Search for Heavy Resonances Coupling to Third Generation Quarks at CMS

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On behalf of the CMS Collaboration

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SUSY2016: The University of Melbourne

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Outline

- The LHC is the perfect place to search for heavy resonances
  - Many new BSM models have heavy particles that decay to 3rd generation quarks
  - This talk will cover four analysis that search for heavy resonances that decay to 3rd generation quarks

Process	Channels	CMS-PAS	Lumi
$Z' \to t\bar{t}$	lvbbjj	B2G-15-002	2.6 fb^{-1}
$Z' \to t\bar{t}$	bbjjjj	B2G-15-003	2.6 fb^{-1}
$W' \to tb$	lvbb	B2G-15-004	2.2 fb^{-1}

Boosted Regime

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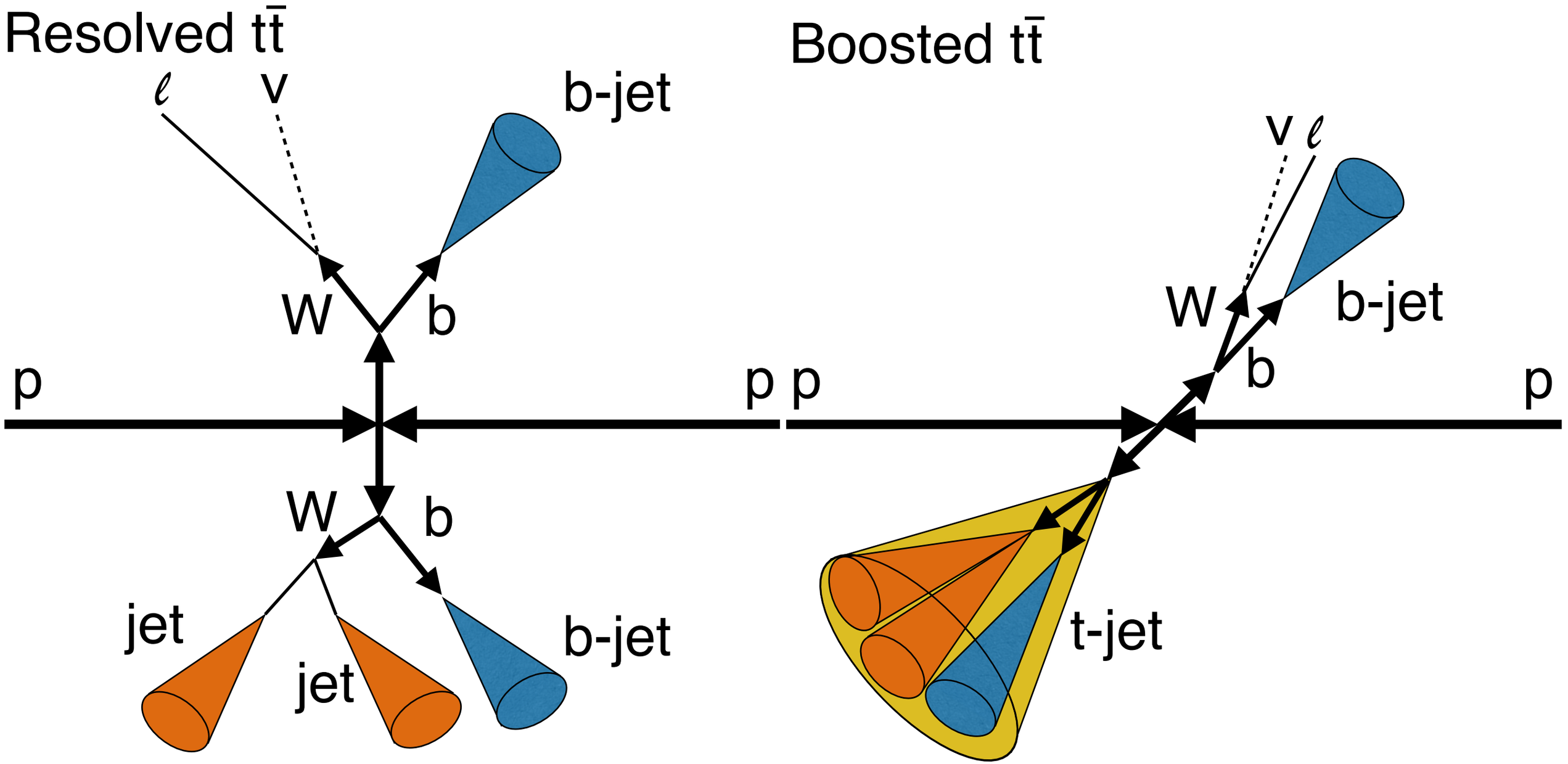

- Boosted top signatures require new triggering and reconstruction strategies
  - Non-Isolated Lepton Trigger
  - Jet p_T Cleaning

Higgs and Top Tagging

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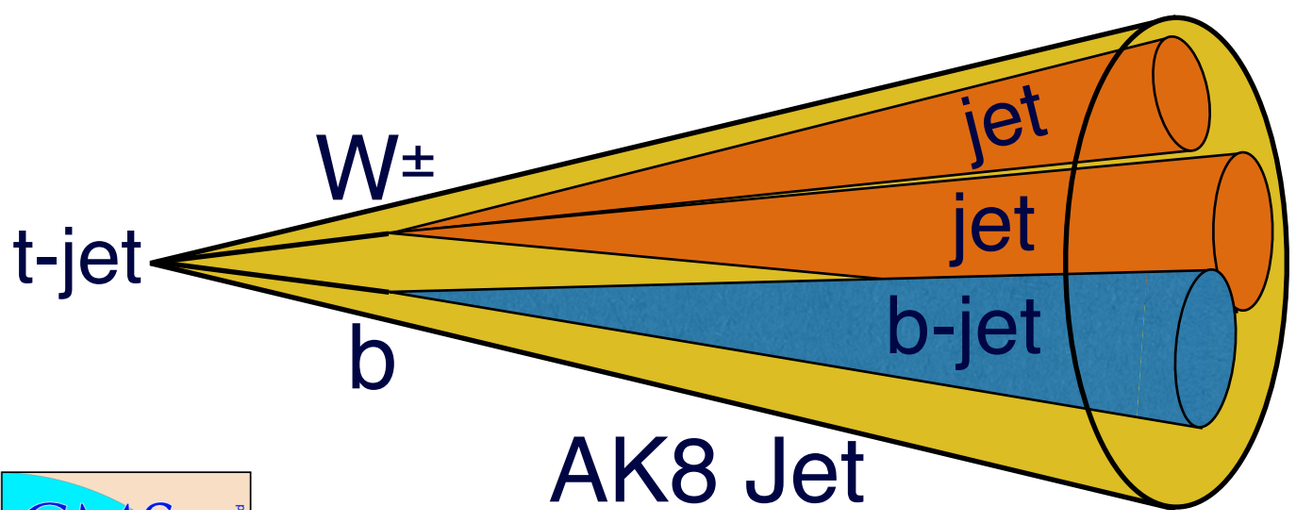
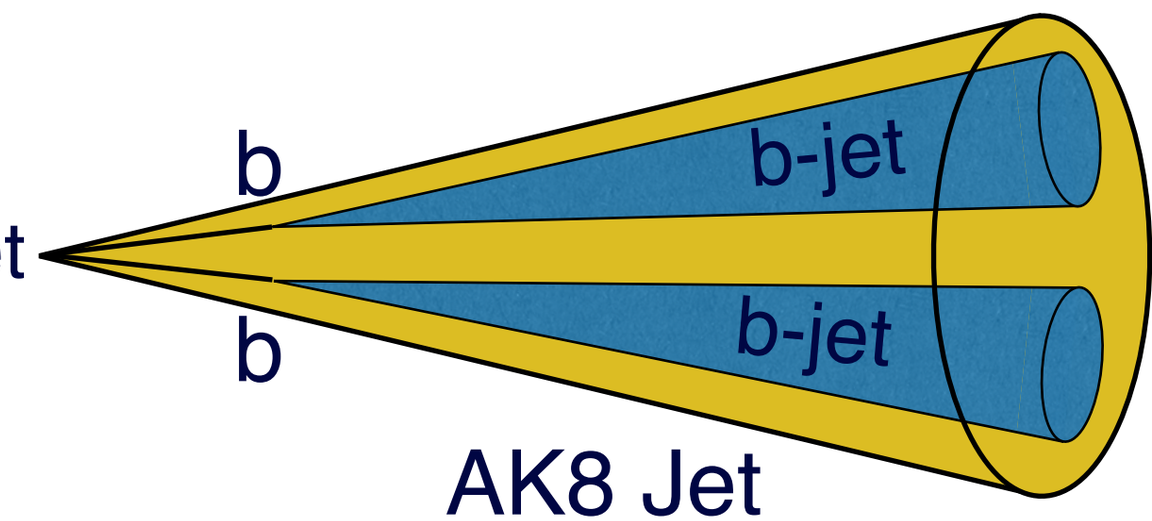
- The CMS Top-Tagger uses AK8 jets
  - $p_T > 200$ GeV and $|\eta| < 2.4$
  - At least 3 AK4 sub-jets
  - Groomed (soft-drop) jet mass used
    - 140 GeV $< M_{jet} <$ 250 GeV
    - Min $M_{Pair\text{-}Wise} > 50$ GeV
  - $\tau_{32} = \tau_3/\tau_2 < 0.7$



- Higgs tagging uses AK8 jets
  - $p_T > 200$ GeV and $|\eta| < 2.4$
  - At least 2 AK4 sub-jet b-tags (CSV loose working point)
  - Groomed (soft-drop) jet mass used
  - 90 GeV $< M_{jet} <$ 160 GeV



$Z' \rightarrow t\bar{t}$ Search

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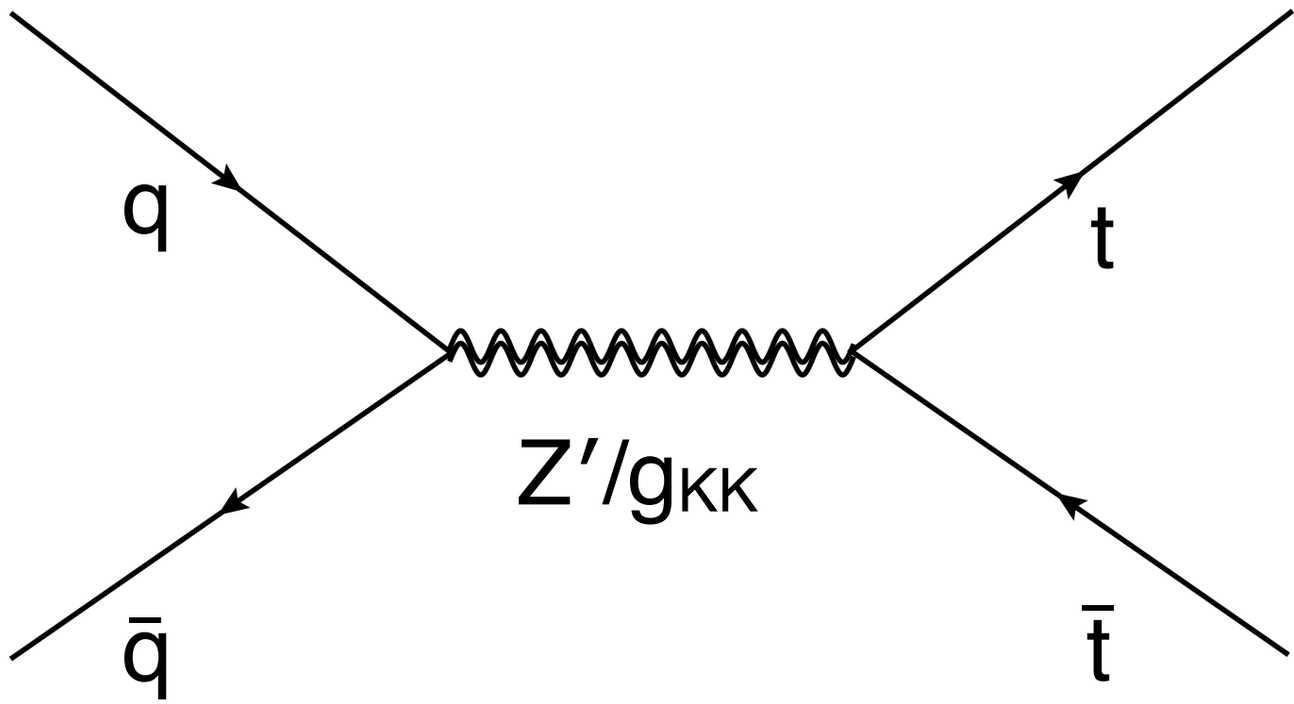
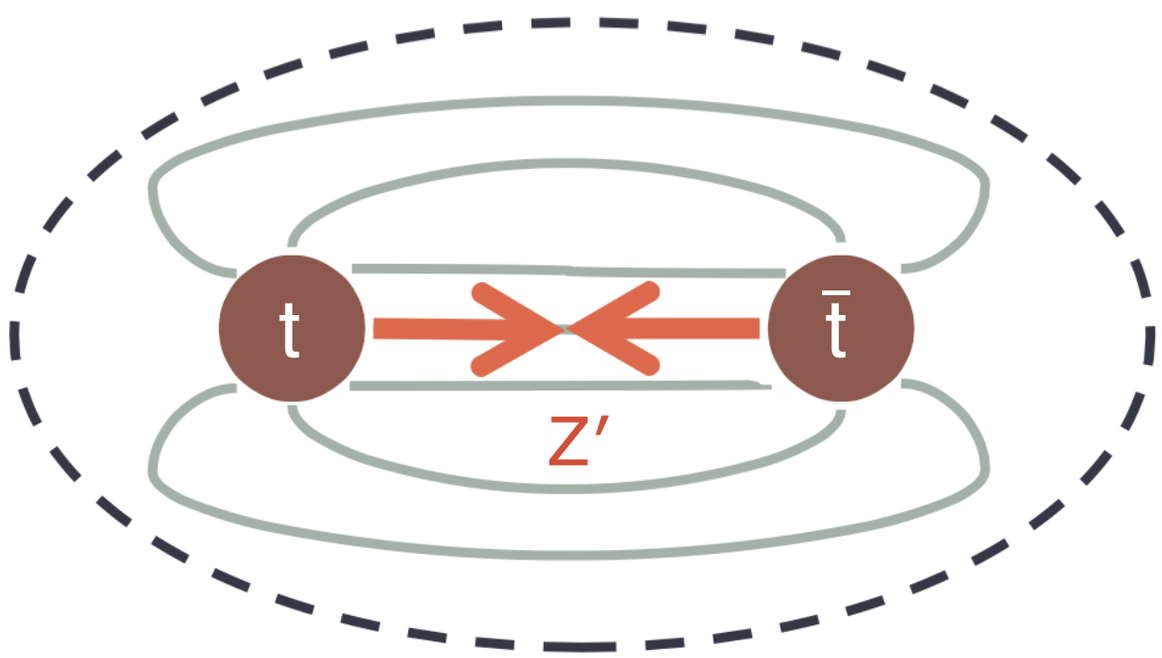
- The $Z' \rightarrow t\bar{t}$ analysis searches for a generic resonance decaying to $t\bar{t}$ pairs
  - Results for the semi-leptonic and all hadronic final states
  - Search sets explicit limits for a Z' boson and g_{KK}
- The analyses are very effective at excluding heavy resonances decaying to $t\bar{t}$ pairs





$Z' \rightarrow t\bar{t}$ Semi-Leptonic Channel

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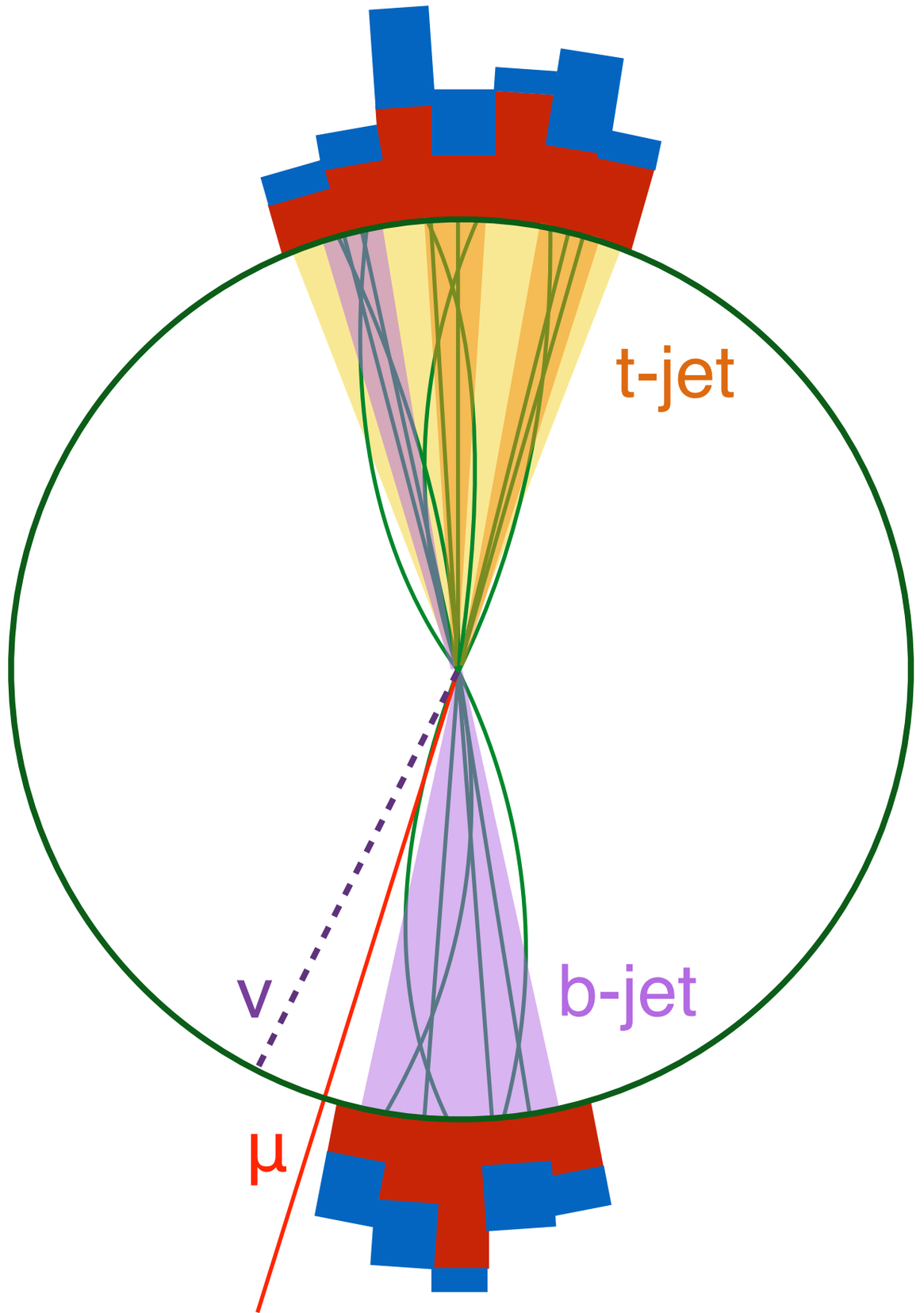
- Requires exactly one lepton and two high pT jets
- 2D-isolation cut is applied to the lepton
  - Triangular cut in electron channel on the MET and leading jet
- MET and $p_{T\ell}$+MET cut reduces multi-jet background
- χ^2 minimization technique is used to reconstruct the $t\bar{t}$ system
- T-tagging and b-tagging are used for categorization that increases analysis sensitivity



$Z' \rightarrow t\bar{t}$ Semi-Leptonic M_{tt} Distribution

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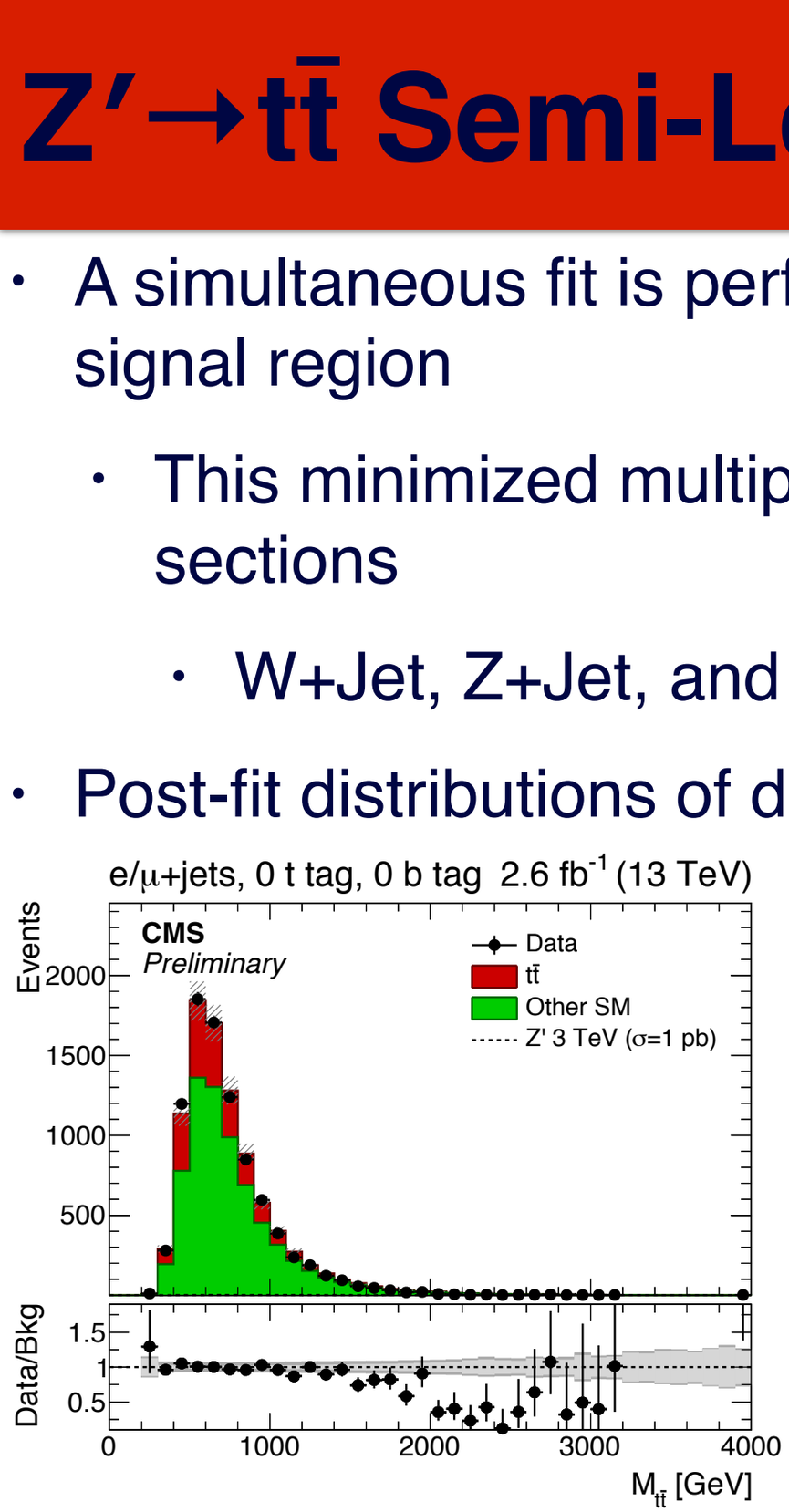
- A simultaneous fit is performed on three different control regions and the signal region
  - This minimized multiple uncertainties and fits the background cross-sections
    - W+Jet, Z+Jet, and Low $M_{t\bar{t}}$
- Post-fit distributions of data and MC are in good agreement



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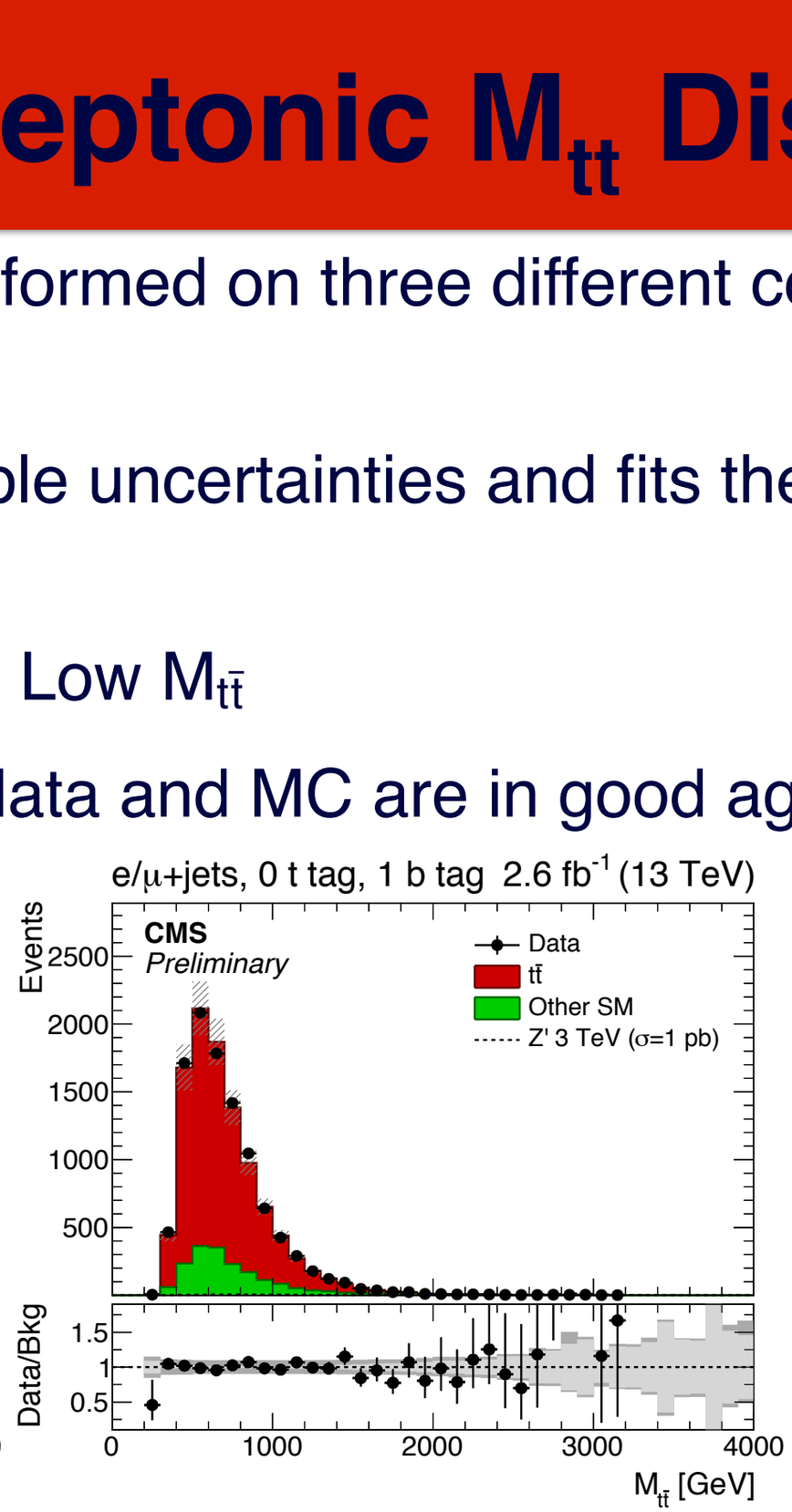

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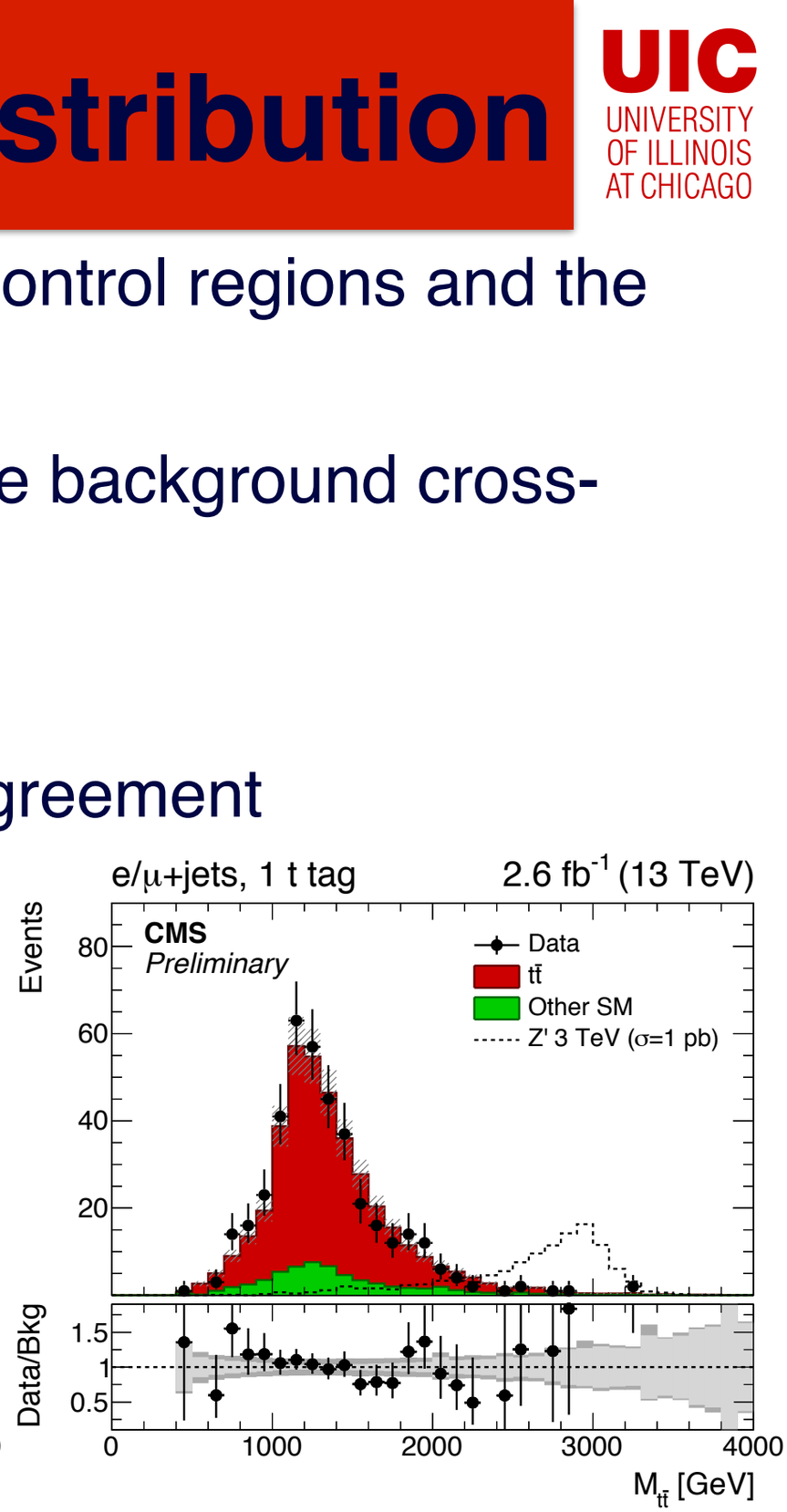

CMS-B2G-15-002

$Z' \rightarrow t\bar{t}$ Semi-Leptonic Limits

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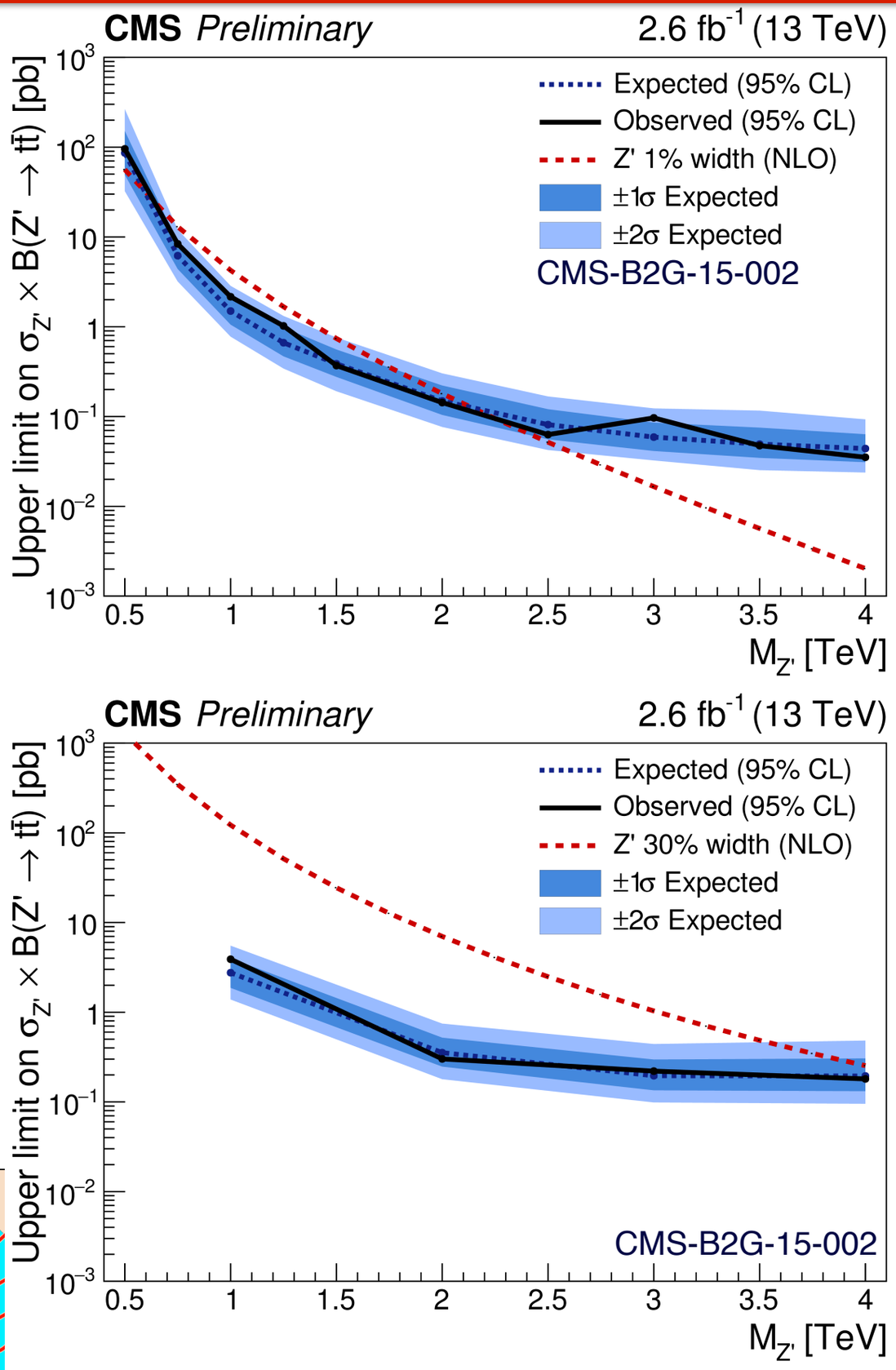

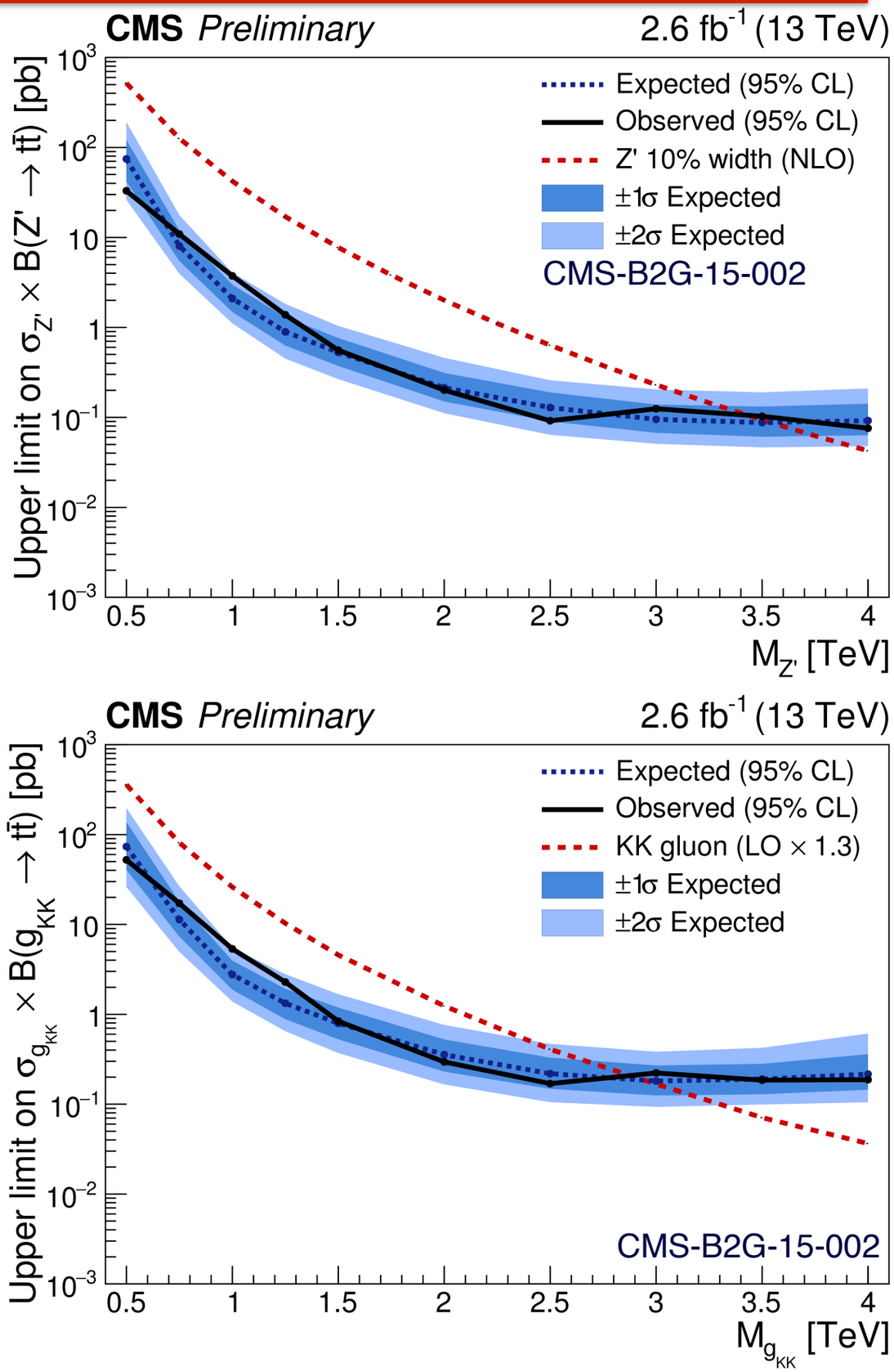

$Z' \rightarrow t\bar{t}$ All Hadronic Channel

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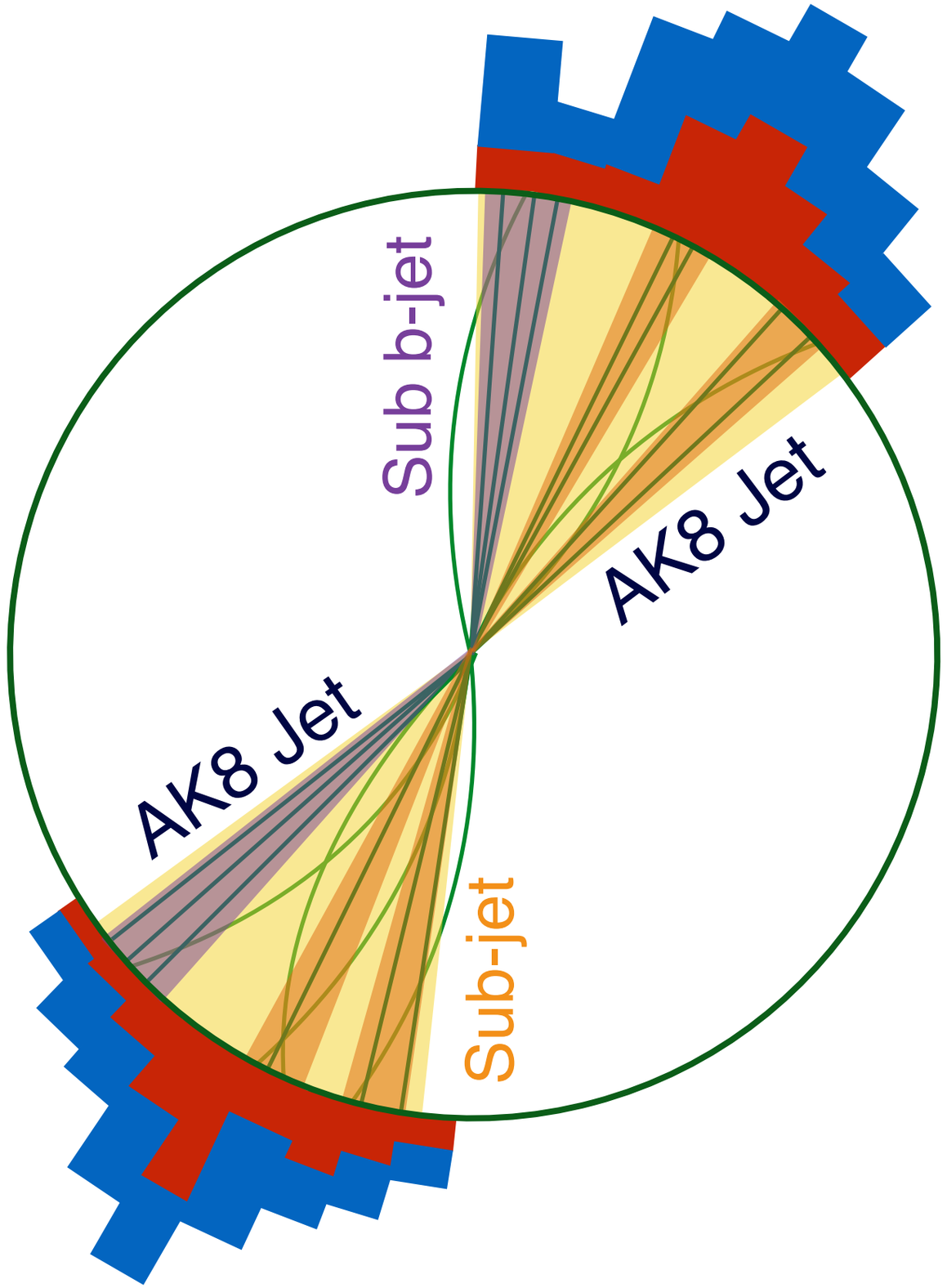
- The Lorentz boost of the top quarks causes this channel to become a di-jet analysis
  - Top tagging used to identify hadronically decaying tops
- Two high p_T top jets with large $\Delta\phi$ separation
- Large H_T cut
- Jet rapidity separation and sub-jet b-tagging used for categorization



$Z' \rightarrow t\bar{t}$ All Hadronic M_{tt} Distribution

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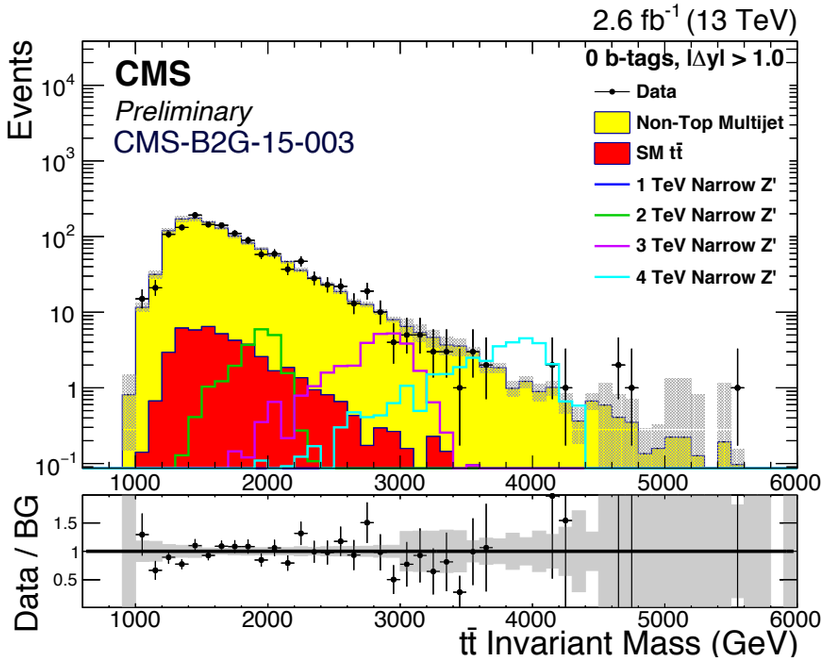

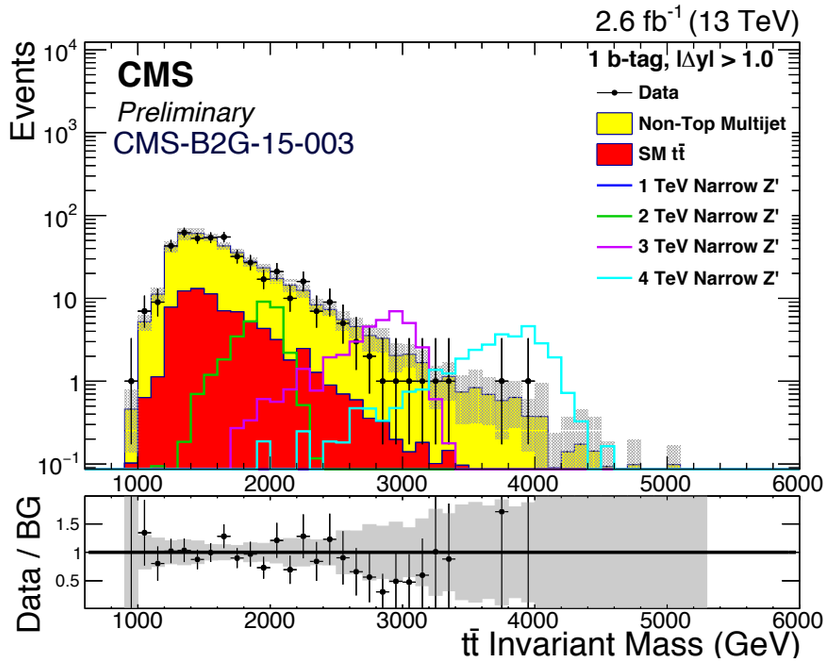

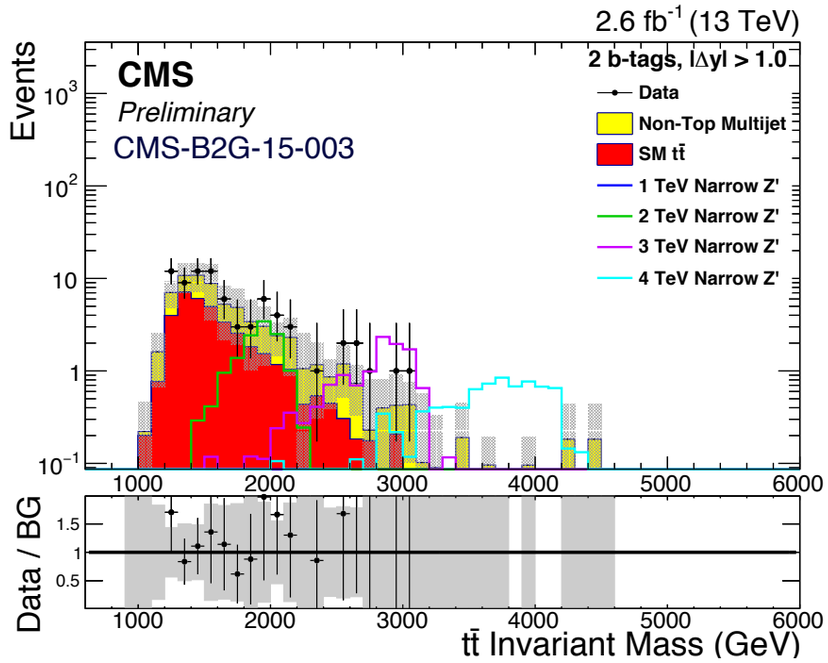

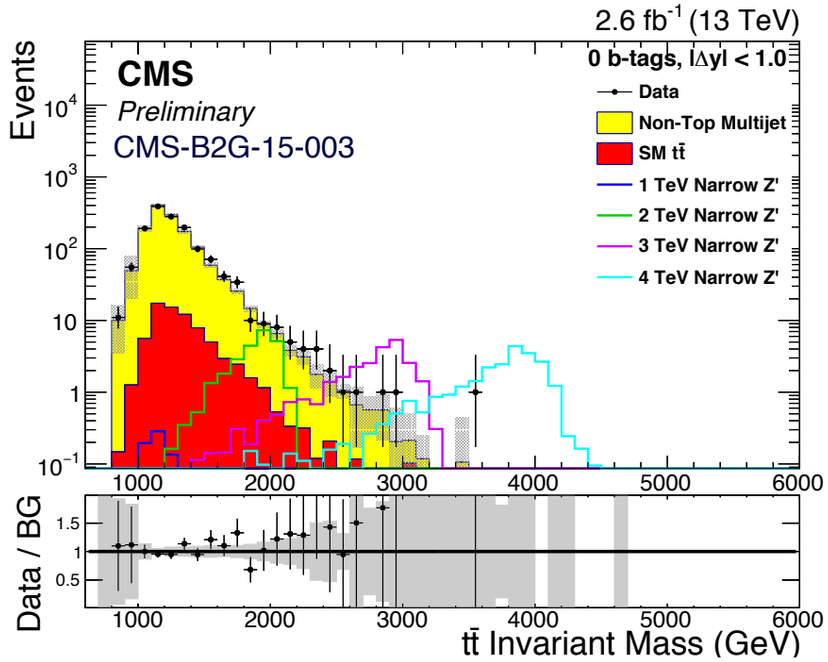

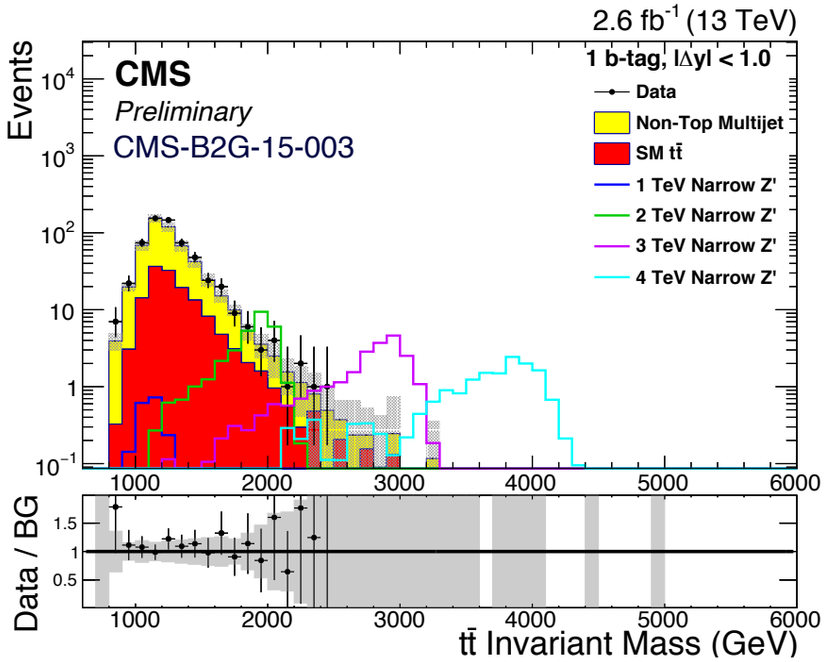

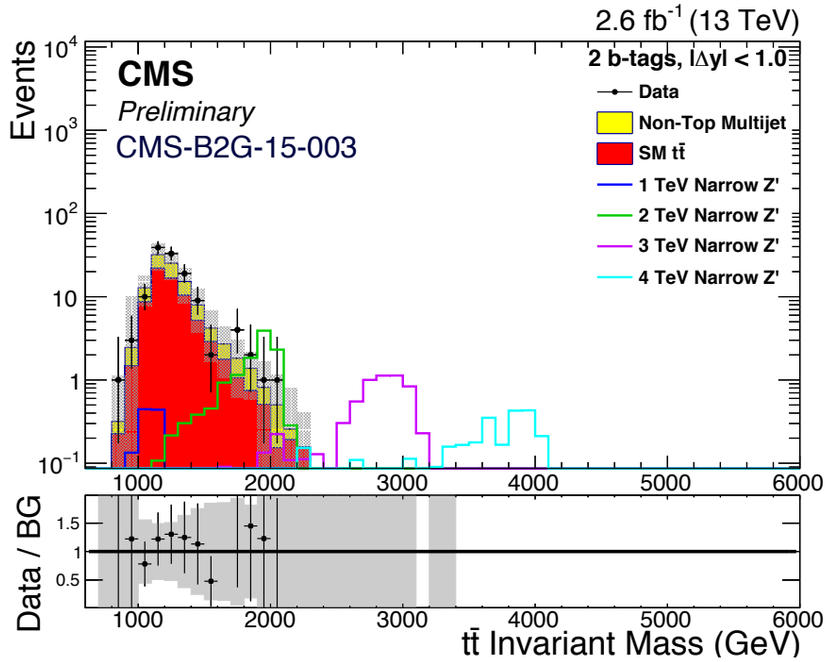

$Z' \rightarrow t\bar{t}$ All Hadronic Limits

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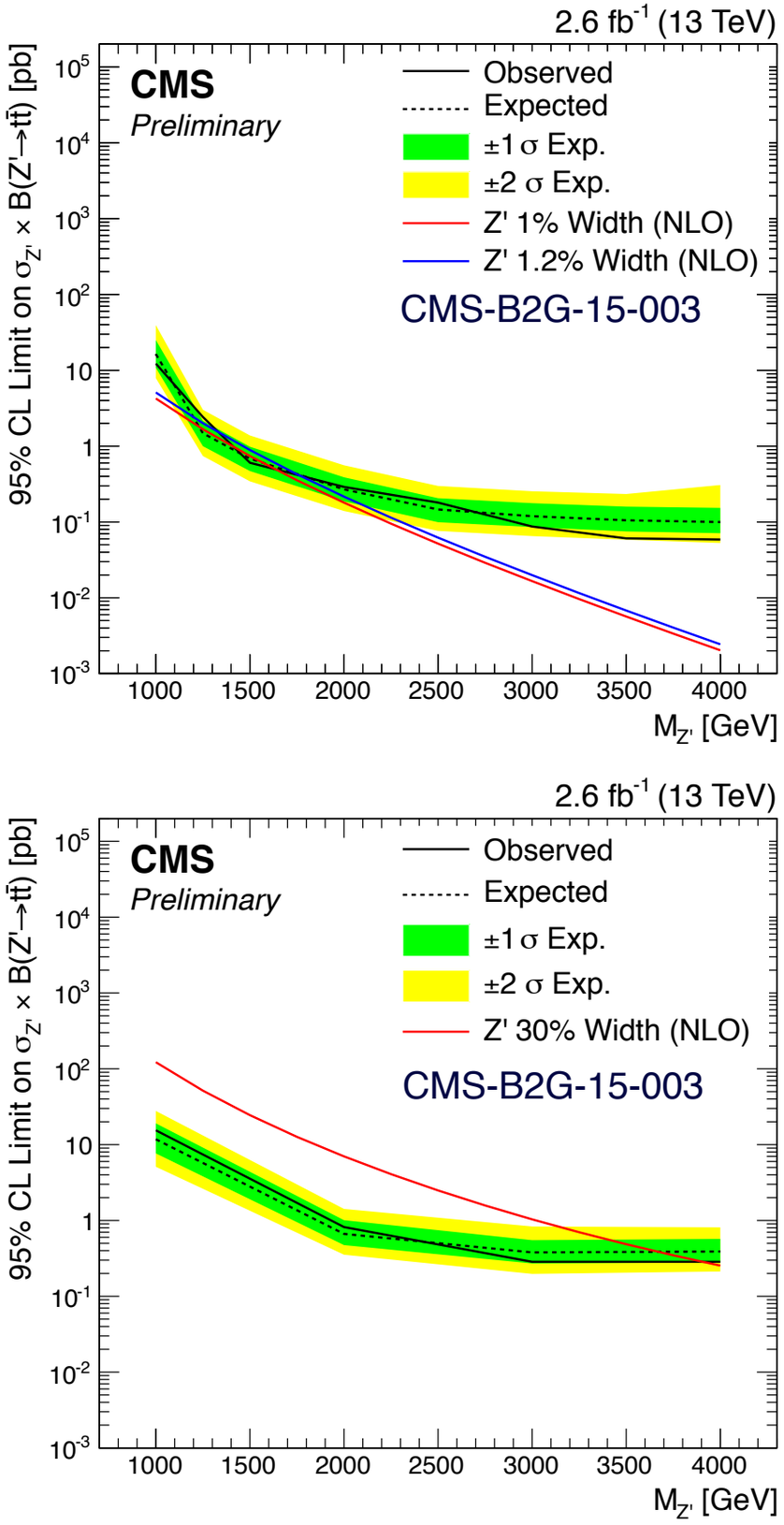

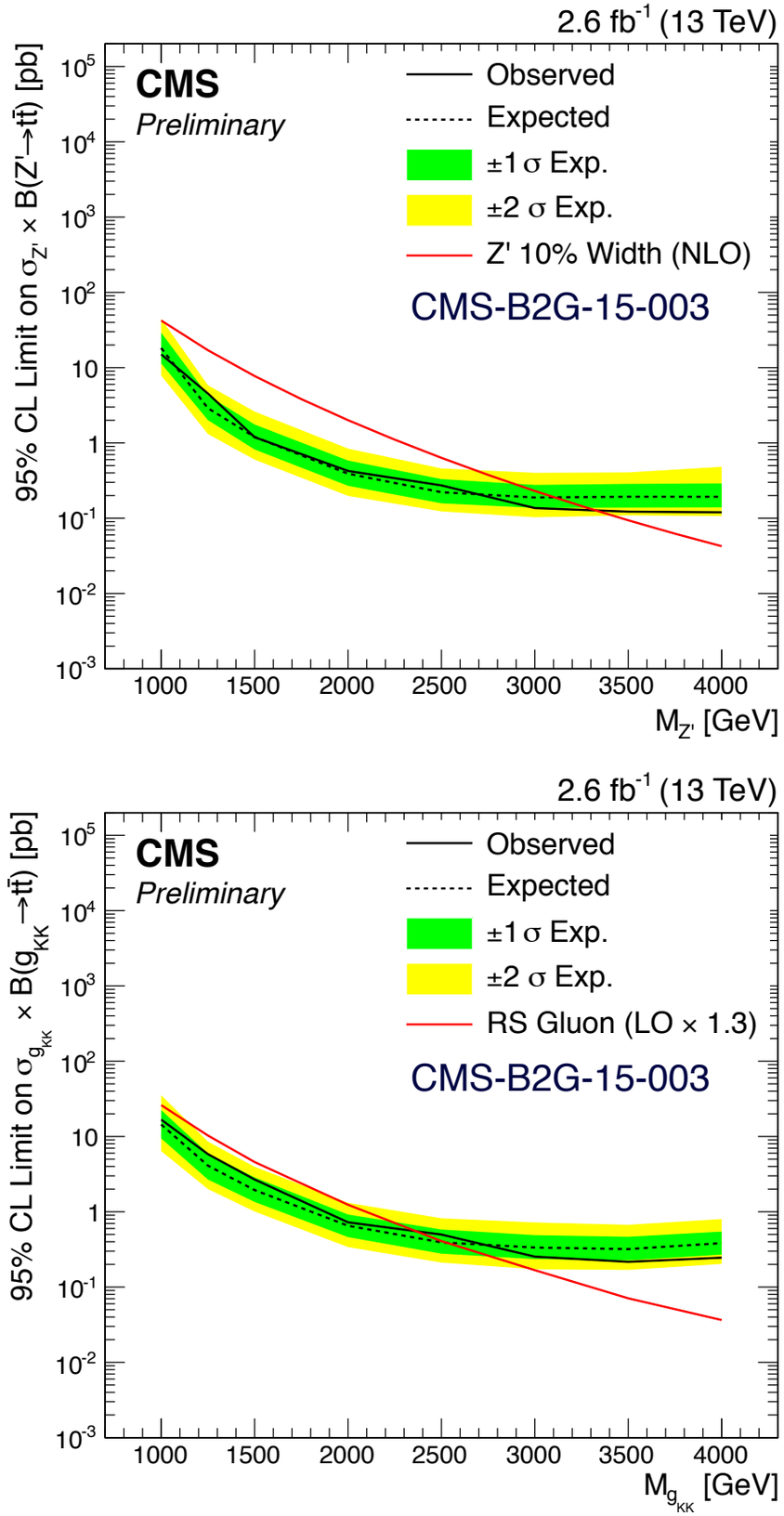

D. B

W′→tb Search

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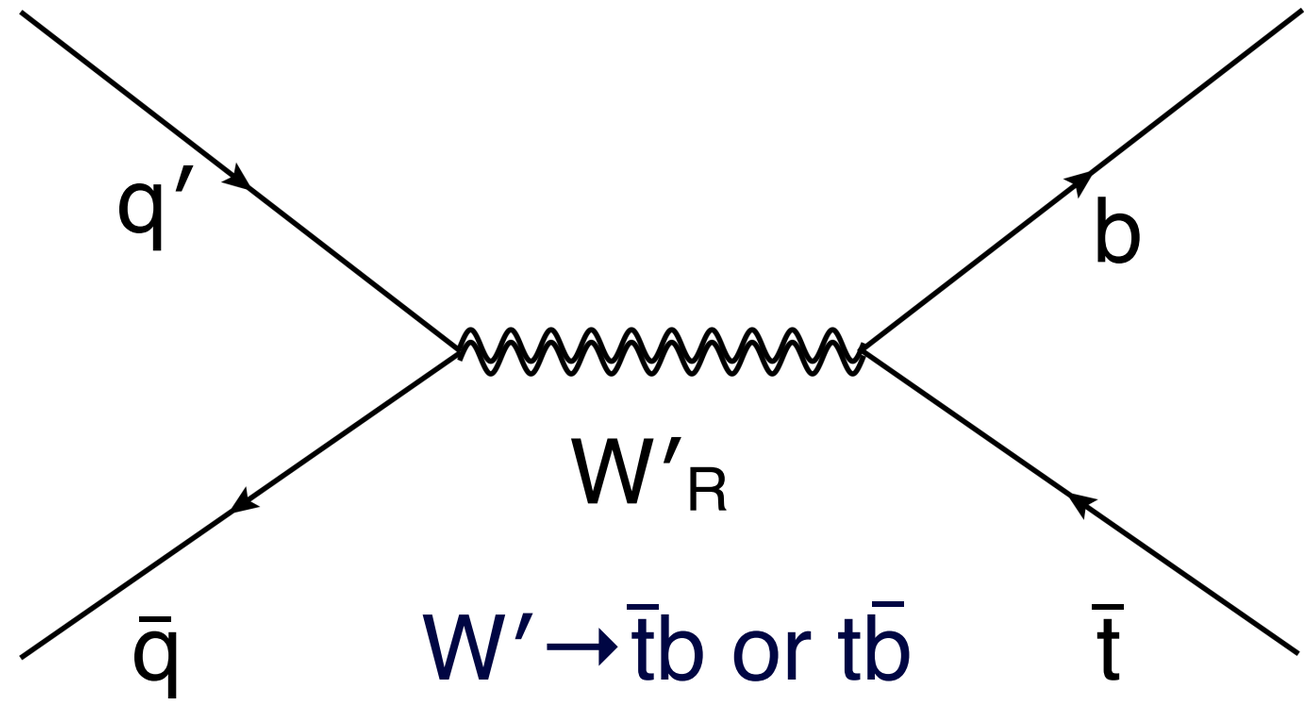
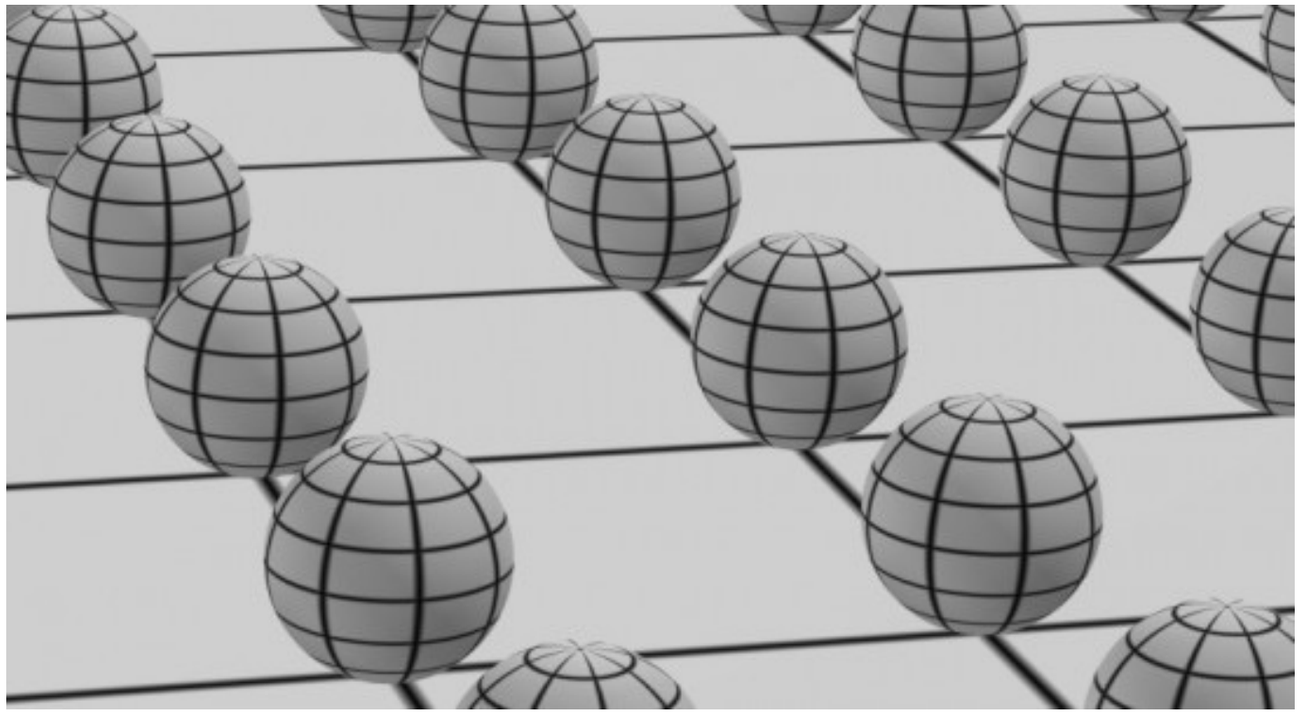
- W′ bosons are present in many BSM theories
  - Little Higgs
  - Kaluza-Klein w/ SU(2)
- The W′→tb analysis searches for a TeV scale particle decaying to tb pairs
  - Results for the semi-leptonic final state
  - Search sets explicit limits for a right-handed W′ boson





$W'_R \rightarrow tb$ Semi-Leptonic Channel

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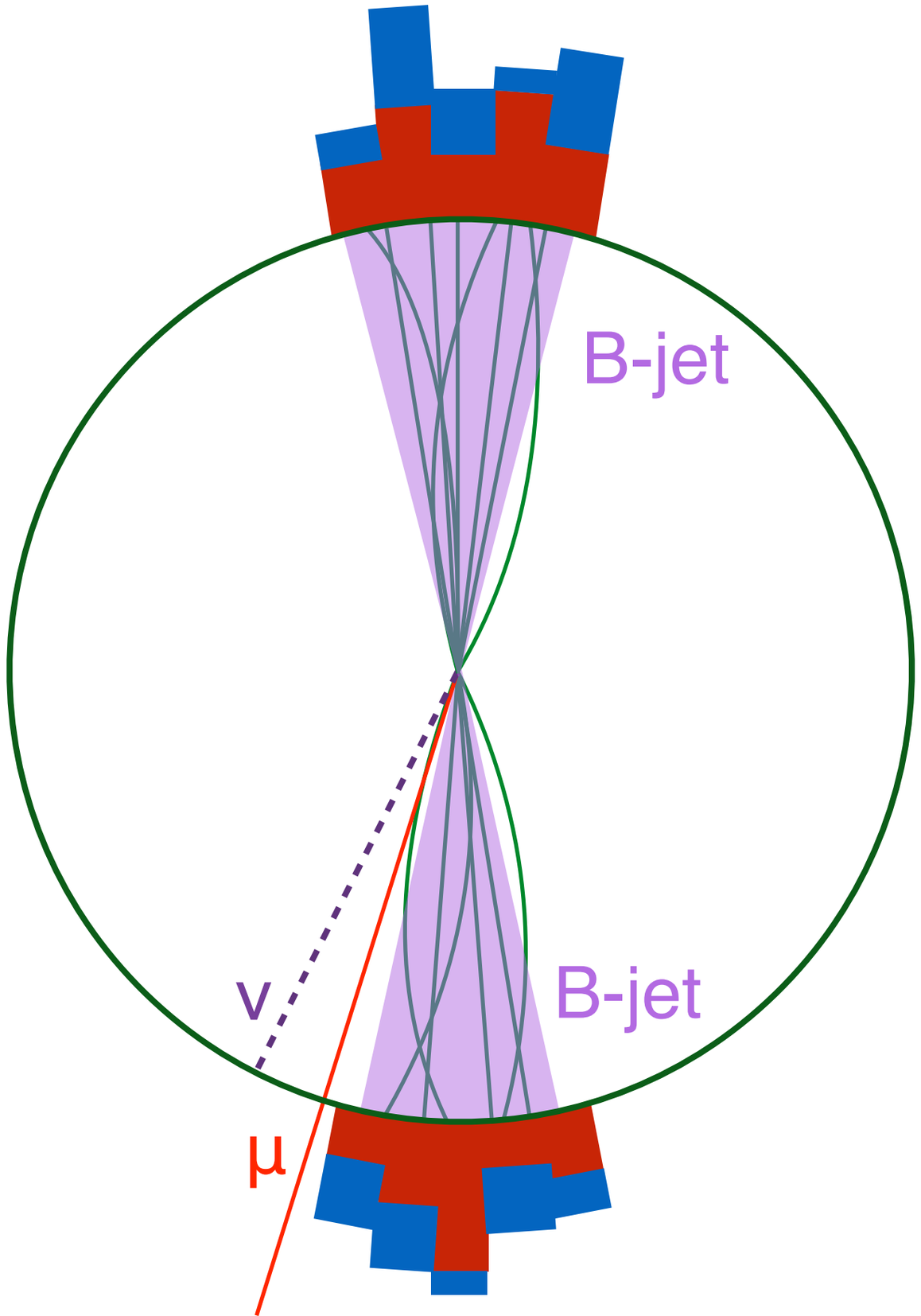
- Requires exactly one high-p_T lepton and two jets
  - One jet must have high p_T
  - One jet must be b-tagged
- 2D-isolation cut is applied to the lepton
- MET reduces multi-jet background
  - MET must be approximately collinear with lepton
- W′ mass is calculated using the reconstructed top and second jet
  - Top is reconstructed using reconstructed neutrino and the “best-jet”
  - Z component of MET is calculated using M_{TLep} and M_W (80.4 GeV)
- Additional selections on the reconstructed top mass, top p_T, and scalar sum on jet p_T
- Categorized based on the number of b-tags for increased analysis sensitivity



$W'_R \rightarrow tb$ Results

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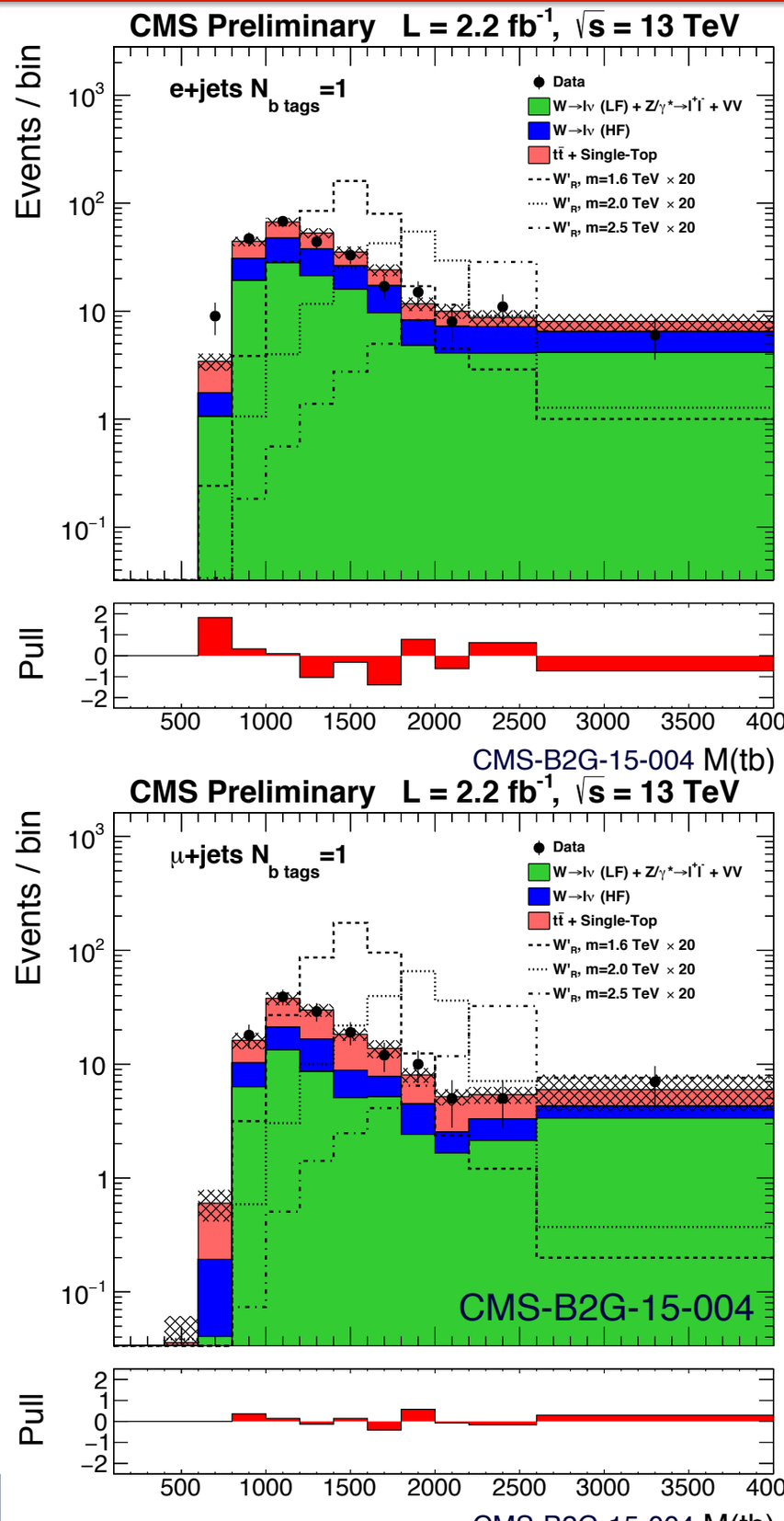
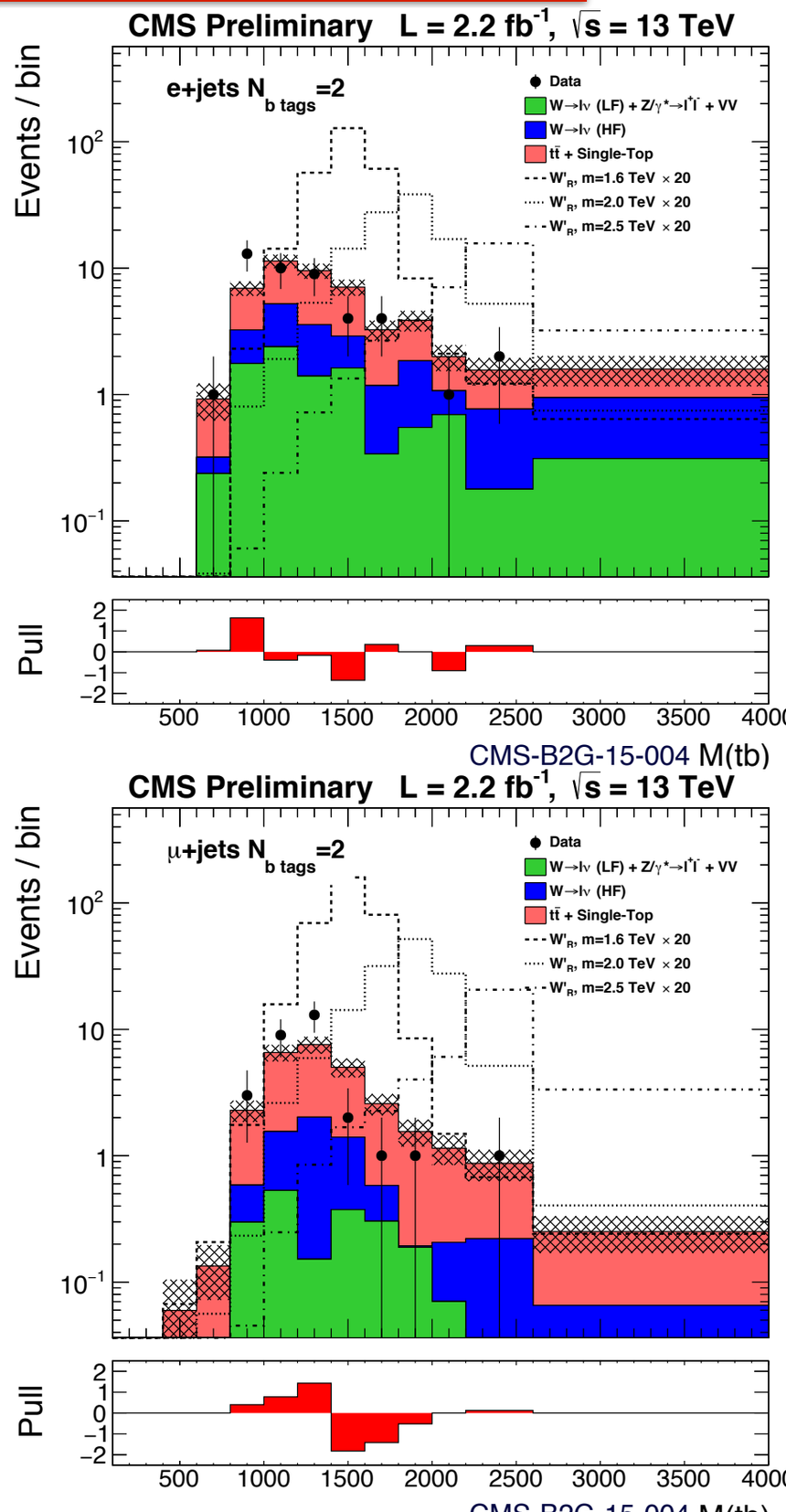
- Post-fit results shown in all 4 categories
  - e/μ with 1 or 2 b-tags
- Good agreement seen in data and MC
- Limits set using a Bayesian approach





$W'_R \rightarrow tb$ Limits

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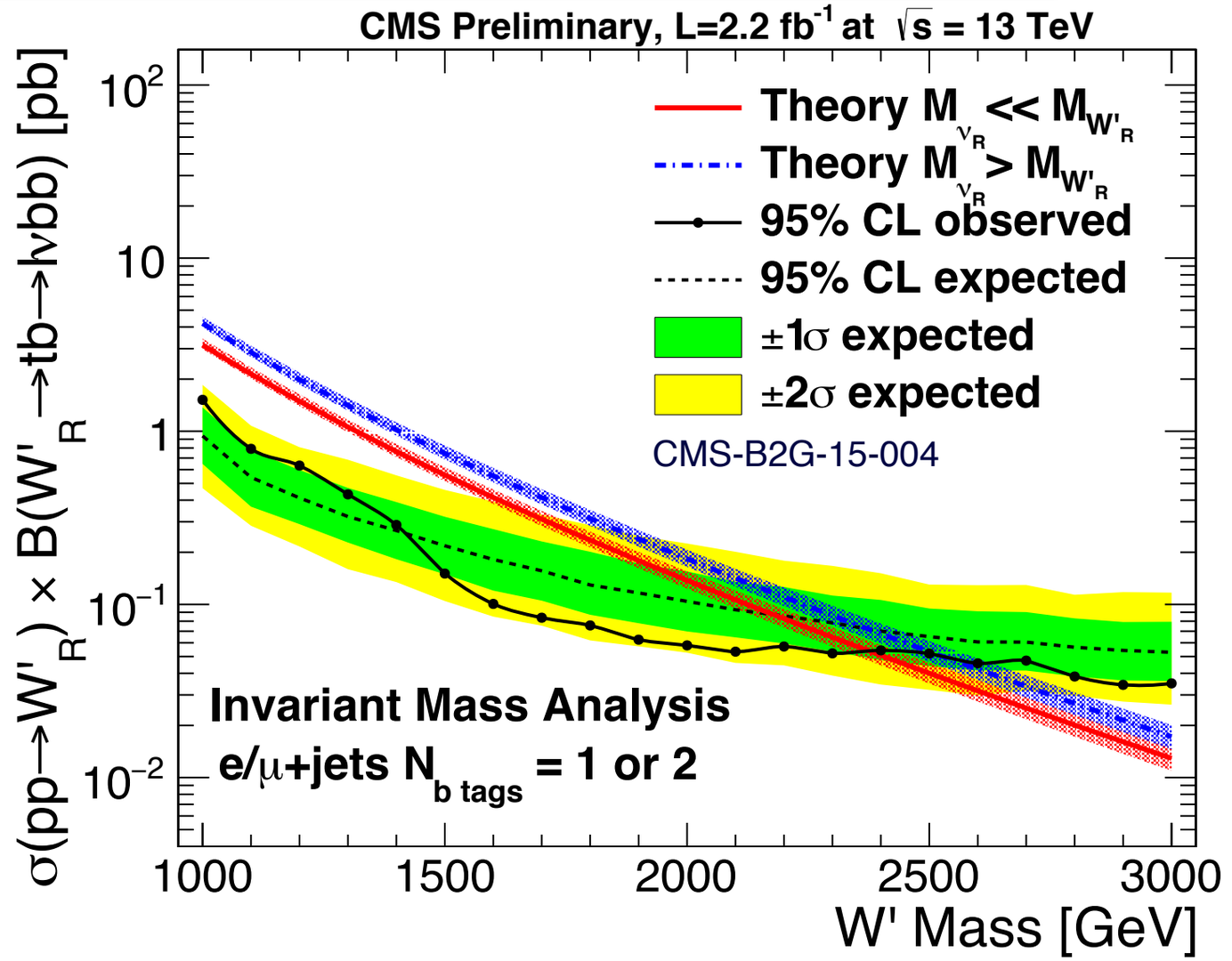
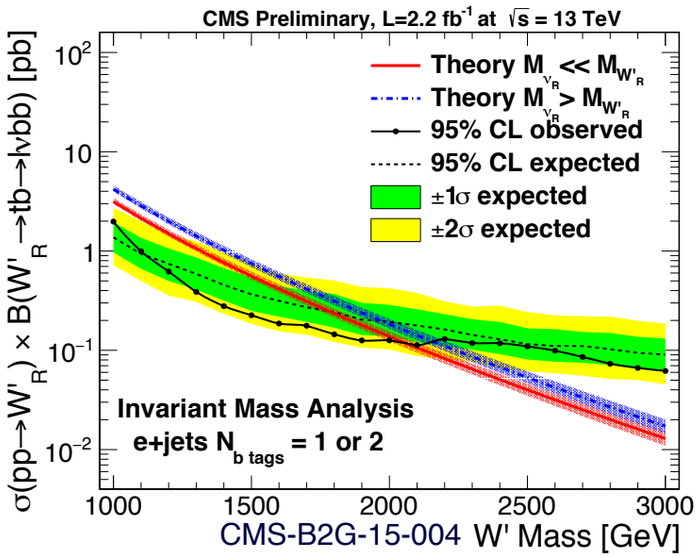
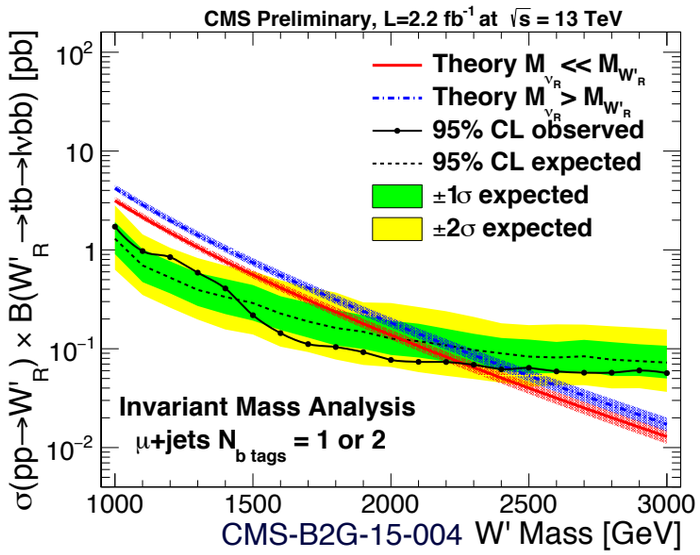
- Limits set for right-handed W′ bosons
  - W′ boson excluded below 2.38 TeV, where 2.17 TeV is expected
  - Limit assumes $M_{\nu_R} \ll M_{W'R}$
  - Under $M_{\nu_R} > M_{W'R}$ hypothesis, limit is 2.5 TeV







Conclusion

- The results of four resonant searches have been presented
  - The semi-leptonic and all hadronic Z′ searches put the most stringent limits on Z′ production to date
    - Z′ semi-leptonic exclusions of 0.6-2.3 TeV, 0.5-3.4 TeV, and 0.5-4.0 TeV for widths 1%, 10%, and 30% of the Z′ mass
    - Z′ all-hadronic exclusions of 1-3.3 TeV and 1-3.8 TeV for widths 10% and 30% of the Z′ mass
    - Combination result coming soon
  - The W′ search excludes a W′ in the mass range 1-2.38 TeV
- All results presented make use of t-tagging or b-tagging techniques
  - Categorizing on these tags significantly increases the power of the analyses

Backup

$Z' \rightarrow t\bar{t}$ Semi-Lepton: Data and MC Samples

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- Z' MC generated in MADGRAPH and NLO cross-sections taken from R. Bonciani et al. Parton showering done in PYTHIA and shower matching done using the MLM-algorithm
- PYTHIA8 used to g_{KK} sample and LO cross-sections from PYTHIA multiplied by a k-factor of 1.3
- $t\bar{t}$ and tW samples generated with POWHEG.
- S and t-channel single top samples generated with aMC@NLO
- W+Jets, Drell-Yan+Jets, and QCD samples generated in MADGRAPHv5 and shower matching via PYTHIA8
  - QCD is enriched in electrons and muons using generator level filters

Dataset	$L_{Int}[pb^{-1}]$
/SingleMuon/Run2015C_25ns-05Oct2015-v1/MINIAOD	17.73
/SingleMuon/Run2015D_05Oct2015-v1/MINIAOD	940.76
/SingleMuon/Run2015D-PromptReco-v4/MINIAOD	1639.00
/SingleElectron/Run2015C_25ns-05Oct2015-v1/MINIAOD	17.73
/SingleElectron/Run2015D_05Oct2015-v1/MINIAOD	940.76
/SingleElectron/Run2015D-PromptReco-v4/MINIAOD	1639.00

$Z' \rightarrow t\bar{t}$ Semi-Lepton: Event Selection

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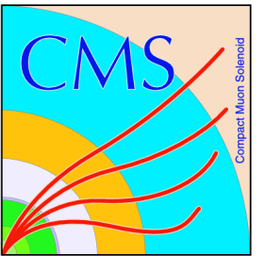
- Muon Channel
- HLT_Mu45_eta2p1 Trigger
- Muon $p_T > 50$ GeV with $|\eta| < 2.1$
- Jet_{Lead} $p_T > 150$ GeV
- $Jet_{SubLead}$ $p_T > 50$ GeV
- $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 20$ GeV
- $HT_{lep} > 150$ GeV
- MET > 50 GeV
- $\chi^2 < 30$

- Electron Channel
- HLT_Ele45_CaloIdVT_GsfTrkIdT_PFJet200_PFJet50 Trigger
- Electron $p_T > 50$ GeV with $|\eta| < 2.5$
- Jet_{Lead} $p_T > 250$ GeV
- $Jet_{SubLead}$ $p_T > 70$ GeV
- $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 20$ GeV
- $HT_{lep} > 150$ GeV
- MET > 120 GeV
- $\chi^2 < 30$



Z′→tt̄ Semi-Lepton: Prompt Lepton Efficiency

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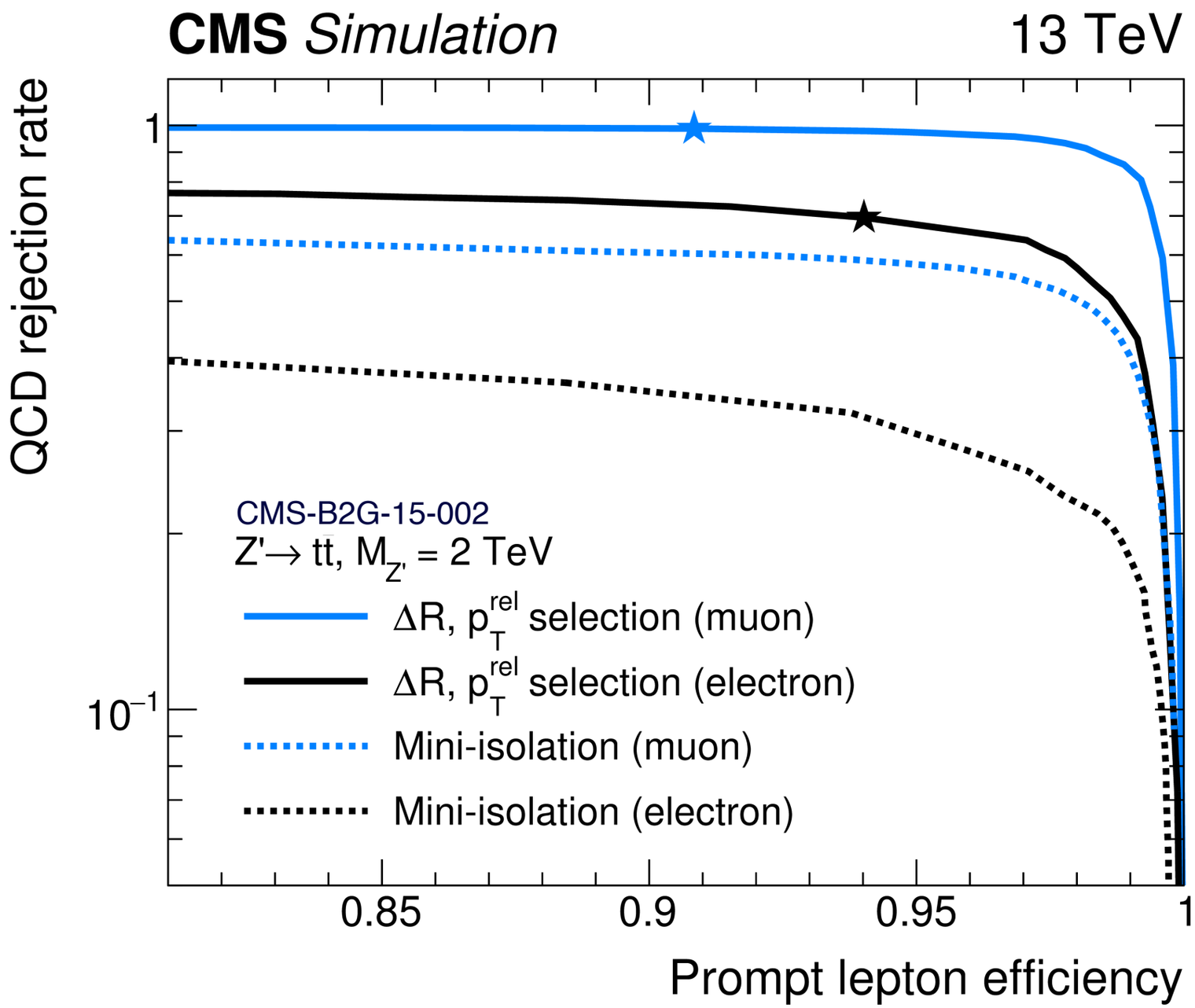
- Lepton selection efficiency for 2 TeV Z′ versus rejection efficiency



$Z' \rightarrow t\bar{t}$ Semi-Lepton: Triangular Cut

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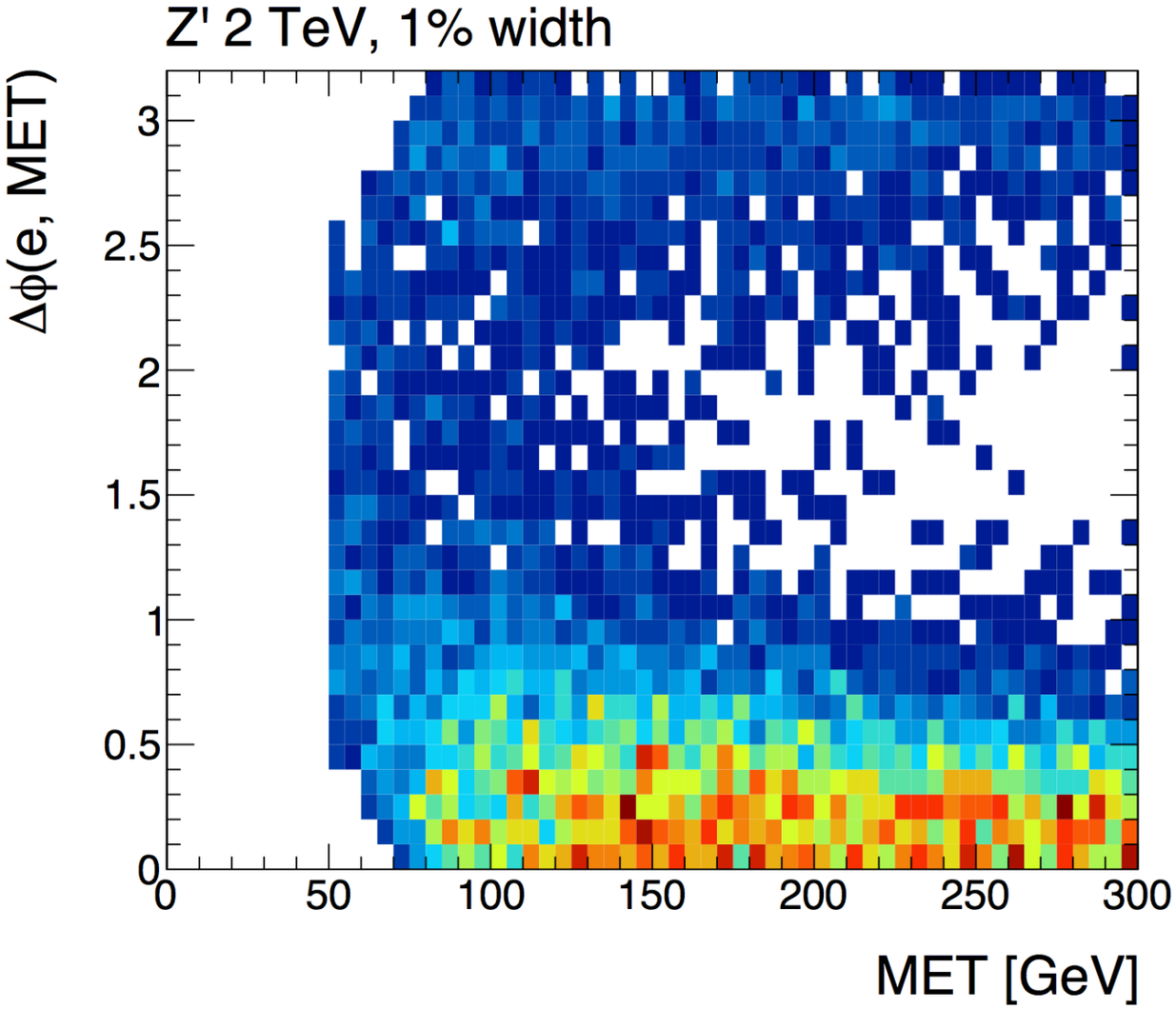
- Triangular Cuts (Electron Only)
  - $|\Delta\phi_{e\text{-}MET} - 1.5| < 1.5/75$ GeV x MET
  - $|\Delta\phi_{J_1\text{-}MET} - 1.5| < 1.5/75$ GeV x MET



$Z' \rightarrow t\bar{t}$ Semi-Lepton: Top Tagging

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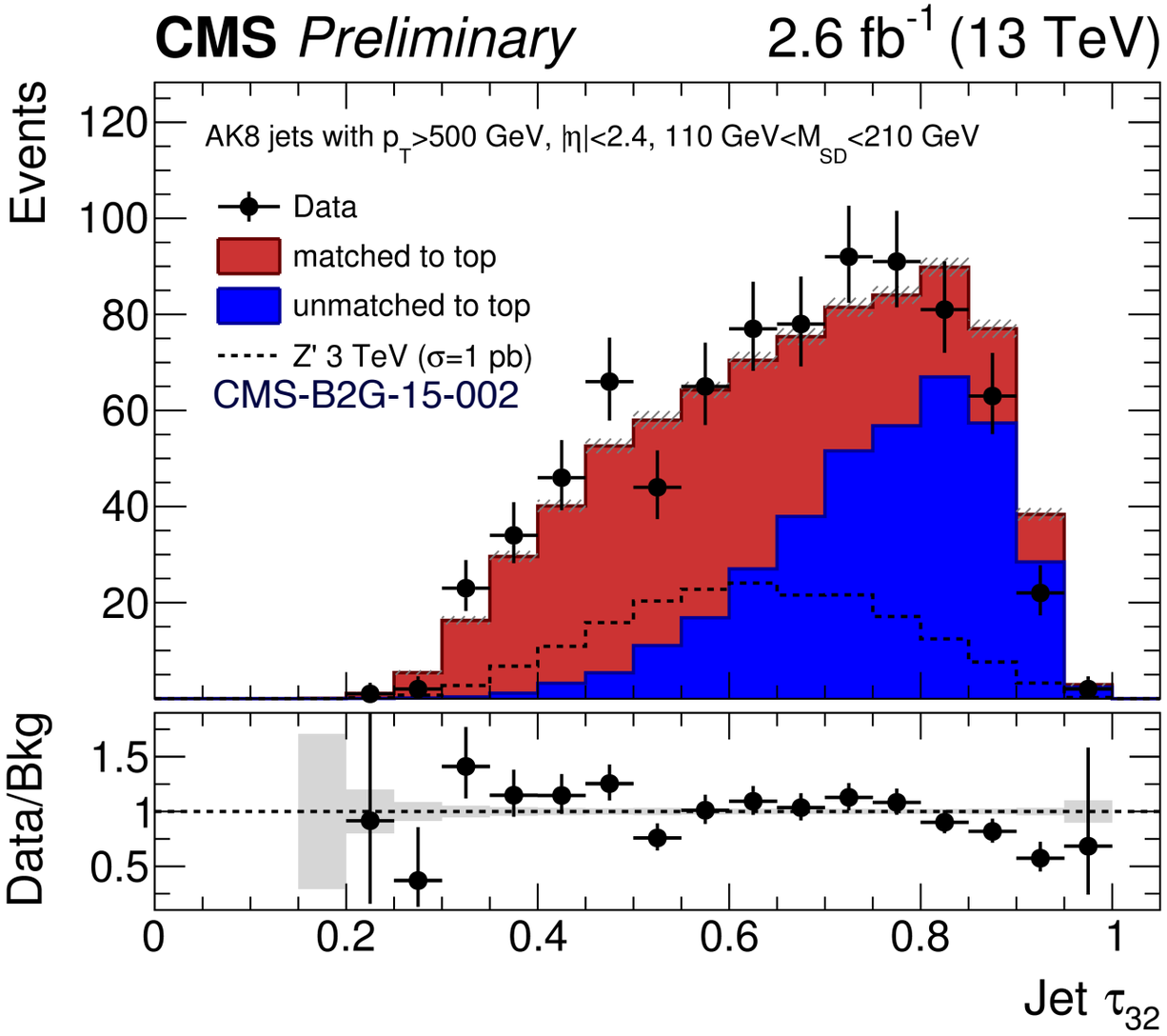
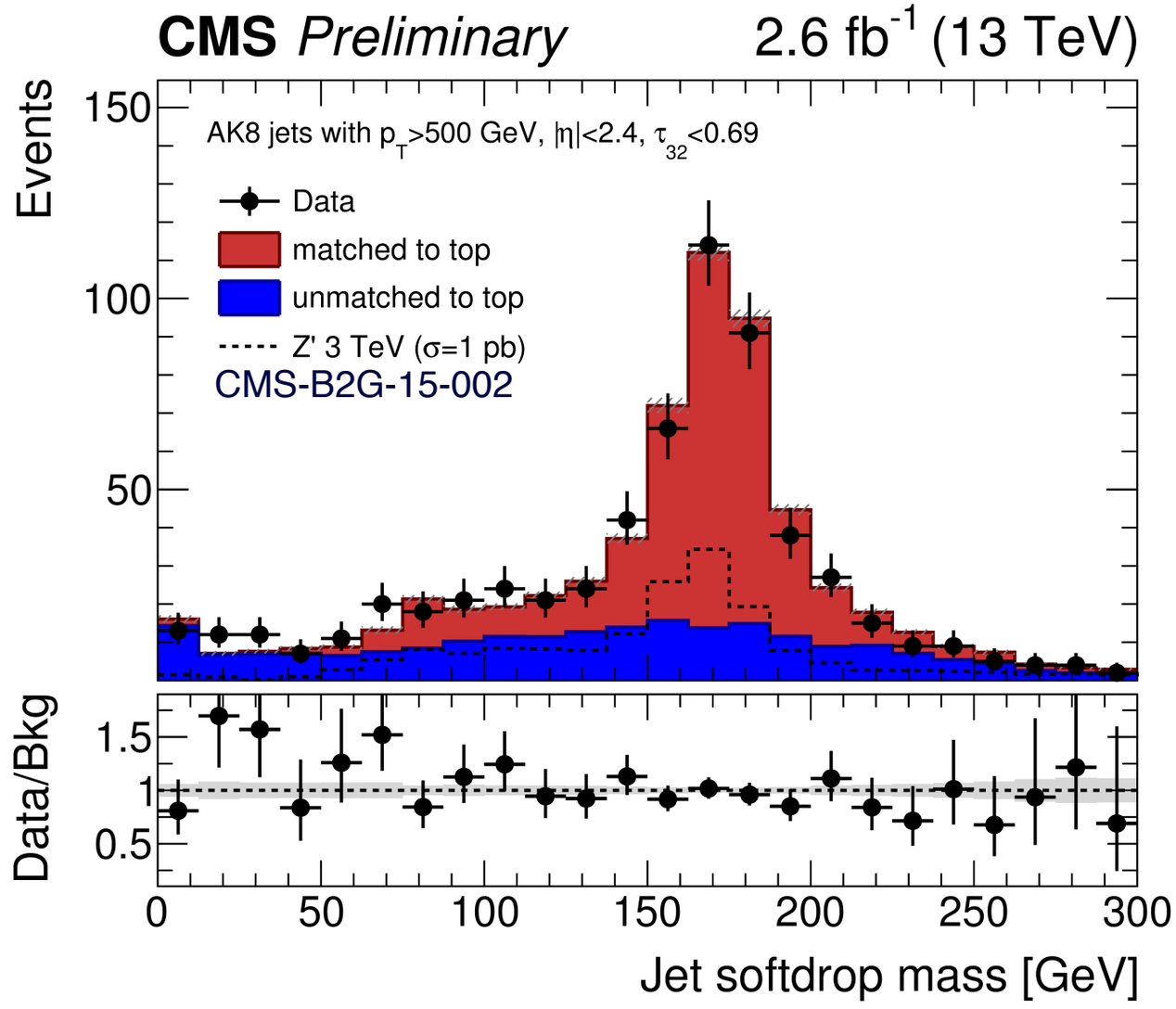
- $\tau 32$ and soft-drop mass for jet with $pT > 500$ GeV and $\chi^2 < 30$





$Z' \rightarrow t\bar{t}$ Semi-Lepton: χ^2

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- For the semi-leptonic top decay kinematic reconstruction is done from the MET, lepton momentum, and the W mass
  - The neutrino's p_z is calculated using these constraints
- The all hadronic top is fully reconstructable
  - In events without a top tag, only AK4 jets are used for the semi-leptonic and hadronic top reconstruction
  - In events with a top tag, the hadronic top is reconstructed from the top tagged AK8 jet and the semi-leptonic top is reconstructed from AK4 jets at least $\Delta R > 1.2$ from the top-tagged jet
- The χ^2 discriminator determines the best reconstruction hypothesis

$$\chi^2 = \left(\frac{M_{lep} - \overline{M}_{lep}}{\sigma_{M_{lep}}} \right)^2 + \left(\frac{M_{had} - \overline{M}_{had}}{\sigma_{M_{had}}} \right)^2$$

$Z' \rightarrow t\bar{t}$ Semi-Lepton: χ^2

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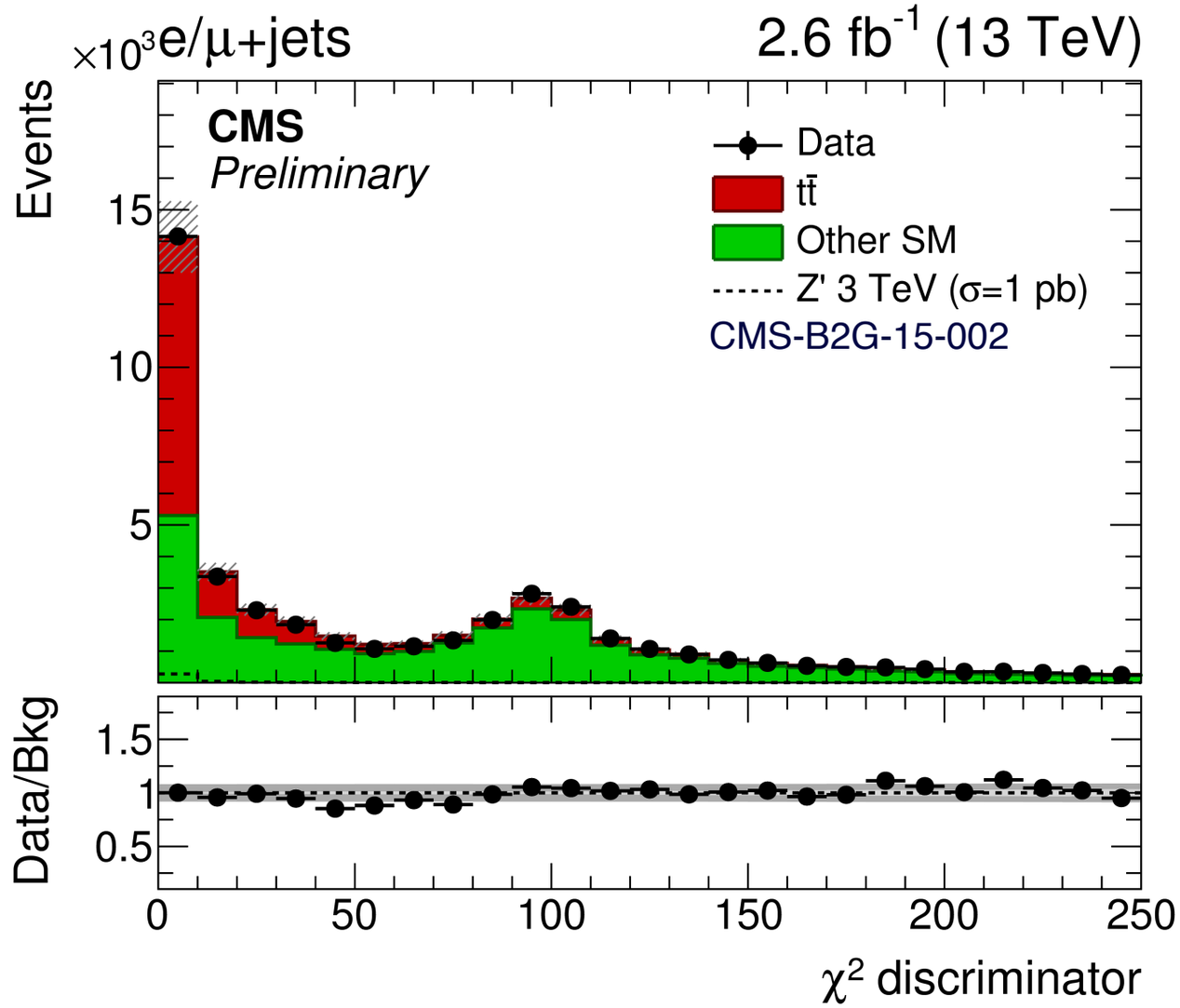
- M_{lep} and M_{had} are calculated on a per event bases
- $\bar{M}_{lep}$, $\bar{M}_{had}$, $\sigma_{M_{lep}}$, and $\sigma_{M_{had}}$ are calculated using MC
- Peak near 100 is due to W+2 jet and 3 jet events where M_{Tlep} is near $\bar{M}_{lep}$



$Z' \rightarrow t\bar{t}$ Semi-Lepton: Jet Distribution

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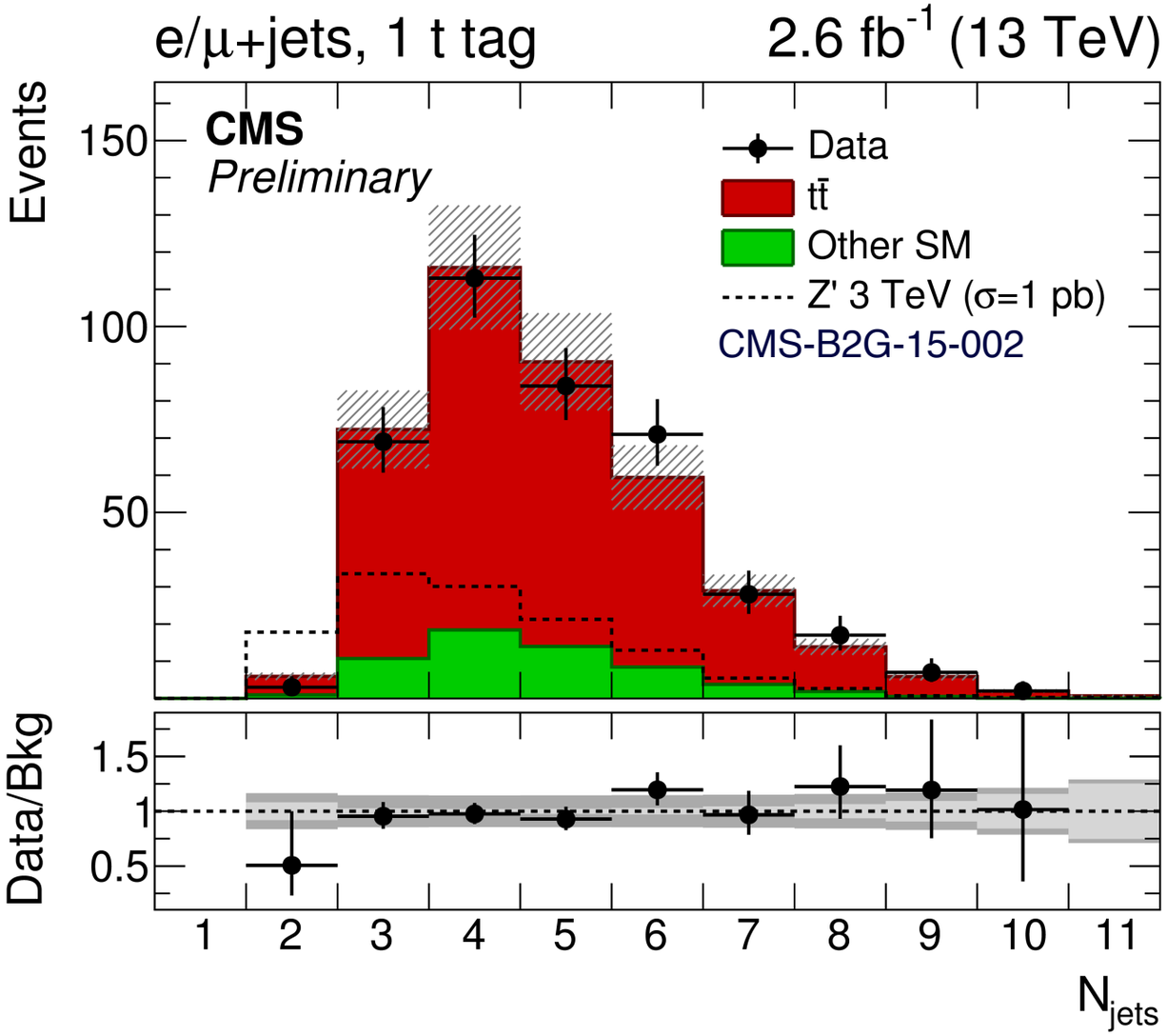
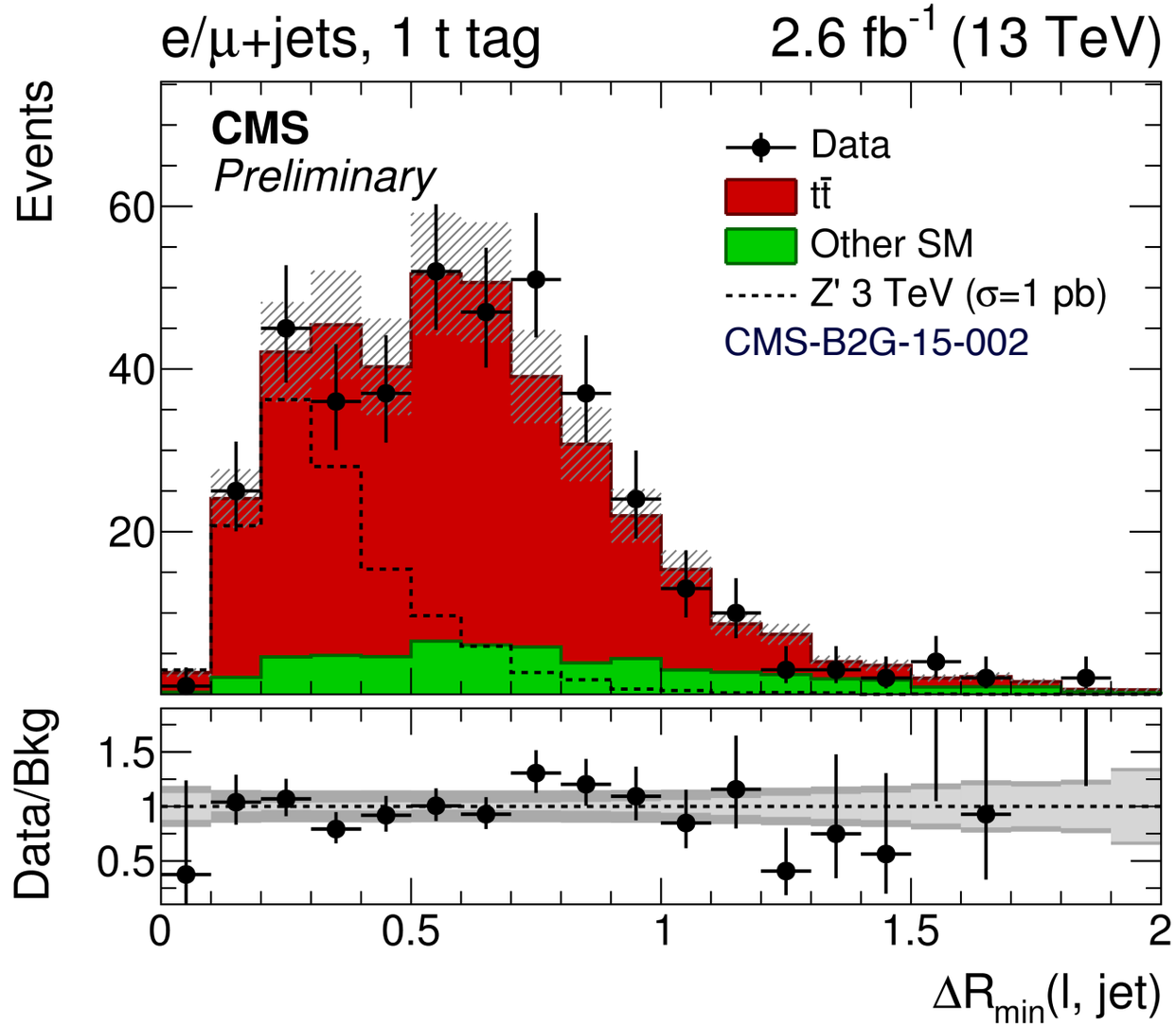
- The jet multiplicity and η distribution is well modeled by MC
  - Below plots are for the 1 top-tagged category





Z′→tt̄ Semi-Lepton: Signal Efficiency

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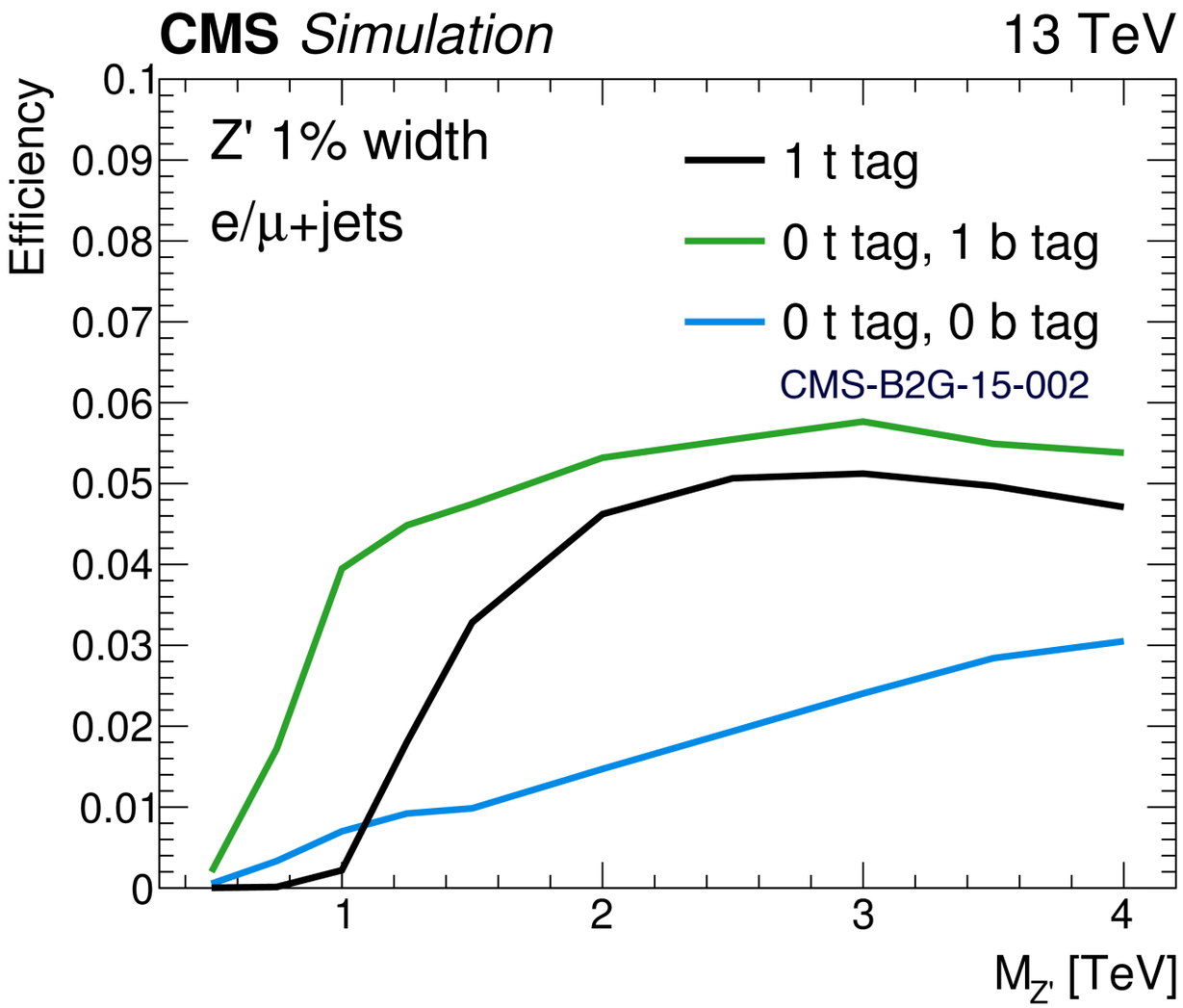
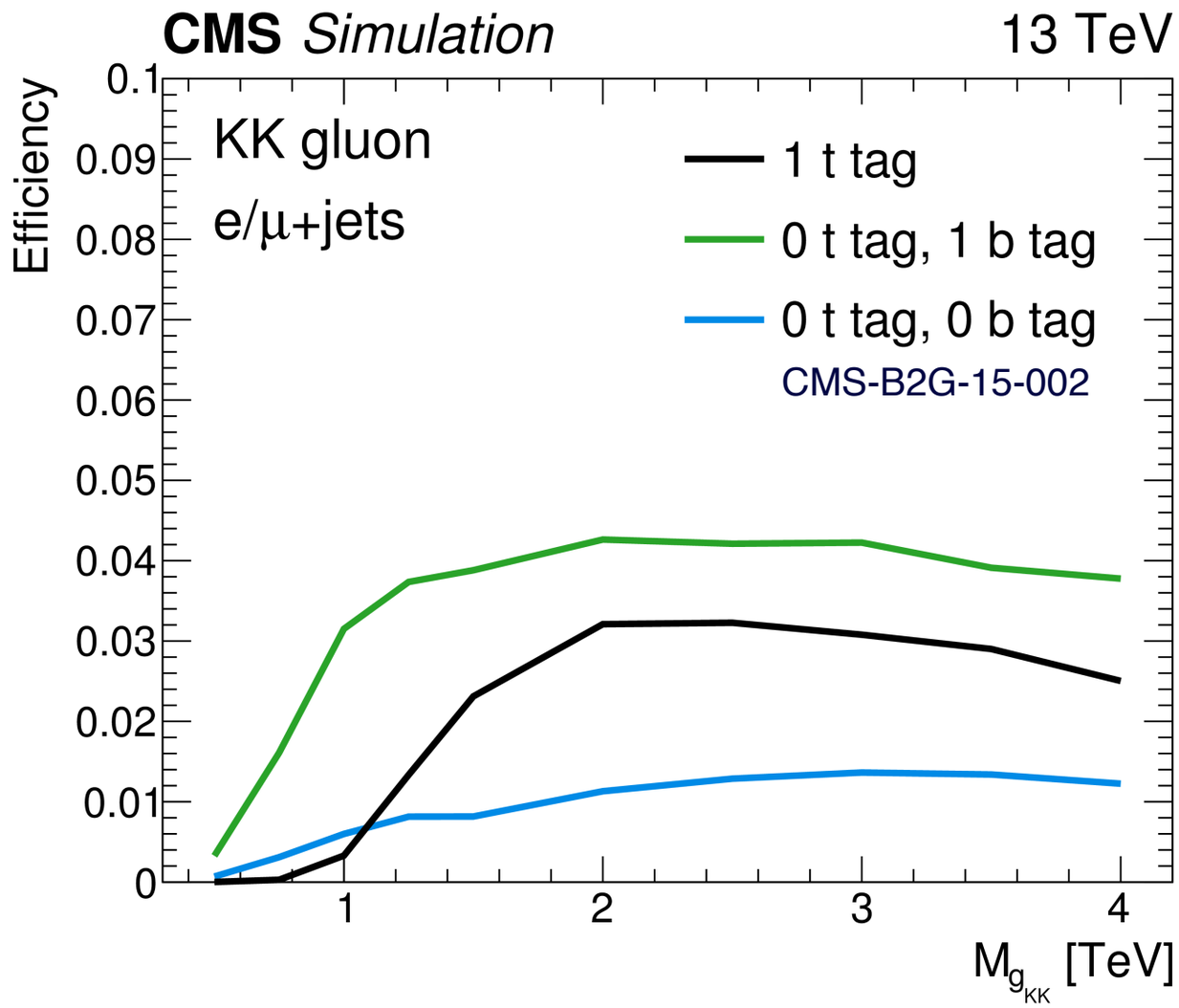
- Combined signal efficiency of the 1% Z′ and g_{KK} signal samples for all three categories





$Z' \rightarrow t\bar{t}$ Semi-Lepton: Data Distribution

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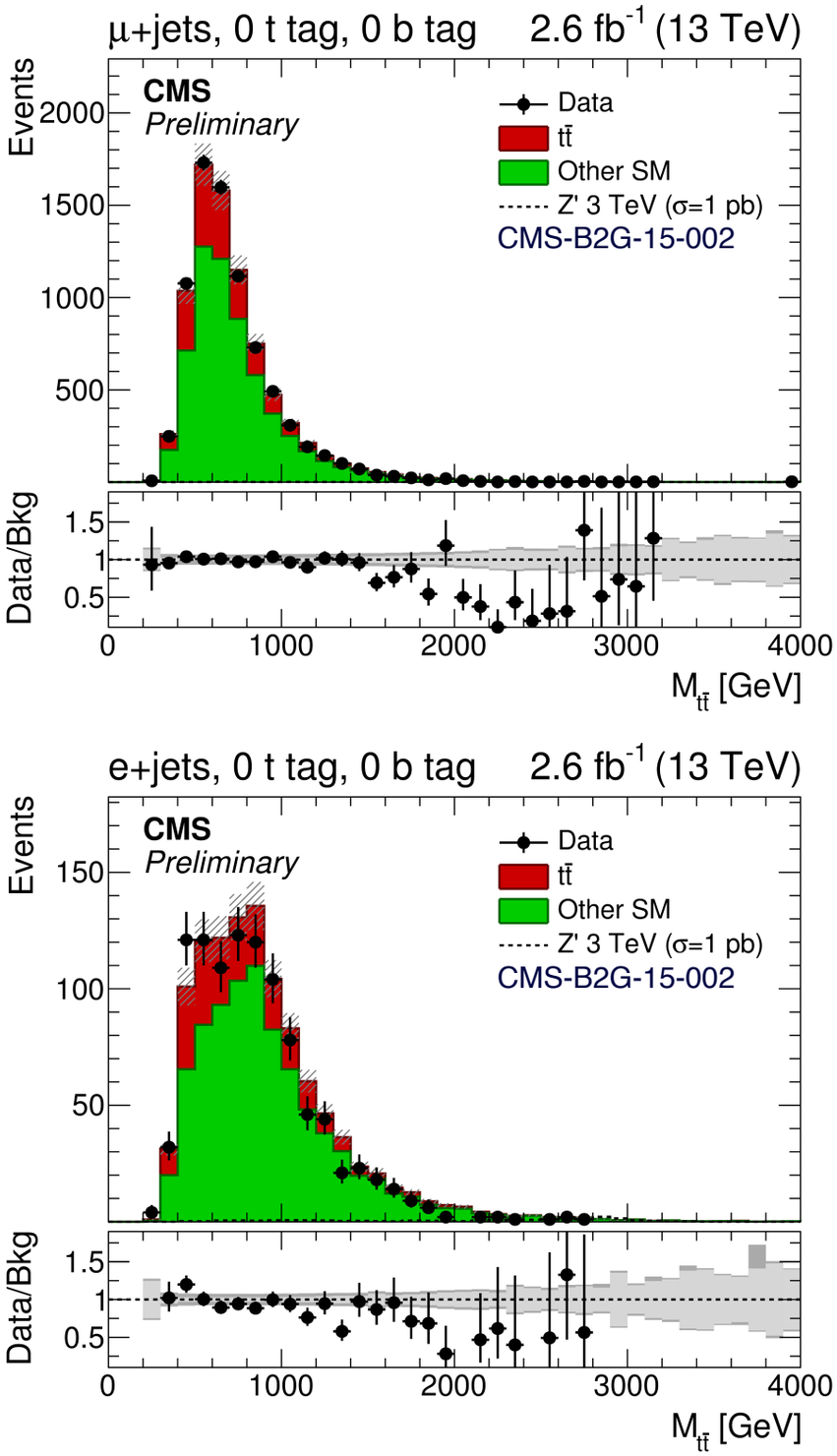

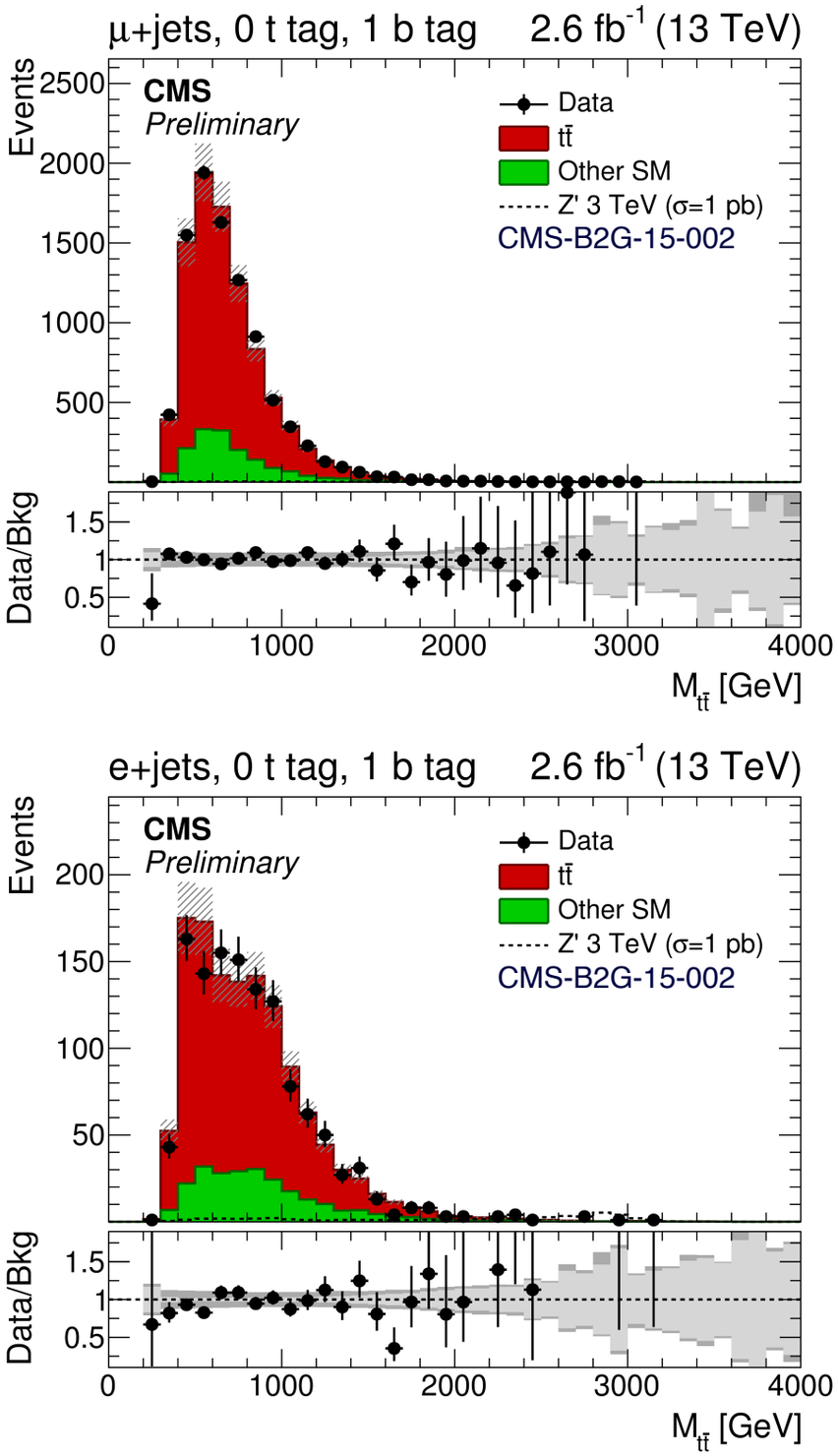

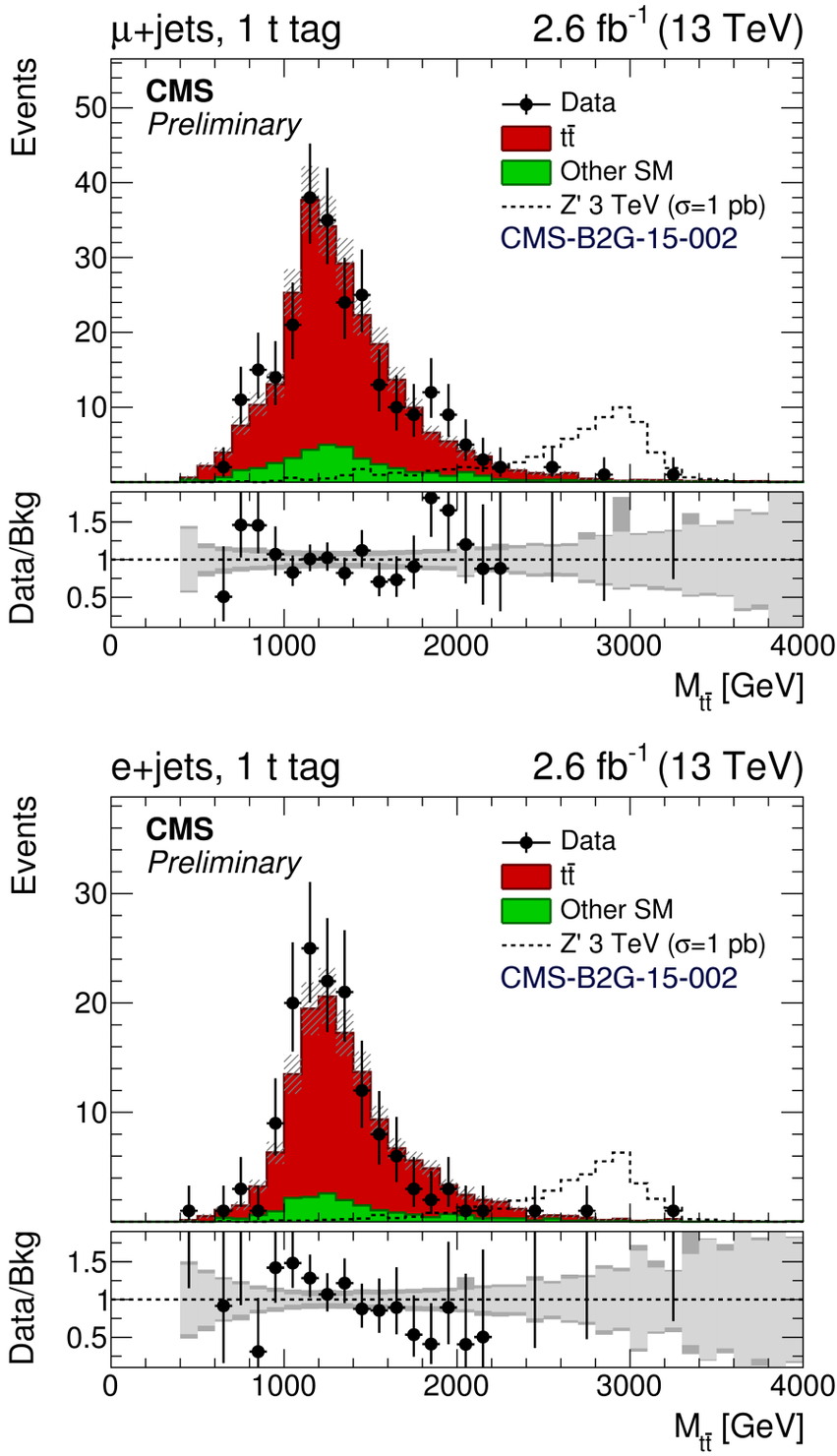

Z′→tt̄ Semi-Lepton: Event Yields

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μ + jets signal region			CMS-B2G-15-002
	1 t tag	0 t tag, 1 b tag	0 t tag, 0 b tag
$t\bar{t}$	218 ± 28	7602 ± 826	1965 ± 229
W + jets (light-f)	27 ± 4	547 ± 54	4675 ± 377
W + jets (heavy-f)	4 ± 1	333 ± 30	780 ± 65
single-top + DY + VV	9 ± 2	682 ± 111	635 ± 85
Total Background	258 ± 29	9164 ± 856	8055 ± 541
DATA	252	9230	7966

e + jets signal region			CMS-B2G-15-002
	1 t tag	0 t tag, 1 b tag	0 t tag, 0 b tag
$t\bar{t}$	119 ± 15	1016 ± 124	248 ± 32
W + jets (light-f)	13 ± 2	97 ± 10	684 ± 58
W + jets (heavy-f)	2 ± 1	44 ± 4	84 ± 8
single-top + DY + VV	4 ± 1	103 ± 18	74 ± 10
Total Background	138 ± 16	1260 ± 129	1090 ± 78
DATA	142	1217	1005

$Z' \rightarrow t\bar{t}$ Semi-Lepton: Systematics

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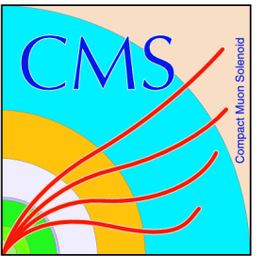
CMS-B2G-15-002

	1 t tag			0 t tag, 1 b tag			0 t tag, 0 b tag		
	$t\bar{t}$	W + jets	Z'	$t\bar{t}$	W + jets	Z'	$t\bar{t}$	W + jets	Z'
t- and b-tagging	6.7%	17.0%	7.3%	1.7%	3.6%	5.8%	6.1%	1.1%	12.1%
Scale uncertainty	4.1%	9.9%	–	5.3%	6.1%	–	5.7%	5.8%	–
PDF	2.7%	4.8%	4.2%	1.5%	3.6%	4.2%	1.8%	3.2%	4.8%



$Z' \rightarrow t\bar{t}$ Semi-Lepton: Limits

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Signal Model	μ+jets channel	e+jets channel	e/μ combination
Z′ (1%)	0.541 - 1.785 (0.606 - 1.901)	0.980 - 1.139 1.335 - 2.159 (0.924 - 1.678)	0.637 - 2.251 (0.591 - 2.140)
Z′ (10%)	0.500 - 3.193 (0.500 - 3.347)	0.500 - 3.153 (0.500 - 3.161)	0.500 - 3.432 (0.500 - 3.540)
Z′ (30%)	0.500 - 3.938 (0.500 - 3.998)	0.500 - 3.818 (0.500 - 3.756)	0.500 - 4.000 (0.500 - 4.000)
G_{kk}	0.500 - 2.737 (0.500 - 2.754)	0.608 - 2.746 (0.630 - 2.523)	0.500 - 2.878 (0.500 - 2.945)

$Z' \to t\bar{t}$ Semi-Lepton: Full Limits

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Z' boson with 1% relative width — CMS-B2G-15-002

$M_{Z'}$ [TeV]	Expected [pb]	Expected $\pm1\sigma$ [pb]	Expected $\pm2\sigma$ [pb]	Observed [pb]
0.5	86.2	150.8 – 49.3	264.8 – 32.4	95.6
0.75	6.2	8.7 – 4.4	12.1 – 3.2	8.4
1.0	1.50	2.07 – 1.06	2.85 – 0.78	2.16
1.25	0.66	0.98 – 0.47	1.32 – 0.34	1.02
1.5	0.39	0.56 – 0.28	0.76 – 0.19	0.37
2.0	0.149	0.221 – 0.104	0.302 – 0.077	0.143
2.5	0.081	0.121 – 0.056	0.167 – 0.042	0.063
3.0	0.059	0.086 – 0.041	0.123 – 0.032	0.097
3.5	0.049	0.075 – 0.035	0.116 – 0.025	0.047
4.0	0.044	0.063 – 0.031	0.093 – 0.024	0.035

Z' boson with 10% relative width — CMS-B2G-15-002

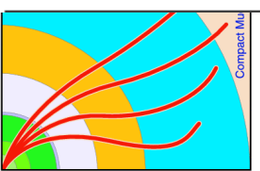
$M_{Z'}$ [TeV]	Expected [pb]	Expected $\pm1\sigma$ [pb]	Expected $\pm2\sigma$ [pb]	Observed [pb]
0.5	74.6	120.8 – 41.9	191.4 – 26.2	33.0
0.75	8.0	12.0 – 5.5	17.7 – 4.0	10.9
1.0	2.09	2.98 – 1.49	4.07 – 1.11	3.74
1.25	0.89	1.29 – 0.63	1.82 – 0.45	1.38
1.5	0.53	0.76 – 0.37	1.04 – 0.27	0.56
2.0	0.21	0.31 – 0.15	0.46 – 0.11	0.20
2.5	0.129	0.189 – 0.090	0.258 – 0.064	0.092
3.0	0.095	0.139 – 0.067	0.204 – 0.051	0.125
3.5	0.088	0.132 – 0.061	0.190 – 0.046	0.103
4.0	0.092	0.142 – 0.063	0.210 – 0.048	0.076

Z' boson with 30% relative width — CMS-B2G-15-002

$M_{Z'}$ [TeV]	Expected [pb]	Expected $\pm1\sigma$ [pb]	Expected $\pm2\sigma$ [pb]	Observed [pb]
1.0	2.8	4.0 – 1.9	5.5 – 1.4	3.9
2.0	0.35	0.52 – 0.25	0.75 – 0.18	0.30
3.0	0.196	0.297 – 0.135	0.442 – 0.099	0.220
4.0	0.195	0.305 – 0.132	0.483 – 0.095	0.180

KK gluon resonance in RS model — CMS-B2G-15-002

$M_{g_{KK}}$ [TeV]	Expected [pb]	Expected $\pm1\sigma$ [pb]	Expected $\pm2\sigma$ [pb]	Observed [pb]
0.5	73.4	137.1 – 40.7	197.4 – 26.1	52.3
0.75	11.3	17.9 – 7.3	26.5 – 5.0	17.2
1.0	2.8	4.0 – 1.9	5.5 – 1.4	5.3
1.25	1.33	1.92 – 0.88	2.79 – 0.65	2.28
1.5	0.79	1.19 – 0.53	1.67 – 0.37	0.84
2.0	0.36	0.52 – 0.23	0.76 – 0.17	0.30
2.5	0.22	0.33 – 0.15	0.47 – 0.11	0.17
3.0	0.181	0.269 – 0.125	0.383 – 0.093	0.222
3.5	0.190	0.281 – 0.129	0.423 – 0.099	0.185
4.0	0.22	0.36 – 0.15	0.61 – 0.11	0.19



$Z' \rightarrow t\bar{t}$ All Hadronic: Data and MC Samples

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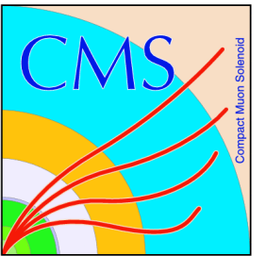
- Z' MC generated in MADGRAPH and NLO cross-sections taken from R. Bonciani et al. Parton showering done in PYTHIA and shower matching done using the MLM-algorithm
- PYTHIA8 used to g_{KK} sample and LO cross-sections from PYTHIA multiplied by a k-factor of 1.3
- $t\bar{t}$ sample generated with POWHEG.
- QCD is modeled from a data driven approach
  - Closure test done on QCD MC generated using POWHEG

Dataset	$L_{Int}[pb^{-1}]$
/JetHT/Run2015D-PromptReco-v4/MINIAOD	1669
/JetHT/Run2015D-05Oct2015-v1/MINIAOD	925



$Z' \rightarrow t\bar{t}$ All Hadronic: Event Selection

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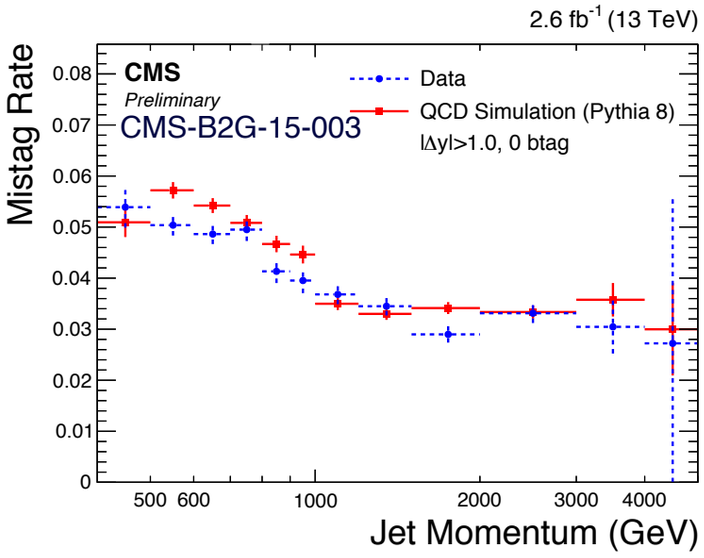
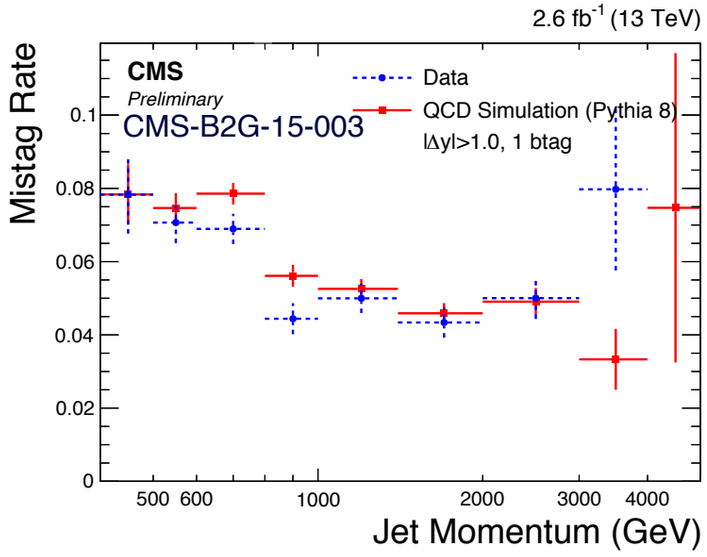
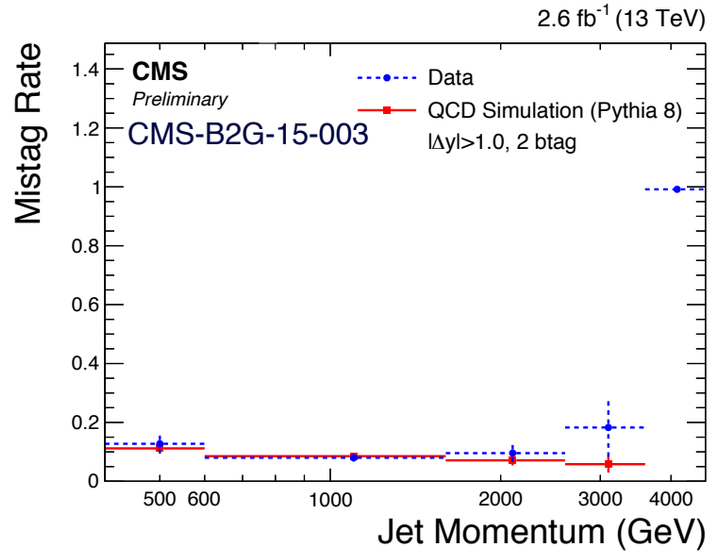
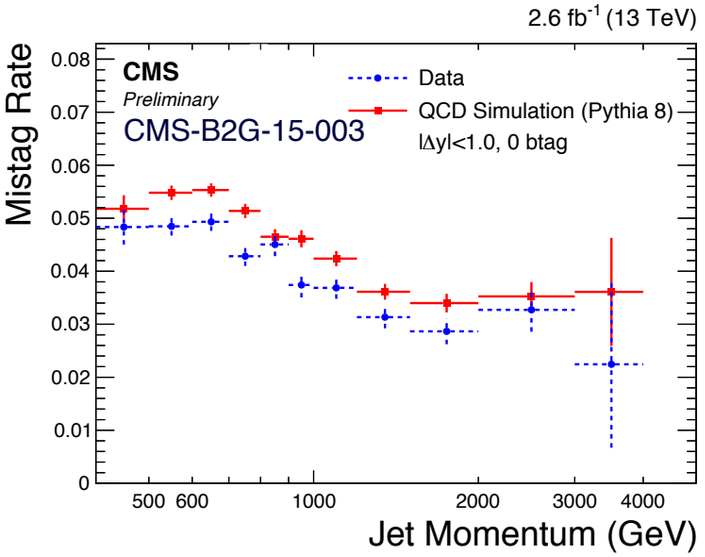
- Pass Particle Flow $H_T > 800$ Trigger
- $p_{Tj1}+p_{Tj2} > 1000$ GeV
- 2 AK8 Jets with
  - pT > 400 GeV with |y| < 2.4
  - $M_{jet} > 120$ GeV
  - Sub-jet b-tag ($CSV_{V2} > 0.89$)
  - Pass CMS Top Tagger V2
  - $|\Delta\phi| > 2.1$
- CMS Top Tagger V2
  - pT > 400 GeV
  - |y| < 2.4
  - $110 < M_{SD} < 210$
  - $\tau_{32} < 0.69$

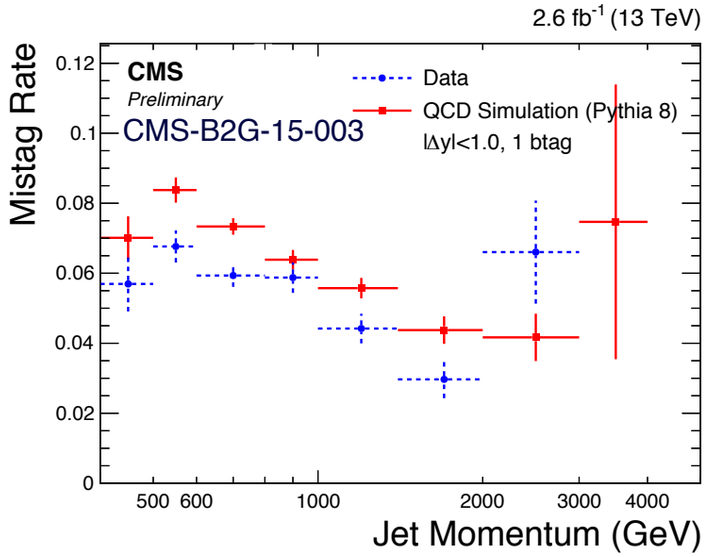
Z′→tt̄ All Hadronic: CMSTTv2 Mis-tag Rate

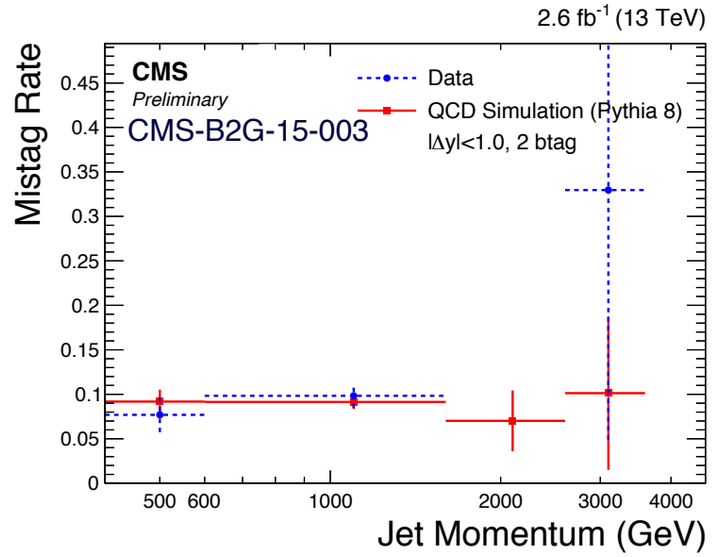












$Z' \to t\bar{t}$ All Hadronic: Systematics

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Systematic Uncertainty Source	Value	Type
Jet b-tag Efficiency	$\pm 1\sigma$	Rate + Shape
Jet t-tag Efficiency	20%	Rate
Jet Energy Scale	$\pm 1\sigma$	Rate + Shape
Jet Energy Resolution	$\pm 1\sigma$	Rate + Shape
Integrated Luminosity Measurement	2.7%	Rate
Parton Distribution Functions	$\pm 1\sigma$	Rate + Shape
Pileup Reweighting	$\pm 1\sigma$	Rate + Shape
Mistag Rate Measurement	$\pm 1\sigma$	Rate + Shape
$t\bar{t}$ Matrix Element Scale	$\pm 1\sigma$	Rate + Shape
$t\bar{t}$ Parton Shower Scale	$\pm 1\sigma$	Rate + Shape
$t\bar{t}$ Cross Section	15%	Rate
NTMJ Jet Kinematics	$\pm 1\sigma$	Rate + Shape
NTMJ Closure Test	$\pm 1\sigma$	Rate + Shape

CMS-B2G-15-003

$Z' \to t\bar{t}$ All Hadronic: Event Yields

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CMS-B2G-15-003

$|\Delta y| > 1.0$

Process	0 b-tags	1 b-tag	2 b-tags
NTMJ	1291 ± 23	371 ± 12	31 ± 5.9
SM $t\bar{t}$	47 ± 9.4	82 ± 13	37 ± 7.9
Total Background	1338 ± 24	454 ± 17	68 ± 10
DATA	1300	441	78

CMS-B2G-15-003

$|\Delta y| < 1.0$

Process	0 b-tags	1 b-tag	2 b-tags
NTMJ	1321 ± 41	402 ± 14	36 ± 8.9
SM $t\bar{t}$	75 ± 16	142 ± 25	72 ± 17
Total Background	1396 ± 44	544 ± 29	108 ± 19
DATA	1414	596	124

$Z' \rightarrow t\bar{t}$ All Hadronic: Limits

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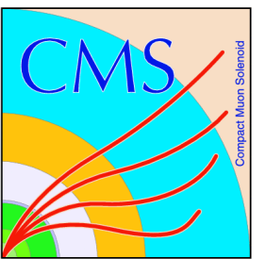
Mass Exclusion Limits

Signal Model CMS-B2G-15-003	Exclusion Ranges (TeV)	
	Expected	Observed
Z′ (1% Width)	1.2 – 1.6	1.4 – 1.6
Z′ (10% Width)	1.0 – 3.1	1.0 – 3.3
Z′ (30% Width)	1.0 – 3.7	1.0 – 3.8
RS Gluon	1.0 – 2.5	1 – 2.4



$Z' \rightarrow t\bar{t}$ All Hadronic: Limits Continued

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CMS-B2G-15-003

Z′ (1% Width) Signal Hypothesis

Mass (GeV)	Observed 95% CL Limit (pb)	Expected 95% CL Limits (pb)				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
1000	**12**	7.9	11	**16**	25	39
1250	**2.4**	0.74	1.0	**1.5**	2.2	3.0
1500	**0.6**	0.34	0.47	**0.68**	0.98	1.4
2000	**0.29**	0.14	0.19	**0.27**	0.39	0.56
2500	**0.18**	0.076	0.099	**0.15**	0.21	0.3
3000	**0.087**	0.065	0.086	**0.12**	0.18	0.25
3500	**0.061**	0.058	0.075	**0.11**	0.16	0.23
4000	**0.059**	0.053	0.071	**0.1**	0.15	0.31

CMS-B2G-15-003

Wide Z′ Signal Hypothesis

Mass (GeV)	Observed 95% CL Limit (pb)	Expected 95% CL Limits (pb)				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
1000	**15**	7.8	11	**18**	29	44
1250	**4.5**	1.3	2.0	**2.9**	4.3	5.8
1500	**1.2**	0.6	0.82	**1.2**	1.8	2.6
2000	**0.42**	0.2	0.27	**0.39**	0.58	0.84
2500	**0.27**	0.12	0.16	**0.22**	0.33	0.46
3000	**0.14**	0.1	0.14	**0.19**	0.28	0.4
3500	**0.12**	0.11	0.14	**0.19**	0.29	0.41
4000	**0.12**	0.11	0.14	**0.19**	0.29	0.48

$Z' \rightarrow t\bar{t}$ All Hadronic: Limits Continued

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CMS-B2G-15-003

Z′ (30% Width) Signal Hypothesis

Mass (GeV)	Observed 95% CL Limit (pb)	Expected 95% CL Limits (pb)				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
1000	**15**	5.1	7.7	**12**	19	28
2000	**0.82**	0.35	0.47	**0.66**	1	1.4
3000	**0.29**	0.2	0.27	**0.38**	0.55	0.83
4000	**0.28**	0.21	0.28	**0.39**	0.57	0.81

CMS-B2G-15-003

RS Gluon Signal Hypothesis

Mass (GeV)	Observed 95% CL Limit (pb)	Expected 95% CL Limits (pb)				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
1000	**17**	6.4	9.4	**14**	22	35
1250	**5.8**	2.0	2.7	**4.1**	6.0	8.6
1500	**2.7**	1.0	1.4	**1.9**	2.9	4.0
2000	**0.72**	0.34	0.46	**0.65**	0.92	1.3
2500	**0.5**	0.21	0.28	**0.39**	0.58	0.82
3000	**0.25**	0.17	0.24	**0.33**	0.49	0.72
3500	**0.22**	0.17	0.23	**0.32**	0.47	0.67
4000	**0.25**	0.20	0.27	**0.38**	0.55	0.8

$W'_R \rightarrow tb$: Data and MC Samples

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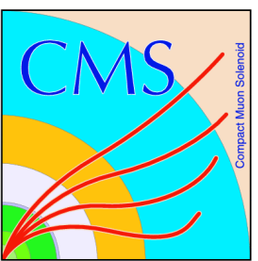
- W'_R sample generated using COMPHEP 4.5.2rc10 with a LO cross-section scaled by 1.2 and a width of 3%
- $t\bar{t}$ and tW samples generated with POWHEG
- S and t-channel single top samples generated with aMC@NLO
- DiBoson samples generated with PYTHIA at LO using scale factors of 1.82, 2.05, and 2.24 for WW, WZ, and ZZ cross-section, respectively
- Z+Jets sample generated in MADGRAPHv5 at NNLO and shower matching via PYTHIA8
- W+Jets (k=1.21) and QCD samples generated in MADGRAPHv5 and shower matching via PYTHIA8
  - QCD is enriched in electrons and muons using generator level filters

Datasets	$L_{Int}[pb^{-1}]$
/SingleMuon/Run2015C-05Oct2015-v1/MINIAOD	
/SingleMuon/Run2015D-05Oct2015-v1/MINIAOD	
/SingleMuon/Run2015D-PromptReco-v4/MINIAOD	2.215
/SingleElectron/Run2015C-05Oct2015-v1/MINIAOD	
/SingleElectron/Run2015D-05Oct2015-v1/MINIAOD	
/SingleElectron/Run2015D-PromptReco-v4/MINIAOD	2.215



$W'_R \rightarrow tb$: Event Selection

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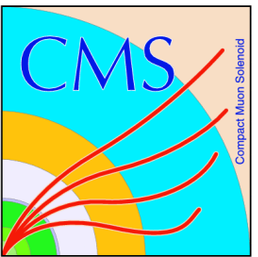
- Muon Channel
  - HLT_Mu45_eta2p1 Trigger
  - $p_T > 180$ GeV and $|\eta| < 2.1$
    - Veto additional leptons with $p_T > 35$ GeV
  - Jet_{Lead} $p_T > 450$ GeV
  - $Jet_{SubLead}$ $p_T > 30$ GeV
    - $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 50$ GeV
    - MET > 50 GeV
- Top Selection
  - 100 GeV < M_{Top} < 250GeV
  - $p_{TTop} > 250$ GeV
  - $p_{Tj1} + p_{Tj2} > 350$ GeV
- Electron Channel
  - HLT_Ele105_CaloIdVT_GsfTrkIdT Trigger
  - $p_T > 180$ GeV and $|\eta| < 2.5$
    - Veto additional leptons with $p_T > 35$ GeV
  - Jet_{Lead} $p_T > 350$ GeV
  - $Jet_{SubLead}$ $p_T > 30$ GeV
  - $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 60$ GeV
  - MET > 120 GeV
  - $|\Delta\phi(_{MET,e})| < 2$



$W'_R \rightarrow tb$: Event Yields (Muon)

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CMS-B2G-15-004

Process	Number of Events					
	Object Selection				Final Selection	
	≥ 0 b-tags	$= 0$ b-tags	$= 1$ b-tags	$= 2$ b-tags	$= 1$ b-tags	$= 2$ b-tags
Data:	770	431	281	58	143	30
Background:						
$t\bar{t}$	124	36	64	25	46	16
tqb	7	2	4	1	3	1
tW	17	5	9	3	4	1
$\bar{t}W$	16	3	9	4	5	2
tb	1	0	0	0	0	0
$W(\rightarrow \ell\nu)$+jj	304	218	80	6	25	1
$W(\rightarrow \ell\nu)$+bb/cc	283	132	128	23	45	7
$Z(\rightarrow \ell\ell)$+jets	47	26	21	0	12	0
VV	20	17	3	0	0	0
Total Background	819±60	439±36	318±24	62±5	140±11	28±3

$W'_R \rightarrow tb$: Event Yields (Electron)

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CMS-B2G-15-004

Process	Number of Events					
	Object Selection				Final Selection	
	≥ 0 b-tags	$= 0$ b-tags	$= 1$ b-tags	$= 2$ b-tags	$= 1$ b-tags	$= 2$ b-tags
Data:	802	435	309	58	256	44
Background:						
$t\bar{t}$	132	40	68	24	52	17
tqb	8	2	5	2	4	1
tW	22	5	11	6	10	5
$\bar{t}W$	20	4	11	4	9	4
tb	1	0	1	0	1	0
$W(\rightarrow \ell\nu)$+jj	359	262	89	8	77	7
$W(\rightarrow \ell\nu)$+bb/cc	306	146	139	22	119	18
$Z(\rightarrow \ell\ell)$+jets	9	8	3	-1	4	-1
VV	26	17	9	0	7	0
Total Background	883±83	484±50	336±32	65±7	283±22	51±5

$W'_R \rightarrow tb$: Systematics

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CMS-B2G-15-004

Source	Rate Uncertainty	Shape?
Luminosity	4.6%	No
Trigger Efficiency (e/μ)	4%/2%	No
Lepton ID Efficiency (e/μ)	5%/2%	No
Jet Energy Scale	$\pm\sigma(p_T, \eta)$	Yes
Jet Energy Resolution	$\pm\sigma(p_T, \eta)$	Yes
b/c-tagging	$\pm\sigma(p_T, \eta)$	Yes
light quark mis-tagging	$\pm\sigma(p_T, \eta)$	Yes
PDF	$\pm\sigma(p_T, \eta)$	Yes
Renormalization and factorization Q^2 scale	$2Q^2$ and $0.5Q^2$	Yes

T→tH Search

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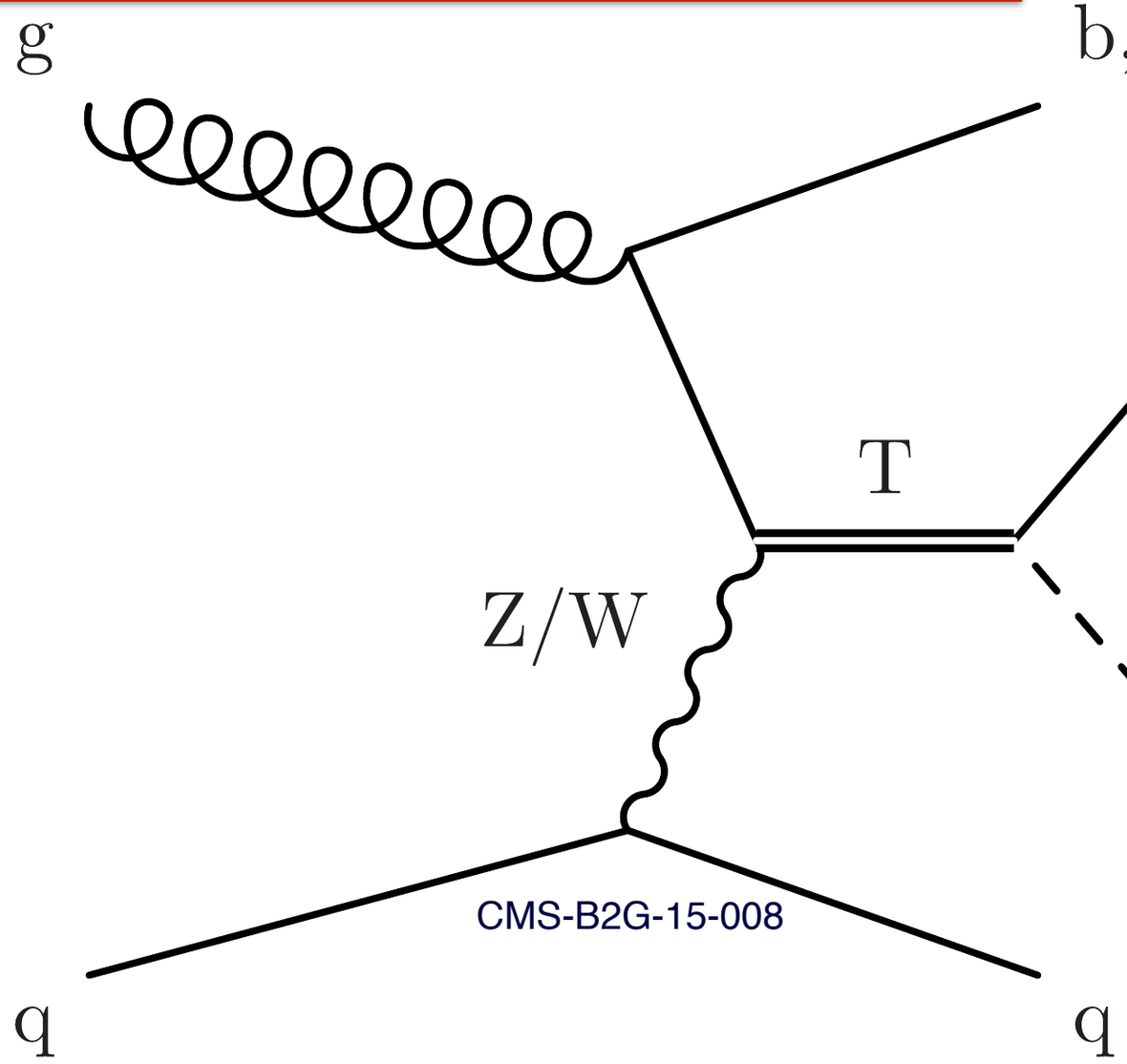
- Heavy vector-like quarks are common in many extensions to the standard model
  - Little and composite Higgs and extra dimension models
  - In these models, T quarks decay primarily to tH, tZ, and bW
- This search will focus on the tH decay mode
  - Explicit limits set for both b and t associated production
  - Explicit limits set for right and left-handed vector-like T-quarks



T→tH Semi-Leptonic Channel

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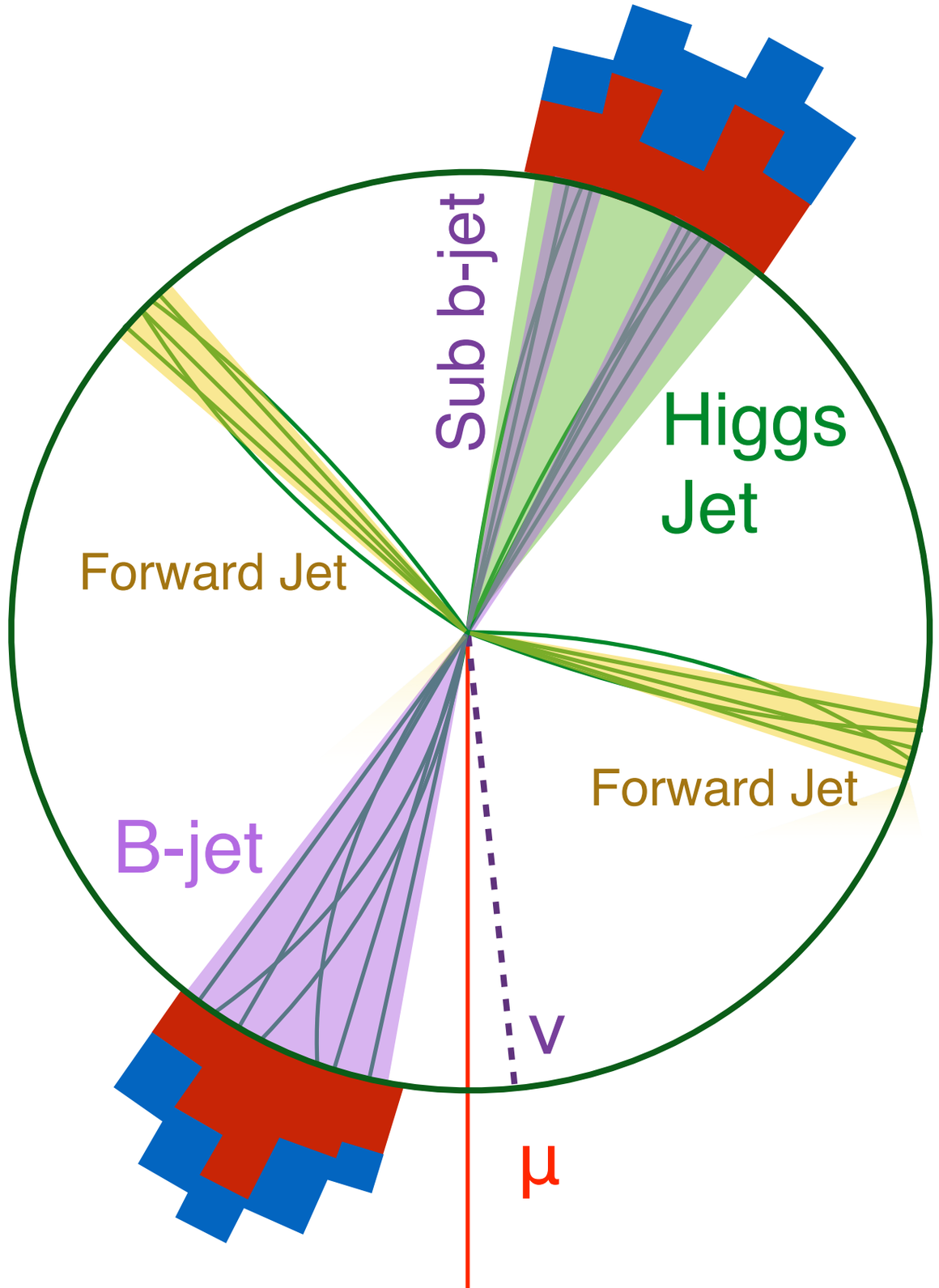
- Requires one lepton
- 2D-isolation cut is applied to the lepton
- Two jets, one with high p_T
  - One additional forward jet
- Selection on scaler sum of MET, lead lepton, and jets
- One angularly separated Higgs candidate with two sub-jet b-tags
- T mass is reconstructed using a χ^2 minimization technique using
  - Higgs candidates
  - Top quark candidates that are reconstructed from a W candidate and up to two central jets
    - Where the Z component of MET is calculated using M_{TLep} and M_W (80.4 GeV)
  - Top and Higgs must be angularly separated in ΔR
- High p_T reconstructed top quark



T→tH Semi-Leptonic Results

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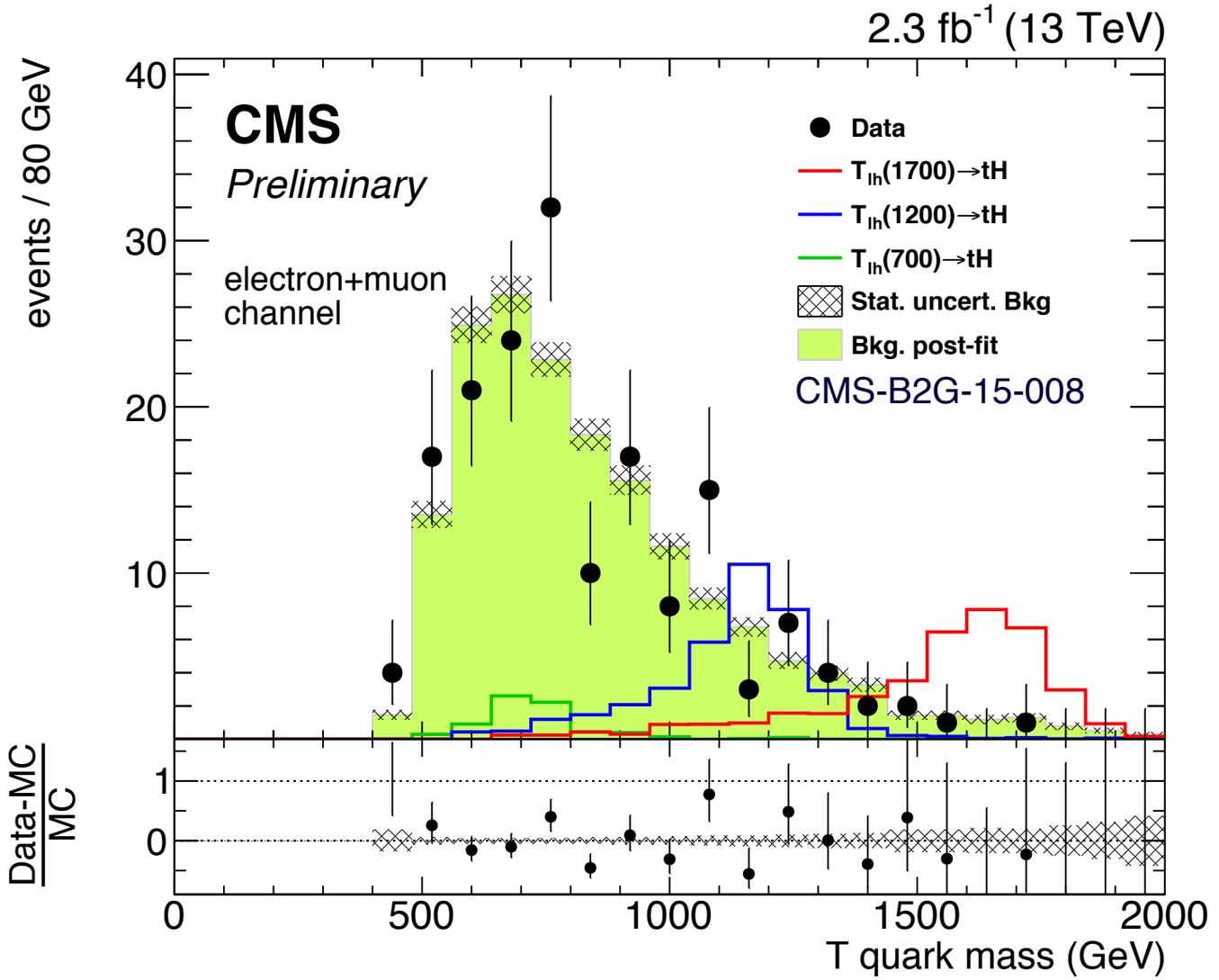
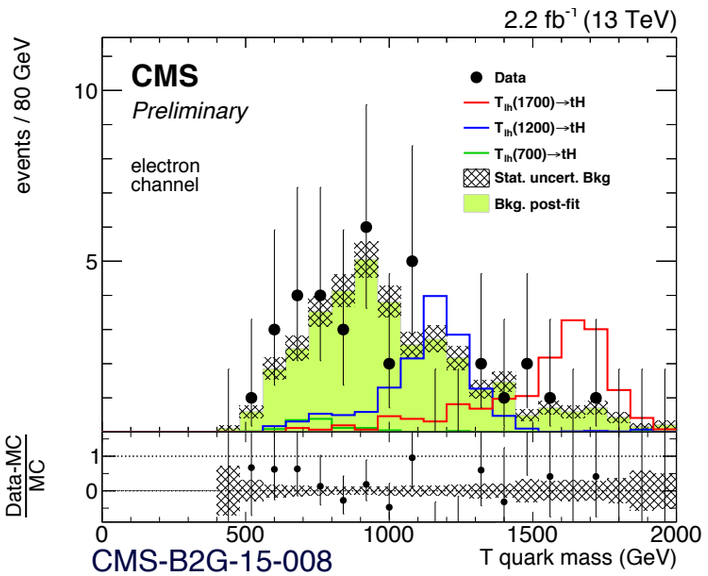
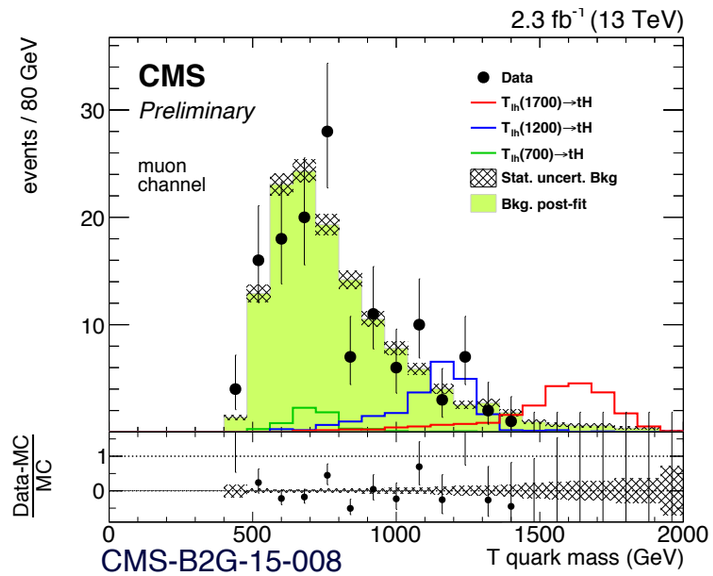
- Observed data is consistent with the standard model
  - MC scaled to best-fit cross-section
- Limits are derived using a Bayesian statistical method
- Tb production has a branching fraction of 50/25/25% to bW/tZ/tH
- Tt production has a branching fraction of 0/50/50% to bW/tZ/tH







T→tH Semi-Leptonic Results

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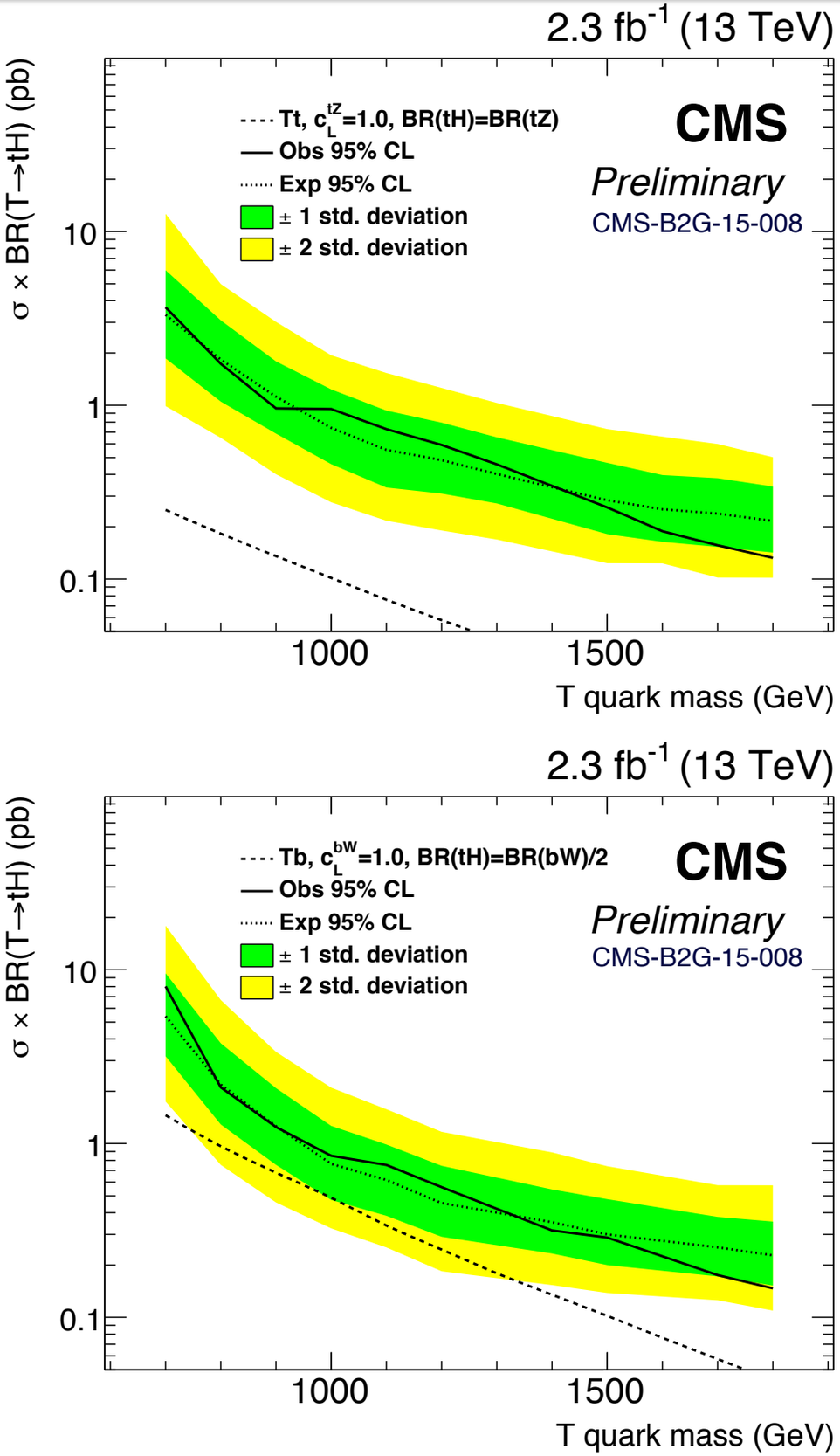

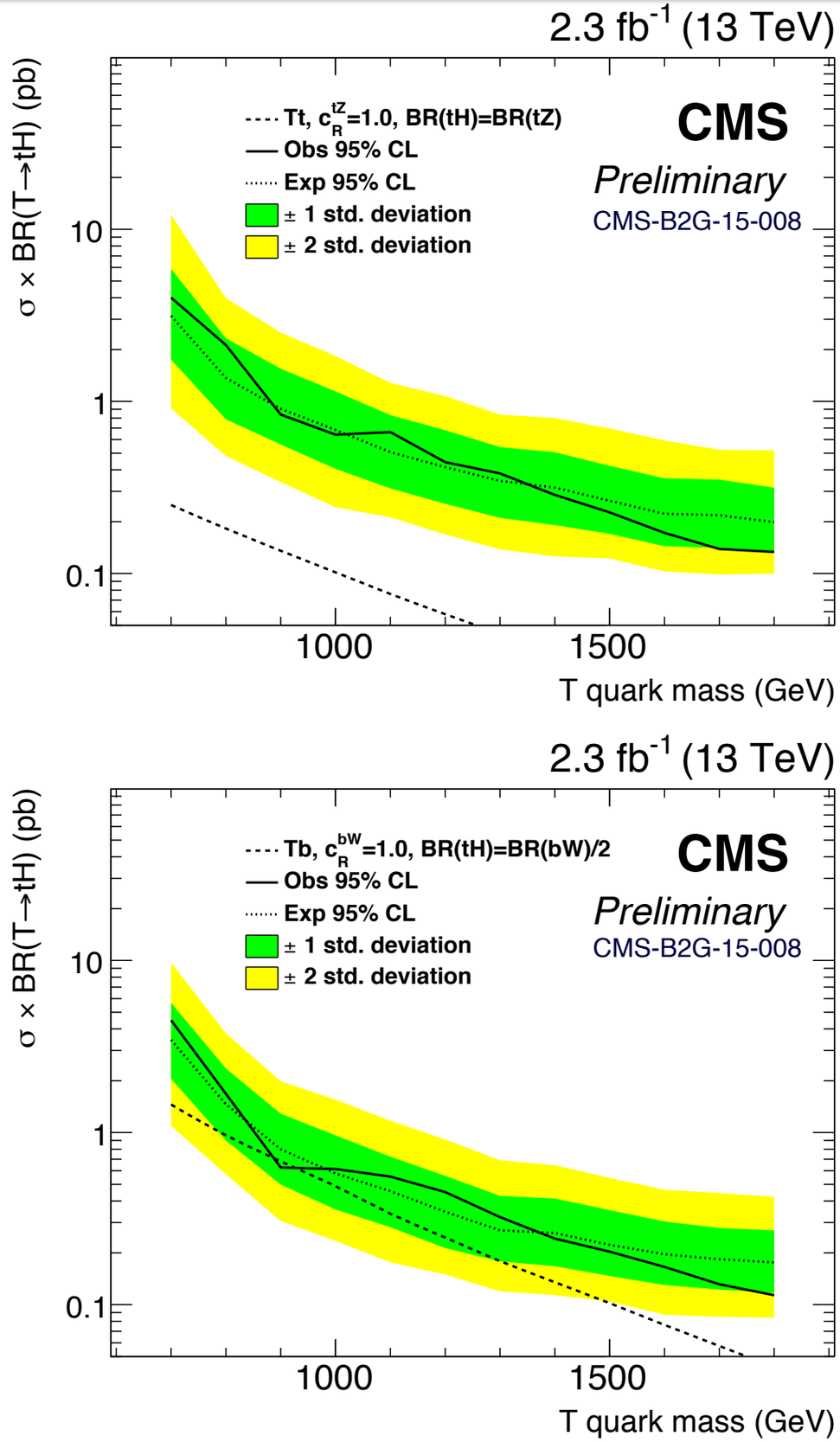

T→tH: Data and MC Samples

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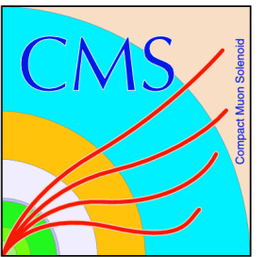
- T sample generated in MADGRAPH and parton shower matching done in PYTHIA8
- $t\bar{t}$ and tW samples generated with POWHEG
- S and t-channel single top samples generated with aMC@NLO
- W+Jets, Drell-Yan+Jets, and QCD samples generated in MADGRAPHv5 and shower matching via PYTHIA8
- QCD is enriched in electrons and muons using generator level filters

Datasets	$L_{Int}[pb^{-1}]$
/SingleMuon/Run2015D-05Oct2015-v1/MINIAOD	
/SingleMuon/Run2015D-PromptReco-v4/MINIAOD	2.225
/SingleElectron/Run2015C-05Oct2015-v1/MINIAOD	
/SingleElectron/Run2015D-PromptReco-v4/MINIAOD	2.318



T→tH: Event Selection

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- Muon Channel
- HLT_Mu45_eta2p1 Trigger
- $p_T > 47$ GeV and $|\eta| < 2.1$
- Jet_{Lead} $p_T > 100$ GeV
- $Jet_{SubLead}$ $p_T > 50$ GeV
- $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 40$ GeV
- $S_T > 400$ GeV
- $\Delta R_{(t,H)} > 2$
- $p_{TTop} > 100$ GeV
- 90 GeV $< M_H <$ 160 GeV

- Electron Channel
- HLT_Ele45_CaloIdVT_GsfTrkIdT_PFJet200_PFJet50 Trigger
- $p_T > 50$ GeV and $|\eta| < 2.5$
- Jet_{Lead} $p_T > 250$ GeV
- $Jet_{SubLead}$ $p_T > 70$ GeV
- $\Delta R_{(l,j)} > 0.4$ or $p_{Trel} > 40$ GeV
- $S_T > 400$ GeV
- $\Delta R_{(t,H)} > 2$
- $p_{TTop} > 100$ GeV
- 90 GeV $< M_H <$ 160 GeV

T→tH: Baseline Distributions

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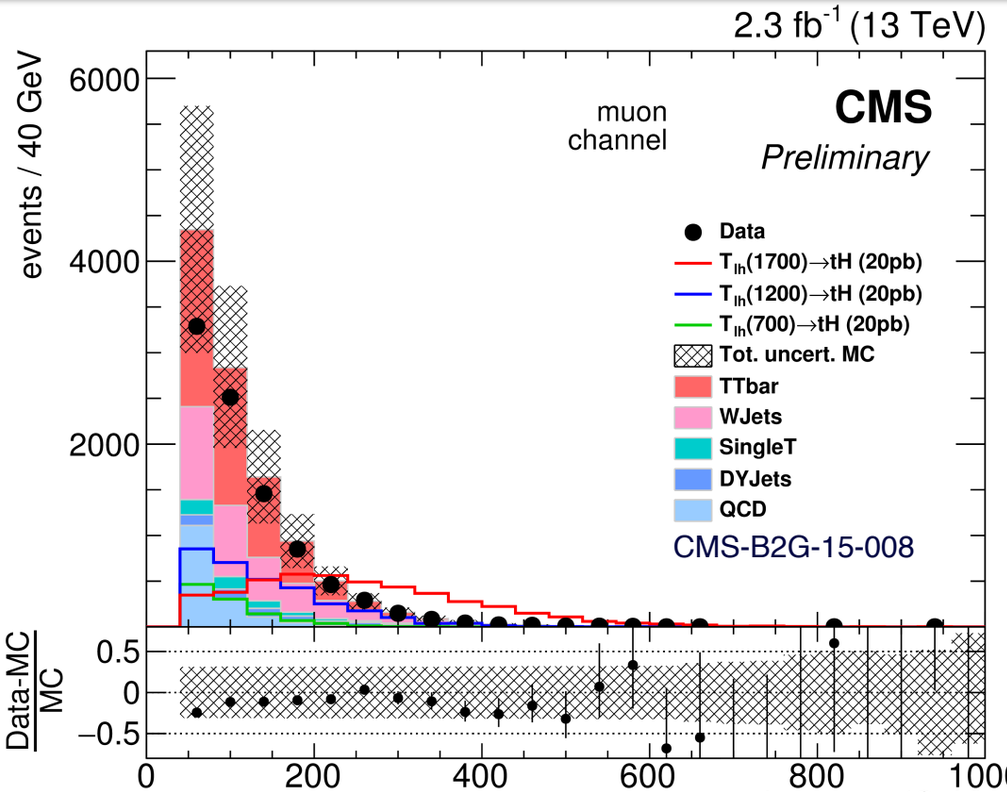

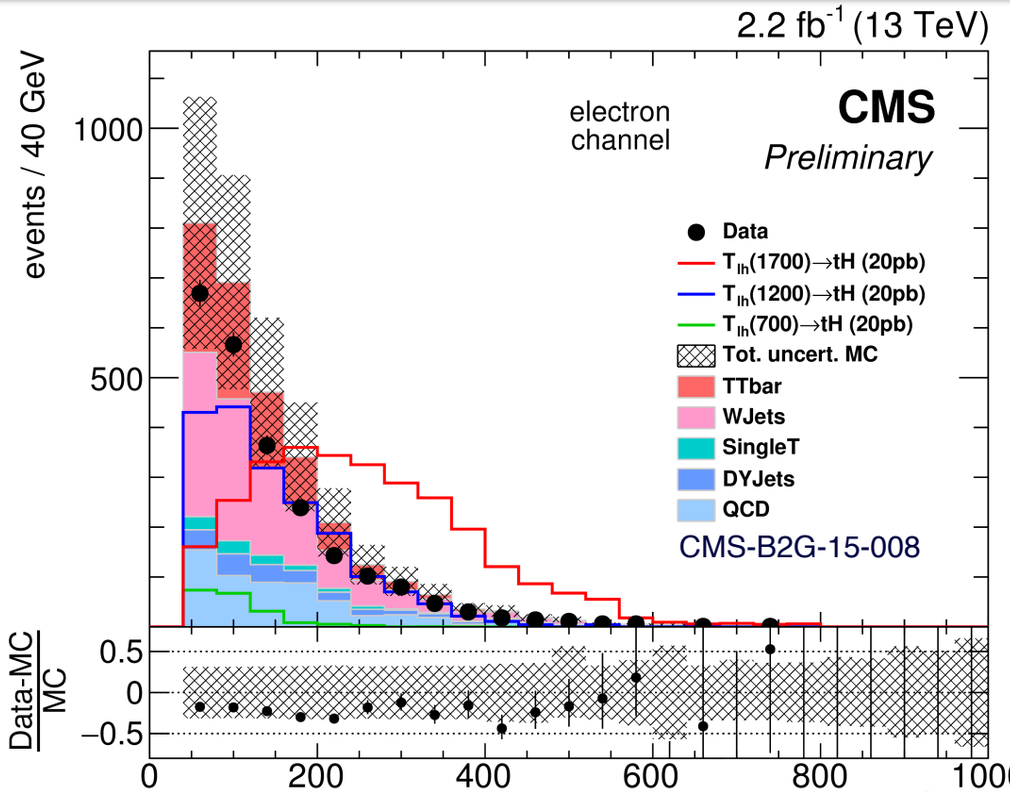

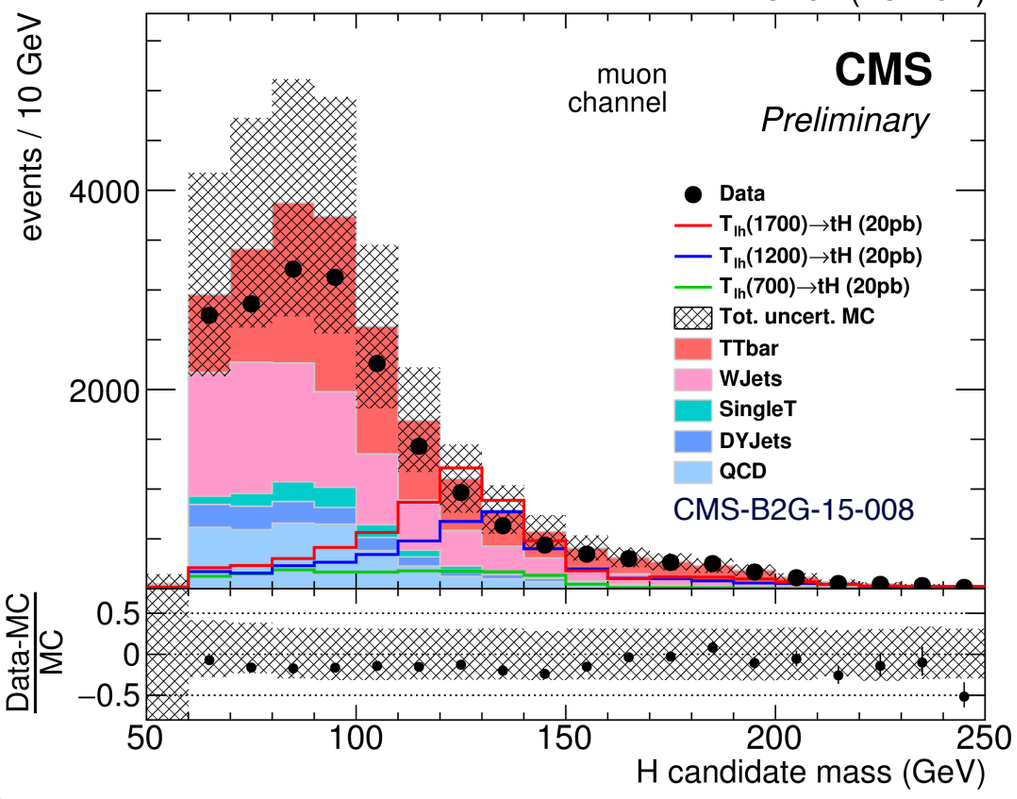

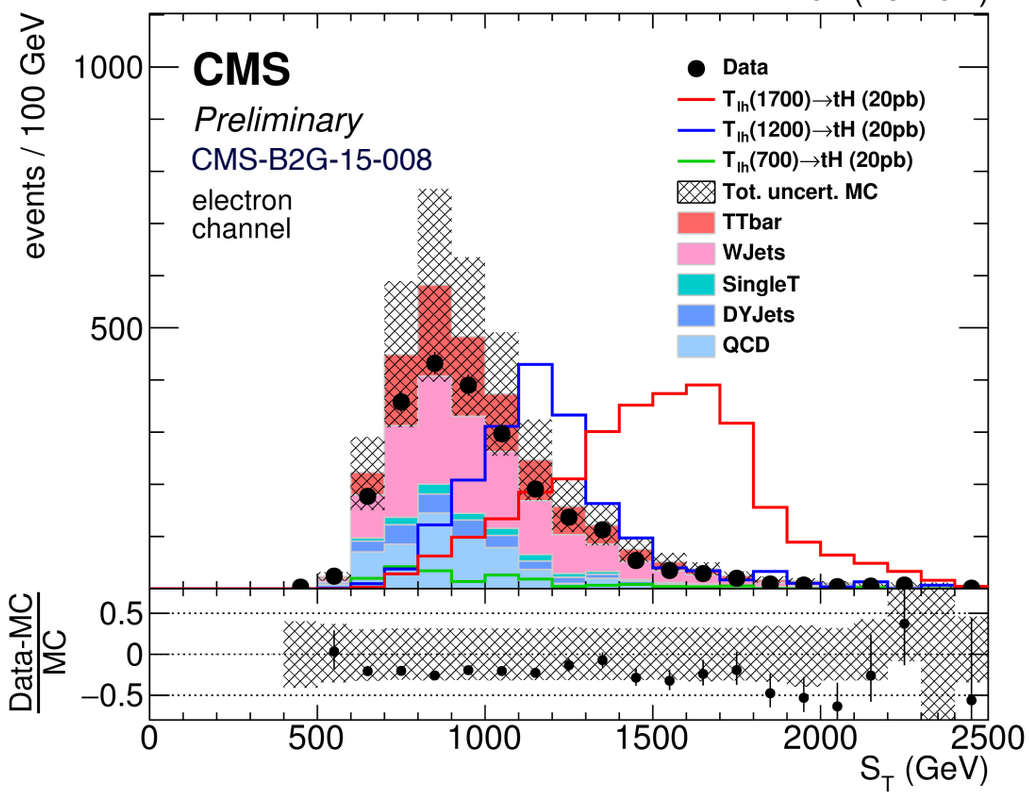

$T \rightarrow tH$: χ^2

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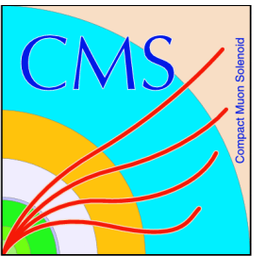
- χ^2 discriminator for $T \rightarrow th$ events where
  - $M_{H,rec}$, $M_{t,rec}$, and $\Delta R(t,H)_{rec}$ are taken from the event
  - $M_{H,MC}$, $M_{t,MC}$, $\Delta R(t,H)_{MC}$, $\sigma_{M_H,MC}$, $\sigma_{M_t,MC}$, and $\sigma_{\Delta R,MC}$ are taken from generator matched objects reconstructed in MC
- Smallest χ^2 is taken as the reconstruction hypothesis
- If $\Delta R(t,H)_{rec} < 1.0$, the event is rejected

$$\chi^2 = \left(\frac{M_{\mathrm{H,MC}} - M_{\mathrm{H,rec}}}{\sigma_{\mathrm{M_H,MC}}}\right)^2 + \left(\frac{M_{\mathrm{t,MC}} - M_{\mathrm{t,rec}}}{\sigma_{\mathrm{M_t,MC}}}\right)^2 + \left(\frac{\Delta R(\mathrm{t,H})_{\mathrm{MC}} - \Delta R(\mathrm{t,H})_{\mathrm{rec}}}{\sigma_{\Delta R,\mathrm{MC}}}\right)^2$$



T→tH: Top Reconstruction

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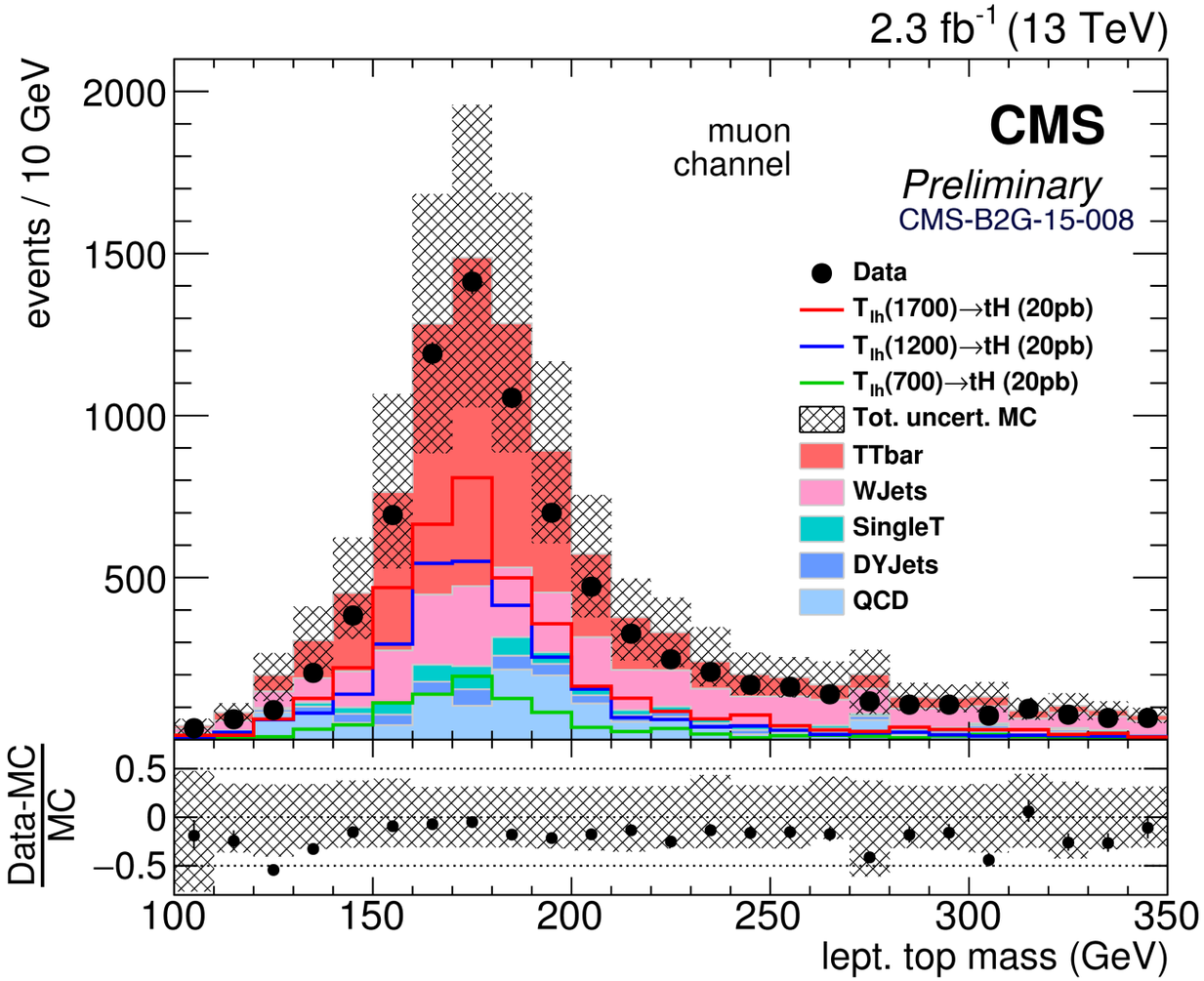
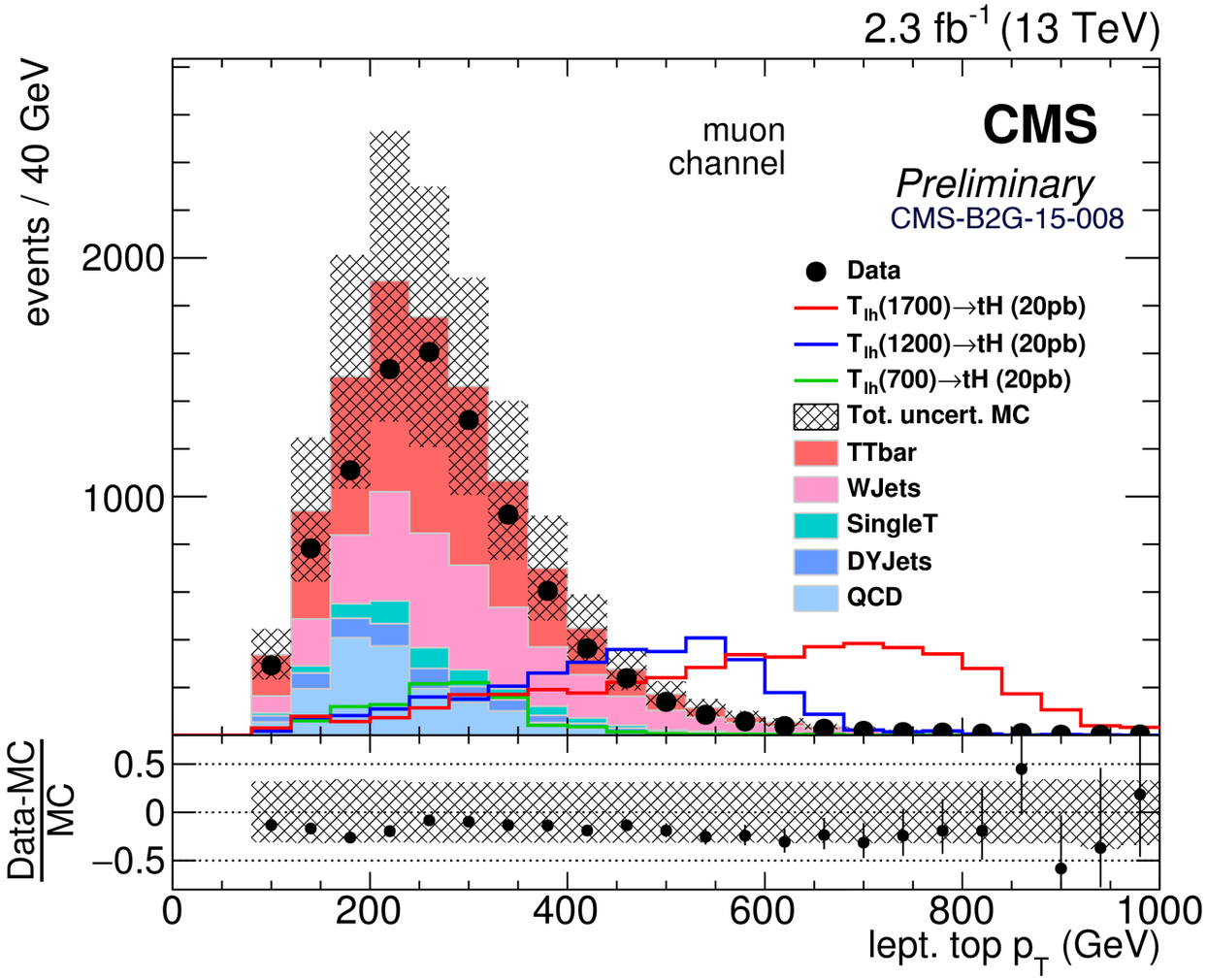
- Mass and pT of the reconstructed top candidates in the muon channel





T→tH: Signal Efficiency

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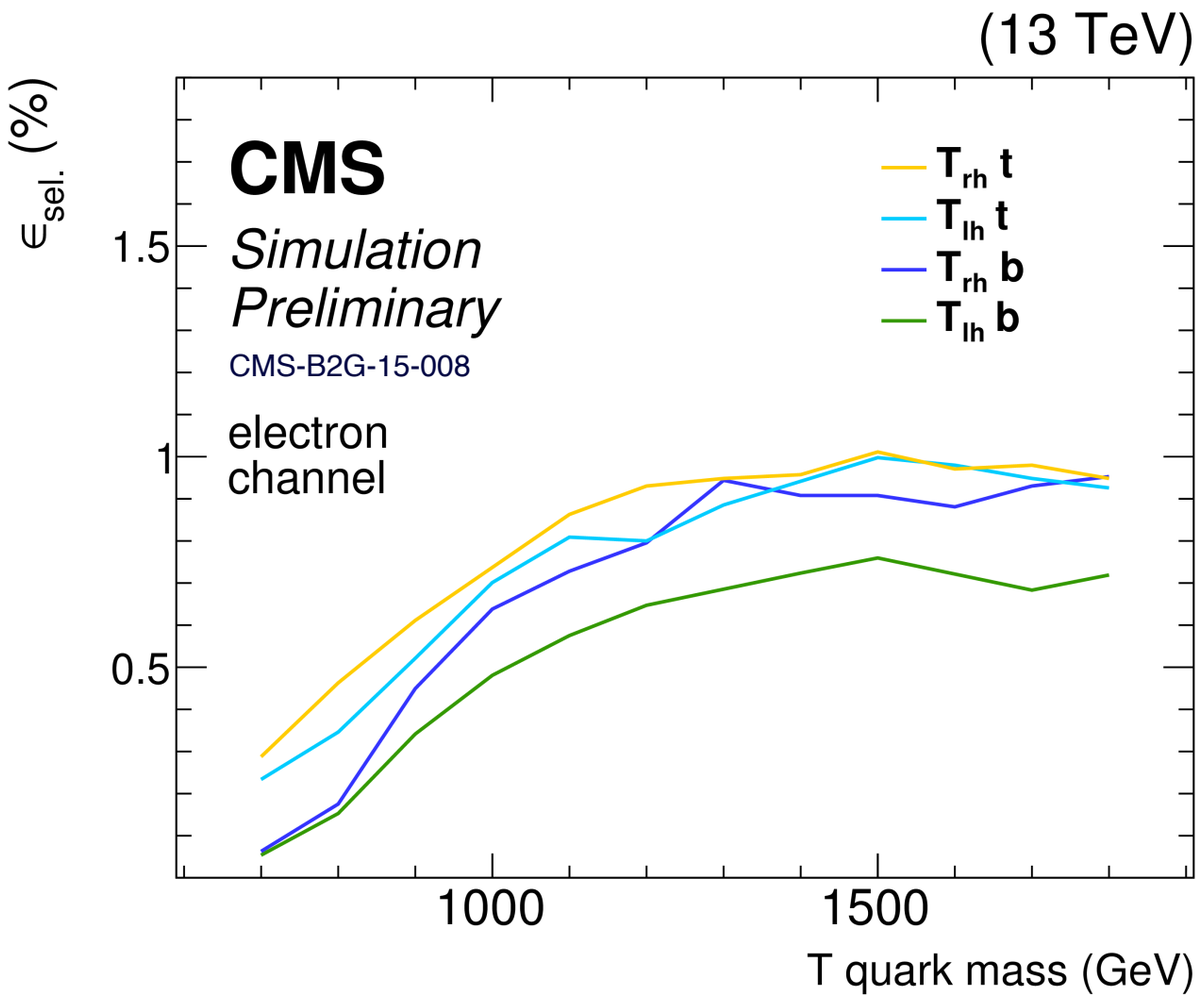
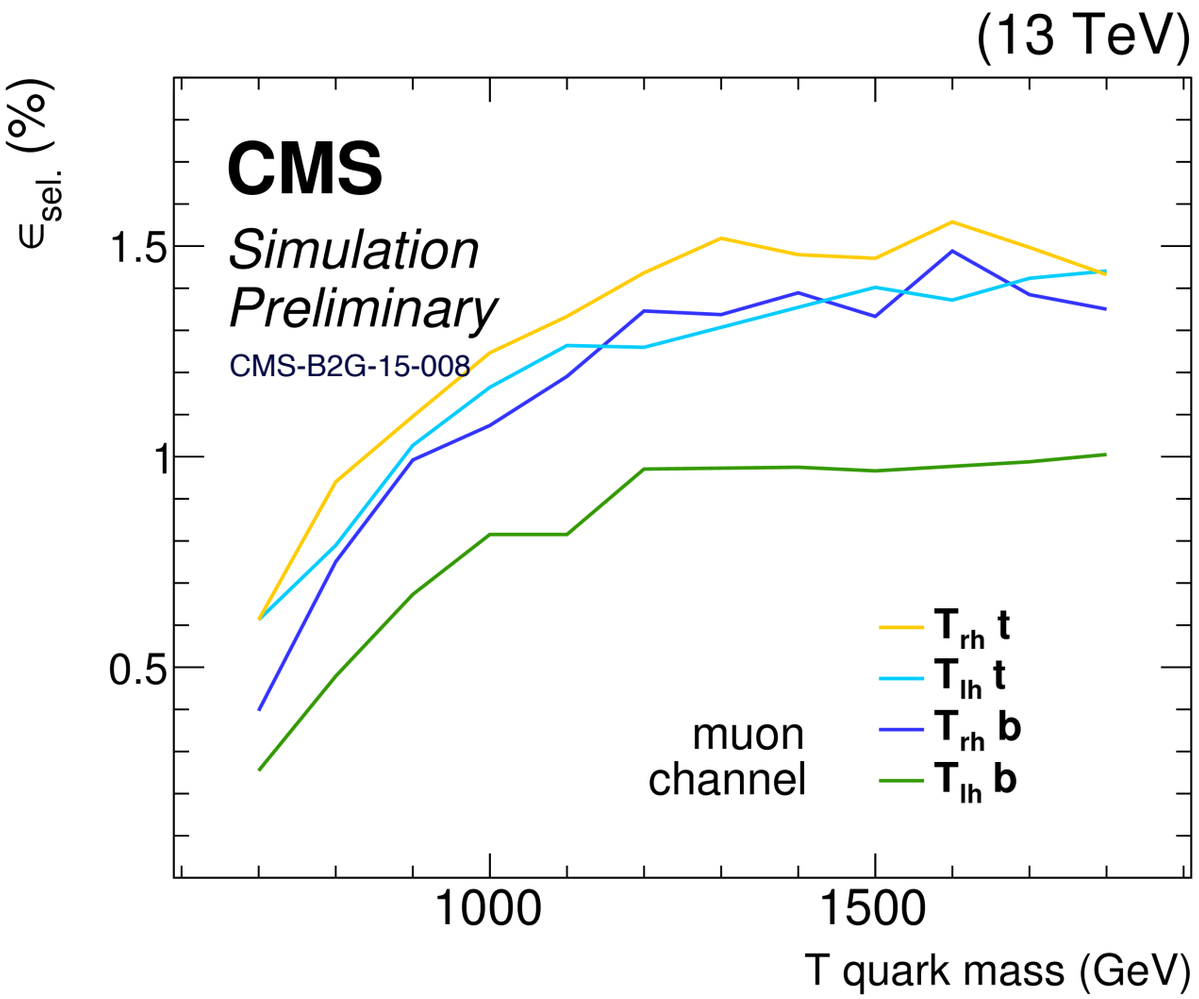
- Combined signal efficiency for right and left-handed T production in the associated t and b channels





T→tH: Reconstructed M_T

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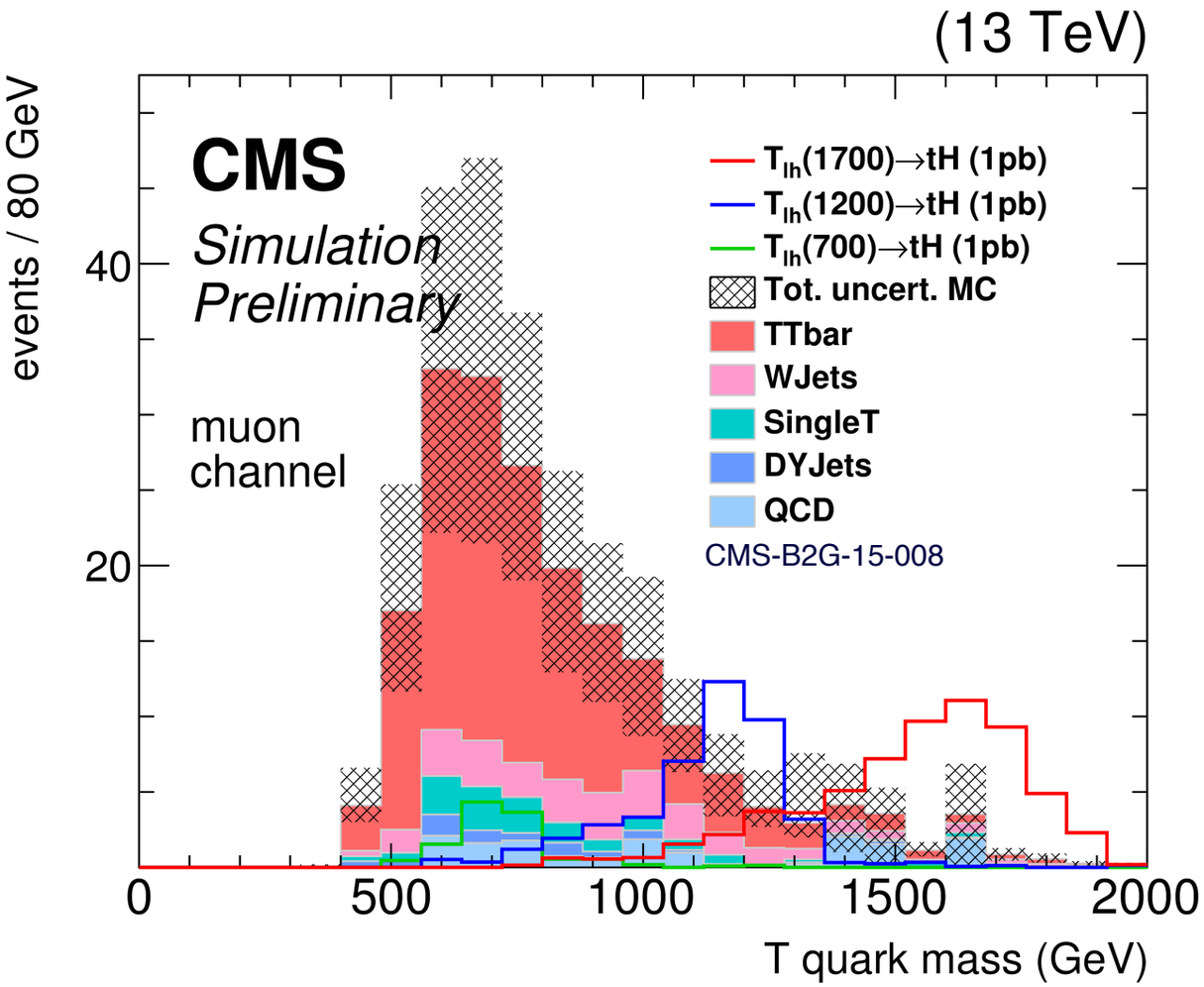
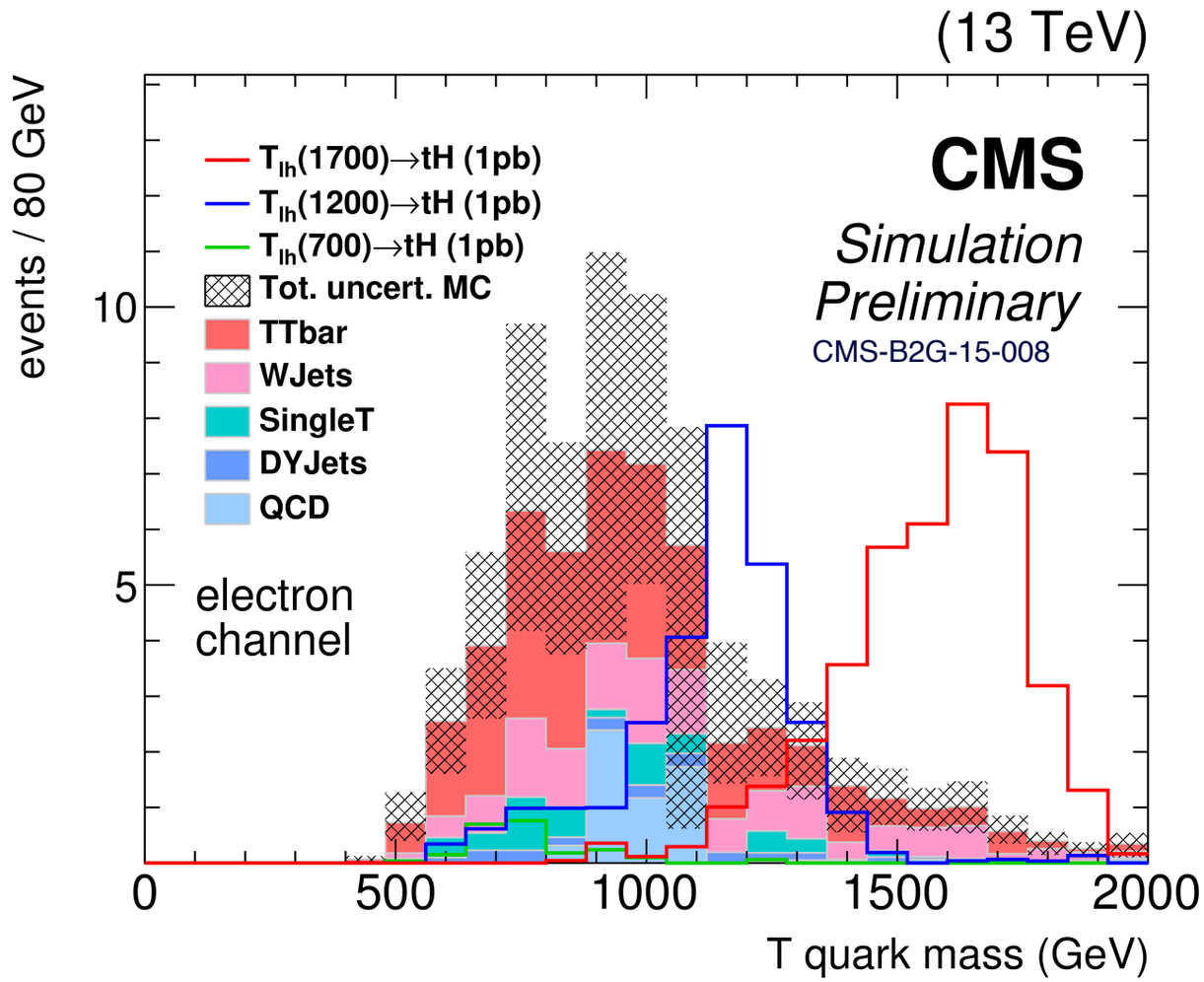
- Vector-like T quark mass in the signal region for the muon (left) and electron (right) channels



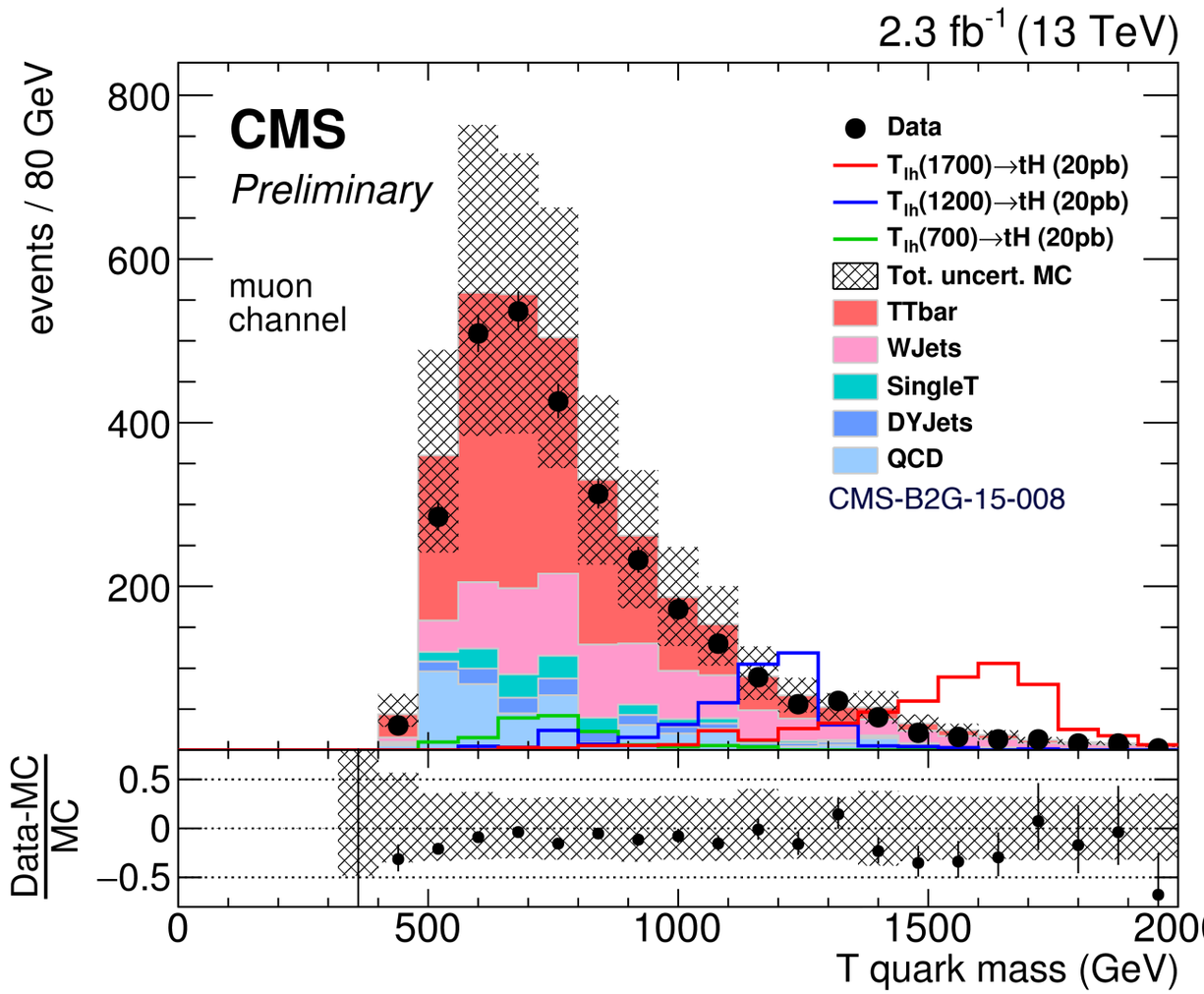


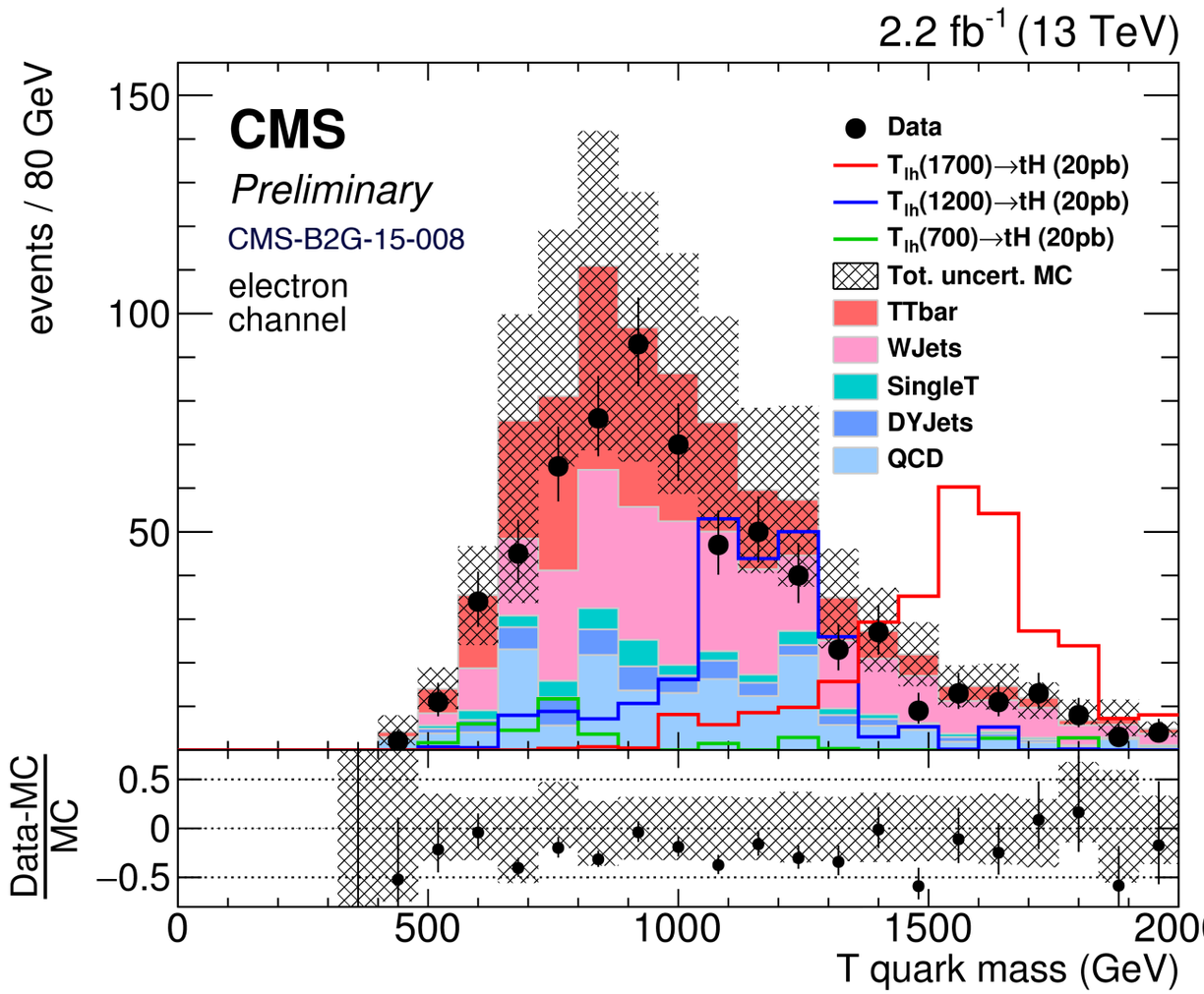
region CMS-B2G-15-008	signal	sideband
number of subjet b-tags (H cand.)	exactly 2	exactly 1
number of forward jets	at least 1	exactly 0

T→tH: Reconstructed M_T

UIC UNIVERSITY OF ILLINOIS AT CHICAGO

- Vector-like T quark mass in the sideband region for the muon (left) and electron (right) channels





region	CMS-B2G-15-008	signal	sideband
number of subjet b-tags (H cand.)		exactly 2	exactly 1
number of forward jets		at least 1	exactly 0

T→tH: Reconstructed M_T

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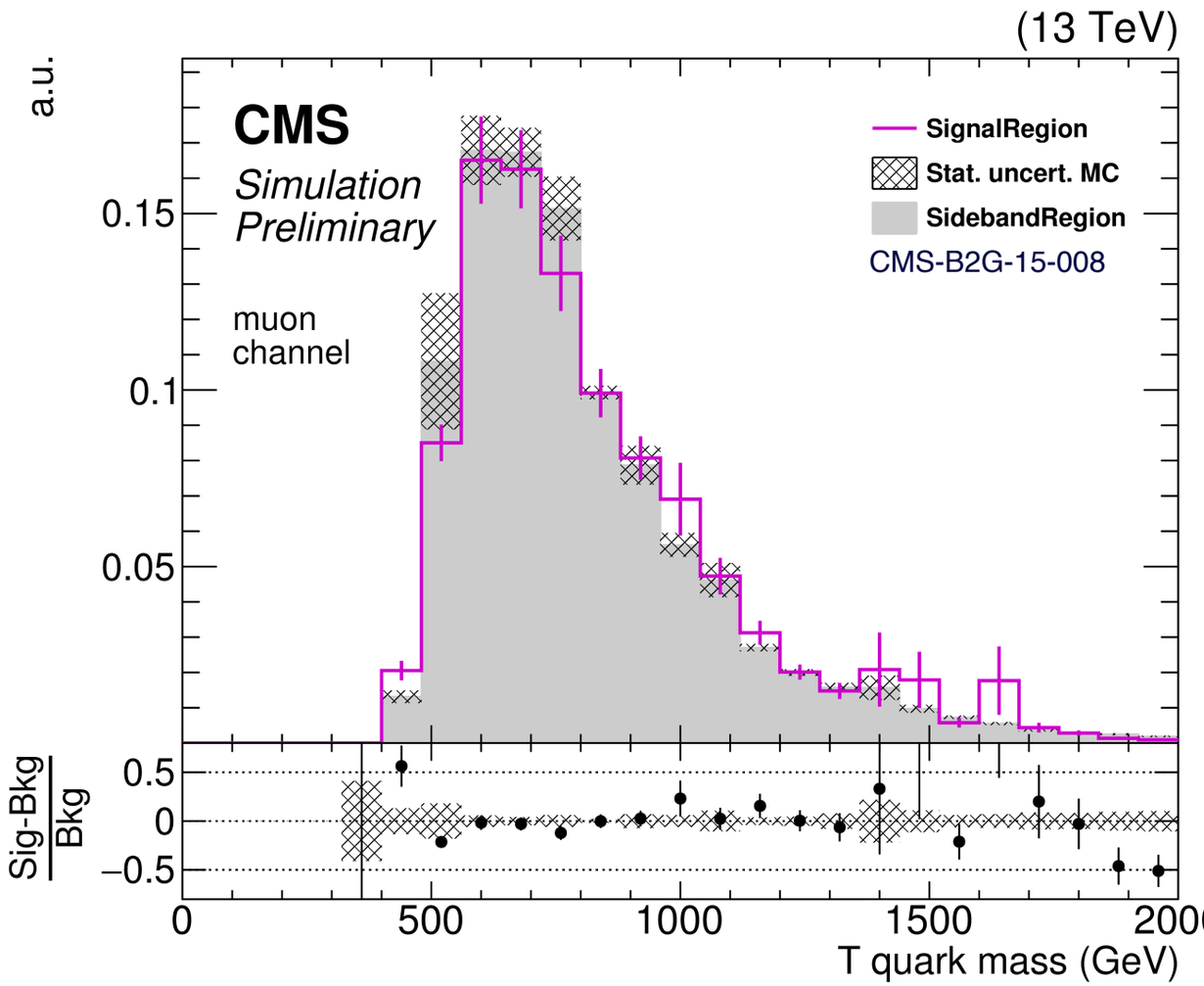
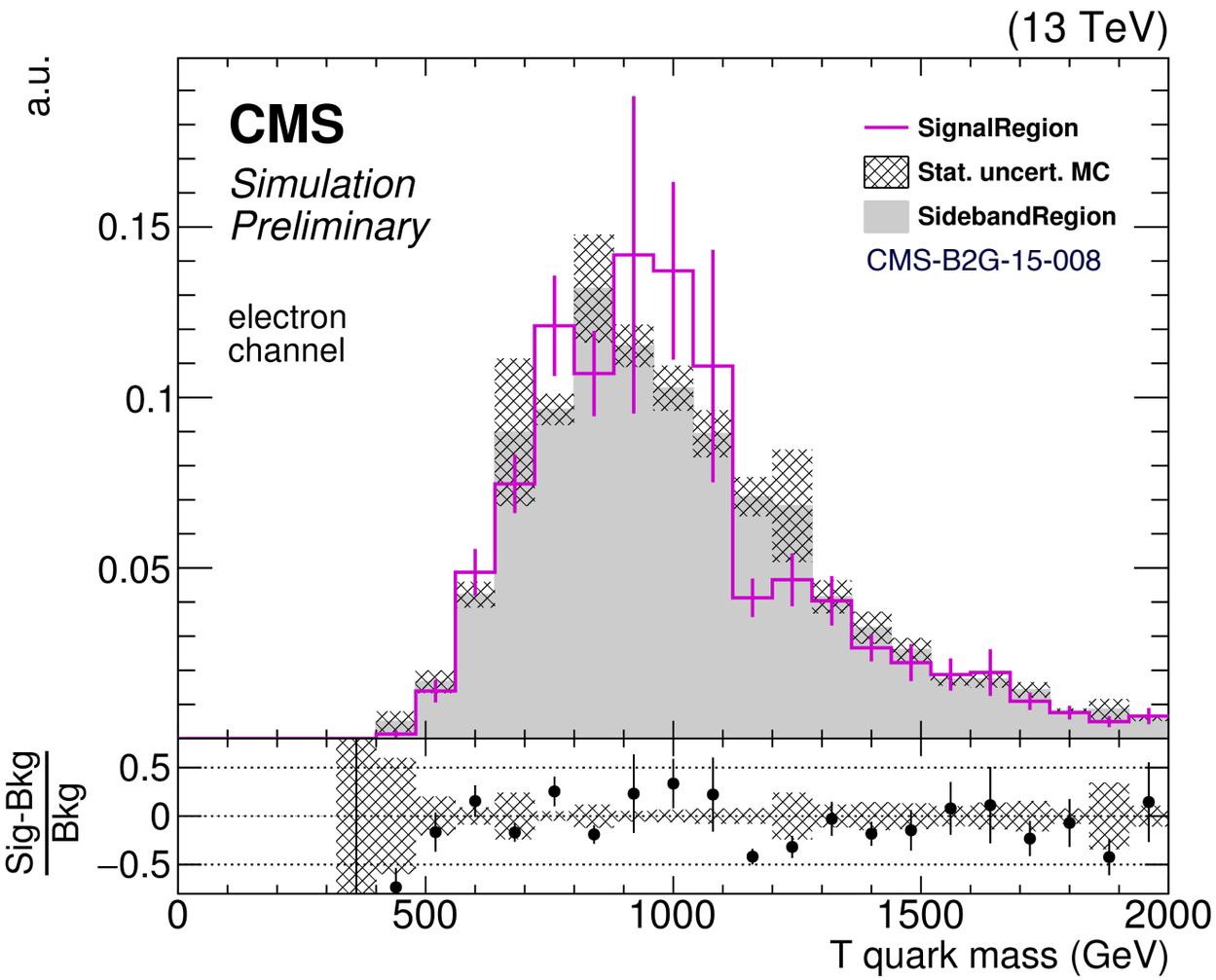
- Vector-like T quark mass in the signal and sideband region for the muon (left) and electron (right) channels





region CMS-B2G-15-008	signal	sideband
number of subjet b-tags (H cand.)	exactly 2	exactly 1
number of forward jets	at least 1	exactly 0

T→tH: Event Yields

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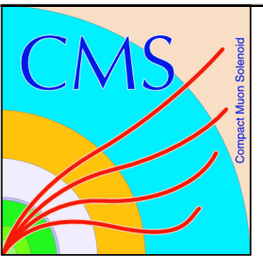
- Selection efficiency and post-fit event yields

CMS-B2G-15-008	electron channel		muon channel	
	$N_{sel} \pm stat \pm sys$	$\epsilon_{sel} \pm stat \pm sys$ (%)	$N_{sel} \pm stat \pm sys$	$\epsilon_{sel} \pm stat \pm sys$ (%)
$T_{lh}(700)$ b	$1.0 \pm 0.2 \pm 0.4$	$0.04 \pm 0.01 \pm 0.02$	$5.9 \pm 0.6 \pm 0.9$	$0.25 \pm 0.03 \pm 0.04$
$T_{lh}(1200)$ b	$13.7 \pm 0.8 \pm 1.6$	$0.62 \pm 0.04 \pm 0.07$	$22.4 \pm 1.1 \pm 2.7$	$0.97 \pm 0.05 \pm 0.12$
$T_{lh}(1700)$ b	$14.9 \pm 0.9 \pm 2.0$	$0.67 \pm 0.04 \pm 0.09$	$22.1 \pm 1.1 \pm 2.3$	$0.95 \pm 0.05 \pm 0.10$
$T_{rh}(700)$ b	$1.3 \pm 0.3 \pm 0.5$	$0.06 \pm 0.01 \pm 0.02$	$8.6 \pm 0.7 \pm 1.6$	$0.37 \pm 0.03 \pm 0.07$
$T_{rh}(1200)$ b	$17.3 \pm 0.9 \pm 2.1$	$0.78 \pm 0.04 \pm 0.09$	$29.9 \pm 1.3 \pm 3.5$	$1.29 \pm 0.06 \pm 0.15$
$T_{rh}(1700)$ b	$20.2 \pm 1.0 \pm 2.3$	$0.91 \pm 0.04 \pm 0.10$	$31.4 \pm 1.3 \pm 2.9$	$1.35 \pm 0.06 \pm 0.13$
$T_{lh}(700)$ t	$5.1 \pm 0.5 \pm 0.8$	$0.23 \pm 0.02 \pm 0.04$	$13.8 \pm 0.9 \pm 2.0$	$0.60 \pm 0.04 \pm 0.09$
$T_{lh}(1200)$ t	$16.8 \pm 0.9 \pm 1.8$	$0.76 \pm 0.04 \pm 0.08$	$29.1 \pm 1.2 \pm 3.1$	$1.26 \pm 0.05 \pm 0.13$
$T_{lh}(1700)$ t	$20.5 \pm 1.0 \pm 1.9$	$0.92 \pm 0.04 \pm 0.09$	$32.4 \pm 1.3 \pm 3.0$	$1.40 \pm 0.06 \pm 0.13$
$T_{rh}(700)$ t	$6.4 \pm 0.6 \pm 1.1$	$0.29 \pm 0.03 \pm 0.05$	$14.2 \pm 0.9 \pm 1.6$	$0.61 \pm 0.04 \pm 0.07$
$T_{rh}(1200)$ t	$19.5 \pm 1.0 \pm 2.0$	$0.88 \pm 0.04 \pm 0.09$	$32.6 \pm 1.3 \pm 2.6$	$1.41 \pm 0.06 \pm 0.11$
$T_{rh}(1700)$ t	$21.2 \pm 1.0 \pm 2.1$	$0.95 \pm 0.04 \pm 0.09$	$33.5 \pm 1.4 \pm 2.9$	$1.45 \pm 0.06 \pm 0.13$
bkg (post-fit)	34.8 ± 1.4		133.4 ± 2.5	
Data	35		134	



T→tH: Systematics

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CMS-B2G-15-008

	electron channel			muon channel		
	T(0700)	T(1200)	T(1700)	T(0700)	T(1200)	T(1700)
forward jet	15.0	15.0	15.0	15.0	15.0	15.0
b tag heavy flav.	7.8	7.6	8.7	6.0	7.5	8.5
JES	8.9	4.9	4.9	3.0	5.7	4.6
lepton iso. and trg.	5.0	5.0	5.0	5.0	5.0	5.0