Search for $t\bar{t}$ Resonances in Boosted Final States in 13 TeV pp Collisions at CMS

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On behalf of the CMS Collaboration

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Resonance Search

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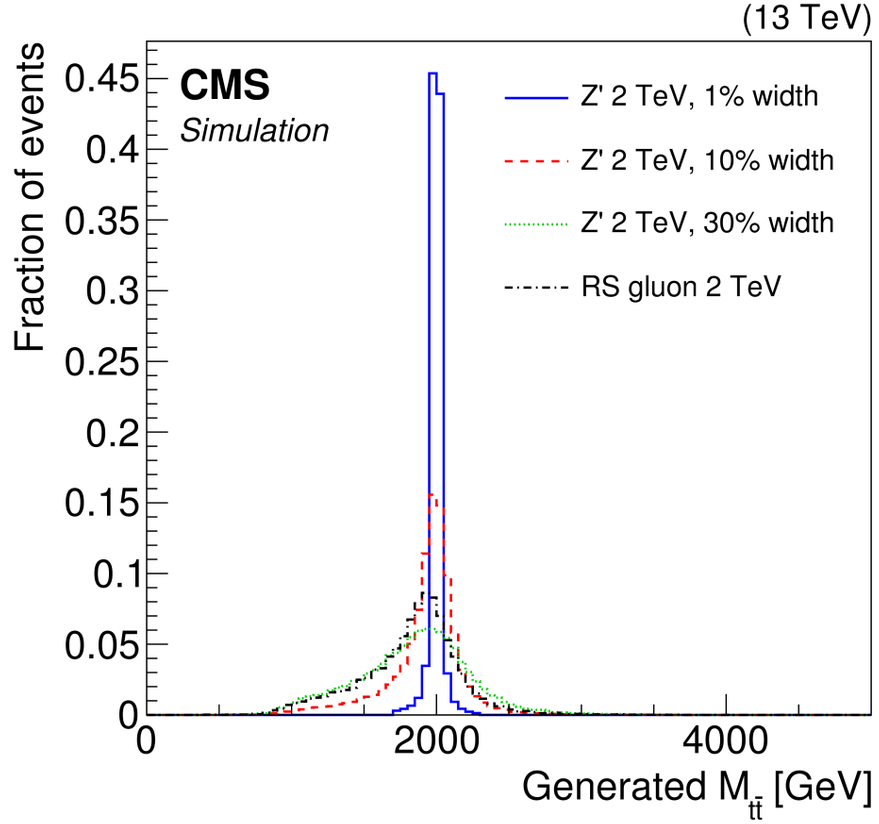
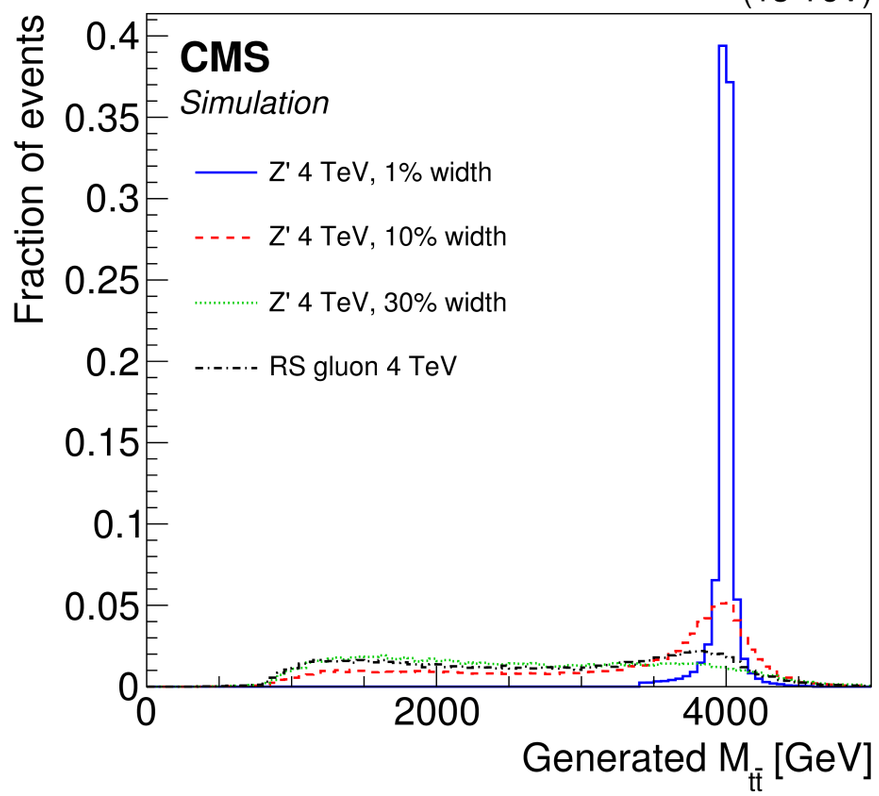
- Analysis searches for a generic $t\bar{t}$ resonance in the 2015 13 TeV CMS dataset ($2.6fb^{-1}$)
- Search channels include semi-leptonic and all hadronic final states
- Uses fitted templates for background and signal modeling
- Analysis sets explicit limits for Z′ (1%, 10%, and 30% widths) and RS gluon
- Results can be found in CMS-PAS-B2G-16-015, arXiv 1704.03366, and JHEP 07 (2017) 001





Motivation

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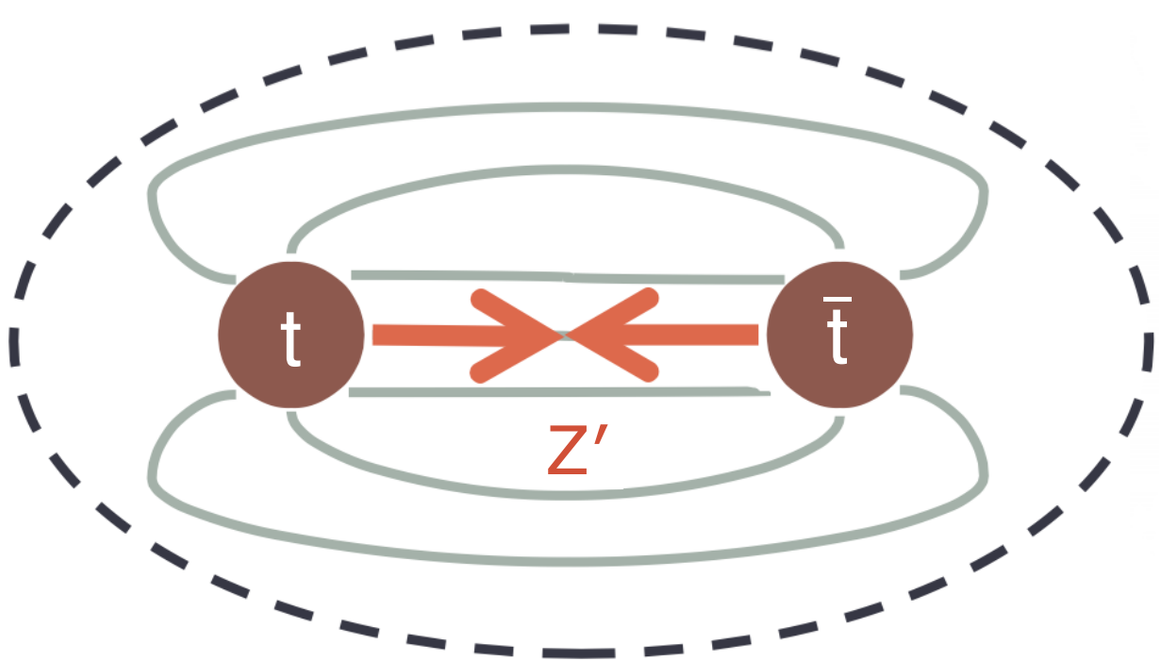
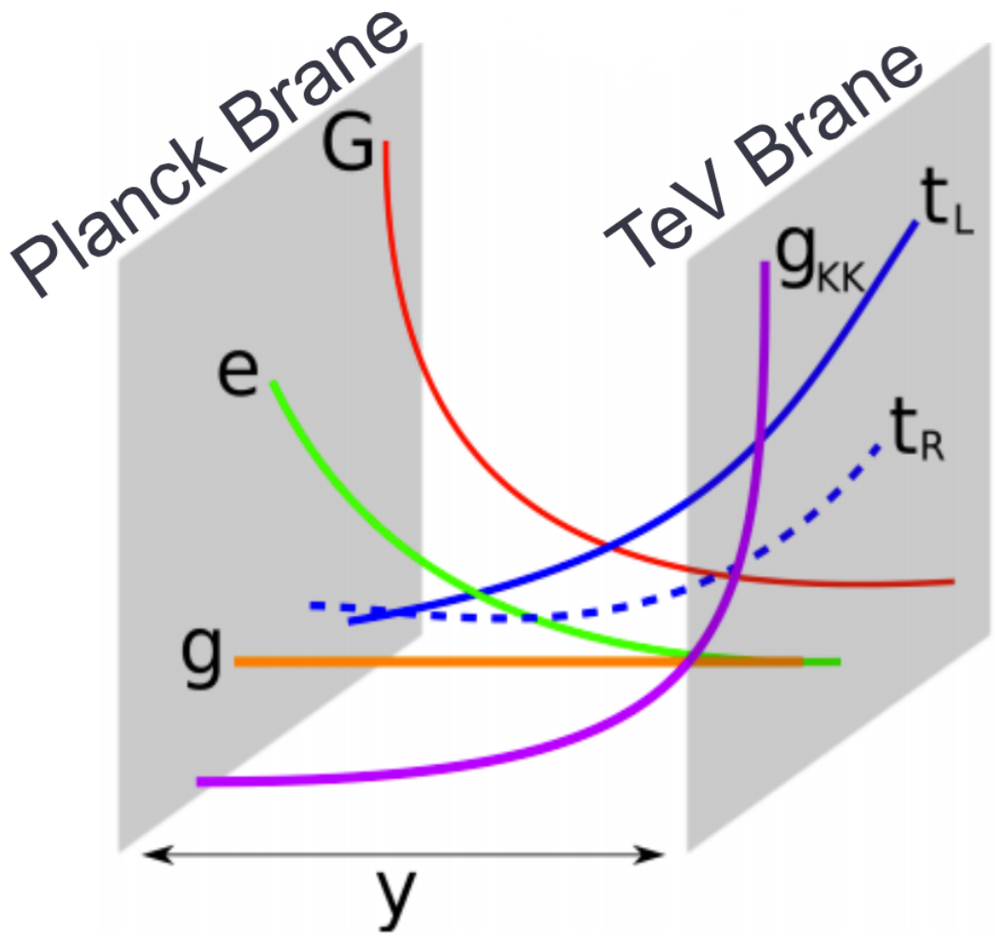
- Top color Z′ explains the large mass of the top quark via dynamical symmetry breaking
  - In this case, the model is a broken symmetry of:
    - $SU(3)_1 \times SU(3)_2 \times SU(2)_L \times U(1)_{Y1} \times U(1)_{Y2} \rightarrow SU(3)_{QCD} \times U(1)_{EM}$
- RS Gluons are the lightest Kaluza-Klein excitation of the gluon in a Randall-Sundrum scenario
  - In this case the universe is a 5-D anti-de sitter space bounded by two 3+1-D Branes





Boosted Top Quarks

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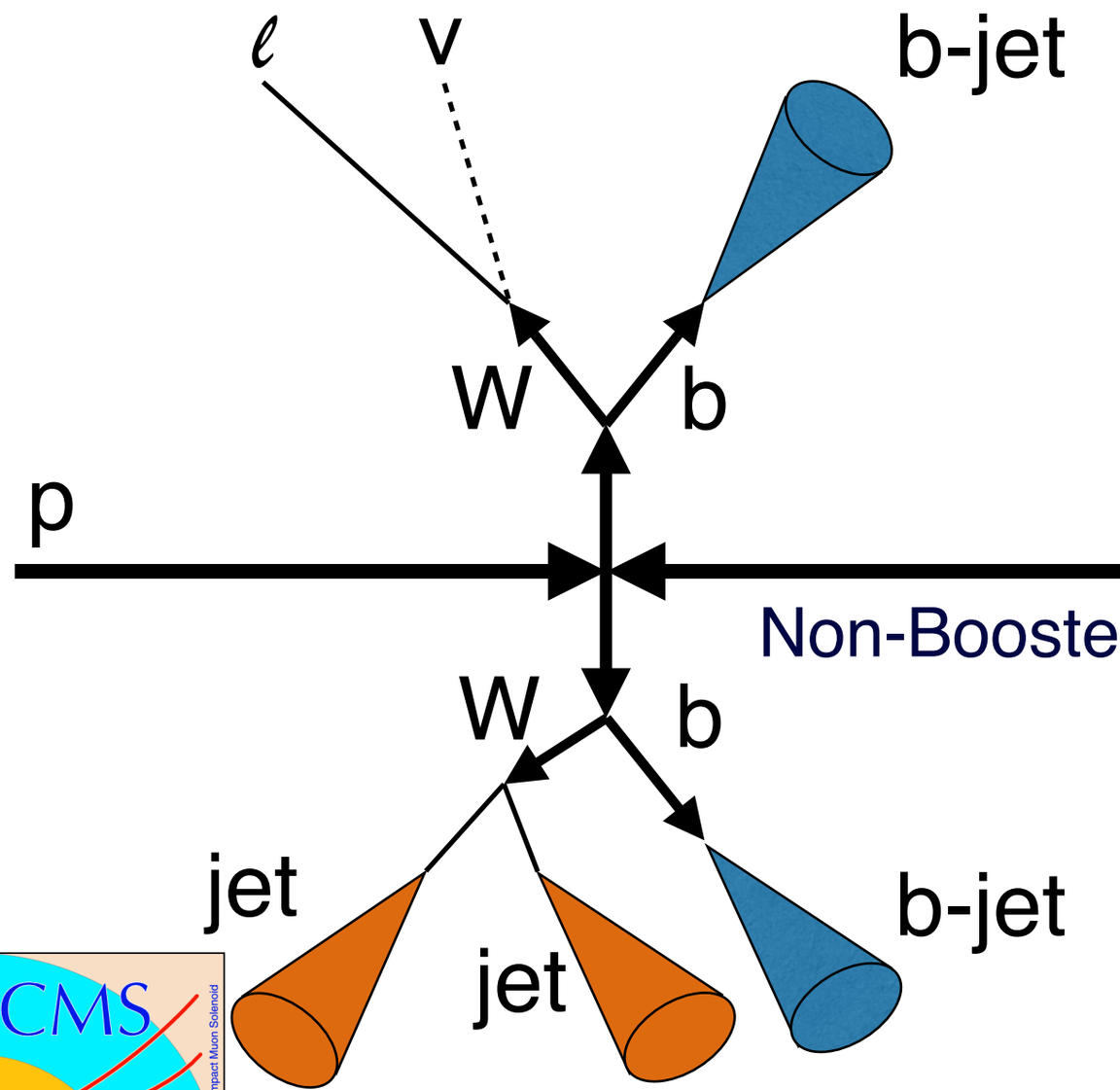
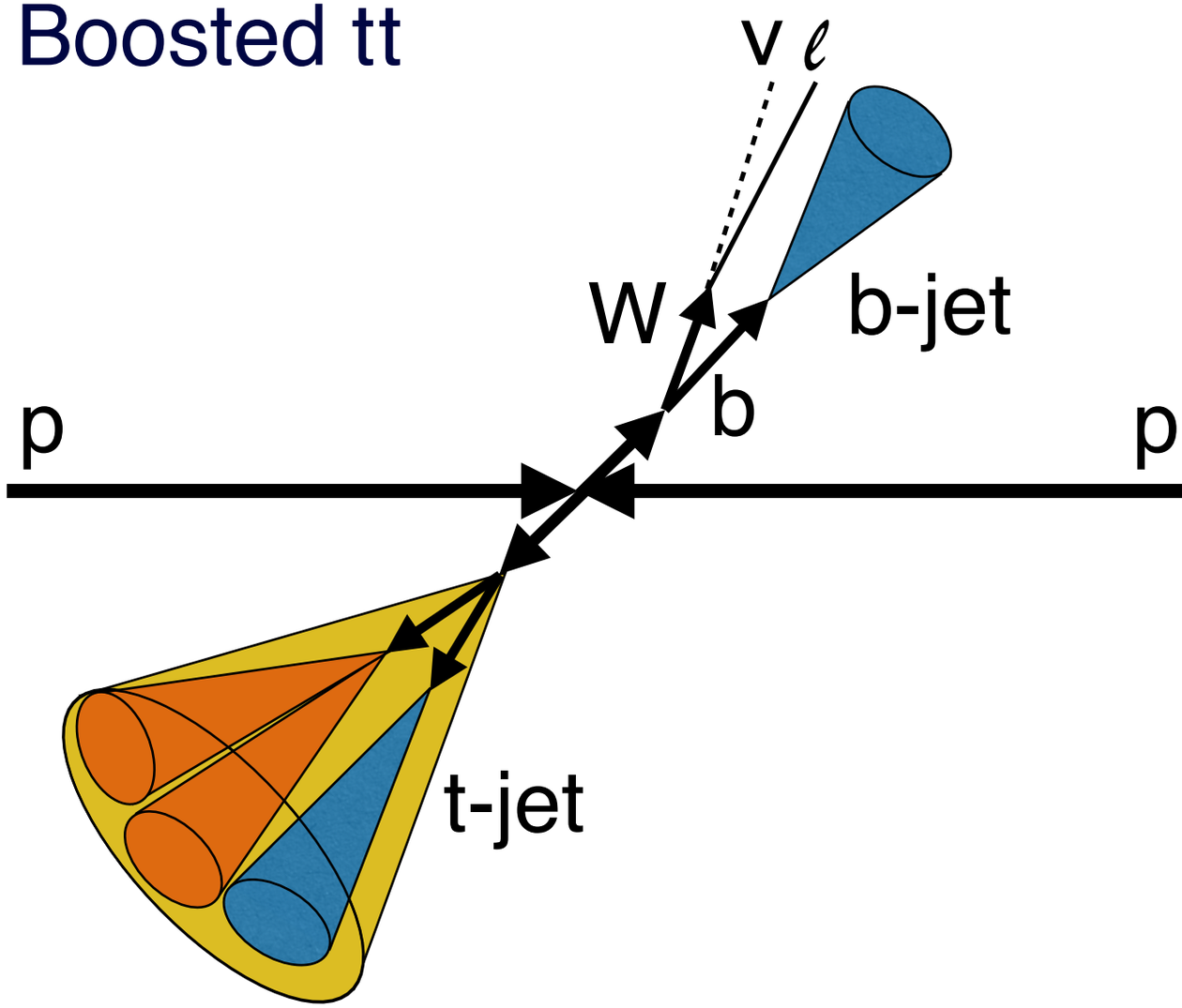
- A top quark with a large Lorentz boost has a new decay topology
- This requires changes to triggering and reconstruction





Top Tagging

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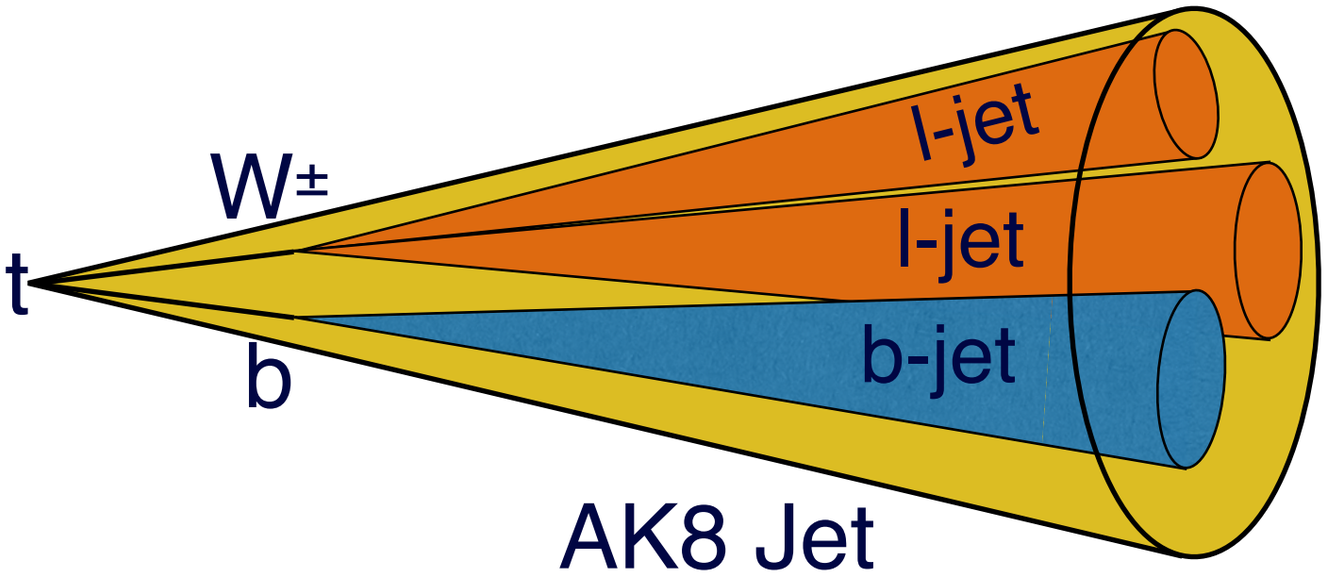
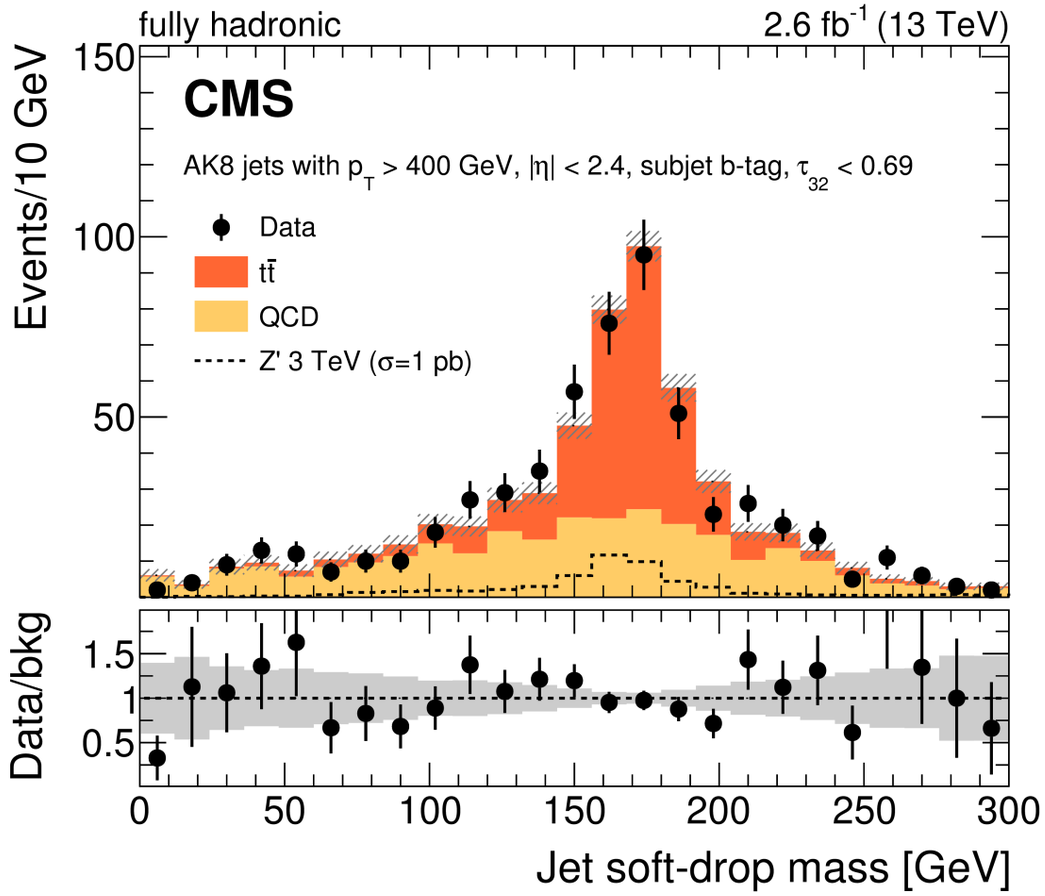
- Since a boosted top quark produces a single ‘fat jet’, it is possible to top tag jets
- The CMS top tagging algorithm is used to identify candidate top jets
  - 110 GeV < M_{SD} < 210 GeV
  - $\tau_{32} < 0.69$
  - b-tagging can used on AK4 sub-jets





Semi-Leptonic Channel

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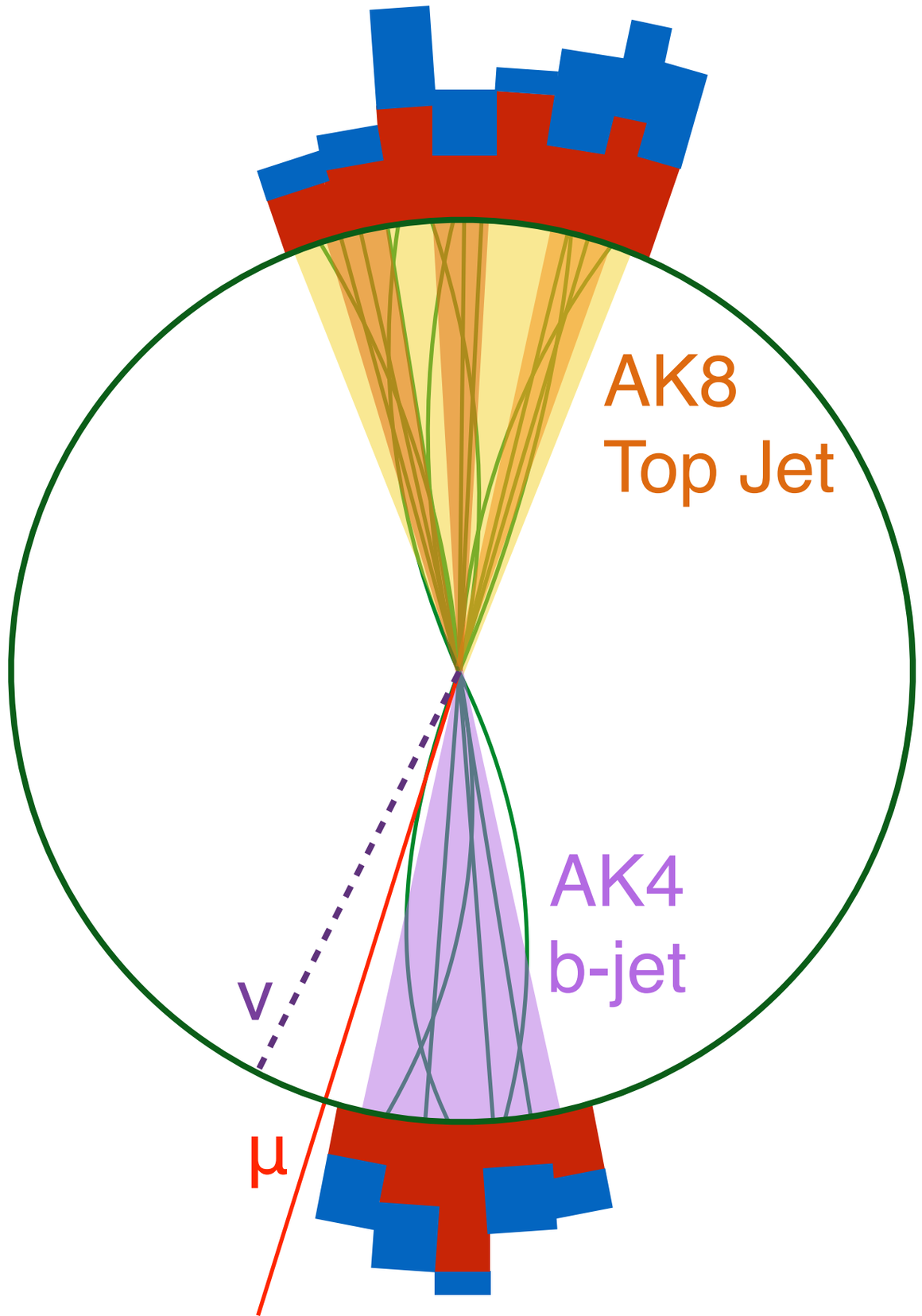
- Requires exactly one lepton and at least two high p_T jets
- 2D-isolation cut is applied to the lepton
- MET and lepton p_T+MET cut reduces multi-jet background
- MET may not be collinear with the leading jet or lepton
- χ^2 minimization technique is used to reconstruct the $t\bar{t}$ system
- t-tagging and b-tagging are used for categorization and increased analysis sensitivity
- Veto events with two top tags
- Total of 6 categories



2-D and χ^2 Selection

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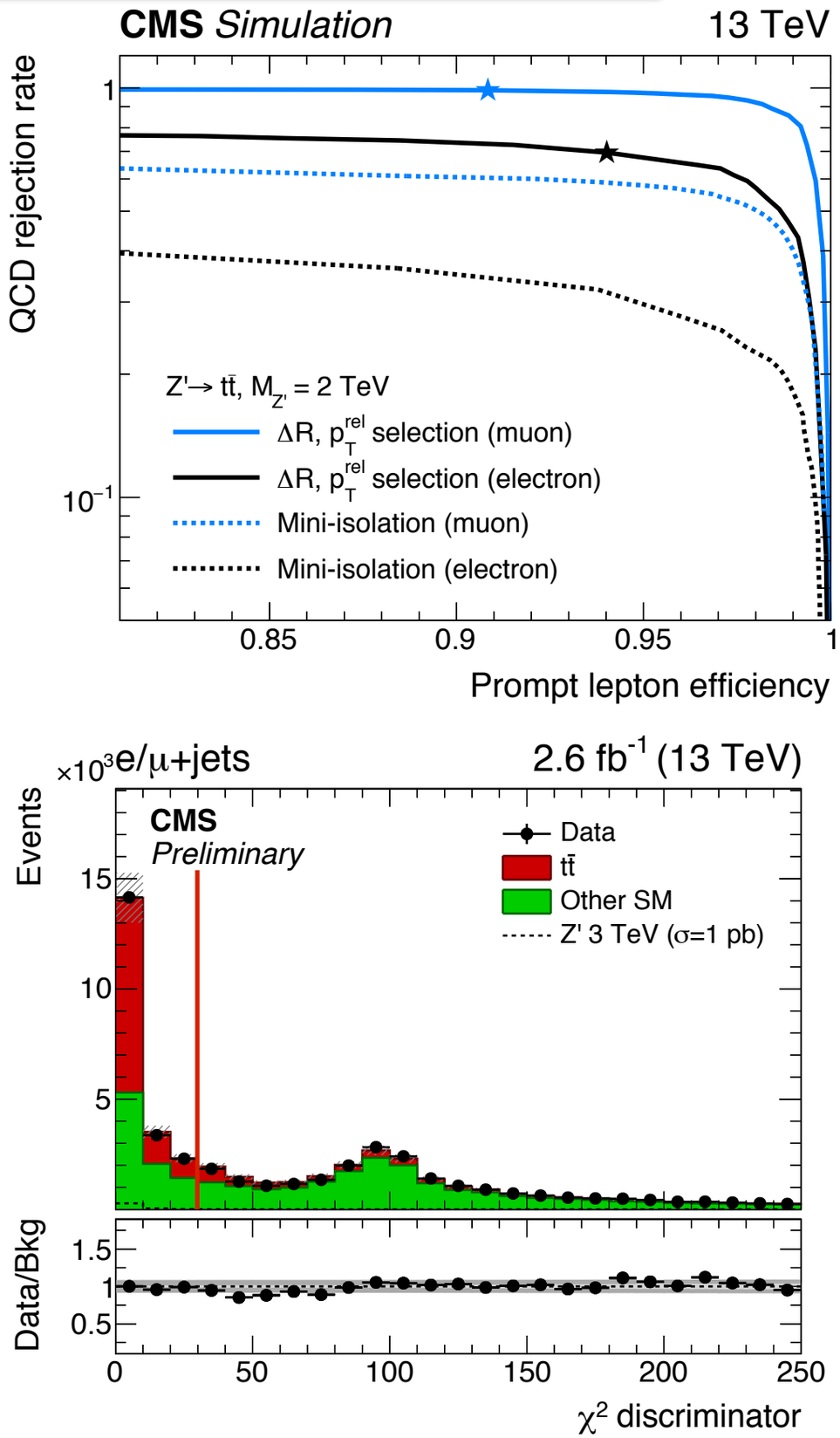
- Non-isolated lepton trigger used for event selection
- If a lepton is with $\Delta R < 0.4$ to an AK4 jet
  - Then the magnitude of the lepton momentum orthogonal to the axis of jet must be greater than 20 GeV
- Else normal lepton isolation criteria is applied
- χ^2 used to reconstruct the hadronic and leptonic legs of the top decay
  - The lepton, MET, W_M, and an AK4 jet used to reconstruct the leptonic leg
  - Either a t-tagged AK8 jet or 3 AK4 jets used to reconstruct the hadronic leg
- Minimum χ^2 used as reconstruction hypothesis
  - Require $\chi^2 < 30$ for signal region

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



Invariant Mass Distributions

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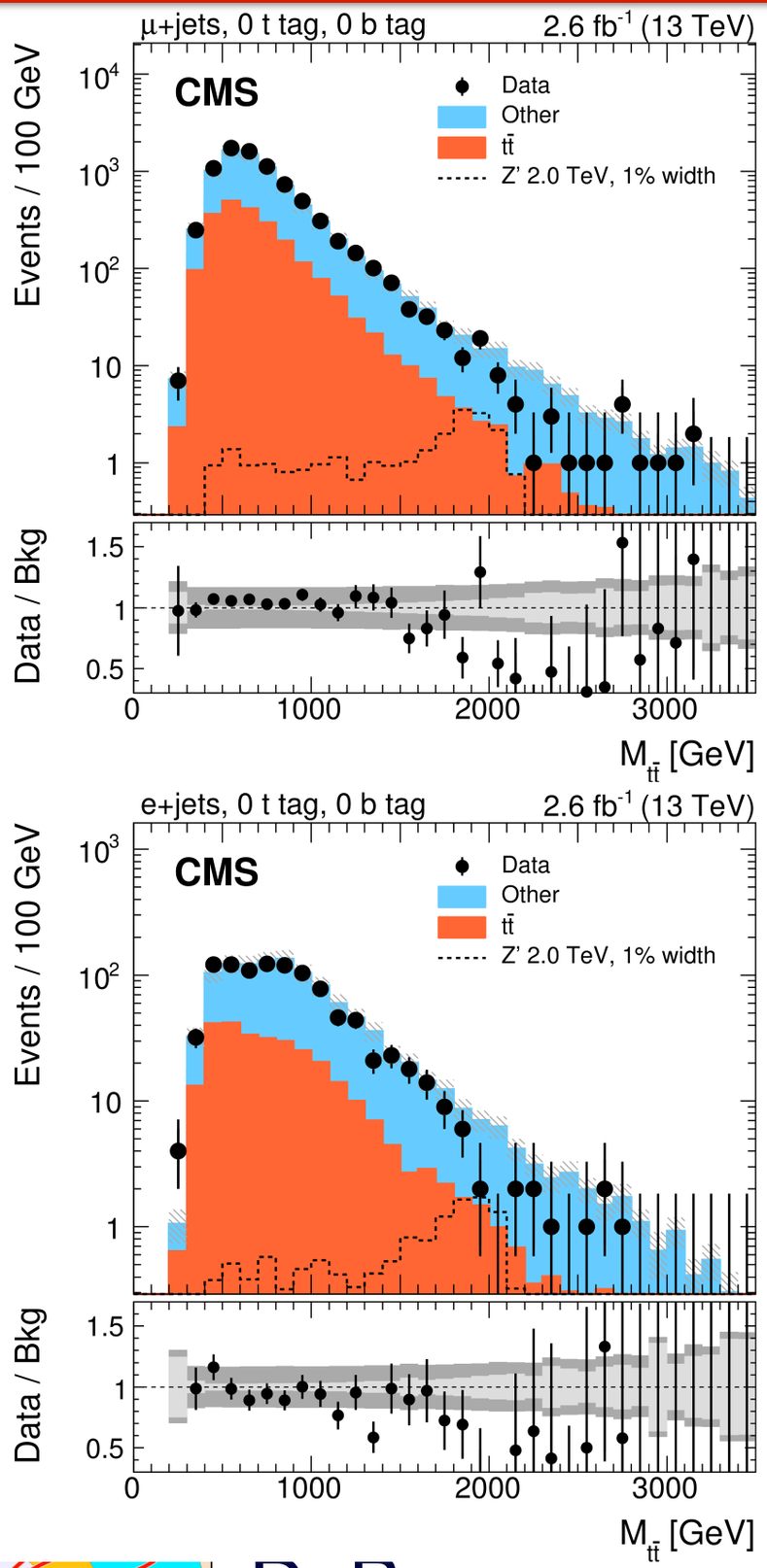

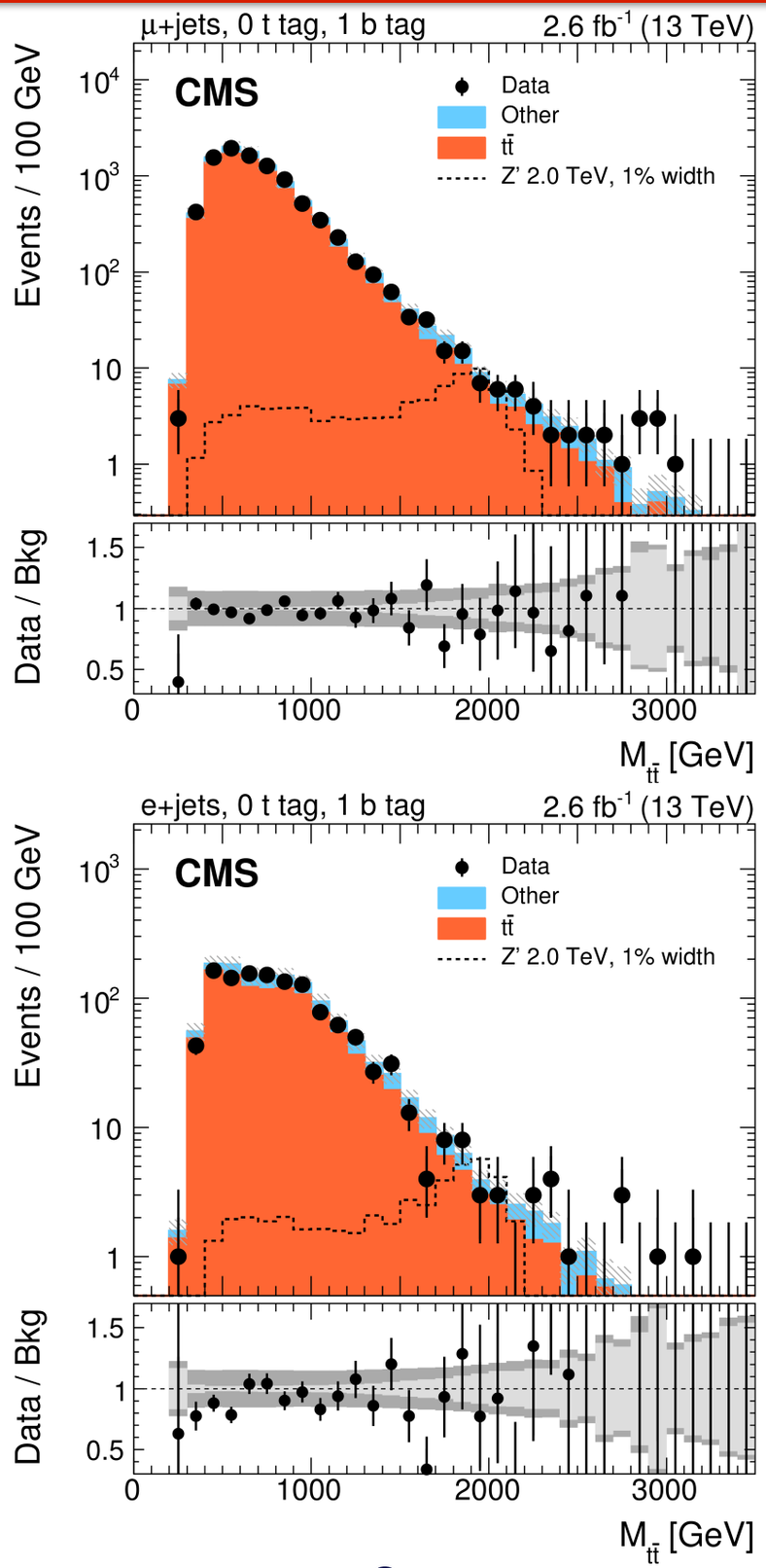

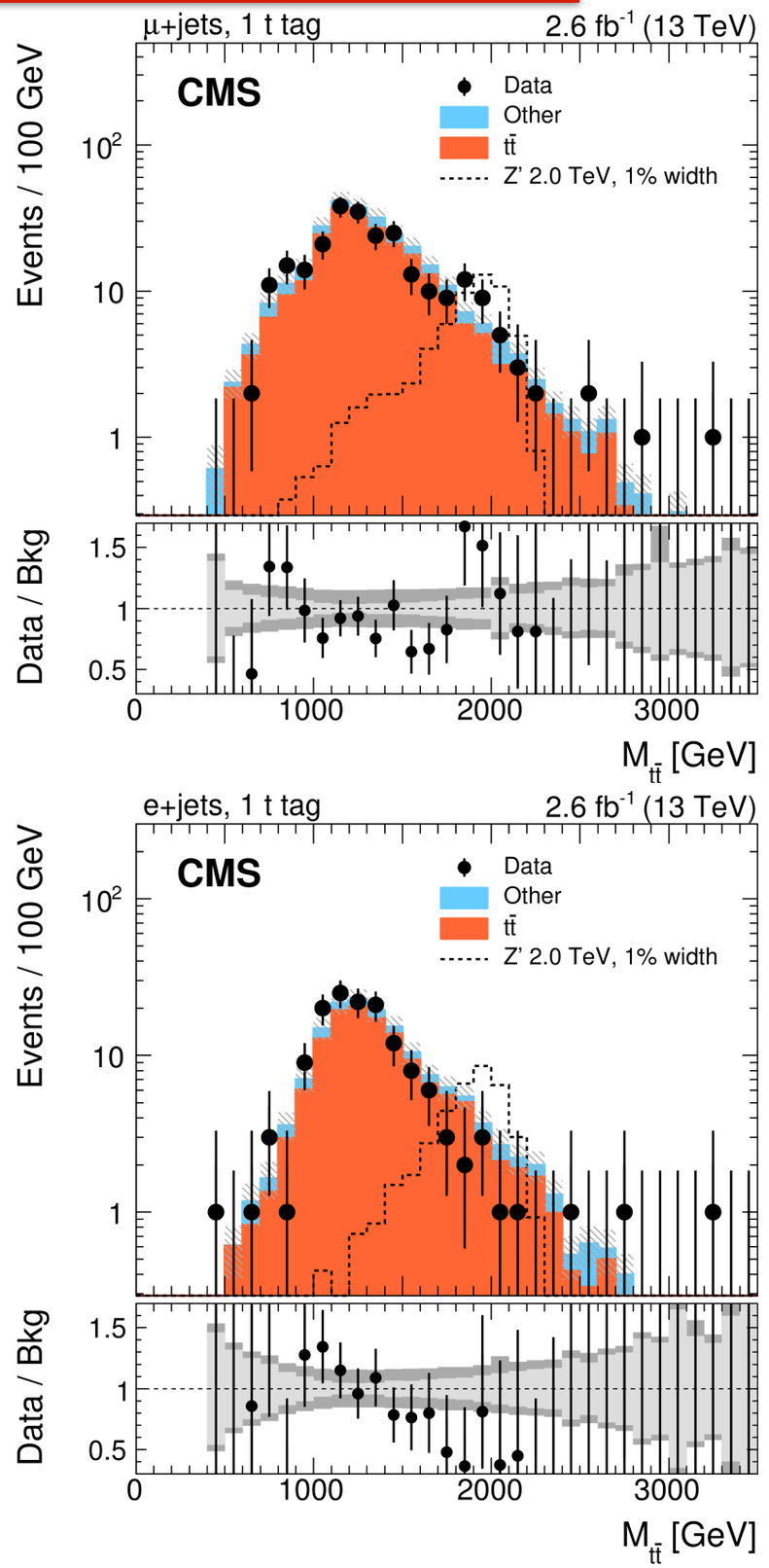

All Hadronic Channel

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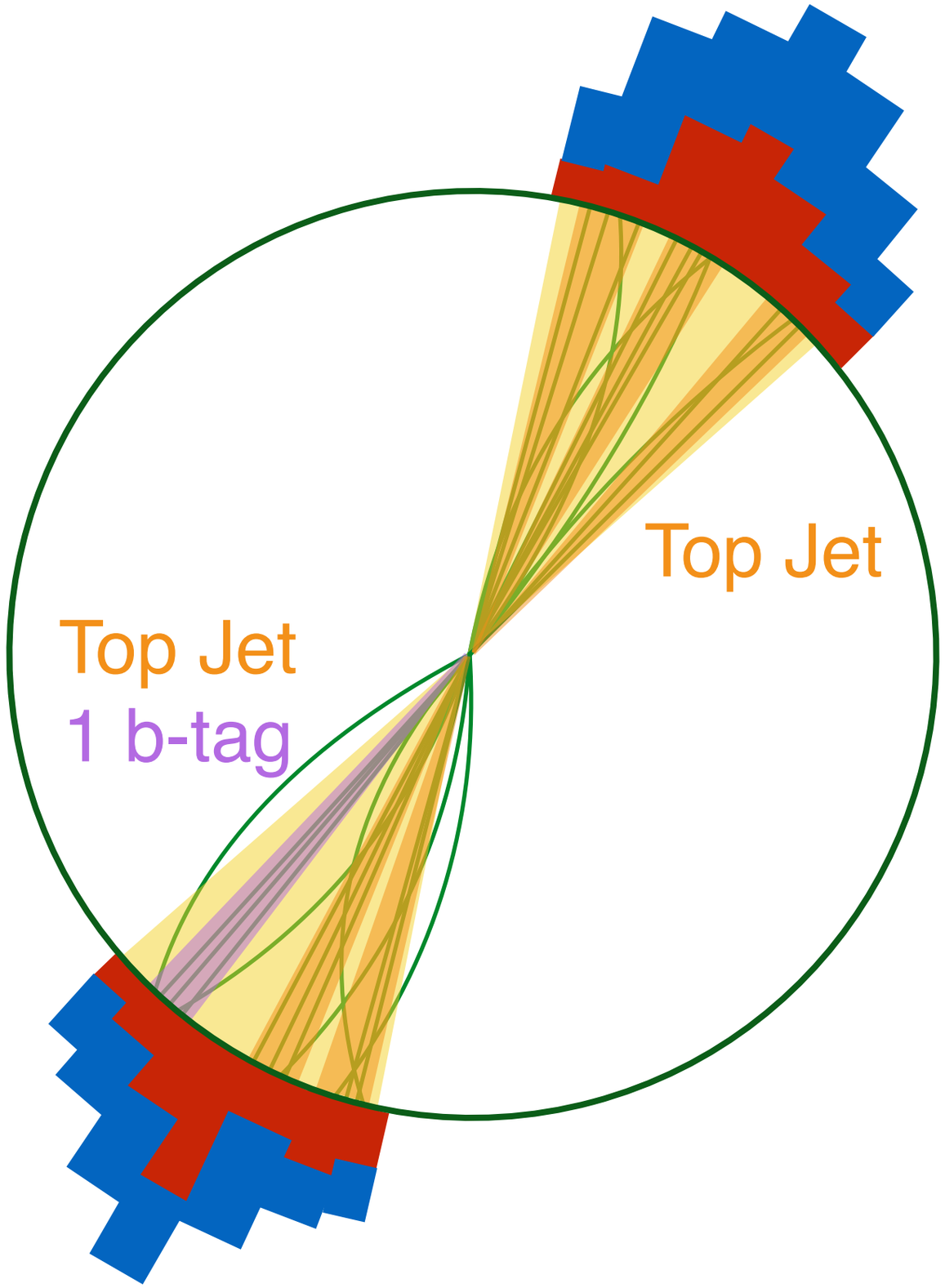
- The Lorentz boost of the top quarks causes this channel to become a di-jet analysis
- At least 1 TeV of H_T in the event
- Both jets are required to be top tagged
- Require jets to be back-to-back ($\Delta\phi > 2.1$)
- Sub-jet b-tagging and $|\Delta y|$ are used for categorization
- A total of 6 categories



Data Distributions

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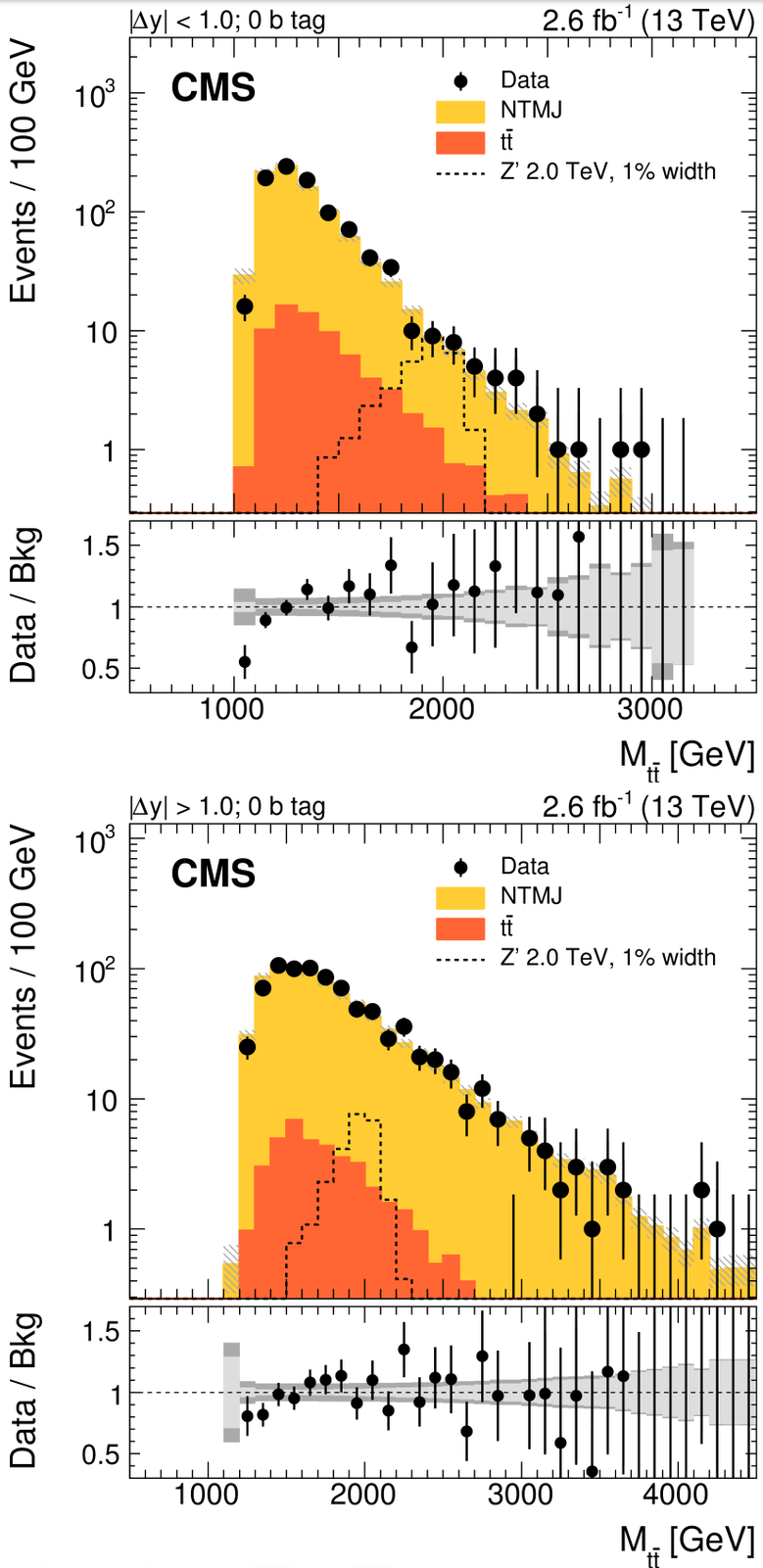

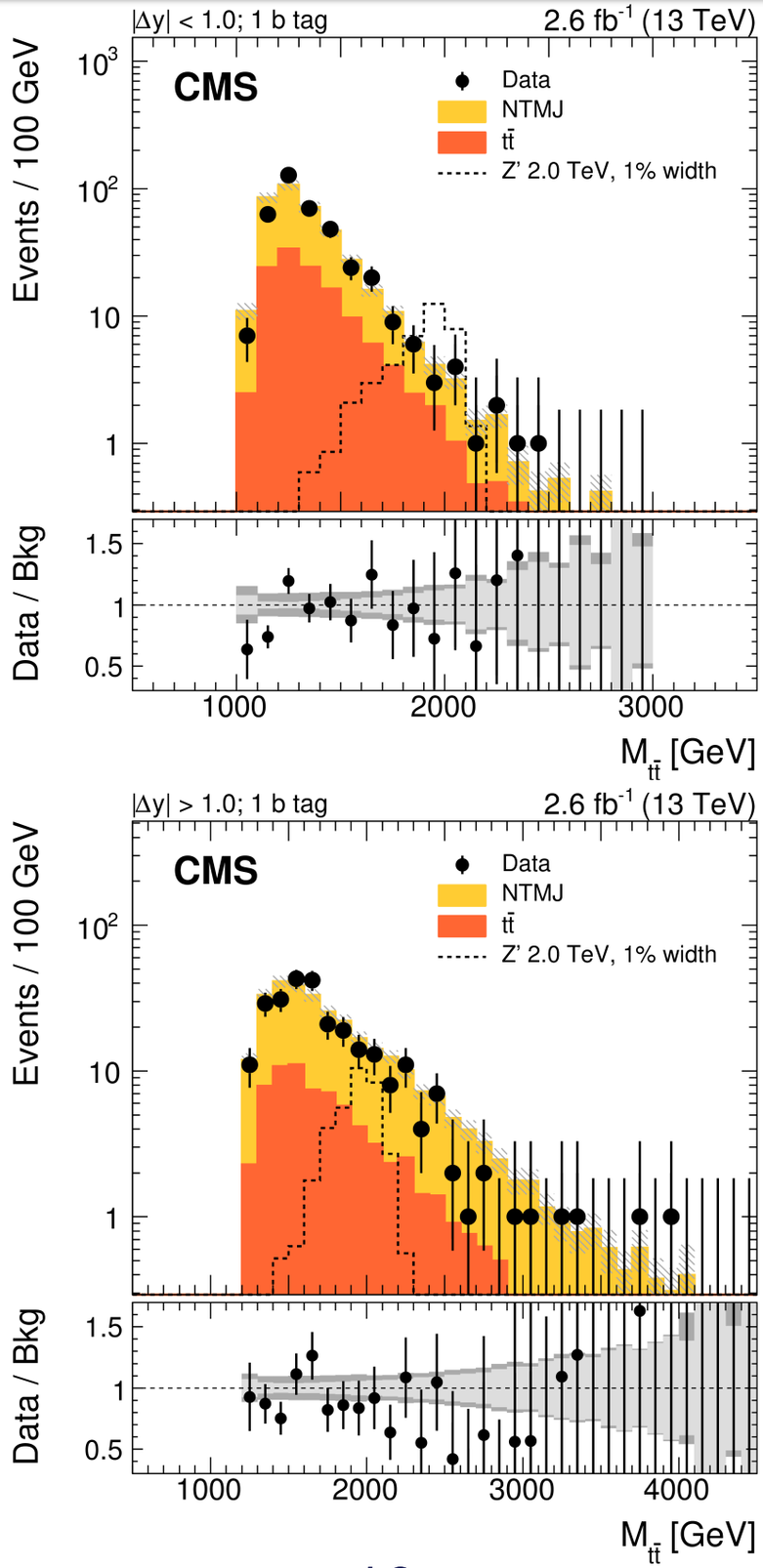

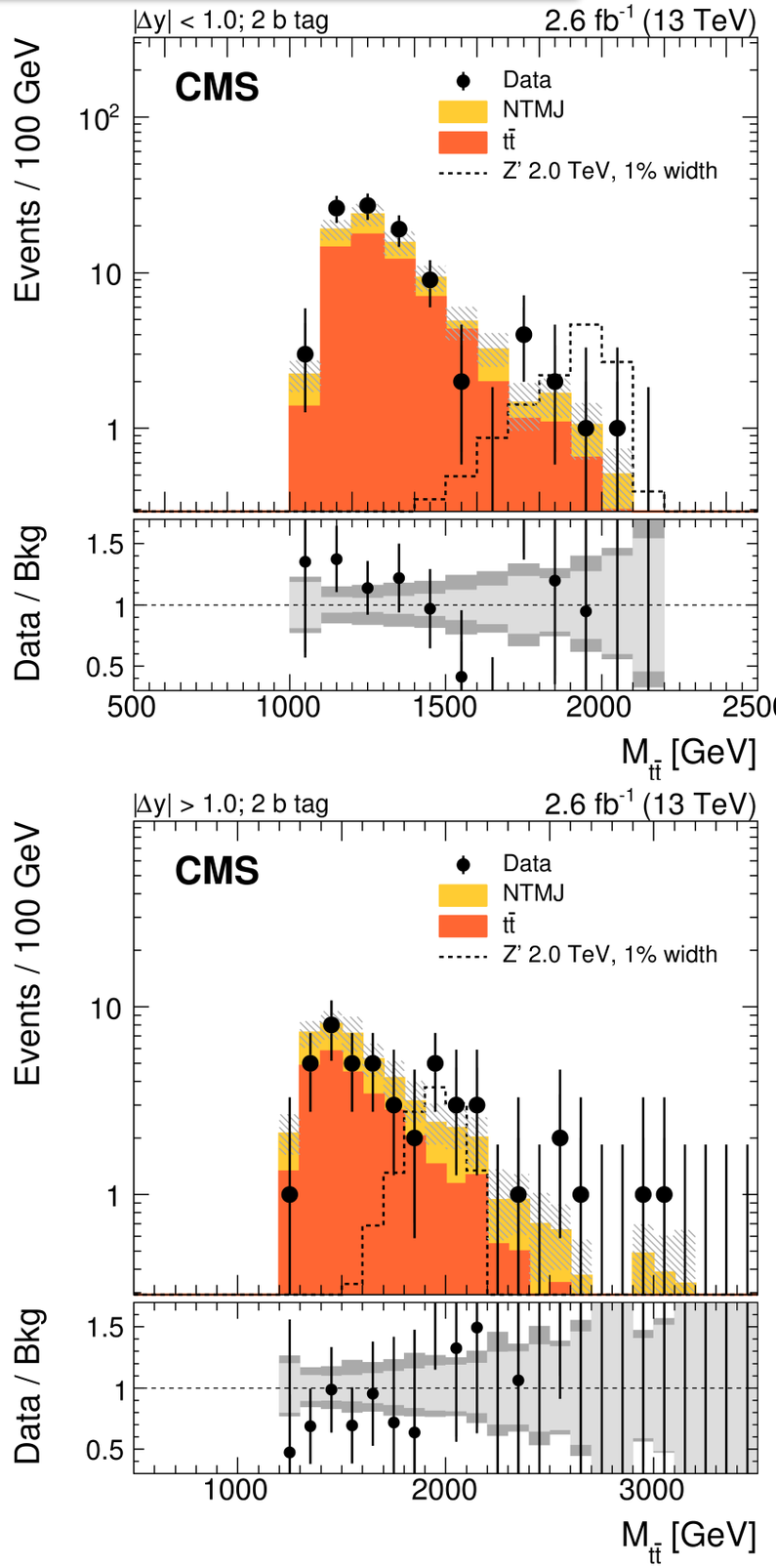

Combined Limits

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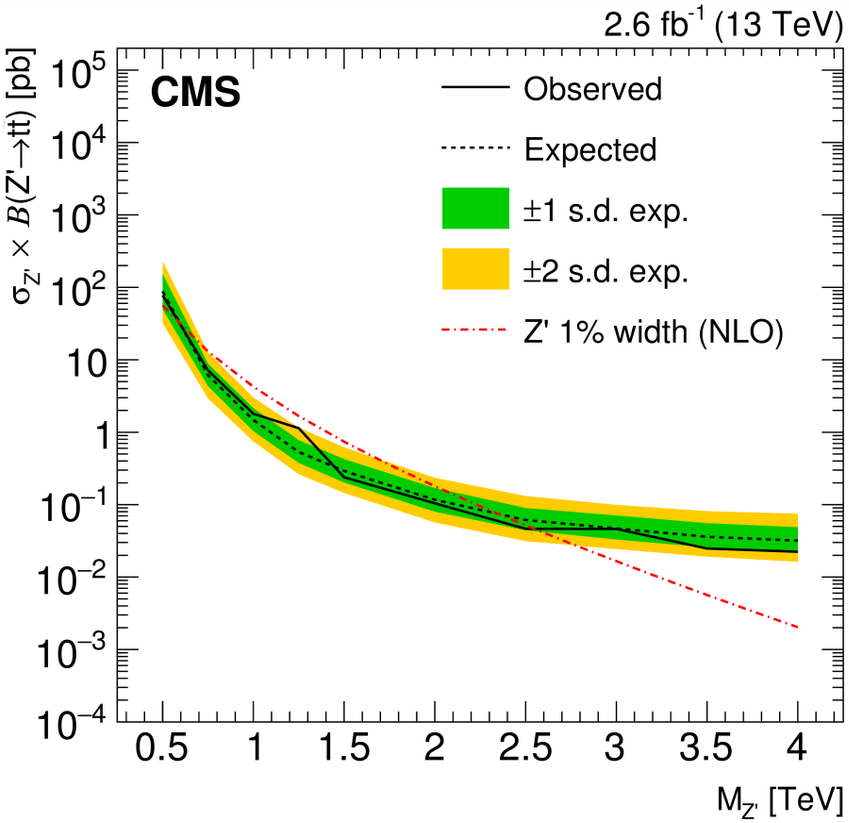
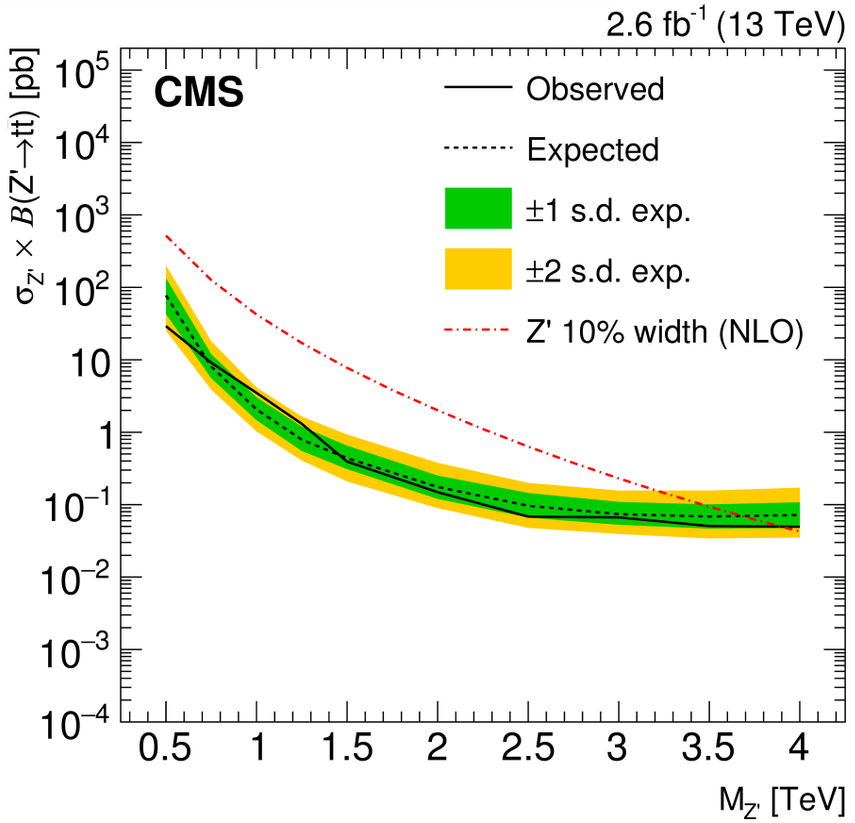
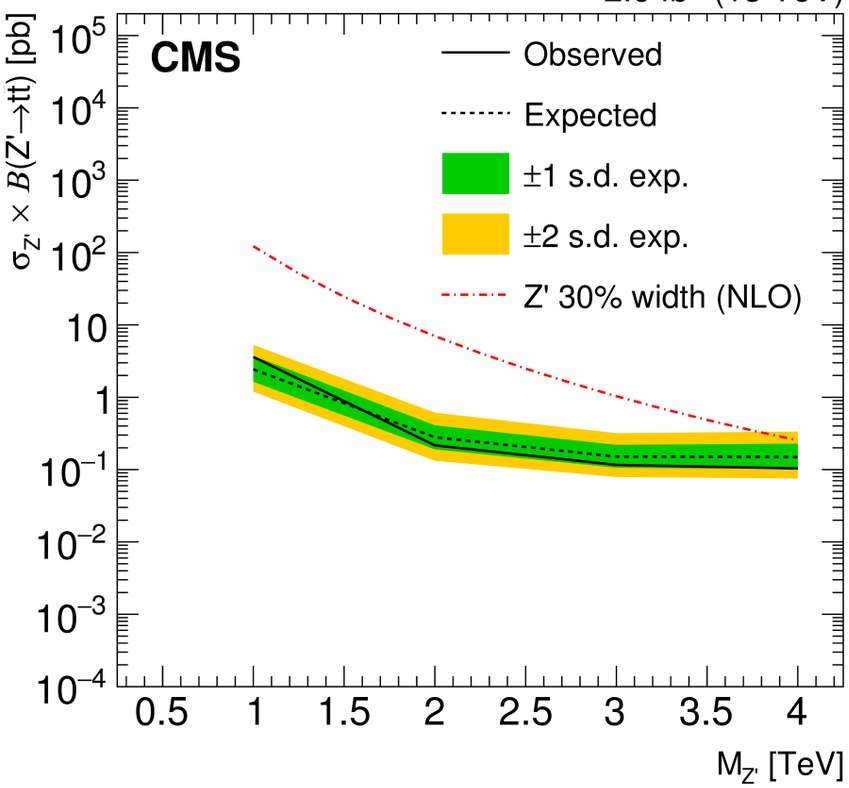
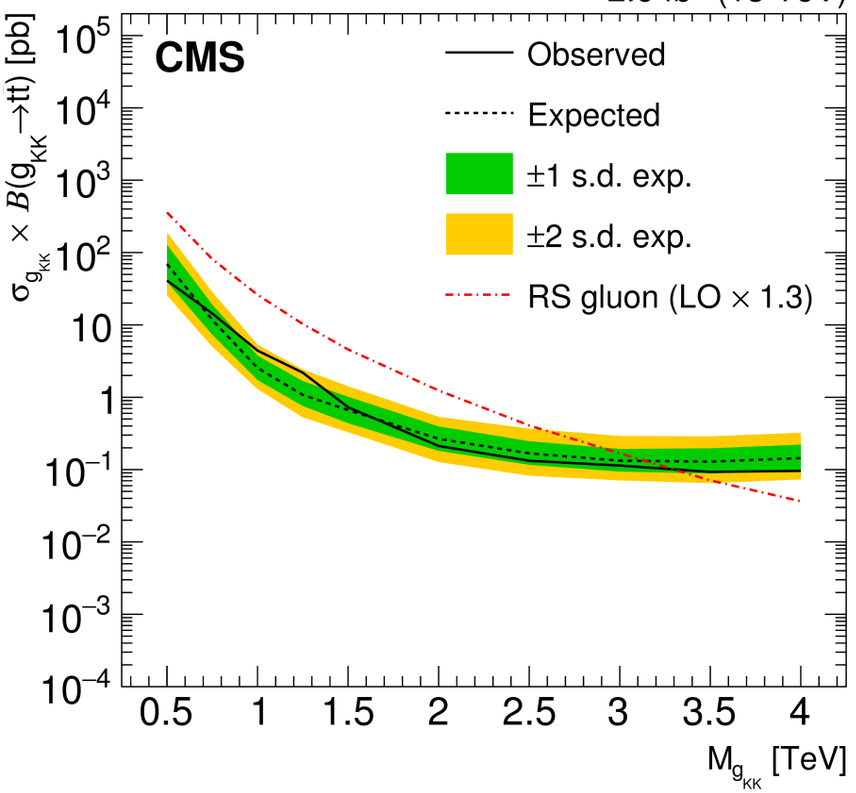
Signal Model	Observed Limit (Exp)
Z′ (Γ/M=1%)	2.5 TeV (2.4 TeV)
Z′ (Γ/M=10%)	3.9 TeV (3.7 TeV)
Z′ (Γ/M=30%)	4.0 TeV (4.0 TeV)
RS Gluon	3.3 TeV (3.1 TeV)









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Future Improvements

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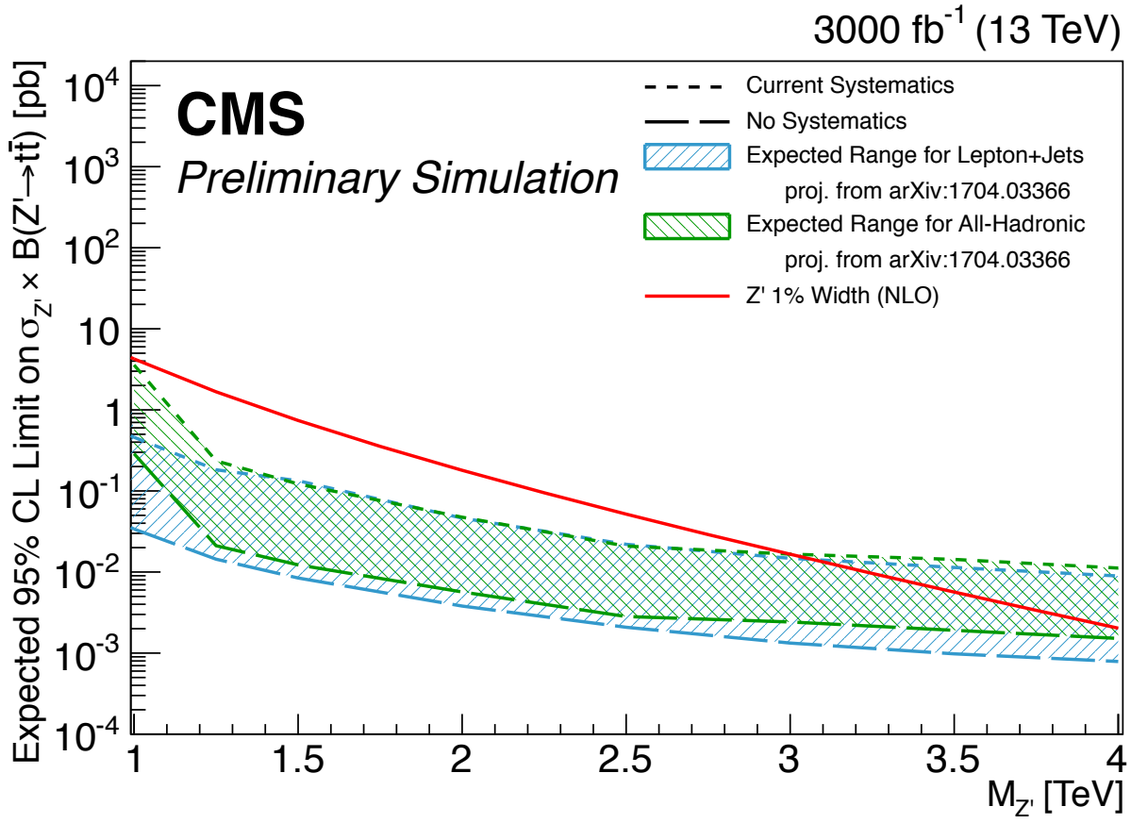
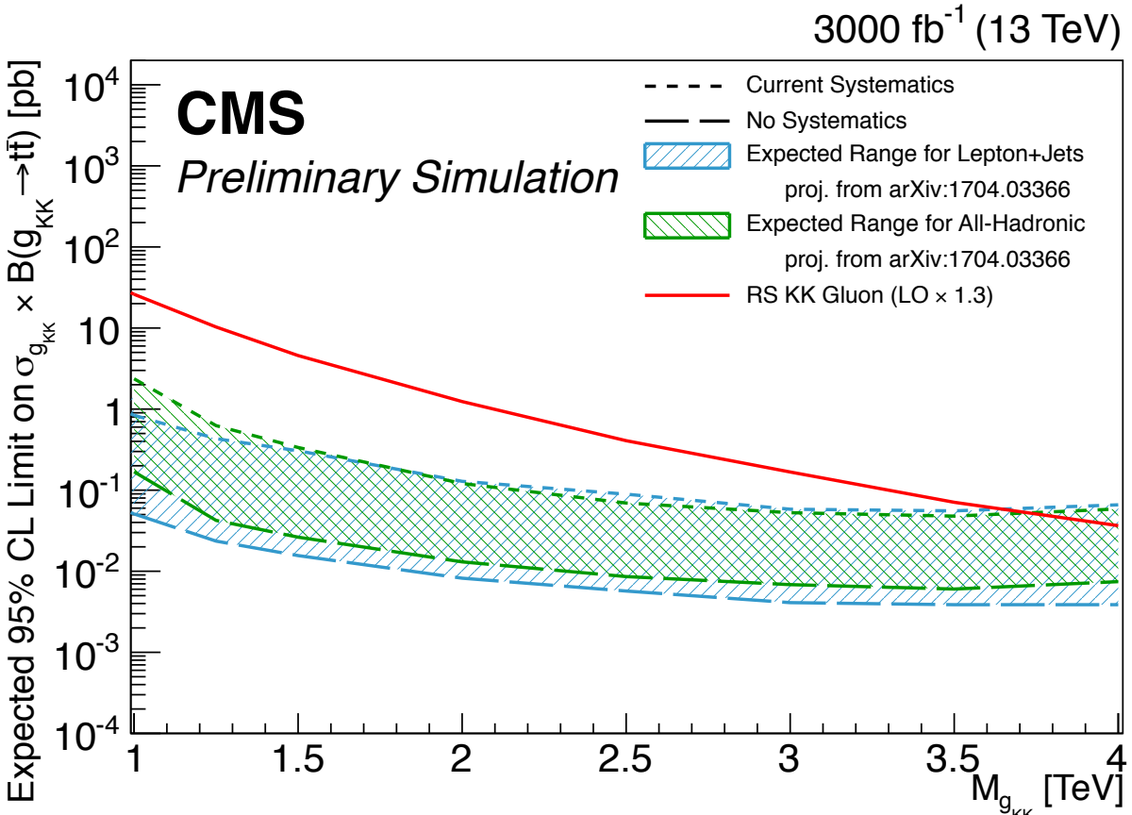
- If there are no analysis improvements, performance becomes systematics limited very quickly
  - 3 TeV exclusion for narrow Z′ and 3.7 TeV exclusion for RS gluon for each channel with 3000 fb^{-1} (CMS-PAS-FTR-16-005)
- Improvements are currently being implemented for the semi-leptonic channel
  - BDT has been created to separate W+Jet and $t\bar{t}$ background from $t\bar{t}$ resonance signal
  - An additional BDT is being created to remove QCD background from the electron channel while keeping $t\bar{t}$ resonance signal
  - Extending the search region up to 5 TeV
- Both the semi-leptonic and all hadronic analysis will be repeated with the full 2016 13 TeV dataset (~36fb^{-1})





Summary

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- A search for a $t\bar{t}$ resonance was presenting using the 2015 13 TeV CMS dataset (2.6 fb^{-1})
  - No excess was seen, so explicit limits were set on a top-color Z′ boson with three different widths (Γ/M = 1.0%, 10%, and 30%) and an RS Gluon
- An improved semi-leptonic analysis and a repeat of the hadronic analysis using the full 2016 13 TeV dataset (~36fb^{-1}) will be made public soon!

	Excluded mass ranges [TeV]							
	Z' ($\Gamma/M = 1\%$)		Z' ($\Gamma/M = 10\%$)		Z' ($\Gamma/M = 30\%$)		RS KK Gluon	
Result	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
Lepton+jets	0.6 – 2.1	0.6 – 2.3	0.5 – 3.5	0.5 – 3.4	0.5 – 4.0	0.5 – 4.0	0.5 – 2.9	0.5 – 2.9
Fully hadronic	1.2 – 1.8	1.4 – 1.8	1.0 – 3.2	1.0 – 3.5	1.0 – 3.7	1.0 – 4.0	1.0 – 2.6	1.0 – 2.4
Combined	0.6 – 2.4	0.6 – 2.5	0.5 – 3.7	0.5 – 3.9	0.5 – 4.0	0.5 – 4.0	0.5 – 3.1	0.5 – 3.3

BACKUP

Top Decay

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$\bar{c}s$				All-Hadronic
$\bar{u}d$				
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	τ + Jets
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	μ + Jets
e^-	ee	$e\mu$	$e\tau$	e + Jets
$W^\pm$ Decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

χ^2 Reconstruction

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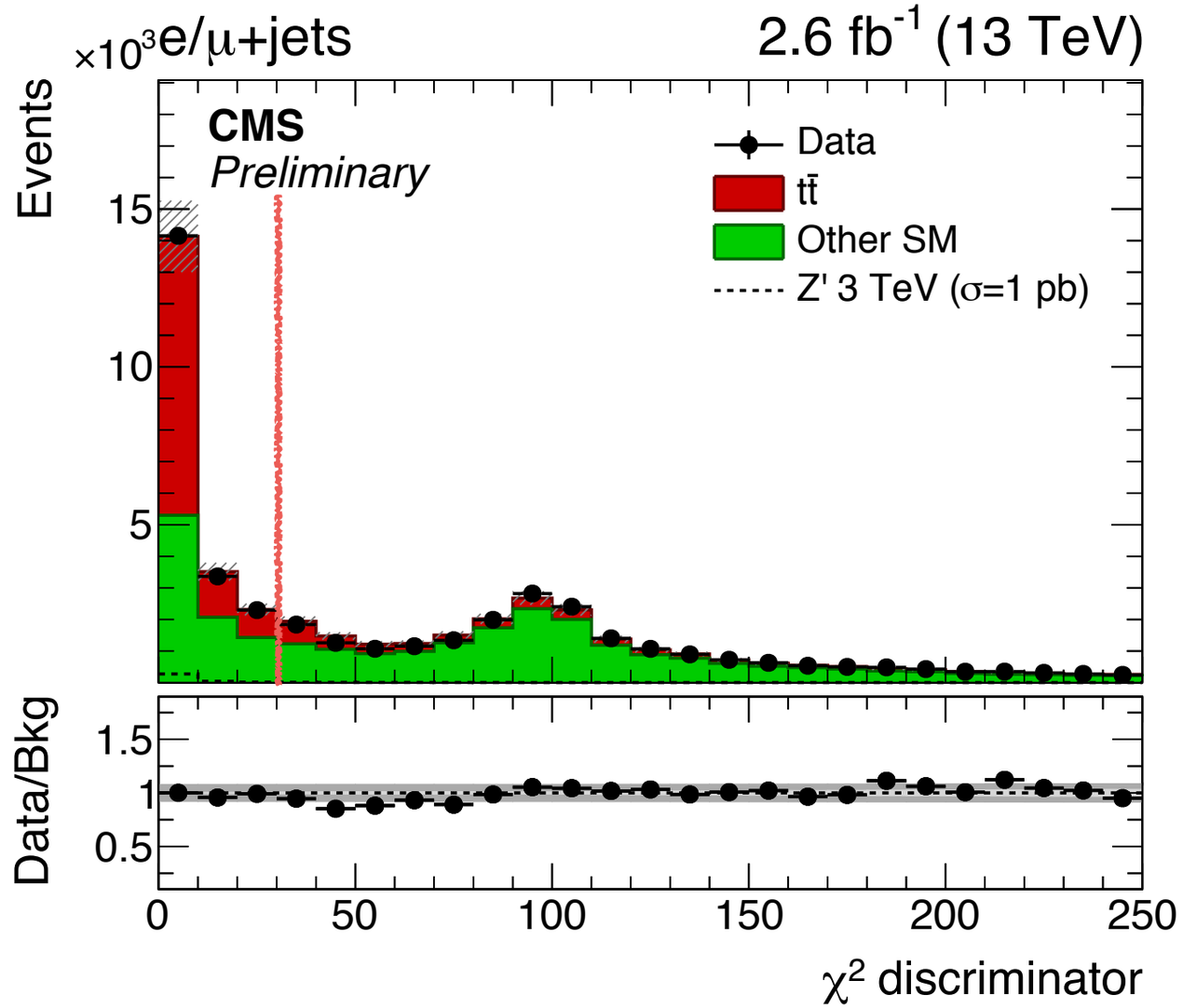
- χ^2 technique used to solve $t\bar{t}$ system
- M_W used to constrain neutrino p_z
  - If both neutrino p_z solutions are complex, then only real part is used
- t-tagged AK8 jet always assigned to hadronic leg
  - Only AK4 jets ($\Delta R > 0.4$) away from the t-tag jet are used for leptonic leg reconstruction
- If no t-tagged jet in the event, then only AK4 jets used in reconstruction in the hadronic leg
- All possible $t\bar{t}$ combinations in the event are tested, but only the minimum is kept
- $\chi^2 < 30$



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

Top Tagging

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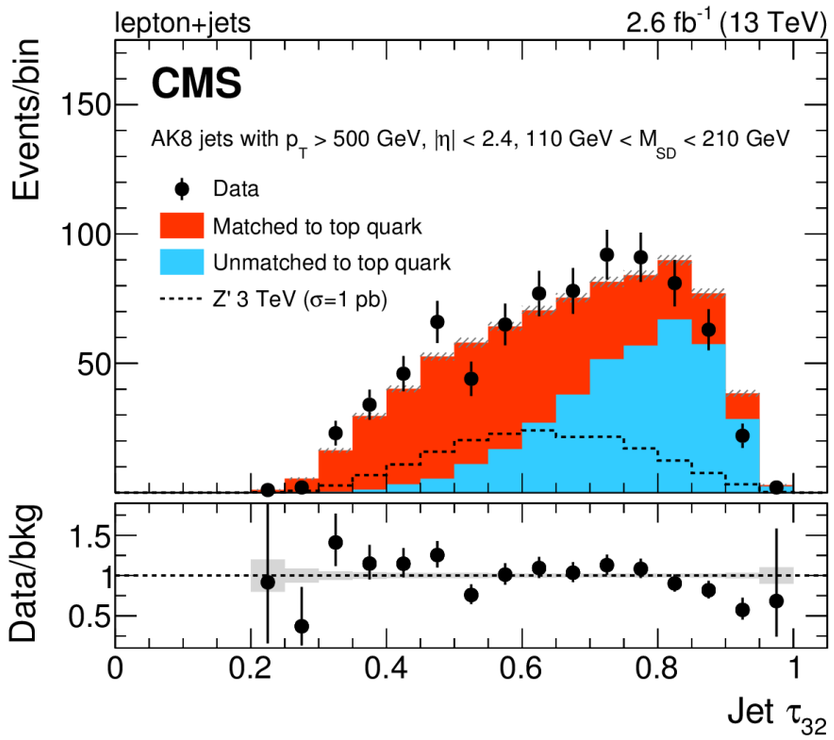
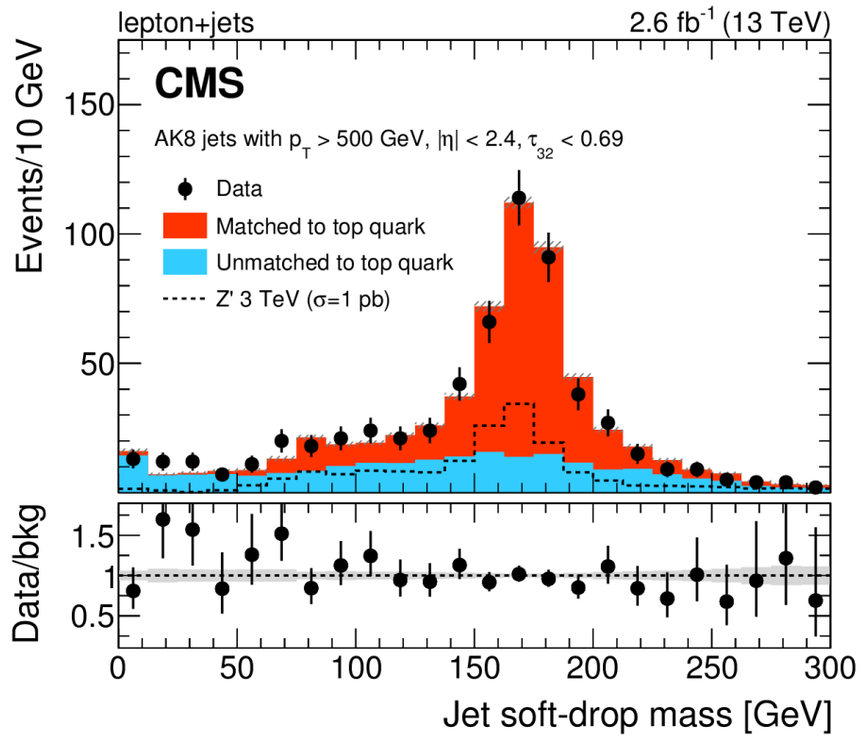
- Top tagging uses two different techniques on 400 GeV AK8 jets
  - Soft-Drop algorithm reclusters the jet into two sub-jets based on ΔR

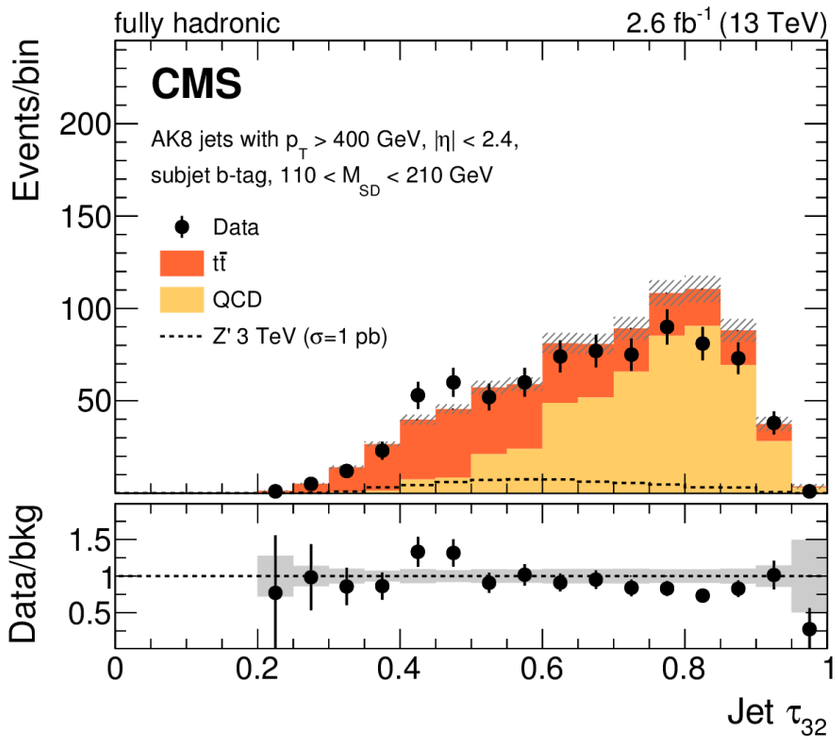
$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \cdot \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

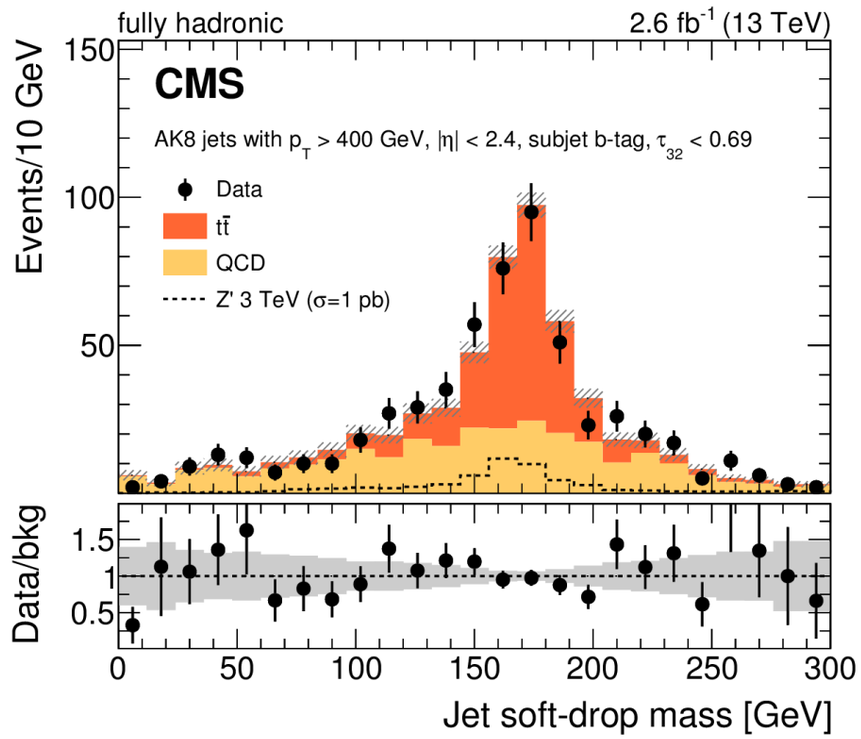
  - Where z = 0.1 and β = 0
  - τ_{32} (τ_3/τ_2) is a χ^2 like quantity that measures the consistency of a jet with the hypothesized number of sub-jets

$$\tau_N = \frac{\sum_{i \in \text{particles}} p_T^i \cdot \min(\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i})}{\sum_{i \in \text{particles}} p_T^i \cdot R_{jet}}$$









Top Tag Mis-tag Rate

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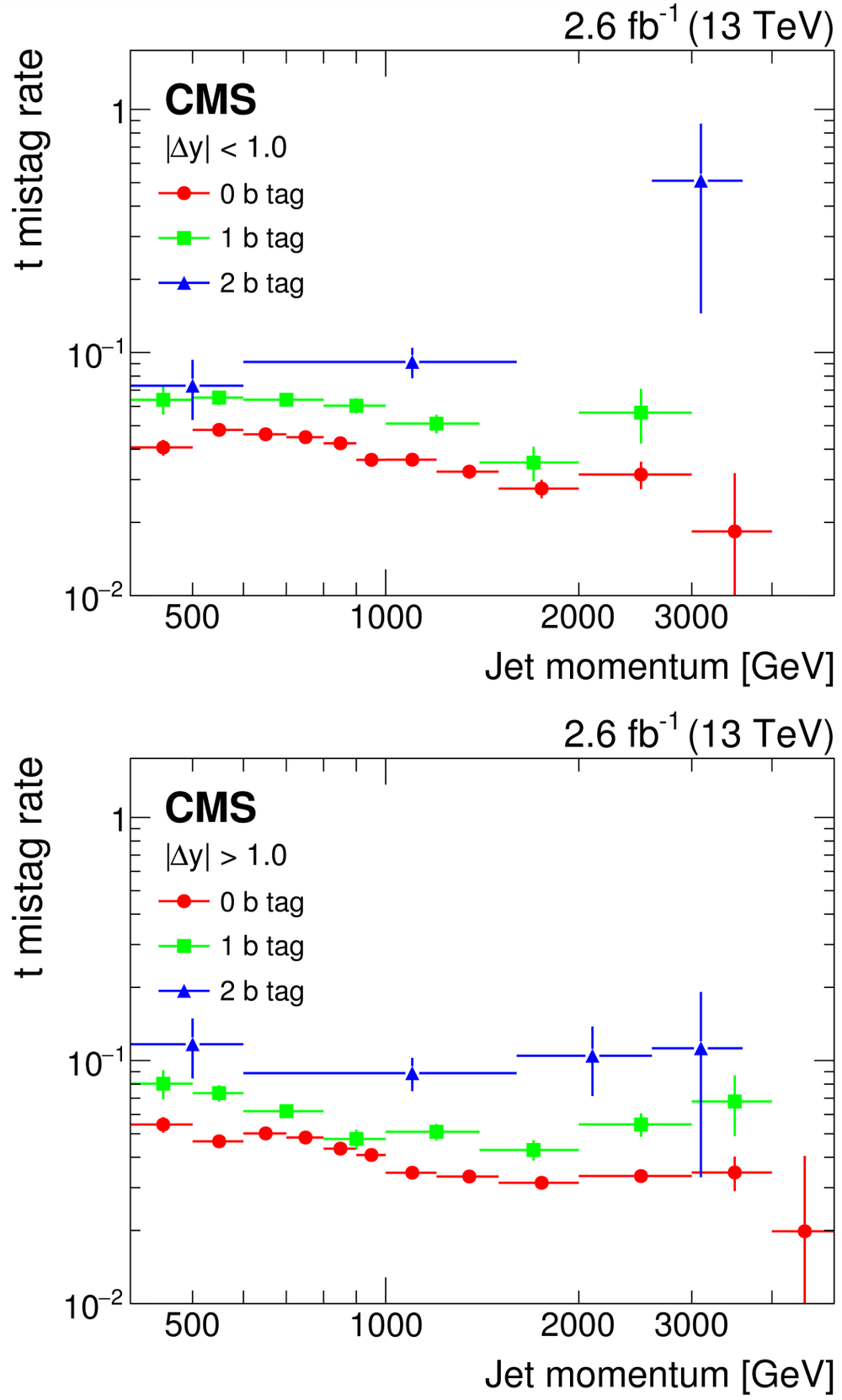
- The mis-tag rate is measured using and anti-top tagged and probe selection
- The mis-tag rate is measured in the all hadronic analysis in all 6 categories
- Contamination from $t\bar{t}$ events is removed by subtracting the simulated $t\bar{t}$ distribution normalized to the standard model cross section



Systematics

	Uncertainty	Channel	
Source	Prior uncertainty	Lepton+jets	Fully hadronic
$t\bar{t}$ cross section	$\pm 8\%$	$\oplus$	$\oplus$
W+jets cross section	$\pm 6\%$	$\odot$	
Z+jets cross section	$\pm 20\%$	$\odot$	
Single-top cross section	$\pm 20\%$	$\odot$	
Diboson cross section	$\pm 20\%$	$\odot$	
Integrated luminosity	$\pm 2.7\%$	$\oplus$	$\oplus$
Pileup modeling	$\pm 1\sigma$	$\oplus$	$\oplus$
Muon identification	$\pm 1\sigma(p_T, \eta)$	$\odot$	
Muon trigger	$\pm 1\sigma(p_T, \eta)$	$\odot$	
Electron identification	$\pm 1\sigma(p_T, \eta)$	$\odot$	
Electron trigger	$\pm 2\%$	$\odot$	
Jet energy scale	$\pm 1\sigma(p_T, \eta)$	$\oplus$	$\oplus$
Jet energy resolution	$\pm 1\sigma(\eta)$	$\oplus$	$\oplus$
Jet b tagging efficiency	$\pm 1\sigma(p_T, \eta)$	$\odot$	
Jet b mistag rate	$\pm 1\sigma(p_T, \eta)$	$\odot$	
Subjet b tagging efficiency	$\pm 1\sigma(p_T, \eta)$		$\odot$
Jet t tagging efficiency	unconstrained	$\oplus$	$\oplus$
Lepton+jets channel t mistag rate	$\pm 19\%$	$\odot$	
Fully hadronic channel t mistag rate	$\pm 1\sigma(p)$		$\odot$
PDFs	$\pm 1\sigma$	$\oplus$	$\oplus$
$t\bar{t}$ matrix element scale	$\pm 1\sigma$	$\oplus$	$\oplus$
$t\bar{t}$ parton shower scale	$\pm 1\sigma$	$\oplus$	$\oplus$
W+jets matrix element scale	$\pm 1\sigma$	$\odot$	
NTMJ background kinematics	$\pm 1\sigma$		$\odot$
NTMJ background closure test	$\pm 1\sigma$		$\odot$

Event Yields

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Semi-leptonic Analysis

μ+jets signal region

Process	1 t tag	0 t tags, 1 b tag	0 t tags, 0 b tags
$t\bar{t}$	218 ± 28	7602 ± 826	1965 ± 229
W+jets (LF)	27 ± 4	547 ± 54	4675 ± 377
W+jets (HF)	4 ± 1	333 ± 30	780 ± 65
Other	9 ± 2	682 ± 111	635 ± 85
Total background	258 ± 29	9164 ± 856	8055 ± 541
Data	252	9230	7966

e+jets signal region

Process	1 t tag	0 t tags, 1 b tag	0 t tags, 0 b tags
$t\bar{t}$	119 ± 15	1016 ± 124	248 ± 32
W+jets (LF)	13 ± 2	97 ± 10	684 ± 58
W+jets (HF)	2 ± 1	44 ± 4	84 ± 8
Other	4 ± 1	103 ± 18	74 ± 10
Total background	138 ± 16	1260 ± 129	1090 ± 78
Data	142	1217	1005

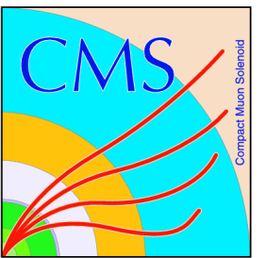
All Hadronic Analysis

$|\Delta y| > 1.0$ signal region

Process	0 b tags	1 b tag	2 b tags
SM $t\bar{t}$	34 ± 4.3	62 ± 5.8	28 ± 3.8
NTMJ	787 ± 6.2	215 ± 4.7	15 ± 1.9
Total background	821 ± 7.5	278 ± 7.4	43 ± 4.2
Data	830	264	46

$|\Delta y| < 1.0$ signal region

Process	0 b tags	1 b tag	2 b tags
SM $t\bar{t}$	66 ± 7.1	121 ± 10	60 ± 7.0
NTMJ	817 ± 8.0	248 ± 7.0	19 ± 1.7
Total background	882 ± 11	369 ± 12	79 ± 7.3
Data	925	387	94



Semi-leptonic Cross Section Limits

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Z′ (Γ/M=1%)

Mass [TeV]	Observed limits [pb]	Expected limits [pb]				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
0.5	77.7	32.1	50	88.2	153	229
0.75	7.14	2.93	4.33	6.14	8.81	12.7
1.0	1.8	0.746	1.04	1.47	2.15	3.01
1.25	1.14	0.264	0.377	0.534	0.778	1.16
1.5	0.239	0.145	0.202	0.291	0.425	0.617
2.0	0.104	0.0568	0.08	0.117	0.17	0.235
2.5	0.0464	0.0314	0.0443	0.0614	0.09	0.132
3.0	0.0462	0.0244	0.033	0.0469	0.0708	0.0992
3.5	0.0248	0.0192	0.0257	0.036	0.0554	0.0813
4.0	0.0224	0.0163	0.022	0.0318	0.0488	0.0749

Z′ (Γ/M=10%)

Mass [TeV]	Observed limits [pb]	Expected limits [pb]				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
0.5	29.1	25.3	42.8	77.4	134	201
0.75	9.12	3.86	5.57	8.06	11.9	18
1.0	3.49	1.03	1.46	2.06	3.02	4.15
1.25	1.31	0.407	0.551	0.789	1.2	1.64
1.5	0.393	0.209	0.31	0.439	0.651	0.929
2.0	0.149	0.0896	0.12	0.176	0.252	0.378
2.5	0.0684	0.0478	0.0663	0.0965	0.145	0.2
3.0	0.0667	0.0394	0.0527	0.0739	0.109	0.156
3.5	0.0507	0.0341	0.0467	0.0686	0.101	0.156
4.0	0.0495	0.0351	0.0476	0.0718	0.108	0.171

Z′ (Γ/M=30%)

Mass [TeV]	Observed limits [pb]	Expected limits [pb]				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
1.0	3.61	1.19	1.64	2.43	3.73	5.27
2.0	0.216	0.133	0.191	0.28	0.409	0.611
3.0	0.116	0.079	0.106	0.151	0.22	0.318
4.0	0.104	0.0754	0.102	0.149	0.228	0.335

RS Gluon

Mass [TeV]	Observed limits [pb]	Expected limits [pb]				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
0.5	41	25.6	39.5	69.3	128	190
0.75	14.4	5	7.34	11.7	19.1	28.5
1.0	4.41	1.3	1.73	2.54	3.77	5.32
1.25	2.18	0.527	0.757	1.08	1.67	2.42
1.5	0.727	0.329	0.438	0.665	1.02	1.42
2.0	0.212	0.127	0.182	0.266	0.396	0.536
2.5	0.132	0.0824	0.117	0.168	0.247	0.368
3.0	0.114	0.0709	0.094	0.133	0.193	0.291
3.5	0.093	0.0651	0.0883	0.129	0.197	0.288
4.0	0.096	0.0732	0.0989	0.144	0.222	0.323