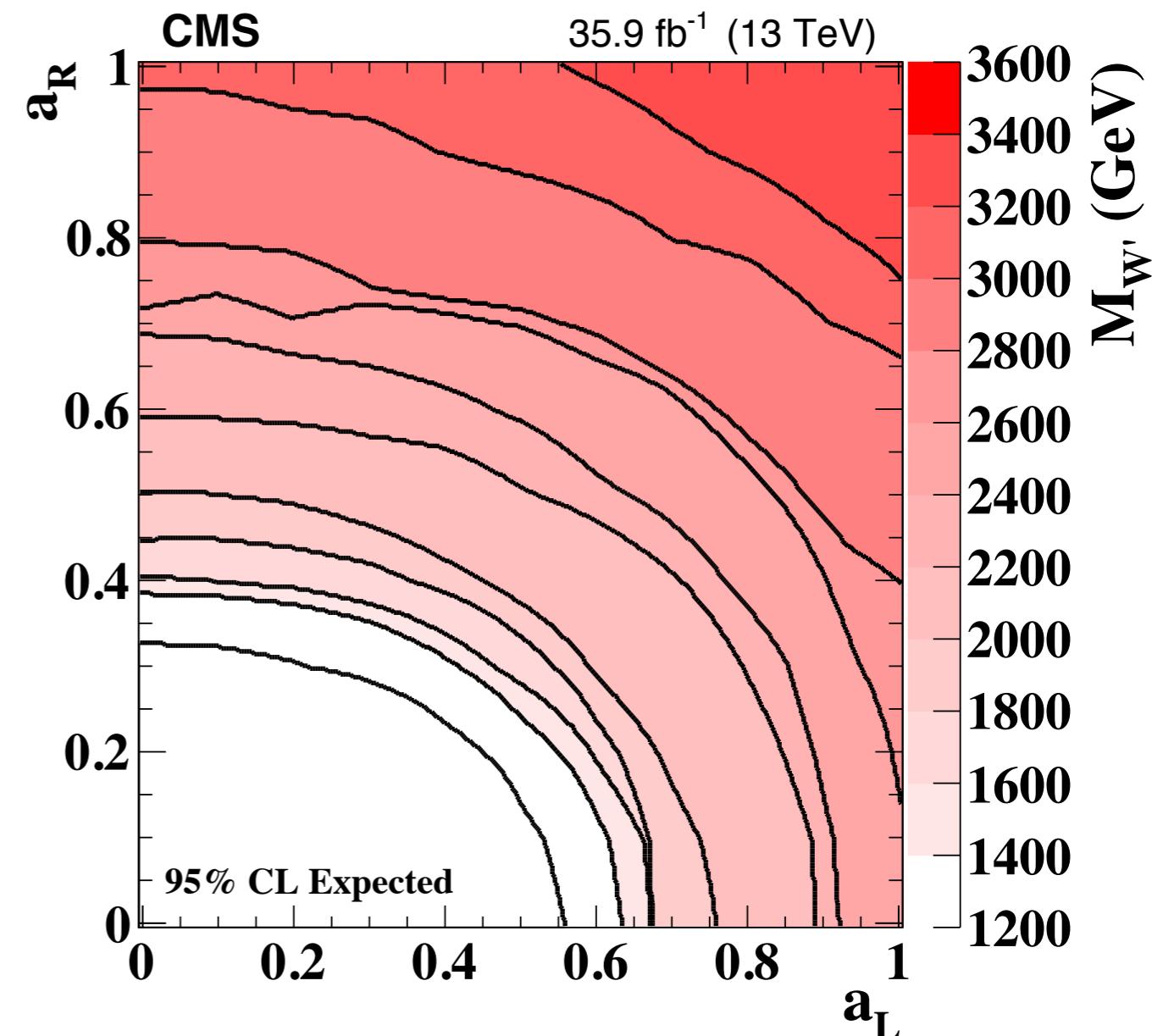


# $W' \rightarrow tb \rightarrow \ell v b\bar{b}$ : Coupling Limits

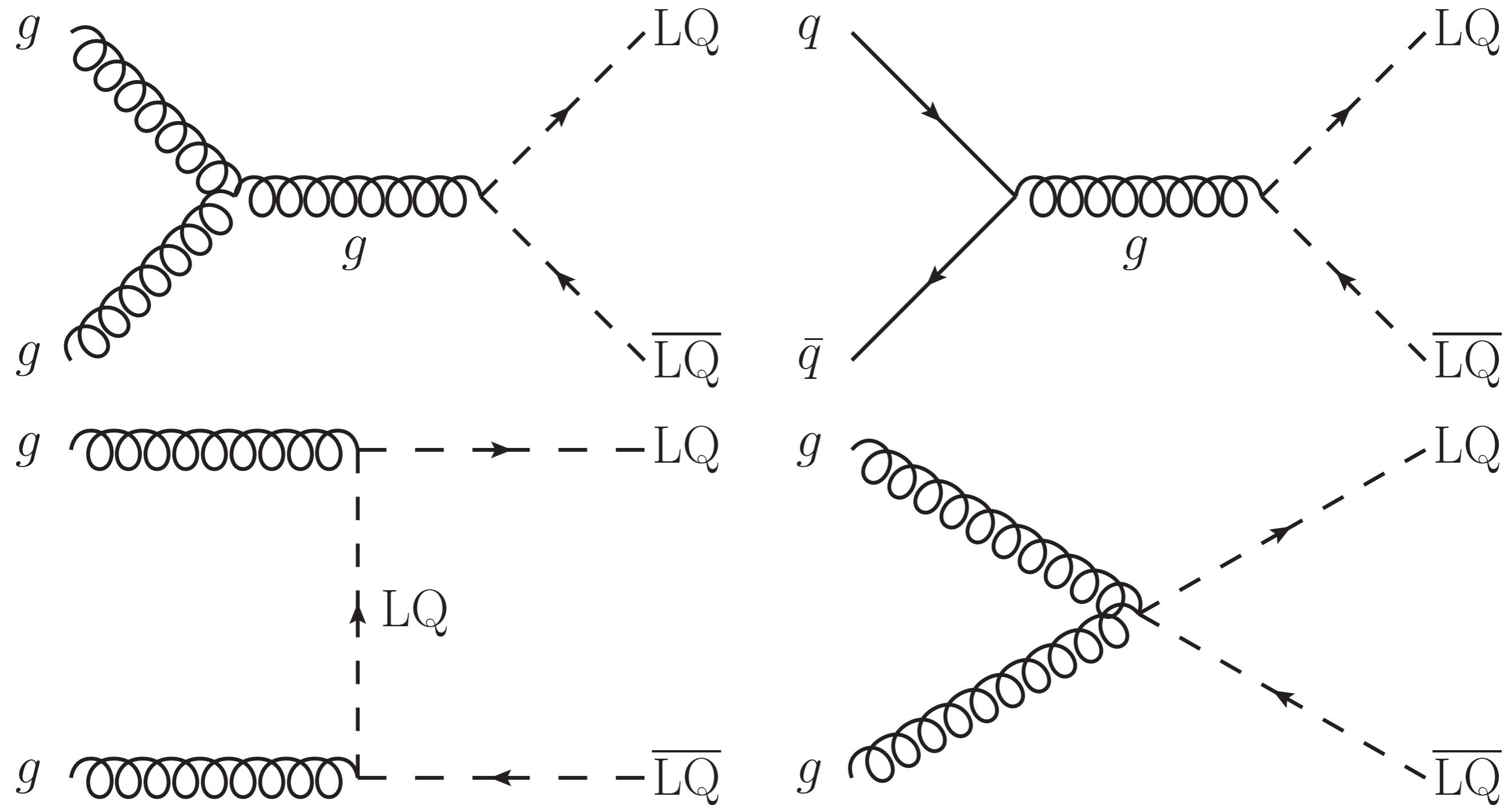
## Observed Limits



## Expected Limits



# $LQ_3 \bar{L} Q_3 \rightarrow T_h t \bar{T}_h \bar{t}$ : Production

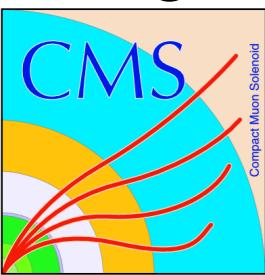


# LQ<sub>3</sub>LQ<sub>3</sub> → τ<sub>h</sub>tτ<sub>h</sub>t: Categories and Systematics

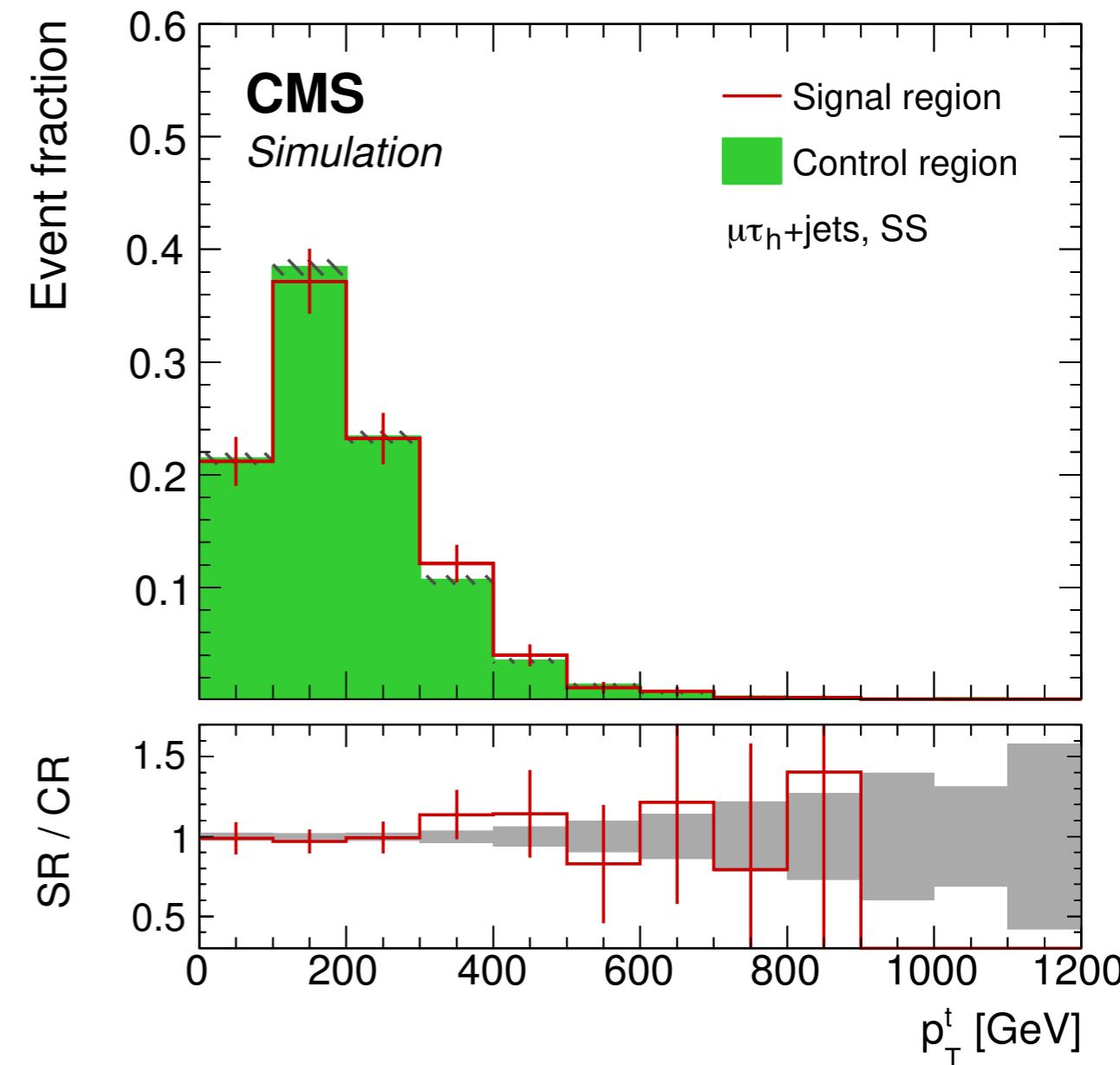
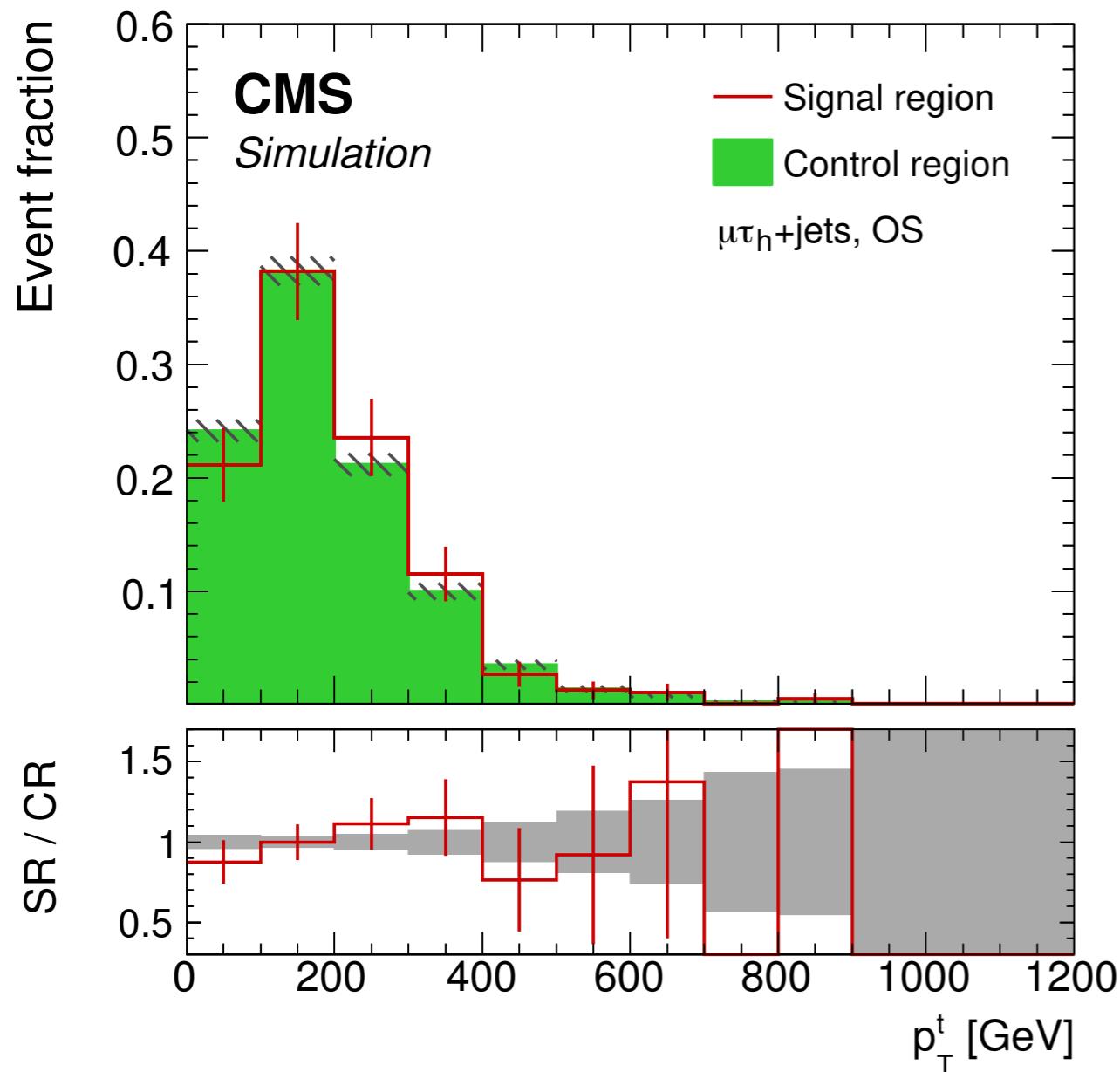
	Category A		Category B
	OS $\ell\tau_h + \text{jets}$	SS $\ell\tau_h + \text{jets}$	$\ell\tau_h\tau_h + \text{jets}$
Jet selection	$\geq 4$ jets	$\geq 3$ jets	$\geq 3$ jets
$p_T^{\text{miss}}$ selection	$p_T^{\text{miss}} > 100 \text{ GeV}$	$p_T^{\text{miss}} > 50 \text{ GeV}$	$p_T^{\text{miss}} > 50 \text{ GeV}$
$\tau_h$ selection	$p_T > 100 \text{ GeV}$		$p_T^{\tau_1} > 65 \text{ GeV}, p_T^{\tau_2} > 35 \text{ GeV}$
b tagging	$\geq 1$ b tag		—
$S_T$ selection	—		$S_T > 350 \text{ GeV}$
Fit variable	$p_T^t$ in two $S_T$ bins		number of events

## Largest Systematics

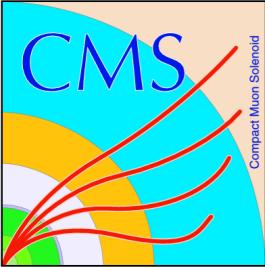
Uncertainty	Category A			Category B		
	$t\bar{t}_p$	$t\bar{t}_f + W + \text{jets}$	$LQ_3$	$t\bar{t}_f$	$t\bar{t}_{p+f}$	$LQ_3$
Scales ( $\mu_F, \mu_R$ )	26–42%	1–7%	—	5–7%	2–6%	—
$\tau$ ID	8–9%	0–1%	9–11%	0%	5–6%	18–20%
Bkg. estimate	—	6–18%	—	26–30%	30–38%	—



# LQ<sub>3</sub>LQ<sub>3</sub> → ThtTht: Background



- Modeling the tt and W+Jets background in the signal and control regions

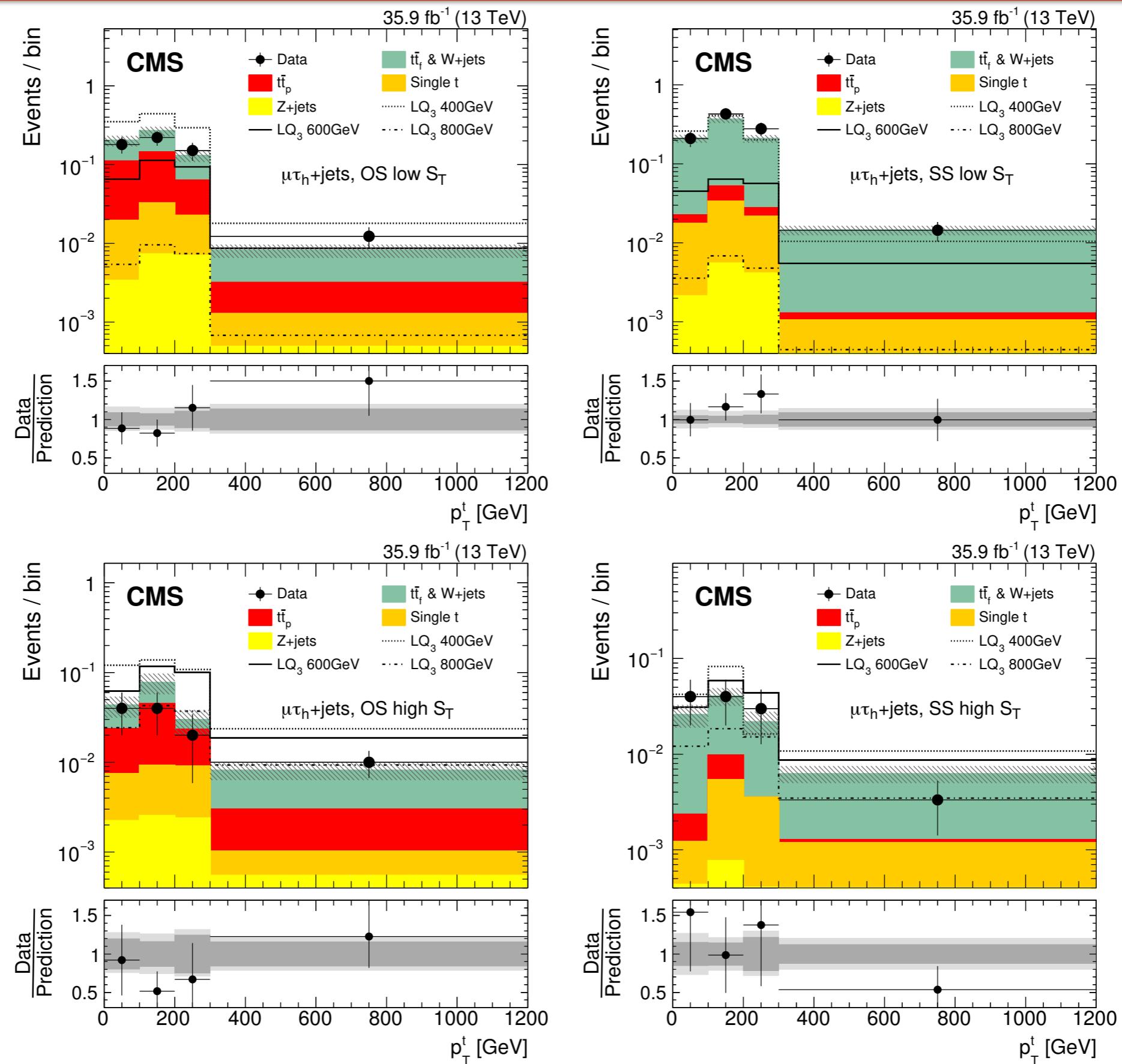


# LQ<sub>3</sub>LQ<sub>3</sub> → τ<sub>h</sub>tτ<sub>h</sub>t: Yields

Process	eτ <sub>h</sub> τ <sub>h</sub> + jets	μτ <sub>h</sub> τ <sub>h</sub> + jets
LQ <sub>3</sub> (300 GeV)	97 <sup>+25</sup> <sub>-24</sub>	167 <sup>+36</sup> <sub>-37</sub>
LQ <sub>3</sub> (400 GeV)	73 <sup>+14</sup> <sub>-13</sub>	98 <sup>+19</sup> <sub>-17</sub>
LQ <sub>3</sub> (500 GeV)	34.1 <sup>+6.6</sup> <sub>-6.2</sub>	44.9 <sup>+8.5</sup> <sub>-7.9</sub>
LQ <sub>3</sub> (600 GeV)	14.1 <sup>+2.8</sup> <sub>-2.7</sub>	21.1 <sup>+4.1</sup> <sub>-3.8</sub>
LQ <sub>3</sub> (700 GeV)	7.3 <sup>+1.5</sup> <sub>-1.4</sub>	7.1 <sup>+1.5</sup> <sub>-1.4</sub>
LQ <sub>3</sub> (800 GeV)	3.2 <sup>+0.7</sup> <sub>-0.7</sub>	4.4 <sup>+1.0</sup> <sub>-0.9</sub>
LQ <sub>3</sub> (900 GeV)	1.5 <sup>+0.4</sup> <sub>-0.3</sub>	1.9 <sup>+0.4</sup> <sub>-0.4</sub>
LQ <sub>3</sub> (1000 GeV)	0.8 <sup>+0.2</sup> <sub>-0.2</sub>	0.9 <sup>+0.2</sup> <sub>-0.2</sub>
t̄t <sub>f</sub>	2.5 <sup>+0.8</sup> <sub>-1.2</sub>	3.2 <sup>+1.5</sup> <sub>-1.2</sub>
t̄t <sub>p+f</sub>	1.5 <sup>+0.8</sup> <sub>-0.8</sub>	2.0 <sup>+0.8</sup> <sub>-0.9</sub>
Single t	0.3 <sup>+0.3</sup> <sub>-0.3</sub>	0.0 <sup>+0.2</sup> <sub>-0.0</sub>
W+jets	0.5 <sup>+1.2</sup> <sub>-0.5</sub>	0.4 <sup>+0.7</sup> <sub>-0.4</sub>
Z+jets	1.4 <sup>+0.5</sup> <sub>-0.5</sub>	1.0 <sup>+0.4</sup> <sub>-0.4</sub>
Diboson	1.6 <sup>+1.7</sup> <sub>-1.6</sub>	1.7 <sup>+1.8</sup> <sub>-1.7</sub>
Total background	7.9 <sup>+2.4</sup> <sub>-2.5</sub>	8.4 <sup>+2.6</sup> <sub>-2.3</sub>
Data	9	11

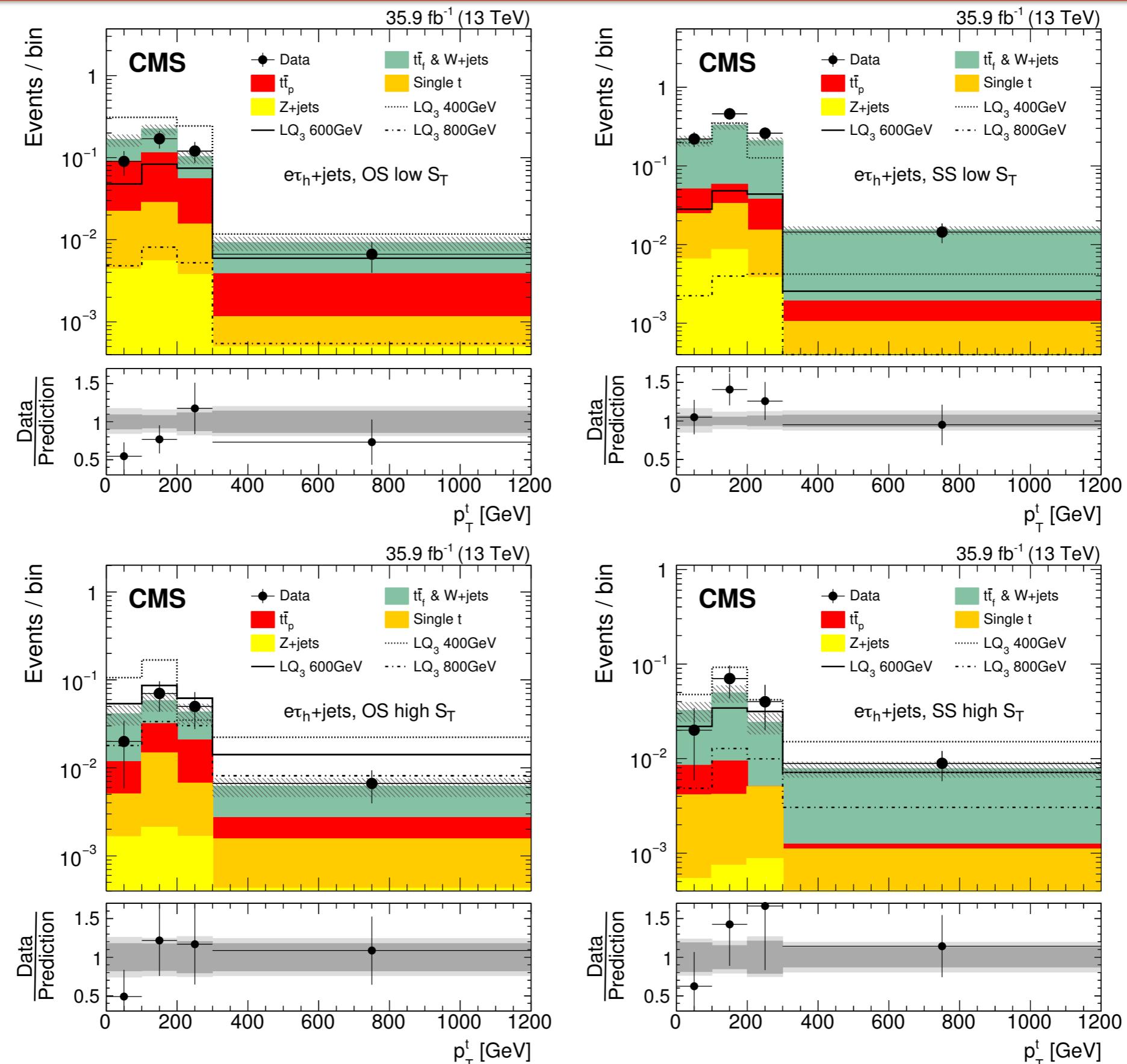


# LQ<sub>3</sub>LQ<sub>3</sub> → T<sub>h</sub>tT<sub>h</sub>t: Muon Channel

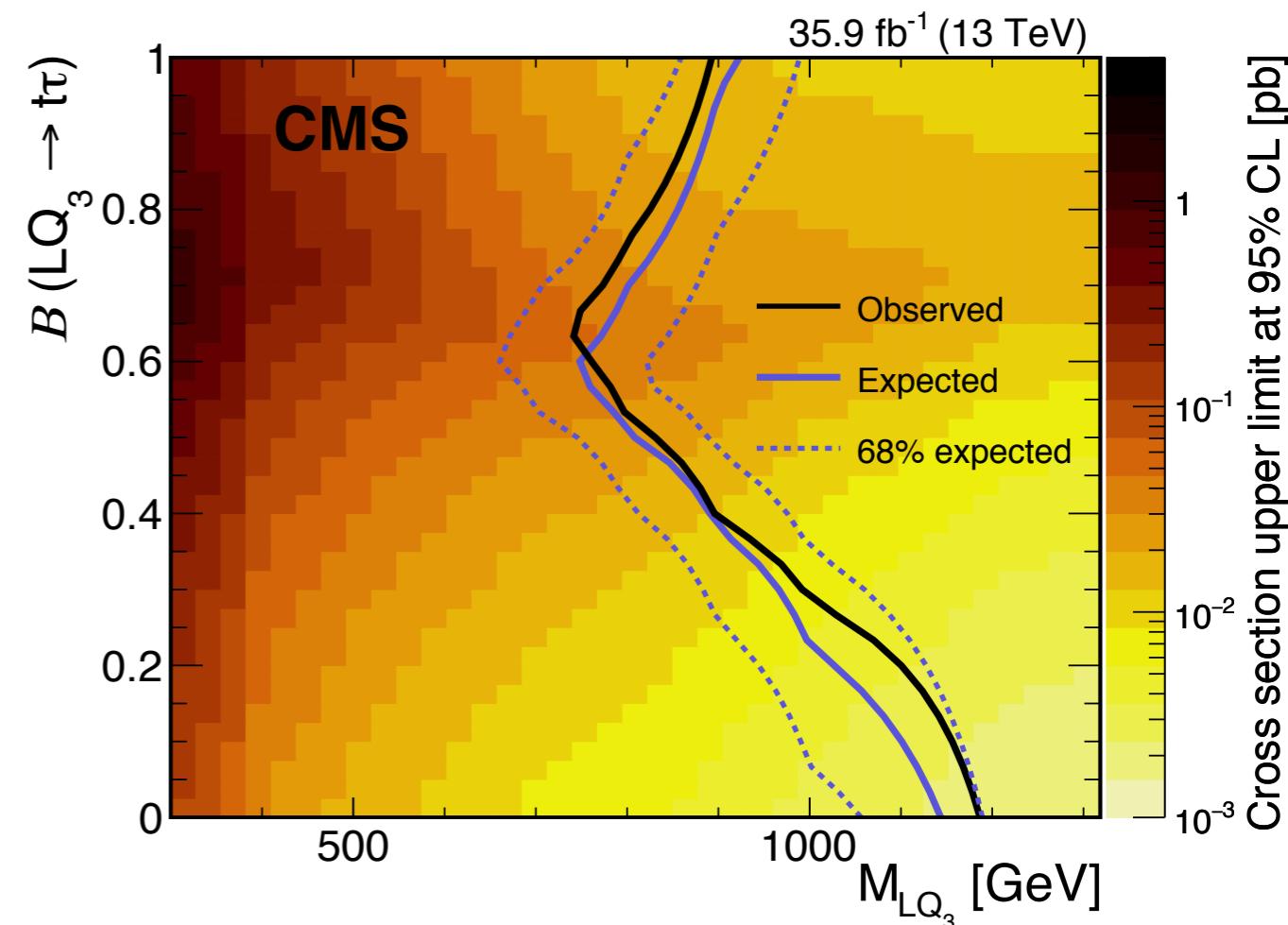
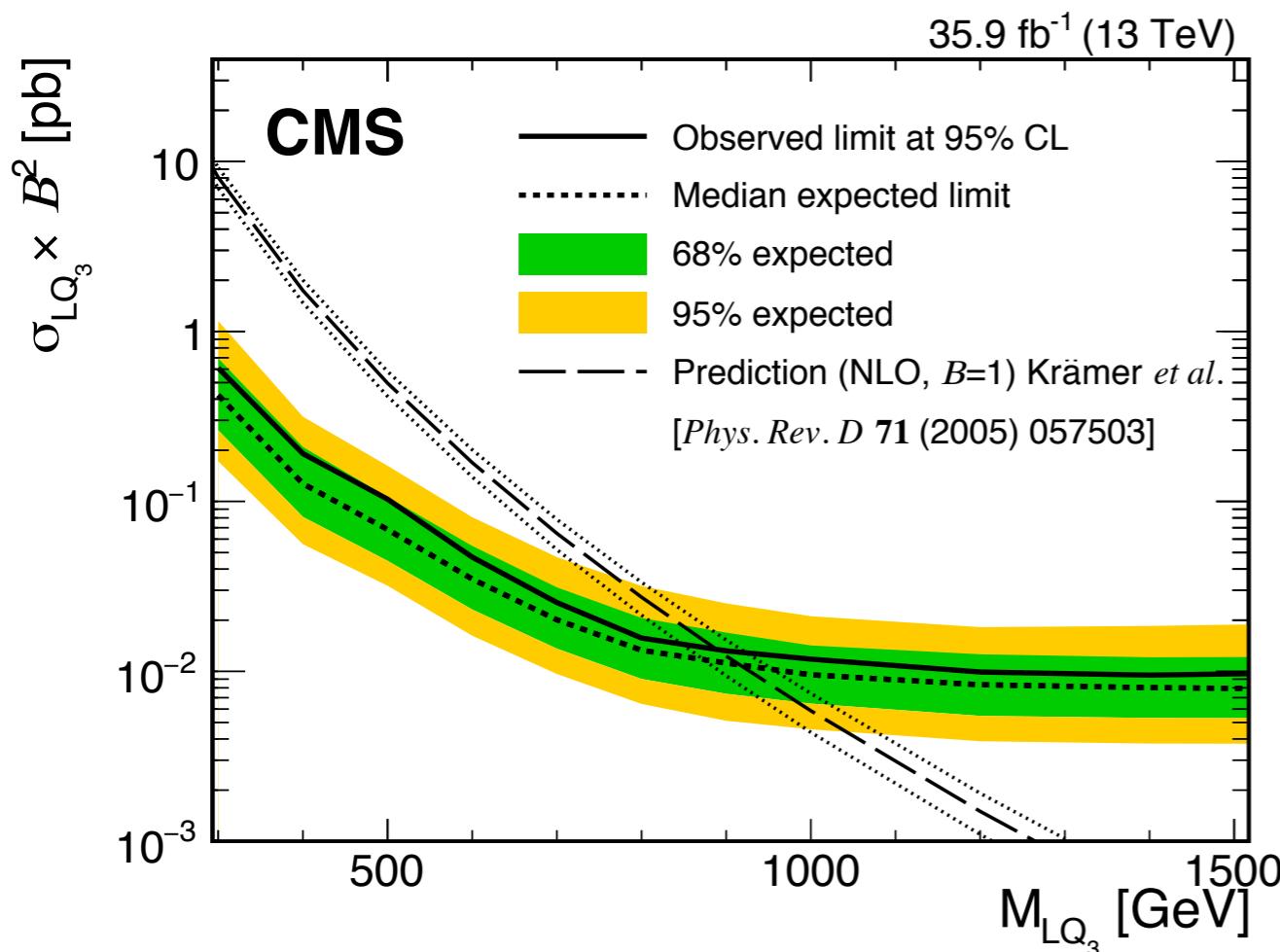


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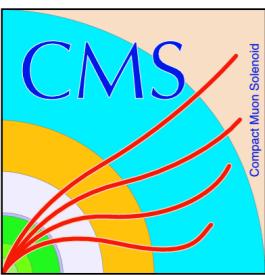
# LQ<sub>3</sub>LQ<sub>3</sub> → τ<sub>h</sub>tτ<sub>h</sub>t: Electron Channel



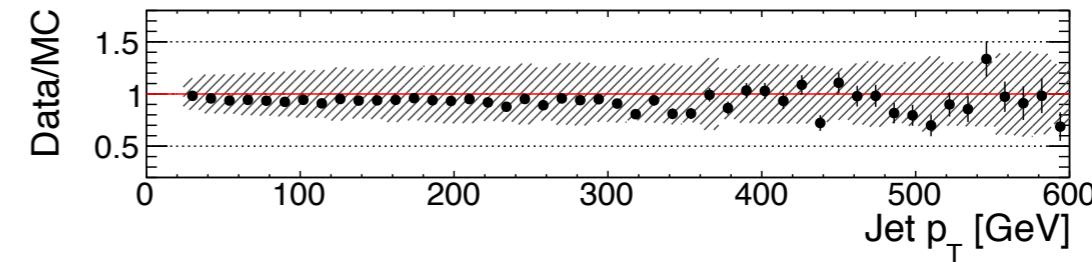
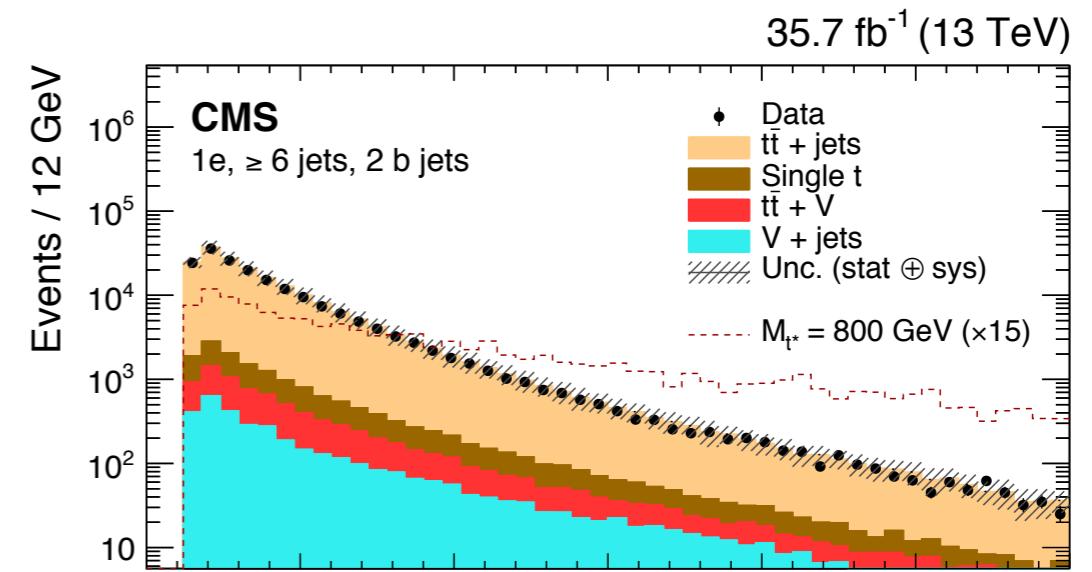
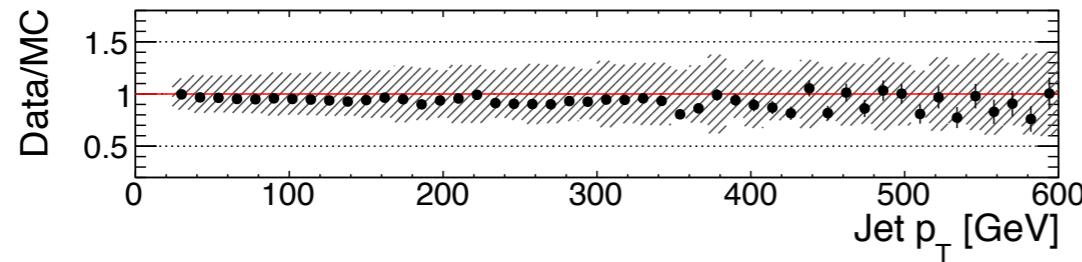
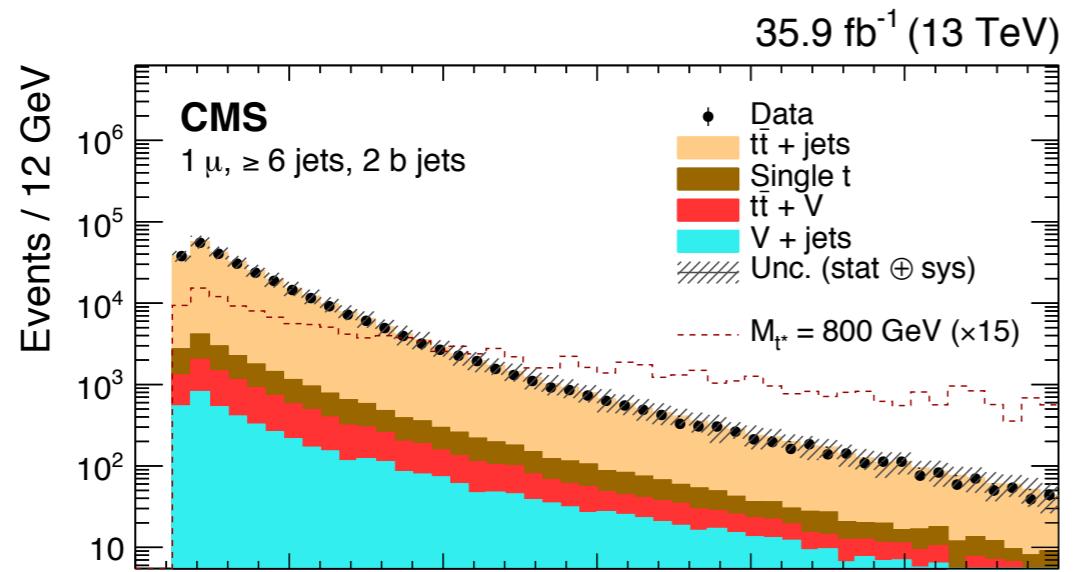
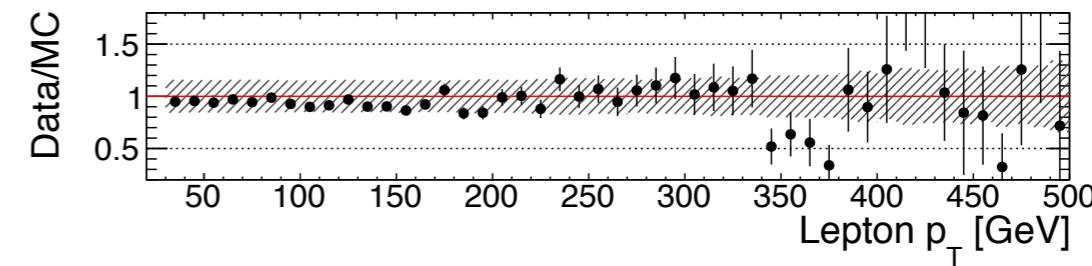
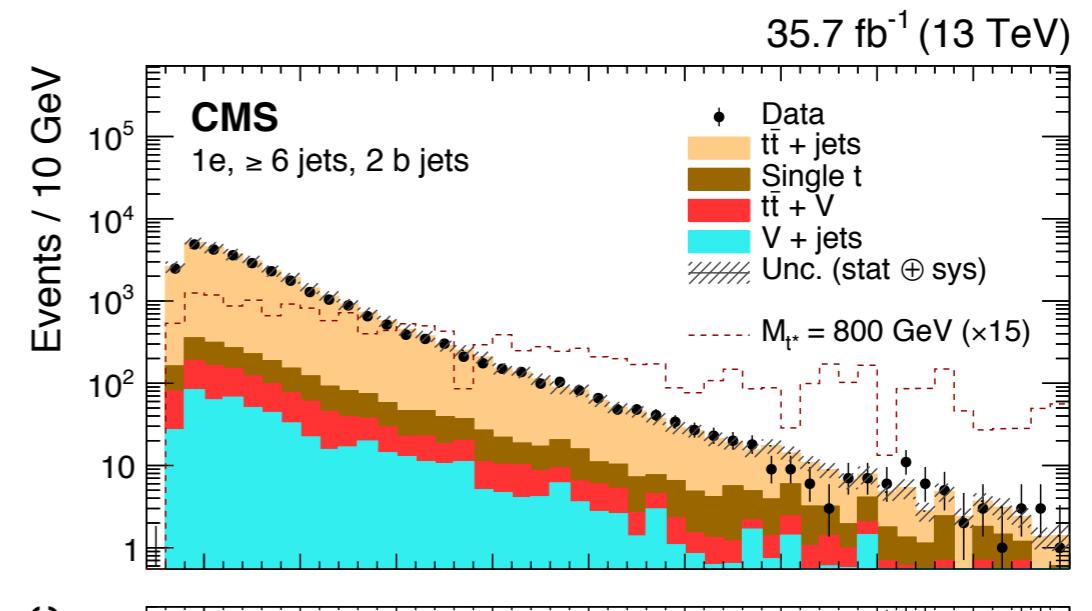
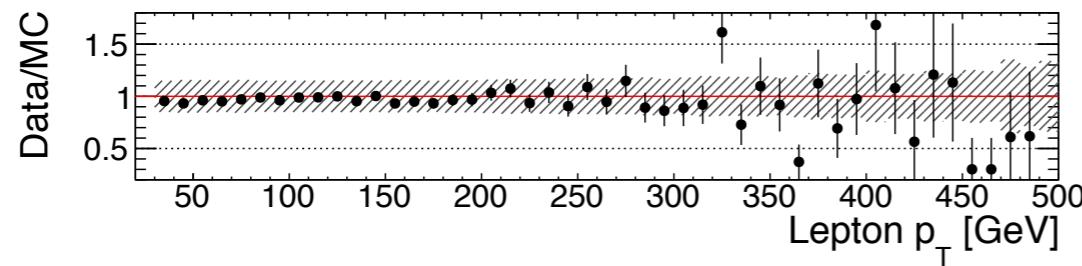
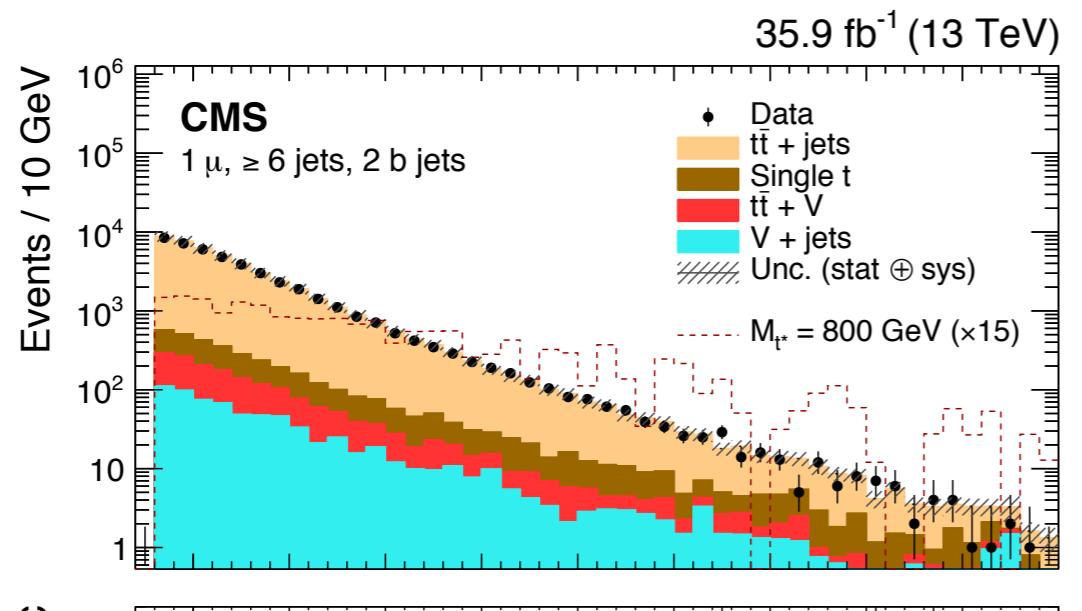
# LQ<sub>3</sub>LQ<sub>3</sub> → T<sub>h</sub>tT<sub>h</sub>t: Limits



- Upper limits at 95% confidence level on the product of the cross section and the branching fraction squared (left)
- And on the leptoquark mass as a function of the branching fraction (right), for the pair production of scalar LQs decaying to a top quark and a  $\tau$  lepton
  - The right plot additionally includes results from a search for pair-produced bottom squarks

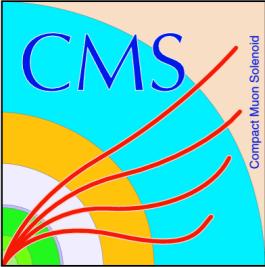


# $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$ : Kinematics



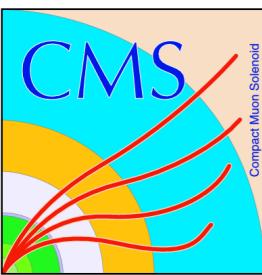
# $t^*\bar{t}^* \rightarrow (tg)(\bar{t}g)$ : Yields

	$\mu + \text{jet}$ final state	$e + \text{jet}$ final state
$t^*\bar{t}^*$ signal, $m_{t^*}$		
700 GeV	3670	2730
800 GeV	1230	1010
900 GeV	483	369
1000 GeV	200	148
1100 GeV	92	69
1200 GeV	40	29
1300 GeV	20	15
1400 GeV	9	7
1500 GeV	4	4
1600 GeV	2	2
SM processes	$(4.66 \pm 0.38) \times 10^4$	$(3.07 \pm 0.23) \times 10^4$
Data	44 573	28 942

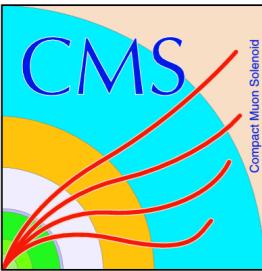
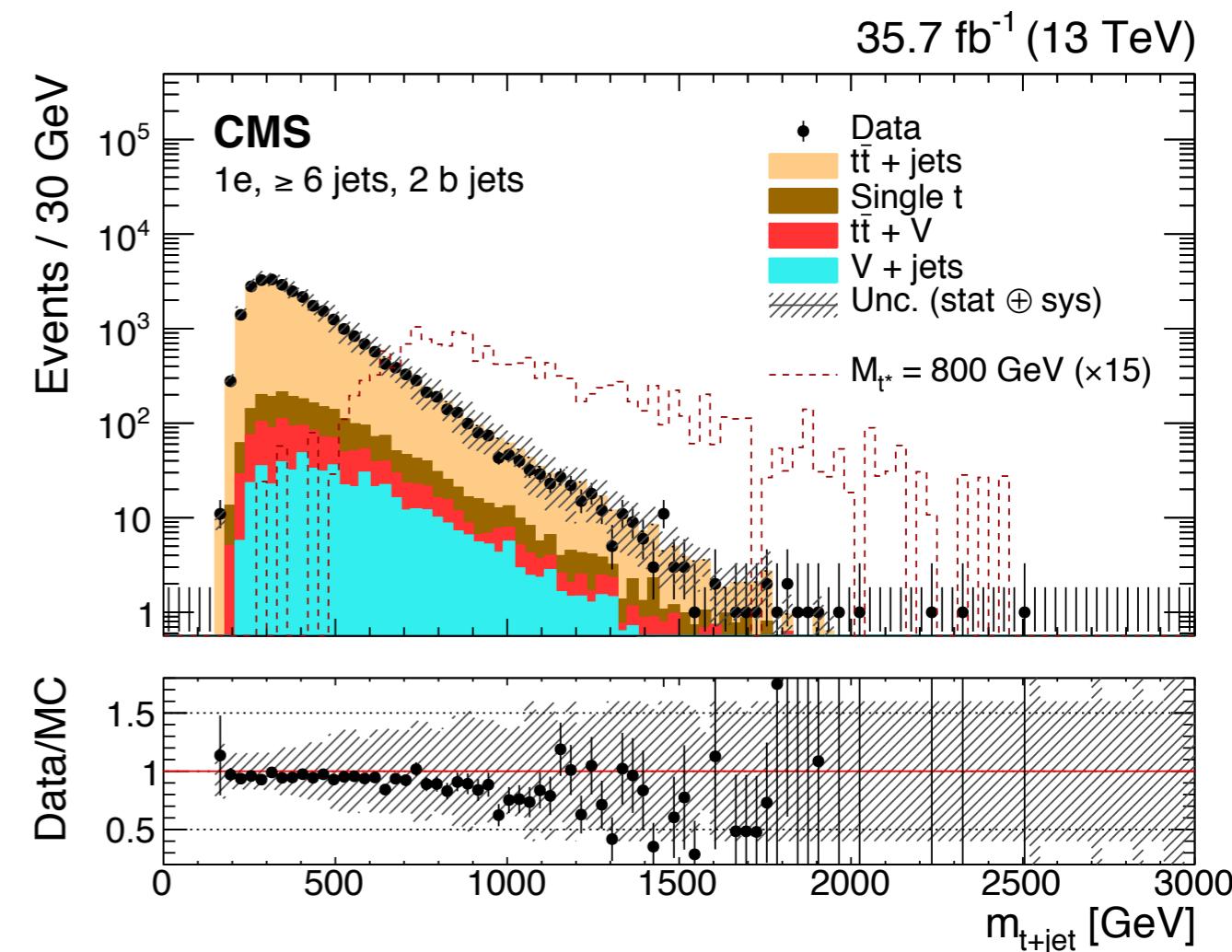
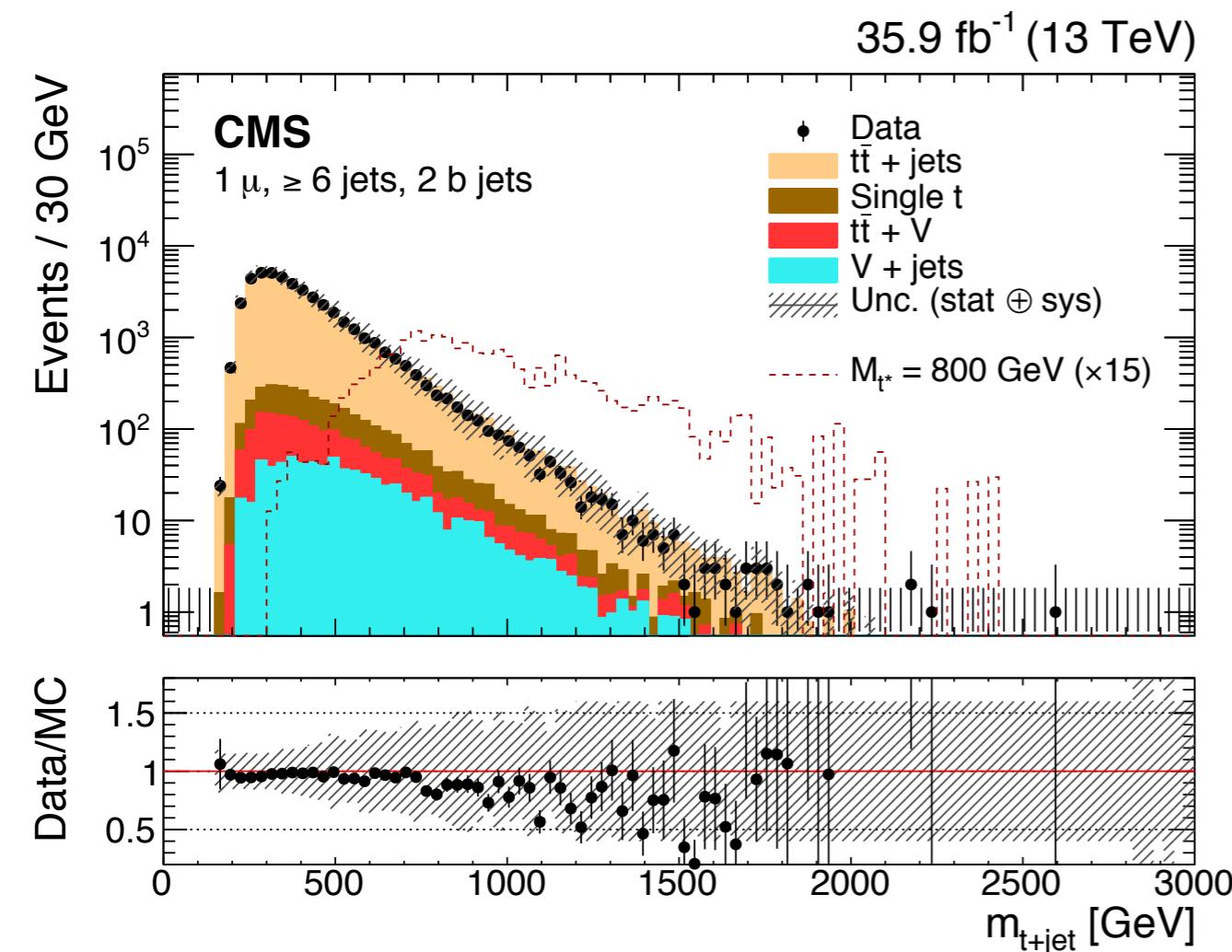


# $t^*\bar{t}^* \rightarrow (tg)(\bar{t}g)$ : Systematics

Source of uncertainty	Implementation on simulated signal sample
Integrated luminosity	Normalization shift by $\pm 2.5\%$
Statistical uncertainty	Normalization shift by $\pm 1$ s.d.
Jet correction	Correction factor varied by $\pm 1$ s.d.
Jet resolution	Jet resolution shift by $\pm 1$ s.d.
b tagging SF	SF varied by $\pm 1$ s.d.
Lepton efficiency SF	SF varied by $\pm 1$ s.d.
Pileup	pp inelastic cross section shifted by $\pm 4.6\%$ [41]
Modeling	Smoothing parameter $\rho$ varied over range [1.17, 1.66]
PDF uncertainty	Generator parameter varied by $\pm 1$ s.d.
Scale uncertainty	Generator parameter varied by $\pm 1$ s.d.

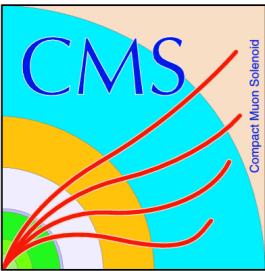
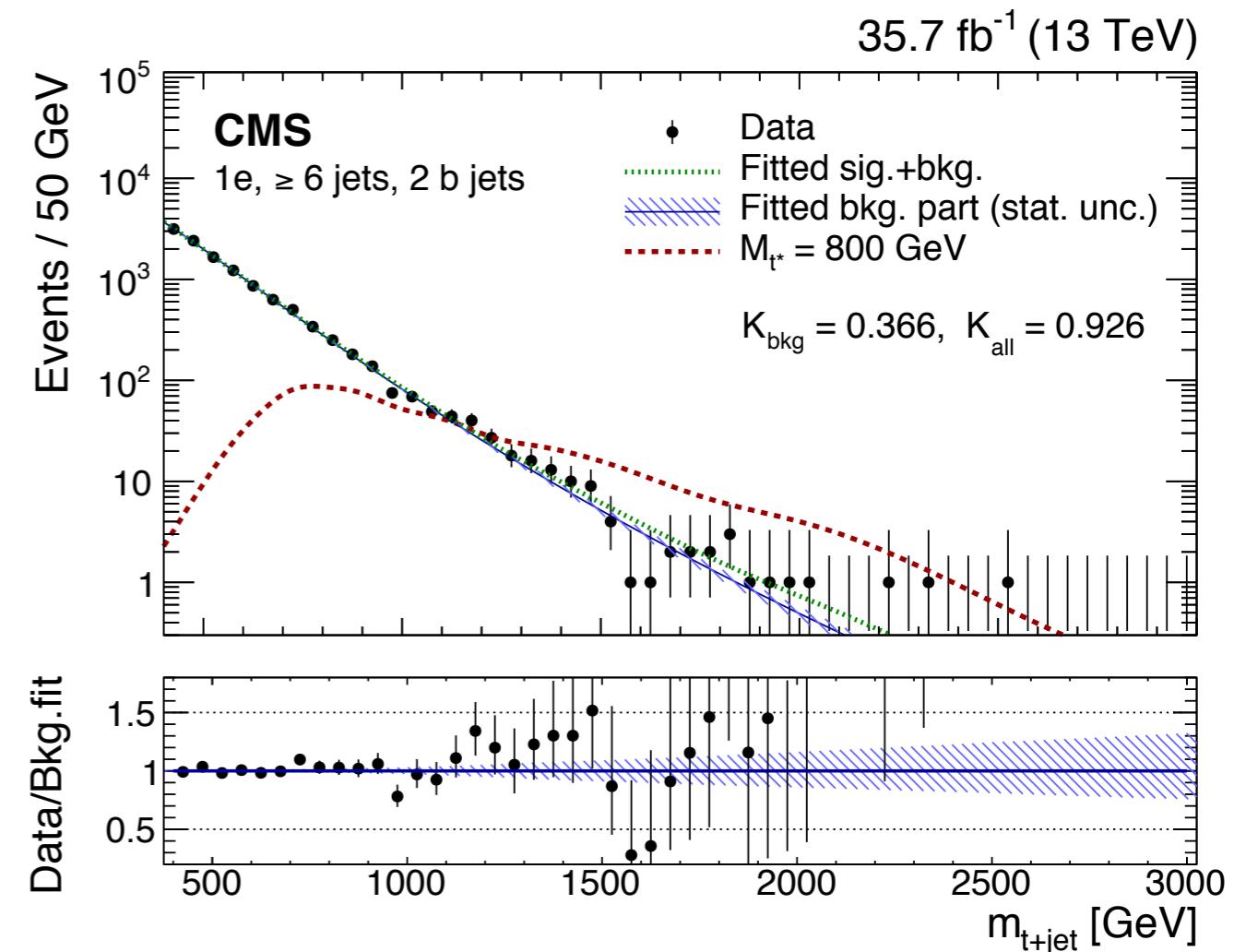
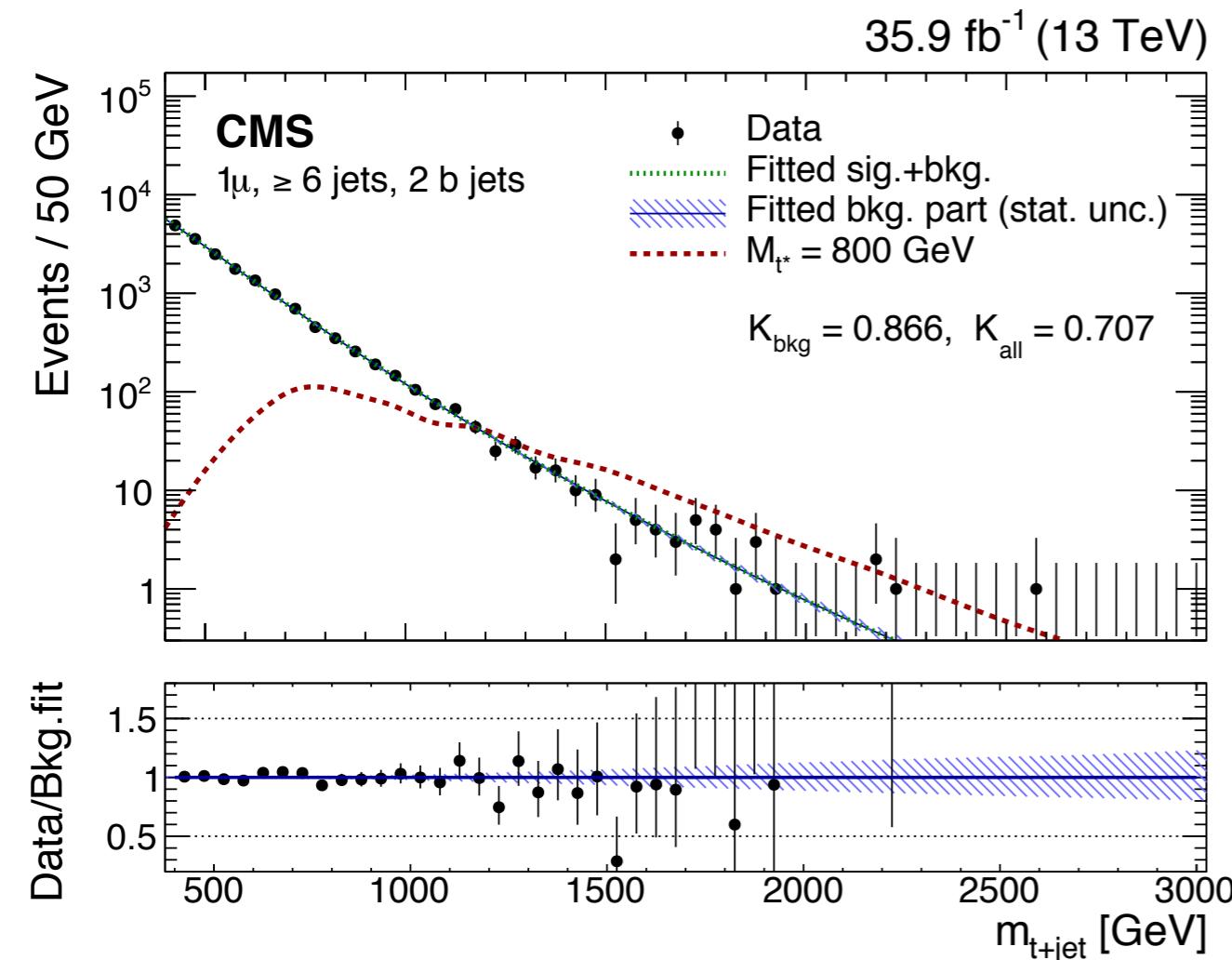


# $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$ : Results



# $t^* \bar{t}^* \rightarrow (tg)(\bar{t}g)$ : Background Fit

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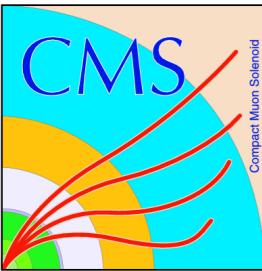
# T $\rightarrow$ tZ: Signal Cross Sections

## Narrow Width Approximation

Mass [TeV]	$\sigma(pp \rightarrow Tbq)$ [pb]	$\sigma(pp \rightarrow Ttq)$ [pb]
0.7	1.455	0.125
0.8	0.965	0.091
0.9	0.680	0.068
1.0	0.488	0.051
1.1	0.338	0.038
1.2	0.246	0.029
1.3	0.179	0.022
1.4	0.135	0.017
1.5	0.102	0.014
1.6	0.076	0.011
1.7	0.058	0.008

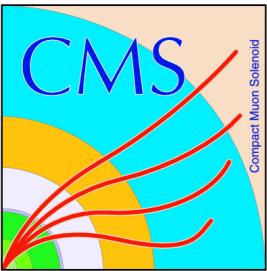
## Cross Section for $\Gamma_T = 10\%, 20\%$ , and $30\%$

Mass [TeV]	$\tilde{\sigma}_{FW}(\sigma)$ for $pp \rightarrow Tbq \rightarrow tZbq$ [pb]			$\tilde{\sigma}_{FW}(\sigma)$ for $pp \rightarrow Ttq \rightarrow tZtq$ [pb]		
	10%	20%	30%	10%	20%	30%
0.8	226 (0.675)	108 (0.650)	70 (0.631)	19 (0.144)	9.3 (0.139)	6.0 (0.135)
1.0	183 (0.314)	87 (0.299)	55 (0.284)	17 (0.075)	7.9 (0.072)	5.0 (0.069)
1.2	145 (0.158)	68 (0.149)	43 (0.141)	14 (0.042)	6.4 (0.039)	4.1 (0.037)
1.4	112 (0.084)	52 (0.079)	33 (0.074)	11 (0.024)	5.0 (0.022)	3.2 (0.021)
1.6	85 (0.047)	39 (0.043)	29 (0.041)	8.2 (0.014)	3.8 (0.013)	2.4 (0.012)



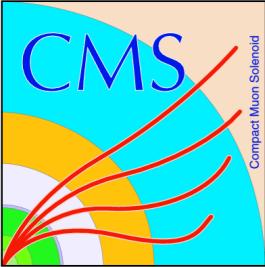
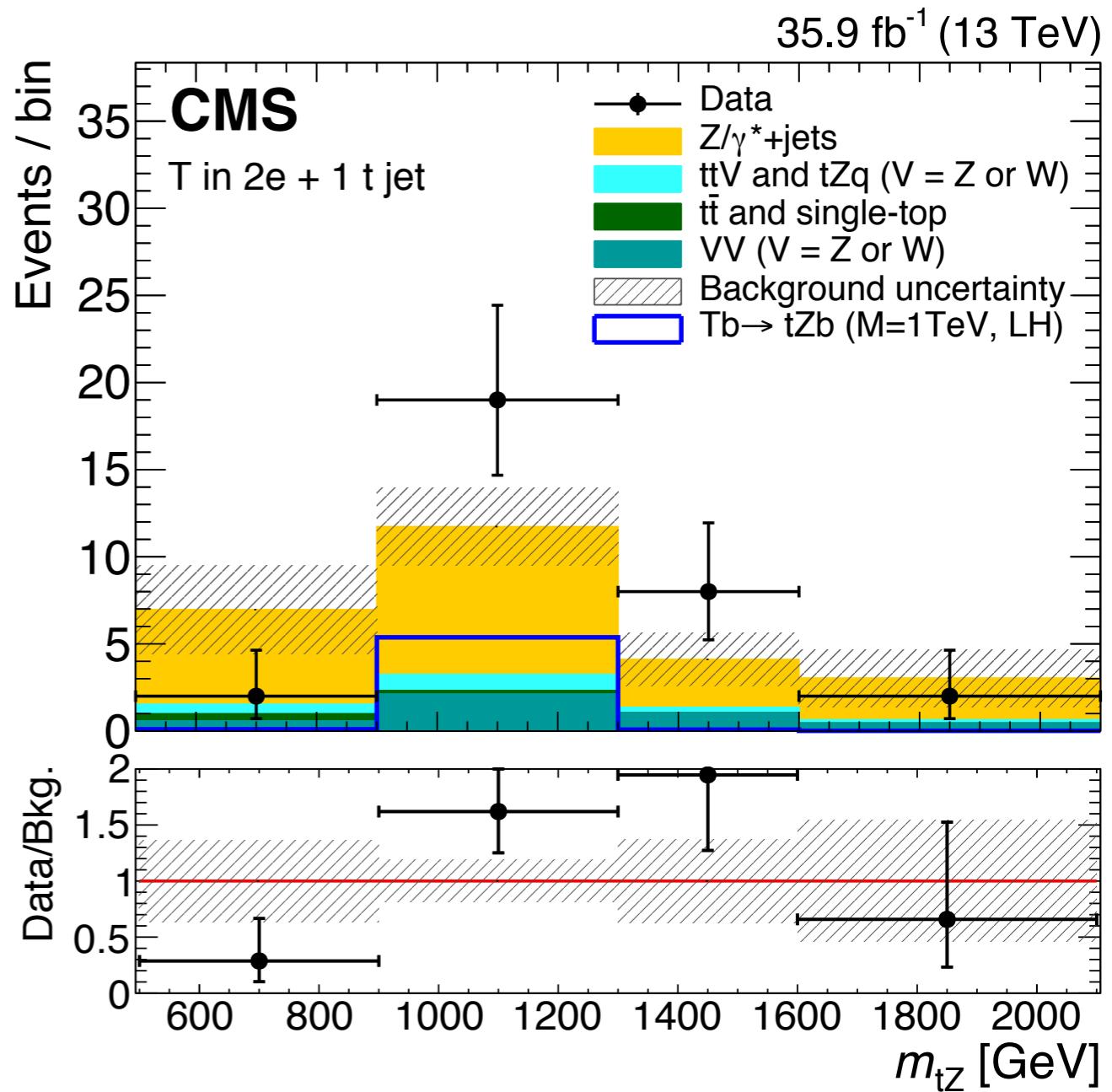
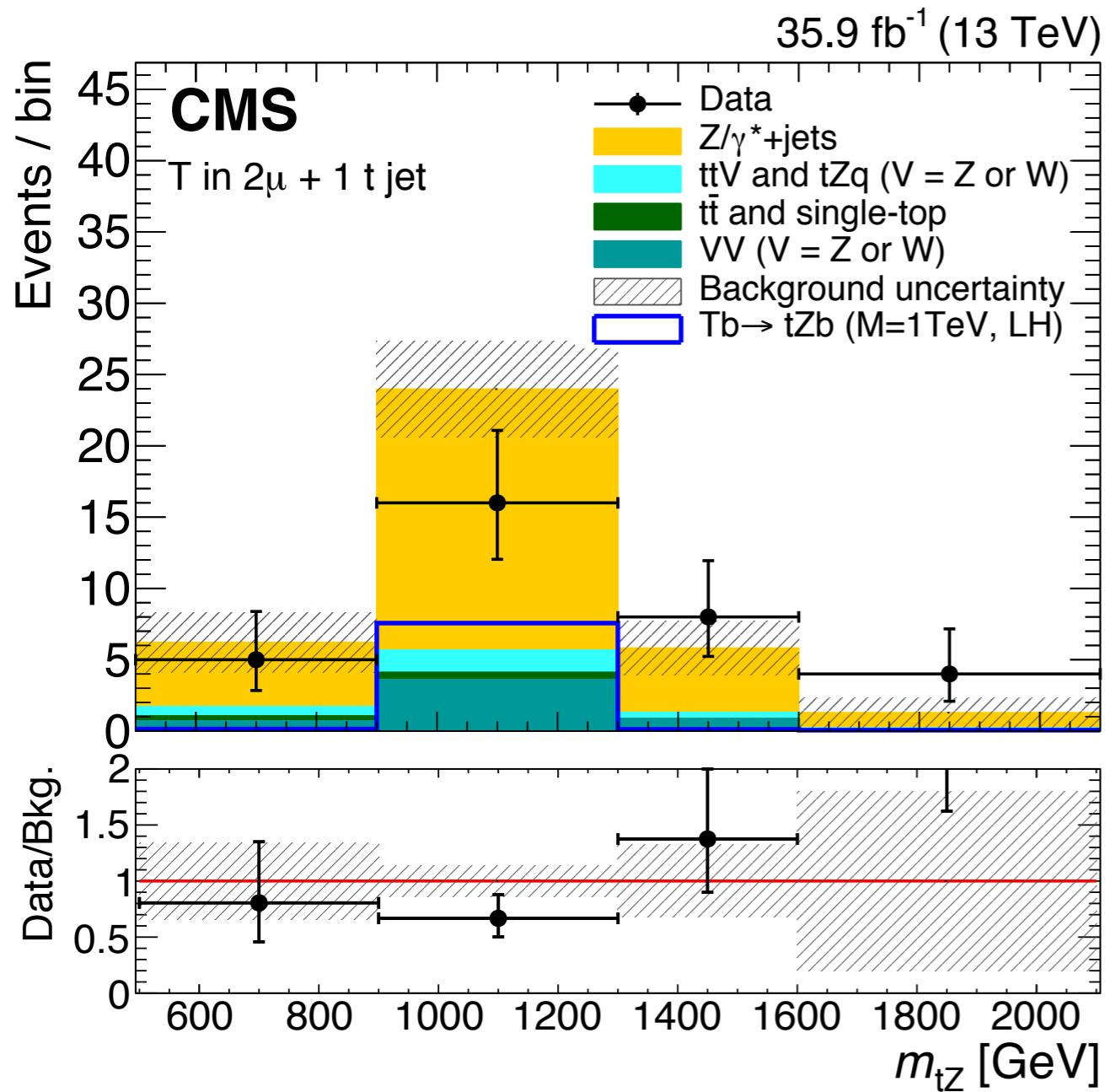
# T $\rightarrow$ tZ: Categories

Category	Z boson	t quark	N(forward jets)
1	two muons	fully merged	$\geq 0$
2	two electrons	fully merged	$\geq 0$
3	two muons	partially merged	0
4	two muons	partially merged	$\geq 1$
5	two electrons	partially merged	0
6	two electrons	partially merged	$\geq 1$
7	two muons	resolved	0
8	two muons	resolved	$\geq 1$
9	two electrons	resolved	0
10	two electrons	resolved	$\geq 1$



# $T \rightarrow tZ$ : Results (Fully Merged)

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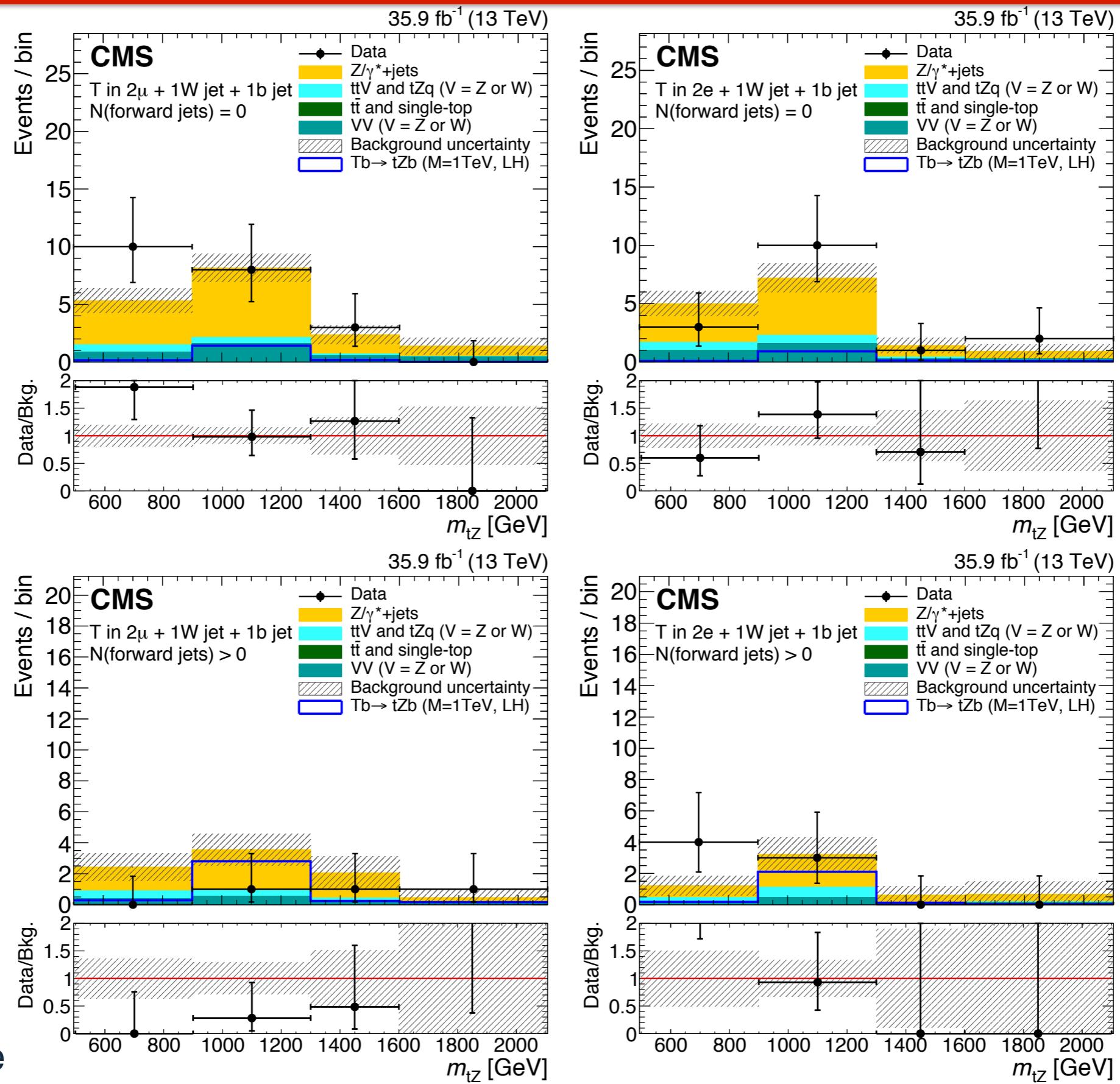


# $T \rightarrow tZ$ : Yields (Fully Merged)

Channel	$2\mu + 1$ t-jet	$2e + 1$ t-jet
Estimated background	$37.3 \pm 4.6$	$25.8 \pm 4.1$
Data events	33	31
$T(b), m_T = 0.8 \text{ TeV}, w \simeq 0$	1.2 (0.2%)	0.9 (0.1%)
$T(b), m_T = 0.8 \text{ TeV}, w = 0.3m_T$	22.9 (1%)	17.1 (1%)
$T(t), m_T = 0.8 \text{ TeV}, w \simeq 0$	1.3 (1%)	1.0 (1%)
$T(t), m_T = 0.8 \text{ TeV}, w = 0.3m_T$	6.3 (2%)	5.4 (2%)
$T(b), m_T = 1.6 \text{ TeV}, w \simeq 0$	2.9 (6%)	2.6 (6%)
$T(b), m_T = 1.6 \text{ TeV}, w = 0.3m_T$	5.3 (5%)	4.8 (5%)
$T(t), m_T = 1.6 \text{ TeV}, w \simeq 0$	0.8 (6%)	0.7 (6%)
$T(t), m_T = 1.6 \text{ TeV}, w = 0.3m_T$	1.5 (5%)	1.4 (5%)



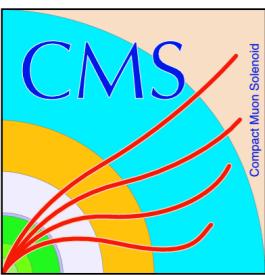
# T $\rightarrow$ tZ: Results (Partially Merged)



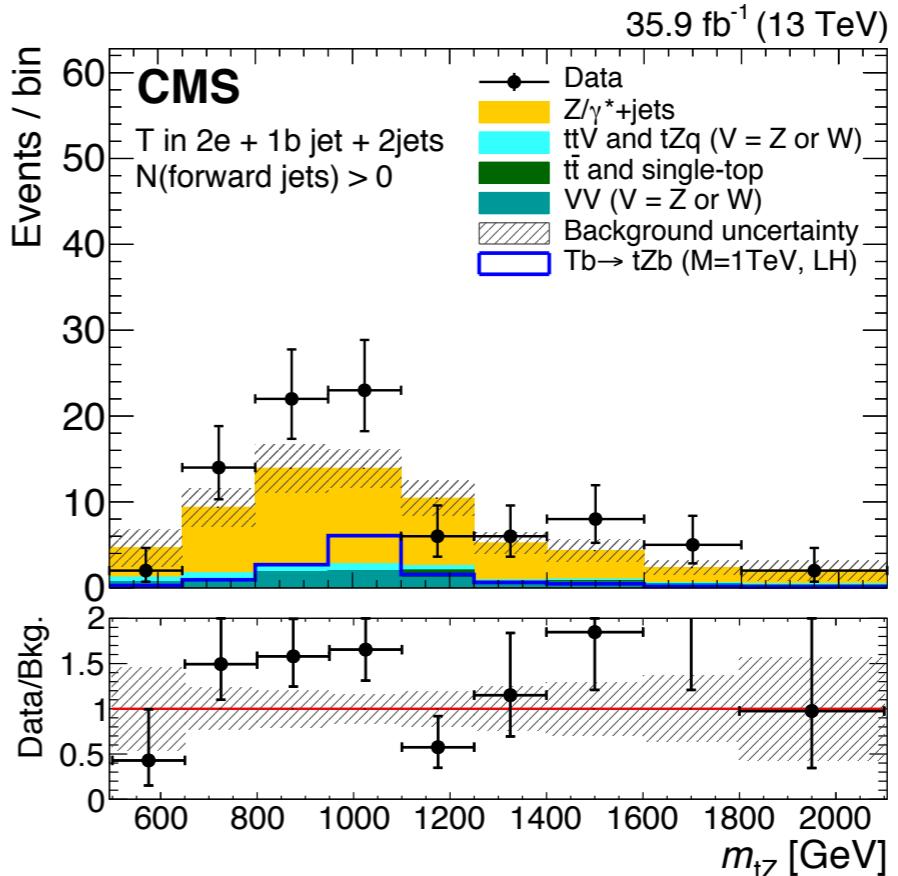
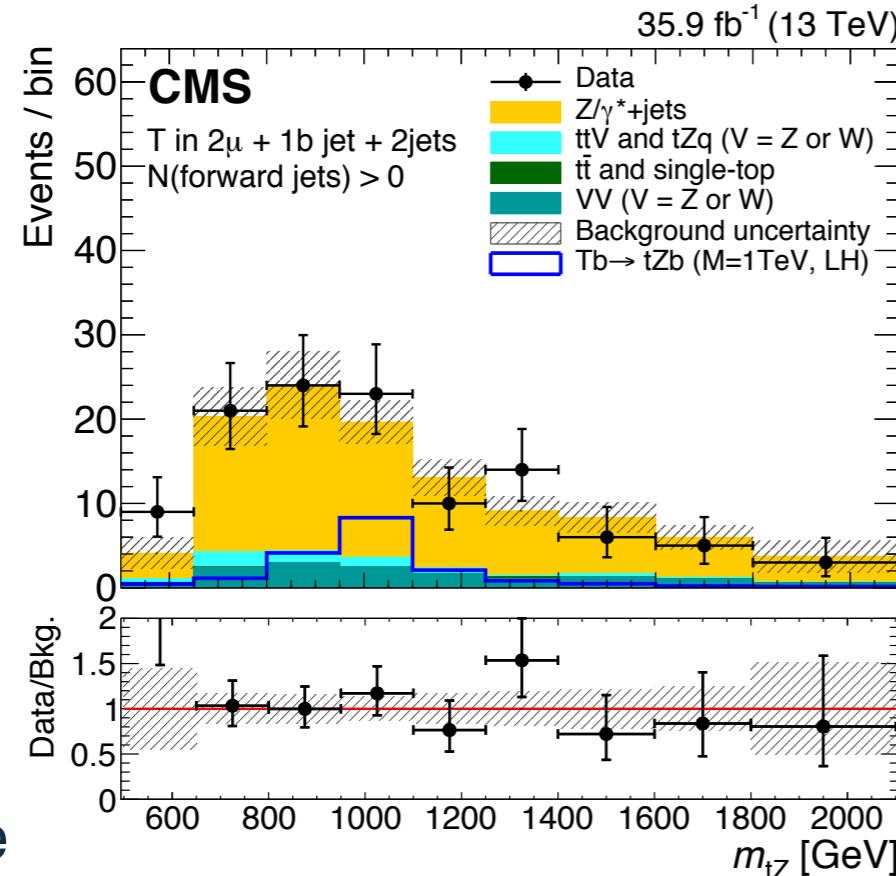
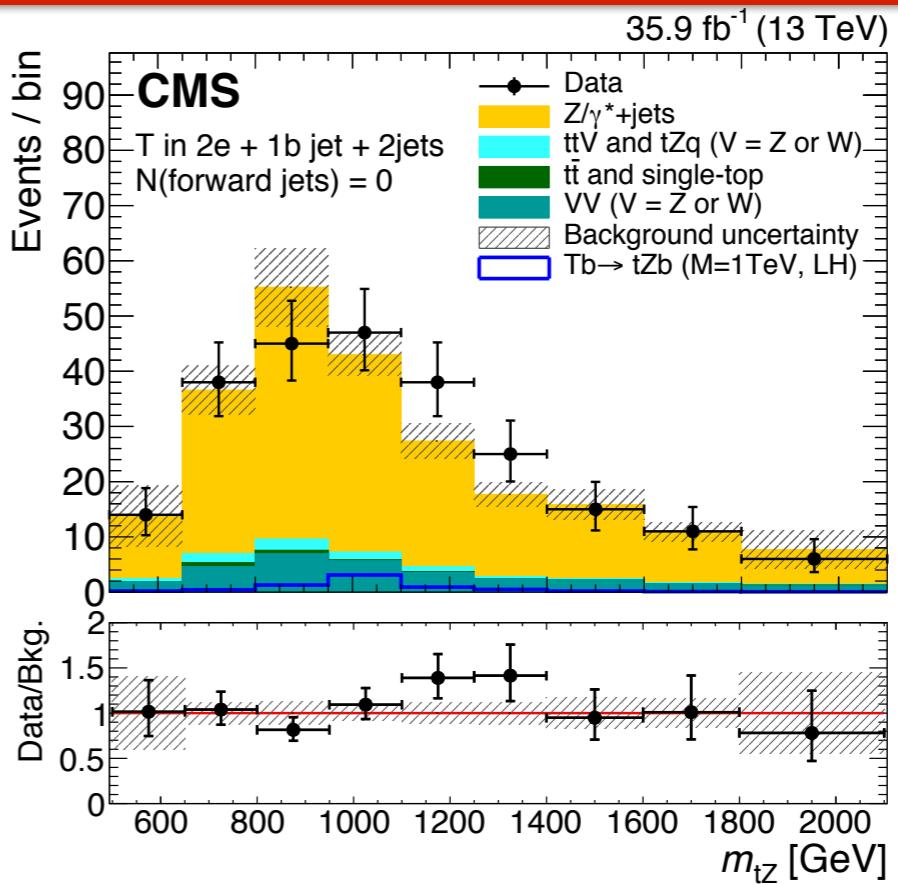
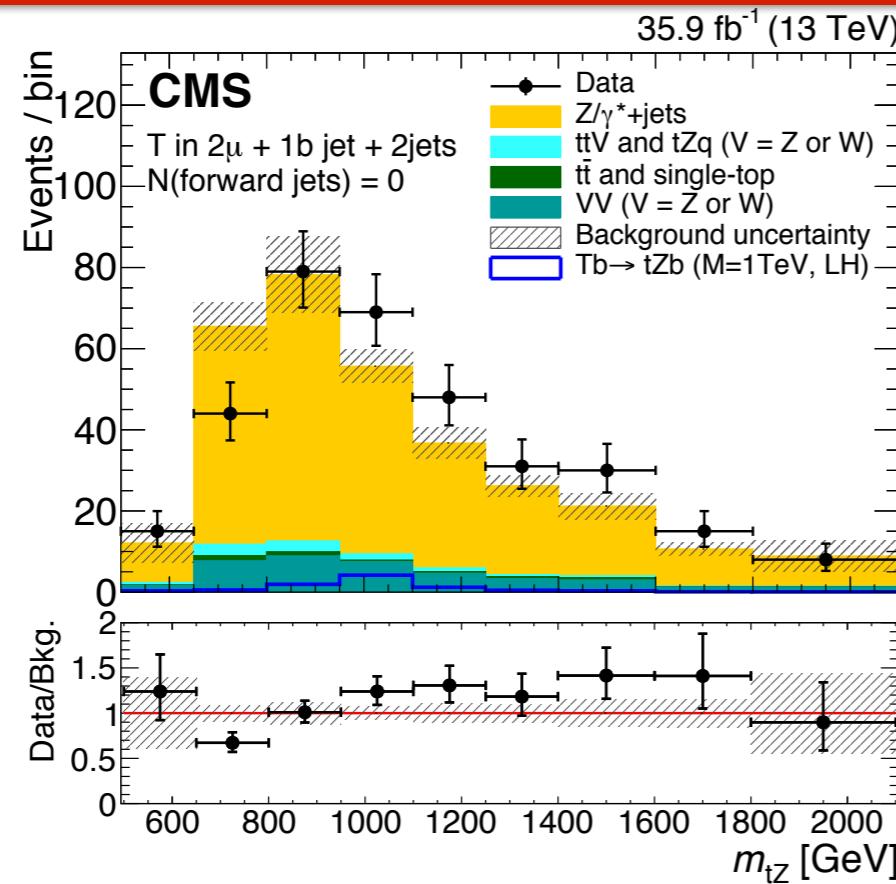
D. Be

# T $\rightarrow$ tZ: Yields (Partially Merged)

Channel	2 $\mu$ +1 W-jet+1 b-jet	2e+1 W-jet+1 b-jet	2 $\mu$ +1 W-jet+1 b-jet	2e+1 W-jet+1 b-jet
	N(forward jets) = 0		N(forward jets) > 0	
Estimated background	17.2 $\pm$ 1.9	14.5 $\pm$ 1.9	8.5 $\pm$ 1.8	5.7 $\pm$ 1.6
Data events	21	16	3	7
T(b), $m_T = 0.8 \text{ TeV}$ , $w \simeq 0$	2.7 (0.5%)	1.7 (0.3%)	5.4 (0.9%)	4.3 (0.7%)
T(b), $m_T = 0.8 \text{ TeV}$ , $w = 0.3m_T$	8.2 (0.5%)	5.0 (0.3%)	12.2 (0.8%)	9.5 (0.6%)
T(t), $m_T = 0.8 \text{ TeV}$ , $w \simeq 0$	0.9 (0.8%)	0.8 (0.7%)	2.0 (2%)	1.5 (1%)
T(t), $m_T = 0.8 \text{ TeV}$ , $w = 0.3m_T$	2.8 (0.9%)	2.1 (0.6%)	4.7 (1%)	3.9 (1%)
T(b), $m_T = 1.6 \text{ TeV}$ , $w \simeq 0$	0.2 (0.3%)	0.2 (0.3%)	0.4 (0.9%)	0.3 (0.6%)
T(b), $m_T = 1.6 \text{ TeV}$ , $w = 0.3m_T$	0.4 (0.4%)	0.3 (0.3%)	0.7 (0.7%)	0.6 (0.6%)
T(t), $m_T = 1.6 \text{ TeV}$ , $w \simeq 0$	0.1 (0.7%)	0.1 (0.5%)	0.2 (1%)	0.2 (1%)
T(t), $m_T = 1.6 \text{ TeV}$ , $w = 0.3m_T$	0.2 (0.7%)	0.2 (0.6%)	0.4 (1%)	0.4 (1%)



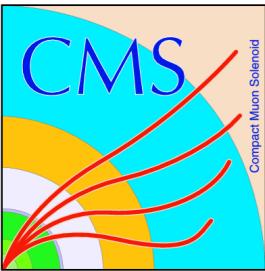
# $T \rightarrow tZ$ : Results (Resolved)



D. Be

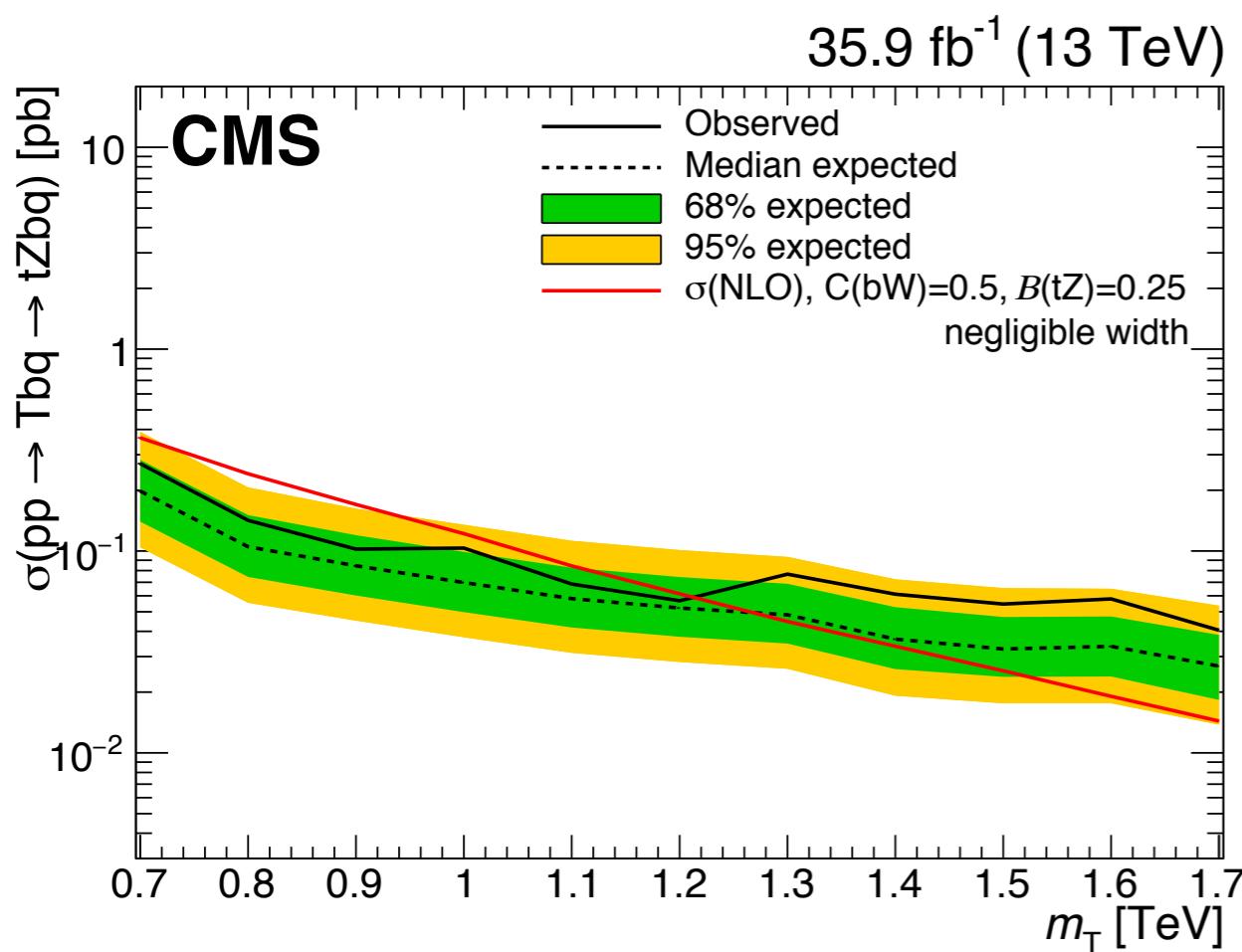
# $T \rightarrow tZ$ : Yields (Resolved)

Channel	$2\mu + 1 \text{ b-jet} + 2 \text{ jets}$	$2e + 1 \text{ b-jet} + 2 \text{ jets}$	$2\mu + 1 \text{ b-jet} + 2 \text{ jets}$	$2e + 1 \text{ b-jet} + 2 \text{ jets}$
	$N(\text{forward jets}) = 0$	$N(\text{forward jets}) > 0$	$N(\text{forward jets}) = 0$	$N(\text{forward jets}) > 0$
Estimated background	$315 \pm 15$	$228 \pm 12$	$108.3 \pm 7.3$	$66.2 \pm 5.6$
Data events	339	239	115	88
$T(b), m_T = 0.8 \text{ TeV}, w \simeq 0$	13.7 (2%)	10.0 (2%)	25.7 (4%)	18.5 (3%)
$T(b), m_T = 0.8 \text{ TeV}, w = 0.3m_T$	35.9 (2%)	29.7 (2%)	66.5 (4%)	52.7 (3%)
$T(t), m_T = 0.8 \text{ TeV}, w \simeq 0$	2.5 (2%)	2.0 (2%)	5.0 (5%)	4.0 (4%)
$T(t), m_T = 0.8 \text{ TeV}, w = 0.3m_T$	8.9 (3%)	6.7 (2%)	15.8 (5%)	12.0 (4%)
$T(b), m_T = 1.6 \text{ TeV}, w \simeq 0$	1.0 (2%)	0.9 (2%)	2.5 (5%)	2.0 (4%)
$T(b), m_T = 1.6 \text{ TeV}, w = 0.3m_T$	2.2 (2%)	1.9 (2%)	4.7 (5%)	3.9 (4%)
$T(t), m_T = 1.6 \text{ TeV}, w \simeq 0$	0.3 (3%)	0.3 (2%)	0.8 (6%)	0.7 (5%)
$T(t), m_T = 1.6 \text{ TeV}, w = 0.3m_T$	0.8 (3%)	0.7 (2%)	1.7 (6%)	1.5 (5%)

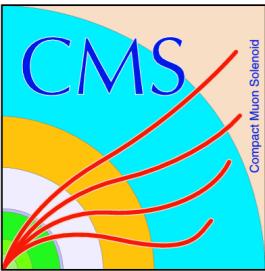
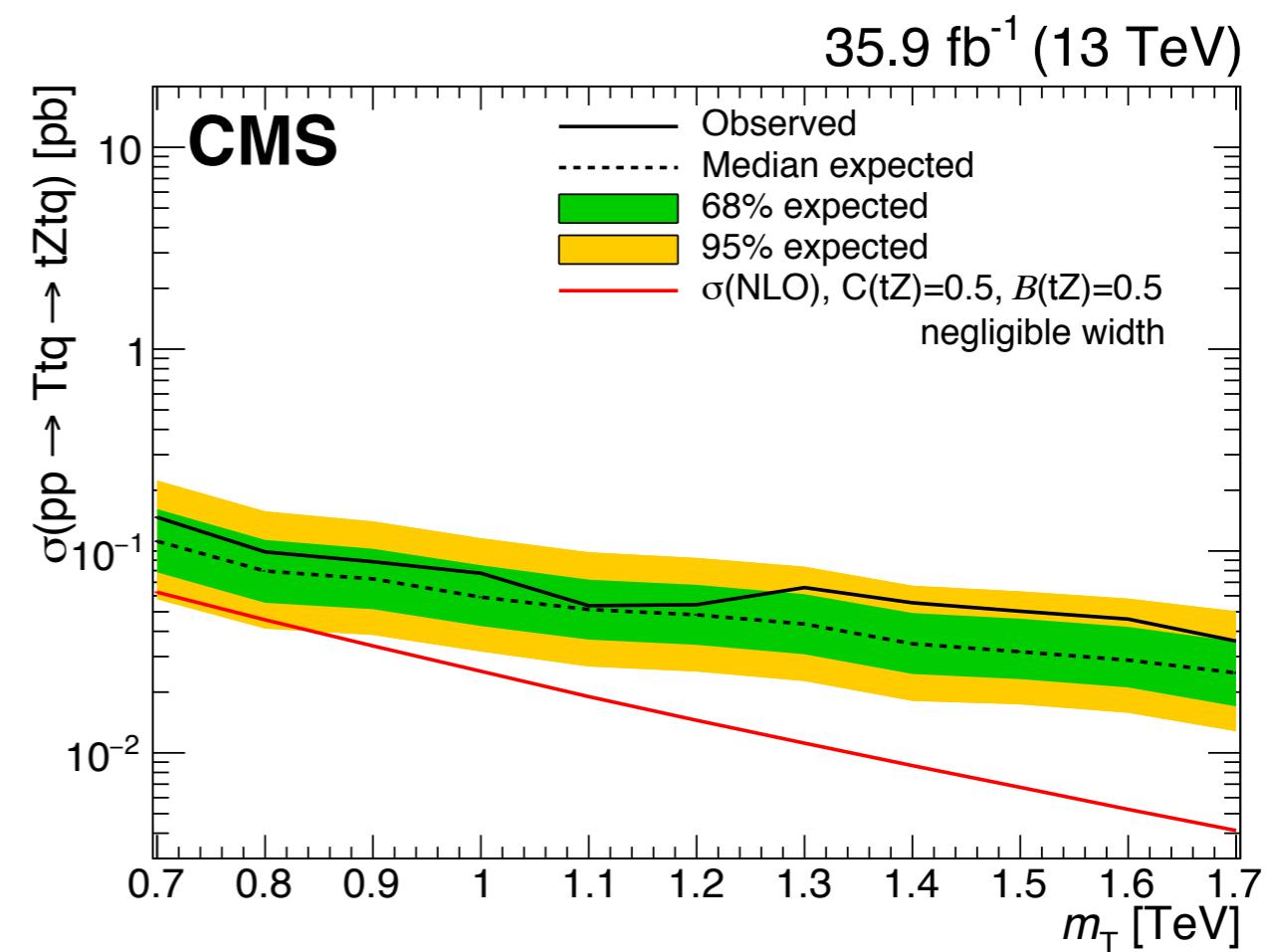


# $T \rightarrow tZ$ : Narrow Width Limits

## Left-Handed

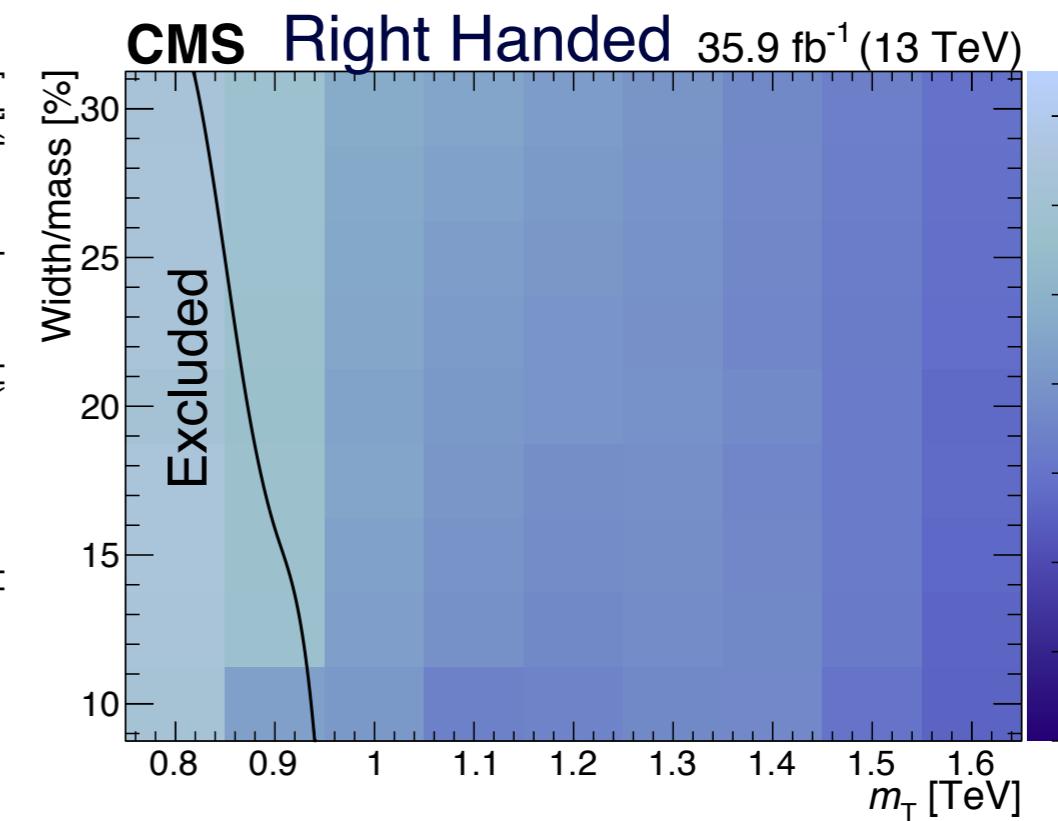
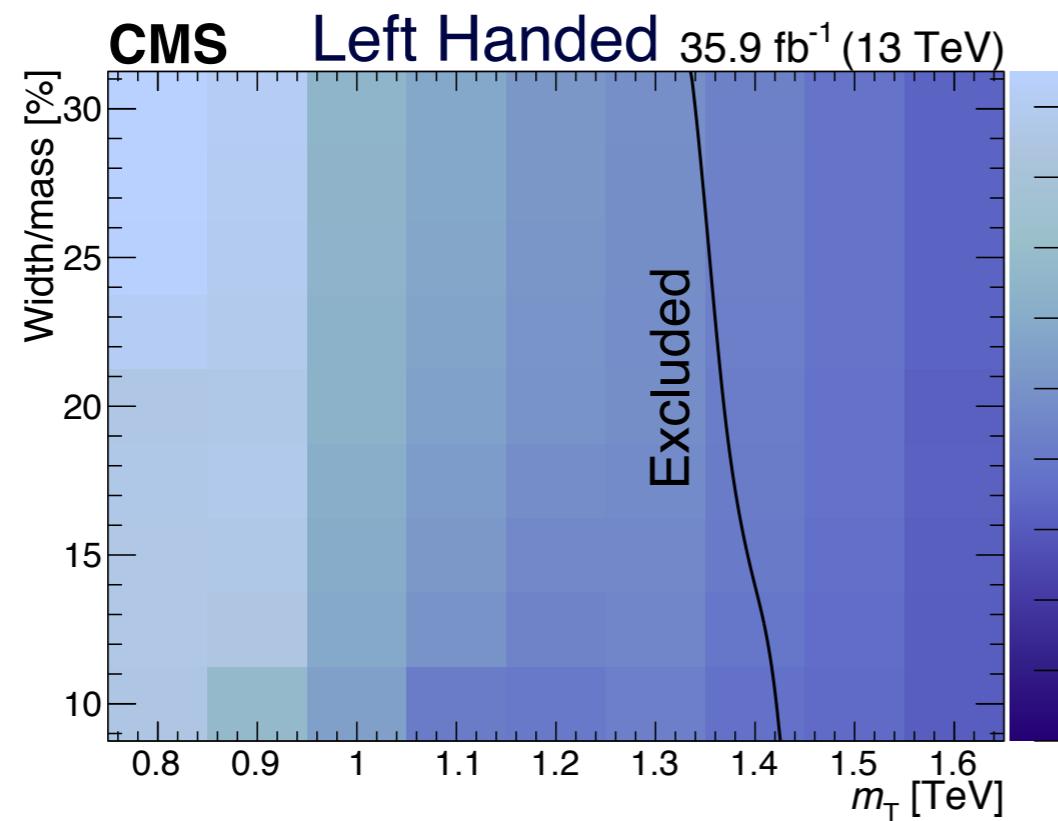


## Right-Handed

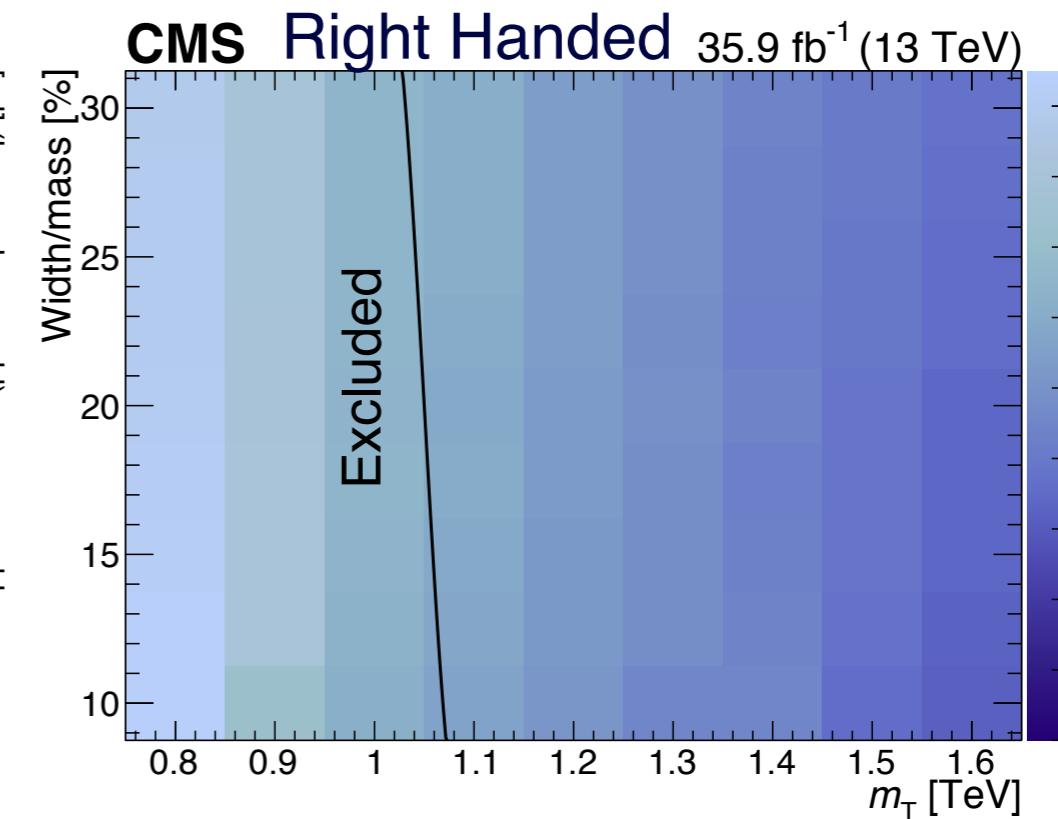
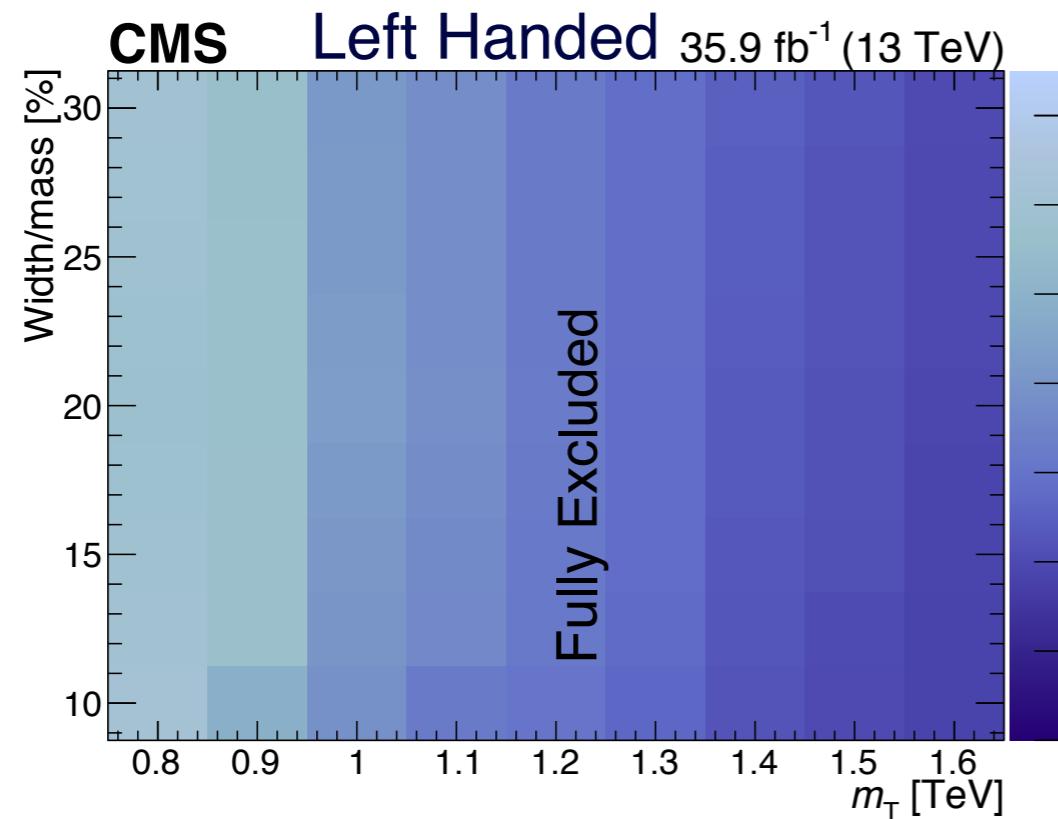


# $T \rightarrow tZ$ : Wide $T$ Limits

Expected



Observed



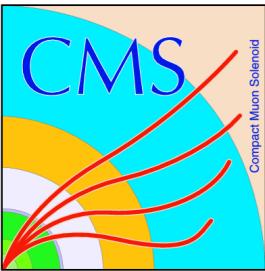
# $Z' \rightarrow Tt \rightarrow ttZ$ : Limits

$m_{Z'} [\text{TeV}]$	$m_T [\text{TeV}]$	Observed	Expected	Expected $-1(2)$ s.d.	Expected $+1(2)$ s.d.
1.5	0.7	0.13	0.10	0.07 (0.05)	0.14 (0.19)
1.5	0.9	0.11	0.08	0.06 (0.04)	0.12 (0.16)
1.5	1.2	0.09	0.05	0.04 (0.03)	0.07 (0.10)
2.0	0.9	0.09	0.06	0.04 (0.03)	0.08 (0.11)
2.0	1.2	0.08	0.05	0.03 (0.03)	0.07 (0.09)
2.0	1.5	0.06	0.03	0.03 (0.02)	0.05 (0.07)
2.5	1.2	0.07	0.05	0.03 (0.02)	0.06 (0.09)
2.5	1.5	0.06	0.04	0.03 (0.02)	0.05 (0.07)



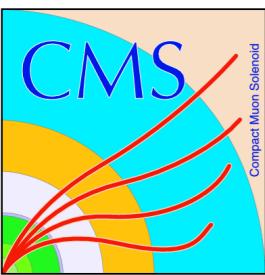
# B $\rightarrow$ Hb $\rightarrow$ bbb: NWA Cross Sections

$m_B$ (GeV)	$\hat{\sigma}_{\text{NWA}}$ (pb)	Singlet model					Doublet model				
		$\kappa$	$B_{B \rightarrow Wt}$	$\mathcal{B}_{B \rightarrow Zb}$	$\mathcal{B}_{B \rightarrow Hb}$	$\sigma_{\text{NWA}}$ (pb)	$\kappa$	$\mathcal{B}_{B \rightarrow Zb}$	$\mathcal{B}_{B \rightarrow Hb}$	$\sigma_{\text{NWA}}$ (pb)	
700	31.30 $^{+28\%}_{-20\%}$	0.18	0.466	0.271	0.263	0.1631	0.25	0.499	0.501	0.5720	
800	21.50 $^{+29\%}_{-21\%}$	0.16	0.474	0.276	0.260	0.0830	0.22	0.499	0.501	0.3003	
900	15.10 $^{+30\%}_{-21\%}$	0.14	0.489	0.263	0.258	0.0451	0.19	0.500	0.500	0.1666	
1000	10.80 $^{+31\%}_{-23\%}$	0.13	0.483	0.261	0.256	0.0257	0.17	0.500	0.500	0.0962	
1100	7.85 $^{+32\%}_{-22\%}$	0.11	0.486	0.259	0.255	0.0153	0.16	0.500	0.500	0.0580	
1200	5.77 $^{+33\%}_{-23\%}$	0.10	0.489	0.257	0.254	0.0094	0.15	0.500	0.500	0.0358	
1300	4.29 $^{+34\%}_{-23\%}$	0.10	0.490	0.256	0.254	0.0059	0.13	0.500	0.500	0.0227	
1400	3.23 $^{+34\%}_{-23\%}$	0.09	0.492	0.255	0.253	0.0038	0.12	0.500	0.500	0.0147	
1500	2.45 $^{+35\%}_{-25\%}$	0.08	0.493	0.254	0.253	0.0025	0.12	0.500	0.500	0.0097	
1600	1.86 $^{+36\%}_{-24\%}$	0.08	0.494	0.254	0.252	0.0017	0.11	0.500	0.500	0.0065	
1700	1.44 $^{+37\%}_{-24\%}$	0.07	0.494	0.254	0.252	0.0011	0.10	0.500	0.500	0.0044	
1800	1.11 $^{+37\%}_{-25\%}$	0.07	0.495	0.253	0.252	0.0008	0.10	0.500	0.500	0.0031	



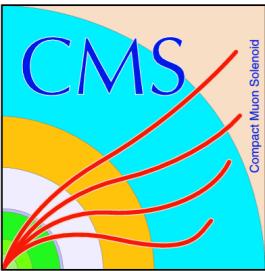
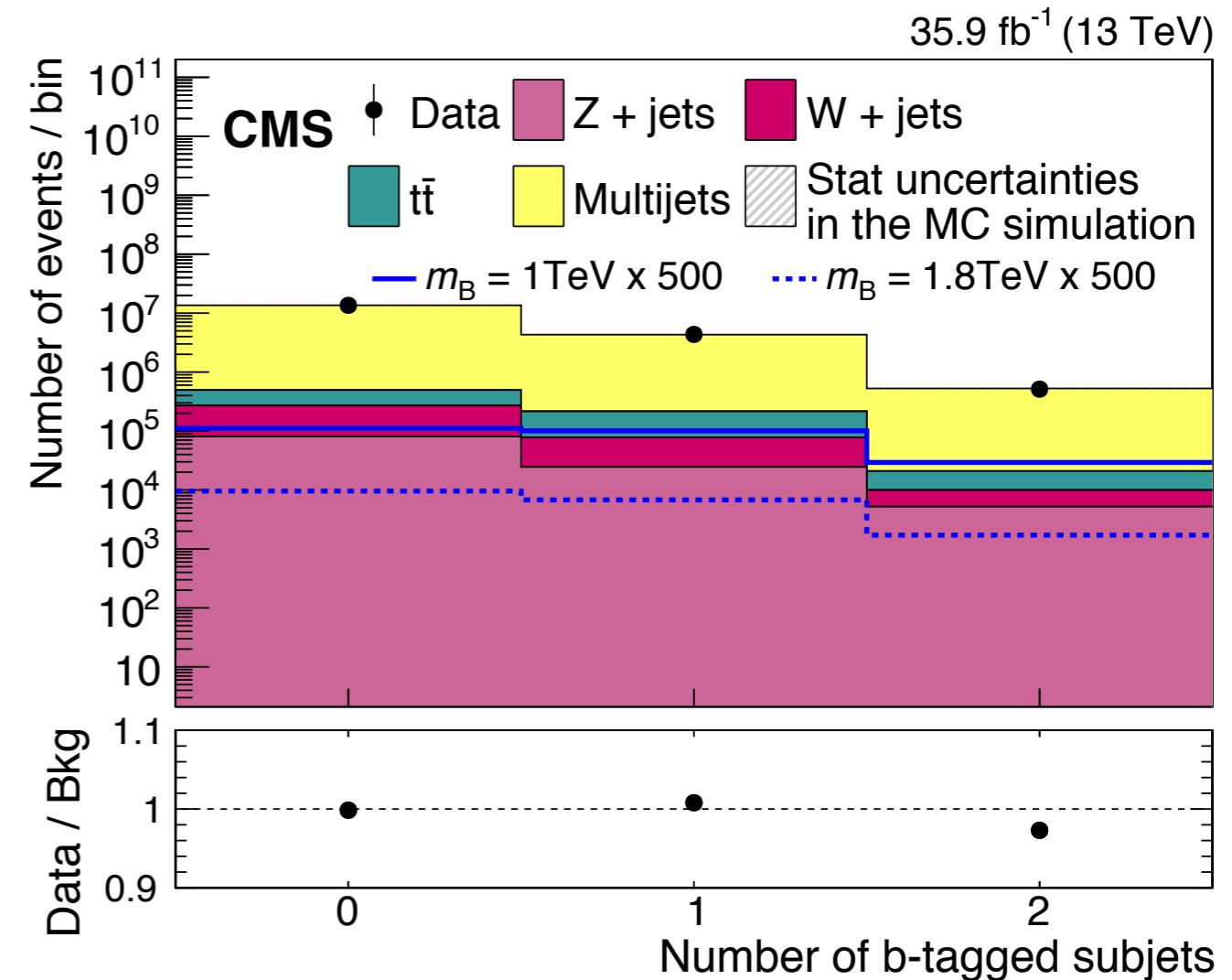
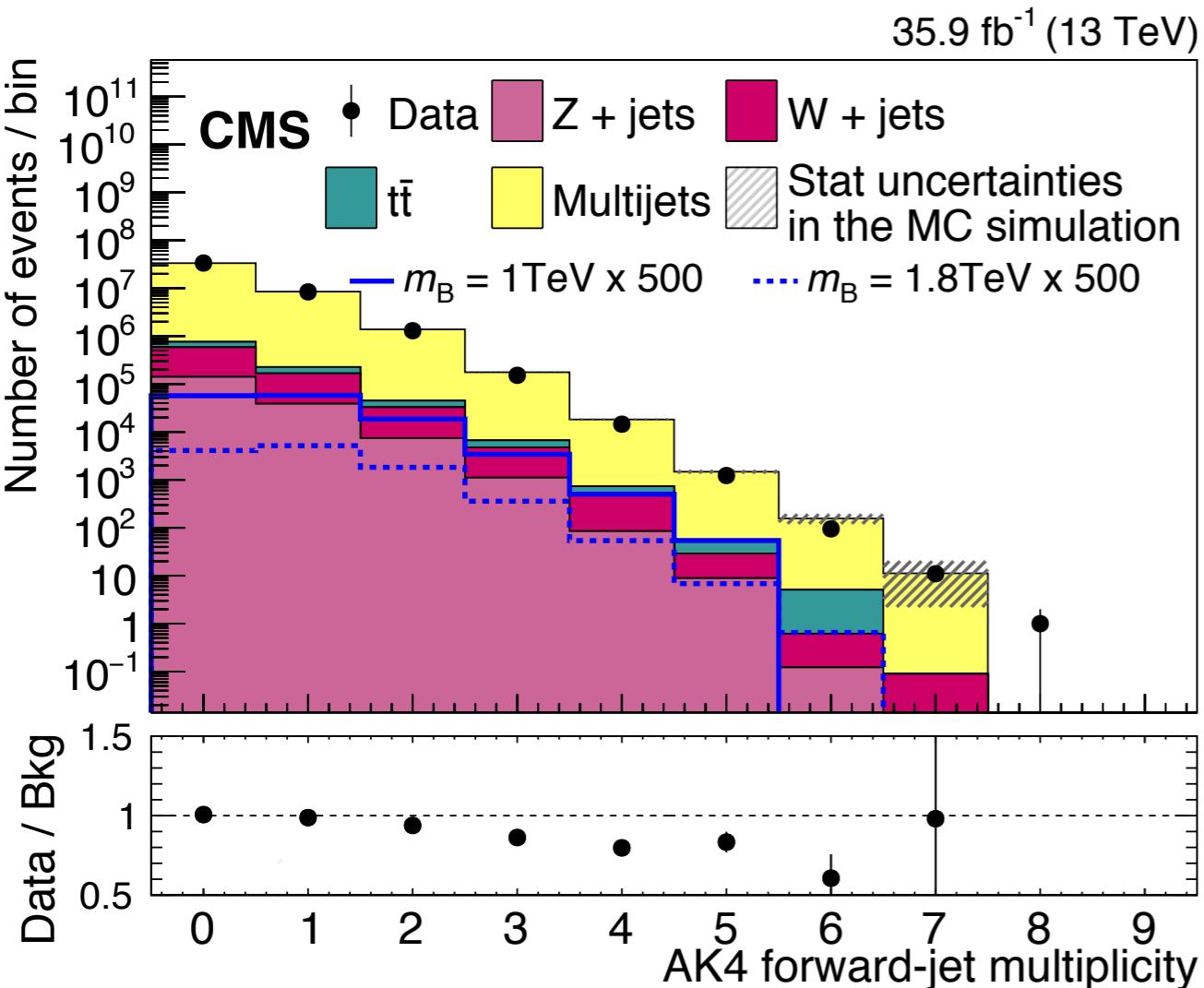
# B $\rightarrow$ Hb $\rightarrow$ bbb: Wide Cross Sections

$m_B$ (GeV)	$\Gamma_B/m_B = 10\%$			$\Gamma_B/m_B = 20\%$			$\Gamma_B/m_B = 30\%$		
	$\tilde{\sigma}_{AW}$ (pb)	$\sigma_S$ (fb) ( $\kappa$ )	$\sigma_D$ (fb) ( $\kappa$ )	$\tilde{\sigma}_{AW}$ (pb)	$\sigma_S$ (fb) ( $\kappa$ )	$\sigma_D$ (fb) ( $\kappa$ )	$\tilde{\sigma}_{AW}$ (pb)	$\sigma_S$ (fb) ( $\kappa$ )	$\sigma_D$ (fb) ( $\kappa$ )
700	3.01	400 (0.588)	1378 (0.8010)	1.43	759 (0.832)	2616 (1.130)	0.899	1074 (1.020)	3703 (1.390)
800	2.10	203 (0.508)	726 (0.699)	1.00	386 (0.719)	1377 (0.9880)	0.634	552 (0.880)	1968 (1.210)
900	1.51	111 (0.448)	406 (0.619)	0.719	212 (0.633)	775 (0.876)	0.454	301 (0.776)	1101 (1.070)
1000	1.09	63.7 (0.401)	237 (0.556)	0.523	122 (0.567)	453 (0.787)	0.331	174 (0.694)	647 (0.964)
1100	0.807	38.2 (0.363)	144 (0.505)	0.386	73.2 (0.513)	276 (0.714)	0.246	105 (0.628)	394 (0.875)
1200	0.601	23.6 (0.331)	89.7 (0.463)	0.290	45.5 (0.468)	173 (0.654)	0.185	65.2 (0.574)	248 (0.801)
1300	0.451	14.9 (0.305)	57.1 (0.427)	0.220	29.0 (0.431)	111 (0.603)	0.141	41.9 (0.528)	160 (0.739)
1400	0.342	9.70 (0.283)	37.2 (0.396)	0.167	18.9 (0.400)	72.9 (0.560)	0.108	27.5 (0.489)	106 (0.686)
1500	0.262	6.42 (0.263)	24.9 (0.369)	0.129	12.6 (0.372)	48.9 (0.522)	0.0836	18.4 (0.456)	71.3 (0.640)
1600	0.203	4.34 (0.246)	16.9 (0.346)	0.101	8.61 (0.349)	33.5 (0.489)	0.0651	12.5 (0.427)	48.7 (0.599)
1700	0.158	2.99 (0.232)	11.6 (0.326)	0.0788	5.94 (0.328)	23.2 (0.460)	0.0514	8.71 (0.401)	34.0 (0.564)
1800	0.124	2.08 (0.219)	8.13 (0.307)	0.0621	4.16 (0.309)	16.3 (0.435)	0.0408	6.14 (0.379)	24.0 (0.532)

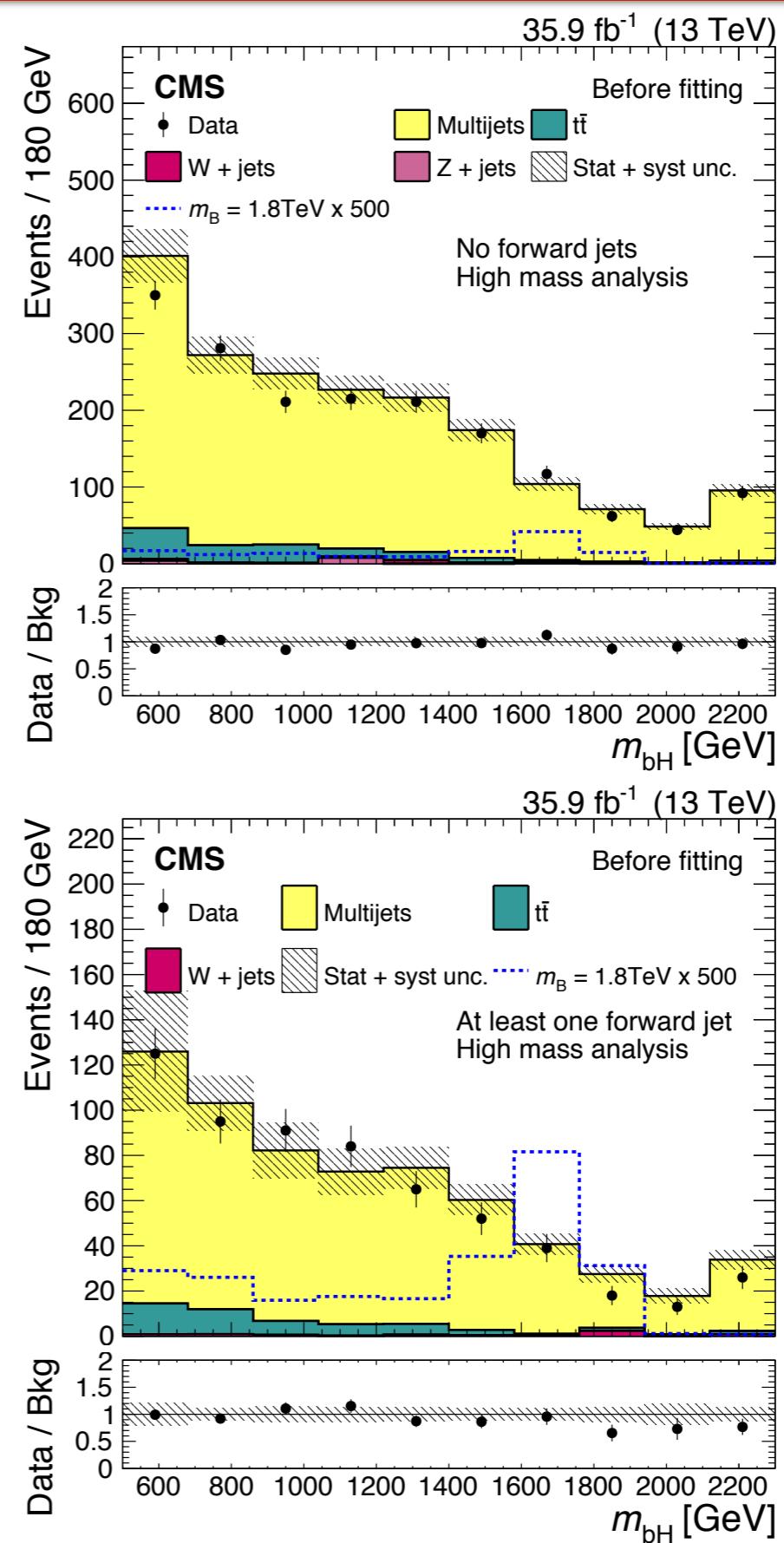
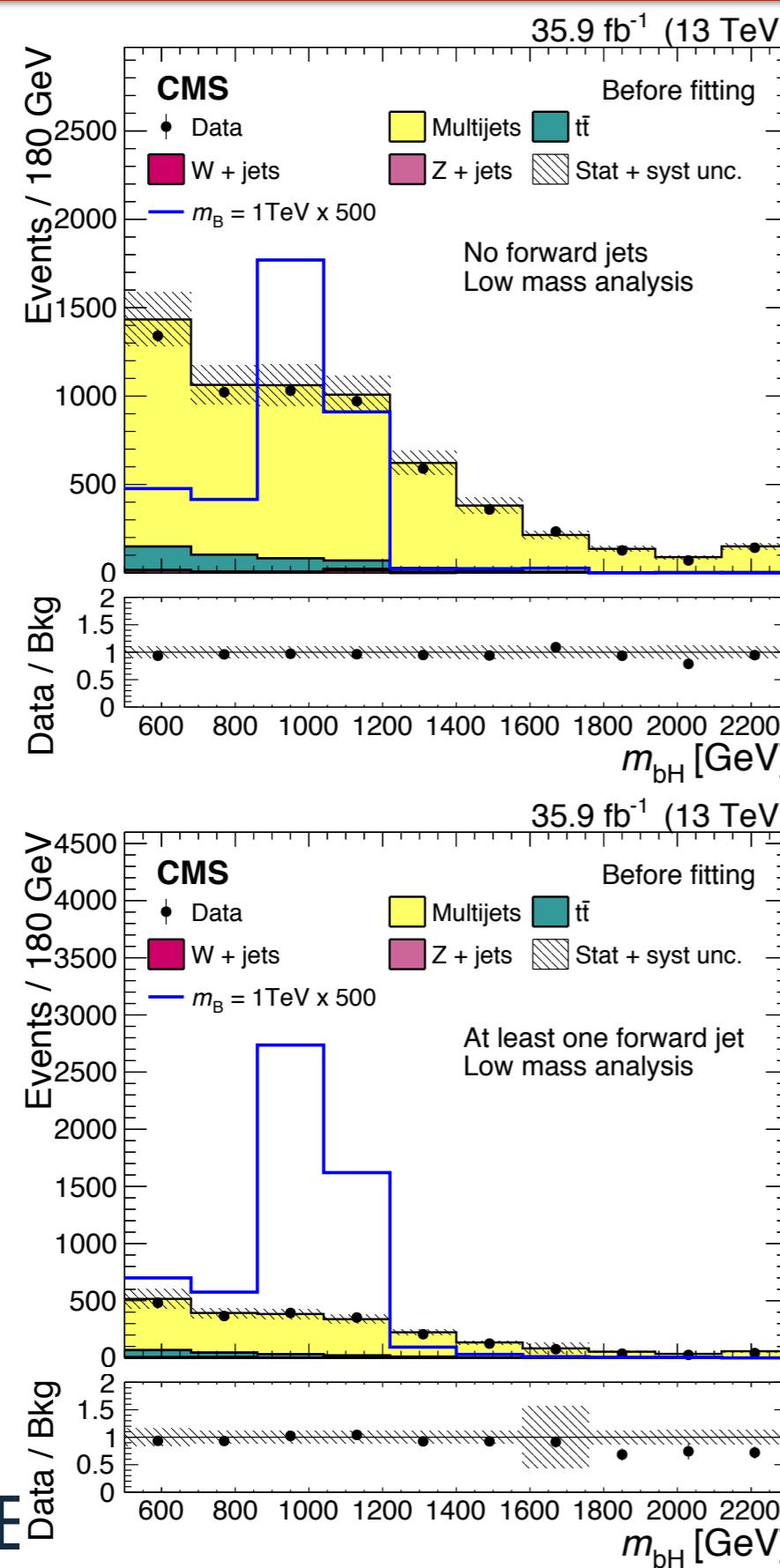


# B $\rightarrow$ Hb $\rightarrow$ bbb: N jet and b-jets

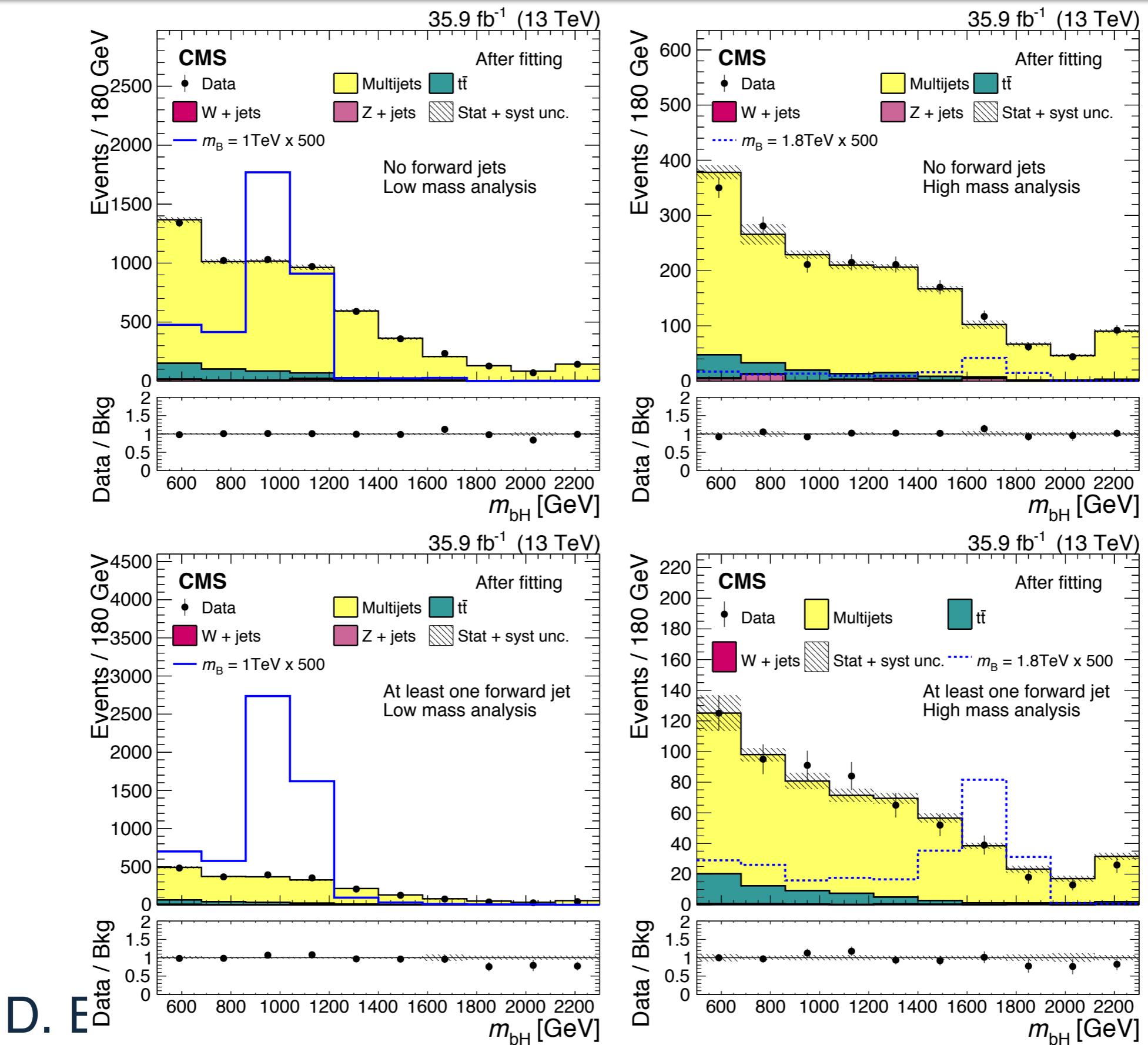
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# B $\rightarrow$ Hb $\rightarrow$ bbb: Pre-fit Distributions

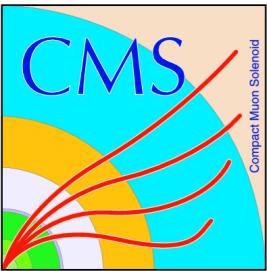


# B $\rightarrow$ Hb $\rightarrow$ bbb: Post-fit Distributions



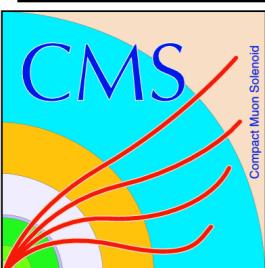
# B $\rightarrow$ Hb $\rightarrow$ bbb: Systematics

Source	Effect
Luminosity	2.5%
b tagging efficiency	0–9%
Misidentification efficiency	0–2%
Pileup modelling	0–12%
Trigger	<0.5%
PDF	1.0–4.5%
$\mu_R$ and $\mu_F$	15–25%
Jet energy scale	1–7%
Jet energy resolution	1.0–1.5%
Jet mass scale	0–5%
Jet mass resolution	0–4%
MC Statistical accuracy	1–4%
Mismodelling of forward jets	0.5/2.0%
Background estimation	5–10%

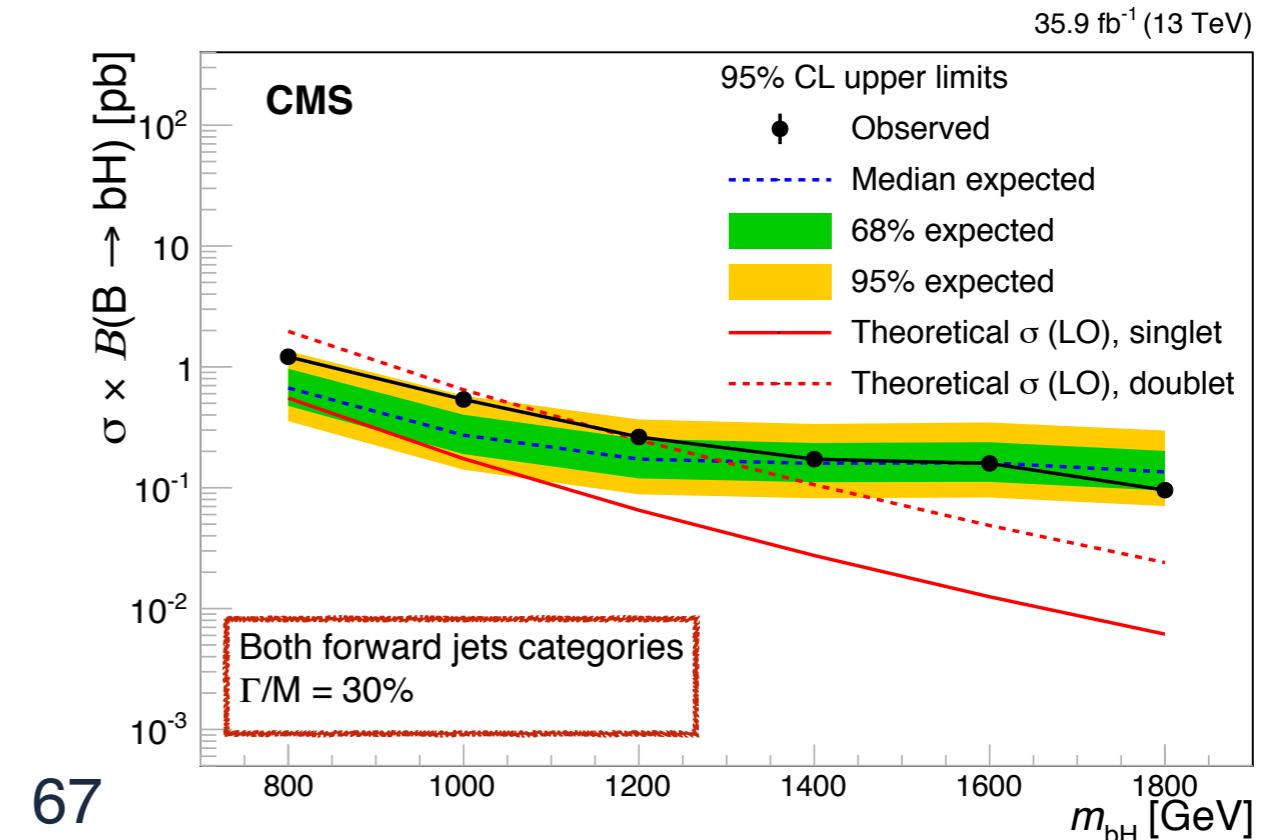
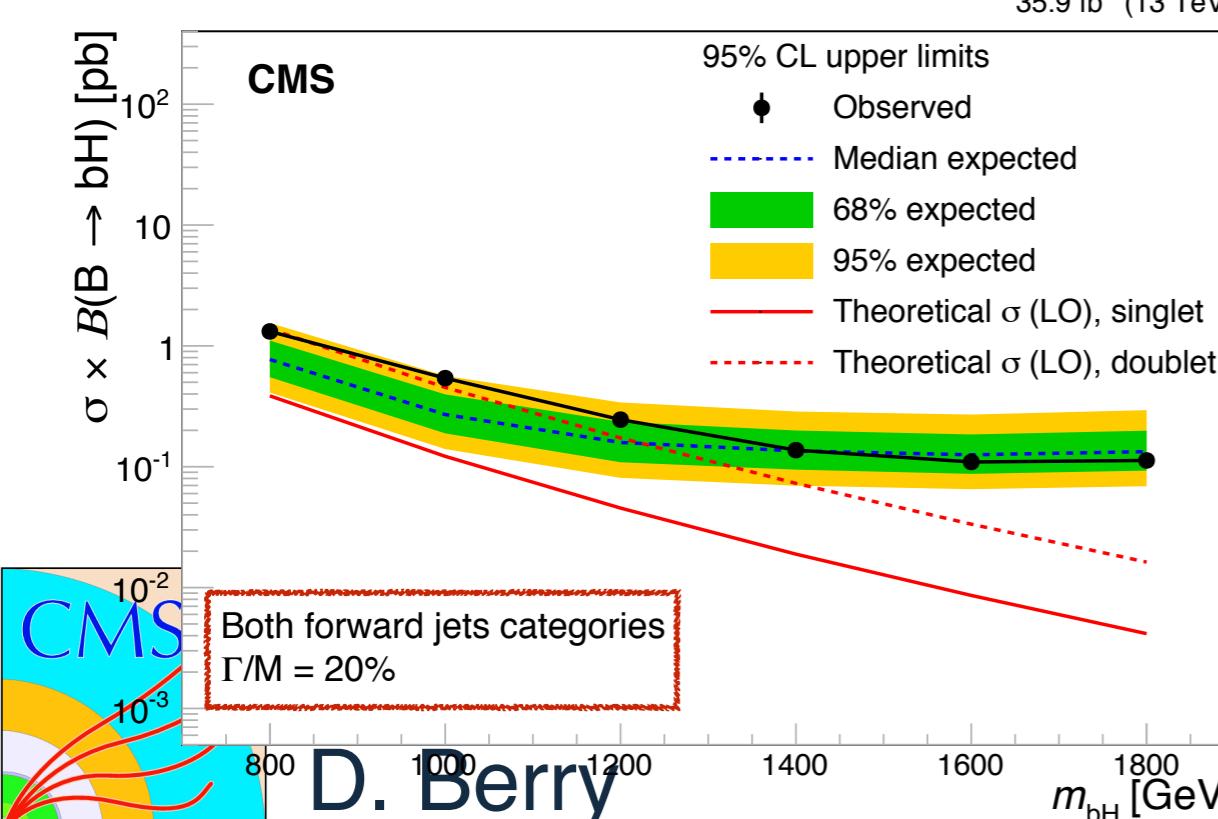
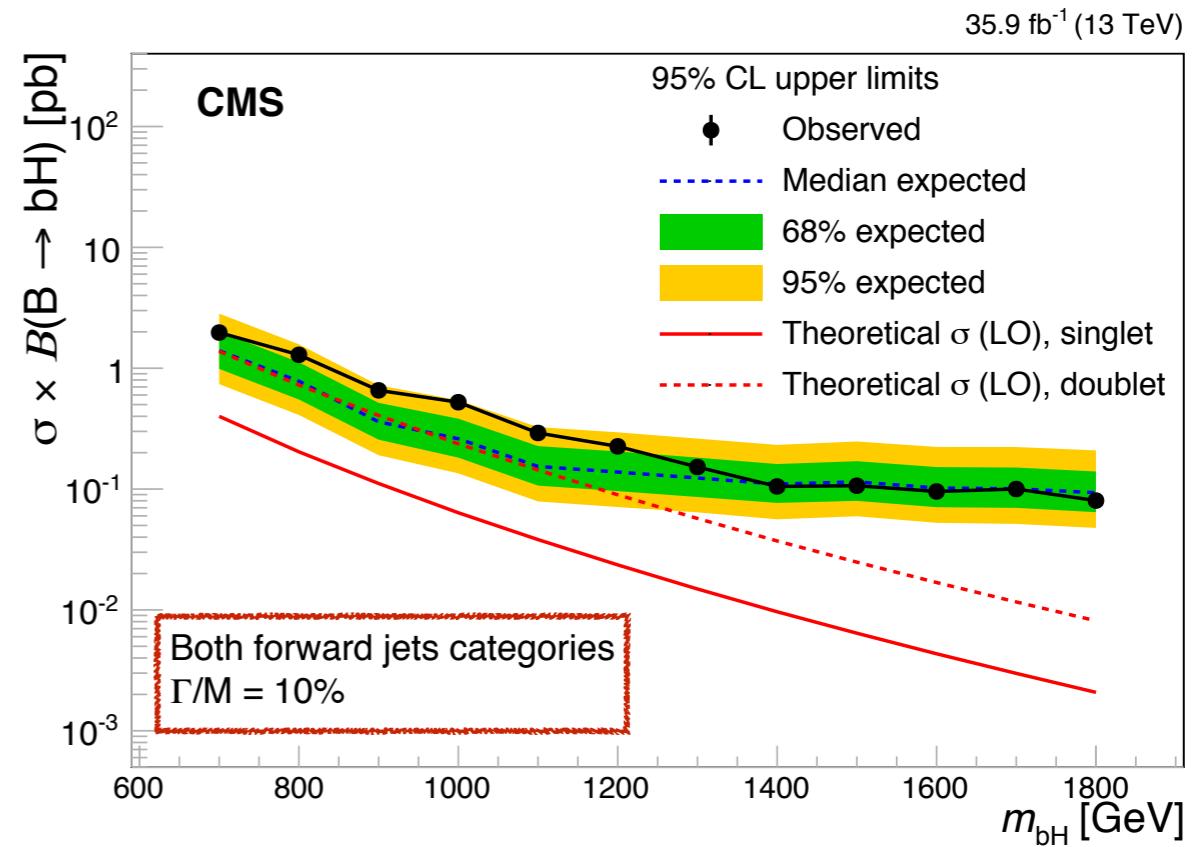
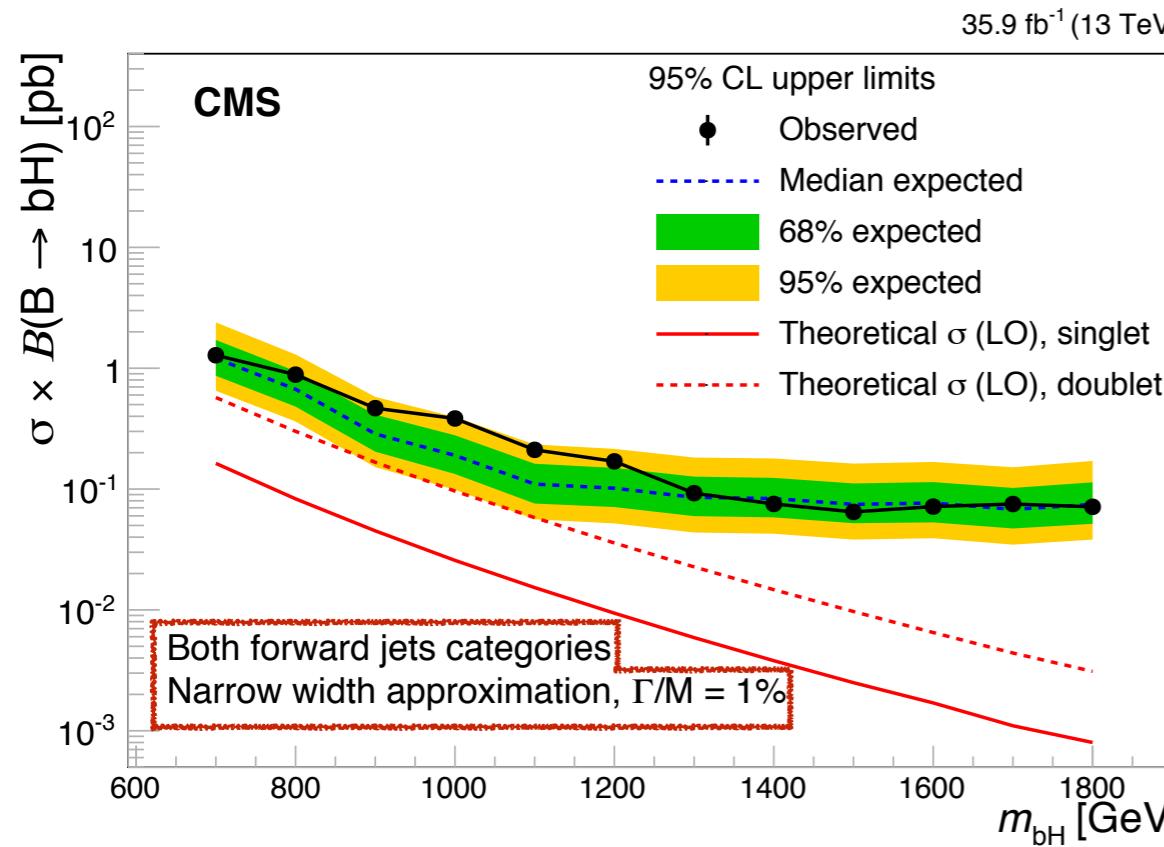


# B $\rightarrow$ Hb $\rightarrow$ bbb: Yields

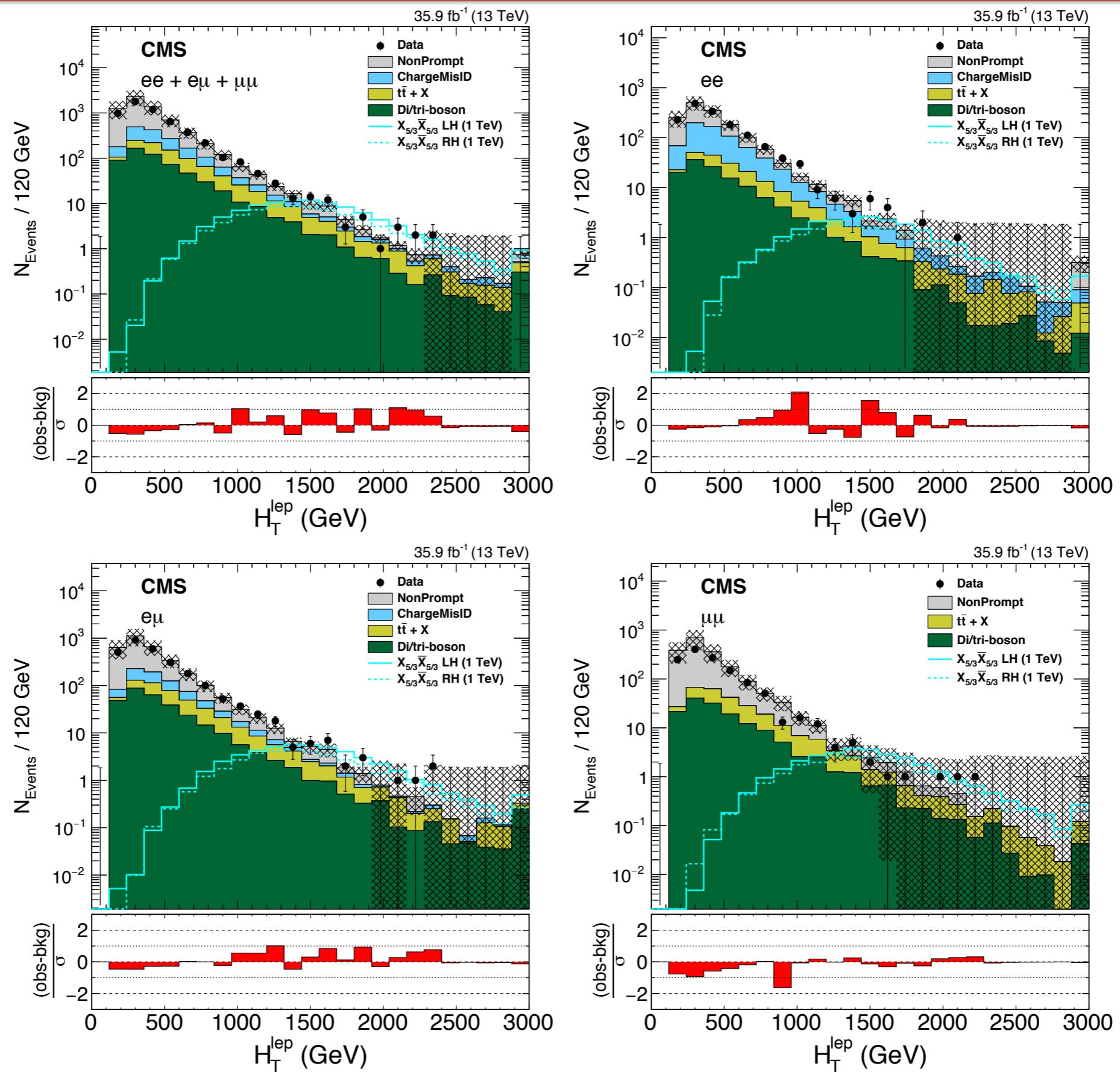
Category	Source	$700 < m_B < 1500 \text{ GeV}$	$1500 < m_B < 1800 \text{ GeV}$
No forward jets	t $\bar{t}$	$394 \pm 46$	$117 \pm 18$
	W+jets	$29 \pm 13$	$10.5 \pm 4.3$
	Z+jets	$43 \pm 15$	$23 \pm 23$
	Multijets	$5416 \pm 60$	$1612 \pm 24$
	Total background	$5882 \pm 42$	$1762 \pm 26$
	Observed in data	$5886 \pm 77$	$1753 \pm 42$
	Expected signal	$7.3 \pm 0.3$	$0.27 \pm 0.01$
>0 forward jets	t $\bar{t}$	$163 \pm 20$	$58 \pm 17$
	W+jets	$11.5 \pm 4.2$	$4.3 \pm 1.4$
	Z+jets	$2^{+10}_{-2}$	—
	Multijets	$1938 \pm 23$	$549 \pm 10$
	Total background	$2115 \pm 21$	$612 \pm 15$
	Observed in data	$2107 \pm 46$	$608 \pm 25$
	Expected signal	$11.5 \pm 0.3$	$0.51 \pm 0.01$



# $B \rightarrow H_b \rightarrow bbb$ : Limits

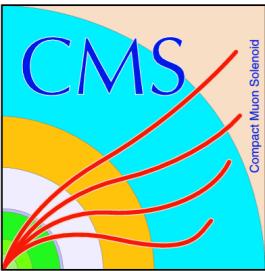
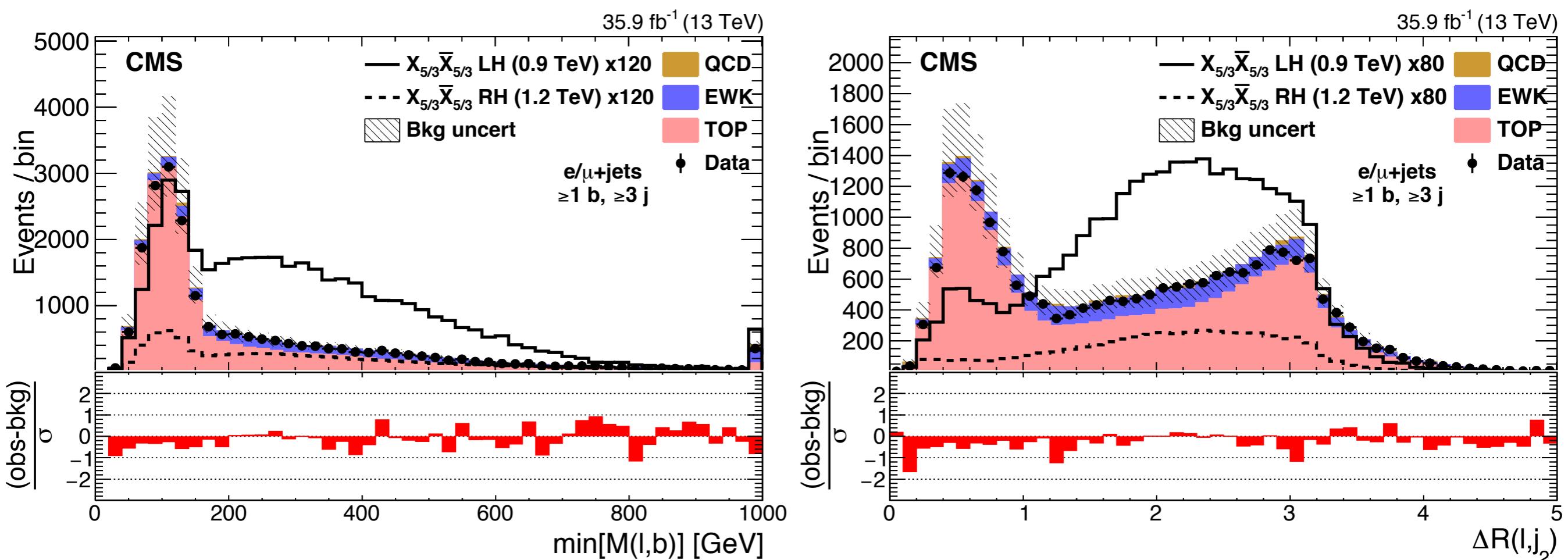


# $X_{5/3}X_{5/3} \rightarrow WtWt: H_T^{\text{lep}}$

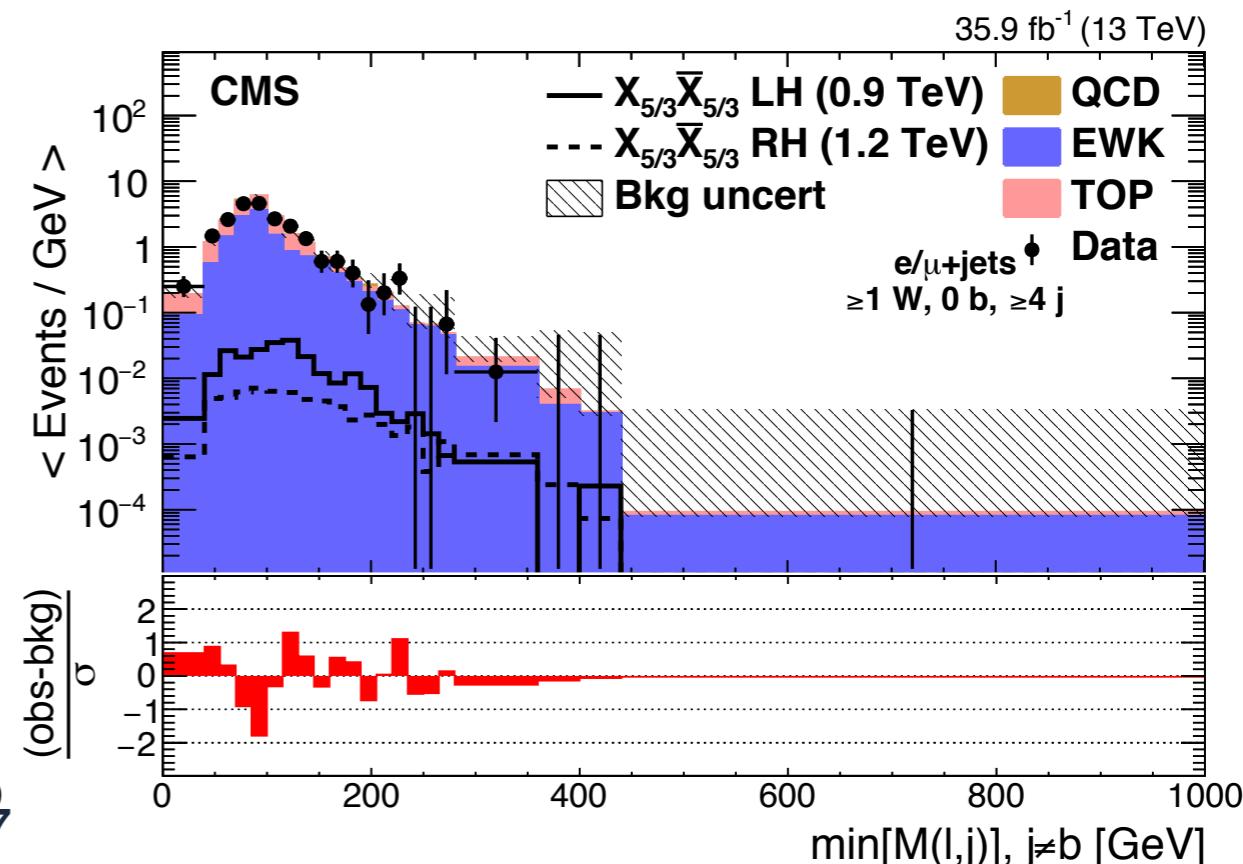
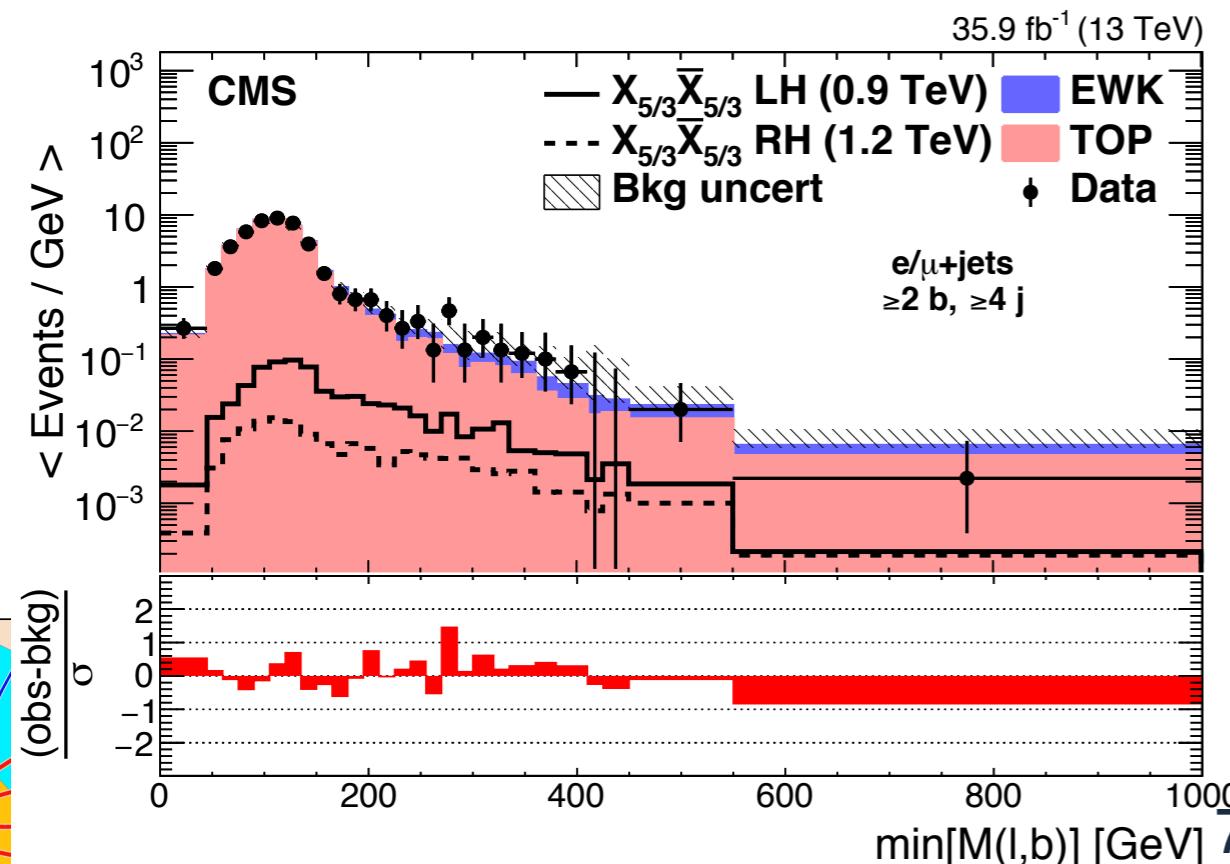
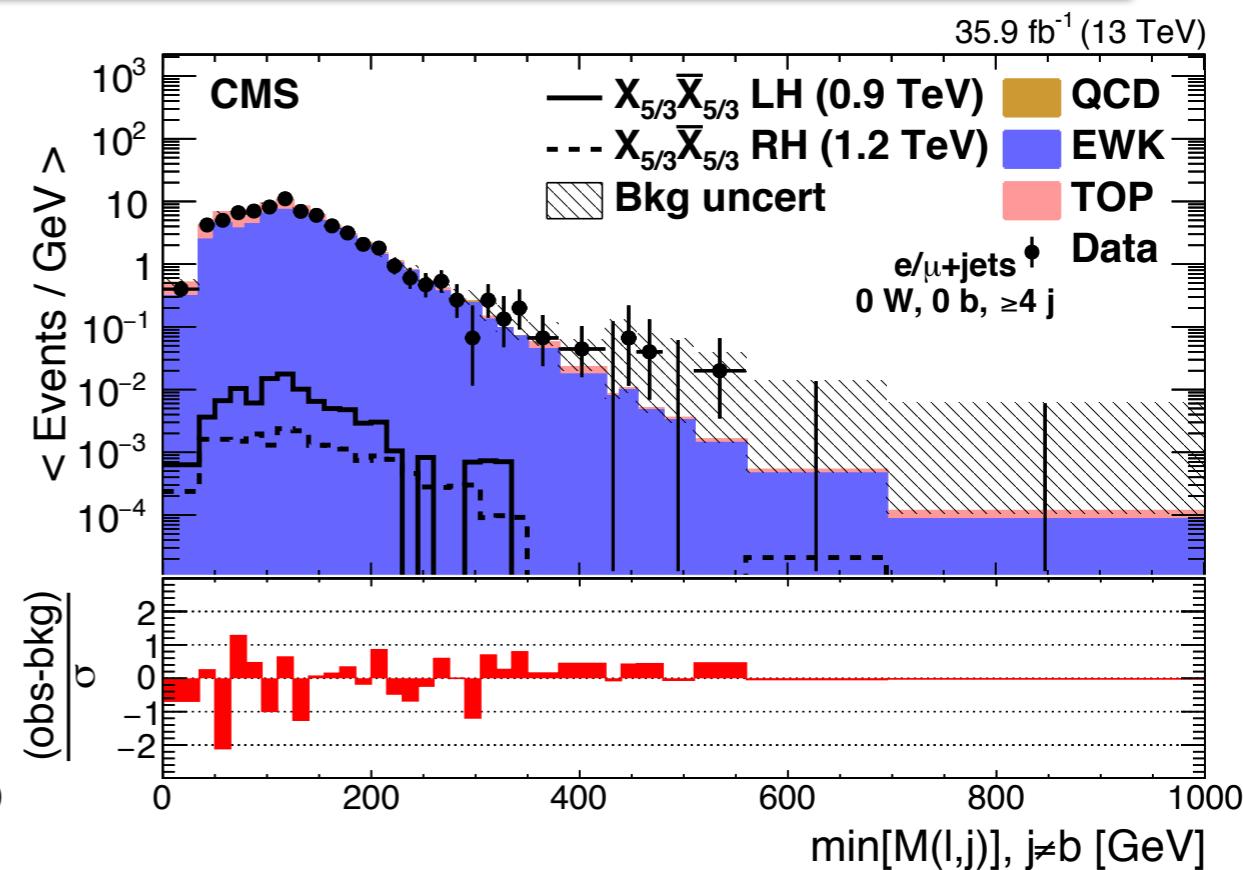
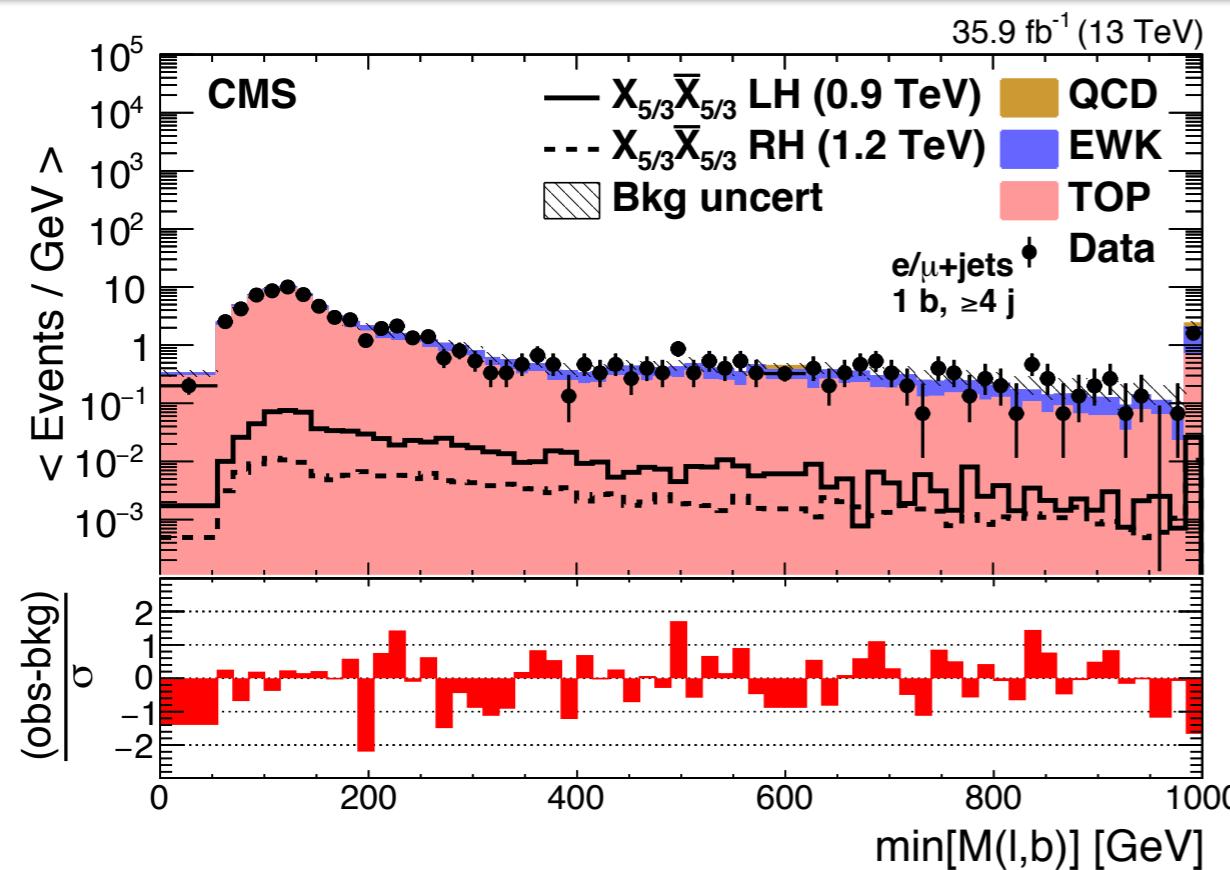


D. E

# $X_{5/3} \bar{X}_{5/3} \rightarrow WtWt$ : $M(l,b)$ and $\Delta R(l,j_2)$ Distributions

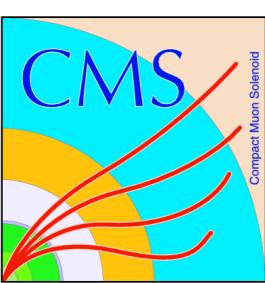


# $X_{5/3}\bar{X}_{5/3} \rightarrow Wt\bar{W}t$ : $M(l,b)$ Distributions $t\bar{t}$ and $W+jets$ CR

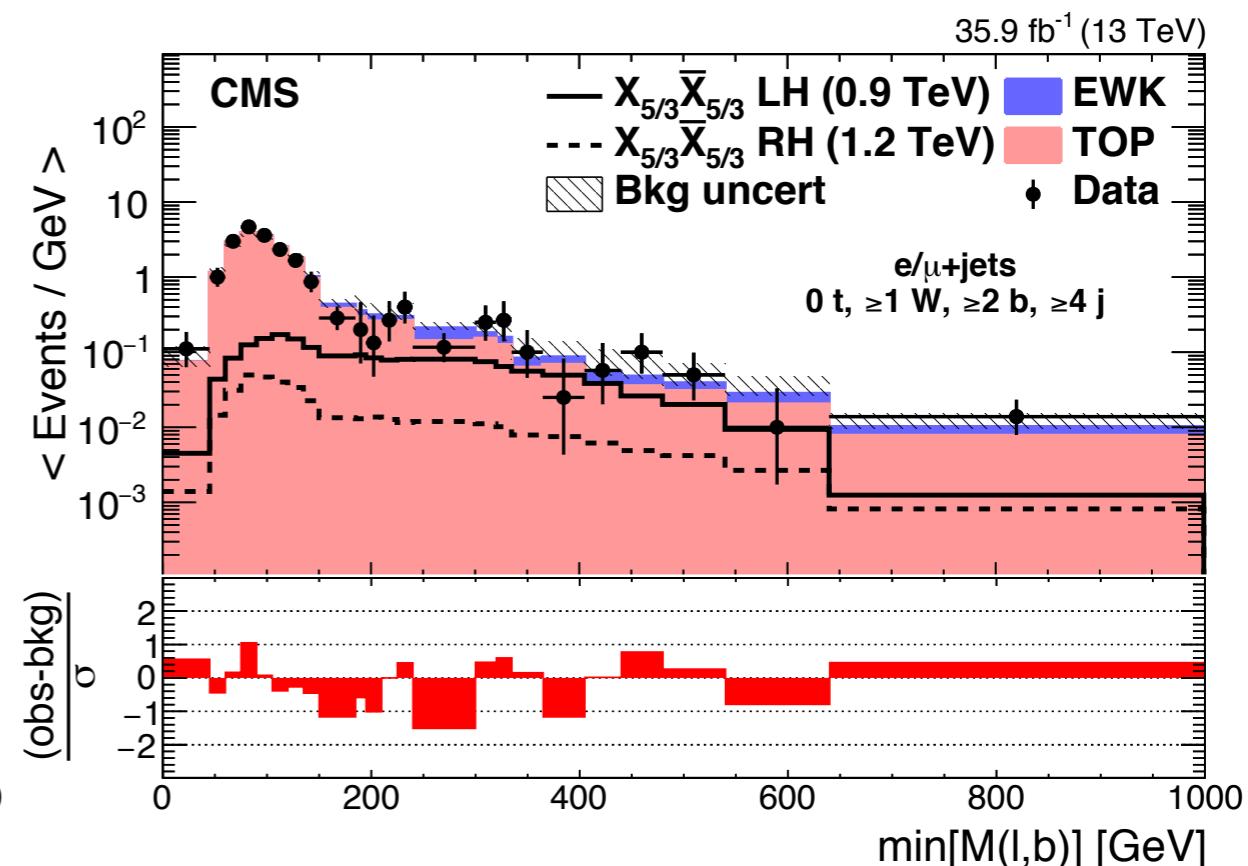
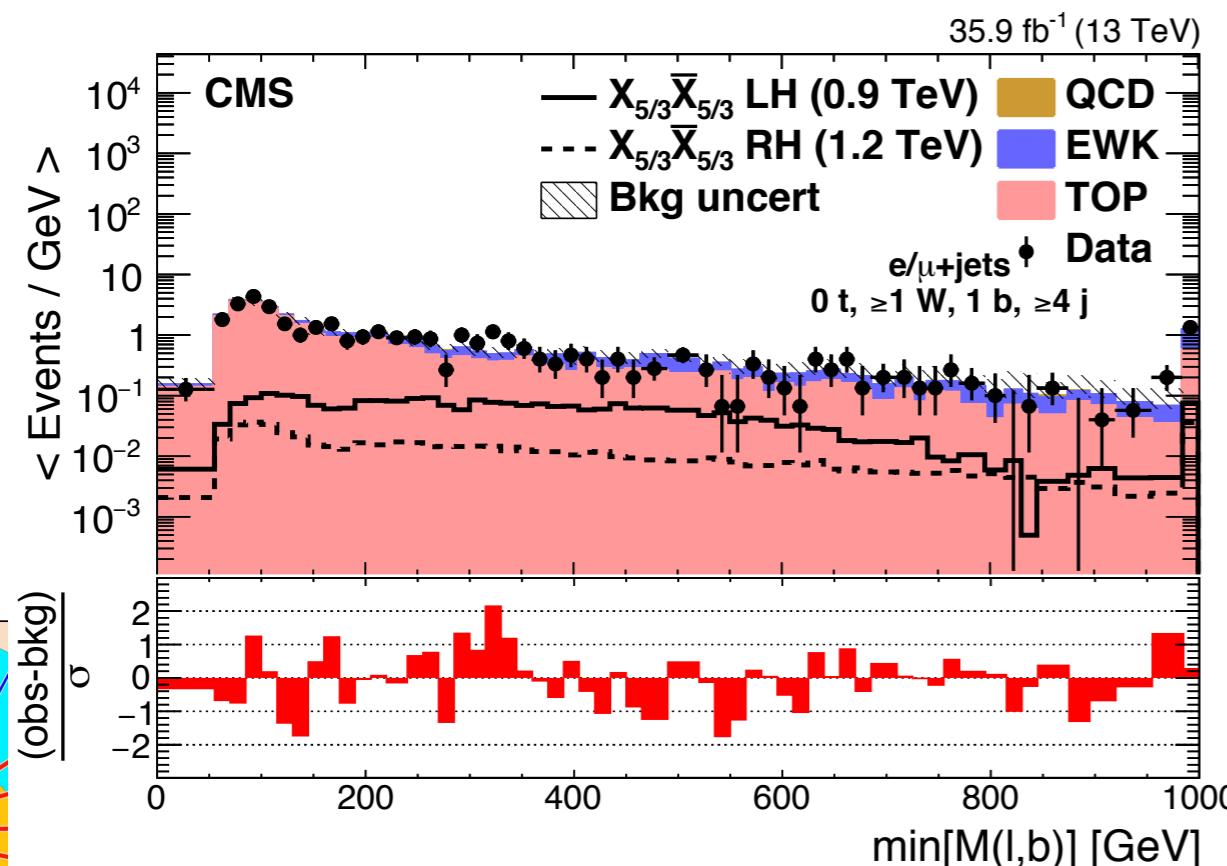
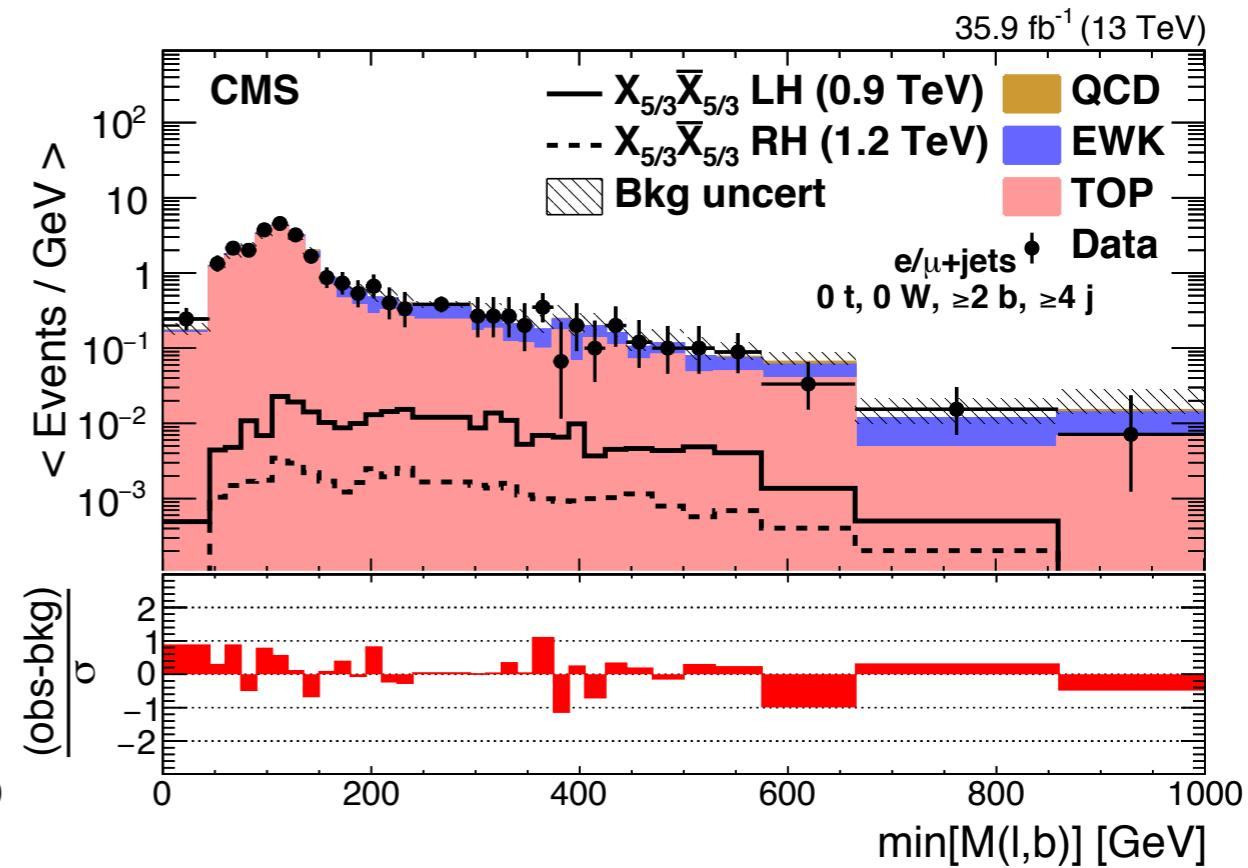
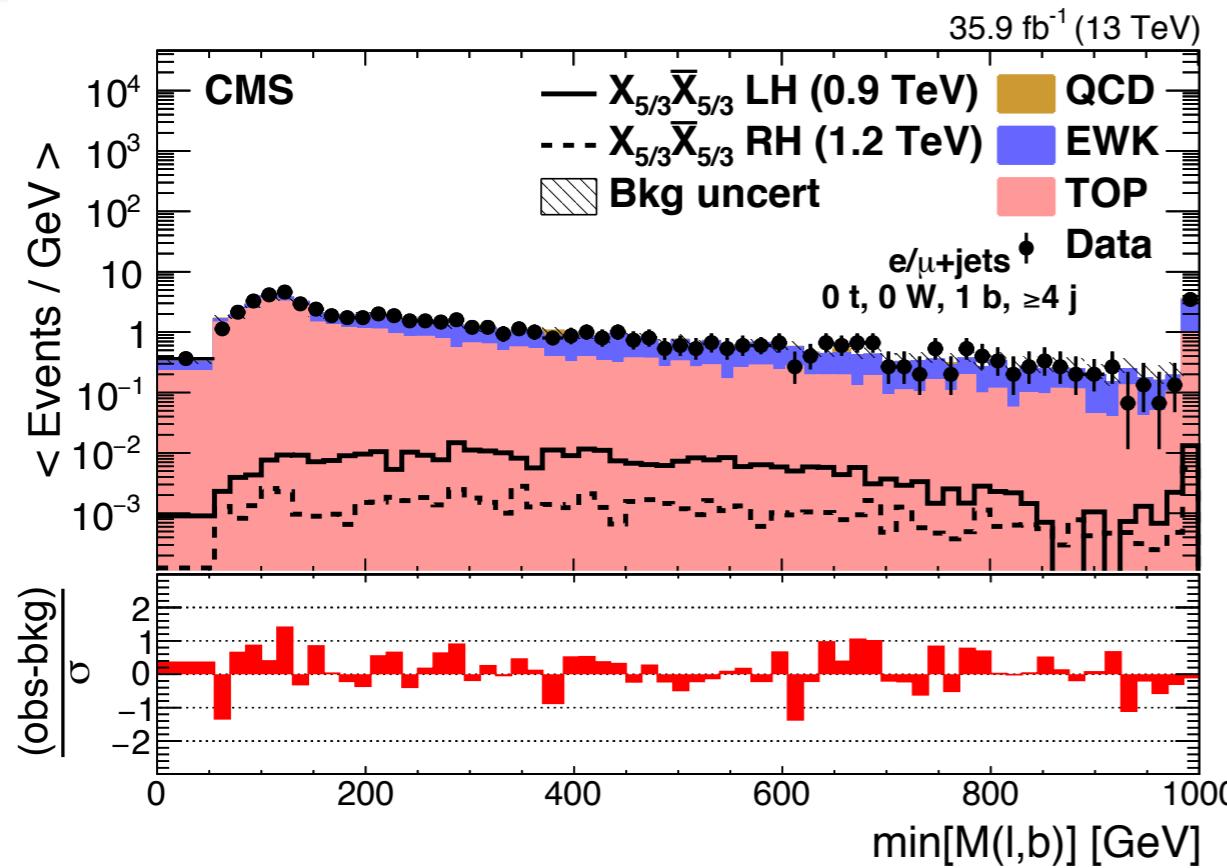


# X<sub>5/3</sub>X<sub>5/3</sub>→WtWt: Yeilds t̄t and W+Jets CR

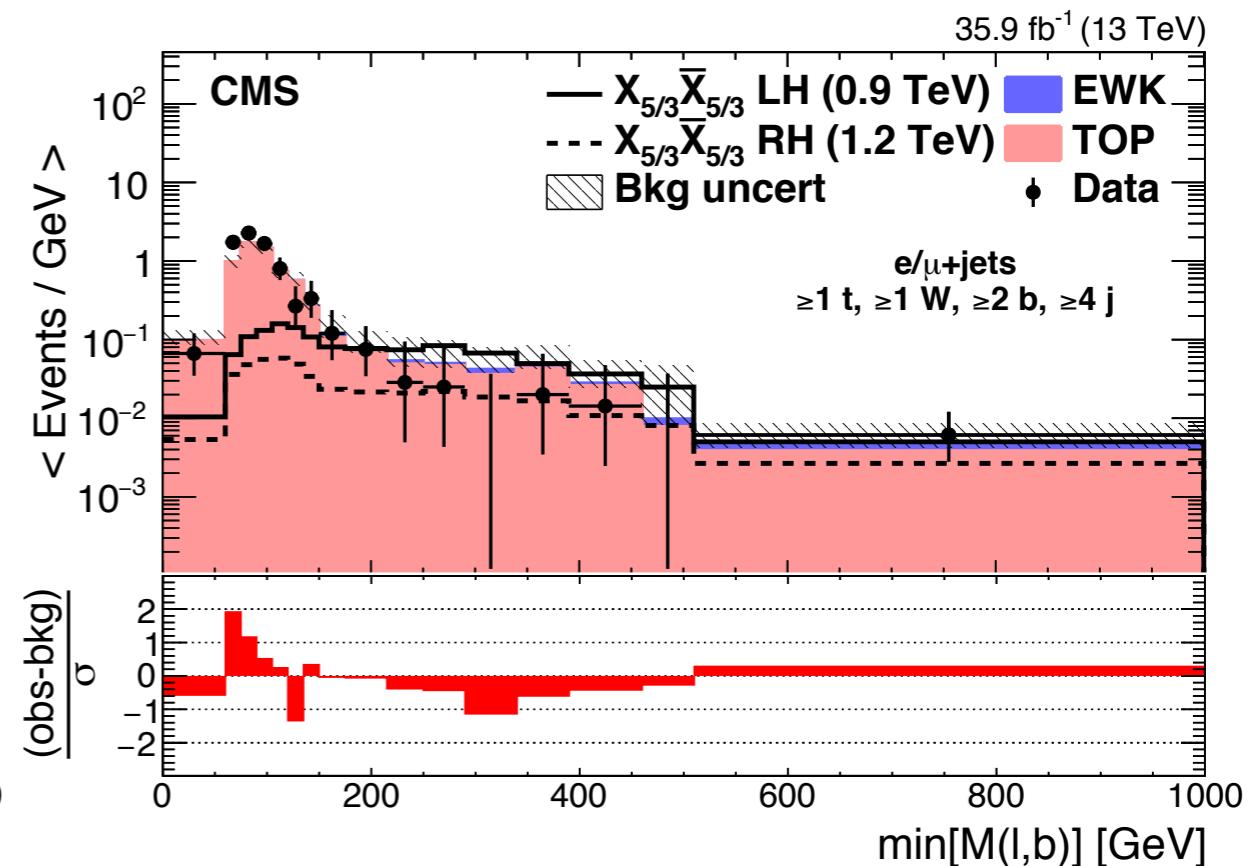
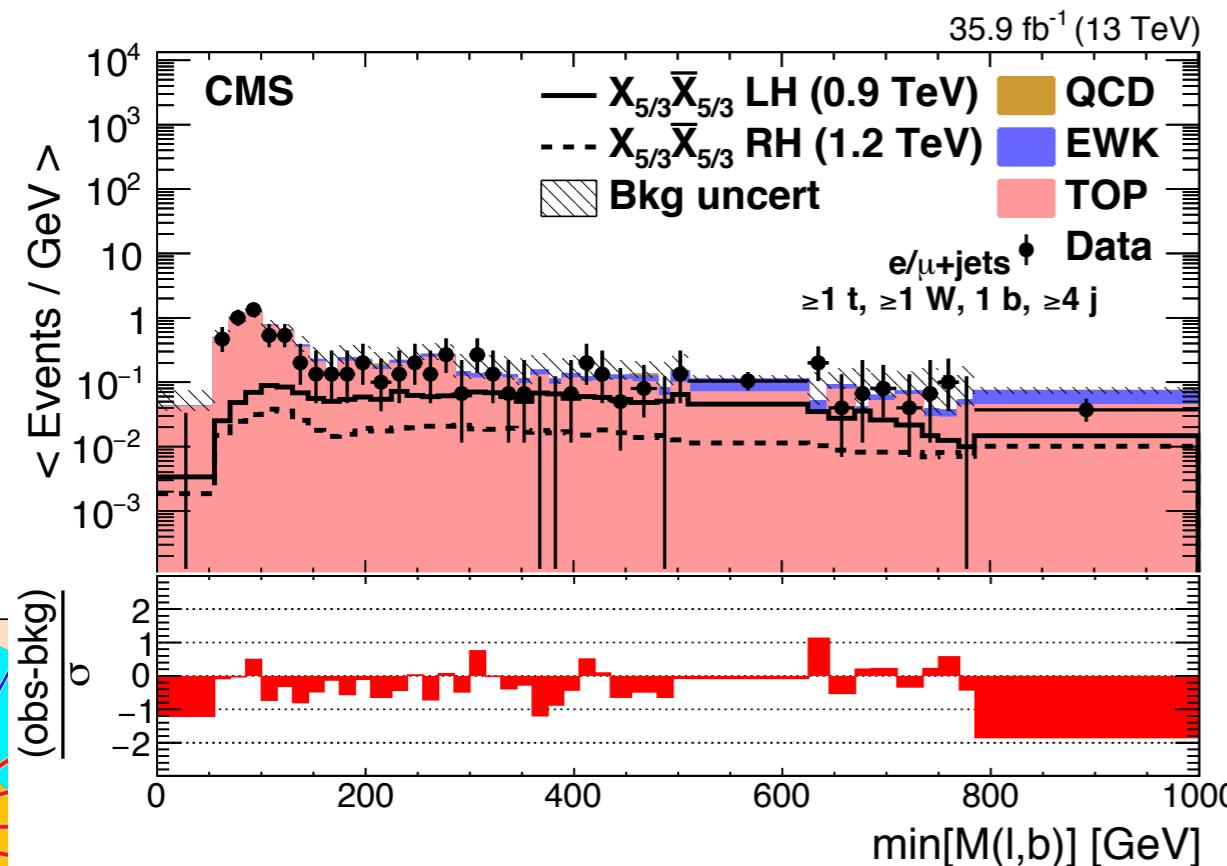
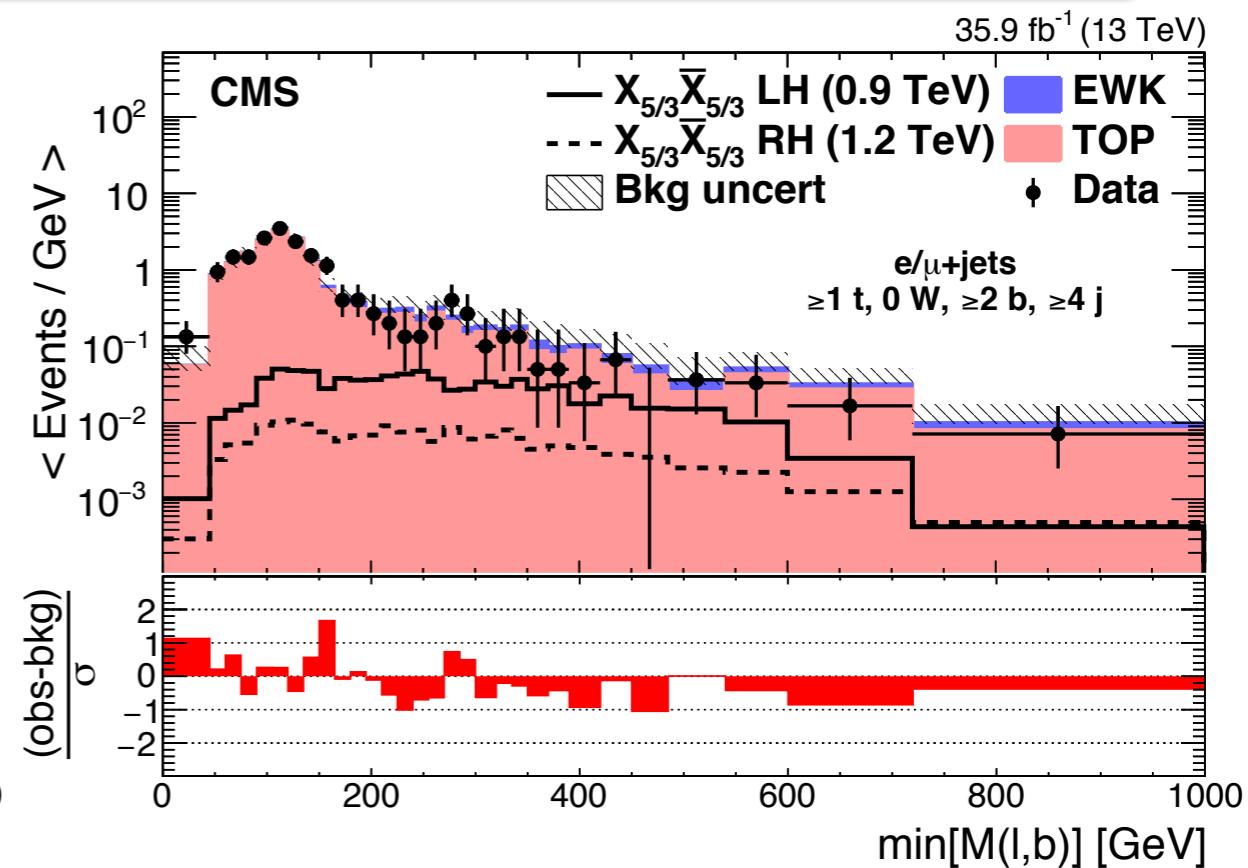
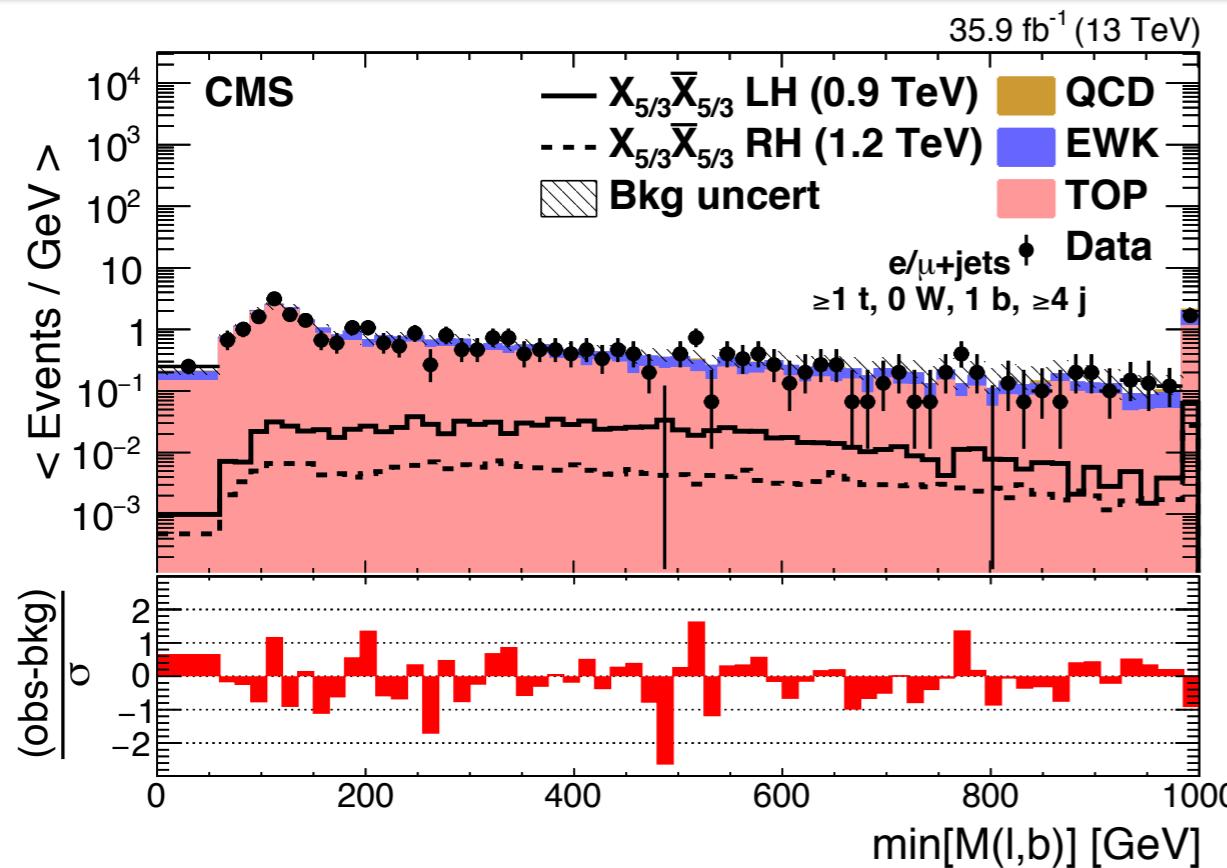
Sample	≥0 t, ≥0 W, 1 b	≥0 t, ≥0 W, ≥2 b	≥0 t, 0 W, 0 b	≥0 t, ≥1 W, 0 b
LH X <sub>5/3</sub> (0.9 TeV)	13.1 ± 0.6	10.9 ± 0.6	1.46 ± 0.27	3.60 ± 0.36
RH X <sub>5/3</sub> (1.2 TeV)	3.02 ± 0.13	2.34 ± 0.12	0.32 ± 0.06	1.00 ± 0.08
TOP	953 ± 97	668 ± 72	274 ± 30	134 ± 14
EWK	200 ± 16	29.5 ± 3.1	789 ± 57	204 ± 15
QCD	12.9 ± 5.4	1.1 ± 0.5	14.5 ± 4.6	7.2 ± 3.9
Total bkg.	1166 ± 100	699 ± 72	1077 ± 70	345 ± 23
Data	1152	710	1062	335



# $X_{5/3}X_{5/3} \rightarrow Wt\bar{W}t$ : $M(l,b)$ Distributions $t\bar{t}$ and $W+jets$ SR



# $X_{5/3}X_{5/3} \rightarrow Wt\bar{W}t$ : $M(l,b)$ Distributions $t\bar{t}$ and $W+Jets$ SR



# X<sub>5/3</sub>X<sub>5/3</sub> → WtWt Yields

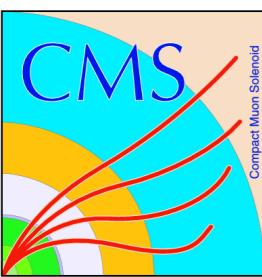
Sample	0 t, 0 W, 1 b	0 t, 0 W, ≥2 b	0 t, ≥1 W, 1 b	0 t, ≥1 W, ≥2 b
LH X <sub>5/3</sub> (0.9 TeV)	5.6 ± 1.3	4.9 ± 1.2	43.6 ± 2.3	36.5 ± 2.3
RH X <sub>5/3</sub> (1.2 TeV)	1.1 ± 0.3	0.8 ± 0.24	10.4 ± 0.66	7.7 ± 0.6
TOP	545 ± 49	334 ± 32	462 ± 44	306 ± 30
EWK	366 ± 27	54.0 ± 4.7	108.5 ± 9.3	19.7 ± 2.7
QCD	24.6 ± 7.6	7.9 ± 3.7	7.6 ± 4.4	0.65 ± 0.71
Total bkg.	935 ± 62	396 ± 33	578 ± 47	327 ± 30
Data	984	416	577	321
Sample	≥1 t, 0 W, 1 b	≥1 t, 0 W, ≥2 b	≥1 t, ≥1 W, 1 b	≥1 t, ≥1 W, ≥2 b
LH X <sub>5/3</sub> (0.9 TeV)	17.6 ± 1.6	15.5 ± 1.5	39.7 ± 2.4	34.5 ± 2.2
RH X <sub>5/3</sub> (1.2 TeV)	4.2 ± 0.5	3.4 ± 0.5	13.8 ± 0.8	11.8 ± 0.8
TOP	367 ± 41	267 ± 31	139 ± 16	108 ± 13
EWK	108.7 ± 9.0	19.3 ± 1.8	22.6 ± 3.6	2.69 ± 0.31
QCD	6.6 ± 2.4	1.4 ± 0.6	1.36 ± 0.66	0.47 ± 0.32
Total bkg.	482 ± 44	287 ± 31	163 ± 17	111 ± 13
Data	465	285	135	123

Channel	SSP MC	NonPrompt	ChargeMisID	Total Background	1000 GeV X <sub>5/3</sub>	Observed
Di-electron	3.9 ± 0.3	4.6 ± 1.7	2.4 ± 0.7	10.9 ± 1.9	11.6	10
Electron-Muon	10.3 ± 0.8	11.3 ± 3.6	1.7 ± 0.5	23.2 ± 3.7	26.9	26
Di-muon	5.7 ± 0.5	5.5 ± 1.9	-	11.2 ± 2.0	16.1	12



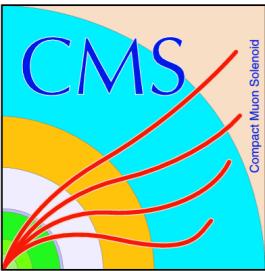
# X<sub>5/3</sub>X<sub>5/3</sub> → WtWt: Systematics

Source	Uncertainty	Signal	Background
Trigger efficiency	±1 s.d. ( $p_T, \eta$ )	Yes	All (2 – 5%)
Jet energy scale	±1 s.d. ( $p_T, \eta$ )	Yes	All (0.5 – 52%)
Jet energy resolution	±1 s.d. ( $\eta$ )	Yes	All (0 – 3%)
b/c tagging	±1 s.d. ( $p_T$ )	Yes	All (0 – 5%)
udsg mistagging	±1 s.d.	Yes	All (0 – 4%)
W tagging: mass resolution	±1 s.d. ( $\eta$ )	Yes	All (0 – 13%)
W tagging: mass scale	±1 s.d. ( $p_T, \eta$ )	Yes	All (0 – 21%)
W tagging: $\tau_2/\tau_1$	±1 s.d.	Yes	All (0 – 2%)
W tagging: $\tau_2/\tau_1$ extrapolation	±1 s.d. ( $p_T$ )	Yes	All (0 – 2%)
t tagging	±1 s.d.	Yes	All (0 – 4%)
Top $p_T$	Δ(weighted, unweighted)	No	t <bar>t&gt; (0 – 19%)</bar>
W+jets $H_T$	±2 s.d. ( $H_{Tgen}$ )	No	W+jets (0.2 – 0.3%)
Pileup	$\sigma_{\text{inel.}} \pm 4.6\%$	Yes	All (0 – 4%)
PDF	±1 s.d.	Shape	All (2 – 9%)
QCD renormalization/factorization scale	Envelope( $\times 2, \times 0.5$ )	Shape	All (12 – 36%)

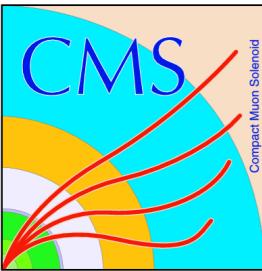
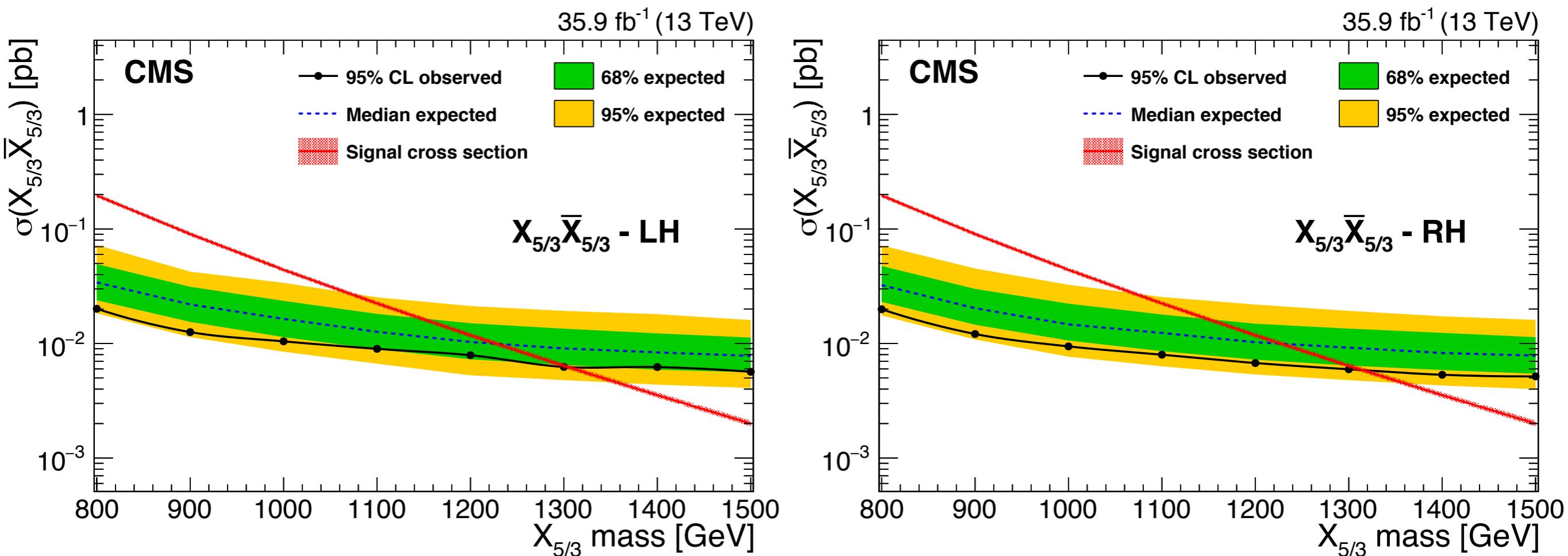


# X<sub>5/3</sub>X<sub>5/3</sub>→WtWt: Dilepton MC Systematics

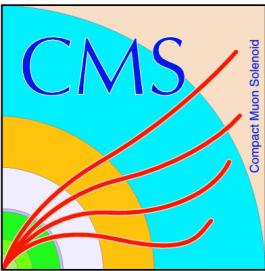
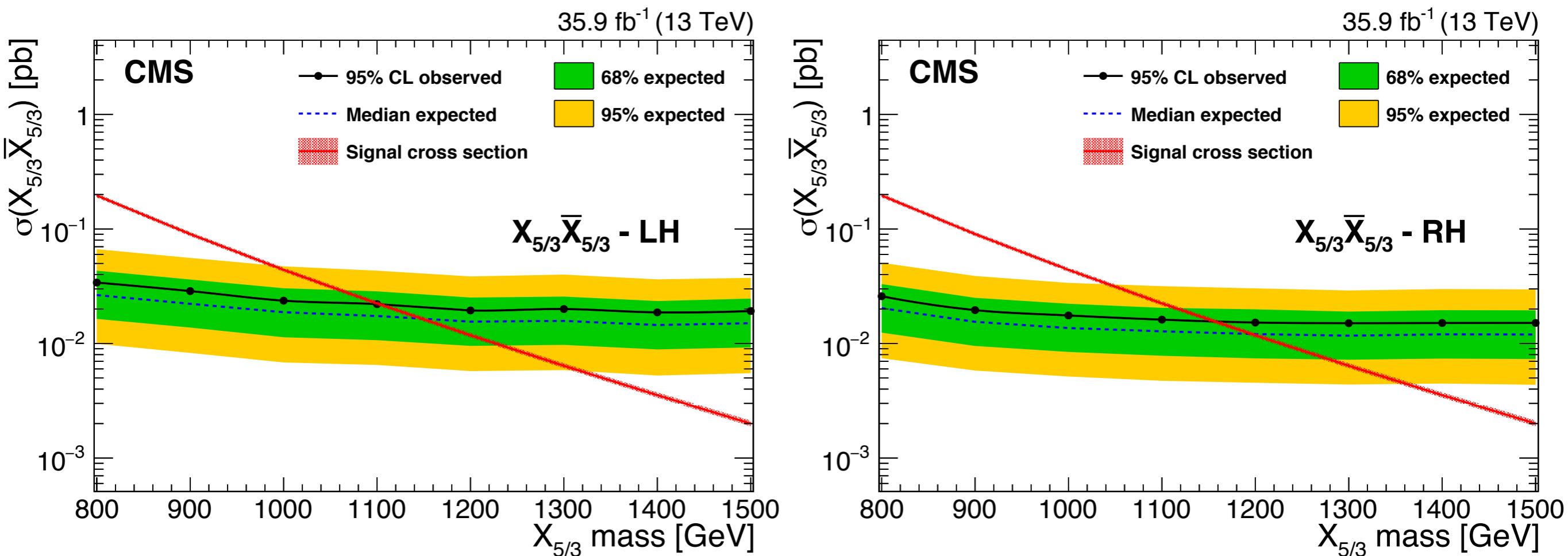
Process	JES	JER	Pileup	Normalization
t <bar>t</bar>	2%	2%	6%	18%
t <bar>t</bar>	3%	2%	6%	11%
t <bar>t</bar>	4%	2%	6%	12%
t <bar>t</bar>	2%	2%	6%	50%
WZ	10%	2%	6%	12%
ZZ	7%	2%	6%	12%
WW	6%	2%	6%	50%
WWZ	7%	2%	6%	50%
WZZ	9%	2%	6%	50%
ZZZ	9%	2%	6%	50%
X <sub>5/3</sub>	5%	3%	1%	2-4%



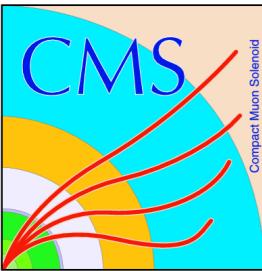
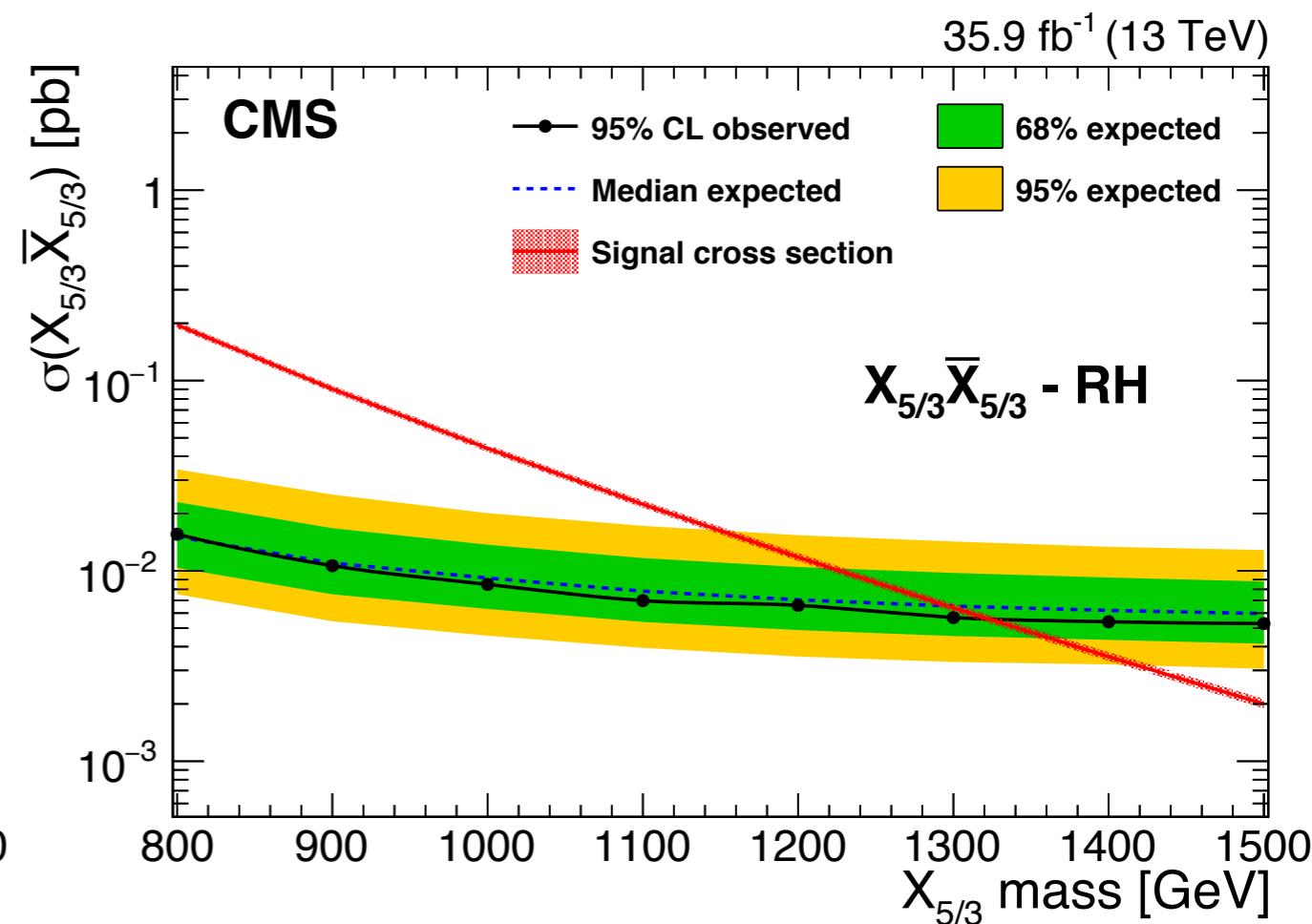
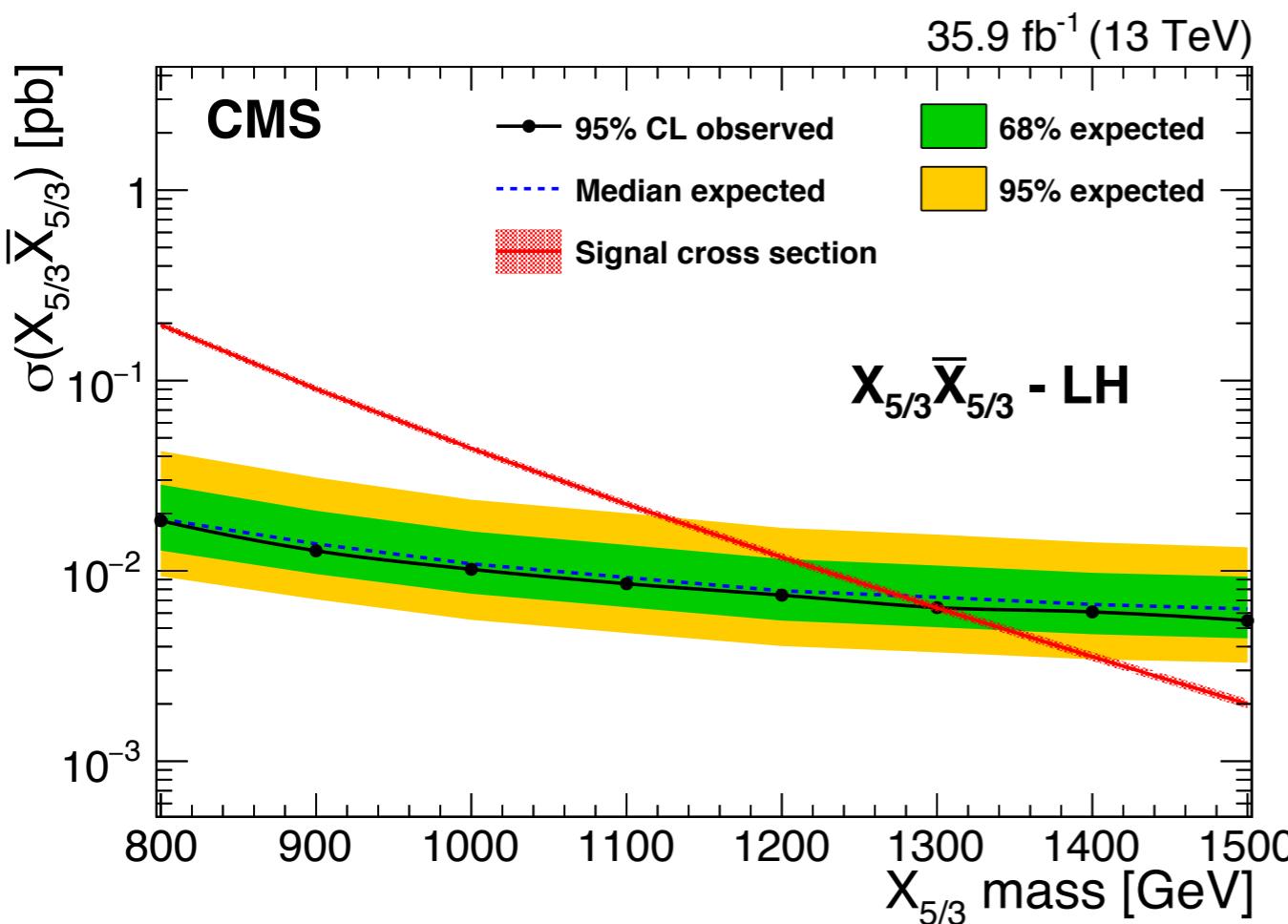
# $X_{5/3}X_{5/3} \rightarrow WtWt$ : Single Lepton Limits



# $X_{5/3} \bar{X}_{5/3} \rightarrow WtWt$ : Dilepton Limits



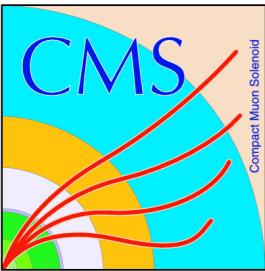
# $X_{5/3} \bar{X}_{5/3} \rightarrow WtWt$ : Combined Limits



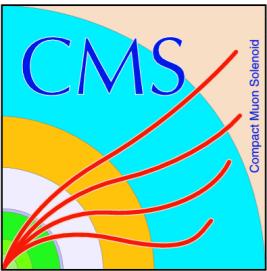
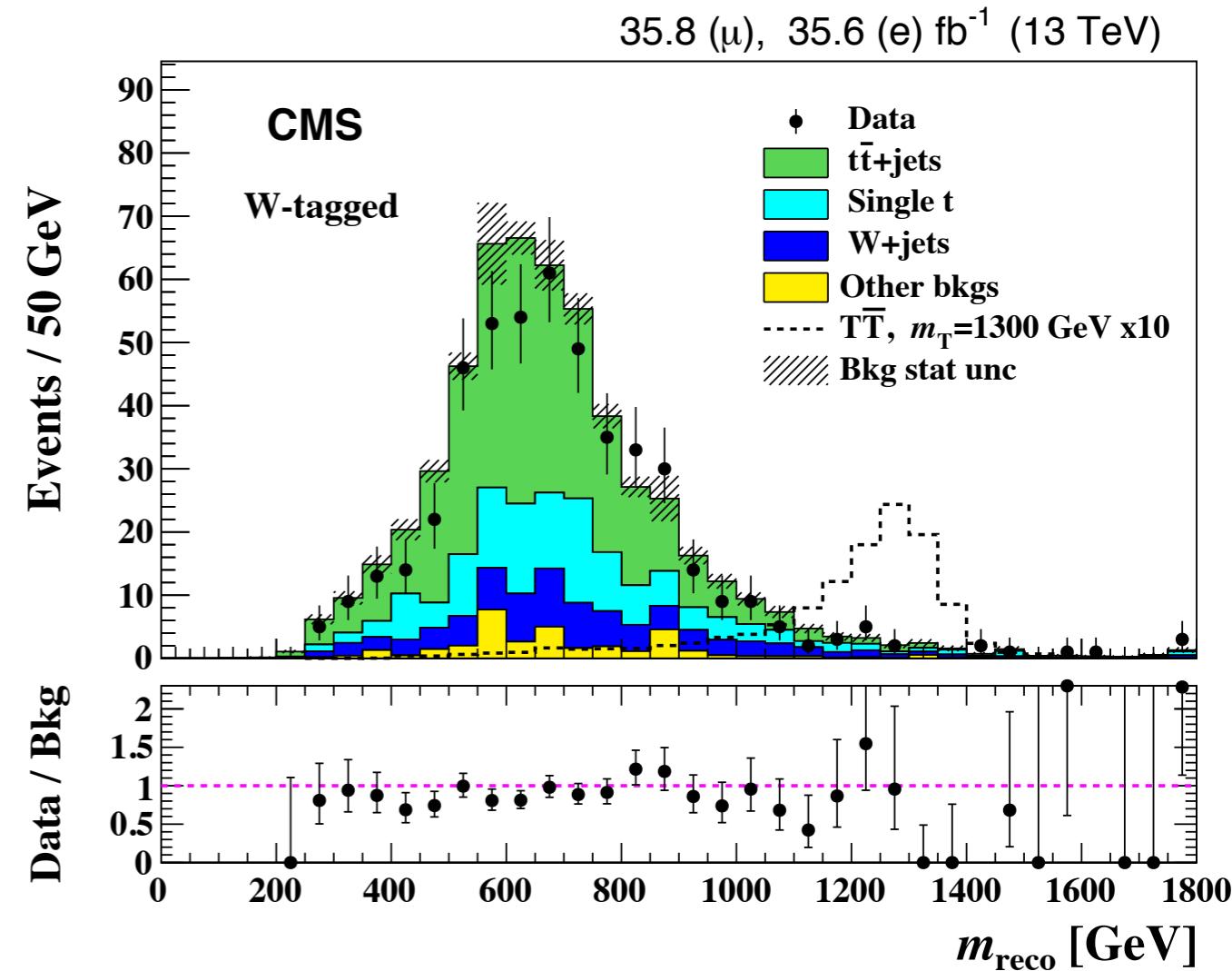
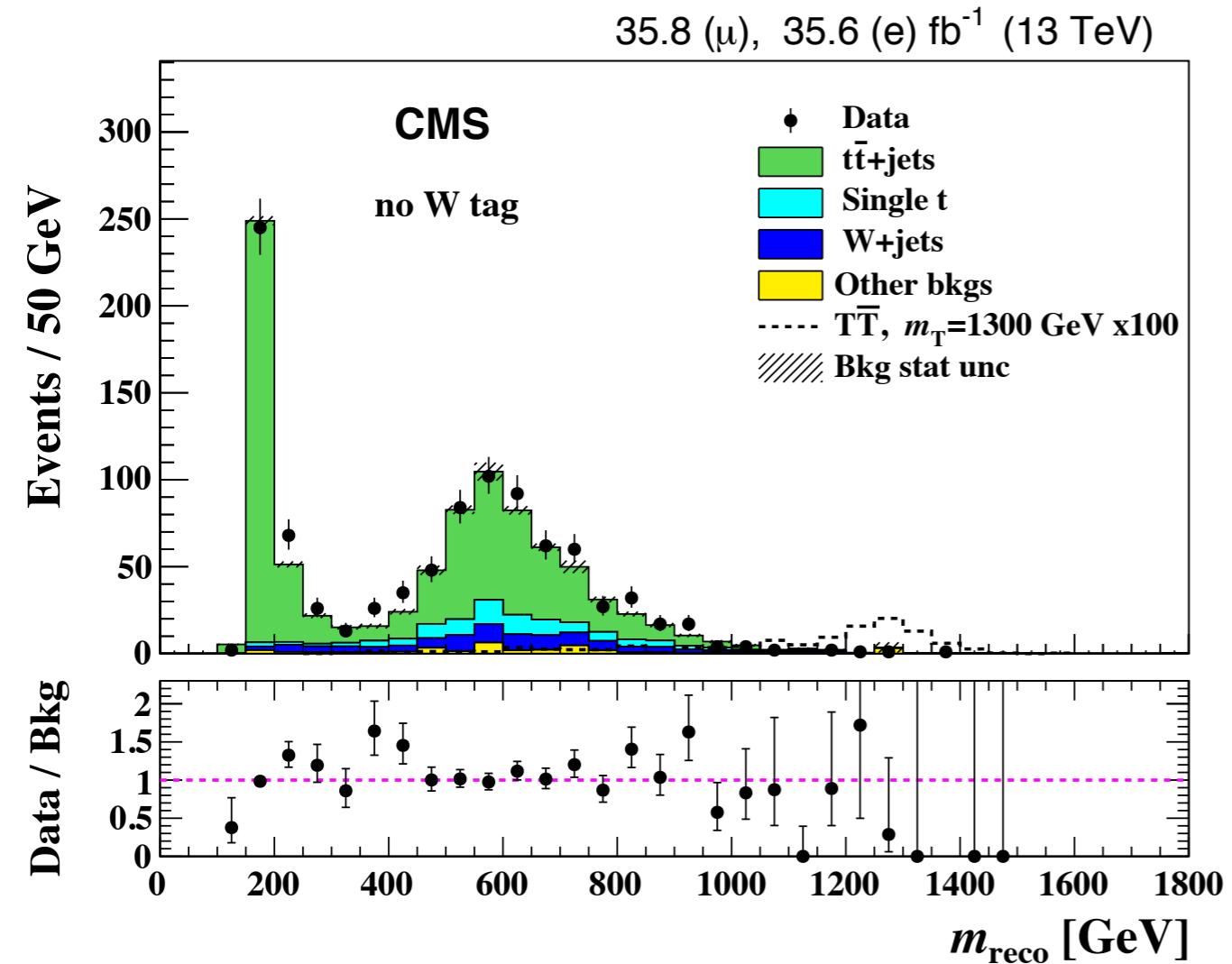
# $T\bar{T} \rightarrow WbW\bar{b}$ : Signal Efficiency

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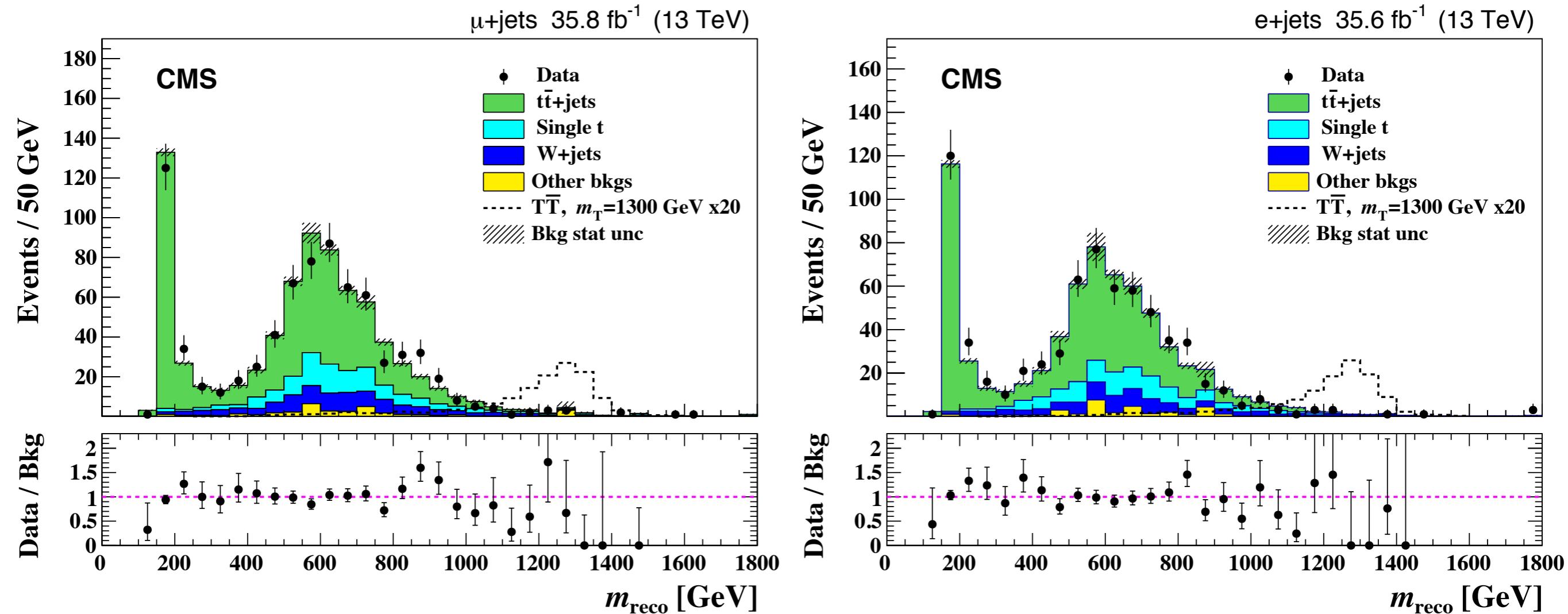
Mass [GeV]	$\mu + \text{jets}$		$e + \text{jets}$	
	Efficiency (%)	Events	Efficiency (%)	Events
800	$2.37 \pm 0.05$	$166.1 \pm 3.7$	$2.20 \pm 0.05$	$153.5 \pm 3.5$
900	$2.71 \pm 0.06$	$87.8 \pm 1.9$	$2.36 \pm 0.05$	$75.8 \pm 1.8$
1000	$2.97 \pm 0.06$	$46.7 \pm 0.9$	$2.69 \pm 0.06$	$42.2 \pm 0.9$
1100	$3.08 \pm 0.06$	$24.7 \pm 0.5$	$2.77 \pm 0.06$	$22.1 \pm 0.4$
1200	$3.14 \pm 0.06$	$13.3 \pm 0.3$	$2.80 \pm 0.06$	$11.8 \pm 0.2$
1300	$3.10 \pm 0.07$	$7.09 \pm 0.15$	$2.79 \pm 0.06$	$6.34 \pm 0.14$
1400	$3.14 \pm 0.06$	$3.98 \pm 0.08$	$2.77 \pm 0.06$	$3.50 \pm 0.07$
1500	$3.21 \pm 0.06$	$2.30 \pm 0.04$	$2.76 \pm 0.06$	$1.96 \pm 0.04$
1600	$3.01 \pm 0.06$	$1.24 \pm 0.02$	$2.84 \pm 0.06$	$1.16 \pm 0.02$



# $T\bar{T} \rightarrow WbW\bar{b}$ : W-tagging

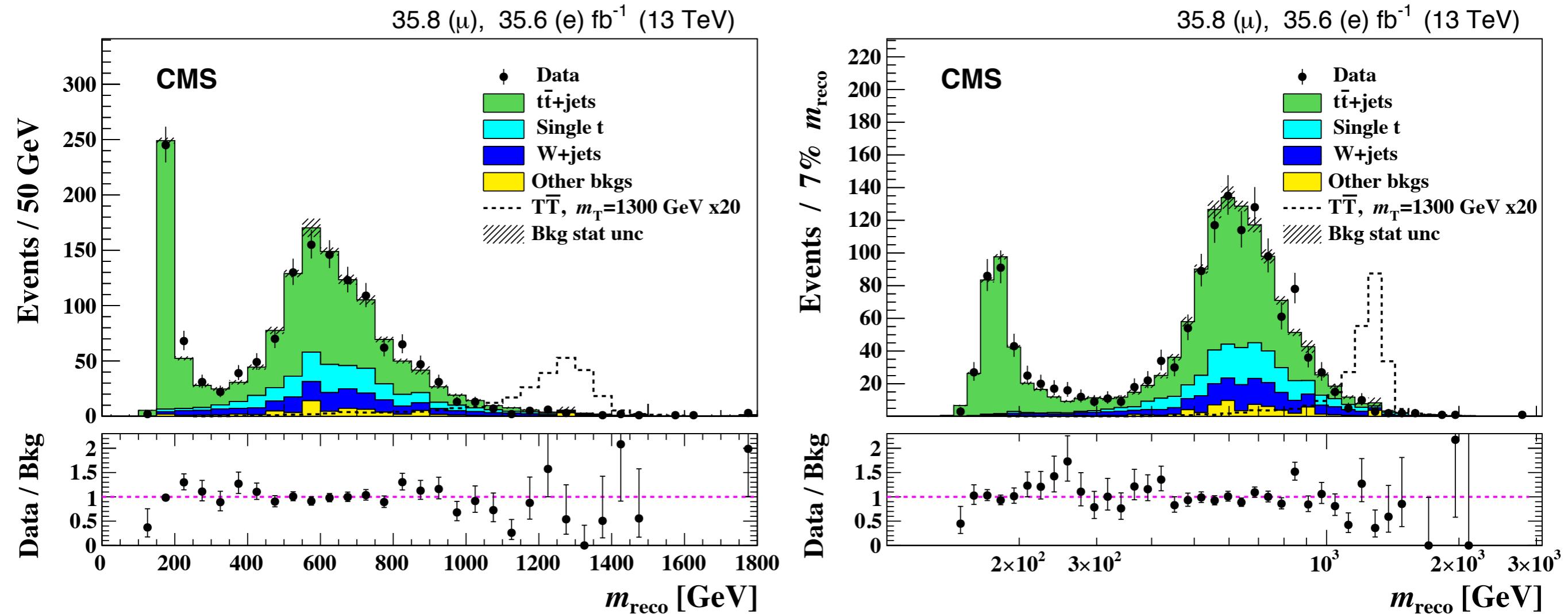


# $T\bar{T} \rightarrow WbW\bar{b}$ : Results



# $T\bar{T} \rightarrow WbW\bar{b}$ : Combined Results

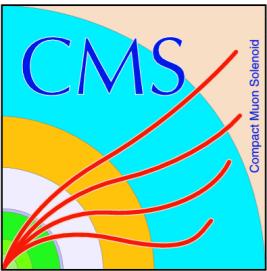
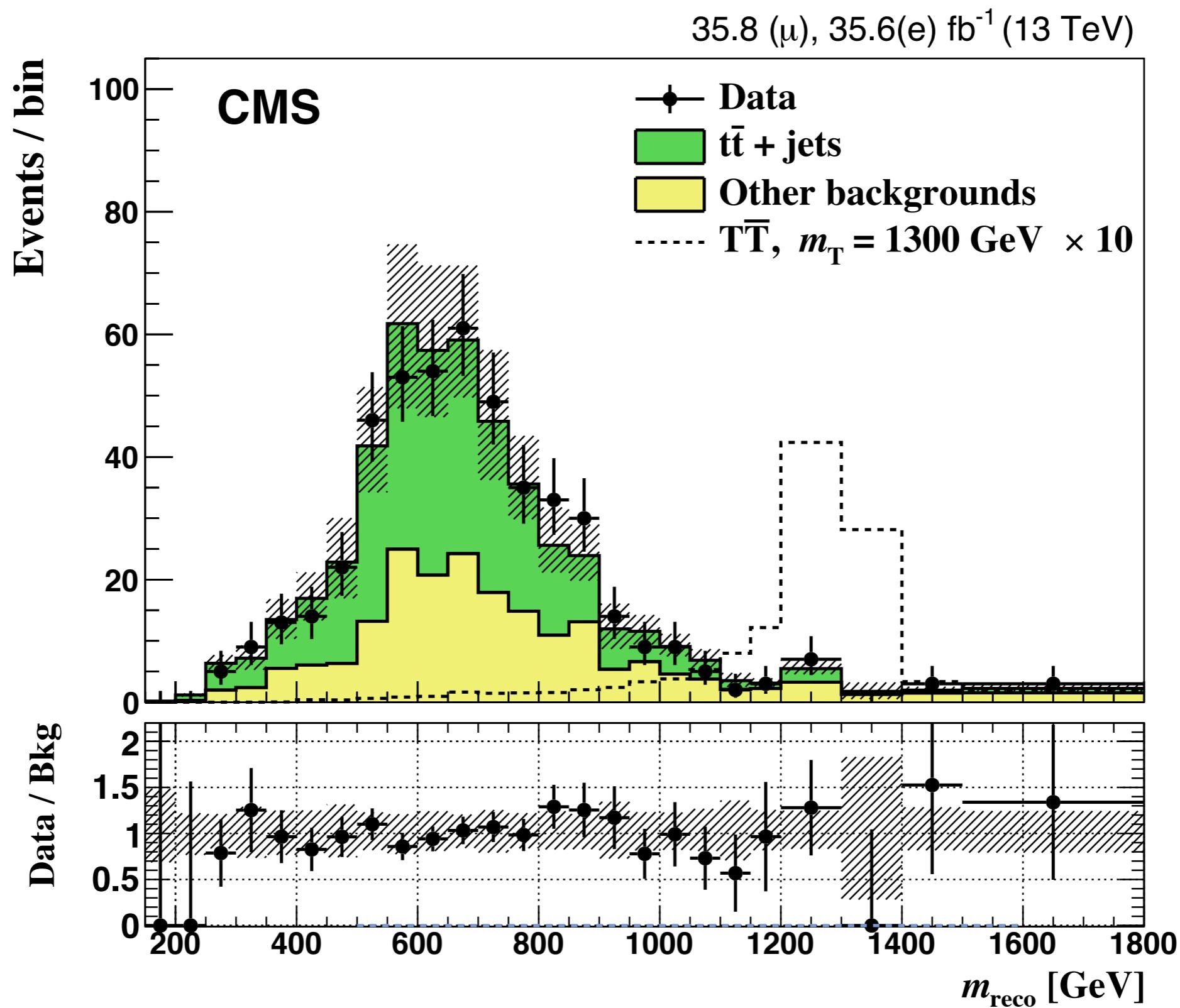
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# $T\bar{T} \rightarrow WbW\bar{b}$ : Combined Post-Fit

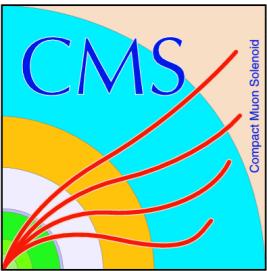
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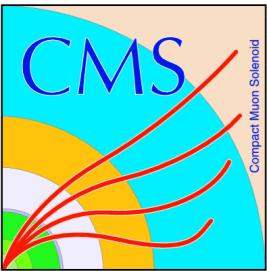
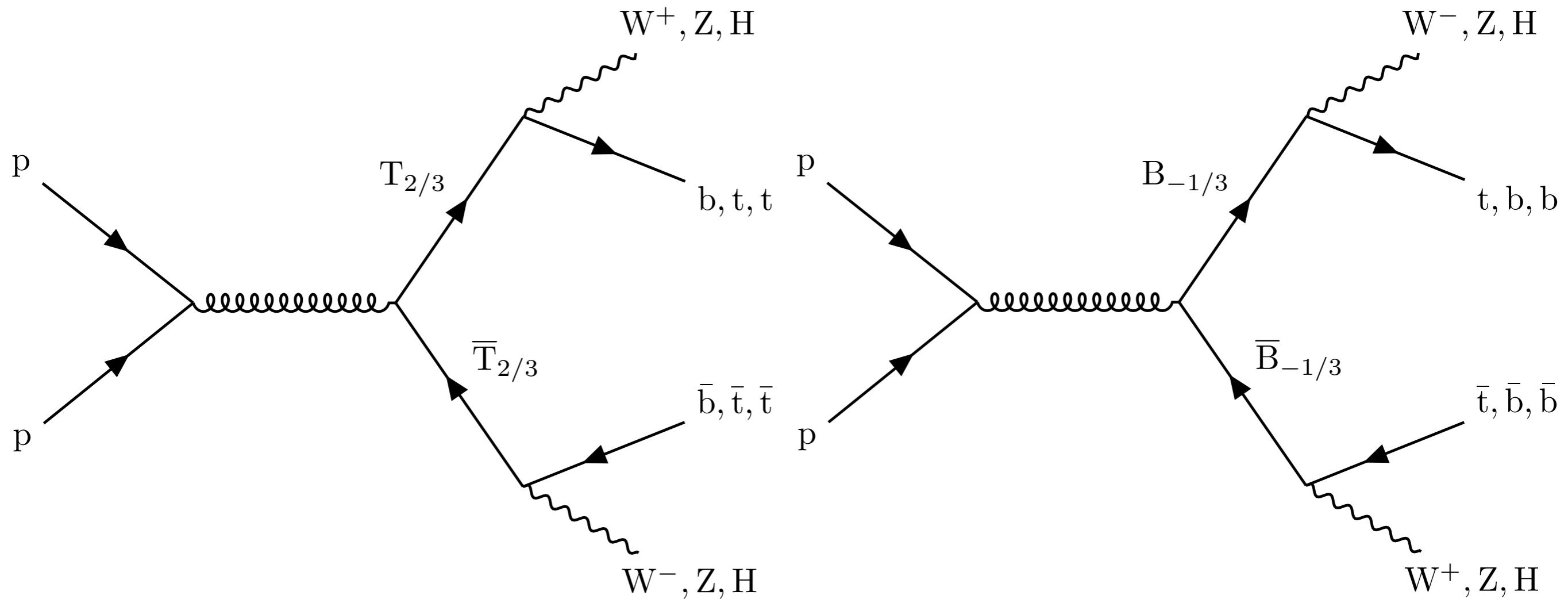
# $T\bar{T} \rightarrow WbW\bar{b}$ : Systematics

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	Signal (%)	Background (%)
JES	+0.2, -2.5	17
JER	+0.02, -0.3	0.03
b tag heavy flavor	2.5	+2.8, -1.4
b tag light flavor	0.2	0.8
Renorm./fact. scales	1.1	+18, -14
Pileup	0.05	0.2
PDF	0.3	2.0
Top quark $p_T$ reweighting	—	11
W+jets reweighting	—	+4.9, -3.3
$\Delta R_{\text{match}}$	+0, -0.8	+0, -1.9



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Production



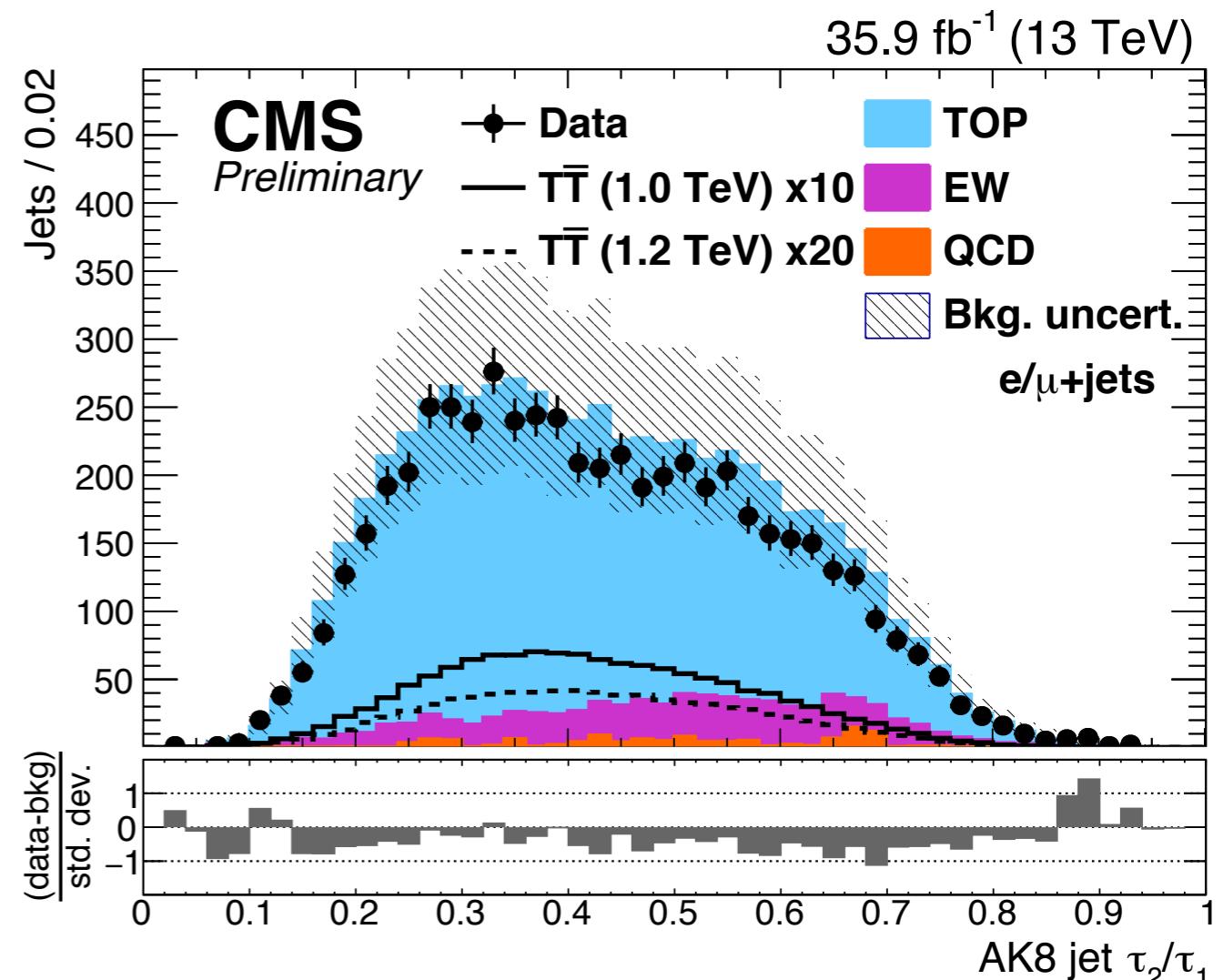
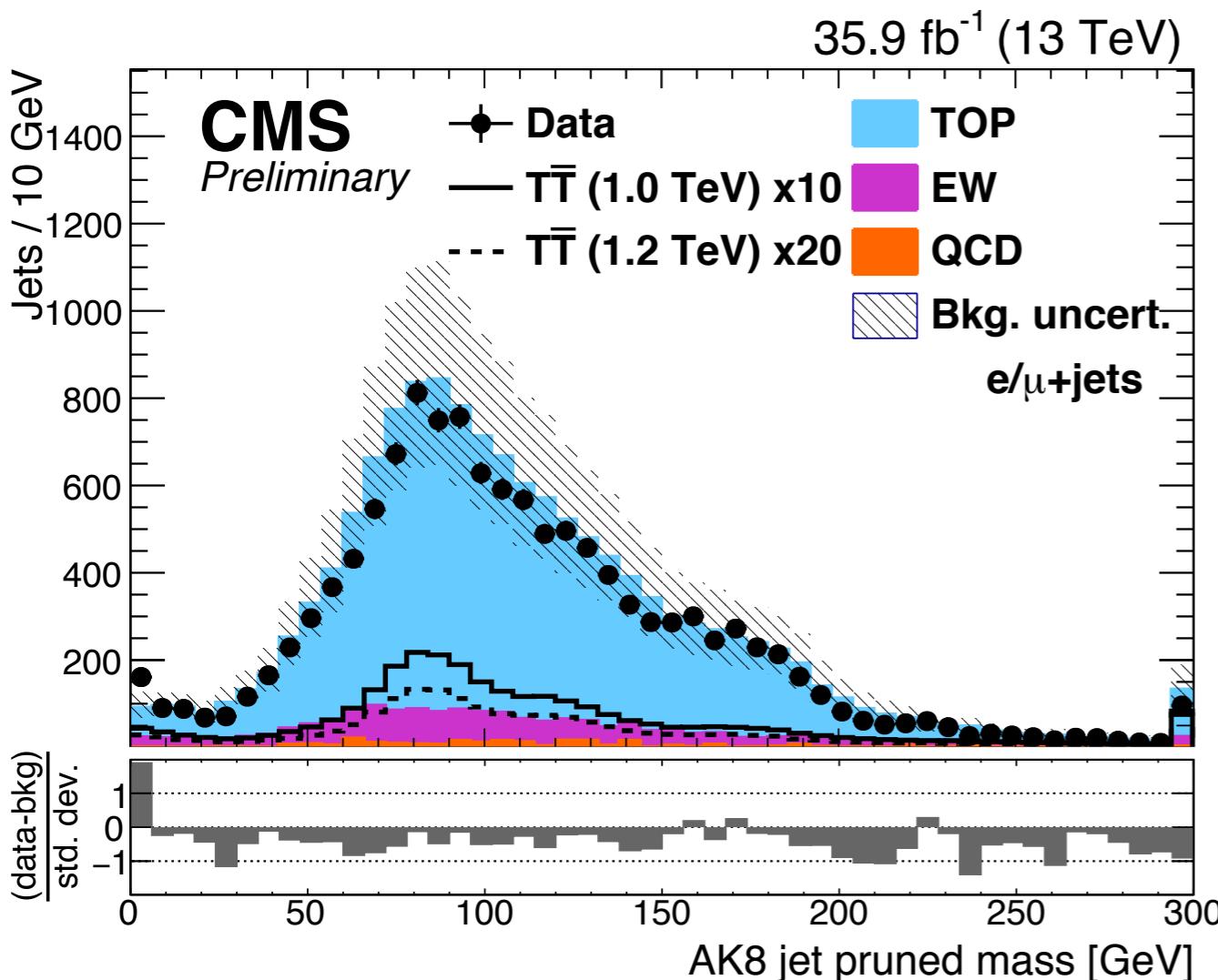
# T $\bar{T}$ /B $\bar{B}$ →bW/tZ/tH(tW/bZ/bH): Signal Cross-Sections

T/B quark mass [GeV]	Cross section [fb]
700	$455 \pm 19$
800	$196 \pm 8$
900	$90 \pm 4$
1000	$44 \pm 2$
1100	$22 \pm 1$
1200	$11.8 \pm 0.6$
1300	$6.4 \pm 0.4$
1400	$3.5 \pm 0.2$
1500	$2.0 \pm 0.1$
1600	$1.15 \pm 0.09$
1700	$0.67 \pm 0.06$
1800	$0.39 \pm 0.04$

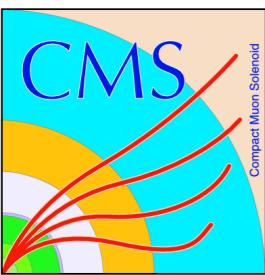
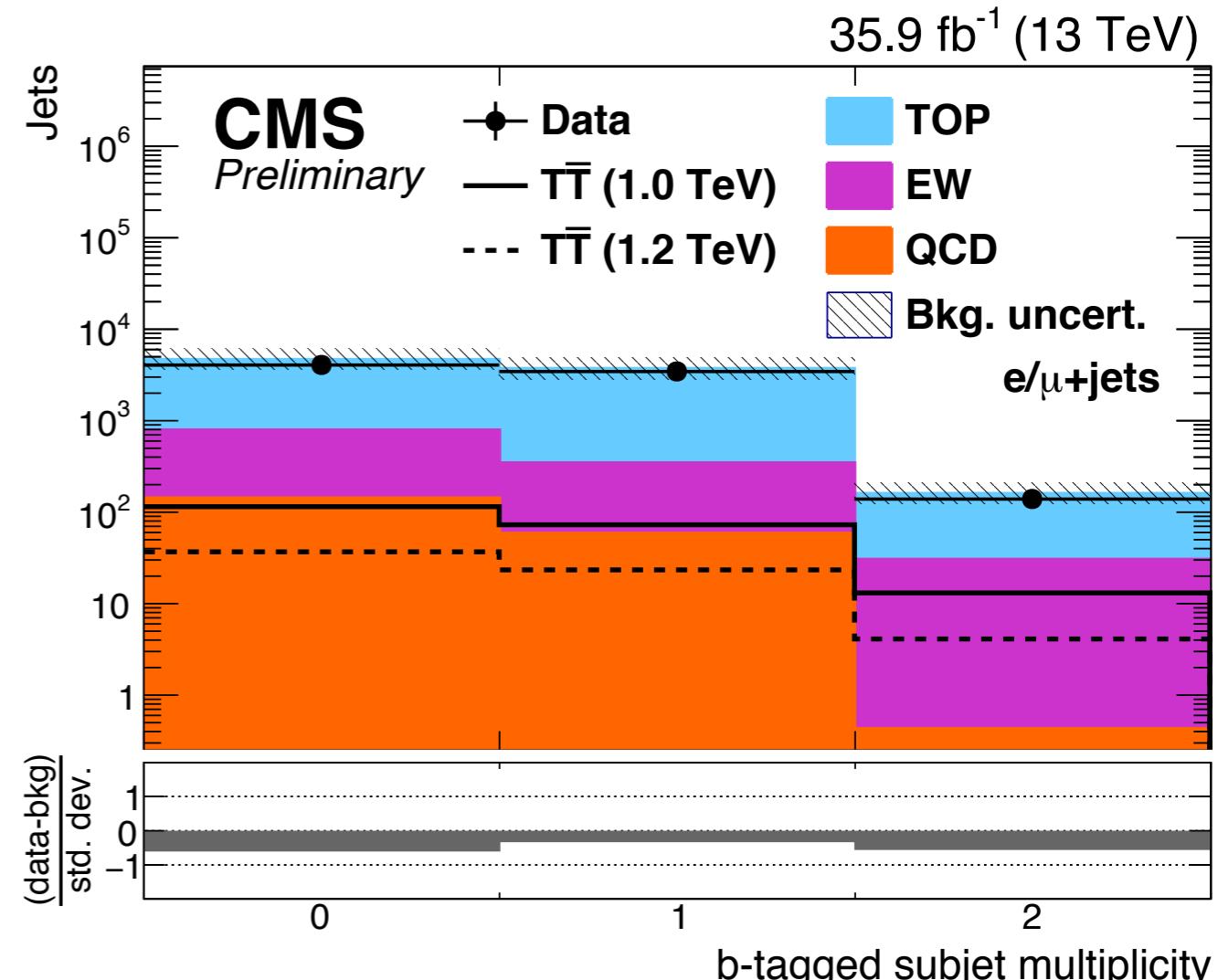
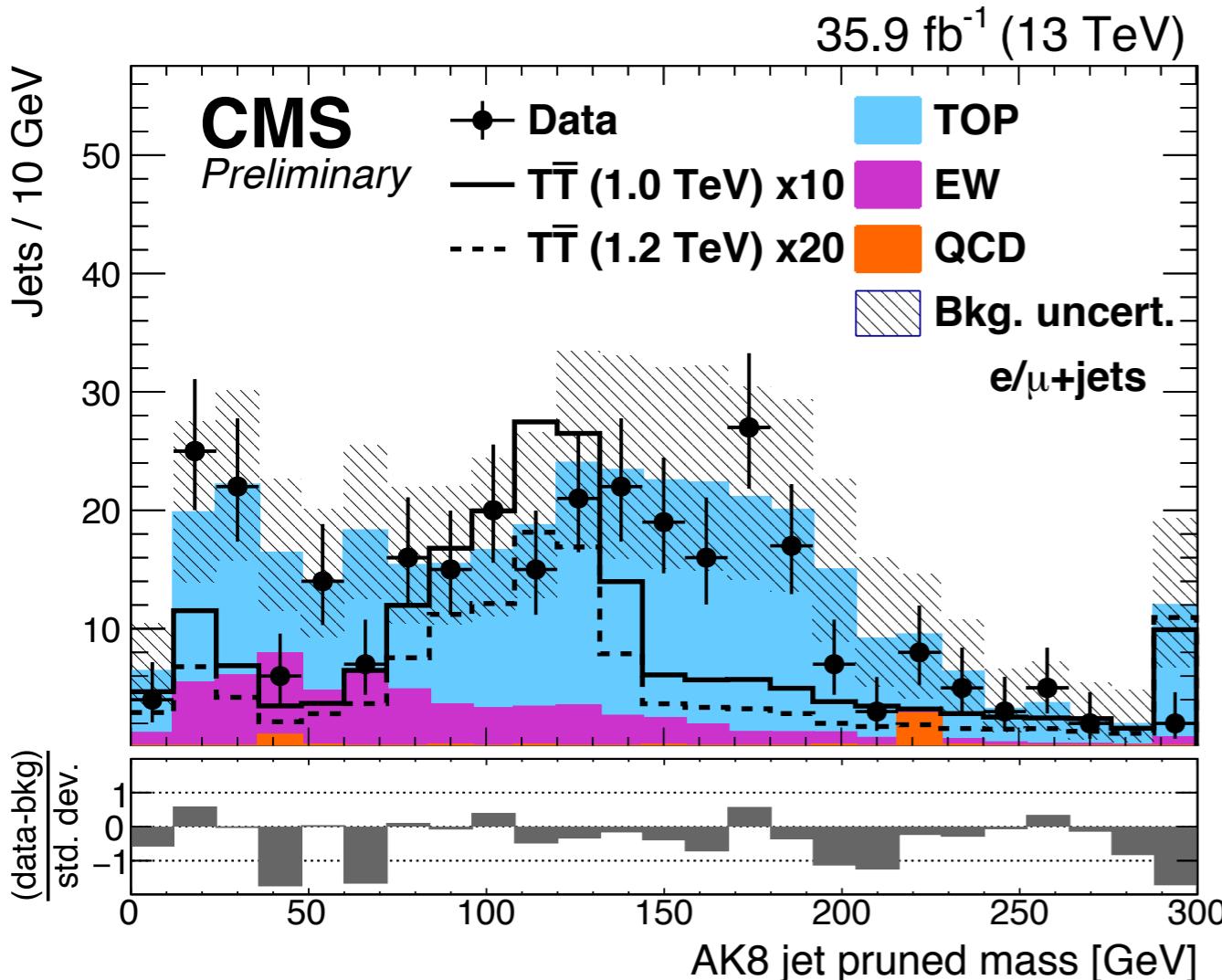


# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : W-tagging Variables

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# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : N-q Pruned Mass and Sub-Jet b-tags



# T $\bar{T}$ /B $\bar{B}$ →bW/tZ/tH(tW/bZ/bH): Single Lepton CR Yields

Sample	0 H, $\geq 0$ W, 0 b	0 H, $\geq 0$ W, $\geq 1$ b	$\geq 1$ H, $\geq 0$ W, $\geq 1$ b
T $\bar{T}$ (1.0 TeV)	$1.99 \pm 0.15$	$6.94 \pm 0.37$	$3.63 \pm 0.22$
T $\bar{T}$ (1.2 TeV)	$0.65 \pm 0.05$	$2.08 \pm 0.11$	$0.94 \pm 0.06$
TOP	$1120 \pm 240$	$2830 \pm 620$	$2360 \pm 450$
EW	$3050 \pm 510$	$580 \pm 100$	$195 \pm 34$
QCD	$322 \pm 73$	$116 \pm 30$	$47 \pm 18$
Total Bkg	$4490 \pm 590$	$3520 \pm 640$	$2600 \pm 450$
Data	$4420$	$3409$	$2476$
Data/Bkg	$0.99 \pm 0.13$	$0.97 \pm 0.18$	$0.95 \pm 0.17$

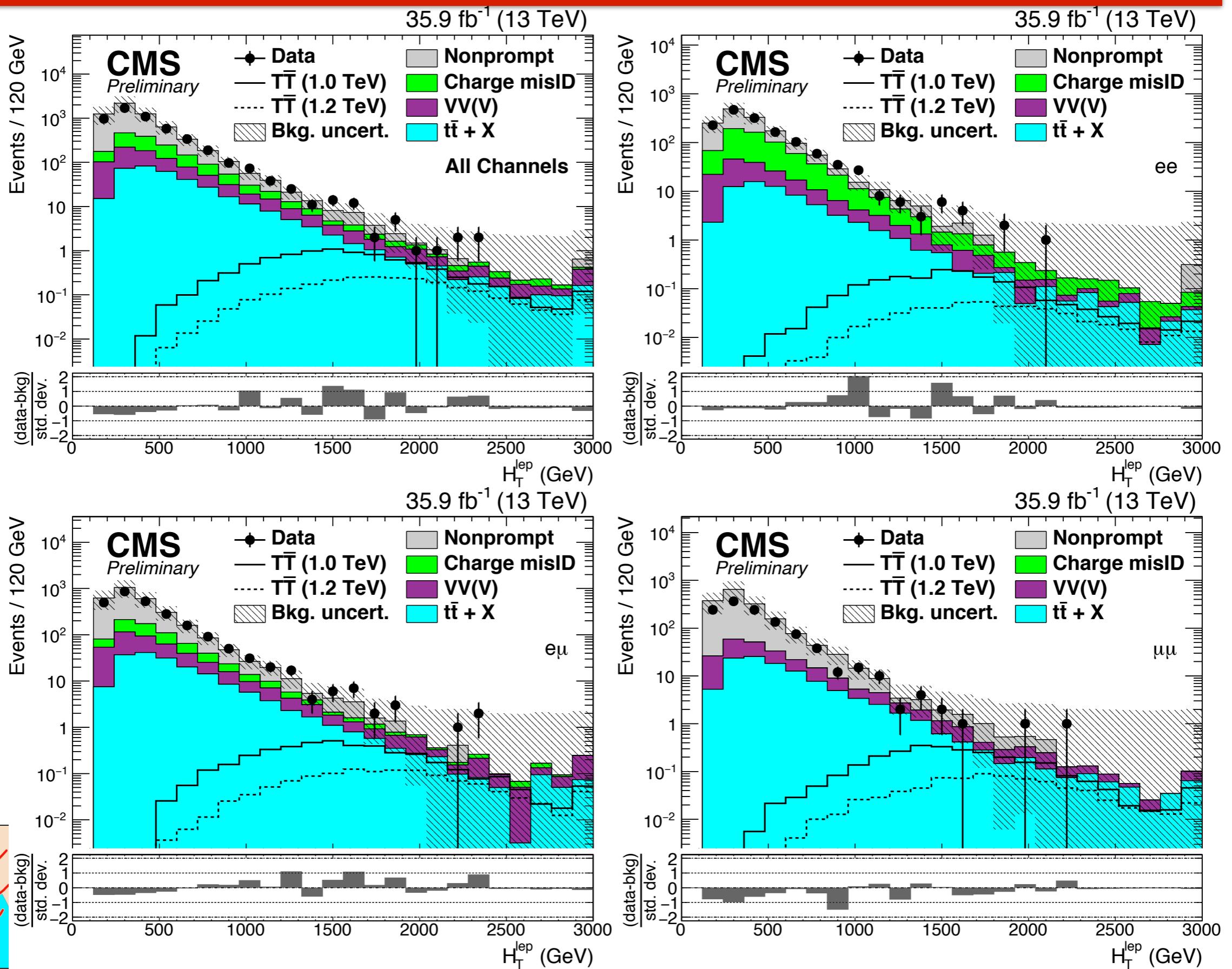


# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Signal Efficiency

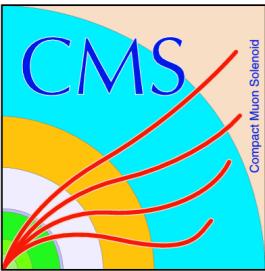
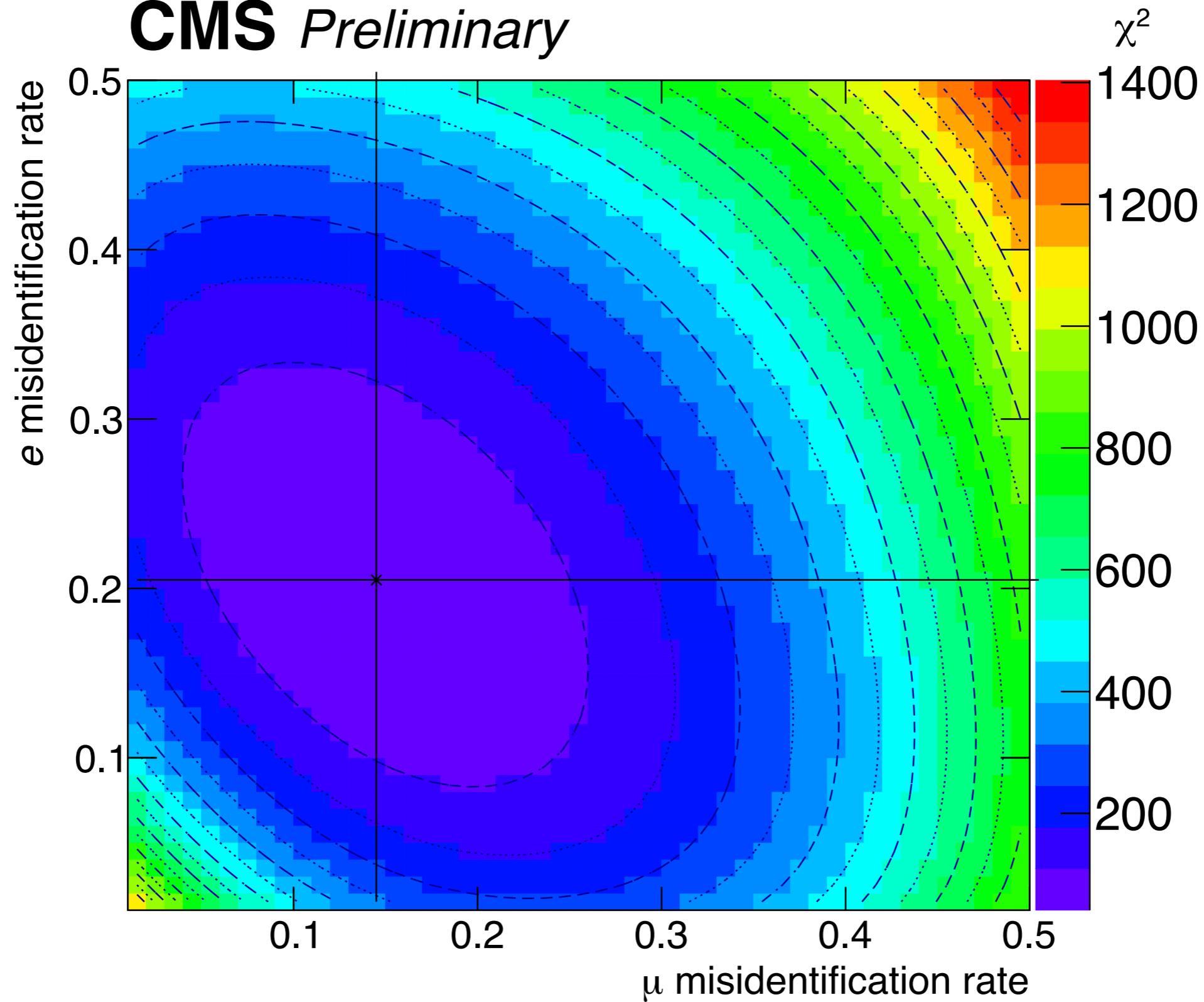
$T\bar{T}$ (1.0 TeV)				$B\bar{B}$ (1.0 TeV)			
Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$	Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$
tHtH	9.1%	1.1%	0.74%	bHbH	2.9%	0.16%	0.08%
tHtZ	8.4%	0.78%	1.50%	bHbZ	1.8%	0.05%	0.22%
tHbW	11.0%	0.61%	0.29%	bHtW	11.2%	0.61%	0.31%
tZtZ	7.4%	0.45%	1.92%	bZbZ	1.0%	0.02%	0.25%
tZbW	9.2%	0.34%	0.88%	bZtW	9.2%	0.23%	0.89%
bWbW	10.8%	0.02%	–	tWtW	12.3%	2.5%	1.28%
$T\bar{T}$ (1.2 TeV)				$B\bar{B}$ (1.2 TeV)			
Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$	Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$
tHtH	10.9%	1.4%	0.81%	bHbH	3.2%	0.19%	0.08%
tHtZ	10.1%	0.93%	1.48%	bHbZ	2.0%	0.08%	0.19%
tHbW	12.4%	0.71%	0.31%	bHtW	12.6%	0.73%	0.29%
tZtZ	8.8%	0.53%	1.98%	bZbZ	1.0%	0.03%	0.20%
tZbW	10.4%	0.27%	0.87%	bZtW	10.4%	0.28%	0.87%
bWbW	11.4%	0.04%	–	tWtW	14.1%	2.8%	1.33%
$T\bar{T}$ (1.4 TeV)				$B\bar{B}$ (1.4 TeV)			
Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$	Decay	$1\ell$	$SS2\ell$	$\geq 3\ell$
tHtH	11.7%	1.5%	0.81%	bHbH	3.2%	0.19%	0.07%
tHtZ	10.8%	0.95%	1.47%	bHbZ	2.0%	0.07%	0.18%
tHbW	13.3%	0.49%	0.30%	bHtW	13.4%	0.75%	0.29%
tZtZ	9.3%	0.29%	1.87%	bZbZ	1.0%	0.02%	0.20%
tZbW	10.9%	0.75%	0.85%	bZtW	11.0%	0.29%	0.81%
bWbW	11.8%	0.03%	–	tWtW	15.4%	3.05%	1.36%



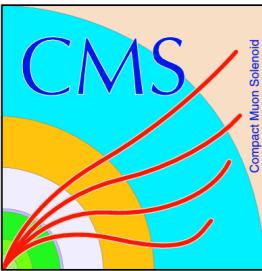
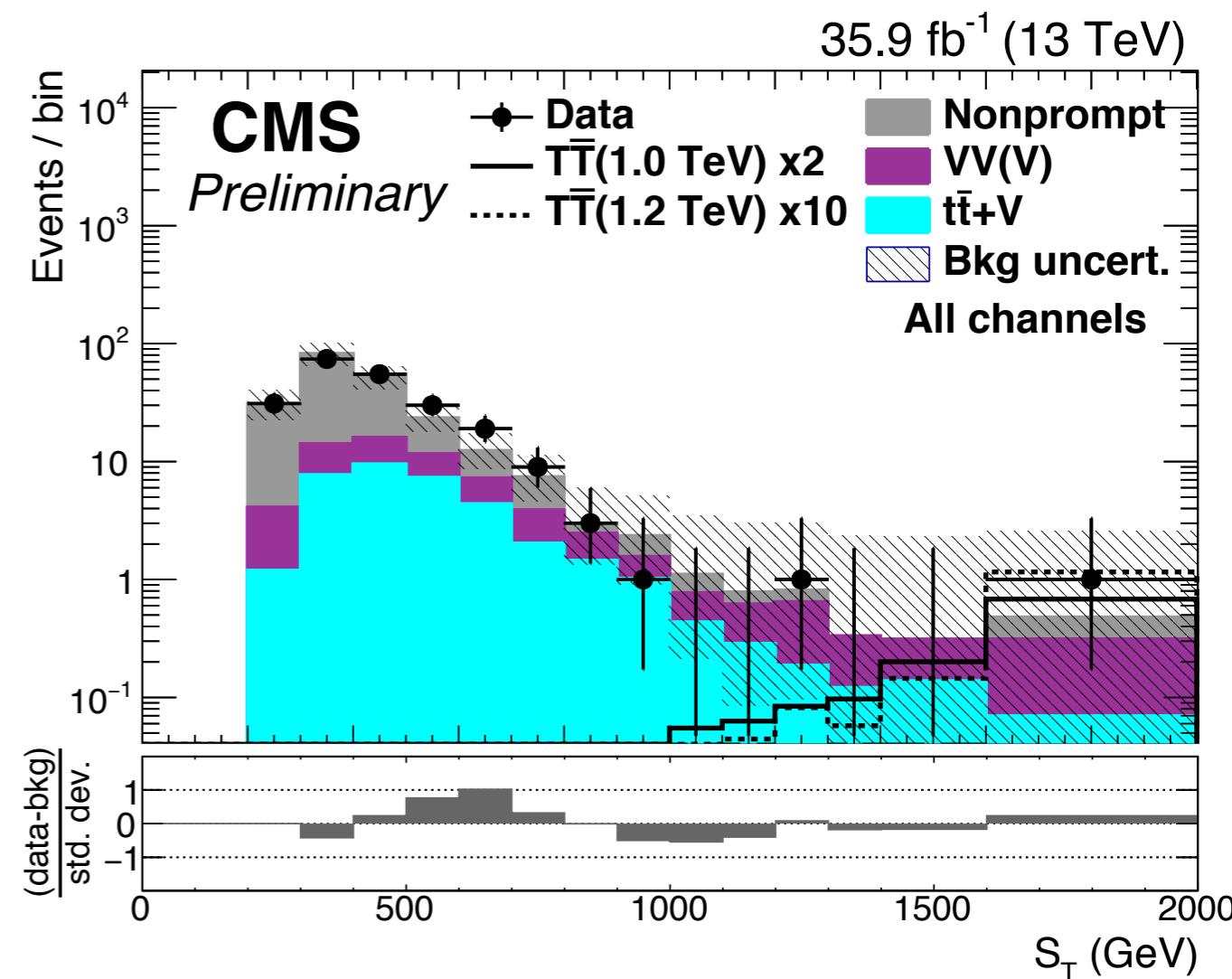
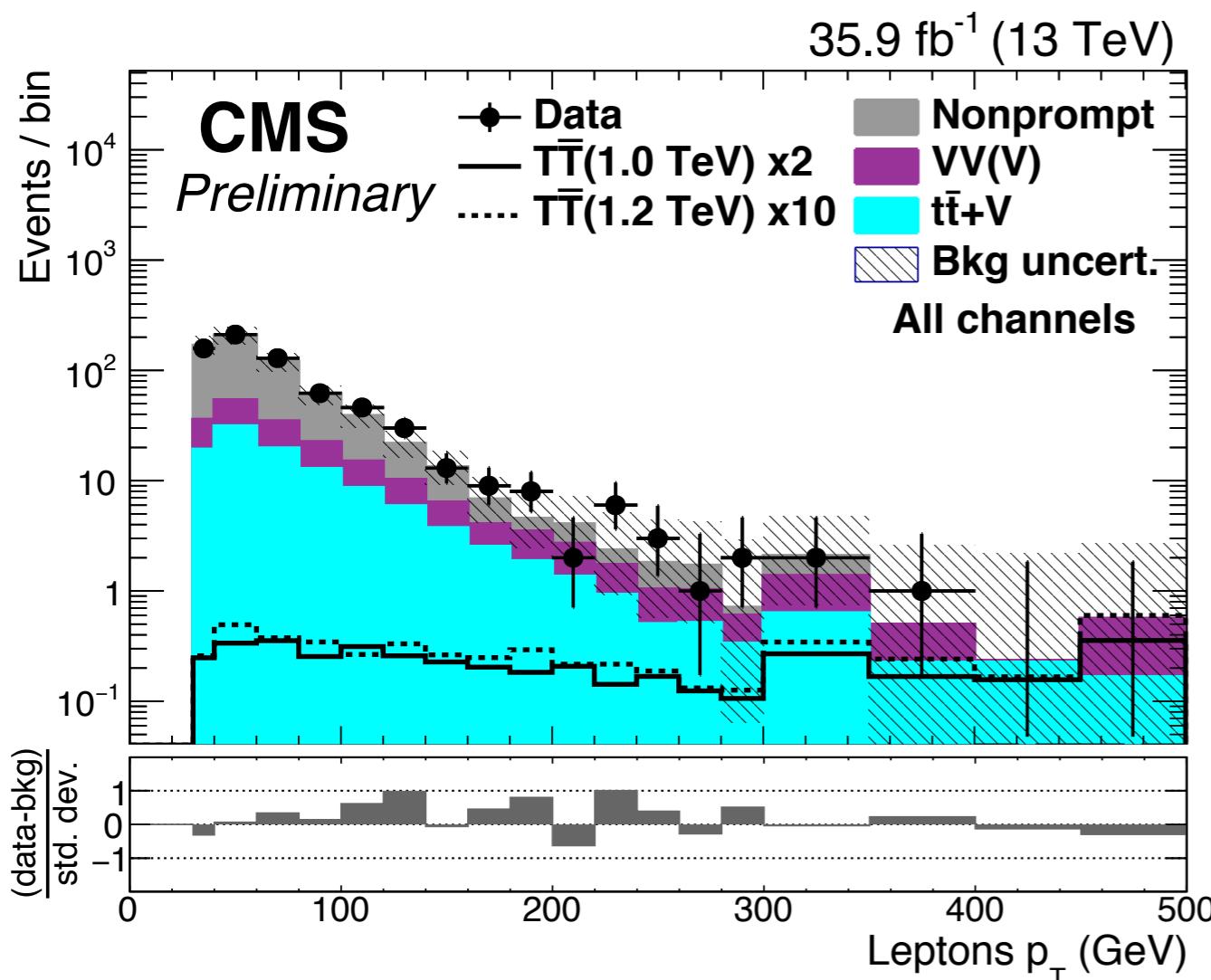
# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : $H_T^{\text{Lep}}$ Same Sign Distributions



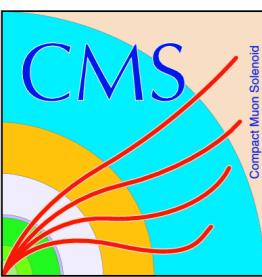
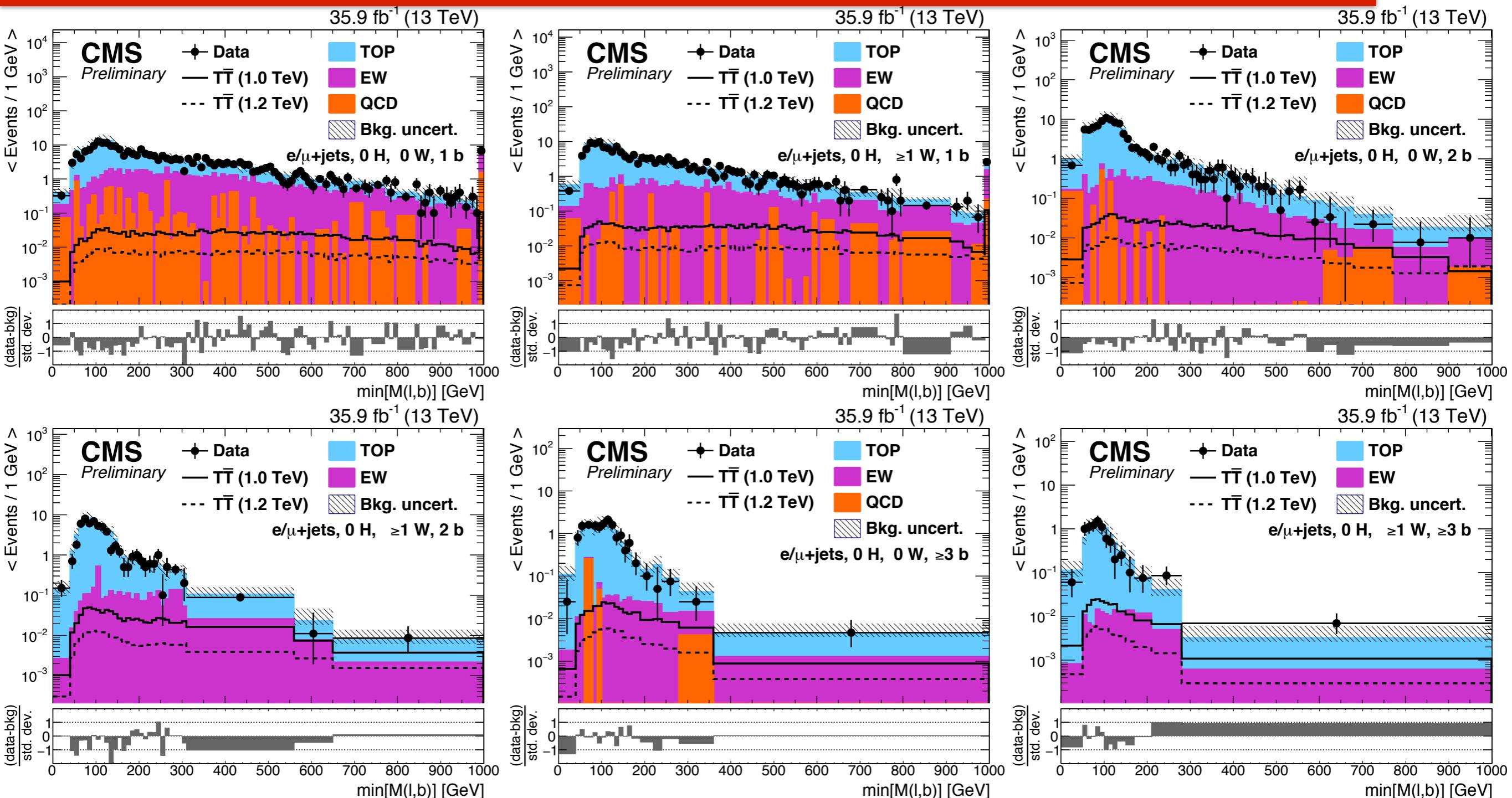
**CMS Preliminary**



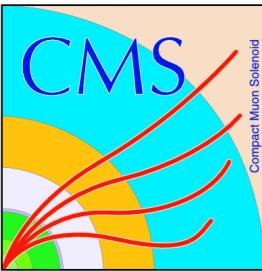
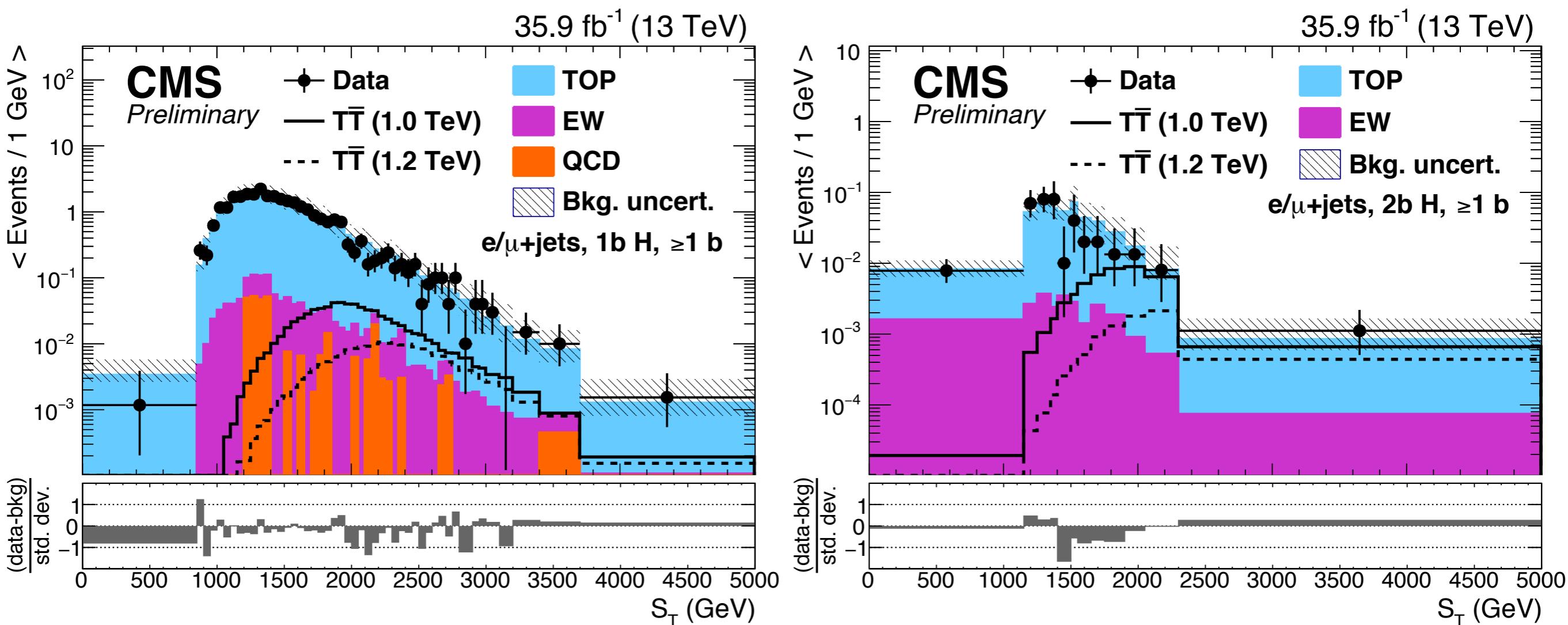
# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Lepton $p_T$ and ST in Trilepton CR



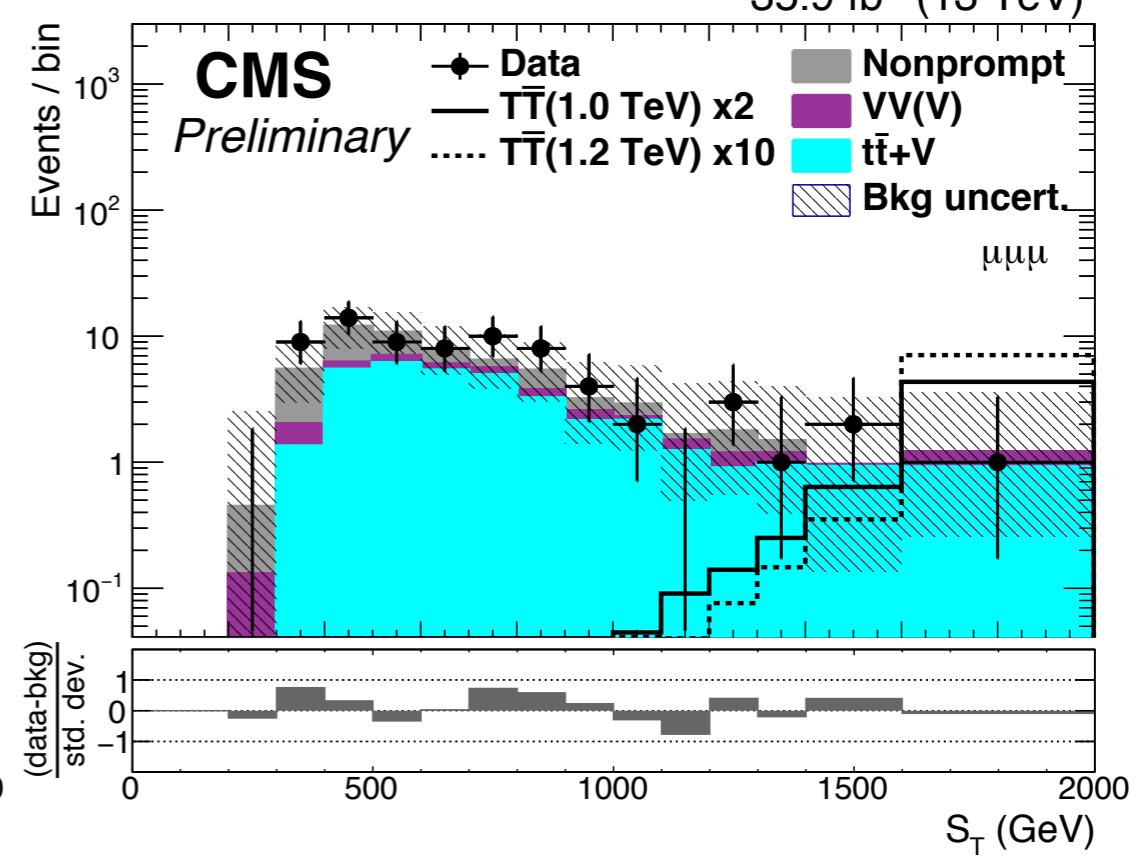
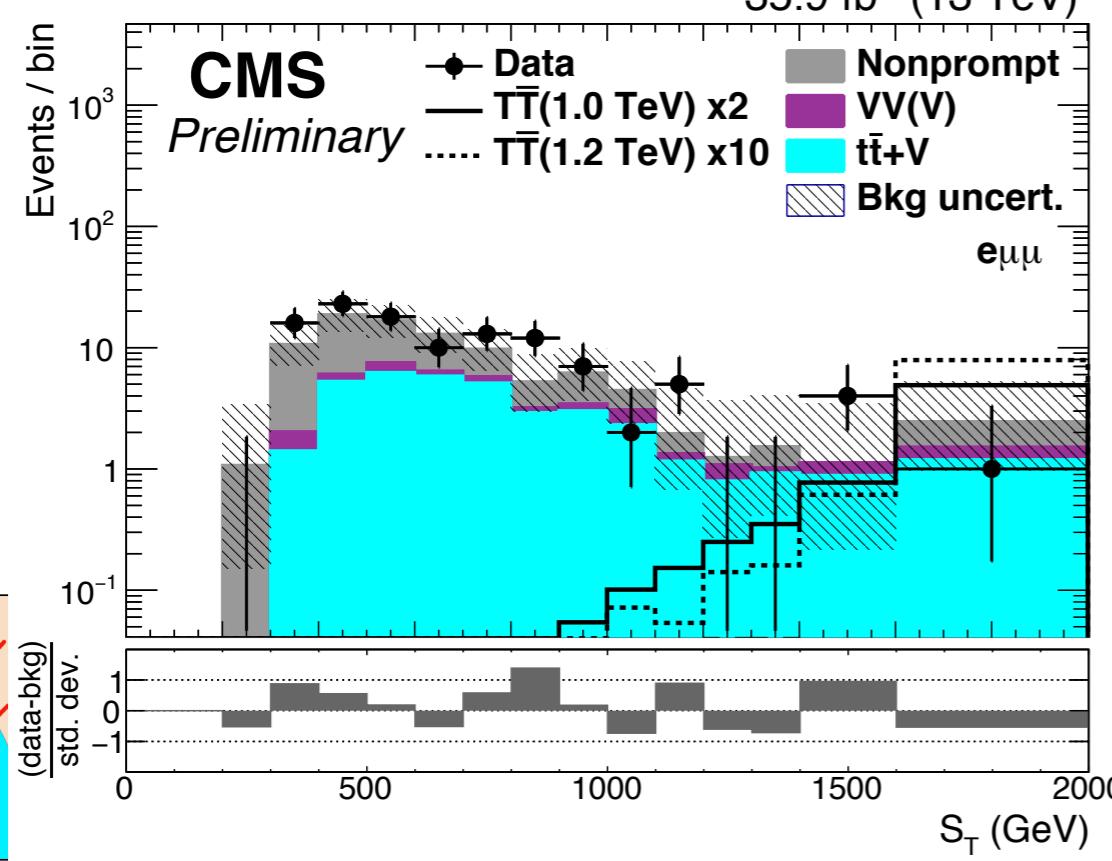
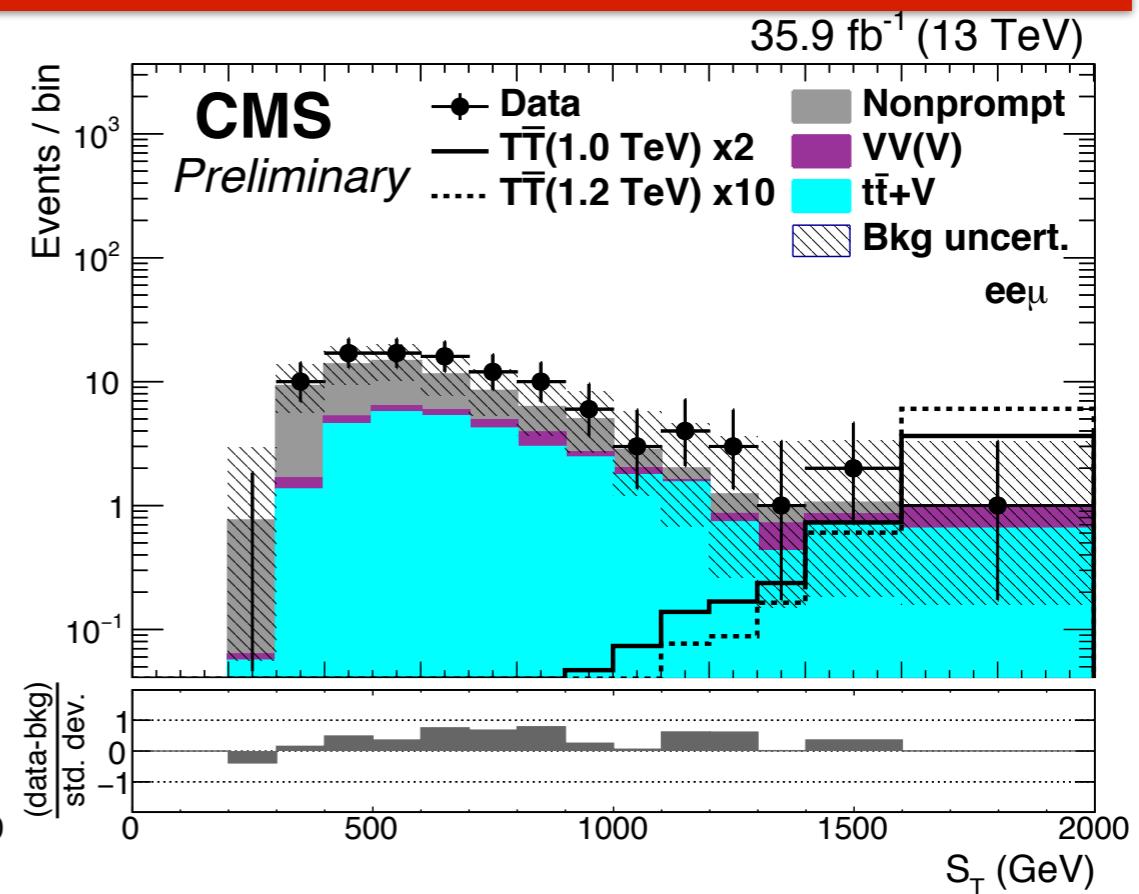
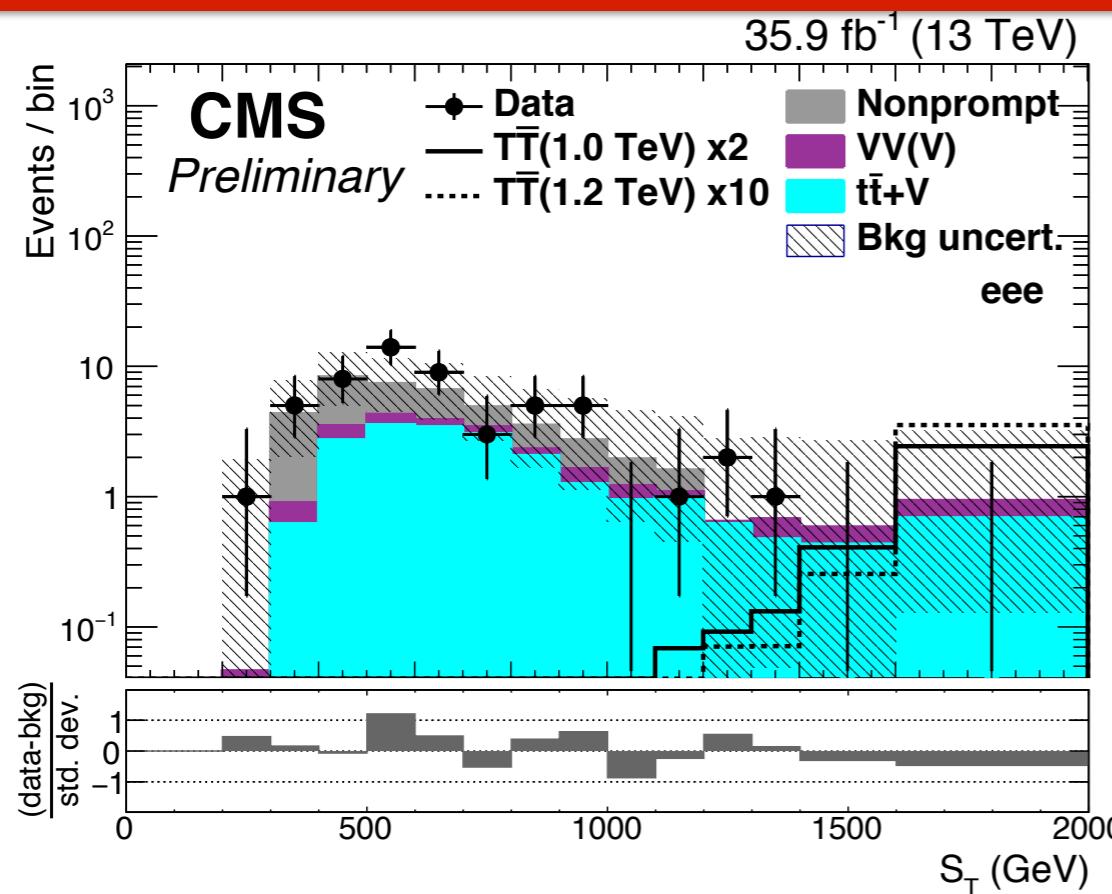
# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Single Lepton Results



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Dilepton Results



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Trilepton Results



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Single Lepton Yields

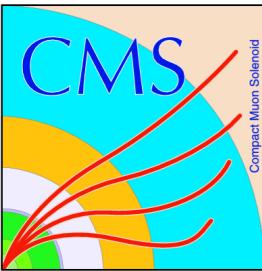
Sample	0 H, 0 W, 1 b	0 H, 0 W, 2 b	0 H, 0 W, $\geq 3$ b
$T\bar{T}$ (1.0 TeV)	$21.5 \pm 1.2$	$12.87 \pm 0.74$	$4.41 \pm 0.29$
$T\bar{T}$ (1.2 TeV)	$6.48 \pm 0.36$	$3.68 \pm 0.21$	$1.22 \pm 0.08$
TOP	$2030 \pm 440$	$1070 \pm 240$	$172 \pm 39$
EW	$720 \pm 120$	$94 \pm 16$	$7.2 \pm 1.4$
QCD	$117 \pm 31$	$18.1 \pm 9.7$	$5.9 \pm 5.2$
Total Bkg	$2870 \pm 470$	$1180 \pm 240$	$185 \pm 40$
Data	2598	1054	182
Data/Bkg	$0.90 \pm 0.15$	$0.89 \pm 0.18$	$0.98 \pm 0.22$
Sample	0 H, $\geq 1$ W, 1 b	0 H, $\geq 1$ W, 2 b	0 H, $\geq 1$ W, $\geq 3$ b
$T\bar{T}$ (1.0 TeV)	$27.7 \pm 1.4$	$13.91 \pm 0.73$	$3.75 \pm 0.22$
$T\bar{T}$ (1.2 TeV)	$8.22 \pm 0.43$	$3.84 \pm 0.20$	$0.92 \pm 0.06$
TOP	$1410 \pm 300$	$660 \pm 140$	$95 \pm 22$
EW	$291 \pm 47$	$38.1 \pm 7.6$	$2.68 \pm 0.58$
QCD	$36 \pm 13$	$6.6 \pm 6.5$	$< 1$
Total Bkg	$1730 \pm 310$	$700 \pm 140$	$98 \pm 22$
Data	1589	594	96
Data/Bkg	$0.92 \pm 0.16$	$0.84 \pm 0.17$	$0.98 \pm 0.24$
Sample	H1b, $\geq 0$ W, $\geq 1$ b	H2b, $\geq 0$ W, $\geq 1$ b	
$T\bar{T}$ (1.0 TeV)	$36.7 \pm 2.0$	$7.92 \pm 0.59$	
$T\bar{T}$ (1.2 TeV)	$11.18 \pm 0.60$	$2.39 \pm 0.19$	
TOP	$1520 \pm 330$	$49 \pm 12$	
EW	$46.9 \pm 8.1$	$4.2 \pm 1.5$	
QCD	$14.4 \pm 6.3$	$< 1$	
Total Bkg	$1570 \pm 330$	$53 \pm 12$	
Data	1488	44	
Data/Bkg	$0.95 \pm 0.20$	$0.83 \pm 0.22$	



# T $\bar{T}$ /B $\bar{B}$ →bW/tZ/tH(tW/bZ/bH): Di and Tri-Lepton Lepton Yields

Sample	ee	e $\mu$	$\mu\mu$
T $\bar{T}$ (1.0 TeV)	$1.34 \pm 0.08$	$3.11 \pm 0.18$	$2.12 \pm 0.12$
T $\bar{T}$ (1.2 TeV)	$0.42 \pm 0.02$	$1.00 \pm 0.06$	$0.66 \pm 0.04$
Prompt SS	$4.03 \pm 0.57$	$10.2 \pm 1.4$	$5.79 \pm 0.82$
Nonprompt	$4.6 \pm 2.6$	$10.6 \pm 5.6$	$5.4 \pm 3.0$
Charge misid.	$4.1 \pm 1.3$	$2.61 \pm 0.81$	—
Total Bkg	$12.8 \pm 3.0$	$23.4 \pm 5.8$	$11.2 \pm 3.1$
Data	12	31	9
Data/Bkg	$0.94 \pm 0.35$	$1.33 \pm 0.41$	$0.80 \pm 0.35$

Sample	eee	ee $\mu$	e $\mu\mu$	$\mu\mu\mu$
T $\bar{T}$ (1.0 TeV)	$1.60 \pm 0.14$	$2.54 \pm 0.18$	$3.32 \pm 0.23$	$2.79 \pm 0.23$
T $\bar{T}$ (1.2 TeV)	$0.40 \pm 0.03$	$0.71 \pm 0.05$	$0.90 \pm 0.06$	$0.78 \pm 0.06$
VV(V)	$4.32 \pm 0.77$	$5.44 \pm 0.78$	$6.52 \pm 0.93$	$5.89 \pm 0.89$
t $\bar{t}$ +V	$20.9 \pm 2.9$	$31.9 \pm 4.1$	$37.0 \pm 4.7$	$35.8 \pm 5.0$
Nonprompt	$19 \pm 11$	$41 \pm 18$	$51 \pm 15$	$20.0 \pm 8.4$
Total Bkg	$44 \pm 11$	$78 \pm 19$	$94 \pm 15$	$61.7 \pm 9.8$
Data	54	102	111	71
Data/Bkg	$1.22 \pm 0.35$	$1.31 \pm 0.34$	$1.18 \pm 0.22$	$1.15 \pm 0.23$



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Systematics

Source	Uncertainty	$1\ell$		SS $2\ell$		$\geq 3\ell$	
		Sig	Bkgd	Sig	Bkgd	Sig	Bkgd
Integrated Luminosity	2.5%	Yes	MC	Yes	MC	Yes	MC
Reconstruction	1%	Yes	MC	Yes	MC	Yes	MC
Identification	2%(e), 3%( $\mu$ )	Yes	MC	Yes	MC	Yes	MC
Isolation (e, $\mu$ )	1%	Yes	MC	Yes	MC	Yes	MC
Trigger (e or $\mu$ )	$\pm\sigma(p_T, \eta)$	Yes	MC	—	—	—	—
Trigger ( $\ell\ell$ )	3%	—	—	Yes	MC	—	—
Trigger ( $\ell\ell\ell$ )	3%	—	—	—	—	Yes	MC
Charge misid. rate	30%	—	—	No	OS	—	—
$\ell$ misid. rate	50%	—	—	No	NP	—	—
$\ell$ misid. rate	4–30%	—	—	—	—	No	NP
$\ell$ misid. rate in $\eta(\mu)$	12–33%	—	—	—	—	No	NP
NP method closure	17–31%	—	—	—	—	No	NP
NP method in CR	2–35%	—	—	—	—	No	NP
$\ell$ prompt rate	2–9% (e), 1–7% ( $\mu$ )	—	—	—	—	No	NP
Pileup	$\sigma_{\text{inel.}} \pm 4.6\%$	Yes	MC	Yes	MC	Yes	MC
Jet energy scale	$\pm\sigma(p_T, \eta)$	Yes	MC	Yes	MC	Yes	MC
Jet energy res.	$\pm\sigma(\eta)$	Yes	MC	Yes	MC	Yes	MC
$H_T$ scaling	env(upper, lower fits)	No	W+jets	—	—	—	—
b tag: b	$\pm\sigma(p_T)$	Yes	MC	—	—	Yes	MC
b tag: light	$\pm\sigma$	Yes	MC	—	—	Yes	MC
W tag: $\tau_2/\tau_1$	$\pm\sigma$	Yes	MC	—	—	—	—
W tag: $\tau_2/\tau_1 p_T$	$\pm\sigma(p_T)$	Yes	MC	—	—	—	—
W/H tag: mass scale	$\pm\sigma(p_T, \eta)$	Yes	MC	—	—	—	—
W/H tag: mass res.	$\pm\sigma(\eta)$	Yes	MC	—	—	—	—
H tag: propagation	5%	Yes	MC	—	—	—	—
Renorm./Fact. scale	env( $\times 2, \times 0.5$ )	Shape	MC	Accept.	MC	Shape	MC
PDF	RMS(replicas)	Shape	MC	Accept.	MC	Shape	MC
VV rate	15%	No	VV	—	—	—	—
Single tW rate	16%	No	tW	—	—	—	—



# $T\bar{T}/B\bar{B} \rightarrow bW/tZ/tH(tW/bZ/bH)$ : Branching Ratio Limits

